The Forward-Backward Asymmetry in $B \to D^* \ell \nu$: One more hint for Scalar Leptoquarks?

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arXiv:2106.09610

GdR-InF annual meeting - 16/11/2021

Alexandre Carvunis - LAPTh (Annecy)

Context & Motivations

Putative B-decay discrepancies involving $b \to s\ell\ell$ and $b \to c\ell\nu$

- Can be interpreted as the manifestation of New Physics in loops at the $\mathcal{O}(TeV)$ scale, at tree level $\mathcal{O}(10TeV)$

Muon magnetic dipole moment anomaly $a_\mu = (g-2)_\mu/2$

- Longstanding discrepancy wrt SM. Update by Fermilab 2021 : 4.2σ pull
- Only receives contributions from loops, natural probe for NP at high energy
- The discrepancy is the same size as the EW contribution, could be NP at $\mathcal{O}(TeV)$ scale

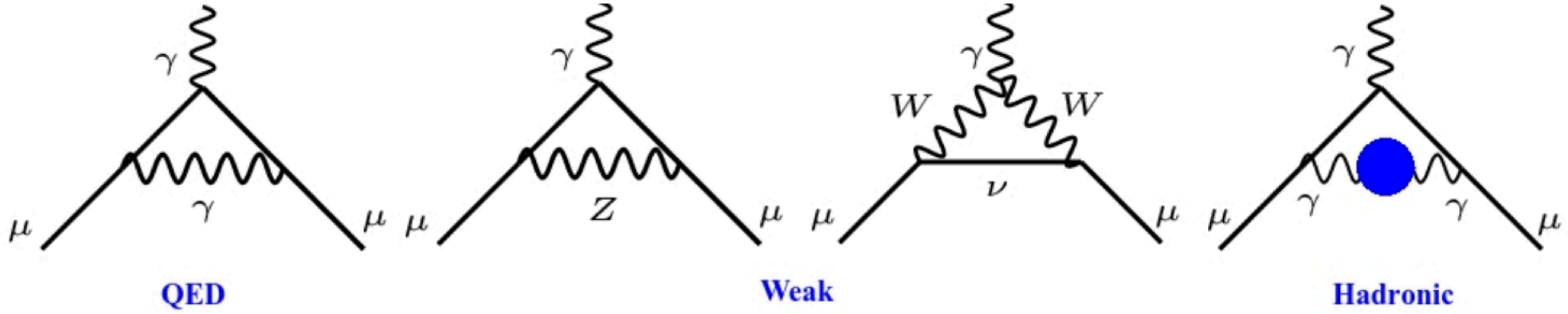

Figure from Lindner et al. (1610.06587)

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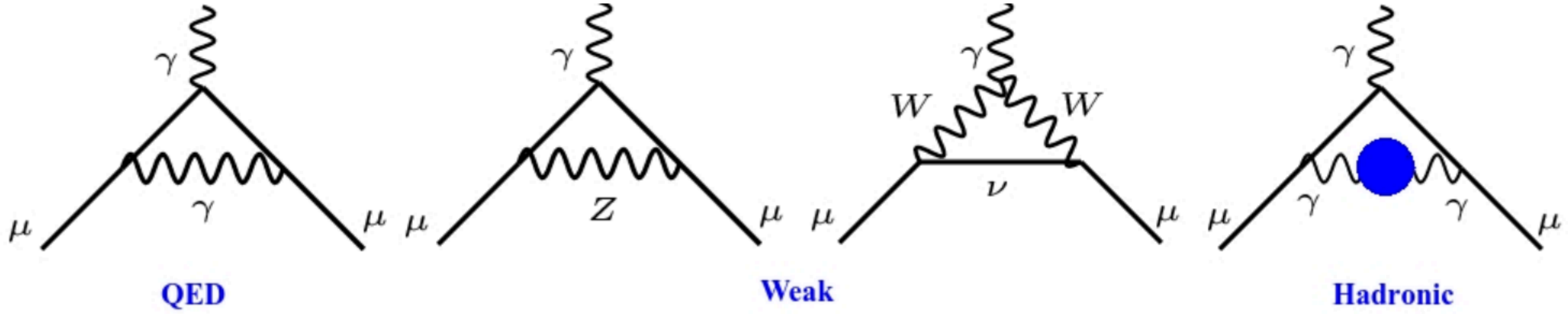


Figure from Lindner et al. (1610.06587)

