B-anomalies beyond the SM

by

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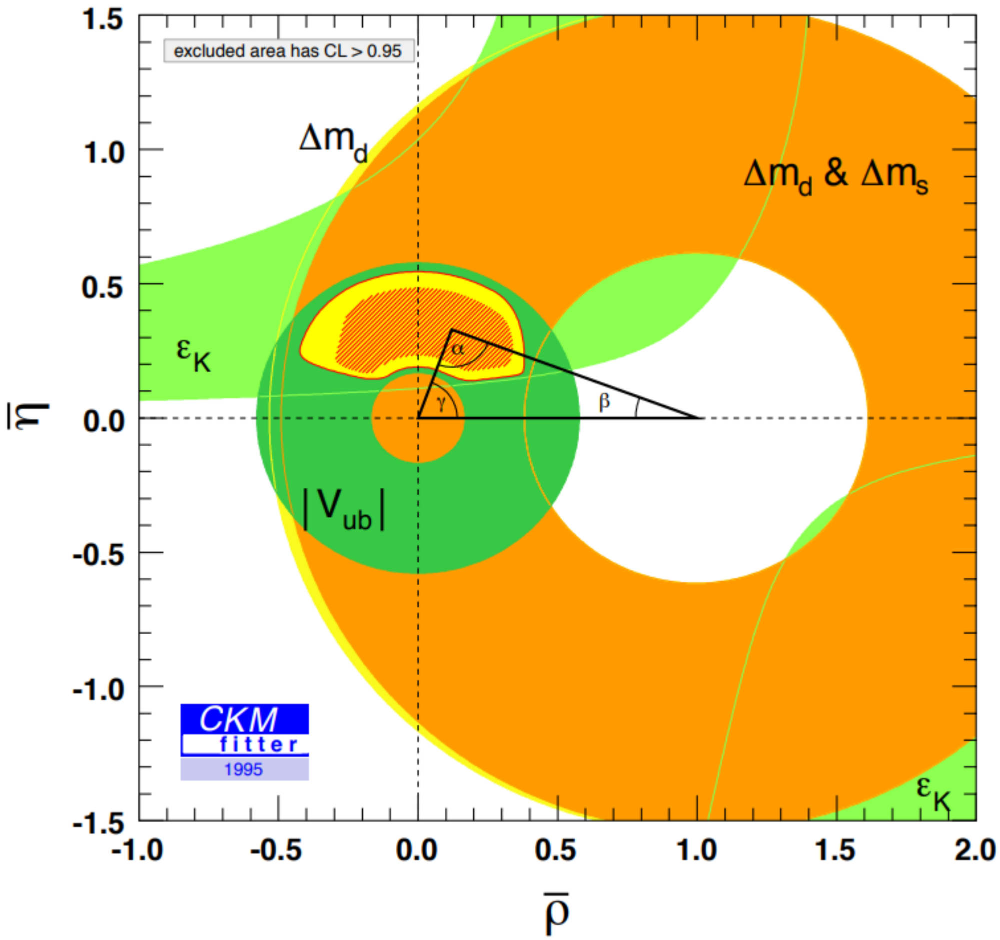
$b \to c\ell\nu_\ell$ anomalies

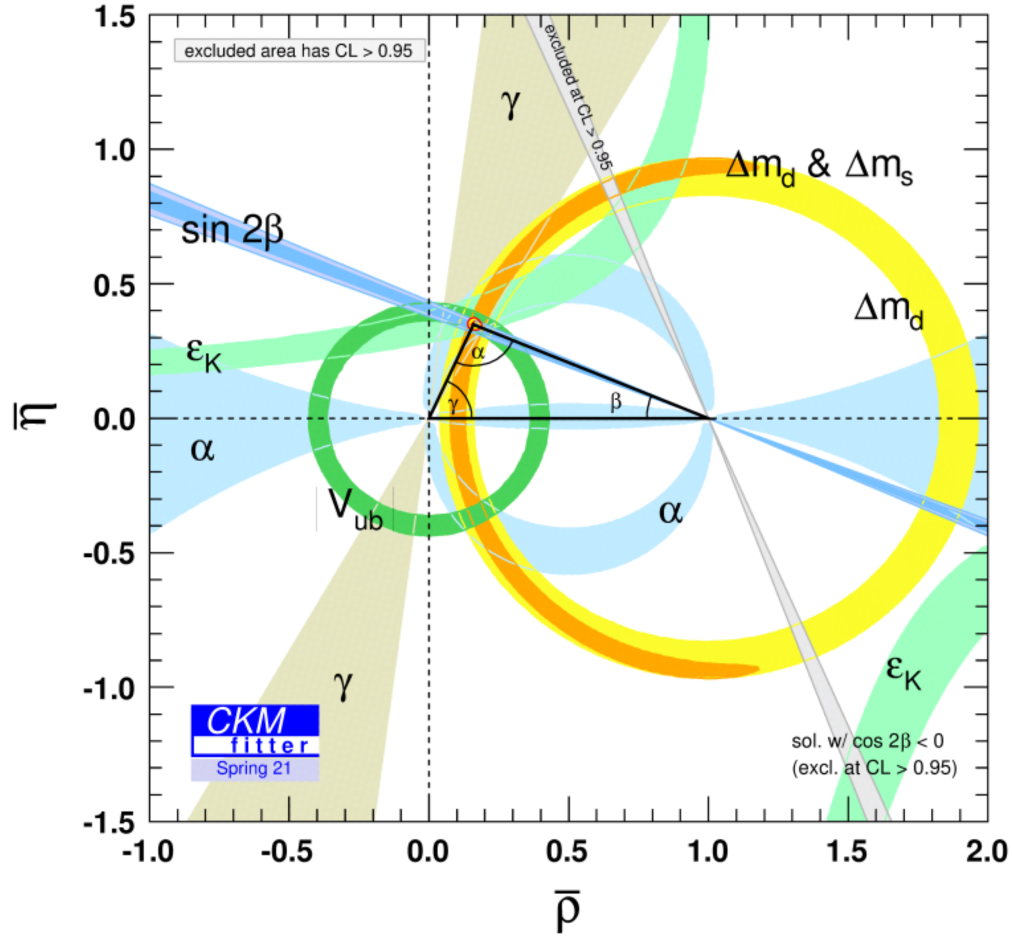
$b \to s\ell^+\ell^-$ anomalies

EFT fits

Models

Impressive Progress





During the 1990s

We wanted to be the Grand Architects, searching for **one string** model **to rule them all**

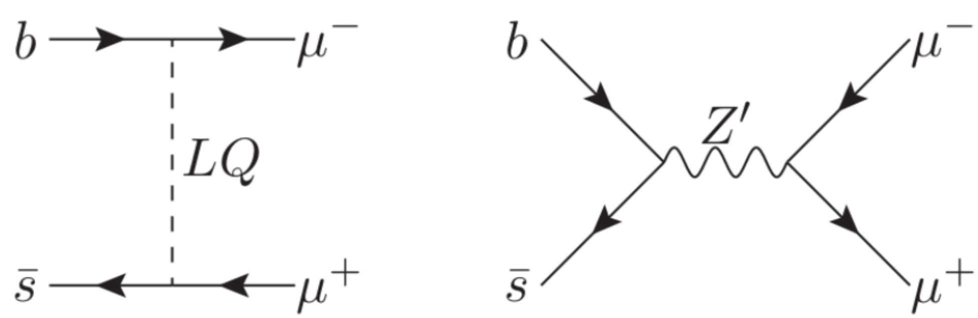
During the 2020s

We are happy with **any** beyond the SM roof

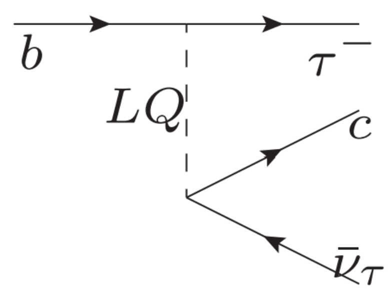
Philosophy and Organisation

Hundreds of specific models reduce to the same important TeV-scale features ⇒ take a bottom up approach

Neutral current

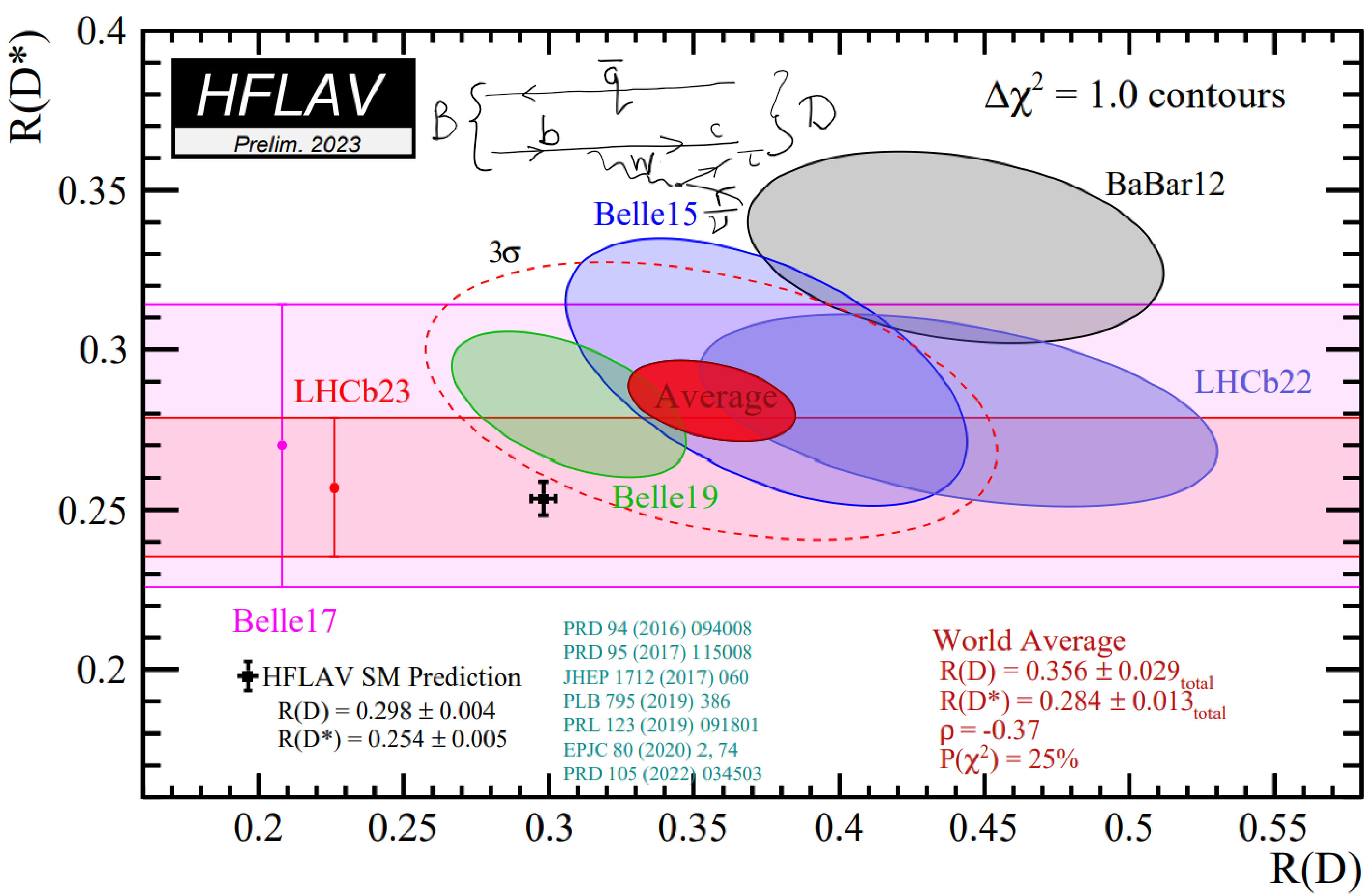


Charged current:

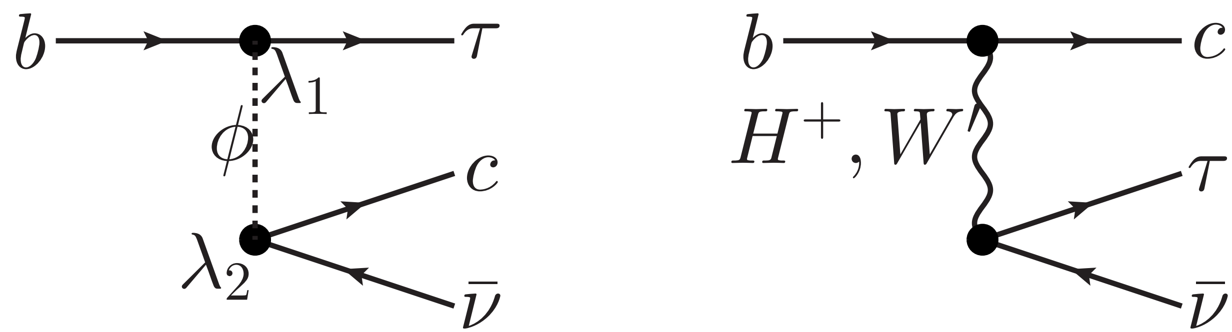


Vector/scalar option for leptoquark (LQ)

$$R_{D^{(*)}} = BR(B \to D^{(*)}\tau\nu)/BR(B \to D^{(*)}\mu\nu)$$



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



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

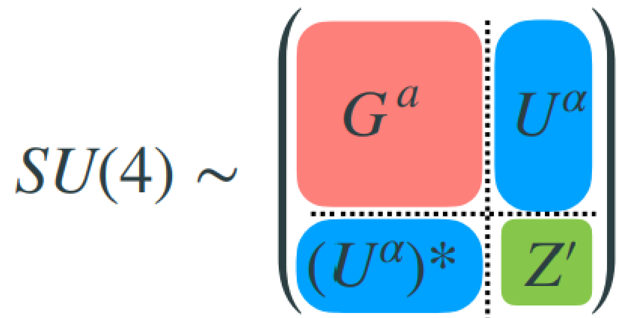
Fit to data tells us

$$M = 3.4 \text{ TeV} \times \sqrt{\lambda_1\lambda_2}$$

U_1 **Vector LQ**

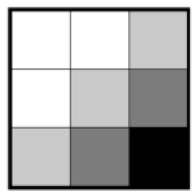
In third family, leptons are the fourth colour and LQ U^μ comes from adjoint $SU(4) \to SU(3)$.

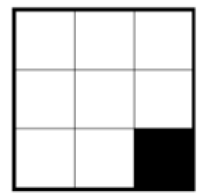
$$F_j = \begin{pmatrix} Q_j^{a=1,2,3} \\ L_j \end{pmatrix}$$

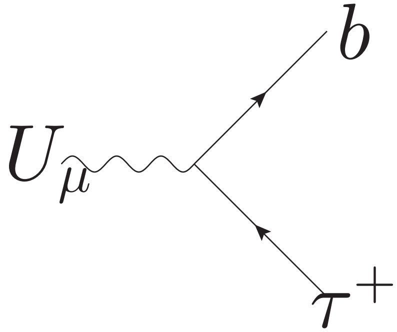


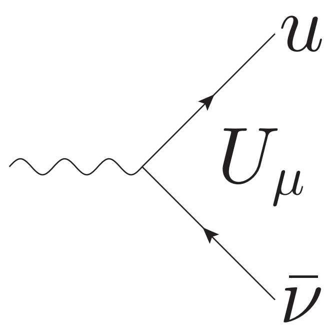
U_1 Vector LQ[1]: U^μ

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U^\mu \left[\beta_L^{i\mu} (\bar{q}_L^i \gamma_\alpha L_L^\alpha) + \beta_R^{i\alpha} (\bar{d}_R^i \gamma_\mu e_R^\alpha) + H.c. \right]$$

