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

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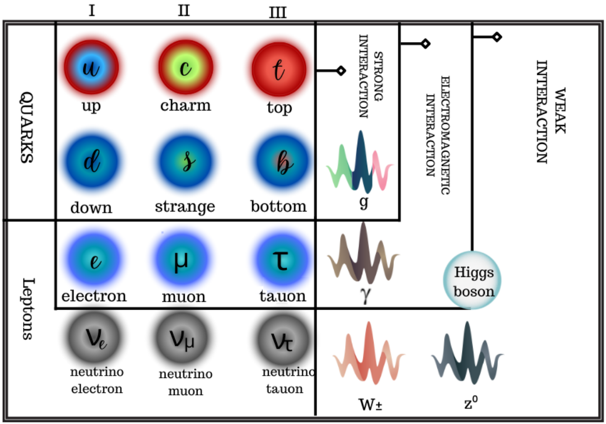
Lepton Flavor Universality in the SM of Particle Physics

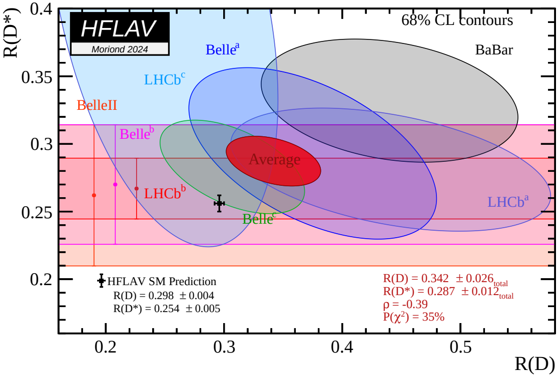
What is it?



Weak bosons mix the different generations of quarks via the CKM matrix, but this does not happen for leptons. This property of the model is known as lepton flavor universality (LFU).

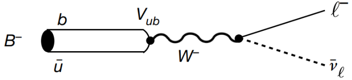
A Hint on Lepton Flavor Universality Violation

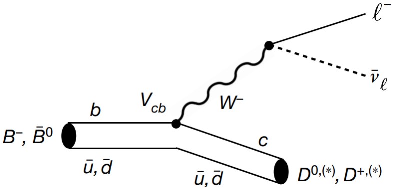
$R(D)$ and $R(D^*)$ anomalies



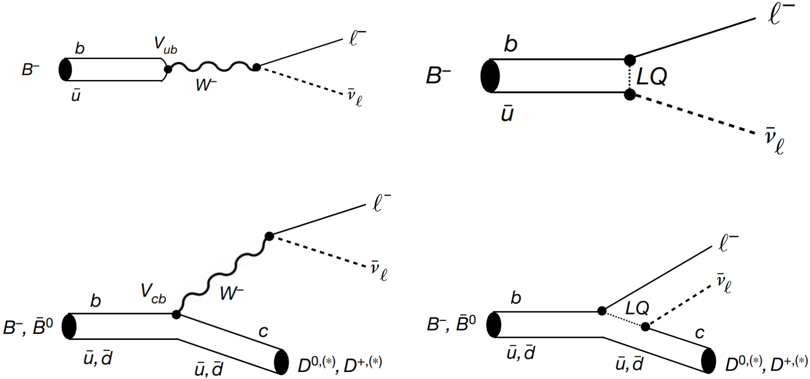
$$R(D) = \frac{\text{BR}\left(B \to D\tau\nu\right)}{\text{BR}\left(B \to D\ell_{(e,\mu)}\nu\right)}, \quad R(D^{(*)}) = \frac{\text{BR}\left(B \to D^{(*)}\tau\nu\right)}{\text{BR}\left(B \to D^{(*)}\ell_{(e,\mu)}\nu\right)} \tag{1}$$

Leptoquarks and $R(D)/\ R(D^*)$ anomalies

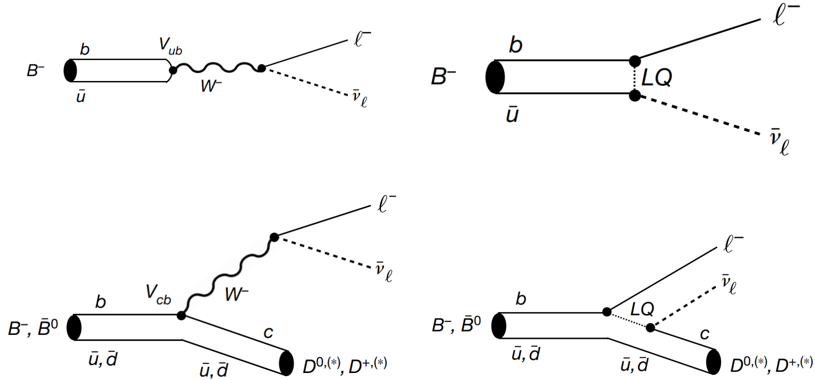




Leptoquarks and $R(D)$/ $R(D^*)$ anomalies



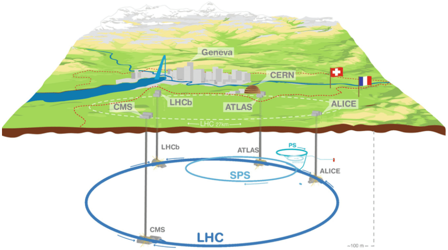
Leptoquarks and $R(D)$/ $R(D^*)$ anomalies



How can we test this hypothesis?

