Z' Searches for Models Explaining NCBAs

by
Ben Allanach
(DAMTP, University of Cambridge)

- Third Family Hypercharge Models (BCA, Davighi, 1809.01158; ibid 1905.10327)
- Global fits (BCA, Camargo-Molina, Davighi, 2103.12056, v2 tomorrow)
- $Z' \to \mu^+\mu^-$ search (BCA, Butterworth, Corbett, 1904.10954)

Cambridge Pheno Working Group

Where data and theory collide

Science & Technology Facilities Council

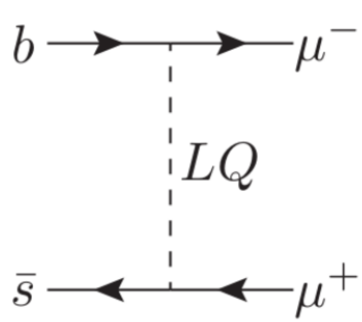
Strange b Activity

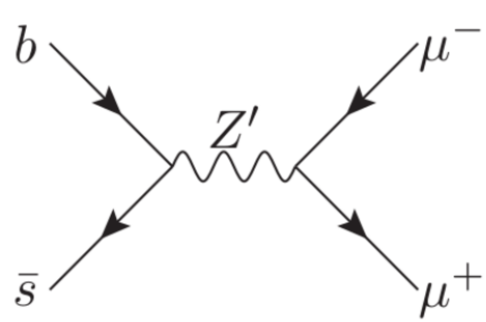
Simplified Models for NCBAs

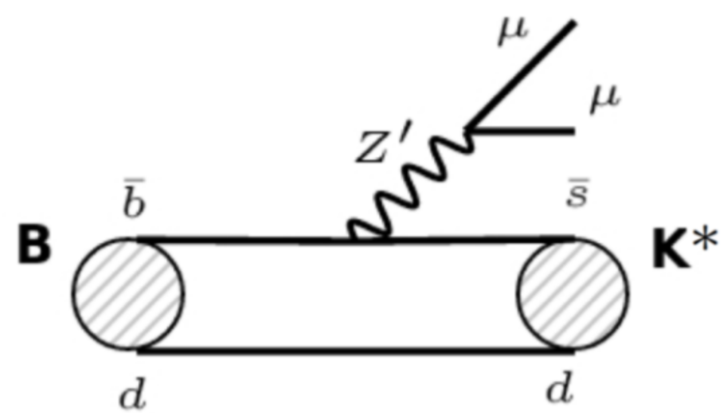
$2-4\sigma$ Discrepancies with SM predictions in (2021):

- R_K, R_{K^*}
- $BR(B_s \to \mu^+\mu^-)$
- $BR(B_s \to \phi\mu^+\mu^-)$
- Angular distributions of $B \to K^*\mu^+\mu^-$

We have tree-level new physics options:







A Simple TFHM Model

BCA, Davighi, 1809.01158: Add complex SM-singlet scalar θ and gauged $U(1)_{Y3}$:

$$SU(3)\times SU(2)_L\times U(1)_Y\times U(1)_{Y3}$$
$$\Big\downarrow \langle\theta\rangle \sim \text{Several TeV}$$
$$SU(3)\times SU(2)_L\times U(1)_Y$$
$$\Big\downarrow \langle H\rangle \sim 246\text{ GeV}$$
$$SU(3)\times U(1)_{em}$$

- SM fermion content, anomaly cancellation
- Zero $Y3$ charges for first two generations
- Third family charge $Y3$ =hypercharge

TFHM Consequences

- Flavour changing TeV-scale Z' to do NCBAs: couples dominantly to third family quarks and second family leptons
- 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

$Z - Z'$ mixing

Because $Y3_H = 1/2$, $B - W3 - Y3$ mix:

$$\mathcal{M}_N^2 = \frac{v^2}{4}\begin{pmatrix} g'^2 & -gg' & g'g_X \\ -gg' & g^2 & -gg_X \\ g'g_X & -gg_X & g_X^2(1+4F_\theta^2 r^2) \end{pmatrix} \begin{matrix} -B_\mu \\ -W_\mu^3 \\ -Y3_\mu \end{matrix}$$

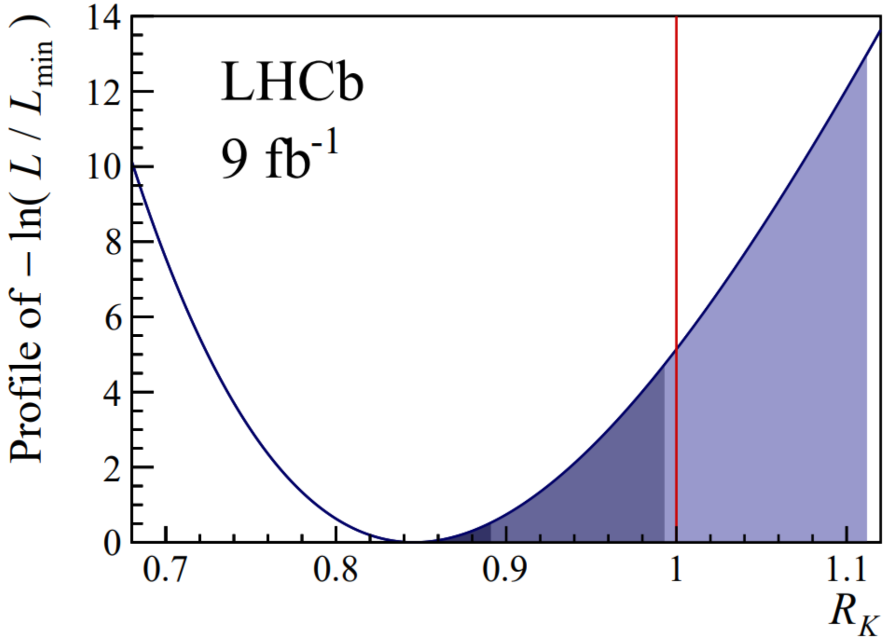
- $v \approx 246$ GeV is SM Higgs VEV
- $g_X = U(1)_{Y3}$ gauge coupling
- $r \equiv v_F/v \gg 1$, where $v_F = \langle\theta\rangle$
- F_θ is $Y3$ *charge* of θ field