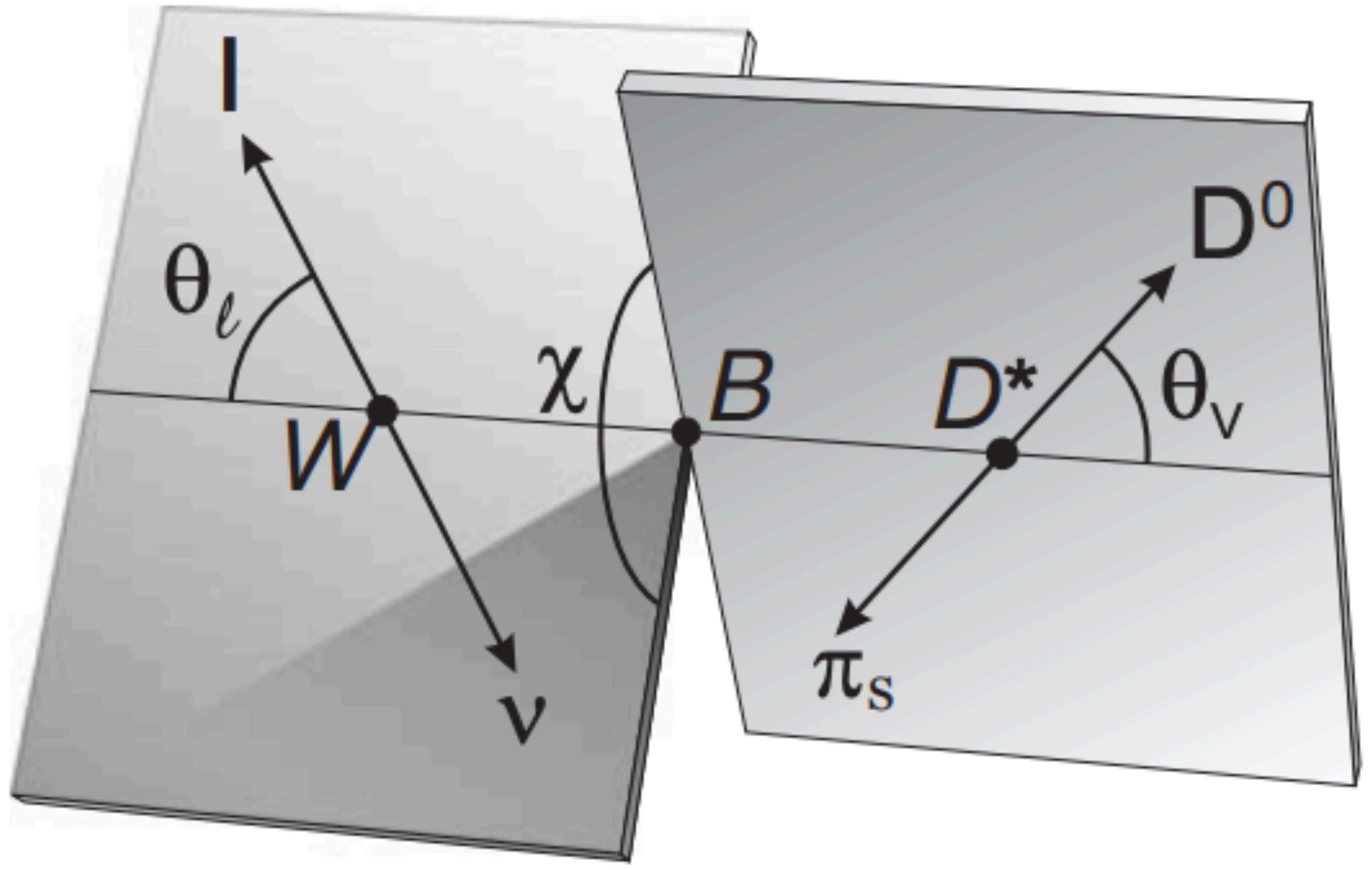
Playground for model builders
Popular solution : *Leptoquarks*

Context & Motivations

New putative discrepancies in $B \to D^*\ell\nu$?

C. Bobeth, M. Bordone, N. Gubernari, M. Jung et D. van Dyk (2104.02094)

- Based on Belle 2018 untagged (1809.03290) which released the first dataset for angular distribution of $B \to D^*\ell\nu$ with separate μ and e modes



- Includes binned decay rates and all angular coefficients in $B \to D^*\ell\nu$

- Among the angular observables Forward-Backward Asymmetry $\equiv A_{\mathrm{FB}}$

$$A_{\mathrm{FB}}(q^2) = \frac{\int_0^1 d^2\Gamma/dq^2 d\cos\theta_l - \int_{-1}^0 d^2\Gamma/dq^2 d\cos\theta_l}{\int_0^1 d^2\Gamma/dq^2 d\cos\theta_l + \int_{-1}^0 d^2\Gamma/dq^2 d\cos\theta_l}$$

- $\Delta A_{\mathrm{FB}} = A_{\mathrm{FB}}^{\mu} - A_{\mathrm{FB}}^{e}$

$$\langle A_{\mathrm{FB}} \rangle = \int_{q^2_{min}}^{q^2_{max}} A_{\mathrm{FB}}(q^2)\, \mathrm{d}q^2$$

