Challenges in Semileptonic B Decays

22 April 2022, Barolo

# Testing New Physics in RD(*) at the LHC

2011.02486, RW, Syuhei Iguro, Michihisa Takeuchi

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# Background 1/2

**NP possibilities:** $\mathcal{L}_X = 2\sqrt{2} G_F V_{cb} C_X^\ell (\bar{c}\,\Gamma b)(\bar{\ell}\,\Gamma' \nu)$

**Tau case:**

— **Solutions to the RD(*) anomaly**

$C^\tau_{\text{SM-like}} \approx 0.09$ $\quad C^\tau_{\text{VRL}} \approx 0.42i$ $\quad C^\tau_T \approx 0.15 + i\,0.19$

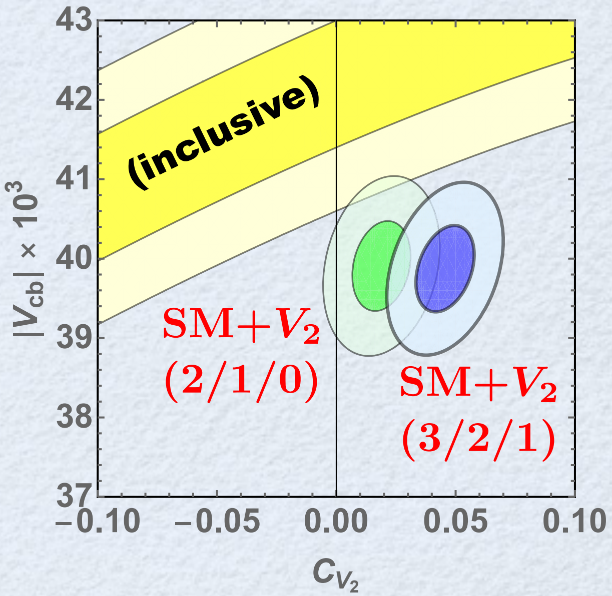
$(\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu)$ $\quad (\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu)$ $\quad (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}\sigma_{\mu\nu} P_L \nu)$

**Electron & muon cases:**

— **NP can be hidden behind the Vcb measurement**

— **possible size is < 5% of the SM size**

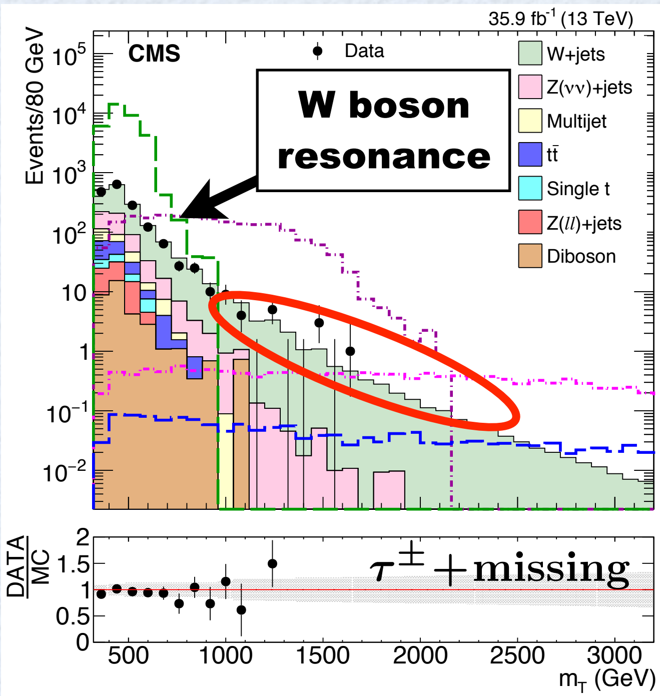
$C_X^{e,\mu} \approx 0.05$ 2004.10208




**So, what about the LHC bounds?**

# Background 2/2

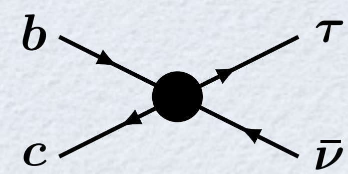
## $\ell^{\pm}$ + missing energy search:




— **Tail of the W boson** has potential to search for NP

— **Missing transverse mass**

$$m_T = \sqrt{2 p_T^l E_T^{\text{miss}} (1 - \cos\phi_{l\nu})},$$




— **Large mT region** (>500GeV) sensitive to NP effect

## Data available:

— **Tau with 36fb^-1** CMS (2019)

— **Light leptons with 139fb^-1** ATLAS (2019)

**The LHC bound is competitive to the RD(*) anomaly solution**

A. Greljo, J. M. Camalich, and J. D. Ruiz-Álvarez, 1811.07920

**ex)** $|C_T^{\tau}|_{\text{LHC}} < 0.20 \ (95\%\text{CL})$

**already excludes** $|C_T^{\tau}|_{R_{D^{(*)}}} \approx |0.15 + i\,0.19| = 0.24$

# Topics

(1) EFT **breakdown** at high-pT tail

(2) Current LHC bounds in **EFT** and **Leptoquark** models

(3) "**+ b-jet tag**" simulation to improve the bound

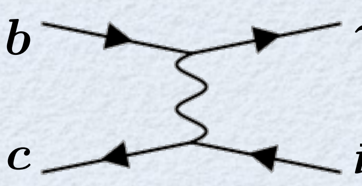
# High-pT tail 1/1

2011.02486

**EFT breakdown at large mT:**

ex) $\mathcal{L}_U = h_U^{ij} \left(\bar{q}_L^i \gamma^\mu \ell_L^j\right) U_\mu + \text{h.c.}$

| | spin | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ |
|---|---|---|---|---|
| $U_1^\mu$ | 1 | 3 | 1 | 4/3 |

