Z' Explanations of Neutral Current B Anomalies

by
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- Neutral Current B Anomalies
- Simplified models
- Third Family Hypercharge Model
- General SM$\times U(1)_F$ model

Cambridge Pheno Working Group

Where data and theory collide

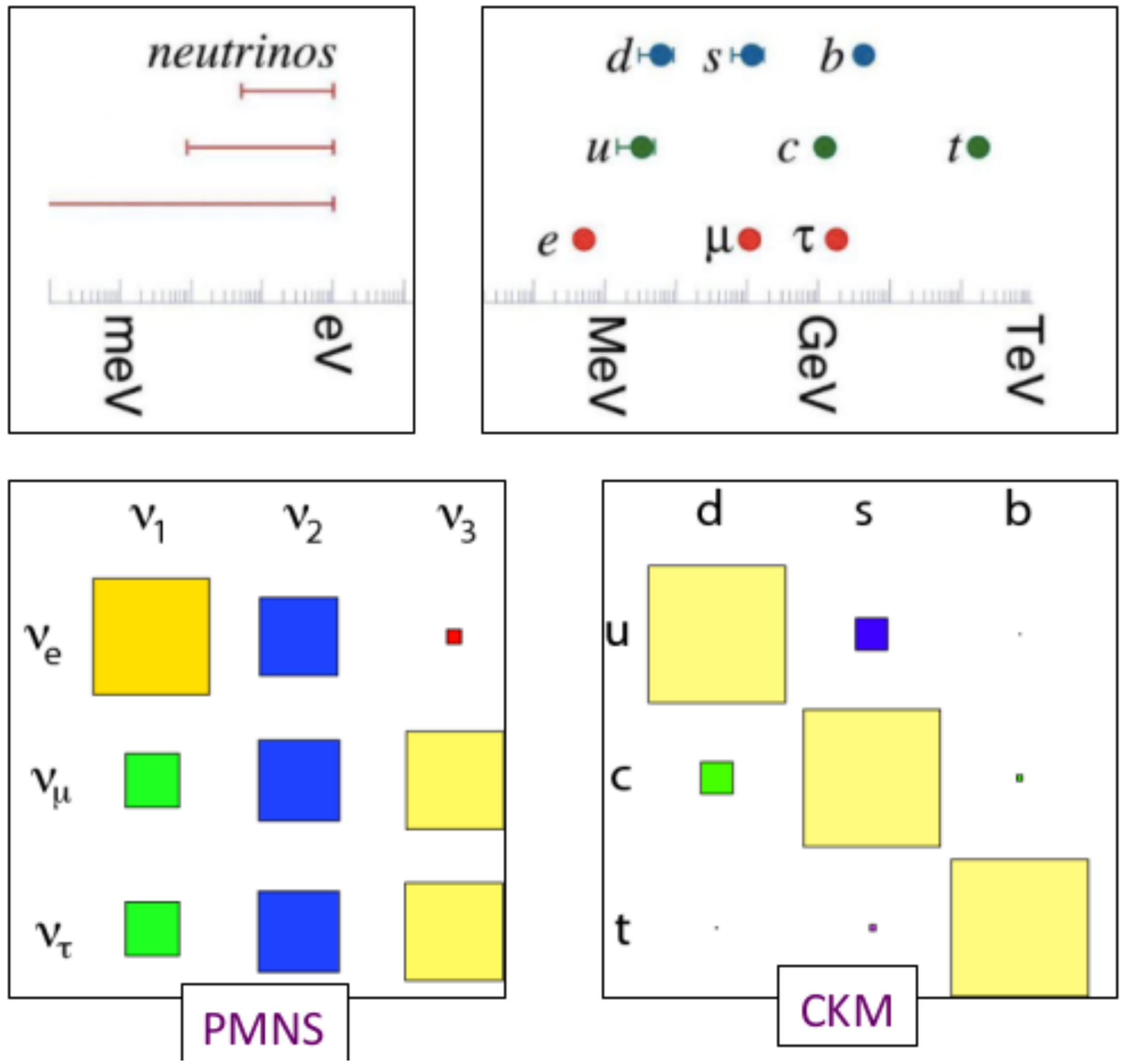
Science & Technology Facilities Council

Based on

- BCA, Gripaios, You, arXiv:1710.06363
- BCA, Davighi, arXiv:1809.01158
- BCA, Corbett, Dolan, You, arXiv:1810.02166
- BCA, Davighi, Melville, arXiv:1812.04602
- BCA, Butterworth, Davighi, arXiv:1904.10954
- BCA, Davighi, arXiv:1905.10327

The Flavour Problem

The Flavour Problem

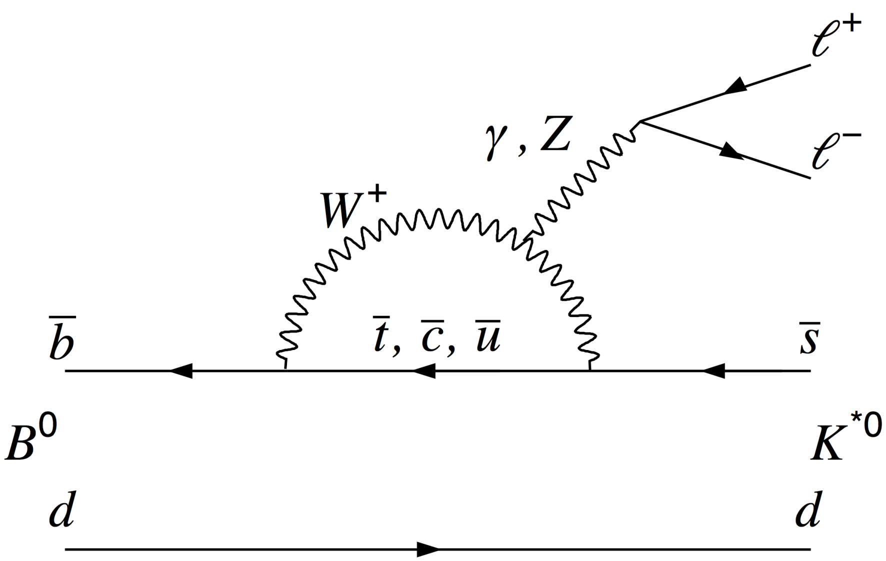


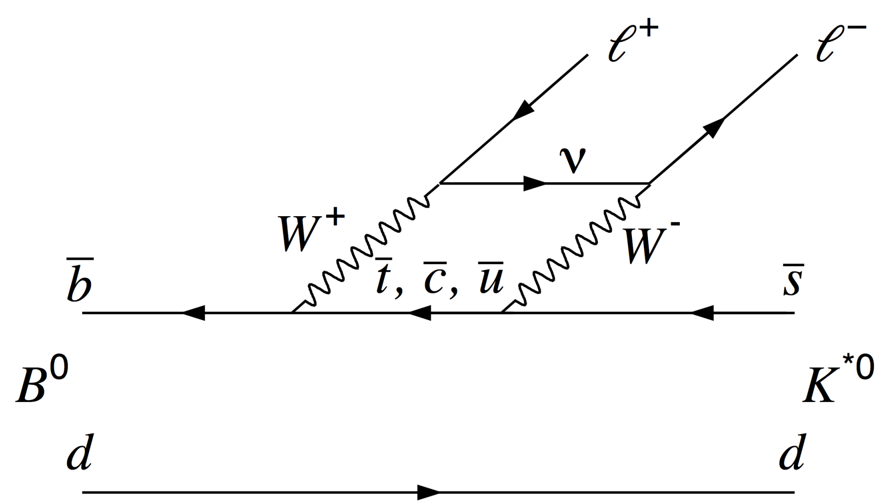
Strange b Activity

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

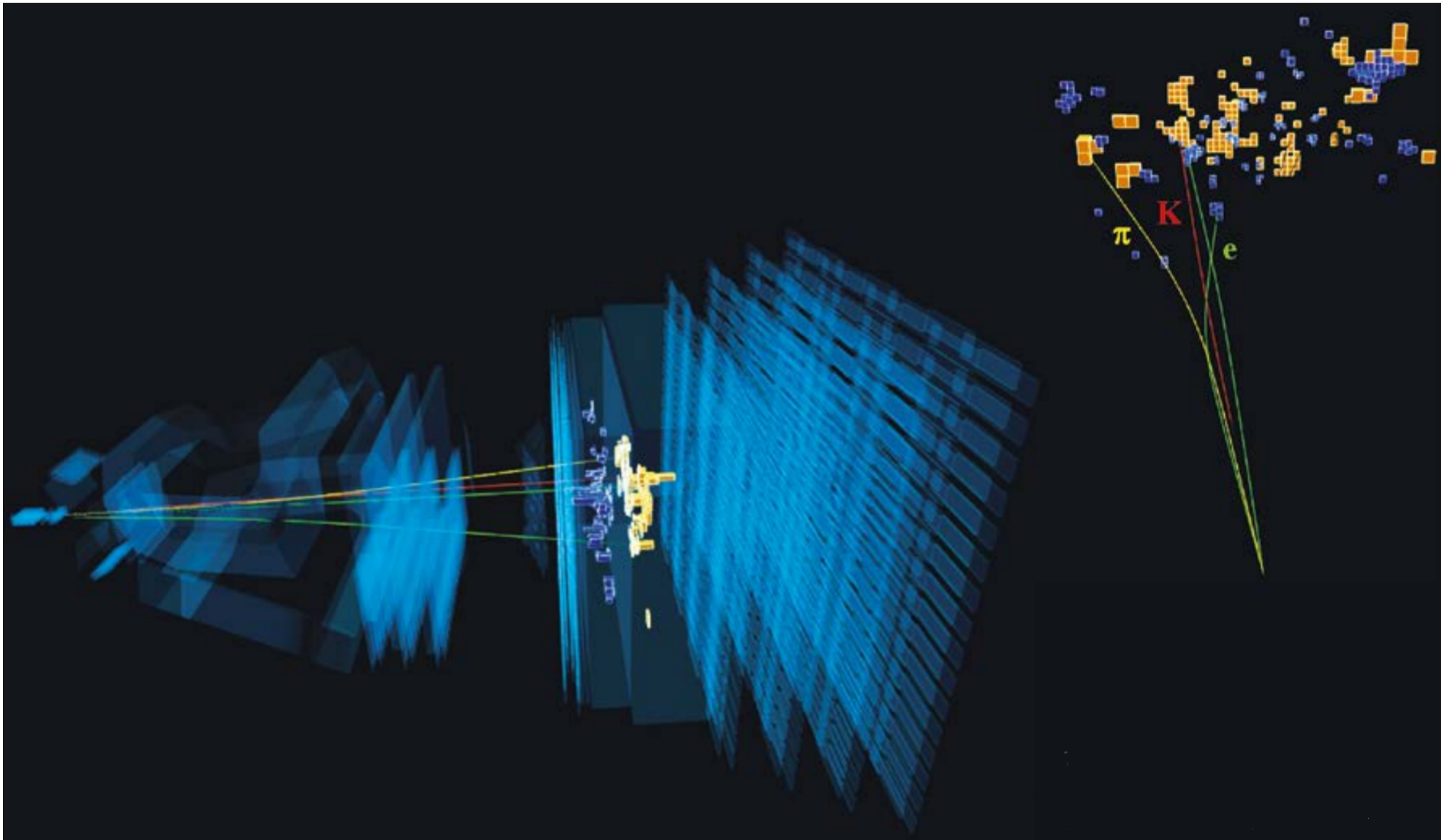
$$R_K = \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to Ke^+e^-)}, \qquad R_{K^*} = \frac{BR(B \to K^*\mu^+\mu^-)}{BR(B \to K^*e^+e^-)}.$$

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





LHCb $B^0 \to K^{0*}e^+e^-$ Event[1]

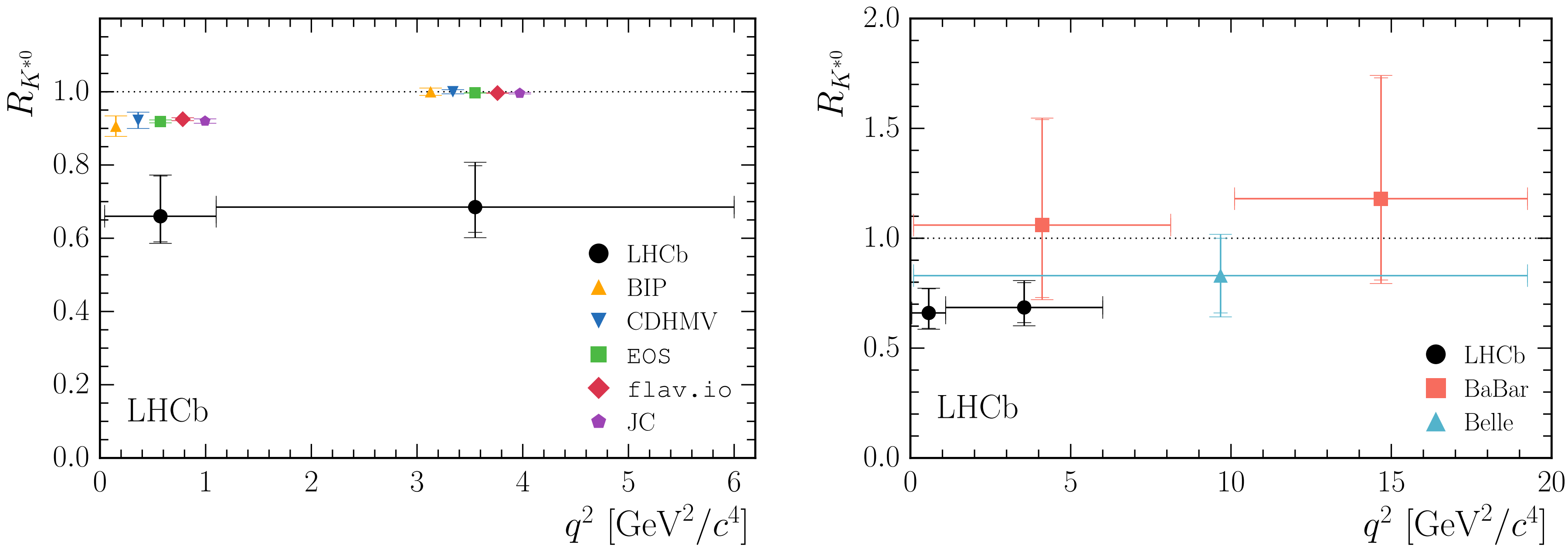


[1] Picture from CERN Courier April 2018

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

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

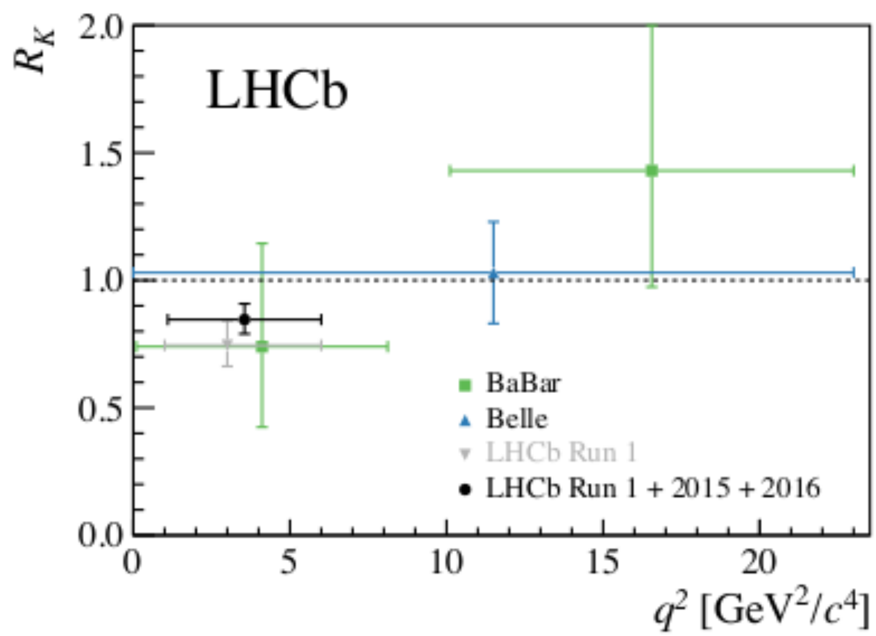
	q^2/GeV^2	SM	LHCb 3 fb^{-1}	σ
R_K	$[1, 6]$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074}$	2.6
R_{K^*}	$[0.045, 1.1]$	0.91 ± 0.03	$0.66^{+0.11}_{-0.07}$	2.2
R_{K^*}	$[1.1, 6]$	1.00 ± 0.01	$0.69^{+0.11}_{-0.07}$	2.5



R_K post Moriond 2019

LHCb results from 7, 8 and 13 TeV: $q^2 = m_{ll}^2$.

q^2/GeV^2	LHCb 5 fb^{-1}	σ
R_K $[1.1, 6]$	~~$0.745^{+0.090}_{-0.074}$~~ $0.846 \pm 0.06 \pm 0.02$	~~2.6~~ 2.5



$R_K^{2016} = 0.93 \pm 0.09$

Reanalysing Run I data

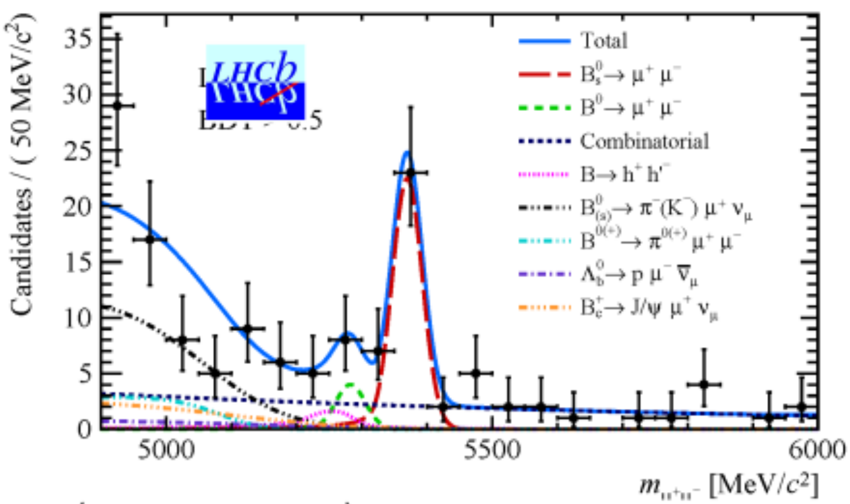
$R_K =$ ~~$0.745^{+0.090}_{-0.074}$~~

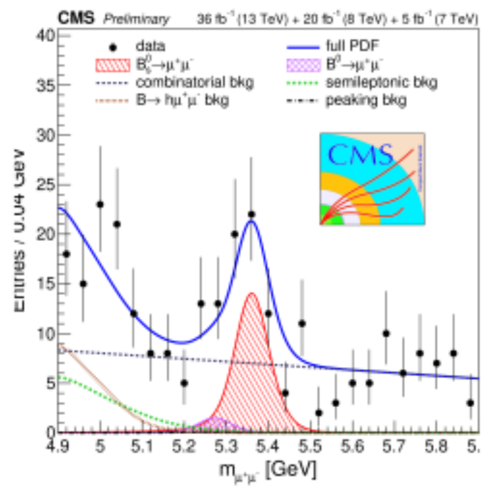
$= 0.717 \pm 0.08$

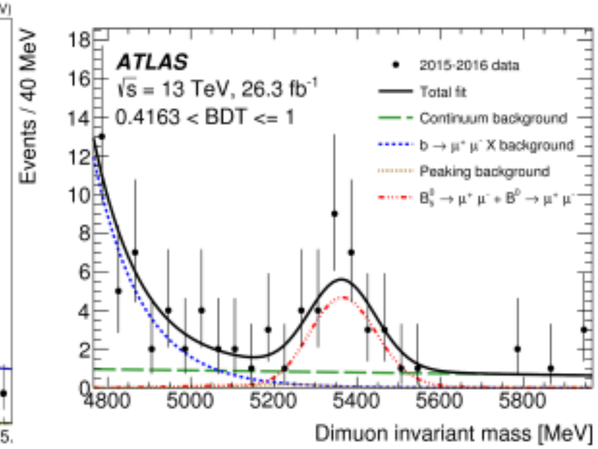
$B_s \to \mu^+\mu^-$

Lattice QCD provides important input to[2]

$$BR(B_s \to \mu\mu)_{SM} = (3.65 \pm 0.23) \times 10^{-9},$$



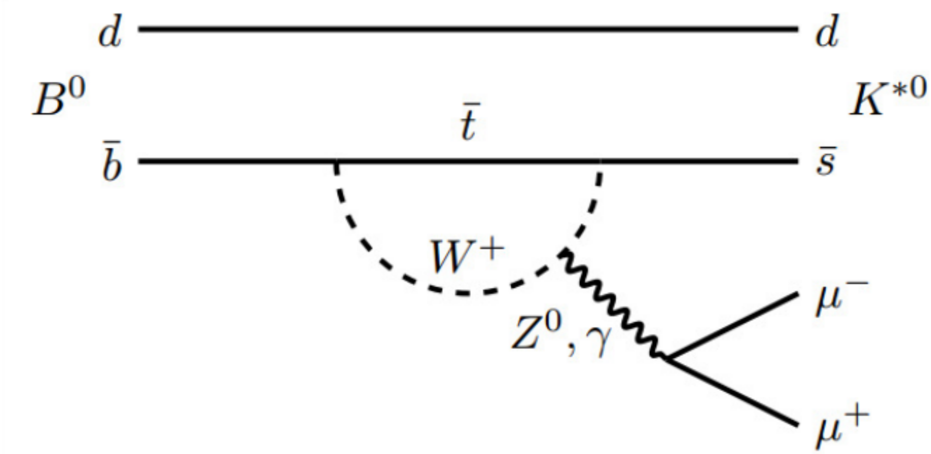


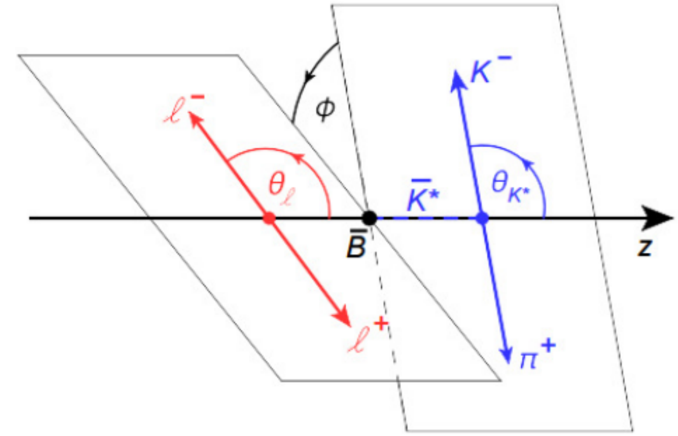


$B\left(B_s \to \mu^+\mu^-\right)$ $\left(3.0 \pm 0.6^{+0.3}_{-0.2}\right) \times 10^{-9}$ $\left(2.9^{+0.7}_{-0.6} \pm 0.2\right) \times 10^{-9}$ $\left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}$

