

# LHC SEARCHES MOTIVATED BY RECENT B-ANOMALIES

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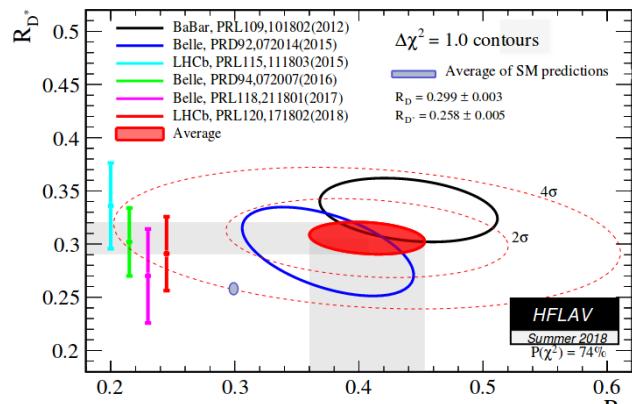
# The B-anomalies

Puzzling hints of **Lepton Flavor Universality** (LFU) violation in B-decays

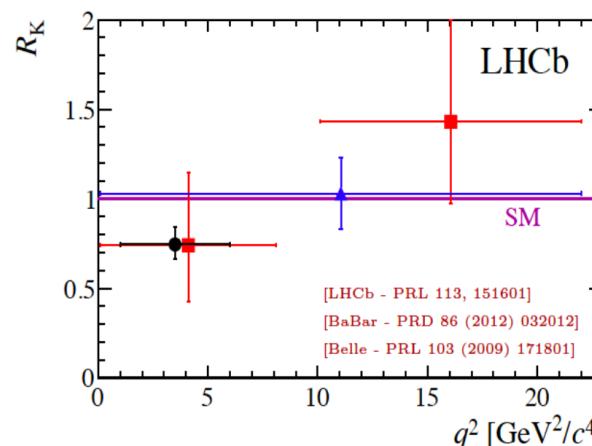
LFU ratios at B-factories:

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \rightarrow D^{(*)}l\bar{\nu})} \Big|_{l \in \{e, \mu\}}$$

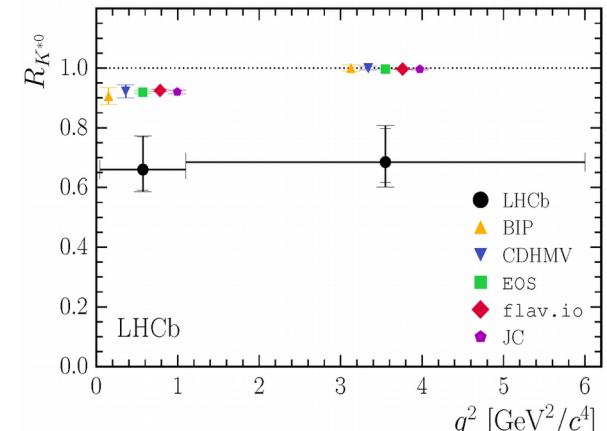
$$R_{K^{(*)}}^{[q_1^2, q_2^2]} = \frac{\mathcal{B}(B \rightarrow K^{(*)}\mu\mu)}{\mathcal{B}'(B \rightarrow K^{(*)}ee)}$$



$$R_{D^{(*)}}^{\text{exp}} > R_{D^{(*)}}^{\text{SM}} \quad 3.8\sigma$$



$$R_{K^{(*)}}^{\text{exp}} < R_{K^{(*)}}^{\text{SM}} \quad 2.5\sigma$$



Recent excess in  $R_{J/\psi} = \frac{\mathcal{B}(B_c \rightarrow J/\psi \tau\bar{\nu})}{\mathcal{B}(B_c \rightarrow J/\psi \mu\bar{\nu})} = 0.71 \pm 0.25 \quad 2.0\sigma$

Deviations consistent with each other! combined above  $4\sigma$

Suggests New Physics (NP) coupling dominantly to 3<sup>rd</sup> generation. *who ordered that?*

## Model building: bottom-up approach

Anomaly in data → EFT → SMEFT → Simplified Models → Ultra-Violet Theory

Guided by data with minimal theoretical bias

Can LFU violating NP in (semi-tauonic) B-decays be tested at high-energy colliders?

Efficient probe: **Di-Tau tails at the LHC**

## Overview of this talk:

Quickly Revisit link between  $R_{D^*}$  anomaly and **di-taus** at the LHC in the SMEFT

NP mediators vs di-Taus

Leptoquarks (LQ): focus on vector LQ solution  $U_1 \sim (3, 1, 2/3)$

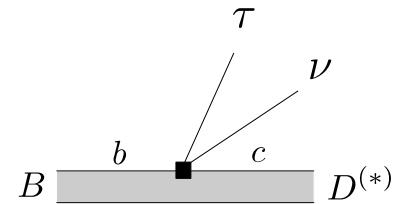
Discuss complementarity between LFV low-energy observables and high- $p_T$  di-Taus

Based on:

DAF, Greljo, Kamenik Phys .Lett. B 764 (2017)126-134

Angelescu, Becirevic, DAF, Sumensari [1808.08179]

# Effective Theory



Effective Lagrangian:  $B \rightarrow D^{(*)} \tau \nu$

$$\mathcal{H}_{eff} = -2\sqrt{2}G_F V_{cb} \left[ (1 + g_{V_L}) \mathcal{O}_{V_L} + g_{V_R} \mathcal{O}_{V_R} + g_{S_L} \mathcal{O}_{S_L} + g_{S_R} \mathcal{O}_{S_R} + g_T \mathcal{O}_T \right]$$

$\mathcal{O}_{V_L} = (\bar{c}_L \gamma^\mu b_L) (\bar{\tau}_L \gamma^\mu \nu_\tau)$	$\mathcal{O}_{S_L} = (\bar{c}_R b_L) (\bar{\tau}_R \nu_\tau)$	$\mathcal{O}_T = (\bar{c}_R \sigma^{\mu\nu} b_L) (\bar{\tau}_R \sigma^{\mu\nu} \nu_\tau)$
$\mathcal{O}_{V_R} = (\bar{c}_R \gamma^\mu b_R) (\bar{\tau}_L \gamma^\mu \nu_\tau)$	$\mathcal{O}_{S_R} = (\bar{c}_L b_R) (\bar{\tau}_R \nu_\tau)$	

