

Machine Learning-enhanced feasibility studies
on the production of new particles with
preferential couplings to third generation
fermions at the LHC

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INTRODUCTION

1

STANDARD MODEL OF PARTICLE PHYSICS

The Standard Model (SM) of particle physics is a quantum field theory (QFT) that describes matter as fermionic particles and their fundamental interactions through the gauge principle. In this framework, force-carrying particles—vector bosons with integer spin, arising from the adjoint representation of symmetry groups (*gauge groups*)—mediate the interactions between matter particles [1, 2]. This elegant formulation unifies three of the four fundamental forces in nature.

In this chapter, we contextualize the SM by introducing the basic concepts of quantum field theory, including the notion of fields and symmetries. We then present the particle content of the SM, its gauge group, and the Lagrangian density that describes its dynamics. The Higgs mechanism and its role in providing mass to the weak gauge bosons and fermions are also discussed. Finally, we address the main deficiencies of the Standard Model and review the experimental evidence that motivates the search for physics beyond the SM.

1.1 FIELDS

Relativistic quantum fields are degrees of freedom in QFT. Formally, they are *operator-valued functions of the spacetime that transform under a representation of the Lorentz group within an invariant subspace* [3, 4]. The different representations of the Lorentz group are mainly characterized by their spin, and their fields obey a different equation of motion (see table 1.1).

In classical field theory, a variational principle is established which generates the equations that govern the dynamics of the different fields in a theory, *the equations of motion*. Hamilton's principle, or principle of minimal action, indicates that all possible physical configurations for a set of fields φ^I , with $I = 1, 2, 3, \dots, n$, are those where the integral of the action S is a minimal [5, 6]:

$$S = \int \mathcal{L}(\varphi^I, \partial_\mu \varphi^I) d^4x, \quad (1.1)$$

here, $d^4x = dx^0 dx^1 dx^2 dx^3$ and $x \equiv (ct, x^1, x^2, x^3) \equiv (x^0, x^1, x^2, x^3) \in \mathcal{M}^4$ are the space-time coordinates in the Minkowskian spacetime \mathcal{M}^4 , and the function $\mathcal{L}(\varphi^I, \partial_\mu \varphi^I)$ is called *the Lagrangian density* of a theory [1, 5]. The problem in classical field dynamics is to find the functions $\varphi^I(x)$ in

a space-time \mathcal{M}^4 , fixing their boundary conditions. The solution to this classical problem is given by the Euler-Lagrange equations:

$$\frac{\partial \mathcal{L}}{\partial \varphi^I} - \frac{\partial}{\partial x^\mu} \frac{\partial \mathcal{L}}{\partial (\partial_\mu \varphi^I)} = 0, \quad (1.2)$$

and they are used to obtain the equations of motion of the set of fields φ^I [6].

In quantum field theory, the situation is more complicated: if we adopt the approach of quantization by path integrals [7, 8], the idea of an equation of motion vanishes and we go on to searching correlations between free particle states. However, the notion of action remains the cornerstone in the description of these observables. Explicitly, the correlation functions are calculated through the LSZ formula from the path integral [9, 10]:

$$\begin{aligned} Z[J] &= \langle \text{out}, 0 | 0, \text{in} \rangle \\ &= \mathcal{N} \int \mathcal{D}(\varphi, \bar{\varphi}) e^{iS[\varphi]} e^{i \int J_1 \varphi^I d^4x} \\ &= \mathcal{N} \int \mathcal{D}(\varphi, \bar{\varphi}) e^{i \int d^4x \mathcal{L}} e^{i \int J_1 \varphi^I d^4x}, \end{aligned} \quad (1.3)$$

taken over the space of fields φ with an appropriate measure $\mathcal{D}(\varphi, \bar{\varphi})$ and normalized by \mathcal{N} . The quantity Z is known as the partition function of the theory and gives the transition amplitude from the initial vacuum $|0, \text{in}\rangle$ to the final vacuum $|0, \text{out}\rangle$ in the presence of a source $J(x)$ producing particles [11]. Therefore, the dynamics, at both the classical and quantum levels, in a theory are entirely determined by the Lagrangian density. Table 1.1 records the Lagrangian density for different types of free fields, i.e., non-interacting fields.

Name	Field	Spin	Free-Lagrangian
Klein-Gordón	ϕ	0	$\mathcal{L} = (\partial^\mu \bar{\phi} \partial_\mu \phi - m^2 \bar{\phi} \phi)$
Dirac	χ	1/2	$\mathcal{L} = \bar{\chi} (i \gamma^\mu \partial_\mu - m \mathbf{1}) \chi$
Maxwell	A^μ	1	$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu}$

Table 1.1: Some relevant representations of the Lorentz group in 4-dimensional space-time. In this notation $\eta_{\mu\nu} = \text{diag}(1, -1, -1, -1)$, γ^μ are the Dirac matrices, $F_{\mu\nu}^A = \partial_\mu A_\nu^A - \partial_\nu A_\mu^A + g f_{BC}^A A_\mu^B A_\nu^C$ is the field strength (for abelian groups, the last term vanishes), and the array of real numbers f_{AB}^C are the structure constants of the gauge group algebra [12]. All equations are written in natural units with $c = \hbar = 1$. Fields are shown in their standard representations.

In this paradigm, our task is to propose a Lagrangian density for a set of fields that correctly models the propagation and interactions of fundamental particles.

1.1.1 INTERACTIONS AND SYMMETRIES

In quantum field theory, the form of the Lagrangian density is not arbitrary: it is shaped by a small set of physical and mathematical principles. These

principles act as “rules” that guide the construction of consistent theories, ensuring both their internal consistency and their predictive power. In particular, if we want a relativistic and renormalizable theory, the Lagrangian must satisfy several conditions that strongly restrict the kind of terms that can appear.

To begin with, relativistic invariance demands that the equations of motion look the same in all inertial frames. This requirement is implemented by asking the action to be invariant under Poincaré transformations [13]. Equivalently, the Lagrangian density must transform as a Lorentz scalar and may change under translations at most by a total derivative [6].

Another basic condition is Hermiticity: the Lagrangian density must be Hermitian so that observables are real and the time evolution of the theory is unitary [10, 13]. In addition, dimensional analysis places further restrictions. In natural units, \mathcal{L} carries dimensions of [mass]⁴ (an energy density). This means that the interaction terms that we can add must be such that the overall operator has the correct dimension, which already rules out many possibilities.

In quantum field theory, loop corrections to scattering amplitudes typically produce divergences. A theory is called renormalizable if all these divergences can be absorbed into a redefinition of a *finite set* of physical parameters (such as masses and couplings). In practice, this requirement translates into a restriction on the operators that may appear in the Lagrangian: only terms of mass dimension ≤ 4 lead to renormalizable interactions. Higher-dimensional operators are still allowed, but they correspond to *effective* interactions that are suppressed at low energies and signal the presence of new physics at higher scales [8, 10].

A classical symmetry of the Lagrangian may not always survive the process of quantization. If it fails to do so, it is said to be anomalous. Chiral anomalies, specifically, arise from the regularization of fermion loops in triangle diagrams and can break the gauge symmetry at the quantum level. Since the gauge symmetry is the very principle that dictates the form of interactions and removes unphysical states, its violation would destroy the renormalizability and unitarity of the theory. Therefore, the particle content must be carefully chosen so that these potential anomalies cancel amongst the fermions, a non-trivial condition famously satisfied by the quarks and leptons of the Standard Model.

Furthermore, the stability of the vacuum is a prerequisite for a physically meaningful theory. This is ensured by demanding that the scalar potential, which governs the self-interactions of the Higgs field, is bounded from below. If the potential were unbounded, it would imply that the system could lower its energy indefinitely by rolling down the potential to field values of ever-greater magnitude, meaning no stable ground state could exist. For a renormalizable potential, this stability condition typically translates into the requirement that the quartic coupling constant $\lambda > 0$. However, this condition must hold not just at tree-level but also at the

In QFT, Poincaré invariance is assumed to be global. Promoting it to a local symmetry leads to gravity, with spin-2 fields (the graviton) as mediators. Perturbatively, such a theory is not renormalizable, so it lacks predictivity at high energies, although it can still be understood as an effective field theory.

quantum level, as running couplings can change sign at different energy scales, potentially leading to metastability or instability of the vacuum.

Summarizing, the main constraints that a relativistic and renormalizable Lagrangian density must satisfy are:

- **Poincaré (global) invariance:** the action must be invariant under Lorentz transformations and translations; the Lagrangian density is a Lorentz scalar and may change by at most a total derivative [6, 13].
- **Hermiticity:** \mathcal{L} must be Hermitian to ensure real observables and unitary evolution [10, 13].
- **Mass dimension:** in natural units, \mathcal{L} has dimension [mass]⁴; interaction terms must be constructed accordingly.
- **Renormalizability:** demanding perturbative renormalizability restricts operators to dimension ≤ 4 , which in practice allows interactions built out of fields with spin 0, 1/2, or 1 and couplings of non-negative mass dimension [8, 10].
- **Absence of chiral anomalies:** gauge symmetries must be free of chiral (gauge) anomalies to ensure the consistency and unitarity of the quantum theory [8, 10, 14]. In the Standard Model, the particle content is such that all gauge anomalies cancel exactly.
- **Stability of the potential:** the scalar potential must be bounded from below to guarantee the existence of a stable vacuum state. This typically requires that the quartic couplings in the potential are positive at the relevant energy scales.

These constraints drastically reduce the number of possible terms in the Lagrangian. As a result, the renormalizable interaction structures that typically arise are limited to: Yukawa couplings between fermions and scalars, scalar self-interactions (up to quartic order), and gauge interactions between matter fields and vector bosons.

At this point, we seem to have total freedom to mix these terms as possible interactions. However, the concept of symmetry has proven to be our most powerful ally for the construction of terms of interaction between fields. The procedure turns out to be simple; once a set of spin 0 and spin 1/2 fields has been established as part of the theory, these are organized to transform under a representation of a unitary gauge group G such that the Lagrangian density must be a global scalar of G . Then, once the global Lagrangian density is known, it is sought to “promote” symmetry to a local symmetry by a slight modification of associated kinematic terms [2, 12, 15–17]. This “promotion” is described in more detail below.

Given a Lagrangian density $\mathcal{L}(\phi_i, \partial_\mu \phi_i)$, a given field ϕ is said to be *globally symmetric* under unitary transformations, $\phi_i \mapsto U_G(\phi_i)$, if the action is invariant under the variations of the fields ϕ^I which are given, at infinitesimal level, by:

$$\delta_G(\theta)\phi^I \approx i\theta^\Lambda(T_A)_J^I \phi^J, \quad (1.4)$$

where θ^A are the parameters of the transformation \mathcal{U} and T_A are the representations of the generators of a unitary continuous group G . This considers an expansion of U at first order in θ^A . This group, G , supports unitary representations of the shape:

$$\mathcal{U}_G \doteq U(\theta) = \exp(i\theta^A T_A). \quad (1.5)$$

The operators T_A satisfy a commutation relation according to the Lie algebra:

$$[T_A, T_B] = if_{ab}^C T_C, \quad (1.6)$$

where f_{AB}^C are the structure constants of G .

If invariance under local symmetry is desired, it is required to replace all the space-time derivatives ∂_μ that appear in \mathcal{L} by a new type known as *covariant derivatives* \mathcal{D}_μ , which implicitly brings the coupling of the given fields with new fields B_μ , known as *gauge fields*:

$$\partial_\mu \rightarrow \mathcal{D}_\mu = \partial_\mu - \delta_G(B_\mu) \implies \mathcal{L}(\varphi_i, \partial_\mu \varphi_i) \rightarrow \mathcal{L}(\varphi_i, \mathcal{D}_\mu \varphi_i; B_\mu). \quad (1.7)$$

Term $\delta_G(B_\mu)$ is called *connection* and it introduces a *gauge field* B_μ^A for each generator T_A of G (note that $\delta_T(B_\mu) \equiv iB_\mu^A T_A$). The covariant derivative is defined such that its transformation is of the form

$$\mathcal{D}'_\mu = U \mathcal{D}_\mu U^\dagger, \implies \mathcal{D}_\mu(\varphi) \rightarrow U \mathcal{D}_\mu(U^\dagger \varphi). \quad (1.8)$$

For this, it is enough that B_μ^C transforms as

$$\delta_G(\theta) B_\mu^C = \theta^A f_{AB}^C B_\mu^B + \partial_\mu \theta^C. \quad (1.9)$$

Since additional fields have been introduced, and, in order to implement local symmetry, it is necessary to construct a kinetic Lagrangian for such fields. Following the ideas of Yang and Mills based on the antisymmetric curvature tensor which is defined as

$$F_{\mu\nu}^C T_C = F_{\mu\nu} = -[\mathcal{D}_\mu, \mathcal{D}_\nu] = (\partial_\mu B_\nu^C - \partial_\nu B_\mu^C + f_{AB}^C B_\mu^A B_\nu^B) T_C, \quad (1.10)$$

and with it the kinetic Lagrangian for gauge fields is generalized as:

$$\mathcal{L} = -\frac{\delta_{AB}}{4g^2} F_{\nu\mu}^A F^{\nu\mu B},$$

where g is known as the gauge coupling constant which indicates the strength of the interaction. Usually, the gauge fields are rescaled so that the coefficient of the kinetic term is 1/4 and g appears in the covariant derivative.

Example

As a way of illustration let us consider a renormalizable theory with a real scalar ϕ and a Dirac spinor ψ so that both are non-interacting, and suppose that this theory is globally invariant under phase transformations,

i.e. the fields $\varphi \in \{\phi, \psi\}$ transform as $\varphi \mapsto e^{i\theta \hat{Q}}\varphi$ such that $\hat{Q}\psi = q\psi$ and $\hat{Q}\phi = 0\phi = 0$. The free lagrangian density for the real scalar field and the Dirac field is

$$\mathcal{L}_{\text{free}} = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}m^2\phi^2 + \bar{\psi}(i\gamma_\mu\partial^\mu - m)\psi \quad (1.11)$$

If we want to add globally symmetric interaction terms, the scalar potential must be an expansion in the fields of order four at maximum, so that it remains renormalizable. The linear term of the potential does not contribute to the action, and the quadratic term of the potential is contained by the mass term. Whereas, a fermionic potential is not allowed since the only term renormalizable is precisely the term of mass. A cross term is allowed $\sim \phi\bar{\psi}\psi$, which is called *Yukawa coupling*, then the globally invariant Lagrangian is

$$\begin{aligned} \mathcal{L}_{\text{global}} &= \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) + \bar{\psi}(i\gamma_\mu\partial^\mu - m)\psi + k_1\phi\bar{\psi}\psi, \\ V(\phi) &= \frac{m^2}{2!}\phi^2 + \frac{\alpha}{3!}\phi^3 + \frac{\lambda}{4!}\phi^4. \end{aligned} \quad (1.12)$$

Promoting to local,

$$\mathcal{L}_{\text{local}} = \frac{1}{2}\mathcal{D}^\mu\phi\mathcal{D}_\mu\phi - V(\phi) + \bar{\psi}(i\gamma_\mu\mathcal{D}^\mu - m)\psi + k_1\phi\bar{\psi}\psi - \frac{1}{4g^2}F_{\mu\nu}F^{\mu\nu}, \quad (1.13)$$

where,

$$\mathcal{D}_\mu\varphi = (\partial_\mu - igA_\mu\hat{Q})\varphi \implies \begin{cases} \mathcal{D}_\mu\phi = \partial_\mu\phi, \\ \mathcal{D}_\mu\psi = \partial_\mu\psi - igqA_\mu\psi. \end{cases} \quad (1.14)$$

With these ingredients and principles, we are now equipped to understand the structure of the Standard Model Lagrangian, which will be discussed in the next section.

1.2 STANDARD MODEL

Fragment extracted and adapted from [18]

To contextualize the SM let me place us in 1965. Tomonaga, Feynman, and Schwinger have just won the Nobel prize for their independent contributions on the development of the Quantum Electrodynamics theory [19]. They calculated the magnetic moment of the electron and other observables using quantum field theory and renormalization to separate out the infinities of the theory from a finite contribution [20] showing that renormalized gauge theories agree with experiment up to very high precision (to more than 13 significant digits)[21].

Unfortunately, in 1965, the models explaining radioactive decay and the strong interaction were not renormalizable. The leading theory was

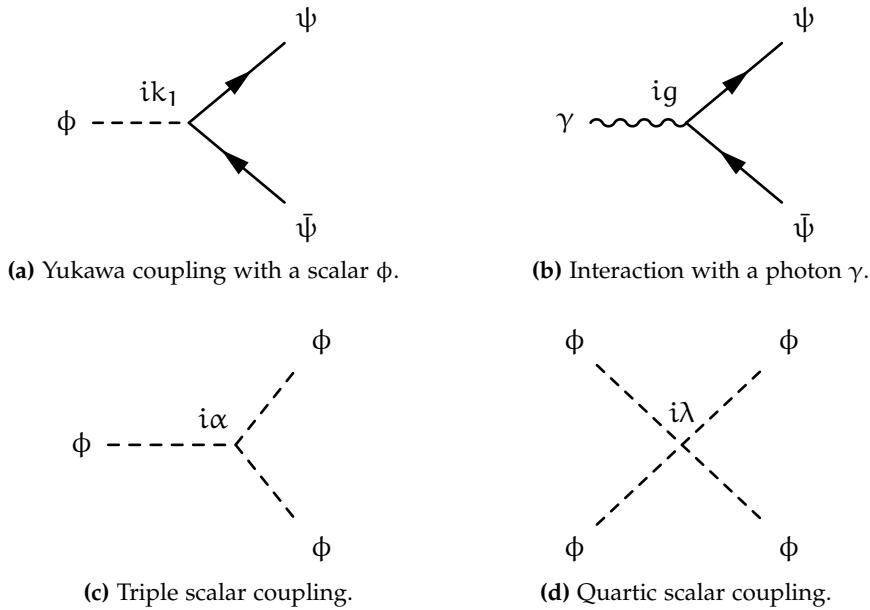


Figure 1.1: Feynman diagrams for Yukawa coupling, gauge boson coupling and quartic scalar coupling.

called *the chiral V – A universal model of weak decays* featuring four-fermion interactions in the combination of vector minus axial currents. The $V - A$ model could not be mathematically broken down into a finite and an infinite component. Although gauge theory and renormalization explained the interaction of electrons with photons, gauge theory was not able to address the strong and weak forces. These forces were known to be short-range forces. To make a force have a short range in QFT, the mediating boson needed a mass. The Yukawa theory of scalar fields included such a term as an early model for the strong force with short range. The force law then fell off as $\exp(-rm)/r^2$ with both the classic inverse square law multiplied by an exponential dampening with distance parameterized by the mass m . To give a gauge boson A_μ a short range, the Lagrangian would need a mass term such as $m_A^2 A_\mu A^\mu$. This term violates gauge symmetry because when $A \mapsto A_\mu + \epsilon_\mu$ we see that $A_\mu A^\mu \neq A'_\mu A'^\mu$. Naively, one would think that gauge symmetry blocks all gauge bosons from having mass; and therefore, all gauge theories (Abelian and the non-Abelian ones) would obey force laws that scale as $1/r^2$. This would mean that all gauge theories would represent long-range forces similar to gravity and electromagnetism (each of which is mediated by a massless boson)¹. There are two known solutions to this quandary:

¹ In 1954 when Yang was first giving a presentation on non-Abelian gauge theories, Pauli interrupted the talk. Pauli wanted to know what the mass of the non-Abelian gauge boson was. Pauli was so insistent that Yang eventually sat down. Pauli realized that a mass term violated gauge symmetry; the mass terms were needed for short-range forces; non-Abelian gauge theories seemed like they should have long-range forces; and therefore, they probably do not explain strong or weak forces. In short, people no less than Pauli felt gauge symmetry's properties made them unlikely candidates for the a short-range force needed to explain the strong and weak forces [18]

1. The Higgs mechanism which gives renormalizable gauge bosons mass without violating gauge symmetry.
2. A spontaneously created mass gap phenomena associated with non-Abelian gauge theories, which is not fully understood yet, and seems to be related to the confinement of individual quarks.

The SM chooses (1) the Higgs mechanism for the weak force, and (2) for QCD.

1.2.1 PARTICLE CONTENT AND GAUGE GROUP

First, let us talk about the chiral nature of particles: Massive half-spin particles are described at the fundamental level by a Dirac spinorial field, see table 1.1. However, Dirac spinors do not transform under an irreducible representation of the Lorentz group. Spinors can be decomposed into two components that do transform under irreducible representations of the Lorentz group: two *Weyl spinors*. The left and right chiral projectors, P_L and P_R , take a Dirac spinor and project it onto each of these invariant subspaces. For a massless Dirac spinor, the left and right components are dynamically decoupled, *i.e.* which are independent fields obeying independent Lagrangian densities; for example, the left component of a massless spinor has the Lagrangian $\mathcal{L} = -i\bar{\psi}\not{D}\psi$ (For more details see Appendix A at [4]).

The discovery of parity asymmetry in radioactive decays [22] indicates that the chiral description of weak interactions couples differently to the left and right chiral components of half-spin particles. Indeed, the chirality of the fermionic spectrum is possibly one of the deepest properties of the Standard Model. Describing particles in terms of Dirac spinors, it means that left- and right-chirality components actually have different EW quantum numbers. This is compatible with a gauge symmetry only if half-spin particles are considered to be massless, at least without a Dirac mass $m\bar{f}_R f_L + h.c.$ Nevertheless, half-integer spin fundamental particles, such as the electron, have a well-measured mass. Therefore, the reconciliation of chiral asymmetry and mass lies in the Higgs mechanism, where the masses of the particles result from an effective Yukawa coupling with a scalar, the Higgs boson.

With this in mind, the SM has a content of matter fields from three generations (or families) of quarks q and leptons ℓ , described as Weyl 2-component spinors, with the structure

$$q_L = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}, u_R^i, d_R^i, \quad \ell_L = \begin{pmatrix} v_L^i \\ e_L^i \end{pmatrix}, e_R^i; \quad i = 1, 2, 3. \quad (1.15)$$

All these particles transform under a group $U(1)$ with different associated (hyper)charges. The doublets formed by the left components of the fields transform under the representation of two components of a $SU(2)$ group. The right components do not transform under $SU(2)$, therefore they are

singlets. In addition, each quark in q_L^i transforms as color triplets under $SU(3)$, while u_R^i, d_R^i transforms as conjugate triplets. Leptons, on the other hand, turn out to be colored singlets. Gauge quantum numbers of the Standard Model fermions are shown in table 1.2.

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{EM}$
$q_L^i = (u^i, d^i)_L$	3	2	+1/3	(2/3, -1/3)
u_R^i	3	1	+4/3	+2/3
d_R^i	3	1	-2/3	-1/3
$\ell_L^i = (\nu^i, e^i)_L$	1	2	-1	(0, -1)
e_R^i	1	1	-2	-1
$H = (H^+, H^0)$	1	2	+1	(+1, 0)

Table 1.2: Gauge quantum numbers of Standard Model quarks, leptons and the Higgs scalar.

Then, we consider the Standard Model as a quantum field theory based on a gauge group

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y, \quad (1.16)$$

with $SU(3)_C$ describing strong interactions via Quantum Chromodynamics (QCD), and $SU(2)_L \times U(1)_Y$ describing electroweak (EW) interactions. Gauge vector bosons that result from taking this group locally are eight gluons (G^a) from each t^a color-generator of $SU(3)_C$, and a linear combination of the three (W^\pm, Z) weak bosons and the (γ) electromagnetic photon from the three T^i isospin-generators of $SU(2)_L$ and Y hyper-charge-generator of $U(1)_Y$.

Electroweak symmetry is spontaneously broken into electromagnetic symmetry $U(1)_{EM}$ via the Higgs mechanism and the Higgs boson H . The hypercharges Y of the Standard Model fermions in table 1.2 are related to their usual electric charges by the Gell-Mann–Nishijima relation [23]

$$Q_{EM} = \frac{1}{2} Y + T_3, \quad (1.17)$$

where $T_3 \doteq \text{diag}(\frac{1}{2}, -\frac{1}{2})$ is an $SU(2)_L$ generator. Thus, they reproduce electric charge quantization, e.g. the equality in magnitude of the proton and electron charges. Although these hypercharge assignments look rather ad hoc, their values are dictated by the quantum consistency of the theory ².

² It is indeed easy to check that these are (modulo an irrelevant overall normalization) the only (family independent) assignments canceling all potential triangle gauge anomalies.

1.2.2 GAUGE BOSONS

The Lie algebra of the gauge group $SU(3) \times SU(2) \times U(1)$ is

$$\begin{aligned} [t^a, t^b] &= if^{abc}t_c, \\ [T^i, T^j] &= i\epsilon^{ijk}T_k, \\ [T^i, Y] &= [t^a, T^j] = [t^a, Y] = 0, \end{aligned} \quad (1.18)$$

where f^{abc} and ϵ^{ijk} are the structure constants of $SU(3)$ and $SU(2)$. And therefore, the gauge fields G_μ , W_μ , and B_μ must transform in the adjoint representation:

$$\begin{aligned} \delta B_\mu &= \partial_\mu \theta, \\ \delta W_\mu^i &= \partial_\mu \theta^i - g\epsilon^{ijk}\theta^j W_\mu^k, \\ \delta G_\mu^a &= \partial_\mu \epsilon^a - g_s f^{abc}\epsilon^b G_\mu^c. \end{aligned} \quad (1.19)$$

Then, the curvature strength tensors are

$$\begin{aligned} G_{\mu\nu}^a &= \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc} G_\mu^b G_\nu^c \\ W_{\mu\nu}^i &= \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g\epsilon^{ijk} W_\mu^j W_\nu^k \\ B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \end{aligned} \quad (1.20)$$

and the “kinetic” term for gauge fields in the Lagrangian is

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu} - \frac{1}{4}W_{\mu\nu}^i W_i^{\mu\nu} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu}. \quad (1.21)$$

while these kinetic terms induce vertices between gauge bosons and in turn do not take into account the masses for such vector bosons, the Higgs mechanism produces the masses for them and gives us the linear combination to the physical bosons W^\pm , Z , γ :

$$\begin{cases} W_\mu^+ = \frac{1}{\sqrt{2}}(W_\mu^1 - iW_\mu^2) \\ W_\mu^- = \frac{1}{\sqrt{2}}(W_\mu^1 + iW_\mu^2) \\ Z_\mu = c_w W_\mu^3 - s_w B_\mu \\ A_\mu = s_w W_\mu^3 + c_w B_\mu \end{cases} \quad \text{where} \quad \begin{cases} s_w = \sin \theta_w = \frac{g}{\sqrt{g^2 + g'^2}} \\ c_w = \cos \theta_w = \frac{g'}{\sqrt{g^2 + g'^2}} \end{cases} \quad (1.22)$$

where to avoid confusion with Dirac matrices, we denote as A_μ the electromagnetic potential.

1.2.3 MATTER FIELDS

We refer to the fermionic fields of the SM as the matter fields. We distinguish fermions in these two categories: leptons, fermions that do not have strong interaction, and quarks that interact both strongly and electroweakly. In table 1.3, we can see that there are six leptons, three charged and three neutral: each charged lepton has an associated neutrino forming between them doublets of $SU(2)_L$ and similarly for quarks.

According to the SM, there are three generations of fermions. Each generation contains a doublet of leptons and a doublet of quarks. Among generations, particles differ by their flavour quantum number and mass, but their strong and electrical interactions are identical. Moreover, the flavour quantum number is a quantity conserved by all interactions except for the weak interaction. Each generation is more massive than the previous one. The second and third generations are unstable and they disintegrate into the first generation. This is why ordinary matter is composed of the first generation. All three generations are produced in nuclear reactors, colliders, and cosmic rays.

Fermion categories		Elementary particle generation		
Type	Subtype	First	Second	Third
Quarks (q)	up-type	(u) up	(c) charm	(t) top
	down-type	(d) down	(s) strange	(b) bottom
Leptons (ℓ)	charged	(e) electron	(μ) muon	(τ) tauon
	neutrino	(ν_e)	(ν_μ)	(ν_τ)

Table 1.3: Three generations of fermions according to the Standard Model of particle physics. Each generation containing two types of leptons and two types of quarks.

Under all the constraints on local gauge invariance and renormalizability of the theory, the fermionic Lagrangian for SM is given by

$$\mathcal{L}_{\text{Fer}} = i\bar{\ell}_L^j \not{\partial} \ell_L^j + i\bar{e}_R^j \not{\partial} e_R^j + i\bar{q}_L^j \not{\partial} q_L^j + i\bar{u}_R^j \not{\partial} u_R^j + i\bar{d}_R^j \not{\partial} d_R^j \quad (1.23)$$

where $\not{\partial} \equiv \gamma^\mu \not{\partial}_\mu$ with covariant derivative

$$\not{\partial}_\mu = \partial_\mu - ig_s t_a G_\mu^a - ig T_i W_\mu^i - ig' \frac{Y}{2} B_\mu, \quad (1.24)$$

and gauge fields G^a , W^i , and B acting on each kind of fermion via

$$\begin{aligned} \not{\partial}_\mu \ell_L^i &= \left(\partial_\mu - ig T_j W_\mu^j + i \frac{g'}{2} B_\mu \right) \ell_L^i \\ \not{\partial}_\mu e_R^i &= \left(\partial_\mu - ig' B_\mu \right) e_R^i \\ \not{\partial}_\mu q_L^i &= \left(\partial_\mu - ig_s t_a G_\mu^a - ig T_j W_\mu^j - i \frac{g'}{6} B_\mu \right) q_L^i \\ \not{\partial}_\mu u_R^i &= \left(\partial_\mu - ig_s t_a G_\mu^a - i \frac{2g'}{3} B_\mu \right) u_R^i \\ \not{\partial}_\mu d_R^i &= \left(\partial_\mu - ig_s t_a G_\mu^a + i \frac{g'}{3} B_\mu \right) d_R^i \end{aligned} \quad (1.25)$$

which couples the fermions to the gauge bosons.

1.2.4 ELETROWEAK SYMMETRY BREAKING

In the SM, the electroweak symmetry $SU(2)_L \times U(1)_Y$ is spontaneously broken down to the electromagnetic $U(1)_{EM}$ symmetry by a complex scalar Higgs field transforming as a $SU(2)_L$ doublet $H = (H^+, H^0)$ and with hypercharge +1. Its dynamics are parametrized in terms of a potential, devised to trigger a non-vanishing Higgs vacuum expectation value (vev) v :

$$V = -\mu^2|H|^2 + \lambda|H|^4 \Rightarrow v^2 \equiv \langle |H| \rangle^2 = \mu^2/2\lambda. \quad (1.26)$$

The vev defines the electrically neutral direction and is set to $\langle H^0 \rangle \simeq 170\text{GeV}$ in order to generate the vector boson masses. Simultaneously, it produces masses for quarks and leptons through the Yukawa couplings:

$$\mathcal{L}_{Yuk} = y_u^{ij} \bar{q}_L^i u_R^j H + y_d^{ij} \bar{q}_L^i d_R^j H + y_\ell^{ij} \bar{\ell}_L^i e_R^j H + \text{h.c.} \quad (1.27)$$

where $y_{u,d,\ell}$ are 3×3 complex coupling matrices. These interactions are actually the most general consistent with gauge invariance and renormalizability, and accidentally are invariant under the global symmetries related to the baryon number B and the three family lepton numbers L_i ³. When H acquires a vacuum expectation value, $\langle H \rangle = (0, v/\sqrt{2})$, \mathcal{L}_{Yuk} yields mass terms for the quarks and leptons. For quarks, the physical states are obtained by diagonalizing $y_{u,d}$ by four unitary matrices, $V_{L,R}^{u,d}$, as $M_{\text{diag}}^f = V_L^f Y^f V_R^{f\dagger} (v/\sqrt{2})$, $f = u, d$. As a result, the charged-current W^\pm interactions couple to the physical u_{Lj} and d_{Lk} quarks with couplings given by

$$\begin{aligned} \mathcal{L}_{\text{Fer}} &\supset \frac{-g}{\sqrt{2}} (\bar{u}_L, \bar{c}_L, \bar{t}_L) \gamma^\mu W_\mu^+ V_{\text{CKM}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}, \\ V_{\text{CKM}} \equiv V_L^u V_L^{d\dagger} &= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}. \end{aligned} \quad (1.28)$$

However, in both flavour-changing charged and neutral currents, the weak interaction at play deals with lepton flavours in a universal manner. This property is known as *Lepton Flavour Universality*; whereas quarks are treated on a different footing due to the CKM matrix. This universality of lepton couplings is assumed when determining the CKM parameters, in particular to combine results from semileptonic and leptonic decays that involve e, μ , and/or τ leptons.

The Lagrangian of the scalar sector is simply

$$\mathcal{L}_H = \mathcal{D}_\mu H^\dagger \mathcal{D}^\mu H - V(H^\dagger, H) \quad (1.29)$$

³ Regarding the Standard Model as an effective theory, non-renormalizable operators violating these symmetries may, however, be present.

where $\mathcal{D}_\mu H = (\partial_\mu + igT_a W_\mu^a + ig' \frac{Y}{2} B_\mu) H$, then

$$\begin{aligned}\mathcal{L}_{(H)} &= -\frac{1}{8} \begin{pmatrix} 0 & v \end{pmatrix} \begin{pmatrix} gW_\mu^3 - g'B_\mu & g(W_\mu^1 - iW_\mu^2) \\ g(W_\mu^1 + iW_\mu^2) & -gW_\mu^3 - g'B_\mu \end{pmatrix}^2 \begin{pmatrix} 0 \\ v \end{pmatrix} \\ &= -\frac{1}{8}v^2 V_\mu^T \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & -g'g \\ 0 & 0 & -g'g & g'^2 \end{pmatrix} V^\mu\end{aligned}\quad (1.30)$$

where $V_\mu^T = (W_\mu^1, W_\mu^2, W_\mu^3, B_\mu)$. Diagonalizing this mass matrix, we have that the mass eigenvalues are $0, -\frac{1}{8}v^2 g^2, -\frac{1}{8}v^2 g^2$, and $-\frac{1}{8}v^2 (g^2 + g'^2)$. The massless boson is the photon, the most massive is the Z boson, and the two intermediate vectors correspond to the bosons W^+ and W^- , that transform under a representation of the unbroken generator Q_{EM} .

Having said that, so far, it is enough to understand how the standard model of particle physics as a relativistic field theory describes the interactions of fundamental matter articles via the fundamental forces, mediated by the force carrying particles, the vector bosons. The Higgs boson, also a fundamental Standard Model particle, plays a central role in the mechanism that determines the masses of the photon and weak bosons, as well as the rest of the standard model particles.

Since then, the standard model has faced several experimental tests and has had unprecedented success in explaining the measurements made so far; it has also been a powerful predictive theory. The Standard model has proven successfully at describing many features of nature that we measure in our experiments. The most famous example is the agreement of the Standard Model prediction and the experimental measurement of the electron magnetic dipole moment to within twelve significant figures of accuracy [24]. The 2012 discovery of the Higgs boson was the culmination of almost fifty years of searching for the particle first predicted to exist in 1965 and first incorporated into the Standard Model in 1967 with Glashow, Weinberg, and Salam's unification of the electromagnetic and weak forces [25, 26]. With the 2012 Higgs discovery, the full predicted particle spectrum of the Standard Model was finally observed.

1.3 DEFICIENCIES OF STANDARD MODEL AND EVIDENCE OF NEW PHYSICS

Pending to be updated

While these and other successes of the Standard Model are an achievement for the field of particle physics, it is well known that this cannot be the ultimate theory of fundamental particles and interactions. Even though the Standard Model is currently the best description there is of the

subatomic world, it does not explain the complete picture; there are also important questions that it does not answer and it is also surrounded by different irregularities. Some of them are completely incompatible with the current Standard Model, and strongly suggest that the Standard Model requires a consistent extension to solve experimental and theoretical problems that we will label as the cosmological problems, phenomenological problems, and theoretical problems. Below we will list very briefly the main representatives of these categories.

1.3.1 THEORETICAL PROBLEMS

HIERARCHY PROBLEM Is the problem concerning the large discrepancy between aspects of the weak force and gravity. Both of these forces involve constants of nature, the Fermi constant for the weak force and the Newtonian constant of gravitation for gravity. If the Standard Model is used to calculate the quantum corrections to Fermi's constant, it appears that Fermi's constant is surprisingly large and is expected to be closer to Newton's constant unless there is a delicate cancellation between the bare value of Fermi's constant and the quantum corrections to it.

In the Standard Model context, the Higgs boson is much lighter than the energy scale on which the standard model is considered valid (ideally the Plank mass), and the quantum corrections to the Higgs mass are on the order of this energy scale; it would inevitably make the Higgs and fermions masses huge, comparable to the scale at which new physics appears, unless there is an incredible fine-tuning cancellation between the quadratic radiative corrections and the bare mass. This level of fine-tuning is deemed unnatural.

STRONG CP PROBLEM QCD Lagrangian supports a term associated with the strength tensor dual for gluons that break CP symmetry in the strong interaction sector. Experimentally, however, no such violation has been found, implying that the coefficient of this term is fine tuned to zero.

QUANTUM TRIVIALITY Suggests that it may not be possible to create a consistent quantum field theory involving elementary scalar Higgs particles because for high momentum particles the renormalization presents inconsistencies unless the renormalization of the charges becomes null, and therefore not interacting, *i.e.* trivial. Nevertheless, because the Higgs boson plays a central role in the Standard Model of particle physics, the question of triviality in Higgs models is of great importance.

NUMBER OF PARAMETERS AND UNEXPLAINED RELATIONS In total, the standard model has too many free parameters (19 in total) that are obtained experimentally, and there are indications that several of

them may be correlated, however the origin of these correlations is beyond the standard model.

For example, Yoshio Koide's empirical formula [27]

$$\frac{m_e + m_\mu + m_\tau}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2} = 0.666661(7) \approx \frac{2}{3}$$

seems to indicate that there is a way to predict the masses of leptons.

1.3.2 COSMOLOGICAL PROBLEMS

GRAVITY Although the Standard Model describes the three important fundamental forces at the subatomic scale, it does not include gravity. However, at larger scales, gravity becomes present and is described by Einstein's theory of general relativity, in which gravity rather than a force is a property that measures the deformation of spacetime then, the most of the conventional machinery of perturbative QFT is profoundly incompatible with the general relativistic framework [28], and a theory of quantum gravity with which we are enabled to perform calculations has yet to be discovered.

DARK MATTER Within the framework of Einstein's general relativity, the cosmological standard model (Λ CDM) is, like the standard model of particle physics, one of the most successful theories of the 20th century. Λ CDM is based on a very specific density of matter that can be explained with ordinary matter from the standard model of particles, baryonic matter; according to Λ CDM, in addition to baryonic matter, there is a kind of matter five times more abundant than baryonic matter, which does not interact electrically (therefore it is dark) and non-relativistic (therefore it is cold), known as cold dark matter (CDM). Yet, the Standard Model does not supply any fundamental particles that are good dark matter candidates.

DARK ENERGY Moreover, according to Lambda CDM only 31% of the energy that makes up the universe is matter, the remaining 69% of the universe's energy should consist of the so-called dark energy, a constant energy density for the vacuum (Λ). If we try to explain dark energy in terms of vacuum energy only from the standard model lead to a mismatch of 120 orders of magnitude [29], sometimes called *The Worst Theoretical Prediction in the History of Physics* [30]; a bit sensationalist title to indicate the fact that we do not fully understand the composition of the particle spectrum of the universe.

MATTER-ANTIMATTER ASYMMETRY In the observable universe there is more matter than antimatter. In 1967, Andrei Sakharov proposed a set of three necessary conditions that a baryon-generating interaction must satisfy to produce matter and antimatter at different rates [31]. While the standard model can satisfy these three conditions [32],

[33], it satisfies them at three different energy scales and therefore presents difficulties in the capability to explain the matter-antimatter asymmetry [18].

1.3.3 PHENOMENOLOGICAL PROBLEMS

NEUTRINO MASSES In the standard model, the right chiral component of neutrinos is not part of the composition of fermionic fields because if they were present they would not interact and consequently neutrinos have no mass. However, the precision measurement [34] of the mixing matrix for neutrino oscillations has shown that neutrinos change flavour in free flight and in turn that the three neutrino flavours cannot have identical mass, meaning that all three cannot have zero mass. There is no single way to extend the standard model to include masses to neutrinos and even more to explain their value so close to zero and results in the open problem confirmed at the phenomenological level present in the standard model.

ANOMALOUS B-MESONS DECAY A B-meson is a bound state made up of an quark-antiquark pair where one of them comes from a b-quark. Various experimental results [35–39] have suggested a surplus over Standard Model predictions in its decays to D-mesons along with a τ , ν_τ doublet. While none of them have reached the statistical threshold of 5σ to declare a break from the standard model, the Capdevila's meta-analysis of all available data reported a 5.0σ deviation from SM [40].

ANOMALOUS MAGNETIC DIPOLE MOMENT OF MUON Unlike the extraordinary agreement between theory and experiment with the magnetic dipole moment of the electron [24]; in the case of the muon, the measurement of Fermilab's Muon g-2 experiment has presented an apparent discrepancy with an accuracy of 4.2σ [41, 42] which strengthen evidence of new physics in the muon sector and apparently in the violation of lepton universality of the standard model.

ANOMALOUS MASS OF THE W BOSON Results from the CDF Collaboration, reported in April 2022, indicate that the mass of a W boson exceeds the mass predicted by the Standard Model with a significance of 7σ [43]. However, this very highly accurate result, unlike the anomaly in B-meson Decay, is in tension with the results of Atlas, LHCb, LEP and Do II [44–47]. Certainly, a review of all the information we possess so far must be done to determine if this anomaly is a window into new physics beyond the standard model.

CCA AND $q\bar{q} \mapsto e^+e^-$ It has been observed that certain nuclear beta decays happen less frequently than expected [48]. This tension, called the Cabibbo Angle anomaly (CAA), displays a significance

around 3σ [21], and can again be interpreted as a sign that electrons and muons behave more differently than predicted by the SM [49]. Furthermore, the CMS experiment at CERN observed more very high-energetic electrons in proton-proton collisions ($q\bar{q} \rightarrow e^+e^-$) compared to muons than expected [50].

2

PHENOMENOLOGICAL FRAMEWORK FOR LHC SEARCHES AND ANALYSIS

Since its formulation, the Standard Model (SM) has proven remarkably successful in describing the fundamental particles and interactions, and its parameters have been measured with increasing precision over several decades. However, as discussed in the previous chapter, various theoretical and experimental observations suggest that the SM is incomplete. As outlined previously, this is motivated by theoretical shortcomings—such as the hierarchy problem, the absence of a dark matter candidate, and non-zero neutrino masses—as well as by experimental anomalies. These limitations motivate the search for new physics (NP) beyond the SM (BSM).

The search for BSM physics proceeds along two main axes: the construction of theoretical extensions to the SM, and the development of experimental methods to probe them. A necessary condition for any viable BSM model is consistency with existing experimental data, which places strong constraints on its parameter space. These constraints include lower limits on the masses of new particles from direct searches at high-energy colliders, and upper bounds on couplings and mixing angles from precision measurements at both high and low energies, which are sensitive to virtual corrections.

Phenomenology connects theoretical models to experimental observables by calculating cross sections, decay rates, and other signatures for given model parameters. A critical function of this field is to assess the experimental feasibility of BSM scenarios—evaluating whether predicted signals would be observable above background processes given the capabilities of current and future detectors. This involves estimating production rates, modeling detector acceptance and efficiency, and developing discrimination variables to maximize signal-to-background ratios. This feasibility assessment is essential for designing analysis strategies, particularly at the Large Hadron Collider (LHC), where signals of new physics must be discriminated from large Standard Model backgrounds.

This feasibility assessment is essential for designing analysis strategies at the Large Hadron Collider (LHC), a proton-proton (pp) collider operating since 2009. The LHC has provided data at center-of-mass energies from 7 TeV to 13.6 TeV. During Run I (2010–2013), operations at 7–8 TeV led to the discovery of the Higgs boson using a dataset corresponding to an integrated luminosity of roughly 30 fb^{-1} . Run II (2015–2018) significantly expanded this dataset, collecting approximately 140 fb^{-1} at 13 TeV. Run III

(2022–2025) is currently underway at 13.6 TeV and is more than doubling the available data, with a target of over 300 fb^{-1} . Future operations will be dominated by the High-Luminosity LHC (HL-LHC), starting around 2029, which is designed to accumulate an unprecedented integrated luminosity of 3000 fb^{-1} . This vast increase in data volume enables searches for exceedingly rare processes but also requires discriminating potential signals of new physics from correspondingly large and complex SM backgrounds, making sophisticated phenomenological tools increasingly important.

2.1 DETECTORS AND SUBSYSTEMS

When two particle bunches from colliding beams cross each other, they generate individual interactions known as events. At the LHC, the beam intensity is so high that multiple interactions can take place in a single event; this phenomenon is referred to as pile-up. In other words, the probability that several proton-proton interactions occur within the same bunch crossing is non-negligible, leading to multiple overlapping events in a single detector readout. These collisions occur at four main interaction points, each hosting a large particle detector designed to record and analyze the outcomes.

Among them, the Compact Muon Solenoid (CMS) and ATLAS are the largest and most comprehensive experiments. Both are multipurpose detectors with broad physics programs, capable of exploring a wide range of phenomena. They perform precision measurements within the electroweak sector of the Standard Model, probe the dynamics of quarks and gluons (including through heavy-ion collisions), and conduct extensive searches for physics beyond the Standard Model using pp collision data. While CMS and ATLAS differ in their detector designs and reconstruction strategies, their physics goals are largely overlapping, and their results are complementary.

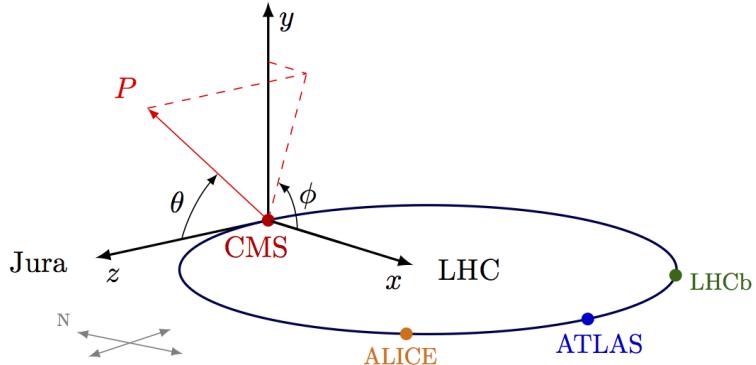


Figure 2.1: Coordinate system employed by the CMS experiment (retrieved from [51]).

Throughout this work, phenomenological studies and comparisons are primarily developed in the context of CMS, although several results from

ATLAS are also referenced, given the close alignment in sensitivity and scope. Measurements performed at CMS adopt a right-handed coordinate system with its origin at the nominal collision point. The z-axis is defined along the beam direction, the x-axis points radially inward toward the center of the LHC ring, and the y-axis points vertically upward. The azimuthal angle ϕ is measured in the transverse (xy) plane from the x-axis, while the polar angle θ is measured from the z-axis, as shown in Fig. 2.1. Moreover, for kinematic analysis at hadron colliders, the Cartesian coordinate system is often reparameterized into quantities that are more physically meaningful and experimentally convenient as shown in Fig. 2.2:

PSEUDO-RAPIDITY (η) Instead of using the polar angle, CMS measurements involve the pseudo-rapidity, defined by

$$\eta = -\ln \left(\tan \frac{\theta}{2} \right)$$

The main advantage of using the pseudo-rapidity is that distributions over it tend to be closer to a uniform distribution than those over the polar angle, see Fig. 2.2. Furthermore, the difference in pseudo-rapidity is invariant under Lorentz boosts along the beam direction [52].

TRANSVERSE MOMENTUM (p_T) Refers to the component of momentum which is perpendicular to the beam line. It is usually preferred over full momentum because momentum along the beamline may just be left over from the beam particles, while the transverse momentum is always associated with whatever physics happened at the vertex, see Fig. 2.2.

AZIMUTHAL ANGLE (ϕ) Measures the angle in the transverse plane relative to the x-axis, providing the directional component perpendicular to the beam line.

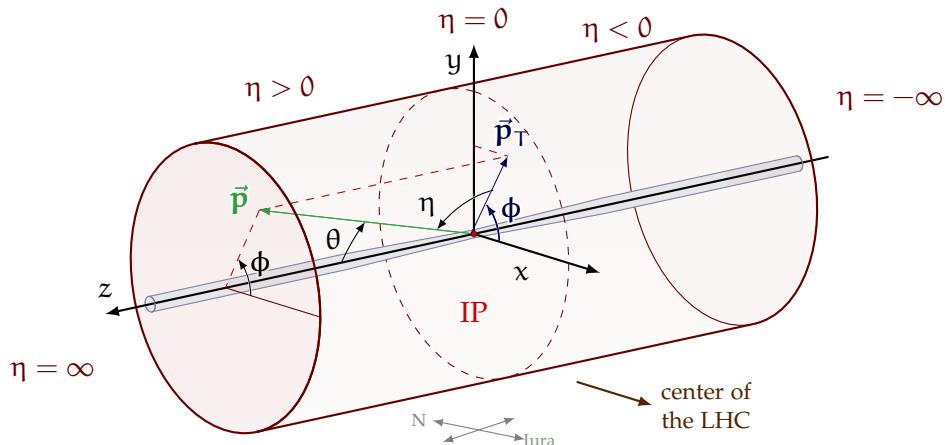


Figure 2.2: Detailed reparametrization of the coordinate system employed by the CMS experiment (retrieved from [51])

Together, the triplet (p_T, ϕ, η) forms a natural coordinate system that fully describes a particle's three-momentum vector at a hadron collider. The full four-momentum (E, p_x, p_y, p_z) can be reconstructed from these quantities, typically supplemented by either the particle's mass hypothesis (for identified particles like electrons or muons) or the energy deposited in the calorimeters (for neutral objects like photons or jets). This (p_T, ϕ, η) system serves as the fundamental framework for defining physical objects, calculating event variables, and performing analyses at the LHC, providing both experimental convenience and physical insight into the collision dynamics.

A key challenge is isolating the primary hard interaction from the additional concurrent pile-up interactions. This is accomplished by reconstructing distinct interaction vertices along the beam direction and associating charged particles to their point of origin. The ultimate aim of the reconstruction chain is to identify all stable particles produced in the collision and measure their four-momenta, thereby enabling the identification of the underlying fundamental process.

However, the reconstruction is complicated by several factors. The initial state of the colliding protons is not fully known, as they are composite particles made up of quarks and gluons (collectively referred to as partons). The fraction of the proton's momentum carried by each parton is described by parton distribution functions (PDFs), which are determined experimentally. Consequently, the total momentum along the beam axis (z) is not balanced on an event-by-event basis. Furthermore, not all particles are stable enough to reach the detector; some decay before being detected, and only their decay products are observed. The design of a collider experiment, illustrated in Fig. 2.3, is optimized for the identification and energy measurement of the particles produced in high-energy collisions.

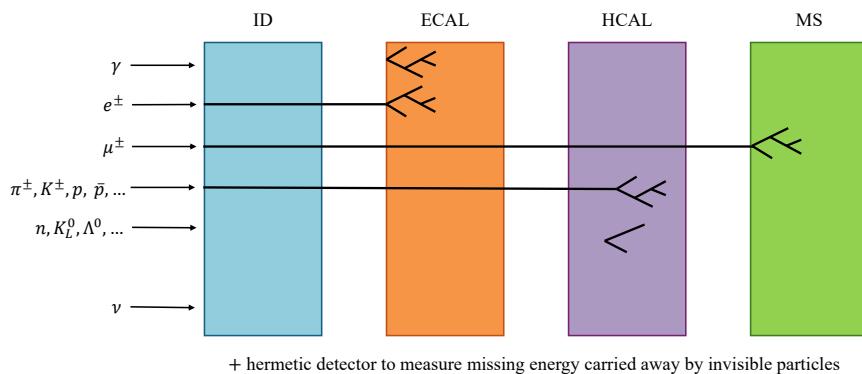


Figure 2.3: Illustration of high-energy particles being identified by consecutive types of subdetectors in a typical collider experiment. The curvature of the tracks in the magnetic field is not shown for simplicity. Representation of which particles and kinds of detectors are used in a multipurpose detector such as CMS or ATLAS.

Finally, some hypothetical particles, such as those comprising dark matter, along with known neutrinos, interact very weakly with matter and

escape direct detection. Therefore, a hermetic detector design is crucial to infer their presence by accurately measuring the imbalance of energy and momentum in the transverse plane, referred to as missing transverse momentum.

In this way, a typical collider experiment comprises several main detector subsystems that are used jointly to detect and measure the properties of particles produced in the collision. A *schematic representation* of such a generic multipurpose detector is shown in Fig. 2.4. The detector features an "onion-like" design of several concentric layers, each optimized to identify different types of particles and measure their properties.

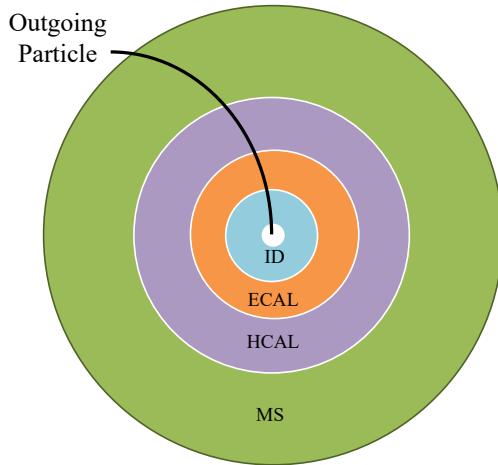


Figure 2.4: Schematic representation of a transverse section of a generic multipurpose detector. The inner detector (ID) is used to measure the trajectories of charged particles, the electromagnetic calorimeter (ECAL) measures the energy of photons and electrons, the hadronic calorimeter (HCAL) measures the energy of hadrons, and the muon system (MS) identifies and measures muons. The missing transverse momentum (MET) is inferred from the momentum imbalance in the transverse plane.

The innermost subsystem, the inner detector (ID) or tracker, is immersed in a strong axial magnetic field (typically 1–4 T). It is designed to reconstruct the trajectories of charged particles, which are bent by the magnetic field. The direction and curvature of these trajectories, called **tracks**, yield the particle's momentum vector and electric charge. The most common long-lived charged particles from the SM are leptons (electrons e and muons μ) and hadrons (pions π , kaons K , and protons p). In some detectors, the ID is complemented by a Cherenkov-light detector to measure particle velocity. Combined with the momentum measurement, this velocity helps determine the particle mass, allowing for differentiation between pions, kaons, and protons.

After the tracker, particles enter the electromagnetic calorimeter (ECAL), which is designed to fully absorb photons, electrons, and positrons. These

particles deposit all their energy in the ECAL by initiating an electromagnetic shower via bremsstrahlung and e^+e^- pair production. Electrons are identified as charged tracks that point to a compact, high-energy deposit in the ECAL.

The hadronic calorimeter (HCAL) surrounds the ECAL. Its purpose is to absorb hadrons (e.g., neutrons, protons, pions, kaons) and measure their energy through hadronic interactions. High-energy quarks and gluons do not appear as individual particles but instead **hadronize** into collimated sprays of hadrons known as **jets**, see Sec. 2.2. A jet's energy is measured by combining the energy deposited in the ECAL and HCAL with the momenta of charged tracks associated with it. This approach, known as particle flow (PF) reconstruction, which combines information from all detector subsystems to identify each individual particle, provides a more accurate measurement.

