On the Effects of Interference in BSM Production and Detection of $\tau\tau$ at the LHC

Cristian Fernando Rodríguez Cruz

Authors:
A. Flórez[1], **C. Rodriguez**[1], J. Reyes-Vega[1],
J. Jones-Pérez[2].

[1]Universidad de los Andes

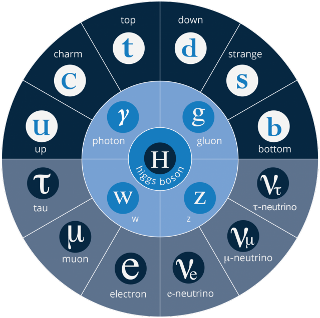
[2]Pontificia Universidad Católica del Perú

December 4, 2024

Outline

The Standard Model of Particle Physics

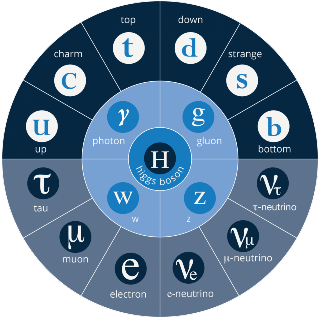
Weak bosons mix the different generations of quarks via the CKM matrix, but this does not happen for leptons. This property of the model is known as **lepton flavor universality (LFU)**.

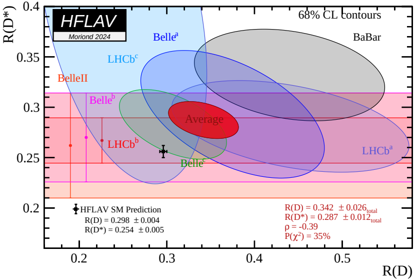


The Standard Model of Particle Physics

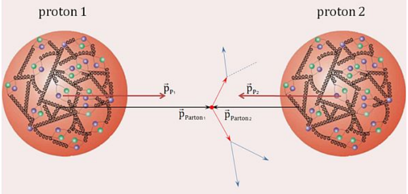
Weak bosons mix the different generations of quarks via the CKM matrix, but this does not happen for leptons. This property of the model is known as **lepton flavor universality (LFU)**.

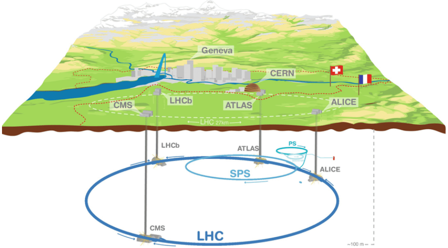
However, recent measurements of the $R(D)$ and $R(D^*)$ ratios show a deviation from the SM predictions. This could be a hint of **lepton flavor violation (LFV)** and then **new physics beyond the SM**.



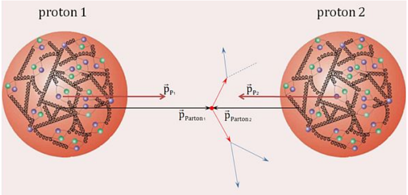


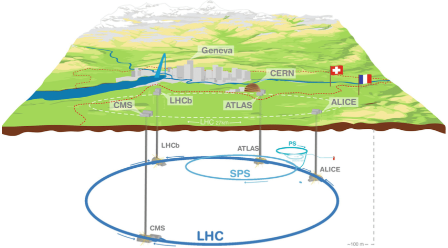
Large Hadron Collider





Large Hadron Collider



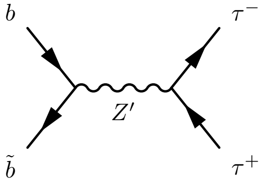


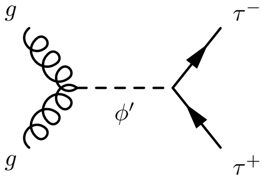
- Feasibility Studies is needed.
- Take Care on the dependence on the different parameters.
- Take care on the content of particles.
- Take care of the signal composition.
- Take care on interference effects.

