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Theory Group of the Laboratory for Particle Physics

Leptoquarks in Flavor 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 flavor anomalies
  - Leptoquark (LQ) representations
- Explanation of
  - δa_μ and correlations with $Z \to \mu^+\mu^-$
  - $b \to s\ell^+\ell^-$ and effects in $\ell \to \ell'\gamma$
  - $b \to c\tau\nu$
- Simultaneous explanation
- Conclusions

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

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

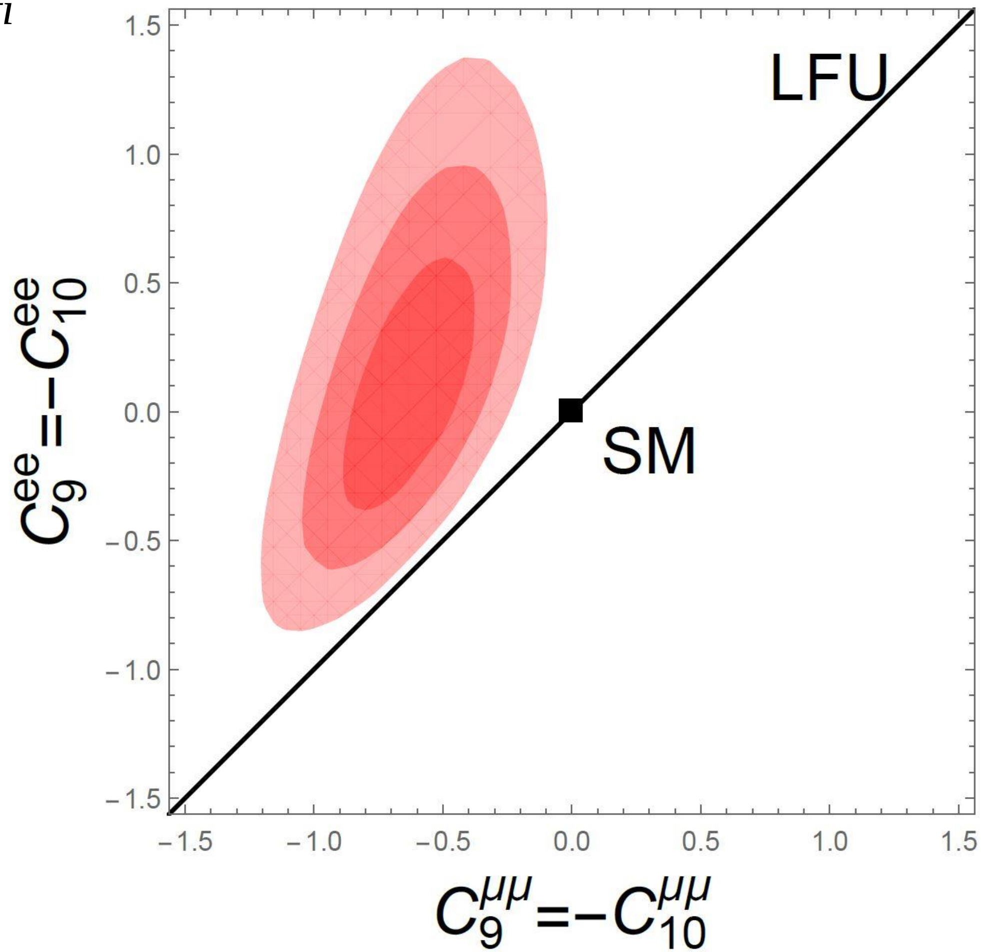
$$O_9^{fi} = \frac{e^2}{16\pi^2} \bar{s}\gamma_\mu P_L b \bar{\ell}_f \gamma^\mu \ell_i$$

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

$NP \gtrsim 5\sigma$

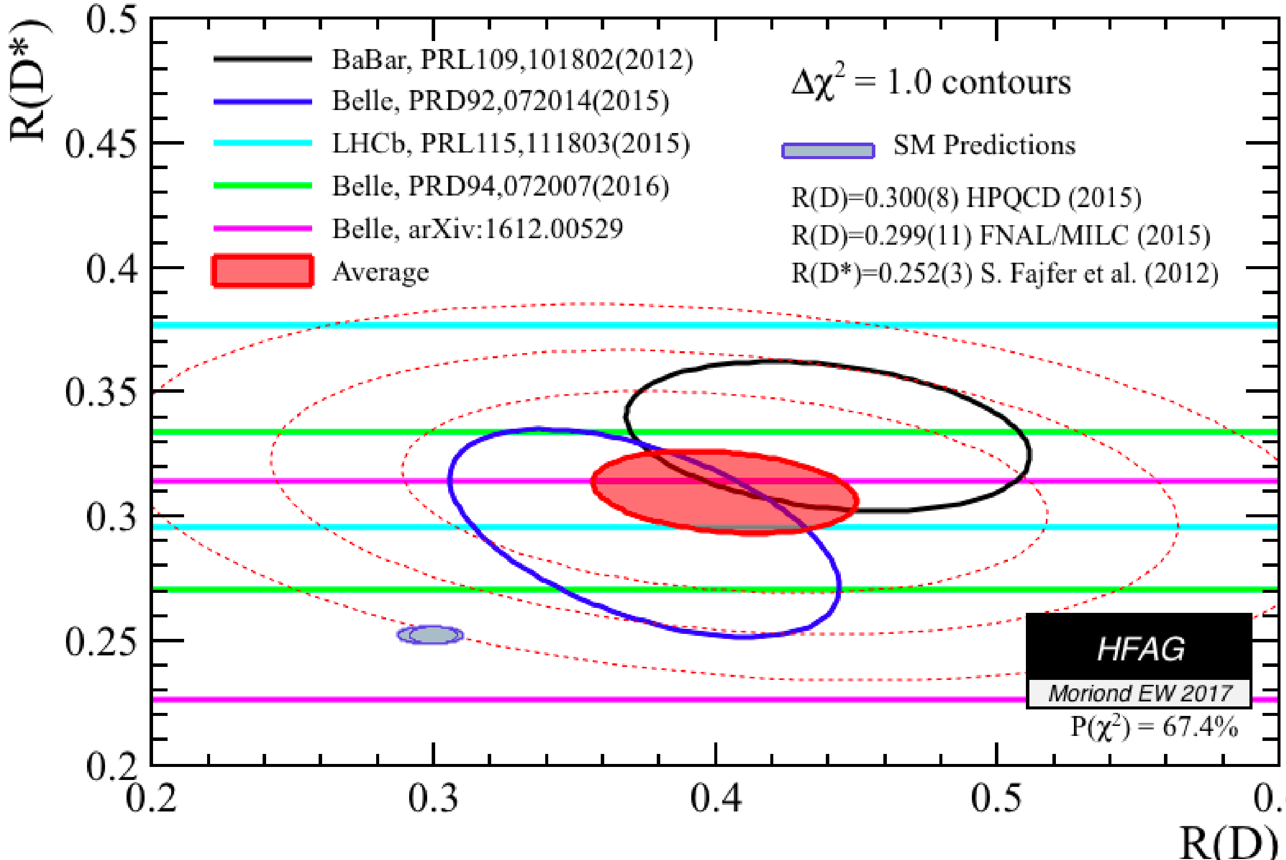
LQs?

