Plan B: New Z' models for $b \to s\ell^+\ell^-$ anomalies

by

Ben Allanach (Cambridge)
Collaborators: Anna Mullin

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

Interpolating in Z'/di-electron couplings

Fits: `BCA, Mullin, 2306.08669`

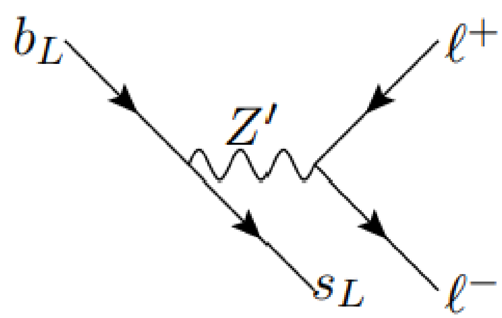
$b \to s\mu^+\mu^-$ anomalies

$B^0 \to K^{*0}\mu^+\mu^-$ angular distributions, BRs

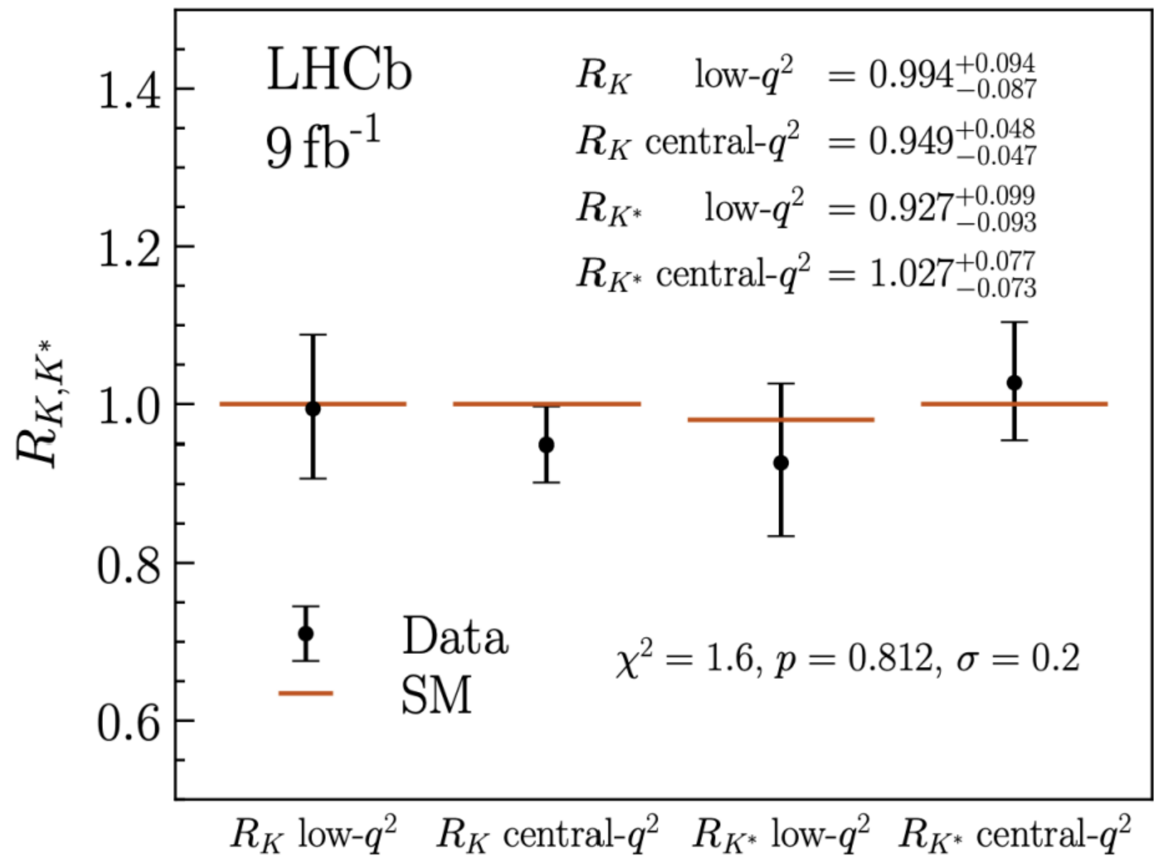
and

$BR(B_s \to \phi\mu^+\mu^-)$

....prefer new physics: $Z' - \mu^+\mu^-$ and $Z' - \bar{b}s$.
But what about coupling to di-electrons?



LHCb 2212.09152



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

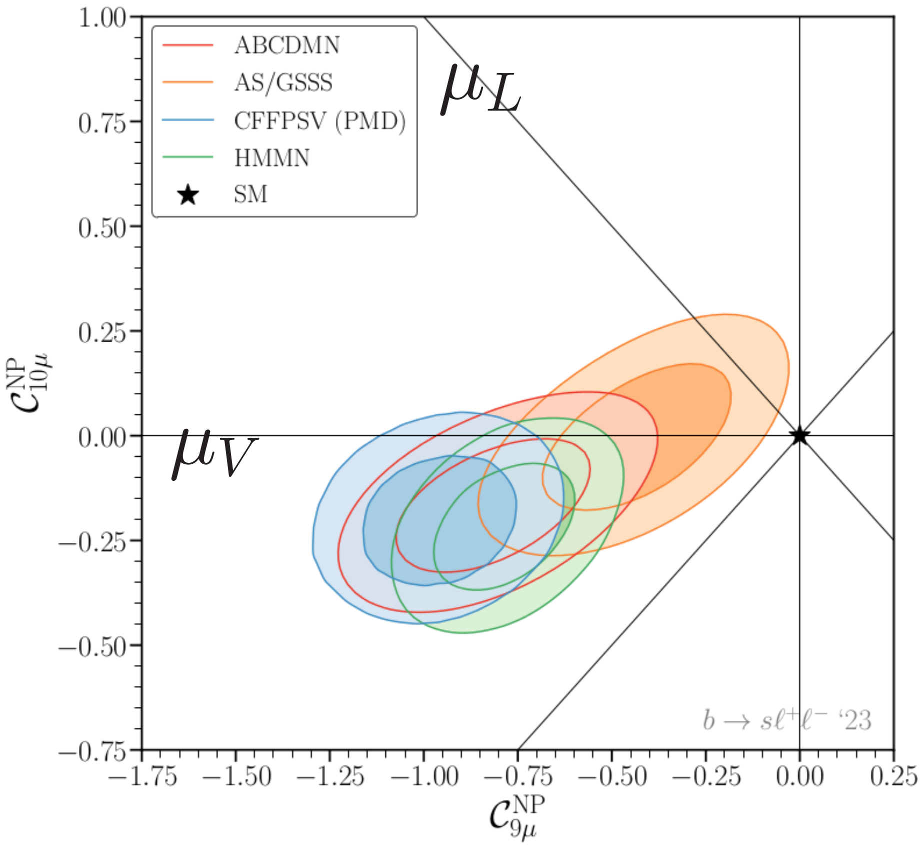
Neutral Current Fits

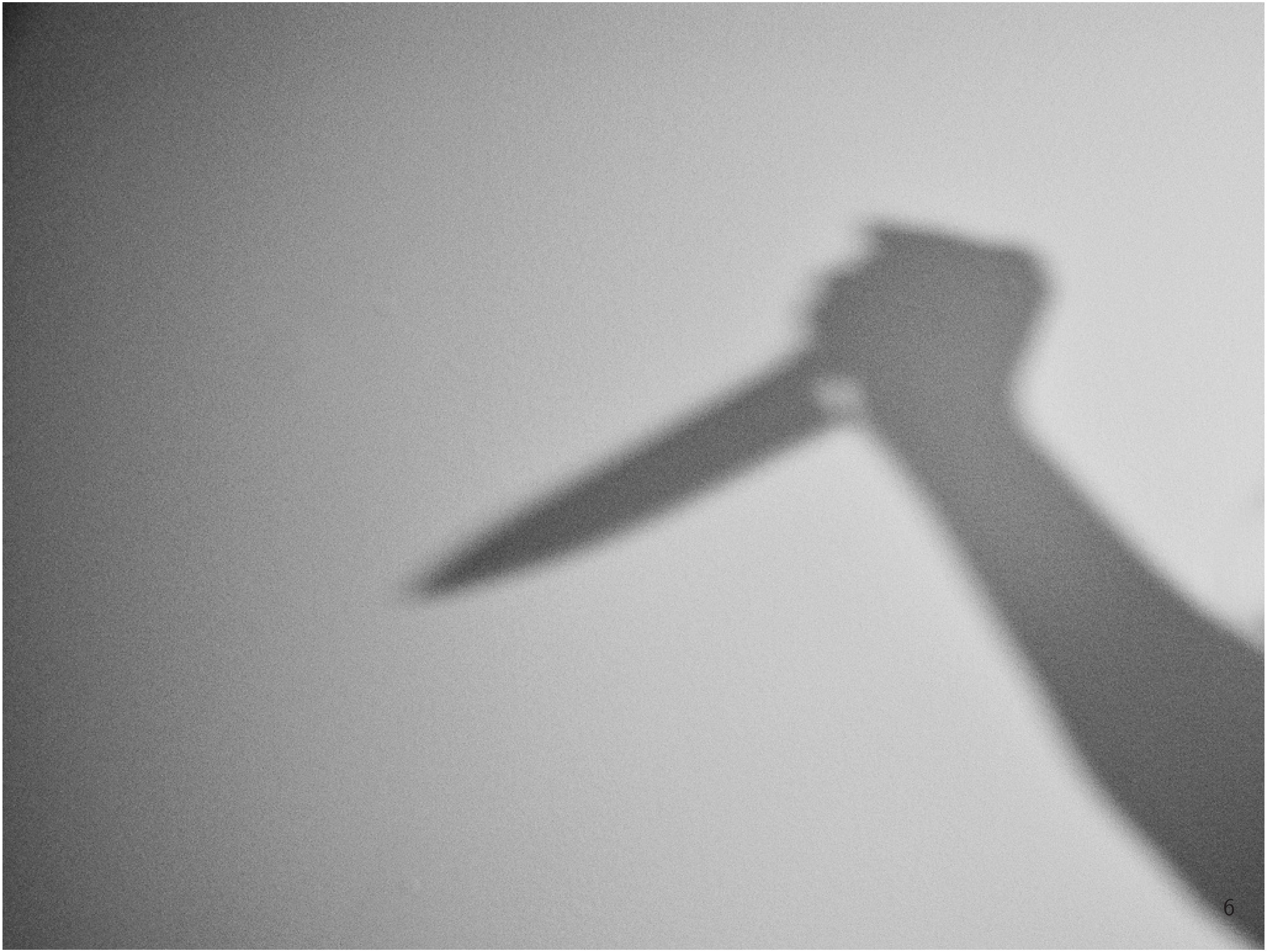
Alguero *et al*, 2304.07330; Altmannshofer, Stangl, flavio 2212.10497

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

$$\mathcal{L} = N[C_9(\bar{b}_L\gamma^\mu s_L)(\bar{\mu}\gamma_\mu\mu) + C_{10}(\bar{b}_L\gamma^\mu s_L)(\bar{\mu}\gamma^5\gamma_\mu\mu)] + H.c.$$

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





Simple Z' Model

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

Postdicts heavy third family quarks[1]

---

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

Anomaly cancellation

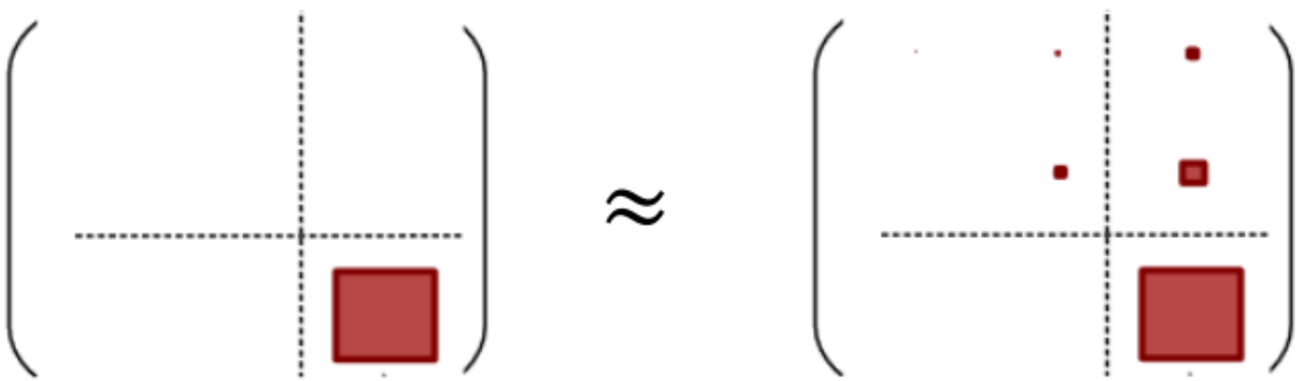
Need to pick X charges for fermions consistent with QFT anomaly cancellation.

