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Leptoquarks in Flavour Physics

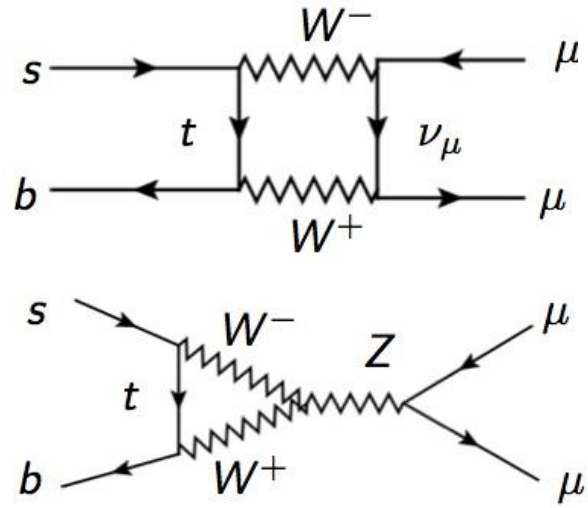
Based on: **E. Leskov, G. D'Ambrosio, A. Crivellin, DM, 1612.06858**
A. Crivellin, T. Ota, DM, 1703.09226
A. Crivellin, A. Signer, Y. Ulrich, DM, 1706.08511

Outline

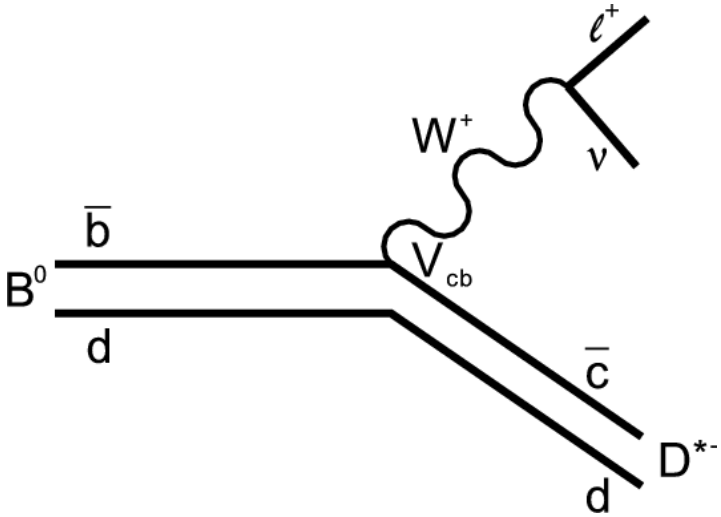
- Introduction:
  - Review of flavour anomalies in $b \to s\ell^+\ell^-$, $b \to c\ell\nu$ and δa_μ
  - Leptoquark representations
- δa_μ and correlations with $Z \to \mu^+\mu^-$
- Simultaneous explanation
- Conclusions

Introduction: Flavour Anomalies

- $b \to s\ell^+\ell^-$ transitions:
  - In the SM suppressed by:
    - The CKM element $V_{ts} \approx 0.04$
    - Electroweak scale
    - Loop factor: $^1/_{16\pi^2}$



- $b \to c\ell\nu$ processes:
  - Tree-level decays in the SM
  - With light leptons ($\ell = e, \mu$) used to determine the CKM element V_{cb}