[2] Bobeth et al, 1311.0903

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

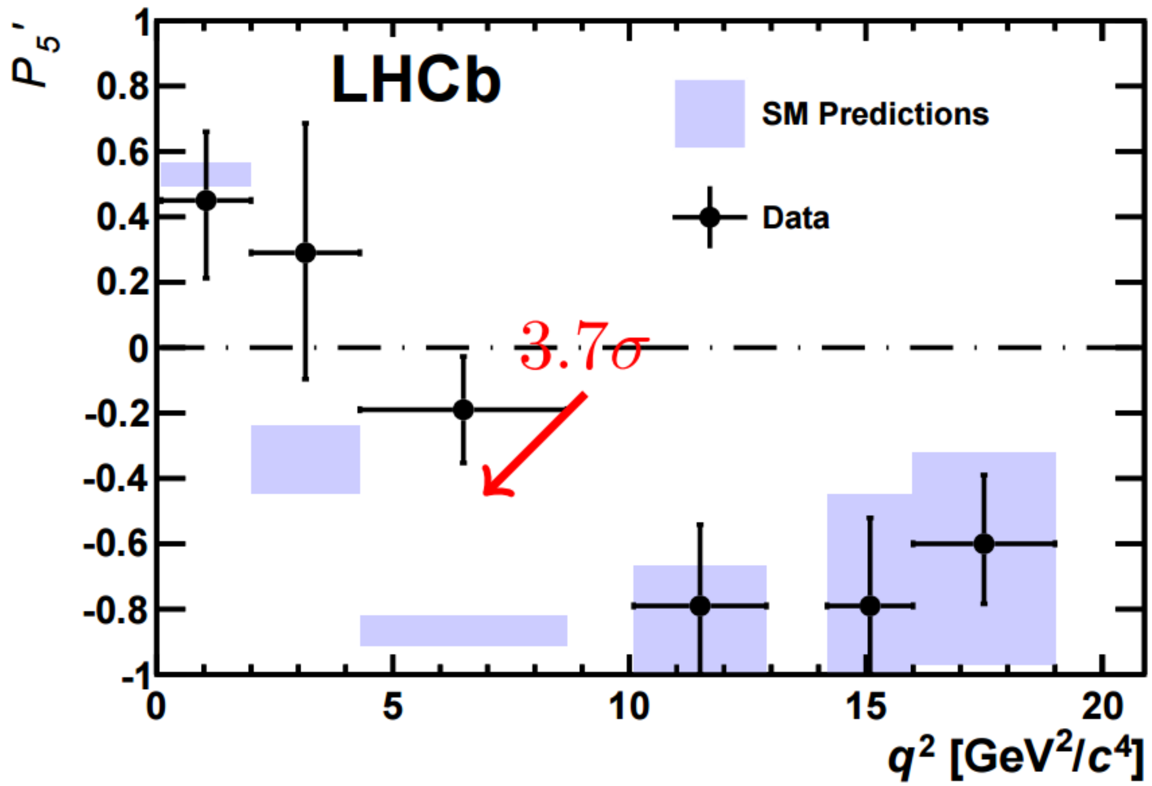




Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

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

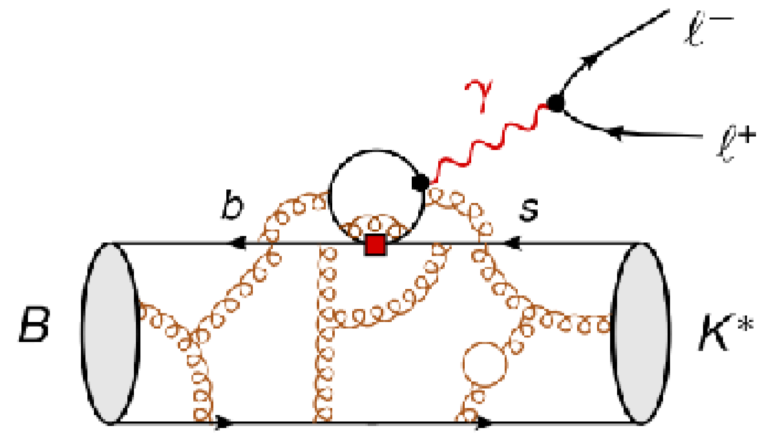
P_5'



$P_5' = S_5/\sqrt{F_L(1-F_L)}$, leading form factor uncertainties cancel. Tension already in 1 fb^{-1} and confirmed in 3 fb^{-1} LHCb-CONF-2015-002

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 $\bar{c}^l_{ij}$

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

$$\mathcal{O}^l_{ij} = (\bar{s}\gamma^\mu P_i b)(\bar{l}\gamma_\mu P_j l)\,.$$

$$\mathcal{L}_{\rm eff} \supset \sum_{l=e,\mu,\tau}\sum_{i=L,R}\sum_{j=L,R}\frac{c^l_{ij}}{\Lambda^2_{l,ij}}\mathcal{O}^l_{ij}\,,$$

$$= \sum_{l=e,\mu,\tau} V_{tb}V^*_{ts}\frac{\alpha}{4\pi v^2}\left(\bar{c}^l_{LL}\mathcal{O}^l_{LL} + \bar{c}^l_{LR}\mathcal{O}^l_{LR}\right.$$

$$\left.+\bar{c}^l_{RL}\mathcal{O}^l_{RL} + \bar{c}^l_{RR}\mathcal{O}^l_{RR}\right)$$

$$\Rightarrow \bar{c}^l_{ij} = (36\ \mathrm{TeV}/\Lambda)^2 c^l_{ij}.$$

$c^l_{ij} \sim \pm\mathcal{O}(1)$ all predicted by weak interactions in SM.

Which Ones Work?

Options *for a single BSM operator*:

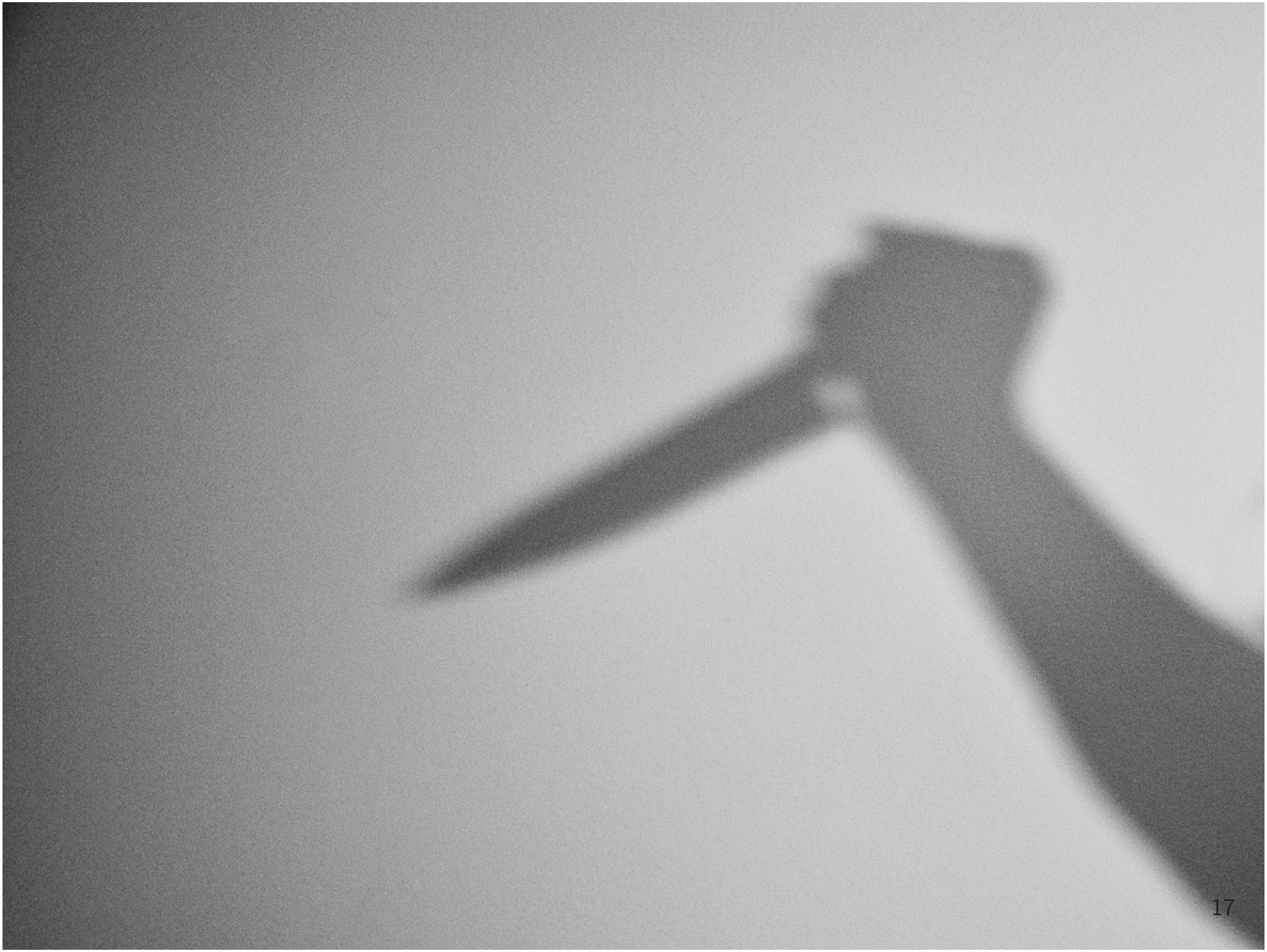
- $\bar{c}^e_{ij}$ operators fine for $R_{K^{(*)}}$ but are disfavoured by global fits including other observables.
- $\bar{c}^\mu_{LR}$ disfavoured: predicts *enhancement* in both R_K and R_{K^*}
- $\bar{c}^\mu_{RR}$, $\bar{c}^\mu_{RL}$ disfavoured: they pull R_K and R_{K^*} in *opposite directions*.
- $\bar{c}^\mu_{LL} =$ ~~-1.33~~ -1.06 fits well globally[3].

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

Statistics[4]

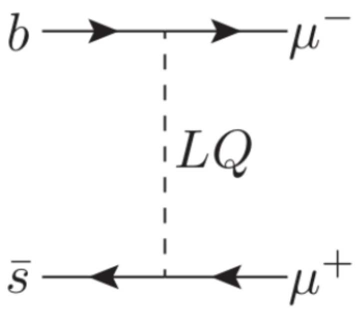
	$\bar{c}^{\mu}_{LL}$	$\sqrt{\chi^2_{SM} - \chi^2_{best}}$
clean	-1.33 ± 0.34	4.1
dirty	-1.33 ± 0.32	4.6
all	~~-1.33 ± 0.23~~ -1.06 ± 0.16	~~6.2~~ 6.5
	$C^{\mu}_9 = (\bar{c}^{\mu}_{LL} + \bar{c}^{\mu}_{LR})/2$	$\sqrt{\chi^2_{SM} - \chi^2_{best}}$
clean	-1.51 ± 0.46	3.9
dirty	-1.15 ± 0.17	5.5
all	~~-1.19 ± 0.15~~ -0.95 ± 0.15	~~6.7~~ 5.8

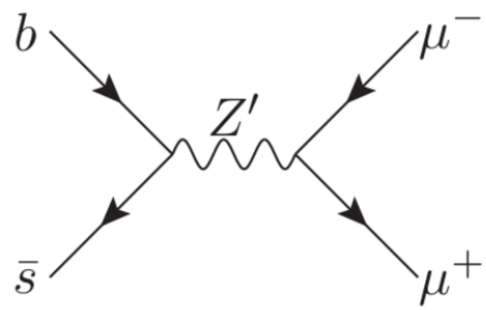
[4] 'clean' (R_K, R_{K^*}, $B_s \to \mu\mu$) and 'dirty' (P'_5, $B \to \phi\mu\mu$+100 others). D'Amico, Nardecchia, Panci, Sannino, Strumia, Torre, Urbano 1704.05438; Aebischer, Altmanshoffer, Guadagnoli, Reboud, Stangl, Straub, 1903.10434

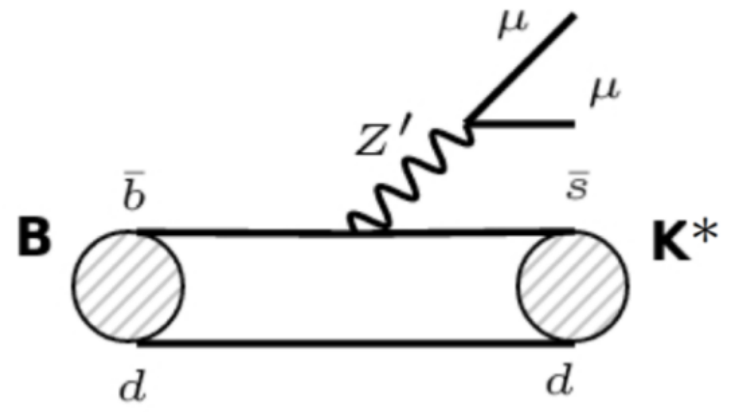


Simplified Models for c_{LL}^{μ}

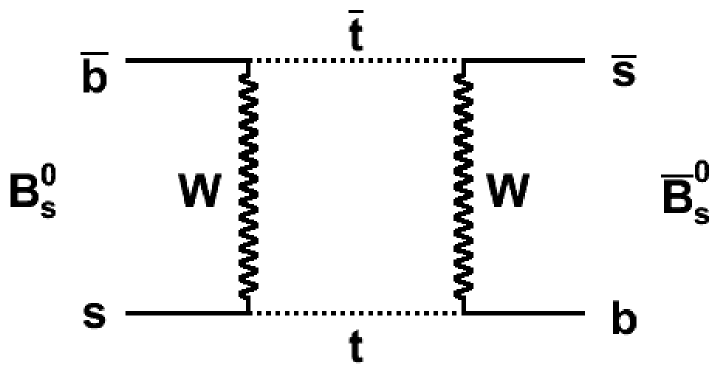
At tree-level, we have:

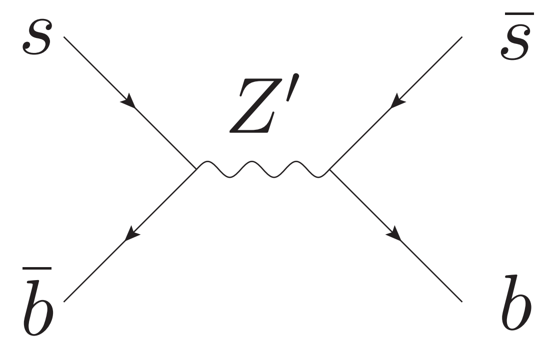






$B_s - \bar{B}_s$ **Mixing**





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

from QCD sum rules and lattice[5]

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

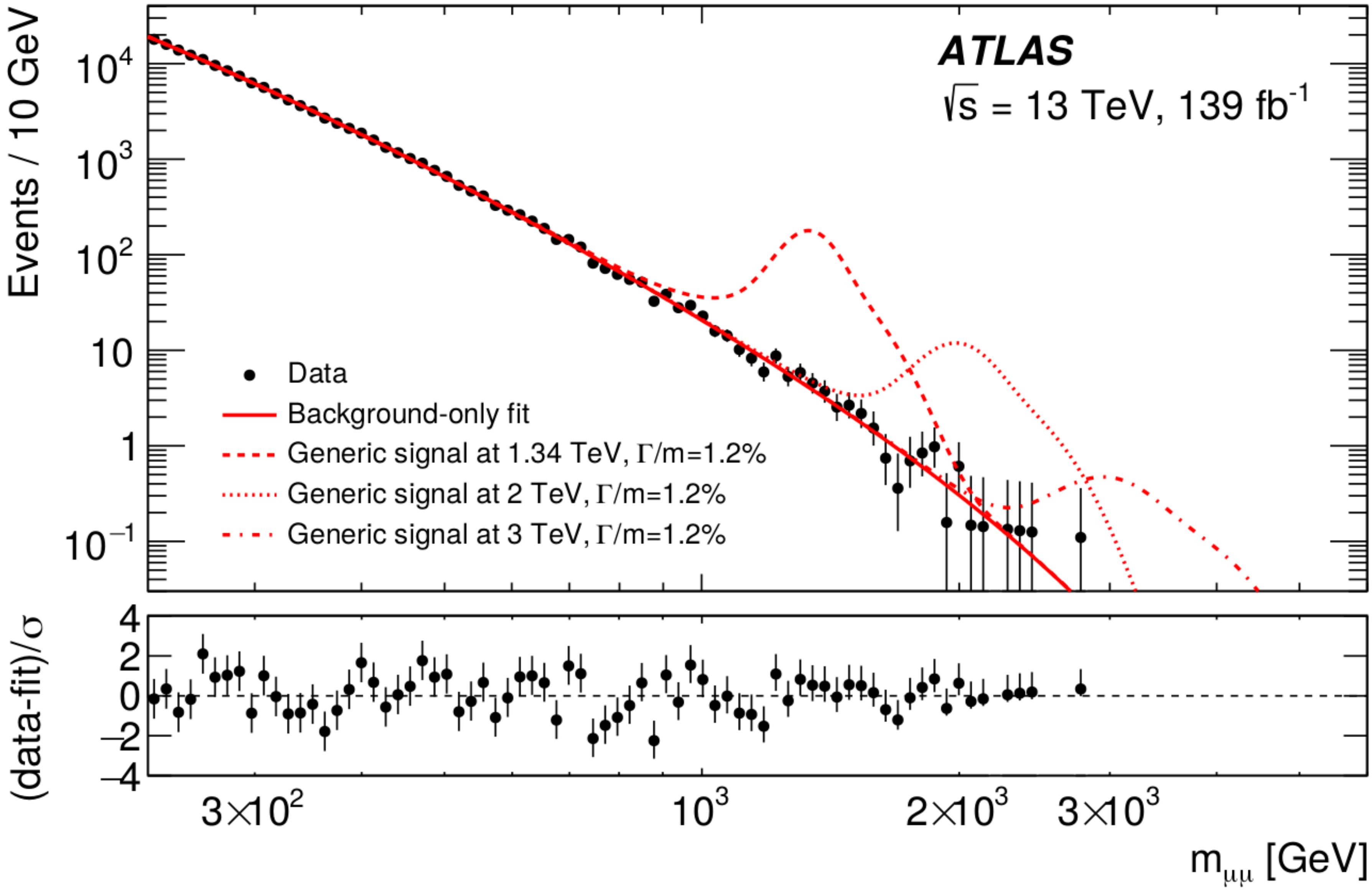
$Z' \to \mu\mu$ ATLAS 13 TeV 139 fb^{-1}

