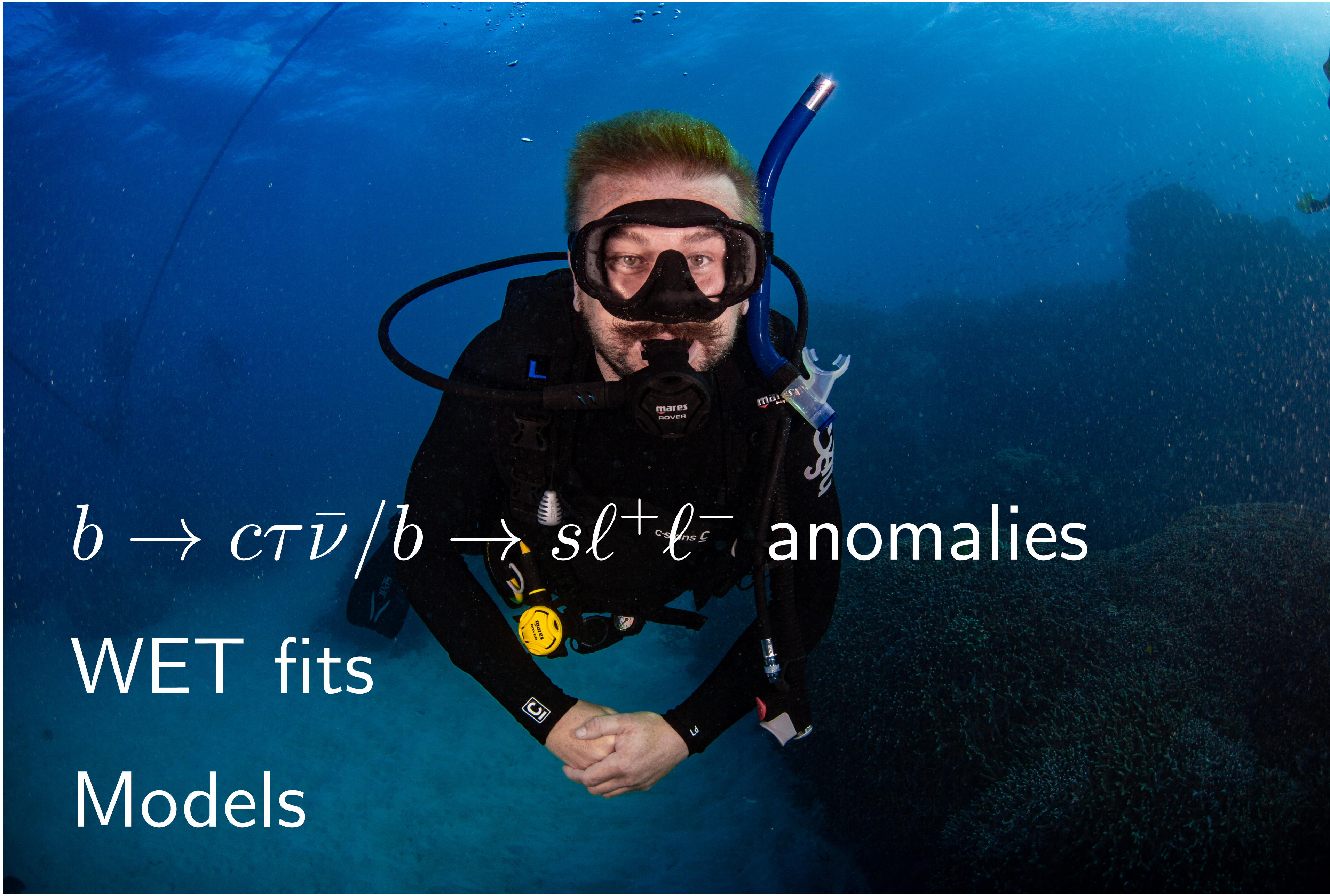
B anomalies in 2023

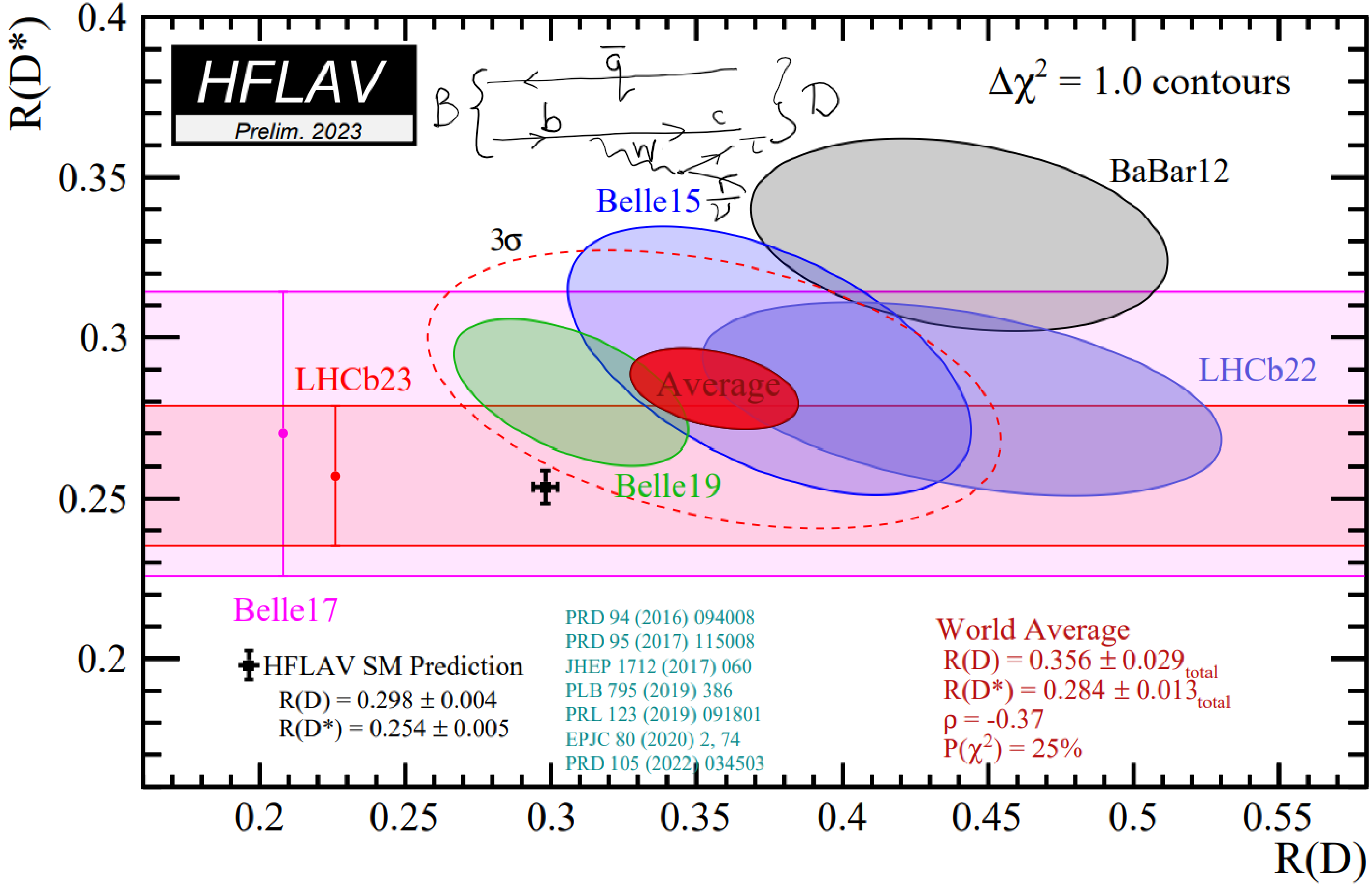


$b \to c\tau\bar{\nu} / b \to s\ell^+\ell^-$ anomalies

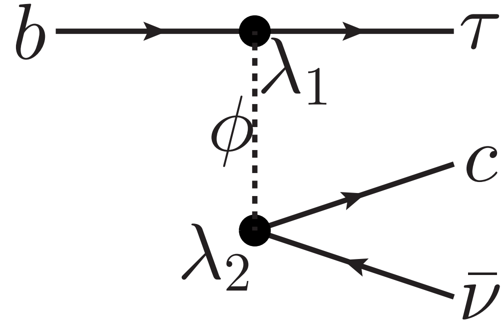
WET fits

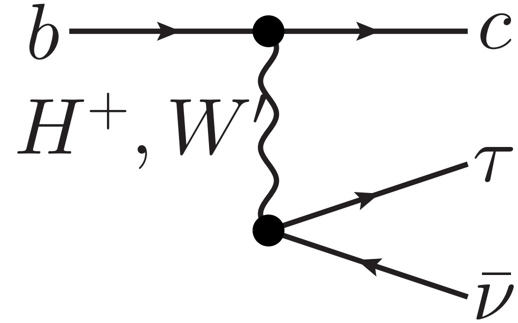
Models

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

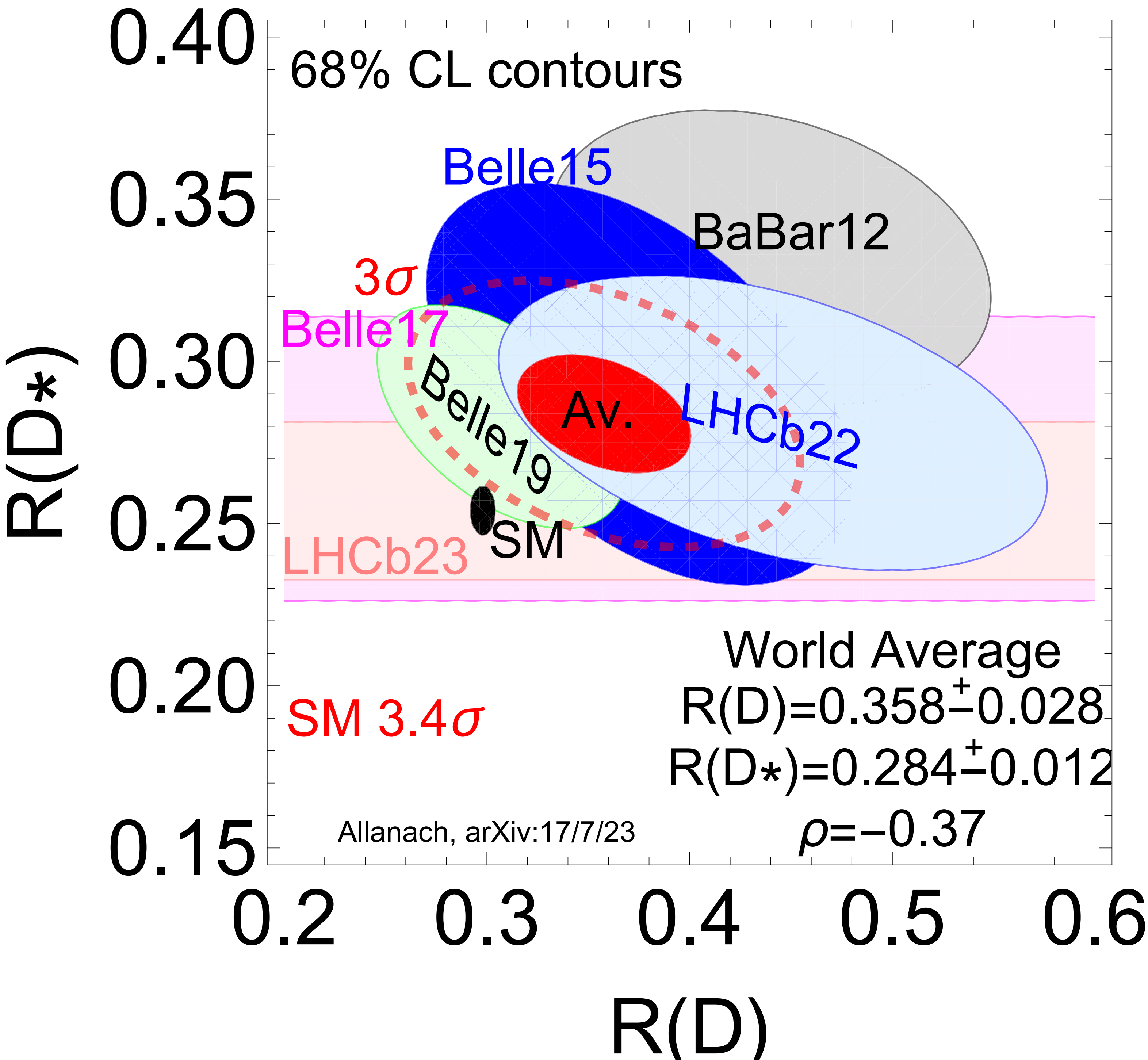


$R_{D^{(*)}}$: BSM Explanations





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


68% CL contours
Belle15
BaBar12
3σ
Belle17
Belle19
Av.
LHCb22
SM
LHCb23
World Average
R(D)=0.358±0.028
R(D*)=0.284±0.012
ρ=−0.37
SM 3.4σ
Allanach, arXiv:17/7/23
R(D*)
R(D)
0.40
0.35
0.30
0.25
0.20
0.15
0.2
0.3
0.4
0.5
0.6

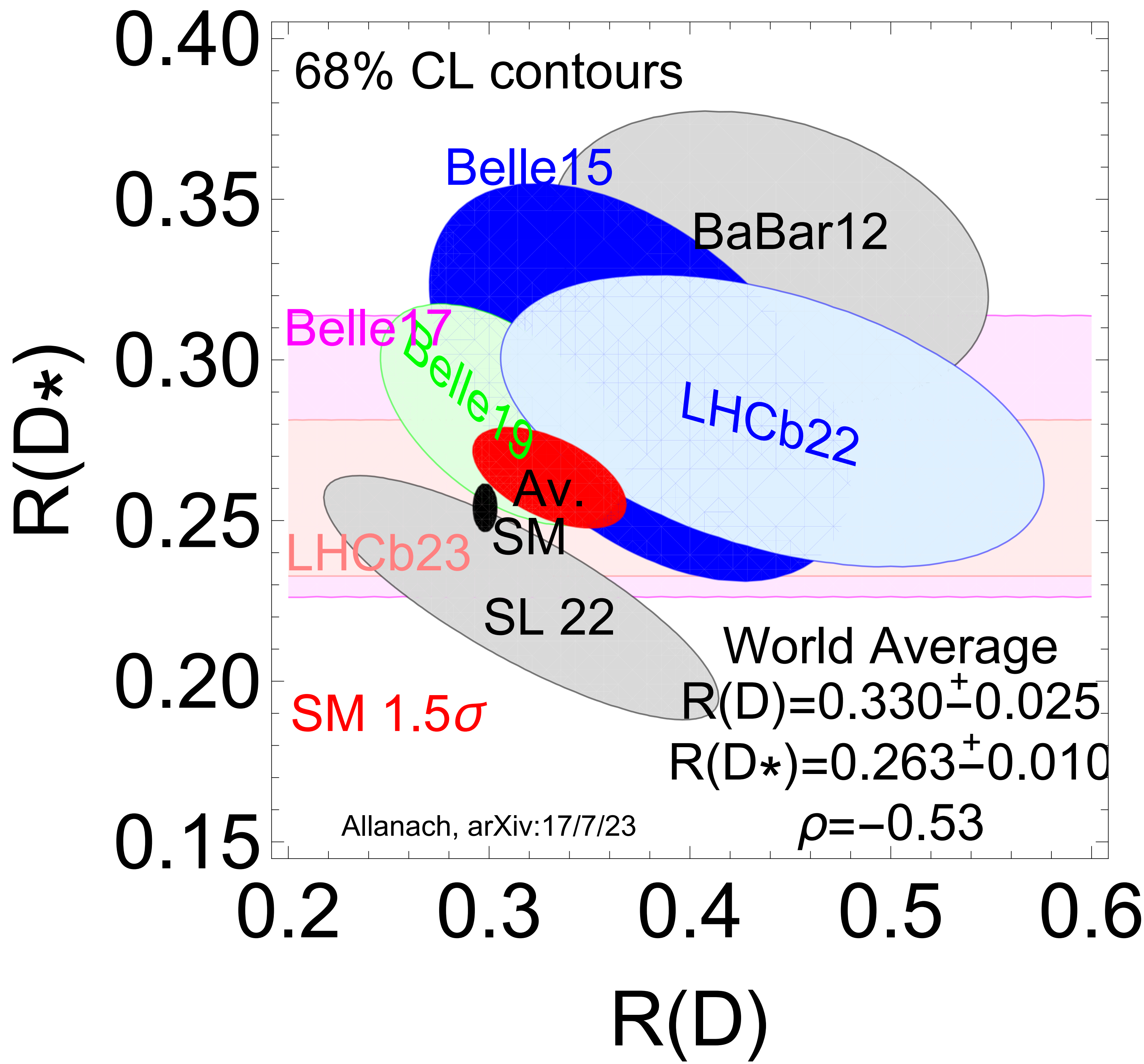
2022 Measurement

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

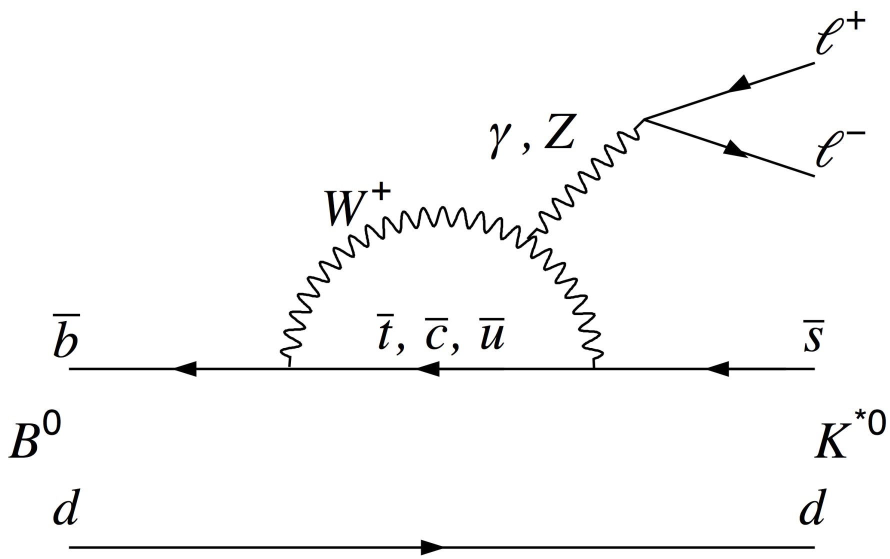


68% CL contours
Belle15
BaBar12
Belle17
Belle19
LHCb22
Av.
SM
LHCb23
SL 22
World Average
R(D)=0.330±0.025
R(D∗)=0.263±0.010
ρ=−0.53
SM 1.5σ
Allanach, arXiv:17/7/23
R(D∗)
R(D)