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

works (proof in 2306.08669).

Flavour problem

$$\mathcal{L}_q = Y_t \overline{Q_3{}'_L} H t'_R + Y_b \overline{Q'_{3L}} H^c b'_R + H.c.,$$



Postdicts small CKM angles

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

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

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

A simple limiting case

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

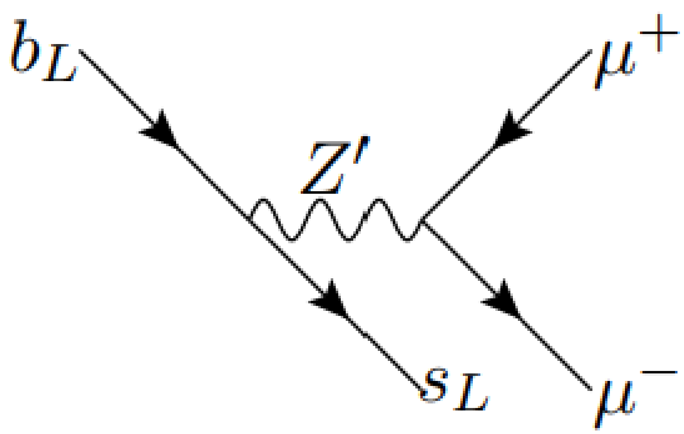
$$V_{d_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{sb} & -\sin\theta_{sb} \\ 0 & \sin\theta_{sb} & \cos\theta_{sb} \end{pmatrix}.$$

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

Important Z' Couplings

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

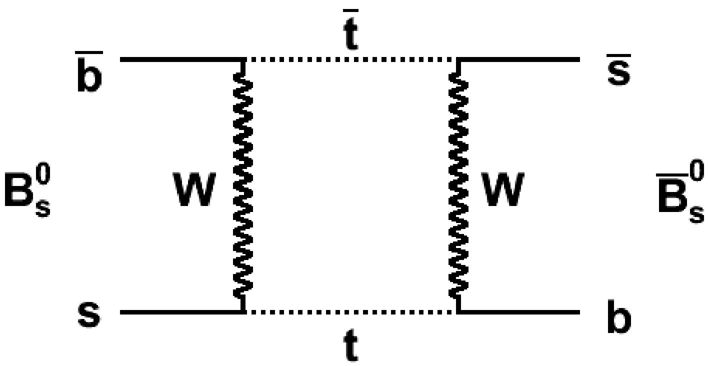
$$\left.-(\overline{e}\ \overline{\mu}\ \overline{\tau})\begin{pmatrix}X_e & 0 & 0\\ 0 & X_\mu & 0\\ 0 & 0 & (3-X_e-X_\mu)\end{pmatrix}\not{Z}'\begin{pmatrix}e\\ \mu\\ \tau\end{pmatrix}\right]$$

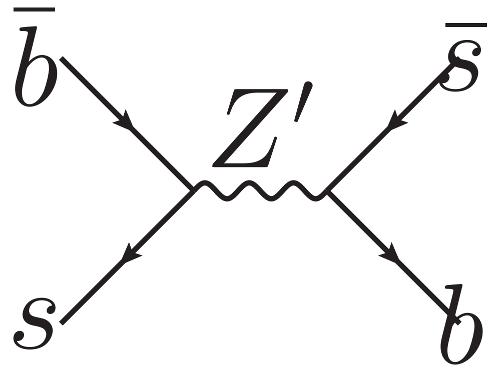


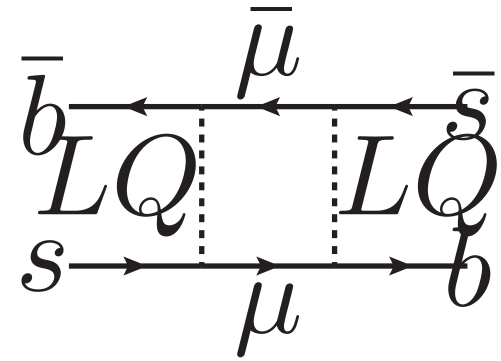
– LFU Violating, $C_9 \neq 0$

$B_s - \bar{B}_s$ 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[2].

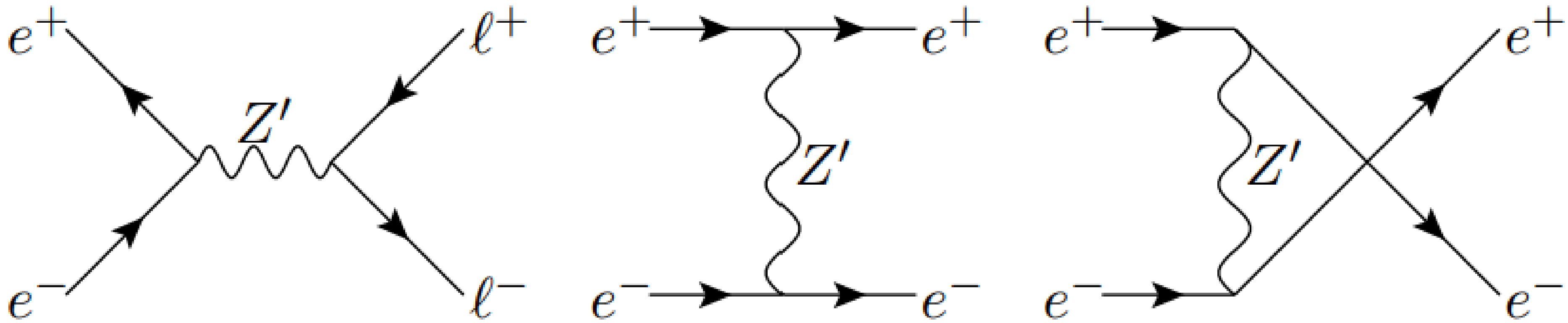
[2] King, Lenz, Rauh, arXiv:1904.00940

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

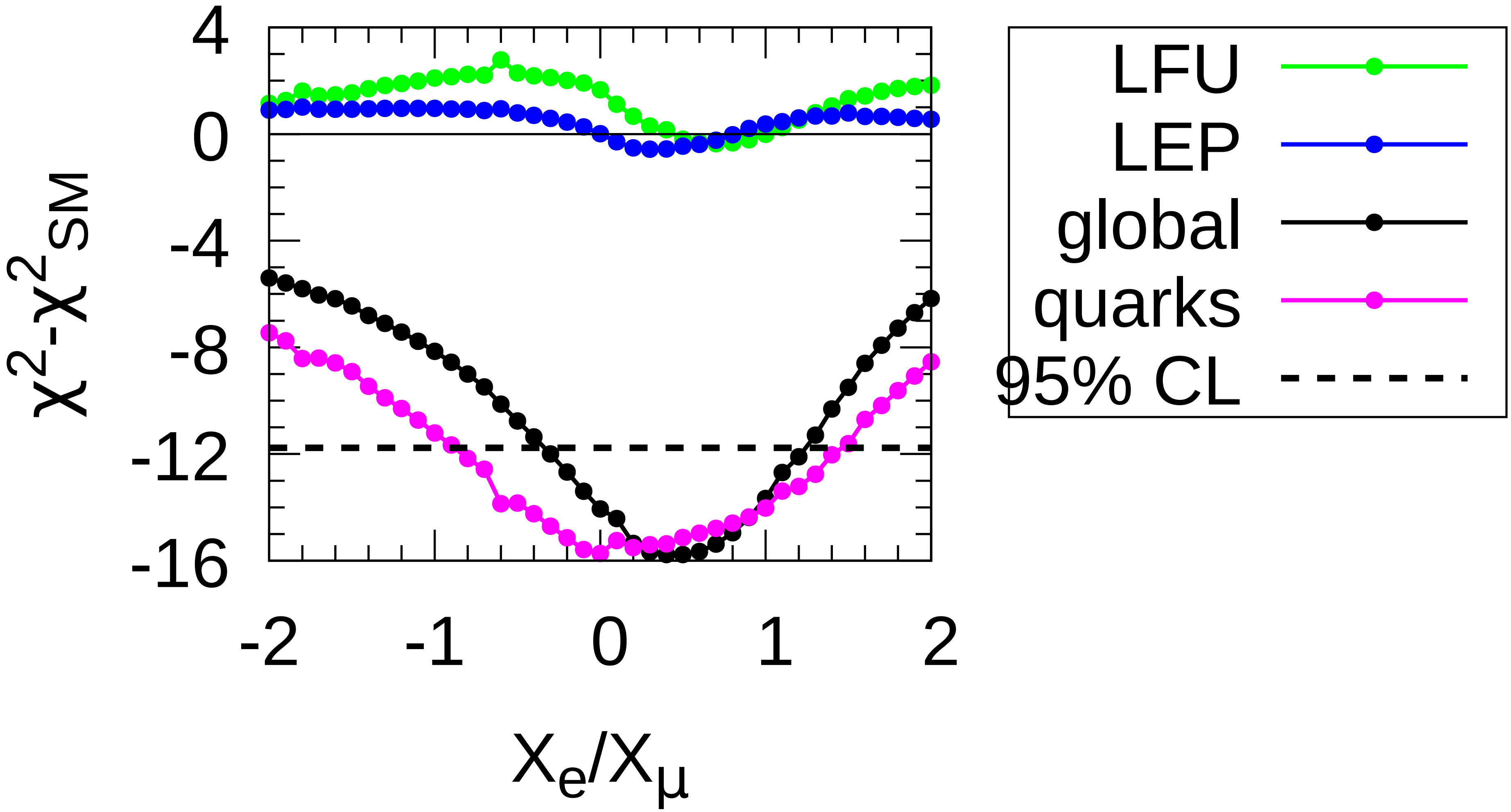
```
| wilson | flavio | smelli > output
```

LEP constraints

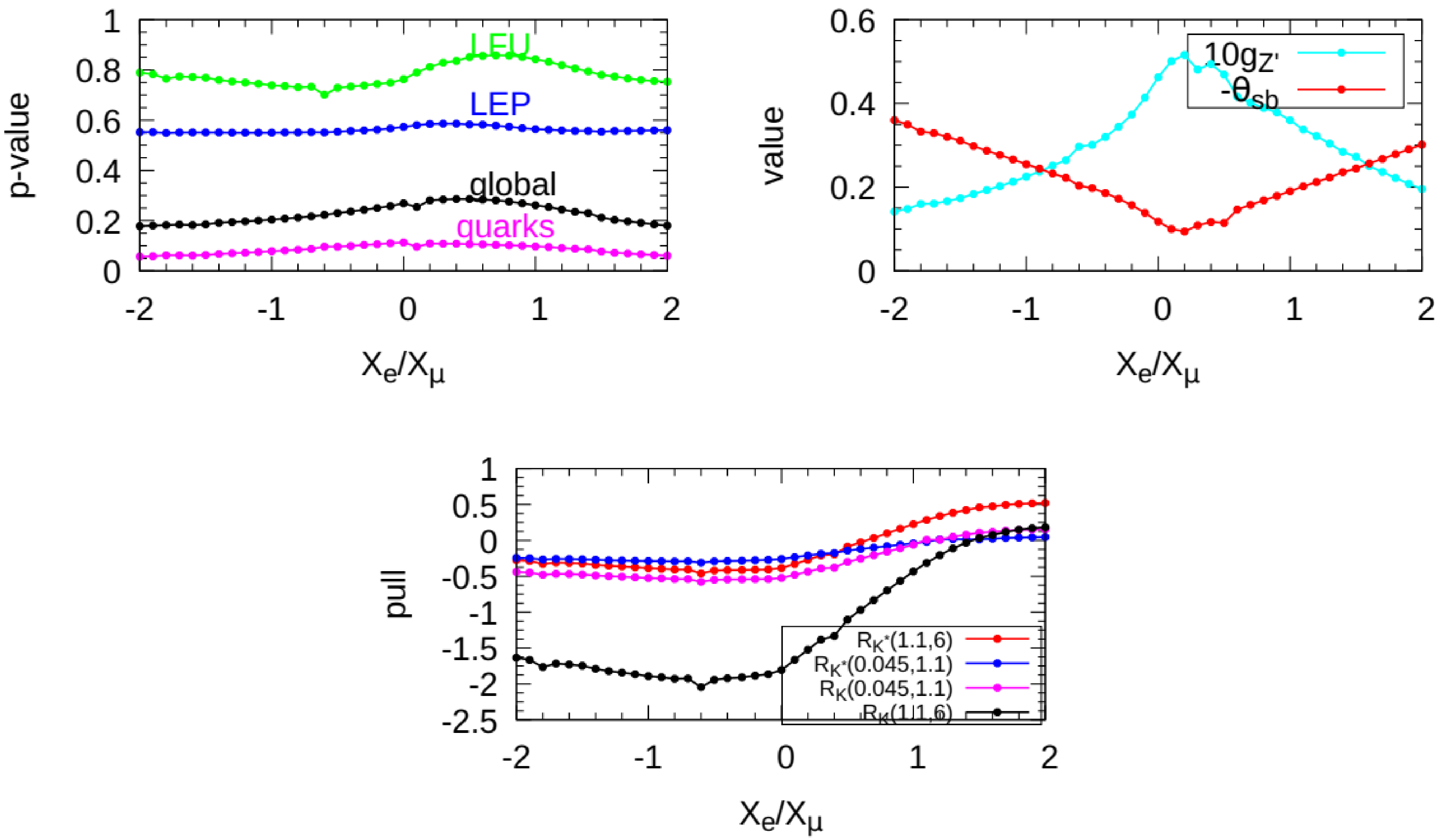


Put into flavio (Falkowski, Mimouni 1511.07434)