$$C_9 = -C_{10}$$



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

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



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

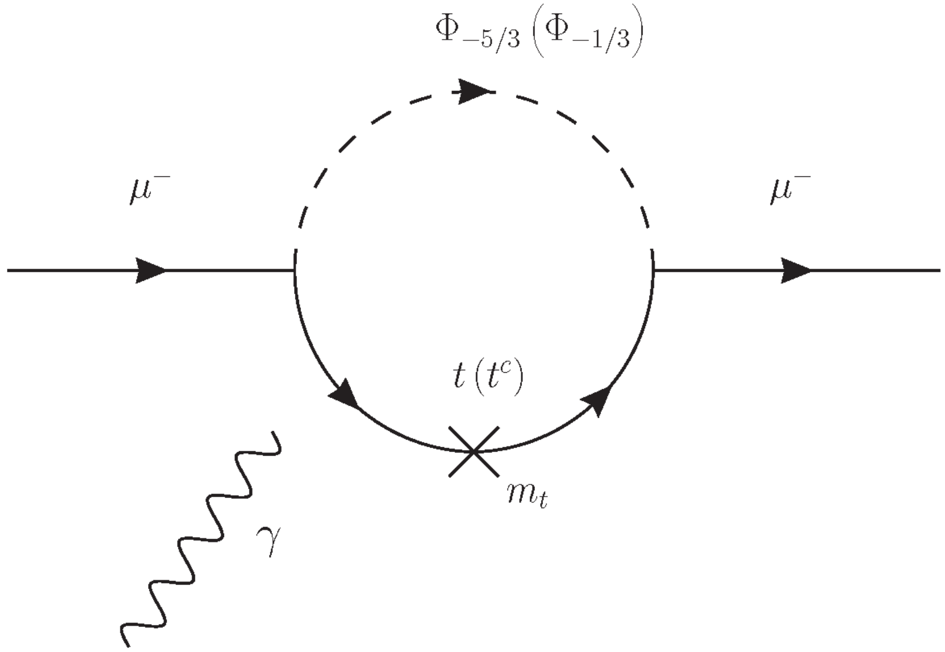
Tree-level NP ≈ 4σ

Introduction: δa_μ

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

Jegerlehner et al., 0902.3360

Enhanced loop-level NP $\approx 3\sigma$



Motivation for Leptoquarks

$b \to s\mu\mu$

- $C_9 = -C_{10}$-contribution

Becirevic et al., 1503.09024
Grejlo et al, 1506.01705
Calibbi et al., 1506.02661
Alonso et al., 1505.05164
Fajfer et al., 1511.06024
Barbieri et al., 1512.01560
…

δa_μ

- m_t-enhancement

Bauer et al., 1511.01900
Djouhadi et al., Z. Phys. C46 679
Chakraverty et al., Phys. Lett. B506 103
Cheung, Phys. Rev. D64 033001
…

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

- Tree-level contribution
- q^2-Distribution unchanged

Fajfer et al., 1206.1872
Deshpande et al., 1208.4134
Dumont et al., 1603.05248
Das et al., 1605.06313
Sahoo et al., 1609.04367
Barbieri et al., 1611.04930
…

Leptoquark (LQ) representations

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

Scalar LQs			Vector LQs		
$\Phi_1:$	$\left(3,1,-\frac{2}{3}\right)$	$\left(\lambda_1^R \overline{u^c}\ell + \lambda_1^L \overline{Q^c} i\tau_2 L\right)\Phi_1^\dagger$	$V_1^\mu:$	$\left(3,1,-\frac{4}{3}\right)$	$\left(\kappa_1^R \overline{d}\gamma_\mu \ell + \kappa_1^L \overline{Q}\gamma_\mu L\right)V_1^{\mu *}$
$\tilde{\Phi}_1:$	$\left(3,1,-\frac{8}{3}\right)$	$\tilde{\lambda}_1 \overline{d^c}\ell\tilde{\Phi}_1^\dagger$	$\tilde{V}_1^\mu:$	$\left(3,1,-\frac{10}{3}\right)$	$\tilde{\kappa}_1 \overline{u}\gamma_\mu \ell \tilde{V}_1^{\mu *}$
$\Phi_2:$	$\left(\overline{3},2,-\frac{7}{3}\right)$	$\left(\lambda_2^{RL} \overline{u}L + \lambda_2^{LR} \overline{Q} i\tau_2 \ell\right)\Phi_2^\dagger$	$V_2^\mu:$	$\left(\overline{3},2,-\frac{5}{3}\right)$	$\left(\kappa_2^{RL} \overline{d^c}\gamma_\mu L + \kappa_2^{LR} \overline{Q^c}\gamma_\mu \ell\right)V_2^{\mu *}$
$\tilde{\Phi}_2:$	$\left(\overline{3},2,-\frac{1}{3}\right)$	$\tilde{\lambda}_2 \overline{d}L\tilde{\Phi}_2^\dagger$	$\tilde{V}_2^\mu:$	$\left(\overline{3},2,-\frac{1}{3}\right)$	$\tilde{\kappa}_2 \overline{u^c}\gamma_\mu L \tilde{V}_2^{\mu *}$
$\Phi_3:$	$\left(3,3,-\frac{2}{3}\right)$	$\lambda_3 \overline{Q^c} i\tau_2 \left(\tau\cdot\Phi_3\right)^\dagger L$	$V_3^\mu:$	$\left(3,3,-\frac{4}{3}\right)$	$\kappa_3 \overline{Q}\gamma_\mu \left(\tau\cdot V_3^{\mu *}\right)^\dagger L$

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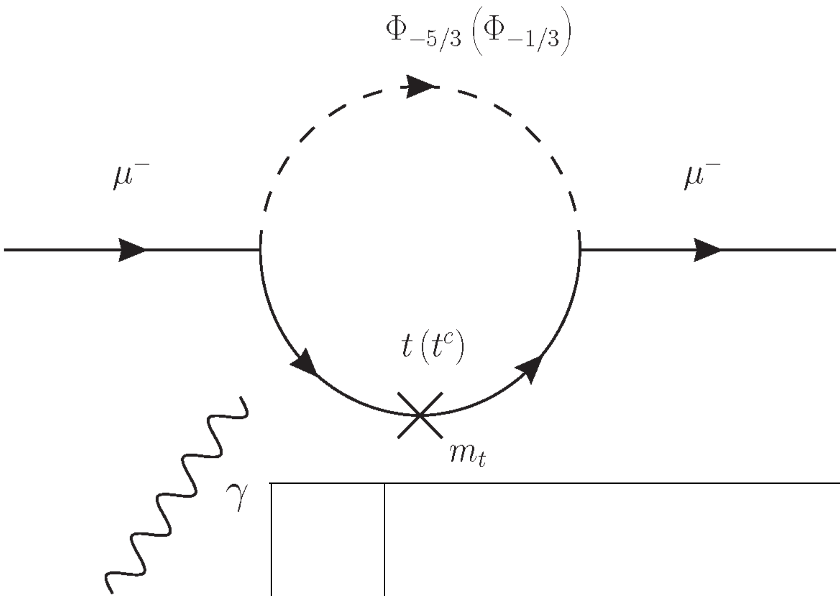
δa_μ and $Z \to \ell^+ \ell^-$

AMM with Scalar LQs



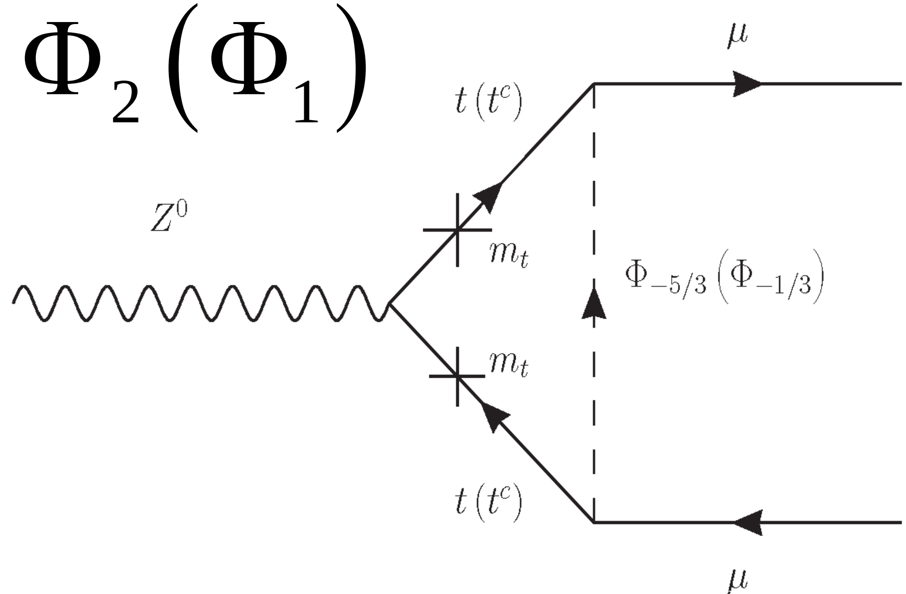
m_t-enhanced terms

	$C_R^{\mu\mu}$
Φ_1	$\left(\lambda_1^{L*}\lambda_1^{L} + \lambda_1^{R*}\lambda_1^{R}\right) m_\mu - 2\lambda_1^{L*}V^{CKM}\lambda_1^{R} m_t \left(7 + 4\log\left(y_t\right)\right)$
$\tilde{\Phi}_1$	$-2\tilde{\lambda}_1^{*}\tilde{\lambda}_1 m_\mu$
Φ_2	$-3\left(\lambda_2^{LR*}\lambda_2^{LR} + \lambda_2^{RL*}\lambda_2^{RL}\right) m_\mu + 2\lambda_2^{LR*}V^{CKM*}\lambda_2^{RL} m_t \left(1 + 4\log\left(y_t\right)\right)$
$\tilde{\Phi}_2$	0
Φ_3	$-3\lambda_3\lambda_3^{*} m_\mu$