Muons are unique as they are the only charged particles (apart from neutrinos) that can penetrate the entire calorimeter system, losing only a small amount of energy via ionization. Therefore, a dedicated muon system (MS) is built outside the calorimeters. Muons are identified as tracks in the ID that are matched to tracks in the MS. The MS, often within its own magnetic field, provides a standalone momentum measurement, which is combined with the ID measurement for high precision.

Since the detector is nearly hermetic (covering almost the full solid angle), momentum conservation in the plane transverse to the beam line (x - y plane) is a powerful tool. The vector sum of the momenta in the transverse plane (\vec{p}_T) of all detected particles should be zero. Any significant imbalance indicates the presence of undetected, neutral particles that did not interact with the detector, such as neutrinos or hypothetical new particles. This imbalance is called missing transverse momentum (MET) and is formally defined as:

$$\vec{p}_T^{\text{miss}} \equiv - \sum_i \vec{p}_{T,i}$$

where the sum runs over all reconstructed particles (e.g., leptons, photons, jets) or calorimeter deposits in the event.

This detector design, optimized for identifying and measuring Standard Model particles, also makes it a powerful instrument for searching for new physics beyond the SM through unusual signatures or an excess of events with large MET.

2.1.1 COLLISION PARAMETERS

A aim of particle physics experiments is to quantify how frequently different processes occur and to characterize the properties of the particles involved. These quantities are expressed in terms of **cross-sections**, normalized to the **luminosity** delivered by the accelerator.

The cross-section (σ) quantifies the probability for a specific process to occur. Formally, it represents the effective area of a target particle presented

to an incoming beam particle for an interaction to happen. It has units of area, typically barn (b), where $1 \text{ b} = 10^{-28} \text{ m}^2$.

In the context of proton-proton (pp) collisions at the LHC, the concept is generalized. Since both colliding particles are composite, the cross-section for a specific process (e.g., Higgs boson production, $t\bar{t}$ production, or BSM particle production) is calculated by considering the interactions between their constituent partons (quarks and gluons). The total cross-section for a process $\text{pp} \rightarrow X$ is given by the convolution of the parton distribution functions (PDFs) and the partonic cross-section $\hat{\sigma}_{ij \rightarrow X}$:

$$\sigma(\text{pp} \rightarrow X) = \sum_{i,j} \int_0^1 dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \hat{\sigma}_{ij \rightarrow X}(\hat{s}, \mu_F^2, \mu_R^2), \quad (2.1)$$

where:

- The sum runs over all possible parton types i, j (e.g., u, d, g) in the two protons.
- $f_i(x, \mu_F^2)$ is the PDF, representing the probability density to find a parton of type i carrying a fraction x of the proton's momentum at a factorization scale μ_F .
- $\hat{s} = x_1 x_2 s$ is the square of the center-of-mass energy for the colliding partons, with s being the square of the pp center-of-mass energy (e.g., 13.6 TeV).
- $\hat{\sigma}_{ij \rightarrow X}$ is the partonic cross-section for the hard scattering process $ij \rightarrow X$.
- μ_R is the renormalization scale.

Then, in one hand, the cross-section σ is a theoretical quantity that encapsulates the fundamental physics of the interaction, independent of the accelerator's performance. On the other hand, the **luminosity** (\mathcal{L}) is a property of the particle accelerator and beams. It measures the density of particles in the colliding beams and thus the rate at which interactions can occur. The instantaneous luminosity is defined by:

$$\mathcal{L} = \frac{fn_1 n_2}{4\pi\sigma_x\sigma_y}, \quad (2.2)$$

where f is the revolution frequency of the bunches, n_1 and n_2 are the numbers of particles in each bunch, and σ_x and σ_y are the transverse dimensions of the beams at the interaction point. The integrated luminosity is the integral of the instantaneous luminosity over time:

$$L = \int \mathcal{L} dt. \quad (2.3)$$

The primary unit of integrated luminosity is the inverse barn (b^{-1}), commonly fb^{-1} .

The expected number of events (N) for a given process in a collider experiment connects the cross-section and integrated luminosity through the relation

$$N = \sigma \cdot L \cdot \epsilon. \quad (2.4)$$

Here, ϵ is the total efficiency and acceptance of the detector for the process in question. It estimates the fraction of produced events that are actually detected and reconstructed, accounting for detector geometry, resolution, and analysis selection criteria.

This equation is the cornerstone of data analysis at colliders. A measurement can proceed in two directions: On one side, if a process is known, we can measure the number of events N , know the integrated luminosity L from accelerator measurements, and calculate the efficiency ϵ from simulation. Equation 2.4 is then solved for σ to provide a measurement of the production rate. On the other side, if we are searching for a new process not predicted by the Standard Model, we calculate the expected background N_{bkg} from known SM processes. We then observe a number of events N_{obs} . Any significant excess, $N_{\text{obs}} - N_{\text{bkg}}$, can be interpreted as a potential signal, and Equation 2.4 can be used to set an upper limit on the cross-section σ_{BSM} of the hypothetical new process.

2.2 JETS RECONSTRUCTION

Quarks and gluons are never observed as free particles because of colour confinement. Nevertheless, perturbative QCD treats them as the relevant short-distance degrees of freedom: factorization theorems and asymptotic freedom justify computing hard-scattering matrix elements for incoming and outgoing partons even though QCD becomes non-perturbative at low scales. The strong coupling α_s grows large and effectively “blows up” around the confinement scale Λ_{QCD} ; consequently something must happen to quarks and gluons before they reach the detector. In practice the gluon and all quarks except the top hadronize, producing cascades of baryons and mesons that themselves undergo further decays. At the LHC these hadrons typically carry energies comparable to the electroweak scale, and relativistic boosts tend to collimate their decay products into narrow bunches. Those collimated collections of hadrons are the jets we measure at hadron colliders and the objects we use to infer the partons produced in the hard interaction.

Each high-energy parton produced in a collision, such as a quark from the process $gg \rightarrow q\bar{q}$, undergoes hadronization over a distance scale of $\sim 10^{-15}\text{m}$, producing a jet of hadrons. The energy composition of these jets is phenomenologically well-established: on average, approximately 60% of the energy is carried by charged particles (mostly π^\pm, K^\pm), 30% by photons from $\pi^0 \rightarrow \gamma\gamma$ decays, and 10% by neutral hadrons (mostly neutrons, K^0, Λ^0). In high-energy jets, the particles are often too collimated to be resolved individually by the calorimeter segmentation. Nevertheless,

the jet’s energy and momentum can be reconstructed from the total energy deposited.

Phenomenologically one usually assumes that each high-energy parton yields a jet and that the measured jet four-momentum can, to useful accuracy, be related to the original parton four-momentum. Jets are therefore defined operationally using recombination (clustering) algorithms such as Cambridge-Aachen or the (anti-) k_T family. Experimentally this means grouping a large number of energy depositions (or particle-flow candidates) observed in the calorimeters and tracker into a much smaller set of jets or subjets. Nothing in the raw detector data, however, indicates a priori how many jets there should be: the clustering procedure and the choice of a resolution scale fix the outcome. In practice one must either specify the desired number of final jets or choose a resolution/stop criterion (for example a distance parameter R , a clustering distance cut, or a jet-mass/subjet-resolution threshold) that determines the smallest substructure to be considered a separate parton-like object.

Modern reconstruction at the LHC typically uses particle-flow (PF) candidates as input together with infrared- and collinear-safe clustering algorithms to define jet four-momenta. The anti- k_T algorithm [53], implemented in FastJet [54], is widely used in ATLAS and CMS; it groups candidates by proximity in the rapidity–azimuth (y, ϕ) plane with a typical distance parameter $R \sim 0.4\text{--}0.6$ and is relatively insensitive to soft radiation and pileup. After clustering, jet energy corrections (JEC) derived from simulation and in-situ calibrations compensate for detector response, pileup, and underlying-event effects, while jet-substructure and tagging algorithms help infer the flavour and origin of the initiating parton.

2.2.1 JET ALGORITHMS

Recombination (or sequential clustering) algorithms formalise the intuitive idea that parton showering produces collinear and soft splittings: two nearby and kinematically compatible subjets are merged if they are more likely to have originated from a single parton. A practical implementation requires a measure of “distance” between objects; common choices combine an angular separation in the rapidity–azimuth plane, ΔR_{ij} , with a transverse-momentum weighting. Typical distance measures are

$$\begin{aligned} k_T : \quad & y_{ij} = \frac{\Delta R_{ij}}{R} \min(p_{T,i}, p_{T,j}), \quad y_{iB} = p_{T,i}, \\ C/A : \quad & y_{ij} = \frac{\Delta R_{ij}}{R}, \quad y_{iB} = 1, \\ \text{anti-}k_T : \quad & y_{ij} = \frac{\Delta R_{ij}}{R} \min(p_{T,i}^{-1}, p_{T,j}^{-1}), \quad y_{iB} = p_{T,i}^{-1}. \end{aligned}$$

The parameter R balances jet–jet and jet–beam criteria and sets the geometric size of jets; in LHC analyses typical values are $R \sim 0.4\text{--}0.7$ depending on the physics target.

Two operational modes are useful to distinguish. In an exclusive algorithm one supplies a resolution scale y_{cut} and proceeds iteratively:

1. compute $y^{\min} = \min_{i,j}\{y_{ij}, y_{iB}\}$;
2. if $y^{\min} = y_{ij} < y_{\text{cut}}$ merge i and j and repeat;
3. if $y^{\min} = y_{iB} < y_{\text{cut}}$ remove i as beam radiation and repeat;
4. stop when $y^{\min} > y_{\text{cut}}$ and keep remaining subjets as jets.

An inclusive algorithm omits y_{cut} and instead declares a subjet a final-state jet when its jet-beam distance is the smallest quantity; iteration continues until no inputs remain. Inclusive algorithms therefore produce a variable number of jets, while exclusive algorithms deliver a scale-dependent fixed set.

A practical question is how to combine the kinematics of merged objects. The most common choice in modern experiments is the E-scheme: four-vectors are added, which preserves energy-momentum and yields a physical jet mass useful for substructure and boosted-object tagging. An alternative is to sum three-momenta and rescale the energy to enforce a massless jet; this can be appropriate when the analysis targets massless parton kinematics, but it discards potentially useful jet-mass information.

From a theoretical and experimental viewpoint important properties are infrared and collinear safety: a jet algorithm should give stable results under emission of soft particles or collinear splittings. The k_T , C/A and anti- k_T families are constructed to satisfy these requirements. Their practical behaviour differs: k_T naturally follows the physical shower history (soft-first clustering), C/A is purely geometric (useful for declustering and substructure studies), while anti- k_T produces regular, cone-like jets that are robust and convenient experimentally.

Corrections for pileup and the underlying event are necessary at the LHC. These corrections depend on the jet area (a well-defined concept for sequential algorithms) and are typically performed by estimating an event-wide transverse-momentum density and subtracting the corresponding contribution proportional to the jet area. Finally, because inclusive algorithms can produce jets arbitrarily close to the beam, a minimum jet p_T threshold (commonly 20–100 GeV depending on the analysis) is imposed to ensure experimental observability and theoretical control.

2.2.2 τ TAGGING AT MULTIPURPOSE DETECTORS

The τ lepton decays hadronically with a probability of $\sim 65\%$, producing a narrow “ τ -jet” that contains only a few charged and neutral hadrons. Hadronic decays are dominated by one- and three-prong topologies and often include neutral pions that promptly convert to photons, giving a sizable electromagnetic fraction in the calorimeters. When the τ momentum is large compared to its mass the decay products are highly collimated: for

$p_T > 50 \text{ GeV}$ roughly 90% of the visible energy is contained within a cone of radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} = 0.2$. These properties motivate the use of small signal cones and narrow isolation annuli in reconstruction.

Identification exploits three complementary classes of observables:

- Calorimetric isolation and shower-shape variables: hadronic τ decays deposit localized energy in ECAL+HCAL. Experiments use isolation sums and shape ratios to quantify peripheral activity. Example variables are

$$\Delta E_T^{12} = \frac{\sum_{0.1 < \Delta R < 0.2} E_{T,j}}{\sum_{\Delta R < 0.4} E_{T,i}}, \quad P_{\text{ISOL}} = \sum_{\Delta R < 0.40} E_T - \sum_{\Delta R < 0.13} E_T,$$

which suppress QCD jets that populate the isolation ring.

- Charged-track isolation and prong topology: the few, collimated charged tracks of a τ allow powerful selections. A common procedure defines a matching cone of radius R_m around the calorimeter jet axis to select candidate tracks above a p_T^{\min} threshold. The leading track (tr_1) is found and a narrow signal cone R_S around tr_1 is used to count associated tracks (1 or 3 prongs preferred). A larger isolation cone R_I is scanned for additional tracks: if no extra tracks with Δz_{impact} consistent with tr_1 are found, the candidate is isolated. Typical CMS/ATLAS choices are $R_S \sim 0.07\text{--}0.15$, $R_I \sim 0.3\text{--}0.4$, and $p_T^{\min} \sim 1\text{--}2 \text{ GeV}$, although values depend on analysis and working point.
- Lifetime and vertexing observables: the finite τ lifetime ($c\tau \approx 87 \mu\text{m}$) produces displaced tracks and, for multi-prong decays, a reconstructible secondary vertex. Impact-parameter significances (2D or 3D) and secondary-vertex properties (mass, flight length significance) are used to separate genuine taus from prompt jets or leptons.

Additional discriminants include the invariant mass of the visible decay products computed from tracks and calorimeter clusters, electromagnetic energy fractions (sensitive to $\pi^0 \rightarrow \gamma\gamma$), and dedicated shower-strip grouping for nearby photons. For example, invariant-mass reconstruction commonly uses a jet cone $\Delta R_{\text{jet}} \lesssim 0.4$ while excluding calorimeter clusters matched to tracks by a minimum separation $\Delta R_{\text{track}} \gtrsim 0.08$ to reduce double counting.

Reconstruction algorithms combine these inputs. CMS's Hadron-Plus-Strips (HPS) and modern DeepTau methods explicitly build decay-mode hypotheses and use strip-clustering of photons plus multivariate or deep-learning discriminators to reject jets, electrons, and muons [55, 56]. ATLAS employs analogous calorimeter+track based MVAs and BDTs [57]. Typical working points trade efficiency versus background: medium points often give τ_h efficiencies of order 50–70% with light-jet misidentification rates in the per-mille to percent range, depending on kinematics and pileup.

Practical implementations tune cone sizes, isolation thresholds, and MVA inputs to the kinematic region and analysis goals; the choice of

working point is driven by the signal-to-background optimization for the search or measurement at hand.

2.2.3 B TAGGING AT MULTIPURPOSE DETECTORS

Jets originating from bottom quarks (b -jets) exhibit several distinctive properties that enable their identification. The relatively long lifetime of b hadrons (order 1.5 ps) produces displaced charged tracks and often reconstructible secondary vertices a few millimetres from the primary interaction point. The large b -hadron mass yields decay products with sizable transverse momentum relative to the jet axis, and semileptonic branching fractions produce soft electrons or muons inside the jet. These features form the basis for b -tagging.

Practical algorithms exploit individual signatures or combine them:

- **Track-counting:** counts tracks with large impact-parameter significance to identify a b -like topology.
- **Jet-probability:** evaluates the compatibility of the jet's track impact-parameter distribution with the primary vertex hypothesis.
- **Secondary-vertex:** explicitly reconstructs displaced vertices and uses their kinematic properties (decay length significance, vertex mass).
- **Soft-lepton taggers:** identify low- p_T leptons inside jets from semileptonic b decays.

Modern taggers combine many observables in multivariate or deep-learning classifiers to maximize discrimination power. Contemporary approaches exploit rich, low-level inputs (track-by-track and PF-candidate information, vertex features and kinematics) and advanced network architectures:

- Deep feed-forward networks (e.g. DeepCSV/DeepJet) ingest a large set of high-level and per-track inputs to produce powerful binary or multi-class discriminants that separate b , c and light-flavour jets.
- Sequence models and recurrent networks (RNN-based taggers) process an arbitrary ordered list of track-level variables, improving sensitivity by directly exploiting per-track correlations and order-dependent information (impact-parameter sequences, track kinematics).
- Graph- and set-based architectures and combined particle+vertex networks (sometimes referred to as “DeepFlavour”-style models) aggregate heterogeneous inputs and return per-flavour probabilities, enabling natural multi-classification and calibrated operating points.

These developments yield measurable performance gains: modern deep classifiers typically improve b efficiency at fixed mistag rate (or reduce

mistag rates at fixed efficiency) relative to classical taggers. The continuous output of such networks permits analyses to choose operating points (loose/medium/tight) corresponding to desired efficiencies or mistag targets. Calibration remains essential: data-driven scale factors derived from control samples (e.g. $t\bar{t}$, multijet, dilepton) are applied to correct simulation, and systematic uncertainties from the calibration, flavour composition, and kinematic extrapolation are propagated to physics results.

Examples in use are CMS DeepCSV / DeepJet and ATLAS MV2 / DL1 [56, 57], which illustrate the transition from expert-designed high-level variables to large-scale machine learning leveraging low-level detector information. Typical medium working points yield b-tag efficiencies of order 60–80% with light-jet misidentification rates at or below the percent level; the precise choice of working point is tuned per analysis to optimise sensitivity while accounting for calibration and systematic uncertainties.

2.3 THE CMS DETECTOR

CMS is a general-purpose detector at the LHC [58]. With a length of 21.6 m, a diameter of 14.6 m, and a weight of 14,000 tonnes, its cylindrical geometry is divided into a central barrel section and two endcaps. This design provides hermetic coverage to accurately measure momentum and energy balance, which is crucial for identifying non-interacting particles like neutrinos through missing transverse energy.

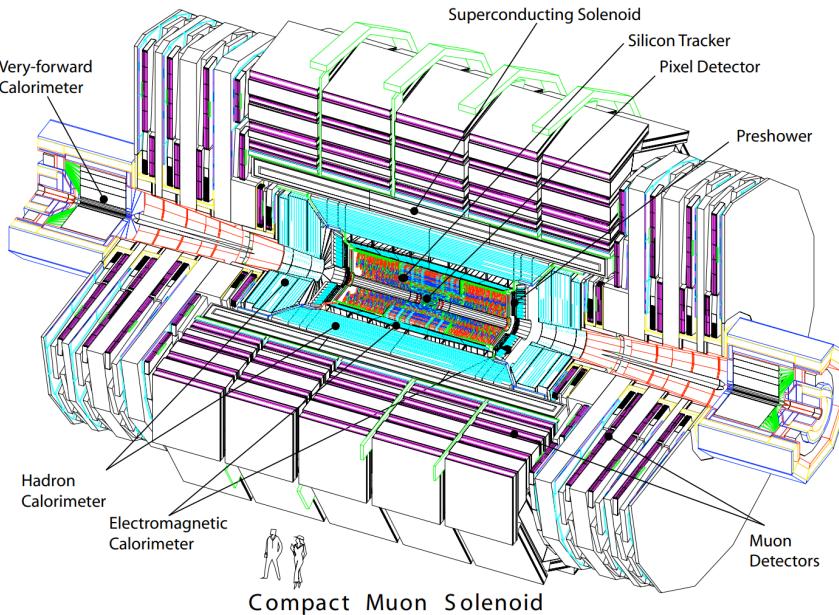


Figure 2.5: Layout of the CMS experiment at the CERN LHC. (retrieved from [58]).

The detector is constructed from concentric layers of sub-detectors, as illustrated in Figure 2.5. The innermost component is the silicon tracker, comprising a pixel detector and silicon strip tracker. It reconstructs the trajectories of charged particles and measures their transverse momenta (p_T)

with a resolution of $\approx 0.7\%$ for 10 GeV particles within a pseudorapidity range of $|\eta| < 2.5$.

Surrounding the tracker is the calorimetric system. The electromagnetic calorimeter (ECAL) is made of lead-tungstate crystals. It is designed to measure electrons and photons with a high resolution of $\approx 0.6\%$ for 50 GeV electrons. The hadronic calorimeter (HCAL), located outside the ECAL, is a brass-scintillator sampling calorimeter that measures hadrons (e.g., charged pions, kaons, protons) with an energy resolution of $\approx 18\%$ for 50 GeV pions. Together, the ECAL and HCAL cover $|\eta| < 3$. The coverage is extended to $|\eta| < 5$ with steel and quartz-fiber hadron calorimeters in the forward regions.

A key feature of CMS is its large superconducting solenoid, which encloses the tracker and calorimeters. The solenoid is constructed from a niobium-titanium alloy and cooled to 4.2 K with liquid helium. It generates a uniform magnetic field of 3.8 T throughout the tracking volume, enabling precise momentum measurement from the curvature of charged particle tracks.

The outermost system is dedicated to muon identification and measurement. Gas-ionization detectors are embedded in the steel flux-return yoke that surrounds the solenoid. This system provides triggering and tracking capabilities for muons up to $|\eta| < 2.4$. The combination of the inner tracker and the muon system allows for a robust identification and momentum measurement of muons across a wide kinematic range.

The geometrical segmentation of the barrel and endcaps defines the detector’s acceptance in terms of pseudorapidity. The central barrel provides optimal coverage for $|\eta| \lesssim 1.5$, while the endcaps extend the acceptance to $|\eta| \lesssim 2.5$ for the tracker and calorimeters, and to $|\eta| \lesssim 2.4$ for the muon system.

This segmentation impacts the detection efficiency. The silicon trackers are highly efficient in the barrel, where particles cross the layers perpendicularly. In the endcaps, the reduced hit multiplicity from shallow-angle traversals leads to a slight decrease in tracking efficiency and resolution. The calorimeters are also optimized to maintain performance across η , though the material budget and granularity vary.

Muon reconstruction performance exhibits regional differences. In the barrel, drift tubes (DTs) provide high spatial resolution, while in the endcaps, cathode strip chambers (CSCs) and resistive plate chambers (RPCs) are used to handle higher background rates and non-uniform magnetic fields. The assumed identification efficiency for muons (electrons) is 95% (85%), with a mis-identification rate of 0.3% (0.6%) [59–61].

For the identification of heavy-flavor jets, we adopt the DeepCSV algorithm [62]. We use its “medium” working point, which provides a b-tagging efficiency of 70% with a light-flavor jet misidentification rate of approximately 1% across the entire p_T spectrum. The “loose” (85% efficiency, 10% mis-id) and “tight” (45% efficiency, 0.1% mis-id) working points were also explored during the analysis optimization.

For hadronically decaying τ leptons (τ_h), we use the DeepTau algorithm [56], which employs a deep neural network combining isolation and lifetime information to identify τ_h decay modes. The “medium” working point is chosen for this analysis, providing a τ_h identification efficiency of 70% and a misidentification rate of 0.5% for jets originating from light quarks and gluons. This working point was selected through an optimization process that maximized the discovery reach of the analysis.

2.4 THE PHENOMENOLOGICAL PIPELINE: FROM THEORY TO OBSERVABLES

The estimation of signal and background event yields is performed through a comprehensive Monte Carlo (MC) simulation pipeline. This approach, a cornerstone of high-energy physics research, enables robust studies of Beyond the Standard Model (BSM) scenarios by emulating the entire data collection and processing chain of a collider experiment. The key advantages of this methodology include:

- The ability to perform automated calculations of theoretical quantities such as cross-sections and decay widths for complex processes.
- Conducting feasibility studies and optimizing analysis strategies prior to data acquisition.
- Estimating the efficiency of complex event selection criteria and the geometric acceptance of the detector.
- Predicting the rates and kinematical distributions of both irreducible and reducible background processes.
- Comparing and distinguishing between different theoretical hypotheses for a potential discovered signal.

The simulation workflow is modular, reflecting the logical progression from a theoretical Lagrangian to simulated detector-level observables. A schematic view of this pipeline is presented in Figure ???. The process begins with the implementation of the theoretical model in FeynRules (v2.3.43) [63, 64]. The Lagrangian of the new physics scenario, including all particle definitions, parameters, and interactions, is translated into a set of Feynman rules. The output is exported in the Universal FeynRules Output (UFO) [65] format, a standard interoperable with modern matrix element generators.

This UFO module, accompanied by a parameter card defining the numerical values of all model parameters (masses, couplings, etc.), serves as input to the `MadGraph5_aMC@NLO` (v3.5.7) [66, 67] framework. Within MadGraph, the hard scattering process is defined, and the corresponding matrix elements (ME) and Feynman diagrams are generated at leading order (LO) in QCD. For this analysis, proton-proton collisions are simulated

at center-of-mass energies of $\sqrt{s} = 13 \text{ TeV}$ and $\sqrt{s} = 13.6 \text{ TeV}$, utilizing the NNPDF3.0 NLO [68] set of parton distribution functions (PDFs). This choice is motivated by its global fit accuracy and consistency for both LO and NLO simulations.

To accurately model processes featuring significant interference effects between the new physics signal (e.g., a Z' boson) and the Standard Model backgrounds, the full squared amplitude (often referred to as the Signal-Discriminated Events or SDE strategy) is employed for the phase-space integration. The MadEvent submodule then generates unweighted parton-level events, which are stored in the Les Houches Event (LHE) format, containing the four-momenta of all final-state particles. The generation is optimized through careful configuration of the `run_card`, setting appropriate kinematic cuts on final-state partons to avoid wasting computational resources on events that would subsequently be rejected by the detector simulation.

Given the presence of additional jet radiation, the MLM matching scheme [69] is applied to mitigate the double-counting of jet emission between the matrix element calculation and the subsequent parton shower. This ensures a smooth transition between the hard process and softer radiative effects.

The parton-level LHE events are then passed to PYTHIA (v8.2.44) [70] for the modeling of QCD and QED radiation (parton showering), hadronization, and particle decays. This step translates the colored partons into stable, color-singlet hadrons and resonances that form the observable final state. The resulting events, which include a full list of generator-level particles, are saved in the HepMC₂ format.

Detector effects are simulated using DELPHES (v3.4.2) [71], a fast parametric detector simulation framework. The `delphes_card_CMS.tcl` configuration card is used to emulate the response of the CMS detector, including the geometric acceptance, tracking efficiency, calorimeter energy resolution and segmentation, and magnetic field. Key reconstruction algorithms are applied within DELPHES:

- Jets are clustered from calorimeter towers using the anti- k_t algorithm [53] with a distance parameter of $R = 0.4$, and b-tagging is simulated based on the efficiency and mis-tag rate of the CMS performance.
- Muons and electrons are identified with efficiency maps that are functions of p_T and η .
- The missing transverse energy (MET) is calculated from the negative vector sum of all reconstructed particle momenta.

The final output, containing reconstructed physics objects (jets, leptons, MET), is stored in ROOT format [**Brun:1997pa**].

At this stage, the analysis of the simulated samples converges with the methodology applied to real collider data. The subsequent steps involve

applying event selection criteria, calibrating and scaling the reconstructed objects (e.g., applying Jet Energy Corrections), and performing statistical interpretation. The reliability of the simulation is validated by comparing the modeling of well-known Standard Model processes (e.g., Drell-Yan, $t\bar{t}$ production) against published results and data-driven control regions. Dominant theoretical systematic uncertainties, such as those arising from the choice of factorization and renormalization scales, PDF variations, and parton shower modeling, are evaluated and propagated through the analysis.

2.5 MEASUREMENT OF THE POWER OF AN ANALYSIS

In high-energy physics experiments, data is often discretized into bins (e.g., histograms of collision events versus energy or momentum) to test competing hypotheses. The fundamental framework compares two scenarios: the *null hypothesis* (H_0), representing background-only processes (b_i in each bin i), and the *alternative hypothesis* (H_1), including both signal and background ($s_i + b_i$). Given the Poissonian nature of event counts n_i , the likelihood for observing the data under each hypothesis is:

$$\mathcal{L}(n_i | \lambda_i) = \frac{e^{-\lambda_i} \lambda_i^{n_i}}{n_i!}, \quad \text{where } \lambda_i = \begin{cases} b_i & \text{for } H_0, \\ s_i + b_i & \text{for } H_1. \end{cases} \quad (2.5)$$

The Neyman-Pearson lemma [NeymanPearson1933] provides a rigorous framework for hypothesis testing by establishing that the *likelihood ratio* $Q = \mathcal{L}(\text{data} | H_1)/\mathcal{L}(\text{data} | H_0)$ is the most powerful test statistic for distinguishing between two simple hypotheses, H_0 and H_1 . This forms the basis for quantifying the evidence for new physics signals against known backgrounds. For binned analyses in particle physics, we define the likelihood ratio Q_i for each bin i as,

$$Q_i = \frac{\mathcal{L}(n_i | s_i + b_i)}{\mathcal{L}(n_i | b_i)} = e^{-s_i} \left(1 + \frac{s_i}{b_i}\right)^{n_i}, \quad (2.6)$$

where n_i is the observed event count, s_i the expected signal, and b_i the expected background in bin i .

The test for the full analysis is constructed as the product of individual bin likelihood ratios:

$$Q = \prod_{i=1}^N Q_i, \quad (2.7)$$

where N is the total number of bins. Under this formulation, each bin is treated as an independent experiment, allowing us to analyze the data in a modular way. This is particularly useful when combining results from multiple search channels or energy ranges.

For convenience and in order to connect with asymptotic distributions, we take the logarithm of the likelihood ratio, turning the product into a sum:

$$-2 \ln Q = 2 \sum_{i=1}^N \left[s_i - n_i \ln \left(1 + \frac{s_i}{b_i} \right) \right], \quad (2.8)$$

where n_i is the observed number of events, b_i the expected background, and s_i the expected signal in bin i . By Wilks' theorem [Wilks1938], the asymptotic distribution of this test statistic under the background-only hypothesis (H_0) follows a χ^2 distribution, facilitating p-value calculations and hypothesis testing.

In practice, the Neyman-Pearson lemma motivates the use of a test statistic t that quantifies the evidence for a signal against the background-only hypothesis, which can be written as

$$t = -2 \ln Q = \sum_{i=1}^N [2s_i - 2n_i w_i], \quad (2.9)$$

with the optimal weight of each bin given by $w_i = \ln \left(1 + \frac{s_i}{b_i} \right)$.

The discovery significance κ quantifies the statistical separation of t if n is distributed according to the background-only hypothesis (H_0) versus the signal-plus-background hypothesis (H_1), normalized by the standard deviation of the H_1 distribution,

$$\kappa = \frac{\langle t \rangle_{H_0} - \langle t \rangle_{H_1}}{\sigma_{H_1}}. \quad (2.10)$$

The expected behavior differs under the signal-plus-background (H_1) and background-only (H_0) hypotheses:

- Under H_1 ($n_i \sim \text{Pois}(s_i + b_i)$):

$$\langle -2 \ln Q \rangle_{s+b} = \sum_i [2s_i - 2(s_i + b_i)w_i] \implies \sigma_{s+b}^2 = 4 \sum_i (s_i + b_i)w_i^2. \quad (2.11)$$

- Under H_0 ($n_i \sim \text{Pois}(b_i)$):

$$\langle -2 \ln Q \rangle_b = \sum_i [2s_i - 2b_i w_i] \implies \sigma_b^2 = 4 \sum_i b_i w_i^2 \quad (2.12)$$

Substituting in κ gives a useful expression for the discovery significance,

$$\kappa = \frac{\sum s_i w_i}{\sqrt{\sum (s_i + b_i) w_i^2}} \quad (2.13)$$

It quantifies the separation between the signal+background ($s + b$) and background-only hypotheses in units of standard deviations (σ), where $\kappa = 5$ corresponds to the traditional 5σ discovery threshold, $\kappa = 3$ to a 3σ

evidence to the traditional anomaly detection threshold, and $\kappa = 1.69$ to the 95% confidence level (CL) exclusion limit.

This figure of merit automatically optimizes sensitivity through the logarithmic weights $w_i = \ln(1 + s_i/b_i)$, which naturally emphasize bins with either high signal-to-background ratios (s_i/b_i) or large absolute signal contributions (s_i). In asymptotic limits, κ simplifies to intuitive forms: for dominant signals ($s_i \gg b_i$), it approaches $\sqrt{\sum s_i}$ (Poisson counting), while in background-dominated regimes ($s_i \ll b_i$), it reduces to an inverse-variance-weighted sum $\sum s_i / \sqrt{\sum b_i (s_i/b_i)^2}$. This dual behavior ensures optimal discrimination power across all signal regimes.

In practice, we must take into account systematic effects by incorporating nuisance parameters into the likelihood and profiling over uncertainty ranges. The power calculation can be extended to include systematic uncertainties by modifying the denominator as,

$$\kappa_{\text{sys}} = \frac{\sum_i s_i w_i}{\sqrt{\sum_i [(s_i + b_i) + \delta_{\text{sys,signal},i}^2 + \delta_{\text{sys,bkg},i}^2] w_i^2}}, \quad (2.14)$$

where δ_{sys} terms represent the systematic uncertainties on signal and background predictions.

3

$U(1)_{T_R^3}$ GAUGE EXTENSION OF THE STANDARD MODEL

Based on [72]

Extensions of the Standard Model (SM) that introduce new $U(1)$ gauge symmetries are among the most widely studied scenarios for physics beyond the SM. In particular, the $U(1)_{T_R^3}$ symmetry is of interest. In this scenario, right-handed SM fermions and possible new states, such as right-handed neutrinos, are charged under $U(1)_{T_R^3}$. This symmetry has been explored in the context of left-right symmetric models [73–75].

In these frameworks, $U(1)_{T_R^3}$ is identified as the diagonal, electrically neutral generator of $SU(2)_R$. It is often related to $U(1)_{B-L}$ through the breaking pattern

$$U(1)_{B-L} \times U(1)_{T_R^3} \rightarrow U(1)_Y.$$

This motivates the existence of a new, massive, electrically neutral gauge boson associated with the extra $U(1)$ symmetry [76–80].

However, the Higgs doublet being a singlet under $U(1)_{B-L}$, acquires its hypercharge from $U(1)_{T_R^3}$. Its vacuum expectation value (VEV) links the symmetry-breaking scales of $U(1)_Y$ and $U(1)_{T_R^3}$. Alternatively, these scales can be decoupled by introducing an additional $U(1)_G$ group, under which SM fermions are singlets but the Higgs is charged. In this case [81]:

$$Y = Q_{T_R^3} + \frac{1}{2}Q_{B-L} + Q_G. \quad (3.1)$$

More generally, scenarios can be constructed where the hypercharge is not directly related to $U(1)_{T_R^3}$.

Recent theoretical and phenomenological work has focused on models where the low-energy gauge symmetry of the SM is extended by an Abelian $U(1)_{T_R^3}$ group. In these models, the spontaneous breaking of $U(1)_{T_R^3}$ is not tied to electroweak symmetry breaking [82–87].

The corresponding gauge boson of the extra $U(1)$ is a neutral vector particle whose physical interpretation depends on its couplings and mass range. If the new boson couples directly to SM fermions with electroweak-strength interactions, it is often referred to as a Z' . If instead the new boson interacts only very weakly with the SM, typically through kinetic mixing with the hypercharge gauge boson, it is commonly called a dark photon A' . In either case, the gauge boson acquires mass through a Higgs-like mechanism. A complex scalar field ϕ , singlet under the SM gauge group,

can provide the longitudinal degree of freedom. Its CP-odd component gives mass to the neutral vector boson, while its CP-even component can manifest as a dark Higgs, ϕ' .

To ensure anomaly cancellation, a right-handed neutrino ν_R is required for each SM generation that couples to $U(1)_{T_R^3}$. In addition, a set of new vector-like fermions ($\chi_u, \chi_d, \chi_\ell, \chi_\nu$) is introduced to generate fermion masses in a UV-complete theory, following the universal see-saw mechanism [88–93]. This mechanism introduces a non-trivial $\chi_u - t - \phi'$ coupling. This vertex allows for the production of $t\chi_u\phi'$ final states via $\chi_u - t$ fusion (see Figure 3.3). Since χ_u couples to SM quarks and gluons, it can be copiously produced. Its energetic decay products, together with a ϕ' mediator carrying significant transverse momentum, can be efficiently detected, especially if ϕ' decays to visible SM particles in the central detector region.

This strategy is effective for reducing SM backgrounds and enhances the LHC discovery potential for heavy top partners and GeV-scale mediators, which are otherwise challenging to probe at hadron colliders. Moreover, $t\chi_u\phi'$ final states can also arise from $\chi_u\bar{\chi}_u$ production via QCD vertices, where one χ_u decays to $t\phi'$ (see Figure 3.4). The presence of energetic decay products and a mediator with substantial transverse momentum provides greater sensitivity than searches considering χ_u or ϕ' alone.

In this chapter, we perform a phenomenological study of search strategies at the LHC for a light (GeV-scale) scalar ϕ' produced in association with a heavy (TeV-scale) top-partner χ_u . We focus on the previously unexplored production channel $pp \rightarrow t\chi_u\phi'$, which contrasts with the more commonly studied $pp \rightarrow TT \rightarrow t\phi't\phi'$ and di-photon ϕ' decay channels, see Section 3.2 and [94–98].

We consider the case where ϕ' has family non-universal couplings to fermions, as proposed in [83]. Such couplings can address several open questions in the SM. Our analysis focuses on $\phi' \rightarrow \mu^+\mu^-$ decays, as muons are efficiently reconstructed and identified. This allows for low $p_T(\mu)$ triggers and provides a characteristically clean signature to suppress QCD multijet backgrounds.

To further maximize the sensitivity to this complex signal, a central component of our analysis is the use of ML. We employ an analysis based on Boosted Decision Trees (BDT) [99]. The BDT output is used in a profile-binned likelihood test to determine the signal significance for each model. The effectiveness of BDTs and other ML algorithms has been demonstrated in numerous experimental and phenomenological studies [80, 100–109]. Our results show that the BDT approach significantly improves sensitivity.

The remainder of this chapter is organized as follows. Section 3.2 describes the minimal $U(1)_{T_R^3}$ model. Section 3.1 reviews current relevant LHC results. Section 3.3 details the Monte Carlo (MC) simulation samples used in this study. Section 3.4 discusses the motivation and implementation of the machine learning workflow, and Section 3.5 presents the main results.

3.1 CURRENT EXCLUSION LIMITS ON VECTOR-LIKE QUARKS

The ATLAS and CMS collaborations at CERN have conducted various searches for heavy vector-like quarks (T). These searches utilized pp collisions at center-of-mass energies of $\sqrt{s} = 8$ and 13 TeV. The studies primarily focused on T production through gluon-mediated QCD processes, either in pair production from quark-antiquark annihilation (Figure 3.1) or in single- T production from electroweak processes involving associated quarks (Figure 3.2).

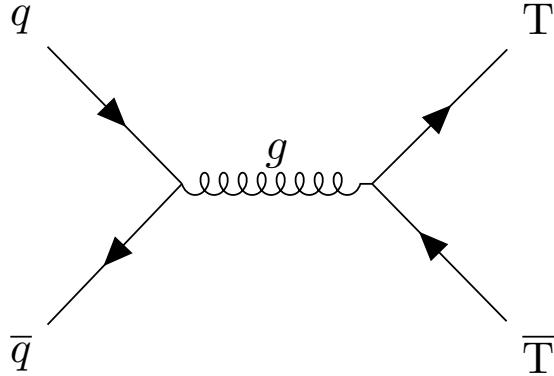


Figure 3.1: Representative Feynman diagram for T pair production via gluon-mediated QCD processes.

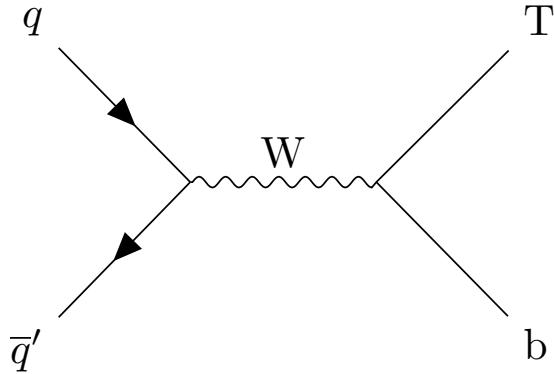


Figure 3.2: Representative Feynman diagram for single T production via electroweak processes.

In those studies, T decays into bW , tZ , or tH have been considered. In the context of T pair production, $T\bar{T}$, via QCD processes, the cross sections are well-known and solely depend on the mass of the vector-like quark. Assuming a narrow T decay width ($\Gamma/m(T) < 0.05$ or 0.1) and a 100% branching fraction to bW , tZ , or tH , these searches have set stringent bounds on $m(T)$, excluding masses below almost 1.5 TeV at 95% confidence level [110–117]. The most recent analysis from the CMS collaboration probes T -quark production via $pp \rightarrow Tqb$, in final states with $T \rightarrow tZ$ or $T \rightarrow tH$, considering scenarios with preferential couplings to third-generation fermions. The analysis sets 95% confidence level upper limits

of 68–1260 fb on the production cross section, for T masses ranging from 600–1200 GeV [111]. The latest studies from ATLAS probe vector-like quarks using the single-T production mode with the $T \rightarrow tH$ decay channel leading to a fully hadronic final state [112], the single-T production mode with the $T \rightarrow tZ$ decay channel leading to a multileptonic final state [113], the TT pair production mode with various T decay channels leading to multileptonic final states [114], and the TT pair production mode with various T decay channels leading to a single lepton plus missing momentum final state [115, 116]. The multilepton search offers the greatest sensitivity in most of the phase space, but the missing transverse energy based search has better sensitivity for low branching fraction $\mathcal{B}(T \rightarrow Wb)$ and high $\mathcal{B}(T \rightarrow Ht)$. These searches have similar sensitivities for the singlet and doublet models, resulting in exclusion bounds for masses below about 1.25 TeV and 1.41 TeV, respectively.

A key consideration in the model interpretations summarized above is that the T branching fractions depend on the chosen model. The excluded mass range is less restrictive for specific branching fraction scenarios, such as $\{\mathcal{B}(T \rightarrow tZ), \mathcal{B}(T \rightarrow bW), \mathcal{B}(T \rightarrow tH)\} = \{0.2, 0.6, 0.2\}$, excluding masses below about 0.95 TeV. Moreover, if the $T \rightarrow \phi't$ decay is allowed, or if the branching fractions $\mathcal{B}(T \rightarrow tH/bW)$ are lower, the limits previously quoted must be re-evaluated. The authors of Ref. [118] emphasize that bounds on $m(T)$ can be around 500 GeV when $T \rightarrow t\phi'$ decays are permitted. Therefore, to facilitate a comprehensive study, benchmark scenarios in this paper are considered down to $m(\chi_u) = 500$ GeV.

3.2 THE MINIMAL $U(1)_{T_R^3}$ MODEL

The model extends the SM by an Abelian gauge symmetry $U(1)_{T_R^3}$, under which only the right-handed fermions are charged. The symmetry breaking is achieved via two independent Higgs mechanisms: one with the SM Higgs doublet H for electroweak symmetry breaking, and another with a Higgs singlet ϕ for breaking $U(1)_{T_R^3}$. These scalars acquire independent vacuum expectation values (VEVs), $\langle H \rangle = v_h/\sqrt{2}$ and $\langle \phi \rangle = v_\phi/\sqrt{2}$. In the Kibble parametrization, the fields are written as:

$$H = \begin{pmatrix} G_+ \\ \frac{1}{\sqrt{2}}(v_h + \rho_0 + iG_0) \end{pmatrix}, \quad (3.2)$$

$$\phi = \frac{1}{\sqrt{2}}(v_\phi + \rho_\phi + iG_\phi). \quad (3.3)$$

In Eqs. (3.2) and (3.3), G_\pm , G_0 , and G_ϕ are the Goldstone bosons absorbed by the SM W^\pm and Z bosons and the dark photon A' (associated with $U(1)_{T_R^3}$) to acquire mass. The fields ρ_h and ρ_ϕ mix to form the physical mass eigenstates, the SM-like Higgs boson h and a dark Higgs ϕ' :

$$\begin{pmatrix} h \\ \phi' \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \rho_0 \\ \rho_\phi \end{pmatrix}. \quad (3.4)$$

This mixing arises from diagonalizing the mass matrix derived from the gauge-invariant scalar potential:

$$\begin{aligned} V(H, \phi) = & \mu_H^2 H^\dagger H + \mu_\phi^2 \phi^* \phi \\ & + \lambda(H^\dagger H)(\phi^* \phi) + \lambda_H(H^\dagger H)^2 + \lambda_\phi(\phi^* \phi)^2. \end{aligned} \quad (3.5)$$

Minimizing the potential yields the tadpole equations:

$$\frac{\partial V}{\partial H} = \frac{v_h}{\sqrt{2}} \left(\mu_H^2 + \lambda_H v_h^2 + \frac{1}{2} \lambda v_\phi^2 \right) = 0, \quad (3.6)$$

$$\frac{\partial V}{\partial \phi} = \frac{v_\phi}{\sqrt{2}} \left(\mu_\phi^2 + \lambda_\phi v_\phi^2 + \frac{1}{2} \lambda v_h^2 \right) = 0. \quad (3.7)$$

The physical scalar masses are given by:

$$m_{h,\phi'}^2 = \frac{1}{2} (\lambda_H v_h^2 + \lambda_\phi v_\phi^2) \pm \sqrt{\lambda^2 v_h^2 v_\phi^2 + (\lambda_H v_h^2 - \lambda_\phi v_\phi^2)^2}, \quad (3.8)$$

and the mixing angle α satisfies:

$$\tan 2\alpha = \frac{-\lambda v_h v_\phi}{\lambda_\phi v_\phi^2 - \lambda_H v_h^2}. \quad (3.9)$$

The quartic couplings can be expressed in terms of the physical parameters:

$$\lambda_H = \frac{m_{\phi'}^2 + m_h^2 + (m_{\phi'}^2 - m_h^2) \cos 2\alpha}{4v_h^2}, \quad (3.10)$$

$$\lambda_\phi = \frac{m_{\phi'}^2 + m_h^2 + (m_{\phi'}^2 - m_h^2) \cos 2\alpha}{4v_\phi^2}, \quad (3.11)$$

$$\lambda = \frac{m_{\phi'}^2 - m_h^2}{2v_h v_\phi} \sin 2\alpha. \quad (3.12)$$

Thus, the scalar sector has four free parameters: the masses m_h and $m_{\phi'}$, the mixing angle α , and the dark Higgs VEV v_ϕ . Similar to how v_h is fixed by the electroweak gauge boson masses, v_ϕ is related to the dark photon mass by $m_A^2 = g_{T_R^3}^2 v_\phi^2$, where $g_{T_R^3}$ is the $U(1)_{T_R^3}$ gauge coupling. Depending on the value of $g_{T_R^3}$, this gauge boson can behave as a heavy Z' or a light dark photon. In this chapter, we assume $g_{T_R^3}$ is sufficiently small such that A' can be treated as a dark photon.

3.2.1 THE UNIVERSAL SEESAW MECHANISM

In this model, the masses of the SM fermions are generated through a universal seesaw mechanism by mixing with vector-like fermions χ_f . The relevant mass terms in the Lagrangian are:

$$-\mathcal{L} \supset Y_{f_L} \bar{f}'_L \chi'_{fR} H + Y_{f_R} \bar{\chi}'_{fL} f'_R \phi^* + m_{\chi'_f} \bar{\chi}'_{fL} \chi'_{fR} + \text{h.c.} \quad (3.13)$$

This leads to the mass matrix:

$$M_f = \begin{pmatrix} 0 & Y_{f_L} v_h / \sqrt{2} \\ Y_{f_R} v_\phi / \sqrt{2} & m_{\chi'_f} \end{pmatrix}. \quad (3.14)$$

The mass eigenstates (f, χ_f) are obtained by rotating the gauge eigenstates:

$$\begin{pmatrix} f_{L,R} \\ \chi_{f_{L,R}} \end{pmatrix} = \begin{pmatrix} \pm \cos \theta_{f_{L,R}} & \mp \sin \theta_{f_{L,R}} \\ \sin \theta_{f_{L,R}} & \cos \theta_{f_{L,R}} \end{pmatrix} \begin{pmatrix} f'_{L,R} \\ \chi'_{f_{L,R}} \end{pmatrix}, \quad (3.15)$$

such that $\mathcal{R}(\theta_{f_L}) M_f \mathcal{R}^{-1}(\theta_{f_R}) = \text{diag}(m_f, m_{\chi_f})$. For real parameters, the physical masses and mixing angles are given by:

$$m_f m_{\chi_f} = \frac{Y_{f_L} v_h Y_{f_R} v_\phi}{2}, \quad (3.16)$$

$$m_f^2 + m_{\chi_f}^2 = m_{\chi'_f}^2 + \frac{1}{2} (Y_{f_L}^2 v_h^2 + Y_{f_R}^2 v_\phi^2), \quad (3.17)$$

$$\tan \theta_{f_{L,R}} = \frac{\sqrt{2}}{m_{\chi'_f}} \left(\frac{Y_{f_{L,R}} v_{h,\phi}}{2} - \frac{m_f^2}{Y_{f_{L,R}} v_{h,\phi}} \right). \quad (3.18)$$

The Yukawa interactions of the physical fermions with the scalars h and ϕ' are:

$$-\mathcal{L}_{\text{yuk}} = h \bar{\psi}_{f_L} \gamma_h \psi_{f_R} + \phi' \bar{\psi}_{f_L} \gamma_\phi \psi_{f_R}, \quad (3.19)$$

where $\psi_f = (f, \chi_f)^T$. The Yukawa matrices are:

$$\gamma_h = \frac{1}{\sqrt{2}} \mathcal{R}(\theta_{f_L}) (Y_{f_L} \sigma_+ \cos \alpha - Y_{f_R} \sigma_- \sin \alpha) \mathcal{R}^{-1}(\theta_{f_R}), \quad (3.20)$$

$$\gamma_\phi = \frac{1}{\sqrt{2}} \mathcal{R}(\theta_{f_L}) (Y_{f_L} \sigma_+ \sin \alpha + Y_{f_R} \sigma_- \cos \alpha) \mathcal{R}^{-1}(\theta_{f_R}), \quad (3.21)$$

with $\sigma_\pm = (\sigma_1 \pm i\sigma_2)/2$ being the ladder Pauli matrices.

The expressions above provide a simplified, one-generation view. The complete model involves a non-trivial flavor structure where the mass matrices are general 3×3 matrices. The diagonalization of the full 6×6 mass matrices, the procedure for absorbing unphysical unitary rotations, and the emergence of the CKM matrix are detailed in Appendix B. Furthermore, the appendix contains a rigorous treatment of the mass eigenvalue problem, deriving the exact relationship between the fundamental parameters (m_L, m_R, m_χ) and the physical observables (m_f, m_F, θ_L) , which leads to critical constraints on the model's parameter space to ensure perturbativity.

3.2.2 MINIMAL UV-COMPLETE THEORY

To generate non-zero masses for all SM fermions and ensure gauge anomaly cancellation, the model must include at least one full generation of vector-like fermions $\{\chi_u, \chi_d, \chi_\ell, \chi\}$ and the right-handed neutrinos ν_R for each SM

generation. Their quantum numbers are listed in Table 3.1. The Yukawa interactions in the UV-complete theory are:

$$\begin{aligned} -\mathcal{L} \supset & Y_{Lu}^{ij} \bar{q}'^i_L \chi'_{uR} \tilde{H} + Y_{Ru}^{ij} \bar{\chi}'^i_{uL} u'_R \phi^* + m_{\chi_u}^{ij} \bar{\chi}'^i_{uL} \chi'_{uR} \\ & + Y_{Ld}^{ij} \bar{q}'^i_L \chi'_{dR} H + Y_{Rd}^{ij} \bar{\chi}'^i_{dL} d'_R \phi + m_{\chi_d}^{ij} \bar{\chi}'^i_{dL} \chi'_{dR} \\ & + Y_{L\ell}^{ij} \bar{\ell}'^i_L \chi'_{\ell R} H + Y_{R\ell}^{ij} \bar{\chi}'^i_{\ell L} \ell'_R \phi + m_{\chi_\ell}^{ij} \bar{\chi}'^i_{\ell L} \chi'_{\ell R} \\ & + Y_{L\nu}^{ij} \bar{\ell}'^i_L \chi'_{\nu R} \tilde{H} + Y_{R\nu}^{ij} \bar{\chi}'^i_{\nu L} \nu'_R \phi^* + m_{\chi_\nu}^{ij} \bar{\chi}'^i_{\nu L} \chi'_{\nu R} + \text{h.c.} \end{aligned} \quad (3.22)$$

Here, $i, j = 1, 2, 3$ are generation indices. The diagonalization of the mass matrices for each fermion type follows the structure outlined in Eqs. (3.16) and (3.17), while the Yukawa matrices generalize the structure of Eqs. (3.20) and (3.21), now encoding the CKM and PMNS mixing matrices. The neutrino sector has a more complex structure due to the possibility of a Majorana mass term for the vector-like neutrinos χ'_ν .

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{T_R^3}$
q'_L	3	2	$1/6$	0
ℓ'_L	1	2	$-1/2$	0
H	1	2	$1/2$	0
u'^c_R	3	1	$-2/3$	-2
d'^c_R	3	1	$1/3$	2
ℓ'^c_R	1	1	1	2
ν'^c_R	1	1	0	-2
ϕ	1	1	0	2
χ'_{uL}	3	1	$2/3$	0
χ'_{uR}	3	1	$-2/3$	0
χ'_{dL}	3	1	$-1/3$	0
χ'_{dR}	3	1	$1/3$	0
$\chi'_{\ell L}$	1	1	-1	0
$\chi'_{\ell R}$	1	1	1	0
$\chi'_{\nu L}$	1	1	0	0
$\chi'_{\nu R}$	1	1	0	0

Table 3.1: Minimal field content of the model and their representations under the SM and $U(1)_{T_R^3}$ gauge groups.

3.3 SAMPLES AND SIMULATION

The minimal $U(1)_{T_R^3}$ model described in Sec. 3.2 is implemented *at tree level* into the FeynRules package [64], which generates the Feynman rules and exports them into a Universal FeynRules Output (UFO) [65]. The resulting UFO is utilized as input for a generator to produce the MC samples. Both signal and background events are generated with the MadGraph5_aMC@NLO v3.2.0 program [66, 67] at leading order (LO) in QCD, considering pp beams colliding with a center-of-mass energy of $\sqrt{s} = 13.6$ TeV. Each

signal and background sample is generated separately, with no interference effects between the signal and background considered. The impact of these interference effects has been evaluated, and for all values of χ_u and ϕ' masses considered, the effect on the signal plus background cross section is found to be less than $< 0.5\%$. Additionally, the effect on the shape of the b-jet p_T distribution is less than 6% for $p_T < 300$ GeV and less than 2% for b-jet $p_T > 300$ GeV. We use the NNPDF3.0 NLO [68] set for parton distribution functions (PDFs) for all event generation. Parton-level events are then interfaced with PYTHIA (v8.2.44) [70] to account for parton showering and hadronization processes. Finally, we use DELPHES (v3.4.2) [71] to simulate smearing and other detector effects using the CMS detector geometric configurations and parameters for particle identification and reconstruction, using the CMS input card with 140 average pileup interactions.