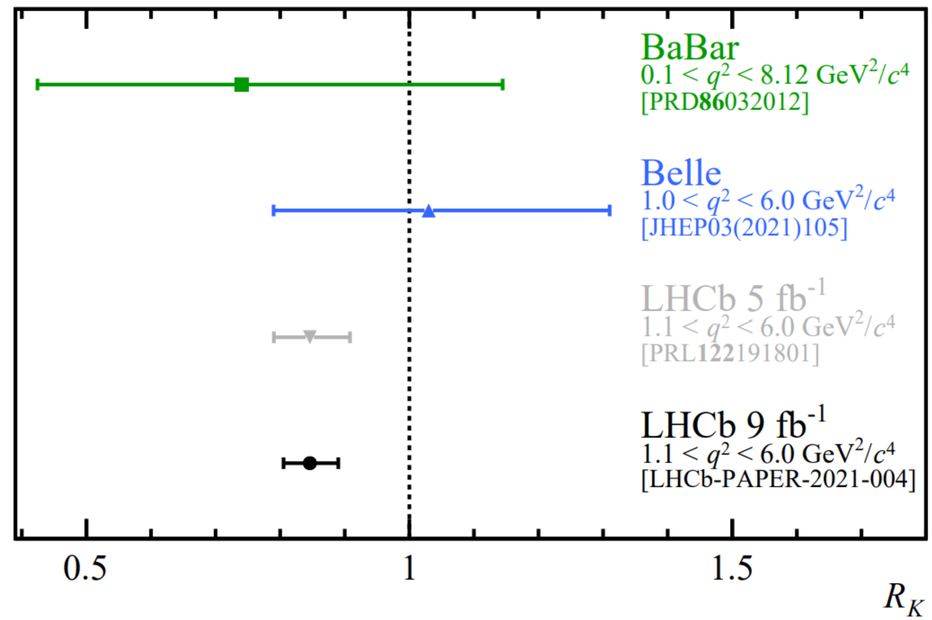
Important Z' Couplings

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

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

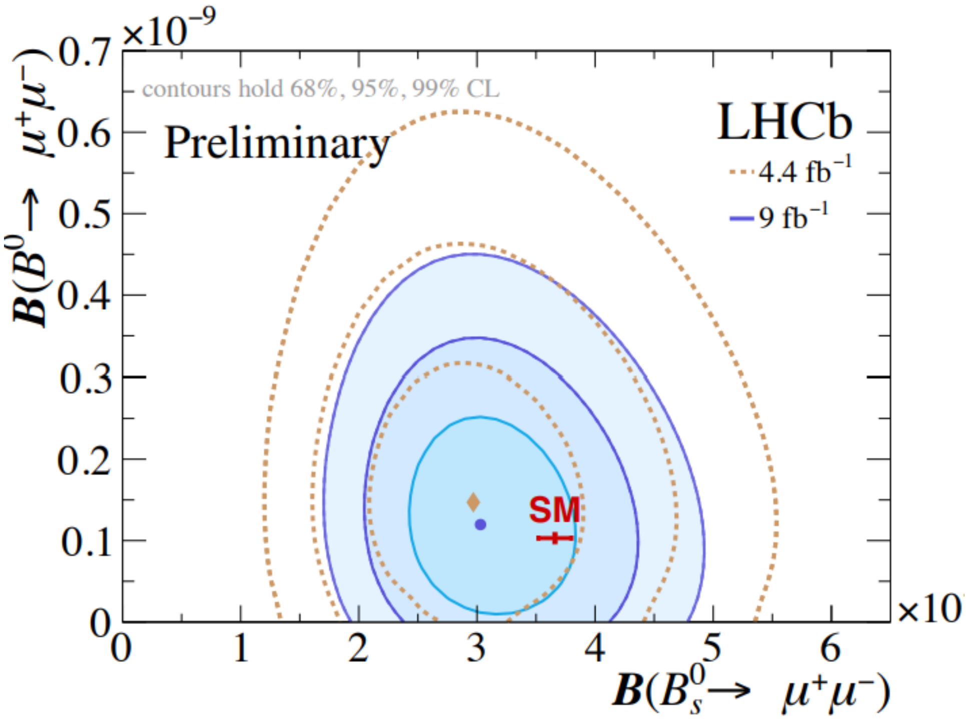
R_K

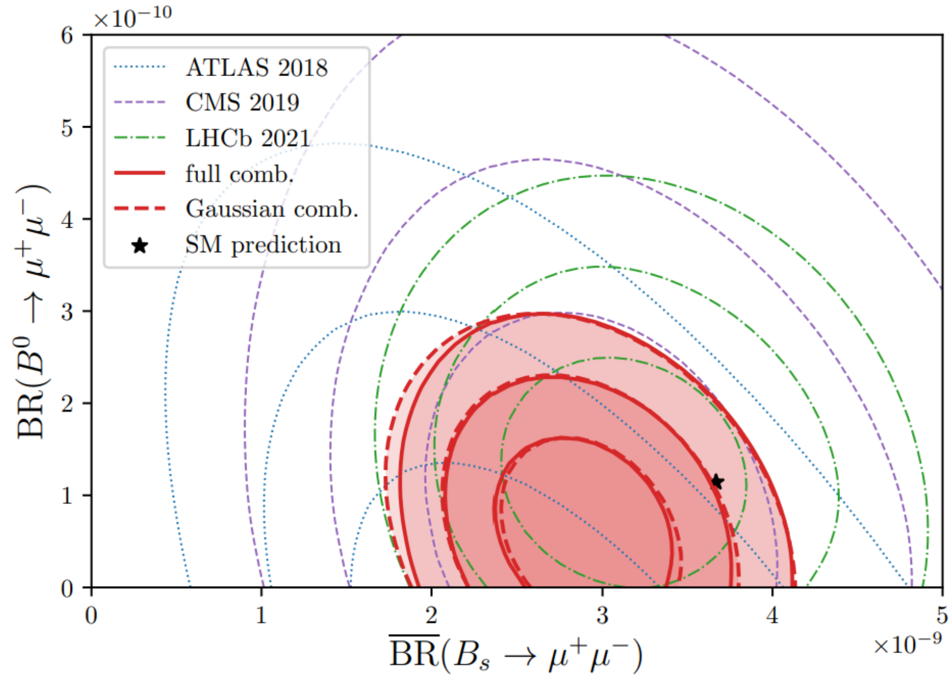




Latest `LHCb`, `arXiv:2103.11769` measurement included.

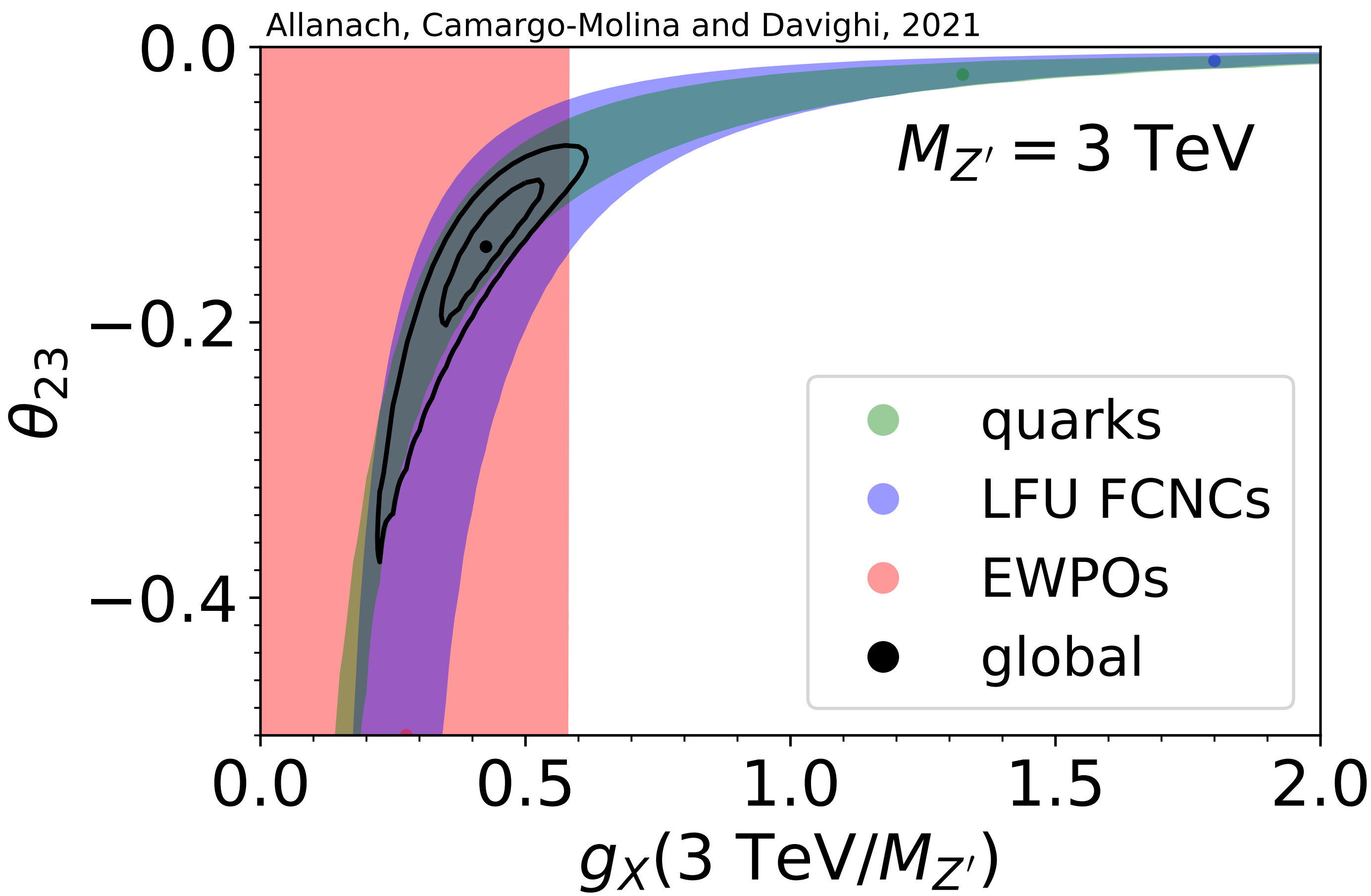
Latest $BR(B_s \to \mu^+\mu^-)$





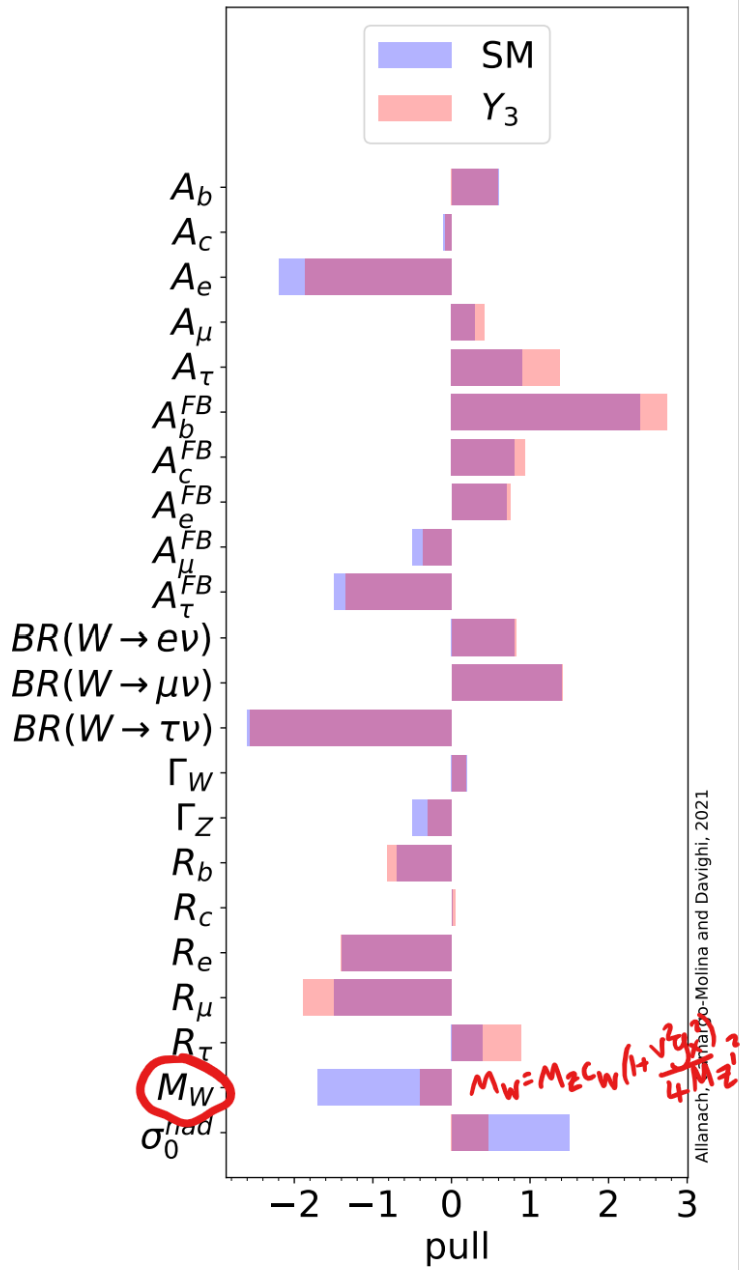
ATLAS + CMS + '21 LHCb measurements, multi-variate Gaussian combination by Altmannshofer, Stangl `2103.13370`

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`)

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

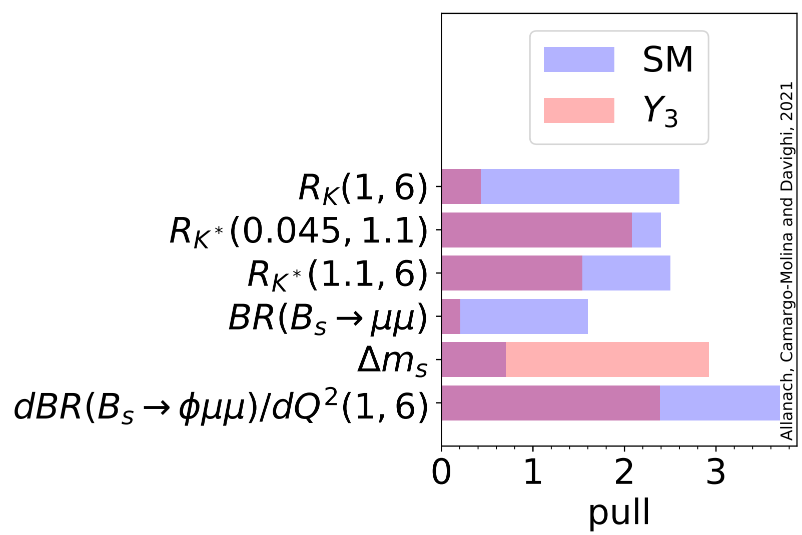


data set	χ^2	n	$p-$value
quarks	221.3	167	.0031
LFU FCNCs	35.3	21	.026
EWPOs	35.7	31	.26
global	292.3	219	.00067

SM

data set	χ^2	n	$p-$value
quarks	192.8	167	.068
LFU FCNCs	21.0	21	.34
EWPOs	36.0	31	.17
global	249.9	219	.062

TFHM



$Z' \to \mu\mu$ 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[1]

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

CMS also have released[2] a 139 fb^{-1} analysis.

