# $Z'$ Explorations at FCC

by
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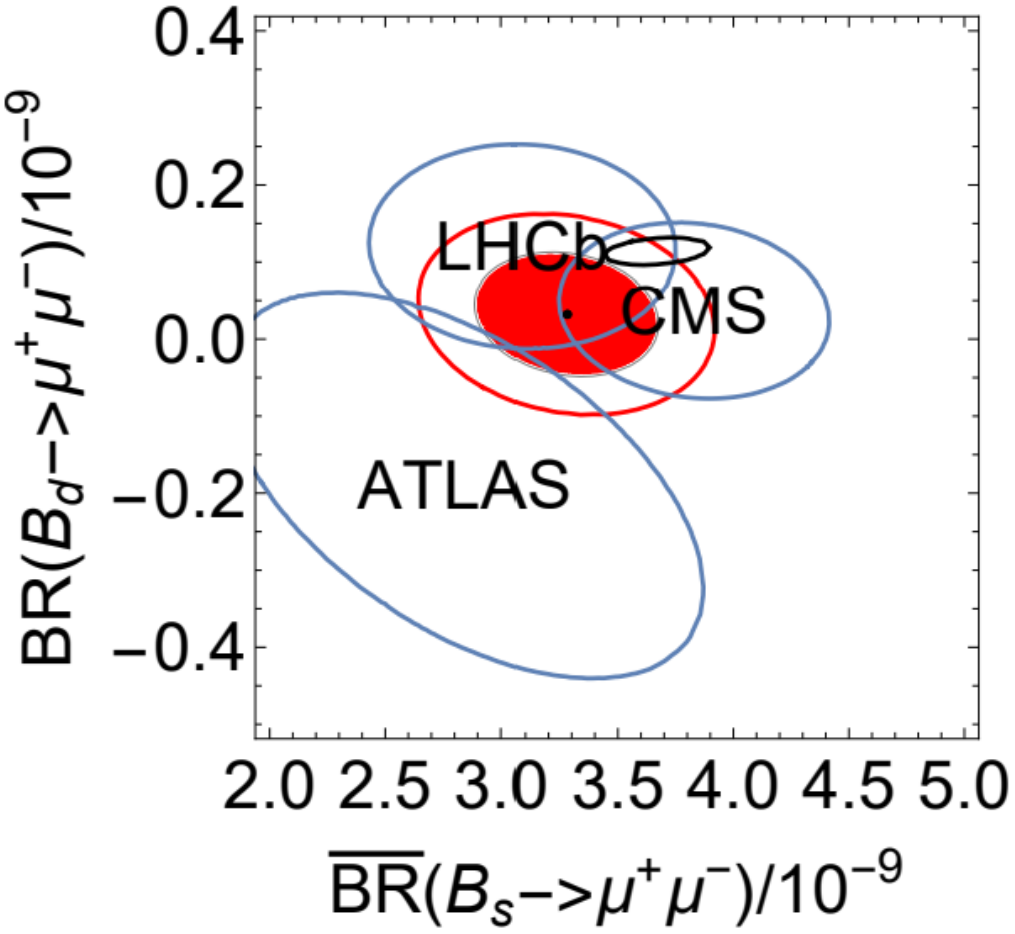
- Current situation with $b \to s\mu^+\mu^-$ anomalies
- Particular emphasis on LFU $R_{K^{(*)}}$
- $B_3 - L_2$ $Z'$ reach at LHC and FCC-hh

Cambridge Pheno Working Group

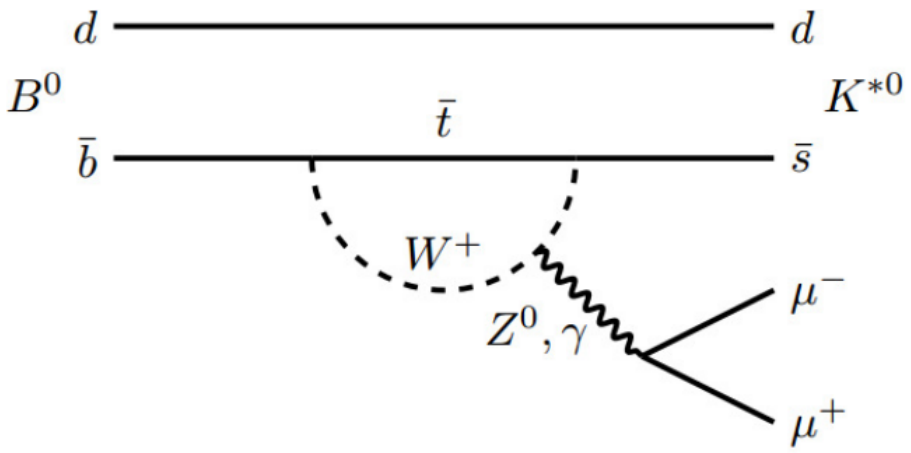
Where data and theory collide

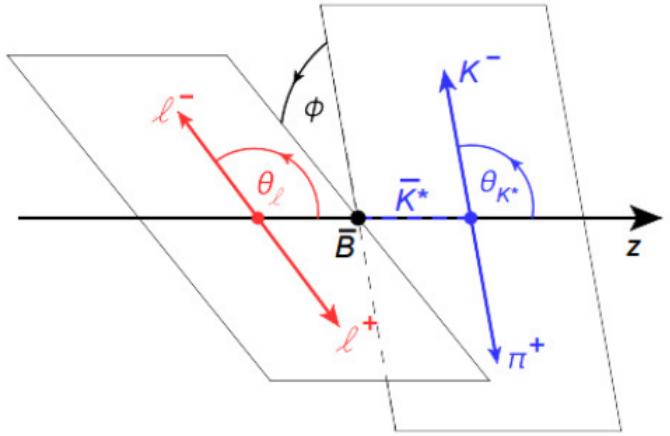
# $BR(B_s \to \mu^+\mu^-)$:[1] $B_s = (\bar{b}s)$, $B^0 = (\bar{b}d)$