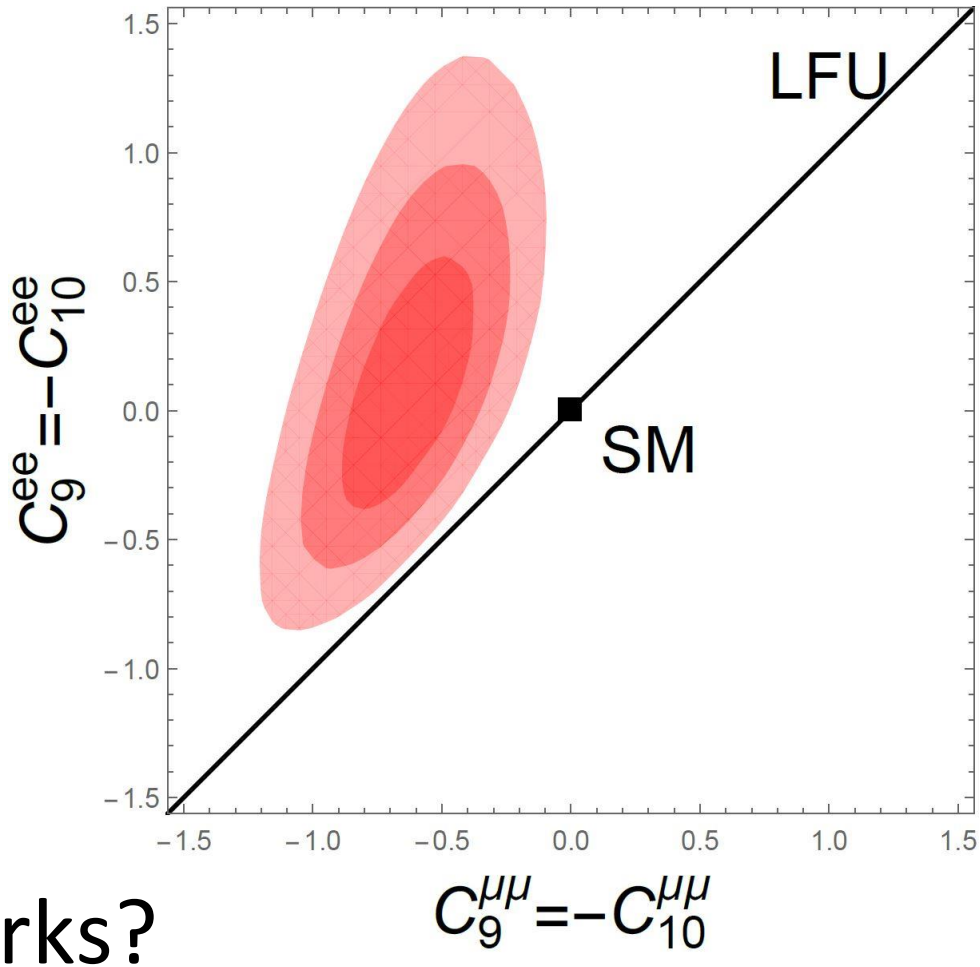
Introduction: $b \to s\ell^+\ell^-$

$$H_{eff}^{\ell_f \ell_i} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_k C_k^{fi} O_k^{fi}$$

$$O_9^{fi} = \frac{e^2}{16\pi^2} \left(\bar{s}\gamma_\mu P_L b\right) \bar{\ell}_f \gamma^\mu \ell_i$$

$$O_{10}^{fi} = \frac{e^2}{16\pi^2} \left(\bar{s}\gamma_\mu P_L b\right) \bar{\ell}_f \gamma^\mu \gamma_5 \ell_i$$

$$C_9 = -C_{10}$$

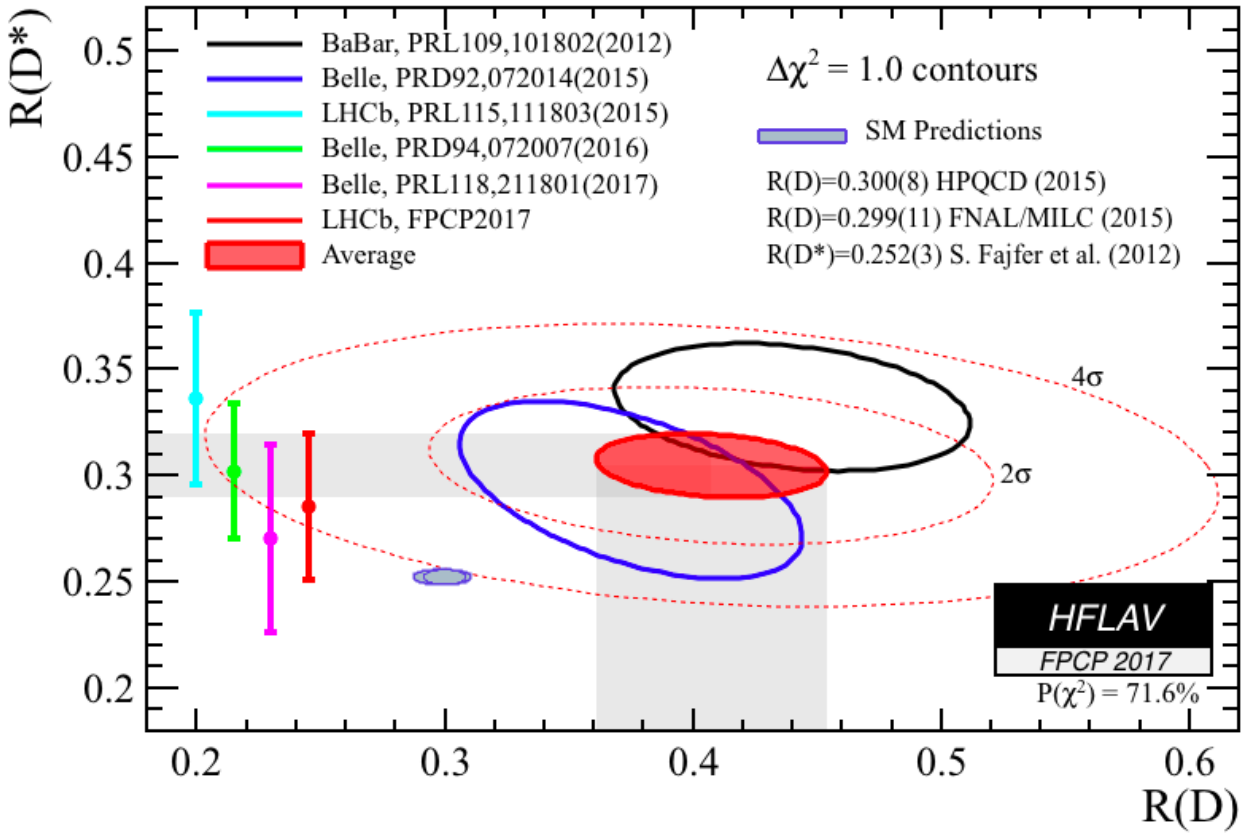


$NP \gtrsim 5\sigma$

Leptoquarks?