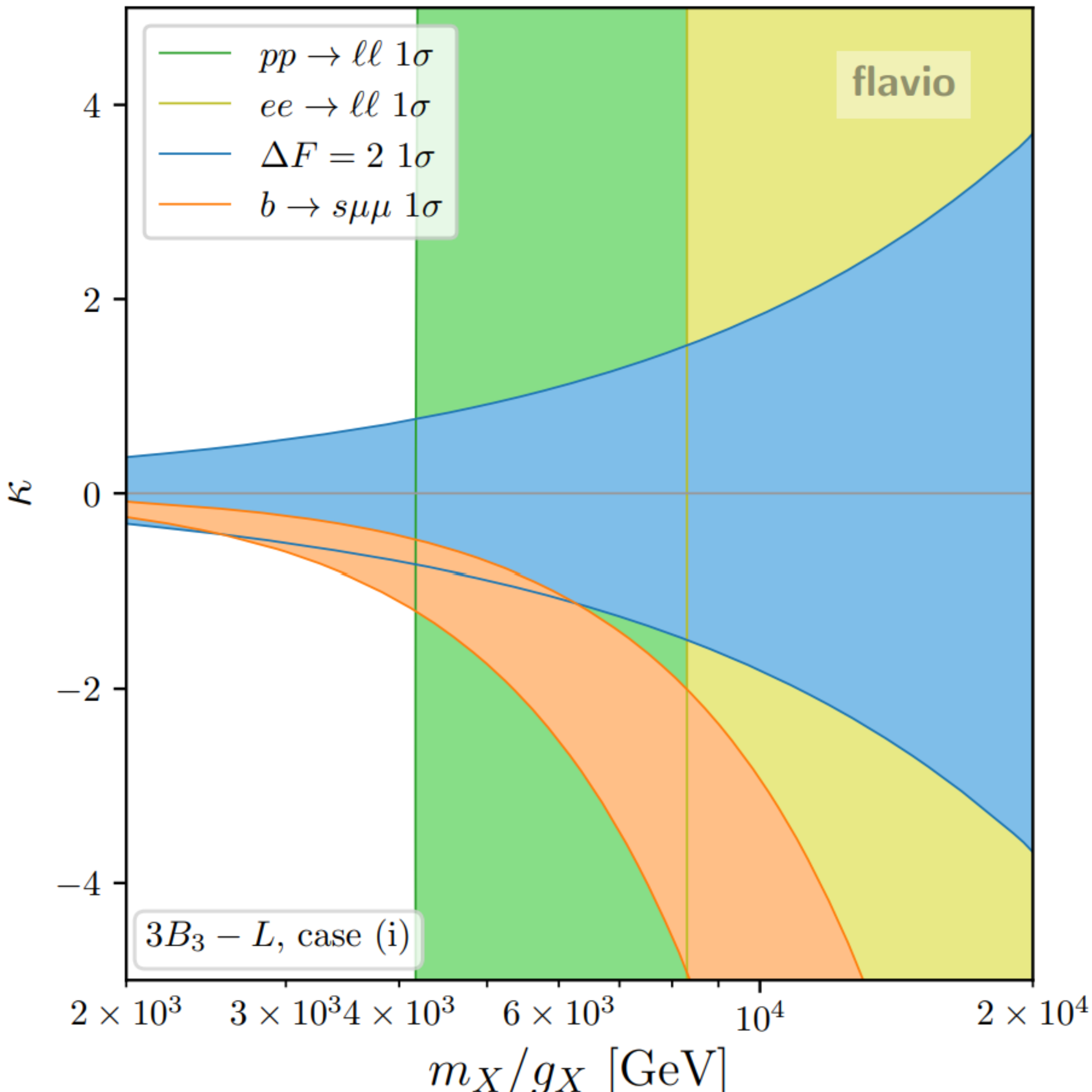
Fit θ_{sb} and $g_{Z'}/M_{Z'}$



4
0
-4
-8
-12
-16
-2
-1
0
1
2
$\chi^2-\chi^2_{SM}$
X_e/X_μ
LFU
LEP
global
quarks
95% CL


p-value
LEU
LEP
global
quarks
Xe/Xμ
value
10gZ'
-θsb
Xe/Xμ
pull
RK*(1.1,6)
RK*(0.045,1.1)
RK(0.045,1.1)
RK(1.1,6)
Xe/Xμ

$3B_3 - L$ model

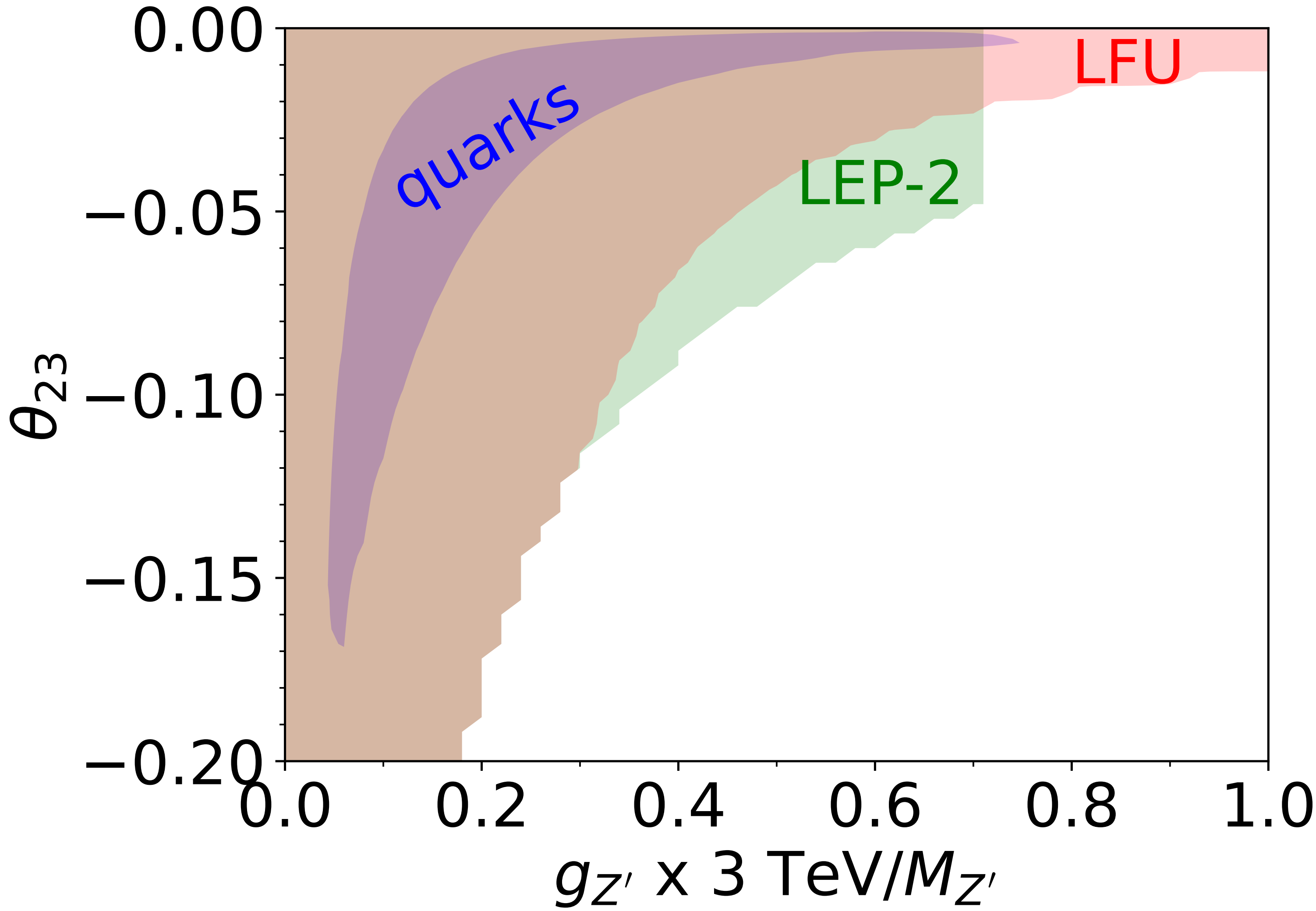


Greljo, Salko, Smolkovic, Stangl, 2212.10497

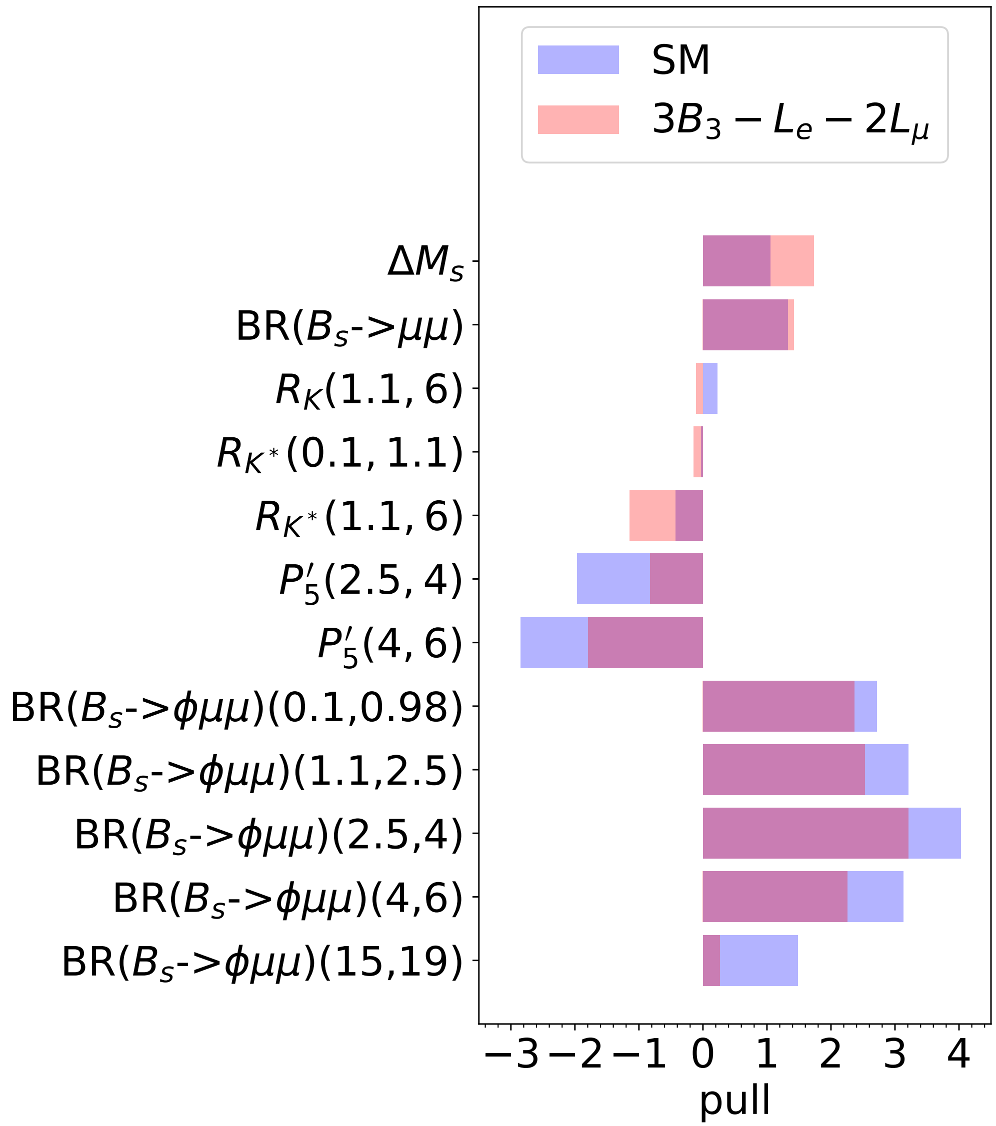
$3B_3 - L_e - 2L_\mu$ model

	$\chi^2 - \chi^2_{SM}$	p−value	measurement	pull
LFU	-0.2	.81	$R_{K^*}(0.045,\ 1.1)$	-0.1
LEP	-0.4	.58	$R_{K^*}(1.1,\ 6)$	-0.1
quarks	-14.6	.10	$R_K(0.045,\ 1.1)$	-0.3
global	-15.3	.27	$R_K(1.1,\ 6)$	-1.1

