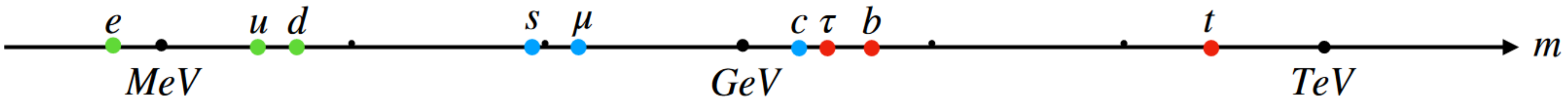
A Unified Approach to the Flavour Puzzle

Joe Davighi, University of Zurich

Particle Physics Seminar @ University of Warwick, 10th November 2022



Outline

1. Review of the flavour puzzle(s)

2. Flavour model building in the LHC era

   a) Horizontal flavour symmetries

   b) Flavour-deconstructed gauge symmetries

   c) Unified (gauge & flavour) symmetries

3. Electroweak flavour unification via $SU(4) \times Sp(6)_L \times Sp(6)_R$ gauge group

Davighi, Tooby-Smith, 2201.07245

The Flavour Puzzle

The Flavour Puzzle(s)

The matter content of the Standard Model is a source of many mysteries!

Puzzle 1: SM fermions in 5 (6) ad hoc representations of SM gauge group:

$$q_L \sim (\mathbf{3},\mathbf{2})_{1/6} \qquad u_R \sim (\mathbf{3},\mathbf{1})_{2/3} \qquad d_R \sim (\mathbf{3},\mathbf{1})_{-1/3}$$
$$l_L \sim (\mathbf{1},\mathbf{2})_{-1/2} \qquad e_R \sim (\mathbf{1},\mathbf{1})_{-1} \qquad \nu_R \sim (\mathbf{1},\mathbf{1})_{0}$$

Hints at unification e.g. quark-lepton unification? $SU(5)$? $SO(10)$?

Traditionally, unification was done **ignoring flavour**.
(More later…)

Georgi, Glashow, 1974
Georgi, 1975, and Fritzsch, Minkowski, 1975

The Flavour Puzzle(s)

The matter content of the Standard Model is a source of many mysteries!

Puzzle 1: SM fermions in 5 (6) ad hoc representations of SM gauge group:

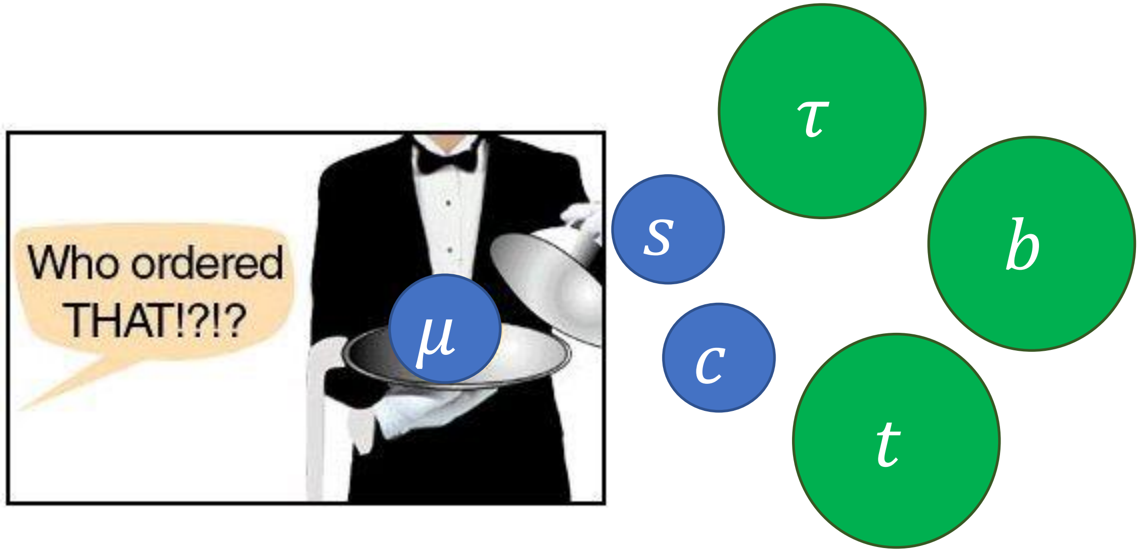
Puzzle 2: This structure is repeated **three times**. Why?

The Flavour Puzzle(s)

The matter content of the Standard Model is a source of many mysteries!

Puzzle 1: SM fermions in 5 (6) ad hoc representations of SM gauge group:

Puzzle 2: This structure is repeated **three times**. Why?



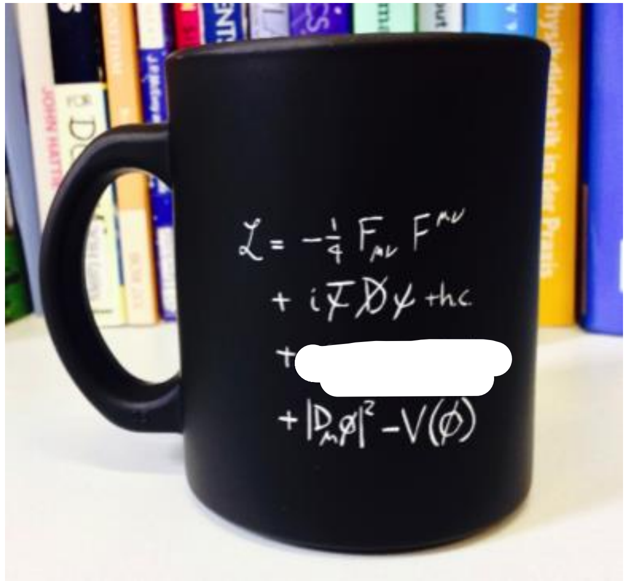
The Flavour Puzzle(s)

Puzzle 1: SM fermions in 5 (6) ad hoc representations of SM gauge group.

Puzzle 2: This structure is repeated **three times**. Why?

Puzzle 3: SM without Yukawa couplings has a big global symmetry

$$G = U(3)^5$$



The Flavour Puzzle(s)

Puzzle 1: SM fermions in 5 (6) ad hoc representations of SM gauge group.

