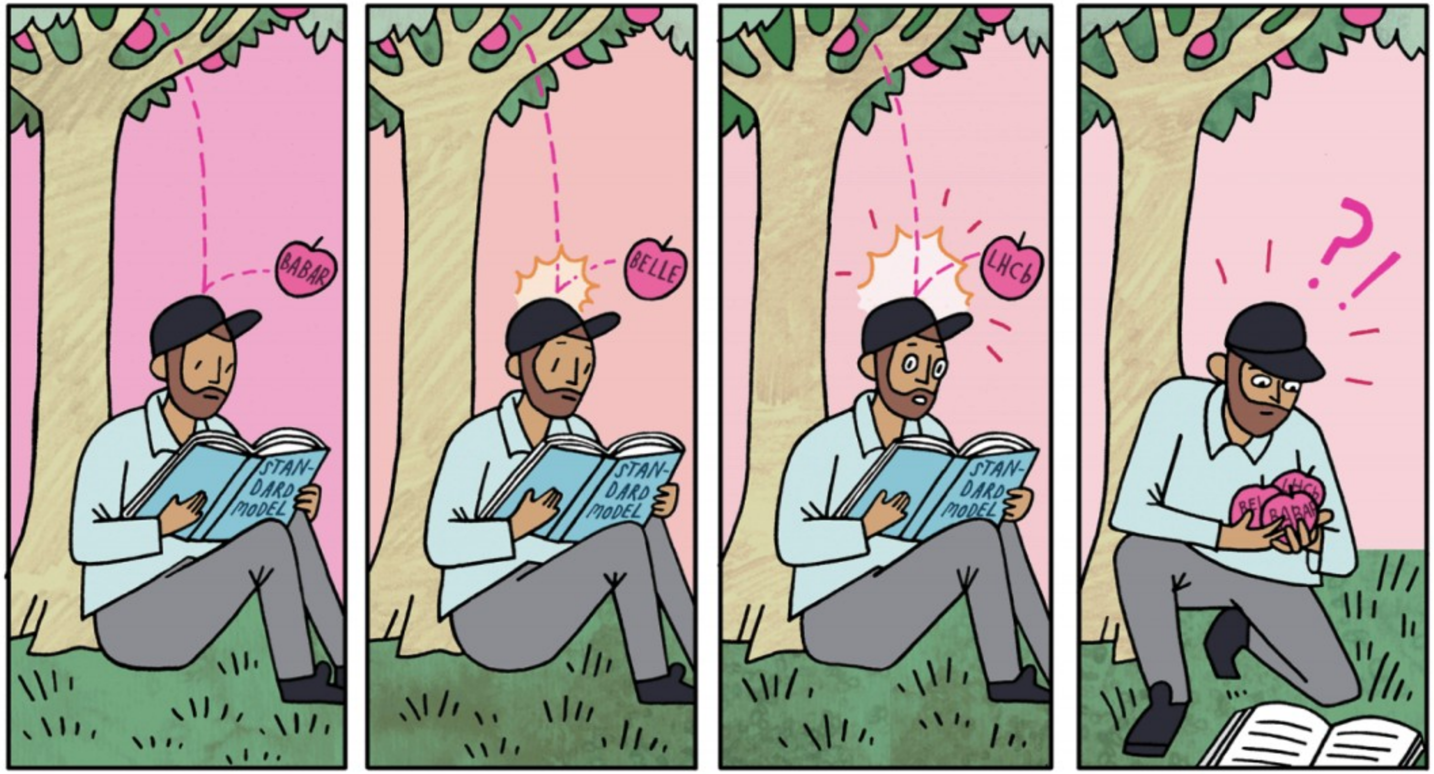
A Top view of the B-anomalies



Artwork by Sandbox Studio, Chicago with Corinne Mucha

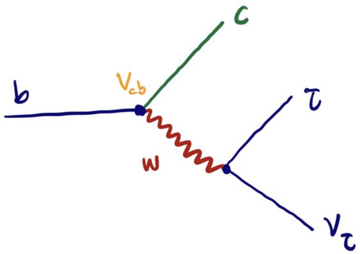
Darius A. Faroughy

Universität Zürich UZH

Top LHC France workshop, IP21 Lyon, 9-10 May 2022

A Decade of B-meson Anomalies

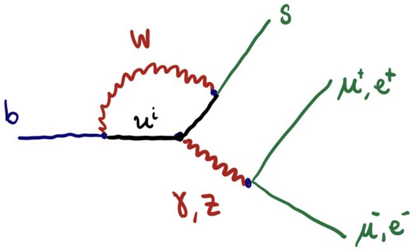
- Evidence of **Lepton Flavor Universality Violation** in semi-leptonic B-decays:



$b \to c$

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

$\sim 3\sigma$ excess



$b \to s$

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

$\sim 3\sigma$ deficit

BABAR

LHCb

Belle II

Multiple “B-anomalies” across different experiments.
All compatible with each other!

$$\mathrm{Br}(B_s \to \mu\mu)\,,\;\; P_5'\,,\;\; \ldots$$

- Theoretical status:

● Effective opearators and Mediators have been classified.

● UV model building in progress… lots of pheno still unexplored.

● Anomaly Fever? $(g-2)_\mu\,,\;\; m_W\,,\;\; V_{us}\,,\;\ldots$

- <u>This talk</u>: brief overview of a few NP models leading to interesting top-physics at the LHC

EFT: neutral currents b→s

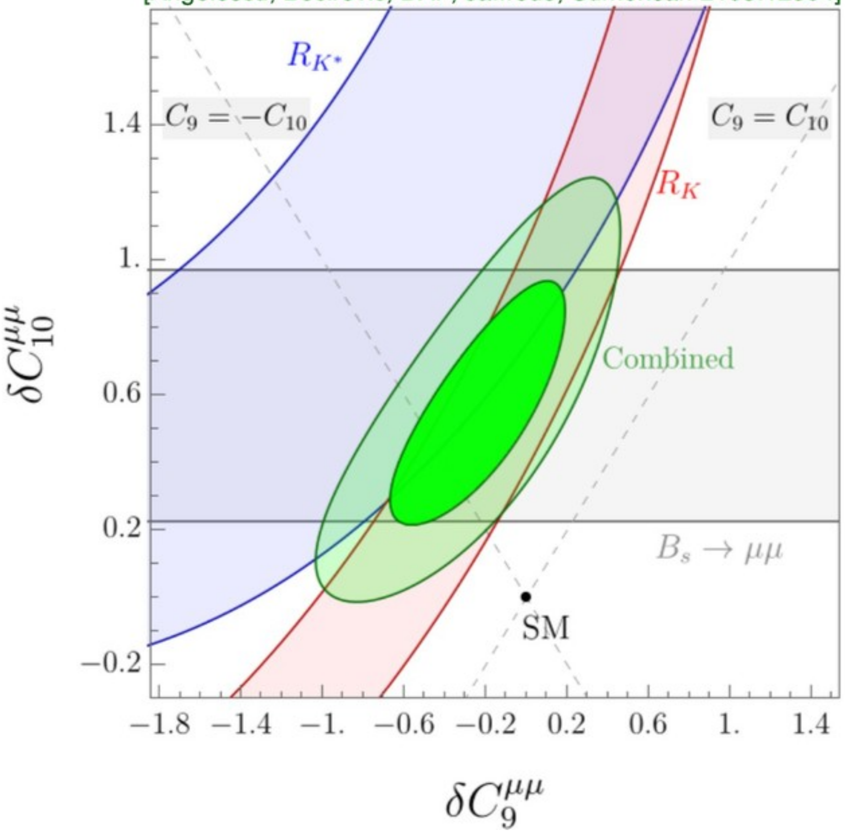
$$\mathcal{L}_{b\to s\ell\bar{\ell}} = \frac{4\,G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i \mathcal{C}_i \mathcal{O}_i^\ell + \text{h.c.}$$

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

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

- Conservative fit to “clean” observables: $R_K\,,\ R_{K^*}\,,\ \mathcal{B}(B_s\to\mu^+\mu^-)$

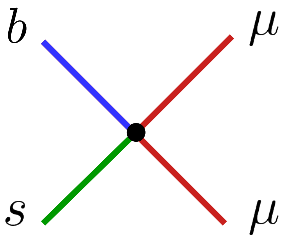
[Angelescu, Becirevic, DAF, Jaffredo, Sumensari 2103.12504]



V-A solution: $\delta C_9^{\mu\mu} = -\delta C_{10}^{\mu\mu}$

NP prefered over SM 4.6σ

Characteristic scale:



$$\frac{1}{\Lambda^2} \sim \frac{1}{(40\,\text{TeV})^2}$$

Large scale!

EFT: charged currents b→c

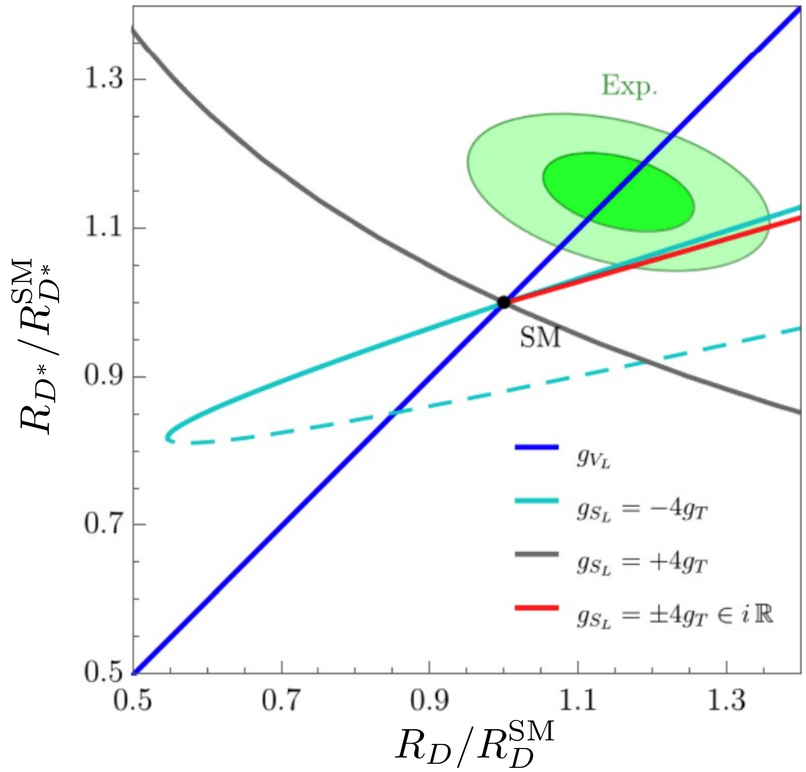
$$\mathcal{L}_{b\to c\tau\nu} = -2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})\,\mathcal{O}_{V_L} + g_{S_L}\,\mathcal{O}_{S_L} + g_T\,\mathcal{O}_T\Big]$$

$$\mathcal{O}_{V_L} = (\bar{c}_L\gamma^\mu b_L)\,(\bar{\tau}_L\gamma^\mu\nu_\tau)$$

$$\mathcal{O}_{S_L} = (\bar{c}_R b_L)\,(\bar{\tau}_R\nu_\tau)$$

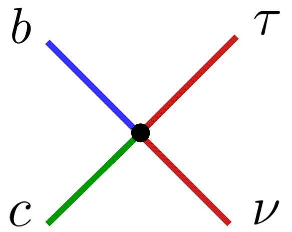
$$\mathcal{O}_T = (\bar{c}_R\sigma^{\mu\nu}b_L)\,(\bar{\tau}_R\sigma^{\mu\nu}\nu_\tau)$$

