BSM hints from rare decays

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Based on
Cornella, JFM, Isidori, coming soon
Baker, JFM, Isidori, König, arXiv:1901.10480
Bordone, Cornella, JFM, Isidori JHEP 1810 (2018) 148
Bordone, Cornella, JFM, Isidori Phys. Lett. B 779 (2018) 317

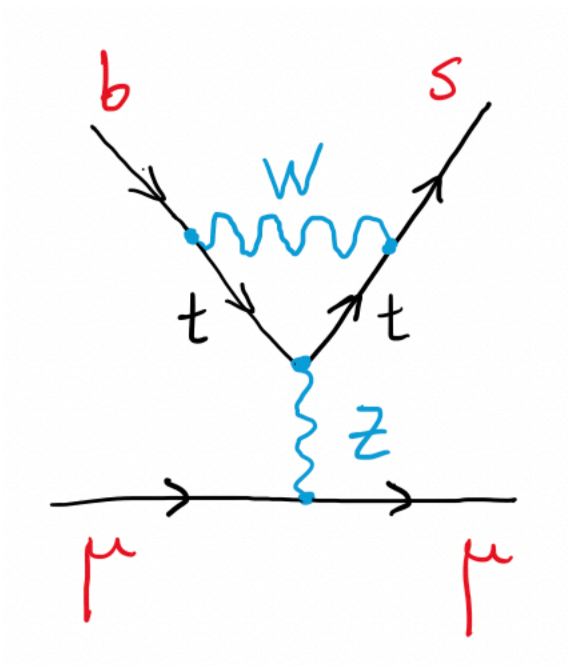
La Thuile 2019 - Les Rencontres de Physique de le Vallée d'Aoste

The B-physics anomalies

Hints of Lepton Flavour Universality Violation in semileptonic B decays

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

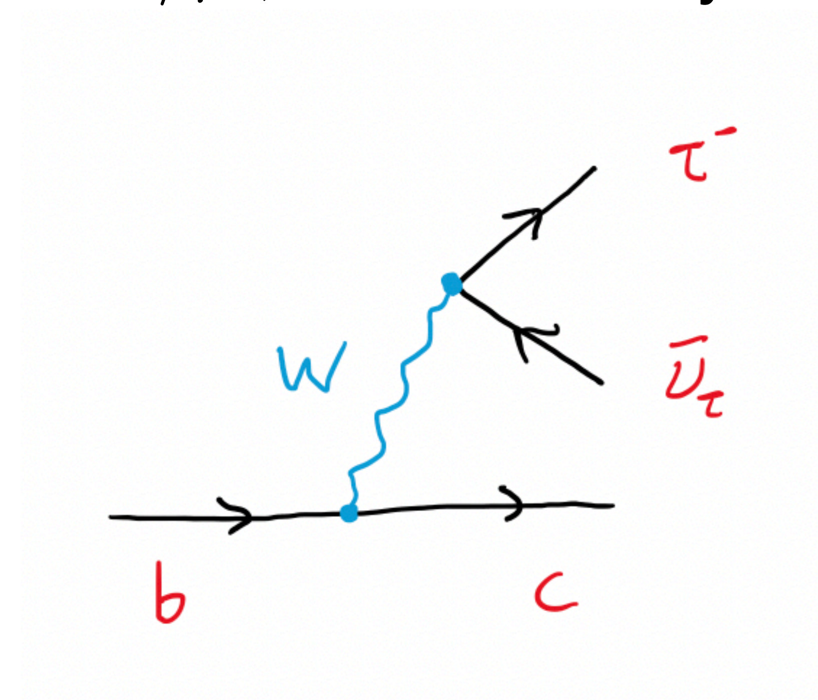
μ/e ~~universality~~



$> 4\,\sigma$

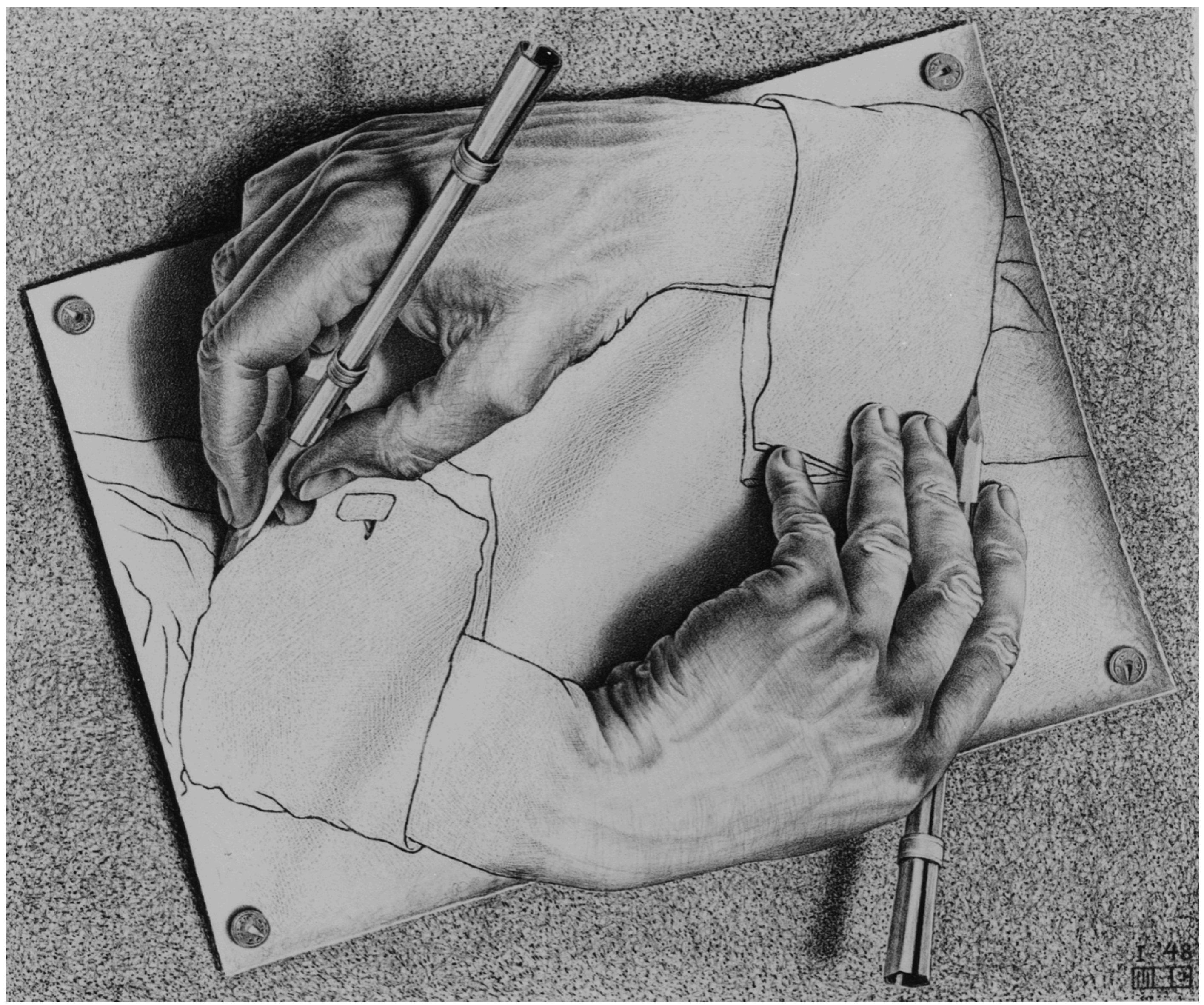
$b \to c\tau\nu$

$\tau/\mu\,,e$ ~~universality~~



$\sim 4\,\sigma$

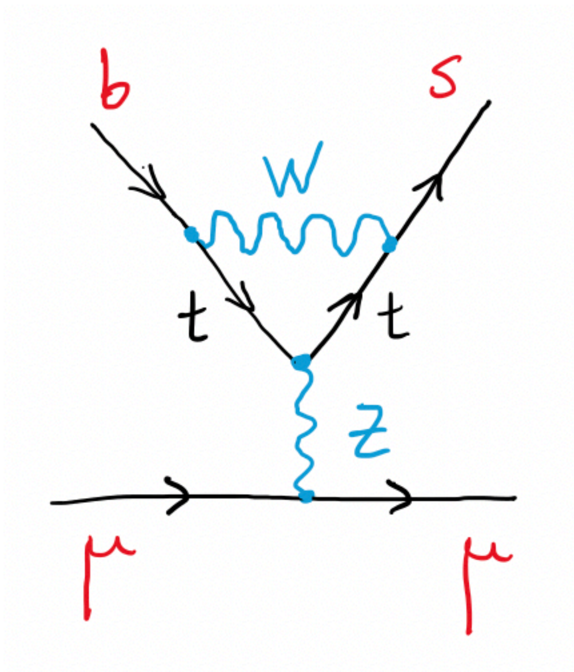
From data to simplified models

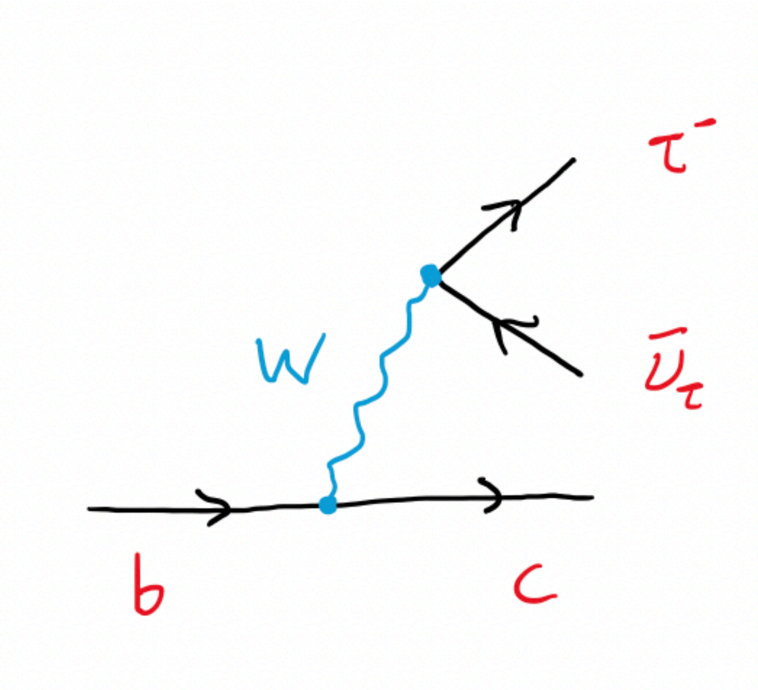


Towards a combined explanation of the anomalies

Taken together, these are a very significant set of deviations from the SM

→ It is worth looking for a **combined explanation** in terms of NP!





$3_Q \to 2_Q 2_L 2_L$ $\ll$ $3_Q \to 2_Q 3_L 3_L$

~25% of a SM **loop** effect

~20% of a SM **tree-level** effect

The only source of **lepton flavor universality violation** in the SM (Yukawas) follows a similar trend: $y_e \ll y_\mu \ll y_\tau$.... Are the anomalies connected to them?