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[6]

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

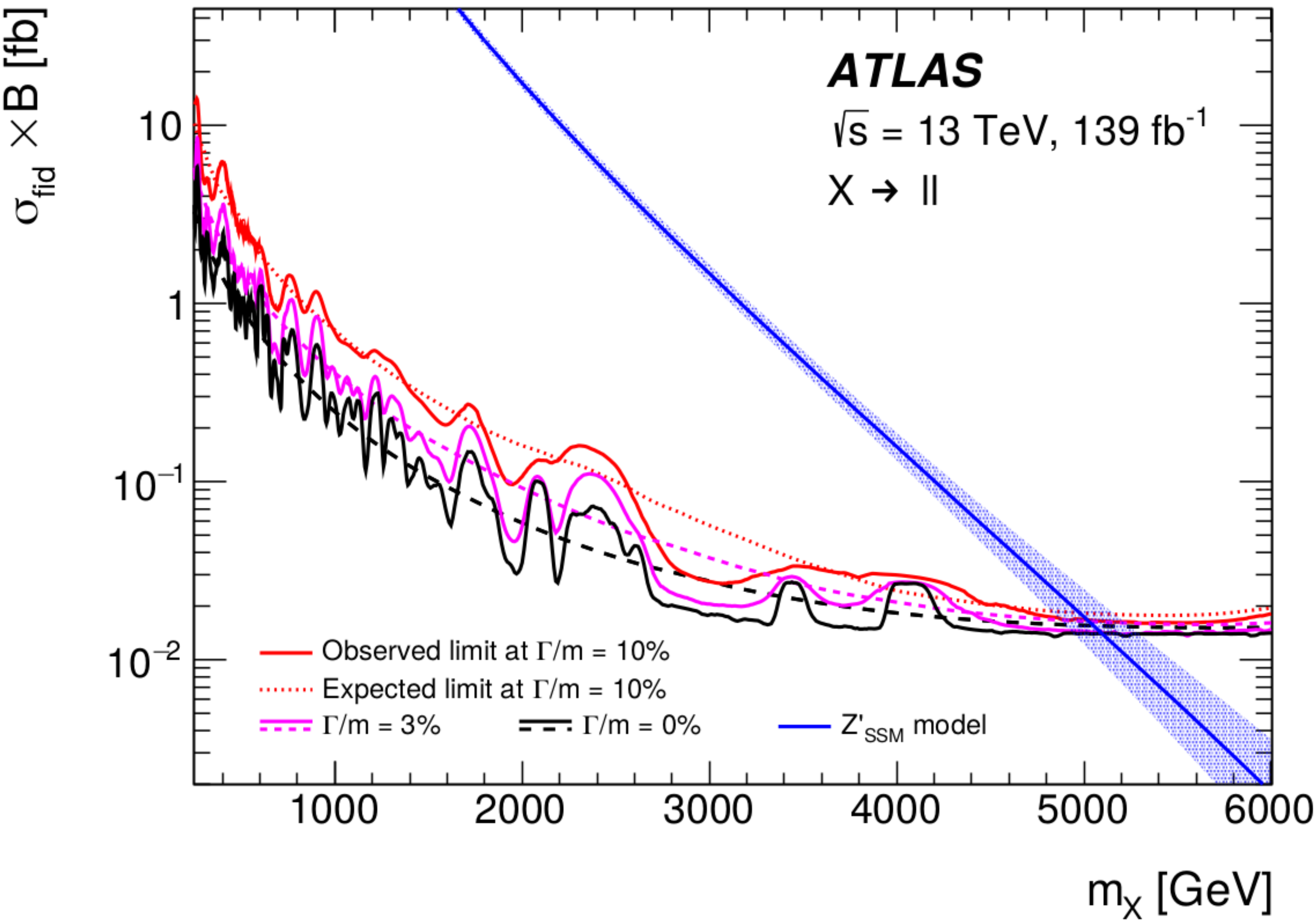
CMS also have released[7] a similar 36 fb^{-1} analysis.

[6] 1903.06248
[7] 1803.06292



ATLAS
√s = 13 TeV, 139 fb-1
Events / 10 GeV
10^4
10^3
10^2
10
1
10^−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%
(data-fit)/σ
4
2
0
−2
−4
3×10^2
10^3
2×10^3
3×10^3
m_μμ [GeV]

ATLAS l^+l^- limits



1903.06248

Simplified Z' Models

Naïve model: only include couplings to $\bar{b}s/b\bar{s}$ and $\mu^+\mu^-$ (*less model dependent*).

$$\mathcal{L}_{Z'}^{\text{min.}} \supset \left(g_L^{sb} Z'_\rho \bar{s}\gamma^\rho P_L b + \text{h.c.}\right) + g_L^{\mu\mu} Z'_\rho \bar{\mu}\gamma^\rho P_L \mu \,,$$

which contributes to the $\mathcal{O}_{LL}^{\mu}$ coefficient with[8]

$$\bar{c}_{LL}^{\mu} = -\frac{4\pi v^2}{\alpha_{\text{EM}} V_{tb} V_{ts}^*} \frac{g_L^{sb} g_L^{\mu\mu}}{M_{Z'}^2},$$

$$\Rightarrow \boxed{g_L^{sb} g_L^{\mu\mu} \left(\frac{36 \text{ TeV}}{M_{Z'}}\right)^2 = \cancel{-1.33 \pm 0.34}\; -1.06 \pm 0.16.}$$

[8] Aebischer *et al*, `arXiv:1903.10434`

Simplified Z' Models[9]

$$\mathcal{L}_{Z'f} = \left(\overline{\mathbf{Q}'_{\mathbf{L}}}_i \lambda^{(Q)}_{ij} \gamma^\rho \mathbf{Q}'_{\mathbf{L}j} + \overline{\mathbf{L}'_{\mathbf{L}}}_i \lambda^{(L)}_{ij} \gamma^\rho \mathbf{L}'_{\mathbf{L}j}\right) Z'_\rho,$$

After CKM mixing of $V = V_{u_L^\dagger} V_{d_L}$ and PMNS $U = V^\dagger_{\nu_L} V_{e_L}$,

$$\begin{aligned}\mathcal{L} \;=\; & \Big(\overline{\mathbf{u_L}} V \Lambda^{(Q)} V^\dagger \gamma^\rho \mathbf{u_L} + \overline{\mathbf{d_L}} \Lambda^{(Q)} \gamma^\rho \mathbf{d_L} + \\ & \overline{\boldsymbol{\nu}_\mathbf{L}} U \Lambda^{(L)} U^\dagger \gamma^\rho \boldsymbol{\nu}_\mathbf{L} + \overline{\mathbf{e_L}} \Lambda^{(L)} \gamma^\rho \mathbf{e_L}\Big) Z'_\rho,\end{aligned}$$

where

$$\Lambda^{(Q)} \equiv V^\dagger_{d_L} \lambda^{(Q)} V_{d_L}, \qquad \Lambda^{(L)} \equiv V^\dagger_{e_L} \lambda^{(L)} V_{e_L}.$$

[9] BCA, Corbett, Dolan, You, `arXiv:1810.02166`

Limiting Cases

Mixed Up Model: all quark mixing is in left-handed ups

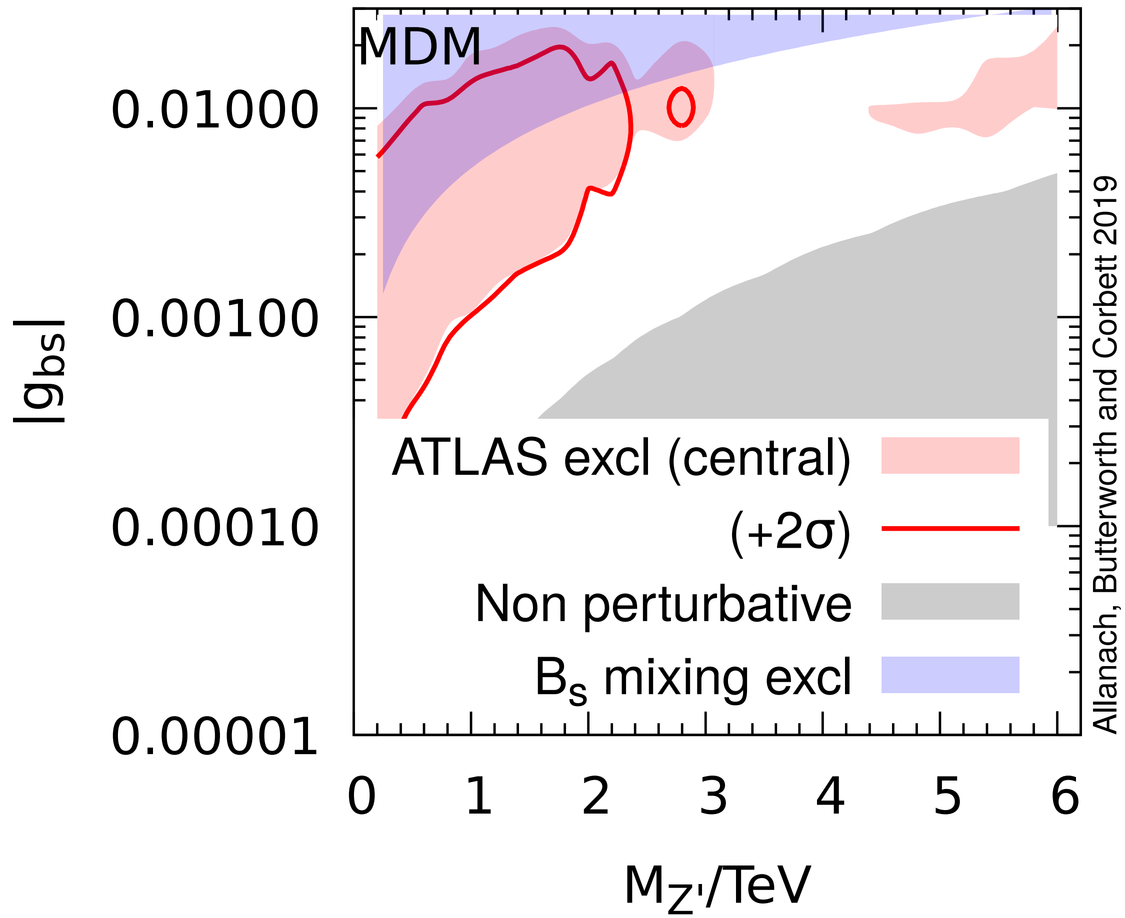
$$\Lambda^{(Q)} = g_{bs} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \qquad \Lambda^{(L)} = g_{\mu\mu} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

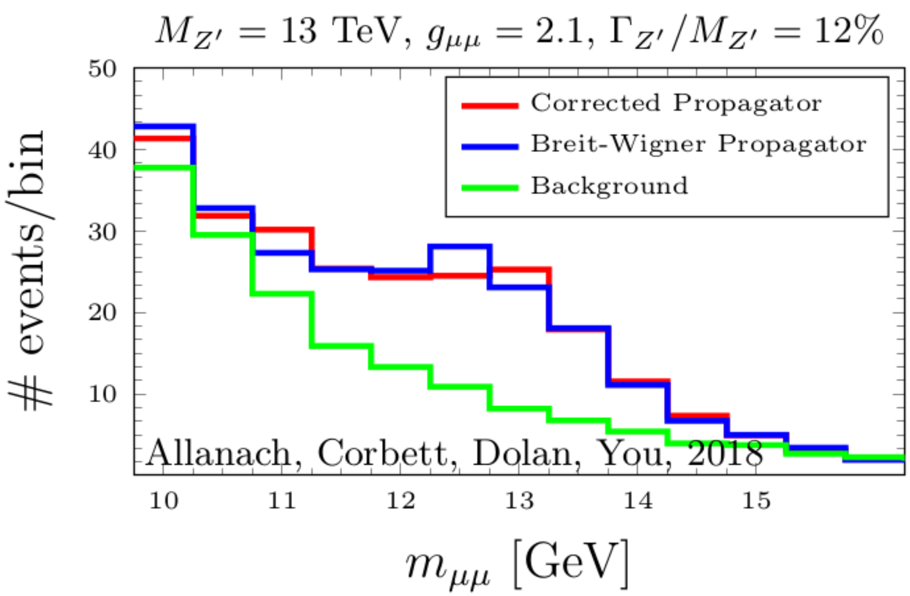
Mixed Down Model: all quark mixing is in left-handed downs

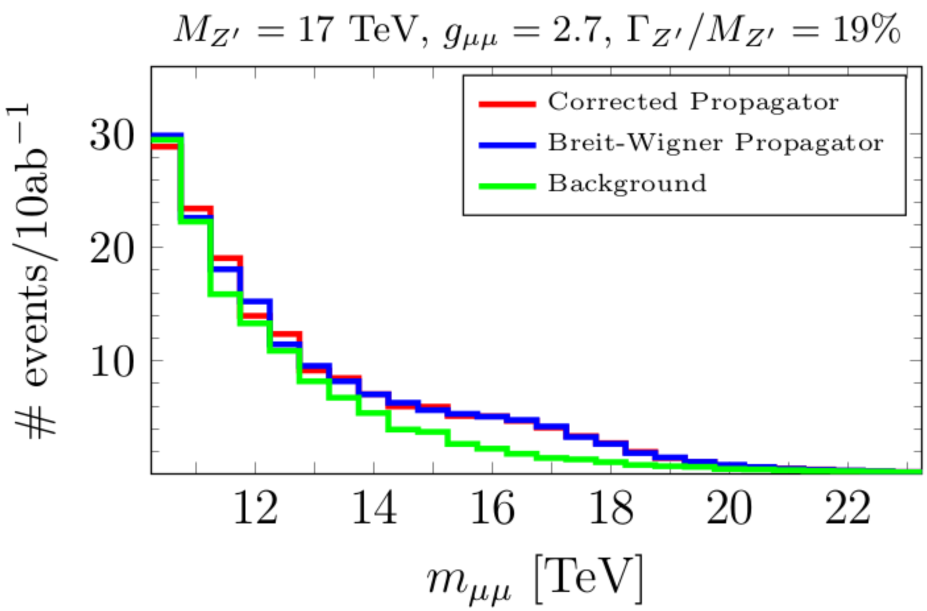
$$\Lambda^{(Q)} = g_{tt} V^{\dagger} \cdot \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot V, \qquad \Lambda^{(L)} = g_{\mu\mu} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

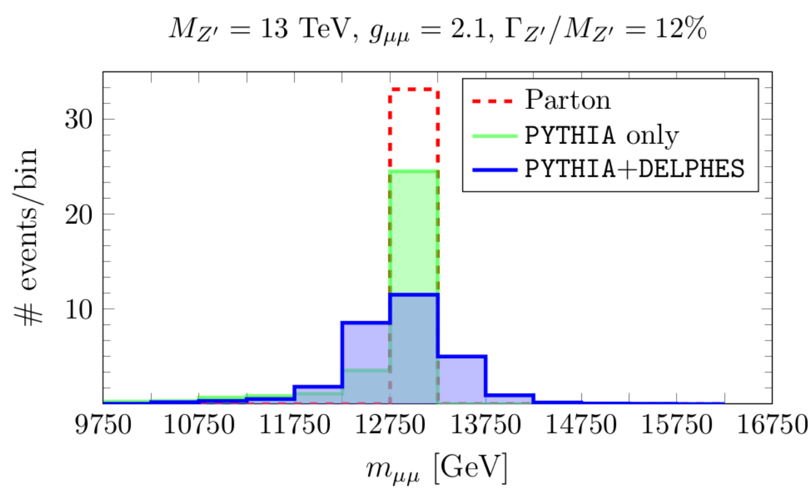
$\Rightarrow g_{bs} = V_{ts}^* V_{tb} g_{tt} \approx -0.04 g_{tt}$: the quark couplings are weaker than the leptonic ones