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

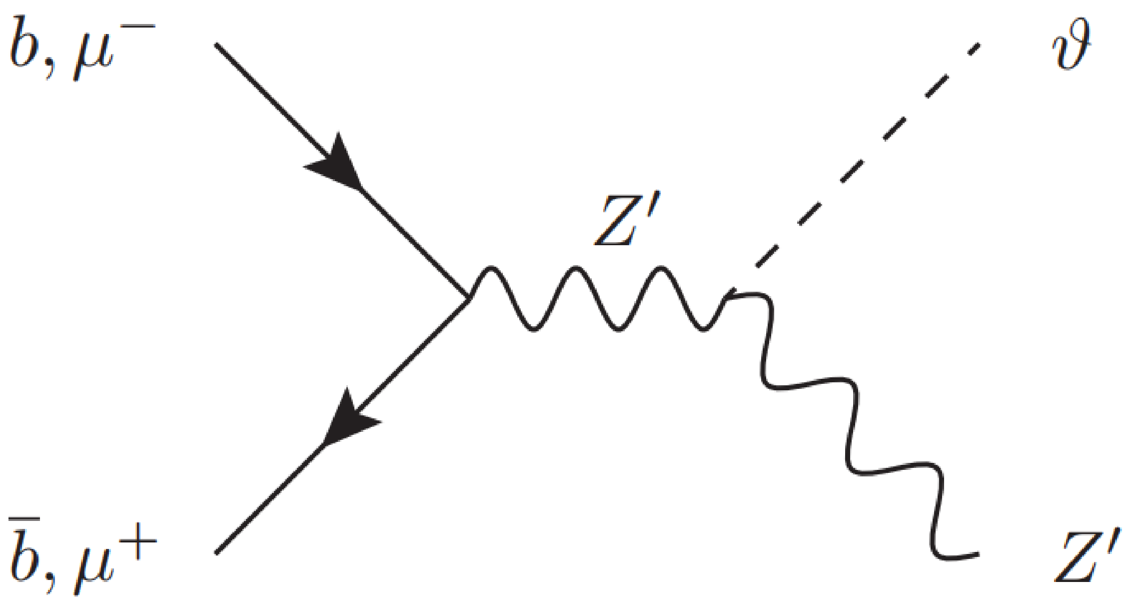


0.00
−0.05
−0.10
−0.15
−0.20
θ_{23}
0.0
0.2
0.4
0.6
0.8
1.0
$g_{Z'}$ x 3 TeV/$M_{Z'}$
quarks
LEP-2
LFU


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:

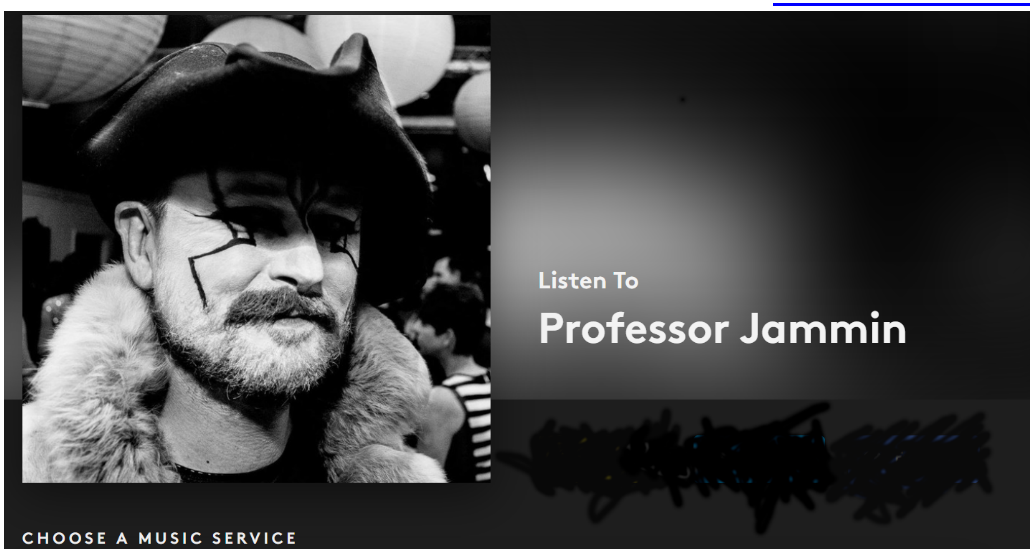


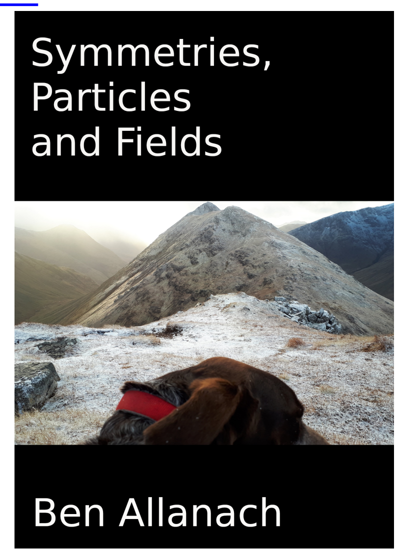
BCA, `2009.02197`; BCA, Loisa, `2212.07440`