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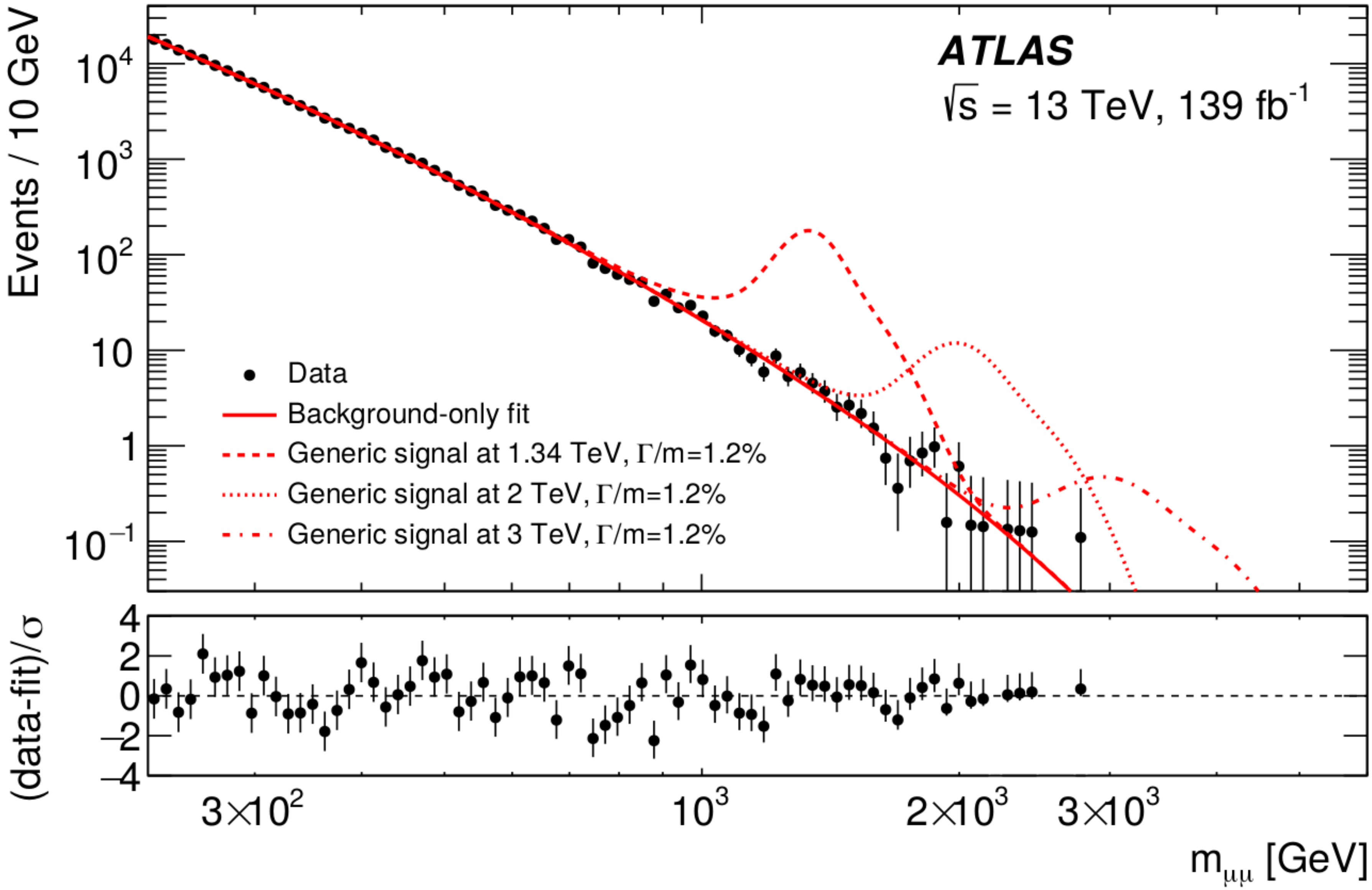
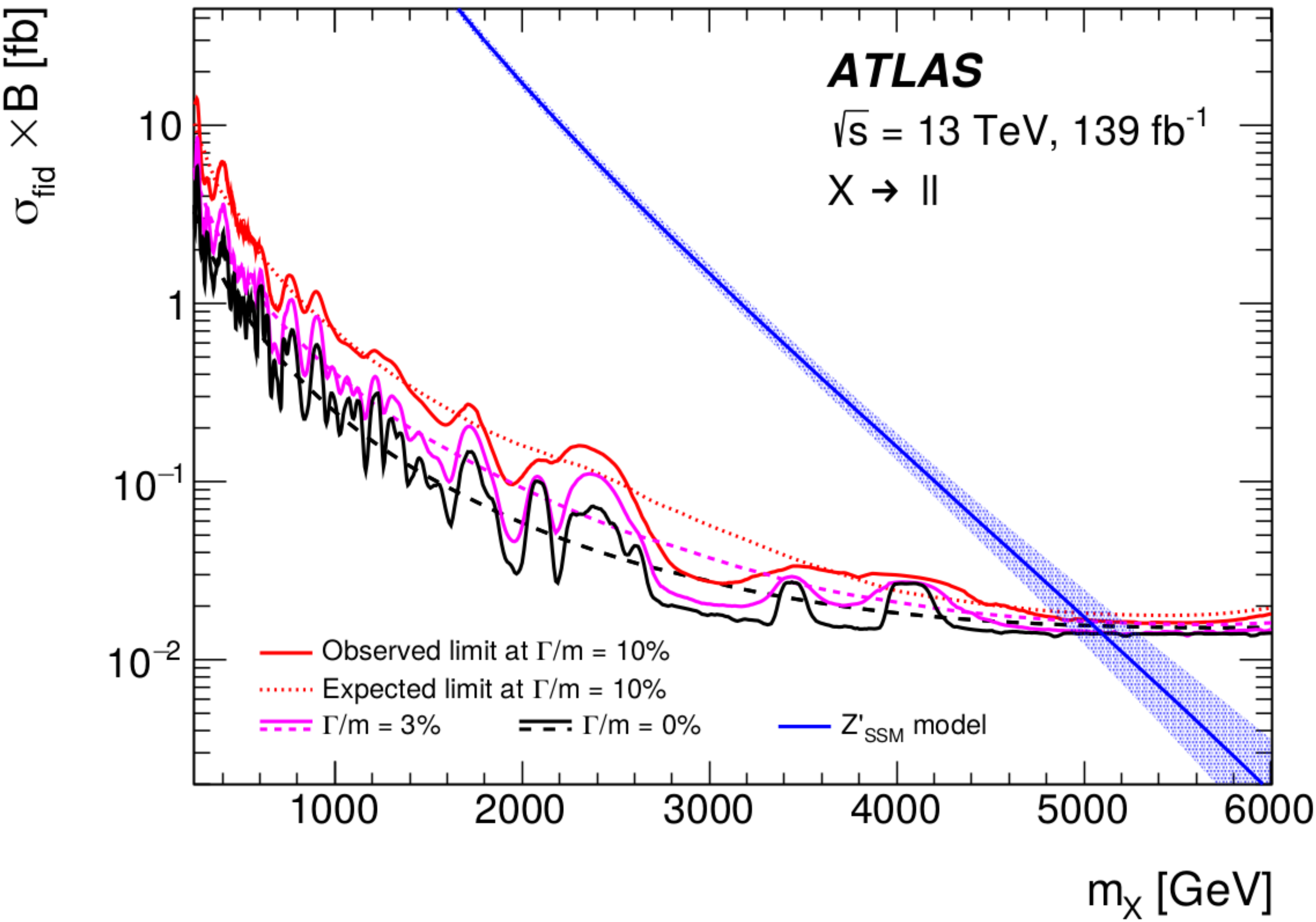
[1] 1903.06248
[2] 2103.02708



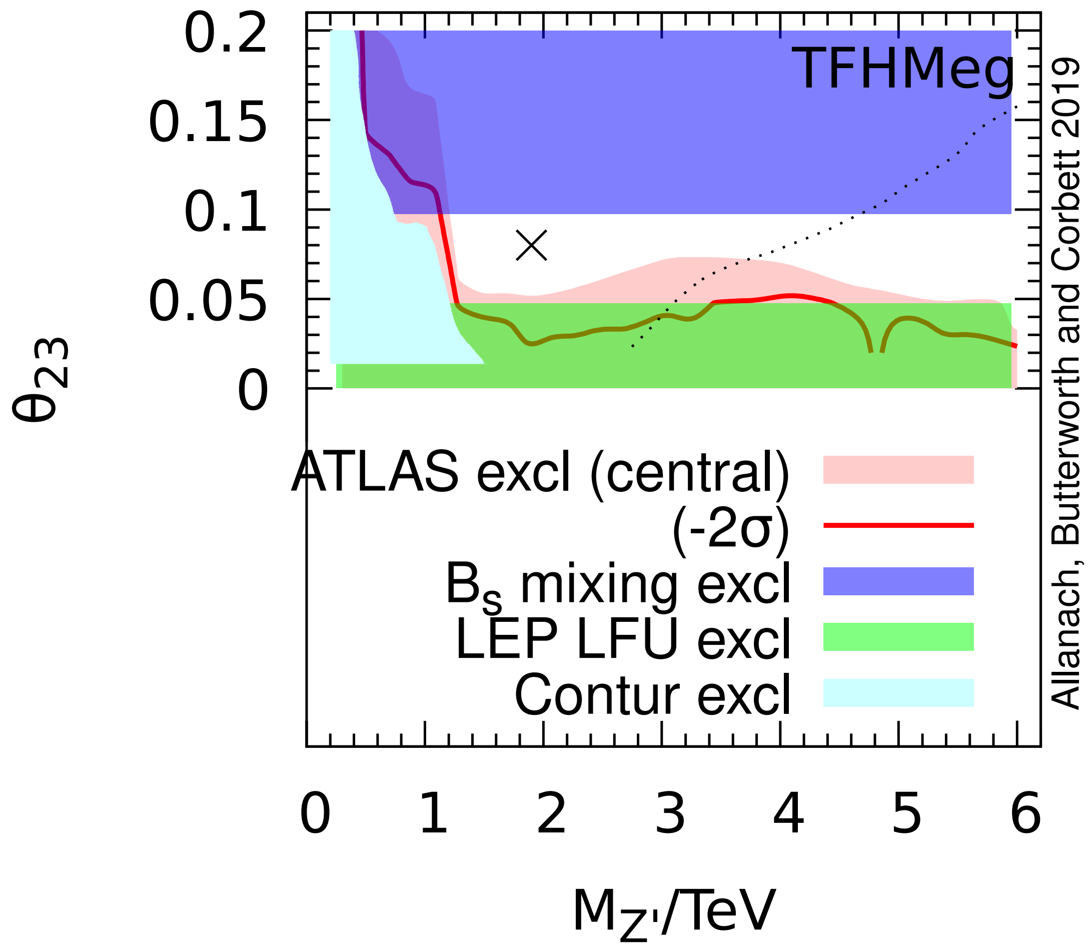
ATLAS
√s = 13 TeV, 139 fb-1
Events / 10 GeV
Data
Background-only fit
Generic signal at 1.34 TeV, Γ/m=1.2%
Generic signal at 2 TeV, Γ/m=1.2%
Generic signal at 3 TeV, Γ/m=1.2%
(data-fit)/σ
m_μμ [GeV]