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



- one single operator: V - A
- two operators: Scalar + Tensor

Characteristic scale:

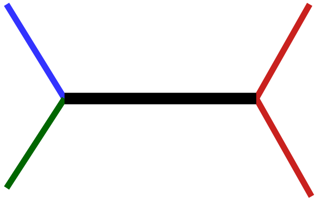


$$\frac{1}{\Lambda^2}\sim\frac{1}{(3\,\mathrm{TeV})^2}$$

Good physics case for High-pT LHC!!

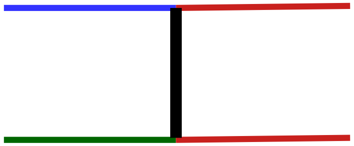
Which Mediators? b→s anomalies

Vector singlet



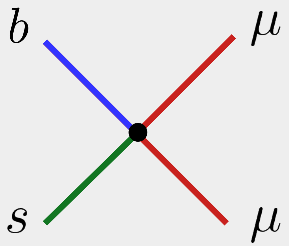
$Z' \, (\mathbf{1}, \mathbf{1}, 0)$

Vector Leptoquarks



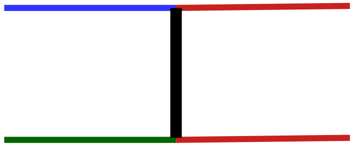
$U_1 \, (\mathbf{3}, \mathbf{1}, 2/3)$

$U_3 \, (\mathbf{3}, \mathbf{3}, 2/3)$



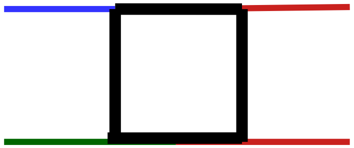
$\Lambda \sim \mathcal{O}(1) - \mathcal{O}(100) \ \text{[TeV]}$

Scalar Leptoquarks



$S_3 \, (\mathbf{3}, \mathbf{3}, -1/3)$

In the Loop



$Z' \, (\mathbf{1}, \mathbf{1}, 0)$, VL fermions

$S_1 \, (\mathbf{3}, \mathbf{1}, -1/3) \, , \; R_2 \, (\mathbf{3}, \mathbf{2}, 7/3)$ ...

Z' models - tree level

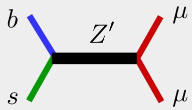
$$\mathcal{L}_{Z'} = g^q_{ij}\,\bar{q}_i \not{Z}' q_j + g^\ell_{ij}\,\bar{\ell}_i \not{Z}' \ell_j + g^e_{ij}\,\bar{e}_i \not{Z}' P_R\, e_j$$

$$q_i = \begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix} \qquad \ell_i = \begin{pmatrix} \nu^i_L \\ e^i_L \end{pmatrix}$$

minimal texture: $g^q = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix}$ $\quad g^\ell = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$

$$\begin{cases} g^e = 0 \implies \mathcal{C}_9 = -\mathcal{C}_{10} & \text{'V-A' solution} \\ g^\ell = g^e \implies \mathcal{C}_9 & \text{'Vectorial' solution} \end{cases}$$

- Pheno:

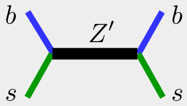


$$\mathcal{O}^{(1)}_{lq} = (\bar{q}_2\gamma^\mu q_3)(\bar{\ell}_2\gamma^\mu \ell_2)$$
$$\supset (\bar{s}_L\gamma^\mu b_L)(\bar{\mu}_L\gamma^\mu \mu_L)$$

$$\frac{1}{\Lambda^2} = \frac{g^q_{bs}\, g^\ell_{\mu\mu}}{M^2_{Z'}}$$

B-decays: $\boxed{b \to s\mu^+\mu^-}$ $\quad b \to s\bar{\nu}_\mu\nu_\mu$

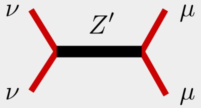
High-pT colliders: $pp \to \mu^+\mu^-$ resonance / tail



$$\mathcal{O}^{(1)}_{qq} = (\bar{q}_2\gamma^\mu q_3)(\bar{q}_2\gamma^\mu q_3)$$
$$\supset (\bar{s}_L\gamma^\mu b_L)(\bar{s}_L\gamma^\mu b_L)$$

$$\frac{1}{\Lambda^2} = \frac{(g^q_{bs})^2}{2M^2_{Z'}}$$

Meson-mixing $B^0_s - \overline{B^0_s}$

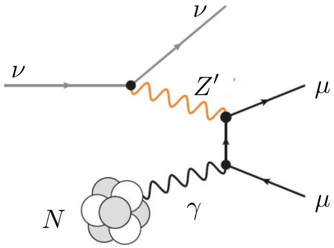


$$\mathcal{O}_{ll} = (\bar{\ell}_2\gamma^\mu \ell_2)(\bar{\ell}_2\gamma^\mu \ell_2)$$
$$\supset (\bar{\nu}_L\gamma^\mu \nu_L)(\bar{\mu}_L\gamma^\mu \mu_L)$$

$$\frac{1}{\Lambda^2} = \frac{(g^\ell_{\mu\mu})^2}{2M^2_{Z'}}$$

Neutrino tridents

$\nu_\mu N \to \nu_\mu N \mu^+\mu^-$



Non-universal abelian models

- Gauge linear combinations of SM accidental symmetries.

$$\begin{tikzcd}\mathcal{G}_{\rm SM} \times U(1)_{aL_\mu + X_3} \arrow[d, "\langle\Phi\rangle \neq 0"] \\ \mathcal{G}_{\rm SM}\end{tikzcd}$$

$$\begin{cases} a \in \mathbb{Z},\, \mathbb{Q} \\ L_\mu \ : \ \text{2}^{\text{nd}} \text{ gen lepton number} \\ X_3 \ : \ \text{3rd gen accidental symmetry} \end{cases}$$

$U(1)_{L_\tau - L_\mu}$

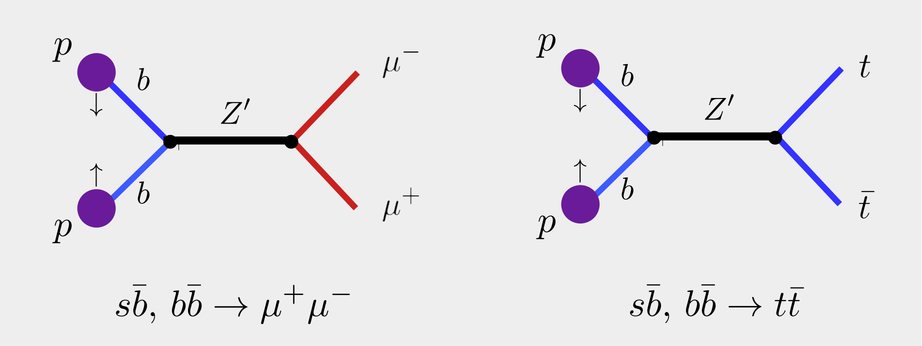
$U(1)_{B_3 - L_\mu}$

$U(1)_{Y_3}$

$U(1)_{Y_3 - \frac{a}{6}(L_\tau - L_\mu)}$

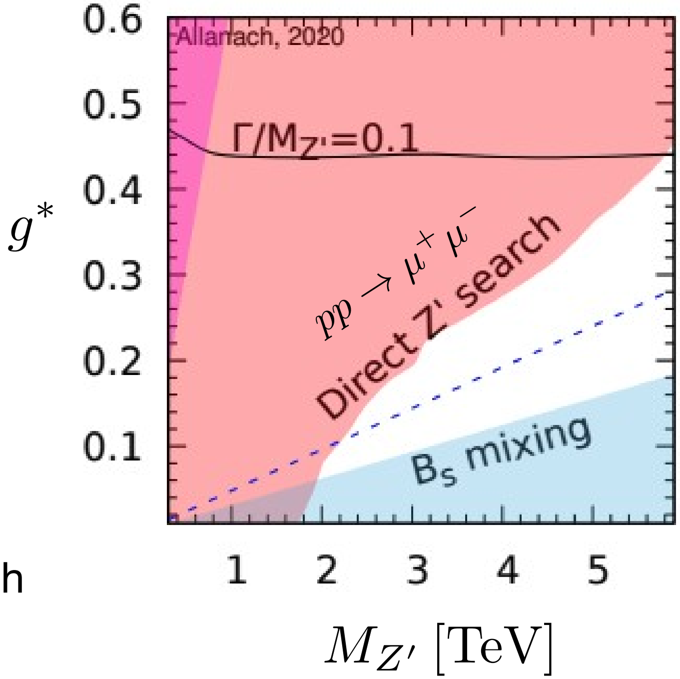
Altmannshofer et al [1403.1269, 1909.02021]
Alonso et al, [1705.03858]
Davighi, Alllanach [1809.01158]
Allanach [2009.02197]
Davighi [2105.06918] . . .

$$U(1)_{B_3 - L_\mu} \qquad g^q \approx g^* \begin{pmatrix} 0 & 0 & 0 \\ 0 & s_\theta^2 & s_\theta \\ 0 & s_\theta & 1 \end{pmatrix} \qquad s_\theta \sim \mathcal{O}(|V_{ts}|)$$



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

PDF suppressed



- **Resonances in top-pairs** are typical predictions of such models, but dimuons are more powerful probes...