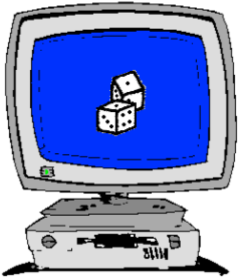
Large Hadron Collider

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.

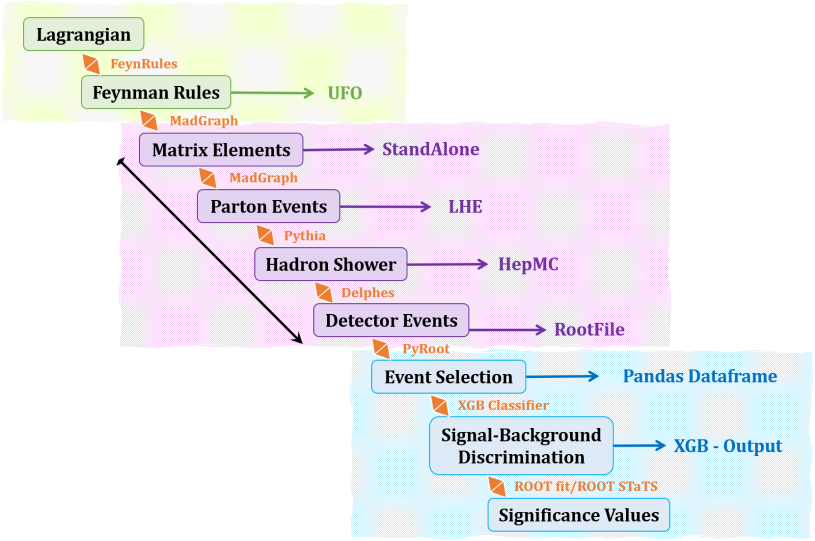
Montecarlo Generators



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

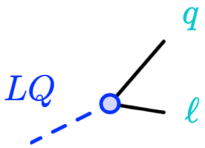
- To perform studies before having the data
- To compute event selection efficiency/acceptance
- To predict the ammount and composition of background events
- To distinguish different signals.

Feasibility Studies Workflow



Vectorial Leptoquark Vertex

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

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

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

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

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 $U_1 \sim (\mathbf{3}_C, \mathbf{1}_I, 4/3_Y)$, and its covariant derivative is

$$\mathcal{D}_\mu U_\nu = \left(\partial_\mu + ig_s T^a G^a_\mu + i\frac{2}{3}g' B_\mu\right) U_\nu.$$

The Vector Leptoquark Lagrangian

The full Lagrangian for the vector leptoquark is

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

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. If U_1 has a gauge origin $\kappa_c = \kappa_Y = 0$.

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\begin{aligned}
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\end{aligned}
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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. If U_1 has a gauge origin $\kappa_c = \kappa_Y = 0$. Defining

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

we have six generators $T_\pm^\alpha$ with closure relation,

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

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.

Take care, you could need a Z' boson

The generator T_{B-L} is associated with the $U(1)_{B-L}$ symmetry with a Z' boson. The interaction terms for the Z' boson have the form

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

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so, the full Lagrangian for the Z' boson is

$$\begin{aligned}\mathcal{L}_{Z'} =& -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} M_{Z'}^2 Z'_\mu Z'^\mu\\ &+ \frac{g_{Z'}}{2\sqrt{6}} Z'^\mu \left(\zeta_q^{ij} \bar{q}_L^i \gamma_\mu q_L^j + \zeta_u^{ij} \bar{u}_R^i \gamma_\mu u_R^j + \zeta_d^{ij} \bar{d}_R^i \gamma_\mu d_R^j - 3\zeta_\ell^{ij} \bar{\ell}_L^i \gamma_\mu \ell_L^j - 3\zeta_e^{ij} \bar{e}_R^i \gamma_\mu e_R^j\right),\end{aligned} \tag{2}$$

where the couplings ζ are complex 3×3 matrices in flavor space.