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

Modified $Z\mu\mu$-Couplings

$$\Phi_2\left(\Phi_1\right)$$



- m_t-squared effect
- LFV Z-decays possible

$$Z^{0\mu}\,\overline{\ell}_i\gamma_\mu\left(\Gamma_{if}^L P_L+\Gamma_{if}^R P_R\right)\ell_f$$

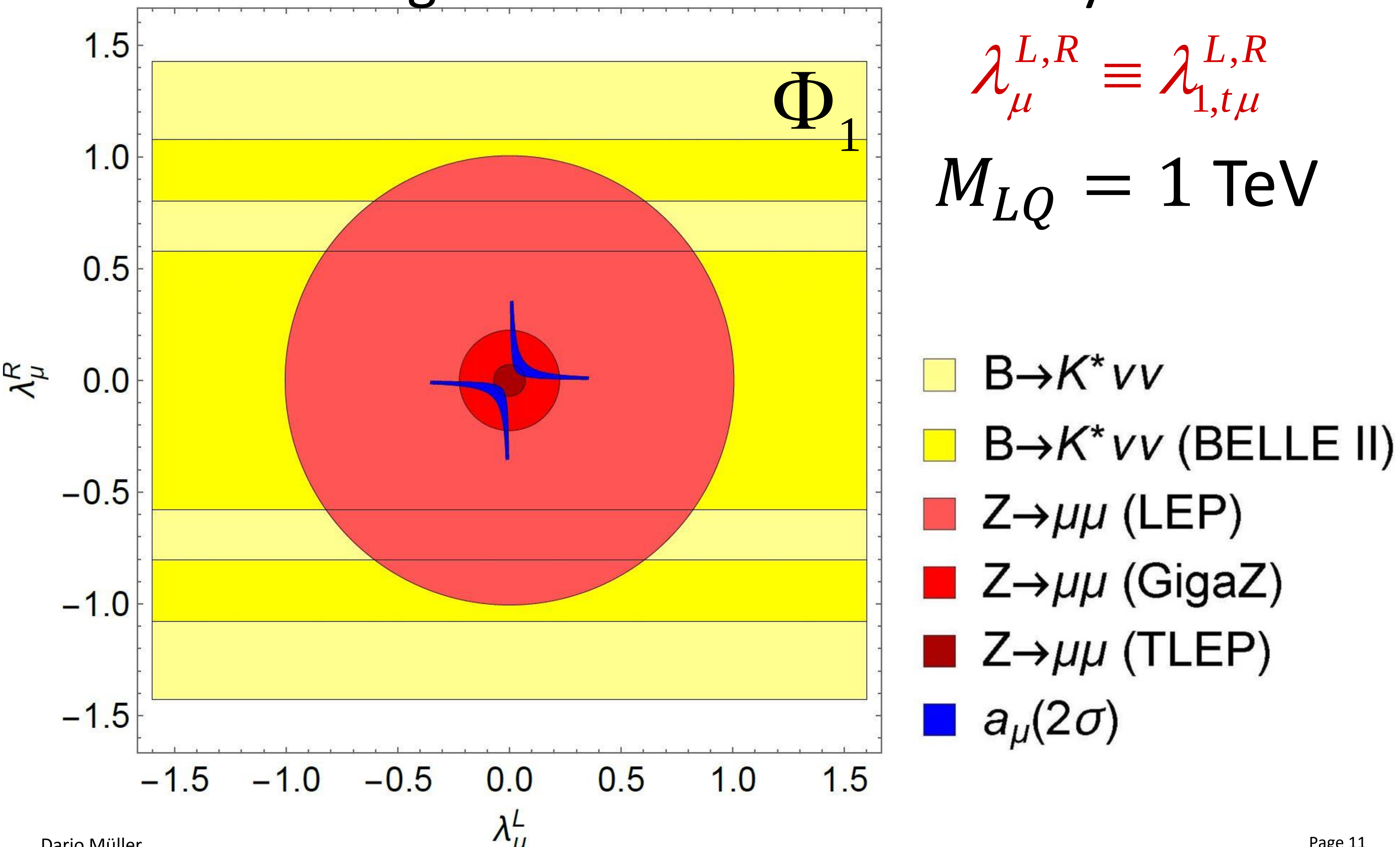
Correlated and enhanced effects in Z→μμ

$$\Delta\Gamma_{\mu\mu}^R \propto \frac{\lambda^{R*}\lambda^R m_t^2}{M^2}\left(1+\log\left(\frac{m_t^2}{M^2}\right)\right)$$

$$\Delta\Gamma_{\mu\mu}^L \propto \frac{\lambda^{L*}\lambda^L m_t^2}{M^2}\left(1+\log\left(\frac{m_t^2}{M^2}\right)\right)$$

Scalar Leptoquarks in a_μ

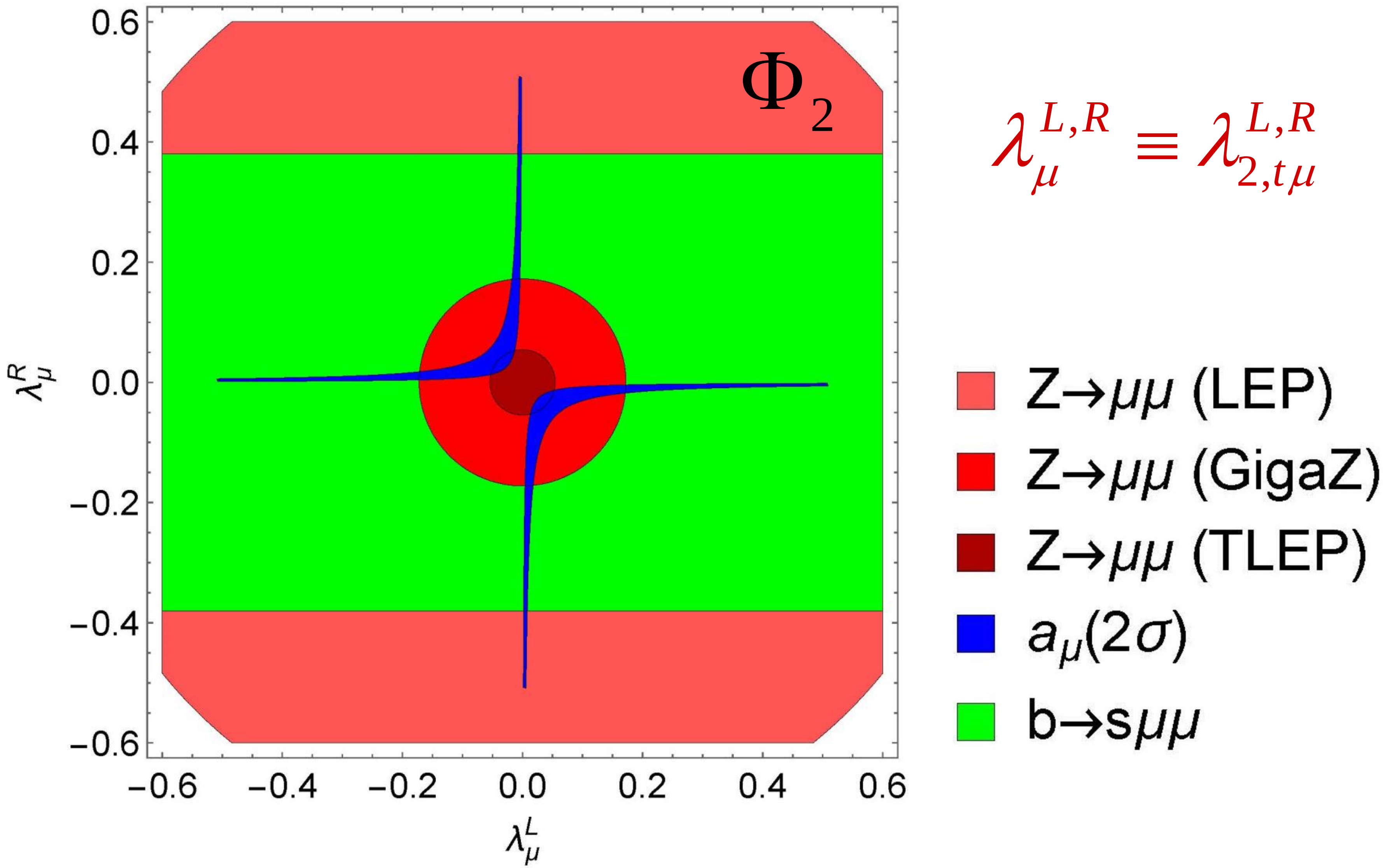
- Allowed regions and future sensitivity