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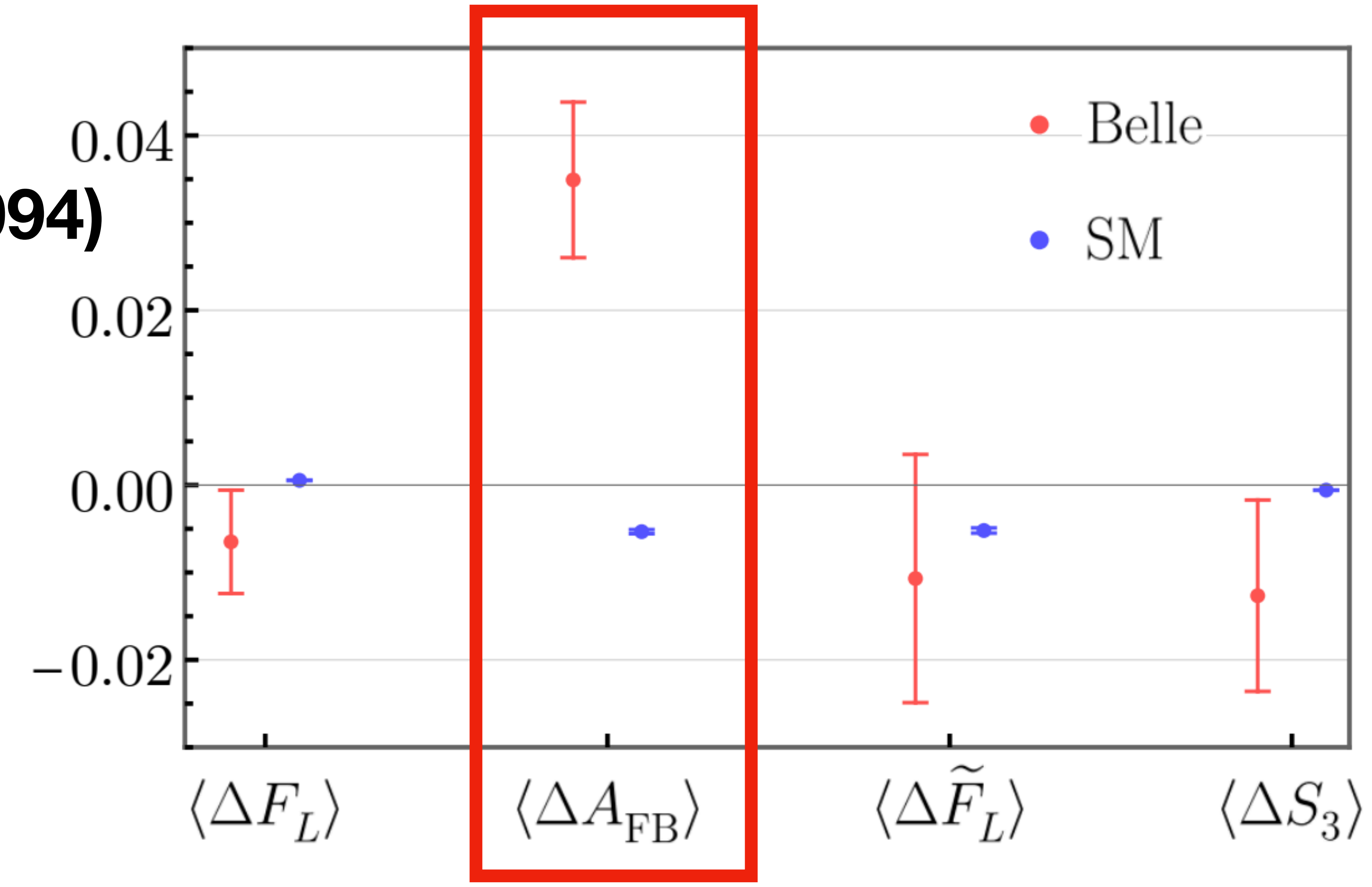
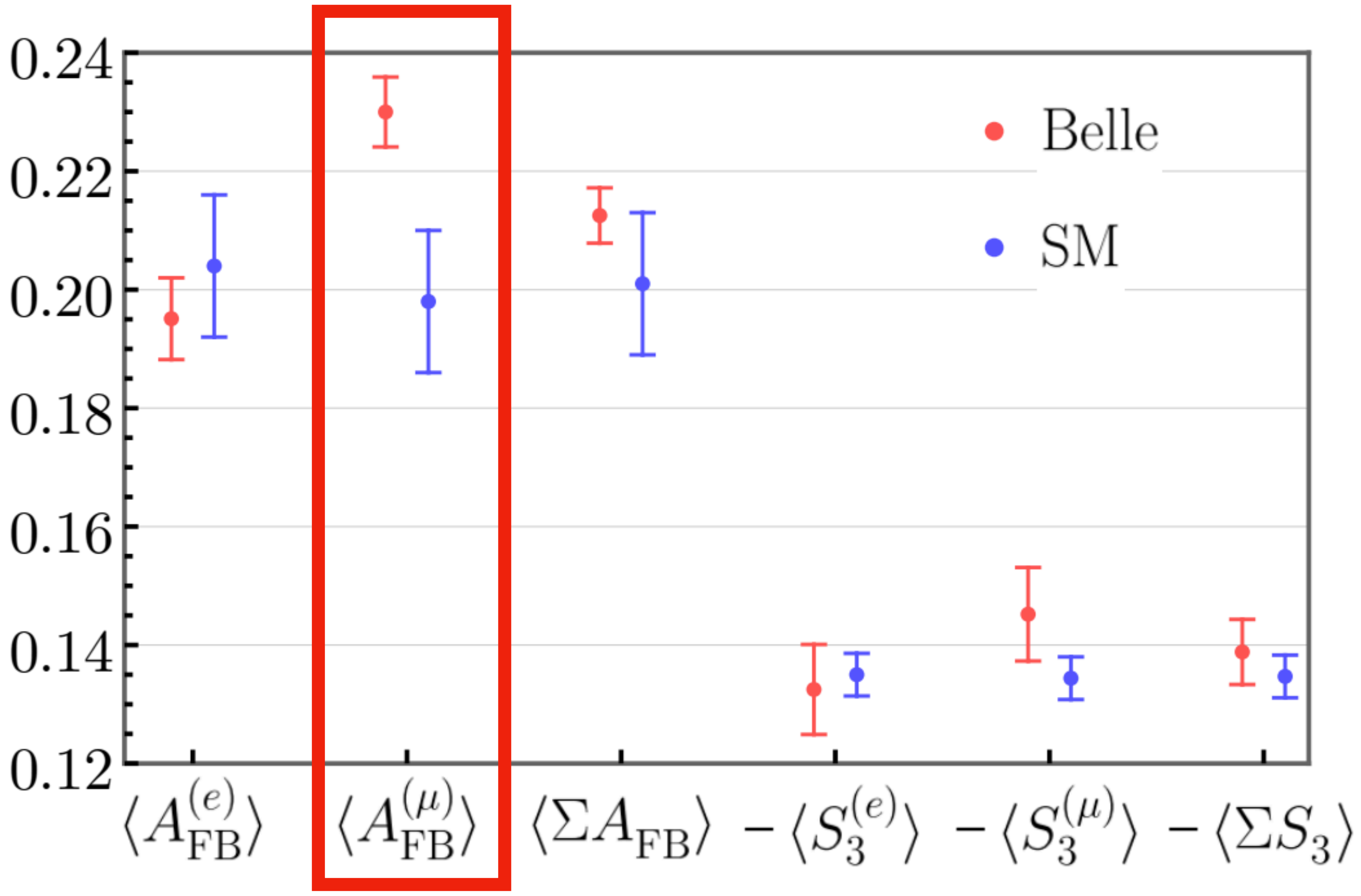


- ~ 4σ pull in $\langle \Delta A_{\rm FB} \rangle$ -> LFUV
- ~ 2σ pull in $\langle A^{\mu}_{\rm FB} \rangle$ -> NP coupled to muons ?
- Reduced uncertainty in theory predictions for « Δ » observables, good probe for LFUV
- Caveat:
  - Correlation between μ and e modes were not provided explicitly -> reconstructed by the authors
  - Inconsistencies in the statistical correlation matrix
- The $\langle \Delta A_{\rm FB} \rangle$ discrepancy holds even in the most unfavorable correlation > 3σ



Leptoquarks Models

Leptoquarks 101

Crivellin et al. (2101.07811)