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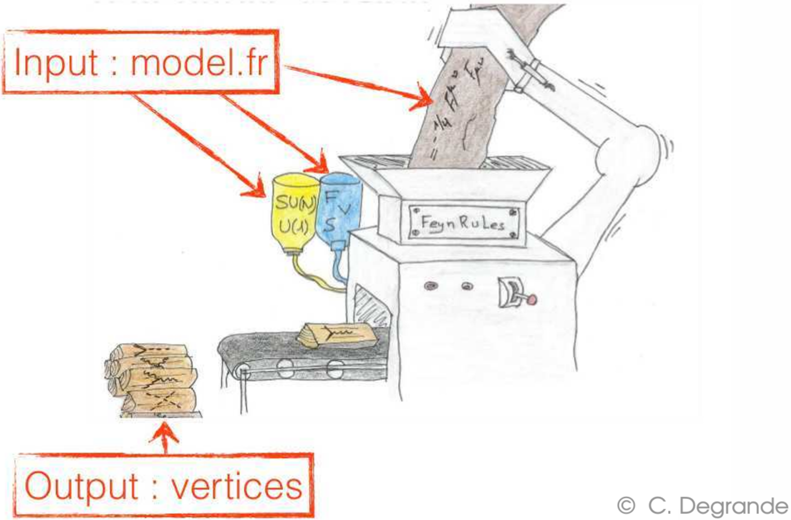
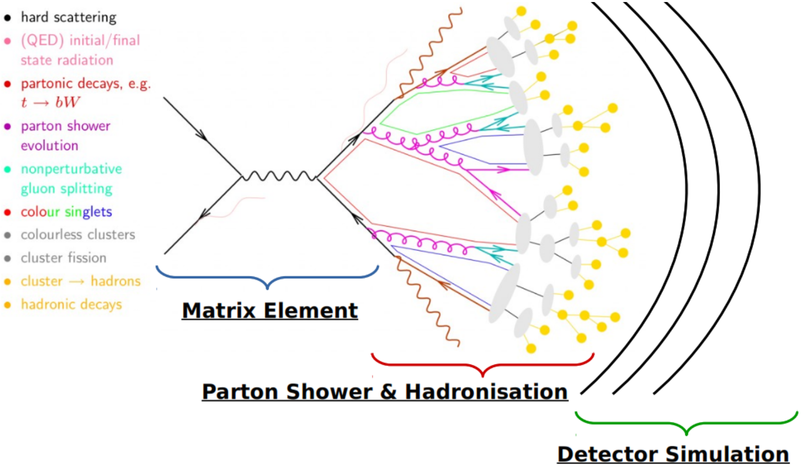
We assume that both, the Z' and the vector leptoquark U_1, have preferential couplings to third generation fermions, so $\beta^{33} \gg \beta^{ij}$ and $\zeta^{33} \gg \zeta^{ij}$.

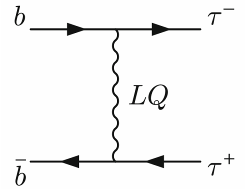
Feynrules

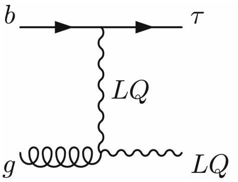

Input : model.fr
SU(N)
U(1)
F
V
S
FeynRules
Output : vertices
© C. Degrande

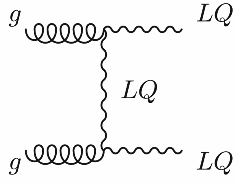
Madgraph-Pythia8-Delphes for the LHC



Leptoquark Production at pp Colliders







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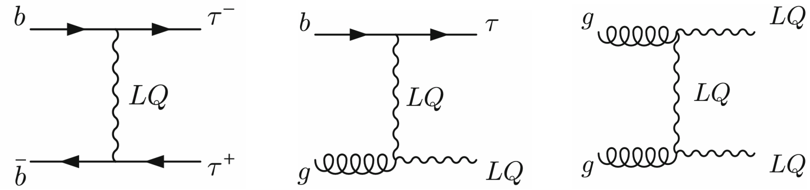
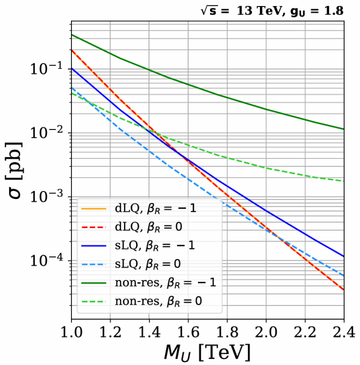
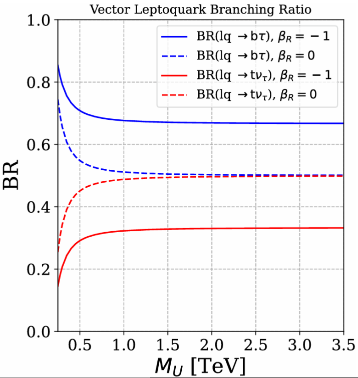
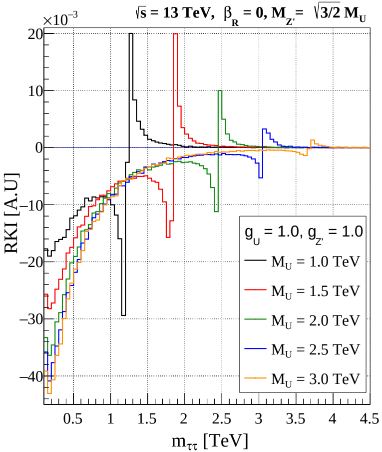
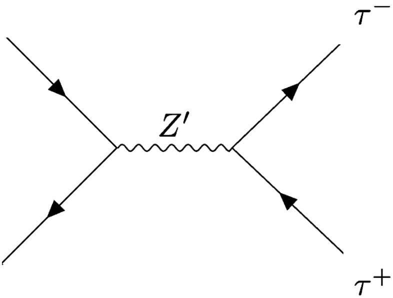






