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?

zoo_2.png

Elementary_particle_interactions.png

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

New Physics in Lepton Flavor Universality Violation

Hints on B-Anomalies

LFUV.png

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

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

$b \to c\ell\nu$ 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],

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

[2] **Capdevila_2018; Aebischer2020**.
[3] **Amhis_2021**.

New Physics in Lepton Flavor Universality Violation

Another Hints

LFUV.png

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] **arxiv.1311.2198**; **Abi_2021**.
[5] **Sirunyan2021**.
[6] **PhysRevLett.125.111801**; **PhysRevC.102.045501**.

Hints for New Physics

Can we explain the anomalous vertex?

NP.png

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

B_SM_3.png

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

B_SM_3.png

B_ZP_3.png

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

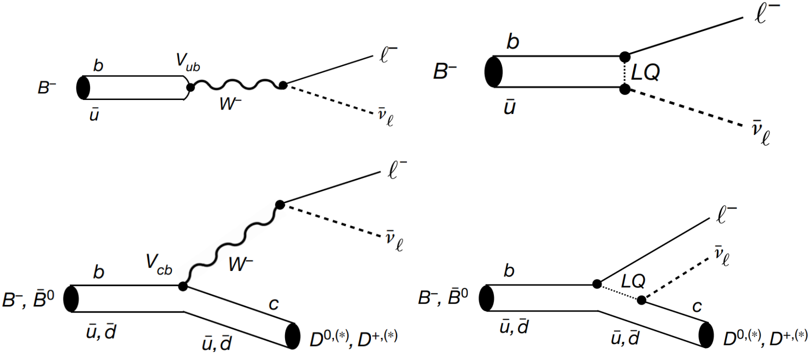
B_SM_3.png

B_LQ_3.png

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?

Hints for New Physics

There are several purposes to solve B-Anomalies

B_WP.png

Hints for New Physics

There are several purposes to solve B-Anomalies

B_3LQ.png

Hints for New Physics

There are several purposes to solve B-Anomalies

B_Axions.png

Hints for New Physics

There are several purposes to solve B-Anomalies

B_Axions.png

Research Problem

What to do with these hints?

What production mechanisms have the potential to be observed at the LHC-experiments?

1. Particles with preferred couplings to third generation fermions.
2. Compare exotic channels with dominant channels.
3. We will use Machine Learning algorithms to optimize data selection.

Large Hadron Collider

How can we test these hypotheses?

LHC.png

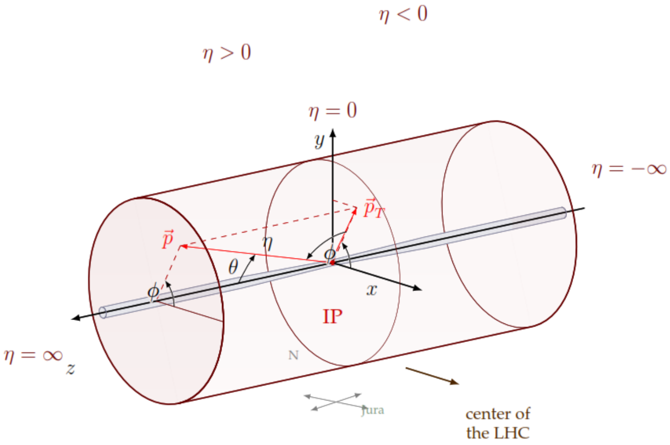
Multipurpose Detectors

How can we test these hypotheses?

Detec.png

Kinematic Variables

How can we test these hypotheses?



Hunting Peaks and Tails

Searches for New Physics

Higgs_CMS.png

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

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

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

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

Montecarlo Generators

- MonteCarlosimulation 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

rules.pdf

Objectives and Methodology

Conduct feasibility studies for the LHC associated with the production of new hypothetical particles through different production mechanism and with preferential couplings to third generation fermions.

