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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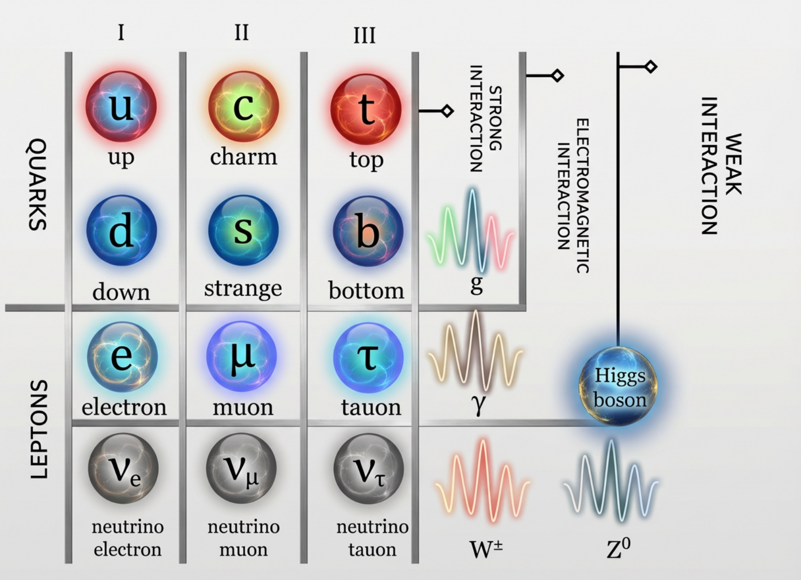
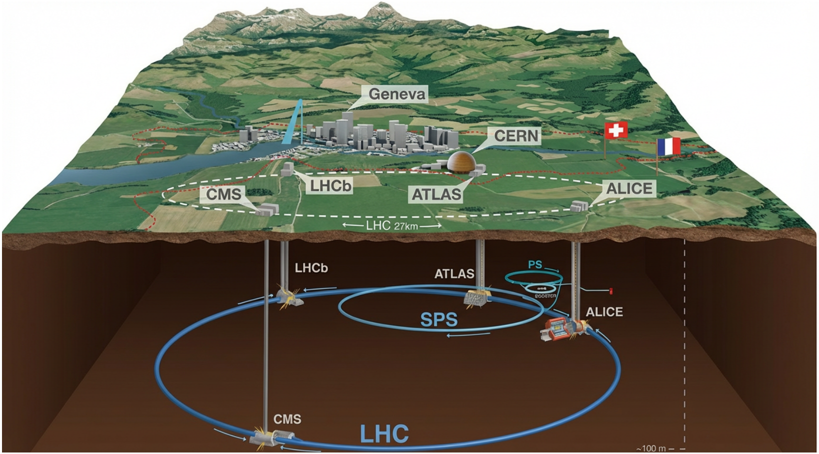
Outline

Introduction

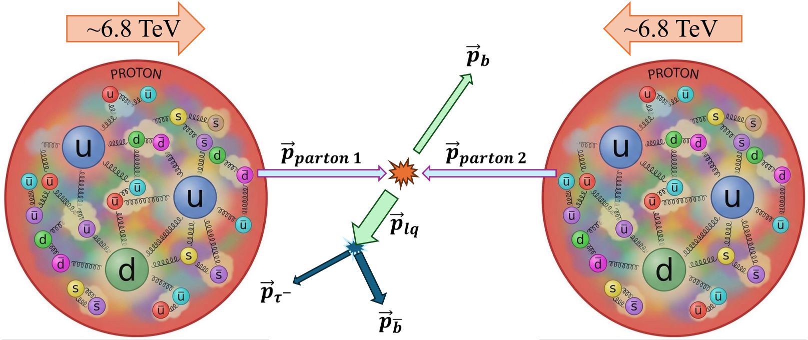
Standard Model of Particle Physics



LHC.