BSM Signatures on the Di-Tau Channel at the LHC

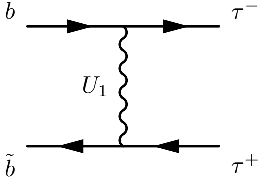
LFV and τ lepton as window to new physics

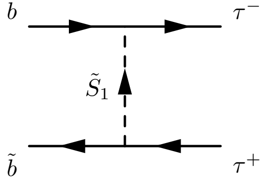
In the different models, we can have different production mechanisms.
For example, resonant ones





or non-resonant ones





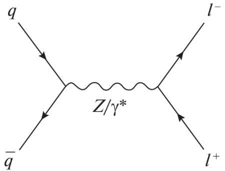
Different Models could have one or several contributions to the di-tau channel, and the **interference between them could be relevant.**

Interference Phenomena in the SM

Photon and Z-boson interference, $q\bar{q} \longrightarrow \tau^+\tau^-$

The squared matrix element can be written as

$$|\mathcal{M}|^2 = \left|\mathcal{M}_{\gamma^*} + \mathcal{M}_Z\right|^2$$
$$= \left|\mathcal{M}_{\gamma^*}\right|^2 + |\mathcal{M}_Z|^2 + 2\,\mathrm{Re}\left(\mathcal{M}^*_{\gamma^*}\mathcal{M}_Z\right).$$

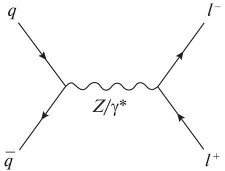


Interference Phenomena in the SM

Photon and Z-boson interference, $q\bar{q} \longrightarrow \tau^+\tau^-$

The squared matrix element can be written as

$$|\mathcal{M}|^2 = \left|\mathcal{M}_{\gamma^*} + \mathcal{M}_Z\right|^2 = \left|\mathcal{M}_{\gamma^*}\right|^2 + |\mathcal{M}_Z|^2 + 2\,\mathrm{Re}\left(\mathcal{M}^*_{\gamma^*}\mathcal{M}_Z\right).$$

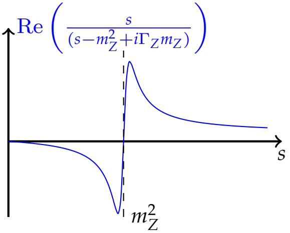


For the case $q_R\bar{q}_L \longrightarrow \tau^+_L\tau^-_R$, the amplitudes are

$$\left|\mathcal{M}_{\gamma^*}\right|^2 = e^4\left[Q^{(f)}Q^{(q)}\right]^2[1+\cos\theta]^2$$

$$|\mathcal{M}_Z|^2 = \frac{s^2 g_Z^4\left[g_R^{(f)}g_R^{(q)}\right]^2}{(s-m_Z^2)^2 + (m_Z\Gamma_Z)^2}[1+\cos\theta]^2$$

$$\mathcal{M}^*_{\gamma^*}\mathcal{M}_Z = \frac{g_Z^2 e^2 Q^{(f)}Q^{(q)}g_R^{(f)}g_R^{(q)}}{(s-m_Z^2+i\Gamma_Z m_Z)}s\,(1+\cos\theta)^2$$

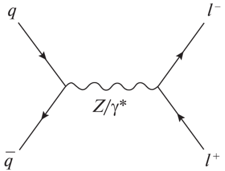


Interference Phenomena in the SM

Photon and Z-boson interference, $q\bar{q} \longrightarrow \tau^+\tau^-$

The squared matrix element can be written as

$$|\mathcal{M}|^2 = \left|\mathcal{M}_{\gamma^*} + \mathcal{M}_Z\right|^2$$
$$= \left|\mathcal{M}_{\gamma^*}\right|^2 + |\mathcal{M}_Z|^2 + 2\,\mathrm{Re}\left(\mathcal{M}^*_{\gamma^*}\mathcal{M}_Z\right).$$

