Machine Learning-Enhanced Feasibility Studies on the Production of New Particles with Preferential Couplings to Third Generation Fermions at the LHC

PhD(c). Cristian Fernando Rodríguez Cruz[1]
c.rodriguez45@uniandes.edu.co

Research advisors:

Prof. Andrés Florez[1] (ca.florez@uniandes.edu.co)

Prof. J. Jones-Pérez[2] (jones.j@pucp.edu.pe)

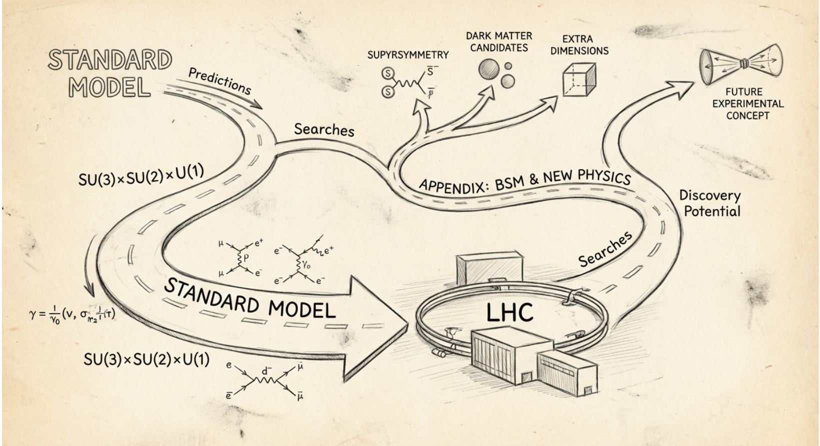
[1]Universidad de los Andes

[2]Pontificia Universidad Católica del Perú

January 21, 2026

Outline

Introduction



Standard Model of Particle Physics: A Successful Framework

Core Theoretical Structure

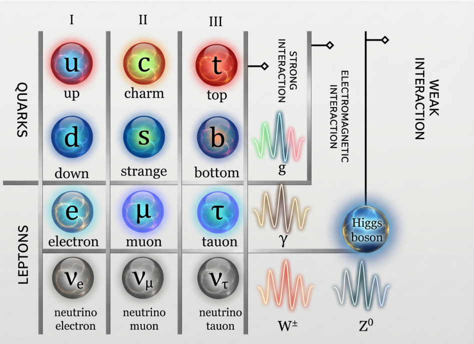
- **Fermion Sector:**
  - 3 generations
  - Left-handed doublets:

$$Q_L = \begin{pmatrix} q_u \\ q_d \end{pmatrix}_L \; ; \quad L_L = \begin{pmatrix} \ell \\ \nu_\ell \end{pmatrix}_L$$

  - Right-handed singlets: $q_{uR}, q_{dR}; \ell_R$
  - Flavor structure from CKM mixing
  - Initially, ν_R not required (no mass)

- **Gauge Group:**
  - $SU(3)_C \times SU(2)_L \times U(1)_Y$
  - Strong force: $SU(3)_C$ (QCD)
  - Electroweak: $SU(2)_L \times U(1)_Y$

- **Higgs Mechanism:**
  - $SU(2)_L \times U(1)_Y \to U(1)_{\text{EM}}$
  - Masses to $W^{\pm}, Z^0$ bosons
  - Massless γ
  - Fermion masses via Yukawa couplings
  - Higgs boson h discovered (LHC 2012)



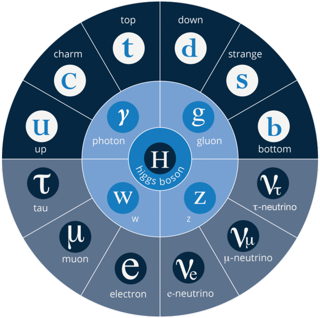
Key Features

- **Particle spectrum:** 12 fermions + 5 bosons
- **QFT:** Renormalizable, gauge invariant, anomaly-free
- **Tested experimentally:** Exceptional agreement with data
- **Predictive power:** Successfully tested at LHC

Deficiencies of the SM

The SM cannot be complete:

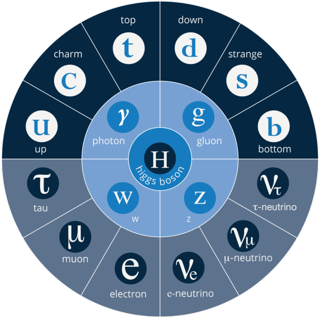
- Unexplained ν masses
- No explanation for DM
- Matter-antimatter asymmetry unsolved
- Gravity not included



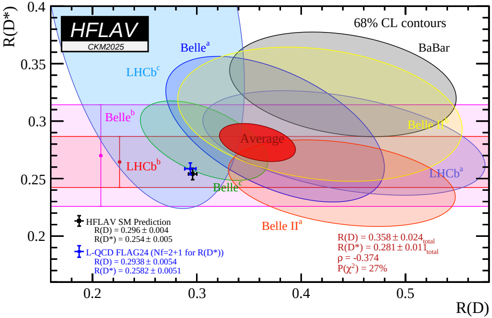
Deficiencies of the SM

The SM cannot be complete:

- Unexplained ν masses
- No explanation for DM
- Matter-antimatter asymmetry unsolved
- Gravity not included

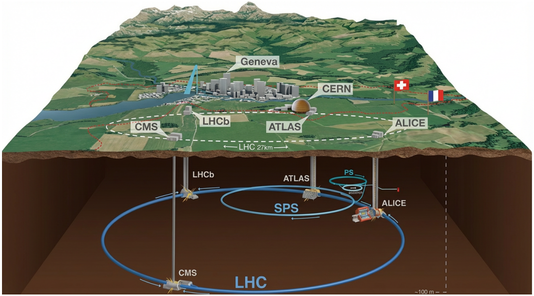


Experimental hints of New Physics:



Recent measurements of the $R(D)$ and $R(D^*)$ ratios show a $\sim 3\sigma$ deviation from SM predictions, suggesting possible lepton universality violation.

The Large Hadron Collider (LHC)



World's largest particle collider:

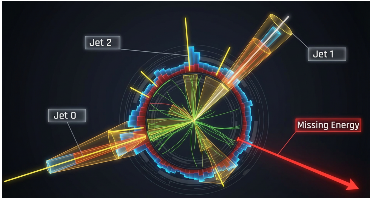
- Located at CERN, at the France-Switzerland border
- 27 km circumference ring
- Currently running proton-proton collisions at $\sqrt{s} = 13.6$ TeV
- Designed to probe the TeV scale
- Four main experiments: ATLAS, CMS, LHCb, ALICE

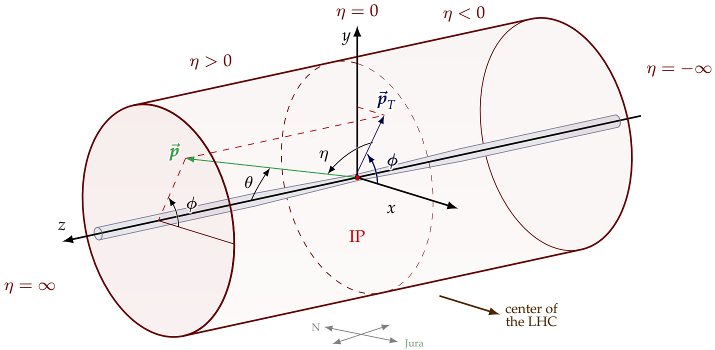
- High luminosity upgrade (HL-LHC) planned for 2029
- Key tool for testing SM and exploring new physics scenarios
- Now searching for physics **beyond the Standard Model**

Collider Observables

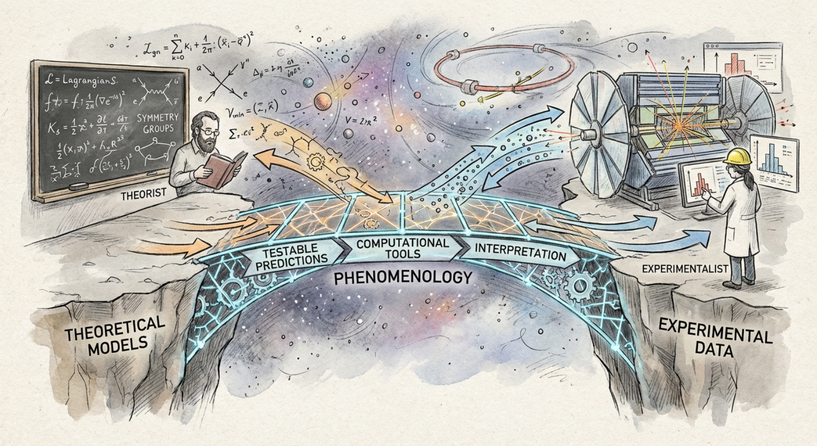
Collider Kinematics

- Pseudorapidity: $\eta = -\ln\tan(\theta/2)$
- Transverse momentum: $p_T = p\sin(\theta)$
- Azimuthal angle: ϕ
- Deposited energy: E