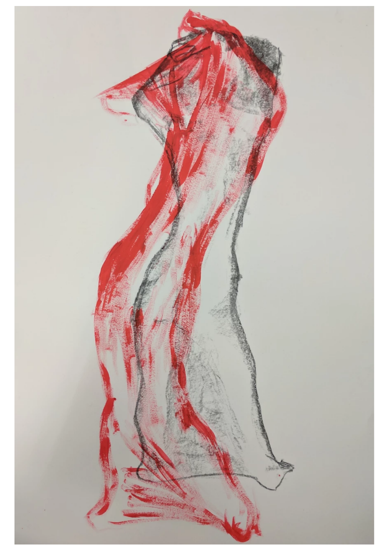
Epilogue

Remarkable that TeV-scale flavour symmetries are still allowed

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





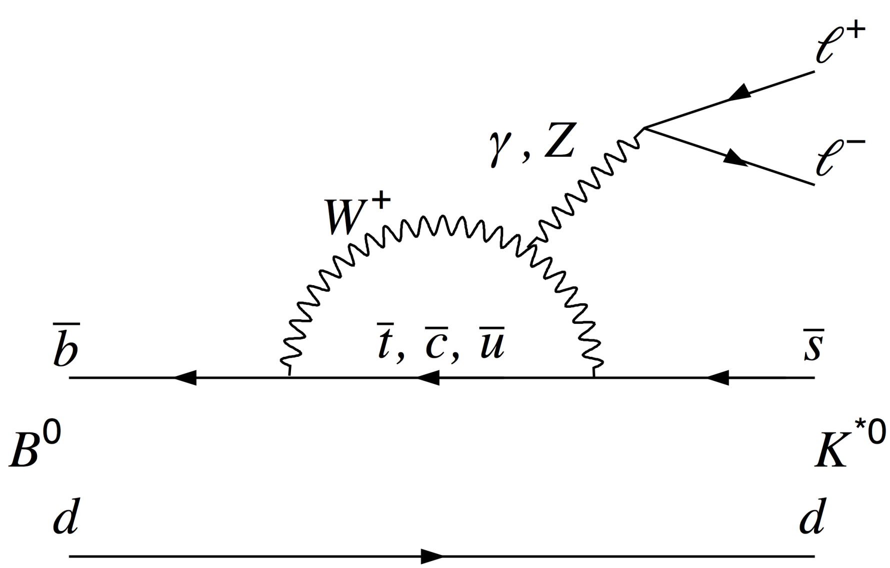


Backup

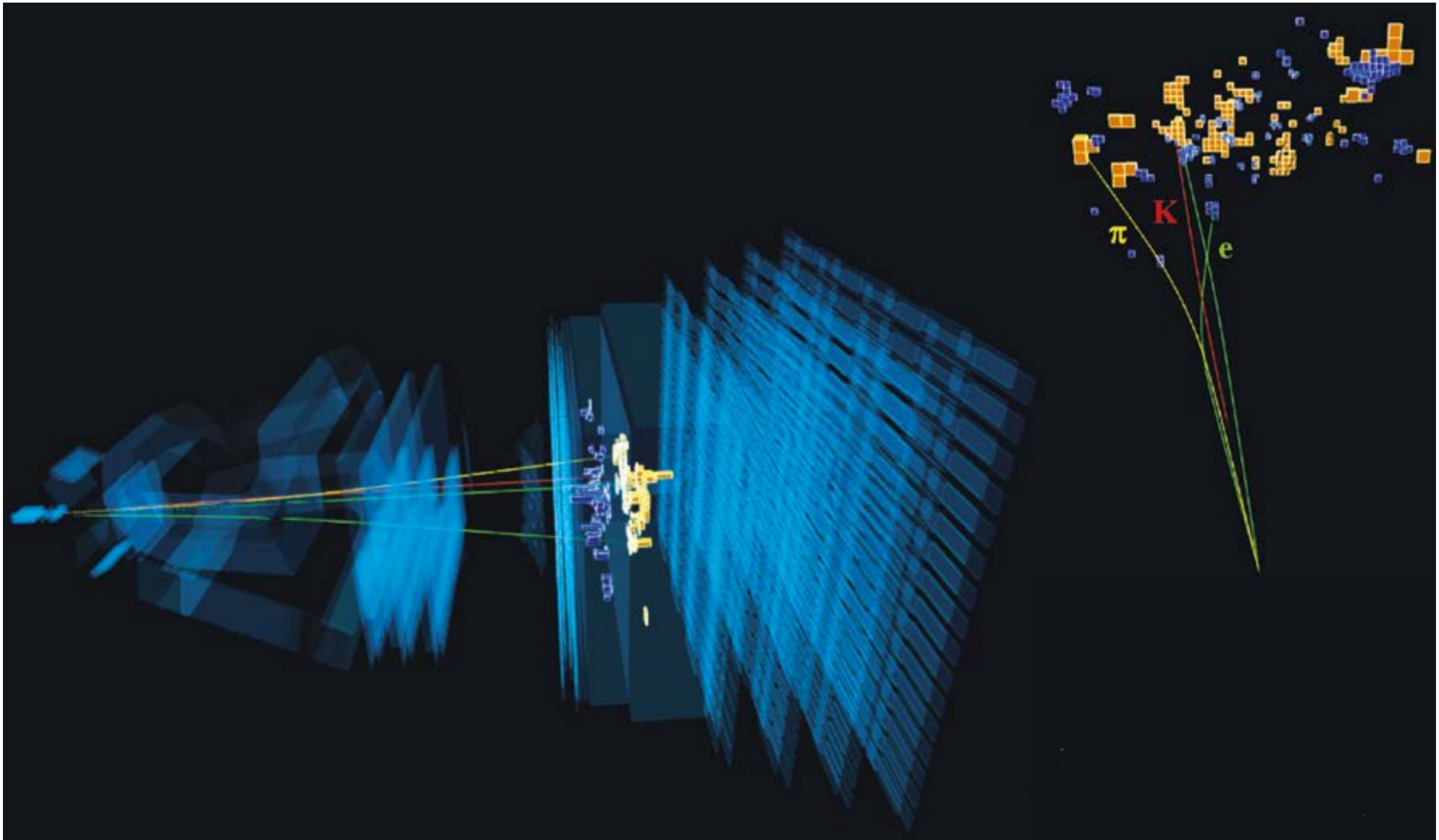
$b \to s l^+ l^-$ in Standard Model

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

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



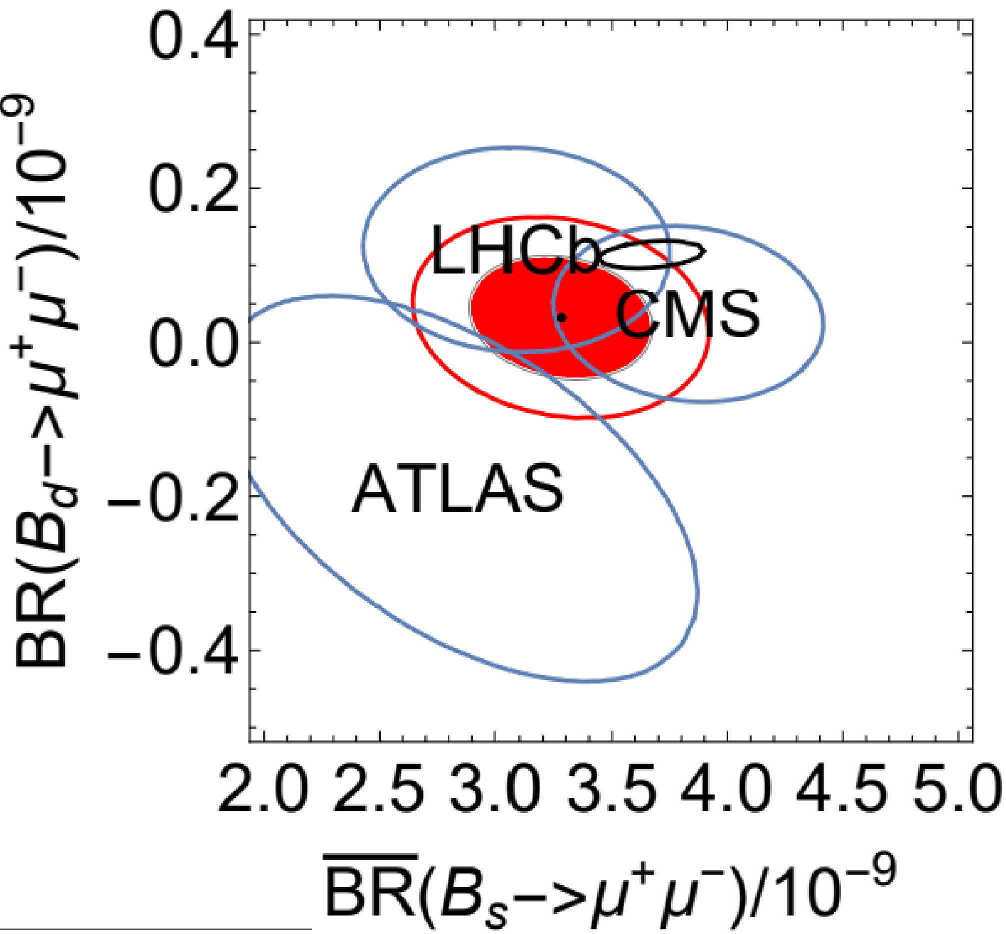
LHCb $B^0 \to K^{0*} e^+ e^-$ Event[3]



[3] Picture from CERN Courier April 2018

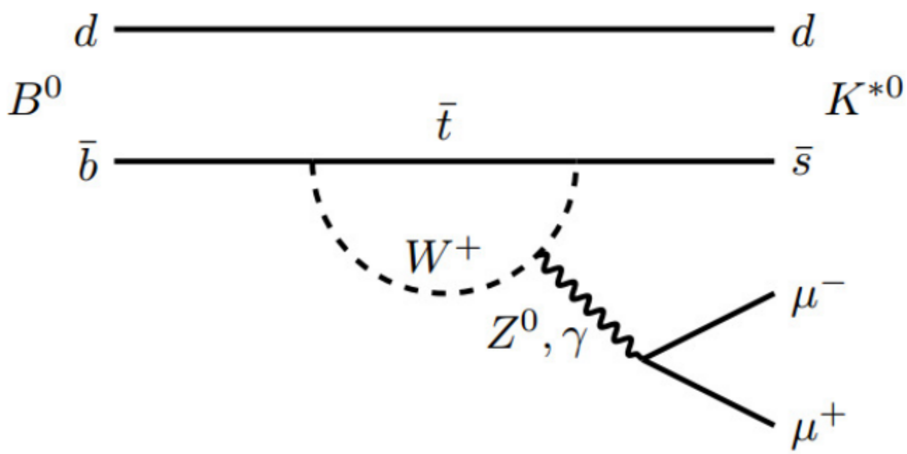
$BR(B_s \to \mu^+\mu^-)$:[4]: SM: 1.6σ

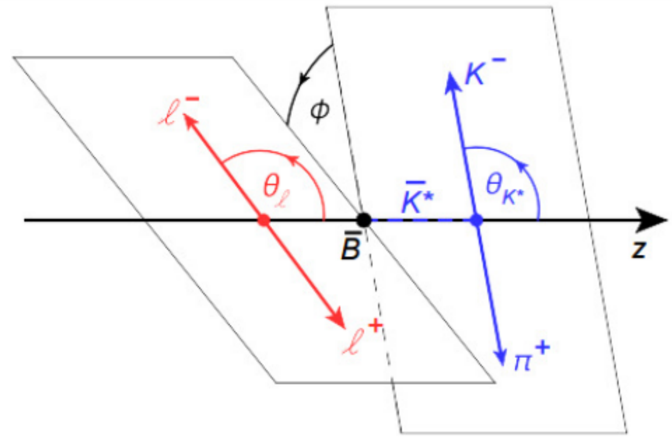
$B_s = (\bar{b}s)$, $B_d = (\bar{b}d)$



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

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

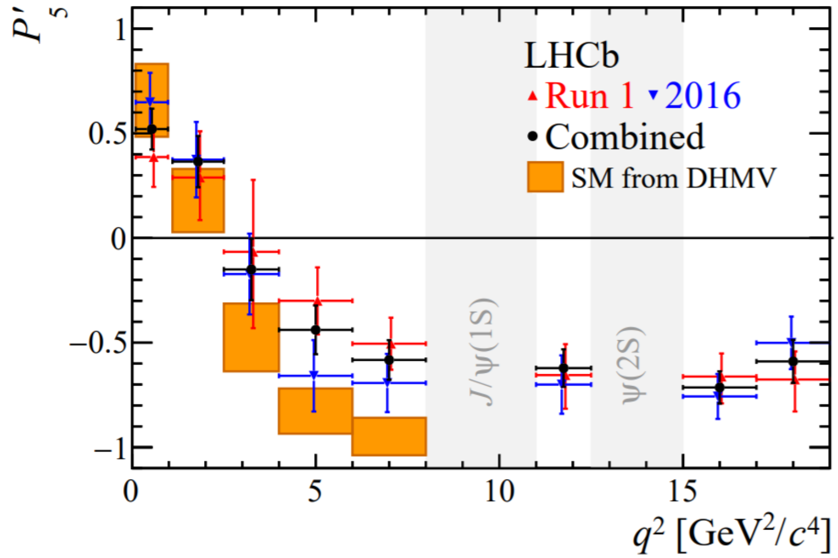


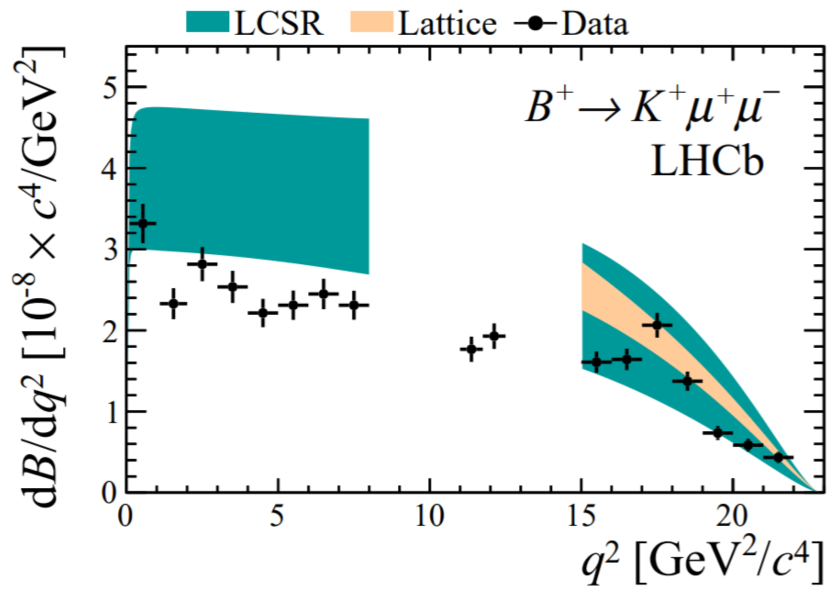


Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

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

P_5'

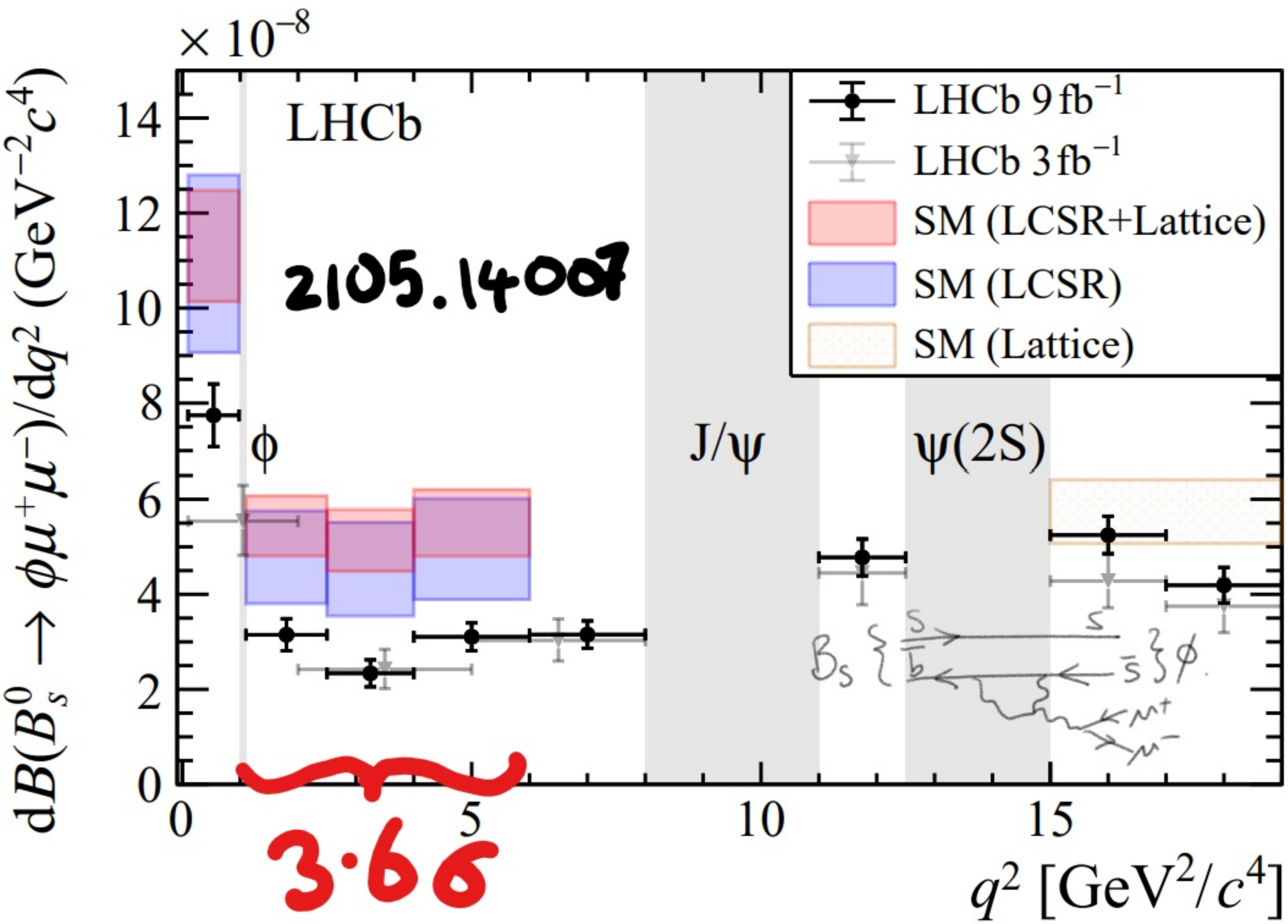




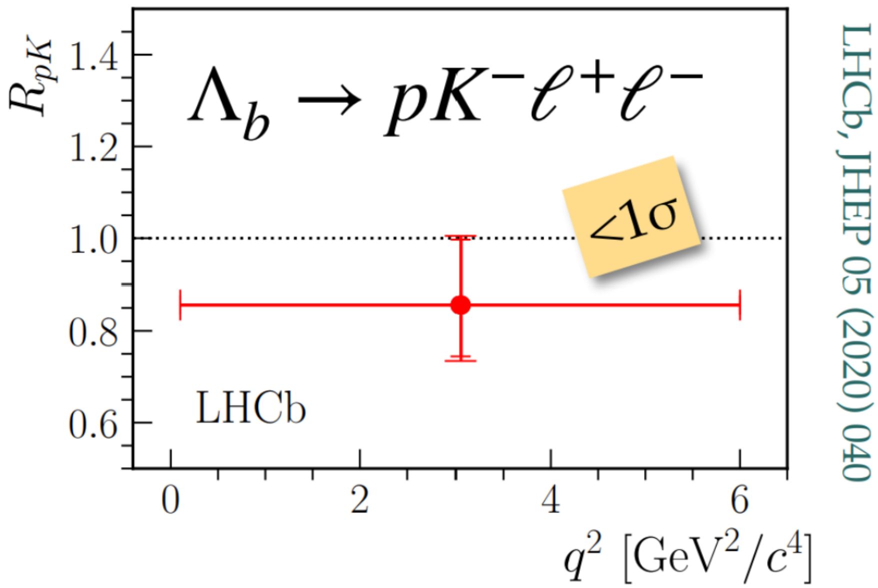
$P_5' = S_5/\sqrt{F_L(1-F_L)}$, leading form factor uncertainties cancel [5]