$\beta_L^{ql} \sim$ 

$\beta_R^{ql} \sim$ 

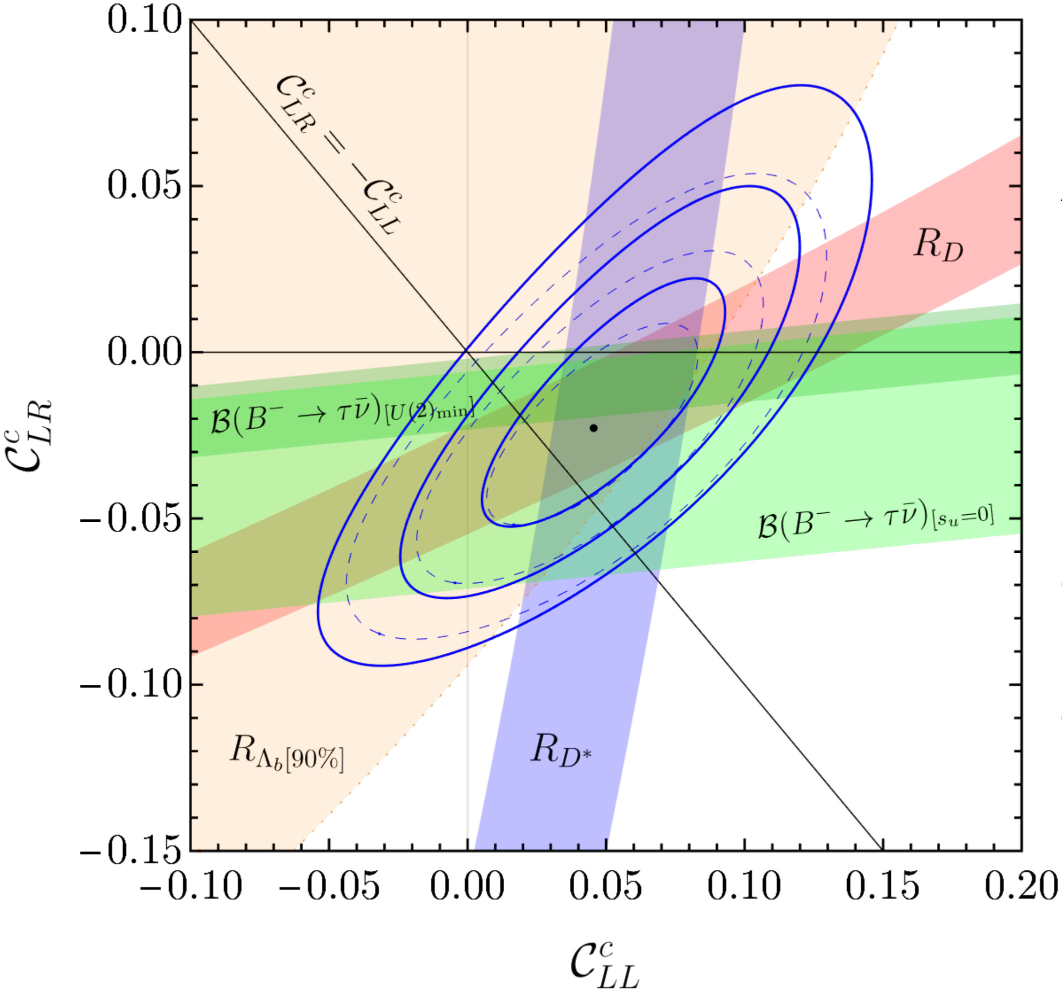




~~$B \to K \nu \bar{\nu}$~~

[1]Thanks to B Stafanek for slide material

2



$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}}(1 + C^c_{LL})V_{cb}\times$$

$$[(1 + C^c_{LL})(\bar{\tau}_L\gamma^\alpha\nu_L)(\bar{c}_L\gamma_\alpha\nu_L) -$$

$$2C_{LR}(\bar{c}_L b_T)(\bar{\tau}_R\nu_L)]$$

$$C^c_{LL} = \frac{g_U^2 v^2}{4M^2}\beta^L_{23}\beta^{L\,*}_{33}$$

$$C^c_{LR} = \frac{g_U^2 v^2}{4M^2}\beta^L_{23}\beta^{R\,*}_{33}$$

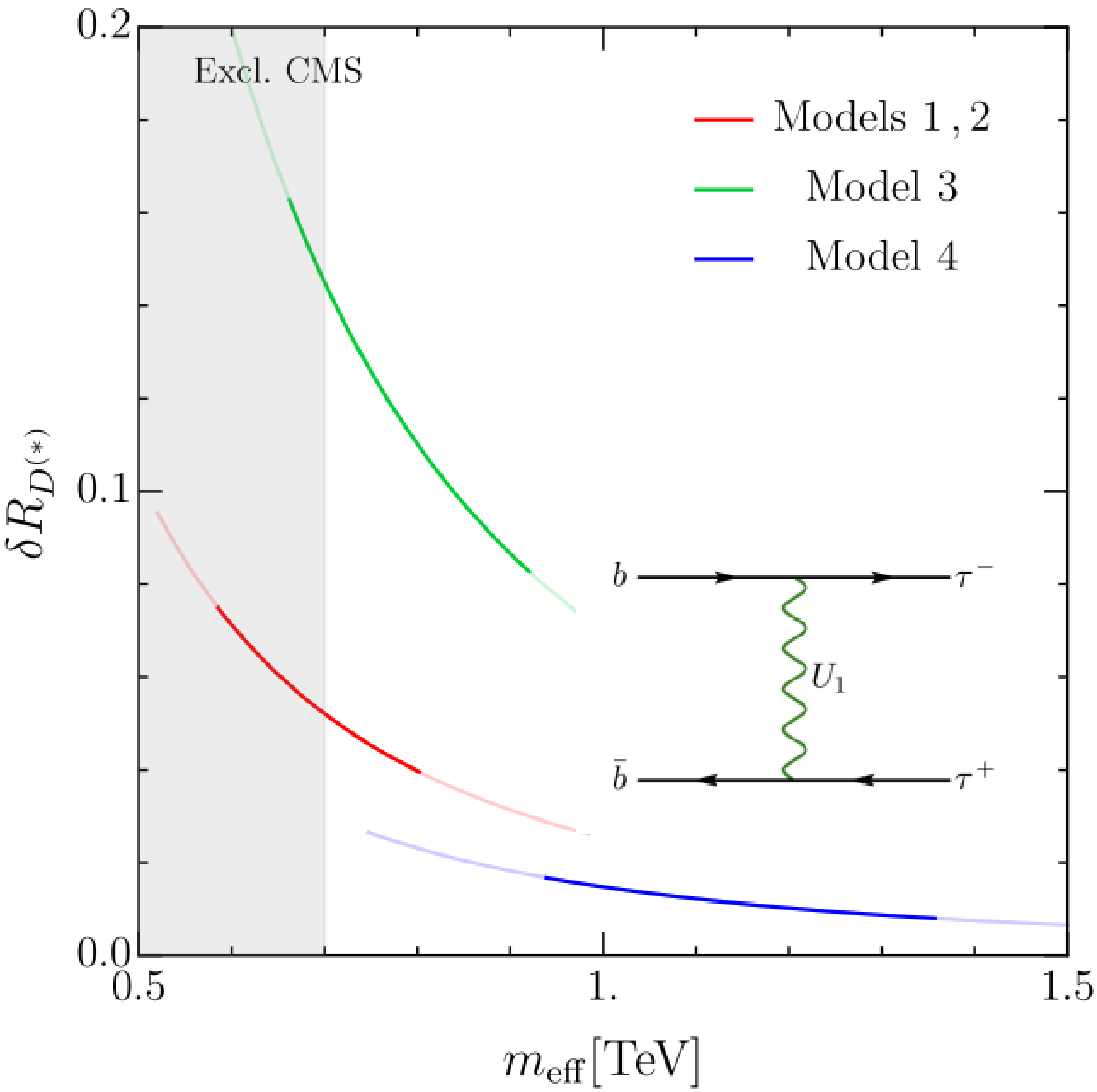
[2] Aebischer, Isidori, Pesut, Stefanek, Wilsch (2210.13422); Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, 2103.16558

Simple models[3] from $SU(4)$

Model	Direct SM Yukawa	$SU(4)$ gauged	min. $U(2)^n_f$ breaking	J
1	yes	no	yes	2
2	yes	yes	yes	1
3	yes	yes	no	2
4	no	no	yes	3(×2)

[3] Barbieri, Cornella and Isidori, 2207.14248

$$m_{eff} = M/g_U$$

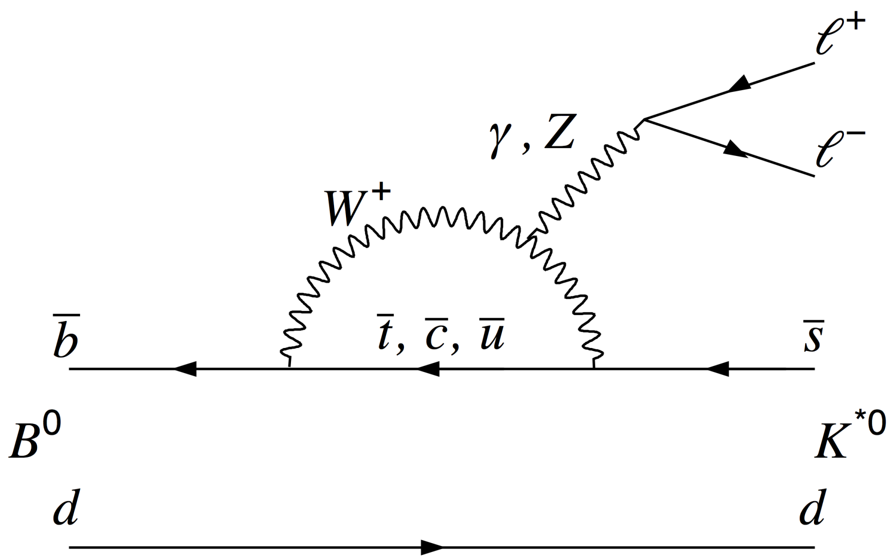


ATLAS (2210.0547) and CMS (2012.04178) direct di-LQ search for $2 \times (q_3 l_{1,2}) \Rightarrow M >$1.7 TeV.

$b \to s l^+ l^-$ in Standard Model

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

BR$\sim \mathcal{O}(10^{-7})$: loop+EW+CKM



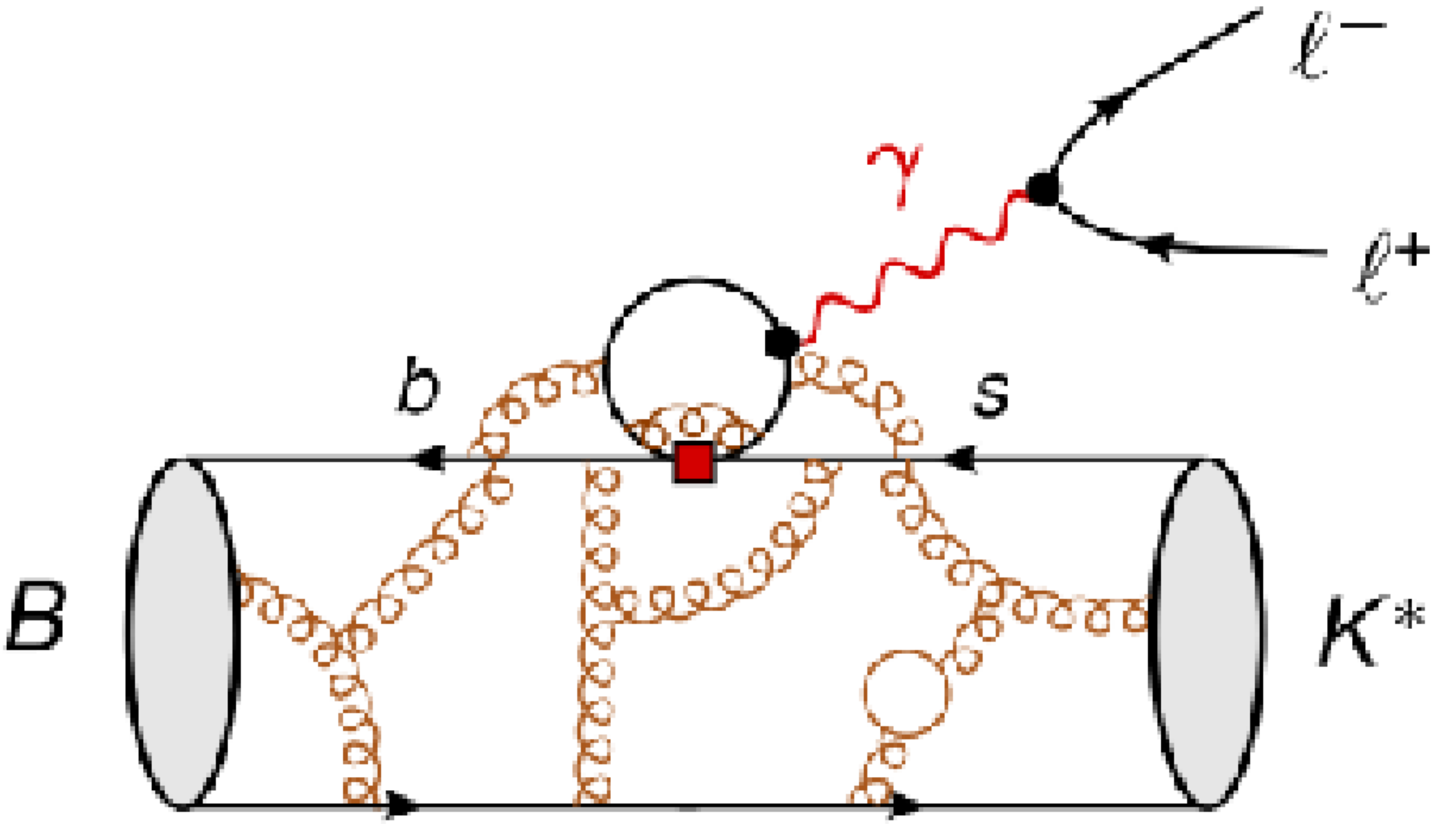
Predicting $B \to M\ell^+\ell^-$

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

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

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

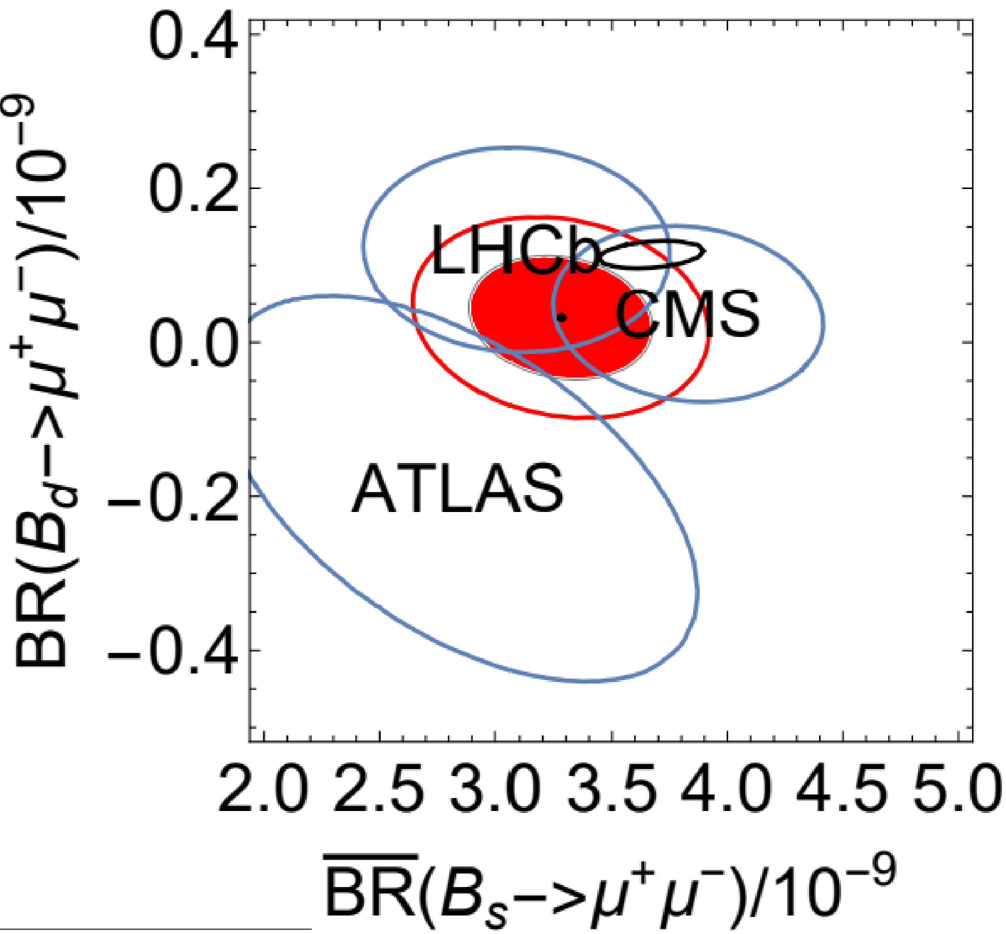
`EOS` approach: interpolate $q^2 < 0$ LCOPE and measurements of BRs/angular dists at $q^2 = M_{J/\psi}^2$.



ℓ^-
γ
ℓ^+
b
s
B
K^*

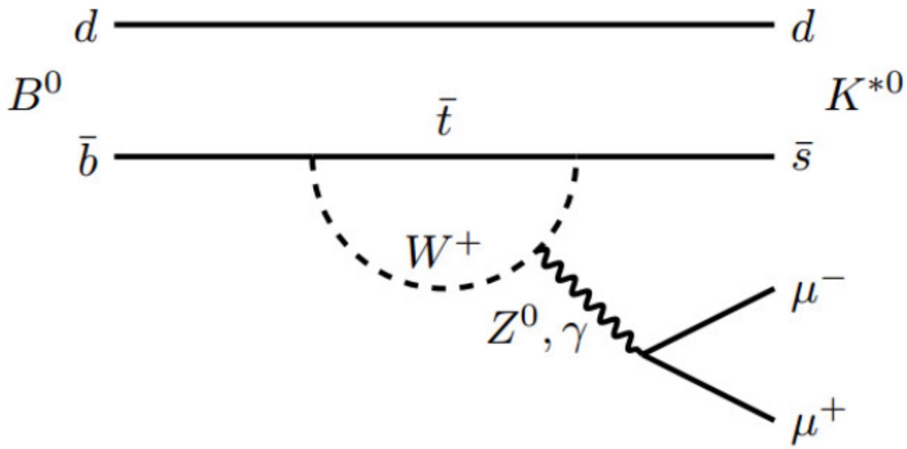
$BR(B_s \to \mu^+\mu^-)$:[4]: SM: 1.6σ

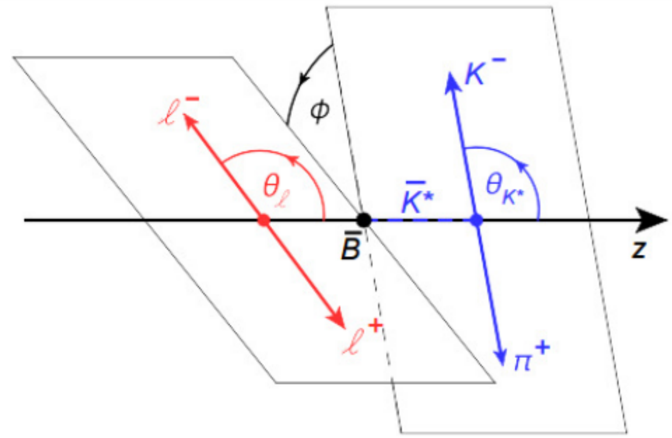
$B_s = (\bar{b}s)$, $B_d = (\bar{b}d)$



[4]SM: Feldmann, Gubernari, Huber, Seitz, 2211.04209; Combination: BCA, Davighi, 2211.11766