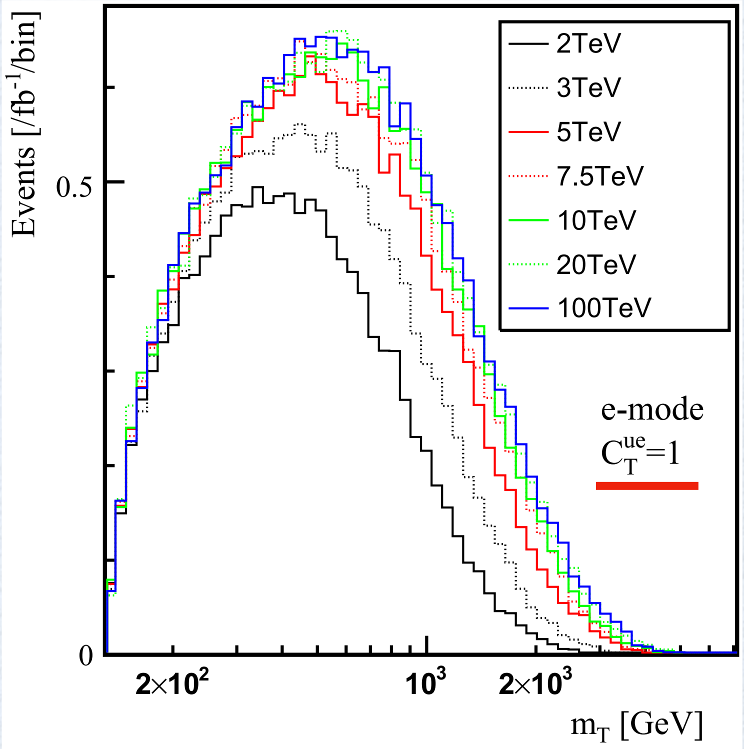



**Total rate:** $\dfrac{h_U^{b\tau} \cdot h_U^{c\nu}}{q^2 - m_{\text{LQ}}^2} \simeq -\dfrac{h_U^{b\tau} \cdot h_U^{c\nu}}{m_{\text{LQ}}^2} \equiv C_{V_1}$

**The region $q^2 \ll m_{\text{LQ}}^2 \sim 1\,\text{TeV}$ is dominant**

**Distribution at high-pT:** $\dfrac{h_U^{b\tau} \cdot h_U^{c\nu}}{q^2 - m_{\text{LQ}}^2} \neq -\dfrac{h_U^{b\tau} \cdot h_U^{c\nu}}{m_{\text{LQ}}^2} \equiv C_{V_1}$

- $q^2 = 2E^2(1 \pm \cos\theta)$ **is no longer negligible**
- **the angular dependence induces non-trivial effect on the distribution**



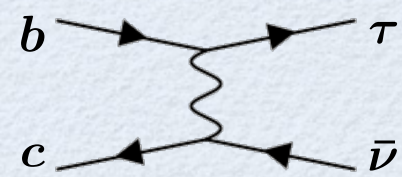
# Analysis setup 1/2

**Prepare LQ interactions that generate 4 Fermi currents:**

$$\mathcal{L}_{[V_1]} = h^{ij}\left(\bar{q}^i_L\gamma^\mu\ell^j_L\right)U_\mu + \text{h.c.} \quad \Longrightarrow \quad C_{V_1}$$

$$\mathcal{L}_{[V_2]} = \left(h^{ij}\bar{u}^i_R\nu^j_L + h'^{ij}\bar{d}^i_R\ell^j_L\right)R_2^{2/3} + \text{h.c.} \quad \Longrightarrow \quad C_{V_2}$$

$$\mathcal{L}_{[S_1]} = \left(h^{ij}\bar{u}^i_L\gamma^\mu\nu^j_L + h'^{ij}\bar{d}^i_R\gamma^\mu\ell^j_R\right)U_\mu + \text{h.c.} \quad \Longrightarrow \quad C_{S_1}$$




⋮

— **Every given LQ mass, the coupling h is constrained from LHC data**

— **The result is represented as the WC bound:** $2\sqrt{2}G_F V_{cb} C_X = N_X \dfrac{h_1 h_2}{M_{\text{LQ}}^2}$

**(Amplitude)**

$$|\mathcal{M}^{\text{LQ}}_{V_1}|^2 = 4\,(h^{21}_{\text{LQ}}h^{31*}_{\text{LQ}})^2 E^4 \hat{C}_t^2 (1-\cos\theta)^2,$$
$$|\mathcal{M}^{\text{LQ}}_{V_2}|^2 = (h^{21}_{\text{LQ}_1}h^{31*}_{\text{LQ}_2})^2 E^4 \hat{C}_t^2 (1+\cos\theta)^2,$$
$$|\mathcal{M}^{\text{LQ}}_{S_1}|^2 = 16\,(h^{21}_{\text{LQ}_1}h^{31*}_{\text{LQ}_2})^2 E^4 \hat{C}_t^2,$$
$$|\mathcal{M}^{\text{LQ}}_{S_2/T}|^2 = (\tilde{h}^{12*}_{\text{LQ}_2}\tilde{h}^{13}_{\text{LQ}_1})^2 E^4 \Big[\hat{C}_t^2(1+\cos\theta)^2 + \hat{C}_u^2(1-\cos\theta)^2 \pm 2\hat{C}_t\hat{C}_u(1-\cos^2\theta)\Big],$$

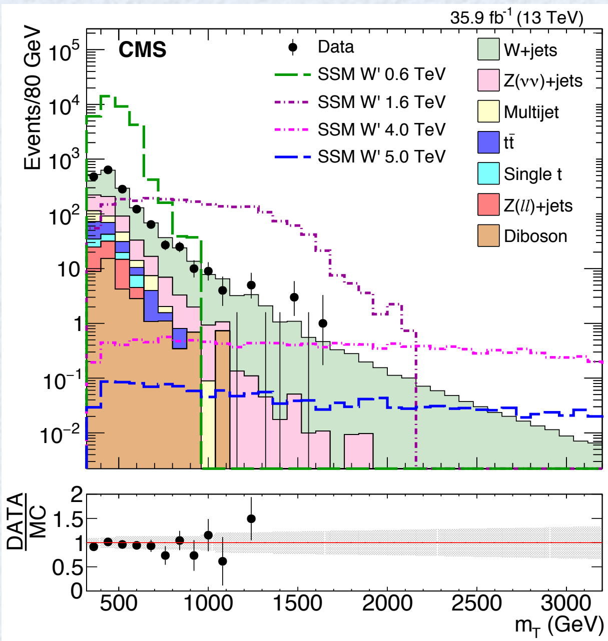
where $\hat{C}_t$ and $\hat{C}_u$ involve the LQ propagator written as