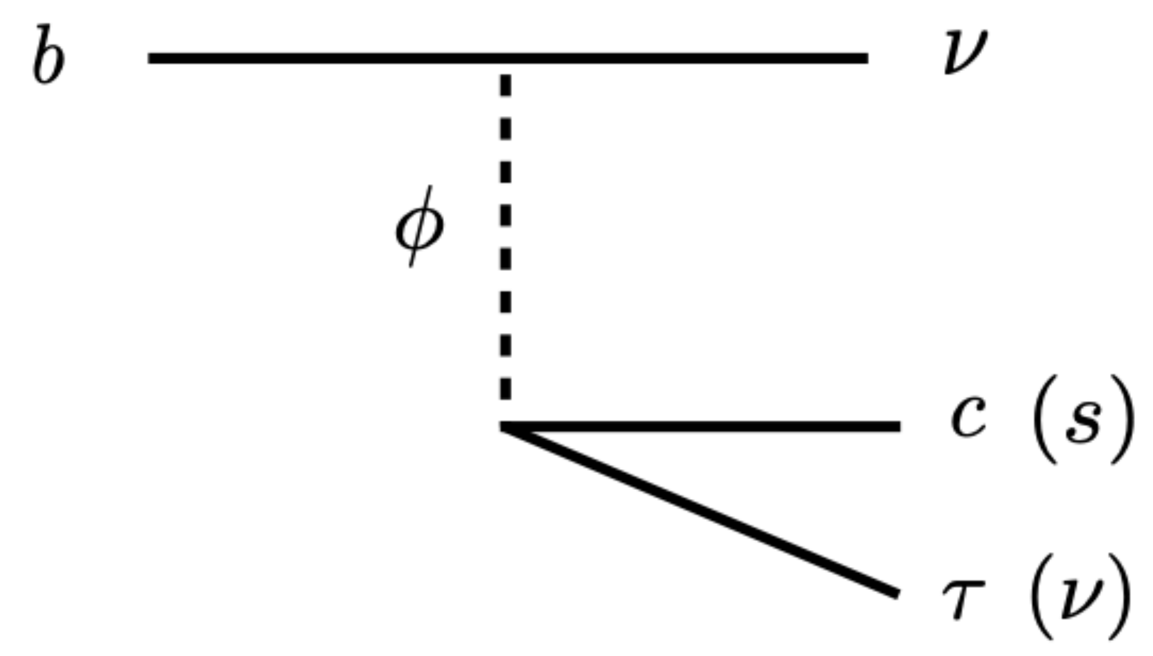
Field	Φ_1	$\tilde{\Phi}_1$	Φ_2	$\tilde{\Phi}_2$	Φ_3	V_1	$\tilde{V}_1$	V_2	$\tilde{V}_2$	V_3
$SU(3)_c$	3	3	3	3	3	3	3	3	3	3
$SU(2)_L$	1	1	2	2	3	1	1	2	2	3
$U(1)_Y$	$-\frac{2}{3}$	$-\frac{8}{3}$	$\frac{7}{3}$	$\frac{1}{3}$	$-\frac{2}{3}$	$\frac{4}{3}$	$\frac{10}{3}$	$-\frac{5}{3}$	$\frac{1}{3}$	$\frac{4}{3}$

- 10 possible representations of LQs
  5 scalars, 5 vectors. $M_{LQ} \gtrsim 1\mathrm{TeV}$

- Tree-level couplings to scalar LQs :

$$\mathcal{L}^{LQ}_{\text{scalar}} = \left(\lambda^{1R}_{fi}\overline{u^c_f}\ell_i + \lambda^{1L}_{fi}\overline{Q^c_f}\mathrm{i}\tau_2 L_i\right)\Phi_1^\dagger + \tilde{\lambda}^1_{fi}\overline{d^c_f}\ell_i\tilde{\Phi}_1^\dagger + \tilde{\lambda}^2_{fi}\overline{d_f}\tilde{\Phi}_2^\dagger L_i$$
$$+ \left(\lambda^{2RL}_{fi}\overline{u_f}L_i + \lambda^{2LR}_{fi}\overline{Q}_f\mathrm{i}\tau_2\ell_i\right)\Phi_2^\dagger + \lambda^3_{fi}\overline{Q^c_f}\mathrm{i}\tau_2(\tau\cdot\Phi_3)^\dagger L_i + \text{h.c.}\,.$$

- LQs affect flavor physics at low energy, eg $b \to c\tau\nu$



Leptoquarks to EFTs

LQ in Weak Effective Theory (WET)

Crivellin et al. (1706.08511)

$$\mathcal{H}_{\text{eff}}^{\ell_f\nu_i} = \frac{4G_F}{\sqrt{2}} V_{cb} \sum_k C_k^{fi} O_k^{fi} + \text{h.c.}$$

$$O_{VL(R)}^{fi} = \bar{c}\gamma^\mu P_{L(R)} b\, \bar{\ell}_f \gamma_\mu P_L \nu_i\,,$$

$$O_{SL(R)}^{fi} = \bar{c} P_{L(R)} b\, \bar{\ell}_f P_L \nu_i\,,$$

$$O_{TL}^{fi} = \bar{c}\sigma^{\mu\nu} P_L b\, \bar{\ell}_f \sigma_{\mu\nu} P_L \nu_i\,.$$

For our model building purpose $f, i = 2$

Each LQ model generates a unique set of WCs

Is one of these LQ models preferred by $b \to c\ell\bar{\nu}$ data?

$b \to c\bar{\nu}_i\ell_f^-$	C_{VL}^{fi}	C_{VR}^{fi}	C_{SL}^{fi}	C_{SR}^{fi}	C_{TL}^{fi}	DOF in WET:
Φ_1	$-\lambda_{3i}^{1L} V_{2j} \lambda_{jf}^{1L*}$	0	$\lambda_{3i}^{1L}\lambda_{2f}^{1R*}$	0	$-\frac{1}{4}\lambda_{3i}^{1L}\lambda_{2f}^{1R*}$	$C_{VL}^{fi}, C_{SL}^{fi} = -8.5C_{TL}^{fi}$
Φ_3	$\lambda_{3i}^{3} V_{2j} \lambda_{jf}^{3*}$	0	0	0	0	C_{VL}^{fi}
Φ_2	0	0	$\lambda_{2i}^{2RL}\lambda_{3f}^{2LR*}$	0	$\frac{1}{4}\lambda_{2i}^{2RL}\lambda_{3f}^{2LR*}$	$C_{SL}^{fi} = 8.5C_{TL}^{fi}$
$\tilde{\Phi}_2$	0	0	0	0	0	
$\tilde{\Phi}_1$	0	0	0	0	0	
V_1^μ	$-2\kappa_{3f}^{1L*} V_{2j} \kappa_{ji}^{1L}$	0	0	$4\kappa_{3f}^{1R*} V_{2j} \kappa_{ji}^{1L}$	0	C_{VL}^{fi}, C_{SR}^{fi}
V_3^μ	$2\kappa_{3f}^{3*} V_{2j} \kappa_{ji}^{3}$	0	0	0	0	C_{VL}^{fi}
V_2^μ	0	0	0	$4\kappa_{3i}^{2RL} V_{2j} \kappa_{jf}^{2LR*}$	0	C_{SR}^{fi}
$\tilde{V}_1^\mu$	0	0	0	0	0	
$\tilde{V}_2^\mu$	0	0	0	0	0	

Table 4. Contribution of the various LQ representation to $b \to c\bar{\nu}_i\ell_f^-$. Each entry should be multiplied by a factor $\frac{-\sqrt{2}}{8G_F V_{cb}}\frac{1}{M^2}$.