ATLAS l^+l^- limits



1903.06248

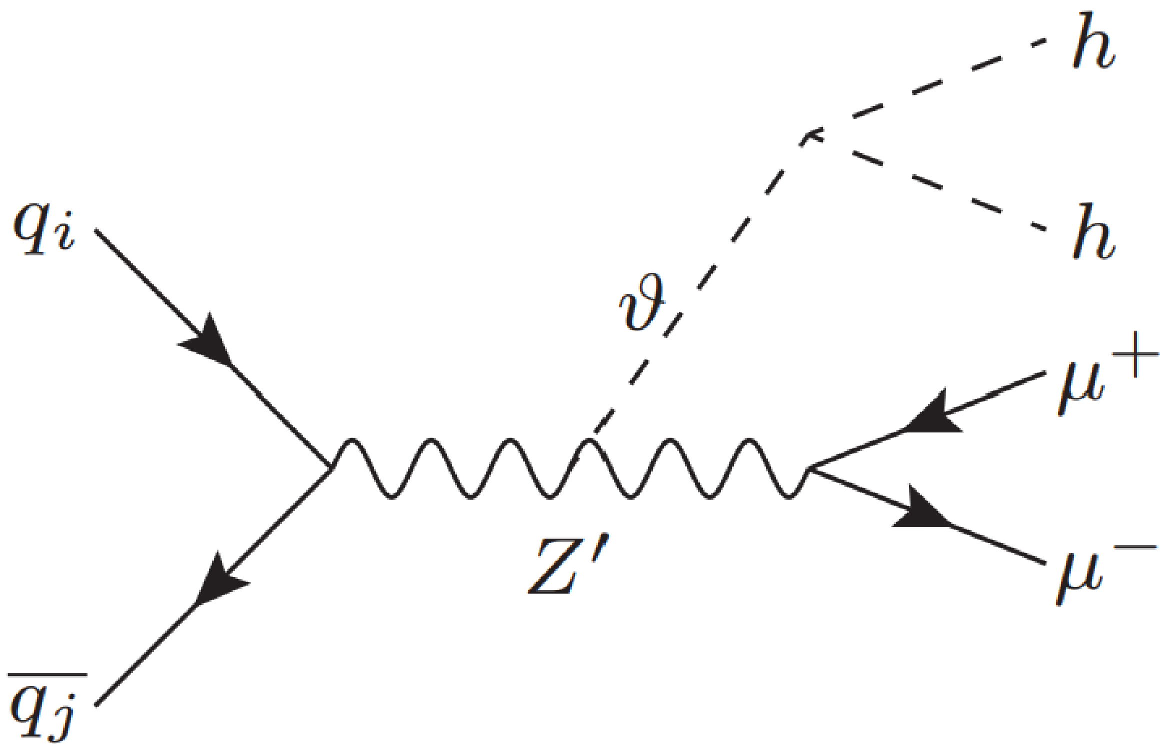
$$g_X \propto M_{Z'}/\sqrt{\sin 2\theta_{23}}^3$$



[3] BCA, Butterworth, Corbett, 1904.10954, *doesn't include 2021 LHCb data*

Flavonstrahlung[4]

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



[4]BCA, 2009.02197

Summary

The Third Family Hypercharge Model is a simple and successful model. Global 2-parameter fits to 217 electroweak and neutral current $B-$anomalies data:

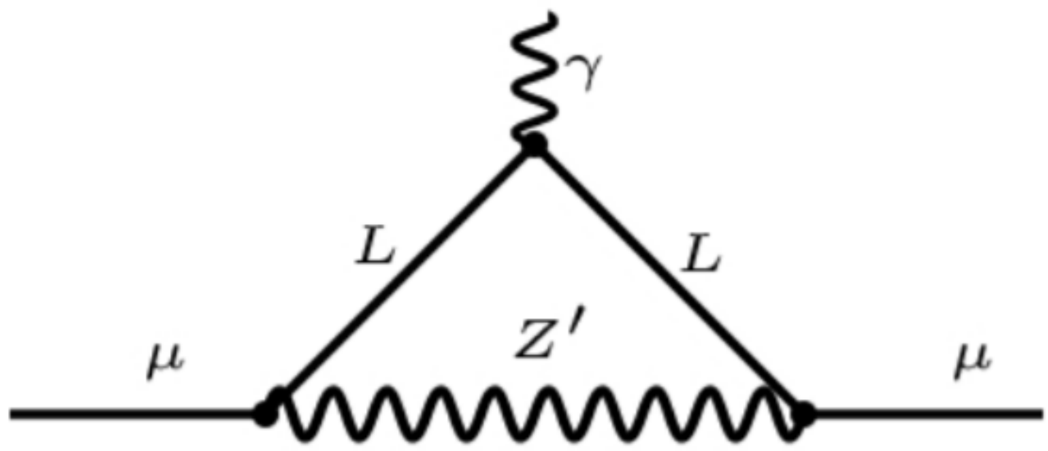
model	$p-$value	$\sqrt{\chi^2_{SM} - \chi^2}$
SM	.00067	0
TFHM	.062	6.5σ

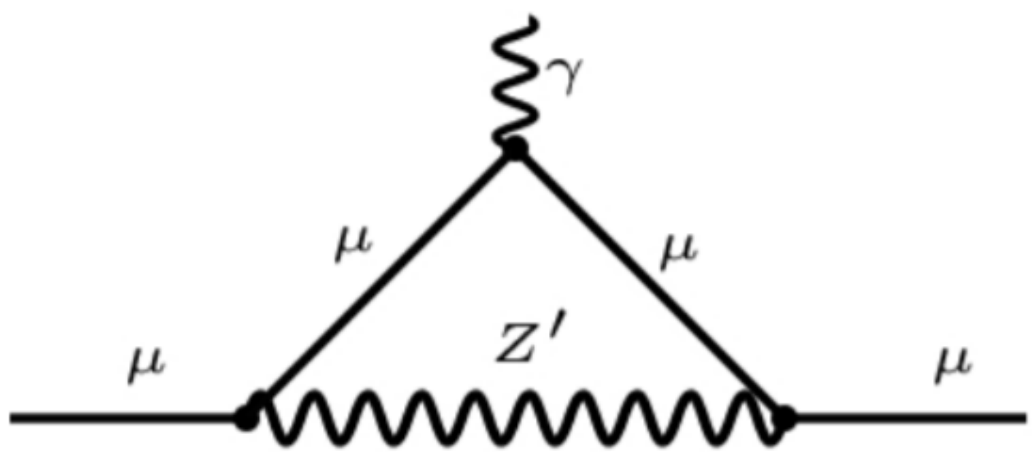
NB perturbativity $\Rightarrow M_{Z'} < 8$ TeV.

The answers to the questions raised by the $B-$anomalies may provide a direct experimental probe into the flavour problem.

Backup

$(g-2)_\mu$





Trident Neutrino Process

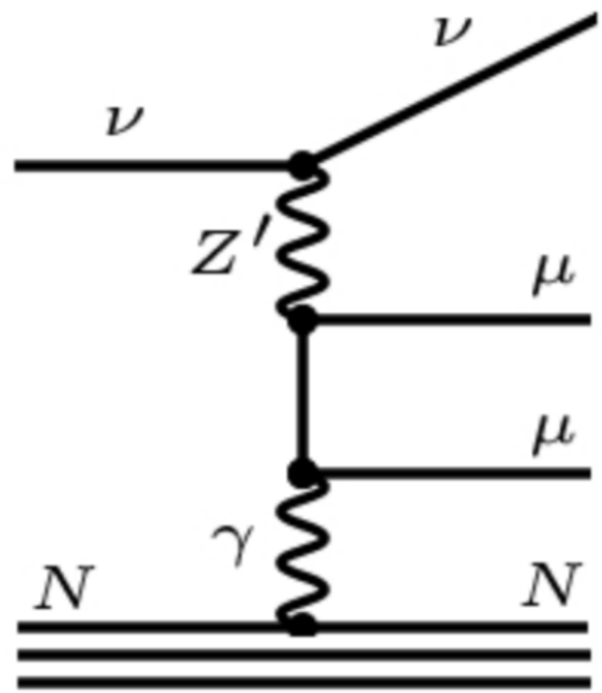


FIG. 10. Neutrino trident process that leads to constraints on the Z^{μ} coupling strength to neutrinos-muons, namely $M_{Z'}/g_{v\mu} \gtrsim 750$ GeV.

