Probing new physics solutions to the B-anomalies at high-energy colliders

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3rd Topical Discussion Session:
Interplay of quark and lepton flavour at Belle II and the LHC,
3rd June 2021

Institut de Physique de l'Univers

Overview

Introduction

- B-anomalies

Flavor at high-energy pp-collider

- Di-taus • Di-muons • LFV tails

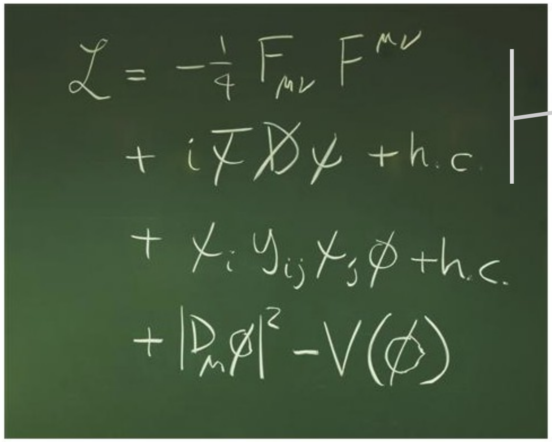
B-anomalies and Leptoquark solutions

- High-pT and low energy complementarity

UV model for the vector leptoquark

Flavor sector of the SM

The SM Lagrangian



Gauge sector

Flavor universal

Well tested experimentally

$$\mathcal{G}_{\text{flavor}} \equiv U(3)^5$$

$$U(3)_Q \otimes U(3)_L \otimes U(3)_u \otimes U(3)_d \otimes U(3)_e$$

Yukawa sector:

$$\mathcal{L}_{\text{Yukawa}} = -Y_d^{ij} \bar{Q}^i \Phi d^j - Y_u^{ij} \bar{Q}^i \tilde{\Phi} u^j - Y_e^{ij} \bar{L}^i \Phi e^j \quad \Longrightarrow \quad \cancel{U(3)^5}$$

- Contains most SM free parameters (fermion masses and mixings) extracted from data

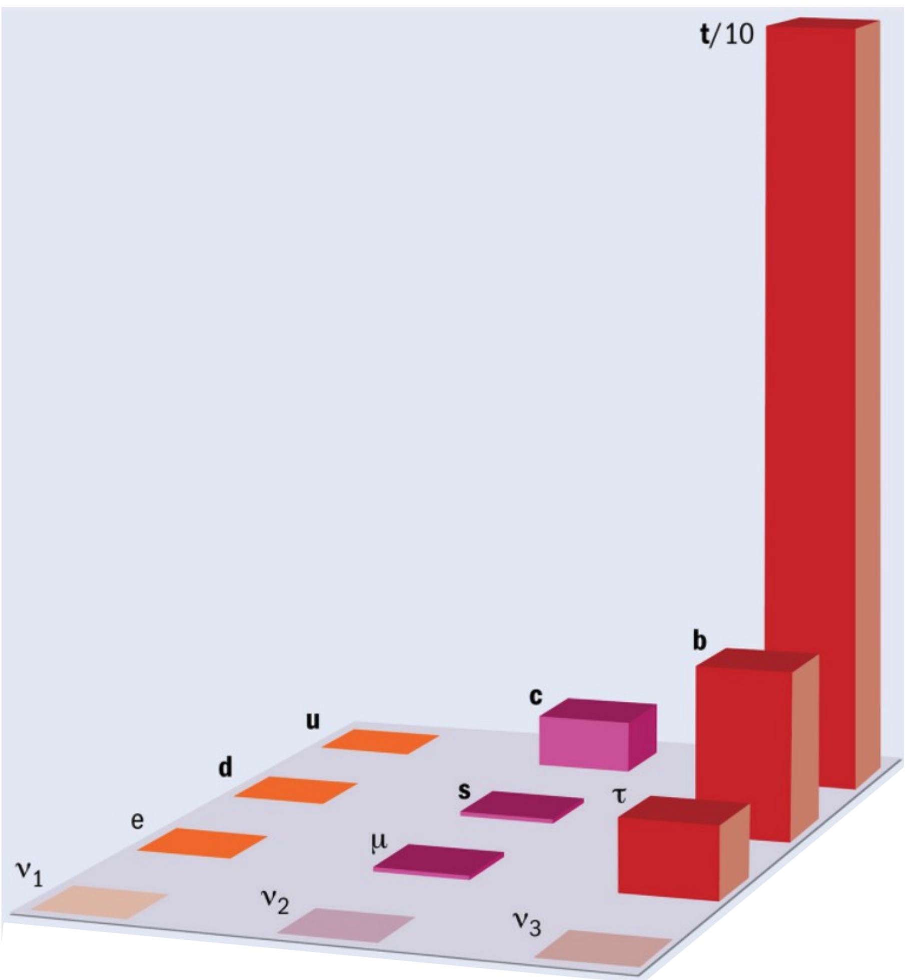
- Lepton flavor universility (LFU) is broken in the SM by the fermion masses

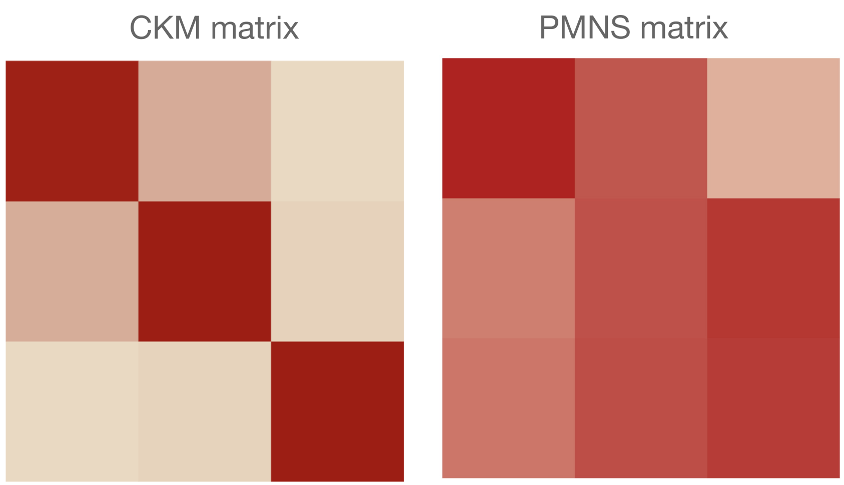
- BSM could introduce new sources of LFU breaking

- Good test for BSM physics in flavor experiments!

The SM Flavor puzzle

Non-generic pattern for the SM fermion masses and mixings

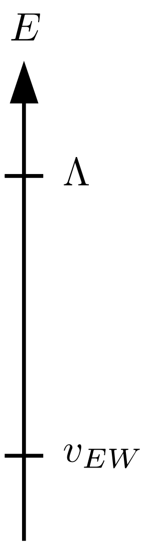




A clear hierarchy suggesting an underlying theory of Flavor!

Th SMEFT

- SM as a low energy effective theory:



Renormalizable (d=4)

Wilson coefficients: parametrizes our ignorance of the UV

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{i,d>4} \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Large mass gap

$\Lambda \gg v_{\rm EW}$

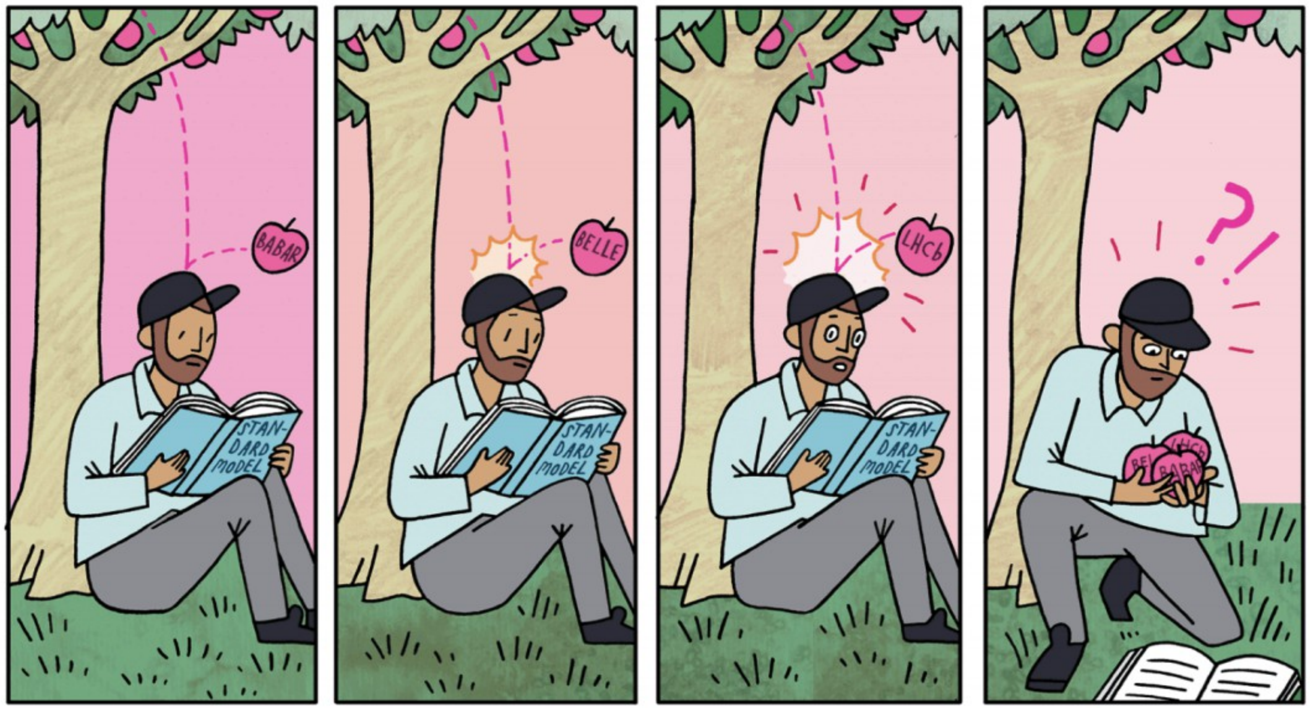
Non-renormalizable operators
typically violate global symmetries!

LFUV, LFV, CP, B, L

$$d = 6 \quad \Longrightarrow \quad N_{\mathcal{O}} = 59\,, \quad N_C = 2599$$

- Testing accidental SM symmetries is of fundamental importance!

A Decade of B-meson Anomalies

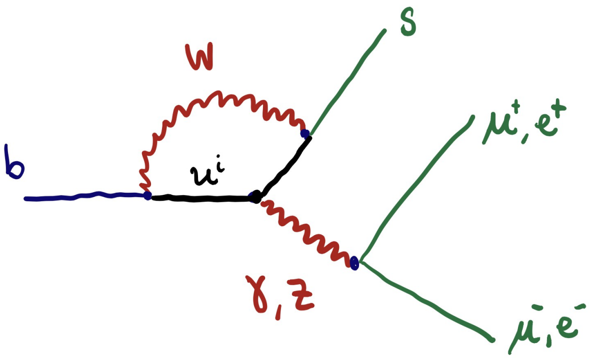


Artwork by Sandbox Studio, Chicago with Corinne Mucha

- Evidence of **LFU violation** in semi-leptonic B-decays: different experiments / different observables
- All B-anomalies seem compatible with each other!
- No single measurment is statistically relevant to claim discovery... yet...
- Anomalies come and go... Need more data
- Completely unexpected from theory side...

B-meson Anomalies – Neutral currents

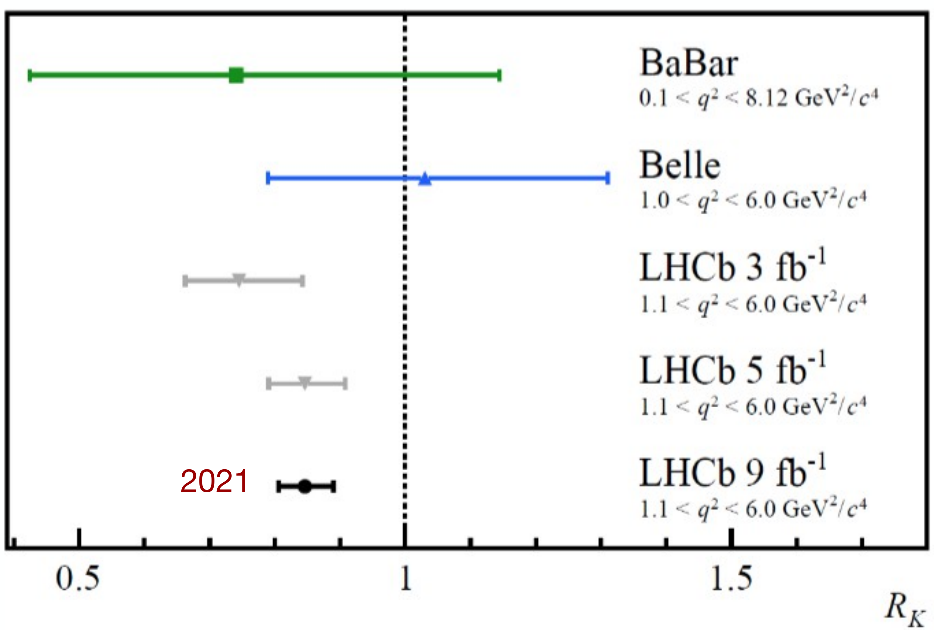
$\boxed{b \to s\ell\bar{\ell}}$



- LFU ratio tau vs light leptons

$$R_{K^{(*)}} = \frac{\mathrm{Br}(B \to K^{(*)}\,\mu\bar{\mu})}{\mathrm{Br}(B \to K^{(*)}\,e\bar{e})}$$

$$\boxed{R^{\mathrm{exp}}_{K^{(*)}} < R^{\mathrm{SM}}_{K^{(*)}} \qquad \text{Deficit!}}$$



Evidence for LFUV in R_K [3.1σ]

[LHCb, 2103.11769]

- Other anomalies (muon specific):

$$B_s \to \mu\mu \qquad B \to K\mu\mu$$

$$B \to \phi\mu\mu \qquad P_5'$$

All consistent with each other!

Low energy effective theory - RK(*)

Effective Lagrangian:

$$\mathcal{L}_{b\to s\ell\bar\ell} = \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i \mathcal{C}_i \mathcal{O}_i^\ell + \text{h.c.}$$

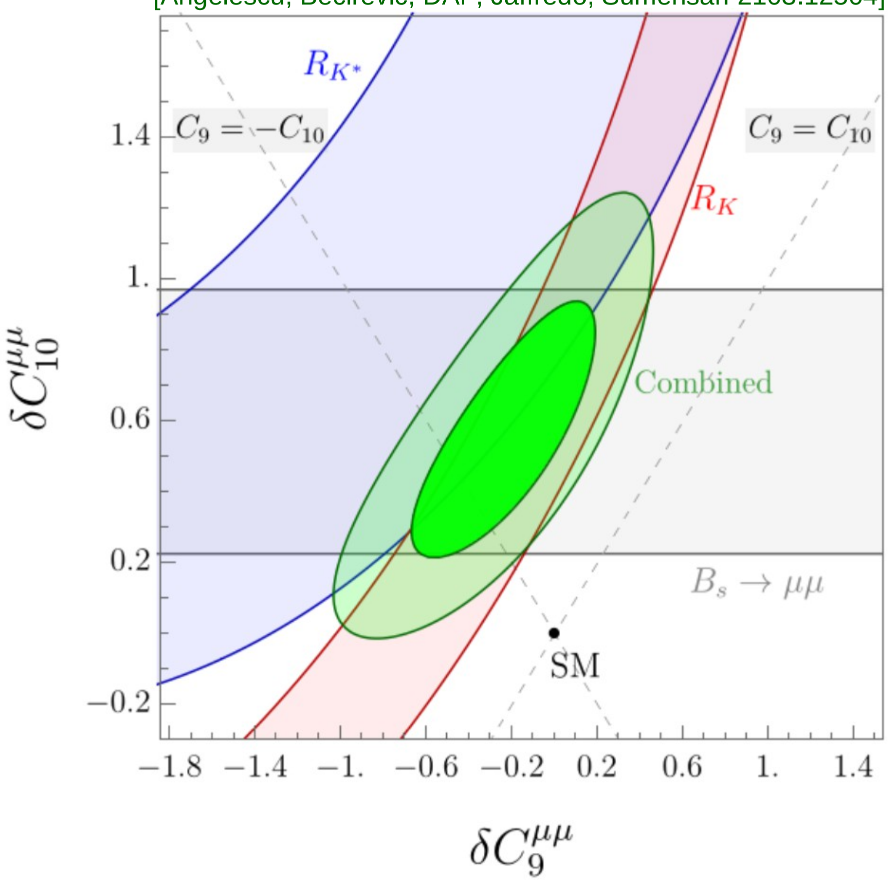
$$\mathcal{O}_9^\ell = \frac{\alpha}{4\pi}(\bar s_L \gamma^\mu b_L)(\bar\ell\gamma^\mu\ell)$$

$$\mathcal{O}_{10}^\ell = \frac{\alpha}{4\pi}(\bar s_L \gamma^\mu b_L)(\bar\ell\gamma^\mu\gamma^5\ell)$$

LFU in SM

- (pseudo) scalar operators very constrained
- Clean observables: $R_K\,,\ R_{K^*}\,,\ \mathcal{B}(B_s\to\mu^+\mu^-)$

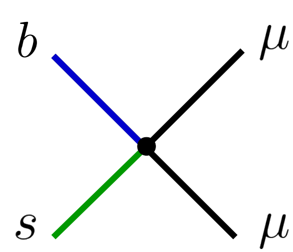
[Angelescu, Becirevic, DAF, Jaffredo, Sumensari 2103.12504]



- Completely consitent V-A solution:

$$\delta C_9^{\mu\mu} = -\delta C_{10}^{\mu\mu} = -0.41 \pm 0.09$$

NP prefered over SM 4.6σ

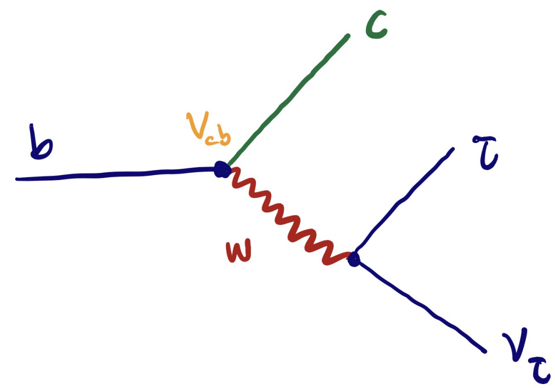


$$\Lambda \sim 30\,\text{TeV}$$

Large NP scale! (At tree level)

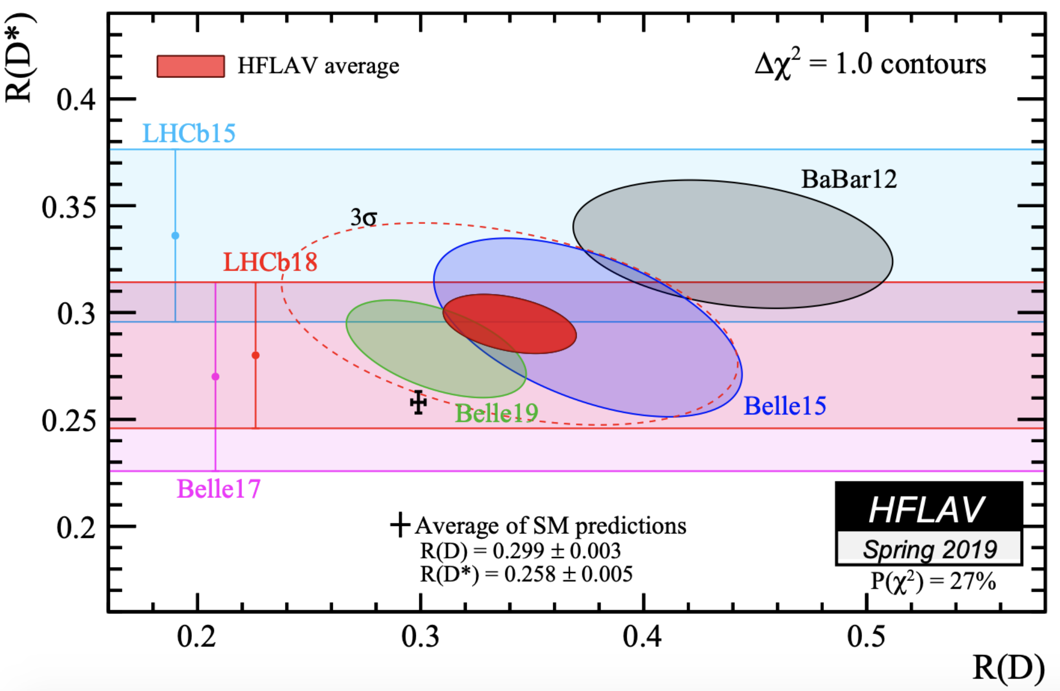
B-meson Anomalies – Charged currents

$$\boxed{b \to c \ell \nu}$$



- LFU ratio tau vs light leptons

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\,\tau\bar{\nu})}{\mathrm{Br}(B \to D^{(*)}\,\ell\bar{\nu})}\Big|_{\ell=e,\mu}$$



BABAR LHCb Belle

$$\boxed{R^{\mathrm{exp}}_{D^{(*)}} > R^{\mathrm{SM}}_{D^{(*)}} \quad \text{Excess!}}$$

CMS Soon joining the party!