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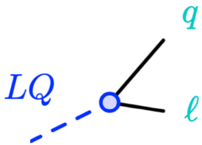
Activities

- Produce simulations of different background processes from the standard model using the LHC conditions.
- Study theoretical models considering the production of leptoquarks, W' and Z' with preferential couplings to third generation fermions.
- Generate simulations for the production of the new hypothetical particles of interest to determine the production cross section, kinematics, topology under the LHC conditions.
- Perform feasibility studies for the different signal models using Machine Learning methods.

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 **Cornella2021**

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 **Baker2019**.

Production Cross Section

Single Leptoquark Channel Feasibility

Cross section for the production of leptoquarks in different channels in the context of the LHC with proton-proton collisions at $\sqrt{s}$=13TeV in both scenarios $\beta_R^{b\tau} = 0$ (left) and $\beta_R^{b\tau} = -1$ (right).

An additional Jet in single leptoquark has cross section similar to single leptoquark. Would we get a cleaner channel if the signal is associated with a jet?

VBF-like production

Single Leptoquark Channel Feasibility

Can we take advantage of the background suppression of a VBF-like channel?
Feynman diagram for a VBF-like production of a single leptoquark.

../d1.pdf

Criteria	Constraint
$\lvert\eta(b)\rvert, \lvert\eta(\tau)\rvert$	< 2.5
$\lvert\eta(j)\rvert$	< 5.0
$\lvert p_T(j)\rvert, \lvert p_T(b)\rvert$	> 30 GeV
$\lvert p_T(\tau)\rvert$	> 20 GeV

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

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

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

Partonic Kinematics

Semi on-Shell Production ($B_W = 15$):

Pure on-Shell Production ($B_W = 1$):

Pre-Selection

Single Leptoquark Channel Feasibility

We propose a simple direct selection

- 1 b-jet.
- 1 light-jet.
- 2 hadronic τ.

Conditions:

1. At least 4 jets
2. At least 1 good jet
3. At least 2 good jets
4. At least 3 good jets
5. At least 4 good jets
6. At least 1 b-jet
7. At least 1 light-jet
8. At least 1 τ-jet
9. At least 2 τ-jet

Efficiency and background composition

Single Leptoquark Channel Feasibility

The dominant backgrounds turn out to be t-tbar, W+jets and Z+jets.

bkg.png

Event Discrimination

Single Leptoquark Channel Feasibility

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

For example, pT for the b-jet is boosted due to the leptoquark mass, and this bjet is strongly correlated with the τ's.

Machine Learning Discrimination

Mass (GeV)	500	1000	1500	2000	2500	3000	3500
$\epsilon_{signal}(\%)$	89.98	96.40	97.80	98.41	98.30	96.09	83.05
$\epsilon_{ttbar}(\%)$	7.73	3.00	1.54	1.28	1.71	3.06	9.60

Significance Test

Single Leptoquark Channel Feasibility

Our selection with hadronic taus shows an exclusion feasibility on a leptoquark mass of 1.4TeV at 150/fb, which is directly competitive with what is reported in CMS searches[7].

Add semileptonic taus, fully leptonic, and channels without associated jets.

[7] **2021136446**.

Expected Results and Timeline

2022

Etapa	Academic Period / Activity	2022-10	2022-19	2022-20
Single Leptoquark	Theoretical study of models	x		
	MC for the production	x		
	Perform feasibility studies	x	x	x
W′	Theoretical study of models		x	x
	MC for the production			x

Expected Results and Timeline

2023

Etapa	Academic Period / Activity	2023-10	2023-19	2023-20
W'	Theoretical study of models	x		
	MC for the production	x	x	
	Perform feasibility studies		x	x
Internship	Internship			x
Z', HN-VBF	Theoretical study of models			x

Expected Results and Timeline

2024

Etapa	Academic Period / Activity	2024-10	2024-19	2024-20
Z', HN-VBF	Theoretical study of models	x		
	MC for the production	x	x	
	Perform feasibility studies		x	x
Thesis	Write	x	x	x

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.