

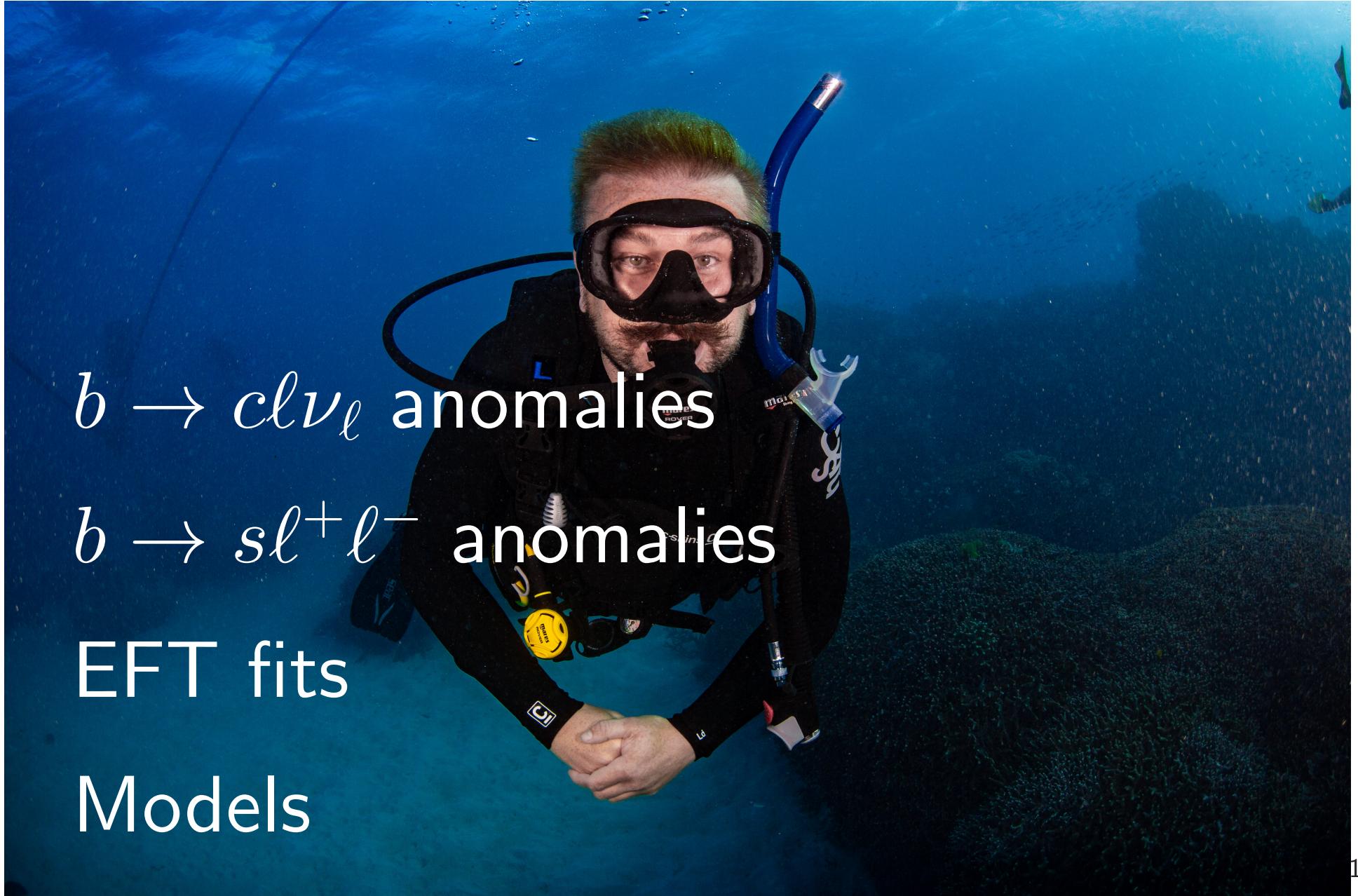
# Fits to rare HF decays

$b \rightarrow c l \bar{\nu}_\ell$  anomalies

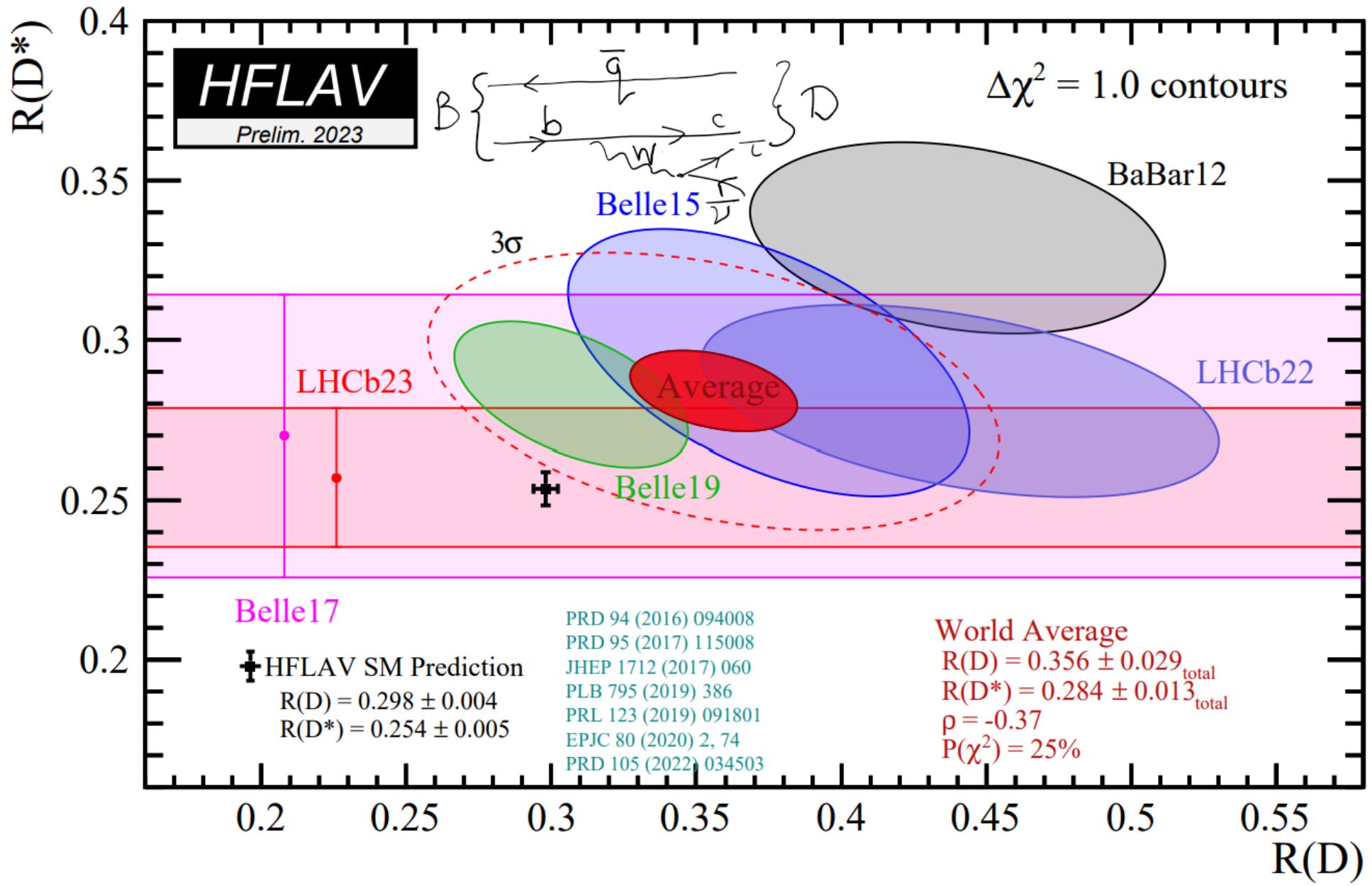
$b \rightarrow s \ell^+ \ell^-$  anomalies

EFT fits

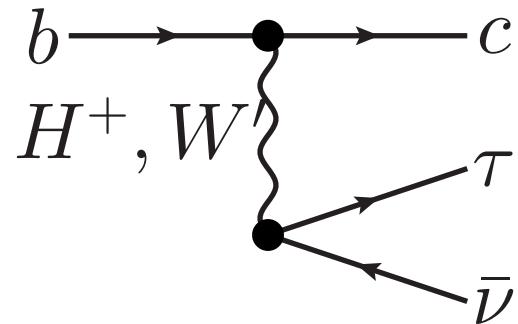
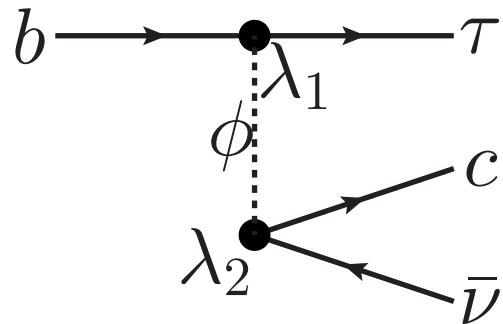
Models



$$R_{D^{(*)}} = BR(B \rightarrow D^{(*)}\tau\nu) / BR(B \rightarrow D^{(*)}\ell\nu_\ell)$$



# $R_{D^{(*)}}$ : BSM Explanations



$$\mathcal{L}_{WET} = -\frac{2\lambda_1\lambda_2}{M^2} (\bar{c}\gamma^\mu P_L \nu) (\bar{\tau}\gamma_\mu P_L b) + H.c.$$

# 2022 Measurement

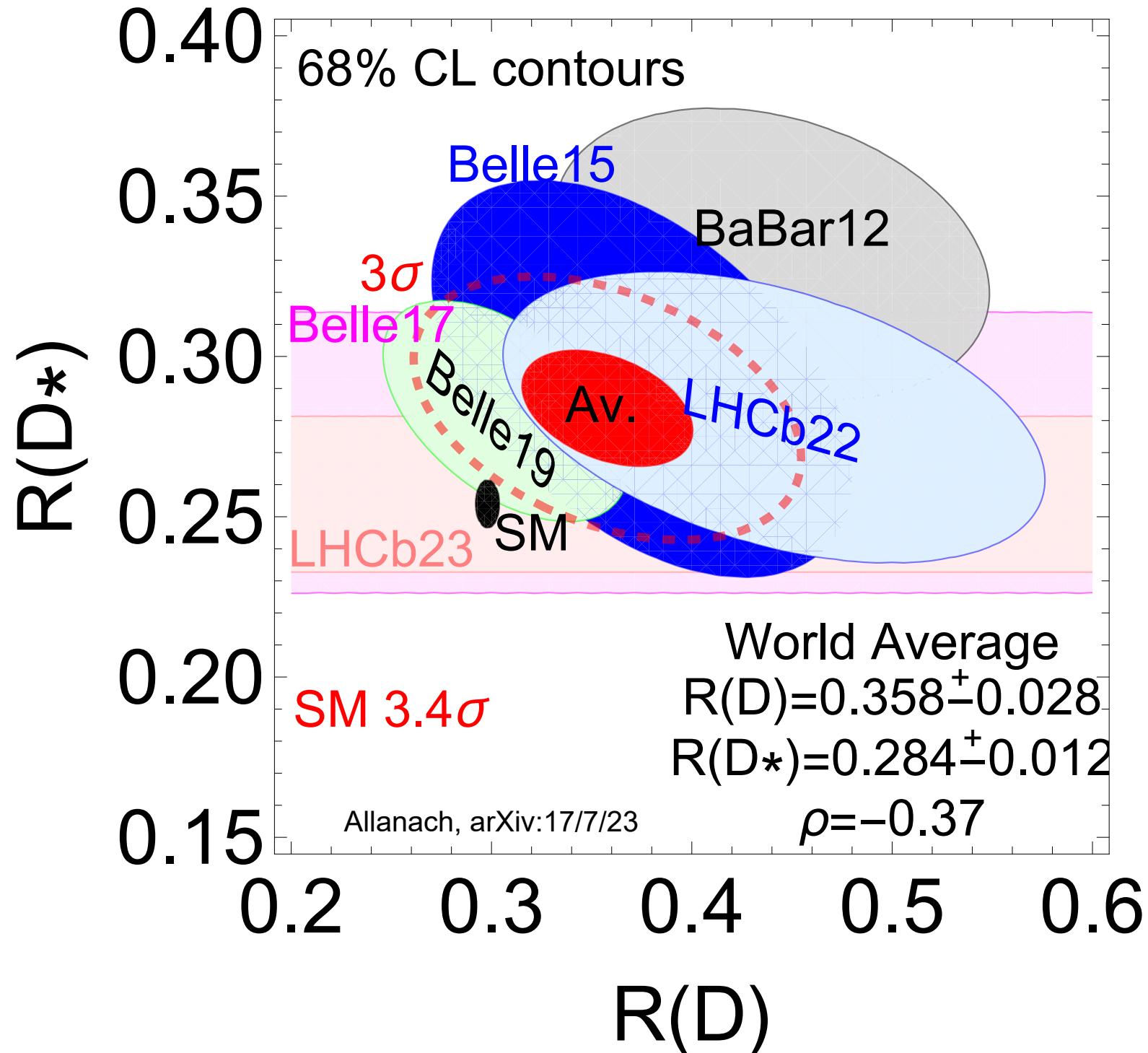
Using BaBar data (not official BaBar analysis)  
and *semi-leptonic* tag: (2012 used *hadronic*)

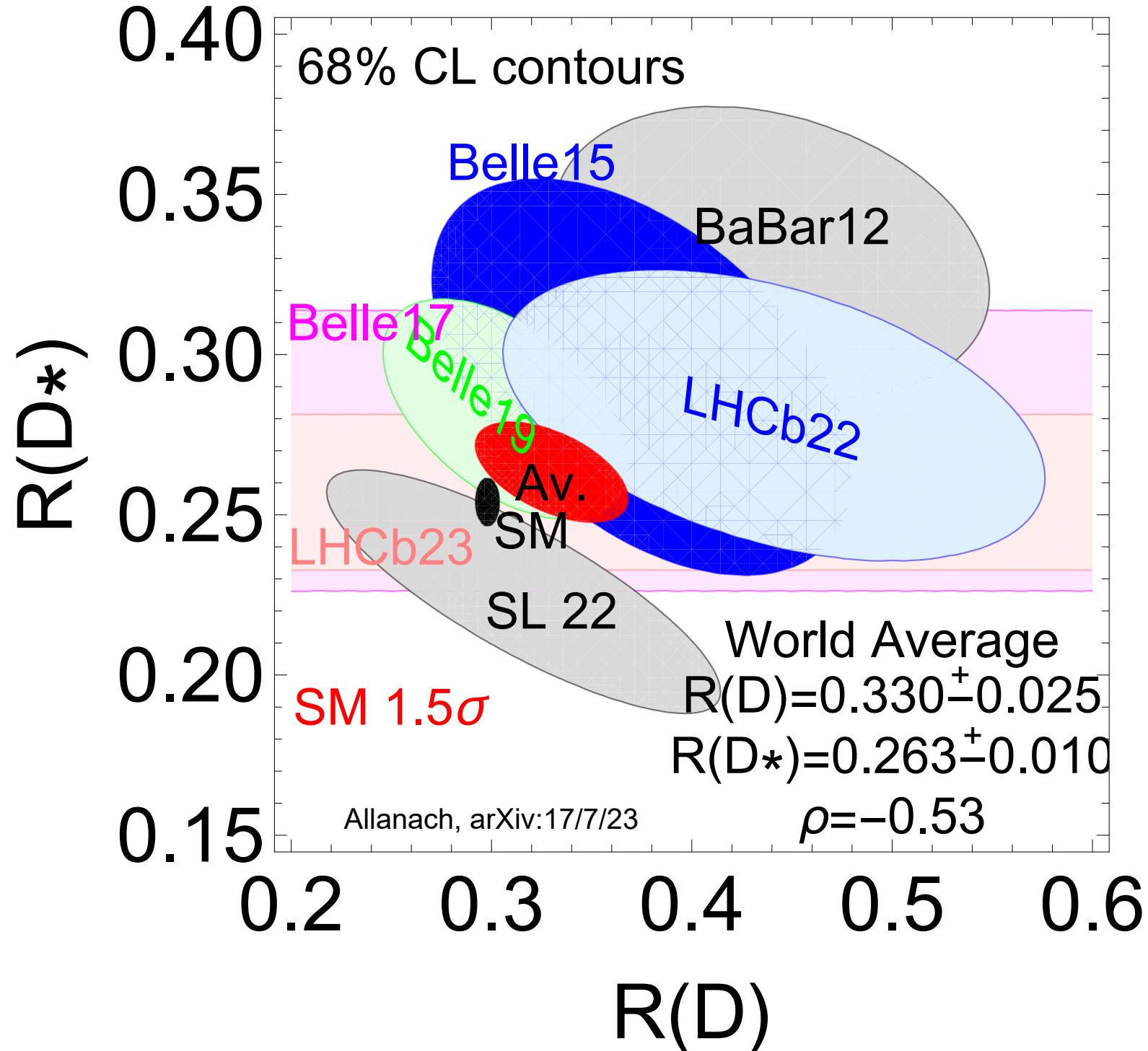
$$R(D) = 0.316 \pm 0.062 \pm 0.019$$

$$R(D^*) = 0.226 \pm 0.022 \pm 0.012$$

$$\rho = -0.82$$

Yunxuan Li, *Search for Beyond Standard Model Physics at BaBar*, (2022), Caltech Ph.D. thesis  
<https://resolver.caltech.edu/CaltechTHESIS:05232022-144829107>