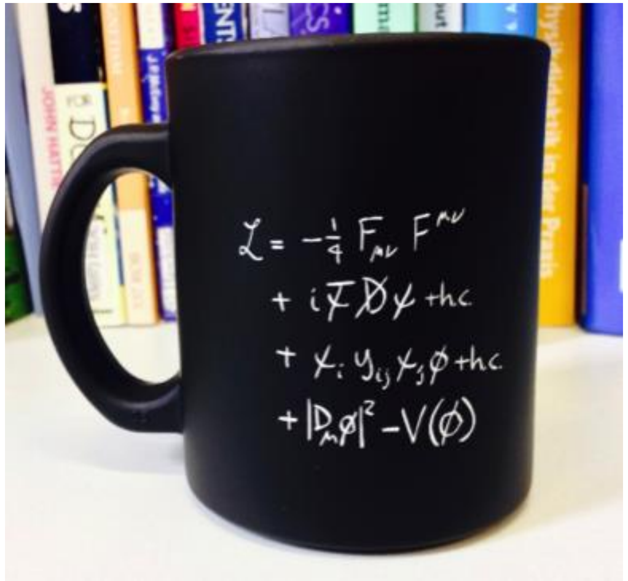
Puzzle 2: This structure is repeated **three times**. Why?

Puzzle 3: SM without Yukawa couplings has a big global symmetry

$$G = U(3)^5$$

Yukawa couplings to the Higgs (**Y**) break this symmetry:

$$U(3)^5 \rightarrow G_{\mathrm{acc}} \coloneqq U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$



The Flavour Puzzle(s)

Puzzle 1: SM fermions in 5 (6) ad hoc representations of SM gauge group.

Puzzle 2: This structure is repeated **three times**. Why?

Puzzle 3: SM without Yukawa couplings has a big global symmetry

$$G = U(3)^5$$

Yukawa couplings to the Higgs (**Y**) break this symmetry:

$$U(3)^5 \rightarrow \mathcal{G}_{\text{acc}} \coloneqq U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

These are **very good symmetries** of Nature, probing scales $\Lambda_{\text{acc}} \gg \text{TeV}$

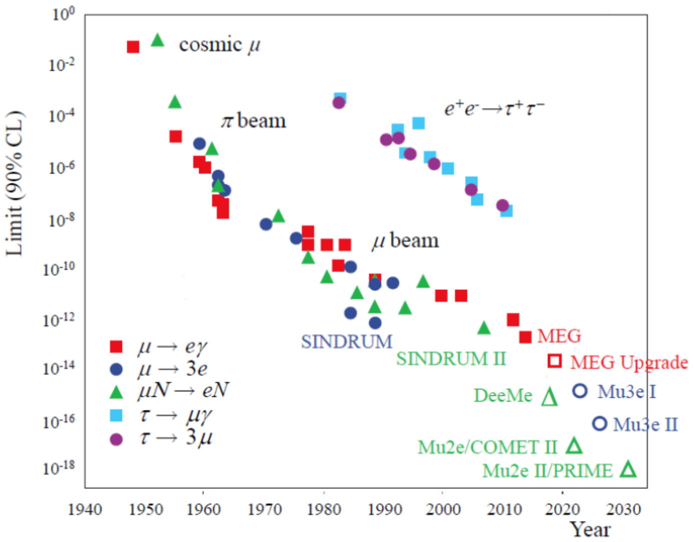
Example: proton half-life

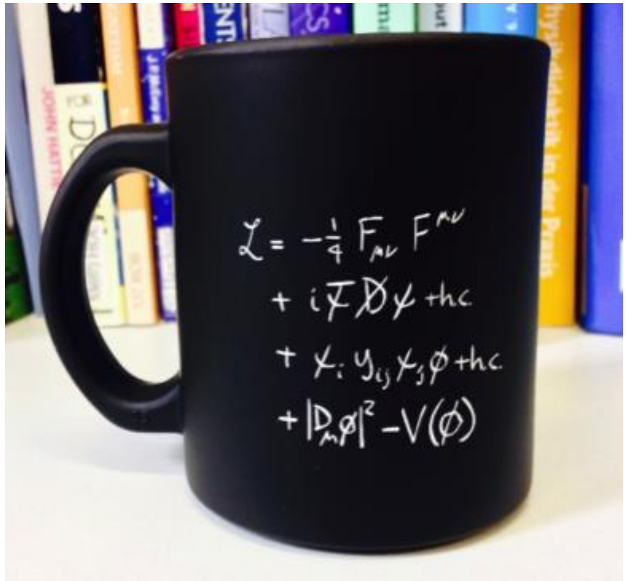
$\tau(p \rightarrow \pi^0 e^+) \gtrsim 10^{34}$ yr,

$\tau(p \rightarrow \bar{\nu} K^+) \gtrsim 10^{34}$ yr

If due to dim-6 SMEFT, $\Lambda \gtrsim 10^{13}$ TeV.

Strongest bound we have on NP!





From F. Cei @ KAON2019

The Flavour Puzzle(s)

Puzzle 1: SM fermions in 5 (6) ad hoc representations of SM gauge group.

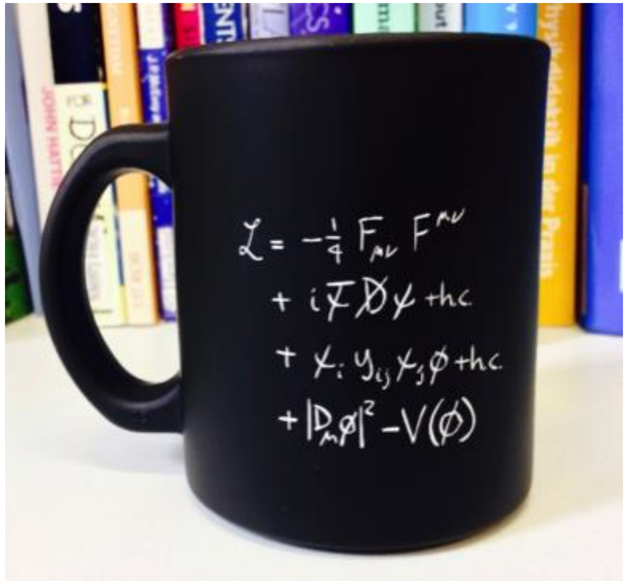
Puzzle 2: This structure is repeated **three times**. Why?