Capdevilla et al., 1704.05340
Altmannshofer et al., 1503.06199

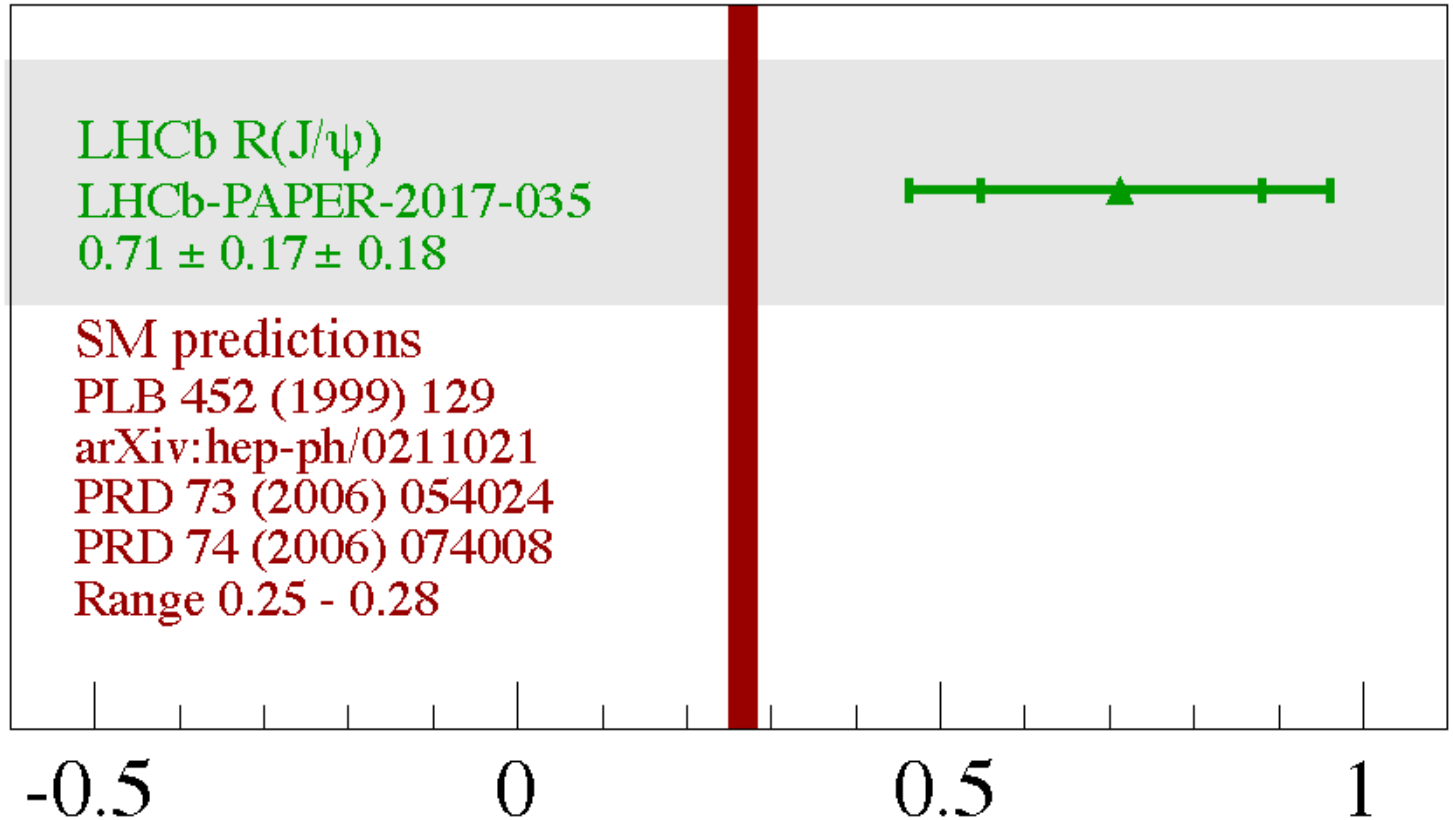
Introduction: $R(D^{(*)})$



$$R\left(D^{(*)}\right) = \mathrm{Br}\left[B \to D^{(*)}\tau\nu\right] \Big/ \mathrm{Br}\left[B \to D^{(*)}\ell\nu\right]$$

Tree-level $NP \approx 4\sigma$

Introduction: $R(J/\psi)$



$$R(J/\psi) = \mathrm{Br}\left[B_c^+ \to J/\psi\,\tau^+\nu\right] / \mathrm{Br}\left[B_c^+ \to J/\psi\,\ell^+\nu\right]$$

All measurments above the SM prediction

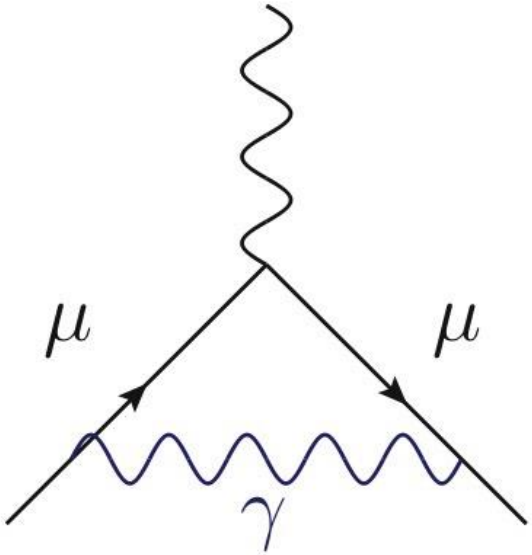
Introduction: δa_μ

$$\delta a_\mu = a_\mu^{\exp} - a_\mu^{SM} = (28 \pm 9) \times 10^{-10}$$

Jegerlehner et al., 0902.3360

Enhanced loop-level

$NP \approx 3\sigma$



Leptoquark (LQ) representations

Buchmuller et al., Phys. Lett. B191, 442-448

Scalar LQ

$$\Phi_1 : \left(3,1,-\frac{2}{3}\right) \quad \left(\lambda_1^R \overline{u^c}\ell + \lambda_1^L \overline{Q^c} i\tau_2 L\right)\Phi_1^\dagger$$