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

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

Scalar Leptoquarks in a_μ

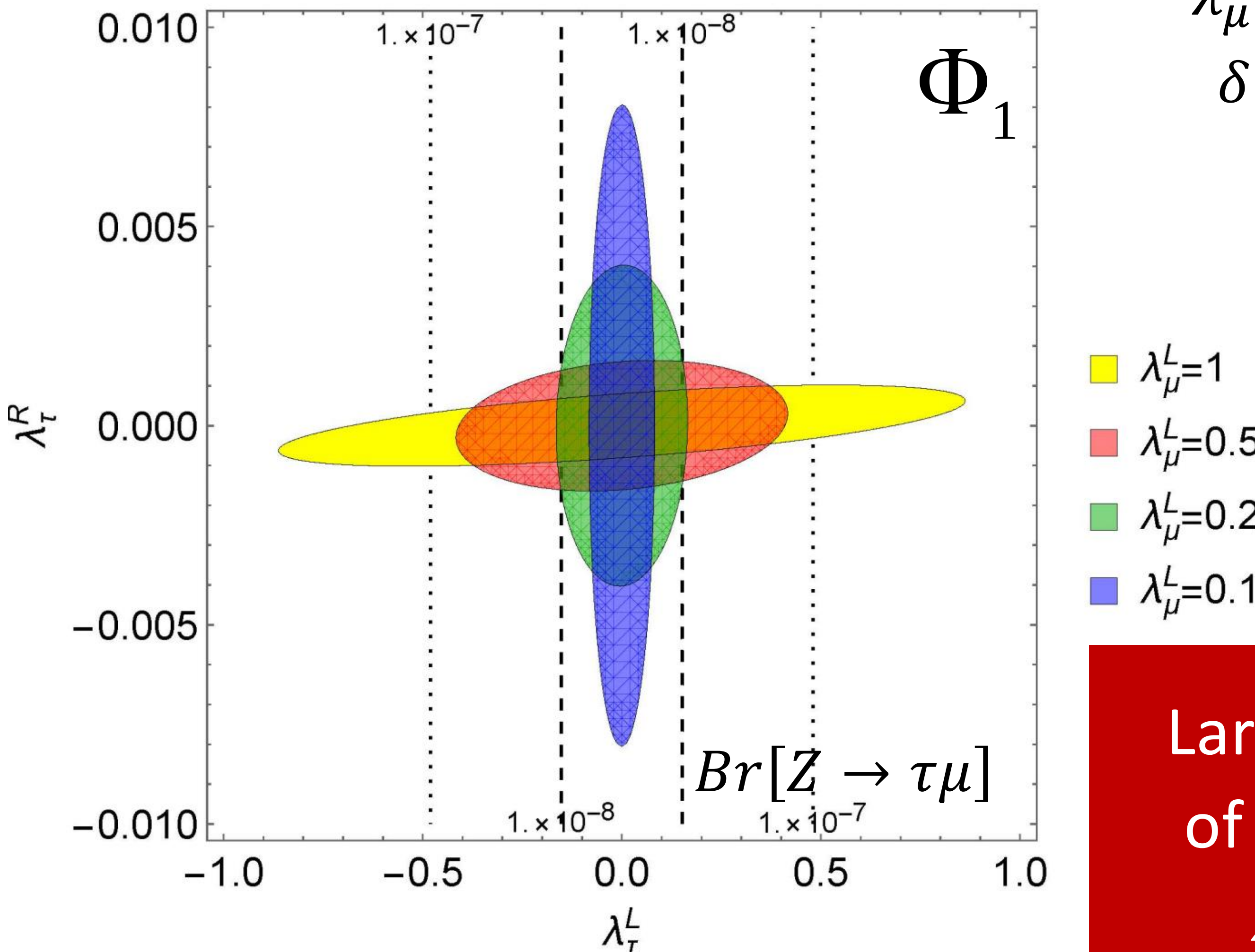


$$\lambda_\mu^{L,R} \equiv \lambda_{2,t\mu}^{L,R}$$

Effects in $\tau \to \mu\gamma$

Introducing couplings to tau leptons:

Allowed regions from $\tau \to \mu\gamma$



λ_μ^R is fixed by $\delta a_\mu = 10^{-9}$

Large hierarchy of τ-couplings $\lambda_\tau^R \ll \lambda_\tau^L$c

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

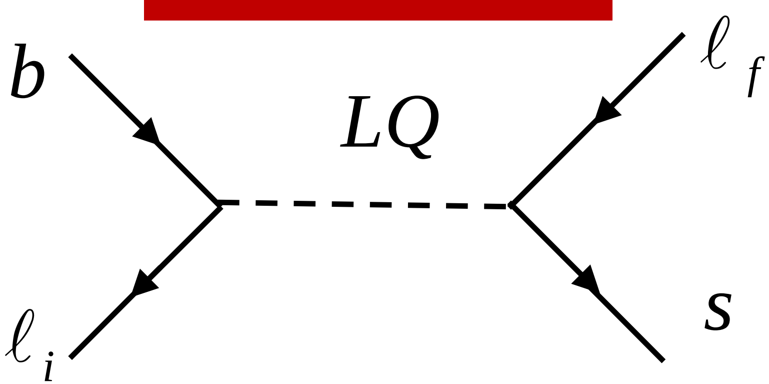
and

$$\mu \to e\gamma$$

$b \to s\ell\ell$ with LQs

	C_9	C_{10}	C_9'	C_{10}'	$C_S^{fi} = C_P^{fi}$	$C_S'^{fi} = -C_P'^{fi}$
V_1^μ	$-2\kappa_1^L\kappa_1^{L*}$	$2\kappa_1^L\kappa_1^{L*}$	$-2\kappa_1^R\kappa_1^{R*}$	$-2\kappa_1^R\kappa_1^{R*}$	$4\kappa_1^L\kappa_1^{R*}$	$4\kappa_1^L\kappa_1^{R*}$
V_3^μ	$-2\kappa_3\kappa_3^*$	$2\kappa_3\kappa_3^*$	0	0	0	0
V_2^μ	$2\kappa_2^{RL}\kappa_2^{RL*}$	$2\kappa_2^{RL}\kappa_2^{RL*}$	$2\kappa_2^{LR}\kappa_2^{LR*}$	$-2\kappa_2^{LR}\kappa_2^{LR*}$	$4\kappa_2^{LR}\kappa_2^{RL*}$	$4\kappa_2^{LR}\kappa_2^{RL*}$
$\tilde{V}_1^\mu$	0	0	0	0	0	0
$\tilde{V}_2^\mu$	0	0	0	0	0	0

$$C_9 = -C_{10}$$



	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
Φ_2	$-\lambda_2^{LR}\lambda_2^{LR*}$	$-\lambda_2^{LR}\lambda_2^{LR*}$	0	0
$\tilde{\Phi}_2$	0	0	$-\tilde{\lambda}_2\tilde{\lambda}_2^*$	$\tilde{\lambda}_2\tilde{\lambda}_2^*$
$\tilde{\Phi}_1$	0	0	$\tilde{\lambda}_1\tilde{\lambda}_1^*$	$\tilde{\lambda}_1\tilde{\lambda}_1^*$

