4321 gauge model for B-anomalies

CrossTalk Workshop: Flavour anomalies

Vrije Universiteit Brussel - 29.03.2018

Luca Di Luzio

[Based on:
LDL, Nardecchia 1706.01868
LDL, Greljo, Nardecchia, 1708.08450
LDL, Kirk, Lenz 1712.06572
LDL, Fuentes-Martin, Greljo, Nardecchia, Renner - work in progress]

Outline

1. Review of "B-anomalies"

   - charged currents

   - neutral currents

2. Combined explanations

   - EFT

   - Simplified models

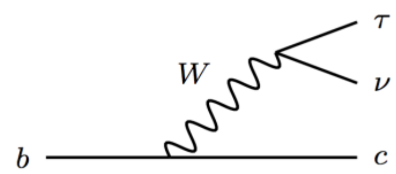
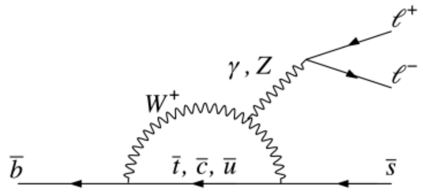
   - UV completions → 4321 model

Part-I

Review of "B-anomalies"

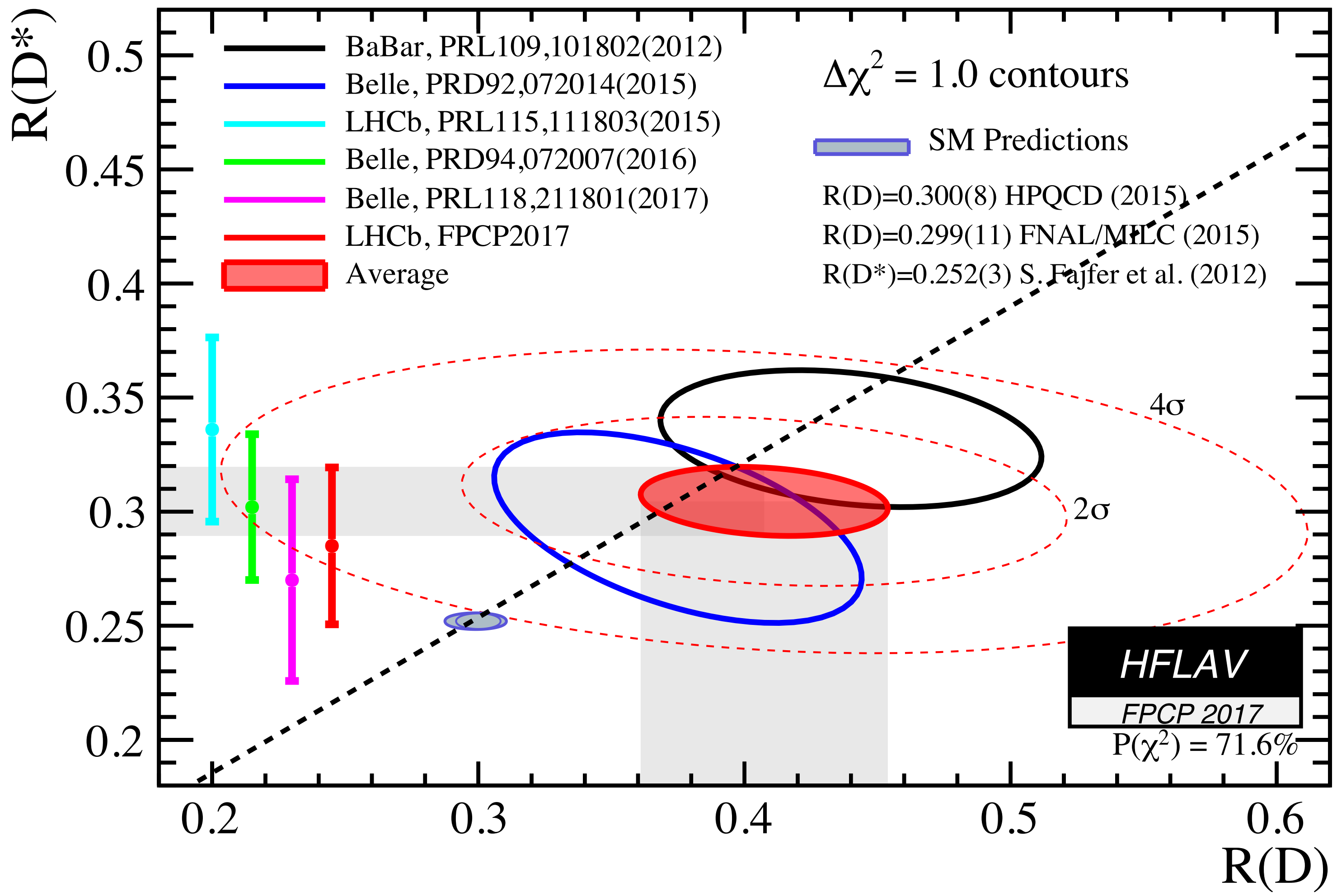
"B-anomalies"

- A seemingly coherent pattern of SM deviations building up since ~ 2013

	$b \to c\tau\nu$	$b \to s\mu\mu$
		
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 currents - R(D) & R(D*)

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



- SM prediction quite robust
- Deviation seen in 3 exp. in a consistent way, combined significance ~ 4**σ**
- R(D) and R(D*) point to constructive interference (+30%) with SM amplitude
- Suggests NP in LH tau currents (NP in e/mu and RH/scalar amplitudes disfavoured)

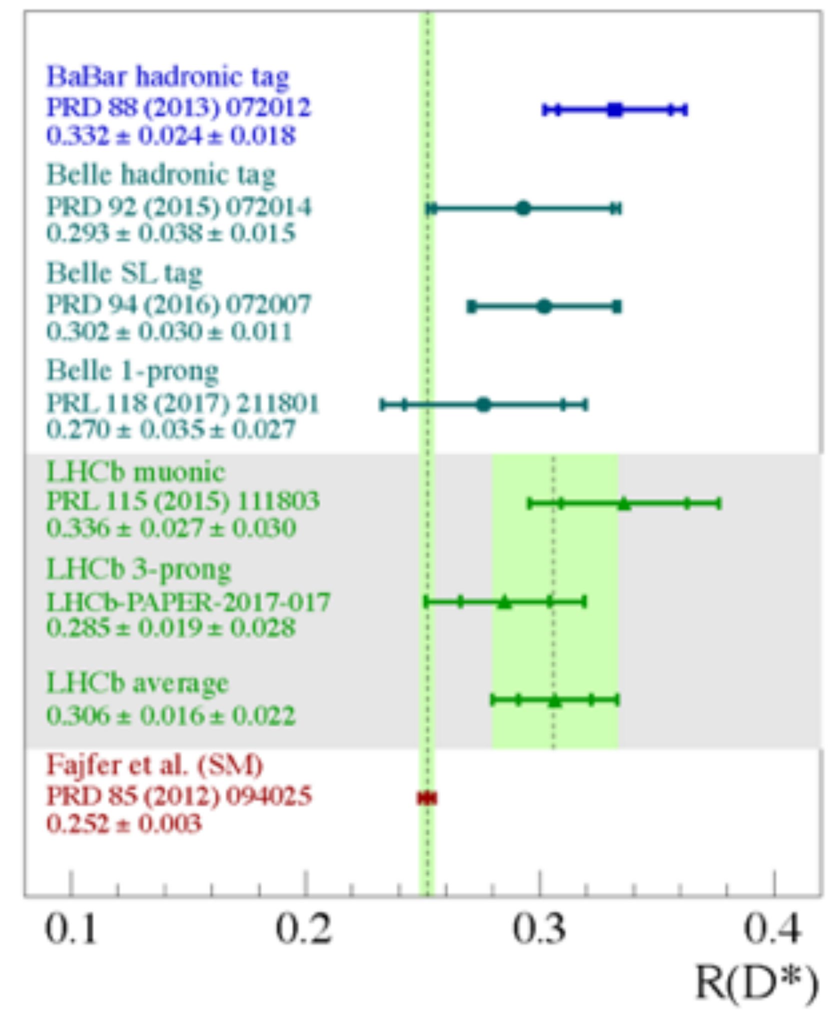
Charged currents - R(D) & R(D*)

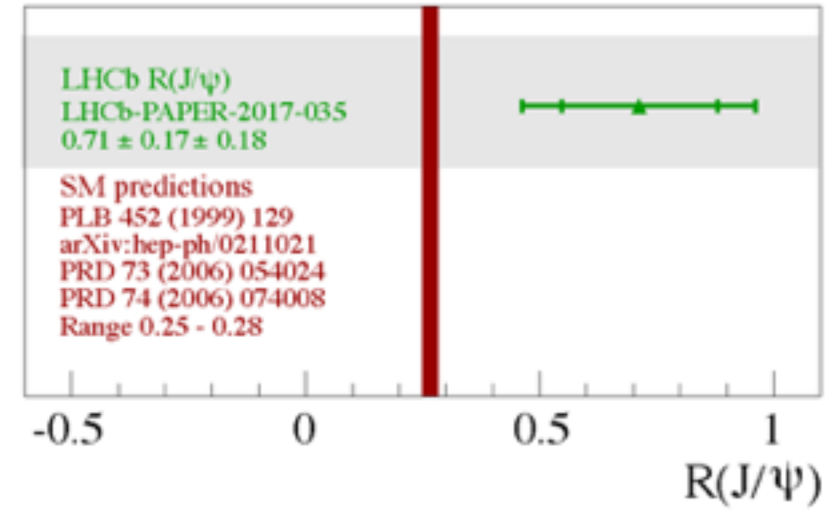
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\overline{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\overline{\nu})}$$

- Recently (as of Sept 2017):