Anomalies in Bottom from NP in tops

- Assumptions [SMEFT]:

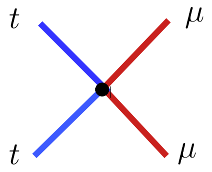
Top-philic New Physics → t_R

LFUV with dominant couplings to 2nd gen.

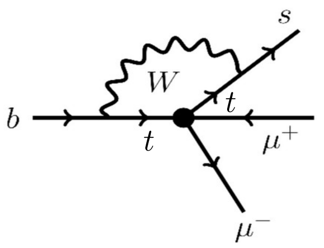
Camargo-Molina, Celis, DAF [1805.04917]

$$\mathcal{O}_{lu} = (\bar{t}_R\gamma^\mu t_R)(\bar{\ell}_2\gamma^\mu \ell_2)$$

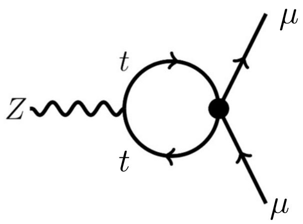
$$\mathcal{O}_{eu} = (\bar{t}_R\gamma^\mu t_R)(\bar{\mu}_R\gamma^\mu \mu_R)$$



- Low-energy pheno: good fit to data

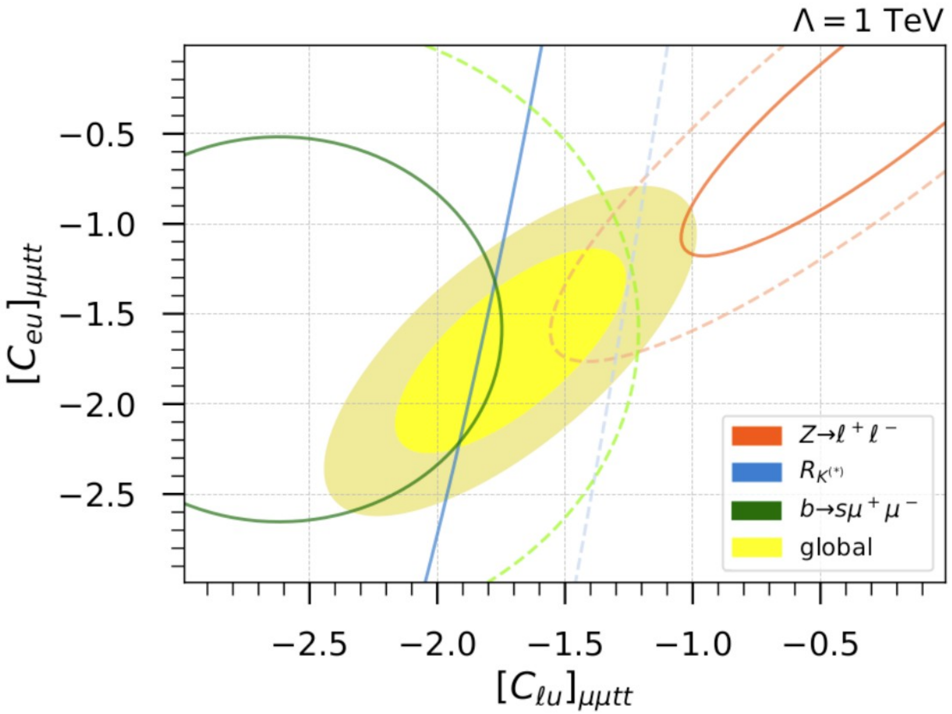


$b \to s\mu^+\mu^-$



Z-pole (LEP)

- 🟢 Minimal Flavor Vioaltion (MFV)
- 🟢 Predicts V-A couplings in quarks
- 🟢 No B-meson mixing
- 🟡 Needs quite large couplings!
- 🔴 Some tension in Z-pole obs.



Prefered region: $\mathcal{C}_{\ell u} \sim \mathcal{C}_{eu} < 0$

vectorial muons

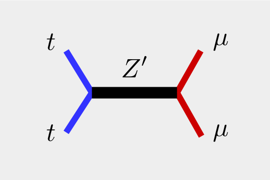
Top-philic Force

$$\mathcal{L}_{int} = g^u_{ij}\,\bar{u}_i \not{Z}' P_R\, u_j + g^\ell_{ij}\,\bar{\ell}_i \not{Z}'\,\ell_j + g^e_{ij}\,\bar{e}_i \not{Z}' P_R\, e_j$$

$$g^u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix} \qquad g^\ell = g^e = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Kamenik, Soreq, Zupan [1704.06005] Fox, Low, Zhang [1801.03505]
Camargo-Molina, Celis, DAF [1805.04917]

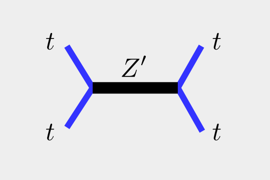
- Exotic top-quark signals at LHC:



$pp \to t\bar{t}Z' \to t\bar{t}\mu^+\mu^-$

recast dimuon resonance search

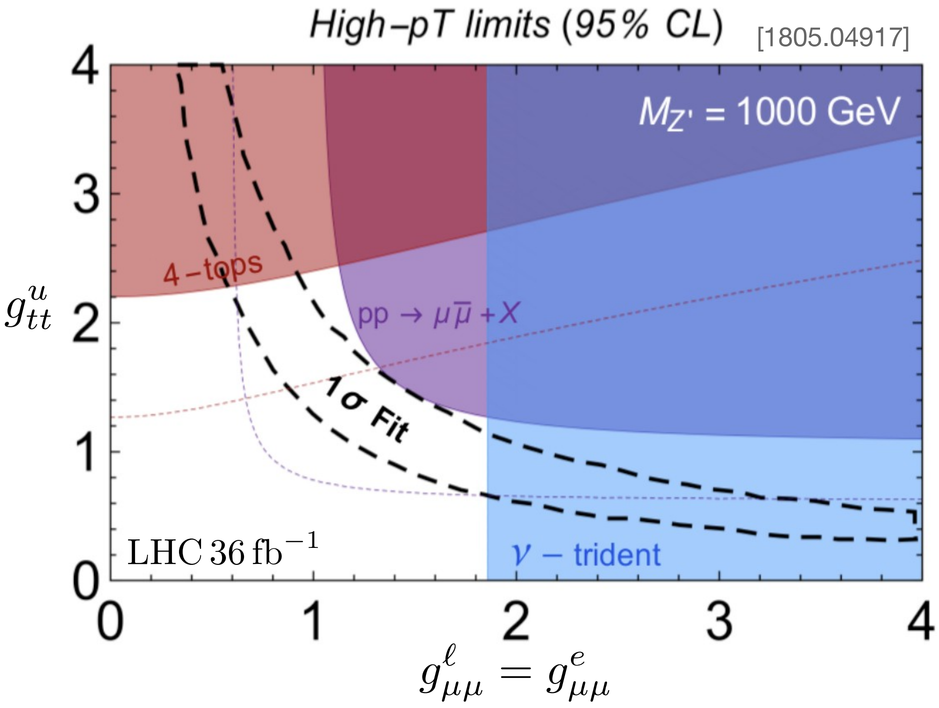
ATLAS 1707.02424



$pp \to t\bar{t}Z' \to t\bar{t}t\bar{t}$

limits on SM 4-top cross-section

CMS 1710.10614



[1805.04917]

- UV completion: $\mathcal{G}_{\rm SM} \times {\rm U}(1)_{L_\mu - L_\tau}$

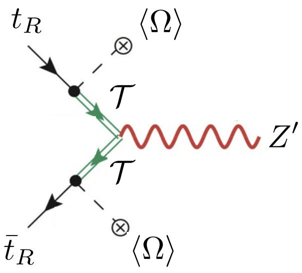
$t_R \sim (\mathbf{3}, \mathbf{1}, 2/3, 0)$

$\mathcal{T} \sim (\mathbf{3}, \mathbf{1}, 2/3, +1)$ vector-like top

$\Omega \sim (\mathbf{1}, \mathbf{1}, 1, +1)$

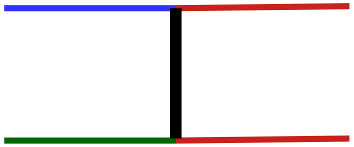
$$\mathcal{L}_{\rm yuk} \supset -y^i_{\mathcal{T}}\,\overline{\mathcal{T}}_L\,\Omega\,u^i_R - m_{\mathcal{T}}\overline{\mathcal{T}}\mathcal{T}$$

$$y^3_{\mathcal{T}} \gg y^2_{\mathcal{T}}, y^1_{\mathcal{T}}$$

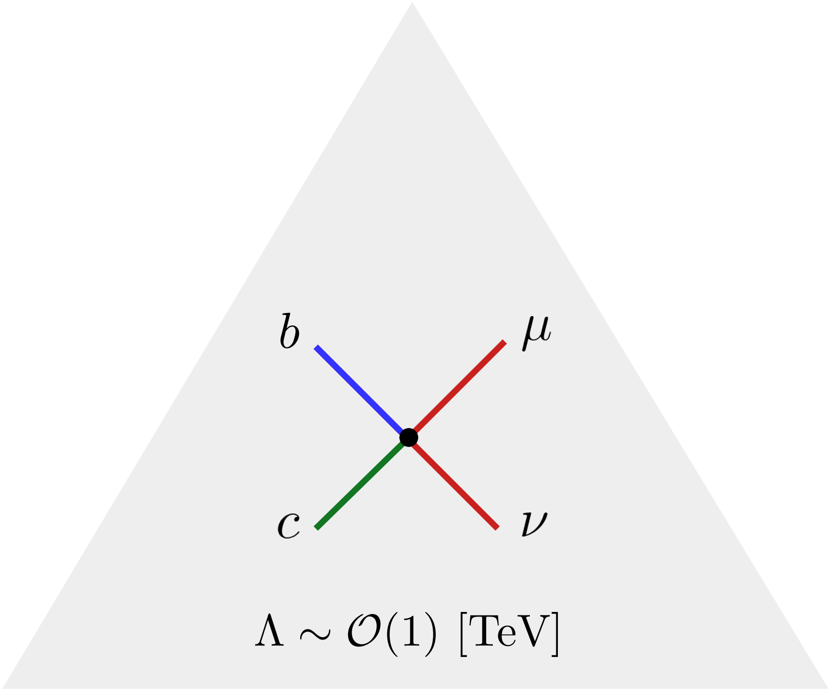


Which Mediators? b→c anomalies

Scalar Leptoquark

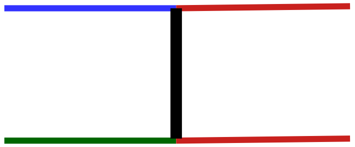


$S_1\,(\mathbf{3},\mathbf{1},-1/3)$



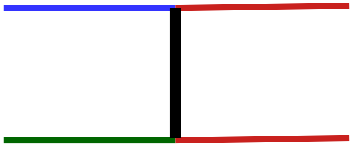
$\Lambda \sim \mathcal{O}(1)\ [\mathrm{TeV}]$

