Universität Zürich[UZH]

New physics implications of the B-physics anomalies

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Based on
Cornella, JFM, Isidori, in preparation
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

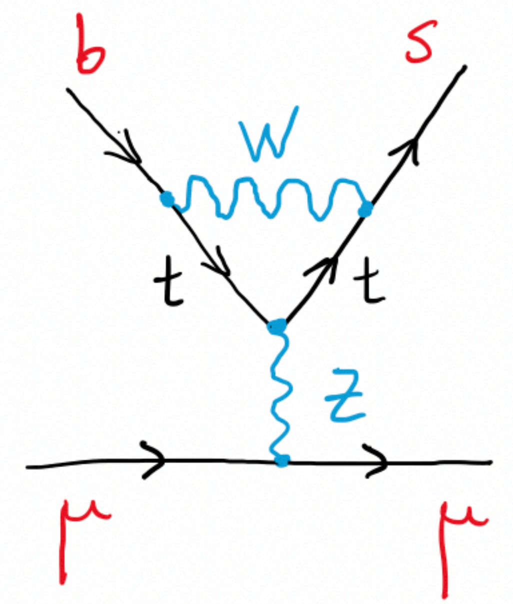
Seminar at IFAE, 1st of March 2019

The B-physics anomalies

Hints of Lepton Flavour Universality Violation in semileptonic B decays

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

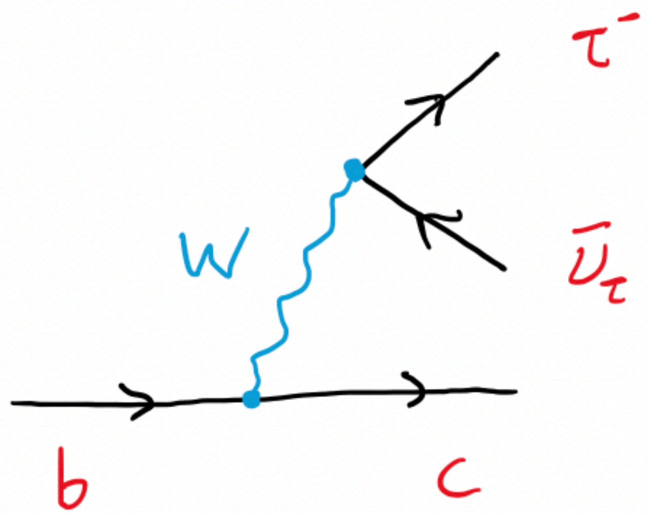
μ/e ~~universality~~



$> 4\,\sigma$

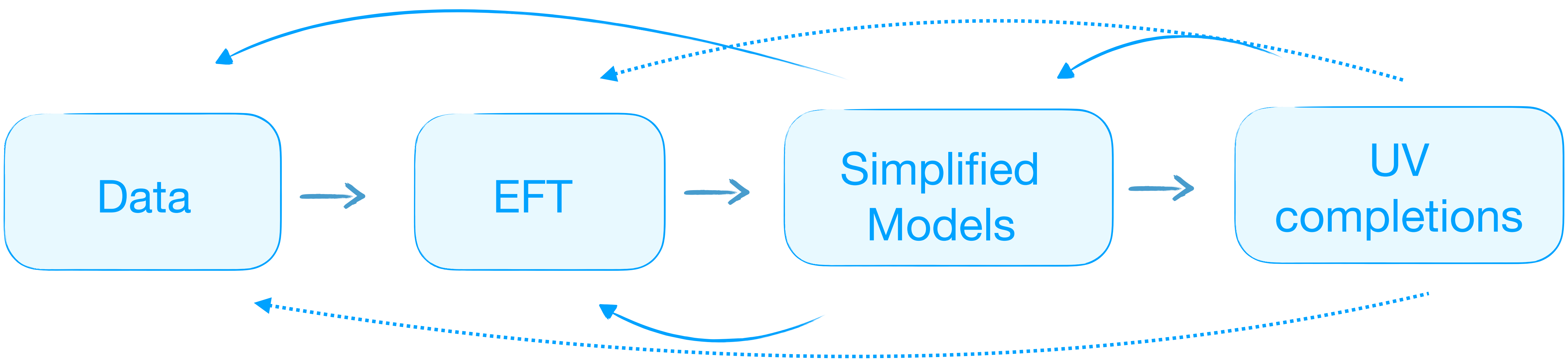
$b \to c\tau\nu$

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



$\sim 4\,\sigma$

The general approach

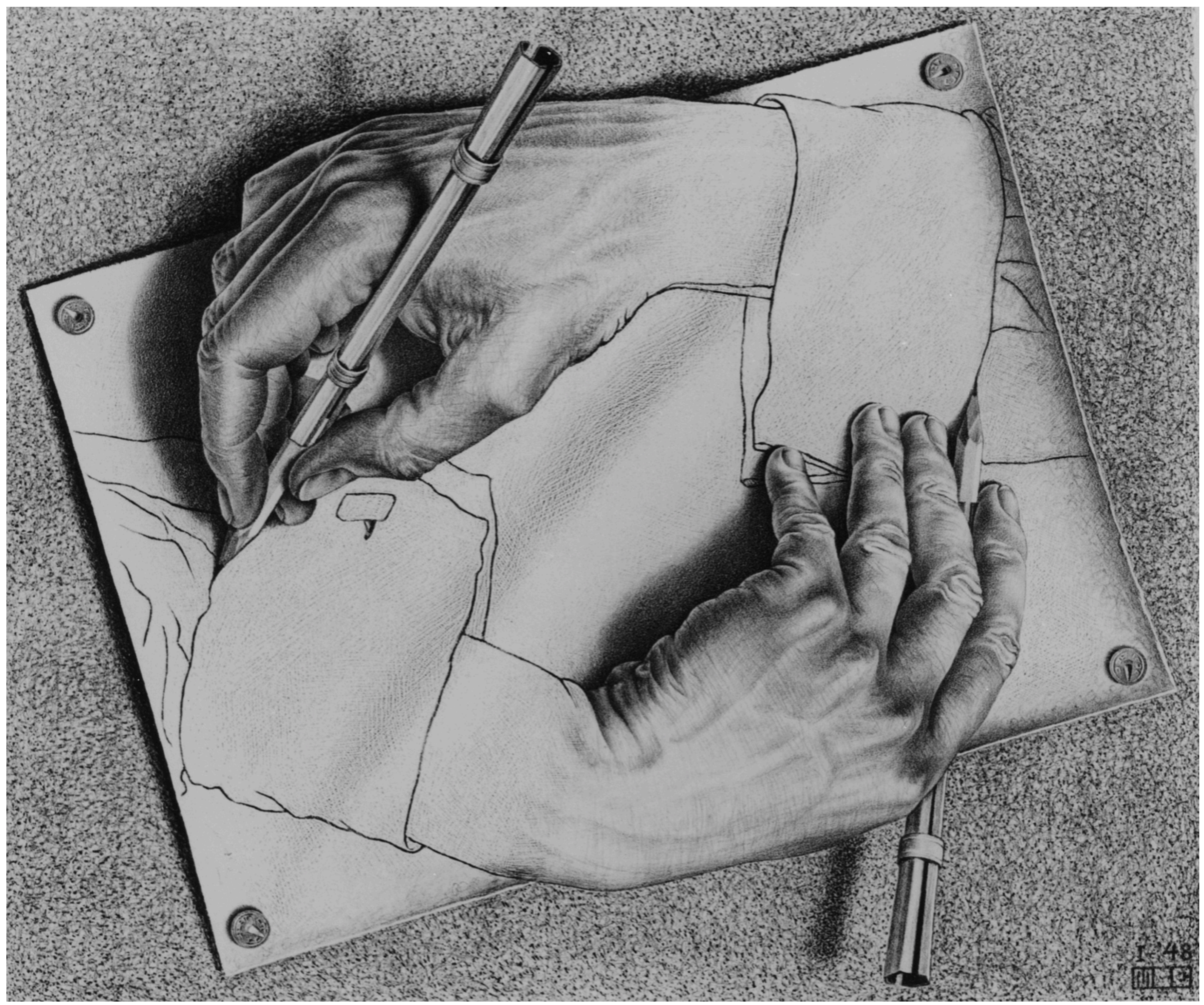


- ★ Analyze the data and compare to the SM
- ★ Find an EFT solution and investigate correlation with other observables
- ★ Implement simplified dynamical models, correlations with even more observables
- ★ Find “reasonable” UV completions, correlations with yet more observables

These steps are complementary and not unidirectional…

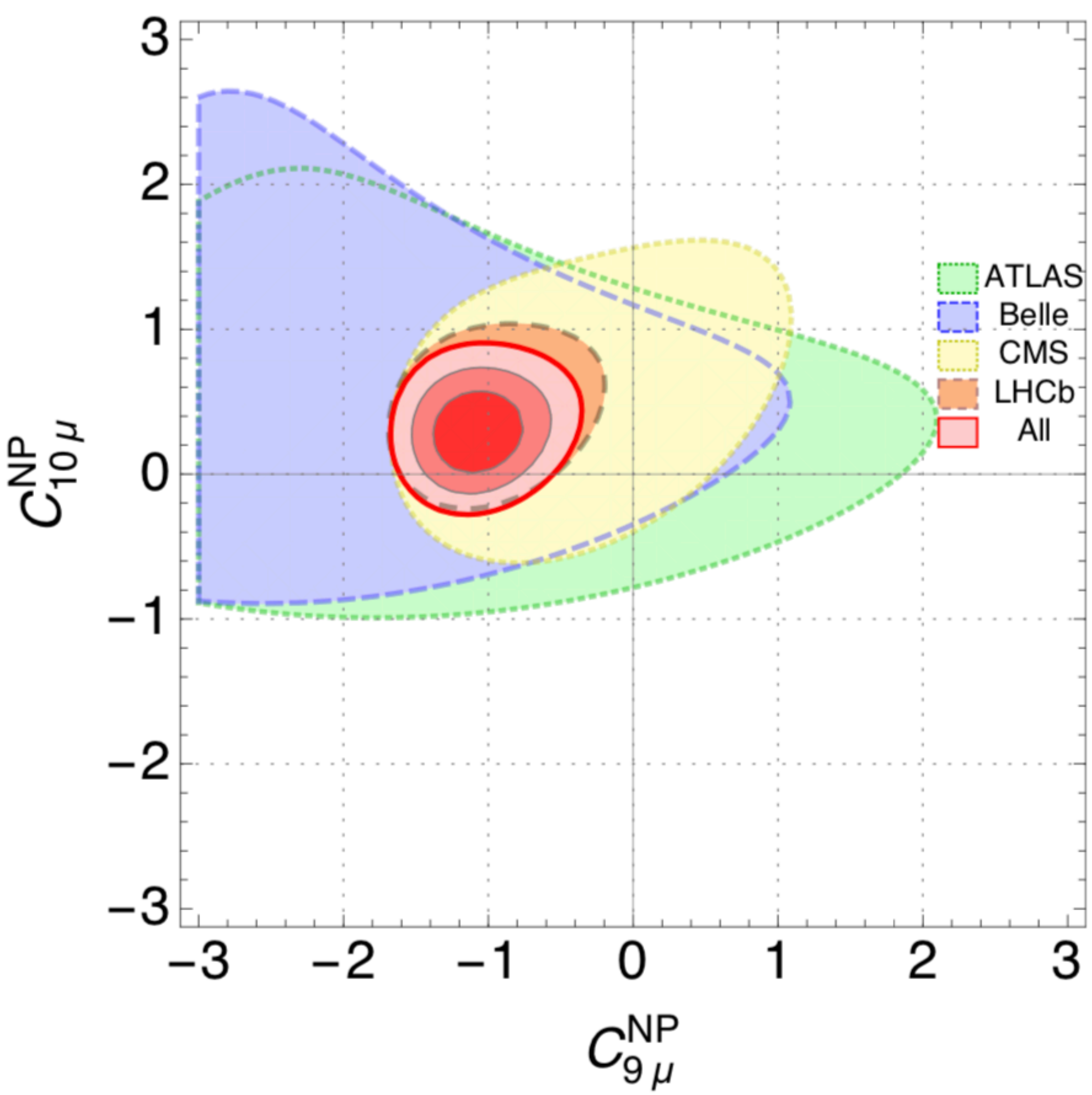
Lots of work has been done in the last years!

From data to simplified models



The $b \to s\ell\ell$ anomalies

[Capdevila et al. 1704.05340]



$$\mathcal{O}_9^\mu = (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$$

$$\mathcal{O}_{10}^\mu = (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

Anomalies observed in $b \to s\ell\ell$ $(\ell = e, \mu)$ transitions [$\sim 5\sigma$ from the SM]

★ Many observables (~ 100) involved [$R_K, R_{K^*}, P_5', b \to s\mu\mu$ branching fractions…]

★ "Theoretically clean" LFU ratios alone give a (combined) $\sim 4\sigma$ deviation

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

★ Mostly driven by LHCb

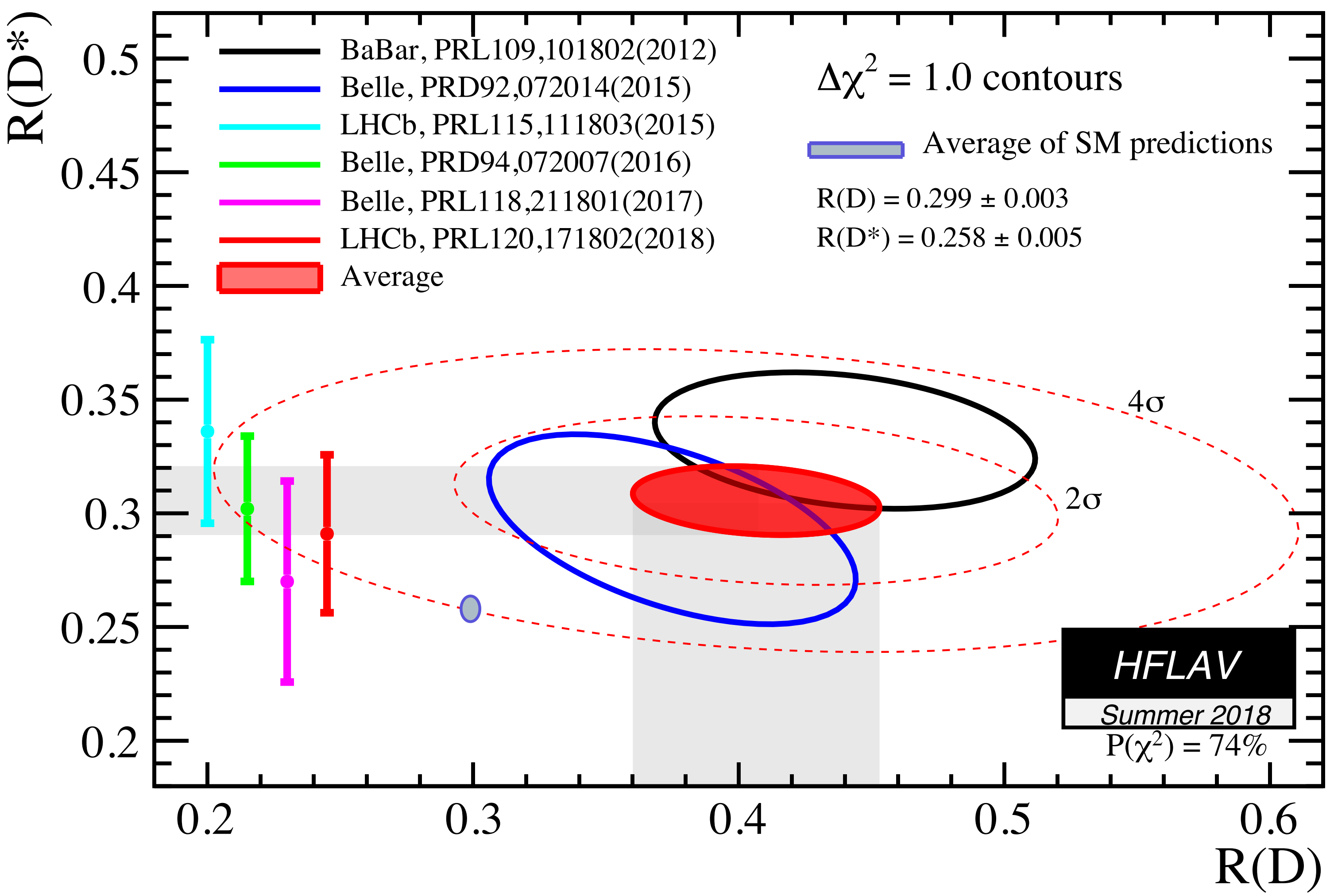
★ New measurements expected this year!

