Feasibility studies for searches enhanced by machine learning methods of leptoquarks with preferencial couplings to third generation fermions at the LHC

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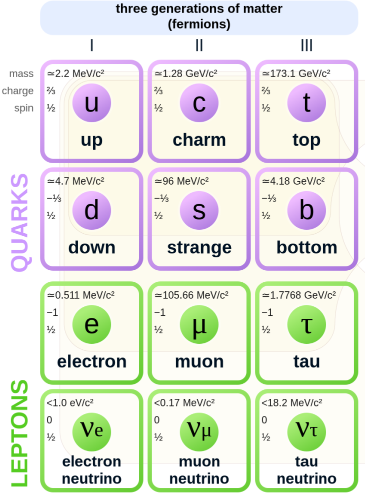
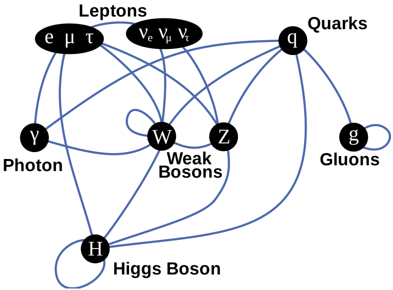
Lepton Flavor Universality in the SM of Particle Physics

What is it?



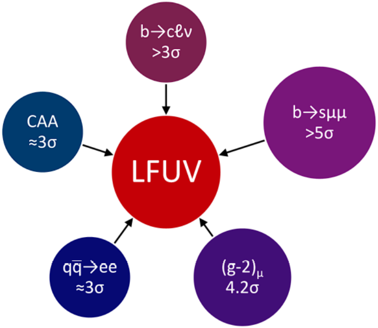


Remark: Weak bosons mix between quarks generation, Weak bosons mix the different generations of quarks via the CKM matrix, but this does not happen for leptons. This property of the model is known as lepton flavor universality (LFU)[1].

[1] Buonaura, "Tests of lepton flavour universality at LHCb" (2020).

New Physics in Lepton Flavor Universality Violation

Hints on B-Anomalies



$b \to s\mu^+\mu^-$ The fraction of branching ratios from B mesons to Kaons and a different pair lepton-antilepton shows a 5σ anomalie[2]

$$R_{K(*)} = \frac{\text{BR}\left(B \to K^{(*)}\mu^+\mu^-\right)}{\text{BR}\left(B \to K^{(*)}e^+e^-\right)}$$

$b \to c\ell\nu$ Similarly to $R\left(K^{(*)}\right)$, the ratios $R\left(D^{(*)}\right)$ show deviations from the SM predictions with a combined significance of about 3σ[3],

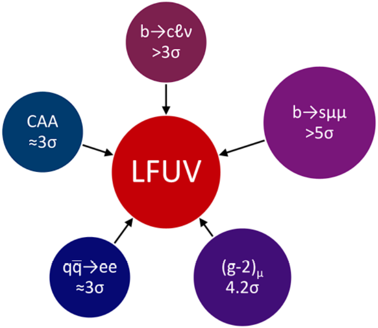
$$R_{D(*)} = \frac{\text{BR}\left(B \to D^{(*)}\tau\nu\right)}{\text{BR}\left(B \to D^{(*)}\ell^{e\mu}\nu\right)}$$

[2] Capdevila et al., "Patterns of New Physics in b $\to s\ell^+\ell^-$ transitions in the light of recent data" (2018); Aebischer et al., "B-decay discrepancies after Moriond 2019" (2020).

[3] Amhis et al., "Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018" (2021).

New Physics in Lepton Flavor Universality Violation

Another Hints



The measurement of Fermilab's Muon g-2 experiment has presented an apparent discrepancy with an accuracy of 4.2 σ[4].

$q\bar{q} \mapsto e^+e^-$ CMS experiment observed more very high-energetic electrons in proton-proton collisions compared to muons than expected[5].

CCA. It has been observed that certain βdecays happen less frequently than expected. This tension, called the Cabibbo Angle anomaly (CAA), displays a significance around 3σ[6].

