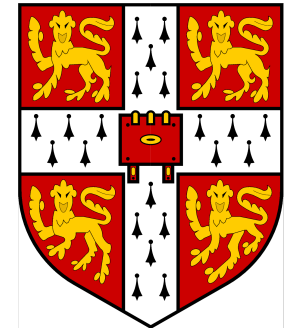


# $Z'$ Explanations of Neutral Current $B$ Anomalies



by

Ben Allanach  
(University of Cambridge)



- Can we directly discover particles from explanations?
- Third Family Hypercharge Model
- General  $SM \times U(1)$  model

BCA, Gripaios, You, [arXiv:1710.06363](https://arxiv.org/abs/1710.06363); BCA, Davighi, [arXiv:1809.01158](https://arxiv.org/abs/1809.01158); BCA, Corbett, Dolan, You, [arXiv:1810.02166](https://arxiv.org/abs/1810.02166)

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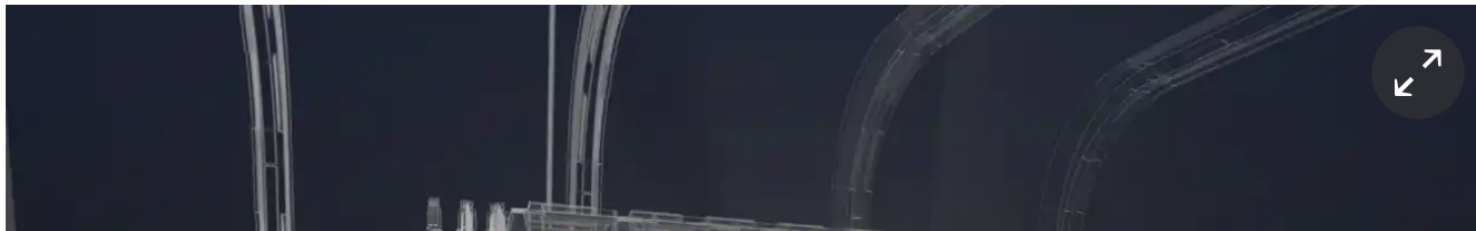


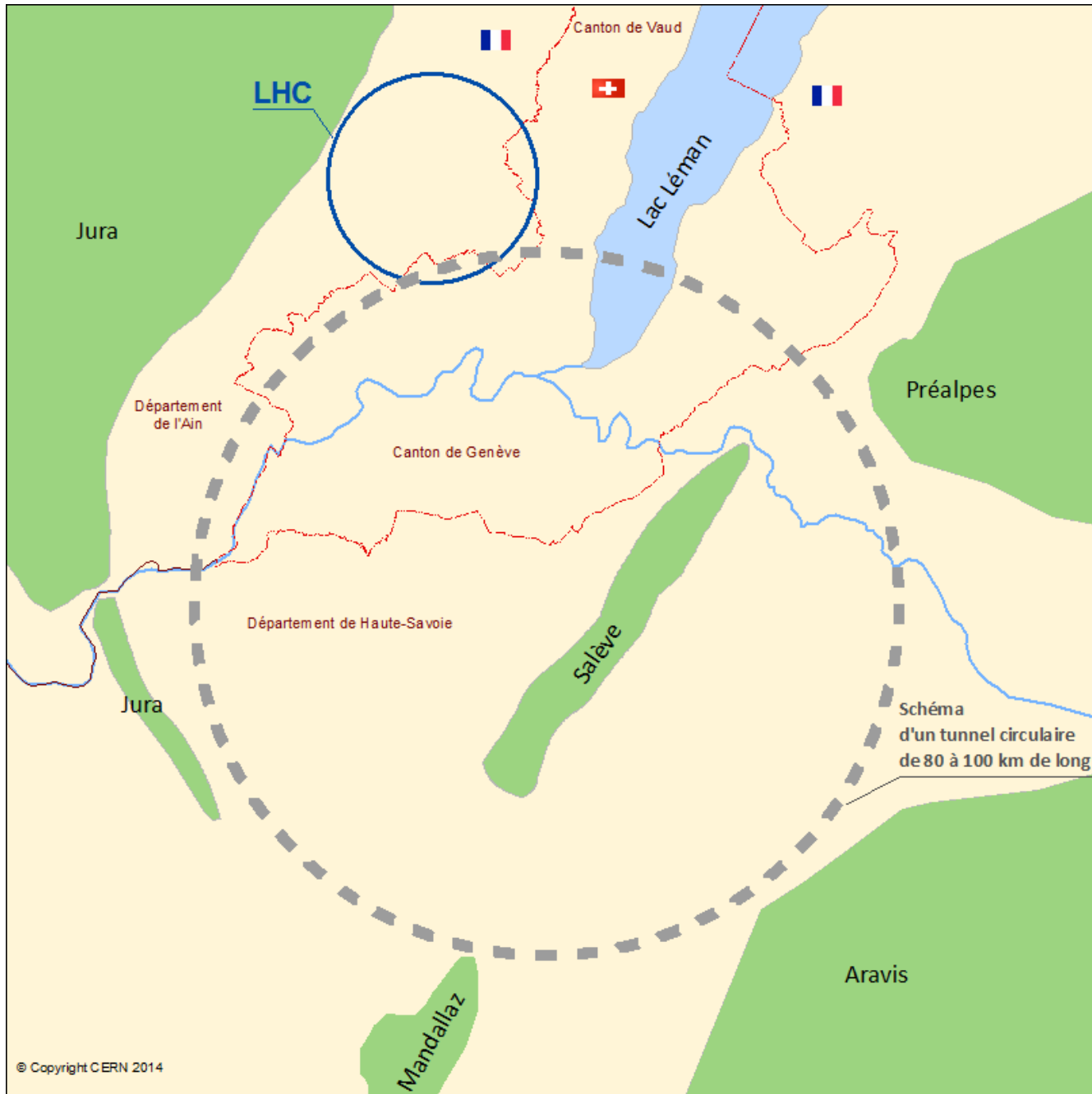
UK World Business Football UK politics Environment Education Society **Science** More

**Cern**

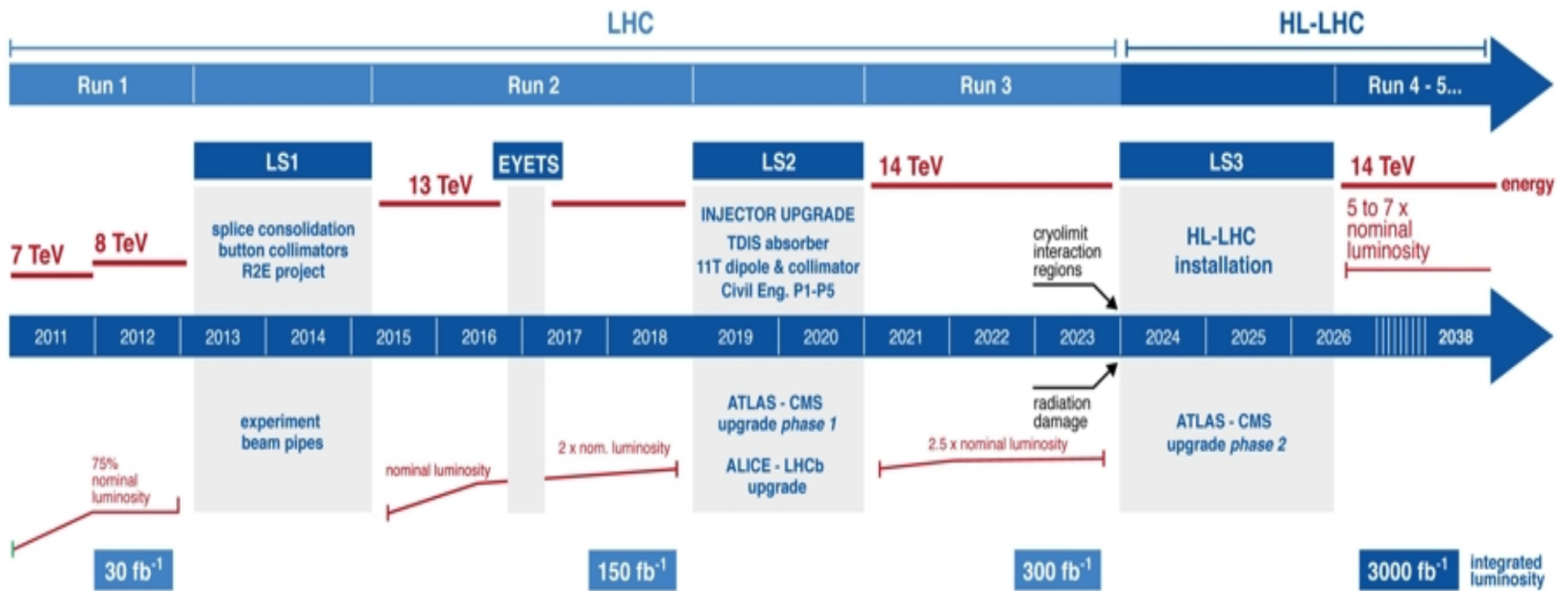
# Cern draws up plans for collider four times the size of Large Hadron

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



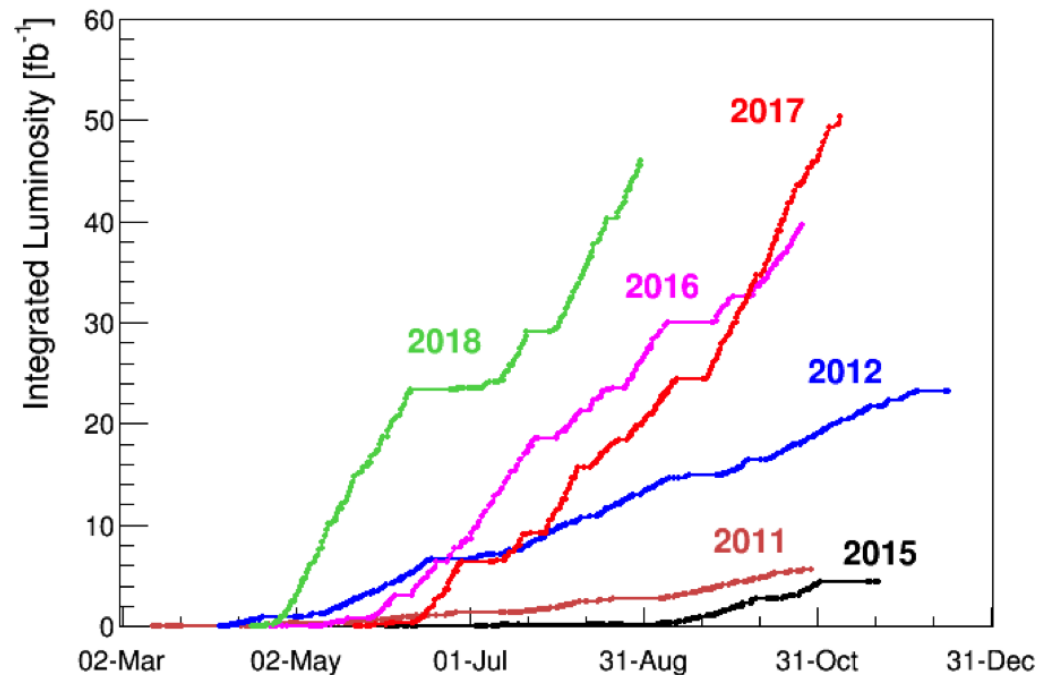


# LHC / HL-LHC Plan





# LHC Upgrades



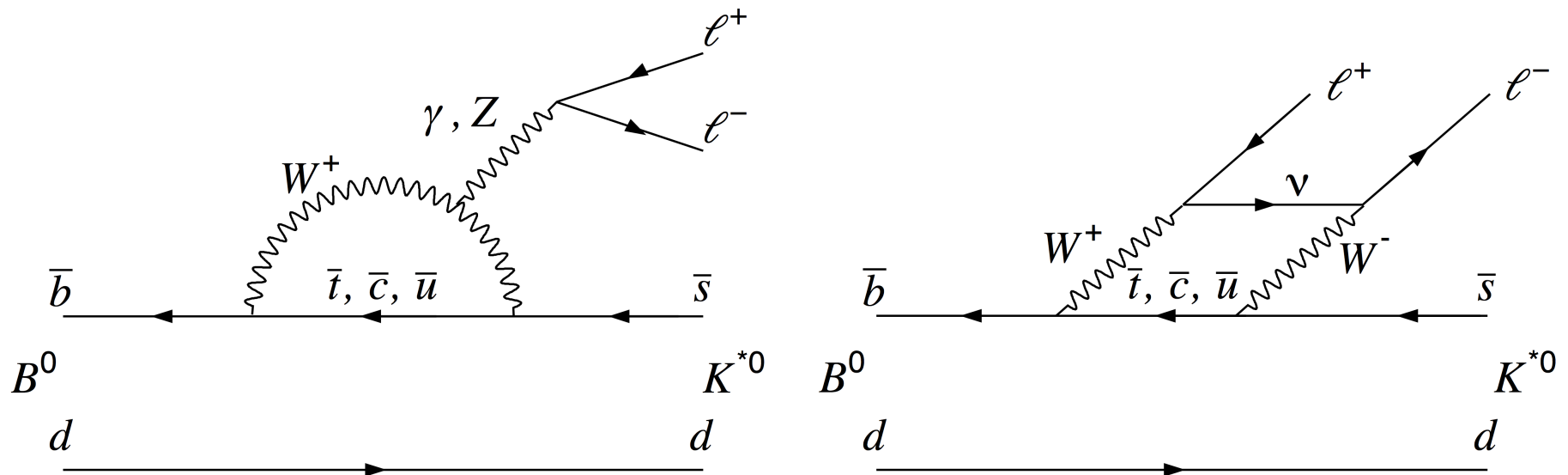
**High Luminosity (HL) LHC:** go to  $3000 \text{ fb}^{-1}$  ( $3 \text{ ab}^{-1}$ ).

**High Energy (HE) LHC:** Put FCC magnets (16 Tesla rather than 8.33 Tesla) into LHC ring: roughly *twice* collision energy: 27 TeV.

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

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

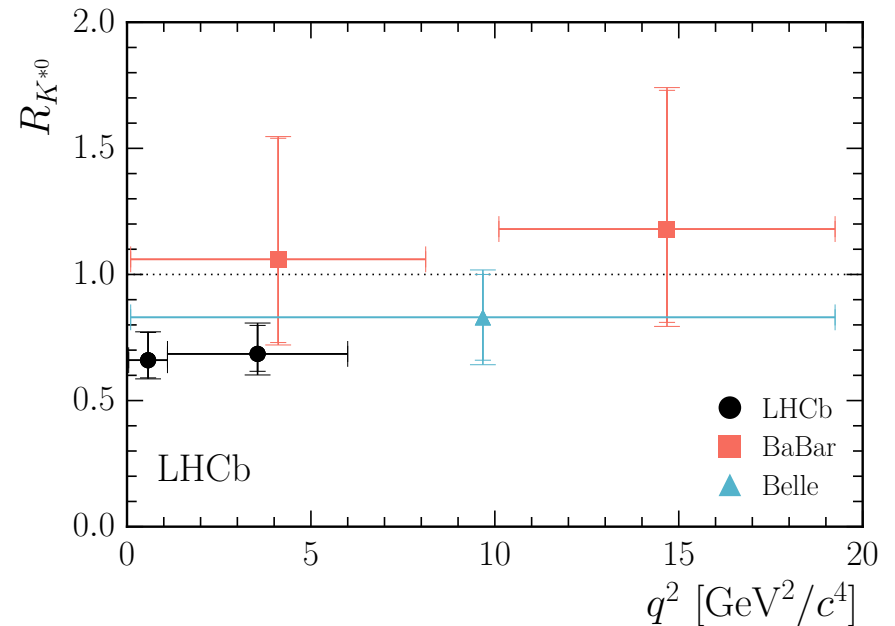
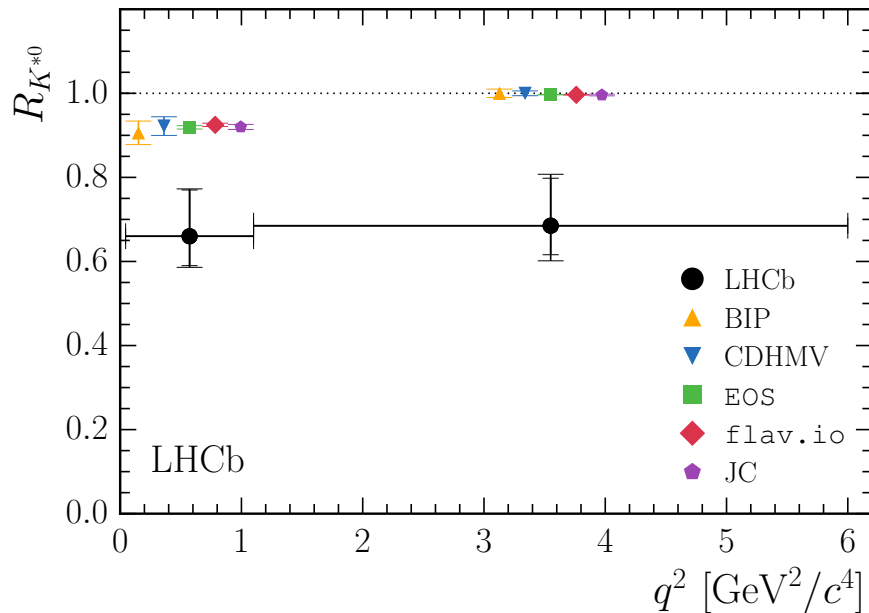
These are **rare decays** (each  $BR \sim \mathcal{O}(10^{-7})$ ) because they are absent at tree level in SM.