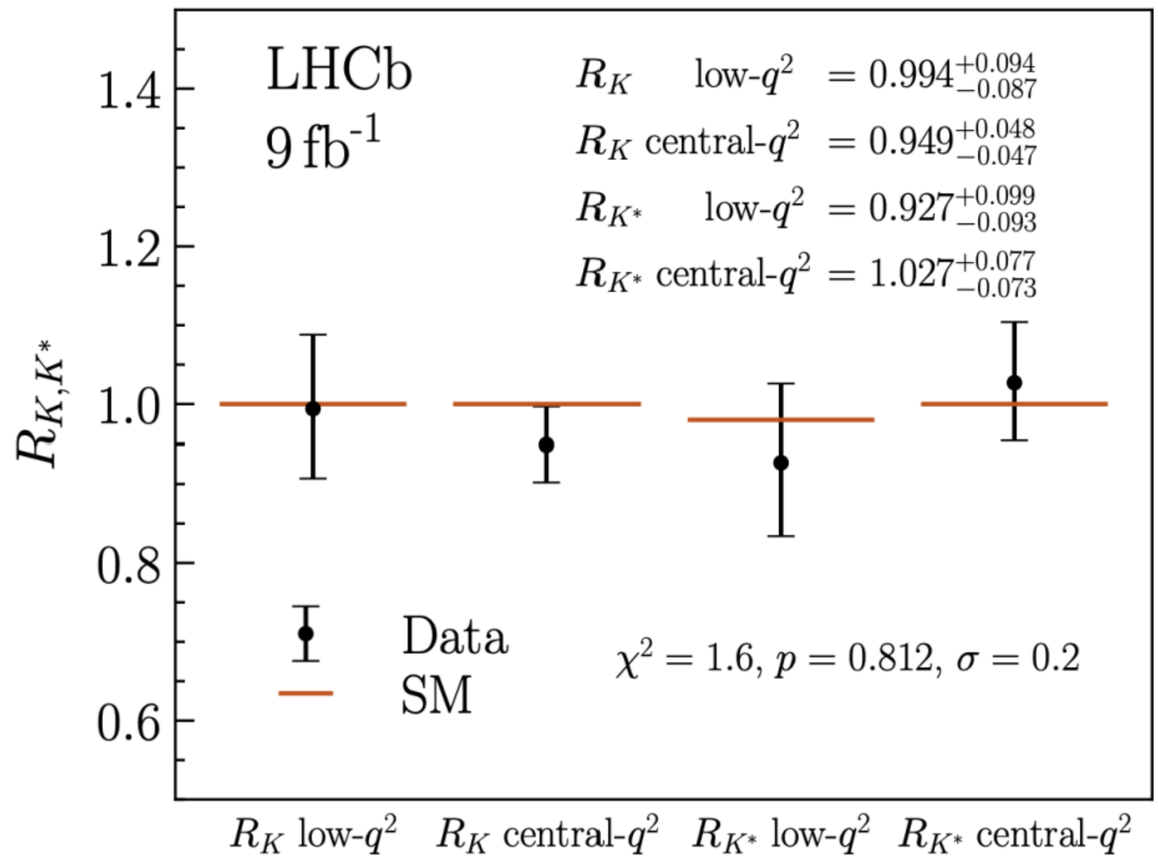
$b \to s l^+ l^-$ in Standard Model

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

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



LHCb 2212.09152

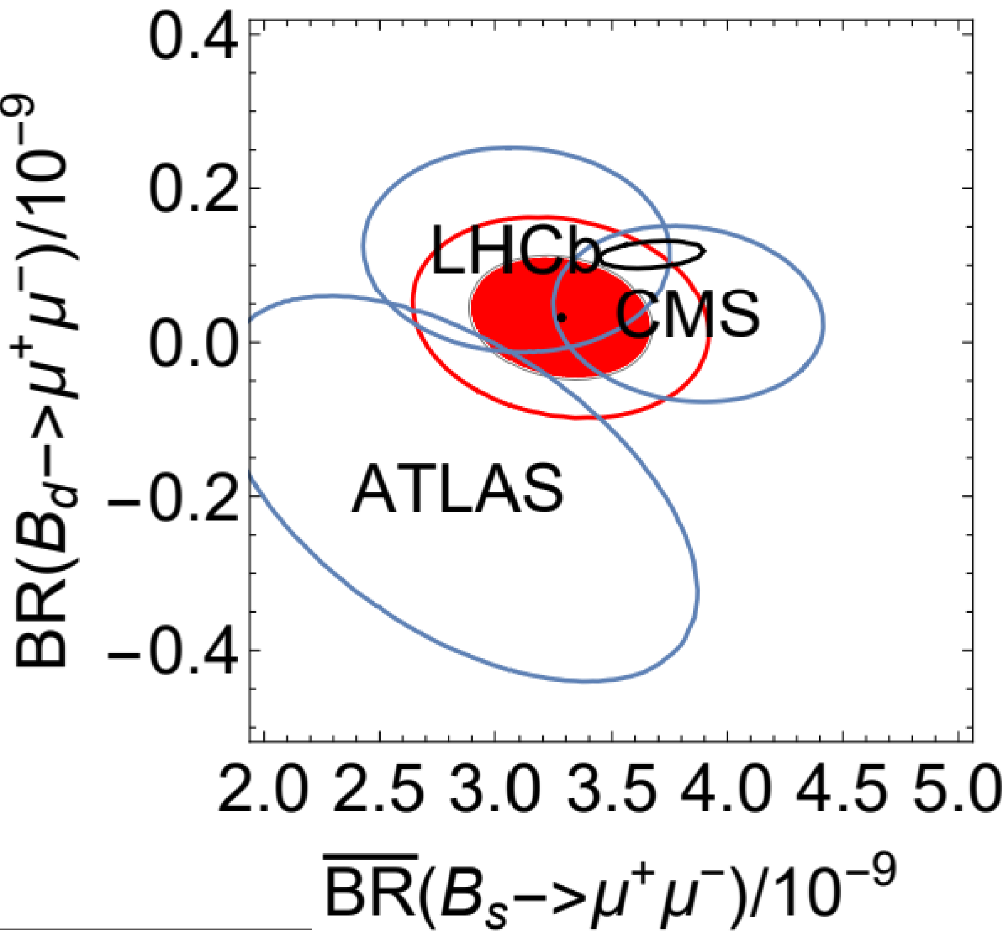


$$R_X(q^2) = \frac{BR(B \to X\mu^+\mu^-)}{BR(B \to Xe^+e^-)}(q^2)$$


MUSTER STATION 1
FIRE HOSE

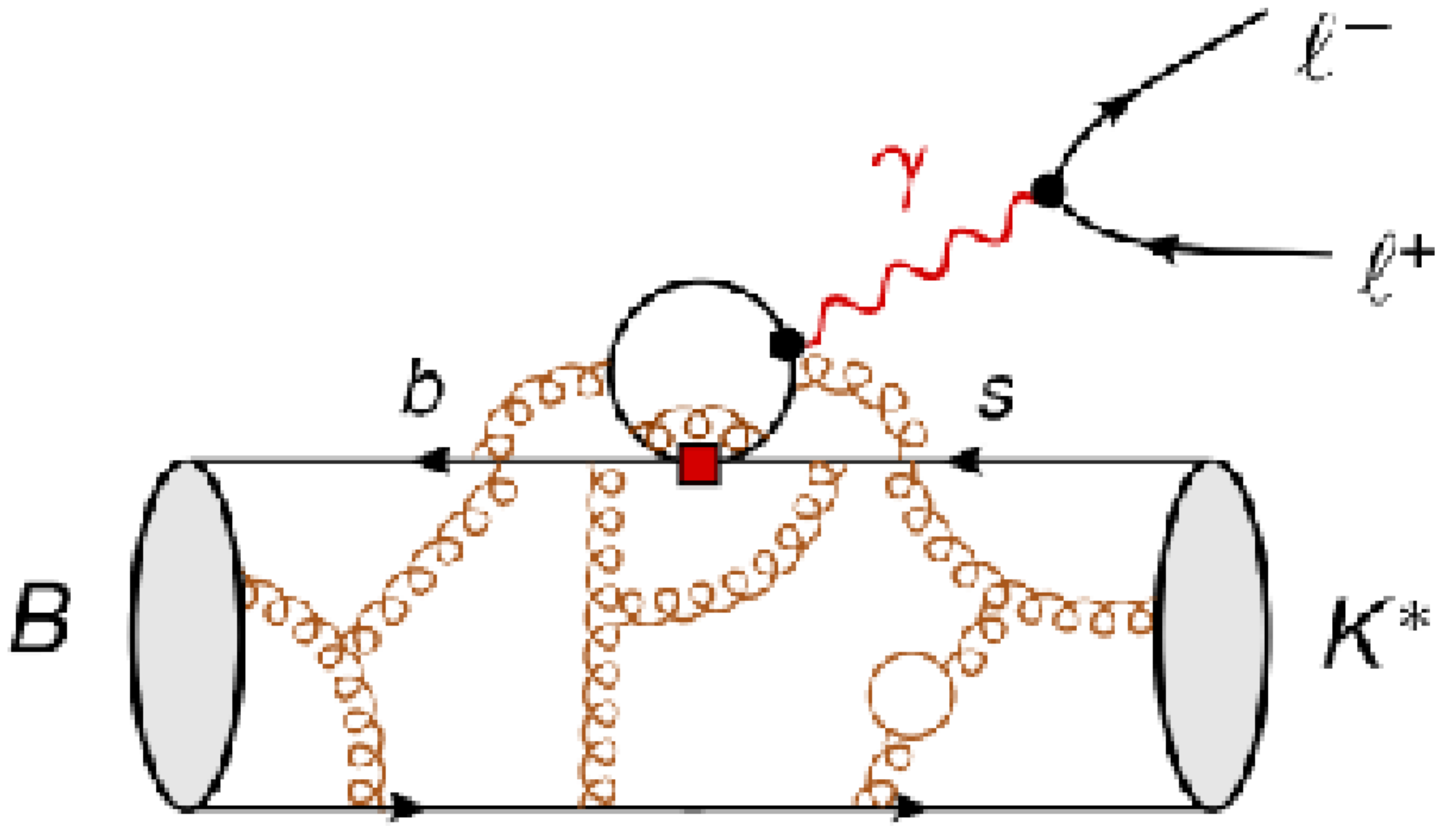
$BR(B_s \to \mu^+\mu^-)$[1] **SM: 1.6σ**

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



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

Form Factors



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

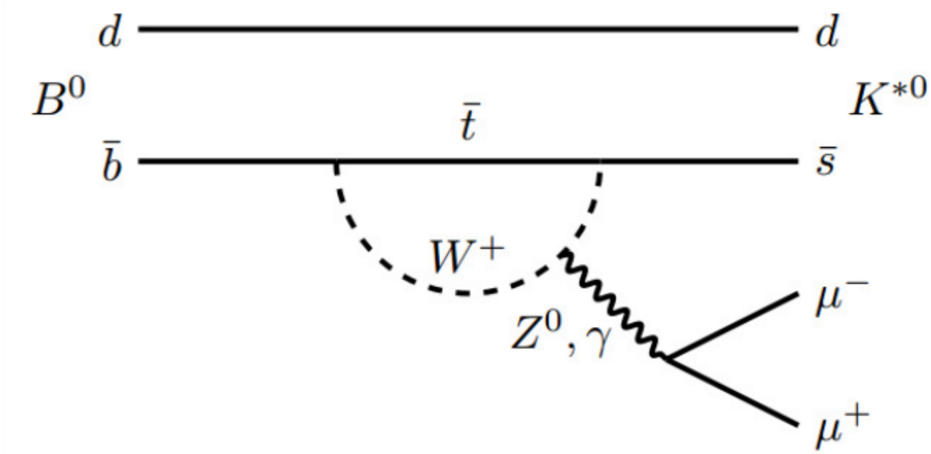
$$\mathcal{A} = \texttt{local} + \texttt{non-local}$$

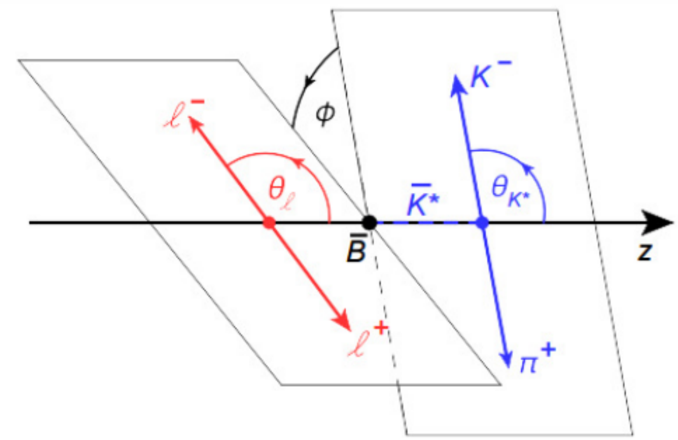
`local`: interpolate lattice at high $q^2 = m_{ll}^2$ and LCSR at low q^2.

`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 $q^2 = M_{J/\psi}^2$.

