Discussion on B-anomalies

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Outline

1. Review of "B-anomalies"

    - charged currents

    - neutral currents

2. Combined explanations

    - EFT

    - Simplified models

    - UV completions

BSM Flavour

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

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

- Flavour puzzle

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

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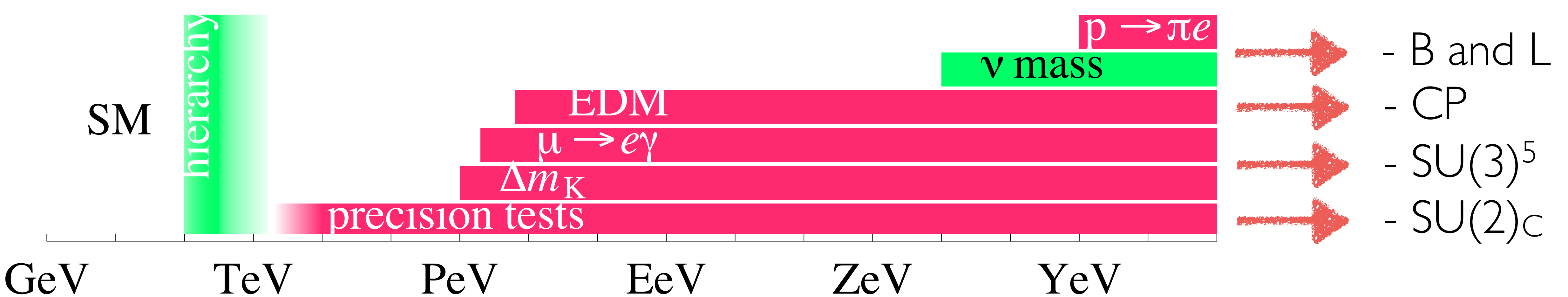
- Flavour puzzle

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

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



[Strumia, Vissani]

BSM Flavour

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

- Flavour puzzle

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

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

- pre-LHC scenario:

 exciting NP at ATLAS/CMS, boring flavour physics at LHCb protected by MFV

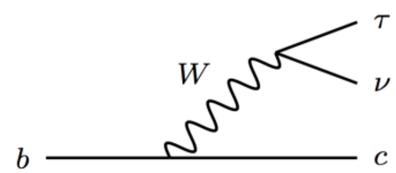
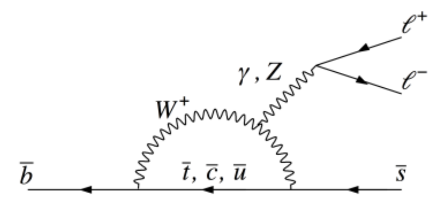
→ data suggest instead <u>unexpected</u> flavour anomalies

Part-I

Review of “B-anomalies”

"B-anomalies"

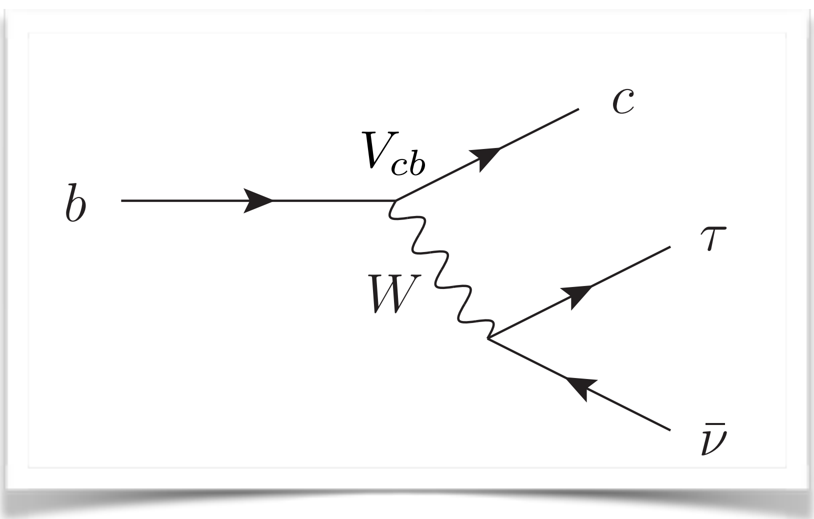
- A seemingly coherent pattern of SM deviations building up since ~ 2012

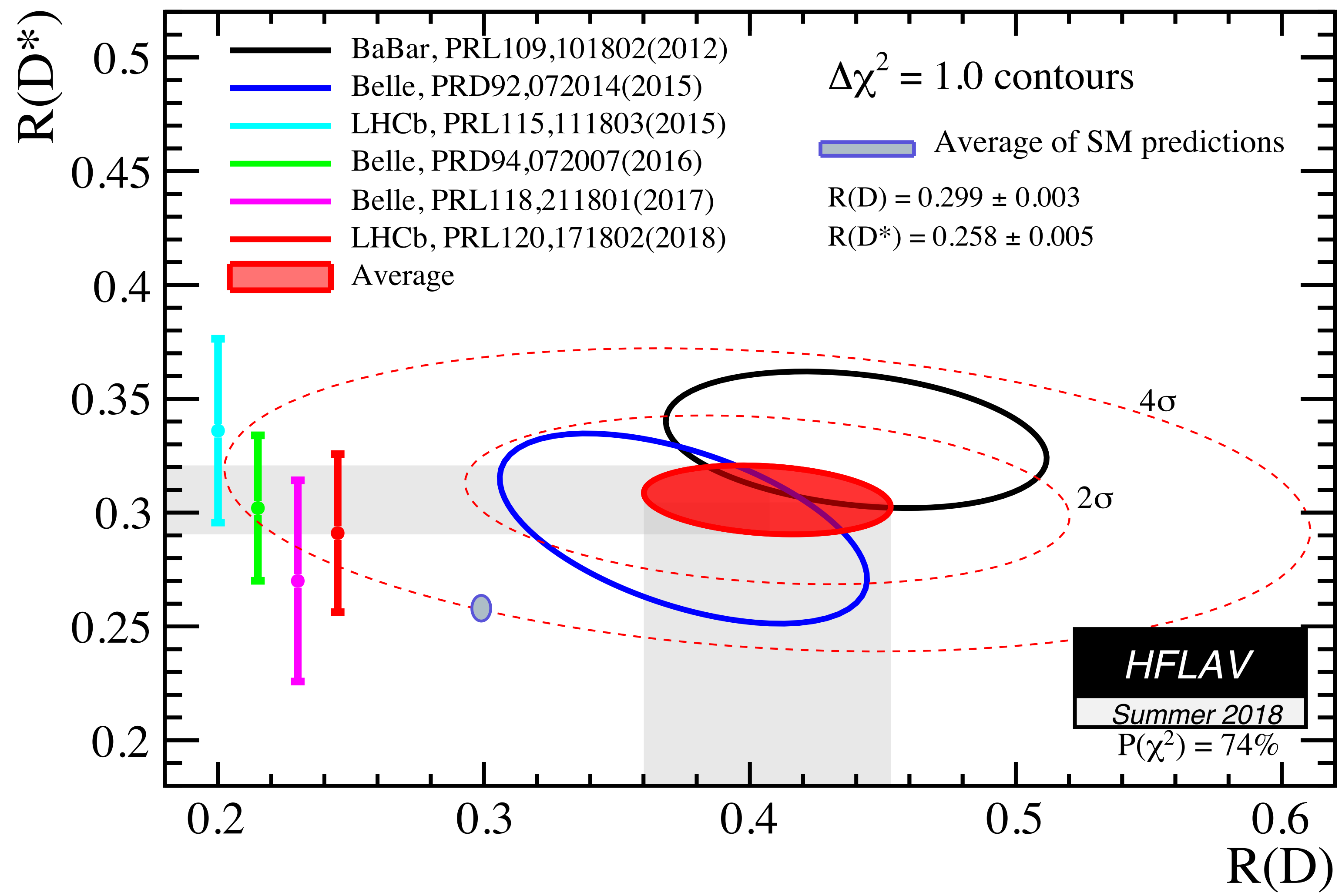
	$b \to c\tau\nu$  	$b \to s\mu\mu$ 
Lepton Universality	$R(D), R(D^*),$ $R(J/\psi)$	$R(K), R(K^*)$
Angular Distributions		$B \to K^*\mu\mu\ \ (P_5')$
Differential BR $(d\Gamma/dq^2)$		$B \to K^{(*)}\mu\mu$ $B_s \to \phi\mu\mu$ $\Lambda_b \to \Lambda\mu\mu$

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 [lot of recent activity - HFLAV 2018]
- Deviation seen in 3 exp. in a consistent way, combined significance ~ 3.7**σ**
- R(D) and R(D*) point to constructive interference (+15%) with SM amplitude

Charged current anomalies

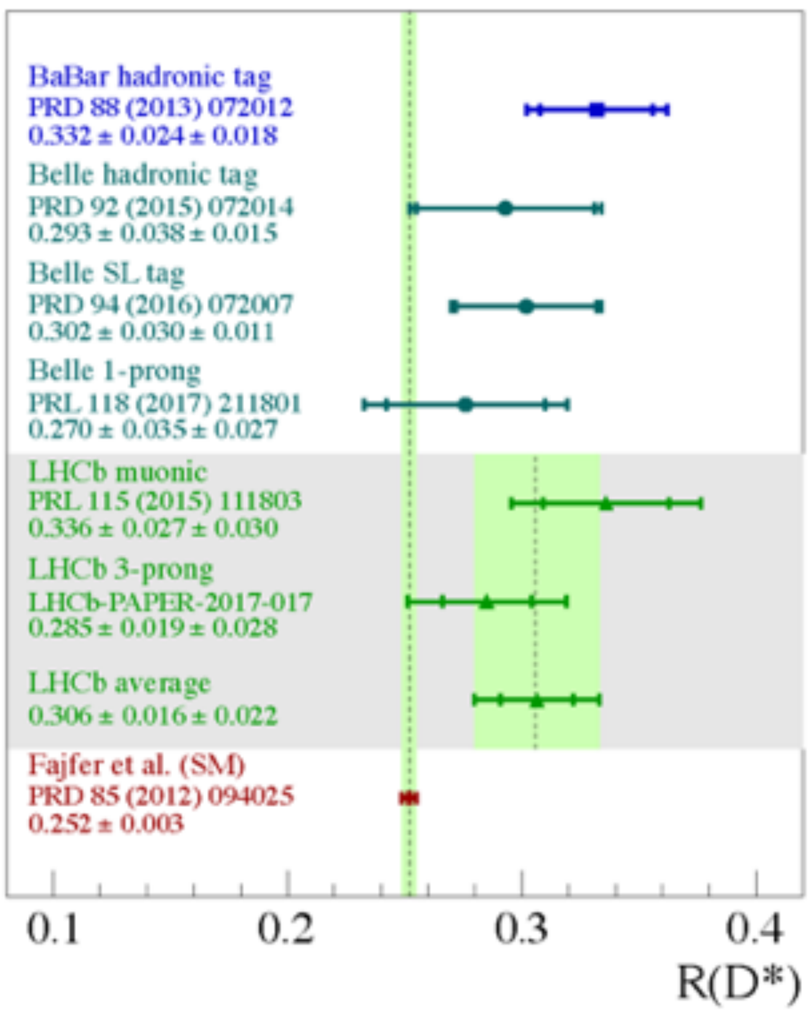
$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)+}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)+}\ell\nu)}$$

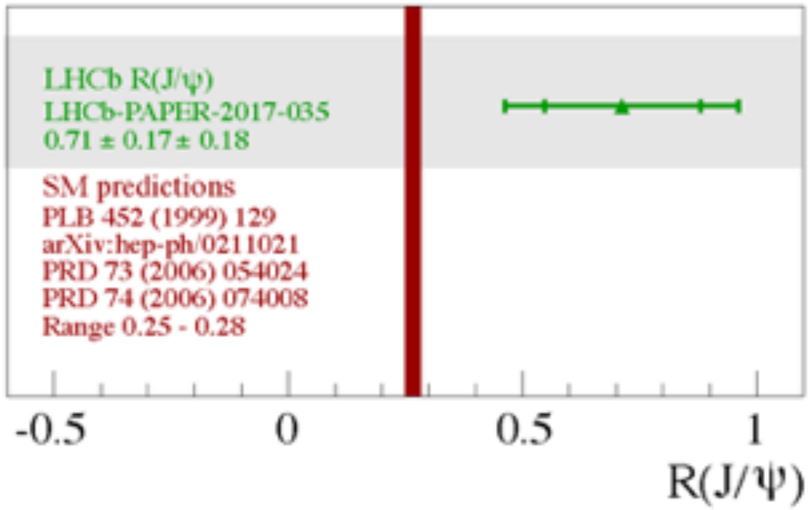
- As of Sept 2017:

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$

~ 2σ above the SM

→ clearly, a systematic effect !

