A Z' Manifesto

by
Ben Allanach
(DAMTP, University of Cambridge)

- $b \to s l^+ l^-$ anomalies
- Z' Models (BCA, Davighi, 1809.01158; ibid 1905.10327)
- Global fit (BCA, Camargo-Molina, Davighi, 2103.12056)
- Direct Z' searches (BCA, Butterworth, Corbett, 1904.10954)

Cambridge Pheno Working Group

Where data and theory collide

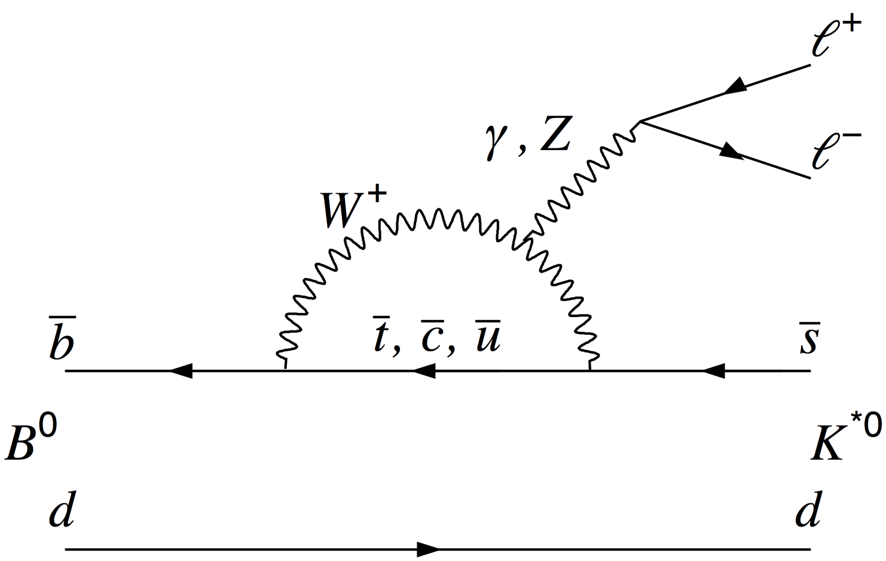
Science & Technology Facilities Council

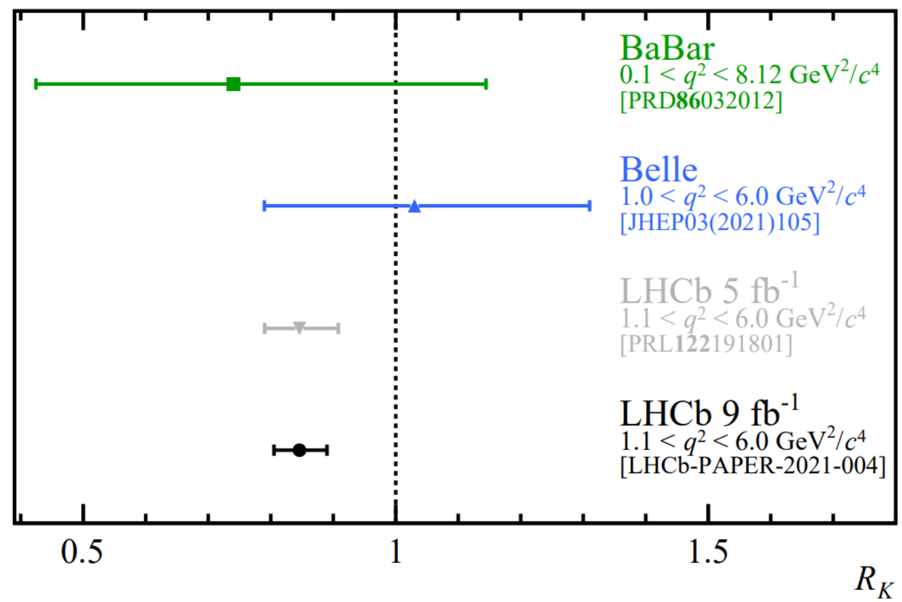
Strange b Activity

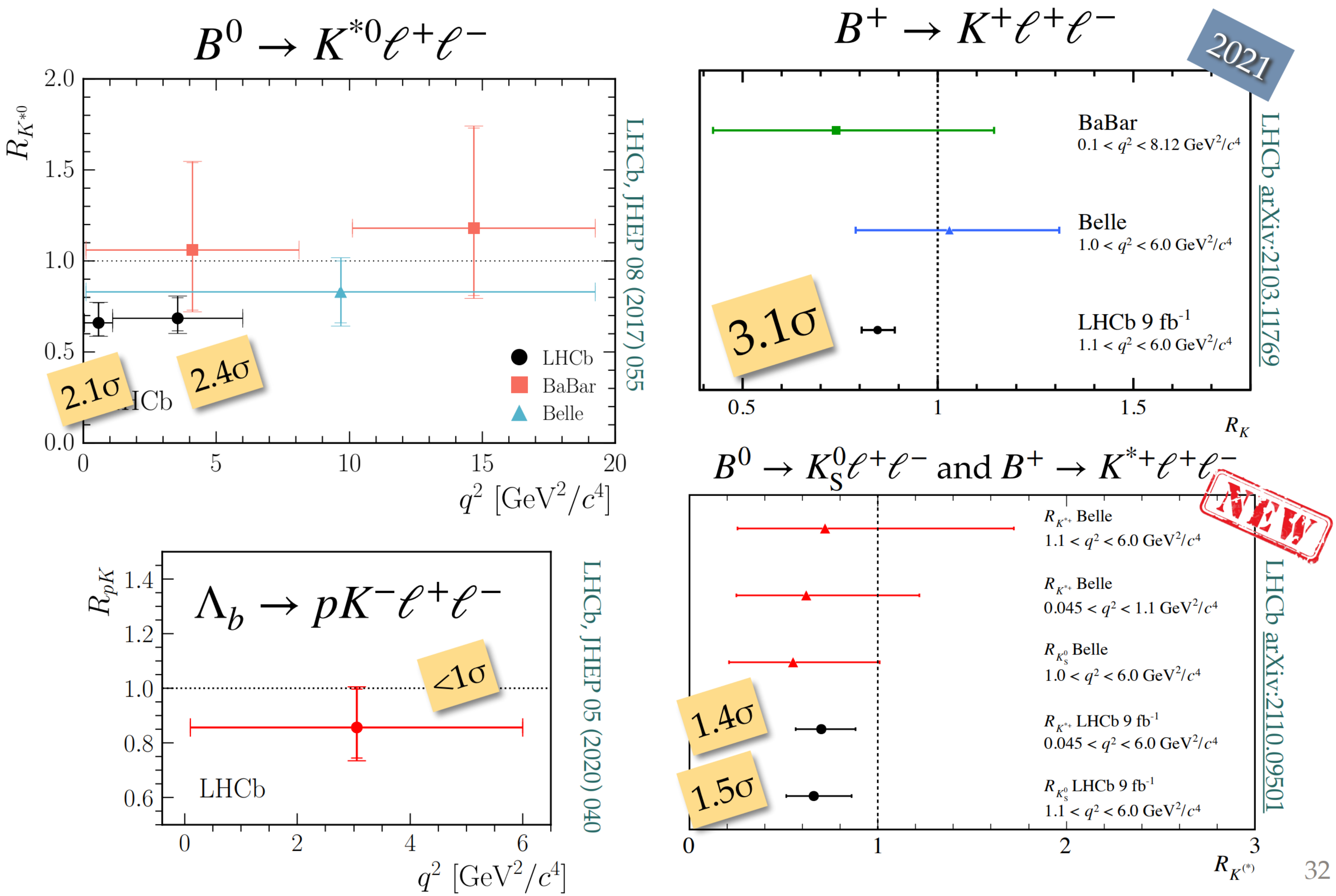
$R_K^{(*)}$ in Standard Model

$$R_K = \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to Ke^+e^-)}, \qquad R_{K^*} = \frac{BR(B \to K^*\mu^+\mu^-)}{BR(B \to K^*e^+e^-)}.$$

These are rare decays (each BR$\sim \mathcal{O}(10^{-7})$) because they are absent at tree level in SM+EW+CKM

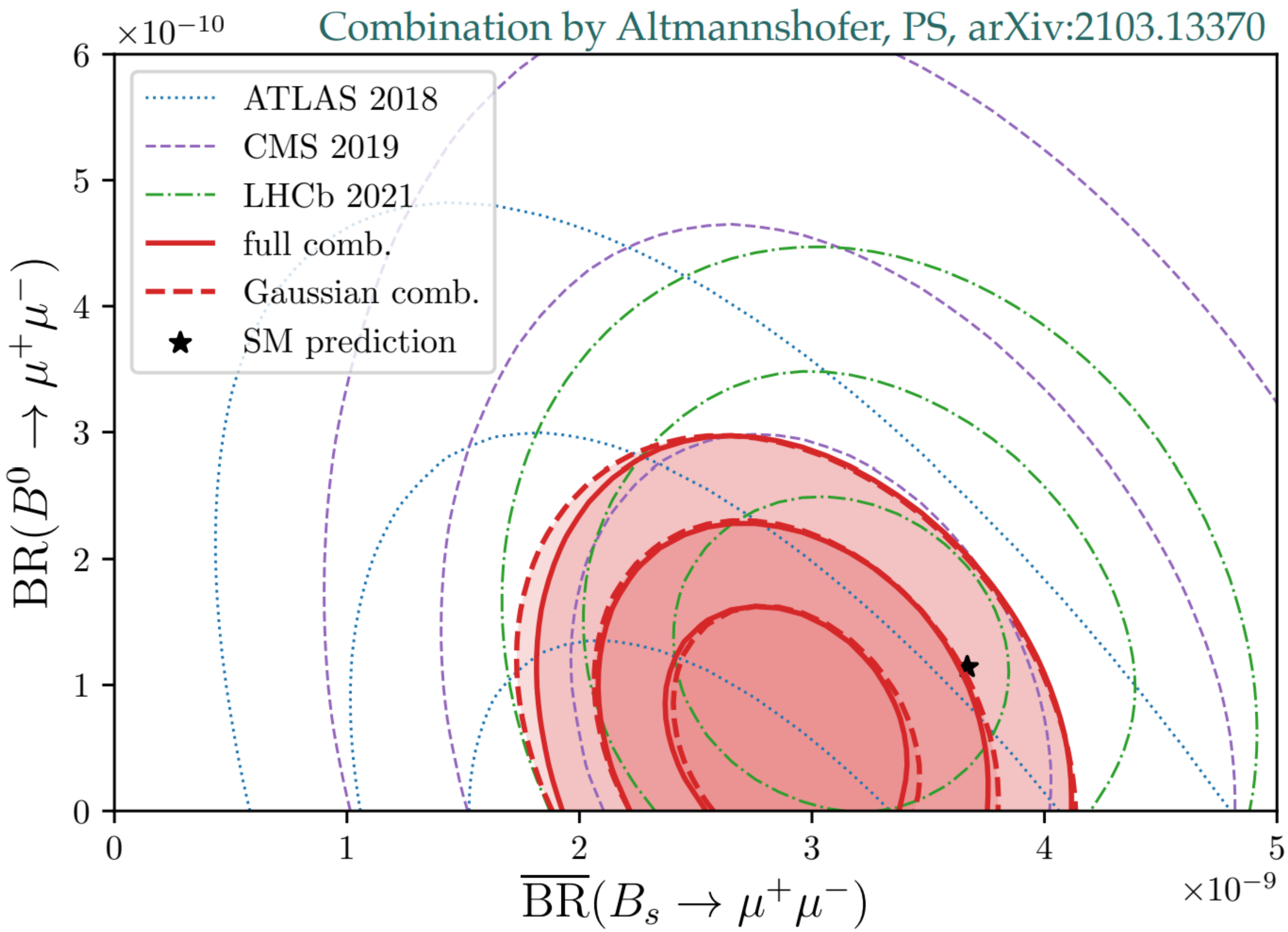




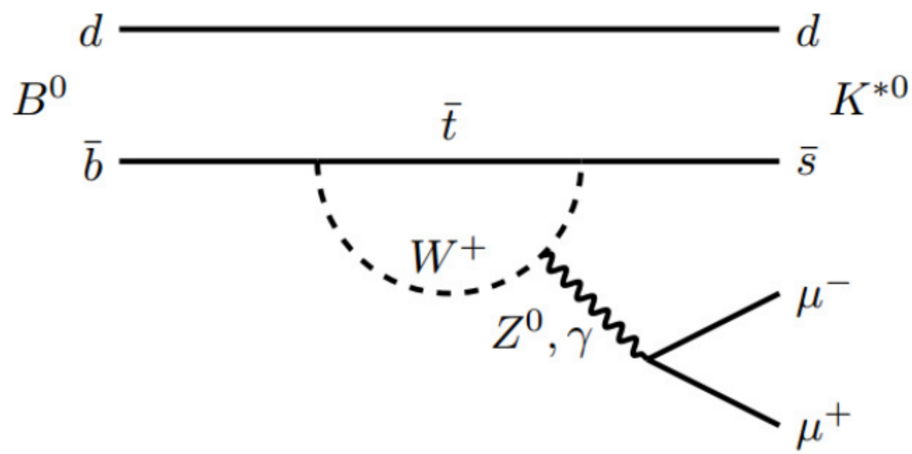


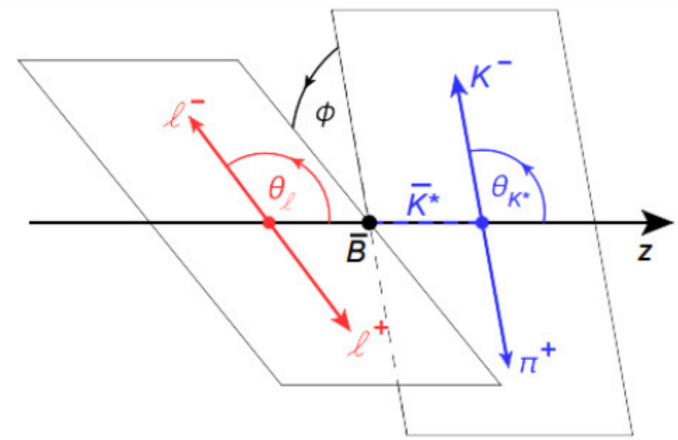
Stolen from Capdevila et al, *Flavour Anomaly Workshop '21*