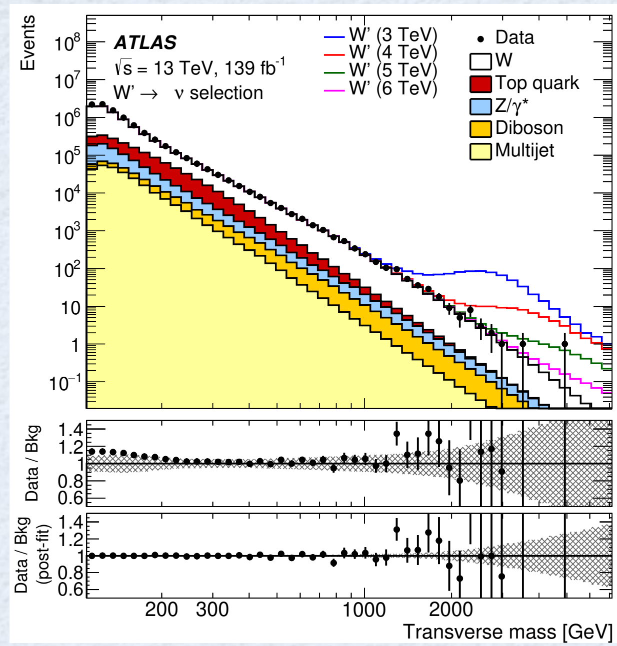
$$\hat{C}_t = \left[2E^2(1+\cos\theta) + M_{\text{NP}}^2\right]^{-1},$$
$$\hat{C}_u = \left[2E^2(1-\cos\theta) + M_{\text{NP}}^2\right]^{-1}.$$

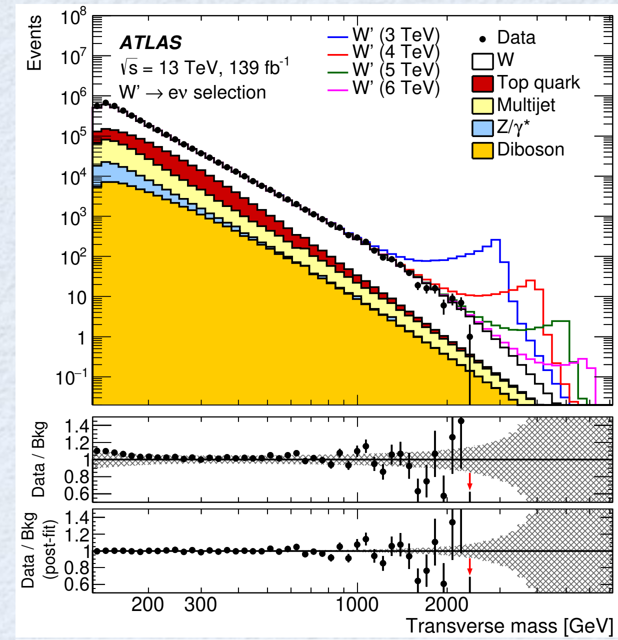
**EFT:** $\hat{C}_t = \hat{C}_u = 1/M_{\text{NP}}^2$

# Analysis setup 2/2

## Available data:




— **Tau** with 36fb^-1 from CMS    *CMS (2019)*

— **Light leptons** with 139fb^-1 from ATLAS    *ATLAS (2019)*

**(Numerical Analysis)**

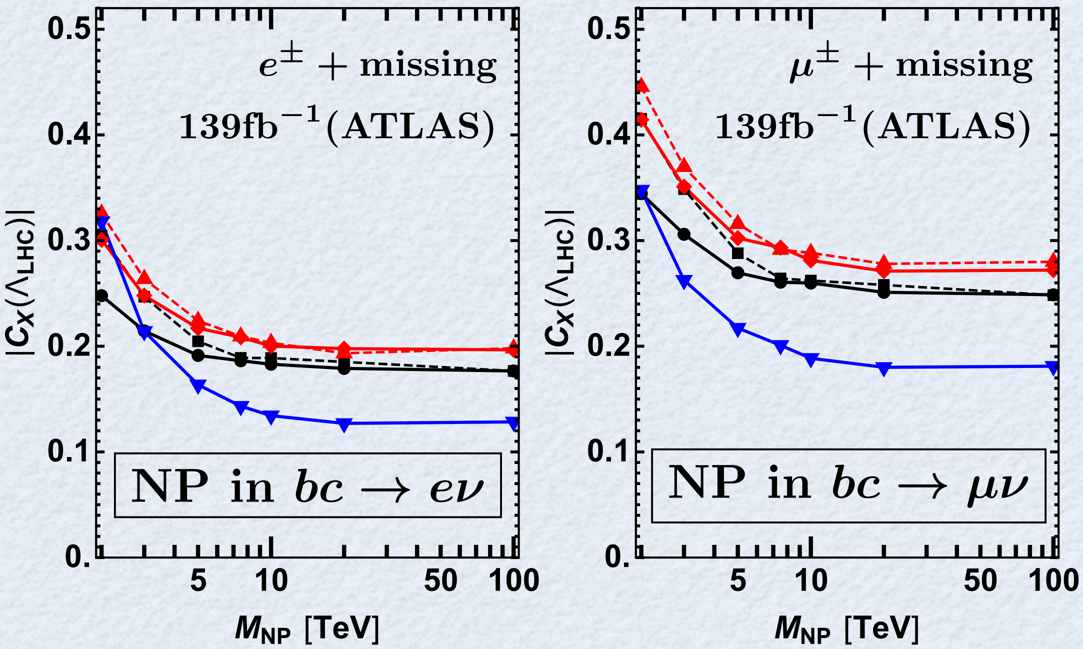
— **Selection cuts exactly following ATLAS (light lepton) / CMS (tau)**

— **Data/Simulated-signal in distribution of mT bin(~ 1TeV) are compared**

— **The mT bin range is provided in the literature**

# Result 1/3
## (Light leptons)

**Mediator (LQ) mass dependence:**




**WC definition:**

V1 $\quad 2\sqrt{2}G_F V_{cb}\Big[C_{V_1}(\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu)$