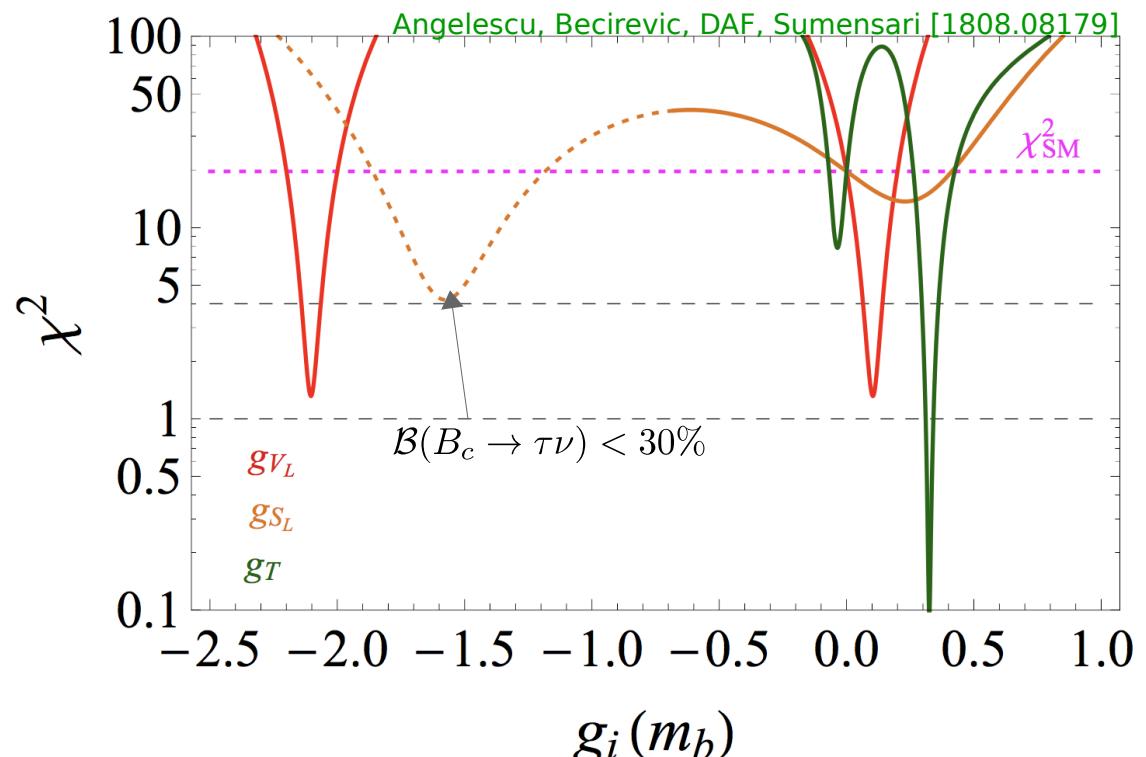
Single operator solutions:

See also Freytsis, Ligeti, Ruderman  
[1506.08896]

Fit to  $R_{D^{(*)}}$  &  $B_c$  lifetime bound  
Pseudoscalar solution excluded

Alonso, Grinstein, Camalich  
[1611.06676]

V-A structure fits well data



Non **V-A** solutions are also allowed!

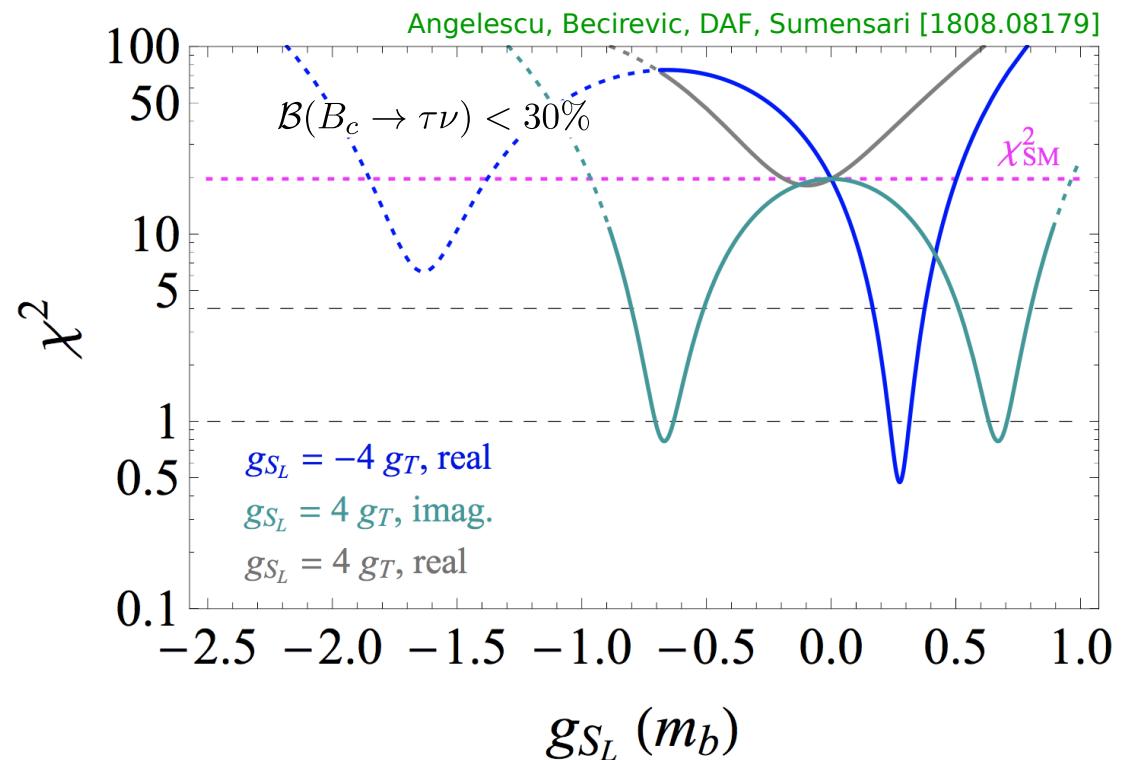
two or more operators

Scalar + Tensor structure fits data

$$g_{S_L} = \pm 4 g_T$$

(at TeV scale)

e.g. scalar LQ scenario



# SMEFT for R(D<sup>(\*)</sup>)

SM EFT (d=6):