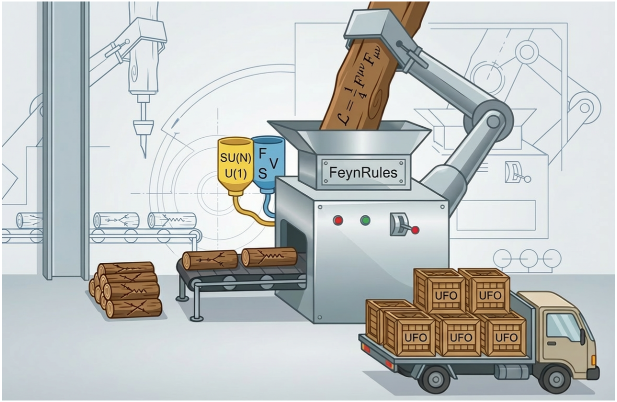




Phenomenological Framework



From Theory to Simulation: FeynRules



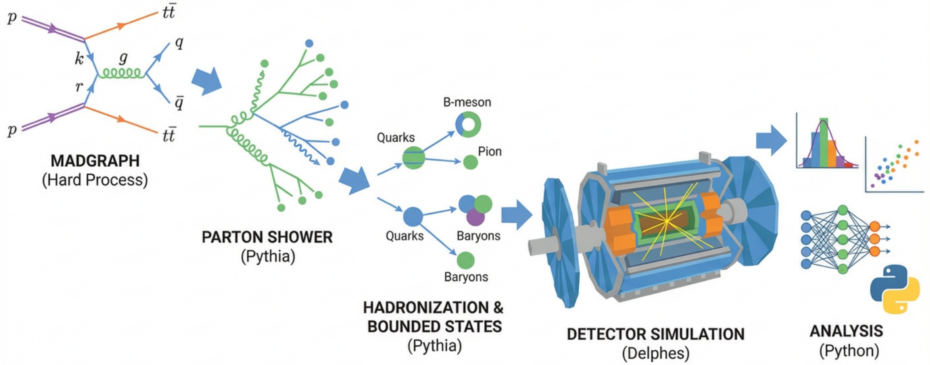
Input: `.fr` Model File

- Lagrangian $\mathcal{L}$ terms
- Particle definitions: F, V, S fields
- Gauge symmetries: $SU(N)$, $U(1)$
- Parameters: masses, couplings
- Mixing matrices, constraints
- Output: UFO model files

Madgraph-Pythia-Delphes

Ecosystem for Event Simulation

Goal: Produce realistic simulated data comparable to experimental observations
Input: BSM model in UFO format, collider setup, process definitions, parameters
Pipeline: UFO model → LHE (parton) → HEPMC (hadron) → ROOT (detector)
Output: Simulated events in ROOT format, ready for physics analysis
Automated: Cross-sections, widths, branching ratios calculated automatically



Statistical Significance

Statistical Significance

It is the parametric test

$$\kappa = \frac{\langle t\rangle_B - \langle t\rangle_{S+B}}{\sigma_{S+B}}$$

where $t \sim \chi^2$ is the optimal test.

Event Yield

The event yield in each bin is $N_i = \sigma_i \cdot \mathcal{L} \cdot \epsilon_i$, where:

- σ_i: cross section
- $\mathcal{L}$: integrated luminosity
- ϵ_i: selection efficiency

The significance becomes:

$$\boxed{\kappa = \frac{\sum_i \sigma_{s_i}\epsilon_{s_i} w_i}{\sqrt{\sum_i (\sigma_{s_i}\epsilon_{s_i} + \sigma_{b_i}\epsilon_{b_i} + \delta^2_{\text{sys}}) {w_i}^2}} \sqrt{\mathcal{L}}} \tag{1}$$

Strategies to improve κ:

- Increase luminosity $\mathcal{L}$
- Optimize cuts to enhance ϵ_s/ϵ_b
- Increase σ_s via higher $\sqrt{s}$ for heavier states
- Use multivariate discriminants (BDT, DNN)
- Reduce systematic uncertainties δ_{sys}
- Exploit correlations between bins

Machine Learning Revolution in HEP

Why ML in Particle Physics?

- **High-dimensional data**: Complex detector outputs
- **Complex patterns**: Jet and event classification
- **Rare signals**: Need optimal background rejection
- **Automation**: Reduce manual feature engineering
- **Computational efficiency**: Speed up workflows

Traditional vs ML Approaches

Traditional:

- Manual cut-based analysis
- Simple kinematic variables
- Univariate methods
- Limited feature engineering

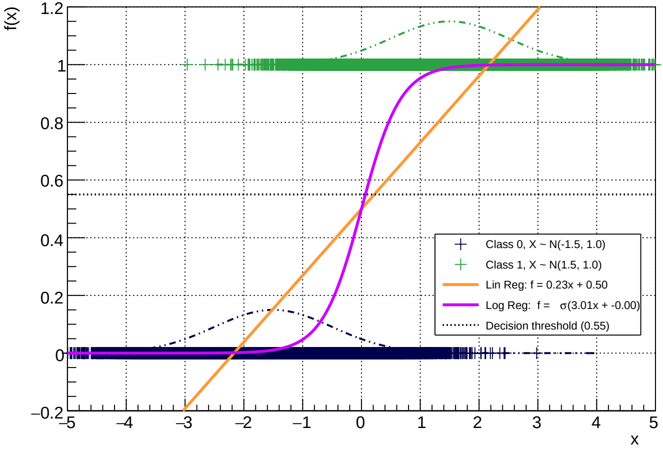
Machine Learning:

- Multivariate classifiers (BDT, NN)
- Deep learning on raw data
- Anomaly detection for BSM searches

Typical Current Applications

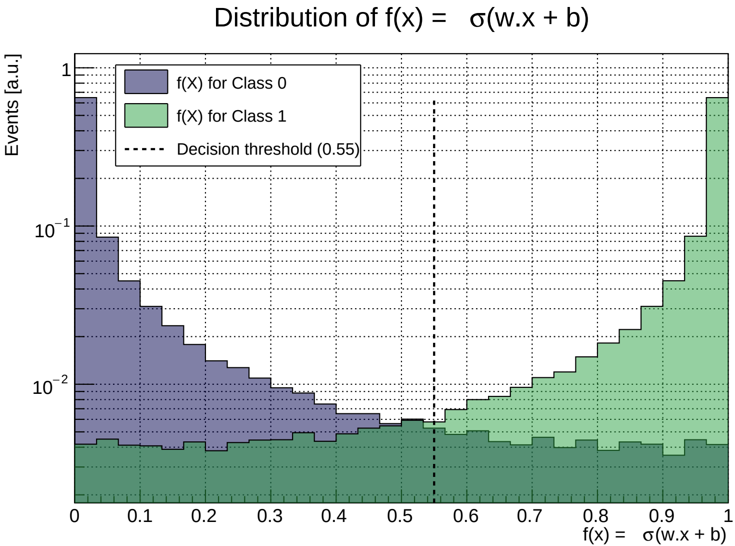
- **Event classification**: Signal/background separation
- **Jet tagging**: $b/c/\tau$-jet identification
- **Object reconstruction**: Particle flow, tracking
- **Anomaly detection**: Model-agnostic BSM searches
- **Simulation acceleration**: Fast calorimeter simulation

How does the binary classifier work?



Be aware: The real performance is the same for both algorithms in terms of classification accuracy. The difference lies in interpretability and probabilistic output.

A New Distribution Emerges



$U(1)_{T_R^3}$ Model

Deeper Origin of Hypercharge?

SM Electric Charge Formula

In the SM, electric charge emerges from electroweak symmetry breaking:

$$Q_{\text{EM}} = T_L^3 + \frac{Y}{2}$$

where T_L^3 is weak isospin ($SU(2)_L$) and Y is hypercharge ($U(1)_Y$).

Could Y emerge from additional gauge symmetries?

Pati-Salam trys to restore left-right symmetry:

$$Y = 2T_R^3 + \frac{B-L}{2}$$

$$Q_{\text{EM}} = T_L^3 + T_R^3 + \frac{B-L}{4}$$

This induce challenges: Anomaly cancellation, Higgs sector, mass scales, fermion masses, among others.

Key Question

Can hypercharge be explained by a more fundamental gauge structure?
This could provide a deeper understanding of the SM's chiral fermion assignments.

Need of modify Higgs Mechanism

SM fermion masses from Yukawa couplings

The SM yukawa couplings are not invariant under the new symmetry,

$$\mathcal{L}_{\text{Yukawa}} = \underbrace{-y_e \bar{L}_L \Phi e_R}_{\text{Lepton Yukawa}} + \underbrace{-y_d \bar{Q}_L \Phi d_R}_{\text{Down quark Yukawa}} + \underbrace{-y_u \bar{Q}_L \tilde{\Phi} u_R}_{\text{Up quark Yukawa}} + \text{h.c.} \tag{2}$$

The SM masses arise after EWSB when $\langle \Phi \rangle = v_h/\sqrt{2} \implies \boxed{m_f = \frac{1}{\sqrt{2}} y_f v_h}$

Need of modify Higgs Mechanism

SM fermion masses from Yukawa couplings

The SM yukawa couplings are not invariant under the new symmetry,

$$\mathcal{L}_{\text{Yukawa}} = \underbrace{-y_e \bar{L}_L \Phi e_R}_{\text{Lepton Yukawa}} + \underbrace{-y_d \bar{Q}_L \Phi d_R}_{\text{Down quark Yukawa}} + \underbrace{-y_u \bar{Q}_L \tilde{\Phi} u_R}_{\text{Up quark Yukawa}} + \text{h.c.} \quad (2)$$

The SM masses arise after EWSB when $\langle \Phi \rangle = v_h/\sqrt{2} \implies \boxed{m_f = \frac{1}{\sqrt{2}} y_f v_h}$

However, if we add the $U(1)_{T_R^3}$ charges to the SM fields as:

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
u_R^c	**3**	**1**	-2/3	-1
d_R^c	**3**	**1**	1/3	1
ℓ_R^c	**1**	**1**	1	1

We get $y_u = y_d = y_e = 0$ is mandatory $\implies$ **No Masses**. **Chiral anomalies** also arise.

The Universal Seesaw Mechanism

Modifications to the Scalar and Fermion Sectors

- We need two scalar fields:
  - The usual Higgs doublet H, with $\langle H\rangle = v_h/\sqrt{2}$.
  - A new complex scalar singlet ϕ, with $\langle \phi\rangle = v_\phi/\sqrt{2}$.

  in order to decouple the energy scales of $U(1)_{T_R^3}$ and $SU(2)_L \times U(1)_Y$ breaking.
- Fermions acquire mass from the mixture with a new vector-like fermion χ_f.
- Right-handed neutrinos ν_R are added to cancel anomalies in the lepton sector.