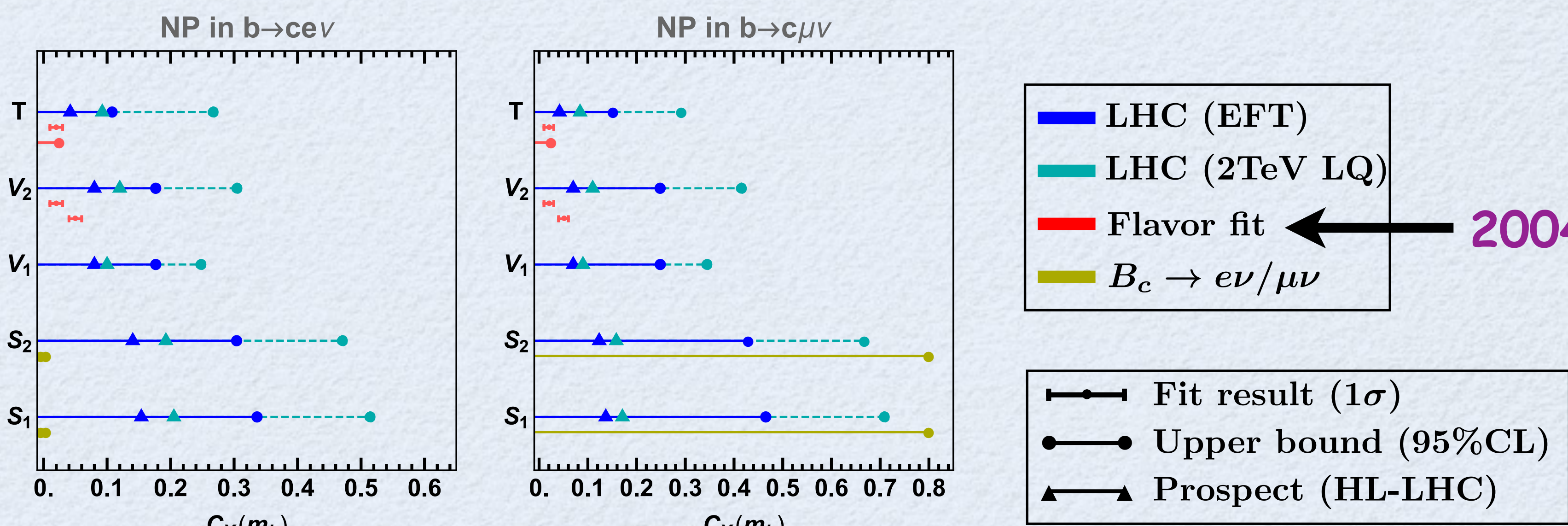
V2 $\quad +C_{V_2}(\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu)$

S1 $\quad +C_{S_1}(\bar{c}P_R b)(\bar{\ell}P_L \nu)$

S2 $\quad +C_{S_2}(\bar{c}P_L b)(\bar{\ell}P_L \nu)$

T $\quad +C_T(\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\ell}\sigma_{\mu\nu}P_L \nu)\Big]$