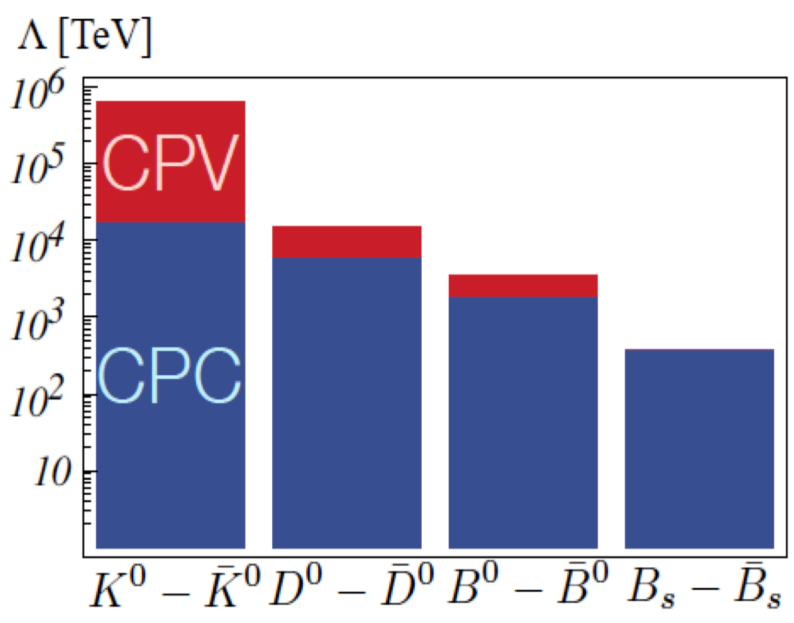
What are the anomalies telling us?

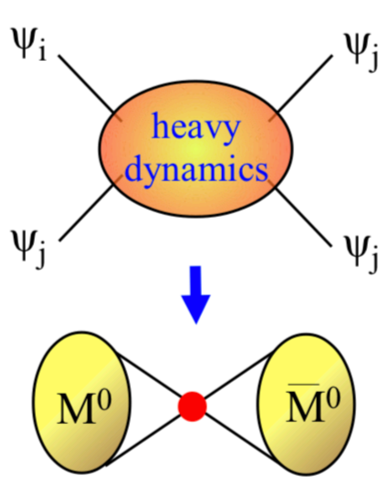
A combined explanation calls for NP: $^{(*)}$

$^{(*)}$ N.B.: conclusions driven (mostly) by $R(D^{(*)})$

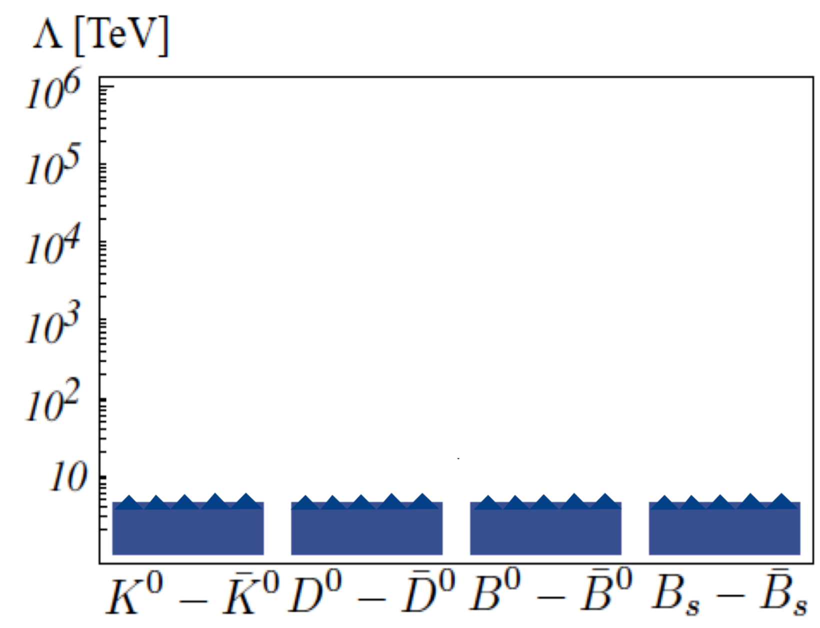
- ★ Coupled dominantly to the **3rd generation**
- ★ $\Lambda_{\rm NP} \sim \mathcal{O}(1\ \text{TeV})$

Anarchical couplings





Hierarchical couplings



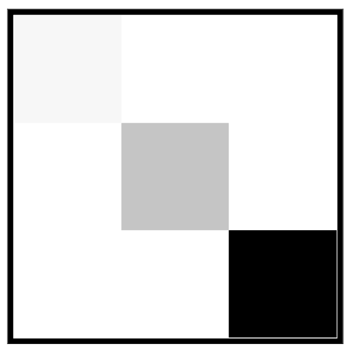
Severe constraints on generic new (BSM) flavor breaking sources
(mis)interpreted as indication of a high flavor scale

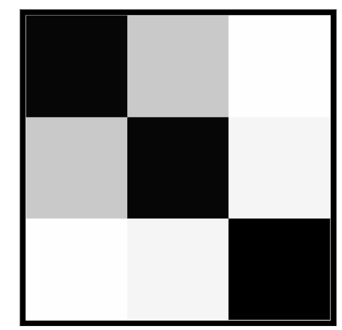
A NP hint to the SM flavor puzzle?

The SM Yukawa sector is characterized by 13 parameters

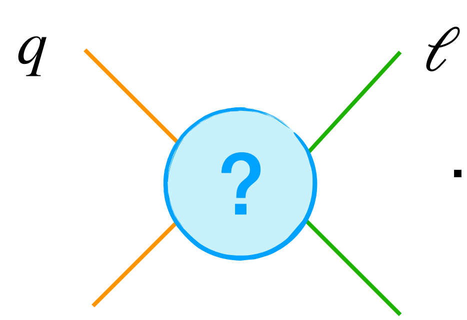
[3 lepton masses + 6 quark masses + 3+1 CKM parameters]

… whose values do not look at all accidental

$M_{u,d,e} \sim$ 

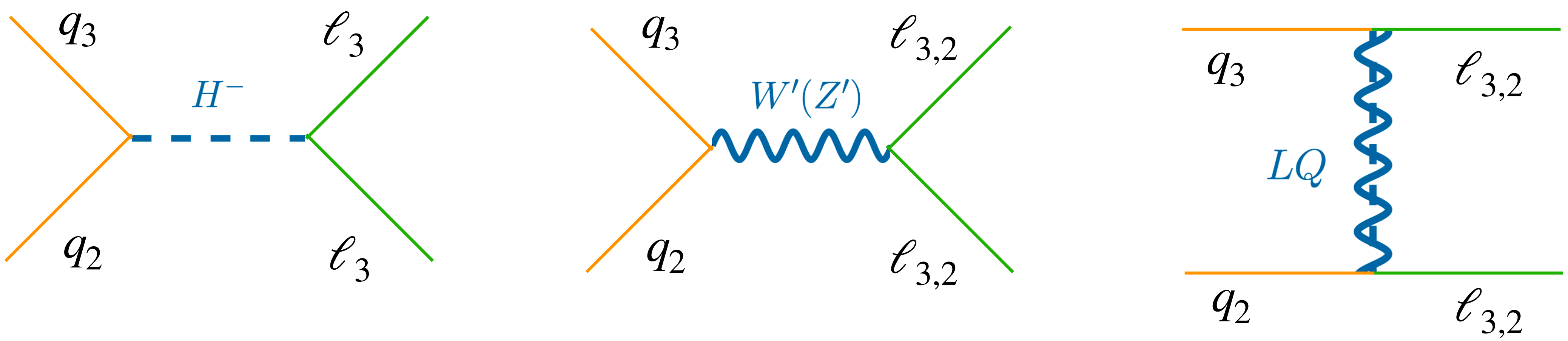
$V_{\rm CKM} \sim$ 

- ✓ The flavor anomalies seem to suggest a similar trend: large NP effects in 3rd generation, gradually smaller effects in the light generations
- ✓ Recent theoretical progress connecting the anomalies to the SM flavor hierarchies
  [Bordone, Cornella, JFM, Isidori 1712.01368; Greljo, Stefanek 1802.04274; Allanach, Davighi 1809.01158]



…..Which mediator?

Which mediator?



Only few possibilities are available

★ **Charged Higgs** solutions ($R(D^{(*)})$ only) are excluded by measurements of τ_{B_c}
[Contributions to $\mathscr{B}(B_c \to \tau\nu)$ are scalar enhanced and huge] [Alonso et al. 1611.06676]

★ **Minimal W'/Z' models** in tension with high-p_T data ($pp \to \tau\tau$ tails)
[Faroughy et al. 1609.07138]

W' + light ν_R in better shape but still in tension with $pp \to \tau\nu$ tails
[Greljo et al. 1811.07920]

★ **Leptoquarks** (scalars or vectors) are the best candidates so far

✔ no 4-lepton (LFV, LFUV) and 4-quark processes ($\Delta F = 2$) at tree level

The main suspects

Faroughi @ CKM18

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

Angelescu, Becirevic, DAF, Sumensari [1808.08179]

Three viable options in the market:

★ U_1 + UV completion

[di Luzio, Greljo, Nardecchia 1708.08450;
Calibbi, Crivellin, Li 1709.00692;
Bordone, Cornella, JF, Isidori 1712.01368;
Barbieri, Tesi, 1712.06844…]

★ $S_1 + S_3$

[Crivellin, Muller, Ota 1703.09226;
Buttazzo et al. 1706.07808;
Marzocca 1803.10972]

★ $S_3 + R_2$

[Bečirević et al., 1806.05689]

The vector leptoquark (U_1) brings some interesting theoretical features into the game

✓ Low-scale bottom-tau unification. Possible link to Pati-Salam unification

✓ Connections to the SM flavor puzzle

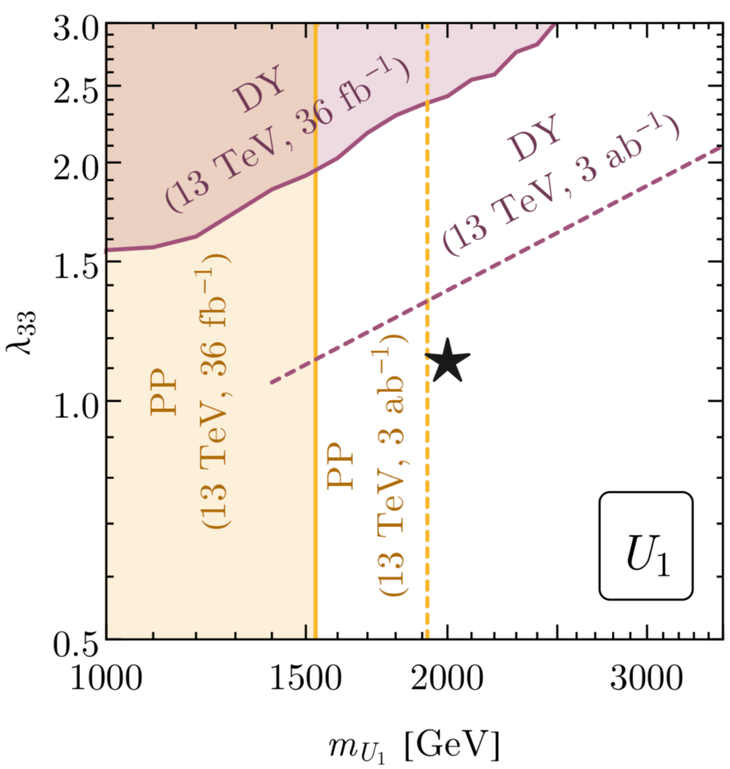
Revisiting the U_1 solution

The U_1 leptoquark: the pure LH case

$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_{i\alpha}^L (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) - \cancel{\beta_{i\alpha}^R (\bar{d}_R^i \gamma_\mu e_R^\alpha)} \right] + \mathrm{h.c.}$$