Global Fit using `flavio`

With a single leptoquark

Including ΔA_{FB}, ΔF_L, ΔS_3, $R^{\mu e}_{D^{(*)}} = \dfrac{BR(B \to D^{(*)}\mu\nu)}{BR(B \to D^{(*)}e\nu)}$, …

Leptoquark	Scenario	SM pull (σ)	p-value
–	SM	–	0.017
Φ_3, V_3^μ	C^μ_{VL}	0.96	0.013
Φ_2	$C^\mu_{SL} = 8.5\, C^\mu_T$	1.60	0.017
V_2^μ	C^μ_{SR}	1.97	0.019
V_1^μ	C^μ_{VL}, C^μ_{SR}	2.28	0.031
–	C^μ_T	3.36	0.093
Φ_1	$C^\mu_{VL}, C^\mu_{SL} = -8.5\, C^\mu_T$	**3.92**	0.240

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Including ΔA_{FB}, ΔF_L, ΔS_3, $R^{\mu e}_{D^{(*)}} = \dfrac{BR(B \to D^{(*)}\mu\nu)}{BR(B \to D^{(*)}e\nu)}$, …

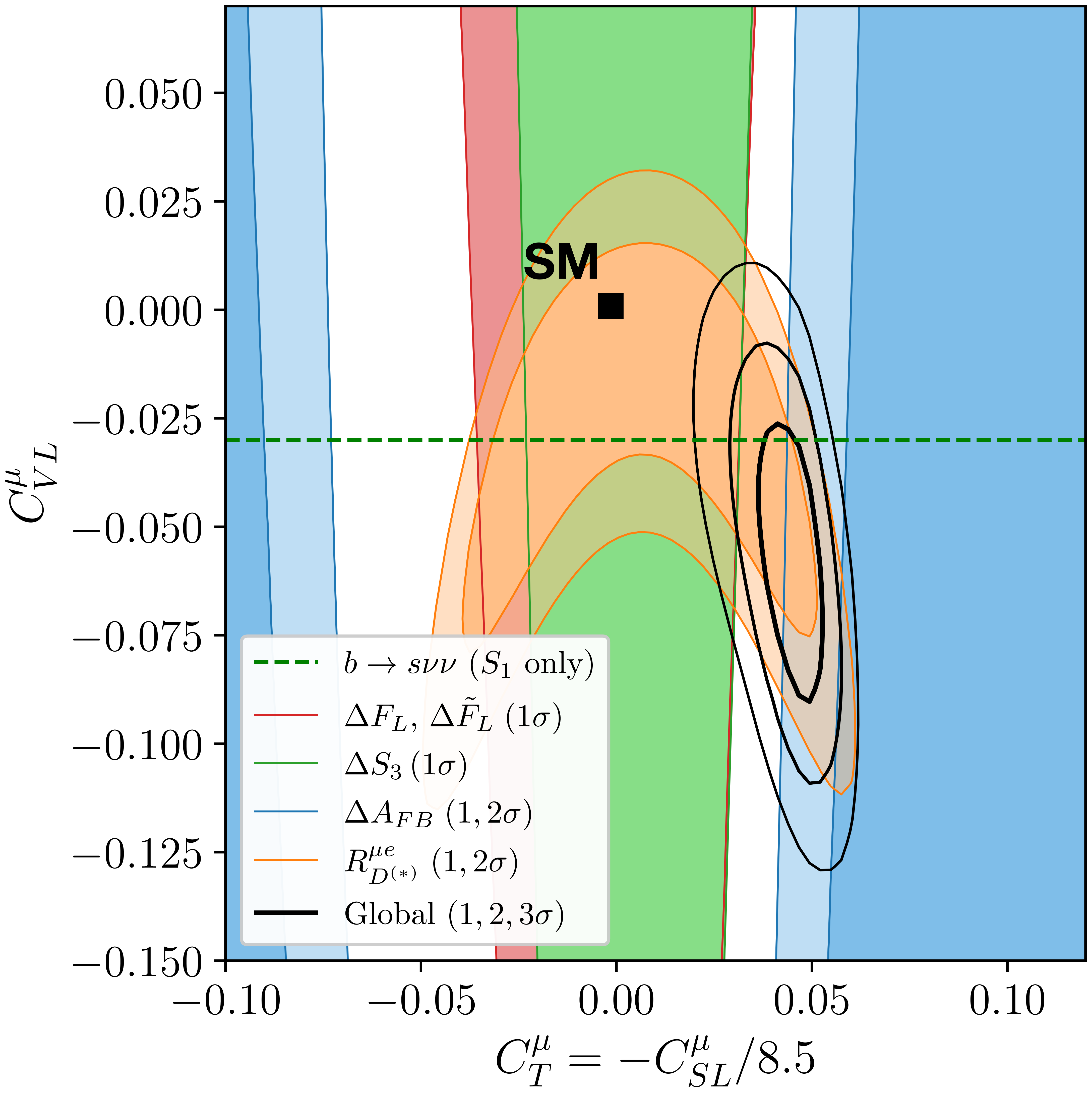
Scenario	SM pull (σ)	p-value
SM	–	0.017
$C^{\mu}_{VL}, C^{\mu}_{SL}, C^{\mu}_{SR}, C^{\mu}_{T}$	**3.39**	0.196
$C^{\mu}_{VL}, C^{\mu}_{SL}, C^{\mu}_{T}$	**3.72**	0.237
$C^{\mu}_{VL}, C^{\mu}_{SL}, C^{\mu}_{SR}$	2.14	0.044
$C^{\mu}_{SL}, C^{\mu}_{SR}, C^{\mu}_{T}$	**3.43**	0.174
$C^{\mu}_{VL}, C^{\mu}_{SL} = -8.5\, C^{\mu}_{T}$	**3.92**	0.240
$C^{\mu}_{VL}, C^{\mu}_{SL} = 8.5\, C^{\mu}_{T}$	2.09	0.037