$$\tilde{\Phi}_1 : \left(3,1,-\frac{8}{3}\right) \quad \tilde{\lambda}_1 \overline{d^c}\ell\tilde{\Phi}_1^\dagger$$

$$\Phi_2 : \left(\overline{3},2,-\frac{7}{3}\right) \quad \left(\lambda_2^{RL}\overline{u}L + \lambda_2^{LR}\overline{Q}i\tau_2\ell\right)\Phi_2^\dagger$$

$$\tilde{\Phi}_2 : \left(\overline{3},2,-\frac{1}{3}\right) \quad \tilde{\lambda}_2 \overline{d}L\tilde{\Phi}_2^\dagger$$

$$\Phi_3 : \left(3,3,-\frac{2}{3}\right) \quad \lambda_3 \overline{Q^c} i\tau_2 \left(\tau\cdot\Phi_3\right)^\dagger L$$

Vector LQ

$$V_1^\mu : \left(3,1,-\frac{4}{3}\right) \quad \left(\kappa_1^R \overline{d}\gamma_\mu\ell + \kappa_1^L \overline{Q}\gamma_\mu L\right)V_1^{\mu *}$$

$$\tilde{V}_1^\mu : \left(3,1,-\frac{10}{3}\right) \quad \tilde{\kappa}_1 \overline{u}\gamma_\mu\ell\tilde{V}_1^{\mu *}$$

$$V_2^\mu : \left(\overline{3},2,-\frac{5}{3}\right) \quad \left(\kappa_2^{RL}\overline{d^c}\gamma_\mu L + \kappa_2^{LR}\overline{Q^c}\gamma_\mu\ell\right)V_2^{\mu *}$$

$$\tilde{V}_2^\mu : \left(\overline{3},2,-\frac{1}{3}\right) \quad \tilde{\kappa}_2 \overline{u^c}\gamma_\mu L\tilde{V}_2^{\mu *}$$

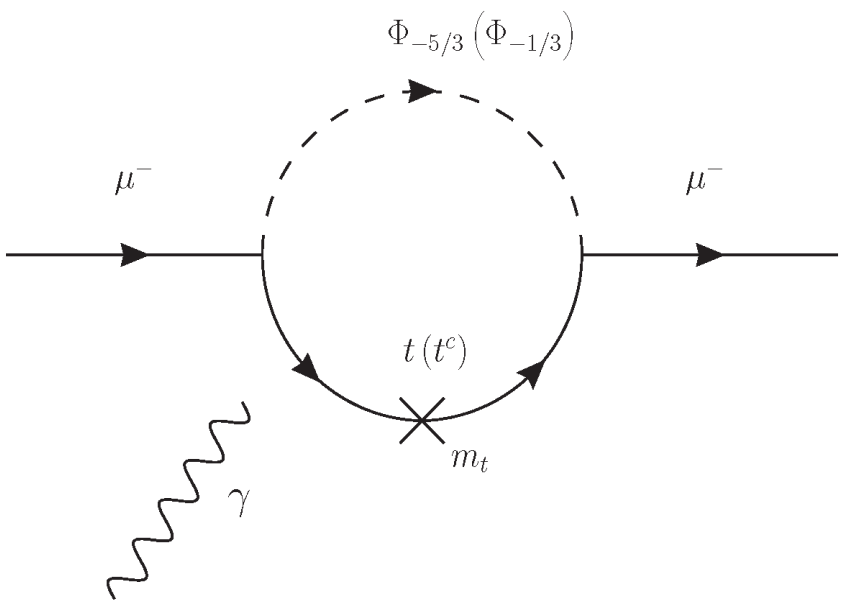
$$V_3^\mu : \left(3,3,-\frac{4}{3}\right) \quad \kappa_3 \overline{Q}\gamma_\mu \left(\tau\cdot V_3^{\mu *}\right)^\dagger L$$