Geneva
CERN
LHCb
CMS
ATLAS
ALICE
LHC 27km
LHCb
ATLAS
PS
ALICE
SPS
CMS
LHC
~100 m

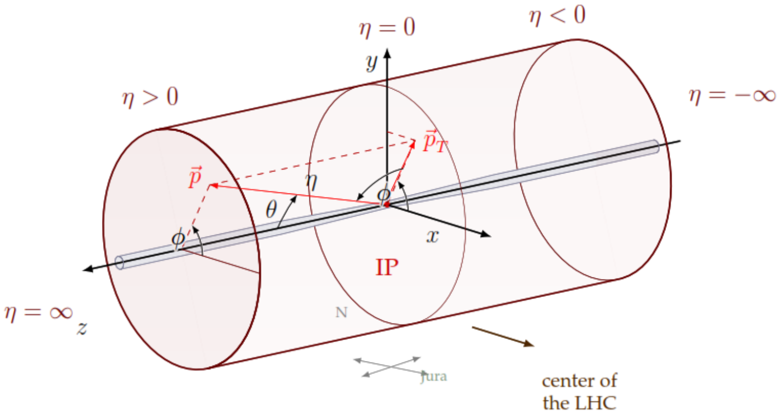
The Quark-Gluon Sea



Kinematic Variables

From Spherical coordinates,

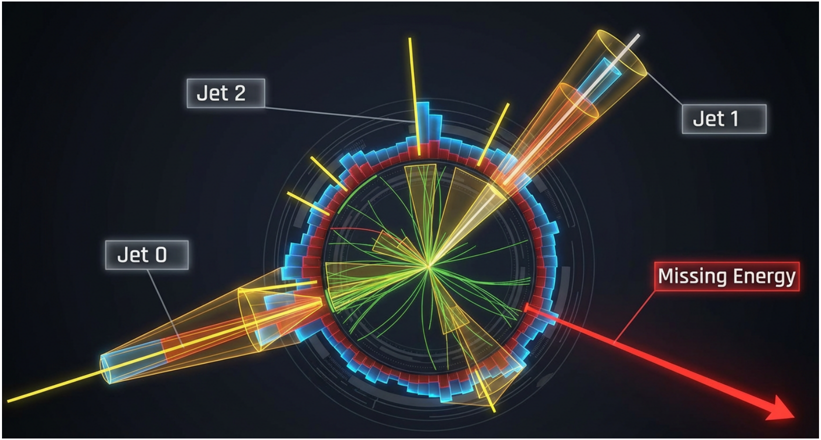
$$\begin{cases} \text{Pseudorapidity: } \eta = -\ln\tan(\theta/2) \\ \text{Transverse momentum: } p_T = p\sin(\theta) \\ \text{Azimuthal angle: } \phi \\ \text{Deposited energy: } E \end{cases}$$



Example of a Event in the CMS Detector

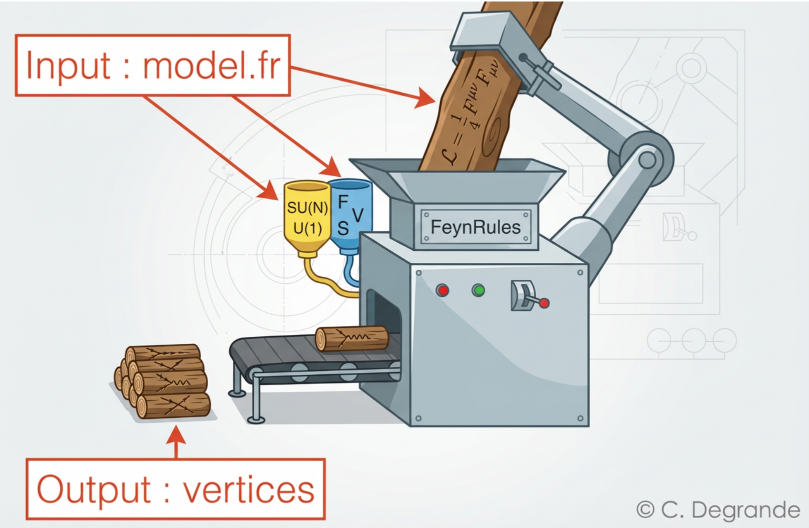
There is not initial momentum in the transverse plane, so from the conservation of momentum, we define the missing transverse momentum as

$$\vec{p}_T^{\,\text{mis}} = -\sum_i \vec{p}_{T,i}^{\,\text{vis}}$$



Phenomenological Framework

Feynrules


Input : model.fr
$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu}$
SU(N)
U(1)
F
V
S
FeynRules
Output : vertices
© C. Degrande