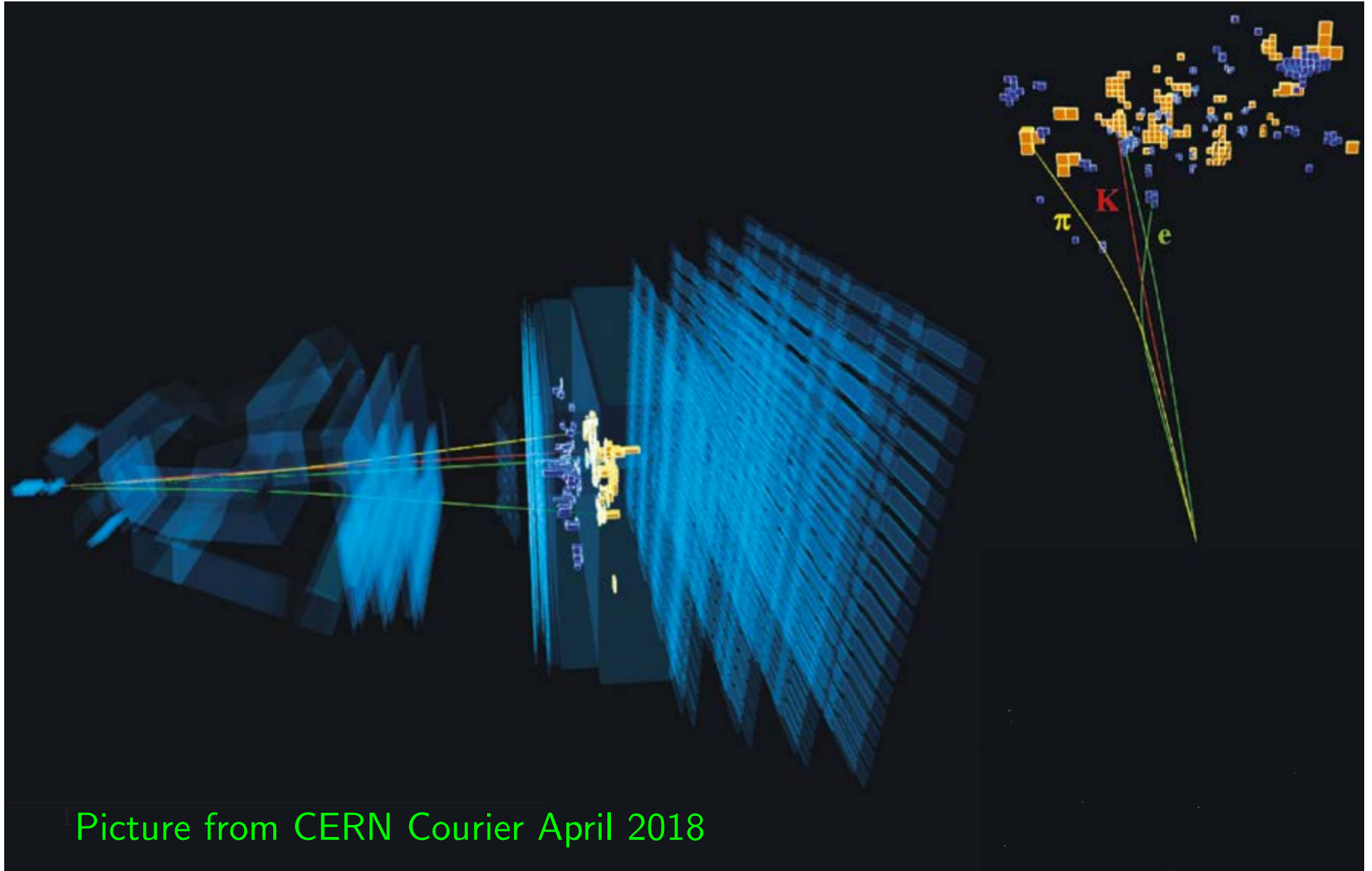
# $R_{K^{(*)}}$ Measurements

LHCb results from 7 and 8 TeV:  $q^2 = m_U^2$ .

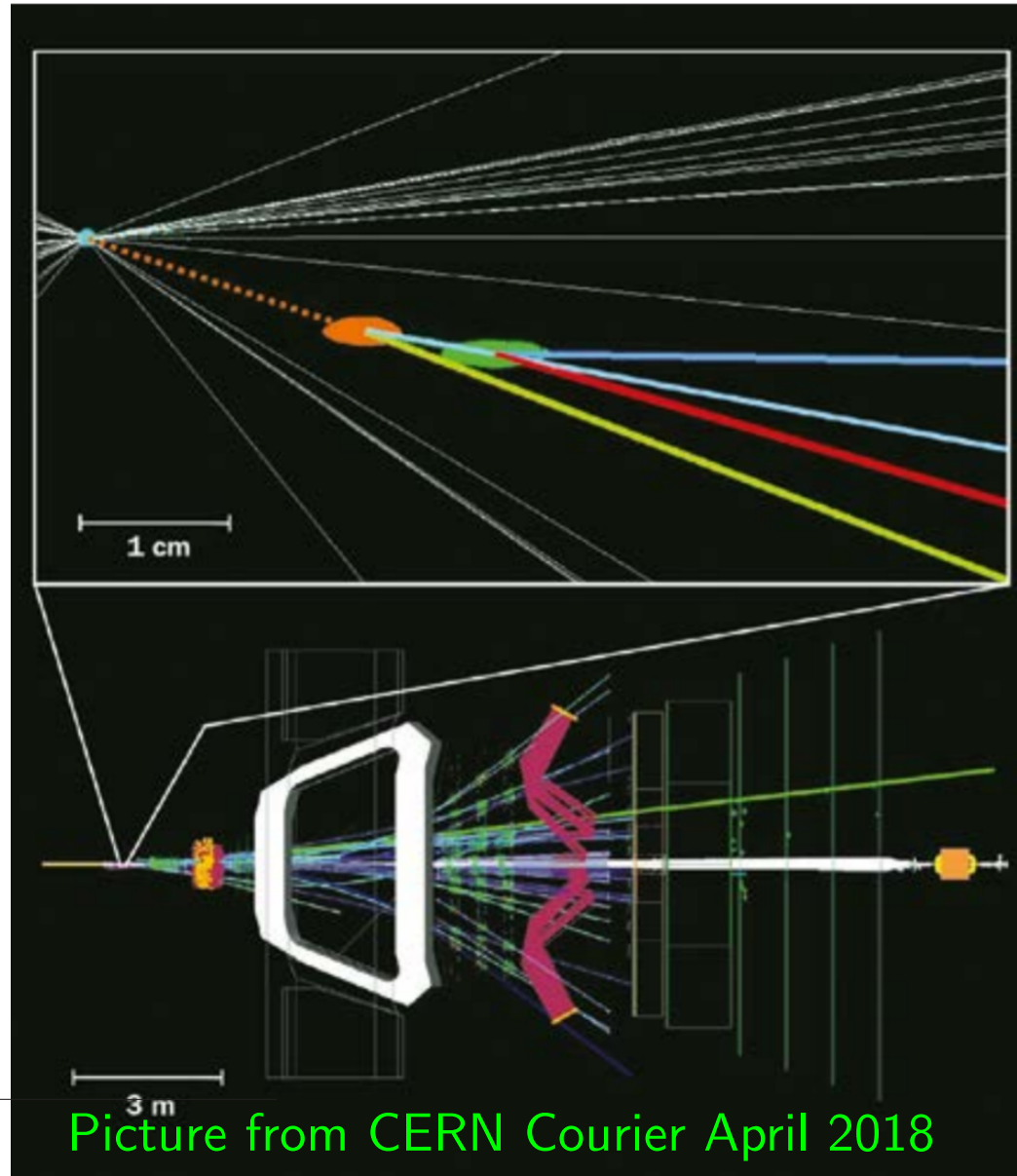
|           | $q^2/\text{GeV}^2$ | SM              | LHCb 3 fb <sup>-1</sup>   | $\sigma$ |
|-----------|--------------------|-----------------|---------------------------|----------|
| $R_K$     | [1, 6]             | $1.00 \pm 0.01$ | $0.745^{+0.090}_{-0.074}$ | 2.6      |
| $R_{K^*}$ | [0.045, 1.1]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



# LHCb $B^0 \rightarrow K^{0*} e^+ e^-$ Event<sup>1</sup>

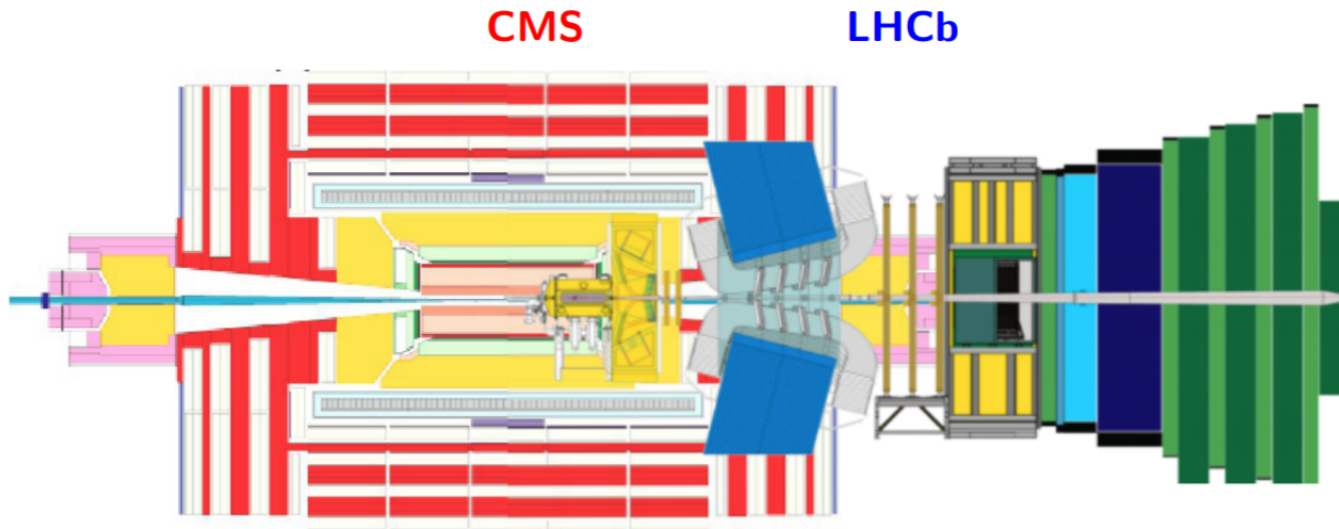


# LHCb Detector II<sup>2</sup>



2

# LHCb Detector<sup>3</sup>



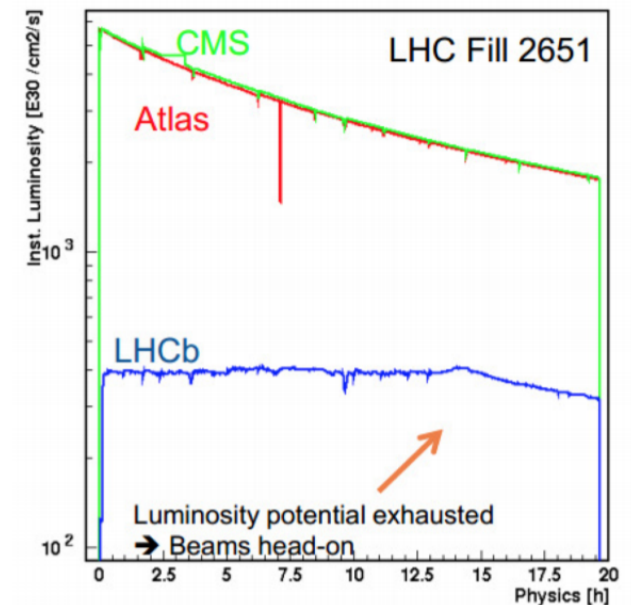
Optimised to study beauty and charm hadrons

→ provides **complementary**  $\eta$  coverage compared with a GPD.

## LHCb as a forward GPD:

- ✓ Precise integrated **luminosity** computation
- ✓ **Stable** data-taking conditions due to **luminosity levelling**
- ✓ Average pile-up  $\sim 2$  (twice design)
- ✓ Excellent **vertexing**, particle ID, momentum resolution...
- ✗ Lower luminosity than to ATLAS/CMS
- ✗ Lower acceptance
- ✗ **Not hermetic!** (can't use  $E_T^{miss}$  variable)

<sup>3</sup> Diaz talk 53rd EW Rencontres de Moriond 2018



# Wilson Coefficients $\bar{c}_{ij}^l$

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

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

$$\begin{aligned}\mathcal{L}_{\text{eff}} &\supset \sum_{l=e,\mu,\tau} \sum_{i=L,R} \sum_{j=L,R} \frac{c_{ij}^l}{\Lambda^{2_{l,ij}}} \mathcal{O}_{ij}^l, \\ &= \sum_{l=e,\mu,\tau} V_{tb} V_{ts}^* \frac{\alpha}{4\pi v^2} (\bar{c}_{LL}^l \mathcal{O}_{LL}^l + \bar{c}_{LR}^l \mathcal{O}_{LR}^l \\ &\quad + \bar{c}_{RL}^l \mathcal{O}_{RL}^l + \bar{c}_{RR}^l \mathcal{O}_{RR}^l) \\ \Rightarrow \bar{c}_{ij}^l &= (36 \text{ TeV}/\Lambda)^2 c_{ij}^l.\end{aligned}$$

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

# Which Ones Work?

Options for a single *BSM* operator:

- $\bar{c}_{ij}^e$  operators fine for  $R_{K^{(*)}}$  but are disfavoured by global fits including other observables.
- $\bar{c}_{LR}^\mu$  disfavoured: predicts *enhancement* in both  $R_K$  and  $R_{K^*}$
- $\bar{c}_{RR}^\mu, \bar{c}_{RL}^\mu$  disfavoured: they pull  $R_K$  and  $R_{K^*}$  in *opposite directions*.
- $\bar{c}_{LL}^\mu = -1.33 \pm 0.34$  fits well globally<sup>4</sup>.

---

<sup>4</sup>D'Amico et al, 1704.05438.



# Statistics<sup>5</sup>

|       | $\bar{c}_{LL}^\mu$                                  | $\sqrt{\chi_{SM}^2 - \chi_{best}^2}$ |
|-------|-----------------------------------------------------|--------------------------------------|
| clean | $-1.33 \pm 0.34$                                    | 4.1                                  |
| dirty | $-1.33 \pm 0.32$                                    | 4.6                                  |
| all   | $-1.33 \pm 0.23$                                    | 6.2                                  |
|       | $C_9^\mu = (\bar{c}_{LL}^\mu + \bar{c}_{LR}^\mu)/2$ | $\sqrt{\chi_{SM}^2 - \chi_{best}^2}$ |
| clean | $-1.51 \pm 0.46$                                    | 3.9                                  |
| dirty | $-1.15 \pm 0.17$                                    | 5.5                                  |
| all   | $-1.19 \pm 0.15$                                    | 6.7                                  |

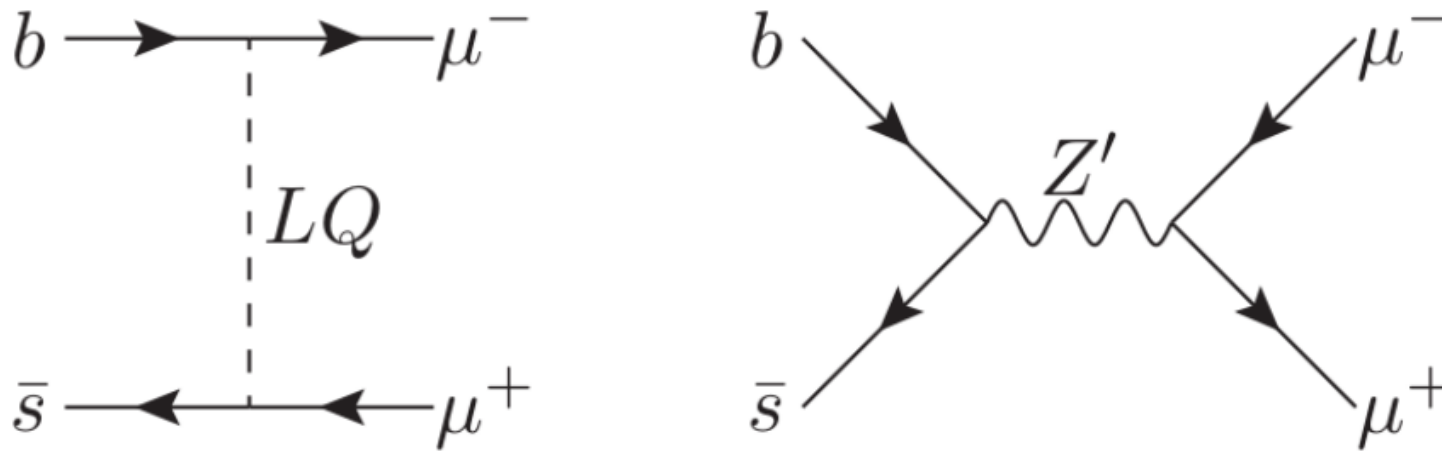
Table 1: A fit to flavour anomalies for ‘clean’ ( $R_K$ ,  $R_{K^*}$ ,  $B_s \rightarrow \mu\mu$ ) and ‘dirty’ (100 others) observables

<sup>5</sup>[D’Amico, Nardecchia, Panci, Sannino, Strumia, Torre, Urbano 1704.05438](#)



# Simplified Models for $C_{LL}^\mu$

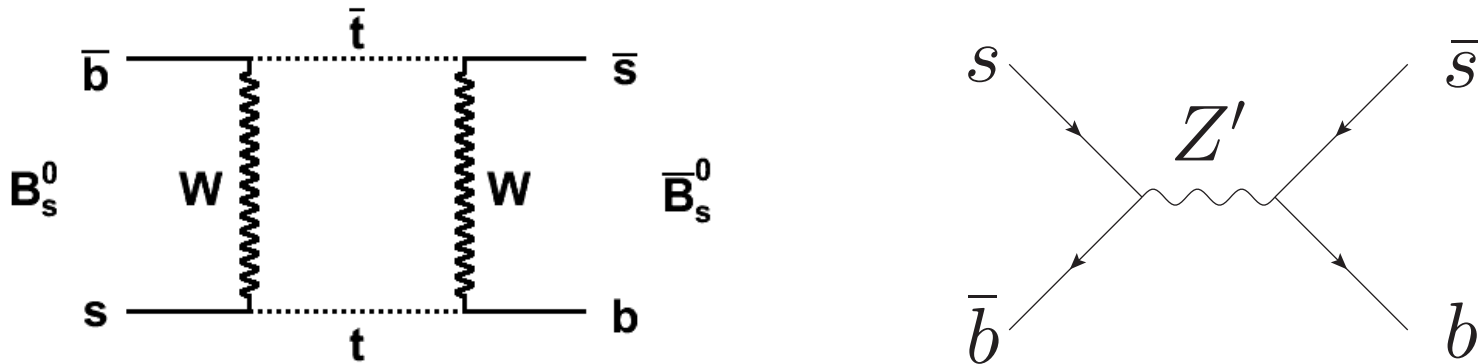
At tree-level, we have:



At loop-level, there are many more possibilities but the particles are  $4\pi$  lighter: they are much easier to detect.