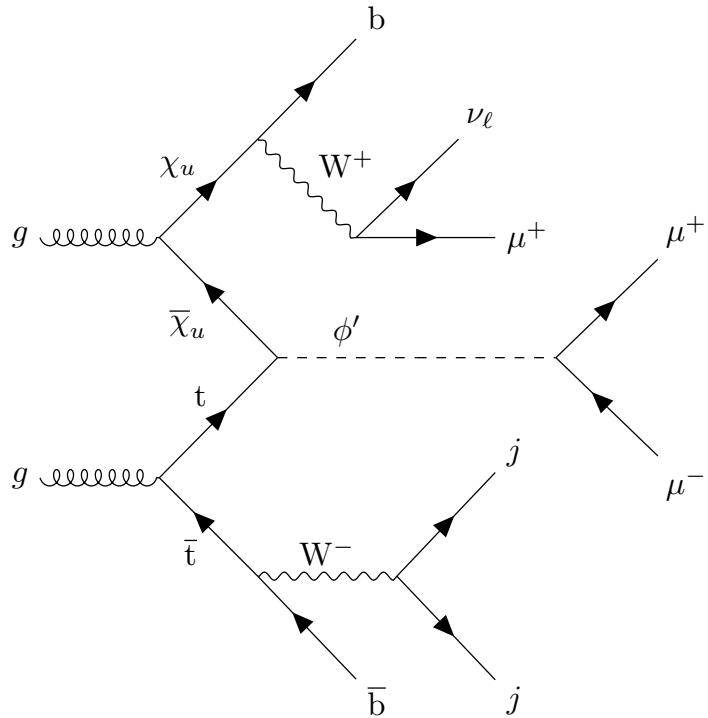


Figure 3.3: Representative Feynman diagram for the production of a ϕ' boson in association with a χ_u vector-like quark through the fusion of a top quark and χ_u vector-like quark. Once again, the ϕ' decays to a pair of muons, the top quark decays fully hadronically, and the χ_u decays semi-leptonically to muons, neutrinos and b-jets.

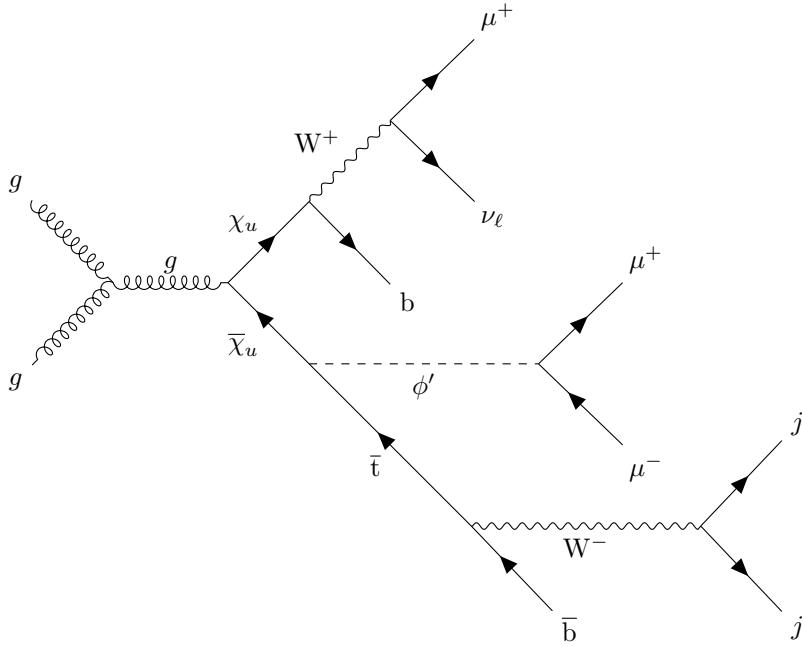


Figure 3.4: Representative Feynman diagram for the production of a ϕ' boson in association with a χ_u vector-like quark through the fusion of a gluon pair from incoming protons. The ϕ' decays to a pair of muons, the top quark that decays fully hadronically, and the χ_u decay semi-leptonically to muons, neutrinos and jets.

All signal cross sections used in this analysis are obtained requiring the following kinematic criteria on leptons ℓ , b quarks, and light-quark/gluon jets (j) at parton level in MadGraph: $p_T(\ell) > 35$ GeV, $|\eta(b)| < 2.5$, $|\eta(\ell)| < 2.3$, $p_T(j) > 20$ GeV, and $|\eta(j)| < 5$. These parton-level selections were applied exclusively to the signal processes to restrict event generation to the relevant phase space regions. For background processes, these default parton level requirements in MadGraph were imposed: $p_T(\ell) > 10$ GeV, $|\eta(\ell)| < 2.5$, $p_T(j) > 20$ GeV, $|\eta(j)| < 5$, and $|\eta(b)| < 5$. This ensures that the phase space regions for the background near the analysis-level selection criteria are adequately described after parton showering since the pre-selections at the analysis level are more stringent than the parton-level requirements. Furthermore, we use the MLM algorithm for jet matching and jet merging. The parameters x_{qcut} and q_{cut} of the MLM algorithm are set to 30 and 45 respectively to ensure continuity of the differential jet rate as a function of jet multiplicity. Each simulated signal and background sample is produced separately at LO, with one million events at the generation level, neglecting potential interference effects between the signal and background due to the suppression caused by the different orders of magnitude in the coupling constants of the signal and background.

Signal samples are generated considering the production of a ϕ' boson, an associated χ_u vector-like quark, and a top quark ($pp \rightarrow \chi_u t \phi'$), inclusive in both α and α_s (see Figures 3.3-3.4). We have used the implementation of the $U(1)_{T_R^3}$ model in Ref. [87]. Signal samples were cre-

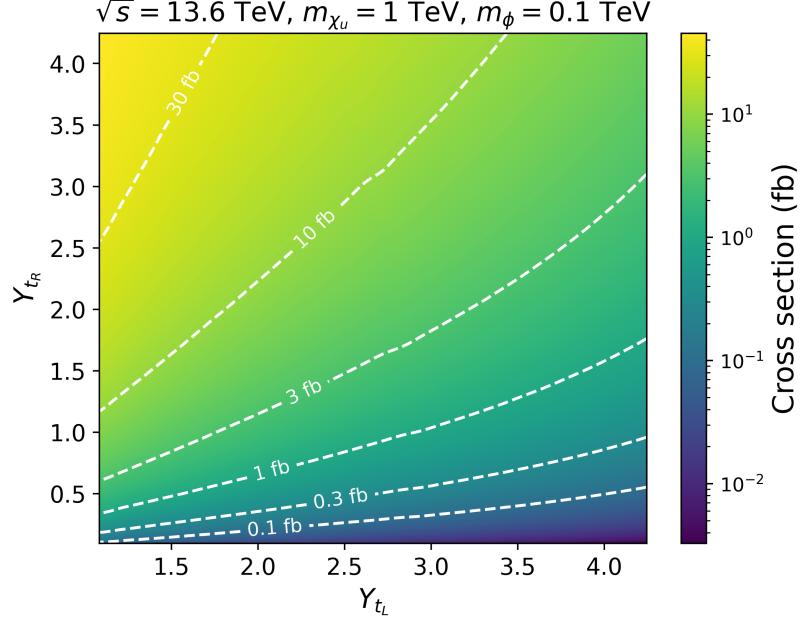


Figure 3.5: Signal production cross section, $pp \rightarrow \chi_u t \phi'$, in the Y_{t_R} versus Y_{t_L} plane, for a benchmark point with $m(\phi') = 100$ GeV and $m(\chi_u) = 1.00$ TeV. The white-dashed contours show specific cross section values in the two dimensional plane.

ated considering coupling values of $Y_{t_R} = Y_{t_L} = 2\sqrt{2}$ in the range of masses $m(\phi') \in \{5, 10, 50, 100, 325\}$ GeV for the dark higgs and $m(\chi_u) \in \{0.50, 0.75, 1.0, 1.5, 2.0, 2.5\}$ TeV for the vector-like quark χ_u [119]. The production cross section for $pp \rightarrow \chi_u t \phi'$ is highly dependent on the choice of the Yukawa couplings in the Lagrangian. The $\chi_u - t$ fusion process shown in Figure 3.3 is dominated by the Y_{t_R} coupling. However, the decay $\chi_u \rightarrow t \phi'$ shown in Figure 3.4 is inversely proportional to the Y_{t_L} coupling. This effect is shown in Figure 3.5, which displays the total signal cross section, as a function of Y_{t_R} and Y_{t_L} , for a benchmark point with $m(\phi') = 100$ GeV and $m(\chi_u) = 1.0$ TeV.

We target signal events where the top quark decays hadronically into a bottom quark and two jets ($t \rightarrow bW \rightarrow bq\bar{q}'$), the χ_u decays semileptonically into a b quark, lepton, and neutrino (via $\chi_u \rightarrow bW$ and $W \rightarrow \mu\nu_\mu$), and the ϕ' produces two muons. We note that the scalar ϕ' particle could result from the mixture of the SM Higgs boson and additional scalar fields, and the Yukawas of the fermions could additionally arise from the mixing of the SM fermions with additional copies of the associated vector-like fermions. Therefore, the ϕ' branching ratios are dependent on the chosen mechanism and model by which this mixture occurs, see for example, Refs. [120–123]. For the purpose of this work, and similar to Refs. [83, 87], the considered benchmark signal scenarios have $\mathcal{B}(\chi_u \rightarrow b W)$ of about 0.5 and $\mathcal{B}(\phi' \rightarrow \mu^+ \mu^-) = 1.00$. Figure 3.6 shows the production cross section in fb, as a function of $m(\phi')$ and $m(\chi_u)$ masses, assuming the aforementioned decays, branching ratios, and couplings.

We note that for the parameter space of focus in this paper, the total mass of the $t\chi_u$ system is larger than $m(\phi')$, thus the large rest energy of the $t\chi_u$ system is converted into potentially large momentum values for the ϕ' . Similarly, the t -quark produced through the χ_u - t fusion interaction can also have large momentum values, and thus in some cases the hadronic t decay products cannot be fully reconstructed independently of each other. This results in three possible t reconstruction scenarios: a fully merged scenario where the $W \rightarrow jj$ system and the b quarks are very collimated and reconstructed as a single “fat jet” (henceforth referred to as a FatJet, FJ); a partially merged scenario, where the decay products of the W boson form a single FatJet but the b quark can still be separately identified; and an unmerged scenario where all decay products can be independently identified. Jets are clustered using the anti- k_t algorithm [124] using the FastJet (v3.4.2) [125] package with a distance parameter of $R = 0.4$ for standard jets and $R = 0.8$ for fat jet objects. Each scenario has an associated identification efficiency and misidentification rate, which depends on the choice of the boosted t/W algorithm (our choice of efficiency and misidentification rates is described later).

Based on the above details, the final state of interest in this paper consists of three muons (two from the ϕ' decay and one from the χ_u decay), a (possibly boosted) top-tagged system, at least one b -tagged jet, and large missing transverse momentum (\vec{p}_T^{miss}). For the partially merged and unmerged scenarios, there will be two b quarks present in the final state (one of which is part of the top tagged system).

We consider background sources from SM processes which can give similar objects in the final state as those expected for signal. Several background sources were considered and studied, such as QCD multijet events, production of vector boson pairs (VV : WW, ZZ, WZ), vector boson triplets (VVV : WWZ, WZZ, ZZZ, WWW), top-quark pairs in association with weak bosons ($t\bar{t}X$), and $t\bar{t}t\bar{t}$ processes. The dominant sources of SM background events are from the $t\bar{t}X$, ZZW , and $t\bar{t}t\bar{t}$ processes. The $t\bar{t}X$ background is primarily associated production of a Z/γ^* from $t\bar{t}$ fusion processes. The ZZW process becomes a background when one Z decays $b\bar{b}$, another Z decays to a pair of muons, and the W decays to a muon and a neutrino. Events from ZZW and $t\bar{t}t\bar{t}$ have been combined, after being weighted by their corresponding production cross section. The combination is presented as the “ $b\bar{b}\mu\mu\nu$ ” background in the remainder of this paper. The $t\bar{t}X$ process is presented as part of the “ $t\bar{t}\mu^+\mu^-$ ” background. Table 3.2 shows the production cross sections for the dominant background sources. The rest of the aforementioned background processes do not contribute meaningfully in our context, accounting for $\ll 1\%$ of the total expected background yield.

The identification of leptons, boosted top quarks, and bottom quarks plays an important role in the ability to identify signal events, the ability to minimize the rate of SM backgrounds, and thus also the discovery reach in the high-luminosity environment of the LHC. It is worth noting that

Background Process	Cross-Section σ [pb]
$pp \rightarrow t\bar{t} \mu^+ \mu^-$	2.574×10^{-3}
$pp \rightarrow b\bar{b} \mu\mu\nu$	4.692×10^{-4}

Table 3.2: A summary of dominant SM backgrounds produced by pp collisions and their cross sections in pb, as computed by MadGraph with $n = 10^6$ events.

the reconstruction and identification of leptons and the decay products of the top/bottom quarks may be non-trivial at the High-Luminosity LHC (HL-LHC) due to the presence of a potentially large number of secondary pp interactions (pileup). The impact of pileup on the new physics discovery reach, and the importance of pileup mitigation at CMS and ATLAS has been outlined in many papers, for example in Ref. [59]. We note the expected performance of the upgraded ATLAS and CMS detectors for the HL-LHC is beyond the scope of this work; however, the studies presented here do attempt to provide reasonable expectations by conservatively assuming some degradation in lepton and hadron identification efficiencies, using Ref. [59] as a benchmark, and considering the case of 140 average pileup interactions.

For muons with $|\eta| < 1.5$, the assumed identification efficiency is 95% with a 0.3% misidentification rate [59, 60]. The performance degrades linearly with η for $1.5 < |\eta| < 2.5$, and we assume an identification efficiency of 65% with a 0.5% misidentification rate at $|\eta| = 2.5$. Similarly, the charged hadron tracking efficiency, which contributes to the jet clustering algorithm and missing transverse momentum (\vec{p}_T^{miss}) calculation, is 97% for $1.5 < |\eta| < 2.5$, and degrades to about 85% at $|\eta| = 2.5$. These potential inefficiencies due to the presence of secondary pp interactions contribute to how well the lepton and top kinematics can be reconstructed. Following Refs. [126, 127], we consider the “Loose” working point for the identification of the fully merged (partially merged) t decays, which results in 80-85% top (W) identification efficiency and 11-25% misidentification rate, depending on the FatJet transverse momentum (p_T^{FJ}). Following Ref. [128], we consider the “Loose” working point of the DeepCSV algorithm [129], which gives a 70-80% b-tagging efficiency and 10% light quark mis-identification rate. The choice of boosted t/W and b-tagging working points is determined through an optimization process that maximizes discovery reach. It is noted the contribution from SM backgrounds with a misidentified boosted t/W is negligible, and thus our discovery projections are not sensitive to uncertainties related to the boosted t/W misidentification rates.

3.4 DATA ANALYSIS USING MACHINE LEARNING

The analysis of signal and background events is performed utilizing machine learning techniques. A machine learning-based approach offers sizeable advantages when compared to traditional event classification techniques. Unlike conventional methods, machine learning models have the

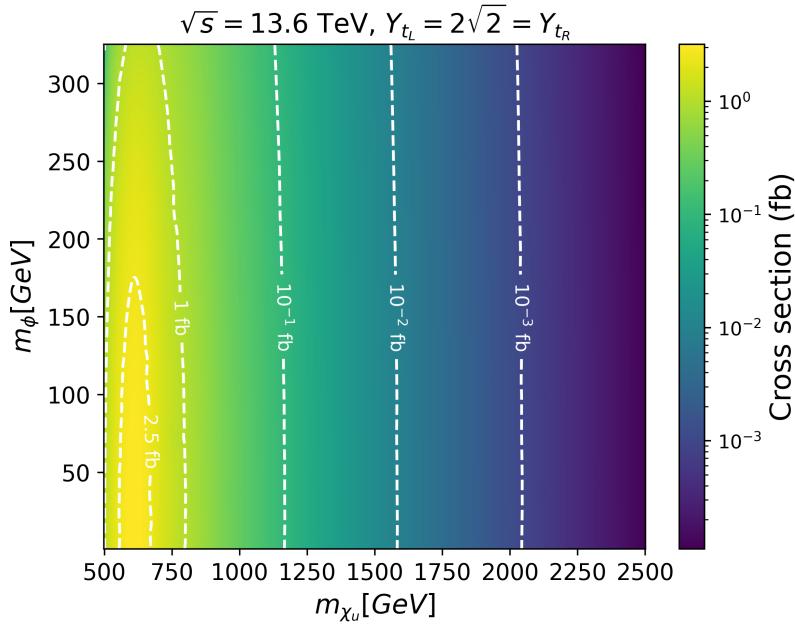


Figure 3.6: Projected cross section (fb) plot for $\text{pp} \rightarrow t\chi_u\phi'$ and subsequent decay as a function of $m(\chi_u)$ and $m(\phi')$.

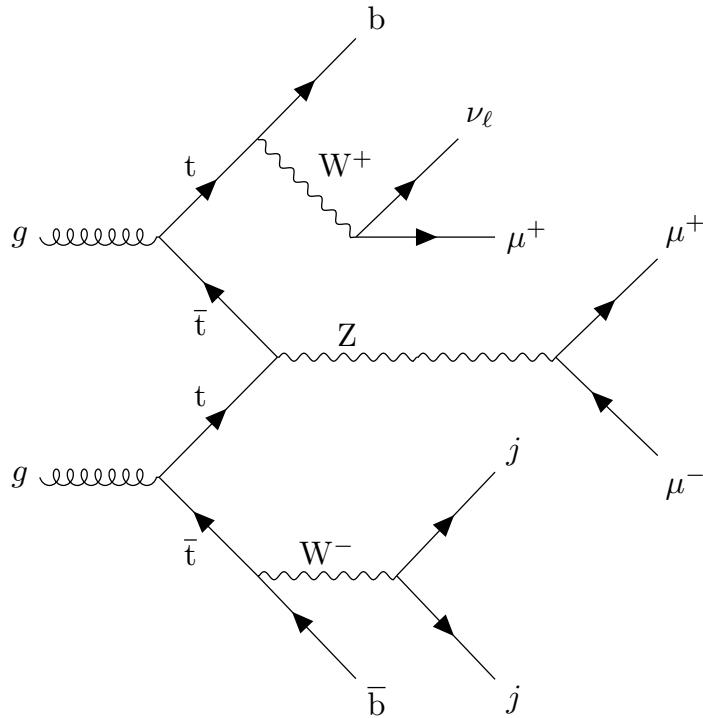


Figure 3.7: Representative Feynman diagram for a background event. A Z boson is produced in association with a top quark through the fusion of a top, anti top pair from incoming protons. The Z boson subsequently decays to a pair of muons and the two spectator top quarks decay semi-leptonically and purely hadronically to muons, neutrinos and jets, resulting in the same final states as the signal event.

capability to simultaneously consider all kinematic variables, allowing them to efficiently navigate the complex and high-dimensional space of event kinematics. Consequently, machine learning models can effectively enact sophisticated selection criteria that take into account the entirety of this high-dimensional space. This makes them ideal for high-energy physics applications.

The BDT method is a powerful machine learning technique that has proven its effectiveness in various applications, particularly in the field of collider physics. In this method, decision trees are trained greedily in a sequential manner, with each tree focusing on learning the discrepancies or residuals between its predictions and the expected values obtained from the previously trained tree. This iterative process aims to progressively minimize errors, making BDTs a particularly effective approach for enhancing model performance.

In the context of collider physics, BDTs have demonstrated their utility in addressing classification problems. In particular, BDTs can effectively discriminate between signal and background events, enabling accurate and efficient event classification. Their ability to handle subtle non-linear relationships within the data with high interpretability makes BDTs a valuable tool to handle large amounts of data with a large number of parameters for each event.

The first step in our workflow involves the use of a specialized `MadAnalysis Expert Mode C++` script [130]. This script extracts essential kinematic and topological information from the simulated samples. The script will process the aforementioned variables contained within these files and transform them into a structured and informative CSV (Comma-Separated Values) format that can be used to train our machine learning models. These kinematic variables include crucial details about the events, such as particle momenta, energies, and topologies, providing the fundamental building blocks for our machine learning analysis. Figure 3.13 shows the features that are used for training the machine learning models and their importance for a benchmark point.

To account for the differential significance of various events, we apply cross-section weighting. This ensures that the relative importance of signal and background events is appropriately balanced in the dataset. This weighting is crucial for addressing the varying likelihood of observing different types of events in high-energy physics experiments. The prepared and weighted datasets are then passed to our `MadAnalysis Expert Mode C++` script, where the simulated signal and background events are initially filtered, before being passed to the CSV file for use by the machine learning algorithm. The filtering process requires at least one well-reconstructed and identified b-jet candidate, at least one jet (regular or FJ) not tagged as a b jet, and exactly three identified muons. The filtering selections are motivated by experimental constraints, such as the geometric constraints of the CMS/ATLAS detectors, the typical kinematic thresholds for the reconstruction of particle objects, and the available lepton triggers which

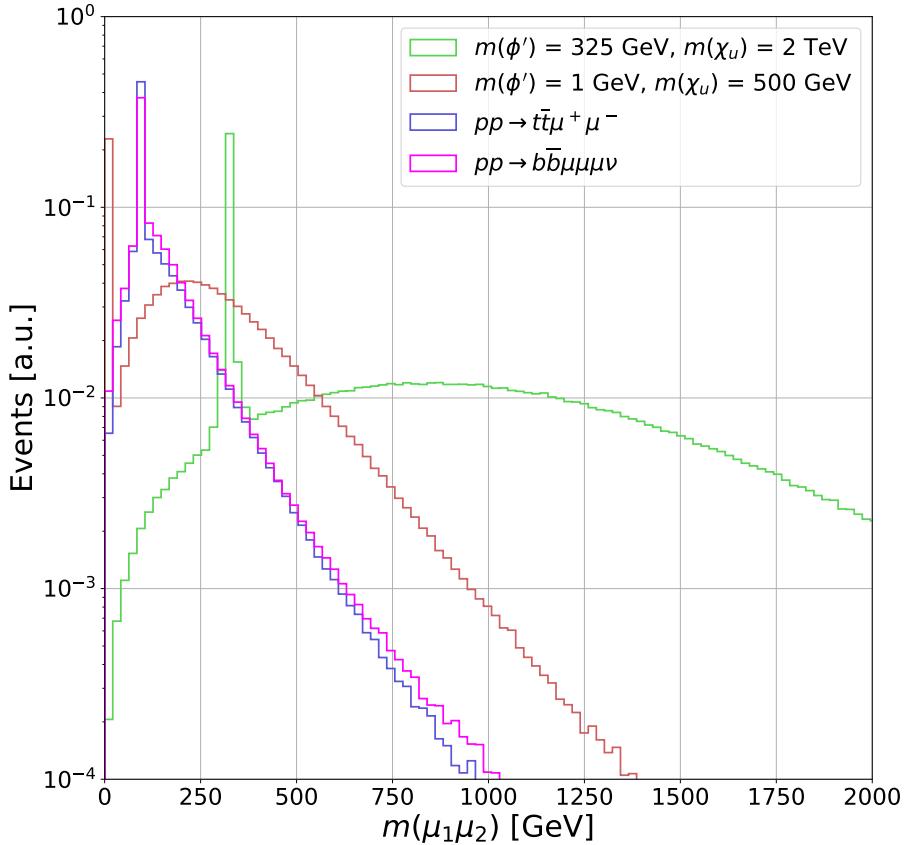


Figure 3.8: Invariant mass distribution of the muon pair with the highest and second highest transverse momentum. The distributions are shown for the two main SM background processes and two signal benchmark points.

also drive the minimal kinematic thresholds. Selected jets must have $p_T > 30$ GeV and $|\eta(j)| < 5.0$, while b-jet candidates with $p_T > 20$ GeV and $|\eta(b)| < 2.5$ are chosen. The μ object must pass a $p_T > 35$ GeV threshold and be within a $|\eta(\ell)| < 2.3$. We will refer to this filtering criteria as pre-selections. The efficiency of the pre-selections depends on $m(\phi')$ and $m(\chi_u)$, but is typically about 25-30% for the signal samples. Events passing this pre-selection are used as input for the machine learning algorithm, which classifies them as signal or background, using a probability factor.

We explore the performance of a diverse set of machine learning models, specifically three neural networks of differing architectures and a BDT algorithm. To ensure robust model assessment, we employed a standard 90-10 train-test split of the dataset, partitioning it into a 90% portion for training and a 10% portion for testing. This division allows us to gauge the generalization capabilities of our models on unseen data.

The training and evaluation of the BDT were carried out in a high-performance computing environment. Specifically, an Nvidia A100 GPU was used. The canonical PyTorch [131] deep learning framework was employed for configuring, training, and evaluating the neural networks.

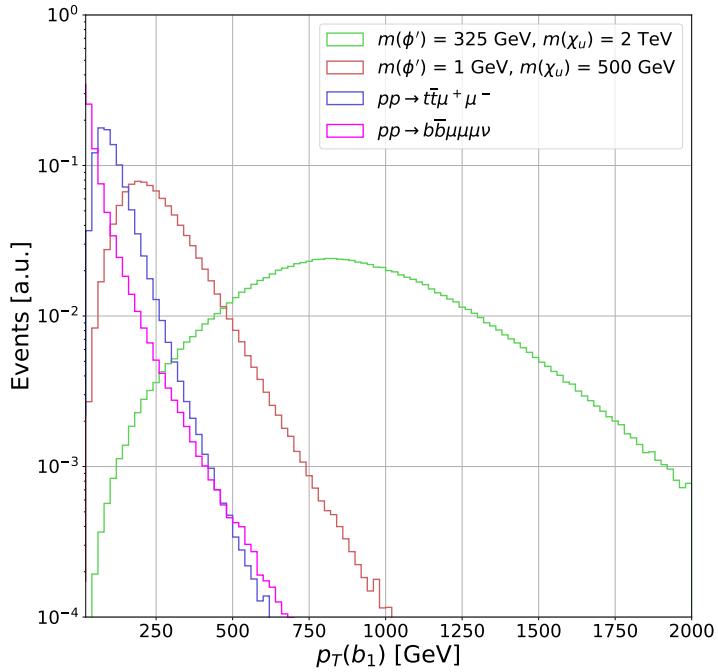


Figure 3.9: Transverse momentum distribution of the leading b-quark jet candidate. The distributions are shown for the two main SM background processes and two signal benchmark points.

Model	Train/Test Acc.	Training Time
BDT	N.A./0.9993	6s
Neural Network 1	0.9999/0.9997	1h 58m
Neural Network 2	0.9999/0.9998	2h 12m
Neural Network 3	0.9999/0.9998	2h 32m

Table 3.3: Train/test results for the ML models.

PyTorch is well-regarded for its flexibility and performance in deep learning applications.

For the BDT algorithm, we used hyperparameters $\eta = 0.3$, $\gamma = 0$, and `max_depth = 6`. The XGBoost [132] library was used for the implementation of the Boosted Decision Tree algorithm. It offers high efficiency, optimization, and interpretability, making it a suitable choice for this particular task.

It is worth mentioning that we experimented with deep neural networks of various architectures. Although we found that they yield similar signal sensitivity to the BDT, the complex nature of the studies in this work (particle objects considered, experimental constraints in a high luminosity LHC, etc.) motivates the use of a BDT over a deep neural network because of its usefulness, efficiency, and simplicity in understanding the machine learning output in addition to significantly shorter training times. Therefore, we perform our proceeding analysis using the BDT. The outcomes of our model training and evaluation are presented in Table 3.

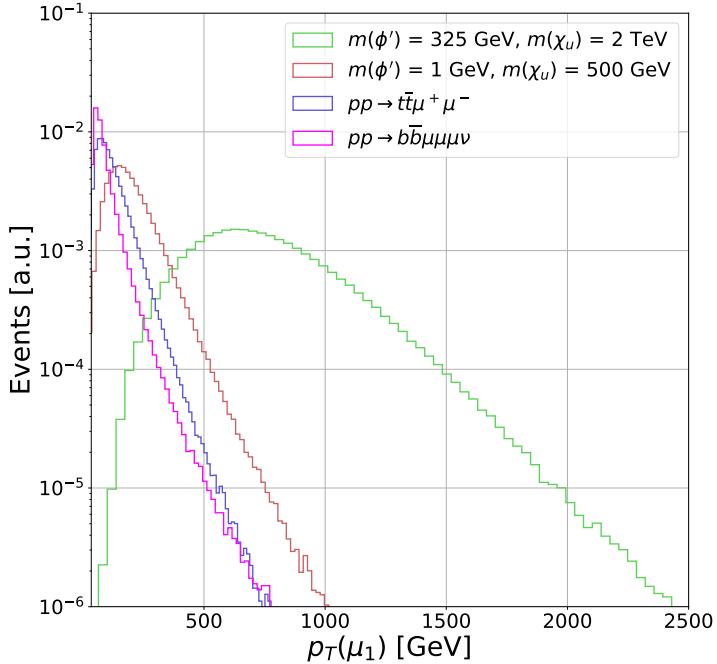


Figure 3.10: Transverse momentum distribution of the leading muon candidate. The distributions are shown for the two main SM background processes and two signal benchmark points.

3.5 RESULTS

Figures 3.8, 3.9, and 3.10 show relevant kinematic distributions for two benchmark signal points and the dominant SM backgrounds, using the subset of events passing the pre-selections defined above. The signal benchmark points in these figures are $m(\phi') = 325 \text{ GeV}$, $m(\chi_u) = 2 \text{ TeV}$, and $m(\phi') = 1 \text{ GeV}$, $m(\chi_u) = 500 \text{ GeV}$. The distributions are normalized such that the area under the curve is unity. These distributions correspond to the reconstructed mass, $m(\mu_1, \mu_2)$, between the two muon candidates with the highest transverse momentum (μ_1 and μ_2), the transverse momentum of the b-jet candidate with the highest transverse momentum $p_T(b_1)$, and the muon candidate with the highest transverse momentum $p_T(\mu_1)$, respectively. These distributions are among the variables identified by the BDT algorithm with the highest signal to background discrimination power (see Figure 3.13).

As can be seen from Figure 3.8, the ϕ' mass can be reconstructed through its associated muon decay pair, which is observed as a peak in the $m(\mu_1, \mu_2)$ distribution around the expected $m(\phi')$ value, and has low- and high-mass tails which are a consequence of cases where the leading and/or subleading muon is not from the ϕ' decay, but rather from the associated W boson from the χ_u decay. For the backgrounds, muons come from Z (W) decays. Therefore, the $m(\mu_1, \mu_2)$ background distributions show a peak near $m_{W/Z}$, combined with a broad distribution indicative of the combination of two muon candidates from different decay vertices.

We note that the $\phi' \rightarrow \mu^+ \mu^-$ decay width depends on the square of the $\phi' \rightarrow \mu^+ \mu^-$ coupling and $\frac{m_\mu^2}{m_{\phi'}^2}$ and is thus suppressed by the relatively small muon mass. For the new physics phase space considered in this paper, the ϕ' decay width is less than 1% of the ϕ' resonant mass. Furthermore, as indicated previously, the signal/background interference effects are small and negligible compared to effects from experimental resolution. Therefore, the width of the $m(\mu_1, \mu_2)$ signal distributions is driven by the experimental resolution in the reconstruction of the muon momenta, as well as the probability that the two leading muons are the correct pair from the ϕ' decay. Since the probability that the two highest- p_T muons are the correct pair from the $\phi' \rightarrow \mu^+ \mu^-$ decay depends on $m(\phi')$ and $m(\chi_u)$, it is important to include all possible combinations of dimuon pairs (i.e., $m(\mu_1, \mu_3)$ and $m(\mu_2, \mu_3)$) in the training of the BDT.

Figure 3.9 shows the distribution for the b-jet candidate with the highest p_T , $p_T(b_1)$, for the same simulated samples shown in Figure 3.8. Based on the signal topology and our choice of parameter space (i.e., $m_{\chi_u} > m_t$), it is expected that the leading b-jet candidate comes from the χ_u decay, with an average p_T close to $\frac{m_{\chi_u} - m_W}{2}$, as observed in Figure 3.9. For the $t\bar{t}\mu^+ \mu^-$ background, the b-jet candidates come from top-quark decays. Therefore, their average transverse momentum is expected to be $\frac{m_t - m_W}{2} \approx 45$ GeV, as observed in Figure 3.9. On the other hand, the b-jet candidates for the $b\bar{b}\mu^+ \mu^-$ background can come from off-mass-shell Z^*/γ^* , and thus typically have an even softer spectrum in comparison to the $t\bar{t}\mu^+ \mu^-$ background.

Figure 3.10 shows the distribution for the muon candidate with the highest p_T , $p_T(\mu_1)$. Similar to Figure 3.9, when $m(\chi_u) > m_t$ it is expected that the leading muon candidate comes from the χ_u decay, with an average p_T of approximately $\frac{m(\chi_u) - m_W}{4}$, as observed in Figure 3.10. For the major SM backgrounds, the muon candidates come from $Z/W/\gamma^*$ decays. Therefore, their average transverse momentum is expected to be much lower, $\frac{m_{Z/W}}{4} \approx 40 - 45$ GeV. This kinematic feature provides a nice handle to discriminate high $m(\chi_u)$ signal events amongst the large SM backgrounds, which have lower average $p_T(\mu)$ constrained by the SM weak boson masses.

In addition to these aforementioned variables in Figures 3.8-3.10, several other kinematic variables were included as inputs to the BDT algorithm. In particular, 27 such variables were used in total, and these included the momenta of b and muon candidates; invariant masses of pairs of muons; angular differences between b jets and between the muons.

As mentioned above, the variables $m(\mu_i, \mu_j)$ for $i, j \neq 1$ provide some additional discrimination between signal and background when the leading muons are not a ϕ' decay candidate. The angular separation variables, such as $\Delta R(\mu_i, \mu_j)$, are designed to be sensitive to lower mass ϕ' , since the low rest mass of those particles means they acquire more boost, and thus smaller angular separation ΔR between the muon candidates. The trained BDT returns the discriminating power of each of its inputs, and the feature

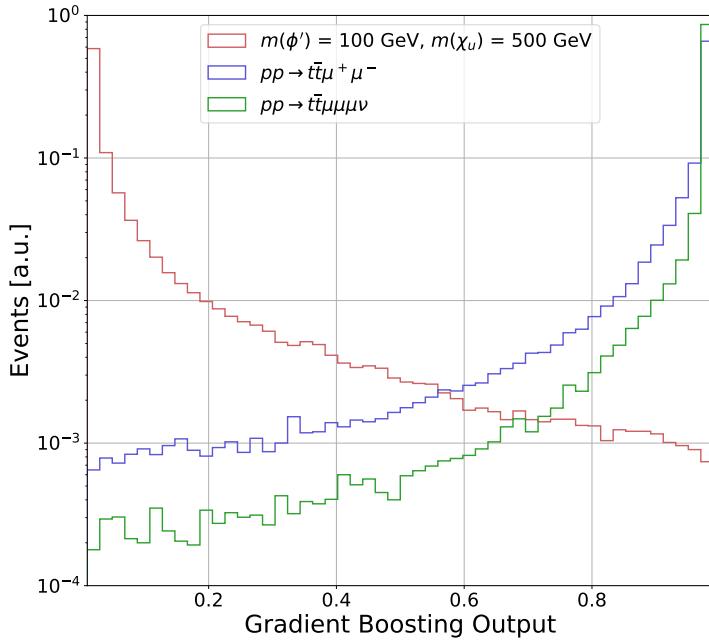


Figure 3.11: Output of the gradient boosting algorithm for a benchmark $m(\phi') = 100$ GeV and $m(\chi_u) = 500$ GeV signal, and dominant backgrounds. The distributions are normalized to unity.

importance for each variable is shown in Figure 3.13 for a signal benchmark point with $m(\phi') = 325$ GeV and $m(\chi_u) = 2000$ GeV.

Figure 3.11 shows the distributions for the output of the BDT algorithm, normalized to unity, for the representative signal benchmark point of $m(\phi') = 1$ GeV, $m(\chi_u) = 0.5$ TeV and the two dominant backgrounds. The output of the BDT algorithm is a value between 0 and 1, which quantifies the likelihood that an event is either background-like (BDT output near 1) or signal-like (BDT output near 0). Figure 3.12 illustrates the true positive rate (TPR), defined as the probability of correctly selecting signal events using the BDT output, plotted against the false positive rate (FPR), defined as the probability of incorrectly selecting background events. For example, for $m(\phi') = 100$ GeV and $m(\chi_u) = 500$ GeV, when signal events are selected at 65% probability, the background is selected at about 10^{-3} probability. We note that the primary discriminating feature between the signal and background is the boosted b-jet p_T coming from the χ_u vector-like quark. The p_T of said b jet increases with $m(\chi_u)$, peaking at around $[m(\chi_u) - m(W)]/2$. This enhanced boost increases the separation between signal and background, improving the performance of the BDT algorithm as $m(\chi_u)$ increases.

The outputs from the BDT machine learning algorithm are used to perform a profile-bin likelihood analysis to estimate the signal significance for a luminosity of 3000 fb^{-1} , corresponding to the expected amount of collected data by the end of the LHC era. For this purpose, the BDT distributions are normalized to cross section times pre-selection efficiency times luminosity for the different signal models. The significance is then calcu-

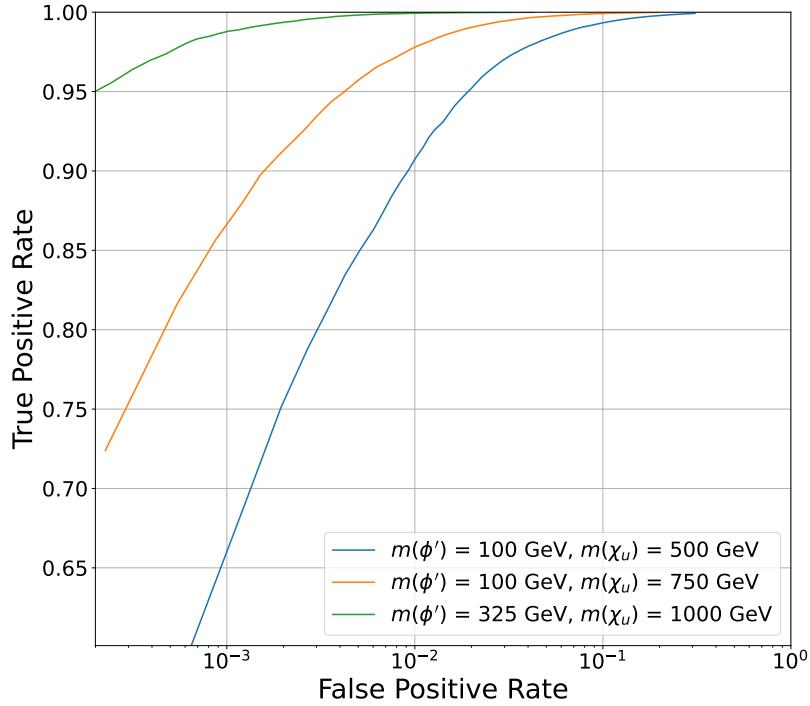


Figure 3.12: Receiver operating characteristic curve of the BDT algorithm for three different signal benchmark scenarios.

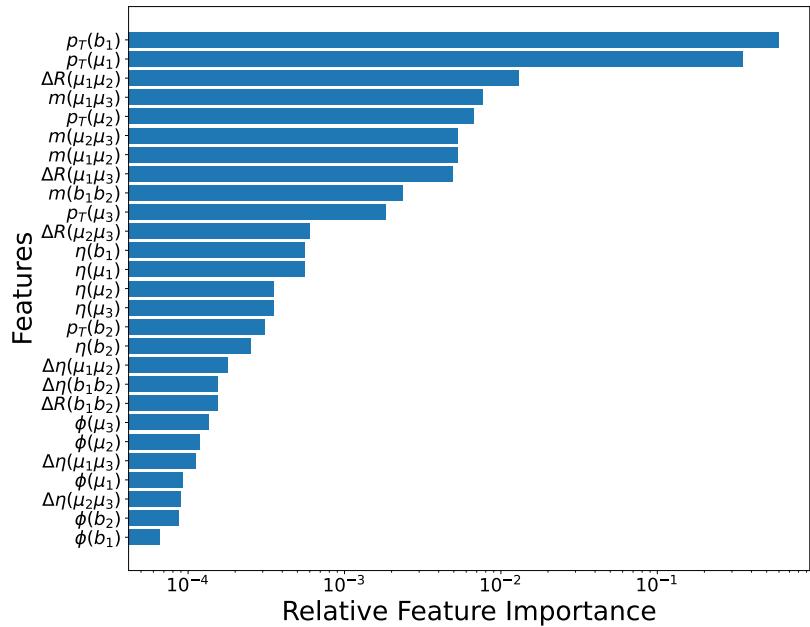


Figure 3.13: Relative importance of features in training for a benchmark signal scenario with $m(\phi') = 325 \text{ GeV}$ and $m(\chi_u) = 2000 \text{ GeV}$.

lated using the expected bin-by-bin yields of the BDT output distribution in a profile likelihood fit, using the ROOTFit [133] package developed by CERN. The expected signal significance Z_{sig} is calculated using the probability of obtaining the same test statistic for the signal plus background and the signal-null hypotheses, defined as the local p-value. Similar to Refs. [134–140], the significance corresponds to the point where the integral of a Gaussian distribution between Z_{sig} and ∞ results in a value equal to the local p-value. The estimation of Z_{sig} incorporates systematic uncertainties. The uncertainty values have been included as nuisance parameters, considering lognormal priors for normalization and Gaussian priors for uncertainties associated with the modeling of the shapes similar to Refs. [141, 142].

The systematic uncertainties that have been included result from experimental and theoretical constraints. A 1-5% systematic uncertainty, depending on the simulated MC sample, has been included to account for the choice of Parton Distribution Function (PDF) set. The systematic uncertainty effect was incorporated following the PDF4LHC [133] recommendations. This systematic uncertainty has a small impact on the expected event yields for signal and background, but it does not affect the shape of the BDT output distribution. We additionally considered theoretical uncertainties related to the absence of higher-order contributions to the signal cross sections, which can change the pre-selection efficiencies and the shapes of kinematic variables used as inputs to the BDT algorithm. This uncertainty was calculated by varying the renormalization and factorization scales by $\times 2$, and studying the resulting change in the bin-by-bin yields of the BDT distributions. They are found to be at most 2% in a given bin.

Regarding experimental uncertainties, following experimental measurements from CMS on the estimation of the integrated luminosity, a conservative 3% effect has been included [143]. A 5% systematic uncertainty associated with the reconstruction and identification of b-quark jets has been included, independent of p_T and η of the b-jet candidates. According to Ref. [128], this uncertainty is correlated between signal and background processes with genuine b-jets and is also correlated across BDT bins for each process. For muons, we include a 2% uncertainty associated with the reconstruction, identification, and isolation requirements, and a 3% systematic uncertainty to account for scale and resolution effects on the momentum and energy measurement. We consider jet energy scale uncertainties ranging from 2-5%, contingent on η and p_T , resulting in shape-based uncertainties on the BDT output distribution. Jet energy scale uncertainties were assumed to range from 1-5%, contingent on η and p_T . These assumptions lead to shape-based uncertainties on the BDT output distribution, varying from 1-2%. Additionally, we include a 10% systematic uncertainty to account for errors in the signal and background predictions. Considering all the various sources of systematic uncertainties, our conservative estimate yields a total effect of about 20%.

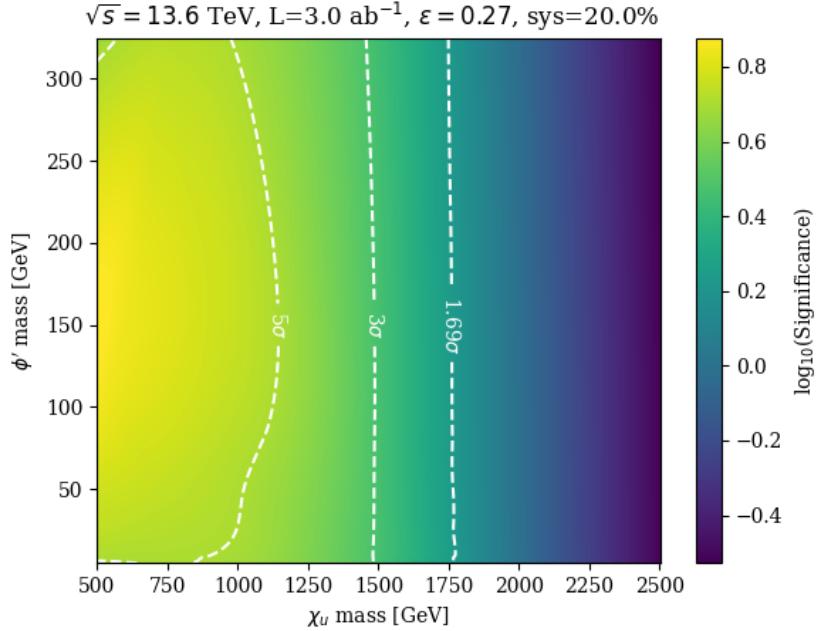


Figure 3.14: Signal significance for the high luminosity LHC era, considering with 3000 fb^{-1} of collected data.

Figure 3.14 shows the expected signal significance considering an integrated luminosity of 3000 fb^{-1} . The significance is shown as a heat map in a two-dimensional plane for different ϕ' and χ_u masses. The x-axis corresponds to $m(\chi_u)$, the y-axis to $m(\phi')$, and the heat map to $\log_{10}(Z_{\text{sig}})$. The white dashed lines are contours of constant signal significances of 1.69σ , 3σ and 5σ to represent regions of possible exclusion, evidence of new physics, and discovery, respectively. Under these conditions, ϕ' (χ_u) masses ranging from 1 to 325 GeV (500 to 1800 GeV) can be probed. The range for a discovery with 5σ signal significance varies from χ_u masses from $m(\chi_u) = 770\text{-}1100 \text{ GeV}$, depending $m(\phi')$. For large $m(\chi_u)$, the significance is almost independent of $m(\phi')$ because the primary discriminating feature—the boosted b-quark originating from ϕ' —is driven predominantly by the large $m(\chi_u)$, with the kinematic impact of $m(\phi')$ being relatively negligible.

3.6 DISCUSSION

The LHC will continue to run with pp collisions at $\sqrt{s} = 13.6 \text{ TeV}$ for the next decade. Given the increase in the integrated luminosity expected from the high-luminosity program, it is important to consider unexplored new physics phase space that diverges from the conventional assumptions made in many BSM theories, and which could have remained hidden in processes that have not yet been thoroughly examined. It is additionally crucial to explore advanced analysis techniques, in particular the use of artificial

intelligence algorithms, to enhance the probability of detecting these rare corners where production cross sections are lower and discrimination from SM backgrounds is difficult.

In this work, we examine a model based on a $U(1)_{T_R^3}$ extension of the SM, which can address various conceptual and experimental issues with the SM, including the mass hierarchy between generations of fermions, the thermal dark matter abundance, and the muon $g - 2$, $R_{(D)}$, and $R_{(D^*)}$ anomalies. This model contains a light scalar boson ϕ' , with potential masses below the electroweak scale, and TeV-scale vector-like quarks χ_u . We consider the scenario where the scalar ϕ' has family non-universal fermion couplings and $m(\phi') \geq 1$ GeV, as was suggested in Ref. [83], and thus the ϕ' can primarily decay to a pair of muons. Previous works in Refs. [87, 97] considered scenarios motivating a search methodology with a merged diphoton system from $\phi' \rightarrow \gamma\gamma$ decays. The authors of Ref [87], in which $m(\phi') < 1$ GeV, indeed pointed out that if the ϕ' is heavier than about 1 GeV, then decays to $\mu^+ \mu^-$ can become the preferable mode for discovery, which is the basis for the work presented in this paper. We further note that the final state topology studied in this paper would represent the most important mode for discovery at $m(\phi') < 2m_t$ where the $\phi' \rightarrow t\bar{t}$ decay is kinematically forbidden.

The main result of this paper is that we have shown that the LHC can probe the visible decays of new bosons with masses below the electroweak scale, down to the GeV-scale, by considering the simultaneous production of heavy QCD-coupled particles, which then decay to the SM particles that contain large momentum values and can be observed in the central regions of the CMS and ATLAS detectors. The boosted system combined with innovative machine learning algorithms allows for the signal extraction above the lower-energy SM background. The LHC search strategy described here can be used to discover the prompt decay of new light particles. An important conclusion from this paper is that the detection prospects for low-mass particles are enhanced when it is kinematically possible to simultaneously access the heavy degrees of freedom which arise in the UV completion of the low-energy model. This specific scenario in which the couplings of the light scalars are generationally dependent, with important coupling values to the top quark, is an ideal example which would be difficult to directly probe at low energy beam experiments.

The proposed data analysis represents a competitive alternative to complement searches already being conducted at the LHC, allowing us to probe ϕ' masses from 1 to 325 GeV, for $m(\chi_u)$ values up to almost 2 TeV, at the HL-LHC. Therefore, we strongly encourage the ATLAS and CMS Collaborations to consider the proposed analysis strategy in future new physics searches.

4

ON VECTORIAL LEPTOQUARKS SENSITIVITY AT THE LHC

Leptoquarks (LQs) are hypothetical bosons carrying both baryon and lepton number, thus interacting jointly with a lepton and a quark. They are a common ingredient in SM extensions where quarks and leptons share the same multiplet. Typical examples of these can be found in the Pati-Salam [144] and SU(5) GUT [145] models. In addition, they can also be found in theories with strong interactions, such as compositeness [146]. Due to their exotic coupling which allows quark-lepton transitions, they have a diverse phenomenology, which naturally leads to several constraints. An important one comes from proton decay, which forces the LQ mass to values close to the Planck scale, unless baryon and lepton numbers are not violated. Furthermore, in models where the latter are conserved, the LQ can still be subject to a wide variety of bounds [147–152]. Examples of these come from meson mixing, electric and magnetic dipole moments, atomic parity violation tests, rare decays, and direct searches. Nevertheless, the significance of each bound is a model dependent question.

In the last years, an increased interest in low scale LQs has emerged due to the anomalies in the precision measurements of the B-meson decay rates. As it is well known, these corresponded mainly to deviations in the $R_{K^{(*)}}$ [153–156] and $R_{D^{(*)}}$ [157–168] ratios, which measure the violation of lepton flavour universality (LFU). What followed was a very intense theoretical development, aiming to explain the anomalies by TeV scale LQ exchange at tree level [169–184]. Before the end of 2022, it was generally agreed that, within proposed single LQ solutions, the only candidate capable of addressing all B-meson anomalies simultaneously and surviving all other constraints was a vector LQ (U_1), transforming as $(\mathbf{3}, \mathbf{1}, 2/3)$, and coupling mainly to third-generation fermions via $b\tau$ and $t\nu_\tau$ vertices [179, 182]. In spite of a recent re-analysis of $R_{K^{(*)}}$ data showing this ratio to be compatible with the SM prediction [185–188], the solution to the $R_{D^{(*)}}$ anomaly is still an open question and remains a valid motivation for the study of scenarios where new particles have preferential couplings to third-generation fermions. Thus, it is still of interest to continue exploring the possibility of observing the U_1 LQ at the LHC [184].

As expected, the theoretical community has extensively participated in probing LQ models by scrutinizing search strategies, recasting LHC results, and predicting the reach in the parameter space via different searches

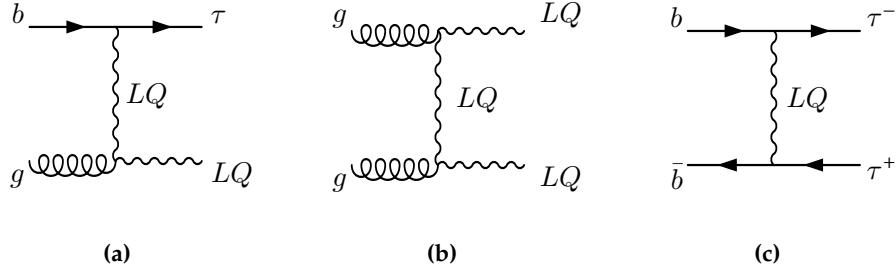


Figure 4.1: Representative Feynman diagrams of single (a), pair (b), and non-resonant (c) production leptoquarks in proton-proton collision experiments. In single and pair production, the diagrams shown involve t-channel LQ exchange, dominant for lower LQ mass. However, for larger mass there exist s-channel diagrams featuring a virtual bottom quark and gluon, respectively.

involving third-generation fermions (see for instance [102, 189–197]). In addition, several 13 TeV searches for LQs decaying into t/b and τ/ν final states have been performed by the CMS [198–206] and ATLAS [207–213] collaborations.

Of the searches above, we find [204] particularly interesting. Here, the CMS collaboration explores signals corresponding to $t\nu b\tau$ and $t\nu\tau$ final states, with 137 fb^{-1} of proton-proton ($p p$) collision data. The former is motivated by LQ pair production, with one LQ decaying into $t\nu$ and the other into $b\tau$, while the latter arises from a single LQ produced in association with a τ , with a subsequent LQ decay into $t\nu$ (see Figure 4.1 for the corresponding diagrams). From the combination of both production channels, the search excludes U_1 masses under $1.3 - 1.7 \text{ TeV}$, with this range depending on the U_1 coupling to gluons and on its coupling g_U in the $b_L \tau_L$ vertex.

What makes this search particularly attractive is that, for the first time, an LHC collaboration directly places (mass dependent) bounds on g_U . This is important, since having information on this parameter is crucial in order to understand if the U_1 is really responsible for the $R_D^{(*)}$ anomaly. The inclusion of the single-LQ production mode is important, since its cross-section is directly proportional to g_U^2 . However, as can be seen in Figure 6 of [204], the current constraints are dominated by pair production, with single-LQ production playing a subleading role. While this is expected [192], it still leads us to ponder the possibility of improving the sensitivity of LHC searches to single-LQ production, and thus on achieving better constraints on g_U . Other complementary and similar searches to [204] were carried out by both ATLAS [212] and CMS [206].

It is also well known, though, that searches for an excess in the high- p_T tails of τ lepton distributions can strongly probe g_U , up to very large LQ masses. Indeed, as shown in [184, 214], the new physics effective operators contributing to $R_D^{(*)}$ also contribute to an enhancement in the $p p \rightarrow \tau\tau$ production rates. This has motivated a large number of recasts [182, 184, 192, 193, 215–219], as well as a CMS search explicitly providing constraints

in terms of U_1 [205]. Nevertheless, it is important to note that for these $p p \rightarrow \tau\tau$ processes, the LQ participates non-resonantly, so contributions to the $p p \rightarrow \tau\tau$ rates and kinematic distributions from non-LQ BSM diagrams containing possible virtual particles, such as a heavy neutral vector boson Z' , could spoil a straightforward interpretation of any possible excess [193]. Thus, it is also necessary to understand how the presence of other virtual particles can affect the sensitivity of an analysis probing g_U .

In this work we study the projected LQ sensitivity at the LHC, considering already available $p p$ data as well as the expected amount of data to be acquired during the High-Luminosity LHC (HL-LHC) runs. We explore a proposed analysis strategy which utilizes a combination of single-, double-, and non-resonant-LQ production, targeting final states with varying τ -lepton and b-jet multiplicities. The studies are performed considering various benchmark scenarios for different LQ masses and couplings, also taking into account distinct chiralities for the third-generation fermions in the LQ vertex. We also assess the impact of a companion Z' , which is typical of gauge models, in non-resonant LQ probes, and find that interference effects can have a significant effect on the discovery reach. We consider this effect to be of high interest, given that non-resonant LQ production can have the largest cross-section, and thus could be an important channel in terms of discovery potential.

An important aspect of this work is that the analysis strategy is developed using a machine learning (ML) algorithm based on Boosted Decision Trees (BDT)[99]. The output of the event classifier is used to perform a profile-binned likelihood test to extract the overall signal significance for each model considered in the analysis. The advantage of using BDTs and other ML algorithms has been demonstrated in several experimental and phenomenological studies [100–106]. In our studies, we find that the BDT algorithm gives sizeable improvement in signal significance.