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



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

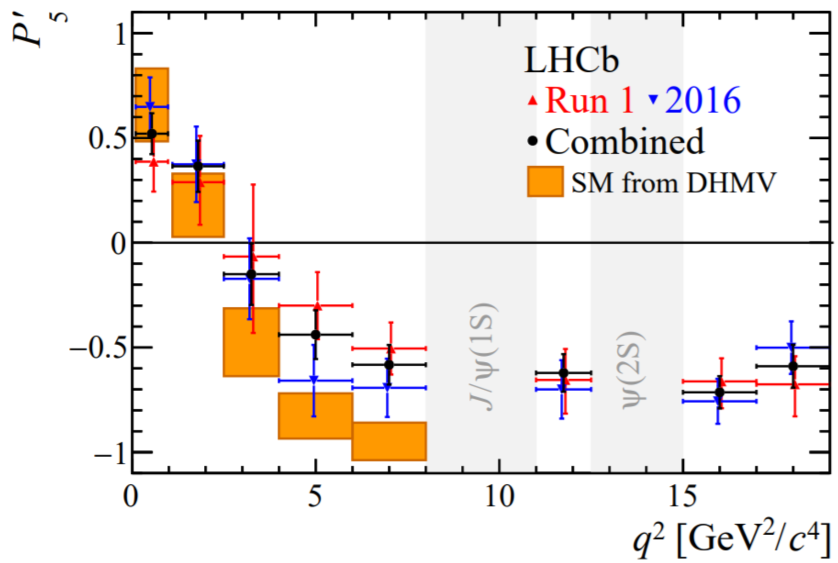


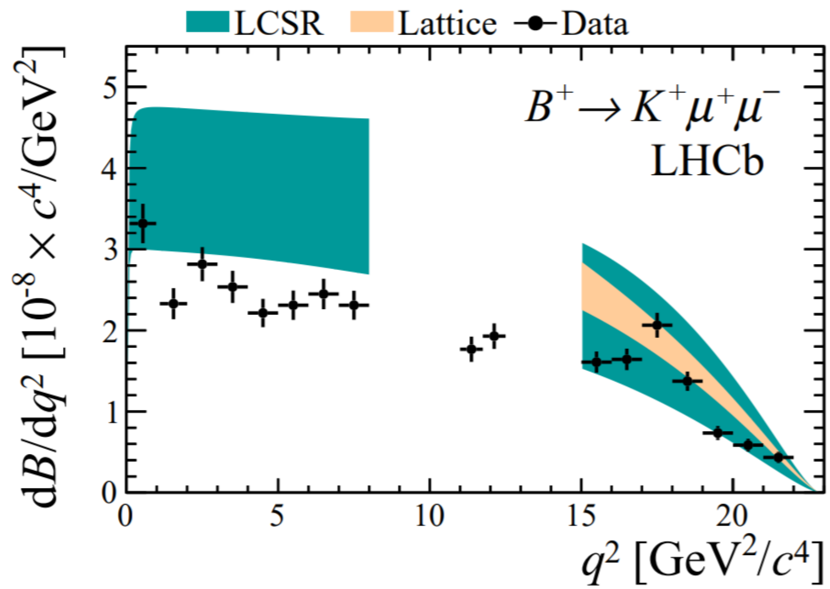


Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

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

P_5'

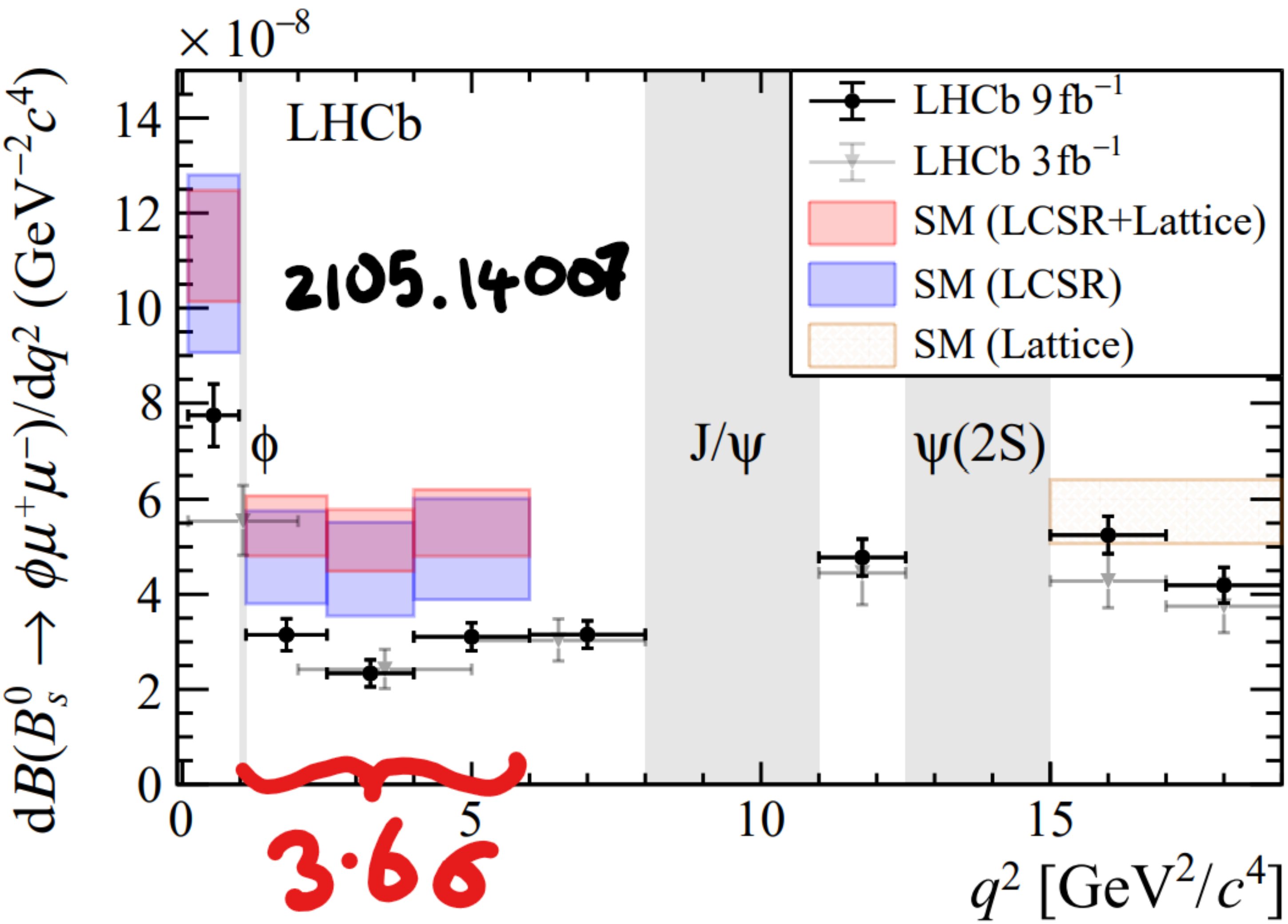




$P_5' = S_5/\sqrt{F_L(1-F_L)}$, leading form factor uncertainties cancel [1]

[1] LHCb, 2003.04831

$B_s \to \phi\mu^+\mu^-$: R_ϕ **coming!**



Caveats[2]

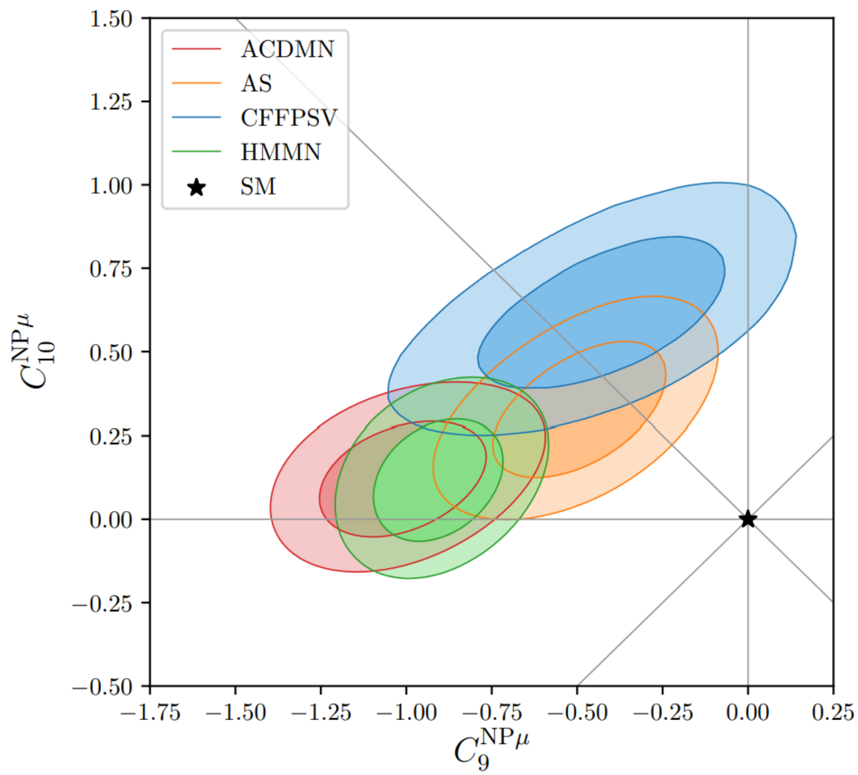
	parametric uncertainties	form factors	non-local matrix elements
$\mathcal{B}(B \to M\ell\ell)$	✗	✗	✗
angular observables	✓	✗	✗
$\overline{\mathcal{B}}(B_s \to \ell\ell)$	✗	✓	✓ (N/A)
LFU observables	✓	✓	✓

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

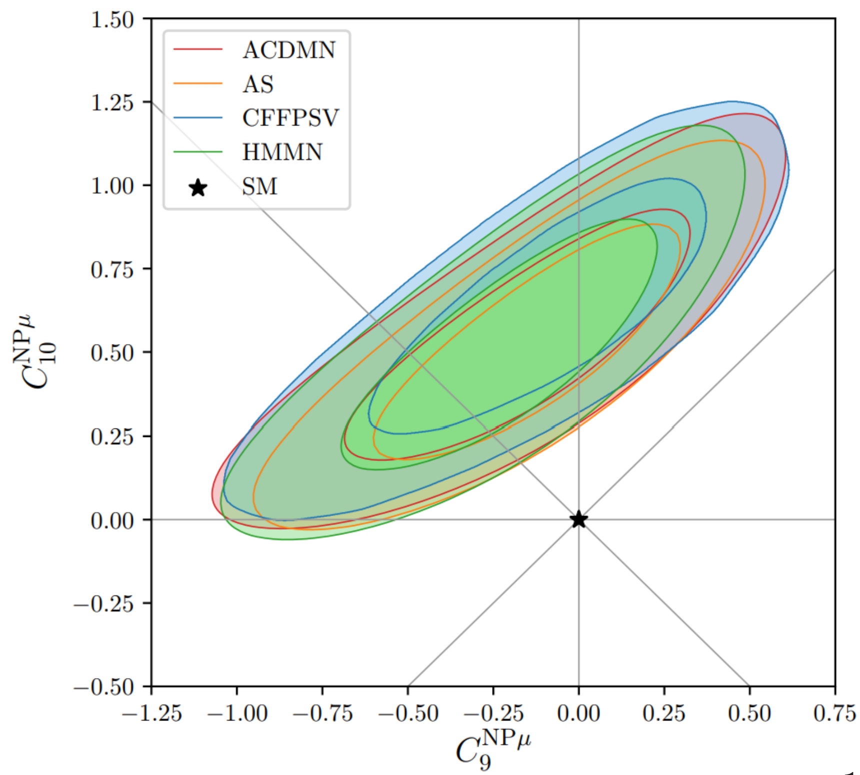
Fits

Alguero *et al*, 2104.08921; Altmannshofer, Stangl, flavio 2103.13370; Ciuchini *et al*, HEPfit 2011.01212; Hurth *et al*, superIso 2104.10058

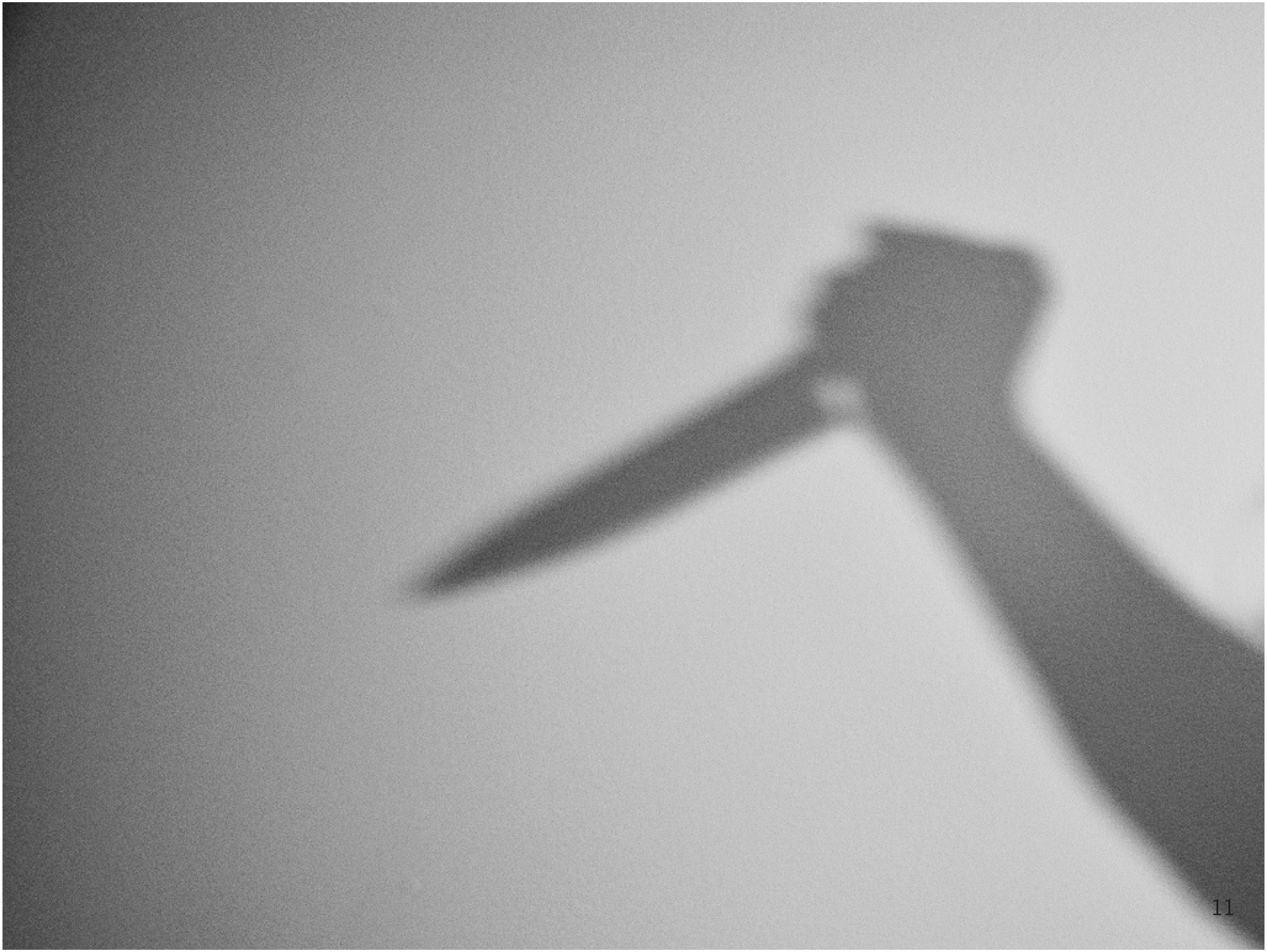
$$\mathcal{L} = N[C_9(\bar{b}_L\gamma^\mu s_L)(\bar{\mu}\gamma_\mu\mu) + C_{10}(\bar{b}_L\gamma^\mu s_L)(\bar{\mu}\gamma^5\gamma_\mu\mu)] + H.c.$$



global fit



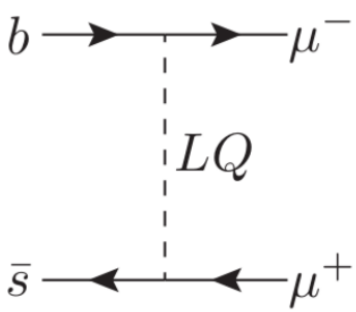
fit to LFU observables + $B_s \to \mu\mu$