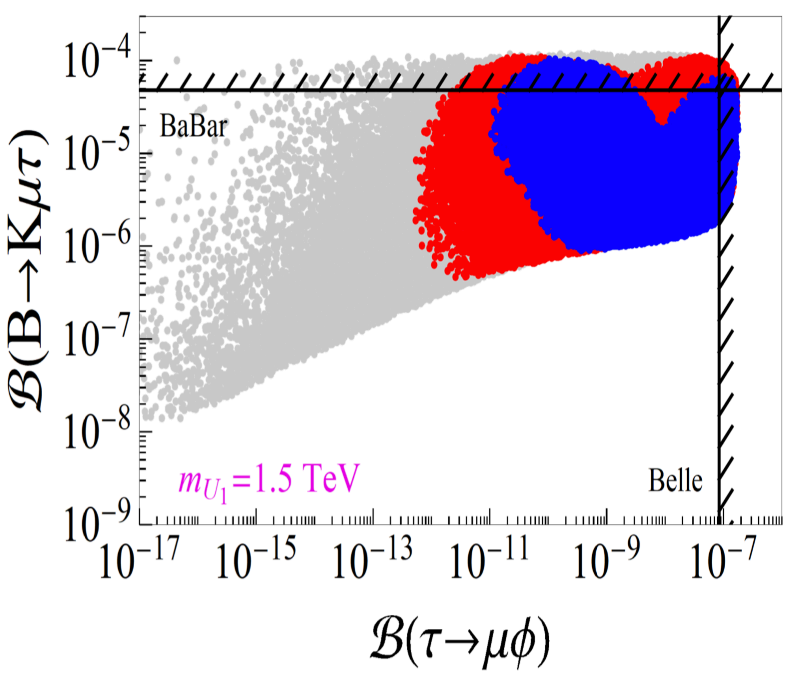
Pure LH U_1 (i.e. $\beta_{i\alpha}^R = 0$) extensively analyzed in the recent literature…

Safe from high-pT



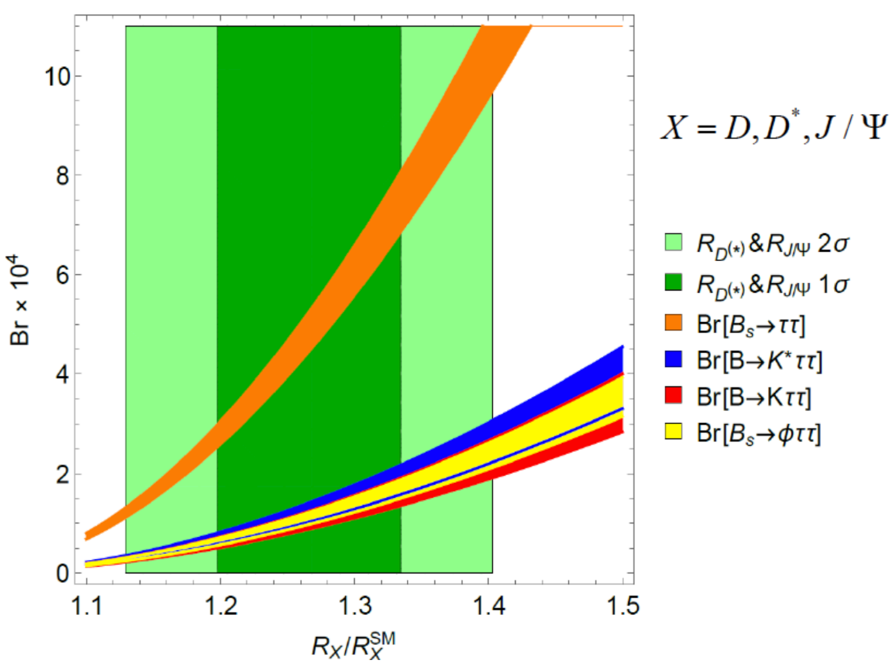
[Schmaltz, Zhong, 1810.10017]
(see also 1808.08179, 1609.07138)

LFV around the corner



[Angelescu et al., 1808.08179]

Huge effects in $b \to s\tau\tau$



[Capdevila et al., 1712.01919]

The U_1 leptoquark: all in

$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_{i\alpha}^L (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) - \beta_{i\alpha}^R (\bar{d}_R^i \gamma_\mu e_R^\alpha)\right] + \mathrm{h.c.}$$

Pure LH U_1 (i.e. $\beta_{i\alpha}^R = 0$) extensively analyzed in the recent literature…

… RH U_1 coupling usually ignored. Important pheno implications!

$$\beta^L = \begin{pmatrix} 0 & 0 & \beta_{d\tau}^L \\ 0 & \beta_{s\mu}^L & \beta_{s\tau}^L \\ 0 & \beta_{b\mu}^L & \beta_{b\tau}^L \end{pmatrix} \qquad \beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta_{b\tau}^R \end{pmatrix}$$

$$C_{V_L} = (\bar{c}_L \gamma_\mu b_L)(\bar{\ell}_L \gamma^\mu \nu_L) \qquad C_{S_R} = (\bar{c}_L b_R)(\bar{\ell}_R \nu_L)$$

(RGE enhanced)

The U_1 leptoquark: flavor structure

$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_{i\alpha}^L (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) - \beta_{i\alpha}^R (\bar{d}_R^i \gamma_\mu e_R^\alpha)\right] + \mathrm{h.c.}$$

Flavor structure (*)

$$\beta^L = \begin{pmatrix} 0 & 0 & \beta_{d\tau}^L \\ 0 & \beta_{s\mu}^L & \beta_{s\tau}^L \\ 0 & \beta_{b\mu}^L & \beta_{b\tau}^L \end{pmatrix} \qquad \beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta_{b\tau}^R \end{pmatrix}$$

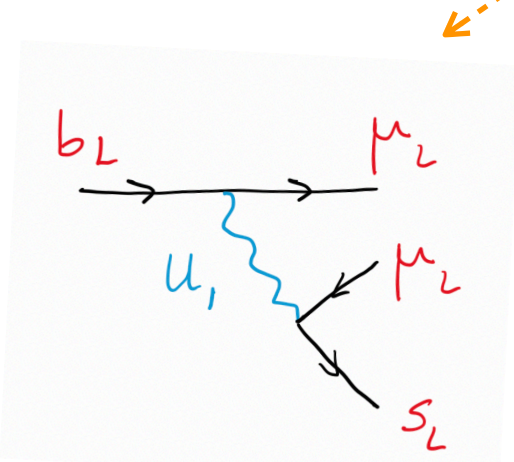
$\beta_{b\tau}^L = 1$

$\beta_{b\tau}^R \sim \mathcal{O}(1)$

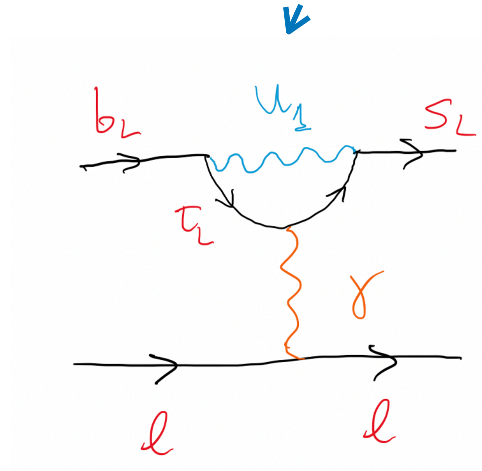
$\beta_{s\tau}^L, \beta_{b\mu}^L \sim \mathcal{O}(0.1)$

$\beta_{s\mu}^L, \beta_{d\tau}^L \sim \mathcal{O}(0.01)$

C_{V_L} $\qquad$ C_{S_R}

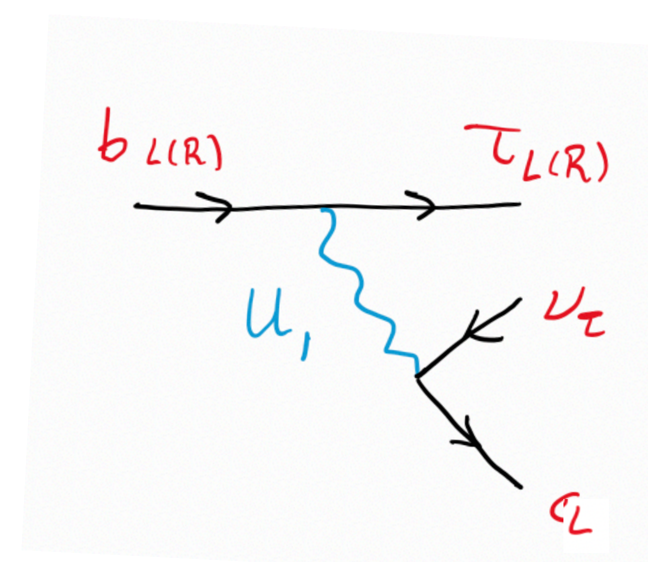


$\Delta C_9^\mu = -\Delta C_{10}^\mu$



$\Delta C_9^{e,\mu,\tau}$

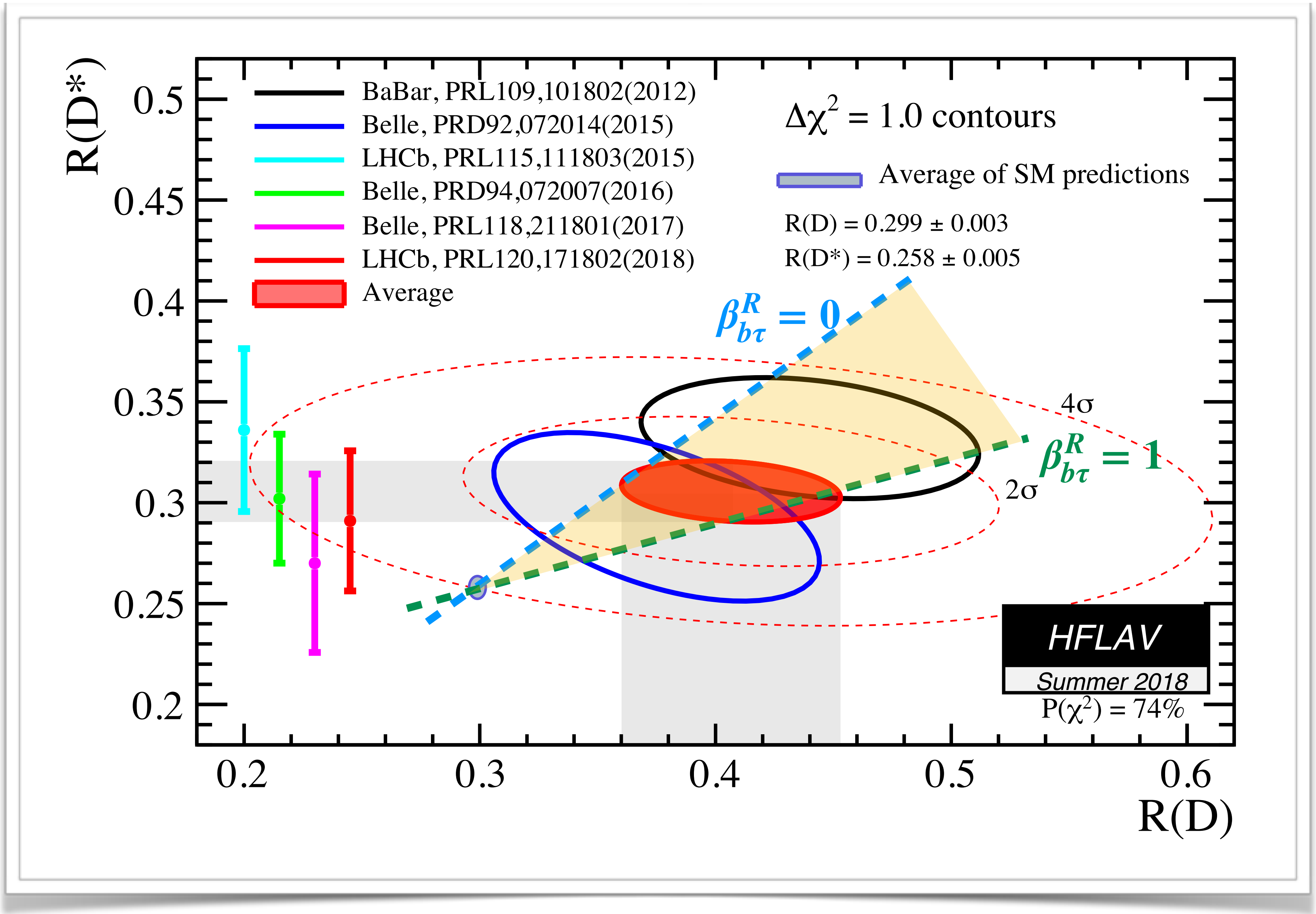
$b \to s\ell\ell \ll R(D^{(*)})$



[Crivellin et al., 1807.02068]