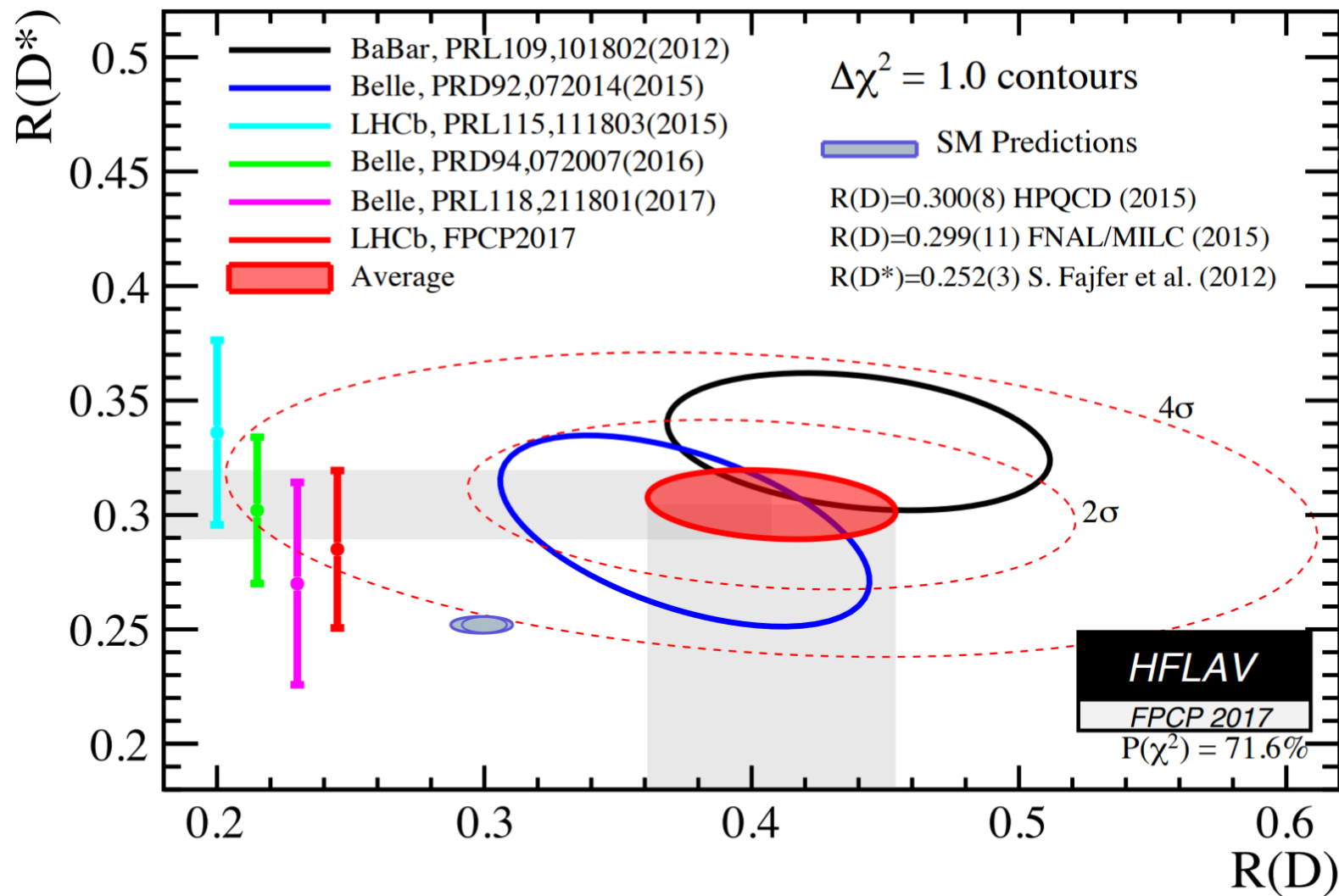
*Principle of Maximal Pessimism*

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



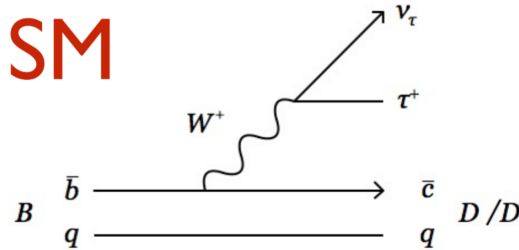
$$\bar{g}_L^{sb} \lesssim \frac{M_{Z'}}{148 \text{ TeV}}.$$

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



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

SM



... has to compete with

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

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

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

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

# $Z' \mu\mu$ ATLAS 13 TeV 36 fb<sup>-1</sup>

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<sup>6</sup>.

$$m_{\mu_1\mu_2}^2 = (p_1^\mu + p_2^\mu) (p_{1\mu} + p_{2\mu})$$

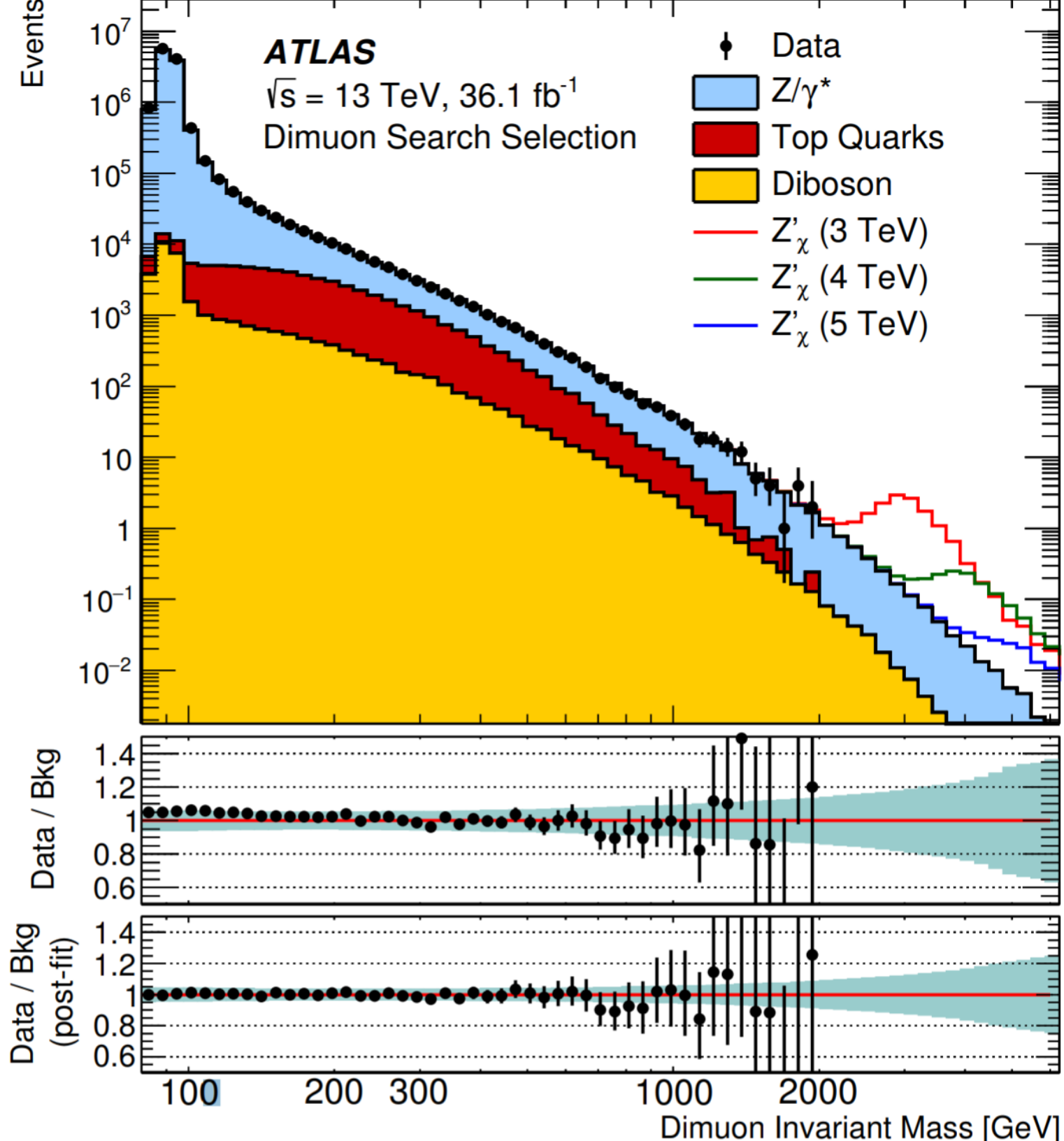
CMS also have released<sup>7</sup> a similar 36 fb<sup>-1</sup> analysis.

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<sup>6</sup>[1707.02424](#)

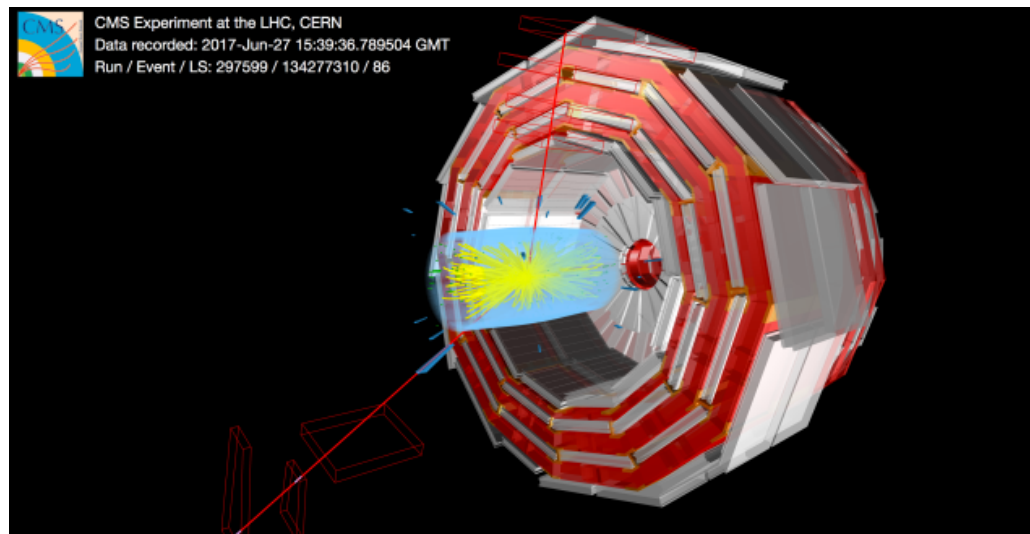
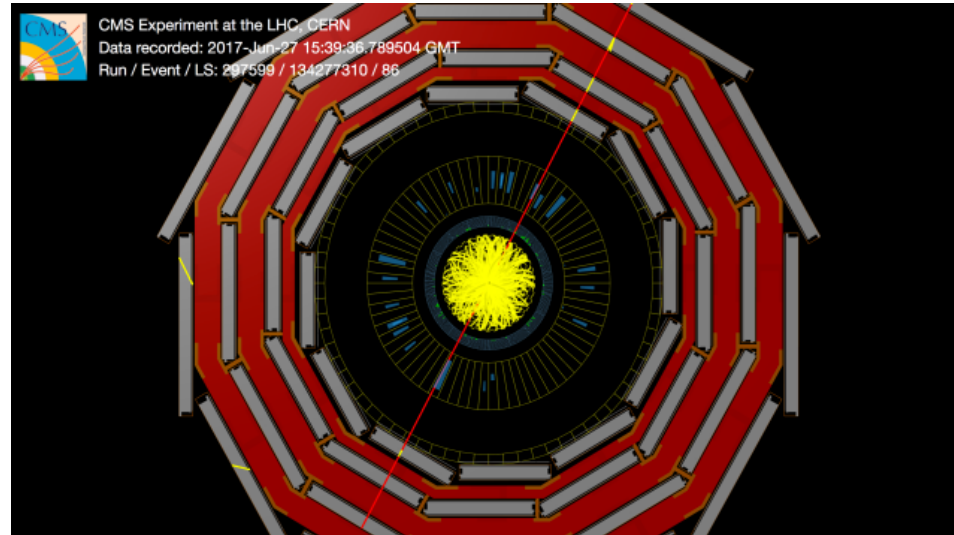
<sup>7</sup>[1803.06292](#)

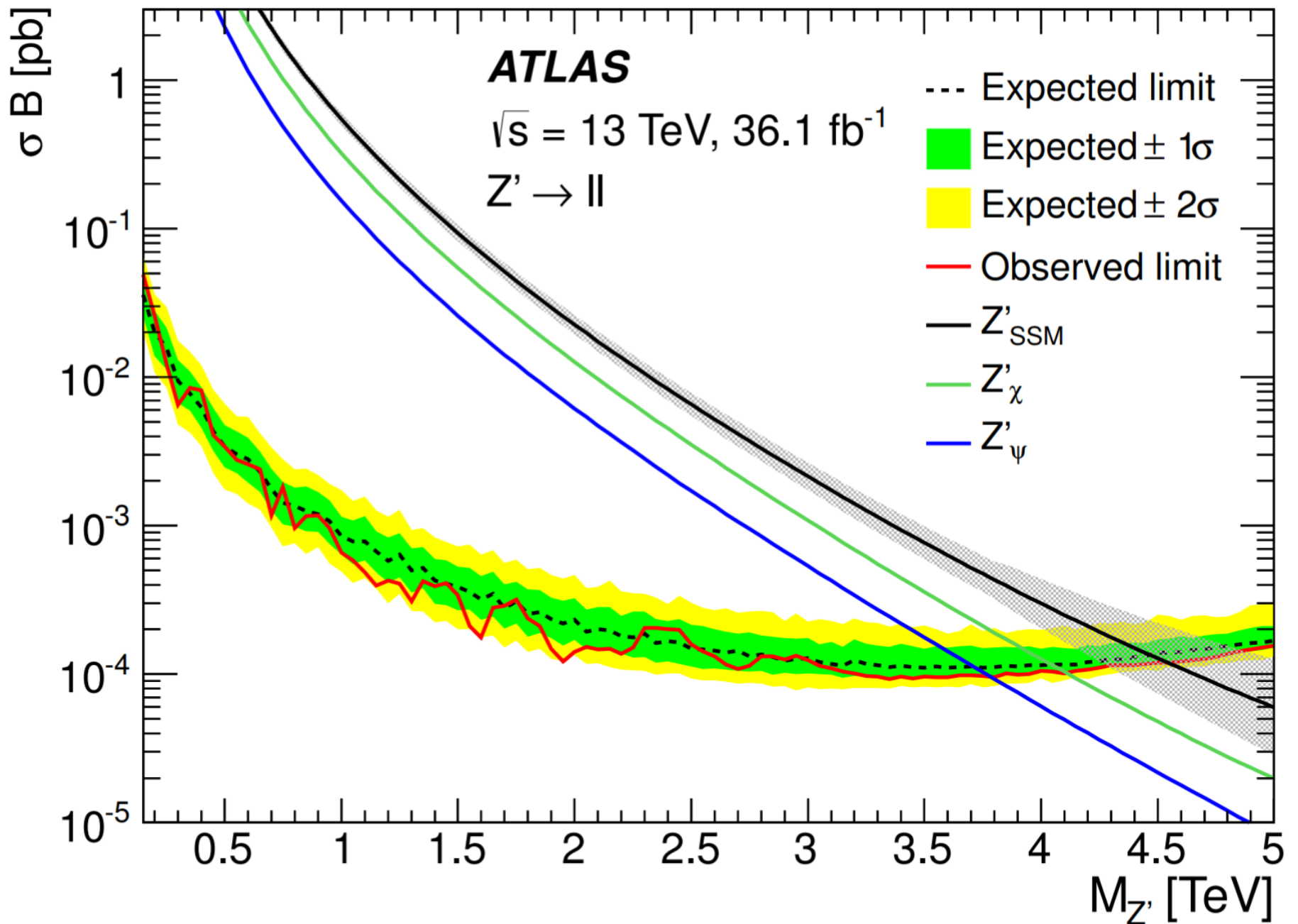






# High $m_{\mu\mu} = 2.4$ TeV Event





# Simplified $Z'$ Models<sup>8</sup>

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

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

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

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

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

---

<sup>8</sup>BCA, Queiroz, Strumia, Sun arXiv:1511.07447

# Simplified $Z'$ Models<sup>9</sup>

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

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

$$\mathcal{L} = \left( \overline{\mathbf{u}_L} V \Lambda^{(Q)} V^\dagger \gamma^\rho \mathbf{u}_L + \overline{\mathbf{d}_L} \Lambda^{(Q)} \gamma^\rho \mathbf{d}_L + \right. \\ \left. \overline{\mathbf{n}_L} U \Lambda^{(L)} U^\dagger \gamma^\rho \mathbf{n}_L + \overline{\mathbf{e}_L} \Lambda^{(L)} \gamma^\rho \mathbf{e}_L \right) Z'_\rho,$$

where

$$\Lambda^{(Q)} \equiv V_{d_L^\dagger}^\dagger \lambda^{(Q)} V_{d_L}, \quad \Lambda^{(L)} \equiv V_{e_L^\dagger}^\dagger \lambda^{(L)} V_{e_L}.$$

<sup>9</sup>[BCA, Corbett, Dolan, You, arXiv:1810.02166](#)