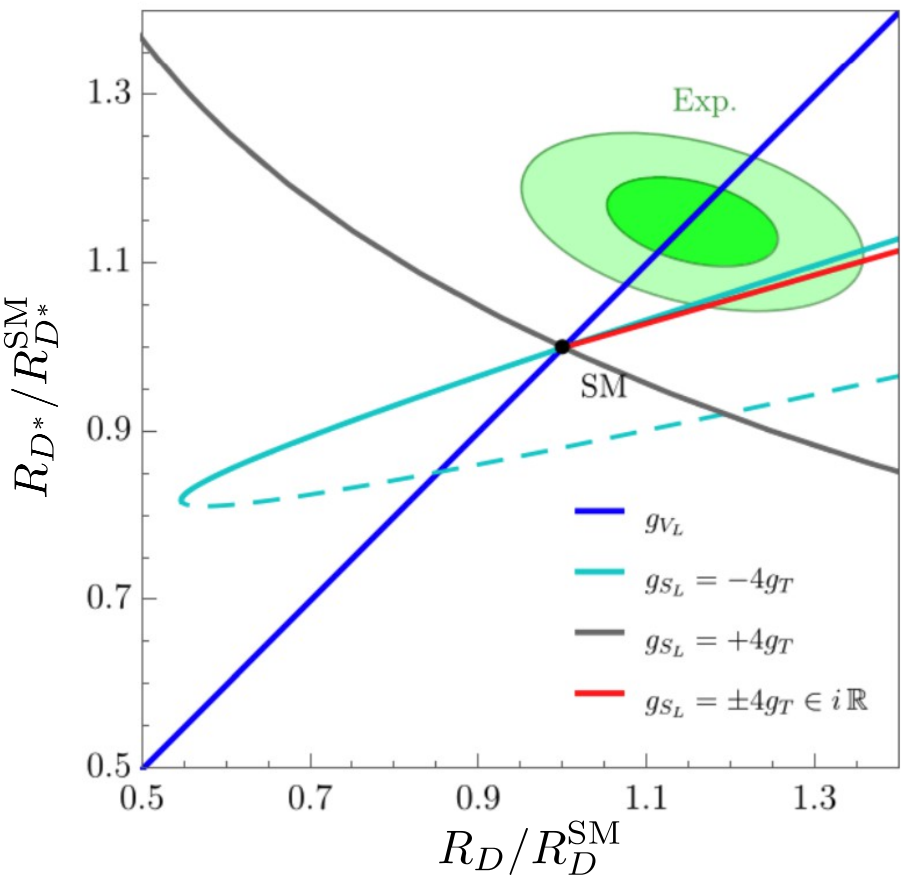
Low energy effective theory - RD(*)

$$\mathcal{L}_{b\to c\tau\nu} = -2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})\,\mathcal{O}_{V_L} + g_{V_R}\,\mathcal{O}_{V_R} + g_{S_L}\,\mathcal{O}_{S_L} + g_{S_R}\,\mathcal{O}_{S_R} + g_T\,\mathcal{O}_T\Big]$$

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

$$\mathcal{O}_{V_R} = (\bar{c}_R\gamma^\mu b_R)(\bar{\tau}_L\gamma^\mu\nu_\tau) \qquad \mathcal{O}_{S_R} = (\bar{c}_L b_R)(\bar{\tau}_R\nu_\tau)$$

- Fit to $R_D\,,\ R_{D^*}\,,\ \mathcal{B}(B_c\to\tau\nu)$

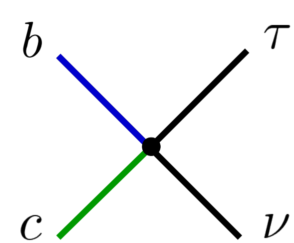


[Angelescu, Becirevic, DAF, Jaffredo, Sumensari 2103.12504]

- V-A only single operator fiting the anomaly

$$g_{V_L} \in [0.05, 0.09]$$

- 2 operators: Scalar + Tensor solutions are also fine

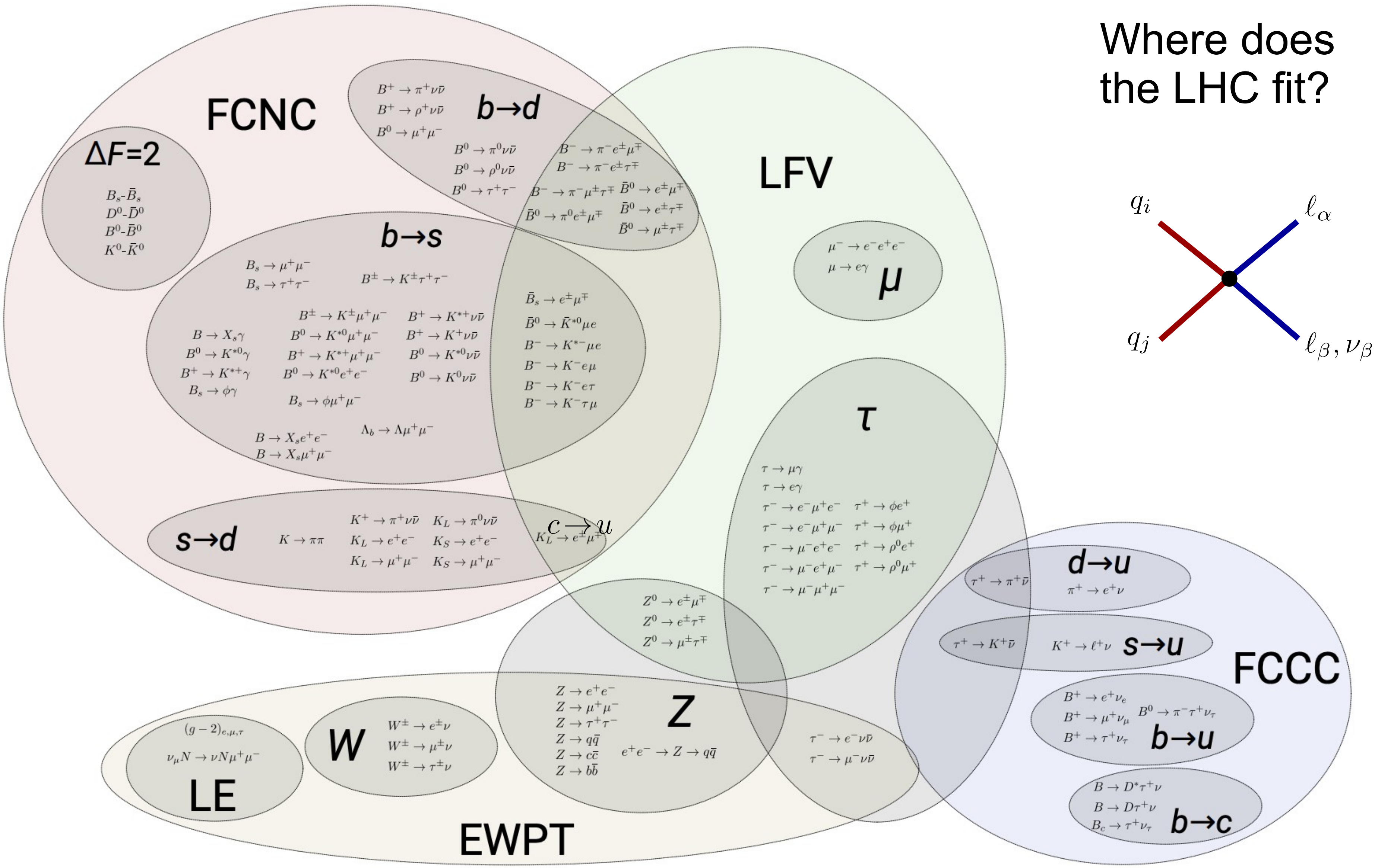


$$\Lambda \sim 2\,\mathrm{TeV}$$

Strong physics case for High-pT LHC!!

- Flavor @ LHC -

Semileptonics: observable Landscape



Where does the LHC fit?

D. Straub

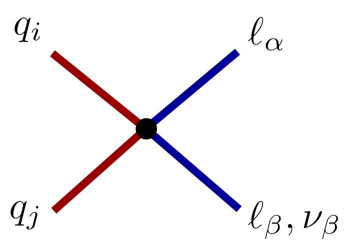
Aebischer et al. 1810.07698

Framework

- Semi-leptonics at the LHC: Drell-Yan process

$$q_i\bar{q}_j \to \ell_\alpha^\pm \ell_\beta^\mp$$

$$q_i\bar{q}_j \to \ell_\alpha^\pm \nu_\beta$$



$$\mathcal{L}_{\rm eff} \supset \sum_I \sum_{ij,\alpha\beta} \left(\frac{C_I^{ij\alpha\beta}}{v^2}\right) \mathcal{O}_I^{ij\alpha\beta}$$

Eff. coeff.	Operator	SMEFT
$C_{V_{LL}}^{ij\alpha\beta}$	$(\bar{q}_{Li}\gamma_\mu q_{Lj})(\bar{\ell}_{L\alpha}\gamma^\mu \ell_{L\beta})$	$\mathcal{O}_{lq}^{(1)}$, $\mathcal{O}_{lq}^{(3)}$
$C_{V_{RR}}^{ij\alpha\beta}$	$(\bar{q}_{Ri}\gamma_\mu q_{Rj})(\bar{\ell}_{R\alpha}\gamma^\mu \ell_{R\beta})$	$\mathcal{O}_{ed}$, $\mathcal{O}_{eu}$
$C_{V_{LR}}^{ij\alpha\beta}$	$(\bar{q}_{Li}\gamma_\mu q_{Lj})(\bar{\ell}_{R\alpha}\gamma^\mu \ell_{R\beta})$	$\mathcal{O}_{qe}$
$C_{V_{RL}}^{ij\alpha\beta}$	$(\bar{q}_{Ri}\gamma_\mu q_{Rj})(\bar{\ell}_{L\alpha}\gamma^\mu \ell_{L\beta})$	$\mathcal{O}_{lu}$, $\mathcal{O}_{ld}$
$C_{S_R}^{ij\alpha\beta}$	$(\bar{q}_{Ri} q_{Lj})(\bar{\ell}_{L\alpha} \ell_{R\beta}) + \text{h.c.}$	$\mathcal{O}_{ledq}$
$C_{S_L}^{ij\alpha\beta}$	$(\bar{q}_{Li} q_{Rj})(\bar{\ell}_{L\alpha} \ell_{R\beta}) + \text{h.c.}$	$\mathcal{O}_{lequ}^{(1)}$
$C_{T}^{ij\alpha\beta}$	$(\bar{q}_{Li}\sigma_{\mu\nu} q_{Rj})(\bar{\ell}_{L\alpha}\sigma^{\mu\nu} \ell_{R\beta}) + \text{h.c.}$	$\mathcal{O}_{lequ}^{(3)}$

- Two sources of flavor in high-energy proton-proton collisions:

$$\sigma(pp \to \ell^\alpha \ell^\beta) = \mathcal{L} \otimes \mathcal{H}^{\alpha\beta} = \sum_{ij} \int \frac{d\tau}{\tau} \mathcal{L}_{q_i\bar{q}_j}(\tau)\, \hat{\sigma}^{ij\alpha\beta}(\tau) \qquad \tau \equiv \frac{\hat{s}}{s} = \frac{m^2_{\ell_\alpha\ell_\beta}}{s}$$

Parton-parton Luminosities
(non-perturbative)

$$\mathcal{L}_{q_i\bar{q}_j}(\tau) = \tau \int_\tau^1 \frac{dx}{x} \left[f_{q_i}(x,\mu_F) f_{\bar{q}_j}(\tau/x,\mu_F) + (q_i \leftrightarrow \bar{q}_j)\right]$$

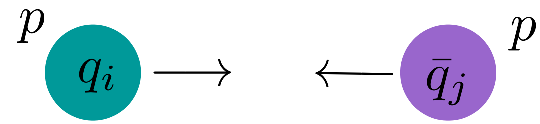
'PDFs'

Hard process

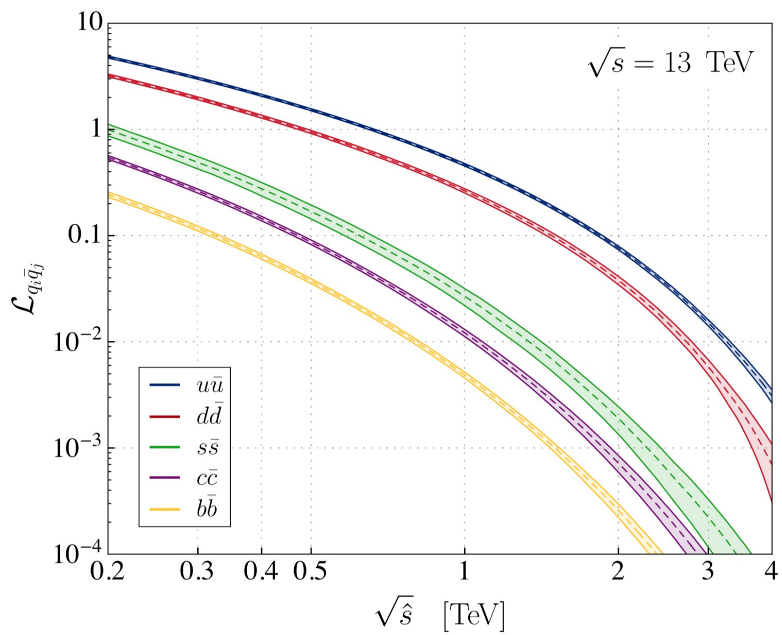
$$\hat{\sigma}^{ij\alpha\beta} \equiv \hat{\sigma}(q_i\bar{q}_j \to \ell_\alpha\ell_\beta) = \frac{\hat{s}}{v^4} \sum_{IJ} C_I^{ij\alpha\beta} C_J^{ij\alpha\beta\,*} M_{IJ}$$

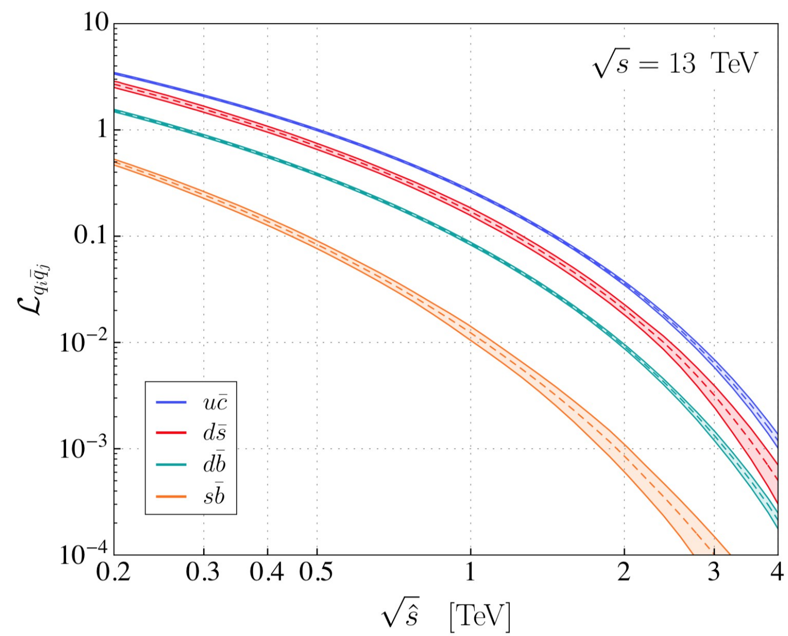
$$\mathcal{G} = \mathcal{G}_q \otimes \mathcal{G}_\ell$$

- Luminosity functions: source of flavor hierearchies



$$\mathcal{L}_{q_i\bar{q}_j}(\tau) = \tau \int_\tau^1 \frac{\mathrm{d}x}{x}\left[f_{q_i}(x,\mu_F) f_{\bar{q}_j}(\tau/x,\mu_F) + (q_i \leftrightarrow \bar{q}_j)\right] \qquad \tau = \hat{s}/s = m^2_{\ell_\alpha\ell_\beta}/s$$





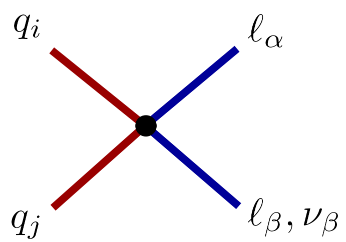
- example: LFV $\qquad \sigma(pp\to\mu\tau) = \dfrac{s}{144\pi\, v^4}\sum_{ij}|C^{ij\mu\tau}_{V_L}|^2 K_{ij}$ (V-A)

$$K_{ij} \equiv \int_{\tau_{\min}}^{\tau_{\max}} \mathrm{d}\tau\, \mathcal{L}_{q_i\bar{q}_j}(\tau) \quad \underset{m_{\mu\tau}\in[1\,\mathrm{TeV}, 5\,\mathrm{TeV}]}{\Longrightarrow} \quad K_u = \kappa \begin{array}{c} \begin{array}{ccc} u & c & \end{array} \\ \begin{pmatrix} 1 & 0.5 & 0 \\ 0.03 & 0.01 & 0 \\ 0 & 0 & 0 \end{pmatrix} \end{array}, \qquad K_d = \frac{\kappa}{2} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1 & 0.6 & 0.3 \\ 0.1 & 0.07 & 0.03 \\ 0.04 & 0.02 & 0.01 \end{pmatrix} \end{array}$$