(*) N.B.: Deviations from this structure highly constrained by low-energy flavor data

Which value of $\beta_{b\tau}^{R}$? $R(D^{(*)})$ projections

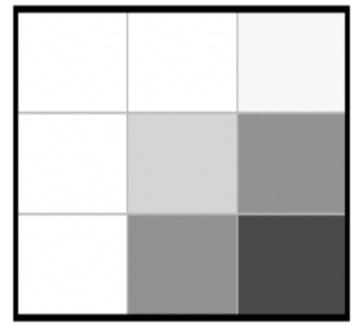


Differential distributions, polarizations,… could also be different from the SM

[Essential to test at future facilities like Belle II]

Low-energy implications of the U_1 leptoquark

$$\beta^L = \begin{pmatrix} 0 & 0 & \beta^L_{d\tau} \\ 0 & \beta^L_{s\mu} & \beta^L_{s\tau} \\ 0 & \beta^L_{b\mu} & 1 \end{pmatrix}$$



$$\beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta^R_{b\tau} \end{pmatrix}$$

$\Delta R_K^{(*)}$

$\Delta R_D^{(*)}$

$B_s \to \tau\tau$

$B_{(c)} \to \tau\nu$

LFV

$B_s \to \tau\mu$

$\tau \to \mu\gamma$

$B \to K\tau\mu$

Non-zero values of $\beta^R_{b\tau}$ have a huge impact on the low energy phenomenology:

- ✓ Different NP contribution for $R(D)$ & $R(D^*)$
- ✓ Chiral-enhanced NP effects (hence very large) in some decays
- ✓ Larger NP scale possible, i.e. larger values for M_U available

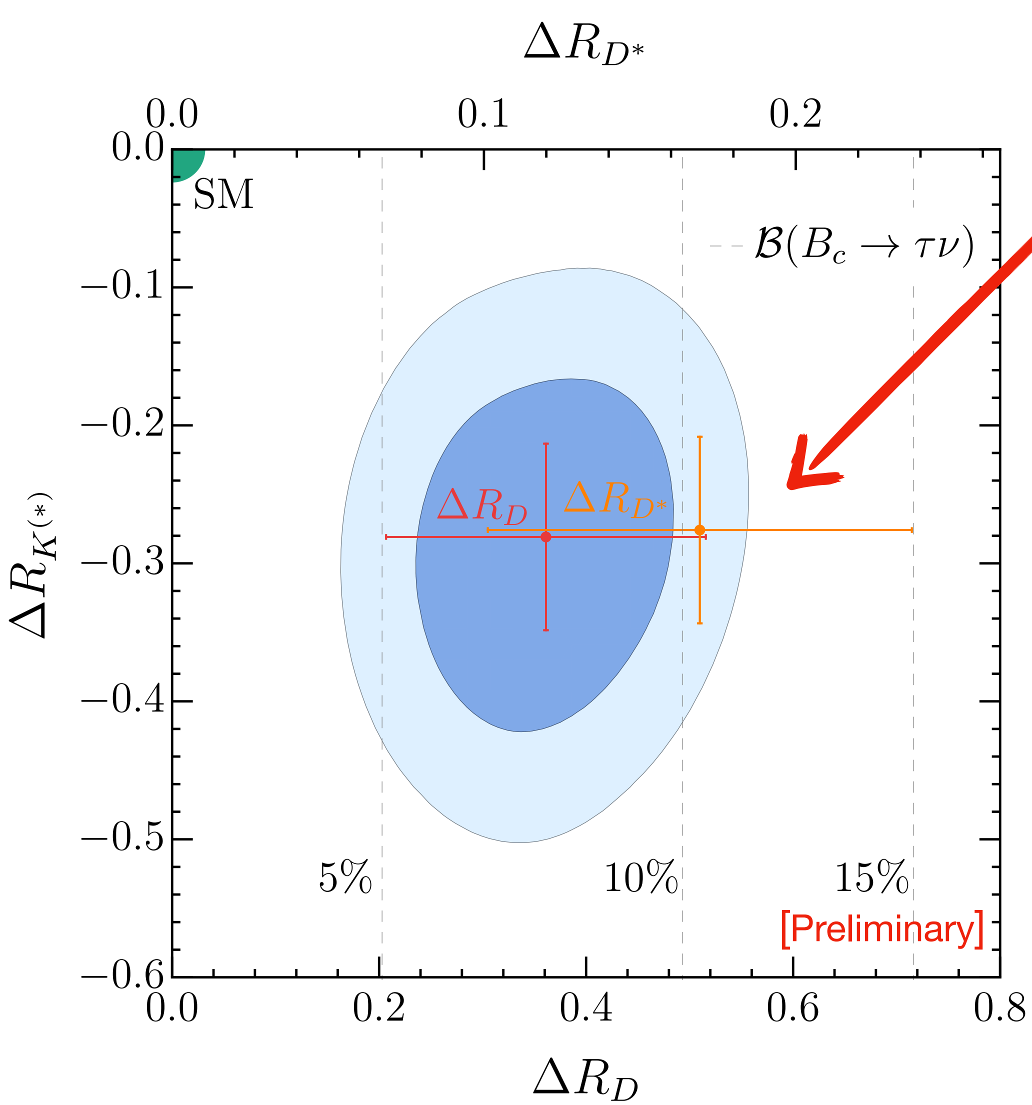
Low-energy fit results

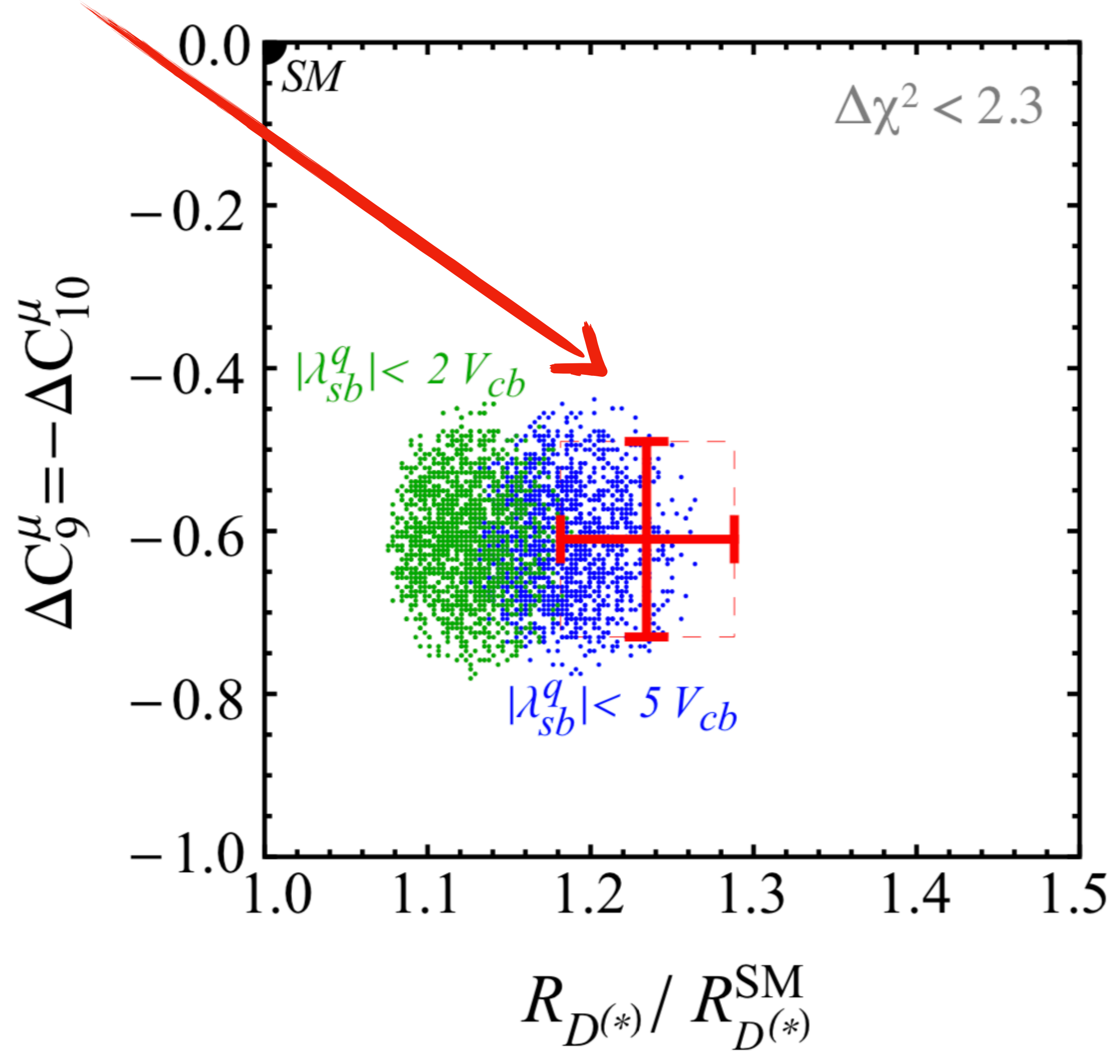
For both extreme cases, the low-energy fit (in particular to the anomalies) is very good!