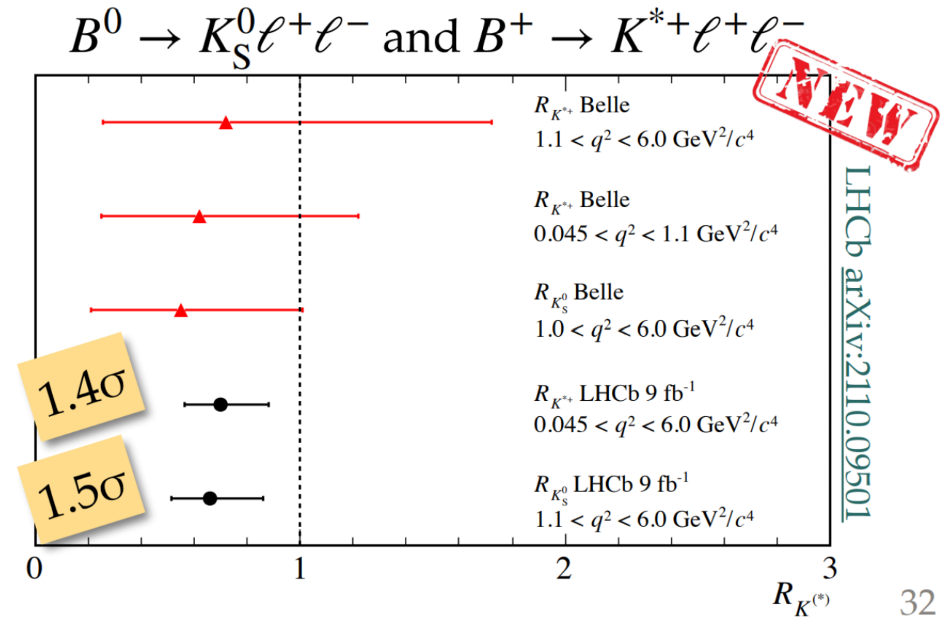
[5] LHCb, 2003.04831

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



Other LFU


R_{pK}
$\Lambda_b \to pK^-\ell^+\ell^-$
<1σ
LHCb
q^2 [GeV^2/c^4]
LHCb, JHEP 05 (2020) 040


$B^0 \to K^0_S\ell^+\ell^-$ and $B^+ \to K^{*+}\ell^+\ell^-$
NEW
$R_{K^{*+}}$ Belle
$1.1 < q^2 < 6.0$ GeV^2/c^4
$R_{K^{*+}}$ Belle
$0.045 < q^2 < 1.1$ GeV^2/c^4
$R_{K^0_S}$ Belle
$1.0 < q^2 < 6.0$ GeV^2/c^4
1.4σ
$R_{K^{*+}}$ LHCb 9 fb^{-1}
$0.045 < q^2 < 6.0$ GeV^2/c^4
1.5σ
$R_{K^0_S}$ LHCb 9 fb^{-1}
$1.1 < q^2 < 6.0$ GeV^2/c^4
$R_{K^{(*)}}$
LHCb arXiv:2110.09501
32

Trident Neutrino Process

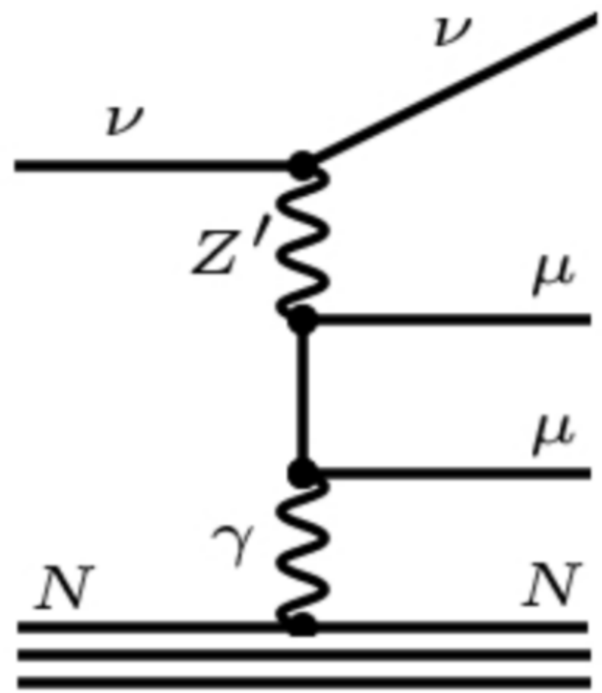
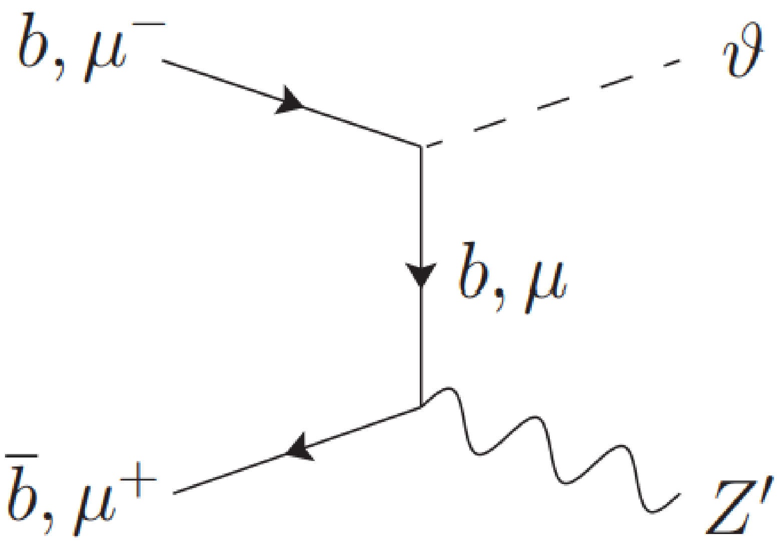
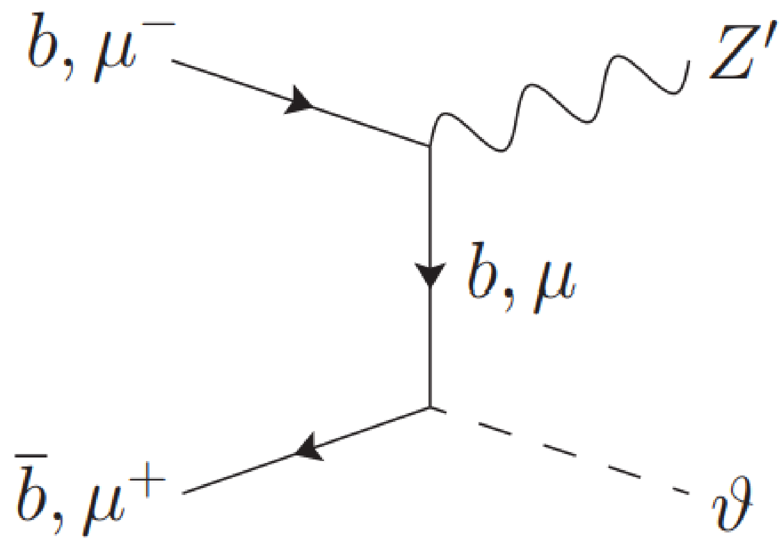


FIG. 10. Neutrino trident process that leads to constraints on the Z^{μ} coupling strength to neutrinos-muons, namely $M_{Z'}/g_{v\mu} \gtrsim 750$ GeV.

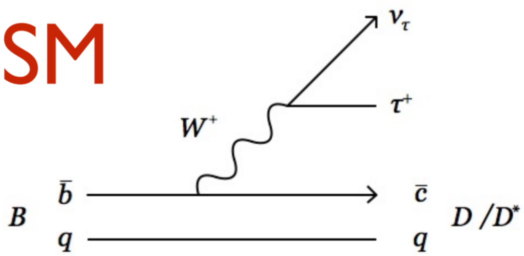
$t-$channel

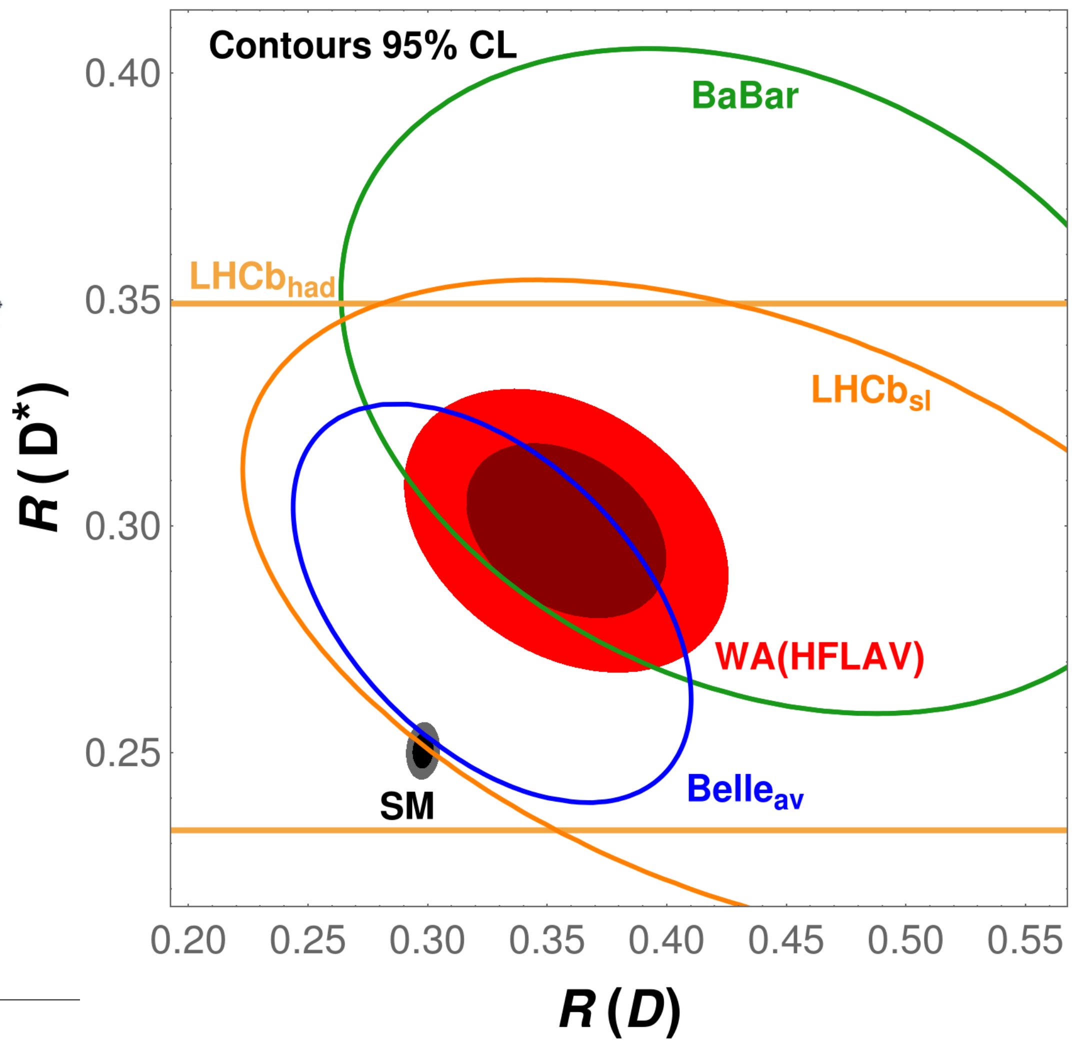




$$R_{D^{(*)}} = BR(B^- \to D^{(*)}\tau\nu)/BR(B^- \to D^{(*)}\mu\nu)$$ [6]