[1] BCA, Davighi, 2211.11766: SM: $1.6\sigma$

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

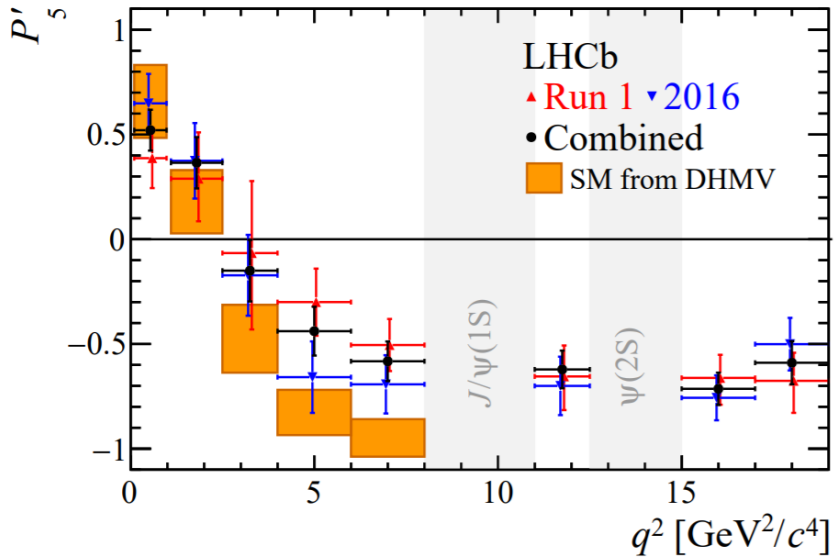


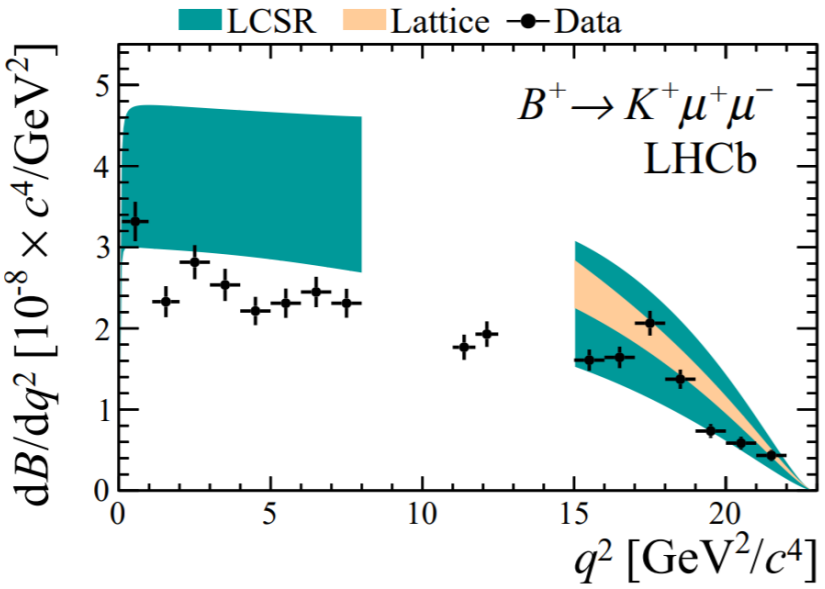




Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

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