The $R(D^{(*)})$ anomalies

Experimental measurements disagree by almost 4σ with the SM in $b \to c\tau\nu$ transitions…

$$R(D^{(*)}) = \frac{\mathscr{B}(B \to D^{(*)}\tau\nu)}{\mathscr{B}(B \to D^{(*)}\ell\nu)}$$

$$(\ell = \mu \text{ or } e + \mu)$$



★ **SM prediction quite solid:** hadronic uncertainties cancel (to a large extent) in the ratio

★ Consistent results by 3 very different experiments

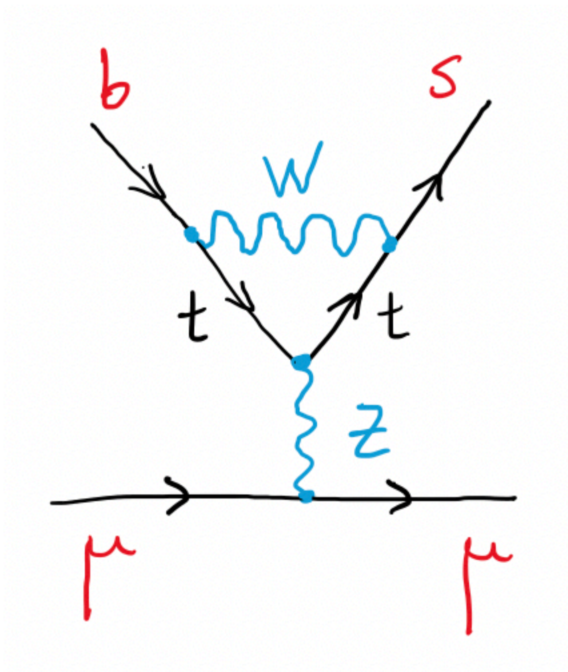
Preliminary hints for deviations in $B_c \to J/\psi\tau\nu$: $R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$

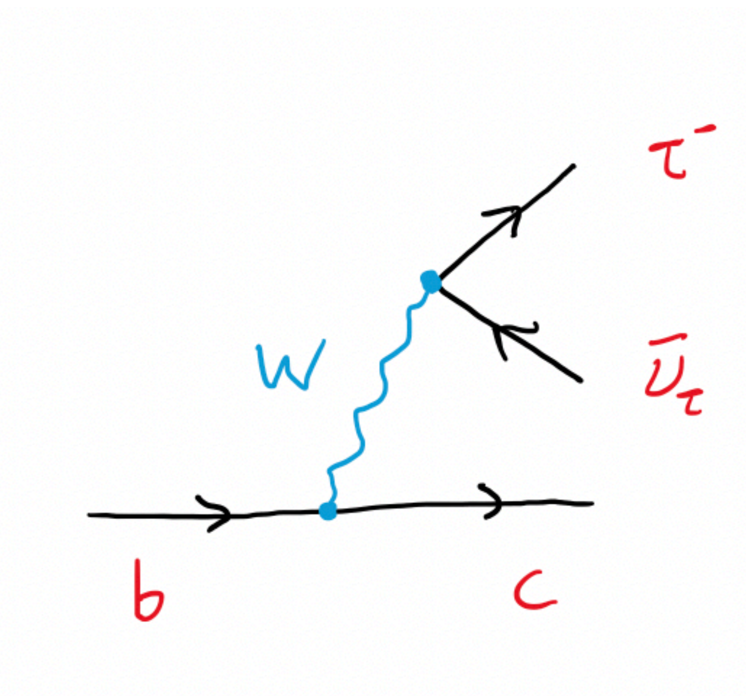
[LHCb Collaboration 1711.05623]

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?

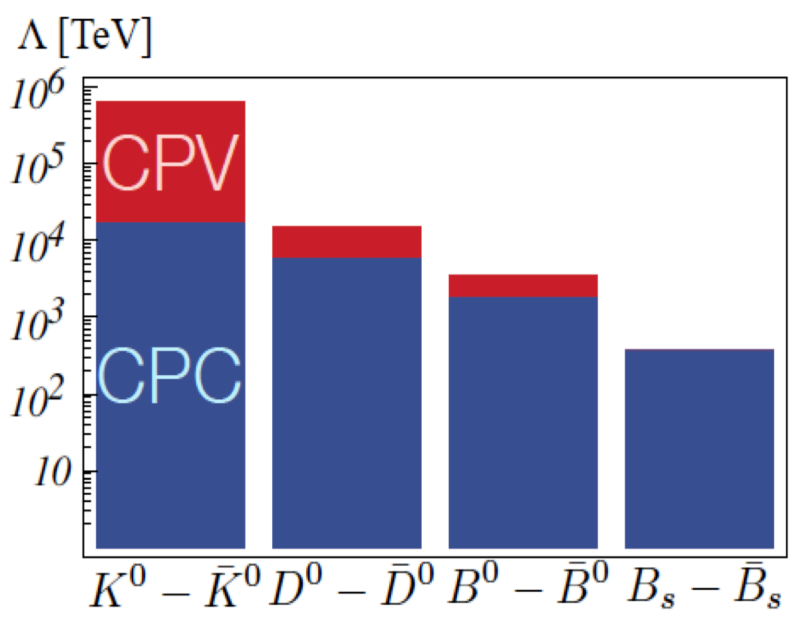
What are the anomalies telling us?

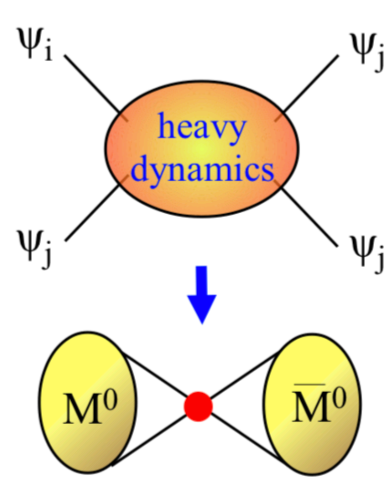
A combined explanation calls for NP: $^{(*)}$

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

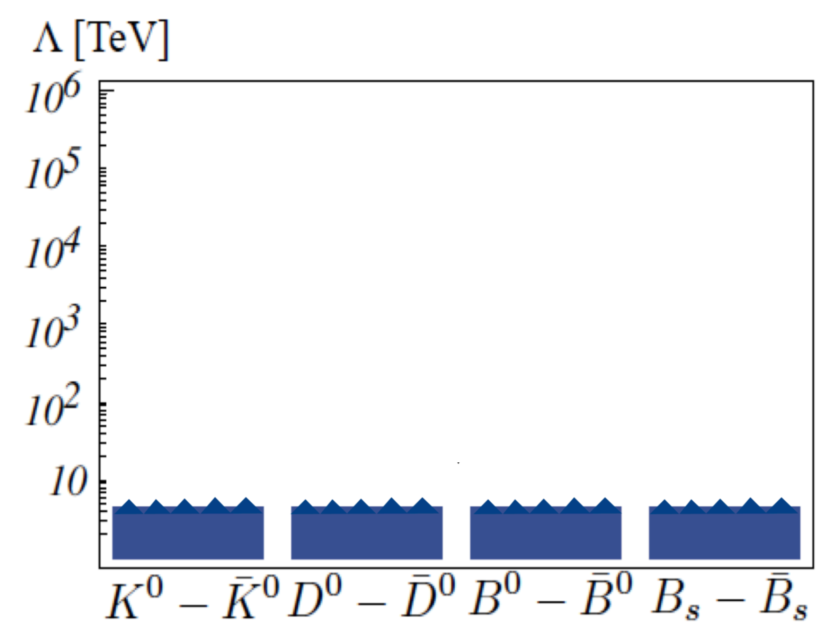
- ★ Coupled dominantly to the **3rd generation**
- ★ $\Lambda_{\rm NP} \sim \mathcal{O}(1\ {\rm TeV})$

Anarchical couplings





Hierarchical couplings

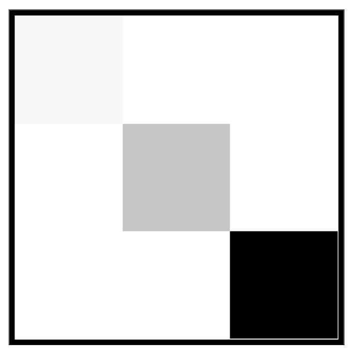


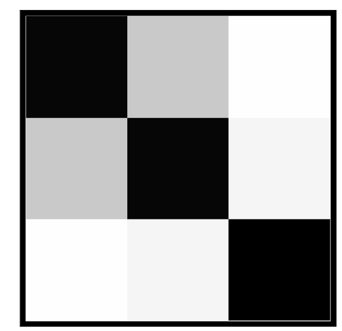
Severe constraints on generic new (BSM) flavor breaking sources
(mis)interpreted as indication of a high flavor scale

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

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

$V_{\mathrm{CKM}} \sim$ 

- ✓ 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]

An EFT solution

Minimal setup for a combined explanation of B anomalies [avoiding too large effects in $b \to s\bar{\nu}\nu$]: SU(2)$_L$ singlet + triplet

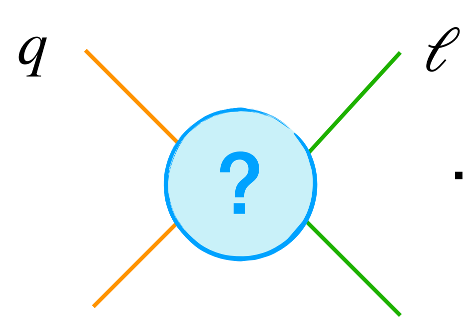
$$\mathscr{L}_{EFT} \supset \frac{1}{\Lambda^2}\left[C_T\,(\bar{q}^i_L\,\gamma^\mu\,\tau^a\,q^j_L)(\ell^\alpha_L\,\gamma_\mu\,\tau^a\,\ell^\beta_L) \;+\; C_S\,(\bar{q}^i_L\,\gamma^\mu\,q^j_L)(\ell^\alpha_L\,\gamma_\mu\,\ell^\beta_L)\right]$$

✓ solution based on an approximate $U(2)_q \times U(2)_\ell$ flavor symmetry is viable

[Buttazzo et al. 1706.07808]

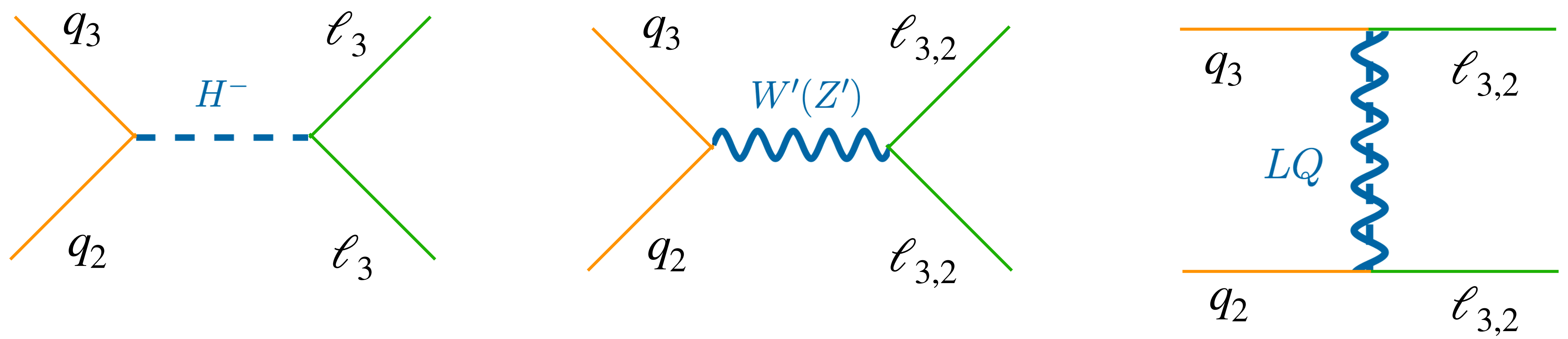
$$\psi = (\,\psi_1\;\psi_2\;\psi_3\,)$$

★ possible modifications (scalar/tensor operators, RH currents) might help for $R_{D^{(*)}}$ and/or $b \to s\mu\mu$