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

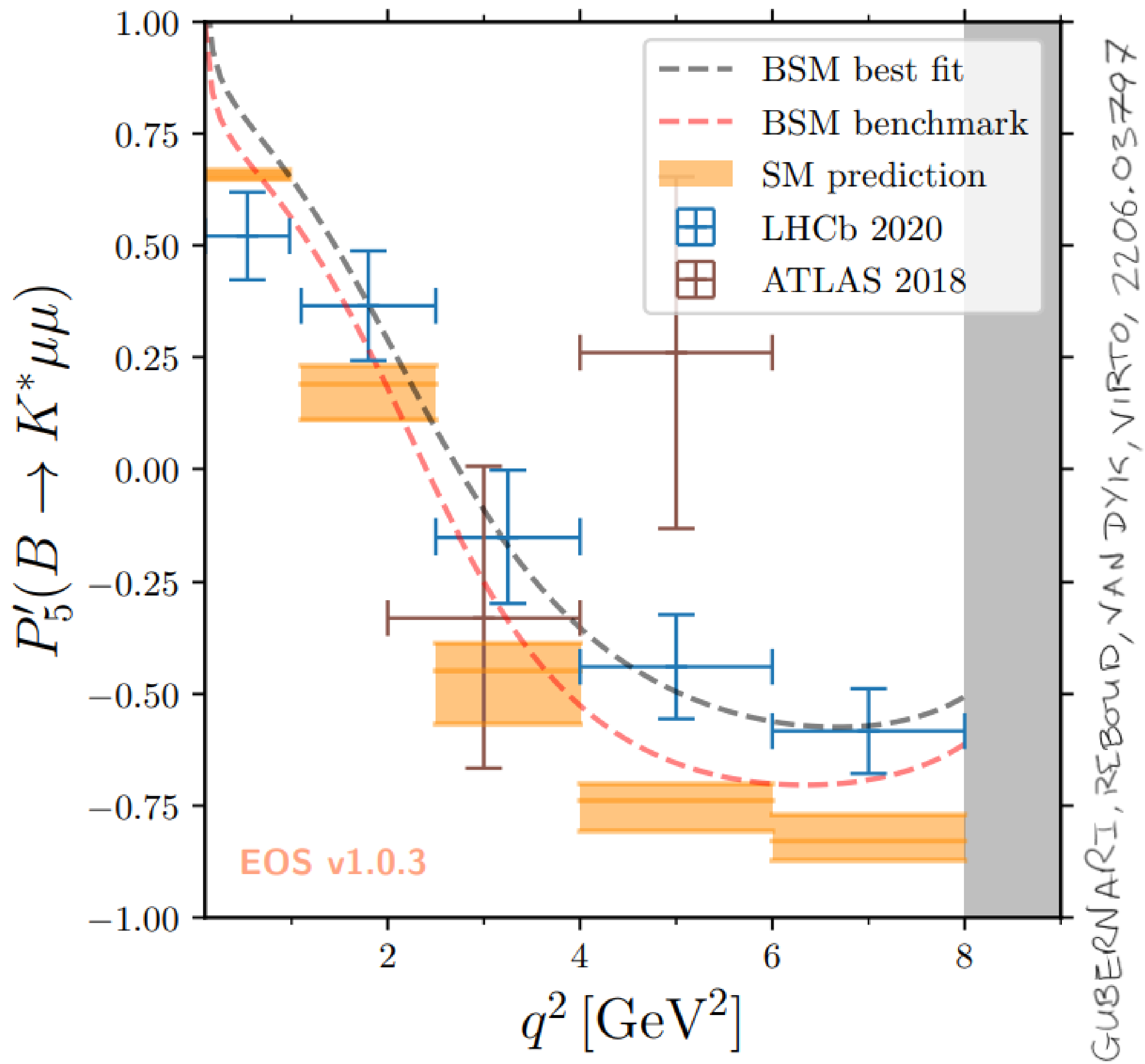




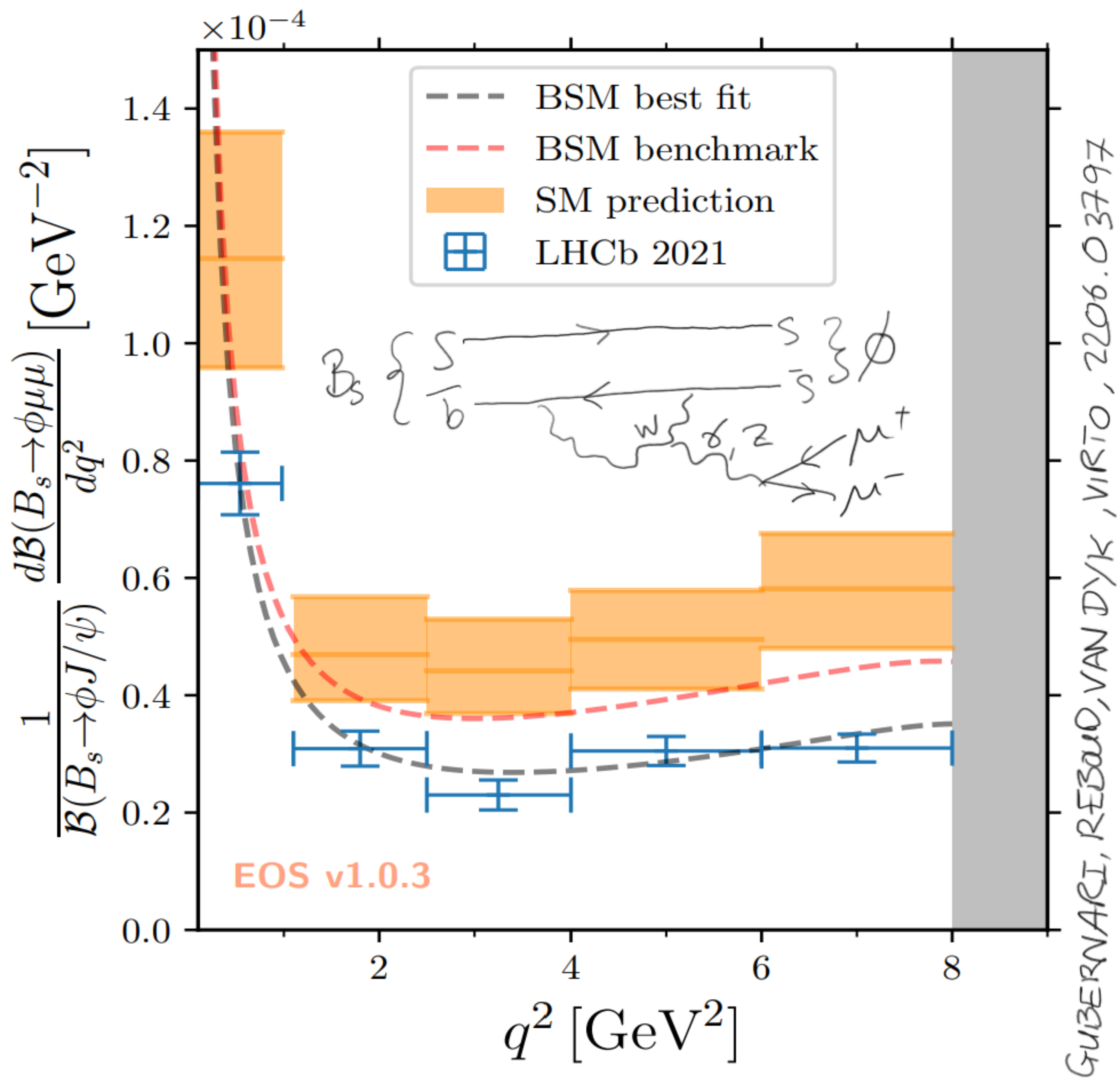
Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

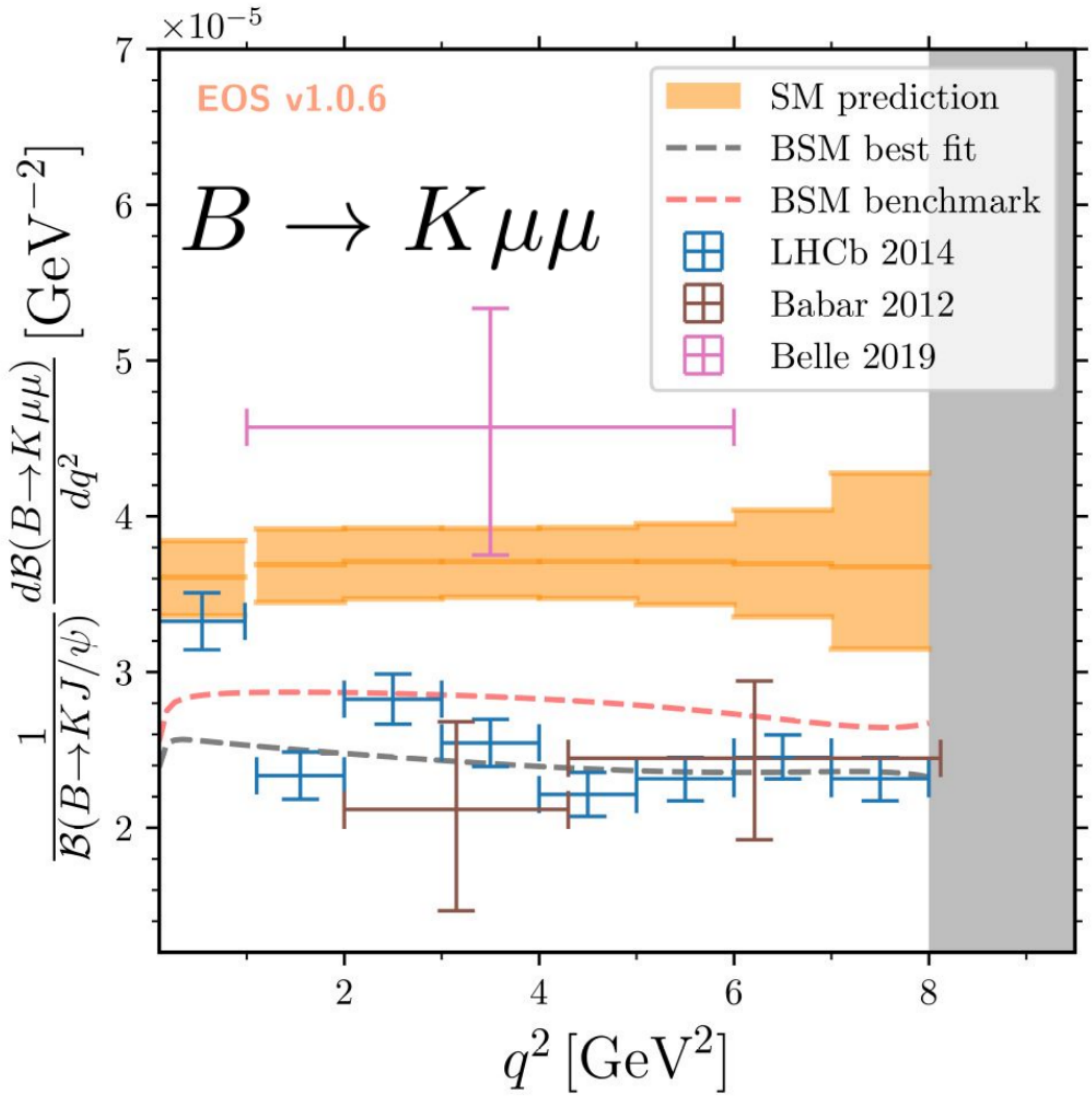
$$P_5' = S_5/\sqrt{F_L(1-F_L)}$$



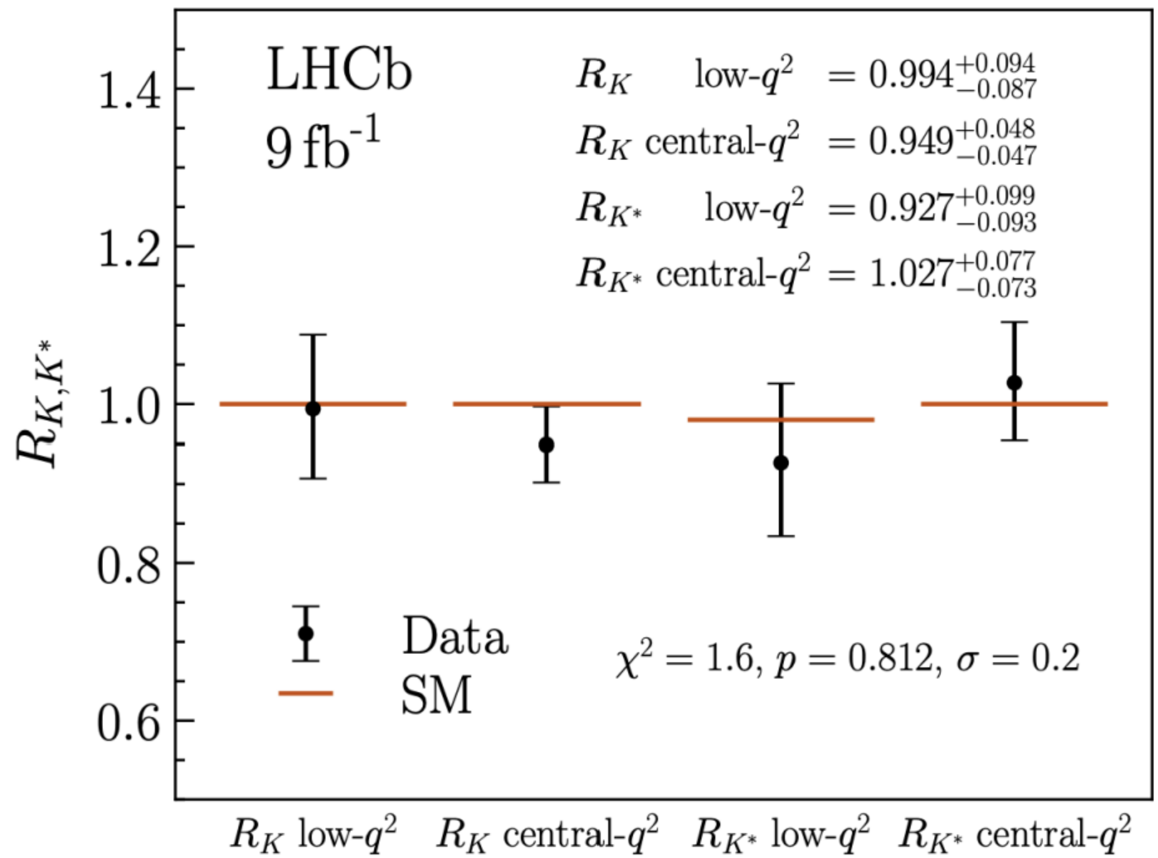
$B_s \to \phi\mu^+\mu^-$: $\phi = (s\bar{s})$



$BR(B \to K\mu^+\mu^-)$


EOS v1.0.6
$B \to K\mu\mu$
SM prediction
BSM best fit
BSM benchmark
LHCb 2014
Babar 2012
Belle 2019
$\times 10^{-5}$
$\frac{1}{\mathcal{B}(B\to KJ/\psi)} \frac{d\mathcal{B}(B\to K\mu\mu)}{dq^2}$ [GeV^{-2}]
q^2 [GeV^2]
2
3
4
5
6
7
8