# Limiting Cases

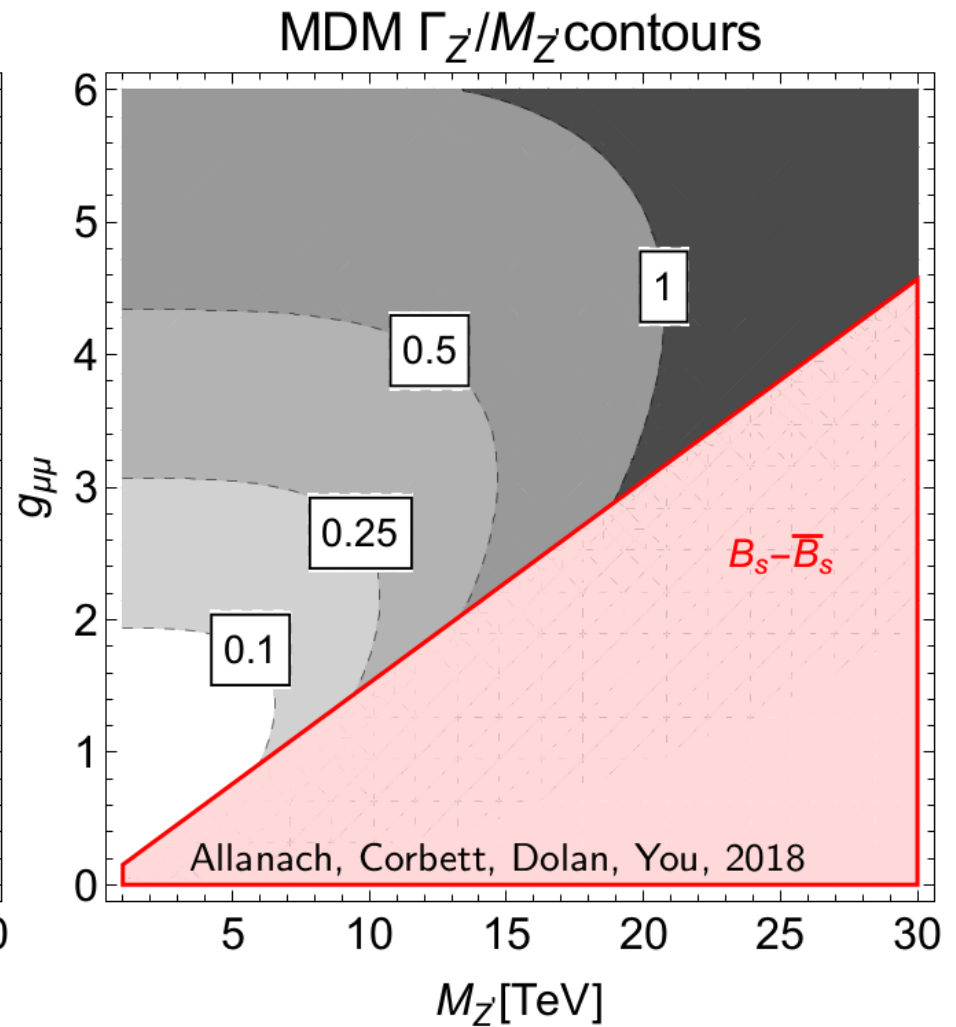
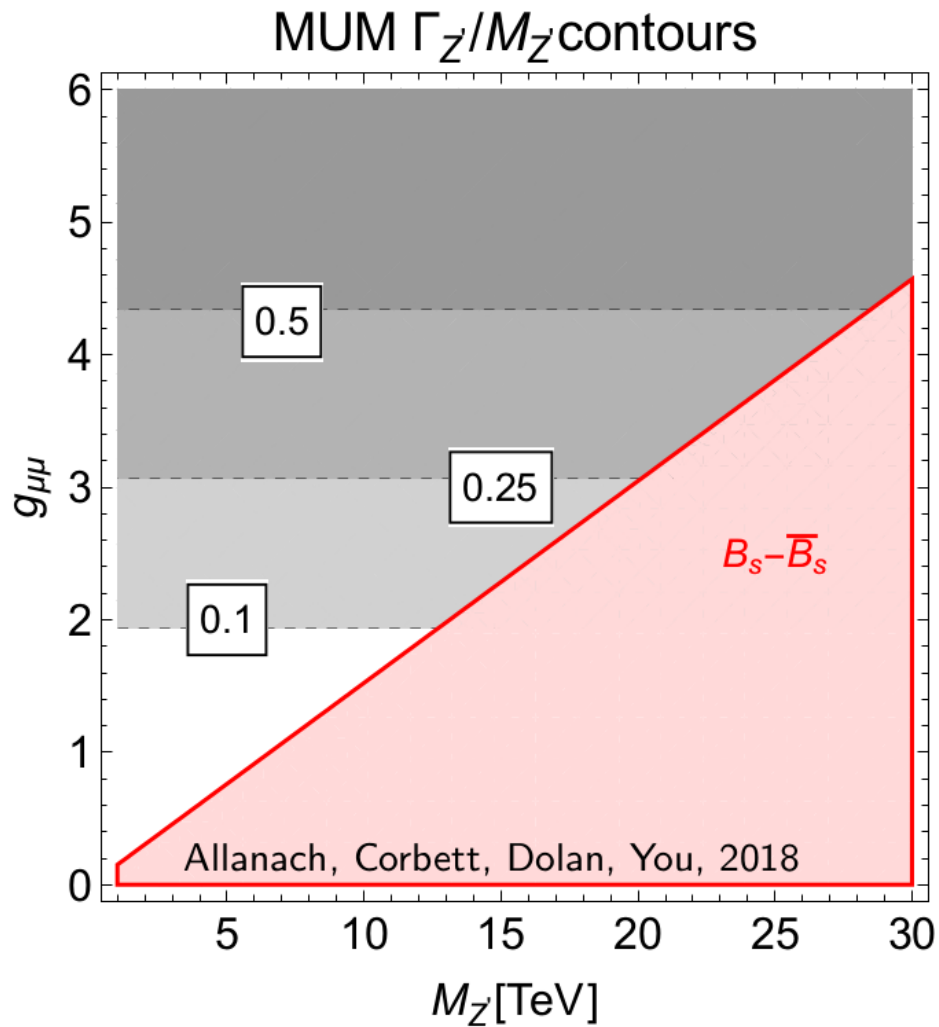
**Mixed Up Model:** all quark mixing is in left-handed ups

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

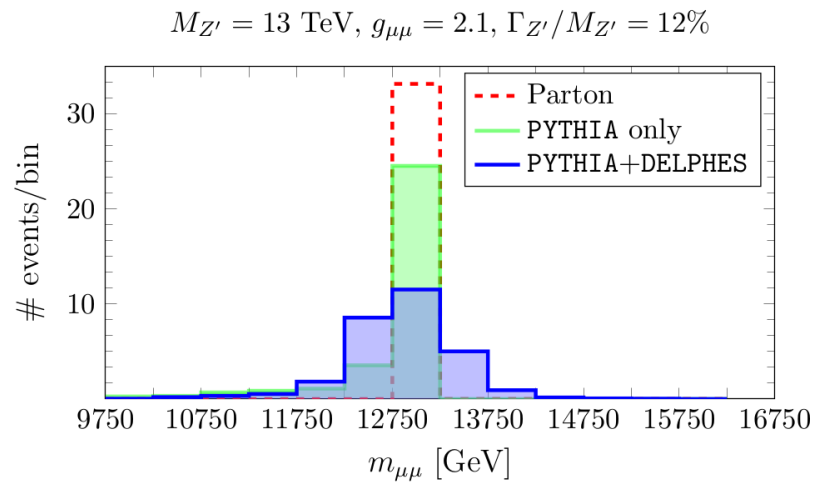
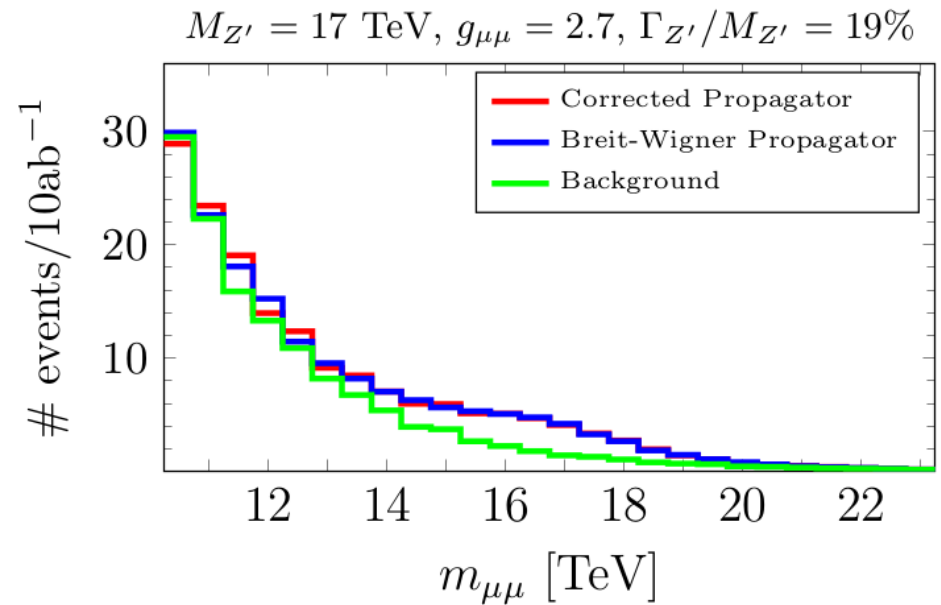
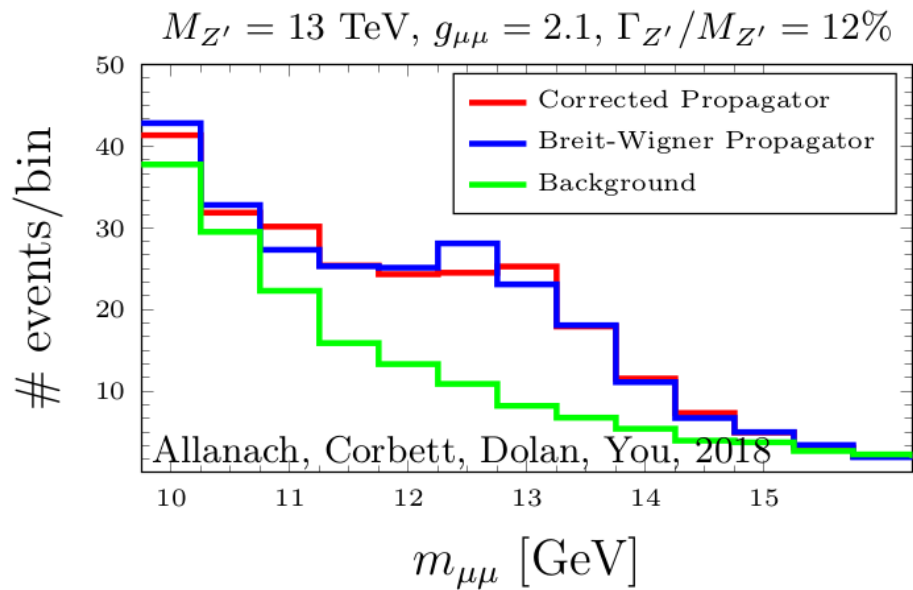
**Mixed Down Model:** all quark mixing is in left-handed downs

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

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

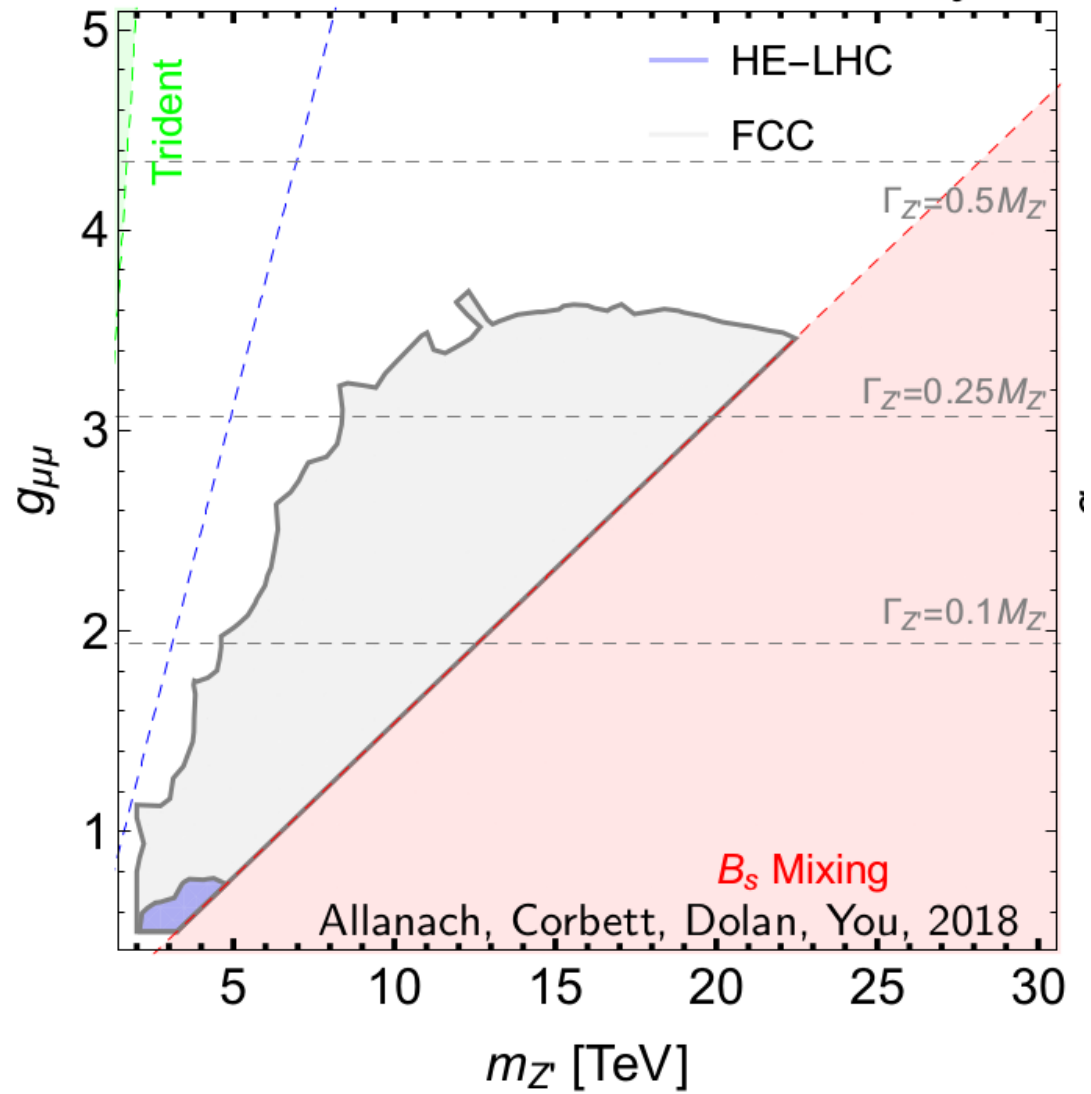


Widths: pick  $g_{bs}$  to fit anomalies at each point.

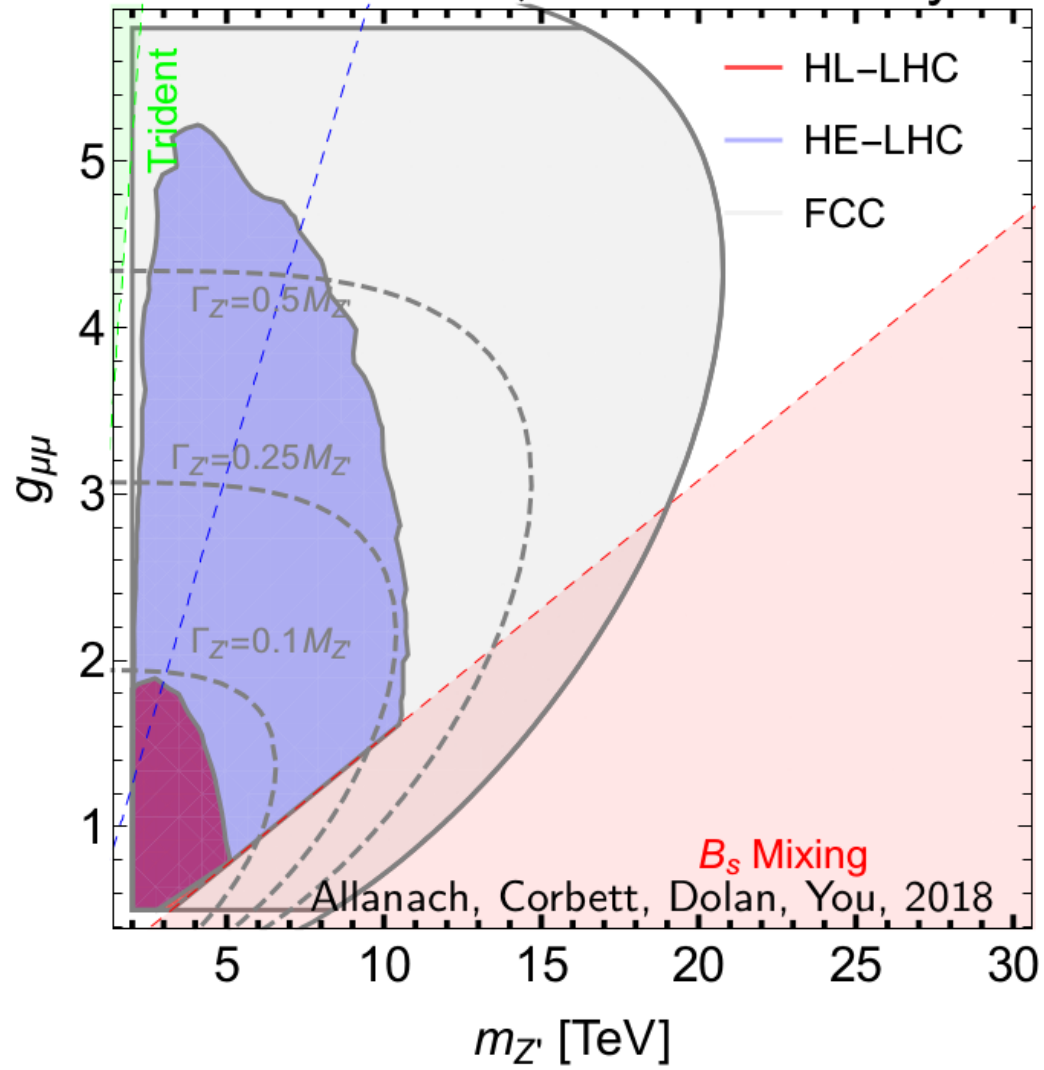




# MUM Model, 95% Sensitivity



# MDM Model, 95% Sensitivity



# 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  $\theta$  and gauged  $U(1)_F$ :

$$\begin{array}{c} SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_F \\ \downarrow \langle \theta \rangle \sim \text{Several TeV} \\ SU(3) \times SU(2)_L \times U(1)_Y \\ \downarrow \langle H \rangle \sim 246 \text{ GeV} \\ SU(3) \times U(1)_{em} \end{array}$$

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

# Unique Solution

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

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

- 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  $v_F = \langle \theta \rangle$
- $F_\theta$  is  $F$  charge of  $\theta$  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 proportional to  $g_F$  and:

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



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

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

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

# Example Case

Take a simple limiting case:

$V_{u_L} = 1 \Rightarrow V_{d_L} = V$ , the CKM matrix.  $V_{u_R} = V_{d_R} = V_{e_R} = 1$  for simplicity and the ease of passing bounds.

$$V_{d_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{sb} & -\sin \theta_{sb} \\ 0 & \sin \theta_{sb} & \cos \theta_{sb} \end{pmatrix}, \quad V_{e_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & U_{\mu 2} & U_{\mu 3} \\ 0 & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