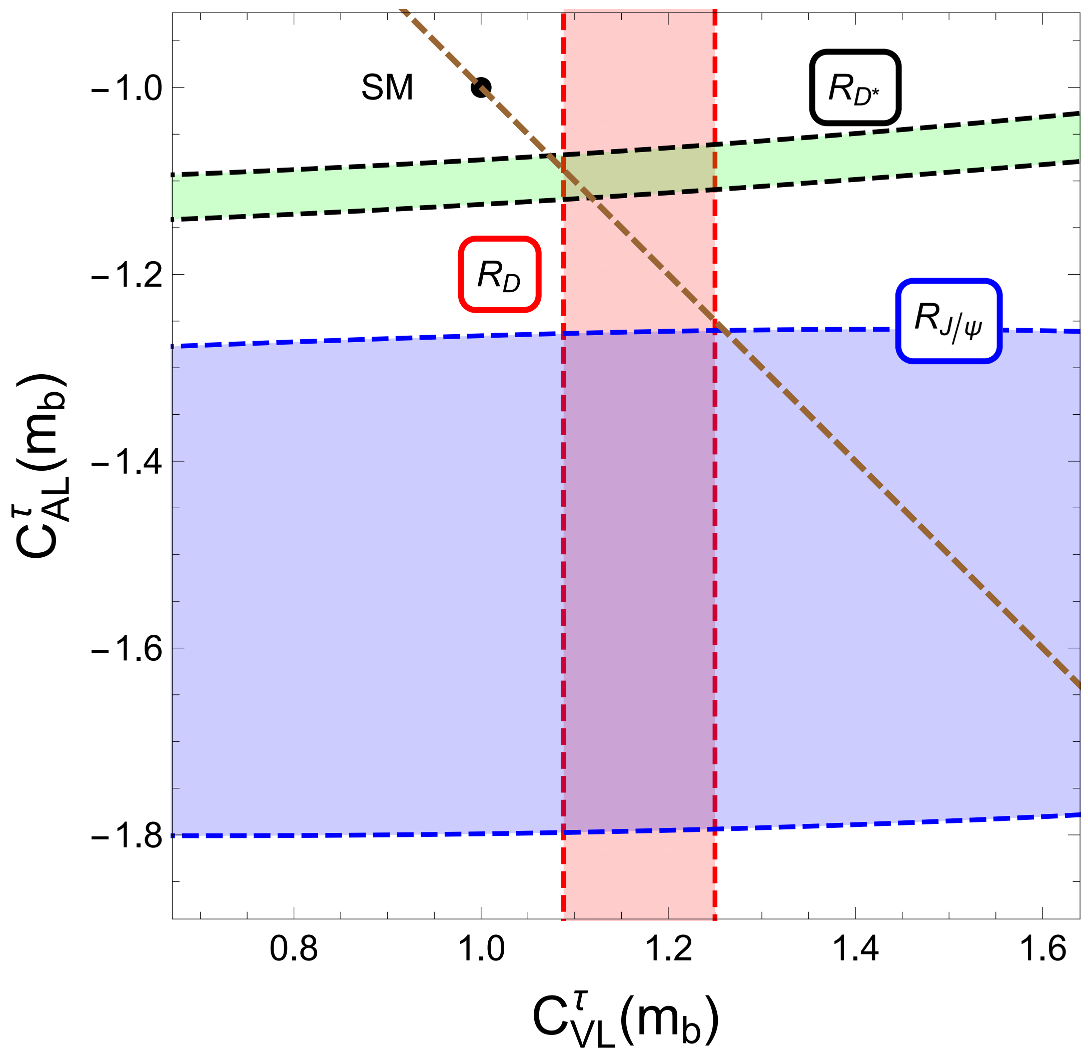


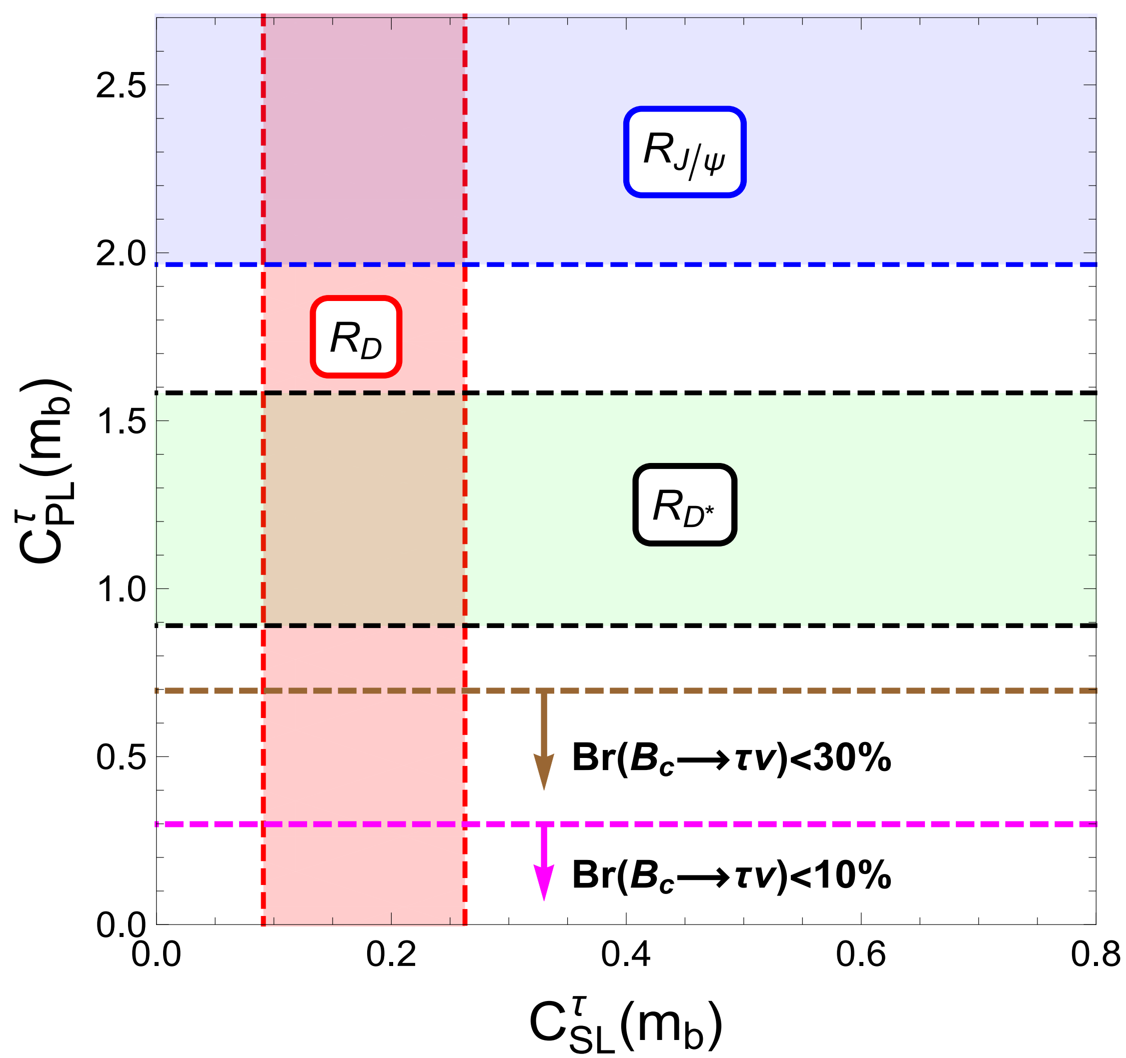


Charged current anomalies

- BSM fit favours NP in LH tau operators (SM interference)* [Freytsis, Ligeti, Ruderman, 1506.08896 Azatov at al, 1805.03209]

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





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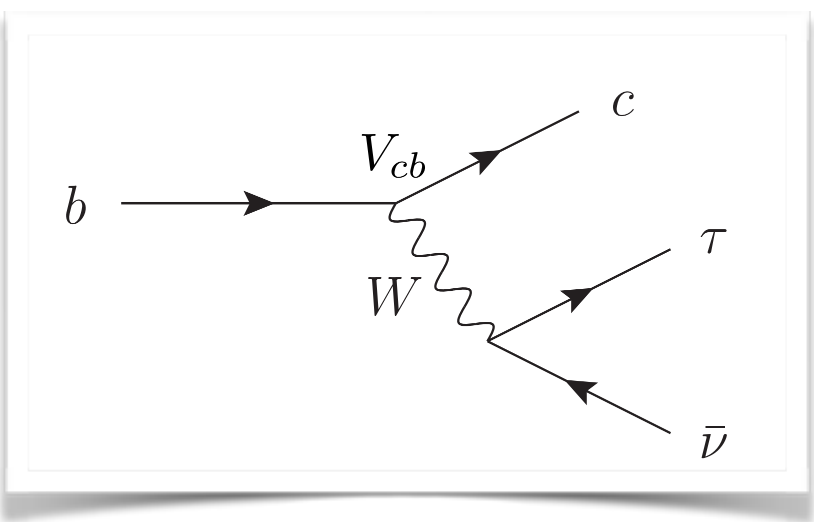
- What is the scale of NP ?



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

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

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

*Exception: < 100 MeV sterile neutrino (no SM interference, relaxes bounds from $SU(2)_L$)

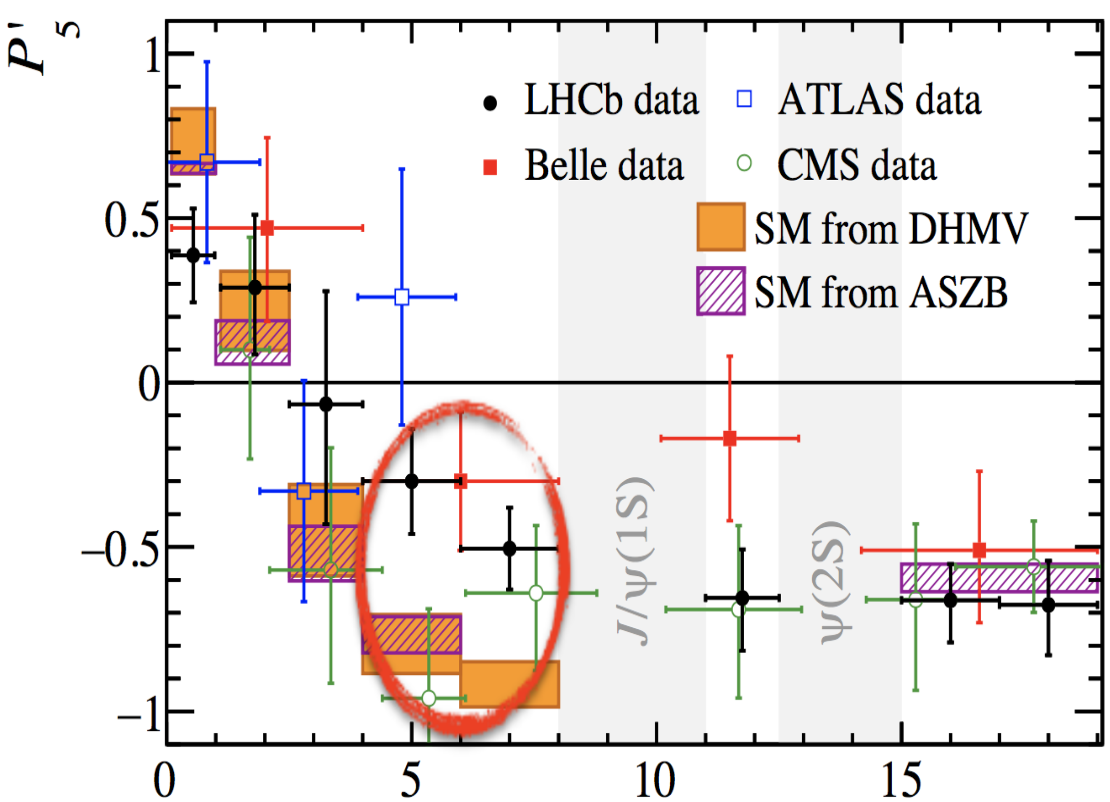
$$\mathcal{L}_{BSM}^{b\to c\tau\nu} = \frac{c_{R_D}}{\Lambda^2} (\bar{c}_R \gamma_\mu b_R)(\bar{\tau}_R \gamma^\mu N_R) \qquad \Lambda/\sqrt{c_{R_D}} = (1.27^{+0.09}_{-0.07})\ \text{TeV}$$

[1804.04135, 1804.04642, 1807.10745]