Puzzle 3: SM without Yukawa couplings has a big global symmetry

$G = U(3)^5$

Yukawa couplings to the Higgs (**Y**) break this symmetry:

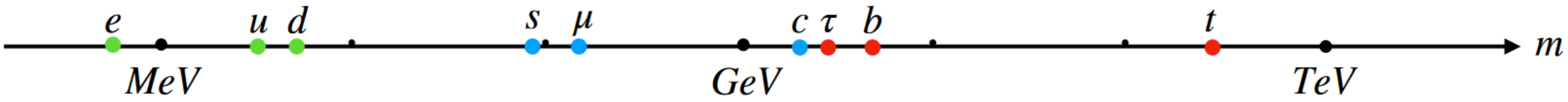
$U(3)^5 \rightarrow G_{\text{acc}} \coloneqq U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$



The breaking by **Y** to G_{acc} is not "random", but very structured:

Mass hierarchies: $m_3 \gg m_2 \gg m_1$

Small mixing angles: $V_{us} \sim \lambda \sim 0.2, \quad V_{cb} \sim \lambda^2, \quad V_{ub} \sim \lambda^3$



*This structure is highly suggestive of a **dynamical BSM theory of flavour**!*

The Flavour Puzzle(s)

Puzzle 1: SM fermions in 5 (6) ad hoc representations of SM gauge group.

Puzzle 2: This structure is repeated **three times**. Why?

Puzzle 3: Mass hierarchies: $m_3 \gg m_2 \gg m_1$

Small mixing angles: $V_{us} \sim \lambda \sim 0.2, \quad V_{cb} \sim \lambda^2, \quad V_{ub} \sim \lambda^3$

Puzzle 4: EW hierarchy problem traditionally suggests New Physics around 100 GeV – 1 TeV.

The Flavour Puzzle(s)

Puzzle 1: SM fermions in 5 (6) ad hoc representations of SM gauge group.

Puzzle 2: This structure is repeated **three times**. Why?

Puzzle 3: Mass hierarchies: $m_3 \gg m_2 \gg m_1$

Small mixing angles: $V_{us} \sim \lambda \sim 0.2, \quad V_{cb} \sim \lambda^2, \quad V_{ub} \sim \lambda^3$

Puzzle 4: EW hierarchy problem traditionally suggests New Physics around 100 GeV – 1 TeV. Some expected fireworks at the LHC!

The Flavour Puzzle(s)

Puzzle 1: SM fermions in 5 (6) ad hoc representations of SM gauge group.

Puzzle 2: This structure is repeated **three times**. Why?

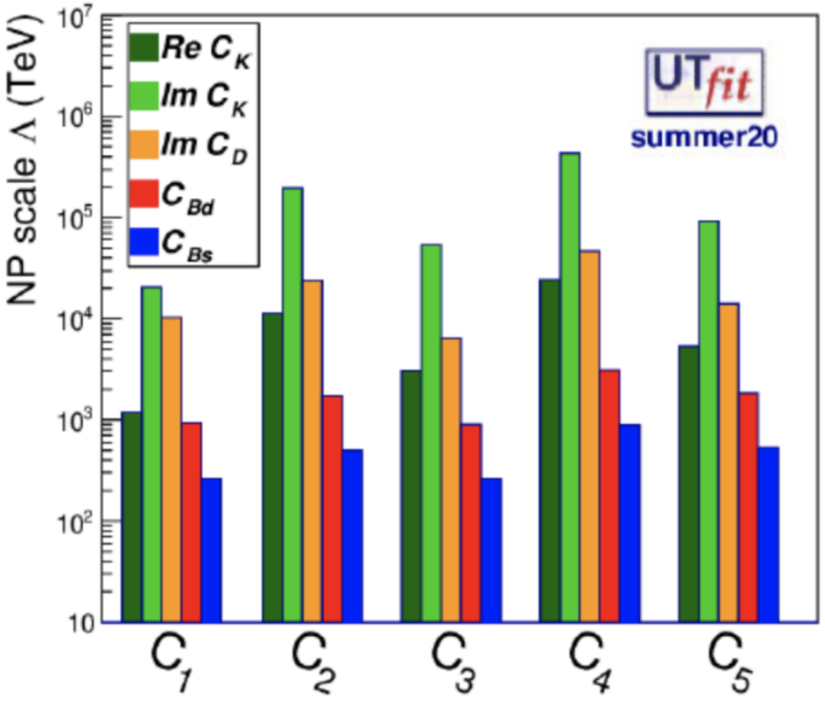
Puzzle 3: Mass hierarchies: $m_3 \gg m_2 \gg m_1$

Small mixing angles: $V_{us} \sim \lambda \sim 0.2, \quad V_{cb} \sim \lambda^2, \quad V_{ub} \sim \lambda^3$

Puzzle 4: EW hierarchy problem traditionally suggests New Physics around 100 GeV – 1 TeV. Some expected fireworks at the LHC!

BUT: indirect limits from flavour physics sets New Physics scale **much higher**; $\mathcal{O}(10^{4-5})$ TeV for flavour changing processes in **1-2 sector**, even higher for **Lepton Flavour Violation** (LFV)

Neutral meson mixing constraints



Barbieri, 2103.15635

The Flavour Puzzle(s)

Puzzle 1: SM fermions in 5 (6) ad hoc representations of SM gauge group.

Puzzle 2: This structure is repeated **three times**. Why?