Machine Learning in High Energy Physics

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

To do ADD production channel diagrams

Feasible Experimental Signatures

Cross Section

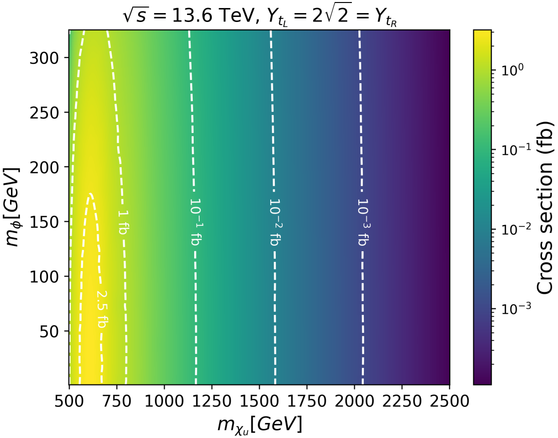
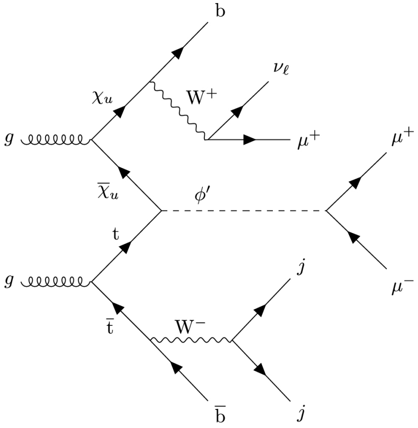


Fig.: Projected cross section (fb) plot for $pp \to t\chi_u\phi'$ and subsequent decay as a function of $m(\chi_u)$ and $m(\phi')$.

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.

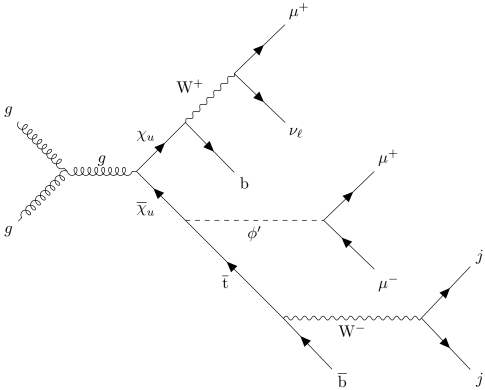


The ϕ' decays to a pair of muons, the top quark decays fully hadronically, and the χ_u decays semi-leptonically to muons, neutrinos and b-jets.

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.

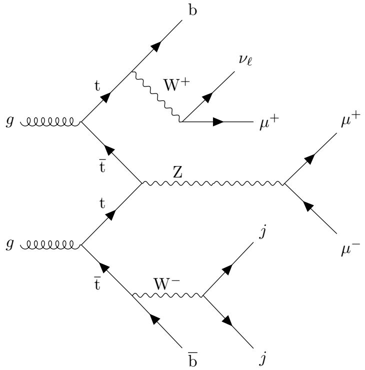


The ϕ' decays to a pair of muons, the top quark that decays fully hadronically, and the χ_u decay semi-leptonically to muons, neutrinos and jets.

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

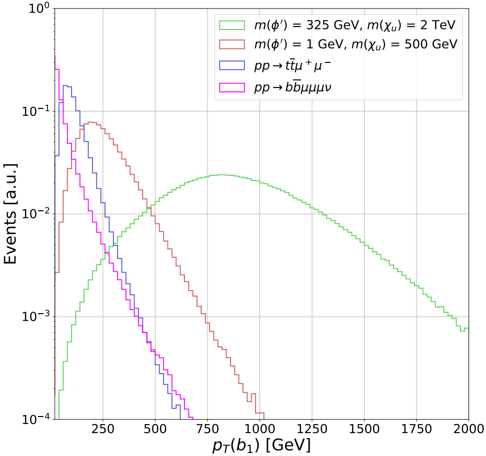


Fig.: Transverse momentum distribution of the leading b-quark jet candidate. The distributions are shown for the two main SM background processes and two signal benchmark points.

Feasible Experimental Signatures

Kinematic Variables

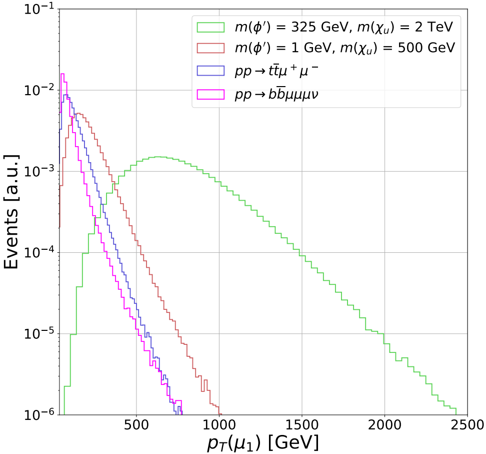


Fig.: Transverse momentum distribution of the leading muon candidate. The distributions are shown for the two main SM background processes and two signal benchmark points.