Neutral current anomalies

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

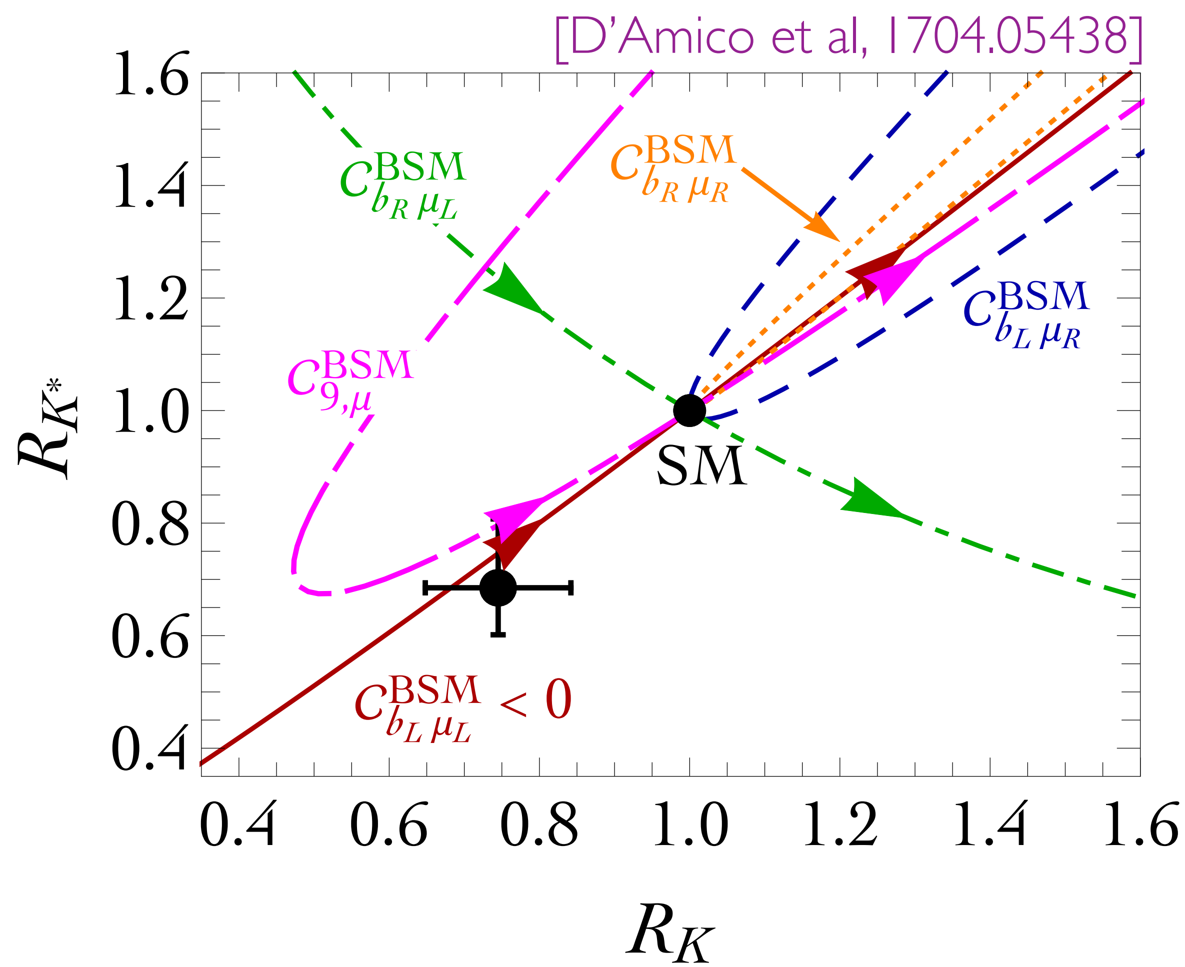
Challenging SM prediction



- 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 correlation)
- Significance of global fits > 4σ

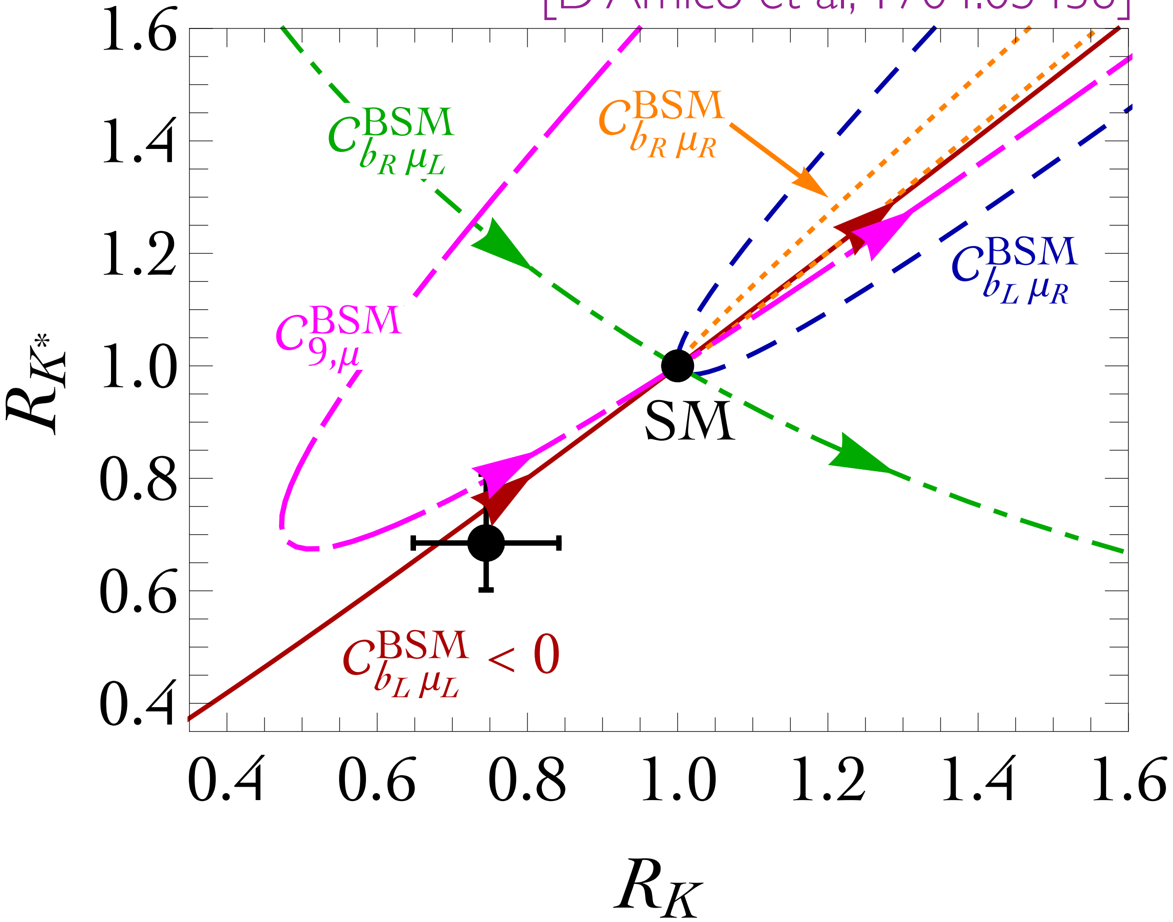
	All		LFUV	
1D Hyp.	Best fit	Pull_{SM}	Best fit	Pull_{SM}
$\mathcal{C}_{9\mu}^{\text{NP}}$	-1.10	5.7	-1.76	3.9
(LH) $\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	-0.61	5.2	-0.66	4.1

Capdevila et al. 1704.05340

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

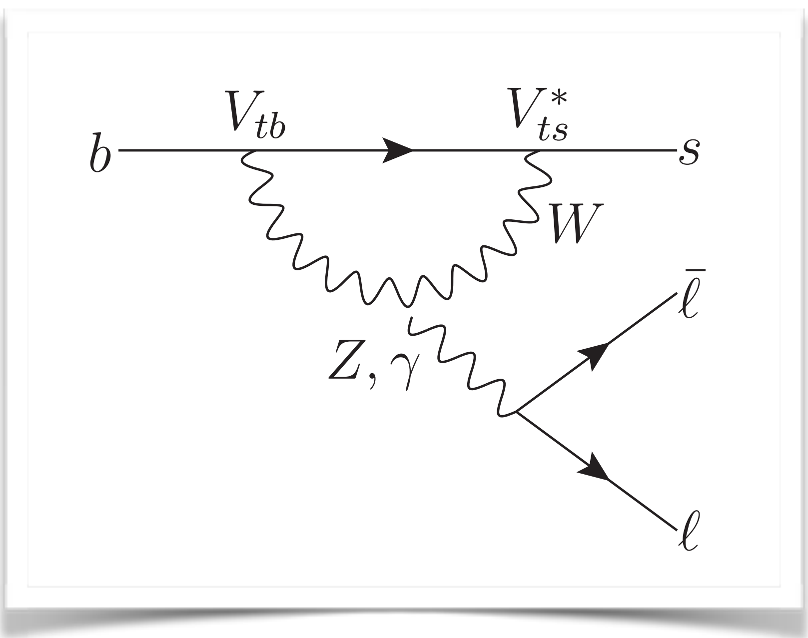
$$O_{10} \propto (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}_L \gamma^\mu \gamma_5 \ell)$$

[D'Amico et al, 1704.05438]



Neutral current anomalies

- Well-described by NP in $b \to s\mu\mu$ (explains also angular distributions)
- RH currents in quark sector disfavoured (predict wrong correlation)
- Significance of global fits > 4**σ**
- What is the scale of NP ?



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

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

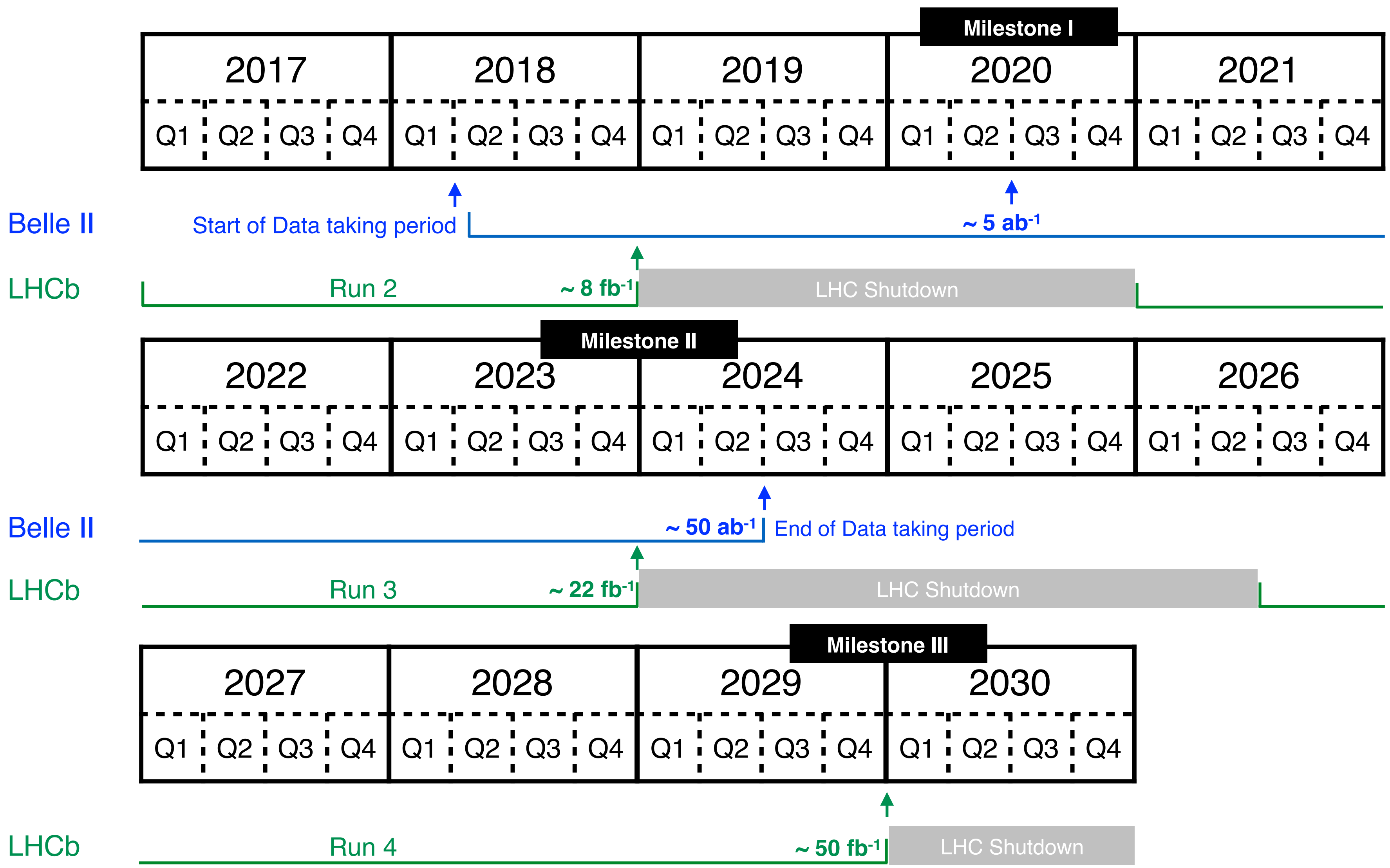
MFV: $c = V_{ts}$ $\qquad \Lambda = 6 \text{ TeV}$

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

Future prospects

- LHCb + Belle-II have the potential to fully establish NP in B-anomalies

[Albrecht et al, 1709.10308]