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

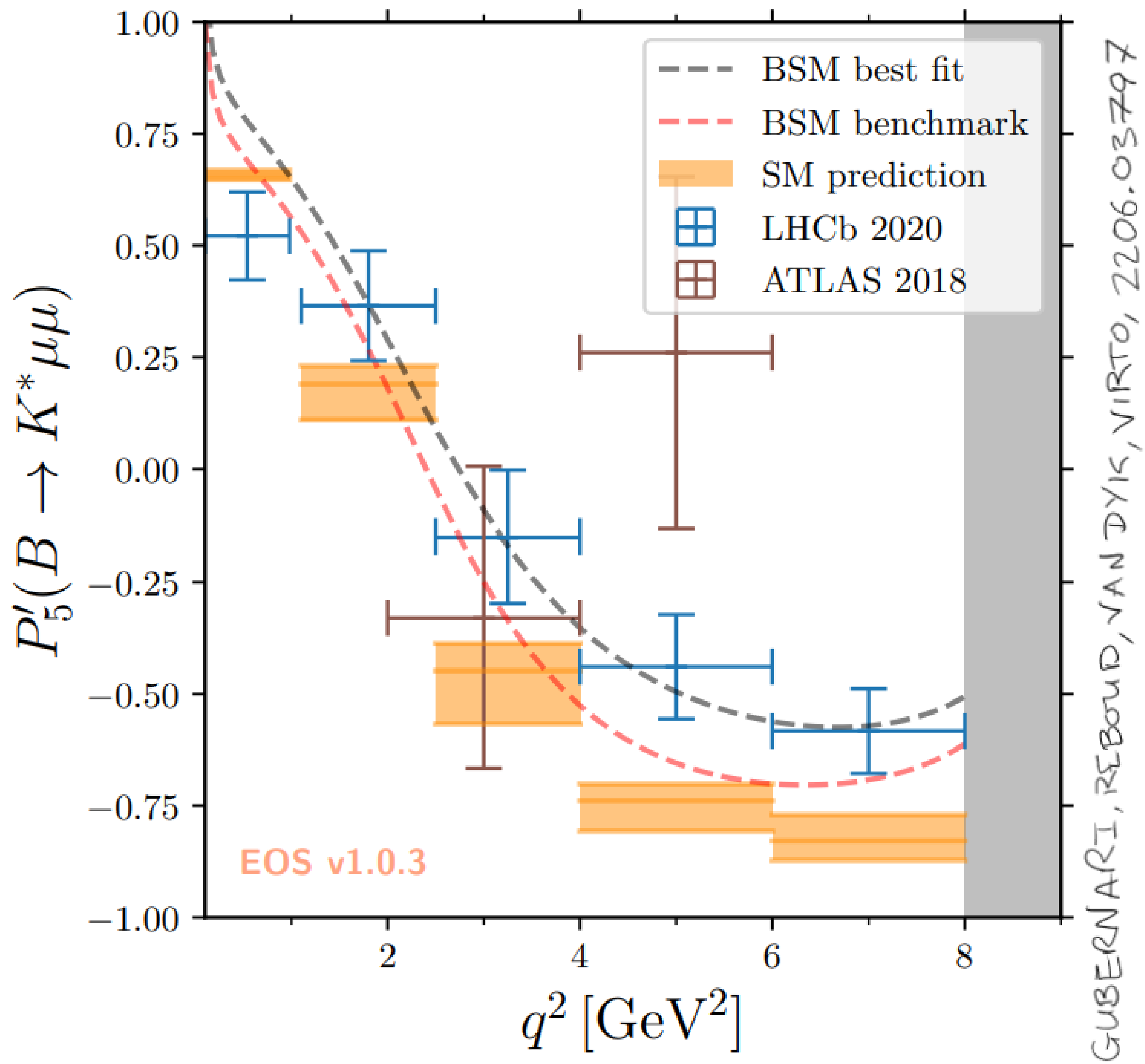




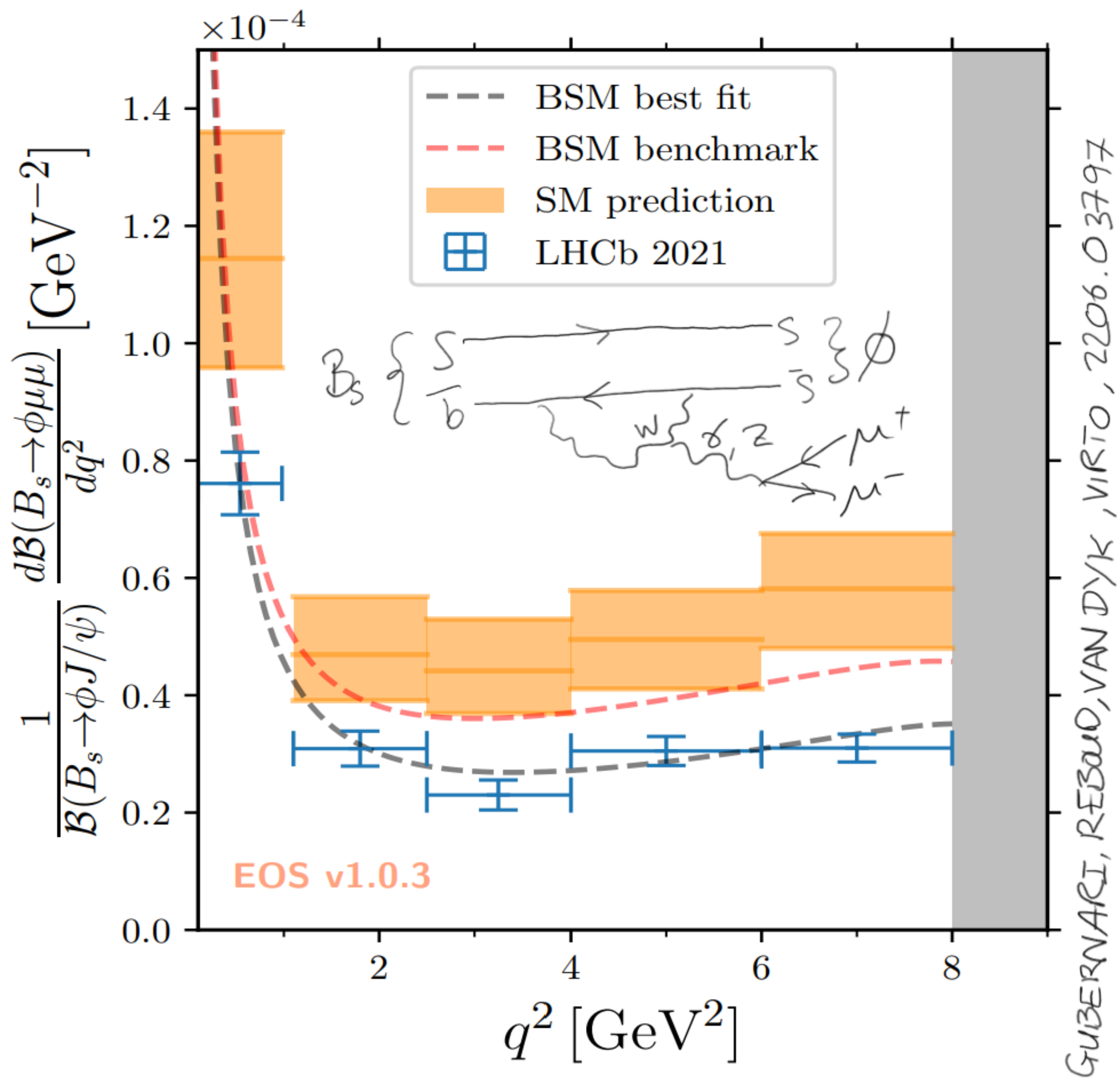
Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

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

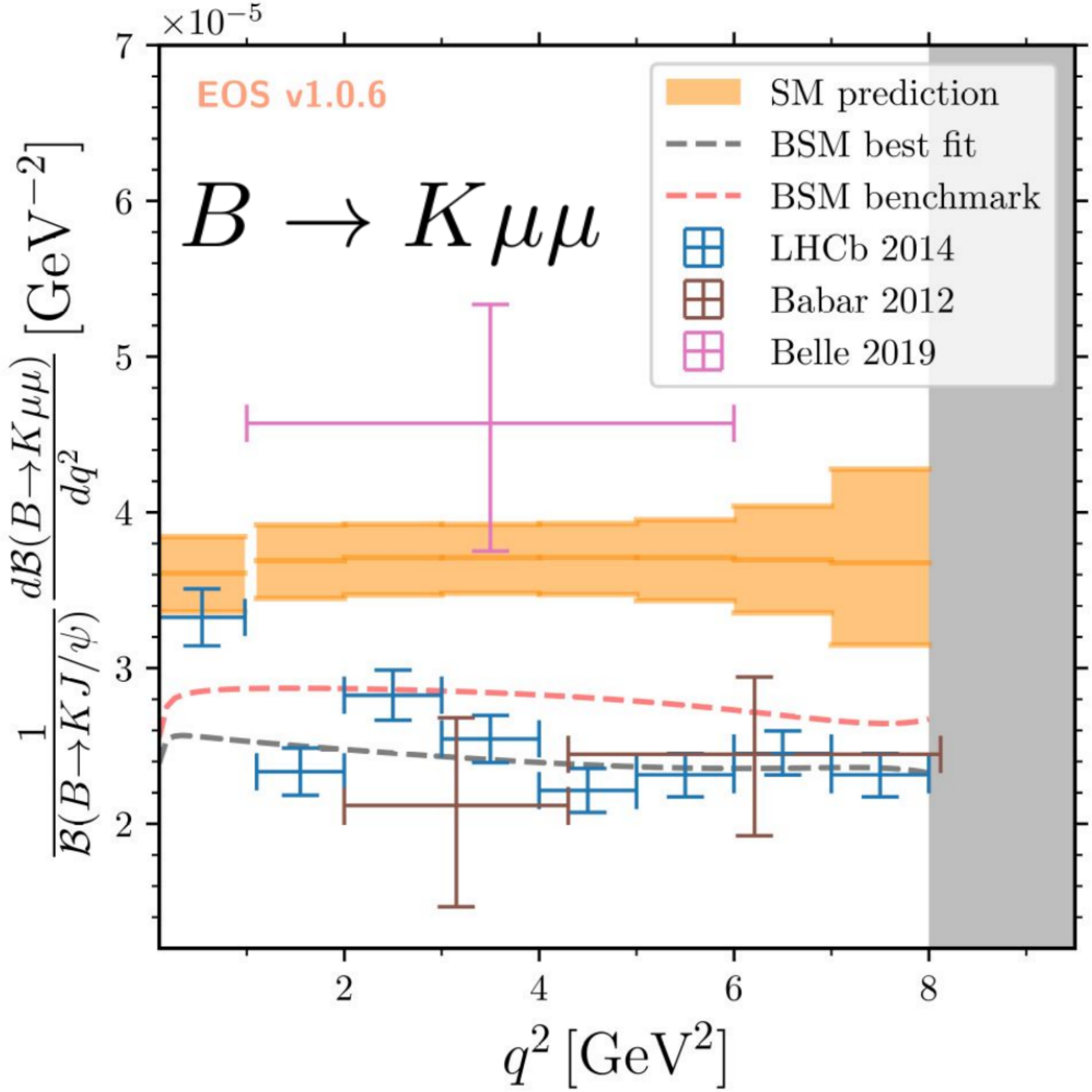
$$P_5' = S_5/\sqrt{F_L(1-F_L)}$$



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



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


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

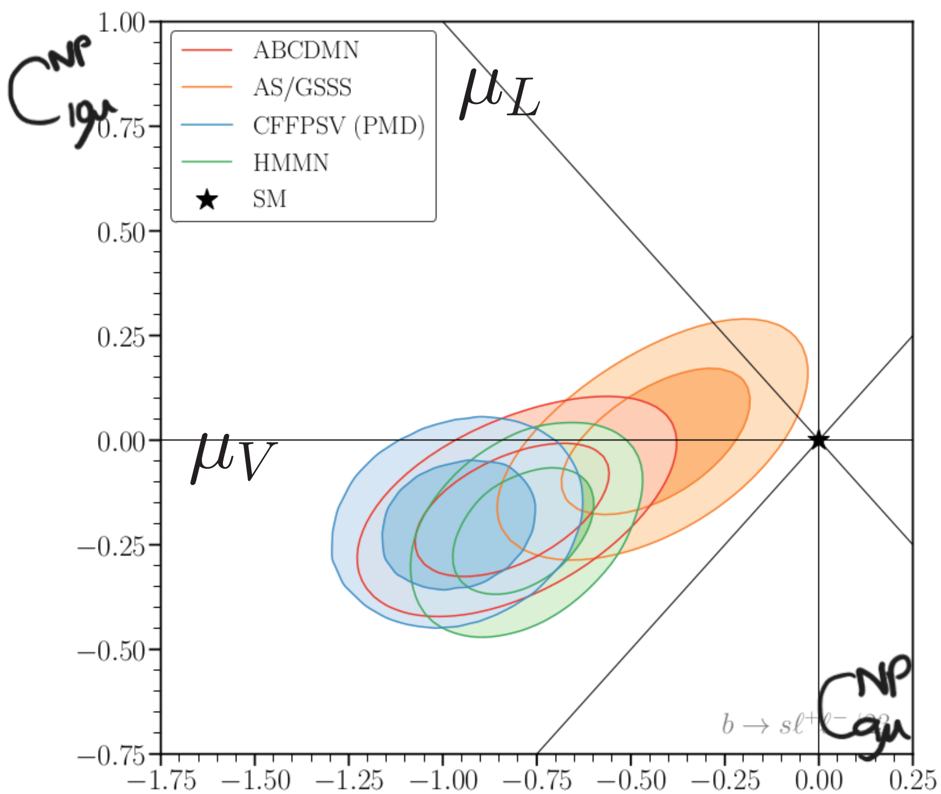
Neutral Current Fits Compare

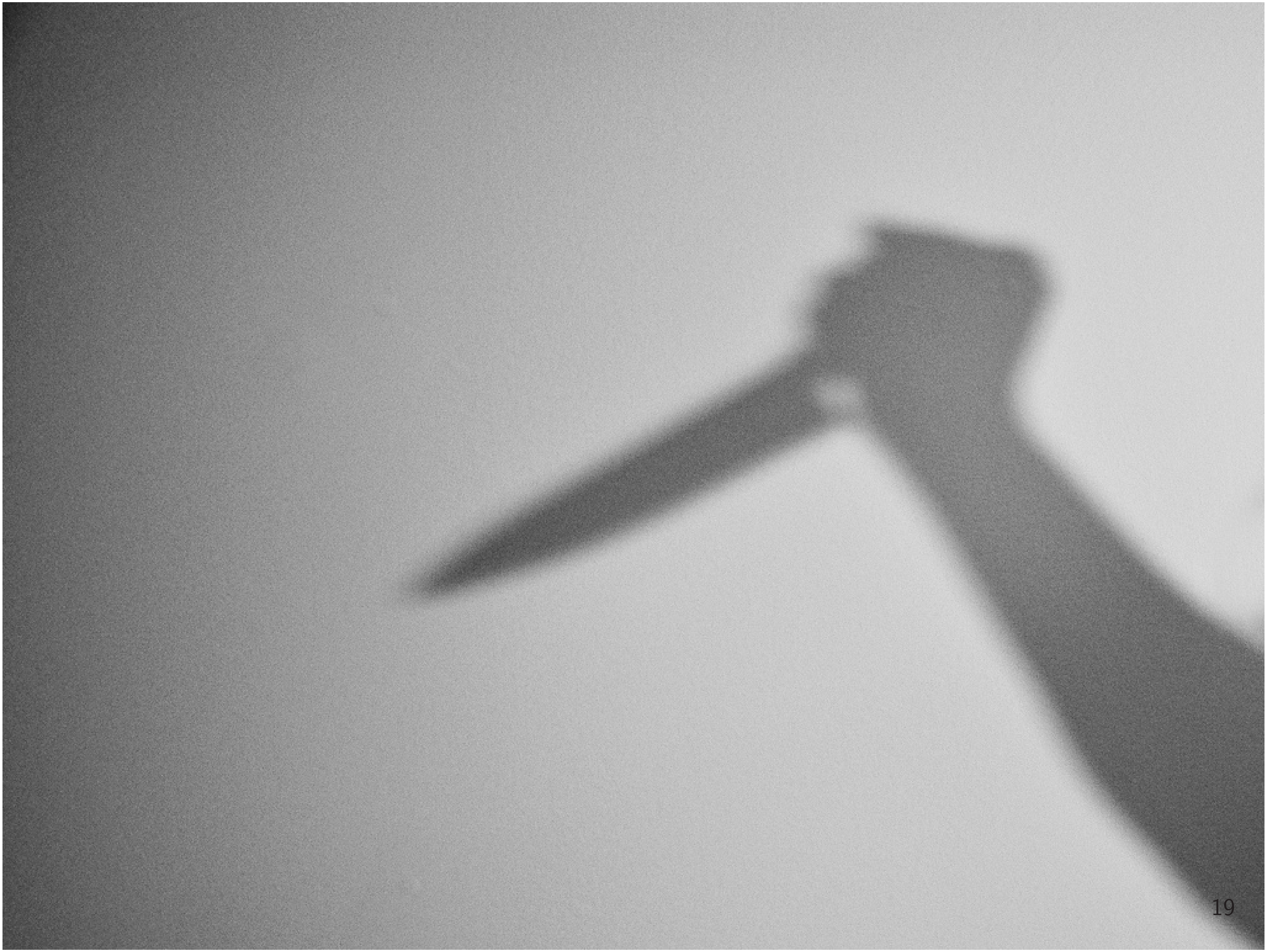
Alguero *et al*, 2304.07330; Altmannshofer, Stangl, flavio 2212.10497