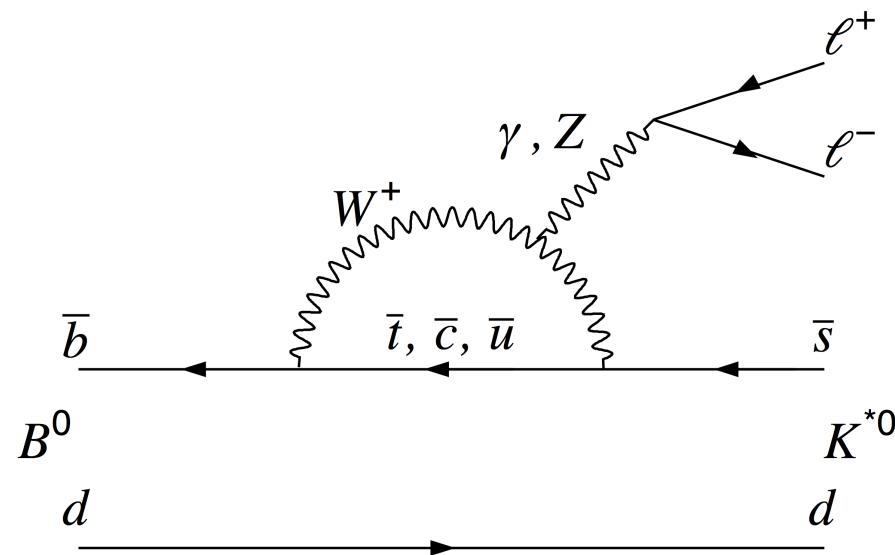




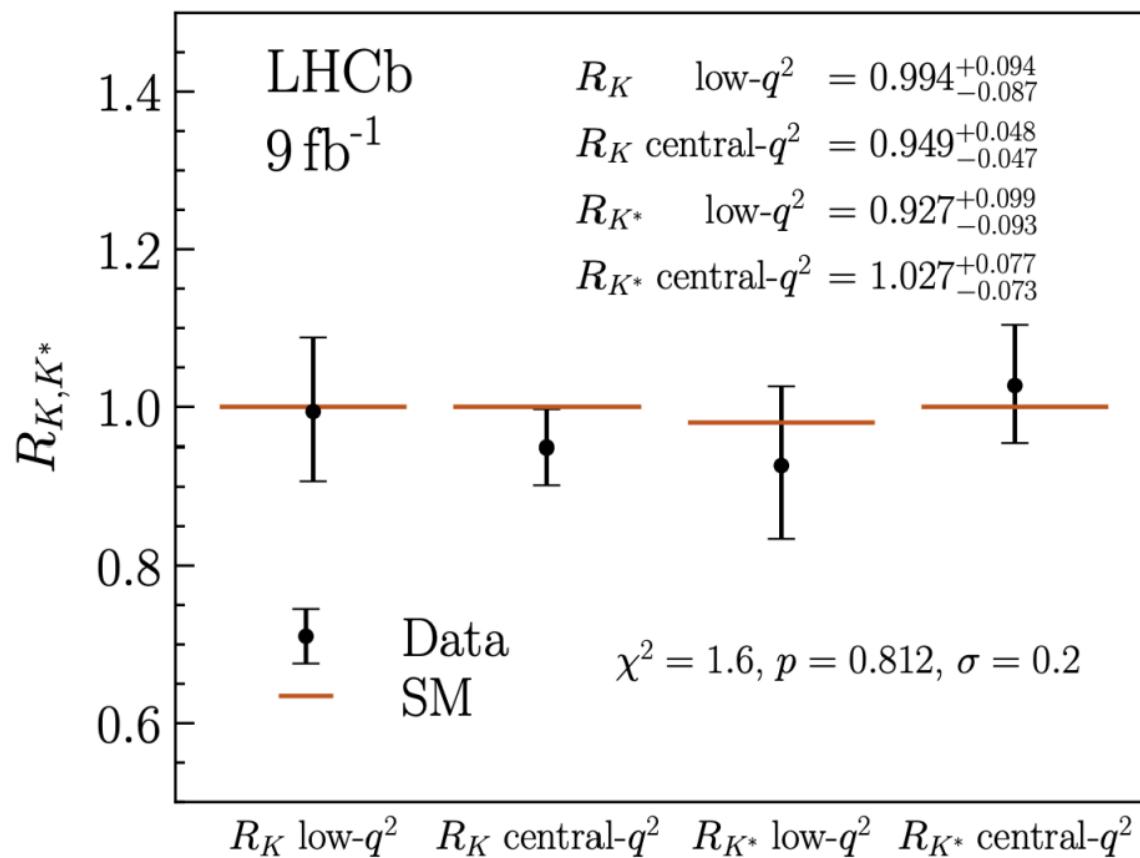
# $b \rightarrow sl^+l^-$ in Standard Model

$$BR(B \rightarrow K\mu^+\mu^-) = BR(B \rightarrow Ke^+e^-)$$

BR  $\sim \mathcal{O}(10^{-6})$ : loop+EW+CKM



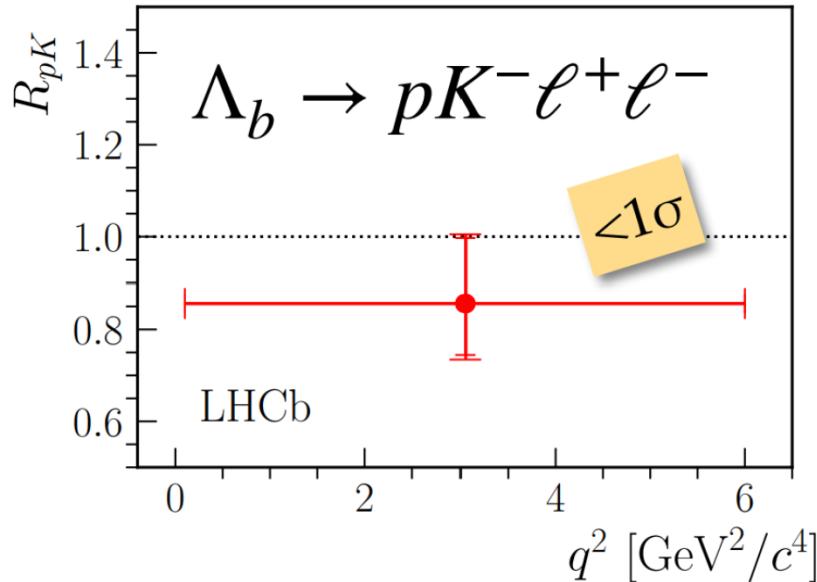
# LHCb 2212.09152



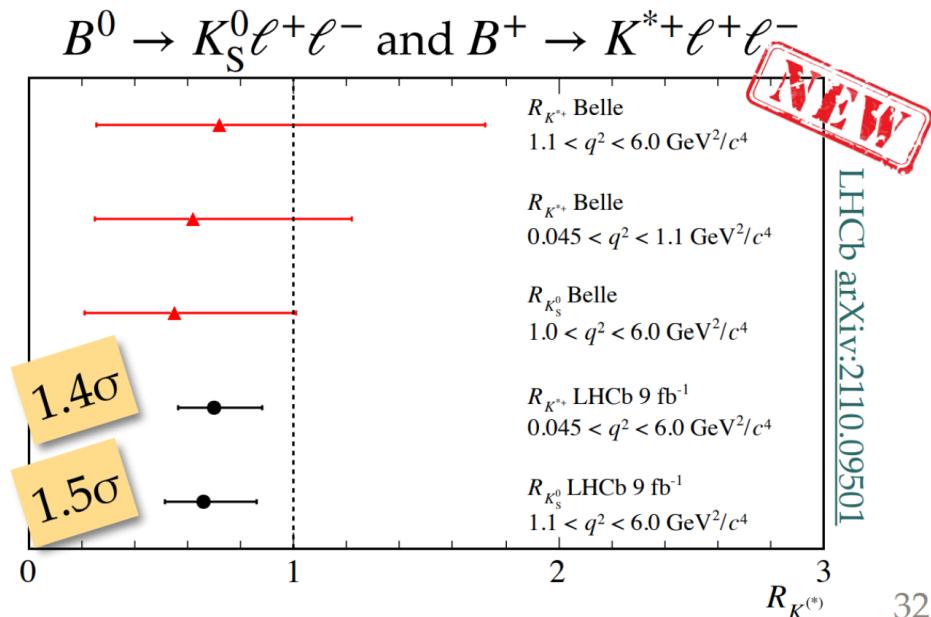
$$R_X(q^2) = \frac{BR(B \rightarrow X \mu^+ \mu^-)}{BR(B \rightarrow X e^+ e^-)}(q^2)$$



# Other LFU



LHCb, JHEP 05 (2020) 040



LHCb arXiv:2110.09501

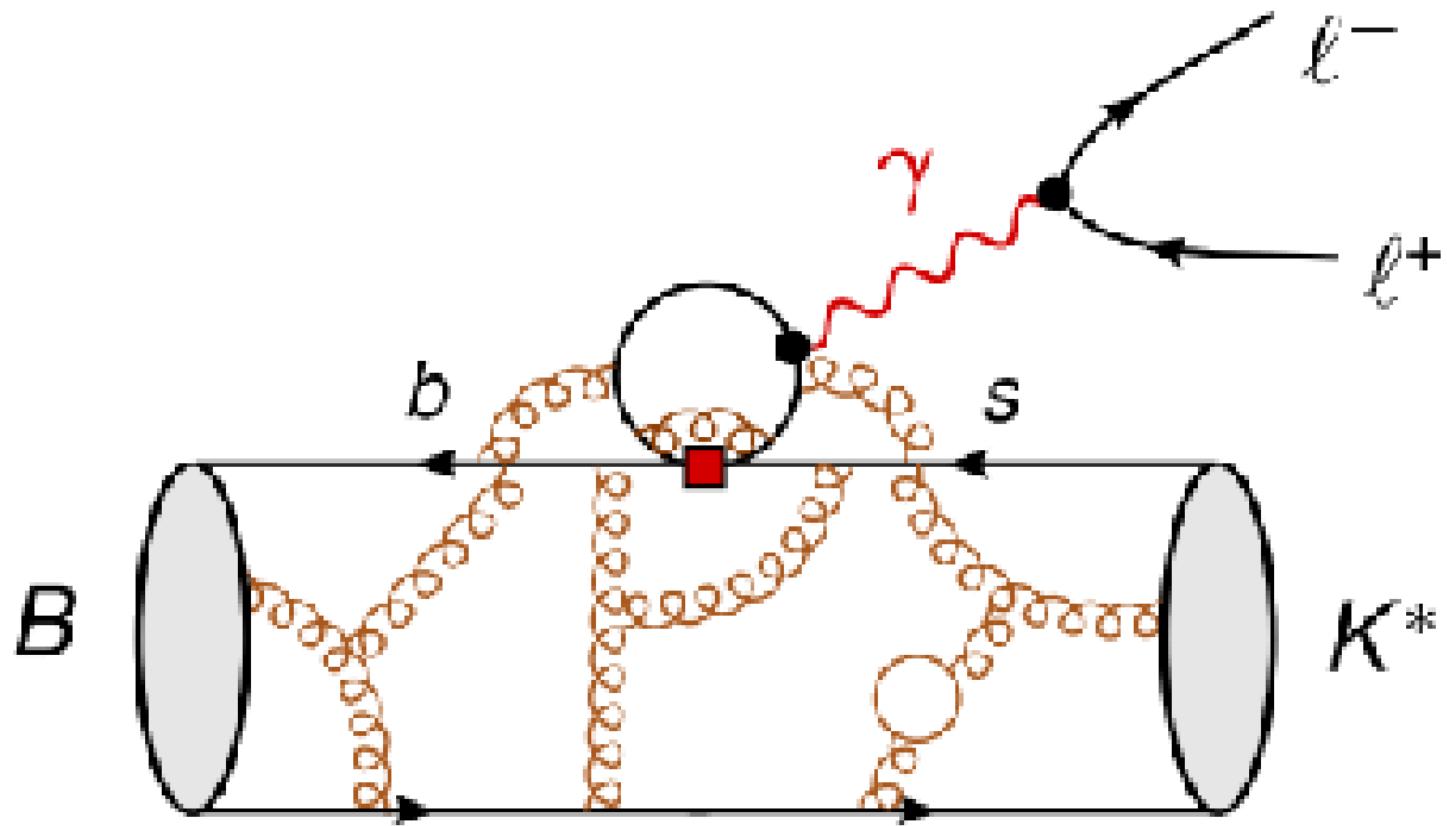
32

$$B_s \rightarrow \phi \ell^+ \ell^- ,$$

$$B \rightarrow \pi \ell^+ \ell^- ,$$

$$B \rightarrow K \pi^+ \pi^- \ell^+ \ell^- , \dots \text{to come}$$

# Form Factors



# Predicting $B \rightarrow M\ell^+\ell^-$ : FFs

$$\mathcal{A} = \text{local} + \text{non-local}$$

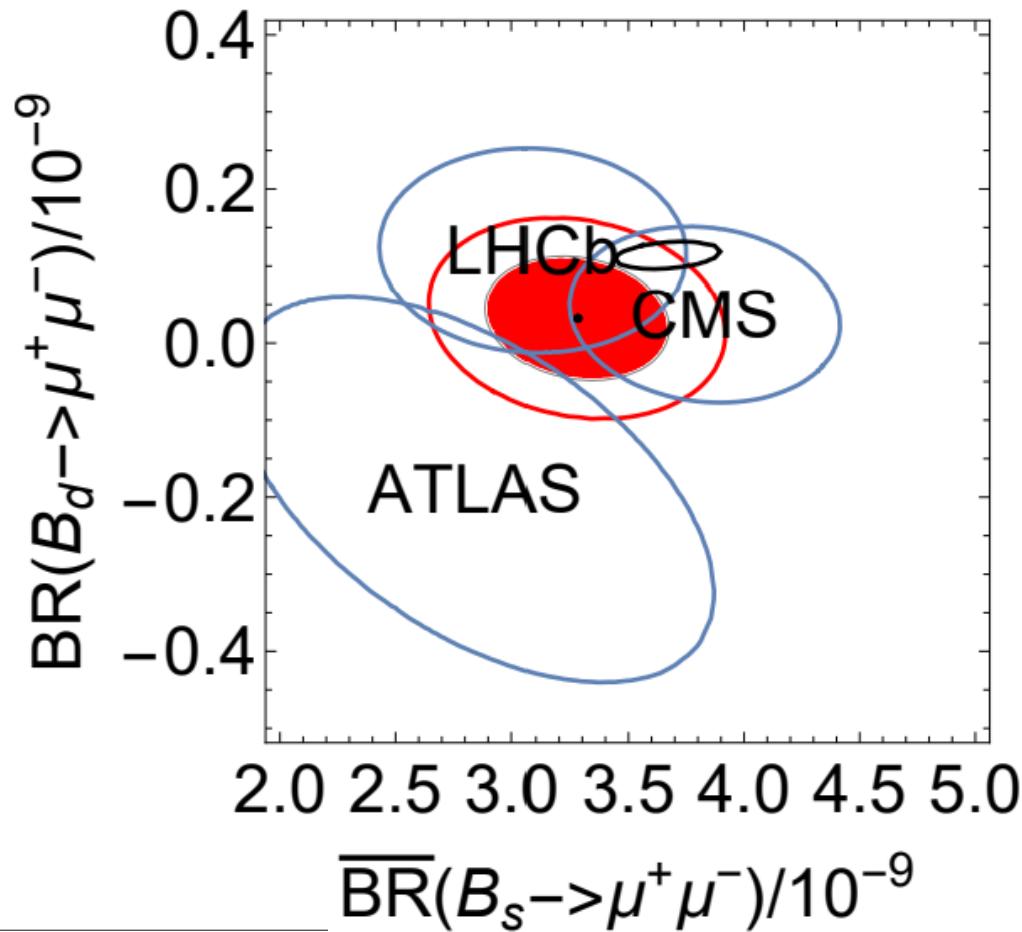
local: interpolate lattice at high  $q^2 = m_{ll}^2$  and LCSR at low  $q^2$ .

non-local: no lattice. Most use QCD factorisation: perturbative charm loop+ad-hoc

EOS approach: interpolate  $q^2 < 0$  LCOPE and measurements of BRs/angular dists at  $q^2 = M_{J/\psi}^2$ .