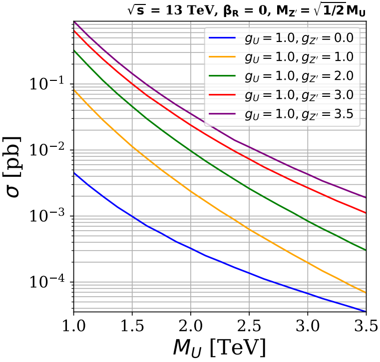
Interferences between the Z' and the Vector Leptoquark

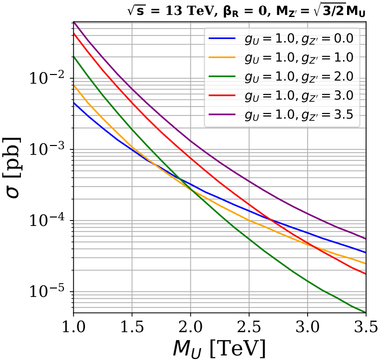




$$\mathrm{RKI} = \frac{1}{\sigma_{LQ+Z'}}\left[\frac{d\sigma_{LQ+Z'}}{dm_{\tau\tau}} - \left(\frac{d\sigma_{LQ}}{dm_{\tau\tau}} + \frac{d\sigma_{Z'}}{dm_{\tau\tau}}\right)\right]$$

Interferences between the Z' and the Vector Leptoquark

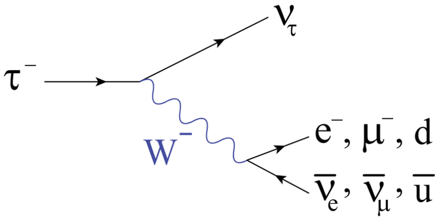




For large values of the couplings, the interference between the Z' and the vector leptoquark mainly destructive, so the cross-section is reduced.

Tau Desintegration Modes

τ Decays



$$BR(\tau \to \ell + 2\nu) \ = 35.21\%, \qquad BR(\tau \to h + \nu) \ = 64.79\%$$

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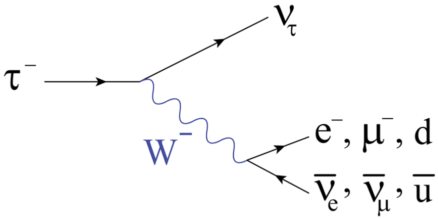
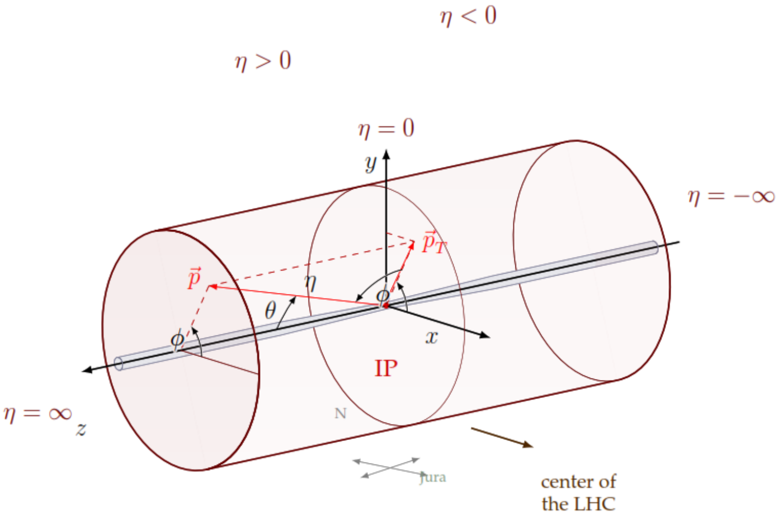


$$BR(\tau \to \ell + 2\nu) \ = 35.21\%, \qquad BR(\tau \to h + \nu) \ = 64.79\%$$