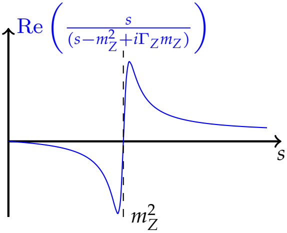


For the case $q_R\bar{q}_L \longrightarrow \tau^+_L\tau^-_R$, the amplitudes are

$$\left|\mathcal{M}_{\gamma^*}\right|^2 = e^4\left[Q^{(f)}Q^{(q)}\right]^2[1+\cos\theta]^2$$

$$|\mathcal{M}_Z|^2 = \frac{s^2 g_Z^4\left[g_R^{(f)}g_R^{(q)}\right]^2}{(s-m_Z^2)^2+(m_Z\Gamma_Z)^2}[1+\cos\theta]^2$$

$$\mathcal{M}^*_{\gamma^*}\mathcal{M}_Z = \frac{g_Z^2 e^2 Q^{(f)}Q^{(q)}g_R^{(f)}g_R^{(q)}}{(s-m_Z^2+i\Gamma_Z m_Z)}s\,(1+\cos\theta)^2$$



Always that you have two or more contributions to a process, the interference between near to the resonances could be relevant.

Example: The Vector Leptoquark Model

Eur. Phys. J. C (2023) 83:1023
https://doi.org/10.1140/epjc/s10052-023-12177-4

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

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

A. Flórez[1,a], J. Jones-Pérez[2,b], A. Gurrola[3,c], C. Rodriguez[1,d], J. Peñuela-Parra[1,e]

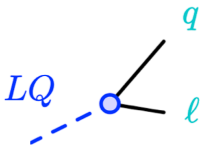
[1] Departamento de Física, Universidad de Los Andes, Cra. 1 # 18a-12, Bogotá, Colombia
[2] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Apartado 1761, Lima, Peru
[3] Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, USA

Received: 31 July 2023 / Accepted: 22 October 2023 / Published online: 11 November 2023

DOI: 10.1140/epjc/s10052-023-12177-4,
ARXIV: 2307.11070 [hep-ph].

Example: The Vector Leptoquark 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

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

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

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

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.

The Vector Leptoquark Lagrangian

The full Lagrangian for the vector leptoquark is

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

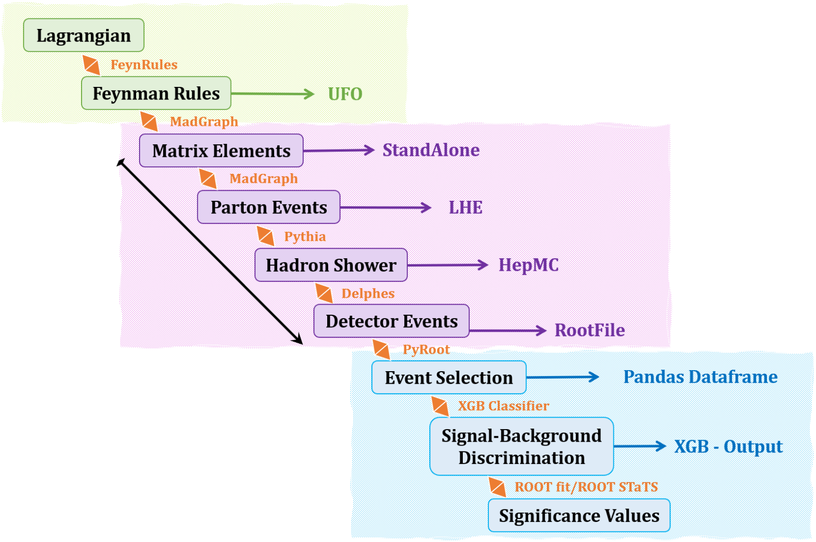
where $U_{\mu\nu} = \mathcal{D}_\mu U_\nu - \mathcal{D}_\nu U_\mu$, $\mathcal{D}_\mu = \partial_\mu - ig_s G^a_\mu T^a - i\frac{2}{3}g_Y B_\mu$, and the couplings β_L and β_R are complex 3×3 matrices in flavor space.

