Probing light scalars and vector-like quarks at the high-luminosity LHC

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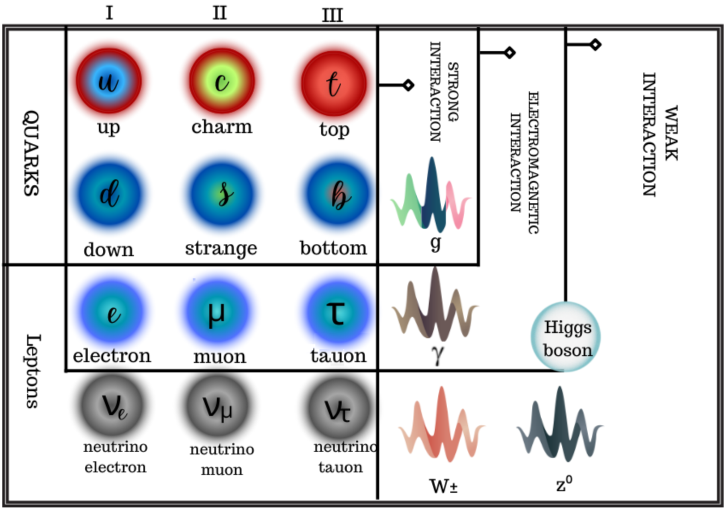
Outline

1. Motivation
   - $B - L$ Symmetry
2. The $U(1)_{T_R^3}$ Gauge Symmetry
3. Experimental Signatures

The Standard Model of Particle Physics



Standard Model Charges (1 Generation)

SM is free of gauge anomalies, which are cancellations of gauge charges in fermion loops. And has two accidental global symmetries: $U(1)_B$ and $U(1)_L$.

Fermion	$SU(3)_c$	$SU(2)_L$	B	L	Y	Q	$B-L$	T^3_L
ν_{eL}	**1**	**2**	0	+1	-1	0	-1	$+\frac{1}{2}$
e_L	**1**	**2**	0	+1	-1	-1	-1	$-\frac{1}{2}$
u_L	**3**	**2**	$\frac{1}{3}$	0	$\frac{1}{3}$	$\frac{2}{3}$	$\frac{1}{3}$	$+\frac{1}{2}$
d_L	**3**	**2**	$\frac{1}{3}$	0	$\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$
e_R	**1**	**1**	0	+1	-2	-1	-1	0
u_R	**3**	**1**	$\frac{1}{3}$	0	$\frac{4}{3}$	$\frac{2}{3}$	$\frac{1}{3}$	0
d_R	**3**	**1**	$\frac{1}{3}$	0	$-\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	0

Could we extend the SM with a new $U(1)$ gauge symmetry related to the accidental global symmetries $U(1)_B$ and $U(1)_L$?

Group Symmetry	$[SU(3)_c]^2U(1)$	$[SU(2)_L]^2U(1)$	**Anomaly-Free?**
$U(1)_B$	$1 \neq 0$	$1 \neq 0$	No
$U(1)_L$	0	$1 \neq 0$	No
$U(1)_{B-L}$	0	0	Yes -> could be gauge symmetry

A possible explanation for the hypercharge of SM fermions

From the EWSB point of view, where the EM gauge group is a subgroup of the electroweak gauge group, which breaks down from $SU(2)_L \times U(1)_Y$ to $U(1)_{\mathrm{EM}}$.
In SM the electric charge is given by the Gell-Mann-Nishijima formula:

$$\hat{Q}_{\mathrm{EM}} = \hat{T}^3_{\mathrm{L}} + \frac{\hat{Y}}{2} \tag{1}$$

where T^3_{L} is the third component of the weak isospin $SU(2)_L$ and Y is the hypercharge of the $U(1)_Y$ gauge group.
For example, for the left-handed electron component:

$$\hat{Q}_{\mathrm{EM}}(e_L) = \hat{T}^3_{\mathrm{L}}(e_L) + \frac{\hat{Y}(e_L)}{2} = \left(-\frac{1}{2} - \frac{1}{2}\right) e_L = (-1)e_L \tag{2}$$

Y values seem arbitrary in SM. Can Y emerge from deeper principles and recover some chiral structure?
If we use the same isospin values for the left-handed fermions, for the right-handed fermions but as a new symmetry $U(1)_{T^3_R}$, we can write the following relation:

$$\hat{Y} = 2\hat{T}^3_{\mathrm{R}} + \frac{\hat{B} - \hat{L}}{2} \tag{3}$$

and the electric charge is given by:

$$\hat{Q}_{\mathrm{EM}} = \hat{T}^3_{\mathrm{L}} + \hat{T}^3_{\mathrm{R}} + \frac{\hat{B} - \hat{L}}{4} \tag{4}$$