Scalar Leptoquark



$R_2\,(\mathbf{3},\mathbf{2},1/6)$

Vector Leptoquark



$U_1\,(\mathbf{3},\mathbf{1},2/3)$

$\cancel{W}'\,(\mathbf{1},\mathbf{3},0)\ \ \cancel{H}'\,(\mathbf{1},\mathbf{2},1/2)$

Color singlets excluded
by direct searches

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

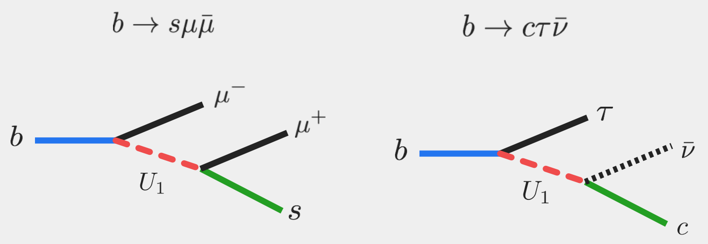
Combined solutions: Leptoquarks

Angelescu, Becirevic, DAF, Sumensari [1808.08179]

	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	$U_1 = (\mathbf{3},\mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3},\mathbf{3})_{2/3}$	✓	✗	✗

Butazzo et al [1706.07808]

Only state that can solve both B-anomalies!



$$m_U \sim \mathcal{O}(1)\ \text{TeV}$$

"SM Yukawa-like" couplings to fermions.

- U₁ vector LQ: a UV-completion necessary: **4321** gauge models (Pati-Salam group)

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

Georgi, Nakai [1606.05865]
Di Luzio et al [1708.08450,1808.00942]
Bordone et al [1712.01368]
Greljo,Stefanek [1802.04274]

- No single scalar LQ solves both neutral & charged B-anomlies
  - 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]

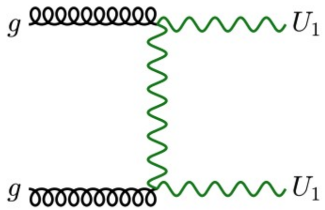
Vector leptoquark $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$

$$\boxed{\mathcal{L}_U^{\rm int} = \frac{g_U}{\sqrt{2}} \left(U_1^\mu J_\mu^U + \text{h.c.} \right)}$$

$$J_\mu^U = \beta_L^{i\alpha} \left(\bar{q}_L^i \gamma_\mu \ell_L^\alpha \right) + \beta_R^{i\alpha} \left(\bar{d}_R^i \gamma_\mu e_R^\alpha \right)$$

Broken $U(2)^5$ flavor symmetry: $|\beta_L^{d\tau, s\mu}| \ll |\beta_L^{s\tau, b\mu}| \ll \beta_L^{b\tau} = 1$

- LQ pair production (QCD):



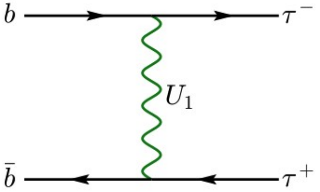
$$U_1 \to t\bar{\nu}\,,\;\; b\tau$$

$$\text{Br}(U_1 \to t\nu) \approx 0.5$$

$$pp \to U_1^+ U_1^- \to b\tau\, t\nu$$

2012.04178

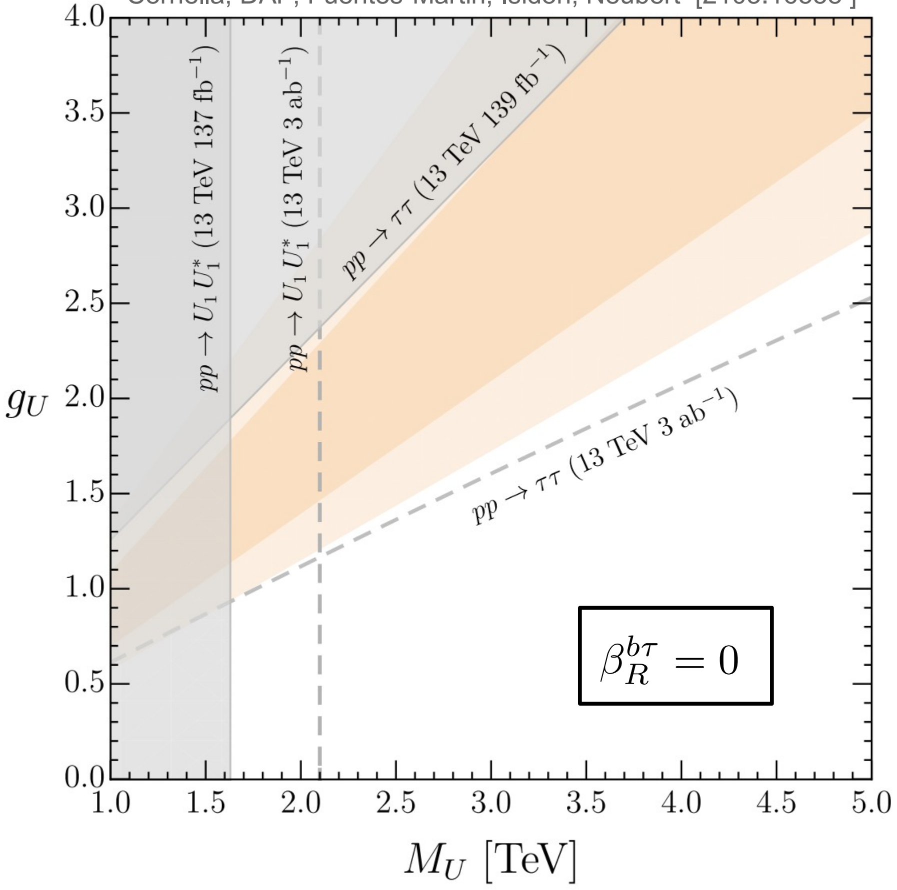
- Drell-Yan t-channel exchange: $\tau\tau$-tails



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

2002.12223
CMS PAS HIG-21-001

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



“4321” gauge models

- Flavor non-universal Gauge group:

$$\overbrace{\underbrace{SU(4)_3 \times SU(3)_{1+2}}_{SU(3)_c} \times SU(2)_L \times U(1)_X}^{U(1)_Y} \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\mathrm{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$$

$$Z' \sim (\mathbf{1}, \mathbf{1}, 0)$$

$$G' \sim (\mathbf{8}, \mathbf{1}, 0)$$

coloron!

$$SU(4) \sim \left(\begin{array}{c:c} G^a & U^\alpha \\ \hdashline (U^\alpha)^* & Z' \end{array}\right)$$

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
q_L^i	**1**	**3**	**2**	$1/6$
u_R^i	**1**	**3**	**1**	$2/3$
d_R^i	**1**	**3**	**1**	$-1/3$
ℓ_L^i	**1**	**1**	**2**	$-1/2$
e_R^i	**1**	**1**	**1**	-1
ψ_L	**4**	**1**	**2**	0
$\psi_R^\pm$	**4**	**1**	**1**	$\pm 1/2$
χ_L^i	**4**	**1**	**2**	0
χ_R^i	**4**	**1**	**2**	0
H	**1**	**1**	**2**	$1/2$
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	$-1/2$
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	$1/6$
Ω_{15}	**15**	**1**	**1**	0

$i = 1, 2$

1st & 2nd families

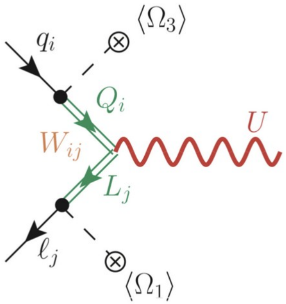
3rd family

Vectorlike

4321 SSB scalars

$$\psi_L = \begin{pmatrix} q_L^3 \\ \ell_L^3 \end{pmatrix} \qquad \psi_R^+ = \begin{pmatrix} t_R \\ \nu_R \end{pmatrix} \qquad \psi_R^- = \begin{pmatrix} b_R \\ \tau_R \end{pmatrix}$$

$$\chi_i = \begin{pmatrix} Q_i \\ L_i \end{pmatrix}$$

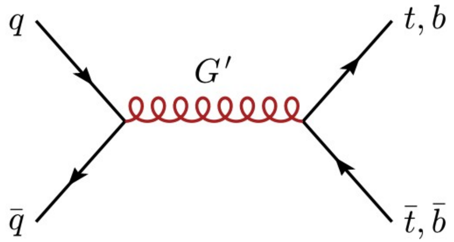


Adjoint of SU(4) $\mathcal{L}_{\mathrm{yuk}} \supset y_{15}\, \bar{\psi}_L \Omega_{15} \chi_R + y'_{15}\, \bar{\chi}_L \Omega_{15} \chi_R$