5

BSM SIGNATURES IN DI-TAU FINAL STATES

5.1 A SIMPLIFIED MODEL FOR THE \tilde{S}_1 SCALAR LEPTOQUARK

Leptoquarks (LQs) are hypothetical bosonic particles that couple simultaneously to a quark and a lepton, thereby mediating lepton-quark interactions at a single vertex. They arise naturally in various extensions of SM, including grand unified theories and models with extended gauge symmetries, and have attracted renewed interest as a possible explanation for observed flavor anomalies and hints of lepton flavor non-universality.

To ensure Lorentz invariance, the interaction vertex involving a leptoquark, a quark, and a lepton must form a scalar or vector operator. Among these possibilities, scalar leptoquarks (scalar-LQs) provide a minimal and renormalizable framework without requiring new gauge interactions, making them an ideal starting point for simplified model studies.

The classification of scalar leptoquarks is determined by their transformation properties under the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$. For simplicity, we focus on scalar-LQs that are singlets under $SU(2)_L$, so that the model contains a single new scalar degree of freedom. This constraint leads to interactions involving two fermions of the same chirality, which requires charge conjugation of one of the fields to build a Lorentz scalar.

There are two classes of gauge-invariant, renormalizable operators that couple such a singlet scalar-LQ to SM fermions. These are:

1. $I_1 = \bar{q}_L^C e \ell_L$ and $I'_1 = \bar{u}_R^C e_R$, where q_L and ℓ_L are left-handed quark and lepton doublets, respectively, and u_R , e_R are right-handed singlets. Both I_1 and I'_1 are $SU(2)_L$ singlets, transform as color triplets under $SU(3)_C$, and carry hypercharge $Y = -2/3$.
2. $\tilde{I}_1 = \bar{d}_R^C e_R$, a gauge-invariant operator involving two right-handed singlets. It is also a color triplet and an $SU(2)_L$ singlet, but with hypercharge $Y = -8/3$.

The corresponding leptoquark representations are:

1. $S_1 \doteq (\bar{\mathbf{3}}, \mathbf{1}, 2/3)$, consistent with the first set of operators.
2. $\tilde{S}_1 \doteq (\bar{\mathbf{3}}, \mathbf{1}, 8/3)$, associated with the second invariant.

In models with flavor alignment or preferential couplings to third-generation fermions, S_1 typically couples to $b\nu_\tau$ and $t\tau$ vertices. However, processes like $pp \rightarrow \tau^+\tau^-$ suffer suppression due to the low parton density of the top quark in the proton.

In contrast, the \tilde{S}_1 leptoquark allows for direct couplings to b quarks and τ leptons via a term of the form $\bar{d}_R^C \tilde{S}_1 e_R$. Despite the relatively small b -quark content in the proton, these channels remain accessible at the LHC.

For these reasons, this section focuses on the simplified model containing only the scalar leptoquark \tilde{S}_1 . The most general renormalizable Lagrangian for the \tilde{S}_1 leptoquark extends the SM one by

$$\mathcal{L} \supset |D_\mu \tilde{S}_1|^2 + \tilde{y}_{ij} \bar{d}_R^C \tilde{S}_1 e_R^j + \tilde{z}_{ij} \bar{u}_R^C \tilde{S}_1^* u_R^j + \text{h.c.} + V_{\text{ext}}(\tilde{S}_1, H) \quad (5.1)$$

Note that \tilde{z} must be antisymmetric (due to fermionic statistics) and is typically assumed to vanish or be highly suppressed to avoid large FCNCs.

where \tilde{y}, \tilde{z} are complex Yukawa matrices in the flavor space, D_μ is the covariant derivative acting on the \tilde{S}_1 field as

$$D_\mu \tilde{S}_1 = \partial_\mu \tilde{S}_1 + ig_s T^a G_\mu^a \tilde{S}_1 + i \frac{4}{3} g' B_\mu \tilde{S}_1, \quad (5.2)$$

and V_{ext} is the extension of the SM Higgs potential to include the leptoquark field given by

$$V_{\text{ext}} = \mu_{\tilde{S}_1}^2 |\tilde{S}_1|^2 + \lambda_{\tilde{S}_1} |\tilde{S}_1|^4 + \lambda_{H\tilde{S}_1} |H|^2 |\tilde{S}_1|^2, \quad (5.3)$$

such that the full scalar potential reads

$$V = \underbrace{-\mu^2 |H|^2 + \lambda |H|^4}_{\text{SM Higgs}} + \underbrace{\mu_{\tilde{S}_1}^2 |\tilde{S}_1|^2 + \lambda_{\tilde{S}_1} |\tilde{S}_1|^4}_{\text{scalar-LQ self-interactions}} + \underbrace{\lambda_{H\tilde{S}_1} |H|^2 |\tilde{S}_1|^2}_{\text{Higgs portal}}. \quad (5.4)$$

After EWSB, $H \rightarrow (0, (v+h)/\sqrt{2})^\top$, the $H\tilde{S}_1$ interactions become interactions between the physical Higgs boson h and the leptoquark \tilde{S}_1 as

$$\mathcal{L}_{\text{int}} \supset \lambda_{H\tilde{S}_1} vh |\tilde{S}_1|^2 + \frac{1}{2} \lambda_{H\tilde{S}_1} h^2 |\tilde{S}_1|^2 \quad (5.5)$$

and a mass shift for the leptoquark field

$$\Delta m_{\tilde{S}_1}^2 = \frac{1}{2} \lambda_{H\tilde{S}_1} v^2 \implies m_{\tilde{S}_1}^2 = \mu_{\tilde{S}_1}^2 + \frac{1}{2} \lambda_{H\tilde{S}_1} v^2. \quad (5.6)$$

Additionally, from the covariant derivative as $B_\mu = c_W A_\mu - s_W Z_\mu$, the \tilde{S}_1 interactions with the SM gauge bosons are given by

$$\mathcal{L} \supset \frac{4}{3} e [(\partial_\mu \tilde{S}_1^*) \tilde{S}_1 - \tilde{S}_1^* (\partial_\mu \tilde{S}_1)] A^\mu + \left(\frac{4}{3} e \right)^2 A_\mu A^\mu |\tilde{S}_1|^2 \quad (5.7)$$

$$\mathcal{L} \supset -\frac{4}{3} g_1 s_W [(\partial_\mu \tilde{S}_1^*) \tilde{S}_1 - \tilde{S}_1^* (\partial_\mu \tilde{S}_1)] Z^\mu + \left(\frac{4}{3} g_1 s_W \right)^2 Z_\mu Z^\mu |\tilde{S}_1|^2. \quad (5.8)$$

For preferential couplings to third-generation fermions in the leptoquark vertices, we assume the texture of the Yukawa matrix \tilde{y}_{33} is such that $\tilde{y}_{33} \gg \tilde{y}_{ij}$ for $i, j \neq 3$. This results in a preferential decay of the scalar-LQ into $b\tau$ final states, with branching ratio $\text{BR}(\tilde{S}_1 \rightarrow b\tau) \approx 1$ for large scalar-LQ masses.

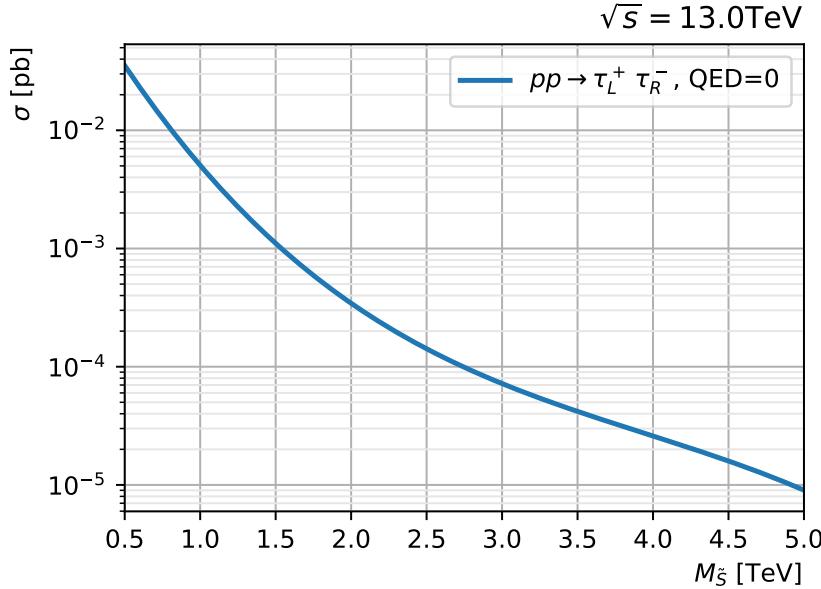


Figure 5.1: Cross section for scalar leptoquark (scalar-LQ) pair production decaying to $\tau^+\tau^-$ final states, showing different τ polarization configurations as a function of scalar-LQ mass at $\sqrt{s} = 13.0$ TeV. The coupling is fixed to $\tilde{y}_{33} = 1.0$.

It is worth noting that, due to the right-handed structure of the Yukawa interaction the scalar leptoquark \tilde{S}_1 couples only to right-chiral tau leptons. As a result, the dominant contribution to the $\tau^+\tau^-$ final state originates from the configuration where the outgoing taus have opposite helicities, specifically $\tau_L^+ \tau_R^-$. This polarization asymmetry provides a characteristic signature that could be probed using polarization-sensitive observables, such as the asymmetry in the charged energy of the products of the τ decay. Figure 5.1 shows the integrated production cross sections at $\sqrt{s} = 13.0$ TeV assuming a fixed coupling $\tilde{y}_{33} = 1.0$.

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5.2 A SIMPLIFIED MODEL FOR THE U_1 VECTOR LEPTOQUARK

In contrast to what is done for the scalar-LQ, vector couplings between fermions of the same helicity are allowed without resorting to the charge conjugation matrix. In this way, the inclusion of a single vectorial LQ (vector-LQ) with signatures in the di-tau final state channel requires a vector that transforms as $U_1 \doteq (\bar{\mathbf{3}}, \mathbf{1}, 4/3)$ under the SM group.

Extending the SM with a massive U_1 vector-LQ is not straightforward, as one has to ensure the renormalizability of the model. Most of the theoretical community has focused on extensions of the Pati-Salam (PS) models which avoid proton decay, such as the scenario found in [73]. Other examples include PS models with vector-like fermions [220–222], the so-called 4321 models [76, 223, 224], the twin PS² model [225, 226], the three-site PS³ model [227–229], as well as composite PS models [230–232].

The couplings in the second line of Eq. (5.9) can be found in the literature as $g_s \rightarrow g_s(1 - \kappa_U)$ and $g' \rightarrow g'(1 - \tilde{\kappa}_U)$, in order to take into account the possibility of an underlying strong interaction.

However, in what follows, we shall restrict ourselves to a simplified non-renormalizable lagrangian for a gauge vector-LQ, understood to be embedded into a more complete model. The SM is thus extended by adding the following terms featuring the U_1 vector – LQ :

$$\begin{aligned} \mathcal{L}_{U_1} = & -\frac{1}{2} U_{\mu\nu}^\dagger U^{\mu\nu} + M_U^2 U_{1\mu}^\dagger U_1^\mu \\ & -ig_s U_{1\mu}^\dagger T^a U_{1\nu} G^{a\mu\nu} - i\frac{2}{3} g' U_{1\mu}^\dagger U_{1\nu} B^{\mu\nu} \\ & + \frac{g_U}{\sqrt{2}} \sum_{ij} [U_{1\mu} (\beta_L^{ij} \bar{Q}_i \gamma^\mu L_i + \beta_R^{ij} \bar{d}_R^i \gamma^\mu e_R^j) + h.c.] \end{aligned} \quad (5.9)$$

where $U_{\mu\nu} \equiv \mathcal{D}_\mu U_{1\nu} - \mathcal{D}_\nu U_{1\mu}$, and $\mathcal{D}_\mu \equiv \partial_\mu + ig_s T^a G_\mu^a + i\frac{2}{3} g' B_\mu$. As evidenced by the second line above, we assume that the vector – LQ has a gauge origin.

The tight constraints from low-energy observables, such as $\Delta F = 2$ amplitudes and lepton flavor violating processes, motivates the following choice of the β_L and β_R matrices, which are 3×3 matrices in flavor space:

$$\beta_L = \begin{pmatrix} 0 & 0 & \beta_L^{d\tau} \\ 0 & 0 & \beta_L^{s\tau} \\ 0 & \beta_L^{b\mu} & 1 \end{pmatrix}, \quad \beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta_R^{b\tau} \end{pmatrix}. \quad (5.10)$$

Several works have studied the structure of the β_L and β_R matrices and the choice above is consistent with the breaking of $U(2)$ symmetry in the flavor space [73, 217, 220, 221].

The third and fourth lines in Eq. (5.9) shows the vector – LQ interactions with SM fermions, with coupling g_U , which we have chosen as preferring the third generation. These are particularly relevant for the vector – LQ decay probabilities, as well as for the single-vector – LQ production cross-section. The $\beta_L^{s\tau}$ parameter, which is the vector – LQ $\rightarrow s\tau$ coupling in the β_L matrix (see marginpar), is chosen to be equal to 0.2, following the fit done in [217], in order to simultaneously solve the $R_{D^{(*)}}$ anomaly and satisfy the $p p \rightarrow \tau^+ \tau^-$ constraints. Although $\beta_L^{s\tau}$ technically alters the single-vector – LQ production cross-section and vector – LQ branching fractions, we have confirmed that a value of $\beta_L^{s\tau} = 0.2$ results in negligible impact on our collider results, and thus is ignored in our subsequent studies.

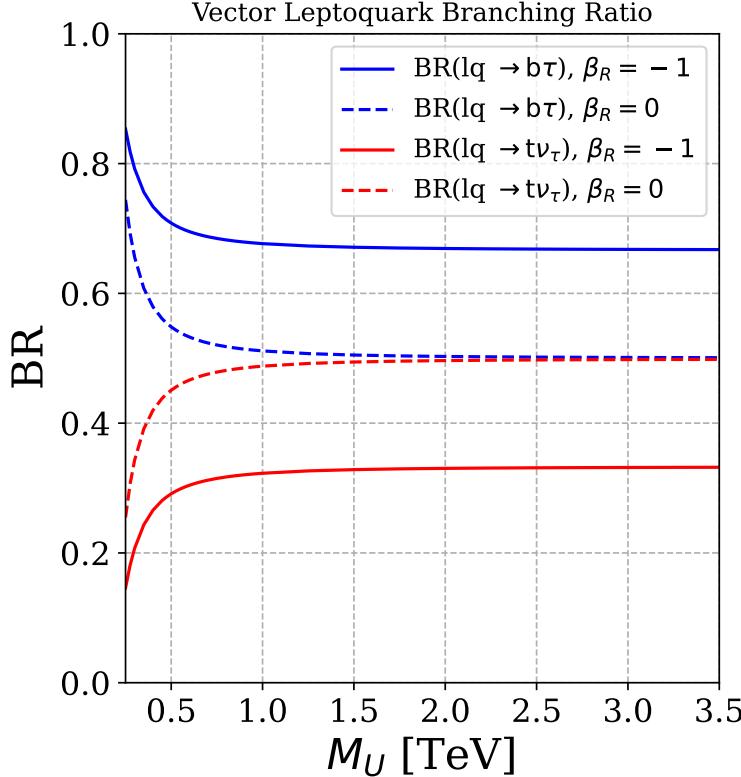


Figure 5.2: The vector – LQ $\rightarrow b\tau$ and vector – LQ $\rightarrow t\nu$ branching ratios for $\beta_R^{b\tau} = 0$ (solid lines) and $\beta_R^{b\tau} = -1$ (dashed lines).

The vector – LQ right-handed coupling is modulated with respect to the left-handed one by the $\beta_R^{b\tau}$ parameter. The choice of $\beta_R^{b\tau}$ is important phenomenologically, as it affects the vector – LQ branching ratios, as well as the single-vector – LQ production cross-section. To illustrate the former, Figure 5.2 (top) shows the vector – LQ $\rightarrow b\tau$ and vector – LQ $\rightarrow t\nu$ branching ratios as functions of the vector – LQ mass, for two values of $\beta_R^{b\tau}$. For large vector – LQ masses, we confirm that with $\beta_R^{b\tau} = 0$ then $\text{BR}(\text{vector – LQ} \rightarrow b\tau) \approx \text{BR}(\text{vector – LQ} \rightarrow t\nu) \approx \frac{1}{2}$. However, for $\beta_R^{b\tau} = -1$, as was chosen in [181], the additional coupling adds a new term to the total amplitude, leading to $\text{BR}(\text{vector – LQ} \rightarrow b\tau) \approx \frac{2}{3}$. The increase in this branching ratio can thus weaken bounds from vector – LQ searches targeting decays into $t\nu$ final states, which motivates exploring the sensitivity in $b\tau$ final states exclusively. Note that although a $\text{BR}(\text{vector – LQ} \rightarrow b\tau) \approx 1$ scenario is possible by having the vector – LQ couple exclusively to right-handed currents (i.e., $g_U \rightarrow 0$, but $g_U \beta_R^{b\tau} \neq 0$), it does not solve the observed anomalies in the $R_{D^{(*)}}$ ratios. Therefore, although some LHC searches assume $\text{BR}(\text{vector – LQ} \rightarrow b\tau) = 1$, we stress that in our studies we assume values of the model parameters and branching ratios that solve the $R_{D^{(*)}}$ ratios.

Having $\beta_L^{s\tau}$ different from zero also opens new decay channels. These, however, are either suppressed by $\beta_L^{s\tau}$ and powers of λ_{CKM} . In any case, this effect would decrease $\text{BR}(\text{vector – LQ} \rightarrow b\tau)$ and $\text{BR}(\text{vector – LQ} \rightarrow t\nu)$ by less than 3%.

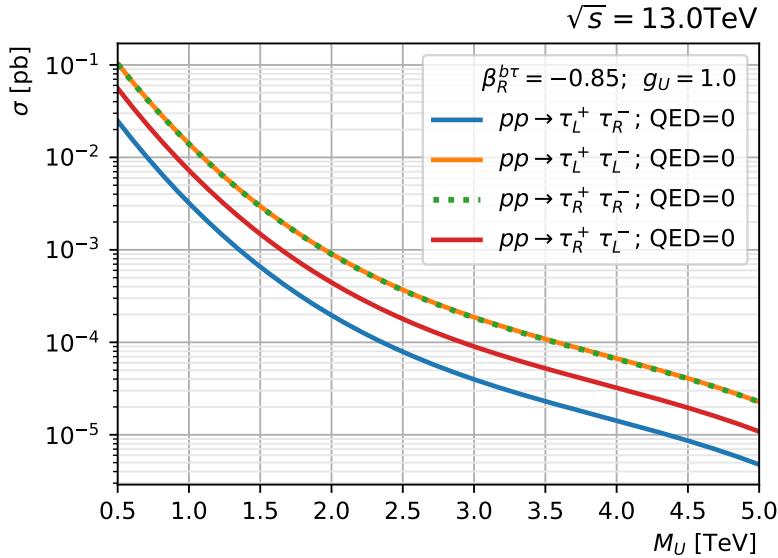


Figure 5.3: Cross section to $\tau^+\tau^-$ final states mediated for a vector-LQ in t-channel, showing different τ polarization configurations as a function of vector-LQ mass at $\sqrt{s} = 13.0\text{TeV}$. The couplings are fixed to $g_U = 1.0$ and $\beta_R^{b\tau} = -0.85$.

Unlike the scalar leptoquark (\tilde{S}_1) model, the vector leptoquark (U_1) couples to both left- and right-handed chiral currents, allowing for distinct polarization configurations in the $b\bar{b} \rightarrow \tau^+\tau^-$ final states. This feature is critical for collider phenomenology, as it influences the kinematic distributions of the final-state particles. The squared amplitudes for each polarization configuration in the center-of-mass frame can be expressed as follows:

$$|\mathcal{M}(\tau_L^+\tau_L^-)|^2 \propto g_U^4 (\tanh \eta + 1)^2, \quad (5.11)$$

$$|\mathcal{M}(\tau_L^+\tau_R^-)|^2 = |\mathcal{M}(\tau_R^+\tau_L^-)|^2 \propto 4g_U^4 \beta_R^2, \quad (5.12)$$

$$|\mathcal{M}(\tau_R^+\tau_R^-)|^2 \propto g_U^4 (\tanh \eta + 1)^2 \beta_R^4, \quad (5.13)$$

where η denotes the pseudorapidity of the τ lepton with respect to the incident b -quark direction, or equivalently, the pseudorapidity of the anti- τ lepton with respect to the incident \bar{b} -quark direction. Figure 5.3 shows the η -integrated production cross sections computed for an intermediate benchmark point with fixed couplings $g_U = 1.0$ and $\beta_R^{b\tau} = -0.85$.

We define the polarization asymmetry \mathcal{P}_{τ^-} of the τ lepton as the difference between the right-handed and left-handed contributions, normalized by their sum:

$$\mathcal{P}_{\tau^-} = \frac{|\mathcal{M}_R|^2 - |\mathcal{M}_L|^2}{|\mathcal{M}_R|^2 + |\mathcal{M}_L|^2} = \frac{(\tanh(\eta) + 1)^2 (\beta_R^4 - 1)}{(\tanh(\eta) + 1)^2 (1 + \beta_R^4) + 8\beta_R^2}, \quad (5.14)$$

could be probed using polarization-sensitive observables like the asymmetry in the charged energy of the products of the τ decay.

$$|\mathcal{M}_R|^2 = \frac{1}{2} \left(|\mathcal{M}(\tau_R^+ \tau_R^-)|^2 + |\mathcal{M}(\tau_L^+ \tau_R^-)|^2 \right), \quad (5.15)$$

$$|\mathcal{M}_L|^2 = \frac{1}{2} \left(|\mathcal{M}(\tau_L^+ \tau_L^-)|^2 + |\mathcal{M}(\tau_R^+ \tau_L^-)|^2 \right). \quad (5.16)$$

Figure 5.4 shows the polarization asymmetry \mathcal{P}_{τ^-} of the τ lepton as a function of its pseudorapidity η for different values of the $\beta_R^{b\tau}$ parameter. The asymmetry is maximal for $\beta_R^{b\tau} = -1$, which corresponds to the scenario where the vector – LQ couples exclusively to right-handed currents, and minimal for $\beta_R^{b\tau} = 0$, where the vector – LQ couples only to left-handed currents. The polarization asymmetry is sensitive to the choice of $\beta_R^{b\tau}$, and thus can be used to probe the underlying BSM model.

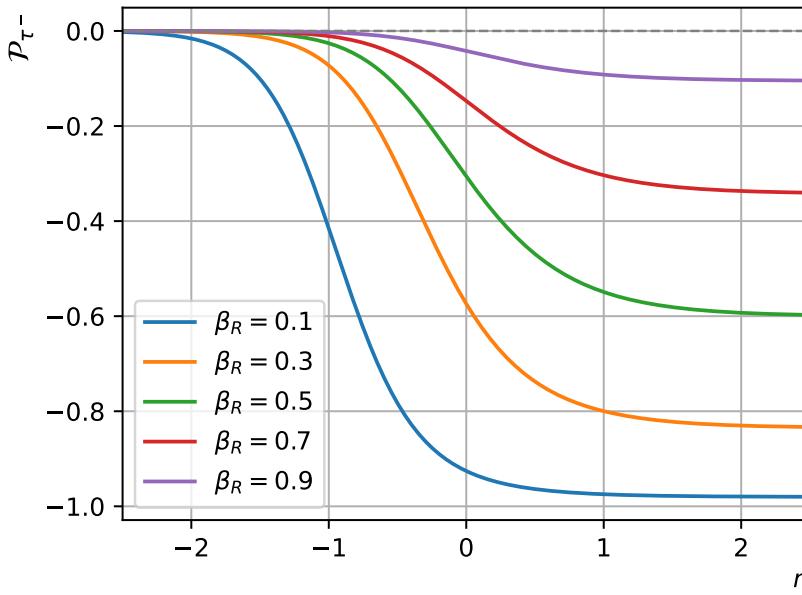


Figure 5.4: The polarization asymmetry \mathcal{P}_{τ^-} of the τ lepton as a function of its pseudorapidity η for different values of the $\beta_R^{b\tau}$ parameter.

Going to the detector frame, in pp collisions we do not have a well-defined direction for the incoming b -quark due to we do not know which proton the b -quark comes from. So in average, we must promediate the two proton directions,

$$\mathcal{P}_{\tau^-}^{\text{avg}} = \frac{1}{2} (\mathcal{P}_{\tau^-}(\eta) + \mathcal{P}_{\tau^-}(-\eta)). \quad (5.17)$$

Figure 5.5 shows the average polarization asymmetry $\mathcal{P}_{\tau^-}^{\text{avg}}$ of the τ lepton as a function of its pseudorapidity η for different values of the $\beta_R^{b\tau}$ parameter. The polarization has a strong non-null dependence on η mainly for small values of $\beta_R^{b\tau}$, where the polarization asymmetry is maximal. For larger values of $\beta_R^{b\tau}$, the polarization asymmetry becomes less sensitive to the

pseudorapidity, and the average polarization asymmetry approaches a constant value near zero. This signature is particularly relevant to differentiate the vector-LQ model from the scalar-LQ model, where the polarization asymmetry is always zero due to the right-handed structure of the Yukawa interaction.

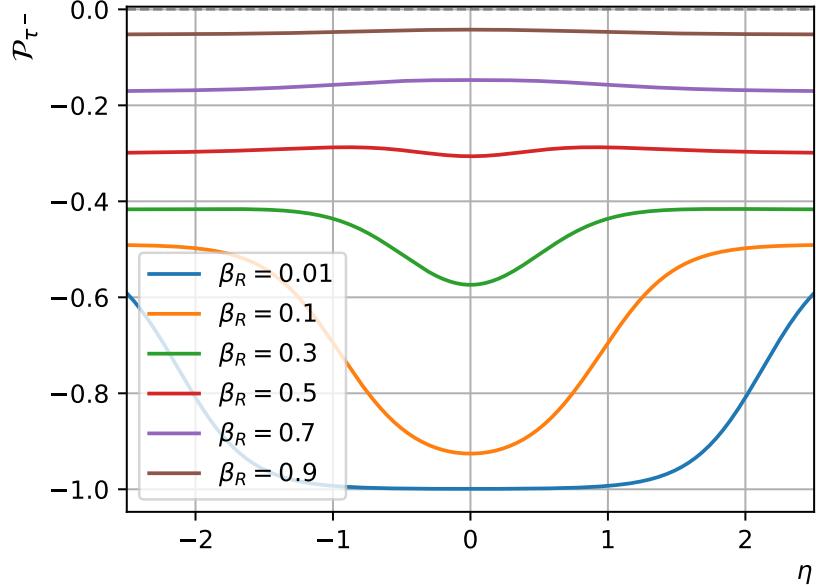


Figure 5.5: The average polarization asymmetry P_{τ}^{avg} of the τ lepton as a function of its pseudorapidity η for different values of the $\beta_R^{b\tau}$ parameter.

The simulated signal and background events are initially filtered using selections which are motivated by experimental constraints, such as the geometric constraints of the CMS detector, the typical kinematic thresholds for reconstruction of particle objects, and the available triggers. The remaining events after the preliminary event selection criteria are used to train and execute a BDT algorithm for each signal point in the $\{ \text{Mu}, g_{\text{t}} \}$ space, in order to maximize the probability to detect signal amongst background events. The BDT algorithm is implemented using the `scikit-learn` [233] and `xgboost` (XGB) [132] python libraries. We use the `XGBClassifier` class from the `xgboost` library, a 10-fold cross validation using the `scikit-learn` method (`GridCV`¹) for a grid in a hyperparameter space with 75, 125, 250, and 500 estimators, maximum depth in 3, 5, 7, 9, as well as learning rates of 0.01, 0.1, 1, and 10. For the cost function, we utilize the default mean square error (MSE). Additionally, we use the tree method based on the approximate greedy algorithm (histogram-optimized), referred to as `hist`, with a uniform sample method. These choices allow us to maximize the detection capability of the BDT algorithm by carefully tuning the hyperparameters, selecting an appropriate cost function, and utilizing an optimized tree construction method.

¹ GridCV is a method that allows to find the best combination of hyperparameter values for the model, as this choice is crucial to achieve an optimal performance.

For both channels and each $\{M_U, g_U\}$ signal point, the binary XGB classifier was trained (tested) with 20% (80%) of the simulated events, for each signal and background MC sample. Over forty kinematic and topological variables were studied as input for the XGB. These included the momenta of b jets and $\tau_{h,\ell}$ candidates; both invariant and transverse masses of pairs of τ objects and of b τ combinations; angular differences between b jets, between τ objects, and between the $\tau_{h,\ell}$ and b jets; and additional variables derived from the missing momentum in the events. After studying correlations between variables and their impact on the performance of the BDT, we found that only eight variables were necessary and responsible for the majority of the sensitivity of the analysis.

The variable that provides the best signal to background separation is the scalar sum of the p_T of the final state objects ($\tau_h, \tau_{h/\ell}$) and the missing transverse momentum, referred to as S_T^{MET} :

$$S_T^{\text{MET}} = |\vec{p}_T^{\text{miss}}| + \sum_{\tau_h, \tau_{h/\ell}} |\vec{p}_T| \quad (5.18)$$

The S_T^{MET} variable has been successfully used in LQ searches at the LHC, since it probes the mass scale of resonant particles involved in the production processes. Other relevant variables include the magnitude of the vectorial difference in p_T between the two lepton candidates ($|\Delta \vec{p}_T|_{\tau_h \tau_{h/\ell}}$), the $\Delta R_{\tau_h \tau_{h/\ell}}$ separation between them, the reconstructed dilepton mass $m_{\tau_h \tau_{h/\ell}}$, and the product of their electric charges ($Q_{\tau_h} \times Q_{\tau_{h/\ell}}$). We also use the $|\Delta \vec{p}_T|$ between the τ_h candidate and \vec{p}_T^{miss} , and (if applicable) the $|\Delta \vec{p}_T|$ between the τ_h candidate and the leading b jet. For the final states including two τ_h candidates, the one with the highest p_T is used.

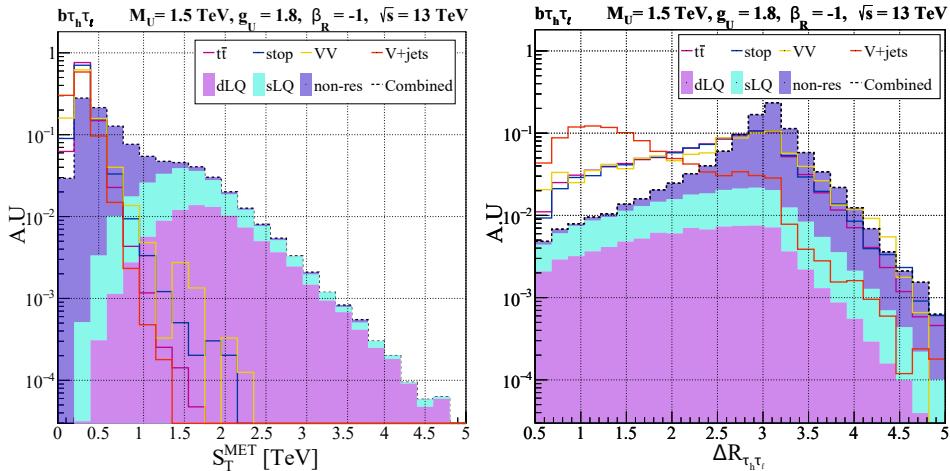


Figure 5.6: $S_T^{\text{MET}}, \Delta R_{\tau_h \tau_\ell}$, signal and background distributions for the $\tau_h \tau_\ell$ channel. The signal distributions are generated for a benchmark sample with LQ mass of 1.5 TeV maximally coupled to right-handed currents assuming a coupling $g_U = 1.0$.

Figure 5.6 shows some relevant topological distributions...

Figure 5.7: The BDT output for the $\tau_h\tau_\ell$ channel, showing the signal and background distributions for a benchmark sample with LQ mass of 1.5 TeV maximally coupled to right-handed currents assuming a coupling $g_U = 1.0$. The BDT output is defined as the logarithm of the ratio of the probability of the event being signal over the probability of it being background.

Figure 5.7

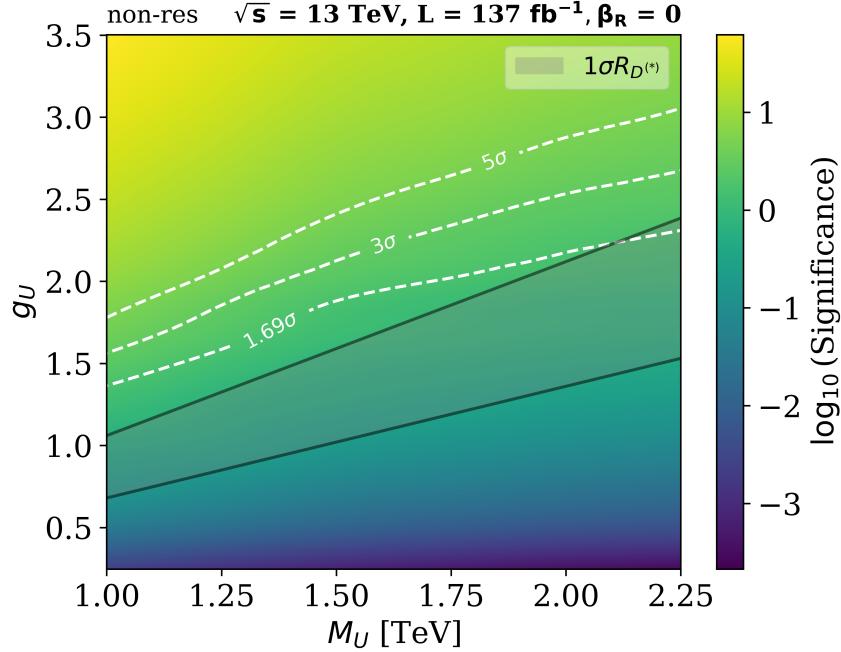


Figure 5.8: The significance of the $\tau\tau$ signal, as a function of the LQ mass and coupling g_U , for the non-resonant production of $\tau\tau$ final states at $\sqrt{s} = 13.0$ TeV, with an integrated luminosity of 137 fb^{-1} .

Figure 5.8...

5.3 A SIMPLIFIED MODEL FOR A Z'_{B-L} BOSON

Hypothetical heavy neutral bosons, such as the Z' boson, are a common feature in many BSM models. They arise from extended gauge symmetries and can couple to fermions in ways that differ from the SM Z boson. Assuming a $U(1)_{B-L}$ extension of the SM gauge group, the Z' boson can couple to fermions through a gauge interaction that is proportional to their baryon minus lepton number ($B - L$). This coupling can lead to new interactions and processes that are not present in the SM, such as flavor-changing neutral currents or enhanced production of certain final states depending on the symmetry breaking pattern and the mass of the Z' boson. Additionally, we could consider textures in the flavor space of the Z' couplings, which can lead to preferential couplings to specific generations

of fermions and to avoid large flavor-changing neutral currents (FCNCs) we assume that they are diagonal in the flavor space.

Accordingly, we assume the Z' only couples to third-generation fermions. Our simplified model is thus extended by:

$$\begin{aligned} \mathcal{L}_{Z'} &= -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} M_{Z'}^2 Z'_\mu Z'^\mu \\ &\quad + \frac{g_{Z'}}{2\sqrt{6}} Z'^\mu (\zeta_q \bar{Q}_3 \gamma_\mu Q_3 - 3\zeta_\ell \bar{L}_3 \gamma_\mu L_3) \end{aligned} \quad (5.19)$$

$$+ \zeta_t \bar{t}_R \gamma_\mu t_R + \zeta_b \bar{b}_R \gamma_\mu b_R - 3\zeta_\tau \bar{\tau}_R \gamma_\mu \tau_R) \quad (5.20)$$

where the constants $M_{Z'}$, $g_{Z'}$, ζ_q , ζ_t , ζ_b , ζ_ℓ , ζ_τ , are model-dependent.

Unlike the U_1 vector leptoquark, the polarization of the τ lepton implies the opposite polarization of the anti- τ lepton, due to their production in the same chiral line. To differentiate the contributions of each ζ parameter, we have calculated the amplitudes for the different initial and final state polarizations, which are given by:

$$|\mathcal{M}(b_L \bar{b}_R \rightarrow \tau_R^+ \tau_L^-)|^2 \propto g_{Z'}^4 \zeta_\ell^2 \zeta_q^2 (1 + \tanh \eta)^2, \quad (5.21)$$

$$|\mathcal{M}(b_R \bar{b}_L \rightarrow \tau_R^+ \tau_L^-)|^2 \propto g_{Z'}^4 \zeta_\ell^2 \zeta_b^2 (1 - \tanh \eta)^2, \quad (5.22)$$

$$|\mathcal{M}(b_L \bar{b}_R \rightarrow \tau_L^+ \tau_R^-)|^2 \propto g_{Z'}^4 \zeta_\tau^2 \zeta_q^2 (1 - \tanh \eta)^2, \quad (5.23)$$

$$|\mathcal{M}(b_R \bar{b}_L \rightarrow \tau_L^+ \tau_R^-)|^2 \propto g_{Z'}^4 \zeta_\tau^2 \zeta_b^2 (1 + \tanh \eta)^2. \quad (5.24)$$

Figure 5.9 shows the integrated production cross sections at $\sqrt{s} = 13.0$ TeV for a fixed set of couplings $g_{Z'} = 1.0$, $\zeta_\ell = 1.0$, $\zeta_q = 1.0$, $\zeta_b = 0.8$, and $\zeta_\tau = 0.6$. The cross section is sensitive to the choice of the couplings, and thus can be used to probe the underlying BSM model.

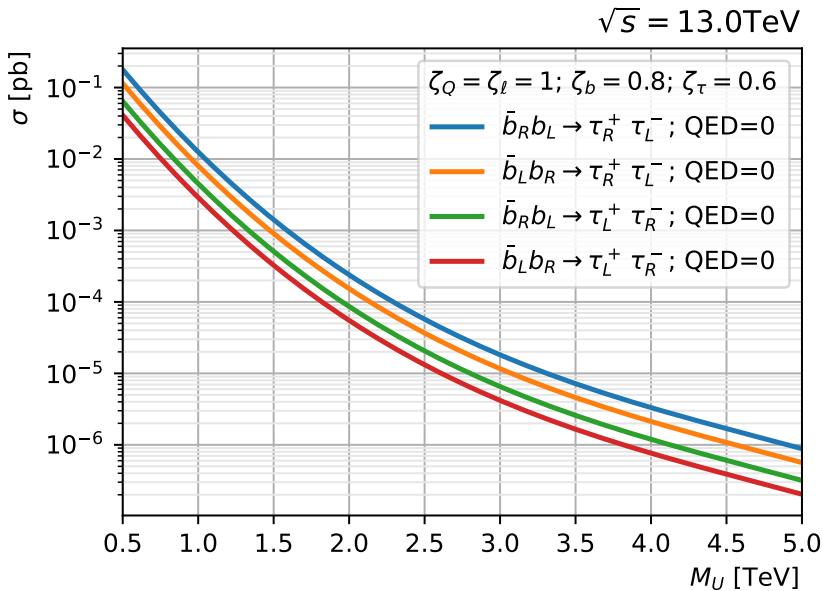


Figure 5.9: Cross section for Z' production decaying to $\tau^+\tau^-$ final states, showing different τ polarization configurations as a function of Z' mass at $\sqrt{s} = 13.0$ TeV. The couplings are fixed to $g_{Z'} = 1.0$, $\zeta_\ell = 1.0$, $\zeta_q = 1.0$, $\zeta_b = 0.8$, and $\zeta_\tau = 0.6$.

The polarization asymmetry \mathcal{P}_{τ^-} of the τ lepton can be defined in a similar way as for the U_1 vector leptoquark, but now it is sensitive to the different couplings ζ_ℓ , ζ_q , ζ_b , and ζ_τ . The polarization asymmetry is given by:

$$\mathcal{P}_{\tau^-} = \frac{|\mathcal{M}_R|^2 - |\mathcal{M}_L|^2}{|\mathcal{M}_R|^2 + |\mathcal{M}_L|^2} \quad (5.25)$$

$$= \frac{(1 + \tanh \eta)^2 (\zeta_\tau^2 \zeta_b^2 - \zeta_\ell^2 \zeta_q^2) + (1 - \tanh \eta)^2 (\zeta_\tau^2 \zeta_q^2 - \zeta_\ell^2 \zeta_b^2)}{(1 + \tanh \eta)^2 (\zeta_\tau^2 \zeta_b^2 + \zeta_\ell^2 \zeta_q^2) + (1 - \tanh \eta)^2 (\zeta_\tau^2 \zeta_q^2 + \zeta_\ell^2 \zeta_b^2)}, \quad (5.26)$$

where we have defined the right-handed and left-handed contributions as

$$|\mathcal{M}_R|^2 = \frac{1}{2} \left(|\mathcal{M}(b_R \bar{b}_L \rightarrow \tau_L^+ \tau_R^-)|^2 + |\mathcal{M}(b_L \bar{b}_R \rightarrow \tau_L^+ \tau_R^-)|^2 \right), \quad (5.27)$$

$$|\mathcal{M}_L|^2 = \frac{1}{2} \left(|\mathcal{M}(b_R \bar{b}_L \rightarrow \tau_R^+ \tau_L^-)|^2 + |\mathcal{M}(b_L \bar{b}_R \rightarrow \tau_R^+ \tau_L^-)|^2 \right). \quad (5.28)$$

Similarly, the polarization of $t\bar{t}$ observables in Z'_{B-L} will depend on the couplings ζ_q , ζ_b , and ζ_t , and can be used to measure the parameters of the underlying BSM model.

5.4 INTERFERENCE BETWEEN THE U_1 AND Z'_{B-L} MODELS

The presence of a Z' boson in LQ models has been justified in various papers, for example, in [193]. The argument is that minimal extensions of the SM which include a massive gauge U_1 LQ, uses the gauge group $SU(4) \times SU(3)' \times SU(2)_L \times U(1)_{T_R^3}$. Such an extension implies the presence of an additional massive boson, Z' , and a color-octet vector, G' , arising from the spontaneous symmetry breaking into the SM. Naively, the LQs are associated to the breaking of $SU(4) \rightarrow SU(3)_{[4]} \times U(1)_{B-L}$, the G' arises from $SU(3)_{[4]} \times SU(3)' \rightarrow SU(3)_c$, and the Z' comes from the breaking of $U(1)_{B-L} \times U(1)_{T_R^3} \rightarrow U(1)_Y$. Notice that the specific pattern of breaking, and the relations between the masses and couplings, are connected to the specific scalar potential used. The Z' in particular can play an important role in the projected LQ discovery reach, as it can participate in $p p \rightarrow \tau\tau$ production by s-channel exchange, both resonantly and as a virtual mediator. To study the effect of a Z' on the $p p \rightarrow \tau\tau$ production cross-sections and kinematics, we extend our benchmark Lagrangian in Eq. (5.9) with further non-renormalizable terms involving the Z' boson according to (5.19).

We study two extreme cases for the Z' mass, following [234], namely $M_{Z'} = \sqrt{\frac{1}{2}} M_U < M_U$ and $M_{Z'} = \sqrt{\frac{3}{2}} M_U > M_U$. We also assume the LQ and Z' are uniquely coupled to left-handed currents, i.e. $\zeta_q = \zeta_\ell = 1$ and $\zeta_t = \zeta_b = \zeta_\tau = 0$. With these definitions, Figure 5.10 shows the effect of the Z' on the $\tau\tau$ production cross-section, considering $g_U = 1$, $\beta_R = 0$, and different $g_{Z'}$ couplings. On the top panel, the cross-sections corresponding to the cases where $M_{Z'} = \sqrt{\frac{1}{2}} M_U$ are shown. As expected, the $\tau\tau$ production cross-section for the inclusive case (i.e., $g_{Z'} \neq 0$) is larger

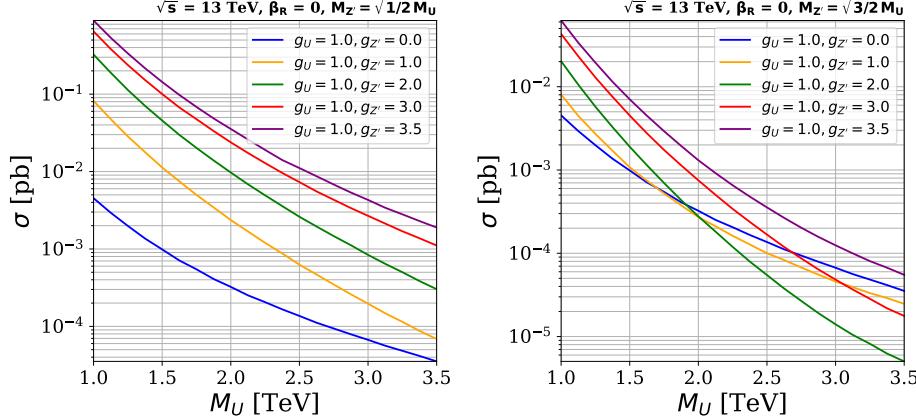


Figure 5.10: $\tau\tau$ cross-section as a function of the LQ mass for different values of g_U and $g_{Z'}$. The estimates are performed at $\sqrt{s} = 13$ TeV, $\beta_R = 0$, $M_{Z'} = \sqrt{1/2}M_U$ (left), and $M_{Z'} = \sqrt{3/2}M_U$ (right).

than that for the LQ-only non-res process ($g_{Z'} = 0$, depicted in blue). This effect increases with $g_{Z'}$ and, within the evaluated values, can exceed the LQ-only cross-section by up to two orders of magnitude. In contrast, a more intricate behaviour can be seen in the bottom panel of Figure 5.10, which corresponds to $M_{Z'} = \sqrt{\frac{3}{2}}M_U$. Here, for low values of M_U , a similar increase in the cross-section is observed. However, for higher values of M_U , the inclusive $p p \rightarrow \tau\tau$ cross-section is smaller than the LQ-only $\tau\tau$ cross-section. This behaviour suggests the presence of a dominant destructive interference at high masses, leaving its imprint on the results.

In order to further illustrate the effect, Figure 5.11 shows the relative kinematic interference (RKI) as a function of the reconstructed invariant mass $m_{\tau\tau}$, for $g_{Z'} = 1$ and varying values of M_U . The RKI parameter is defined as

$$\text{RKI}(m_{\tau\tau}) = \frac{1}{\sigma_{LQ+Z'}} \left[\frac{d\sigma_{LQ+Z'}}{dm_{\tau\tau}} - \left(\frac{d\sigma_{LQ}}{dm_{\tau\tau}} + \frac{d\sigma_{Z'}}{dm_{\tau\tau}} \right) \right], \quad (5.29)$$

where σ_X is the production cross-section arising due to contributions from X particles. For example, $\sigma_{LQ+Z'}$ represents the inclusive cross-section where both virtual LQ and s-channel Z' exchange contribute. For both cases, we can observe the presence of deep valleys in the RKI curves when $m_{\tau\tau} \rightarrow 0$, indicating destructive interference between the LQ and the Z' contributions. This interference generates a suppression of the differential cross-section for lower values of $m_{\tau\tau}$ and, therefore, in the integrated cross-section.

The change in sensitivity on the non-res signal significance due this interference effect with the Z' boson is shown in Figure 5.12. We consider two opposite cases for the Z' mass: $M_{Z'}^2 = M_U^2/2$ (top) and $M_{Z'}^2 = 3M_U^2/2$ (bottom). Our results are shown on the $g_{Z'} - M_U$ plane, for a fixed $g_U = 1.8$ and $\beta_R = 0$. For the $M_{Z'}^2 = M_U^2/2$ scenario, there is an overall increase in the total cross-section, with a larger $g_{Z'}$ implying a larger sensitivity. This

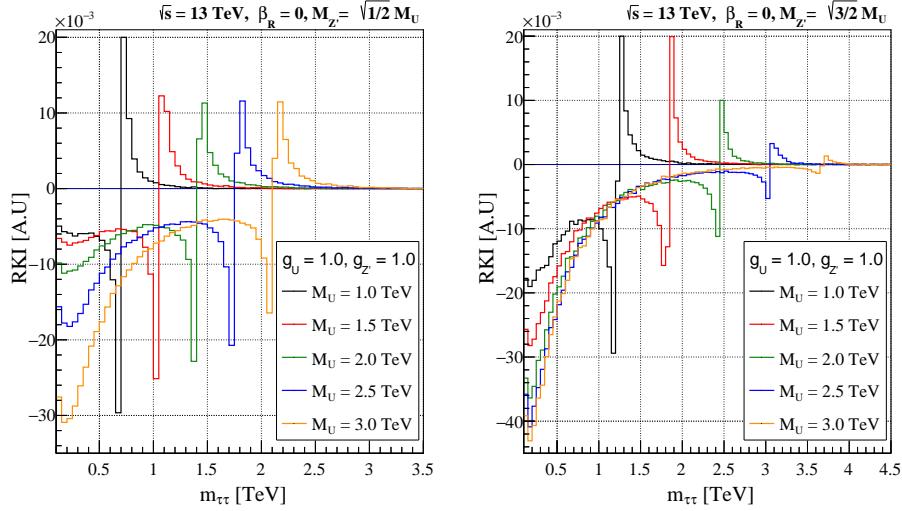


Figure 5.11: The relative kinematic interference (RKI), as a function of the reconstructed mass of two taus, for different LQ masses. The studies are performed assuming $\sqrt{s} = 13 \text{ TeV}$, $\beta_R = 0$, $g_U = 1.0$, $g_{Z'} = 1.0$, $M_{Z'} = \sqrt{1/2}M_U$ (left), and $M_{Z'} = \sqrt{3/2}M_U$ (right).

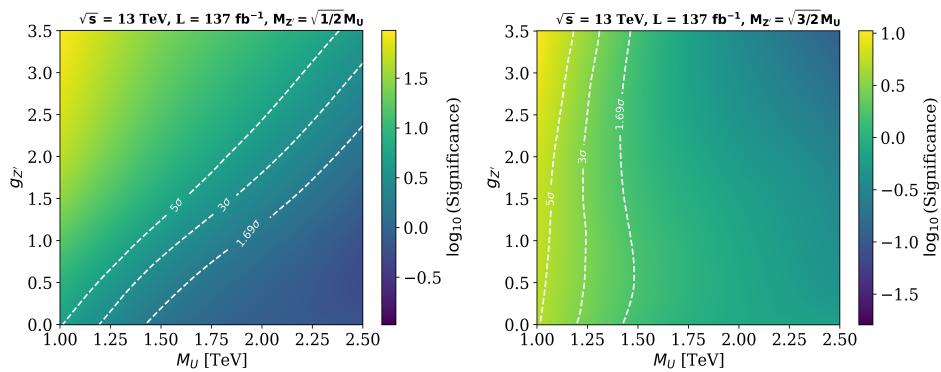


Figure 5.12: Change on the non-res signal significance for different Z' coupling scenarios and LQ masses. The estimates are performed at $\sqrt{s} = 13.0 \text{ TeV}$, $\beta_R = 0$, $g_U = 1.8$, $M_{Z'} = \sqrt{1/2}M_U$ (top), and $M_{Z'} = \sqrt{3/2}M_U$ (bottom).

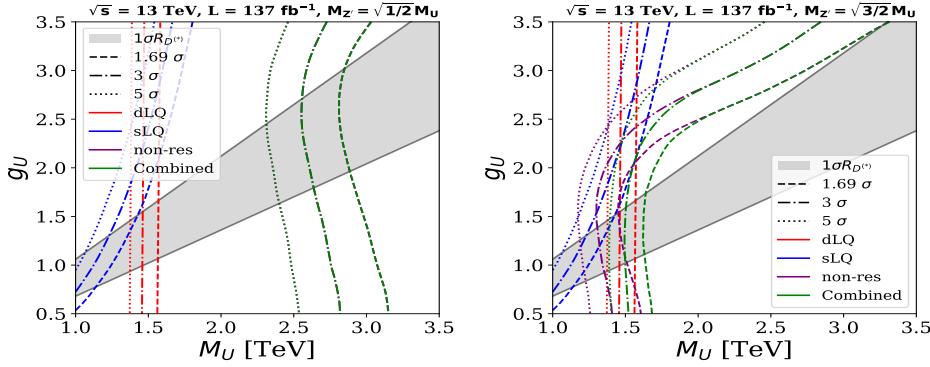


Figure 5.13: Signal significance for different coupling scenarios and LQ masses, for all channels, with an additional Z' contribution to non-res production. We set $\beta_R = 0$ and $g_{Z'} = 3.5$, taking $M_{Z'}^2$ equal to $M_U^2/2$ ($3M_U^2/2$) on the top (bottom) panel.

means that our ability to probe smaller values of g_U could be enhanced, as a given observation would be reproduced with both a specific g_U and vanishing $g_{Z'}$, or a smaller g_U with large $g_{Z'}$. Thus, for a large enough $g_{Z'}$, it could be possible to enhance non-res to the point that the entire region favoured by B-anomalies could be ruled out. In contrast, for $M_{Z'}^2 = 3M_U^2/2$ the cross-section is strongly affected by the large destructive interference, such that a larger $g_{Z'}$ does not necessarily imply an increase in sensitivity. In fact, as can be seen in the bottom panel, for large M_U the significance is reduced as $g_{Z'}$ increases, leading to the opposite conclusion than above, namely, that a large $g_{Z'}$ could reduce the effectiveness of non-res.

The impact of the above can be seen in Figure 5.13, which shows our previous sensitivity curves on the $M_U - g_U$ plane, but this time with a Z' contribution to non-res. We use the same values of $M_{Z'}$ as before, but fix $g_{Z'} = 3.5$. For smaller $M_{Z'}$ (top), the non-res contribution is enhanced so much, that both sLQ and dLQ play no role whatsoever in determining the exclusion region. We find that, for small g_U , the sensitivity is dominated by Z' production such that, since M_U is related to $M_{Z'}$, LQ masses up to ~ 3 TeV are excluded. This bound is slightly relaxed for larger values of g_U , which is attributed to destructive interference effects due to an increased LQ contribution.

The bottom panel of Figure 5.13 shows that case where $M_{Z'}$ is larger than M_U . As expected from our previous discussion, the behaviour and impact of non-res is modified. For small g_U , we again have the pure Z' production dominating the non-res cross-section, leading to a null sensitivity on g_U , similar to what happens in dLQ. In contrast, for very large g_U , we find that the pure LQ non-res production is the one that dominates, and we recover sensitivity regions with a slope similar to those shown in Figures 5.14-5.18, shifted towards larger values of g_U . For intermediate values of this coupling, the destructive interference have an important effect again, twisting the exclusion region slightly towards the left. Still, even in this case, we find that sLQ plays a marginal role in

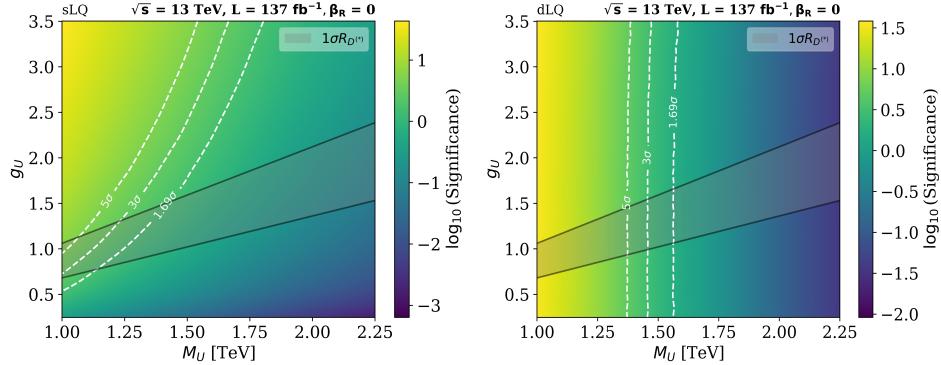


Figure 5.14: Signal significance for different coupling scenarios and LQ masses, without right-handed currents, using the combination of all search channels. The results pertaining to sLQ, dLQ and non-res production are displayed respectively from the top. These results are for $\sqrt{s} = 13 \text{ TeV}$ and 137 fb^{-1} .

defining the combined exclusion region, and that the final result again depends primarily on dLQ and non-res production.