.....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

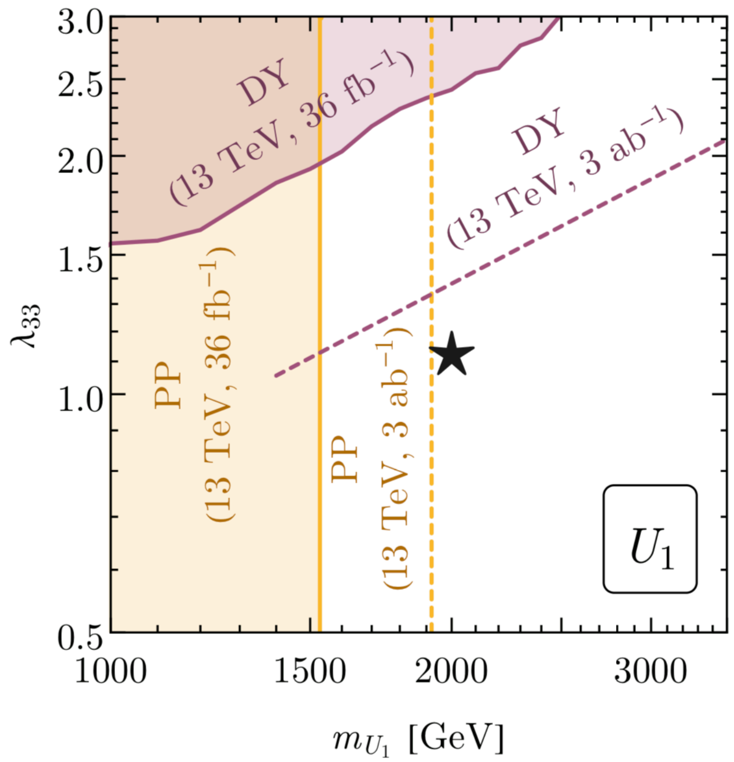
Revisiting the U_1 solution

The U_1 leptoquark: the pure LH case

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

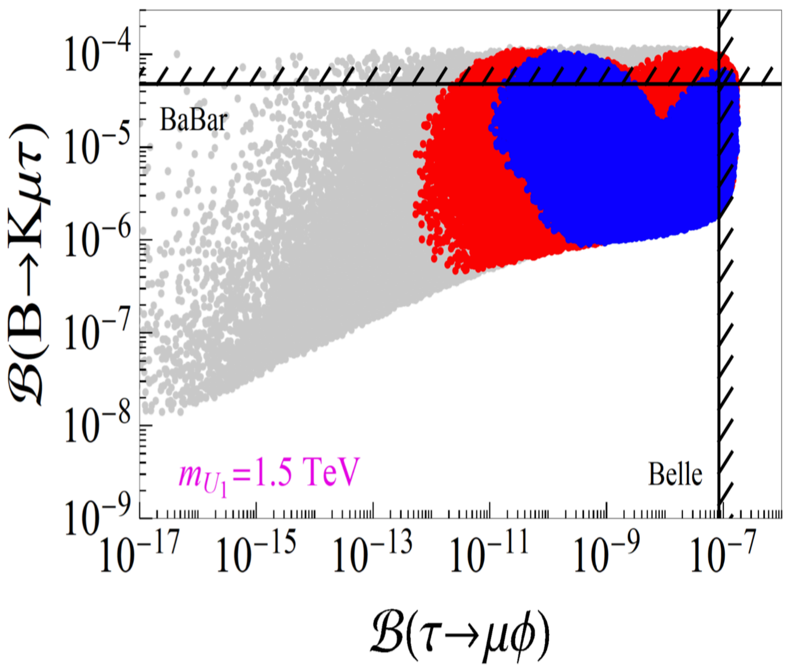
Pure LH U_1 (i.e. $\beta_{i\alpha}^R = 0$) extensively analyzed in the recent literature…

Safe from high-pT



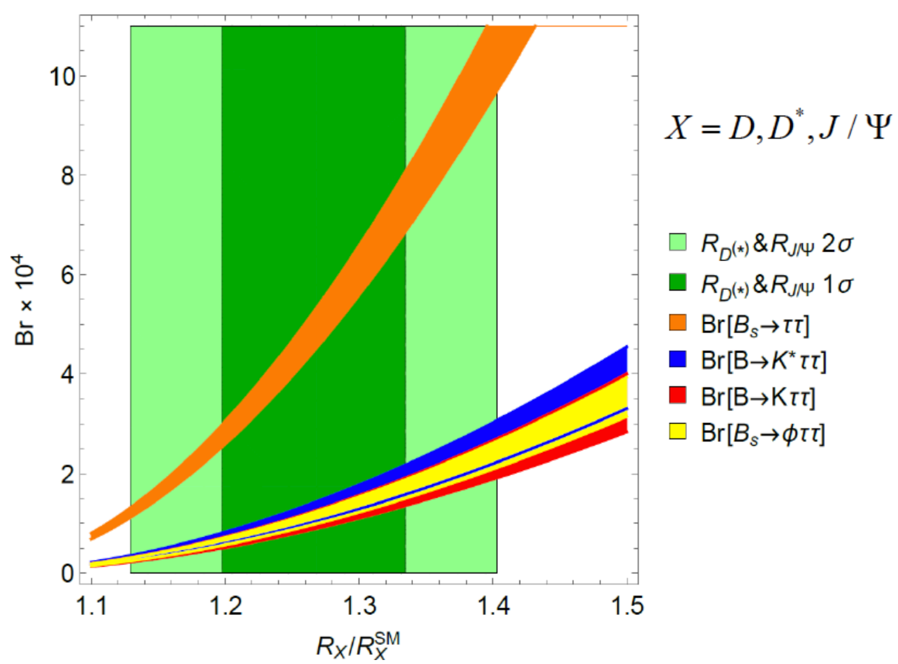
[Schmaltz, Zhong, 1810.10017]
(see also 1808.08179, 1609.07138)

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

$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta^L_{i\alpha} (\bar{q}^i_L \gamma_\mu \ell^\alpha_L) - \beta^R_{i\alpha} (\bar{d}^i_R \gamma_\mu e^\alpha_R) \right] + \mathrm{h.c.}$$

Flavor structure$^{(*)}$

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

$\beta^L_{b\tau} = 1$

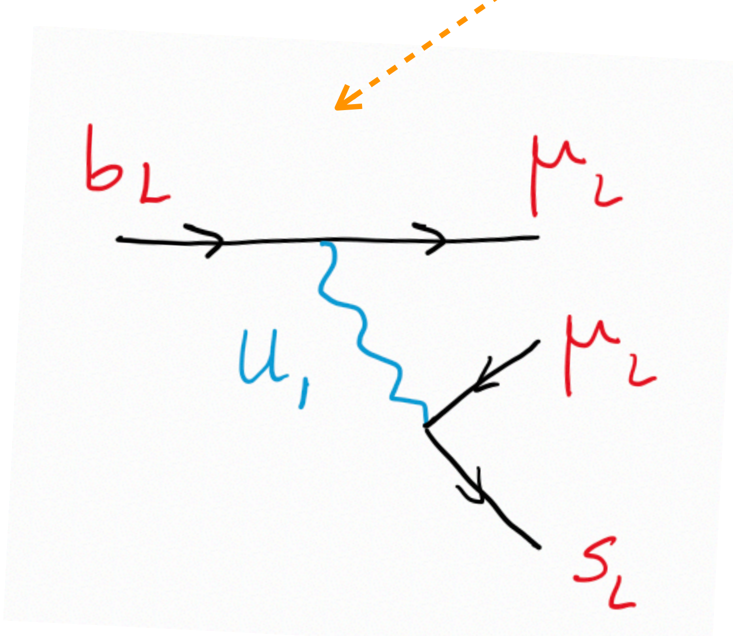
$\beta^R_{b\tau} \sim \mathcal{O}(1)$

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

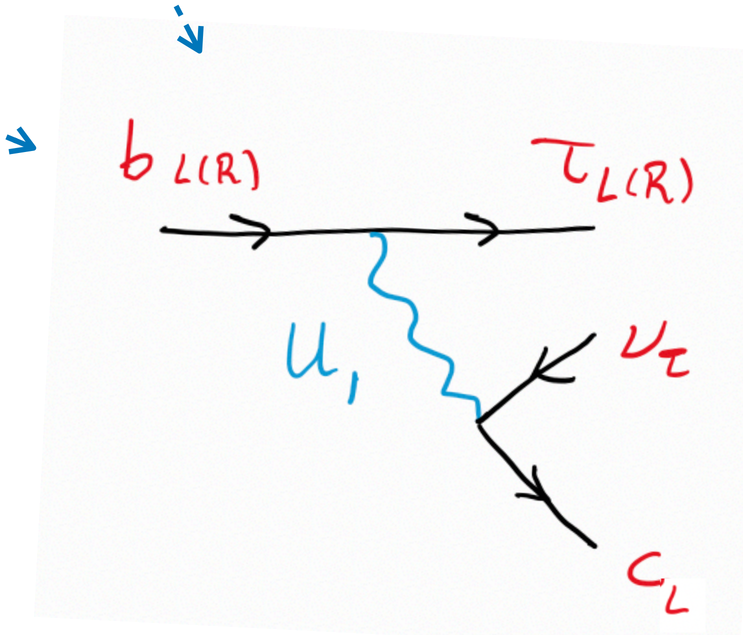
$\beta^L_{s\mu}, \beta^L_{d\tau} \sim \mathcal{O}(0.01)$

C_{V_L}

C_{S_R}

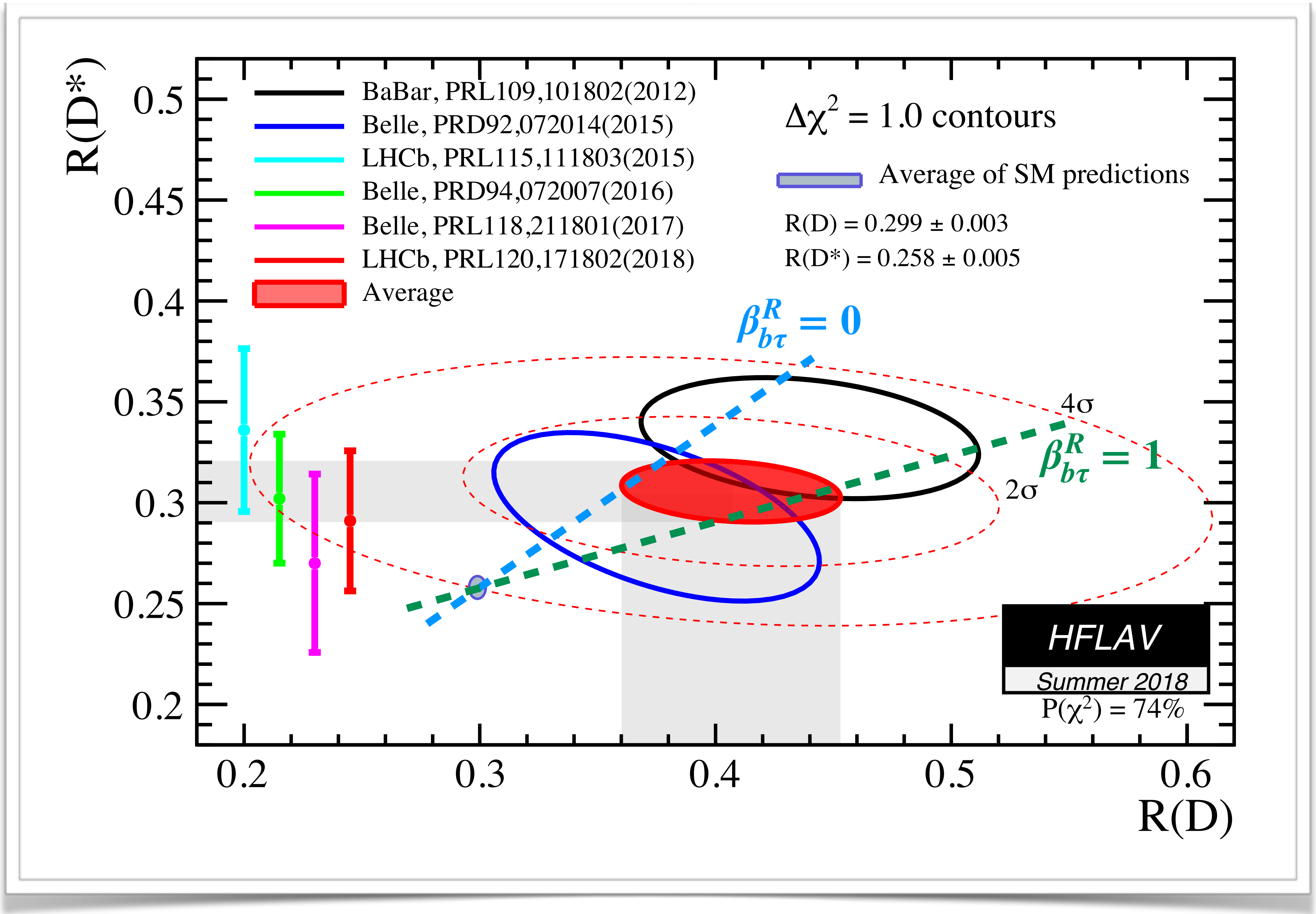


$R(K^{(*)}) \ll R(D^{(*)})$



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

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

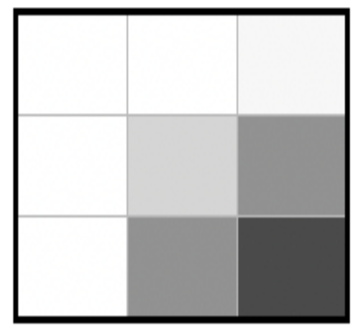


Differential distributions, polarizations,… could also be different from the SM

[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 observables

Observable	Experiment	Corr.	SM
R_D	$0.407(46)$	-0.20	$0.299(3)$
R_{D^*}	$0.304(15)$		$0.260(8)$
$\mathcal{B}(B \to \tau\bar{\nu})$	$1.09(24) \cdot 10^{-4}$	–	$0.807(61) \cdot 10^{-4}$
$\Delta\mathcal{C}_9^{\mu\mu} = -\Delta\mathcal{C}_{10}^{\mu\mu}$	$-0.64(13)$ (*)	-0.01	–
$\Delta\mathcal{C}_9^{U} = \Delta\mathcal{C}_{10}^{U}$	$-0.44(15)$		–
$\mathcal{B}(B_s \to \tau^+\tau^-)$	$0.0(3.4) \cdot 10^{-3}$	–	$7.73(49) \cdot 10^{-7}$
$\mathcal{B}(\tau \to \mu\gamma)$	$0(3) \cdot 10^{-8}$	–	–
$\mathcal{B}(B^+ \to K^+\tau^+\mu^-)$	$0.0(1.7) \cdot 10^{-5}$	–	–
$\mathcal{B}(\tau \to \mu\phi)$	$0.0(5.1) \cdot 10^{-8}$	–	–
$(g_\tau/g_\mu)_{\ell,\pi,K}$	1.0000 ± 0.0014	–	$1.$