Φ_1 LQ model preferred

Global fit

In the C^{μ}_{VL} vs $C^{\mu}_{T} = -C^{\mu}_{SL}/8.5$ plane

- Pull with SM $\approx 4\sigma$
- $\Delta F_L, \Delta S_3$ do not allow large deviations in $C^{\mu}_{T} = -C^{\mu}_{SL}/8.5$
- Additional bound from $R^{\nu\bar{\nu}}_{K^{(*)}}$, which can be lowered by the addition of a triplet scalar leptoquark Φ_3
- Φ_1 and Φ_3 together can explain $R_{D^{(*)}}$, a_μ and $b \to s\ell\ell$ (Crivellin et al. 1703.09226)



Conclusion

- In addition to existing hints at LFUV, and more specifically NP in muons, Bobeth et al. (2104.02094) finds a potential 4σ pull in $\Delta A_{FB} = A_{FB}^{\mu} - A_{FB}^{e}$ with respect to the SM
- We find that the $SU(2)_L$-singlet LQ Φ_1 is the only scenario that improves significantly the description of data
- The bound from $R_{K*}^{\nu\bar{\nu}}$ and the $R_{D^{(*)}}$ discrepancy call for Φ_3
- Need reanalysis of Belle 2018 data with full lepton specific correlation matrix
- More updates are coming soon, eg R_{D*} at CMS

Thank you!

Leptoquarks to EFTs

LQ in Weak Effective Theory (WET), eg $SU(2)_L$-singlet scalar Φ_1

$$\mathcal{H}_{\text{eff}}^{\ell\nu} = \frac{4G_F}{\sqrt{2}} V_{cb} \left(C_{VL}^{\ell} O_{VL}^{\ell} + C_{SL}^{\ell} O_{SL}^{\ell} + C_T^{\ell} O_T^{\ell} \right)$$

$$O_{VL}^{\ell} = \bar{c}\gamma^{\mu} P_L b \;\; \bar{\ell}\gamma_{\mu} P_L \nu_{\ell} \,,$$
$$O_{SL}^{\ell} = \bar{c} P_L b \;\; \bar{\ell} P_L \nu_{\ell} \,,$$
$$O_T^{\ell} = \bar{c}\sigma^{\mu\nu} P_L b \;\; \bar{\ell}\sigma_{\mu\nu} P_L \nu_{\ell} \,.$$

In the SM: $C^{\mu}_{VL} = 1, C^{\mu}_{SL} = 0, C^{\mu}_{T} = 0$ at the EW scale

Matching of singlet scalar Φ_1 LQ to this effective Hamiltonian:

$$C_{VL}^{\ell} = \frac{\sqrt{2}}{8G_F V_{cb}} \frac{V_{cj}\lambda_{j\ell}^{L*}\lambda_{3\ell}^{L}}{M^2} \,,$$

$$\boxed{C_{SL}^{\ell} = -4C_T^{\ell}} = -\frac{\sqrt{2}}{8G_F V_{cb}} \frac{\lambda_{2\ell}^{R*}\lambda_{3\ell}^{L}}{M^2} \,.$$

RGE evolution from scale M to m_b provides $\begin{pmatrix} C_{SL}^{\ell}(m_b) \\ C_T^{\ell}(m_b) \end{pmatrix} \approx \begin{pmatrix} 1.8 & -0.3 \\ 0 & 0.8 \end{pmatrix} \begin{pmatrix} C_{SL}^{\ell}(M) \\ C_T^{\ell}(M) \end{pmatrix}$

At the b mass scale this implies $\boxed{C^{\ell}_{SL} \approx -8.5 C^{\ell}_{T}}$

Log-Likelihood with flavio

A python package for flavour physics

Parameters: $G_F, m_q, V_{CKM}, \ldots$

Wilson Coeff: $WC_j = WC_j^{SM} + WC_j^{NP}$

MCMC

Theory prediction $\vec{O}^{\mathrm{th}}$

Covariance matrix C_{th}

$$\vec{O} = \left[\Delta A_{FB}, R_{D*}^{\mu e}, \ldots\right]$$

Experimental data
$\vec{O}^{\mathrm{exp}}$ and C_{exp}

$$-2\ln \widetilde{L}_{\mathrm{exp}} = \vec{x}^T (C_{\mathrm{exp}} + C_{\mathrm{th}})^{-1} \vec{x}\,,$$