Feasible Experimental Signatures

Kinematic Variables

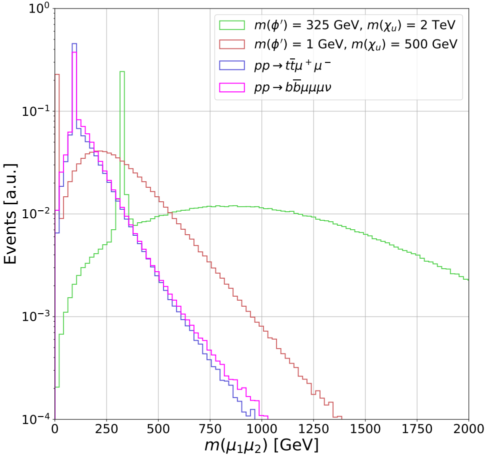


Fig.: Invariant mass distribution of the muon pair with the highest and second highest transverse momentum. The distributions are shown for the two main SM background processes and two signal benchmark points.

Feasible Experimental Signatures

Gradient Boosting

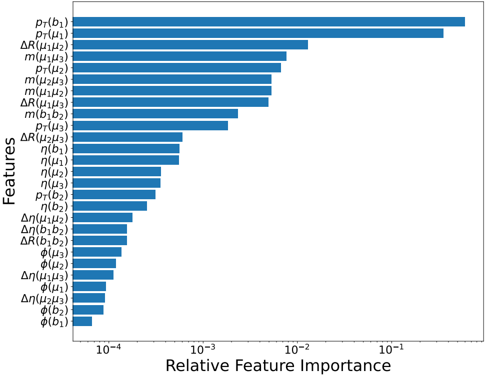


Fig.: Relative importance of features in training for a benchmark signal scenario with $m(\phi') = 325\,\text{GeV}$ and $m(\chi_u) = 2000\,\text{GeV}$.

Feasible Experimental Signatures

Gradient Boosting

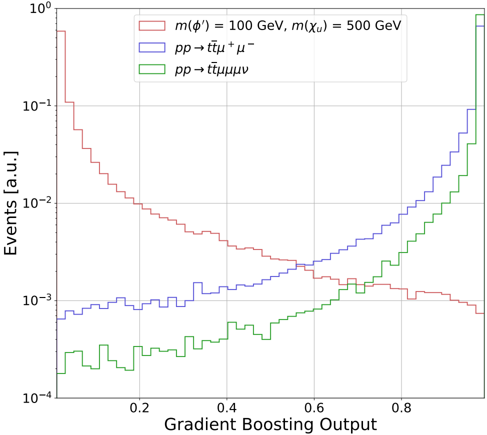


Fig.: Output of the gradient boosting algorithm for a benchmark $m(\phi') = 100$ GeV and $m(\chi_u) = 500$ GeV signal, and dominant backgrounds. The distributions are normalized to unity.

Signal Significance

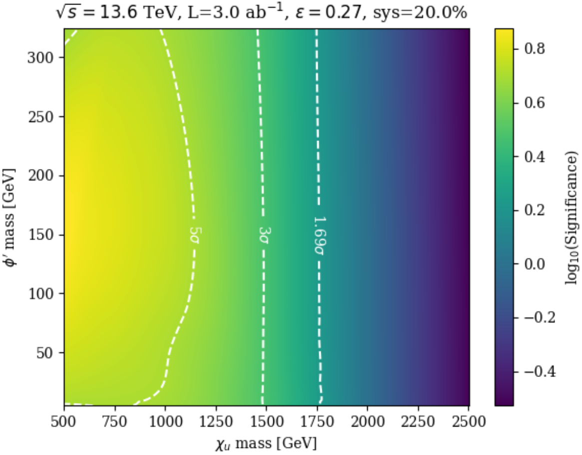
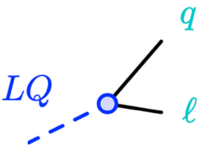


Fig.: Signal significance for the high luminosity LHC era, considering with 3000 fb^{-1} of collected data.

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.

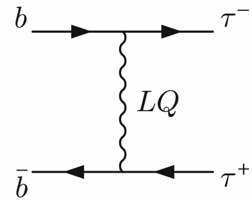


If U_1 is a vector leptoquark that preserves the chirality on the vertex, we expect an interaction term like

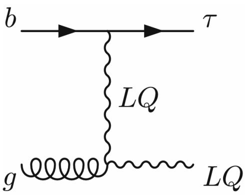
$$\sim \beta_L U_1^{\mu} \bar{q}_L \gamma_\mu \ell_L,$$

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

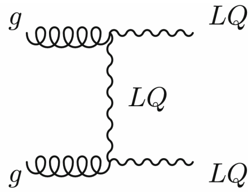
$$\sim \beta_R U_1^{\mu} \bar{d}_R \gamma_\mu e_R.$$