The terms in the Lagrangian density that contribute to the mass of physical fermions are,

$$-\mathcal{L} \supset Y_{f_L}\bar{f}'_L\chi'_{fR}H + Y_{f_R}\bar{\chi}'_{fL}f'_R\phi^* + m_{\chi'_f}\bar{\chi}'_{fL}\chi'_{fR} + \text{ h.c.} \tag{3}$$

Therefore, in the vacuum, the mass matrix for each fermion f is given by

$$M_f = \begin{pmatrix} 0 & Y_{f_L}v_h/\sqrt{2} \\ Y_{f_R}v_\phi/\sqrt{2} & m_{\chi'_f} \end{pmatrix}, \quad \Longrightarrow \begin{cases} m_f m_{\chi_f} = \frac{Y_{f_L}v_h Y_{f_R}v_\phi}{2} \\ m_f^2 + m_{\chi_f}^2 = m_{\chi'_f}^2 + \frac{1}{2}\left(Y_{f_L}^2 v_h^2 + Y_{f_R}^2 v_\phi^2\right) \end{cases}, \tag{4}$$

The masses will rise from diagonalizing this matrix.

The Universal Seesaw Mechanism

Modifications to the Scalar and Fermion Sectors

- We need two scalar fields:
  - The usual Higgs doublet H, with $\langle H\rangle = v_h/\sqrt{2}$.
  - A new complex scalar singlet ϕ, with $\langle \phi\rangle = v_\phi/\sqrt{2}$.

  in order to decouple the energy scales of $U(1)_{T_R^3}$ and $SU(2)_L \times U(1)_Y$ breaking.
- Fermions acquire mass from the mixture with a new vector-like fermion χ_f.
- Right-handed neutrinos ν_R are added to cancel anomalies in the lepton sector.

After spontaneous symmetry breaking

$$H = \begin{pmatrix} G_+ \\ \frac{1}{\sqrt{2}}\left(v_h + \rho_0 + iG_0\right) \end{pmatrix}, \quad \phi = \frac{1}{\sqrt{2}}\left(v_\phi + \rho_\phi + iG_\phi\right), \tag{3}$$

where $G^\pm$, G^0 are the Goldstone bosons eaten by $W^\pm$ and Z^0, and G_ϕ is the Goldstone boson eaten by the new Z'/dark photon.
While the scalar parts ρ_0 and ρ_ϕ mix to get the physical mass eigenstates h and ϕ'

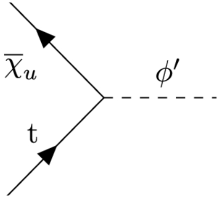
$$M^2_{\text{scalar}} = \begin{pmatrix} 2\lambda_H v_h^2 & \lambda_{H\phi} v_h v_\phi \\ \lambda_{H\phi} v_h v_\phi & 2\lambda_\phi v_\phi^2 \end{pmatrix} \implies \begin{cases} m_h^2 - m_{\phi'}^2 = \sqrt{(4\lambda_{H\phi}^2 v_h^2 v_\phi^2) + (\lambda_H v_h^2 - \lambda_\phi v_\phi^2)^2} \\ m_h^2 + m_{\phi'}^2 = \lambda_H v_h^2 + \lambda_\phi v_\phi^2 \end{cases} \tag{4}$$

The Universal Seesaw Mechanism

The Yukawa interactions of the physical fermions with the scalar bosons have the form

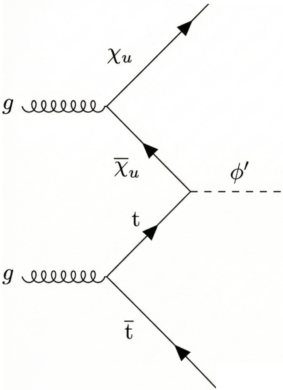
$$-\mathcal{L}_{\text{yuk}} = h\bar{\psi}_{f_L}\mathcal{Y}_h\psi_{f_R} + \phi'\bar{\psi}_{f_L}\mathcal{Y}_\phi\psi_{f_R}, \tag{5}$$

with $\psi_f = (f, \chi_f)^T$, and $\mathcal{Y}_{f_{L,R}}$ are 2×2 yukawa masses after rotation to the mass basis. So, you have new vertex like



TO DO ADD THE OTHER VERTEX ()

Production Channel



TO ADD THE OTHER DIAGRAM

Feasible Experimental Signatures

Cross Section

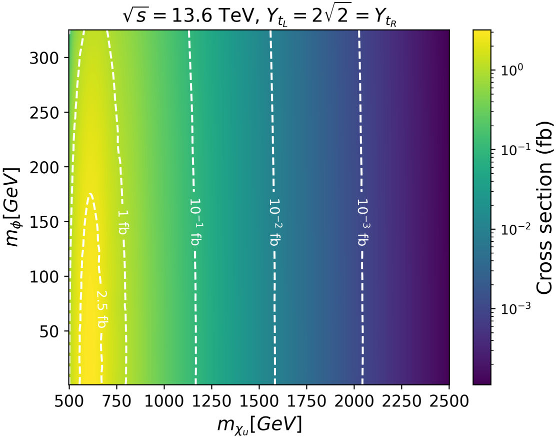
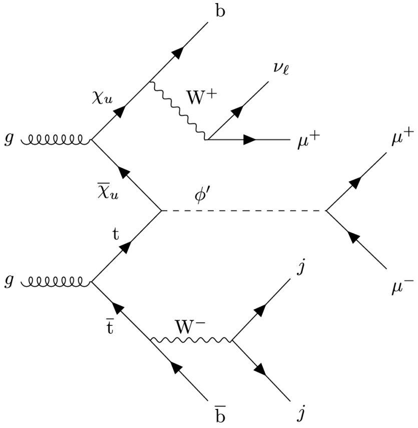


Fig.: Projected cross section (fb) plot for $pp \to t\chi_u\phi'$ and subsequent decay as a function of $m(\chi_u)$ and $m(\phi')$.

Feasible Experimental Signatures

Search Channel

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.

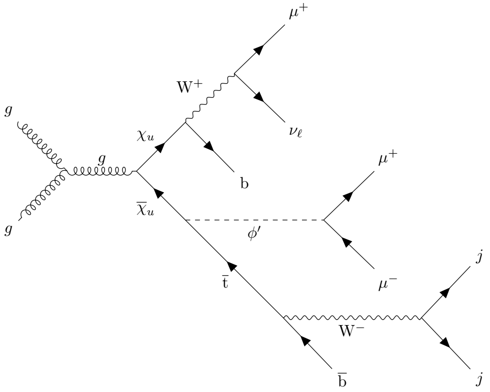


The ϕ' decays to a pair of muons, the top quark decays fully hadronically, and the χ_{u} decays semi-leptonically to muons, neutrinos and b-jets.

Feasible Experimental Signatures

Search Channel

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.

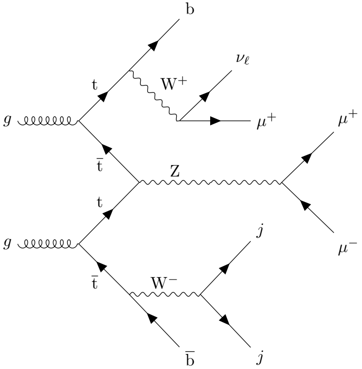


The ϕ' decays to a pair of muons, the top quark that decays fully hadronically, and the χ_u decay semi-leptonically to muons, neutrinos and jets.

Feasible Experimental Signatures

Background

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.

Feasible Experimental Signatures

Kinematic Variables

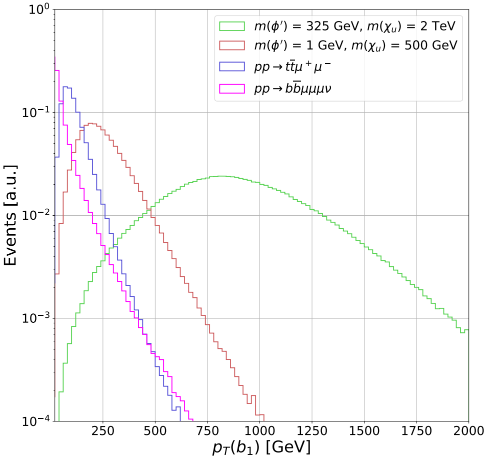


Fig.: Transverse momentum distribution of the leading b-quark jet candidate. The distributions are shown for the two main SM background processes and two signal benchmark points.

Feasible Experimental Signatures
Kinematic Variables

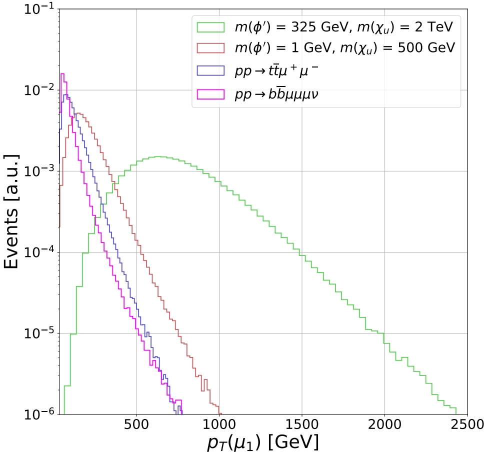


Fig.: Transverse momentum distribution of the leading muon candidate. The distributions are shown for the two main SM background processes and two signal benchmark points.

Feasible Experimental Signatures

Kinematic Variables

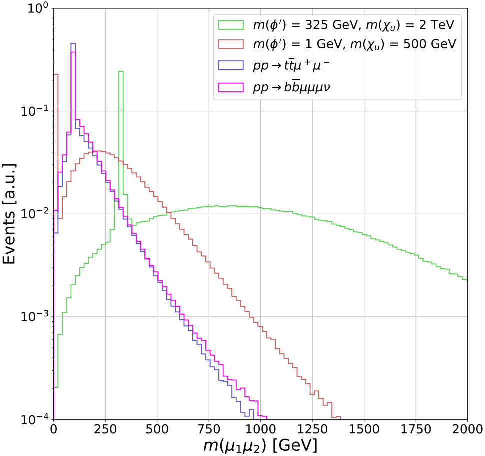


Fig.: Invariant mass distribution of the muon pair with the highest and second highest transverse momentum. The distributions are shown for the two main SM background processes and two signal benchmark points.