Puzzle 3: Mass hierarchies: $m_3 \gg m_2 \gg m_1$

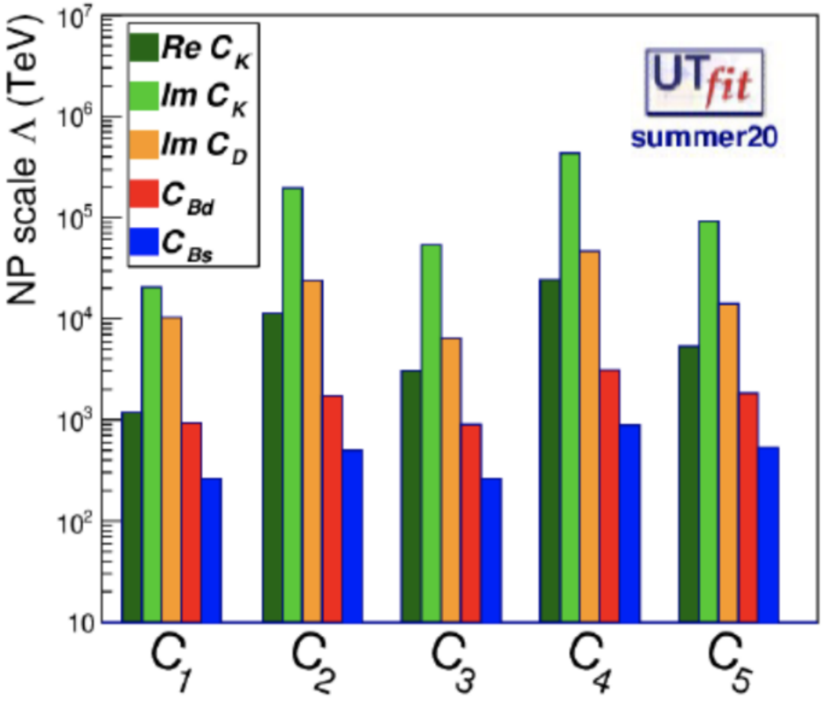
Small mixing angles: $V_{us} \sim \lambda \sim 0.2, \quad V_{cb} \sim \lambda^2, \quad V_{ub} \sim \lambda^3$

Puzzle 4: EW hierarchy problem traditionally suggests New Physics around 100 GeV – 1 TeV. Some expected fireworks at the LHC!

BUT: indirect limits from flavour physics sets New Physics scale **much higher**; $\mathcal{O}(10^{4-5})$ TeV for flavour changing processes in **1-2 sector**, even higher for **Lepton Flavour Violation** (LFV)

... So, should we really have expected fireworks at the LHC? Certainly, they could not have had "generic" flavour structure. Either way, no fireworks yet...

Neutral meson mixing constraints



Barbieri, 2103.15635

Flavour model building

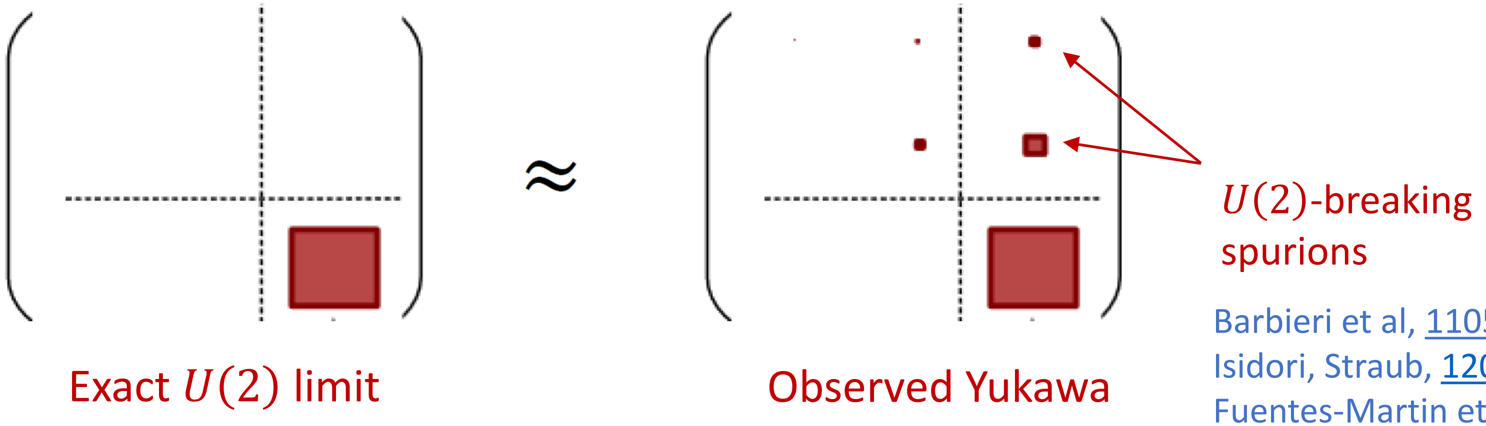
(in the LHC era)

Global symmetries: a big clue for model building

Puzzle 3

Mass hierarchies:	$m_3 \gg m_2 \gg m_1$
Small mixing angles:	$V_{us} \sim \lambda \sim 0.2, \quad V_{cb} \sim \lambda^2, \quad V_{ub} \sim \lambda^3$

Yukawa matrices have approximate global symmetries: $G_{\text{approx}} = U(2)^5$ acting on light families



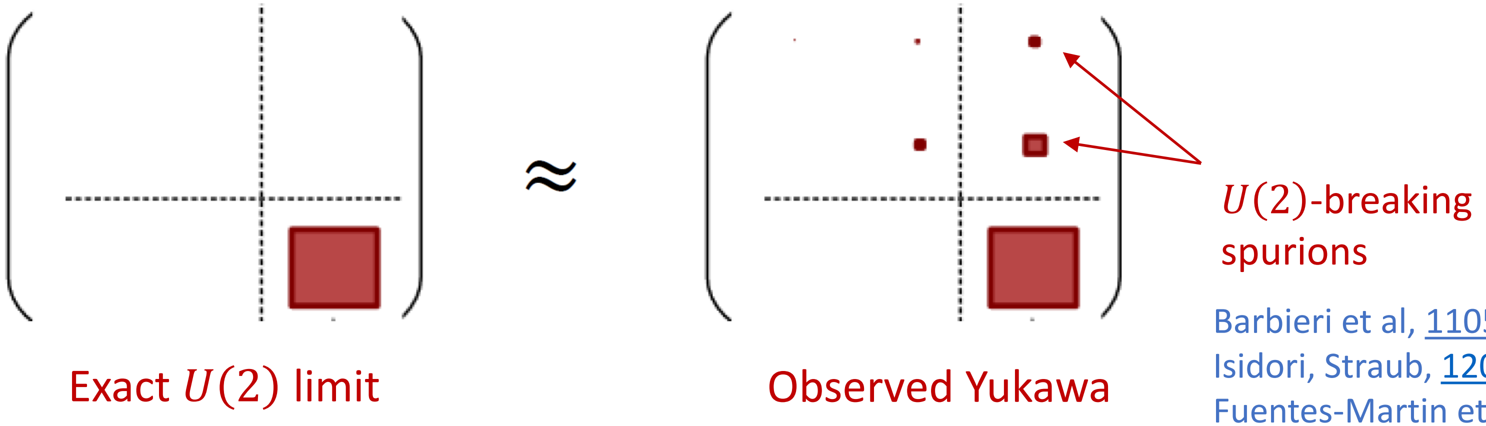
Barbieri et al, 1105.2296
Isidori, Straub, 1202.0464
Fuentes-Martin et al, 1909.02519