Non-resonant

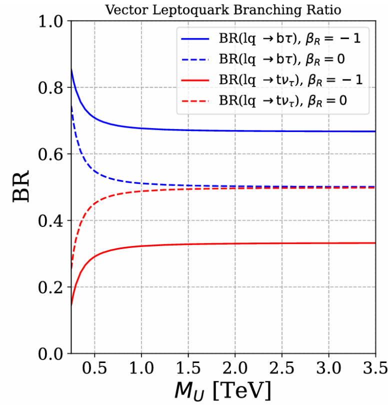


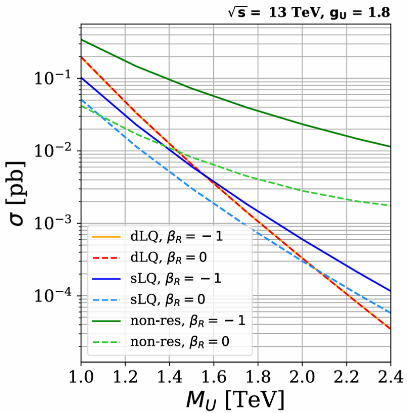
Single LQ



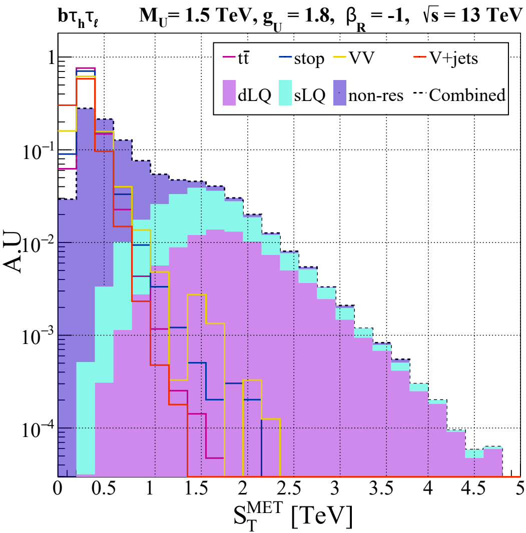
Double LQ

Leptoquark Production at pp Colliders

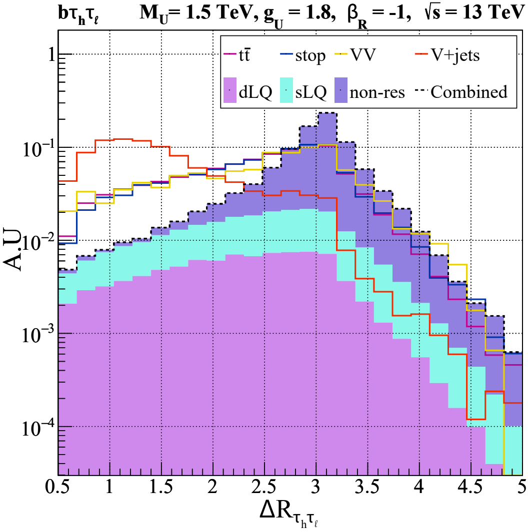




$S_T^{\mathrm{meT}} = \mathrm{met} + \sum_i |p_T^i|$



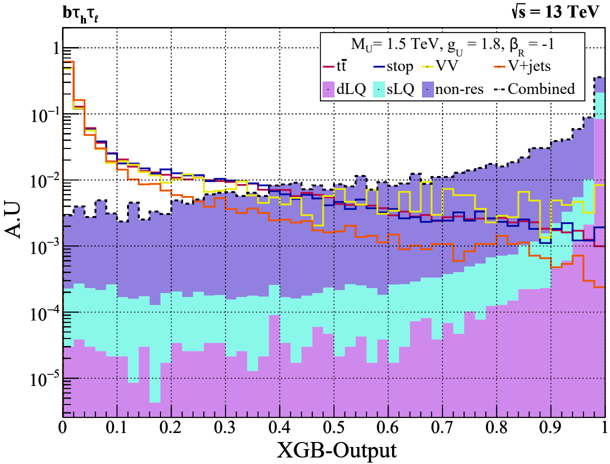
$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$



The optimized observable

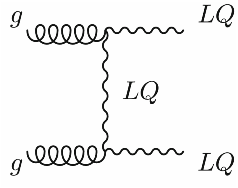
XGB-output

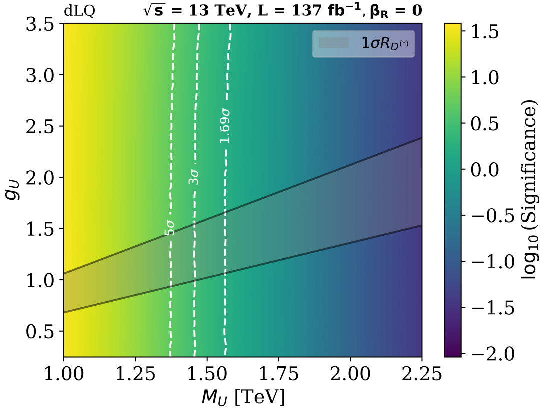
We can evaluate a score for the signal and background events using the discriminator algorithm.