The $\Delta F = 2$ and constrains on lepton flavor violating processes indicates an structure as

$$\beta_L = \begin{pmatrix} 0 & 0 & \beta_L^{13} \\ 0 & 0 & \beta_L^{23} \\ 0 & \beta_L^{32} & \beta_L^{33} \end{pmatrix}, \quad \beta_R = \text{diag}\left(0, 0, \beta_R^{33}\right)$$

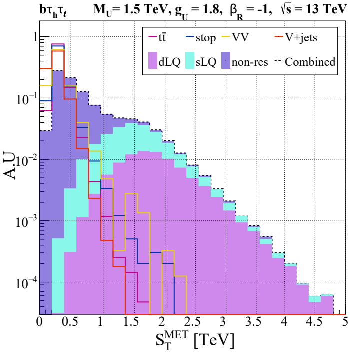
If U_1 has a gauge origin $\kappa_c = \kappa_Y = 0$. We choose $U(2)$ in quark and leptons space, in a way that you have an hierarchy, $\left|\beta_L^{31}\right| \ll \left|\beta_L^{23}\right|, \left|\beta_L^{32}\right| \ll \left|\beta_R^{33}\right|, \left|\beta_L^{33}\right| = \mathcal{O}(1)$.

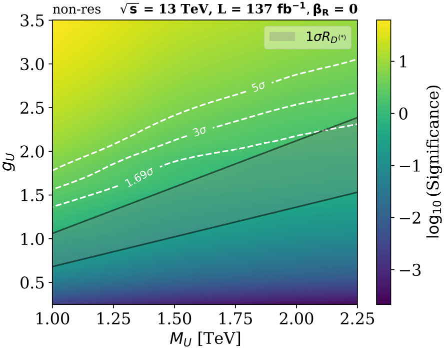
Feasibility Studies Workflow



Sensitivity Reach of the U_1 Leptoquark

$S_T^{\text{meT}} = \left|\vec{\mathbf{p}}_T^{\,\text{miss}}\right| + \sum_i \left|\vec{\mathbf{p}}_T^{\,i}\right|$





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

Take care, you could need a Z' boson

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,

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

So, the gauge group with this leptoquark must include a $U(1)_{B-L}$ symmetry.

Take care, you could need a Z' boson

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,

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

So, the gauge group with this leptoquark must include a $U(1)_{B-L}$ symmetry.
The generator T_{B-L} is associated with the $U(1)_{B-L}$ symmetry with a Z' boson.

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

Take care, you could need a Z' boson

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,

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

So, the gauge group with this leptoquark must include a $U(1)_{B-L}$ symmetry.
The generator T_{B-L} is associated with the $U(1)_{B-L}$ symmetry with a Z' boson.

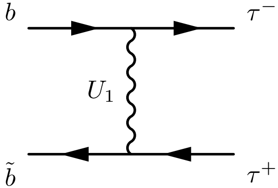
$$\begin{aligned} \mathcal{L}_{\text{int}} &\sim Z'_\mu \left(\bar{\psi}_L^{\text{SM}} \gamma^\mu (3T_{B-L}) \psi_L^{\text{SM}}\right) \\ &\sim Z'_\mu \left(\bar{q}_L \gamma^\mu q_L - 3\bar{\ell}_L \gamma^\mu \ell_L\right). \end{aligned}$$

so, the full Lagrangian for the Z' boson is

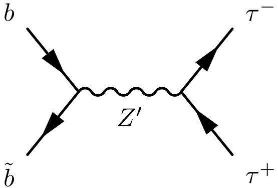
$$\begin{aligned} \mathcal{L}_{Z'} = &-\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} M_{Z'}^2 Z'_\mu Z'^\mu \\ &+ \frac{g_{Z'}}{2\sqrt{6}} Z'^\mu \left(\zeta_q^{ij} \bar{q}_L^i \gamma_\mu q_L^j + \zeta_u^{ij} \bar{u}_R^i \gamma_\mu u_R^j + \zeta_d^{ij} \bar{d}_R^i \gamma_\mu d_R^j - 3\zeta_\ell^{ij}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

Interference with a Z' vector boson

Non-Resonant Production (leptoquarks)



Resonant Production (neutral bosons)