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

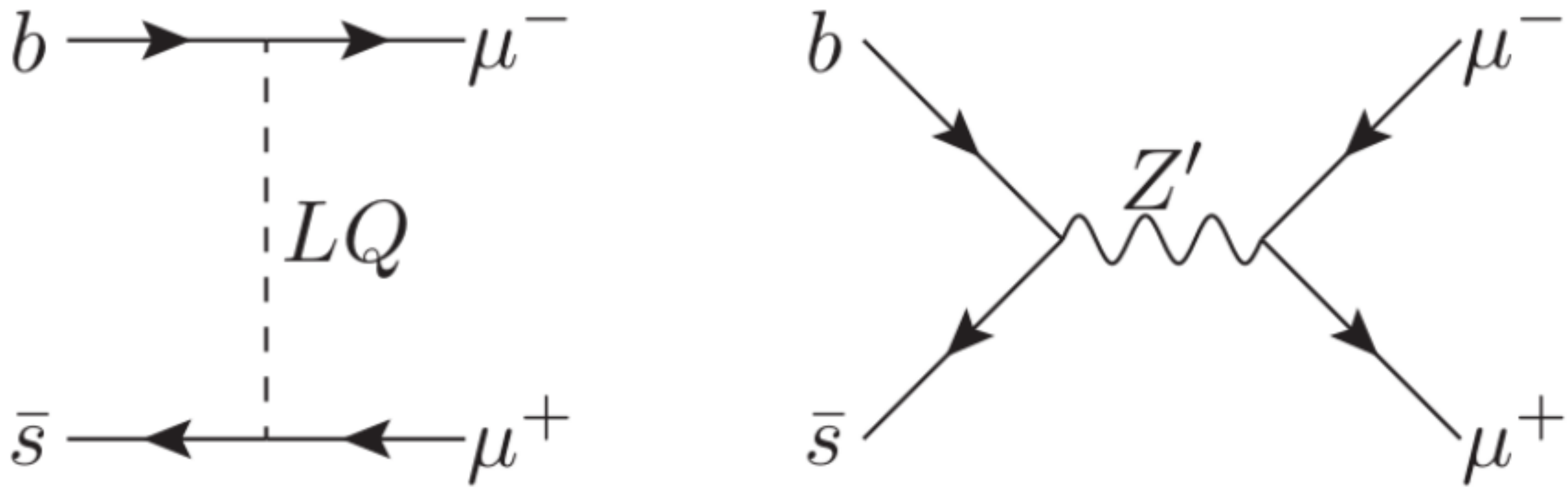
$$\mathcal{L} = N[C_{9\mu}^{NP}(\bar{b}_L\gamma^\alpha s_L)(\bar{\mu}\gamma_\alpha\mu) + C_{10\mu}^{NP}(\bar{b}_L\gamma^\alpha s_L)(\bar{\mu}\gamma_\alpha\gamma^5\mu)] + H.c.$$

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





Tree-level Explanations



Simple Z' Models

SM-singlet scalar 'flavon' θ

Additional $U(1)_X$ gauge symmetry broken by $\langle\theta\rangle \sim$TeV$\Rightarrow M_{Z'} \sim$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[2]

---

[2] BCA, Mullin, 2306.08669

$B_3 - L_2$

Consider *no* coupling to electrons: set $X_e = 0$, $X_\mu = 3$, leads to the $B_3 - L_2$ model:

`Bonilla, Modak, Srivastava, Valle, 1705.00915; Alonso, Cox, Han, Yanagida, 1705.03858`

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

The Rumble in the Meson

Let us now compare a Z' model which doesn't couple to electrons ($X_e = 0$, i.e. $B_3 - L_2$): $C_{9\mu}^{NP} \neq 0, C_{10\mu}^{NP} = 0$.

with

a LQ $S_3 = (\bar{\mathbf{3}}, \mathbf{3}, \frac{\mathbf{1}}{\mathbf{3}})$ that doesn't couple to electrons: $C_{9\mu}^{NP} = -C_{10\mu}^{NP}$.

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

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

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

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

A simple limiting case

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

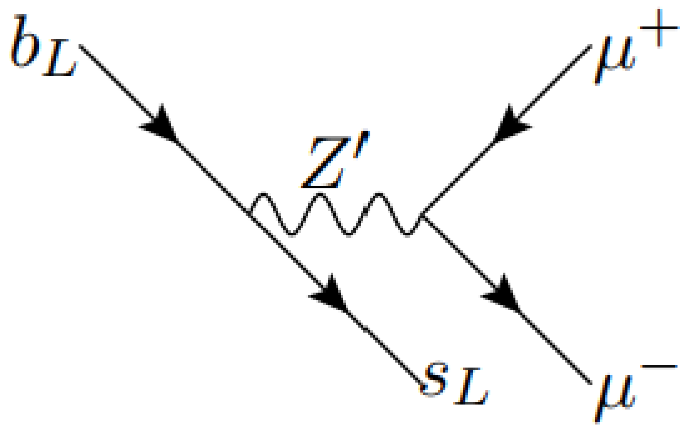
$$V_{d_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{sb} & -\sin\theta_{sb} \\ 0 & \sin\theta_{sb} & \cos\theta_{sb} \end{pmatrix} .$$

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

Important Z' Couplings

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

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

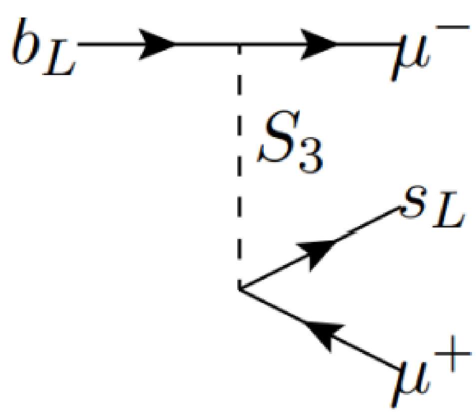


– LFU Violating, $C_9 \neq 0$

S_3 Leptoquark Model

TeV scale Scalar[3] $S_3 = (\bar{3},\ 3,\ 1/3)$:

$$\mathcal{L} = \ldots + \lambda Q_3' S_3 L_2 + \cancel{Y_{ij} Q_i Q_j S_3^\dagger} + \text{h.c.}$$
$$= \ldots + \lambda(\cos\theta_{23} Q_3 L_2 + \sin\theta_{23} Q_2 L_2) + \text{h.c.}$$

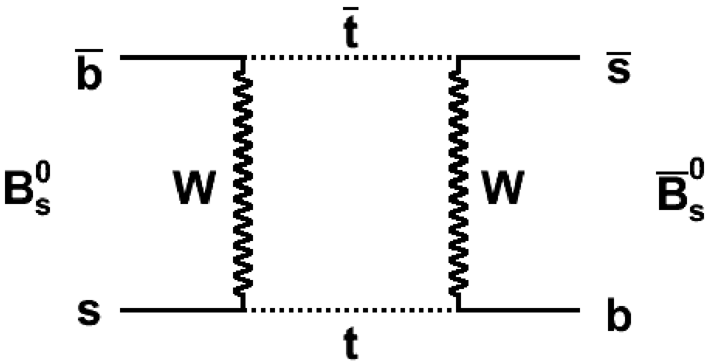


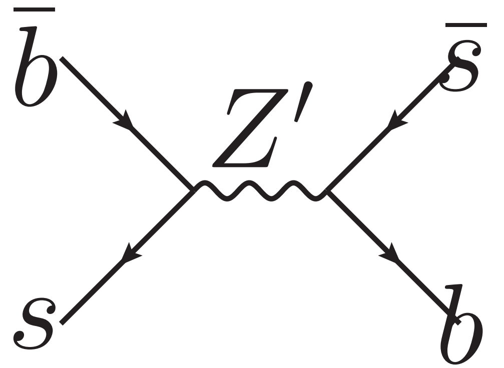
$$C_9 = -C_{10}$$

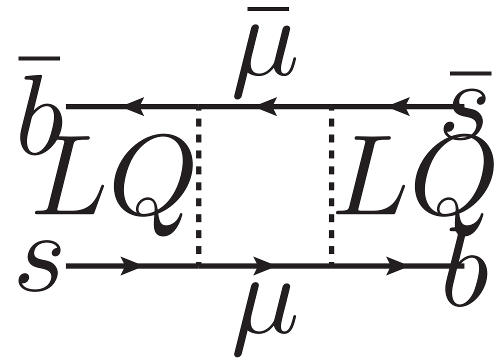
[3]Capdevila *et al* 1704.05340, Hiller and Hisandzic 1704.05444, D'Amico *et al* 1704.05438

$B_s - \bar{B}_s$ 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[4].

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

Best fits `BCA, Davighi, 2211.11766`

2-parameter fits to 247 flavour observables:

```
parameters | Wilson | flavio | smelli > output
```

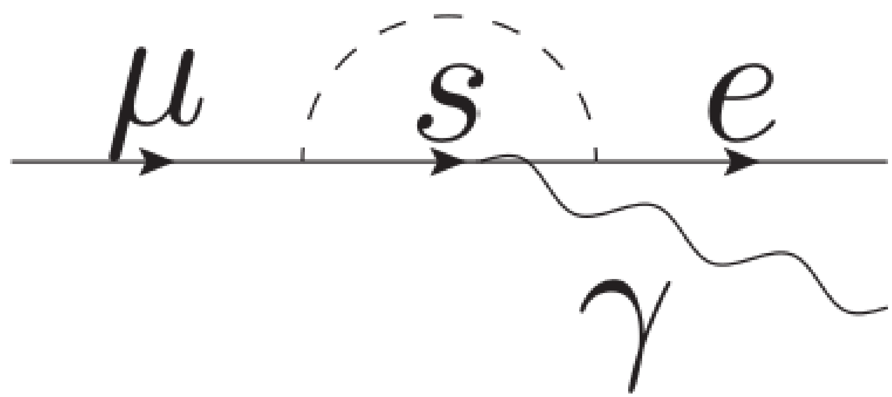
Model	$\sqrt{\chi^2_{SM} - \chi^2}$
S_3 LQ	3.6
$B_3 - L_2$ Z'	3.6

Coupling to electrons as well

Let's now switch on electron couplings in each model (eg $X_e \neq 0$ in Z' model).

Leptoquark Explanation

Coupling LQ to electrons as well will lead to trouble: $BR(\mu \to e\gamma) < 4.2\ 10^{-13}$ (MEG 2016)