LH + RH ($\beta_{b\tau}^R = 1$)

Experiment
$@\,1\sigma$

LH only ($\beta_{b\tau}^R = 0$)



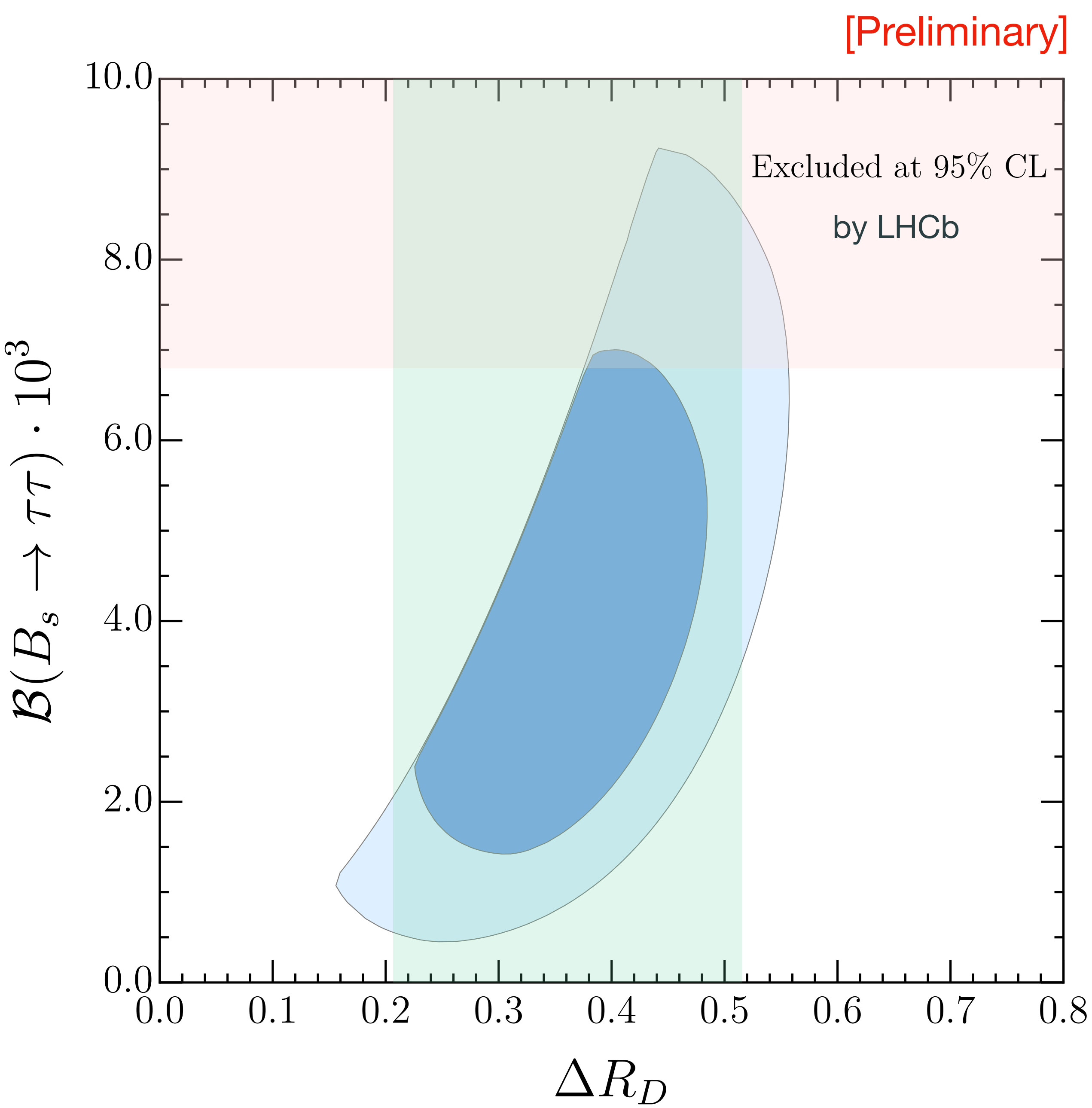


NP scale naturally higher
(thanks to the C_{S_R} contribution)

[Cornella, JFM, Isidori, in preparation]

[Buttazzo et al. 1706.07808]

$\mathscr{B}(B_s \to \tau\tau) \quad (\beta_{b\tau}^R = 1)$



The NP enhancement in $\mathscr{B}(B_s \to \tau\tau)$ is huge, about one order of magnitude above the chiral (pure LH) case:

$$\mathscr{B}(B_s \to \tau\tau) \sim \text{few} \cdot 10^{-3}$$

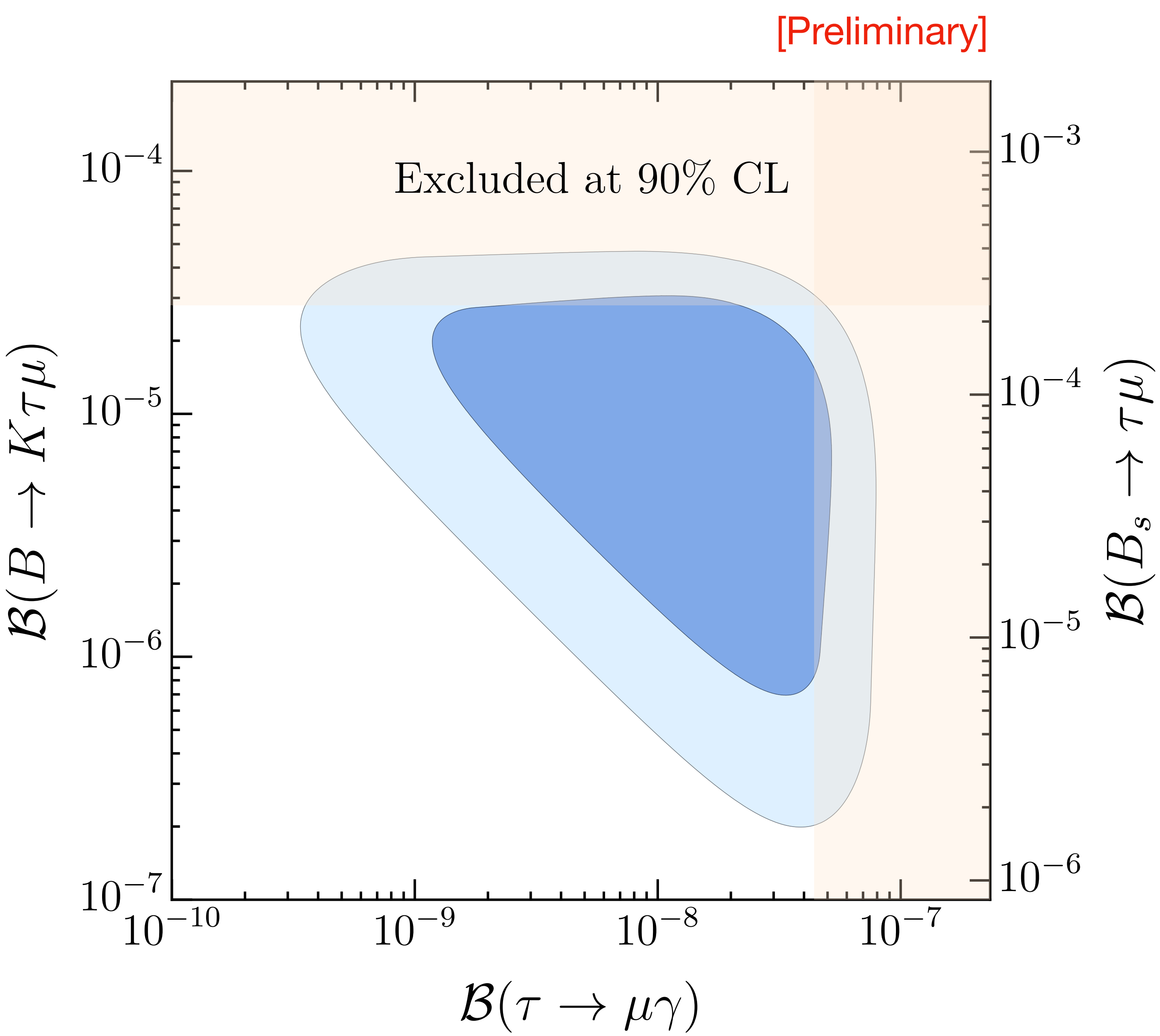
$$\mathscr{B}(B_s \to \tau\tau)_{\text{SM}} = (7.73 \pm 0.49) \cdot 10^{-7}$$

[Bobeth et al. 1311.0903]

→ Exp. limit around the corner

[Cornella, JFM, Isidori, in preparation]

LFV in $\tau \to \mu$ transitions $(\beta_{b\tau}^{R} = 1)$



The explanation of $R_{K^{(*)}}$ implies a large $\tau\mu$ LFV

→ strong enhancement of $B_s \to \tau\mu\,,\ B \to K\tau\mu\,,\ \tau \to \mu\gamma$

$$\mathscr{B}(\tau \to \mu\gamma) \sim 10^{-8}$$

$$\mathscr{B}(B \to K\tau\mu) \sim 10^{-5}$$

$$\mathscr{B}(B_s \to \tau\mu) \sim 10^{-4}$$

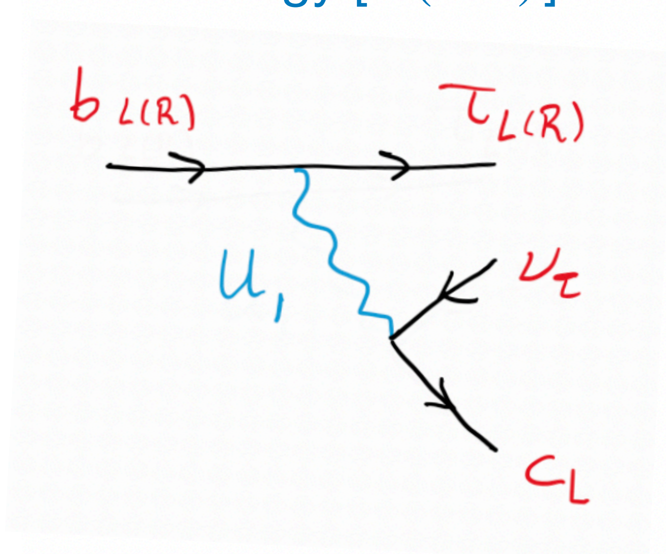
Great experimental perspectives at LHCb and Belle II

[Cornella, JFM, Isidori, in preparation]

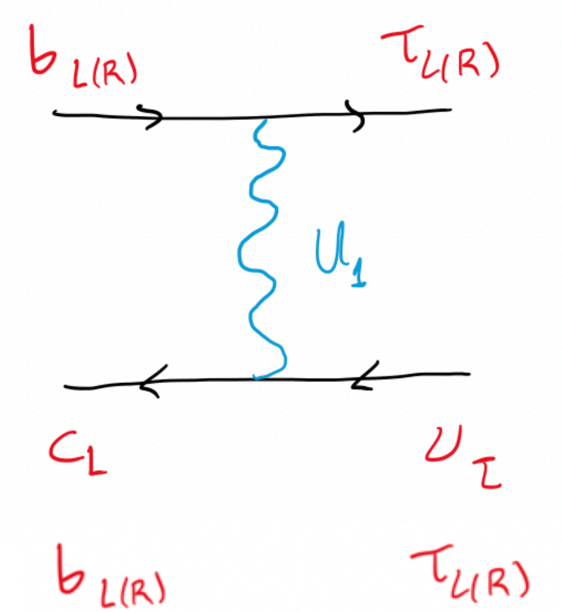
Hunting the U_1 at high-pT

The U_1 is a clear target for the high-pT program at LHC!