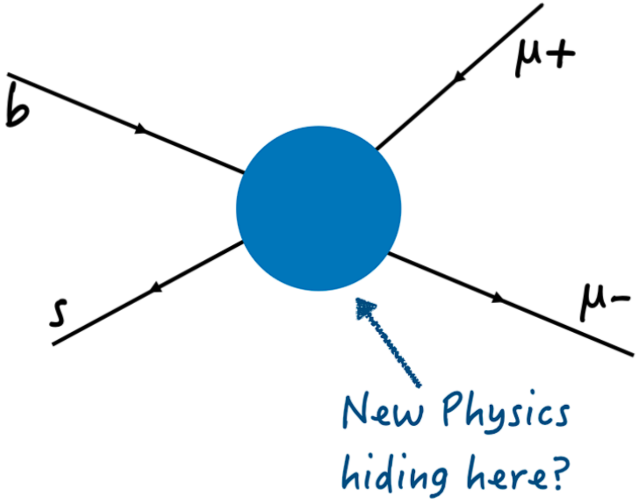
[4] Blum et al., "The Muon (g-2) Theory Value: Present and Future" (2013); Abi et al., "Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm" (2021).

[5] The-CMS-collaboration, "Search for resonant and nonresonant new phenomena in high-mass dilepton final states at $\sqrt{s}$= 13 TeV" (2021).

[6] Crivellin and Hoferichter, "β Decays as Sensitive Probes of Lepton Flavor Universality" (2020); Hardy and Towner, "Superallowed $0^+ \rightarrow 0^+$ nuclear β decays: 2020 critical survey, with implications for V_{ud} and CKM unitarity" (2020).

Hints for New Physics

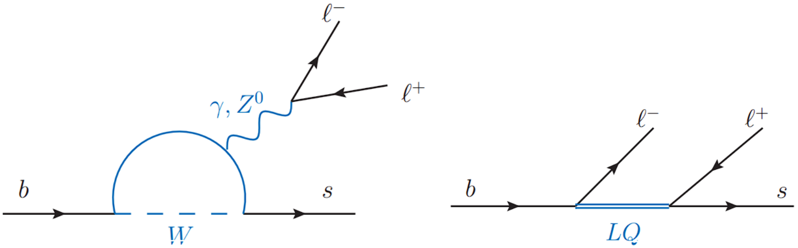
Can we explain the anomalous vertex?



Hints for New Physics

There are several purposes to solve B-Anomalies

In the standard model, the $b \mapsto s\ell\ell$ process is gived by

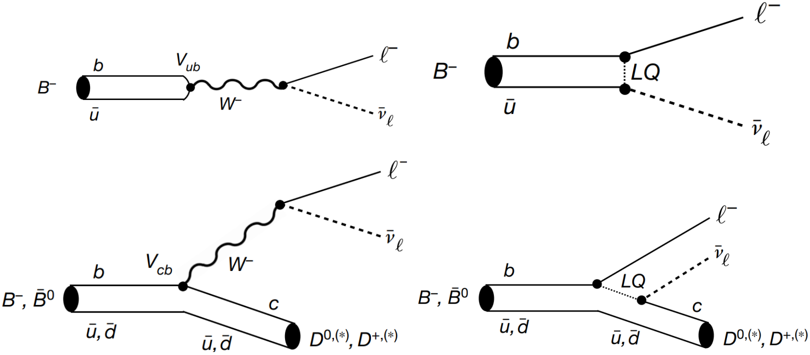


Is the anomaly caused by a leptoquark?

Hints for New Physics

There are several purposes to solve B-Anomalies

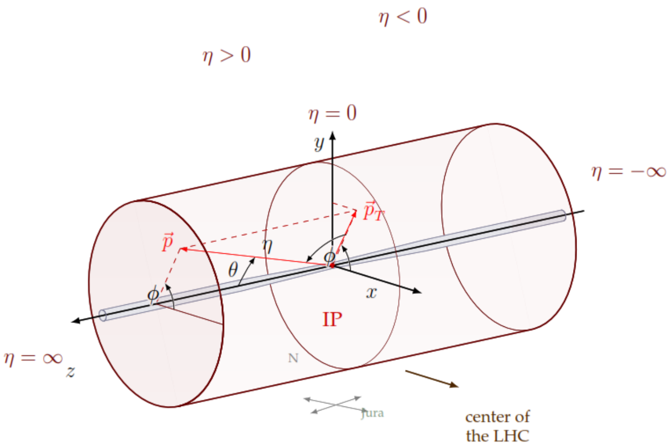
And the others B-Meson Anomalies?