$BR(B_s \rightarrow \mu^+ \mu^-)^1$  SM:  $1.6\sigma$

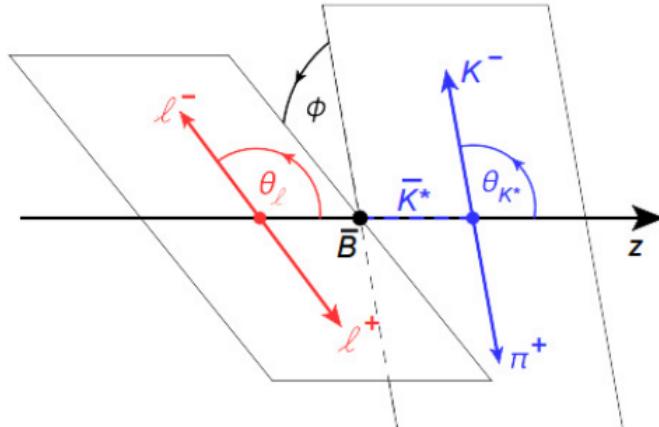
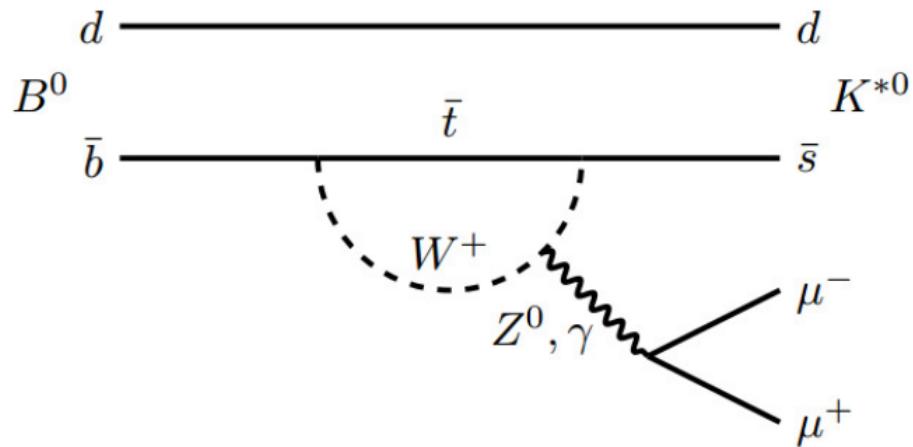
$B_s = (\bar{b}s)$ ,  $B_d = (\bar{b}d)$



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<sup>1</sup>SM: Feldmann, Gubernari, Huber, Seitz, 2211.04209;  
Combination: BCA, Davighi, 2211.11766

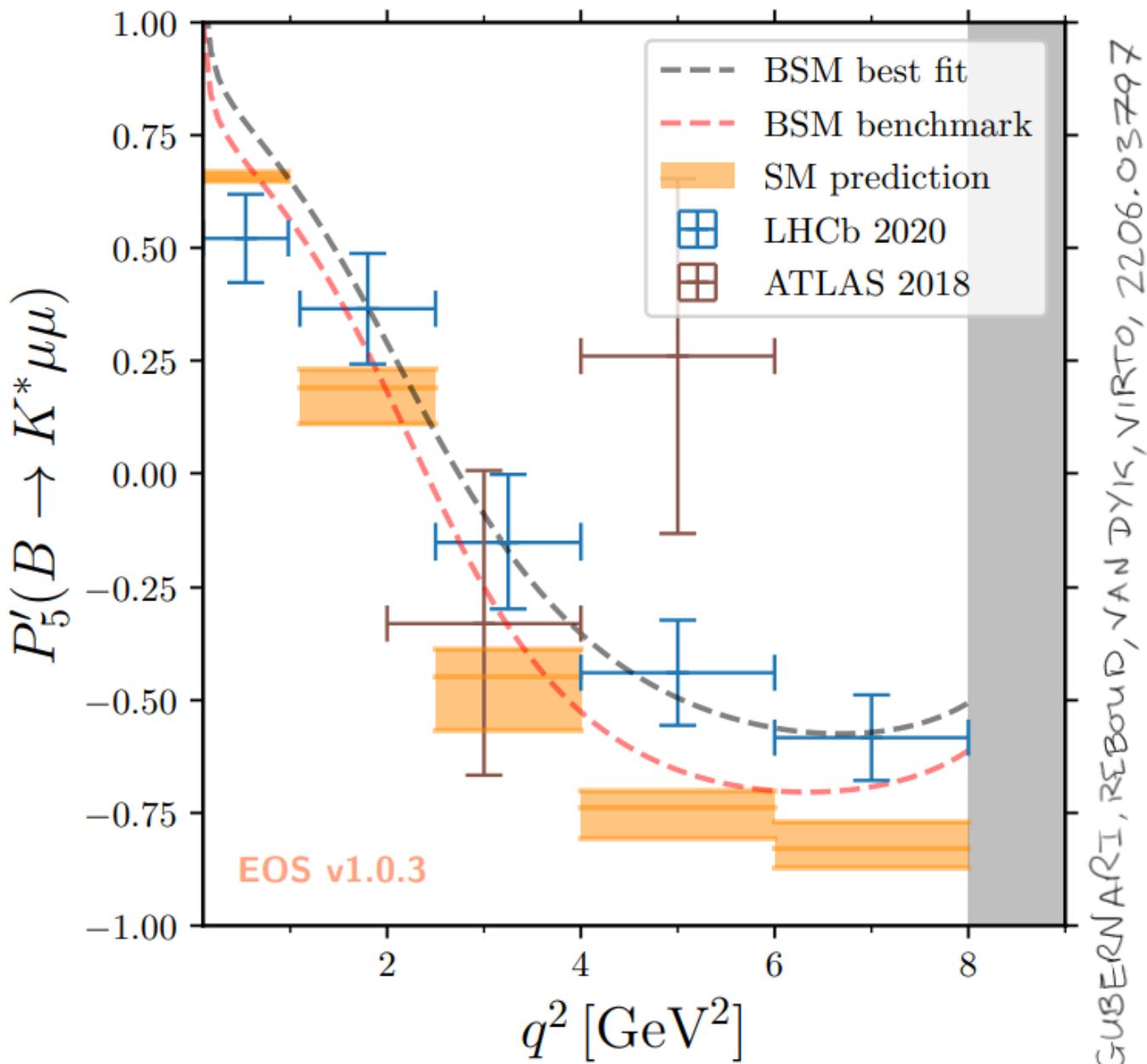
$$B^0 \rightarrow K^{*0} (\rightarrow K^+ \pi^-) \mu^+ \mu^-$$



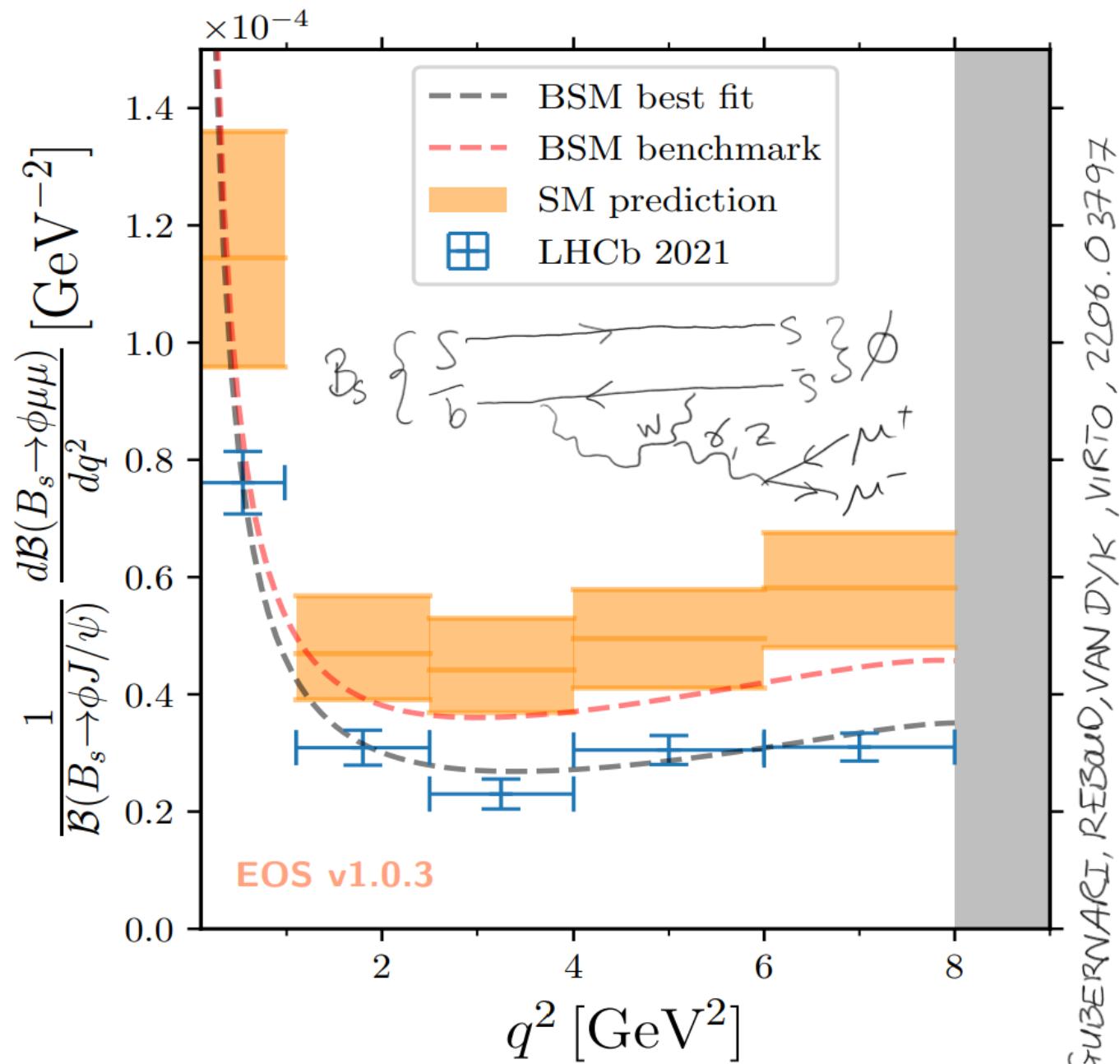
Decay fully described by three helicity angles  $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$  and  $q^2 = m_{\mu\mu}^2$

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - \textcolor{blue}{F}_L) \sin^2 \theta_K + \textcolor{blue}{F}_L \cos^2 \theta_K + \frac{1}{4}(1 - \textcolor{blue}{F}_L) \sin^2 \theta_K \cos 2\theta_\ell - \textcolor{blue}{F}_L \cos^2 \theta_K \cos 2\theta_\ell + \textcolor{blue}{S}_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + \textcolor{blue}{S}_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + \textcolor{blue}{S}_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + \frac{4}{3}\textcolor{blue}{A}_{\text{FB}} \sin^2 \theta_K \cos \theta_\ell + \textcolor{blue}{S}_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + \textcolor{blue}{S}_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + \textcolor{blue}{S}_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$$