Low energy [$R(D^{(*)})$]



High-pT



… however many of the current searches are not optimized to look for it

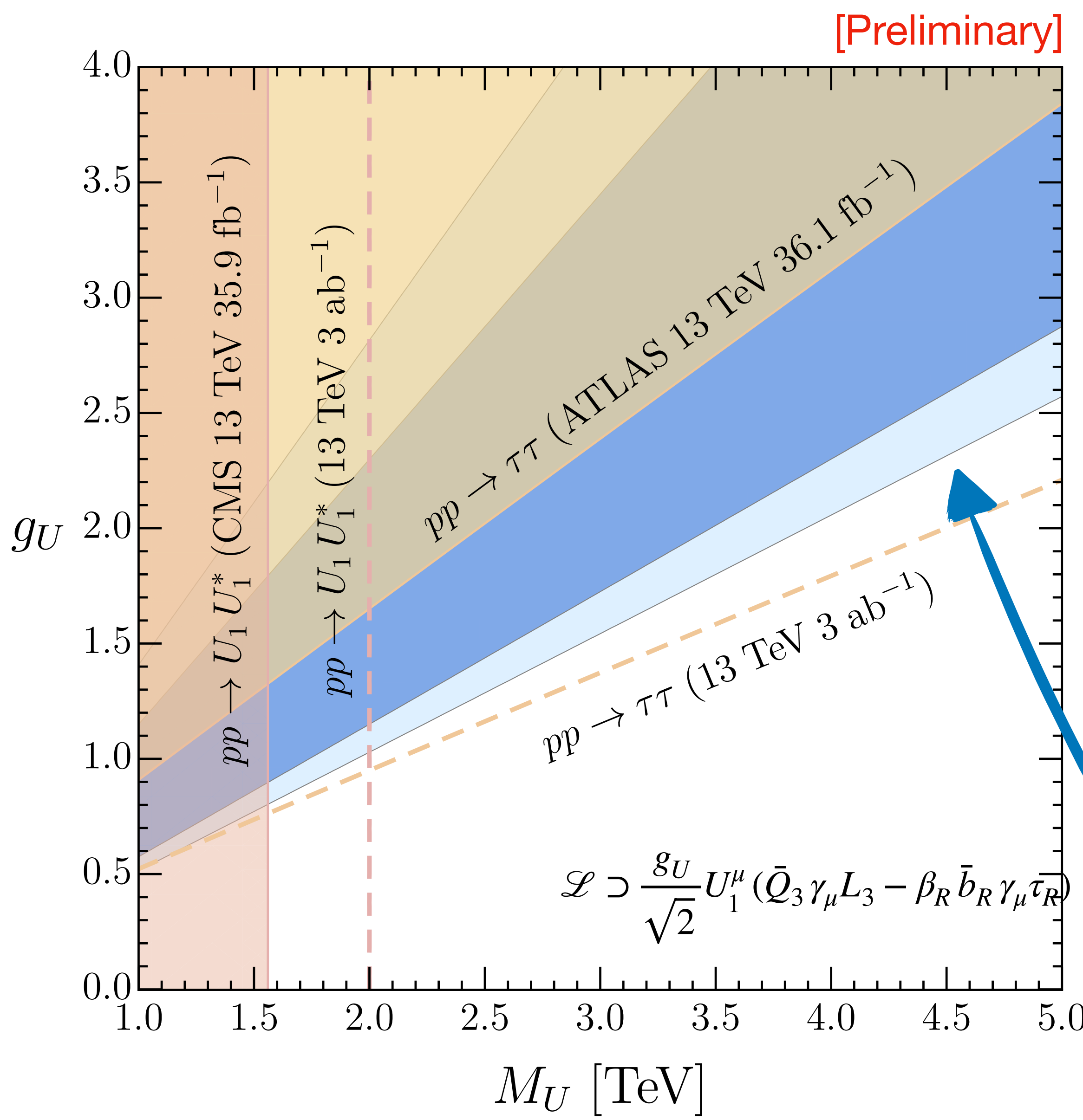
NP effects do not show up as bumps but rather as modifications in the tails of some kinematical distribution (e.g. dilepton transverse mass)

A recast of the high-pT data is needed! [Baker, JFM, Isidori, König, 1901.10480]

High-pT + Low energy

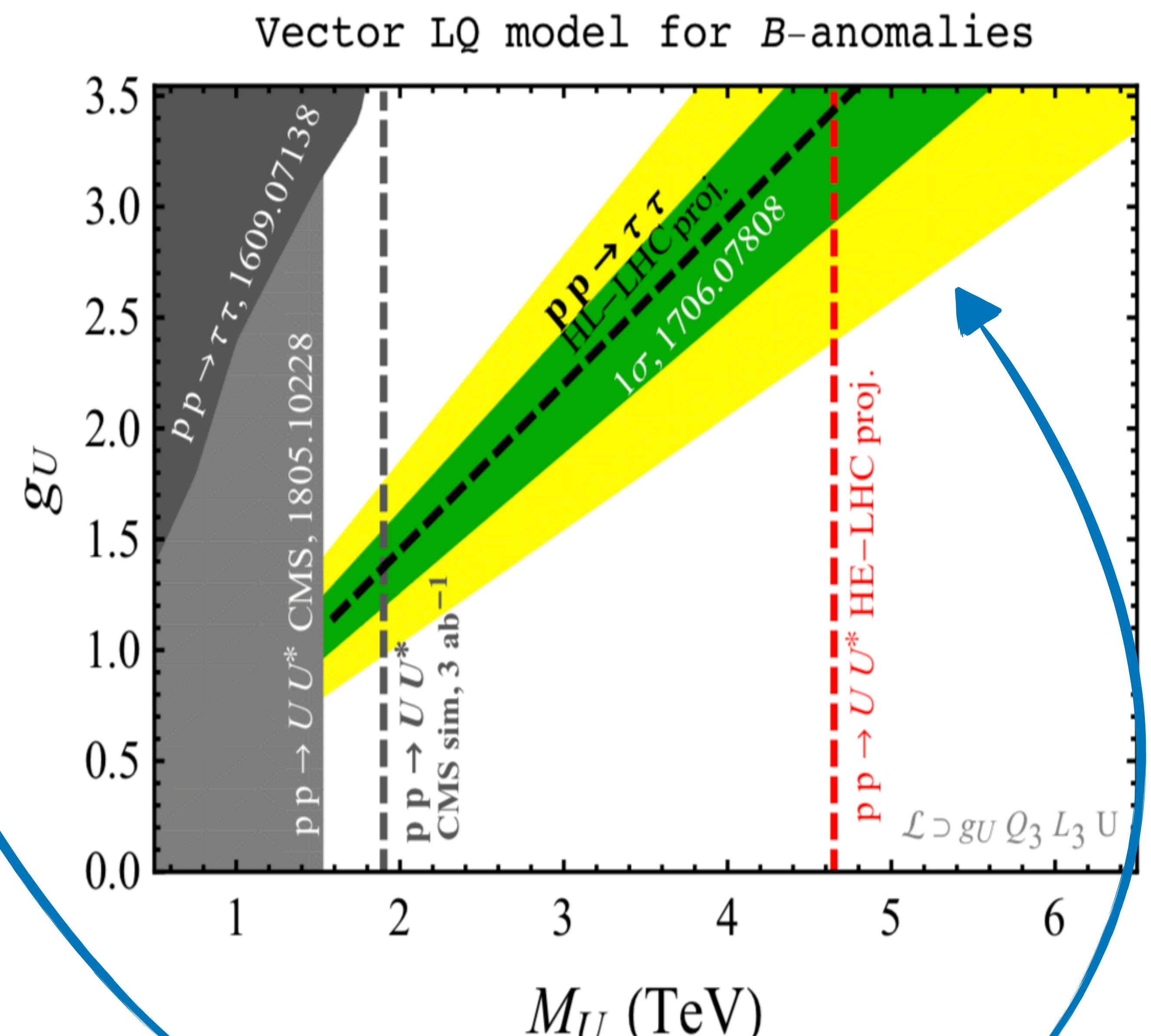
LH + RH

[Cornella, JFM, Isidori, in preparation]



LH only

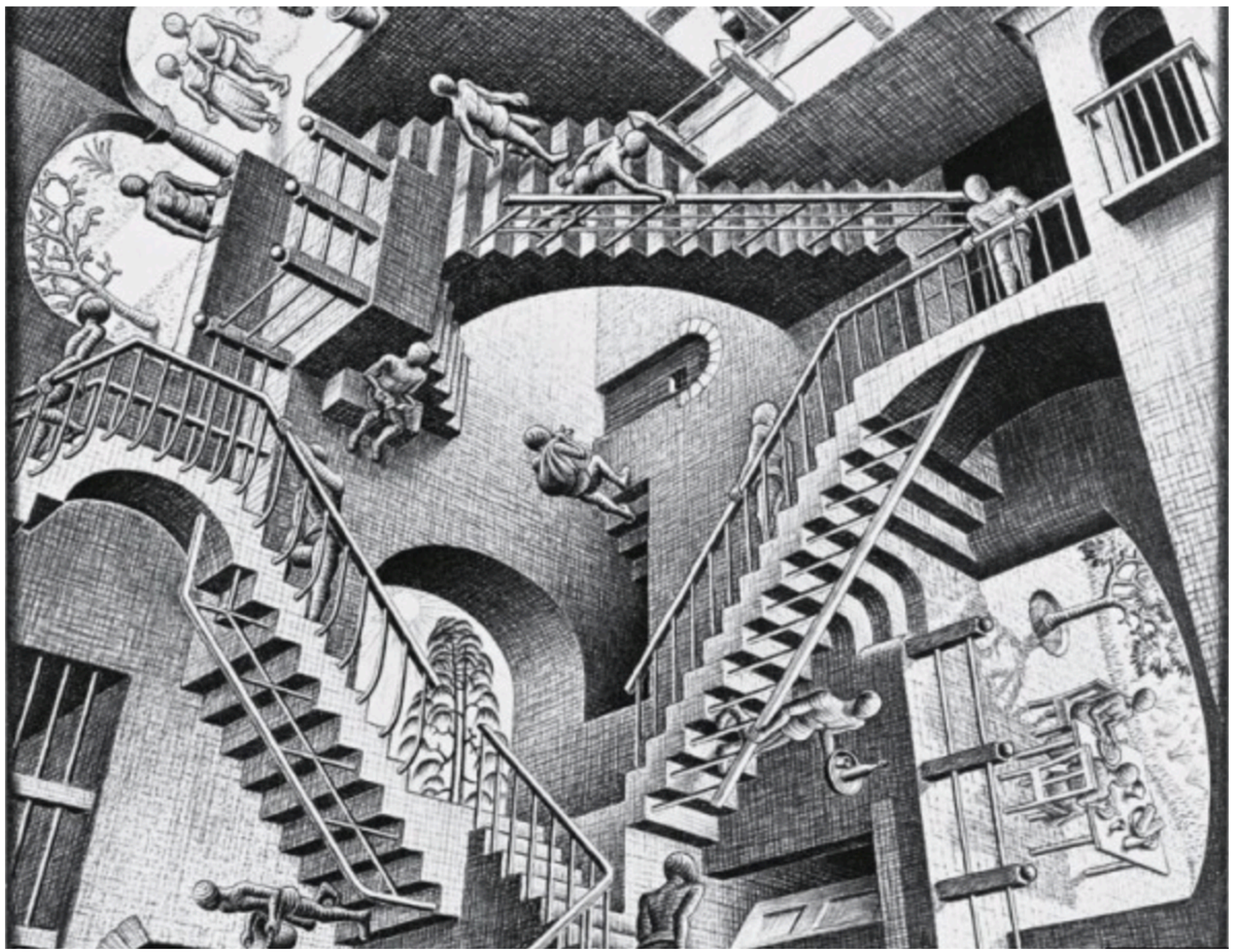
[A. Cerri et al, 1812.07638]



LH + RH $(\beta^R_{b\tau} = 1)$ scenario will be fully probed by the HL-LHC!

1 and 2 σ regions preferred by the low-energy fit

Beyond the simplified picture



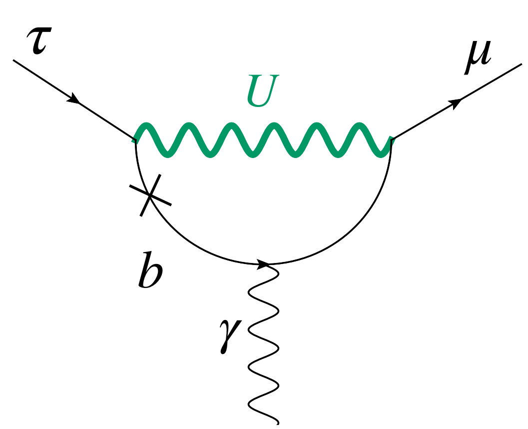
The need for a UV completion

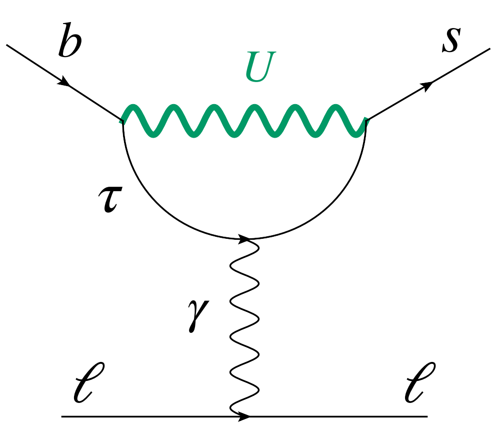
✔ The simplified model analysis captures many relevant aspects of the low and high-energy phenomenology

✘ Radiative effects are relevant!