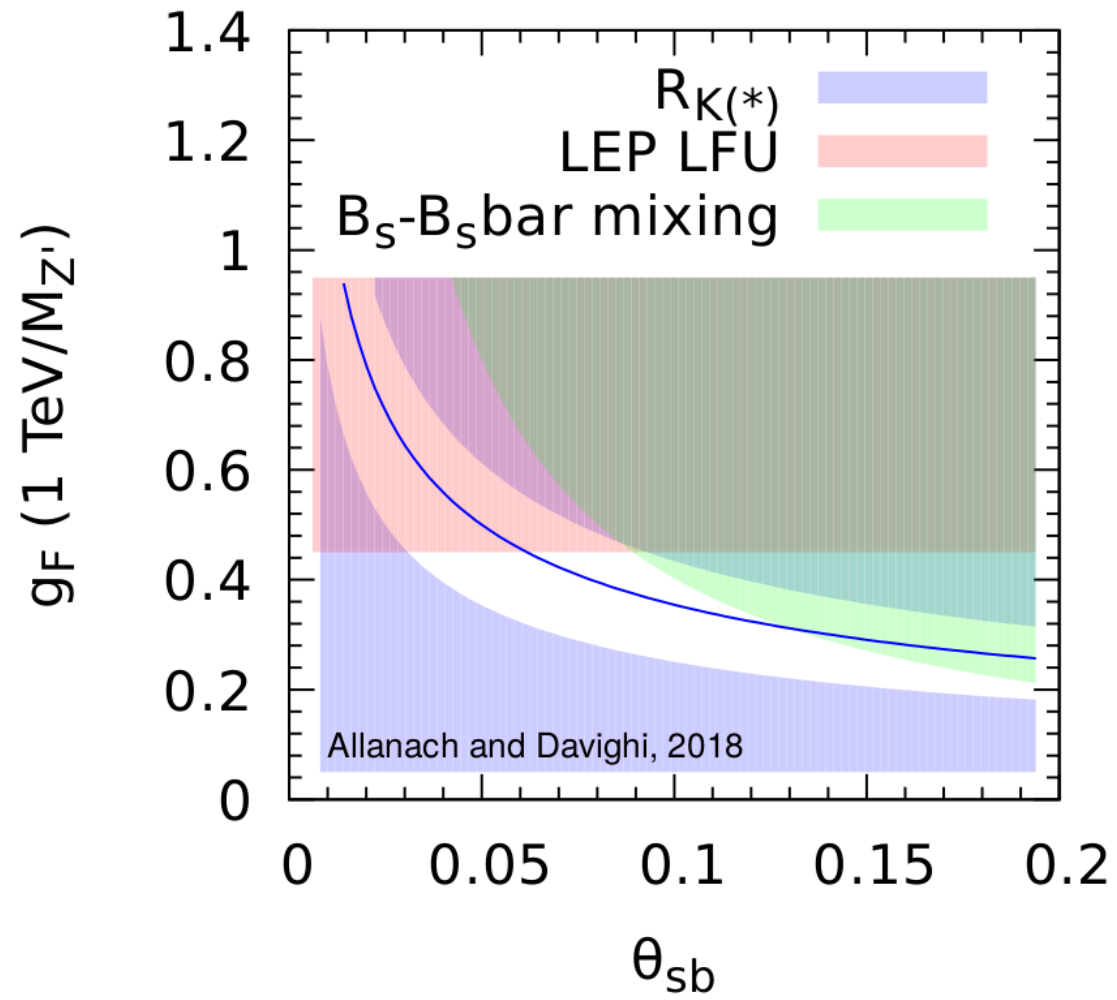
$V_{e_R} = 1 \Rightarrow V_{\nu_L} = V_{e_L} U^\dagger$ , where  $U$  is the PMNS matrix.

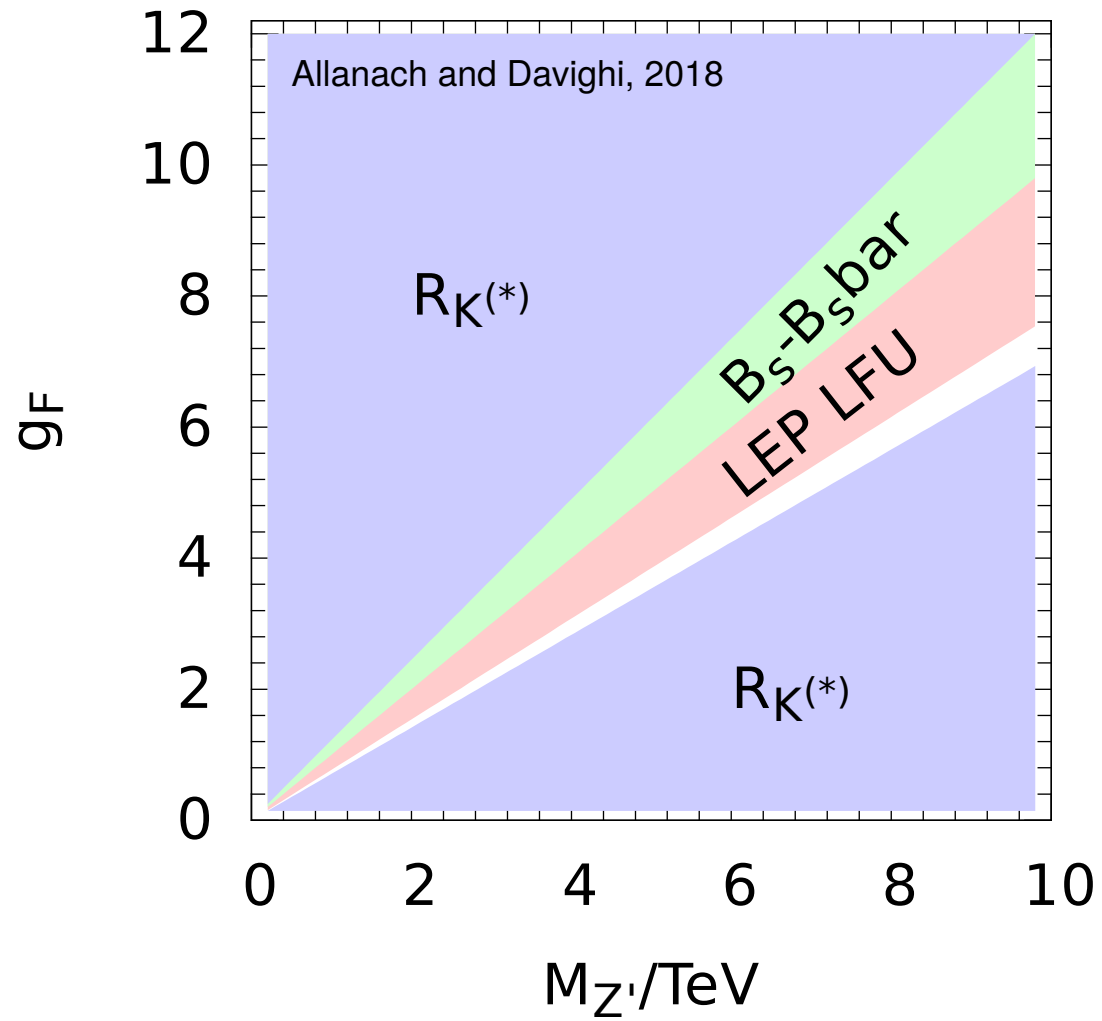
# Important $Z'$ Couplings

$$g_F \left( \frac{1}{6} \overline{\mathbf{d}}_L \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin^2 \theta_{sb} & \frac{1}{2} \sin 2\theta_{sb} \\ 0 & \frac{1}{2} \sin 2\theta_{sb} & \cos^2 \theta_{sb} \end{pmatrix} Z' \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \right.$$

$$\left. - \frac{1}{2} \overline{\mathbf{e}}_L \begin{pmatrix} 0 & 0 & 0 \\ 0 & |U_{\tau 2}|^2 & U_{\tau 2}^* U_{\tau 3} \\ 0 & U_{\tau 2} U_{\tau 3}^* & |U_{\tau 3}|^2 \end{pmatrix} Z' \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} \right)$$

$|U_{\tau 2}| \approx 0.6$ ,  $|U_{\tau 3}| \approx 0.7$ . Put  $|\sin \theta_{sb}| = |V_{ts}| = 0.04$ , so  $g_{\mu\mu} \gg g_{bs}$ , which helps us survive  $B_s - \overline{B}_s$  constraint





# 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 | $\mu^\pm\tau^\mp$ | 0.03 | $\tau^+\tau^-$  | 0.30 |

ATLAS<sup>10</sup>  $BR(Z \rightarrow \mu\tau) < 1.3 \times 10^{-5}$  at 95%, results in  $g_F \leq M_{Z'}/(0.8 \text{ TeV})$ , less stringent than LEP LFU

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

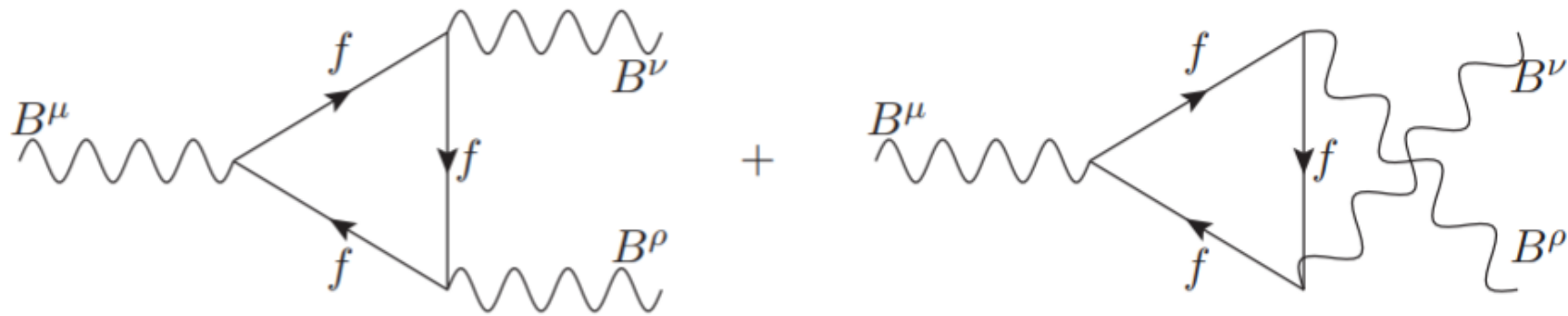
It's worth LHCb, BELLE II chasing  $BR(B \rightarrow K^{(*)}\mu^\pm\tau^\mp)$ .

---

<sup>10</sup>[arXiv:1804.09568](https://arxiv.org/abs/1804.09568)

# Quantum Field Theory

## Anomalies



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

# 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 **rational numbers**. Also, re-scaling invariance means that can re-scale to **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.

| $Q$ | $Q$ | $Q$ | $\nu$ | $\nu$ | $\nu$ | $e$ | $e$ | $e$ | $u$ | $u$ | $u$ | $L$ | $L$ | $L$ | $d$ | $d$ | $d$ |
|-----|-----|-----|-------|-------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 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*.

| $Q_{\max}$ | <b>Solutions</b> | Symmetry | Quadratics | Cubics  | Time/sec |
|------------|------------------|----------|------------|---------|----------|
| 1          | <b>8</b>         | 8        | 32         | 8       | 0.0      |
| 2          | <b>22</b>        | 14       | 1861       | 161     | 0.0      |
| 3          | <b>82</b>        | 32       | 23288      | 1061    | 0.0      |
| 4          | <b>251</b>       | 56       | 303949     | 7757    | 0.0      |
| 5          | <b>626</b>       | 114      | 1966248    | 35430   | 0.0      |
| 6          | <b>1983</b>      | 144      | 11470333   | 143171  | 0.2      |
| 7          | <b>3902</b>      | 252      | 46471312   | 454767  | 0.6      |
| 8          | <b>7068</b>      | 336      | 176496916  | 1311965 | 2.2      |
| 9          | <b>14354</b>     | 492      | 539687692  | 3310802 | 6.7      |
| 10         | <b>23800</b>     | 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  $R_{K^{(*)}}$  may provide a direct experimental probe into the flavour problem.

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https://aeon.co/essays/has-the-quest-for-top-down-...

# 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

**I**n 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 raised 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  $5\sigma$  by mid 2021. LHCb's  $R_{K^*}$  would be close to<sup>11</sup>  $5\sigma$  by 2020.
- $R_{K^{(*)}} \Rightarrow$  *HL-LHC, HE-LHC and FCC-hh*

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<sup>11</sup>[Albrecht et al, 1709.10308](#)

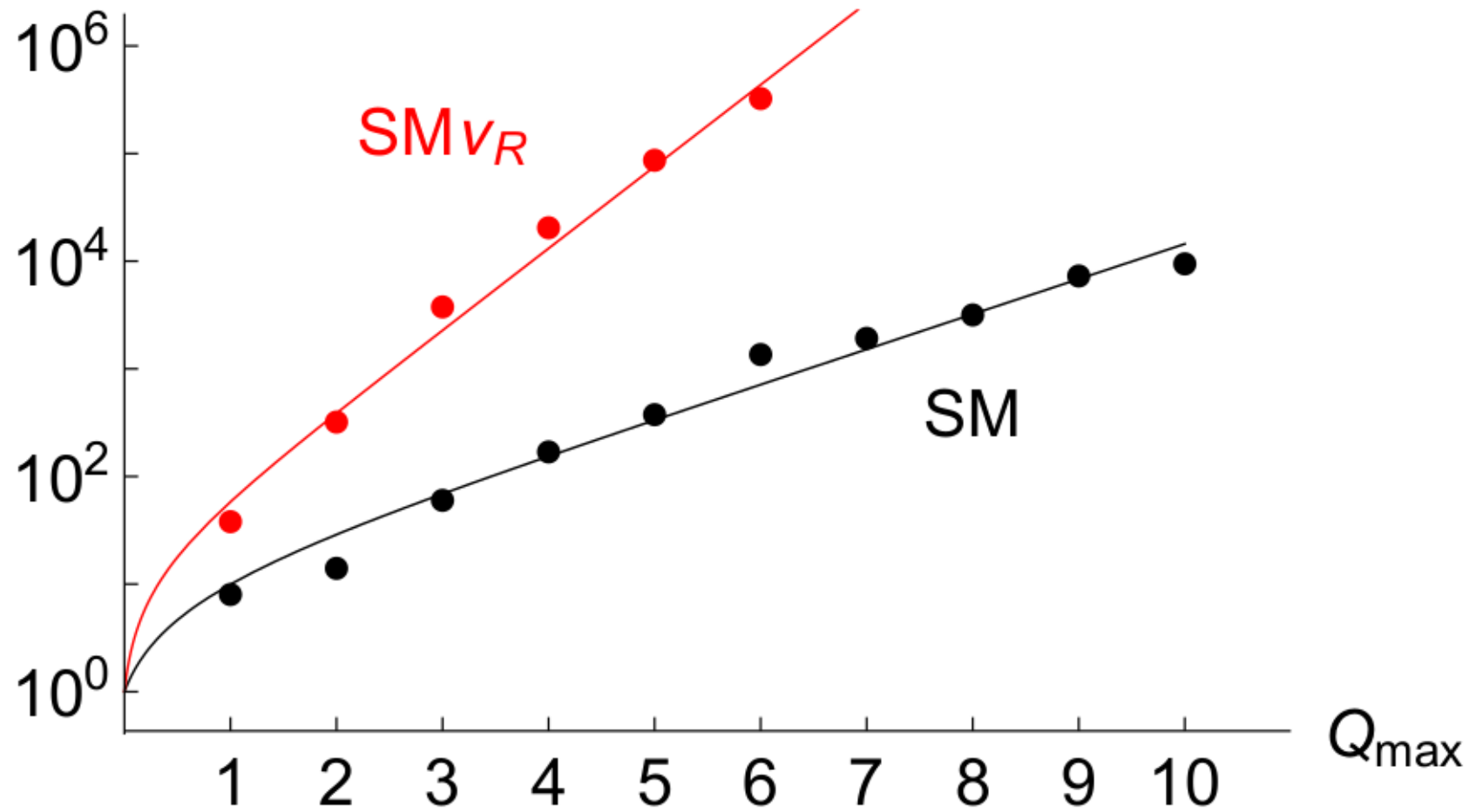
# Backup



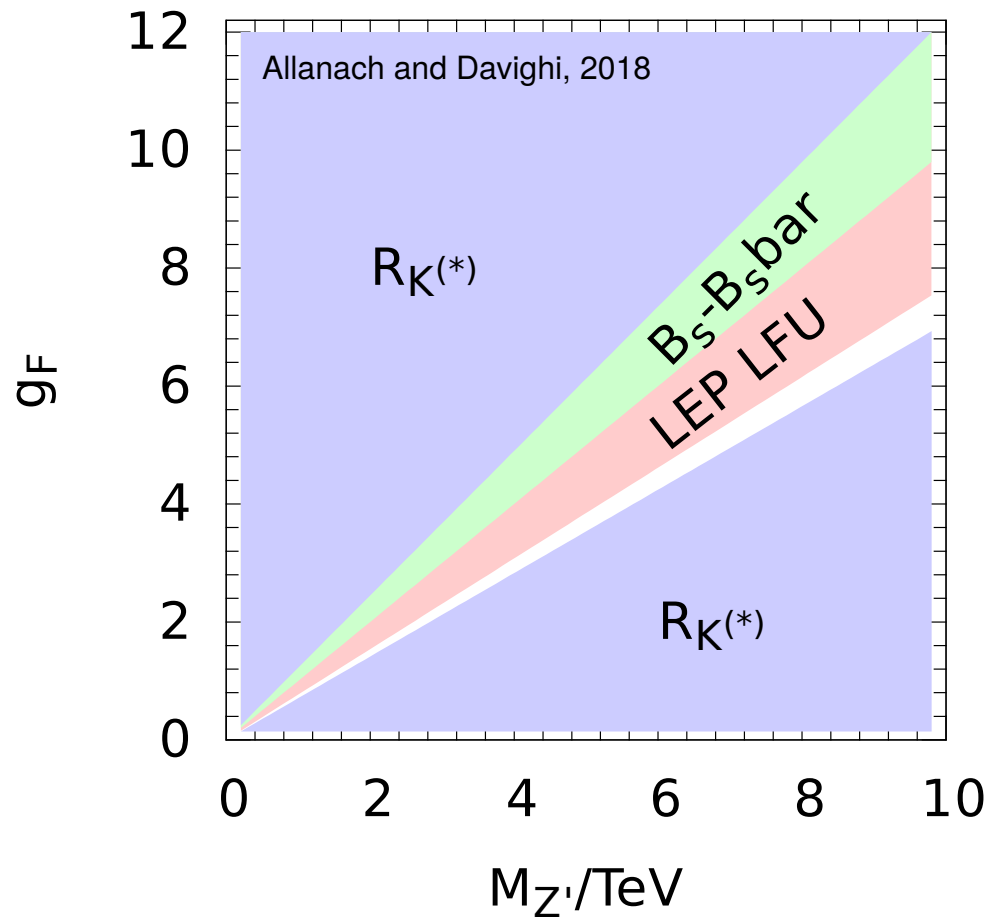
| $Q_{\max}$ | <b>Solutions</b> | Symmetry | Quadratics | Cubics   | Time/sec |
|------------|------------------|----------|------------|----------|----------|
| 1          | <b>38</b>        | 16       | 144        | 38       | 0.0      |
| 2          | <b>358</b>       | 48       | 31439      | 2829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