Global symmetries: a big clue for model building

Puzzle 3

Mass hierarchies:	$m_3 \gg m_2 \gg m_1$
Small mixing angles:	$V_{us} \sim \lambda \sim 0.2, \quad V_{cb} \sim \lambda^2, \quad V_{ub} \sim \lambda^3$

Yukawa matrices have approximate global symmetries: $G_{\text{approx}} = U(2)^5$ acting on light families



Barbieri et al, 1105.2296
Isidori, Straub, 1202.0464
Fuentes-Martin et al, 1909.02519

An excellent starting point is for the new physics sector (i.e. new gauge symmetries) to **only** allow renormalizable Yukawa couplings for the **third family**. Other Yukawas from higher-dimension operators:

$$\mathcal{L} \supset \bar{\psi}_3 H \psi_3 + \left(\frac{w}{\Lambda}\right)^{n_{ij}} \bar{\psi}_i H \psi_j$$

w = vev of some BSM scalar
Λ = some heavier NP scale
n_{ij} = an integer

Global symmetries: a big clue for model building

Puzzle 3

Mass hierarchies:	$m_3 \gg m_2 \gg m_1$
Small mixing angles:	$V_{us} \sim \lambda \sim 0.2, \quad V_{cb} \sim \lambda^2, \quad V_{ub} \sim \lambda^3$

An excellent starting point is for the new physics sector (i.e. new gauge symmetries) to only allow renormalizable Yukawa couplings for the third family. Other Yukawas from higher-dimension operators:

$$\mathcal{L} \supset \bar{\psi}_3 H \psi_3 + \left(\frac{W}{\Lambda}\right)^{n_{ij}} \bar{\psi}_i H \psi_j$$

→The NP is **flavour non-universal**, typically coupled predominantly to **3rd family**! The same $U(2)$ flavour symmetries protect large effects in e.g. 1-2 flavour transitions (kaon mixing)

Global symmetries: a big clue for model building

Puzzle 3

Mass hierarchies:	$m_3 \gg m_2 \gg m_1$
Small mixing angles:	$V_{us} \sim \lambda \sim 0.2, \quad V_{cb} \sim \lambda^2, \quad V_{ub} \sim \lambda^3$

An excellent starting point is for the new physics sector (i.e. new gauge symmetries) to only allow renormalizable Yukawa couplings for the third family. Other Yukawas from higher-dimension operators:

$$\mathcal{L} \supset \bar{\psi}_3 H \psi_3 + \left(\frac{w}{\Lambda}\right)^{n_{ij}} \bar{\psi}_i H \psi_j$$

→The NP is **flavour non-universal**, typically coupled predominantly to **3rd family**! The same $U(2)$ flavour symmetries protect large effects in e.g. 1-2 flavour transitions (kaon mixing)

→Naturally reconciles puzzle 3 **with puzzle 4** – new physics could still stabilize (or at least not destabilize) the Higgs sector (TeV scale) while being consistent with flavour bounds, and be **hard to discover directly** at ATLAS & CMS due to PDF suppression in pp collisions

Global symmetries: a big clue for model building

Puzzle 3

Mass hierarchies:	$m_3 \gg m_2 \gg m_1$
Small mixing angles:	$V_{us} \sim \lambda \sim 0.2, \quad V_{cb} \sim \lambda^2, \quad V_{ub} \sim \lambda^3$

An excellent starting point is for the new physics sector (i.e. new gauge symmetries) to only allow renormalizable Yukawa couplings for the third family. Other Yukawas from higher-dimension operators:

$$\mathcal{L} \supset \bar{\psi}_3 H \psi_3 + \left(\frac{w}{\Lambda}\right)^{n_{ij}} \bar{\psi}_i H \psi_j$$

→The NP is **flavour non-universal**, typically coupled predominantly to **3rd family**! The same $U(2)$ flavour symmetries protect large effects in e.g. 1-2 flavour transitions (kaon mixing)

→Naturally reconciles puzzle 3 **with puzzle 4** – new physics could still stabilize (or at least not destabilize) the Higgs sector (TeV scale) while being consistent with flavour bounds, and be **hard to discover directly** at ATLAS & CMS due to PDF suppression in pp collisions

→Perhaps as likely to see **indirect evidence of NP** in rare heavy flavoured decays e.g. at LHCb, Belle II

Anchoring the low scale

By and large, any theory of flavour takes the form:

$$\mathcal{L} \supset \bar{\psi}_3 H \psi_3 + \left(\frac{w}{\Lambda}\right)^{n_{ij}} \bar{\psi}_i H \psi_j$$

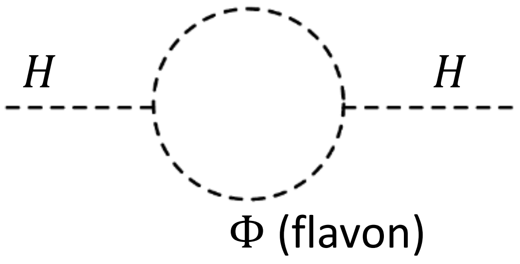
w = vev of some BSM scalar
Λ = some heavier NP scale
n_{ij} = an integer

All the observed hierarchies depend only on *ratios of scales*. E.g. $\frac{m_2}{m_3} \sim \left(\frac{w}{\Lambda}\right)^{n_{22}}$

Unfortunately, this means the scales of NP responsible for flavour *could* be very far off…
(the old rationale for postponing the flavour puzzle)