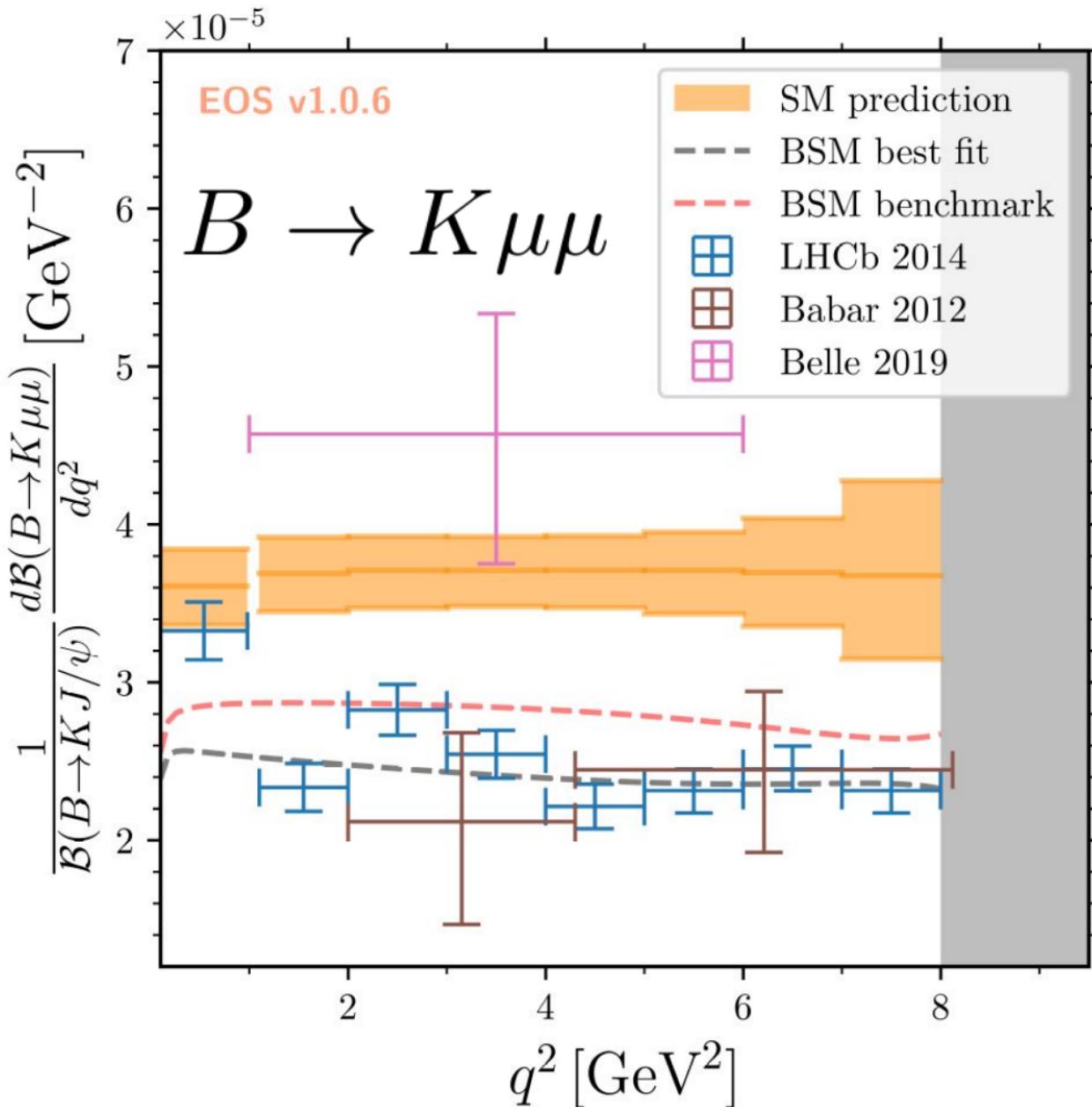
$$P'_5 = S_5 / \sqrt{F_L(1 - F_L)}$$



$$B_s \rightarrow \phi \mu^+ \mu^- : \phi = (s\bar{s})$$



# $BR(B \rightarrow K\mu^+\mu^-)$

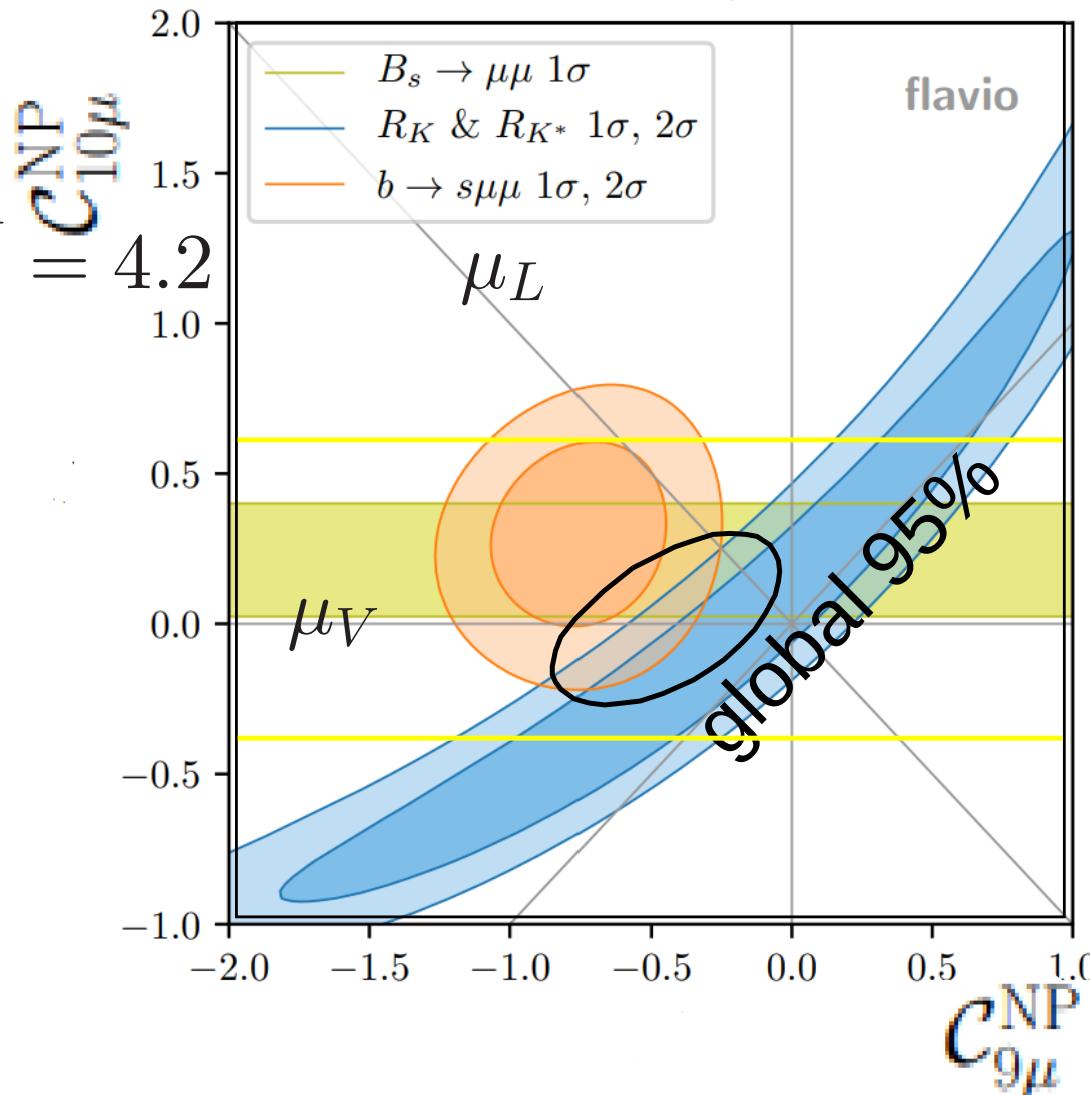


# $\mu$ Neutral Current Fits

Greljo, Salko, Smolkovic, Stangl, 2212.10497

$$\mathcal{L} = N[C_{9\mu}^{NP}(\bar{b}_L \gamma^\alpha s_L)(\bar{\mu} \gamma_\alpha \mu) + C_{10\mu}^{NP}(\bar{b}_L \gamma^\alpha s_L)(\bar{\mu} \gamma_\alpha \gamma^5 \mu)] + H.c.$$

$$C_9^{SM} = -C_{10}^{SM} = 4.2$$



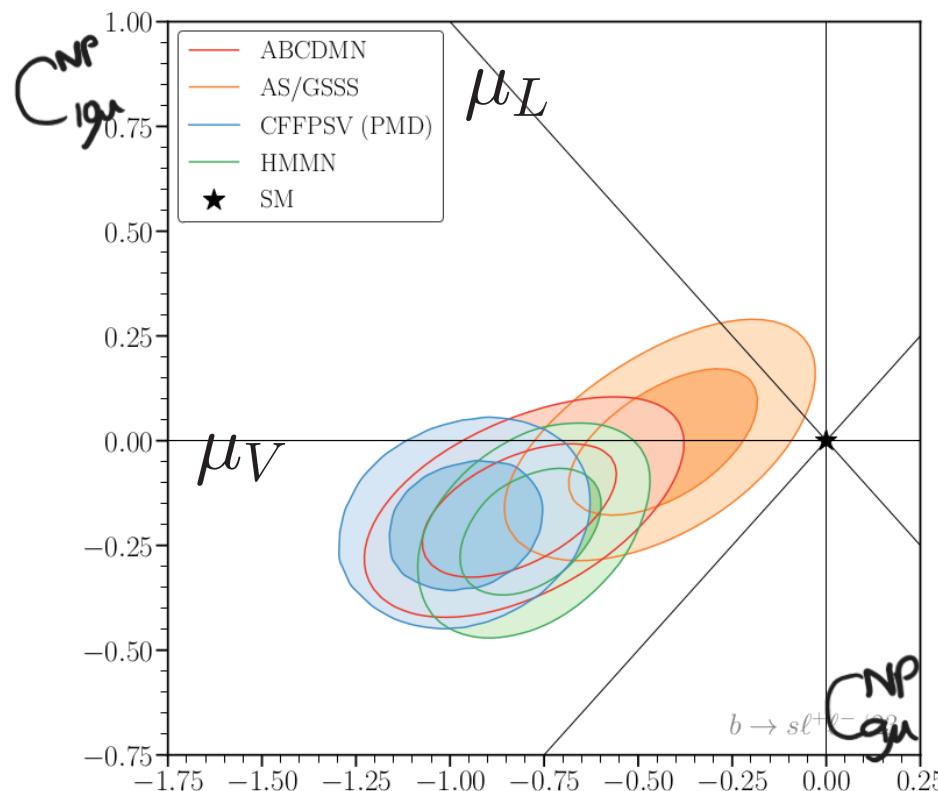
# $\mu$ Neutral Current Fits

Alguero et al, 2304.07330; Altmannshofer, Stangl, flavio 2212.10497

Ciuchini et al, HEPfit 2212.10516; Hurth et al, superIso 23???.?????

$$\mathcal{L} = N[C_{9\mu}^{NP}(\bar{b}_L \gamma^\alpha s_L)(\bar{\mu} \gamma_\alpha \mu) + C_{10\mu}^{NP}(\bar{b}_L \gamma^\alpha s_L)(\bar{\mu} \gamma_\alpha \gamma^5 \mu)] + H.c.$$

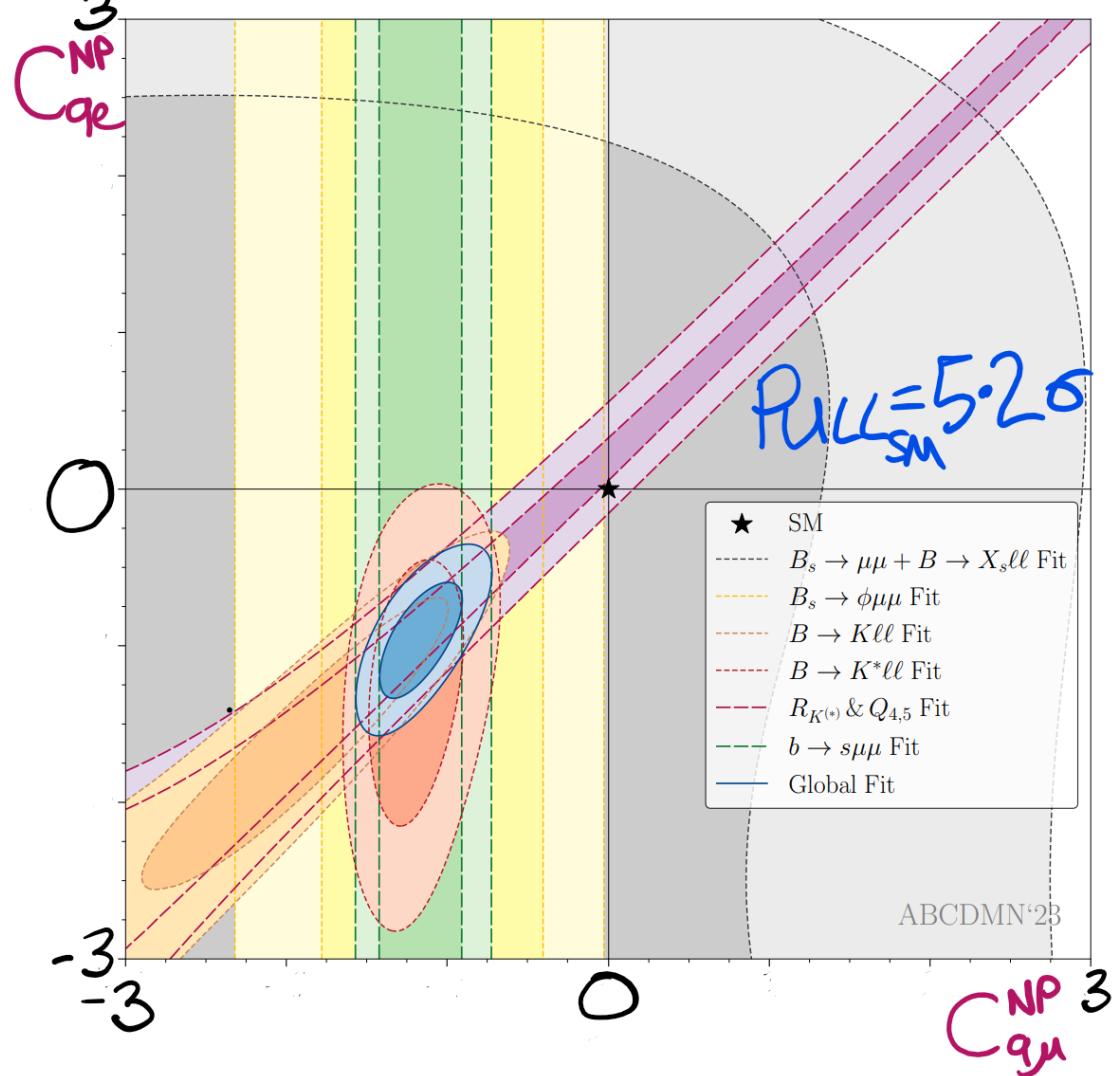
Plot from B Capdevila-Soler Beyond Flavour Anomalies workshop



# $\mu/e$ Neutral Current Fits

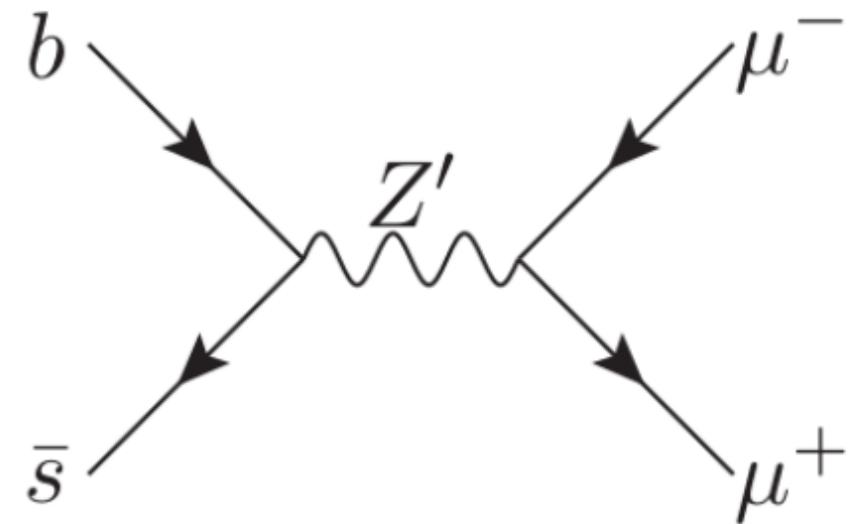
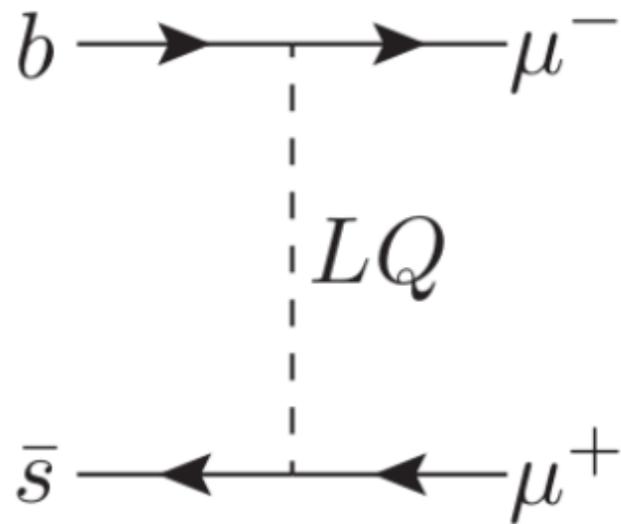
Alguero et al, 2304.07330

$$\mathcal{L} = N[C_{9\mu}^{NP}(\bar{b}_L \gamma^\alpha s_L)(\bar{\mu} \gamma_\alpha \mu) + C_{9e}^{NP}(\bar{b}_L \gamma^\alpha s_L)(\bar{e} \gamma_\alpha e)] + H.c.$$