Other Z' Decay Modes

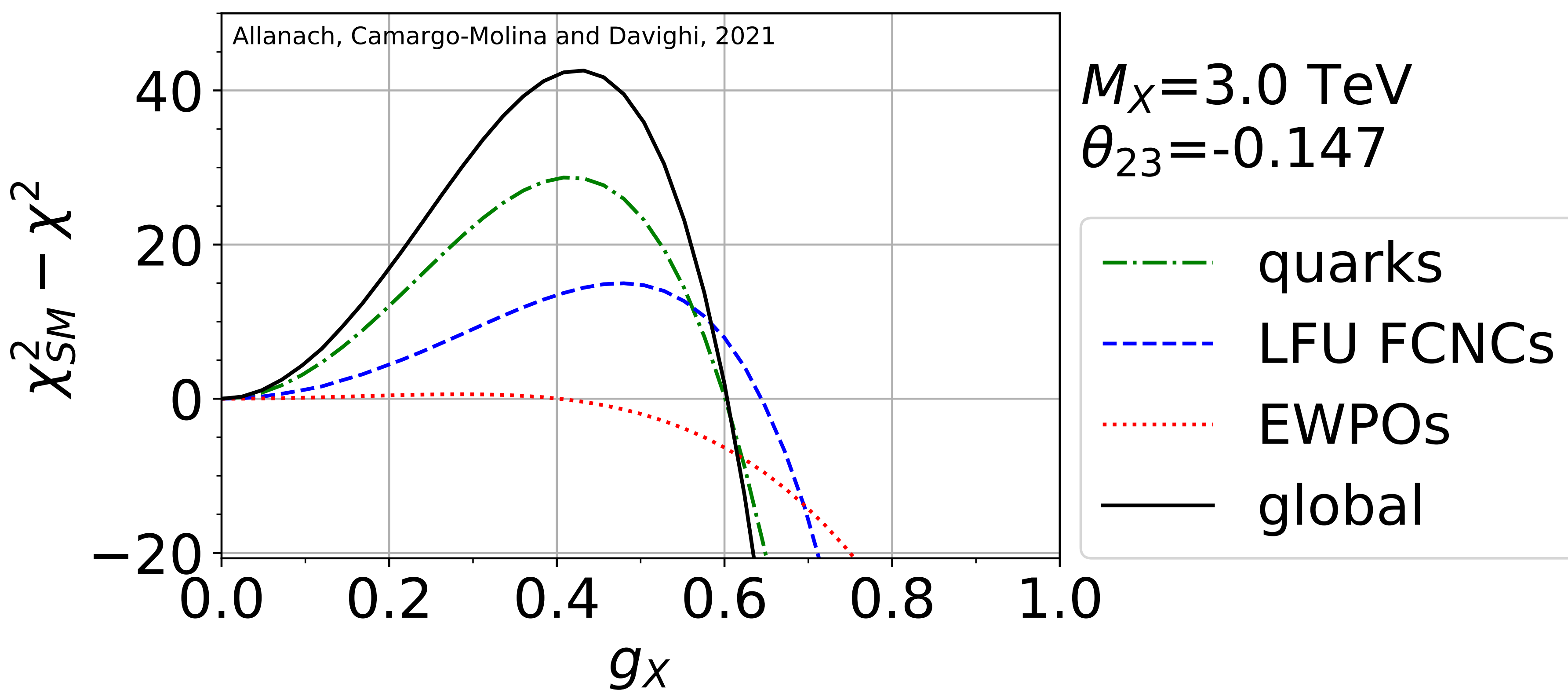
Mode	BR	Mode	BR	Mode	BR
$t\bar{t}$	0.42	$b\bar{b}$	0.12	$\nu\bar{\nu}'$	0.08
$\mu^+\mu^-$	0.08	$\tau^+\tau^-$	0.30	other $f_i f_j$	$\sim \mathcal{O}(10^{-4})$

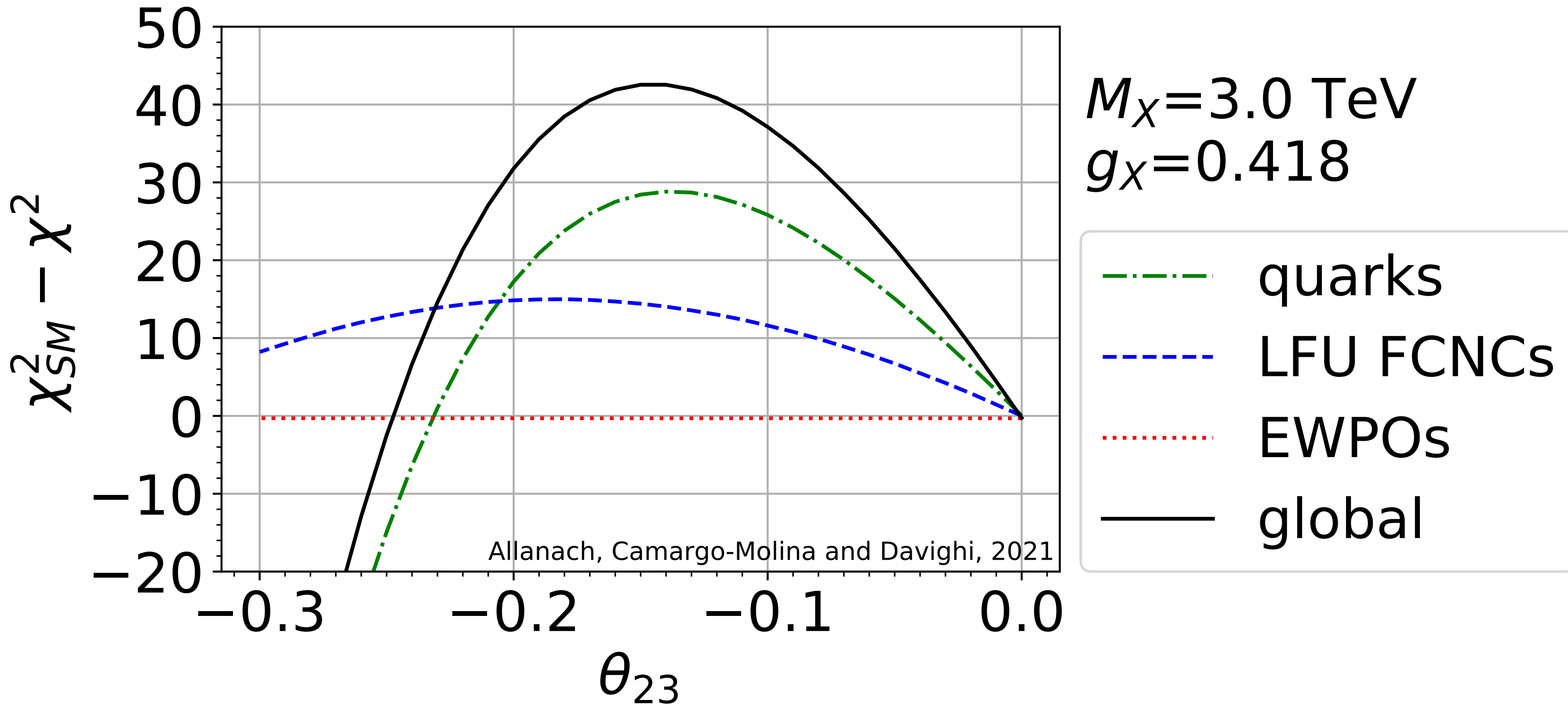
LEP LFU

$$g_X^2 \left(\frac{M_Z}{M_{Z'}}\right)^2 \leq 0.004 \Rightarrow g_X \leq \frac{M_{Z'}}{1.3\ \text{TeV}}.$$

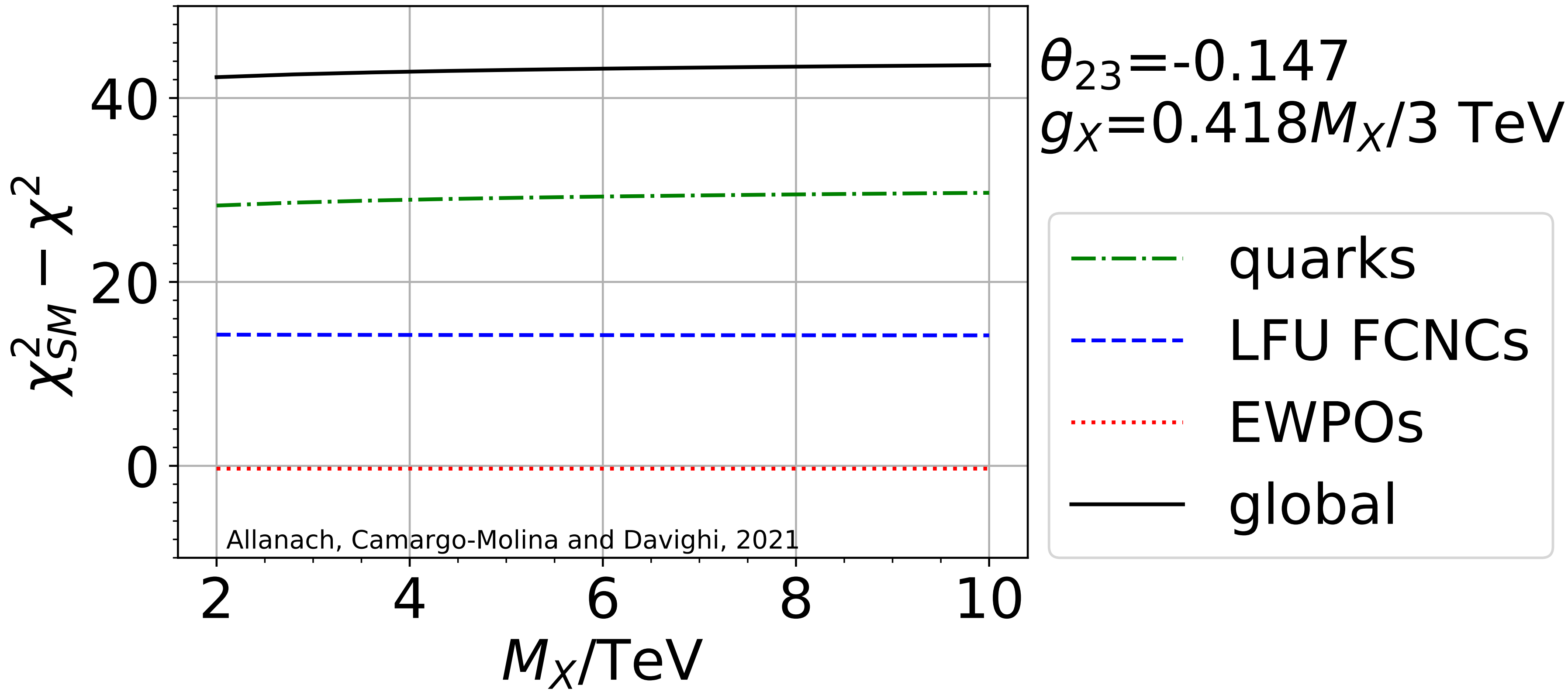
It's worth chasing $BR(B \to K^{(*)}\tau^\pm\tau^\mp)$.