SM + 3  $\nu_R$ : number of solutions etc

# Solutions



# Constraints on Example Case

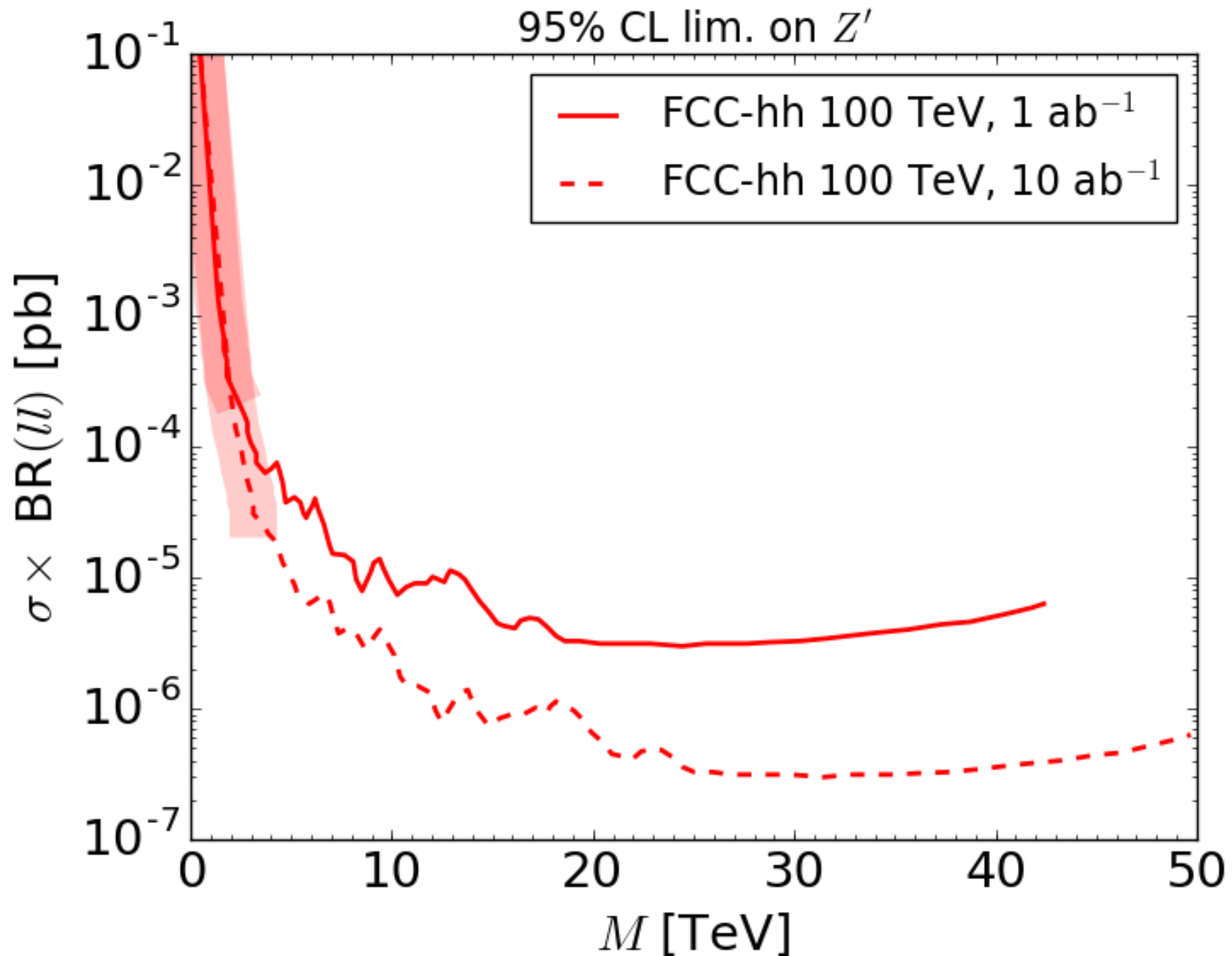


Widen allowed white sliver with less strong assumptions?

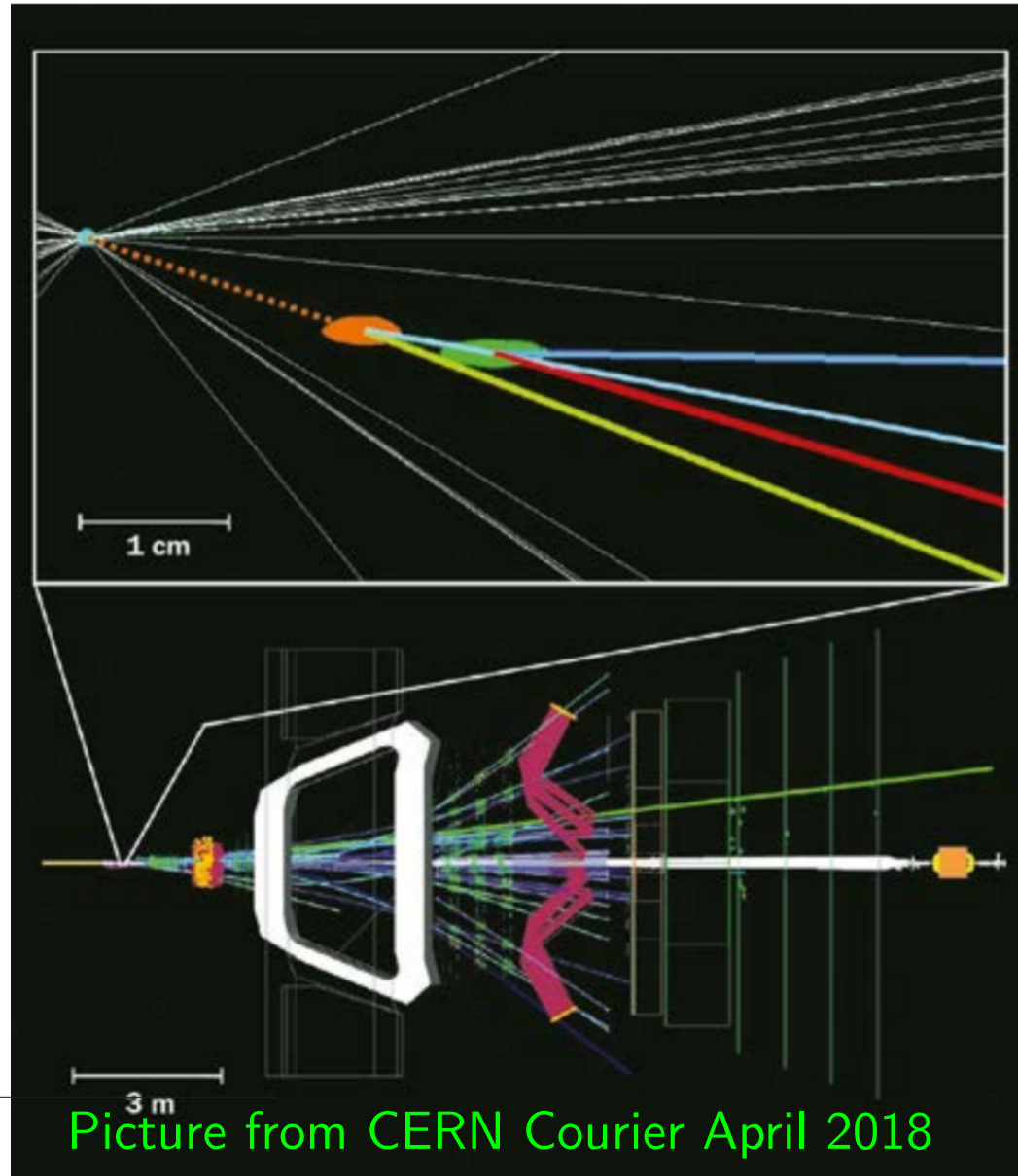
# Known Solutions

| Model            | $Q$ | $Q$ | $Q$ | $\nu$ | $\nu$ | $\nu$ | $e$ | $e$ | $e$ | $u$ | $u$ | $u$ | $L$ | $L$ | $L$ | $d$ | $d$ | $d$ |
|------------------|-----|-----|-----|-------|-------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $L_\mu - L_\tau$ | 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   |

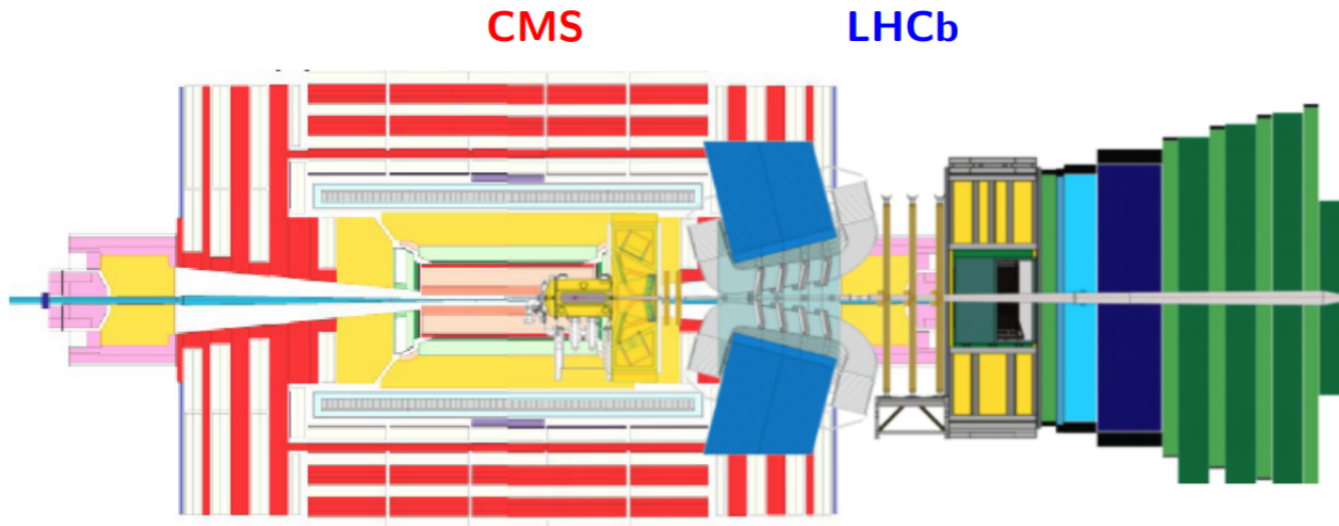
# 13 TeV ATLAS 3.2 fb<sup>-1</sup> $\mu\mu$



# LHCb Detector II<sup>12</sup>



# LHCb Detector<sup>13</sup>

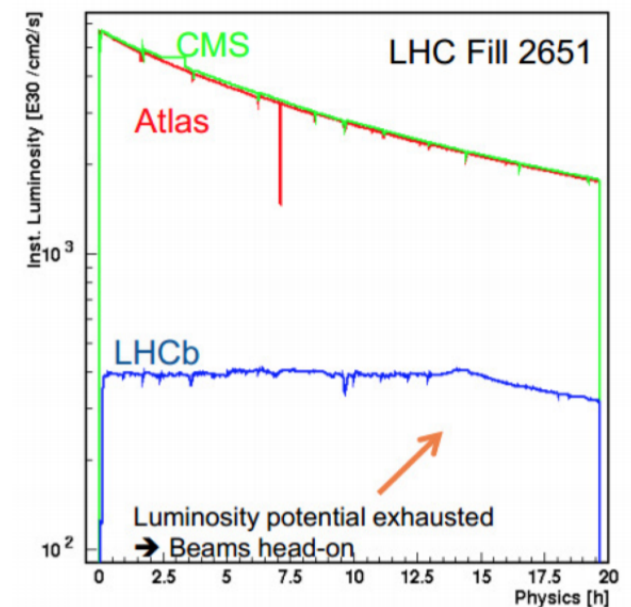


Optimised to study beauty and charm hadrons

→ provides **complementary**  $\eta$  coverage compared with a GPD.

## LHCb as a forward GPD:

- ✓ Precise integrated **luminosity** computation
- ✓ **Stable** data-taking conditions due to **luminosity levelling**
- ✓ Average pile-up  $\sim 2$  (twice design)
- ✓ Excellent **vertexing**, particle ID, momentum resolution...
- ✗ Lower luminosity than to ATLAS/CMS
- ✗ Lower acceptance
- ✗ **Not hermetic!** (can't use  $E_T^{miss}$  variable)



<sup>13</sup> Diaz talk 53rd EW Rencontres de Moriond 2018

# 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

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

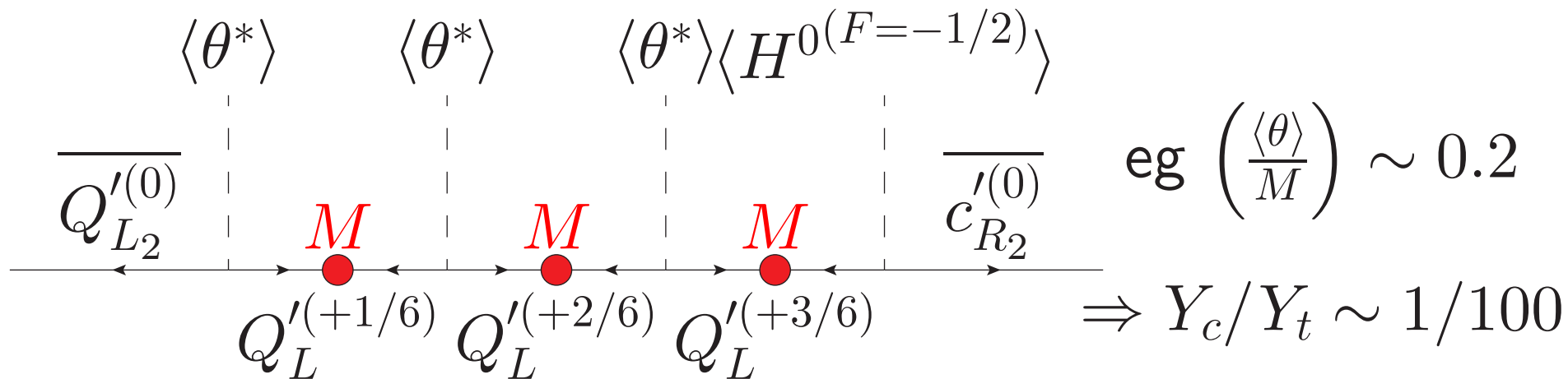
where now  $(M^{-1})_{ij}$  may well have a non-trivial structure. If  $(M^{-1})_{ij}$  are of same order, large PMNS mixing results.



# Froggatt Neilsen Mechanism<sup>14</sup>

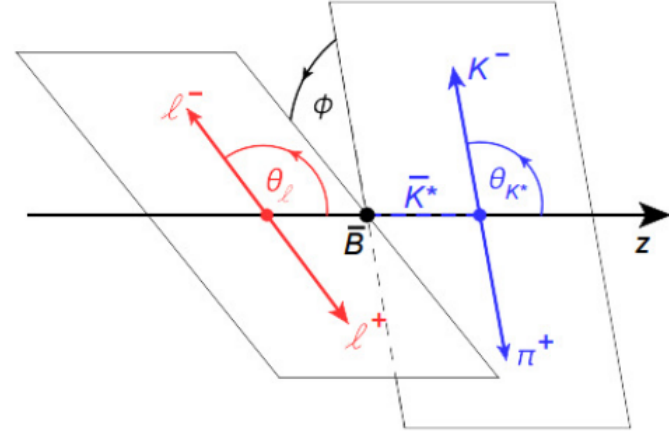
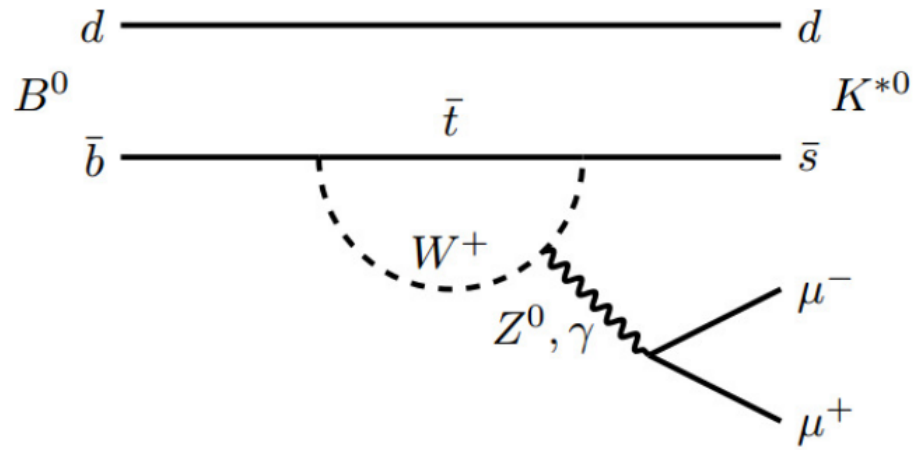
A means of generating the non-renormalisable Yukawa terms, e.g.  $F_\theta = 1/6$ :