Double Leptoquark Production

The Sensitivity Reach / only left-handed currents

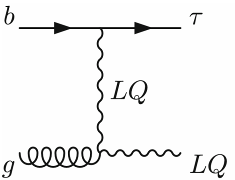


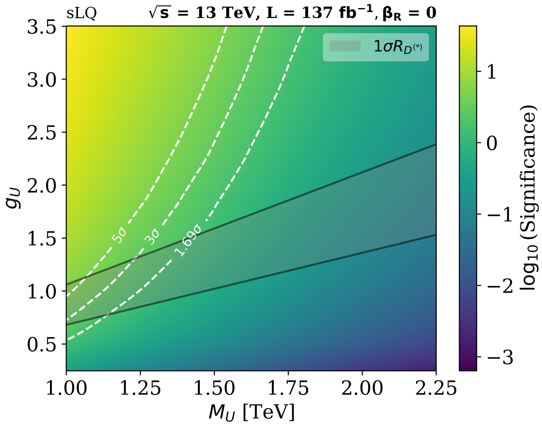


Double leptoquark production is sensitive to the leptoquark mass, its production depends only on the QCD coupling constant and the available energy.

Single leptoquark production

The Sensitivity Reach / only left-handed currents

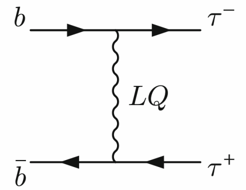


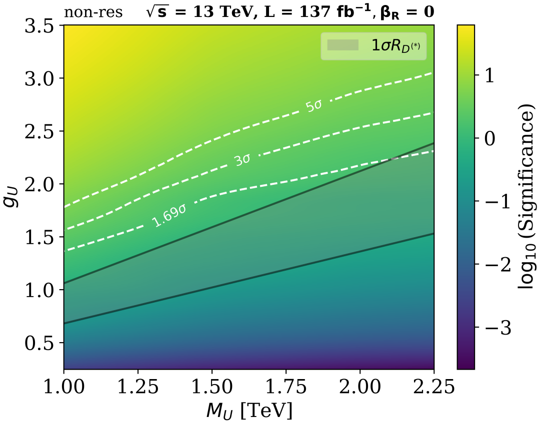


Single leptoquark production is sensitive to both, mass and couplings. It contributes to the regions of high coupling constants at higher masses than double leptoquark production.

Non-resonant Production

The Sensitivity Reach / only left-handed currents

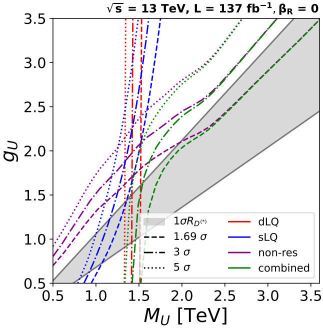




Non-resonant production is highly dependent on the couplings, so it dominates the regions of high coupling constants at all masses.

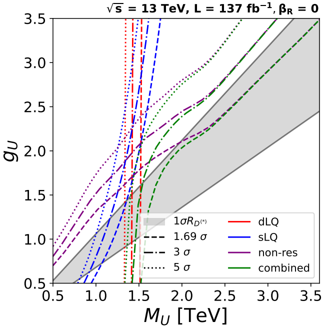
Combined Sensitivity Reach

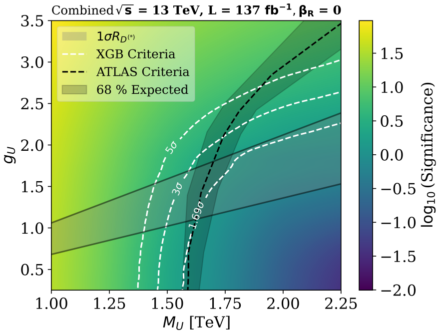
The Sensitivity Reach / only left-handed currents