SM

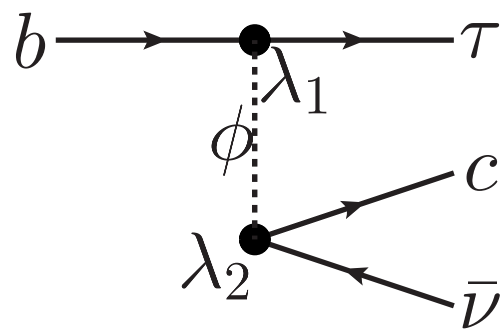


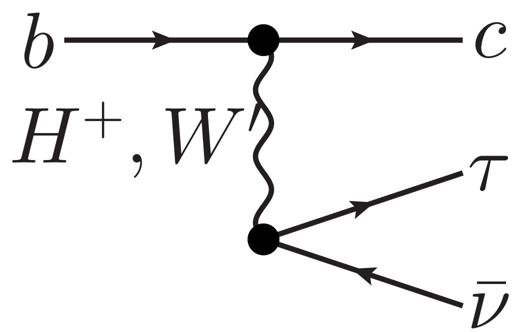


SM: 3.1σ

[6] Kind courtesy of M Jung

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





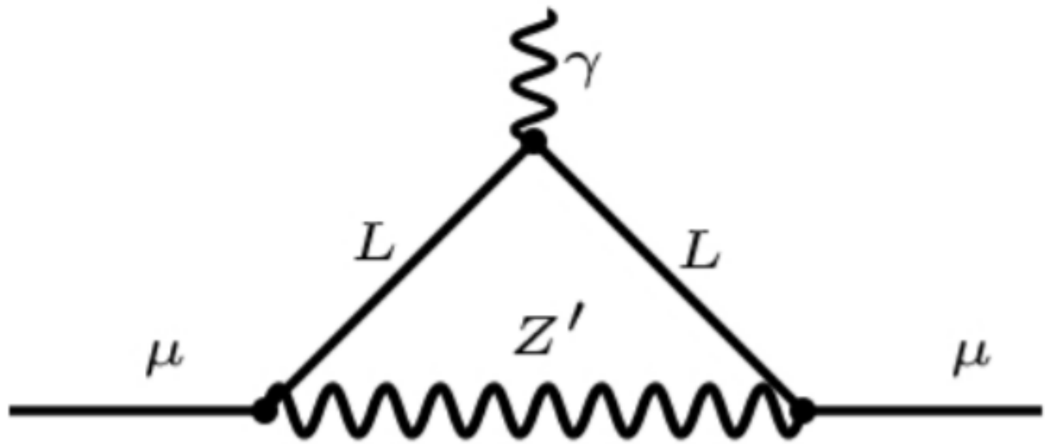
Make an effective theory with heavy BSM particle:

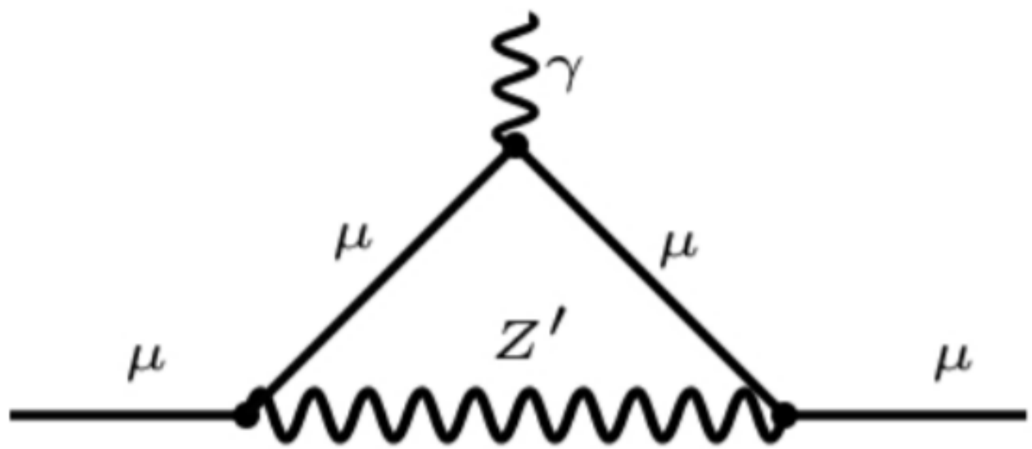
$$\mathcal{L}_{WET} = -\frac{2\lambda_1\lambda_2}{M^2}\left(\bar{c}\gamma^\mu P_L \nu\right)\left(\bar{\tau}\gamma_\mu P_L b\right) + H.c.$$

Fit to data tells us

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

$(g-2)_\mu$





$H\vartheta$ 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**

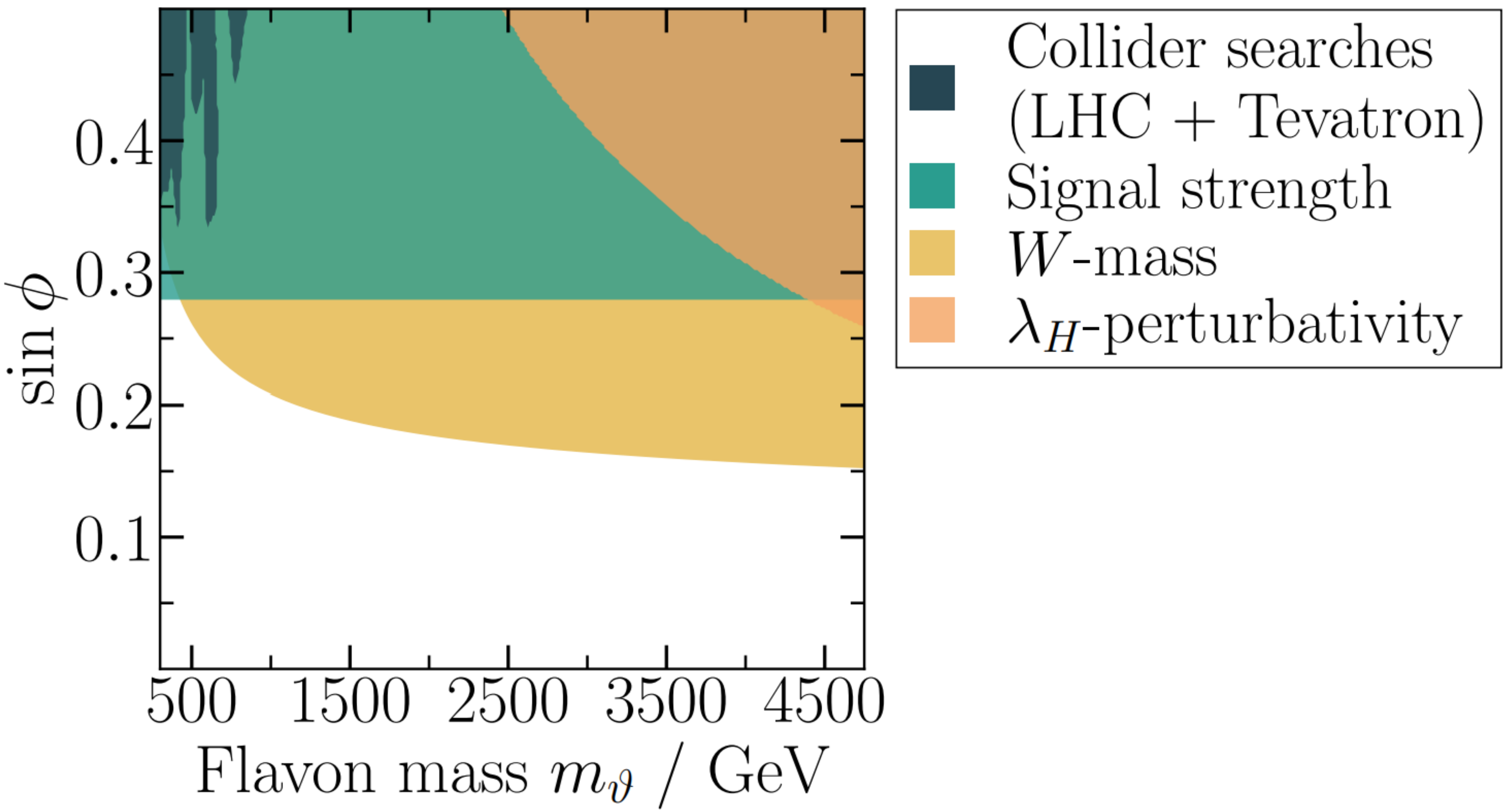
$$\begin{pmatrix} h \\ \vartheta \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} h' \\ \vartheta' \end{pmatrix}$$

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

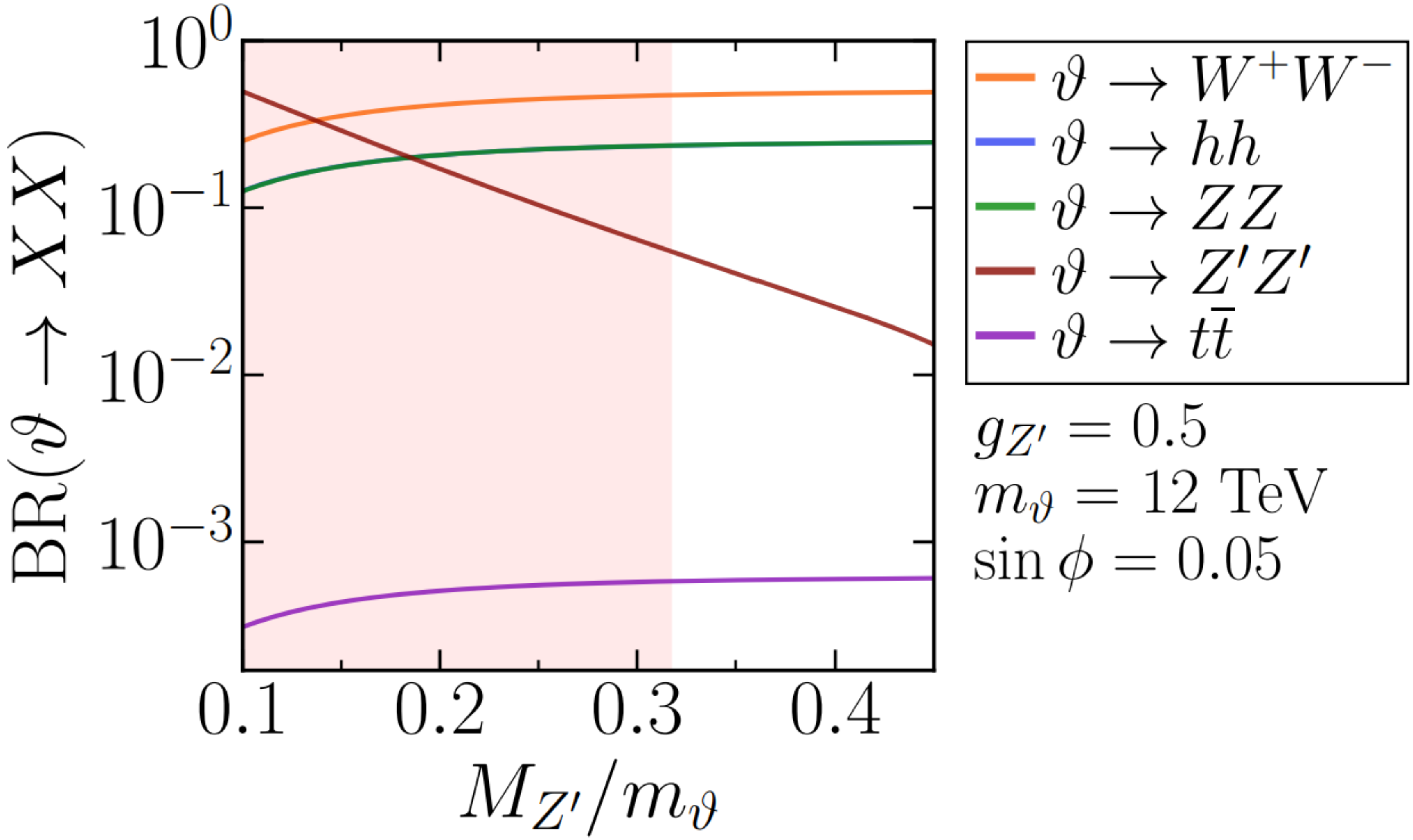
Three parameters: $v_\theta = M_{Z'}/g_{Z'}$, m_ϑ and ϕ.