$$\delta a_\mu$$

and

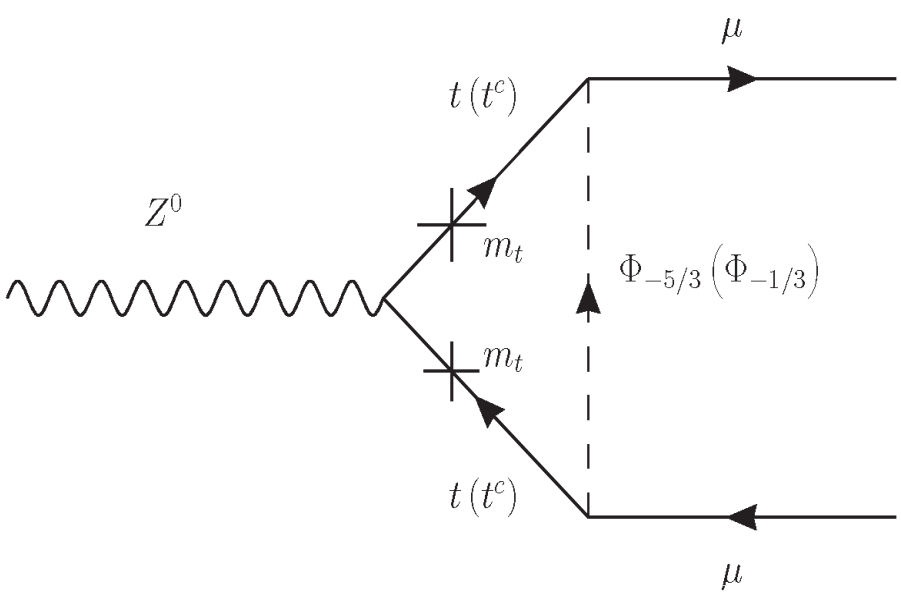
$$Z \to \ell^+ \ell^-$$

a_μ with Scalar LQ



- δa_μ is quite large (order of SM weak interaction)
- Φ_2 and Φ_1 give an m_t-enhancement

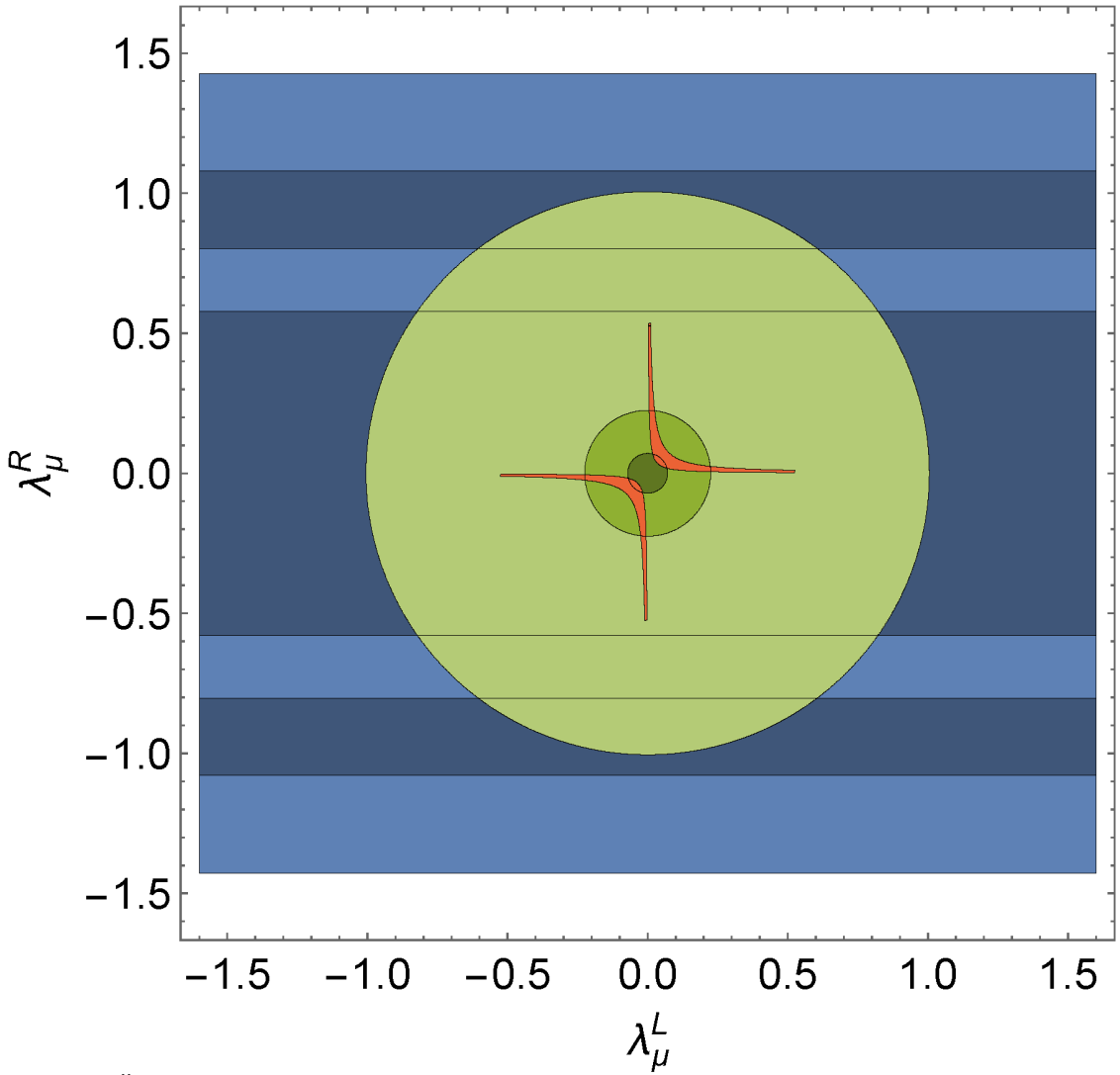
Correlated and enhanced effects in $Z \to \mu^+\mu^-$