5.5 SINGLE AND DOUBLE LEPTOQUARK CONTRIBUTIONS

The expected signal significance for sLQ, dLQ and non-res production, and their combination, is presented in Figure 5.14. Here, the significance is shown as a heat map in a two dimensional plane of g_U versus M_U , considering exclusive couplings to left-handed currents, *i.e.* $\text{BR}(\text{LQ} \rightarrow b\tau) = \frac{1}{2}$. The dashed lines show the contours of constant signal significance. The 1.69σ contour represents exclusion at 95% confidence level, and the $3-5\sigma$ contours represent potential discovery. The grey band defines the set of $\{M_U, g_U\}$ values that can explain the B-meson anomalies, $C_U \sim 0.01$ for this scenario. The estimates are performed under the conditions for the second run, RUN-II, of the LHC ($\sqrt{s} = 13 \text{ TeV}$ and $L = 137 \text{ fb}^{-1}$). We find that the dLQ interpretation plot (Figure 5.14 second from the top) does not depend on g_U , which is expected due to dLQ production arising exclusively from interactions with gluons. For this reason, the dLQ production process provides the best mode for discovery when g_U is small. On the other hand, the non-res channel is more sensitive to changes in the coupling parameter g_U , as its production cross-section depends on g_U^4 . Therefore, the non-res production process provides the best mode for discovery when g_U is large. These results confirm the expectations from previous analyses (see for instance [192]), in the sense that the dLQ and non-res processes complement each other nicely at low and high g_U scenarios. The sLQ channel combines features from both the dLQ and non-res channels, in principle making it an interesting option to explore different scenarios and gain a better understanding of LQ properties, but the evolution of the signal significance in the full phase space is more complicated as it involves resonant LQ production with a cross-section that depends non-trivially on M_U , g_U ,

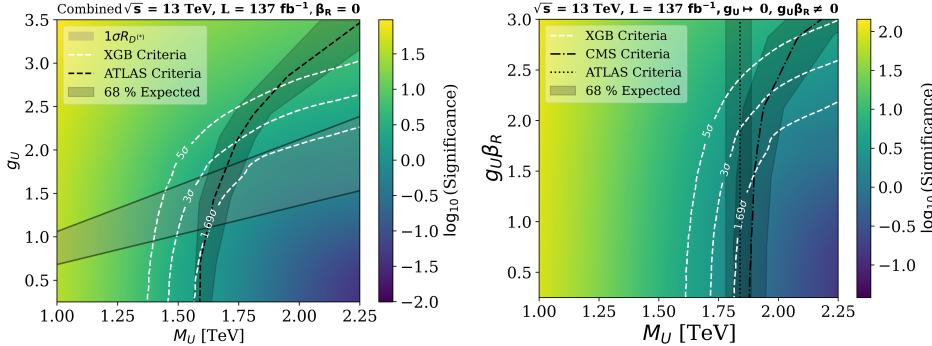


Figure 5.15: The top (bottom) panel shows signal significance comparison with ATLAS [212] (CMS and ATLAS [206, 213]) background only hypothesis, for the combination of all channels, with uniquely coupling to left-handed (right-handed) currents. The estimates are performed at $\sqrt{s} = 13 \text{ TeV}$ and 137 fb^{-1} .

and the LQ coupling to gluons. However, Figure 5.14 shows that the sLQ production process can provide complementary and competitive sensitivity to the non-res and dLQ processes, in certain parts of the phase space. The top panel of Figure 5.15 presents the sensitivity of all signal production processes combined, and compares our expected exclusion region with the latest one from the ATLAS Collaboration [212]. The comparison suggests that our proposed analysis strategy provides better sensitivity than current methods being carried out at ATLAS, especially at large values of g_U . In particular, we find that with the pp data already available from RUN-II, our expected exclusion curves begin to probe solutions to the B-anomalies for LQ masses up to 2.25 TeV.

Figure 5.15 shows the expected signal significance considering $\text{BR}(\text{LQ} \rightarrow b\tau) = 1$, in order to compare our analysis with the corresponding results from the CMS [206] and ATLAS [213] Collaborations. Let us emphasize again that $\text{BR}(\text{LQ} \rightarrow b\tau)$ depends on β_R , as illustrated on the top panel of Figure 5.2. Thus, although the $\text{BR}(\text{LQ} \rightarrow b\tau) = 1$ scenario is a possible physical case, it does not solve the observed anomalies in the $R_{D^{(*)}}$ ratios, as it corresponds to the case where LQs couple exclusively to right-handed currents.

With this in mind, the scenario studied by CMS in [206] considers couplings only to left-handed currents, setting artificially the condition $\text{BR}(\text{LQ} \rightarrow b\tau) = 1$. In order to compare, we scale the efficiency \times acceptance of our selection criteria for $\beta_R = 0$, by a factor of 2.0 for s LQ and 4.0 for d LQ. According to Figure 5.15, the ML approach that we have followed again suggests an optimization of the signal and background separation, having the potential of improving the regions of exclusion (1.69σ) with respect to that of CMS. In the bottom panel of the Figure we have also included a similar exclusion by ATLAS [213]. However, since ATLAS only considers d LQ production in the analysis, the results are not entirely comparable, so are included only as a reference.

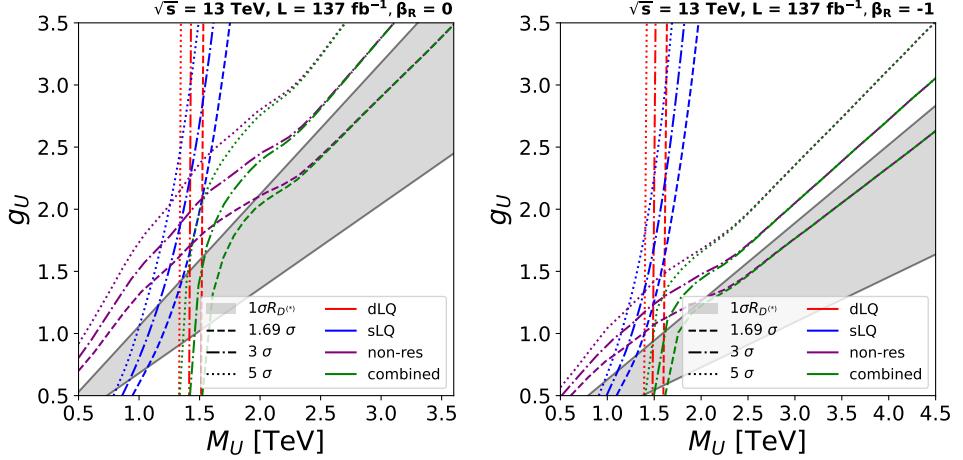


Figure 5.16: Signal significance for different coupling scenarios and LQ masses for all channels. This plot summarizes our results with $\beta_R = 0$ (without right-handed currents) and $\beta_R = -1$ (maximally coupled to right-handed currents). The estimates are performed at $\sqrt{s} = 13$ TeV and 137 fb^{-1} .

We now turn to the role of β_R , and our capacity of probing the regions solving the B-meson anomalies. Figure 5.16 shows the maximum significant contours, under LHC RUN-II conditions, for the different LQ production mechanisms and their combination, considering scenarios with only left-handed currents ($\beta_R = 0$, top) and with maximal right-handed currents ($\beta_R = -1$, bottom). We find a noticeable improvement in signal significance in all channels when taking $\beta_R = -1$, as is expected from the increase in $\text{BR}(\text{LQ} \rightarrow b\tau)$ branching ratio and production cross-sections (see Figure 5.2). However, the region solving the B-meson anomalies also changes, preferring lower values of g_U , such that in both cases we find ourselves just starting to probe this region at large M_U .

The combined significance contours for the different BR scenarios that have been considered is presented in Figure 5.17. These contours illustrate the regions of exclusion for the three cases of interest, namely exclusive left-handed currents ($\text{BR}(\text{LQ} \rightarrow b\tau) = \frac{1}{2}$, $\beta_R = 0$), maximal left and right couplings ($\text{BR}(\text{LQ} \rightarrow b\tau) = \frac{2}{3}$, $\beta_R = -1$), and exclusive right-handed currents ($\text{BR}(\text{LQ} \rightarrow b\tau) = 1$, $g_U \rightarrow 0$, $g_U \beta_R = 1$). For small g_U , we find that the exclusive right-handed scenario is most sensitive, while the exclusive left-handed case is the worst. The reason for this is that this region is excluded principally by dLQ production, such that having the largest branching ratio is crucial in order to have a large number of events. For larger couplings, both exclusive scenarios end up having similar exclusion regions, with the $\beta_R = -1$ case being significantly more sensitive. The reason in this case is that the exclusion is dominated by non-res, which has a much larger production cross-section if both currents are turned on.

In order to finalise our analysis of the LQ-only model, we show in Figure 5.18 the expected combined significance in the relatively near future. For this, considering $\sqrt{s} = 13.6$ TeV, we show contours for the sensitiv-

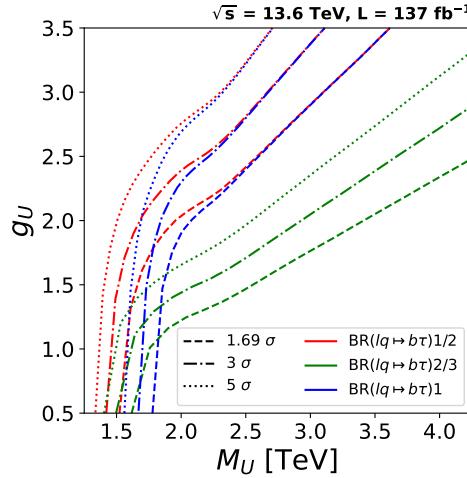


Figure 5.17: Signal significance for different coupling scenarios and LQ masses, considering the case without coupling to right-handed currents $\text{BR}(\text{LQ} \rightarrow b\tau) = \frac{1}{2}$, the case maximally coupled to right- and left-handed currents $\text{BR}(\text{LQ} \rightarrow b\tau) = \frac{2}{3}$, and the case uniquely coupled to right-handed currents $\text{BR}(\text{LQ} \rightarrow b\tau) = 1$. The estimates are performed at $\sqrt{s} = 13 \text{ TeV}$ and 137 fb^{-1} .

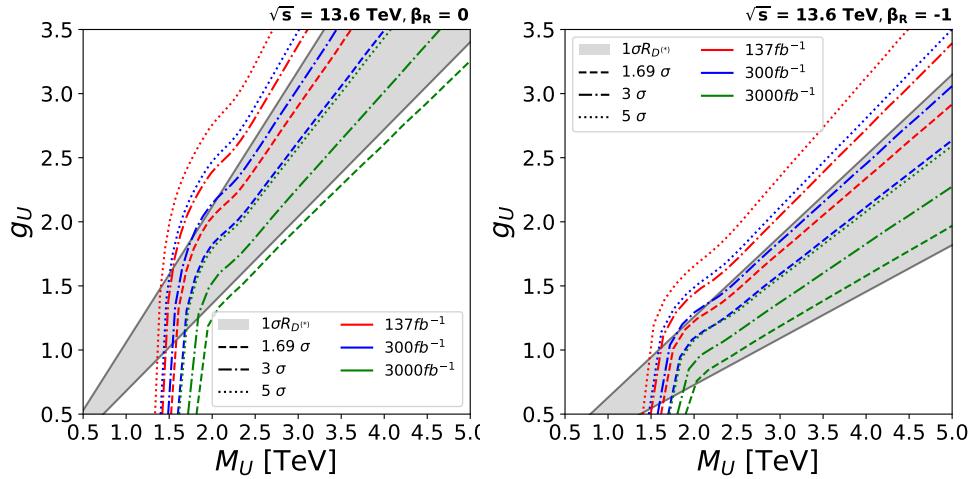


Figure 5.18: Projected signal significance for different coupling scenarios and LQ masses maximally coupled to right-handed currents. The estimates are performed at $\sqrt{s} = 13.6 \text{ TeV}$, 137 fb^{-1} , 300 fb^{-1} and 3000 fb^{-1} .

ity corresponding to integrated luminosities of 137 fb^{-1} , 300 fb^{-1} , and 3000 fb^{-1} , for scenarios with only left-handed currents (top) and with maximal coupling to right-handed currents (bottom). Note that for $\beta_R = 0$ ($\beta_R = -1$), couplings g_U close to 3.18 (1.85) and $M_U = 5.0\text{ TeV}$ can be excluded with 1.69σ significance for the high luminosity LHC era, allowing us to probe the practically the entirety of the B-meson anomaly favored region. Note that the background yields for the high luminosity LHC might be larger due to pileup effects. Nevertheless, as it was mentioned in Section ??, we have included a conservative 10% systematic uncertainty associated with possible fluctuations on the background estimations. Although effects from larger pileup might be significant, they can be mitigated by improvements in the algorithms for particle reconstruction and identification, and also on the data-analysis techniques.

A

SUPERVISED LEARNING

Supervised learning represents one of the most fundamental paradigms in machine learning and artificial intelligence. In this framework, algorithms learn to make predictions by examining labeled training data—examples where both the input features and the desired output are known. This approach mirrors, in many ways, how humans learn: by observing patterns, receiving feedback, and gradually improving performance through experience.

The power of supervised learning lies in its ability to discover complex relationships between input variables and target outcomes that may not be immediately apparent to human observers. In the context of high-energy physics, this capability has proven invaluable for tasks ranging from particle identification and signal-background discrimination to the reconstruction of physical parameters from detector measurements [[guest2018machine](#)]. The sophisticated detectors at the Large Hadron Collider (LHC), for instance, generate petabytes of data annually, making supervised learning techniques essential tools for extracting meaningful physics insights from this vast information landscape.

Historically, the foundations of supervised learning can be traced back to the early developments in statistics and pattern recognition in the mid-20th century. The perceptron algorithm, introduced by Frank Rosenblatt in 1957 [[rosenblatt1958perceptron](#)], marked one of the first attempts to create machines capable of learning from examples. However, it was not until the advent of more sophisticated algorithms and the exponential growth in computational power that supervised learning truly came into its own as a practical tool for scientific discovery.

In this chapter, we provide a comprehensive introduction to supervised learning, emphasizing both the theoretical foundations and practical applications relevant to particle physics research. We begin by formalizing the supervised learning problem within a rigorous mathematical framework, drawing parallels to the optimization principles familiar from field theory. We then explore the two primary categories of supervised learning: classification, where the goal is to assign discrete labels to inputs, and regression, where we seek to predict continuous-valued outputs.

A.1 MATHEMATICAL FRAMEWORK OF SUPERVISED LEARNING

To establish a solid foundation, we begin by formalizing the supervised learning problem in mathematical terms. Let \mathcal{X} denote the input space (also called the feature space) and \mathcal{Y} the output space (or target space). In supervised learning, we assume the existence of an unknown joint probability distribution $P(X, Y)$ over $\mathcal{X} \times \mathcal{Y}$, from which our training data is drawn.

A.1.1 THE LEARNING PROBLEM

Given a training dataset $\mathcal{D} = \{(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)\}$ consisting of n independent and identically distributed (i.i.d.) samples from $P(X, Y)$, the goal of supervised learning is to find a function $f : \mathcal{X} \rightarrow \mathcal{Y}$ that can accurately predict the output y for any given input x .

More precisely, we seek to minimize the *expected risk* (also known as the *generalization error*):

$$R(f) = \mathbb{E}_{(X, Y) \sim P} [\ell(f(X), Y)] = \int_{\mathcal{X} \times \mathcal{Y}} \ell(f(x), y) dP(x, y), \quad (\text{A.1})$$

where $\ell : \mathcal{Y} \times \mathcal{Y} \rightarrow \mathbb{R}_+$ is a *loss function* that quantifies the cost of making prediction $f(x)$ when the true output is y .

Since the true distribution $P(X, Y)$ is unknown, we cannot directly minimize the expected risk. Instead, we resort to *empirical risk minimization* (ERM), where we minimize the *empirical risk*:

$$\hat{R}_n(f) = \frac{1}{n} \sum_{i=1}^n \ell(f(x_i), y_i). \quad (\text{A.2})$$

This approach is analogous to the principle of least action in classical mechanics, where the true dynamics emerge from minimizing an action functional over all possible paths. Similarly, in supervised learning, the optimal predictor emerges from minimizing the empirical risk over all functions in our hypothesis class.

A.1.2 HYPOTHESIS CLASSES AND MODEL COMPLEXITY

In practice, we cannot search over all possible functions $f : \mathcal{X} \rightarrow \mathcal{Y}$, as this would be computationally intractable and would likely lead to overfitting. Instead, we restrict our search to a specific *hypothesis class* $\mathcal{H} = \{h_\theta : \theta \in \Theta\}$, where Θ is the parameter space.

The choice of hypothesis class represents a fundamental trade-off between expressiveness and complexity. A more expressive class can potentially capture more complex patterns in the data, but it also has a higher capacity to memorize noise, leading to poor generalization. This trade-off is formalized in the *bias-variance decomposition*.

For a given input x , if we denote the true relationship as $y = f^*(x) + \epsilon$, where ϵ is irreducible noise with $\mathbb{E}[\epsilon] = 0$ and $\text{Var}(\epsilon) = \sigma^2$, then the expected squared error of any predictor \hat{f} can be decomposed as:

$$\mathbb{E}[(y - \hat{f}(x))^2] = \underbrace{(f^*(x) - \mathbb{E}[\hat{f}(x)])^2}_{\text{Bias}^2} + \underbrace{\text{Var}(\hat{f}(x))}_{\text{Variance}} + \underbrace{\sigma^2}_{\text{Irreducible Error}}. \quad (\text{A.3})$$

The **bias** measures how far the expected prediction is from the true value, capturing systematic errors due to oversimplified assumptions. The **variance** measures how much the predictions vary across different training sets, reflecting the model's sensitivity to fluctuations in the data.

The bias-variance trade-off is reminiscent of the uncertainty principle in quantum mechanics: reducing bias (systematic error) typically increases variance (statistical fluctuations), and vice versa.

A.1.3 REGULARIZATION AND OCCAM'S RAZOR

To control model complexity and achieve good generalization, we often employ *regularization* techniques. Instead of minimizing only the empirical risk, we minimize a regularized objective:

$$\hat{R}_{\text{reg}}(f) = \hat{R}_n(f) + \lambda \Omega(f), \quad (\text{A.4})$$

where $\Omega(f)$ is a *regularization term* that penalizes complex functions, and $\lambda > 0$ is the *regularization parameter* that controls the strength of the penalty.

This approach embodies a mathematical formalization of Occam's razor: among competing hypotheses that explain the data equally well, the simplest one is preferred. Common regularization terms include:

- **L₁ regularization (Lasso):** $\Omega(f) = \|\theta\|_1 = \sum_i |\theta_i|$, which promotes sparsity by driving some parameters to exactly zero.
- **L₂ regularization (Ridge):** $\Omega(f) = \|\theta\|_2^2 = \sum_i \theta_i^2$, which shrinks parameters toward zero without necessarily making them exactly zero.
- **Elastic Net:** A combination of L₁ and L₂ regularization.

A.2 THE CLASSIFICATION PROBLEM

Classification represents one of the two fundamental categories of supervised learning, where the goal is to assign discrete labels to input examples. In the context of particle physics, classification problems are ubiquitous: distinguishing signal from background events, identifying particle types based on detector signatures, or determining the decay modes of reconstructed particles.

A.2.1 BINARY CLASSIFICATION

We begin with the simplest case: binary classification, where $\mathcal{Y} = \{0, 1\}$ or $\mathcal{Y} = \{-1, +1\}$. The goal is to learn a decision function $f : \mathcal{X} \rightarrow \mathcal{Y}$ that can accurately classify new examples.

A natural approach is to model the conditional probability $P(Y = 1|X = x)$ and classify based on whether this probability exceeds a threshold (typically 0.5). This leads us to consider the *logistic regression* model:

$$P(Y = 1|X = x) = \frac{1}{1 + e^{-\theta^T x}} = \sigma(\theta^T x), \quad (\text{A.5})$$

where $\sigma(z) = 1/(1 + e^{-z})$ is the *sigmoid function* and θ are the model parameters.

The sigmoid function has several desirable properties: it maps any real number to the interval $(0, 1)$, it is smooth and differentiable everywhere, and it has a natural interpretation as a probability. The corresponding loss function is the *cross-entropy* or *log-likelihood*:

$$\ell(f(x), y) = -y \log f(x) - (1 - y) \log(1 - f(x)). \quad (\text{A.6})$$

This loss function has a profound connection to information theory: it measures the number of bits needed to encode the true label given the predicted probability distribution. Minimizing cross-entropy is equivalent to maximizing the likelihood of the observed data under the model.

A.2.2 SUPPORT VECTOR MACHINES

An alternative approach to classification is the *Support Vector Machine* (SVM), which seeks to find the optimal separating hyperplane between classes. For linearly separable data, the SVM finds the hyperplane that maximizes the *margin*—the distance between the hyperplane and the nearest data points from each class.

Mathematically, for binary classification with labels $y_i \in \{-1, +1\}$, the SVM optimization problem is:

$$\min_{\mathbf{w}, b} \frac{1}{2} \|\mathbf{w}\|^2 \quad (\text{A.7})$$

$$\text{subject to } y_i(\mathbf{w}^T \mathbf{x}_i + b) \geq 1, \quad i = 1, \dots, n. \quad (\text{A.8})$$

For non-separable data, we introduce *slack variables* $\xi_i \geq 0$ and the *soft-margin* SVM:

$$\min_{\mathbf{w}, b, \xi} \frac{1}{2} \|\mathbf{w}\|^2 + C \sum_{i=1}^n \xi_i \quad (\text{A.9})$$

$$\text{subject to } y_i(\mathbf{w}^T \mathbf{x}_i + b) \geq 1 - \xi_i, \quad \xi_i \geq 0. \quad (\text{A.10})$$

The parameter C controls the trade-off between margin maximization and classification error. The beauty of SVMs lies in their ability to handle

non-linear decision boundaries through the *kernel trick*, which implicitly maps the input space to a higher-dimensional feature space where linear separation may be possible.

A.2.3 MULTI-CLASS CLASSIFICATION

Real-world classification problems often involve more than two classes. For $K > 2$ classes, several strategies can be employed:

- **One-vs-Rest (OvR):** Train K binary classifiers, each distinguishing one class from all others.
- **One-vs-One (OvO):** Train $\binom{K}{2}$ binary classifiers for each pair of classes.
- **Direct extension:** Extend binary algorithms directly to handle multiple classes (e.g., multinomial logistic regression).

The kernel trick allows SVMs to learn non-linear decision boundaries without explicitly computing the high-dimensional feature representations, making them computationally efficient for complex classification tasks.

For multinomial logistic regression, we use the *softmax function*:

$$P(Y = k|X = x) = \frac{e^{\theta_k^T x}}{\sum_{j=1}^K e^{\theta_j^T x}}, \quad (\text{A.11})$$

which generalizes the sigmoid function to multiple classes while ensuring that the predicted probabilities sum to unity.

A.3 THE REGRESSION PROBLEM

Regression problems involve predicting continuous-valued outputs, making them particularly relevant for estimating physical parameters from experimental measurements. In particle physics, regression tasks include determining particle energies, reconstructing invariant masses, or estimating detector calibration constants.

A.3.1 LINEAR REGRESSION

The simplest regression model assumes a linear relationship between inputs and outputs:

$$f(x) = \theta_0 + \theta_1 x_1 + \theta_2 x_2 + \cdots + \theta_d x_d = \theta^T x, \quad (\text{A.12})$$

where we have included a bias term θ_0 by augmenting the input vector with a constant feature.

The most common loss function for regression is the *squared error*:

$$\ell(f(x), y) = (f(x) - y)^2. \quad (\text{A.13})$$

Minimizing the empirical risk with squared error loss leads to the famous *normal equations*:

$$\theta^* = (\mathbf{X}^\top \mathbf{X})^{-1} \mathbf{X}^\top \mathbf{y}, \quad (\text{A.14})$$

where \mathbf{X} is the design matrix with training examples as rows and \mathbf{y} is the vector of target values.

The squared error loss has a deep statistical interpretation: it corresponds to maximum likelihood estimation under the assumption that the noise follows a Gaussian distribution. If we assume $y = \theta^\top x + \epsilon$ where $\epsilon \sim \mathcal{N}(0, \sigma^2)$, then minimizing squared error is equivalent to maximizing the likelihood of the observed data.

A.3.2 POLYNOMIAL REGRESSION AND FEATURE ENGINEERING

Linear regression can be extended to capture non-linear relationships through *polynomial regression*. By transforming the input features, we can fit polynomial functions while maintaining linearity in the parameters:

$$f(x) = \theta_0 + \theta_1 x + \theta_2 x^2 + \cdots + \theta_k x^k. \quad (\text{A.15})$$

More generally, we can apply any non-linear transformation $\phi : \mathcal{X} \rightarrow \mathbb{R}^p$ to create new features, leading to the model:

$$f(x) = \theta^\top \phi(x). \quad (\text{A.16})$$

This approach, known as *feature engineering*, allows linear models to capture complex non-linear patterns. Common transformations include polynomial features, trigonometric functions, radial basis functions, and domain-specific features derived from physical principles.

A.3.3 ROBUST REGRESSION

The squared error loss is sensitive to outliers—data points that deviate significantly from the general pattern. In experimental physics, outliers can arise from detector malfunctions, rare background processes, or measurement errors. To mitigate their impact, we can employ robust loss functions:

- **Absolute error (L1 loss):** $\ell(f(x), y) = |f(x) - y|$
- **Huber loss:** A hybrid that behaves quadratically for small errors and linearly for large errors:

$$\ell_\delta(f(x), y) = \begin{cases} \frac{1}{2}(f(x) - y)^2 & \text{if } |f(x) - y| \leq \delta \\ \delta(|f(x) - y| - \frac{1}{2}\delta) & \text{otherwise} \end{cases} \quad (\text{A.17})$$

These robust loss functions provide better performance when the dataset contains outliers or when the noise distribution has heavy tails.

A.3.4 PERFORMANCE EVALUATION

Evaluating the performance of supervised learning models requires careful consideration of appropriate metrics. For classification problems, common evaluation metrics include:

- **Accuracy:** The fraction of correctly classified examples.
- **Precision:** The fraction of positive predictions that are actually positive.
- **Recall (Sensitivity):** The fraction of actual positive examples that are correctly identified.
- **F₁-score:** The harmonic mean of precision and recall.
- **Area Under the ROC Curve (AUC-ROC):** A threshold-independent measure of classification performance.

For regression problems, typical metrics include:

- **Mean Squared Error (MSE):** $\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2$
- **Root Mean Squared Error (RMSE):** $\sqrt{\text{MSE}}$
- **Mean Absolute Error (MAE):** $\frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i|$
- **Coefficient of Determination (R²):** The proportion of variance explained by the model.

The selection of appropriate evaluation metrics depends on the specific requirements of the physics analysis. For signal detection in rare processes, maximizing sensitivity (recall) might be more important than overall accuracy. For precision measurements, minimizing systematic uncertainties requires careful attention to model bias and calibration.

In conclusion, supervised learning provides a powerful framework for extracting patterns from labeled data and making predictions on new examples. The mathematical foundations we have established—from empirical risk minimization to the bias-variance trade-off—provide the theoretical underpinning for understanding when and why these methods work. As we progress to more advanced topics, these fundamental concepts will serve as the building blocks for more sophisticated algorithms and applications in particle physics research.

In particle physics, the choice of evaluation metric should align with the physics goals. For rare signal detection, recall might be more important than precision, while for precision measurements, minimizing systematic biases (related to model bias) is crucial.

B

ON THE UNIVERSAL SEESAW MECHANISM: A DETAILED ANALYSIS

The masses of the SM fermions are generated not through direct Yukawa couplings to the Higgs, but via a universal seesaw mechanism by mixing with new vector-like fermions χ_f . The most general gauge-invariant and renormalizable Lagrangian for the quark sector is given by:

$$\begin{aligned} \mathcal{L}_{\text{mass}}^{\text{quark}} \supset & \bar{Q}_L^i (Y_{uL})_{ij} \chi_{uR}^j \tilde{H} + \bar{Q}_L^i (Y_{dL})_{ij} \chi_{dR}^j H \\ & + \bar{\chi}_{uL}^i (Y_{uR})_{ij} u_R^j \phi^* + \bar{\chi}_{dL}^i (Y_{dR})_{ij} d_R^j \phi \\ & + \bar{\chi}_{uL}^i (m_{\chi u})_{ij} \chi_{uR}^j + \bar{\chi}_{dL}^i (m_{\chi d})_{ij} \chi_{dR}^j + \text{h.c.}, \end{aligned} \quad (\text{B.1})$$

where $i, j = 1, 2, 3$ are flavor indices. An entirely analogous set of terms exists for the lepton sector. The Yukawa matrices $Y_{uL}, Y_{dL}, Y_{uR}, Y_{dR}$ and the vector-like mass matrices $m_{\chi u}, m_{\chi d}$ are general complex 3×3 matrices, making the flavor structure highly non-trivial.

B.1 DIAGONALIZATION AND FIELD REDEFINITIONS

To make physical predictions, we must diagonalize these matrices. We express them in terms of their singular value decompositions (i.e., their diagonal forms) and the associated unitary mixing matrices:

$$\begin{aligned} Y_{uL} &= U_{LL}^\dagger Y_{uL}^d U_{LR}, & Y_{uR} &= U_{RL}^\dagger Y_{uR}^d U_{RR}, \\ Y_{dL} &= V_{LL}^\dagger Y_{dL}^d V_{LR}, & Y_{dR} &= V_{RL}^\dagger Y_{dR}^d V_{RR}, \\ m_{\chi u} &= W_{uL}^\dagger m_{\chi u}^d W_{uR}, & m_{\chi d} &= W_{dL}^\dagger m_{\chi d}^d W_{dR}. \end{aligned}$$

Here, the matrices Y^d and m^d are real, diagonal, and non-negative. The unitary matrices U, V, W are not physical by themselves but encode the mixing between flavor states.

We now perform a series of field redefinitions to absorb the maximal number of these unitary matrices into the definitions of the fermion fields. The goal is to make as many mass parameters diagonal as possible. The redefinitions are:

$$\begin{aligned} Q_L &\rightarrow U_{LL} Q_L, & \chi_{uR} &\rightarrow W_{uR} \chi_{uR}, & \chi_{uL} &\rightarrow W_{uL} \chi_{uL}, & u_R &\rightarrow U_{RR} u_R, \\ \chi_{dR} &\rightarrow W_{dR} \chi_{dR}, & \chi_{dL} &\rightarrow W_{dL} \chi_{dL}, & d_R &\rightarrow V_{RR} d_R. \end{aligned}$$

Applying these transformations to the Lagrangian (B.1) and using the definitions above, we obtain the simplified form:

$$\begin{aligned}\mathcal{L}_{\text{Yuk}} = & \bar{Q}_L Y_{uL}^d (U_{LR} W_{uR}^\dagger) \chi_{uR} \tilde{H} + \bar{Q}_L (U_{LL} V_{LL}^\dagger) Y_{dL}^d (V_{LR} W_{dR}^\dagger) \chi_{dR} H \\ & + \bar{\chi}_{uL} (W_{uL} U_{RL}^\dagger) Y_{uR}^d u_R \phi^* + \bar{\chi}_{dL} (W_{dL} V_{RL}^\dagger) Y_{dR}^d d_R \phi \\ & + \bar{\chi}_{uL} m_{\chi u}^d \chi_{uR} + \bar{\chi}_{dL} m_{\chi d}^d \chi_{dR} + \text{h.c.}\end{aligned}$$

The matrix $\tilde{V}_{\text{CKM}} \equiv U_{LL} V_{LL}^\dagger$ is identified as the unitary matrix that will yield the observed Cabibbo-Kobayashi-Maskawa (CKM) quark mixing. For simplicity, and to focus on the essential mass generation mechanism, we adopt a *flavor-aligned* scenario. This assumes that all other unitary matrices (U_{LR} , W_{uR} , W_{uL} , U_{RL} , etc.) are equal to the identity matrix. This is a strong assumption that minimizes new sources of flavor violation beyond the SM. Under this assumption, the Lagrangian simplifies dramatically to:

$$\begin{aligned}\mathcal{L}_{\text{Yuk}} = & \bar{Q}_L Y_{uL}^d \chi_{uR} \tilde{H} + \bar{Q}_L \tilde{V}_{\text{CKM}} Y_{dL}^d \chi_{dR} H \\ & + \bar{\chi}_{uL} Y_{uR}^d u_R \phi^* + \bar{\chi}_{dL} Y_{dR}^d d_R \phi \\ & + \bar{\chi}_{uL} m_{\chi u}^d \chi_{uR} + \bar{\chi}_{dL} m_{\chi d}^d \chi_{dR} + \text{h.c.}\end{aligned}$$

All matrices Y^d and m^d are now diagonal. The only remaining off-diagonal flavor structure is in \tilde{V}_{CKM} .

B.2 SYMMETRY BREAKING AND THE MASS MATRIX

After the electroweak symmetry breaking ($\langle H \rangle = v_h/\sqrt{2}$) and the $U(1)_{T_R^3}$ breaking ($\langle \phi \rangle = v_\phi/\sqrt{2}$), the mass terms for the up-type quarks (and analogously for down-type and leptons) are generated. For a single generation, the mass terms in the basis $(\bar{u}_L, \bar{\chi}_{uL}), (u_R, \chi_{uR})^\top$ form a 2×2 matrix:

$$\mathcal{L}_{\text{mass}} = - (\bar{u}_L \quad \bar{\chi}_{uL}) \begin{pmatrix} 0 & m_L \\ m_R & m_\chi \end{pmatrix} \begin{pmatrix} u_R \\ \chi_{uR} \end{pmatrix} + \text{h.c.}, \quad (\text{B.2})$$

where the Dirac masses are:

$$\begin{aligned}m_L &= \frac{v_h}{\sqrt{2}} Y_{uL}, \\ m_R &= \frac{v_\phi}{\sqrt{2}} Y_{uR}.\end{aligned}$$

The entry m_χ is the vector-like mass. For three generations, this generalizes to a 6×6 matrix:

$$M_f = \begin{pmatrix} 0 & m_L \\ m_R & m_\chi \end{pmatrix}, \quad (\text{B.3})$$

where each entry is now a 3×3 matrix: $m_L = \frac{v_h}{\sqrt{2}} Y_{fL}^d$, $m_R = \frac{v_\phi}{\sqrt{2}} Y_{fR}^d$, and $m_\chi = m_{\chi f}^d$.

B.3 BI-UNITARY TRANSFORMATION AND MASS EIGENVALUES

The general mass matrix M_f is diagonalized by a bi-unitary transformation:

$$U_R^\dagger M_f U_L = M_f^d = \text{diag}(m_{f_1}, m_{f_2}, m_{f_3}, m_{F_1}, m_{F_2}, m_{F_3}), \quad (\text{B.4})$$

where U_L and U_R are 6×6 unitary matrices. The physical masses are found by solving the eigenvalues of the Hermitian matrices $H_L = M_f M_f^\dagger$ and $H_R = M_f^\dagger M_f$, as U_L diagonalizes H_L and U_R diagonalizes H_R .

For the one-generation case, these matrices are:

$$\begin{aligned} H_L &= M_f M_f^\dagger = \begin{pmatrix} m_L m_L^\dagger & m_L m_X^\dagger \\ m_X m_L^\dagger & m_R m_R^\dagger + m_X m_X^\dagger \end{pmatrix} = \begin{pmatrix} |m_L|^2 & m_L m_X^* \\ m_X m_L^* & |m_R|^2 + |m_X|^2 \end{pmatrix}, \\ H_R &= M_f^\dagger M_f = \begin{pmatrix} m_R m_R^\dagger & m_R m_X^\dagger \\ m_X m_R^\dagger & m_L m_L^\dagger + m_X m_X^\dagger \end{pmatrix} = \begin{pmatrix} |m_R|^2 & m_R m_X^* \\ m_X m_R^* & |m_L|^2 + |m_X|^2 \end{pmatrix}. \end{aligned}$$

The eigenvalues λ of H_L (and H_R) are found from the characteristic equation $\det(H_L - \lambda I) = 0$:

$$\begin{aligned} &| |m_L|^2 - \lambda | |m_R|^2 + |m_X|^2 - \lambda | - |m_L|^2 |m_X|^2 = 0 \\ &\Rightarrow \lambda^2 - \lambda(|m_L|^2 + |m_R|^2 + |m_X|^2) + |m_L|^2 |m_R|^2 = 0. \end{aligned}$$

The solutions to this quadratic equation are the squared masses of the two mass eigenstates:

$$m_f^2 = \frac{1}{2} \left(m_X^2 + m_L^2 + m_R^2 - \sqrt{(m_X^2 + m_L^2 + m_R^2)^2 - 4m_L^2 m_R^2} \right), \quad (\text{B.5})$$

$$m_F^2 = \frac{1}{2} \left(m_X^2 + m_L^2 + m_R^2 + \sqrt{(m_X^2 + m_L^2 + m_R^2)^2 - 4m_L^2 m_R^2} \right), \quad (\text{B.6})$$

where we have now assumed all parameters are real for clarity. m_f is the light SM-like fermion mass, and m_F is the heavy vector-like partner mass.

B.4 YUKAWA COUPLING ENHANCEMENT AND PERTURBATIVITY

Equation (B.5) is fundamental. It shows that the light mass m_f is not simply proportional to m_L (the SM Higgs VEV). We can solve Eq. (B.5) for m_L^2 :

$$\begin{aligned} m_f^2(m_X^2 + m_L^2 + m_R^2 - m_f^2) &= m_L^2 m_R^2 \quad (\text{from the exact seesaw relation}) \\ m_L^2(m_R^2 - m_f^2) &= m_f^2(m_X^2 + m_R^2 - m_f^2) \\ m_L^2 &= m_f^2 \left(\frac{m_X^2 + m_R^2 - m_f^2}{m_R^2 - m_f^2} \right) = m_f^2 \left(1 + \frac{m_X^2}{m_R^2 - m_f^2} \right). \end{aligned}$$

Expressing this in terms of the original Yukawa couplings, where $m_L = \frac{v_h}{\sqrt{2}} Y_{fL}$ and the SM Yukawa is defined by $m_f = \frac{v_h}{\sqrt{2}} Y_f^{\text{SM}}$, we find:

$$Y_{fL}^2 = (Y_f^{\text{SM}})^2 \left(1 + \frac{m_X^2}{m_R^2 - m_f^2} \right). \quad (\text{B.7})$$

This relation reveals the core of the universal seesaw mechanism: the Yukawa coupling Y_{fL} that couples the SM fermions to the Higgs is *enhanced* compared to the standard model value Y_f^{SM} . The enhancement factor is $\sqrt{1 + m_\chi^2/(m_R^2 - m_f^2)}$.

This has profound implications:

- **Light Fermions (e.g., electron, u-quark):** Here, $Y_f^{\text{SM}} \ll 1$. A large hierarchy $m_\chi^2 \gg m_R^2 \gg m_f^2$ can generate this tiny mass from a more “natural” $Y_{fL} \sim \mathcal{O}(0.1 - 1)$.
- **Top Quark:** Here, $Y_t^{\text{SM}} \approx 1$ is already large. An enhancement could easily push Y_{tL} into the non-perturbative regime ($Y_{tL}^2/4\pi > 1$). To avoid this, we must require the enhancement factor to be $\mathcal{O}(1)$, which implies $m_\chi^2 \lesssim m_R^2 - m_t^2$. Since $m_R = \frac{v_\phi}{\sqrt{2}} Y_{fR}$, this suggests $v_\phi > m_\chi$ is a natural condition.

B.5 EXACT DIAGONALIZATION AND MIXING ANGLES

The bi-unitary transformation (B.4) is performed by matrices that can be parameterized by a mixing angle. For one generation, the left-handed mixing matrix is:

$$U_L = \begin{pmatrix} \cos \theta_L & \sin \theta_L \\ -\sin \theta_L & \cos \theta_L \end{pmatrix}. \quad (\text{B.8})$$

The angle θ_L quantifies the mixing between the SM fermion and its vector-like partner. The exact expressions for the fundamental parameters m_L, m_R, m_χ in terms of the physical masses m_f, m_F and the mixing angle θ_L can be found by equating $U_L^\dagger H_L U_L = \text{diag}(m_f^2, m_F^2)$. This yields the system of equations:

$$\begin{aligned} m_L^2 &= m_f^2 \cos^2 \theta_L + m_F^2 \sin^2 \theta_L, \\ m_R^2 + m_\chi^2 &= m_f^2 \sin^2 \theta_L + m_F^2 \cos^2 \theta_L, \\ m_L m_\chi &= (m_F^2 - m_f^2) \sin \theta_L \cos \theta_L. \end{aligned}$$

Solving this system (and a similar one from H_R for θ_R) gives:

$$m_L^2 = \frac{1}{2} (m_f^2 + m_F^2 - (m_F^2 - m_f^2) \cos 2\theta_L), \quad (\text{B.9})$$

$$m_R^2 = \frac{m_f^2 m_F^2}{m_L^2} = \frac{2m_f^2 m_F^2}{m_f^2 + m_F^2 - (m_F^2 - m_f^2) \cos 2\theta_L}, \quad (\text{B.10})$$

$$m_\chi^2 = m_R^2 + m_F^2 + m_f^2 - m_L^2 - \frac{m_f^2 m_F^2}{m_L^2} = \frac{(m_F^2 - m_f^2)^2 \sin^2 2\theta_L}{4m_L^2}. \quad (\text{B.11})$$

Substituting Eq. (B.9) into the expression for m_χ^2 yields the form shown in the original text.

The critical constraint to keep the top Yukawa perturbative is $m_\chi^2 < m_R^2$. Using Eqs. (B.10) and (B.11), the ratio is:

$$\frac{m_\chi^2}{m_R^2} = \frac{(m_F^2 - m_f^2)^2 \sin^2 2\theta_L}{4m_f^2 m_F^2} < 1. \quad (\text{B.12})$$

For the top quark with $m_f = m_t \approx 173$ GeV and assuming a heavy partner $m_F \gg m_t$, this simplifies to:

$$\frac{m_F^4 \sin^2 2\theta_L}{4m_t^2 m_F^2} \approx \frac{m_F^2}{4m_t^2} \sin^2 2\theta_L < 1 \Rightarrow \sin^2 2\theta_L < \frac{4m_t^2}{m_F^2}. \quad (\text{B.13})$$

This is a very strong constraint. For example, if $m_F = 1$ TeV, then $\sin^2 2\theta_L < 0.12$, meaning $\theta_L < 10^\circ$. In the small θ_L limit, $\cos 2\theta_L \approx 1 - 2\theta_L^2$ and $\sin^2 2\theta_L \approx 4\theta_L^2$. Substituting this into Eq. (B.9):

$$\begin{aligned} m_L^2 &\approx \frac{1}{2} (m_t^2 + m_F^2 - (m_F^2 - m_t^2)(1 - 2\theta_L^2)) \\ &= \frac{1}{2} (m_t^2 + m_F^2 - m_F^2 + m_t^2 + 2(m_F^2 - m_t^2)\theta_L^2) \\ &= \frac{1}{2} (2m_t^2 + 2(m_F^2 - m_t^2)\theta_L^2) = m_t^2 + (m_F^2 - m_t^2)\theta_L^2. \end{aligned}$$

From the constraint (B.13), $\theta_L^2 < m_t^2/m_F^2$. Therefore:

$$m_L^2 < m_t^2 + (m_F^2 - m_t^2) \frac{m_t^2}{m_F^2} = m_t^2 + m_t^2 - \frac{m_t^4}{m_F^2} = 2m_t^2 - \frac{m_t^4}{m_F^2}. \quad (\text{B.14})$$

Converting back to Yukawa couplings:

$$Y_{tL}^2 \lesssim (Y_t^{\text{SM}})^2 \left(2 - \frac{m_t^2}{m_F^2} \right). \quad (\text{B.15})$$

This shows that the maximum enhancement for the top Yukawa is less than a factor of $\sqrt{2}$, which is perfectly perturbative.

The generalization to three generations involves the diagonalization of the full 6×6 matrices. The matrix \tilde{V}_{CKM} introduced during field redefinition will manifest in the charged current weak interactions of the mass eigenstates. After diagonalization, the SM W boson will couple not only to the three light quarks but also to the heavy vector-like quarks, with couplings suppressed by the mixing angles θ_L^i . The observed 3×3 CKM matrix emerges as the effective mixing matrix among the three light quarks when the heavy states are integrated out.

The lepton sector follows an identical procedure for the charged leptons. The neutrino sector, however, offers further richness. The right-handed neutrinos ν_R can possess both Dirac masses (m_R) from coupling to ϕ and Majorana mass terms $M_R \bar{\nu}_R^c \nu_R$, which are allowed by the gauge symmetry. The vector-like neutrinos χ_ν can also have Majorana masses. This combination of Dirac and Majorana masses for both ν_R and χ_ν can generate a double or triple seesaw mechanism, providing a natural explanation for the tiny masses of the observed light neutrinos. The diagonalization of this extended neutrino mass matrix also generates the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix.

C

THE 4321 MODEL

This appendix summarises the main features of the 4321 model presented in [223], based on the construction showed in [76]. The model is built upon the extended gauge group

$$\mathcal{G}_{4321} \equiv \mathrm{SU}(4) \times \mathrm{SU}(3)' \times \mathrm{SU}(2)_L \times \mathrm{U}(1)'.$$

The Standard Model (SM) gauge group, $\mathcal{G}_{321} \equiv \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$, is embedded into \mathcal{G}_{4321} through two key identifications.

First, the SM strong force is identified with the diagonal subgroup of the two $\mathrm{SU}(3)$ factors:

$$\mathrm{SU}(3)_c = (\mathrm{SU}(3)_{[4]} \times \mathrm{SU}(3)')_{\text{diag}}, \quad (\text{C.1})$$

where $\mathrm{SU}(3)_{[4]} \subset \mathrm{SU}(4)$. Second, and more crucially, the SM hypercharge is a linear combination of charges from the $\mathrm{SU}(4)$ and $\mathrm{U}(1)'$ sectors:

$$Y = Q_{B-L} + Y'. \quad (\text{C.2})$$

Here, the baryon minus lepton number (Q_{B-L}) is generated by a diagonal $\mathrm{SU}(4)$ generator, $Q_{B-L} = 2\sqrt{6}T^{15}/3$,

The spontaneous breaking of the full \mathcal{G}_{4321} symmetry down to the SM \mathcal{G}_{321} gives mass to the gauge bosons associated with the broken generators. The spectrum of these new massive vectors and their quantum numbers under the SM group are:

- A vector leptoquark, $U \sim (\mathbf{3}, \mathbf{1}, 2/3)$,
- A coloron, $g' \sim (\mathbf{8}, \mathbf{1}, 0)$,
- A massive neutral boson, $Z' \sim (\mathbf{1}, \mathbf{1}, 0)$.

Heuristically, each of these bosons originates from a distinct part of the symmetry breaking pattern: the leptoquark (U) emerges from the breaking $\mathrm{SU}(4) \rightarrow \mathrm{SU}(3)_{[4]} \times \mathrm{U}(1)_{B-L}$, the coloron (g') from $\mathrm{SU}(3)_{[4]} \times \mathrm{SU}(3)' \rightarrow \mathrm{SU}(3)_c$, and the Z' from $\mathrm{U}(1)_{B-L} \times \mathrm{U}(1)_{T_R^3} \rightarrow \mathrm{U}(1)_Y$.

The spontaneous breaking of the \mathcal{G}_{4321} symmetry down to the Standard Model \mathcal{G}_{321} and subsequently to electromagnetism is achieved through a scalar sector comprising four multiplets. The primary breaking $\mathcal{G}_{4321} \rightarrow \mathcal{G}_{321}$ is induced by the vacuum expectation values (vevs) of three scalar fields:

As we see in chapter 3, the $\mathrm{U}(1)'$ charge could be identified with twice the third component of right-handed isospin, $Y' \equiv 2Q_{T_R^3}$. This specific embedding reveals the model's left-right symmetric foundation; the SM electric charge operator can now be expressed in the manifestly left-right symmetric form:

$$Q = Q_{T_L^3} + Q_{T_R^3} + \frac{1}{2}Q_{B-L}.$$

- $\Omega_1 \sim (\bar{\mathbf{4}}, \mathbf{1}, \mathbf{1}, -1/2)$,
- $\Omega_3 \sim (\bar{\mathbf{4}}, \mathbf{3}, \mathbf{1}, 1/6)$,
- $\Omega_{15} \sim (\mathbf{15}, \mathbf{1}, \mathbf{1}, 0)$ (taken to be a real field).

The final electroweak symmetry breaking, $\mathcal{G}_{321} \rightarrow U(1)_{EM}$, is triggered by the Higgs doublet $H \sim (\mathbf{1}, \mathbf{1}, \mathbf{2}, 1/2)$.

A suitable scalar potential (analysed in detail in Section ??) allows for a vev configuration that ensures this breaking pattern. Phenomenological constraints suggest a clear hierarchy between these scales:

$$\langle \Omega_3 \rangle > \langle \Omega_1 \rangle \gg \langle \Omega_{15} \rangle \gg \langle H \rangle. \quad (C.3)$$

Given this hierarchy, we simplify the analysis by first considering the Ω_3 and Ω_1 system in isolation to understand the primary TeV-scale breaking. The effects of incorporating the smaller vevs of Ω_{15} and H will be discussed subsequently.

To analyze the Ω_3 - Ω_1 subsystem, we represent these fields as a 4×3 matrix and a 4-vector, transforming as $\Omega_3 \rightarrow U_4^* \Omega_3 U_3^T$, and $\Omega_1 \rightarrow U_4^* \Omega_1$ under $SU(4) \times SU(3)'$, respectively. The desired vacuum configuration that breaks \mathcal{G}_{4321} to \mathcal{G}_{321} is:

$$\langle \Omega_3 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_3 & 0 & 0 \\ 0 & v_3 & 0 \\ 0 & 0 & v_3 \\ 0 & 0 & 0 \end{pmatrix}, \quad \langle \Omega_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ v_1 \end{pmatrix}. \quad (C.4)$$

The most general renormalizable scalar potential that admits this vacuum as a stationary point, and in the limit where the bare masses vanish ($\mu_3 = \mu_1 = 0$) and the cubic coupling is absent ($\lambda_6 = 0$), can be written as:

$$\begin{aligned} V_{\Omega_3, \Omega_1} = & \mu_1^2 |\Omega_1|^2 + \mu_3^2 \text{Tr}(\Omega_3^\dagger \Omega_3) \\ & + \lambda_1 \left(\text{Tr}(\Omega_3^\dagger \Omega_3) - \frac{3}{2} v_3^2 \right)^2 + \lambda_2 \text{Tr} \left(\Omega_3^\dagger \Omega_3 - \frac{1}{2} v_3^2 \mathbb{1}_3 \right)^2 \\ & + \lambda_3 \left(|\Omega_1|^2 - \frac{1}{2} v_1^2 \right)^2 + \lambda_4 \left(\text{Tr}(\Omega_3^\dagger \Omega_3) - \frac{3}{2} v_3^2 \right) \left(|\Omega_1|^2 - \frac{1}{2} v_1^2 \right) \\ & + \lambda_5 \Omega_1^\dagger \Omega_3 \Omega_3^\dagger \Omega_1 + \lambda_6 ([\Omega_3 \Omega_3 \Omega_3 \Omega_1]_1 + \text{h.c.}). \end{aligned} \quad (C.5)$$

Here, $\mathbb{1}_3$ denotes the 3×3 identity matrix. We have used a relative rephasing between the fields Ω_1 and Ω_3 to remove the phase of λ_6 . The unique quartic term,

$$[\Omega_3 \Omega_3 \Omega_3 \Omega_1]_1 \equiv \epsilon_{\alpha \beta \gamma \delta} \epsilon^{abc} (\Omega_3)_a^\alpha (\Omega_3)_b^\beta (\Omega_3)_c^\gamma (\Omega_1)^\delta, \quad (C.6)$$

is required to avoid accidental global symmetries in the scalar potential that would lead to unwanted massless Goldstone bosons.

The inclusion of the other two representations, Ω_{15} and H , in the scalar potential can be safely considered as a perturbation. They are assumed to take the vevs $\langle \Omega_{15} \rangle = T_{15} v_{15}$ and $\langle H \rangle = \frac{1}{\sqrt{2}} (0, v)^T$, with $v = 246$ GeV. This

treatment is justified because their vevs are subleading for phenomenological reasons and they do not alter the pattern of global symmetries of the $\Omega_3 - \Omega_1$ potential. Finally, the decomposition of Ω_{15} under \mathcal{G}_{321} is $\Omega_{15} \rightarrow (\mathbf{1}, \mathbf{1}, 0) \oplus (\mathbf{3}, \mathbf{1}, 2/3) \oplus (\bar{\mathbf{3}}, \mathbf{1}, -2/3) \oplus (\mathbf{8}, \mathbf{1}, 0)$. The mixing of these states with those contained in $\Omega_{3,1}$ is parametrically suppressed by the ratio $v_{15}^2/v_{3,1}^2$, hence they play a subleading role in phenomenology.

Given the extended gauge group \mathcal{G}_{4321} , we denote the gauge fields by $H_\mu^\alpha, G'_\mu^a, W_\mu^i, B'_\mu$; the gauge couplings by g_4, g_3, g_2, g_1 ; and the generators by T^α, T^a, T^i, Y' (with indices $\alpha = 1, \dots, 15$, $a = 1, \dots, 8$, $i = 1, 2, 3$).