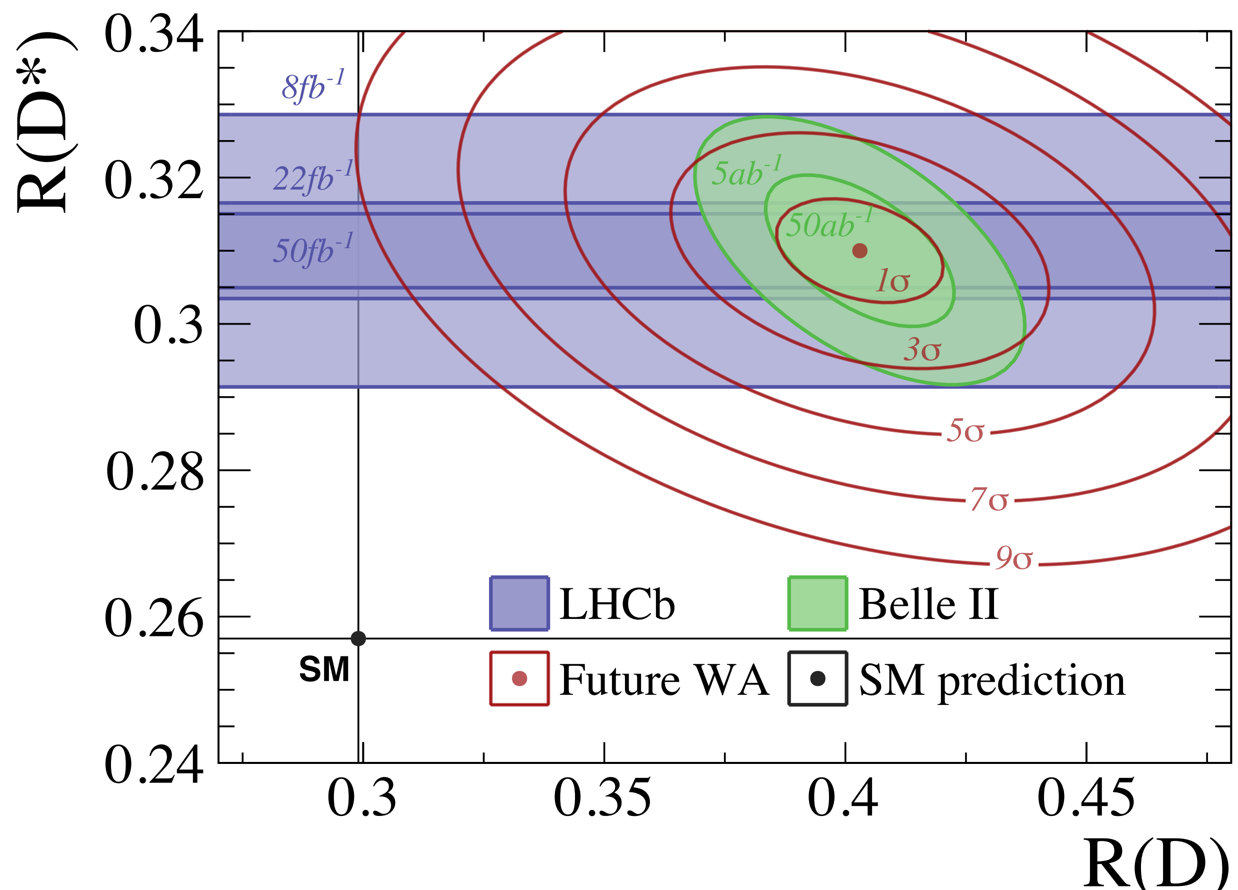
Future prospects

- LHCb + Belle-II have the potential to fully establish NP in B-anomalies

[Albrecht et al, 1709.10308]

Belle II		LHCb		
$5\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$	$8\,\mathrm{fb}^{-1}$	$22\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$
2020	2024	2019	2024	2030

charged currents



+ LHCb will measure R(D)

neutral currents

assuming current central values:

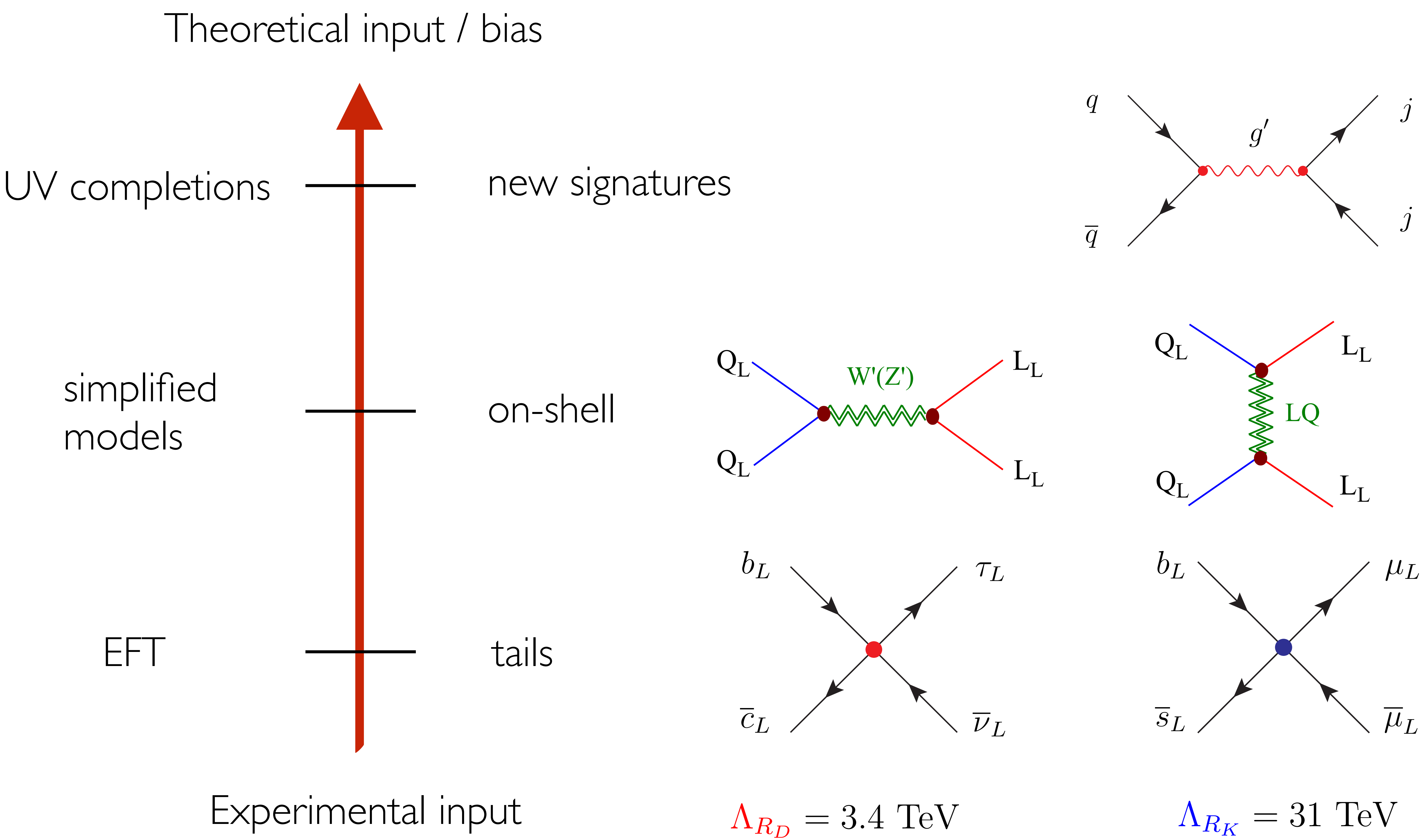
- LHCb will measure R(K) and R(K*) at > 5**σ** by 2019 and ~15**σ** by 2030

- Belle-II will reach ~ 7**σ** by 2024

Part-II

Combined explanations

Bottom-up approach



EFT [general considerations]

- SU(2)$_L$ triplet operator (neutral+charged currents in SMEFT)

$$\frac{\lambda^q_{ij}\lambda^\ell_{kl}}{\Lambda^2}(\overline{Q}^i_L\sigma^a\gamma_\mu Q^j_L)(\overline{L}^k_L\sigma^a\gamma^\mu L^l_L)$$

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

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

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

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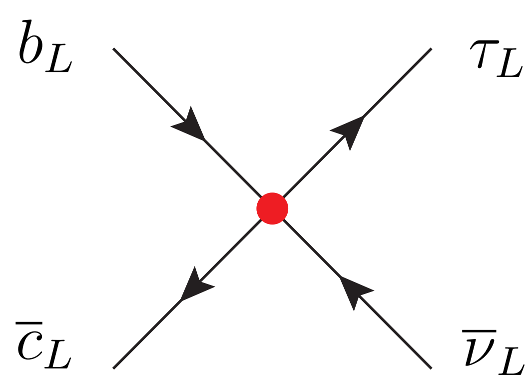
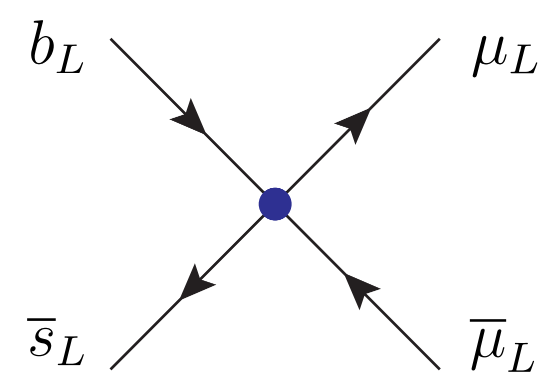
- SU(2)$_L$ triplet operator

$$\frac{\lambda^q_{ij}\lambda^\ell_{kl}}{\Lambda^2}(\overline{Q}^i_L\sigma^a\gamma_\mu Q^j_L)(\overline{L}^k_L\sigma^a\gamma^\mu L^l_L) \supset -\frac{1}{\Lambda^2_{R_D}} 2\,\bar{c}_L\gamma^\mu b_L\bar{\tau}_L\gamma_\mu\nu_L + \frac{1}{\Lambda^2_{R_K}}\bar{s}_L\gamma^\mu b_L\bar{\mu}_L\gamma_\mu\mu_L$$





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

- What is the scale of NP ?

Measured "Fermi constant" of the anomaly $\longleftarrow$ $\dfrac{1}{\Lambda^2} = \dfrac{C}{M^2}$

$\longrightarrow$ model dependent part

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

$\longrightarrow$ on-shell effects @ colliders

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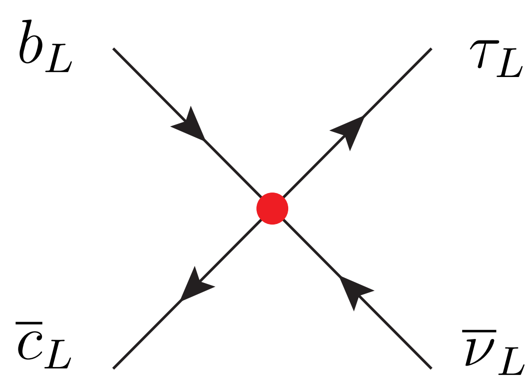
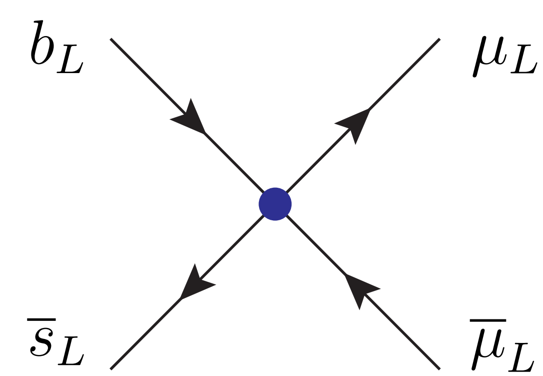




$$\Lambda_{R_D} = 3.4 \text{ TeV} \qquad \ll \qquad \Lambda_{R_K} = 31 \text{ TeV}$$

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

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

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

EFT [general considerations]

- SU(2)$_L$ triplet operator

$$\frac{\lambda^q_{ij}\lambda^\ell_{kl}}{\Lambda^2}(\overline{Q}^i_L\sigma^a\gamma_\mu Q^j_L)(\overline{L}^k_L\sigma^a\gamma^\mu L^l_L) \supset -\frac{1}{\Lambda^2_{R_D}}2\,\overline{c}_L\gamma^\mu b_L\overline{\tau}_L\gamma_\mu\nu_L + \frac{1}{\Lambda^2_{R_K}}\overline{s}_L\gamma^\mu b_L\overline{\mu}_L\gamma_\mu\mu_L$$

- 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 ?