LHCb 2212.09152

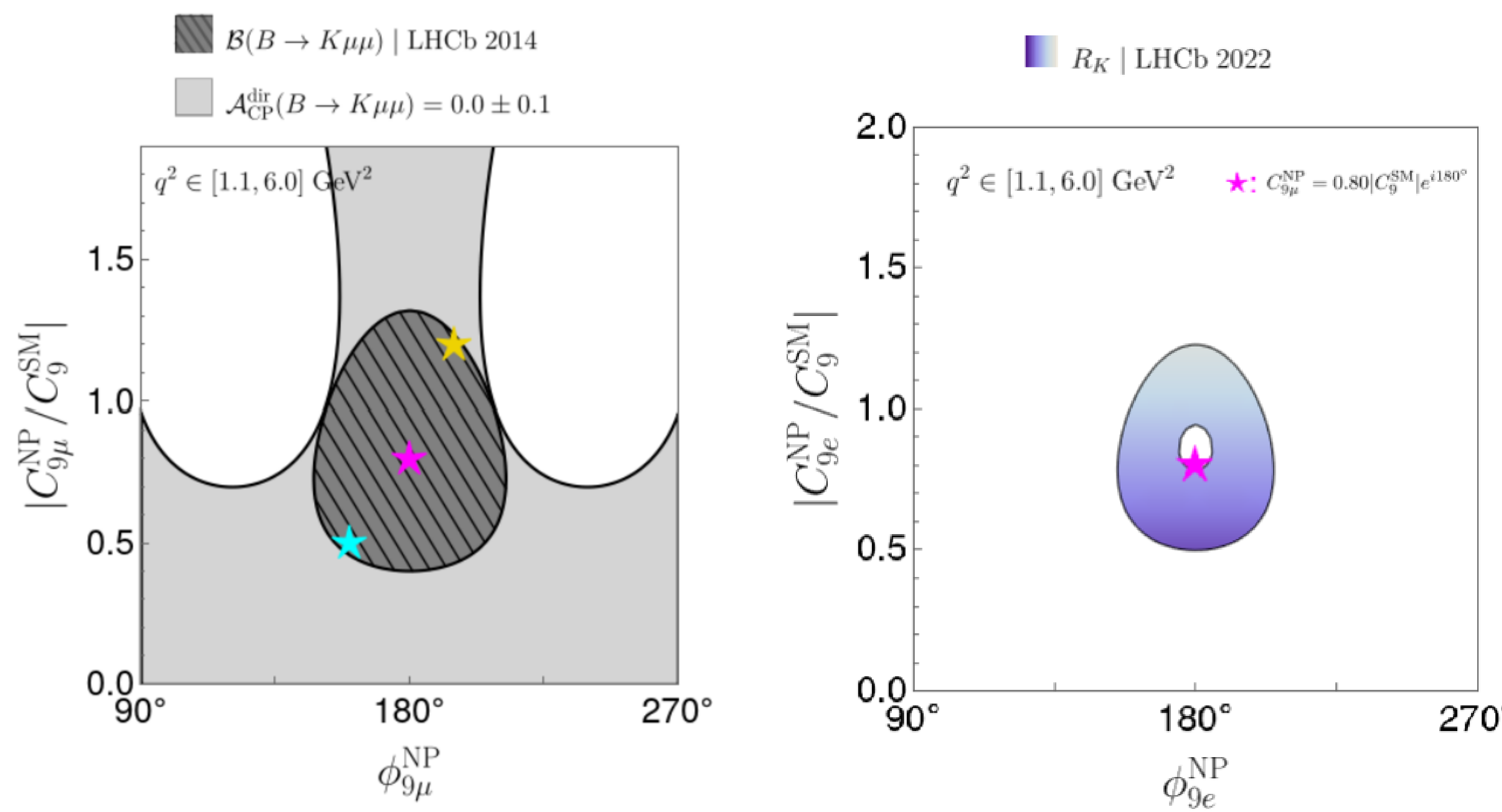


$$R_X(q^2) = \frac{BR(B \to X\mu^+\mu^-)}{BR(B \to Xe^+e^-)}(q^2)$$

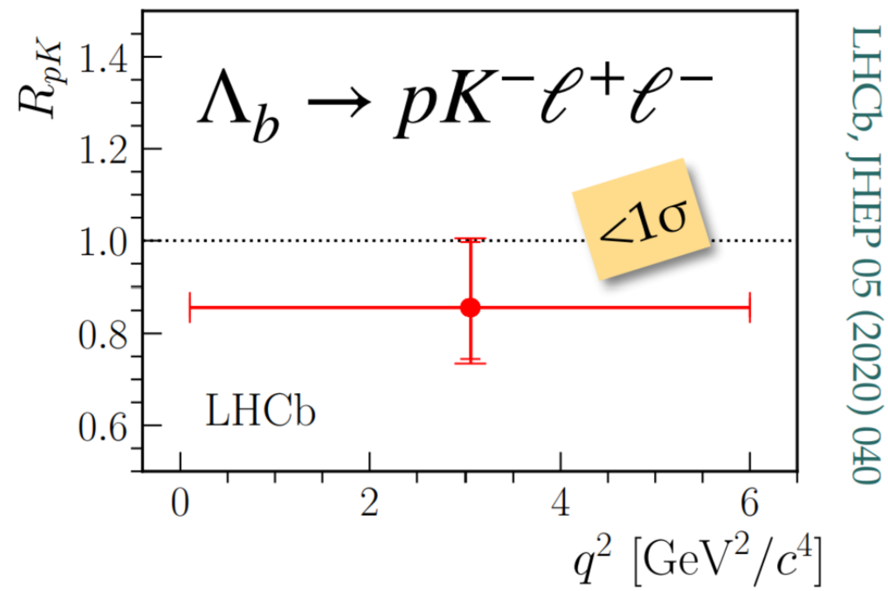
$e \neq \mu$ allowed

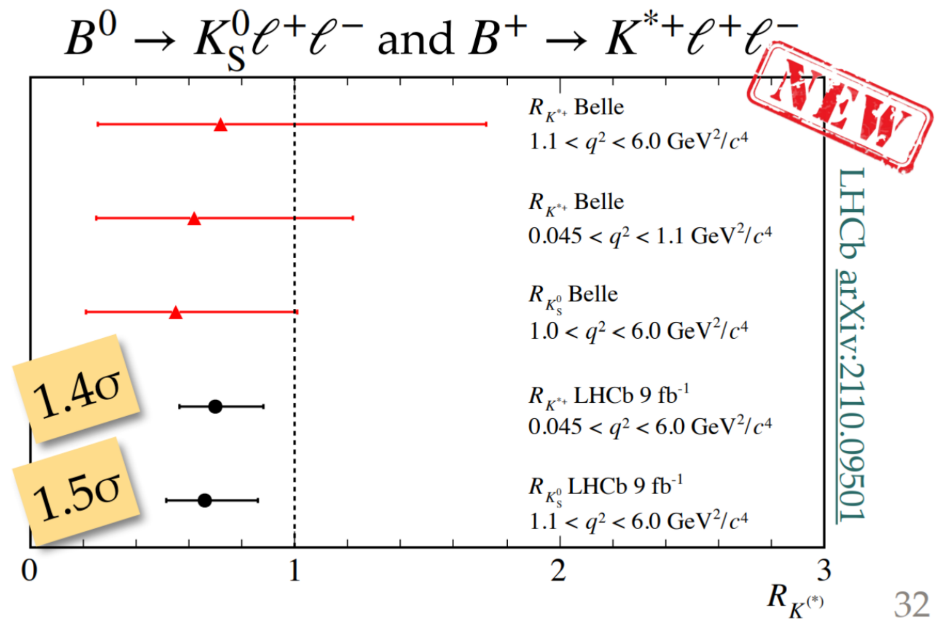
Fleischer, Malami, Rehult, Keri Vos, 2303.08764; $C_{9\ell}^{NP} = |C_{9\ell}^{NP}| e^{i\phi_{9\ell}^{NP}}$

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



Other LFU





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

$$B \to \pi\ell^+\ell,$$

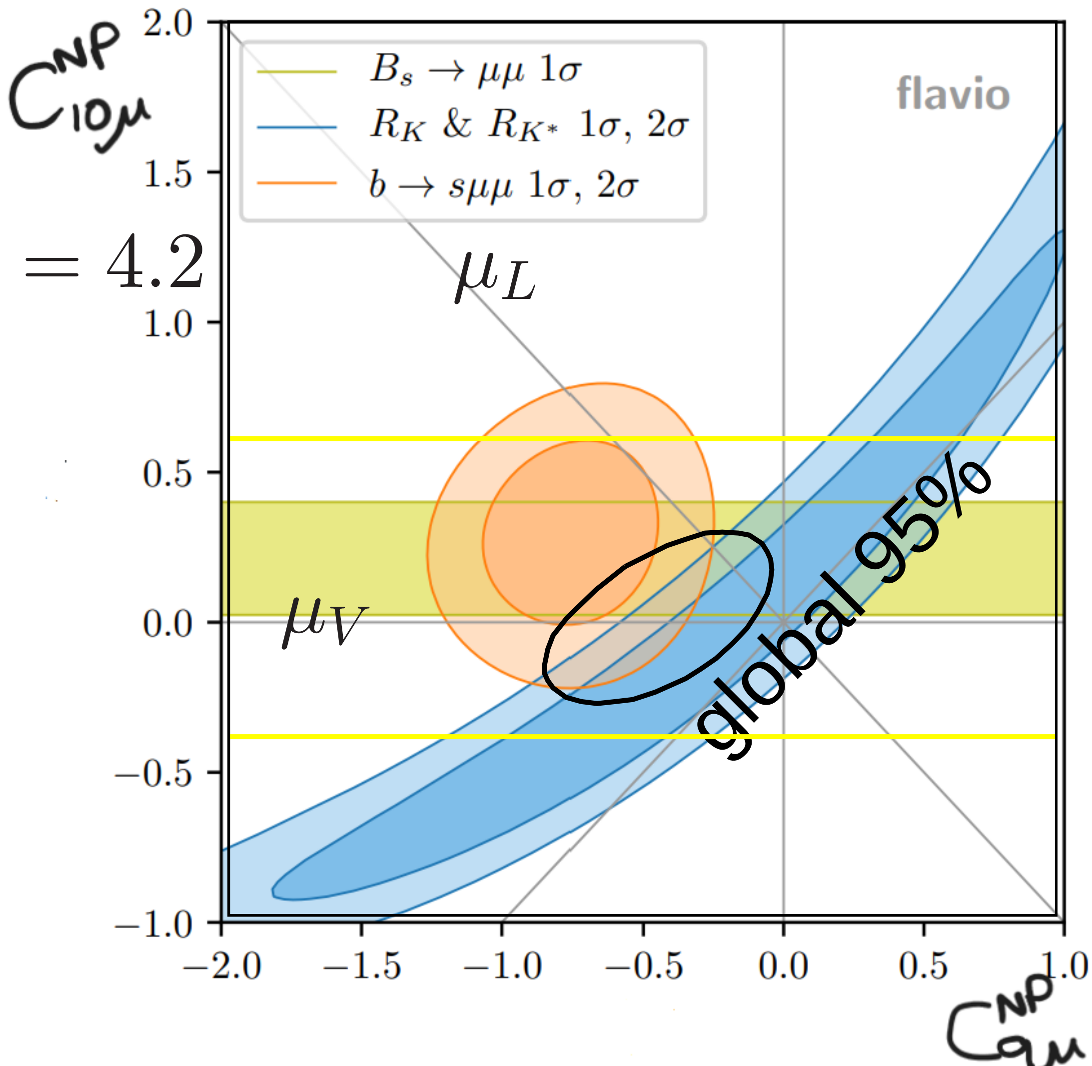
$B \to K\pi^+\pi^-\ell^+\ell^-, \ldots$ to come

μ Neutral Current Fits

Greljo, Salko, Smolkovic, Stangl, 2212.10497

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

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



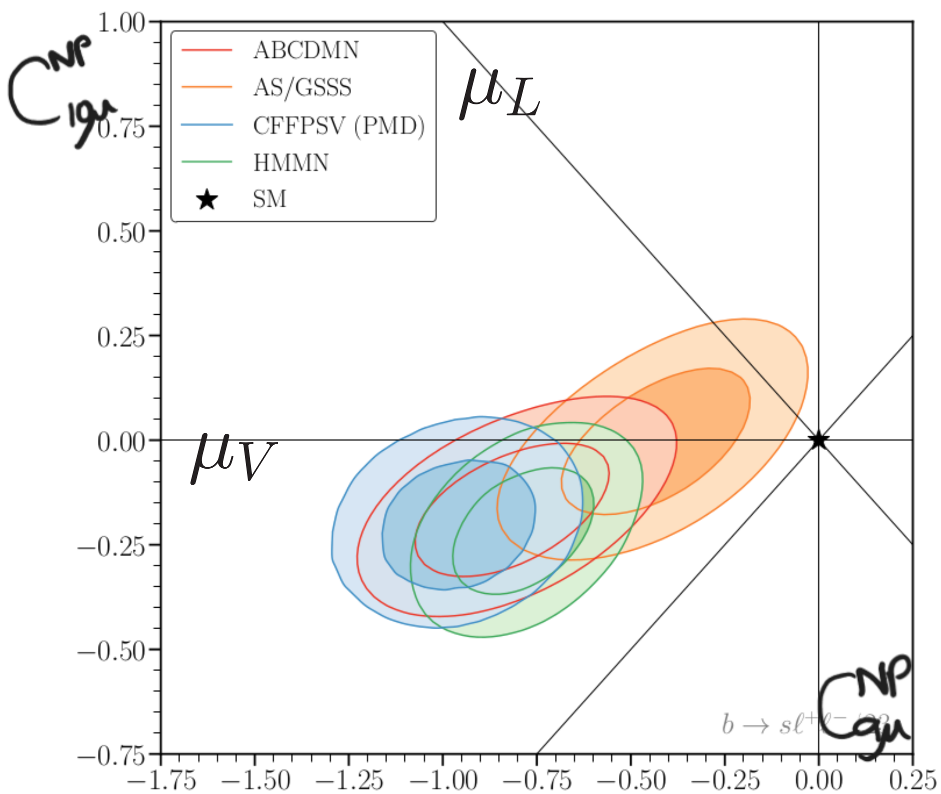
μ Neutral Current Fits

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

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

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

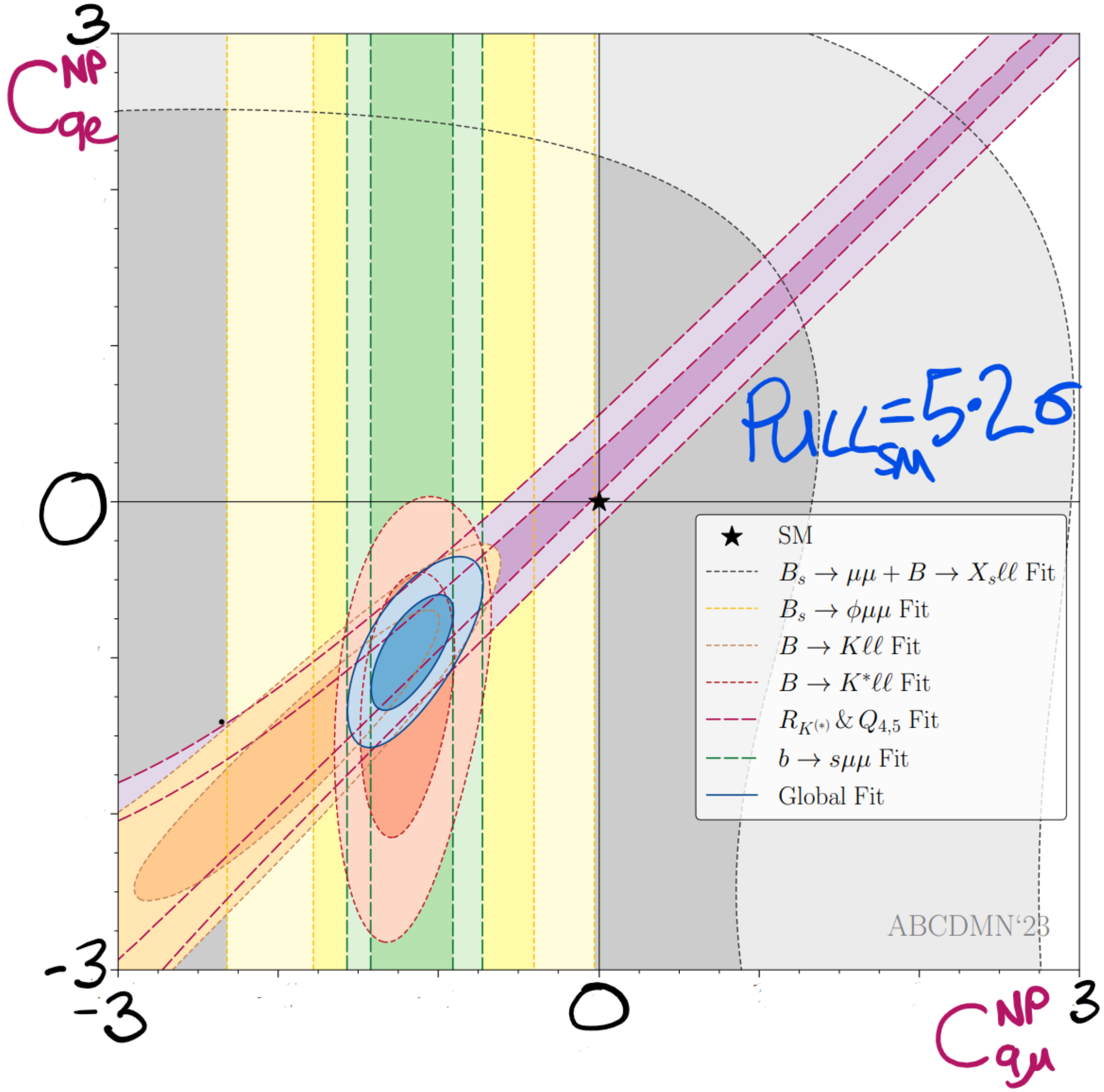
Plot from B Capdevila-Soler *Beyond Flavour Anomalies* workshop

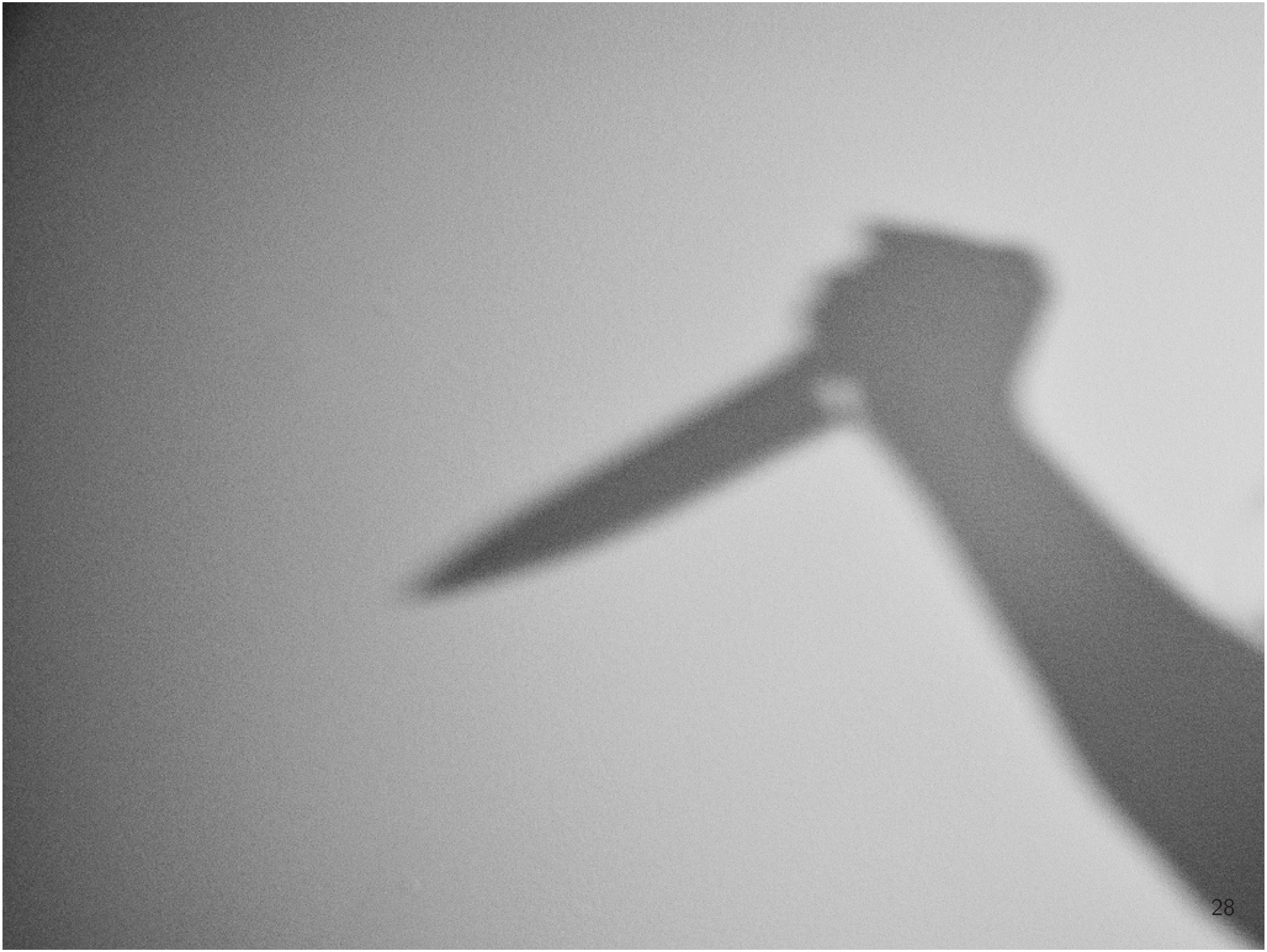


μ/e Neutral Current Fits

`Alguero et al, 2304.07330`

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





Simple Z' Models

SM-singlet scalar 'flavon' θ

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

SM$+3\nu_R$ fermion content

Zero charges for first two generations of quark

Postdicts heavy third family quarks[5]