To determine the gauge boson spectrum, we start from the covariant derivatives acting on the scalar fields $\Omega_{3,1,15}$:

$$\begin{aligned} D_\mu \Omega_1 &= (\partial_\mu + ig_4 H_\mu^\alpha T^{\alpha*} - \frac{1}{2}ig_1 B'_\mu) \Omega_1, \\ D_\mu \Omega_3 &= (\partial_\mu + ig_4 H_\mu^\alpha T^{\alpha*} - ig_3 G'_\mu^a T^a + \frac{1}{6}ig_1 B'_\mu) \Omega_3, \\ D_\mu \Omega_{15} &= \partial_\mu \Omega_{15} - ig_4 [T^\alpha, \Omega_{15}] H_\mu^\alpha. \end{aligned}$$

We define the index $A = 9, \dots, 14$ to span the $SU(4)/(SU(3)_4 \times U(1)_4)$ coset. Neglecting electroweak symmetry breaking effects, the gauge boson masses are extracted from the canonically normalized kinetic terms of the scalar fields:

$$\begin{aligned} \mathcal{L} \supset &+ \frac{1}{2} \left(g_4^2 v_1^2 + g_4^2 v_3^2 + \frac{4}{3} g_4^2 v_{15}^2 \right) H_\mu^A H^{\mu A} \\ &+ \frac{v_3^2}{4} (H_\mu^a \quad G'_\mu^a) \begin{pmatrix} g_4^2 & -g_4 g_3 \\ -g_4 g_3 & g_3^2 \end{pmatrix} (H^{b\mu} \quad G'^{b\mu}) \\ &+ \frac{3v_1^2 + v_3^2}{4} (H_\mu^{15} \quad B'_\mu) \begin{pmatrix} \frac{g_4^2}{4} & -\frac{g_4 g_1}{2\sqrt{6}} \\ -\frac{g_4 g_1}{2\sqrt{6}} & \frac{g_1^2}{6} \end{pmatrix} (H^{15\mu} \quad B'^{\mu}). \end{aligned} \tag{C.7}$$

Diagonalizing these mass matrices, we obtain the massive gauge boson spectrum:

$$U_\mu^{1,2,3} = \frac{1}{\sqrt{2}} (H_\mu^{9,11,13} - i H_\mu^{10,12,14}), \quad M_U^2 = \frac{1}{4} g_4^2 \left(v_1^2 + v_3^2 + \frac{4}{3} v_{15}^2 \right), \tag{C.8}$$

$$g'_\mu^a = \frac{g_4 H_\mu^a - g_3 G'_\mu^a}{\sqrt{g_4^2 + g_3^2}}, \quad M_{g'}^2 = \frac{1}{2} (g_4^2 + g_3^2) v_3^2, \tag{C.9}$$

$$Z'_\mu = \frac{g_4 H_\mu^{15} - \sqrt{\frac{2}{3}} g_1 B'_\mu}{\sqrt{g_4^2 + \frac{2}{3} g_1^2}}, \quad M_{Z'}^2 = \frac{1}{4} \left(g_4^2 + \frac{2}{3} g_1^2 \right) \left(v_1^2 + \frac{1}{3} v_3^2 \right). \tag{C.10}$$

The combinations orthogonal to (C.9) and (C.10) correspond to the massless $SU(3)_c \times U(1)_Y$ gauge bosons of \mathcal{G}_{321} prior to electroweak symmetry breaking:

$$g_\mu^a = \frac{g_3 H_\mu^a + g_4 G'_\mu^a}{\sqrt{g_4^2 + g_3^2}}, \quad (C.11)$$

$$B_\mu = \frac{\sqrt{\frac{2}{3}} g_1 H_\mu^{15} + g_4 B'_\mu}{\sqrt{g_4^2 + \frac{2}{3} g_1^2}}. \quad (C.12)$$

The matching between the fundamental couplings g_4, g_3, g_1 and the SM couplings g_s, g_Y is readily obtained by acting with the covariant derivative on a field which transforms trivially under $SU(4)$. This yields:

$$g_s = \frac{g_4 g_3}{\sqrt{g_4^2 + g_3^2}}, \quad (C.13)$$

$$g_Y = \frac{g_4 g_1}{\sqrt{g_4^2 + \frac{2}{3} g_1^2}}. \quad (C.14)$$

Evolving the SM gauge couplings up to $\mu = 2$ TeV, we obtain $g_s = 1.02$ and $g_Y = 0.363$. Since $g_s \leq g_{4,3}$ and $g_Y \leq \sqrt{\frac{3}{2}} g_4, g_1$, the hierarchy $g_s \gg g_Y$ also implies $g_{4,3} \gg g_Y \simeq g_1$. In the limit $v_3 \gg v_1 \gg v_{15}$, the mass spectrum simplifies. For example, if the gauge couplings also satisfy $g_4 \sim g_3$, one finds $M_{g'} \simeq \sqrt{2} M_U$ and $M_{Z'} \simeq \frac{1}{\sqrt{2}} M_U$.

In the 4321 model, the observed SM fermion masses and mixings arise from the mixing between elementary chiral fermions—charged under $SU(3)' \times SU(2)_L \times U(1)'$ with SM-like quantum numbers—and three generations of vector-like fermions transforming as fundamentals of $SU(4)$. This mixing is triggered once the scalars Ω_1 and Ω_3 acquire VEVs (see Figure C.1). The full matter content of the model is summarized in Table C.1.

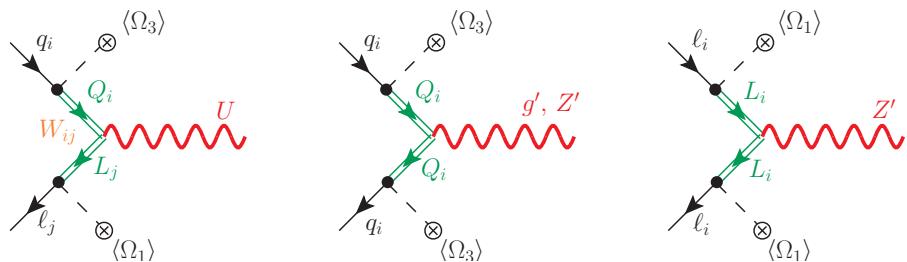


Figure C.1: Diagrammatic representation of the interactions between the SM fermions and the heavy vector-like fermions Ψ , induced by the Yukawa couplings to Ω_1 and Ω_3 after symmetry breaking.

Field	SU(4)	SU(3)'	SU(2) _L	U(1)'
q_L ⁱ	1	3	2	1/6
u_R ⁱ	1	3	1	2/3
d_R ⁱ	1	3	1	-1/3
ℓ_L ⁱ	1	1	2	-1/2
e_R ⁱ	1	1	1	-1
Ψ_L ⁱ	4	1	2	0
Ψ_R ⁱ	4	1	2	0
H	1	1	2	1/2
Ω ₁	4	1	1	-1/2
Ω ₃	4	3	1	1/6
Ω ₁₅	15	1	1	0

Table C.1: Field content of the 4321 model. The index $i = 1, 2, 3$ runs over generations.

The mixing between the elementary fermions and the vector-like fermions is described by the Yukawa Lagrangian $\mathcal{L}_Y = \mathcal{L}_{\text{SM-like}} + \mathcal{L}_{\text{mix}}$, where

$$\mathcal{L}_{\text{SM-like}} = -\bar{q}'_L Y_d H d'_R - \bar{q}'_L Y_u \tilde{H} u'_R - \bar{\ell}'_L Y_e H e'_R + \text{h.c.}, \quad (\text{C.15})$$

$$\mathcal{L}_{\text{mix}} = -\bar{q}'_L \lambda_q \Omega_3^T \Psi_R - \bar{\ell}'_L \lambda_\ell \Omega_1^T \Psi_R - \bar{\Psi}_L (M + \lambda_{15} \Omega_{15}) \Psi_R + \text{h.c..} \quad (\text{C.16})$$

Here, $\tilde{H} = i\sigma_2 H^*$, and $Y_{u,d,e}, \lambda_{q,\ell,15}, M$ are 3×3 matrices in flavour space.

The vector-like fermions transform under \mathcal{G}_{4321} as

$$\Psi_{L,R} = \begin{pmatrix} Q'_{L,R} \\ L'_{L,R} \end{pmatrix} \sim (\mathbf{4}, \mathbf{1}, \mathbf{2}, 0). \quad (\text{C.17})$$

Under the breaking $\text{SU}(4) \rightarrow \text{SU}(3)_{[4]} \times \text{U}(1)_{B-L}$, they decompose as $Q'_{L,R} \sim (\mathbf{3}, \mathbf{2}, 1/6)$ and $L'_{L,R} \sim (\mathbf{1}, \mathbf{2}, -1/2)$. Their vector-like masses are generated by the M term and are split by the VEV of Ω_{15} :

$$M_Q = M + \frac{\lambda_{15} v_{15}}{2\sqrt{6}}, \quad M_L = M - \frac{3\lambda_{15} v_{15}}{2\sqrt{6}}. \quad (\text{C.18})$$

To comply with flavour constraints, the authors on [76] employ the following Yukawa textures as a starting point

$$\lambda_q = \hat{\lambda}_q \equiv \text{diag}(\lambda_{12}^q, \lambda_{12}^q, \lambda_3^q),$$

$$\lambda_\ell = \hat{\lambda}_\ell W^\dagger \equiv \text{diag}(\lambda_1^\ell, \lambda_2^\ell, \lambda_3^\ell) \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{LQ} & -\sin \theta_{LQ} \\ 0 & \sin \theta_{LQ} & \cos \theta_{LQ} \end{pmatrix}, \quad (\text{C.19})$$

$$\lambda_{15} \propto \hat{M} \propto \mathbb{1}.$$

After the $\text{SU}(3)_{[4]} \times \text{SU}(3)' \rightarrow \text{SU}(3)_c$ symmetry breaking, the 6×6 fermion mass matrices for the quarks read:

$$\mathcal{M}_u = \begin{pmatrix} V^\dagger \hat{Y}_u \frac{v}{\sqrt{2}} & \hat{\lambda}_q \frac{v_3}{\sqrt{2}} \\ 0 & \hat{M}_Q \end{pmatrix}, \quad \mathcal{M}_d = \begin{pmatrix} \hat{Y}_d \frac{v}{\sqrt{2}} & \hat{\lambda}_q \frac{v_3}{\sqrt{2}} \\ 0 & \hat{M}_Q \end{pmatrix}. \quad (\text{C.20})$$

Similarly, after the $U(1)_{B-L} \times U(1)_{T_R^3} \rightarrow U(1)_Y$ symmetry breaking, the 6×6 fermion mass matrices for the leptons read:

$$\mathcal{M}_N = \begin{pmatrix} 0 & \hat{\lambda}_\ell \frac{v_1}{\sqrt{2}} \\ 0 & \hat{M}_L \end{pmatrix}, \quad \mathcal{M}_e = \begin{pmatrix} \hat{Y}_e \frac{v}{\sqrt{2}} & \hat{\lambda}_\ell W^\dagger \frac{v_1}{\sqrt{2}} \\ 0 & \hat{M}_L \end{pmatrix}. \quad (C.21)$$

Here, $\hat{Y}_{u,d,e}$ and $\hat{\lambda}_{q,\ell}$ are diagonal matrices, V and W are unitary Cabibbo-like mixing matrices, and M_Q, M_L are proportional to the identity matrix.

The structure of the mass matrices in Eqs. (C.21) allows them to be diagonalized by unitary transformations of the form $\psi'_x = U_x \psi_x$, where ψ_x ($x = q, u, d, \ell, e, N$) denotes a 6-dimensional vector containing both the chiral and vector-like fermions, and the unprimed fields represent the mass eigenstates.

The chosen flavour structure in Eq. (C.19) ensures that in the limit $W \rightarrow \mathbb{1}$, the mixing is family-specific: each vector-like fermion generation mixes predominantly with only one generation of chiral fermions (up to CKM rotations). At leading order, the unitary mixing matrices are given by:

$$\begin{aligned} U_q &\approx R_{14}(\theta_{q_1}) R_{25}(\theta_{q_2}) R_{36}(\theta_{q_3}), & U_\ell &\approx R_{14}(\theta_{\ell_1}) R_{25}(\theta_{\ell_2}) R_{36}(\theta_{\ell_3}), \\ U_u &\approx R_{14}(\theta_{u_R}) R_{25}(\theta_{c_R}) R_{36}(\theta_{t_R}), & U_e &\approx \begin{pmatrix} 1 & 0 \\ 0 & W \end{pmatrix} R_{14}(\theta_{e_R}) R_{25}(\theta_{\mu_R}) R_{36}(\theta_{\tau_R}), \\ U_d &\approx R_{14}(\theta_{d_R}) R_{25}(\theta_{s_R}) R_{36}(\theta_{b_R}), & U_N &\approx \begin{pmatrix} 0 & 0 \\ 0 & W \end{pmatrix}. \end{aligned}$$

Here, we have adopted a flavour basis for the SM $SU(2)_L$ fermion multiplets defined by:

$$q^i = \begin{pmatrix} V_{ji}^* u_L^j \\ d_L^i \end{pmatrix}, \quad \ell^\alpha = \begin{pmatrix} v_L^\alpha \\ e_L^\alpha \end{pmatrix}, \quad (C.22)$$

where V is the CKM matrix. The mixing angles are related to the Lagrangian parameters by:

$$\begin{aligned} \sin \theta_{q_i} &= \frac{\lambda_i^q v_3}{\sqrt{|\lambda_i^q|^2 v_3^2 + 2\hat{M}_Q^2}}, & \cos \theta_{q_i} &= \frac{\sqrt{2}\hat{M}_Q}{\sqrt{|\lambda_i^q|^2 v_3^2 + 2\hat{M}_Q^2}}, \\ \sin \theta_{\ell_i} &= \frac{\lambda_i^\ell v_1}{\sqrt{|\lambda_i^\ell|^2 v_1^2 + 2\hat{M}_L^2}}, & \cos \theta_{\ell_i} &= \frac{\sqrt{2}\hat{M}_L}{\sqrt{|\lambda_i^\ell|^2 v_1^2 + 2\hat{M}_L^2}}, \\ \sin \theta_{u_R^i} &= \frac{m_{u_i}}{M_{Q_i}} \tan \theta_{q_i}, & \sin \theta_{d_R^i} &= \frac{m_{d_i}}{M_{Q_i}} \tan \theta_{q_i}, \\ \sin \theta_{e_R^i} &= \frac{m_{e_i}}{M_{L_i}} \tan \theta_{\ell_i}, & \cos \theta_{f_R^i} &= 1 \quad (f = u, d, e). \end{aligned} \quad (C.23)$$

In these expressions, m_i and M_i denote the physical fermion masses. Up to corrections of $\mathcal{O}(m_i^2/M_i^2)$, these are given by:

$$\begin{aligned} M_{L_i} &= \sqrt{\frac{|\lambda_i^\ell|^2 v_1^2}{2} + \hat{M}_L^2}, & M_{Q_i} &= \sqrt{\frac{|\lambda_i^q|^2 v_3^2}{2} + \hat{M}_Q^2}, \\ m_{f_i} &\approx |\hat{Y}_f| \cos \theta_{f_i} \frac{v}{\sqrt{2}} \quad (f = u, d, e). \end{aligned} \quad (C.24)$$

The interaction terms of the massive gauge bosons with the fermions in the interaction basis are derived from the covariant derivative. For the left-handed fields, we find:

$$\begin{aligned} \mathcal{L}_L &= \frac{g_4}{\sqrt{2}} \bar{Q}'_L \gamma^\mu L'_L U_\mu + \text{h.c.} \\ &+ g_s \left(\frac{g_4}{g_3} \bar{Q}'_L \gamma^\mu T^a Q'_L - \frac{g_3}{g_4} \bar{q}'_L \gamma^\mu T^a q'_L \right) g'_\mu{}^a \\ &+ g_Y \left(\sqrt{\frac{3}{2}} \frac{g_4}{g_1} Y(Q'_L) \bar{Q}'_L \gamma^\mu Q'_L - \sqrt{\frac{2}{3}} \frac{g_1}{g_4} Y(q'_L) \bar{q}'_L \gamma^\mu q'_L \right) Z'_\mu \\ &+ g_Y \left(\sqrt{\frac{3}{2}} \frac{g_4}{g_1} Y(L'_L) \bar{L}'_L \gamma^\mu L'_L - \sqrt{\frac{2}{3}} \frac{g_1}{g_4} Y(\ell'_L) \bar{\ell}'_L \gamma^\mu \ell'_L \right) Z'_\mu, \end{aligned} \quad (\text{C.25})$$

and for the right-handed fields:

$$\begin{aligned} \mathcal{L}_R &= \frac{g_4}{\sqrt{2}} \bar{Q}'_R \gamma^\mu L'_R U_\mu + \text{h.c.} \\ &+ g_s \left(\frac{g_4}{g_3} \bar{Q}'_R \gamma^\mu T^a Q'_R - \frac{g_3}{g_4} \bar{u}'_R \gamma^\mu T^a u'_R - \frac{g_3}{g_4} \bar{d}'_R \gamma^\mu T^a d'_R \right) g'_\mu{}^a \\ &+ g_Y \left(\sqrt{\frac{3}{2}} \frac{g_4}{g_1} Y(Q'_R) \bar{Q}'_R \gamma^\mu Q'_R - \sqrt{\frac{2}{3}} \frac{g_1}{g_4} Y(u'_R) \bar{u}'_R \gamma^\mu u'_R - \sqrt{\frac{2}{3}} \frac{g_1}{g_4} Y(d'_R) \bar{d}'_R \gamma^\mu d'_R \right) Z'_\mu \\ &+ g_Y \left(\sqrt{\frac{3}{2}} \frac{g_4}{g_1} Y(L'_R) \bar{L}'_R \gamma^\mu L'_R - \sqrt{\frac{2}{3}} \frac{g_1}{g_4} Y(\ell'_R) \bar{\ell}'_R \gamma^\mu \ell'_R \right) Z'_\mu. \end{aligned} \quad (\text{C.26})$$

The SM hypercharges are: $Y(Q'_L) = Y(Q'_R) = Y(q'_L) = \frac{1}{6}$, $Y(u'_R) = \frac{2}{3}$, $Y(d'_R) = -\frac{1}{3}$, $Y(L'_L) = Y(L'_R) = Y(\ell'_L) = -\frac{1}{2}$, and $Y(e'_R) = -1$.

To express the interactions in Eqs. (C.25) and (C.26) in the fermion mass basis, we collect the fields into 6-dimensional multiplets, ψ_x ($x = q, u, d, \ell, e$), and apply the corresponding unitary transformations U_x . Neglecting the right-handed rotations—which are suppressed by the small masses of the SM fermions—we obtain:

$$\begin{aligned} \mathcal{L}_U &= \frac{g_4}{\sqrt{2}} U_\mu [\beta \bar{\Psi}_q \gamma^\mu \psi_\ell + W \bar{Q}_R \gamma^\mu L_R] + \text{h.c.}, \\ \mathcal{L}_{g'} &= g_s \frac{g_4}{g_3} g'_\mu{}^a [\kappa_q \bar{\Psi}_q \gamma^\mu T^a \psi_q + \kappa_u \bar{\Psi}_u \gamma^\mu T^a \psi_u + \kappa_d \bar{\Psi}_d \gamma^\mu T^a \psi_d], \\ \mathcal{L}_{Z'} &= \frac{g_Y}{2\sqrt{6}} \frac{g_4}{g_1} Z'_\mu [\zeta_q \bar{\Psi}_q \gamma^\mu \psi_q + \zeta_u \bar{\Psi}_u \gamma^\mu \psi_u \\ &\quad + \zeta_d \bar{\Psi}_d \gamma^\mu \psi_d - 3\zeta_\ell \bar{\Psi}_\ell \gamma^\mu \psi_\ell - 3\zeta_e \bar{\Psi}_e \gamma^\mu \psi_e]. \end{aligned} \quad (\text{C.27})$$

The coupling matrices are defined as follows (with indices $A, B = 4, 5, 6$ spanning the heavy vector-like states, and $\alpha, \beta = 1, \dots, 6$ spanning the full 6-dimensional space):

$$\begin{aligned} \beta^{\alpha\beta} &= [U_q]_{A\alpha}^* [W]_{AB} [U_\ell]_{B\beta}, \\ \kappa_q^{\alpha\beta} &= [U_q]_{A\alpha}^* [U_q]_{A\beta} - \frac{g_3^2}{g_4^2} \delta_{\alpha\beta}, \quad \kappa_u \approx \kappa_d \approx \begin{pmatrix} 0 & 0 \\ 0 & \mathbb{1}_{3\times 3} \end{pmatrix} - \frac{g_3^2}{g_4^2} \mathbb{1}_{6\times 6}, \\ \zeta_q^{\alpha\beta} &= [U_q]_{A\alpha}^* [U_q]_{A\beta} - \frac{2g_1^2}{3g_4^2} \delta_{\alpha\beta}, \quad \zeta_u \approx \zeta_d \approx \begin{pmatrix} 0 & 0 \\ 0 & \mathbb{1}_{3\times 3} \end{pmatrix} - \frac{2g_1^2}{3g_4^2} \mathbb{1}_{6\times 6}, \\ \zeta_\ell^{\alpha\beta} &= [U_\ell]_{A\alpha}^* [U_\ell]_{A\beta} - \frac{2g_1^2}{3g_4^2} \delta_{\alpha\beta}, \quad \zeta_e \approx \begin{pmatrix} 0 & 0 \\ 0 & \mathbb{1}_{3\times 3} \end{pmatrix} - \frac{2g_1^2}{3g_4^2} \mathbb{1}_{6\times 6}. \end{aligned} \tag{C.28}$$

A key result of the assumed flavour structure is that the matrix W cancels due to unitarity in the Z' and g' interactions. This cancellation is crucial for suppressing unwanted flavour-changing neutral currents (FCNCs) in these sectors.

Assuming $W = \mathcal{R}_{56}(\theta_{LQ})$ and no CP violation in the mixing angles, the left-handed coupling matrices can be explicitly written as:

$$\beta \approx \begin{pmatrix} \text{diag}(s_{q_1}s_{\ell_1}, s_{q_2}s_{\ell_2}, s_{q_3}s_{\ell_3})W & -\text{diag}(s_{q_1}c_{\ell_1}, s_{q_2}c_{\ell_2}, s_{q_3}c_{\ell_3})W \\ \text{diag}(c_{q_1}s_{\ell_1}, c_{q_2}s_{\ell_2}, c_{q_3}s_{\ell_3})W & -\text{diag}(c_{q_1}c_{\ell_1}, c_{q_2}c_{\ell_2}, c_{q_3}c_{\ell_3})W \end{pmatrix}, \tag{C.29}$$

$$\kappa_q \approx \begin{pmatrix} \text{diag}(s_{q_1}^2, s_{q_2}^2, s_{q_3}^2) & -\frac{1}{2}\text{diag}(s_{2q_1}, s_{2q_2}, s_{2q_3}) \\ -\frac{1}{2}\text{diag}(s_{2q_1}, s_{2q_2}, s_{2q_3}) & \text{diag}(c_{q_1}^2, c_{q_2}^2, c_{q_3}^2) \end{pmatrix} - \frac{g_3^2}{g_4^2} \mathbb{1}_{6\times 6}, \tag{C.30}$$

$$\zeta_q \approx \begin{pmatrix} \text{diag}(s_{q_1}^2, s_{q_2}^2, s_{q_3}^2) & -\frac{1}{2}\text{diag}(s_{2q_1}, s_{2q_2}, s_{2q_3}) \\ -\frac{1}{2}\text{diag}(s_{2q_1}, s_{2q_2}, s_{2q_3}) & \text{diag}(c_{q_1}^2, c_{q_2}^2, c_{q_3}^2) \end{pmatrix} - \frac{2g_1^2}{3g_4^2} \mathbb{1}_{6\times 6}, \tag{C.31}$$

$$\zeta_\ell \approx \begin{pmatrix} \text{diag}(s_{\ell_1}^2, s_{\ell_2}^2, s_{\ell_3}^2) & -\frac{1}{2}\text{diag}(s_{2\ell_1}, s_{2\ell_2}, s_{2\ell_3}) \\ -\frac{1}{2}\text{diag}(s_{2\ell_1}, s_{2\ell_2}, s_{2\ell_3}) & \text{diag}(c_{\ell_1}^2, c_{\ell_2}^2, c_{\ell_3}^2) \end{pmatrix} - \frac{2g_1^2}{3g_4^2} \mathbb{1}_{6\times 6}. \tag{C.32}$$

Following the flavour structure in [179], the assumption of a single $U(2)_q$ breaking spurion in both the leptoquark and SM Yukawa couplings implies the relation $\beta_L^{13} = V_{td}^*/V_{ts}^* \beta_L^{23}$. More generally, from $U(2)$ symmetries acting on both quark and lepton sectors, we expect the hierarchy:

$$|\beta_L^{31}| \ll |\beta_L^{23}|, |\beta_L^{32}| \ll |\beta_R^{33}|, |\beta_L^{33}| = \mathcal{O}(1),$$

and analogously for the $\zeta_{\ell,e,Q}^{ij}$ and κ_Q^{ij} couplings.

This structure can be achieved with a specific choice of the λ parameters in the potential, leading to particular values for the mixing angles θ_{q_i} and θ_{ℓ_i} . To explain the B-physics anomalies, a large mixing angle θ_{ℓ_3} is required, while the other two angles $\theta_{\ell_{1,2}}$ must be small to avoid large contributions to muon and electron observables. The quark mixing angles

θ_{q_i} should be small for the first two generations to avoid large contributions to meson mixing observables, while a moderate value of θ_{q_3} is needed to explain the B-physics anomalies.

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On the sensitivity reach of LQ production with preferential couplings to third generation fermions at the LHC

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Abstract Leptoquarks (LQs) are hypothetical particles that appear in various extensions of the Standard Model (SM), that can explain observed differences between SM theory predictions and experimental results. The production of these particles has been widely studied at various experiments, most recently at the Large Hadron Collider (LHC), and stringent bounds have been placed on their masses and couplings, assuming the simplest beyond-SM (BSM) hypotheses. However, the limits are significantly weaker for LQ models with family non-universal couplings containing enhanced couplings to third-generation fermions. We present a new study on the production of a LQ at the LHC, with preferential couplings to third-generation fermions, considering proton-proton collisions at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 13.6$ TeV. Such a hypothesis is well motivated theoretically and it can explain the recent anomalies in the precision measurements of B-meson decay rates, specifically the $R_{D^{(*)}}$ ratios. Under a simplified model where the LQ masses and couplings are free parameters, we focus on cases where the LQ decays to a τ lepton and a b quark, and study how the results are affected by different assumptions about chiral currents and interference effects with other BSM processes with the same final states, such as diagrams with a heavy vector boson, Z' . The analysis is performed using machine learning techniques, resulting in an increased discovery reach at the LHC, allowing us to probe new physics phase space which addresses the B-meson anomalies, for LQ masses up to 5.00 TeV, for the high luminosity LHC scenario.

1 Introduction

After more than ten years collecting data, the LHC has confirmed that the Standard Model (SM) is indeed the correct theory describing particle physics for energies below the TeV scale. Nevertheless, there exist reasons to expect the SM to be a low-energy effective realization of a more complete theory. On the theoretical side, we do not know if gravity should be quantized, or if the gauge interactions should be unified, and if so, we do not know how to solve the associated hierarchy problems on the Higgs mass. Moreover, we have no explanation for fermion family replication, nor for the lack of CP violation in the strong sector. This expectation for physics beyond the SM (BSM) is reinforced experimentally, where the observation of neutrino masses, dark matter, and the baryon asymmetry in the Universe, cannot be explained by the SM.

Leptoquarks (LQs) are hypothetical bosons carrying both baryon and lepton number, thus interacting jointly with a lepton and a quark. They are a common ingredient in SM extensions where quarks and leptons share the same multiplet. Typical examples of these can be found in the Pati-Salam [1] and $SU(5)$ GUT [2] models. In addition, they can also be found in theories with strong interactions, such as compositeness [3]. Due to their exotic coupling which allows quark-lepton transitions, they have a diverse phenomenology, which naturally leads to several constraints. An important one comes from proton decay, which forces the LQ mass to values close to the Planck scale, unless baryon and lepton numbers are not violated. Furthermore, in models where the latter are conserved, the LQ can still be subject to a wide variety of bounds [4–9]. Examples of these come from meson mixing, electric and magnetic dipole moments, atomic parity violation tests, rare decays, and direct searches. Nevertheless, the significance of each bound is a model dependent question.

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In the last years, an increased interest in low scale LQs has emerged due to the anomalies in the precision measurements of the B-meson decay rates. As it is well known, these corresponded mainly to deviations in the $R_{K^{(*)}}$ [10–13] and $R_{D^{(*)}}$ [14–25] ratios, which measure the violation of lepton flavour universality (LFU). What followed was a very intense theoretical development, aiming to explain the anomalies by TeV scale LQ exchange at tree level [26–41]. Before the end of 2022, it was generally agreed that, within proposed single LQ solutions, the only candidate capable of addressing all B-meson anomalies simultaneously and surviving all other constraints was a vector LQ (U_1), transforming as $(\mathbf{3}, \mathbf{1}, 2/3)$, and coupling mainly to third-generation fermions via $b \tau$ and $t \nu_\tau$ vertices [36, 39]. In spite of a recent re-analysis of $R_{K^{(*)}}$ data showing this ratio to be compatible with the SM prediction [42–45], the solution to the $R_{D^{(*)}}$ anomaly is still an open question and remains a valid motivation for the study of scenarios where new particles have preferential couplings to third-generation fermions. Thus, it is still of interest to continue exploring the possibility of observing the U_1 LQ at the LHC [41].

As expected, the theoretical community has extensively participated in probing LQ models by scrutinizing search strategies, recasting LHC results, and predicting the reach in the parameter space via different searches involving third-generation fermions (see for instance [46–55]). In addition, several 13 TeV searches for LQs decaying into t/b and τ/ν final states have been performed by the CMS [56–64] and ATLAS [65–71] collaborations.

Of the searches above, we find [62] particularly interesting. Here, the CMS collaboration explores signals corresponding to $t \nu b \tau$ and $t \nu \tau$ final states, with 137 fb^{-1} of proton-proton (pp) collision data. The former is motivated by LQ pair production, with one LQ decaying into $t \nu$ and the other into $b \tau$, while the latter arises from a single LQ produced in association with a τ , with a subsequent LQ decay into $t \nu$ (see Fig. 1 for the corresponding diagrams). From the combination of both production channels, the search excludes U_1 masses under $1.3 - 1.7 \text{ TeV}$, with this range depending on the U_1 coupling to gluons and on its coupling g_U in the $b_L \tau_L$ vertex.

What makes this search particularly attractive is that, for the first time, an LHC collaboration directly places (mass dependent) bounds on g_U . This is important, since having information on this parameter is crucial in order to understand if the U_1 is really responsible for the $R_{D^{(*)}}$ anomaly. The inclusion of the single-LQ production mode is important, since its cross-section is directly proportional to g_U^2 . However, as can be seen in Fig. 6 of [62], the current constraints are dominated by pair production, with single-LQ production playing a subleading role. While this is expected [49], it still leads us to ponder the possibility of improving the sensitivity of LHC searches to single-LQ production, and thus

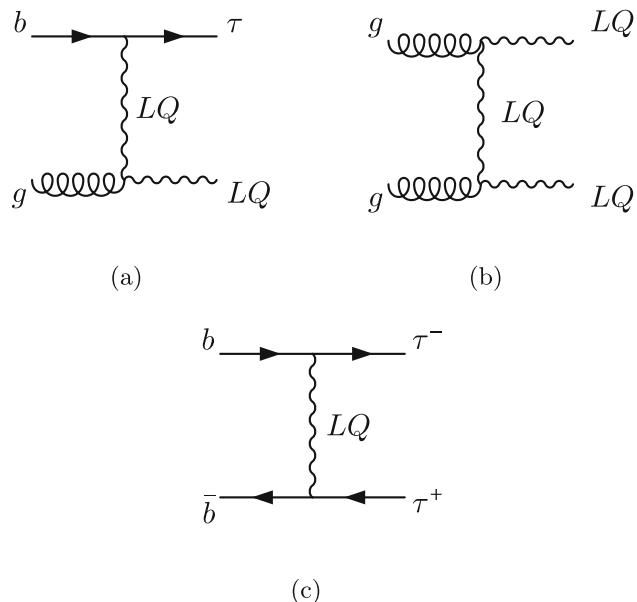


Fig. 1 Representative Feynman diagrams of single (a), pair (b), and non-resonant (c) leptoquark production in proton-proton collision experiments. In single and pair production, the diagrams shown involve t-channel LQ exchange, dominant for lower LQ mass. However, for larger mass there exist s-channel diagrams featuring a virtual bottom quark and gluon, respectively

on achieving better constraints on g_U . Other complementary and similar searches to [62] were carried out by both ATLAS [70] and CMS [64].

It is also well known, though, that searches for an excess in the high- p_T tails of τ lepton distributions can strongly probe g_U , up to very large LQ masses. Indeed, as shown in [41, 72], the new physics effective operators contributing to $R_{D^{(*)}}$ also contribute to an enhancement in the $\text{p p} \rightarrow \tau\tau$ production rates. This has motivated a large number of recasts [39, 41, 49, 51, 73–77], as well as a CMS search explicitly providing constraints in terms of U_1 [63]. Nevertheless, it is important to note that for these $\text{p p} \rightarrow \tau\tau$ processes, the LQ participates non-resonantly, so contributions to the $\text{p p} \rightarrow \tau\tau$ rates and kinematic distributions from non-LQ BSM diagrams containing possible virtual particles, such as a heavy neutral vector boson Z' , could spoil a straightforward interpretation of any possible excess [51]. Thus, it is also necessary to understand how the presence of other virtual particles can affect the sensitivity of an analysis probing g_U .

In this work we study the projected LQ sensitivity at the LHC, considering already available pp data as well as the expected amount of data to be acquired during the High-Luminosity LHC (HL-LHC) runs. We explore a proposed analysis strategy which utilizes a combination of single-, double-, and non-resonant-LQ production, targeting final states with varying τ -lepton and b-jet multiplicities. The

studies are performed considering various benchmark scenarios for different LQ masses and couplings, also taking into account distinct chiralities for the third-generation fermions in the LQ vertex. We also assess the impact of a companion Z' , which is typical of gauge models, in non-resonant LQ probes, and find that interference effects can have a significant effect on the discovery reach. We consider this effect to be of high interest, given that non-resonant LQ production can have the largest cross-section, and thus could be an important channel in terms of discovery potential.

An important aspect of this work is that the analysis strategy is developed using a machine learning (ML) algorithm based on Boosted Decision Trees (BDT)[78]. The output of the event classifier is used to perform a profile-binned likelihood test to extract the overall signal significance for each model considered in the analysis. The advantage of using BDTs and other ML algorithms has been demonstrated in several experimental and phenomenological studies [50, 79–84]. In our studies, we find that the BDT algorithm gives sizeable improvement in signal significance.

This paper is organized as follows. In Sect. 2 we present our simplified model and review the model parameters which are relevant for solving the B-meson anomalies. Section 3 describes the details associated with the analysis strategy and the simulation of signal and background samples. Section 4 contains the results of the study, including the projected sensitivity for different benchmark scenarios considered. Finally, in Sect. 5 we discuss the implication of our results and prospects for future studies.

2 A simplified model for the U_1 leptoquark

Extending the SM with a massive U_1 vector LQ is not straightforward, as one has to ensure the renormalizability of the model. Most of the theoretical community has focused on extensions of the Pati-Salam (PS) models which avoid proton decay, such as the scenario found in [85]. Other examples include PS models with vector-like fermions [86–88], the so-called 4321 models [89–91], the twin PS² model [92, 93], the three-site PS³ model [94–96], as well as composite PS models [97–99].

In what follows, we shall restrict ourselves to a simplified non-renormalizable lagrangian, understood to be embedded into a more complete model. The SM is thus extended by adding the following terms featuring the U_1 LQ:

$$\begin{aligned} \mathcal{L}_{U_1} = & -\frac{1}{2} U_{\mu\nu}^\dagger U^{\mu\nu} + M_U^2 U_{1\mu}^\dagger U_1^\mu \\ & -ig_s U_{1\mu}^\dagger T^a U_{1\nu} G^{a\mu\nu} - i\frac{2}{3}g' U_{1\mu}^\dagger U_{1\nu} B^{\mu\nu} \\ & + \frac{g_U}{\sqrt{2}} [U_{1\mu} (\bar{Q}_3 \gamma^\mu L_3 + \beta_L^{st} \bar{Q}_2 \gamma^\mu L_3 \\ & + \beta_R \bar{b}_R \gamma^\mu \tau_R) + h.c.] \end{aligned} \quad (1)$$

where $U_{\mu\nu} \equiv \mathcal{D}_\mu U_{1\nu} - \mathcal{D}_\nu U_{1\mu}$, and $\mathcal{D}_\mu \equiv \partial_\mu + ig_s T^a G_\mu^a + i\frac{2}{3}g' B_\mu$. As evidenced by the second line above, we assume that the LQ has a gauge origin.¹

The third and fourth lines in Eq. (1) shows the LQ interactions with SM fermions, with coupling g_U , which we have chosen as preferring the third generation.² These are particularly relevant for the LQ decay probabilities, as well as for the single-LQ production cross-section. The β_L^{st} parameter, which is the $LQ \rightarrow s\tau$ coupling in the β_L matrix (see footnote), is chosen to be equal to 0.2, following the fit done in [75], in order to simultaneously solve the $R_{D^{(*)}}$ anomaly and satisfy the $p p \rightarrow \tau^+ \tau^-$ constraints. Although β_L^{st} technically alters the single-LQ production cross-section and LQ branching fractions, we have confirmed that a value of $\beta_L^{st} = 0.2$ results in negligible impact on our collider results, and thus is ignored in our subsequent studies.

The LQ right-handed coupling is modulated with respect to the left-handed one by the β_R parameter. The choice of β_R is important phenomenologically, as it affects the LQ branching ratios,³ as well as the single-LQ production cross-section. To illustrate the former, Fig. 2 (top) shows the LQ $\rightarrow b\tau$ and LQ $\rightarrow t\nu$ branching ratios as functions of the LQ mass, for two values of β_R . For large LQ masses, we confirm that with $\beta_R = 0$ then $BR(LQ \rightarrow b\tau) \approx BR(LQ \rightarrow t\nu) \approx \frac{1}{2}$. However, for $\beta_R = -1$, as was chosen in [38], the additional coupling adds a new term to the total amplitude, leading to $BR(LQ \rightarrow b\tau) \approx \frac{2}{3}$. The increase in this branching ratio can thus weaken bounds from LQ searches targeting decays into $t\nu$ final states, which motivates exploring the sensitivity in $b\tau$ final states exclusively. Note that although a $BR(LQ \rightarrow b\tau) \approx 1$ scenario is possible by having the LQ couple exclusively to right-handed currents (i.e., $g_U \rightarrow 0$, but $g_U \beta_R \neq 0$), it does not solve the observed anomalies in the $R_{D^{(*)}}$ ratios. Therefore, although some LHC searches assume $BR(LQ \rightarrow b\tau) = 1$, we stress that in our studies we assume values of the model parameters and branching ratios that solve the $R_{D^{(*)}}$ ratios.

To further understand the role of β_R at colliders, Fig. 2 (bottom) shows the cross-section for single-LQ (sLQ), double-LQ (dLQ), and non-resonant (non-res) production, as a function of mass and for a fixed coupling $g_U = 1.8$, assuming $p p$ collisions at $\sqrt{s} = 13$ TeV. We note that this benchmark scenario with $g_U = 1.8$ results in a LQ $\rightarrow b\tau$ decay width that is <5% of the LQ mass, for mass values

¹ The couplings in the second line of Eq. (1) can be found in the literature as $g_s \rightarrow g_s(1 - \kappa_U)$ and $g' \rightarrow g'(1 - \tilde{\kappa}_U)$, in order to take into account the possibility of an underlying strong interaction.

² Before the demise of the $R_{K^{(*)}}$ anomaly [42–45], a 3×3 β_L matrix would be used instead, with values fitted to solve all B meson anomalies.

³ Having β_L^{st} different from zero also opens new decay channels. These, however, are either suppressed by β_L^{st} and powers of λ_{CKM} . In any case, this effect would decrease $BR(LQ \rightarrow b\tau)$ and $BR(LQ \rightarrow t\nu)$ by less than 3%.

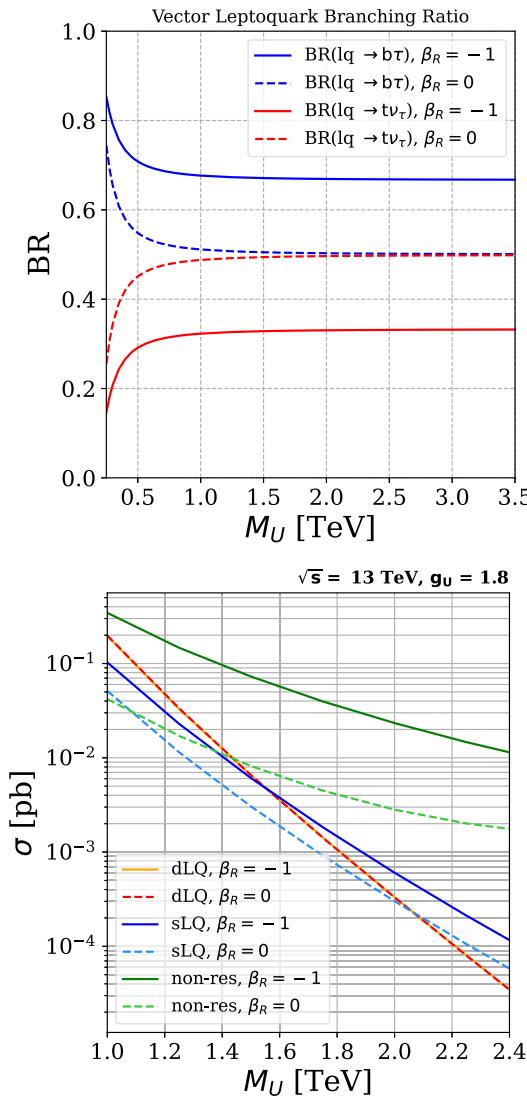


Fig. 2 Top: The LQ \rightarrow $b\tau$ and LQ \rightarrow $t\nu$ branching ratios for $\beta_R = 0$ (solid lines) and $\beta_R = -1$ (dashed lines). Bottom: Signal cross-section as a function of the LQ mass, for $\sqrt{s} = 13 \text{ TeV}$, with $g_U = 1.8$. We show single, pair, and non-resonant production, for $\beta_R = -1, 0$ in solid and dashed lines, respectively

from 250 GeV to 2.5 TeV. In the figure, we observe that, since dLQ production is mainly mediated by events from quantum chromodynamic processes, the choice of β_R does not affect the cross-section. However, for sLQ production, a non-zero value for β_R increases the cross-section by about a factor of 2 and by almost one order of magnitude in the case of non-res production. These results shown in Fig. 2 are easily understood by considering the diagrams shown in Fig. 1. The LQ mass value where the sLQ production cross-section exceeds the dLQ cross-section depends on the choice of g_U .

We also note that to solve the $R_{D^{(*)}}$ anomaly, the authors of [75] point out that the wilson coefficient $C_U \equiv g_U^2 v_{SM}^2 / (4 M_U^2)$ is constrained to a specific range of values,

and this range depends on the value of the β_R parameter. Therefore, the allowed values of the coupling g_U depend on M_U and β_R , and thus our studies are performed in this multi-dimensional phase space.

As noted in Sect. 1, we study the role of a Z' boson in $p p \rightarrow \tau\tau$ production. The presence of a Z' boson in LQ models has been justified in various papers, for example, in [51]. The argument is that minimal extensions of the SM which include a massive gauge U_1 LQ, uses the gauge group $SU(4) \times SU(3)' \times SU(2)_L \times U(1)_{T_R^3}$. Such an extension implies the presence of an additional massive boson, Z' , and a color-octet vector, G' , arising from the spontaneous symmetry breaking into the SM.⁴ The Z' in particular can play an important role in the projected LQ discovery reach, as it can participate in $p p \rightarrow \tau\tau$ production by s-channel exchange, both resonantly and as a virtual mediator. To study the effect of a Z' on the $p p \rightarrow \tau\tau$ production cross-sections and kinematics, we extend our benchmark Lagrangian in Eq. (1) with further non-renormalizable terms involving the Z' . Accordingly, we assume the Z' only couples to third-generation fermions. Our simplified model is thus extended by:

$$\begin{aligned} \mathcal{L}_{Z'} = & -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} M_{Z'}^2 Z'_\mu Z'^\mu \\ & + \frac{8Z'}{2\sqrt{6}} Z'^\mu (\zeta_q \bar{Q}_3 \gamma_\mu Q_3 + \zeta_t \bar{t}_R \gamma_\mu t_R \\ & + \zeta_b \bar{b}_R \gamma_\mu b_R - 3\zeta_\ell \bar{L}_3 \gamma_\mu L_3 - 3\zeta_\tau \bar{\tau}_R \gamma_\mu \tau_R) \end{aligned} \quad (2)$$

where the constants $M_{Z'}$, $g_{Z'}$, ζ_q , ζ_t , ζ_b , ζ_ℓ , ζ_τ , are model dependent.

We study two extreme cases for the Z' mass, following [100], namely $M_{Z'} = \sqrt{\frac{1}{2}} M_U < M_U$ and $M_{Z'} = \sqrt{\frac{3}{2}} M_U > M_U$. We also assume the LQ and Z' are uniquely coupled to left-handed currents, i.e. $\zeta_q = \zeta_\ell = 1$ and $\zeta_t = \zeta_b = \zeta_\tau = 0$. With these definitions, Fig. 3 shows the effect of the Z' on the $\tau\tau$ production cross-section, considering $g_U = 1$, $\beta_R = 0$, and different $g_{Z'}$ couplings. On the top panel, the cross-sections corresponding to the cases where $M_{Z'} = \sqrt{\frac{1}{2}} M_U$ are shown. As expected, the $\tau\tau$ production cross-section for the inclusive case (i.e., $g_{Z'} \neq 0$) is larger than that for the LQ-only non-res process ($g_{Z'} = 0$, depicted in blue). This effect increases with $g_{Z'}$ and, within the evaluated values, can exceed the LQ-only cross-section by up to two orders of magnitude. In contrast, a more intricate behaviour can be seen in the bottom panel of Fig. 3, which corresponds to $M_{Z'} = \sqrt{\frac{3}{2}} M_U$. Here, for low values of M_U , a similar

⁴ Naively, the LQs are associated to the breaking of $SU(4) \rightarrow SU(3)_{[4]} \times U(1)_{B-L}$, the G' arises from $SU(3)_{[4]} \times SU(3)' \rightarrow SU(3)_c$, and the Z' comes from the breaking of $U(1)_{B-L} \times U(1)_{T_R^3} \rightarrow U(1)_Y$. Notice that the specific pattern of breaking, and the relations between the masses and couplings, are connected to the specific scalar potential used.

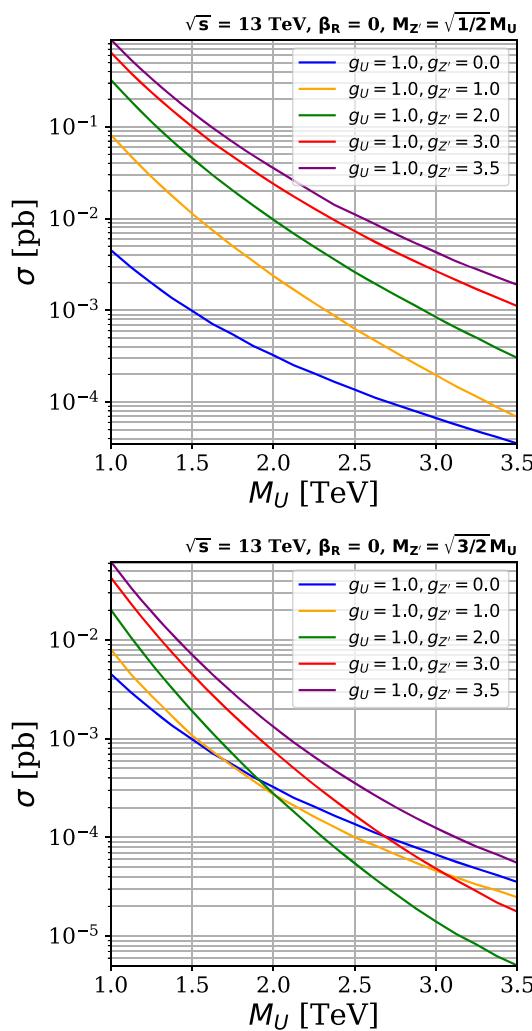


Fig. 3 $\tau\tau$ cross-section as a function of the LQ mass for different values of g_U and $g_{Z'}$. The estimates are performed at $\sqrt{s} = 13$ TeV, $\beta_R = 0$, $M_{Z'} = \sqrt{1/2}M_U$ (top), and $M_{Z'} = \sqrt{3/2}M_U$ (bottom)

increase in the cross-section is observed. However, for higher values of M_U , the inclusive $p p \rightarrow \tau\tau$ cross-section is smaller than the LQ-only $\tau\tau$ cross-section. This behaviour suggests the presence of a dominant destructive interference at high masses, leaving its imprint on the results.

In order to further illustrate the effect, Fig. 4 shows the relative kinematic interference (RKI) as a function of the reconstructed invariant mass $m_{\tau\tau}$, for $g_{Z'} = 1$ and varying values of M_U . The RKI parameter is defined as

$$\text{RKI}(m_{\tau\tau}) = \frac{1}{\sigma_{\text{LQ}+Z'}} \left[\frac{d\sigma_{\text{LQ}+Z'}}{dm_{\tau\tau}} - \left(\frac{d\sigma_{\text{LQ}}}{dm_{\tau\tau}} + \frac{d\sigma_{Z'}}{dm_{\tau\tau}} \right) \right], \quad (3)$$

where σ_X is the production cross-section arising due to contributions from X particles. For example, $\sigma_{\text{LQ}+Z'}$ represents the inclusive cross-section where both virtual LQ and s-channel Z' exchange contribute. For both cases, we can

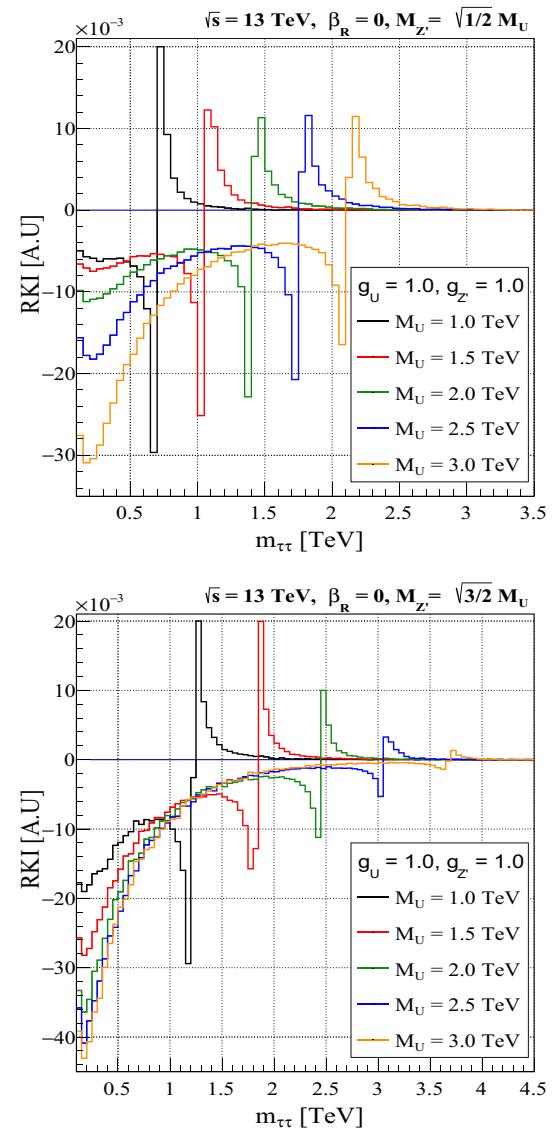


Fig. 4 The relative kinematic interference (RKI), as a function of the reconstructed mass of two taus, for different LQ masses. The studies are performed assuming $\sqrt{s} = 13$ TeV, $\beta_R = 0$, $g_U = 1.0$, $g_{Z'} = 1.0$, $M_{Z'} = \sqrt{1/2}M_U$ (top), and $M_{Z'} = \sqrt{3/2}M_U$ (bottom)

observe the presence of deep valleys in the RKI curves when $m_{\tau\tau} \rightarrow 0$, indicating destructive interference between the LQ and the Z' contributions. This interference generates a suppression of the differential cross-section for lower values of $m_{\tau\tau}$ and, therefore, in the integrated cross-section.

The observed interference effects are consistent with detailed studies on resonant and non-resonant $p p \rightarrow t\bar{t}$ production, performed in reference [101].

3 LQ search strategy and simulation

Our proposed analysis strategy utilizes single-LQ (i.e. $p p \rightarrow \tau\tau$ LQ), double-LQ (i.e. $p p \rightarrow \text{LQ LQ}$), and non-resonant LQ

production (i.e. $p p \rightarrow \tau\tau$) as shown in Fig. 1. At leading order in α_s , since we focus on $U_1 \rightarrow b\tau$ decays, the sLQ process results in the $b\tau\tau$ mode, the dLQ process results in the $bb\tau\tau$ mode, and the non-res process results in the $\tau\tau$ mode. Therefore, in all cases we obtain two τ leptons, with either 0, 1, or 2 b jets. The τ leptons decay to hadrons (τ_h) or semi-leptonically to electrons or muons (τ_ℓ , $\ell = e$ or μ). To this end, we study six final states: $\tau_h\tau_{h/\ell}$, $b\tau_h\tau_{h/\ell}$, and $bb\tau_h\tau_{h/\ell}$, which can be naively associated to non-res, sLQ and dLQ production, respectively. Nevertheless, experimentally it is possible for b jets to not be properly identified or reconstructed, leading, for instance, to a fraction of dLQ signal events falling into the $b\tau_h\tau_{h/\ell}$ and $\tau_h\tau_{h/\ell}$ categories. Similarly, soft jets can fake b jets, such that non-res processes can contribute to the $b\tau_h\tau_{h/\ell}$ and $bb\tau_h\tau_{h/\ell}$ final states. This kind of signal loss and mixing is taken into account in our analysis.⁵

The contributions of signal and background events are estimated using Monte Carlo (MC) simulations. We implemented the U_1 model from [51], adjusted to describe the lagrangian in Eqs. (1) and (2), using FeynRules (v2.3.43) [102, 103]. The branching ratios and cross-sections have been calculated using MadGraph5_aMC (v3.1.0) [104, 105], the latter at leading order in α_s . The corresponding samples are generated considering $p p$ collisions at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 13.6$ TeV. All samples are generated using the NNPDF3.0 NLO [106] set for parton distribution functions (PDFs) and using the full amplitude square SDE strategy for the phase-space optimization due to strong interference effects with the Z' boson. Parton level events are then interfaced with the PYTHIA (v8.2.44) [107] package to include parton fragmentation and hadronization processes, while DELPHES (v3.4.2) [108] is used to simulate detector effects, using the input card for the CMS detector geometric configurations, and for the performance of particle reconstruction and identification.

At parton level, jets and leptons are required to have a minimum transverse momentum (p_T) of 20 GeV, while b jets are required to have a minimum p_T of 30 GeV. Additionally, we constrain the pseudorapidity (η) to $|\eta| < 2.5$ for b jets and leptons, and $|\eta| < 5.0$ for jets. The production cross-sections shown in the bottom panel of Figs. 2 and 3 are obtained with the aforementioned selection criteria.

Table 1 shows the preliminary event selection criteria for each channel at analysis level. The channels are divided based on the multiplicity of b jets, $N(b)$, number of light leptons, $N(\ell)$, number of hadronic tau leptons, $N(\tau_h)$, and kinematic

⁵ Note that further signal mixing can also occur at the event generation level by including terms at larger order in α_s . For example, in the non-res diagram in Fig. 1, one of the initial b could come from a $g \rightarrow b\bar{b}$ splitting, leading to non resonant production of $b\tau_h\tau_{h/\ell}$. Simulating and studying the role of such NLO contributions is outside the scope of this work.

