The Rumble in the Meson

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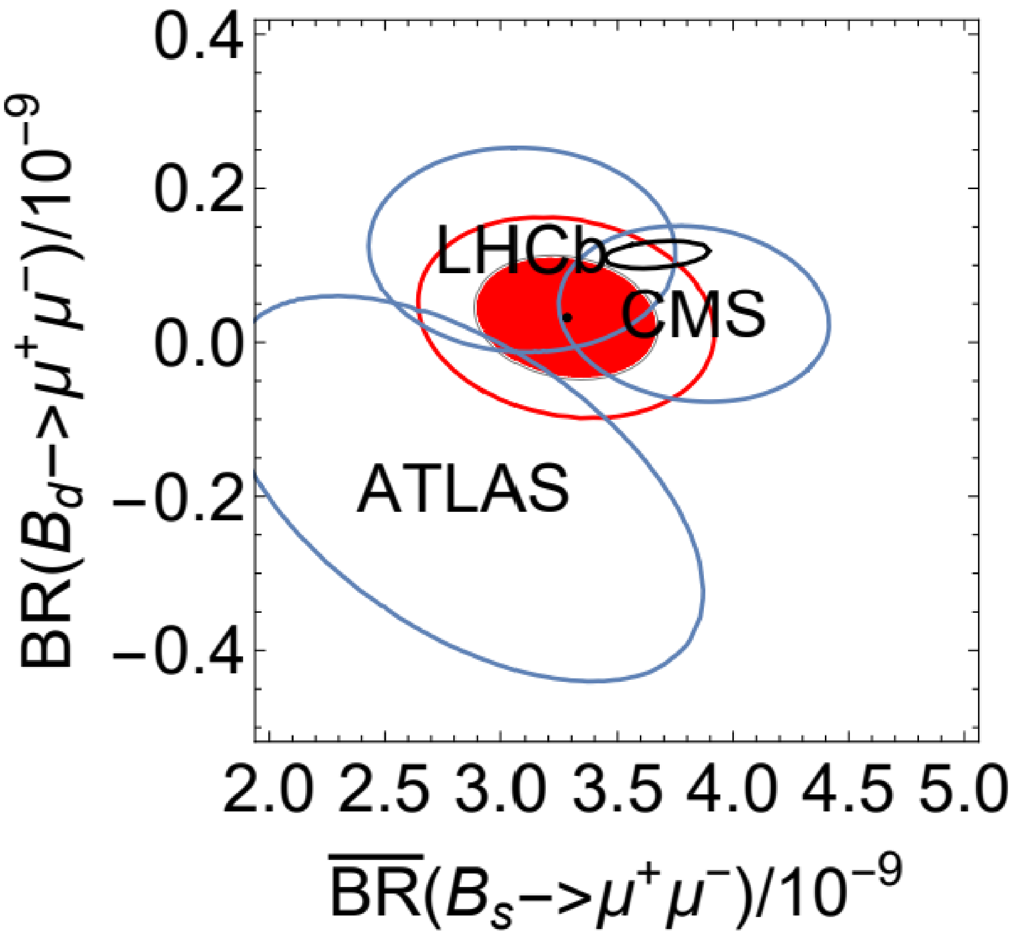
$b \to s\mu^+\mu^-$ anomalies

$B_3 - L_2$ Z'

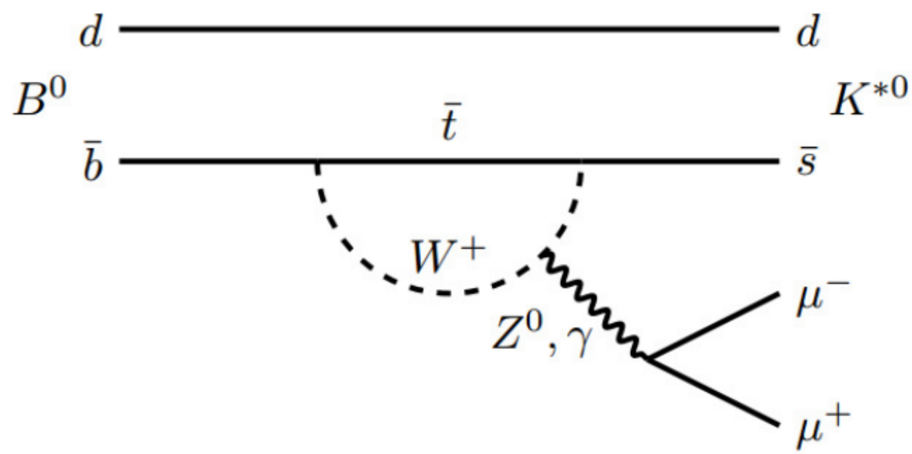
S_3 Leptoquark

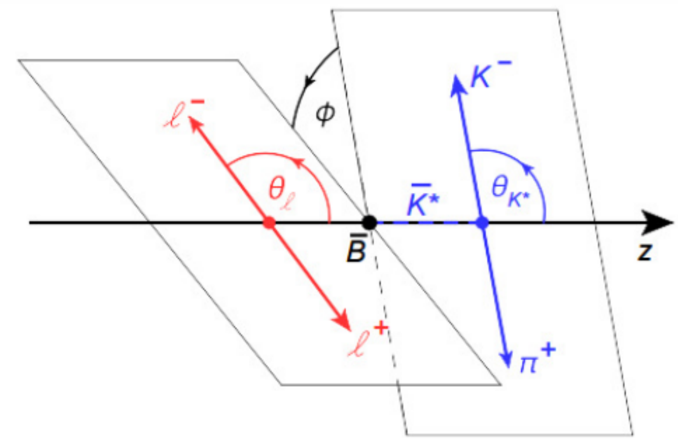
$BR(B_s \to \mu^+\mu^-)$:[1] $B_s = (\bar{b}s)$, $B^0 = (\bar{b}d)$



[1] BCA, Davighi, 2211.11766: SM: 1.6σ

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

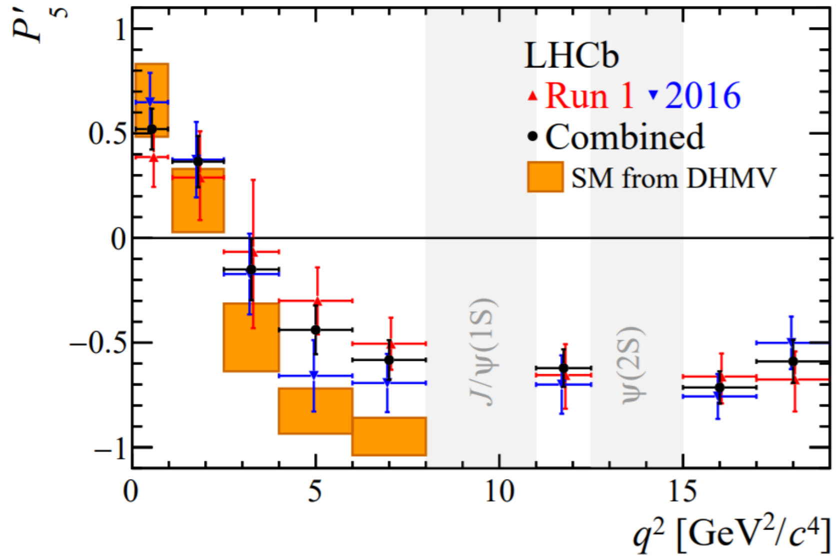


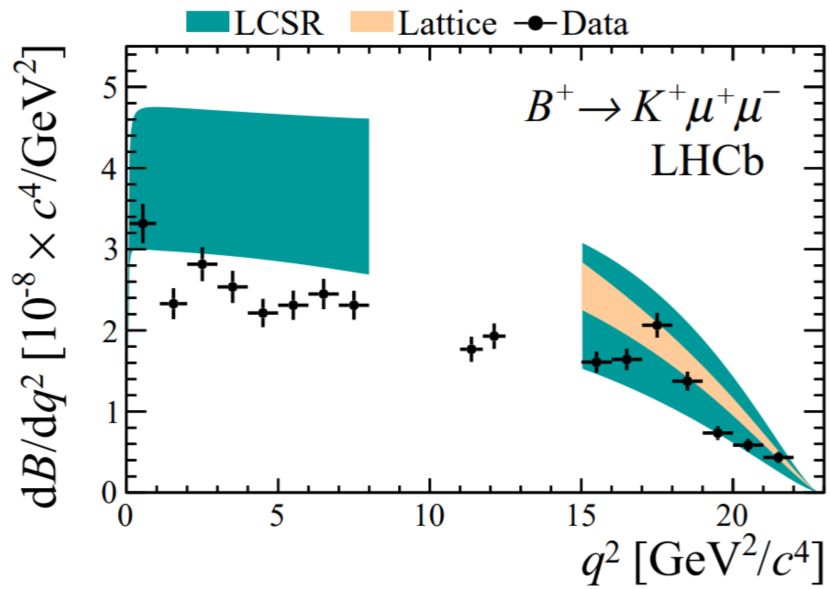


Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

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

P_5'

