Models for B-anomalies

UK HEP Forum: The Spice of Flavour
The Cosener's House - 27 Nov 2018

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Outline

1. Review of “B-anomalies” *[see also talk by Mika Vesterinen]*
   - charged currents
   - neutral currents
2. Combined (charged + neutral currents) explanations
   - EFT
   - Simplified models
   - UV completions → 4321 model

Flavour from a BSM perspective

- Almost all the "oddities" of the SM related to the Higgs

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{gauge}} + \left(y_{ij}\overline{\psi}_i\psi_j H + \text{h.c.}\right) - \lambda \left|H\right|^4 + \mu^2 \left|H\right|^2 - \Lambda_{\text{cc}}^4$$

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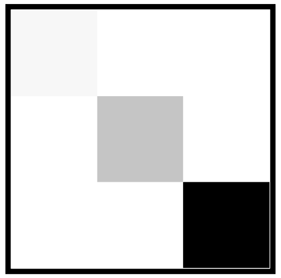
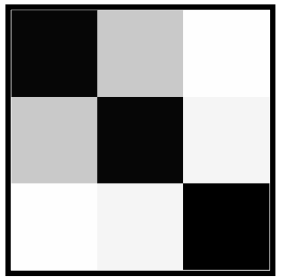
- Flavour problems

1. Is there a dynamics behind the pattern of fermion masses and mixings ?

$M_{u,d} \sim$



$V_{\text{CKM}} \sim$



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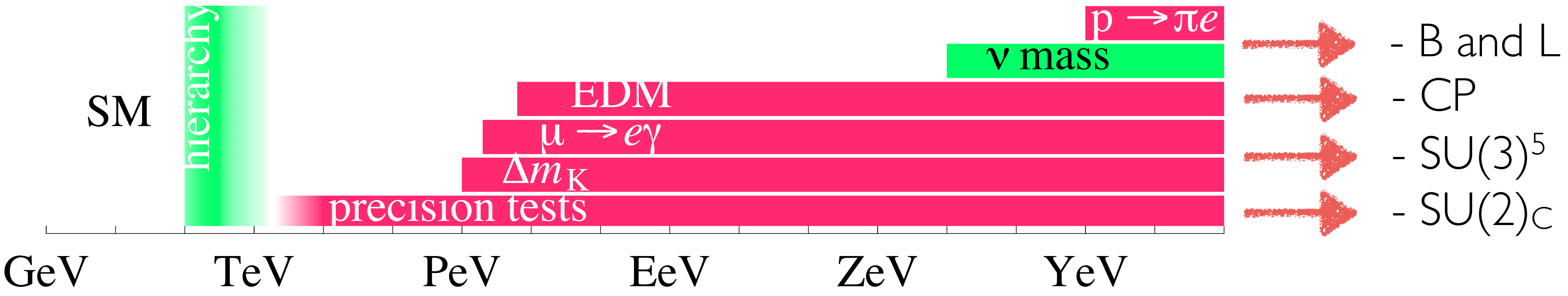
1. Is there a dynamics behind the pattern of fermion masses and mixings ?

2. How is it possible to reconcile TeV-scale NP with the absence of indirect signals ?



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→ exciting NP at ATLAS/CMS *[suggested by hierarchy problem]*
boring flavour physics at LHCb *[protected by MFV]*

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→ exciting NP at ATLAS/CMS *[suggested by hierarchy problem]*
boring flavour physics at LHCb *[protected by MFV]*

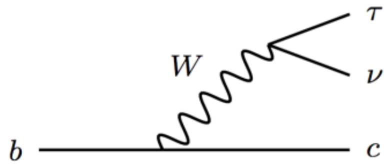
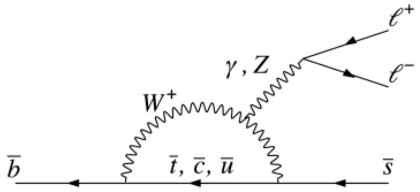
- instead, <u>unexpected</u> flavour anomalies challenging the old flavour paradigm !

Part-I

Review of “B-anomalies”

“B-anomalies”

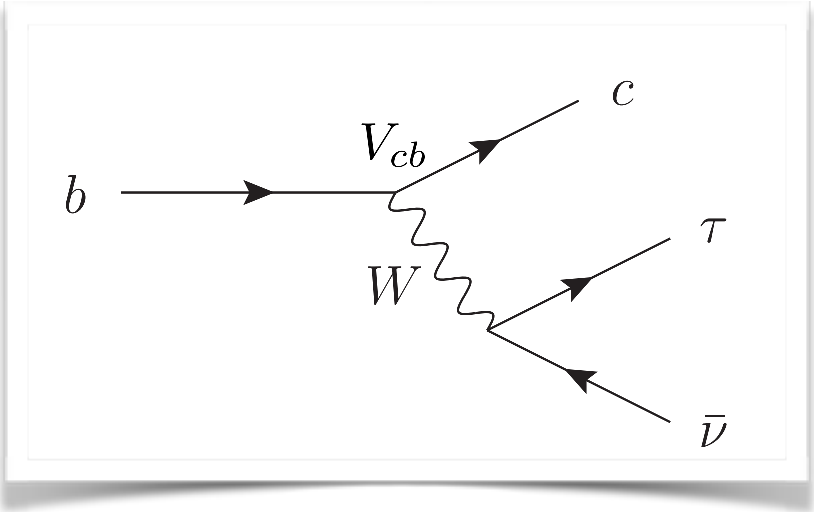
- So far the largest coherent pattern of SM deviations, building up since ~ 2012

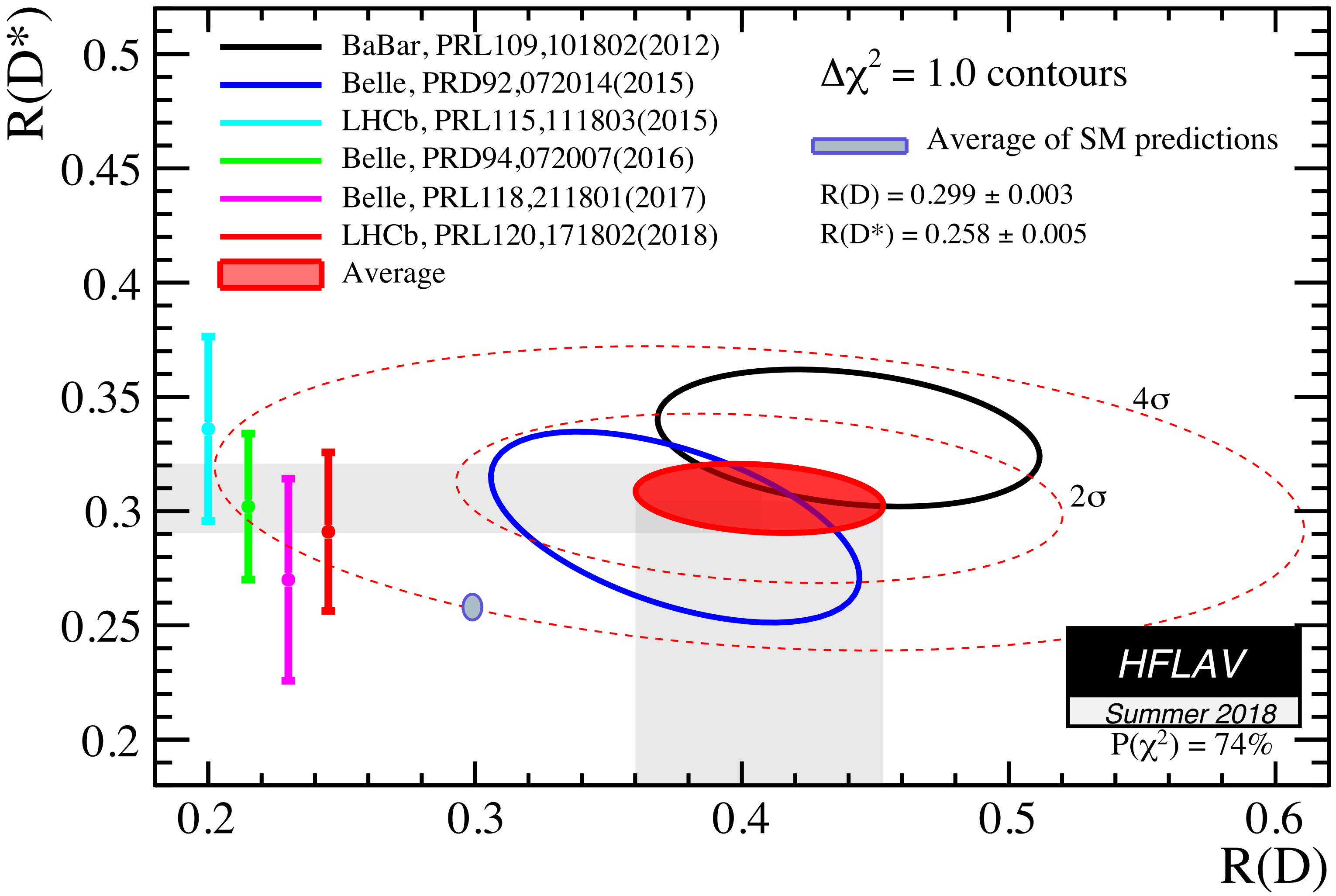
	$b \to c\tau\nu$  	$b \to s\mu\mu$ 
Lepton Universality	$R(D), R(D^*),$ $R(J/\psi)$	$R(K), R(K^*)$
Angular Distributions		$B \to K^*\mu\mu\ \ (P_5')$
Differential BR $(d\Gamma/dq^2)$		$B \to K^{(*)}\mu\mu$ $B_s \to \phi\mu\mu$ $\Lambda_b \to \Lambda\mu\mu$

Charged current anomalies

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)+}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)+}\ell\nu)}$$

$$\ell = \mu, e$$





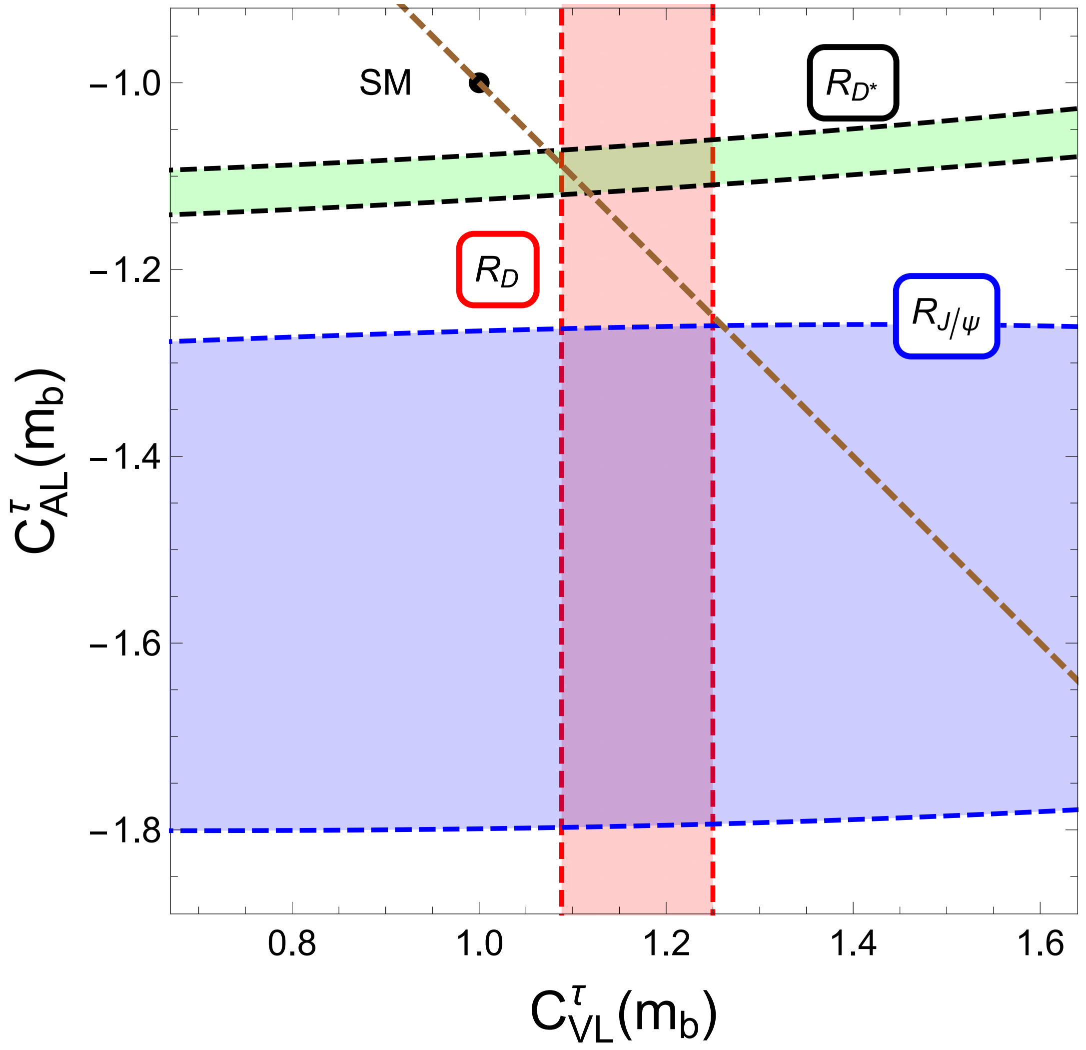
- SM prediction reasonably robust *[HFLAV 2018]*
- Deviation seen in 3 exp.'s in a consistent way, combined significance ~ 3.8σ
- R(D) and R(D*) point to constructive interference (+15%) with SM amplitude

Charged current anomalies

- BSM fit favours NP in LH tau operators

[See e.g. Azatov at al, 1805.03209]

$$\mathcal{L}_{\text{SM}} = -\frac{4G_F}{\sqrt{2}} V_{cb} (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_\tau) \quad \longrightarrow \quad \mathcal{L}_{\text{BSM}} = \frac{2c}{\Lambda^2} (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_\tau)$$



$$\mathcal{O}^{cb\ell\nu}_{\text{VL}} = [\bar{c}\,\gamma^\mu\, b][\bar{\ell}\,\gamma_\mu\, P_L\, \nu]$$
$$\mathcal{O}^{cb\ell\nu}_{\text{AL}} = [\bar{c}\,\gamma^\mu\, \gamma_5\, b][\bar{\ell}\,\gamma_\mu\, P_L\, \nu]$$
$$\mathcal{O}^{cb\ell\nu}_{\text{SL}} = [\bar{c}\, b][\bar{\ell}\, P_L\, \nu]$$
$$\mathcal{O}^{cb\ell\nu}_{\text{PL}} = [\bar{c}\,\gamma_5\, b][[\bar{\ell}\, P_L\, \nu]$$
$$\mathcal{O}^{cb\ell\nu}_{\text{TL}} = [\bar{c}\,\sigma^{\mu\nu}\, b][\bar{\ell}\,\sigma_{\mu\nu}\, P_L\, \nu]$$

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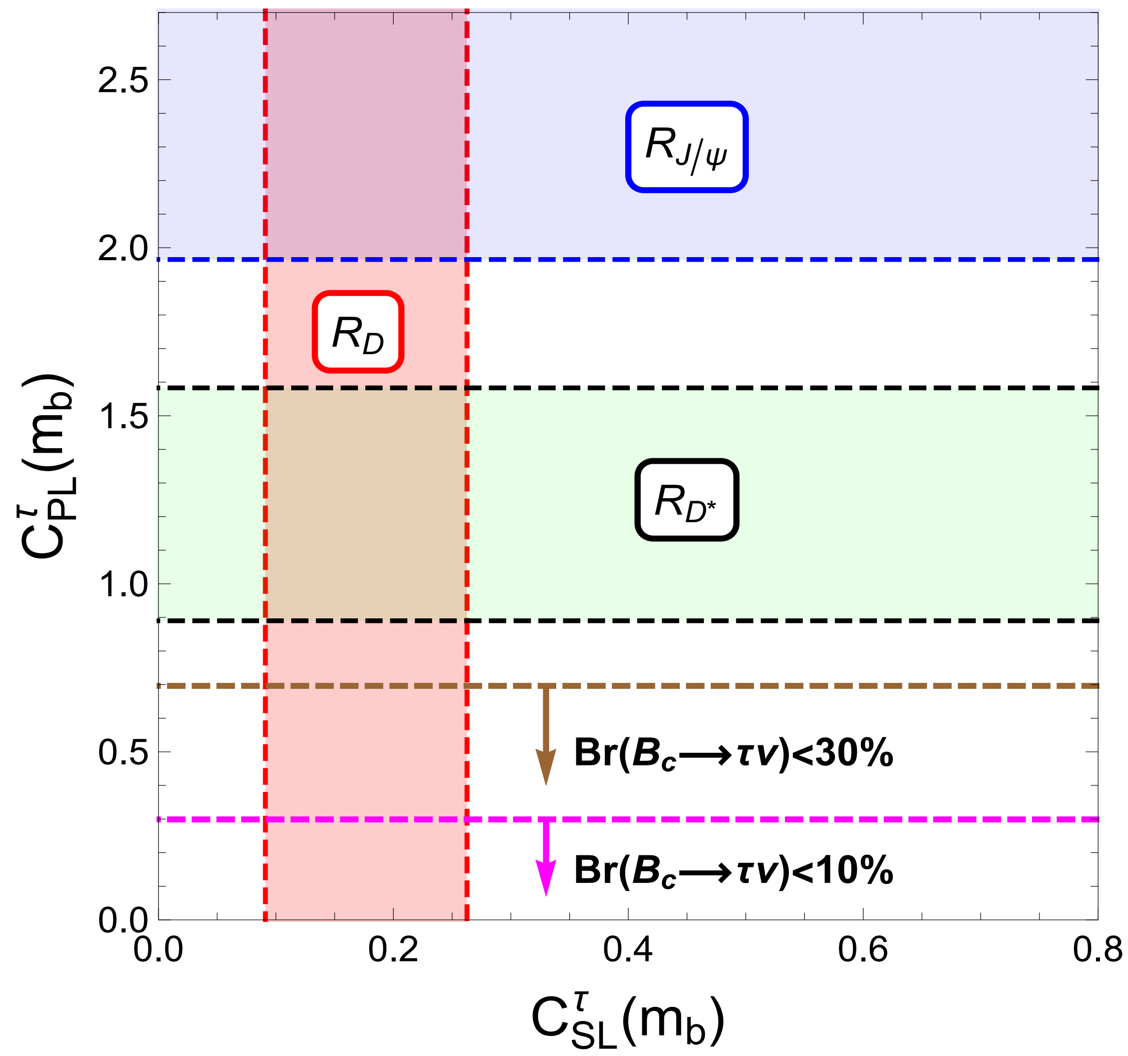

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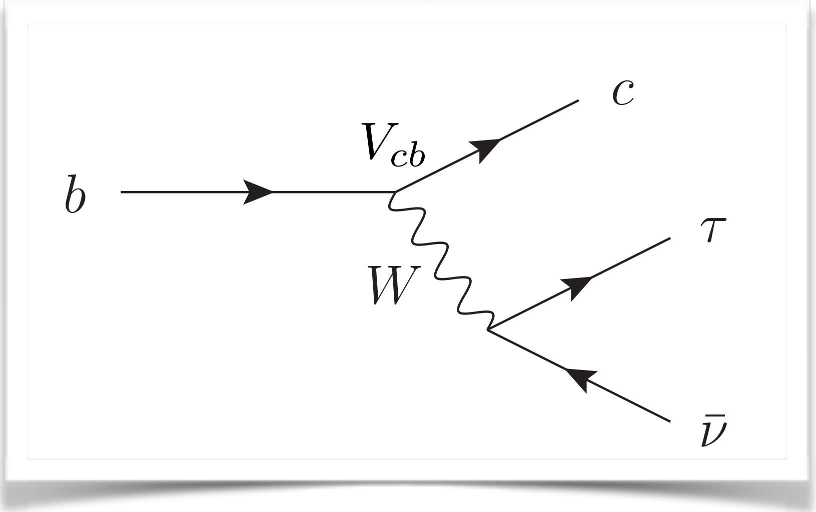
- What is the scale of NP ?



No suppression: $c = 1$ $\Lambda = 3.4 \text{ TeV}$

MFV: $c = V_{cb}$ $\Lambda = 0.7 \text{ TeV}$

MFV + loop: $c = V_{cb}/4\pi$ $\Lambda = 0.1 \text{ TeV}$

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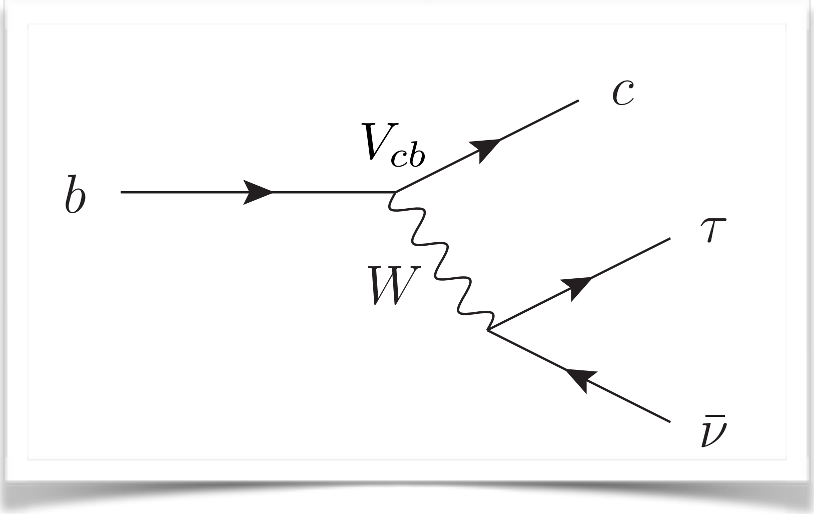

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*<u>Exception</u>: light (< 100 MeV) sterile neutrino

[Becirevic, Fajfer, Koskik, Sumensari 1608.08501 +1804.04135, 1804.04642, 1807.10745, …]

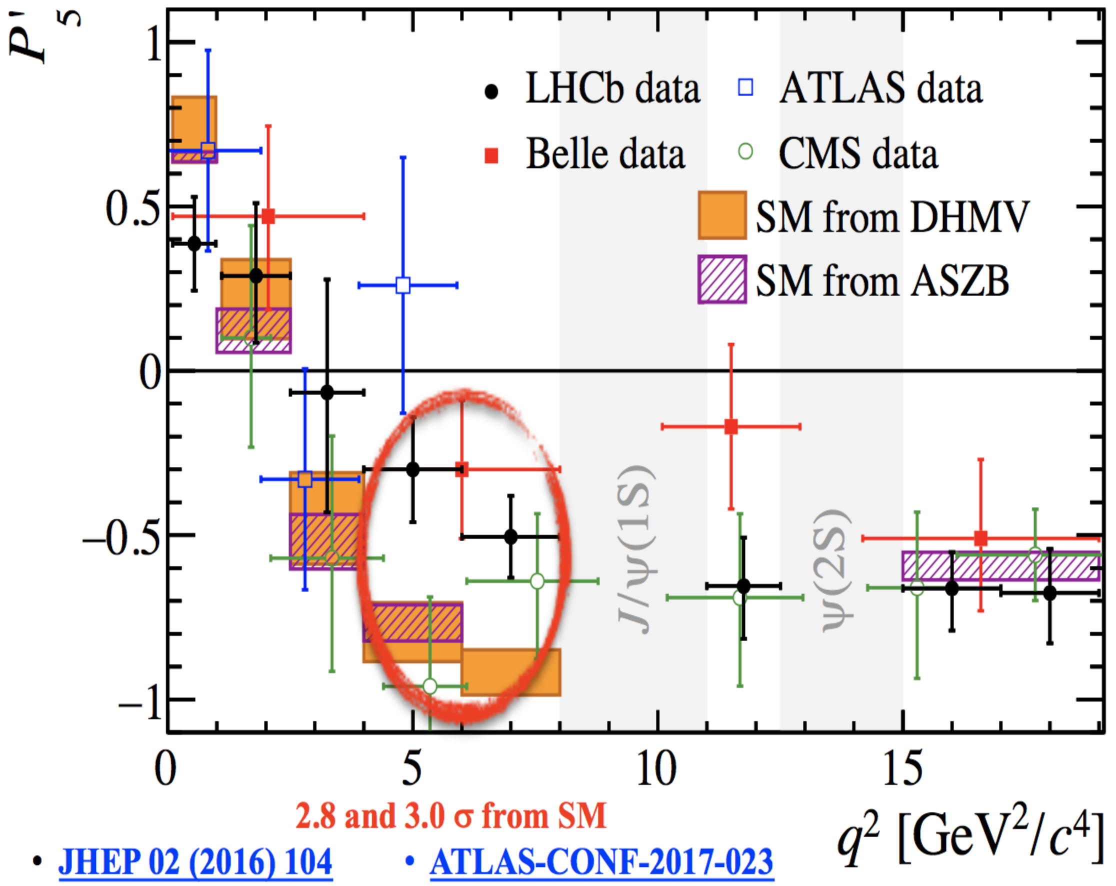
$$\mathcal{L}^{b\to c\tau\nu}_{BSM} = \frac{c_{R_D}}{\Lambda^2} (\bar{c}_R \gamma_\mu b_R) (\bar{\tau}_R \gamma^\mu N_R) \qquad \Lambda/\sqrt{c_{R_D}} = (1.27^{+0.09}_{-0.07})\ \ \text{TeV}$$

Neutral current anomalies

- Angular distributions $B \to (K^* \to K\pi)\mu\mu$

Challenging SM prediction

[see talk by Roman Zwicky]

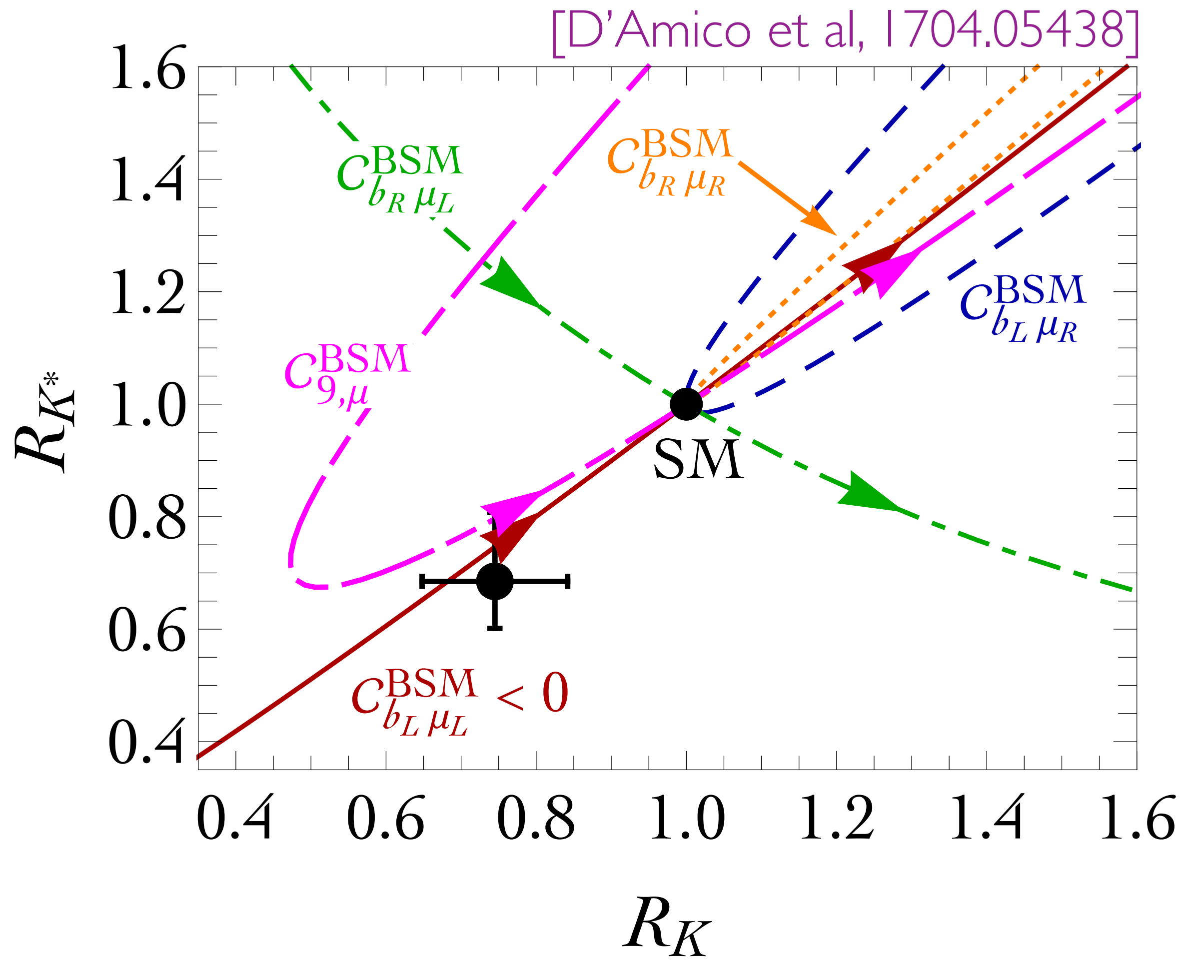


2.8 and 3.0 σ from SM

- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

- LFU ratios $R(K^{(*)}) = \dfrac{\mathcal{B}(B \to K^{(*)}\mu\bar{\mu})}{\mathcal{B}(B \to K^{(*)}e\bar{e})}$

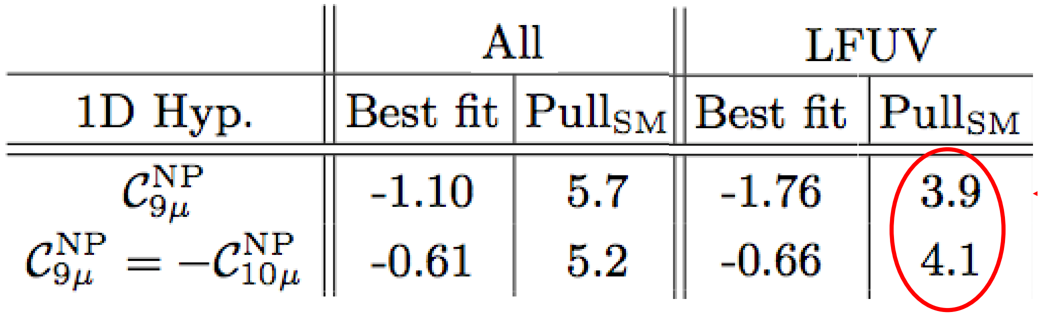
Very clean SM prediction



Combined R(K$^{(*)}$) significance ~ 4σ

Neutral current anomalies

- Well-described by NP in $b \to s\mu\mu$ *[explains also angular distributions]*
- RH currents in quark sector disfavoured *[predict wrong R(K)-R(K*) correlation]*
- Significance of global fits > 4σ



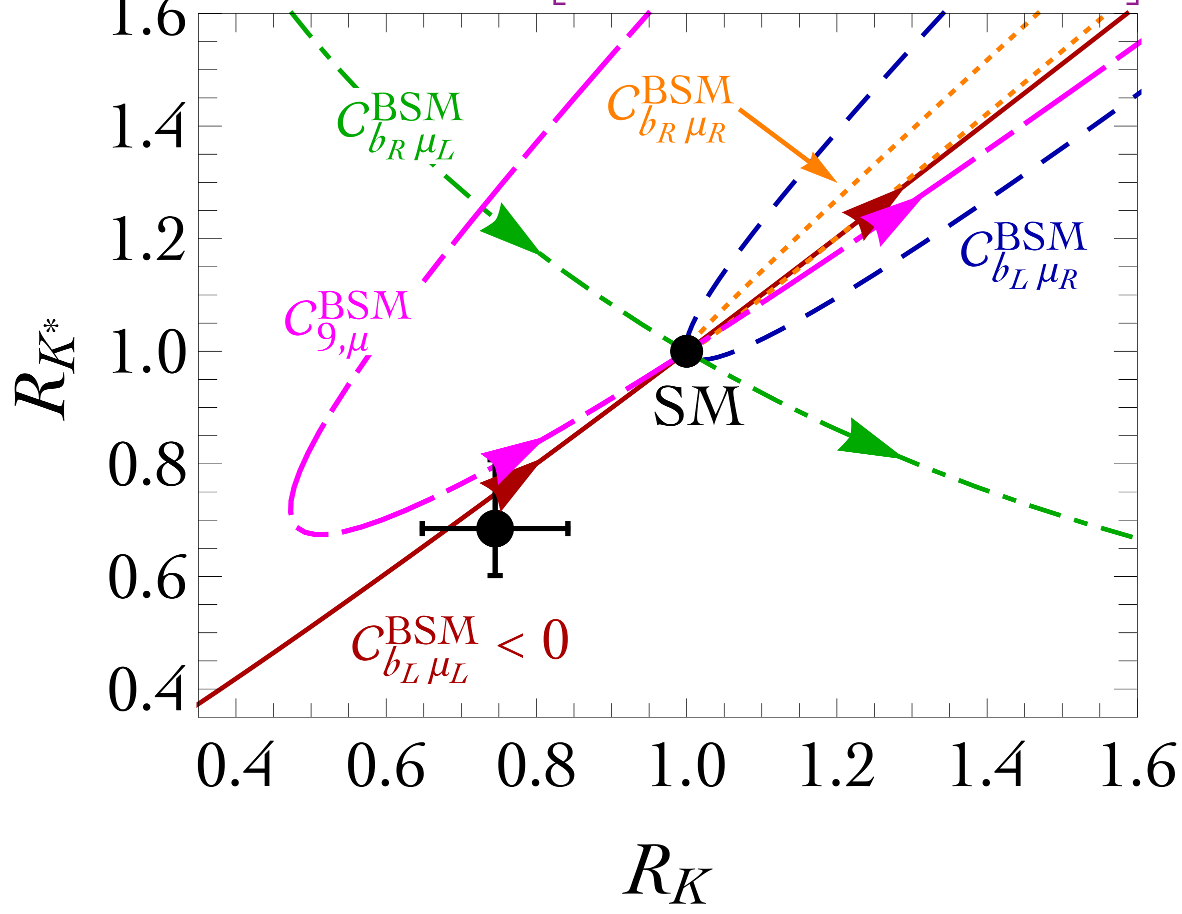
	All		LFUV	
1D Hyp.	Best fit	$\mathrm{Pull}_{\mathrm{SM}}$	Best fit	$\mathrm{Pull}_{\mathrm{SM}}$
$\mathcal{C}_{9\mu}^{\mathrm{NP}}$	-1.10	5.7	-1.76	3.9
(LH) $\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}$	-0.61	5.2	-0.66	4.1

Capdevila et al. 1704.05340

$$O_9 \propto (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}_L\gamma^\mu\ell)$$

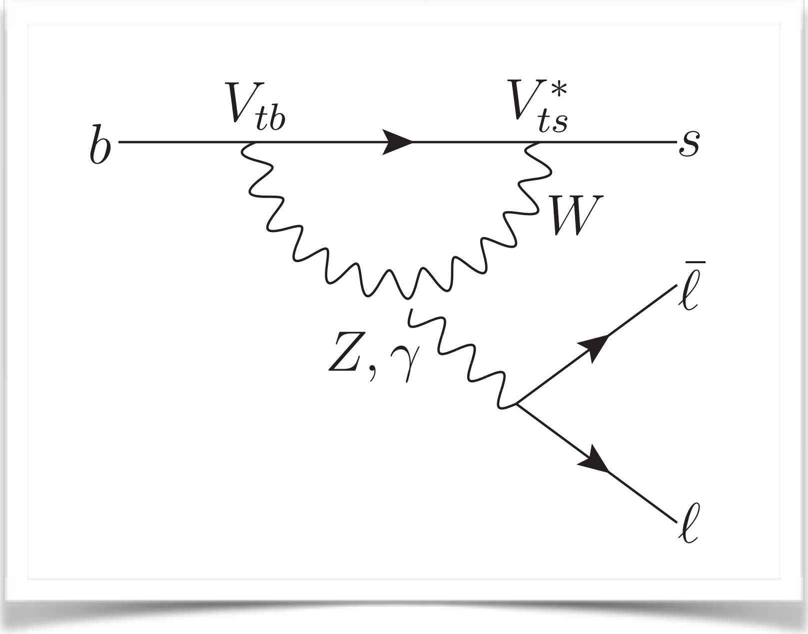
$$O_{10} \propto (\bar{s}_L\gamma_\mu b_L\bar{)}(\ell_L\gamma^\mu\gamma_5\ell)$$

[D'Amico et al, 1704.05438]



Neutral current anomalies

- Well-described by NP in $b \to s\mu\mu$
- RH currents in quark sector disfavoured
- Significance of global fits > 4**σ**
- What is the scale of NP ?



$$\mathcal{L}_{\rm BSM} = \frac{c}{\Lambda^2}\left(\overline{s}_L\gamma_\alpha b_L\right)\left(\overline{\mu}_L\gamma^\alpha\mu_L\right)$$

No suppression: $c = 1$ $\Lambda = 31\ \text{TeV}$

MFV: $c = V_{ts}$ $\Lambda = 6\ \text{TeV}$

MFV + loop: $c = V_{ts}/4\pi$ $\Lambda = 0.5\ \text{TeV}$

Part-II

Combined explanations

Why combined explanations ?

- Of course, it could be that only a subset of anomalies is due to NP

  - e.g. one could try to fit only $R(K^{(*)})$

→ many possibilities: tree, loop, light mediators, NP in electrons, … [> 100 papers]

Why combined explanations ?

- Of course, it could be that only a subset of anomalies is due to NP

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→ many possibilities: tree, loop, light mediators, NP in electrons, … [> 100 papers]

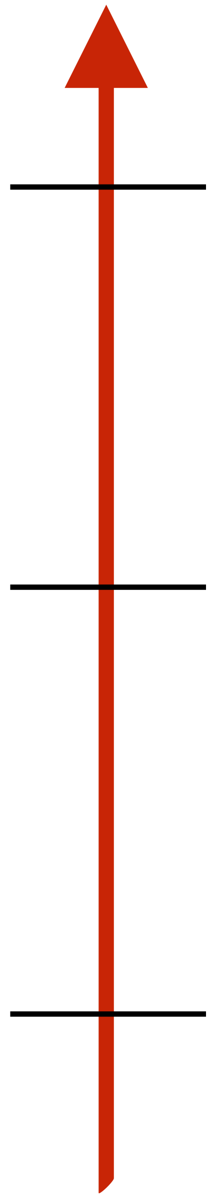
- However, if lepton flavour universality (LFU) is violated in $R(K^{(*)})$

→ <u>theoretically motivated</u> to expect large effects in $R(D^{(*)})$

1. neutral and charged currents naturally connected by $SU(2)_L$ *invariance*

2. LFU violation might be related to dynamics responsible for $m_\tau \gg m_\mu \gg m_e$

Bottom-up approach



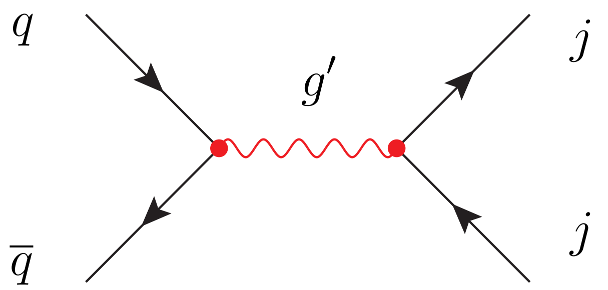
Theoretical input / bias

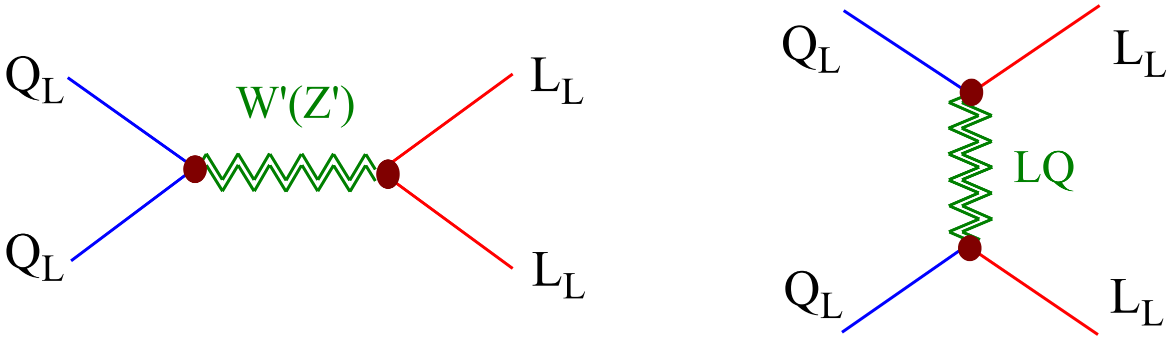
UV completions — new signatures

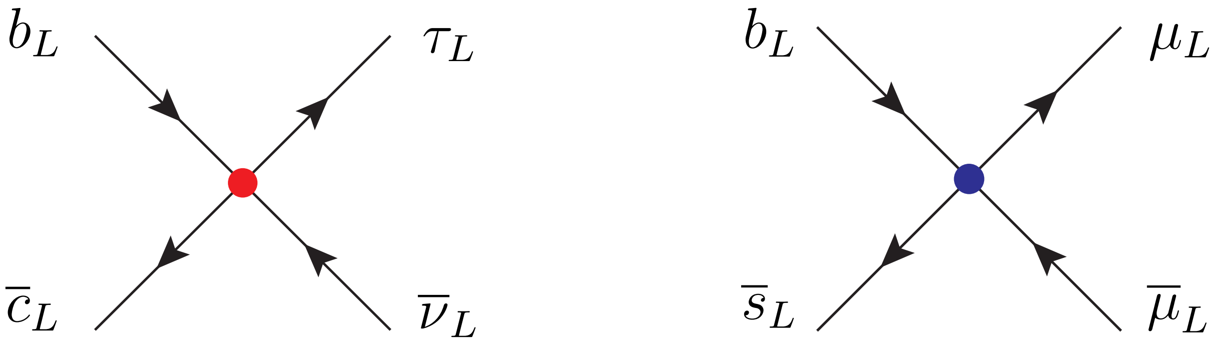
simplified models — on-shell

EFT — tails

Experimental input







$\Lambda_{R_D} = 3.4 \text{ TeV}$

$\Lambda_{R_K} = 31 \text{ TeV}$

From EFT to simplified models

- SU(2)L <u>triplet</u> operator as a natural starting point for explaining R(D) + R(K)

$$- \frac{1}{v^2} \lambda^q_{ij} \lambda^\ell_{\alpha\beta} \Big[C_T \; (\bar{Q}^i_L \gamma_\mu \sigma^a Q^j_L)(\bar{L}^\alpha_L \gamma^\mu \sigma^a L^\beta_L)$$

[Bhattacharya et al 1412.7164
Alonso, Grinstein, Camalich 1505.05164,
Greljo, Isidori, Marzocca 1506.01705,
Calibbi, Crivellin, Ota 1506.02661, …]

$$Q^i_L = \begin{pmatrix} (V^\dagger_{\rm CKM} u_L)^i \\ d^i_L \end{pmatrix}$$

$$L^\alpha_L = \begin{pmatrix} \nu^\alpha_L \\ e^\alpha_L \end{pmatrix}$$

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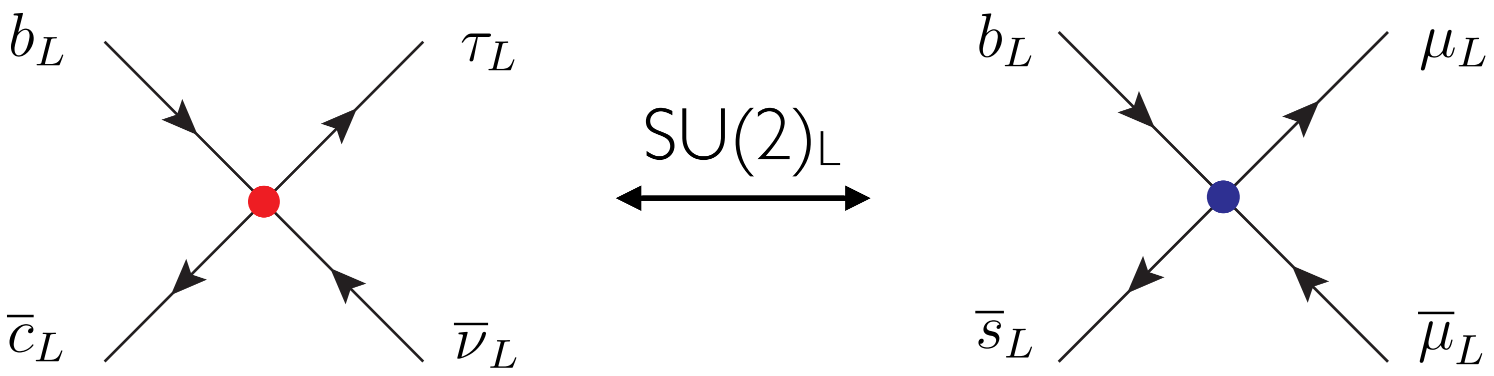
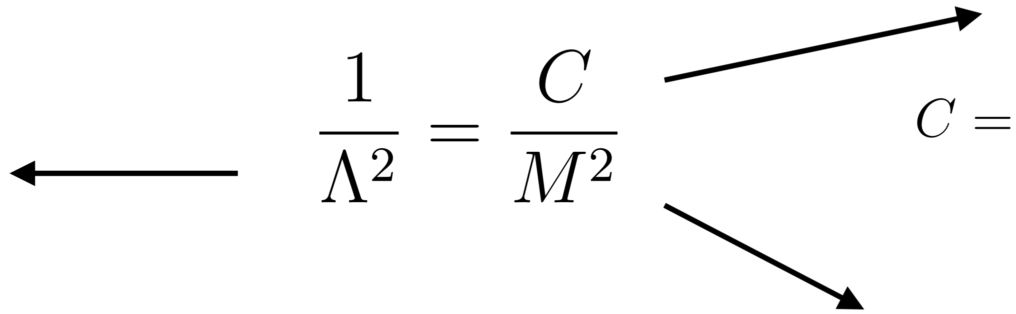


$$\Lambda_{R_D} = 3.4\ \text{TeV} \qquad \ll \qquad \Lambda_{R_K} = 31\ \text{TeV}$$



"Fermi constant"
of the anomaly

$$\frac{1}{\Lambda^2} = \frac{C}{M^2}$$

model dependent part

$$C = (\text{loops}) \times (\text{couplings}) \times (\text{flavour})$$

on-shell effects @ colliders

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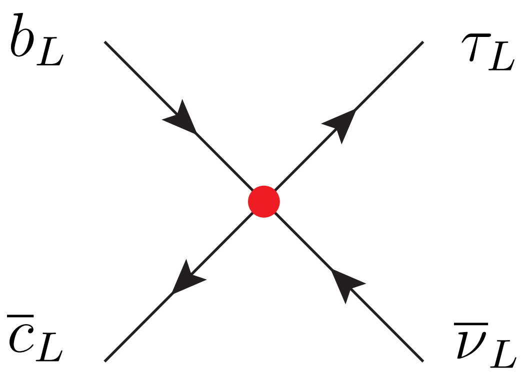

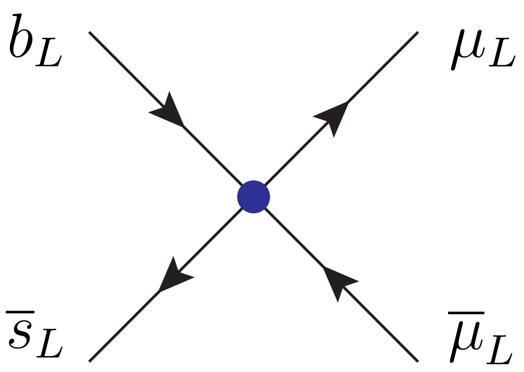

$\Lambda_{R_D} = 3.4$ TeV $\ll$ $\Lambda_{R_K} = 31$ TeV

- Perturbative unitarity bound from 2 → 2 fermion scatterings (worse case scenario)

$\sqrt{s_{R_D}} < 9.2$ TeV $\sqrt{s_{R_K}} < 84$ TeV

→ no-loose theorem for HL/HE-LHC ? [LDL, Nardecchia 1706.01868]

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- Flavour structure:

1. large couplings in taus *[SM tree level]*
2. sizable couplings in muons *[SM one loop]*
3. negligible couplings in electrons *[well tested, not much room]*

$$\lambda^{q,\ell}_{ij} = \delta_{i3}\delta_{j3} + \text{corrections} \qquad U(2)_q \times U(2)_\ell$$

approx flavor symmetry

[Barbieri et al 1105.2296, 1512.01560]

→ link to SM Yukawa pattern ?

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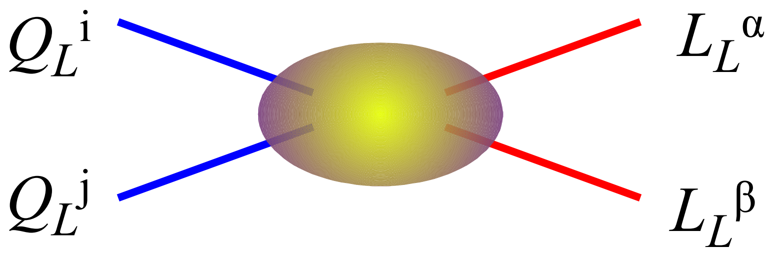
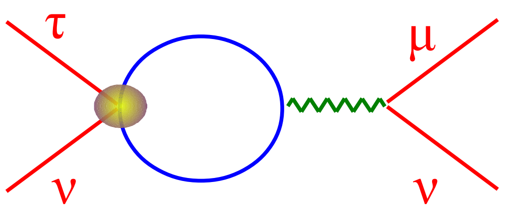
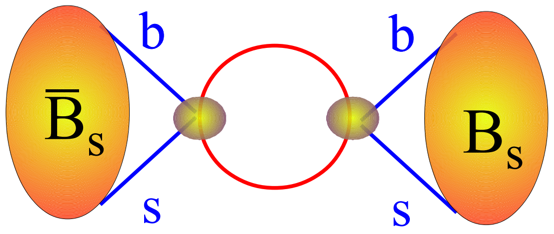
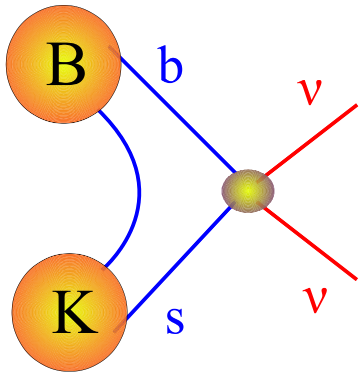


- Long list of constraints:

- FCNCs, tau-decays, EWPOs, Bs-mixing, semi-leptonic B decays, …







[Feruglio, Paradisi, Pattori
1606.00524, 1705.00929]

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$$-\frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)+C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

- Finite list of tree-level mediators

[Zürich's guide for combined explanations, 1706.07808]

Simplified Model	Spin	SM irrep	C_S/C_T	$R_{D^{(*)}}$	$R_{K^{(*)}}$
Z'	1	$(1,1,0)$	∞	×	✓
V'	1	$(1,3,0)$	0	✓	✓
S_1	0	$(\bar{3},1,1/3)$	-1	✓	×
S_3	0	$(\bar{3},3,1/3)$	3	✓	✓
U_1	1	$(3,1,2/3)$	1	✓	✓
U_3	1	$(3,3,2/3)$	-3	✓	✓

From EFT to simplified models

- SU(2)$_L$ triplet operator as a natural starting point for explaining R(D) + R(K)

$$-\frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

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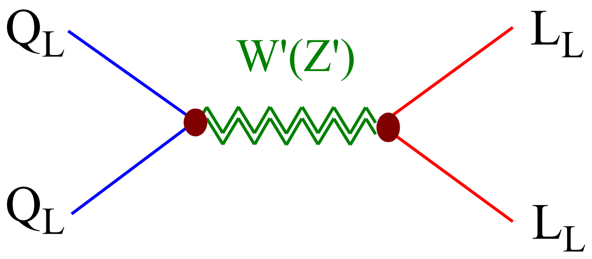

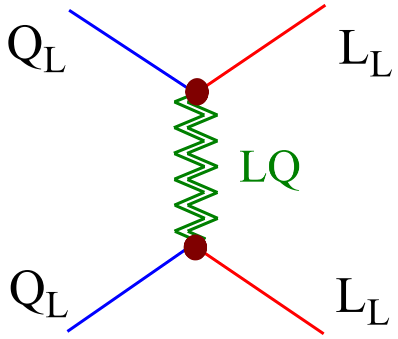

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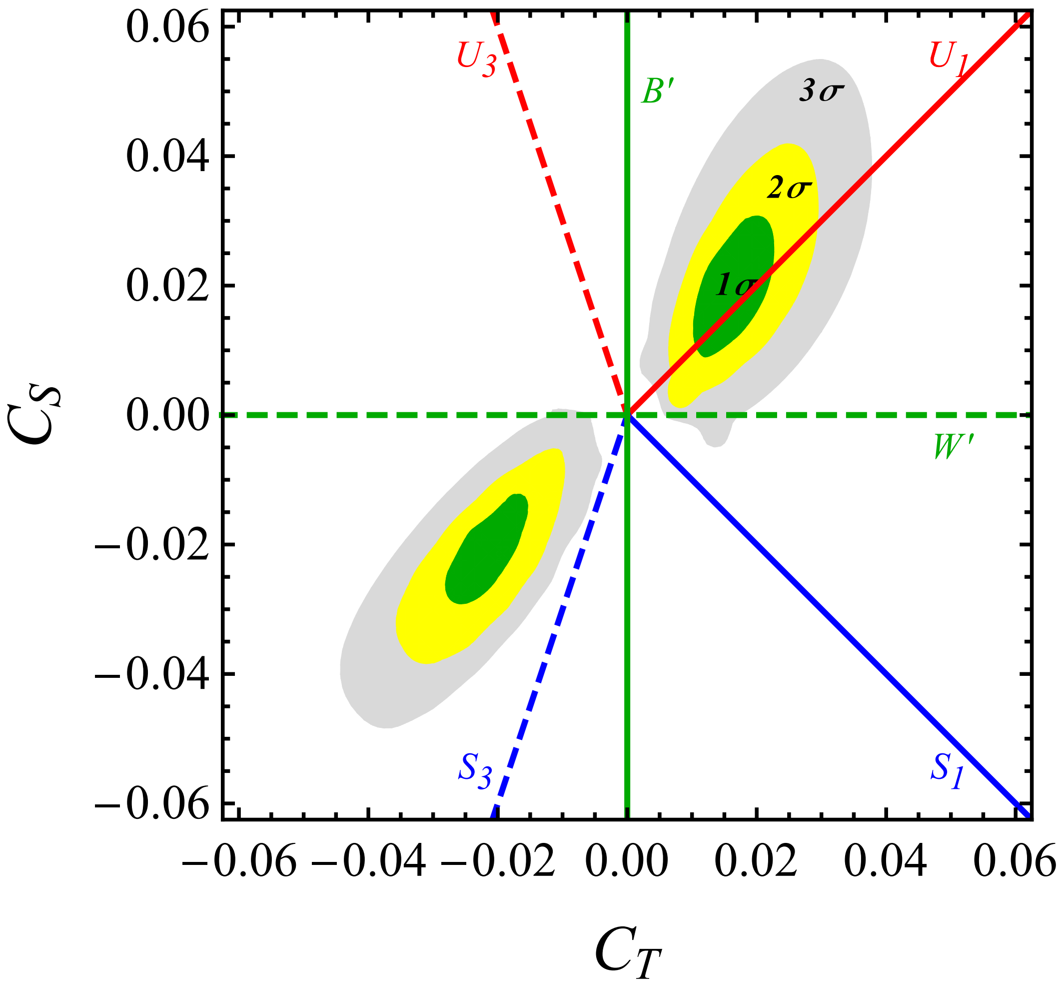

U_1 emerges as an exceptional single mediator consistent with various flavour/EW constraints

$$\overline{B}_s - B_s \quad B \to K^{(*)}\nu\nu \quad Z \to \tau\tau$$

[for details see backup slides]

UV completion: $U_1 \sim (3,1,2/3)$

- Massive vectors point to UV dynamics at the TeV scale

composite resonance of
a new strong dynamics

gauge boson of an
extended gauge sector

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- Massive vectors point to UV dynamics at the TeV scale

composite resonance of
a new strong dynamics

$$\frac{G}{H} = \frac{SU(4) \times SO(5) \times U(1)_X}{SU(4) \times SO(4) \times U(1)_X}$$

[Barbieri, Isidori, Pattori, Senia 1502.01560
Barbieri, Murphy, Senia 1611.0493
Buttazzo, Greljo, Isidori, Marzocca 1706.07808
Barbieri, Tesi 1712.06844]

- pNGB Higgs + U_1 as composite state of G

🙂 conceptual link with the naturalness issue of EW scale

🙁 light LQ lowers the whole resonances' spectrum (direct searches + EWPTs)

🙁 intrinsically non-calculable (e.g. Bs-mixing quadratically divergent)

UV completion: $U_1 \sim (3,1,2/3)$

- Pati-Salam ?

$$G_{PS} = SU(4)_{PS} \times SU(2)_L \times SU(2)_R$$

$$G_{PS}/G_{SM} = U_1 + Z' + W_R$$

gauge boson of an
extended gauge sector

🙂 hinted by SM chiral structure and neutrino masses

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🙂 hinted by SM chiral structure and neutrino masses

🙁 $M_{U_1} \gtrsim 100 \text{ TeV}$ from $K_L^0, B^0, B_s \to \ell \, \ell'$ *[L x R couplings both present by unitarity]*

🙁 Z' direct searches *[$M_{U_1} \sim M_{Z'} \sim \text{TeV}$ + O(g$_s$) Z' couplings to valence quarks]*

🙁 neutrino masses also suggest $M_{U_1} \gg \text{TeV}$ *[$y_{\text{top}} \sim y_{\nu_3-\text{Dirac}}$]*

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→ LQ of minimal PS <u>cannot</u> explain B-anomalies

[Non-minimal PS options lack the beauty and simplicity of the minimal construction: Calibbi, Crivellin, Li 1709.00692, Bordone, Cornella, Fuentes-Martin, Isidori 1712.01368 + 1805.09328, Blanke, Crivellin 1801.07256, Heeck, Teresi 1808.07492 …]

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🙁 neutrino masses also suggest $M_{U_1} \gg \text{TeV}$ *[*$y_{\text{top}} \sim y_{\nu_3-\text{Dirac}}$*]*

→ <u>step 0</u>: *does a gauge UV completion of U₁ addressing these three phenomenological issues (in order to be a viable solution of B-anomalies) exist ?*

The '4321' model

[LDL, Greljo, Nardecchia 1708.08450,
See also Diaz, Schmaltz, Zhong 1706.05033]

$$SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$$

The '4321' model

[LDL, Greljo, Nardecchia 1708.08450,
See also Diaz, Schmaltz, Zhong 1706.05033]

$$\overbrace{\underbrace{SU(4) \times SU(3)'}_{SU(3)_C} \times SU(2)_L \times U(1)'}^{U(1)_Y} \xrightarrow[\langle \Omega_{1,3} \rangle]{} G_{\rm SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$g_4 \gg g_3 \gg g_1$$

$$\downarrow$$

SM embedding:

$$SU(3)_C = (SU(3)_4 \times SU(3)')_{diag} \qquad g_s = \frac{g_4 g_3}{\sqrt{g_4^2 + g_3^2}} \simeq g_3$$

$$U(1)_Y = (U(1)_4 \times U(1)')_{diag} \qquad g_Y = \frac{g_4 g_1}{\sqrt{g_4^2 + \frac{2}{3} g_1^2}} \simeq g_1$$

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SM embedding:

Massive gauge bosons:

$$G/G_{\rm SM} = U + Z' + g'$$

$$M_{g'} \simeq \sqrt{2}\, M_U \qquad M_{Z'} \simeq \frac{1}{\sqrt{2}} M_U$$

$$\left(\begin{array}{c:c} (g'^a_\mu)^\alpha_\beta & U^\alpha_\mu \\ \hdashline (U^\beta_\mu)^\dagger & Z'_\mu \end{array} \right)$$

→ cannot decouple g' and Z' from LQ mass scale !

[a theorem (?) that in whatever UV construction U always comes with a Z' - while the coloron is a specific consequence of the 4321 model]

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Matter content:

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$q_L'^i$	1	3	2	$1/6$
$u_R'^i$	1	3	1	$2/3$
$d_R'^i$	1	3	1	$-1/3$
$\ell_L'^i$	1	1	2	$-1/2$
$e_R'^i$	1	1	1	-1
Ψ_L^i	4	1	2	0
Ψ_R^i	4	1	2	0
H	1	1	2	$1/2$
Ω_3	$\overline{4}$	3	1	$1/6$
Ω_1	$\overline{4}$	1	1	$-1/2$

Would-be SM fields

Vector-like fermions (Ψ = Q'+L')

} mix after SSB

SSB

The '4321' model

$$\overbrace{\underbrace{SU(4) \times SU(3)'}_{SU(3)_C} \times SU(2)_L \times U(1)'}^{U(1)_Y} \xrightarrow[\langle \Omega_{1,3} \rangle]{} G_{\text{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

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[matches in first approx. EFT analysis for B-anomalies + relaxes flavour bounds from chirality enhanced meson decays]

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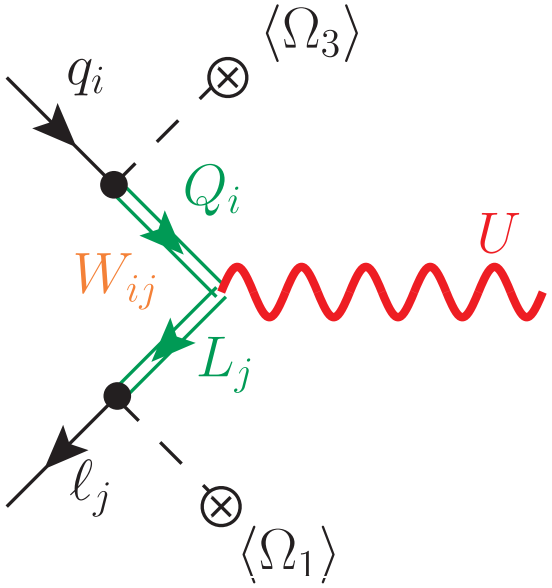

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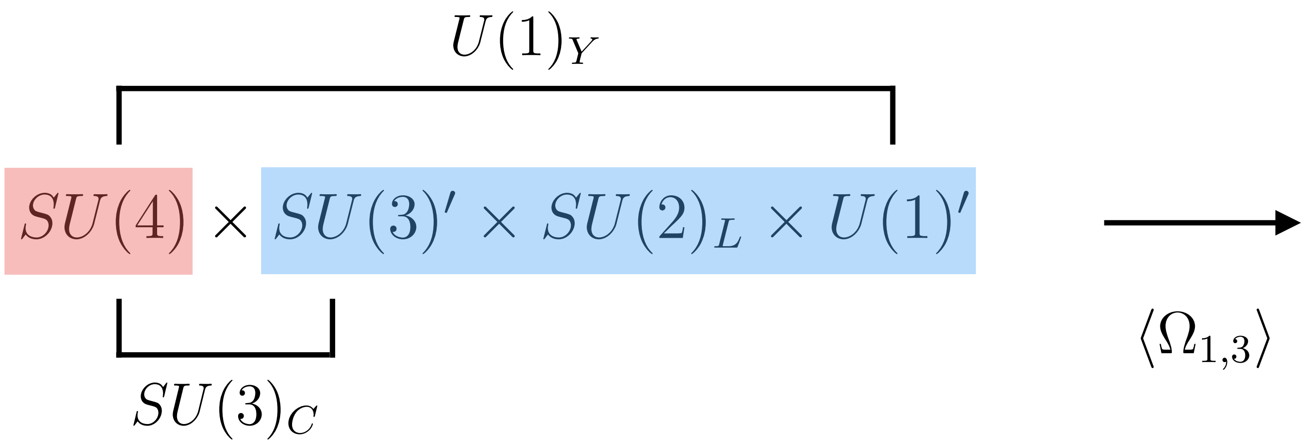

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→ LQ dominantly couples to 3rd generation LH fields:

[matches in first approx. EFT analysis for B-anomalies + relaxes flavour bounds from chirality enhanced meson decays]

$$\begin{aligned} \mathcal{L}_L = {} & \frac{g_4}{\sqrt{2}} \overline{Q}'_L \gamma^\mu L'_L \, U_\mu + \text{h.c.} \\ & + g_s \left(\frac{g_4}{g_3} \overline{Q}'_L \gamma^\mu T^a Q'_L - \frac{g_3}{g_4} \, \overline{q}'_L \gamma^\mu T^a q'_L \right) g'^a_\mu \\ & + \frac{1}{6} \sqrt{\frac{3}{2}} g_Y \left(\frac{g_4}{g_1} \overline{Q}'_L \gamma^\mu Q'_L - \frac{2}{3} \frac{g_1}{g_4} \, \overline{q}'_L \gamma^\mu q'_L \right) Z'_\mu \\ & - \frac{1}{2} \sqrt{\frac{3}{2}} g_Y \left(\frac{g_4}{g_1} \overline{L}'_L \gamma^\mu L'_L - \frac{2}{3} \frac{g_1}{g_4} \, \overline{\ell}'_L \gamma^\mu \ell'_L \right) Z'_\mu \end{aligned}$$

→ Suppressed Z’ and g’ couplings to light generations

[requires phenomenological limit $g_4 \gg g_3 \simeq g_s \gg g_1 \simeq g_Y$]

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- Suppressed Z’ and g’ couplings to light generations

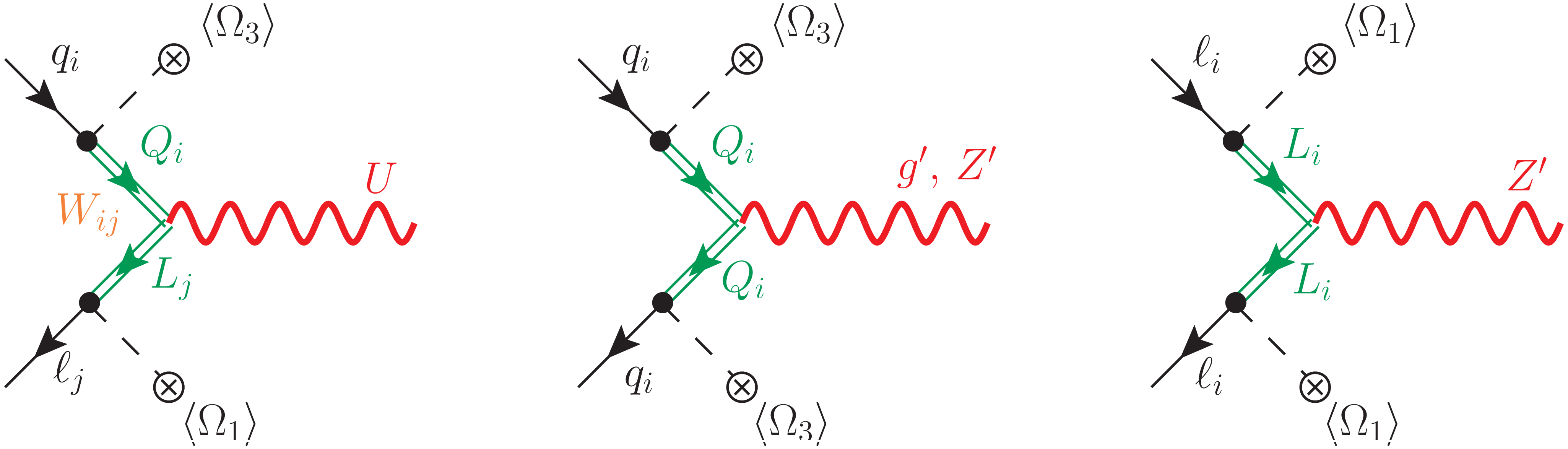
  [requires phenomenological limit $g_4 \gg g_3 \simeq g_s \gg g_1 \simeq g_Y$*]*

- B and L accidental global symmetries

  [neutrino massless as in the SM]

Key phenomenological features

1. Large quark-lepton transitions in 3-2 sector
2. Tree-level FCNC involving down quarks and leptons are absent
3. Tree-level FCNC involving up quarks are U(2) protected



[see backup slides for the discussion of the flavour structure]

[LDL, Fuentes-Martin, Greljo, Nardecchia, Renner 1808.00942]

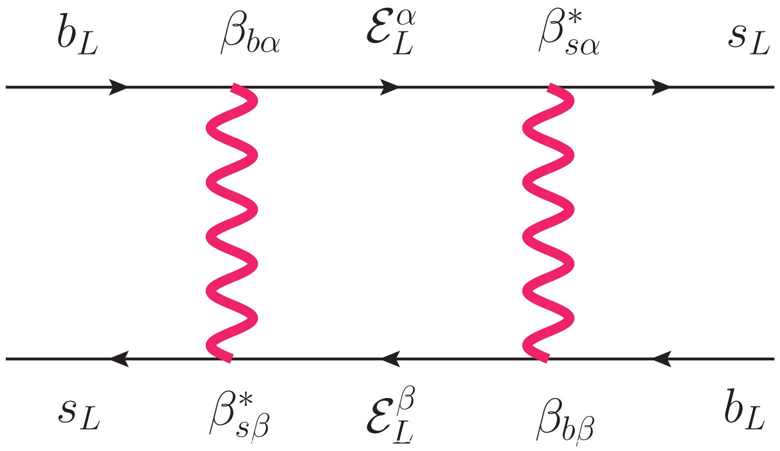
Key phenomenological features

1. Large quark-lepton transitions in 3-2 sector

2. Tree-level FCNC involving down quarks and leptons are absent

3. Tree-level FCNC involving up quarks are U(2) protected

4. FCNC @ 1-loop under control



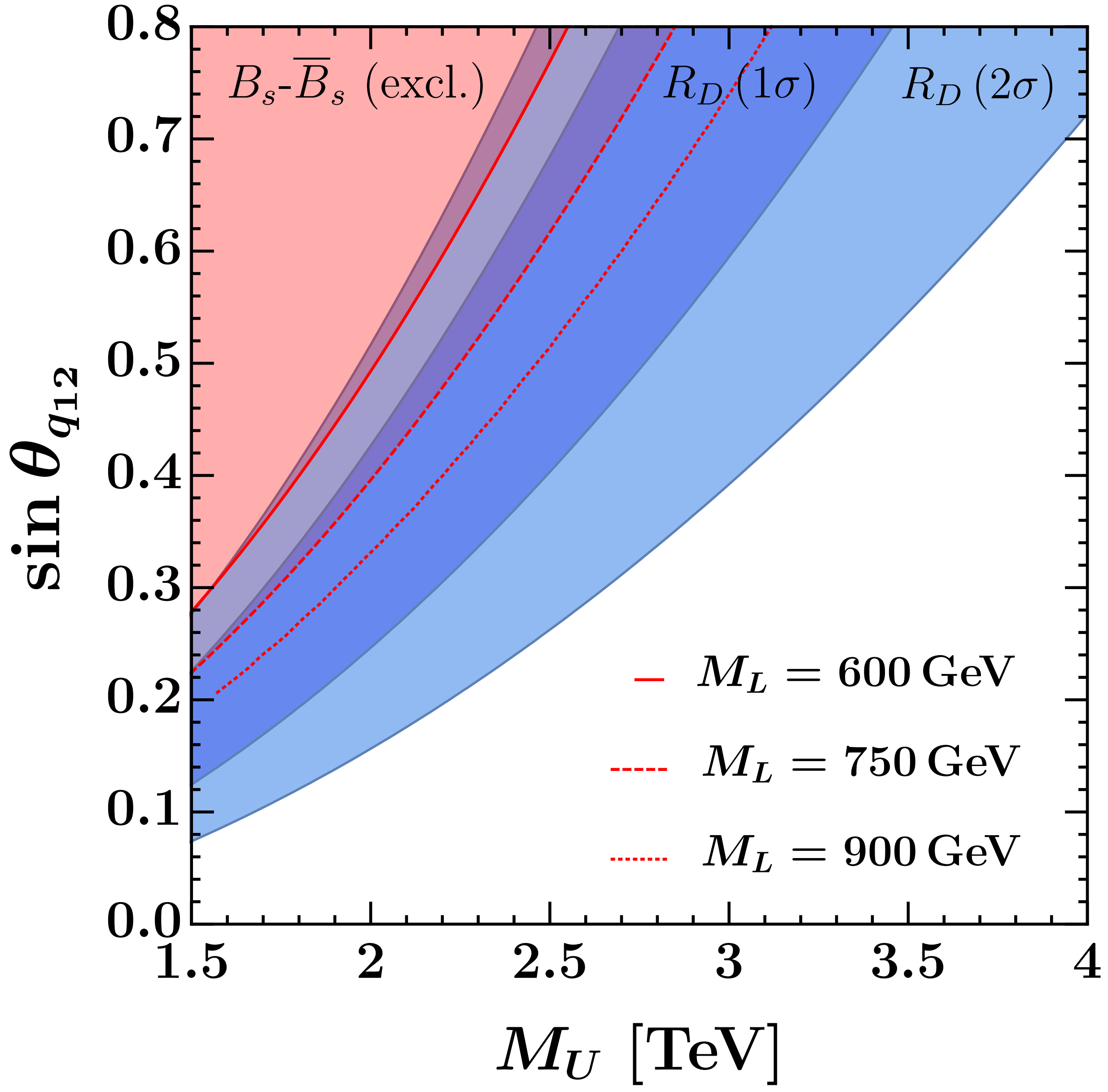
$$\mathcal{H}_{\rm eff}^{\rm NP} = -\frac{g_4^4}{128\pi^2 m_U^2} \left(\bar{b}_L \gamma^\mu s_L\right) \left(\bar{b}_L \gamma_\mu s_L\right) \sum_{\alpha,\,\beta} \lambda_\alpha \lambda_\beta F(x_\alpha, x_\beta)$$

$$\lambda_\alpha = \beta_{b\alpha}\beta^*_{s\alpha} \qquad x_\alpha = m_\alpha^2/M_U^2 \qquad \alpha = (1,\dots,6)$$

$\sum_\alpha \lambda_\alpha = 0$ *[ensures cancellation of quadratic divergences]*

$F(x_\alpha, x_\beta) \simeq \cancel{1} + x_\alpha + x_\beta + \dots$ → dynamical suppression from light lepton partners

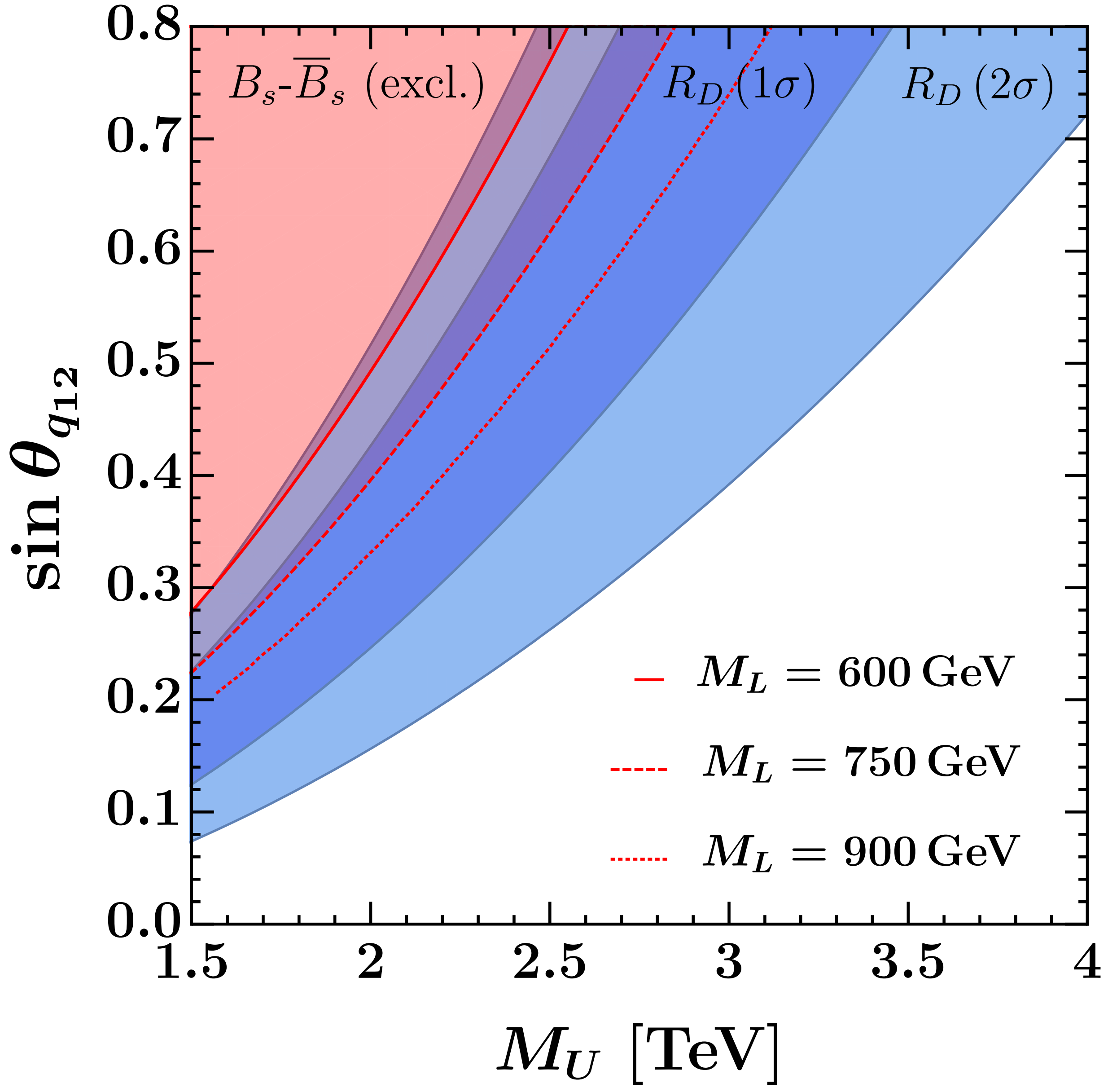
Low-energy / high-pT interplay



$$C_{bs}^{LL} \sim \Delta R^2_{D^{(*)}} \, M_L^2$$

vector-like leptons are predicted to be the lightest new states !

Low-energy / high-pT interplay



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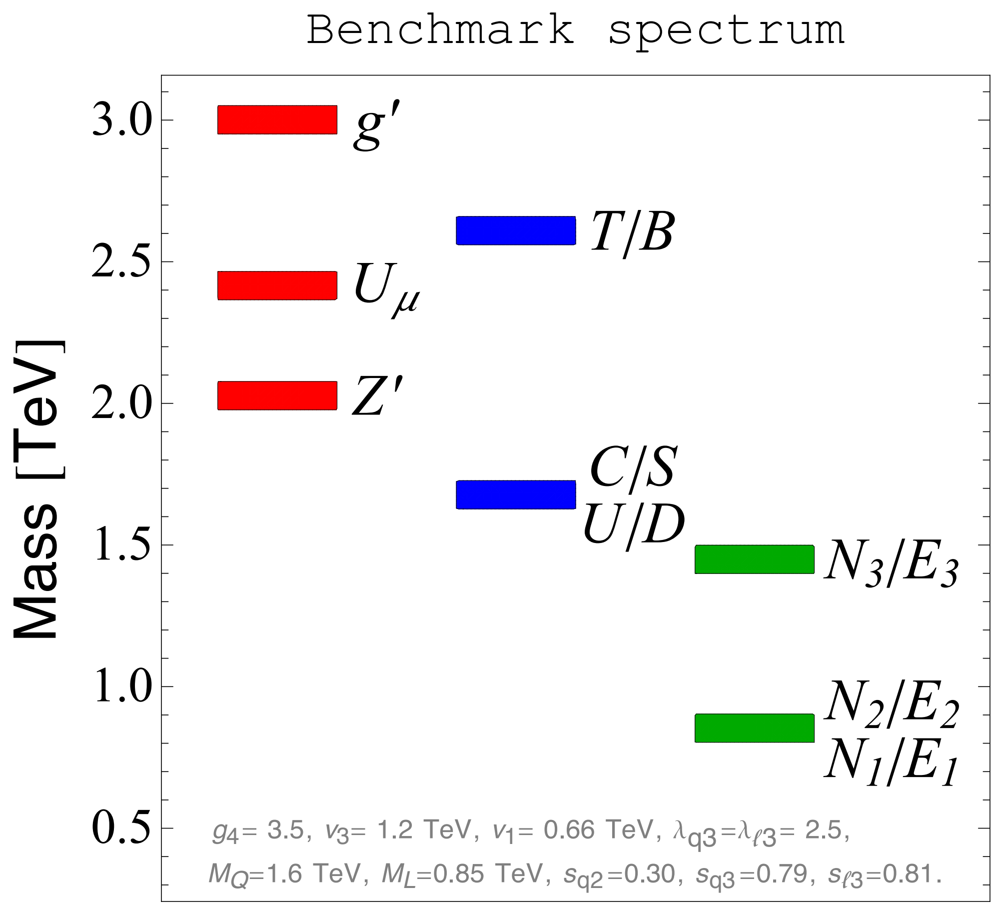
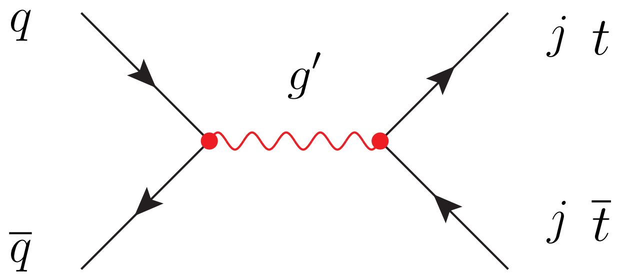
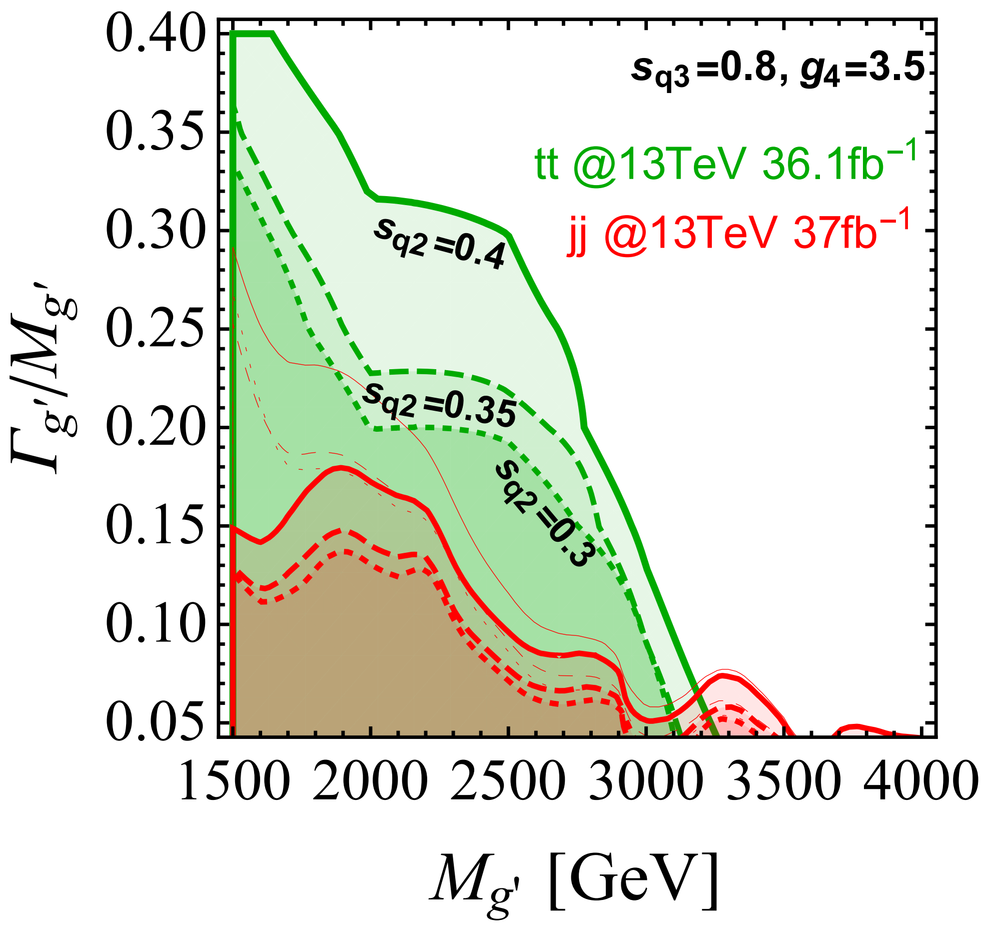
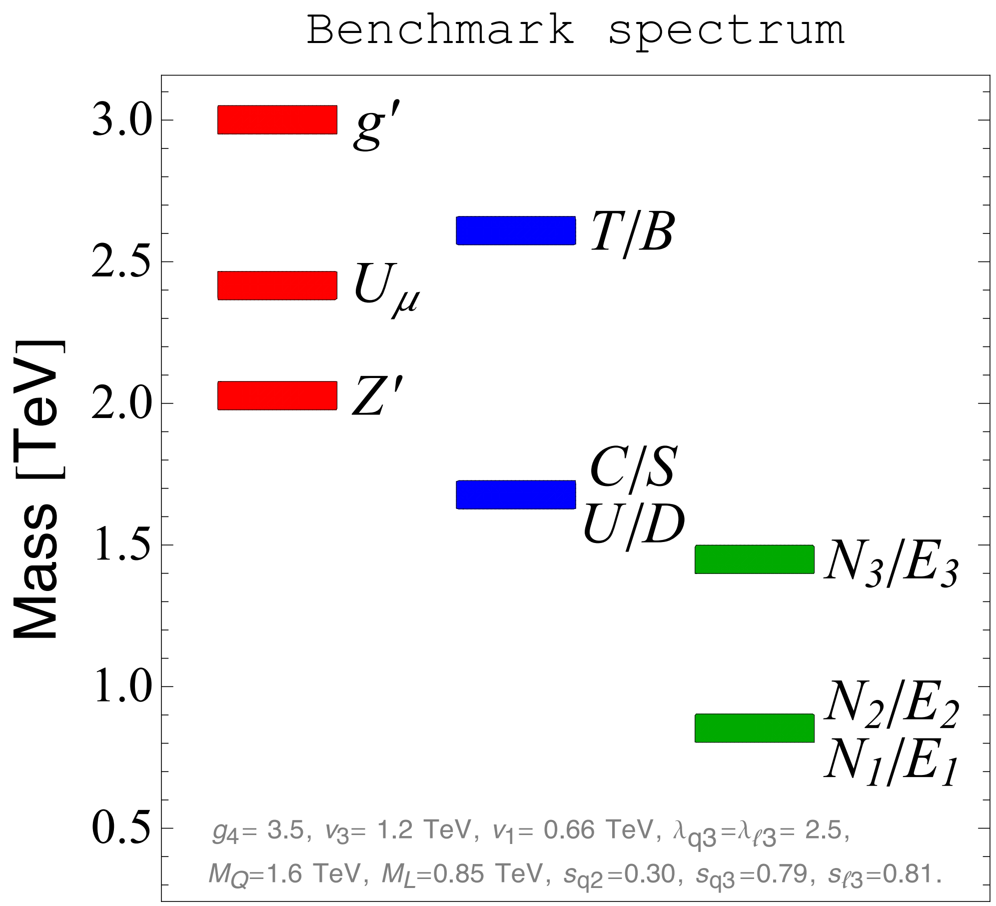


High-pT highlights

- Coloron searches push the whole spectrum up



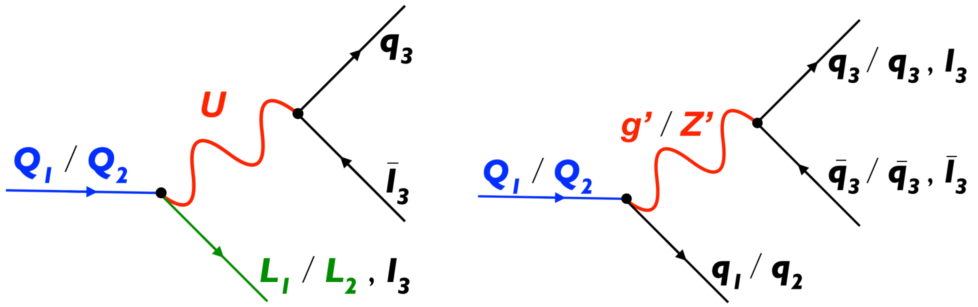


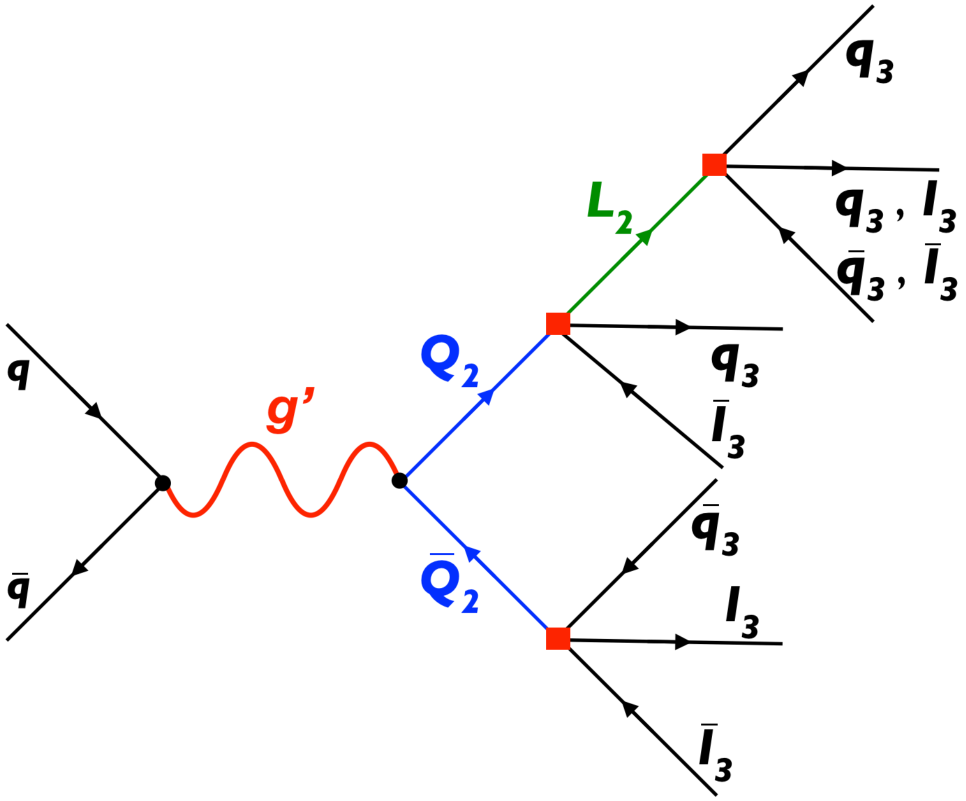


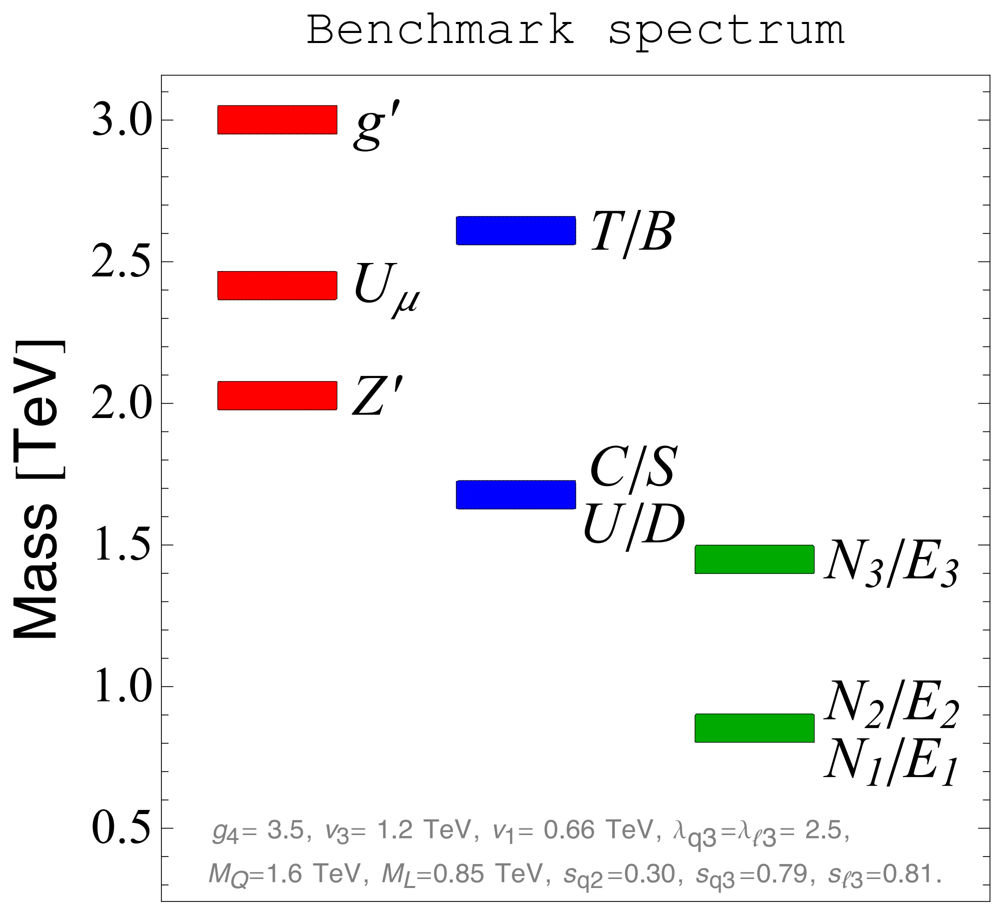
High-pT highlights

- Coloron searches push the whole spectrum up
- Exotic multi-lepton & multi-jet signatures

[Dominant decays of new fermions are 1 → 3]





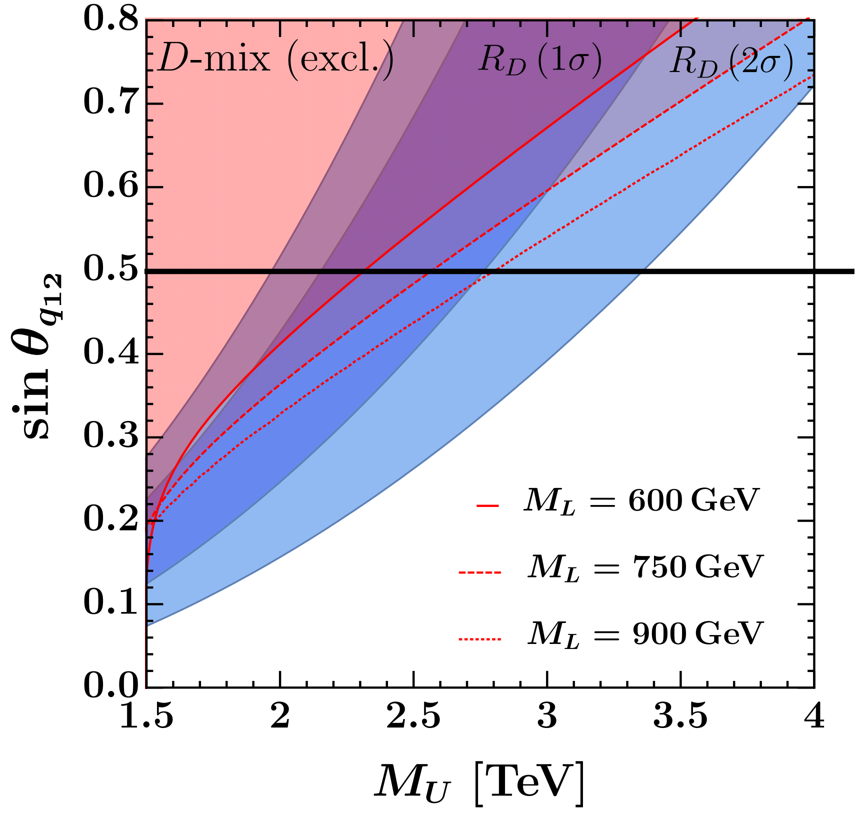


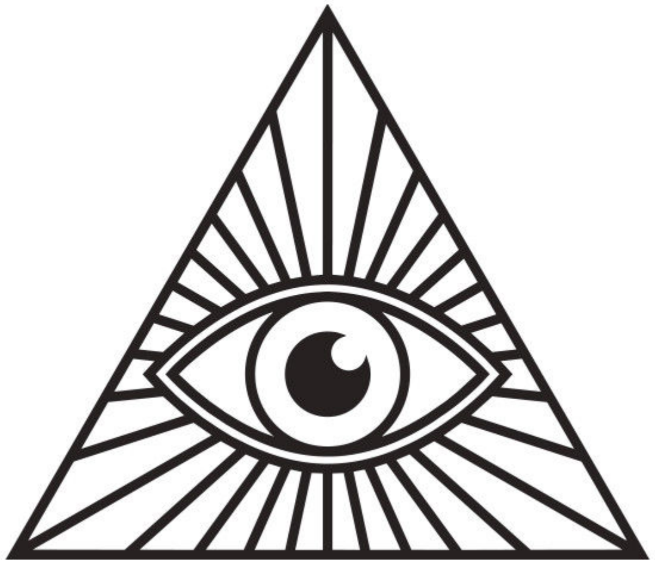
The leptoquark paradox

- NP expected to be seen yesterday ?

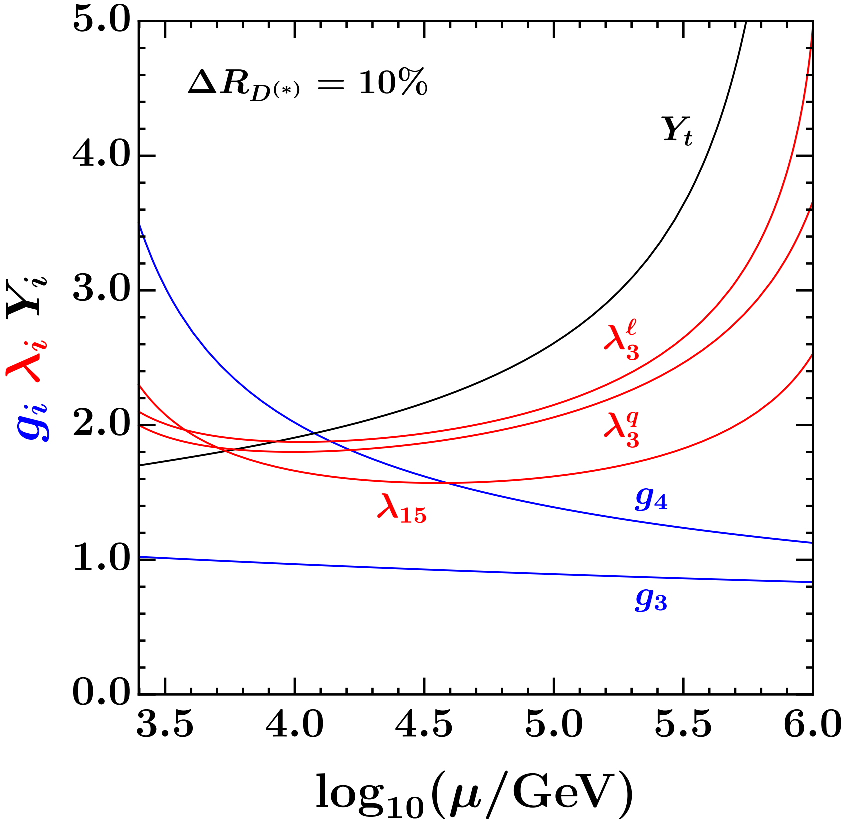
$$\Delta R_{D^{(*)}} \approx 0.2 \left(\frac{2\ \text{TeV}}{M_U}\right)^2 \left(\frac{g_4}{3.5}\right)^2 \sin(2\theta_{LQ}) \left(\frac{s_{\ell_3}}{0.8}\right)^2 \left(\frac{s_{q3}}{0.8}\right) \left(\frac{s_{q2}}{0.3}\right)$$

ΔF = 2 + direct searches





Perturbativity



Conclusions

1. Early speculations point to TeV-scale vector leptoquark *[R(D$^{(*)}$)+R(K$^{(*)}$) explanation]*

   - who ordered that ?

   - connection to EW naturalness and SM flavour ?

2. In the meanwhile, lesson from 4321 *[UV complete / calculable model]*

   → unexpected experimental signatures (coloron, vector-like leptons, …)
   \+ playground to compute correlations

3. Situation looks tough, but not impossible *[e.g. if deviation in R(D$^{(*)}$) gets reduced]*

4. Without R(D$^{(*)}$) still (too) many possibilities…

$\sqrt{s}_{R_D} < 9.2\ \text{TeV}$ $\qquad$ $\sqrt{s}_{R_K} < 84\ \text{TeV}$

Backup slides

More on R(D$^{(*)}$) fits

$$\mathcal{L}_{\rm eff} = -2\sqrt{2}G_F V_{ud}\Big[(1+g_{V_L})\,(\overline{u}_L\gamma_\mu d_L)(\overline{\ell}_L\gamma^\mu\nu_L) + g_{V_R}\,(\overline{u}_R\gamma_\mu d_R)(\overline{\ell}_L\gamma^\mu\nu_L) \tag{9}$$

$$+\, g_{S_L}(\mu)\,(\overline{u}_R d_L)(\overline{\ell}_R\nu_L) + g_{S_R}(\mu)\,(\overline{u}_L d_R)(\overline{\ell}_R\nu_L) + g_T(\mu)\,(\overline{u}_R\sigma_{\mu\nu}d_L)(\overline{\ell}_R\sigma^{\mu\nu}\nu_L)\Big] + \text{h.c.}\,,$$

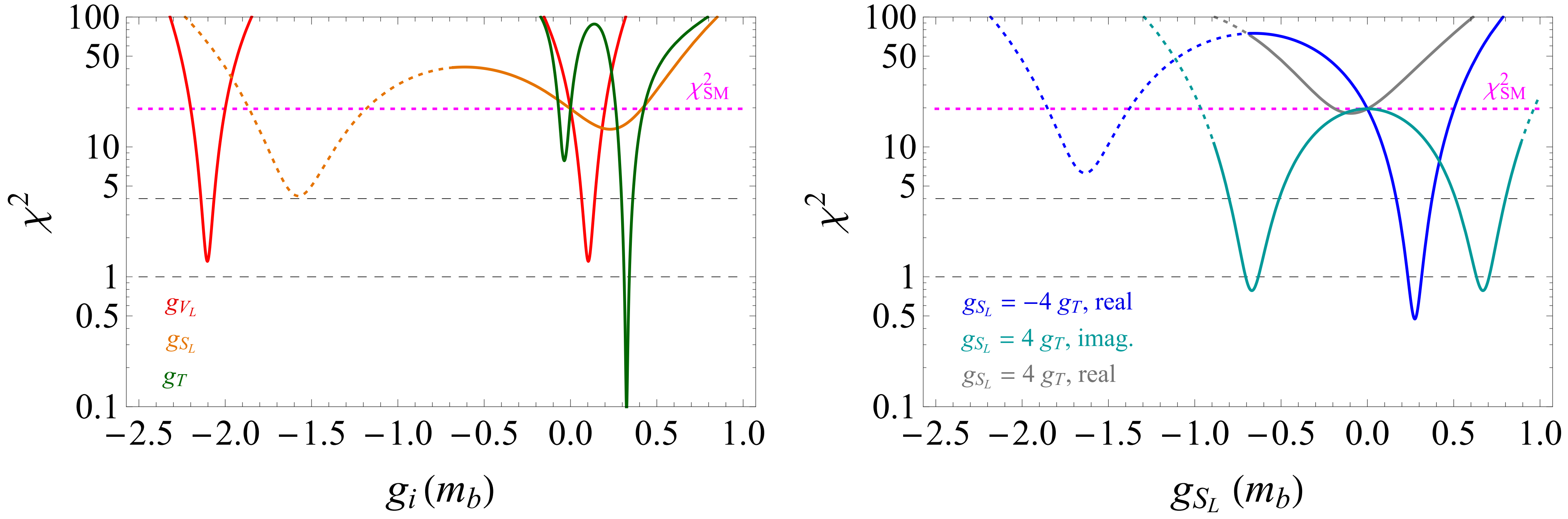


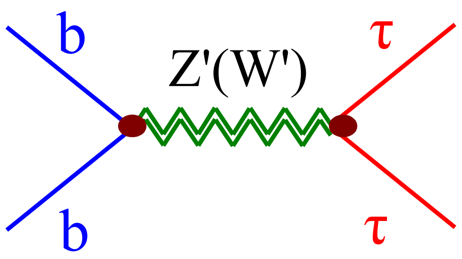
Figure 2: χ^2 *values for individual effective coefficients fits of* R_D *and* R_{D^*}*, compared to the SM value,* $\chi^2_{\rm SM} \approx 19.7$*. In the left panel,* χ^2 *is plotted against* g_{V_L}*,* g_{S_L} *and* g_T *at* $\mu = m_b$*. In the right panel,* χ^2 *is plotted against* $g_{S_L}(m_b)$ *by assuming* $g_{S_L} = \pm 4\, g_T$ *at* $\mu = 1$ TeV*, for purely imaginary and real couplings. The dashed regions correspond to the values excluded by the* B_c*-lifetime constraints, see text for details.*

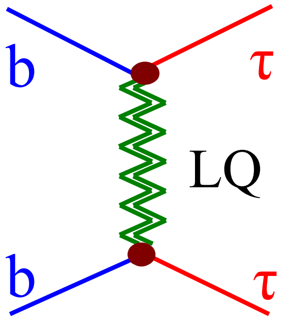
[Angelescu et al 1808.08179]

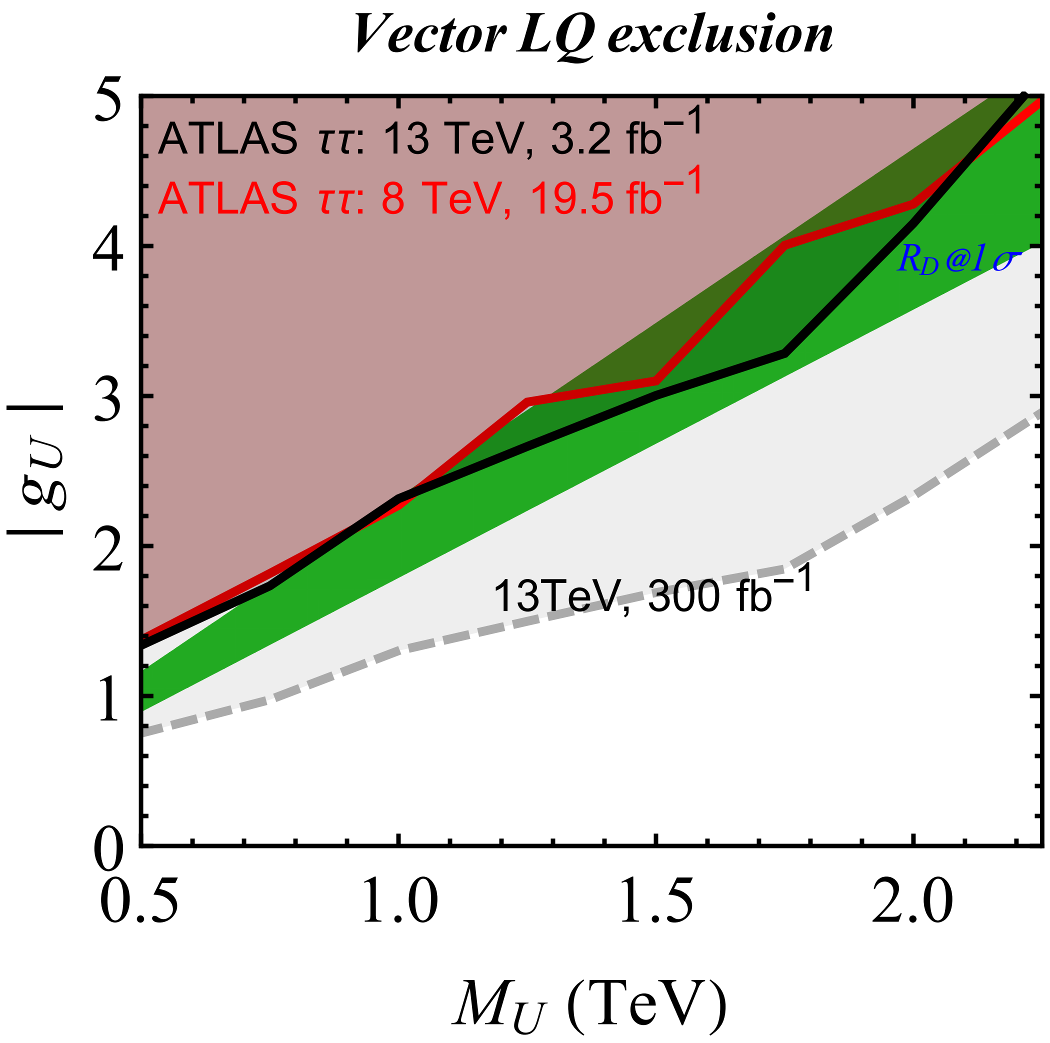
EFT *[problems]*

- Three main problems mainly driven by R(D) *[in the pure mixing scenario]*

1. High-p_T constraints







$$\overline{Q}_3 Q_3 \longrightarrow V_{cb}\, \overline{c}_L b_L$$

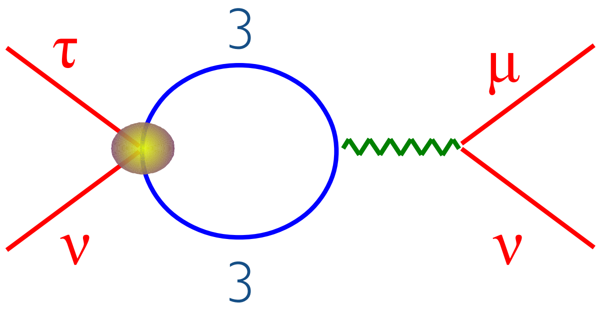
$$\frac{1}{\Lambda^2_{R_D}} = \frac{V_{cb}}{\Lambda^2_{33}} \qquad \Lambda_{33} = \sqrt{V_{cb}}\,\Lambda_{R_D} \simeq 0.7\,\text{TeV}$$

[Faroughy, Greljo, Kamenik 1609.07138]

EFT *[problems]*

- Three main problems mainly driven by R(D) *[in the pure mixing scenario]*

1. High-p$_T$ constraints
2. Radiative constraints



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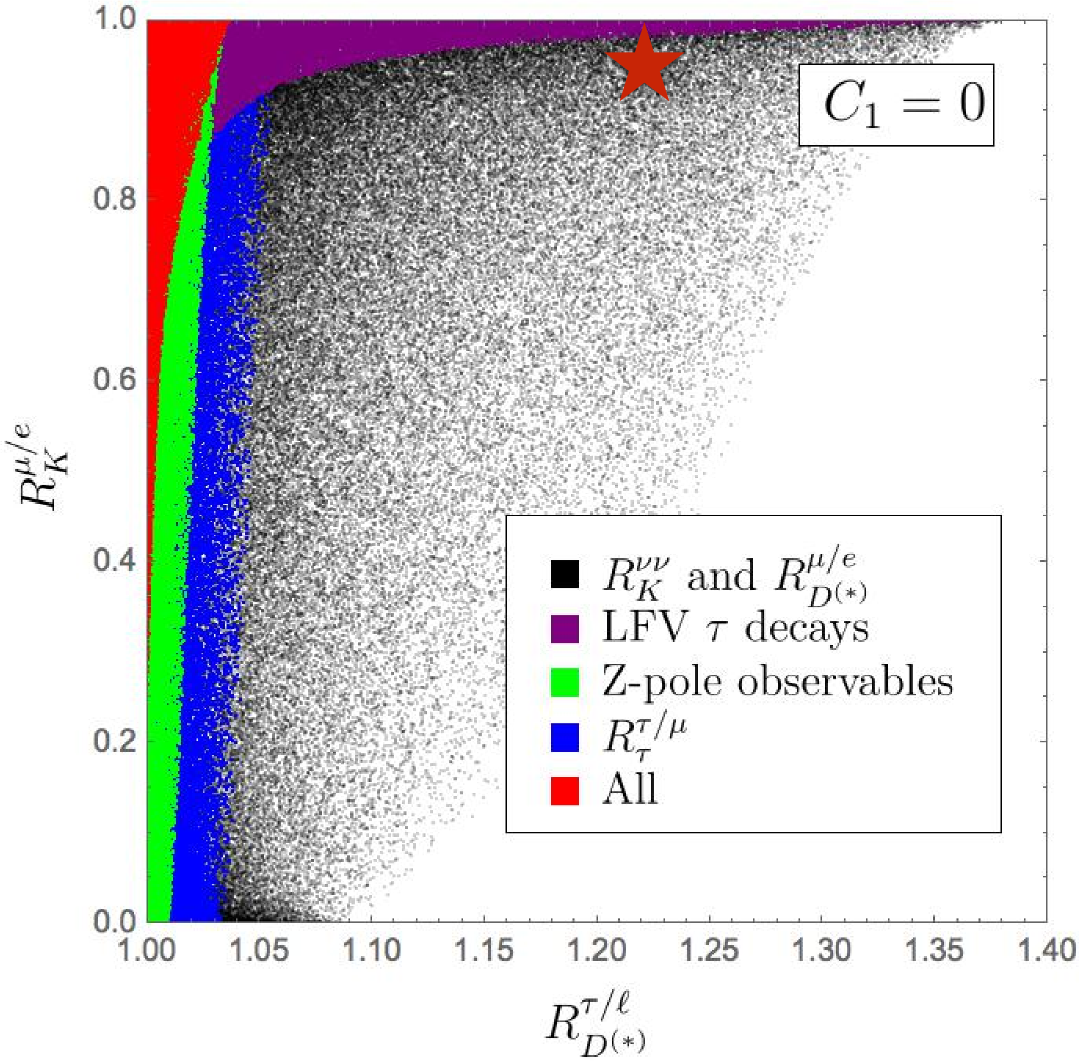
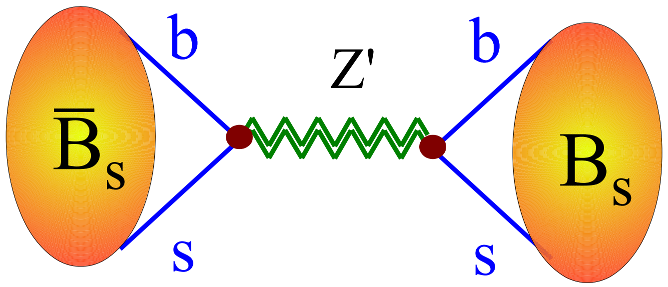


[Feruglio, Paradisi, Pattori 1606.00524, 1705.00929]

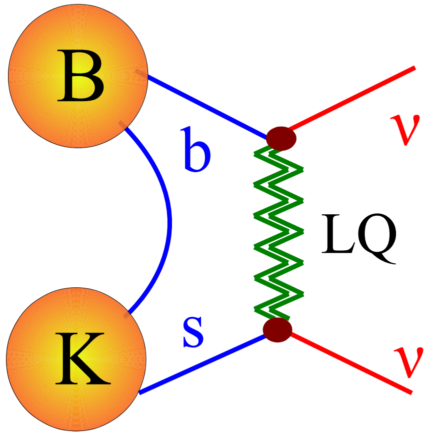
EFT *[problems]*

- Three main problems mainly driven by R(D)

1. High-p_T constraints
2. Radiative constraints
3. Flavour bounds



(absent at tree-level with LQ)



(consequence of $SU(2)_L$ invariance)

EFT *[solutions]*

- Tension gets drastically alleviated if

[Zürich's guide for combined explanations, 1706.07808]

1. Triplet + Singlet operator (more freedom in SU(2)$_L$ structure)

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

EFT *[solutions]*

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2. Deviation from pure-mixing scenario

$$\overline{Q}^i\lambda^q_{ij}Q^j = \begin{pmatrix}\overline{u}^k V_{ki} & \overline{d}^i\end{pmatrix}\lambda^q_{ij}\begin{pmatrix}V^\dagger_{jl}u^l \\ d^j\end{pmatrix} \supset \bar{c}\,(V_{cb}\lambda^q_{bb} + \boxed{V_{cs}\lambda^q_{sb}} + \ldots)\,b$$

$$R^{\tau\ell}_{D^{(*)}} \approx 1 + 2C_T\left(1 - \lambda^q_{sb}\frac{V^*_{tb}}{V^*_{ts}}\right)$$ → $\lambda^q_{sb} > \mathcal{O}(V_{cb})$ allows for larger NP scale

EFT *[solutions]*

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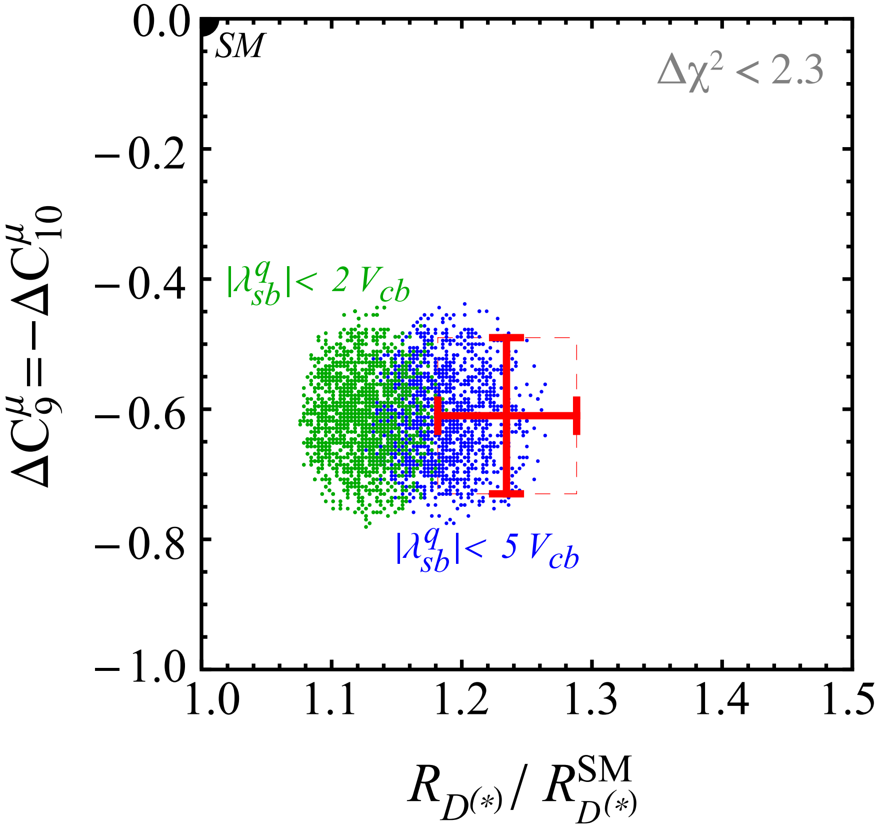
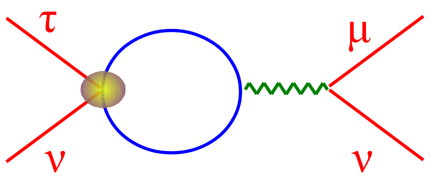


$\lambda^q_{sb} > \mathcal{O}(V_{cb})$ allows for larger NP scale

EFT *[details]*

- 4 parameters fit: $C_S, C_T, \lambda^q_{bs}, \lambda^\ell_{\mu\mu} \quad (\lambda^q_{bb} = \lambda^\ell_{\tau\tau} = 1)$ [Zürich's guide for combined explanations, 1706.07808]

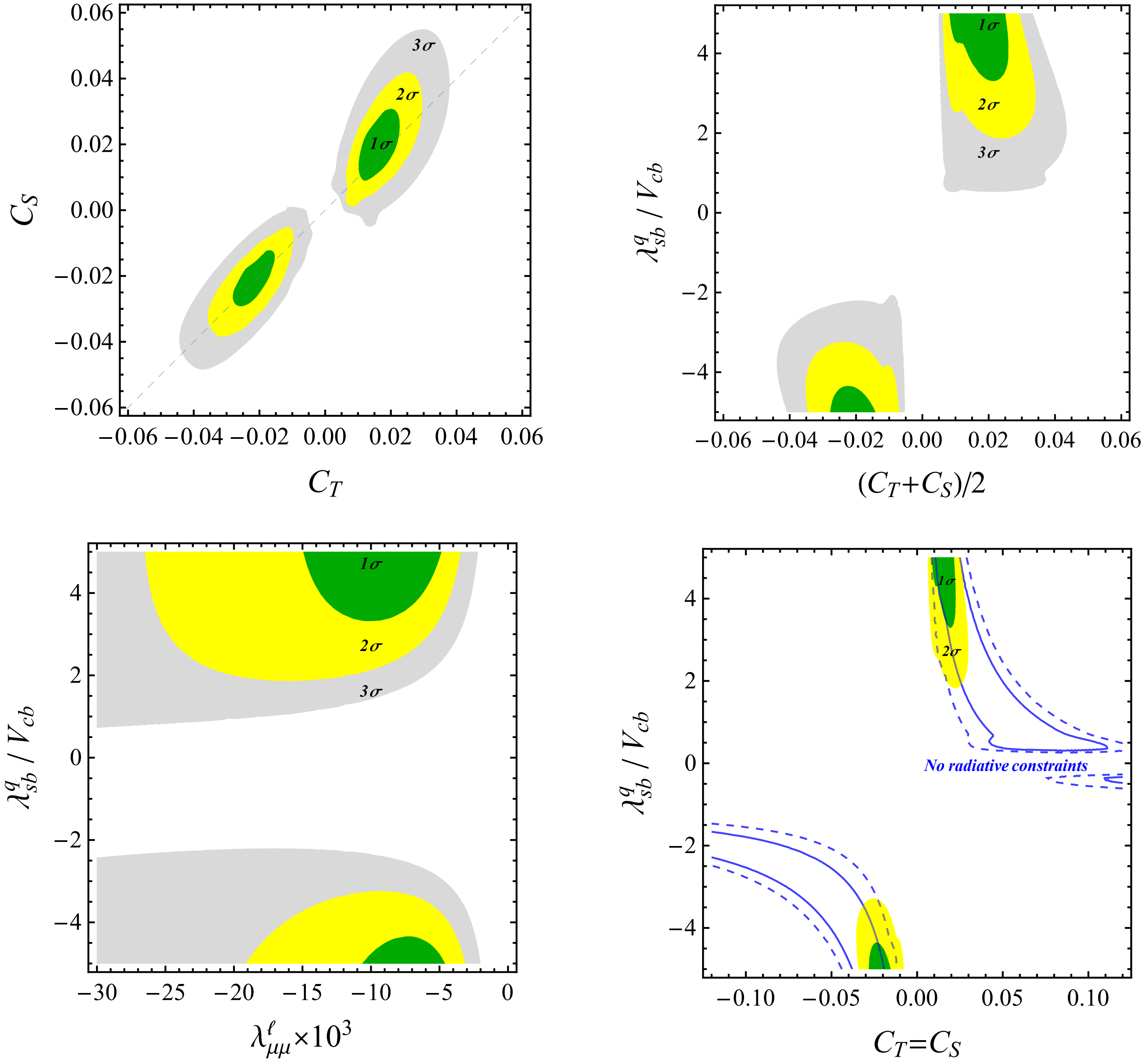
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$



	Observable	Experimental bound	Linearised expression
	$R^{\tau\ell}_{D^{(*)}}$	1.237 ± 0.053	$1 + 2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})(1 - \lambda^\ell_{\mu\mu}/2)$
	$\Delta C^\mu_9 = -\Delta C^\mu_{10}$	-0.61 ± 0.12 [36]	$-\frac{\pi}{\alpha_{\text{em}}V_{tb}V^*_{ts}}\lambda^\ell_{\mu\mu}\lambda^q_{sb}(C_T + C_S)$
	$R^{\mu e}_{b\to c} - 1$	0.00 ± 0.02	$2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})\lambda^\ell_{\mu\mu}$
	$B_{K^{(*)}\nu\bar{\nu}}$	0.0 ± 2.6	$1 + \frac{2}{3}\frac{\pi}{\alpha_{\text{em}}V_{tb}V^*_{ts}C^{\text{SM}}_\nu}(C_T - C_S)\lambda^q_{sb}(1 + \lambda^\ell_{\mu\mu})$
LH Z-τ-τ coupling	$\delta g^Z_{\tau_L}$	-0.0002 ± 0.0006	$0.033C_T - 0.043C_S$
LH Z-ν-ν coupling	$\delta g^Z_{\nu_\tau}$	-0.0040 ± 0.0021	$-0.033C_T - 0.043C_S$
LFUV in τ decays	$\lvert g^W_\tau/g^W_\ell\rvert$	1.00097 ± 0.00098	$1 - 0.084C_T$
LFV in τ decays	$\mathcal{B}(\tau \to 3\mu)$	$(0.0 \pm 0.6) \times 10^{-8}$	$2.5 \times 10^{-4}(C_S - C_T)^2(\lambda^\ell_{\tau\mu})^2$

EFT *[details]*

- 4 parameters fit: $C_S, C_T, \lambda^q_{bs}, \lambda^\ell_{\mu\mu} \quad (\lambda^q_{bb} = \lambda^\ell_{\tau\tau} = 1)$ [Zürich's guide for combined explanations, 1706.07808]



Flavour structure

- Pick-up a basis exploiting U(3)^7 symmetry of kinetic term

$$\mathcal{L}_{\text{SM}-\text{like}} = -\overline{q}'_L \hat{Y}_d \, d'_R \, H - \overline{q}'_L V^\dagger \hat{Y}_u \, u'_R \, \tilde{H} - \overline{\ell}'_L \hat{Y}_e \, e'_R \, H$$

$$\mathcal{L}_{\text{mix}} = -\overline{q}'_L \lambda_q \Psi_R \, \Omega_3 - \overline{\ell}'_L \lambda_\ell \Psi_R \, \Omega_1 - \overline{\Psi}_L \hat{M} \Psi_R$$

**hat denotes a diagonal matrix*

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
q'^i_L	1	3	2	$1/6$
u'^i_R	1	3	1	$2/3$
d'^i_R	1	3	1	$-1/3$
ℓ'^i_L	1	1	2	$-1/2$
e'^i_R	1	1	1	-1
Ψ^i_L	4	1	2	0
Ψ^i_R	4	1	2	0
H	1	1	2	$1/2$
Ω_3	$\overline{4}$	3	1	$1/6$
Ω_1	$\overline{4}$	1	1	$-1/2$

$$\Psi = \begin{pmatrix} Q' \\ L' \end{pmatrix}$$

Flavour structure

- $\mathcal{L}_{\text{mix}} \to 0$

$$\mathcal{L}_{\text{SM}-\text{like}} = -\overline{q}'_L \hat{Y}_d \, d'_R \, H - \overline{q}'_L V^\dagger \hat{Y}_u \, u'_R \, \tilde{H} - \overline{\ell}'_L \hat{Y}_e \, e'_R \, H$$

- A well-known story:

- $Y_u \to 0: \;\; U(1)_d \times U(1)_s \times U(1)_b$
- $Y_d \to 0: \;\; U(1)_u \times U(1)_c \times U(1)_t$

Flavour structure

- $\mathcal{L}_{\rm mix} \to 0$

$$\mathcal{L}_{\rm SM-like} = -\overline{q}'_L \hat{Y}_d \, d'_R \, H - \overline{q}'_L V^\dagger \hat{Y}_u \, u'_R \, \tilde{H} - \overline{\ell}'_L \hat{Y}_e \, e'_R \, H$$

- A well-known story:

$$\left.\begin{array}{l} - \;\; Y_u \to 0 : \;\; U(1)_d \times U(1)_s \times U(1)_b \\ - \;\; Y_d \to 0 : \;\; U(1)_u \times U(1)_c \times U(1)_t \end{array}\right] \xrightarrow{SU(2)_L} U(1)_{d+u} \times U(1)_{s+c} \times U(1)_{b+t} \xrightarrow{V} U(1)_B$$

- Collective breaking in the SM ensures:

1. No FCNC in either up or down sector [forbidden by the two U(1)^3 in isolation]
2. FCCC from up/down misalignement [due to CKM ≠ 1]

Flavour structure

- Let us assume:

$$\mathcal{L}_{\rm mix} = -\overline{q}'_L \lambda_q \Psi_R \, \Omega_3 - \overline{\ell}'_L \lambda_\ell \Psi_R \, \Omega_1 - \overline{\Psi}_L \hat{M} \Psi_R$$

$$\mathcal{L}_{\rm SM-like} = -\overline{q}'_L \hat{Y}_d \, d'_R \, H - \overline{q}'_L V^\dagger \hat{Y}_u \, u'_R \, \tilde{H} - \overline{\ell}'_L \hat{Y}_e \, e'_R \, H$$

$$\lambda_q = \mathrm{diag}\,(\lambda^q_{12}, \lambda^q_{12}, \lambda^q_3)$$

$$\lambda_\ell = \mathrm{diag}\left(\lambda^\ell_1, \lambda^\ell_2, \lambda^\ell_3\right) W \qquad W = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{LQ} & \sin\theta_{LQ} \\ 0 & -\sin\theta_{LQ} & \cos\theta_{LQ} \end{pmatrix} \qquad \hat{M} \propto \mathbb{1}$$

Flavour structure

- Let us assume:

$$\mathcal{L}_{\rm mix} = -\overline{q}'_L \lambda_q \Psi_R \, \Omega_3 - \xcancel{\overline{\ell}'_L \lambda_\ell \Psi_R} \, \Omega_1 - \overline{\Psi}_L \hat{M} \Psi_R$$

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- $\lambda_\ell \to 0$

$\mathcal{G}_Q = U(2)_{q'+\Psi} \times U(1)_{q'_3+\Psi_3}$ *[promoting approximate $U(2)_{q'}$ of SM to NP]*

1. No tree-level FCNC in the down sector (λ_q and Y_d diagonal in the same basis)
2. CKM-induced tree-level FCNC in the up sector (D-mixing) protected by $U(2)_{q'}$

$$C_1^D \propto (V_{cb} V^*_{ub})^2 \sim 10^{-8}$$

Flavour structure

- Let us assume:

$$\mathcal{L}_{\mathrm{mix}} = -\bar{q}'_L \xcancel{\lambda_q \Psi}_R\, \Omega_3 - \bar{\ell}'_L \lambda_\ell \Psi_R\, \Omega_1 - \overline{\Psi}_L \hat{M} \Psi_R$$

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- $\lambda_q \to 0$

$$\mathcal{G}_L = U(1)_{\ell'_1 + \tilde{\Psi}_1} \times U(1)_{\ell'_2 + \tilde{\Psi}_2} \times U(1)_{\ell'_3 + \tilde{\Psi}_3} \qquad [\,\tilde{\Psi} = W \Psi\,]$$

1. No tree-level FCNC in the lepton sector (λ_ℓ and Y_e diagonal in the same basis)
2. W is unphysical

Flavour structure

- Let us assume:

$$\mathcal{L}_{\mathrm{mix}} = -\overline{q}'_L \lambda_q \Psi_R \Omega_3 - \overline{\ell}'_L \lambda_\ell \Psi_R \Omega_1 - \overline{\Psi}_L \hat{M} \Psi_R$$

$$\mathcal{L}_{\mathrm{SM-like}} = -\overline{q}'_L \hat{Y}_d d'_R H - \overline{q}'_L V^\dagger \hat{Y}_u u'_R \tilde{H} - \overline{\ell}'_L \hat{Y}_e e'_R H$$

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- Collective breaking (Q and L locked by SU(4) gauge symmetry)

$$\mathcal{G}_Q \cap \mathcal{G}_L \xrightarrow{SU(4)+W} U(1)_{q'_1+\ell'_1+\Psi_1} \times U(1)_{q'+\ell'+\Psi}$$

1. no FV involving down and electrons

2. only LQ feels W matrix

$$\Psi_L = (Q'_L, L'_L)^T = (Q_L, W L_L)^T \qquad \longrightarrow \qquad i\overline{\Psi}_L \gamma^\mu D_\mu \Psi_L \supset \frac{g_4}{\sqrt{2}} U_\mu \overline{Q}_L \gamma^\mu W L_L$$

A suggestive analogy*

321	4321
θ_C	θ_{LQ}
V	W
W^μ	U^μ
$q_L = \left(\begin{array}{c} u_L \\ V d_L \end{array} \right)$	$\Psi_L = \left(\begin{array}{c} Q_L \\ W L_L \end{array} \right)$
Y_u, Y_d	λ_q, λ_ℓ
$SU(2)_L$	$SU(4)$
$U(1)_u \times U(1)_c \times U(1)_t$	$U(2)_{q'+\Psi} \times U(1)_{q'_3+\Psi_3}$
$U(1)_d \times U(1)_s \times U(1)_b$	$U(1)_{\ell'_1+\tilde{\Psi}_1} \times U(1)_{\ell'_2+\tilde{\Psi}_2} \times U(1)_{\ell'_3+\tilde{\Psi}_3}$
$U(1)_B$	$U(1)_{q'_1+\ell'_1+\Psi_1} \times U(1)_{q'+\ell'+\Psi}$
$u \to d$ tree level	$Q \to L$ tree level
$u_i \to u_j$ loop level	$Q_i \to Q_j$ loop level
$d_i \to d_j$ loop level	$L_i \to L_j$ loop level

* symmetries in 321 accidental, in 4321 imposed (still, helpful for understanding pheno)

Fermion mass basis

$$\mathcal{M}_u = \begin{pmatrix} V^\dagger \, \hat{Y}_u \, \frac{v}{\sqrt{2}} & \hat{\lambda}_q \, \frac{v_3}{\sqrt{2}} \\ 0 & \hat{M}_Q \end{pmatrix} , \qquad \mathcal{M}_d = \begin{pmatrix} \hat{Y}_d \, \frac{v}{\sqrt{2}} & \hat{\lambda}_q \, \frac{v_3}{\sqrt{2}} \\ 0 & \hat{M}_Q \end{pmatrix} ,$$

$$\mathcal{M}_N = \begin{pmatrix} 0 & \hat{\lambda}_\ell \, \frac{v_1}{\sqrt{2}} \\ 0 & \hat{M}_L \end{pmatrix} , \qquad \mathcal{M}_e = \begin{pmatrix} \hat{Y}_e \, \frac{v}{\sqrt{2}} & \hat{\lambda}_\ell \, W^\dagger \, \frac{v_1}{\sqrt{2}} \\ 0 & \hat{M}_L \end{pmatrix} ,$$

$$M_{L_i} = \sqrt{\frac{|\lambda_i^\ell|^2 \, v_1^2}{2} + \hat{M}_L^2} \, , \qquad M_{Q_i} = \sqrt{\frac{|\lambda_i^q|^2 \, v_3^2}{2} + \hat{M}_Q^2} \, ,$$

$$m_{f_i} \approx |\hat{Y}_f^i| \, \cos\theta_{f_i} \, \frac{v}{\sqrt{2}} \qquad (f = u, d, e) \, .$$

$$\sin\theta_{q_i} = \frac{\lambda_i^q \, v_3}{\sqrt{|\lambda_i^q|^2 \, v_3^2 + 2 \, \hat{M}_Q^2}} \, ,$$

$$\sin\theta_{\ell_i} = \frac{\lambda_i^\ell \, v_1}{\sqrt{|\lambda_i^\ell|^2 \, v_1^2 + 2 \, \hat{M}_L^2}} \, ,$$

LQ interactions

1. Large quark-lepton transitions in 3-2 sector

$$\mathcal{L}_U \supset \frac{g_4}{\sqrt{2}} \beta_{ij}\, \overline{q}^i_L \gamma^\mu \ell^j_L U_\mu$$

$$\beta = \mathbf{diag}(s_{q_{12}}, s_{q_{12}}, s_{q_3})\, W\, \mathbf{diag}(0, s_{\ell_2}, s_{\ell_3}) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & c_{\theta_{LQ}} s_{q12} s_{\ell_2} & \boxed{s_{\theta_{LQ}} s_{q12} s_{\ell_3}} \\ 0 & -s_{\theta_{LQ}} s_{q3} s_{\ell_2} & c_{\theta_{LQ}} s_{q3} s_{\ell_3} \end{pmatrix}$$

$$\Delta R_{D^{(*)}} = \frac{g_4^2 v^2}{2\, M_U^2} \beta_{b\tau} \left(\beta_{b\tau} + \boxed{\beta_{s\tau}} \frac{V^*_{tb}}{V^*_{ts}} \right)$$

$\beta_{s\tau} > V_{ts} \sim 0.04$ → allows to raise the LQ mass scale

we need: $\theta_{LQ} \sim \pi/4$ $\theta_{\ell_3} \sim \pi/2$ $\theta_{q3} \sim \pi/2$ $\theta_{q_{12}} \sim \mathcal{O}(1)$

Z' / g' interactions

$$\mathcal{L}_{g'} \supset g_s \frac{g_4}{g_3} g'^{a}_{\mu} \left[\kappa_q^{ij}\, \overline{q}^i \gamma^\mu T^a q^j + \kappa_u^{ij}\, \overline{u}^i_R \gamma^\mu T^a u^j_R + \kappa_d^{ij}\, \overline{d}^i_R \gamma^\mu T^a d^j_R \right]$$

$$\mathcal{L}_{Z'} \supset \frac{g_Y}{2\sqrt{6}} \frac{g_4}{g_1} Z'_\mu \left[\xi_q^{ij}\, \overline{q}^i \gamma^\mu q^j + \xi_u^{ij}\, \overline{u}^i_R \gamma^\mu u^j_R + \xi_d^{ij}\, \overline{d}^i_R \gamma^\mu d^j_R - 3\, \xi_\ell^{ij}\, \overline{\ell}^i \gamma^\mu \ell^j - 3\, \xi_e^{ij}\, \overline{e}^i_R \gamma^\mu e^j_R \right]$$

$$\kappa_q \approx \begin{pmatrix} s^2_{q_1} & 0 & 0 \\ 0 & s^2_{q_2} & 0 \\ 0 & 0 & s^2_{q_3} \end{pmatrix} - \frac{g_3^2}{g_4^2} \mathbb{1}\,, \qquad \kappa_u \approx \kappa_d \approx -\frac{g_3^2}{g_4^2} \mathbb{1}\,,$$

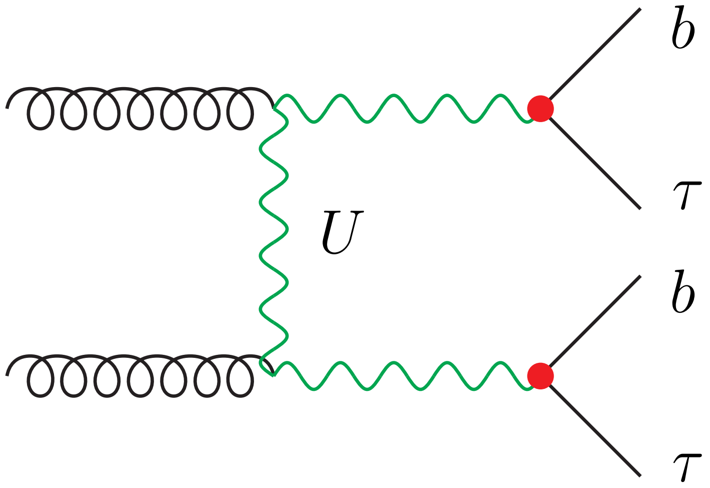
$$\xi_q \approx \begin{pmatrix} s^2_{q_1} & 0 & 0 \\ 0 & s^2_{q_2} & 0 \\ 0 & 0 & s^2_{q_3} \end{pmatrix} - \frac{2\, g_1^2}{3\, g_4^2} \mathbb{1}\,, \qquad \xi_u \approx \xi_d \approx -\frac{2\, g_1^2}{3\, g_4^2} \mathbb{1}\,,$$

$$\xi_\ell \approx \begin{pmatrix} s^2_{\ell_1} & 0 & 0 \\ 0 & s^2_{\ell_2} & 0 \\ 0 & 0 & s^2_{\ell_3} \end{pmatrix} - \frac{2\, g_1^2}{3\, g_4^2} \mathbb{1}\,, \qquad \xi_e \approx -\frac{2\, g_1^2}{3\, g_4^2} \mathbb{1}\,.$$

High-p$_T$ searches

- LQ pair production via QCD

- 3rd generation final states (fixed by anomaly and SU(2)$_L$ invariance)



$$\begin{cases} U \to b\tau^+, \quad \mathrm{BR} = 50\ \% \\ U \to t\overline{\nu}, \quad \mathrm{BR} = 50\ \% \end{cases}$$

[CMS search for spin-0, 1703.03995
recast for spin-1 1706.01868 (see also 1706.05033) + Moriond EW update]

$m_U \gtrsim 1.5\ \mathrm{TeV}$ → LQ mass sets the overall scale: $M_{g'} \simeq \sqrt{2}\, M_U \quad M_{Z'} \simeq \frac{1}{\sqrt{2}} M_U$

High-p_T searches

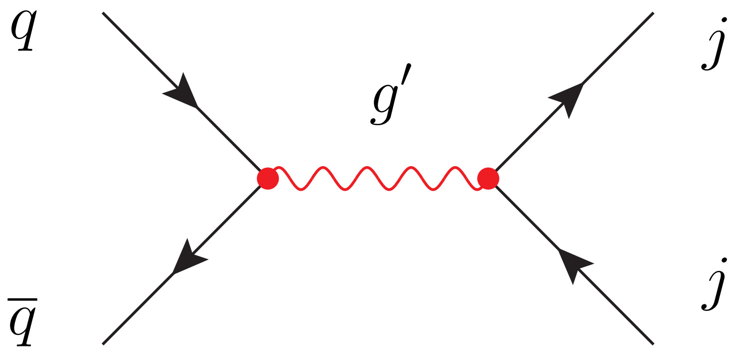
- LQ pair production via QCD

- Z' Drell-Yan production naturally suppressed

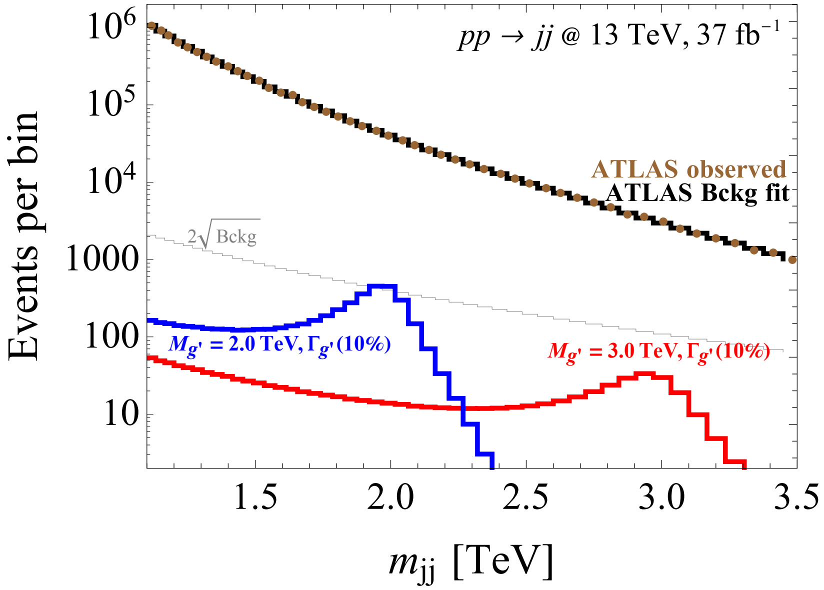
$$\sin\theta_{Z'} = \sqrt{\frac{3}{2}}\frac{g_Y}{g_4} \simeq 0.09 \quad \longrightarrow \quad \text{requires } g_4 \gtrsim 3$$

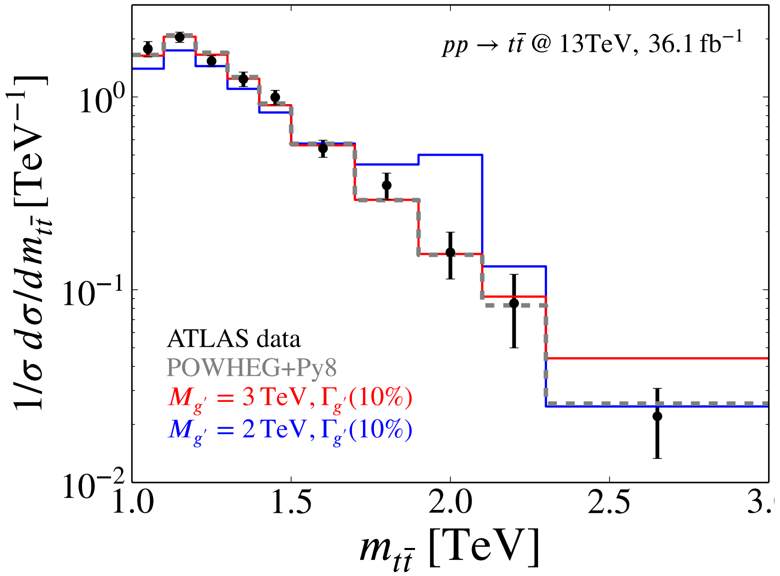
- g' resonant di-jet searches [ATLAS, 1703.09127]

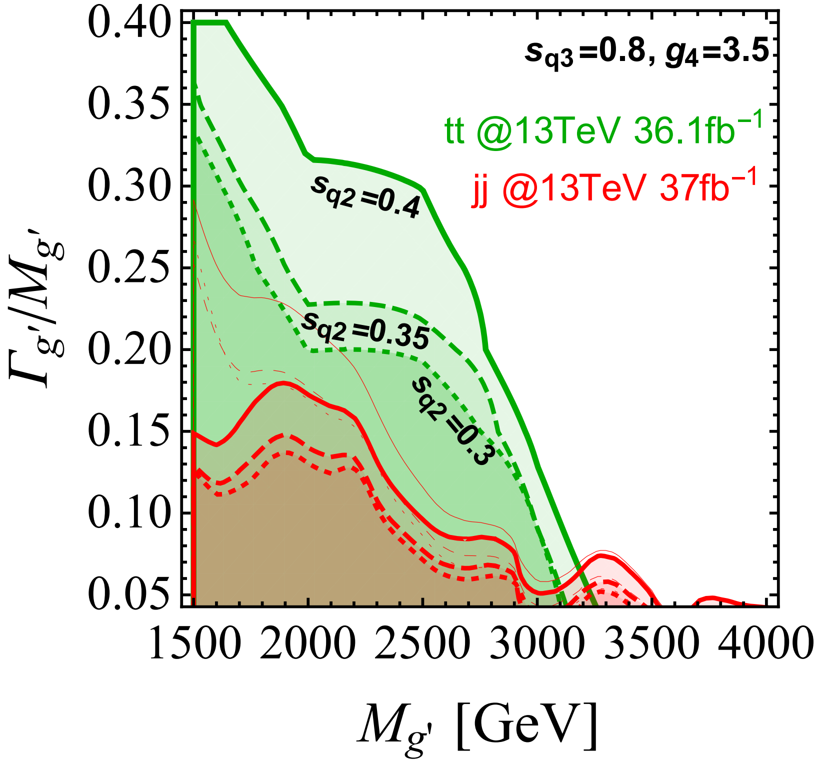
$$\sin\theta_{g'} = \frac{g_s}{g_4} \simeq 0.3 \quad \longrightarrow \quad \text{2 TeV coloron naively excluded}$$

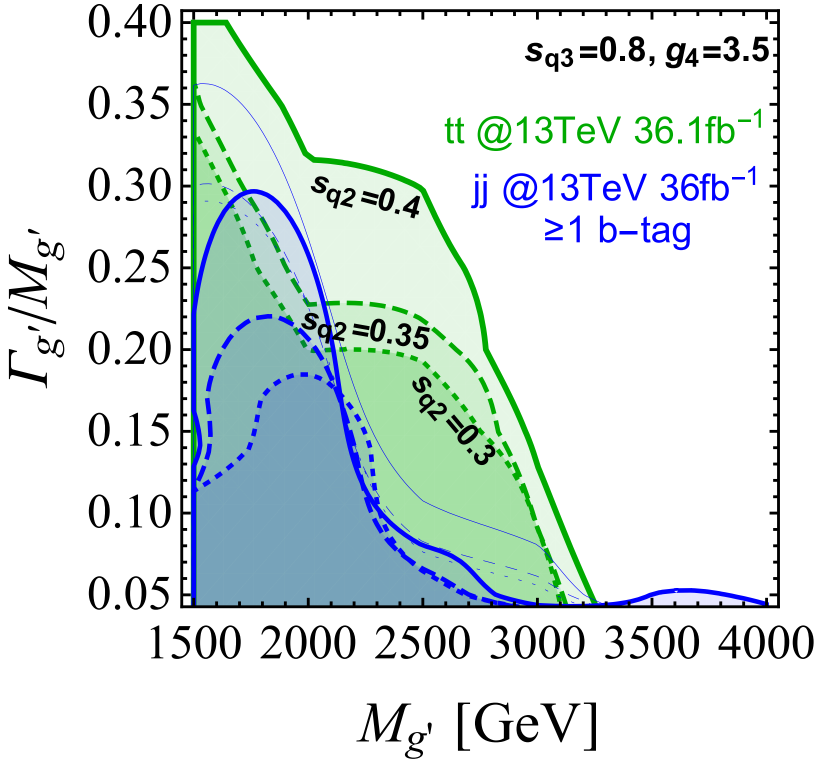


Coloron


$pp \to jj$ @ 13 TeV, 37 fb^{-1}
ATLAS observed
ATLAS Bckg fit
$2\sqrt{\text{Bckg}}$
$M_{g'}$ = 2.0 TeV, $\Gamma_{g'}$(10%)
$M_{g'}$ = 3.0 TeV, $\Gamma_{g'}$(10%)
Events per bin
10^6
10^5
10^4
1000
100
10
1.5
2.0
2.5
3.0
3.5
m_{jj} [TeV]


$pp \to t\bar{t}$ @ 13TeV, 36.1 fb^{-1}
ATLAS data
POWHEG+Py8
$M_{g'}$ = 3 TeV, $\Gamma_{g'}$(10%)
$M_{g'}$ = 2 TeV, $\Gamma_{g'}$(10%)
$1/\sigma\ d\sigma/dm_{t\bar{t}}$ [TeV^{-1}]
10^0
10^{-1}
10^{-2}
1.0
1.5
2.0
2.5
3.
$m_{t\bar{t}}$ [TeV]


s_{q3}=0.8, g_4=3.5
tt @13TeV 36.1fb^{-1}
jj @13TeV 37fb^{-1}
s_{q2}=0.4
s_{q2}=0.35
s_{q2}=0.3
$\Gamma_{g'}/M_{g'}$
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
1500
2000
2500
3000
3500
4000
$M_{g'}$ [GeV]


s_{q3}=0.8, g_4=3.5
tt @13TeV 36.1fb^{-1}
jj @13TeV 36fb^{-1}
≥1 b−tag
s_{q2}=0.4
s_{q2}=0.35
s_{q2}=0.3
$\Gamma_{g'}/M_{g'}$
0.40
0.35
0.30
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0.10
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2000
2500
3000
3500
4000
$M_{g'}$ [GeV]