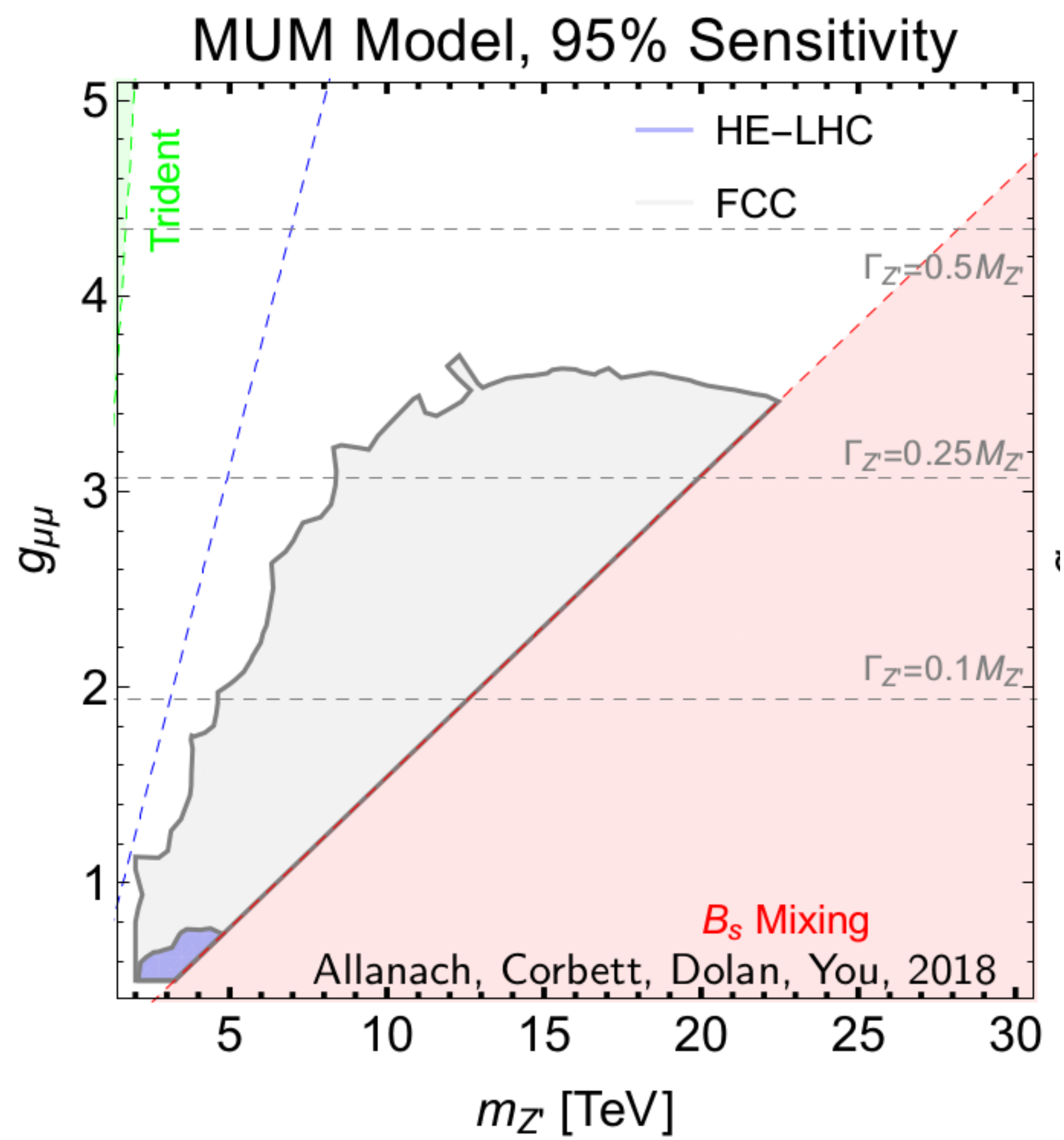
ATLAS $\mu\mu$ Constraint: MDM

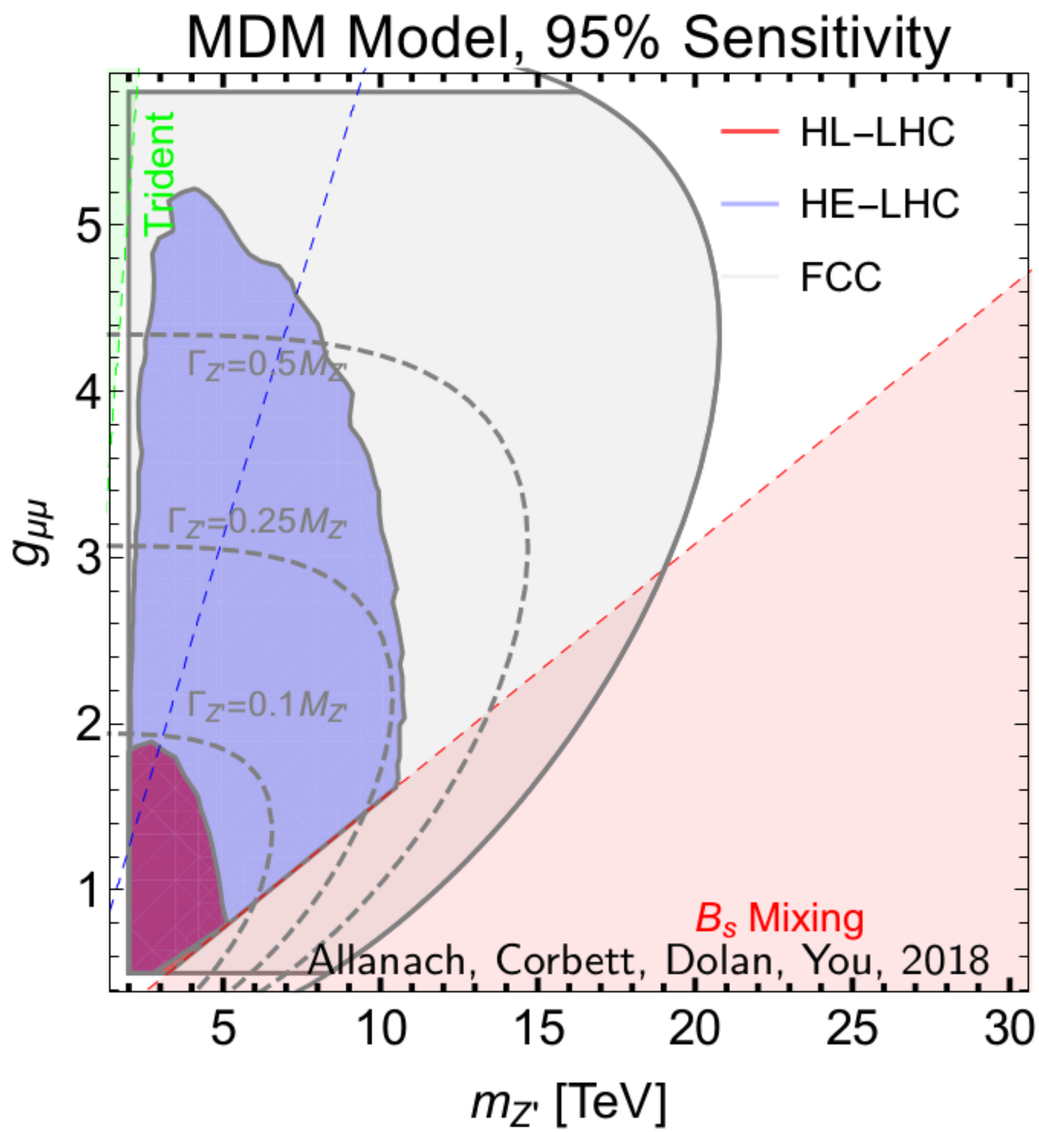



$M_{Z'} = 13$ TeV, $g_{\mu\mu} = 2.1$, $\Gamma_{Z'}/M_{Z'} = 12\%$
Corrected Propagator
Breit-Wigner Propagator
Background
Allanach, Corbett, Dolan, You, 2018
events/bin
$m_{\mu\mu}$ [GeV]


$M_{Z'} = 17$ TeV, $g_{\mu\mu} = 2.7$, $\Gamma_{Z'}/M_{Z'} = 19\%$
Corrected Propagator
Breit-Wigner Propagator
Background
events/10ab^{-1}
$m_{\mu\mu}$ [TeV]


$M_{Z'} = 13$ TeV, $g_{\mu\mu} = 2.1$, $\Gamma_{Z'}/M_{Z'} = 12\%$
Parton
PYTHIA only
PYTHIA+DELPHES
events/bin
$m_{\mu\mu}$ [GeV]


MUM Model, 95% Sensitivity
HE−LHC
FCC
Trident
$\Gamma_{Z'}=0.5M_{Z'}$
$\Gamma_{Z'}=0.25M_{Z'}$
$\Gamma_{Z'}=0.1M_{Z'}$
B_s Mixing
Allanach, Corbett, Dolan, You, 2018
$g_{\mu\mu}$
$m_{Z'}$ [TeV]
1
2
3
4
5
5
10
15
20
25
30


MDM Model, 95% Sensitivity
HL−LHC
HE−LHC
FCC
Trident
$\Gamma_{Z'}=0.5M_{Z'}$
$\Gamma_{Z'}=0.25M_{Z'}$
$\Gamma_{Z'}=0.1M_{Z'}$
B_s Mixing
Allanach, Corbett, Dolan, You, 2018
$g_{\mu\mu}$
1
2
3
4
5
5
10
15
20
25
30
$m_{Z'}$ [TeV]

During the 1990s

We wanted to be the Grand Architects, searching for **the** string model to rule them all

During the 2010s

We are happy with **any** beyond the Standard Model roof

Third Family Hypercharge Model

Add complex SM singlet scalar θ and gauged $U(1)_F$:

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

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

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

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

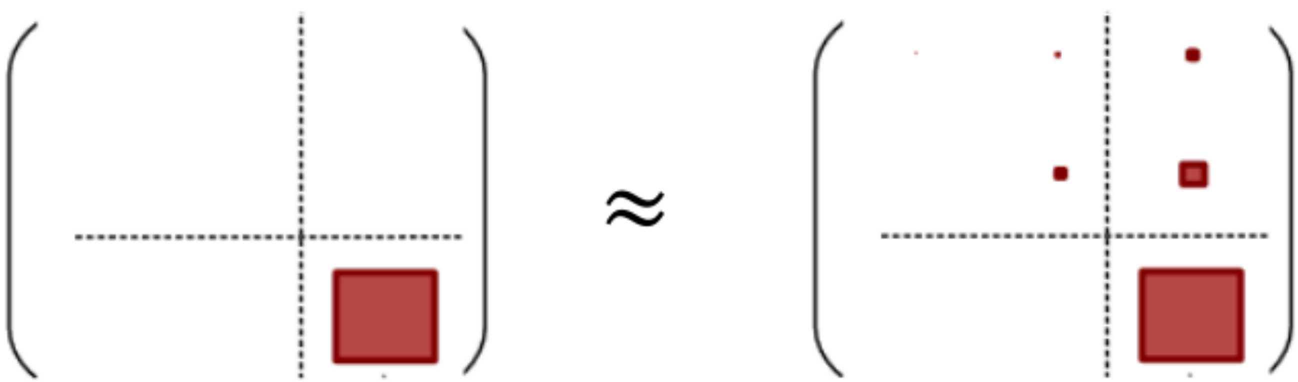
$$SU(3) \times U(1)_{em}$$

- SM fermion content
- anomaly cancellation
- 0 F charges for first two generations

Unique Solution

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

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



Yukawa Advantages

- First two 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

$Z - X$ mixing

Because $F_H = -1/2$, $Z - X$ mix:

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

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

$Z - X$ mixing angle

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

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

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

$$
\begin{aligned}
\mathcal{L}_{X\psi} = g_F \Bigg(& \frac{1}{6}\overline{\mathbf{u_L}}\Lambda^{(u_L)}\gamma^\rho\mathbf{u_L} + \frac{1}{6}\overline{\mathbf{d_L}}\Lambda^{(d_L)}\gamma^\rho\mathbf{d_L} - \\
& \frac{1}{2}\overline{\mathbf{n_L}}\Lambda^{(n_L)}\gamma^\rho\mathbf{n_L} - \frac{1}{2}\overline{\mathbf{e_L}}\Lambda^{(e_L)}\gamma^\rho\mathbf{e_L} + \\
& \frac{2}{3}\overline{\mathbf{u_R}}\Lambda^{(u_R)}\gamma^\rho\mathbf{u_R} - \\
& \frac{1}{3}\overline{\mathbf{d_R}}\Lambda^{(d_R)}\gamma^\rho\mathbf{d_R} - \overline{\mathbf{e_R}}\Lambda^{(e_R)}\gamma^\rho\mathbf{e_R} \Bigg) Z'_\rho,
\end{aligned}
$$

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

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

A simple limiting case

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

for simplicity and the ease of passing bounds.

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

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

Important Z' Couplings

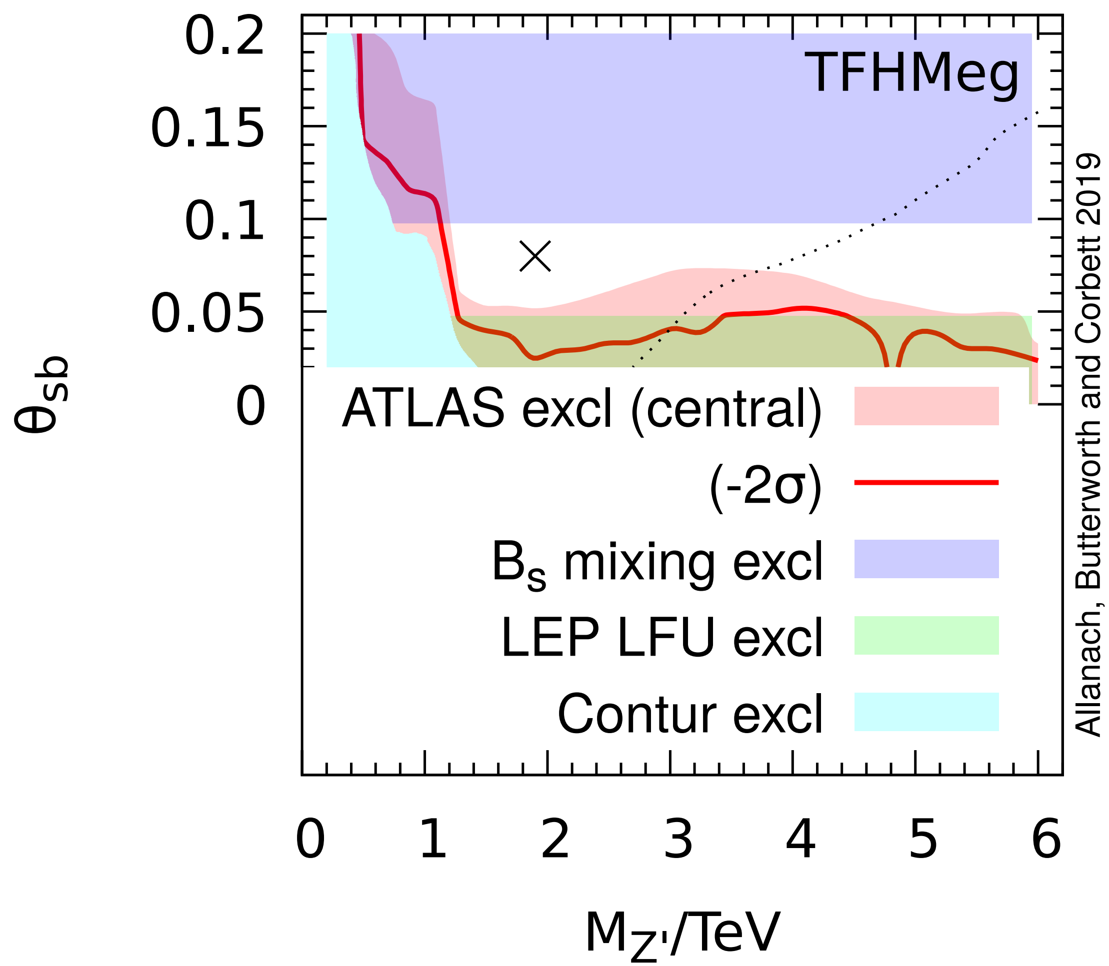
$$g_F \left[\frac{1}{6}\overline{\mathbf{d_L}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin^2\theta_{sb} & \frac{1}{2}\sin 2\theta_{sb} \\ 0 & \frac{1}{2}\sin 2\theta_{sb} & \cos^2\theta_{sb} \end{pmatrix} \not{Z}' \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \right.$$

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

Put $|\theta_{sb}| \sim \mathcal{O}(|V_{ts}|) = 0.04$, so $|g_{\mu\mu}| \gg |g_{bs}|$, which helps us survive $B_s - \overline{B_s}$ constraint.

$c_{LL} = g_F^2 \sin 2\theta_{sb}/(24 M_{Z'}^2)$.

$$g_F \propto M_{Z'}/\sqrt{\sin 2\theta_{bs}}$$



Example Case Predictions

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

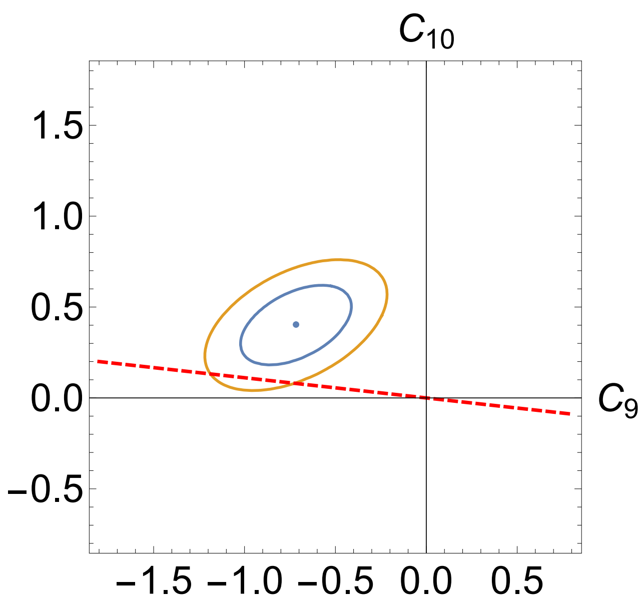
$$g_F^2 \left(\frac{M_Z}{M_{Z'}}\right)^2 \leq 0.004 \Rightarrow g_F \leq \frac{M_{Z'}}{1.3 \text{ TeV}}.$$

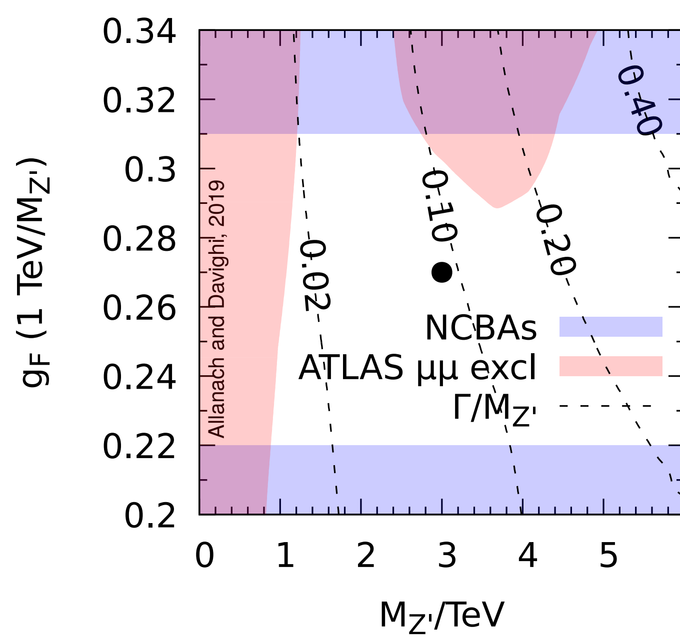
It's worth LHCb, BELLE II chasing $BR(B \to K^{(*)}\tau^\pm\tau^\mp)$.

Deformed TFHM

$F_{Q'_i} = 0$	$F_{u_{R'_i}} = 0$	$F_{d_{R'_i}} = 0$	$F_H = -1/2$
$F_{e_{R'_1}} = 0$	$F_{e_{R'_2}} = 2/3$	$F_{e_{R'_3}} = -5/3$	
$F_{L'_1} = 0$	$F_{L'_2} = 5/6$	$F_{L'_3} = -4/3$	
$F_{Q'_3} = 1/6$	$F_{u'_{R3}} = 2/3$	$F_{d'_{R3}} = -1/3$	$F_\theta \neq 0$

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





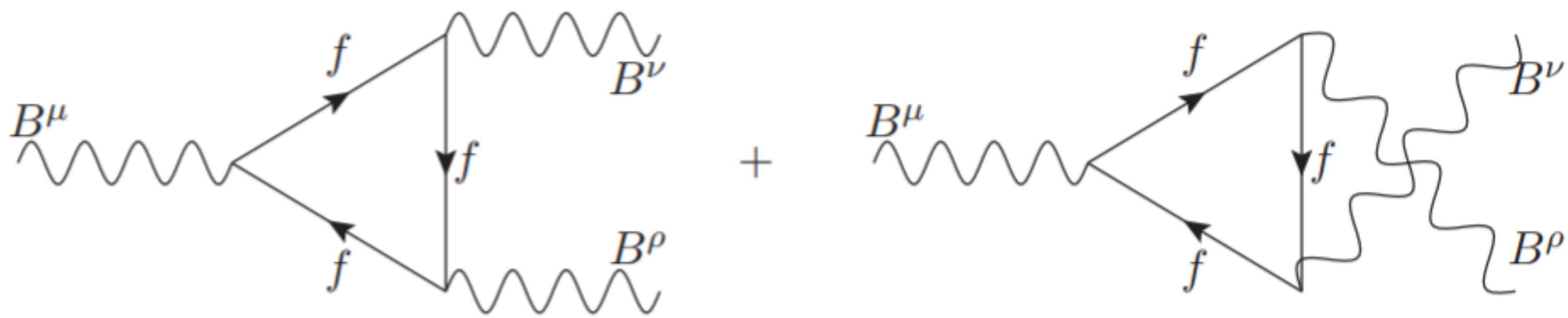
Invisible Width of Z Boson

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

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

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

Quantum Field Theory
Anomalies



$$A \equiv \sum_{LH\ f_i} Y_i^3 - \sum_{RH\ f_i} Y_i^3$$

Hypercharge anomaly cancellation

Deforming the SM to $SU(3) \times SU(2) \times \mathbb{R}_Y$, and allowing the hypercharges Y of the chiral fermionic fields to float, the combination of gauge ACC and gravitational ACC implies that the hypercharges must be quantised[10] (i.e. that ratios of hypercharges of different chiral fermions are rational). Conversely, if the hypercharges are quantised but otherwise free, the gauge ACC implies the gravitational ACC [11].

[10] Weinberg, *The Quantum Theory of Fields (1995), CUP*
[11] Lohitsiri and Tong, `arXiv:1907.00514`

Anomaly equations

4 linear ones, and

$$\sum_{i=1}^{3}(F_{Q_i}^2 - F_{L_i}^2 - 2F_{u_i}^2 + F_{d_i}^2 + F_{e_i}^2) = 0,$$

ACC is the cubic

$$\sum_{i=1}^{3}(6F_{Q_i}^3 + 2F_{L_i}^3 - 3F_{u_i}^3 - 3F_{d_i}^3 - F_{e_i}^3 - F_{\nu_i}^3) = 0,$$

Look for solutions in integers.