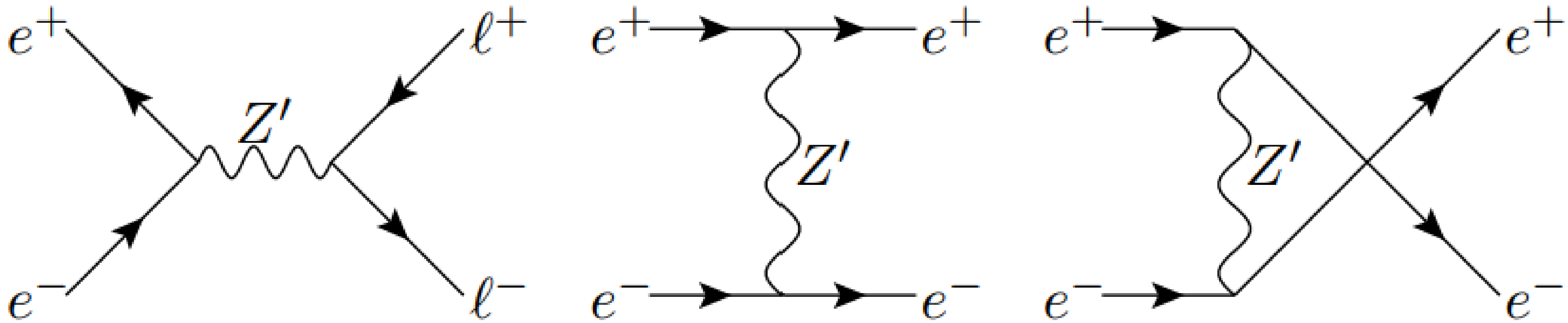


SMEFT WCs$/(g_{Z'}^2/M_{Z'}^2)$

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_{ee}^{iijj} $(i \neq j)$	$-L_i L_j$	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}	$-L_i L_j$
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
```

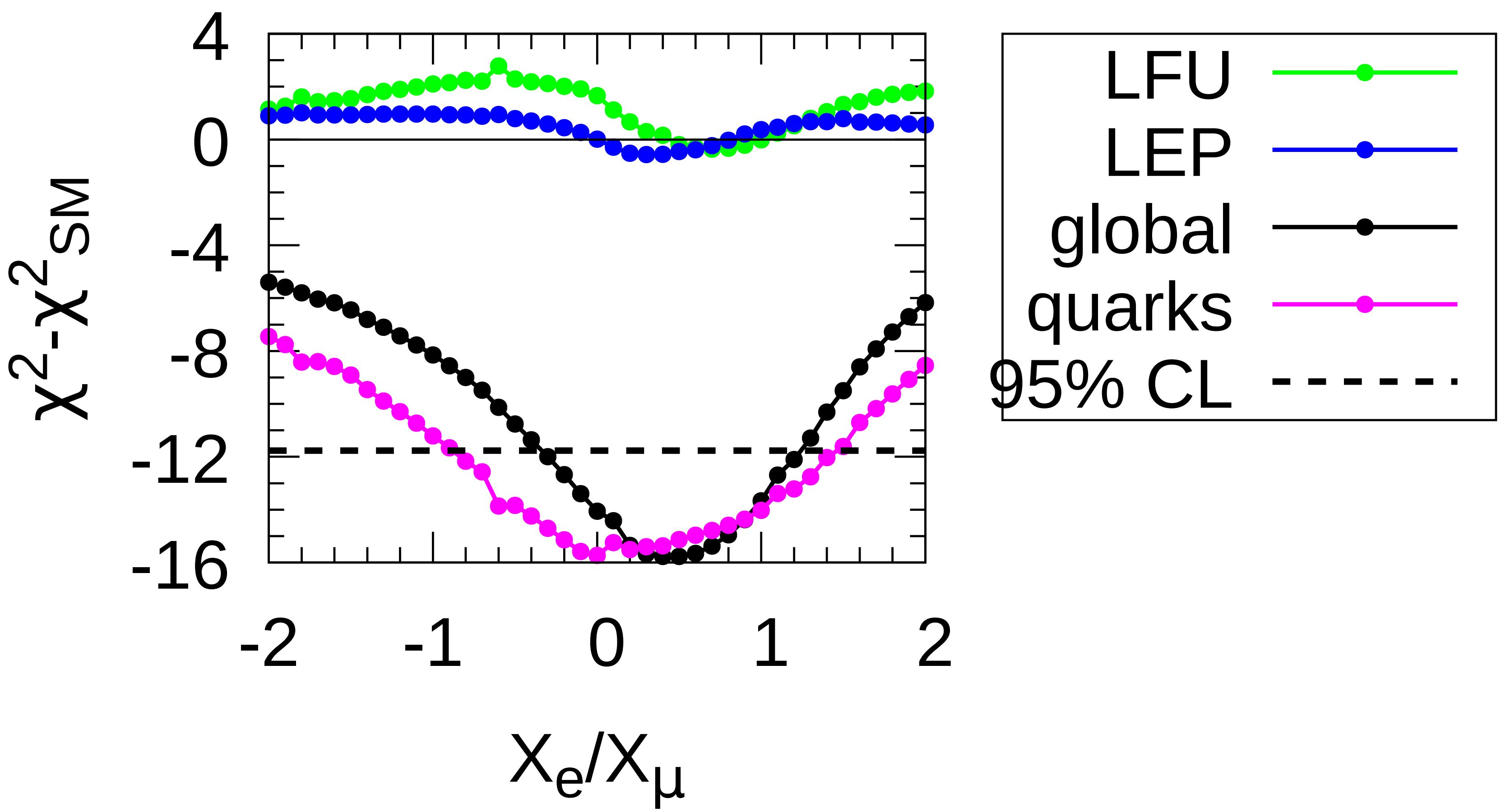
LEP constraints



Put into `flavio` (`Falkowski, Mimouni 1511.07434`)

Fit θ_{sb} and $g_{Z'}/M_{Z'}$

BCA, Mullin, 2306.08669

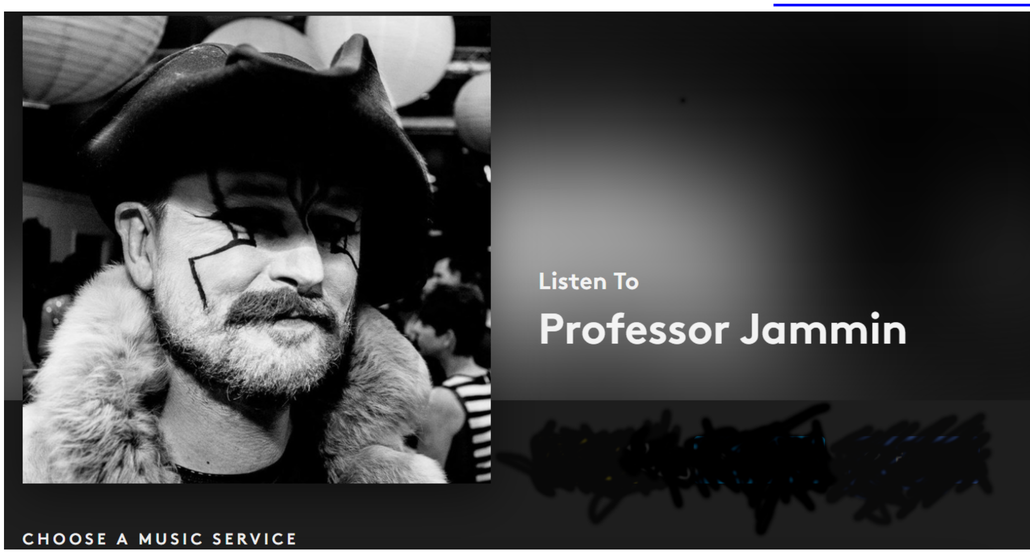


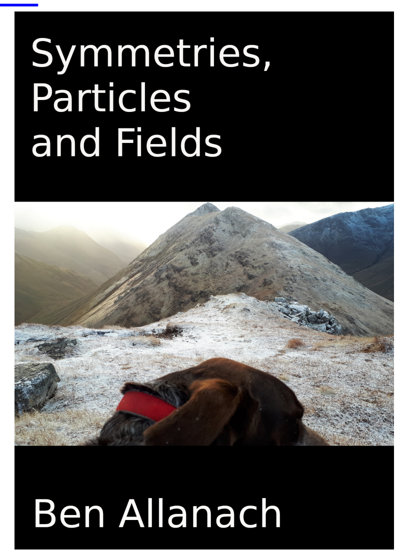
Epilogue

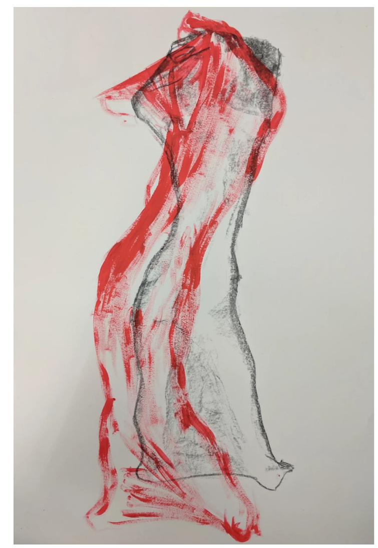
$b \to s\ell^+\ell^-$ anomalies are alive and well

Search in electrons as well as muons

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







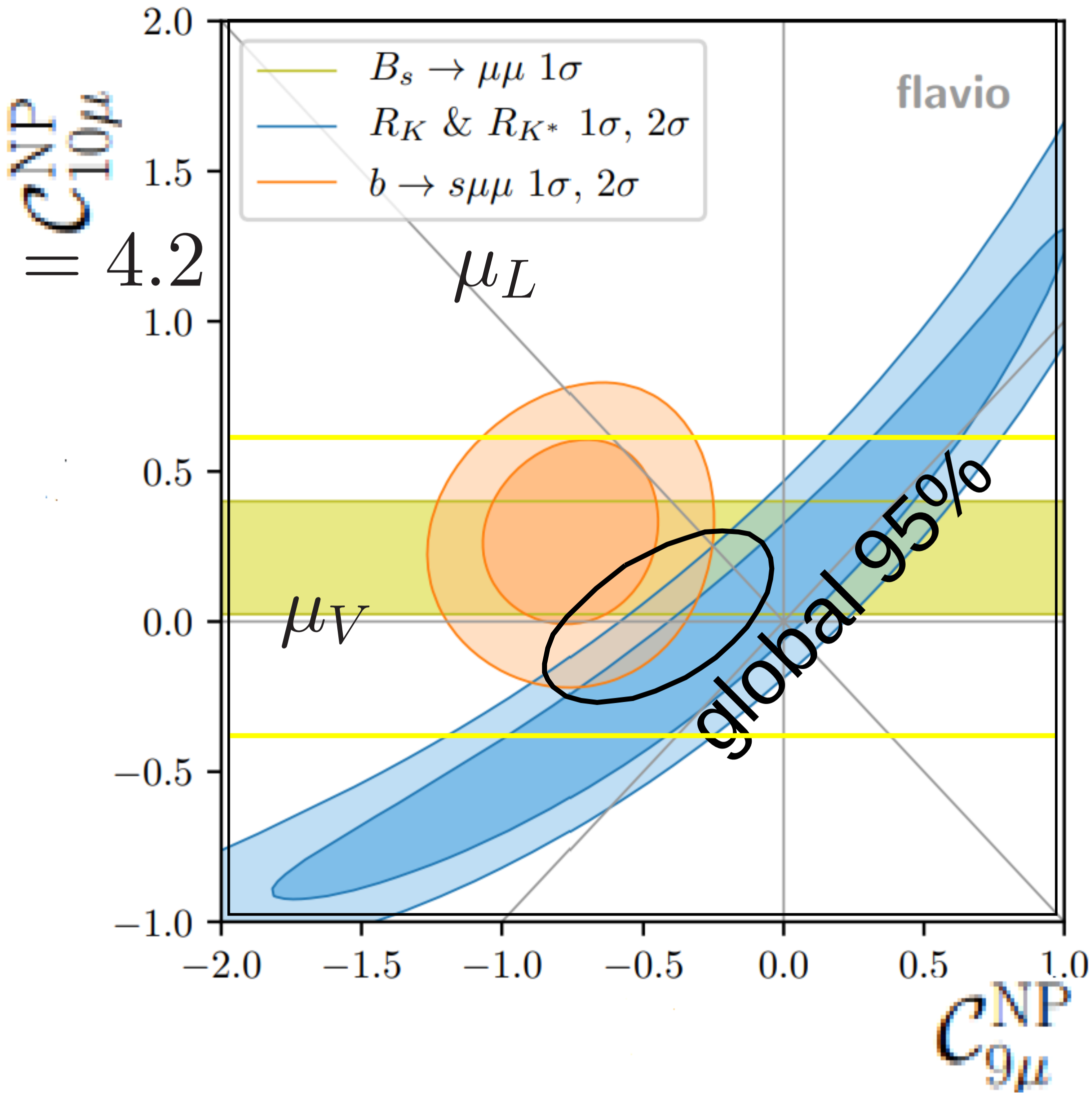
Backup

μ Neutral Current Fits

Greljo, Salko, Smolkovic, Stangl, 2212.10497

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

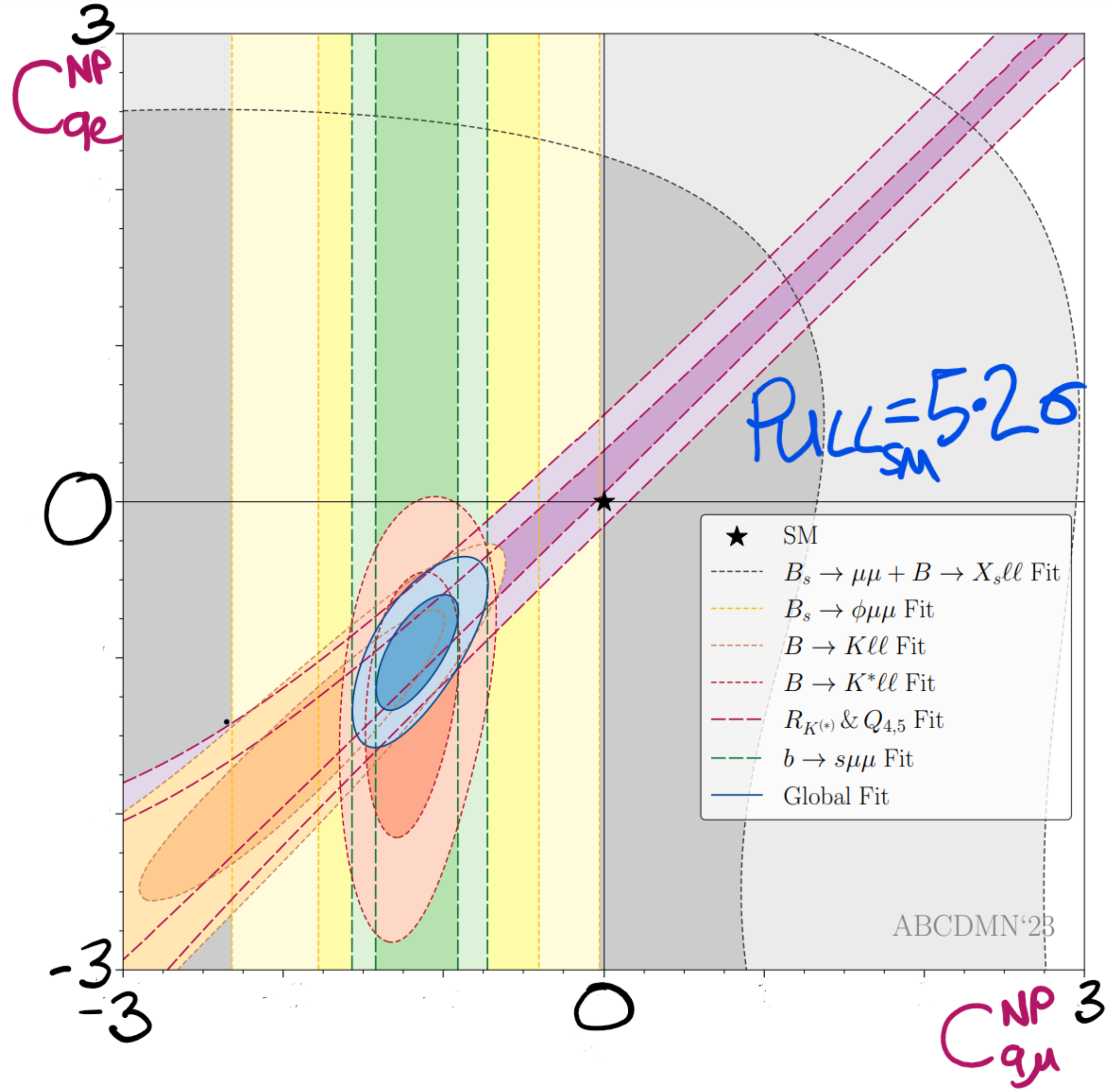
$$C_9^{SM} = -C_{10}^{SM} = 4.2$$

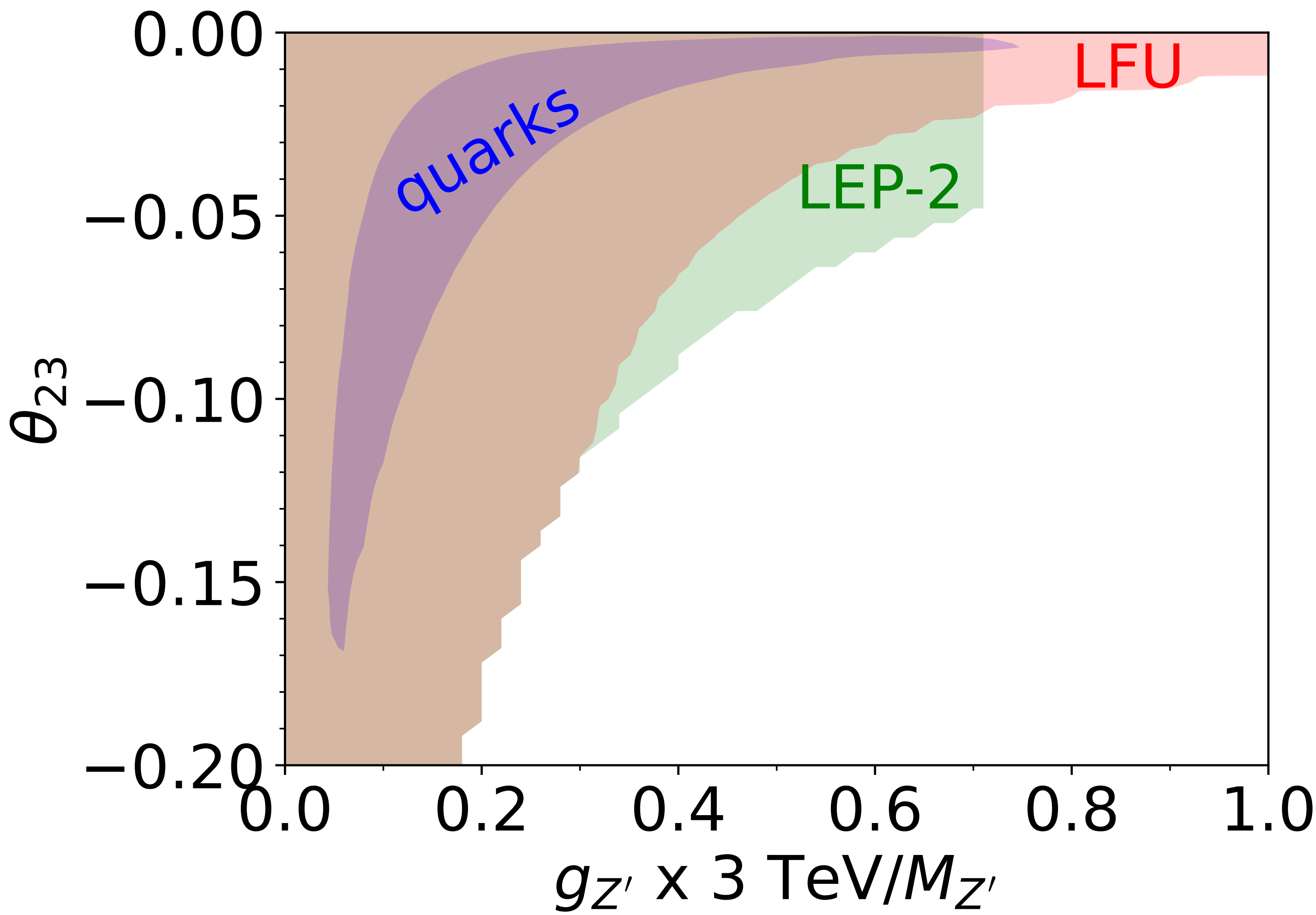


μ/e Neutral Current Fits

Alguero et al, 2304.07330