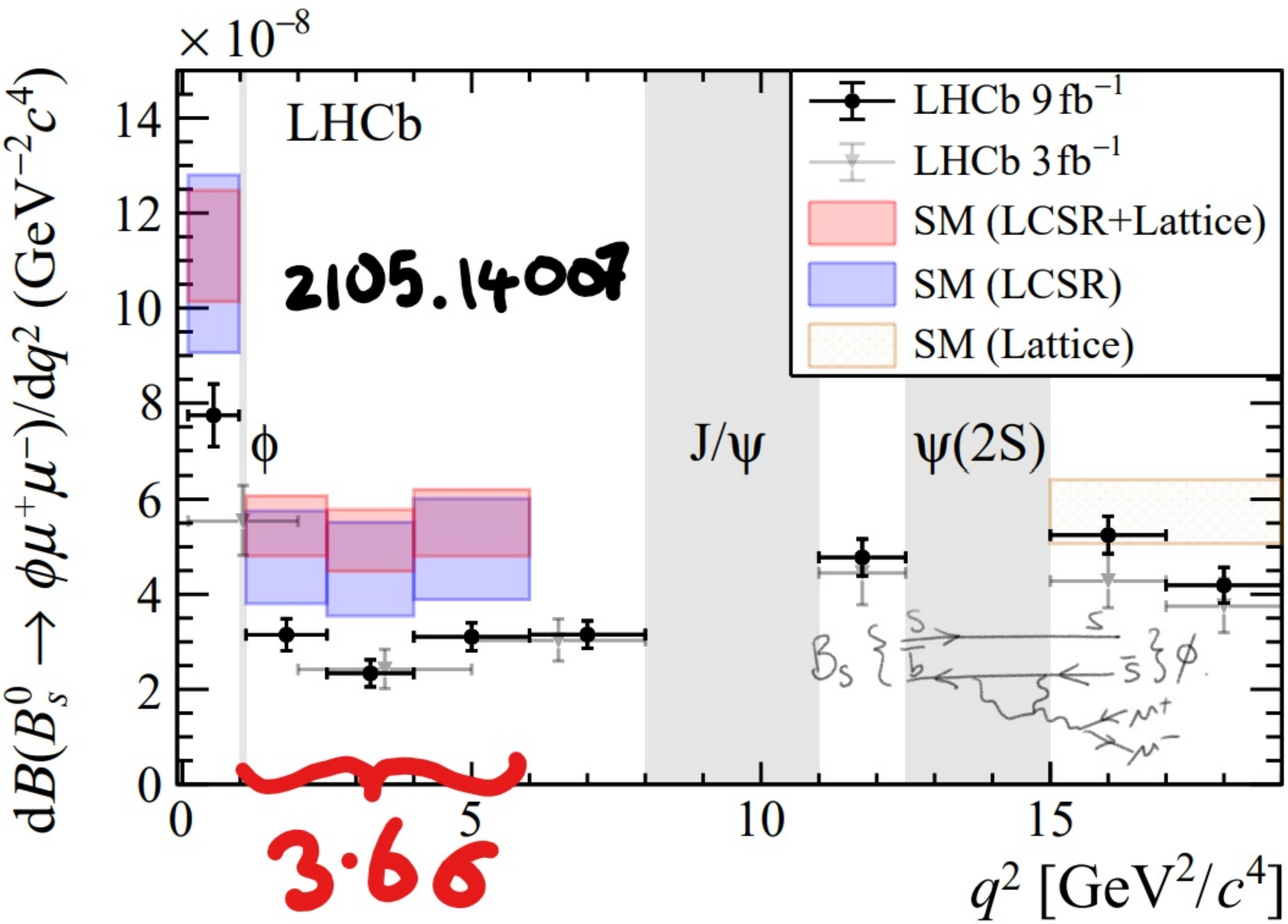




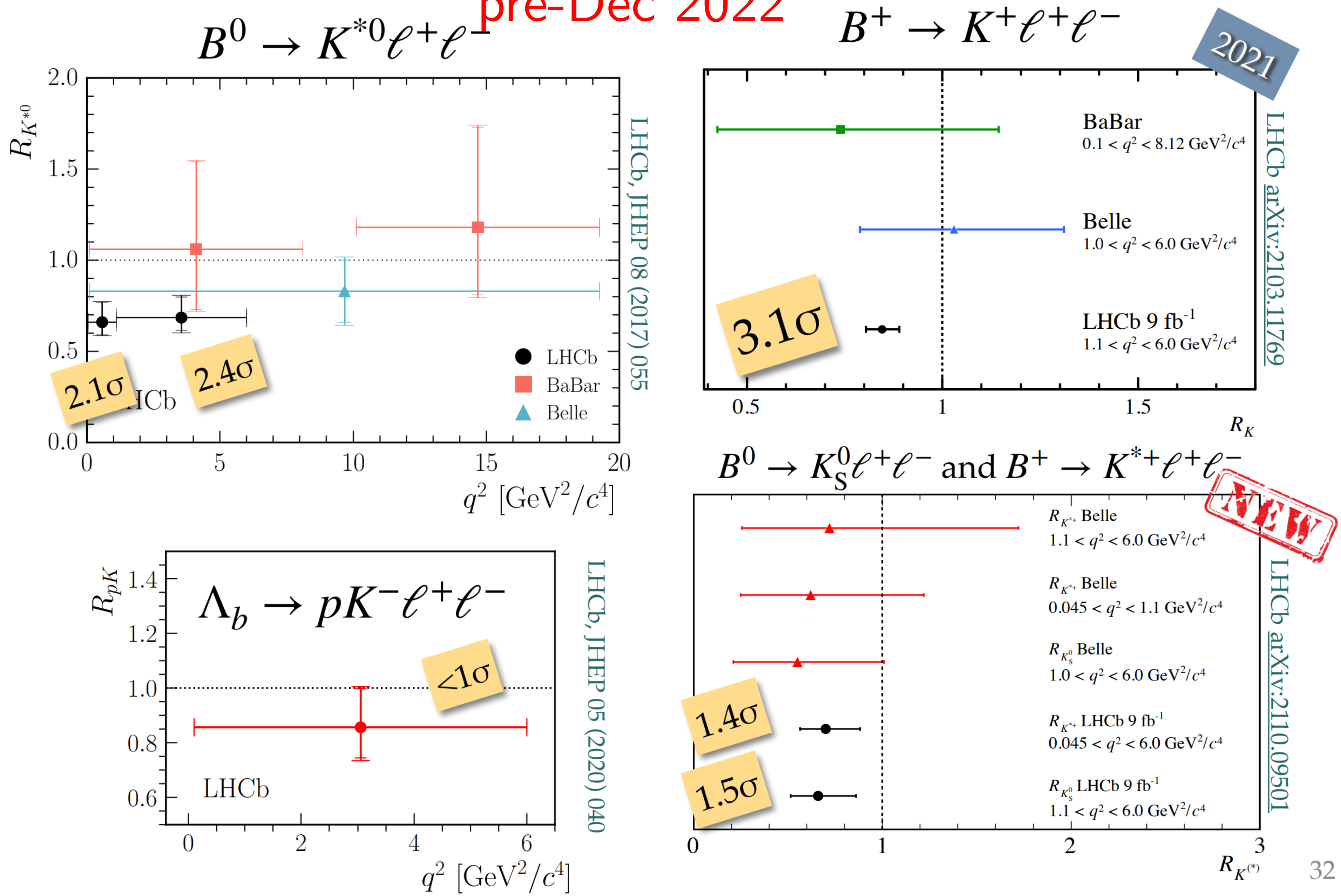
$P_5' = S_5/\sqrt{F_L(1-F_L)}$, leading form factor uncertainties cancel [2]