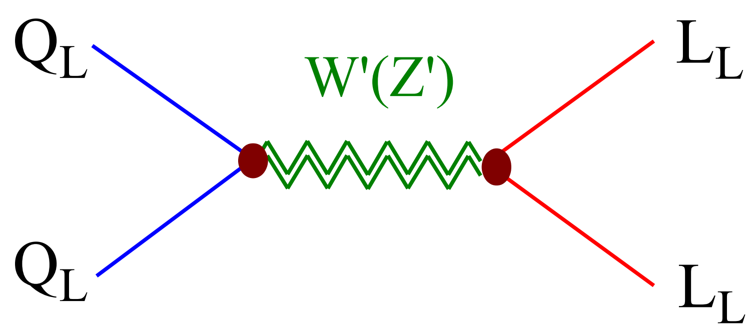
$$\overline{Q}_3 Q_3 \longrightarrow V_{cb}\,\overline{c}_L b_L$$ (pure mixing scenario)

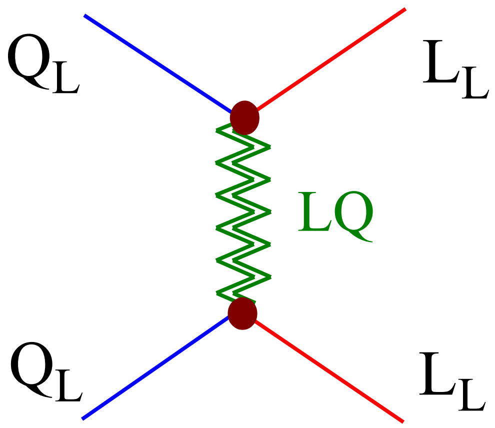
EFT [general considerations]

- SU(2)$_L$ triplet operator

$$\frac{\lambda^q_{ij}\lambda^\ell_{kl}}{\Lambda^2}(\overline{Q}^i_L\sigma^a\gamma_\mu Q^j_L)(\overline{L}^k_L\sigma^a\gamma^\mu L^l_L)$$

- Tree-level mediators:

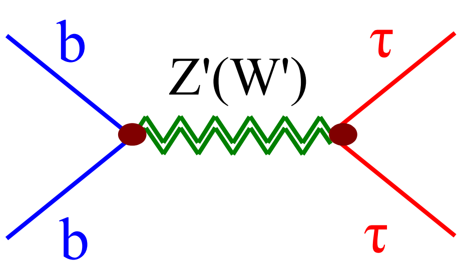


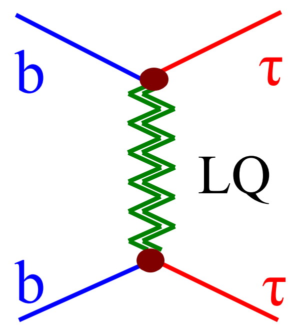


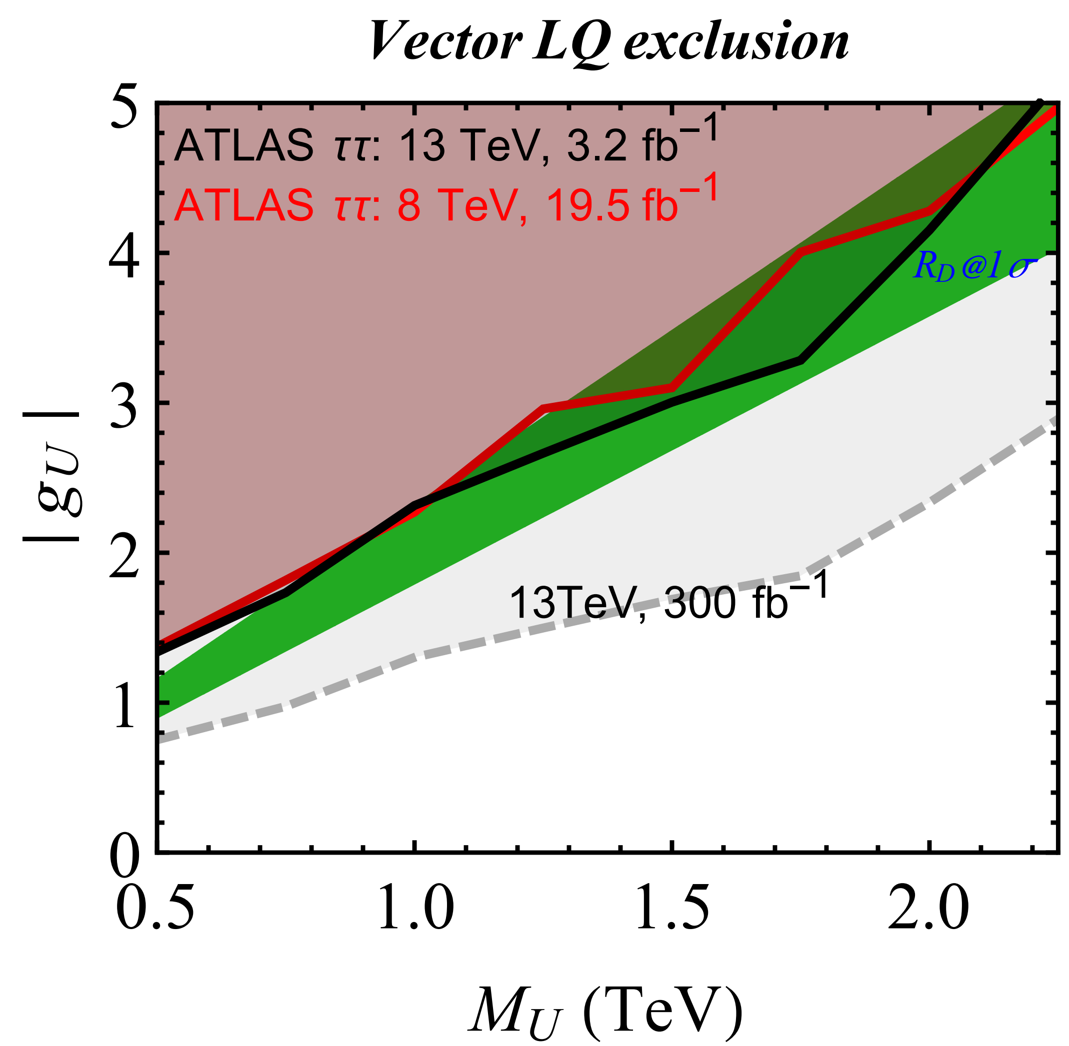
EFT [problems]

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

1. High-p$_T$ constraints







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

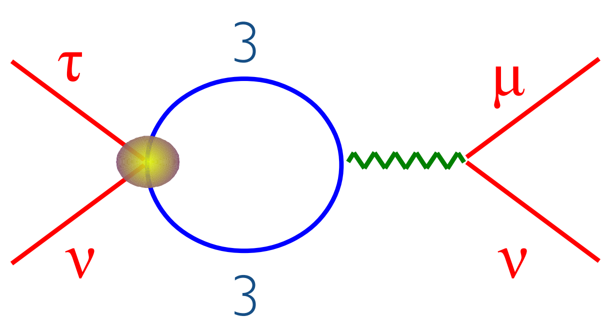
$$\Lambda_{33} = \Lambda_{R_D} V_{cb} = 0.7 \text{ TeV}$$

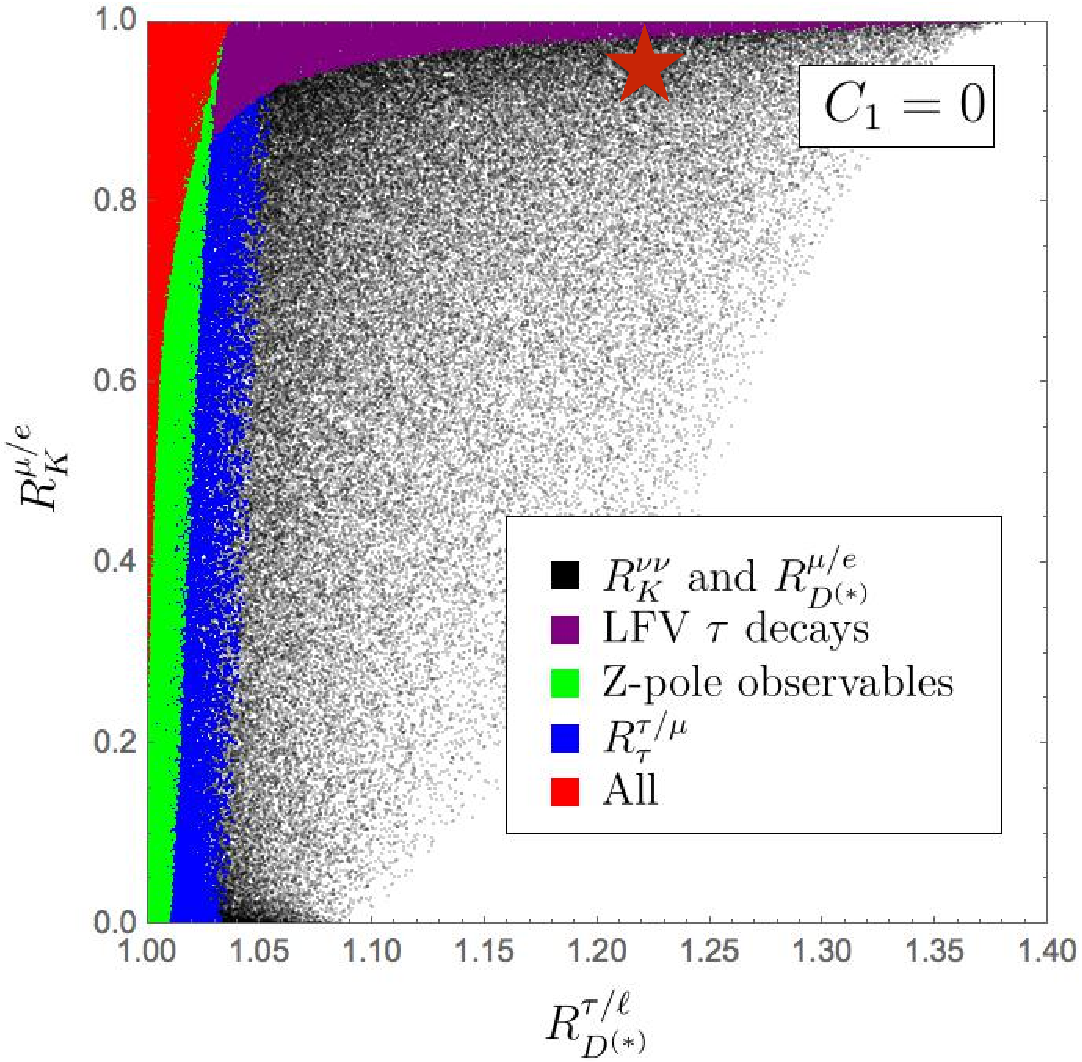
[Faroughy, Greljo, Kamenik 1609.07138]

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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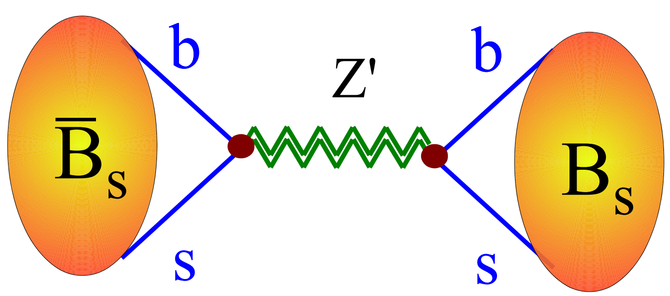
[Feruglio, Paradisi, Pattori 1606.00524, 1705.00929]

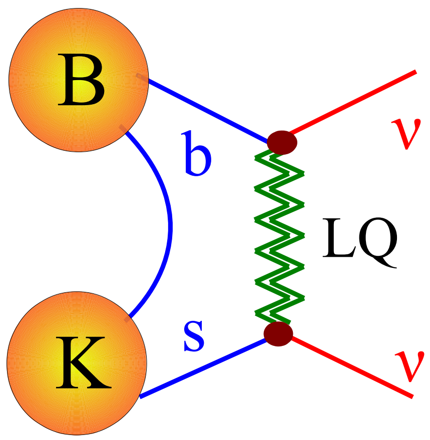
EFT [problems]

- 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)

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

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2. Deviation from pure-mixing scenario

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

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

allows for larger NP scale

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[Zürich's guide for combined explanations, 1706.07808]

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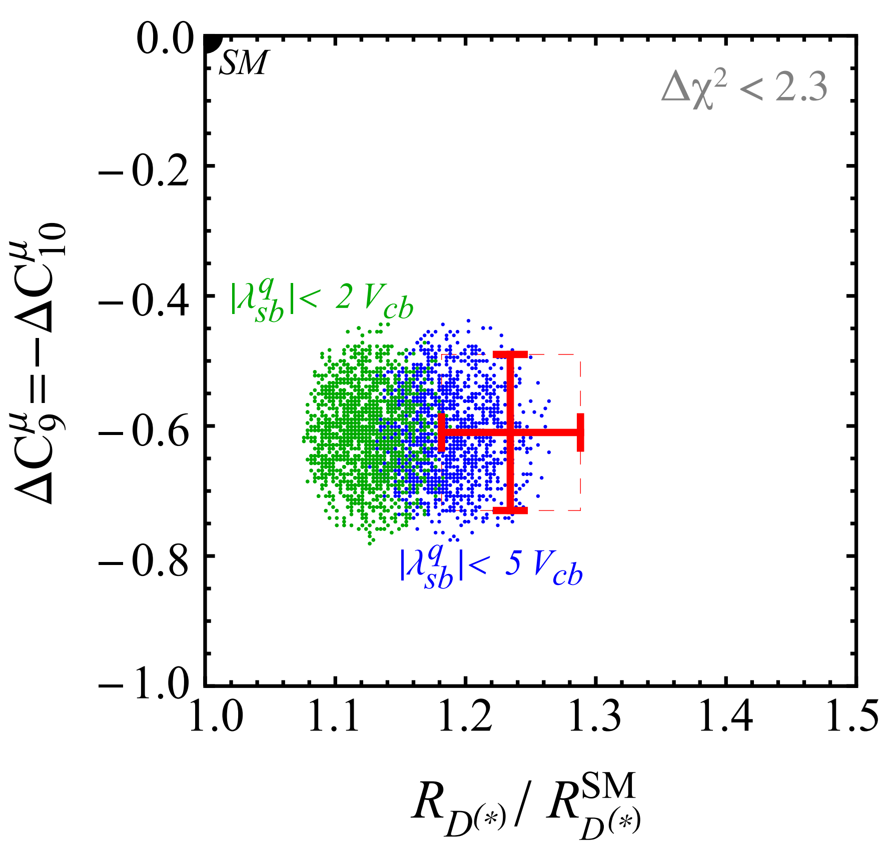