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



<sup>14</sup>C Froggatt and H Neilsen, NPB147 (1979) 277

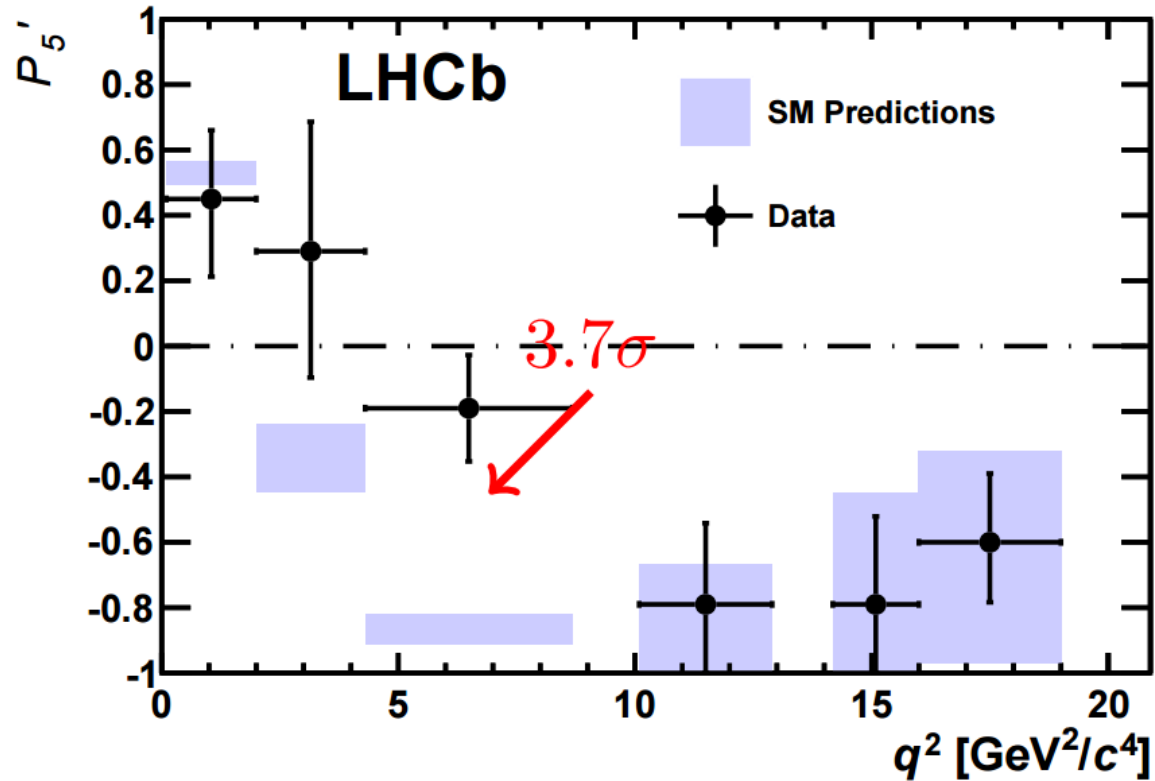
$$B^0 \rightarrow K^{*0} (\rightarrow K^+ \pi^-) \mu^+ \mu^-$$



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

$$\begin{aligned} \frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} &= \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right. \\ &\quad - F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi \\ &\quad + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \\ &\quad + \frac{4}{3} A_{\text{FB}} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \\ &\quad \left. + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right] \end{aligned}$$

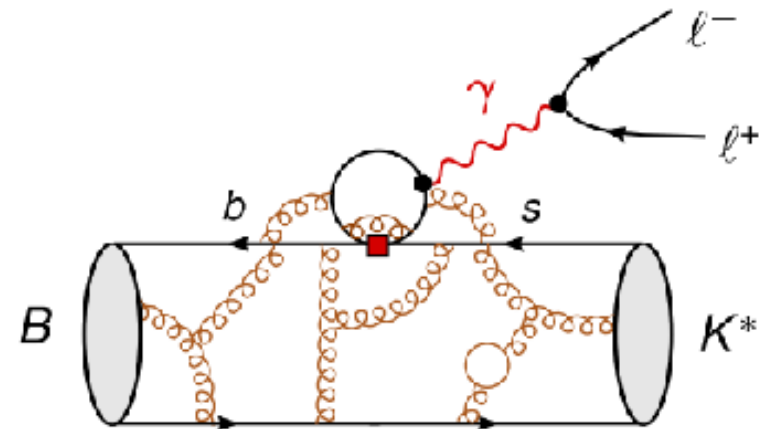
$$P'_5$$



$P'_5 = S_5 / \sqrt{F_L(1 - F_L)}$ , leading form factor uncertainties cancel. Tension already in  $1 \text{ fb}^{-1}$  and confirmed in  $3 \text{ fb}^{-1}$   
[LHCb-CONF-2015-002](#)

# Hadronic Uncertainties

- ▶ Hadronic effects like charm loop are photon-mediated  $\Rightarrow$  vector-like coupling to leptons just like  $C_9$



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

# LQ Models

**Scalar**<sup>15</sup>  $S_3 = (\bar{3}, 3, 1/3)$  of  $SU(2) \times SU(2)_L \times U(1)_Y$ :

$$\mathcal{L} = \dots + y_3 Q L S_3 + y_q Q Q S_3^\dagger + \text{h.c.}$$

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

$$\mathcal{L} = \dots + y'_3 V_3^\mu \bar{Q} \gamma_\mu L + y_1 V_1^\mu \bar{Q} \gamma_\mu L + y'_1 V_1^\mu \bar{d} \gamma_\mu l + \text{h.c.}$$

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

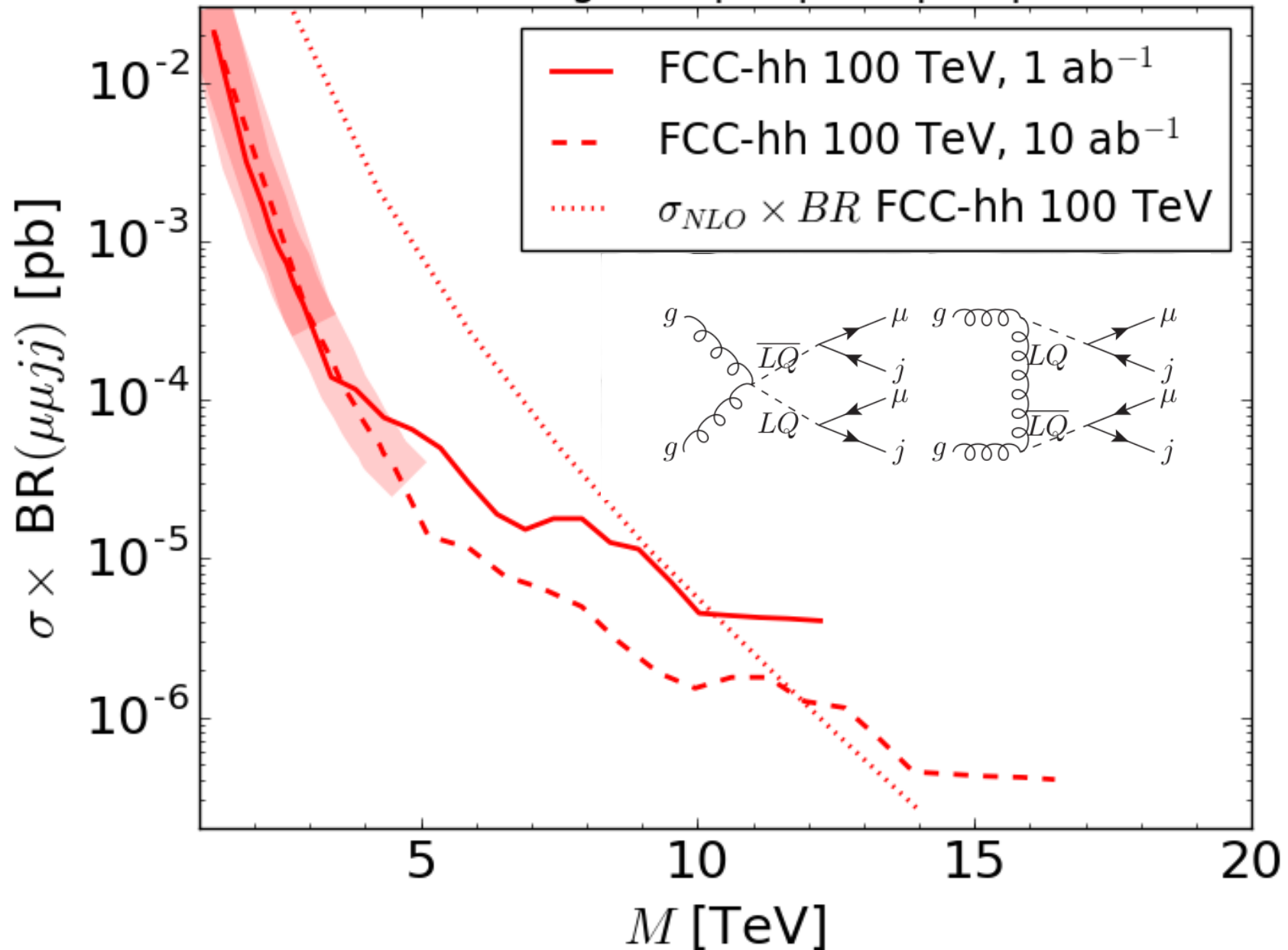
$\kappa = 1, -1, -1$  and  $y = y_3, y_1, y'_3$  for  $S_3, V_1, V_3$ .

<sup>15</sup>Capdevila *et al* 1704.05340, Hiller and Hisandzic 1704.05444, D'Amico *et al* 1704.05438.

# CMS 8 TeV 20fb<sup>-1</sup> 2nd gen

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

95% CL lim. 2nd gen. leptoquark pair production



# 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:

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

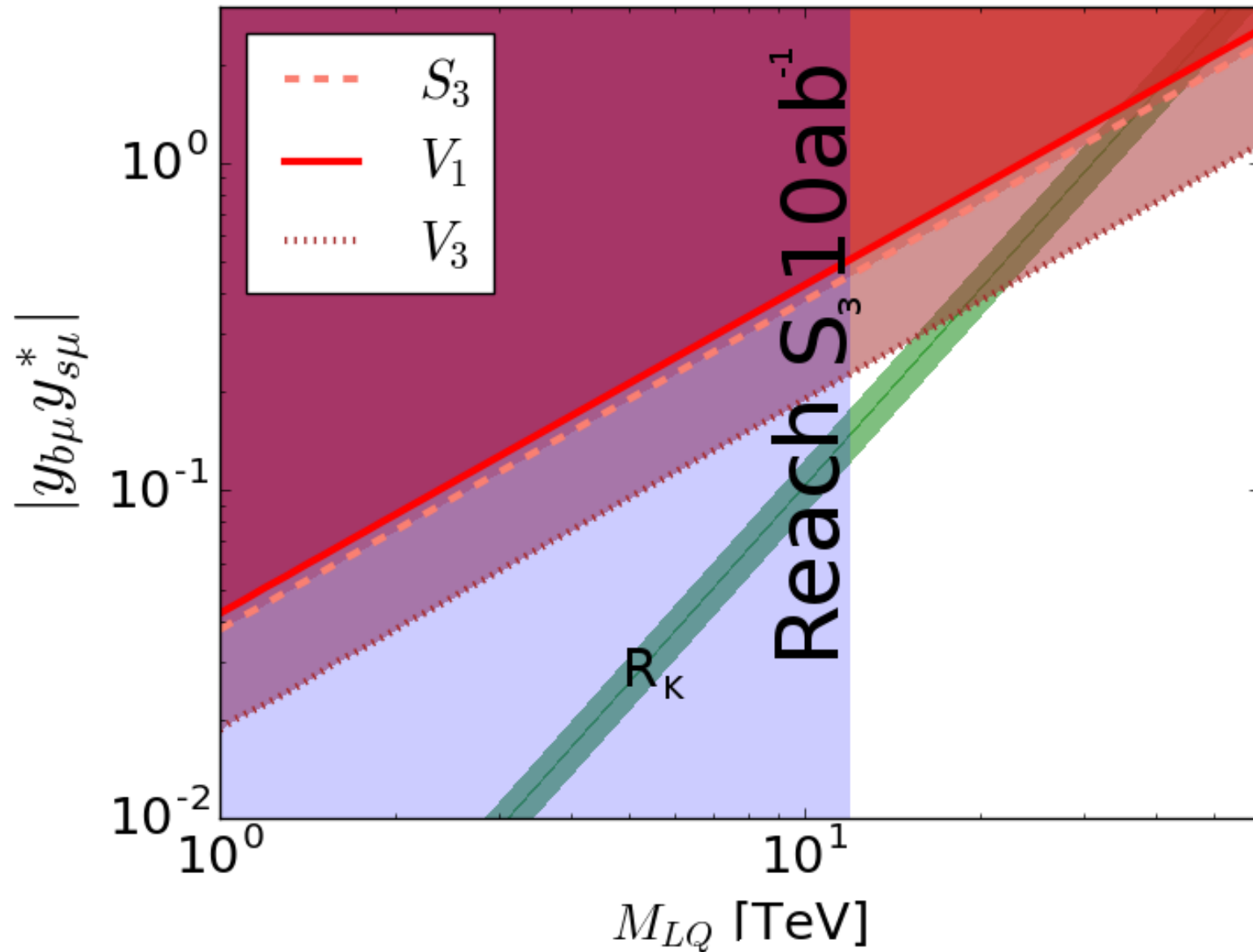
$y = y_3, y_1, y'_3$  and  $k = 5, 4, 20$  for  $S_3, V_1, V_3$ .

Data  $\Rightarrow c_{LL}^{bb} < 1/(210\text{TeV})^2$ . Recently, some<sup>16</sup> used a Fermilab MILC lattice determination of  $f_B$  which **makes the SM differ from experiment at the  $2\sigma$  level.**

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<sup>16</sup>Lenz *et al*, 1712.06572

# 8 TeV CMS 20fb<sup>-1</sup> 2nd gen



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



# LQ Mass Limits

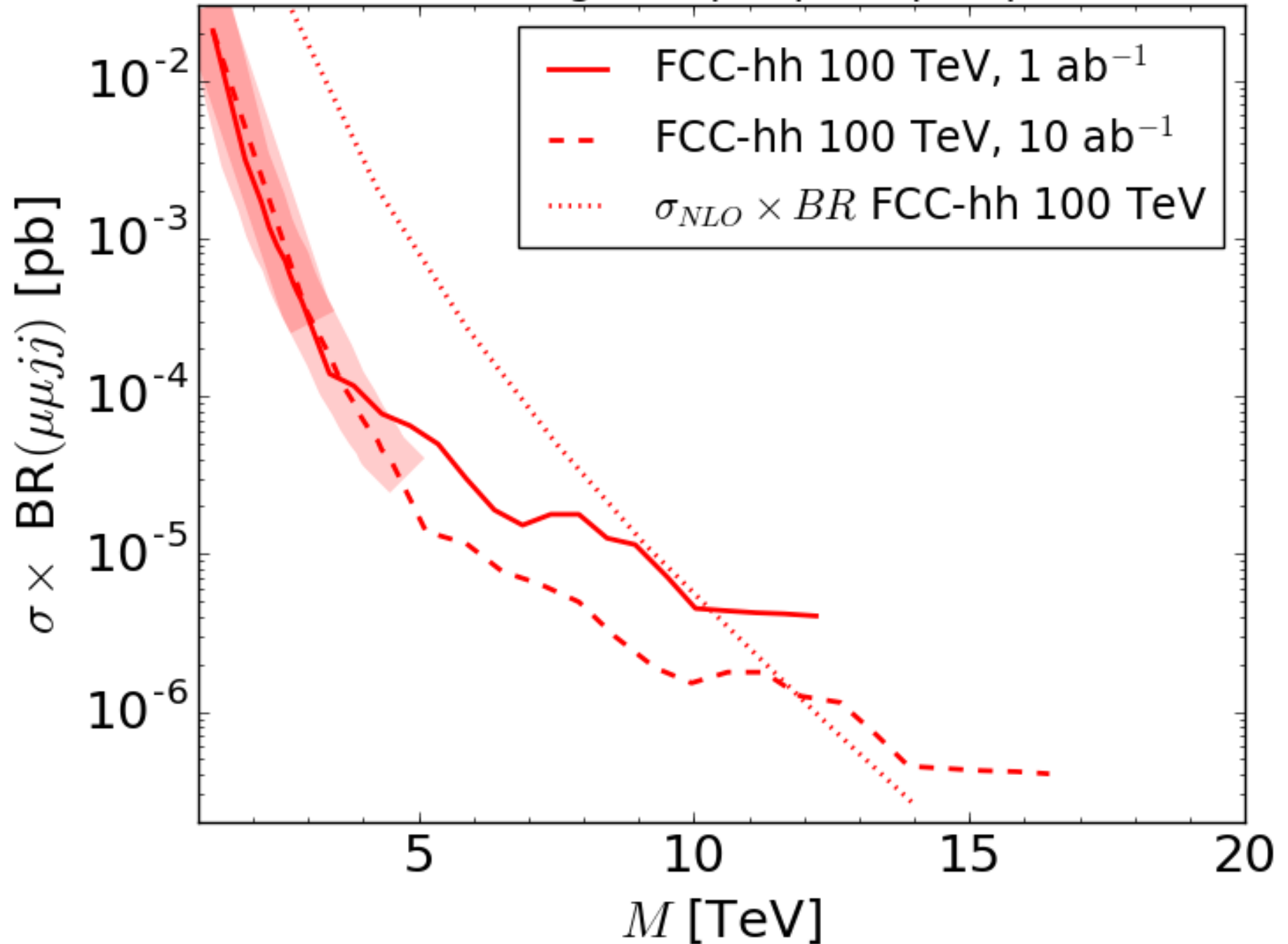
|       |        |
|-------|--------|
| $S_3$ | 41 TeV |
| $V_1$ | 41 TeV |
| $V_3$ | 18 TeV |

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

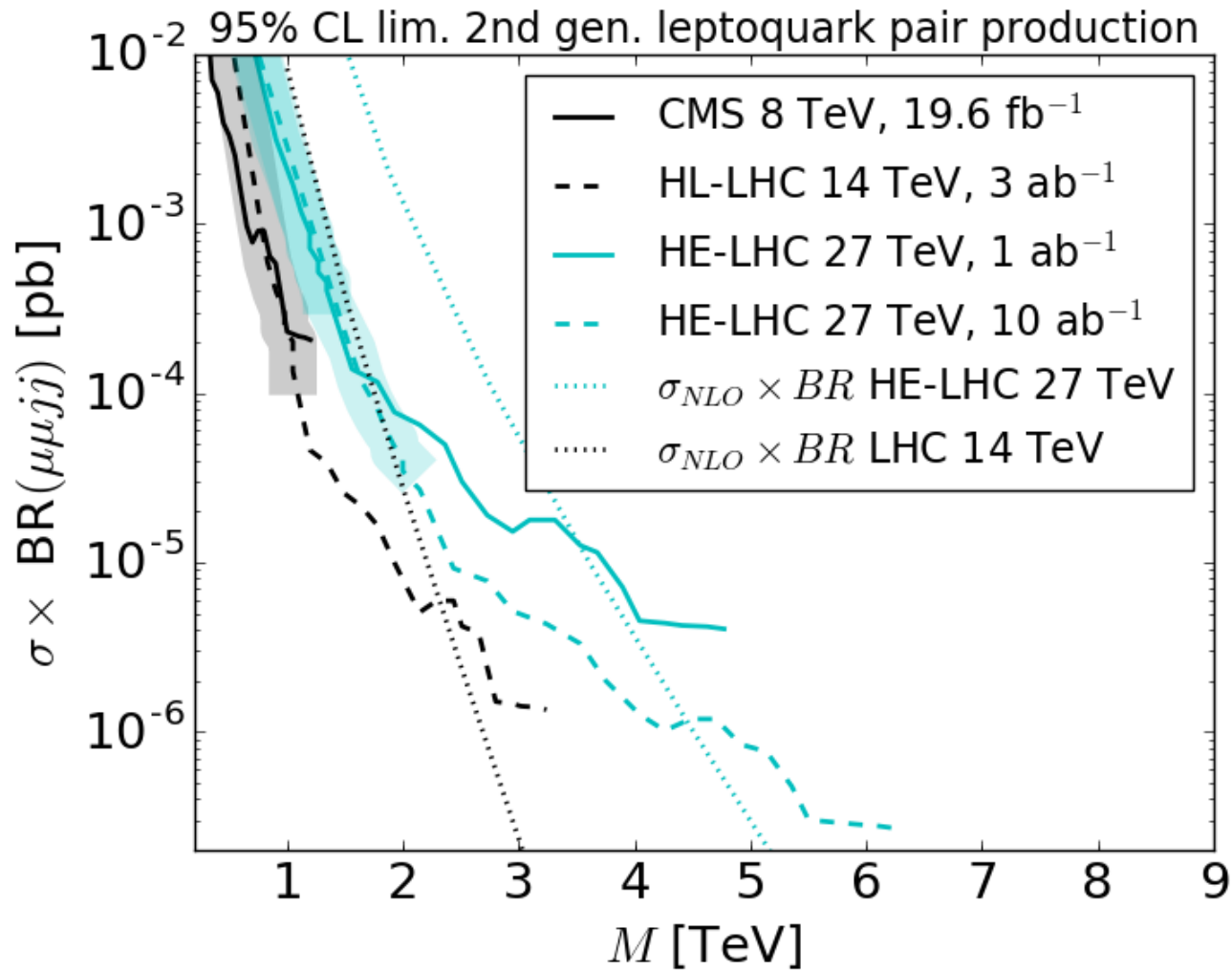
Pair production has a reach up to 12 TeV.