"PDF" tensor containing the proton flavor hierarchies

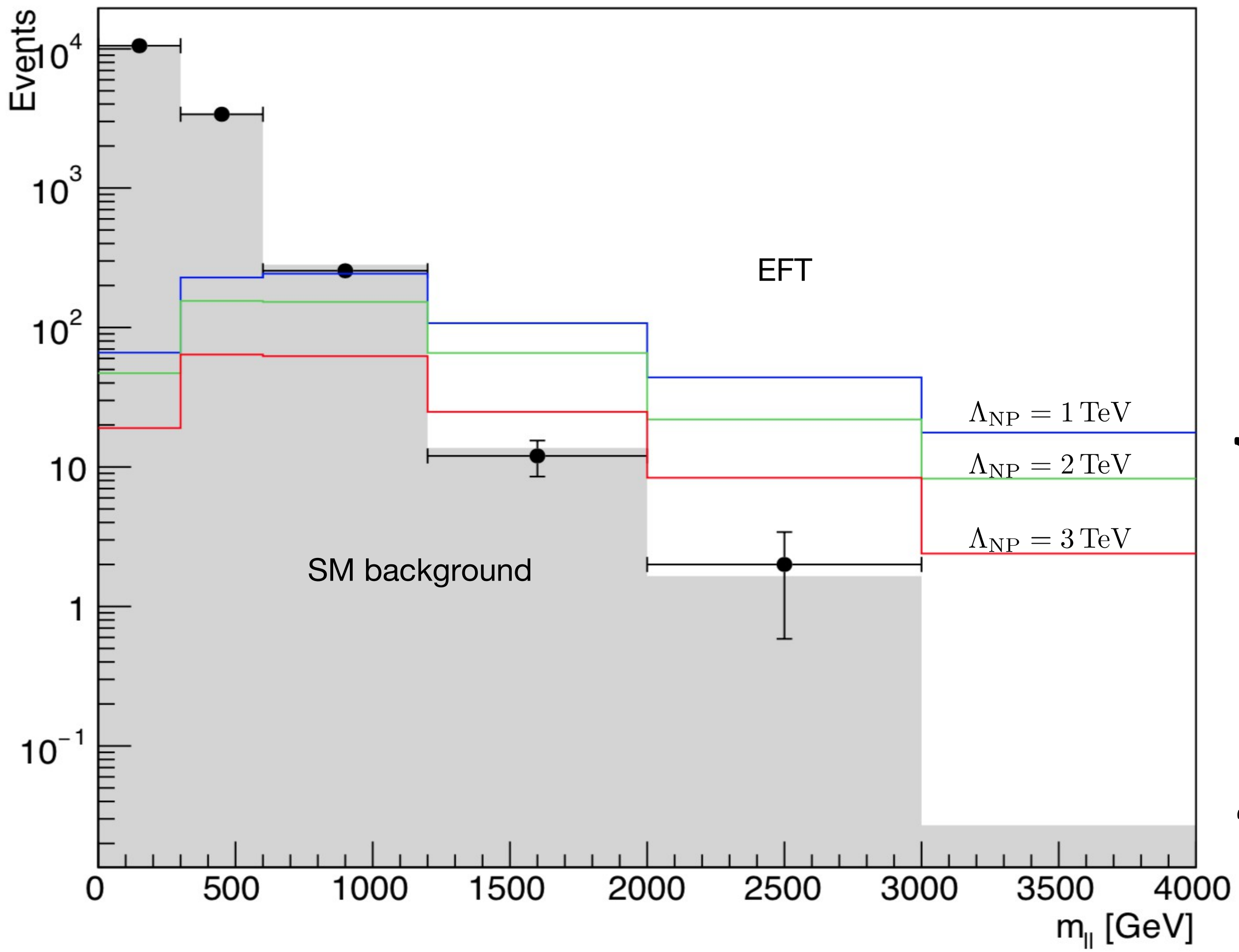
Very hierarchical!

'High-pT' Tails



$$q_i \bar{q}_j \to \ell_\alpha^\pm \ell_\beta^\mp$$

$$q_i \bar{q}_j \to \ell_\alpha^\pm \nu_\beta$$

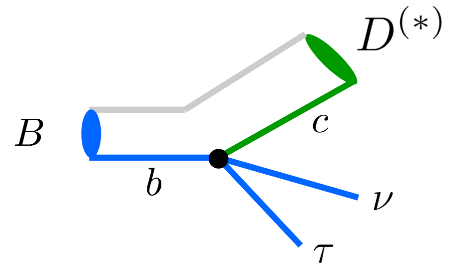


Wide tails in the invariant mass spectrum!

Di-tau tails - RD(*)

- SM EFT (d=6):

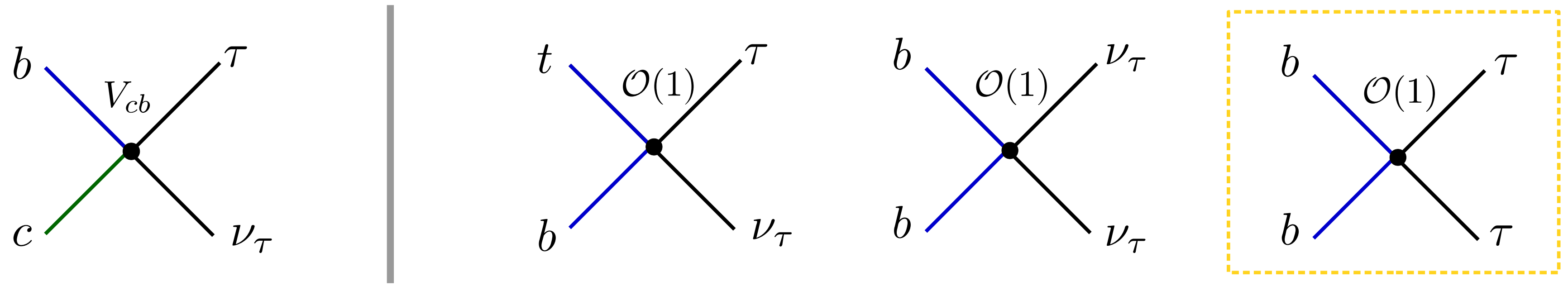
$$\mathcal{L}_{eff} \supset C^{(3)\ ij\alpha\beta}_{lq}\ (\bar{Q}^i\gamma_\mu\sigma^a Q^j)(\bar{L}^\alpha\gamma^\mu\sigma^a L^\beta) + C^{ij\alpha\beta}_{ledq}\ (\bar{d}^i Q^j)(\bar{L}^\alpha e^\beta) + C^{(1)\ ij\alpha\beta}_{lequ}\ (\bar{Q}_i u^j) i\sigma^2 (\bar{L}^\alpha e^\beta) + C^{(3)\ ij\alpha\beta}_{lequ}\ (\bar{Q}^i\sigma_{\mu\nu}u^j)\,(\bar{L}^\alpha\sigma_{\mu\nu}e^\beta)$$



- (Minimal) Flavor structure assumptions:

1. Alignment with **down quarks** & **charged leptons:** $Q_i = (V^{ij*}_{CKM} u^j_L, d^i_L)^T$ $\quad L_i = (U^{ij*}_{PMNS}\nu^j_L, \ell^i_L)^T$

2. Dominant effects in **3rd generation fermions**: $C^{ij\alpha\beta} \approx C\ \delta_{i3}\delta_{j3}\delta_{3\alpha}\delta_{3\beta}$



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

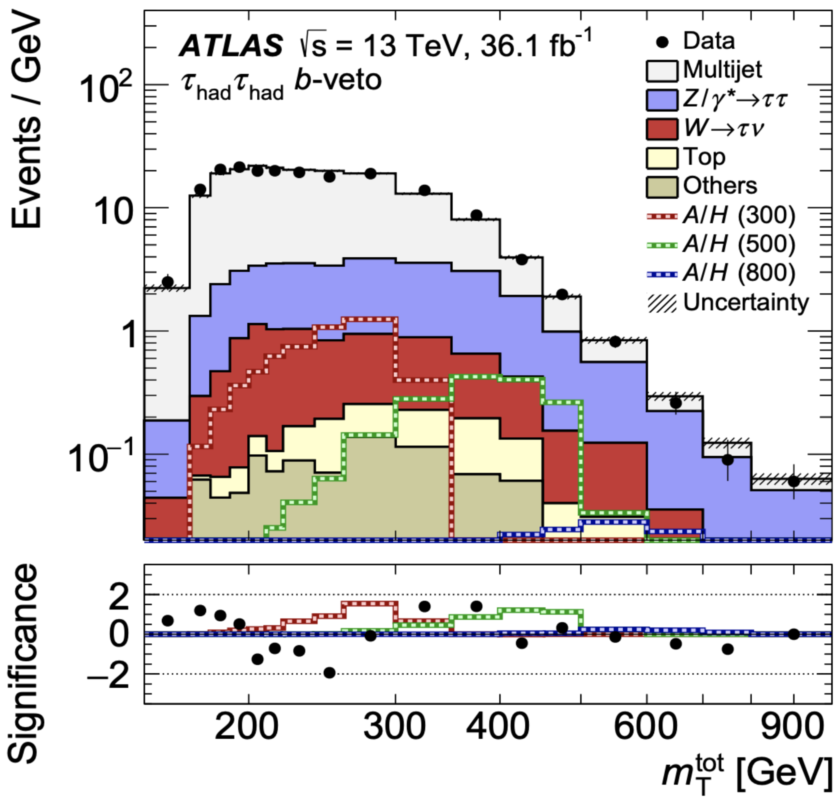
- Enhanced ditau production $b\bar{b} \to \tau\tau$ compared to mono-tau $b\bar{c} \to \tau\nu$

- We can probe generic NP solution to RD(*) in **Di-Tau** production at the LHC! $pp \to \tau^+\tau^- + X$

Di-tau tails - RD(*)

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

Z' Sequential SM	8 TeV	19.5 fb^{-1}
	13 TeV	3.2 fb^{-1}
MSSM Higgs	13 TeV	36.1 fb^{-1}
	13 TeV	139 fb^{-1}



- Recast Z' di-Tau searches:
  - Inclusive category $pp \to \tau^+\tau^- + X$
  - Hadronic mode $\tau_{\rm had}\tau_{\rm had}$

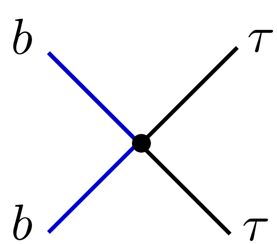
$$m_T^{\rm tot} \equiv \sqrt{m_T^2(\tau_1,\tau_2) + m_T^2(E_T^{\rm miss},\tau_1) + m_T^2(E_T^{\rm miss},\tau_2)}$$

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

- Results for EFT limits @ 13 TeV, 3.2 fb^{-1}:

$$\mathcal{L}_{eff} \supset C_{lq}^{(3)\ ij\alpha\beta}\,(\bar{Q}^i\gamma_\mu\sigma^a Q^j)(\bar{L}^\alpha\gamma^\mu\sigma^a L^\beta)$$

$$|C_{lq}^{(3)\ bb\tau\tau}| < \frac{2.6}{(1\,\mathrm{TeV})^2}$$



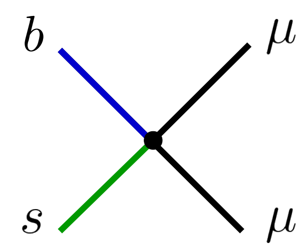
DAF, Greljo, Kamenik '16

- LHC is becoming sensitive to the B-anomaly mass scale!

Di-muons tails - RK(*)

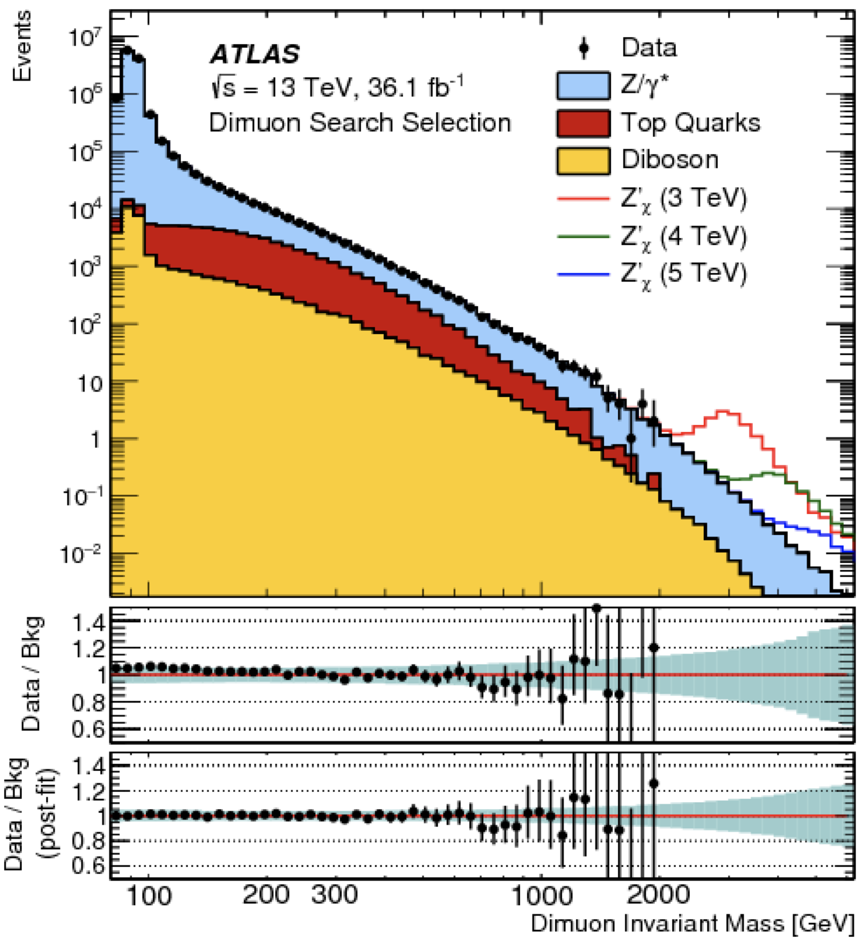
Greljo, Marzocca '17

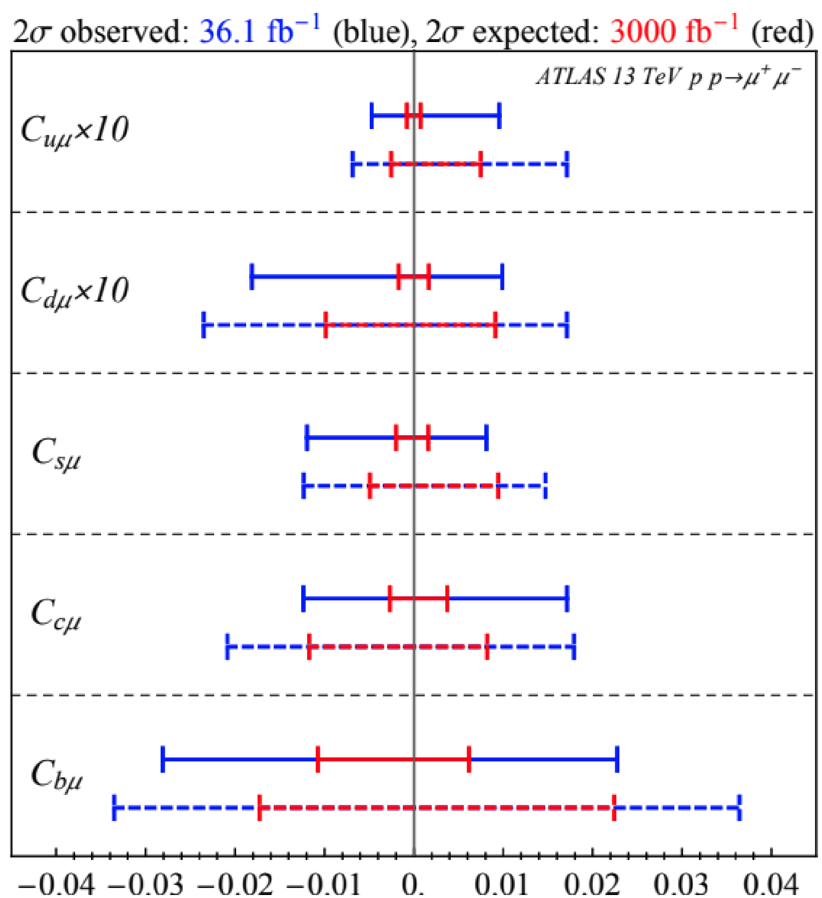
$$\mathscr{L}^{\rm eff} \supset \frac{\mathbf{C}^{U\mu}_{ij}}{v^2}(\bar{u}^i_L \gamma_\mu u^j_L)(\bar{\mu}_L \gamma^\mu \mu_L) + \frac{\mathbf{C}^{D\mu}_{ij}}{v^2}(\bar{d}^i_L \gamma_\mu d^j_L)(\bar{\mu}_L \gamma^\mu \mu_L) \qquad \mathbf{C}^{D\mu}_{ij} = \begin{pmatrix} C_{d\mu} & 0 & 0 \\ 0 & C_{s\mu} & C^*_{bs\mu} \\ 0 & C_{bs\mu} & C_{b\mu} \end{pmatrix}$$



$s\bar{b} \to \mu^- \mu^+$

Light-lepton tails

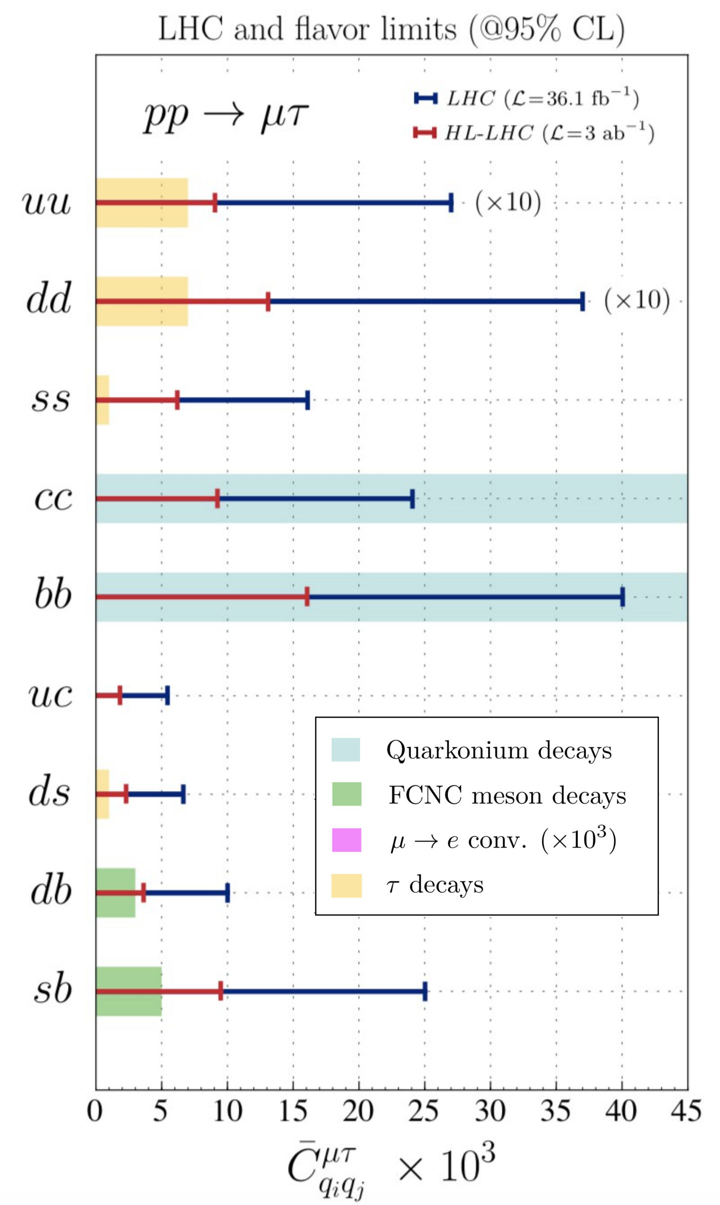




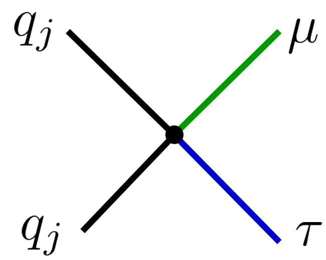
$\Lambda_{NP}(\text{valence}) > 8\,\text{TeV}$

$\Lambda_{NP}(\text{heavy sea}) > 1.5\,\text{TeV}$

LFV tails!