**Impact on Flavor (Vcb+NP fit): competitive only at future HL-LHC (3ab^-1)**

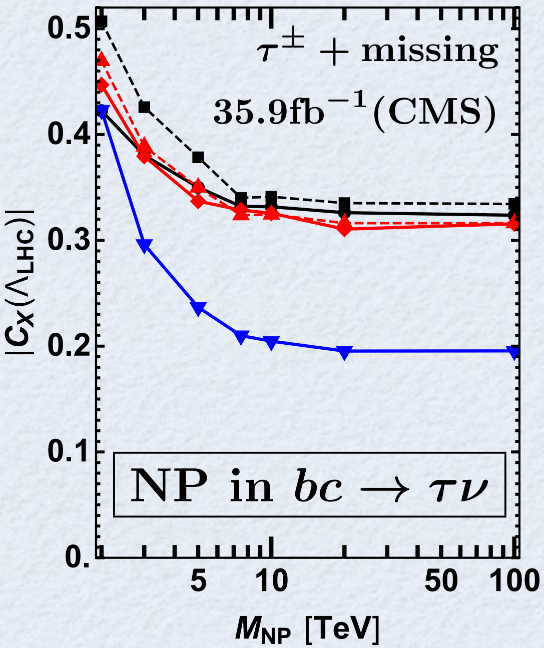



2004.10208

# Result 2/3

## (Tau lepton)

**Mediator (LQ) mass dependence:**




**Summary for both tau & light leptons:**

**2TeV LQ: EFT bound is 40~100% overestimated**

**5TeV LQ: 10~20% overestimated**

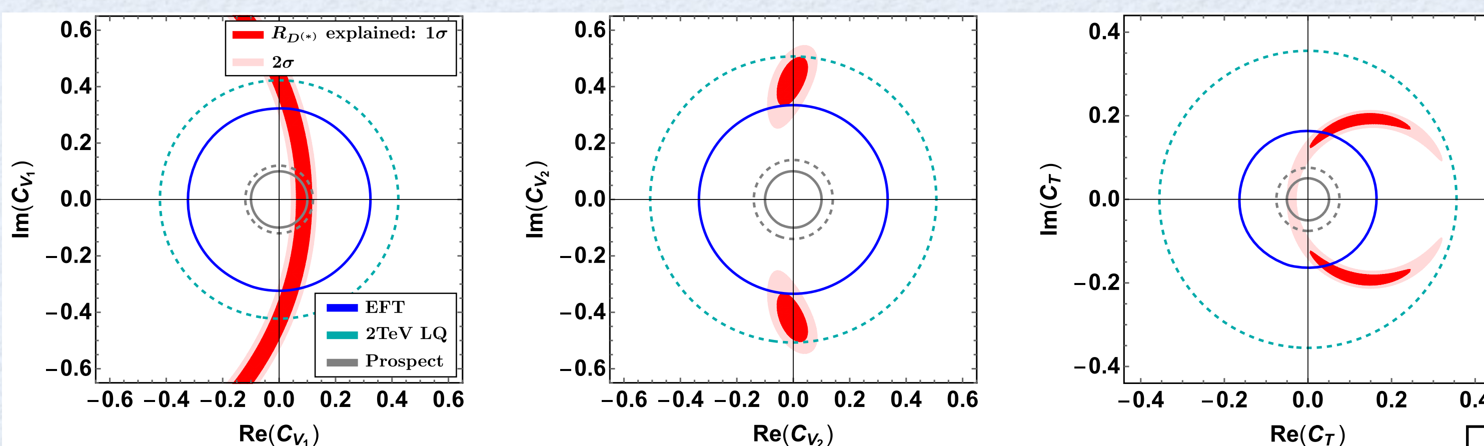
**Impact on Flavor (RD(*) anomaly):**

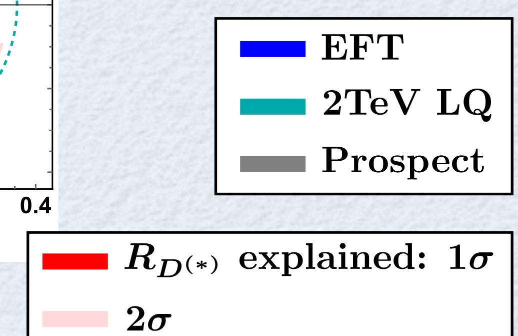
**EFT)** $|C_T|_{\rm LHC} < 0.20$ (95%CL)

↓

**LQ)** $|C_T|_{\rm LHC} < 0.42$ (95%CL)

$\leftrightarrow \; |C_T|_{R_{D^{(*)}}} \approx |0.15 + i\,0.19| = 0.24$




**SM-like vector** **VRL** **Tensor**

# Result 3/3

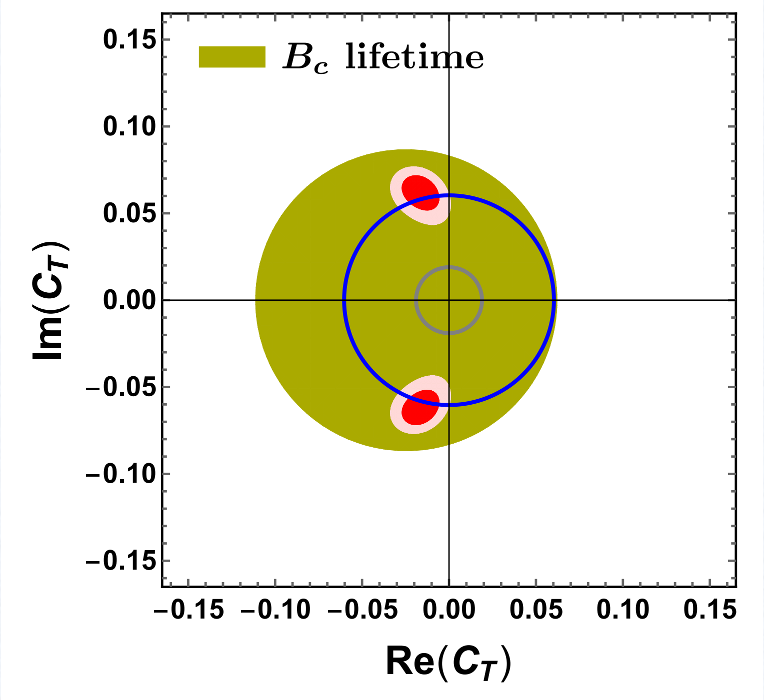
## (Tau lepton)

**Specific LQ case:**

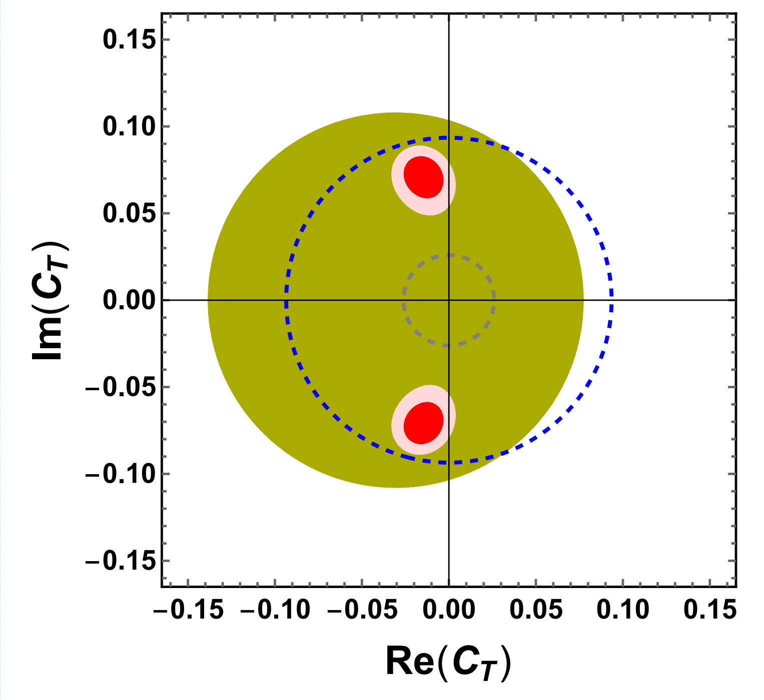
— **Singlet/Doublet scalar LQs (S1/R2) induce Scalar-Tensor current**

$$C_{S_2}(\Lambda_{\rm LQ}) = +4C_T(\Lambda_{\rm LQ}) \quad \text{for } \Lambda_{\rm LQ} \approx M_{\rm LQ} = 2\,\text{TeV}/100\,\text{TeV}$$

— **R2-LQ has solution to the RD(*) anomaly, in which non-EFT is crucial as well**




**EFT limit of R2-LQ**




**2TeV R2-LQ**

# + b-jet tag

2111.104748

— Requiring additional b-jet greatly reduces the SM background

$$\ell^\pm \nu + b\Big|_{\rm SM} \quad \Rightarrow \quad gq \to b\ell\nu \quad (q = u, c) \quad \Rightarrow \quad |V_{ub,cb}|^2 \text{ suppression}$$