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[5] Bonilla *et al*, 1705.00915; Alonso *et al* 1705.03858, BCA 2009.02197 (*simplified EFT*)

Flavour problem

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

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

$$
\begin{aligned}
\mathcal{L}_{X\psi} = g_X & \Big(\overline{\mathbf{u_L}} \Lambda_{\xi}^{(u_L)} \not{Z}' \mathbf{u_L} + \overline{\mathbf{u_R}} \Lambda_{\xi}^{(u_R)} \not{Z}' \mathbf{u_R} \\
& + \overline{\mathbf{d_L}} \Lambda_{\xi}^{(d_L)} \not{Z}' \mathbf{d_L} + \overline{\mathbf{d_R}} \Lambda_{\xi}^{(d_R)} \not{Z}' \mathbf{d_R} \\
& - \overline{\mathbf{e_L}} \Lambda_{\Xi}^{(e_L)} \not{Z}' \mathbf{e_L} - \overline{\mathbf{e_R}} \Lambda_{\Xi}^{(e_R)} \not{Z}' \mathbf{e_R} \\
& - \overline{\boldsymbol{\nu}_L} \Lambda_{\Xi}^{(\nu_L)} \not{Z}' \boldsymbol{\nu}_L - \overline{\boldsymbol{\nu}_R} \Lambda_{\Xi}^{(\nu_R)} \not{Z}' \boldsymbol{\nu}_R \Big),
\end{aligned}
$$

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

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

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

A simple limiting case

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

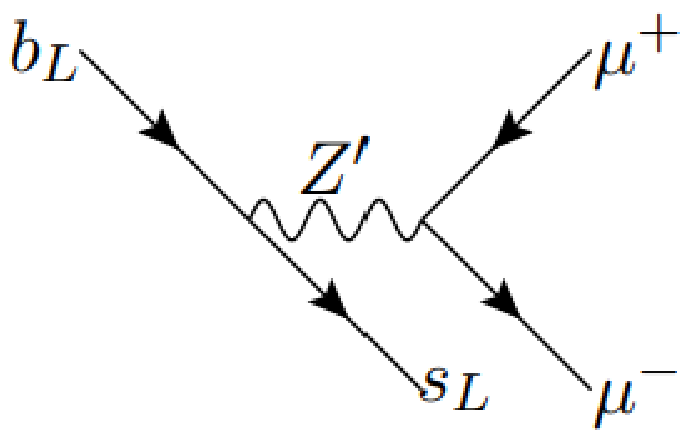
$$V_{d_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{sb} & -\sin\theta_{sb} \\ 0 & \sin\theta_{sb} & \cos\theta_{sb} \end{pmatrix}.$$

$\Rightarrow V_{u_L} = V_{d_L} V^\dagger_{CKM}$ and $V_{\nu_L} = V_{e_L} U^\dagger_{PMNS}$.

Important Z' Couplings

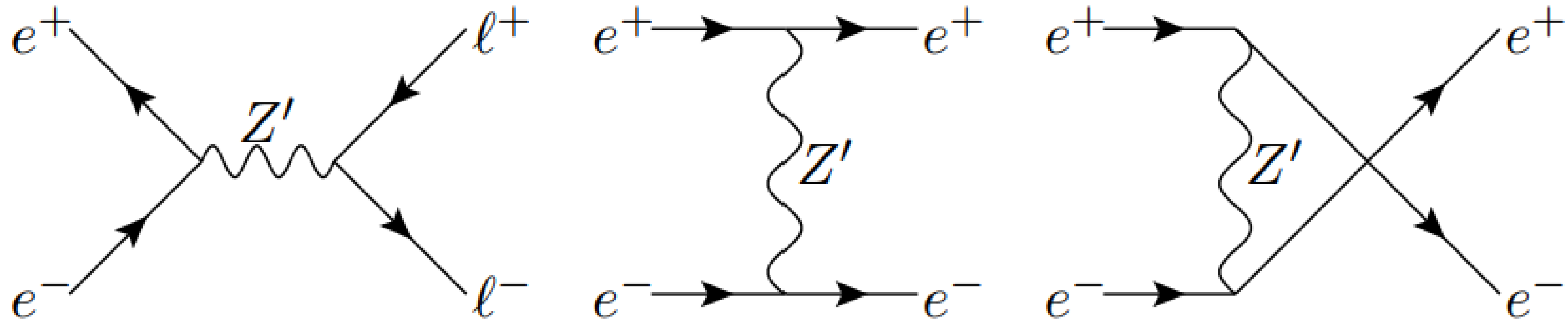
$$g_{Z'}\left[(\overline{d_L}\ \overline{s_L}\ \overline{b_L})\begin{pmatrix}0 & 0 & 0\\ 0 & \sin^2\theta_{sb} & \frac{1}{2}\sin 2\theta_{sb}\\ 0 & \frac{1}{2}\sin 2\theta_{sb} & \cos^2\theta_{sb}\end{pmatrix}\not{Z}'\begin{pmatrix}d_L\\ s_L\\ b_L\end{pmatrix}\right.$$

$$\left.-(\overline{e}\ \overline{\mu}\ \overline{\tau})\begin{pmatrix}X_e & 0 & 0\\ 0 & X_\mu & 0\\ 0 & 0 & (3-X_e-X_\mu)\end{pmatrix}\not{Z}'\begin{pmatrix}e\\ \mu\\ \tau\end{pmatrix}\right]$$

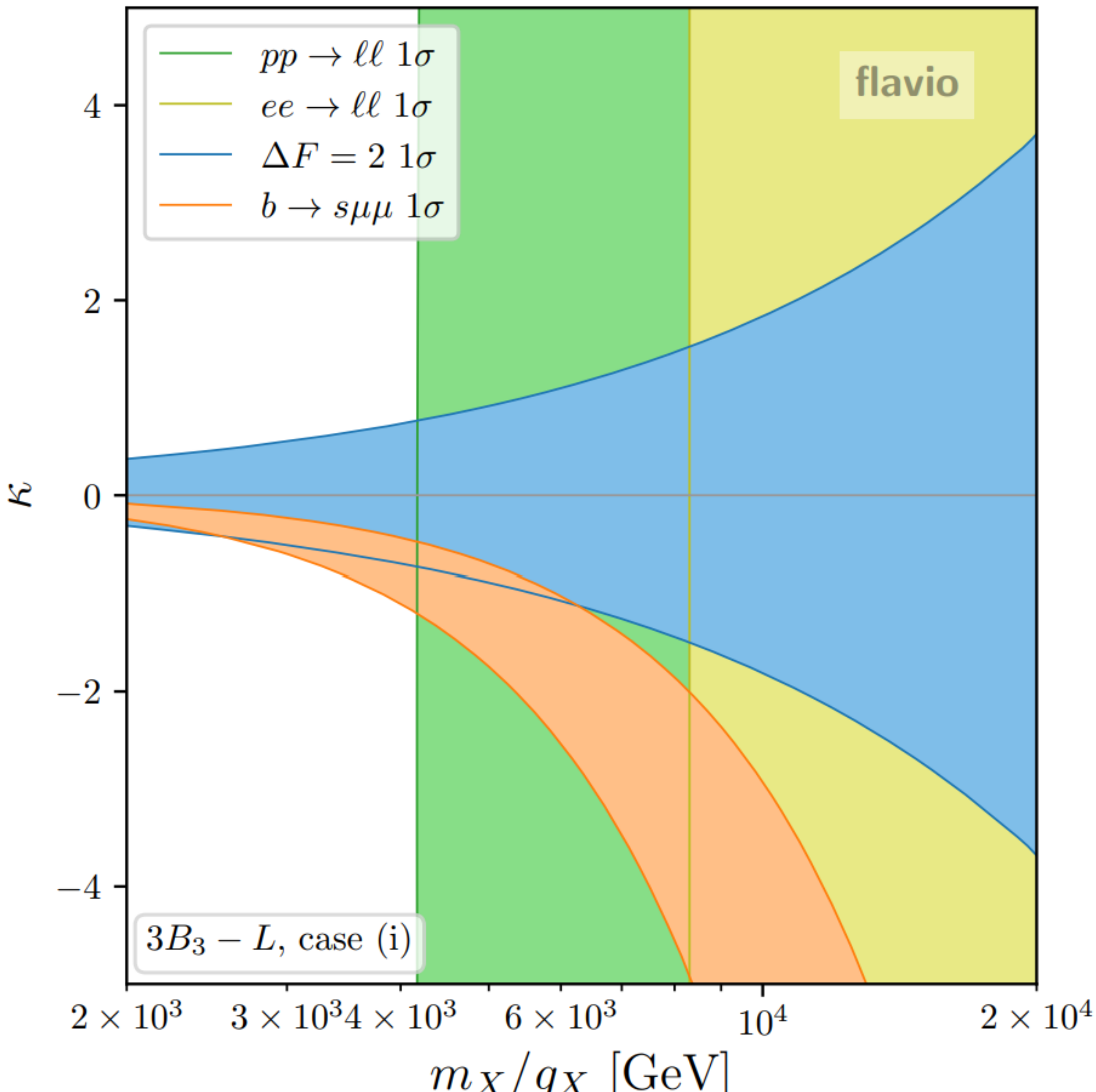


– LFU Violating, $C_9 \neq 0$

LEP constraints

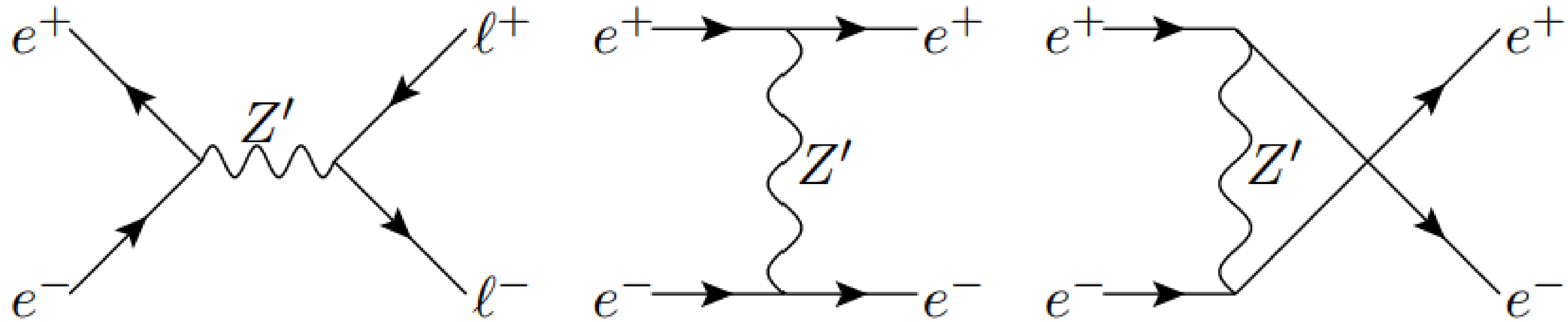


$3B_3 - L_e - L_\mu - L_\tau$ model



Greljo, Salko, Smolkovic, Stangl, 2212.10497

LEP constraints

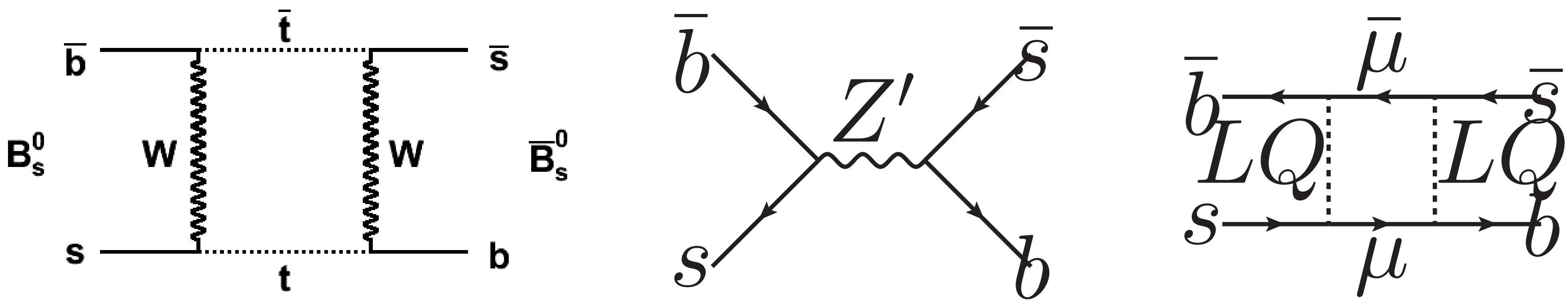


Put into flavio (Falkowski, Mimouni 1511.07434)

Fit θ_{sb} and $g_{Z'}/M_{Z'}$

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

Measurement agrees with SM.

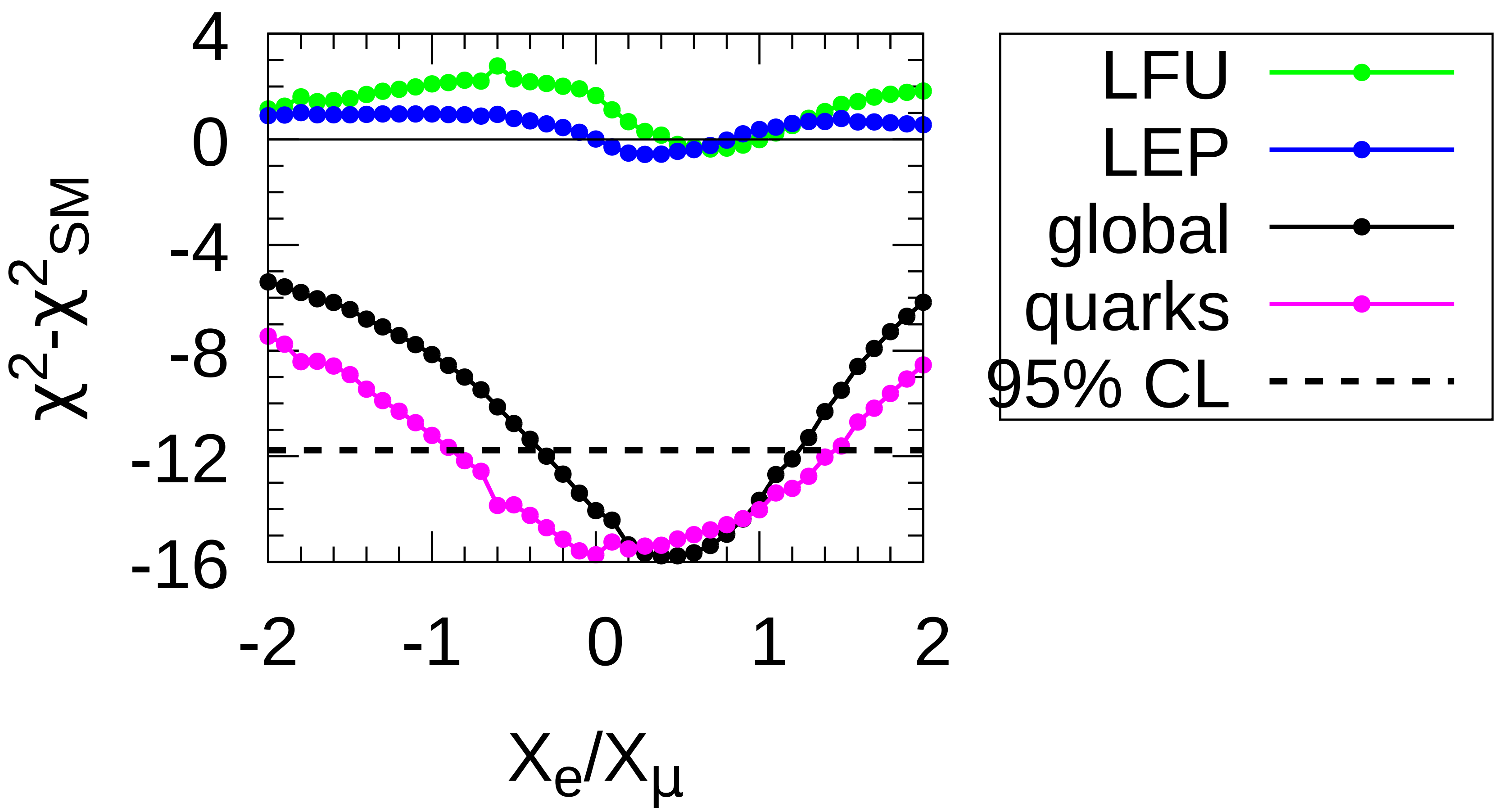


$$g_{sb} = \frac{g_X}{2} \sin 2\theta_{sb} \lesssim \frac{M_{Z'}}{194 \text{ TeV}}$$ but uncertain

from QCD sum rules and lattice[6].