# Tree-level Explanations



# Simple $Z'$ Models

SM-singlet scalar ‘flavon’  $\theta$

Additional  $U(1)_X$  gauge symmetry broken by  
 $\langle \theta \rangle \sim \text{TeV} \Rightarrow M_{Z'} \sim \text{TeV}$

SM+ $3\nu_R$  fermion content

**Zero** charges for first two generations of quark

$$X = 3B_3 - [X_e L_e + X_\mu L_\mu + (3 - X_e - X_\mu) L_\tau]$$

postdicts some small CKM<sup>2</sup>

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<sup>2</sup>BCA, Mullin, 2306.08669

# Flavour problem

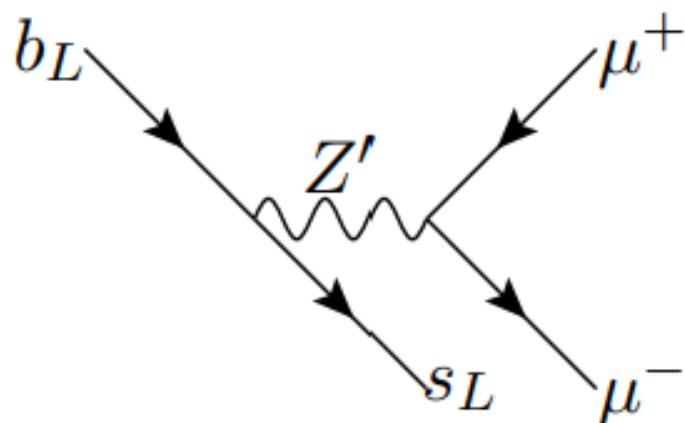
$$Y_u \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}, \quad Y_d \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix},$$

Postdicts CKM angles  $|V_{cb}|$ ,  $|V_{ub}|$ ,  $|V_{ts}|$ ,  
 $|V_{td}|$  to be small

# Important $Z'$ Couplings

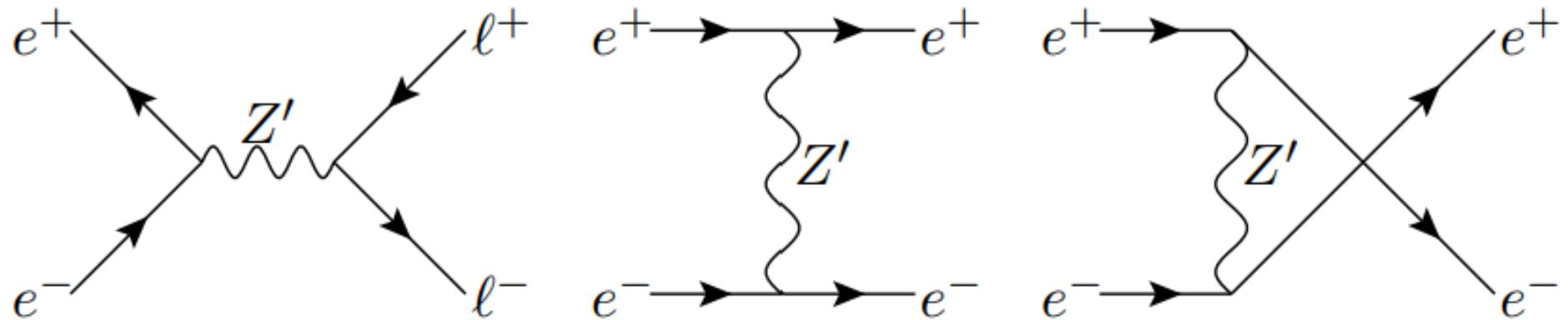
$$g_{Z'} \left[ (\overline{d}_L \ \overline{s}_L \ \overline{b}_L) \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin^2 \theta_{sb} & \frac{1}{2} \sin 2\theta_{sb} \\ 0 & \frac{1}{2} \sin 2\theta_{sb} & \cos^2 \theta_{sb} \end{pmatrix} Z' \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} \right]$$

$$- (\overline{e} \ \overline{\mu} \ \overline{\tau}) \begin{pmatrix} X_e & 0 & 0 \\ 0 & X_\mu & 0 \\ 0 & 0 & (3 - X_e - X_\mu) \end{pmatrix} Z' \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} ]$$



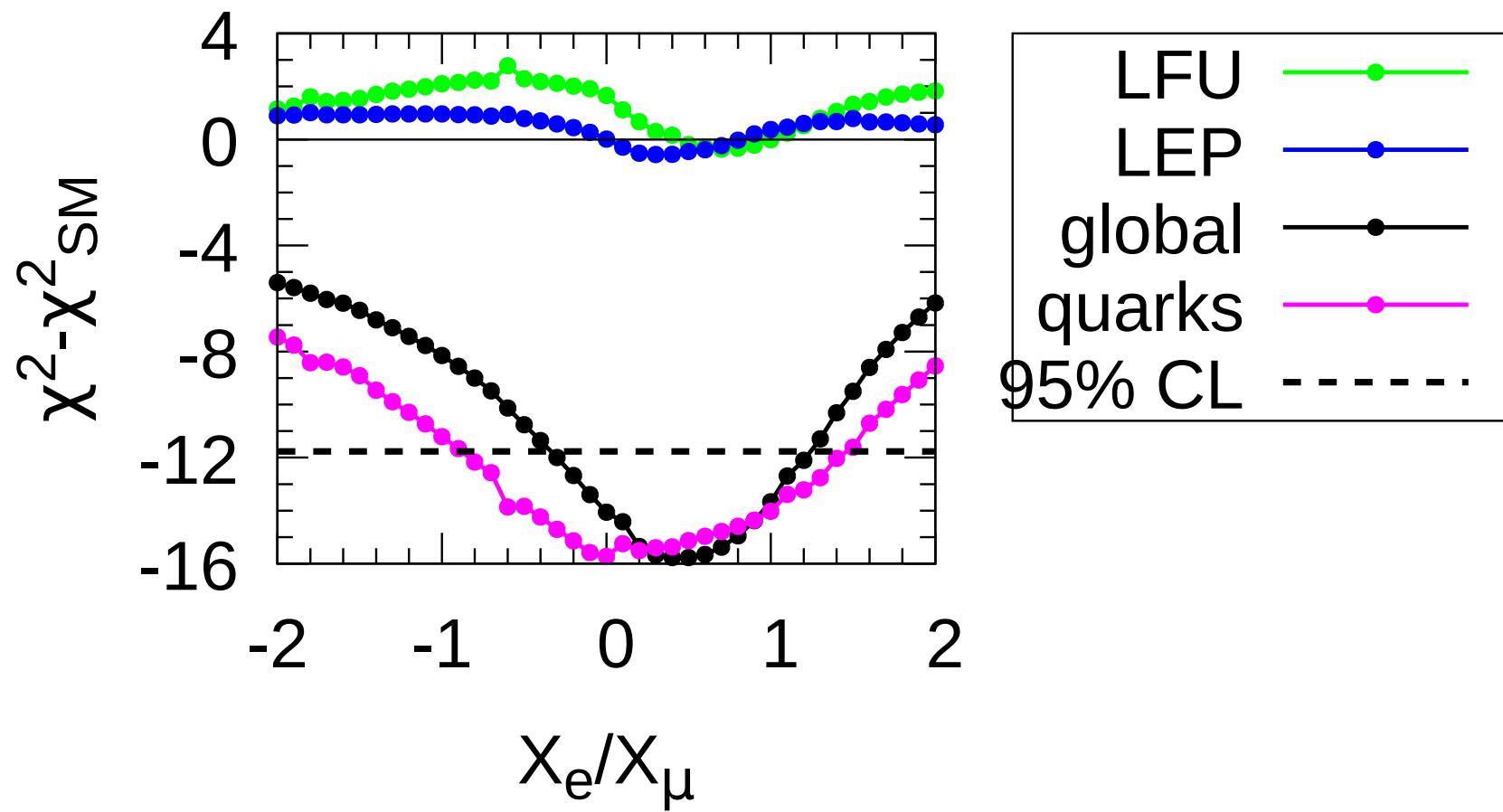
- LFU Violating,  $C_9 \neq 0$

# LEP constraints



Put into flavio (Falkowski,  
Mimouni 1511.07434)

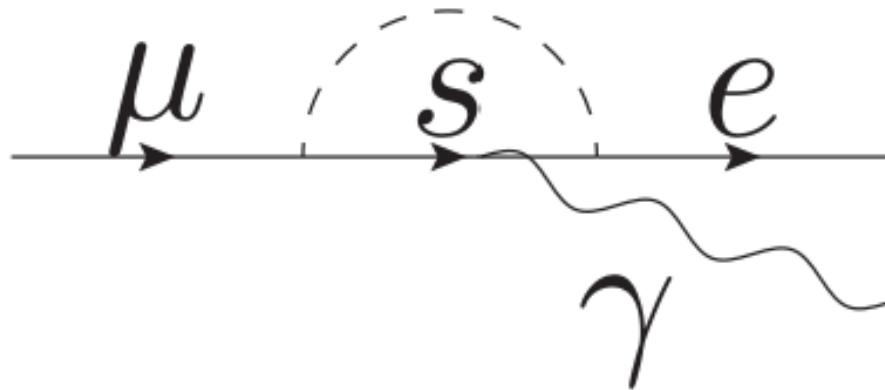
Fit  $\theta_{sb}$  and  $g_{Z'}/M_{Z'}$



# Leptoquark Explanation

$S_3 = (\bar{3}, \bar{3}, \frac{1}{3})$  only coupling to  $q\mu$  ( $C_{9\mu}^{NP} = -C_{10\mu}^{NP}$ ) as good as  $Z'$  only coupling to  $\mu\mu$  ( $C_{10\mu}^{NP} = 0$ ) (BCA, Davighi, 2211.11766)

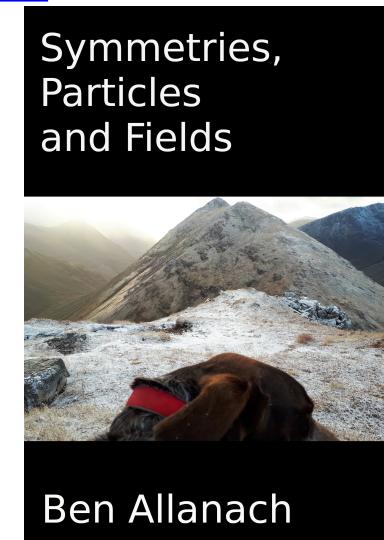
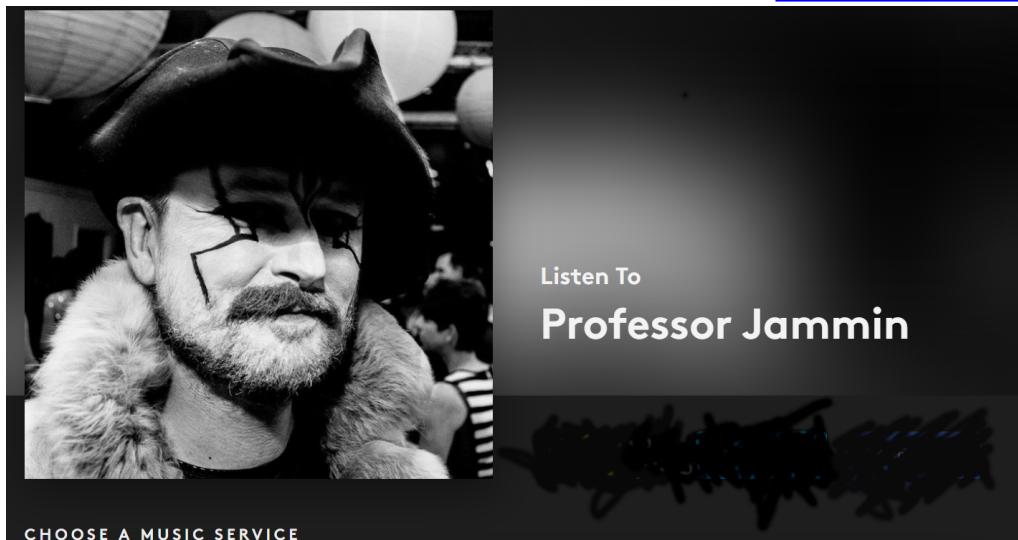
But coupling LQ to electrons as well leads to trouble:  $BR(\mu \rightarrow e\gamma) < 4.2 \cdot 10^{-13}$  (MEG 2016)



# Epilogue

Remarkable that TeV-scale flavour symmetries are still allowed

Plug for my [music](#), [book \(18€\)](#) and [Quantum Selves art](#):

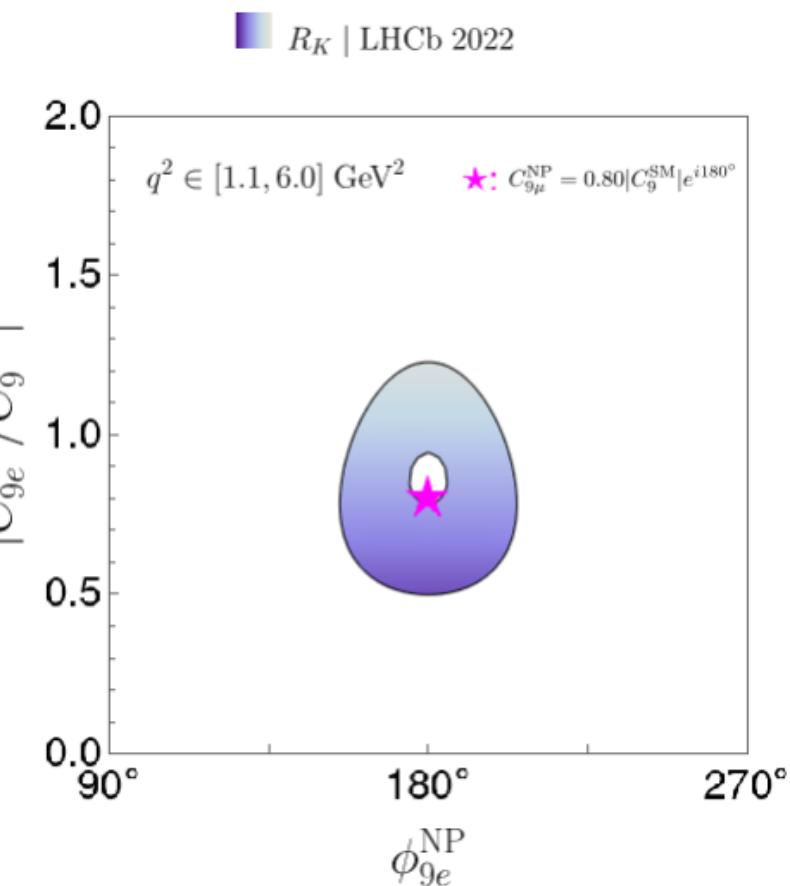
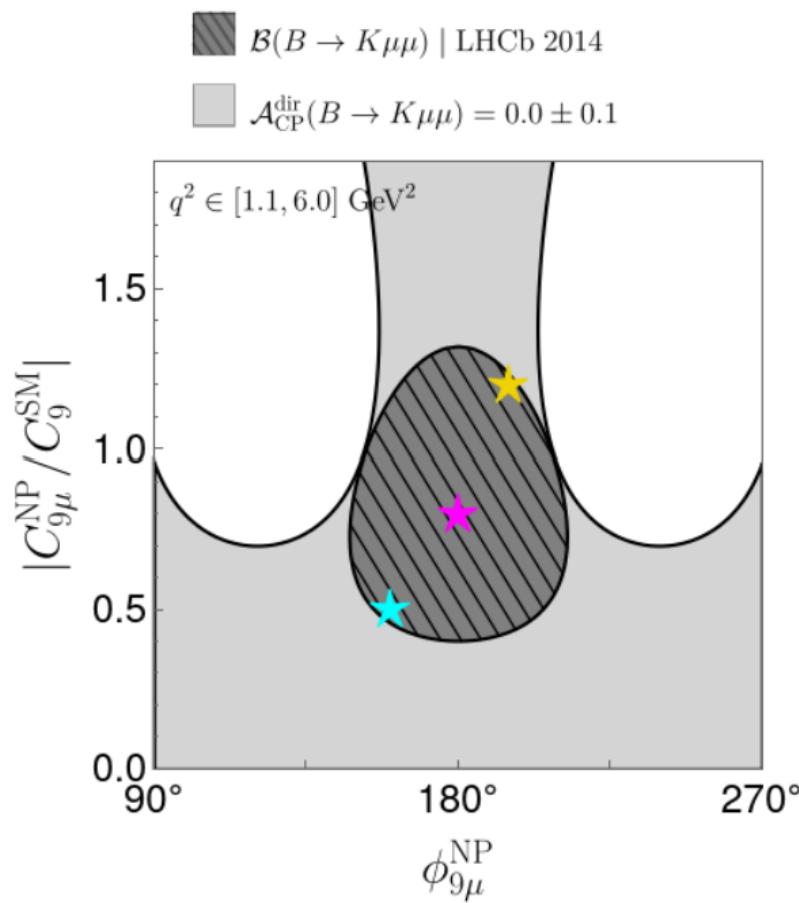