**Improvement ①: stronger bound is simply expected**

— can look into detail of the U1-LQ model = SM-like vector operator

$$\mathcal{L}_U = h_U^{ij} \left( \bar{q}_L^i \gamma^\mu \ell_L^j \right) U_\mu + \text{h.c.} \qquad C_{V_1} \equiv -\frac{h_U^{b\tau} \cdot h_U^{c\nu}}{m_{\rm LQ}^2}, \quad \text{but indeed } h_U^{c\nu} = h_U^{s\ell}$$

$$\ell^\pm \nu\Big|_{U_1\text{-LQ}} \quad \Rightarrow \quad cb, cs \to \ell\nu \quad \Rightarrow \quad \text{The } C_{V_1} \text{ bound is valid only if } h_U^{b\tau} \gg h_U^{c\nu} \text{ for } U_1\text{-LQ}$$

$$\ell^\pm \nu + b\Big|_{U_1\text{-LQ}} \quad \Rightarrow \quad cg \to b\ell\nu \quad \Rightarrow \quad \text{no } s \text{ quark, (but could be mis-tagged)}$$

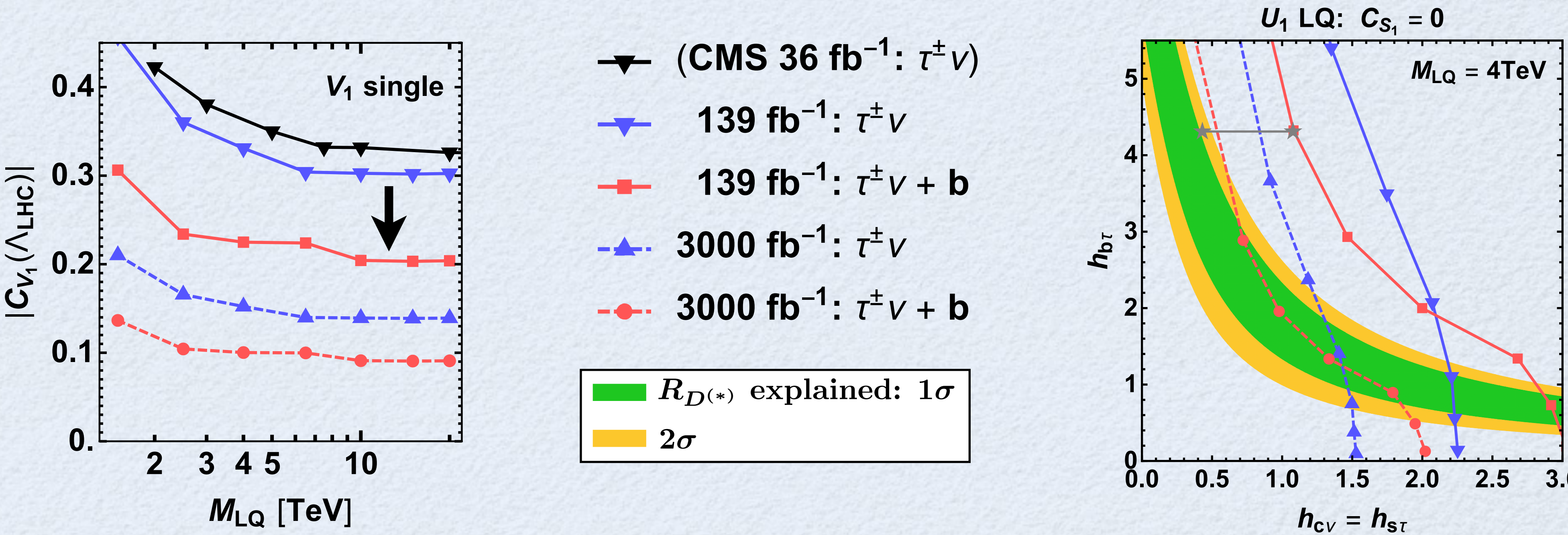
**Improvement ②: complementary bound on the two couplings**

# + b-jet tag

2111.104748

**(BG/Signal events generated & simulated: details skipped)**

**Improvement ①:** **Improvement ②:**




**Observations:**

- **+b search improves the bound by ~50%**
- **+b search at HL_LHC can achieve Cx~0.1, i.e. 10% NP effect**
- **Given the LQ mass, the two couplings (not combination) are constrained**

# Closing

- The process for RD(*) can be searched at the LHC from “lepton + missing”

- EFT breakdown is crucial for the LHC search at high-pT

  — Tau: EFT bound kills some RD(*) solutions, but it survives in the LQ model.

  — Light lepton: LHC bound is not significant yet, but HL-LHC can be competitive.

- lepton + b + missing greatly reduces the SM backgrounds

  — The bound can be improved by ~50%

  — HL-LHC has search potential for 10% NP effect (of the SM size)

  — The famous U1 leptoquark scenario for RD(*) can be tested at the LHC

# Backup

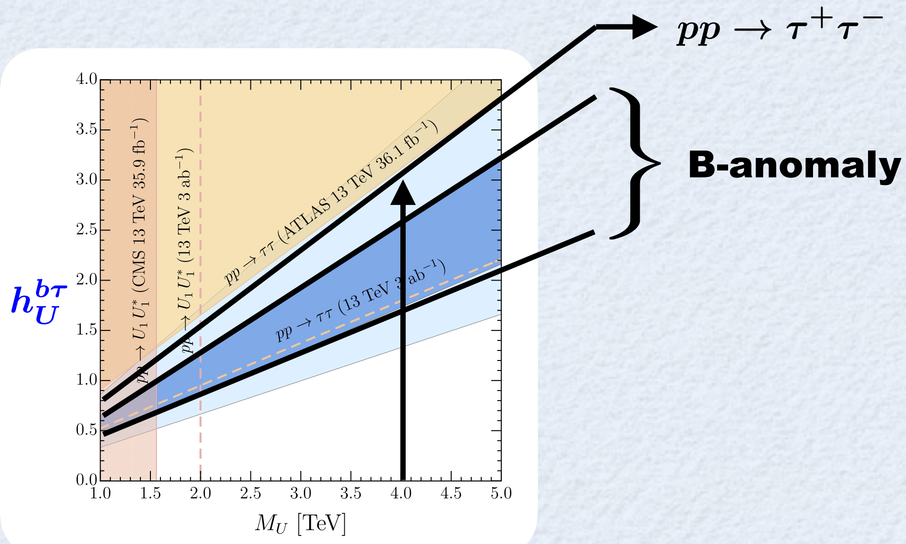
# U1 leptoquark with symmetry

**Scenario by Isidori** 1903.11517 $\mathcal{L}_{\mathrm{U_1LQ}} = h_L^{ij}\left(\bar{u}_i\gamma_\mu P_L \nu_j + \bar{d}_i \gamma_\mu P_L \ell_j\right)\mathrm{U}_1^\mu + h_R^{ij}\left(\bar{d}_i\gamma_\mu P_R \ell_j\right)\mathrm{U}_1^\mu + \mathrm{h.c.}.$