Feasible Experimental Signatures
Gradient Boosting

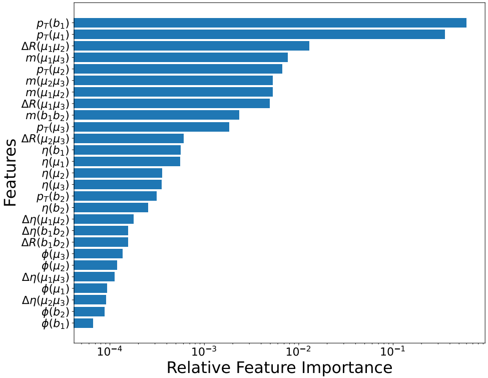


Fig.: Relative importance of features in training for a benchmark signal scenario with $m(\phi') = 325\,\text{GeV}$ and $m(\chi_u) = 2000\,\text{GeV}$.

Feasible Experimental Signatures

Gradient Boosting

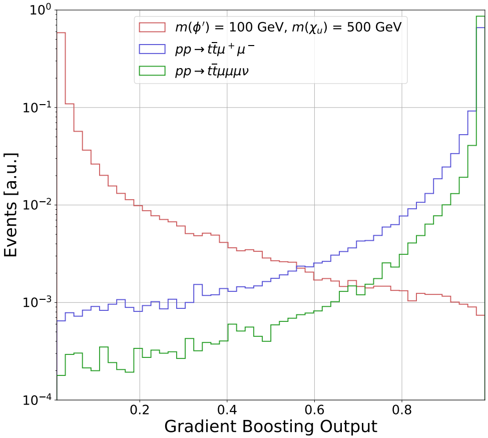


Fig.: Output of the gradient boosting algorithm for a benchmark $m(\phi') = 100$ GeV and $m(\chi_u) = 500$ GeV signal, and dominant backgrounds. The distributions are normalized to unity.

Signal Significance

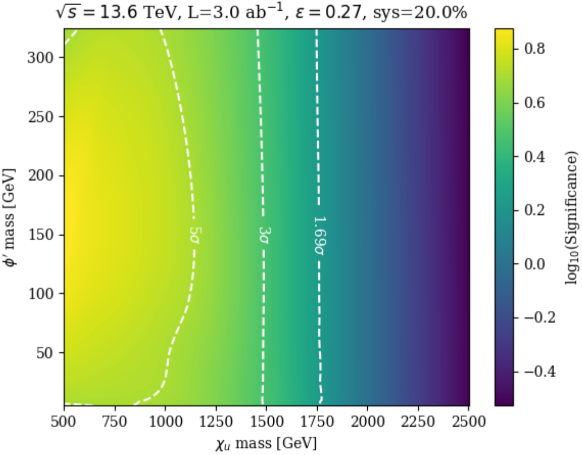
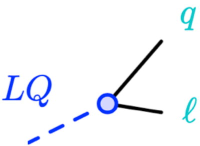


Fig.: Signal significance for the high luminosity LHC era, considering with 3000 fb^{-1} of collected data.

U_1 Leptoquark Model

The vector leptoquark U_1 model

A leptoquark is defined as a particle with a vertex that mix vectors and quarks.

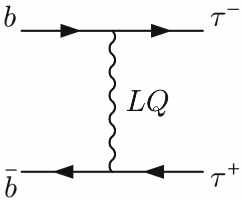


If U_1 is a vector leptoquark that preserves the chirality on the vertex, we expect an interaction term like

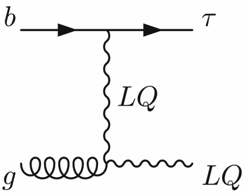
$$\sim \beta_L U_1^{\mu} \bar{q}_L \gamma_\mu \ell_L,$$

and these allows a similar interaction term for the right handed currents

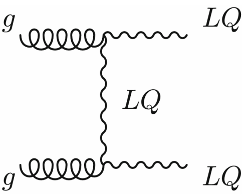
$$\sim \beta_R U_1^{\mu} \bar{d}_R \gamma_\mu e_R.$$



Non-resonant



Single LQ



Double LQ

Where the SM charges for the leptoquark, in the $Y = 2(Q - T_3)$ convention, are

	$\bar{q}_L$	ℓ_L^j	$\bar{q}_L \gamma_\mu \ell_L$	U_1^μ
$U(1)$	$-1/3$	-1	$-4/3$	$+4/3$
SU(2)	$\overline{\mathbf{2}}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
SU(3)	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{3}$

Then, the leptoquark $U_1 \sim (\mathbf{3}_C, \mathbf{1}_I, 4/3_Y)$.

Where the SM charges for the leptoquark, in the $Y = 2(Q - T_3)$ convention, are

	$\bar{q}_L$	ℓ_L^j	$\bar{q}_L \gamma_\mu \ell_L$	U_1^μ
$U(1)$	$-1/3$	-1	$-4/3$	$+4/3$
SU(2)	$\bar{\mathbf{2}}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
SU(3)	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{3}$

Then, the leptoquark $U_1 \sim (\mathbf{3}_C, \mathbf{1}_I, 4/3_Y)$.

The full Lagrangian for the vector leptoquark is

$$\begin{aligned}\mathcal{L}_U = & -\frac{1}{2} U_{\mu\nu}^\dagger U^{\mu\nu} + M_U^2 U_\mu^\dagger U^\mu - i g_s U_\mu^\dagger T^a U_\nu G_a^{\mu\nu} - \frac{2i}{3} g' U_\mu^\dagger U_\nu B^{\mu\nu} \\ & + \frac{g_U}{\sqrt{2}} \left[U_1^\mu \left(\beta_L^{ij} \bar{q}_L^i \gamma_\mu e_L^j + \beta_R^{ij} \bar{d}_R^i \gamma_\mu e_R^j \right) + \text{ h.c. } \right]\end{aligned}$$

where $U_{\mu\nu} = \mathcal{D}_\mu U_\nu - \mathcal{D}_\nu U_\mu$, $\mathcal{D}_\mu = \partial_\mu - i g_s G_\mu^a T^a - i \frac{2}{3} g_Y B_\mu$, and the couplings β_L and β_R are complex 3×3 matrices in flavor space.

Where the SM charges for the leptoquark, in the $Y = 2(Q - T_3)$ convention, are

	$\bar{q}_L$	ℓ_L^j	$\bar{q}_L\gamma_\mu\ell_L$	U_1^μ
$U(1)$	$-1/3$	-1	$-4/3$	$+4/3$
SU(2)	$\bar{\mathbf{2}}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
SU(3)	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{3}$

Then, the leptoquark $U_1 \sim (\mathbf{3}_C, \mathbf{1}_I, 4/3_Y)$.

The full Lagrangian for the vector leptoquark is

$$\begin{aligned}\mathcal{L}_U = &-\frac{1}{2}U^\dagger_{\mu\nu}U^{\mu\nu} + M_U^2 U^\dagger_\mu U^\mu - ig_s U^\dagger_\mu T^a U_\nu G_a^{\mu\nu} - \frac{2i}{3}g' U^\dagger_\mu U_\nu B^{\mu\nu} \\ &+ \frac{g_U}{\sqrt{2}}\left[U_1^\mu\left(\beta_L^{ij}\bar{q}_L^i\gamma_\mu e_L^j + \beta_R^{ij}\bar{d}_R^i\gamma_\mu e_R^j\right) + \text{ h.c. }\right]\end{aligned}$$

where $U_{\mu\nu} = \mathcal{D}_\mu U_\nu - \mathcal{D}_\nu U_\mu$, $\mathcal{D}_\mu = \partial_\mu - ig_s G^a_\mu T^a - i\frac{2}{3}g_Y B_\mu$, and the couplings β_L and β_R are complex 3×3 matrices in flavor space.

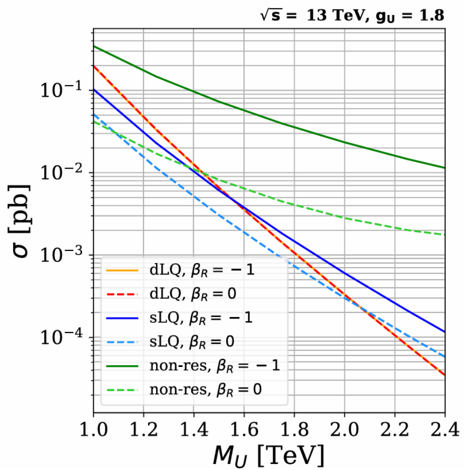
Constraints from $\Delta F = 2$ and lepton flavor violation impose a hierarchy with dominant third generation couplings:

$$\left|\beta_L^{11}\right|, \left|\beta_L^{12}\right|, \left|\beta_L^{21}\right|, \left|\beta_L^{22}\right|, \left|\beta_L^{31}\right| \ll \left|\beta_L^{13}\right| \ll \left|\beta_L^{23}\right|, \left|\beta_L^{32}\right| \ll \left|\beta_R^{33}\right|, \left|\beta_L^{33}\right| = \mathcal{O}(1), \quad (6)$$

where β_R is diagonal.