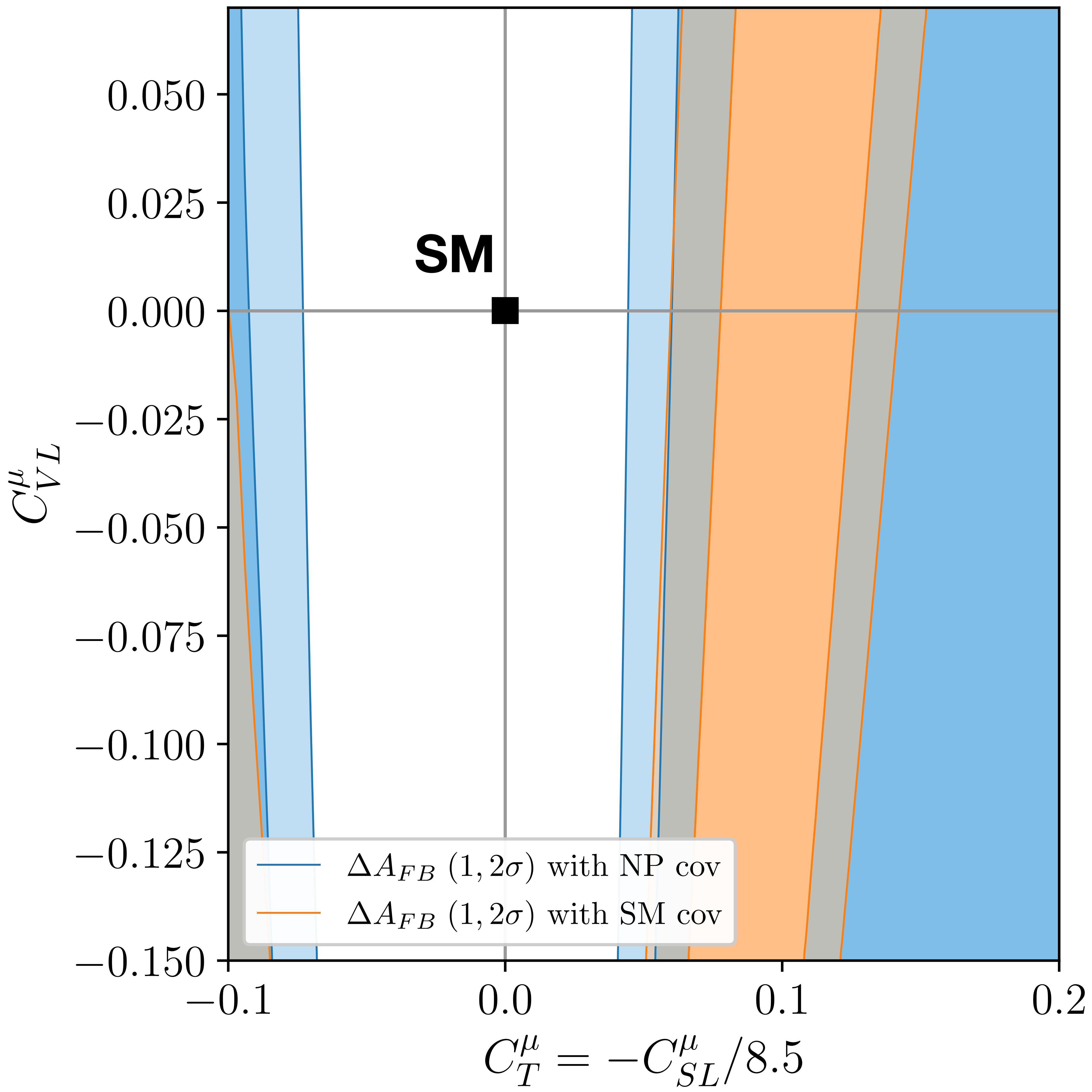
$$\vec{x} = \vec{O}^{exp} - \vec{O}^{th}$$

Log-Likelihood

Partial Fit

Theoretical covariance

- Using flavio we compute the likelihood of NP contributions to WCs
- Large theoretical uncertainty for $C_T^\mu, C_{SL}^\mu \neq 0$
- ΔA_{FB} is independent of C_{VL}^μ at leading order in NP Wilson Coefficients.



LQ analysis

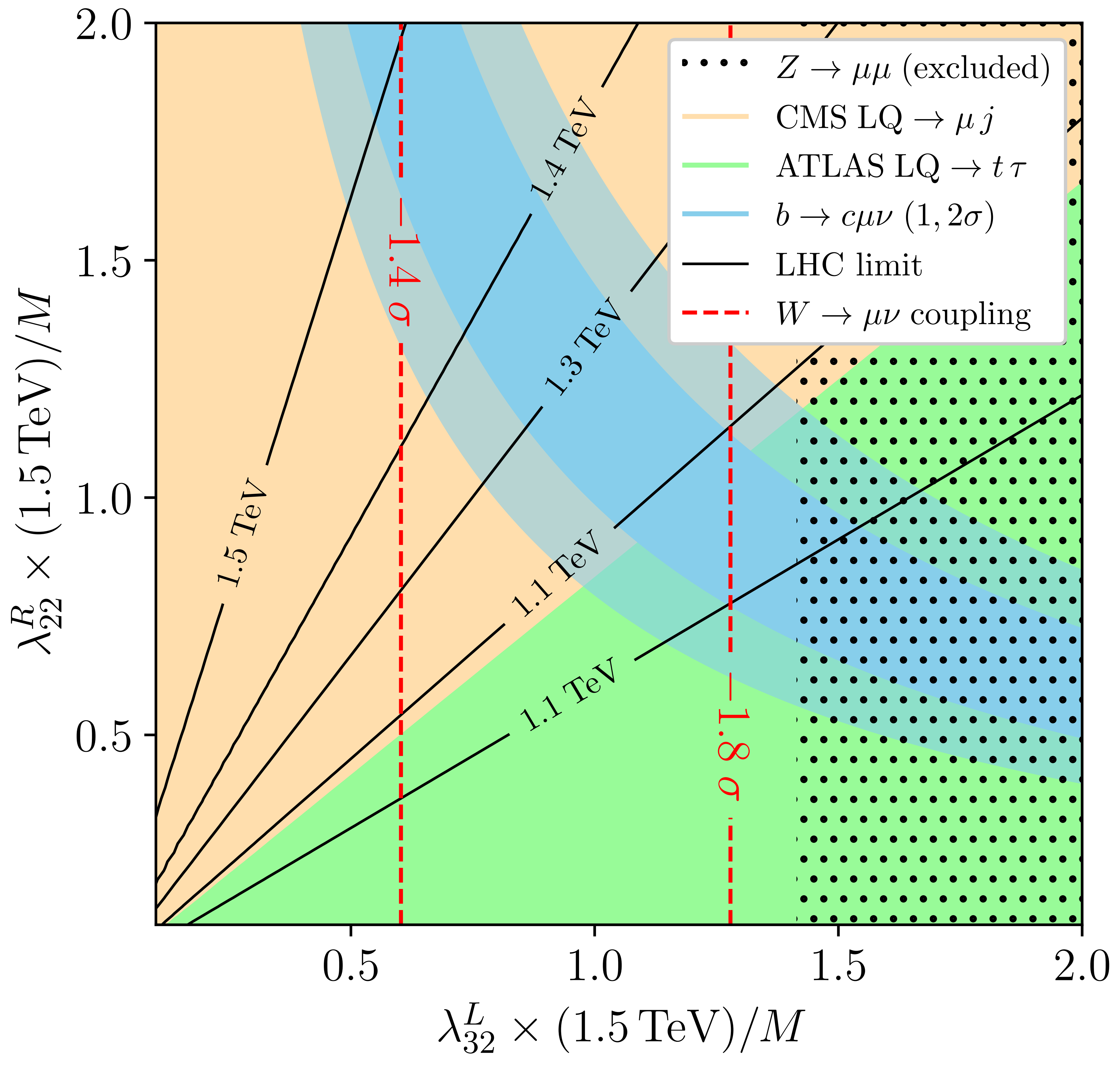
$$\mathcal{L} = \left(\lambda^L_{fi}\overline{Q^c_f}i\tau_2 L_i + \lambda^R_{fi}\overline{u^c_f}\ell_i\right)\Phi_1^\dagger + \text{h.c.}\,.$$