The challenge of the $U(1)_{T^3_R}$ Gauge Symmetry

Add a $U(1)_{T^3_R}$ gauge add a lot of complications:

- Which is the origin of the hyptercharge of the Higgs doublet?

$$\hat{Y} = 2\hat{T}^3_{\mathrm{R}} + \frac{\hat{B} - \hat{L}}{2} + \hat{Q}_G \tag{5}$$

A dark sector or discard the connection between the hypercharge and the new gauge symmetry is needed.

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Sub-GeV dark matter model

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(Received 4 June 2019; published 22 October 2019)

Add a $U(1)_{T^3_R}$ gauge add a lot of complications:

- A new gauge boson is needed, and it is not near to the electroweak scale.

$$m_V \propto g_V$$

It could be a dark photon with small mass and coupling, or a Z' boson with mass in the TeV range.

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THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Theoretical Physics

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

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Contributions to ΔN_{eff} from the dark photon of $U(1)_{T3R}$

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(Received 10 February 2020; accepted 30 June 2020; published 16 July 2020)

A new electroweak symmetry breaking scale is needed, a new scalar ϕ is needed.

$$\begin{aligned}\mathcal{V}(\phi, H) &= \mu_H^2 H^\dagger H + \mu_\phi^2 \phi^* \phi \\ &\quad + \lambda \left(H^\dagger H\right)(\phi^* \phi) + \lambda_H \left(H^\dagger H\right)^2 + \lambda_\phi (\phi^* \phi)^2 \,.\end{aligned} \tag{6}$$

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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

$$H = \begin{pmatrix} G_+ \\ \frac{1}{\sqrt{2}}\left(v_h + \rho_0 + iG_0\right) \end{pmatrix} \tag{7}$$

$$\phi = \frac{1}{\sqrt{2}}\left(v_\phi + \rho_\phi + iG_\phi\right) . \tag{8}$$

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This give us a matrix mass term for the scalar fields:

$$m_{mH} = \begin{pmatrix} 2\lambda_H v_h^2 & \lambda_{\phi h} v_h v_\phi \\ \lambda v_h v_\phi & 2\lambda_\phi v_\phi \end{pmatrix} \tag{9}$$

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$$\mathcal{V}(\phi,H) = \mu_H^2 H^\dagger H + \mu_\phi^2 \phi^*\phi + \lambda\left(H^\dagger H\right)(\phi^*\phi) + \lambda_H\left(H^\dagger H\right)^2 + \lambda_\phi(\phi^*\phi)^2 \,. \tag{6}$$

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The ρ_h and ρ_ϕ are an orthogonal mixture of the SM Higgs boson and the dark Higgs

$$\begin{pmatrix} h \\ \phi' \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} \rho_0 \\ \rho_\phi \end{pmatrix}, \tag{10}$$

that results from the diagonalization of the mass matrix.

We need to add right-handed neutrinos

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{T^3_R}$
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	-1
d^c_R	**3**	**1**	1/3	1
ℓ^c_R	**1**	**1**	1	1
ν^c_R	**1**	**1**	0	-1
ϕ	**1**	**1**	0	1

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u^c_R	**3**	**1**	-2/3	-1
d^c_R	**3**	**1**	1/3	1
ℓ^c_R	**1**	**1**	1	1
ν^c_R	**1**	**1**	0	-1
ϕ	**1**	**1**	0	1

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

$$\mathcal{L}_{\text{Yukawa}} = \underbrace{-y_e \bar{L}_L \Phi e_R}_{\text{Lepton Yukawa}} + \underbrace{-y_d \bar{Q}_L \Phi d_R}_{\text{Down quark Yukawa}} + \underbrace{-y_u \bar{Q}_L \tilde{\Phi} u_R}_{\text{Up quark Yukawa}} + \text{h.c.} \tag{11}$$

so $y_u = y_d = y_e = 0$ is mandatory. So the masses of the SM fermions are generated by a new mechanism.