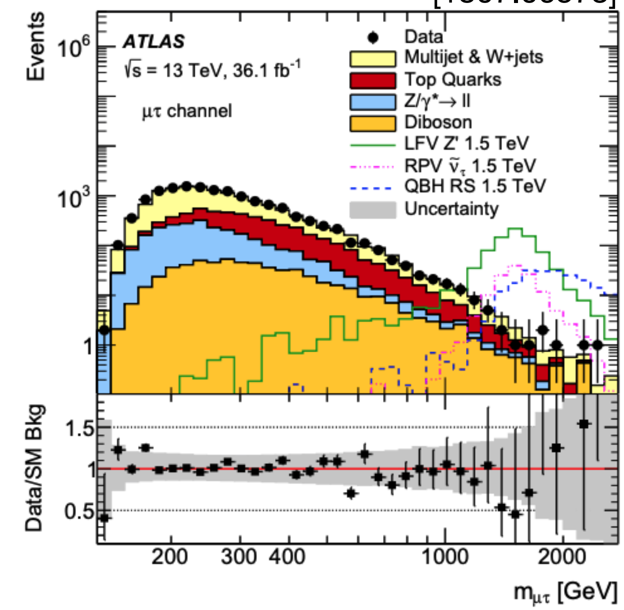


Angelescu, DAF, Sumensari '20



$pp \to \mu\tau$

[1807.06573]



- Recast results:

$$\Lambda_{NP}(\text{valence}) > 8\,\text{TeV}$$

$$\Lambda_{NP}(\text{sea}) > 1.5\,\text{TeV}$$

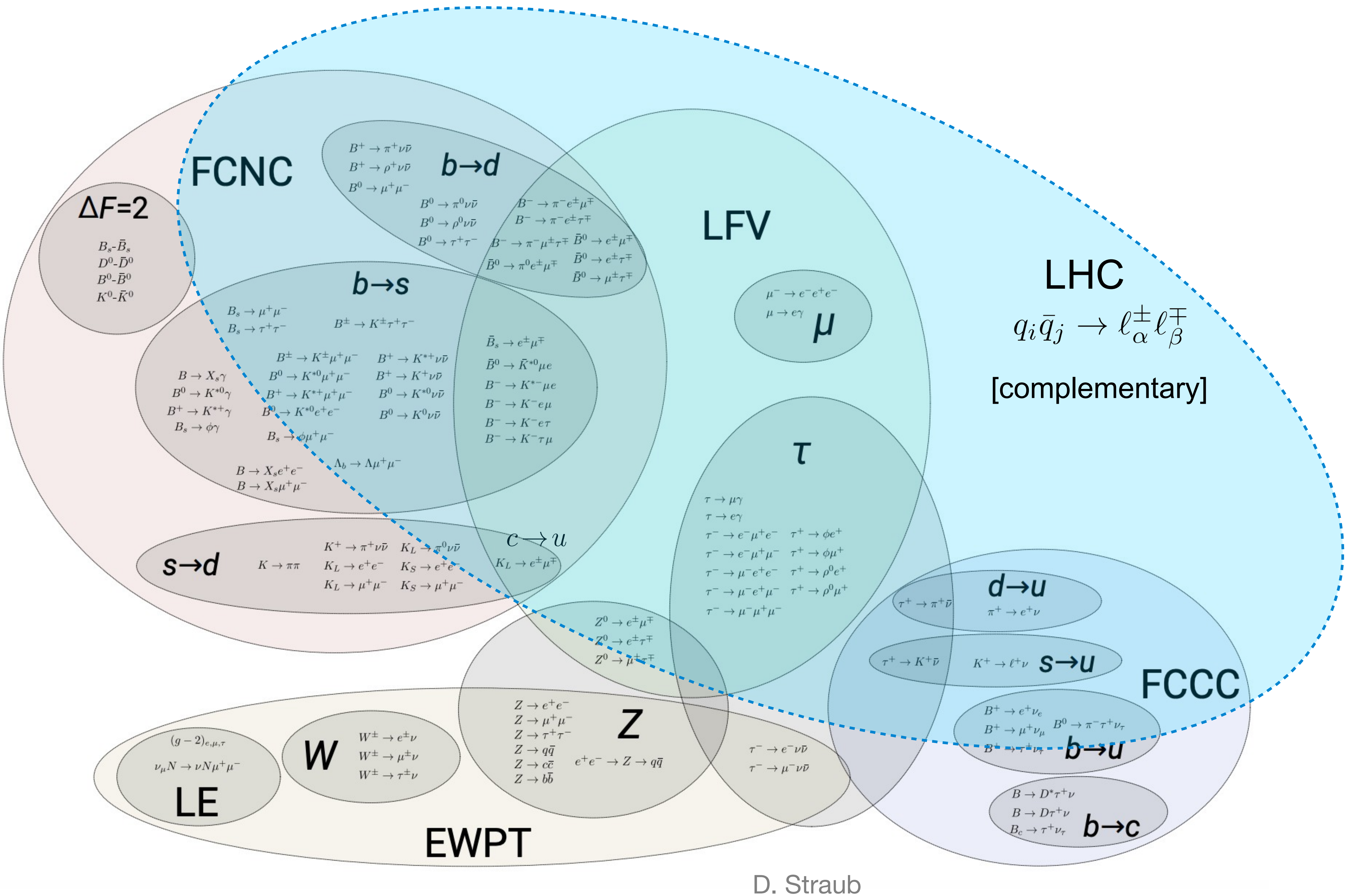
- Similar for results for $pp \to e\mu,\, e\tau$

$q\bar{q} \to \ell_\alpha^\pm \ell_\beta^\mp$ tails perform better than Flavor experiments.

$q\bar{q}' \to \ell_\alpha^\pm \ell_\beta^\mp$ tails worst than FCNC meson and tau decays.

Remarkable LHC / flavor complementarity!

Semileptonics: observables Landscape

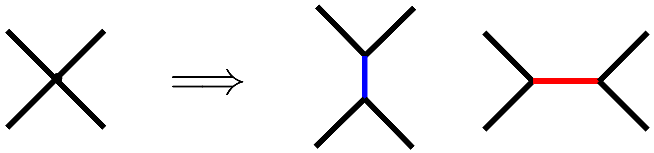


Aebischer et al. 1810.07698

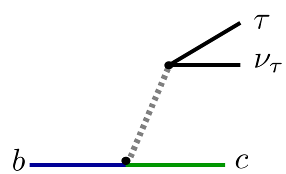
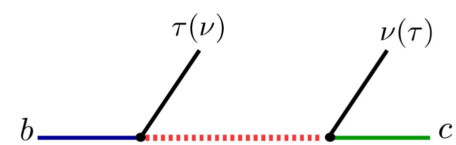
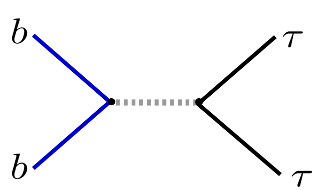
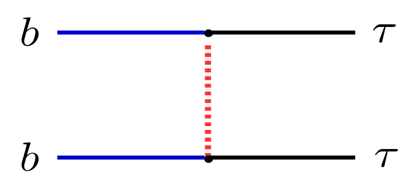
B-anomalies:

- Leptoquark solutions -

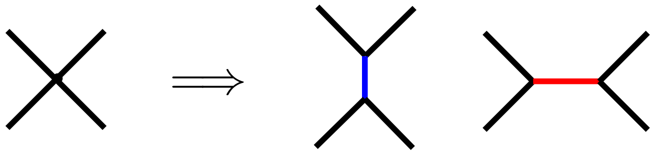
Simplified models - RD(*)



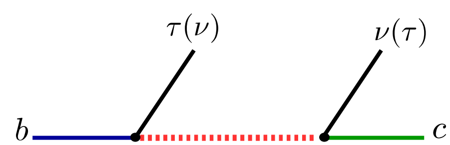
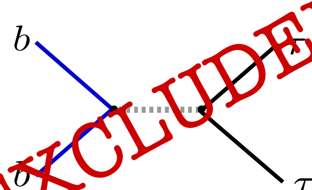
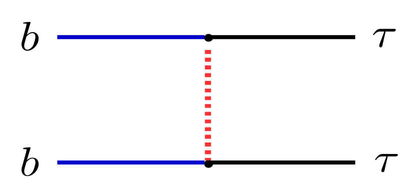
> Necessary for reliable high-pT collider studies
> Less parameters...
> Paves the way towards UV complete models

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

Simplified models - RD(*)



- Necessary for reliable high-pT collider studies
- Less parameters...
- Paves the way towards UV complete models

	mediators:	Colorless	Colorful
	Spin 0	2HDM (EXCLUDED)	Scalar Leptoquark
	Spin 1	Vector Triplet W’	Vector Leptoquark
Flavor	$b \to c$		
LHC phenomenology	$b\,\bar{b} \to \tau^+\tau^-$		
	Signature	di-Tau Resonance	Non-resonant excess in di-Tau tails

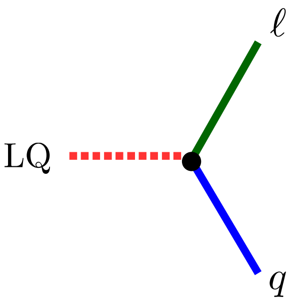
Color singlet solutions ruled out by ditau searches! [DAF, Greljo, Kamenik 1609.07138]

Leptoquarks

- Quintesential 'semi-leptonic' state!

Hypothetical Scalar / Vector boson

Color triplet, $Q_{em} = \{\pm\frac{1}{3},\ \pm\frac{2}{3}, \pm\frac{4}{3}, \pm\frac{5}{3}\}$



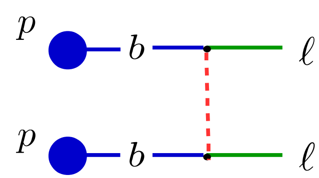
Leptoquark Bestiary

$(SU(3), SU(2), U(1))$	Spin	Symbol
$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3
$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2
$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$
$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$
$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1
$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$
$(\mathbf{3}, \mathbf{3}, 2/3)$	1	U_3
$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	1	V_2
$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	1	$\tilde{V}_2$
$(\mathbf{3}, \mathbf{1}, 5/3)$	1	$\tilde{U}_1$
$(\mathbf{3}, \mathbf{1}, 2/3)$	1	U_1
$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$

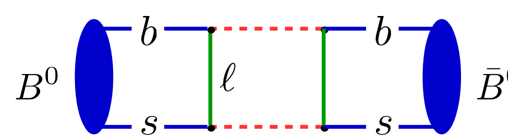
Relevant LQs for B-anoamlies

- Some general features:

- Non-resonant Drell-Yan production
- No 4-quark / 4-lepton effective interactions at tree level
- Induces semi-leptonic tree level LFV $K_L \to e\mu$
- Some leptoquarks can mediate proton decay...



t-channel

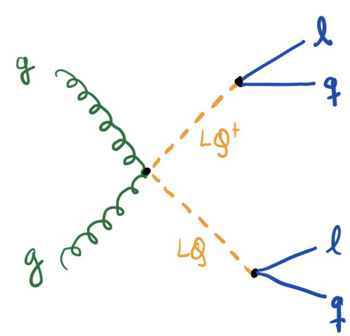


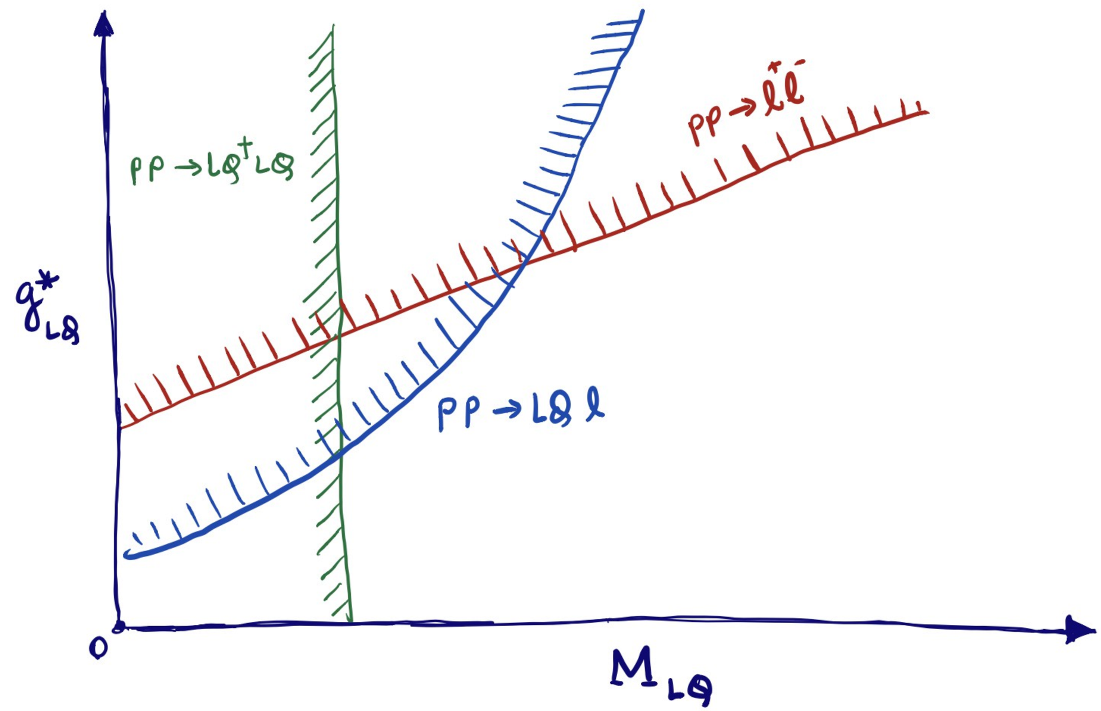
Leptoquarks @ LHC

LQ pair production

$$pp \to \mathrm{LQ}^*\mathrm{LQ} \to \ell\ell qq$$

$$\sigma \sim g_*^0$$

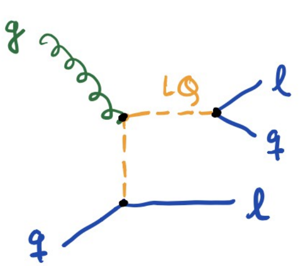




Single LQ production

$$pp \to \mathrm{LQ}\ \ell \to \ell\ell q$$

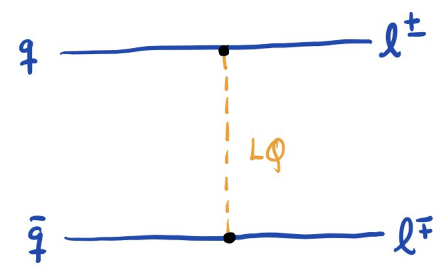
$$\sigma \sim g_*^2$$



Non-resonant Drell-Yan

$$pp \to \mu\mu, \tau\tau$$

$$\sigma \sim g_*^4$$



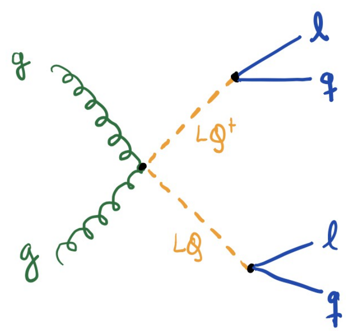
Leptoquarks @ LHC

LQ pair production

$$pp \to \mathrm{LQ}^*\mathrm{LQ} \to \ell\ell qq$$

$$\sigma \sim g_*^0$$

$\Longrightarrow$



Run 2 pair production limits

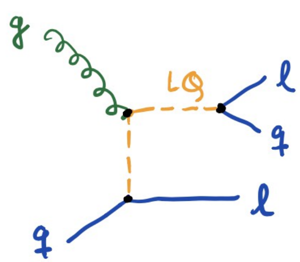
Decays	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\mathrm{int}}$ / Ref.
$jj\,\tau\bar{\tau}$	–	–	–
$b\bar{b}\,\tau\bar{\tau}$	1.0 (0.8) TeV	1.5 (1.3) TeV	36 fb^{-1} [39]
$t\bar{t}\,\tau\bar{\tau}$	1.4 (1.2) TeV	2.0 (1.8) TeV	140 fb^{-1} [40]
$jj\,\mu\bar{\mu}$	1.7 (1.4) TeV	2.3 (2.1) TeV	140 fb^{-1} [41]
$b\bar{b}\,\mu\bar{\mu}$	1.7 (1.5) TeV	2.3 (2.1) TeV	140 fb^{-1} [41]
$t\bar{t}\,\mu\bar{\mu}$	1.5 (1.3) TeV	2.0 (1.8) TeV	140 fb^{-1} [42]
$jj\,\nu\bar{\nu}$	1.0 (0.6) TeV	1.8 (1.5) TeV	36 fb^{-1} [43]
$b\bar{b}\,\nu\bar{\nu}$	1.1 (0.8) TeV	1.8 (1.5) TeV	36 fb^{-1} [43]
$t\bar{t}\,\nu\bar{\nu}$	1.2 (0.9) TeV	1.8 (1.6) TeV	140 fb^{-1} [44]