# Backup

# $e \neq \mu$ allowed

Fleischer, Malami, Rehult, Keri Vos, 2303.08764;  $C_{9\ell}^{NP} = |C_{9\ell}^{NP}|e^{i\phi_{9\ell}^{NP}}$

$$\mathcal{L} = N(\bar{b}_L \gamma^\alpha s_L) [C_{9\mu}^{NP} (\bar{\mu} \gamma_\alpha \mu) + C_{9e}^{NP} (\bar{e} \gamma_\alpha e)] + H.c.$$

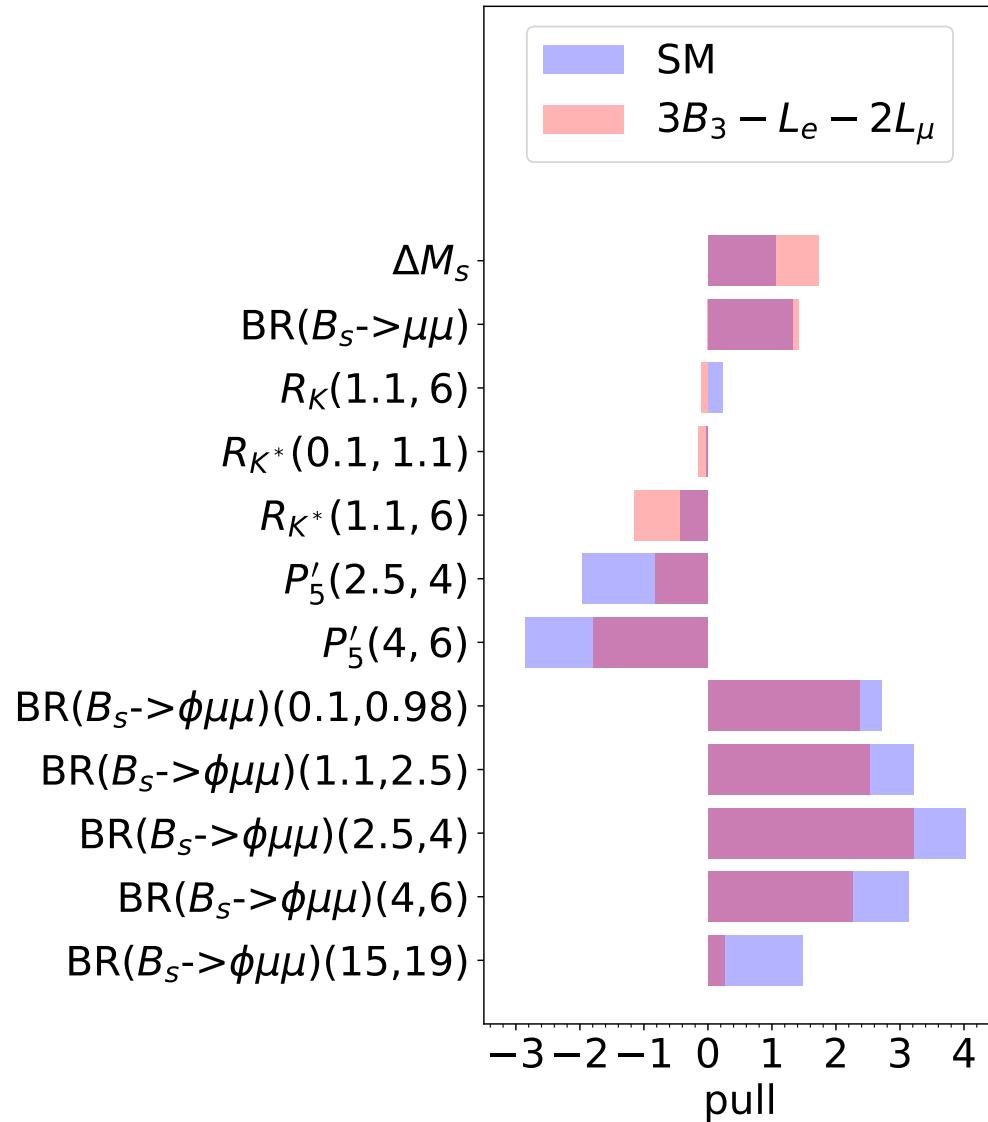


# $3B_3 - L_e - 2L_\mu$ model

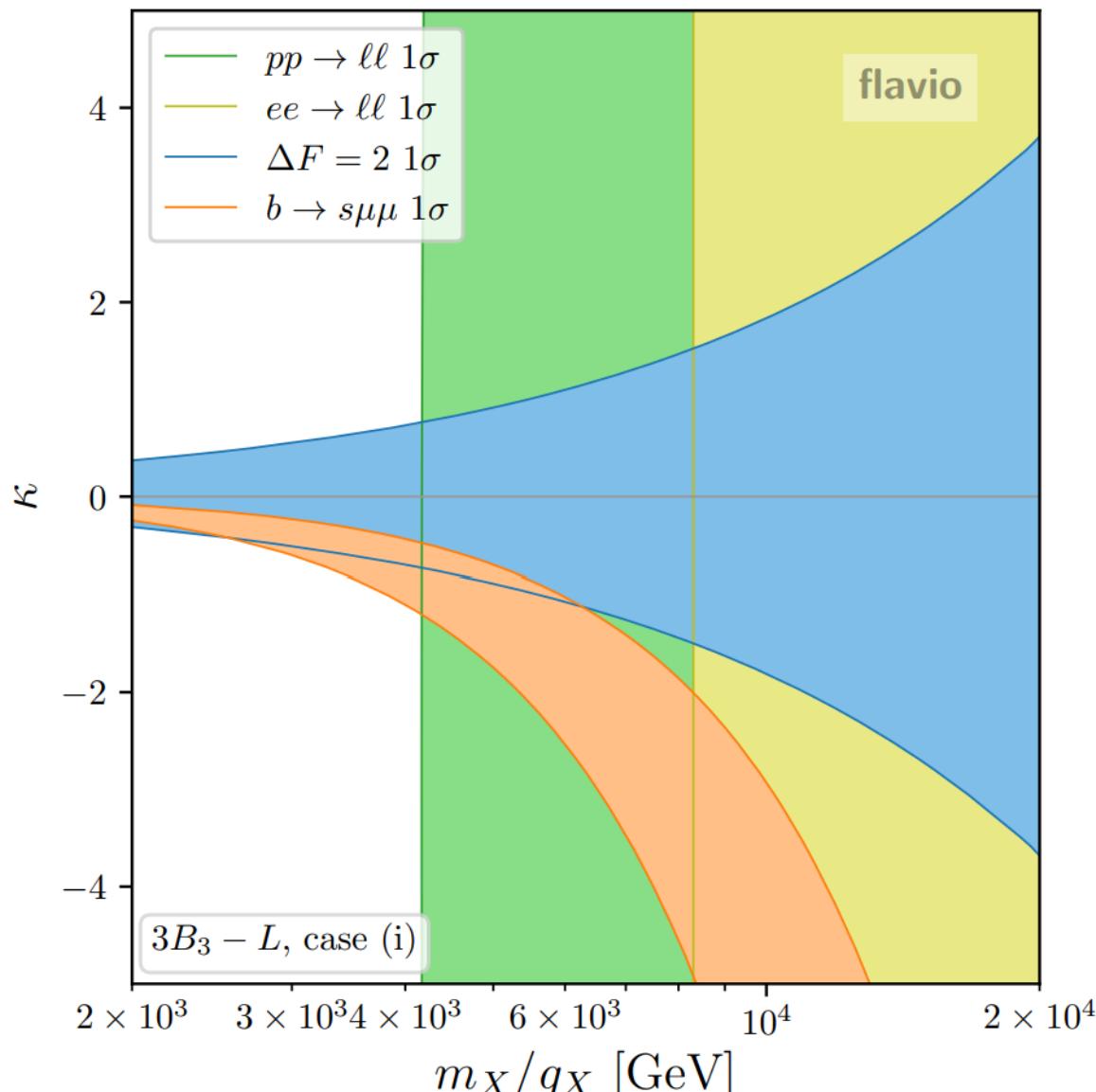
	$\chi^2 - \chi^2_{SM}$	$p$ -value	measurement	pull
LFU	-0.2	.85	$R_{K^*}(0.1, 1.1)$	-0.1
LEP	-0.4	.58	$R_{K^*}(1.1, 6)$	-1.1
quarks	-14.7	.10	$R_K(0.1, 1.1)$	-0.3
global	-15.3	.28	$R_K(1.1, 6)$	-0.1

$g_{Z'} = 0.2, \theta_{sb} = -0.03$  best-fit

BCA, Mullin, 2306.08669

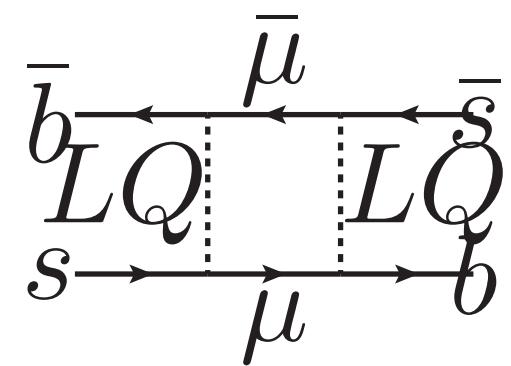
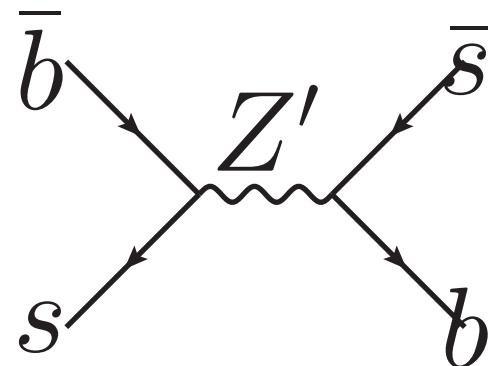
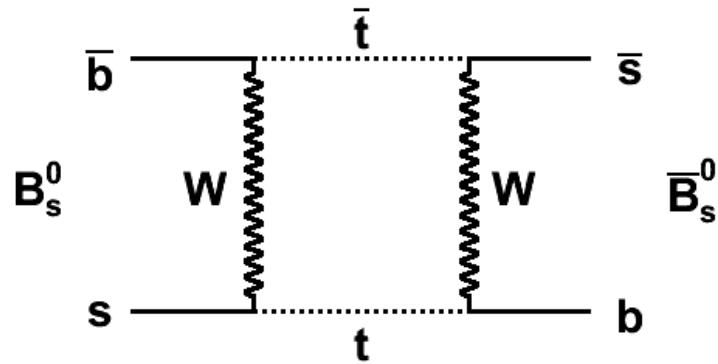


# $3B_3 - L_e - L_\mu - L_\tau$ model



# $B_s - \bar{B}_s$ Mixing

Measurement agrees with SM.



$$g_{sb} = \frac{g_X}{2} \sin 2\theta_{sb} \lesssim \frac{M_{Z'}}{194 \text{ TeV}} \text{ but uncertain}$$

from QCD sum rules and lattice<sup>3</sup>.

---

<sup>3</sup>King, Lenz, Rauh, arXiv:1904.00940

$$\begin{aligned}\mathcal{L}_{X\psi} &= g_X \left( \overline{\mathbf{u}_L} \Lambda_\xi^{(u_L)} Z' \mathbf{u}_L + \overline{\mathbf{u}_R} \Lambda_\xi^{(u_R)} Z' \mathbf{u}_R \right. \\ &\quad + \overline{\mathbf{d}_L} \Lambda_\xi^{(d_L)} Z' \mathbf{d}_L + \overline{\mathbf{d}_R} \Lambda_\xi^{(d_R)} Z' \mathbf{d}_R \\ &\quad - \overline{\mathbf{e}_L} \Lambda_\Xi^{(e_L)} Z' \mathbf{e}_L - \overline{\mathbf{e}_R} \Lambda_\Xi^{(e_R)} Z' \mathbf{e}_R \\ &\quad \left. - \overline{\boldsymbol{\nu}_L} \Lambda_\Xi^{(\nu_L)} Z' \boldsymbol{\nu}_L - \overline{\boldsymbol{\nu}_R} \Lambda_\Xi^{(\nu_R)} Z' \boldsymbol{\nu}_R \right),\end{aligned}$$

$$\Lambda_{\substack{\xi \\ \Xi}}^{(I)} \equiv V_I^{\dagger \xi} V_I, \quad \xi = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \Xi = \begin{pmatrix} X_e & 0 & 0 \\ 0 & X_\mu & 0 \\ 0 & 0 & X_\tau \end{pmatrix}$$