TFHM Near best-fit point





50
40
30
20
10
0
−10
−20
$\chi^2_{SM} - \chi^2$
−0.3
−0.2
−0.1
0.0
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
$\chi^2_{SM} - \chi^2$
M_X/TeV
Allanach, Camargo-Molina and Davighi, 2021
40
20
0
2
4
6
8
10

$$
\begin{aligned}
\mathcal{L}_{X\psi} &= g_X \left(\frac{1}{6}\overline{\mathbf{u_L}}\Lambda^{(u_L)}\gamma^\rho \mathbf{u_L} + \frac{1}{6}\overline{\mathbf{d_L}}\Lambda^{(d_L)}\gamma^\rho \mathbf{d_L} - \right. \\
&\quad \frac{1}{2}\overline{\mathbf{n_L}}\Lambda^{(n_L)}\gamma^\rho \mathbf{n_L} - \frac{1}{2}\overline{\mathbf{e_L}}\Lambda^{(e_L)}\gamma^\rho \mathbf{e_L} + \\
&\quad \frac{2}{3}\overline{\mathbf{u_R}}\Lambda^{(u_R)}\gamma^\rho \mathbf{u_R} - \\
&\quad \left. \frac{1}{3}\overline{\mathbf{d_R}}\Lambda^{(d_R)}\gamma^\rho \mathbf{d_R} - \overline{\mathbf{e_R}}\Lambda^{(e_R)}\gamma^\rho \mathbf{e_R} \right) Z'_\rho, \\
\Lambda^{(I)} &\equiv V_I^\dagger \xi V_I, \qquad \xi = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}
\end{aligned}
$$

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

A simple limiting case

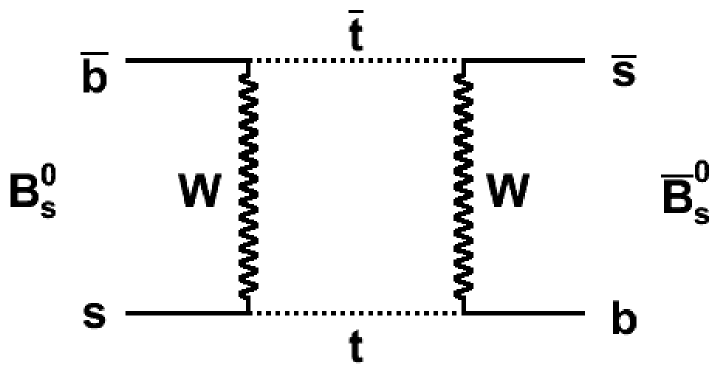
$$V_{u_R} = V_{d_R} = V_{e_R} = 1$$

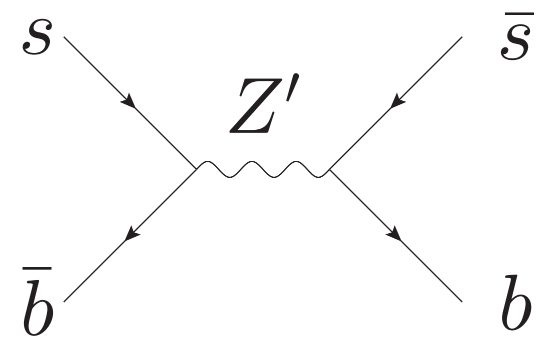
for simplicity and the ease of passing bounds.

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

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

$B_s - \bar{B}_s$ Mixing





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

from QCD sum rules and lattice[5]. Weaker on LQs (see later).

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

$Z - Z'$ mixing angle

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

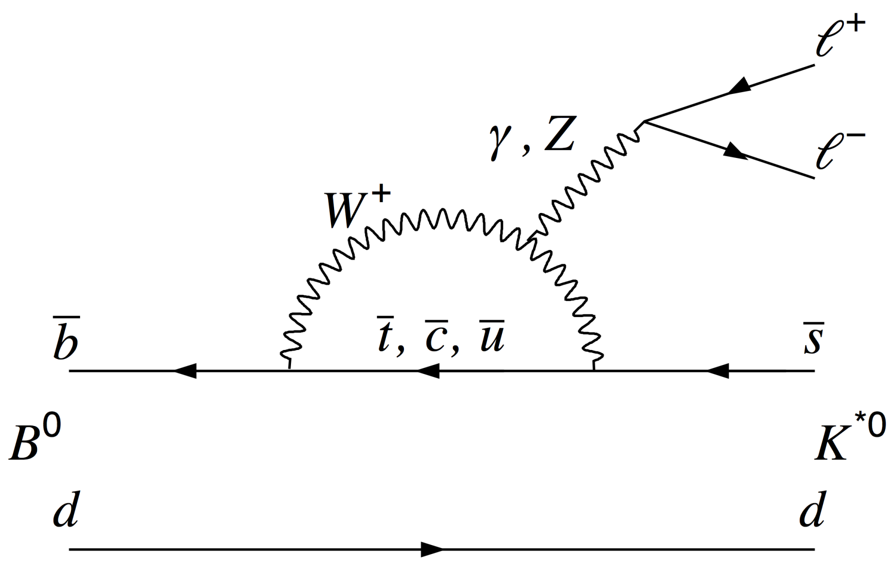
This gives small non-flavour universal couplings to the Z boson propotional to g_X and:

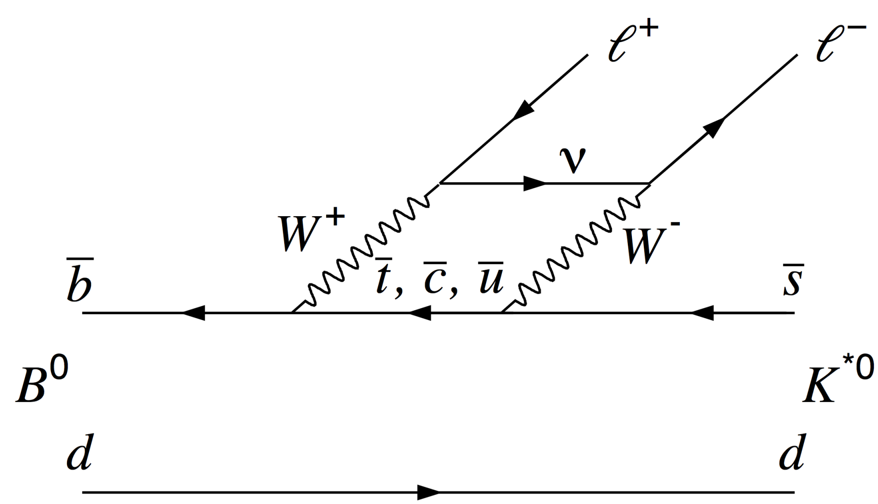
$$Z_\mu = \cos\alpha_z \left(-\sin\theta_w B_\mu + \cos\theta_w W^3_\mu\right) + \sin\alpha_z X_\mu,$$

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

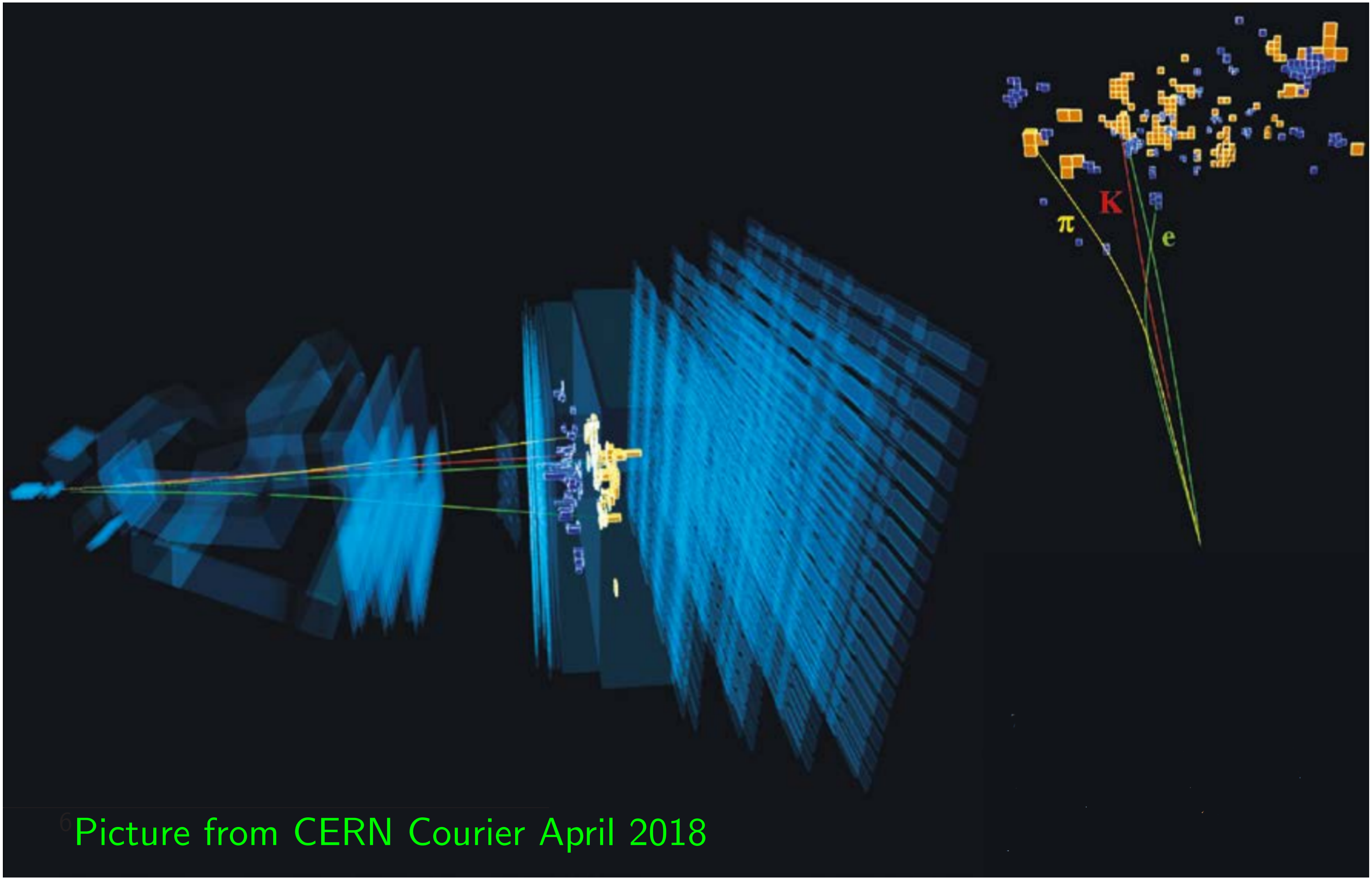
$$R_K = \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to Ke^+e^-)}, \qquad R_{K^*} = \frac{BR(B \to K^*\mu^+\mu^-)}{BR(B \to K^*e^+e^-)}.$$