Table 1 Preliminary event selection criteria used to filter events before feeding them to the BDT algorithm. A $\Delta R(p_i, p_j) > 0.3$ requirement is imposed between all pairs of reconstructed particle candidates p_i, p_j

Variable	Threshold					
	$\tau_h\tau_h$	$b\tau_h\tau_h$	$bb\tau_h\tau_h$	$\tau_h\tau_\ell$	$b\tau_h\tau_\ell$	$bb\tau_h\tau_\ell$
$N(b)$	= 0	= 1	≥ 2	= 0	= 1	≥ 2
$p_T(b)$	–	≥ 30 GeV	–	≥ 30 GeV	–	≤ 2.4
$ \eta(b) $	–	≤ 2.4	–	≤ 2.4	–	≤ 2.4
$N(\ell)$	= 0	–	–	= 1	–	–
$p_T(e)$	–	–	≥ 35 GeV	–	–	–
$p_T(\mu)$	–	–	≥ 30 GeV	–	–	–
$ \eta(\ell) $	–	–	≤ 2.4	–	–	–
$N(\tau_h)$	= 2	–	–	= 1	–	–
$p_T(\tau_h)$	≥ 50 GeV	–	–	–	–	–
$ \eta(\tau_h) $	≤ 2.3	–	–	–	–	–
$\Delta R(p_i, p_j)$	≥ 0.3	–	–	–	–	–

criteria based on η , p_T and spatial separation of particles in the detector volume ($\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$). The minimum p_T thresholds for leptons are chosen following references [62, 63, 67], based on experimental constraints associated to trigger performance. Following reference [109], we use a flat identification efficiency for b jets of 70% across the entire p_T spectrum with misidentification rate of 1%. These values correspond with the “medium working point” of the CMS algorithm to identify b jets, known as DeepCSV. We also explored the “Loose” (“Tight”) working point using an efficiency of 85% (45%) and mis-identification rate of 10% (0.1%). The “medium working point” was selected as it gives the best signal significance for the analysis.

For the performance of τ_h identification in DELPHES, we consider the latest technique described in [110], which is based on a deep neural network (i.e. DeepTau) that combines variables related to isolation and τ -lepton lifetime as input to identify different τ_h decay modes. Following [110], we consider three possible DeepTau “working points”: (i) the “Medium” working point of the algorithm, which gives a 70% τ_h -tagging efficiency and 0.5% light-quark and gluon jet mis-identification rate; (ii) the “Tight” working point, which gives a 60% τ_h -tagging efficiency and 0.2% light-quark and gluon jet mis-identification rate; and (iii) the “VTight” working point, which gives a 50% τ_h -tagging efficiency and 0.1% light-quark and gluon jet mis-identification rate. Similar to the choice of b-tagging working point, the choice of τ_h -tagging working point is determined through an optimization process which maximizes discovery reach. The “Medium” working point was ultimately shown to provide the best sensitivity and therefore chosen for this study. For muons (electrons), the assumed identification efficiency is 95% (85%), with a 0.3% (0.6%) mis-identification rate [111–113].

Table 2 The number of simulated events for the signal and background samples

Sample	$t\bar{t}$	single t	VV	$V+\text{jets}$	signals
$N_{\text{events}} \times 10^{-6}$	24.31	11.50	32.35	39.45	0.60

After applying the preliminary selection criteria, the primary sources of background are production of top quark pairs ($t\bar{t}$), and single-top quark processes (single t), followed by production of vector bosons with associated jets from initial or final state radiation ($V+\text{jets}$), and pair production of vector bosons (VV). The number of simulated MC events used for each sample is shown in Table 2.

We use two different sets of signal samples. The first set includes various $\{M_U, g_U\}$ scenarios, for two different values of $\beta_R \in \{0, -1\}$. We generate signal samples for M_U values between 250 and 5000 GeV, in steps of 250 GeV. The considered g_U coupling values are between 0.25 and 3.5, in steps of 0.25. Although the signal cross-sections depend on both M_U and g_U , the efficiencies of our selections only depend on M_U (for all practical purposes) since the decay widths are relatively small compared to the mass of M_U ($\frac{\Gamma_U}{M_U} < 5\%$), and thus more sensitive to experimental resolution. In total there are 280 $\{M_U, g_U, \beta_R\}$ scenarios simulated for this first set of signal samples, and for each of these scenarios two subsets of samples are generated, which are used separately for the training and testing of the machine learning algorithm. The second set of signal samples is used to evaluate interference effects between LQs and the Z' bosons in non-res production. Using benchmark values $g_U = 1.8$ and $\beta_R = 0$, we consider various $\{M_U, g_{Z'}\}$ scenarios for two different Z' mass hypotheses, $(M_{Z'}/M_U)^2 \in \{\frac{1}{2}, \frac{3}{2}\}$. The M_U values vary between 500 and 5000 GeV, in steps of 250 GeV. The $g_{Z'}$ coupling values are between 0.25 and 3.5, in steps of 0.25. Therefore, in total there are 280 $\{M_U, g_{Z'}, (M_{Z'}/M_U)^2\}$ scenarios simulated for this second set of signal samples, and for each of these scenarios a total of 6.0×10^5 MC events are generated.

As noted previously, the simulated signal and background events are initially filtered using selections which are motivated by experimental constraints, such as the geometric constraints of the CMS detector, the typical kinematic thresholds for reconstruction of particle objects, and the available triggers. The remaining events after the preliminary event selection criteria are used to train and execute a BDT algorithm for each signal point in the $\{M_U, g_U\}$ space, in order to maximize the probability to detect signal amongst background events. The BDT algorithm is implemented using the scikit-learn [114] and xgboost (XGB) [115] python libraries. We use the XGBClassifier class from the xgboost library, a 10-fold cross validation using

the scikit-learn method (GridCV⁶) for a grid in a hyperparameter space with 75, 125, 250, and 500 estimators, maximum depth in 3, 5, 7, 9, as well as learning rates of 0.01, 0.1, 1, and 10. For the cost function, we utilize the default mean square error (MSE). Additionally, we use the tree method based on the approximate greedy algorithm (histogram-optimized), referred to as hist, with a uniform sample method. These choices allow us to maximize the detection capability of the BDT algorithm by carefully tuning the hyperparameters, selecting an appropriate cost function, and utilizing an optimized tree construction method.

For each of the six analysis channels and $\{M_U, g_U\}$ signal point, the binary XGB classifier was trained (tested) with 20% (80%) of the simulated events, for each signal and background MC sample. Over forty kinematic and topological variables were studied as input for the XGB. These included the momenta of b jets and $\tau_{h,\ell}$ candidates; both invariant and transverse masses of pairs of τ objects and of b τ combinations; angular differences between b jets, between τ objects, and between the $\tau_{h,\ell}$ and b jets; and additional variables derived from the missing momentum in the events. After studying correlations between variables and their impact on the performance of the BDT, we found that only eight variables were necessary and responsible for the majority of the sensitivity of the analysis. The variable that provides the best signal to background separation is the scalar sum of the p_T of the final state objects (τ_h , $\tau_{h/\ell}$, and b jets) and the missing transverse momentum, referred to as S_T^{MET} :

$$S_T^{MET} = |\vec{p}_T^{miss}| + \sum_{\tau_h, \tau_{h/\ell}, b} |\vec{p}_T| \quad (4)$$

The S_T^{MET} variable has been successfully used in LQ searches at the LHC, since it probes the mass scale of resonant particles involved in the production processes. Other relevant variables include the magnitude of the vectorial difference in p_T between the two lepton candidates ($|\Delta \vec{p}_T|_{\tau_h \tau_{h/\ell}}$), the $\Delta R_{\tau_h \tau_{h/\ell}}$ separation between them, the reconstructed dilepton mass $m_{\tau_h \tau_{h/\ell}}$, and the product of their electric charges ($Q_{\tau_h} \times Q_{\tau_{h/\ell}}$). We also use the $|\Delta \vec{p}_T|$ between the τ_h candidate and \vec{p}_T^{miss} , and (if applicable) the $|\Delta \vec{p}_T|$ between the τ_h candidate and the leading b jet. For the final states including two τ_h candidates, the one with the highest p_T is used.

Figure 5 shows some relevant topological distributions, including S_T^{MET} on the top, for the b $\tau_h \tau_\ell$ category. In the Figure we include all signal production modes to this channel, with each component weighted with respect to their total contribution to the combined signal. The combined signal distribution is normalised to unity. We also show all background processes contributing to this channel, each of them

⁶ GridCV is a method that allows to find the best combination of hyperparameter values for the model, as this choice is crucial to achieve an optimal performance.

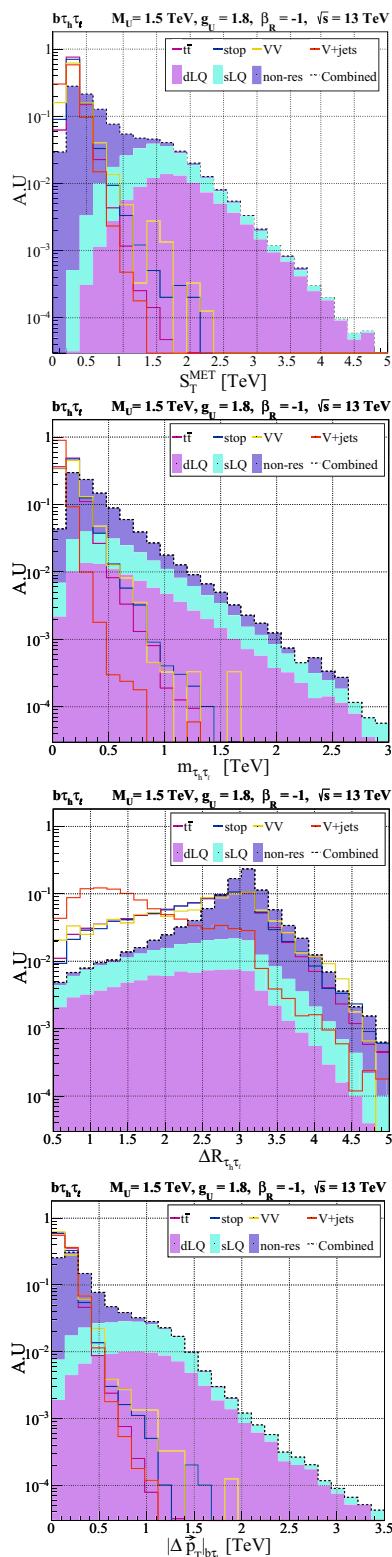


Fig. 5 S_T^{MET} , $m_{\tau_h \tau_\ell}$, $\Delta R_{\tau_h \tau_\ell}$, $|\Delta \vec{p}_T|_{b\tau_h}$ signal and background distributions for the $b\tau_h \tau_\ell$ channel. The signal distributions are generated for a benchmark sample with LQ mass of 1.5 TeV maximally coupled to right-handed currents. The combined distribution (shown as a stacked histogram) is the sum of the distributions, correctly weighted according to their respective cross-sections, assuming a coupling $g_U = 1.8$

individually normalised to unity. We find that the combined signal is dominated by sLQ production for large values of S_T^{MET} , while non-res production dominates for small S_T^{MET} . Interestingly, the backgrounds also sit at low S_T^{MET} values, since S_T^{MET} is driven by the mass scale of the SM particles being produced, in this case top quarks and Z/W bosons. This suggest that the sLQ and dLQ signals can indeed be separated from the SM background. As expected, the S_T^{MET} sLQ and dLQ signal distributions have a mean near M_U , representative of resonant production, and a broad width as expected for large mass M_U hypotheses when information about the z -components of the momenta of objects is not utilised in the S_T^{MET} calculation.

Figure 5 (second from the top) shows the reconstructed mass of the ditau system, for the $b\tau_h \tau_\ell$ search channel. Since the two τ candidates in signal events arise from different production vertices (e.g., each τ candidate in dLQ production comes from a different LQ decay chain), the ditau mass distribution for signal scales as $m_{\tau_h \tau_\ell} \sim p_T(\tau_h) + p_T(\tau_\ell)$, and thus has a tail which depends on M_U and sits above the expected SM spectrum. On the other hand, the SM $m_{\tau_h \tau_\ell}$ distributions sit near $m_{Z/W}$ since the τ candidates in SM events arise from Z/W decays.

Figure 5 (third from the top) shows the $\Delta R_{\tau_h \tau_\ell}$ distribution for the $b\tau_h \tau_\ell$ channel. In the case of the $p p \rightarrow \tau \tau$ non-res signal distribution, the two τ leptons must be back-to-back to preserve conservation of momentum. Therefore, the visible τ candidates, τ_h and τ_ℓ , give rise to a $\Delta R_{\tau_h \tau_\ell}$ distribution that peaks near π radians. In the case of sLQ production, although the LQ and associated τ candidate must be back-to-back, the second τ candidate arising directly from the decay of the LQ does not necessarily move along the direction of the LQ (since the LQ also decays to a b quark). As a result, the $\Delta R_{\tau_h \tau_\ell}$ distribution for the sLQ signal process is smeared out, is broader, and has a mean below π radians. On the other hand, the τ_h candidate in $t\bar{t}$ events is often a jet being misidentified as a genuine τ_h . When this occurs, the fake τ_h candidate can arise from the same top quark decay chain as the τ_ℓ candidate, thus giving rise to small $\Delta R_{\tau_h \tau_\ell}$ values. This difference in the signal and background distributions provides a nice way for the ML algorithm to help decipher signal and background processes.

As noted above, the $|\Delta \vec{p}_T|$ distribution between the visible τ candidates and the b-quark jets is an important variable to help the BDT distinguish between signal and background processes. The discriminating power can be seen in Fig. 5 (bottom), which shows the $|\Delta \vec{p}_T|$ between the τ_h and b-jet candidate of the $b\tau_h \tau_\ell$ channel. In the case of dLQ production, the b quarks and τ leptons from the LQ $\rightarrow b\tau$ decay acquire transverse momentum of $p_T \sim M_U/2$. However, when the τ lepton decays hadronically (i.e. $\tau \rightarrow \tau_h \nu$), a large fraction of the momentum is lost to the neutrino. Therefore, the $|\Delta \vec{p}_T|_{b\tau_h}$ distribution for the dLQ (and sLQ)

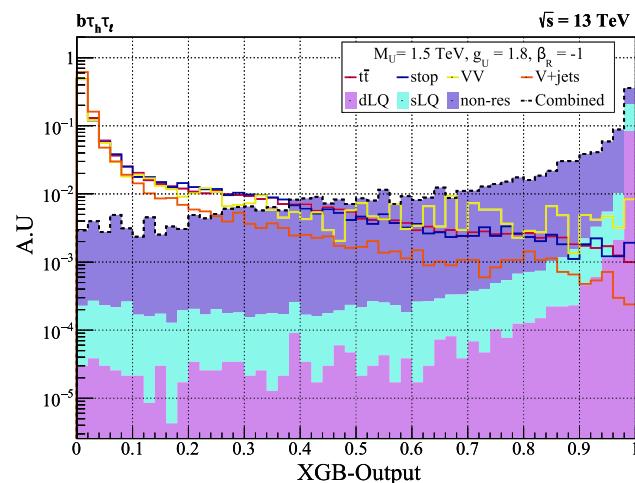


Fig. 6 Postfit XGB-output normalised distribution in the $b\tau_h\tau_\ell$ channel, for LQ mass of 1.5 TeV, constant coupling $g_U = 1.8$, and maximally coupled to right-handed currents

process peaks below $M_U/2$. On the other hand, for a background process such as $V+jets$, the b jet arises due to initial state radiation, and thus must balance the momentum of the associated vector boson (i.e. $p_T(b) \sim p_T(V) \sim m_V$). Since the visible τ candidate is typically produced from the V boson decay chain, its momentum (on average) is approximately $p_T(\tau_h) \sim p_T(V)/4 \sim m_V/4$. Therefore, to first order, the $|\Delta\vec{p}_T|$ distribution for the $V+jets$ background is expected to peak below the m_V mass.

Lets us turn to the results of the $b\tau_h\tau_\ell$ BDT classifier, which is shown in Fig. 6 for the different signal production modes and backgrounds. Similar to Fig. 5, the distribution for each individual signal production mode is weighted with respect to their total contribution to the combined signal. The background distributions and combined signal distribution are normalized to an area under the curve of unity. Figure 6 shows the XGB distributions for a signal benchmark point with $M_U = 1.5$ TeV, $g_U = 1.8$, and $\beta_R = -1$. The XGB output is a value between 0 and 1, which quantifies the likelihood that an event is either signal-like (XGB output near 1) or background-like (XGB output near 0). We see that the presence of the sLQ and dLQ production modes is observed as an enhancement near a XGB output of unity, while the backgrounds dominate over the low end of the XGB output spectrum, especially near zero. In fact, over eighty percent of the sLQ and dLQ distributions reside in the last two bins, XGB output greater than 0.96, while more than sixty percent of the backgrounds fall in the first two bins, XGB output less than 0.04. It is also interesting to note that in comparison to the sLQ and dLQ distributions in Fig. 6, non-res is broader and not as narrowly peaked near XGB output of 1, which is expected due to the differences in kinematics described

above. Overall, if we focus on the last bin in this distribution, we find approximately 0.2% of the background, in contrast to 22% of the non-res, 78% of the sLQ, and 91% of the dLQ signal distributions. These numbers highlight the effectiveness of the XGB output in reducing the background in the region where the signal is expected.

The output signal and background distributions of the XGB classifier, normalised to their cross section times pre-selection efficiency times luminosity, are used to perform a profile binned likelihood statistical test in order to determine the expected signal significance. The estimation is performed using the `RooFit` [116] package, following the same methodology as in Refs. [117–132]. The value of the significance (Z_{sig}) is measured using the probability to obtain the same outcome from the test statistic in the background-only hypothesis, with respect to the signal plus background hypothesis. This allows for the determination of the local p-value and thus the calculation of the signal significance, which corresponds to the point where the integral of a Gaussian distribution between Z_{sig} and ∞ results in a value equal to the local p-value.

Systematic uncertainties are incorporated as nuisance parameters, considering log-priors for normalization and Gaussian priors for shape uncertainties. Our consideration of systematic uncertainties includes both experimental and theoretical effects, focusing on the dominant sources of uncertainty. Following [133], we consider a 3% systematic uncertainty on the measurement of the integrated luminosity at the LHC. A 5% uncertainty arises due to the choice of the parton distribution function used for the MC production, following the PDF4LHC prescription [134]. The chosen PDF set only has an effect on the overall expected signal and background yields, but the effect on the shape of the XGB output distribution is negligible. Reference [110] reports a systematic uncertainty of 2–5%, depending on the p_T and η of the τ_h candidate. Therefore, we utilize a conservative 5% uncertainty per τ_h candidate, independent of p_T and η , which is correlated between signal and background processes with genuine τ_h candidates, and correlated across XGB bins for each process. We assumed a 5% τ_h energy scale uncertainty, independent of p_T and η , following the CMS measurements described in [110]. Finally, we assume a conservative 3% uncertainty per b -jet candidate, following reference [135], and an additional 10% uncertainty in all the background predictions to account for possible mismodeling by the simulated samples. The uncertainties on the background estimates are typically derived from collision data using dedicated control samples that have negligible signal contamination and are enriched with events from the specific targeted background. The systematic uncertainties on the background estimates are treated as uncorrelated between background processes.

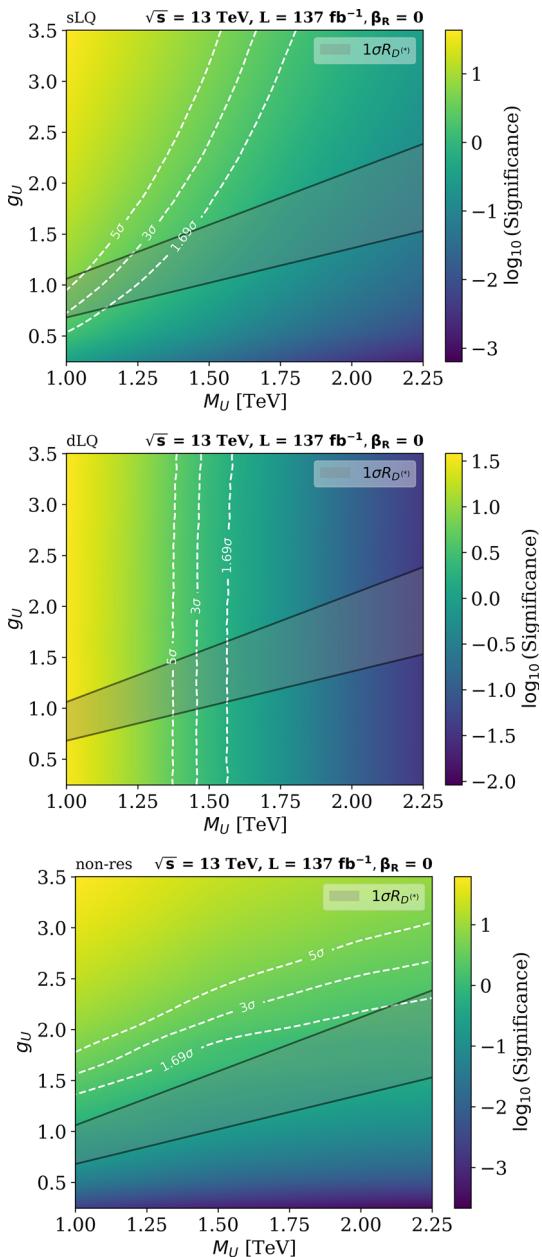


Fig. 7 Signal significance for different coupling scenarios and LQ masses, without right-handed currents, using the combination of all search channels. The results pertaining to sLQ, dLQ and non-res production are displayed respectively from the top. These results are for $\sqrt{s} = 13 \text{ TeV}$ and 137 fb^{-1}

4 Results

The expected signal significance for sLQ, dLQ and non-res production, and their combination, is presented in Fig. 7. Here, the significance is shown as a heat map in a two dimensional plane of g_U versus M_U , considering exclusive couplings to left-handed currents, i.e. $\text{BR}(\text{LQ} \rightarrow b\tau) = \frac{1}{2}$. The dashed lines show the contours of constant signal significance. The 1.69σ contour represents exclusion at 95%

confidence level, and the $3-5\sigma$ contours represent potential discovery. The grey band defines the set of $\{M_U, g_U\}$ values that can explain the B-meson anomalies, $C_U \sim 0.01$ for this scenario. The estimates are performed under the conditions for the second run, RUN-II, of the LHC ($\sqrt{s} = 13 \text{ TeV}$ and $L = 137 \text{ fb}^{-1}$). We find that the dLQ interpretation plot (Fig. 7 second from the top) does not depend on g_U , which is expected due to dLQ production arising exclusively from interactions with gluons. For this reason, the dLQ production process provides the best mode for discovery when g_U is small. On the other hand, the non-res channel is more sensitive to changes in the coupling parameter g_U , as its production cross-section depends on g_U^4 . Therefore, the non-res production process provides the best mode for discovery when g_U is large. These results confirm the expectations from previous analyses (see for instance [49]), in the sense that the dLQ and non-res processes complement each other nicely at low and high g_U scenarios. The sLQ channel combines features from both the dLQ and non-res channels, in principle making it an interesting option to explore different scenarios and gain a better understanding of LQ properties, but the evolution of the signal significance in the full phase space is more complicated as it involves resonant LQ production with a cross-section that depends non-trivially on M_U , g_U , and the LQ coupling to gluons. However, Fig. 7 shows that the sLQ production process can provide complementary and competitive sensitivity to the non-res and dLQ processes, in certain parts of the phase space.

The top panel of Fig. 8 presents the sensitivity of all signal production processes combined, and compares our expected exclusion region with the latest one from the ATLAS Collaboration [70]. The comparison suggests that our proposed analysis strategy provides better sensitivity than current methods being carried out at ATLAS, especially at large values of g_U . In particular, we find that with the pp data already available from RUN-II, our expected exclusion curves begin to probe solutions to the B-anomalies for LQ masses up to 2.25 TeV .

Figure 8 shows the expected signal significance considering $\text{BR}(\text{LQ} \rightarrow b\tau) = 1$, in order to compare our analysis with the corresponding results from the CMS [64] and ATLAS [71] Collaborations. Let us emphasize again that $\text{BR}(\text{LQ} \rightarrow b\tau)$ depends on β_R , as illustrated on the top panel of Fig. 2. Thus, although the $\text{BR}(\text{LQ} \rightarrow b\tau) = 1$ scenario is a possible physical case, it does not solve the observed anomalies in the $R_{D^{(*)}}$ ratios, as it corresponds to the case where LQs couple exclusively to right-handed currents.

With this in mind, the scenario studied by CMS in [64] considers couplings only to left-handed currents, setting artificially the condition $\text{BR}(\text{LQ} \rightarrow b\tau) = 1$. In order to compare, we scale the efficiency \times acceptance of our selection criteria for $\beta_R = 0$, by a factor of 2.0 for sLQ and 4.0 for dLQ. According to Fig. 8, the ML approach that we have followed

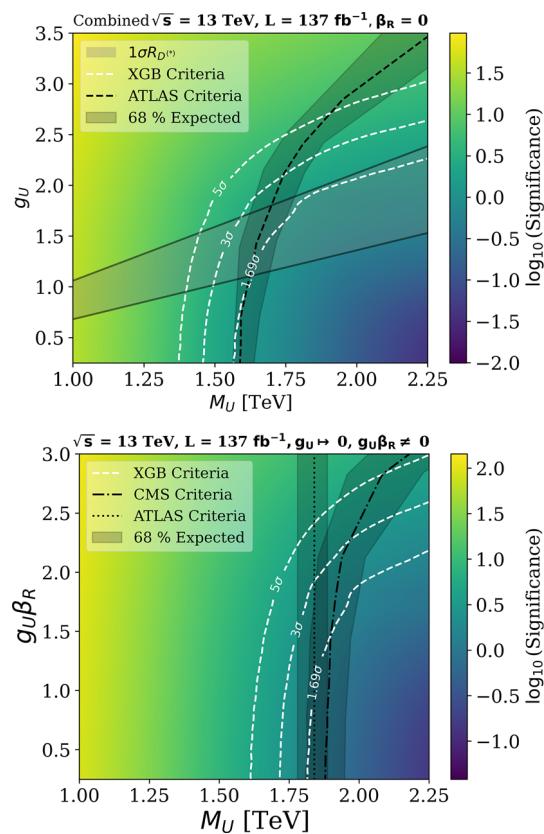


Fig. 8 The top (bottom) panel shows signal significance comparison with ATLAS [70] (CMS and ATLAS [64, 71]) background only hypothesis, for the combination of all channels, with uniquely coupling to left-handed (right-handed) currents. The estimates are performed at $\sqrt{s} = 13$ TeV and 137 fb^{-1}

again suggests an optimisation of the signal and background separation, having the potential of improving the regions of exclusion (1.69σ) with respect to that of CMS. In the bottom panel of the figure we have also included a similar exclusion by ATLAS [71]. However, since ATLAS only considers dLQ production in the analysis, the results are not entirely comparable, so are included only as a reference.

We now turn to the role of β_R , and our capacity of probing the regions solving the B-meson anomalies. Figure 9 shows the maximum significant contours, under LHC RUN-II conditions, for the different LQ production mechanisms and their combination, considering scenarios with only left-handed currents ($\beta_R = 0$, top) and with maximal right-handed currents ($\beta_R = -1$, bottom). We find a noticeable improvement in signal significance in all channels when taking $\beta_R = -1$, as is expected from the increase in $\text{BR}(\text{LQ} \rightarrow b\tau)$ branching ratio and production cross-sections (see Fig. 2). However, the region solving the B-meson anomalies also changes, preferring lower values of g_U , such that in both cases we find ourselves just starting to probe this region at large M_U .

The combined significance contours for the different BR scenarios that have been considered is presented in Fig. 10.

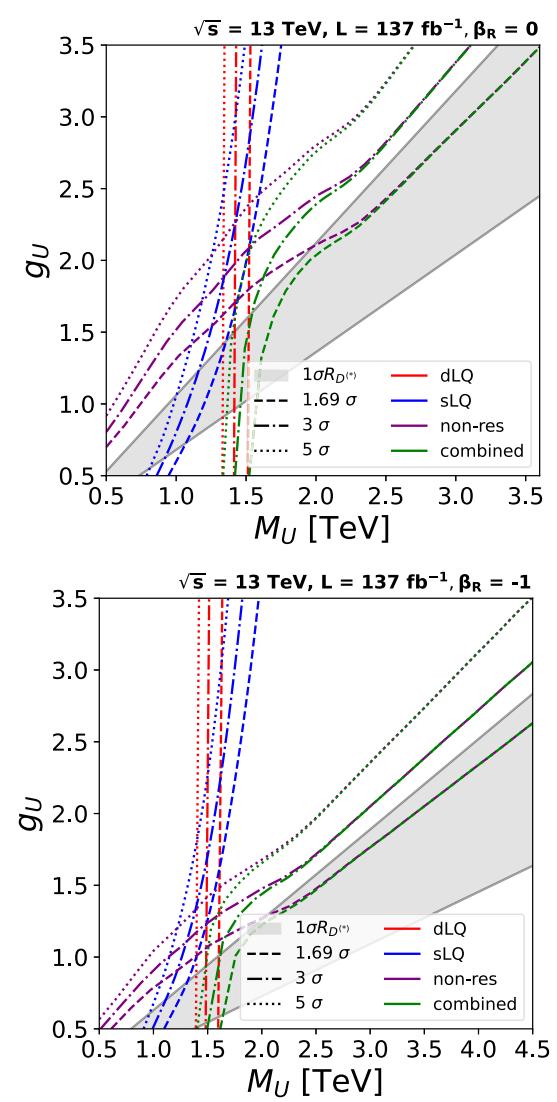


Fig. 9 Signal significance for different coupling scenarios and LQ masses for all channels. This plot summarizes our results with $\beta_R = 0$ (without right-handed currents) and $\beta_R = -1$ (maximally coupled to right-handed currents). The estimates are performed at $\sqrt{s} = 13$ TeV and 137 fb^{-1}

These contours illustrate the regions of exclusion for the three cases of interest, namely exclusive left-handed currents ($\text{BR}(\text{LQ} \rightarrow b\tau) = \frac{1}{2}, \beta_R = 0$), maximal left and right couplings ($\text{BR}(\text{LQ} \rightarrow b\tau) = \frac{2}{3}, \beta_R = -1$), and exclusive right-handed currents ($\text{BR}(\text{LQ} \rightarrow b\tau) = 1, g_U \rightarrow 0, g_U \beta_R = 1$). For small g_U , we find that the exclusive right-handed scenario is most sensitive, while the exclusive left-handed case is the worst. The reason for this is that this region is excluded principally by dLQ production, such that having the largest branching ratio is crucial in order to have a large number of events. For larger couplings, both exclusive scenarios end up having similar exclusion regions, with the $\beta_R = -1$ case being significantly more sensitive. The reason in this case is that the exclusion is dominated by

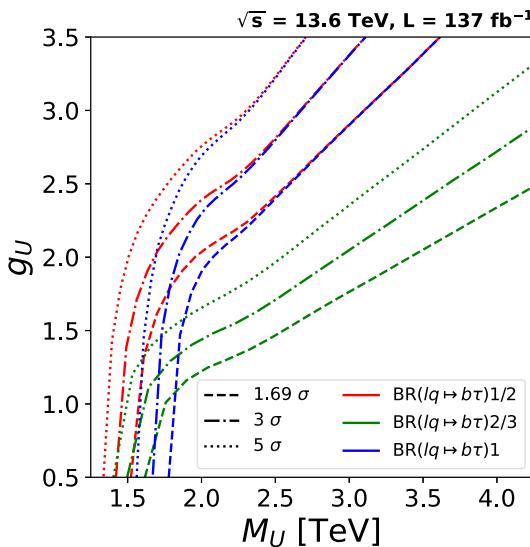


Fig. 10 Signal significance for different coupling scenarios and LQ masses, considering the case without coupling to right-handed currents $\text{BR}(\text{LQ} \rightarrow b\tau) = \frac{1}{2}$, the case maximally coupled to right- and left-handed currents $\text{BR}(\text{LQ} \rightarrow b\tau) = \frac{2}{3}$, and the case uniquely coupled to right-handed currents $\text{BR}(\text{LQ} \rightarrow b\tau) = 1$. The estimates are performed at $\sqrt{s} = 13 \text{ TeV}$ and 137 fb^{-1}

non-res, which has a much larger production cross-section if both currents are turned on.

In order to finalise our analysis of the LQ-only model, we show in Fig. 11 the expected combined significance in the relatively near future. For this, considering $\sqrt{s} = 13.6 \text{ TeV}$, we show contours for the sensitivity corresponding to integrated luminosities of 137 fb^{-1} , 300 fb^{-1} , and 3000 fb^{-1} , for scenarios with only left-handed currents (top) and with maximal coupling to right-handed currents (bottom). Note that for $\beta_R = 0$ ($\beta_R = -1$), couplings g_U close to 3.18 (1.85) and $M_U = 5.0 \text{ TeV}$ can be excluded with 1.69σ significance for the high luminosity LHC era, allowing us to probe the practically the entirety of the B-meson anomaly favored region. Note that the background yields for the high luminosity LHC might be larger due to pileup effects. Nevertheless, as it was mentioned in Sect. 3, we have included a conservative 10% systematic uncertainty associated with possible fluctuations on the background estimations. Although effects from larger pileup might be significant, they can be mitigated by improvements in the algorithms for particle reconstruction and identification, and also on the data-analysis techniques.

As commented on the Introduction, non-res production can be significantly affected by the presence of a companion Z' , which provides additional s-channel diagrams that add to the total cross-section and can interfere destructively with the LQ t-channel process (see Figs. 3 and 4). From our previous results, we see that non-res always is of high importance in determining the exclusion region, particularly at large M_U .

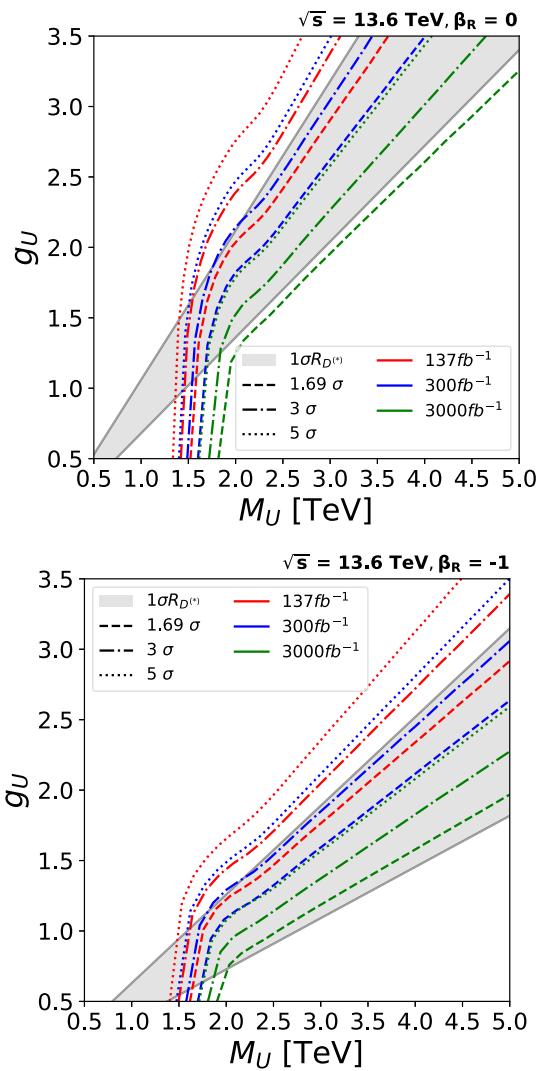


Fig. 11 Projected signal significance for different coupling scenarios and LQ masses maximally coupled to right-handed currents. The estimates are performed at $\sqrt{s} = 13.6 \text{ TeV}$, 137 fb^{-1} , 300 fb^{-1} and 3000 fb^{-1}

and g_U , meaning it is crucial to understand how this role is affected in front of a Z' with similar mass.

The change in sensitivity on the non-res signal significance due this interference effect with the Z' boson is shown in Fig. 12. We consider two opposite cases for the Z' mass: $M_{Z'}^2 = M_U^2/2$ (top) and $M_{Z'}^2 = 3M_U^2/2$ (bottom). Our results are shown on the $g_{Z'} - M_U$ plane, for a fixed $g_U = 1.8$ and $\beta_R = 0$. For the $M_{Z'}^2 = M_U^2/2$ scenario, there is an overall increase in the total cross-section, with a larger $g_{Z'}$ implying a larger sensitivity. This means that our ability to probe smaller values of g_U could be enhanced, as a given observation would be reproduced with both a specific g_U and vanishing $g_{Z'}$, or a smaller g_U with large $g_{Z'}$. Thus, for a large enough $g_{Z'}$, it could be possible to enhance non-res to the point that the entire region favoured by B-anomalies could

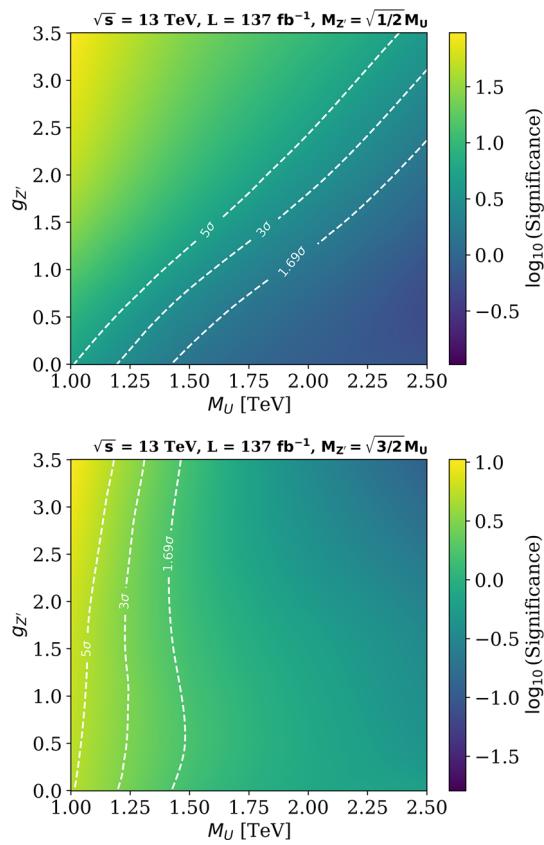


Fig. 12 Change on the non-res signal significance for different Z' coupling scenarios and LQ masses. The estimates are performed at $\sqrt{s} = 13.0$ TeV, $\beta_R = 0$, $g_U = 1.8$, $M_{Z'} = \sqrt{1/2}M_U$ (top), and $M_{Z'} = \sqrt{3/2}M_U$ (bottom)

be ruled out. In contrast, for $M_{Z'}^2 = 3M_U^2/2$ the cross-section is strongly affected by the large destructive interference, such that a larger $g_{Z'}$ does not necessarily imply an increase in sensitivity. In fact, as can be seen in the bottom panel, for large M_U the significance is reduced as $g_{Z'}$ increases, leading to the opposite conclusion than above, namely, that a large $g_{Z'}$ could reduce the effectiveness of non-res.

The impact of the above can be seen in Fig. 13, which shows our previous sensitivity curves on the $M_U - g_U$ plane, but this time with a Z' contribution to non-res. We use the same values of $M_{Z'}$ as before, but fix $g_{Z'} = 3.5$. For smaller $M_{Z'}$ (top), the non-res contribution is enhanced so much, that both sLQ and dLQ play no role whatsoever in determining the exclusion region. We find that, for small g_U , the sensitivity is dominated by Z' production such that, since M_U is related to $M_{Z'}$, LQ masses up to ~ 3 TeV are excluded. This bound is slightly relaxed for larger values of g_U , which is attributed to destructive interference effects due to an increased LQ contribution.

The bottom panel of Fig. 13 shows that case where $M_{Z'}$ is larger than M_U . As expected from our previous discussion, the behaviour and impact of non-res is modified. For small

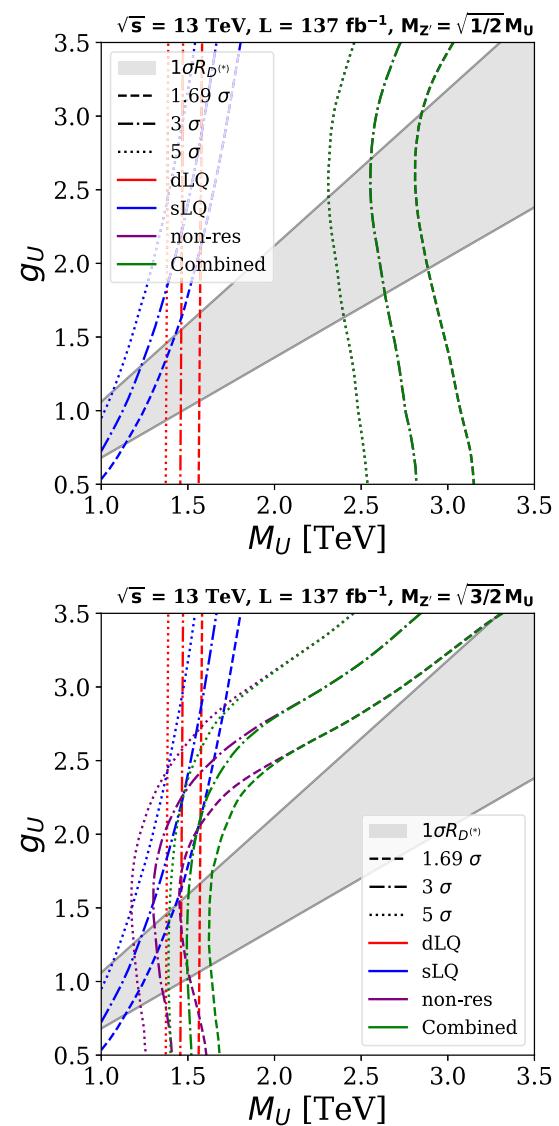


Fig. 13 Signal significance for different coupling scenarios and LQ masses, for all channels, with an additional Z' contribution to non-res production. We set $\beta_R = 0$ and $g_{Z'} = 3.5$, taking $M_{Z'}^2$ equal to $M_U^2/2$ (3 $M_U^2/2$) on the top (bottom) panel

g_U , we again have the pure Z' production dominating the non-res cross-section, leading to a null sensitivity on g_U , similar to what happens in dLQ. In contrast, for very large g_U , we find that the pure LQ non-res production is the one that dominates, and we recover sensitivity regions with a slope similar to those shown in Figs. 7, 8, 9, 10 and 11, shifted towards larger values of g_U . For intermediate values of this coupling, the destructive interference have an important effect again, twisting the exclusion region slightly towards the left. Still, even in this case, we find that sLQ plays a marginal role in defining the combined exclusion region, and that the final result again depends primarily on dLQ and non-res production.

5 Discussion and conclusions

Experimental searches for LQs with preferential couplings to third generation fermions are currently of great interest due to their potential to explain observed tensions in the $R_{(D)}$ and $R_{(D^*)}$ decay ratios of B mesons with respect to the SM predictions. Although the LHC has a broad physics program on searches for LQs, it is very important to consider the impact of each search within wide range of different theoretical assumptions within a specific model. In addition, in order to improve the sensitivity to detect possible signs of physics beyond the SM, it is also important to strongly consider new computational techniques based on machine learning (ML). Therefore, we have studied the production of U_1 LQs with preferential couplings to third generation fermions, considering different couplings, masses and chiral currents. These studies have been performed considering p p collisions at $\sqrt{s} = 13$ TeV and 13.6 TeV and different luminosity scenarios, including projections for the high luminosity LHC. A ML algorithm based on boosted decision trees is used to maximize the signal significance. The signal to background discrimination output of the algorithm is taken as input to perform a profile binned-likelihood test statistic to extract the expected signal significance.

The expected signal significance for sLQ, dLQ and non-res production, and their combination, is presented as contours on a two dimensional plane of g_U versus M_U . We present results for the case of exclusive couplings to left-handed, mixed, and exclusive right-handed currents. For the first two, the region of the phase space that could explain the B meson anomalies is also presented. We confirm the findings of previous works that the largest production cross-section and best overall significance comes from the combination of dLQ and non-res production channels. We also find that the sensitivity to probe the parameter space of the model is highly dependent on the chirality of the couplings. Nevertheless, the region solving the B-meson anomalies also changes with each choice, such that in all evaluated cases we find ourselves just starting to probe this region at large M_U .

Our studies compare our exclusion regions with respect to the latest reported results from the ATLAS and CMS Collaborations. The comparison suggests that our ML approach has a better sensitivity than the standard cut-based analyses, especially at large values of g_U . In addition, our projections for the HL-LHC cover the whole region solving the B-anomalies, for masses up to 5.00 TeV.

Finally, we consider the effects of a companion Z' boson on non-res production. We find that such a contribution can have a considerable impact on the LQ sensitivity regions, depending on the specific masses and couplings. In spite of this, we still consider non-res production as an essential channel for probing LQs in the future.

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Probing light scalars and vector-like quarks at the high-luminosity LHC

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Abstract A model based on a $U(1)_{T_R^3}$ extension of the Standard Model can address the mass hierarchy between generations of fermions, explain thermal dark matter abundance, and the muon $g - 2$, $R_{(D)}$, and $R_{(D^*)}$ anomalies. The model contains a light scalar boson ϕ' and a heavy vector-like quark χ_u that can be probed at CERN's large hadron collider (LHC). We perform a phenomenology study on the production of ϕ' and χ_u particles from proton–proton (pp) collisions at the LHC at $\sqrt{s} = 13.6$ TeV, primarily through $g-g$ and $t-\chi_u$ fusion. We work under a simplified model approach and directly take the χ_u and ϕ' masses as free parameters. We perform a phenomenological analysis considering χ_u final states to b-quarks, muons, and neutrinos, and ϕ' decays to $\mu^+\mu^-$. A machine learning algorithm is used to maximize the signal sensitivity, considering an integrated luminosity of 3000 fb^{-1} . The proposed methodology can be a key mode for discovery over a large mass range, including low masses, traditionally considered difficult due to experimental constraints.

1 Introduction

The Standard Model (SM) of particle physics, despite its successful account of numerous experimental findings involving strong, electromagnetic, and weak interactions, confirmed by CERN's large hadron collider (LHC) is regarded as a lower-energy manifestation of a more comprehensive theory. This perspective arises from unresolved questions regarding the origins of dark matter, electroweak symmetry breaking scales, lepton flavor universality, the anomalous muon mag-

netic moment [1–8], discrepancies in the $R_{(D)}$ and $R_{(D^*)}$ ratios from b-meson decays [9–21], as well as theoretical conundrums about whether gravity should be quantized, how gauge interactions can be unified, and the fine-tuning problem associated with the Higgs boson mass. Furthermore, the SM offers no explanation for fermion family replication nor for the lack of CP violation in the strong sector. These theoretical gaps, coupled with the experimental observation of phenomena such as neutrino masses, dark matter, and the baryon asymmetry in the universe, which cannot be explained by the SM, reinforce the expectation for physics beyond the SM (BSM).

As a result, several theoretical models have been put forth to address the limitations of the SM over the past decade. Despite differing theoretical motivations and resulting implications, a common thread among these ideas is the introduction of new particles, that, depending on the model, might be probed via proton–proton (pp) collisions at the LHC. A myriad of ideas have been suggested to investigate BSM physics, driving a substantial amount of exploration at the LHC. Said research has significantly limited the scope of theories and established exclusion bounds, extending to multi-TeV ranges for the masses of newly predicted particles within certain models [22–28]. Possible reasons for the absence of evidence could be attributed to new particle masses being at the scale where they are too large to be produced at the LHC energies and likely with exceptionally low production rates. In the scenario where the masses of the new particles might be probed at the LHC, a vast amount of data might be needed, together with advanced analysis techniques, to enhance the probability of detection. Alternatively, it is conceivable that new physics diverges from the conventional assumptions made in many BSM theories and the associated explorations. As a result, these new physics phenomena could remain hidden in processes that have not yet been thoroughly examined.

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Minimal extensions to the SM, considering new $U(1)_\chi$ symmetry groups, are among the most studied BSM scenarios. For example, the $U(1)_{T_R^3}$ symmetry, where families of right-handed fermions of the SM and possible extensions, such as right-handed neutrinos, are charged, was originally studied in the context of left-right symmetry models [29–31]. In these studies, $U(1)_{T_R^3}$ is identified as the subgroup of $SU(2)_R$ defined by its diagonal (electric-charge neutral) generator, T_R^3 . In addition, it is often suggested that $U(1)_{T_R^3}$ is a subspecies of a $U(1)_{B-L}$ symmetry since the breaking of the $U(1)_{B-L} \times U(1)_{T_R^3}$ leads to the $U(1)_Y$ symmetry. This naturally motivates the presence of a massive and electrically neutral Z' gauge boson [32–36]. However, in the breaking of $U(1)_{B-L} \times U(1)_{T_R^3} \rightarrow U(1)_Y$, it follows that the Higgs doublet H , since it is a singlet of $U(1)_{B-L}$, acquires its hypercharge by inheritance from a charge under $U(1)_{T_R^3}$. Consequently, the vacuum expectation value (VEV) of H couples both symmetry-breaking scales for $U(1)_Y$ and $U(1)_{T_R^3}$. Alternatively, these symmetry-breaking scales can be decoupled by adding an additional $U(1)_G$ group where fermions of the SM are singlets and H is not. Therefore, the hypercharge comes from $U(1)_G$ for the H and from $U(1)_{T_R^3}$ for fermions, i.e. $Y = Q_{T_R^3} + \frac{1}{2}Q_{B-L} + Q_G$ [37]. Moreover, one can ask for scenarios where the hypercharge is not related to the $U(1)_{T_R^3}$ charge.

Recently, theoretical and phenomenological efforts have emerged around scenarios where the low-energy gauge symmetry of the SM is extended by appending the Abelian gauge group $U(1)_{T_R^3}$, whose spontaneous symmetry-breaking is not linked to the electroweak one [38–43]. In these scenarios, the gauge boson of $U(1)_{T_R^3}$ is associated with a massive dark photon A' whose longitudinal mode arises from a Higgs-like mechanism involving a complex scalar field, ϕ . This field is a singlet under the SM group, with its CP-odd component associated with the A' mass and the CP-even giving rise to a dark Higgs, ϕ' . To cancel gauge anomalies, a right-handed ν_R neutrino must be included for each generation of the SM that couples to $U(1)_{T_R^3}$. Furthermore, to correctly explain the origin of fermion masses in a UV-complete theory, a set of new vector-like quarks ($\chi_u, \chi_d, \chi_\ell, \chi_\nu$) must be included. These new particles are singlets under $U(1)_{T_R^3}$ and charged like SM right-handed fermions, as in the universal see-saw mechanism [44–49].

In this phenomenology study, we devise a LHC search strategy for the light GeV-scale scalar boson ϕ' produced in association with a heavy TeV-scale χ_u , the partner particle of the top quark, through a previously unexplored production and final state channel. Particularly, we explore the production of $pp \rightarrow t\chi_u\phi'$, in contrast to $pp \rightarrow TT \rightarrow t\phi't\phi'$ with hadronic [50–52] di-photon ϕ' [53, 54] decays. Due to the non-trivial $\chi - t - \phi'$ coupling, processes where the final state includes $t\chi_u\phi'$ are allowed in pp colliders through the $\chi_u - t$

fusion, see Fig. 1. Since the χ_u couples to SM quarks and gluons, it can be produced in large quantities. Furthermore, its energetic decay products can be detected alongside the ϕ' mediator particle that has significant transverse momentum. Therefore, if the ϕ' decays into SM particles that are observable in the detector's central region, this strategy can be very effective at reducing the SM background, and thus improve the long-term LHC discovery reach for heavy top partners and GeV-scale mediators, which are typically hard to detect using conventional methods at hadron colliders. Moreover, since it is possible to have $\chi_u \rightarrow t\phi'$ decays (and $\bar{\chi}_u \rightarrow \bar{t}\phi'$), the same $pp \rightarrow t\chi_u\phi'$ state may arise from $\chi_u\bar{\chi}_u$ production diagrams with quantum chromodynamic (QCD) vertices, where one χ_u decays to $t\phi'$, as shown in Fig. 2. As a consequence, the energetic products from $\chi_u\bar{\chi}_u$ decays can be readily detected, particularly when they occur alongside a mediator particle that carries substantial transverse momentum, providing greater sensitivity than that of searches where either χ_u or ϕ' are considered in isolation.

We probe the scenario where the scalar ϕ' has family non-universal fermion couplings, as was suggested in [39], and thus can address several issues with the SM. We focus on the ϕ' decay to a pair of muons since, at the experimental level, muons generally have high reconstruction and identification efficiencies, which allow for the development of relatively low $p_T(\mu)$ triggers, and provide clean signatures to remove the copious QCD multijet SM background. A key component of this study is the development of an analysis strategy utilizing a machine learning (ML) algorithm based on Boosted Decision Trees (BDT) [55]. The event classifier's output is employed to conduct a profile-binned likelihood test, which is used to determine the overall signal significance for each model examined in the analysis. The effectiveness of BDTs and other ML algorithms has been validated in numerous experimental and phenomenological studies [36, 56–65]. Our findings indicate that the BDT algorithm significantly enhances signal significance.

The rest of this paper is structured as follows. Section 3 discusses details of the minimal $U(1)_{T_R^3}$ model. Section 2 provides an overview of current relevant results at the LHC. Section 4 explains how the Monte Carlo (MC) simulation samples are produced for this study. In Sect. 5 we discuss the motivation and details of our machine learning workflow, and in Sect. 6, the main results are presented. We conclude with a short discussion in Sect. 7.

2 Experimental considerations

The ATLAS and CMS collaborations at CERN have conducted various searches for heavy vector-like quarks (T). These searches utilized pp collisions at center-of-mass energies of $\sqrt{s} = 8$ and 13 TeV. The studies primarily focused

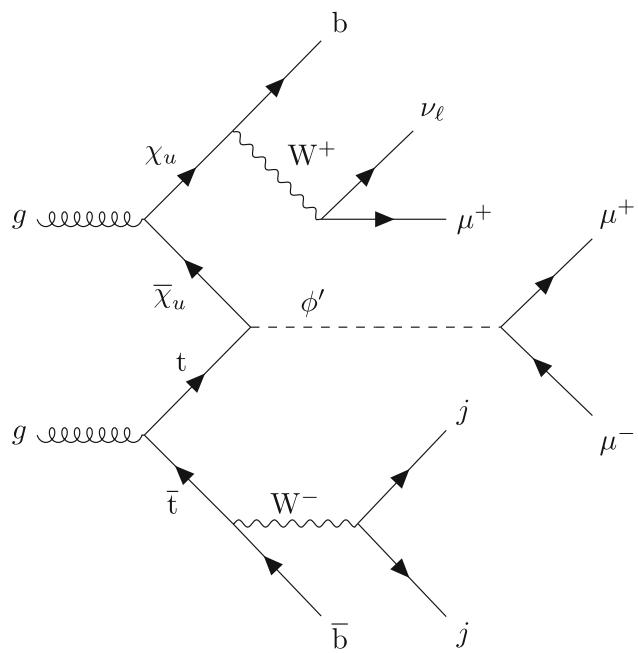


Fig. 1 Representative Feynman diagram for the production of a ϕ' boson in association with a χ_u vector-like quark through the fusion of a top quark and χ_u vector-like quark. Once again, the ϕ' decays to a pair of muons, the top quark decays fully hadronically, and the χ_u decays semi-leptonically to muons, neutrinos and b -jets

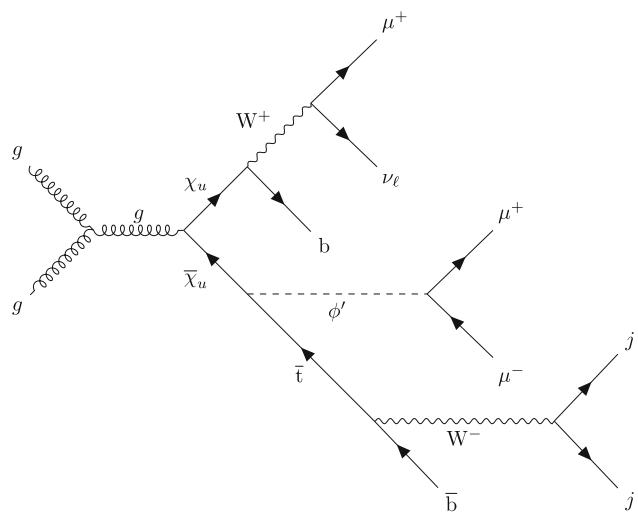


Fig. 2 Representative Feynman diagram for the production of a ϕ' boson in association with a χ_u vector-like quark through the fusion of a gluon pair from incoming protons. The ϕ' decays to a pair of muons, the top quark that decays fully hadronically, and the χ_u decay semi-leptonically to muons, neutrinos and jets

on T production through gluon-mediated QCD processes, either in pair production from quark-antiquark annihilation (Fig. 3) or in single-T production from electroweak processes involving associated quarks (Fig. 4).