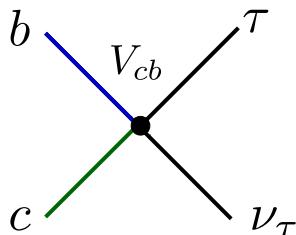
$$\begin{aligned}\mathcal{L}_{eff} \supset & c_{QQLL}^{ijkl} (\bar{Q}_i \gamma_\mu \sigma^a Q_j) (\bar{L}_k \gamma^\mu \sigma^a L_l) \\ & + c_{dQLe}^{ijkl} (\bar{d}_R^i Q_j) (\bar{L}_k e_R^l) \\ & + c_{QuLe}^{ijkl} (\bar{Q}_i u_R^j) i\sigma^2 (\bar{L}_k e_R^l) \\ & + c_{QuLe'}^{ijkl} (\bar{Q}_i \sigma_{\mu\nu} u_R^j) (\bar{L}_k \sigma_{\mu\nu} e_R^l)\end{aligned}$$

$$\Lambda_{NP} \lesssim 3 \text{ TeV}$$

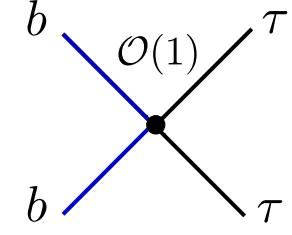
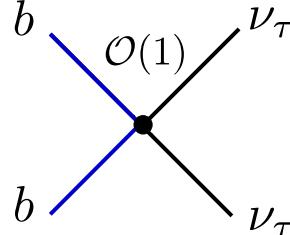
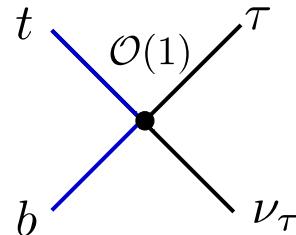
LHC sweet spot!

Flavor structure assumptions:

1. Alignment with **down quarks & charged leptons**:  $Q_i = (V_{CKM}^{ij*} u_L^j, d_L^i)^T$   $L_i = (U_{PMNS}^{ij*} \nu_L^j, \ell_L^i)^T$
2. Dominant effects in **3<sup>rd</sup> generation fermions**:  $c^{ijkl} \approx c \delta_{i3} \delta_{j3} \delta_{k3} \delta_{l3}$



$b \rightarrow c$



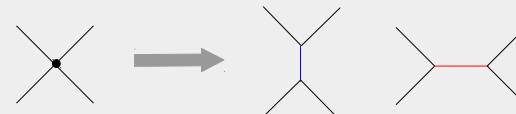
$V_{cb}^{-1}$  enhancement with respect to  $b \rightarrow c$  transitions

Enhanced coupling to Tauonic neutral currents  $b\bar{b} \rightarrow \tau\bar{\tau}$

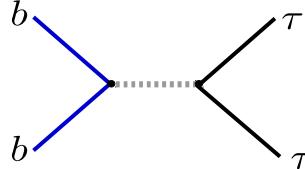
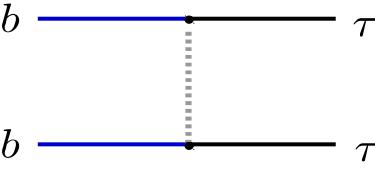
We can probe NP models in **Di-Tau** production at high-p<sub>T</sub> LHC!  $pp \rightarrow \tau^+ \tau^- + X$

# Simplified Models

- Necessary for reliable high-pT collider studies
- Correlates Wilson Coeffs.
- Paves the way towards UV complete models



Classification of mediators:

Spin	Colorless	Colorful
0	2HDM	Scalar Leptoquark
1	Vector Triplet W'	Vector Leptoquark
$b\bar{b} \rightarrow \tau^+\tau^-$	$b$ 	$b$ 
Signature	di-Tau Resonance	Non-resonant excess in di-Tau tails

## Colorless solution:

- Existing  $\tau\tau$  resonance searches @ LHC

Z' Sequential SM

MSSM Higgs

$$\left\{ \begin{array}{ll} 8 \text{ TeV} & 19.5 \text{ fb}^{-1} \\ 13 \text{ TeV} & 3.2 \text{ fb}^{-1} \\ 13 \text{ TeV} & 36.1 \text{ fb}^{-1} \end{array} \right.$$

JHEP 1507, 157 (2015)

CERN-EP-2016-0165

JHEP 1801 055 (2018)



# Vector Triplet Model

$$\mathcal{L}_{W'} = -\frac{1}{4} W'_{\mu\nu} W'^{\mu\nu} + \frac{M_{W'}^2}{2} W'^{\mu} W'^{\nu} W'_{\mu} W'_{\nu} + W'_{\mu} J_{W'}^{a\mu}$$

$$J_{W'}^{a\mu} \equiv g_b \bar{Q}_3 \gamma_{\mu} \tau^a Q_3 + g_{\tau} \bar{L}_3 \gamma_{\mu} \tau^a L_3$$

Integrate out heavy  $W'^a \sim W'^{\pm}, Z'$

$$\mathcal{L}_{eff} \supset -\frac{g_b g_{\tau}}{M_{Z'}^2} (2V_{cb} \bar{c}_L \gamma^{\mu} b_L \bar{\tau}_L \gamma_{\mu} \nu_L + \cancel{\bar{b}_L \gamma^{\mu} b_L \bar{\tau}_L \gamma_{\mu} \tau_L})$$

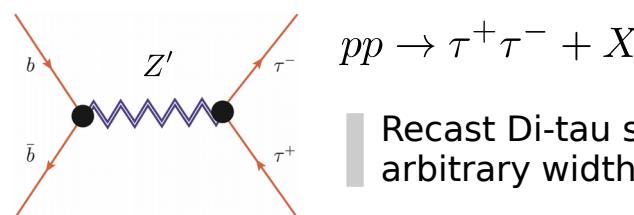
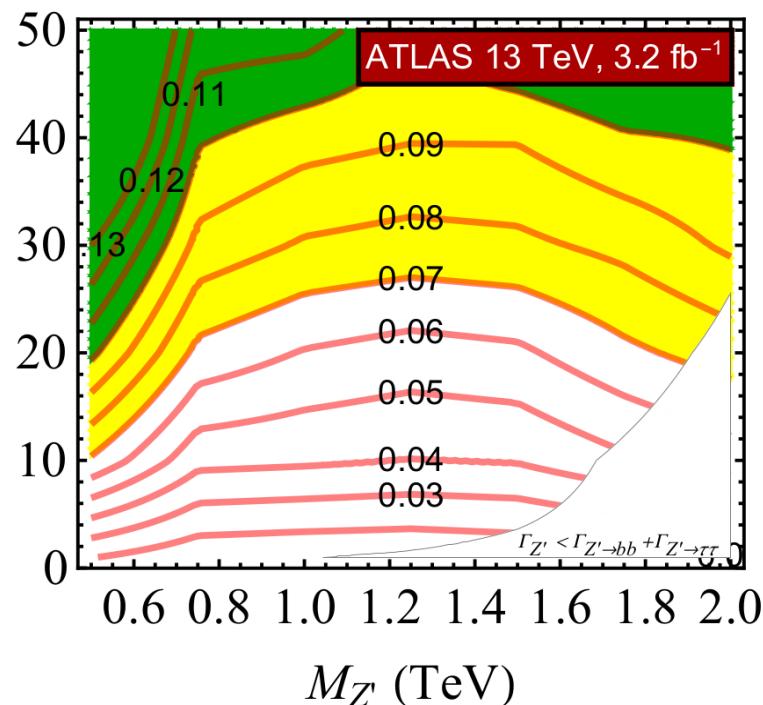
$R_{D(*)}$  fit:

$$|g_b g_{\tau}| \times v^2 / M_{Z'} = 0.13 \pm 0.03$$

$$m_{W'} \approx m_{Z'}$$

Decay width taken as free parameter

$$|g_b g_{\tau}| \times v^2 / M_{Z'}^2$$



Recast Di-tau search for  $Z'$  with arbitrary width

**High-pT di-tau searches excludes colorless scenario!**

See DAF, Greljo, Kamenik Phys. Lett. B 764(2017)126-134

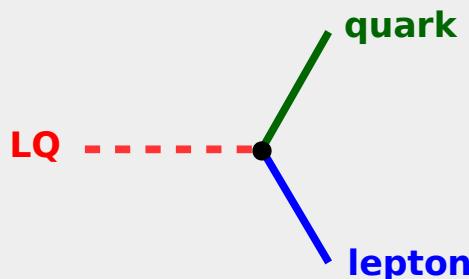
Caveat: Right-handed colorless mediators can (still) evade di-Tau searches.. Sterile neutrino needed

Greljo et al [1804.04642] Asadi et al [1804.04135]

# Leptoquarks! which ones?

## ■ What is a Leptoquark?

Hypothetical Scalar or Vector boson with color and hypercharge such that:



## ■ Which Leptoquark (LQ) explains which B-anomaly?

Model	$R_{K(*)}$	$R_{D(*)}$	$R_{K(*)} \& R_{D(*)}$
$S_1 = (3, 1)_{-1/3}$	✗	✓	✗
$R_2 = (3, 2)_{7/6}$	✗	✓	✗
$\tilde{R}_2 = (3, 2)_{1/6}$	✗	✗	✗
$S_3 = (3, 3)_{-1/3}$	✓	✗	✗
$U_1 = (3, 1)_{2/3}$	✓	✓	✓
$U_3 = (3, 3)_{2/3}$	✓	✗	✗

Angelescu, Becirevic, DAF, Sumensari [1808.08179]

■ Only one vector LQ can solve both B-anomalies!  $U_1 \sim (3, 1, 2/3)$  Butazzo et al [1706.07808]

UV completion necessary! e.g. Pati-Salam boson  $G_{4321} = SU(4) \times SU(3)' \times SU(2)_L \times U(1)' \rightarrow G_{SM}$

Di Luzio et al [1708.08450] Bordone et al [1712.01368] Blanke, Crivellin [1709.00692]

■ No single scalar LQ solves both B-anomalies! Two (or more) scalar LQ solutions needed:

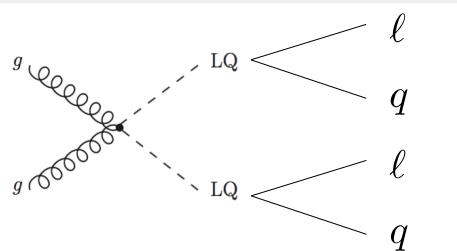
R<sub>2</sub> & S<sub>3</sub> (Scalar + Tensor & V-A) e.g. GUT inspired model Becirevic, Dorsner, Fajfer, DAF, Kosnik, Sumensari [1808.08179]

S<sub>1</sub> & S<sub>3</sub> (V-A) e.g. Strongly coupled model Marzocca [1803.10972]

# Leptoquarks at the LHC

## LQ pair production

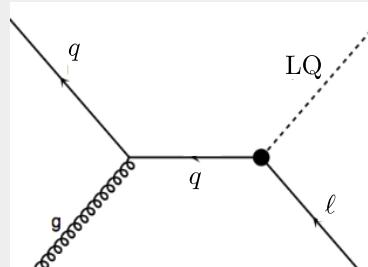
$$pp \rightarrow \text{LQ}^*\text{LQ} \rightarrow \ell\ell qq$$



Model independent limits  
on LQ mass!

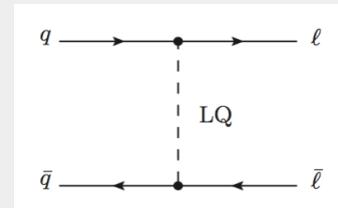
## Single LQ production

$$pp \rightarrow \text{LQ} \ell \rightarrow \ell\ell q$$



## t-channel non-resonant Drell-Yan

$$pp \rightarrow \ell\ell$$



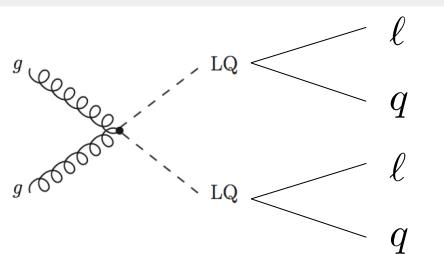
# Leptoquarks at the LHC



Angelescu, Becirevic, DAF, Sumensari [1808.08179]

## LQ pair production

$$pp \rightarrow \text{LQ}^*\text{LQ} \rightarrow \ell\ell qq$$



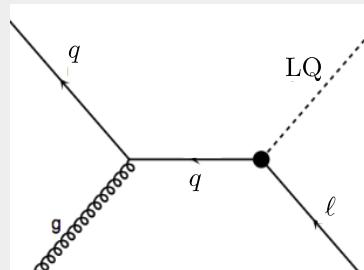
Model independent limits  
on LQ mass!

Decays	LQs	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\text{int}}$
$jj\tau\bar{\tau}$	$S_1, R_2, S_3, U_1, U_3$	—	—	—
$b\bar{b}\tau\bar{\tau}$	$R_2, S_3, U_1, U_3$	850 (550) GeV	1550 (1290) GeV	$12.9 \text{ fb}^{-1}$
$t\bar{t}\tau\bar{\tau}$	$S_1, R_2, S_3, U_3$	900 (560) GeV	1440 (1220) GeV	$35.9 \text{ fb}^{-1}$
$jj\mu\bar{\mu}$	$S_1, R_2, S_3, U_1, U_3$	1530 (1275) GeV	2110 (1860) GeV	$35.9 \text{ fb}^{-1}$
$b\bar{b}\mu\bar{\mu}$	$R_2, U_1, U_3$	1400 (—) GeV	1900 (1700) GeV	$36.1 \text{ fb}^{-1}$
$t\bar{t}\mu\bar{\mu}$	$S_1, R_2, S_3, U_3$	1420 (950) GeV	1780 (1560) GeV	$36.1 \text{ fb}^{-1}$
$jj\nu\bar{\nu}$	$R_2, S_3, U_1, U_3$	980 (640) GeV	1790 (1500) GeV	$35.9 \text{ fb}^{-1}$
$b\bar{b}\nu\bar{\nu}$	$S_1, R_2, S_3, U_3$	1100 (800) GeV	1810 (1540) GeV	$35.9 \text{ fb}^{-1}$
$t\bar{t}\nu\bar{\nu}$	$R_2, S_3, U_1, U_3$	1020 (820) GeV	1780 (1530) GeV	$35.9 \text{ fb}^{-1}$

Table: Second and third columns:  $\beta = 1$  ( $\beta = 0.5$ ), with  $\beta = \mathcal{B}(\text{LQ} \rightarrow q\ell \text{ or } q\nu)$ .