$\lambda^q_{sb} > \mathcal{O}(V_{cb})$ allows for larger NP scale

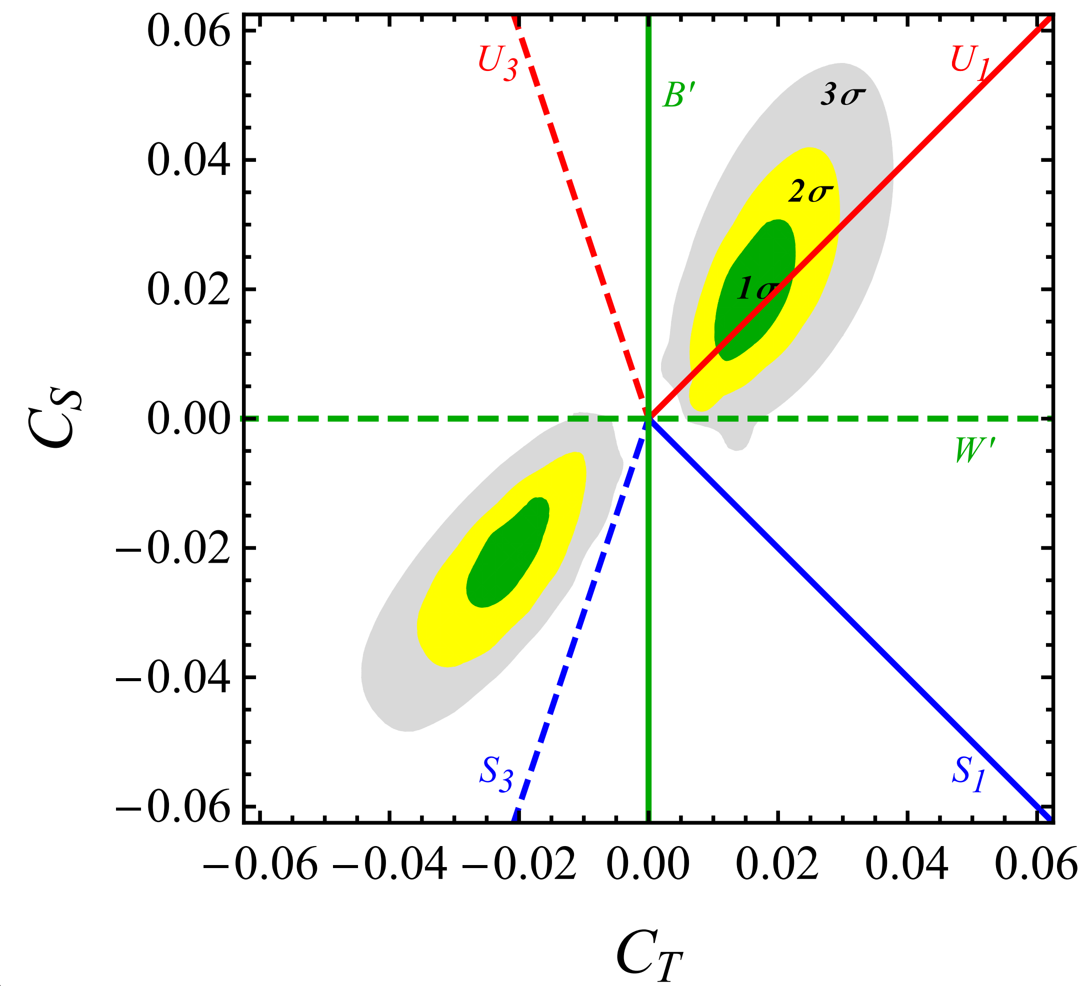
Simplified models

- 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	$(1,1,0)$	∞	$\times$	✓
V'	1	$(1,3,0)$	0	✓	✓
S_1	0	$(\overline{3},1,1/3)$	-1	✓	$\times$
S_3	0	$(\overline{3},3,1/3)$	3	✓	✓
U_1	1	$(3,1,2/3)$	1	✓	✓
U_3	1	$(3,3,2/3)$	-3	✓	✓

$$\mathcal{B}(B \to K^* \nu\nu) \propto (C_T - C_S)$$



A clear winner: U_1 ⟶ $C_T = C_S$ (at threshold)

Linear combinations also possible (e.g. $S_1 + S_3$ or $Z' + V'$) ⟶ tuning required

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

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

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

[Barbieri, Isidori, Pattori, Senia 1502.01560
Barbieri, Murphy, Senia 1611.0493
Buttazzo et al, 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 (divergent loop observables)

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

- An interesting option: minimal Pati-Salam (PS)

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

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

gauge boson of an extended gauge sector

🙂 hinted by SM chiral structure + everything's calculable

🙁 $M_{U_1} \gtrsim 86\ \text{TeV}$ from $K_L^0, B^0, B_s \to \ell\,\ell'$ decays (L x R couplings)

[Kutznetsov et al 1203.0196 + update from A. D. Smirnov 1801.02895]

mass basis

$$\mathcal{L}_{PS} \supset \frac{g_4}{\sqrt{2}}\left(\overline{d}_L^i \delta_{ij}\gamma_\mu e_L^j + \overline{d}_R^i \delta_{ij}\gamma_\mu e_R^j\right) U_1^\mu \longrightarrow \frac{g_4}{\sqrt{2}}\left(\overline{d}_L^i \beta_{ij}^L\gamma_\mu e_L^j + \overline{d}_R^i \beta_{ij}^R\gamma_\mu e_R^j\right) U_1^\mu$$

$$\beta^{L,R} = U^\dagger_{d_{L,R}} U_{e_{L,R}}$$ (unitary matrices)

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

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gauge boson of an extended gauge sector

🙂 hinted by SM chiral structure + everything's calculable

🙁 $M_{U_1} \gtrsim 86 \text{ TeV}$ from $K_L^0, B^0, B_s \to \ell\,\ell'$ decays (L x R couplings)

🙁 Z' direct searches ($M_{U_1} \sim M_{Z'} \sim \text{TeV}$ + O(g_s) Z' couplings to valence quarks)

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

→ Minimal PS <u>cannot</u> explain B-anomalies

Beyond minimal PS

- We look for something like

$$\beta^L \sim \begin{pmatrix} \epsilon & \epsilon & \epsilon \\ \epsilon & 0.01 & 0.2 \\ \epsilon & 0.05 & 1 \end{pmatrix} \qquad \beta^R \sim \epsilon \qquad \left(\, \beta^\dagger \beta \neq 1 \,\right)$$

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1): non-minimal matter content (mixing with heavy fermions) [Calibbi, Crivellin, Li 1709.00692]

$$\frac{g_4}{\sqrt{2}} \overline{\mathcal{D}}^A \hat{\beta}_{AB} \gamma_\mu \mathcal{E}^B U_1^\mu \qquad \hat{\beta} = \begin{pmatrix} \beta_{\mathrm{LL}} & \beta_{\mathrm{LH}} \\ \beta_{\mathrm{HL}} & \beta_{\mathrm{HH}} \end{pmatrix} \qquad \begin{array}{c} \hat{\beta}^\dagger \hat{\beta} = 1 \\ \beta^\dagger_{\mathrm{LL}} \beta_{\mathrm{LL}} \neq 1 \end{array}$$

🙁 Z' direct searches

🙁 neutrino masses

Beyond minimal PS

- We look for something like

$$\beta^L \sim \begin{pmatrix} \epsilon & \epsilon & \epsilon \\ \epsilon & 0.01 & 0.2 \\ \epsilon & 0.05 & 1 \end{pmatrix} \qquad \beta^R \sim \epsilon \qquad (\,\beta^\dagger \beta \neq 1\,)$$

1): non-minimal matter content (mixing with heavy fermions) [Calibbi, Crivellin, Li 1709.00692]

2): non-universal gauge interactions [Bordone, Cornella, Fuentes-Martin, Isidori 1712.01368]

$$(422)^3 \qquad \sum_{i=1,2,3} \frac{g_4^i}{\sqrt{2}} \overline{Q}^i \gamma^\mu L^i U_\mu^i \xrightarrow[m_{U_1} \gg m_{U_2} \gg m_{U_3}]{} \beta^{LO} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

🙂 flavour hierarchies

🙁 neutrino masses [Greljo, Stefanek 1802.04274]

Beyond minimal PS

- We look for something like

$$\beta^L \sim \begin{pmatrix} \epsilon & \epsilon & \epsilon \\ \epsilon & 0.01 & 0.2 \\ \epsilon & 0.05 & 1 \end{pmatrix} \qquad \beta^R \sim \epsilon \qquad (\, \beta^\dagger \beta \neq 1 \,)$$

1): non-minimal matter content (mixing with heavy fermions) [Calibbi, Crivellin, Li 1709.00692]

2): non-universal gauge interactions [Bordone, Cornella, Fuentes-Martin, Isidori 1712.01368]

3): non-minimal matter and gauge content (<u>4321 model</u>)

$$G = SU(4) \times SU(3)' \times SU(2)_L \times U(1)' \; + \text{heavy fermions}$$

[LDL, Greljo, Nardecchia 1708.08450,
See also Diaz, Schmaltz, Zhong 1706.05033,
for a similar constructions]

The '4321' model

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

The ‘4321’ model

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

<u>Gauge boson spectrum:</u>

$$G_{4321}/G_{\rm SM} = U + Z' + g'$$

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

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

Three TeV-scale massive vectors

$$g_s = \frac{g_4 g_3}{\sqrt{g_4^2+g_3^2}} \simeq g_3$$

$$g_Y = \frac{g_4 g_1}{\sqrt{g_4^2+\frac{2}{3}g_1^2}} \simeq g_1$$

The '4321' model

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

<u>Matter content:</u>

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	$\bar{4}$	3	1	$1/6$
Ω_1	$\bar{4}$	1	1	$-1/2$

Would-be SM fields

Vector-like fermions (Q'+L')

mix after SSB

SSB

The '4321' model

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

$$\underbrace{SU(4) \times SU(3)'}_{SU(3)_C}$$

Matter content:

LQ dominantly couples to 3rd generation LH fields [can satisfy Zürich's EFT criteria]

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
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$\ell_L'^i$	1	1	2	−1/2
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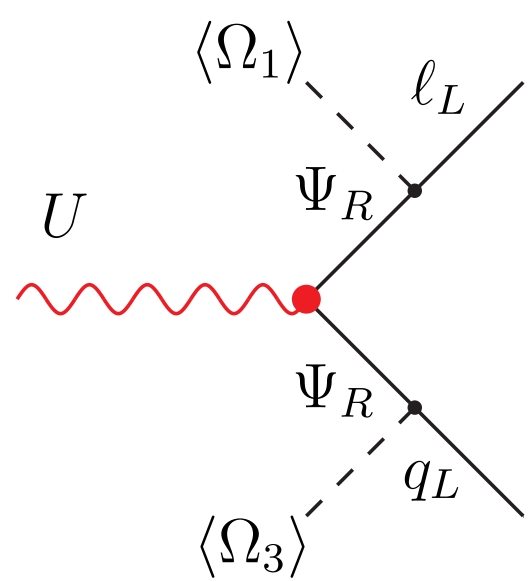

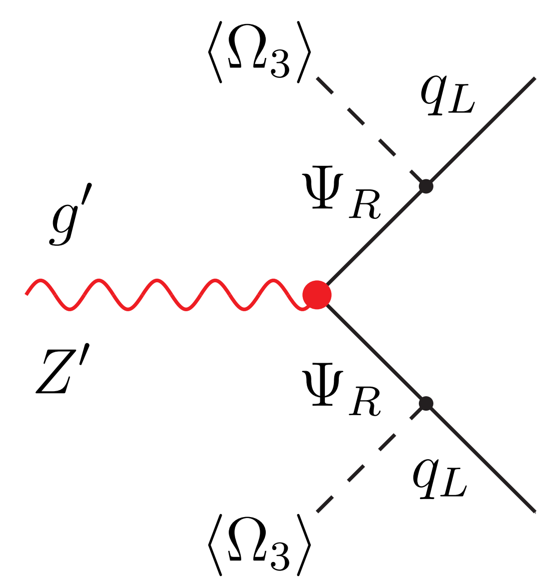

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- NP interpretations of B-anomalies still challenged by

1. Large quark-lepton transitions in 3-2 sector [mainly driven by R(D$^{(*)}$)] ✔
2. Severe constraints from quark-quark transitions [ΔF = 2, …] ?
3. Severe constraints from lepton-lepton transitions [LFV, …] ?
4. Absence of signals in direct searches @ high-pT ?