Leptoquark Production Mechanisms at 13 TeV

Cross Sections for $g_U = 1.8$, $\sqrt{s} = 13$ TeV



Production Channels

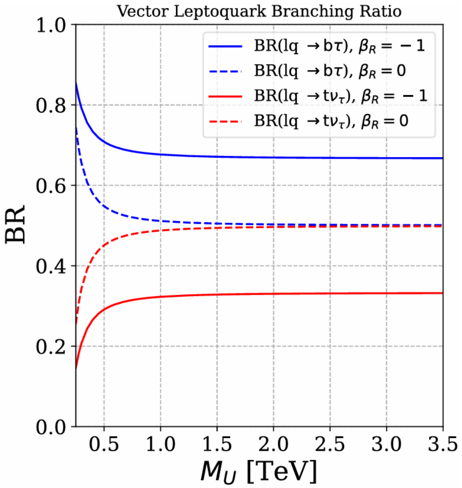
- **dLQ**: Pair production
  QCD-mediated
  β_R independent
- **sLQ**: Single production
  β_R sensitive
  $\times 2$ enhancement
- **non-res**: Non-resonant
  β_R sensitive
  $\times 10$ enhancement

Cross-over Point

$\sigma_{\mathrm{sLQ}} > \sigma_{\mathrm{dLQ}}$ for $M_{\mathrm{LQ}} \gtrsim 1.5$ TeV
(exact value depends on g_U)

Leptoquark Branching Fractions

Branching Ratios vs. β_R Parameter



Main Decay Channels

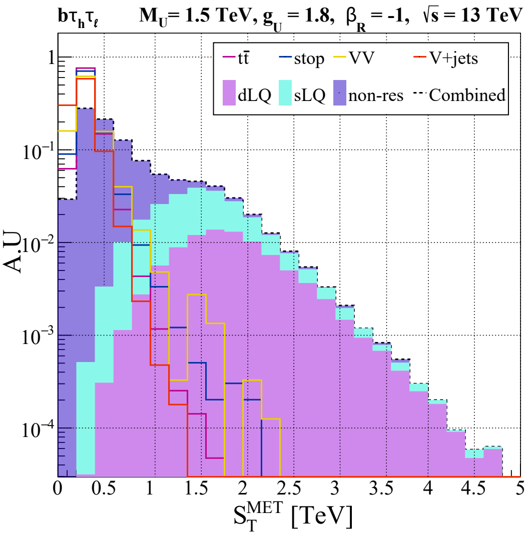
- LQ $\to b\tau$: Dominant
  Primary for $R(D^{(*)})$ anomalies
- LQ $\to t\nu_\tau$: Competing
  Affects total width
- LQ $\to c\tau, s\nu_\tau$: Subdominant

β_R Dependence

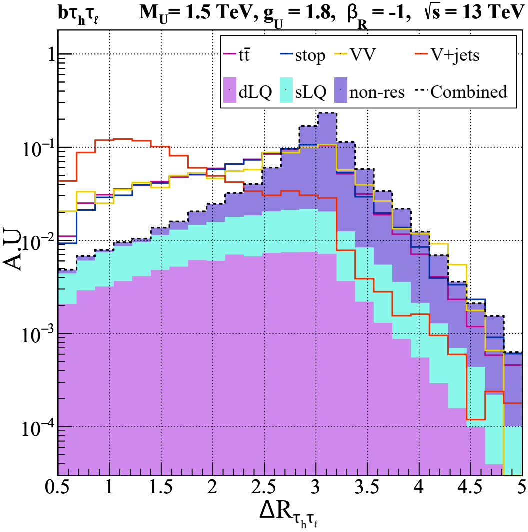
Controls right-handed couplings:

- $\beta_R = 0$: Pure left-handed
- $\beta_R > 0$: Mixed chirality
- Affects collider signatures

$S_T^{\text{meT}} = \text{met} + \sum_i |p_T^i|$



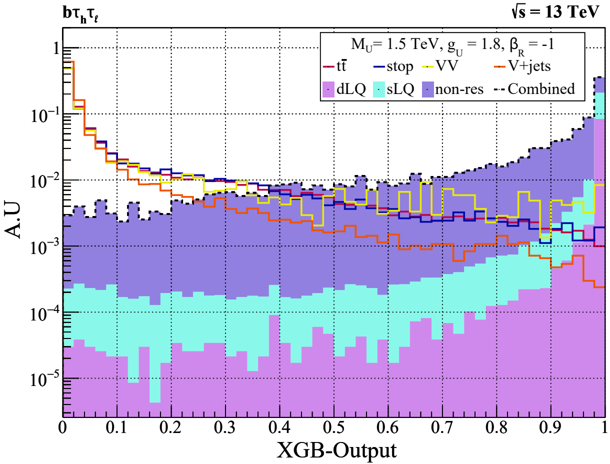
$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$



The optimized observable

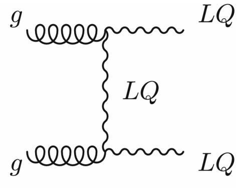
XGB-output

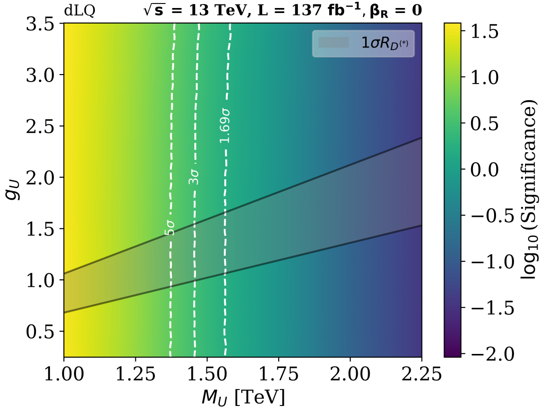
We can evaluate a score for the signal and background events using the discriminator algorithm.



Double Leptoquark Production

The Sensitivity Reach / only left-handed currents

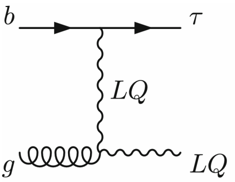


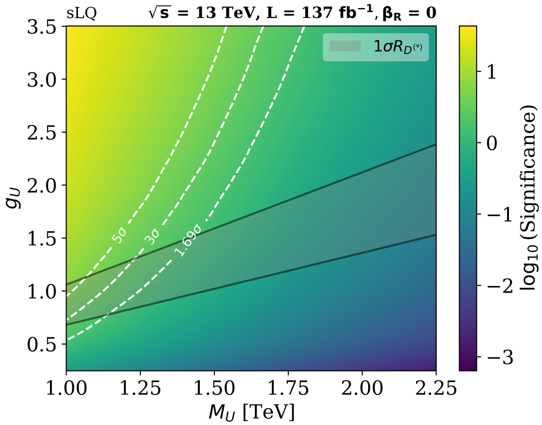


Double leptoquark production is sensitive to the leptoquark mass, its production depends only on the QCD coupling constant and the available energy.

Single leptoquark production

The Sensitivity Reach / only left-handed currents

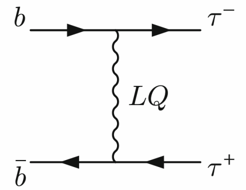


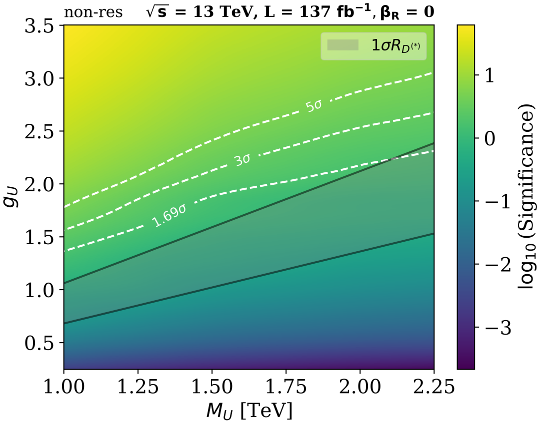


Single leptoquark production is sensitive to both, mass and couplings. It contributes to the regions of high coupling constants at higher masses than double leptoquark production.

Non-resonant Production

The Sensitivity Reach / only left-handed currents

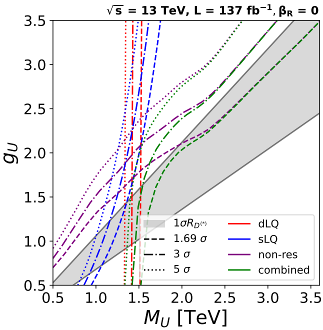




Non-resonant production is highly dependent on the couplings, so it dominates the regions of high coupling constants at all masses.

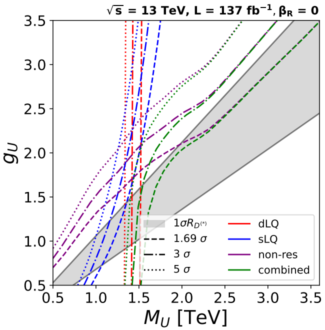
Combined Sensitivity Reach

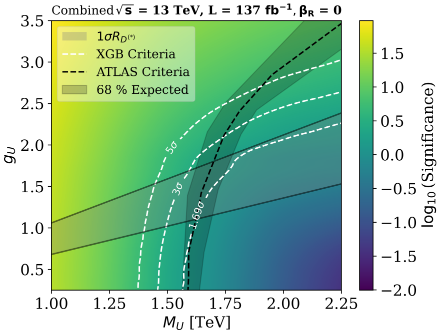
The Sensitivity Reach / only left-handed currents



Combined Sensitivity Reach

The Sensitivity Reach / only left-handed currents

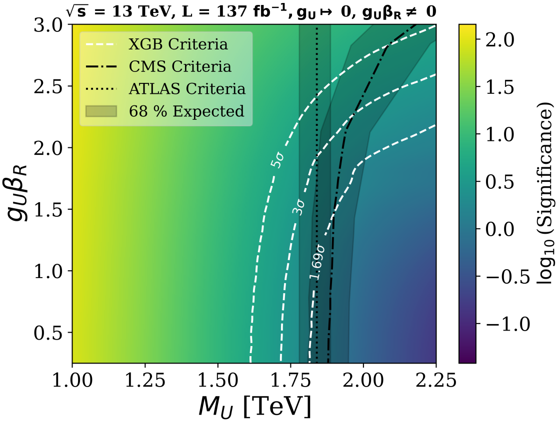




The sensitivity of all signal production processes combined compares our expected exclusion region with the latest one from the ATLAS Collaboration [ArXiv:2305.15962], but we suggest better sensitivity for high coupling constants.