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





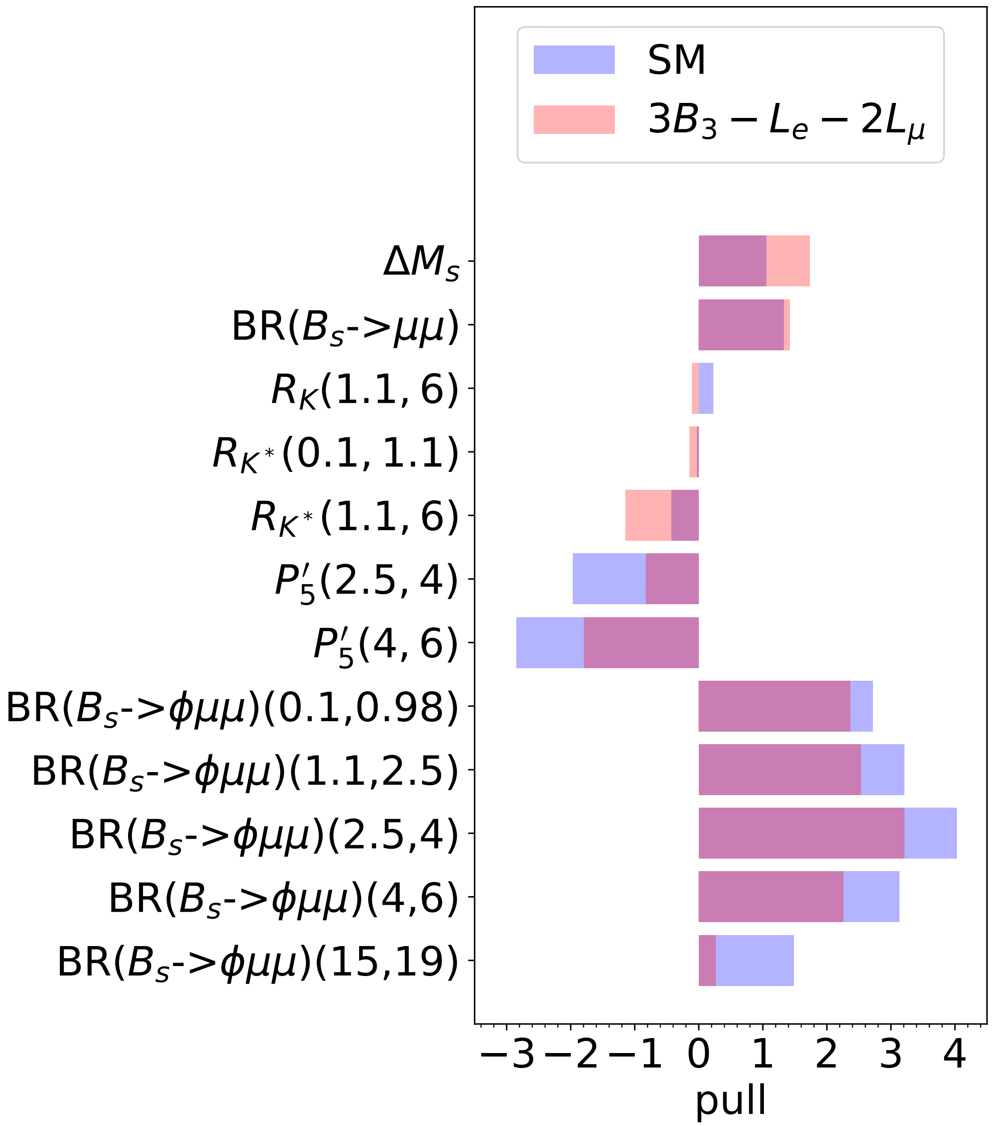
BCA, Mullin, 2306.08669

$3B_3 - L_e - 2L_\mu$ 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

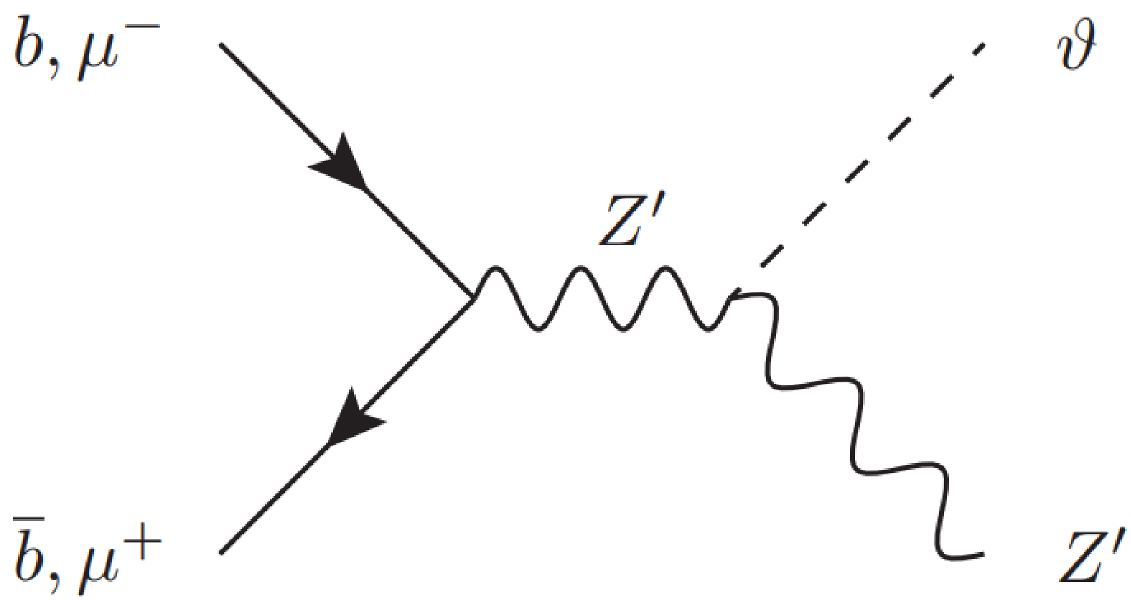
$g_{Z'} = 0.2,\ \theta_{sb} = -0.03$ best-fit

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

Flavonstrahlung

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

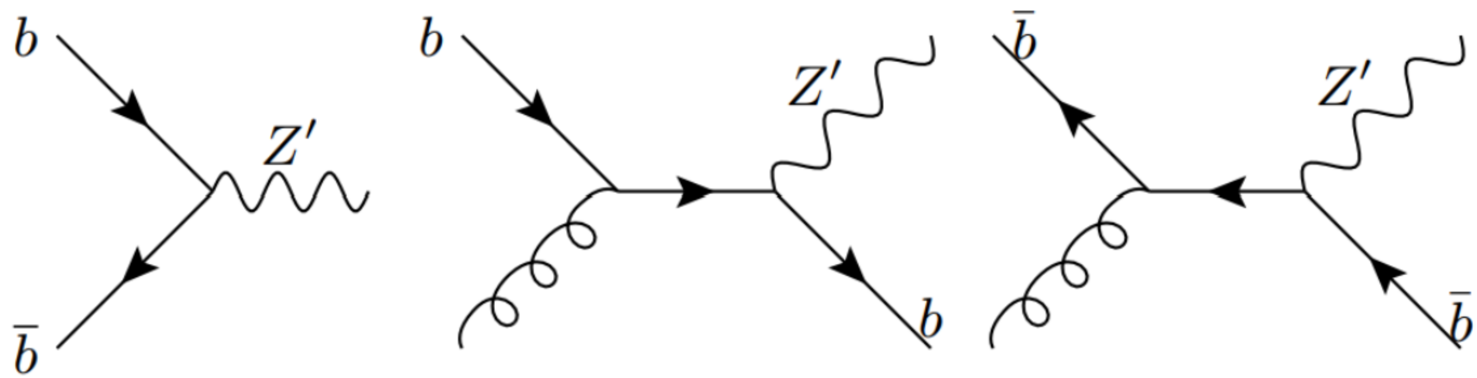


BCA, 2009.02197; BCA, Loisa, 2212.07440

Z' Decay Modes

Mode	BR	Mode	BR	Mode	BR
$t\bar{t}$	0.15	$b\bar{b}$	0.15	$\nu\bar{\nu}'$	0.23
$\mu^+\mu^-$	0.46				

pp Z' Production:



$$\sigma_{prod} \propto g_X^2 \cos^4\theta_{sb} = g_X^2 \left(1 - 2\theta_{sb}^2 + \mathcal{O}(\theta_{sb}^4)\right)$$

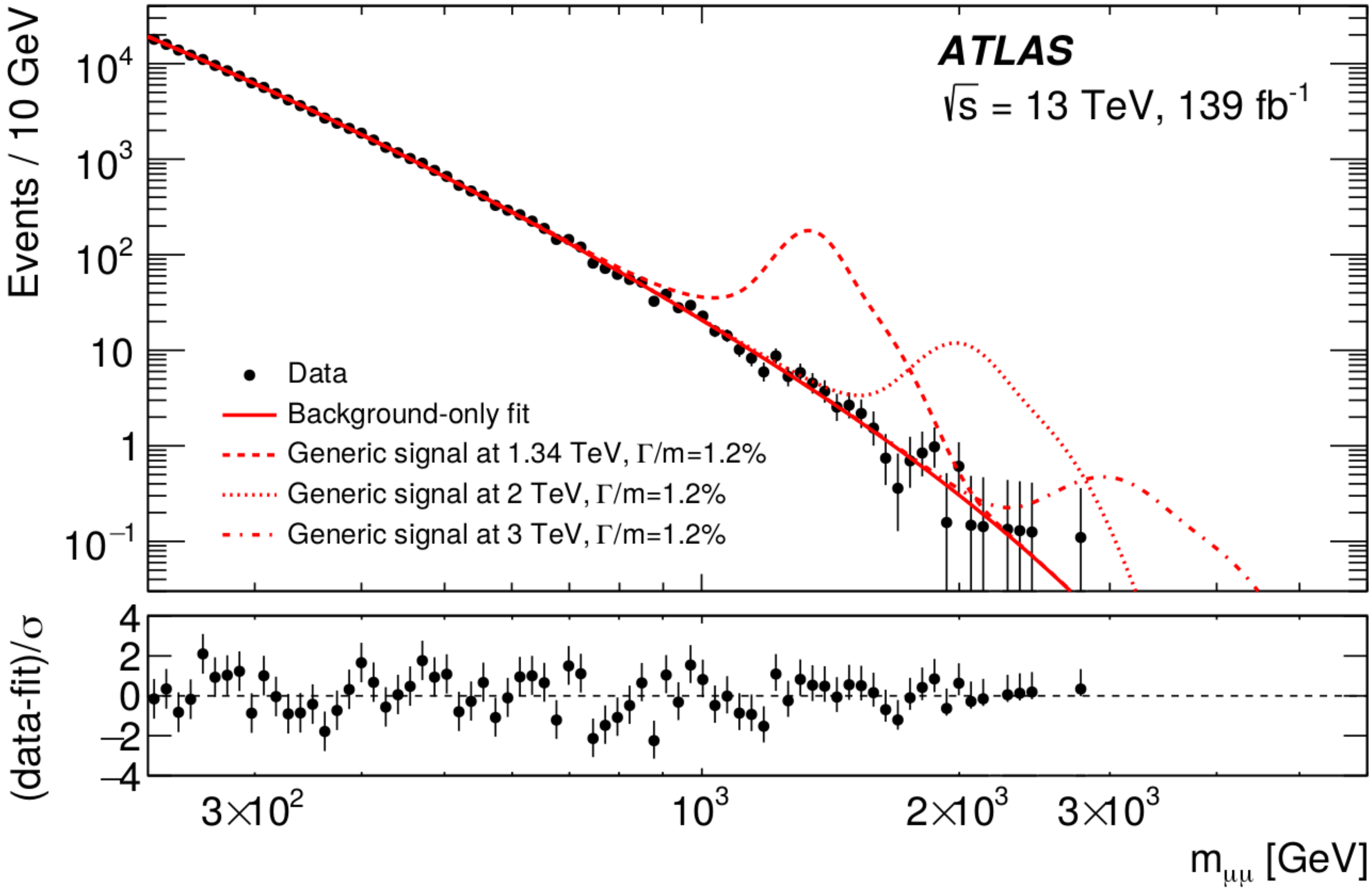
$\mu\mu$ ATLAS 13 TeV 139 fb^{-1}

2 track-based isolated μ, $p_T > 30$ GeV with reconstructed vertex.[5] Only keep pair with highest $(|p_{T_1}| + |p_{T_2}|)$.

$$m^2_{\mu_1\mu_2} = (p_1^\mu + p_2^\mu)\left(p_{1_\mu} + p_{2_\mu}\right)$$

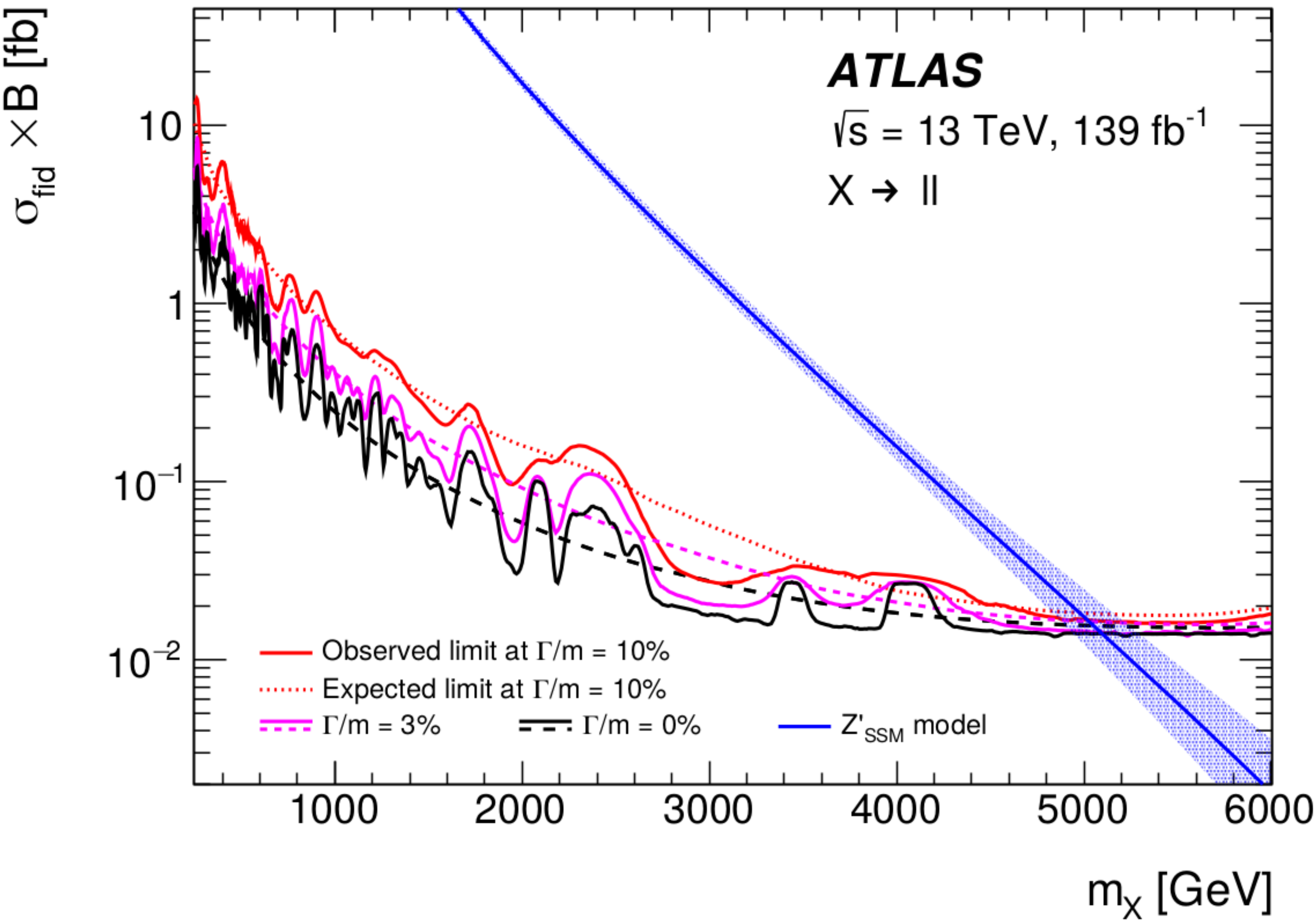