Solve case for 1 or 2 families of charges *analytically*, using old Diophantine methods. For 3 families, wrote a efficient computer program to search through $(2Q_{max}+1)^{18}$ sets of charges for SM and SM$+3\nu_R$, find all those that solve the anomaly equations.

Integer charges

We argue ratios of charges are *rationals*: in a holographic setting, boundary CFT is finitely generated (finite number of fields in path integral) then gauge group must be compact[12]. Also, otherwise they wouldn't fit into some unified non-abelian group.

ACCs have rescaling invariance: so we can rescale rationals by highest denominator to obtain integers. Note that we shall *mod out* by the permutation invariance of switching a species family indices around in the ACCs by strictly ordering them.

[12] Harlow, Ooguri, arXiv:1810.05338

Q	Q	Q	ν	ν	ν	e	e	e	u	u	u	L	L	L	d	d	d
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	-1	0	1	-1	0	1
0	0	0	0	0	0	-1	0	1	0	0	0	-1	0	1	0	0	0
0	0	0	0	0	0	-1	0	1	-1	0	1	0	0	0	-1	0	1
-1	0	1	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0
-1	0	1	0	0	0	0	0	0	-1	0	1	0	0	0	-1	0	1
-1	0	1	0	0	0	-1	0	1	-1	0	1	0	0	0	0	0	0
-1	0	1	0	0	0	-1	0	1	-1	0	1	-1	0	1	-1	0	1

eg: $Q_{max} = 1.$ Charges within a species are listed in *increasing order*.

$Q_{\max}$	**Solutions**	Symmetry	Quadratics	Cubics	Time/sec
1	**8**	8	32	8	0.0
2	**22**	14	1861	161	0.0
3	**82**	32	23288	1061	0.0
4	**251**	56	303949	7757	0.0
5	**626**	114	1966248	35430	0.0
6	**1983**	144	11470333	143171	0.2
7	**3902**	252	46471312	454767	0.6
8	**7068**	336	176496916	1311965	2.2
9	**14354**	492	539687692	3310802	6.7
10	**23800**	582	1580566538	7795283	20

SM solutions

An Anomaly-Free Atlas

The atlas is available for public use:
`http://doi.org/10.5281/zenodo.1478085`

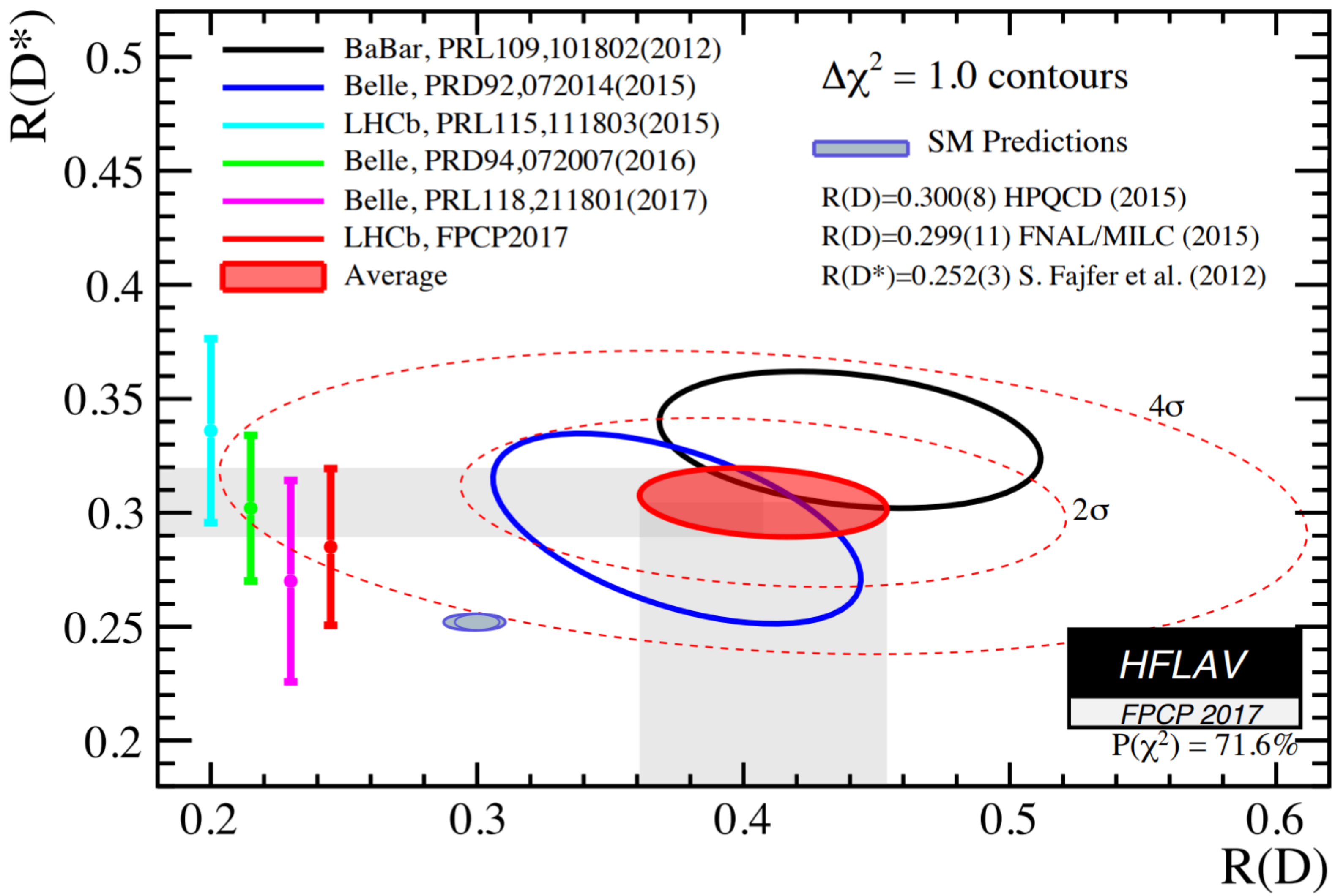
We did various checks (are solutions that were found in the literature before present, and are classes that have been banned not present?)

BCA, Davighi, Melville, `arXiv:1812.04602`

Conclusions

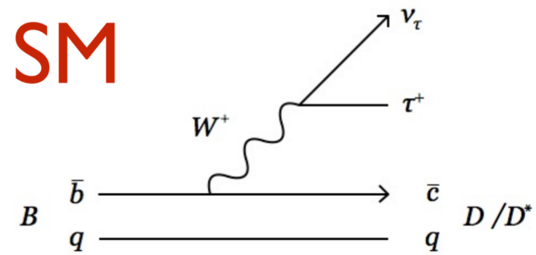
The answers to the questions raised by the neutral current $B-$anomalies may provide a direct experimental probe into the flavour problem.

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



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

... has to compete with

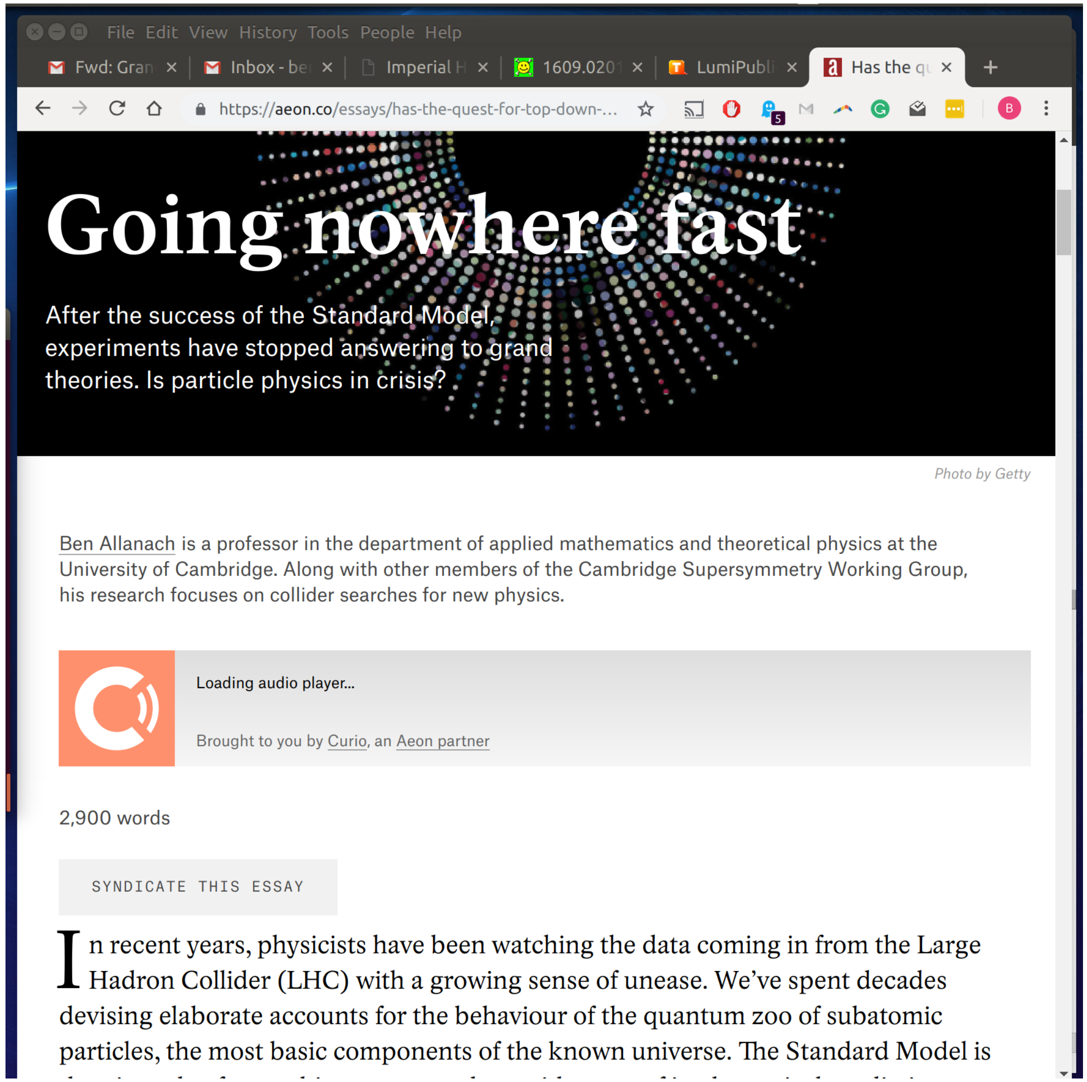


$$\mathcal{L}_{eff} = -\frac{2}{\Lambda^2}\left(\bar{c}_L\gamma^\mu b_L\right)\left(\bar{\tau}_L\gamma_\mu\nu_{\tau L}\right) + H.c.$$

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

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

PMP$\Rightarrow$we ignore $R_{D^{(*)}}$.



Going nowhere fast

After the success of the Standard Model, experiments have stopped answering to grand theories. Is particle physics in crisis?

Photo by Getty

Ben Allanach is a professor in the department of applied mathematics and theoretical physics at the University of Cambridge. Along with other members of the Cambridge Supersymmetry Working Group, his research focuses on collider searches for new physics.

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2,900 words

SYNDICATE THIS ESSAY

In recent years, physicists have been watching the data coming in from the Large Hadron Collider (LHC) with a growing sense of unease. We've spent decades devising elaborate accounts for the behaviour of the quantum zoo of subatomic particles, the most basic components of the known universe. The Standard Model is

Other conclusions

- The answers to the questions raise by $R_{K^{(*)}}$ may provide a direct experimental probe into the flavour problem.
- Focused on *tree-level* explanations of $R_{K^{(*)}}$ as they are usually harder to discover: Z' and leptoquarks.
- News on $R_K^{(*)}$ expected *in 2019*. At the current central value, Belle II can reach 5σ by mid 2021. LHCb's R_{K^*} would be close to[13] 5σ by 2020.
- $R_{K^{(*)}} \Rightarrow$ *HL-LHC, HE-LHC and FCC-hh*

[13] Albrecht *et al*, 1709.10308

Backup

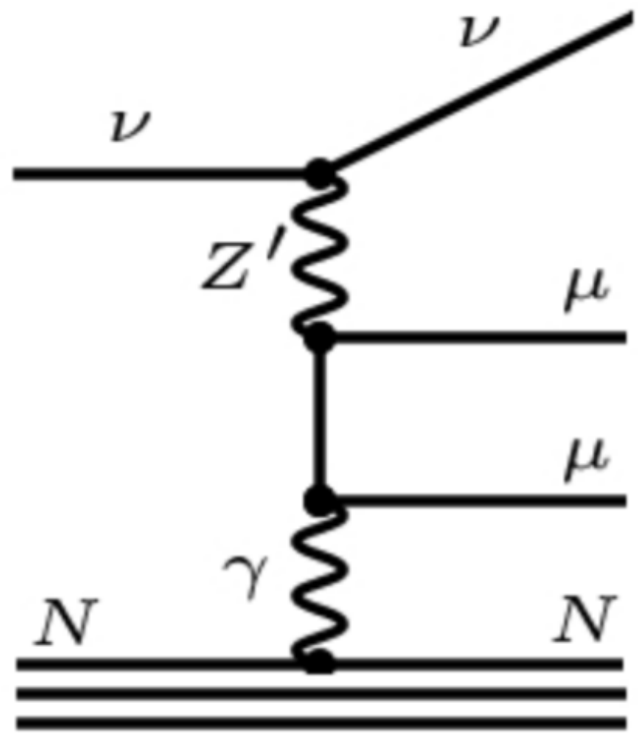
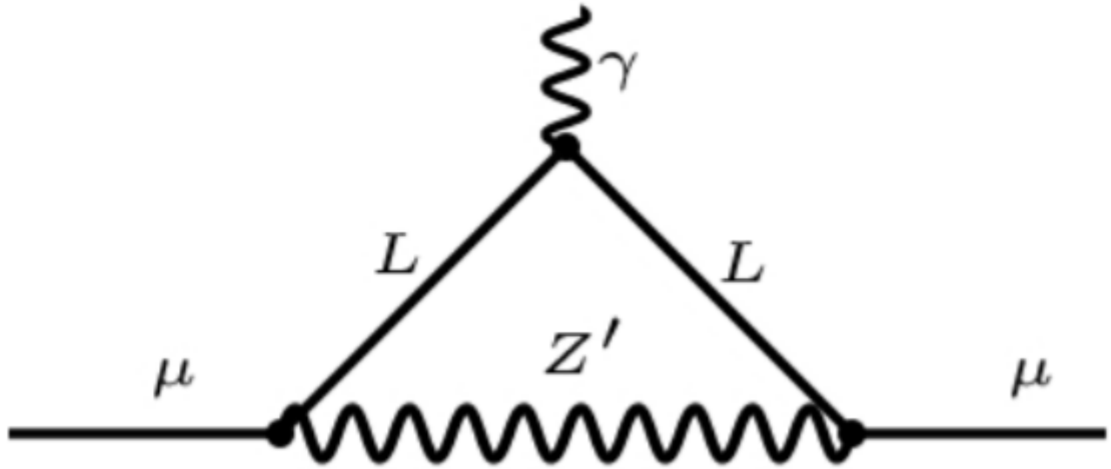
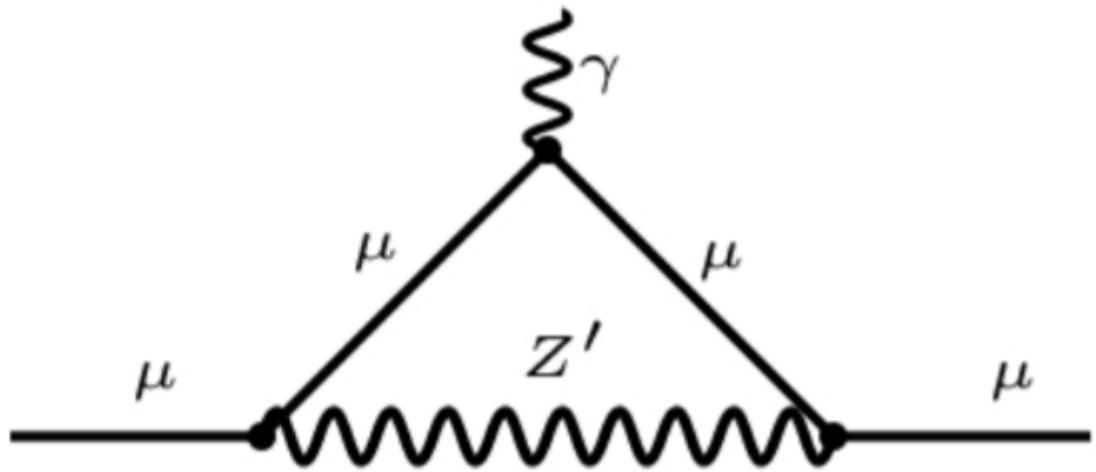


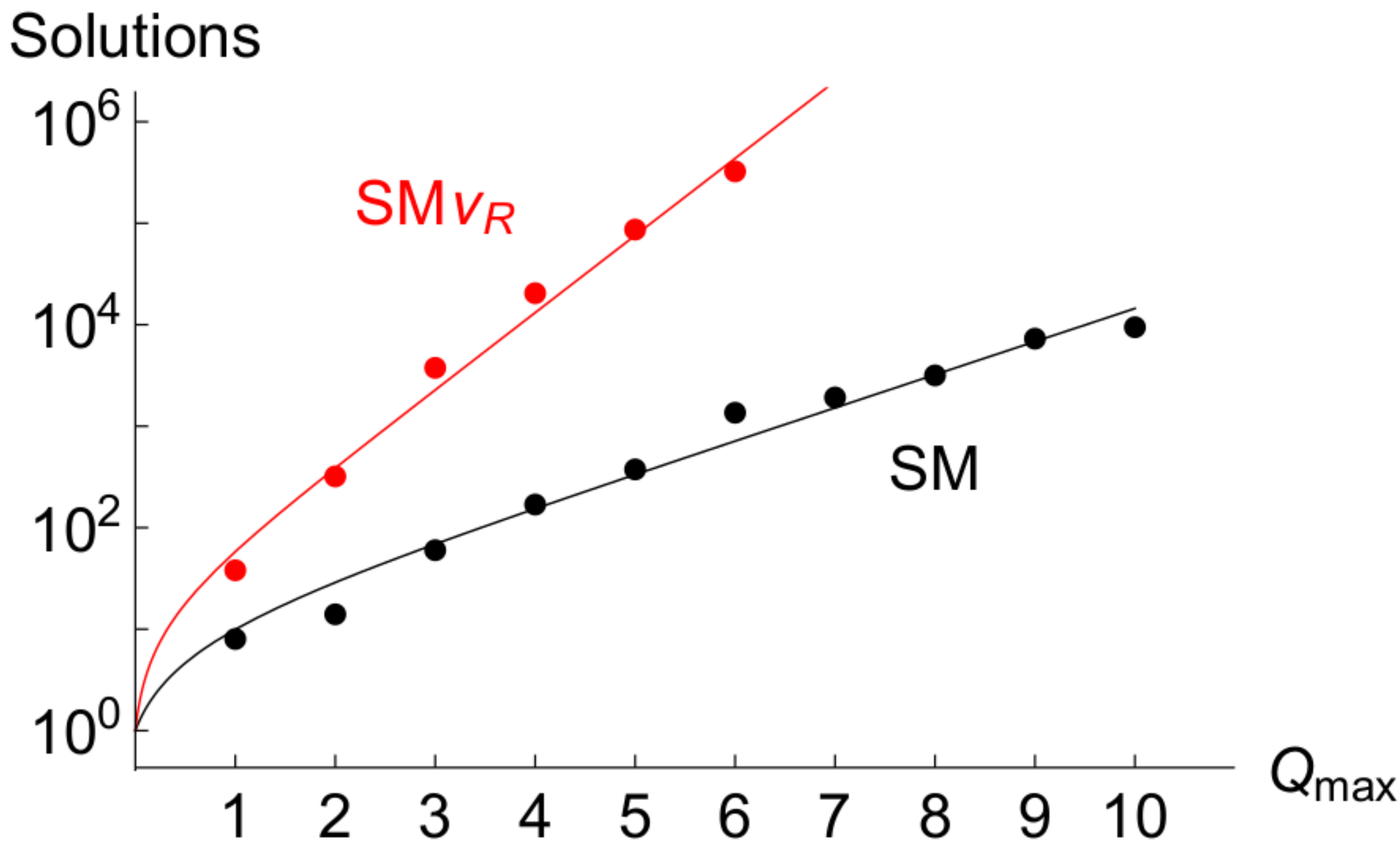
FIG. 10. Neutrino trident process that leads to constraints on the Z^{μ} coupling strength to neutrinos-muons, namely $M_{Z'}/g_{v\mu} \gtrsim 750$ GeV.