$\mathrm{BR} = 1\,(0.5)$

Single LQ production

$$pp \to \mathrm{LQ}\ \ell \to \ell\ell q$$

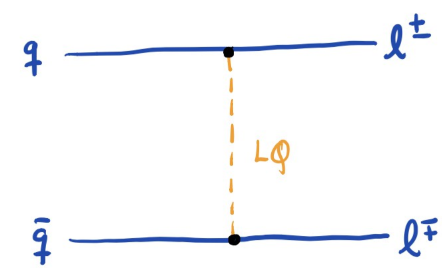
$$\sigma \sim g_*^2$$



Non-resonant Drell-Yan

$$pp \to \mu\mu, \tau\tau$$

$$\sigma \sim g_*^4$$

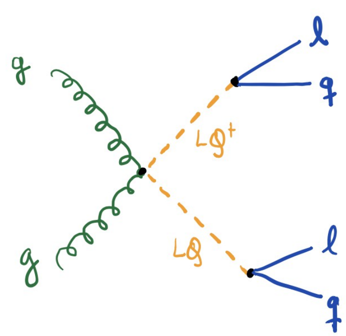


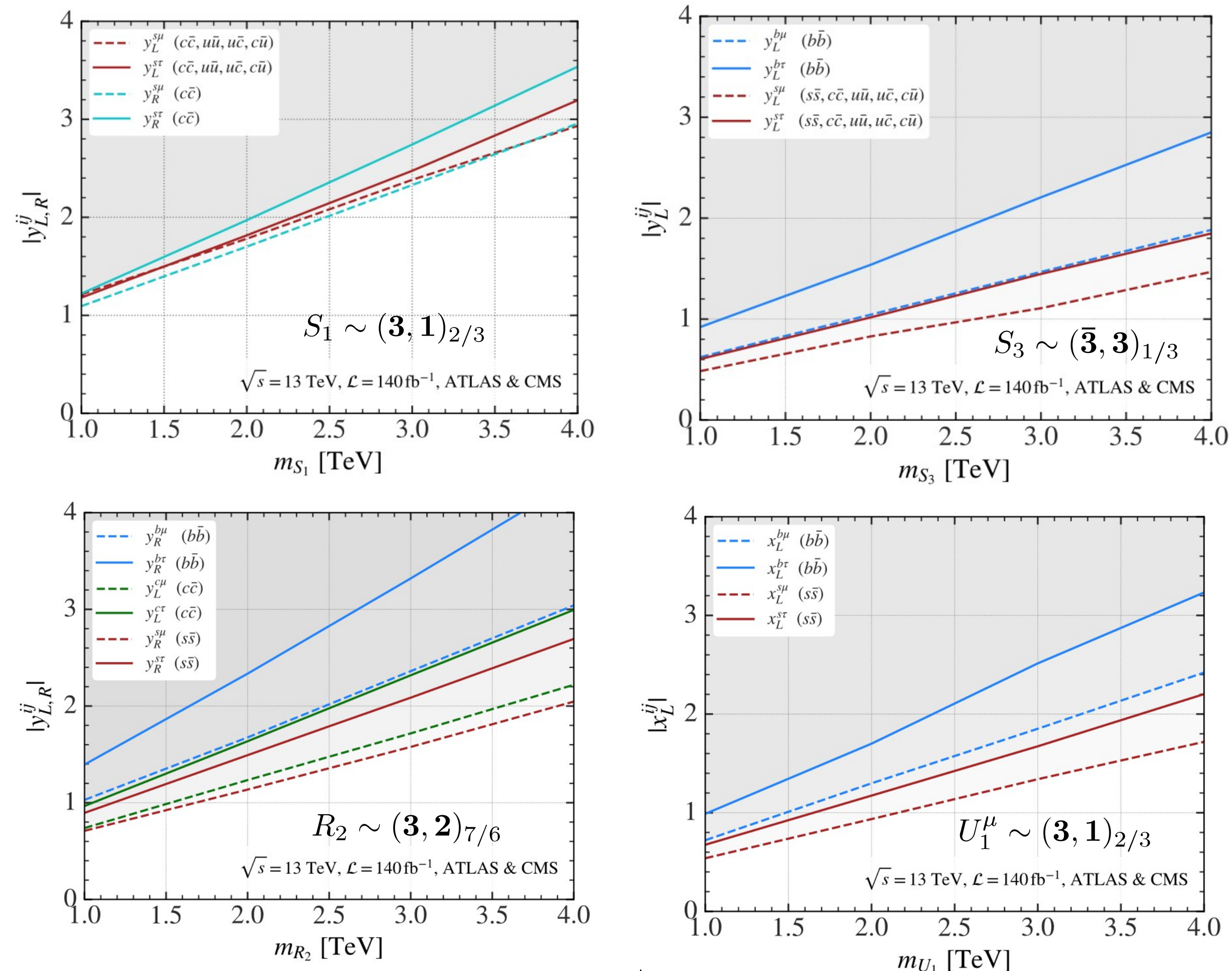
Leptoquarks @ LHC

LQ pair production

$$pp \to \mathrm{LQ}^*\mathrm{LQ} \to \ell\ell qq$$

$$\sigma \sim g_*^0$$



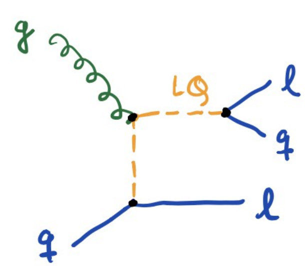


$\Uparrow$

Single LQ production

$$pp \to \mathrm{LQ}\ \ell \to \ell\ell q$$

$$\sigma \sim g_*^2$$



Non-resonant Drell-Yan

$$pp \to \mu\mu, \tau\tau$$

$$\sigma \sim g_*^4$$

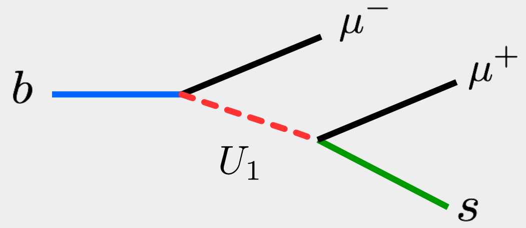
Run-2 Drell-Yan Recast limits

(Include previously ignored interference effects)

U_1 Vector LQ

$$U_1^\mu \sim (\mathbf{3},\mathbf{1})_{2/3} \qquad \mathcal{L}_{U1} = U_1^\mu \left[x_L^{ij} (\bar{d}_{Li}\gamma_\mu \ell_{Lj}) + (V\, x_L)^{ij} (\bar{u}_{Li}\gamma_\mu \nu_{Lj}) - x_R^{ij} (\bar{d}_{Ri}\gamma_\mu \ell_{Rj}) \right] + \text{h.c.}$$

$b \to s\mu\bar{\mu}$



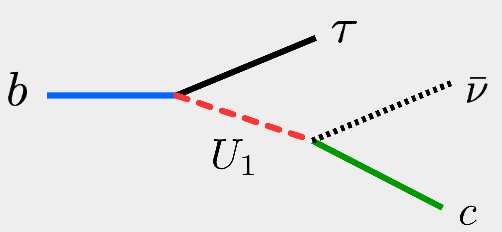
$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & 0 \\ 0 & x_L^{b\mu} & 0 \end{pmatrix}$$

$$x_R = 0$$

$$C_9 = -C_{10} = -\frac{\pi v^2}{V_{tb}V_{ts}^*\alpha} \frac{x_L^{s\mu}(x_L^{b\mu})^*}{m_U^2}$$

$$\boxed{R_{K^{(*)}} < R_{K^{(*)}}^{\text{SM}}}$$

$b \to c\tau\bar{\nu}$



$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & x_L^{b\tau} \end{pmatrix}$$

$$x_R = 0$$

$$g_{V_L} = -\frac{v^2\,|x_L^{b\tau}|^2}{2m_U^2}$$

$$\boxed{R_{D^{(*)}} > R_{D^{(*)}}^{\text{SM}}}$$

- This solution can accomodate both anomalies! Butazzo, Greljo, Isidori, Marzocca [1706.07808]

- This solution has no (tree-level) contribution to $b \to s\nu\bar{\nu}$

Leptoquark 'catalog' (spring 2021 edition)

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

Angelescu, Becirevic, DAF, Sumensari [1808.08179]

V−A structure

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

Only state that can solve both B-anomalies!

Butazzo et al [1706.07808]

- UV completion necessary: e.g. '4321' models

$$G_{4321} = SU(4) \times SU(3)_{c'} \times SU(2)_L \times U(1)_{Y'} \;\to\; G_{SM}$$

Di Luzio et al [1708.08450]

Bordone, Cornella, Fuentes-Martin, Isidori '18

No single scalar LQ solves both B-anomalies.

Two (or more) scalar LQ needed:

R_2 & S_3 (Scalar + Tensor & V-A) e.g. GUT inspired model Becirevic et al [1808.08179]

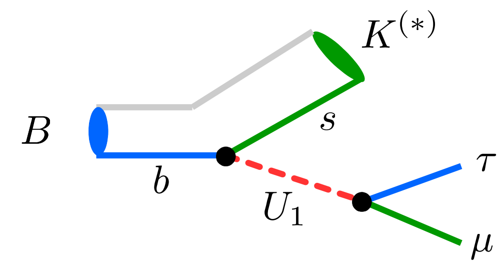
S_1 & S_3 (V-A) e.g. Strongly coupled model Marzocca [1803.10972]

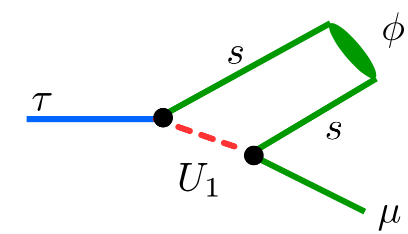
Cornering U_1

Can we fully test the U_1 model using tree-level observables?

Complementarity between LFV low-energy and LFC high-pT observables

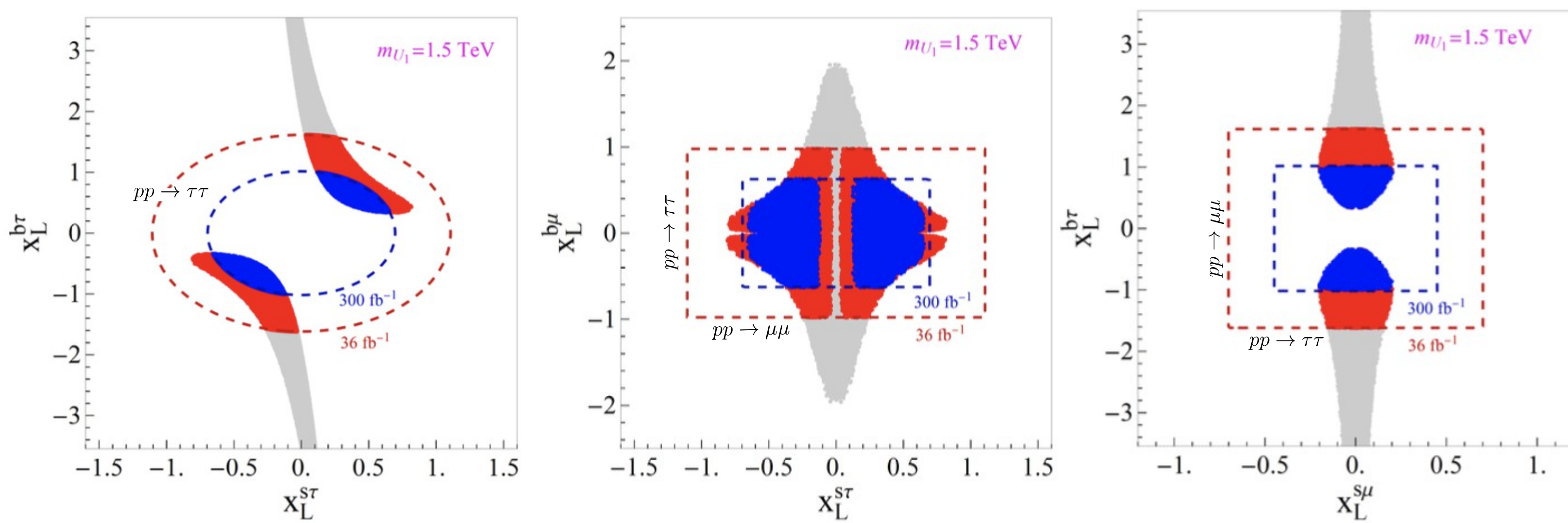
$pp \to \tau^+\tau^- + X$	$B \to K\mu\tau$	$\tau \to \mu\phi$
$\begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}$





Fixed mass fit with tree-level observables

Angelescu, Becirevic, DAF, Sumensari [1808.08179]



Observable
$b \to s\mu\mu$
$b \to c\tau\nu$
$\mathcal{B}(\tau \to \mu\phi)$
$\mathcal{B}(B \to \tau\nu)$
$\mathcal{B}(D_s \to \mu\nu)$
$\mathcal{B}(D_s \to \tau\nu)$
$r_K^{e/\mu}$
$r_K^{\tau/\mu}$
$R_D^{\mu/e}$

- LHC di-lep allowed regions at 36/fb (blue) & 300/fb (red)

- U_1- strange - tau coupling must be non-zero!

$$g_{V_L} = -\frac{v^2}{2m_U^2}\left[|x_L^{b\tau}|^2 + \frac{V_{cs}}{V_{cb}} x_L^{s\tau}(x_L^{b\tau})^*\right]$$

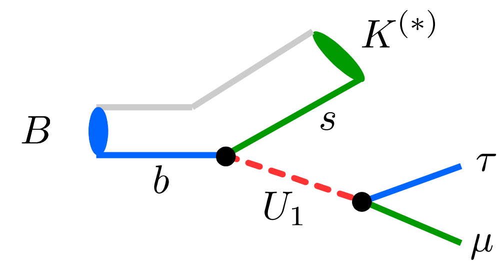
$$\boxed{x_{s\tau} = \mathcal{O}(1) \times V_{cb}}$$

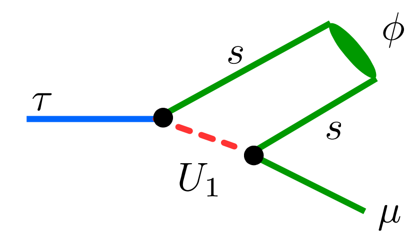
Cornering U_1

Can we fully test the U_1 model using tree-level observables?

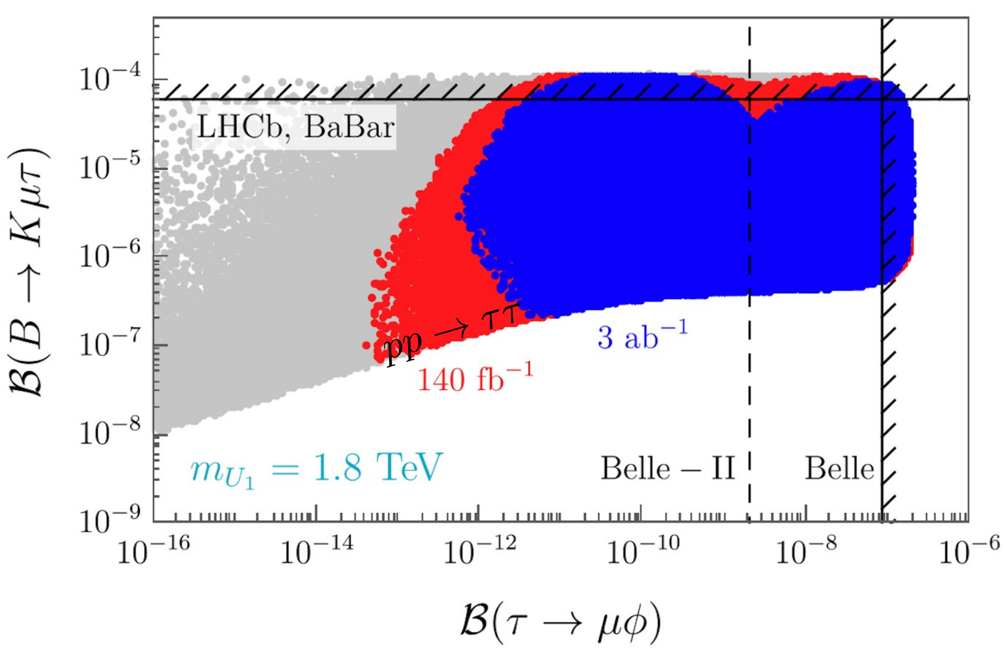
Complementarity between LFV low-energy and LFC high-pT observables

$pp \to \tau^+\tau^- + X$	$B \to K\mu\tau$	$\tau \to \mu\phi$
$\begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}$





- Predictions for LFV low-energy observables for U1



LHC Di-Taus tails push lower bounds on both LFV observables!

Model Potentially within reach at LHCb & Belle 2!

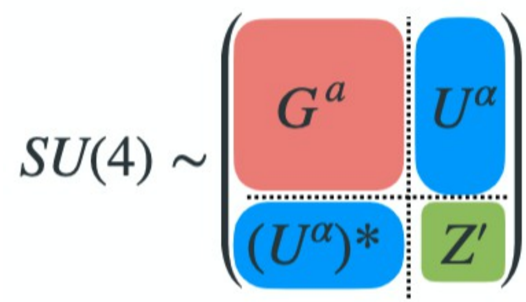
Angelescu, Becirevic, DAF, Jaffredo, Sumensari, [2021]

- a UV model -

'4321' model

Pati-Salam Leptoquark $U_1^\mu \sim (\mathbf{3},\mathbf{1})_{2/3}$

Coloron (vector octet)

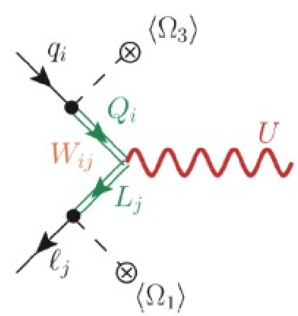


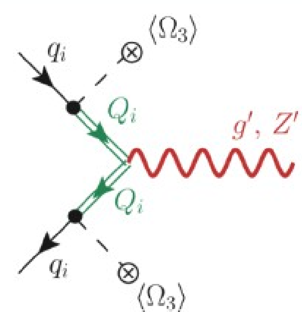
$$\overbrace{\underbrace{SU(4)\times SU(3)'}_{SU(3)_c}\times SU(2)_L\times U(1)_X}^{U(1)_Y} \xrightarrow[\langle\Omega_i\rangle]{SSB} SU(3)_c\times SU(2)_L\times U(1)_Y$$

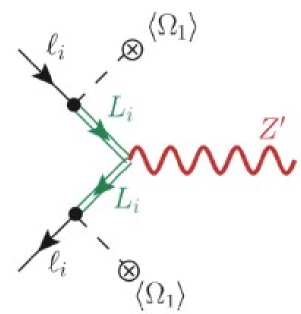
$$\boxed{+U_1, Z', G'}$$

[Flavor non-universal]

	Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
SM fields	q_L^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
	u_R^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
	d_R^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
	ℓ_L^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
	e_R^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
$\chi = \begin{pmatrix} Q \\ L \end{pmatrix}$	$\chi_{L,R}^i$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
	H	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
4321 SSB scalars	Ω_1	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
	Ω_3	$\bar{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$
	Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0