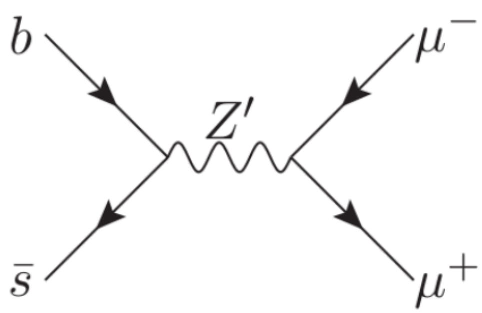


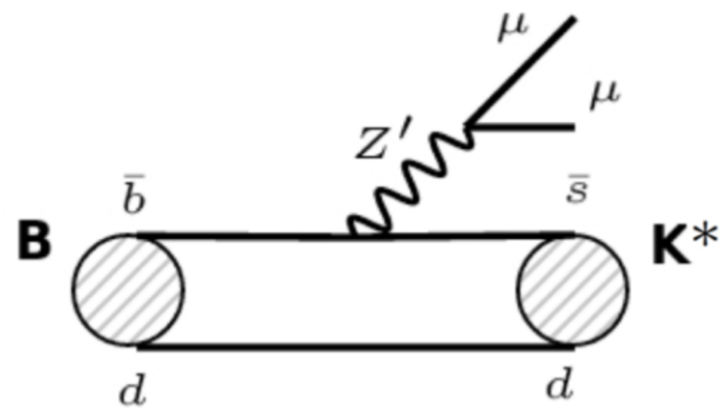
Simplified Models for NCBAs

A good few $2 - 4\sigma$ Discrepancies with SM predictions. Computing with look elsewhere effect implies a 4.3σ discrepancy with the SM (conservative theory errors).[3]

We have tree-level flavour changing new physics options:

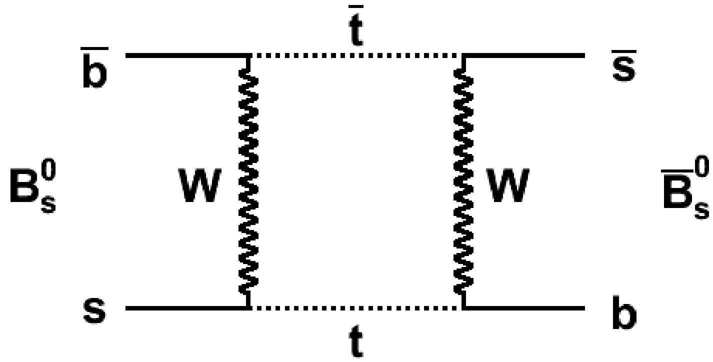


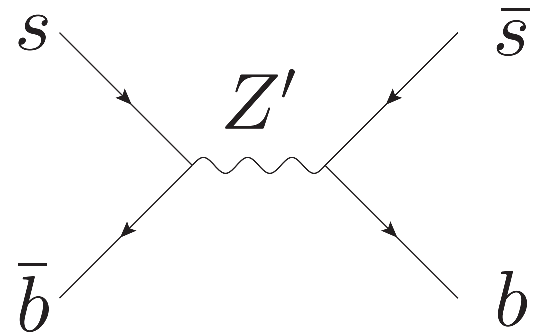




[3] Isidori, Lancierini, Owen and Serra, arXiv:2104.05631

$B_s - \bar{B}_s$ Mixing





$$\bar{g}_L^{sb} \lesssim \frac{M_{Z'}}{194\ \text{TeV}}$$

from QCD sum rules and lattice[4]. Weaker on LQs (see later).

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

A Simple Z' Model

BCA, Davighi, 1809.01158: Add complex SM-singlet scalar 'flavon' $\theta_{X\neq 0}$ which breaks gauged $U(1)_X$:

$$SU(3)\times SU(2)_L\times U(1)_Y\times U(1)_X$$

$$\Big\downarrow \langle\theta\rangle \sim \text{Several TeV}$$

$$SU(3)\times SU(2)_L\times U(1)_Y$$

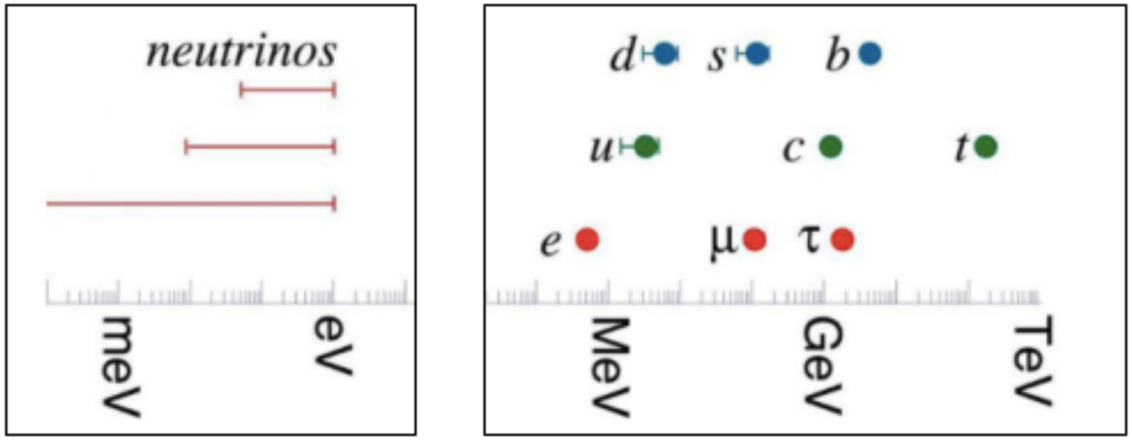
$$\Big\downarrow \langle H\rangle \sim 246 \text{ GeV}$$

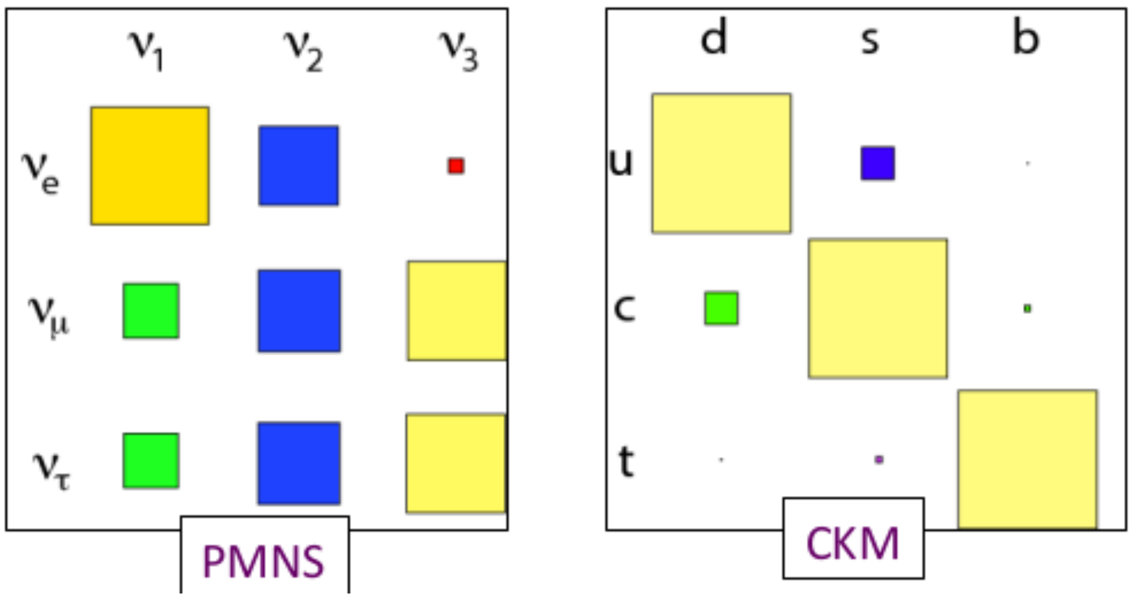
$$SU(3)\times U(1)_{em}$$

- SM fermion content
- Zero X charges for first two generations
- Solve anomaly cancellation for $U(1)_X$

The Flavour Problem

The Flavour Problem

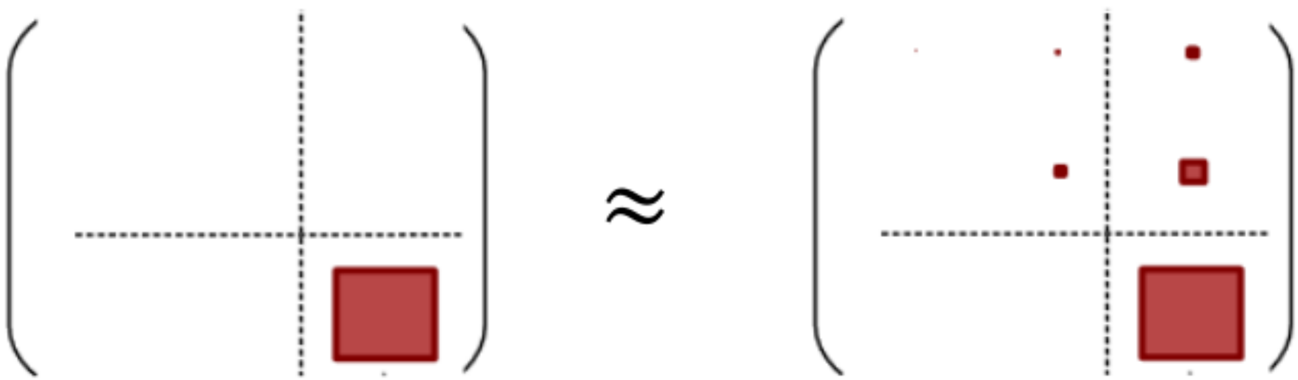




Unique Solution: $X = Y_3$

$$\begin{array}{cccc} X_{Q'_{1,2}} = 0 & X_{u_{R'_{1,2}}} = 0 & X_{d_{R'_{1,2}}} = 0 & X_{L'_{1,2}} = 0 \\ X_{e_{R'_{1,2}}} = 0 & X_H = -1/2 & X_{Q'_3} = 1/6 & X_{u'_{R3}} = 2/3 \\ X_{d'_{R3}} = -1/3 & X_{L'_3} = -1/2 & X_{e'_{R3}} = -1 & X_\theta \neq 0 \end{array}$$

$$\mathcal{L} = Y_t \overline{Q_3{}'_L} H t'_R + Y_b \overline{Q'_{3L}} H^c b'_R + Y_\tau \overline{L_3{}'_L} H^c \tau'_R + H.c.,$$



Y_3 Consequences

- Flavour changing TeV-scale Z' to do NCBAs: couples dominantly to quarks and leptons of the third family
- First two fermion families massless at renormalisable level
- Their masses and fermion mixings generated by small non-renormalisable operators

This explains the hierarchical heaviness of the third family and small CKM angles

$$\mathcal{L}_{X\psi} = g_X \left(\frac{1}{6}\overline{\mathbf{u_L}}\Lambda^{(u_L)}\gamma^\rho \mathbf{u_L} + \frac{1}{6}\overline{\mathbf{d_L}}\Lambda^{(d_L)}\gamma^\rho \mathbf{d_L} - \frac{1}{2}\overline{\mathbf{n_L}}\Lambda^{(n_L)}\gamma^\rho \mathbf{n_L} - \frac{1}{2}\overline{\mathbf{e_L}}\Lambda^{(e_L)}\gamma^\rho \mathbf{e_L} + \frac{2}{3}\overline{\mathbf{u_R}}\Lambda^{(u_R)}\gamma^\rho \mathbf{u_R} - \frac{1}{3}\overline{\mathbf{d_R}}\Lambda^{(d_R)}\gamma^\rho \mathbf{d_R} - \overline{\mathbf{e_R}}\Lambda^{(e_R)}\gamma^\rho \mathbf{e_R} \right) Z'_\rho,$$

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

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

A simple limiting case

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

for simplicity and the ease of passing bounds.

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

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

Important Z' Couplings

$$g_X \left[\frac{1}{6} (\overline{d_L}\ \overline{s_L}\ \overline{b_L}) \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin^2\theta_{23} & \frac{1}{2}\sin 2\theta_{23} \\ 0 & \frac{1}{2}\sin 2\theta_{23} & \cos^2\theta_{23} \end{pmatrix} \not{Z}' \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \right.$$

$$\left. -\frac{1}{2} (\overline{e_L}\ \overline{\mu_L}\ \overline{\tau_L}) \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \not{Z}' \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} \right]$$

$Z - Z'$ mixing

Because $Y_3(H) = 1/2$, $B - W^3 - X$ bosons mix:

$$\mathcal{M}_N^2 = \frac{1}{4}\begin{pmatrix} g'^2v^2 & -gg'v^2 & g'g_Xv^2 \\ -gg'v^2 & g^2v^2 & -gg_Xv^2 \\ g'g_Xv^2 & -gg_Xv^2 & 4g_X^2\langle\theta\rangle^2\left(1+\frac{\epsilon^2}{4}\right) \end{pmatrix} \begin{matrix} -B_\mu \\ -W_\mu^3 \\ -(X)_\mu \end{matrix}$$

- $v \approx 246$ GeV is SM Higgs VEV,
- $\langle\theta\rangle$ ~TeV. $M_{Z'} = g_X\langle\theta\rangle$.
- $g_X = U(1)_X$ gauge coupling
- $\epsilon \equiv v/\langle\theta\rangle \ll 1$

$Z - Z'$ mixing angle

$$\sin\alpha_z \approx \frac{g_X}{\sqrt{g^2 + g'^2}} \left(\frac{M_Z}{M'_Z}\right)^2 \ll 1.$$

This gives small non-flavour universal couplings to the Z boson propotional to g_X and:

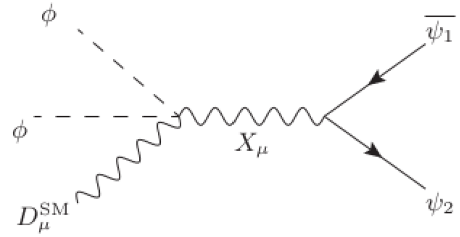
$$Z_\mu = \cos\alpha_z \left(-\sin\theta_w B_\mu + \cos\theta_w W^3_\mu\right) + \sin\alpha_z X_\mu,$$

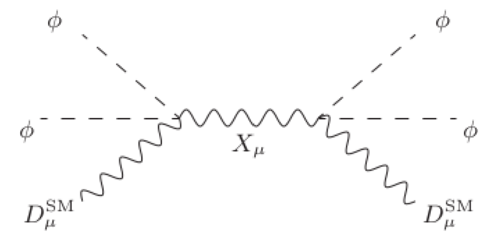
B/EW Observables

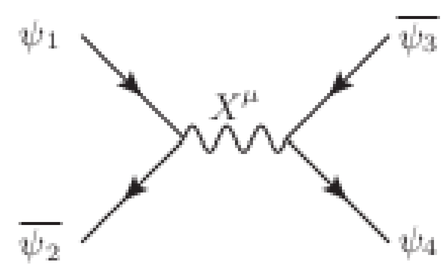
SMEFT$(M_{Z'})$ $\rightarrow$`smelli`$\rightarrow$WET(M_W) $\rightarrow$obs(m_B)