- $\tau_\ell \tau_\ell$
$$BR(\tau\tau \to 2\ell + 4\nu) = BR(\tau \to \ell + 2\nu)^2 \approx 12.39\%$$
- $\tau_\ell \ \tau_h$
$$BR(\tau\tau \to h + \ell + 3\nu) = 2 \times BR(\tau \to h + \nu) \times BR(\tau \to \ell + 2\nu) \ \approx 45.62\%$$
- $\tau_h \ \tau_h$
$$BR(\tau\tau \to 2h + 2\nu) = BR(\tau \to h + \nu)^2 \approx 41.97\%$$

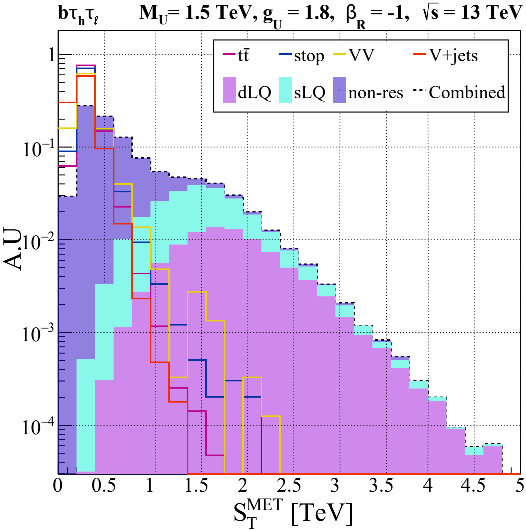
Kinematic Variables



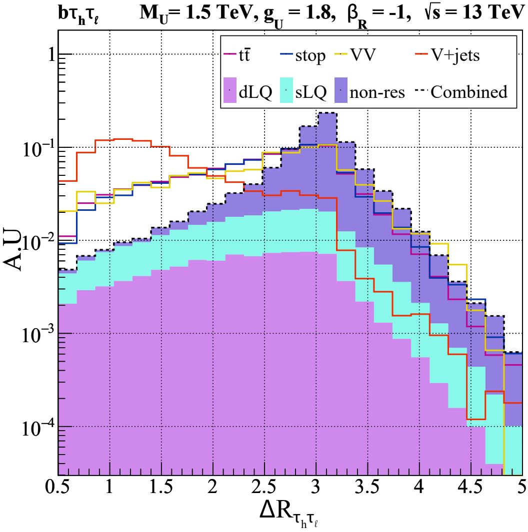
Preselection Criteria

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
$p_T(b)$	-	≥ 30GeV		-	≥ 30GeV	
$\lvert\eta(b)\rvert$	-	≤ 2.4		-	≤ 2.4	
$N(\ell)$	$= 0$			$= 1$		
$N(\tau_h)$	$= 2$			$= 1$		
$p_T(\ell)$	-			≥ 35GeV		
$p_T(\mu)$	-			≥ 30GeV		
$\lvert\eta(\ell)\rvert$	-			≤ 2.4		
$p_T(\tau_h)$	≥ 50 GeV					
$\lvert\eta(\tau_h)\rvert$	≤ 2.3					
$\Delta R(p_i, p_j)$	≥ 0.3					

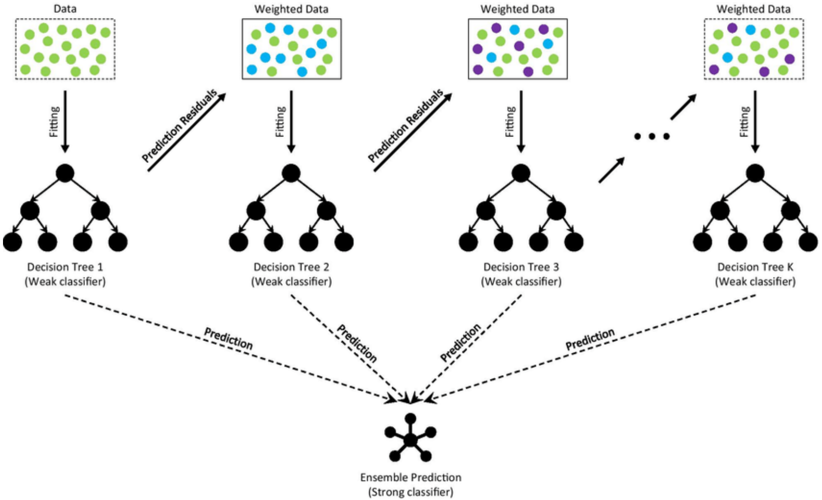
$S_T^{\mathrm{meT}} = \mathrm{met} + \sum_i |p_T^i|$