Some can be estimated already at the level of the simplified model…

$\tau \to \mu\gamma$

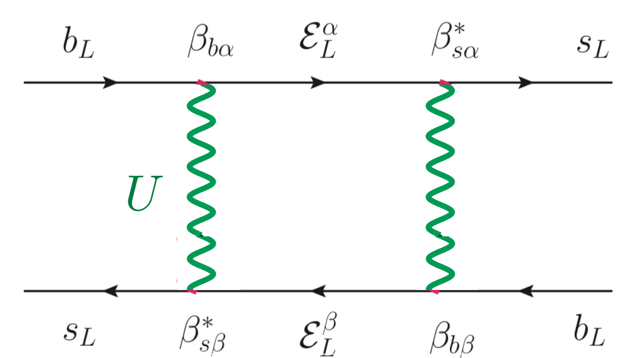




$\Delta C_9^{e,\mu,\tau}$

…but this is not possible for others!

$\Delta F = 2$



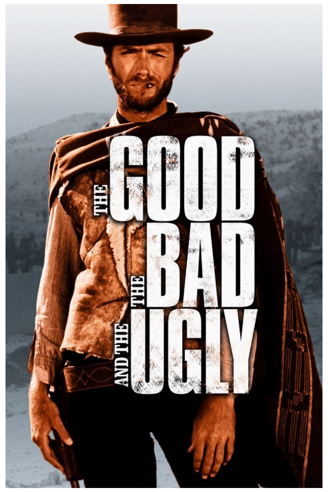
UV completion needed! (gauge model)

“Flavored” 4321

Bordone et al. 1712.01368
Cornella, JFM, Isidori, in preparation

$$\overbrace{SU(4)_3 \times SU(3)_{1+2} \times SU(2)_L \times U(1)}^{U(1)_Y} \xrightarrow{\langle \Omega_{1,3,15} \rangle} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\underbrace{SU(4)_3 \times SU(3)_{1+2}}_{SU(3)_c}$$



$+$

$U^{\alpha} \sim (\mathbf{3}, \mathbf{1})_{2/3}$

$G'^{\,a} \sim (\mathbf{8}, \mathbf{1})_0$ (heavy “gluon”)

$Z' \sim (\mathbf{1}, \mathbf{1})_0$

$M_{U,Z',G'} \sim 3 - 4$ TeV

	Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
1st & 2nd families	$q_L'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
	$u_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
	$d_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
	$\ell_L'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
	$e_R'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
3rd family	ψ_L^3	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
	$\psi_{R_{u,d}}^3$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$\pm 1/2$
$n_{\mathrm{VL}} = 2$	χ_L^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
	χ_R^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
	$H_{1,15}$	$\mathbf{1}, \mathbf{15}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
	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

✔ U(2)-like Yukawa textures (explanation to the SM flavor hierarchies)

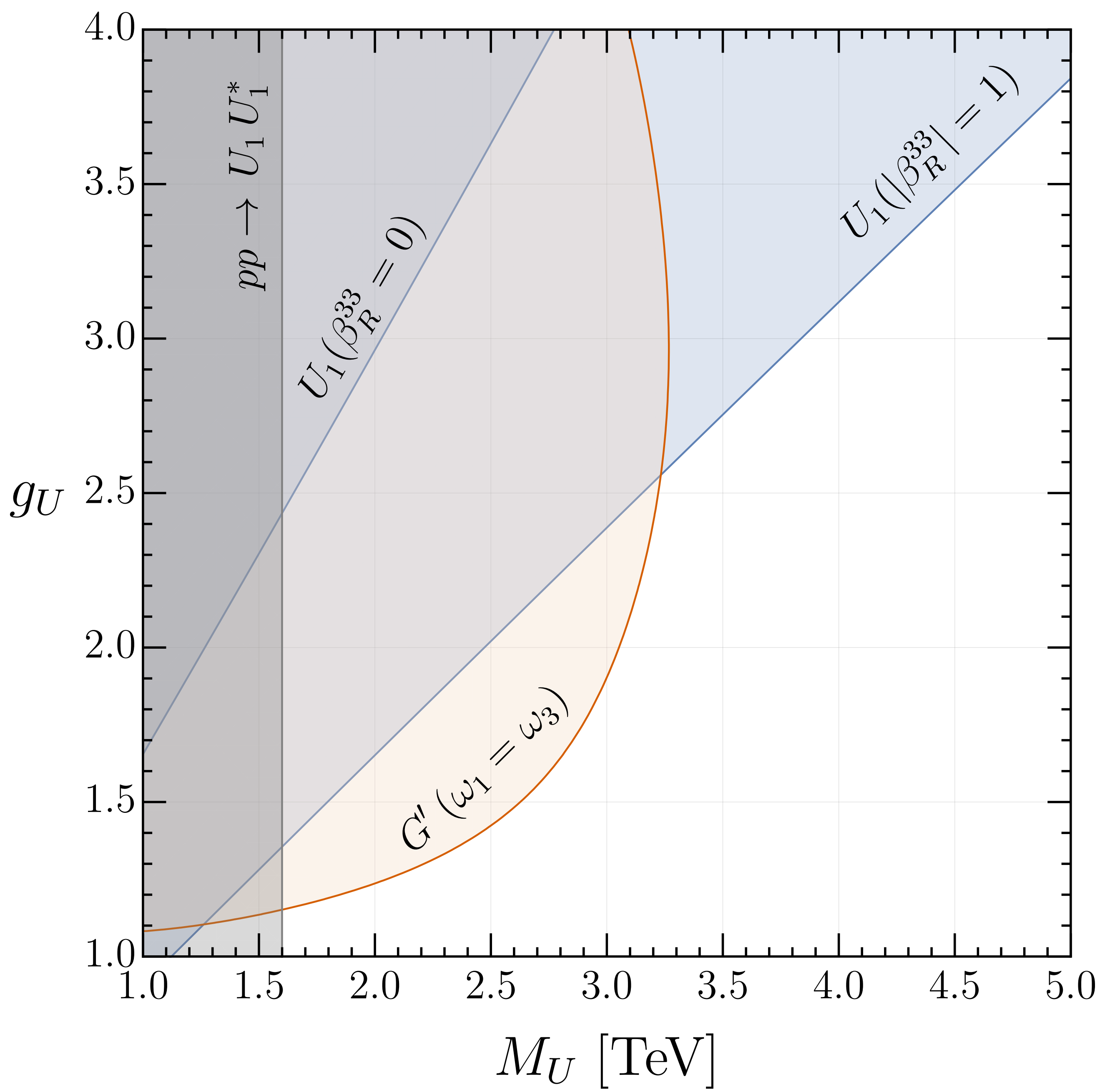
✔ Couplings to 3rd family naturally big

→ Smaller effects in 1st & 2nd families through SM-Vector-like mixing

Gauge anomaly cancellation implies large U_1 **couplings also to RH fields**

High-pT interplay among the new vectors

[Baker, JFM, Isidori, König, 1901.10480]



In particular models the U_1, G' and Z' masses are related

$$M_{G'} = M_U \frac{g_U}{\sqrt{g_U^2 - g_c^2}} \sqrt{\frac{2\omega_3^2}{\omega_1^2 + \omega_3^2}}$$

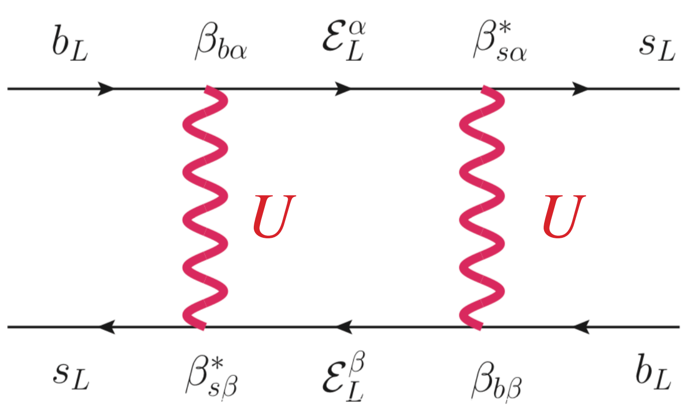
ω_i : scalar vevs

G' searches are very important for the LH leptoquark ($\beta_R = 0$)… but not so much for $\beta_R = 1$

Z' searches typically less relevant

Exotic multi-jet plus multi-lepton signatures

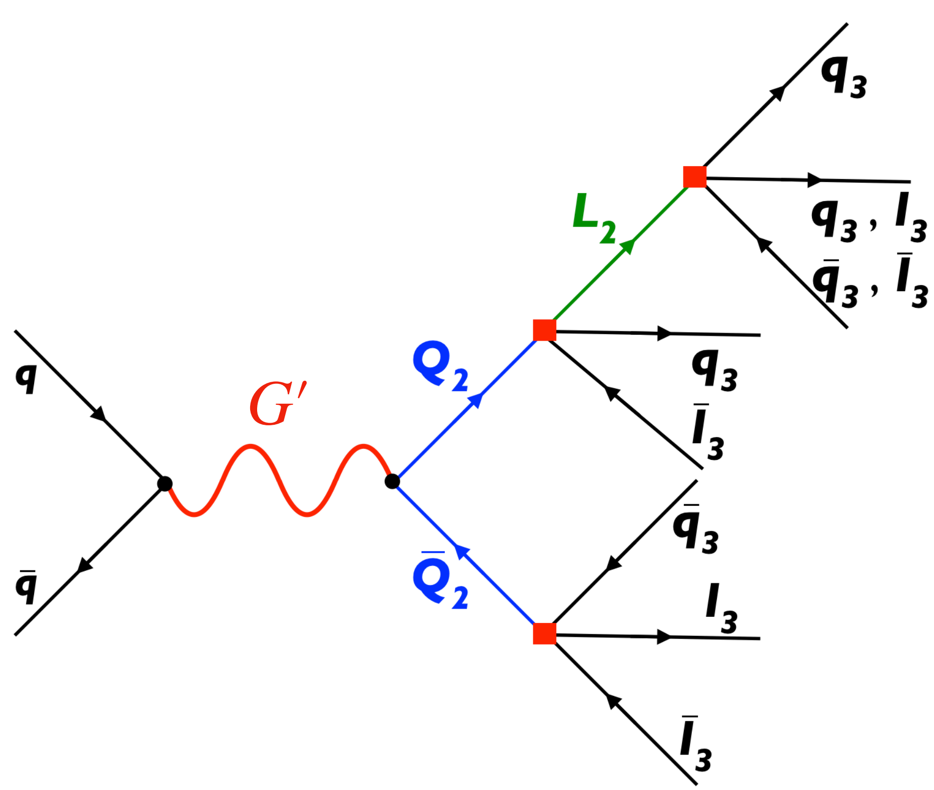
Rather generically, vector-like fermions are needed to make U_1 loops finite. Similar to the SM case with the W and the prediction of the charm quark



$$\boxed{C^{LL}_{B_s-\text{mixing}} \sim \Delta R^2_{D^{(*)}} M_L^2}$$

Vector-like fermions are expected to be the lightest states in the theory!