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

~ 2**σ** above the SM

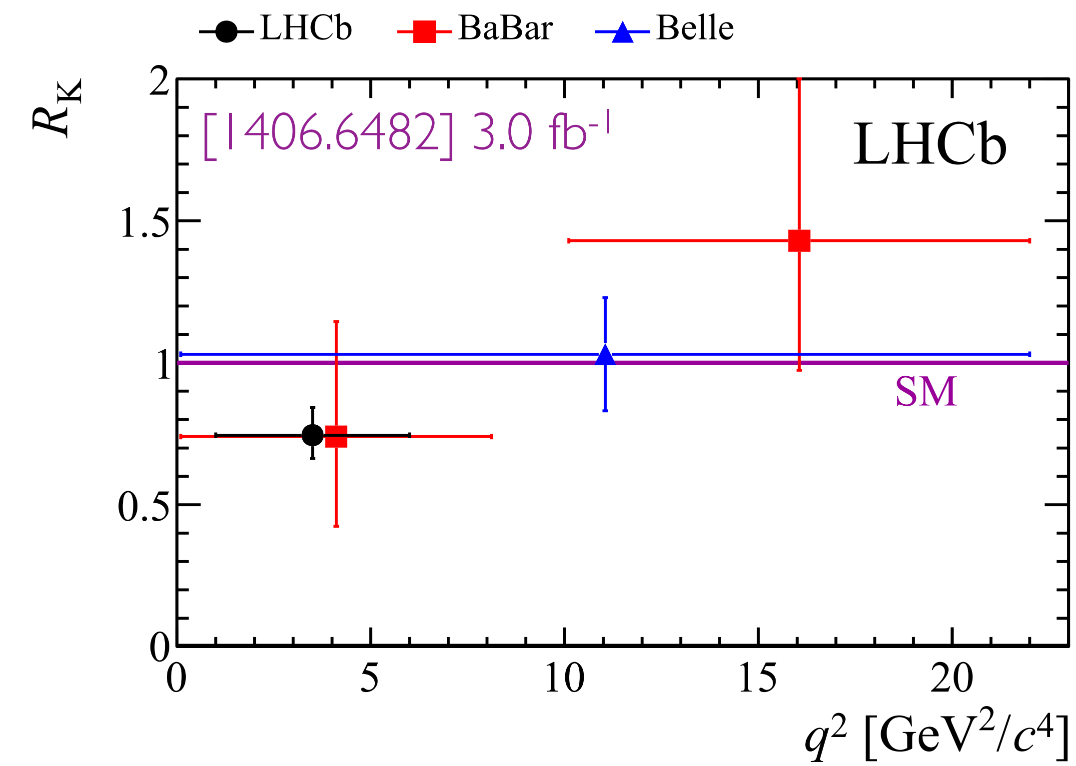


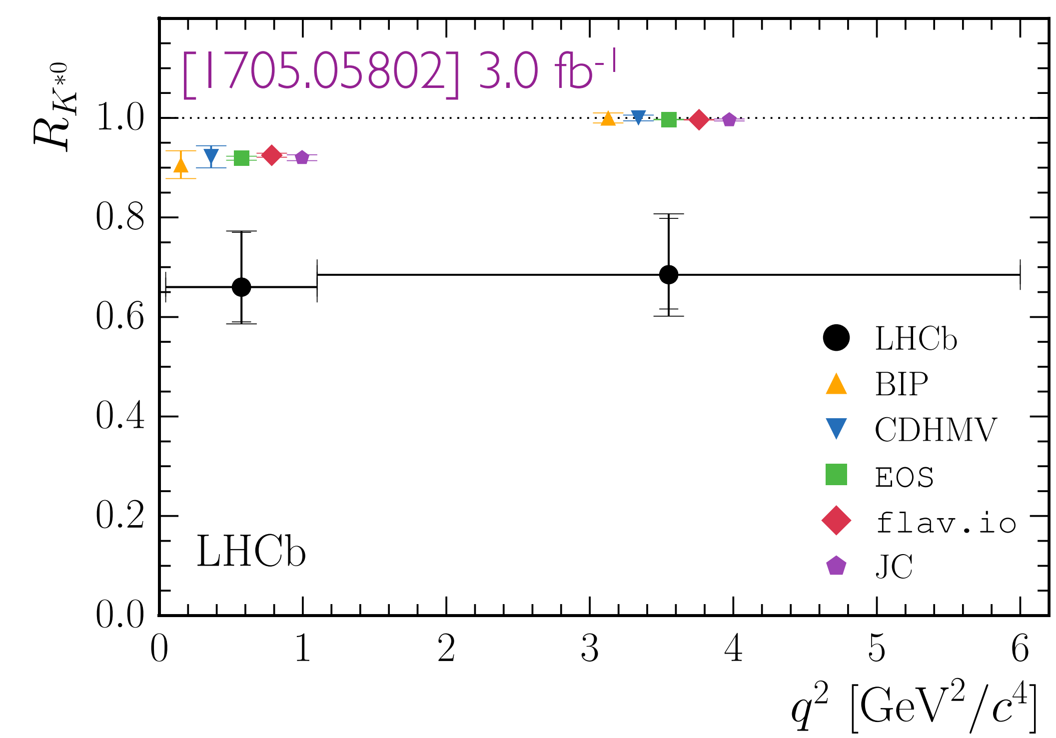


Neutral currents - R(K) & R(K*)

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

- SM prediction = 1 ± O(1%) [1406.6482]
- Combined significance ~ 4σ



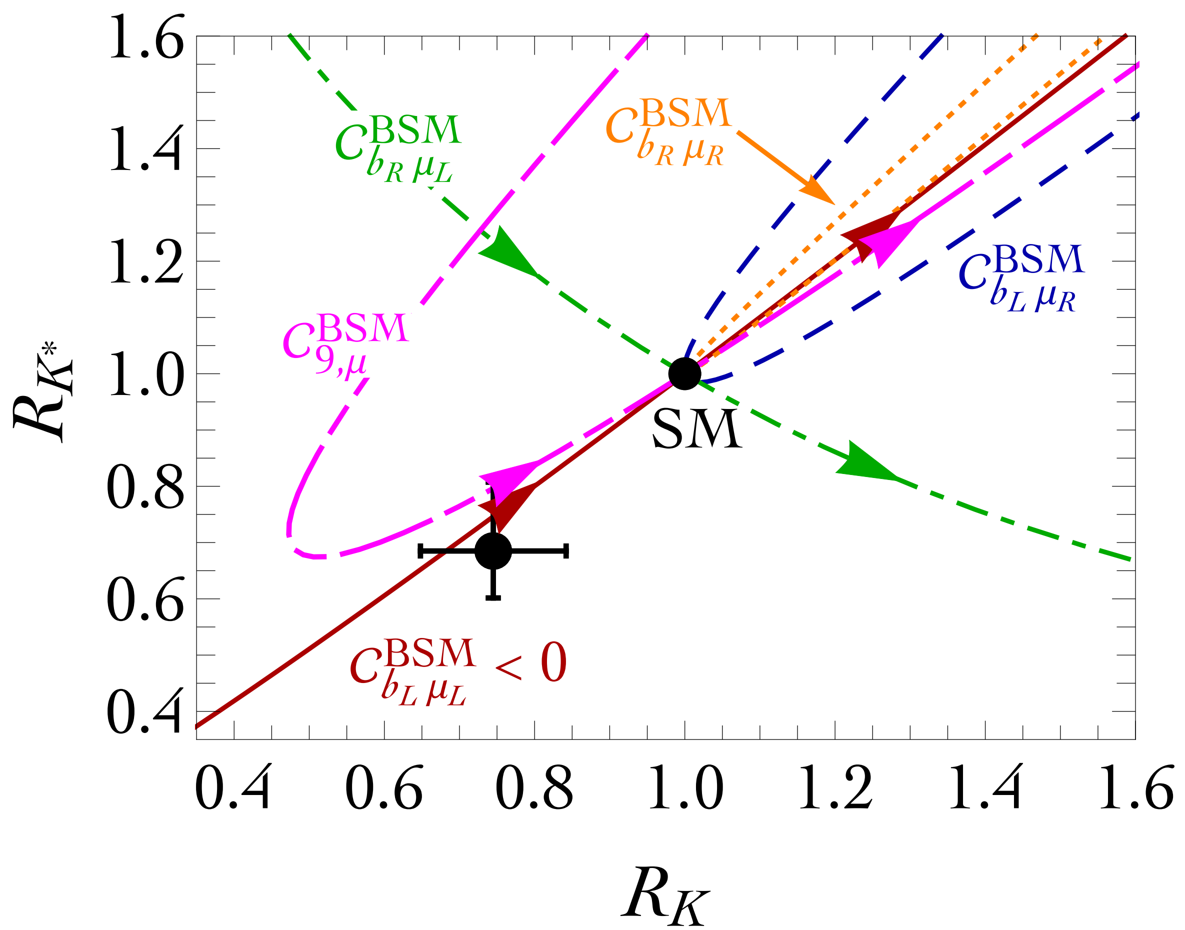


Neutral currents - R(K) & R(K*)

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

$$R_{K^*} \simeq R_K - 4p \frac{\mathrm{Re}\, C^{\mathrm{BSM}}_{b_R(\mu-e)_L}}{C^{\mathrm{SM}}_{b_L\mu_L}}$$

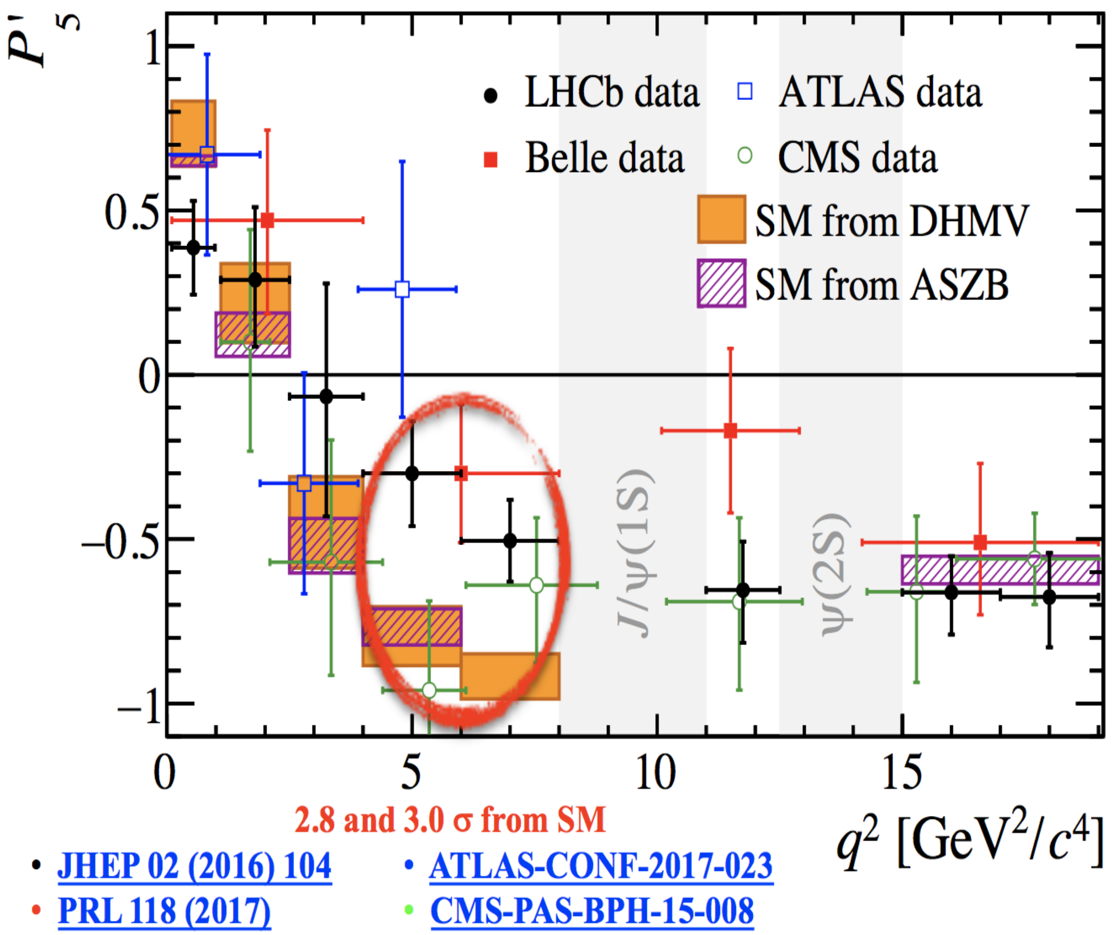
[D'Amico et al, 1704.05438]