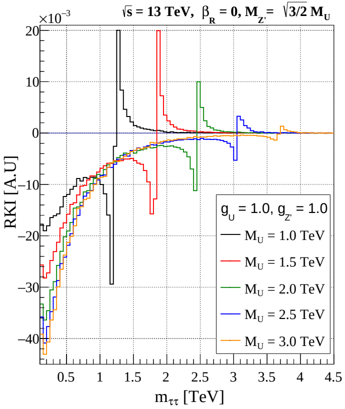
$$\mathcal{M}_{U_1} \sim \frac{1}{t - m_{U_1}^2 + i m_{U_1}\Gamma_{U_1}}, \qquad (1) \qquad \mathcal{M}_{Z'} \sim \frac{1}{s - m_{Z'}^2 + i m_{Z'}\Gamma_{Z'}}, \qquad (2)$$

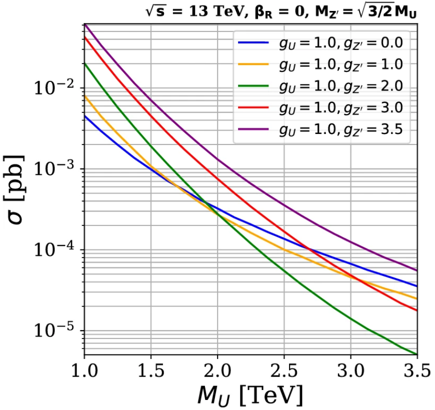
so the interference has the form

$$\sim \frac{m_{LQ} m_{Z'} \Gamma_{LQ} \Gamma_{Z'} - (t - m_{LQ}^2)(s - m_{Z'}^2)}{\left[(t - m_{LQ}^2)^2 + m_{LQ}^2 \Gamma_{LQ}^2\right]\left[(s - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2\right]}.$$

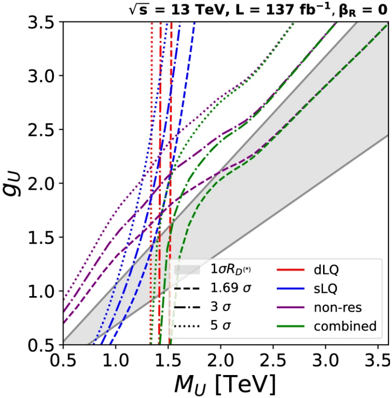
Interference with a Z' vector boson

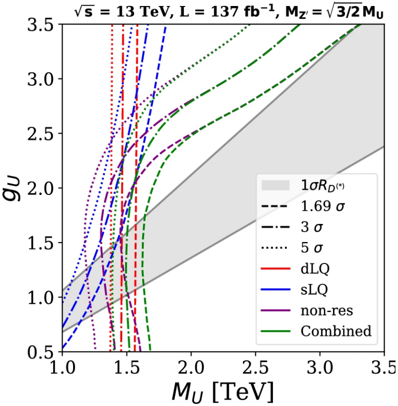
$$\frac{\mathrm{d}}{\mathrm{d}m}\left[\sigma_{LQ+Z'} - \left(\sigma_{LQ} + \sigma_{Z'}\right)\right] \sim \frac{g_{Z'}g_U}{s}\frac{m_{LQ}m_{Z'}\Gamma_{LQ}\Gamma_{Z'} - (t-m_{LQ}^2)(s-m_{Z'}^2)}{\left[(t-m_{LQ}^2)^2 + m_{LQ}^2\Gamma_{LQ}^2\right]\left[(s-m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2\right]}.$$





Effects on the Sensitivity reach





Final Remarks

- We showed that LFV could be a window to new physics that could be explored at the LHC in searches with final states with *tau* leptons.

- It is necessary to consider possible interferences when looking for excesses in the ditaus channel that can significantly affect the sensitivity of the different parameter spaces.

- Different models, in particular gauge models, have compressed mass sectors of newly physical particles that can be extremely susceptible to interference in different production mechanisms.

- Fingerprints in the two-taus channel can inherit information from the spin of the new physics mediator, so polarization studies of each model and the associated interference effects may also be relevant.