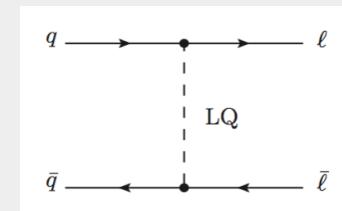
## Single LQ production

$$pp \rightarrow \text{LQ} \ell \rightarrow \ell\ell q$$

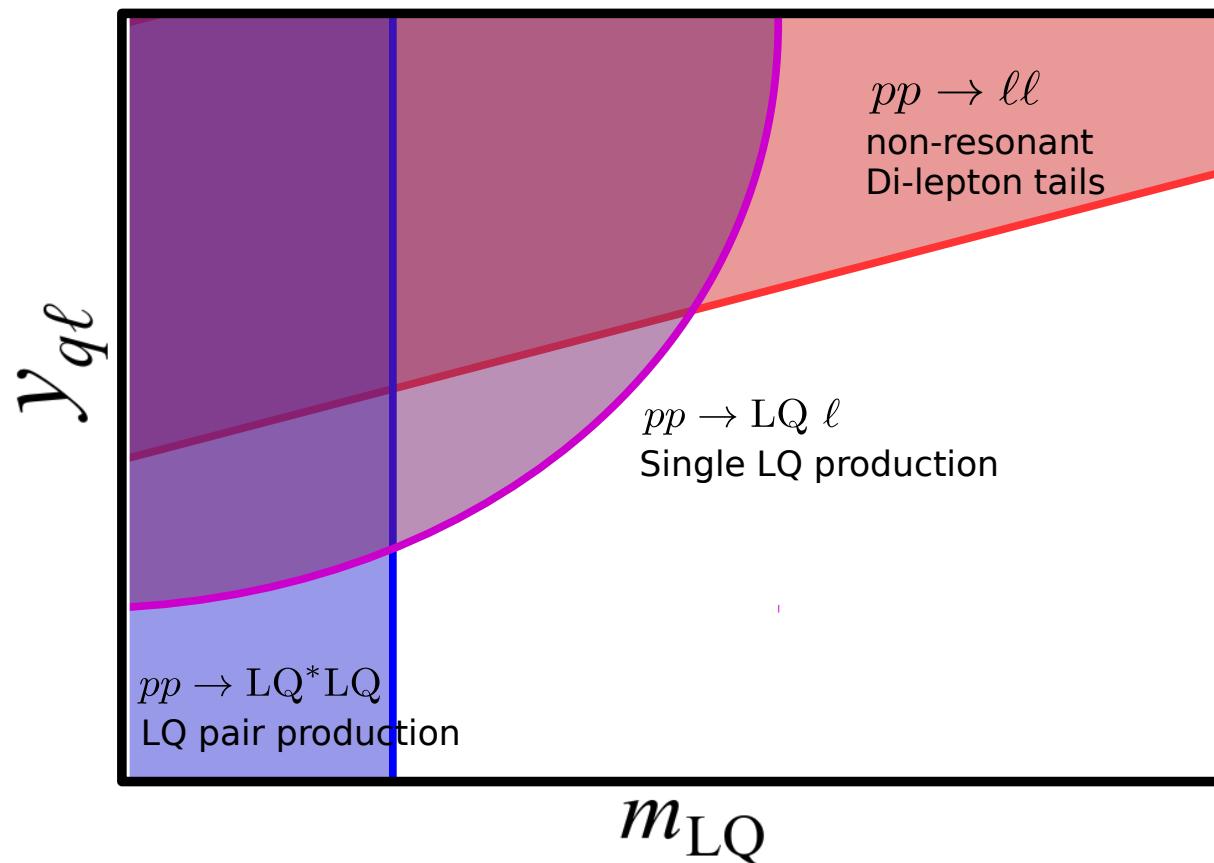


## t-channel non-resonant Drell-Yan

$$pp \rightarrow \ell\ell$$

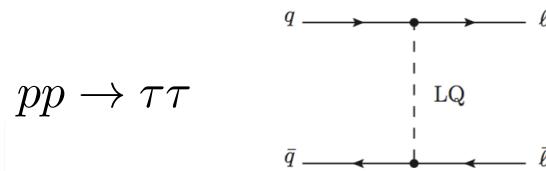


## Sketch of High-pT process complementary at LHC



**ATLAS and CMS: a dedicated LQ search in Di-tau tails is Needed!**

# Leptoquarks & Di-taus



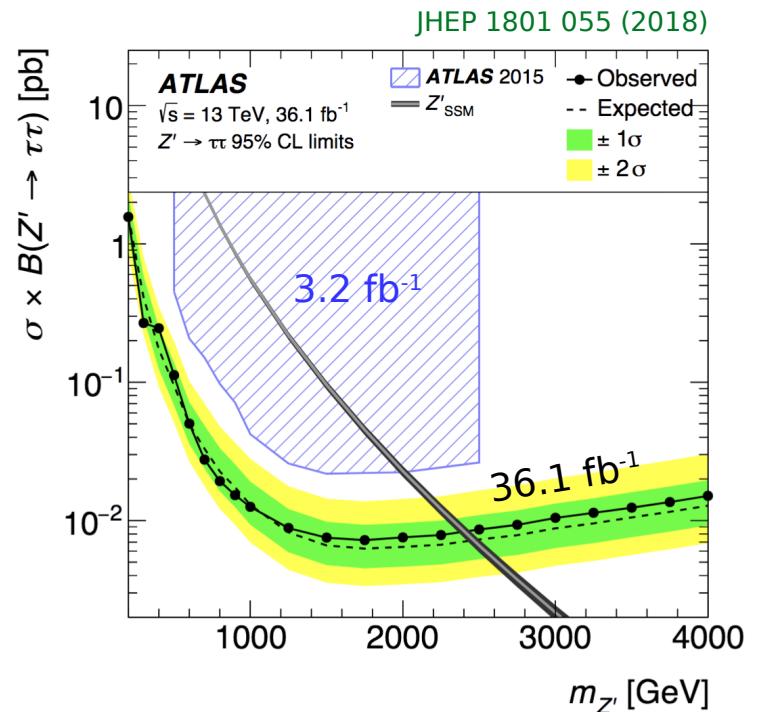
Recast Z' di-Tau searches JHEP 1801 055 (2018)