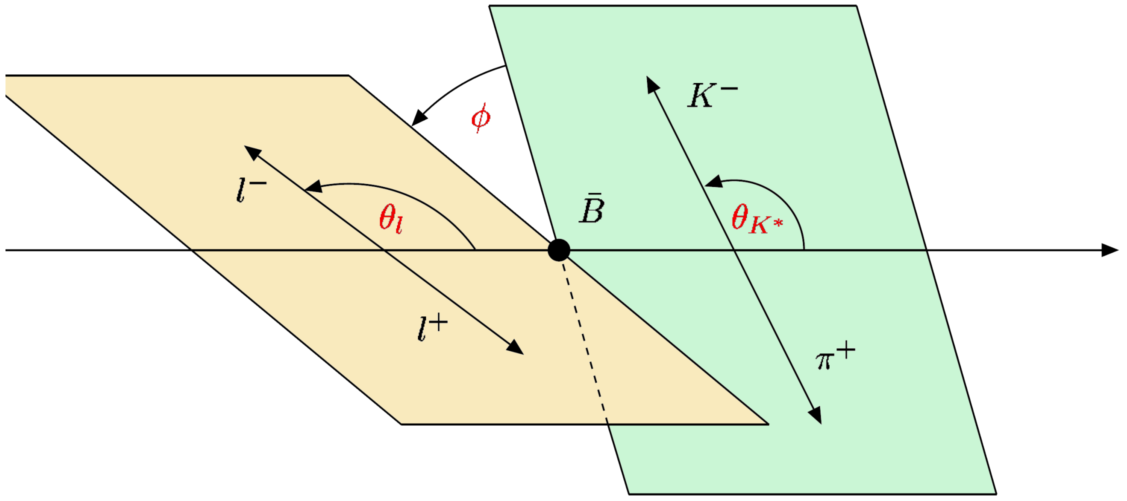


- NP in muons requires destructive interference with the SM (-15%)
- RH currents in quark sector disfavoured (predict wrong correlation)
- NP in electrons possible, but cannot explain anomalies in $b \to s\mu\mu$ angular observables

Neutral currents - P'5 et al

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





$$P'_5 \; : \; \frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi}$$

[Descotes-Genon, Matias, Ramon, Virto 1207.2753]

*Hadronic uncertainties potentially large

[See e.g. Chiuchini et al, 1512.07157]

+ other low BR w.r.t. the SM ($B_S^0 \to \phi\mu^+\mu^-$)

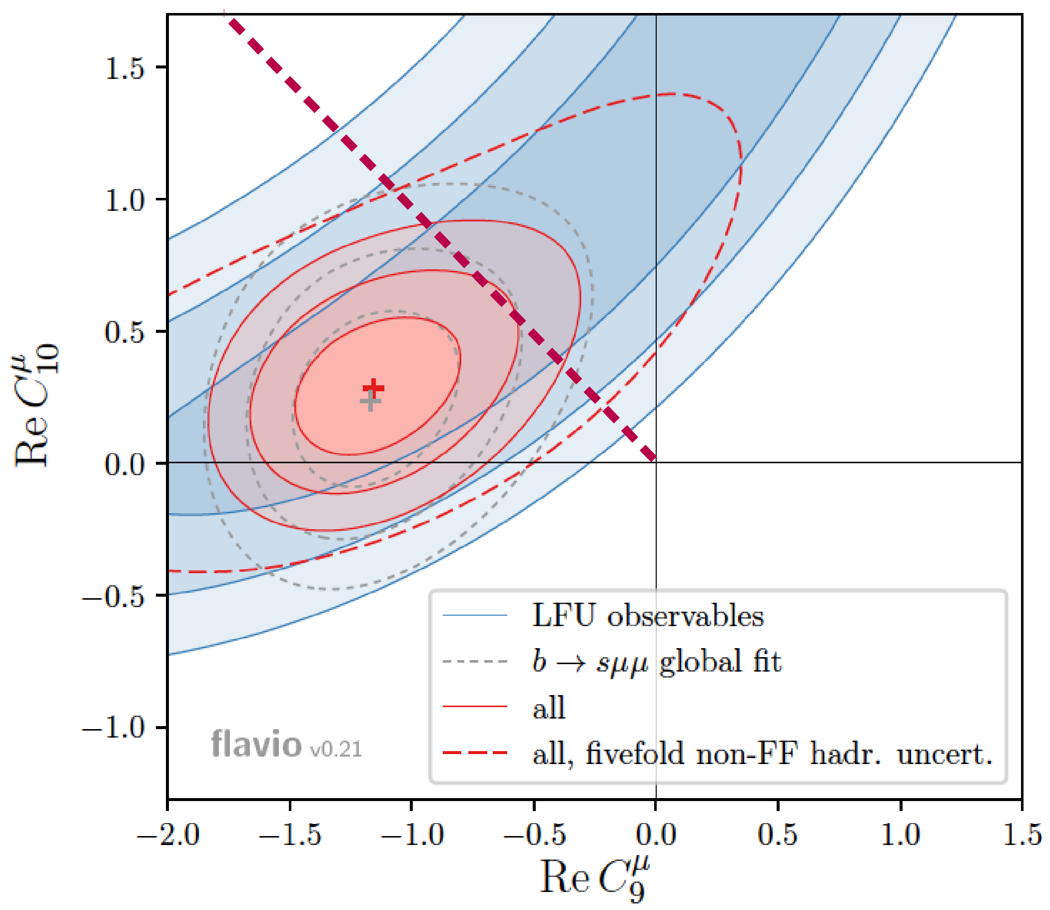
Neutral currents - global fits

- Effects well-described by NP in $b \to s\mu\mu$ (explains also angular distributions, etc.)

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

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

Altmannshofer, Stangl, Straub '17



Part-II

Combined explanations

EFT [general considerations]

- SU(2)$_L$ triplet operator (combined explanation 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, …]

EFT [general considerations]

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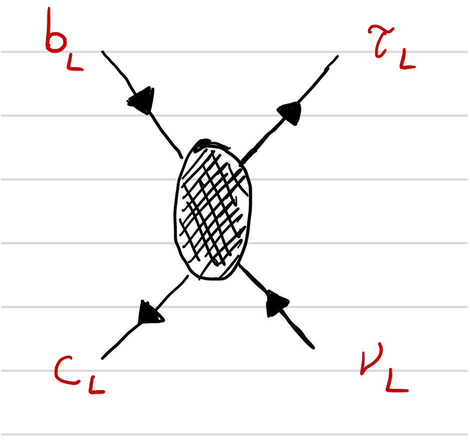
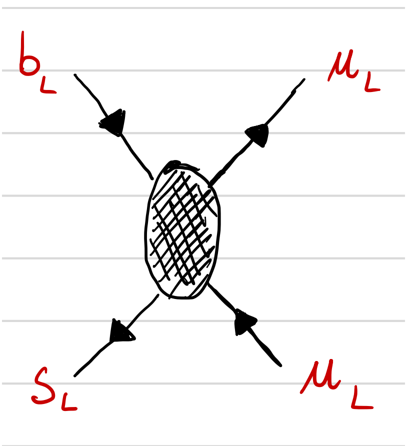
$$\frac{\lambda^q_{ij}\lambda^\ell_{kl}}{\Lambda^2}(\overline{Q}^i_L\sigma^a\gamma_\mu Q^j_L)(\overline{L}^k_L\sigma^a\gamma^\mu L^l_L) \supset -\frac{1}{\Lambda^2_{R_D}} 2\,\overline{c}_L\gamma^\mu b_L\overline{\tau}_L\gamma_\mu\nu_L + \frac{1}{\Lambda^2_{R_K}}\overline{s}_L\gamma^\mu b_L\overline{\mu}_L\gamma_\mu\mu_L$$





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

what is the scale of NP ? (energy/coupling/mass ambiguity: $1/\Lambda^2 = g^2/M^2$)

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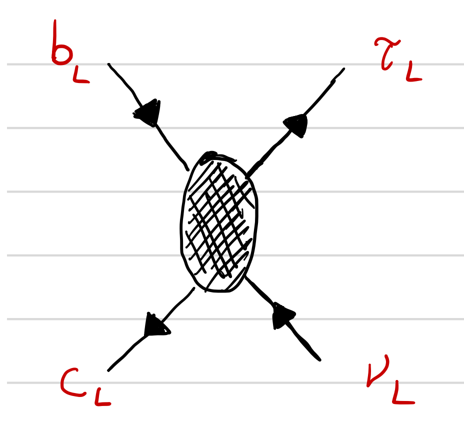

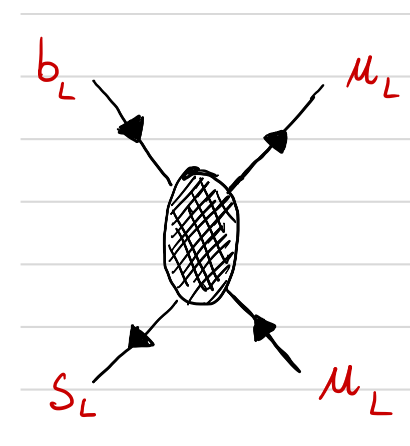

$$\Lambda_{R_D} = 3.4 \text{ TeV} \qquad \ll \qquad \Lambda_{R_K} = 31 \text{ TeV}$$

- Perturbative unitarity bound from 2 → 2 fermion scatterings $\quad a_{J=0} = \frac{\sqrt{3}}{8\pi}\frac{s}{\Lambda^2} < \frac{1}{2}$

$$\sqrt{s}_{R_D} < 9.2 \text{ TeV } (1.9 \text{ TeV}) \qquad \sqrt{s}_{R_K} < 84 \text{ TeV } (17 \text{ TeV})$$

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

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- Flavour structure:

1. large couplings in taus (compete with SM tree level)
2. sizable couplings in muons (compete with 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]

$$Q^{(3)}_L \sim q^{(b)}_L = \begin{pmatrix} V^*_{ib}u^i_L \\ b_L \end{pmatrix}$$

→ link to SM Yukawa pattern ?

EFT [general considerations]

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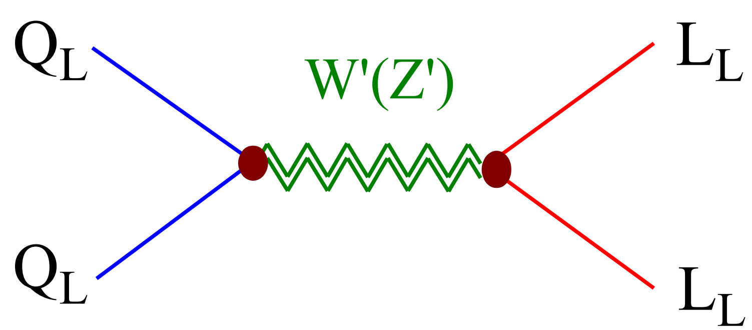
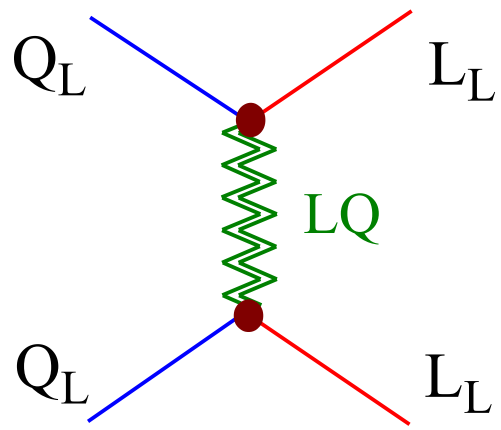
$$\frac{\lambda^q_{ij}\lambda^\ell_{kl}}{\Lambda^2}(\overline{Q}^i_L\sigma^a\gamma_\mu Q^j_L)(\overline{L}^k_L\sigma^a\gamma^\mu L^l_L)$$

- Tree-level mediators:

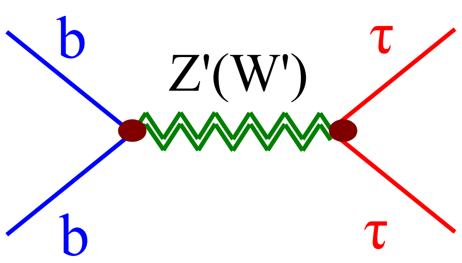


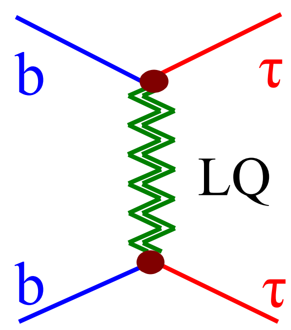


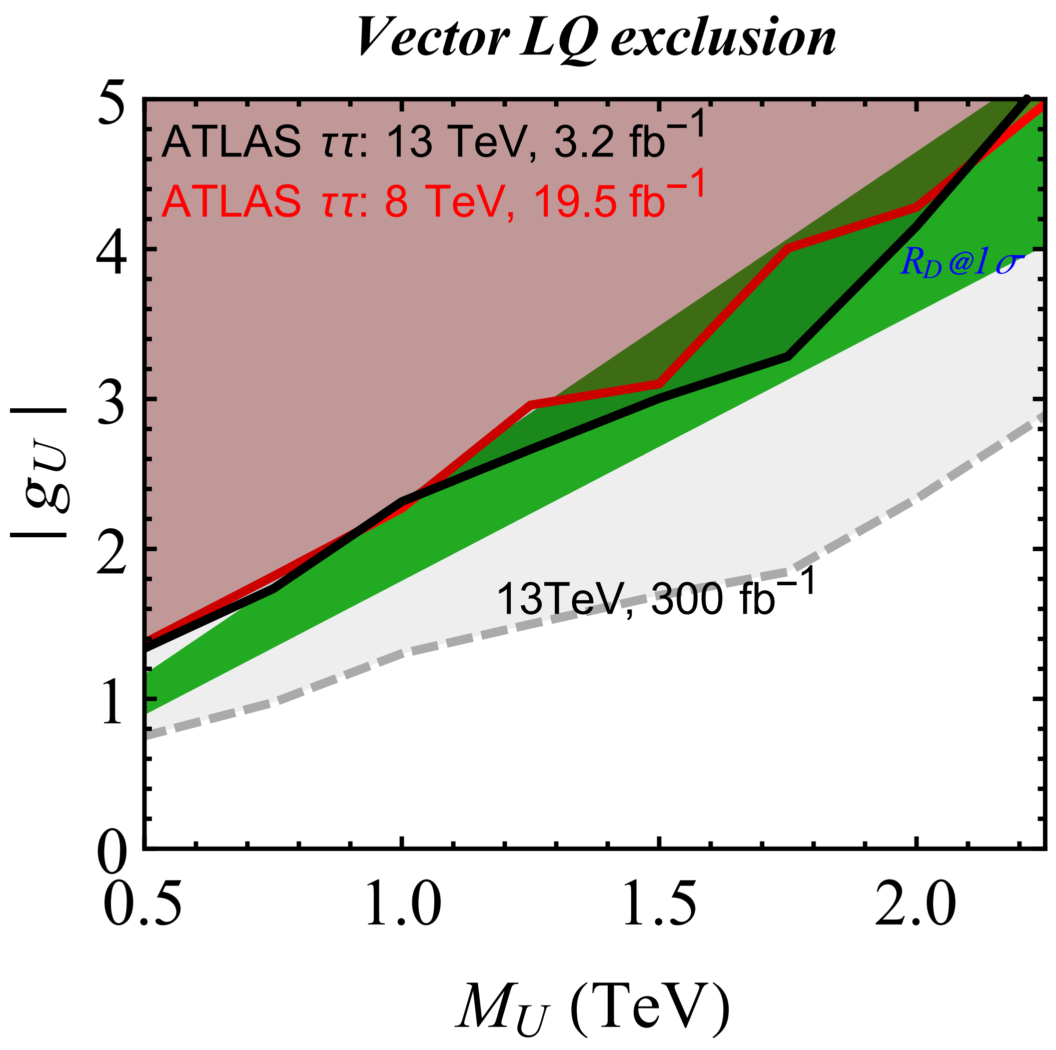
EFT [problems]

- Three main problems mainly driven by R(D)

1. High-p$_T$ constraints





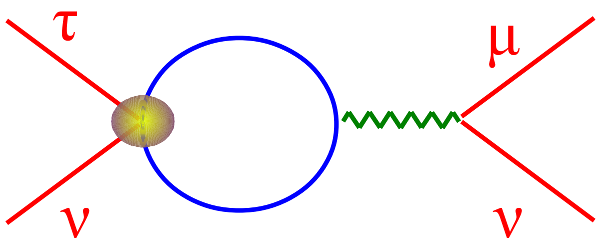


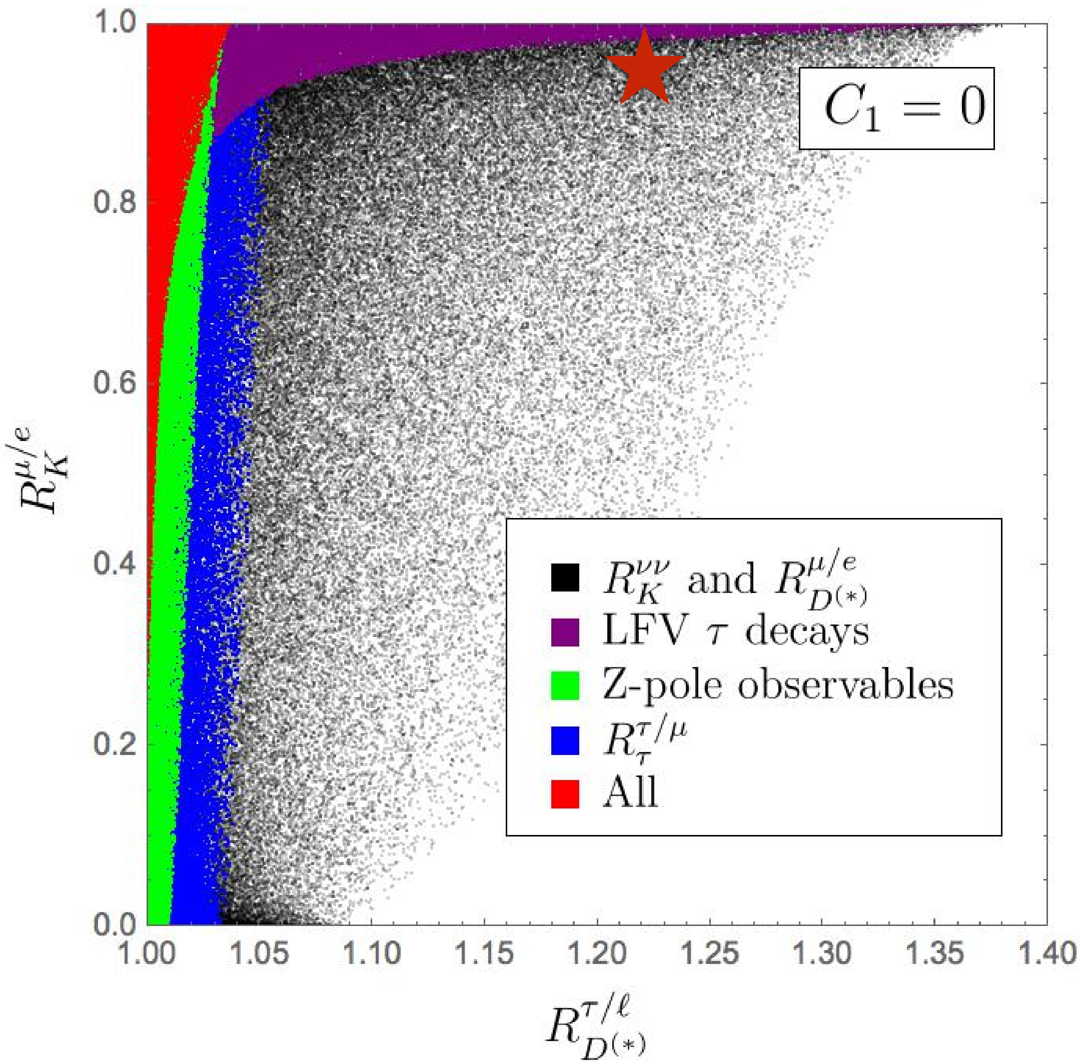
[Faroughy, Greljo, Kamenik 1609.07138]

EFT [problems]

- Three main problems mainly driven by R(D)

1. High-p_T constraints
2. Radiative constraints



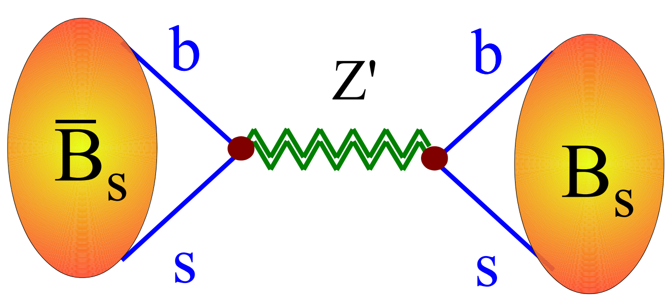


[Feruglio, Paradisi, Pattori 1606.00524, 1705.00929]

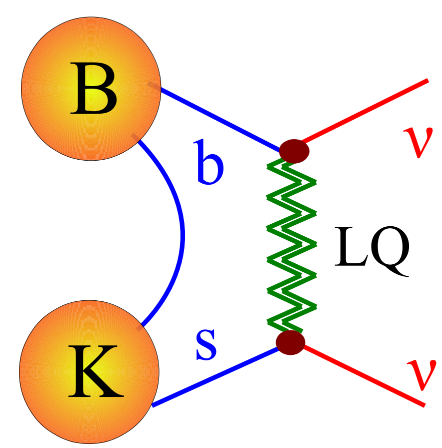
EFT [problems]

- 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)

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B_s-mixing

- Lattice results suggest a small discrepancy $\Delta M_s^{\text{SM}} > \Delta M_s^{\text{exp}} = (17.757 \pm 0.021)\ \text{ps}^{-1}$ (1.8 σ)

Source	$f_{B_s}\sqrt{\hat{B}}$	ΔM_s^{SM}
HPQCD14 [128]	(247 ± 12) MeV	$(16.2 \pm 1.7)\ \text{ps}^{-1}$
ETMC13 [129]	(262 ± 10) MeV	$(18.3 \pm 1.5)\ \text{ps}^{-1}$
HPQCD09 [130] = FLAG13 [131]	(266 ± 18) MeV	$(18.9 \pm 2.6)\ \text{ps}^{-1}$
FLAG17 [69]	$\mathbf{(274 \pm 8)}$ **MeV**	$\mathbf{(20.01 \pm 1.25)\ ps^{-1}}$
Fermilab16 [71]	(274.6 ± 8.8) MeV	$(20.1 \pm 1.5)\ \text{ps}^{-1}$
HQET-SR [76, 132]	(278^{+28}_{-24}) MeV	$(20.6^{+4.4}_{-3.4})\ \text{ps}^{-1}$
HPQCD06 [133]	(281 ± 20) MeV	$(21.0 \pm 3.0)\ \text{ps}^{-1}$
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[LDL, Kirk, Lenz 1712.06572]