$\mu \to e\gamma$ and $B \to Ke\mu$

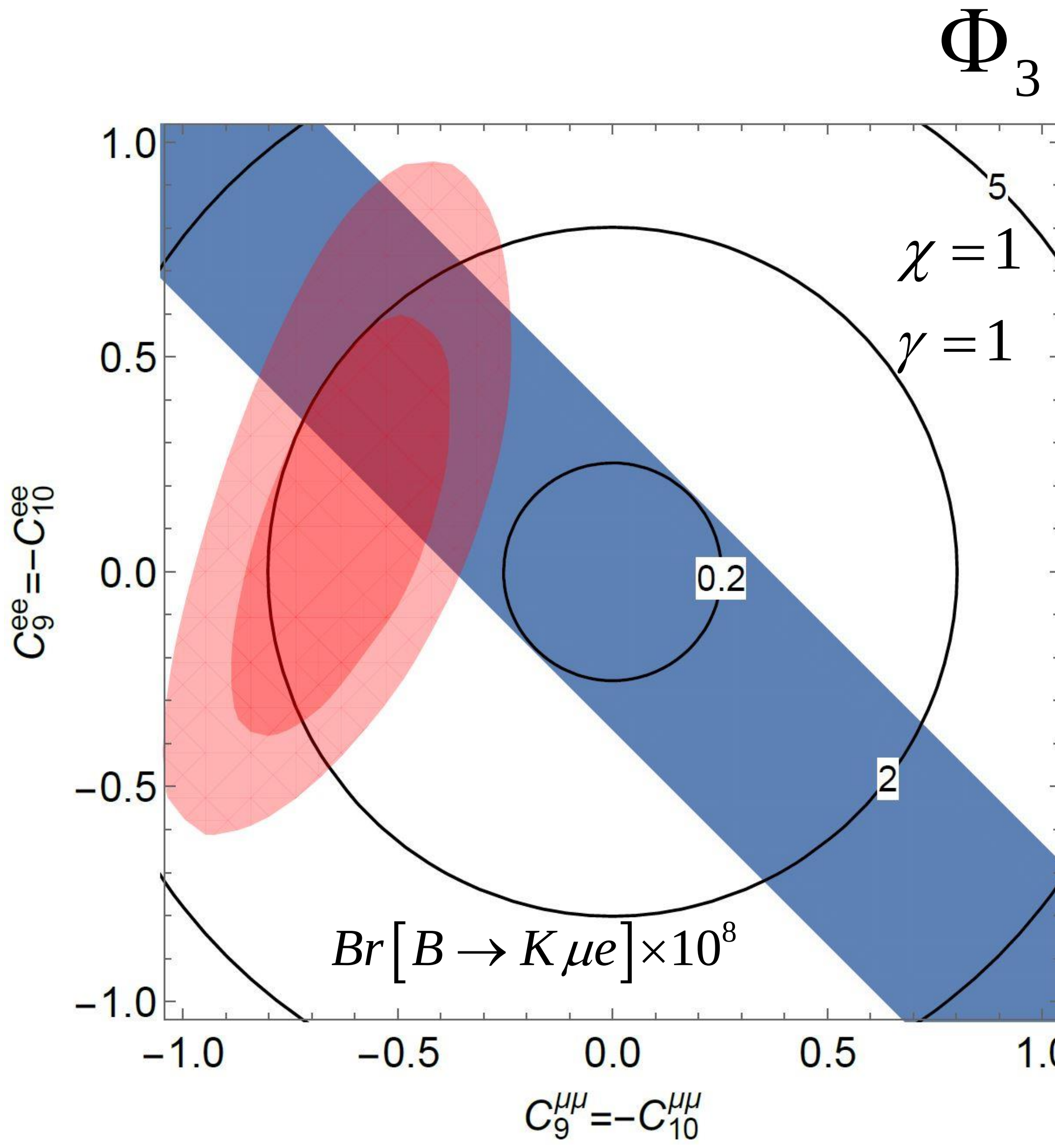
- $C_9 = -C_{10}$-contribution
  - Φ_3, V_1^μ and V_3^μ

$$Br[\mu \to e\gamma] \propto \left|\chi C_9^{ee} + \frac{C_9^{\mu\mu}}{\chi}\right|^2$$

$$Br[B \to K\mu e] \propto \left|\frac{C_9^{ee}}{\gamma}\right|^2 + \left|\gamma C_9^{\mu\mu}\right|^2$$

$$\gamma = \frac{\lambda_{3,21}^*}{\lambda_{3,22}^*} \qquad \chi = \frac{\lambda_{3,32}}{\lambda_{3,21}}$$

- For $C_9^{\mu\mu} = -\chi^2 C_9^{ee}$:
  - $Br[\mu \to e\gamma] = 0$



$\mu \to e\gamma$ and $B \to K e\mu$

- $C_9 = -C_{10}$-contribution
  - Φ_3, V_1^μ and V_3^μ

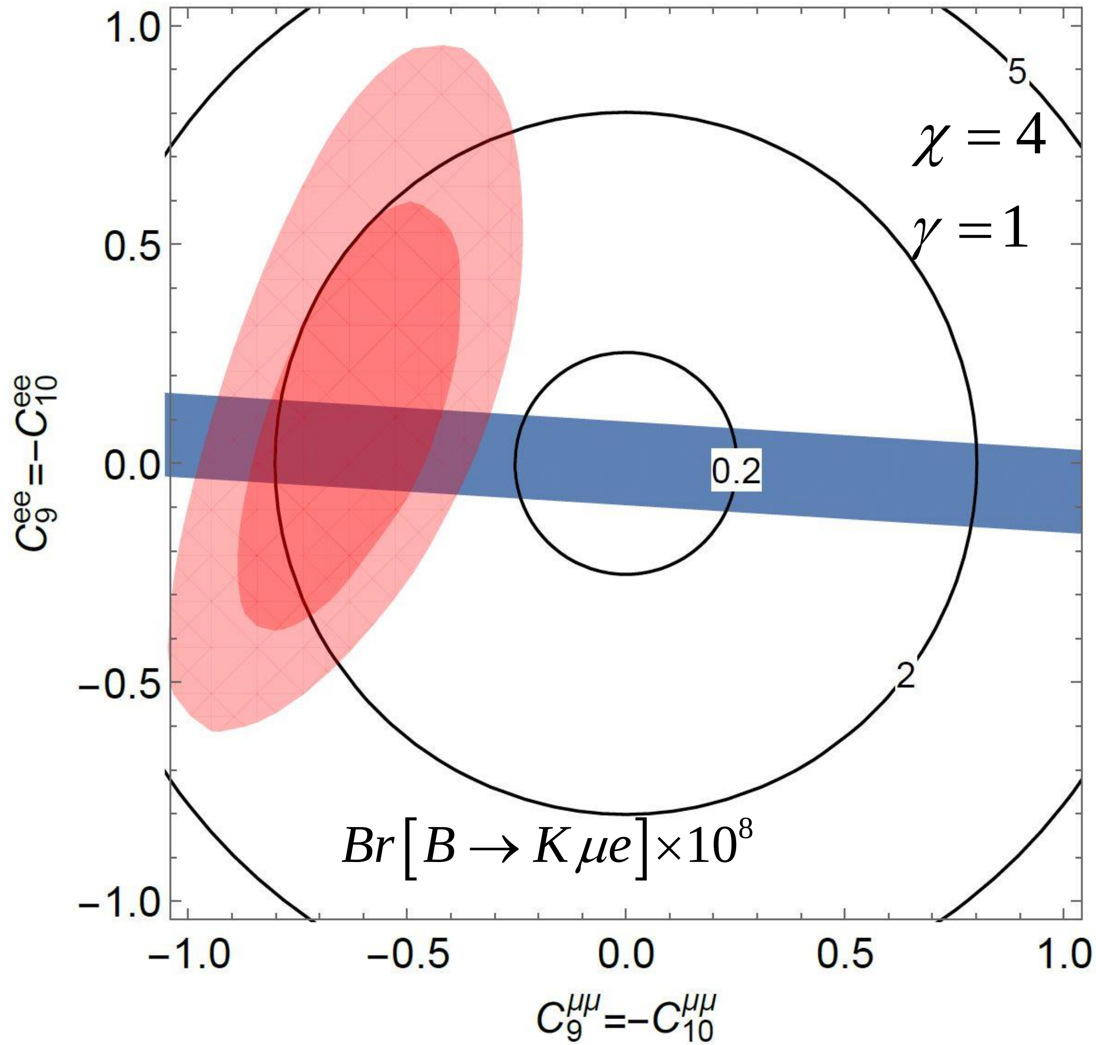
$$Br[\mu \to e\gamma] \propto \left|\chi C_9^{ee} + \frac{C_9^{\mu\mu}}{\chi}\right|^2$$