(*) From Algueró, Capdevila, Descotes-Genon, Masjuan, Matias, 1809.08447

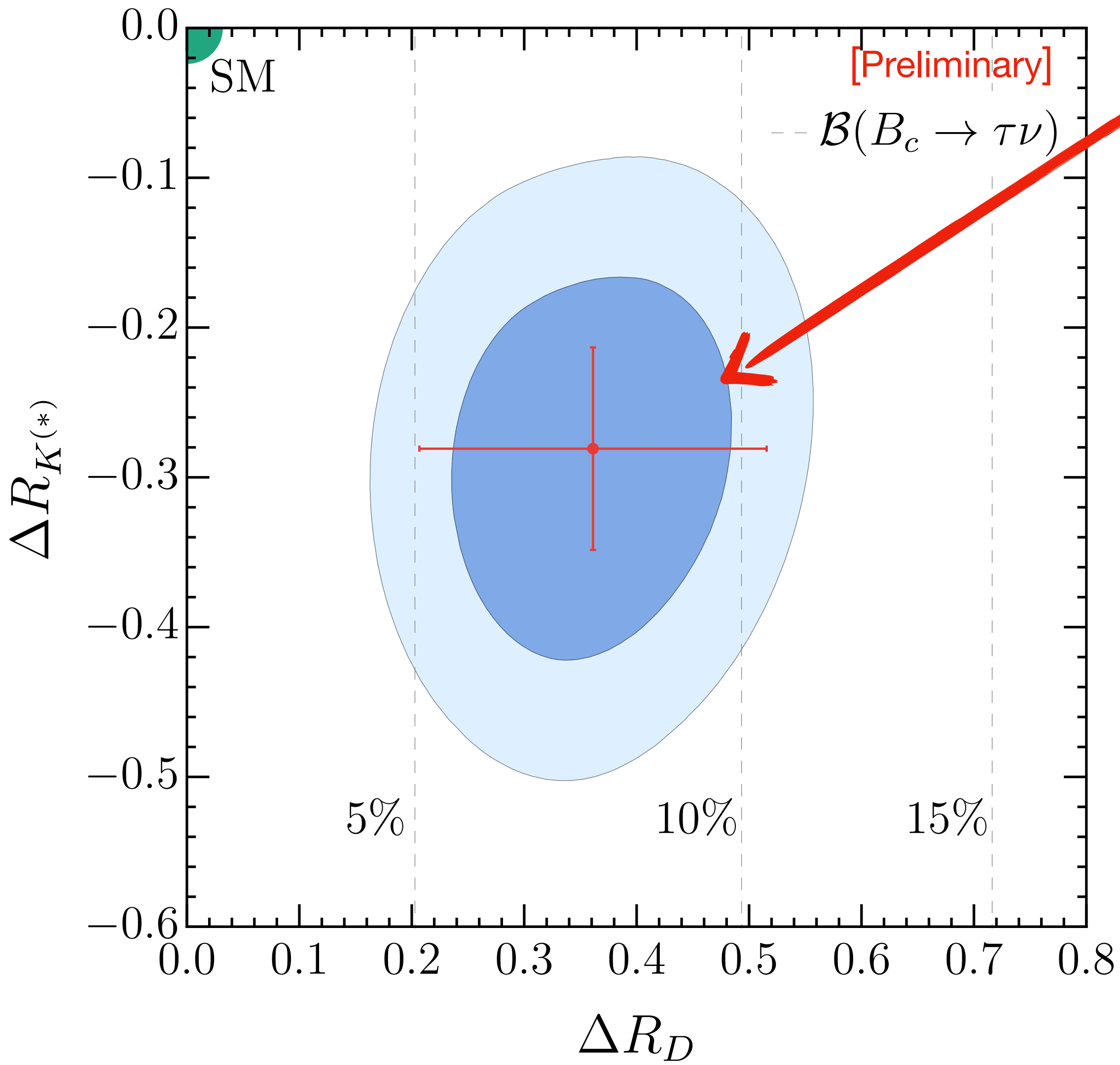
Low-energy fit results

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

Experiment

@ 1σ

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

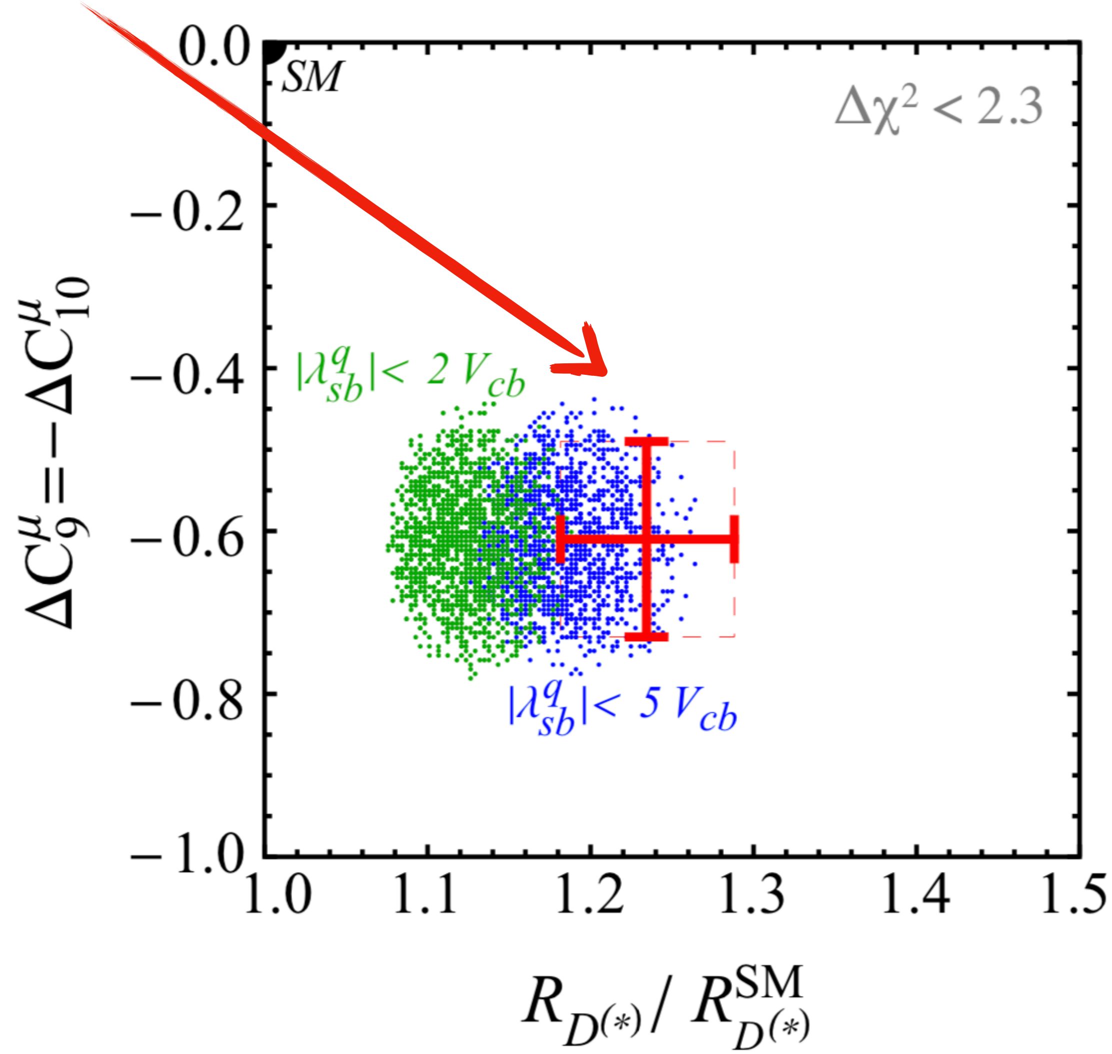


NP scale naturally higher

(thanks to the C_{S_R} contribution)

[Cornella, JFM, Isidori, in preparation]

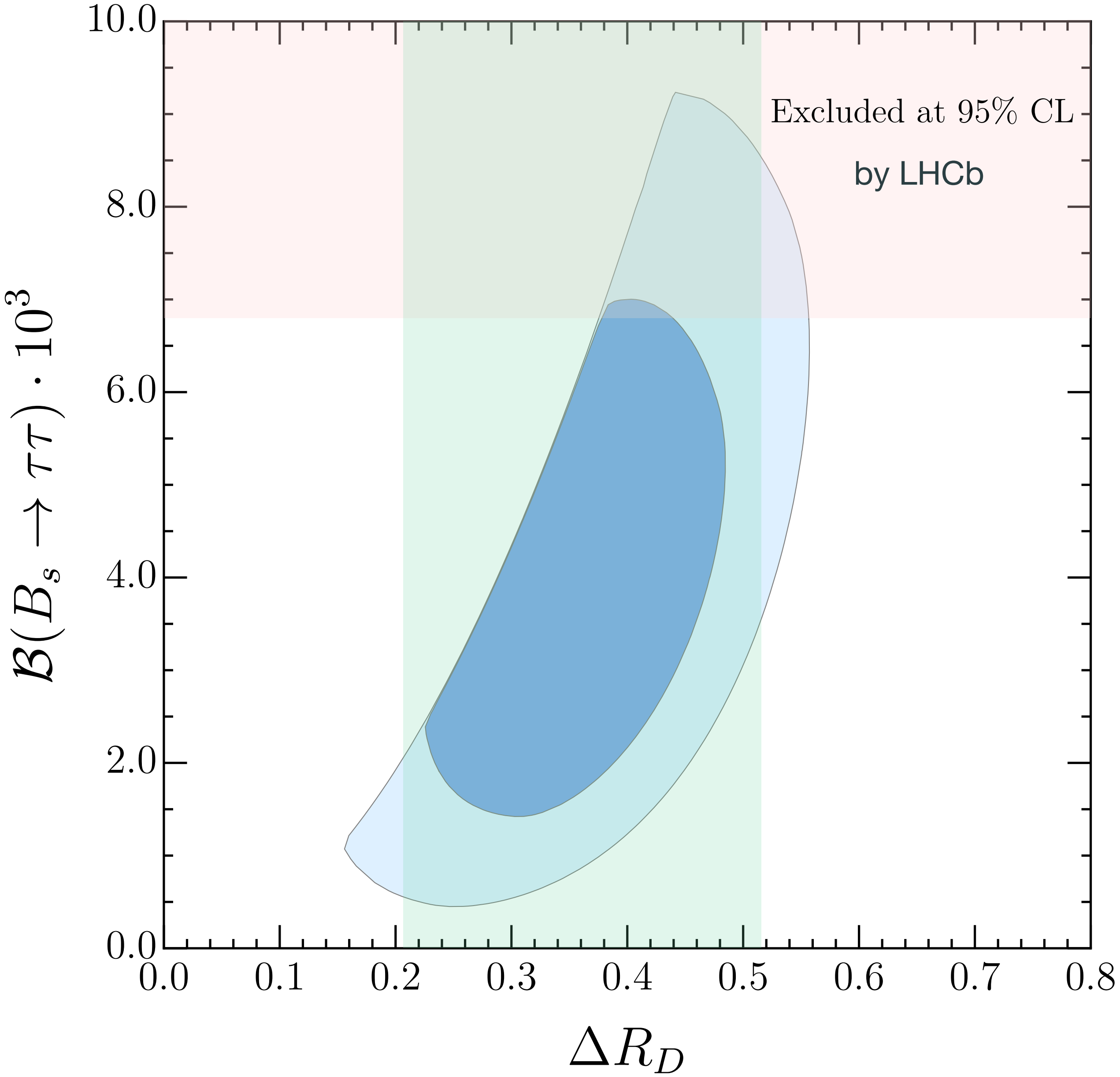
LH only $(\beta_{b\tau}^{R} = 0)$



[Buttazzo et al. 1706.07808]

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

[Preliminary]



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

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

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

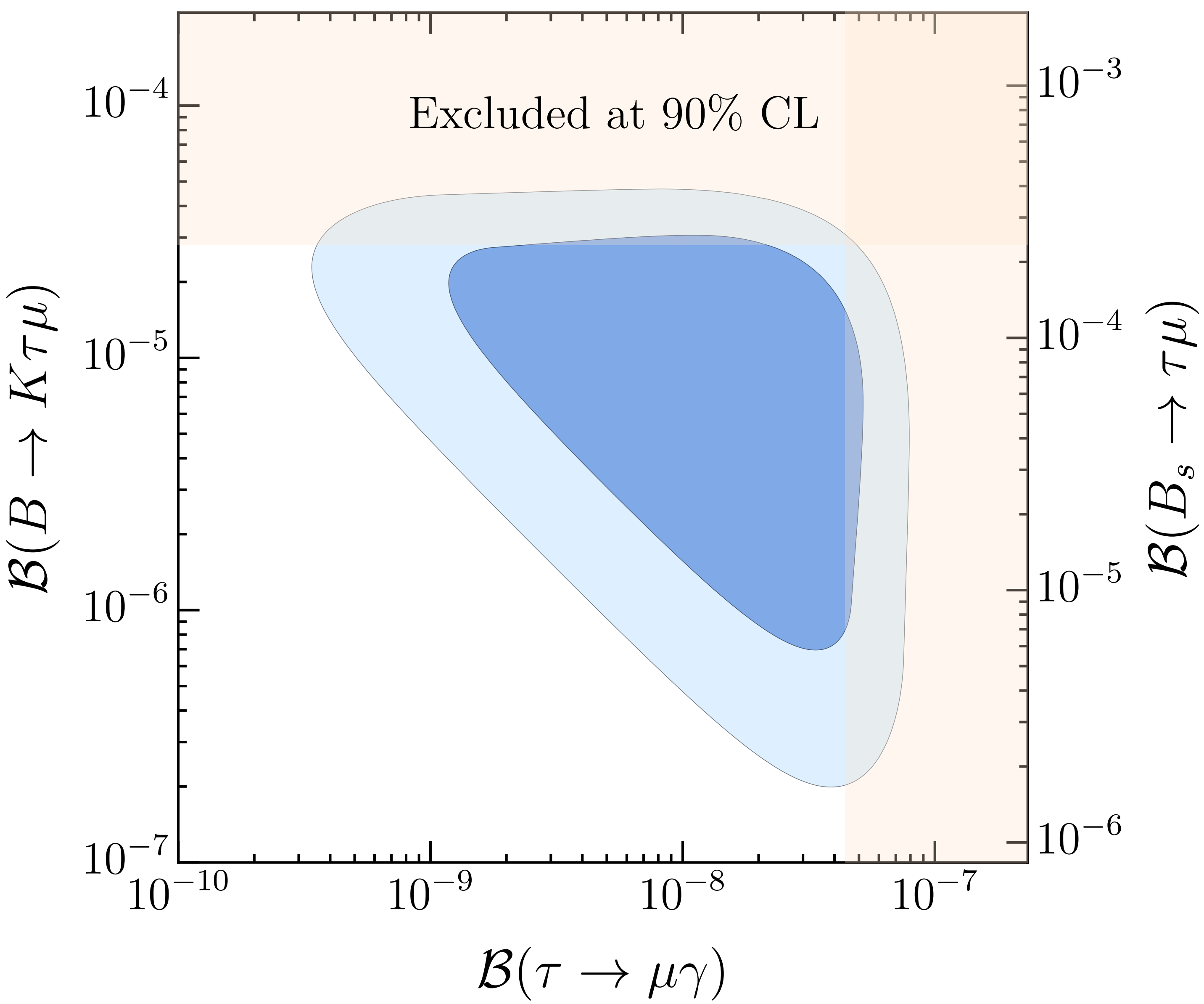
[Bobeth et al. 1311.0903]

→ Exp. limit around the corner

[Cornella, JFM, Isidori, in preparation]

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

[Preliminary]



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

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

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

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

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

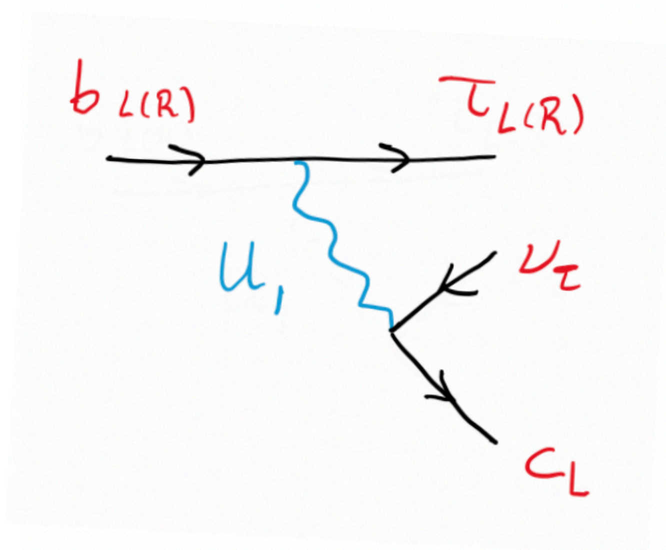
Great experimental perspectives at LHCb and Belle II

[Cornella, JFM, Isidori, in preparation]