- In blue: allowed $\lambda^L_{32} - \lambda^R_{22}$ in the best fit region from $b \to c\ell\nu$, profiling over C_{VL}
- Strong bound from $\tau \to \mu\nu\nu/\tau \to e\nu\nu$ via $W \to \mu\nu$ coupling

$$\mathcal{L} = \frac{g_2}{\sqrt{2}}\Lambda^W_{22}\left(\bar{\mu}\gamma^\alpha P_L \nu_\mu W^-_\alpha\right) + \text{h.c.}$$

$$\Lambda^W_{22} = 1.0018 \pm 0.0014$$

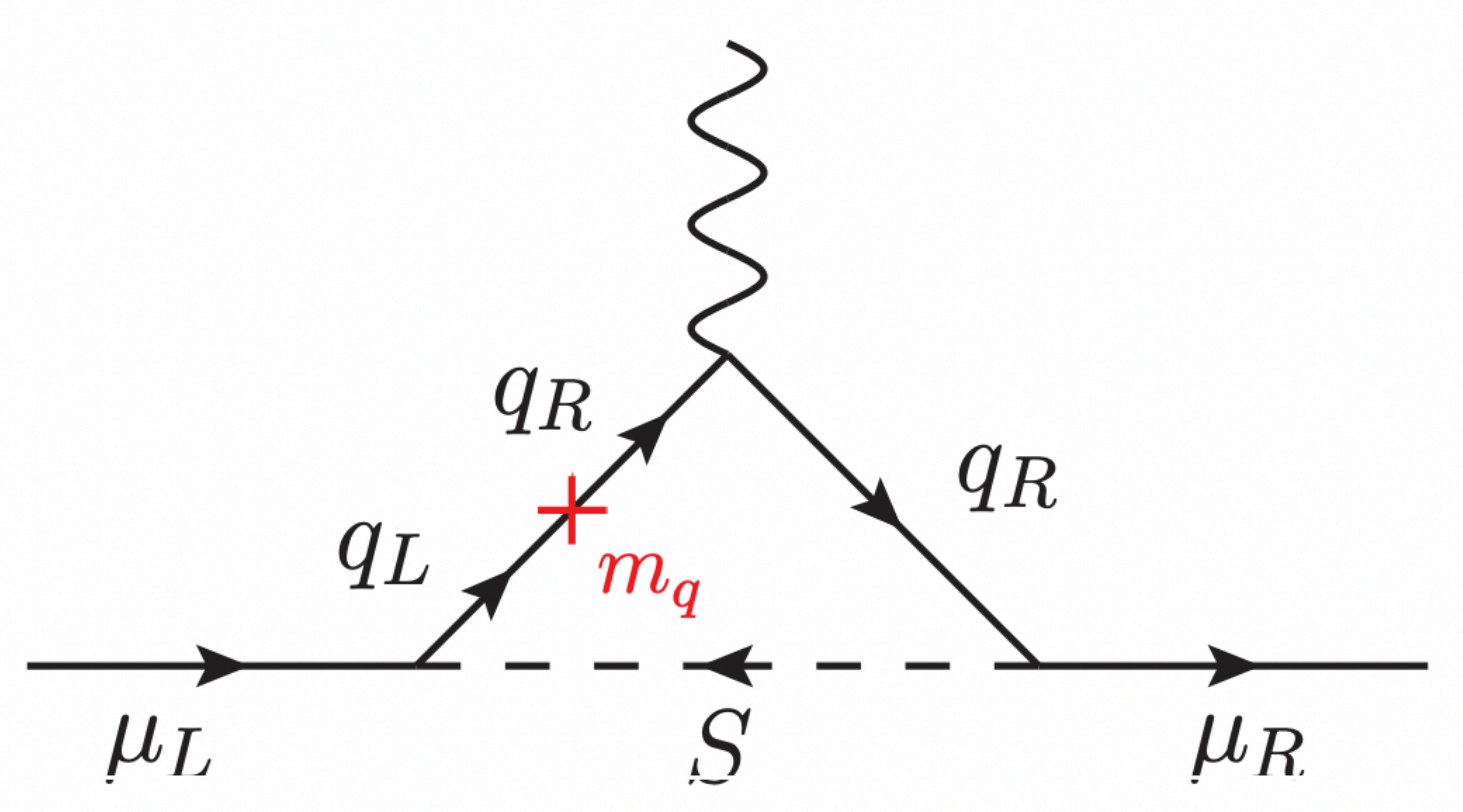
- Lower limit on LQ mass by CMS and ATLAS leptoquark searches via $\mu\, j$ and $t\,\tau$ final states respectively



Scalar LQs and $(g-2)_\mu$

Effective operator for muon g-2

$$\mathcal{L} = y \frac{v}{M^2} \bar{\mu}_R \sigma^{\mu\nu} \mu_L F_{\mu\nu} + \text{h.c.}$$



$$\lambda^R_{fi} \overline{u^c_f} \ell_i \Phi_1^\dagger + h.c.\,. \tag{18}$$

In this case the numerically relevant m_t enhanced contribution to a_μ is given by

$$\delta a_\mu = \frac{m_\mu}{4\pi^2} \mathrm{Re}\left[C_R^{22}\right], \tag{19}$$

with

$$C_L^{fi} = -\frac{N_c}{12M^2} m_t \lambda^R_{3f} \lambda^{L*}_{3i} \left(7 + 4\log\left(\frac{m_t^2}{M^2}\right)\right), \tag{20}$$

and C_R^{23} is obtained from C_L^{23} by $L \leftrightarrow R$. We will assume that λ^R_{32} is small compared to λ^L_{32}.

Crivellin et al. 1703.09226