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





LHCb $B^0 \to K^{0*}e^+e^-$ Event[6]

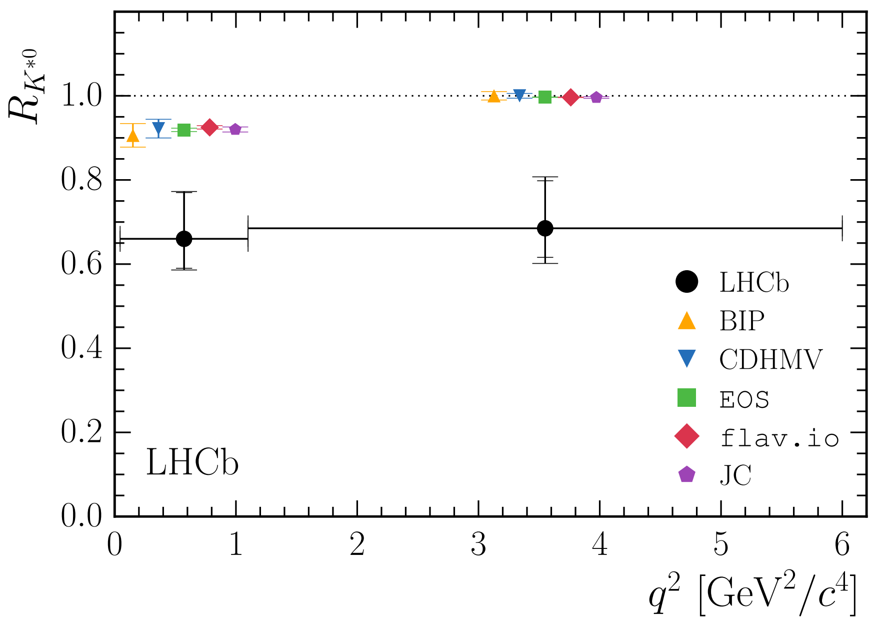


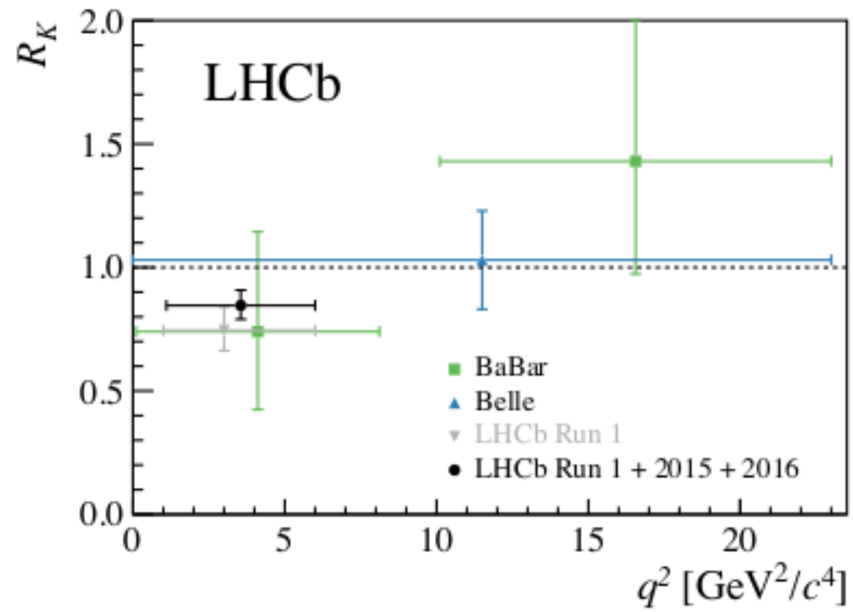
[6] Picture from CERN Courier April 2018

$R_{K^{(*)}}$

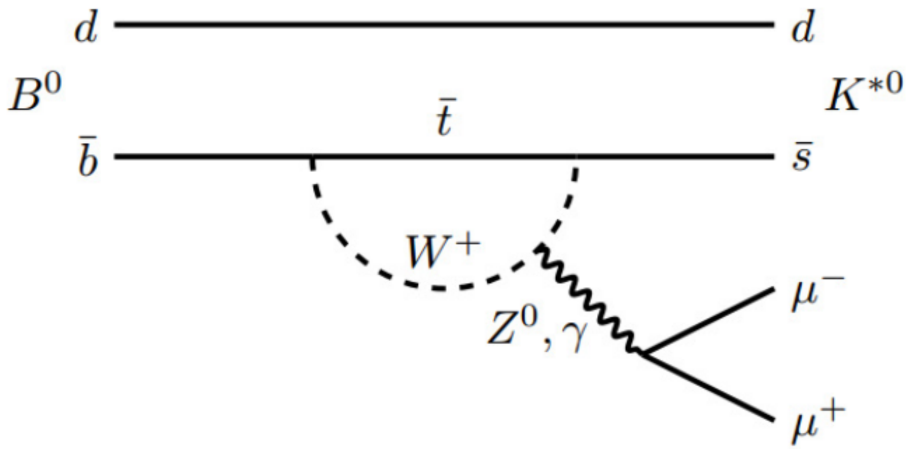
LHCb results: $q^2 = m_{ll}^2$.

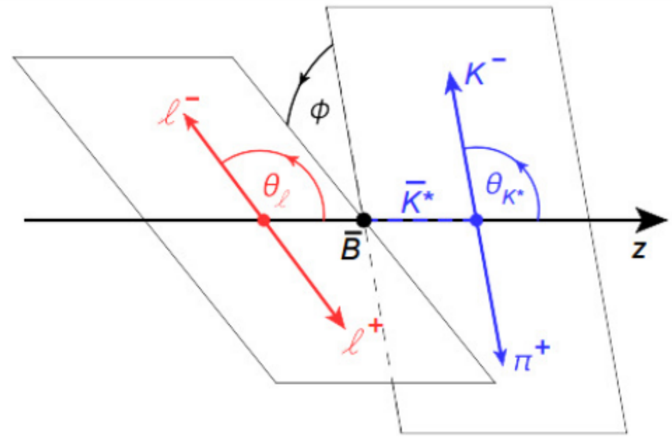
	q^2/GeV^2	SM	LHCb 3 fb^{-1}	σ
R_K	$[1, 6]$	1.00 ± 0.01	0.846 ± 0.06	2.5
R_{K^*}	$[0.045, 1.1]$	0.91 ± 0.03	$0.66^{+0.11}_{-0.07}$	2.2
R_{K^*}	$[1.1, 6]$	1.00 ± 0.01	$0.69^{+0.11}_{-0.07}$	2.5





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

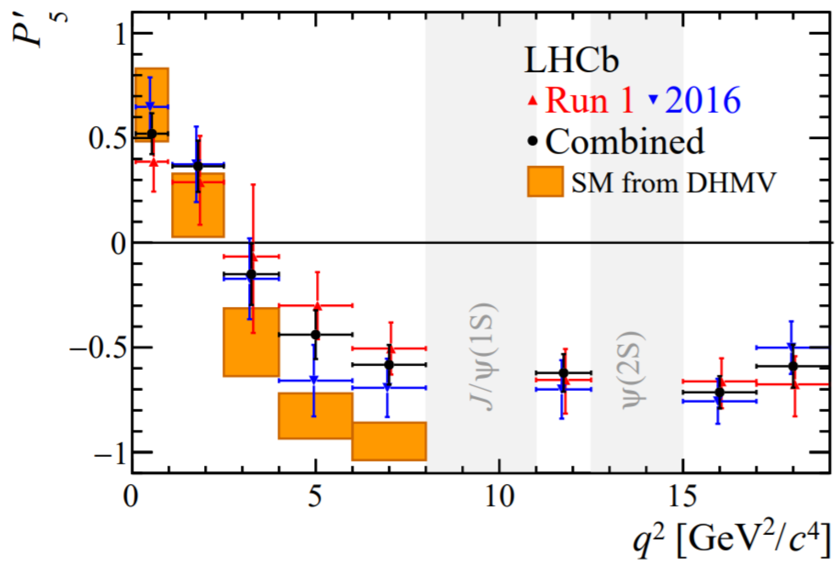


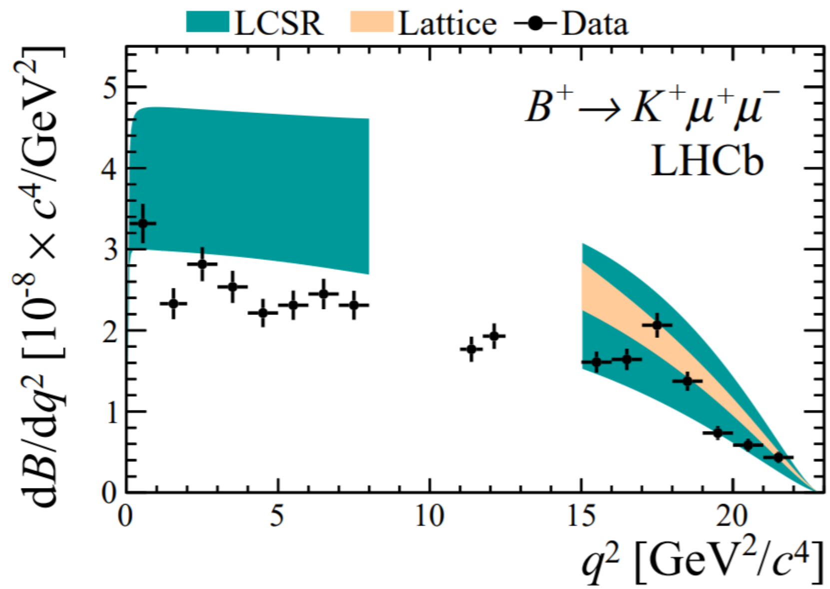


Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

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

P_5'



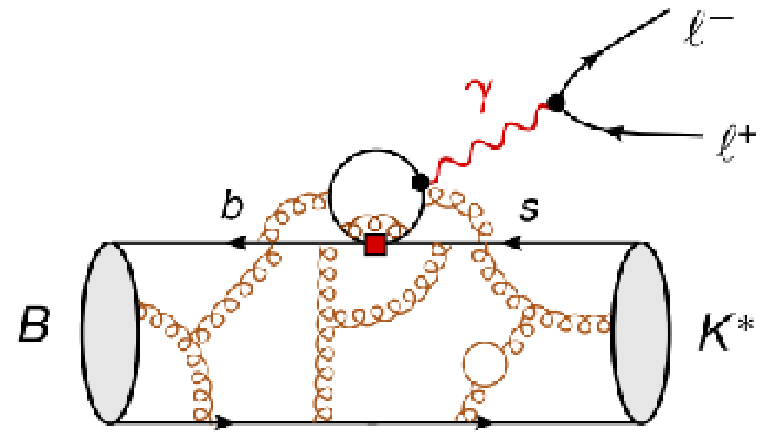


$P_5' = S_5/\sqrt{F_L(1-F_L)}$, leading form factor uncertainties cancel [7]

[7] LHCb, 2003.04831

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 ($\to R_K$!)