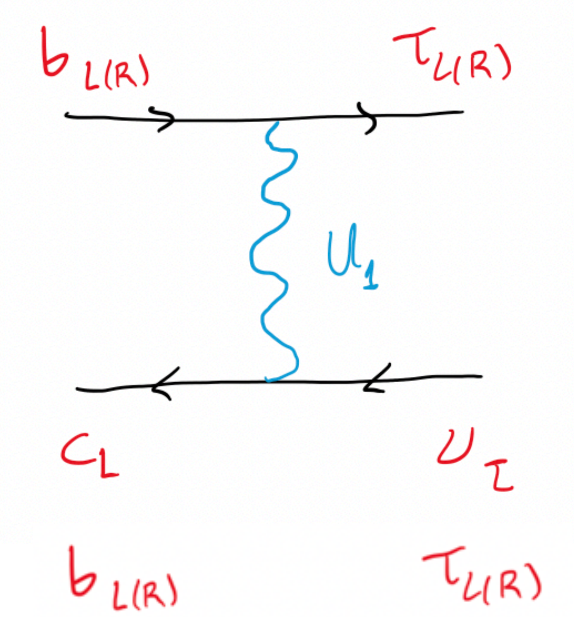
Hunting the U_1 at high-pT

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

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



High-pT

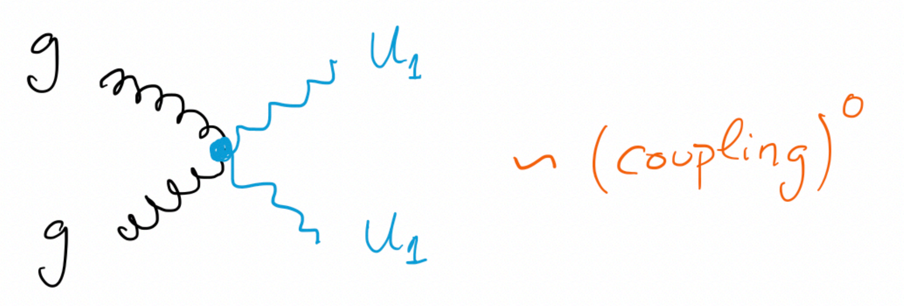


… however many of the current searches are not optimized to look for it

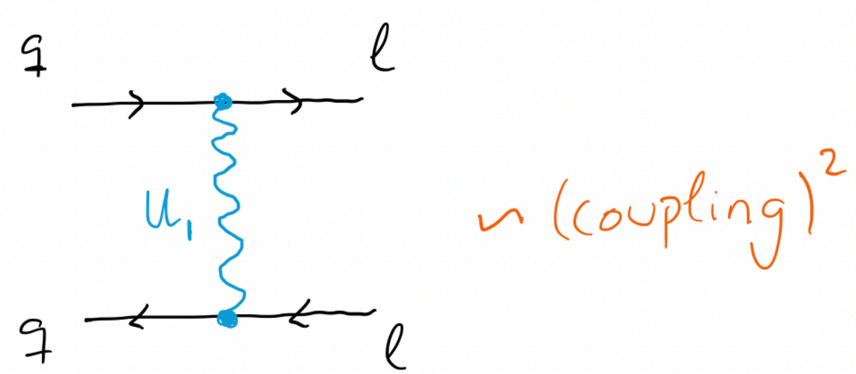
NP effects do not show up as bumps but rather as modifications in the tails of some kinematical distribution (e.g. dilepton transverse mass)

High-pT leptoquark limits

Pair production (PP)

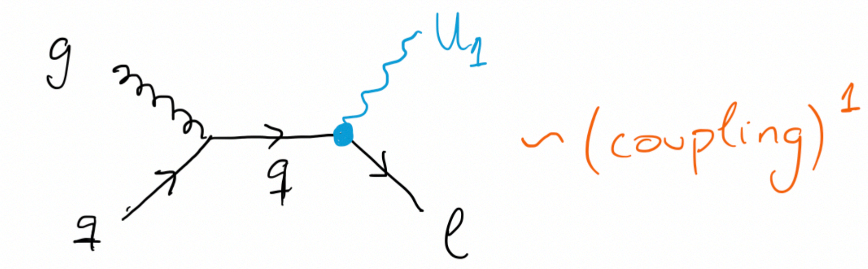


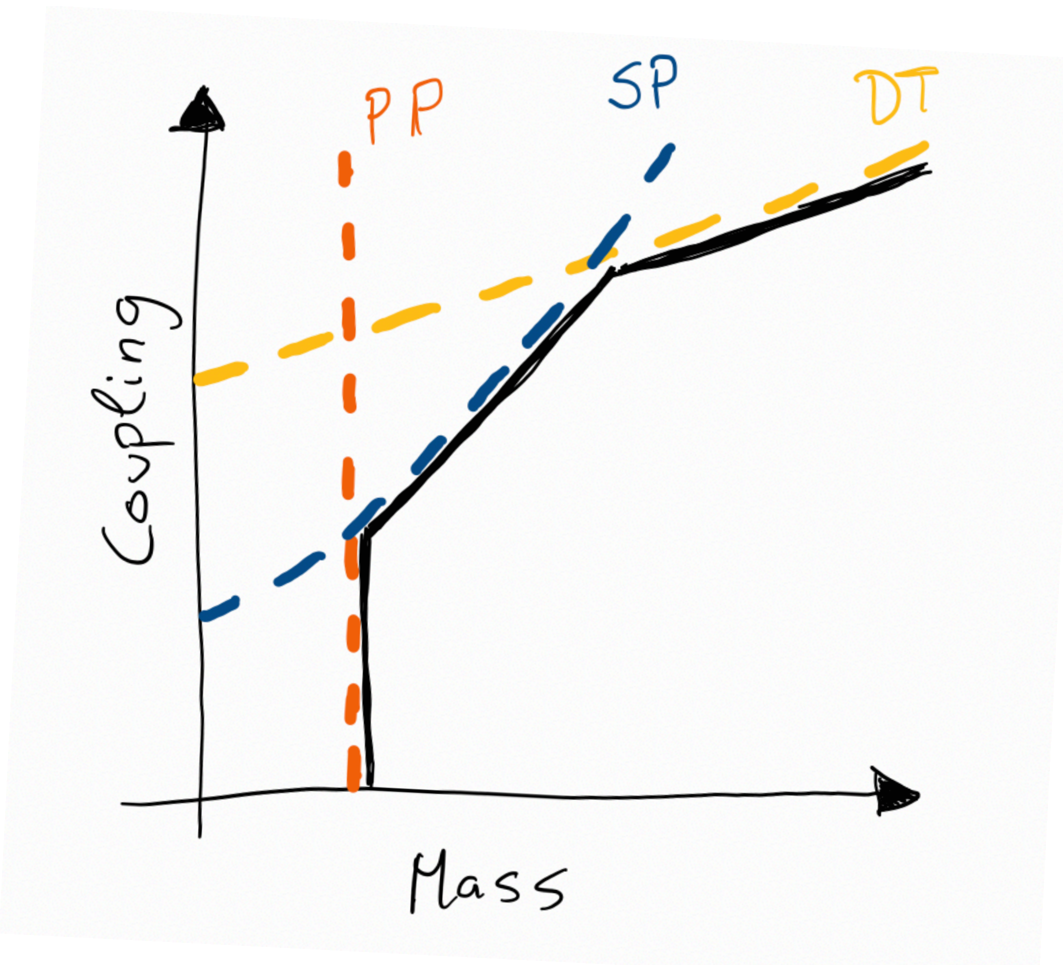
Dilepton tails (DT)



This talk!

Single production (SP)

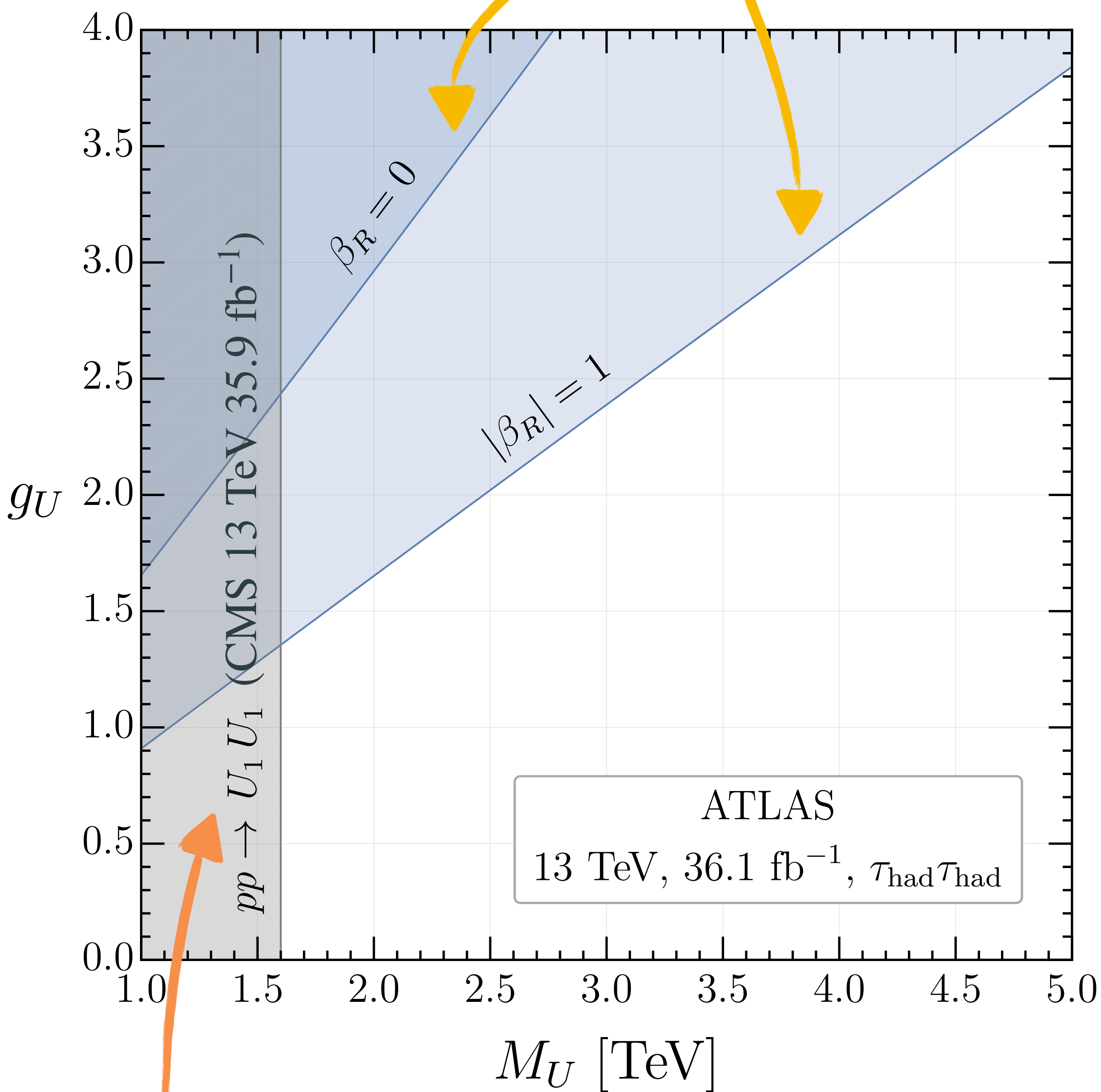




Recast of the high-pT data

[Baker, JFM, Isidori, König, 1901.10480]

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



U_1 pair production

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

$pp \to \tau\tau$ 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 $g_U = 3.0$]

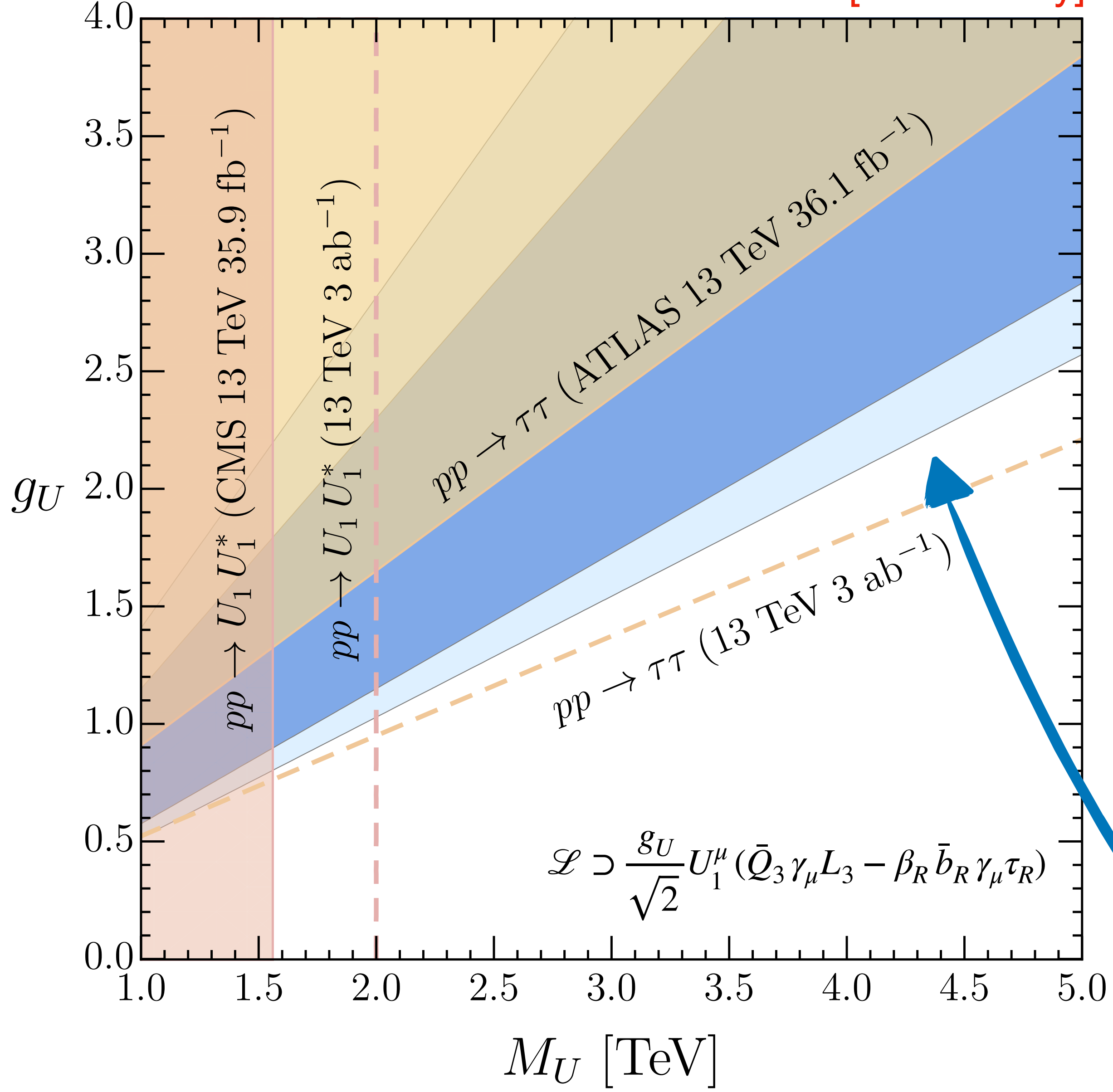
Pair production limits quite similar in both cases