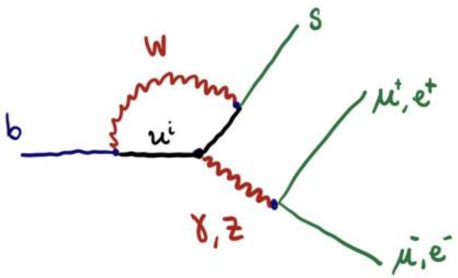
BUT, there are two good reasons for **anchoring** the low scale w not too far above TeV

1. Naturalness – a big scale separation would destabilize the Higgs
2. There are already **hints** of new flavoured physics at TeV scale, in **rare B decays**



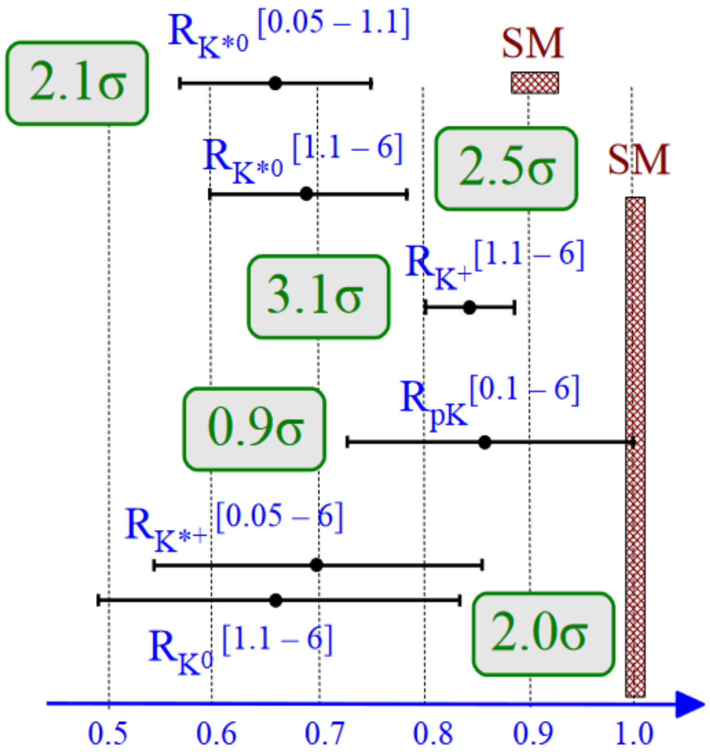
Interlude: a quick review of the flavour anomalies…

Neutral current $b \to sll$



LFUV ratios (clean) @ LHCb

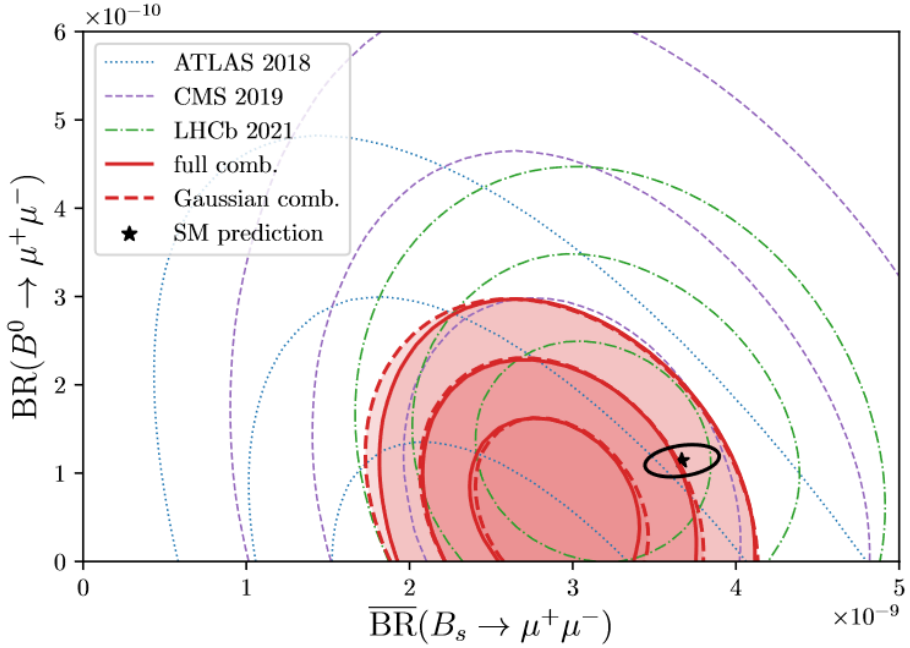
$$R_H = \frac{\text{BR}(B \to H\mu\mu)}{\text{BR}(B \to Hee)}$$



Summary from G. Isidori @ Planck 22

$\text{BR}(B_s \to \mu\mu)$ (clean)