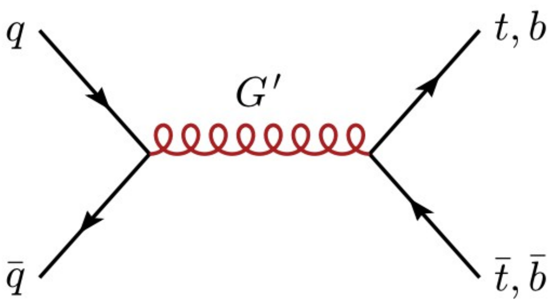






Coloron search

$$pp \to G' \to t\bar{t}, b\bar{b}$$



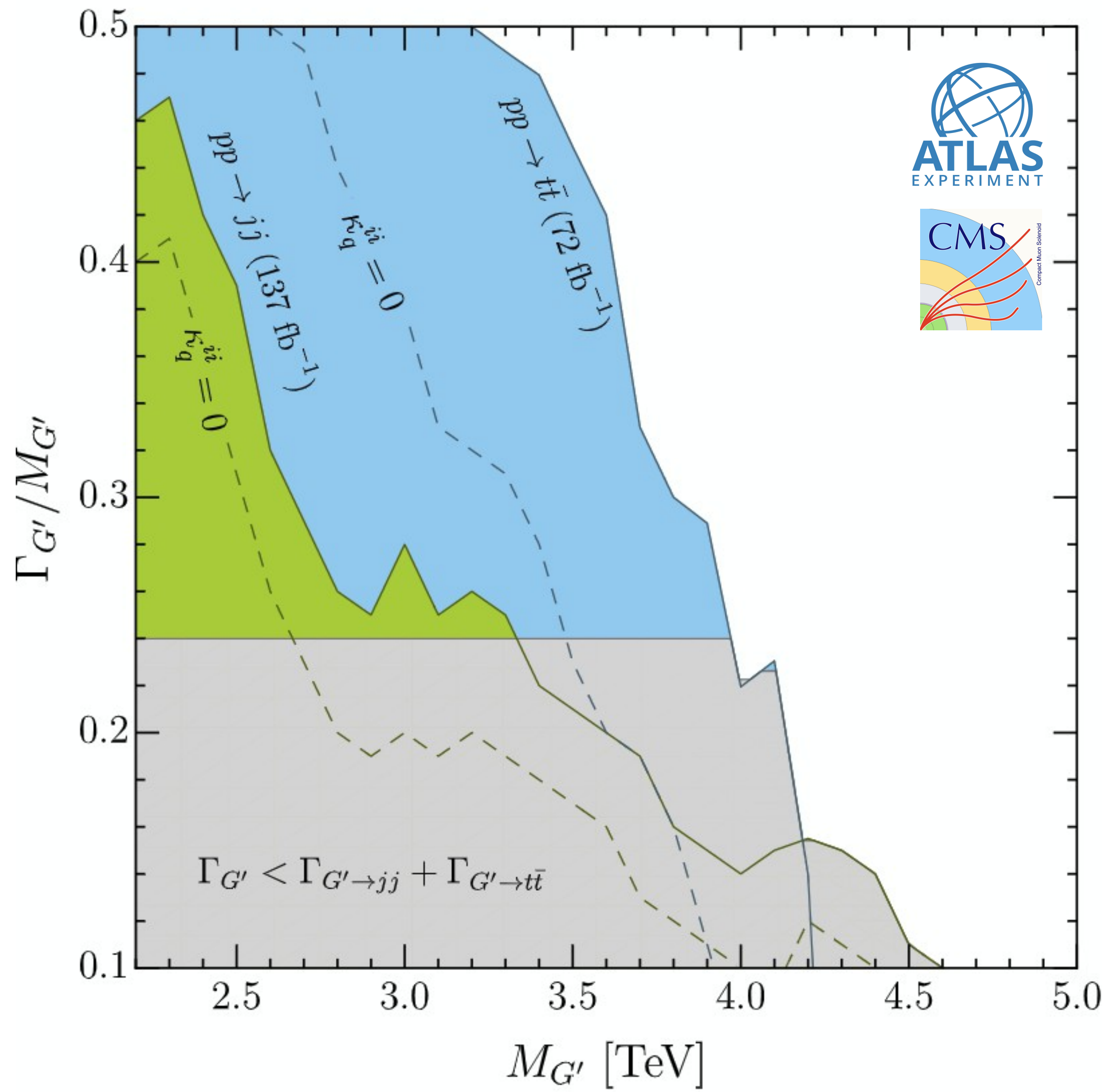
- 4321 models have broad resonances

- Recast of ditop/dijet searches

High mass normalized
invariant mass distrubtiuon

Best limits on the 4321 model!

Cornella, DAF, Fuentes-Martin, Isidori, Neubert [2103.16558]



Conclusions

- B-anomalies are alive and kicking: LHCb recently anounced evidence of LFUV in R_K
- Combined anomalies in neutral currents are approaching the 5 sigma level.
- B-anomalies opened the doors to explore flavorp physics at high-energy pp-colliders.

$$q_i \bar{q}_j \to \ell_\alpha^\pm \ell_\beta^\mp \qquad\qquad q_i \bar{q}_j \to \ell_\alpha^\pm \nu_\beta$$

- We described a remarkable complementarity between high-pT and low energy LFV flavor observables for effective operators.
- High-pT observables are a crucial input for model building efforts $\Longrightarrow$ Leptoquarks
- Leptoquark solutions exhibit specific **complementary** beteen ditaus and LFV searches:

$$pp \to \tau^+\tau^- + X \quad \Longleftrightarrow \quad B \to K\mu\tau \quad \Longleftrightarrow \quad \tau \to \mu\phi$$

ATLAS/CMS LHCb Belle 2

- UV and simplified models can be efficiently tested at colliders!

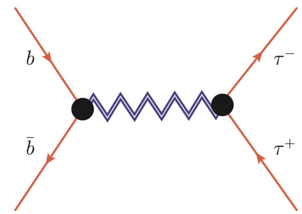
- extra slides -

Di-tau tails & colorless mediators

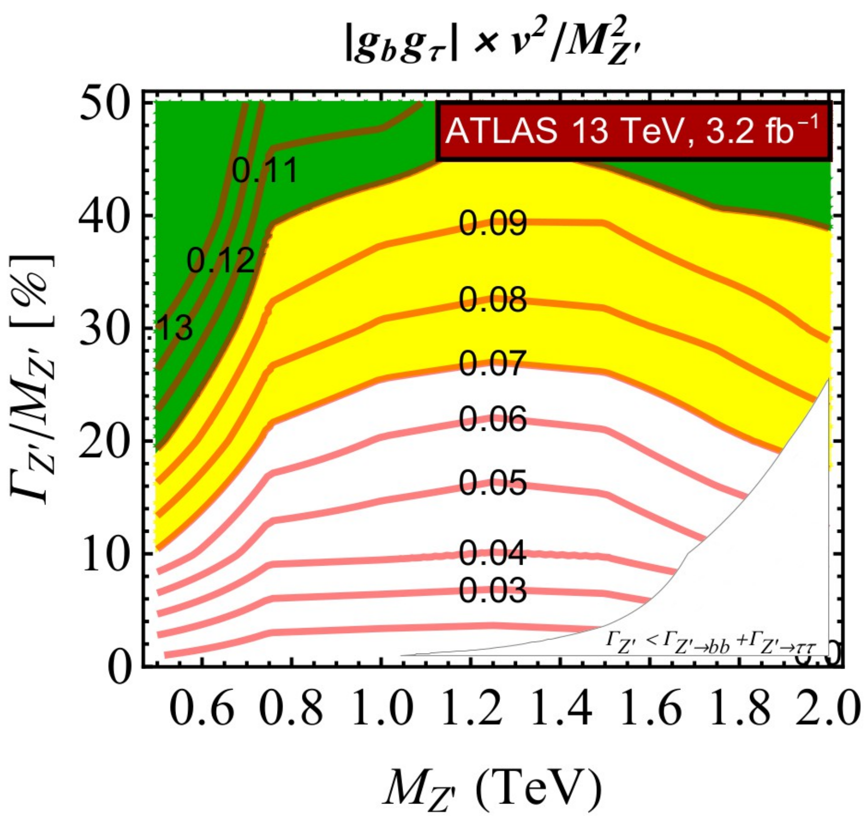
Vector triplet model:

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

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



$$pp \to \tau^+\tau^- + X$$



Recast Di-tau search for Z' with arbitrary width

JHEP 1801 055 (2018)

High-pT di-tau searches excludes **colorless** solution to B-anomalies!

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

Di-lepton tails - RK(*)

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Rev. Lett.

CERN-EP-2021-065
May 31, 2021

Search for new phenomena in final states with two leptons and one or no b-tagged jets at $\sqrt{s} = 13$ TeV using the ATLAS detector

dimuon + b-jet

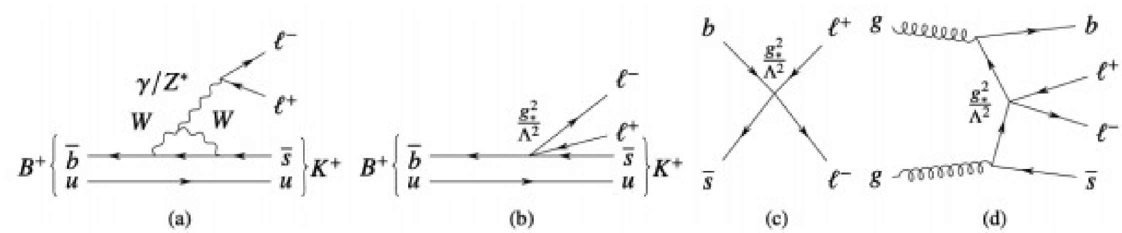
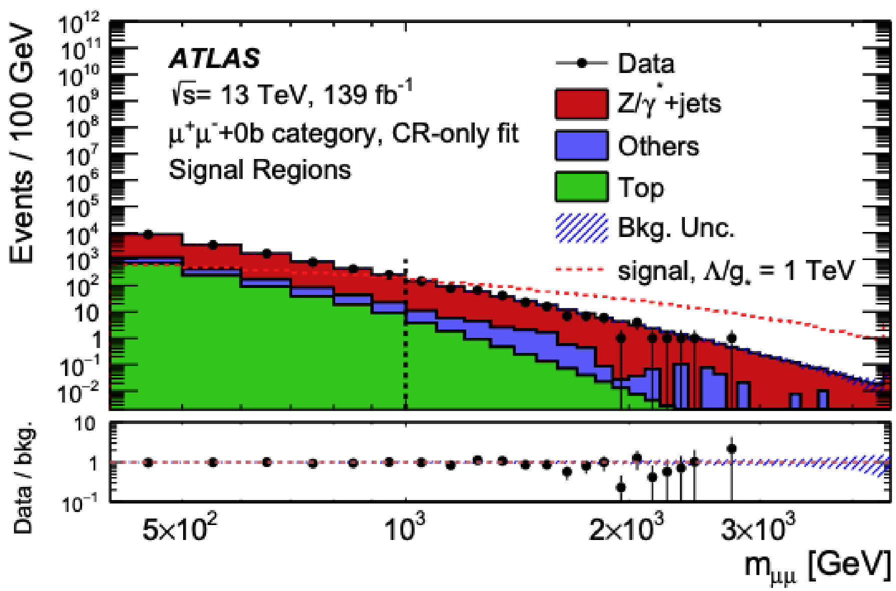
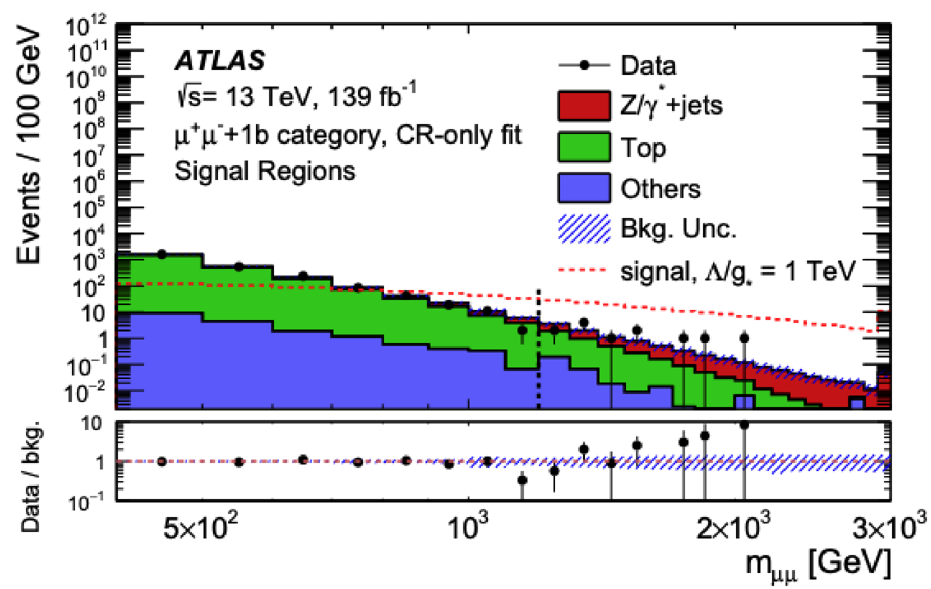


Figure 1: Representative Feynman diagrams for the decay of a B^+ meson to a K^+ meson in association with two leptons (a) in the SM and (b) in the EFT approach, and for production of two leptons via a $bs\ell\ell$ contact interaction in pp collisions (c) without and (d) with a b-jet in the final state.





- First limits on contact interaction $bs\mu\mu$

$$\boxed{\Lambda/g^* > 2\ \text{TeV}}$$

Di-lepton SMEFT

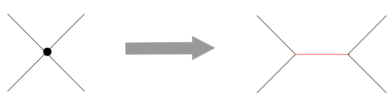
Greljo, Marzocca '17

$$\mathscr{L}^{\text{eff}} \supset \frac{\mathbf{C}^{U\mu}_{ij}}{v^2}(\bar{u}^i_L \gamma_\mu u^j_L)(\bar{\mu}_L \gamma^\mu \mu_L) + \frac{\mathbf{C}^{D\mu}_{ij}}{v^2}(\bar{d}^i_L \gamma_\mu d^j_L)(\bar{\mu}_L \gamma^\mu \mu_L) \qquad \mathbf{C}^{D\mu}_{ij} = \begin{pmatrix} C_{d\mu} & 0 & 0 \\ 0 & C_{s\mu} & C^*_{bs\mu} \\ 0 & C_{bs\mu} & C_{b\mu} \end{pmatrix}$$

Minimal Flavor Violation (MFV) for $R_{K^{(*)}}$

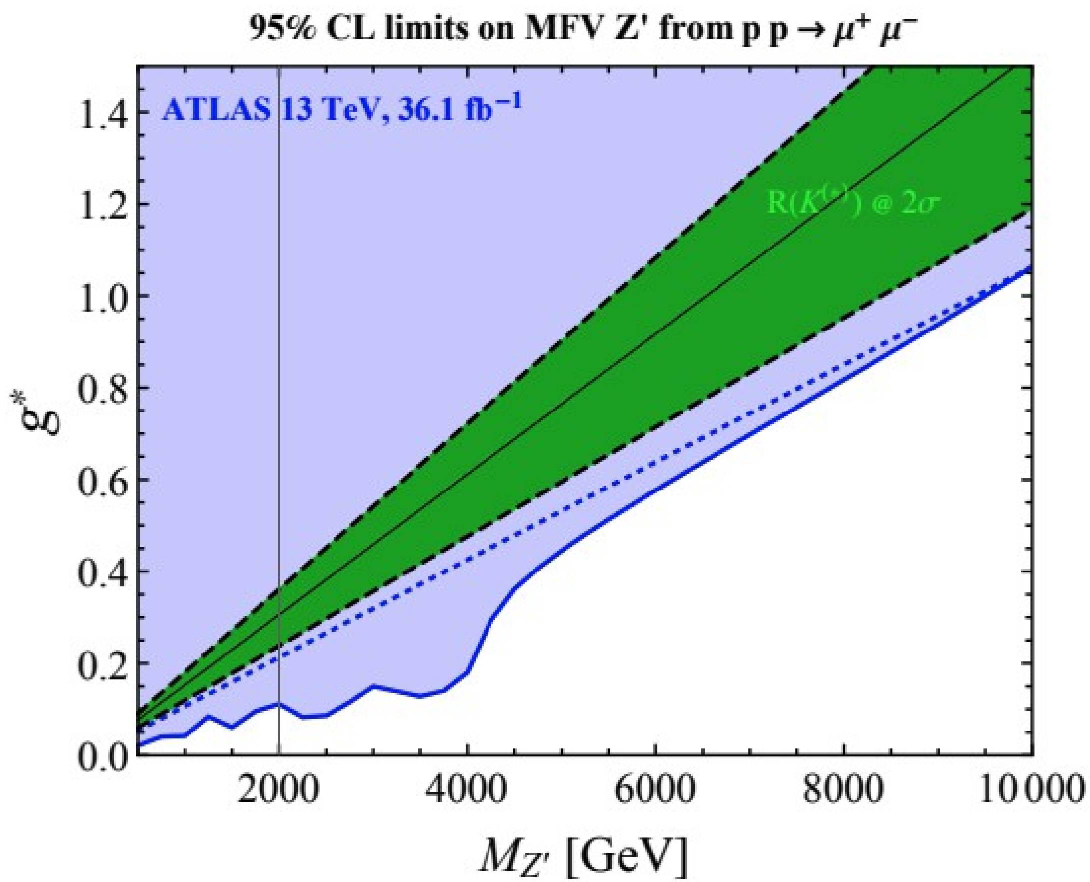
$$C_{d\mu} = C_{s\mu} = C_{b\mu} \equiv C_{D\mu}$$

$$|C_{bs\mu}| \sim |V_{tb} V^*_{ts} y_t^2 C_{D\mu}|$$



$$\frac{C}{v^2} = \frac{g_*^2}{M_{Z'}^2}$$

Scenario excluded by dileptons!



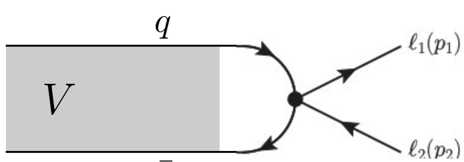
Di-lepton tails - LFV

Four relevant LFV low energy experiments:

1) $\mu \to e$ conversion rate in Nuclei [Only relevant for valence quarks...]