Combined Sensitivity Reach

The Sensitivity Reach / only right-handed currents



The case $BR(lq \to b\tau) = 1$ corresponds to the only right-handed currents coupling. The sensitivity compared with the latest one from the CMS [2308.07826] and ATLAS Collaborations [2303.01294], again we suggest better sensitivity for high coupling constants.

Z' Interferences

The need of a Z' boson in gauge U_1 models

If U_1 has a gauge origin, we could rewrite the interaction term in the covariant derivative as

$$\psi_L^{\text{SM}} = \begin{pmatrix} q_{Lr} \\ q_{Lg} \\ q_{Lb} \\ \ell_L \end{pmatrix} \implies \mathcal{L}_{\text{int}} \sim U^{\mu}_{1\alpha} \bar{\psi}_L^{\text{SM}} \gamma_\mu T^\alpha_+ \psi_L^{\text{SM}} + \text{h.c.}, \quad T^\alpha_+ = \begin{pmatrix} 0 & 0 & 0 & \delta_{r\alpha} \\ 0 & 0 & 0 & \delta_{g\alpha} \\ 0 & 0 & 0 & \delta_{b\alpha} \\ 0 & 0 & 0 & 0 \end{pmatrix},$$

we have six generators $T^\alpha_\pm$ with closure relation and projecting into a color singlet operator:

$$\sum_\alpha \left[T^\alpha_+, T^\alpha_-\right] = 3T_{B-L} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -3 \end{pmatrix}.$$

So, the gauge group with this leptoquark must include a $U(1)_{B-L}$ symmetry (The right-handed currents also have a similar interaction term).

The need of a Z' boson in gauge U_1 models

If U_1 has a gauge origin, we could rewrite the interaction term in the covariant derivative as

$$\psi_L^{\text{SM}} = \begin{pmatrix} q_{Lr} \\ q_{Lg} \\ q_{Lb} \\ \ell_L \end{pmatrix} \Longrightarrow \quad \mathcal{L}_{\text{int}} \sim U^{\mu}_{1\alpha} \bar{\psi}_L^{\text{SM}} \gamma_\mu T^\alpha_+ \psi_L^{\text{SM}} + \text{h.c.}, \quad T^\alpha_+ = \begin{pmatrix} 0 & 0 & 0 & \delta_{r\alpha} \\ 0 & 0 & 0 & \delta_{g\alpha} \\ 0 & 0 & 0 & \delta_{b\alpha} \\ 0 & 0 & 0 & 0 \end{pmatrix},$$

we have six generators $T^\alpha_\pm$ with closure relation and projecting into a color singlet operator:

$$\sum_\alpha \left[T^\alpha_+, T^\alpha_-\right] = 3T_{B-L} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -3 \end{pmatrix}.$$

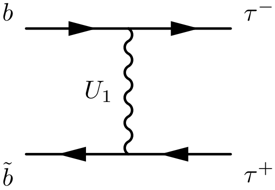
So, the gauge group with this leptoquark must include a $U(1)_{B-L}$ symmetry (The right-handed currents also have a similar interaction term).

The interaction terms for the Z' boson have the form

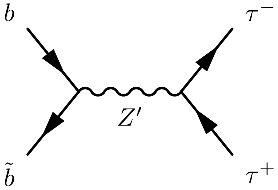
$$\begin{aligned} \mathcal{L}_{\text{int}} &\sim Z'_\mu \left(\bar{\psi}_L^{\text{SM}} \gamma^\mu (3T_{B-L}) \psi_L^{\text{SM}} \right) \\ &\sim Z'_\mu \left(\bar{q}_L \gamma^\mu q_L - 3\bar{\ell}_L \gamma^\mu \ell_L \right). \end{aligned}$$

Interference with a Z' vector boson

Non-Resonant Production (leptoquarks)



Resonant Production (neutral bosons)



so

$$\mathcal{M}_{U_1} \sim \frac{1}{t - m_{U_1}^2 + i m_{U_1} \Gamma_{U_1}}, \qquad (7)$$

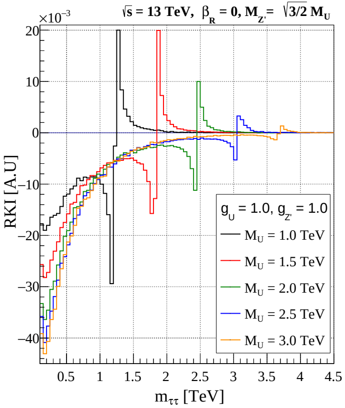
$$\mathcal{M}_{Z'} \sim \frac{1}{s - m_{Z'}^2 + i m_{Z'} \Gamma_{Z'}}, \qquad (8)$$

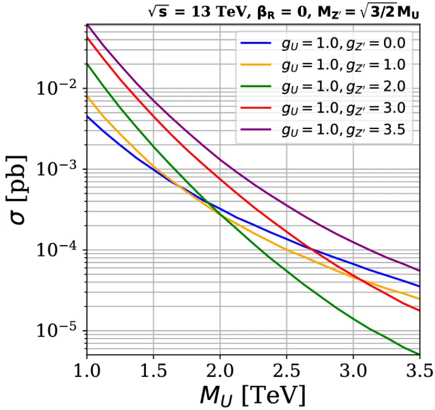
the interference has the form

$$\frac{\mathrm{d}}{\mathrm{d}m}\left[\sigma_{LQ+Z'} - \left(\sigma_{LQ} + \sigma_{Z'}\right)\right] \sim \frac{g_{z'} g_U}{s} \frac{m_{LQ} m_{Z'} \Gamma_{LQ} \Gamma_{Z'} - (t - m_{LQ}^2)(s - m_{Z'}^2)}{\left[(t - m_{LQ}^2)^2 + m_{LQ}^2 \Gamma_{LQ}^2\right]\left[(s - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2\right]}.$$

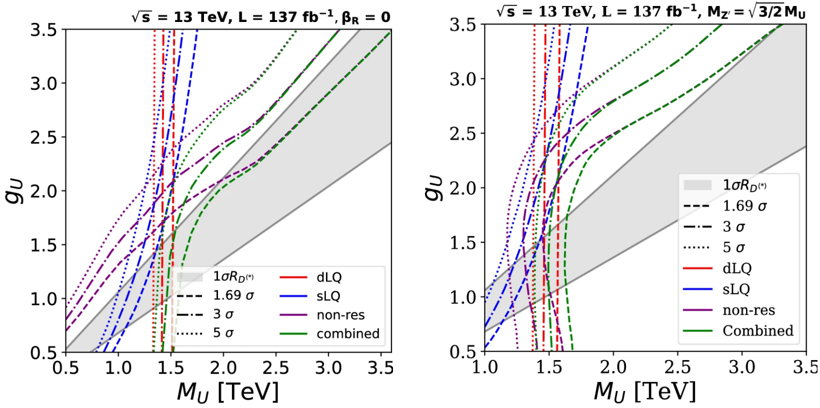
Similary for Polarized final states.

Interference with a Z' vector boson





Effects on the Sensitivity reach



Summary and Conclusions

Backup Slides

What Do We Look For at the LHC?

Three Complementary Approaches

- **SM Parameter Determination**
  - Precisely measure fundamental SM parameters
  - Test consistency of the SM framework
  - Reduce theoretical uncertainties
- **Indirect Searches (Precision Tests)**
  - Measure SM processes with high precision
  - Look for deviations in predicted distributions
  - Constrain new physics through virtual effects
- **Direct Searches**
  - Look for new particles in final states (resonances, excesses)
  - Examples: SUSY particles, Z', leptoquarks, dark matter mediators

Key Types of Measurements

Direct Signatures:

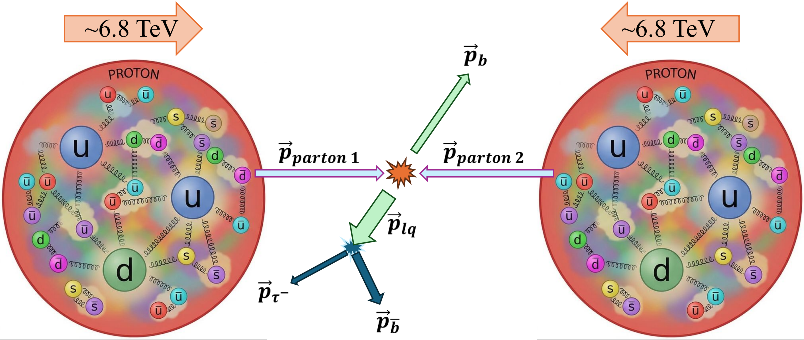
- Resonant mass peaks
- Excess events over SM background
- Missing transverse energy (MET)
- Unusual kinematic features

Precision Observables:

- Differential cross sections
- Angular correlations
- Rare decay rates
- Lepton flavor universality ratios
- Charge-parity (CP) asymmetries

The Quark-Gluon Sea

Partons are the fundamental constituents inside protons: valence quarks (uud) and a **sea** of virtual quark-antiquark pairs and gluons.



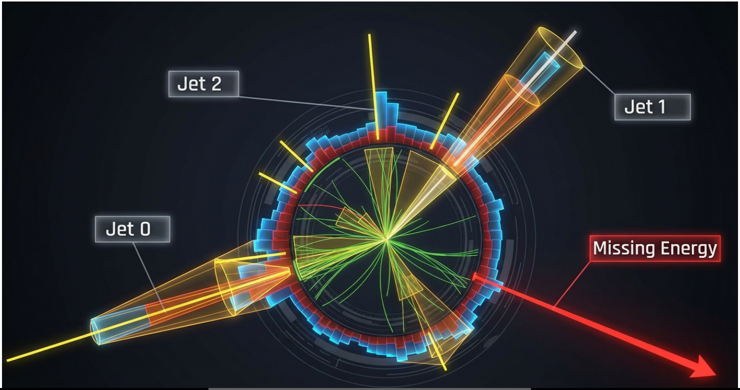
The interacting partons are typically **sea quarks or gluons**, which carry only a fraction of the proton's momentum but dominate the cross-section at high energies.