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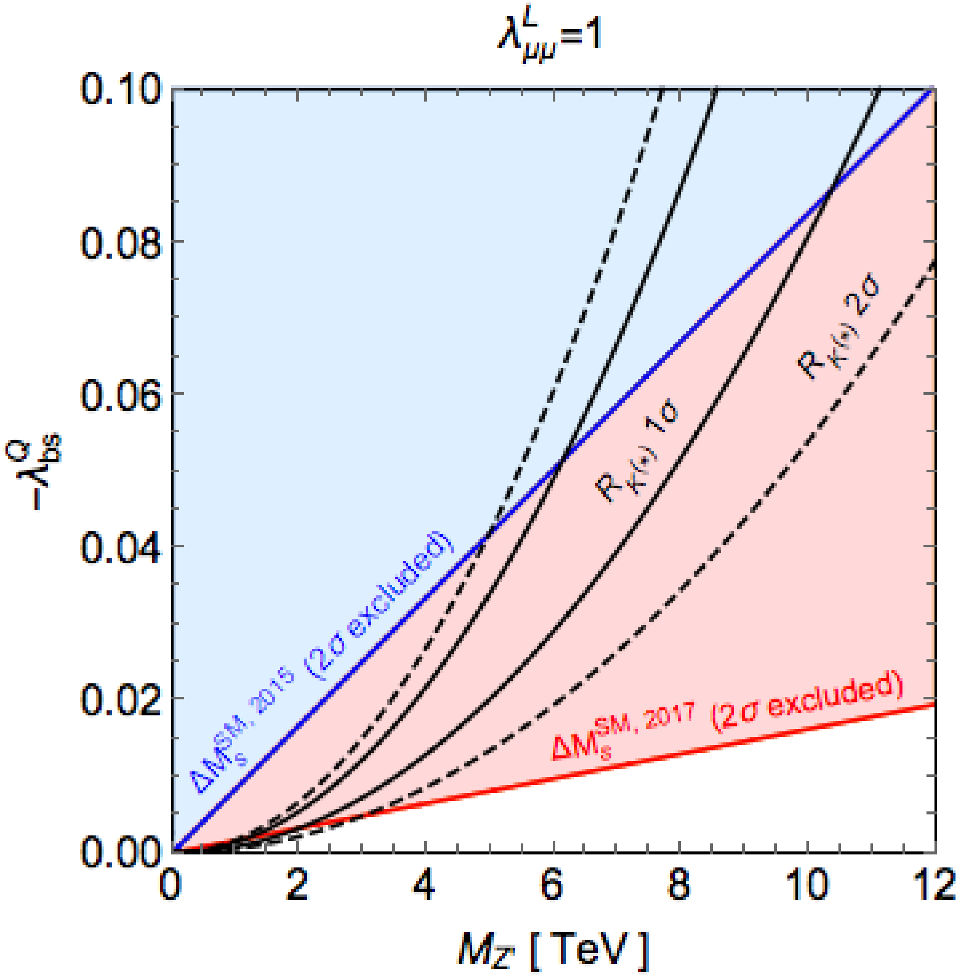
$$\frac{\Delta M_s^{\rm SM+NP}}{\Delta M_s^{\rm SM}} = \left|1 + \frac{\kappa}{\Lambda_{\rm NP}^2}\right|$$ if κ > 0 → $$\frac{\Lambda_{\rm NP}^{2017}}{\Lambda_{\rm NP}^{2015}} \simeq 5$$ (2 σ bound)



$$\mathcal{L}_{Z'} = \frac{1}{2} M_{Z'}^2 (Z'_\mu)^2 + \left(\lambda^Q_{ij}\, \overline{d}^i_L \gamma^\mu d^j_L + \lambda^L_{\alpha\beta}\, \overline{\ell}^\alpha_L \gamma^\mu \ell^\beta_L\right) Z'_\mu$$

severe impact on Z' models for $b \to s\mu\mu$ anomalies

[LDL, Kirk, Lenz 1712.06572]

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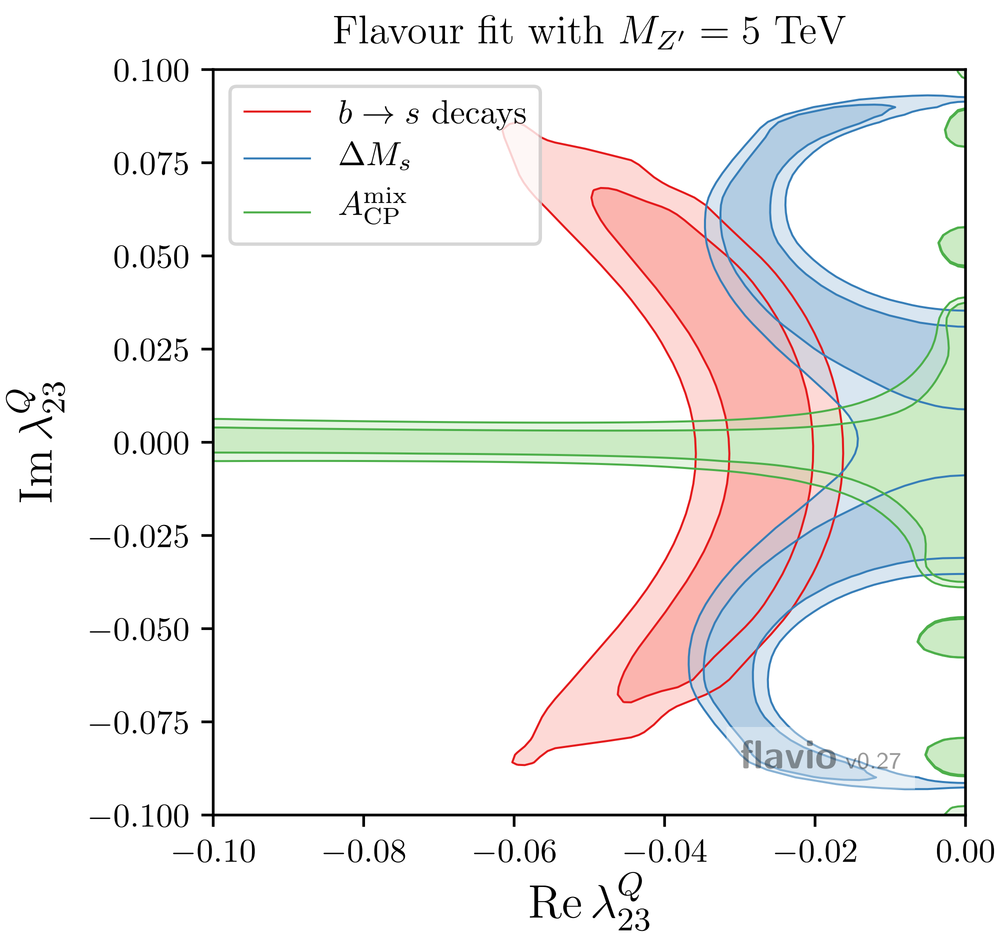

$$\mathcal{L}_{Z'} = \tfrac{1}{2} M_{Z'}^2 (Z'_\mu)^2 + \left(\lambda_{ij}^Q\, \overline{d}_L^i \gamma^\mu d_L^j + \lambda_{\alpha\beta}^L\, \overline{\ell}_L^\alpha \gamma^\mu \ell_L^\beta\right) Z'_\mu$$

Possible ways to obtain **κ** < 0 :

1) Imaginary coupling $\kappa \sim (\lambda_{bs}^Q)^2$

2) RH currents contamination $\kappa \sim \lambda_{bs}^Q \lambda_{bs}^{d_R}$

- looking forward for lattice updates !

[LDL, Kirk, Lenz 1712.06572]

}

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)

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

2. Deviation from 'pure-mixing' scenario

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

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

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[Zürich's guide for combined explanations, 1706.07808]

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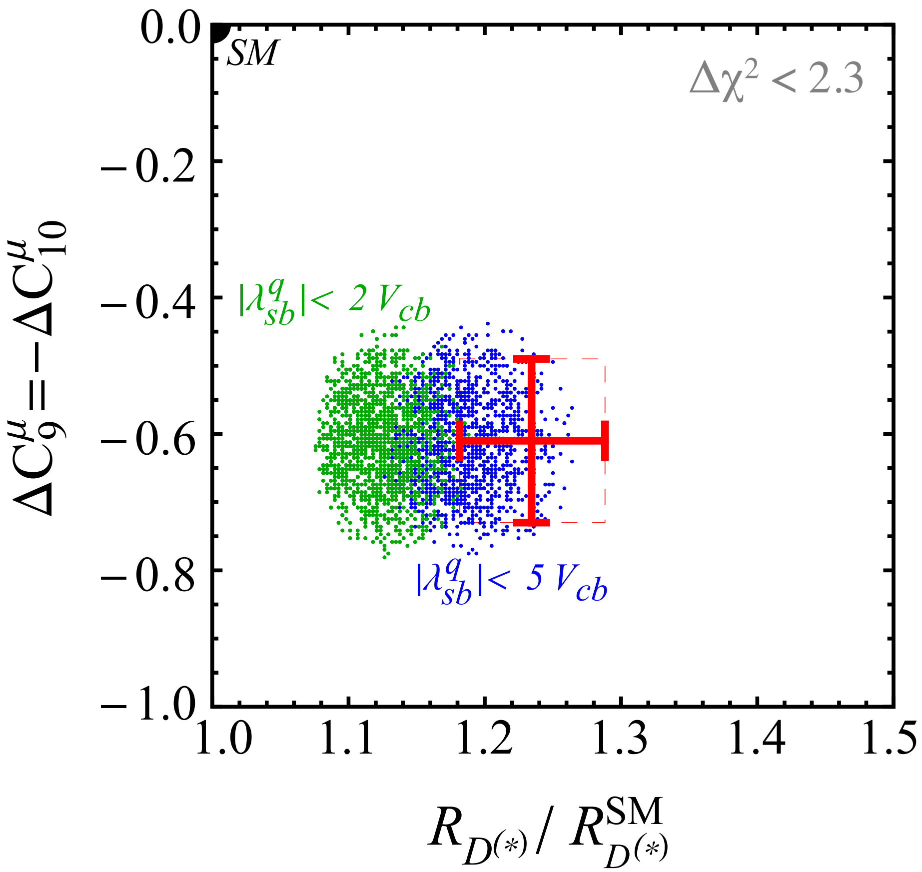