In those studies, T decays into bW , tZ , or tH have been considered. In the context of T pair production, $T\bar{T}$, via

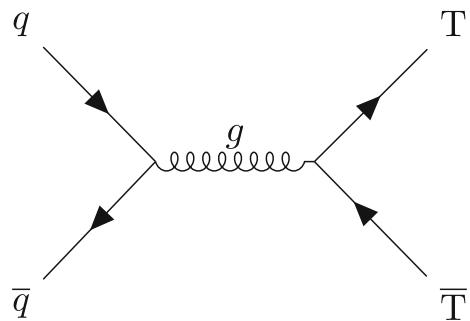


Fig. 3 Representative Feynman diagram for T pair production via gluon-mediated QCD processes

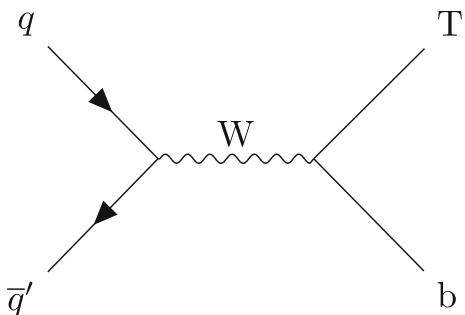


Fig. 4 Representative Feynman diagram for single T production via electroweak processes

QCD processes, the cross sections are well-known and solely depend on the mass of the vector-like quark. Assuming a narrow T decay width ($\Gamma/m(T) < 0.05$ or 0.1) and a 100% branching fraction to bW , tZ , or tH , these searches have set stringent bounds on $m(T)$, excluding masses below almost 1.5 TeV at 95% confidence level [66–73]. The most recent analysis from the CMS collaboration probes T-quark production via $pp \rightarrow Tqb$, in final states with $T \rightarrow tZ$ or $T \rightarrow tH$, considering scenarios with preferential couplings to third-generation fermions. The analysis sets 95% confidence level upper limits of 68–1260 fb on the production cross section, for T masses ranging from 600–1200 GeV [67]. The latest studies from ATLAS probe vector-like quarks using the single-T production mode with the $T \rightarrow tH$ decay channel leading to a fully hadronic final state [68], the single-T production mode with the $T \rightarrow tZ$ decay channel leading to a multileptonic final state [69], the TT pair production mode with various T decay channels leading to multileptonic final states [70], and the TT pair production mode with various T decay channels leading to a single lepton plus missing momentum final state [71, 72]. The multilepton search offers the greatest sensitivity in most of the phase space, but the missing transverse energy based search has better sensitivity for low branching fraction $\mathcal{B}(T \rightarrow Wb)$ and high $\mathcal{B}(T \rightarrow Ht)$. These searches have similar sensitivities for the singlet and doublet models, resulting in exclusion bounds for masses below about 1.25 TeV and 1.41 TeV, respectively.

A key consideration in the model interpretations summarized above is that the T branching fractions depend on the chosen model. The excluded mass range is less restrictive for specific branching fraction scenarios, such as $\{\mathcal{B}(T \rightarrow tZ), \mathcal{B}(T \rightarrow bW), \mathcal{B}(T \rightarrow tH)\} = \{0.2, 0.6, 0.2\}$, excluding masses below about 0.95 TeV. Moreover, if the $T \rightarrow \phi't$ decay is allowed, or if the branching fractions $\mathcal{B}(T \rightarrow tH/bW)$ are lower, the limits previously quoted must be re-evaluated. The authors of Ref. [74] emphasize that bounds on $m(T)$ can be around 500 GeV when $T \rightarrow t\phi'$ decays are permitted. Therefore, to facilitate a comprehensive study, benchmark scenarios in this paper are considered down to $m(\chi_u) = 500$ GeV.

3 The minimal $U(1)_{T_R^3}$ model

3.1 Scalar potential

In this model, the SM is extended by the Abelian gauge symmetry $U(1)_{T_R^3}$, where only right-handed fermions are charged. We assume two independent Higgs mechanisms, one with a Higgs doublet H for electroweak symmetry breaking and the other with a Higgs singlet ϕ for the $U(1)_{T_R^3}$ symmetry breaking. Both scalars have independent vacuum expectation values (VEVs), $\langle H \rangle = v_h/\sqrt{2}$ and $\langle \phi \rangle = v_\phi/\sqrt{2}$, allowing us to express the doublet and singlet Higgs fields, following a Kibble parametrization, as

$$H = \begin{pmatrix} G_+ \\ \frac{1}{\sqrt{2}}(v_h + \rho_0 + iG_0) \end{pmatrix} \quad (1)$$

$$\phi = \frac{1}{\sqrt{2}}(v_\phi + \rho_\phi + iG_\phi). \quad (2)$$

In Eqs. (1) and (2), G_\pm , G_0 , and G_ϕ are the Goldstone bosons that allow the SM W^\pm and Z bosons and the dark photon A' , associated with the $U(1)_{T_R^3}$ symmetry, to acquire mass. The ρ_h and ρ_ϕ are an orthogonal mixture of the SM Higgs boson and the dark Higgs

$$\begin{pmatrix} h \\ \phi' \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \rho_0 \\ \rho_\phi \end{pmatrix}, \quad (3)$$

that results from the diagonalization of the mass matrices arising from the gauge invariant potential

$$\begin{aligned} \mathcal{V}(\phi, H) = & \mu_H^2 H^\dagger H + \mu_\phi^2 \phi^* \phi \\ & + \lambda (H^\dagger H)(\phi^* \phi) + \lambda_H (H^\dagger H)^2 + \lambda_\phi (\phi^* \phi)^2. \end{aligned} \quad (4)$$

The tadpole equations are given from the minimization of the potential as

$$\frac{\partial \mathcal{V}}{\partial H} = \frac{v_h}{\sqrt{2}} \left(\mu_H^2 + \lambda_H v_h^2 + \frac{1}{2} \lambda v_\phi^2 \right) = 0, \quad (5)$$

$$\frac{\partial \mathcal{V}}{\partial \phi} = \frac{v_\phi}{\sqrt{2}} \left(\mu_\phi^2 + \lambda_\phi v_\phi^2 + \frac{1}{2} \lambda v_h^2 \right) = 0. \quad (6)$$

The masses of the scalar bosons can be written as

$$\begin{aligned} m_{h,\phi'}^2 = & \frac{1}{2} \left(\lambda_H v_h^2 + \lambda_\phi v_\phi^2 \right) \\ & \pm \sqrt{\lambda^2 v_h^2 v_\phi^2 + \left(\lambda_H v_h^2 - \lambda_\phi v_\phi^2 \right)^2}, \end{aligned} \quad (7)$$

and the mixing angle α as

$$\tan \alpha = \frac{-\lambda v_h v_\phi}{\lambda_H v_h^2 - \lambda_\phi v_\phi^2 - \sqrt{\lambda^2 v_h^2 v_\phi^2 + \left(\lambda_H v_h^2 - \lambda_\phi v_\phi^2 \right)^2}}. \quad (8)$$

3.2 The universal seesaw mechanism

In the model, each electrically charged SM fermion f has a mass protected by both VEVs. In turn, they acquire mass from the mixture with a vector-like fermion χ_f , which is charged as the right-handed component of the respective SM fermion, in a UV complete theory. The terms in the Lagrangian density that contribute to the mass of physical fermions are,

$$\begin{aligned} -\mathcal{L} \supset & Y_{f_L} \bar{f}'_L \chi'_{fR} H + Y_{f_R} \bar{\chi}'_{fL} f'_R \phi^* + m_{\chi'_f} \bar{\chi}'_{fL} \chi'_{fR} \\ & + \text{h.c.} \end{aligned} \quad (9)$$

Therefore, in the vacuum, the mass matrix is

$$M_f = \begin{pmatrix} 0 & Y_{f_L} v_h / \sqrt{2} \\ Y_{f_R} v_\phi / \sqrt{2} & m_{\chi'_f} \end{pmatrix}. \quad (10)$$

The left- and right-handed components of the physical fermions (f , χ_f) are given by two rotations $\mathcal{R}(\theta_{f_{L,R}})$ as,

$$\begin{pmatrix} f_{L,R} \\ \chi_{f_{L,R}} \end{pmatrix} = \begin{pmatrix} \pm \cos \theta_{f_{L,R}} & \mp \sin \theta_{f_{L,R}} \\ \sin \theta_{f_{L,R}} & \cos \theta_{f_{L,R}} \end{pmatrix} \begin{pmatrix} f'_{L,R} \\ \chi'_{f_{L,R}} \end{pmatrix}, \quad (11)$$

in a way that $\mathcal{R}(\theta_{f_L}) M_f \mathcal{R}^{-1}(\theta_{f_R}) = \text{diag}(m_f, m_{\chi_f})$ up to a phase. Assuming real parameters, the physical masses and the mixing angles are given by

$$m_f m_{\chi_f} = \frac{(Y_{f_L} v_h)(Y_{f_R} v_\phi)}{2}, \quad (12)$$

$$m_f^2 + m_{\chi_f}^2 = m_{\chi'_f}^2 + \frac{1}{2} \left(Y_{f_L}^2 v_h^2 + Y_{f_R}^2 v_\phi^2 \right), \quad (13)$$

$$\tan \theta_{f_{L,R}} = \frac{\sqrt{2}}{m_{\chi'_f}} \left(\frac{Y_{f_{L,R}} v_{h,\phi}}{2} - \frac{m_f^2}{Y_{f_{L,R}} v_{h,\phi}} \right). \quad (14)$$

The Yukawa interactions of the physical fermions with the scalar bosons have the form

$$-\mathcal{L}_{\text{yuk}} = h \bar{\psi}_{f_L} \mathcal{Y}_h \psi_{f_R} + \phi' \bar{\psi}_{f_L} \mathcal{Y}_\phi \psi_{f_R}, \quad (15)$$

with $\psi_f = (f, \chi_f)^T$, and the matrices $\mathcal{Y}_{f_{L,R}}$ given by

$$\mathcal{Y}_h = \frac{1}{\sqrt{2}} \mathcal{R}(\theta_{f_L}) (Y_{f_L} \sigma_+ \cos \alpha - Y_{f_R} \sigma_- \sin \alpha) \mathcal{R}^{-1}(\theta_{f_R}) \quad (16)$$

$$\mathcal{Y}_\phi = \frac{1}{\sqrt{2}} \mathcal{R}(\theta_{f_L}) (Y_{f_L} \sigma_+ \sin \alpha + Y_{f_R} \sigma_- \cos \alpha) \mathcal{R}^{-1}(\theta_{f_R}), \quad (17)$$

where $\sigma_\pm = (\sigma_1 \pm i\sigma_2)/2$ are the ladder Pauli matrices.

3.3 Minimal UV-complete theory

The model must provide non-zero masses for all the SM fermions and be free of gauge anomalies. So, we must have at least one full generation of vector-like fermions $\{\chi_u, \chi_d, \chi_\ell, \chi_v\}$ and the right-handed component of the SM neutrinos, ν_R , charged as shown in Table 1. Therefore, the Yukawa interactions in the UV-complete theory must be of the form

$$\begin{aligned} -\mathcal{L} \supset & Y_{Lu}^i \bar{q}_L^i \chi'_{uR} \tilde{H} + Y_{Ru}^i \bar{\chi}'_{uL} u_R^i \phi^* + m_{\chi_u} \bar{\chi}'_{uL} \chi'_{uR} \\ & + Y_{Ld}^i \bar{q}_L^i \chi'_{dR} H + Y_{Rd}^i \bar{\chi}'_{dL} d_R^i \phi + m_{\chi_d} \bar{\chi}'_{dL} \chi'_{dR} \\ & + Y_{L\ell}^i \bar{\ell}_L^i \chi'_{\ell R} H + Y_{R\ell}^i \bar{\chi}'_{\ell L} \ell_R^i \phi + m_{\chi_\ell} \bar{\chi}'_{\ell L} \chi'_{\ell R} \\ & + Y_{Lv}^i \bar{\ell}_L^i \chi'_{vR} \tilde{H} + Y_{Rv}^i \bar{\chi}'_{vL} \nu_R^i \phi^* + m_{\chi_v} \bar{\chi}'_{vL} \chi'_{vR} \\ & + \text{h.c.}, \end{aligned} \quad (18)$$

where the i index runs over the three generations of fermions. The simultaneous diagonalization of the mass matrices of each fermion sector will have a similar structure to the one presented in Eqs. (12) and (13) and the Yukawa matrices will have a similar structure of Eqs. (16) and (17) but codifying the CKM matrix. For the neutrino sector, the structure of the mass matrix will be more complex due to the presence of the additional Majorana mass term for the vector-like neutrino χ'_v .

Table 1 Minimal field content of the model and their representations under the SM and $U(1)_{T_R^3}$ gauge groups

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{T_R^3}$
q'_L	3	2	1/6	0
ℓ'_L	1	2	-1/2	0
H	1	2	1/2	0
u'^c_R	3	1	-2/3	-2
d'^c_R	3	1	1/3	2
ℓ'^c_R	1	1	1	2
ν'^c_R	1	1	0	-2
ϕ	1	1	0	2
χ'_{uL}	3	1	2/3	0
χ'^c_{uR}	3	1	-2/3	0
χ'_{dL}	3	1	-1/3	0
χ'^c_{dR}	3	1	1/3	0
$\chi'_{\ell L}$	1	1	-1	0
$\chi'^c_{\ell R}$	1	1	1	0
χ'_{vL}	1	1	0	0
χ'^c_{vR}	1	1	0	0

The numbers in bold indicate the dimensional representation under $SU(2)_L$ and $SU(3)_C$ in which the field transforms

4 Samples and simulation

The minimal $U(1)_{T_R^3}$ model described in Sect. 3 is implemented into the `FeynRules` package [75], which generates the Feynman rules and exports them into a Universal `FeynRules Output` (`UFO`) [76]. The resulting `UFO` is utilized as input for a generator to produce the MC samples. Both signal and background events are generated with the `MadGraph5_aMC@NLO` v3.2.0 program [77, 78] at leading order (LO) in QCD, considering pp beams colliding with a center-of-mass energy of $\sqrt{s} = 13.6$ TeV. Each signal and background sample is generated separately, with no interference effects between the signal and background considered. The impact of these interference effects has been evaluated, and for all values of χ_u and ϕ' masses considered, the effect on the signal plus background cross section is found to be less than $< 0.5\%$. Additionally, the effect on the shape of the b-jet p_T distribution is less than 6% for $p_T < 300$ GeV and less than 2% for b-jet $p_T > 300$ GeV. We use the `NNPDF3.0 NLO` [79] set for parton distribution functions (PDFs) for all event generation. Parton-level events are then interfaced with `PYTHIA` (v8.2.44) [80] to account for parton showering and hadronization processes. Finally, we use `DELPHES` (v3.4.2) [81] to simulate smearing and other detector effects using the CMS detector geometric configurations and parameters for particle identification and reconstruction, using the CMS input card with 140 average pileup interactions. All signal cross sections used

in this analysis are obtained requiring the following kinematic criteria on leptons (ℓ), b quarks, and light-quark/gluon jets (j) at parton level in MadGraph: $p_T(\ell) > 35$ GeV, $|\eta(b)| < 2.5$, $|\eta(\ell)| < 2.3$, $p_T(j) > 20$ GeV, and $|\eta(j)| < 5$. These parton-level selections were applied exclusively to the signal processes to restrict event generation to the relevant phase space regions. For background processes, these default parton level requirements in MadGraph were imposed: $p_T(\ell) > 10$ GeV, $|\eta(\ell)| < 2.5$, $p_T(j) > 20$ GeV, $|\eta(j)| < 5$, and $|\eta(b)| < 5$. This ensures that the phase space regions for the background near the analysis-level selection criteria are adequately described after parton showering since the pre-selections at the analysis level are more stringent than the parton-level requirements. Furthermore, we use the MLM algorithm for jet matching and jet merging. The parameters $x_{q\bar{q}cut}$ and $qcut$ of the MLM algorithm are set to 30 and 45 respectively to ensure continuity of the differential jet rate as a function of jet multiplicity. Each simulated signal and background sample is produced separately at LO, with one million events at the generation level, neglecting potential interference effects between the signal and background due to the suppression caused by the different orders of magnitude in the coupling constants of the signal and background.

Signal samples are generated considering the production of a ϕ' boson, an associated χ_u vector-like quark, and a top quark ($pp \rightarrow \chi_u t \phi'$), inclusive in both α and α_s (see Figs. 1 and 2). We have used the implementation of the $U(1)_{T_R^3}$ model in Ref. [43]. Signal samples were created considering coupling values of $Y_{t_R} = Y_L = 2\sqrt{2}$ in the range of masses $m(\phi') \in \{5, 10, 50, 100, 325\}$ GeV for the dark higgs and $m(\chi_u) \in \{0.50, 0.75, 1.0, 1.5, 2.0, 2.5\}$ TeV for the vector-like quark χ_u [82]. The production cross section for $pp \rightarrow \chi_u t \phi'$ is highly dependent on the choice of the Yukawa couplings in the Lagrangian. The χ_u-t fusion process shown in Fig. 1 is dominated by the Y_{t_R} coupling. However, the decay $\chi_u \rightarrow t \phi'$ shown in Fig. 2 is inversely proportional to the Y_{t_L} coupling. This effect is shown in Fig. 5, which displays the total signal cross section, as a function of Y_{t_R} and Y_{t_L} , for a benchmark point with $m(\phi') = 100$ GeV and $m(\chi_u) = 1.0$ TeV.

We target signal events where the top quark decays hadronically into a bottom quark and two jets ($t \rightarrow bW \rightarrow bqq\bar{q}'$), the χ_u decays semileptonically into a b quark, lepton, and neutrino (via $\chi_u \rightarrow bW$ and $W \rightarrow \mu\nu_\mu$), and the ϕ' produces two muons. We note that the scalar ϕ' particle could result from the mixture of the SM Higgs boson and additional scalar fields, and the Yukawas of the fermions could additionally arise from the mixing of the SM fermions with additional copies of the associated vector-like fermions. Therefore, the ϕ' branching ratios are dependent on the chosen mechanism and model by which this mixture occurs, see for example, Refs. [83–86]. For the purpose of this work, and similar to Refs. [39, 43], the considered bench-

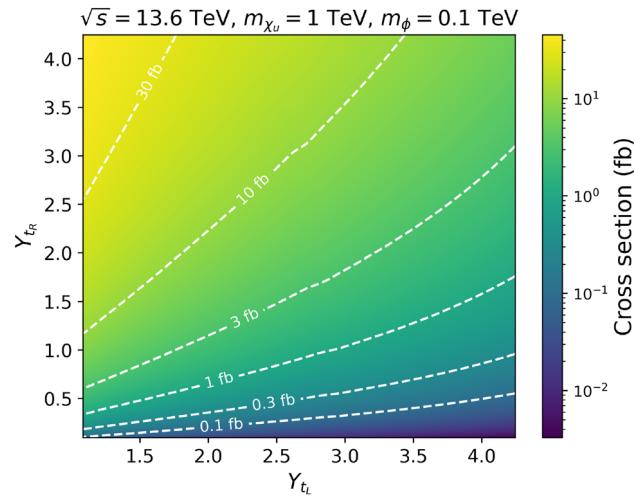


Fig. 5 Signal production cross section, $pp \rightarrow \chi_u t \phi'$, in the Y_{t_R} versus Y_{t_L} plane, for a benchmark point with $m(\phi') = 100$ GeV and $m(\chi_u) = 1.00$ TeV. The white-dashed contours show specific cross section values in the two dimensional plane

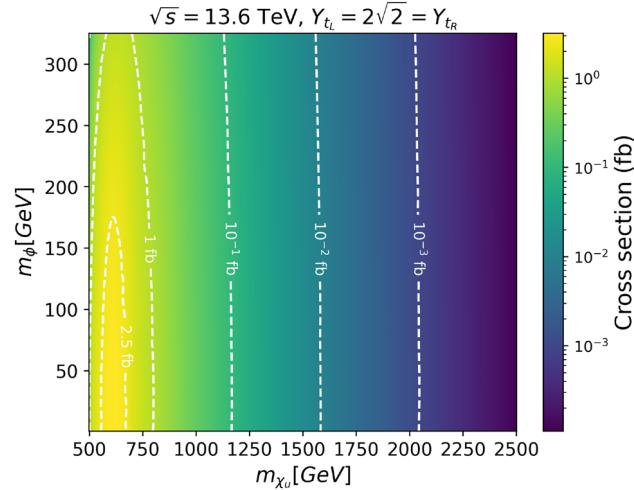


Fig. 6 Projected cross section (fb) plot for $pp \rightarrow t \chi_u \phi'$ and subsequent decay as a function of $m(\chi_u)$ and $m(\phi')$

mark signal scenarios have $\mathcal{B}(\chi_u \rightarrow b W)$ of about 0.5 and $\mathcal{B}(\phi' \rightarrow \mu^+ \mu^-) = 0.98$. Figure 6 shows the production cross section in fb, as a function of $m(\phi')$ and $m(\chi_u)$ masses, assuming the aforementioned decays, branching ratios, and couplings.

We note that for the parameter space of focus in this paper, the total mass of the $t-\chi_u$ system is larger than $m(\phi')$, thus the large rest energy of the $t-\chi_u$ system is converted into potentially large momentum values for the ϕ' . Similarly, the t -quark produced through the χ_u-t fusion interaction can also have large momentum values, and thus in some cases the hadronic t decay products cannot be fully reconstructed independently of each other. This results in three possible t reconstruction scenarios: a fully merged scenario where the

$W \rightarrow jj$ system and the b quarks are very collimated and reconstructed as a single “fat jet” (henceforth referred to as a FatJet, FJ); a partially merged scenario, where the decay products of the W boson form a single FatJet but the b quark can still be separately identified; and an un-merged scenario where all decay products can be independently identified. Jets are clustered using the anti- k_t algorithm [87] using the FastJet (v3.4.2) [88] package with a distance parameter of $R = 0.4$ for standard jets and $R = 0.8$ for fat jet objects. Each scenario has an associated identification efficiency and misidentification rate, which depends on the choice of the boosted t/W algorithm (our choice of efficiency and misidentification rates is described later).

Based on the above details, the final state of interest in this paper consists of three muons (two from the ϕ' decay and one from the χ_u decay), a (possibly boosted) top-tagged system, at least one b -tagged jet, and large missing transverse momentum (\vec{p}_T^{miss}). For the partially merged and un-merged scenarios, there will be two b quarks present in the final state (one of which is part of the top tagged system).

We consider background sources from SM processes which can give similar objects in the final state as those expected for signal. Several background sources were considered and studied, such as QCD multijet events, production of vector boson pairs (VV : WW, ZZ, WZ), vector boson triplets (VVV : WWZ, WZZ, ZZZ, WWW), top-quark pairs in association with weak bosons ($t\bar{t}X$), and $t\bar{t}\bar{t}\bar{t}$ processes. The dominant sources of SM background events are from the $t\bar{t}X$, ZZW, and $t\bar{t}\bar{t}\bar{t}$ processes. The $t\bar{t}X$ background is primarily associated production of a Z/γ^* from $t\bar{t}$ fusion processes. The ZZW process becomes a background when one Z decays $b\bar{b}$, another Z decays to a pair of muons, and the W decays to a muon and a neutrino. Events from ZZW and $t\bar{t}\bar{t}\bar{t}$ have been combined, after being weighted by their corresponding production cross section. The combination is presented as the “ $b\bar{b}\mu\mu\nu\nu$ ” background in the remainder of this paper. The $t\bar{t}X$ process is presented as part of the “ $t\bar{t}\mu^+\mu^-$ ” background. Table 2 shows the production cross sections for the dominant background sources. The rest of the aforementioned background processes do not contribute meaningfully in our context, accounting for $\ll 1\%$ of the total expected background yield.

The identification of leptons, boosted top quarks, and bottom quarks plays an important role in the ability to identify signal events, the ability to minimize the rate of SM backgrounds, and thus also the discovery reach in the high-luminosity environment of the LHC. It is worth noting that the reconstruction and identification of leptons and the decay products of the top/bottom quarks may be non-trivial at the High-Luminosity LHC (HL-LHC) due to the presence of a potentially large number of secondary pp interactions (pileup). The impact of pileup on the new physics discovery reach, and the importance of pileup mitigation at CMS

Table 2 A summary of dominant SM backgrounds produced by pp collisions and their cross sections in pb, as computed by MadGraph with $n = 10^6$ events

Background process	Cross-section σ [pb]
$pp \rightarrow t\bar{t} \mu^+ \mu^-$	2.574×10^{-3}
$pp \rightarrow b\bar{b} \mu\mu\nu\nu$	4.692×10^{-4}

and ATLAS has been outlined in many papers, for example in Ref. [89]. We note the expected performance of the upgraded ATLAS and CMS detectors for the HL-LHC is beyond the scope of this work; however, the studies presented here do attempt to provide reasonable expectations by conservatively assuming some degradation in lepton and hadron identification efficiencies, using Ref. [89] as a benchmark, and considering the case of 140 average pileup interactions.

For muons with $|\eta| < 1.5$, the assumed identification efficiency is 95% with a 0.3% misidentification rate [89, 90]. The performance degrades linearly with η for $1.5 < |\eta| < 2.5$, and we assume an identification efficiency of 65% with a 0.5% misidentification rate at $|\eta| = 2.5$. Similarly, the charged hadron tracking efficiency, which contributes to the jet clustering algorithm and missing transverse momentum (\vec{p}_T^{miss}) calculation, is 97% for $1.5 < |\eta| < 2.5$, and degrades to about 85% at $|\eta| = 2.5$. These potential inefficiencies due to the presence of secondary pp interactions contribute to how well the lepton and top kinematics can be reconstructed. Following Refs. [91, 92], we consider the “Loose” working point for the identification of the fully merged (partially merged) t decays, which results in 80–85% top (W) identification efficiency and 11–25% misidentification rate, depending on the FatJet transverse momentum (p_T^{FJ}). Following Ref. [93], we consider the “Loose” working point of the DeepCSV algorithm [94], which gives a 70–80% b-tagging efficiency and 10% light quark mis-identification rate. The choice of boosted t/W and b-tagging working points is determined through an optimization process that maximizes discovery reach. It is noted the contribution from SM backgrounds with a misidentified boosted t/W is negligible, and thus our discovery projections are not sensitive to uncertainties related to the boosted t/W misidentification rates (Fig. 7).

5 Data analysis using machine learning

The analysis of signal and background events is performed utilizing machine learning techniques. A machine learning-based approach offers sizeable advantages when compared to traditional event classification techniques. Unlike conventional methods, machine learning models have the capability to simultaneously consider all kinematic variables, allowing them to efficiently navigate the complex and

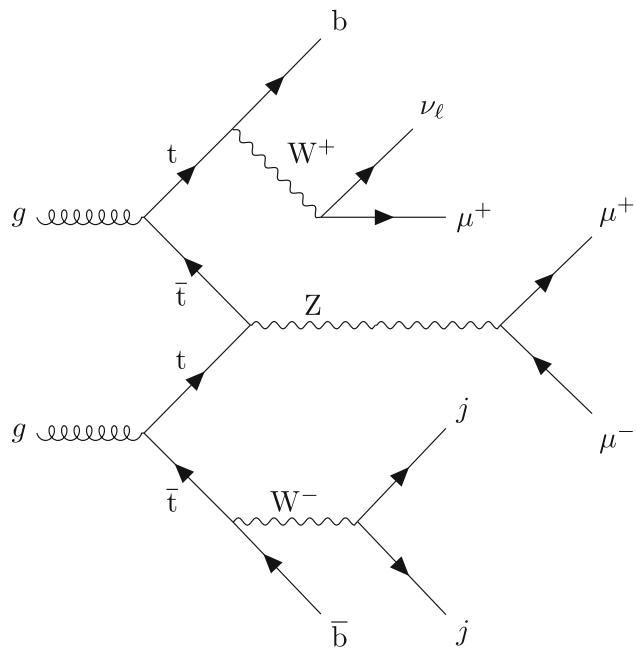


Fig. 7 Representative Feynman diagram for a background event. A Z boson is produced in association with a top quark through the fusion of a top, anti top pair from incoming protons. The Z boson subsequently decays to a pair of muons and the two spectator top quarks decay semi-leptonically and purely hadronically to muons, neutrinos and jets, resulting in the same final states as the signal event

high-dimensional space of event kinematics. Consequently, machine learning models can effectively enact sophisticated selection criteria that take into account the entirety of this high-dimensional space. This makes them ideal for high-energy physics applications.

The BDT method is a powerful machine learning technique that has proven its effectiveness in various applications, particularly in the field of collider physics. In this method, decision trees are trained greedily in a sequential manner, with each tree focusing on learning the discrepancies or residuals between its predictions and the expected values obtained from the previously trained tree. This iterative process aims to progressively minimize errors, making BDTs a particularly effective approach for enhancing model performance.

In the context of collider physics, BDTs have demonstrated their utility in addressing classification problems. In particular, BDTs can effectively discriminate between signal and background events, enabling accurate and efficient event classification. Their ability to handle subtle non-linear relationships within the data with high interpretability makes BDTs a valuable tool to handle large amounts of data with a large number of parameters for each event.

The first step in our workflow involves the use of a specialized *MadAnalysis Expert Mode C++* script [95]. This script extracts essential kinematic and topological information from the simulated samples. The script will process the aforementioned variables contained within these

files and transform them into a structured and informative CSV (Comma-Separated Values) format that can be used to train our machine learning models. These kinematic variables include crucial details about the events, such as particle momenta, energies, and topologies, providing the fundamental building blocks for our machine learning analysis. Figure 13 shows the features that are used for training the machine learning models and their importance for a benchmark point.

To account for the differential significance of various events, we apply cross-section weighting. This ensures that the relative importance of signal and background events is appropriately balanced in the dataset. This weighting is crucial for addressing the varying likelihood of observing different types of events in high-energy physics experiments. The prepared and weighted datasets are then passed to our *MadAnalysis Expert Mode C++* script, where the simulated signal and background events are initially filtered, before being passed to the CSV file for use by the machine learning algorithm. The filtering process requires at least one well-reconstructed and identified b -jet candidate, at least one jet (regular or FJ) not tagged as a b jet, and exactly three identified muons. The filtering selections are motivated by experimental constraints, such as the geometric constraints of the CMS/ATLAS detectors, the typical kinematic thresholds for the reconstruction of particle objects, and the available lepton triggers which also drive the minimal kinematic thresholds. Selected jets must have $p_T > 30 \text{ GeV}$ and $|\eta(j)| < 5.0$, while b -jet candidates with $p_T > 20 \text{ GeV}$ and $|\eta(b)| < 2.5$ are chosen. The μ object must pass a $p_T > 35 \text{ GeV}$ threshold and be within a $|\eta(\ell)| < 2.3$. We will refer to this filtering criteria as pre-selections. The efficiency of the pre-selections depends on $m(\phi')$ and $m(\chi_u)$, but is typically about 25–30% for the signal samples. Events passing this pre-selection are used as input for the machine learning algorithm, which classifies them as signal or background, using a probability factor.

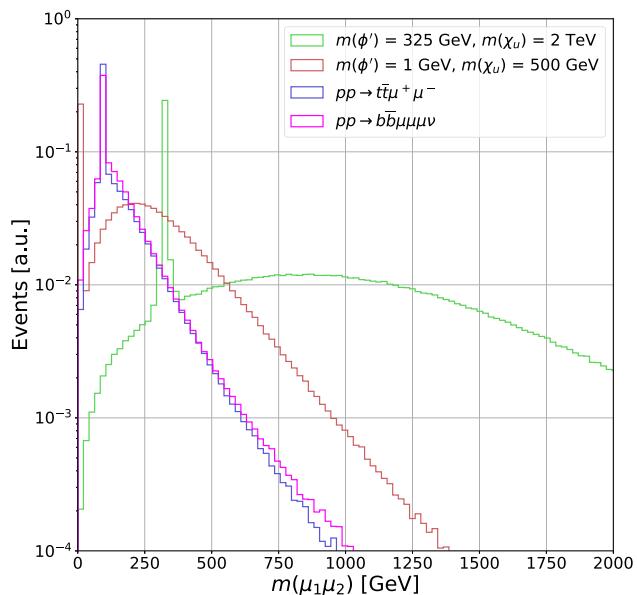
We explore the performance of a diverse set of machine learning models, specifically three neural networks of differing architectures and a BDT algorithm. To ensure robust model assessment, we employed a standard 90–10 train-test split of the dataset, partitioning it into a 90% portion for training and a 10% portion for testing. This division allows us to gauge the generalization capabilities of our models on unseen data.

The training and evaluation of the BDT were carried out in a high-performance computing environment. Specifically, an Nvidia A100 GPU was used. The canonical PyTorch [96] deep learning framework was employed for configuring, training, and evaluating the neural networks. PyTorch is well-regarded for its flexibility and performance in deep learning applications.

For the BDT algorithm, we used hyperparameters $\eta = 0.3$, $\gamma = 0$, and $\text{max_depth} = 6$. The XGBoost [97]

Table 3 Train/test results for the ML models

Model	Train/test acc.	Training time
BDT	N.A./0.9993	6s
Neural network 1	0.9999/0.9997	1 h 58 min
Neural network 2	0.9999/0.9998	2 h 12 min
Neural network 3	0.9999/0.9998	2 h 32 min

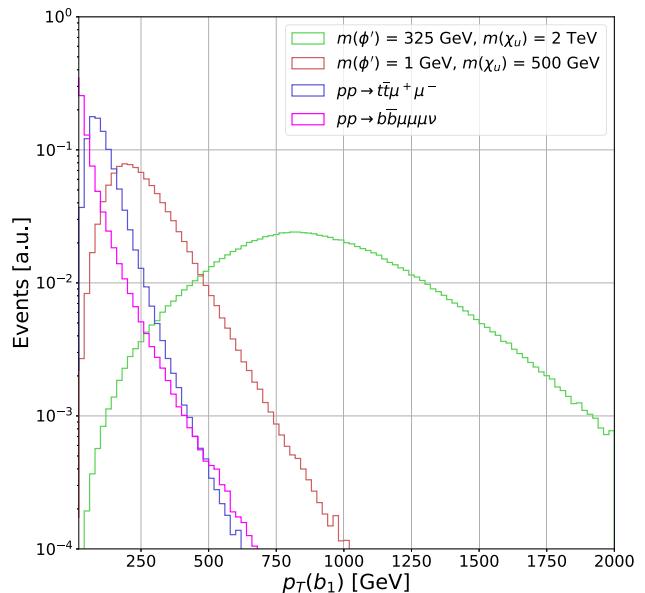
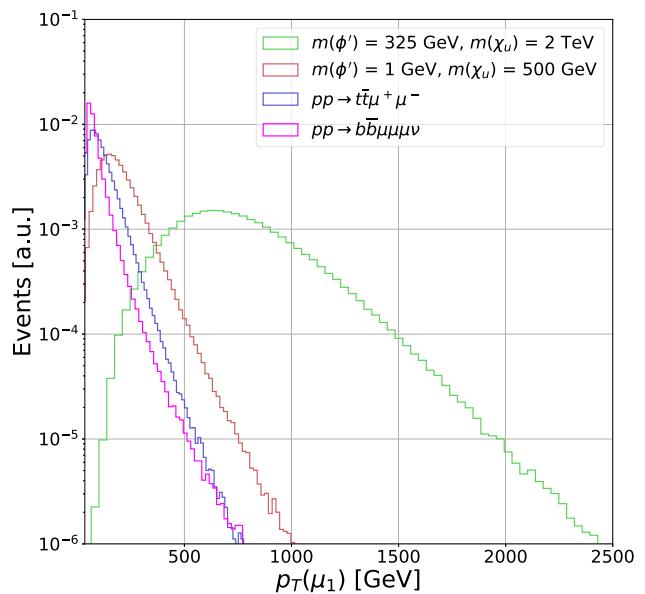
**Fig. 8** Invariant mass distribution of the muon pair with the highest and second highest transverse momentum. The distributions are shown for the two main SM background processes and two signal benchmark points

library was used for the implementation of the Boosted Decision Tree algorithm. It offers high efficiency, optimization, and interpretability, making it a suitable choice for this particular task (Table 3).

It is worth mentioning that we experimented with deep neural networks of various architectures. Although we found that they yield similar signal sensitivity to the BDT, the complex nature of the studies in this work (particle objects considered, experimental constraints in a high luminosity LHC, etc.) motivates the use of a BDT over a deep neural network because of its usefulness, efficiency, and simplicity in understanding the machine learning output in addition to significantly shorter training times. Therefore, we perform our proceeding analysis using the BDT. The outcomes of our model training and evaluation are presented in Table 3.

6 Results

Figures 8, 9, and 10 show relevant kinematic distributions for two benchmark signal points and the dominant SM back-

**Fig. 9** Transverse momentum distribution of the leading b-quark jet candidate. The distributions are shown for the two main SM background processes and two signal benchmark points**Fig. 10** Transverse momentum distribution of the leading muon candidate. The distributions are shown for the two main SM background processes and two signal benchmark points

grounds, using the subset of events passing the pre-selections defined above. The signal benchmark points in these figures are $m(\phi') = 325 \text{ GeV}, m(\chi_u) = 2 \text{ TeV}$, and $m(\phi') = 1 \text{ GeV}, m(\chi_u) = 500 \text{ GeV}$. The distributions are normalized such that the area under the curve is unity. These distributions correspond to the reconstructed mass, $m(\mu_1, \mu_2)$, between the two muon candidates with the highest transverse momentum (μ_1 and μ_2), the transverse momentum of the b-jet can-

dicate with the highest transverse momentum p_T (b_1), and the muon candidate with the highest transverse momentum p_T (μ_1), respectively. These distributions are among the variables identified by the BDT algorithm with the highest signal to background discrimination power (see Fig. 13).

As can be seen from Fig. 8, the ϕ' mass can be reconstructed through its associated muon decay pair, which is observed as a peak in the $m(\mu_1, \mu_2)$ distribution around the expected $m(\phi')$ value, and has low- and high-mass tails which are a consequence of cases where the leading and/or sub-leading muon is not from the ϕ' decay, but rather from the associated W boson from the χ_u decay. For the backgrounds, muons come from Z (W) decays. Therefore, the $m(\mu_1, \mu_2)$ background distributions show a peak near $m_{W/Z}$, combined with a broad distribution indicative of the combination of two muon candidates from different decay vertices. We note that the $\phi' \rightarrow \mu^+ \mu^-$ decay width depends on the square of the $\phi' \rightarrow \mu^+ \mu^-$ coupling and $\frac{m_\mu^2}{m(\phi')^2}$ and is thus suppressed by the relatively small muon mass. For the new physics phase space considered in this paper, the ϕ' decay width is less than 1% of the ϕ' resonant mass. Furthermore, as indicated previously, the signal/background interference effects are small and negligible compared to effects from experimental resolution. Therefore, the width of the $m(\mu_1, \mu_2)$ signal distributions is driven by the experimental resolution in the reconstruction of the muon momenta, as well as the probability that the two leading muons are the correct pair from the ϕ' decay. Since the probability that the two highest- p_T muons are the correct pair from the $\phi' \rightarrow \mu^+ \mu^-$ decay depends on $m(\phi')$ and $m(\chi_u)$, it is important to include all possible combinations of dimuon pairs (i.e., $m(\mu_1, \mu_3)$ and $m(\mu_2, \mu_3)$) in the training of the BDT.

Figure 9 shows the distribution for the b-jet candidate with the highest p_T , $p_T(b_1)$, for the same simulated samples shown in Fig. 8. Based on the signal topology and our choice of parameter space (i.e., $m(\chi_u) > m_t$), it is expected that the leading b-jet candidate comes from the χ_u decay, with an average p_T close to $\frac{m(\chi_u) - m_W}{2}$, as observed in Fig. 9. For the $t\bar{t}\mu^+ \mu^-$ background, the b-jet candidates come from top-quark decays. Therefore, their average transverse momentum is expected to be $\frac{m_t - m_W}{2} \approx 45$ GeV, as observed in Fig. 9. On the other hand, the b-jet candidates for the $bb\bar{\mu}\mu\mu\nu$ background can come from off-mass-shell Z^*/γ^* , and thus typically have an even softer spectrum in comparison to the $t\bar{t}\mu^+ \mu^-$ background.

Figure 10 shows the distribution for the muon candidate with the highest p_T , $p_T(\mu_1)$. Similar to Fig. 9, when $m(\chi_u) > m_t$ it is expected that the leading muon candidate comes from the χ_u decay, with an average p_T of approximately $\frac{m(\chi_u) - m_W}{4}$, as observed in Fig. 10. For the major SM backgrounds, the muon candidates come from Z/W/ γ^* decays. Therefore, their average transverse momentum is expected to be much lower,

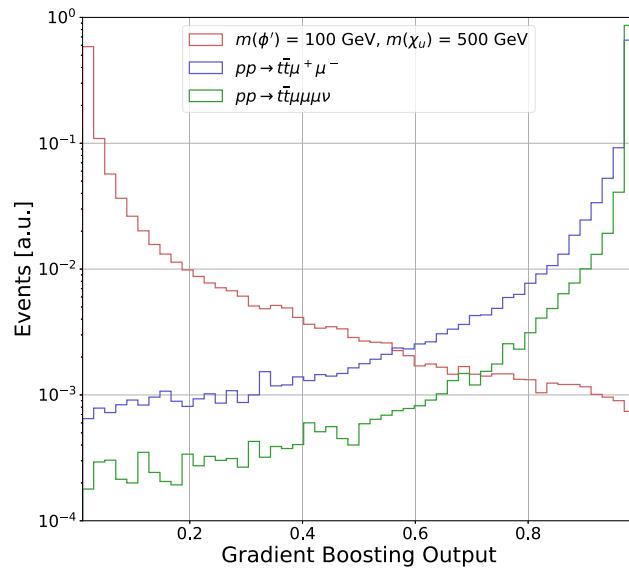


Fig. 11 Output of the gradient boosting algorithm for a benchmark $m(\phi') = 100$ GeV and $m(\chi_u) = 500$ GeV signal, and dominant backgrounds. The distributions are normalized to unity

$\frac{m_{Z/W}}{4} \approx 40 - 45$ GeV. This kinematic feature provides a nice handle to discriminate high $m(\chi_u)$ signal events amongst the large SM backgrounds, which have lower average $p_T(\mu)$ constrained by the SM weak boson masses.

In addition to these aforementioned variables in Figs. 8, 9 and 10, several other kinematic variables were included as inputs to the BDT algorithm. In particular, 27 such variables were used in total, and these included the momenta of b and muon candidates; invariant masses of pairs of muons; angular differences between b jets and between the muons.

As mentioned above, the variables $m(\mu_i, \mu_j)$ for $i, j \neq 1$ provide some additional discrimination between signal and background when the leading muons are not a ϕ' decay candidate. The angular separation variables, such as $\Delta R(\mu_i, \mu_j)$, are designed to be sensitive to lower mass ϕ' , since the low rest mass of those particles means they acquire more boost, and thus smaller angular separation ΔR between the muon candidates. The trained BDT returns the discriminating power of each of its inputs, and the feature importance for each variable is shown in Fig. 13 for a signal benchmark point with $m(\phi') = 325$ GeV and $m(\chi_u) = 2000$ GeV.

Figure 11 shows the distributions for the output of the BDT algorithm, normalized to unity, for the representative signal benchmark point of $m(\phi') = 1$ GeV, $m(\chi_u) = 0.5$ TeV and the two dominant backgrounds. The output of the BDT algorithm is a value between 0 and 1, which quantifies the likelihood that an event is either background-like (BDT output near 1) or signal-like (BDT output near 0). Figure 12 illustrates the true positive rate (TPR), defined as the probability of correctly selecting signal events using the BDT output, plotted against the false positive rate (FPR), defined as the

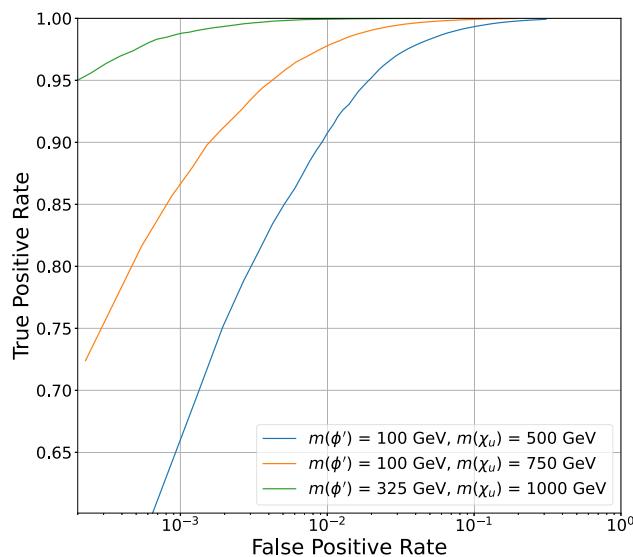


Fig. 12 Receiver operating characteristic curve of the BDT algorithm for three different signal benchmark scenarios

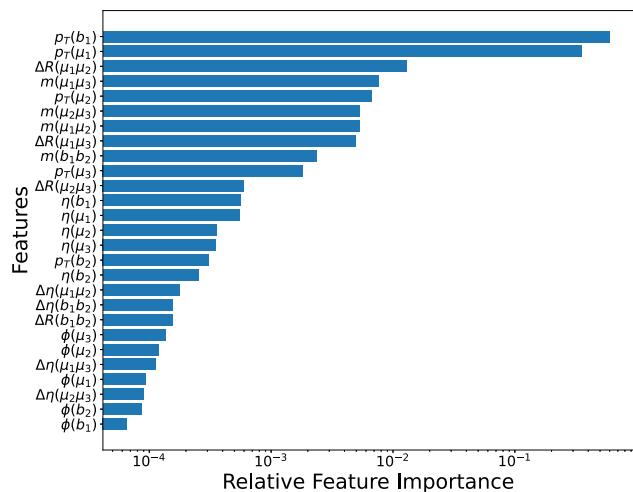


Fig. 13 Relative importance of features in training for a benchmark signal scenario with $m(\phi') = 325 \text{ GeV}$ and $m(\chi_u) = 2000 \text{ GeV}$

probability of incorrectly selecting background events. For example, for $m(\phi') = 100 \text{ GeV}$ and $m(\chi_u) = 500 \text{ GeV}$, when signal events are selected at 65% probability, the background is selected at about 10^{-3} probability. We note that the primary discriminating feature between the signal and background is the boosted b-jet p_T coming from the χ_u vector-like quark. The p_T of said b jet increases with $m(\chi_u)$, peaking at around $[m(\chi_u) - m(W)]/2$. This enhanced boost increases the separation between signal and background, improving the performance of the BDT algorithm as $m(\chi_u)$ increases (Fig. 13).

The outputs from the BDT machine learning algorithm are used to perform a profile-bin likelihood analysis to estimate the signal significance for a luminosity of 3000 fb^{-1} ,

corresponding to the expected amount of collected data by the end of the LHC era. For this purpose, the BDT distributions are normalized to cross section times pre-selection efficiency times luminosity for the different signal models. The significance is then calculated using the expected bin-by-bin yields of the BDT output distribution in a profile likelihood fit, using the ROOTFit [98] package developed by CERN. The expected signal significance Z_{sig} is calculated using the probability of obtaining the same test statistic for the signal plus background and the signal-null hypotheses, defined as the local p -value. Similar to Refs. [99–105], the significance corresponds to the point where the integral of a Gaussian distribution between Z_{sig} and ∞ results in a value equal to the local p -value. The estimation of Z_{sig} incorporates systematic uncertainties. The uncertainty values have been included as nuisance parameters, considering lognormal priors for normalization and Gaussian priors for uncertainties associated with the modeling of the shapes similar to Refs. [106, 107].

The systematic uncertainties that have been included result from experimental and theoretical constraints. A 1–5% systematic uncertainty, depending on the simulated MC sample, has been included to account for the choice of Parton Distribution Function (PDF) set. The systematic uncertainty effect was incorporated following the PDF4LHC [98] recommendations. This systematic uncertainty has a small impact on the expected event yields for signal and background, but it does not affect the shape of the BDT output distribution. We additionally considered theoretical uncertainties related to the absence of higher-order contributions to the signal cross sections, which can change the pre-selection efficiencies and the shapes of kinematic variables used as inputs to the BDT algorithm. This uncertainty was calculated by varying the renormalization and factorization scales by $\times 2$, and studying the resulting change in the bin-by-bin yields of the BDT distributions. They are found to be at most 2% in a given bin.

Regarding experimental uncertainties, following experimental measurements from CMS on the estimation of the integrated luminosity, a conservative 3% effect has been included [108]. A 5% systematic uncertainty associated with the reconstruction and identification of b-quark jets has been included, independent of p_T and η of the b-jet candidates. According to Ref. [93], this uncertainty is correlated between signal and background processes with genuine b-jets and is also correlated across BDT bins for each process. For muons, we include a 2% uncertainty associated with the reconstruction, identification, and isolation requirements, and a 3% systematic uncertainty to account for scale and resolution effects on the momentum and energy measurement. We consider jet energy scale uncertainties ranging from 2–5%, contingent on η and p_T , resulting in shape-based uncertainties on the BDT output distribution. Jet energy scale uncertainties were assumed to range from 1–5%, contingent on η and p_T . These assumptions lead to shape-based uncertainties on the

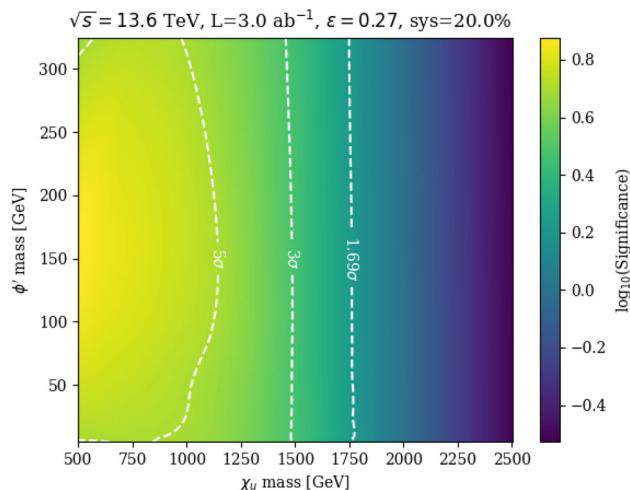


Fig. 14 Signal significance for the high luminosity LHC era, considering with 3000 fb^{-1} of collected data

BDT output distribution, varying from 1–2%. Additionally, we include a 10% systematic uncertainty to account for errors in the signal and background predictions. Considering all the various sources of systematic uncertainties, our conservative estimate yields a total effect of about 20%.

Figure 14 shows the expected signal significance considering an integrated luminosity of 3000 fb^{-1} . The significance is shown as a heat map in a two-dimensional plane for different ϕ' and χ_u masses. The x-axis corresponds to $m(\chi_u)$, the y-axis to $m(\phi')$, and the heat map to $\log_{10}(Z_{\text{sig}})$. The white dashed lines are contours of constant signal significances of 1.69σ , 3σ and 5σ to represent regions of possible exclusion, evidence of new physics, and discovery, respectively. Under these conditions, $\phi'(\chi_u)$ masses ranging from 1 to 325 GeV (500 to 1800 GeV) can be probed. The range for a discovery with 5σ signal significance varies from χ_u masses from $m(\chi_u) = 770$ – 1100 GeV, depending $m(\phi')$. For large $m(\chi_u)$, the significance is almost independent of $m(\phi')$ because the primary discriminating feature—the boosted b -quark originating from ϕ' —is driven predominantly by the large $m(\chi_u)$, with the kinematic impact of $m(\phi')$ being relatively negligible.

7 Discussion

The LHC will continue to run with pp collisions at $\sqrt{s} = 13.6$ TeV for the next decade. Given the increase in the integrated luminosity expected from the high-luminosity program, it is important to consider unexplored new physics phase space that diverges from the conventional assumptions made in many BSM theories, and which could have remained hidden in processes that have not yet been thoroughly examined. It is additionally crucial to explore advanced analysis techniques, in particular the use of artificial intelligence

algorithms, to enhance the probability of detecting these rare corners where production cross sections are lower and discrimination from SM backgrounds is difficult.

In this work, we examine a model based on a $U(1)_{T_R^3}$ extension of the SM, which can address various conceptual and experimental issues with the SM, including the mass hierarchy between generations of fermions, the thermal dark matter abundance, and the muon $g - 2$, $R_{(D)}$, and $R_{(D^*)}$ anomalies. This model contains a light scalar boson ϕ' , with potential masses below the electroweak scale, and TeV-scale vector-like quarks χ_u . We consider the scenario where the scalar ϕ' has family non-universal fermion couplings and $m(\phi') \geq 1$ GeV, as was suggested in Ref. [39], and thus the ϕ' can primarily decay to a pair of muons. Previous works in Refs. [43, 53] considered scenarios motivating a search methodology with a merged diphoton system from $\phi' \rightarrow \gamma\gamma$ decays. The authors of Ref [43], in which $m(\phi') < 1$ GeV, indeed pointed out that if the ϕ' is heavier than about 1 GeV, then decays to $\mu^+\mu^-$ can become the preferable mode for discovery, which is the basis for the work presented in this paper. We further note that the final state topology studied in this paper would represent the most important mode for discovery at $m(\phi') < 2m_t$ where the $\phi' \rightarrow t\bar{t}$ decay is kinematically forbidden.

The main result of this paper is that we have shown that the LHC can probe the visible decays of new bosons with masses below the electroweak scale, down to the GeV-scale, by considering the simultaneous production of heavy QCD-coupled particles, which then decay to the SM particles that contain large momentum values and can be observed in the central regions of the CMS and ATLAS detectors. The boosted system combined with innovative machine learning algorithms allows for the signal extraction above the lower-energy SM background. The LHC search strategy described here can be used to discover the prompt decay of new light particles. An important conclusion from this paper is that the detection prospects for low-mass particles are enhanced when it is kinematically possible to simultaneously access the heavy degrees of freedom which arise in the UV completion of the low-energy model. This specific scenario in which the couplings of the light scalars are generationally dependent, with important coupling values to the top quark, is an ideal example which would be difficult to directly probe at low energy beam experiments.

The proposed data analysis represents a competitive alternative to complement searches already being conducted at the LHC, allowing us to probe ϕ' masses from 1 to 325 GeV, for $m(\chi_u)$ values up to almost 2 TeV, at the HL-LHC. Therefore, we strongly encourage the ATLAS and CMS Collaborations to consider the proposed analysis strategy in future new physics searches.

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Code Availability Statement Code/software will be made available on reasonable request. [Authors' comment: The code/software generated during and/or analysed during the current study is available from the corresponding author on reasonable request.]

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