Inclusive category  $pp \rightarrow \tau^+ \tau^- + X$

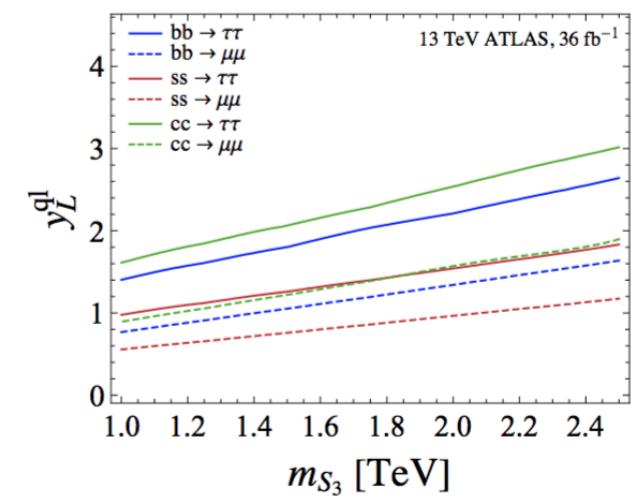
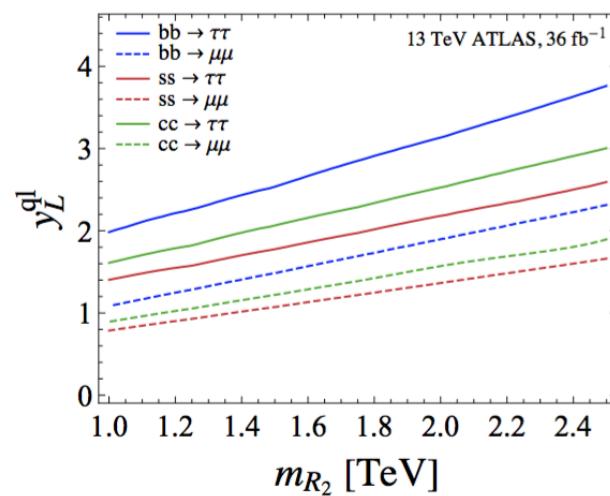
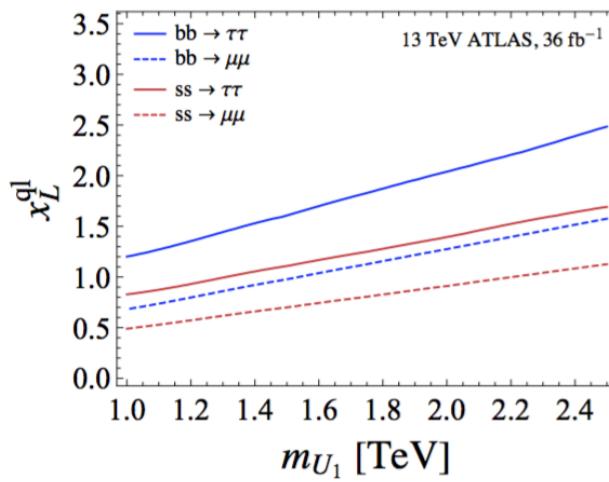
Hadronic mode  $\tau_{\text{had}} \tau_{\text{had}}$

$$m_T^{\text{tot}} \equiv \sqrt{m_T^2(\tau_1, \tau_2) + m_T^2(E_T^{\text{miss}}, \tau_1) + m_T^2(E_T^{\text{miss}}, \tau_2)}$$

High-mass tail cut  $m_T^{\text{tot}} > 800 \text{ GeV}$



95% CL limits:



Angelescu, Becirevic, DAF, Sumensari [1808.08179]

# The $U_1$ model at high- $p_T$

Minimal Lagrangian & flavor structure:

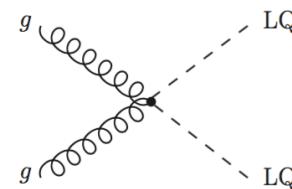
$$\mathcal{L}_{U_1} = x_L^{ij} \bar{Q}_L i \gamma_\mu U_1^\mu L_L j + x_R^{ij} \bar{d}_R i \gamma_\mu U_1^\mu \ell_R j + \text{h.c.}$$

$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix} \quad x_R = 0.$$

LQ pair production via QCD @ LHC:

CMS-PAS-EXO-17-003

$m_{U_1} > 1.5$  TeV



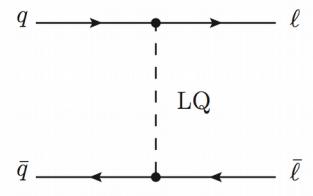
$$BR(U \rightarrow \tau b) = BR(U \rightarrow t\nu) = 0.5$$

Di-Tau & Di-muon tails

Recast 13 TeV @ 36/fb

JHEP 1801 055 (2018)

JHEP 1710 182 (2017)