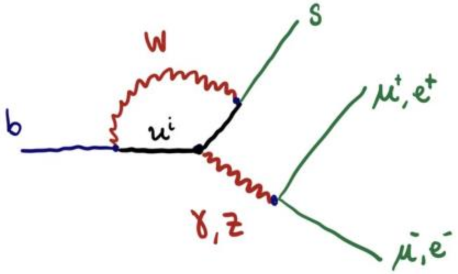
In 2021



Pull = $2.3\ \sigma$

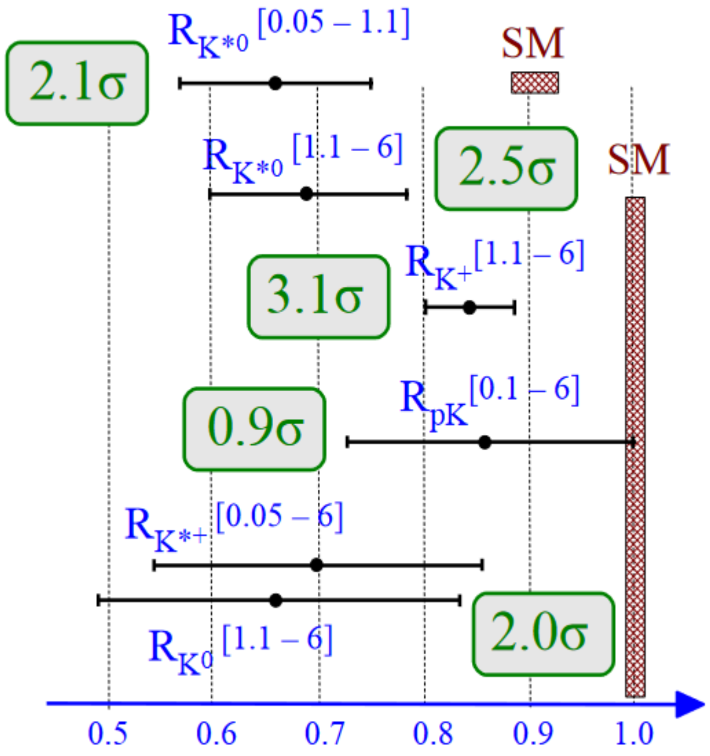
Altmannshofer, Stangl 2103.13370

Neutral current $b \to sll$



LFUV ratios (clean) @ LHCb

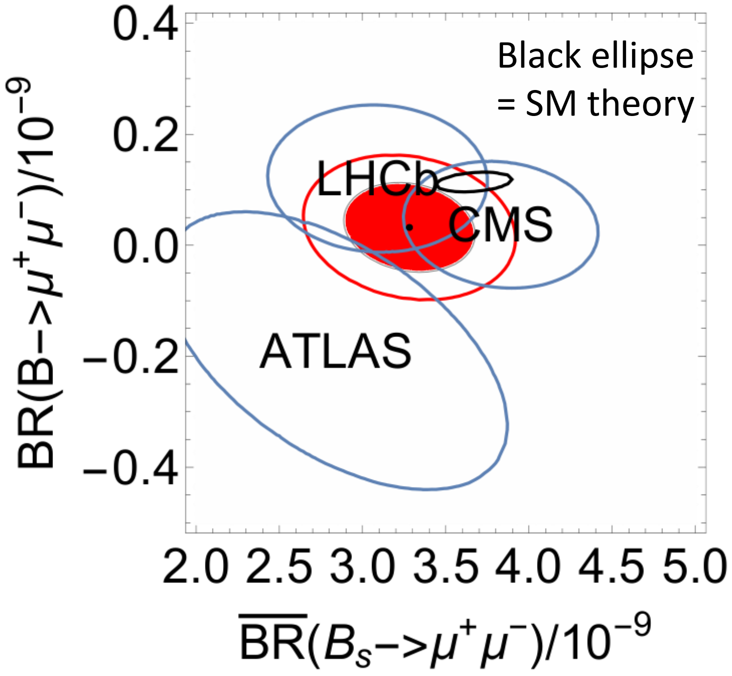
$$R_H = \frac{\mathrm{BR}(B \to H\mu\mu)}{\mathrm{BR}(B \to Hee)}$$



Summary from G. Isidori @ Planck 22

$\mathrm{BR}(B_s \to \mu\mu)$ (clean)

In 2022



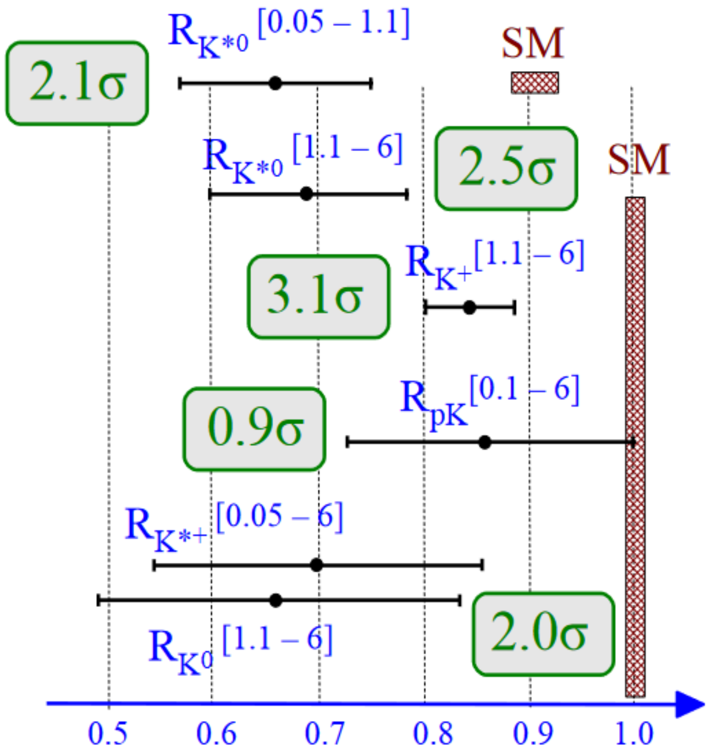
Pull = 1.6 σ (agrees with SM now)

Allanach, Davighi (in progress)

Neutral current $b \to sll$

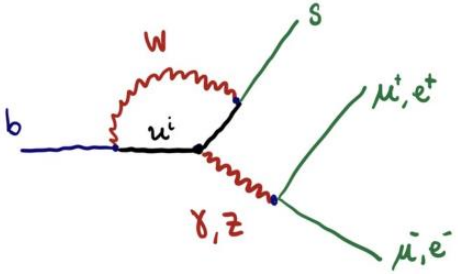
LFUV ratios (clean) @ LHCb

$$R_H = \frac{\mathrm{BR}(B \to H\mu\mu)}{\mathrm{BR}(B \to Hee)}$$



Summary from G. Isidori @ Planck 22

Also tensions in muon-only observables where hadronic uncertainties in TH predictions could be unexpectedly big. E.g. angular analyses for



1. $B \to K^* \mu\mu$
2. $B_s \to \varphi\mu\mu$

A more or less **coherent** set of deviations in $bsll$ that can be explained by NP contribution to e.g.

$$(\overline{s_L}\gamma_\rho b_L)(\overline{\mu_L}\gamma^\rho \mu_L)$$

Conservative estimate in 2021: global significance $\sim \mathbf{4.3}\ \boldsymbol{\sigma}$
Expect similar conclusion despite $\mathrm{BR}(B_s \to \mu\mu)$ update