4321 Coloron $G' = (\mathbf{8}, \mathbf{1}, 0)$

$$\mathcal{L}_{G'}^{\rm int} = g_{G'}\, G'^{\,a\,\mu}\, (\kappa_q^{ij}\, \bar{q}_L^i\, T^a\, \gamma_\mu\, q_L^j + \kappa_u^{ij}\, \bar{u}_R^i\, T^a\, \gamma_\mu\, u_R^j + \kappa_d^{ij}\, \bar{d}_R^i\, T^a\, \gamma_\mu\, d_R^j)$$

Di Luzio et al. [1808.00942]
Baker et al. [1901.10480]
Cornella et al. [2103.16558]



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

$pp \to G' \to b\bar{b}$

(broad resonances)

- Recast of dijet & ditop searches

CMS-PAS-TOP-18-013
[1801.02052]
[1906.0320]

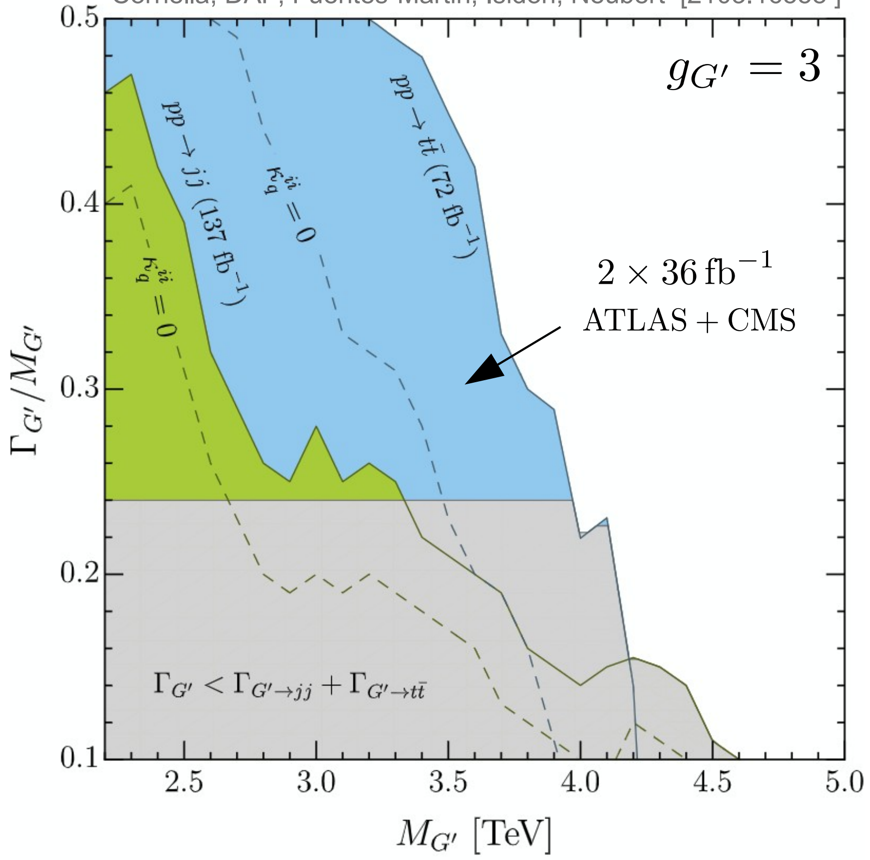
- broad $pp \to jj$ resonance

- Unfolded inv. Mass spectrum

$d\sigma/dm_{t\bar{t}}$

Ditop searches provide the best direct limits on the scale of the 4321 model!

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



Vector-like fermions

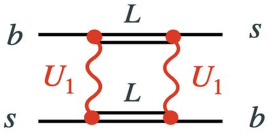
4321 vector-like fermion $\chi = (Q, L)^T \sim (\mathbf{4}, \mathbf{1}, \mathbf{2}, 0)$

$$\begin{cases} Q \sim (\mathbf{3}, \mathbf{2}, 1/6) & Q = \begin{pmatrix} U \\ D \end{pmatrix} \\ L \sim (\mathbf{1}, \mathbf{2}, -1/2) & L = \begin{pmatrix} N \\ E^{\pm} \end{pmatrix} \end{cases}$$

Di Luzio et al. [1808.00942]

Important 4321 prediction:

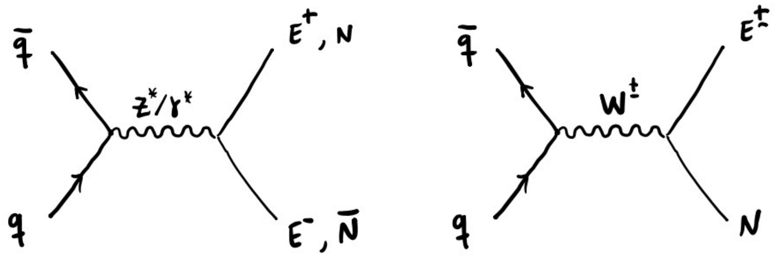
$m_L \sim 1 - 2\,\mathrm{TeV}$

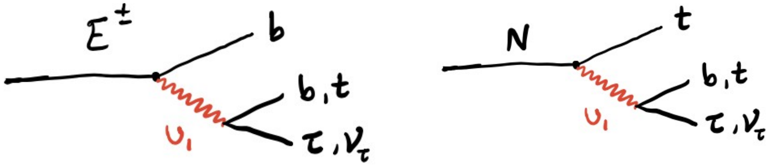


$B_s^0 - \overline{B_s^0}$

vector-like lepton needs to be light!

- These heavy leptons can be pair production at LHC via EW interactions $pp \to E^+E^-,\, N\bar{N},\, E^{\pm}N$





3-body decay modes into 3rd gen.

- Very rich top-quark pheno!

Multi-top Signatures at LHC

$pp \to E^+E^- \to b\bar{b}b\bar{b}\,\tau\tau$

$pp \to E^+N \to t\bar{b}b\bar{b}\,\tau\tau$

$pp \to E^+E^- \to t\bar{t}b\bar{b}\,\nu\nu$

$pp \to N\bar{N} \to t\bar{t}b\bar{b}\,\tau\tau$

$pp \to N\bar{N} \to t\bar{t}t\bar{b}\,\tau\nu$

$pp \to N\bar{N} \to t\bar{t}t\bar{t}\,\nu\nu$

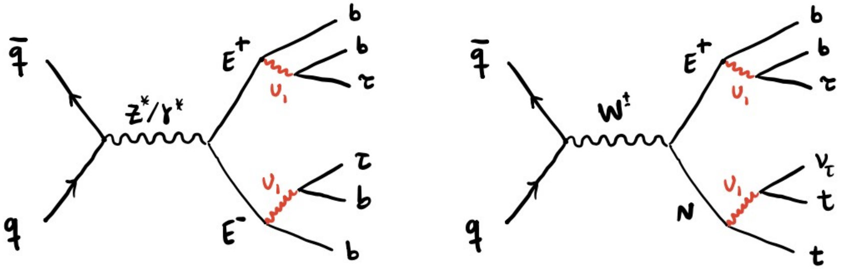
New search for vector-like leptons

Cormier, DAF, Fuentes-Martin, Mikuni [CMS-PAS-B2G-21-004]

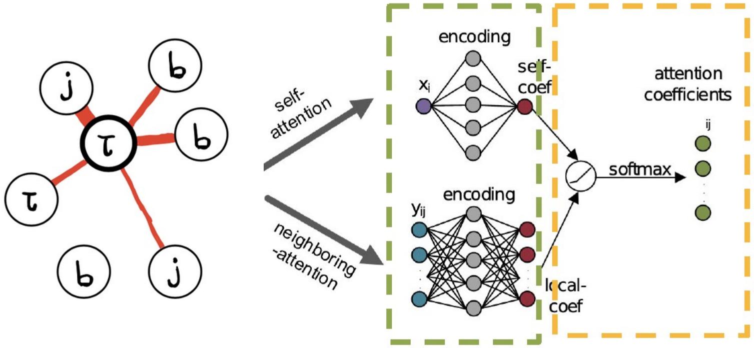
- Targets all-hadronic modes $t \to bqq, \;\; \tau \to qq\nu_\tau$

Event selection:

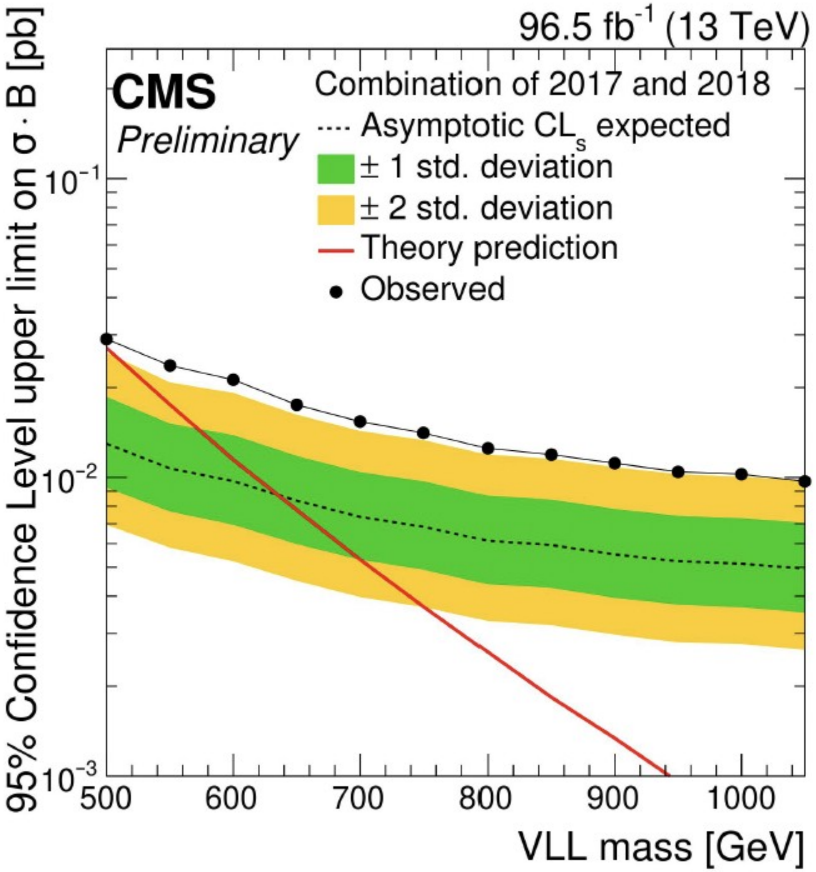
- 3 or more b-tagged jets
- 0,1 or 2 tau-tagged jets
- cut in missing transverse energy