In units of g_X^2/M_X^2:

WC	value	WC	value
C_{ll}^{2222}	$-\frac{1}{8}$	$(\mathbf{C}_{\mathbf{lq}}^{(1)})^{22ij}$	$\frac{1}{12}\Lambda_{\xi\ ij}^{(d_L)}$
$(C_{qq}^{(1)})^{ijkl}$	$\Lambda_{\xi\ ij}^{(d_L)}\Lambda_{\xi\ kl}^{(d_L)}\frac{\delta_{ik}\delta_{jl}-2}{72}$	C_{ee}^{3333}	$-\frac{1}{2}$
C_{uu}^{3333}	$-\frac{2}{9}$	C_{dd}^{3333}	$-\frac{1}{18}$
C_{eu}^{3333}	$\frac{2}{3}$	C_{ed}^{3333}	$-\frac{1}{3}$
$(C_{ud}^{(1)})^{3333}$	$\frac{2}{9}$	C_{le}^{2233}	$-\frac{1}{2}$
C_{lu}^{2233}	$\frac{1}{3}$	C_{ld}^{2233}	$-\frac{1}{6}$
C_{qe}^{ij33}	$\frac{1}{6}\Lambda_{\xi\ ij}^{(d_L)}$	$(C_{qu}^{(1)})^{ij33}$	$-\frac{1}{9}\Lambda_{\xi\ ij}^{(d_L)}$
$(C_{qd}^{(1)})^{ij33}$	$\frac{1}{18}\Lambda_{\xi\ ij}^{(d_L)}$	$(C_{\phi l}^{(1)})^{22}$	$\frac{1}{4}$
$(C_{\phi q}^{(1)})^{ij}$	$-\frac{1}{12}\Lambda_{\xi\ ij}^{(d_L)}$	$C_{\phi e}^{33}$	$\frac{1}{2}$
$C_{\phi u}^{33}$	$-\frac{1}{3}$	$C_{\phi d}^{33}$	$\frac{1}{6}$
$C_{\phi D}$	$-\frac{1}{2}$	$C_{\phi\Box}$	$-\frac{1}{8}$







smelli observables

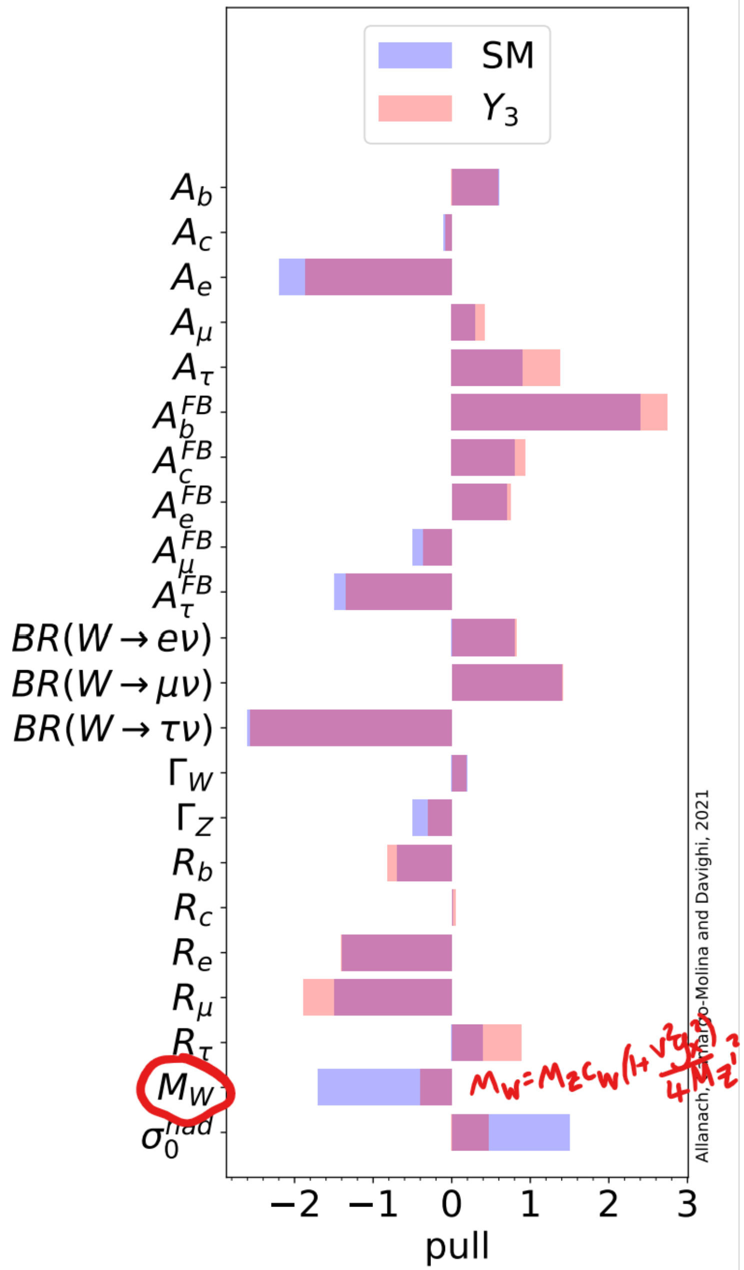
- 167 quarks: P_5', $BR(B_s \to \mu^+\mu^-)$ and others with significant theory errors
- 21 LFU FCNCs: $R_K, R_{K^\star}$, $B \to$di-tau decays
- 31 EWPOs from LEP not assuming lepton flavour universality

Theory uncertainties modelled as multi-variate Gaussians: approximated to be independent of new physics.

SM:

data set	χ^2	n	$p-$value
quarks	221.6	167	.003
LFU FCNCs	35.3	21	.026
EWPOs	35.7	31	.26
global	292.6	219	.00065

Global Fits $M_{Z'} = 3$ TeV

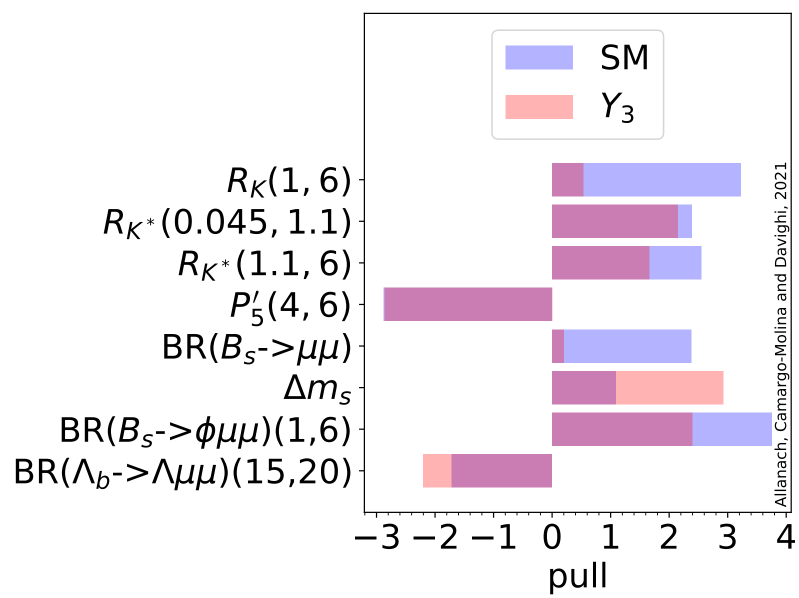


SM

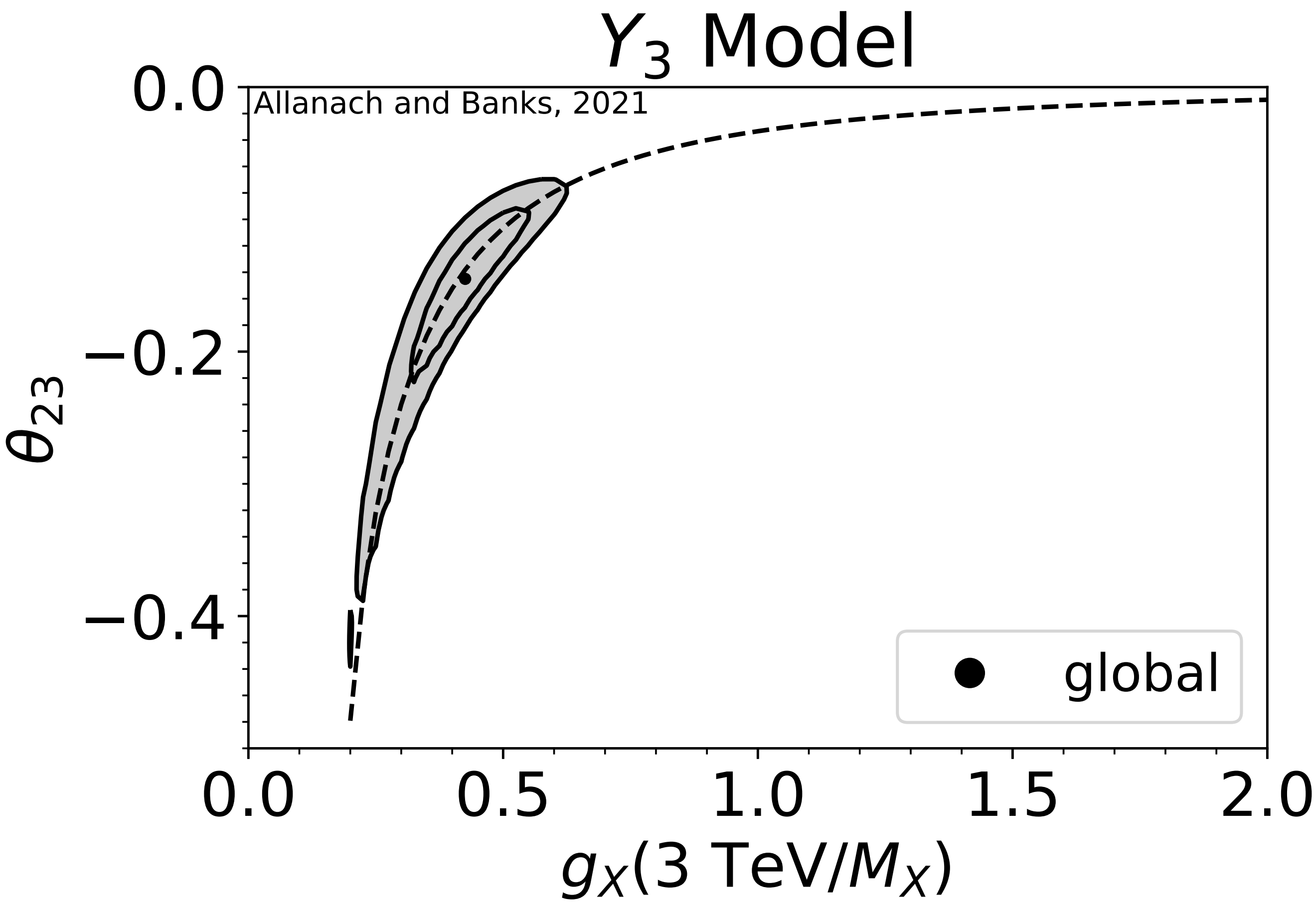
data set	χ^2	n	p−value
quarks	221.6	167	.003
LFU FCNCs	35.3	21	.026
EWPOs	35.7	31	.26
global	292.6	219	.00065

Y_3

data set	χ^2	n	p−value
quarks	192.5	167	.071
LFU FCNCs	21.0	21	.34
EWPOs	36.0	31	.17
global	249.5	219	.064



TFHM Fit, 95% CL

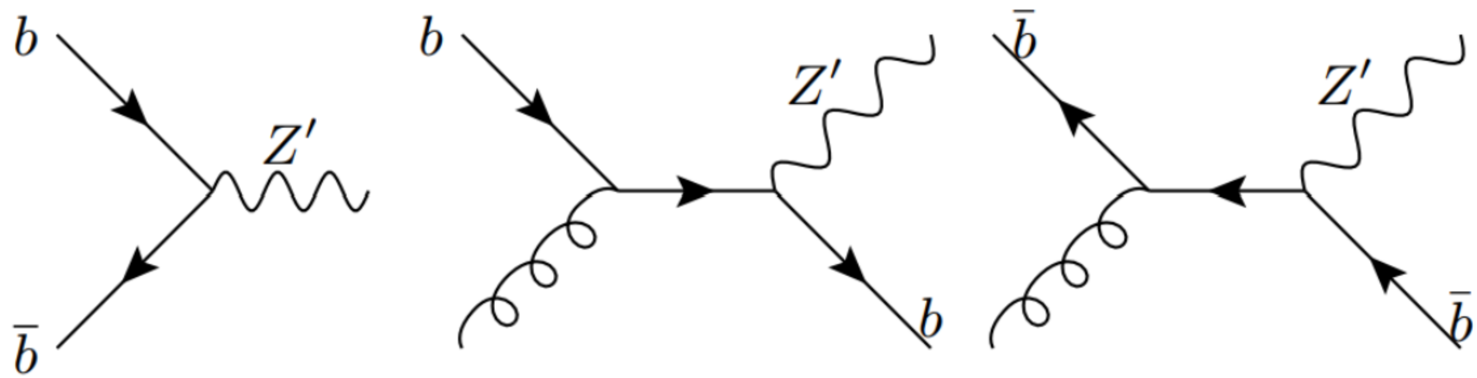


Relies on: `smelli-2.2.0` (Aebischer, Kumar, Stangl, Straub, `1810.07698`), `flavio-2.2.0` (Straub, `1810.08132`), `Wilson` (Aebischer *et al*, `1712.05298`)

Z' Decay Modes

Mode	BR	Mode	BR	Mode	BR
$t\bar{t}$	0.42	$b\bar{b}$	0.12	$\nu\bar{\nu}'$	0.08
$\mu^+\mu^-$	0.08	$\tau^+\tau^-$	0.30	other $f_i f_j$	$\sim \mathcal{O}(10^{-4})$

LHC Z' Production:



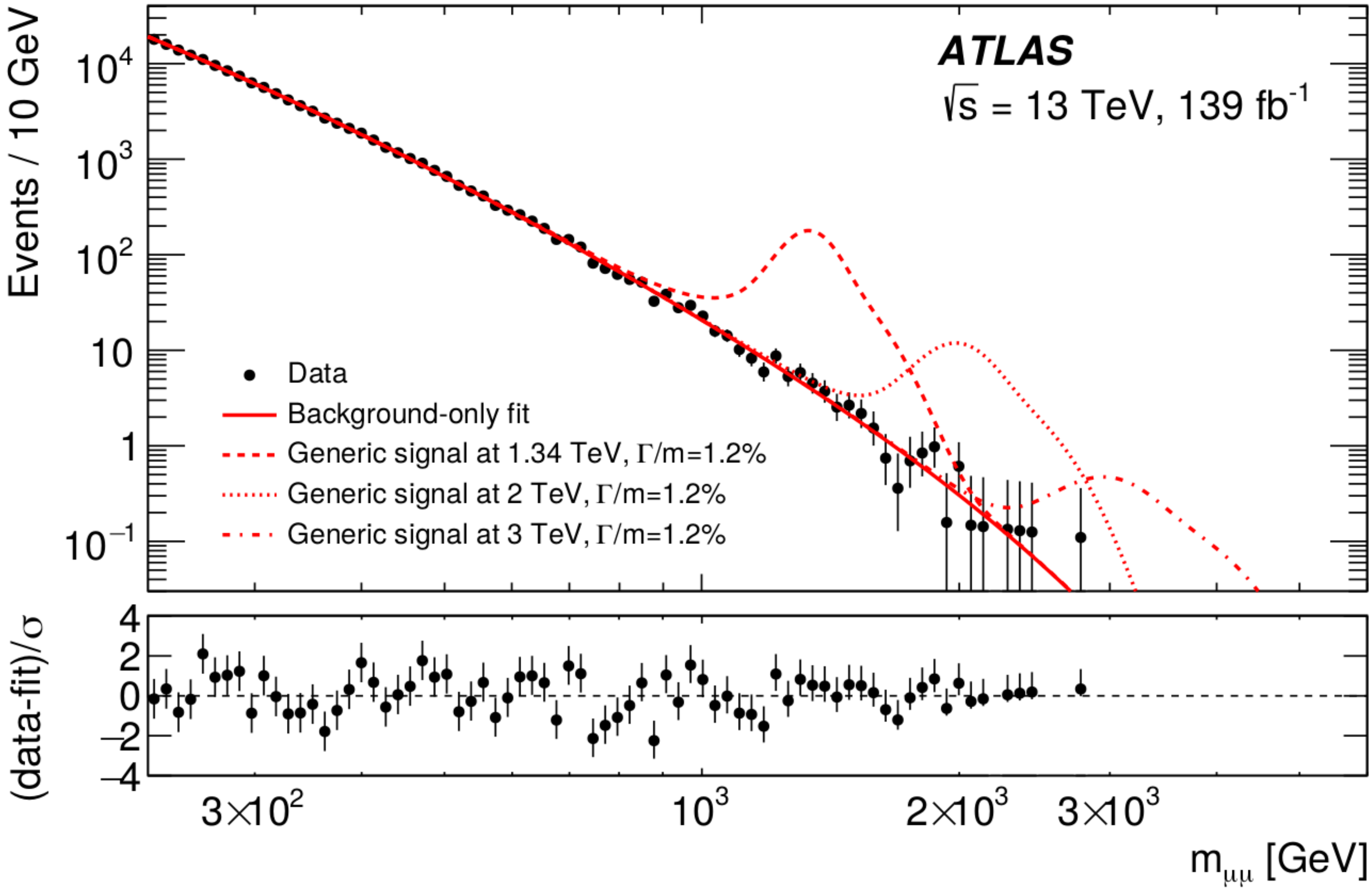
$Z' \to \mu\mu$ ATLAS 13 TeV 139 fb^{-1}

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[5]

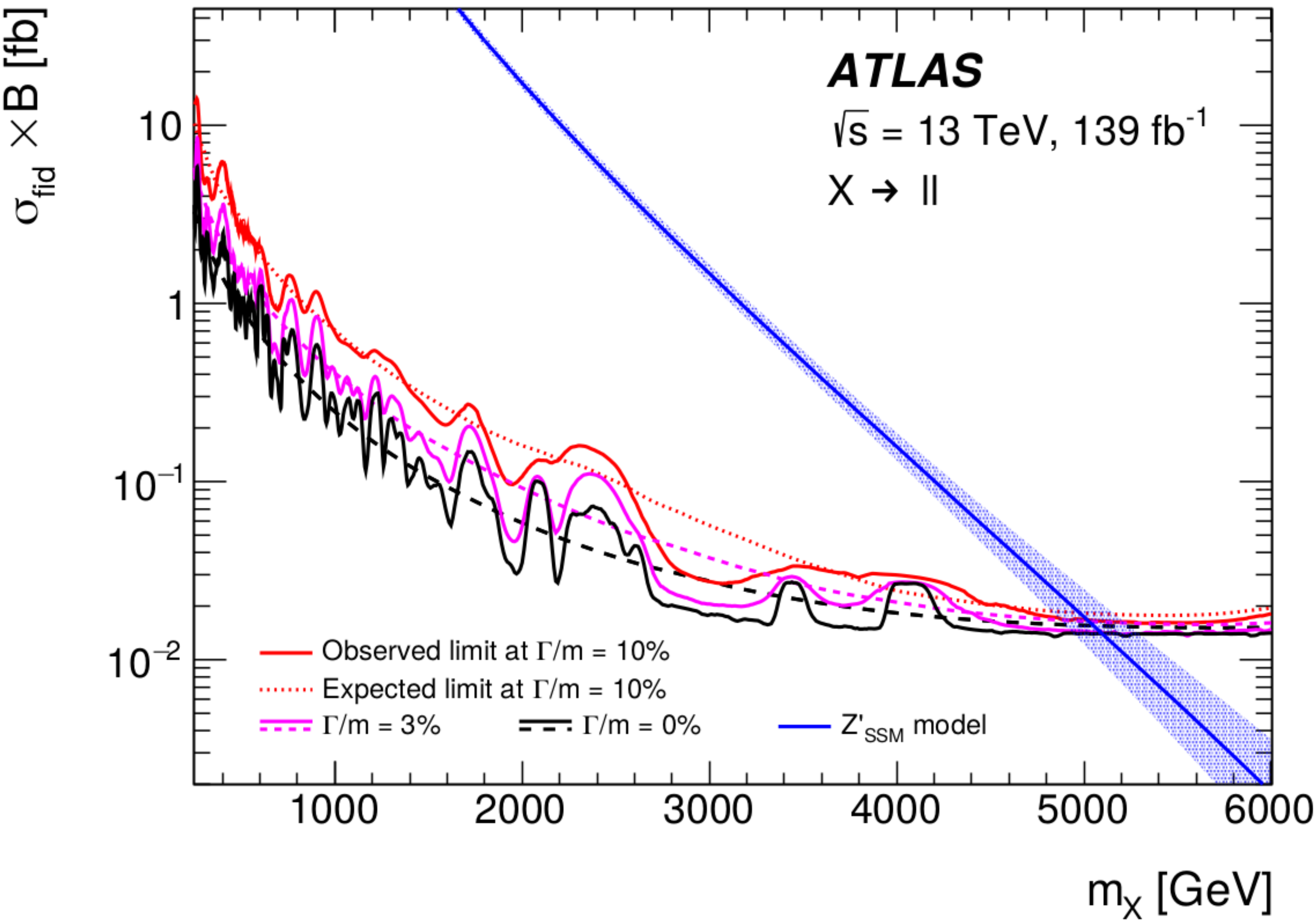
$$m^2_{\mu_1\mu_2} = (p_1^\mu + p_2^\mu)\left(p_{1_\mu} + p_{2_\mu}\right)$$

CMS also have released[6] a 139 fb^{-1} analysis.

[5] 1903.06248
[6] 2103.02708

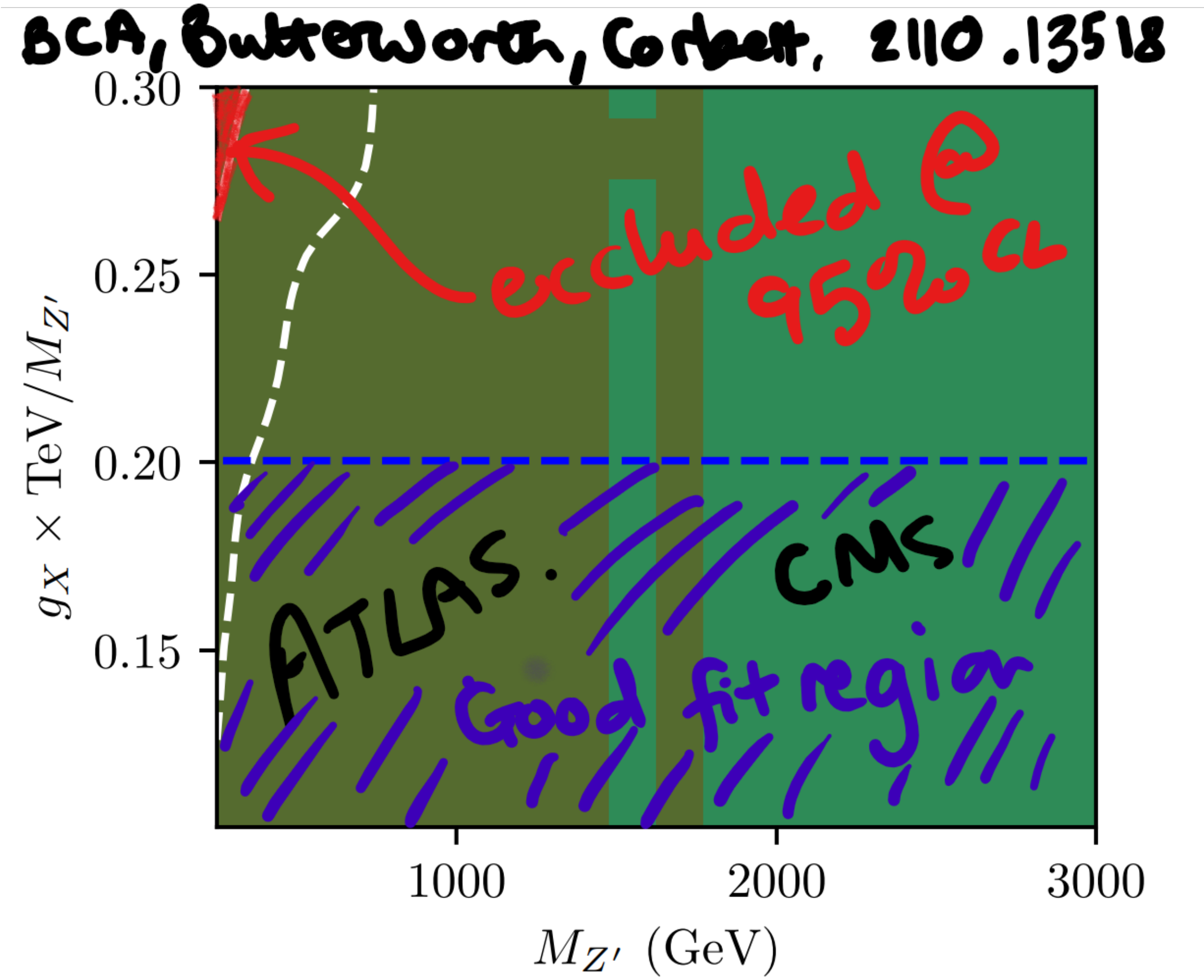

ATLAS
√s = 13 TeV, 139 fb-1
Events / 10 GeV
Data
Background-only fit
Generic signal at 1.34 TeV, Γ/m=1.2%
Generic signal at 2 TeV, Γ/m=1.2%
Generic signal at 3 TeV, Γ/m=1.2%
(data-fit)/σ
m_μμ [GeV]