$$X_\tau = 3 - X_e - X_\mu \text{ (BCA, Mullin, 2306.08669)}$$

**Z' couplings**,  $I \in \{u_L, d_L, e_L, \nu_L, u_R, d_R, e_R\}$

# A simple limiting case

$$V_{u_R} = V_{d_R} = V_{e_L} = V_{e_R} = 1$$

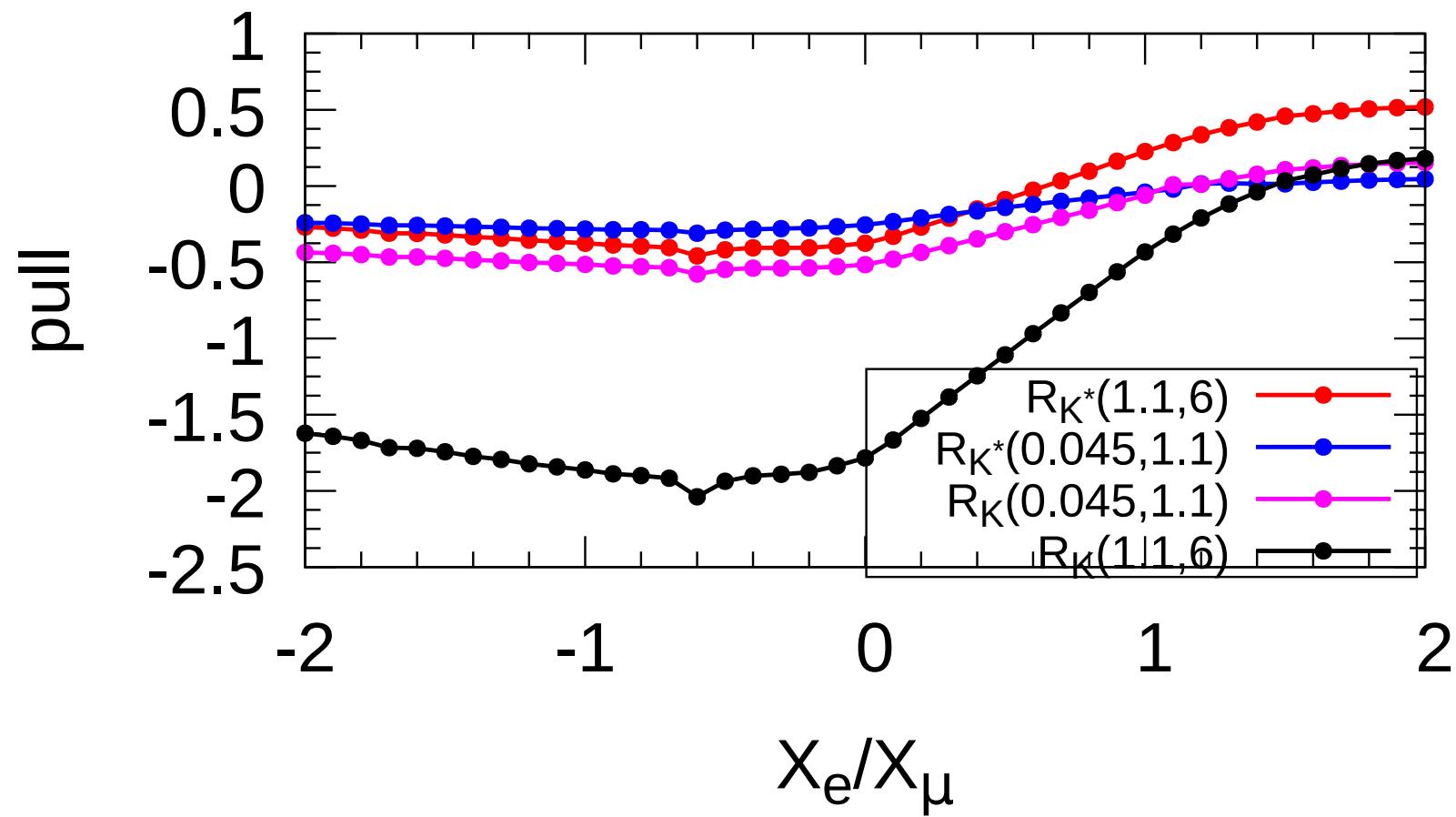
$$V_{d_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{sb} & -\sin \theta_{sb} \\ 0 & \sin \theta_{sb} & \cos \theta_{sb} \end{pmatrix}.$$

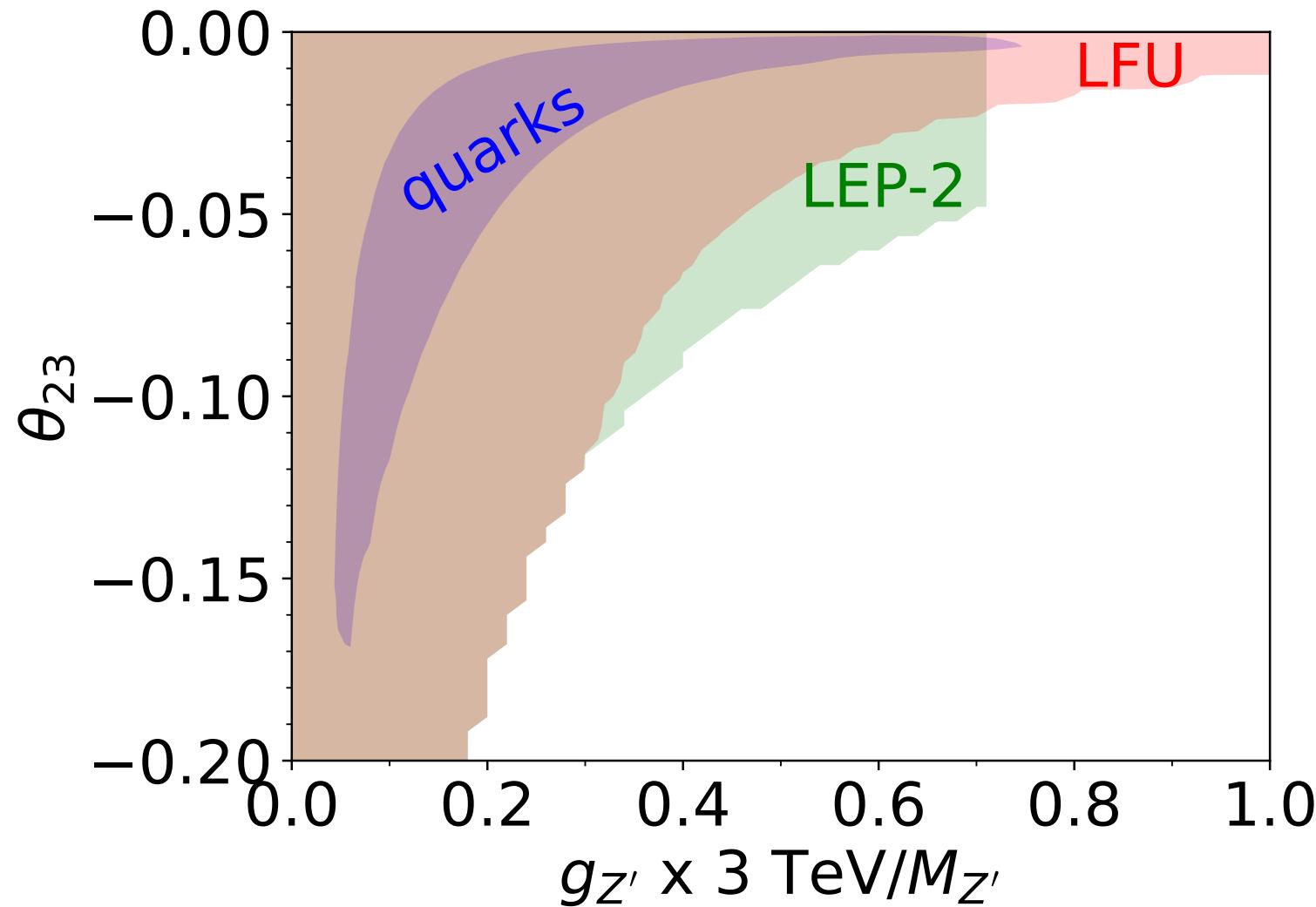
$$\Rightarrow V_{u_L} = V_{d_L} V_{CKM}^\dagger \text{ and } V_{\nu_L} = V_{e_L} U_{PMNS}^\dagger.$$

# SMEFT WCs/ $(g_{Z'}^2/M_{Z'}^2)$

WC	value	WC	value
$C_{ll}^{iiii}$	$-\frac{1}{2}L_i^2$	$C_{ll}^{iijj} \ (i \neq j)$	$-L_i L_j$
$(C_{lq}^{(1)})^{iijk}$	$L_i (\Lambda_{\Xi}^{(d_L)})_{jk}$	$C_{uu}^{3333}$	$-\frac{1}{2}$
$C_{ee}^{iijj} \ (i \neq j)$	$-L_i L_j$	$C_{ee}^{iiii}$	$-\frac{1}{2}L_i^2$
$C_{dd}^{3333}$	$-\frac{1}{2}$	$C_{ed}^{ii33}$	$L_i$
$C_{eu}^{ii33}$	$L_i$	$C_{le}^{iijj}$	$-L_i L_j$
$C_{ud}^{(1)3333}$	$-1$	$C_{qu}^{(1)ij33}$	$-(\Lambda_{\Xi})_{ij}$
$C_{qe}^{ijkk}$	$L_k (\Lambda_{\Xi})_{ij}$	$C_{qq}^{(1)ijkl}$	$(\Lambda_{\Xi})_{ij} (\Lambda_{\Xi})_{kl} \frac{\delta_{ik}\delta_{jl}-2}{2}$
$C_{qd}^{(1)ij33}$	$-(\Lambda_{\Xi})_{ij}$	$C_{ld}^{ii33}$	$L_i$
$C_{lu}^{ii33}$	$L_i$		

| wilson | flavio | smelli > output

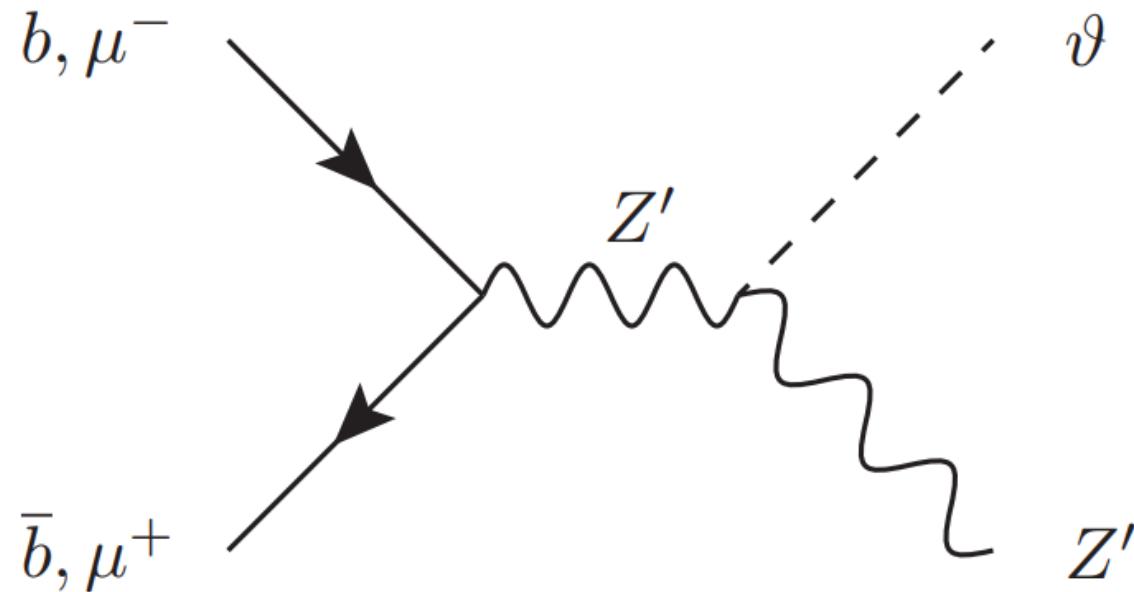




BCA, Mullin, 2306.08669

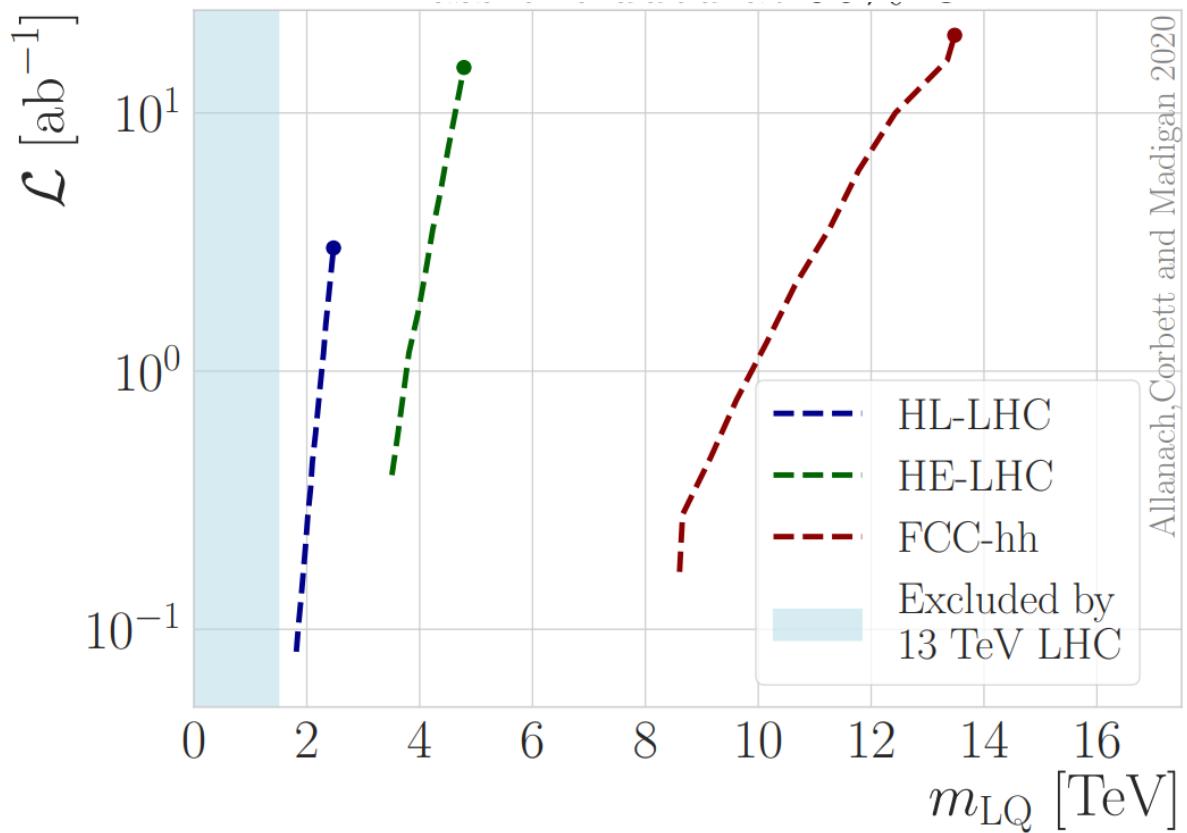
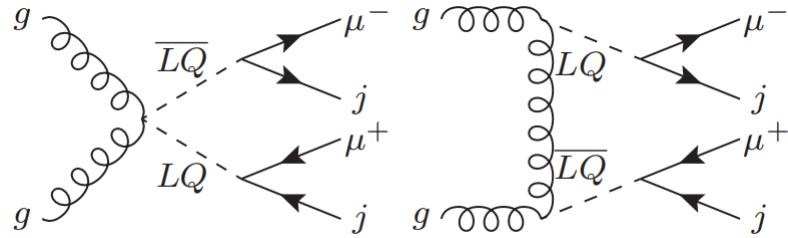
# Flavonstrahlung

Models of  $Z'$  ilk possess  $\mathcal{L} = \lambda HH^\dagger \theta\theta^\dagger \Rightarrow$  a *flavonstrahlung* signature:



BCA, 2009.02197; BCA, Loisa, 2212.07440

# Scalar LQ<sup>4</sup>: eg $S_3 \sim (\bar{3}, 3, 1/3)$



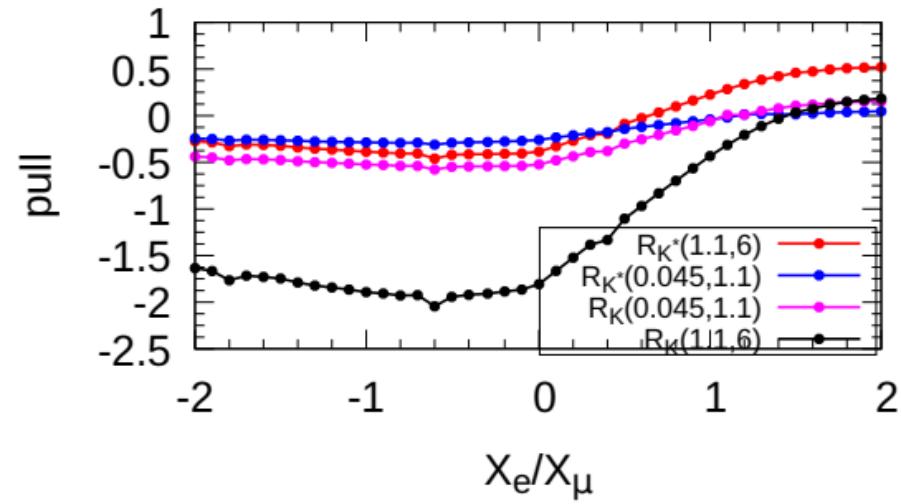
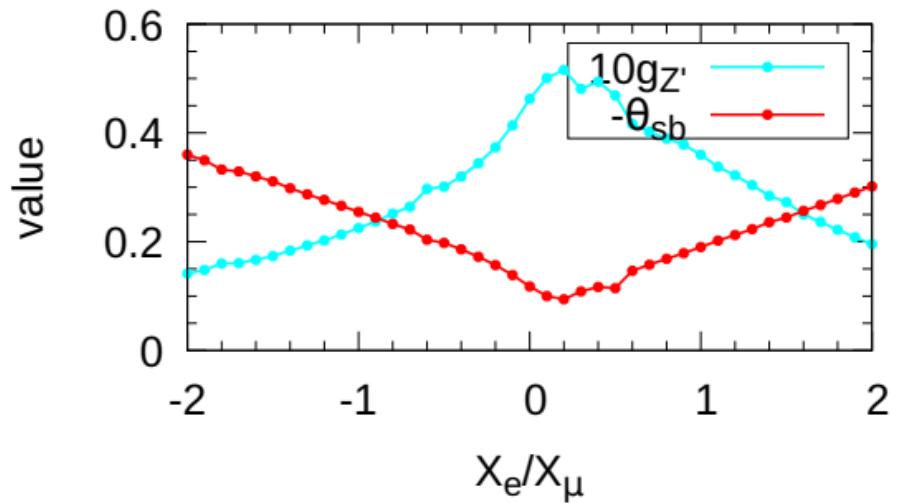
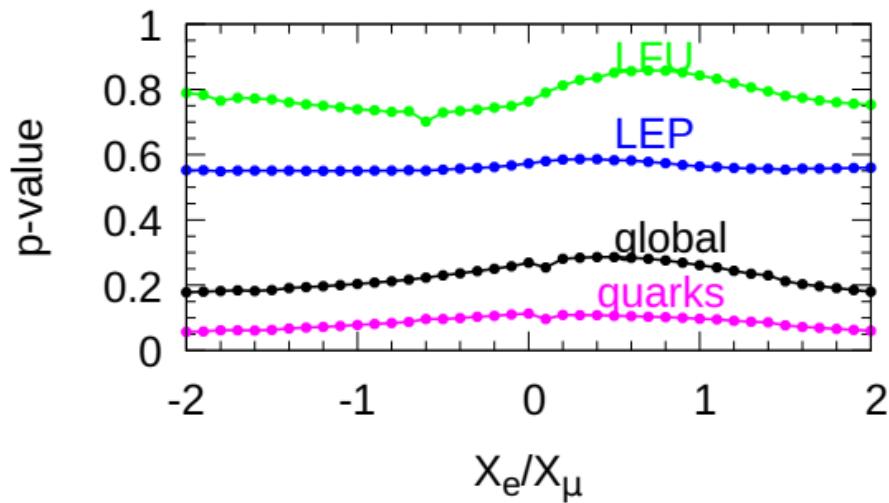
# Anomaly cancellation

Need to pick  $X$  charges for fermions consistent with QFT anomaly cancellation.

$$X = 3B_3 -$$

$$(X_e L_e + X_\mu L_\mu + [3 - X_e - X_\mu] L_\tau)$$

works (proof in 2306.08669).



# Trident Neutrino Process

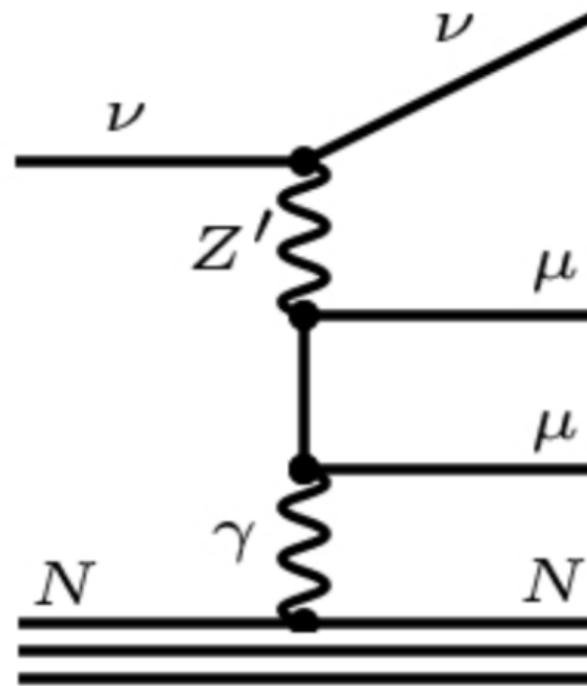
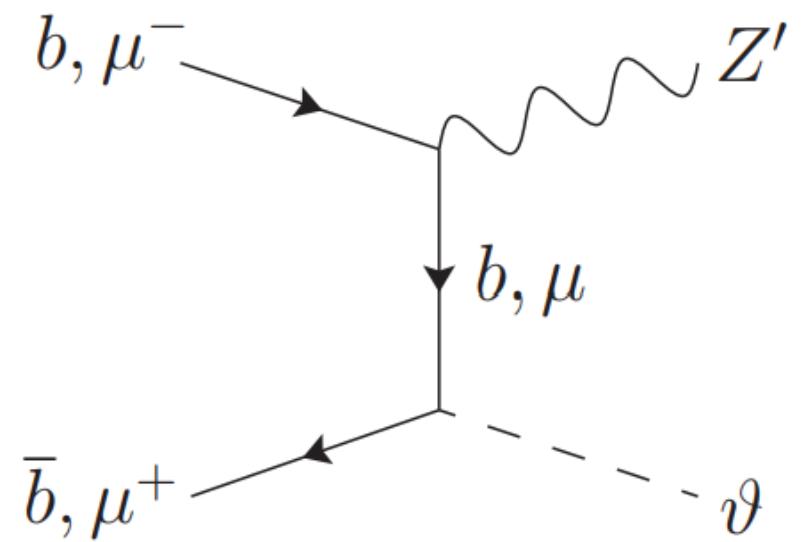
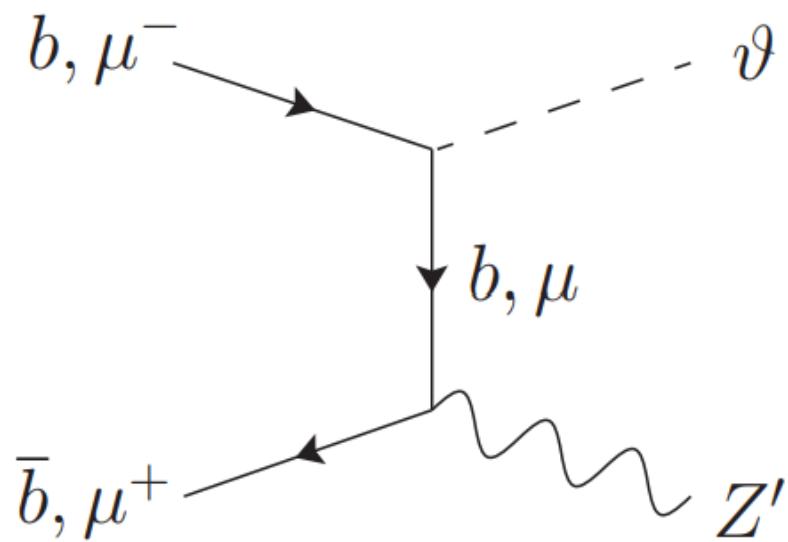
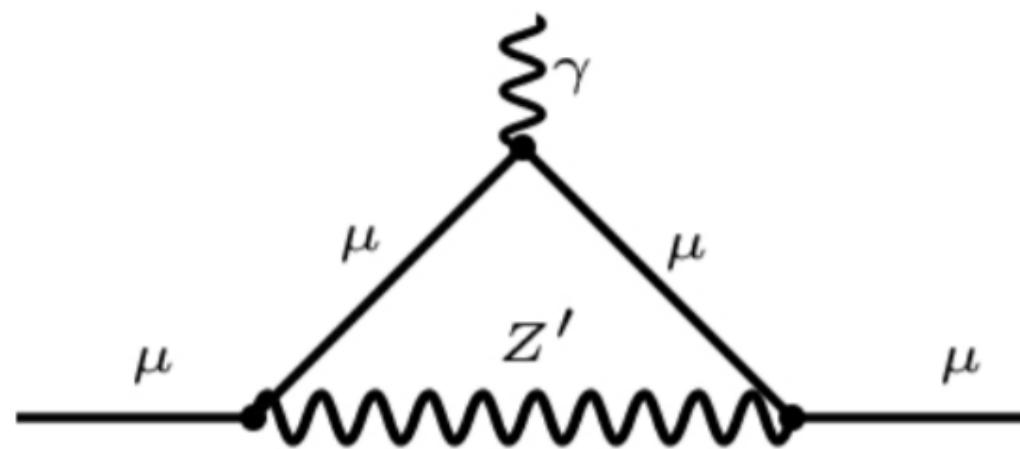
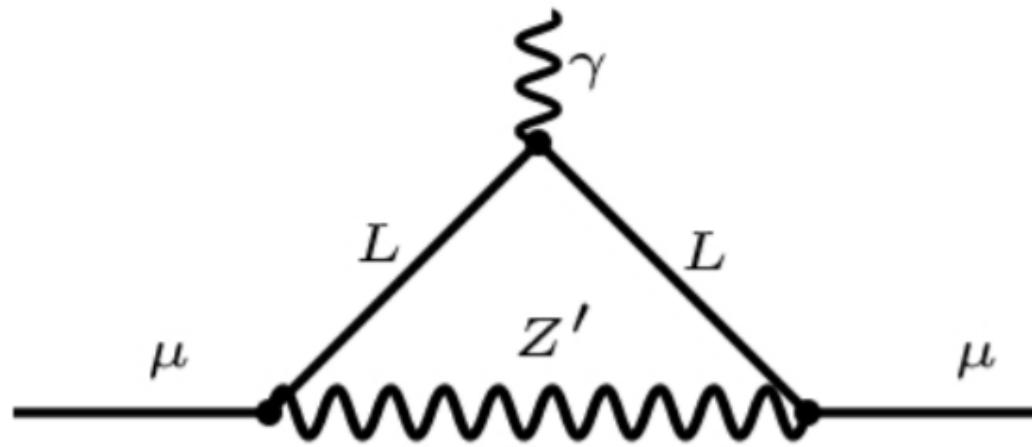


FIG. 10. Neutrino trident process that leads to constraints on the  $Z^\mu$  coupling strength to neutrinos-muons, namely  $M_{Z'}/g_{\nu\mu} \gtrsim 750$  GeV.

# $t$ -channel



$$(g - 2)_\mu$$



# $H\vartheta$ potential

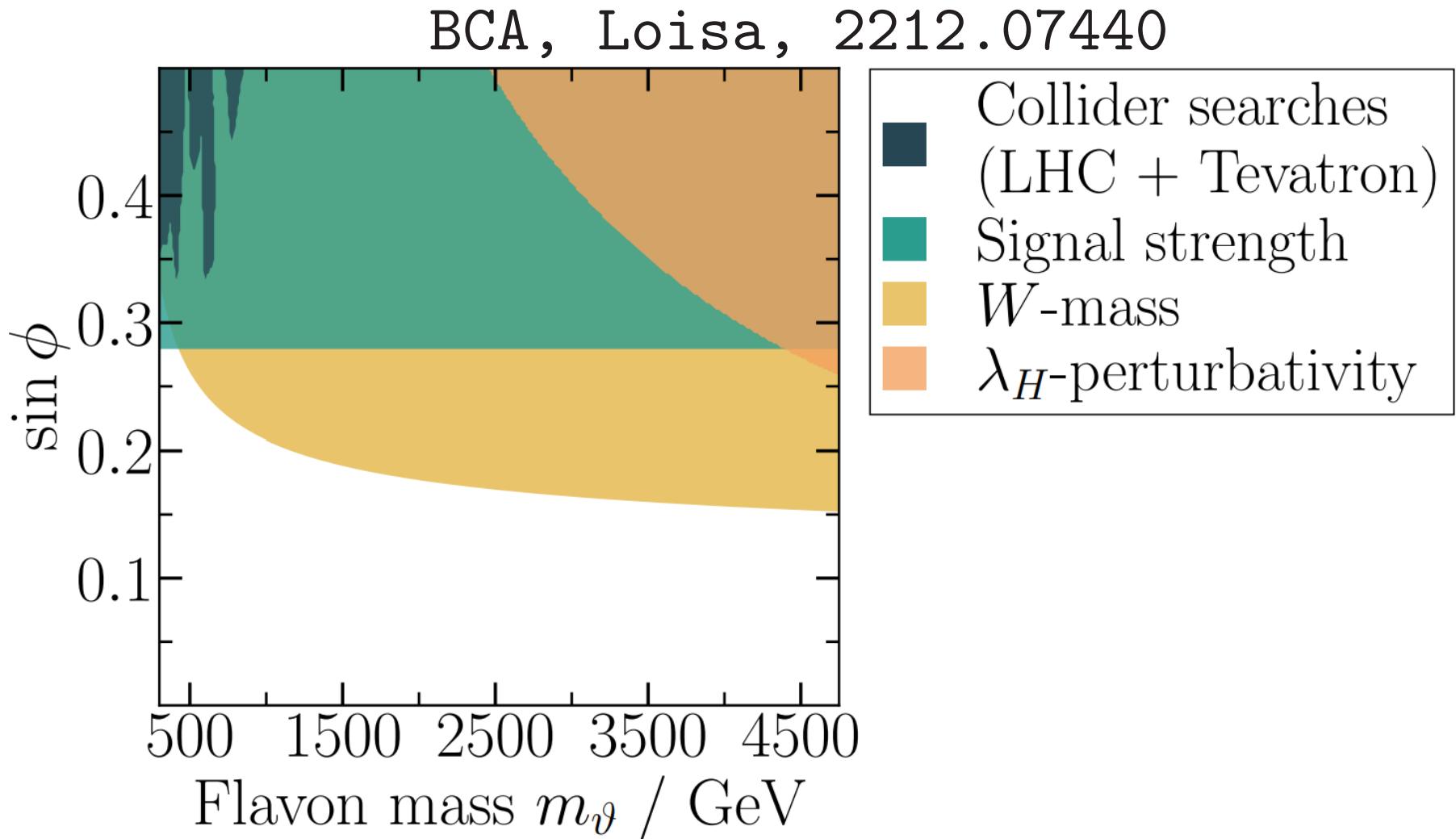
$$\begin{aligned} V &= -\mu^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_\theta^2 \theta^* \theta + \\ &\quad \lambda_\theta (\theta^* \theta)^2 + \lambda_{\theta H} \theta^* \theta H^\dagger H \\ &= -\frac{1}{2} \begin{pmatrix} h' & \vartheta' \end{pmatrix} M^2 \begin{pmatrix} h' \\ \vartheta' \end{pmatrix} + \dots \\ M^2 &= \begin{pmatrix} 2\lambda_H v_H^2 & \lambda_{\theta H} v_H v_\theta \\ \lambda_{\theta H} v_H v_\theta & 2\lambda_\theta v_\theta^2 \end{pmatrix} \end{aligned}$$

# $H\vartheta$ mixing

$$\begin{pmatrix} h \\ \vartheta \end{pmatrix} = \begin{pmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{pmatrix} \begin{pmatrix} h' \\ \vartheta' \end{pmatrix}$$
$$\sin 2\phi = \frac{2\lambda_{\theta H} v_h v_\theta}{m_\vartheta^2 - m_h^2}. \quad (-13)$$

Three parameters:  $v_\theta = M_{Z'}/g_{Z'}$ ,  $m_\vartheta$  and  $\phi$ .

# Higgs Signal Strength



# $\vartheta$ BRs