$\lambda^q_{sb} > \mathcal{O}(V_{cb})$ allows for larger NP scale

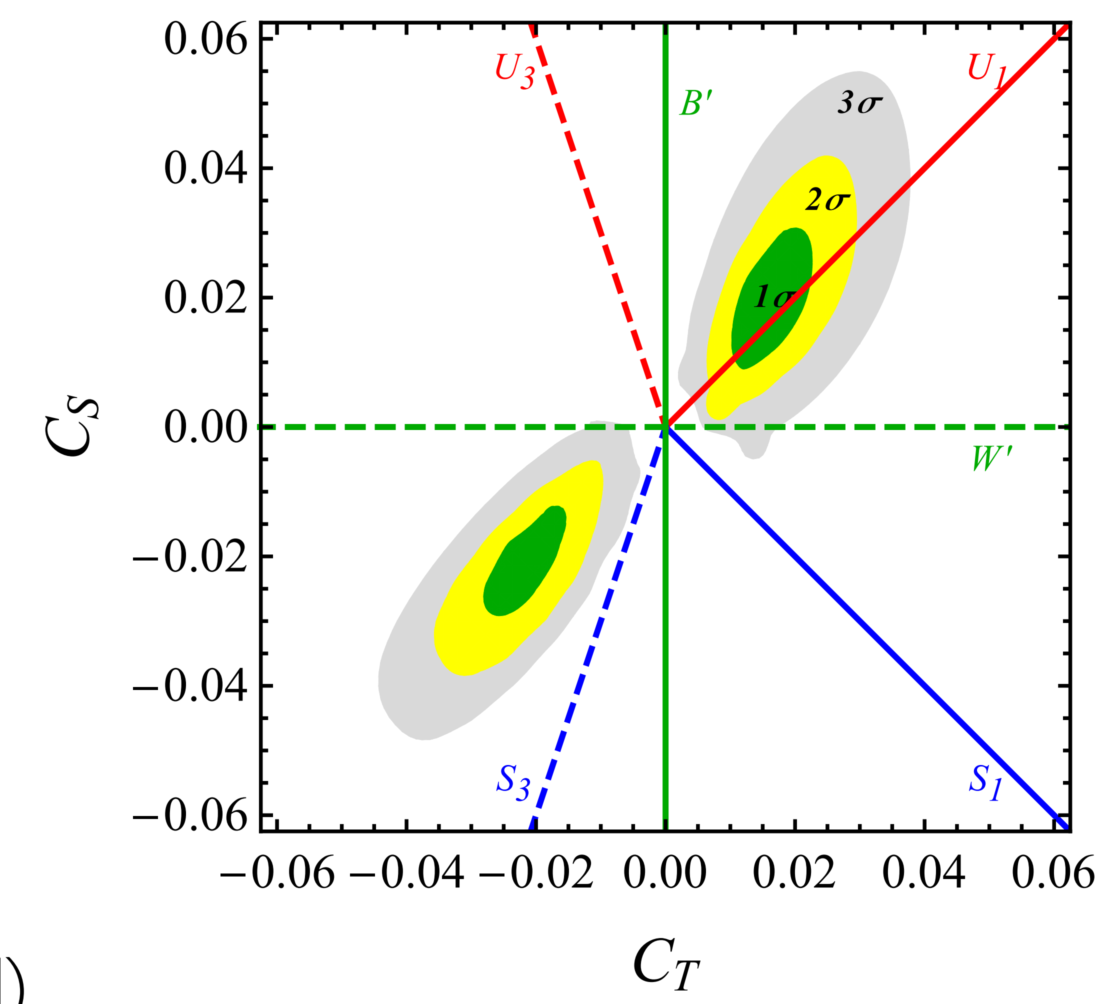
Simplified models

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

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



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]

- Ambitious program: 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: issue with direct searches + EWPTs

🙁 intrinsically non-calculable (e.g. divergent loop observables)

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

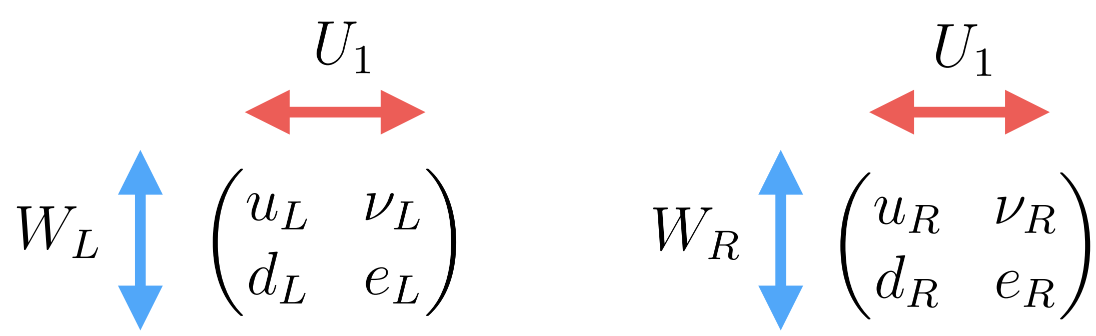
- An interesting option: minimal Pati-Salam (PS)

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

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

gauge boson of an extended gauge sector

🙂 hinted by SM chiral structure + everything's calculable



$$SU(4)_{PS} \supset SU(3)_C \times U(1)_{B-L}$$

$$Y = T^3_R + (B-L)/2$$

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)

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

$$\mathcal{L}_{PS} \supset \frac{g_4}{\sqrt{2}} \left(\overline{d}^i_L \delta_{ij} \gamma_\mu e^j_L + \overline{d}^i_R \delta_{ij} \gamma_\mu e^j_R \right) U_1^\mu$$

mass basis →

$$\frac{g_4}{\sqrt{2}} \left(\overline{d}^i_L \beta^L_{ij} \gamma_\mu e^j_L + \overline{d}^i_R \beta^R_{ij} \gamma_\mu e^j_R \right) U_1^\mu$$

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

UV completion: U$_1$ ~ (3,1,2/3)

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

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

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🙁 $M_{U_1} \gtrsim 86 \text{ TeV}$ 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 cannot explain B-anomalies

Beyond minimal PS

- We want something like

$$\beta^L \sim \begin{pmatrix} \epsilon & \epsilon & \epsilon \\ \epsilon & 0.02 & 0.2 \\ \epsilon & 0.06 & 1 \end{pmatrix} \qquad \beta^R \sim \epsilon \qquad (\, \beta^\dagger \beta \neq 1 \,)$$

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

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

$$\beta_{\rm LL}^\dagger \beta_{\rm LL} \neq 1$$

🙁 Z' direct searches

🙁 neutrino masses

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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]

🙂 low-energy effective theory similar to 4321 model

Beyond minimal PS

- We want something like

$$\beta^L \sim \begin{pmatrix} \epsilon & \epsilon & \epsilon \\ \epsilon & 0.02 & 0.2 \\ \epsilon & 0.06 & 1 \end{pmatrix} \qquad \beta^R \sim \epsilon \qquad (\,\beta^\dagger \beta \neq 1\,)$$

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

3): non-minimal matter and gauge content (4321 model) [LDL, Greljo, Nardecchia 1708.08450]

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

The '4321' model

[LDL, Greljo, Nardecchia 1708.08450. Inspired by Diaz, Schmaltz, Zhong 1706.05033, Georgi, Nakai 1606.05865]

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

<u>Embedding</u>:

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

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

<u>Gauge boson spectrum</u>:

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

$$M_{g'} \simeq \sqrt{2}\, M_U \qquad M_{Z'} \simeq \sqrt{\tfrac{3}{2}}\, M_U$$

$$\begin{pmatrix} (G^a_\mu)^\alpha_\beta & U^\alpha_\mu \\ (U^\alpha_\mu)^\dagger & Z'_\mu \end{pmatrix}$$

→ Structure of gauge symmetry breaking does not allow to decouple g' and Z'

The '4321' model

[LDL, Greljo, Nardecchia 1708.08450. Inspired by Diaz, Schmaltz, Zhong 1706.05033, Georgi, Nakai 1606.05865]

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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 (Q'+L')

} mix after SSB

SSB

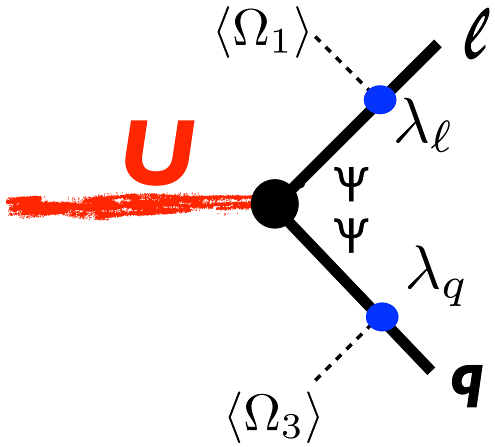
Yukawa sector:

$$\mathcal{L}_Y = -\,\overline{q}'_L\, Y_d\, H d'_R - \overline{q}'_L\, Y_u\, \tilde{H} u'_R - \overline{\ell}'_L\, Y_e\, H e'_R$$
$$- \,\overline{q}'_L\, \lambda_q\, \Omega_3^T \Psi_R - \overline{\ell}'_L\, \lambda_\ell\, \Omega_1^T \Psi_R - \overline{\Psi}_L\, M\, \Psi_R$$

Key phenomenological features

1. LQ couples dominantly 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
$d_R'^i$	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



$$\mathcal{L}_Y = -\,\overline{q}'_L\, Y_d\, H d'_R - \overline{q}'_L\, Y_u\, \tilde{H} u'_R - \overline{\ell}'_L\, Y_e\, H e'_R \\ -\,\overline{q}'_L\, \lambda_q\, \Omega_3^T \Psi_R - \overline{\ell}'_L\, \lambda_\ell\, \Omega_1^T \Psi_R - \overline{\Psi}_L\, M\, \Psi_R$$

Key phenomenological features

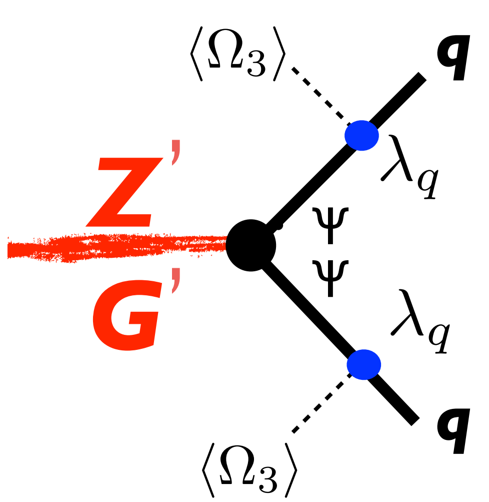
1. LQ couples dominantly to 3rd generation LH fields (can satisfy Zürich's EFT criteria)

2. Down-alignment to avoid tree-level FCNC in the down sector

$$\mathcal{M}_d = \begin{pmatrix} \frac{v}{\sqrt{2}} Y_d^{\rm diag} & \frac{v_3}{\sqrt{2}} \lambda_q \\ 0 & M^{\rm diag} \end{pmatrix} \qquad \lambda_q = \begin{pmatrix} \lambda_q^d & 0 & 0 \\ 0 & \lambda_q^s & 0 \\ 0 & 0 & \lambda_q^b \end{pmatrix}$$

$$\mathcal{M}_u = \begin{pmatrix} \frac{v}{\sqrt{2}} V^\dagger Y_u^{\rm diag} & \frac{v_3}{\sqrt{2}} \lambda_q \\ 0 & M^{\rm diag} \end{pmatrix}$$

→ CKM-induced D-mixing



$$\mathcal{L}_Y = -\,\overline{q}'_L\, Y_d\, H d'_R - \overline{q}'_L\, Y_u\, \tilde{H} u'_R - \overline{\ell}'_L\, Y_e\, H e'_R$$
$$-\,\overline{q}'_L\, \lambda_q\, \Omega_3^T \Psi_R - \overline{\ell}'_L\, \lambda_\ell\, \Omega_1^T \Psi_R - \overline{\Psi}_L\, M\, \Psi_R$$

Key phenomenological features

1. LQ couples dominantly to 3rd generation LH fields (can satisfy Zürich's EFT criteria)

2. Down-alignment to avoid tree-level FCNC in the down sector

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

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

Key phenomenological features

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& - \frac{1}{2} \frac{\sqrt{3}\, g_4 g_Y}{\sqrt{2}\, g_1} \left(\overline{L}'_L \gamma^\mu L'_L - \frac{2 g_1^2}{3 g_4^2}\, \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. LQ couples dominantly to 3rd generation LH fields (can satisfy Zürich's EFT criteria)