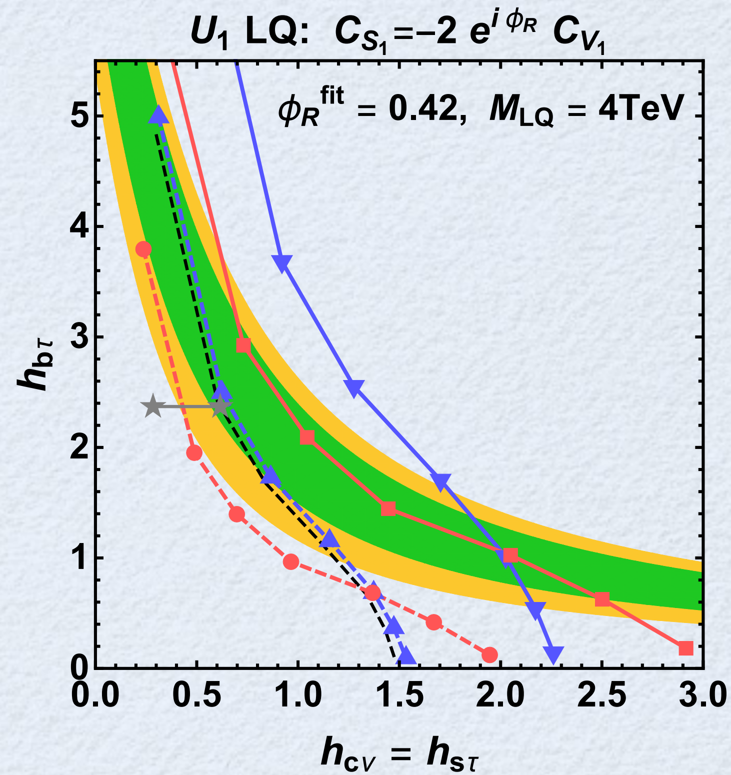
$$2\sqrt{2}G_F V_{cb} C_{V_1} = +\frac{(V_{\mathrm{CKM}} h_L)^{23}\, h_L^{*33}}{M_{\mathrm{LQ}}^2}, \qquad 2\sqrt{2}G_F V_{cb} C_{S_1} = -2\frac{(V_{\mathrm{CKM}} h_L)^{23}\, h_R^{*33}}{M_{\mathrm{LQ}}^2}.$$

**U(2) flavor symmetry:** $C_{S_1} = -2\beta_R C_{V_1}\,,\qquad \beta_R = e^{i\phi_R}$ denotes a relative phase

**LHC search from** $pp \to \tau^+\tau^-$ **:**

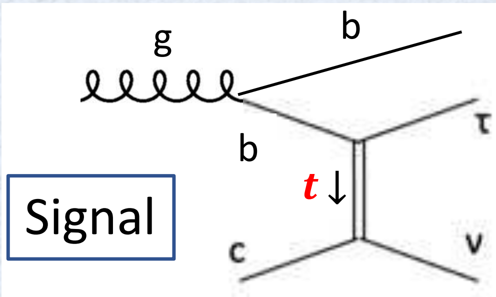


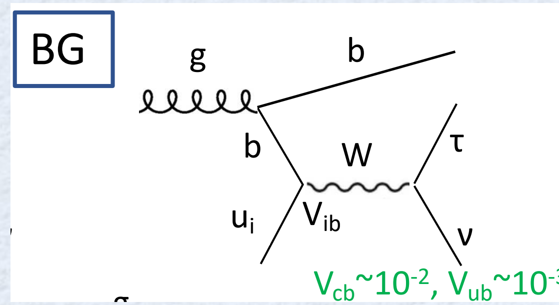

**Comparison:**

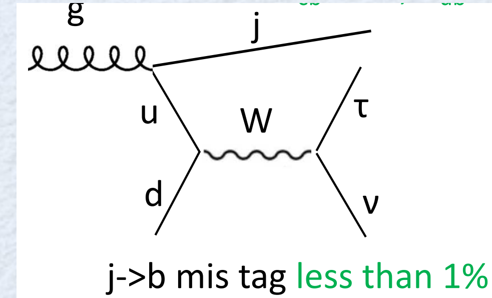



$\tau^+\tau^-$ (ATLAS 139fb$^{-1}$)