Combined Sensitivity Reach

The Sensitivity Reach / only left-handed currents

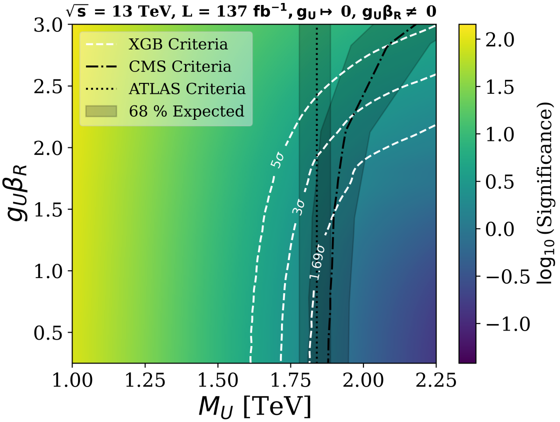




The sensitivity of all signal production processes combined compares our expected exclusion region with the latest one from the ATLAS Collaboration [ArXiv:2305.15962], but we suggest better sensitivity for high coupling constants.

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

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

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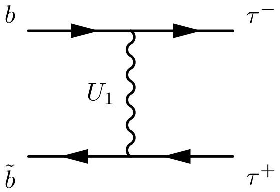
So, the gauge group with this leptoquark must include a $U(1)_{B-L}$ symmetry (The right-handed currents also have a similar interaction term).

The interaction terms for the Z' boson have the form

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

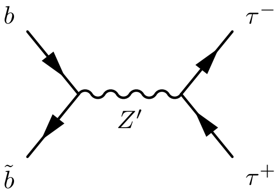
Interference with a Z' vector boson

Non-Resonant Production (leptoquarks)



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

Resonant Production (neutral bosons)



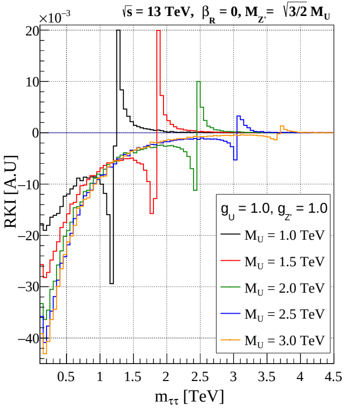
$$\mathcal{M}_{Z'} \sim \frac{1}{s - m_{Z'}^2 + i m_{Z'} \Gamma_{Z'}}, \qquad (2)$$

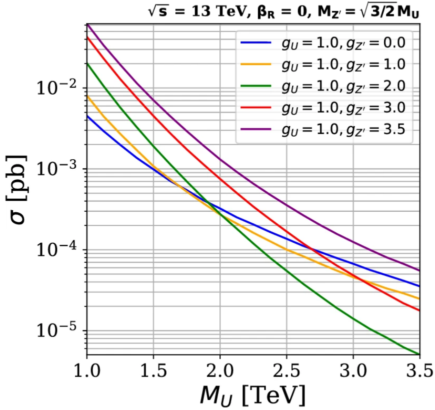
so the interference has the form

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

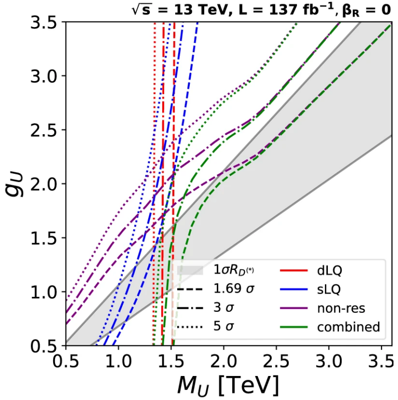
Similary for Polarized final states.

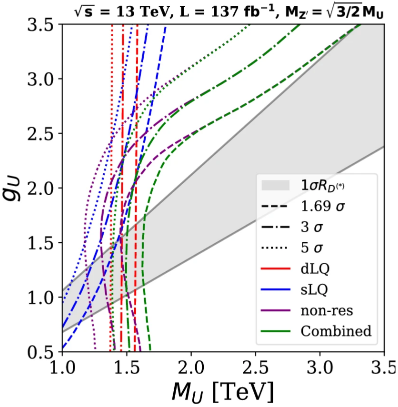
Interference with a Z' vector boson





Effects on the Sensitivity reach





Summary and Conclusions

Backup Slides

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

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

The full Lagrangian for the vector leptoquark is

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

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
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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 $U_{\mu\nu} = \mathcal{D}_\mu U_\nu - \mathcal{D}_\nu U_\mu$, $\mathcal{D}_\mu = \partial_\mu - ig_s G_\mu^a T^a - i\frac{2}{3}g_Y B_\mu$, 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:

$$\left|\beta_L^{11}\right|, \left|\beta_L^{12}\right|, \left|\beta_L^{21}\right|, \left|\beta_L^{22}\right|, \left|\beta_L^{31}\right| \ll \left|\beta_L^{13}\right| \ll \left|\beta_L^{23}\right|, \left|\beta_L^{32}\right| \ll \left|\beta_R^{33}\right|, \left|\beta_L^{33}\right| = \mathcal{O}(1), \quad (3)$$

where β_R is diagonal.