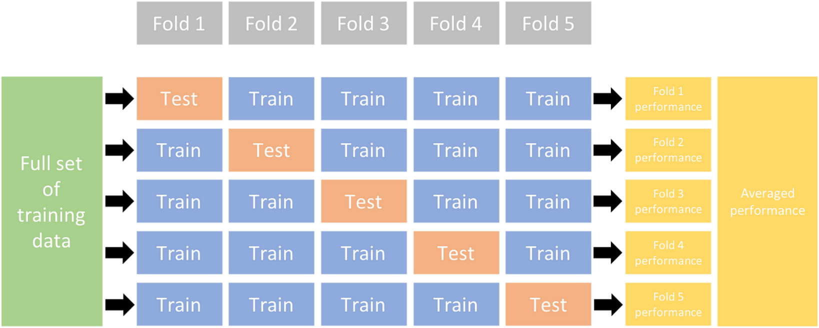
$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$



Boosted Decision Tree



Cross-Validation



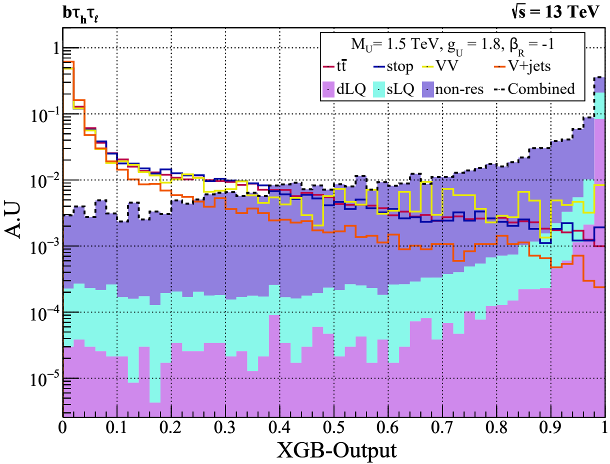
We made this for the XGBoost discriminator algorithm with a 10-fold cross-validation for each point in the hyperparameter space:

- `max_depth` $\in \{3, 5, 7, 9\}$
- `learning_rate` $\in \{0.01, 0.1, 1, 10\}$
- `n_estimators` $\in \{75, 125, 250, 500\}$

So, we have one optimized discriminator for each mass point, each channel, and each value of β_R^{33}.

The optimized observable
XGB-output

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

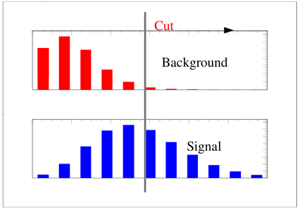


One can construct a test that estimates how significant the deviation from the background in a distribution:

$$k' = \frac{N^{(hyp)} - N^{(null)}}{\sigma_{N^{(hyp)}}}.$$

If S and B are the number of events for the signal and background, then

$$k' = \frac{S}{\sqrt{S+B}}.$$



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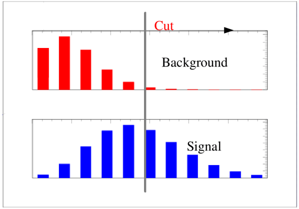

If you add gaussian systematic uncertainties, then

$$k' = \frac{S}{\sqrt{S+B+\delta_{\text{sys}}^2}}.$$

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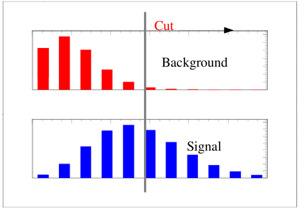


If you add gaussian systematic uncertainties, then

$$k' = \frac{S}{\sqrt{S+B+\delta^2_{\text{sys}}}}.$$

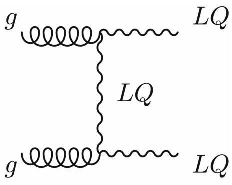
If we treat each bin as an independent Poisson variable and we add the systematic uncertainties, then

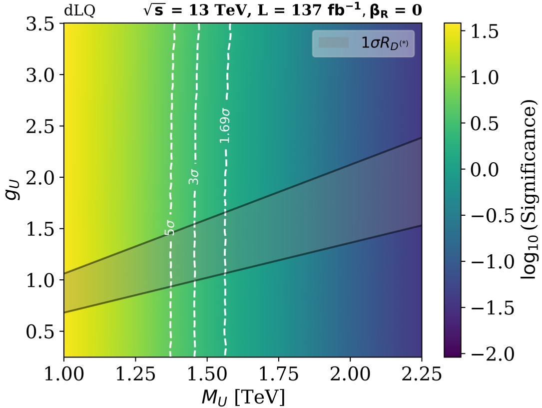
$$\boxed{k \approx \frac{\sum_i w_i S_i}{\sqrt{\sum_i w_i^2 (S_i + B_i + \delta^2_{\text{sys}})}},}$$

where $w_i = A \ln\left(1 + \frac{S_i}{B_i}\right)$, with A a normalization constant, is the weight for each bin.