The Universal Seesaw Mechanism

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,

$$-\mathcal{L} \supset Y_{f_L} \bar{f}'_L \chi'_{fR} H + Y_{f_R} \bar{\chi}'_{fL} f'_R \phi^* + m_{\chi'_f} \bar{\chi}'_{fL} \chi'_{fR} + \text{h.c.} \tag{12}$$

Therefore, in the vacuum, the mass matrix is

$$M_f = \begin{pmatrix} 0 & Y_{f_L} v_h/\sqrt{2} \\ Y_{f_R} v_\phi/\sqrt{2} & m_{\chi'_f} \end{pmatrix}. \tag{13}$$

The left- and right-handed components of the physical fermions $(f,\ \chi_f)$ are given by two rotations $\mathcal{R}(\theta_{f_{L,R}})$ as,

$$\begin{pmatrix} f_{L,R} \\ \chi_{f_{L,R}} \end{pmatrix} = \begin{pmatrix} \pm\cos\theta_{f_{L,R}} & \mp\sin\theta_{f_{L,R}} \\ \sin\theta_{f_{L,R}} & \cos\theta_{f_{L,R}} \end{pmatrix} \begin{pmatrix} f'_{L,R} \\ \chi'_{f_{L,R}} \end{pmatrix}, \tag{14}$$

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.

The Universal Seesaw Mechanism

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

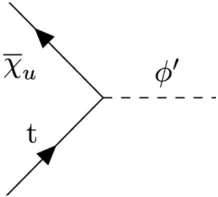
$$-\mathcal{L}_{\text{yuk}} = h\bar{\psi}_{f_L}\mathcal{Y}_h\psi_{f_R} + \phi'\bar{\psi}_{f_L}\mathcal{Y}_\phi\psi_{f_R}, \tag{15}$$

with $\psi_f = (f, \chi_f)^T$, and the matrices $\mathcal{Y}_{f_{L,R}}$ given by

$$\mathcal{Y}_h = \frac{1}{\sqrt{2}}\mathcal{R}(\theta_{f_L})\left(Y_{f_L}\sigma_+ \cos\alpha - Y_{f_R}\sigma_- \sin\alpha\right)\mathcal{R}^{-1}(\theta_{f_R}) \tag{16}$$

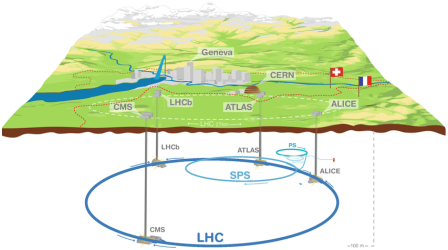
$$\mathcal{Y}_\phi = \frac{1}{\sqrt{2}}\mathcal{R}(\theta_{f_L})\left(Y_{f_L}\sigma_+ \sin\alpha + Y_{f_R}\sigma_- \cos\alpha\right)\mathcal{R}^{-1}(\theta_{f_R}), \tag{17}$$

where $\sigma_\pm = (\sigma_1 \pm i\sigma_2)/2$ are the ladder Pauli matrices.
So, you have new vertex like



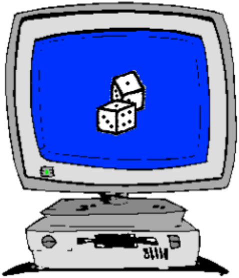
Large Hadron Collider

How can we test the leptoquark hypothesis?



- A Feasibility Study is needed.
- Take Care on the dependence on the different parameters.
- Take care on the content of particles.
- Take care of the signal composition.
- Take care on interference effects.