[6] King, Lenz, Rauh, arXiv:1904.00940

BCA, Mullin, 2306.08669

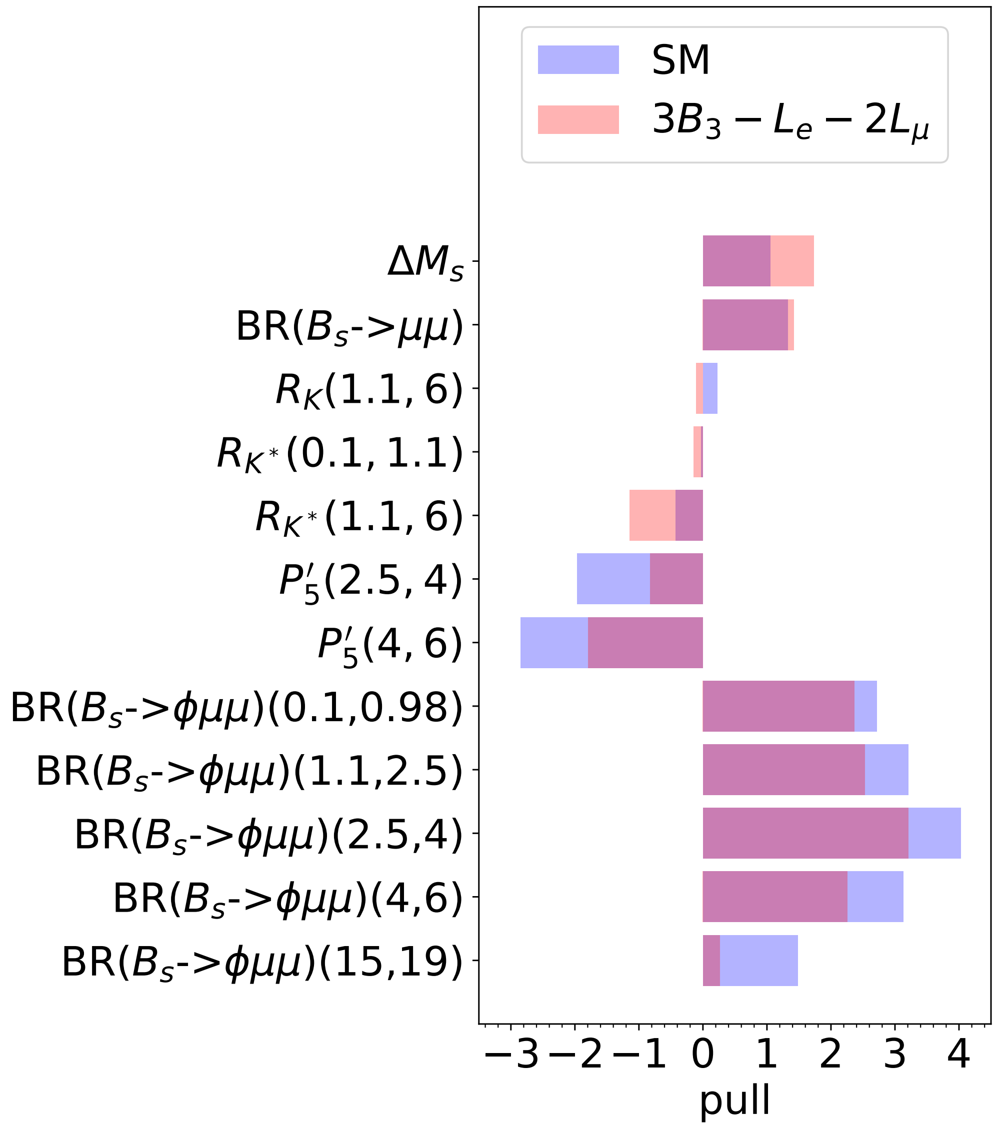


$3B_3 - L_e - 2L_\mu$ model

	$\chi^2 - \chi^2_{SM}$	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

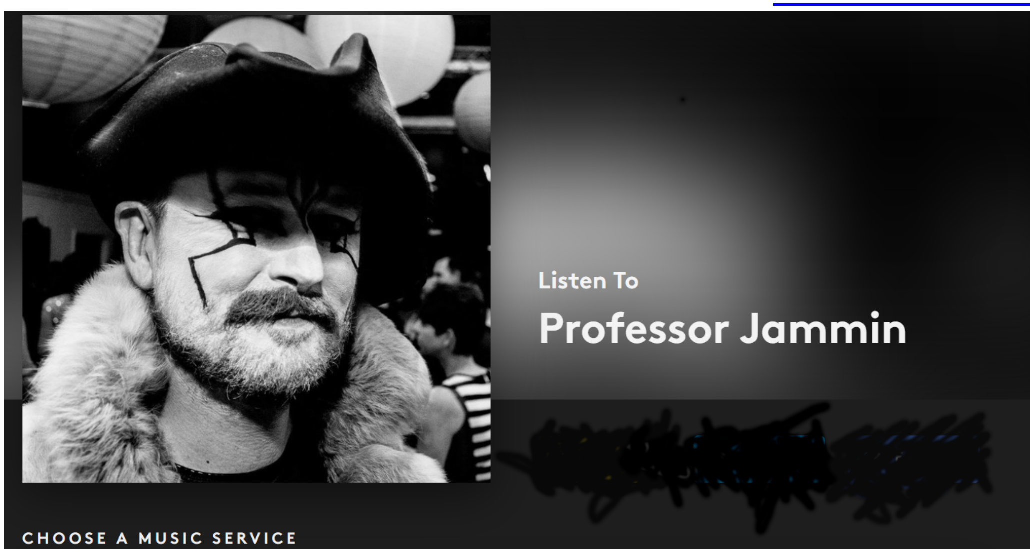
BCA, Mullin, 2306.08669

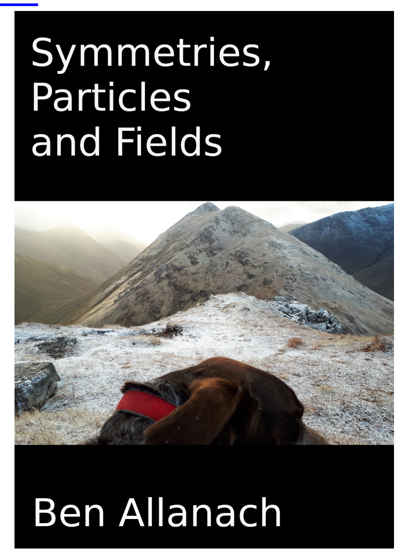

SM
$3B_3 - L_e - 2L_\mu$
ΔM_s
BR(B_s->$\mu\mu$)
$R_K(1.1, 6)$
$R_{K^*}(0.1, 1.1)$
$R_{K^*}(1.1, 6)$
$P_5'(2.5, 4)$
$P_5'(4, 6)$
BR(B_s->$\phi\mu\mu$)(0.1,0.98)
BR(B_s->$\phi\mu\mu$)(1.1,2.5)
BR(B_s->$\phi\mu\mu$)(2.5,4)
BR(B_s->$\phi\mu\mu$)(4,6)
BR(B_s->$\phi\mu\mu$)(15,19)
−3 −2 −1 0 1 2 3 4
pull

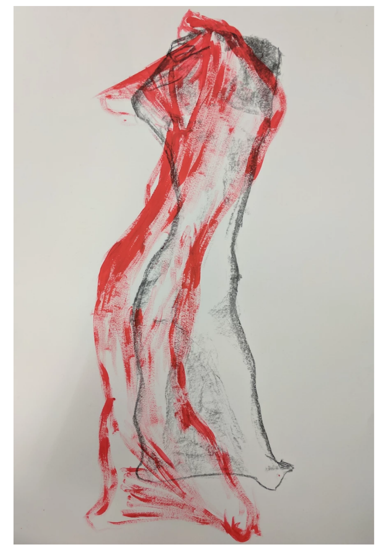
Epilogue

Remarkable that TeV-scale flavour symmetries are still allowed

Plug for my music, book (18€) and Quantum Selves art:







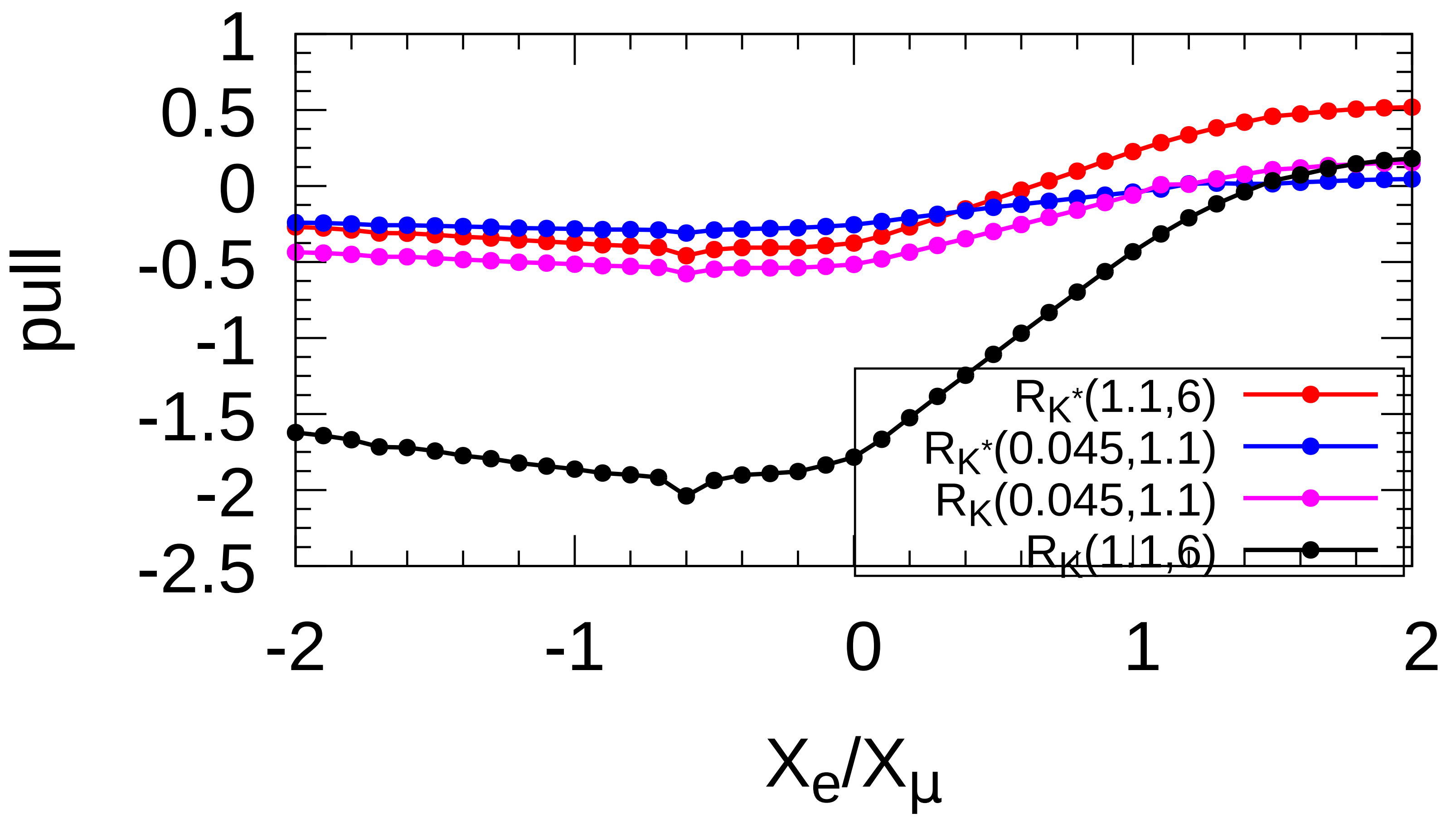
Backup

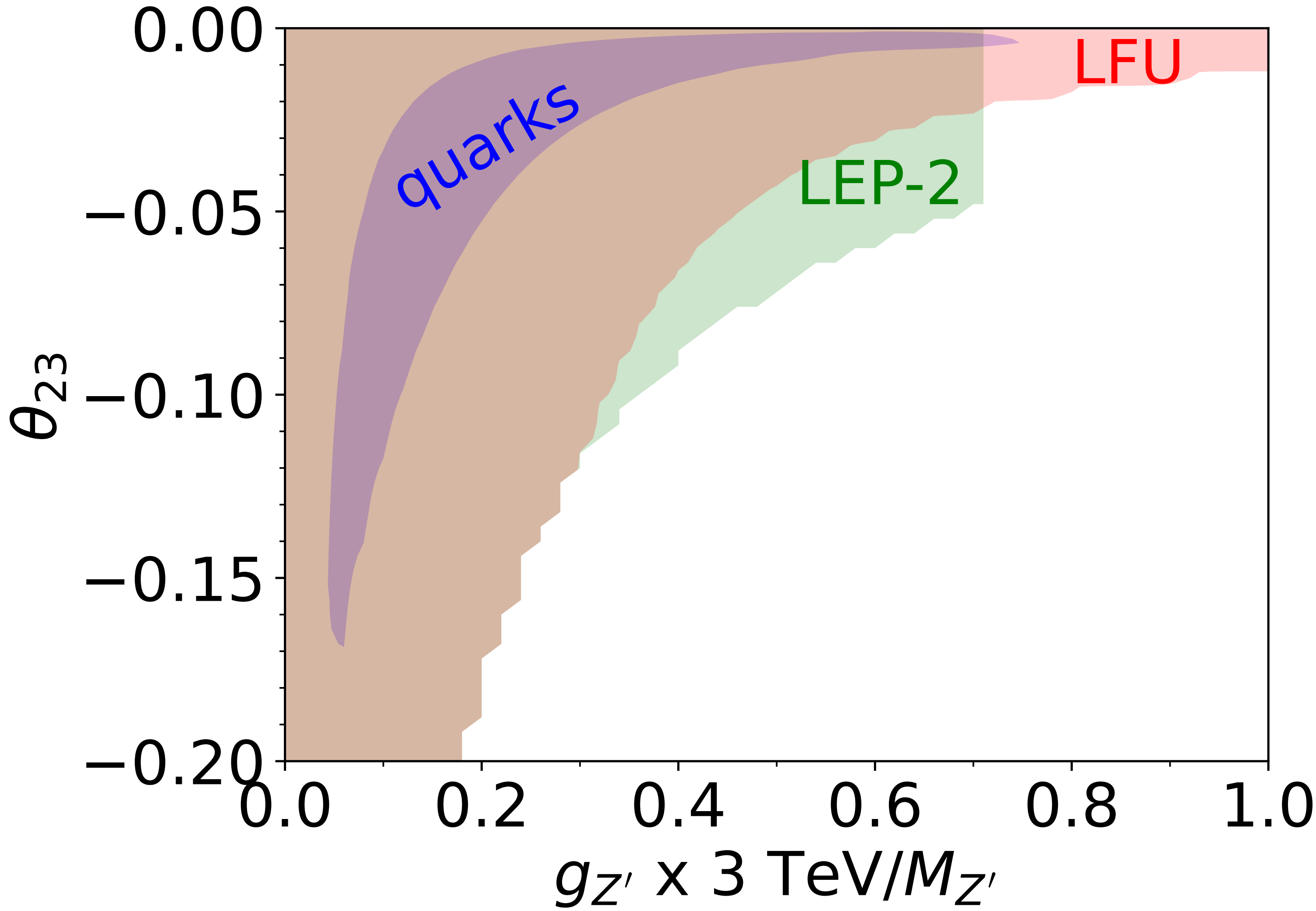
SMEFT WCs$/(g_{Z'}^2/M_{Z'}^2)$

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

| wilson | flavio | smelli > output

BCA, Mullin, 2306.08669

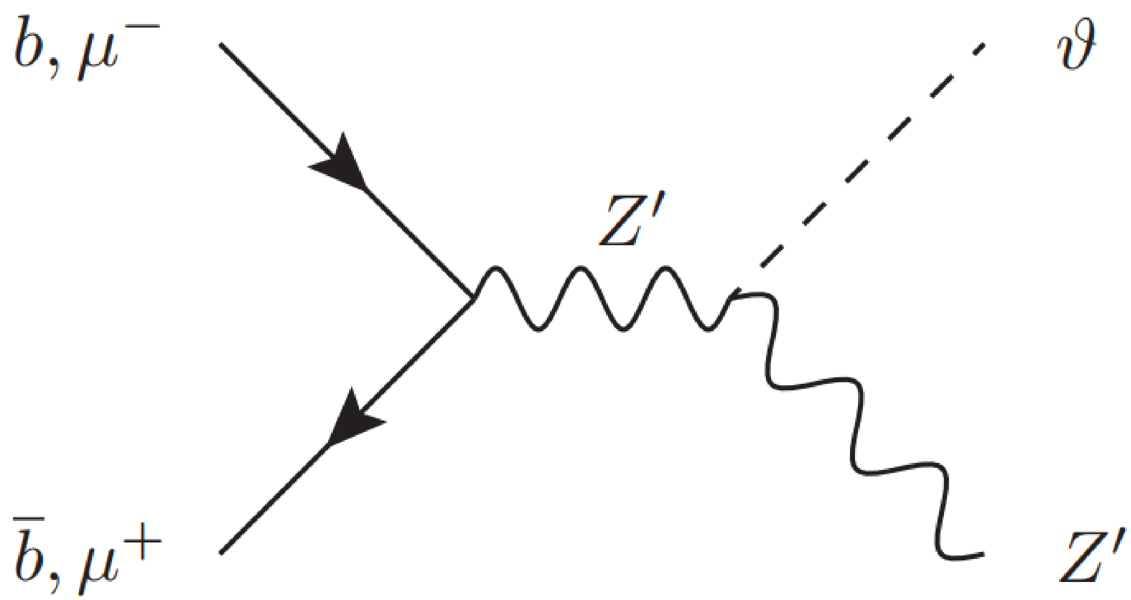




BCA, Mullin, 2306.08669

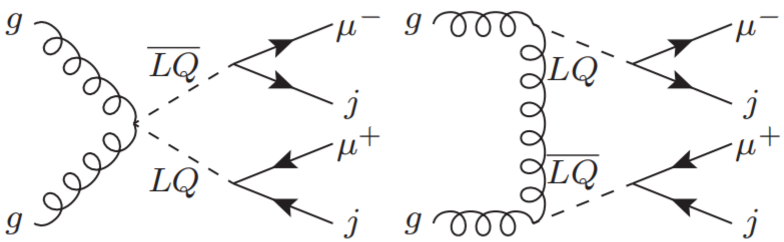
Flavonstrahlung

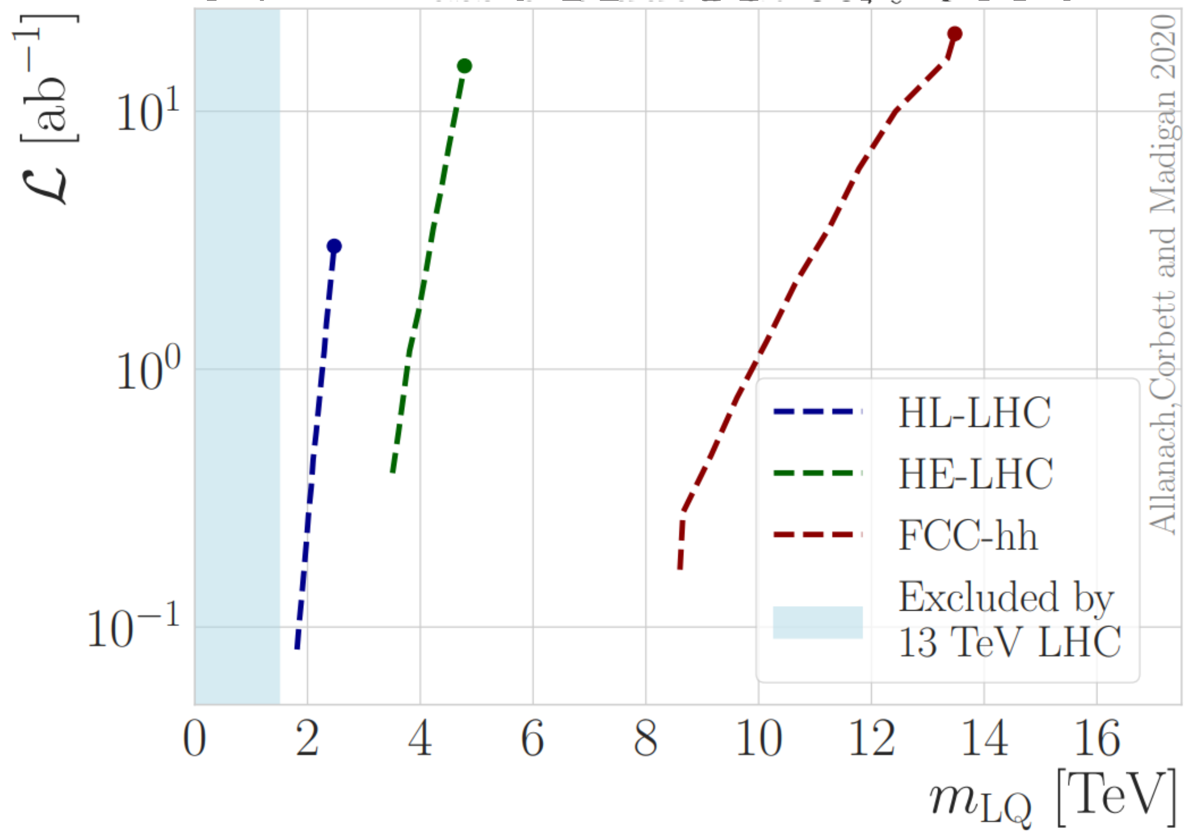
Models of Z' ilk possess $\mathcal{L} = \lambda H H^\dagger \theta \theta^\dagger \Rightarrow$ a *flavonstrahlung* signature:



BCA, `2009.02197`; BCA, Loisa, `2212.07440`

Scalar LQ[7]:





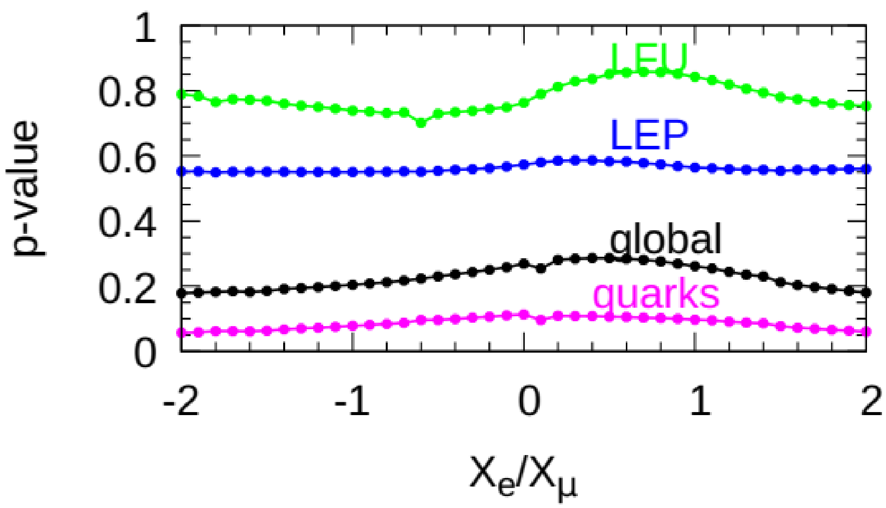
[7]BCA, Corbett, Madigan, 1911.0445

Anomaly cancellation

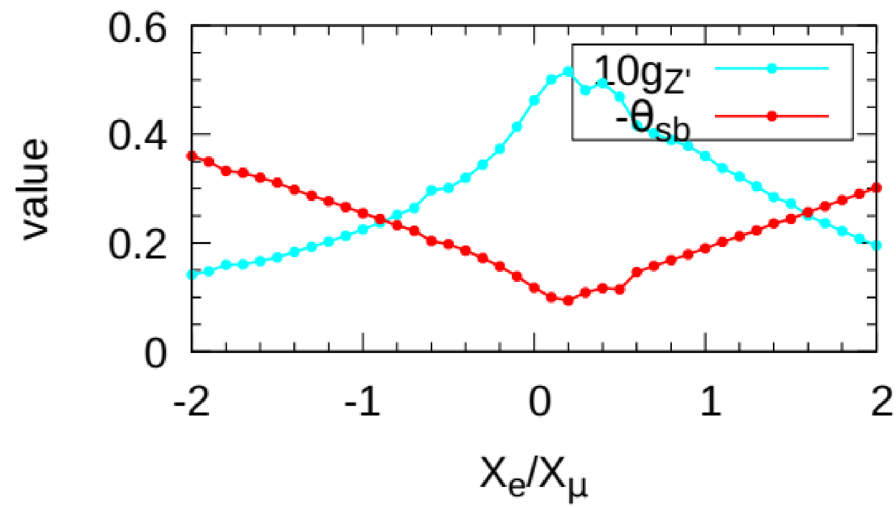
Need to pick X charges for fermions consistent with QFT anomaly cancellation.

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

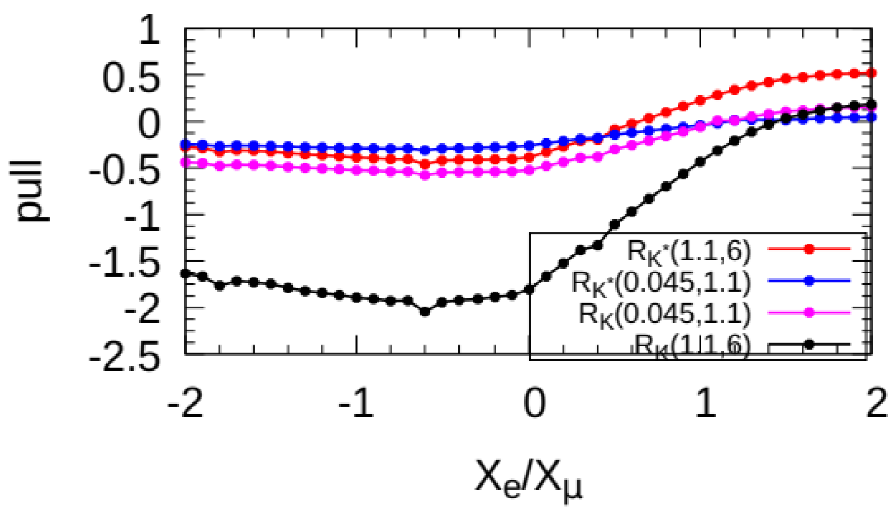
works (proof in `2306.08669`).



LFU
LEP
global
quarks
p-value
X_e/X_μ



$10g_{Z'}$
$-\theta_{sb}$
value
X_e/X_μ



$R_{K^*}(1.1,6)$
$R_{K^*}(0.045,1.1)$
$R_K(0.045,1.1)$
$R_K(1.1,6)$
pull
X_e/X_μ

Trident Neutrino Process

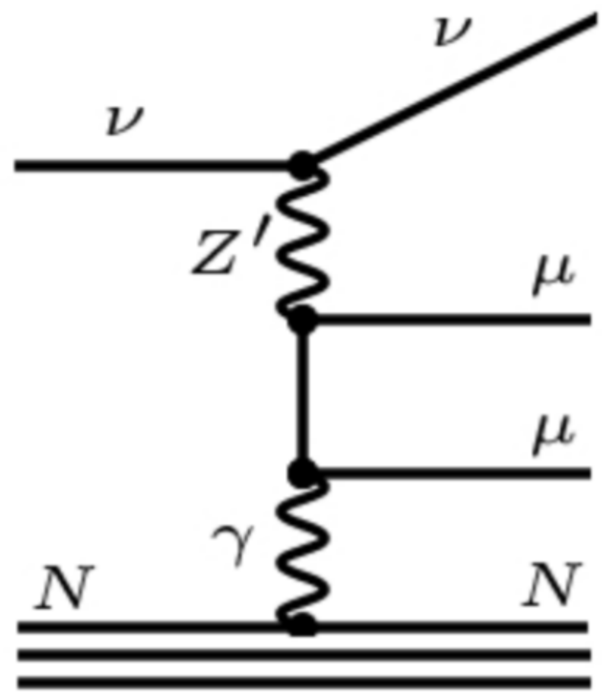
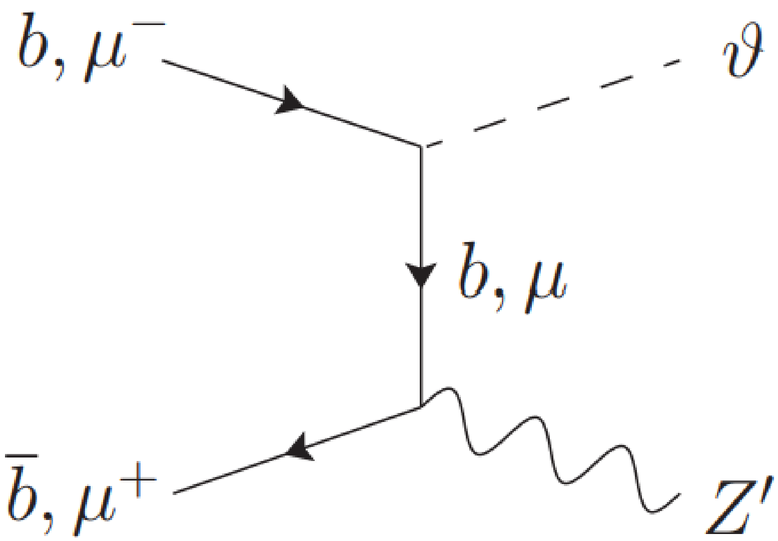
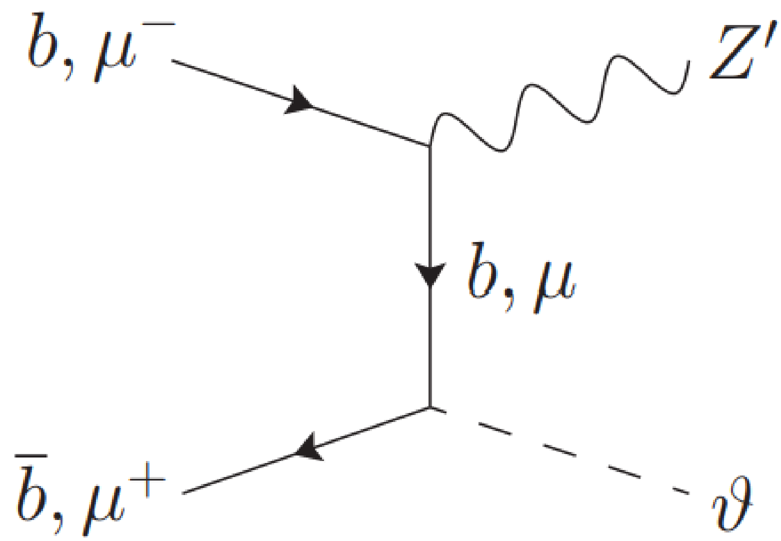


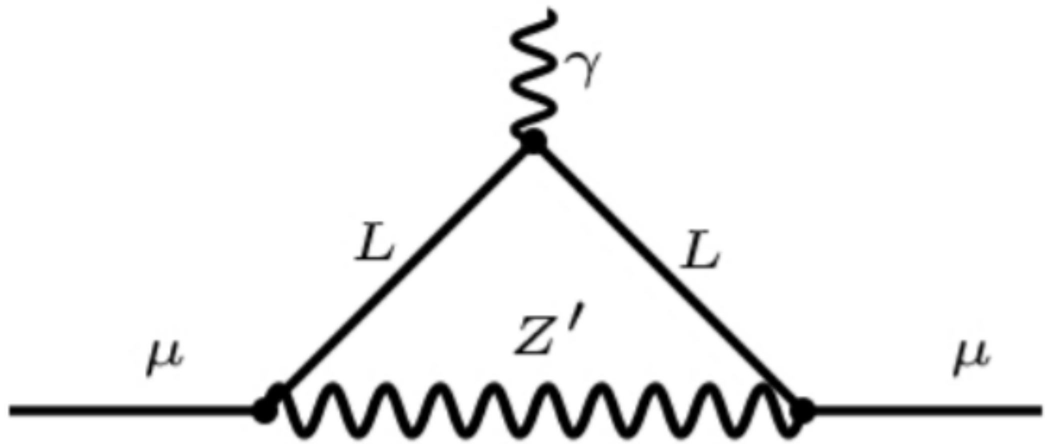
FIG. 10. Neutrino trident process that leads to constraints on the Z^{μ} coupling strength to neutrinos-muons, namely $M_{Z'}/g_{v\mu} \gtrsim 750$ GeV.

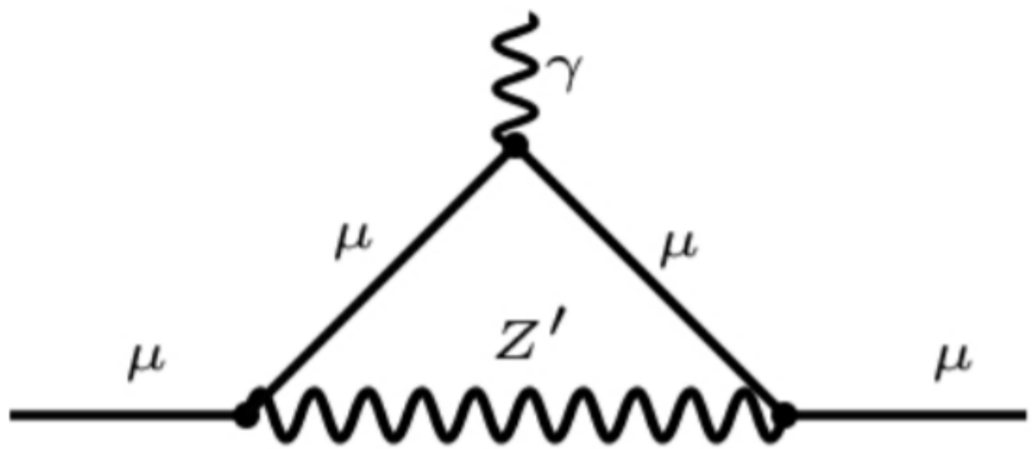
$t-$channel





$(g-2)_\mu$





$H\vartheta$ potential

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

$H\vartheta$ mixing

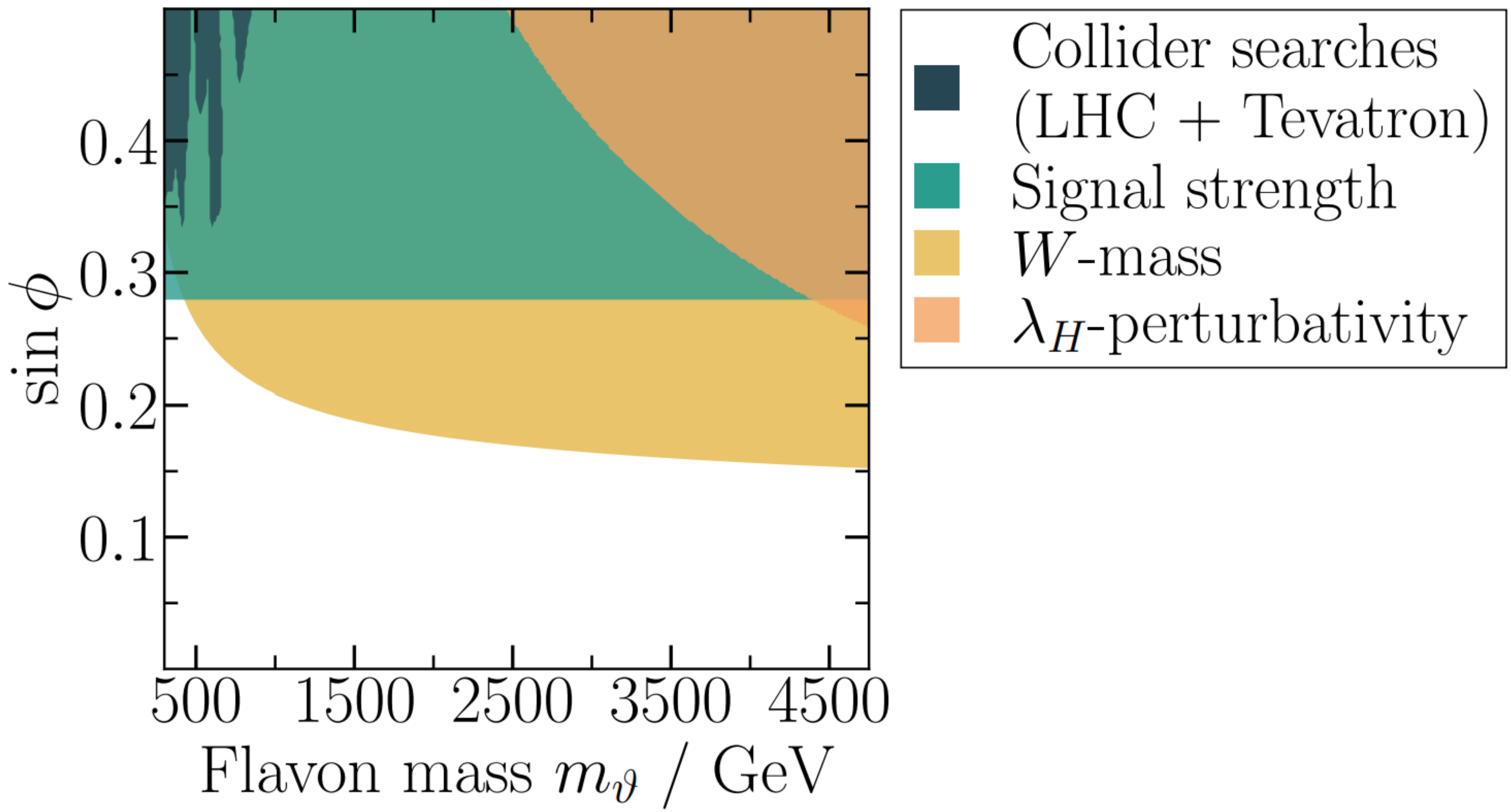
$$\begin{pmatrix} h \\ \vartheta \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} h' \\ \vartheta' \end{pmatrix}$$

$$\sin 2\phi = \frac{2\lambda_{\theta H} v_h v_\theta}{m_\vartheta^2 - m_h^2}. \qquad (-13)$$