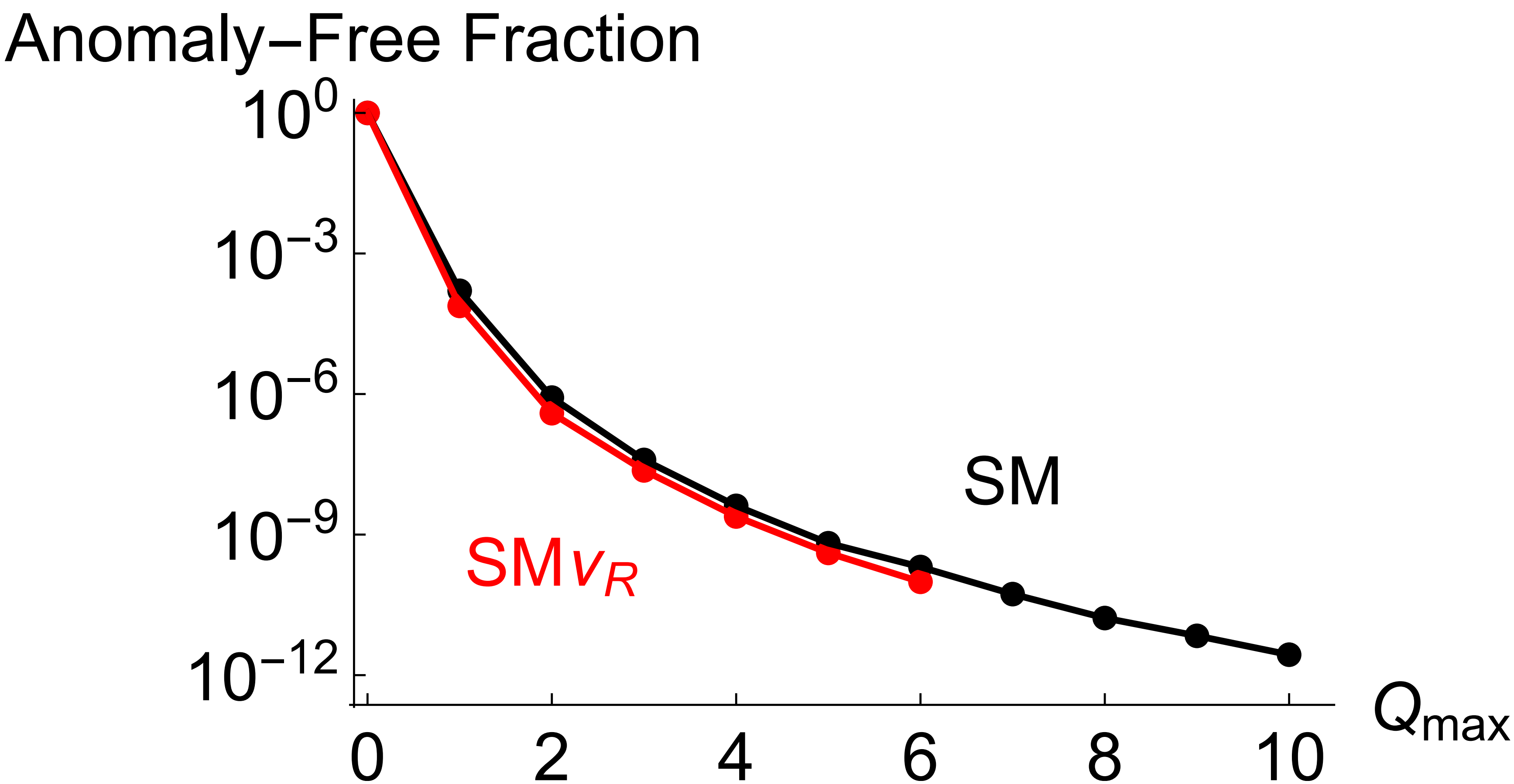

γ
L
L
Z′
μ
μ


γ
μ
μ
Z′
μ
μ

$Q_{\max}$	**Solutions**	Symmetry	Quadratics	Cubics	Time/sec
1	**38**	16	144	38	0.0
2	**358**	48	31439	2829	0.0
3	**4116**	154	1571716	69421	0.1
4	**24552**	338	34761022	932736	0.6
5	**111152**	796	442549238	7993169	6.8
6	**435305**	1218	3813718154	49541883	56

SM + 3 ν_R: number of solutions etc

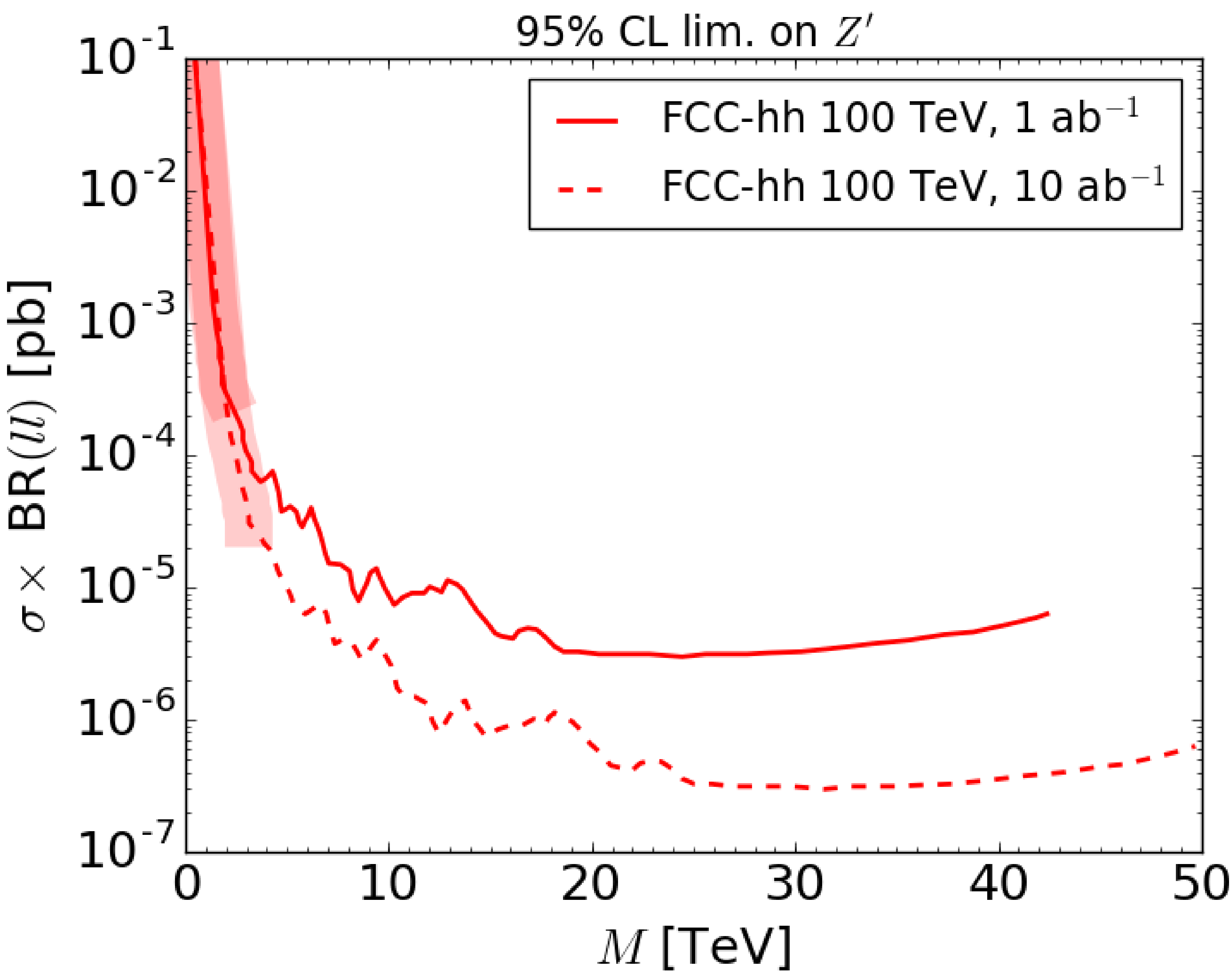

Solutions
10^6
10^4
10^2
10^0
$SM\nu_R$
SM
1
2
3
4
5
6
7
8
9
10
Q_{max}


Anomaly–Free Fraction
10^0
10^−3
10^−6
10^−9
10^−12
SM
SMν_R
0
2
4
6
8
10
Q_max

Known Solutions

Model	Q	Q	Q	ν	ν	ν	e	e	e	u	u	u	L	L	L	d	d	d
$L_\mu - L_\tau$	0	0	0	-1	0	1	-1	0	1	0	0	0	-1	0	1	0	0	0
TFHM	-1	0	0	0	0	0	0	0	6	-4	0	0	0	0	3	0	0	2
$B_3 - L_3$	-1	0	0	0	0	3	0	0	3	-1	0	0	0	0	3	-1	0	0

13 TeV ATLAS 3.2 fb^{-1} $\mu\mu$



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

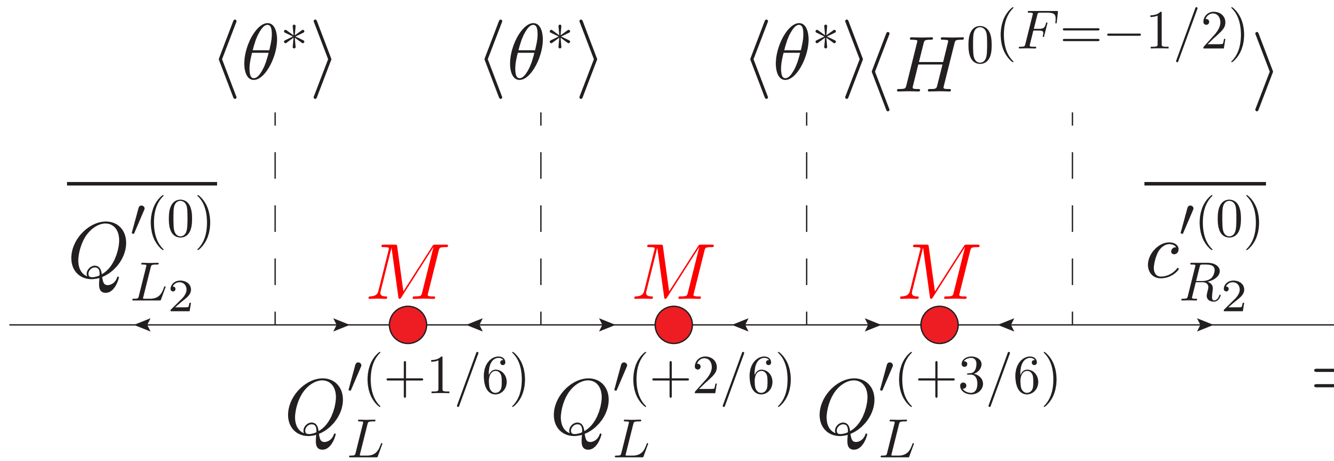
$$\mathcal{L}_{SS} = 1/2 \sum_{ij} (L'_i H^c)(M^{-1})_{ij}(L'_j H^c),$$

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[14]

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

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

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

LQ Models

Scalar[15] $S_3 = (\bar{3},\ 3,\ 1/3)$ of $SU(2) \times SU(2)_L \times U(1)_Y$:

$$\mathcal{L} = \ldots + y_{3b\mu} Q_3 L_2 S_3 + y_{3s\mu} Q_2 L_2 S_3 + y_q Q Q S_3^\dagger + \text{h.c.}$$

Vector $V_1 = (\bar{3}, 1, 2/3)$ or $V_3 = (3, 3, 2/3)$

$$\mathcal{L} = \ldots + y_3' V_3^\mu \bar{Q} \gamma_\mu L + y_1 V_1^\mu \bar{Q} \gamma_\mu L + y_1' V_1^\mu \bar{d} \gamma_\mu l + \text{h.c.}$$

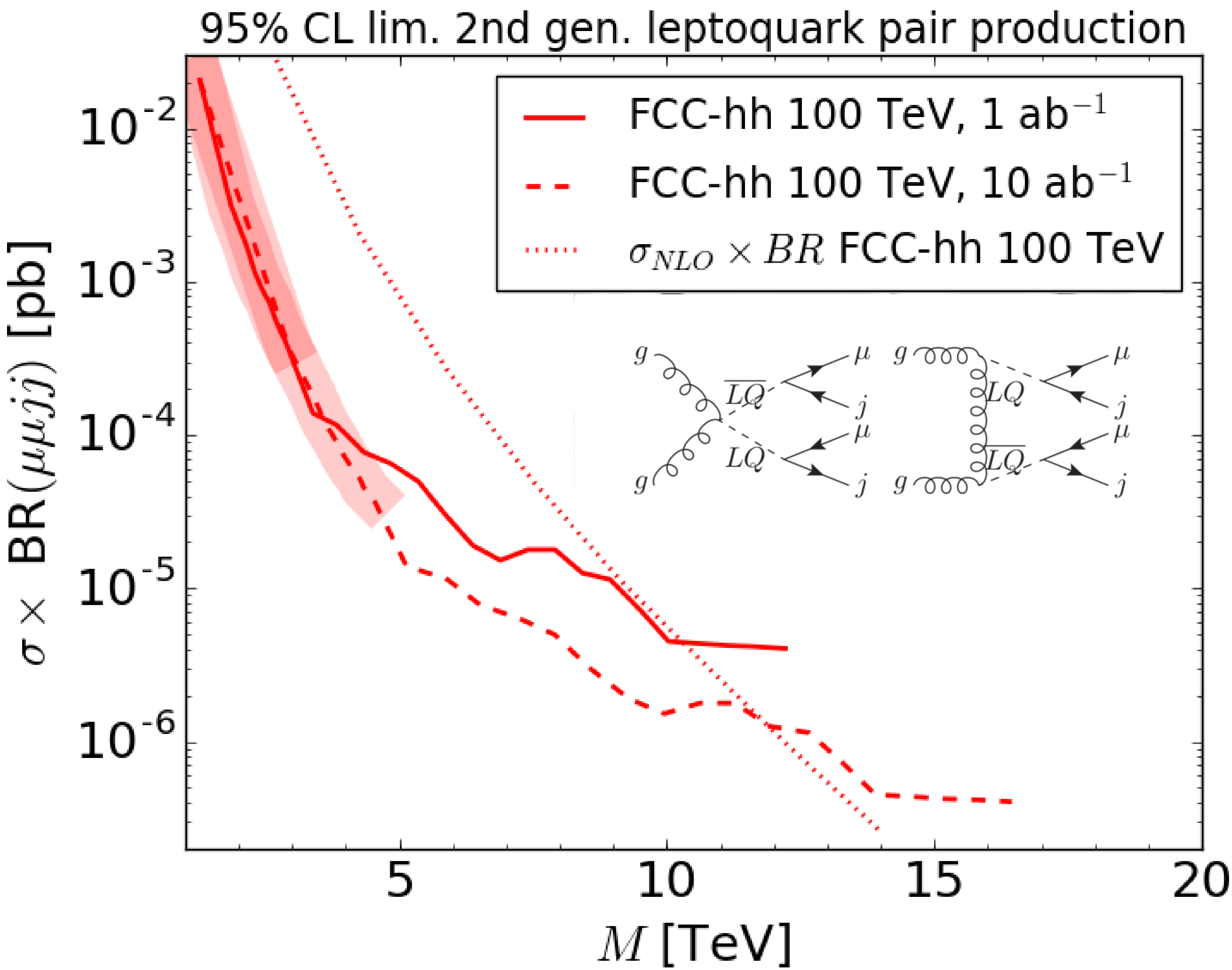
$$\Rightarrow \bar{c}_{LL}^\mu = \kappa \frac{4\pi v^2}{\alpha_{\text{EM}} V_{tb} V_{ts}^*} \frac{y_{3b\mu}^* y_{3s\mu}}{M^2}.$$

$\kappa = 1, -1, -1$ and $y = y_3, y_1, y_3'$ for S_3, V_1, V_3.

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

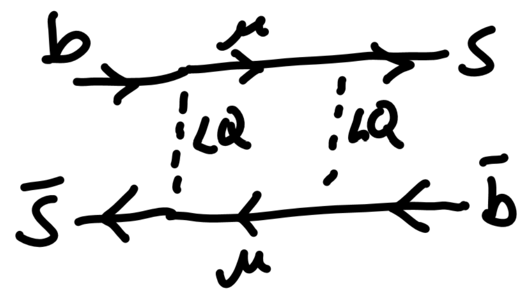
CMS 8 TeV 20fb^{-1} 2nd gen

CMS-PAS-EXO-12-042: $M > 1.07$ TeV.



Other Constraints On LQs

Note that the extrapolation is very rough for pair production. Fix $M = 2M_{LQ}$, assuming they are produced



close to threshold: $\Delta = 0.1$. $B_s - \bar{B}_s$ mixing is at one-loop:

$$\mathcal{L}_{\bar{b}s\bar{b}s} = k\frac{\left|y_{b\mu}y^*_{s\mu}\right|^2}{32\pi^2 M_{LQ}^2}\left(\bar{b}\gamma_\mu P_L s\right)\left(\bar{s}\gamma^\mu P_L b\right) + \text{h.c.}$$

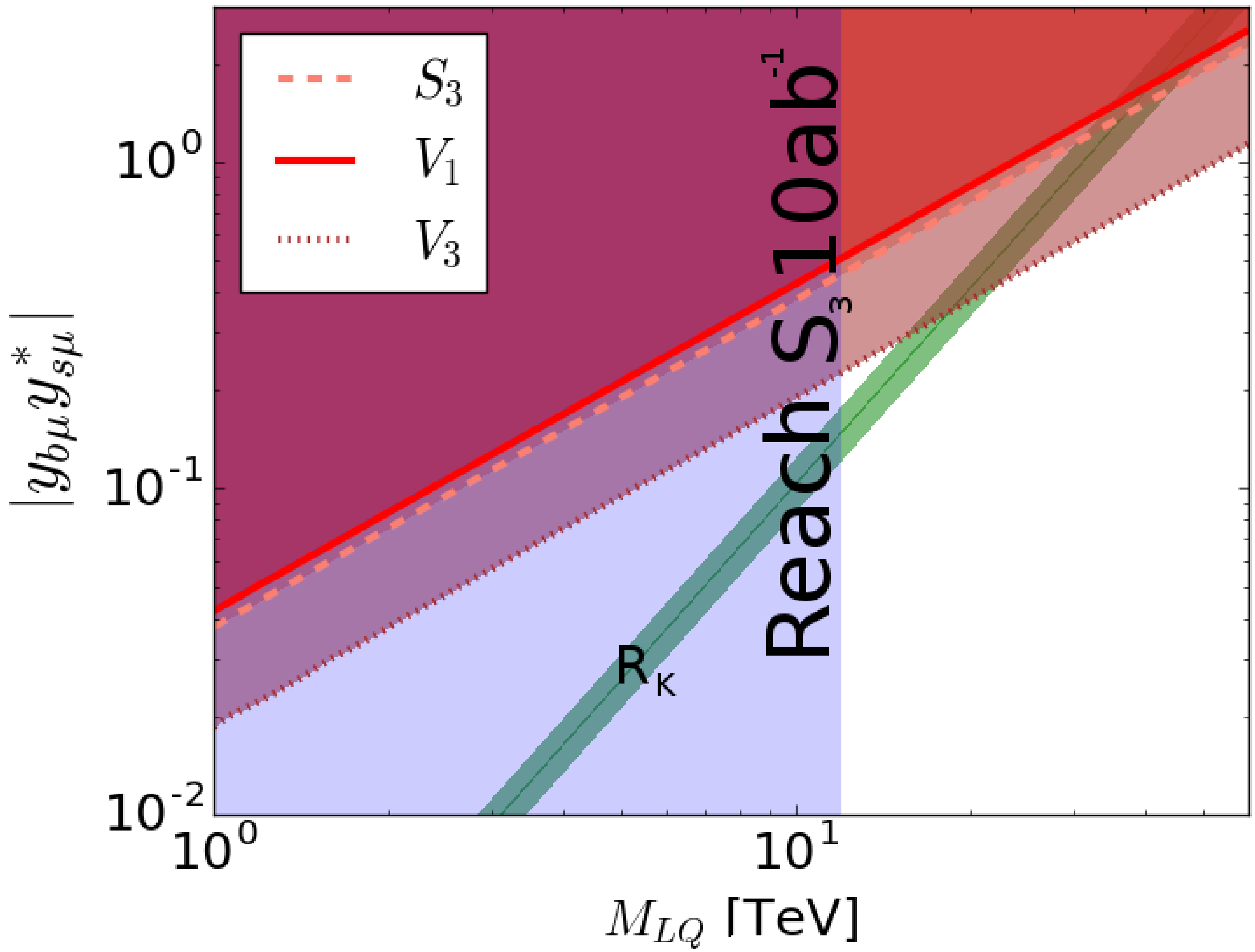
$y = y_3, y_1, y_3'$ and $k = 5, 4, 20$ for S_3, V_1, V_3.
Data $\Rightarrow c_{LL}^{bb} < 1/(210\text{TeV})^2$.