Double Leptoquark Production

The Sensitivity Reach / only left-handed currents

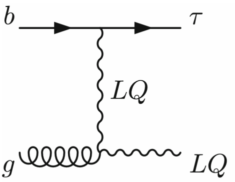


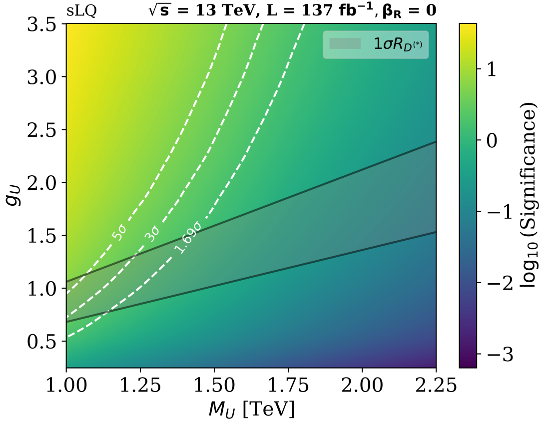


Double leptoquark production is sensitive to the leptoquark mass, its production depends only on the QCD coupling constant and the available energy.

Single leptoquark production

The Sensitivity Reach / only left-handed currents

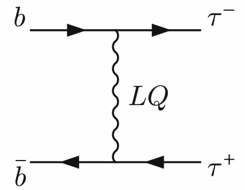


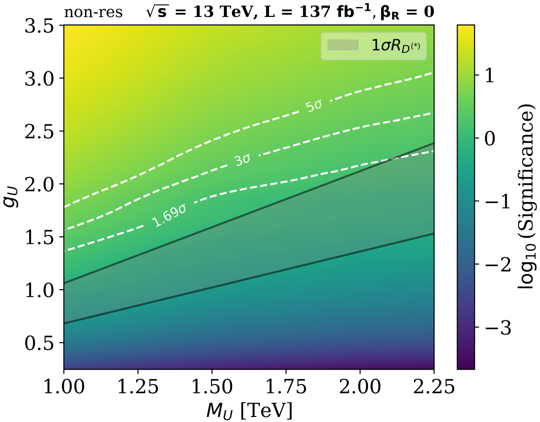


Single leptoquark production is sensitive to both, mass and couplings. It contributes to the regions of high coupling constants at higher masses than double leptoquark production.

Non-resonant Production

The Sensitivity Reach / only left-handed currents

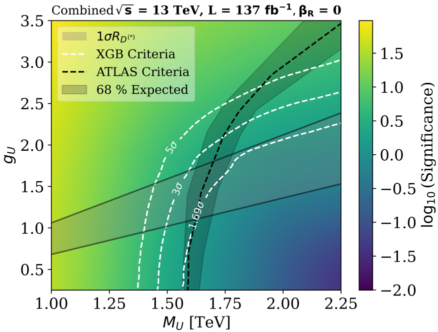


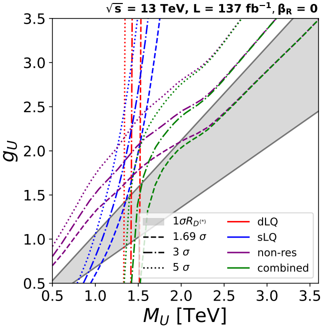


Non-resonant production is highly dependent on the couplings, so it dominates the regions of high coupling constants at all masses.

Combined Sensitivity Reach

The Sensitivity Reach / only left-handed currents

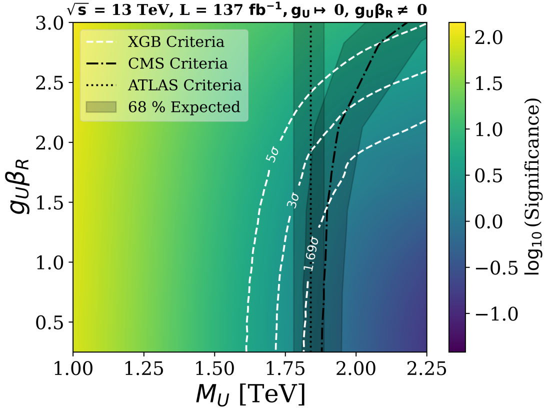




The sensitivity of all signal production processes combined compares our expected exclusion region with the latest one from the ATLAS Collaboration [ArXiv:2305.15962], but we suggest better sensitivity for high coupling constants.