# $P_5'$

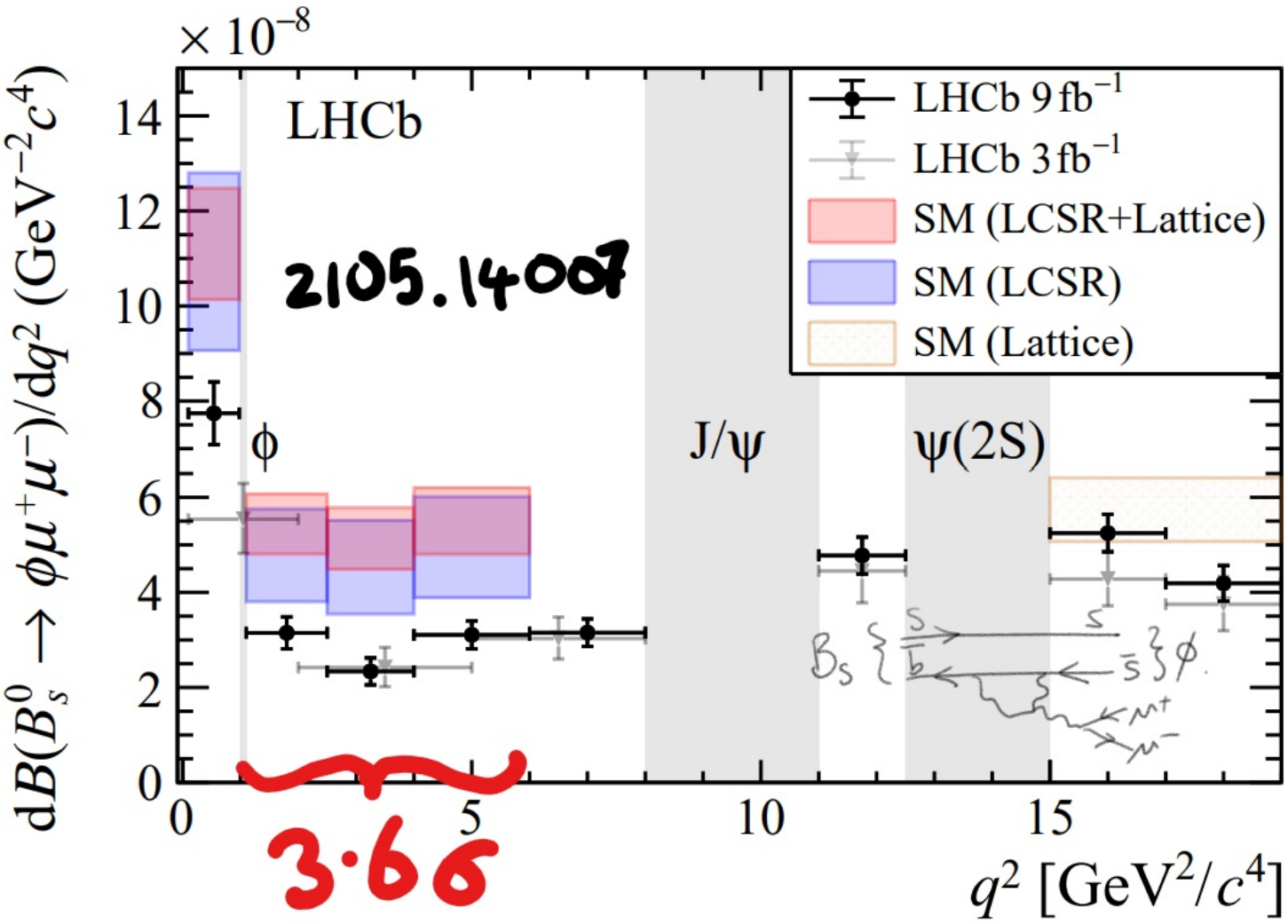


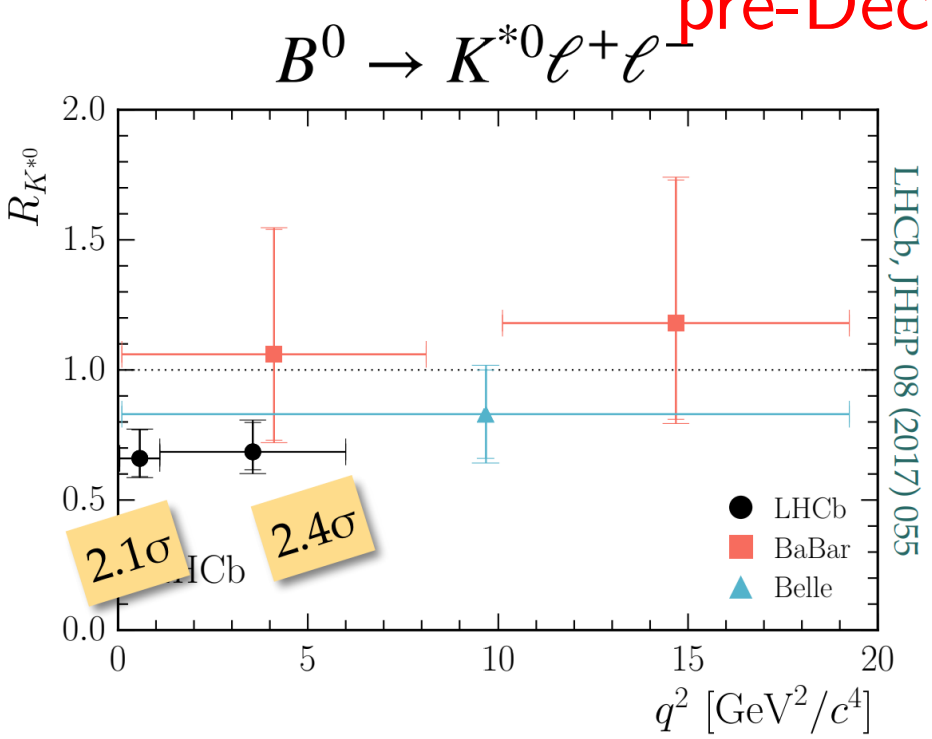

$P_5' = S_5/\sqrt{F_L(1-F_L)}$, leading form factor uncertainties cancel [2]

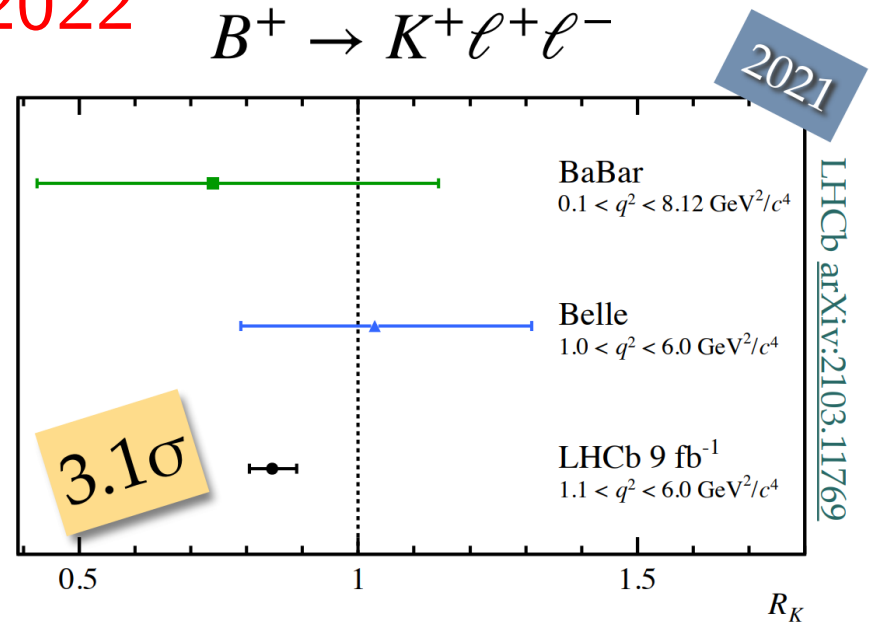
[2] LHCb, 2003.04831

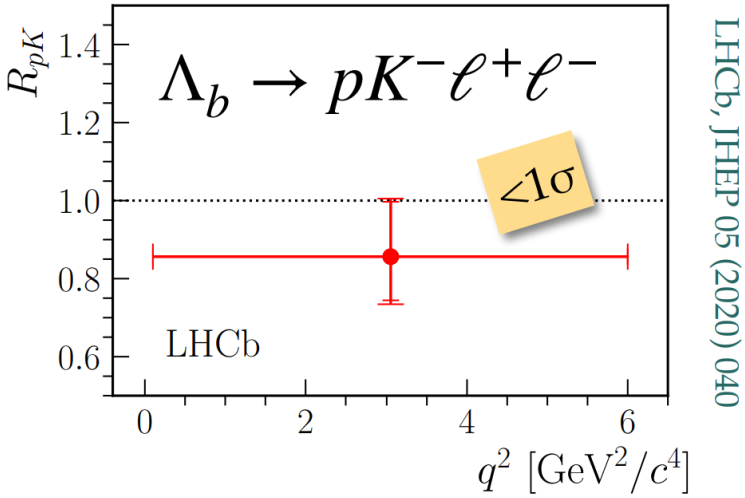
# $B_s \to \phi\mu^+\mu^-$: $\phi = (s\bar{s})$