2. Down-alignment to avoid tree-level FCNC in the down sector

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

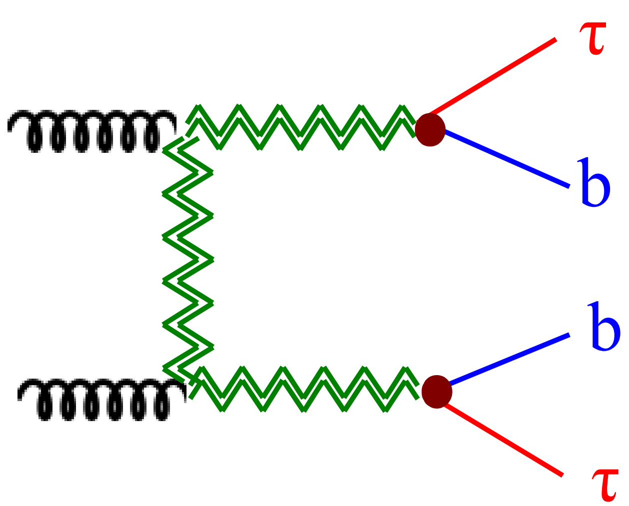
4. B and L accidental global symmetries as in the SM ($m_\nu = 0$)

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

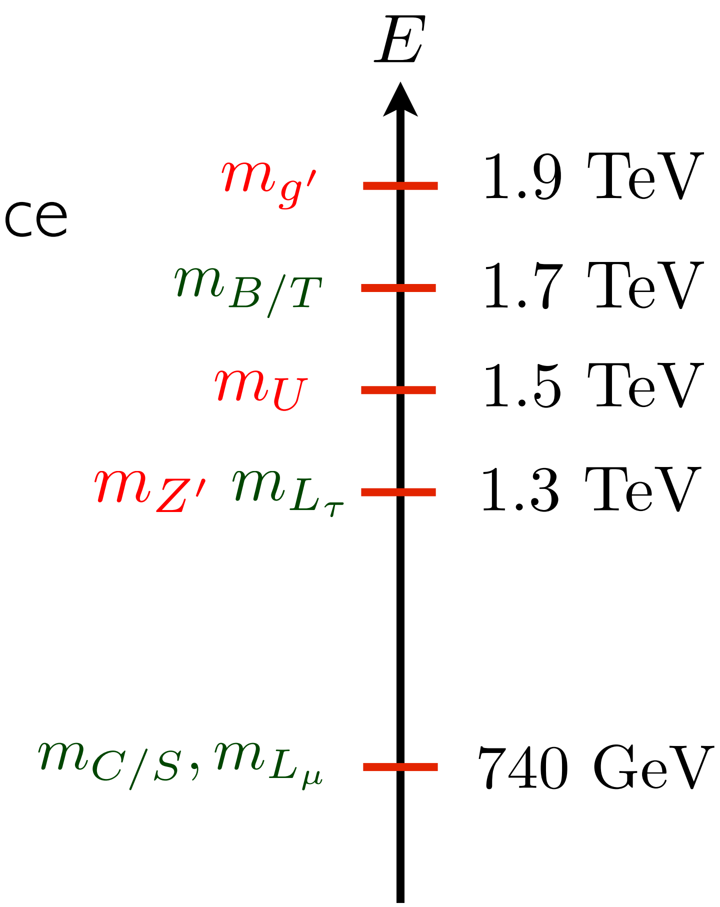
High-p_T searches

- 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: $M_{g'} \simeq \sqrt{2}\, M_U \quad M_{Z'} \simeq \sqrt{\frac{3}{2}}\, M_U$

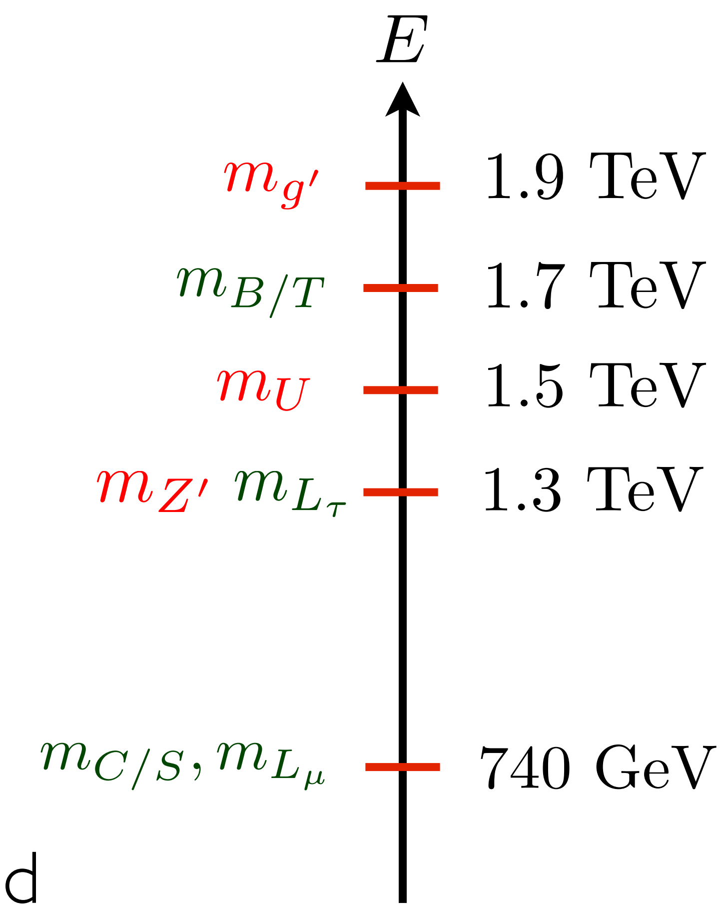
High-p$_T$ searches

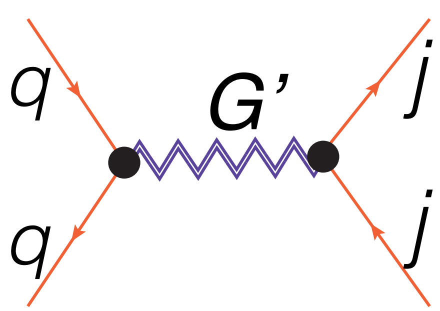
- LQ pair production via QCD
- Z' Drell-Yan production enough suppressed

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

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

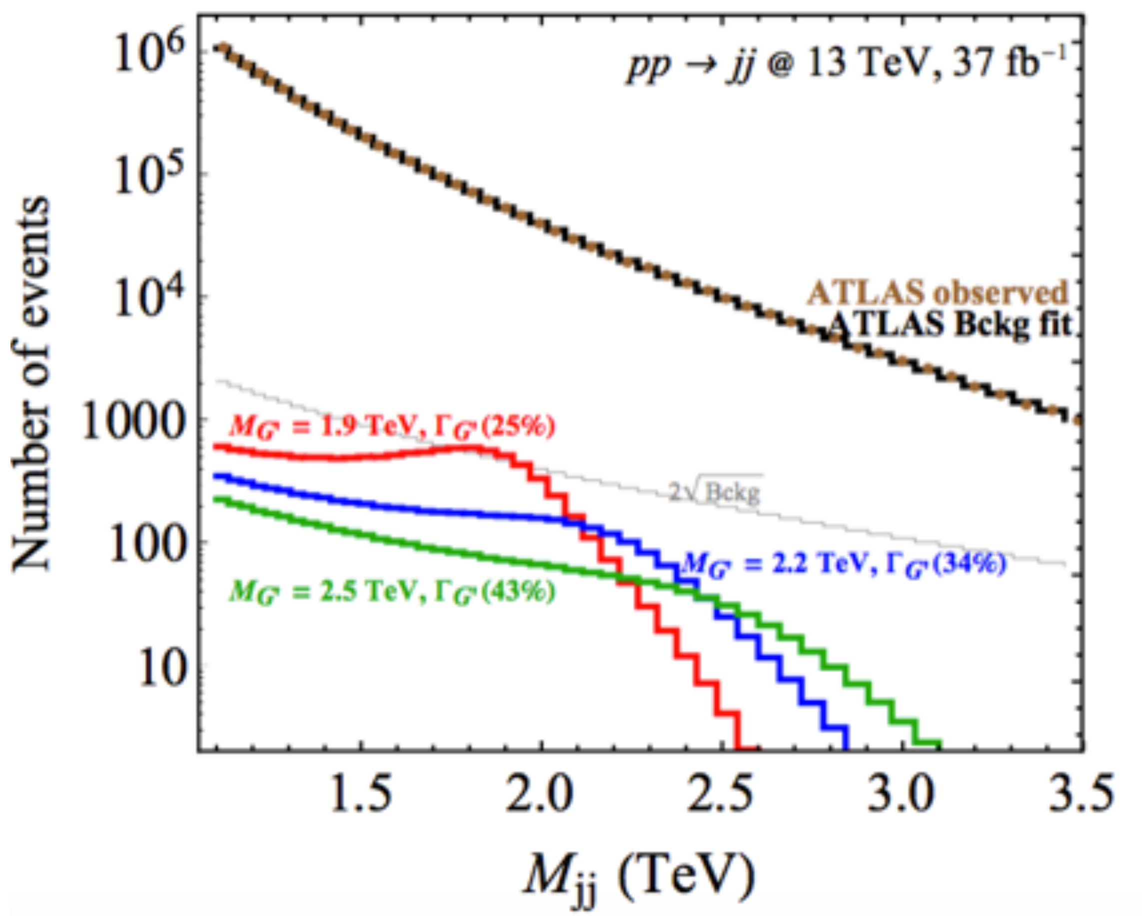
$$\sin\theta_{g'} = \frac{g_s}{g_4} \simeq 0.3 \quad \longrightarrow \quad \text{2 TeV coloron naively excluded}$$

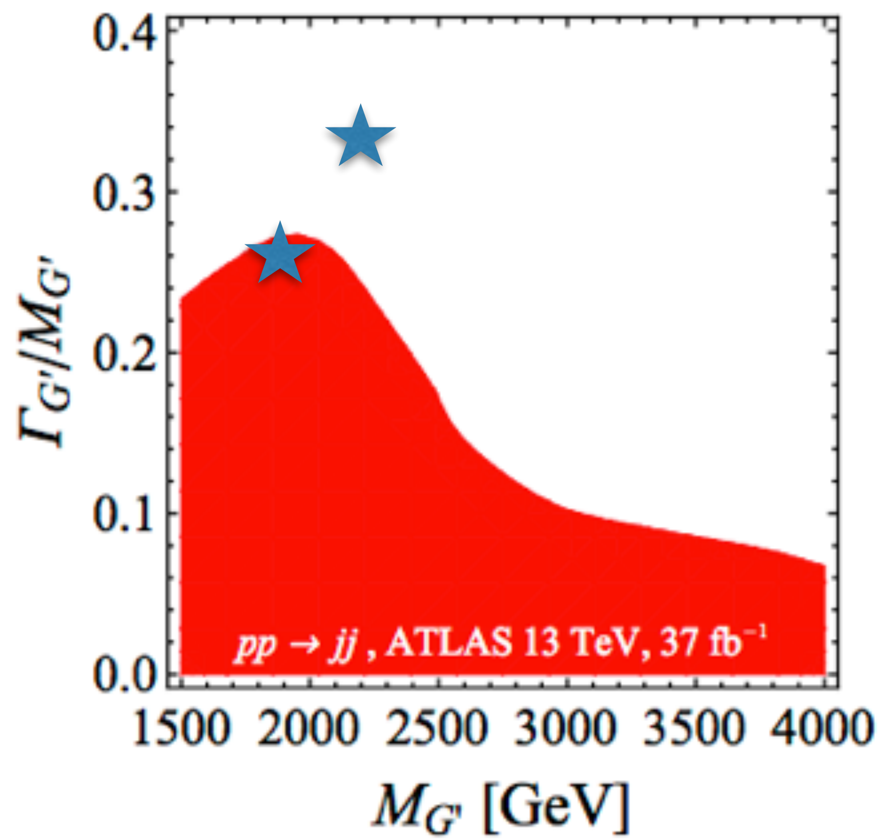




High-p$_T$ searches

[LDL, Fuentes-Martin, Greljo, Nardecchia, Renner (work in progress)]





- However, bump-searches loose in sensitivity for large width/mass

$\frac{\Gamma}{m} \lesssim 15\%$ (exp. analysis)

$\frac{\Gamma_{g'}}{m_{g'}} \simeq 25\%$ (unavoidable in our scenario: large g_4 + extra channel in VLF)

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. Are flavour anomalies part of a bigger picture ?