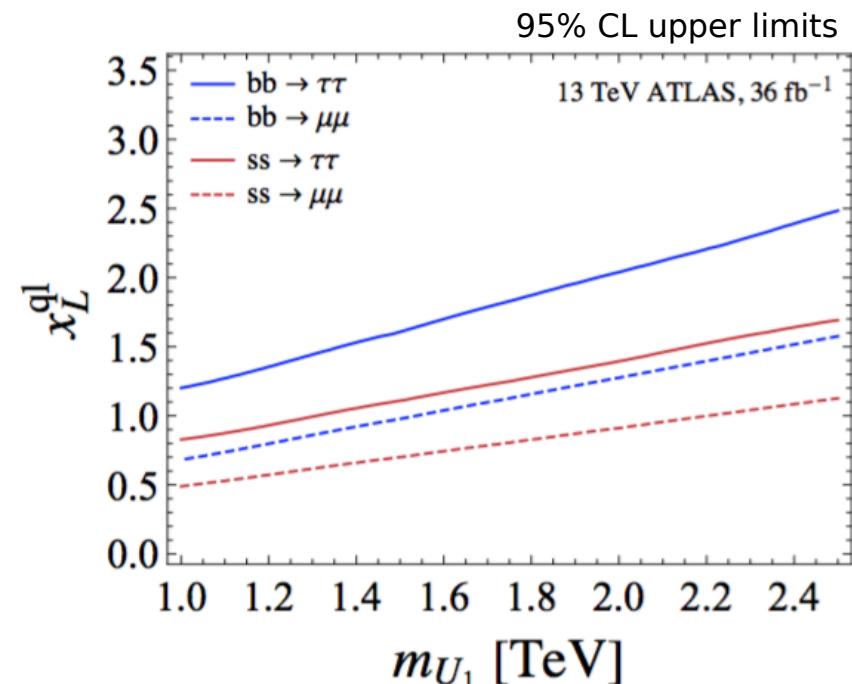


Limits approaching couplings  $\sim 1$

Starting to probe the  $R_{D^{(*)}}$  anomaly region

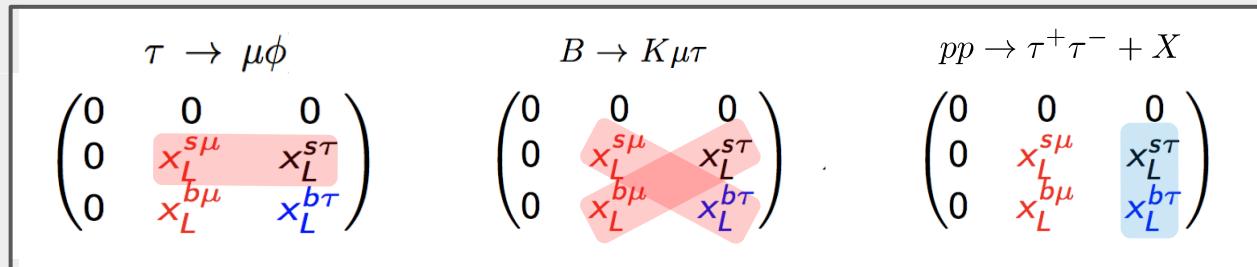
$R_{D^{(*)}}$  anomaly for  $U_1$

$$g_{V_L} = \frac{v^2}{2 m_{U_1}^2 V_{cb}} (x_L^{b\tau})^* (V_{cs} x_L^{s\tau} + V_{cb} x_L^{b\tau}) \Rightarrow x_L^{b\tau} \neq 0.$$



# Cornering $U_1$

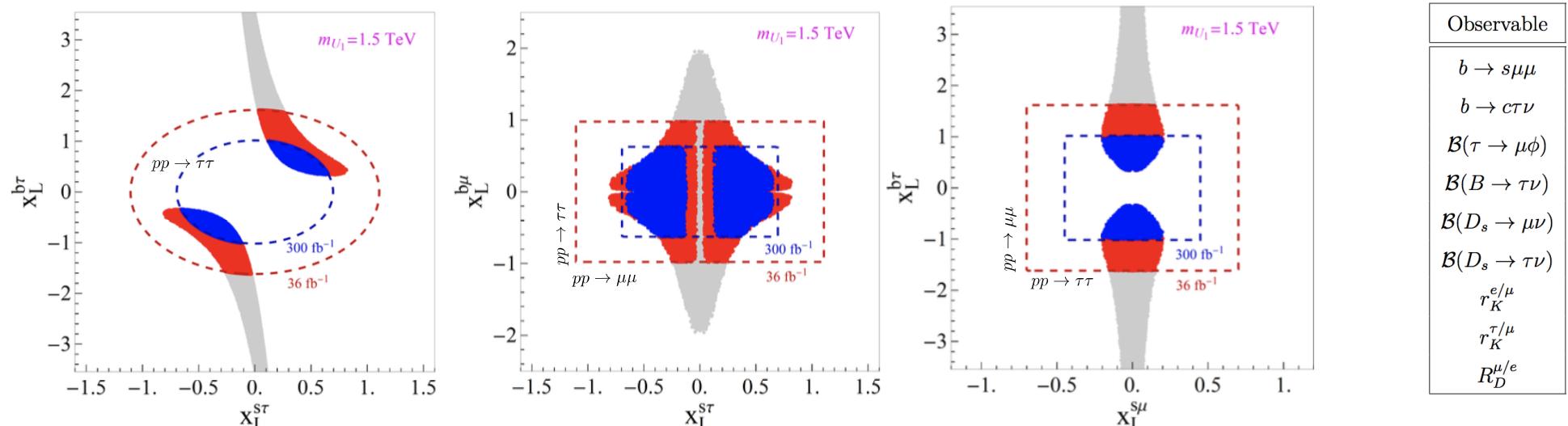
Can we “fully” test the  $U_1$  model using **tree-level** observables?



Probes the flavor structure of the model!