2) Quarkonia LFV decays:

$$\boxed{V \to \ell_\alpha \ell_\beta}$$

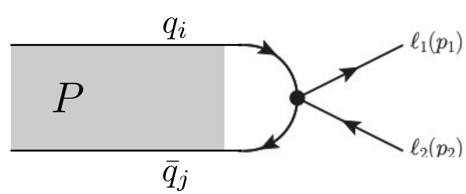


$$\mathcal{B}(V \to \ell_\alpha^- \ell_\beta^+) = \frac{\tau_V\, m_V^3 f_V^2}{24\pi v^4}\left(1 - \frac{m_{\ell_\beta}^2}{m_V^2}\right)^2 \times \left\{\left[|\mathcal{C}_{VL}|^2 + |\mathcal{C}_{VR}|^2\right]\left(1 + \frac{m_{\ell_\beta}^2}{2m_V^2}\right) + 6\frac{f_V^T}{f_V}\frac{m_{\ell_\beta}}{m_V}\mathrm{Re}(\mathcal{C}_T\, \mathcal{C}_{VR}^* + \widehat{\mathcal{C}}_T\, \mathcal{C}_{VL}^*) + 2\left(\frac{f_V^T}{f_V}\right)^2\left[|\mathcal{C}_T|^2 + |\widehat{\mathcal{C}}_T|^2\right]\left(1 + \frac{2m_{\ell_\beta}^2}{m_V^2}\right)\right\}$$

3) FCNC Pseudo-scalar meson decays:

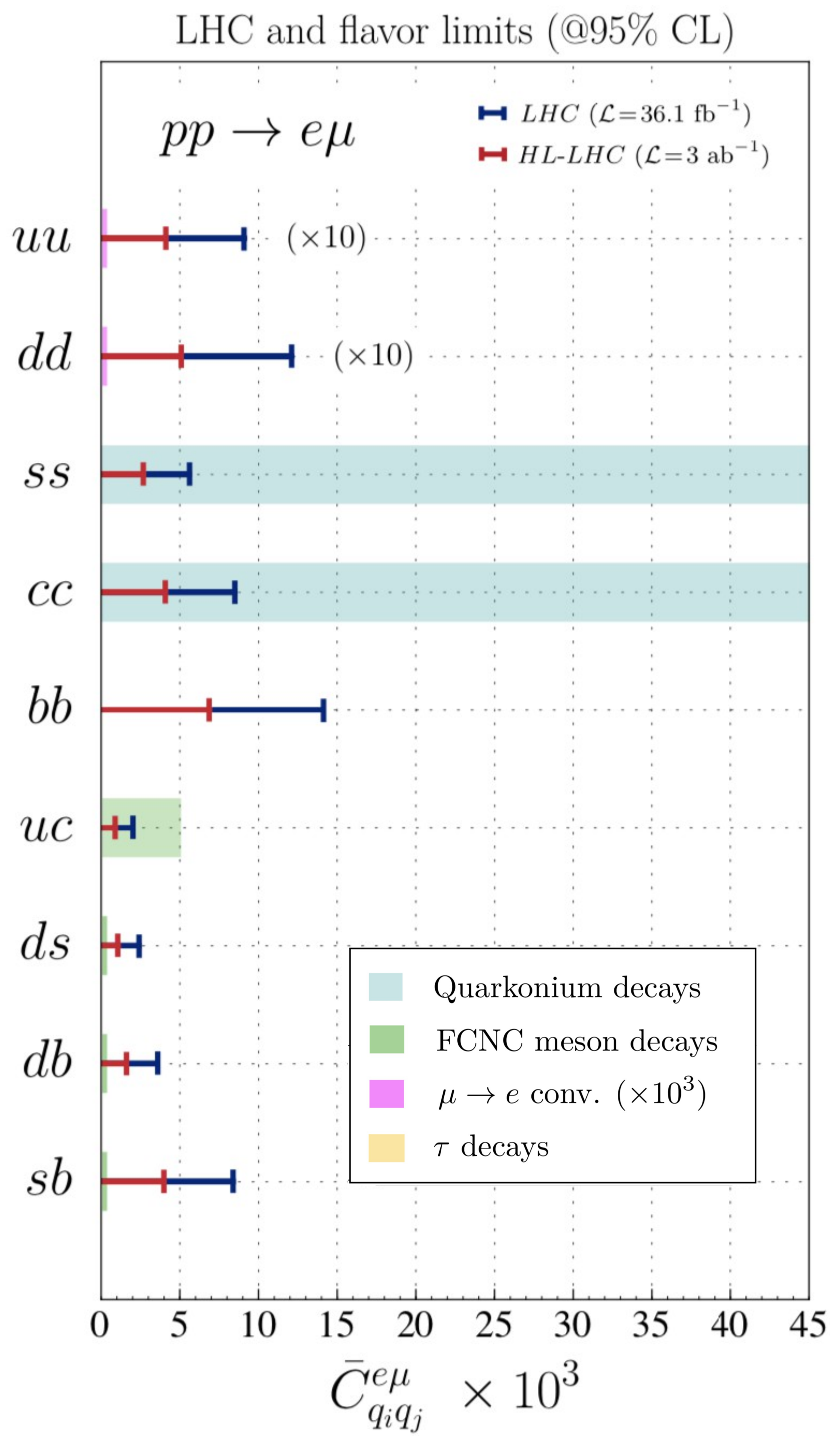
$$\boxed{\begin{array}{l} P \to \ell_\alpha \ell_\beta \\ P \to M \ell_\alpha \ell_\beta \end{array}}$$

$$P = K_{L,S}, D^0, B_s$$



[Helicity suppression]

4) LFV tau decays: $\boxed{\tau \to P \ell_\alpha, \quad \tau \to V \ell_\alpha}$



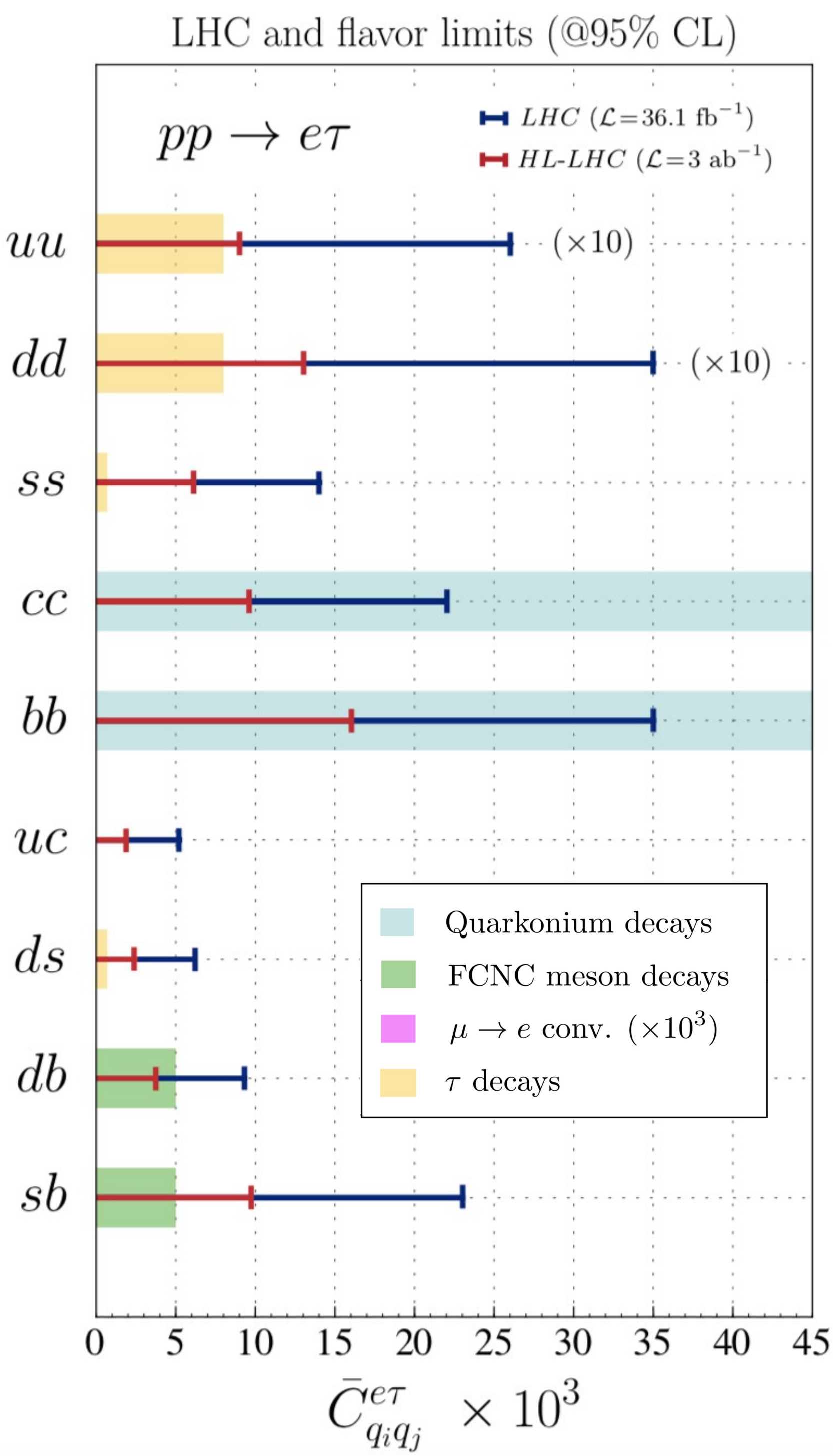
LHC vs Flavor $e\mu$

Decay mode	Exp. limit
$K_L \to \mu^\mp e^\pm$	6.1×10^{-12}
$K^+ \to \pi^+ \mu^+ e^-$	1.7×10^{-11}
$\phi \to \mu^\pm e^\mp$	2.6×10^{-6}
$D \to \mu^\pm e^\mp$	1.6×10^{-8}
$J/\psi \to \mu^\pm e^\mp$	2.1×10^{-7}
$B_d \to \mu^\mp e^\pm$	1.3×10^{-9}
$B^+ \to \pi^+ \mu^\mp e^\pm$	2.2×10^{-7}
$B_s \to \mu^\mp e^\pm$	6.3×10^{-9}
$B^+ \to K^+ \mu^+ e^-$	8.8×10^{-9}
$B^0 \to K^* \mu^\mp e^\pm$	2.3×10^{-7}

Selected LHC limits (left-handed scenario)

Decay mode	Current (36 fb^{-1})	Future (3 ab^{-1})
$\phi \to \mu^\pm e^\mp$	6.2×10^{-18}	1.4×10^{-18}
$D^0 \to \mu^\pm e^\mp$	2.8×10^{-9}	5.0×10^{-10}
$J/\psi \to \mu^\pm e^\mp$	7.1×10^{-12}	1.6×10^{-12}
$B_d \to \mu^\mp e^\pm$	7.8×10^{-8}	1.4×10^{-9}
$B^+ \to \pi^+ \mu^\mp e^\pm$	3.5×10^{-5}	6.4×10^{-6}
$B_s \to \mu^\mp e^\pm$	6.4×10^{-7}	1.4×10^{-7}
$B^+ \to K^+ \mu^\mp e^\pm$	2.8×10^{-4}	6.2×10^{-5}
$B^0 \to K^* \mu^\mp e^\pm$	5.8×10^{-4}	1.3×10^{-4}
$\Upsilon(3S) \to \mu^\pm e^\mp$	5.6×10^{-9}	1.3×10^{-9}

LHC vs Flavor $e\tau$



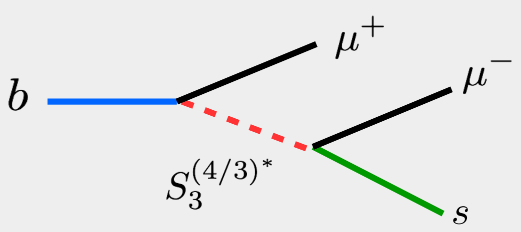
Decay mode	Exp. limit
$\tau \to e\rho$	2.3×10^{-8}
$\tau \to eK^*$	4.2×10^{-8}
$\tau \to e\phi$	4.0×10^{-8}
$J/\psi \to \tau^\pm e^\mp$	1.1×10^{-5}
$B_d \to \tau^\pm e^\mp$	3.6×10^{-5}
$B^+ \to \pi^+\tau^\pm e^\mp$	9.7×10^{-5}
$B^+ \to K^+\tau^\pm e^\mp$	3.9×10^{-5}
$\Upsilon(3S) \to \tau^\pm e^\mp$	5.4×10^{-6}

Selected LHC limits (left-handed scenario)		
Decay mode	Current (36 fb^{-1})	Future (3 ab^{-1})
$D^0 \to \tau^\pm e^\mp$	5.1×10^{-8}	6.8×10^{-9}
$J/\psi \to \tau^\pm e^\mp$	2.6×10^{-11}	4.9×10^{-12}
$B_d \to \tau^\pm e^\mp$	1.2×10^{-4}	1.9×10^{-5}
$B^+ \to \pi^+\tau^\pm e^\mp$	1.6×10^{-4}	2.5×10^{-5}
$B_s \to \tau^\mp e^\pm$	1.1×10^{-3}	2.0×10^{-4}
$B^+ \to K^+\tau^\pm e^\mp$	1.4×10^{-3}	2.5×10^{-4}
$B^0 \to K^*\tau^\pm e^\mp$	2.4×10^{-3}	4.2×10^{-4}
$\Upsilon(3S) \to \tau^\pm e^\mp$	3.4×10^{-8}	7.0×10^{-9}

S_3 Scalar Triplet

$$S_3 \sim (\bar{\mathbf{3}}, \mathbf{3})_{1/3} \qquad \mathcal{L}_{S_3} = -\, y_L^{ij}\, \bar{d^c_L}_i \nu_{L\,j}\, S_3^{(1/3)} - \boxed{\sqrt{2}\, y_L^{ij}\, \bar{d^c_L}_i \ell_{L\,j}\, S_3^{(4/3)}}$$
$$+ \sqrt{2}\, (V^* y_L)_{ij}\, \bar{u^C_L}_i \nu_{L\,j}\, S_3^{(-2/3)} - (V^* y_L)_{ij}\, \bar{u^C_L}_i \ell_{L\,j}\, S_3^{(1/3)} + \text{h.c.}$$

$b \to s\mu\bar{\mu}$



Minimal texture

$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{s\mu} & 0 \\ 0 & y_L^{b\mu} & 0 \end{pmatrix}$$

$$\mathcal{C}_9 = -\,\mathcal{C}_{10} = \frac{\pi v^2}{V_{ts}^* V_{tb}} \frac{y_L^{b\mu} (y_L^{s\mu})^*}{m_S^2}$$

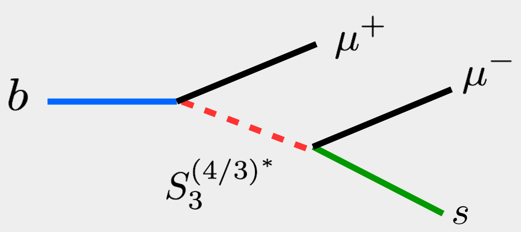
$$\boxed{R_{K^{(*)}} < R_{K^{(*)}}^{\text{SM}}}$$

explains anomaly

S_3 Scalar Triplet

$$S_3 \sim (\bar{\mathbf{3}}, \mathbf{3})_{1/3} \qquad \mathcal{L}_{S_3} = \boxed{- y_L^{ij}\, \overline{d^c_L}_i\, \nu_{L\,j}\, S_3^{(1/3)}} - \sqrt{2}\, y_L^{ij}\, \overline{d^c_L}_i\, \ell_{L\,j}\, S_3^{(4/3)} + \sqrt{2}\, (V^* y_L)_{ij}\, \overline{u^C_L}_i\, \nu_{L\,j}\, S_3^{(-2/3)} - \boxed{(V^* y_L)_{ij}\, \overline{u^C_L}_i\, \ell_{L\,j}\, S_3^{(1/3)}} + \text{h.c.}$$

$b \to s\mu\bar{\mu}$



Minimal texture

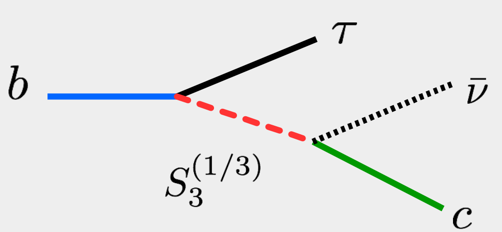
$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{s\mu} & 0 \\ 0 & y_L^{b\mu} & 0 \end{pmatrix}$$

$$\mathcal{C}_9 = -\mathcal{C}_{10} = \frac{\pi v^2}{V_{ts}^* V_{tb}} \frac{y_L^{b\mu} (y_L^{s\mu})^*}{m_S^2}$$

$$\boxed{R_{K^{(*)}} < R_{K^{(*)}}^{\text{SM}}}$$

explains anomaly

$b \to c\tau\bar{\nu}$



$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{s\tau} \\ 0 & 0 & y_L^{b\tau} \end{pmatrix}$$

$$g_{V_L} = -\frac{v^2\, y_L^{b\tau}\, (V y_L^*)_{c\nu}}{4 V_{cb}\, m_{S_3}^2} = -\frac{v^2}{4 m_{S_3}^2} \left[|y_L^{b\tau}|^2 + \frac{V_{cs}}{V_{cb}} y_L^{b\tau} (y_L^{s\tau})^* \right].$$

V-A structure but $\quad g_{V_L} < 0 \quad \boxed{R_{D^{(*)}} < R_{D^{(*)}}^{\text{SM}}}$

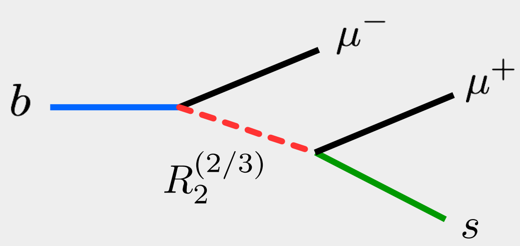
wrong direction

B-anomalies: R_2 scalar leptoquark

$R_2 \sim (\mathbf{3}, \mathbf{2})_{7/6}$

$$\mathcal{L}_{R_2} = y_R^{ij}(\overline{u}_{Li}\ell_{Rj})R_2^{(5/3)} + \boxed{y_R^{ij}(d_{Li}\ell_{Rj})R_2^{(2/3)}} + y_L^{ij}(\overline{u}_{Ri}\nu_{Lj})R_2^{(2/3)} - y_L^{ij}(u_{Ri}\ell_{Lj})R_2^{(5/3)}$$

$b \to s\mu\bar{\mu}$ tree-level solution



$$y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_R^{s\mu} & 0 \\ 0 & x_R^{b\mu} & 0 \end{pmatrix} \qquad \mathcal{C}_9 = \mathcal{C}_{10} = -\frac{\pi v^2}{2V_{tb}V_{ts}^*\alpha}\,\frac{y_R^{s\mu}(y_R^{b\mu})^*}{m_R^2}$$

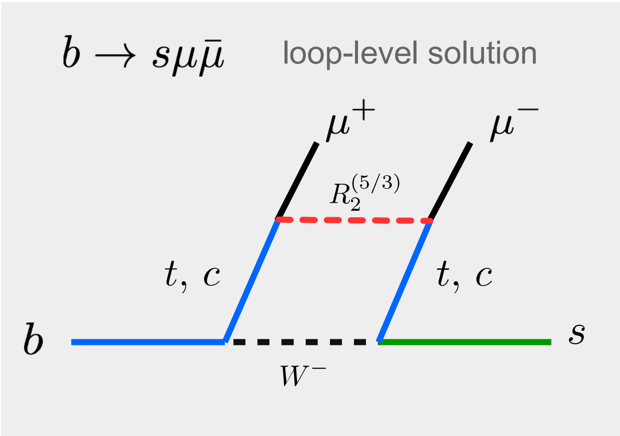
$$\boxed{R_{K^{(*)}} > R_{K^{(*)}}^{\mathrm{SM}}}$$

wrong direction

R_2 Scalar LQ

$$R_2 \sim (\mathbf{3}, \mathbf{2})_{7/6}$$

$$\mathcal{L}_{R_2} = \boxed{y_R^{ij} (\overline{u}_{Li} \ell_{Rj}) R_2^{(5/3)}} + y_R^{ij} (d_{Li} \ell_{Rj}) R_2^{(2/3)} + y_L^{ij} (\overline{u}_{Ri} \nu_{Lj}) R_2^{(2/3)} - y_L^{ij} (u_{Ri} \ell_{Lj}) R_2^{(5/3)}$$

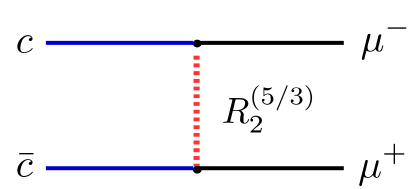


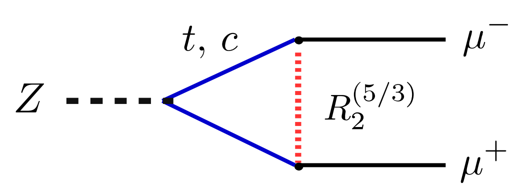
[Becirevic, Sumensari 2016]