Flavour structure

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

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

$$\mathcal{L}_{\rm mix} = -\overline{q}'_L\,\lambda_q\,\Omega_3^T\Psi_R - \overline{\ell}'_L\,\lambda_\ell\,\Omega_1^T\Psi_R - \overline{\Psi}_L\hat{M}\Psi_R$$

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
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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	$-1/2$

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

Flavour structure

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

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

- 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

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

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

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

$$\xrightarrow{SU(2)_L} \; U(1)_{d+u} \times U(1)_{s+c} \times U(1)_{b+t} \xrightarrow{V} U(1)_B$$

- 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 $\neq$ 1]

Flavour structure

- We <u>assume</u>:

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

$$\mathcal{L}_{\mathrm{mix}} = -\overline{q}'_L\, \lambda_q\, \Omega_3^T \Psi_R - \overline{\ell}'_L\, \lambda_\ell\, \Omega_1^T \Psi_R - \overline{\Psi}_L \hat{M} \Psi_R$$

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

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

Flavour structure

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

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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 $U(2)_{q'}$

Flavour structure

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

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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

- We <u>assume</u>:

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

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

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

- Collective breaking:

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

1. $\lambda^\ell_1 = 0:\;\; U(1)_{q'_1+\ell'_1+\Psi_1} \to U(1)_{q'_1+\Psi_1} \times U(1)_{\ell'_1+\Psi_1}$ [no FV involving down and electrons]

2. Large effects in 3-2 lepto-quark transitions via W: $\quad i\overline{\Psi}_L \gamma^\mu D_\mu \Psi_L \supset \frac{g_4}{\sqrt{2}} U_\mu\, \overline{Q}_L \gamma^\mu W L_L$

An suggestive analogy*

321	4321
θ_C	θ_{LQ}
V	W
W^μ	U^μ
$q_L = \left(\begin{array}{c} u_L \\ V d_L \end{array} \right)$	$\Psi_L = \left(\begin{array}{c} Q_L \\ W L_L \end{array} \right)$
$Y_u,\, Y_d$	$\lambda_q,\, \lambda_\ell$
$SU(2)_L$	$SU(4)$
$U(1)_u \times U(1)_c \times U(1)_t$	$U(2)_{q'+\Psi} \times U(1)_{q'_3+\Psi_3}$
$U(1)_d \times U(1)_s \times U(1)_b$	$U(1)_{\ell'_1+\tilde{\Psi}_1} \times U(1)_{\ell'_2+\tilde{\Psi}_2} \times U(1)_{\ell'_3+\tilde{\Psi}_3}$
$U(1)_B$	$U(1)_{q'_1+\ell'_1+\Psi_1} \times U(1)_{q'+\ell'+\Psi}$
$u \to d$ 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 <u>accidental</u>, in 4321 <u>imposed</u> (still, helpful for understanding pheno)

Key phenomenological features

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

$$\mathcal{L}_U \supset \frac{g_4}{\sqrt{2}}\beta_{ij}\,\overline{q}^i_L\gamma^\mu\ell^j_L U_\mu \qquad\qquad \beta = \begin{pmatrix} 0 & 0 & 0 \\ 0 & c_{\theta_{LQ}} s_{12} s_{\mu_L} & s_{\theta_{LQ}} s_{12} s_{\tau_L} \\ 0 & -s_{\theta_{LQ}} s_{b_L} s_{\mu_L} & c_{\theta_{LQ}} s_{b_L} s_{\tau_L} \end{pmatrix}$$

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

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

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

we need: $\theta_{LQ} \sim \pi/4 \quad \theta_{\tau_L} \sim \pi/2 \quad \theta_{b_L} \sim \pi/2 \quad \theta_{12} \sim \mathcal{O}(1)$

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

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

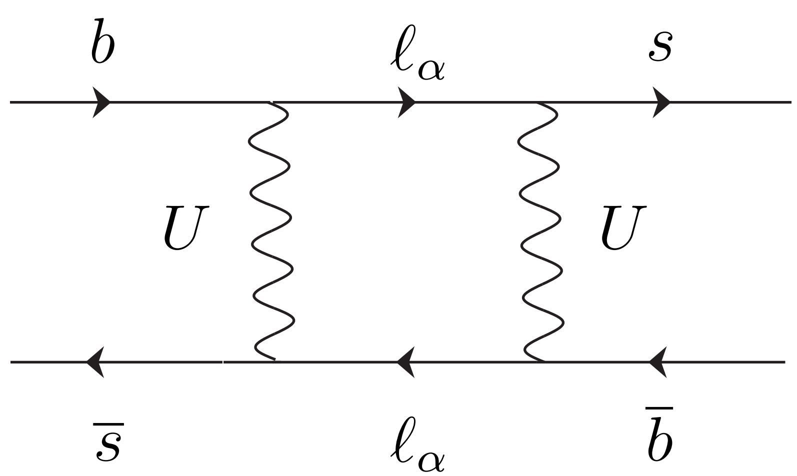
Key phenomenological features

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



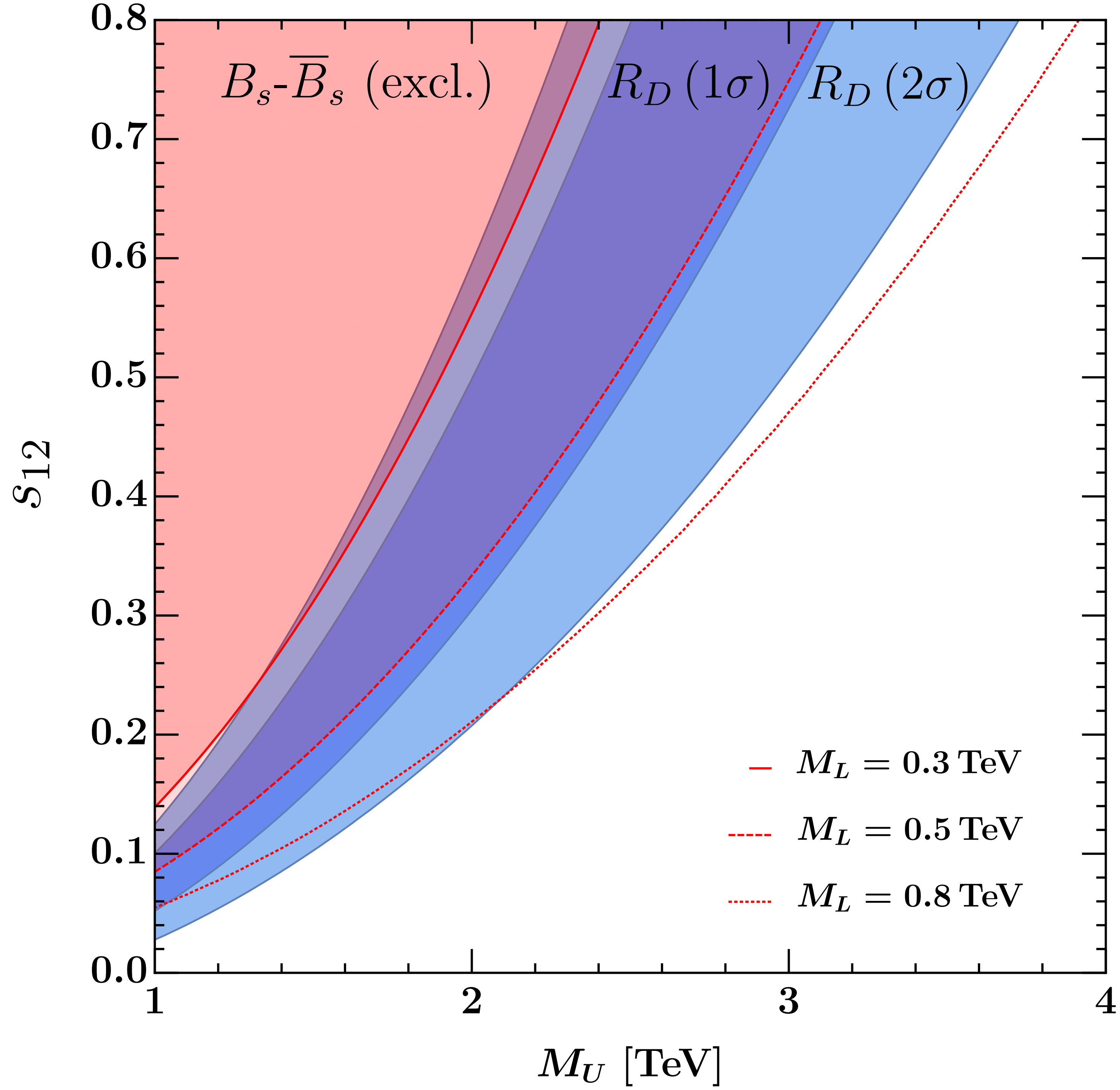
$$\mathcal{H}_{\rm eff}^{\rm NP} = -\frac{g_4^4}{128\pi^2 m_U^2} \left(\bar{b}_L \gamma^\mu s_L\right) \left(\bar{b}_L \gamma_\mu s_L\right) \sum_{\alpha,\,\beta} \lambda_\alpha \lambda_\beta F(x_\alpha, x_\beta)$$

$$\lambda_\alpha = (\mathcal{V}^\dagger)^*_{\alpha b} \mathcal{V}^\dagger_{\alpha s} \qquad x_\alpha = m_\alpha^2 / M_U^2$$

$\sum_\alpha \lambda_\alpha = 0$ ensures cancellation of quadratic divergencies + GIM-like suppression

$F(x_\alpha, x_\beta) \simeq \cancel{1} + x_\alpha + x_\beta + \ldots$ $\longrightarrow$ light lepton partners welcomed !

Key phenomenological features



Key phenomenological features

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5. Suppressed Z' and g' couplings to light generations

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

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\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}
$$

requires the phenomenological limit

$g_4 \gg g_3 \simeq g_s \gg g_1 \simeq g_Y$

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

5. Suppressed Z' and g' couplings to light generations

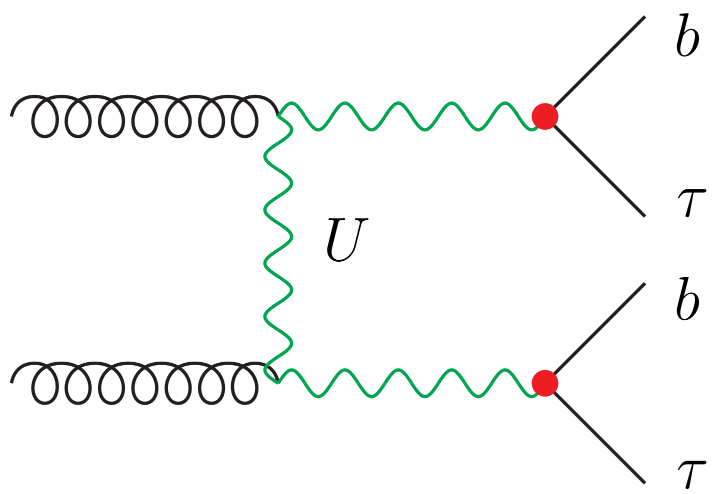
6. B and L accidental global symmetries as in the SM ($m_\nu = 0$)

$$\mathcal{O}_5 = \frac{1}{\Lambda_{\not{L}}} \ell' \ell' H H \qquad\qquad \Lambda_{\not{L}} \gg v$$

High-p$_T$ searches

- LQ pair production via QCD

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



$$\begin{cases} U \to b\tau^+, & \text{BR} = 50\ \% \\ U \to t\bar{\nu}, & \text{BR} = 50\ \% \end{cases}$$

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

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

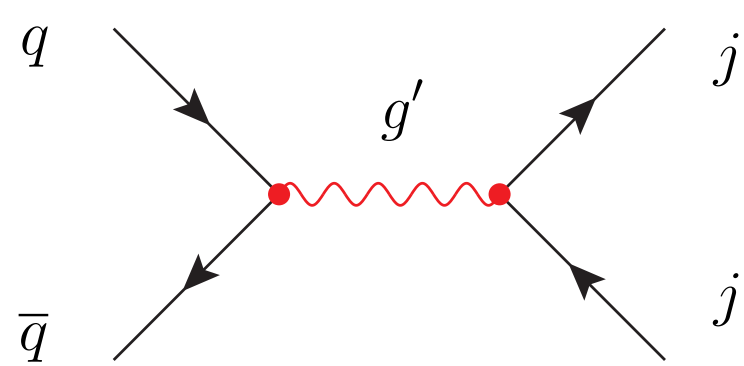
High-p$_T$ searches

- LQ pair production via QCD
- Z' Drell-Yan production naturally suppressed

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

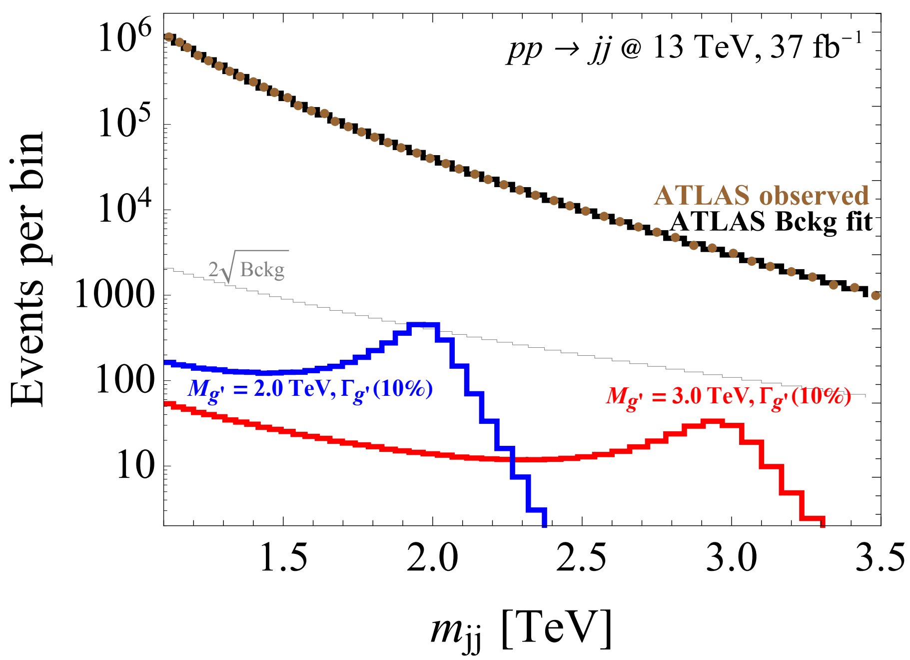
- g' resonant di-jet searches [ATLAS, 1703.09127]