Nice complementarity between **LFV low-energy** and **high-pT** observables

Fixed mass fit with tree-level observables  $\Delta\chi^2 < 6.18$

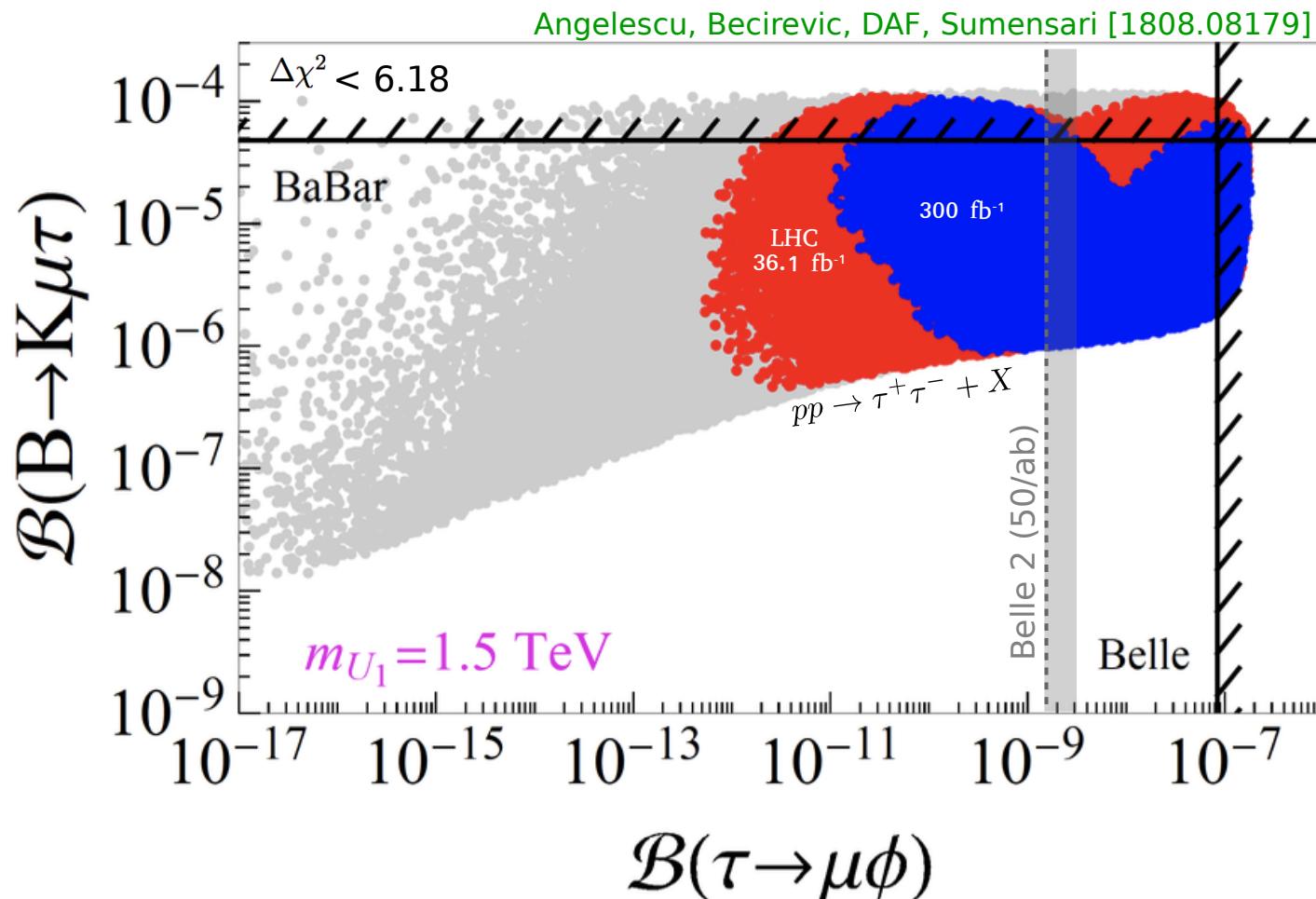


LHC di-tau limits at 36/fb (red) & 300/fb (blue)

Angelescu, Becirevic, DAF, Sumensari [1808.08179]

$U_1$ - strange - tau coupling non-zero!

## Predictions for LFV low-energy observables for $U_1$



LHC Di-Taus tails push **lower bounds** on both LFV observables!  
Model Potentially within reach at LHCb & Belle 2!

BaBar:  $\mathcal{B}(B \rightarrow K\mu\tau) < 4.8 \times 10^{-5}$  (90%CL). Can LHCb do better?

# Conclusions

We have shown that high-PT searches at the LHC are relevant for setting limits on NP for the B-anomalies. In particular, the tails of the **Di-Tau spectrum is very sensitive**:

Excludes LH colorless mediator solutions to the charged current anomaly

Gives relevant bounds on Leptoquark solutions

Di-Tau high-pT searches are complementary to low energy flavor observables

In particular with LFV semi-tauonic B-decays and LFV tau decays for the  $U_1$  model

$$pp \rightarrow \tau^+ \tau^- + X \quad \longleftrightarrow \quad B \rightarrow K \mu \tau \quad \longleftrightarrow \quad \tau \rightarrow \mu \phi$$

More experimental input for these processes is needed!

Thank You!

# BACKUP SLIDES

# Scalar (GUT) LQ model at high-p<sub>T</sub>

GUT Leptoquarks:  $R_2 \sim (3,2)_{7/6}$  and  $S_3 \sim (3,3)_{-1/3}$

Becirevic, Dorsner, Fajfer,  
DAF, Kosnik, Sumensari  
[1808.08179]

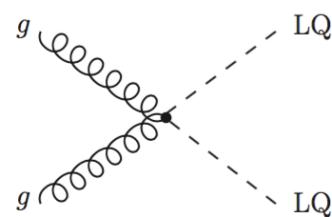
↓  
for  $R_{D^{(*)}}$       ↓  
for  $R_{K^{(*)}}$

See S. Fajfer's talk

Good Benchmark:

$R_2$  with  $\sim O(1)$  Yukawa couplings  
Couples to both **charm** and **bottom**  
 $m_R \sim 800$  GeV

LQs decaying into tauonic channels



$$R_2^{\frac{2}{3}} \rightarrow \tau b, \nu c$$

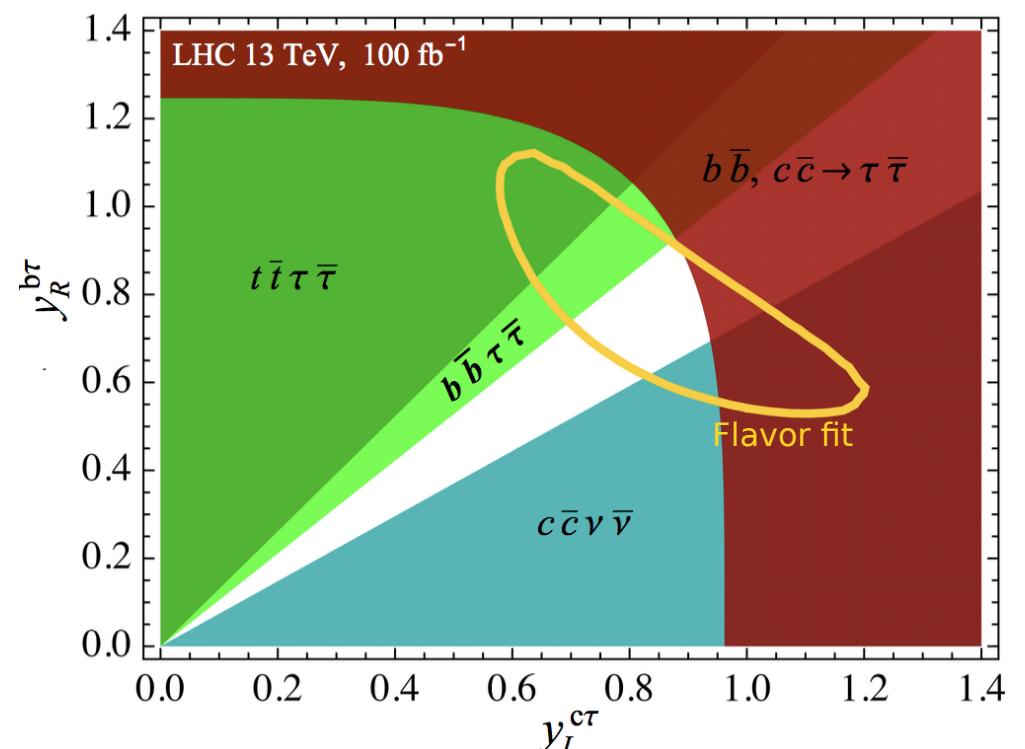
$$R_2^{\frac{5}{3}} \rightarrow \tau t, \tau c$$

LQ pair production & DY di-Tau searches

Model can be put to test at the LHC!

Complementarity: **Flavor obs.** & **high-p<sub>T</sub>** di-Taus

Becirevic, Dorsner, Fajfer, DAF, Kosnik, Sumensari [1808.08179]



Predictions for LFV low-energy observables for  $U_1$  (floating LQ mass in fit)