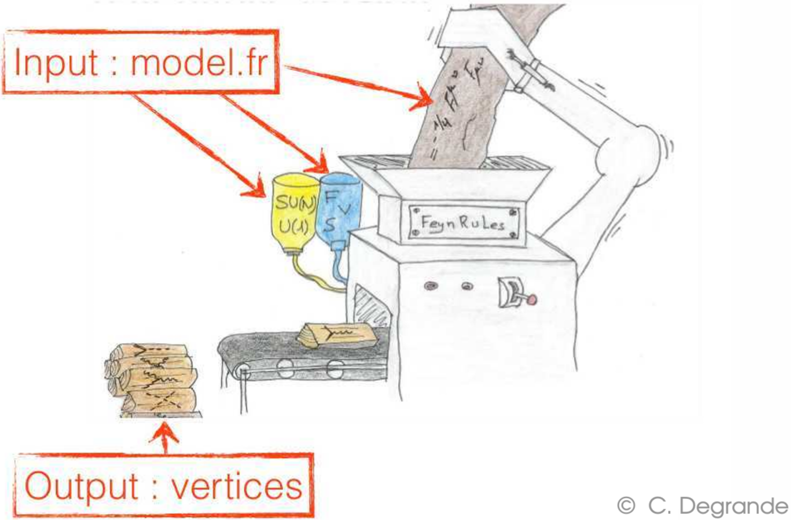
Montecarlo Generators



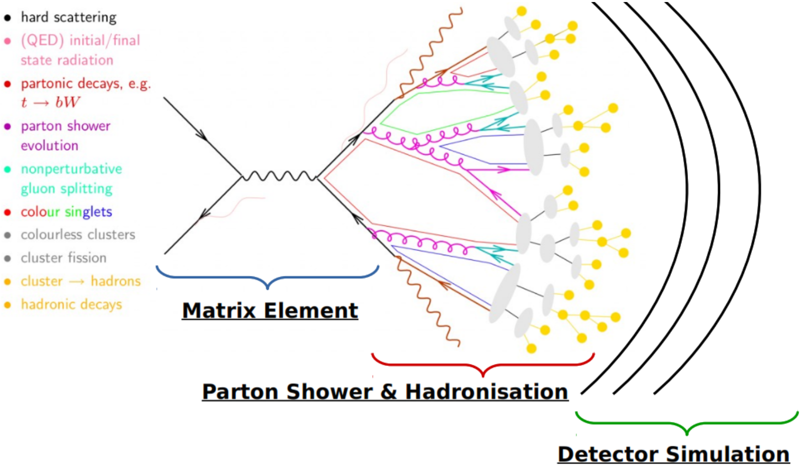
Useful to predict what we expect to see under certain conditions:

- To perform studies before having the data
- To compute event selection efficiency/acceptance
- To predict the ammount and composition of background events
- To distinguish different signals.

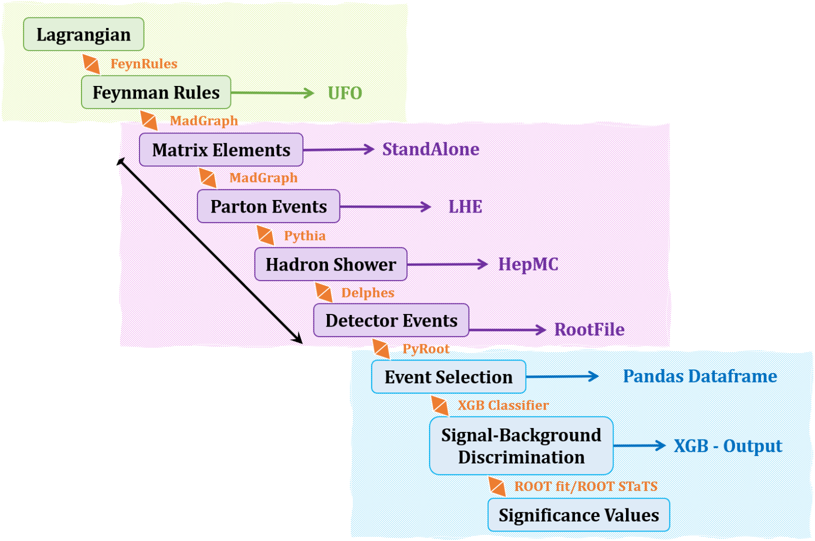
Feynrules


Input : model.fr
SU(N)
U(1)
F
V
S
FeynRules
Output : vertices
© C. Degrande

Madgraph-Pythia8-Delphes for the LHC



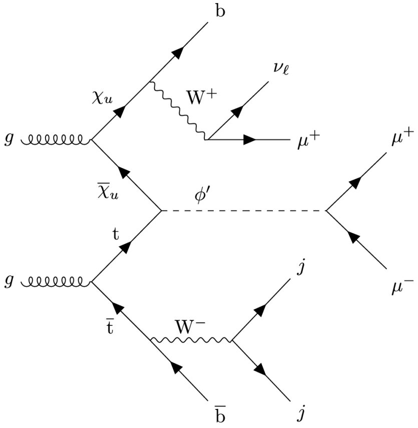
Feasibility Studies Workflow



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.

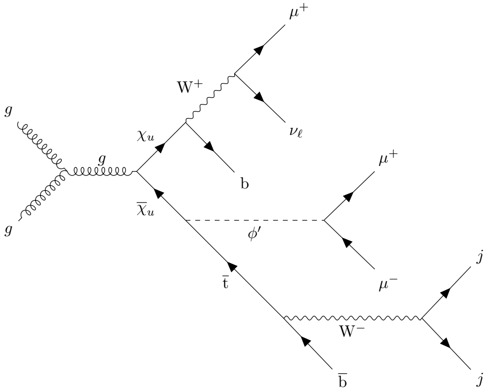


The ϕ' decays to a pair of muons, the top quark decays fully hadronically, and the χ_{u} decays semi-leptonically to muons, neutrinos and b-jets.