ATLAS l^+l^- limits

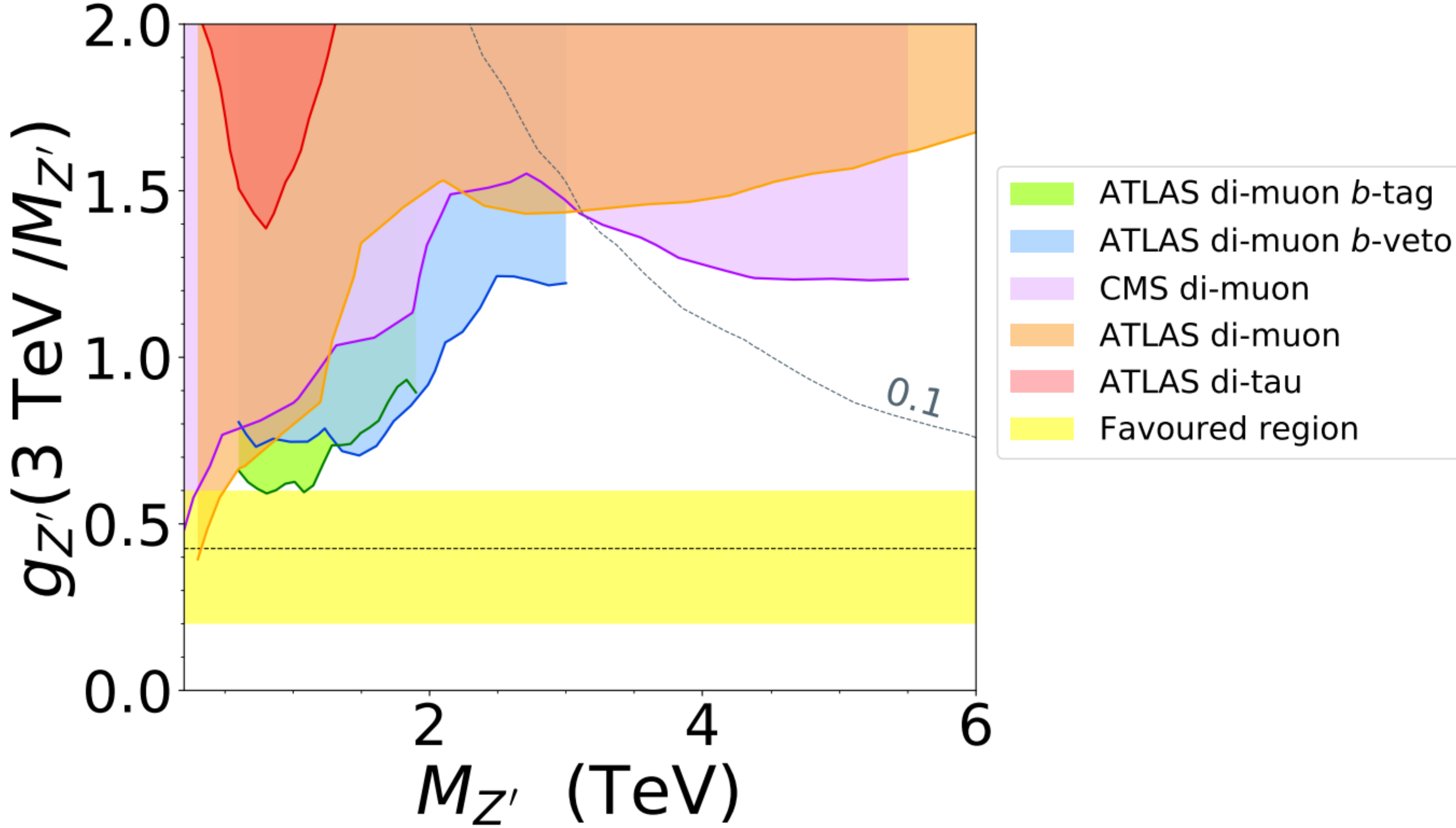


1903.06248

TFHM $Z' \to \mu^+\mu^-$+SM obs

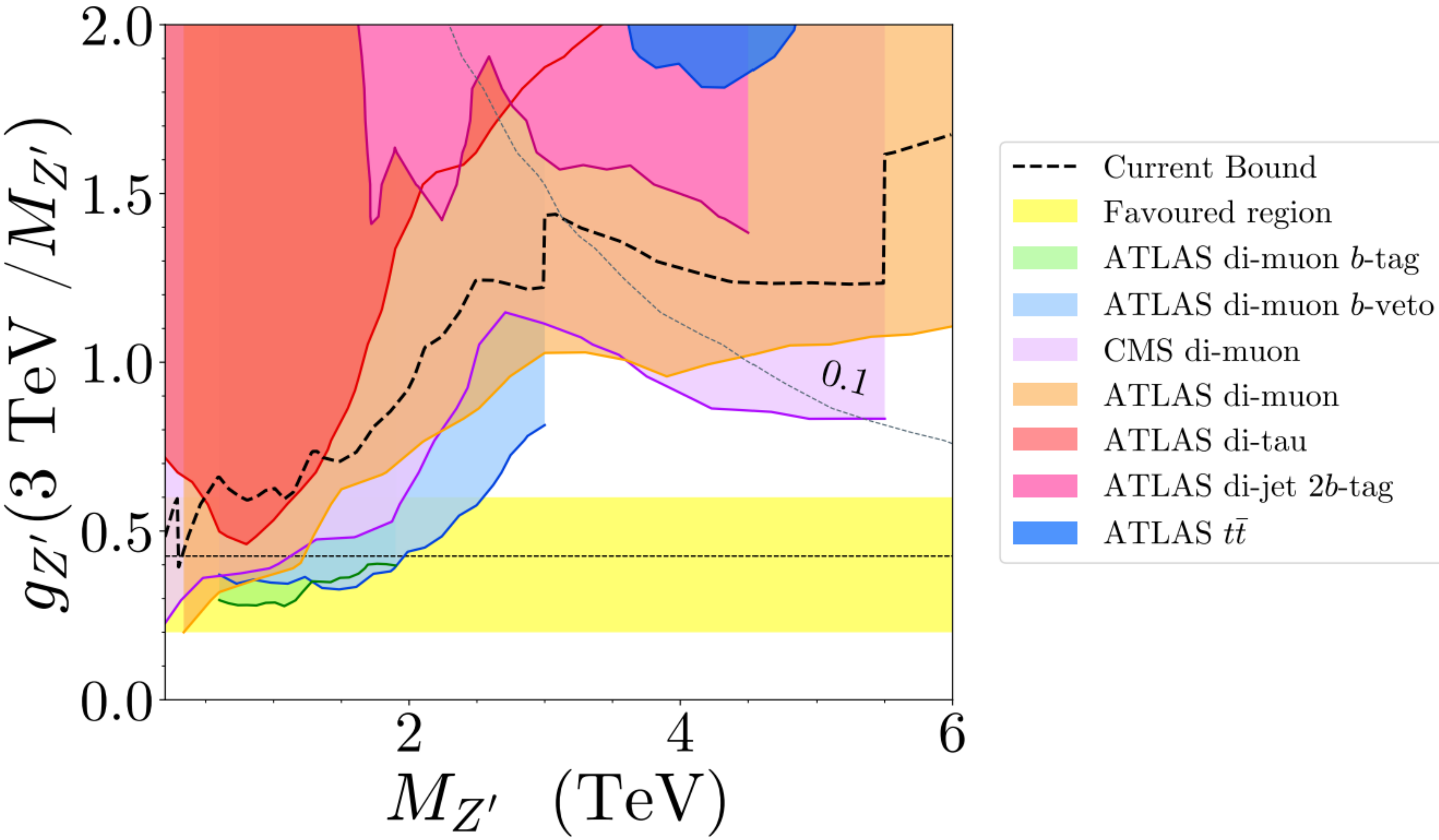


Other Z' Searches[7]



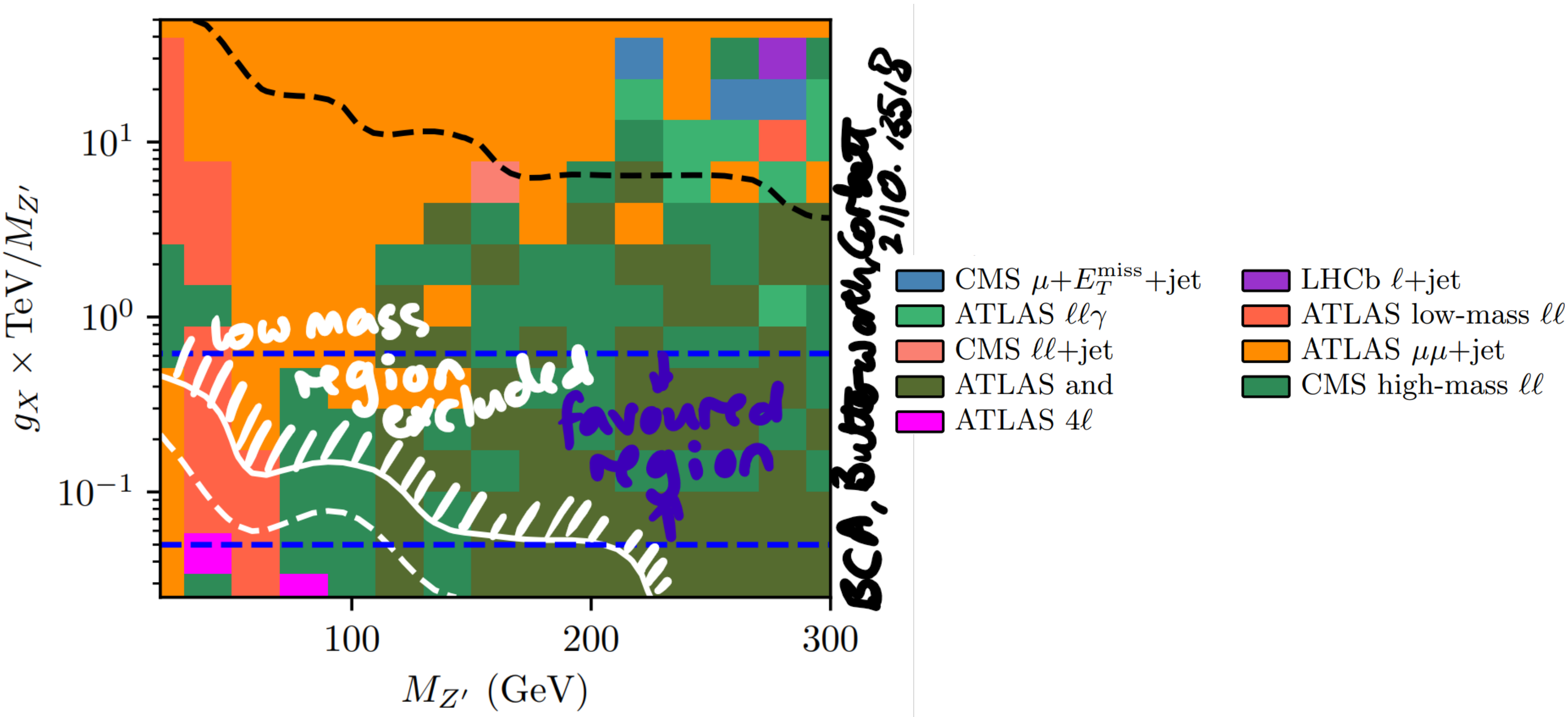
[7] BCA, Banks, 2111.06691

HL-LHC sensitivity[8]



[8] BCA, Banks, 2111.06691

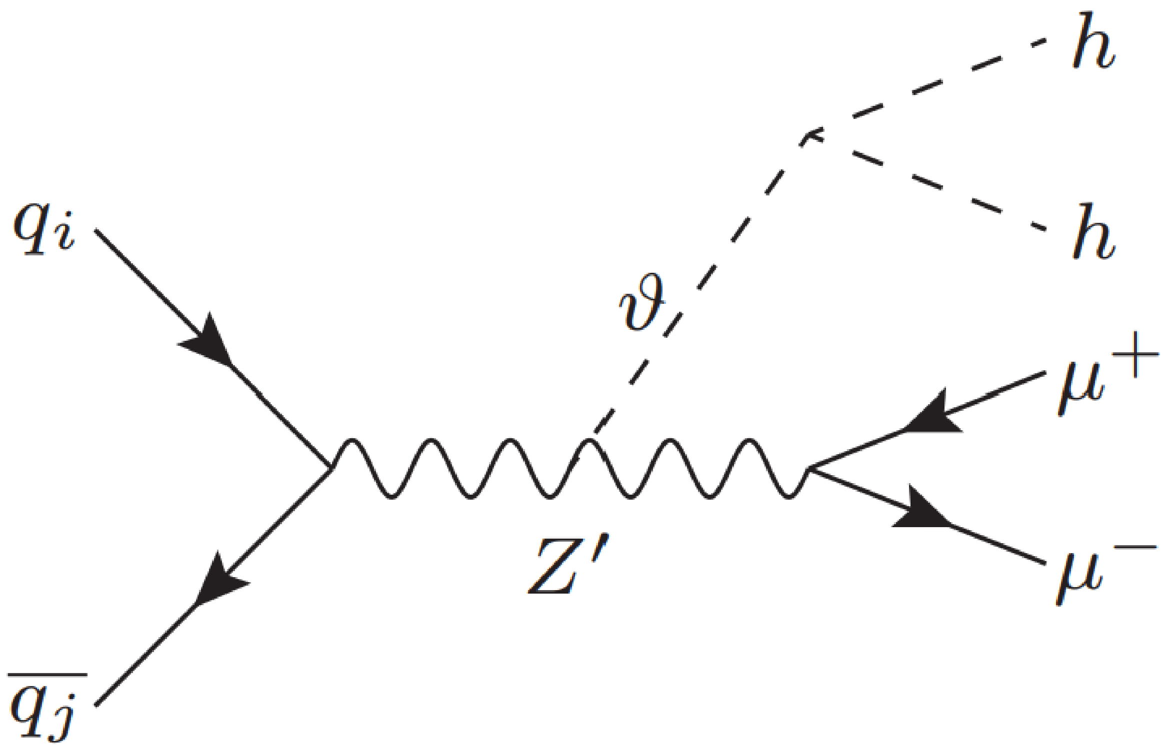
$B_3 - L_2$ model's[9] Z'



[9] Bonilla, Modak, Srivastava, Valle, 1705.00915, Alonso, Cox, Han, Yanagida 1705.03858

Flavonstrahlung[10]

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



[10]BCA, 2009.02197

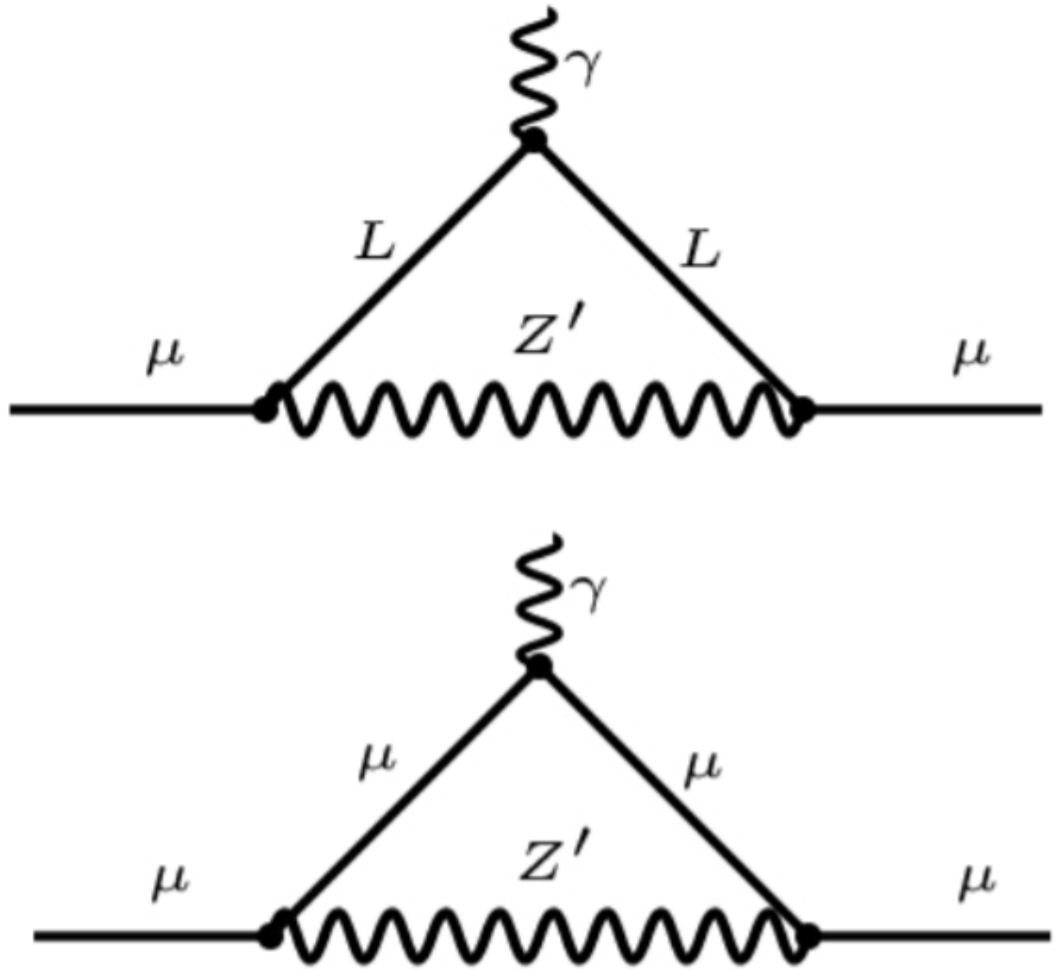
Why $\bar{b}s\mu^+\mu^-$?

If we take these $B-$anomalies seriously, we may ask: why are we seeing the first BSM flavour changing effects particularly in the $b \to s\mu^+\mu^-$ transition, not another one?

Perhaps it's because, in hindsight:

- The largest BSM flavour effects are in heavier generations
- We have many more bs than ts, particularly in LHCb
- Leptons in final states are good experimentally but not (yet) τs: they are too difficult!