Mass Constraints: Summary

S_3	41 TeV
V_1	41 TeV
V_3	18 TeV

Upper mass limits for leptoquarks that satisfy neutral current $B-$anomaly fits and B_s-mixing constraints.

8 TeV CMS 20fb^{-1} 2nd gen



Up to 14 TeV LQs with 100 TeV 10 ab^{-1} FCC-hh. $M_{LQ} < 41$ TeV.

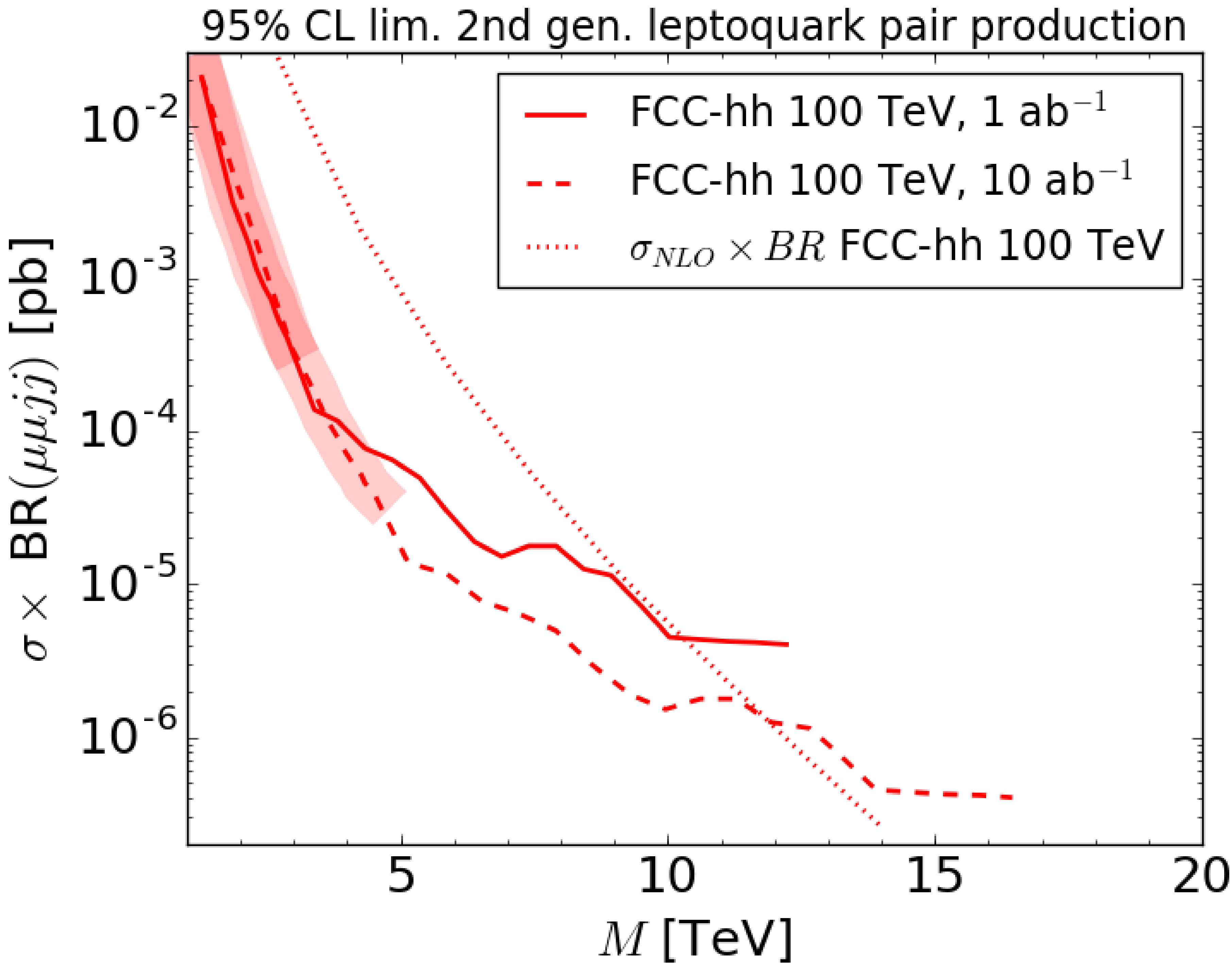
LQ Mass Limits

S_3	41 TeV
V_1	41 TeV
V_3	18 TeV

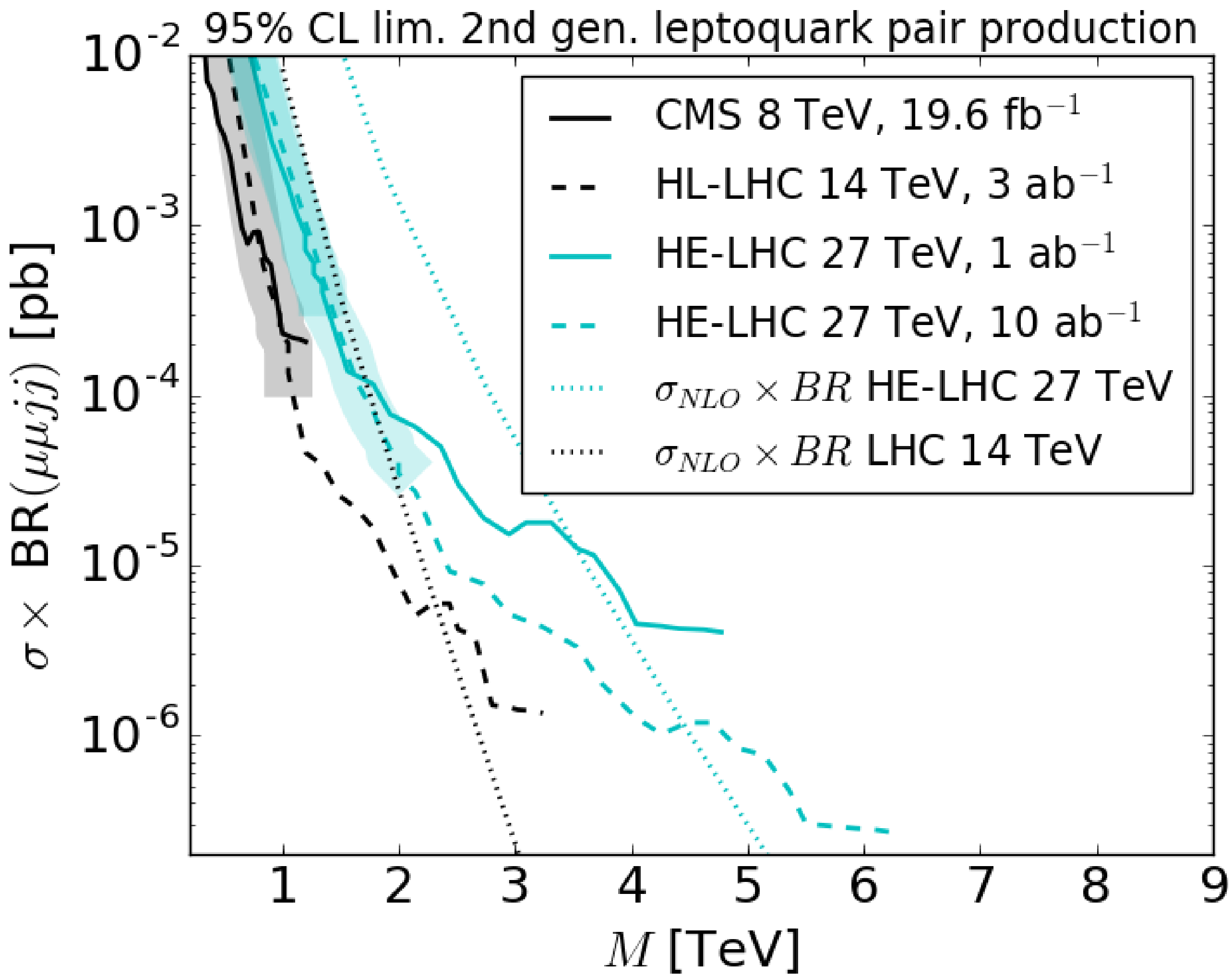
From $B_s - \bar{B}_s$ mixing and fitting $b-$anomalies.

Pair production has a reach up to 12 TeV.

The pair production cross-section is insensitive to the representation of $SU(2)$ in this case.


95% CL lim. 2nd gen. leptoquark pair production
FCC-hh 100 TeV, 1 ab^{-1}
FCC-hh 100 TeV, 10 ab^{-1}
$\sigma_{NLO} \times BR$ FCC-hh 100 TeV
$\sigma \times$ BR$(\mu\mu jj)$ [pb]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
5
10
15
20
M [TeV]

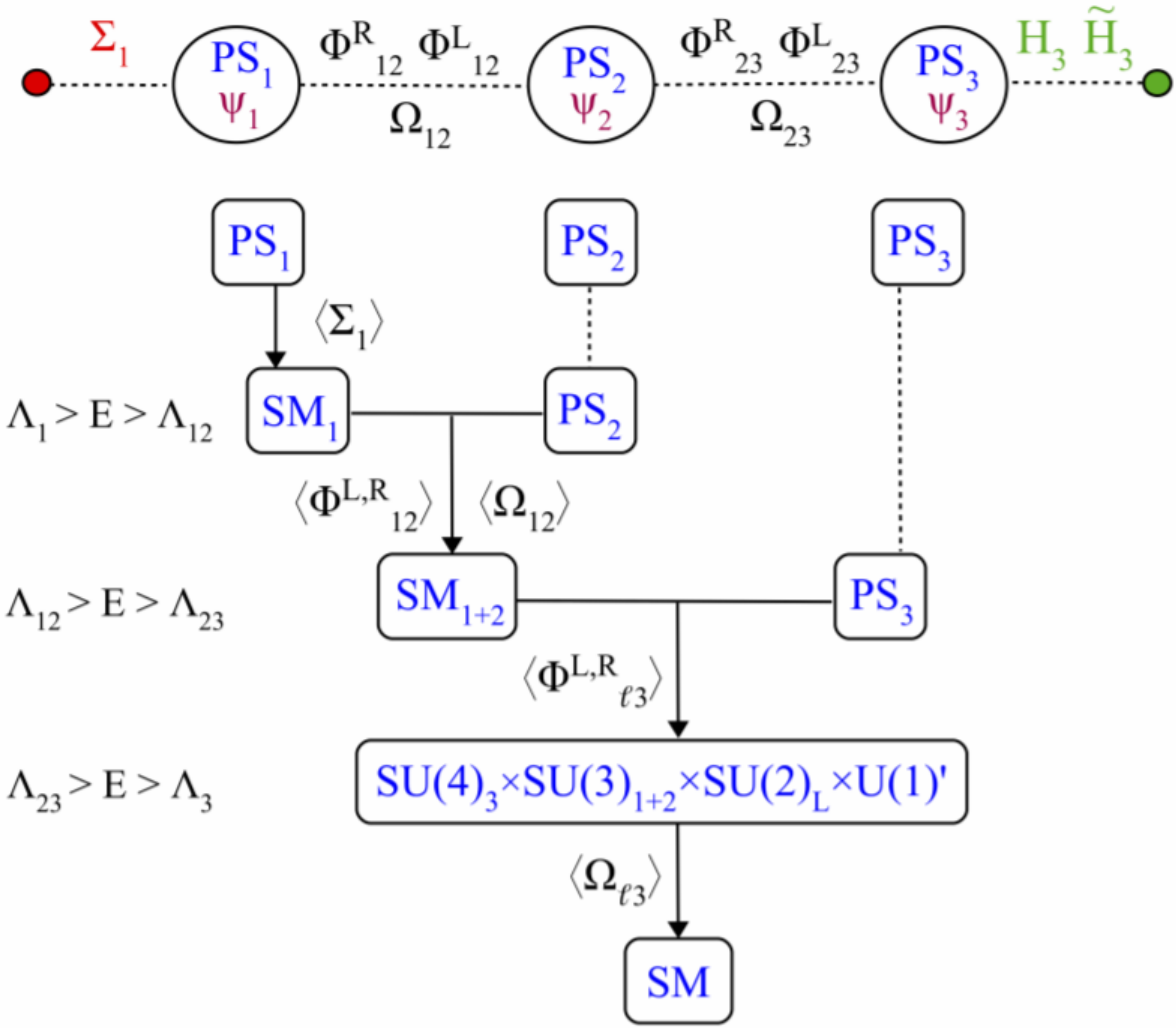
HL-LHC/HE-LHC LQs



Other Flavour Models

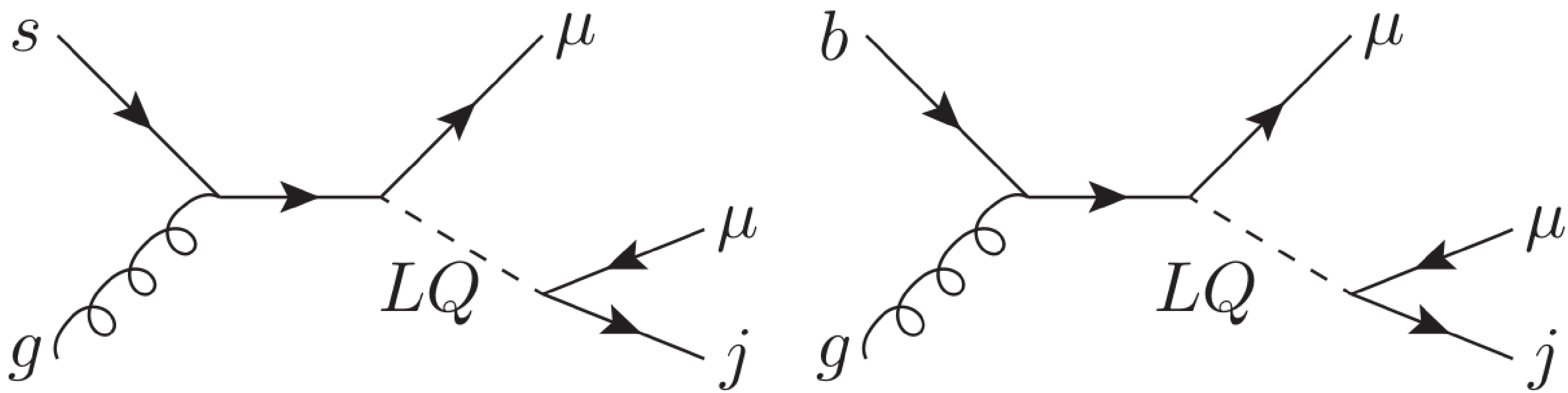
Realising[16] the vector LQ solution based on $PS = [SU(4) \times SU(2)_L \times SU(2)_R]^3$. SM-like Higgs lies in third generation PS group, explaining large Yukawas (others come from VEV hierarchies). Get $U(2)_Q \times U(2)_L$ approximate global flavour symmetry.

[16] Di Luzio Greljo, Nardecchia arXiv:1708.08450, Bordone, Cornella, Fuentes-Martin, Isidori, arXiv:1712.01368

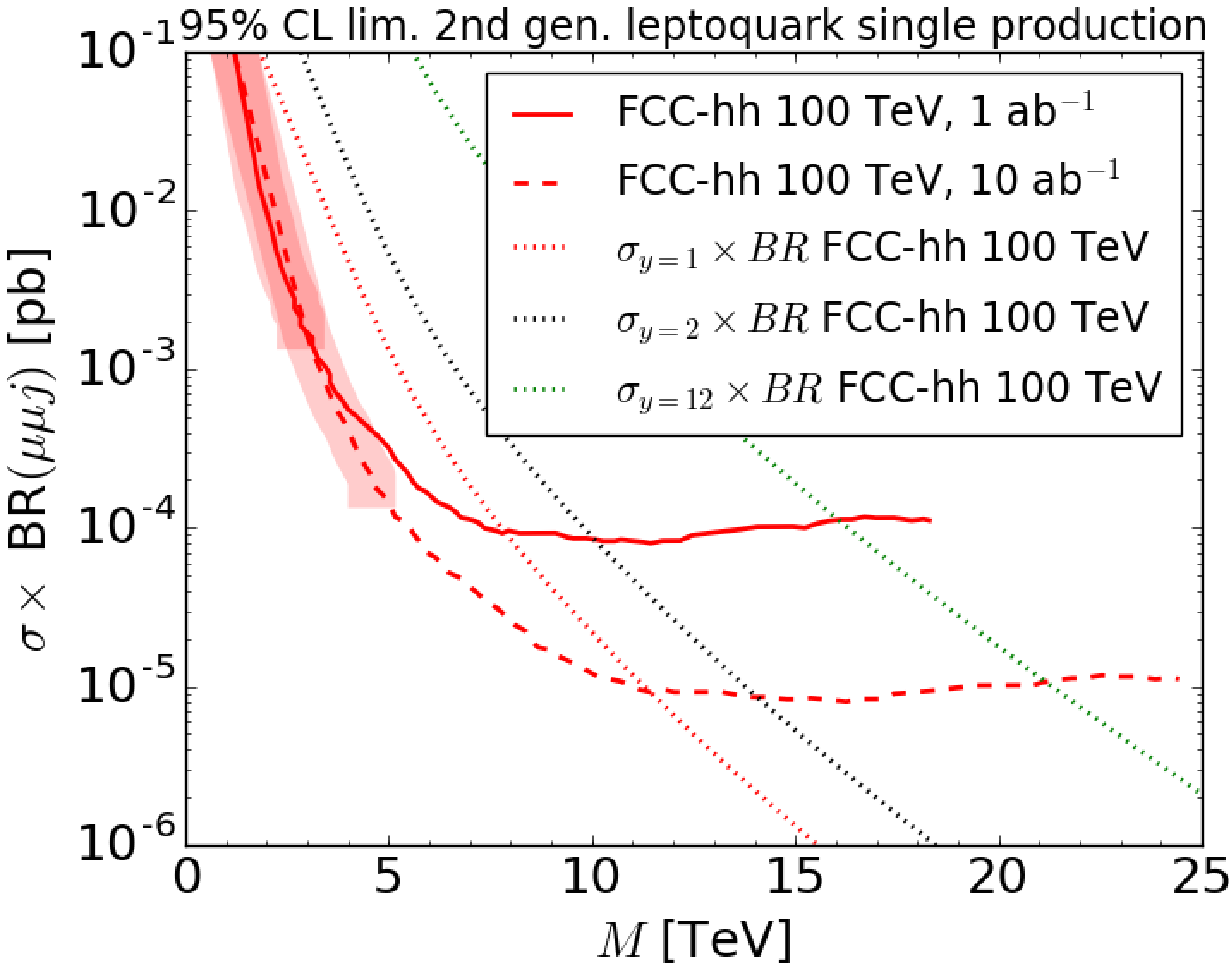

Σ1
PS1 ψ1
ΦR12 ΦL12
Ω12
PS2 ψ2
ΦR23 ΦL23
Ω23
PS3 ψ3
H3 H̃3
PS1
PS2
PS3
⟨Σ1⟩
Λ1 > E > Λ12
SM1
PS2
⟨ΦL,R12⟩
⟨Ω12⟩
Λ12 > E > Λ23
SM1+2
PS3
⟨ΦL,Rℓ3⟩
Λ23 > E > Λ3
SU(4)3×SU(3)1+2×SU(2)L×U(1)'
⟨Ωℓ3⟩
SM

Single Production of LQ

Depends upon LQ coupling as well as LQ mass



Current bound by CMS from 8 TeV 20 fb^{-1}: $M_{LQ} > 660$ GeV for $s\mu$ coupling of 1. We include b as well from `NNPDF2.3LO` ($\alpha_s(M_Z) = 0.119$), re-summing large logs from initial state b. Integrate $\hat{\sigma}$ with `LHAPDF`.