High-pT + Low energy

LH + RH

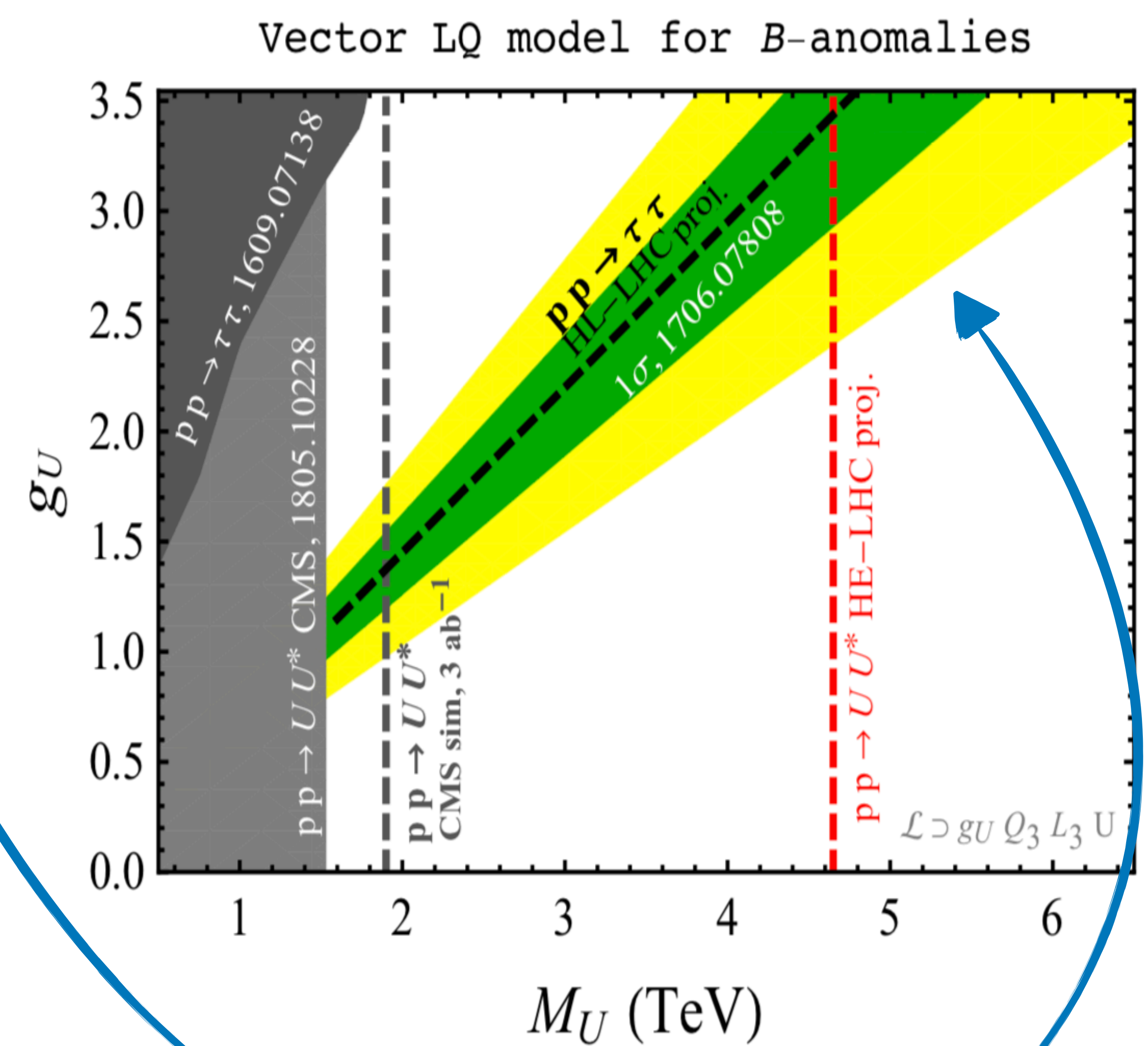
[Cornella, JFM, Isidori, in preparation]

[Preliminary]



LH only

[A. Cerri et al, 1812.07638]



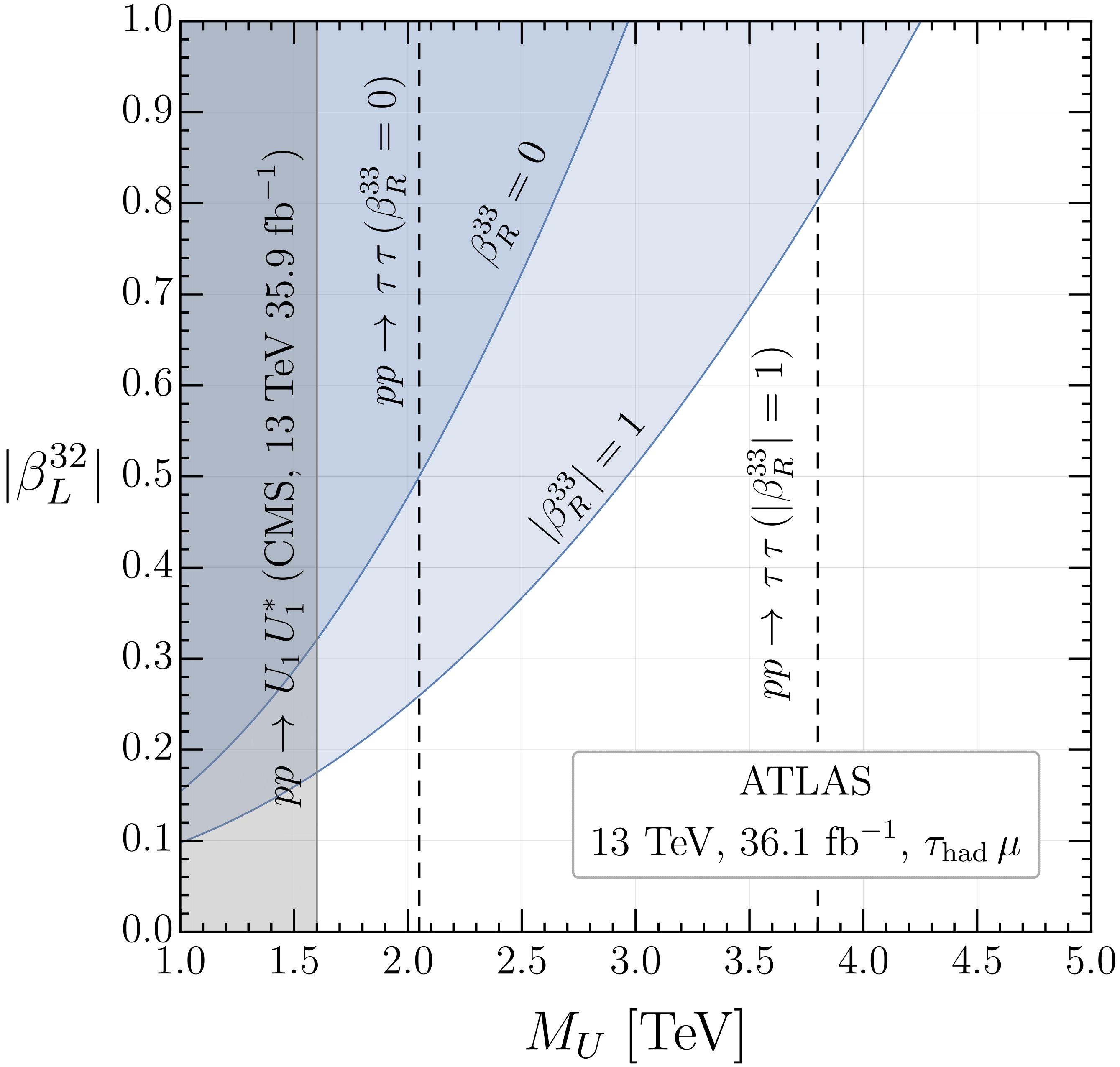
LH + RH ($\beta^R_{b\tau} = 1$) scenario will be fully probed by the HL-LHC!

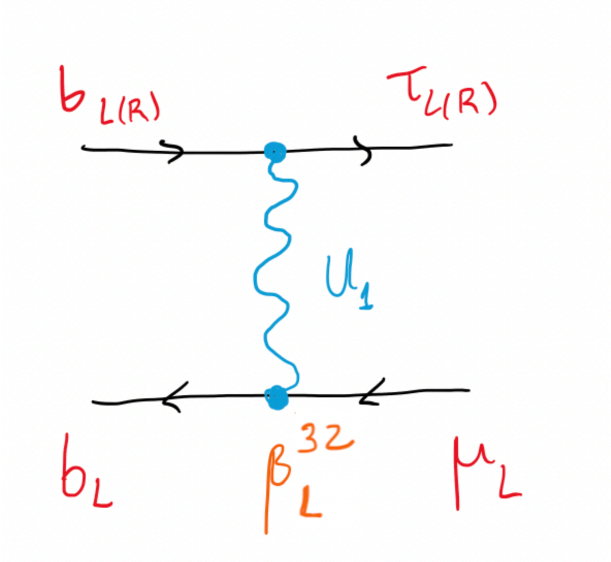
1 and 2 σ regions preferred by the low-energy fit

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

[Baker, JFM, Isidori, König, 1901.10480]

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



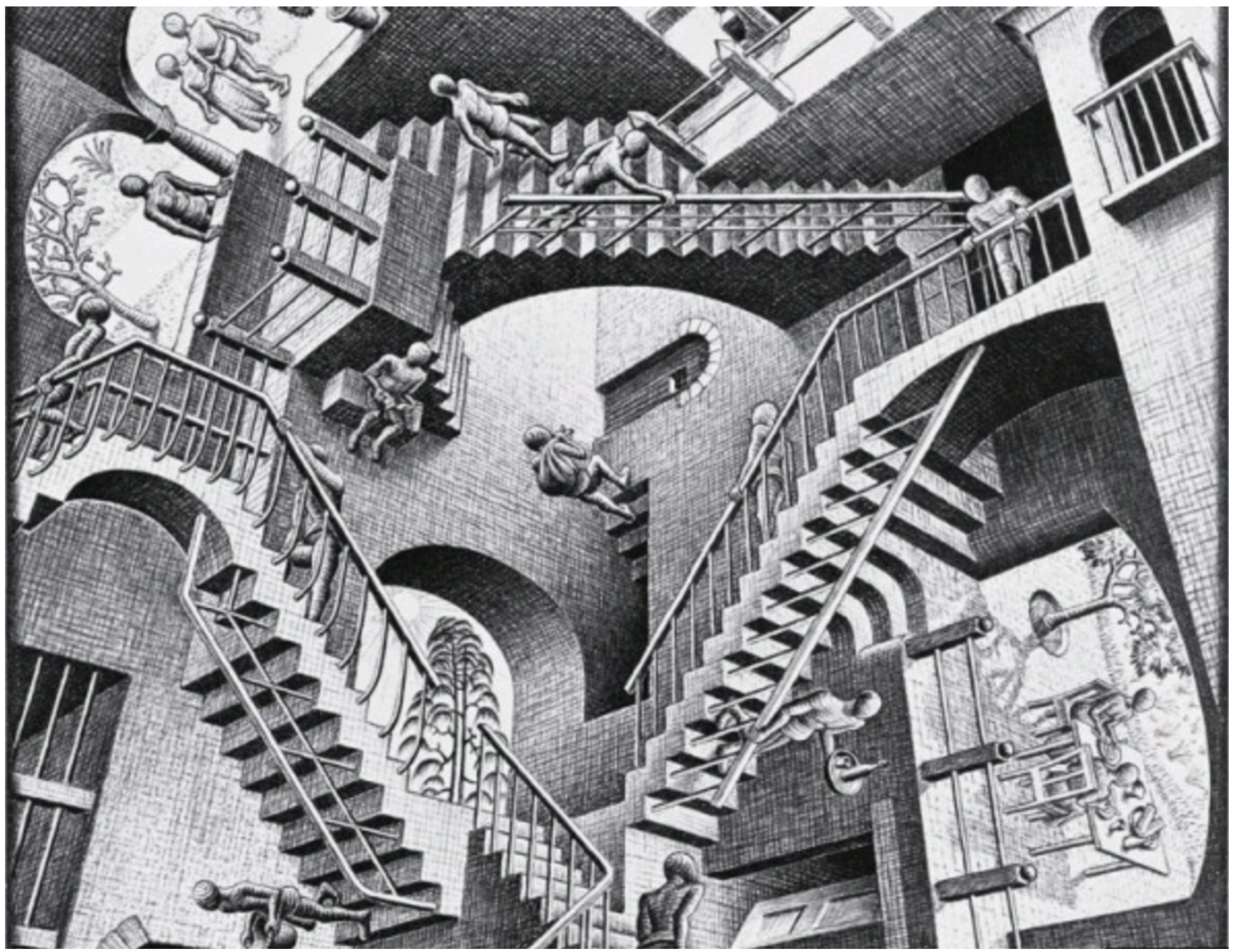


Present data not very constraining ($\beta_L^{32} \sim 0.2$ preferred) but future prospects are very interesting

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

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

Beyond the simplified picture



Leptoquark vector companions

Rather generically the U_1 leptoquark comes along with vector companions

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

$G'^{\,a} \sim (\mathbf{8}, \mathbf{1})_{0}$ (heavy “gluon”)

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

$$M_U \sim M_{Z'} \sim M_{G'} \sim \mathcal{O}(\mathrm{TeV})$$

As a gauge boson

$$SU(4) \sim \begin{pmatrix} G'^{\,a} & U^{\alpha} \\ (U^{\alpha})^{*} & Z' \end{pmatrix}$$

As a quark-lepton (composite) bound state

$$G' + Z' \sim \langle \bar{Q} Q \rangle$$

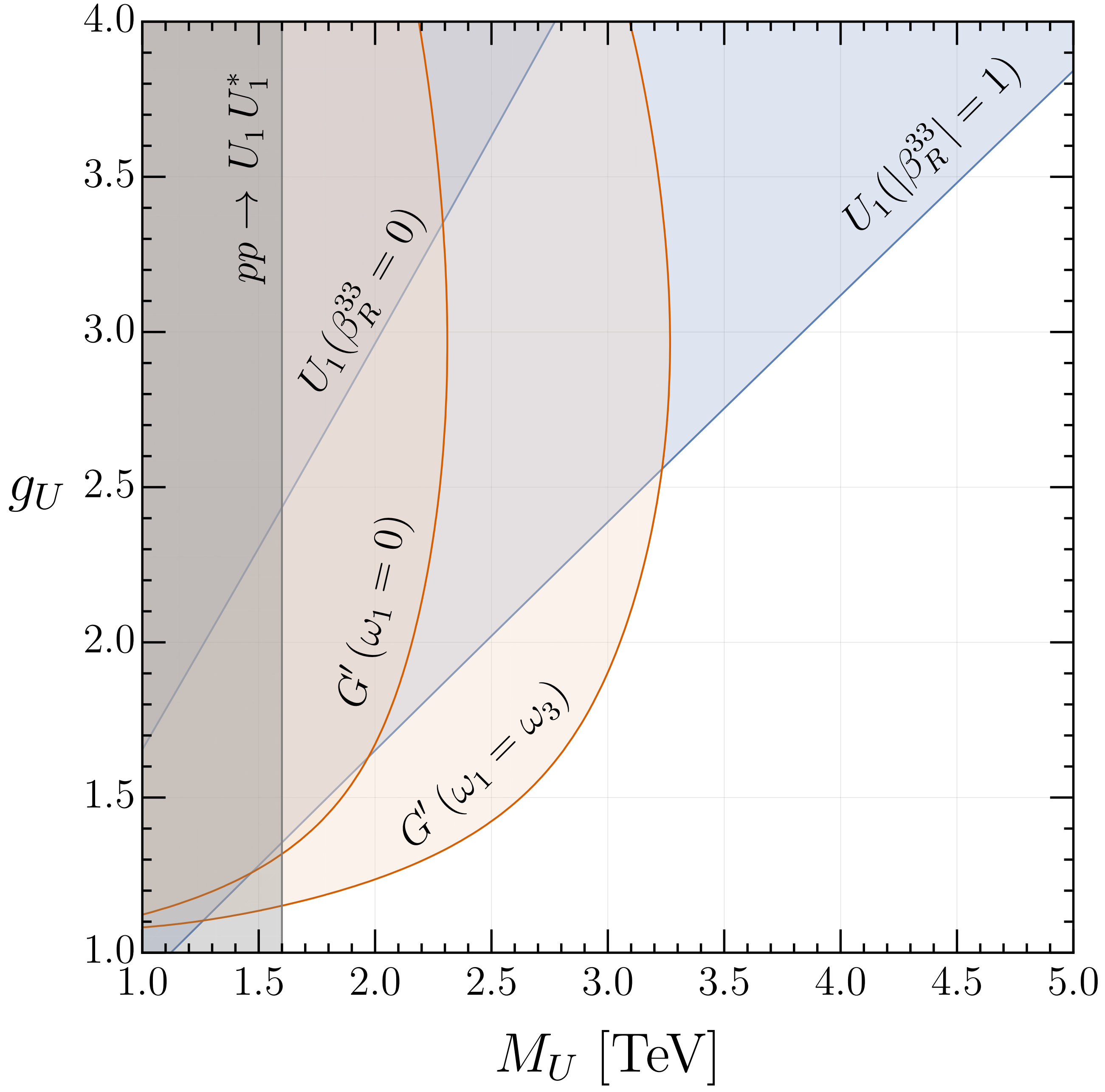
$$U \sim \langle \bar{L} Q \rangle$$

$$Z' \sim \langle \bar{L} L \rangle$$

Other states, e.g. vector-like fermions, are also commonly needed

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

$$M_{G'} = M_U \frac{g_U}{\sqrt{g_U^2 - g_c^2}} \sqrt{\frac{2\omega_3^2}{\omega_1^2 + \omega_3^3}}$$

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

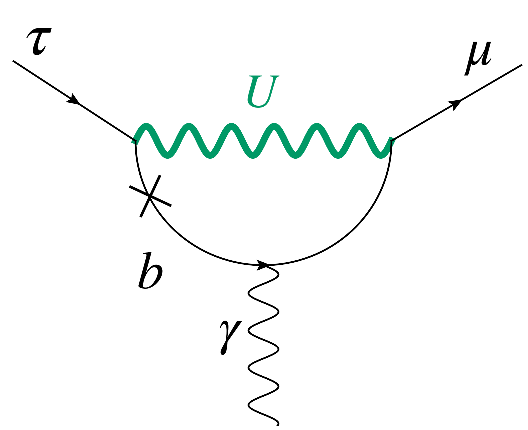
The need for a UV completion

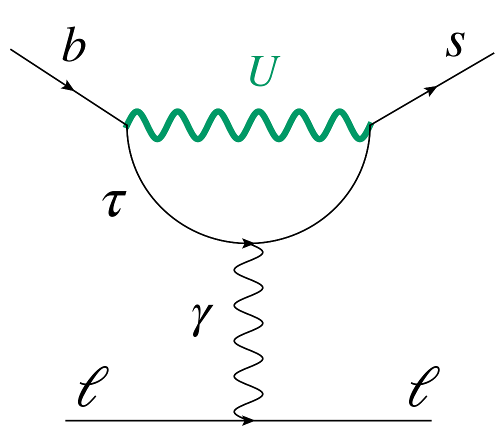
✓ The simplified model analysis captures many relevant aspects of the low and high-energy phenomenology.

✗ Radiative effects [relevant!]

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

$\tau \to \mu\gamma$



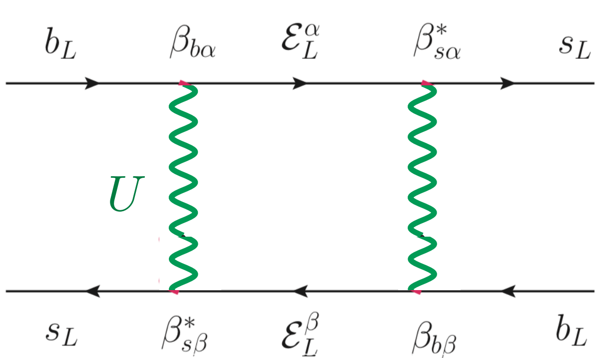


$$\Delta C_9^{\ell} = \Delta C_{10}^{\ell}$$

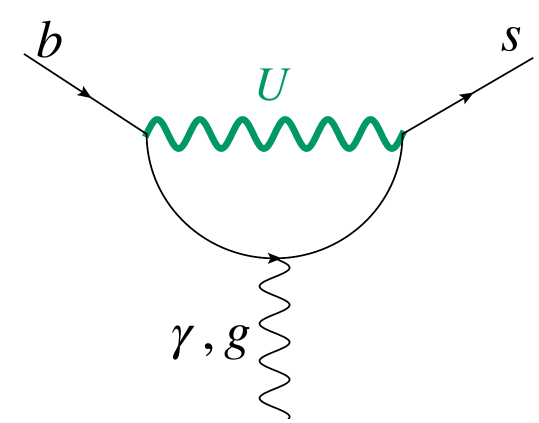
[Bobeth, Haisch, 1109.1826
Crivellin, et al., 1807.02068]

…but this is not possible for many others!

$\Delta F = 2$



$\Delta C_{7(8)}$



→ UV completion needed! (gauge model)

Why not the Pati Salam model?

The vector-leptoquark solution points to Pati-Salam unification

$$\mathbf{PS \equiv SU(4) \times SU(2)_L \times SU(2)_R}$$

Pati, Salam, Phys. Rev. D10 (1974) 275

$$\Psi_{L,R} = \begin{pmatrix} Q^1_{L,R} \\ Q^2_{L,R} \\ Q^3_{L,R} \\ L_{L,R} \end{pmatrix}$$

[Lepton number as the 4th "color"]

✔ $\mathrm{SU}(4)$ is the smallest group containing the required vector LQ $[U_1 \sim (\mathbf{3},\mathbf{1})_{2/3}]$

✔ No proton decay (protected by symmetry)

✘ The (flavor blind) Pati-Salam model cannot work

→ The bounds from $K_L \to \mu e$ and $D - \bar{D}$ lift the LQ mass to 100 TeV

✘ The associated Z' would be excessively produced at LHC

→ $M_U \sim M_{Z'} \sim \mathcal{O}(\mathrm{TeV})$ & $\mathcal{O}(g_s)$ Z' couplings to valence quarks

Pati Salam… cubed!

Bordone, Cornella, JF, Isidori, 1712.01368

“Flavouring” of gauge group:

each family is charged under an independent group

[gauge bosons carry flavour!]

$\sim 10^3$ TeV

$$PS^3 \equiv PS_1 \times PS_2 \times PS_3$$

$$\downarrow$$

~ 1 TeV

$$SU(4)_3 \times SU(3)_{1+2} \times SU(2)_L \times U(1)$$

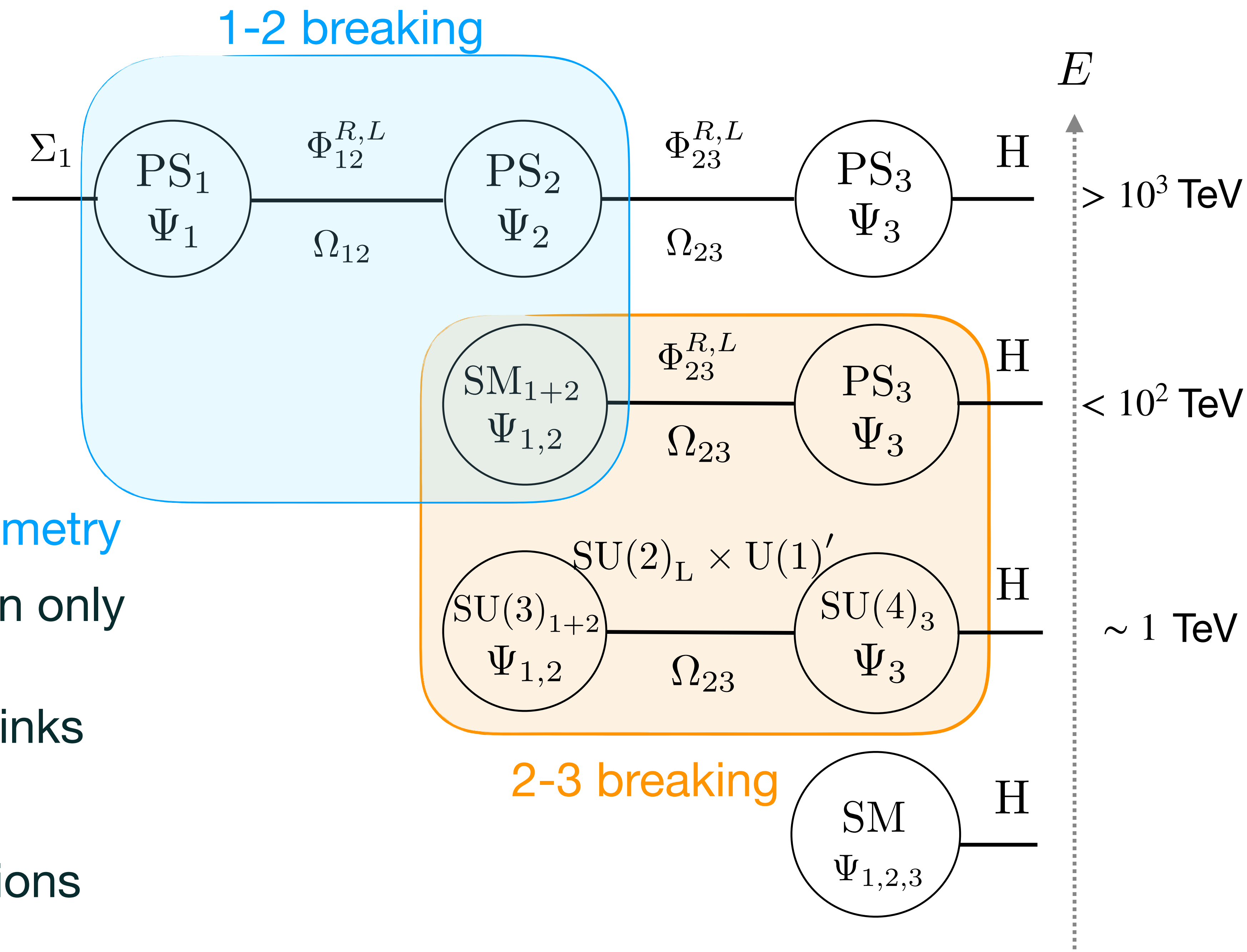
$$\downarrow$$

$$SM \; + U_1, G', Z'$$

As a result of this flavouring + SSB pattern, we have

- ✓ TeV scale U_1 [LH + RH] + Z', G' <u>coupled mainly to 3rd generation</u>
- ✓ link between B-anomalies and the SM flavor puzzle

Symmetry breaking pattern



Accidental $U(2)^5$ flavour symmetry

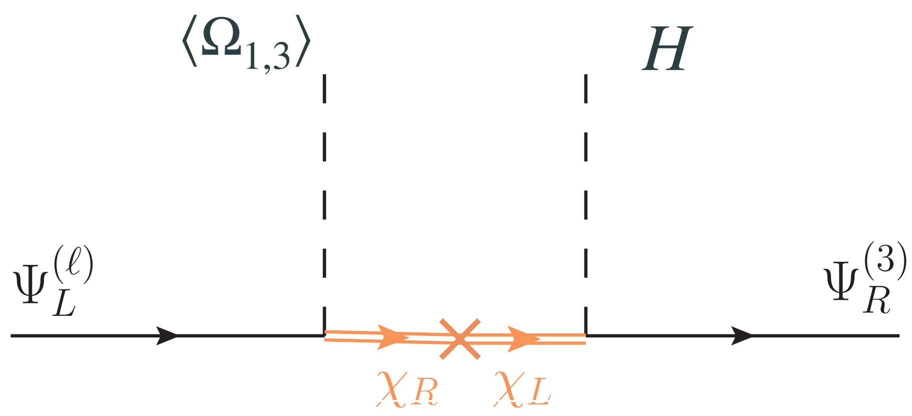
→ Yukawa for 3rd generation only

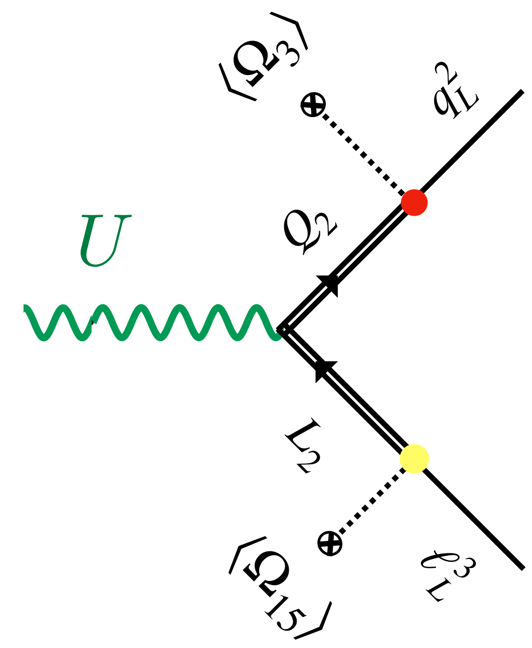
$U(2)^5$ breaking via vev of 2-3 links and vector-like fermions

→ Yukawa for light generations

$$Y_f = \begin{pmatrix} \Delta & V \\ 0 & y_3 \end{pmatrix}$$

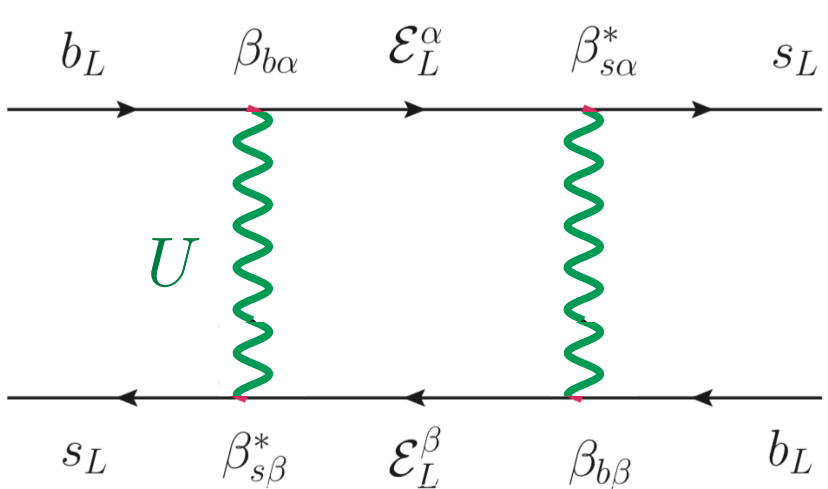
A closer look at the U(2) breaking





$$| V | \sim \frac{\lambda_H \lambda_3 \langle \Omega_3 \rangle}{M_\chi} \sim V_{cb}$$