$(g-2)_\mu$



Trident Neutrino Process

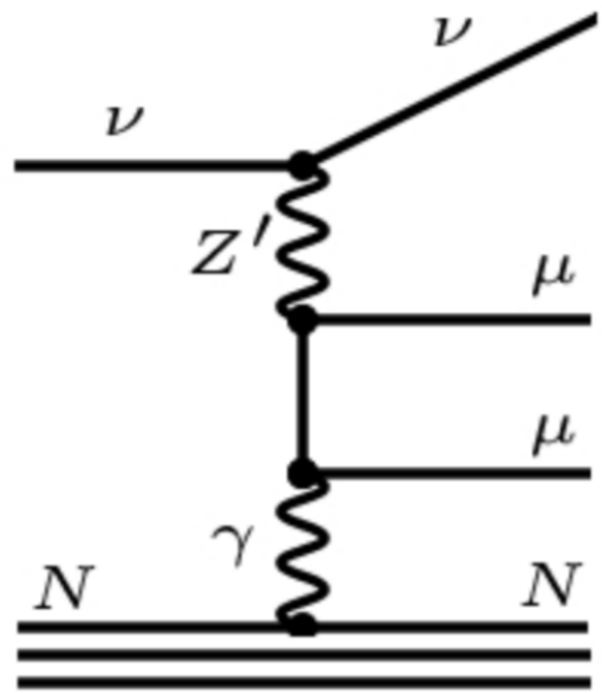
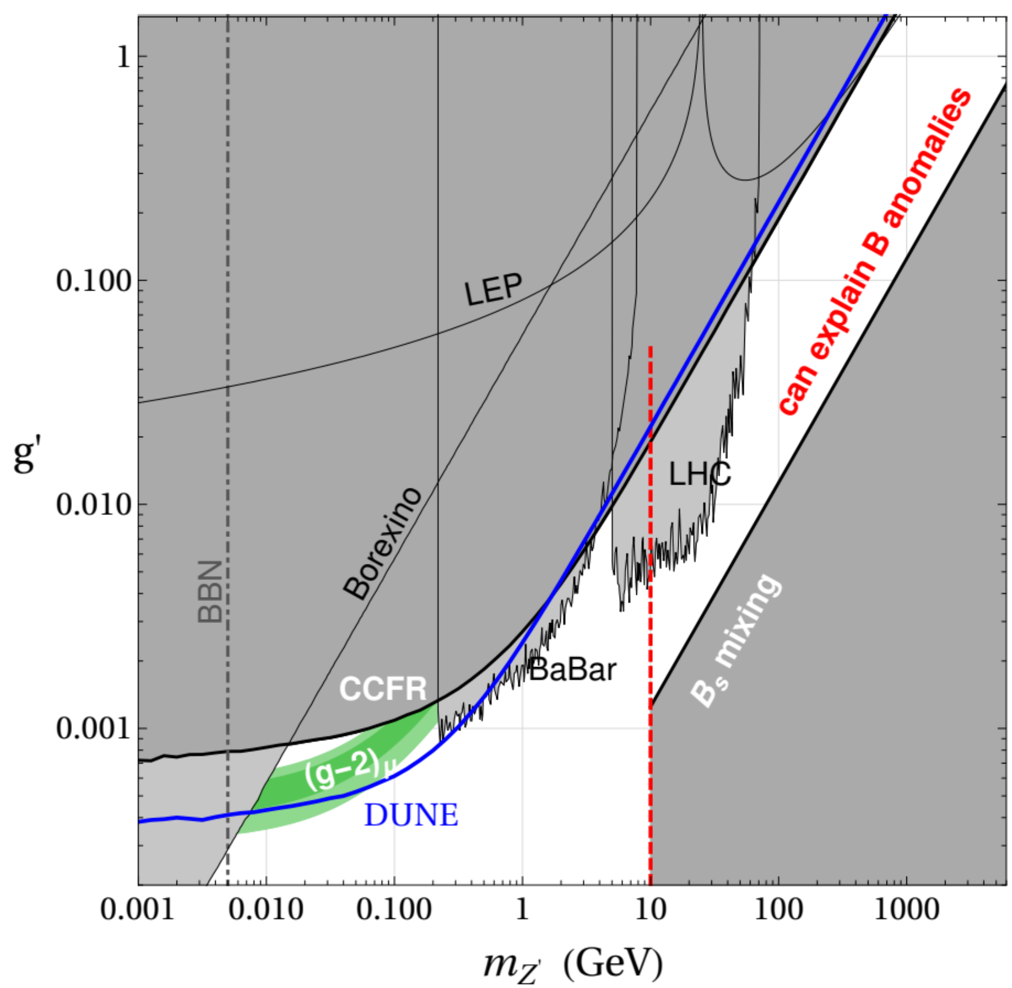


FIG. 10. Neutrino trident process that leads to constraints on the Z^{μ} coupling strength to neutrinos-muons, namely $M_{Z'}/g_{v\mu} \gtrsim 750$ GeV.

Light Z' for $(g-2)_\mu$: $L_\mu - L_\tau$

Altmannshofer, Gori, Martin-Albo, Sousa, Wallbank 1902.06765



Manifesto

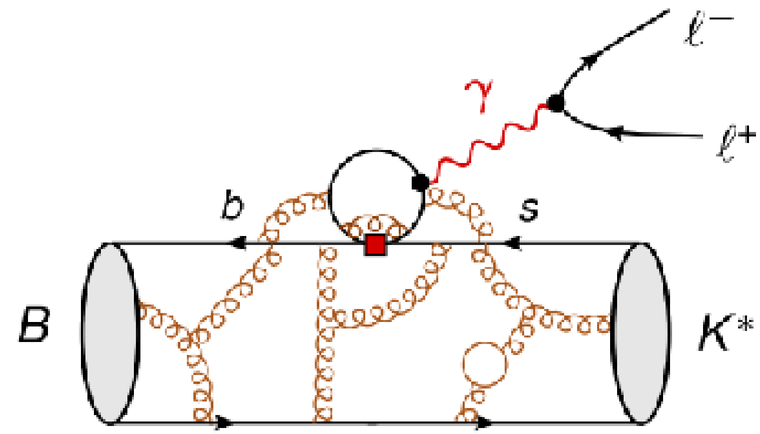
If we (the Z' party) are elected to Nature, we pledge to:

- Explain the $b \to s\mu^+\mu^-$ anomalies.
- Explain some features of the fermion mass puzzle.
- We might explain $(g-2)_\mu$. But then in two years we might do a massive U-turn (if the SM prediction shifts to the measurement).
- Have a mass less than 8 TeV for perturbativity.
- Be found in a hadron collider. You can then measure our couplings and get a direct experimental handle on the fermion mass puzzle.

Backup

Hadronic Uncertainties

- Hadronic effects like charm loop are photon-mediated ⇒ vector-like coupling to leptons just like C_9



- How to disentangle NP ↔ QCD?
  - Hadronic effect can have different q^2 dependence
  - Hadronic effect is lepton flavour universal ($\rightarrow R_K$!)

Wilson Coefficients c^l_{ij}

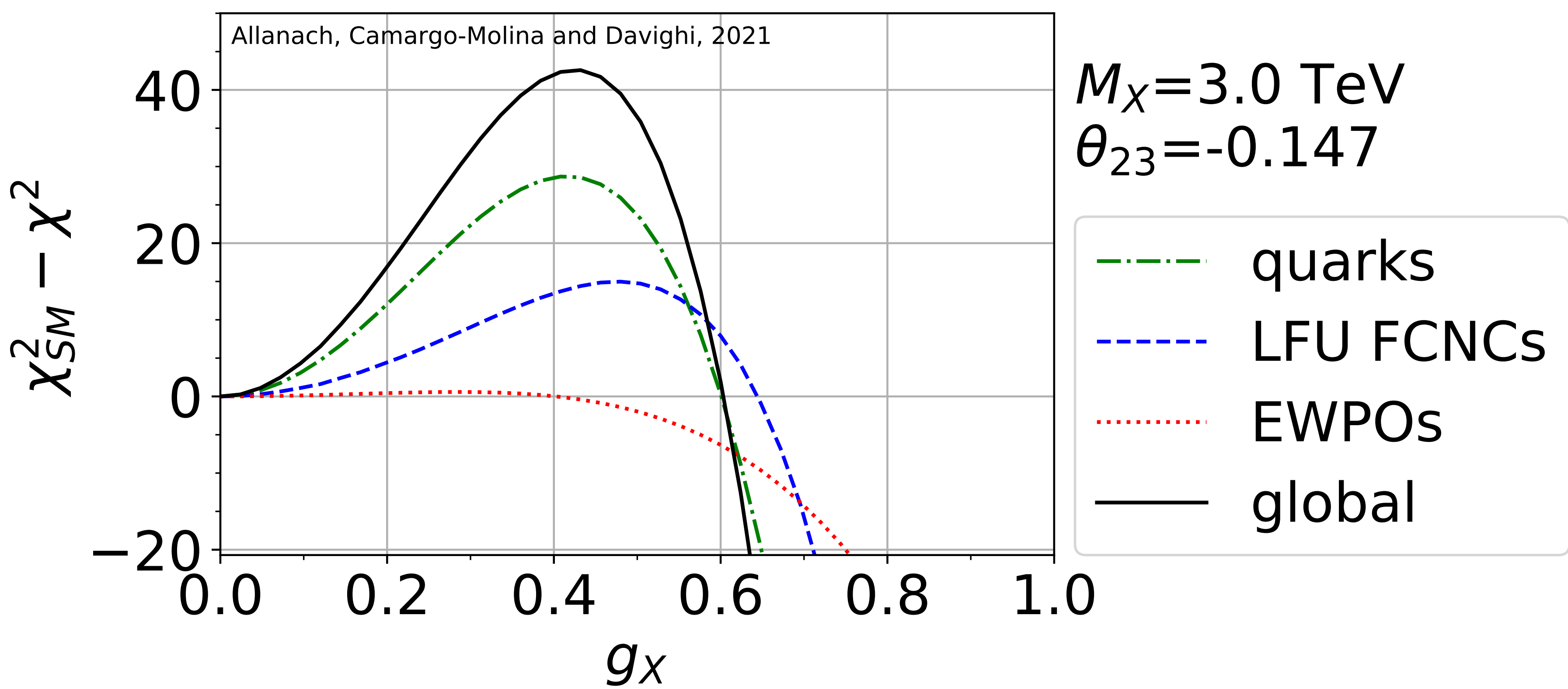
In SM, can form an EFT since $m_B \ll M_W$:

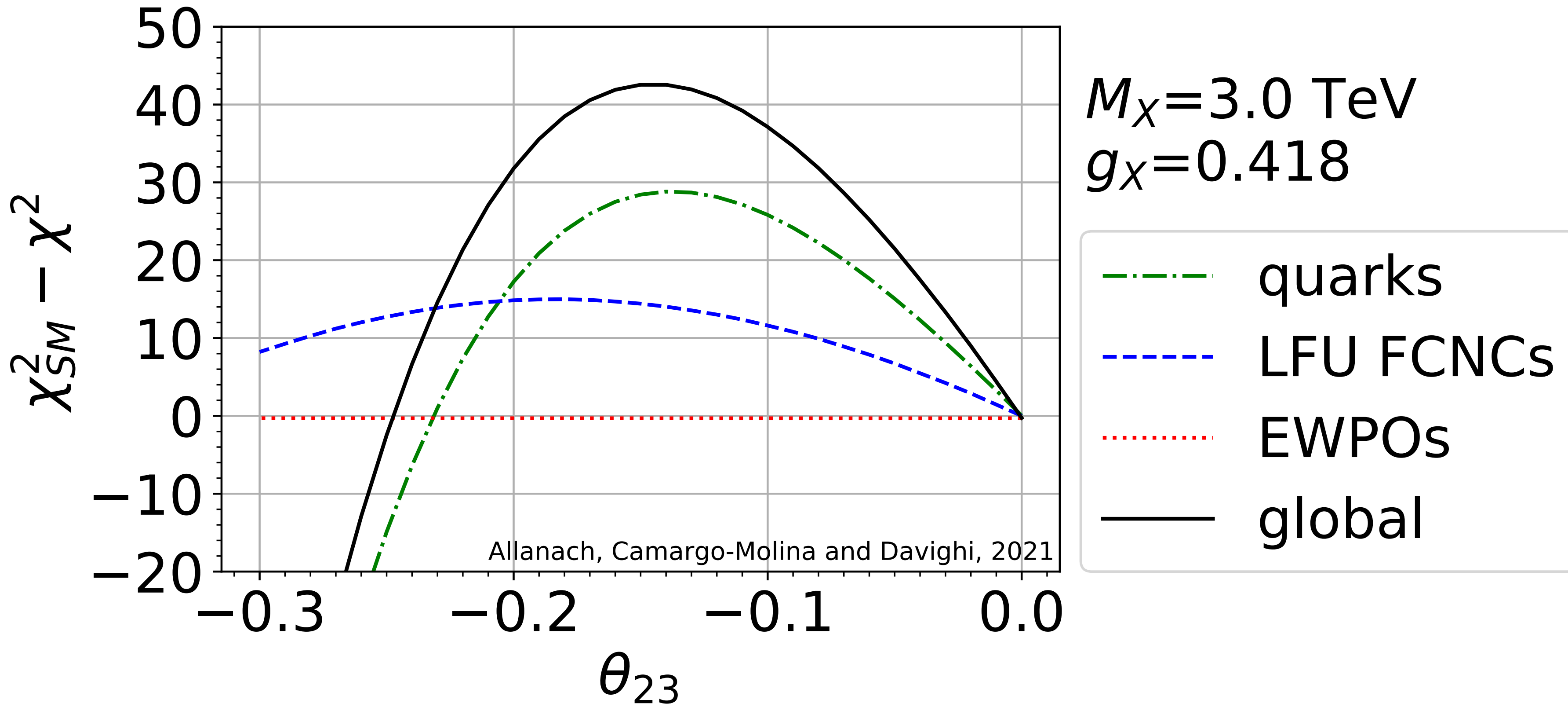
$$\mathcal{L}_{\text{eff}} = \frac{1}{(36 \text{ TeV})^2} c^l_{ij} (\bar{s}\gamma^\mu P_i b)(\bar{l}\gamma_\mu P_j l) \qquad (1)$$

One loop weak interactions give $c^l_{ij} \sim \pm\mathcal{O}(1)$ in SM. $(1/36 \text{ TeV})^2 = V_{tb}V^*_{ts}\alpha/(4\pi v^2)$.

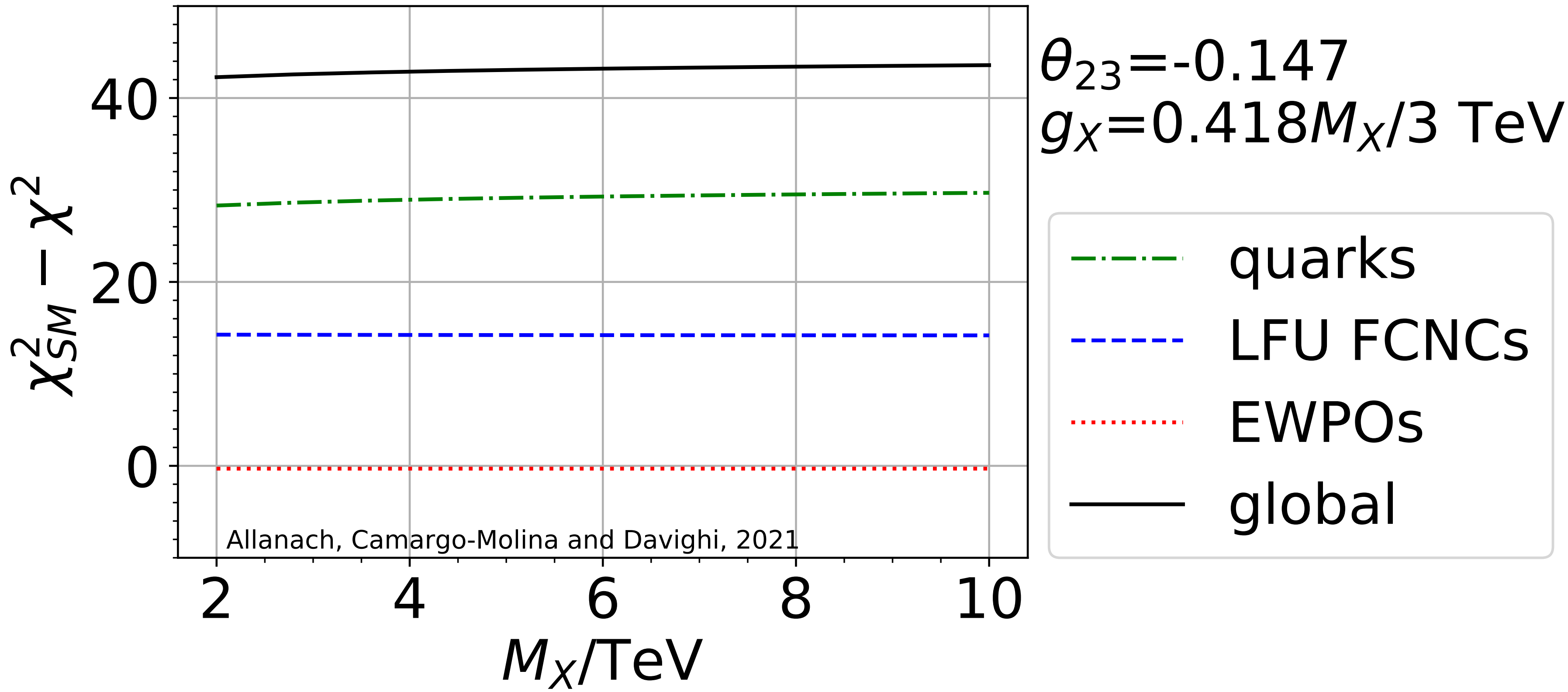
From now on, c^l_{ij} refer to *beyond* SM contribution.