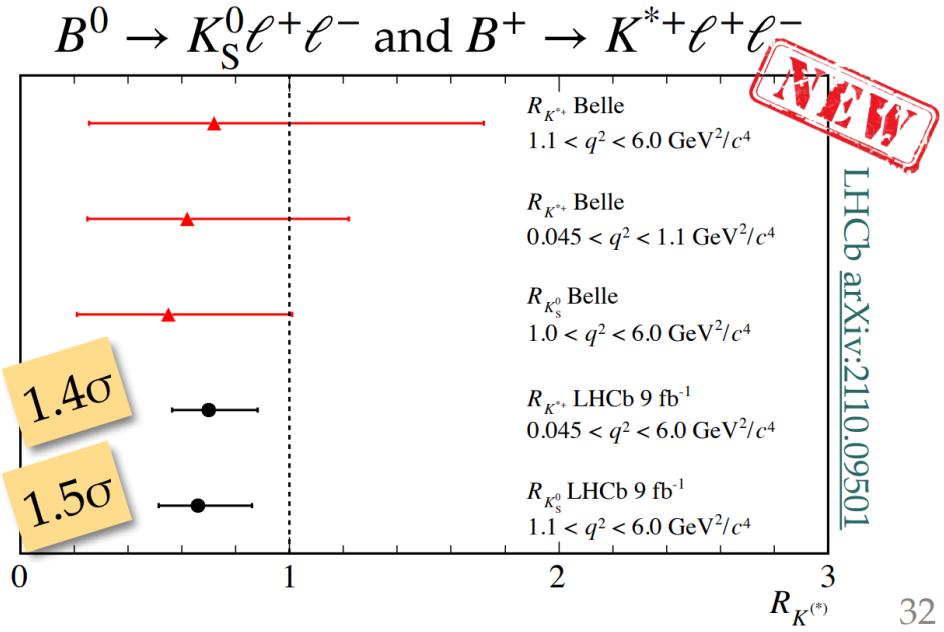


pre-Dec 2022






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

# 20/12/22 LHCb $R_{K^{(*)}}$ update

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

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

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

| category | $n_{obs}$ | $\chi^2_{SM}$ | $p$ | $s/\sigma$ |
|---|---|---|---|---|
| '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) |

# 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 (eg $V_{ts}$) easy to deal with
- Large theory uncertainties are taken into account in fits and are a subject of current research[3]

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

# Simple $Z'$ Model

Add complex SM-singlet scalar 'flavon' $\theta_{X\neq 0}$ which breaks gauged $U(1)_X$:

$$SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_X$$
$$\downarrow \langle\theta\rangle \sim \text{Several TeV. } M_{Z'} = g\langle\theta\rangle$$
$$SU(3) \times SU(2)_L \times U(1)_Y$$
$$\downarrow \langle H\rangle \sim 246 \text{ GeV}$$
$$SU(3) \times U(1)_{em}$$

- SM+$3\nu_R$ fermion content
- Zero $X$ charges for first two generations of quark
- Anomaly cancellation[4]

[4] $X = B_3 - L_2$: Bonilla *et al*, 1705.00915; Alonso *et al* 1705.03858,

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

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

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

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# A simple limiting case

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

for simplicity and the ease of passing bounds.

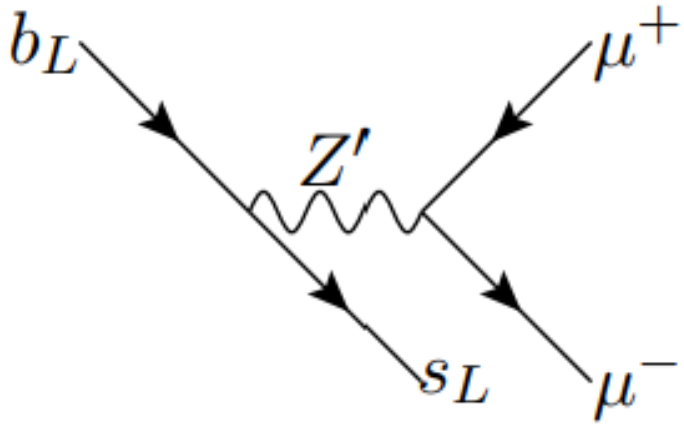
$$V_{d_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & -\sin\theta_{23} \\ 0 & \sin\theta_{23} & \cos\theta_{23} \end{pmatrix}, \qquad V_{e_{L,R}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

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

# Important $Z'$ Couplings

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

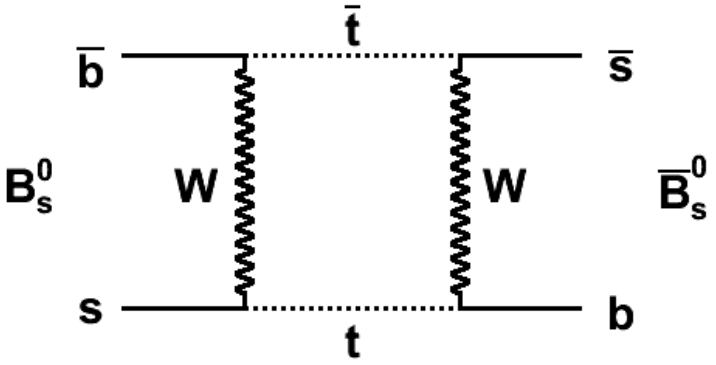
$$\left. -3(\overline{e_L}\ \overline{\mu_L}\ \overline{\tau_L}) \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \not{Z}' \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} \right]$$

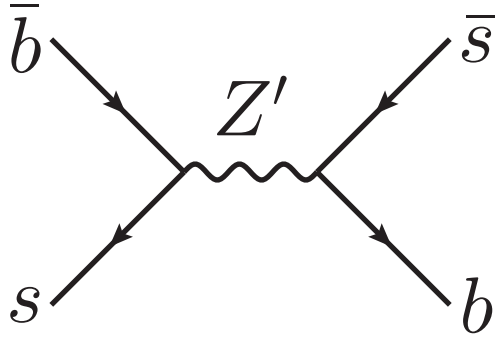



– LFU Violating

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

Measurement pretty much agrees with SM calculations.




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

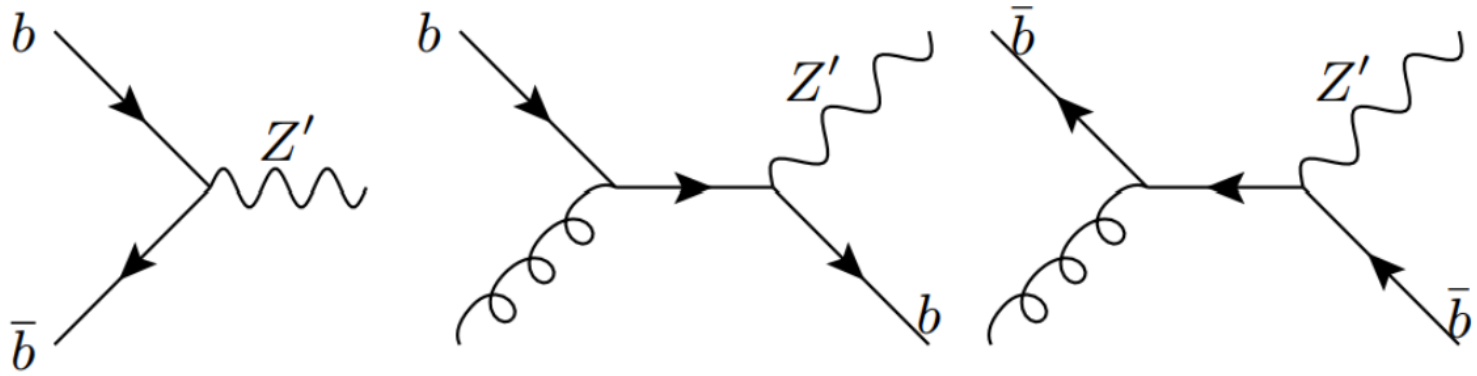
from QCD sum rules and lattice[5].

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

# $Z'$ 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:




$$\sigma_{prod} \propto g_X^2 \cos^4 \theta_{sb}$$

# Fit to $B_3 - L_2$ model

New LFU $\Delta\chi^2 = \chi^2_{SM} - \chi^2$

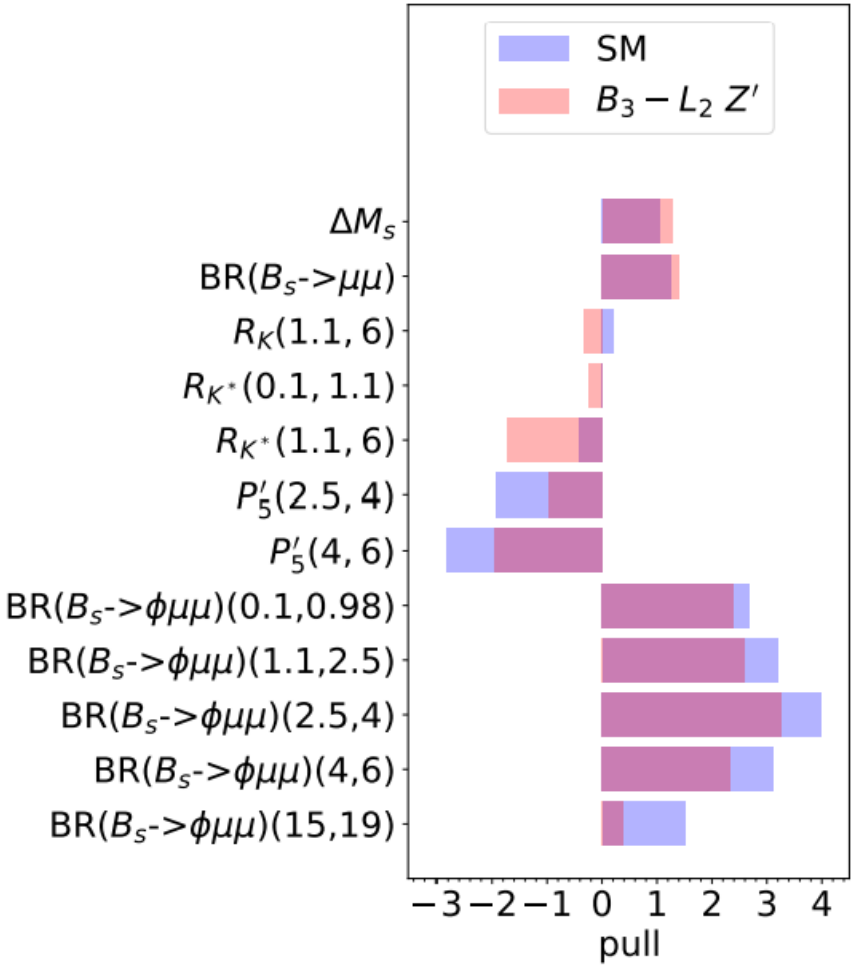
| $Z'$ model | $\chi^2$ | $n$ | $p$ | $s\sqrt{\lvert\Delta\chi^2\rvert}$ |
|---|---|---|---|---|
| quarks | 249.1 | 224 | .12 | 3.7 |
| LFU | 18.2 | 23 | .75 | -1.0 |
| global | 267.4 | 247 | .16 | 3.6 |

Old LFU

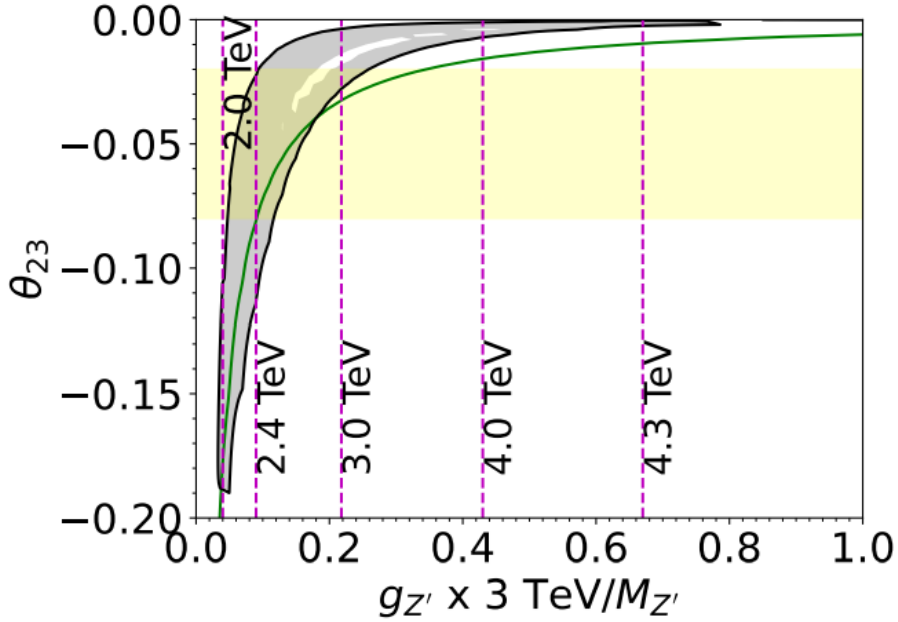
| $Z'$ model | $\chi^2$ | $n$ | $p$ | $s\sqrt{\lvert\Delta\chi^2\rvert}$ |
|---|---|---|---|---|
| quarks | 249.3 | 224 | .12 | 3.1 |
| LFU | 22.8 | 23 | .47 | 4.1 |
| global | 272.1 | 247 | .11 | 5.1 |

BCA, Davighi, 2211.11766

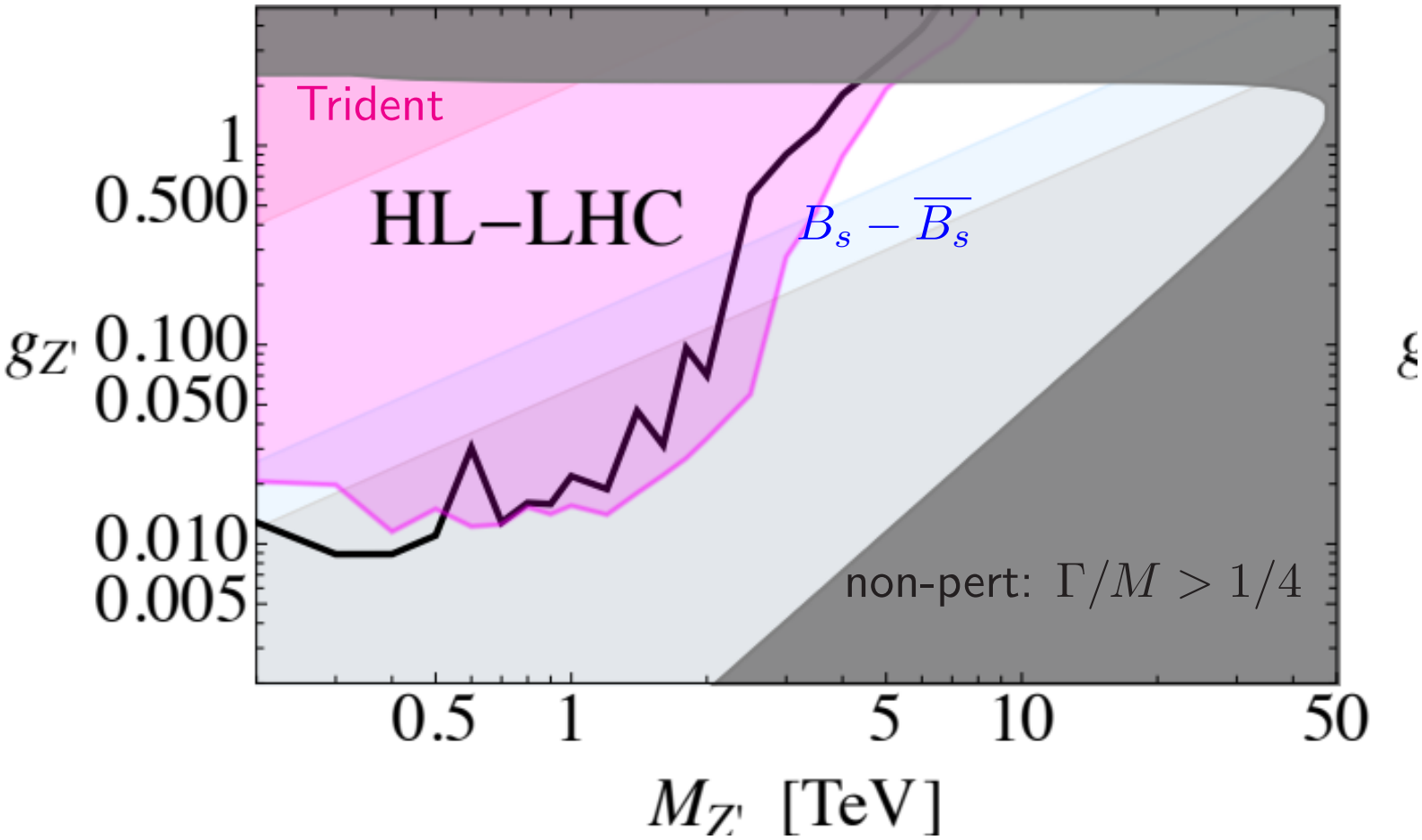
# Pull=(theory-exp)/error




BCA, Davighi, 2211.11766

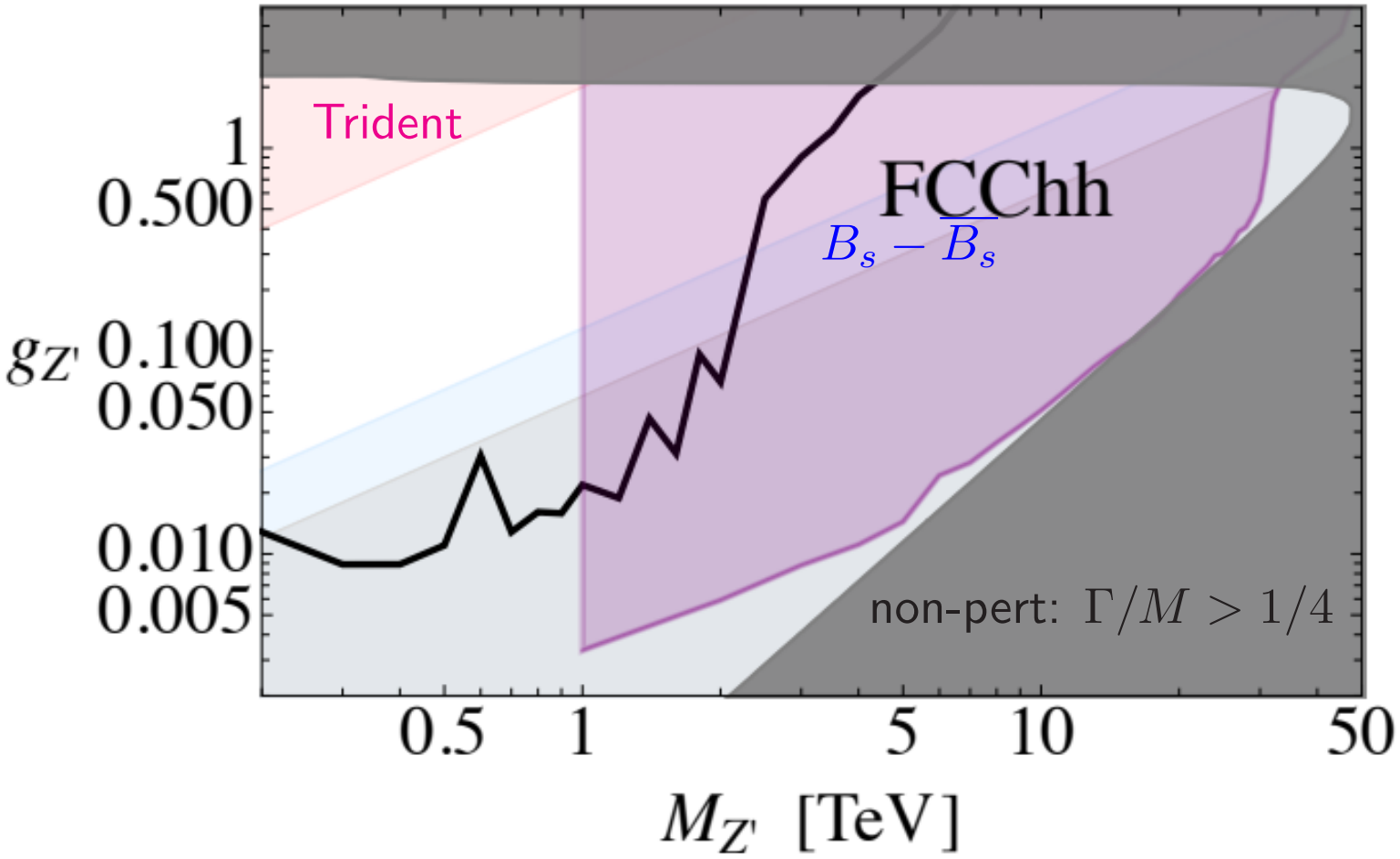


# $B_3 - L_2$ $Z'$ at HL-LHC




Azatov, Garosi, Greljo, Marzocca, Salko, 2205.13552; *without* new $R_{K^{(*)}}$

# $B_3 - L_2$ $Z'$ at FCChh




Azatov, Garosi, Greljo, Marzocca, Salko, 2205.13552; *without* new $R_{K^{(*)}}$

# Summary

- Evidence for neutral current LFU has gone away
- Other $b \to s\mu^+\mu^-$ anomalies remain, albeit with a caveat regarding non-perturbative corrections
- $B_3 - L_2$ $Z'$ model can still fit the anomalies and new LFU data reasonably, with good prospects for FCC $\mu^+\mu^-$ bump hunt

# Backup

# Trident Neutrino Process

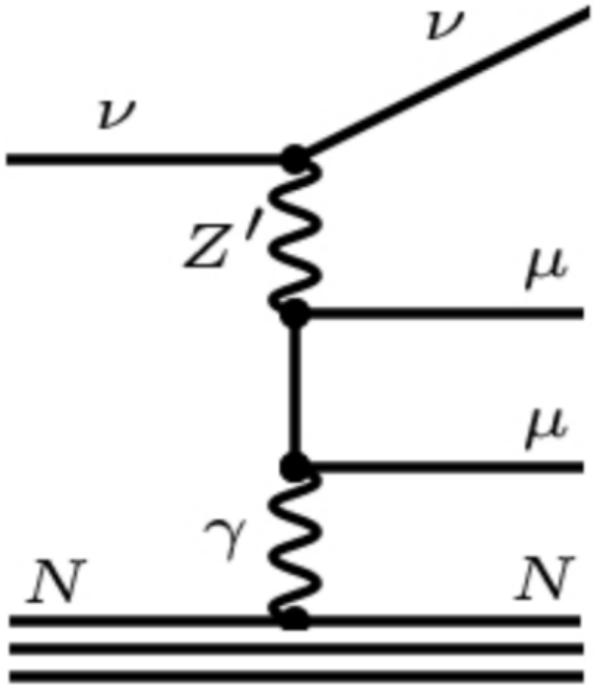



FIG. 10. Neutrino trident process that leads to constraints on the $Z^\mu$ coupling strength to neutrinos-muons, namely $M_{Z'}/g_{\nu\mu} \gtrsim 750$ GeV.

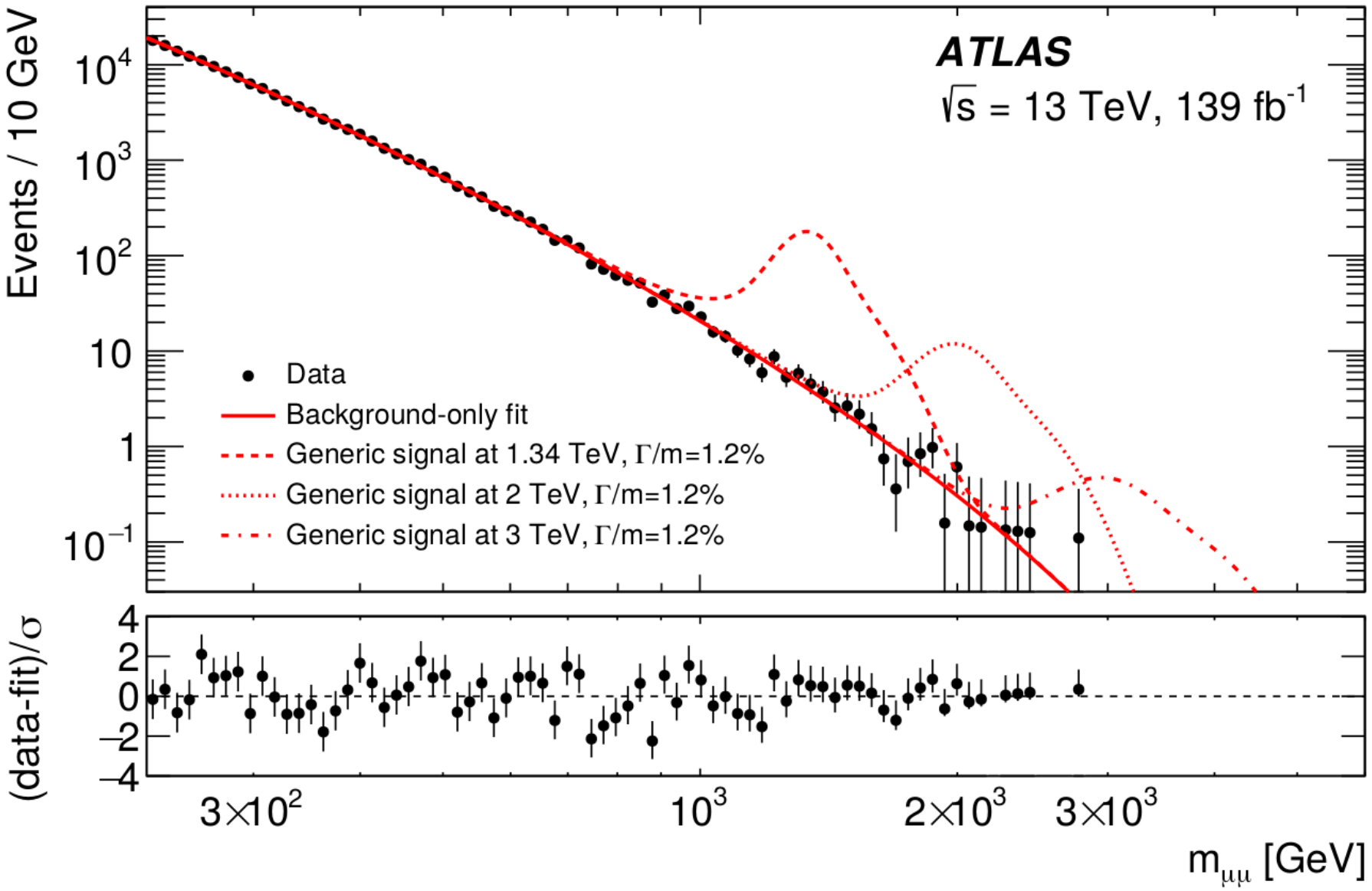
# $Z' \to \mu\mu$ ATLAS 13 TeV 139 fb$^{-1}$

ATLAS analysis: look for two track-based isolated $\mu$, $p_T > 30$ GeV. One reconstructed primary vertex. Keep only highest scalar sum $p_T$ pair[6]

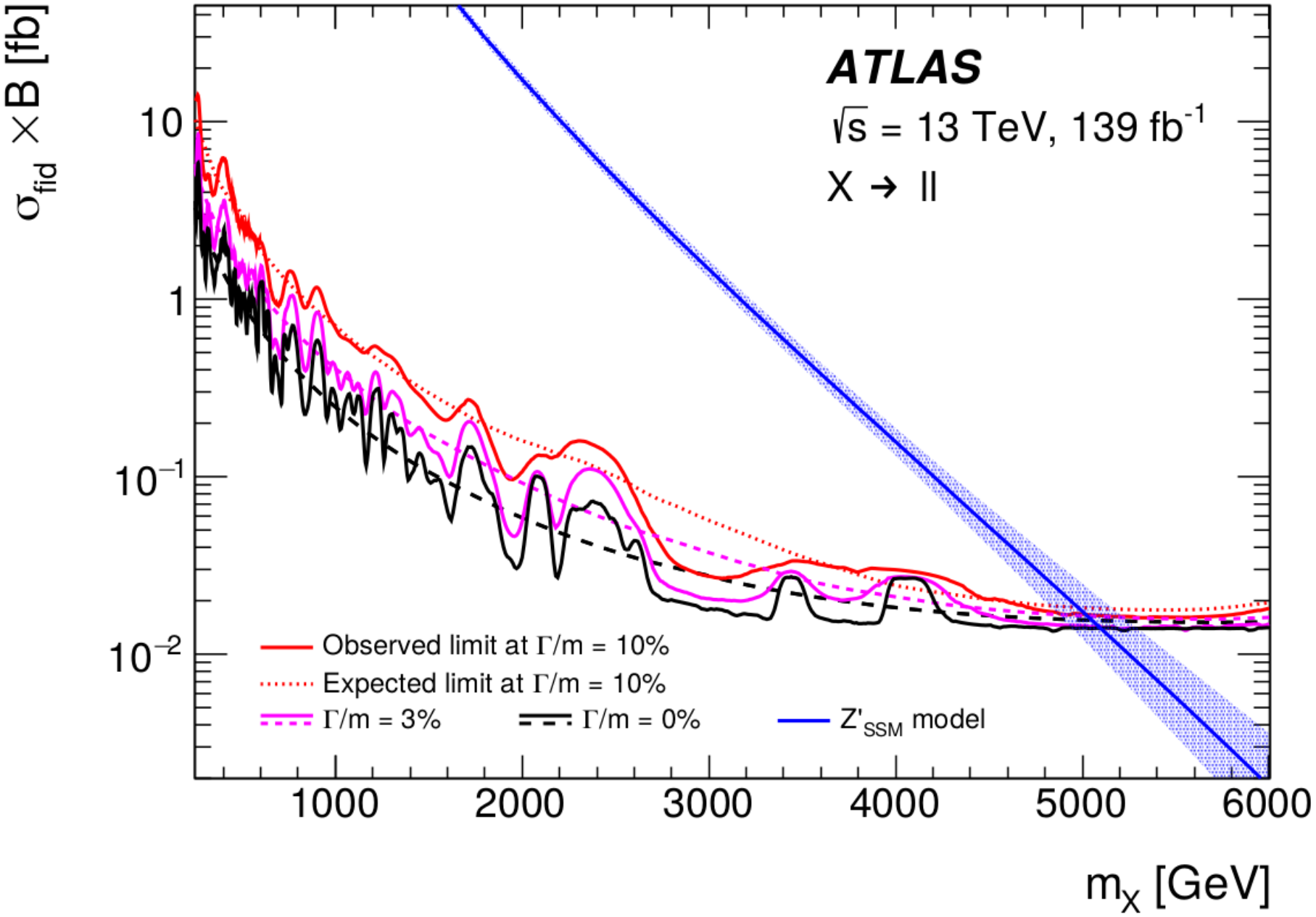
$$m^2_{\mu_1\mu_2} = (p_1^\mu + p_2^\mu)\left(p_{1\mu} + p_{2\mu}\right)$$

CMS also have released[7] a 139 fb$^{-1}$ analysis.

[6] 1903.06248
[7] 2103.02708


ATLAS
√s = 13 TeV, 139 fb-1
Events / 10 GeV
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
mμμ [GeV]

# ATLAS $l^+l^-$ limits






1903.06248