CMS also has a similar analysis[6]

[5] ATLAS, 1903.06248
[6] CMS, 2103.02708



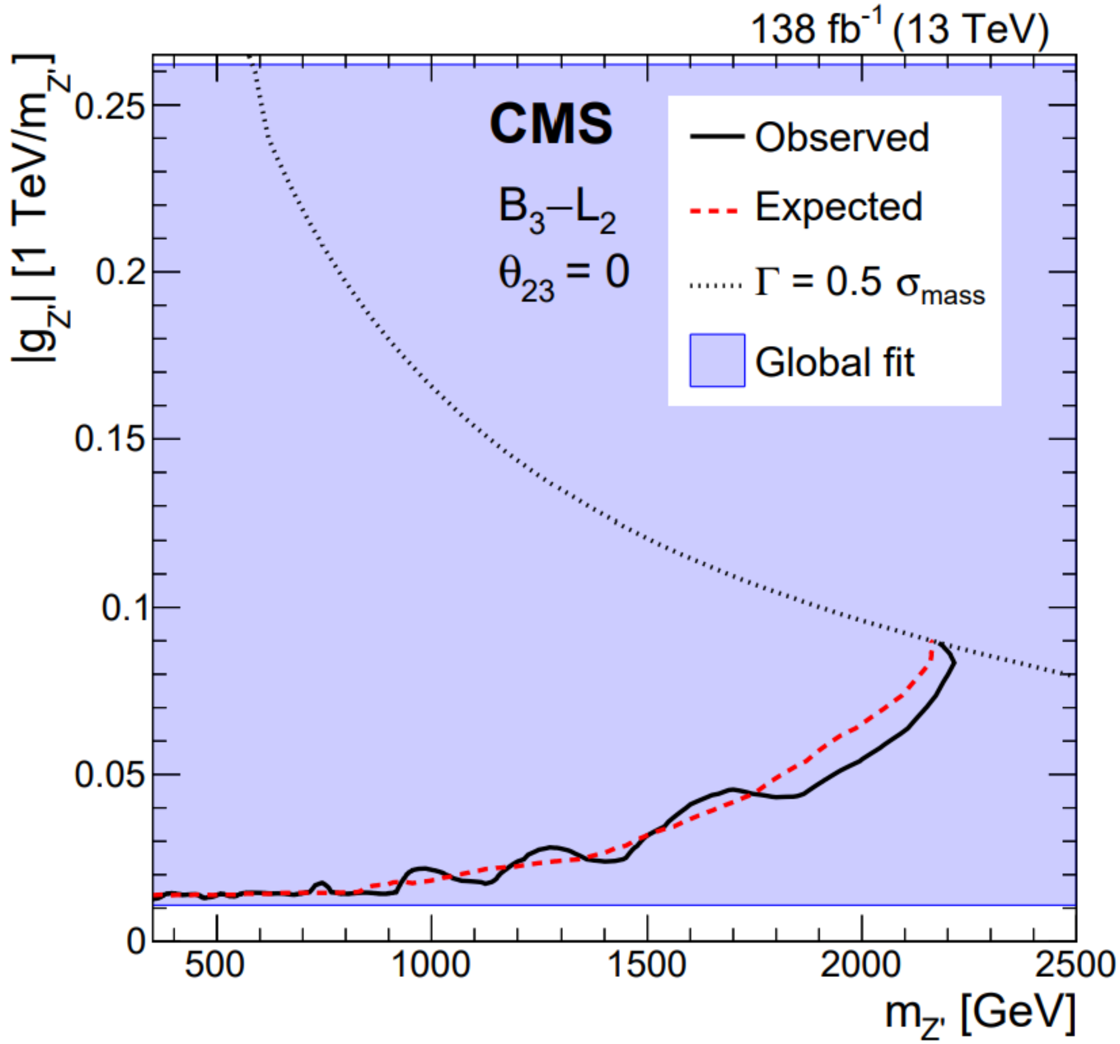
ATLAS
√s = 13 TeV, 139 fb-1
Events / 10 GeV
10^4
10^3
10^2
10
1
10^{-1}
Data
Background-only fit
Generic signal at 1.34 TeV, Γ/m=1.2%
Generic signal at 2 TeV, Γ/m=1.2%
Generic signal at 3 TeV, Γ/m=1.2%
(data-fit)/σ
4
2
0
−2
−4
3×10^2
10^3
2×10^3
3×10^3
$m_{\mu\mu}$ [GeV]

ATLAS l^+l^- limits

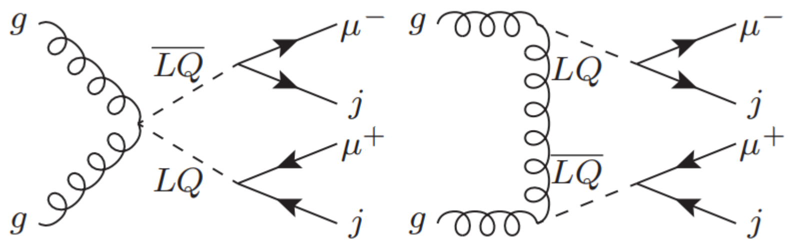


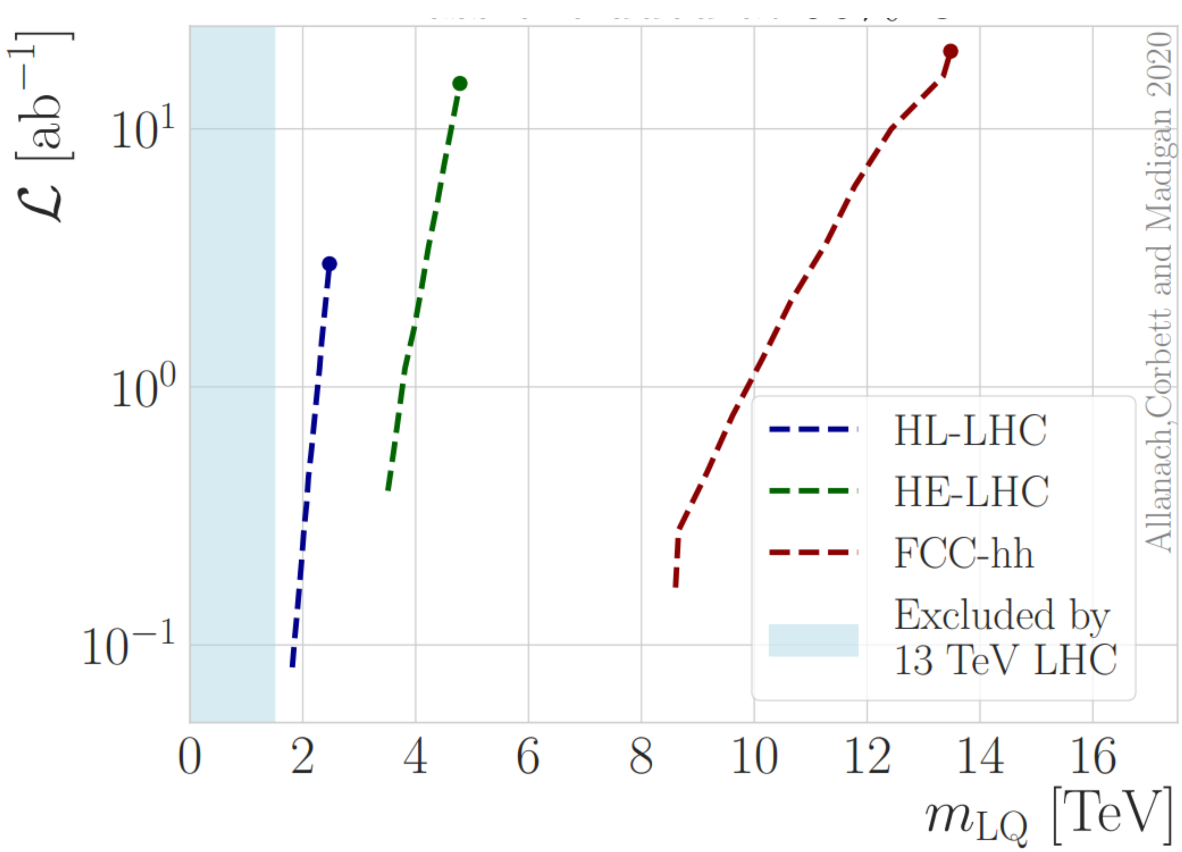
ATLAS, 1903.06248

CMS $\mu^+\mu^- b$ 2307.08708



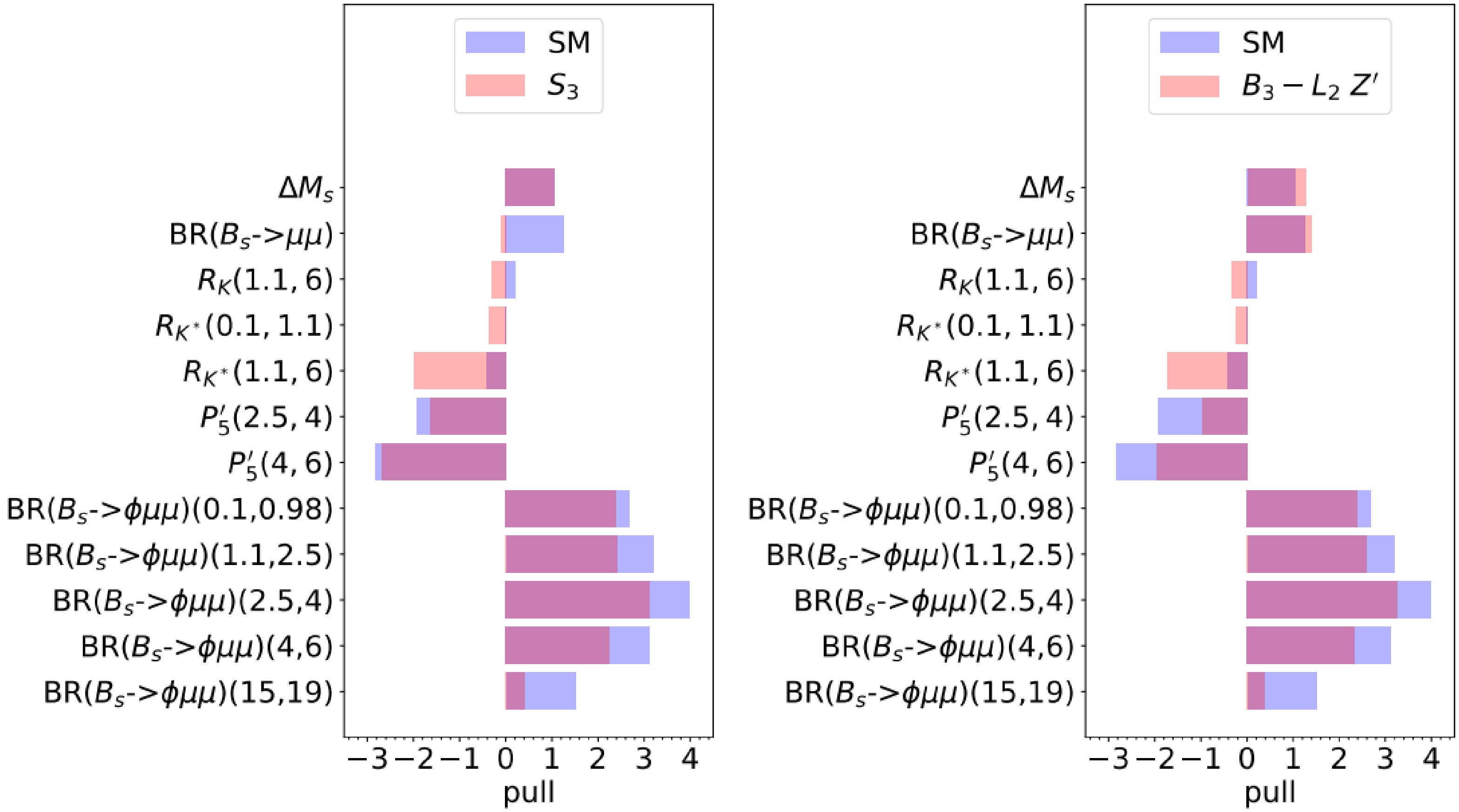
Scalar LQ[7]: eg $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$





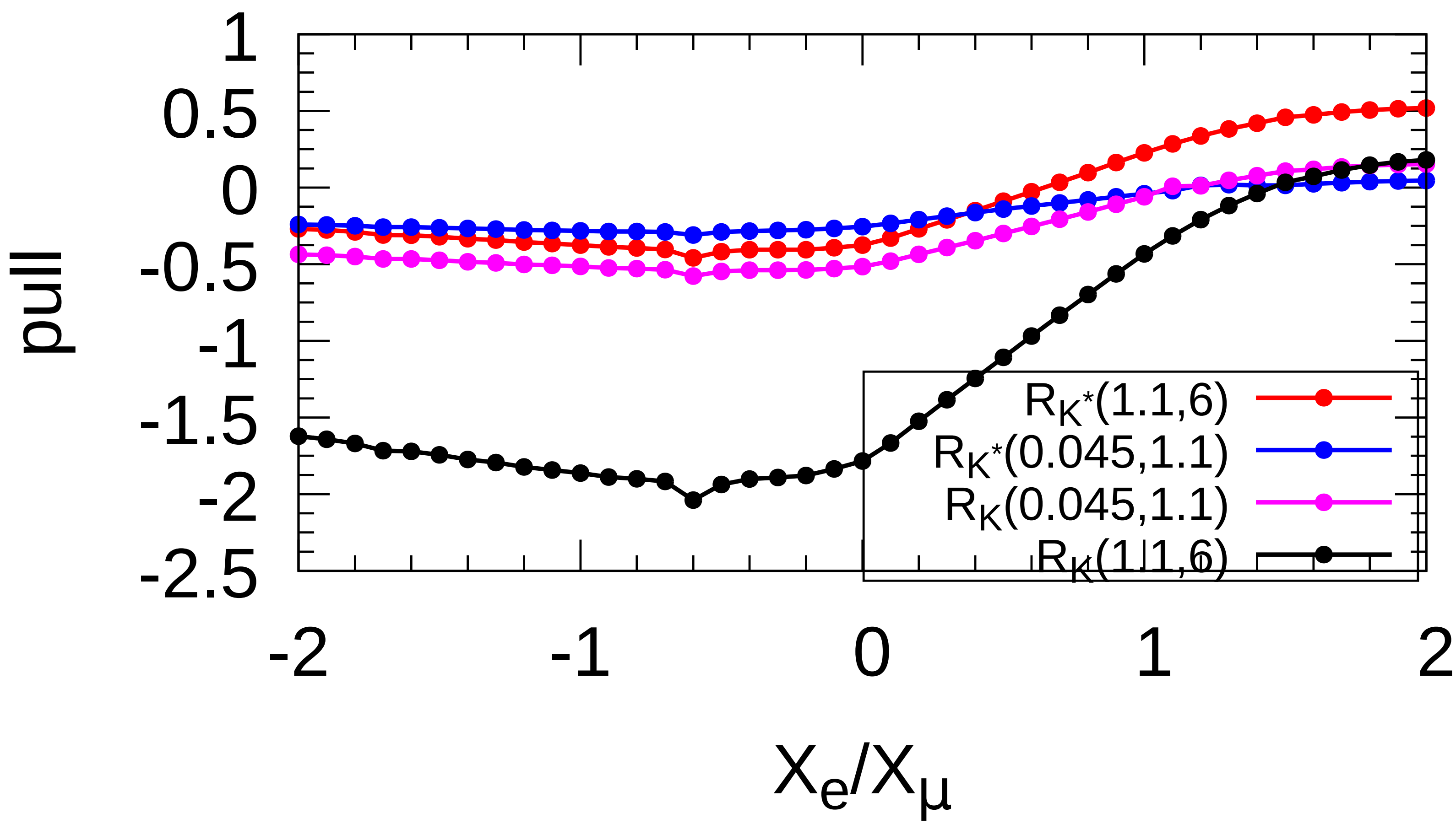
[7]BCA, Corbett, Madigan, 1911.0445

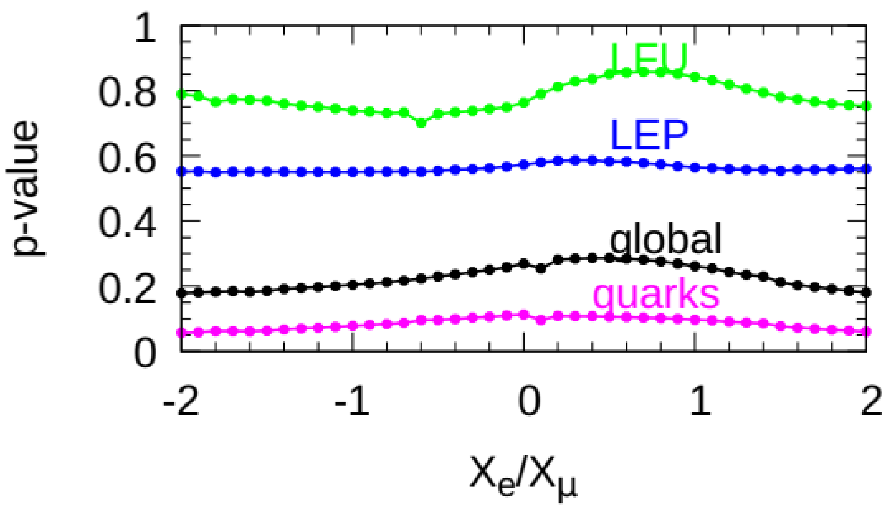
Pull=(theory-exp)/error



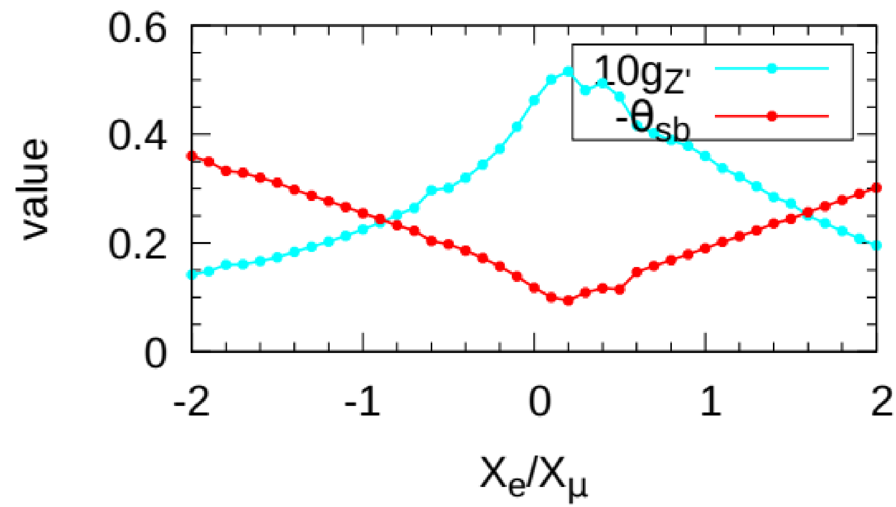
BCA, Davighi, 2211.11766

BCA, Mullin, 2306.08669

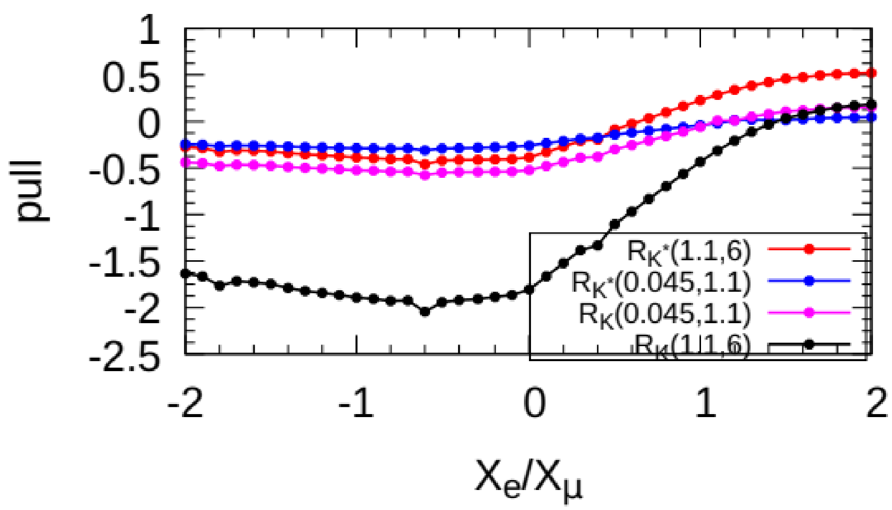




LFU
LEP
global
quarks
p-value
1
0.8
0.6
0.4
0.2
0
-2
-1
0
1
2
X_e/X_μ



$10g_{Z'}$
$-\theta_{sb}$
value
0.6
0.4
0.2
0
-2
-1
0
1
2
X_e/X_μ