TFHM Near best-fit point





50
40
30
20
10
0
−10
−20
−0.3
−0.2
−0.1
0.0
$\chi^2_{SM} - \chi^2$
θ_{23}
Allanach, Camargo-Molina and Davighi, 2021
M_X=3.0 TeV
g_X=0.418
quarks
LFU FCNCs
EWPOs
global



θ_{23}=-0.147
g_X=0.418M_X/3 TeV
quarks
LFU FCNCs
EWPOs
global
$\chi^2_{SM} - \chi^2$
40
20
0
2
4
6
8
10
M_X/TeV
Allanach, Camargo-Molina and Davighi, 2021

Which Ones Work?

Options *for a single* *BSM* *operator*:

- c^e_{ij} operators fine for $R_{K^{(*)}}$ but are disfavoured by global fits including other observables.
- c^μ_{LR} disfavoured: predicts *enhancement* in both R_K and R_{K^*}
- c^μ_{RR}, c^μ_{RL} disfavoured: they pull R_K and R_{K^*} in *opposite directions*.
- $c^\mu_{LL} = -1.06$ fits well globally[11].

[11] D'Amico et al, 1704.05438; Aebischer et al 1903.10434.

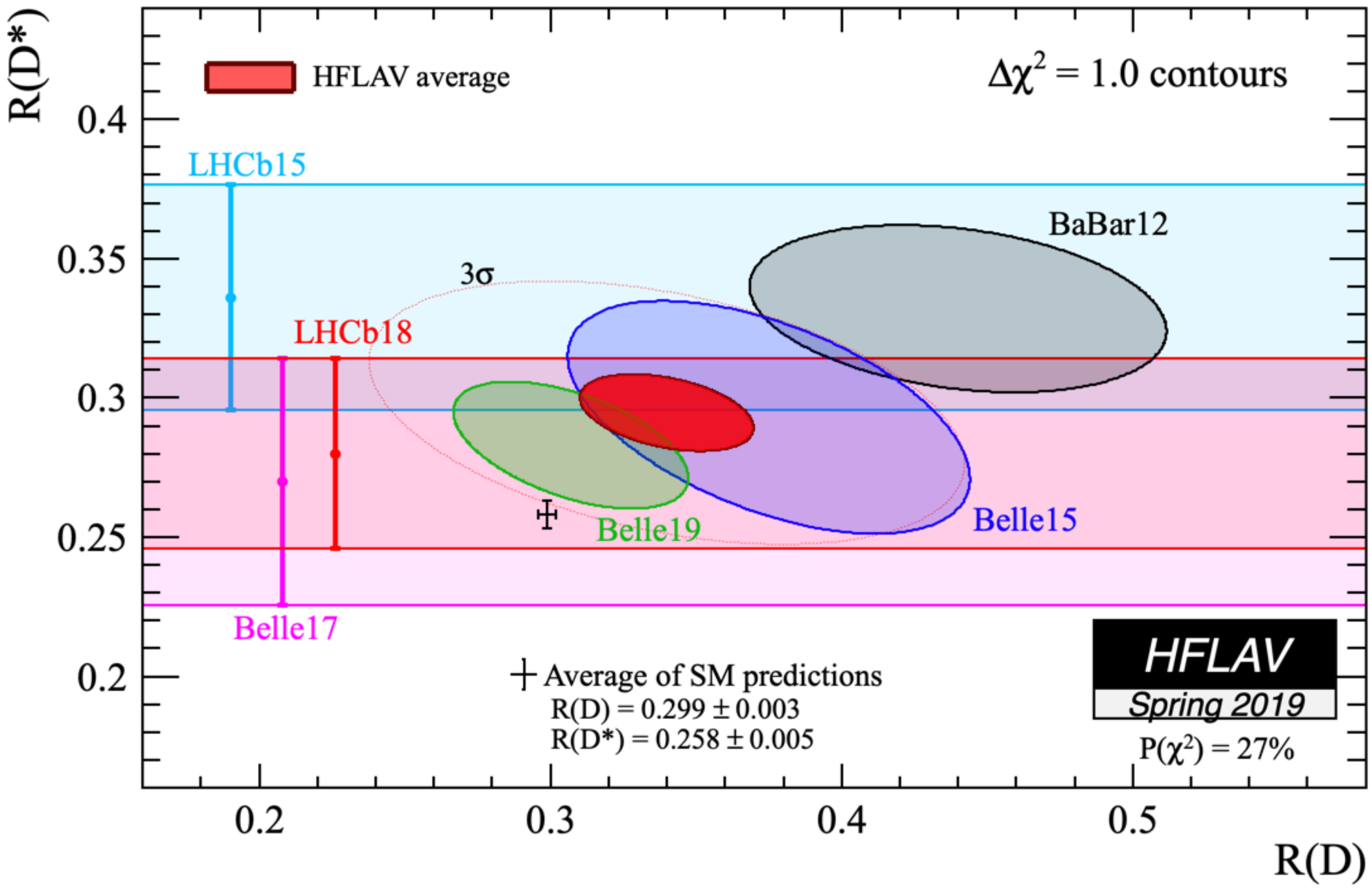
Invisible Width of Z Boson

$\Gamma_{\text{inv}}^{(\text{exp})} = 499.0 \pm 1.5$ MeV, whereas $\Gamma_{\text{inv}}^{(\text{SM})} = 501.44$ MeV.

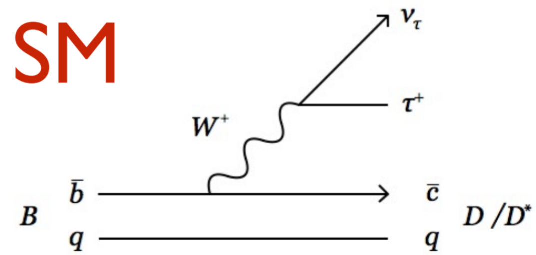
$$\Rightarrow \Delta\Gamma^{(\text{exp})} = \Gamma_{\text{inv}}^{(\text{exp})} - \Gamma_{\text{inv}}^{(\text{SM})} = -2.5 \pm 1.5 \text{ MeV}.$$

$$\begin{aligned}\mathcal{L}_{\bar{\nu}\nu Z} &= -\frac{g}{2\cos\theta_w}\overline{\nu'_{Le}}\not{Z} P_L \nu'_{Le} \\ &\quad -\overline{\nu'_{L\mu}}\left(\frac{g}{2\cos\theta_w} + \frac{5}{6} g_F \sin\alpha_z\right)\not{Z}\nu'_{L\mu} \\ &\quad -\overline{\nu'_{L\tau}}\left(\frac{g}{2\cos\theta_w} - \frac{8}{6} g_F \sin\alpha_z\right)\not{Z}\nu'_{L\tau}.\end{aligned}$$

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



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



. . . has to compete with

$$\mathcal{L}_{eff} = -\frac{2}{\Lambda^2}\left(\bar{c}_L\gamma^\mu b_L\right)\left(\bar{\tau}_L\gamma_\mu\nu_{\tau L}\right) + H.c.$$

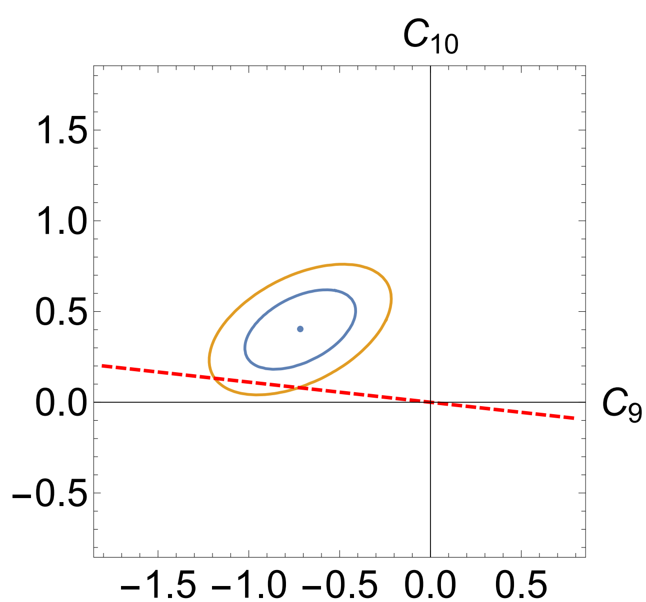
$$\Lambda = 3.4 \text{ TeV}$$

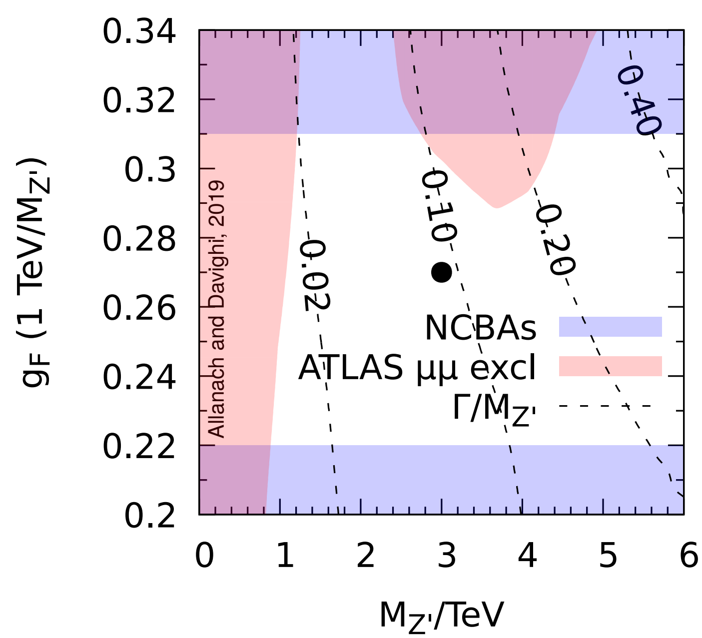
A factor 10 lower than required for $R_{K^{(*)}} \Rightarrow$ *different explanation?*

Deformed TFHM

$$\begin{array}{llll} F_{Q_i'} = 0 & F_{u_{Ri}'} = 0 & F_{d_{Ri}'} = 0 & F_H = -1/2 \\ F_{e_{R1}'} = 0 & F_{e_{R2}'} = 2/3 & F_{e_{R3}'} = -5/3 & \\ F_{L_1'} = 0 & F_{L_2'} = 5/6 & F_{L_3'} = -4/3 & \\ F_{Q_3'} = 1/6 & F_{u'_{R3}} = 2/3 & F_{d'_{R3}} = -1/3 & F_\theta \neq 0 \end{array}$$

$$\mathcal{L} = Y_t \overline{Q_3'{}_L} H t_R' + Y_b \overline{Q_{3L}'} H^c b_R' + H.c.,$$





Neutrino Masses

At dimension 5:

$$\mathcal{L}_{SS} = \frac{1}{2M}({L'_3}^T H^c)(L'_3 H^c),$$

but if we add RH neutrinos, then integrate them out

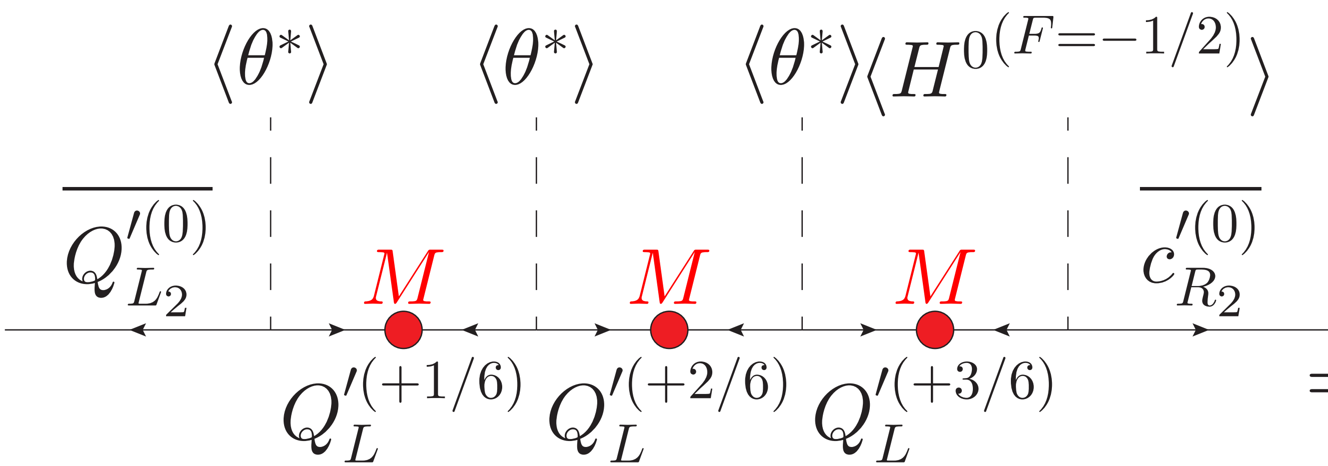
$$\mathcal{L}_{SS} = 1/2 \sum_{ij} (L'_i H^c)(M^{-1})_{ij}(L'_j H^c),$$

where now $(M^{-1})_{ij}$ may well have a non-trivial structure. If $(M^{-1})_{ij}$ are of same order, large PMNS mixing results.

Froggatt Neilsen Mechanism[12]

A means of generating the non-renormalisable Yukawa terms, e.g. $X_\theta = 1/6$:

$$Y_c \overline{Q'_{L2}}^{(F=0)} H^{(F=-1/2)} {c'_R}^{(F=0)} \sim \mathcal{O}\left[\left(\frac{\langle\theta\rangle}{M}\right)^3 \overline{Q'_{L2}} H c'_R\right]$$



eg $\left(\frac{\langle\theta\rangle}{M}\right) \sim 0.2$

$\Rightarrow Y_c/Y_t \sim 1/100$

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[12] C Froggatt and H Neilsen, NPB **147** (1979) 277