Jet Clustering & Missing Transverse Momentum

Jet clustering groups collimated particle showers into jets to reconstruct the original quarks/gluons from the hard scatter.

Missing p_T appears as transverse momentum imbalance, signaling undetected particles like neutrinos:

$$\vec{p}_T^{\,\text{miss}} = -\sum_{\text{visible prods}} \vec{p}_T$$

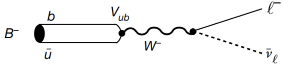


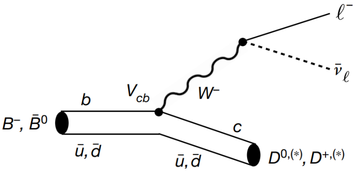
$R(D)$ and $R(D^*)$ anomalies

Flavor Observables

$$R(D) = \frac{\mathrm{BR}(B\to D\tau\nu)}{\mathrm{BR}\left(B\to D\ell_{(e,\mu)}\nu\right)}, \quad R(D^{(*)}) = \frac{\mathrm{BR}\left(B\to D^{(*)}\tau\nu\right)}{\mathrm{BR}\left(B\to D^{(*)}\ell_{(e,\mu)}\nu\right)}$$

Standard Model (Tree-level)





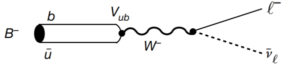
$B^- \to D^0\ell^-\bar{\nu}_\ell$ via W^- exchange

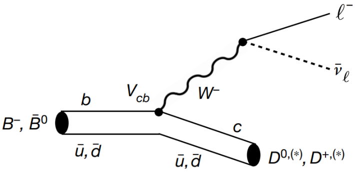
$R(D)$ and $R(D^*)$ anomalies

Flavor Observables

$$R(D) = \frac{\mathrm{BR}(B \to D\tau\nu)}{\mathrm{BR}\left(B \to D\ell_{(e,\mu)}\nu\right)}, \quad R(D^{(*)}) = \frac{\mathrm{BR}\left(B \to D^{(*)}\tau\nu\right)}{\mathrm{BR}\left(B \to D^{(*)}\ell_{(e,\mu)}\nu\right)}$$

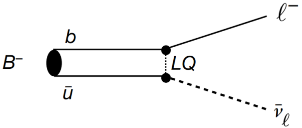
Standard Model (Tree-level)

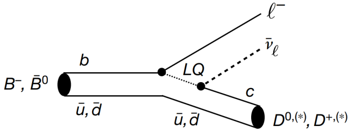




$B^- \to D^0\ell^-\bar{\nu}_\ell$ via W^- exchange

Leptoquark Mediated





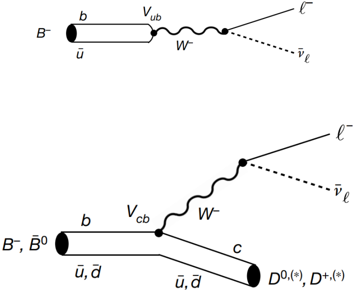
$B^- \to D^0\ell^-\bar{\nu}_\ell$ via leptoquark exchange

$R(D)$ and $R(D^*)$ anomalies

Flavor Observables

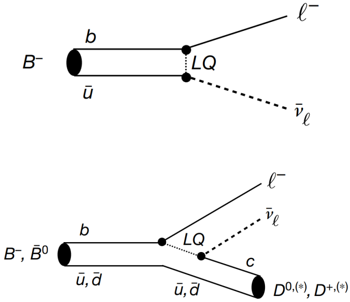
$$R(D) = \frac{\mathrm{BR}(B \to D\tau\nu)}{\mathrm{BR}\left(B \to D\ell_{(e,\mu)}\nu\right)}, \quad R(D^{(*)}) = \frac{\mathrm{BR}\left(B \to D^{(*)}\tau\nu\right)}{\mathrm{BR}\left(B \to D^{(*)}\ell_{(e,\mu)}\nu\right)}$$

Standard Model (Tree-level)



$B^- \to D^0\ell^-\bar{\nu}_\ell$ via W^- exchange

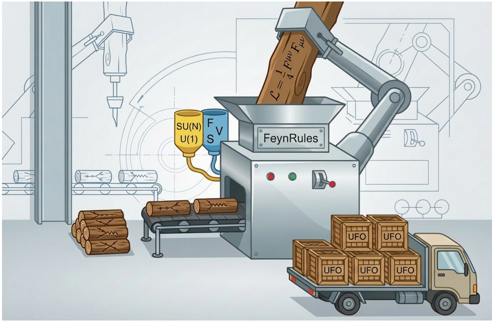
Leptoquark Mediated



$B^- \to D^0\ell^-\bar{\nu}_\ell$ via leptoquark exchange

How can we test this hypothesis?

From Theory to Simulation: FeynRules



Input: `.fr` Model File

- Lagrangian $\mathcal{L}$ terms
- Particle definitions: F, V, S fields
- Gauge symmetries: $SU(N)$, $U(1)$
- Parameters: masses, couplings
- Mixing matrices, constraints

Output: UFO Format

- Complete Feynman rules (vertices)
- Lorentz and color structures
- Parameter definitions
- Ready to simulate

Why Simulate New Physics Models?

- **Predict signals** for experimental searches
- **Test theoretical consistency** (unitarity, constraints)
- **Optimize analyses** before data collection
- **Interpret potential discoveries** from LHC data
- **Compare predictions** across different models

Features

$\nearrow$ **Standardized** UFO format
$\nearrow$ **Flexible** for BSM models
$\nearrow$ **Community-driven**
$\searrow$ **NLO complexity**
$\searrow$ **Poor debugging**
$\searrow$ **Performance issues**

Statistical Significance

The statistical significance for discovery is a parametric test defined as:

$$\kappa = \frac{\langle t \rangle_B - \langle t \rangle_{S+B}}{\sigma_{S+B}} \tag{9}$$

where $t = -2\ln[\mathcal{L}(n|S+B)/\mathcal{L}(n|B)] \sim \chi^2$ is the optimal test statistic.

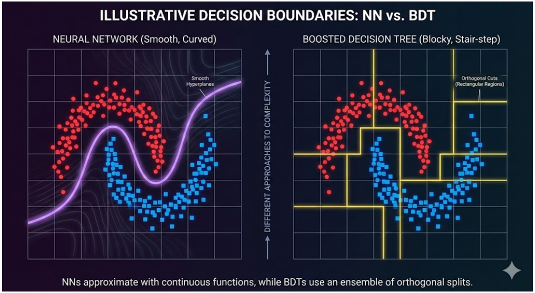
We denote $\mathcal{L}$ as the likelihood for Poisson-distributed event counts n in each bin and gaussian systematic uncertainties.

For binned data analysis, this simplifies to:

$$\kappa = \frac{\sum_i s_i w_i}{\sqrt{\sum_i (s_i + b_i + \delta_{\text{sys}}^2) w_i^2}} \tag{10}$$

where s_i, b_i are signal/background events in bin i, $w_i \sim \ln(1 + s_i/b_i)$ are optimal weights, and δ_{sys} is the systematic uncertainty.

Boosted Decision Trees vs Neural Networks



BDTs

Strengths:

- **Interpretable**: Feature importance rankings
- **Robust**: Handle missing data well
- **Fast training**: Efficient on tabular data
- **Low hyperparameter tuning**: Reasonable defaults work

Limitations:

- **Extrapolation**: Poor outside training range
- **High-dimensional**: Can struggle with many features
- **Discontinuous**: Piecewise constant predictions

Deep NNs

Strengths:

- **Flexible**: Can learn complex non-linearities
- **High-dimensional**: Excel with many features
- **Continuous**: Smooth function approximations
- **Transfer learning**: Pretrained models possible

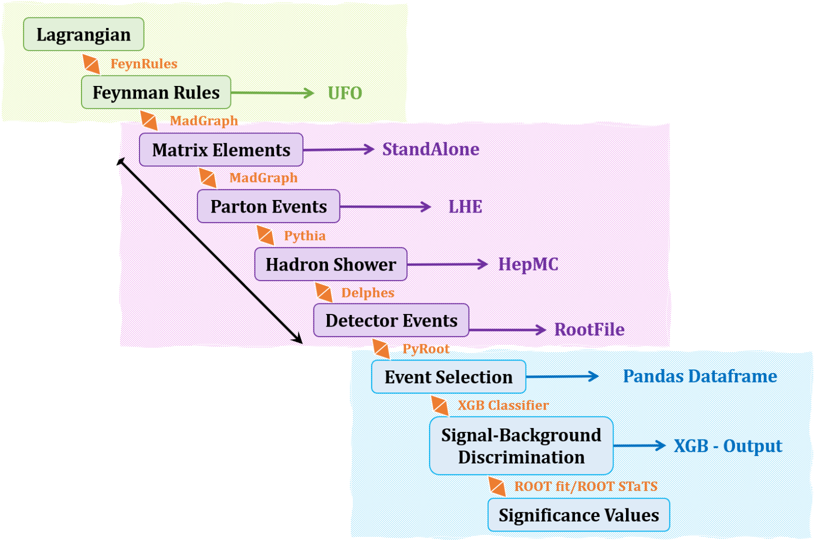
Limitations:

- **Black box**: Difficult to interpret
- **Data hungry**: Need large training sets
- **Computational**: Require GPUs for large networks
- **Sensitive**: Require careful hyperparameter tuning

HEP Use Cases

BDTs: Preferred for $\sim 10 - 100$ features
NNs: Preferred for low-level data (images, graphs)

Feasibility Studies Workflow



Where the SM charges for the leptoquark, in the $Y = 2(Q - T_3)$ convention, are

	$\bar{q}_L$	ℓ^j_L	$\bar{q}_L \gamma_\mu \ell_L$	U_1^μ
$U(1)$	$-1/3$	-1	$-4/3$	$+4/3$
SU(2)	$\bar{\mathbf{2}}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
SU(3)	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{3}$

Then, the leptoquark $U_1 \sim (\mathbf{3}_C, \mathbf{1}_I, 4/3_Y)$.