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

95% CL lim. 2nd gen. leptoquark pair production



# HL-LHC/HE-LHC LQs



$$B_s \rightarrow \mu^+ \mu^-$$

Lattice QCD provides important input to

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

$$BR(B_s \rightarrow \mu\mu)_{exp} = (3.0 \pm 0.6) \times 10^{-9}.$$

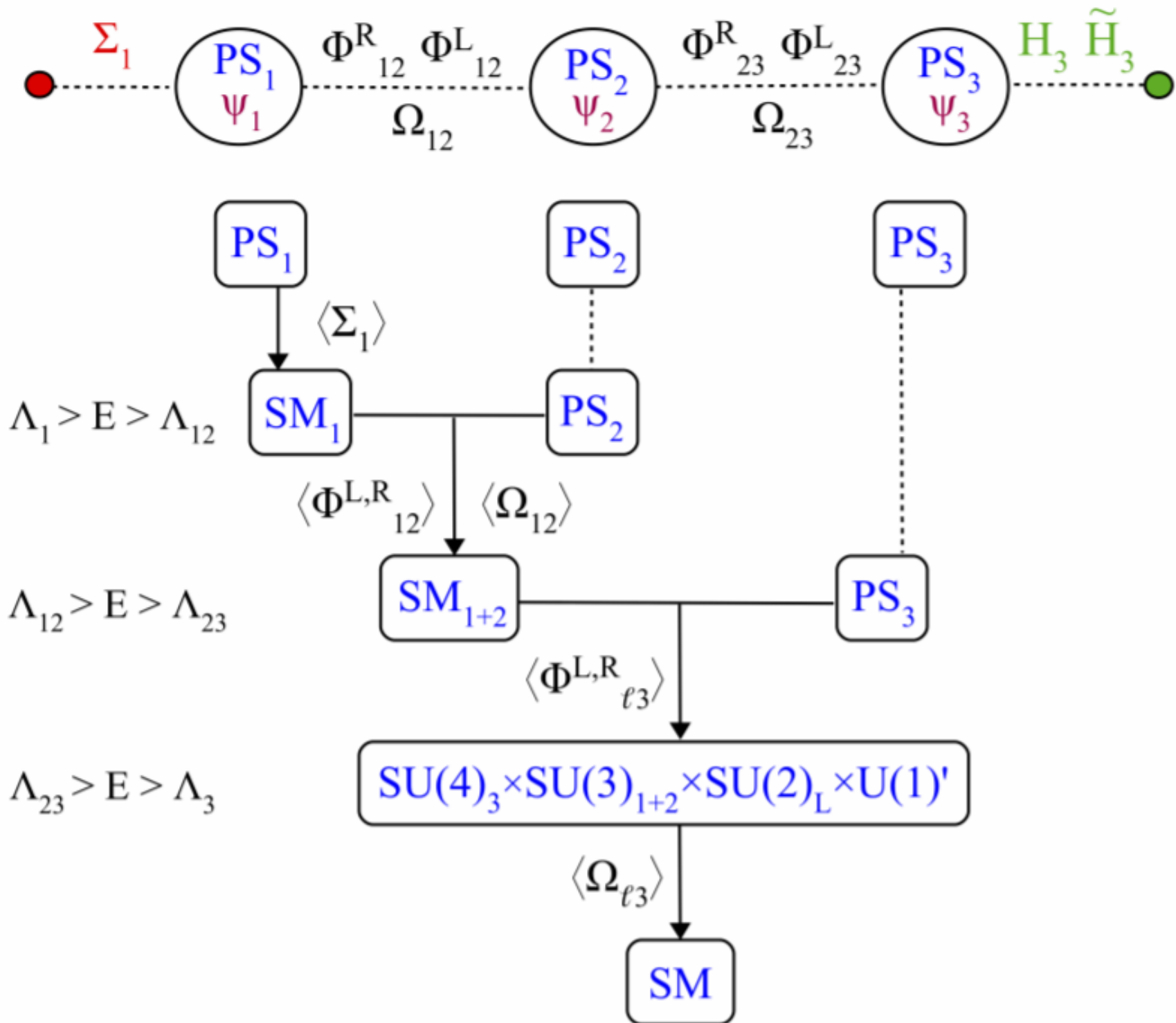
$$\frac{BR(B_s \rightarrow \mu\mu)}{BR(B_s \rightarrow \mu\mu)_{SM}} = \left| \frac{(\bar{c}_{LL}^\mu + \bar{c}_{RR}^\mu - \bar{c}_{LR}^\mu - \bar{c}_{RL}^\mu)^{tot}}{(\bar{c}_{LL}^\mu + \bar{c}_{RR}^\mu - \bar{c}_{LR}^\mu - \bar{c}_{RL}^\mu)^{SM}} \right|^2.$$

# Other Flavour Models

Realising<sup>17</sup> 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.

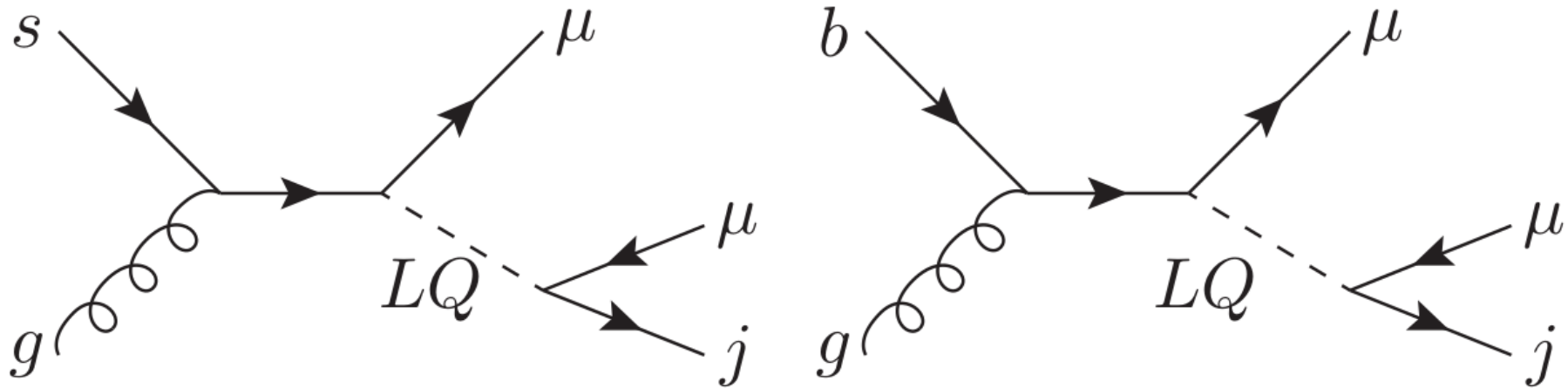
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<sup>17</sup>Di Luzio Greljo, Nardecchia arXiv:1708.08450, Bordone, Cornella, Fuentes-Martin, Isidori, arXiv:1712.01368

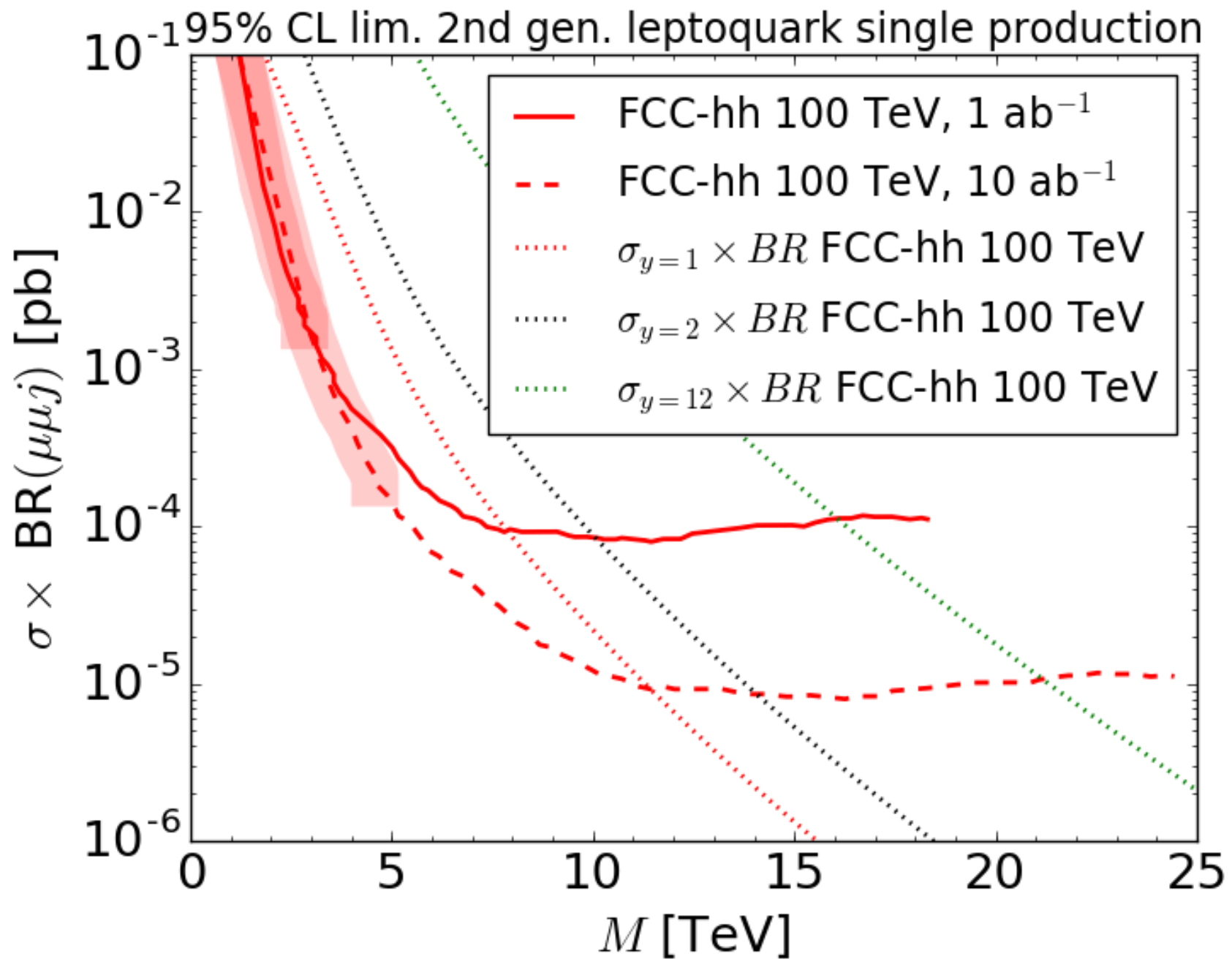


# Single Production of LQ

Depends upon **LQ coupling** as well as LQ mass



Current bound by CMS from 8 TeV  $20 \text{ fb}^{-1}$ :  $M_{LQ} > 660$  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.



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



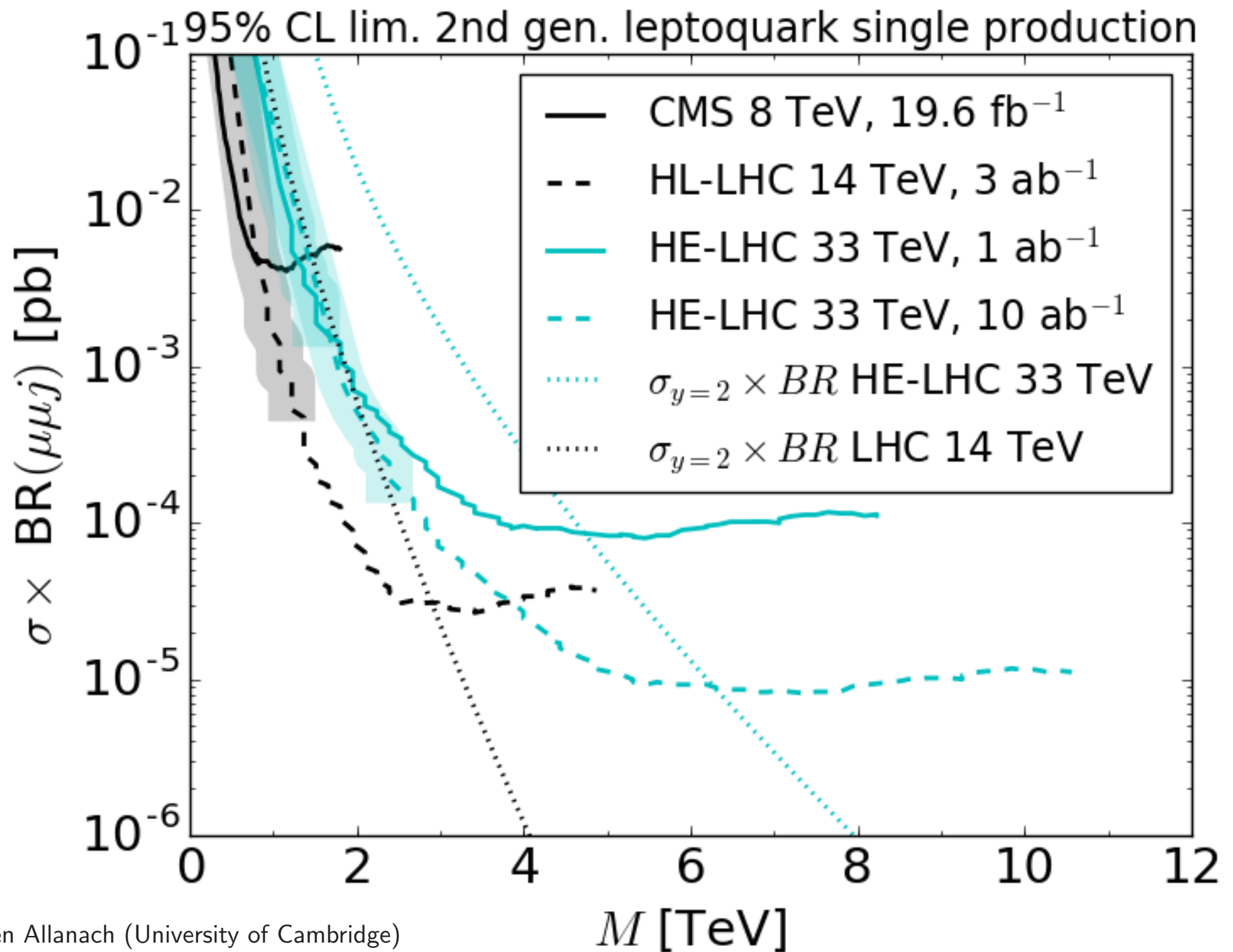
# Single LQ Production $\sigma$

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

where<sup>18</sup>  $r = M_{LQ}^2 / \hat{s}$  and we set  $y_{s\mu} = y_{b\mu} = y$ .

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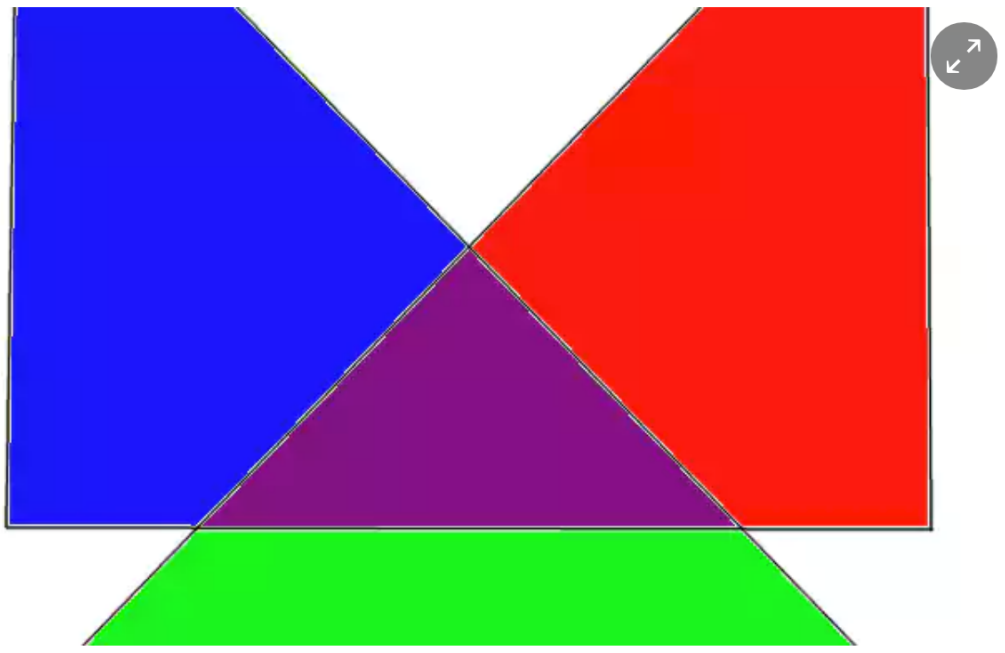
<sup>18</sup>Hewett and Pakvasa, PRD **57** (1988) 3165.



**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

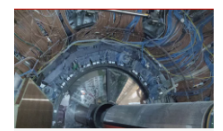


▲ Four colours (or colors?) Photograph: Ben Allanach

**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 [Tevon 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

[Read more](#)

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