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.

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[8].

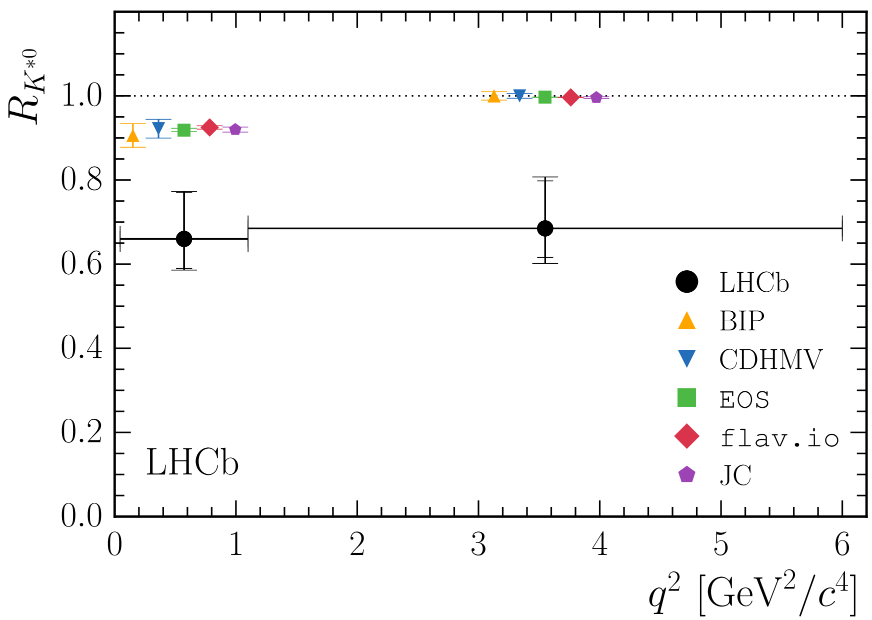
[8] D'Amico et al, 1704.05438; Aebischer et al 1903.10434.

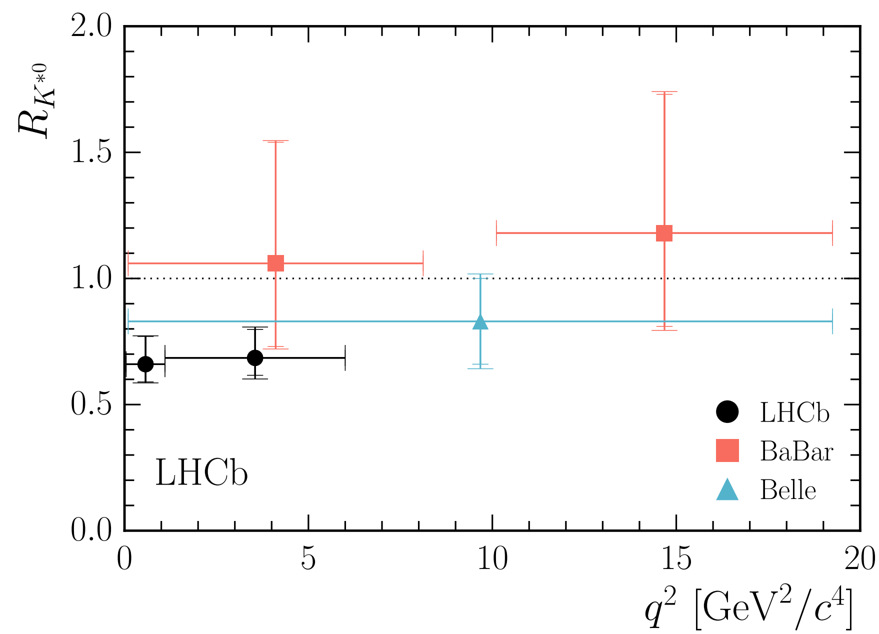
The Flavour Problem

$R_{K^{(*)}}$ pre Moriond 2019

LHCb results from 7 and 8 TeV: $q^2 = m_{ll}^2$.

	q^2/GeV^2	SM	LHCb 3 fb^{-1}	σ
R_K	$[1, 6]$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074}$	2.6
R_{K^*}	$[0.045, 1.1]$	0.91 ± 0.03	$0.66^{+0.11}_{-0.07}$	2.2
R_{K^*}	$[1.1, 6]$	1.00 ± 0.01	$0.69^{+0.11}_{-0.07}$	2.5





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.

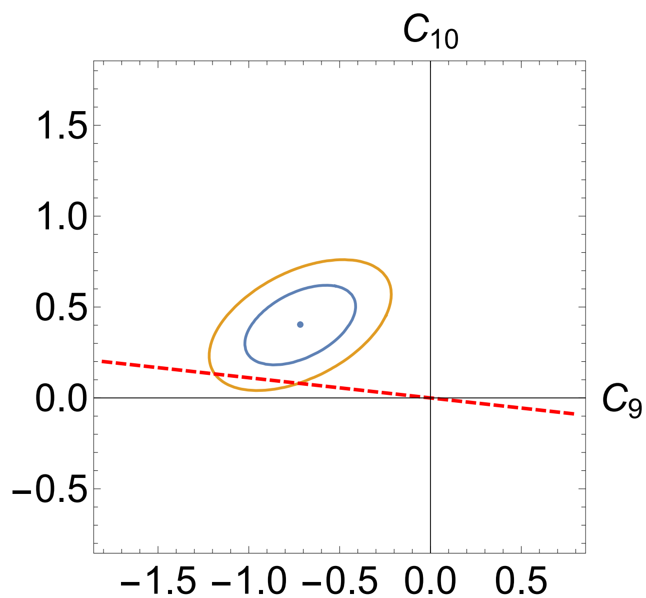
$$\Rightarrow \Delta\Gamma^{(\text{exp})} = \Gamma_{\text{inv}}^{(\text{exp})} - \Gamma_{\text{inv}}^{(\text{SM})} = -2.5 \pm 1.5 \text{ MeV}.$$

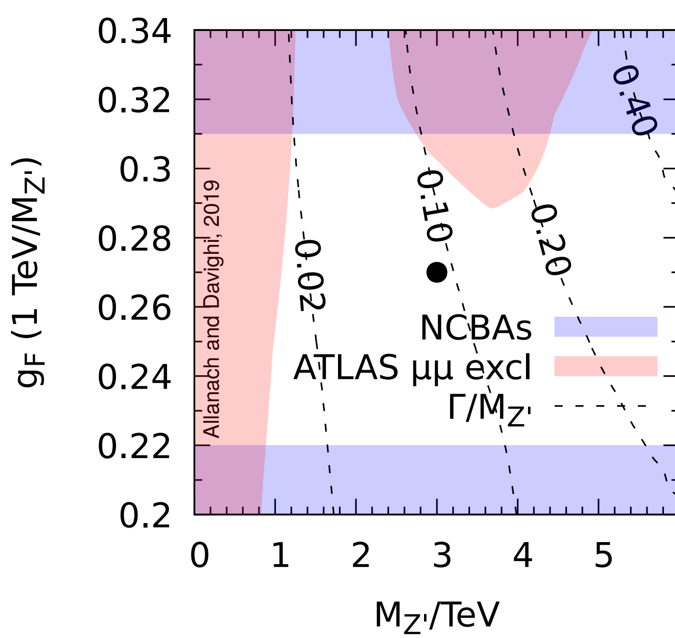
$$\begin{aligned}
\mathcal{L}_{\bar{\nu}\nu Z} &= -\frac{g}{2\cos\theta_w}\overline{\nu'_{Le}} \not{Z} P_L \nu'_{Le} \\
&\quad -\overline{\nu'_{L\mu}}\left(\frac{g}{2\cos\theta_w} + \frac{5}{6} g_F \sin\alpha_z\right) \not{Z} \nu'_{L\mu} \\
&\quad -\overline{\nu'_{L\tau}}\left(\frac{g}{2\cos\theta_w}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

Deformed TFHM

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

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





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

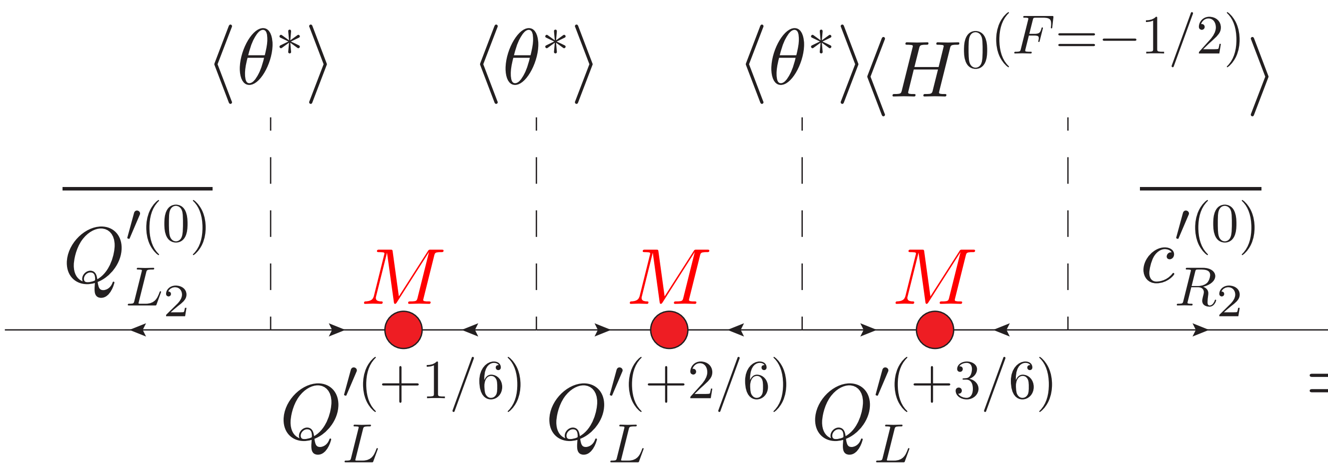
$$\mathcal{L}_{SS} = 1/2 \sum_{ij} (L'_i H^c)(M^{-1})_{ij}(L'_j H^c),$$

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[9]

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

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



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

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

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