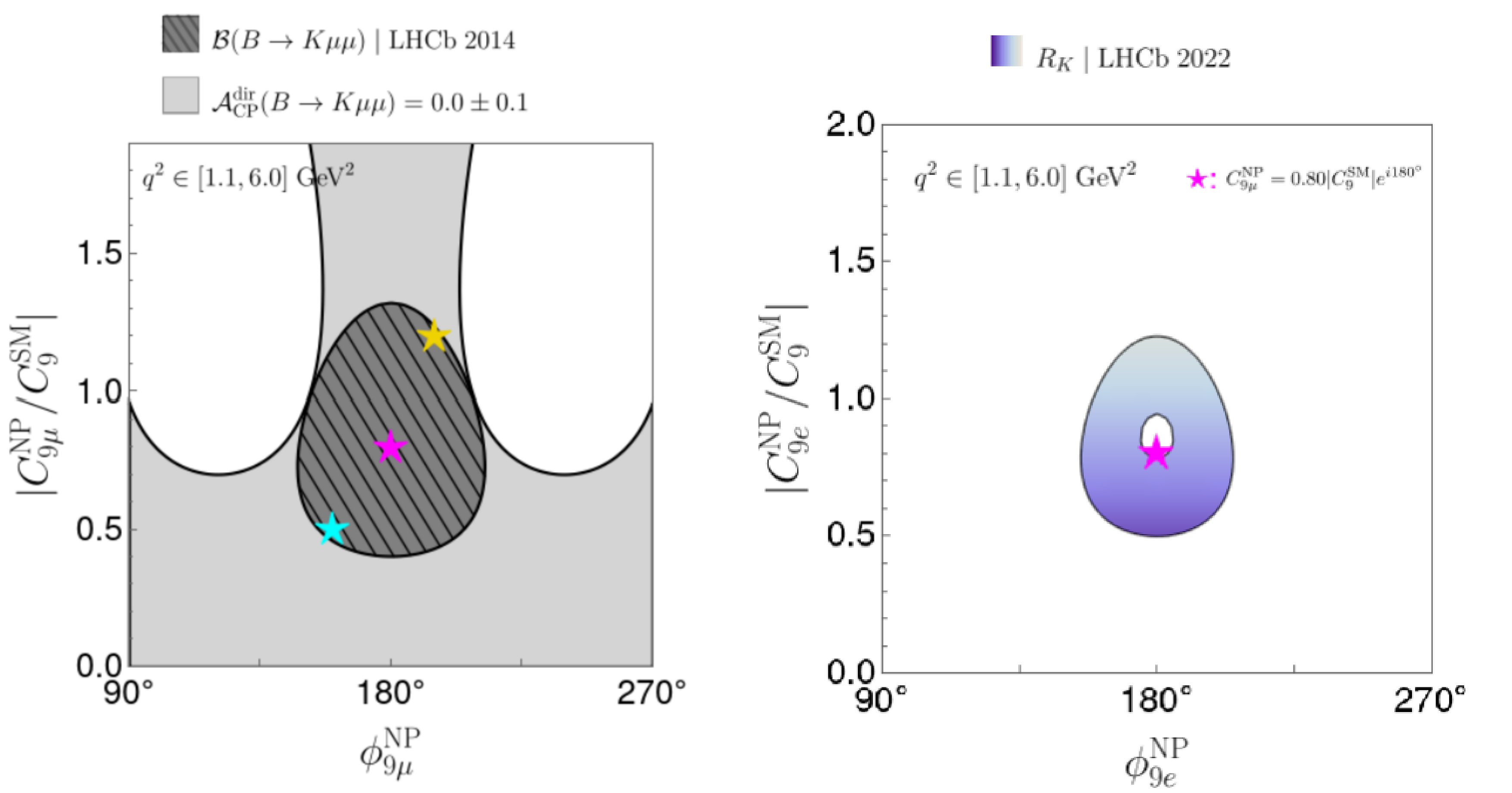


$R_{K^*}(1.1,6)$
$R_{K^*}(0.045,1.1)$
$R_K(0.045,1.1)$
$R_K(1.1,6)$
pull
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-2
-1
0
1
2
X_e/X_μ

$e \neq \mu$ allowed

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

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



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

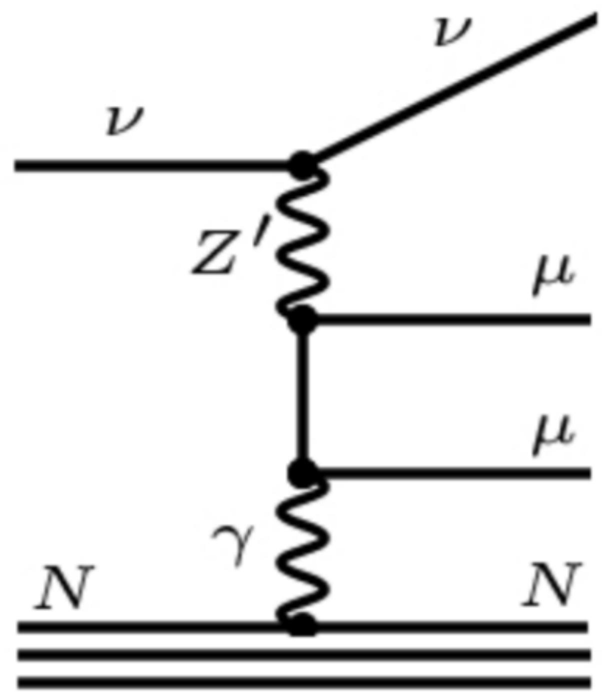
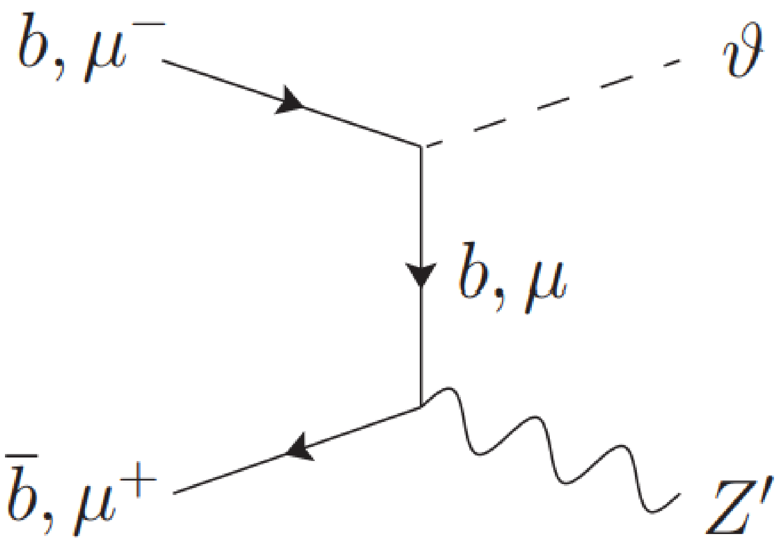
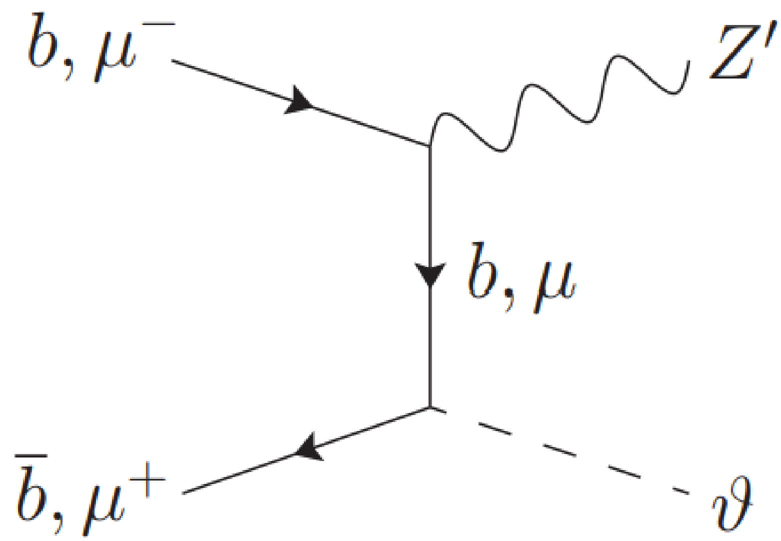


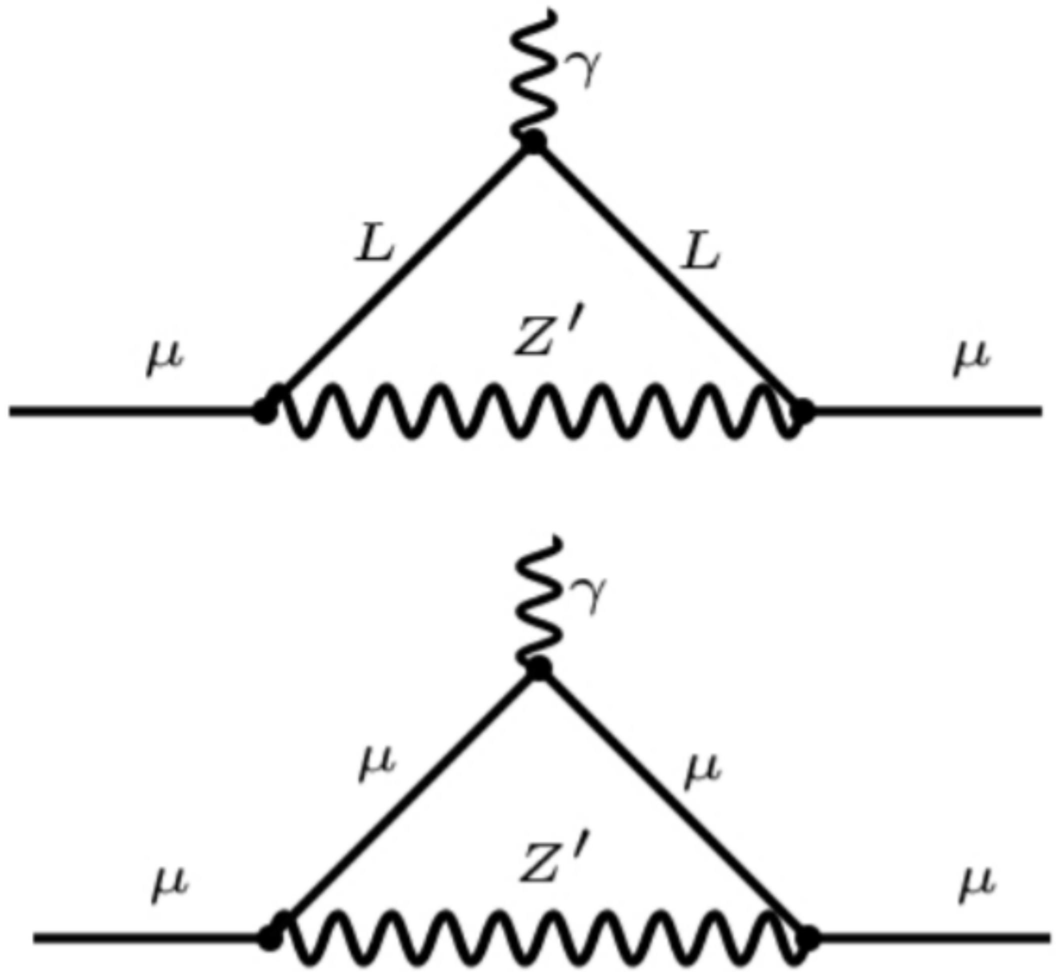
FIG. 10. Neutrino trident process that leads to constraints on the Z^{μ} coupling strength to neutrinos-muons, namely $M_{Z'}/g_{v\mu} \gtrsim 750$ GeV.

$t-$channel





$(g-2)_\mu$



$H\vartheta$ potential

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

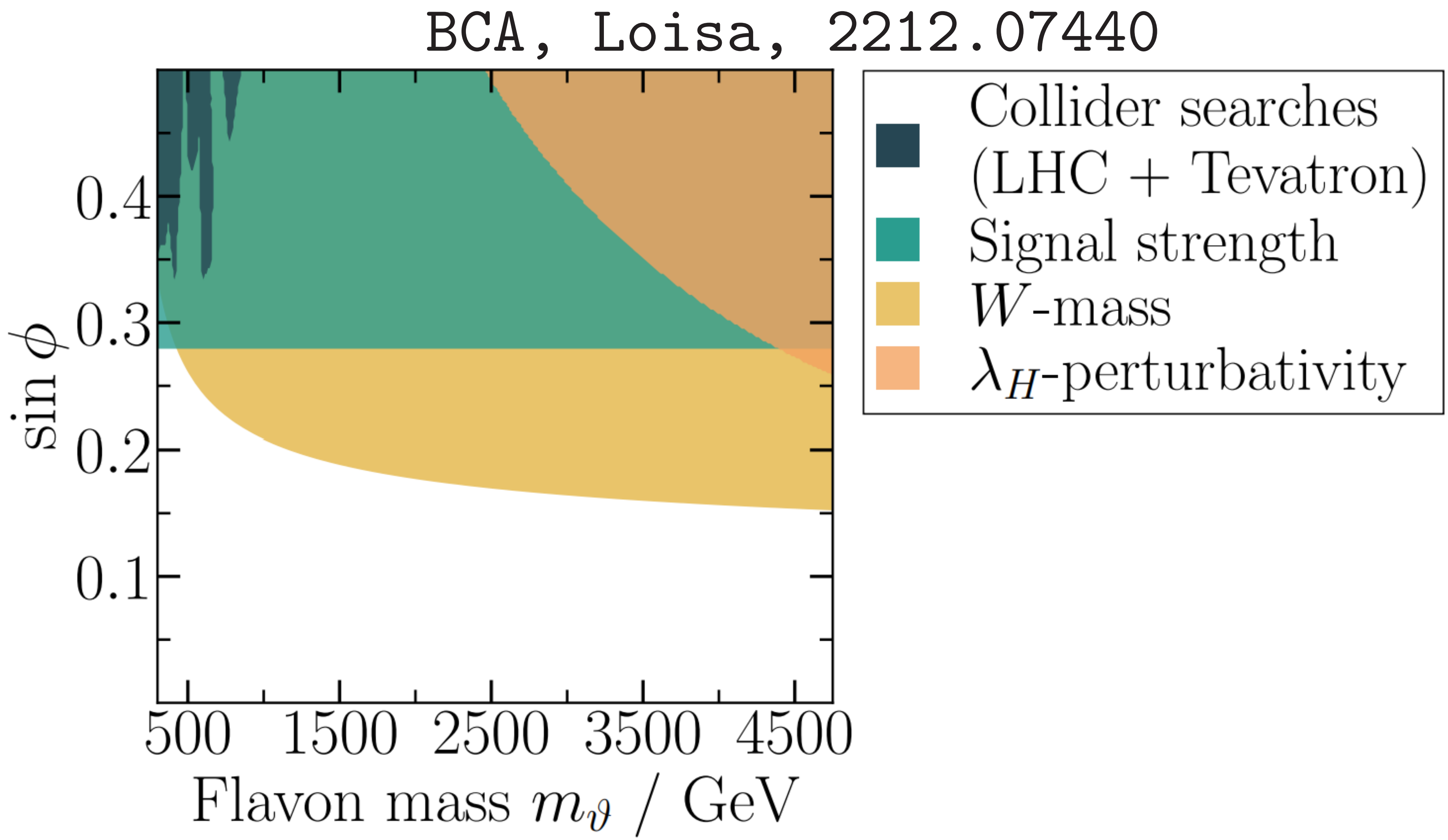
$H\vartheta$ **mixing**

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

$$\sin 2\phi = \frac{2\lambda_{\theta H} v_h v_\theta}{m_\vartheta^2 - m_h^2}. \qquad (1)$$

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

Higgs Signal Strength



ϑ BRs