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

Cross Section

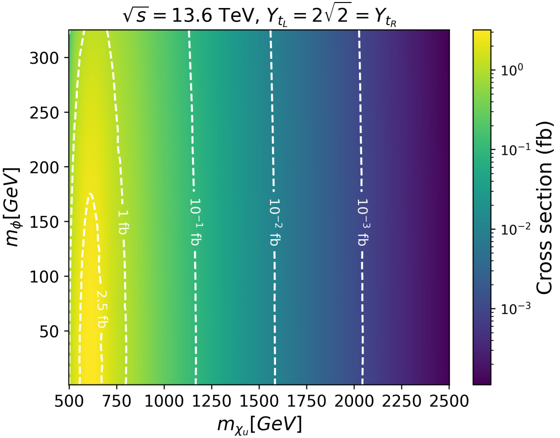
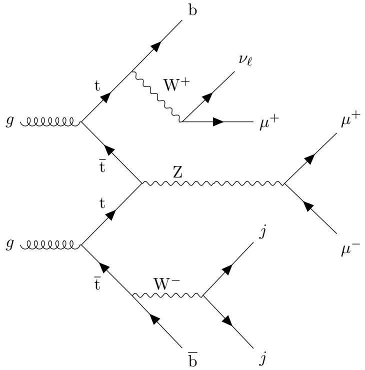


Fig.: Projected cross section (fb) plot for $pp \to t\chi_u\phi'$ and subsequent decay as a function of $m(\chi_u)$ and $m(\phi')$.

Feasible Experimental Signatures

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

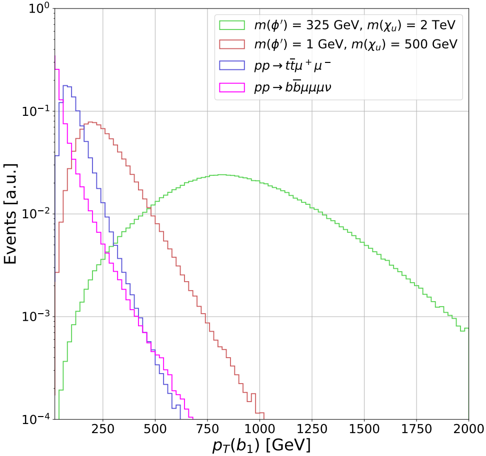


Fig.: Transverse momentum distribution of the leading b-quark jet candidate. The distributions are shown for the two main SM background processes and two signal benchmark points.

Feasible Experimental Signatures

Kinematic Variables

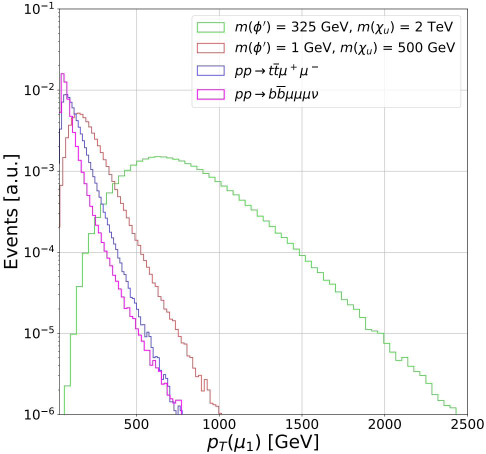


Fig.: Transverse momentum distribution of the leading muon candidate. The distributions are shown for the two main SM background processes and two signal benchmark points.

Feasible Experimental Signatures

Kinematic Variables

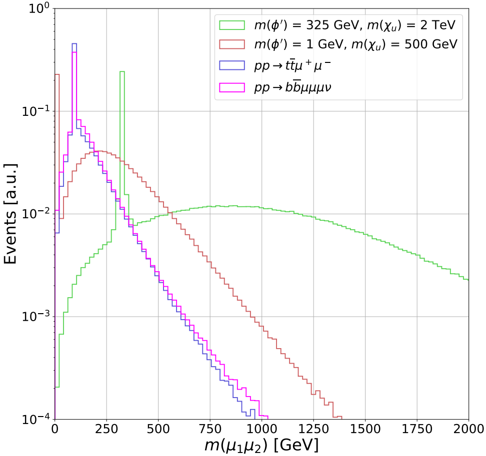


Fig.: Invariant mass distribution of the muon pair with the highest and second highest transverse momentum. The distributions are shown for the two main SM background processes and two signal benchmark points.