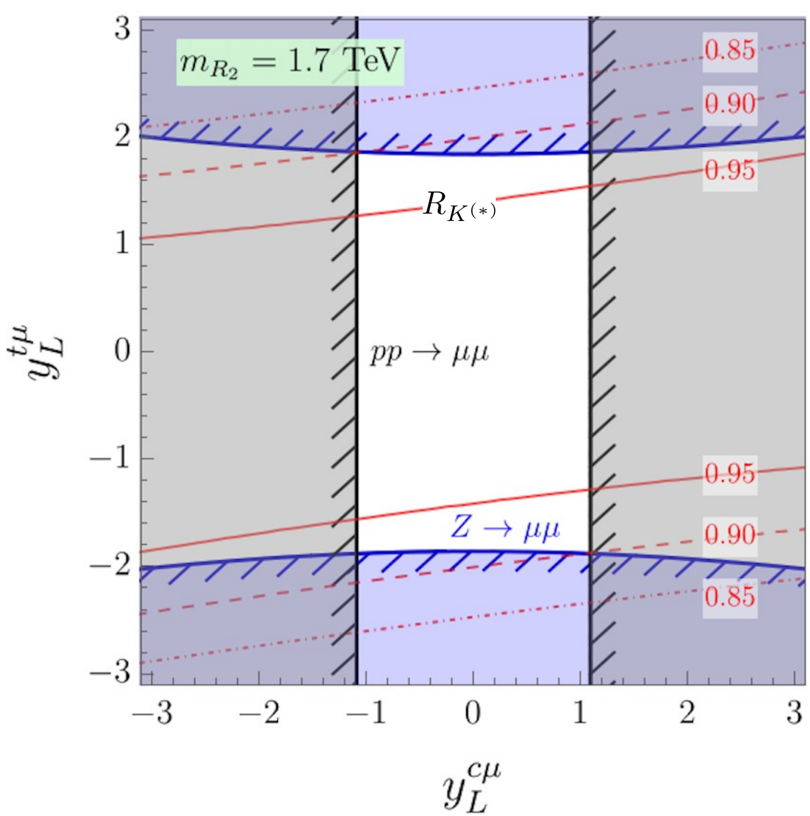
$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_R^{c\mu} & 0 \\ 0 & x_R^{t\mu} & 0 \end{pmatrix}$$

$$\boxed{R_{K^{(*)}} < R_{K^{(*)}}^{\mathrm{SM}}}$$

Unfavoured by
Drell-Yan + Z-pole





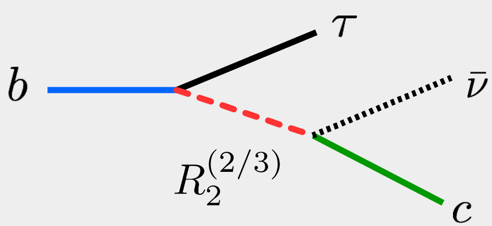


R_2 Scalar LQ

$$R_2 \sim (\mathbf{3}, \mathbf{2})_{7/6}$$

$$\mathcal{L}_{R_2} = y_R^{ij} (\overline{u}_{Li} \ell_{Rj}) R_2^{(5/3)} + \boxed{y_R^{ij} (d_{Li} \ell_{Rj}) R_2^{(2/3)}} + \boxed{y_L^{ij} (\overline{u}_{Ri} \nu_{Lj}) R_2^{(2/3)}} - y_L^{ij} (u_{Ri} \ell_{Lj}) R_2^{(5/3)}$$

$b \to c \tau \bar{\nu}$



$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

$$y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}$$

$$g_{S_L} = 4 g_T = \frac{v^2}{4V_{cb}} \frac{y_L^{c\tau} (y_R^{b\tau})^*}{m_R^2}$$

$$\boxed{R_{D^{(*)}} > R_{D^{(*)}}^{\mathrm{SM}}}$$

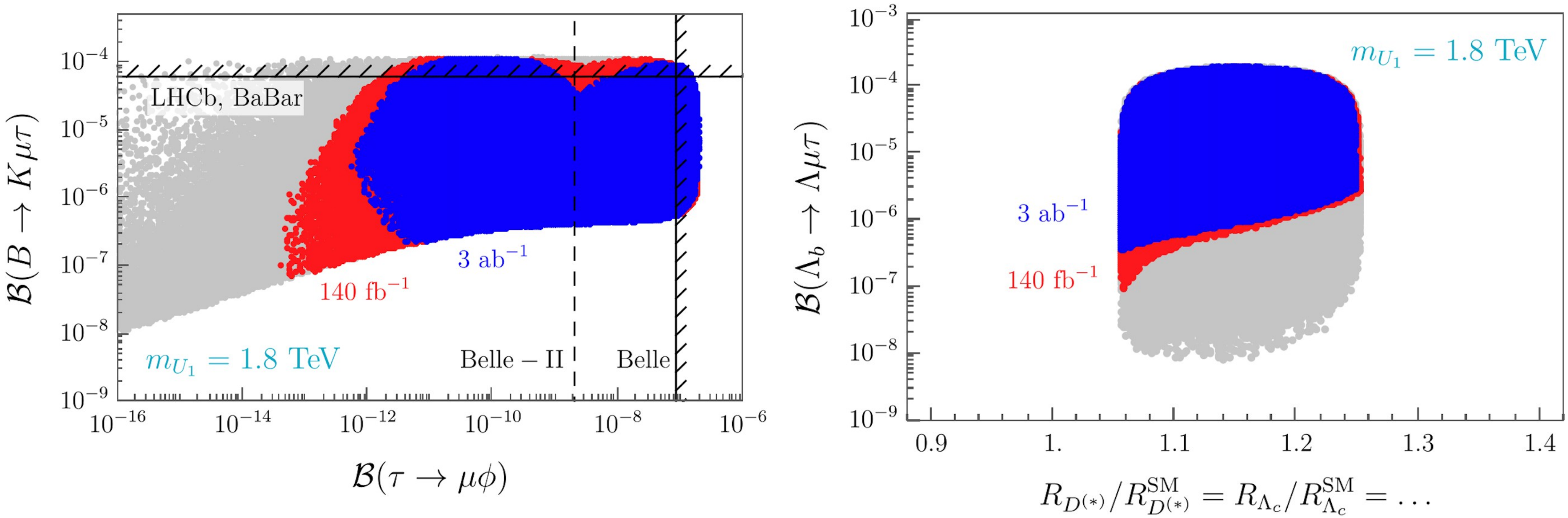
$$y_L^{c\tau} \in \mathbb{R} \qquad y_L^{b\tau} \in \mathbb{C}$$

Scalar + Tensor solution!

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

Non-V-A solution to anomaly!

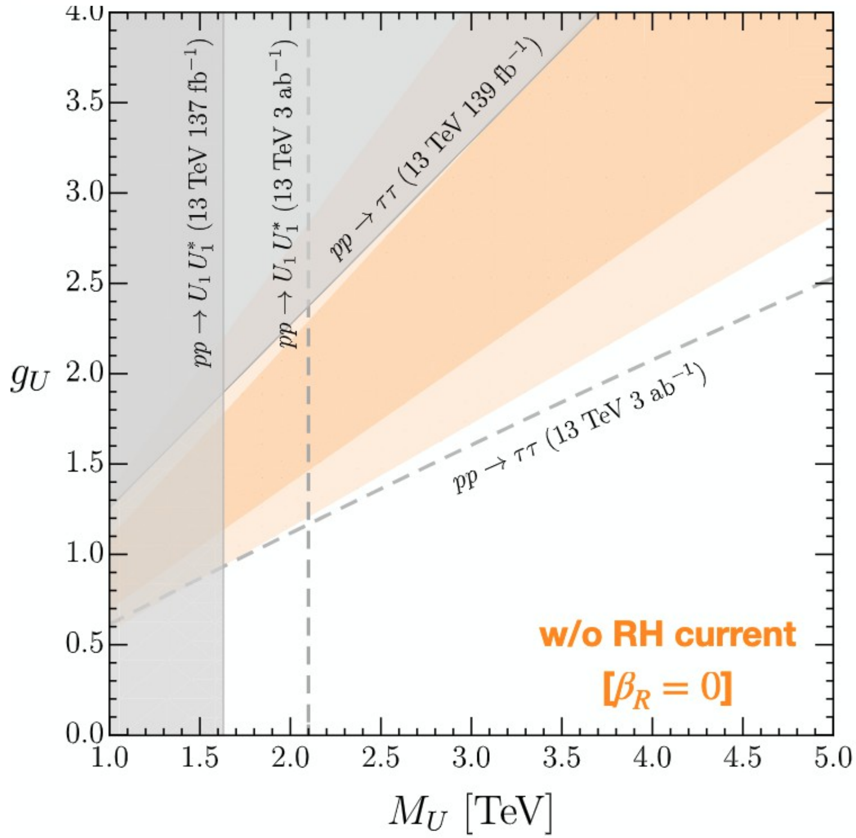
- Predictions for LFV low-energy observables for U_1

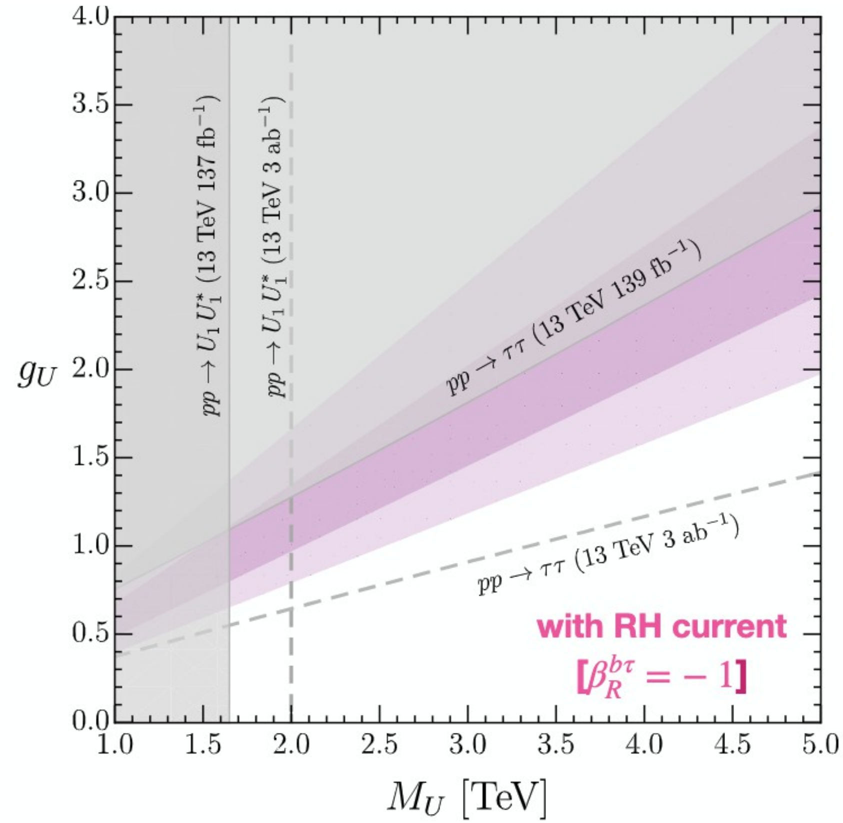


Angelescu, Becirevic, DAF, Jaffredo, Sumensari, [2021]

LHC Di-Taus tails push lower bounds on both LFV observables!

Model Potentially within reach at LHCb & Belle 2!





[Cornella et al., 2103.16558]

[$pp \to \tau\tau$ for U_1 originally proposed in Faroughy, Greljo, Kamenik, 1609.07138]

GUT-inspired leptoquarks

- 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]

R_2 ↓ for $R_{D^{(*)}}$ $\qquad$ S_3 ↓ for $R_{K^{(*)}}$

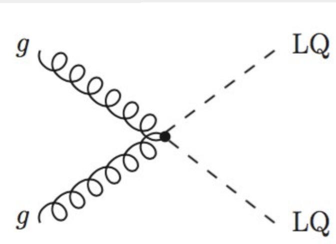
Good Benchmark:

- R_2 with ~O(1) Yukawa couplings

Couples to both **charm** and **bottom**

$m_R \sim 800$ GeV

- LQs decaying into tauonic channels



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

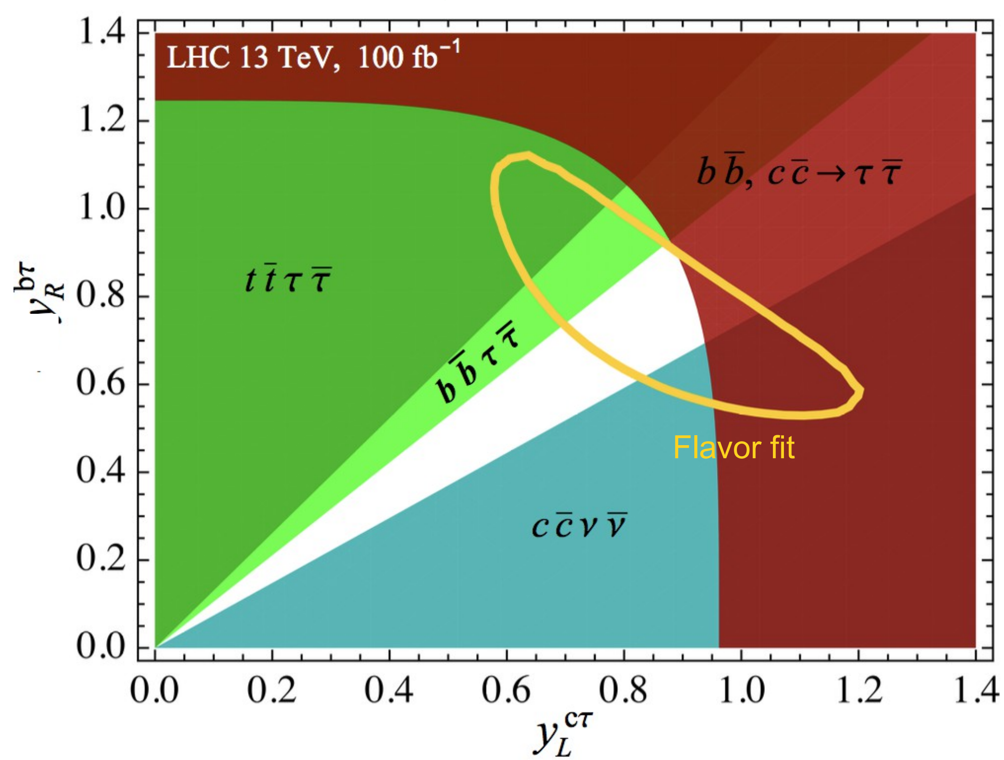
$$R_2^{\frac{5}{3}} \to \tau t,\ \tau c$$

- LQ pair production & DY di-Tau searches

Model can be put to test at the LHC!

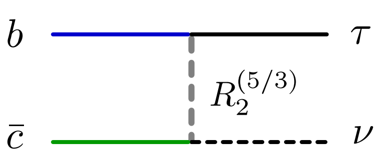
Complementarity:
Flavor obs. & high-p_T di-Taus

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

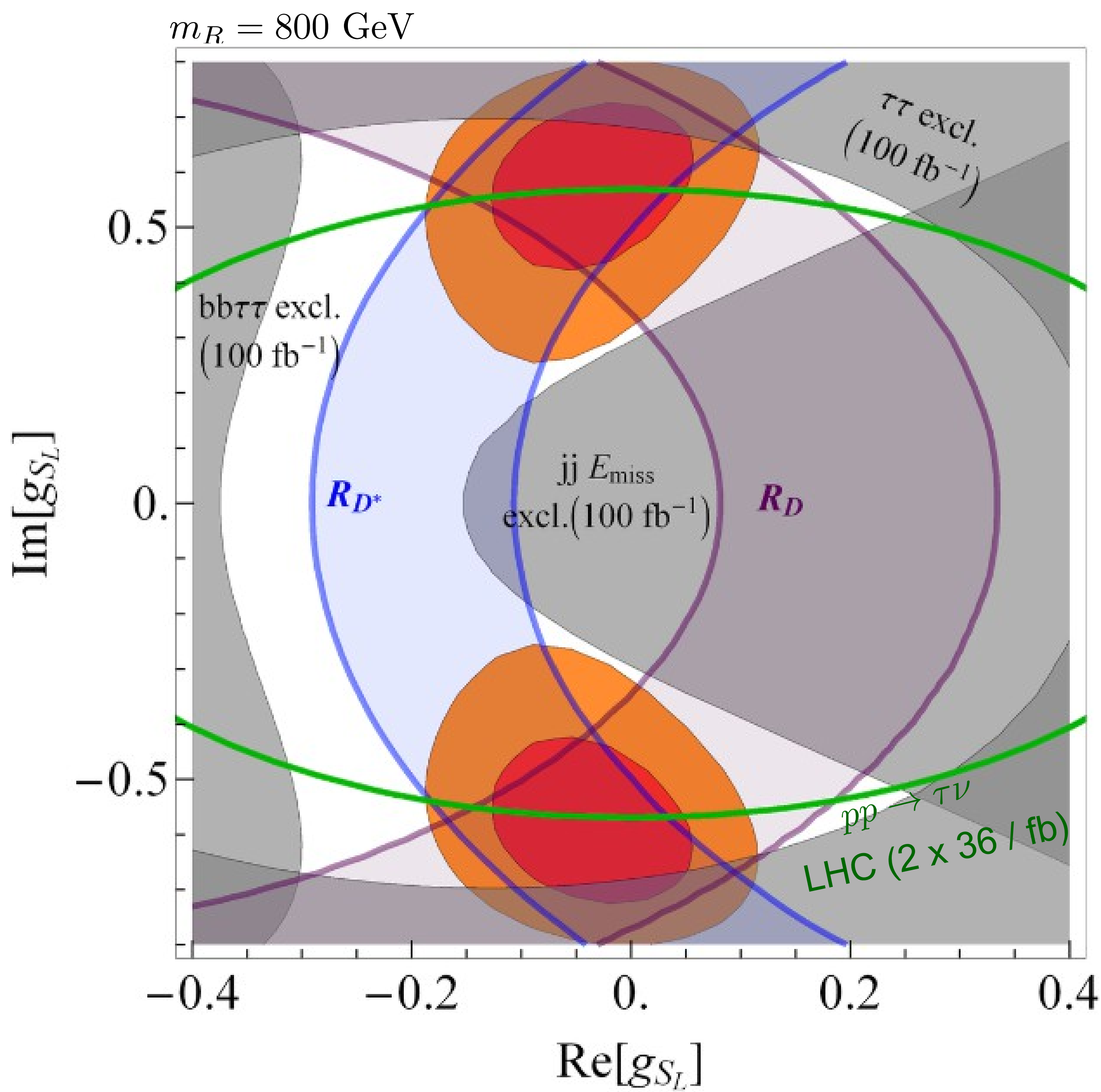


Mono-Tau searches

$pp \to \tau\nu + X$



Greljo,Camalich, Ruiz-Alvarez '18



LFV low-energy observables for other LQ models: