Establishing connections between B-physics & High-pT

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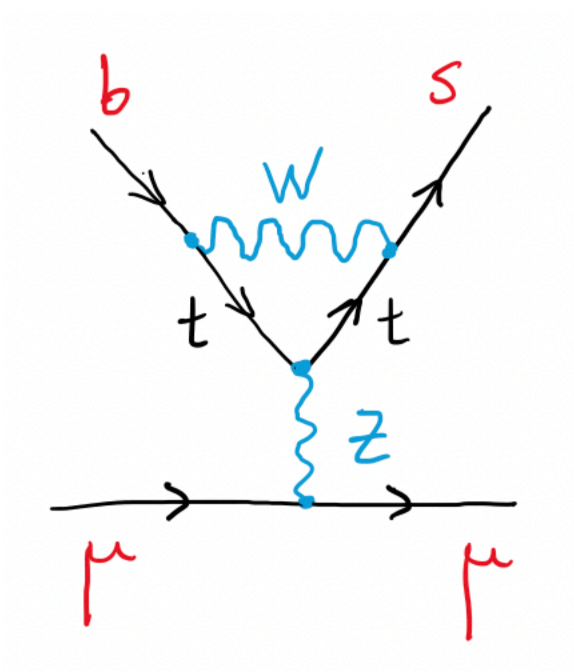
The B-physics anomalies

See talk by Thibaud Humair

Hints of Lepton Flavour Universality Violation in semileptonic B decays

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

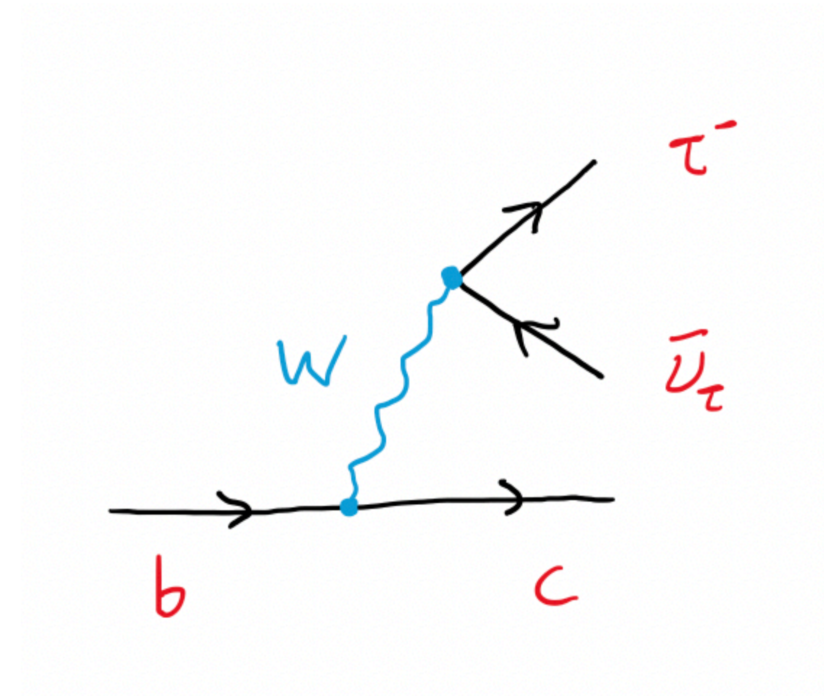
μ/e ~~universality~~



$> 4\,\sigma$

$b \to c\tau\nu$

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



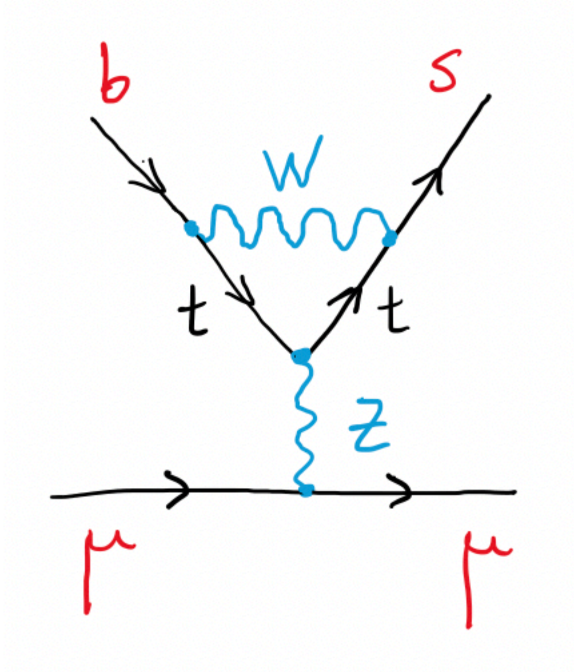
$\sim 3\,\sigma$

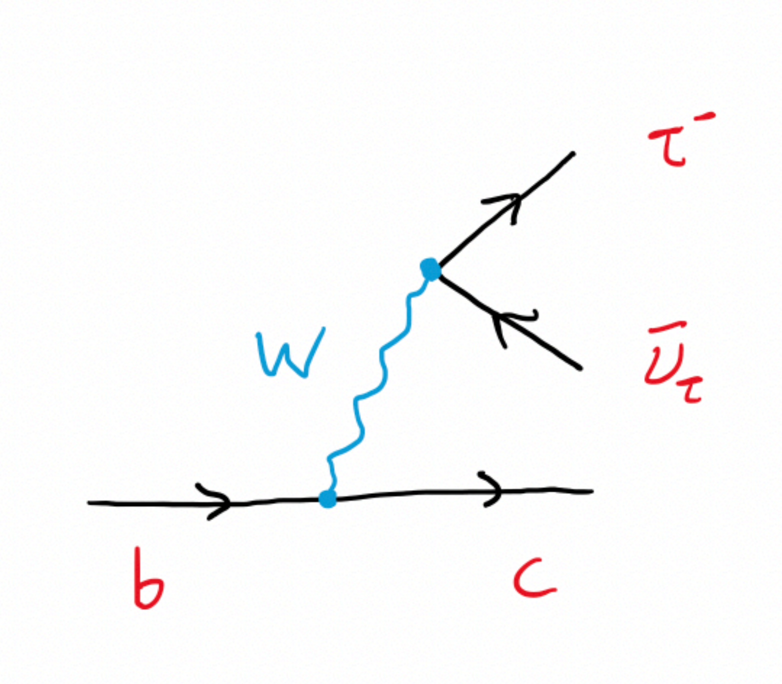
- ★ New R_K measurement by LHCb and R_{K^*} by Belle
- ★ New $R_{D^{(*)}}$ measurement by Belle

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!





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

~20% of a SM **loop** effect

~15% 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?

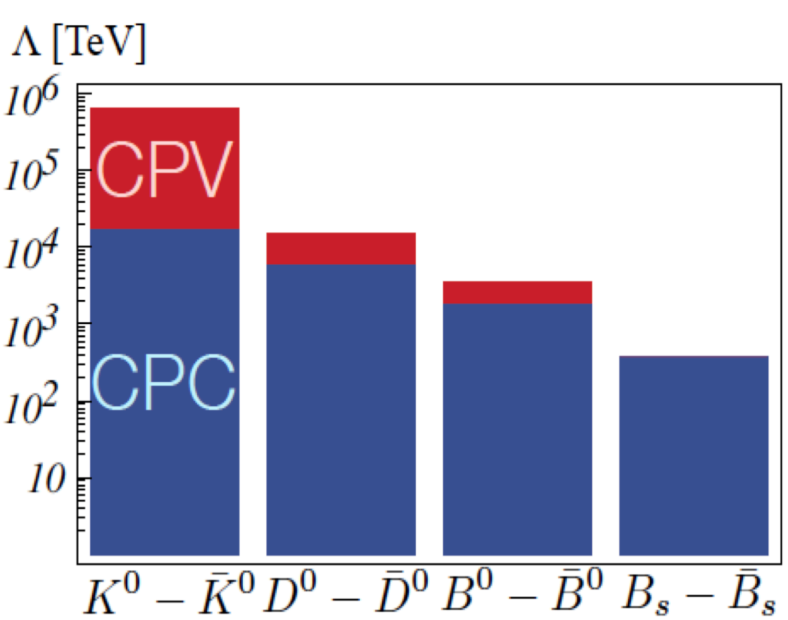
What are the anomalies telling us?

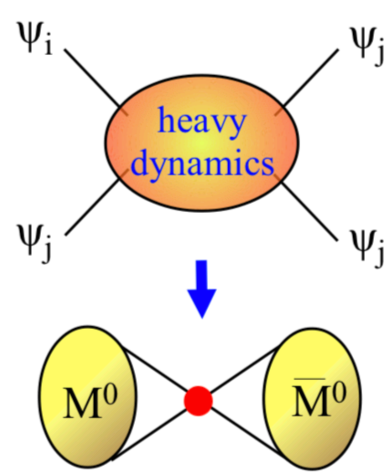
A combined explanation calls for NP:$^{(*)}$

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

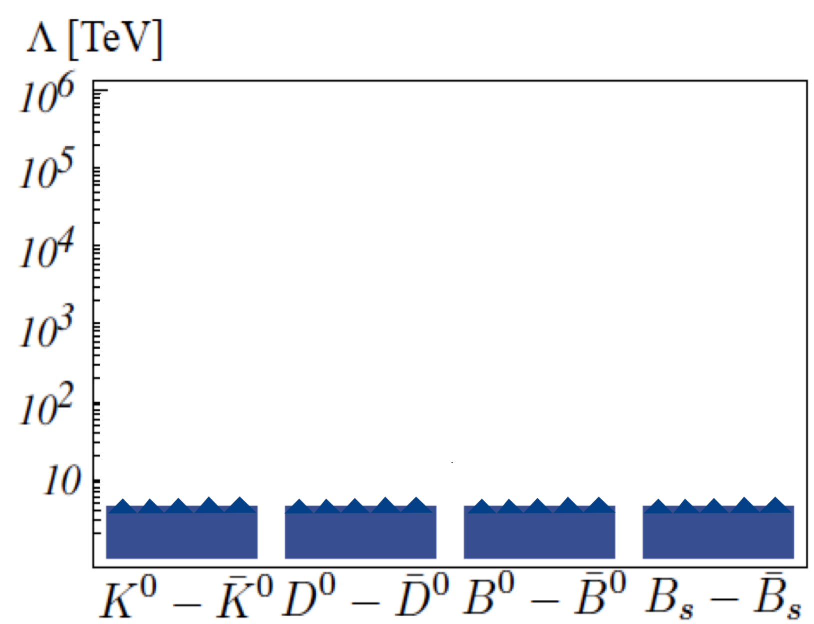
- ★ Coupled dominantly to the **3rd generation**
- ★ $\Lambda_{\rm NP} \sim \mathcal{O}(1\ {\rm TeV})$

Anarchical couplings





Hierarchical couplings



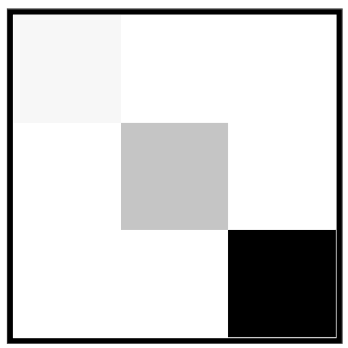
Severe constraints on generic new (BSM) flavor breaking sources
(mis)interpreted as indication of a high flavor scale

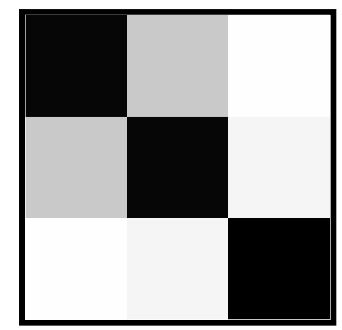
A NP hint to the SM flavor puzzle?

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

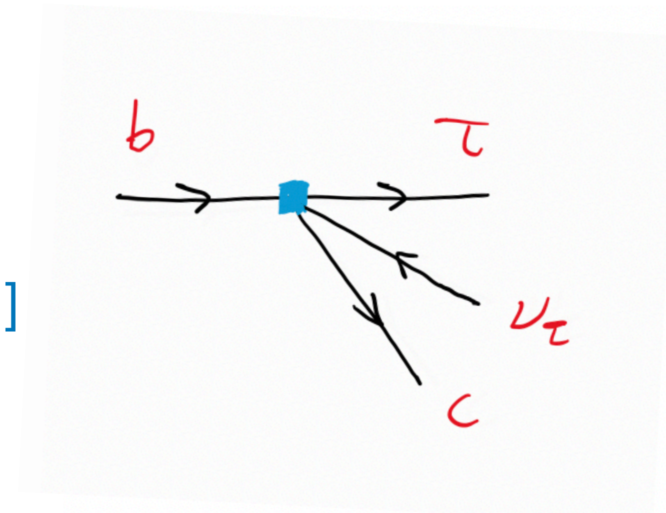
✓ Recent theoretical progress connecting the anomalies to the SM flavor hierarchies

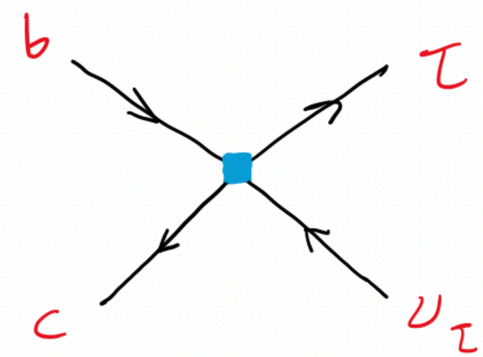
[Bordone, Cornella, JFM, Isidori 1712.01368; Greljo, Stefanek 1802.04274; Allanach, Davighi 1809.01158; Barbieri, Ziegler 1904.04121]

Complementarity with high-pT data

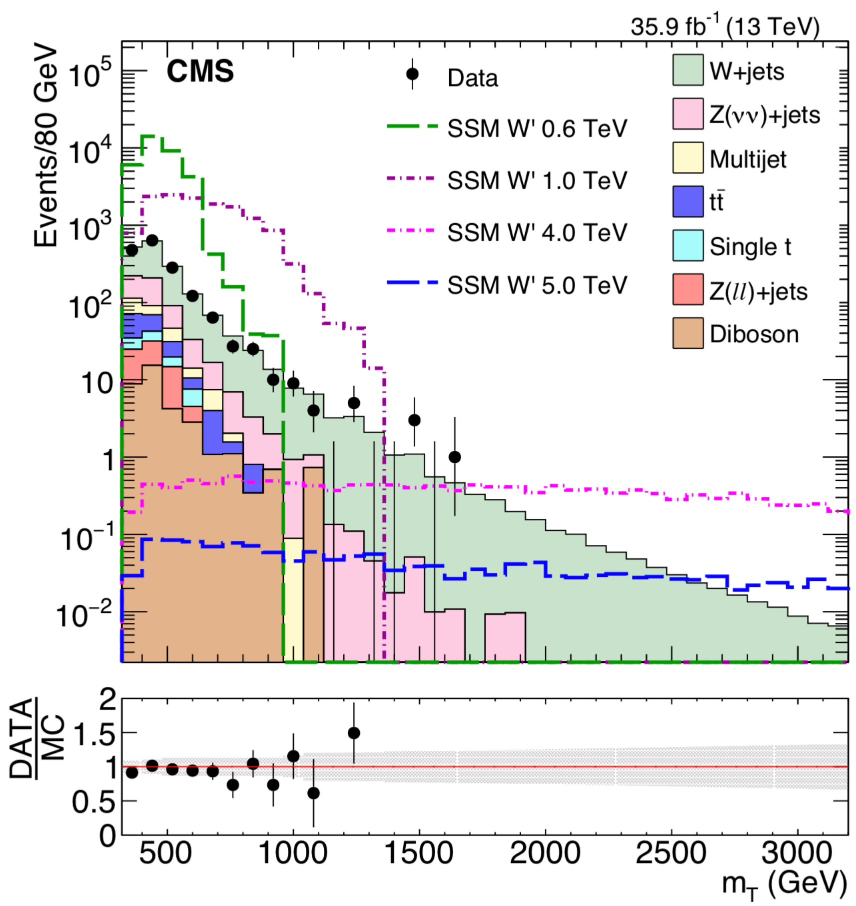
The same NP (specially in $R(D^{(*)})$) is within the reach of high-pT searches at LHC!

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

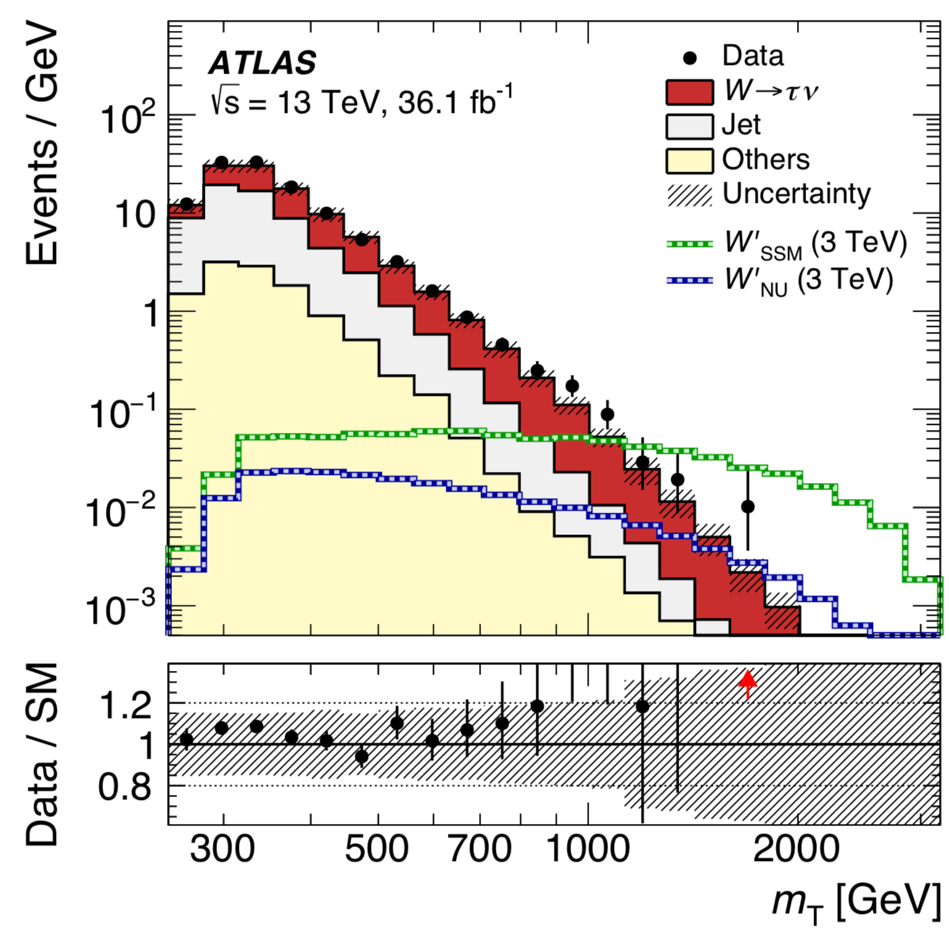




High-pT



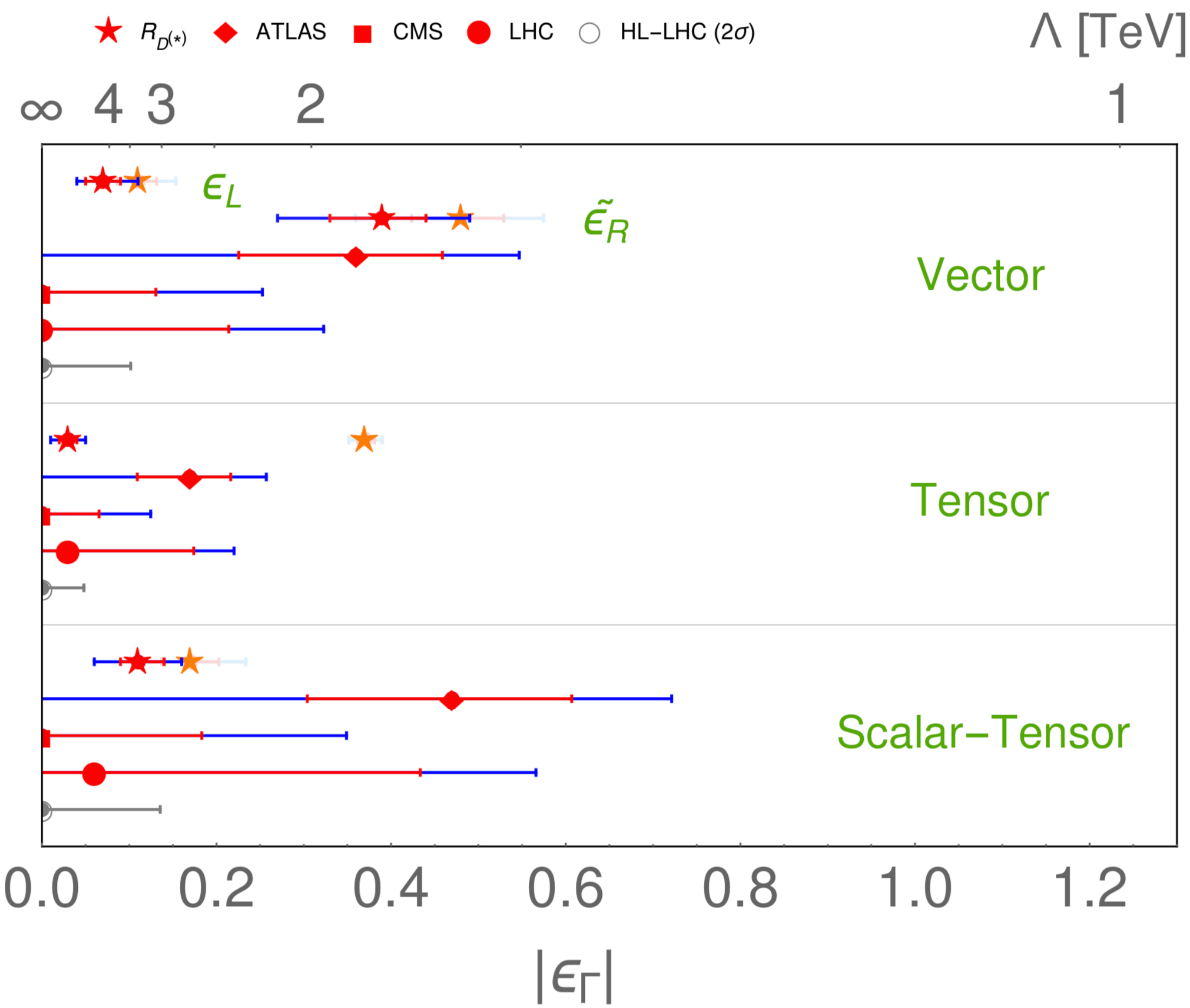
1807.11421



1801.06992

High-pT limits on EFT operators

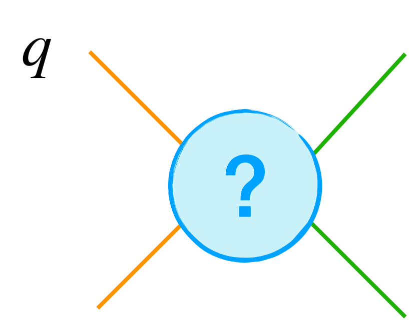
$$\mathcal{L}_{\rm EFT} \supset -\frac{2V_{cb}}{v^2}\Big[(1+\epsilon_L)(\bar\tau\gamma_\mu P_L\nu_\tau)(\bar c\gamma^\mu P_L b) + \epsilon_R(\bar\tau\gamma_\mu P_L\nu_\tau)(\bar c\gamma^\mu P_R b) + \epsilon_{S_L}(\bar\tau P_L\nu_\tau)(\bar c P_L b)$$
$$+\epsilon_{S_R}(\bar\tau P_L\nu_\tau)(\bar c P_R b) + \epsilon_T(\bar\tau\sigma_{\mu\nu}P_L\nu_\tau)(\bar c\sigma^{\mu\nu}P_L b)\Big] + h.c.$$



[Greljo, Camalich, Ruiz-Álvarez, 1811.07920 (updated in Portorož 2019)]

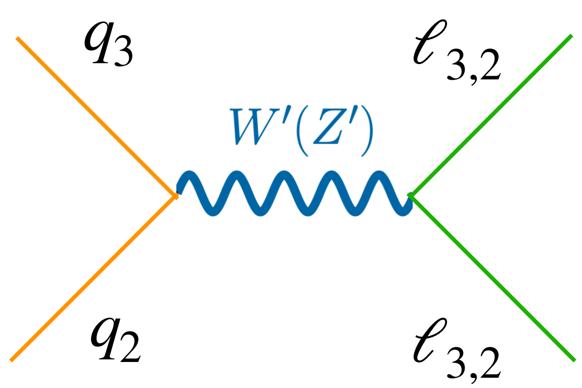
Caveats

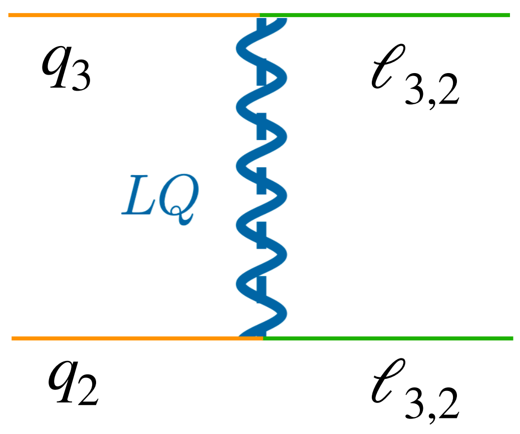
- ★ EFT stops being valid when $E \approx \Lambda$
- ★ UV models typically involve additional effects



…Which mediator?

Which mediator?





Only few possibilities for a combined explanation

★ **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]

Talk by Y. Takahashi

★ **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

The U_1 leptoquark solution

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

Flavor structure$^{(*)}$

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

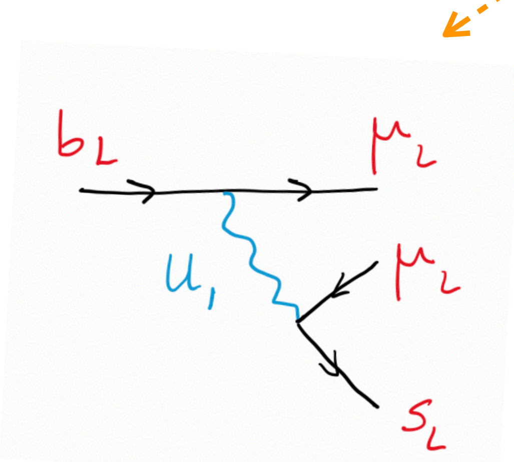
$\beta_{b\tau}^L = 1$

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

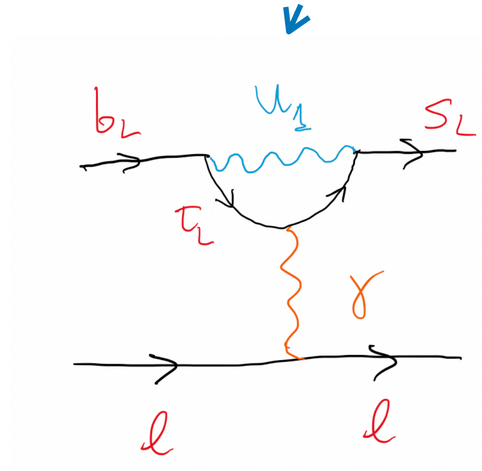
$\beta_{s\tau}^L, \beta_{b\mu}^L \sim \mathcal{O}(0.1)$

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

ϵ_{V_L} $\qquad$ ϵ_{S_R}

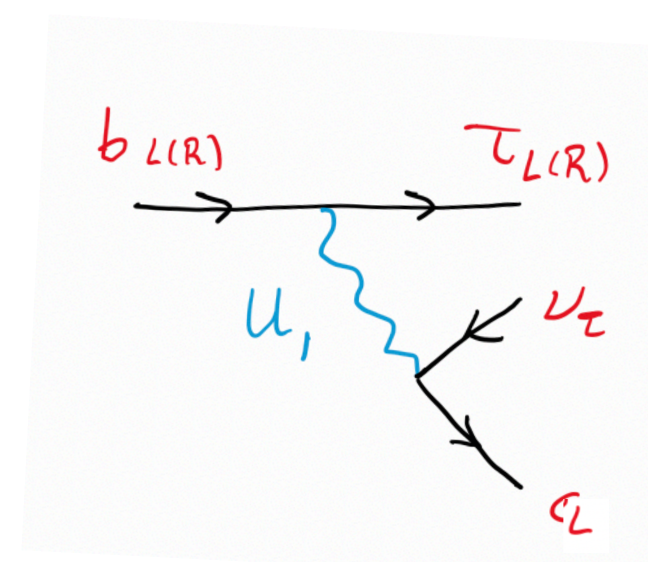


$\Delta C_9^\mu = -\Delta C_{10}^\mu$



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

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



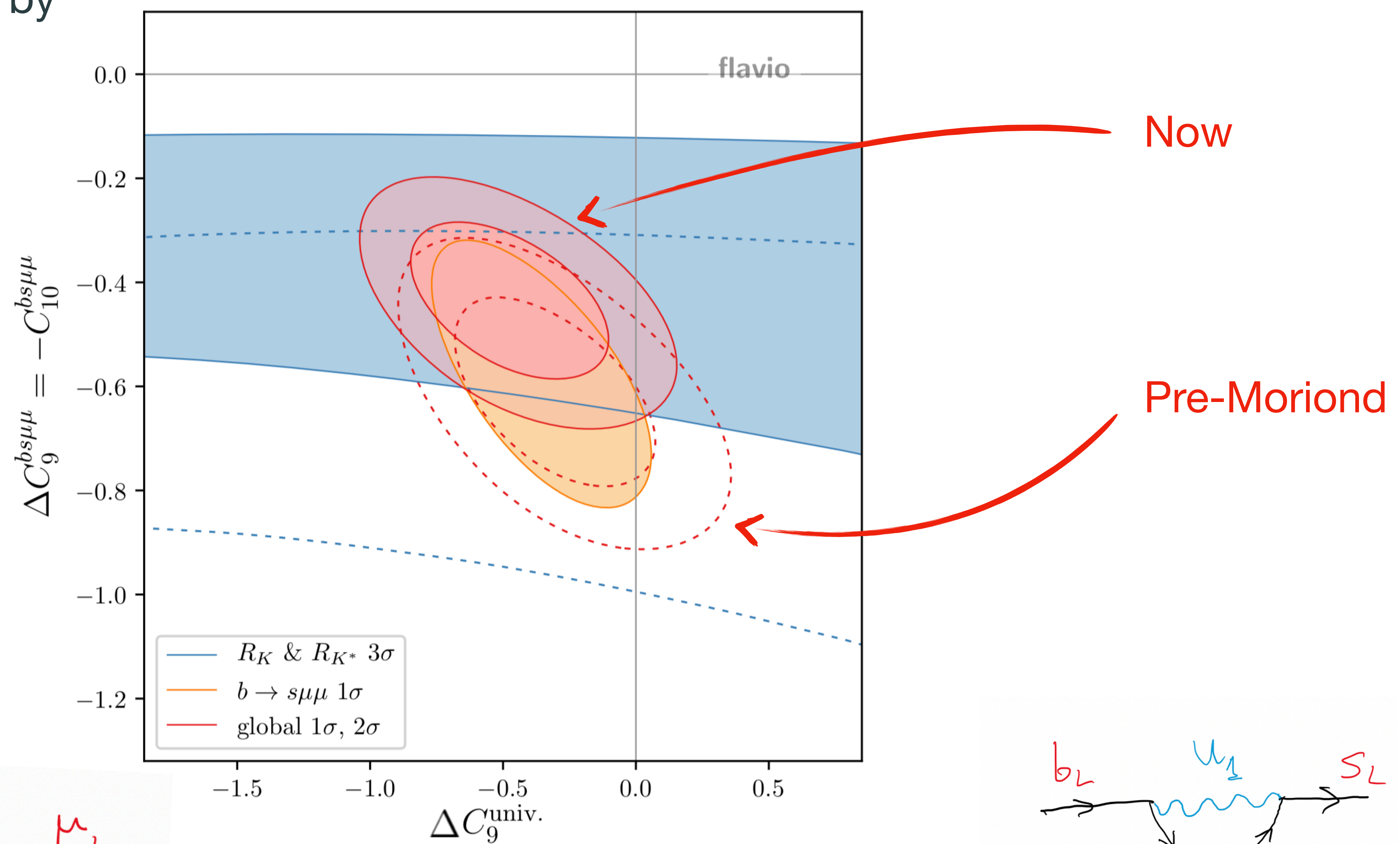
[Crivellin et al., 1807.02068]

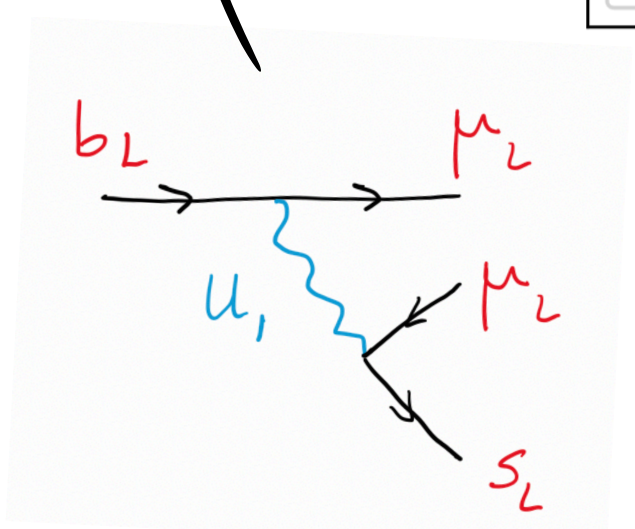
(*) N.B.: Deviations from this structure highly constrained by low-energy flavor data

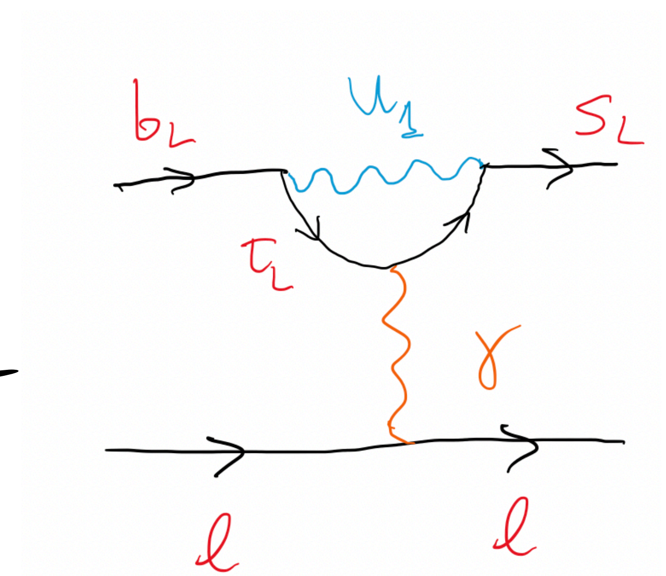
Universal contribution to ΔC_9

… as discussed by David Straub

[Aebischer et al., 1903.10434]







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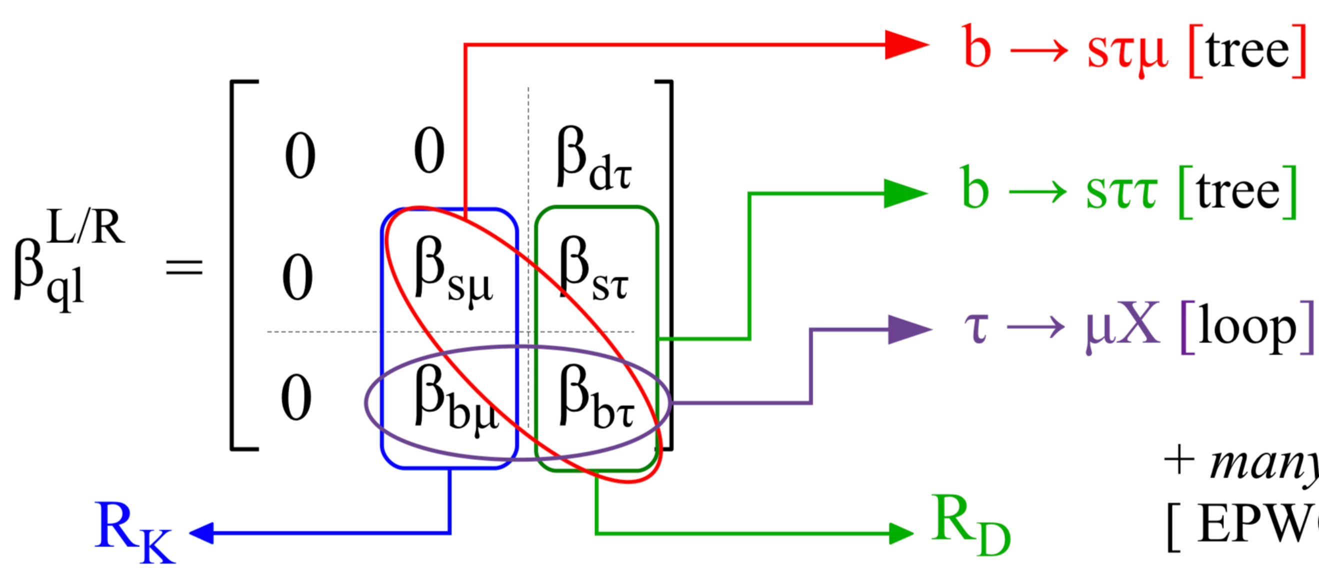


+ *many other effects*
[EPWO, LFU in τ's...]

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

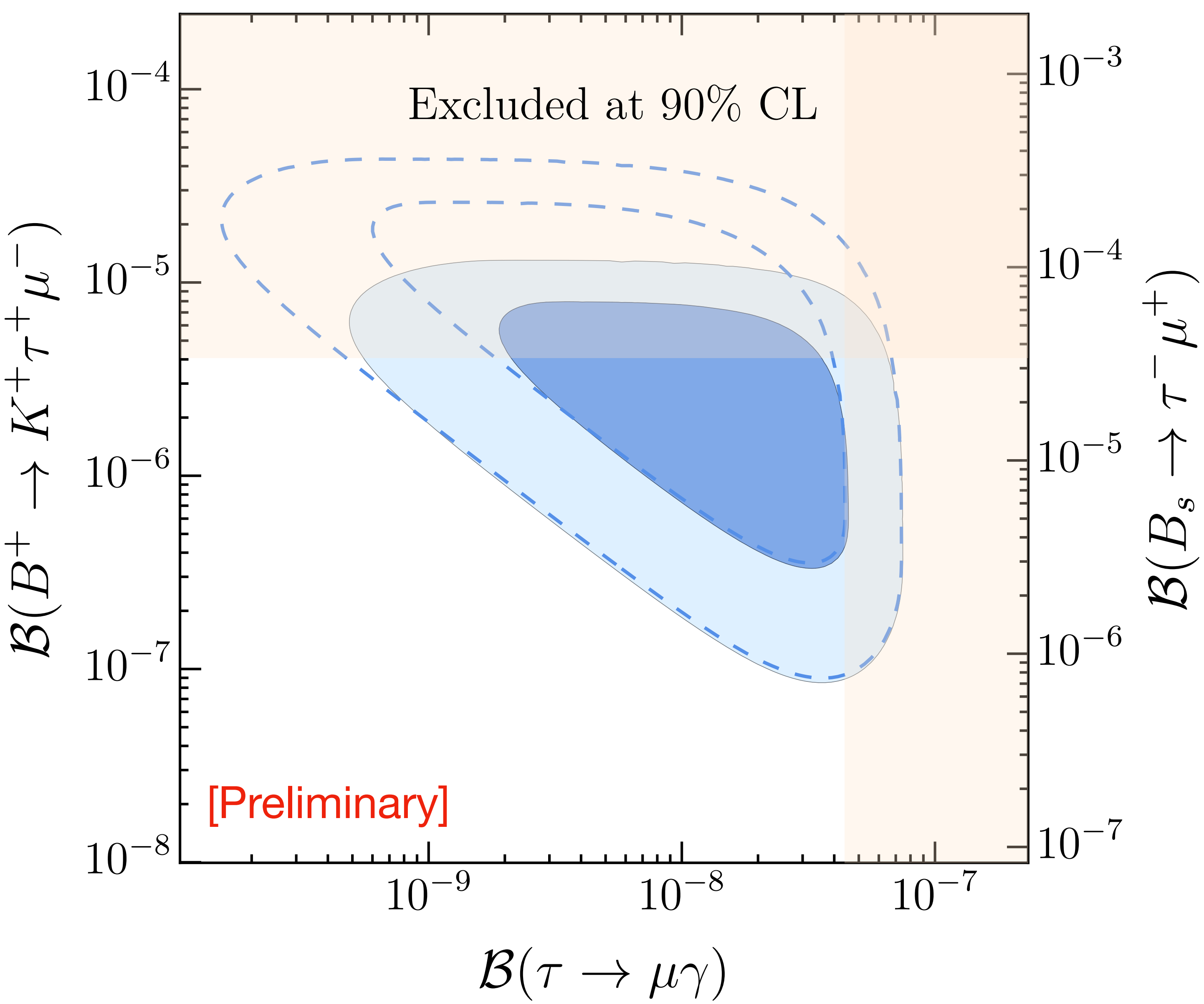
$\beta_{b\tau}^R \sim \mathcal{O}(1)$

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

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

A non-zero $\beta_{b\tau}^R$ leads to a series of interesting effects both at low-energy and at high-pT

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



Large $\tau\mu$ LFV is expected

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

$$\mathscr{B}(\tau \to \mu\gamma) \sim 10^{-9}$$

$$\mathscr{B}(B \to K\tau\mu) \sim 10^{-6}$$

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

★ First measurement of $\mathscr{B}(B_s \to \tau\mu)$ by LHCb presented here!

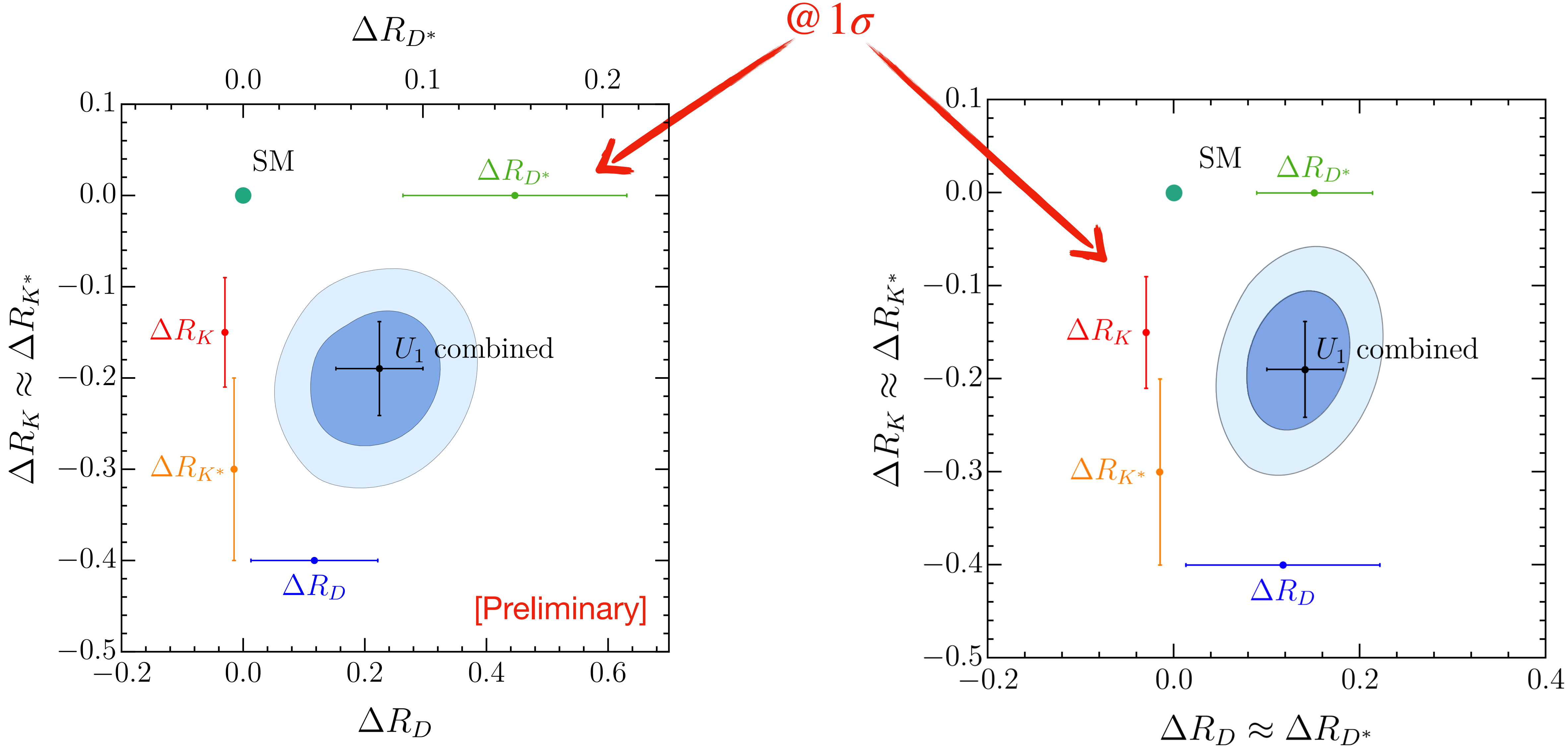
See talk by Giampiero Mancinelli

[Cornella, JFM, Isidori, 1903.11517]

Low-energy fit results

Both options give a good the low-energy fit (in particular to the anomalies)

LH + RH ($\beta^L_{b\tau} = \beta^R_{b\tau}$) Experiment @ 1σ **LH only ($\beta^R_{b\tau} = 0$)**



NP scale naturally higher

[thanks to the additional NP contribution from $\beta^R_{b\tau}$]

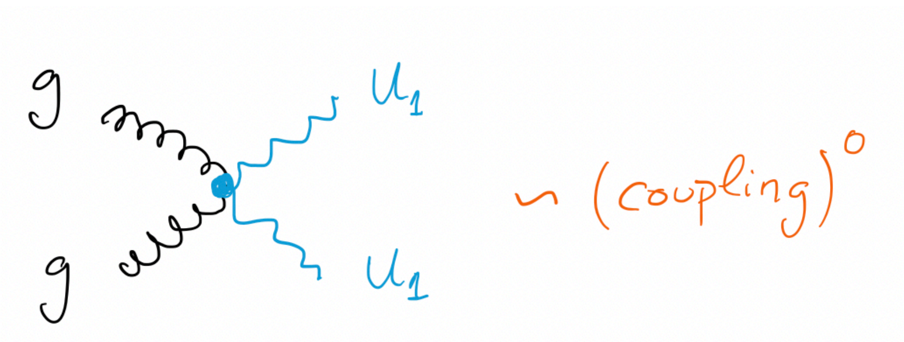
Slightly better fit

[driven by the new (preliminary) Belle measurement]

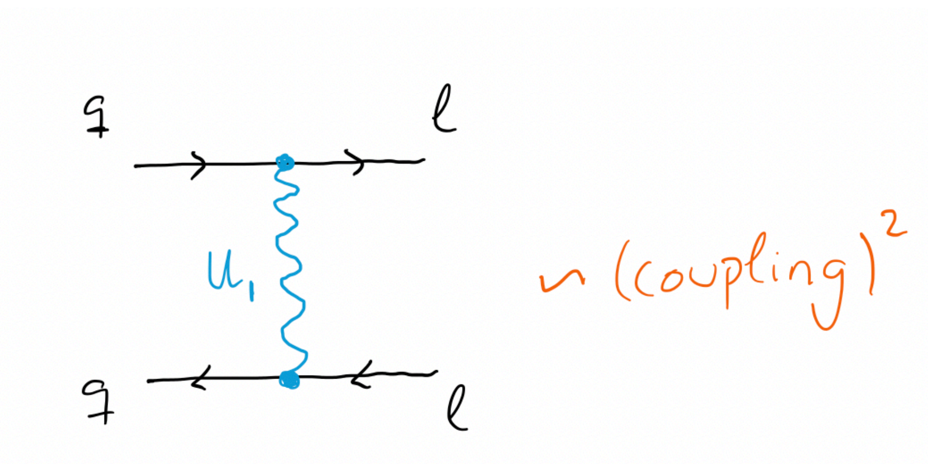
[Cornella, JFM, Isidori, 1704.06659]

High-pT leptoquark limits

Pair production (PP)

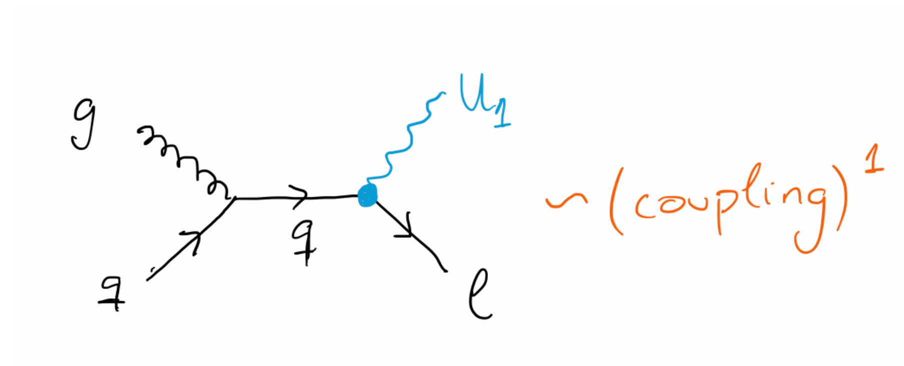


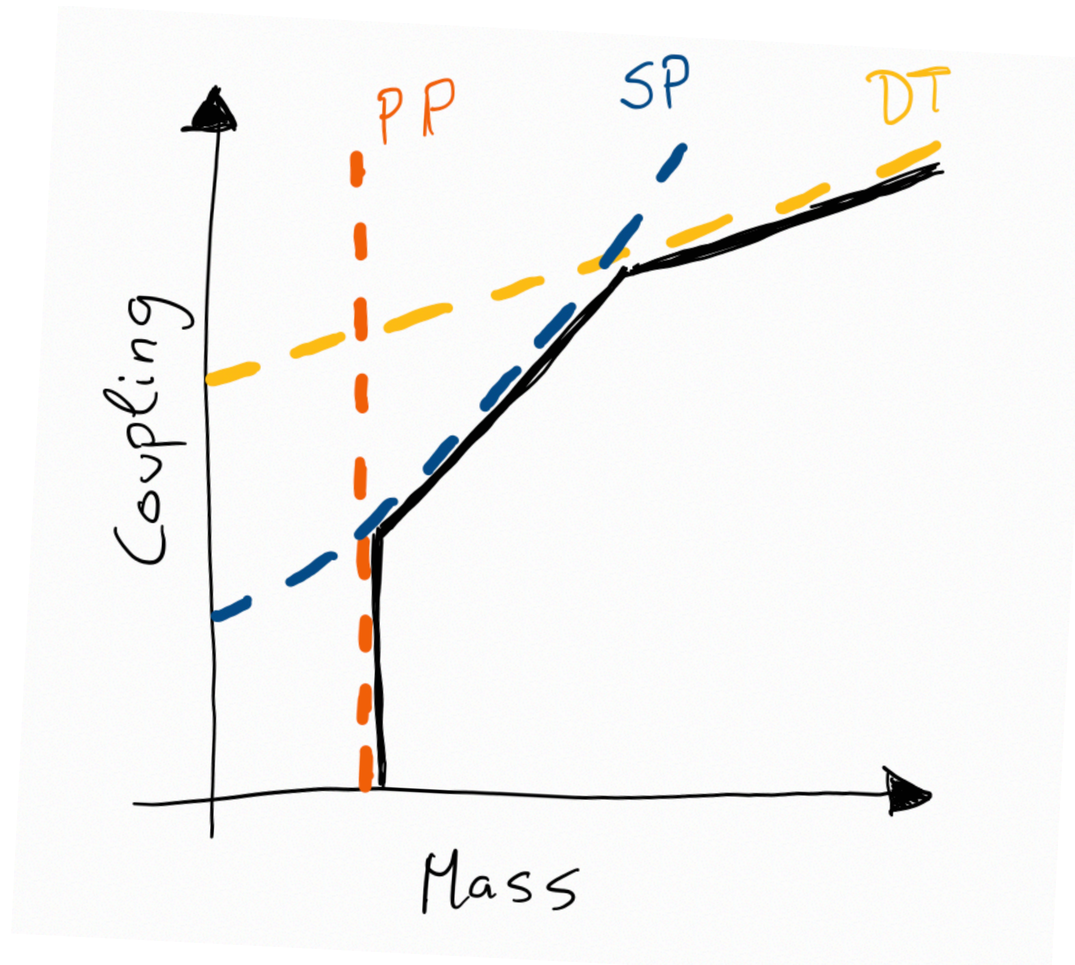
Dilepton tails (DT)



This talk!

Single production (SP)

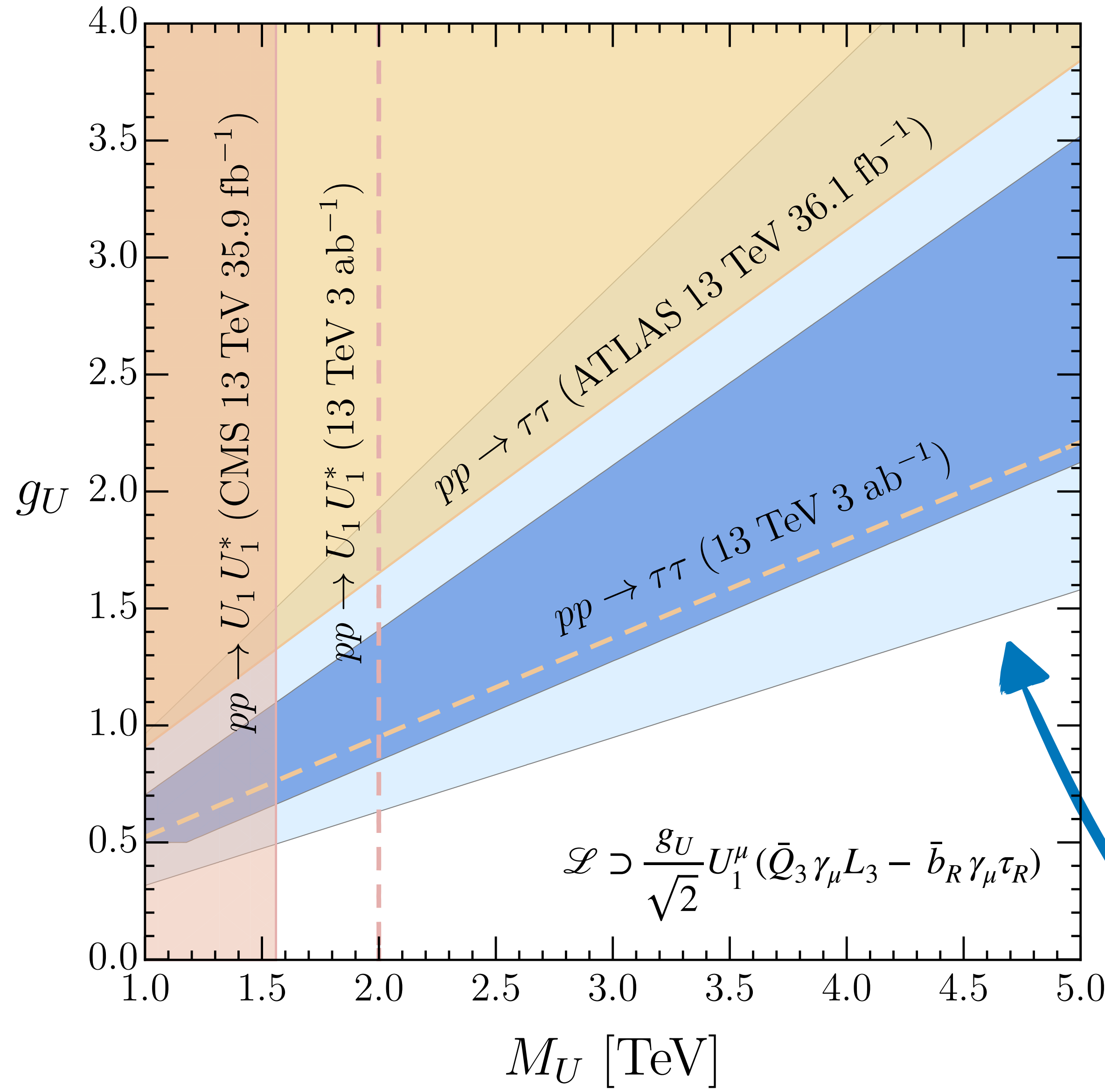




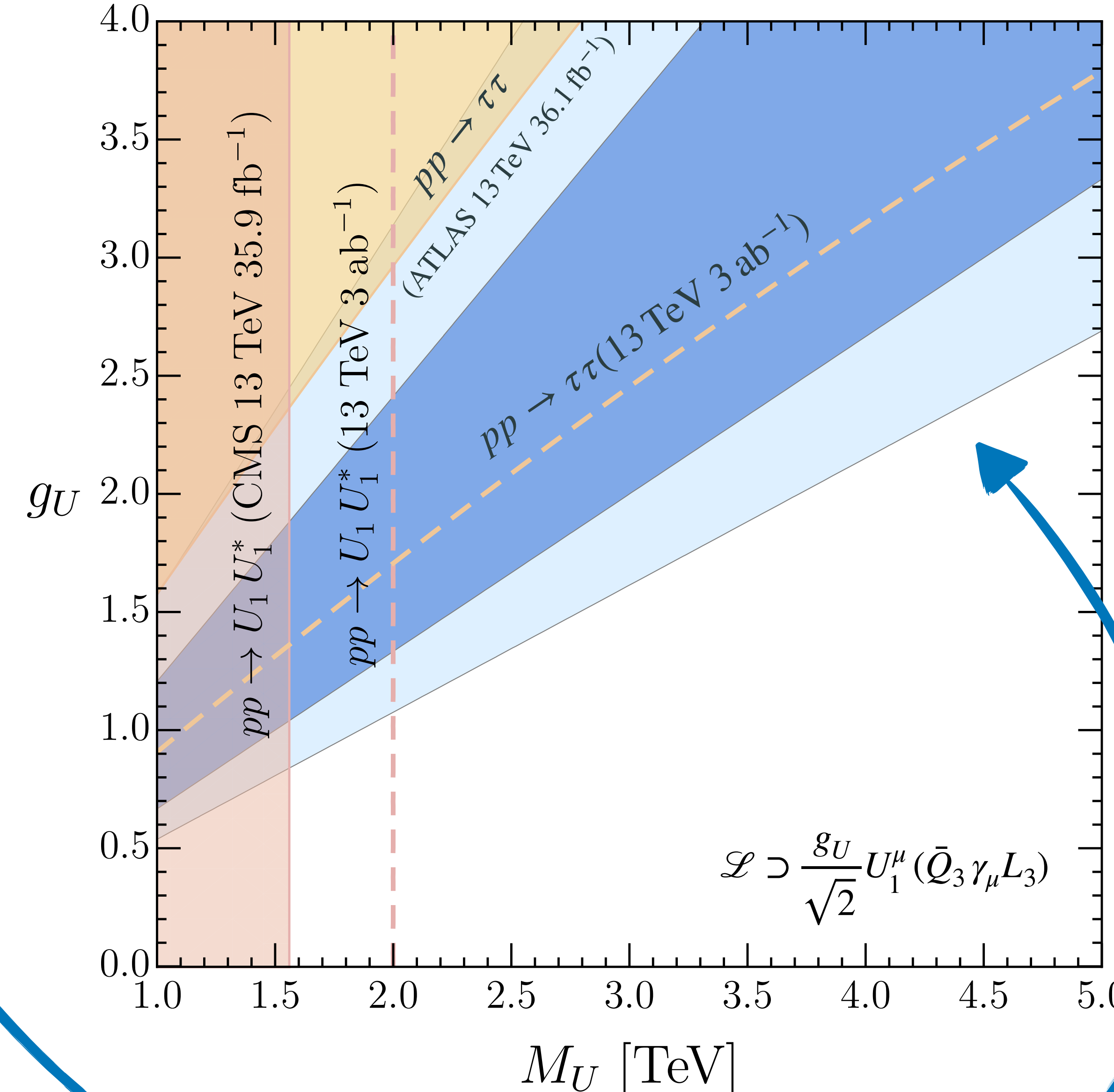
High-pT + low energy

[High-pT bounds from Baker, JFM, Isidori, König, 1901.10480]

LH + RH $(\beta^L_{b\tau} = \beta^R_{b\tau})$



LH only $(\beta^R_{b\tau} = 0)$



[Cornella, JFM, Isidori, 1903.11517]

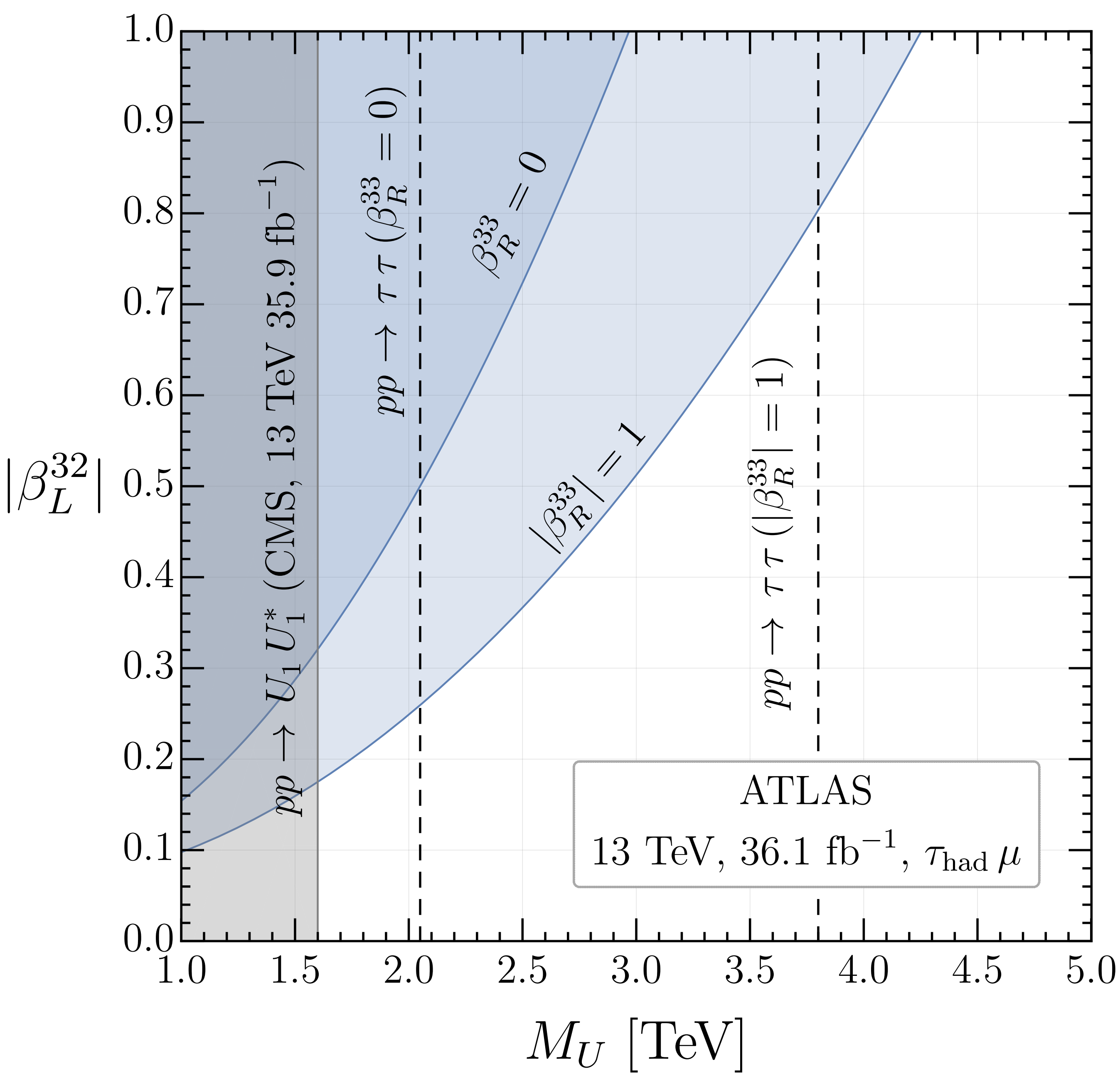
1 and 2 σ regions
preferred by the low-energy fit

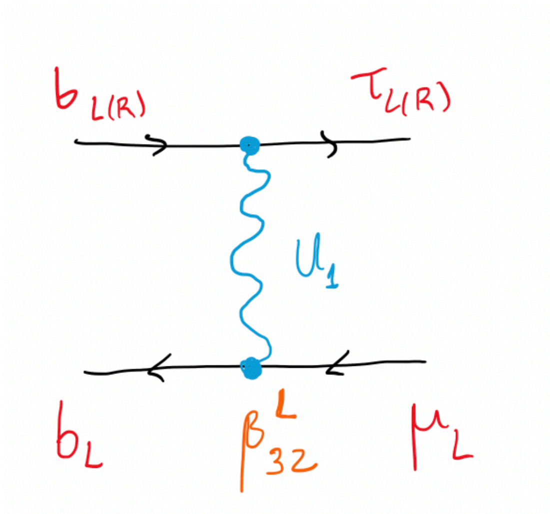
$^{(*)}$ N.B.: Assuming $\beta_{s\tau} < 0.25$

Recast of the $pp \to \tau\mu$ data

[Baker, JFM, Isidori, König, 1901.10480]

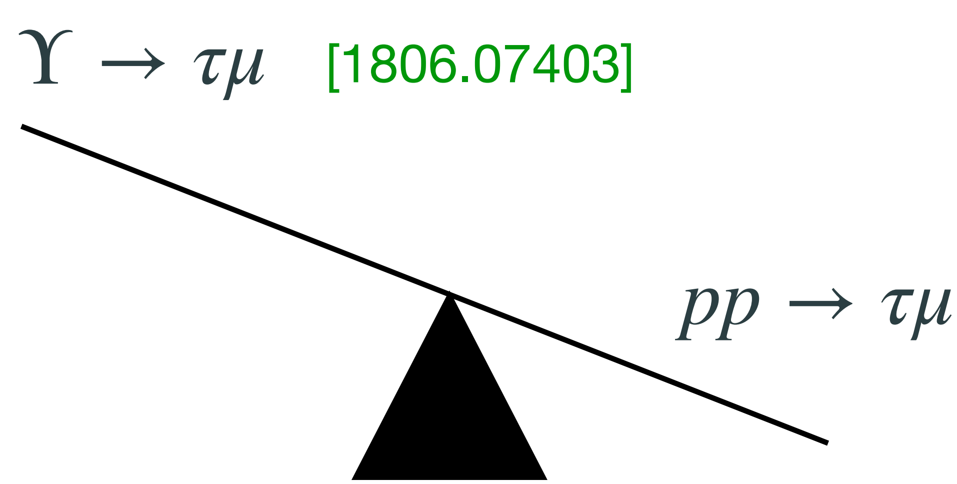
$$\mathscr{L} \supset \frac{3}{\sqrt{2}} U_\mu \left(\beta^L_{32}\, \bar{Q}_3 \gamma^\mu L_2 + \bar{Q}_3 \gamma^\mu L_3 - \beta_R\, \bar{b}_R \gamma^\mu \tau_R\right)$$





Stronger limits from $pp \to \tau\tau$

($\beta^L_{32} \sim 0.1$ preferred by $R(D^{(*)})$ fit)



Beyond the (over-)simplified U_1 picture

The U_1 leptoquark is a massive vector…

→ It is not well-defined without specifying a UV origin

There are two ways to UV-complete the vector leptoquark

- U_1 as a gauge boson from an extended symmetry, like the W and Z in the SM

  Minimal working setup: $SU(4) \times SU(3) \times SU(2)_L \times U(1) \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y$

  [di Luzio, Greljo, Nardecchia 1708.08450; Calibbi, Crivellin, Li 1709.00692; Bordone, Cornella, JFM, Isidori 1712.01368; Greljo, Stefanek 1802.04274…]

- U_1 as a composite resonance from a strongly coupled sector, similar to QCD resonances

  [Barbieri, Tesi, 1712.06844, Barbieri, Murphy, Senia, 1611.04930, Barbieri, Isidori, Pattori, Senia, 1512.01560,…]

Leptoquark vector companions

… but no matter the approach (or the model details), the U_1 leptoquark always 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 bound state

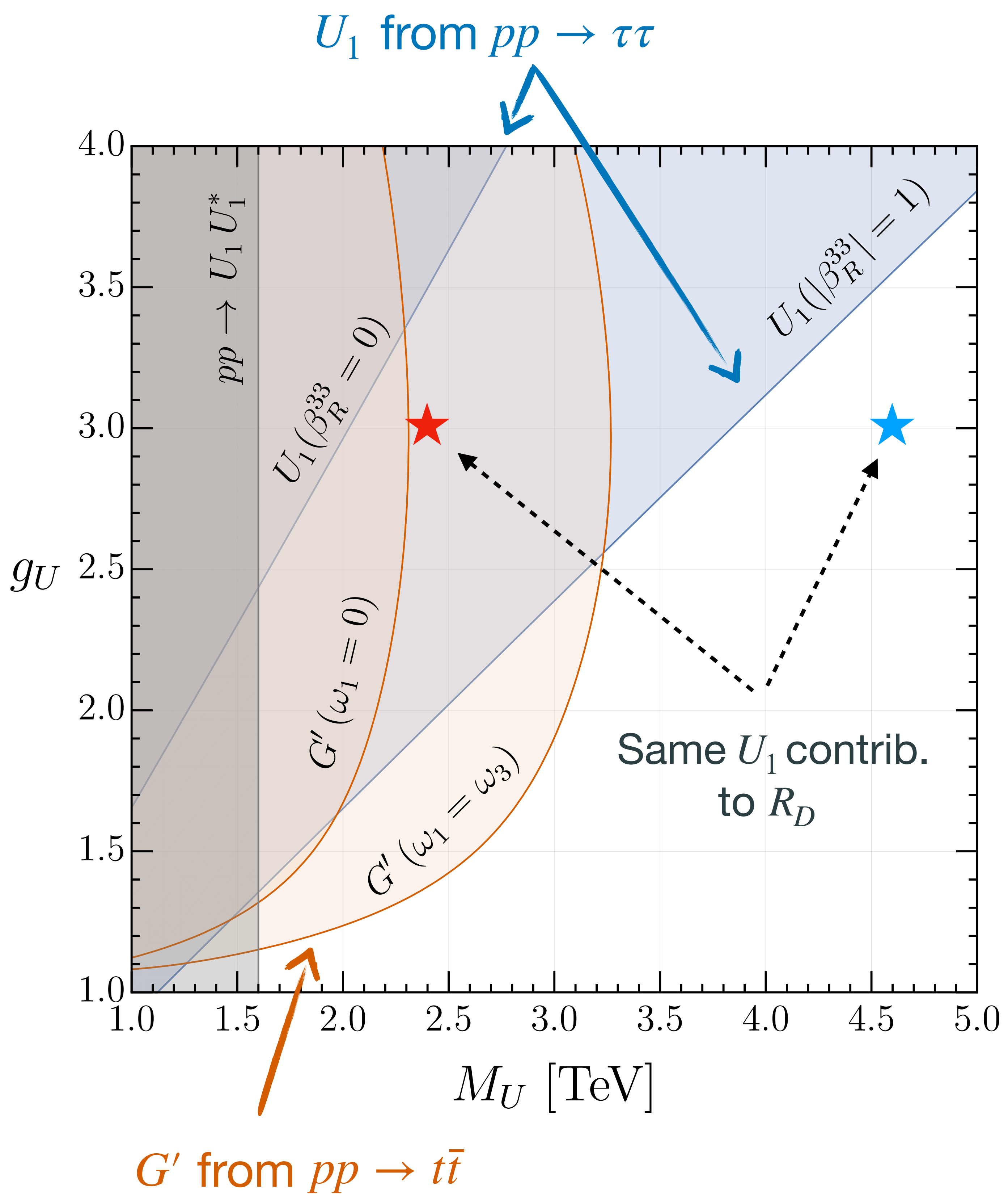
$$G' + Z' \sim \langle \bar{Q} Q \rangle$$

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

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

Other states, e.g. vector-like fermions (important later!), are commonly needed

High-pT interplay with the new vectors



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

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

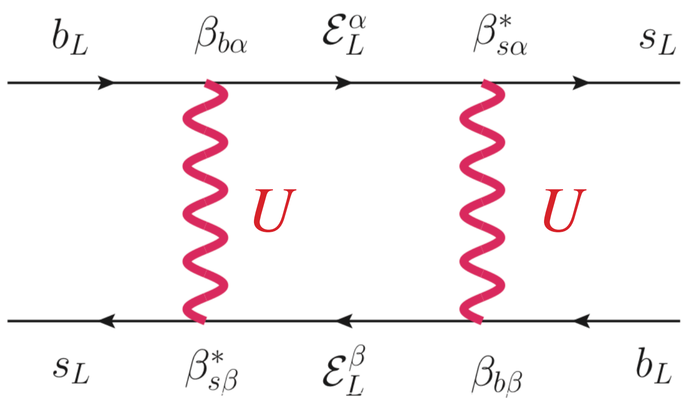
ω_i : scalar vevs

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

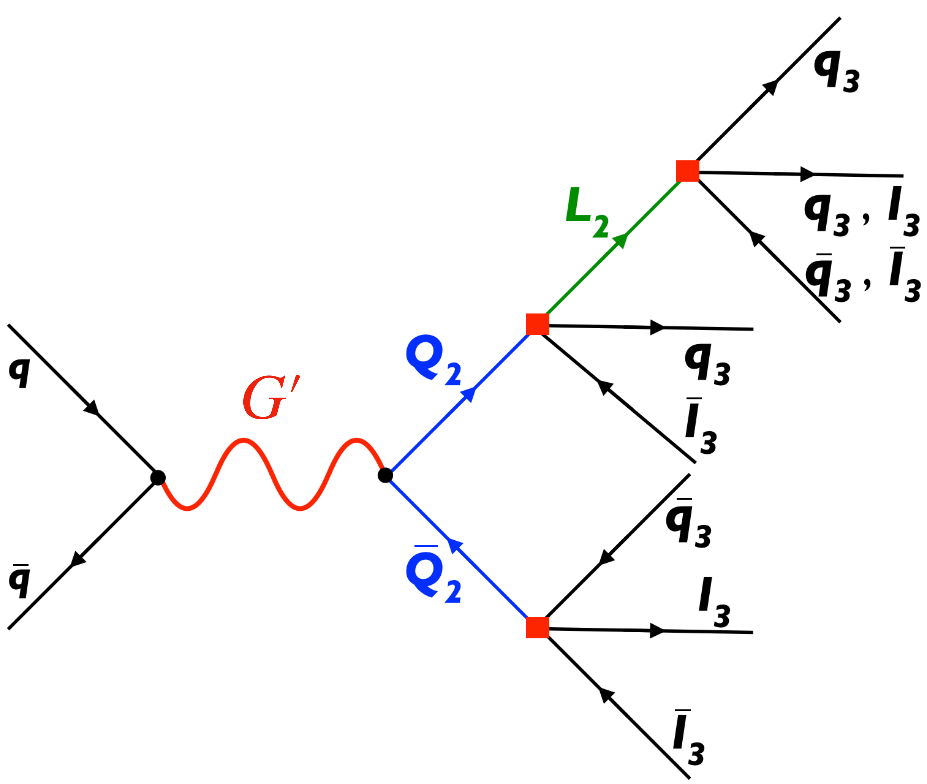
Exotic multi-jet plus multi-lepton signatures

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



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

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



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 inconclusive and the overall picture may 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**)

Great **complementarity** between low-energy and high-pT

Going beyond simplified models is important

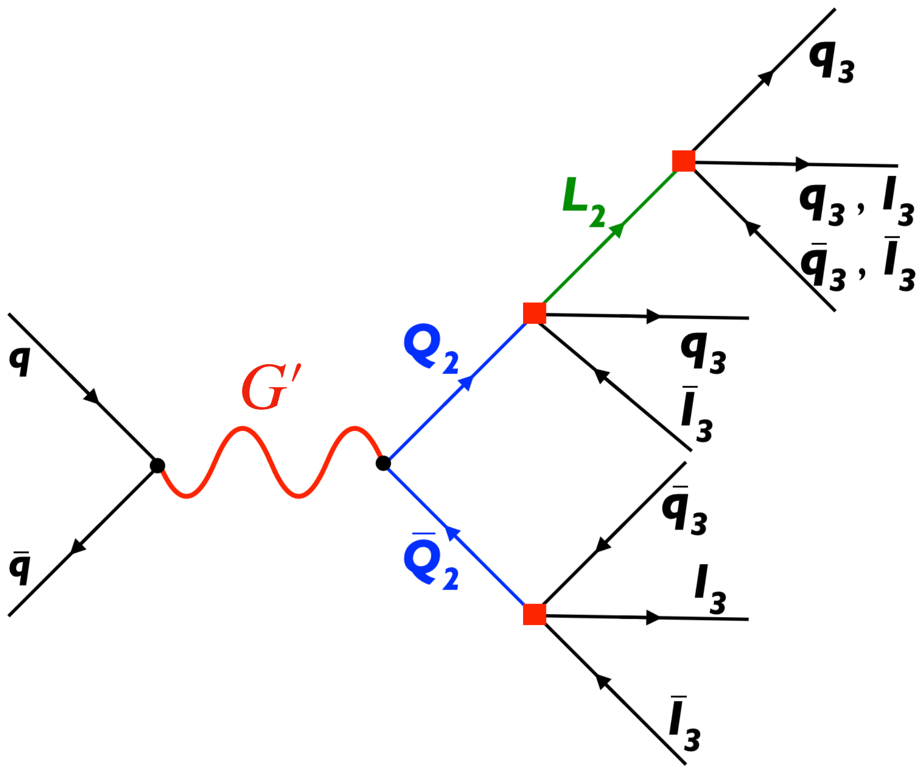
→ unexpected experimental signatures (G', Z', VL fermions,…)

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

…and summary

High-pT signatures

	LQ, Z'	G'	LQ LQ*
$pp \to$	$\tau\tau, \tau\nu$	$t\bar{t}, b\bar{b}$	$b\tau b\tau, t\nu t\nu, \ldots$
	$\tau\mu$	jj	$b\tau b\mu, t\nu b\mu, \ldots$
	$\mu\mu$		$b\mu b\mu, \ldots$



Generic characteristics of the new exotic states:

- Masses **around the TeV scale** [2-6 TeV]
- Flavor non-universal, with much **stronger couplings to 3rd generation**
- **Large widths** for Z' and G'

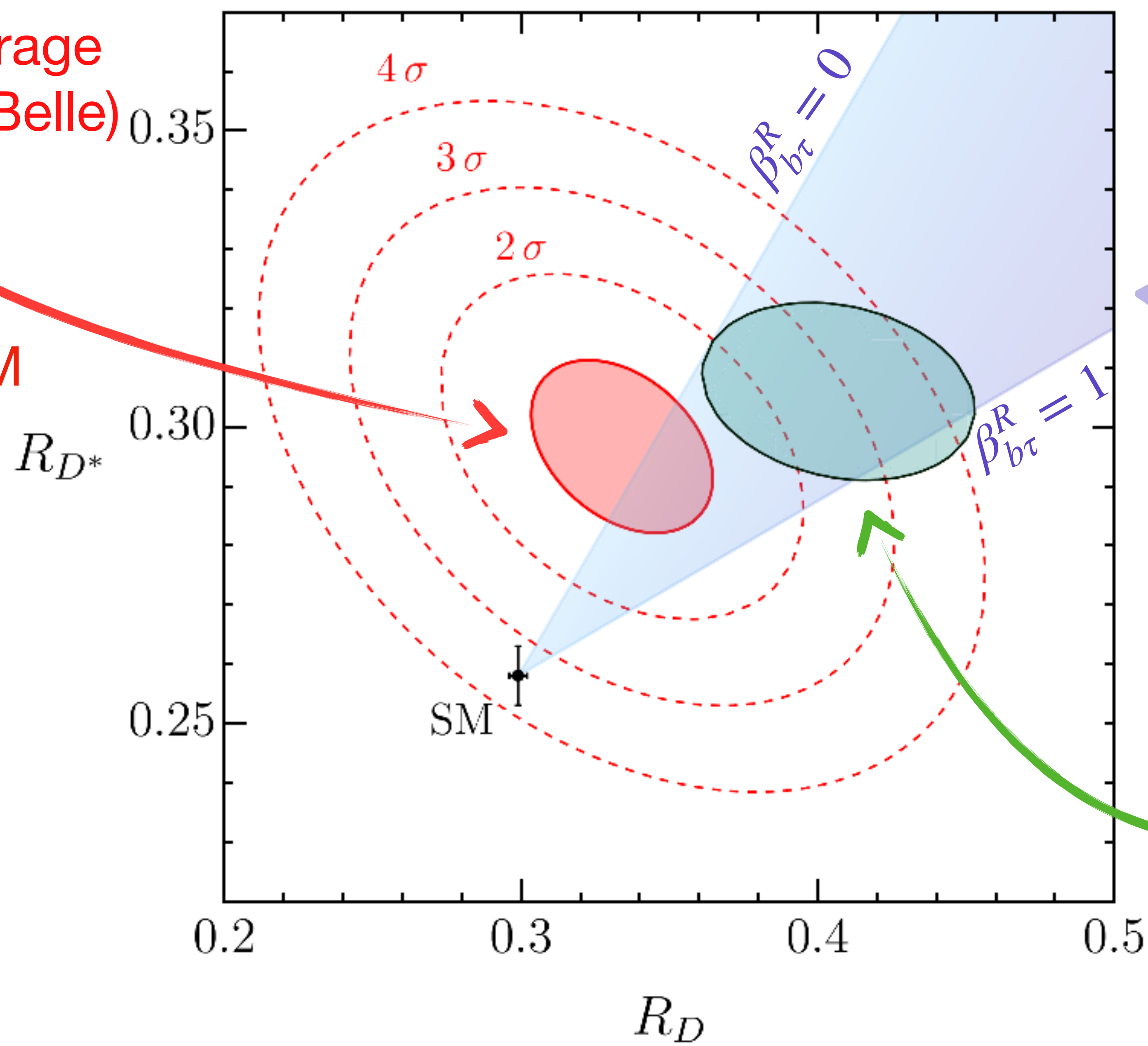
UFO model publicly available at https://feynrules.irmp.ucl.ac.be/wiki/LeptoQuark

Backup slides

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

New world average (preliminary by Belle)

$3.1\,\sigma$ w.r.t SM



U_1 leptoquark projections

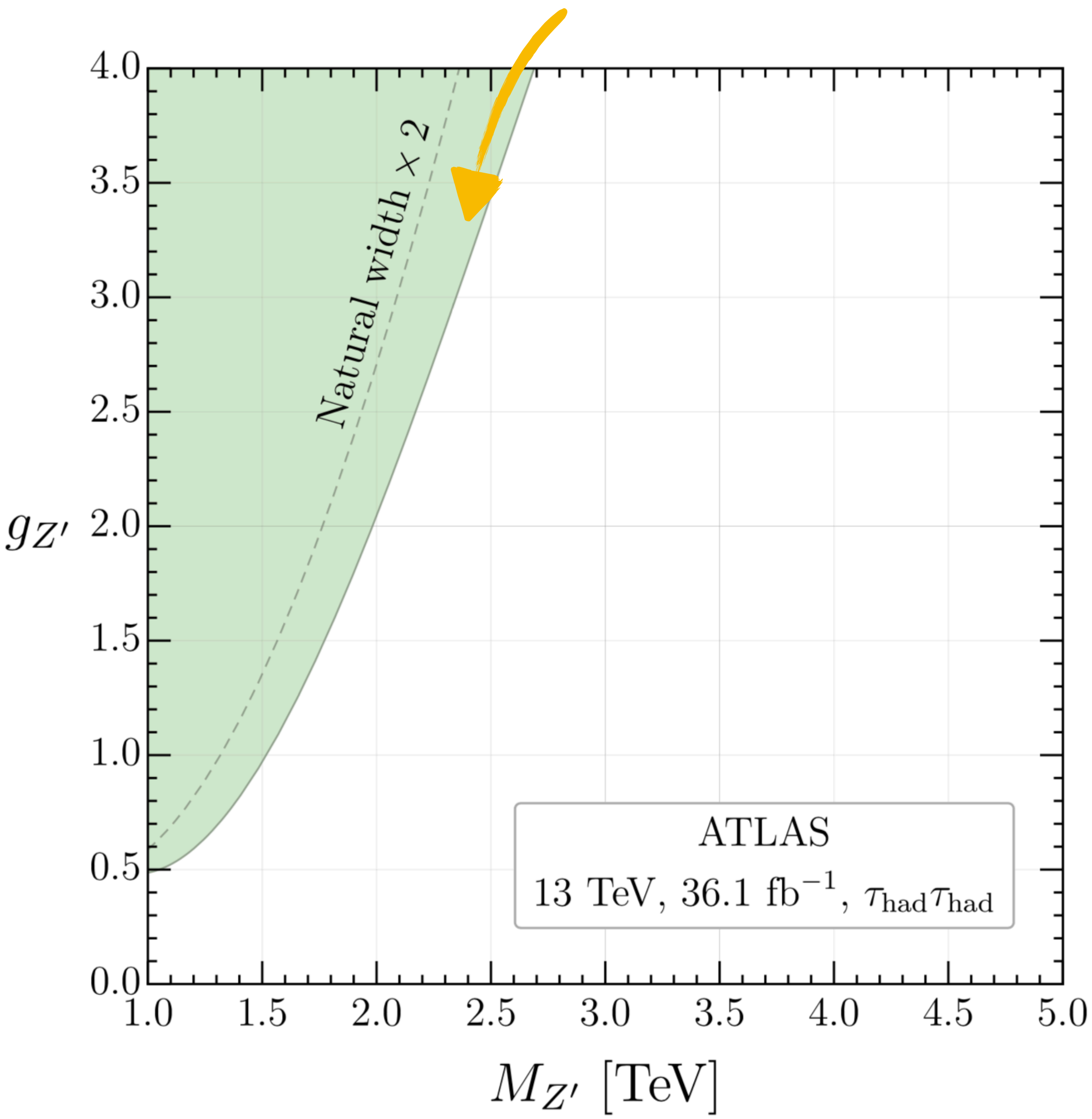
HFLAV world average (pre-Moriond)

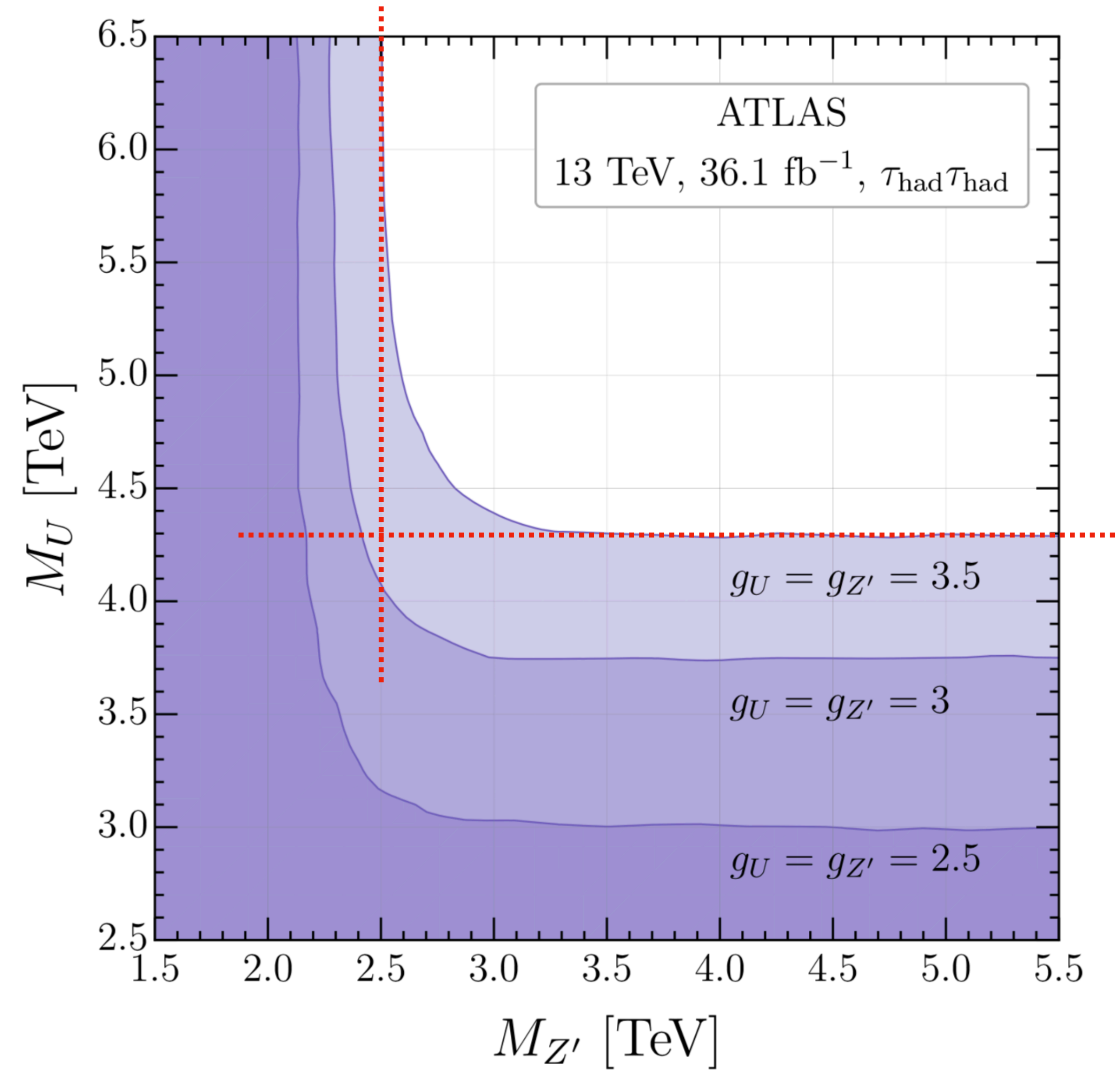
$3.8\,\sigma$ w.r.t SM

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

Recast of the $pp \to \tau\tau$ data: Z' search and combined

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





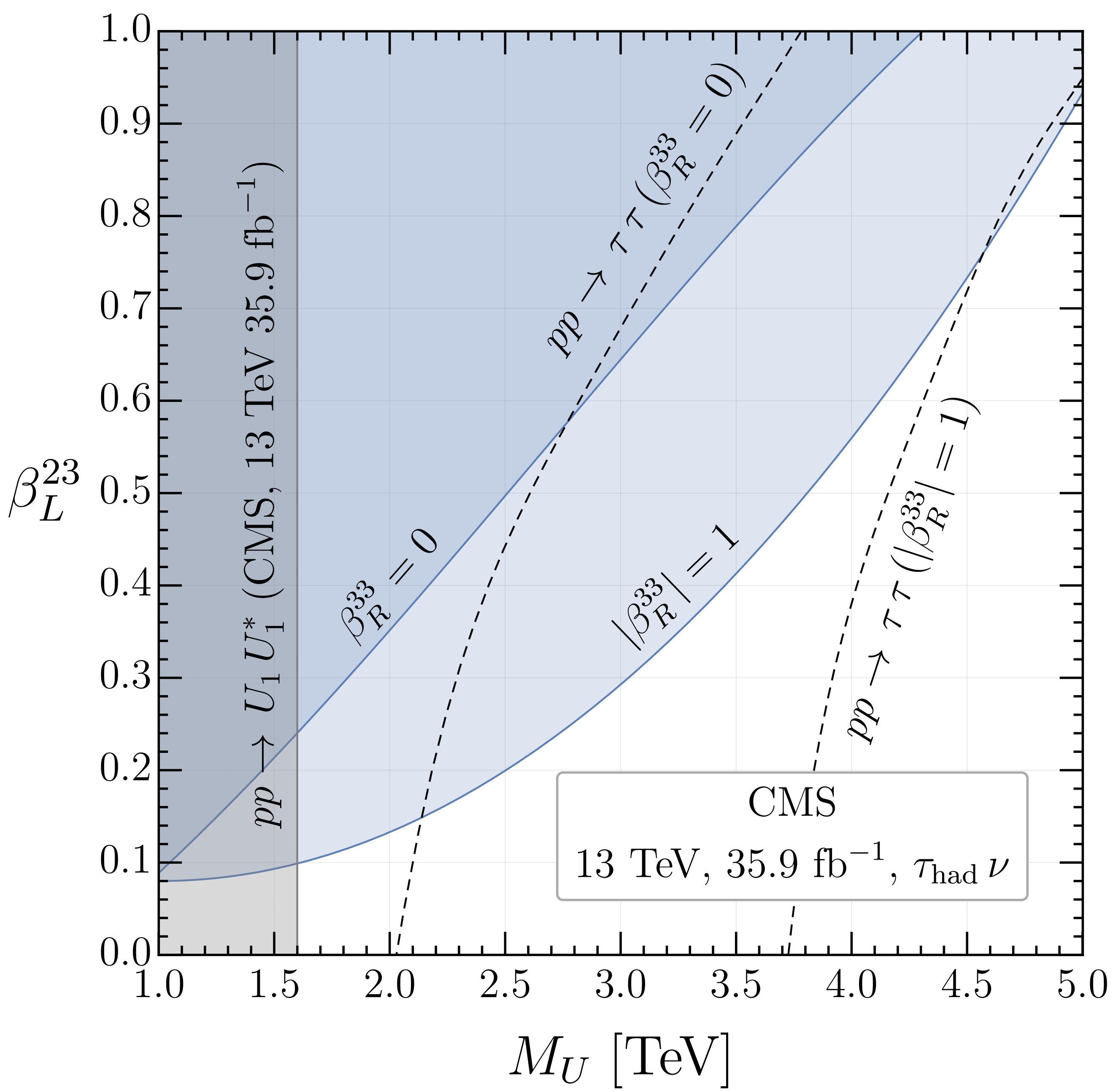
Distortions in the tails of the m_T^{tot} distribution, as in the U_1 case

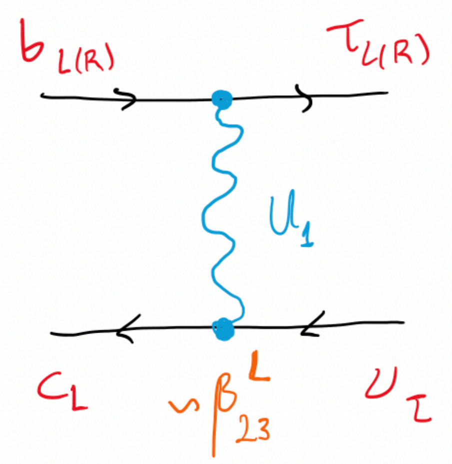
The mass region where the two particles overlap is small

Recast of the $pp \to \tau\nu$ data

[Baker, JFM, Isidori, König, 1901.10480]

$$\mathscr{L} \supset \frac{3}{\sqrt{2}} U_\mu \left(\beta^L_{23}\, \bar{Q}_2 \gamma^\mu L_3 + \bar{Q}_3 \gamma^\mu L_3 - \beta_R\, \bar{b}_R \gamma^\mu \tau_R\right)$$





Contrary to other NP scenarios for $R(D^{(*)})$,

here $pp \to \tau\tau$ gives stronger limits

($\beta^L_{23} \sim 0.1$ preferred by $R(D^{(*)})$ fit)

Interesting prospects. Good complementarity between $pp \to \tau\tau$ and $pp \to \tau\nu$