- Analysis using Graph neural network (GNN)



Attention-based Cloud Network (ABCNet)



- LHC limits of **10-30 fb** on EW production xsection

$$M_L \sim 500 \text{ GeV}$$

Conclusions

- Evidence of LFU violation in **semi-leptonic *b*→*c,s* transitions**

NP solutions: Z' , LQs couplings to 3rd generation fermions

Many models predict new effects in top-physics at the LHC

- We described a simple **top-philic** solution to *b*→*s* anomaly

$$pp \to t\bar{t}Z' \to t\bar{t}\ell^+\ell^- \qquad pp \to t\bar{t}Z' \to t\bar{t}t\bar{t}$$

- Combined explantions of the B-anomalies requires Leptoquark mediators

UV completion for the U₁ solution: **4321 gauge model.**

- 4321 has a rich pheno in the top-quark sector:

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

$$pp \to N\bar{N}, E^{\pm}N \to t\bar{t}t\,\bar{b}\tau\nu$$

$$pp \to N\bar{N} \to t\bar{t}t\bar{t}\,\nu\nu$$

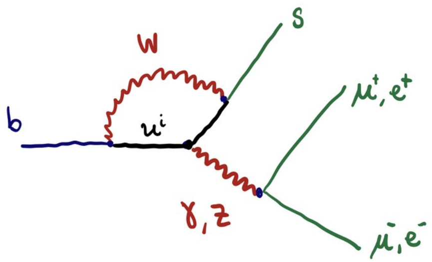
LHC could test these predicitons in the near future.

- extra slides -

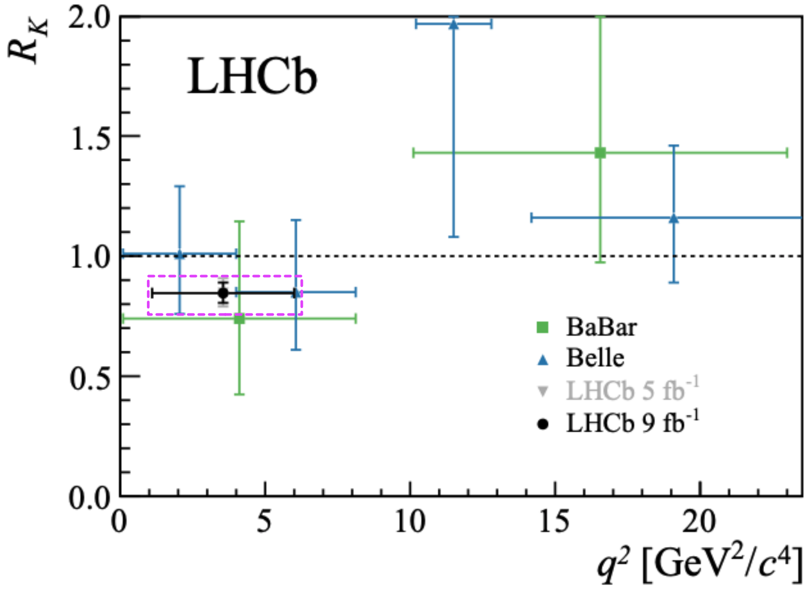
B-meson anomalies – LFU ratios

- Evidence of LFU violation in $b \to s\ell\ell$ transitions.
- LFU ratios: $R_{X_s} = \dfrac{\mathcal{B}(B \to X_s\,\mu\bar{\mu})}{\mathcal{B}(B \to X_s\,e\bar{e})}$

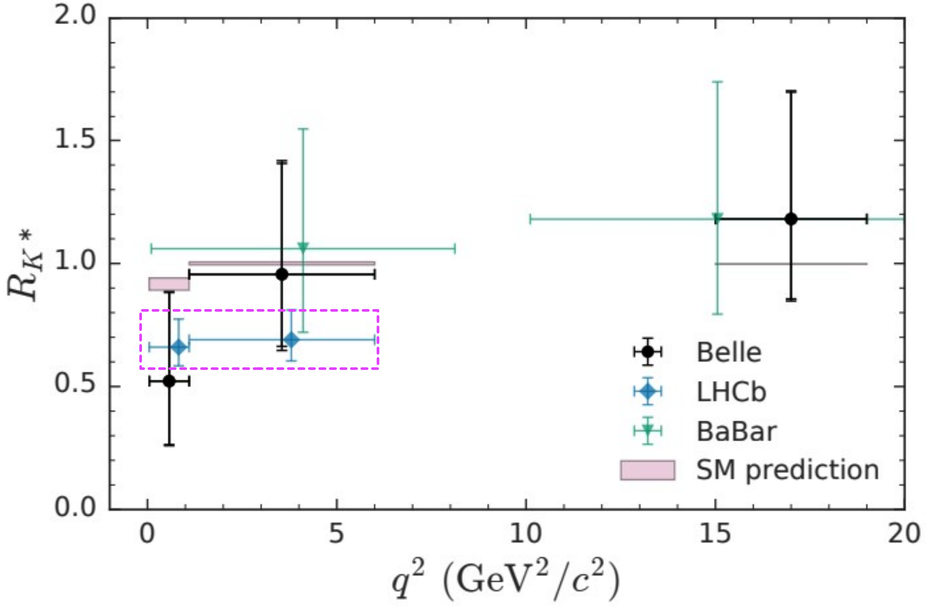
Hiller, Kruger
Phys.Rev.D 69 (2004) 074020



$B^+ \to K^+\ell^+\ell^-$



$B^0 \to K^{*0}\ell^+\ell^-$



$$\begin{cases} R^{\text{exp}}_{K^+} < R^{\text{SM}}_{K^+} \\ R^{\text{exp}}_{K^{*0}} < R^{\text{SM}}_{K^{*0}} \end{cases}$$

$3.1\,\sigma,\ \ 2.5\,\sigma$ deficits

LHCb, arXiv:1705.05802, arXiv:2103.11769
Belle, arXiv:1904.02440, arXiv:1908.01848

B-meson anomalies – LFU ratios

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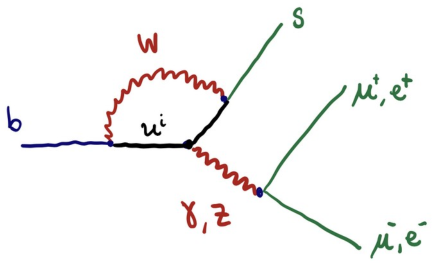
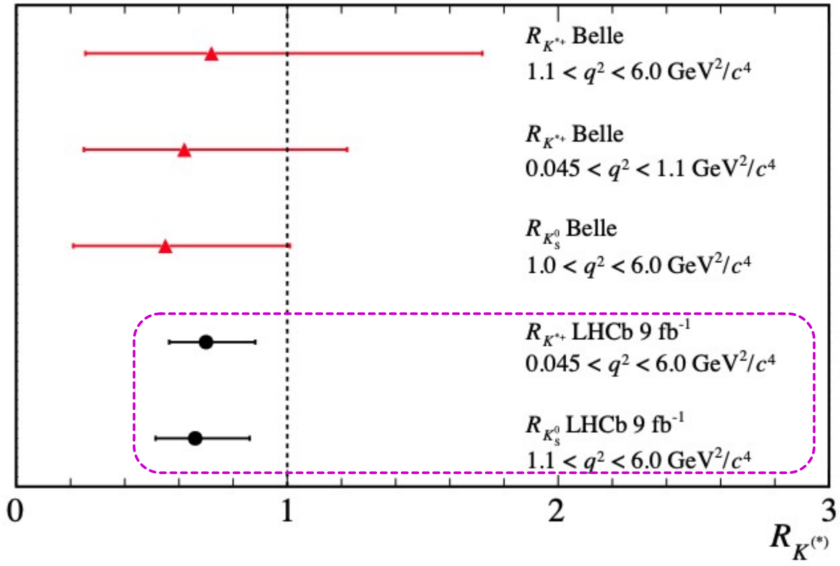
Hiller, Kruger
Phys.Rev.D 69 (2004) 074020



2021: New ratios!

$$\begin{cases} B^0 \to K^0_s \ell^+\ell^- \\ B^+ \to K^{*+}\ell^+\ell^- \end{cases}$$



LHCb arXiv:2110.09501

$$\begin{cases} R^{\mathrm{exp}}_{K_s} < R^{\mathrm{SM}}_{K_s} \\ R^{\mathrm{exp}}_{K^{*+}} < R^{\mathrm{SM}}_{K^{*+}} \end{cases}$$

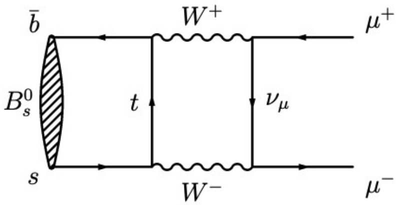
$1.5\,\sigma,\quad 1.4\,\sigma$ deficit!

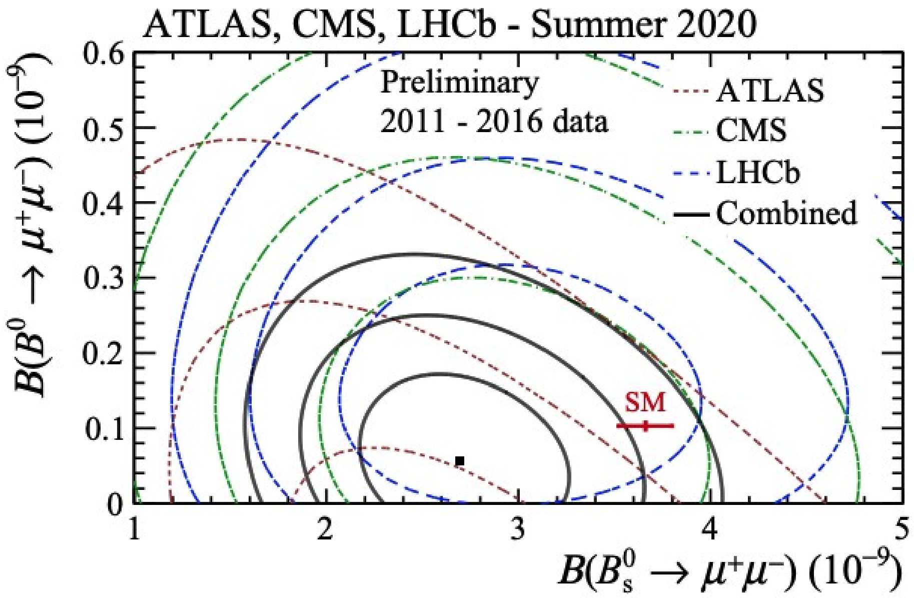
Compatible with previous results!