Djouadi et al., Z. Phys. C46, 679

Scalar LQ in a_μ

- Allowed regions and future sensitivity



Φ_1

$$\lambda_\mu^{L,R} \equiv \lambda_{1,t\mu}^{L,R}$$

$$M_{LQ} = 1 \text{ TeV}$$

- B→$K^*\nu\nu$
- B→$K^*\nu\nu$ (BELLE II)
- Z→$\mu\mu$ (LEP)
- Z→$\mu\mu$ (GigaZ)
- Z→$\mu\mu$ (TLEP)
- $a_\mu(2\sigma)$

Simultaneous Explanation of $R\left(D^{(*)}\right)$, $b \to s\mu^+\mu^-$ and δa_μ

$R(D^{(*)}), b \to s\ell^+\ell^-$ and $b \to s\nu\nu$

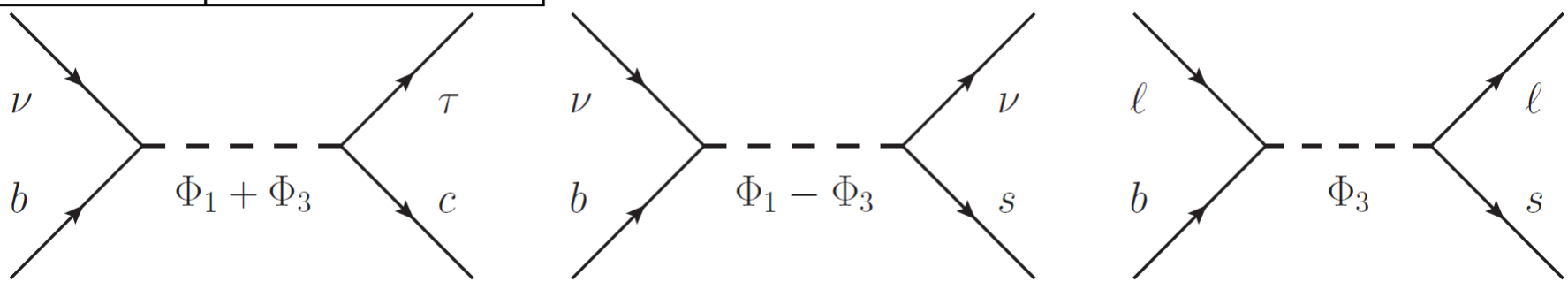
$b \to c\bar{\nu}\ell$	C_{VL}	C_{VR}
Φ_1	$-\lambda_1^L \lambda_1^{L*} V^{CKM}$	0
Φ_3	$\lambda_3 \lambda_3^* V^{CKM}$	0

$b \to s\ell\ell$	C_9	C_{10}	C_9'	C_{10}'
Φ_1	0	0	0	0
Φ_3	$2\lambda_3\lambda_3^*$	$-2\lambda_3\lambda_3^*$	0	0

$b \to s\bar{\nu}\nu$	C_L	C_R
Φ_1	$\lambda_1^L \lambda_1^{L*}$	0
Φ_3	$\lambda_3 \lambda_3^*$	0

Impose a discrete symmetry:

$$\lambda_{1,jk}^L \equiv \lambda_{jk}^L$$
$$\lambda_{3,jk} \equiv (-1)^j \lambda_{jk}^L$$



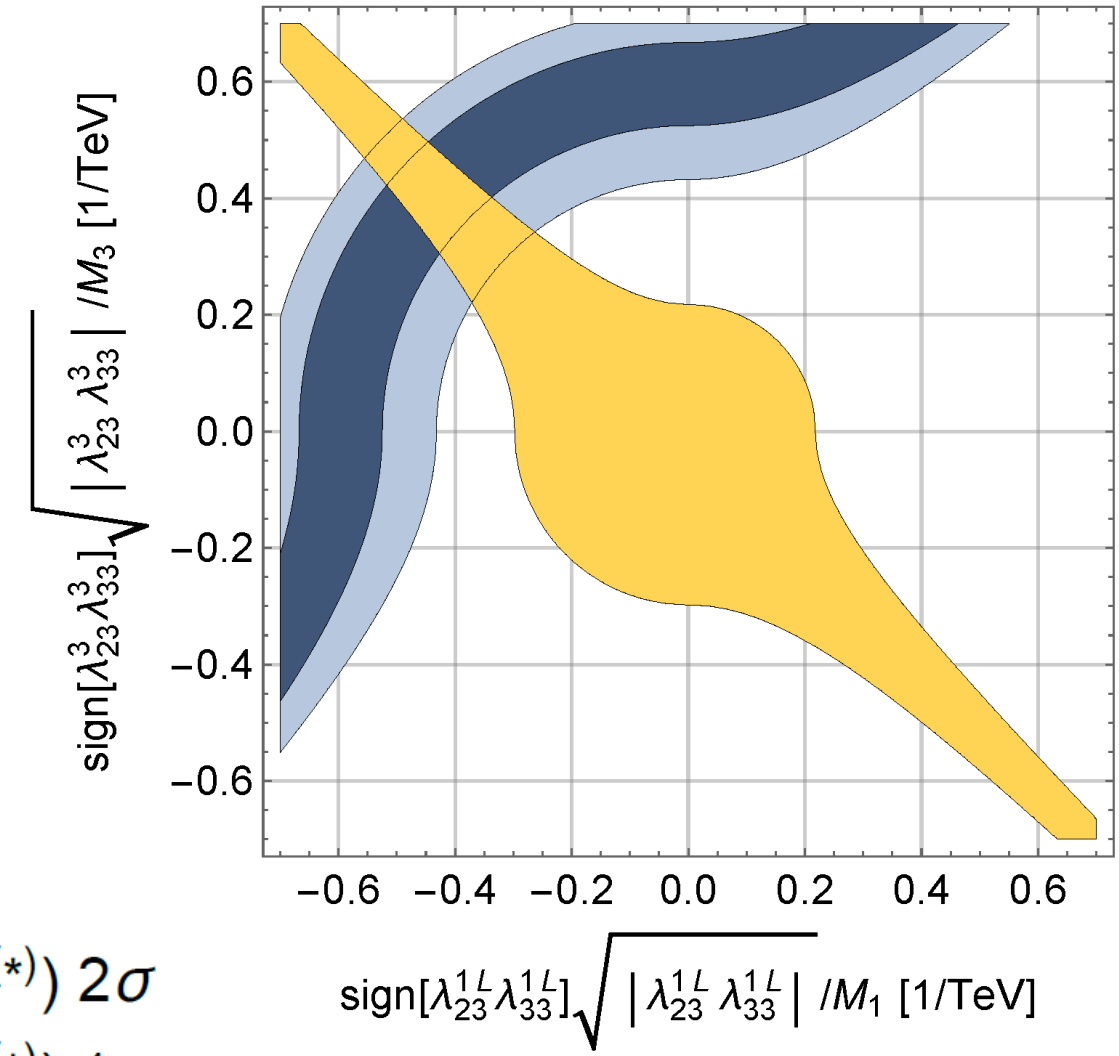
The vector LQ V_1^μ has the same feature without this symmetry