Higgs Signal Strength

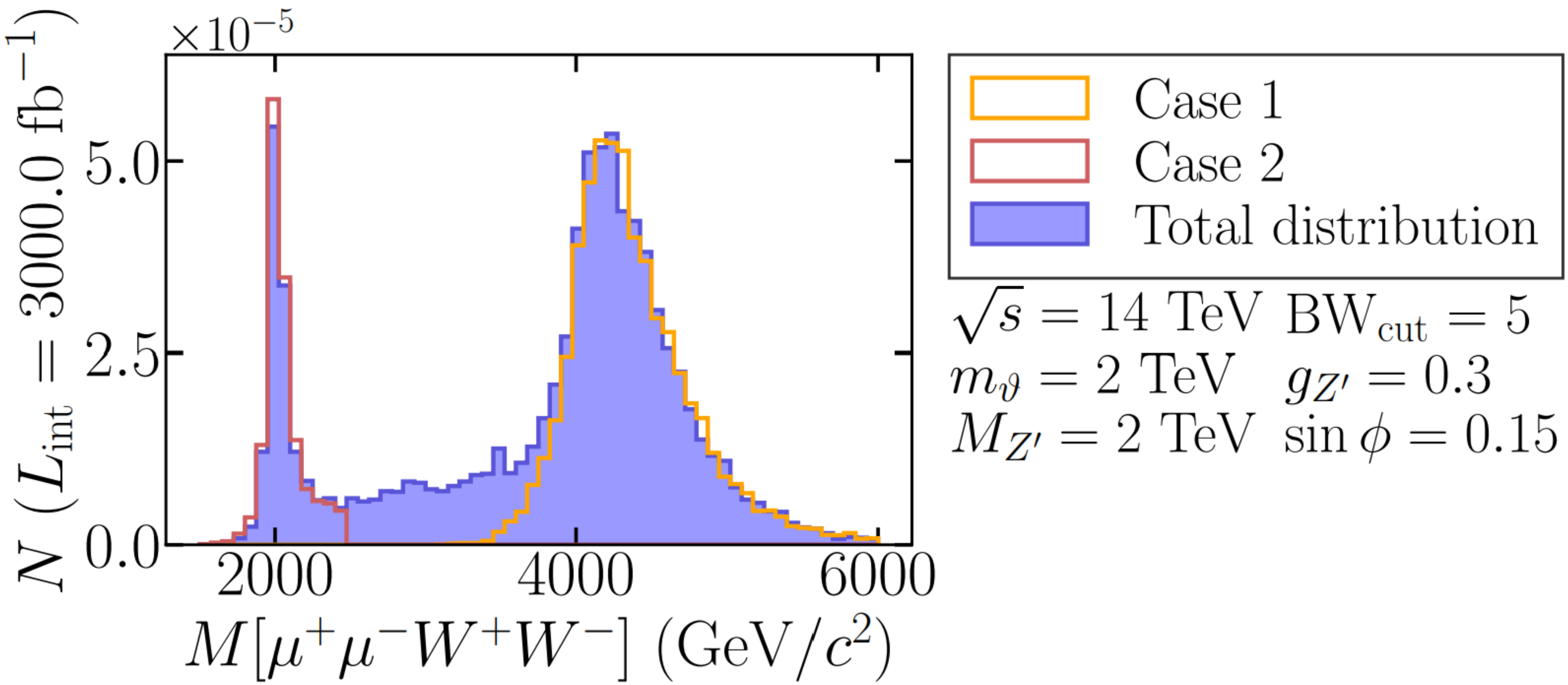
BCA, Loisa, 2212.07440



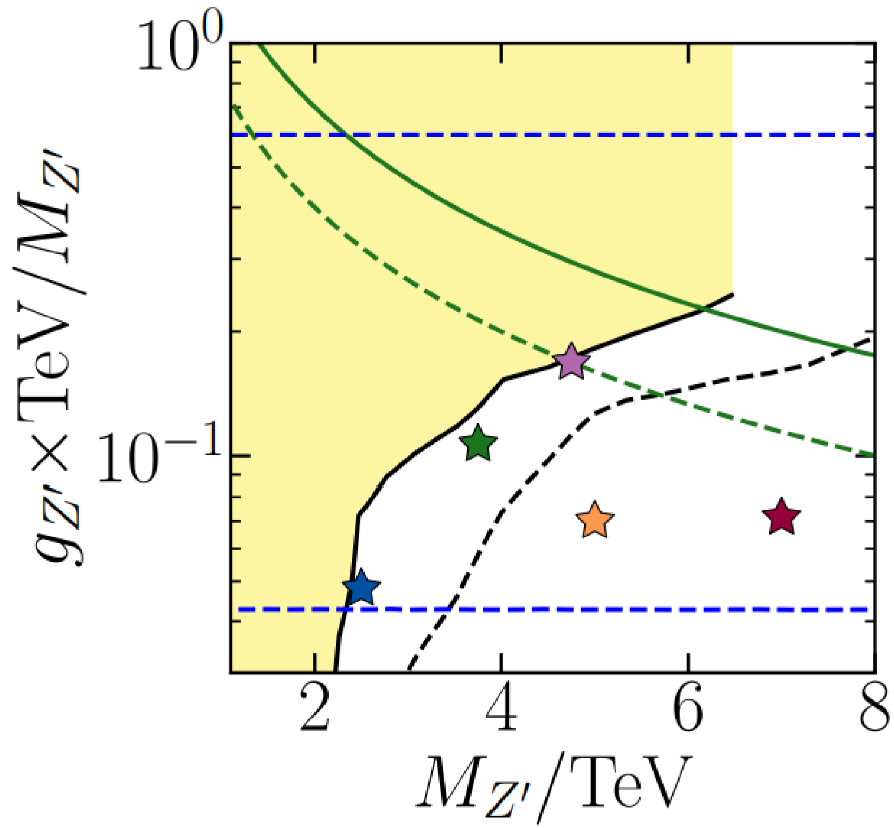
ϑ BRs

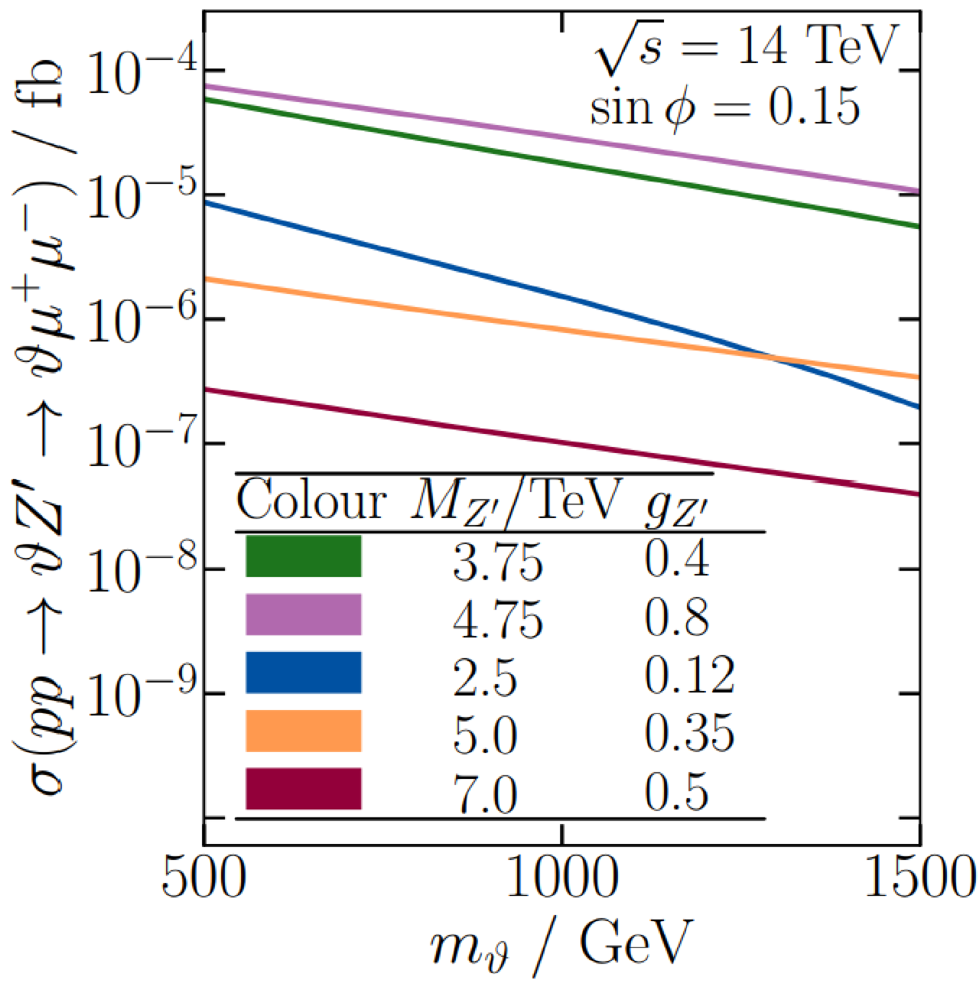


2 resonances



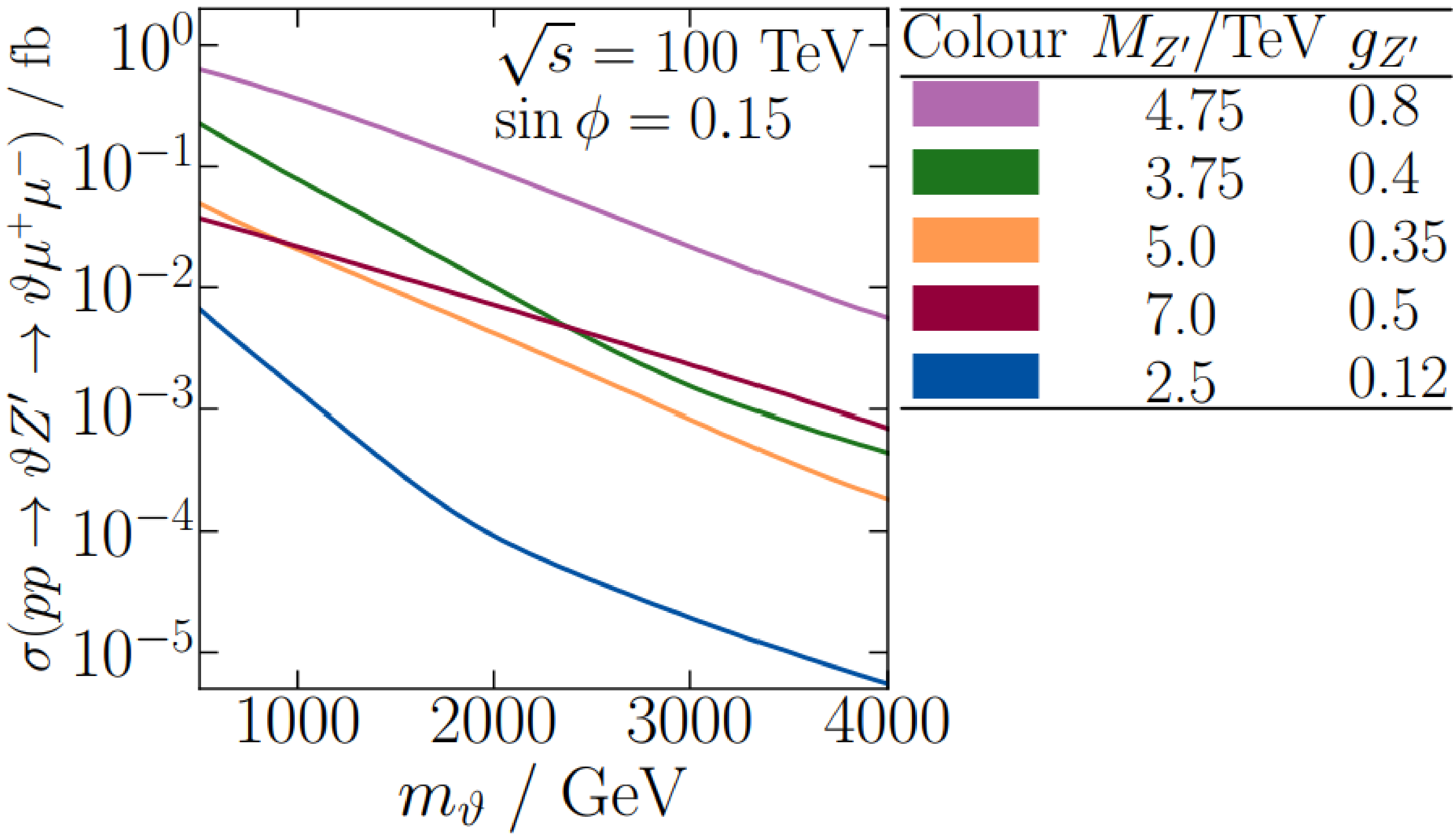
(HL-)LHC searches





No flavonstrahlung LHC

FCC Flavonstrahlung



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