Where the SM charges for the leptoquark, in the $Y = 2(Q - T_3)$ convention, are

	$\bar{q}_L$	ℓ^j_L	$\bar{q}_L\gamma_\mu\ell_L$	U_1^μ
$U(1)$	$-1/3$	-1	$-4/3$	$+4/3$
SU(2)	$\bar{\mathbf{2}}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
SU(3)	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{3}$

Then, the leptoquark $U_1 \sim (\mathbf{3}_C, \mathbf{1}_I, 4/3_Y)$.

The full Lagrangian for the vector leptoquark is

$$
\begin{aligned}
\mathcal{L}_U = &- \frac{1}{2}U^\dagger_{\mu\nu}U^{\mu\nu} + M_U^2 U^\dagger_\mu U^\mu - i g_s U^\dagger_\mu T^a U_\nu G_a^{\mu\nu} - \frac{2i}{3} g' U^\dagger_\mu U_\nu B^{\mu\nu} \\
&+ \frac{g_U}{\sqrt{2}} \left[U_1^\mu \left(\beta_L^{ij} \bar{q}^i_L \gamma_\mu e^j_L + \beta_R^{ij} \bar{d}^i_R \gamma_\mu e^j_R \right) + \text{ h.c. } \right]
\end{aligned}
$$

where $U_{\mu\nu} = \mathcal{D}_\mu U_\nu - \mathcal{D}_\nu U_\mu$, $\mathcal{D}_\mu = \partial_\mu - i g_s G^a_\mu T^a - i\frac{2}{3} g_Y B_\mu$, and the couplings β_L and β_R are complex 3×3 matrices in flavor space.

Where the SM charges for the leptoquark, in the $Y = 2(Q - T_3)$ convention, are

	$\bar{q}_L$	ℓ_L^j	$\bar{q}_L\gamma_\mu\ell_L$	U_1^μ
$U(1)$	$-1/3$	-1	$-4/3$	$+4/3$
SU(2)	$\bar{\mathbf{2}}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
SU(3)	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{3}$

Then, the leptoquark $U_1 \sim (\mathbf{3}_C, \mathbf{1}_I, 4/3_Y)$.

The full Lagrangian for the vector leptoquark is

$$\begin{aligned}\mathcal{L}_U = &-\frac{1}{2}U_{\mu\nu}^\dagger U^{\mu\nu} + M_U^2 U_\mu^\dagger U^\mu - ig_s U_\mu^\dagger T^a U_\nu G_a^{\mu\nu} - \frac{2i}{3}g' U_\mu^\dagger U_\nu B^{\mu\nu} \\ &+ \frac{g_U}{\sqrt{2}}\left[U_1^\mu\left(\beta_L^{ij}\bar{q}_L^i\gamma_\mu e_L^j + \beta_R^{ij}\bar{d}_R^i\gamma_\mu e_R^j\right) + \text{ h.c. }\right]\end{aligned}$$

where $U_{\mu\nu} = \mathcal{D}_\mu U_\nu - \mathcal{D}_\nu U_\mu$, $\mathcal{D}_\mu = \partial_\mu - ig_s G_\mu^a T^a - i\frac{2}{3}g_Y B_\mu$, and the couplings β_L and β_R are complex 3×3 matrices in flavor space.

Constraints from $\Delta F = 2$ and lepton flavor violation impose a hierarchy with dominant third generation couplings:

$$\left|\beta_L^{11}\right|, \left|\beta_L^{12}\right|, \left|\beta_L^{21}\right|, \left|\beta_L^{22}\right|, \left|\beta_L^{31}\right| \ll \left|\beta_L^{13}\right| \ll \left|\beta_L^{23}\right|, \left|\beta_L^{32}\right| \ll \left|\beta_R^{33}\right|, \left|\beta_L^{33}\right| = \mathcal{O}(1), \quad (11)$$

where β_R is diagonal.

Two body scattering

CM-Frame

Consider the process

$$A(\vec{\boldsymbol{p}}_1) + B(\vec{\boldsymbol{p}}_2) \longrightarrow C(\vec{\boldsymbol{p}}_3) + D(\vec{\boldsymbol{p}}_4), \tag{12}$$

From the Golden Rule, the cross section is given by

$$\sigma = \frac{n!(2\pi)^4}{4\sqrt{(\vec{\boldsymbol{p}}_1 \cdot \vec{\boldsymbol{p}}_2)^2 - (m_1 m_2)^2}} \int |\mathcal{M}|^2 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) \frac{d^3\vec{\boldsymbol{p}}_3}{(2\pi)^3 2E_3} \frac{d^3\vec{\boldsymbol{p}}_4}{(2\pi)^3 2E_4}. \tag{13}$$

But, in the CM frame, $\vec{\boldsymbol{p}}_1 + \vec{\boldsymbol{p}}_2 = 0$, where

$$\sqrt{(\vec{\boldsymbol{p}}_1 \cdot \vec{\boldsymbol{p}}_2)^2 - (m_1 m_2)^2} = E_1 E_2 |\vec{\boldsymbol{p}}_1|, \tag{14}$$

$$\delta^{(4)}(p_1 + p_2 - p_3 - p_4) = \delta\left(E_1 + E_2 - E_3 - E_4\right) \delta^{(3)}(\vec{\boldsymbol{p}}_3 + \vec{\boldsymbol{p}}_4). \tag{15}$$

Thus

$$\sigma = \left(\frac{1}{8\pi}\right)^2 \frac{n!}{(E_1 E_2)|\vec{\boldsymbol{p}}_1|} \int |\mathcal{M}|^2 \frac{\delta\left(E_1 + E_2 - \sqrt{\vec{\mathbf{p}}_3^2 + m_3^2} - \sqrt{\vec{\mathbf{p}}_3^2 + m_4^2}\right)}{\sqrt{\vec{\mathbf{p}}_3^2 + m_3^2}\sqrt{\vec{\mathbf{p}}_3^2 + m_4^2}} d\vec{\mathbf{p}}_3 \tag{16}$$

Integrating over the radial part $|\vec{\mathbf{p}}_3|$, we get

$$\sigma = \left(\frac{1}{8\pi}\right)^2 \frac{n!|\vec{\boldsymbol{p}}_3|}{(E_1+E_2)^2|\vec{\boldsymbol{p}}_1|} \int |\mathcal{M}|^2 \mathrm{d}\Omega, \tag{17}$$

with

$$|\vec{\boldsymbol{p}}_3| = \frac{1}{2} \frac{\sqrt{((E_1+E_2)^2 - m_3^2 - m_4^2)^2 - 4m_3^2 m_4^2}}{E_1+E_2}, \tag{18}$$

the outgoing momentum in the CM frame.

We prefer work with differential cross section as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{64\pi^2} \frac{n!}{(E_1+E_2)^2} \frac{|\vec{\boldsymbol{p}}_3|}{|\vec{\boldsymbol{p}}_1|} |\mathcal{M}|^2. \tag{19}$$

Defining $\sqrt{s} = E_1 + E_2$, we have

$$|\vec{\boldsymbol{p}}_3| = \frac{1}{2} \frac{\sqrt{(s - m_3^2 - m_4^2)^2 - 4m_3^2 m_4^2}}{\sqrt{s}}, \quad |\vec{\boldsymbol{p}}_1| = \frac{1}{2} \frac{\sqrt{(s - m_1^2 - m_2^2)^2 - 4m_1^2 m_2^2}}{\sqrt{s}}. \tag{20}$$

so the differential cross section is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{64\pi^2} \frac{n!}{s} \sqrt{\frac{(s-(m_3+m_4)^2)(s-(m_3-m_4)^2)}{(s-(m_1+m_2)^2)(s-(m_1-m_2)^2)}} |\mathcal{M}|^2. \tag{21}$$

Note that at this point, we don't need to know the explicit form of the matrix element $\mathcal{M}$, so it is a generic result.

Writting t in terms of s and θ

In general, there are three Lorentz-invariant useful kinematical variables to describe the scattering process, known as Mandelstam variables:

$$\hat{s} = (p_1 + p_2)^2 = (p_3 + p_4)^2 = m_1^2 + m_2^2 + 2p_1^\mu p_{2\mu} = m_3^2 + m_4^2 + 2p_3^\mu p_{4\mu}, \tag{22}$$

$$\hat{t} = (p_1 - p_3)^2 = (p_2 - p_4)^2 = m_1^2 + m_3^2 - 2p_1^\mu p_{3\mu} = m_2^2 + m_4^2 - 2p_2^\mu p_{4\mu}, \tag{23}$$

$$\hat{u} = (p_1 - p_4)^2 = (p_2 - p_3)^2 = m_1^2 + m_4^2 - 2p_1^\mu p_{4\mu} = m_2^2 + m_3^2 - 2p_2^\mu p_{3\mu}. \tag{24}$$

In the CM-frame, $\hat{s} = s = (E_1 + E_2)^2$. If, $m_3 = m_4$ and $m_1 = m_2$ with $E_1 = E_2 = E_3 = E_4 = E$, we have

$$t = -\left(\vec{\mathbf{p}}_1 - \vec{\mathbf{p}}_3\right)^2 = -\vec{\mathbf{p}}_1^2 - \vec{\mathbf{p}}_3^2 + 2\vec{\mathbf{p}}_1\vec{\mathbf{p}}_3 \tag{25}$$

where $\vec{\mathbf{p}}_1^2 = E^2 - m_1^2$ and $\vec{\mathbf{p}}_3^2 = E^2 - m_3^2$.

So, in terms of s, t could be written as

$$t = -2s + (m_1^2 + m_3^2) + 2\sqrt{(s/4 - m_1^2)(s/4 - m_3^2)}\cos\theta, \tag{26}$$

with θ the scattering angle in the CM-frame.