# Signal & Background



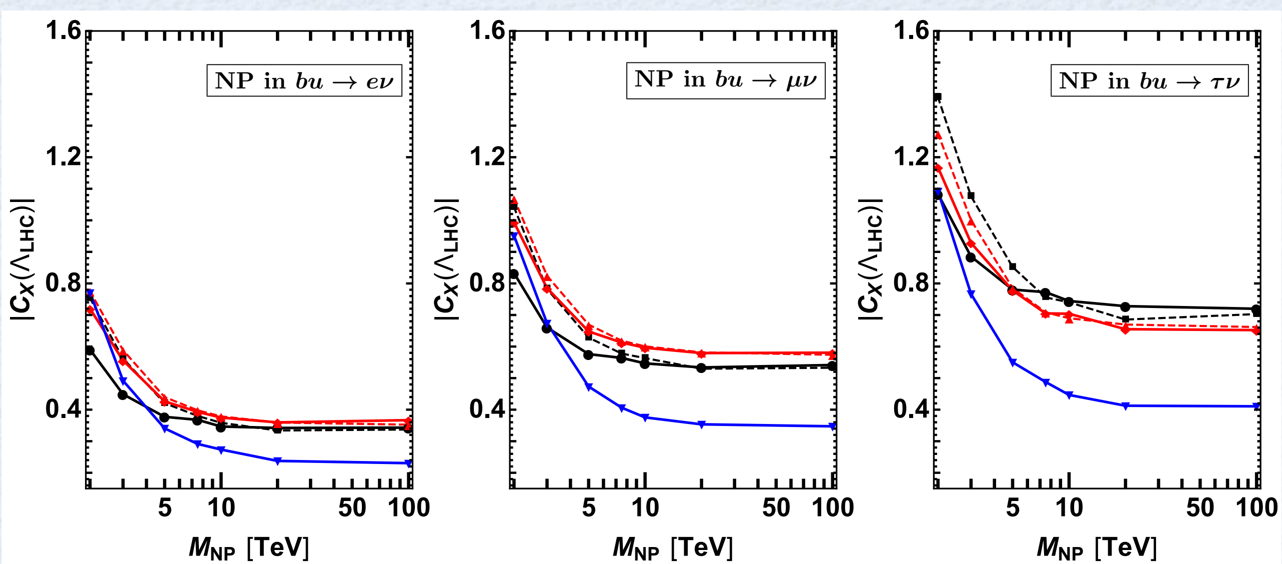




| BG (**cut b**) | $Wjj$ | $Zjj\ (Z\to\nu\bar{\nu})$ | $t\bar{t}$ | $Z,\gamma$ DY | $VV$ | single $t$ | total |
|---|---|---|---|---|---|---|---|
| $0.7 < m_T < 1$ TeV | 0.58 | 0.37 | 0.056 | 0.28 | 0.018 | 0.029 | 1.33 |
| 1 TeV $< m_T$ | 0.16 | 0.06 | 0.01 | 0.007 | 0.005 | 0.005 | 0.25 |
| 1 TeV $< m_T$ [34] | 0.18(5) | 0.21(12) | 0.29(3) | $4.2(4)\times10^{-5}$ | 0.35(5) | 0.067(7) | 1.10(14) |

**Table 2.** Expected number of SM background events after **cut b** (the $\tau^\pm\nu+b$ search) for $\int\mathcal{L}dt = 35.9\ \text{fb}^{-1}$

# Results for b → u



# Leptoquark search

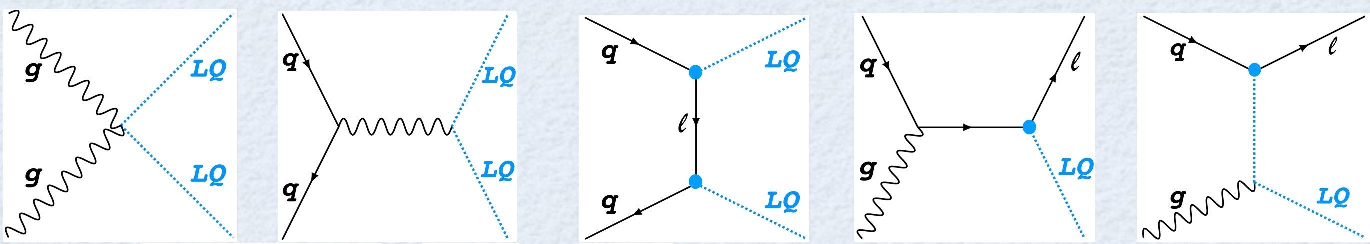
## Vector boson coupled to quark & lepton

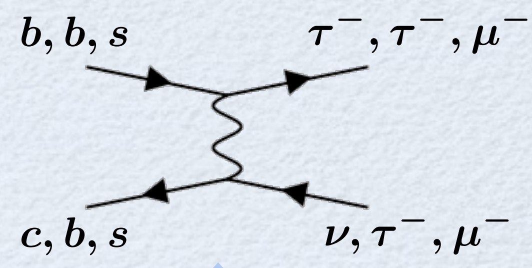
$$\mathcal{L}_U = h_U^{ij} \left( \bar{q}_L^i \gamma^\mu \ell_L^j \right) U_\mu + \text{h.c.}$$

| | spin | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ |
|---|---|---|---|---|
| $U_1^\mu$ | 1 | 3 | 1 | 4/3 |

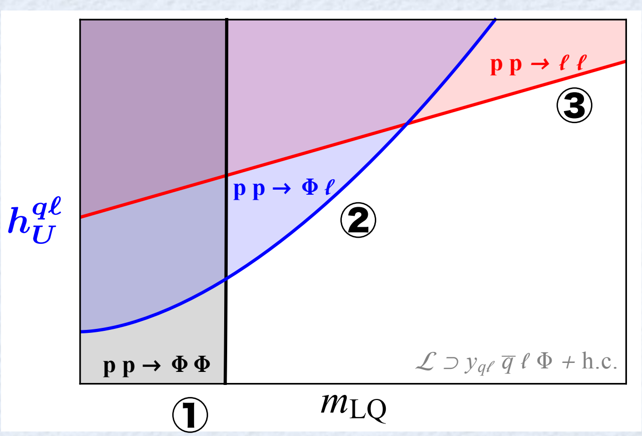
**Productions at LHC:**

→ ① **QCD pair production** ② **LQ coupling induced (pair and single)** ③ **B anomaly specific**



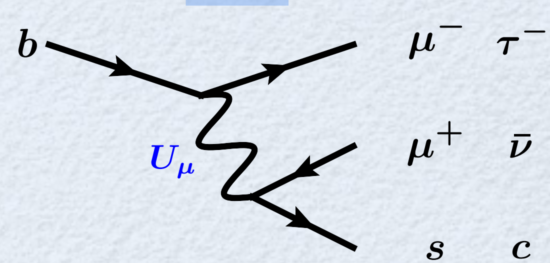

→ **Sketch of the LHC bound** 1801.07641




① **provides absolute limit (Br = 1)**

$m_{\text{LQ}} > 1.5\,\text{TeV}$ (1st & 2nd gen.)
$m_{\text{LQ}} > 0.9\,\text{TeV}$ $(t\,\tau)$
$m_{\text{LQ}} > 1.0\,\text{TeV}$ $(b\,\tau)$
$m_{\text{LQ}} > 0.5\,\text{TeV}$ $(b\,\nu)$

PDG (2021)




② **not much studied yet**