Two body scattering
CM-Frame

Consider the process

$$A(\vec{p}_1) + B(\vec{p}_2) \longrightarrow C(\vec{p}_3) + D(\vec{p}_4), \tag{4}$$

From the Golden Rule, the cross section is given by

$$\sigma = \frac{n!(2\pi)^4}{4\sqrt{(\vec{p}_1 \cdot \vec{p}_2)^2 - (m_1 m_2)^2}} \int |\mathcal{M}|^2 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) \frac{d^3\vec{p}_3}{(2\pi)^3 2E_3} \frac{d^3\vec{p}_4}{(2\pi)^3 2E_4}. \tag{5}$$

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

$$\sqrt{(\vec{p}_1 \cdot \vec{p}_2)^2 - (m_1 m_2)^2} = E_1 E_2 |\vec{p}_1|, \tag{6}$$

$$\delta^{(4)}(p_1 + p_2 - p_3 - p_4) = \delta\left(E_1 + E_2 - E_3 - E_4\right) \delta^{(3)}(\vec{p}_3 + \vec{p}_4). \tag{7}$$

Thus

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

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

$$\sigma = \left(\frac{1}{8\pi}\right)^2 \frac{n!|\vec{\boldsymbol{p}}_3|}{(E_1+E_2)^2|\vec{\boldsymbol{p}}_1|} \int |\mathcal{M}|^2 \mathrm{d}\Omega, \tag{9}$$

with

$$|\vec{\boldsymbol{p}}_3| = \frac{1}{2}\frac{\sqrt{((E_1+E_2)^2 - m_3^2 - m_4^2)^2 - 4m_3^2 m_4^2}}{E_1+E_2}, \tag{10}$$

the outgoing momentum in the CM frame.

We prefer work with differential cross section as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{64\pi^2}\frac{n!}{(E_1+E_2)^2}\frac{|\vec{\boldsymbol{p}}_3|}{|\vec{\boldsymbol{p}}_1|}|\mathcal{M}|^2. \tag{11}$$

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

$$|\vec{\boldsymbol{p}}_3| = \frac{1}{2}\frac{\sqrt{(s - m_3^2 - m_4^2)^2 - 4m_3^2 m_4^2}}{\sqrt{s}}, \quad |\vec{\boldsymbol{p}}_1| = \frac{1}{2}\frac{\sqrt{(s - m_1^2 - m_2^2)^2 - 4m_1^2 m_2^2}}{\sqrt{s}}. \tag{12}$$

so the differential cross section is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{64\pi^2}\frac{n!}{s}\sqrt{\frac{(s-(m_3+m_4)^2)(s-(m_3-m_4)^2)}{(s-(m_1+m_2)^2)(s-(m_1-m_2)^2)}}|\mathcal{M}|^2. \tag{13}$$

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:

$$\hat{s} = (p_1 + p_2)^2 = (p_3 + p_4)^2 = m_1^2 + m_2^2 + 2p_1^\mu p_{2\mu} = m_3^2 + m_4^2 + 2p_3^\mu p_{4\mu}, \tag{14}$$

$$\hat{t} = (p_1 - p_3)^2 = (p_2 - p_4)^2 = m_1^2 + m_3^2 - 2p_1^\mu p_{3\mu} = m_2^2 + m_4^2 - 2p_2^\mu p_{4\mu}, \tag{15}$$

$$\hat{u} = (p_1 - p_4)^2 = (p_2 - p_3)^2 = m_1^2 + m_4^2 - 2p_1^\mu p_{4\mu} = m_2^2 + m_3^2 - 2p_2^\mu p_{3\mu}. \tag{16}$$

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

$$t = -\left(\vec{\mathbf{p}}_1 - \vec{\mathbf{p}}_3\right)^2 = -\vec{\mathbf{p}}_1^2 - \vec{\mathbf{p}}_3^2 + 2\vec{\mathbf{p}}_1\vec{\mathbf{p}}_3 \tag{17}$$

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

$$t = -2s + (m_1^2 + m_3^2) + 2\sqrt{(s/4 - m_1^2)(s/4 - m_3^2)}\cos\theta, \tag{18}$$

with θ the scattering angle in the CM-frame.