Bordone et al., 1712.06844
Calibbi et al., 1709.00692
Di Luzio et al., 1708.08450
Barbieri et al., 1611.04930

$R(D^{(*)})$ and $b \to s\nu\nu$

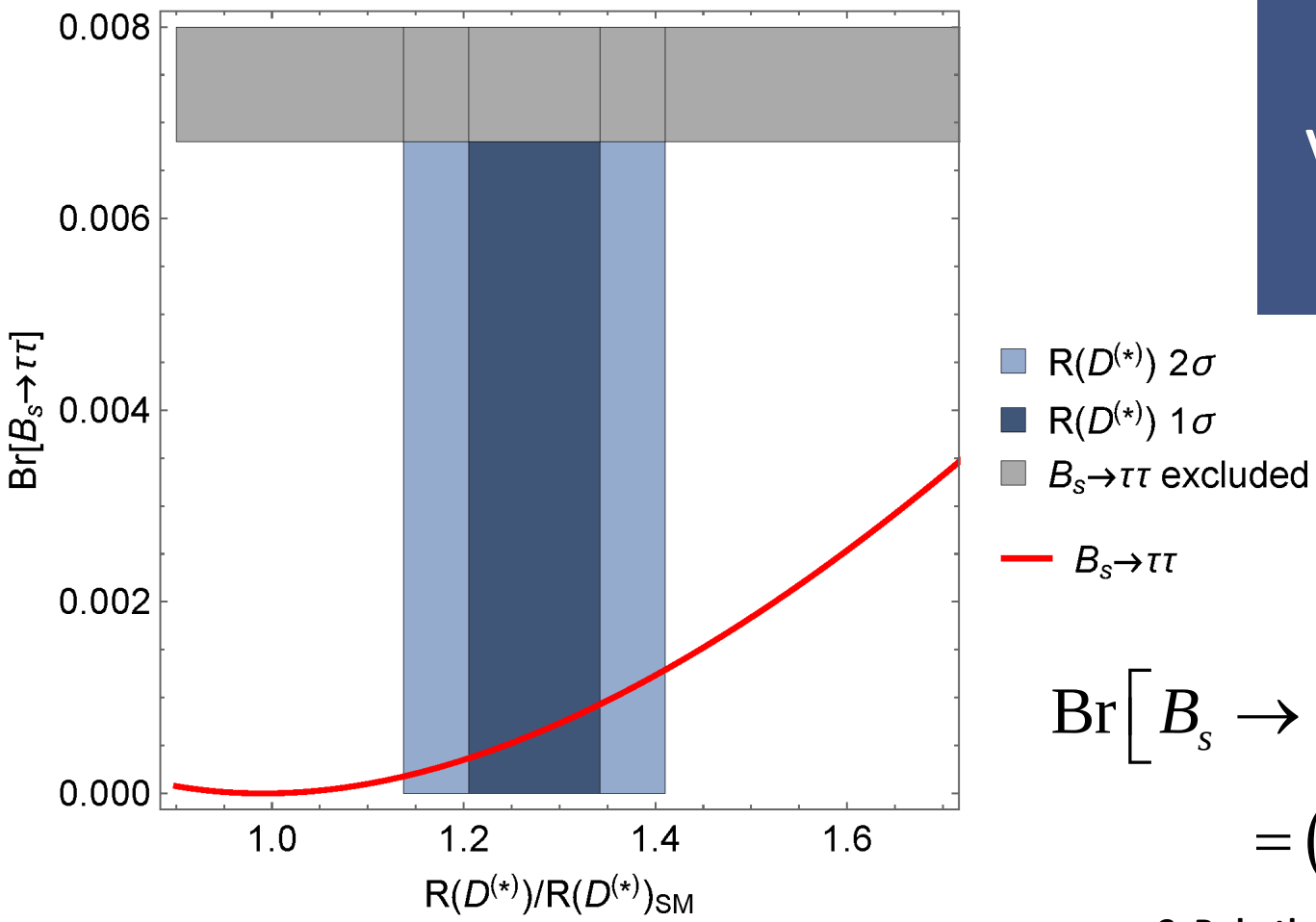
- Avoid effect in $b \to s\nu\nu$
- Sizable couplings to second quark generations