   → EW naturalness / SM Yukawa puzzle / DM / …

4. Lesson from UV complete models

   → unexpected experimental signatures (coloron, D-mixing, …)
   + playground to compute correlations

[More pheno to come: LDL, Fuentes-Martin, Greljo, Nardecchia, Renner (work in progress)]

Backup slides

Down-alignment (flavour symmetry)

- Down-alignment to avoid tree-level FCNC in the down sector

- Identify d'_R, Ψ_L, Ψ_R as triplets of the flavour group $U(3)_{d'_R} \equiv U(3)_{\Psi_L} \equiv U(3)_{\Psi_R}$

- $M \propto$ identity

- Y_d and $\lambda_q \propto$ to the same spurion $(\overline{3}, 3)$ of $U(3)_{q'_L} \times U(3)_{d'_R}$ → simultaneously diagonalizable

$$\mathcal{M}_d = \begin{pmatrix} \frac{v}{\sqrt{2}} Y_d^{\rm diag} & \frac{v_3}{\sqrt{2}} \lambda_q \\ 0 & M^{\rm diag} \end{pmatrix} \qquad \lambda_q = \begin{pmatrix} \lambda_q^d & 0 & 0 \\ 0 & \lambda_q^s & 0 \\ 0 & 0 & \lambda_q^b \end{pmatrix} \qquad |\lambda_q^{d,s}| \ll |\lambda_q^b|$$

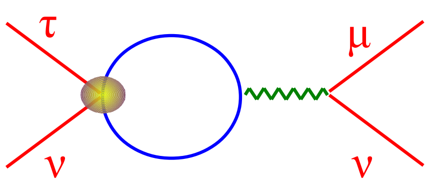
$$\mathcal{M}_u = \begin{pmatrix} \frac{v}{\sqrt{2}} V^\dagger Y_u^{\rm diag} & \frac{v_3}{\sqrt{2}} \lambda_q \\ 0 & M^{\rm diag} \end{pmatrix}$$

$$\mathcal{L}_Y = - \overline{q}'_L \, Y_d \, H d'_R - \overline{q}'_L \, Y_u \, \tilde{H} u'_R - \overline{\ell}'_L \, Y_e \, H e'_R \\ - \overline{q}'_L \, \lambda_q \, \Omega_3^T \Psi_R - \overline{\ell}'_L \, \lambda_\ell \, \Omega_1^T \Psi_R - \overline{\Psi}_L \, M \, \Psi_R$$

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]

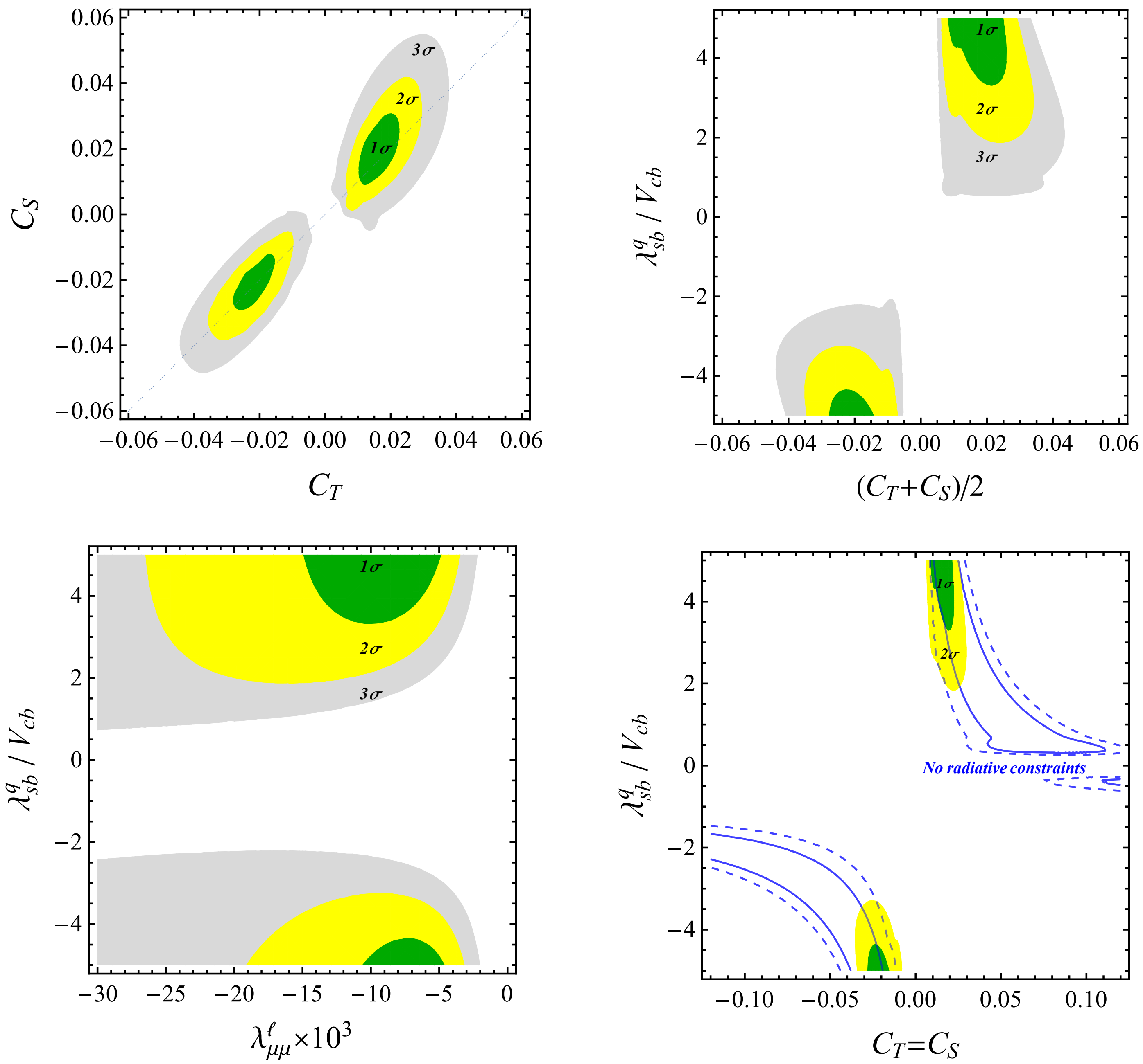
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$



	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]	$-\frac{\pi}{\alpha_{\rm em}V_{tb}V^*_{ts}}\lambda^\ell_{\mu\mu}\lambda^q_{sb}(C_T + C_S)$
	$R^{\mu e}_{b\to c} - 1$	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	$1 + \frac{2}{3}\frac{\pi}{\alpha_{\rm em}V_{tb}V^*_{ts}C^{\rm SM}_\nu}(C_T - C_S)\lambda^q_{sb}(1 + \lambda^\ell_{\mu\mu})$
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]

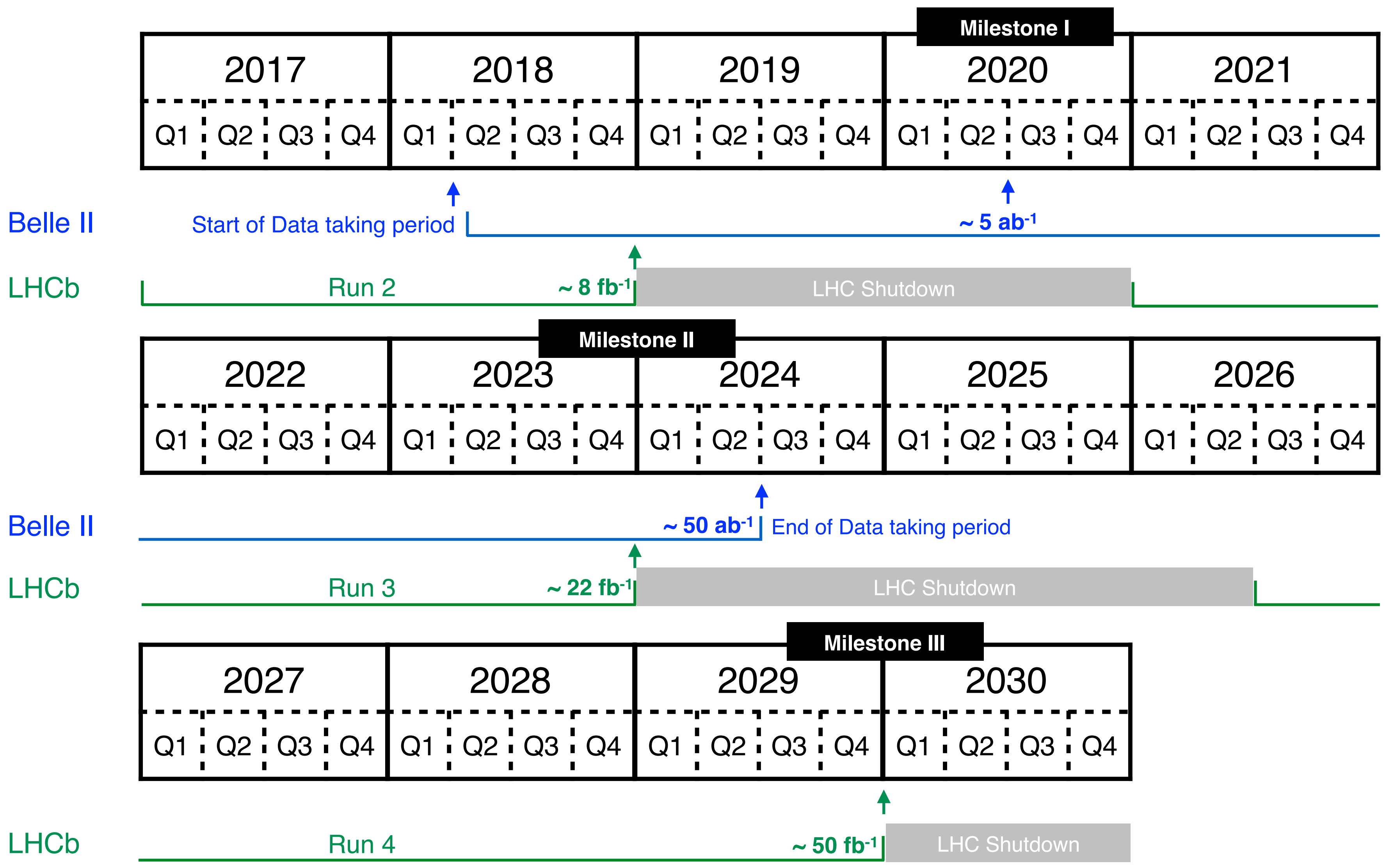
- 4 parameters fit: $C_S, C_T, \lambda^q_{bs}, \lambda^\ell_{\mu\mu} \quad (\lambda^q_{bb} = \lambda^\ell_{\tau\tau} = 1)$ [Zürich's guide for combined explanations, 1706.07808]



Future prospects

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

[Albrecht et al, 1709.10308]



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- 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