[2] LHCb, 2003.04831

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



pre-Dec 2022



Stolen from Capdevila et al, *Flavour Anomaly Workshop '21*

LHCb: 20/12/22

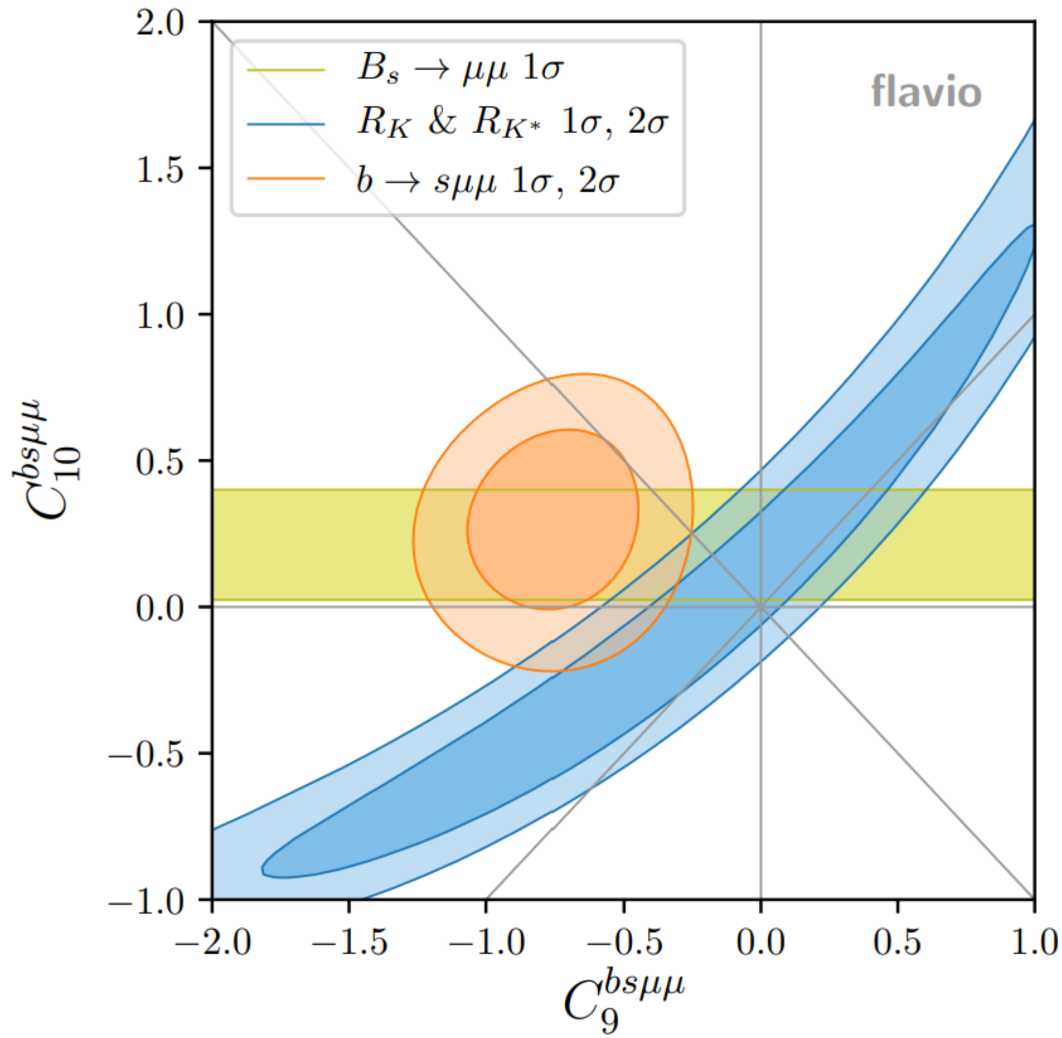
$$\text{low-}q^2 \begin{cases} R_K & = 0.994\ ^{+0.090}_{-0.082}\,(\text{stat})\,^{+0.029}_{-0.027}\,(\text{syst}), \\ R_{K^*} & = 0.927\ ^{+0.093}_{-0.087}\,(\text{stat})\,^{+0.036}_{-0.035}\,(\text{syst}), \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K & = 0.949\ ^{+0.042}_{-0.041}\,(\text{stat})\,^{+0.022}_{-0.022}\,(\text{syst}), \\ R_{K^*} & = 1.027\ ^{+0.072}_{-0.068}\,(\text{stat})\,^{+0.027}_{-0.026}\,(\text{syst}). \end{cases}$$

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

LHCb `2212.09152`: evidence for lepton flavour universality violation has *gone away*; `smelli2.3.2`:

category	n_{obs}	χ^2_{SM}	p	s/σ
'quarks'	224	**262.9** 259.1 (261.2)	**.038** .054 (.044)	**2.1** 2.0 (2.0)
'LFU'	23	**17.1** 39.4 (39.4)	**.80** .018 (.018)	**0.2** 2.4 (2.4)
combined	247	**280.0** 298.5 (300.7)	**.073** .014 (.011)	**1.8** 2.5 (2.5)



Greljo, Salko, Smolkovic, Stangl, 2212.10497

$$\mathcal{L} = N(\bar{s}\gamma^\alpha P_L b)\left[C_9(\bar{\mu}\gamma_\alpha\mu) + C_{10}(\bar{\mu}\gamma_\alpha\gamma_5\mu)\right]$$

Theory: uncertainties

	parametric	form factors	non-local MEs
$BR(B \to Mll)$	yes	large	large
angular	no	small	large
$BR(B_s \to ll)$	yes	small	no
LFU	no	tiny	no

Parametric uncertainties easy

Large theory uncertainties[3] are taken into account

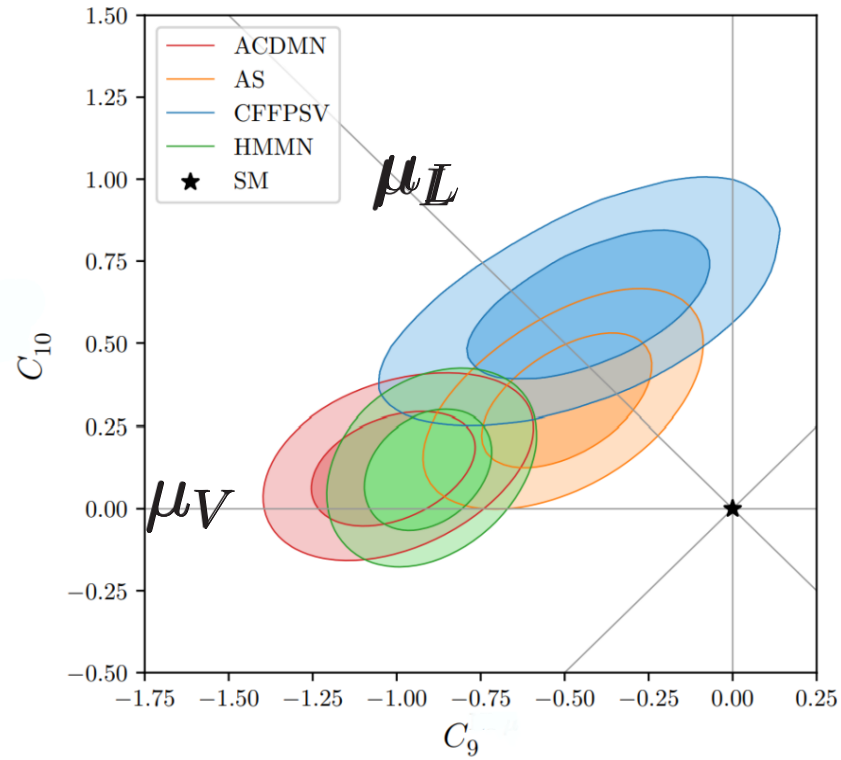
[3] Gubernari, Reboud, van Dyk, Virto 2206.03797

Neutral Current Fits

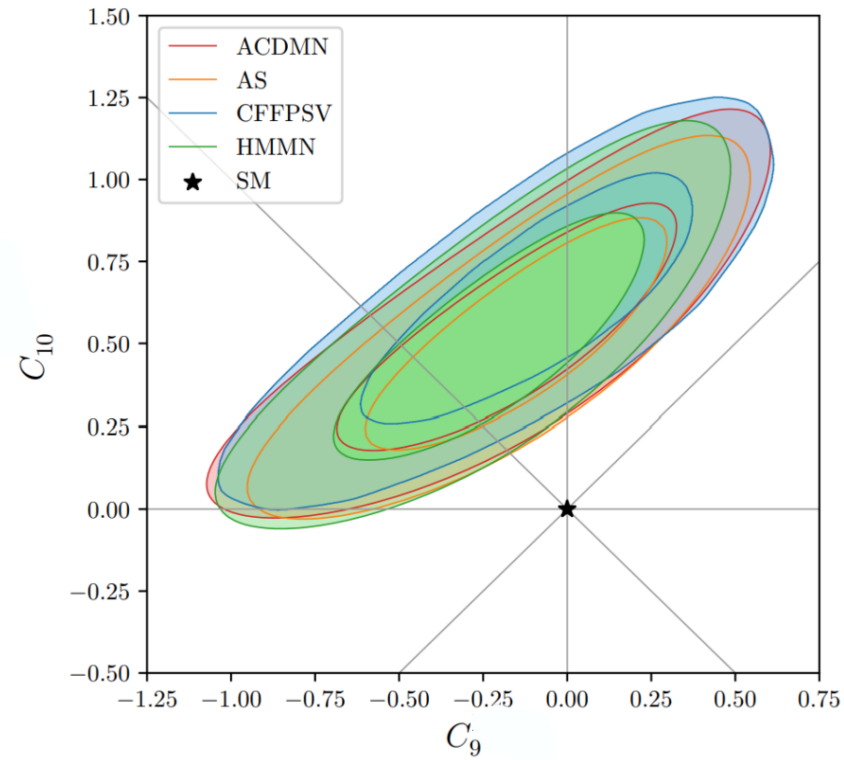
Alguero *et al*, 2104.08921; Altmannshofer, Stangl, flavio 2103.13370

Ciuchini *et al*, HEPfit 2011.01212; Hurth *et al*, superIso 2104.10058;

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



global fit



fit to LFU observables + $B_s \to \mu\mu$

Simple Z' Model

SM-singlet scalar 'flavon' $\theta_{X\neq 0}$

Additional $U(1)_X$ gauge symmetry broken by $\langle\theta\rangle$ ~TeV

SM+$3\nu_R$ fermion content

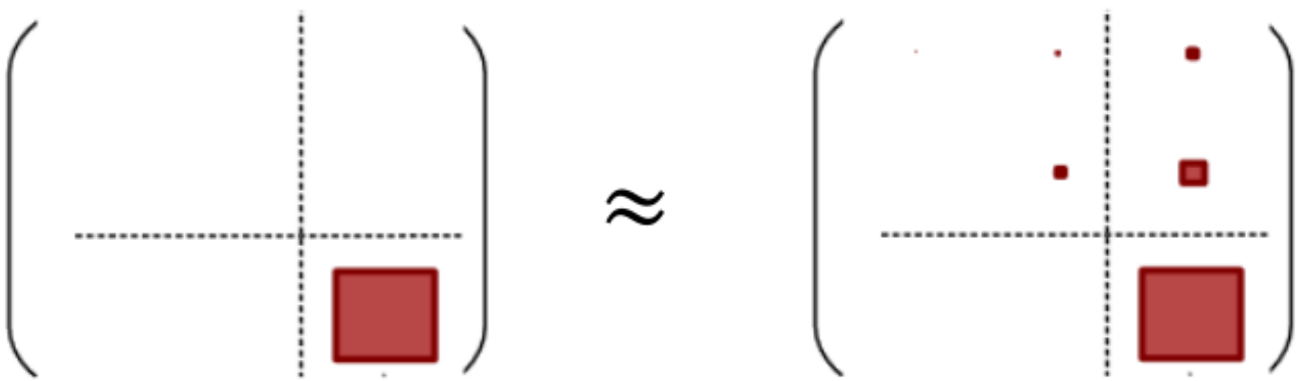
Zero X charges for first two generations of quark, electrons and taus

Postdicts heavy third family quarks[4]

[4] $X = B_3 - L_2$: Bonilla *et al*, 1705.00915; Alonso *et al* 1705.03858, BCA 2009.02197 (*simplified EFT*)

Flavour problem

$$\mathcal{L}_q = Y_t \overline{Q_{3\,L}'} H t_R' + Y_b \overline{Q_{3\,L}'} H^c b_R' + H.c.,$$



Postdicts small CKM angles

$$\mathcal{L}_{X\psi} = g_X \Big(\overline{\mathbf{u_L}} \Lambda^{(u_L)} \not{Z}' \mathbf{u_L} + \overline{\mathbf{u_R}} \Lambda^{(u_R)} \not{Z}' \mathbf{u_R}$$
$$+ \overline{\mathbf{d_L}} \Lambda^{(d_L)} \not{Z}' \mathbf{d_L} + \overline{\mathbf{d_R}} \Lambda^{(d_R)} \not{Z}' \mathbf{d_R}$$
$$-3 \overline{\mathbf{e_L}} \Lambda^{(e_L)} \not{Z}' \mathbf{e_L} - 3 \overline{\mathbf{e_R}} \Lambda^{(e_R)} \not{Z}' \mathbf{e_R}$$
$$-3 \overline{\boldsymbol{\nu}_L} \Lambda^{(\nu_L)} \not{Z}' \boldsymbol{\nu}_L - 3 \overline{\boldsymbol{\nu}_R} \Lambda^{(\nu_R)} \not{Z}' \boldsymbol{\nu}_R \Big),$$

$$\Lambda^{(I)} \equiv V_I^\dagger \xi V_I, \qquad \xi = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

A simple limiting case

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

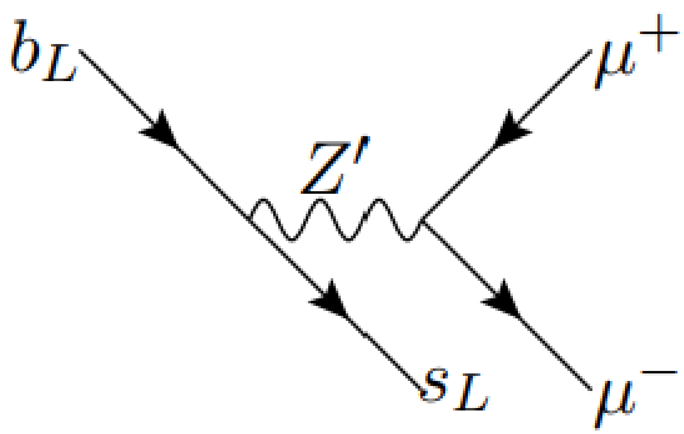
$$V_{d_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & -\sin\theta_{23} \\ 0 & \sin\theta_{23} & \cos\theta_{23} \end{pmatrix}, \qquad V_{e_{L,R}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

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

Important Z' Couplings

$$g_X \left[(\overline{d_L}\ \overline{s_L}\ \overline{b_L}) \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin^2\theta_{23} & \frac{1}{2}\sin 2\theta_{23} \\ 0 & \frac{1}{2}\sin 2\theta_{23} & \cos^2\theta_{23} \end{pmatrix} \not{Z}' \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} \right.$$

$$\left. -3(\overline{e}\ \overline{\mu}\ \overline{\tau}) \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \not{Z}' \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} \right]$$

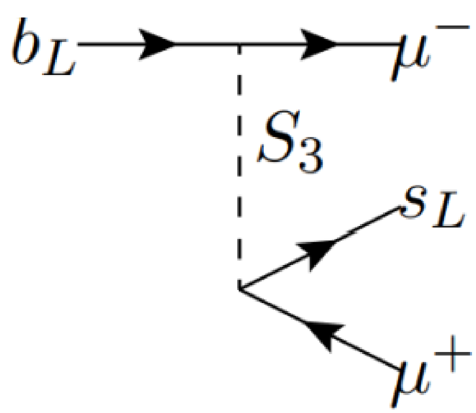


– LFU Violating, $C_9 \neq 0$

S_3 Leptoquark Model

TeV scale Scalar[5] $S_3 = (\bar{3},\ 3,\ 1/3)$:

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

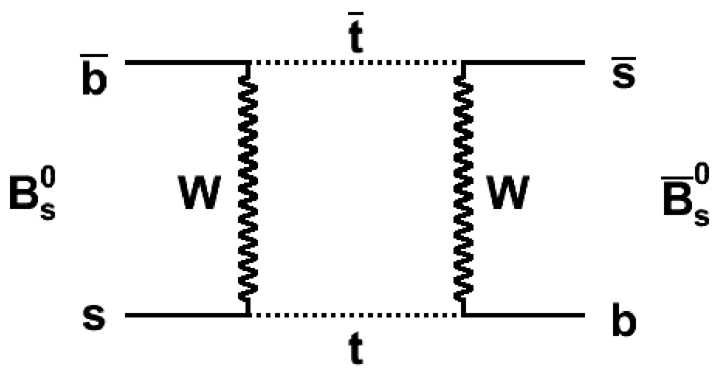


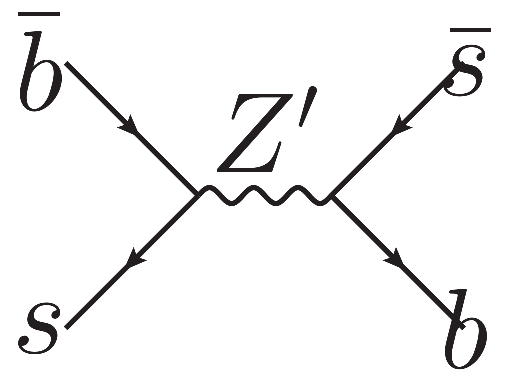
$$C_9 = -C_{10}$$

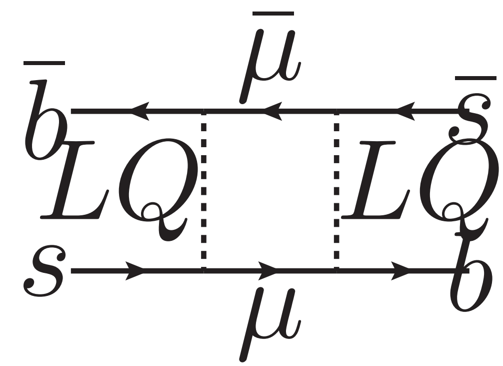
[5] Capdevila *et al* 1704.05340, Hiller and Hisandzic 1704.05444, D'Amico *et al* 1704.05438

$B_s - \bar{B}_s$ 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[6].

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

Best fits BCA, Davighi, 2211.11766

Dec 2022 $R_{K^{(*)}}$ [7]

S_3 model	χ^2	n	p	$s\sqrt{\lvert\Delta\chi^2\rvert}$
quarks	247.3	224	.14	3.9
LFU	19.7	23	.66	-1.6
global	267.0	247	.16	3.6

Z' model	χ^2	n	p	$s\sqrt{\lvert\Delta\chi^2\rvert}$
quarks	249.1	224	.12	3.7
LFU	18.2	23	.75	-1.0
global	267.4	247	.16	3.6

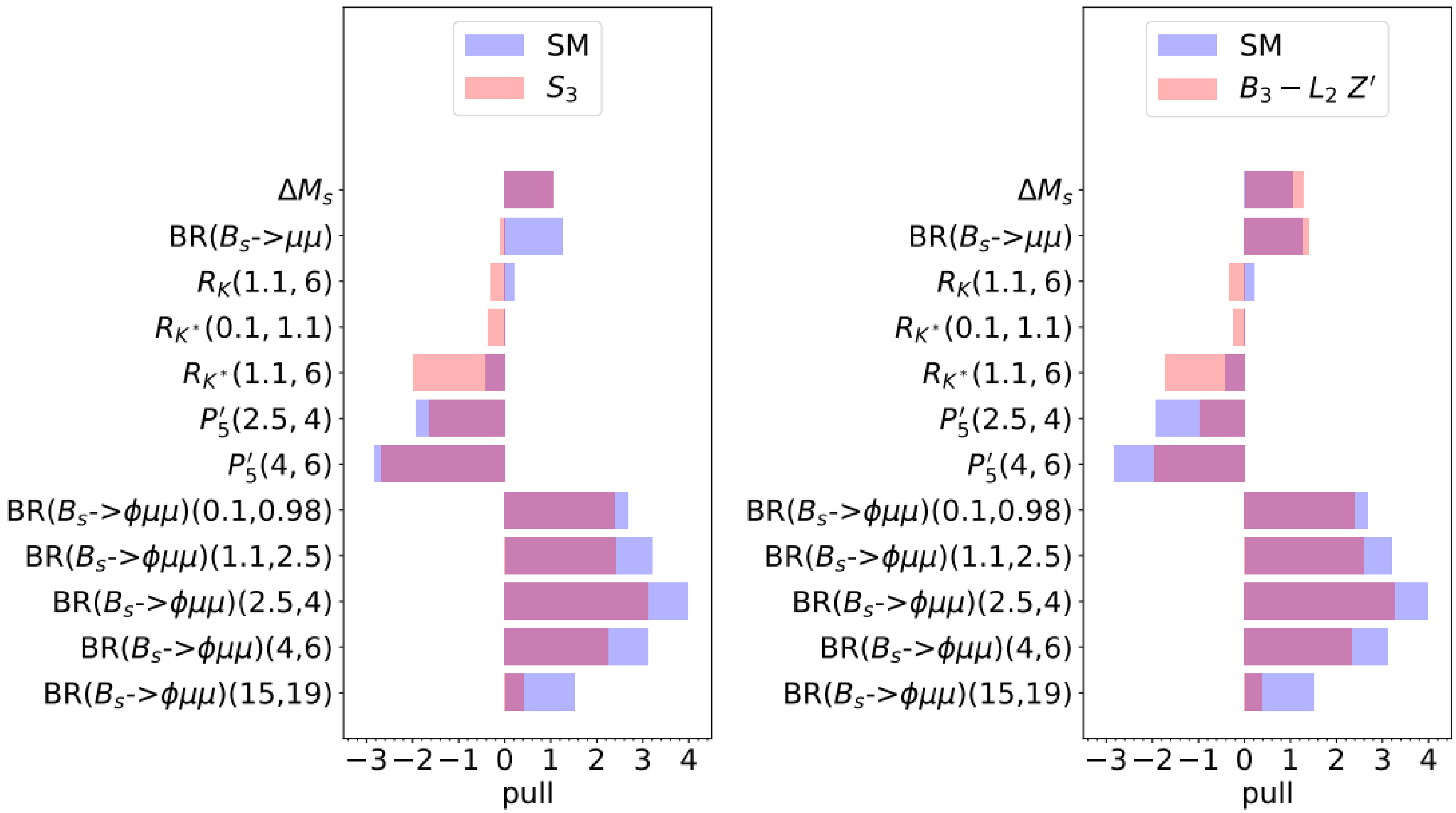
Previous $R_{K^{(*)}}$ [1–3]

S_3 model	χ^2	n	p	$s\sqrt{\lvert\Delta\chi^2\rvert}$
quarks	245.7	224	.15	3.7
LFU	22.2	23	.51	4.2
global	267.9	247	.15	5.5

Z' model	χ^2	n	p	$s\sqrt{\lvert\Delta\chi^2\rvert}$
quarks	249.3	224	.12	3.1
LFU	22.8	23	.47	4.1
global	272.1	247	.11	5.1

Wilson, flavio, smelli

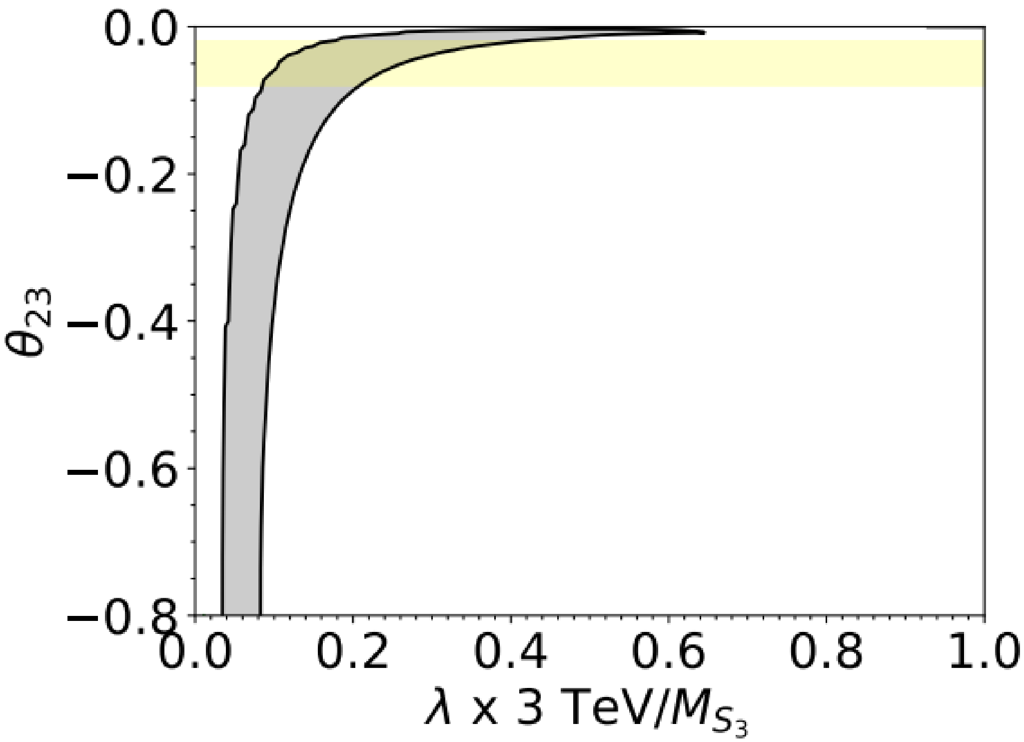
Pull=(theory-exp)/error

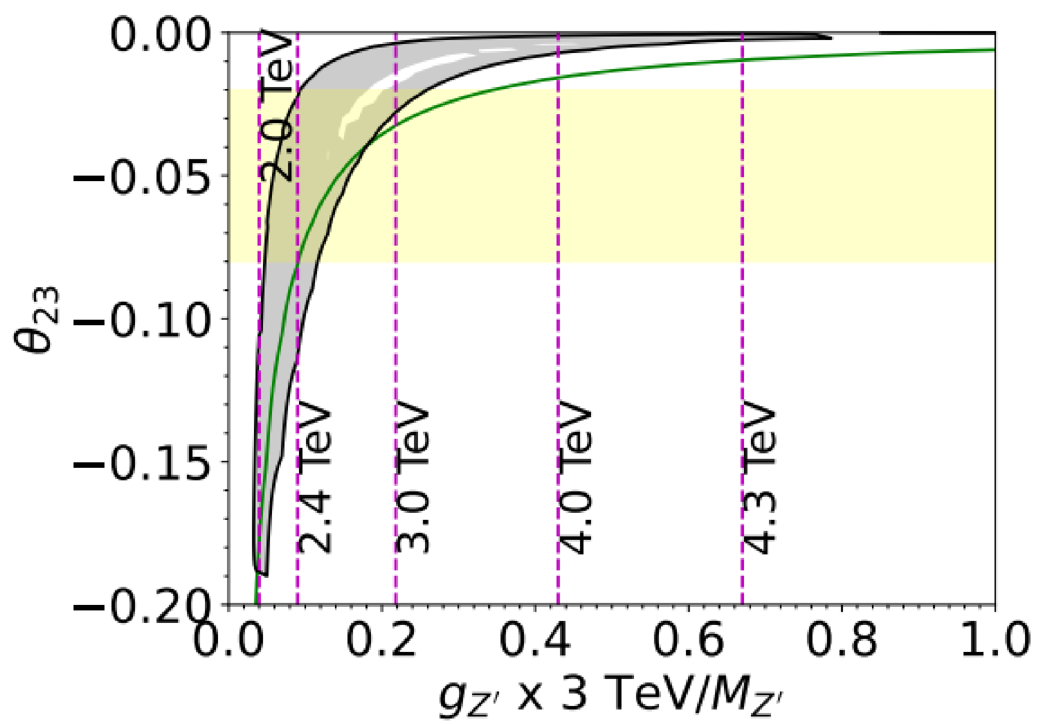


BCA, Davighi, 2211.11766

Parameter Space

BCA, Davighi, 2211.11766



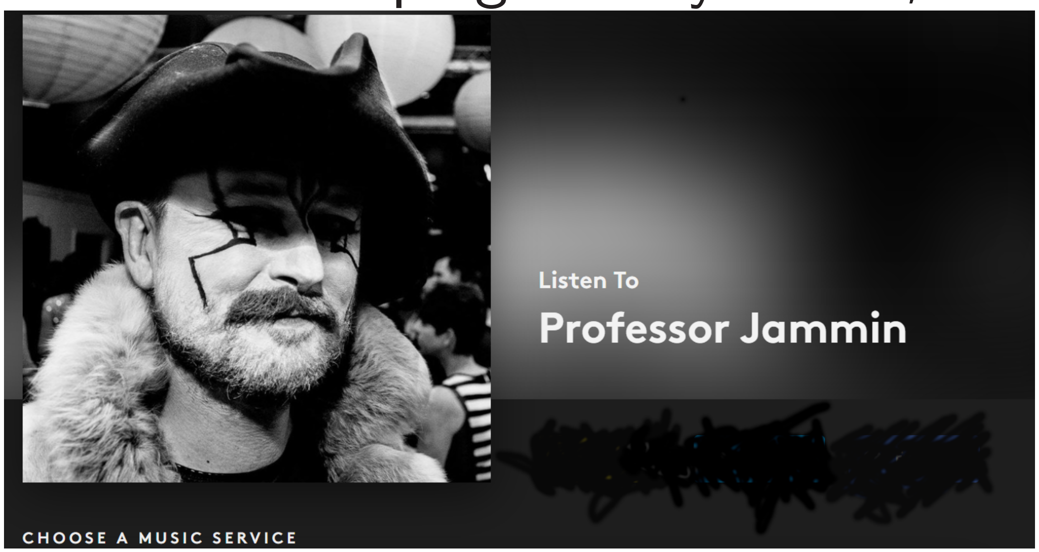


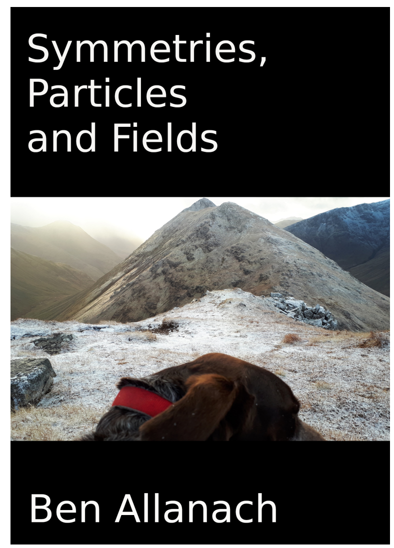
Summary

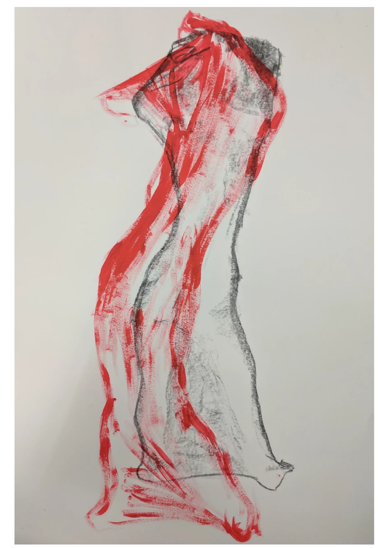
$b \to s\mu^+\mu^-$ anomalies remain with caveat

Remarkable that models with TeV-scale flavour symmetry are still allowed

Shameless plug for my music, textbook and *Quantum Selves* art:







Backup

Trident Neutrino Process

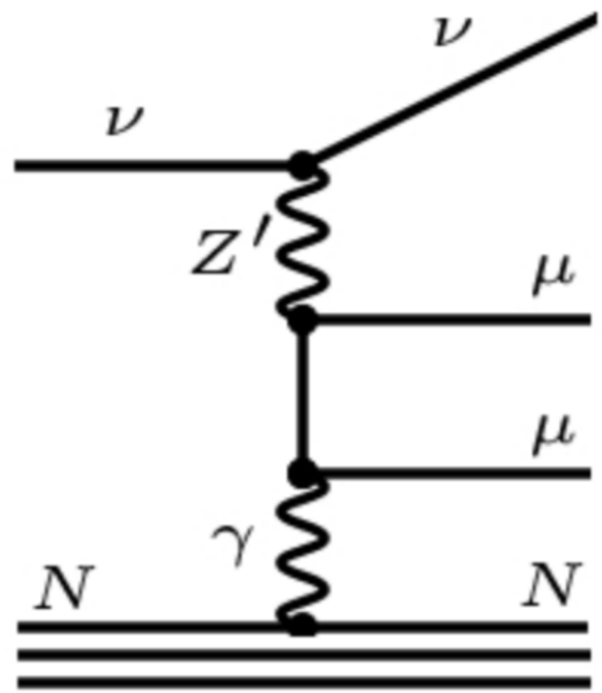
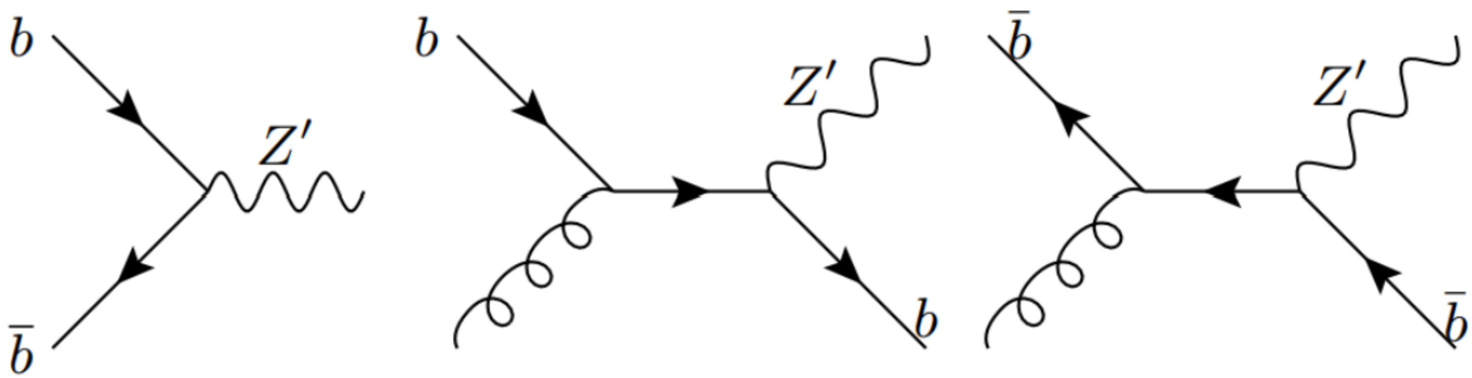


FIG. 10. Neutrino trident process that leads to constraints on the Z^{μ} coupling strength to neutrinos-muons, namely $M_{Z'}/g_{v\mu} \gtrsim 750$ GeV.

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:



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

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

ATLAS analysis: look for two track-based isolated μ, $p_T > 30$ GeV. One reconstructed primary vertex. Keep only highest scalar sum p_T pair[7]

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

CMS also have released[8] a 139 fb^{-1} analysis.

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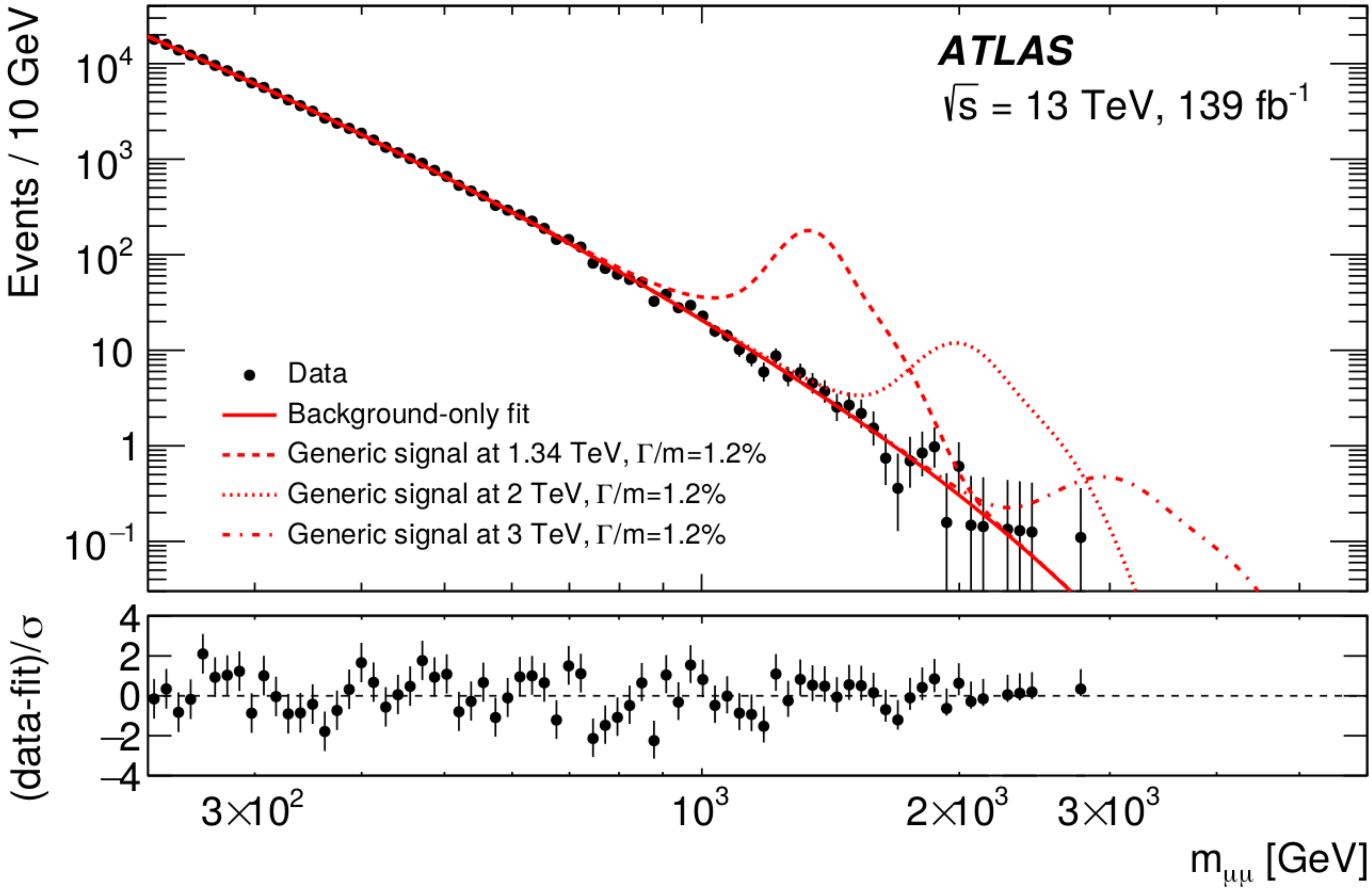
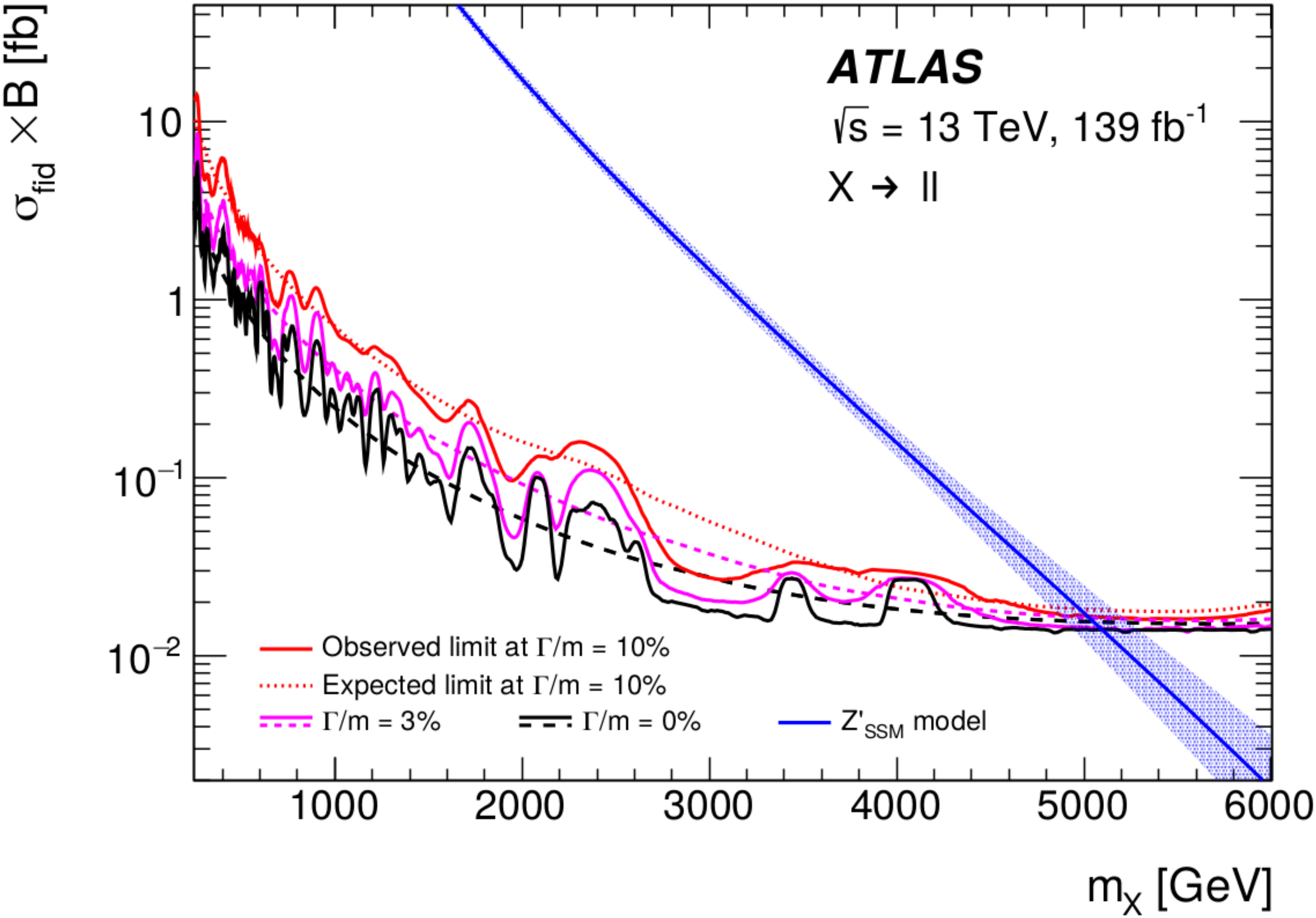
[7] 1903.06248
[8] 2103.02708

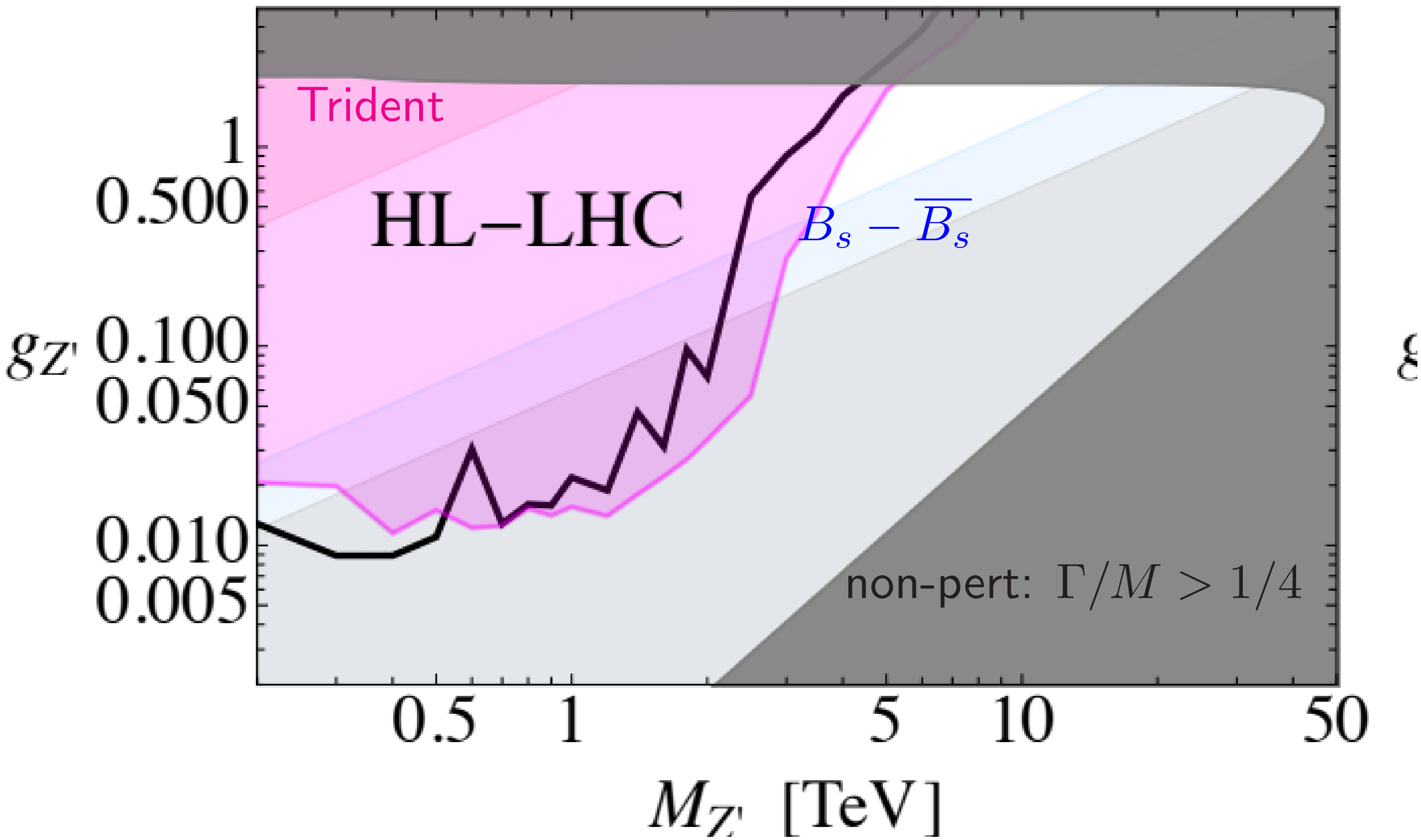

ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
Data
Background-only fit
Generic signal at 1.34 TeV, Γ/m=1.2%
Generic signal at 2 TeV, Γ/m=1.2%
Generic signal at 3 TeV, Γ/m=1.2%
Events / 10 GeV
(data-fit)/σ
$m_{\mu\mu}$ [GeV]

ATLAS l^+l^- limits



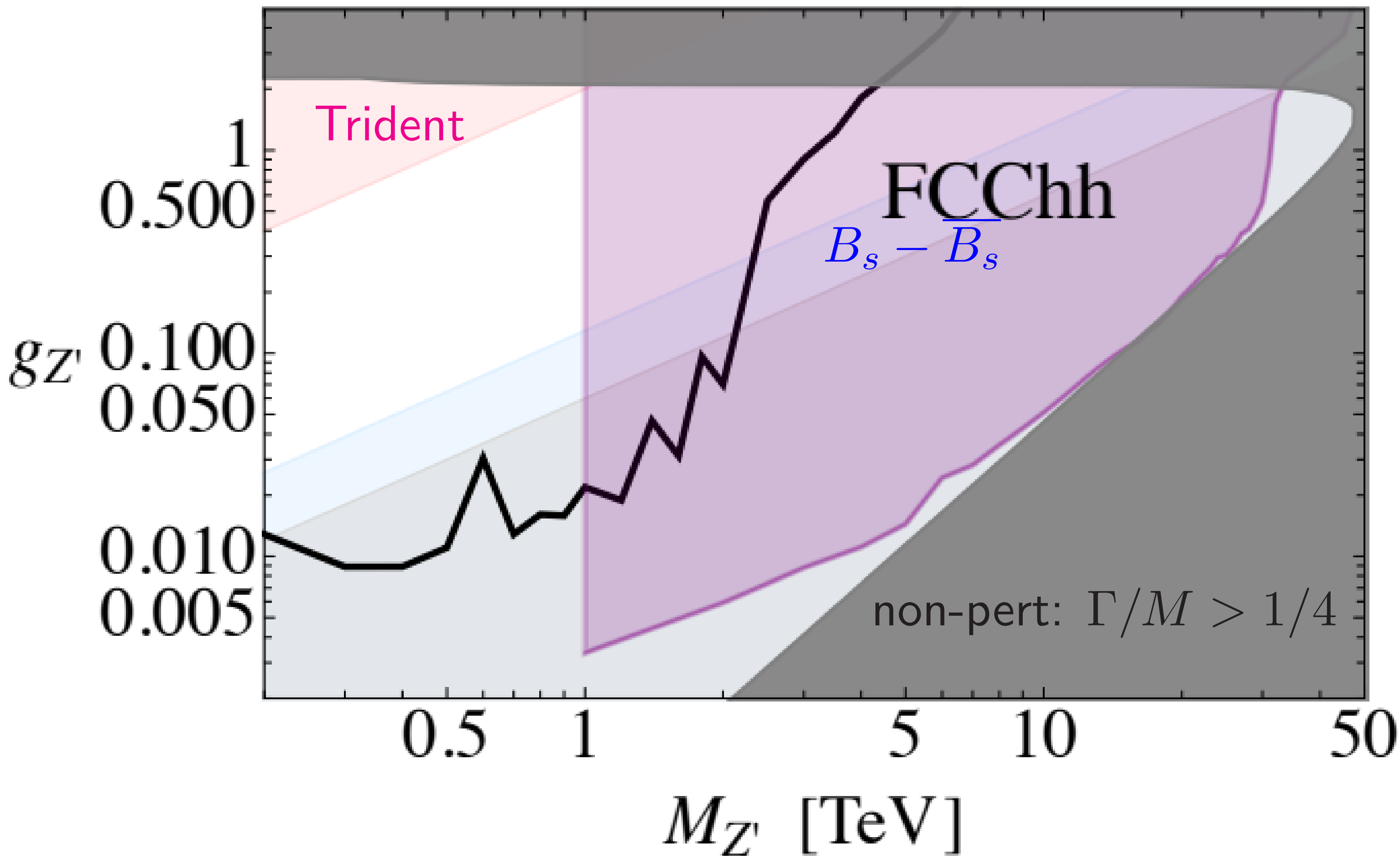
1903.06248

$B_3 - L_2\ Z'$ at HL-LHC



Azatov, Garosi, Greljo, Marzocca, Salko, 2205.13552 with old $R_{K^{(*)}}$

$B_3 - L_2$ Z' at FCChh



Azatov, Garosi, Greljo, Marzocca, Salko, 2205.13552 with old $R_{K^{(*)}}$