Is the $b \mapsto c\ell\nu$ anomaly caused by a leptoquark?

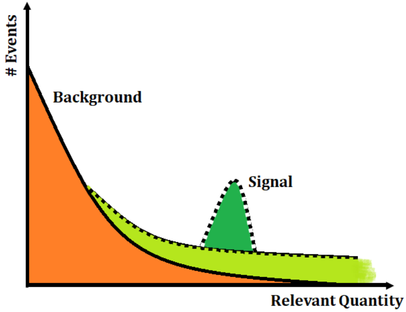
Kinematic Variables

How can we test these hypotheses?



Hunting Peaks and Tails

Searches for New Physics



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

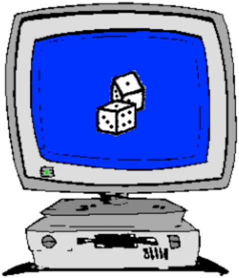
$$s_k \approx \frac{N^{(obs)} - N^{(bkg)}}{\sigma_{N^{(bkg)}}}.$$

It is said that a new discovery has $s_k \sim 5\sigma$. For MC events, if S is the number of signal events expected and B is the number of events coming from the background, we can then determine the significance of a Poissonic signal via the simple formula

$$s_k \approx \frac{S}{\sqrt{S+B}}.$$

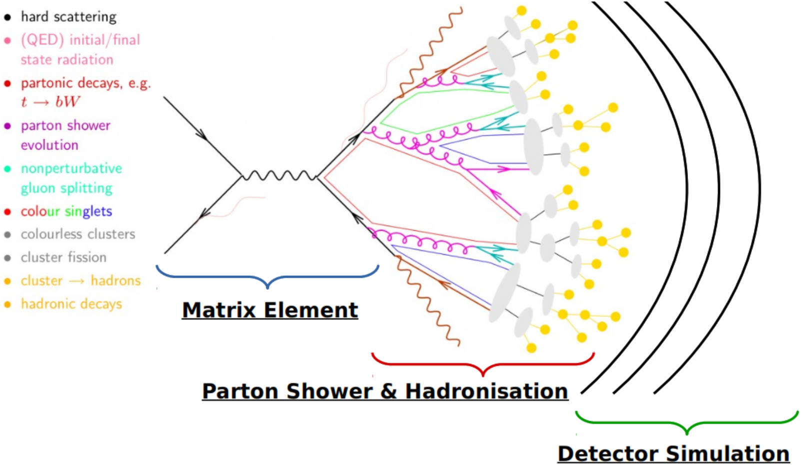
Montecarlo Generators

- Monte Carlo Simulation used 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.

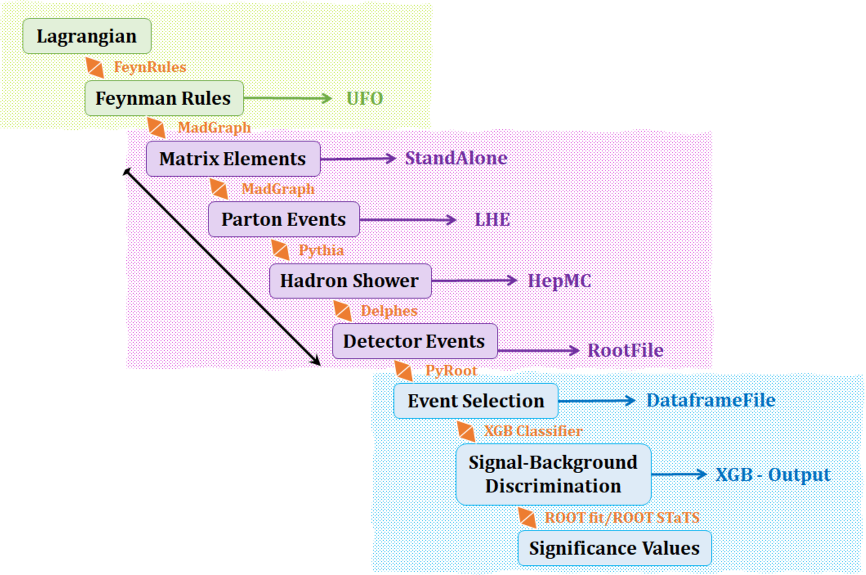


Methodology

What do we hope to simulate?