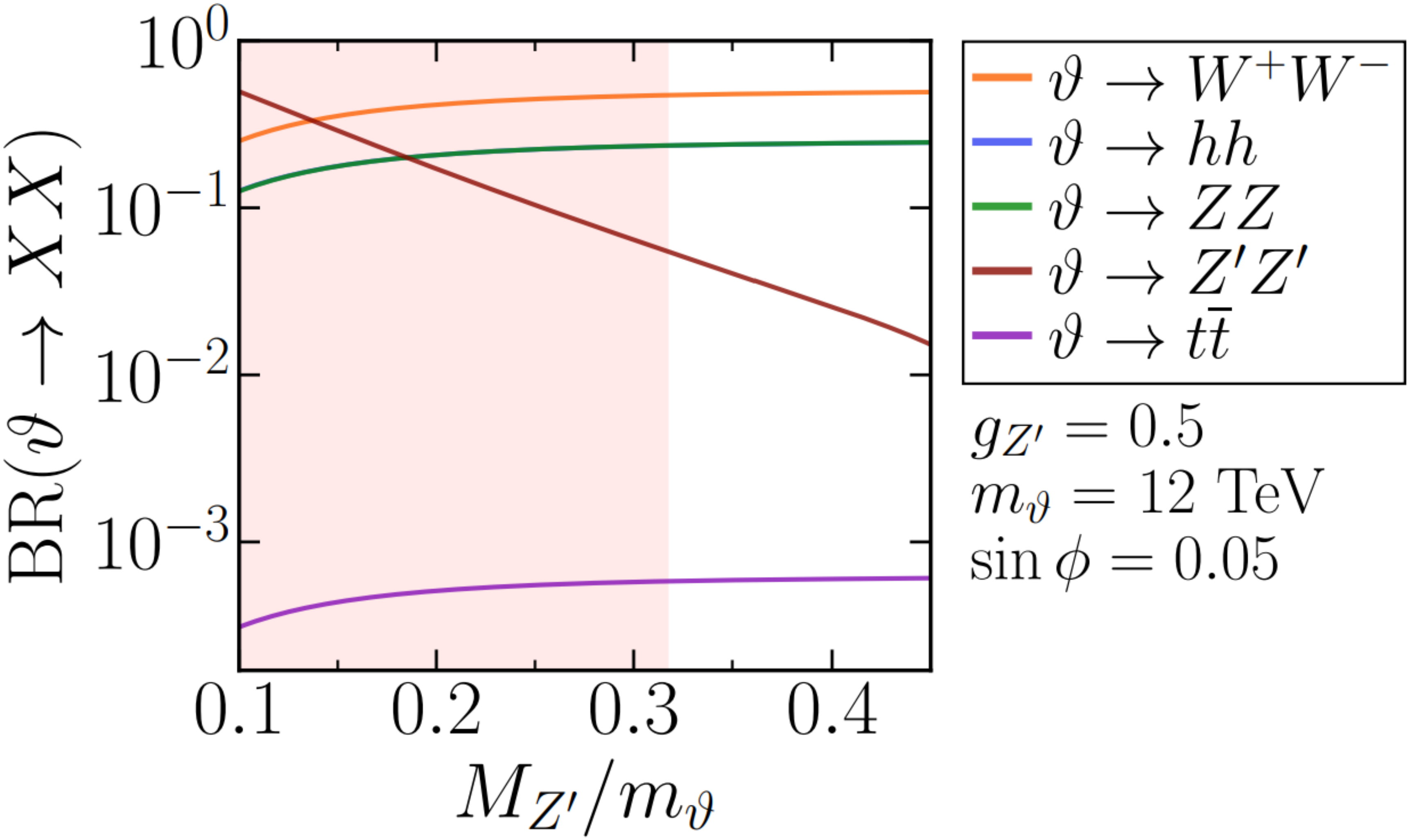
Three parameters: $v_\theta = M_{Z'}/g_{Z'}$, m_ϑ and ϕ.

Higgs Signal Strength

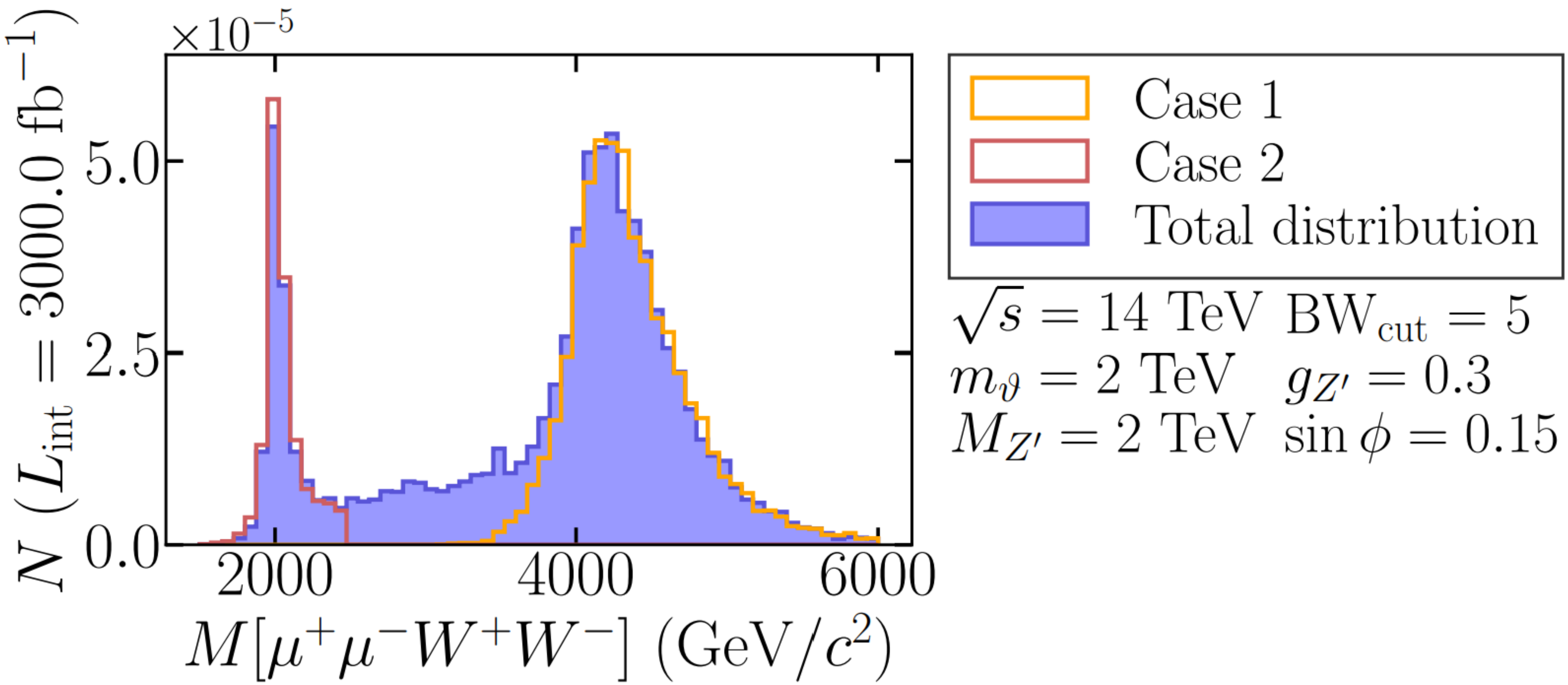
BCA, Loisa, 2212.07440



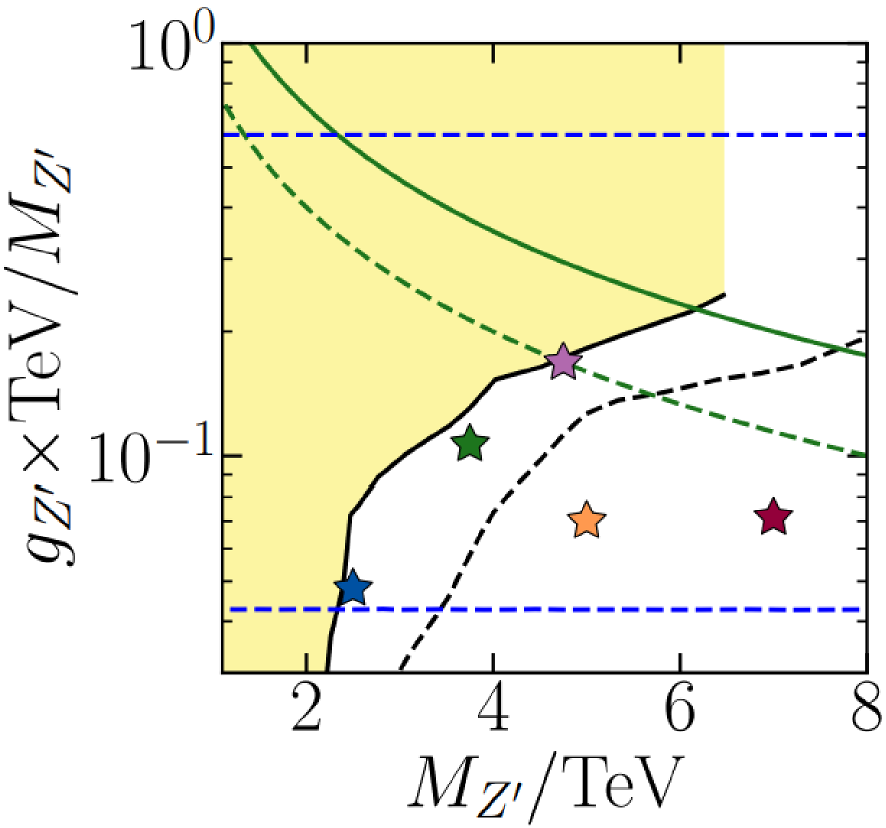
ϑ BRs

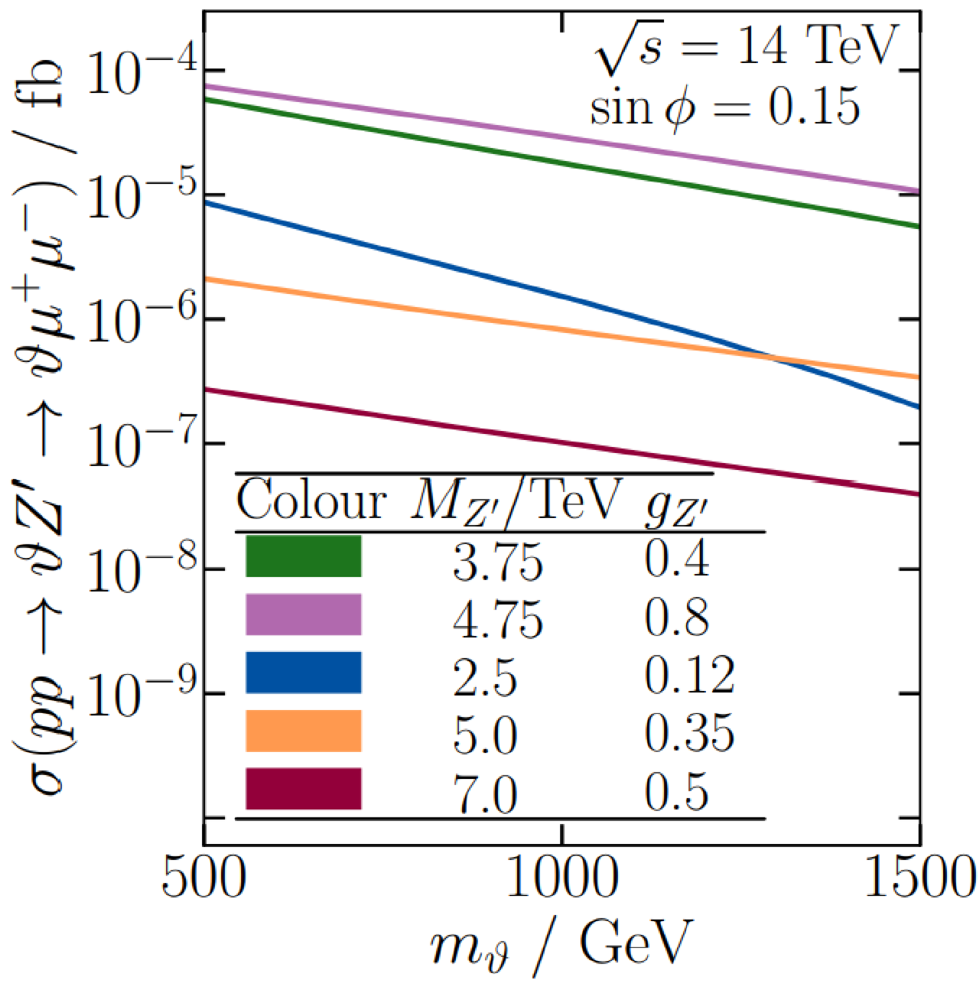


2 resonances



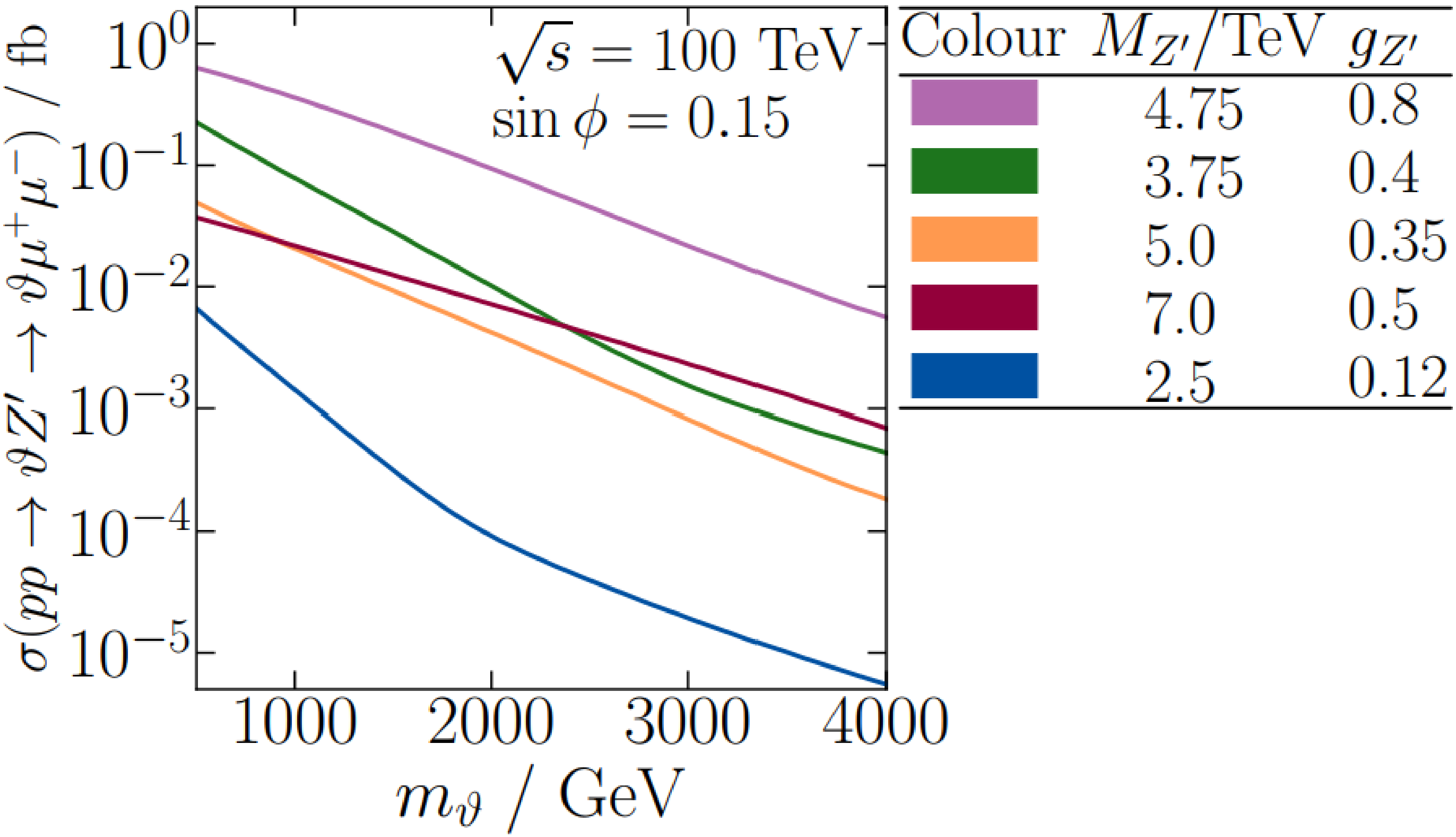
(HL-)LHC searches





No flavonstrahlung LHC

FCC Flavonstrahlung



10 TeV $\mu^+\mu^-$ Flavonstrahlung