$$Br[B \to K\mu e] \propto \left|\frac{C_9^{ee}}{\gamma}\right|^2 + \left|\gamma C_9^{\mu\mu}\right|^2$$

$$\gamma = \frac{\lambda_{3,21}^*}{\lambda_{3,22}^*} \qquad \chi = \frac{\lambda_{3,32}}{\lambda_{3,21}}$$

- For $C_9^{\mu\mu} = -\chi^2 C_9^{ee}$:
  - $Br[\mu \to e\gamma] = 0$

Φ_3



$\mu \to e\gamma$ and $B \to K e\mu$

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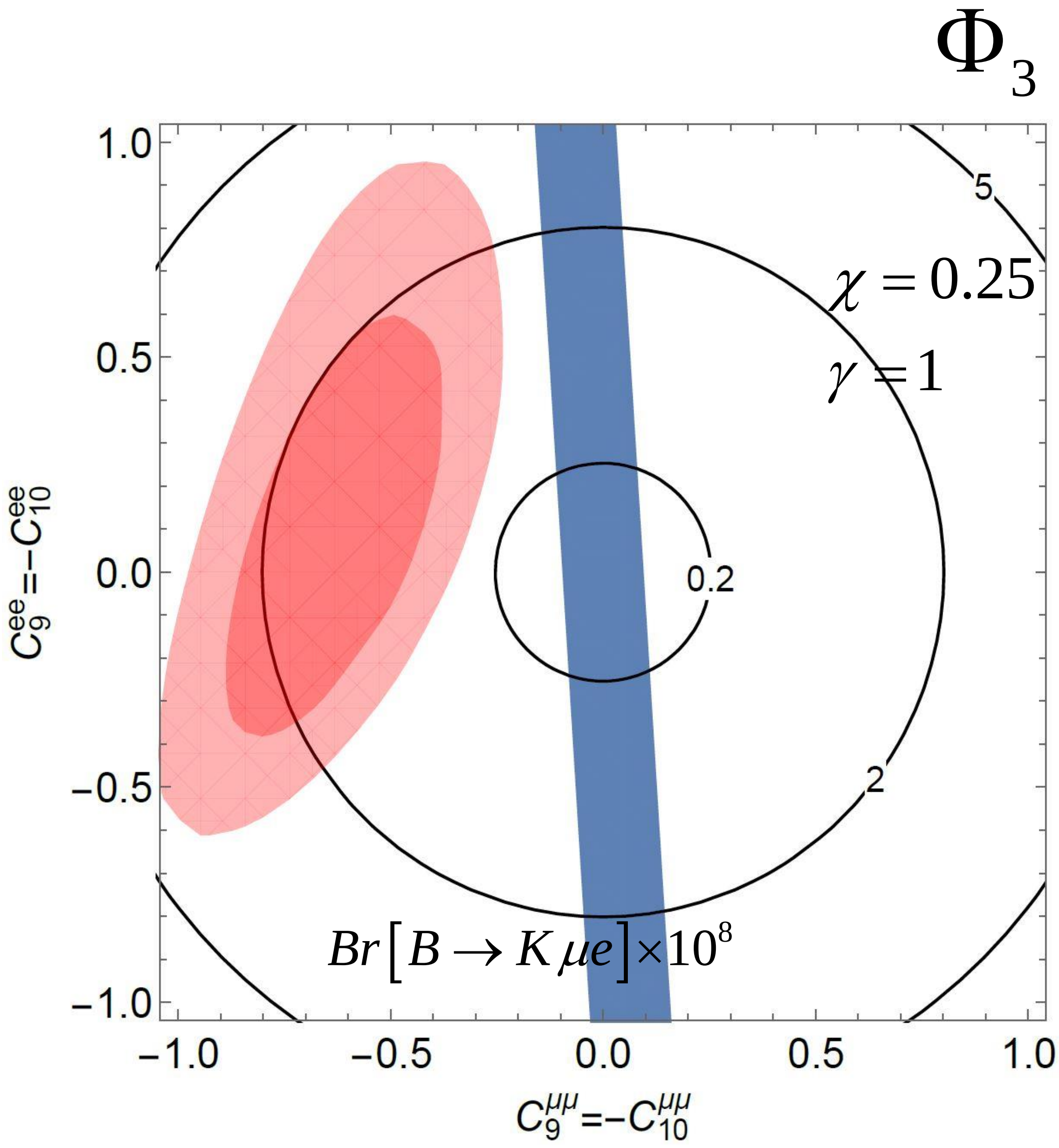
- $C_9 = -C_{10}$-contribution
  - Φ_3, V_1^μ and V_3^μ

$$Br[\mu \to e\gamma] \propto \left| \chi C_9^{ee} + \frac{C_9^{\mu\mu}}{\chi} \right|^2$$

$$Br[B \to K\mu e] \propto \left| \frac{C_9^{ee}}{\gamma} \right|^2 + \left| \gamma C_9^{\mu\mu} \right|^2$$

$$\gamma = \frac{\lambda_{3,21}^*}{\lambda_{3,22}^*} \qquad \chi = \frac{\lambda_{3,32}}{\lambda_{3,21}}$$

- For $C_9^{\mu\mu} = -\chi^2 C_9^{ee}$:
  - $Br[\mu \to e\gamma] = 0$



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Simultaneous Explanation of $R(D)$, $R(D^*)$, a_μ and $b \to s\mu\mu$

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

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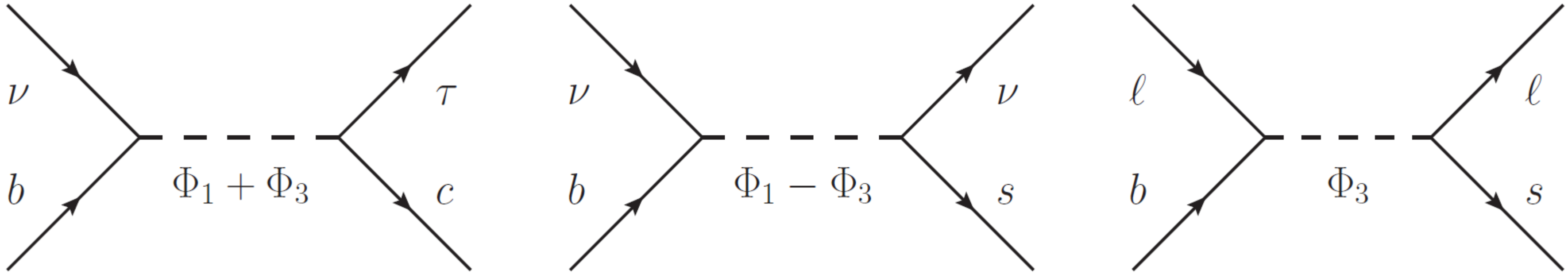
$b \to c\bar{\nu}\ell$	C_{VL}	C_{VR}
Φ_1	$-\lambda_1^L \lambda_1^{L*} V^{CKM}$	0
Φ_3	$\lambda_3 \lambda_3^* V^{CKM}$	0