$M_L \sim 1$ TeV $\quad M_Q \sim 2$ TeV



Exotic multi-jet plus multi-lepton signatures within the reach of the LHC are predicted [rich signal with b-tags and τ-tags]

Similar existing SUSY searches by ATLAS (1706.03731) but a dedicated analysis is needed

[Di Luzio, JFM, Greljo, Nardecchia, Renner, 1808.00942]

Conclusions

Current data is still inconclusive and the overall picture might change but…

… it is possible to find solutions to the flavor anomalies while remaining consistent with all the other data

Interesting **connections to the SM Yukawa structure** (hinting to a possible solution of the **SM flavor puzzle**)

Going beyond simplified dynamical models is important

→ unexpected experimental signatures and constraints (G', Z', VL fermions,…)

Very interesting interplay between low-energy and high-pT data

If the anomalies are really pointing to NP, **new experimental indications** (both in high-pT and at low energies) should show up soon in several observables

… However this conclusion is strongly driven by $R(D^{(*)})$

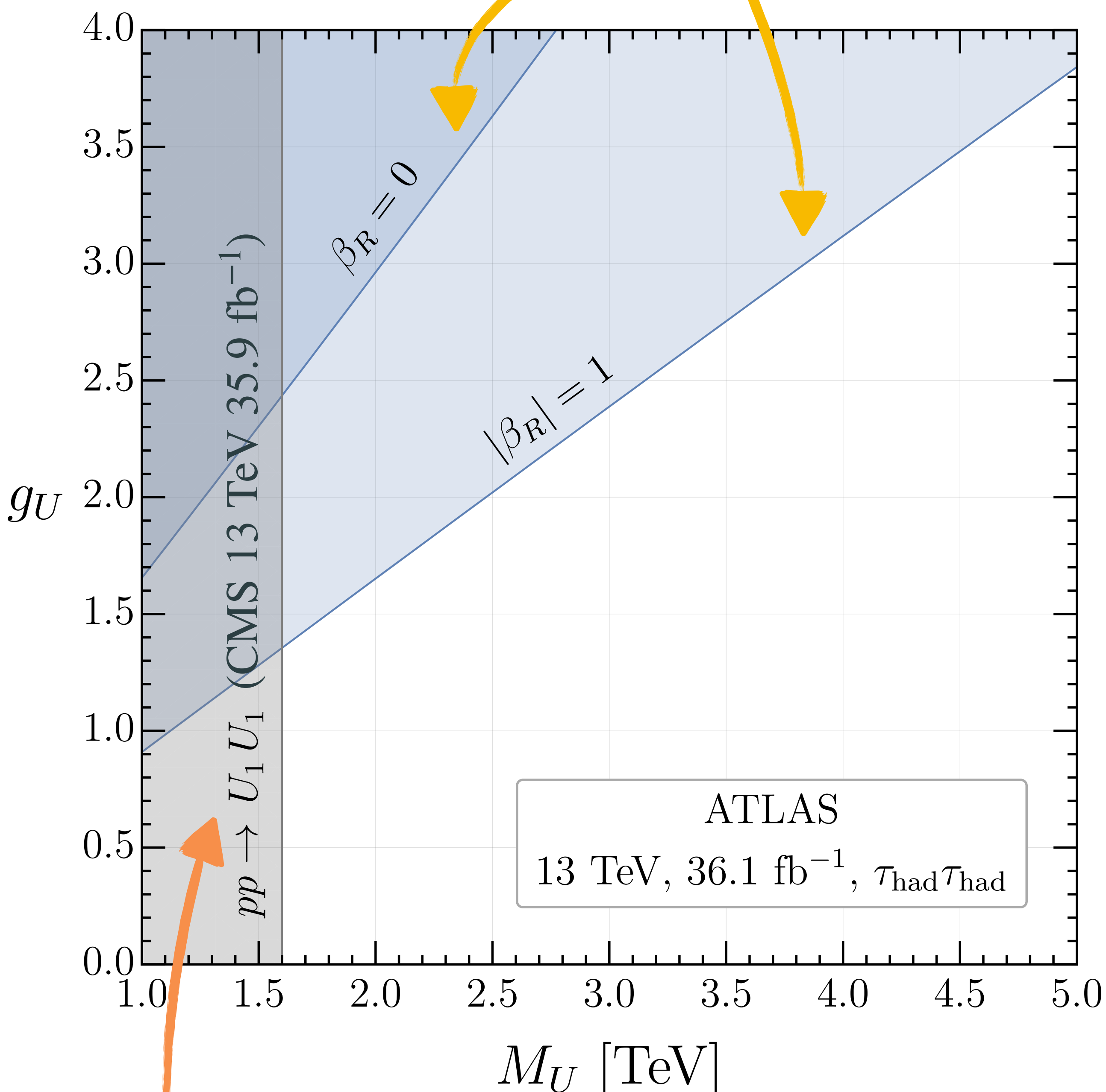
Thank you!

Backup slides

Recast of the high-pT data

$pp \to \tau\tau$ tails (in m_T^{tot})

[Baker, JFM, Isidori, König, 1901.10480]



U_1 pair production

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left(\bar{Q}_3 \gamma_\mu L_3 - \beta_R \bar{b}_R \gamma_\mu \tau_R\right)$$

$pp \to \tau\tau$ limit considerably stronger when $|\beta_R| = 1$

$M_U \gtrsim 3.8$ TeV **[LH + RH]**

$M_U \gtrsim 2$ TeV **[LH only]**

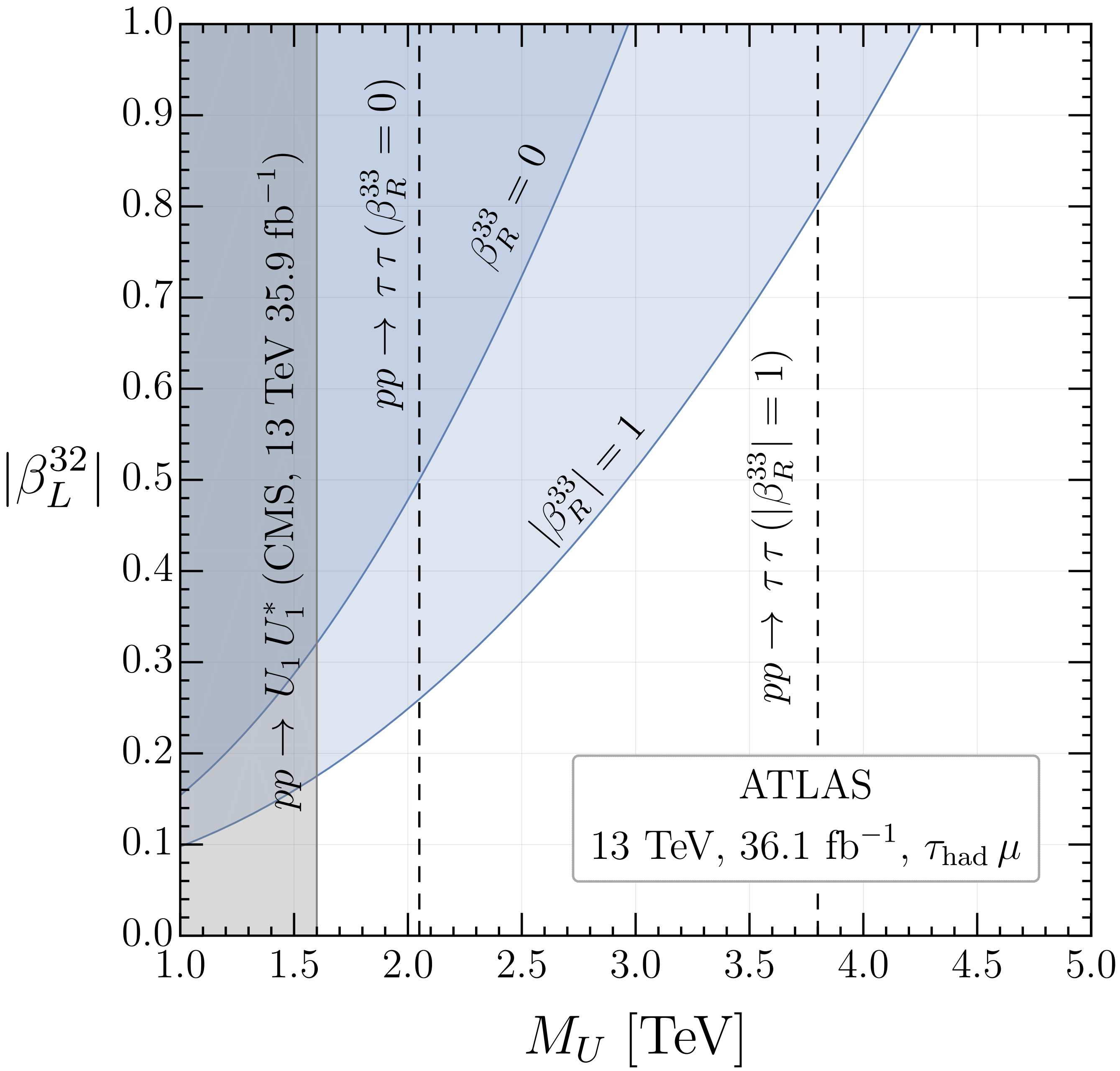
[For a benchmark of $g_U = 3.0$]

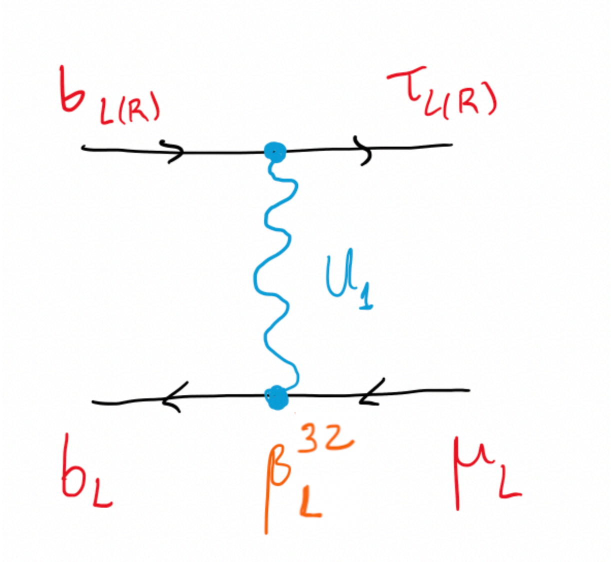
Pair production limits quite similar in both cases

Flavor physics across the scales: $pp \to \tau\mu$

[Baker, JFM, Isidori, König, 1901.10480]

$$\mathscr{L} \supset \frac{3}{\sqrt{2}} U_\mu \left(\beta_L^{32}\, \bar{Q}_3 \gamma^\mu L_2 + \bar{Q}_3 \gamma^\mu L_3 - \beta_R\, \bar{b}_R \gamma^\mu \tau_R\right)$$





Present data not very constraining ($\beta_L^{32} \sim 0.2$ preferred) but future prospects are very interesting

High-pT already provides better bounds than low-energy flavor data

$$\Upsilon \to \tau\mu \quad \ll \quad pp \to \tau\mu$$

The 4321 model(s)

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

The “original” 4321

	Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$n_{\mathrm{SM-like}} = 3$	$q_L'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
	$u_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
	$d_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
	$\ell_L'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
	$e_R'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
$n_{\mathrm{VL}} = 3$	χ_L^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
	χ_R^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
	H	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
	Ω_1	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
	Ω_3	$\overline{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$
	Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0

U_1 LH only

The “flavored” 4321

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	
$q_L'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	1st & 2nd families
$u_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	
$d_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	
$\ell_L'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	
$e_R'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1	
ψ_L^3	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0	3rd family
$\psi_{R_{u,d}}^3$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$\pm 1/2$	
χ_L^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0	$n_{\mathrm{VL}} = 2$
χ_R^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0	
$H_{1,15}$	$\mathbf{1}, \mathbf{15}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	
Ω_1	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$	
Ω_3	$\overline{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$	
Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0	

U_1 LH + RH