Combined Sensitivity Reach

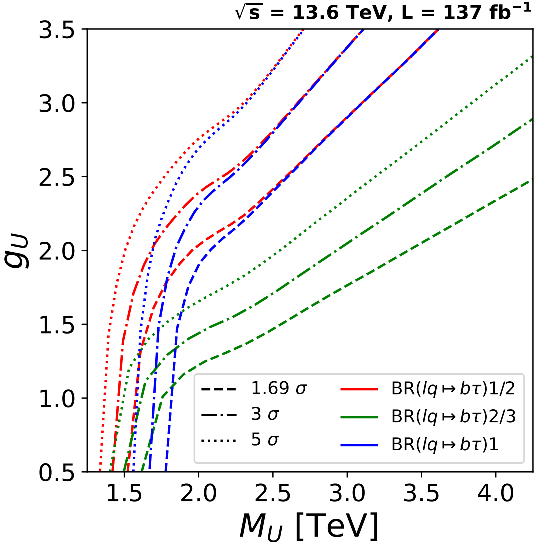
The Sensitivity Reach / only right-handed currents



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.

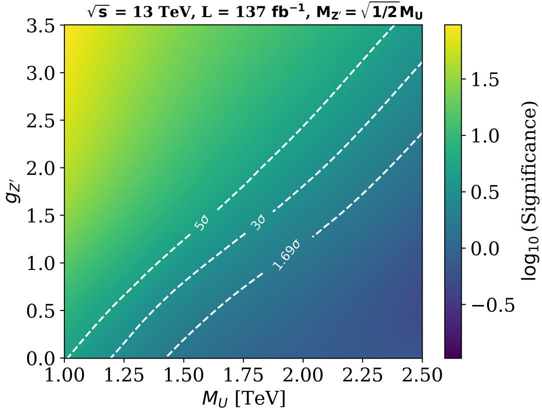
Combined Sensitivity Reach

Comparison between different Branching ratios



Including the Z' boson contribution

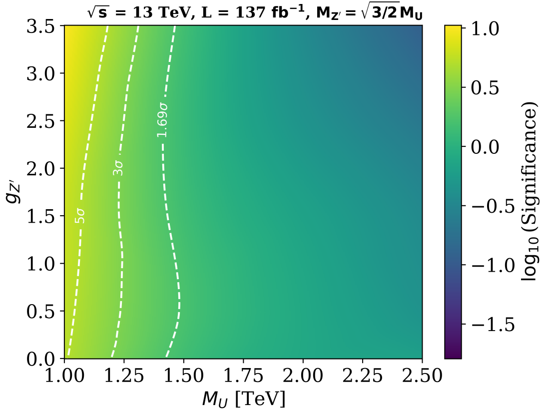
The Sensitivity Reach / only left-handed currents



As is expected if the Z' boson is lighter than the leptoquark, the sensitivity is incresed for higher leptquark masses, due to the additional contribution to the cross section.

Including the Z' boson contribution

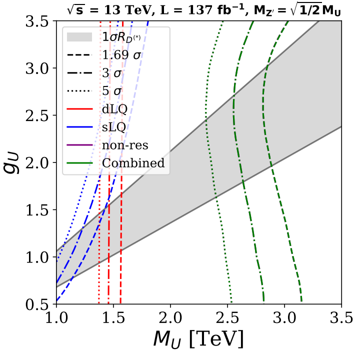
The Sensitivity Reach / only left-handed currents

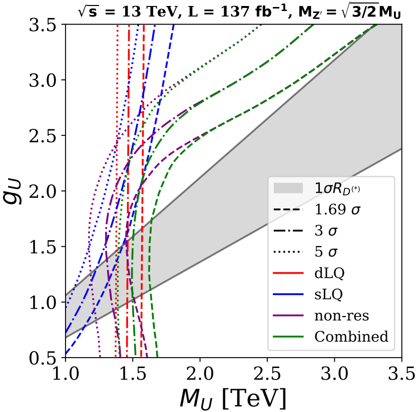


If the Z' boson is heavier than the leptoquark, the sensitivity looks like the one without the Z' boson, except for the region near to the leptoquark coupling constant.

Including the Z' boson contribution

The Sensitivity Reach / only left-handed currents





Summary

- Experimental searches for LQs with preferential couplings to third generation fermions are of great interest due to their potential to explain tensions in the $R(D)$ and $R(D^*)$ decay ratios of B mesons with respect to SM predictions.
- Studies on the production of U_1 LQs with preferential couplings to third generation fermions, considering different couplings, masses, and chiral currents performed using p p collisions at $\sqrt{s} = 13 TeV$ and their interferences with a Z' boson.
- New computational techniques based on machine learning (ML) as BDTs are important to improve sensitivity to potential signs of physics beyond the SM.
- Expected signal significance for sLQ, dLQ, and non-res production, and their combination, presented as contours on a two-dimensional plane of g_U versus M_U for exclusive couplings to left-handed, mixed, and exclusive right-handed currents making enfasis in the region of phase space that could explain B meson anomaly is presented.
- Sensitivity to probe the parameter space is highly dependent on the chirality of the couplings and effects of a companion Z' boson on non-res production can significantlyimpact the results.
- Non-res production remains an essential channel for probing LQs in the future.