$b \to s\ell\ell$	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:

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



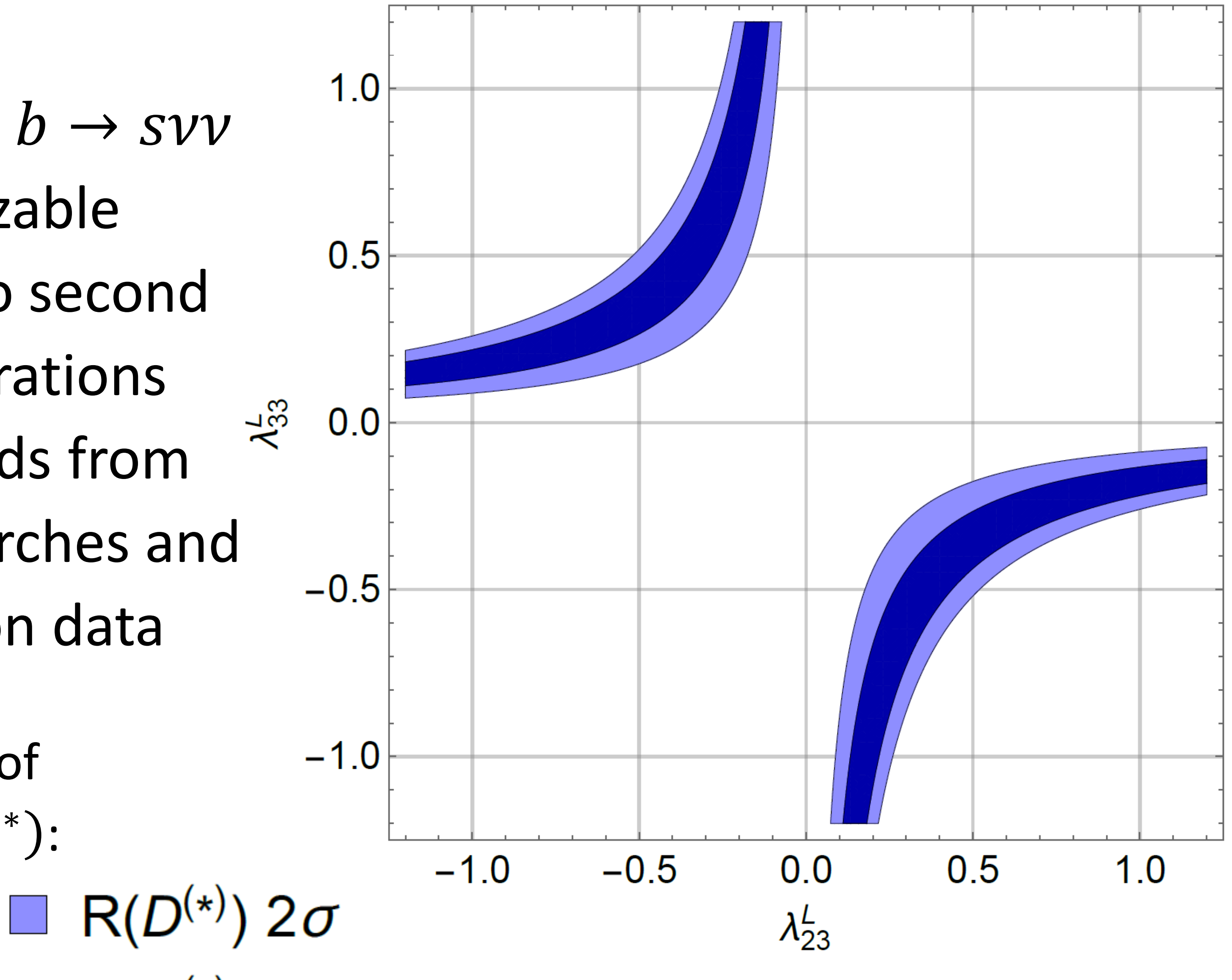
The vector LQ V_1^μ has the same feature without this symmetry

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

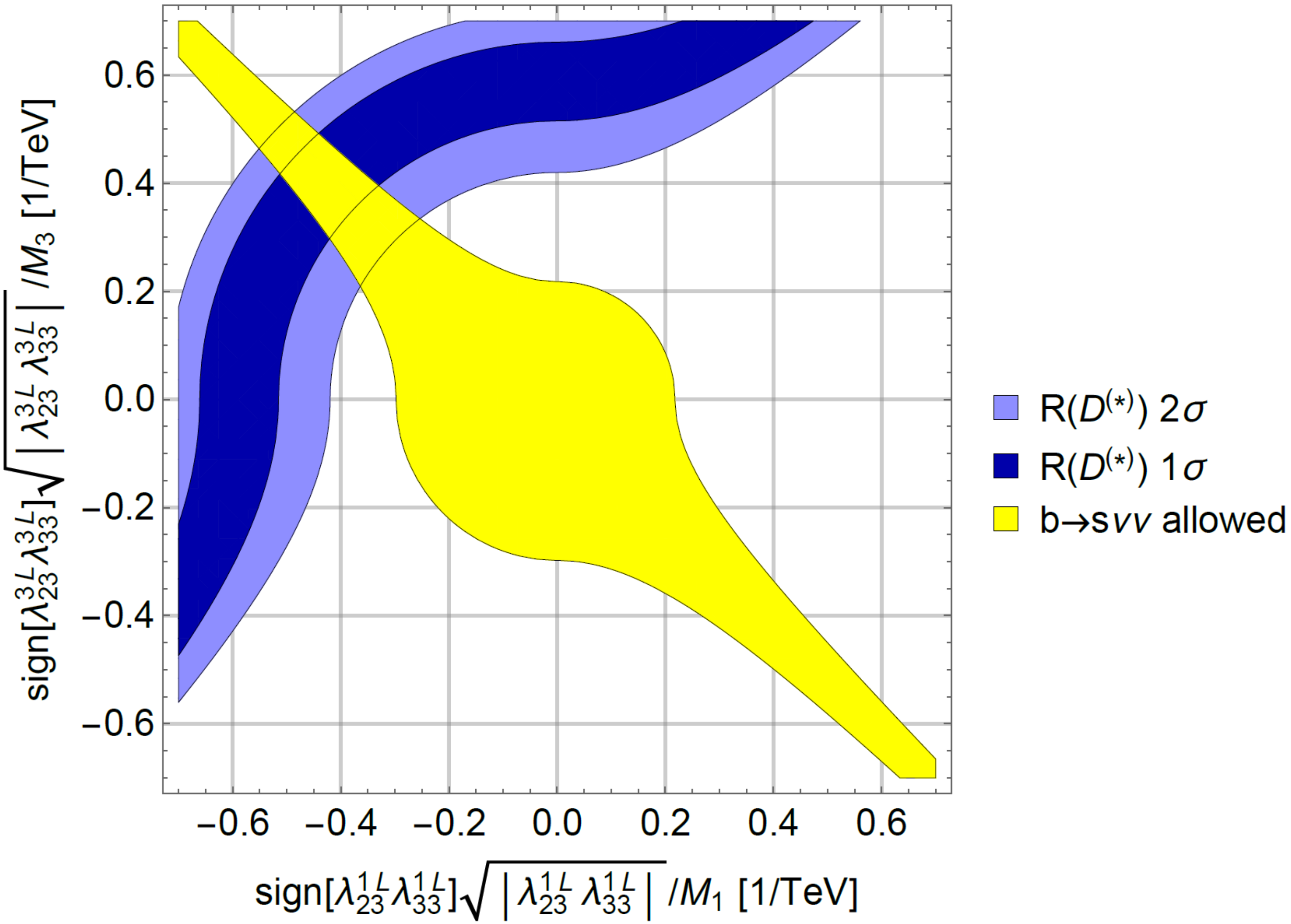
$R(D^{(*)})$

- No effect in $b \to s\nu\nu$
- Allow for sizable couplings to second quark generations
- Weak bounds from collider searches and EW precision data

Weighted sum of $R(D)$ and $R(D^*)$:

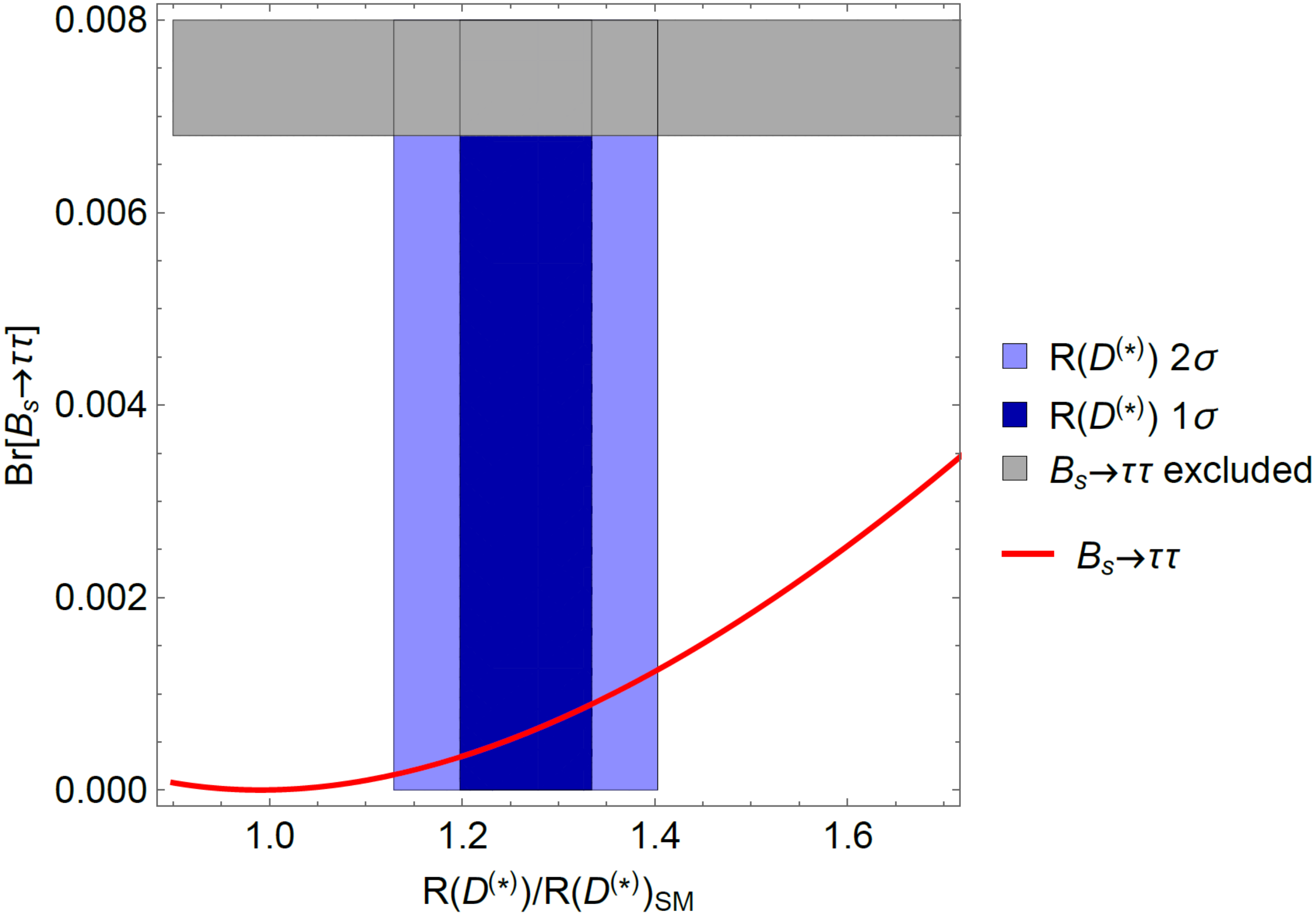


Finetuning in our Model



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

- Cancelation in b→sνν needed $C^{(1)} \sim C^{(3)}$



$B_s \to \tau\tau$ very strongly enhanced

Alonso et al., 1505.05164

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

C. Bobeth et al., 1311.0903

$R(D^{(*)})$, $b \to s\mu\mu$ and a_μ with Leptoquarks

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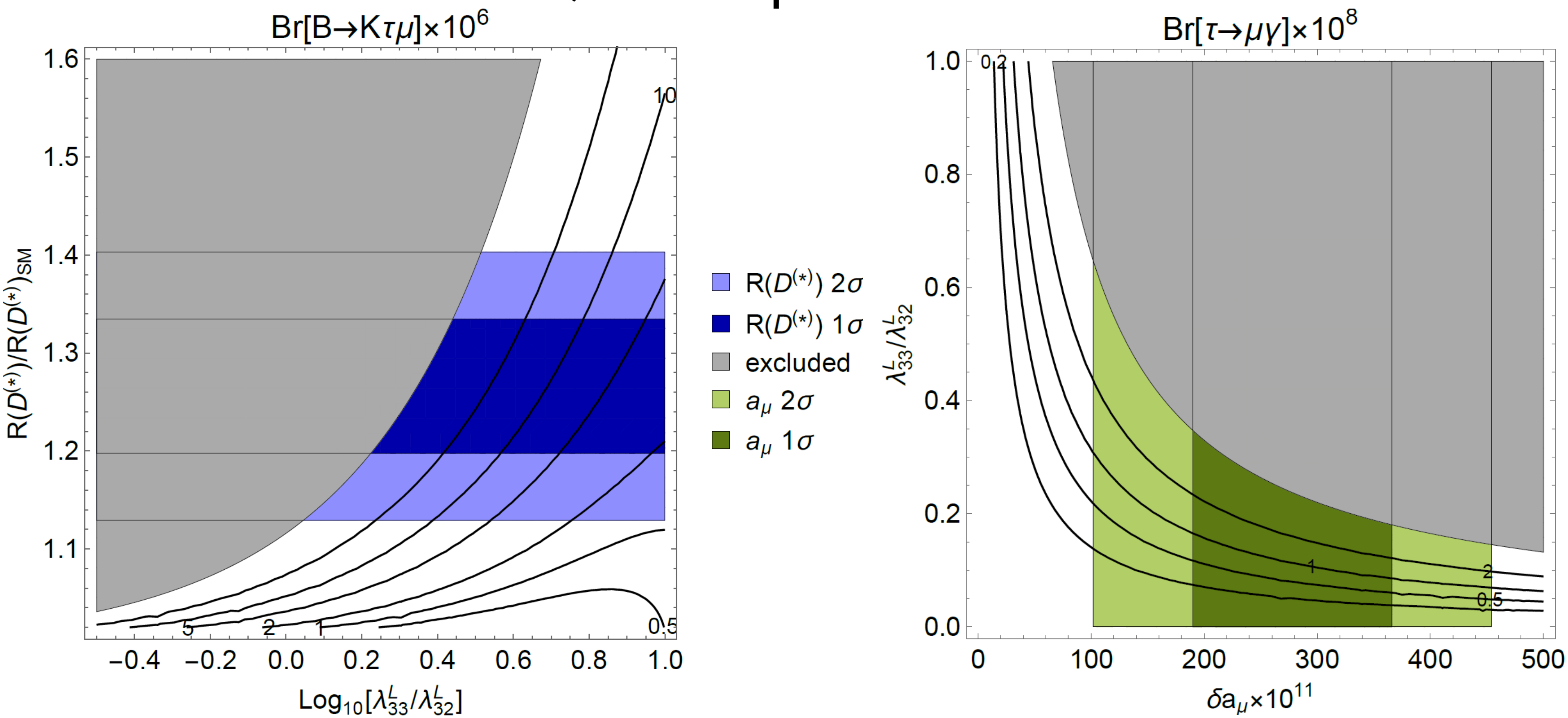
- Scalar leptoquark singlet + triplet with Y=-2/3
- Cancelation in $b \to s\nu\nu$ imposed



2 out of 3 can be explained

Conclusions

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- 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, $b \to s\mu\mu$ and $R\left(D^{(*)}\right)$ simultaneously