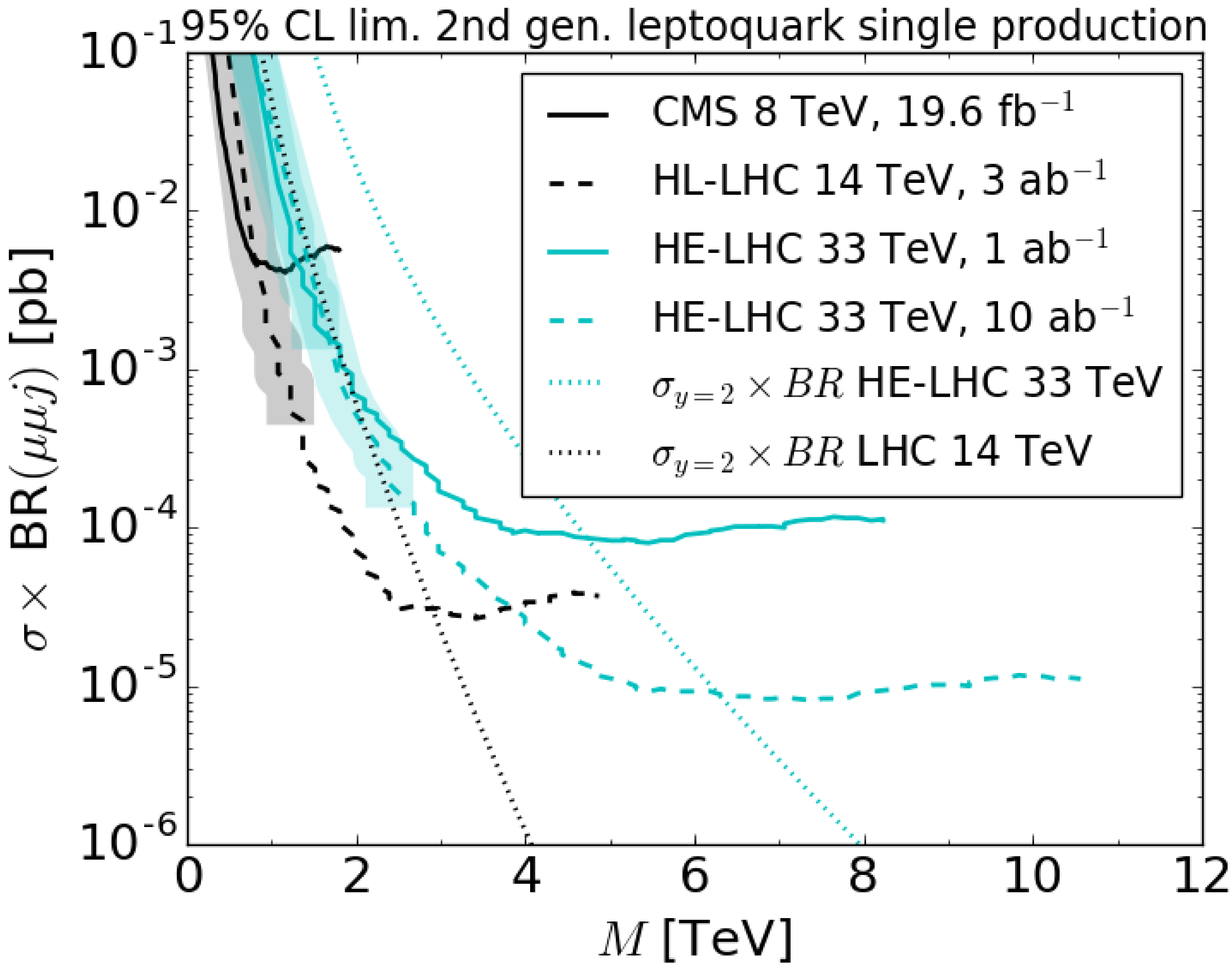
σs for S_3 with $y_{s\mu} = y_{b\mu} = y$.

Single LQ Production σ

$$\hat{\sigma}(qg \to \phi l) = \frac{y^2 \alpha_S}{96 \hat{s}} \left(1 + 6r - 7r^2 + 4r(r+1)\ln r\right) \ ,$$

where[17] $r = M_{LQ}^2/\hat{s}$ and we set $y_{s\mu} = y_{b\mu} = y$.

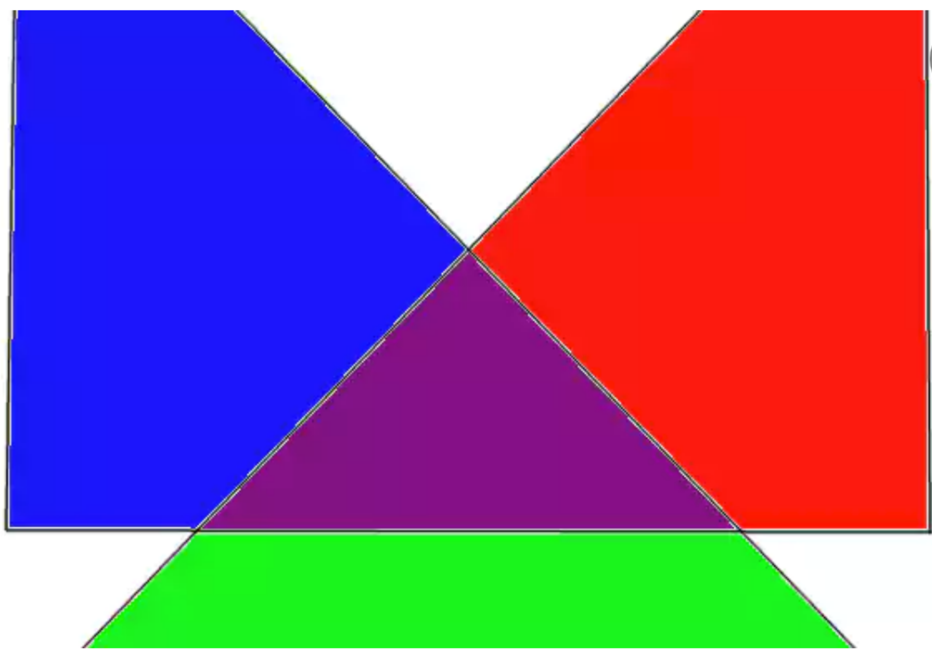
[17] Hewett and Pakvasa, PRD **57** (1988) 3165.


95% CL lim. 2nd gen. leptoquark single production
$\sigma \times$ BR$(\mu\mu j)$ [pb]
M [TeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
2
4
6
8
10
12
CMS 8 TeV, 19.6 fb^{-1}
HL-LHC 14 TeV, 3 ab^{-1}
HE-LHC 33 TeV, 1 ab^{-1}
HE-LHC 33 TeV, 10 ab^{-1}
$\sigma_{y=2} \times BR$ HE-LHC 33 TeV
$\sigma_{y=2} \times BR$ LHC 14 TeV

Science Life and Physics

Modelling the fourth colour: dispatch from de Moriond

At the particle physics conference, it's clear inconclusive LHCb data are stimulating strange new ideas



▲ Four colours (or colors?) Photograph: Ben Allanach

Ben Allanach
Sat 17 Mar 2018 10.15 GMT

In the middle of the Rencontres de Moriond particle physics conference in Italy, the scientific talks stopped to allow a standing ovation dedicated to the memory and achievements of my inspirational colleague Stephen Hawking, who we heard had died earlier that day.

The talks quickly resumed, which I think Stephen would have approved of. The most striking thing about the scientific content of the conference this year was that a whole day was dedicated to the weirdness in bottom particles that Tevong You and I wrote about last November. As Marco Nardecchia reviewed in his talk (PDF), bottom particles produced in the LHCb detector in proton collisions are decaying too often in certain particular ways, compared to predictions from the Standard Model of particle physics. Their decay products are coming out with the wrong angles too often compared with predictions, too.

Anomalous bottoms at Cern and the case for a new collider

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We were hoping for an update on the data at the conference: the amount of data has roughly doubled since they were last released, and we need to see the new data to be convinced that something really new is happening in the collisions. I strongly suspect that if the effect is seen in the new data, the theoretical physics community will "go nuts" and we will quickly see the resulting avalanche of papers. If the new data look ordinary, the effect will be forgotten and everyone will move on. Taking such measurements correctly takes care and time, however, and the LHCb experiment didn't release them. We shall have to wait until other conferences later this year for the LHCb to present its analyses of the new data.

There were interesting theory talks on how new forces could explain the strange properties of the bottom particle decays. The full mathematical models look quite baroque: they need a lot of "bells and whistles" in order to pass other experimental tests. But these models prove that it can be done, and they are quite different to what has been proposed before.

One of them even unifies different classes of particle (leptons and quarks), describing the lepton as the "fourth colour" of a quark. We are used to the idea that quarks come in three (otherwise identical) copies: physicists label them red, green and blue to distinguish them. As Javier Fuentes-Martin describe (PDF), once you design the mathematics to make leptons the fourth colour, the existence of a new force-carrying particle with just the correct properties to break up the

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Cern

Cern draws up plans for collider four times the size of Large Hadron

The Future Circular Collider would smash particles together in a tunnel 100km long

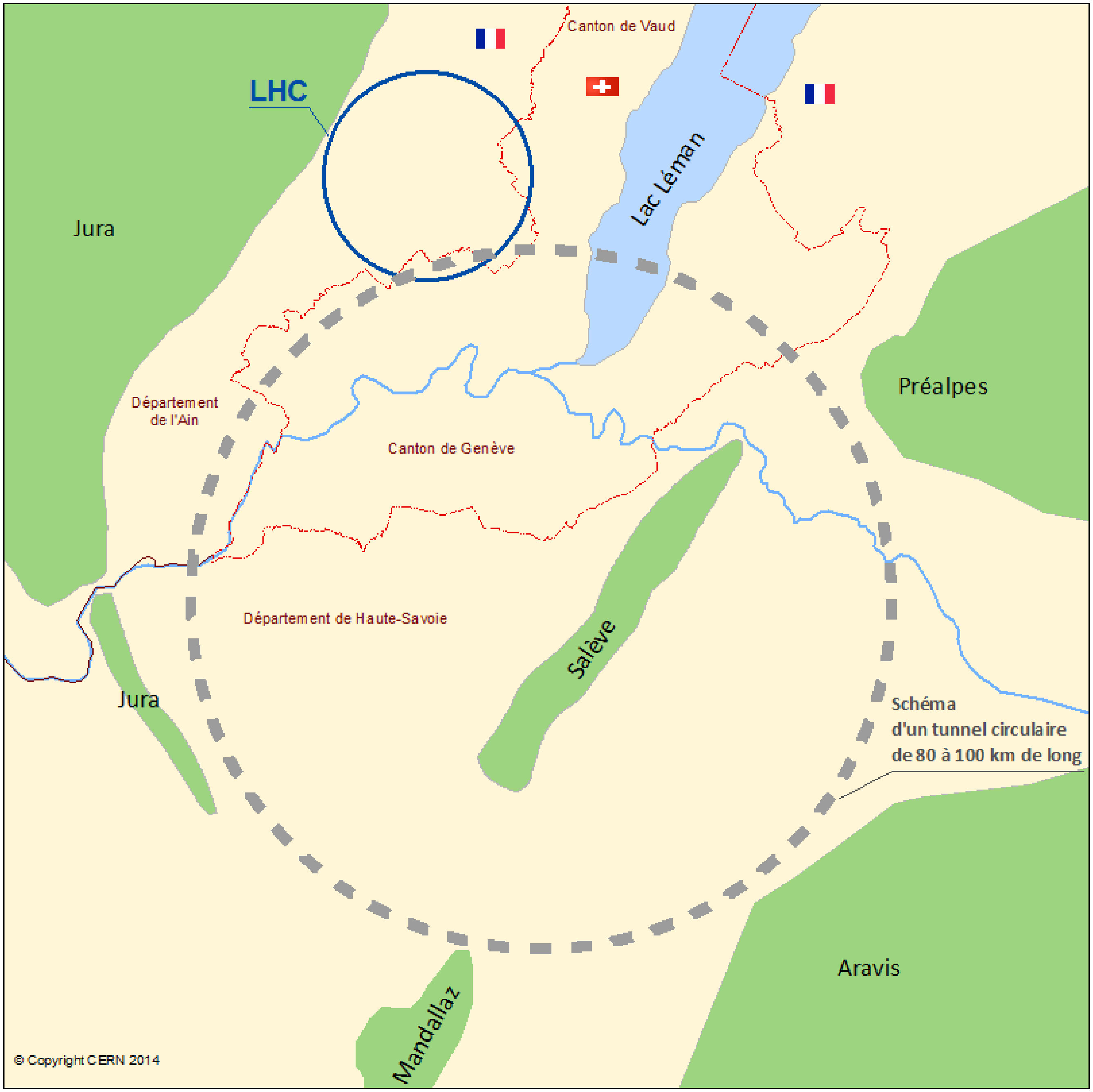
LHC
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Schéma
d'un tunnel circulaire
de 80 à 100 km de long
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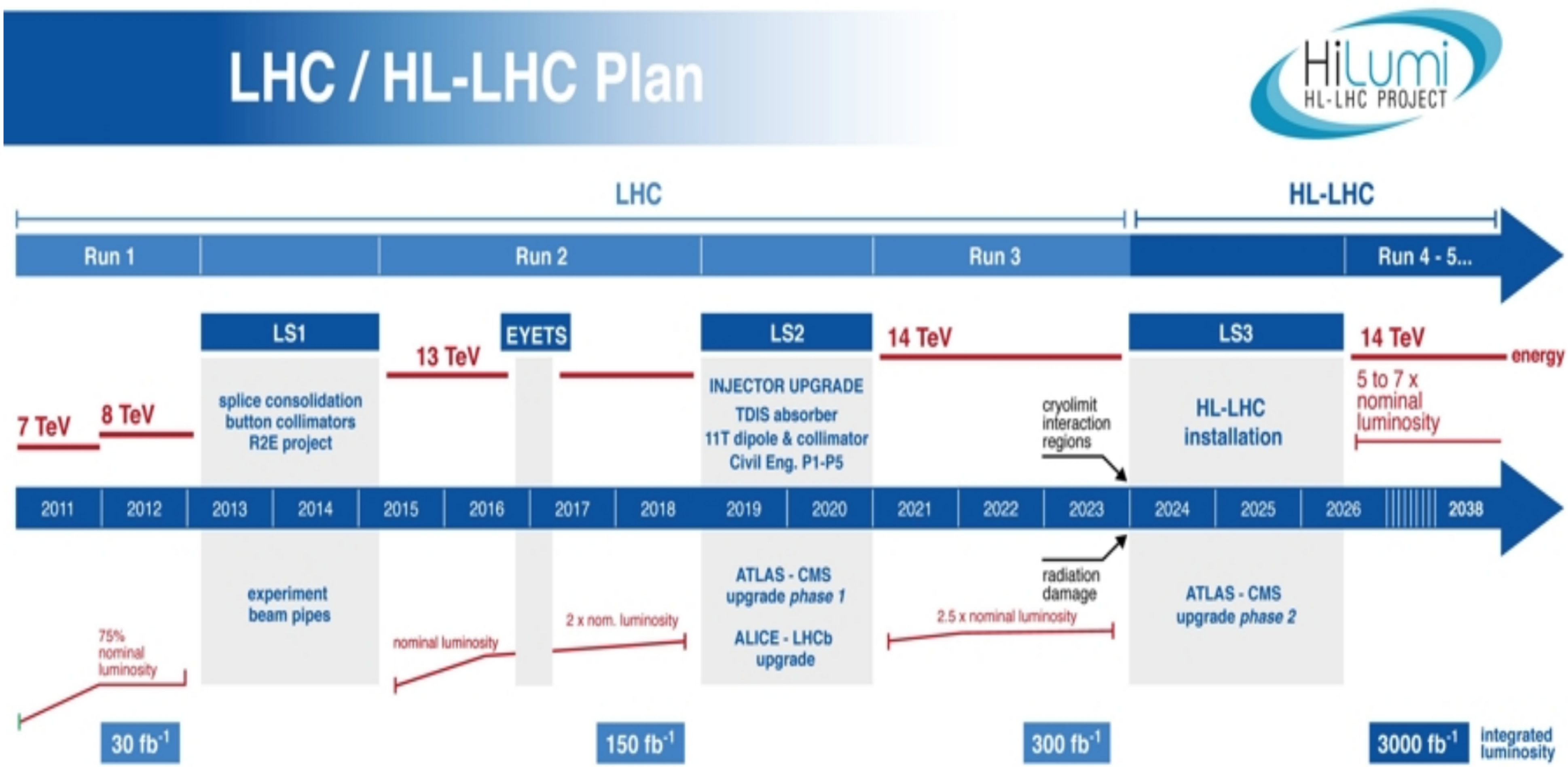
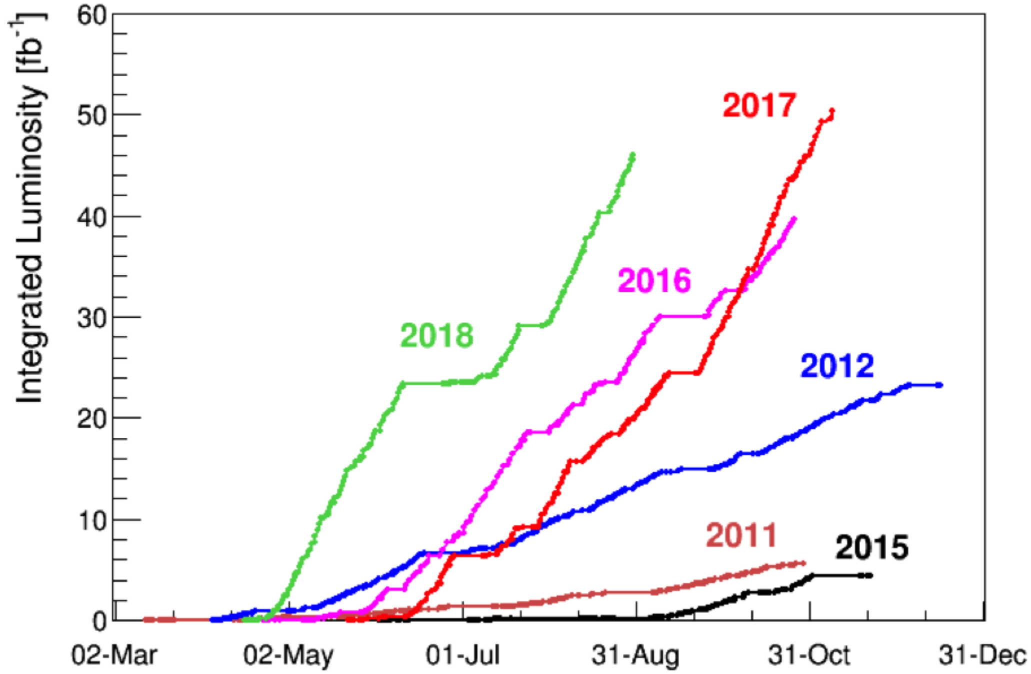
LHC / HL-LHC Plan



LHC Upgrades



High Luminosity (HL) LHC: go to 3000 fb^{-1} (3 ab^{-1}).
High Energy (HE) LHC: Put FCC magnets (16 Tesla rather than 8.33 Tesla) into LHC ring: roughly *twice* collision energy: 27 TeV.

Properties of anomaly-free solutions