B-meson Anomalies – muon specific $b \to s\mu^+\mu^-$

$B_s \to \mu^+\mu^-$

$B \to M\mu^+\mu^-$

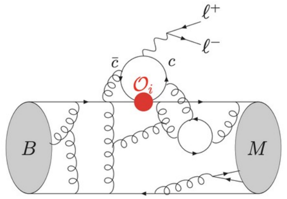


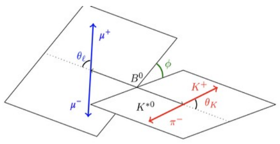


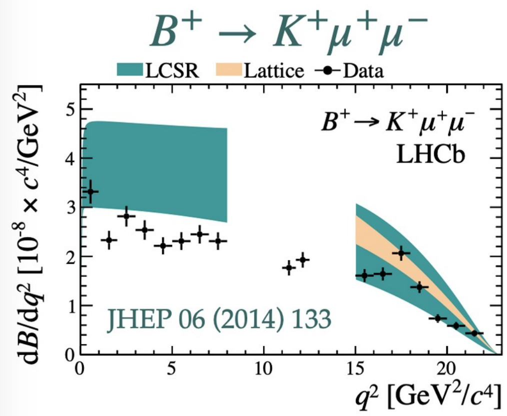
$\sim 2\,\sigma$ deviation

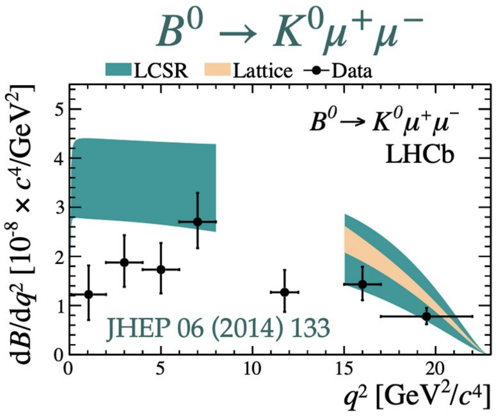
- Theoretically clean!

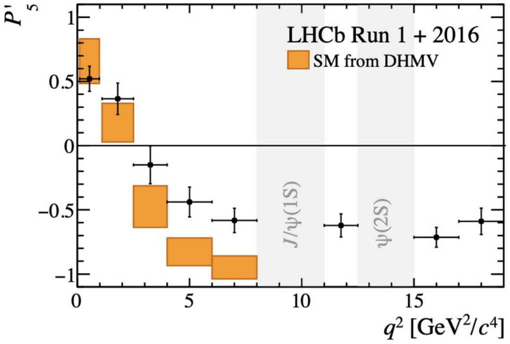
LHCb, arXiv:1703.05747
ATLAS, arXiv:1812.03017
CMS, arXiv:1910.12127
LHCb arXiv:2108.09283











$\sim 1 - 3\,\sigma$
deviations

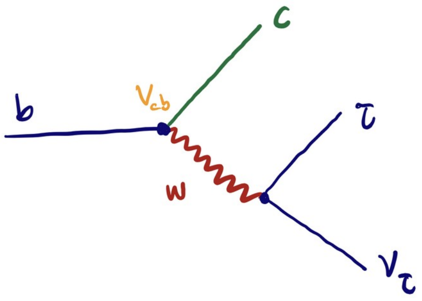
- Theoretically “dirty”

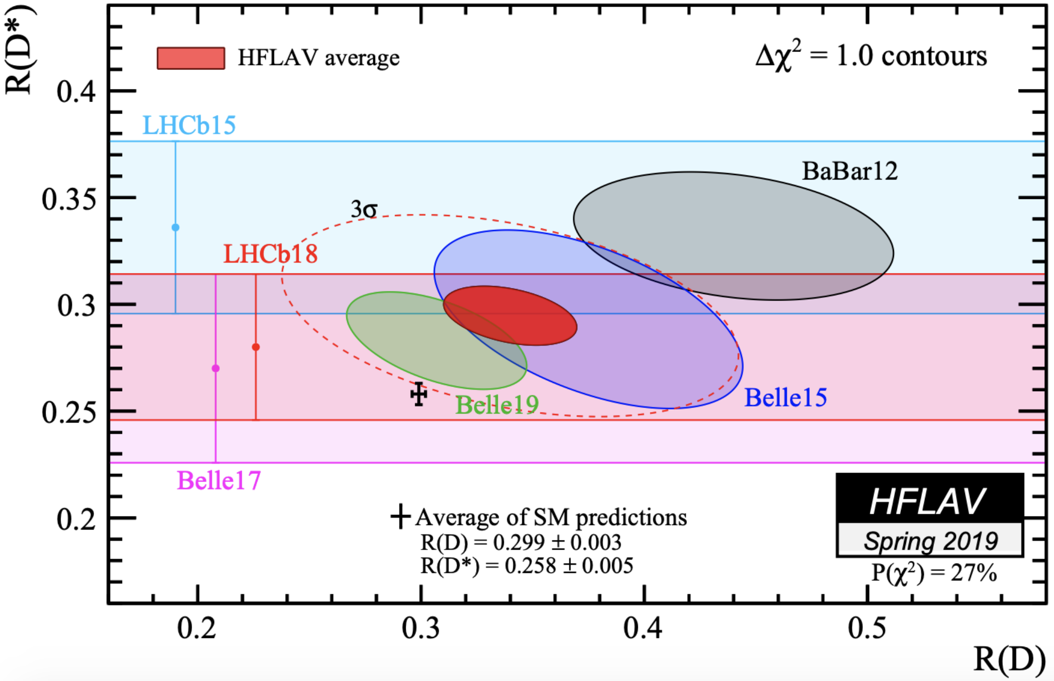
No clear consensus on theoretical treatment of hadronic uncertainties...

B-meson Anomalies in charged currents

- Indications of LFU violation in $b \to c \ell \nu$ transitions.

- LFU ratio: $$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\, \tau \bar{\nu})}{\mathcal{B}(B \to D^{(*)}\, \ell \bar{\nu})}\Bigg|_{\ell=e,\mu}$$ Taus vs light leptons





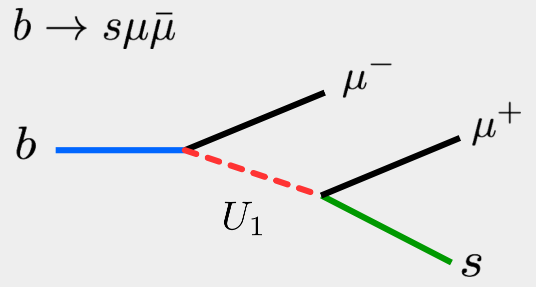
$$R^{\mathrm{exp}}_{D^{(*)}} > R^{\mathrm{SM}}_{D^{(*)}}$$

$3\,\sigma$ Excess!

Soon joining the party!

U_1 Vector LQ

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

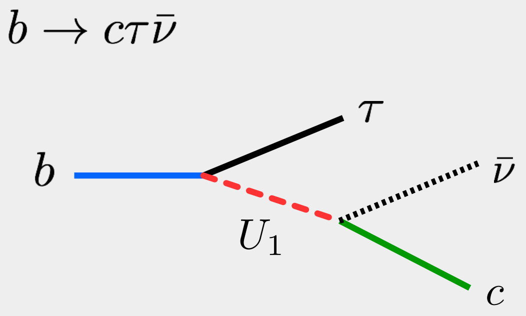


$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & 0 \\ 0 & x_L^{b\mu} & 0 \end{pmatrix}$$

$$x_R = 0$$

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

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



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

$$x_R = 0$$

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

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

- This solution can accomodate both anomalies!

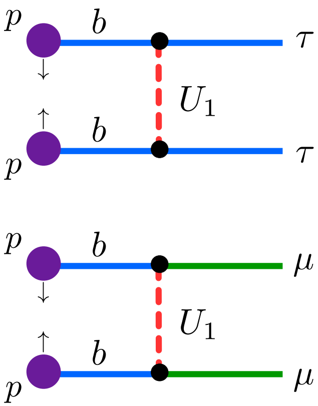
Butazzo, Greljo, Isidori, Marzocca [1706.07808]

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

U_1 Phenomenology: LHC + flavor

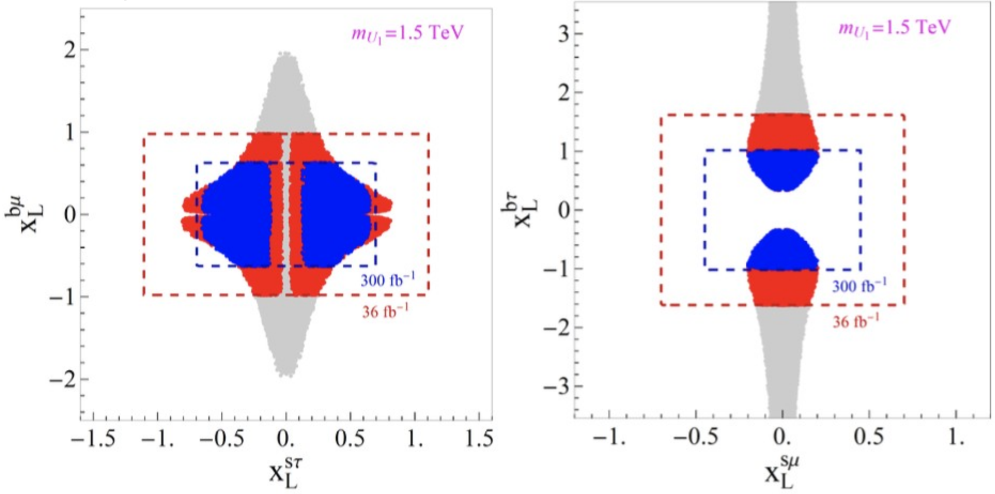
$$x = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}$$

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



Fit to low-energy obs + high-pT ditau limits:

Angelescu, Becirevic, DAF, Sumensari [1808.08179]



$$\begin{cases} x_{s\tau} > \mathcal{O}(1) \times V_{cb} & \leftarrow \text{ coupling \underline{must} be non-zero!} \\ x_{b\tau} = \mathcal{O}(1) & \leftarrow \text{ 3}^{\text{rd}} \text{ generation dominance} \\ x_{s\mu} < \mathcal{O}(0.1) & \end{cases}$$

Data suggests non-trivial flavor structure!   e.g. Broken $U(2)^5$ symmetry!