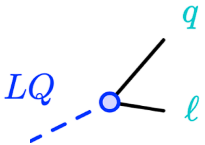
The Toolchain



The Vector Leptoquark Lagrangian

Single Leptoquark Channel Feasibility

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

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

Where the SM charges for the leptoquark must to be

	$\bar{q}_L$	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)	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{3}$

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

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

The Vector Leptoquark Lagrangian

Single Leptoquark Channel Feasibility

We consider a vector Leptoquark in a SM-representation $(\mathbf{3}_C, \mathbf{1}_I, 2/3_Y)$

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

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

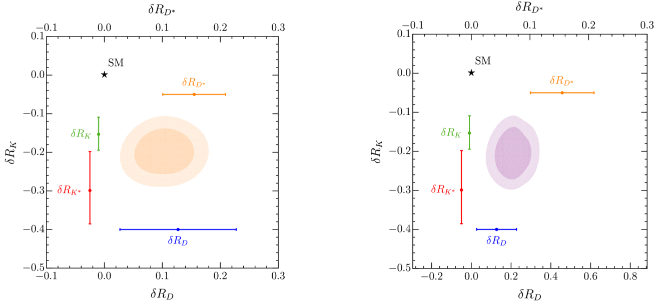
$$
\beta_L = \begin{pmatrix} 0 & 0 & \beta_L^{d\tau} \\ 0 & \beta_L^{s\mu} & \beta_L^{s\tau} \\ 0 & \beta_L^{b\mu} & 1 \end{pmatrix}, \beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta_R^{b\tau} \end{pmatrix}.
$$

Where, we assume that the new vectors are coupled dominantly to third generation fermions.

Parameters to solve B-Anomalies

Single Leptoquark Channel Feasibility

From Cornella et al., "Reading the footprints of the B-meson flavor anomalies" (2021)



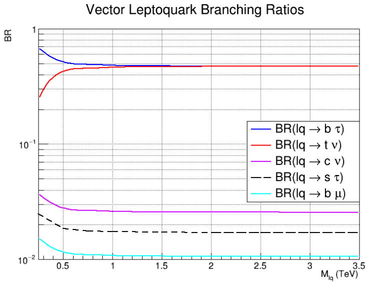
Scenario	Parameter	best fit	1 σ
max. RH currents $\left(\beta_R^{b\tau} = -1\right)$	C_U	0.004	[0.002,0.006]
	$\beta_L^{b\mu}$	-0.21	[-0.25,-0.14]
	$\beta_L^{s\tau}$	0.21	[0.12,0.26]
	$\beta_L^{s\mu}$	0.03	[0.01,0.04]

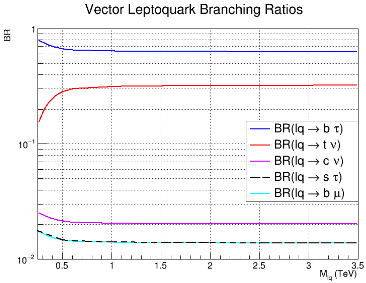
where $C_U \equiv g_U^2 v^2 / \left(4M_U^2\right)$.

Leptoquark Branching Ratios

Single Leptoquark Channel Feasibility

Branching ratios of two body vector-leptoquark decay from the best fit for two scenarios $\beta_R^{b\tau} = 0$ (left) and $\beta_R^{b\tau} = -1$ (right).

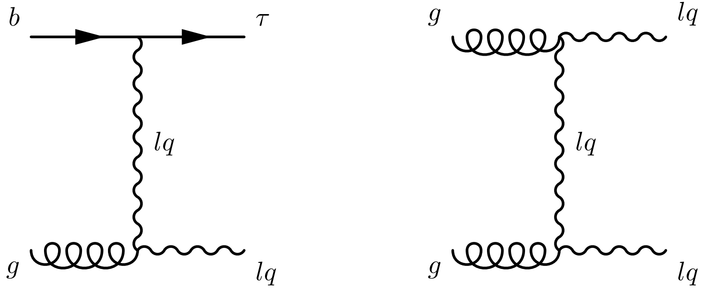




We calculate the decay width for all the process $LQ \mapsto$all all in madgraph width the implementation in feynrules from Baker et al., "High-pTsignatures in vector–leptoquark models" (2019).

Resonant Production Channels

Feynman diagrams for a VBF-like production



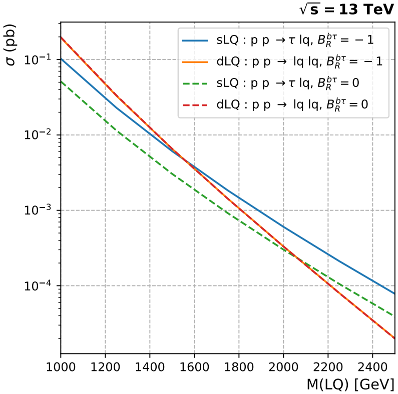
Remark: Baker's implementation is not efficient, we have made modifications to take the dominant terms at the vertices:

$$\sim U_1^{\mu}(\bar{t}_L\gamma_\mu\nu_L + \bar{b}_L\gamma_\mu\tau_L - \bar{b}_R\gamma_\mu\tau_R) + h.c.$$

This in turn allows us to study separately the channels with a single leptoquark and pair production.

Production Cross Section

In madgraph, we calculate the cross section for leptoquarks on-shell production with $g_u = 1.8$ (narrow approximation for all masses).



Note that, for pair production w/w.o. RHC coupling the production comes from pure QCD. For single leptoquark production, we have a suppression due to the right handed current from the b component of p.

Pre-Selection

The leptonic τ decay has $BR(\tau \mapsto \ell\nu\nu) \approx 34\%$. Then the semileptonic channel has $BR(\tau + \tau \mapsto \tau_h + \ell) \approx 45\%$ and the hadronic channel has $BR(\tau + \tau \mapsto \tau_h + \tau_h) \approx 44\%$

$b\tau_h\tau_h$

- At least two hadronic τ.
- Exactly one b-jet.

$b\tau_h\tau_\ell$

- Exactly one hadronic τ.
- At least one charged lepton ℓ.
- Exactly one b-jet.

$bb\tau_h\tau_h$

- At least two hadronic τ.
- At least two b-jets.

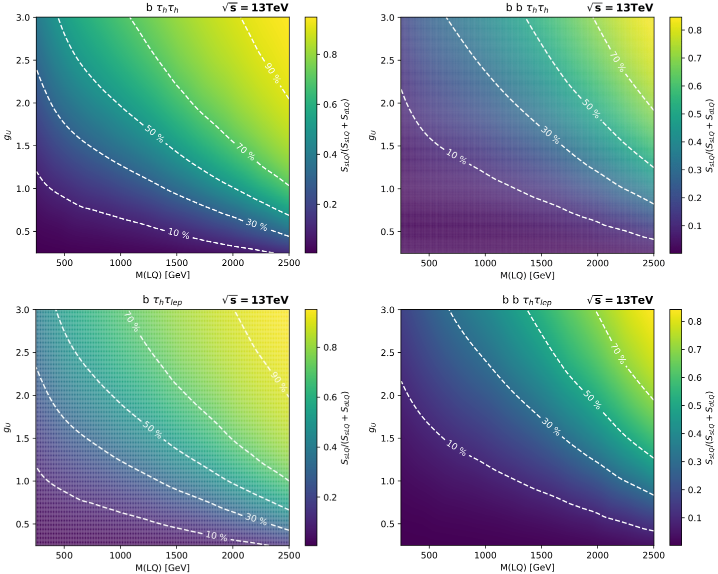
$bb\tau_h\tau_\ell$

- Exactly one hadronic τ.
- At least one charged lepton ℓ.
- At least two b-jets.

With the experimental-detector constrains:

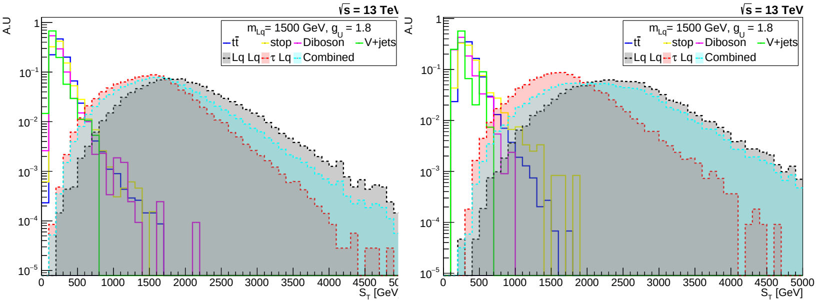
Criteria	Constraint
$\lvert\eta(\tau)\rvert$	< 2.3
$\lvert\eta(b)\rvert, \lvert\eta(\ell)\rvert$	< 2.4
$\lvert p_T(b)\rvert$	> 30 GeV
$\lvert p_T(\tau)\rvert$	> 20 GeV
$\lvert p_T(\ell)\rvert$	> 25 GeV

Signal Composition



Event Discrimination

The differentiation between signal and background is made via the kinematic and topological differences between signal and background.

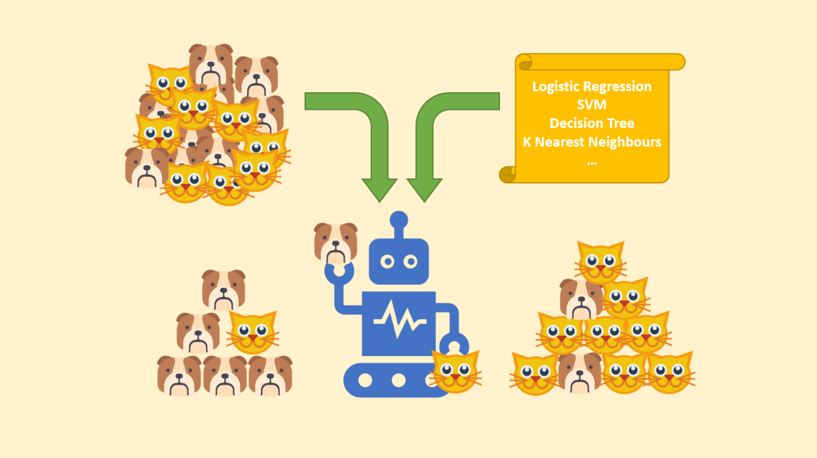


For example, as is shown in the figure for $m_{LQ} = 1.5$TeV (at the left $b\tau_h\tau_h$, right $bb\tau_h\tau_h$), the

$$s_T^{MET} \equiv MeT + p_{\tau_1} + p_{\tau_2} + \sum_i p_{b_i}$$

is higher for the Leptoquark signal because its decay products receive a boost in pT from their mass values.

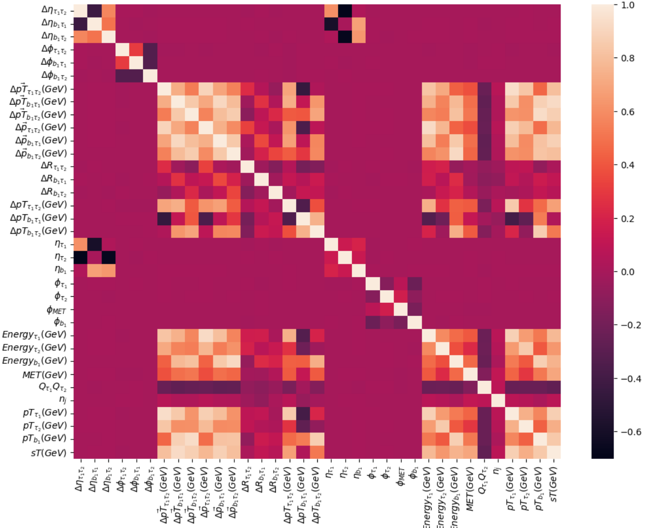
Binary Machine Learning Classification



Obtaining Best Variables

$b\tau_h\tau_h$ case

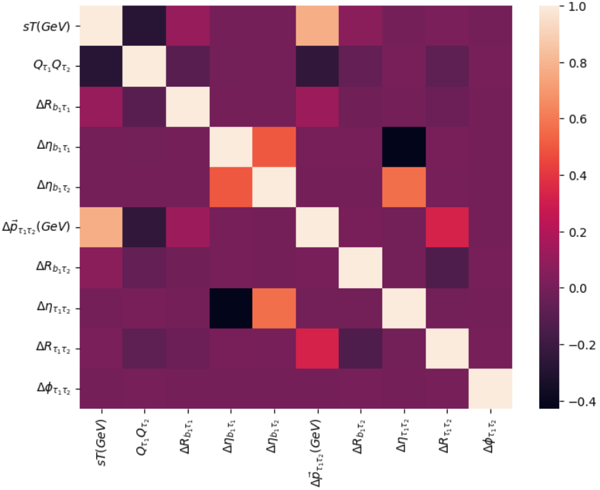
For all the Kinematic Variables we have the correlation map:



Obtaining Best Variables

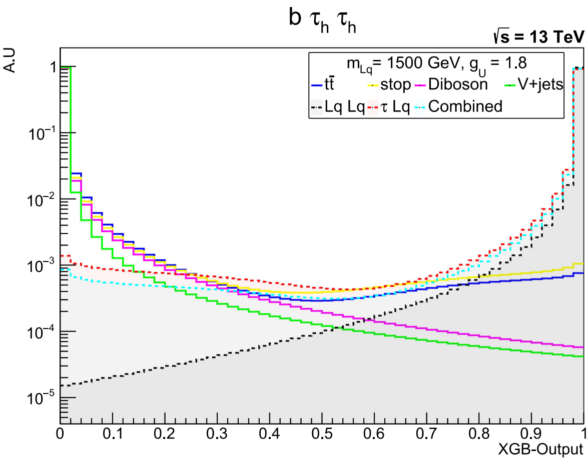
$b\tau_h\tau_h$ case

Taking the ten best variables with correlation less than 0.6 we have the following variables as the most optimal



(X) Gradient Boosting Classifier

The performance of the classifier is

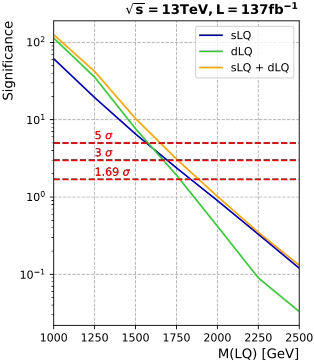


Correct normalization for each background is gived by $N = \epsilon\sigma L$.

Significance Test

Single Leptoquark Channel Feasibility

Our selection in the resonant case shows an exclusion feasibility on a leptoquark mass of 1.9TeV at 137/fb for a leptoquark coupled maximally to RHC, which is competitive with what is reported in CMS searches[7],[8].



[7] The-CMS-Collaboration, "Search for singly and pair-produced leptoquarks coupling to third-generation fermions in proton-proton collisions at s=13 TeV" (2021).

[8] **The search for a third-generation leptoquark coupling to a τ lepton and a b quark through single, pair and nonresonant production at $\sqrt{s} = 13$ TeV** (2022).

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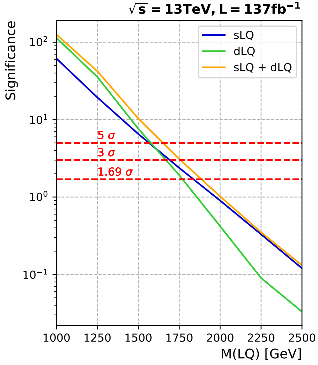

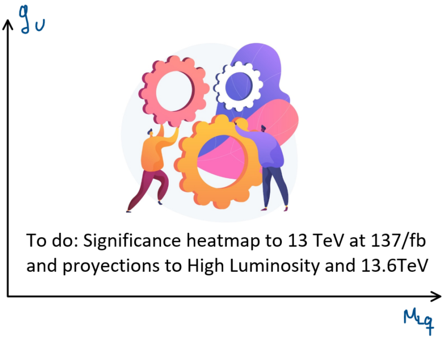

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Summary

- The lepton flavour physics is a wide window to find physics beyond the standard model.
- New particles with preferred couplings to third generation fermions can give clues in LFUV.
- The Monte Carlo Method is one of the most useful tools in understanding experimental results and helps describe what the results of different models would look like.
- Machine learning methods show that they have the potential to optimize and refine searches for new physics.