➡ Weak bounds from collider searches and EW precision data



$R(D^{(*)})$ and $b \to s\tau^+\tau^-$

- Cancelation in $b \to s\nu\nu$ needed $C^{(1)} \sim C^{(3)}$



$B_s \to \tau^+\tau^-$

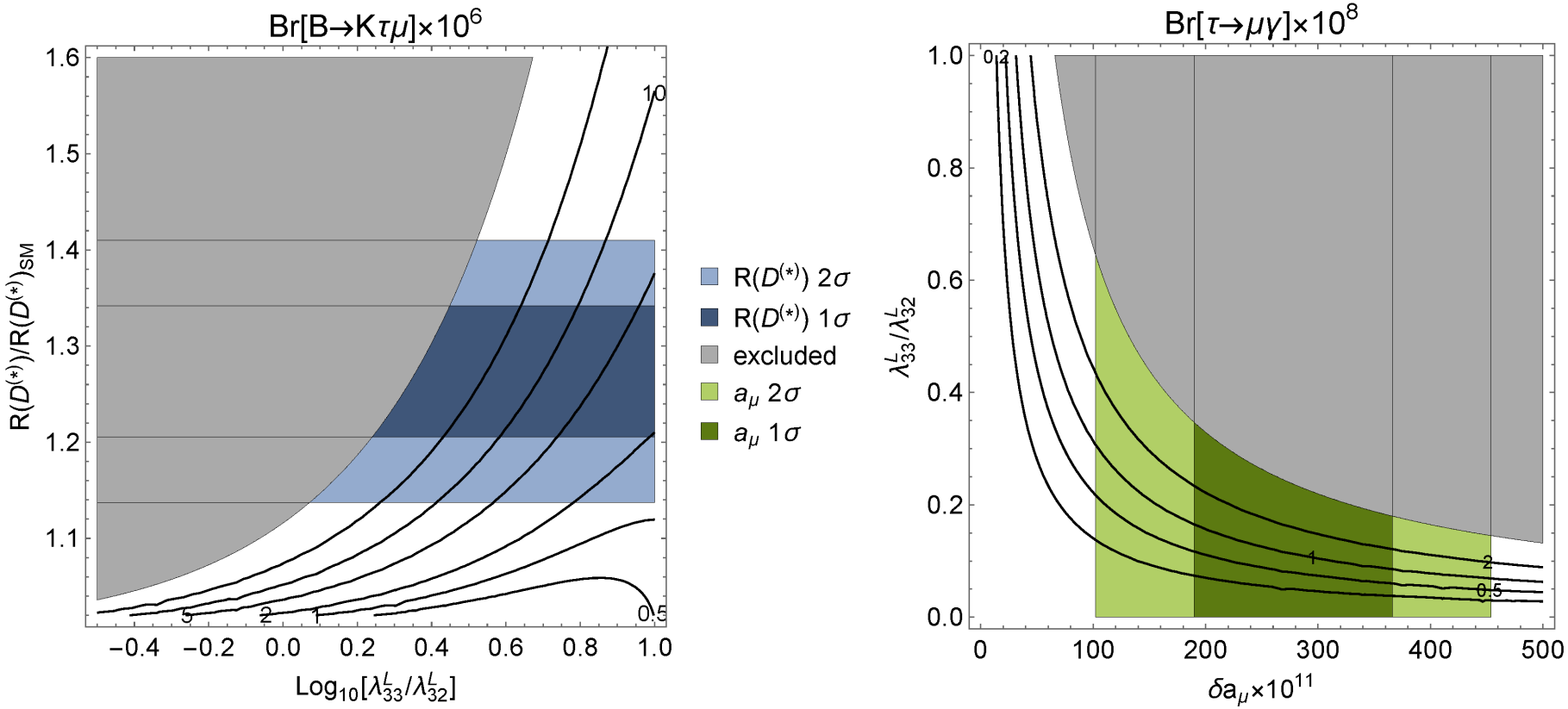
very strongly enhanced

$$\mathrm{Br}\left[B_s \to \tau^+\tau^-\right]_{SM} = (7.73 \pm 0.49) \times 10^{-7}$$

C. Bobeth et al., 1311.0903

$R(D^{(*)})$, $b \to s\mu^+\mu^-$ and δa_μ

- Scalar LQ singlet + triplet with $Y = -2/3$
- Cancelation in $b \to s\nu\nu$ is imposed by discrete symmetry



2 out of 3 can be explained

Conclusions

- We can explain δa_μ by m_t-enhancement
  - $Z\mu\mu$-couplings as a future experimental check
- Three LQ representations give a good fit to $b \to s\mu^+\mu^-$ with $C_9 = -C_{10}$
- $R\left(D^{(*)}\right)$ can be explained, giving a 10^3-enhancement in $\mathrm{Br}[B_s \to \tau^+\tau^-]$
- One can explain any two of δa_μ, $R\left(D^{(*)}\right)$ and $b \to s\mu^+\mu^-$ simultaneously