Feasible Experimental Signatures

Gradient Boosting

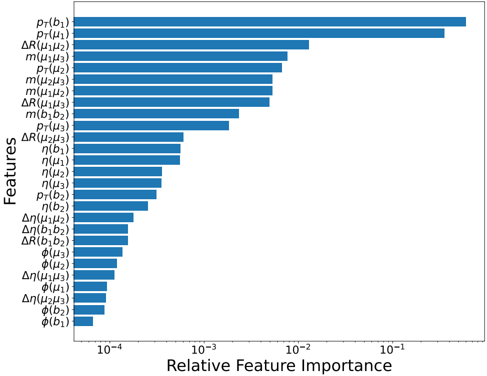


Fig.: Relative importance of features in training for a benchmark signal scenario with $m(\phi') = 325\,\text{GeV}$ and $m(\chi_u) = 2000\,\text{GeV}$.

Feasible Experimental Signatures

Gradient Boosting

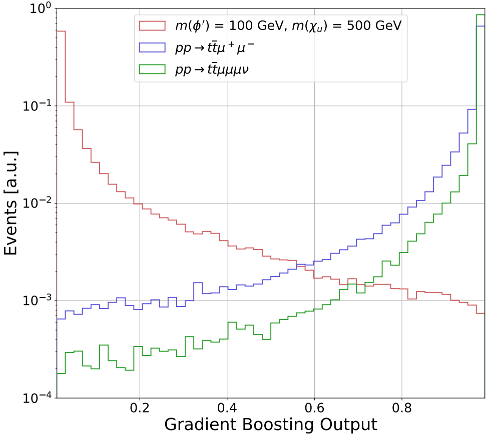


Fig.: Output of the gradient boosting algorithm for a benchmark $m(\phi') = 100$ GeV and $m(\chi_\mathrm{u}) = 500$ GeV signal, and dominant backgrounds. The distributions are normalized to unity.

Hypothesis Testing

In a distribution of events, the data follows a Poisson distribution (they are independent events), so the likelihood function is given by the Poisson distribution:

$$\mathcal{L}(n_i \mid \lambda_i) = \frac{e^{-\lambda_i}\lambda_i^{n_i}}{n_i!}, \quad \text{where } \lambda_i = \begin{cases} b_i & \text{for } H_0, \\ s_i + b_i & \text{for } H_1. \end{cases} \tag{18}$$

The best discriminator is the ratio of the likelihoods,

$$\mathrm{Q}_1 = \frac{\mathcal{L}\left(\mathrm{n}_1 \mid \mathrm{s}_1 + \mathrm{b}_1\right)}{\mathcal{L}\left(\mathrm{n}_1 \mid \mathrm{b}_1\right)} = e^{-s_1}\left(1 + \frac{s_1}{b_1}\right)^{n_1}, \tag{19}$$

The total likelihood is $Q = \prod_{i=1}^{N} Q_i$. To simplify we define the χ^2 like test as

$$t = -2\ln Q = \sum_{i=1}^{N}\left[2s_i - 2n_i w_i\right] \tag{20}$$

so, the sensitivity of our analysis is given by the difference between the expected number of events in the signal and background hypotheses

$$\kappa = \frac{\langle t|t\rangle_{H_0} - \langle t|t\rangle_{H_1}}{\sigma_{H_1}} = \frac{\sum s_i w_i}{\sqrt{\sum (s_i + b_i) w_i^2}} \tag{21}$$

The number of events is estimated from $N = \epsilon\sigma\mathcal{L}$, where ϵ is the efficiency of the selection, σ is the cross section and $\mathcal{L}$ is the integrated luminosity.

Signal Significance

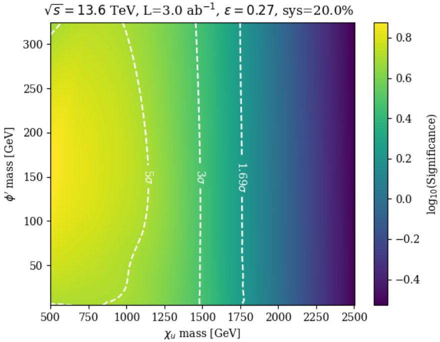


Fig.: Signal significance for the high luminosity LHC era, considering with 3000 fb^{-1} of collected data.

Reference

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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Probing light scalars and vector-like quarks at the high-luminosity LHC

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