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



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

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

PS^3 from extra dimensions

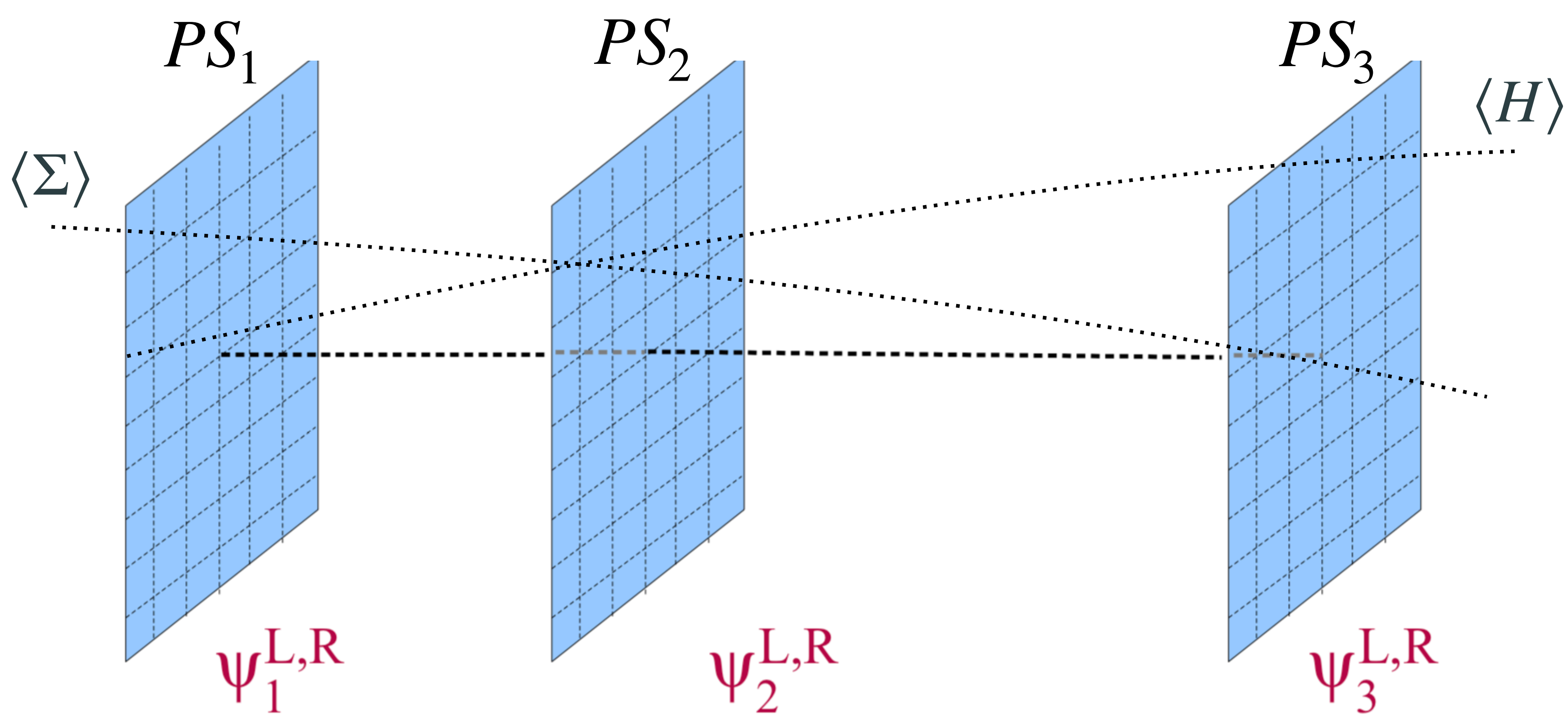
This construction offers an interesting hint to extra dimensions:

4d multisite models
[gauge group G^N]

duality ⟷

5d models
1 flat, compact xds discretized in N points
[G in the bulk, G_i at the sites]

[Arkhani-Ahmed et al. 2001]



"*flavour de-construction*" of the gauge group

[Work in progress]

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 (G', Z', VL fermions,…) and constraints

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

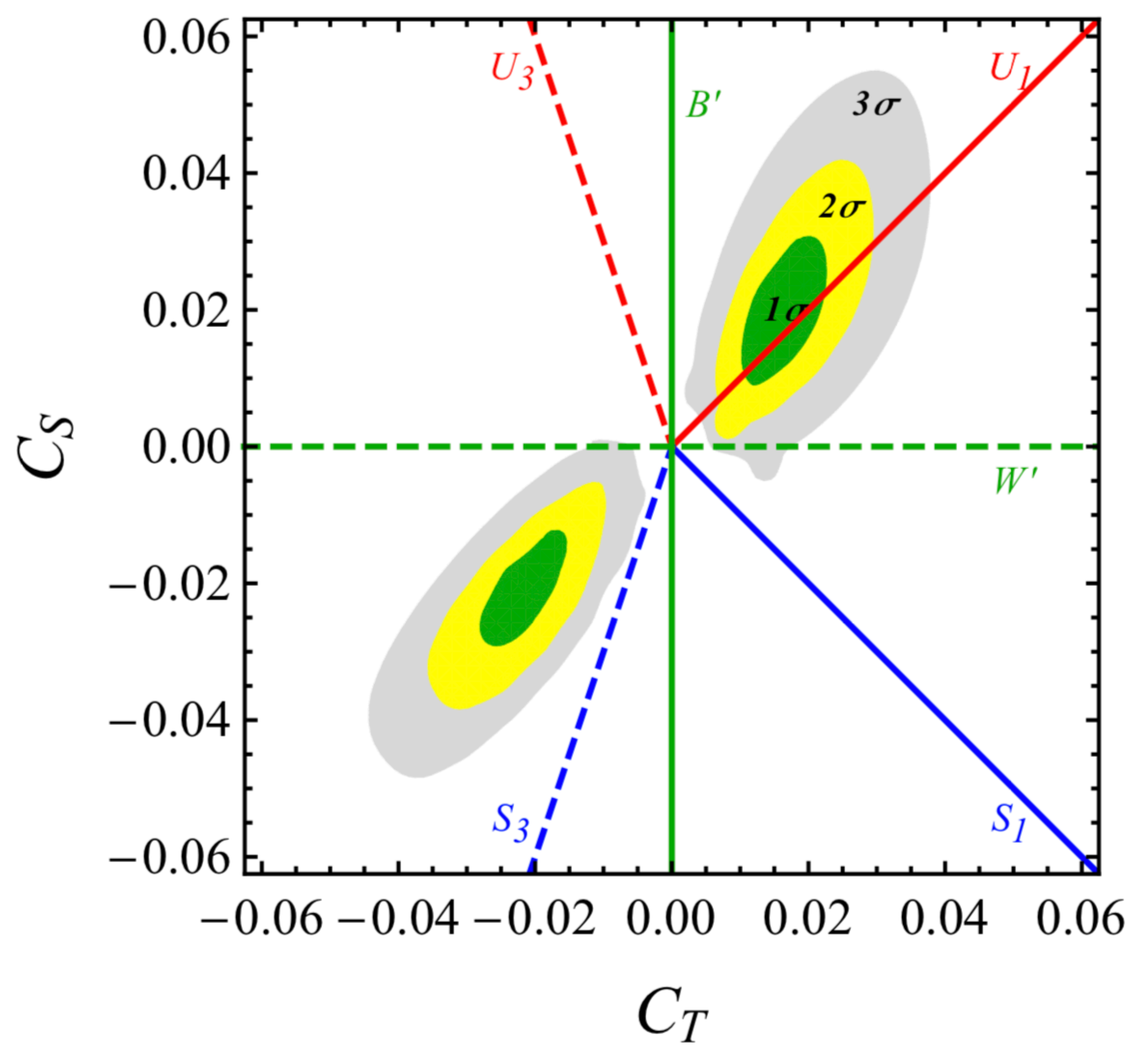
… However this conclusion is strongly driven by $R(D^{(*)})$

Thank you!

Backup slides

C_S vs C_T

$$\mathcal{L}_{EFT} \supset \frac{1}{\Lambda^2}\left[C_T\,(\bar{q}^i_L\gamma^\mu\tau^a b_L)(\ell^\alpha_L\gamma_\mu\tau^a\ell^\beta_L) + C_S\,(\bar{q}^i_L\gamma^\mu b_L)(\ell^\alpha_L\gamma_\mu\ell^\beta_L)\right]$$



The 4321 model(s)

$$SU(3)_c = (SU(4) \times SU(3))_{\text{diag}}$$
$$U(1)_Y = (SU(4) \times U(1))_{\text{diag}}$$

$U(1)_Y$

$$SU(4) \times SU(3) \times SU(2)_L \times U(1) \xrightarrow{SSB} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$SU(3)_c$

$+\, U_1, G', Z'$ [2-5 TeV]

Why an additional $SU(3)$?

✘ The extra $SU(3)$ gives a G' (**coloron**), apart from the Z' already present in PS

✔ It allows to **decorrelate** the $SU(4)$ from the SM color group. In the limit $g_4 \gg g_{3,1}$, this "solves" the high-p_T problem

→ $\mathcal{O}(g_3/g_4)$ and $\mathcal{O}(g_1/g_4)$ G' and Z' couplings to valence quarks

The 4321 model(s)

$$U(1)_Y$$

$$SU(4) \times SU(3) \times SU(2)_L \times U(1) \xrightarrow{SSB} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$SU(3)_c$$

Different fermion embeddings give two distinct solutions:

★ The "original" 4321 [**pure LH U_1**]
[di Luzio, JFM, Greljo, Nardecchia, Renner 1808.00942; di Luzio, Greljo, Nardecchia 1708.08450; Diaz, Schmaltz, Zhong 1706.05033,…]

★ PS^3 (at low energies) [**LH + RH U_1**]
[Bordone, Cornella, JF, Isidori 1712.01368, 1805.09328; Greljo, Stefanek, 1802.04274]

The 4321 model(s)

$U(1)_Y$

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

$SU(3)_c$

The "original" 4321

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$q_L'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
$u_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
$d_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
$\ell_L'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
$e_R'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
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	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
Ω_3	$\bar{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$
Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0

$n_{\rm SM-like} = 3$

$n_{\rm VL} = 3$

U_1 LH only

PS^3 low-energy limit

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$q_L'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
$u_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
$d_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
$\ell_L'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
$e_R'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
ψ_L^3	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
$\psi_{R_{u,d}}^3$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$\pm 1/2$
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

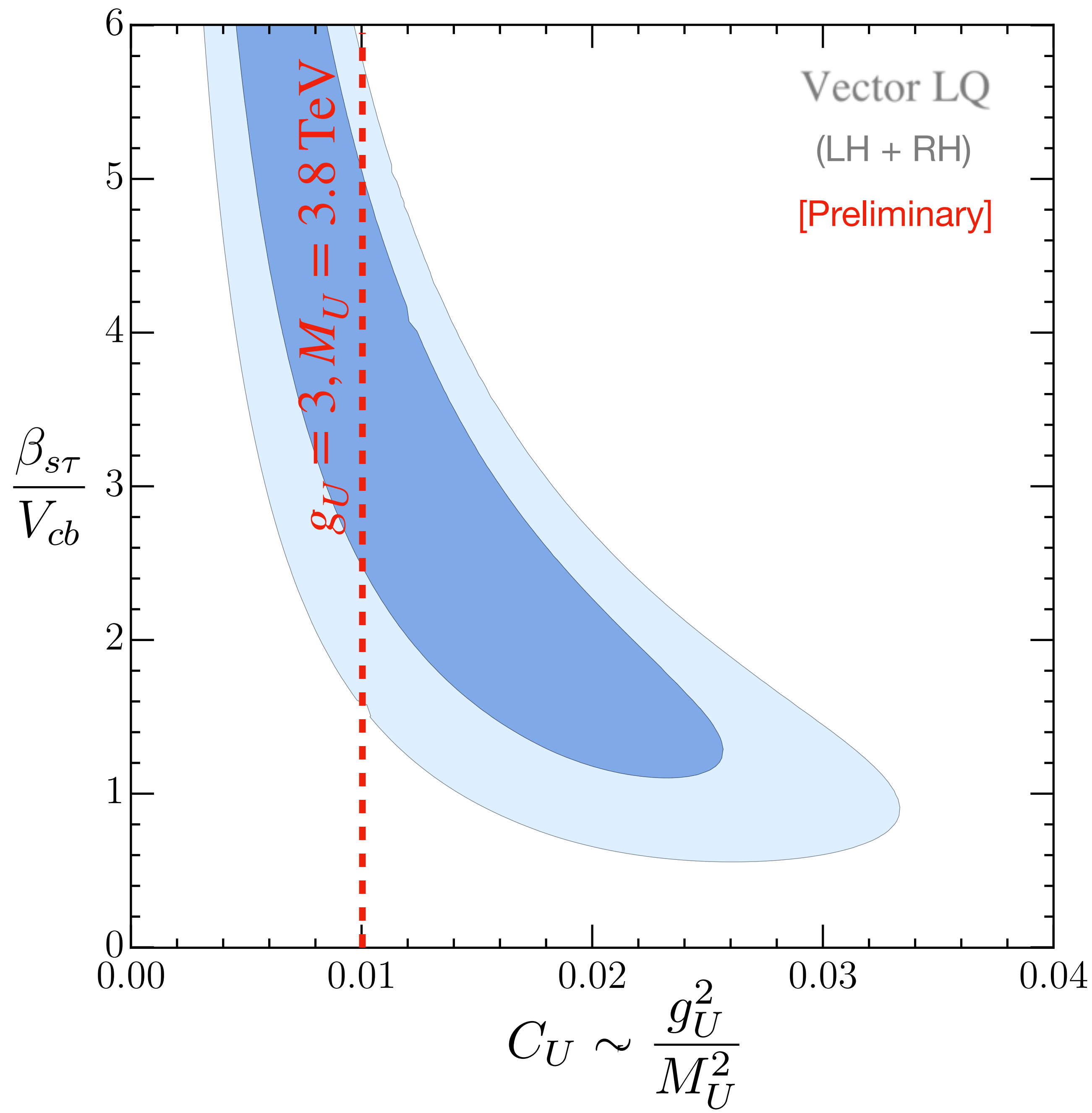
1st & 2nd families

3rd family

$n_{\rm VL} = 2$

U_1 LH + RH

Comparison among U_1 solutions



LH + RH

[JFM, Cornella, Isidori, in preparation]

LH only

[Buttazzo et al. 1706.07808]