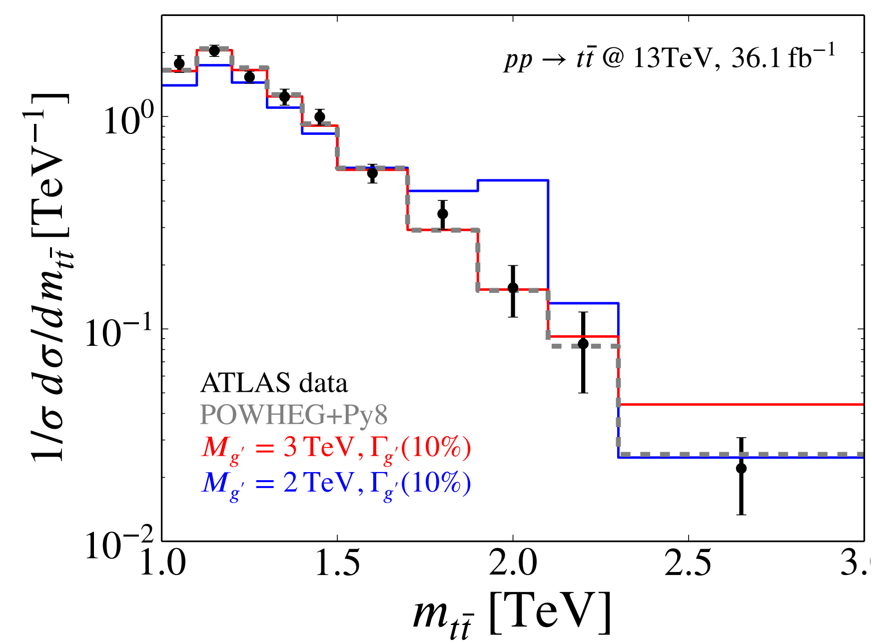
$$\sin\theta_{g'} = \frac{g_s}{g_4} \simeq 0.3 \quad \longrightarrow \quad \text{2 TeV coloron naively excluded}$$

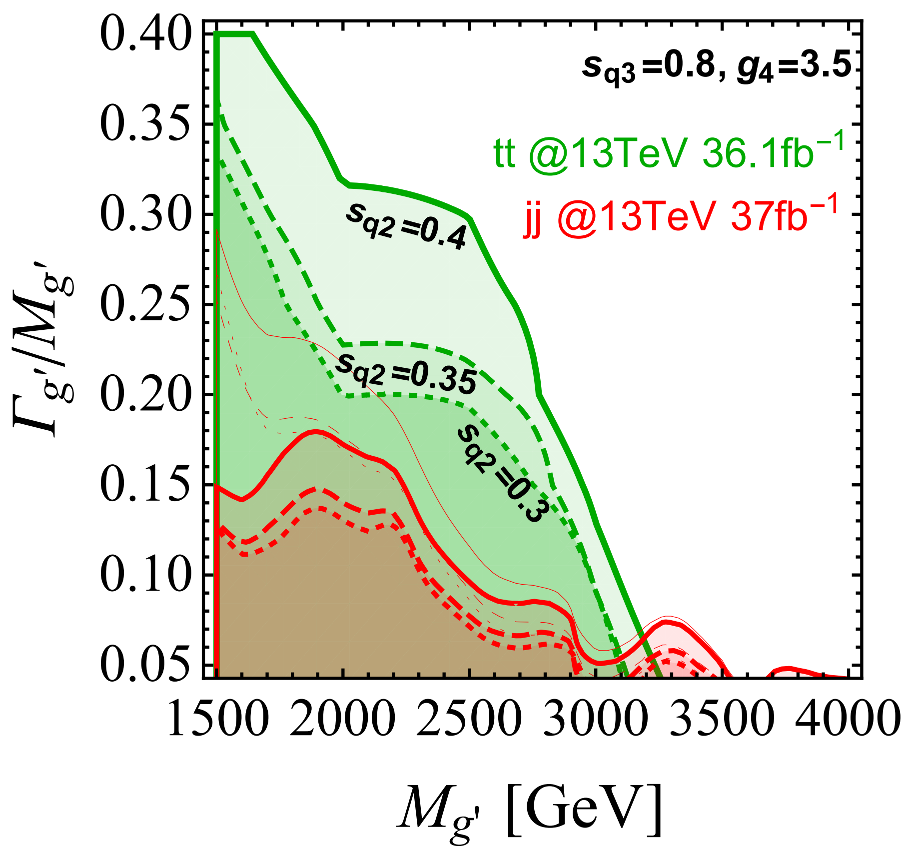


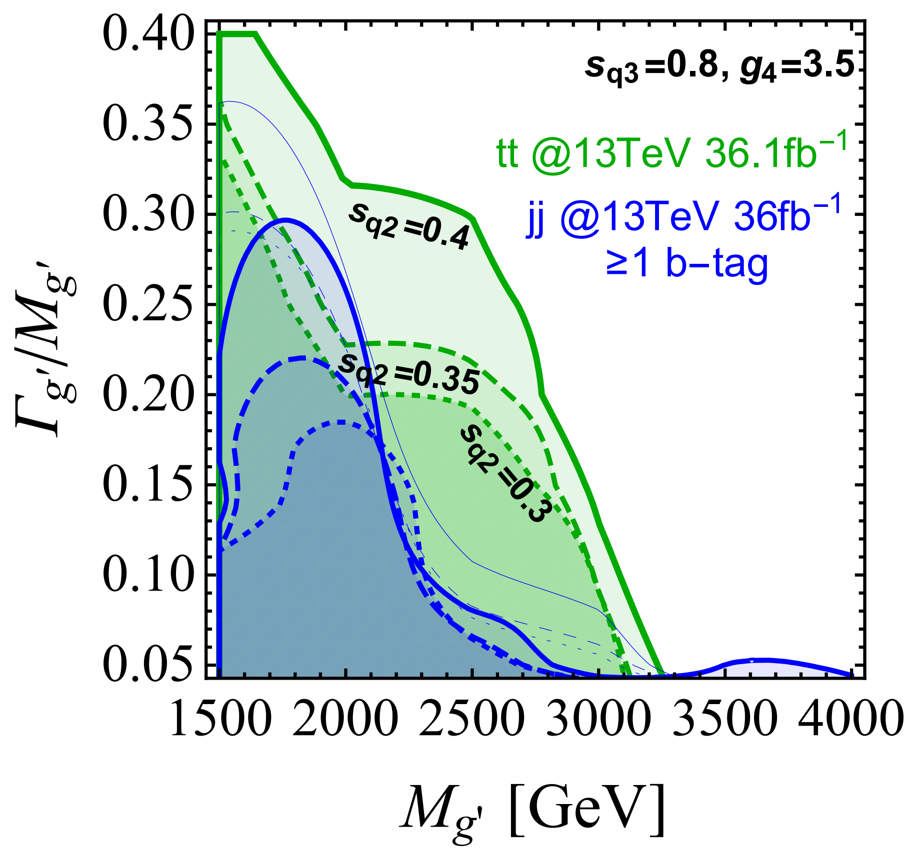
High-pT searches

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









Conclusions

1. We will know much more by ~ 2020 (LHCb + Belle II)

2. Early speculations point to TeV-scale vector leptoquark (R(D)+R(K) explanation)

   → who ordered that ?

3. In the meantime, lesson from UV complete models

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

Backup slides

A tale of scales

Anomaly	$\mathcal{O}$	FS_Q	FS_L	$\Lambda_A[\text{TeV}]$	$\lvert\Lambda_{\mathcal{O}}\rvert\,[\text{TeV}]$	$\Lambda_U[\text{TeV}]$	$M_\star[\text{TeV}]$
$b \to c\tau\bar{\nu}$	$Q_{23}L_{33}$	1	1	3.4	3.4	9.2	43
$b \to c\tau\bar{\nu}$	$Q_{33}L_{33}$	$\lvert V_{cb}\rvert$	1	3.4	0.7	1.9	8.7
$b \to s\mu\bar{\mu}$	$Q_{23}L_{22}$	1	1	31	31	84	390
$b \to s\mu\bar{\mu}$	$Q_{33}L_{22}$	$\lvert V_{ts}\rvert$	1	31	6.2	17	78
$b \to s\mu\bar{\mu}$	$Q_{33}L_{33}$	$\lvert V_{ts}\rvert$	$^\ddagger m_\mu/m_\tau$	31	1.5	4.1	19
$b \to s\mu\bar{\mu}$	$Q_{33}L_{33}$	$\lvert V_{ts}\rvert$	$^*(m_\mu/m_\tau)^2$	31	0.4	1.0	4.7

[LDL, Nardecchia 1706.01868]

- "Fermi constant" of the process [$SU(3)_C \times U(1)_{EM}$ invariant EFT]

$$\mathcal{L}_{\text{eff}} \supset -\frac{1}{\Lambda_{R_D}^2} 2\,\bar{c}_L\gamma_\mu b_L \bar{\tau}_L \gamma^\mu \nu_L + \frac{1}{\Lambda_{R_K}^2} \bar{s}_L\gamma_\mu b_L \bar{\mu}_L\gamma^\mu \mu_L$$

- fixed by anomaly

A tale of scales

Anomaly	$\mathcal{O}$	FS_Q	FS_L	$\Lambda_A[\text{TeV}]$	$\|\Lambda_{\mathcal{O}}\|\,[\text{TeV}]$	$\Lambda_U[\text{TeV}]$	$M_\star[\text{TeV}]$
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[LDL, Nardecchia 1706.01868]

- Scale of the SMEFT operator [SU(3)$_\text{C}$ × SU(2)$_\text{L}$ × U(1)$_\text{EM}$ invariant EFT]

$$\mathcal{L}_\text{SMEFT} \supset \frac{1}{\Lambda^2_{Q_{ij}L_{kl}}} \left(\overline{Q}_i \gamma^\mu \sigma^A Q_j\right) \left(\overline{L}_k \gamma_\mu \sigma^A L_l\right)$$

- can be effectively reduced by flavour structure, e.g.

$$Q^i = \begin{pmatrix} (V^\dagger_\text{CKM} u_L)^i \\ d^i_L \end{pmatrix} \qquad \overline{Q}_3 Q_3 \longrightarrow V_{cb}\, \overline{c}_L b_L \qquad \Longrightarrow \qquad \Lambda_{Q_{33}L_{33}} / \sqrt{|V_{cb}|} = \Lambda_{R_{D^{(*)}}}$$

A tale of scales

Anomaly	$\mathcal{O}$	FS_Q	FS_L	Λ_A[TeV]	$\lvert\Lambda_{\mathcal{O}}\rvert$ [TeV]	Λ_U[TeV]	$M_\star$[TeV]
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[LDL, Nardecchia 1706.01868]

- Scale of unitarity violation ($\sqrt{s} = \Lambda_U$ saturates pert. unitarity criterium)

$$\Lambda_U = \sqrt{\frac{4\pi}{\sqrt{3}}}\,|\Lambda_{Q_{ij}L_{kl}}|$$

- strongest bound from leading op. (effectively rescale by $\sqrt{\mathrm{FS}_Q \times \mathrm{FS}_L}$)

- correlation of the partial wave in SM-group space strengthens the bound by ~2

A tale of scales

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[LDL, Nardecchia 1706.01868]

- NDA mass scale in the strongly-coupled regime $|g_\star| = 4\pi$ [Manohar, Georgi NPB234 (1984)]

$$\frac{1}{|\Lambda_{\mathcal{O}}|} = \frac{4\pi}{M_\star}$$

- unitarity bound sets in earlier !

$$[\mathcal{L}] = [\hbar]/L^4$$

$$[M_\star] = L^{-1}$$

$$\mathcal{L}_{\mathrm{EFT}} = \frac{M_\star^4}{g_\star^2}\hat{\mathcal{L}}_{\mathrm{tree}}\left[\frac{\partial}{M_\star}, \frac{g_\star\Phi}{M_\star}, \frac{g_\star\Psi}{M_\star^{3/2}}\right] + \frac{g_\star^2\hbar}{16\pi^2}\frac{M_\star^4}{g_\star^2}\hat{\mathcal{L}}_{1-\mathrm{loop}}\left[\frac{\partial}{M_\star}, \frac{g_\star\Phi}{M_\star}, \frac{g_\star\Psi}{M_\star^{3/2}}\right] + \ldots$$

$$[g_\star] = [\hbar^{-1}]$$

A tale of scales

Anomaly	$\mathcal{O}$	FS_Q	FS_L	$\Lambda_A[\text{TeV}]$	$\lvert\Lambda_{\mathcal{O}}\rvert$ [TeV]	$\Lambda_U[\text{TeV}]$	$M_\star[\text{TeV}]$
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[LDL, Nardecchia 1706.01868]

- Most conservative unitarity bounds (no flavour enhancement)

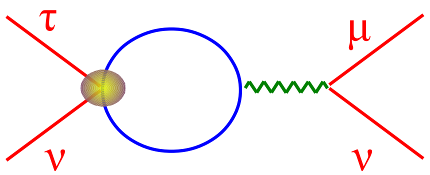
$$\sqrt{s}_{R_D} < 9.2 \text{ TeV} \qquad\qquad \sqrt{s}_{R_K} < 84 \text{ TeV}$$

→ no-loose theorem for HL/HE-LHC ?

EFT [details fit]

- 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 fit]

- 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]