U_1 Phenomenology: LFV

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

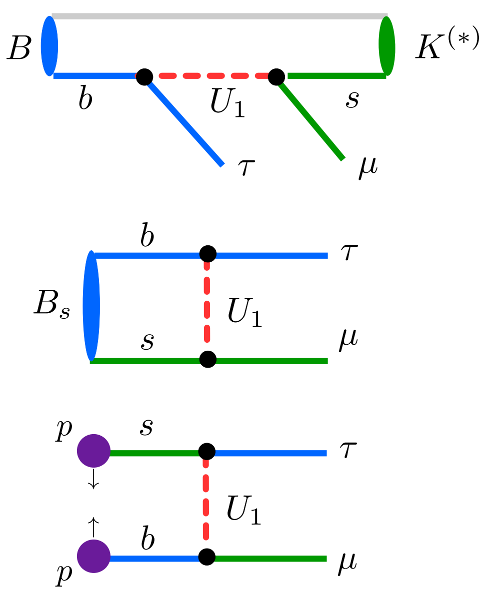
Complementarity between
LFV at low-energy and high-pT tails

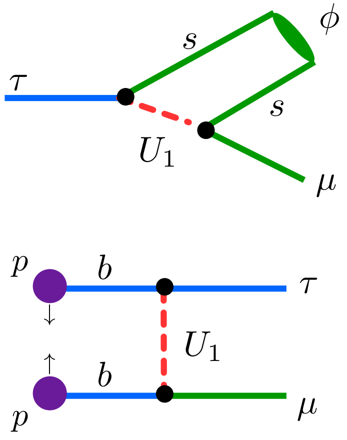
$B \to K\tau^+\mu^-$
$B_s \to \tau^+\mu^-$

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

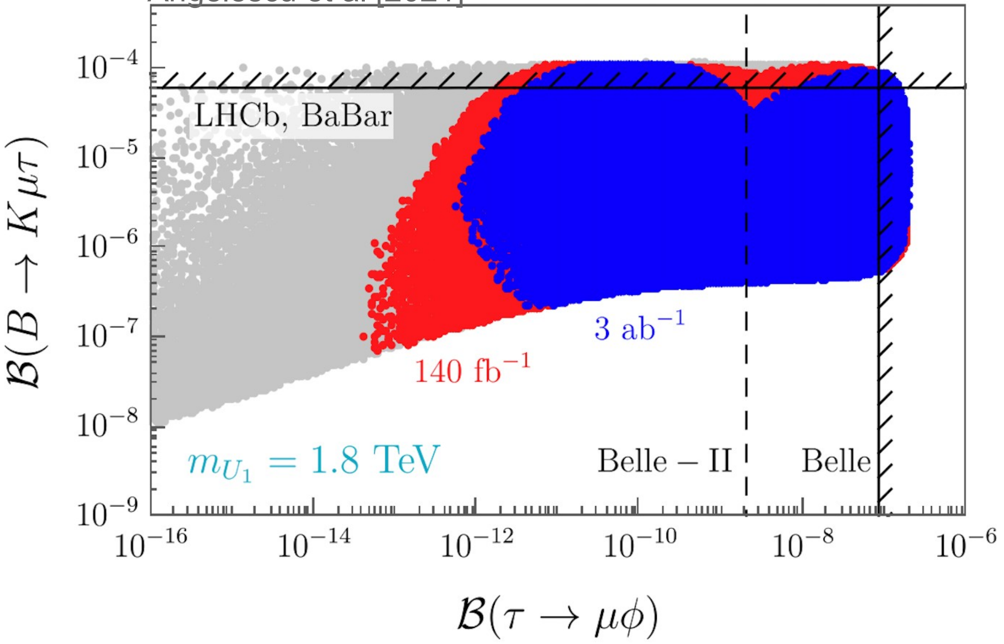
$\tau \to \mu\phi$

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





Angelescu et al [2021]

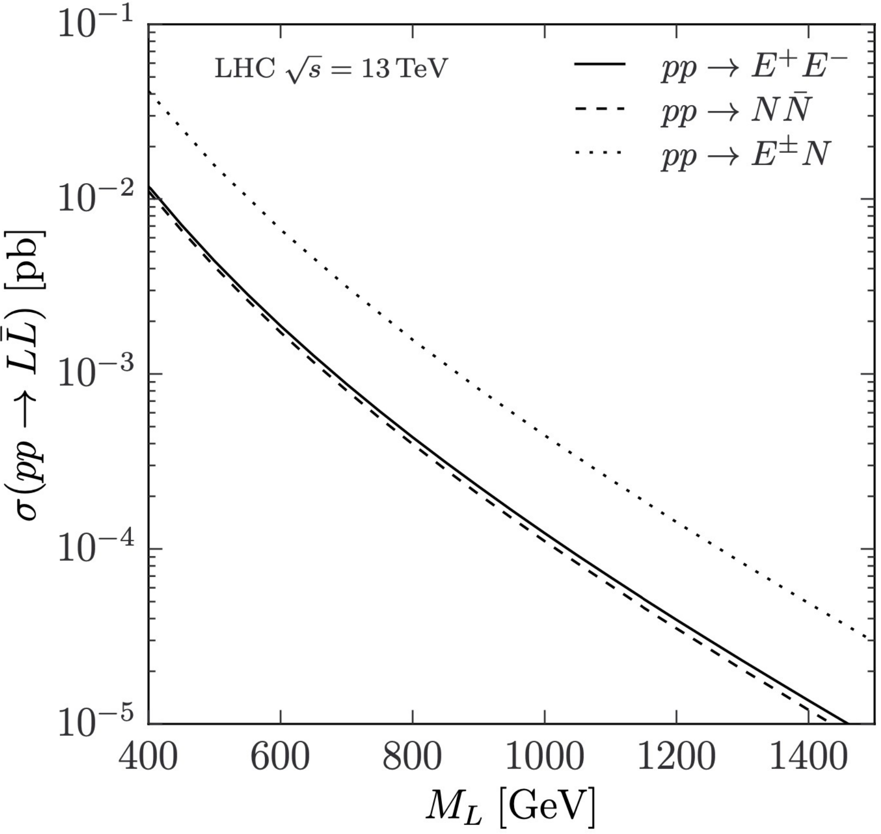


Model Potentially within
reach at LHCb & Belle 2!

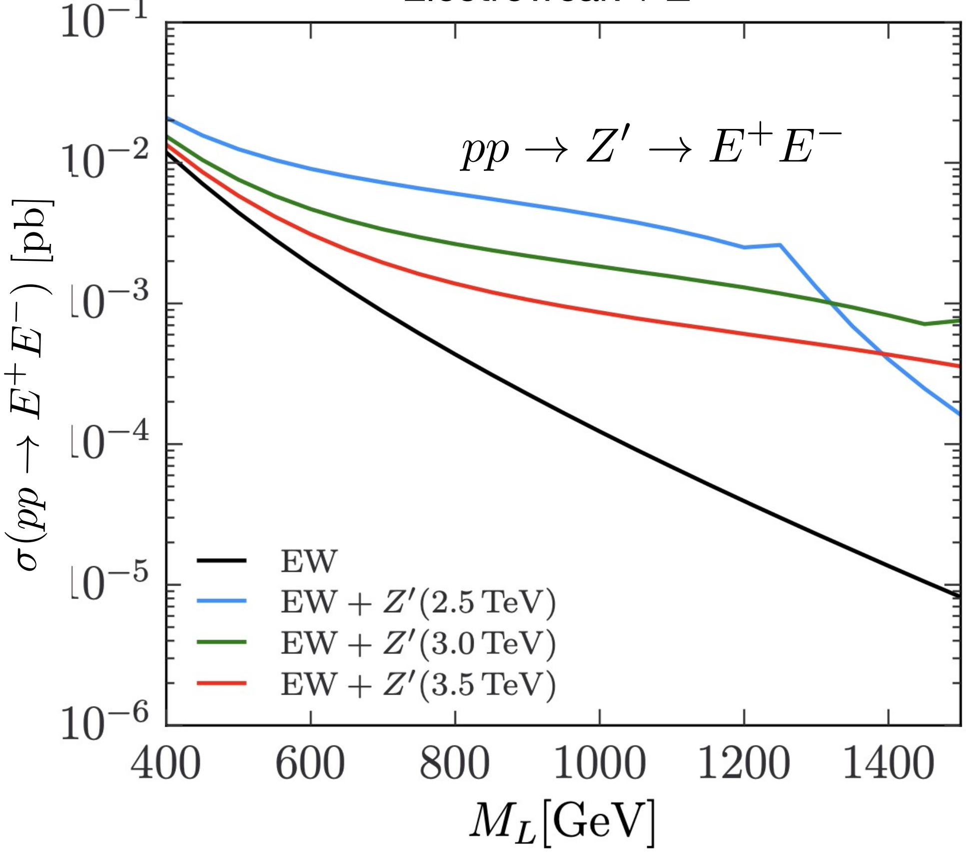
Vector-like leptons

$$L = \begin{pmatrix} N \\ E^{\pm} \end{pmatrix}$$

Electroweak production



Electroweak + Z'



Looks promising, but currently no heavy lepton search by ATLAS or CMS