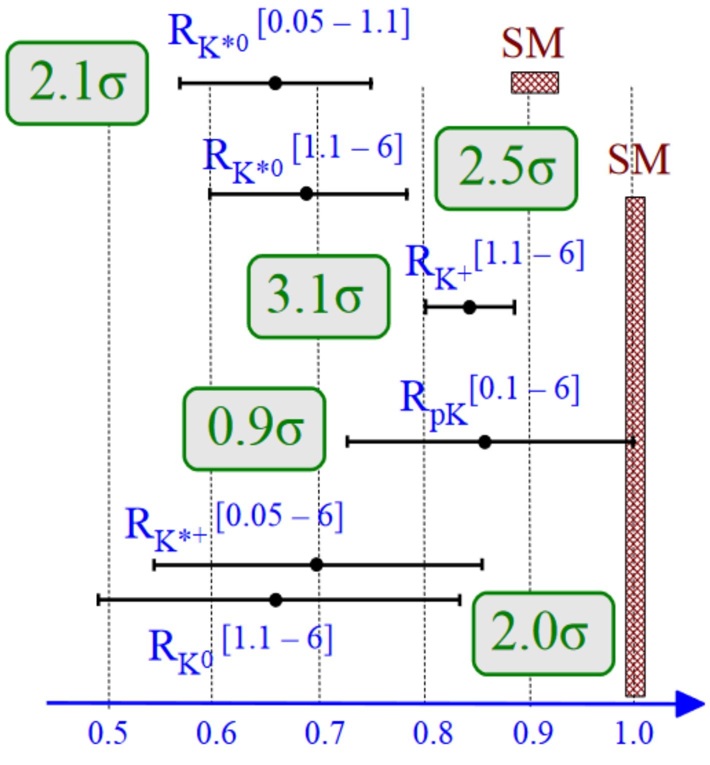
Isidori, Lancierini, Owen, Serra, 2104.05631

25

Neutral current $b \to sll$

LFUV ratios (clean) @ LHCb

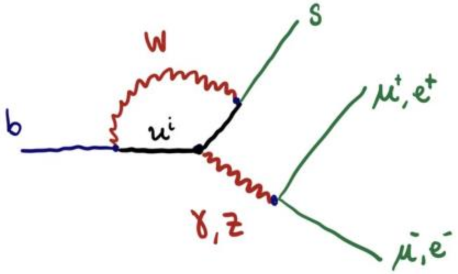
$$R_H = \frac{\mathrm{BR}(B \to H\mu\mu)}{\mathrm{BR}(B \to Hee)}$$



Summary from G. Isidori @ Planck 22

Also tensions in muon-only observables where hadronic uncertainties in TH predictions could be unexpectedly big. E.g. angular analyses for

1. $B \to K^* \mu\mu$
2. $B_s \to \varphi\mu\mu$



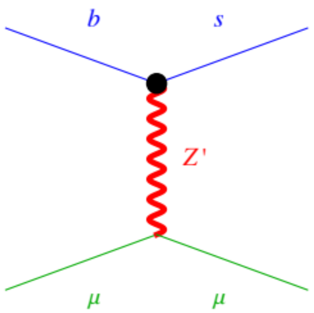
A more or less **coherent** set of deviations in $bsll$ that can be explained by NP contribution to e.g.

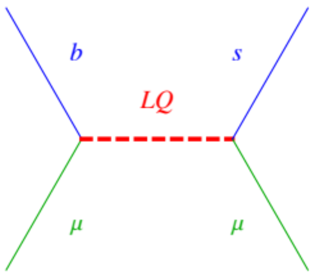
$$(\overline{s_L}\gamma_\rho b_L)(\overline{\mu_L}\gamma^\rho \mu_L)$$

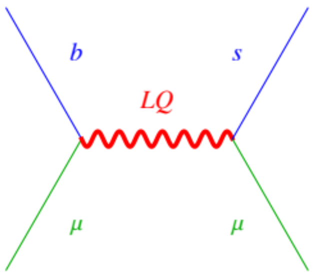
Conservative estimate in 2021: global significance $\sim \mathbf{4.3\ \sigma}$
Expect similar conclusion despite $\mathrm{BR}(B_s \to \mu\mu)$ update

Isidori, Lancierini, Owen, Serra, 2104.05631

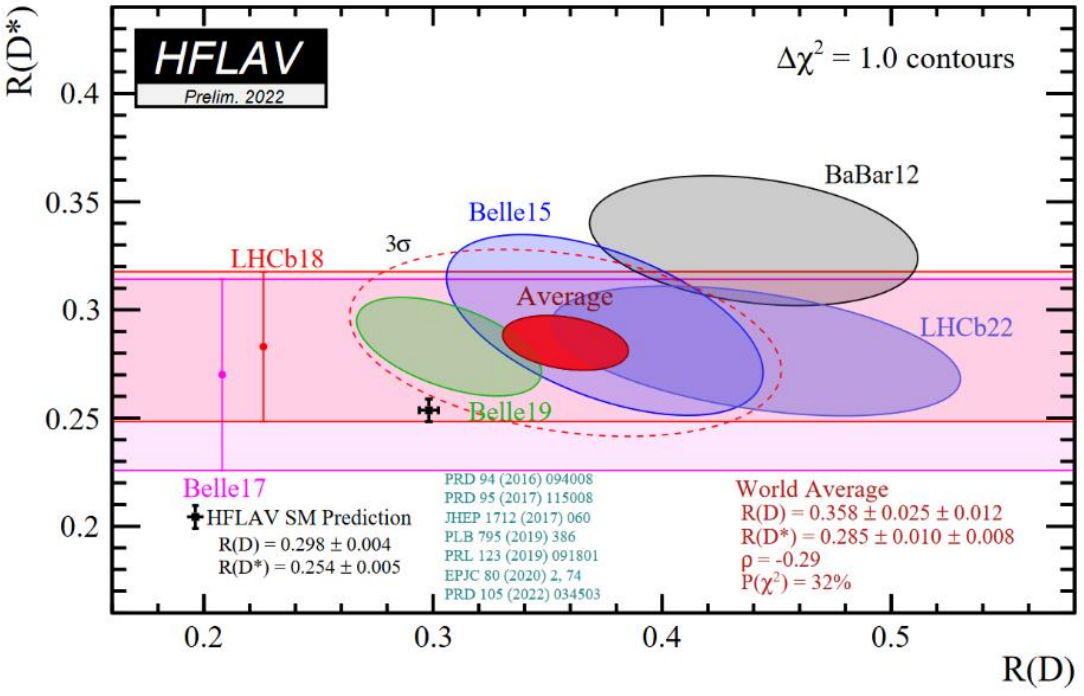
New particle explanations. Mass/g ~ 3 TeV/0.1 (weak effect)

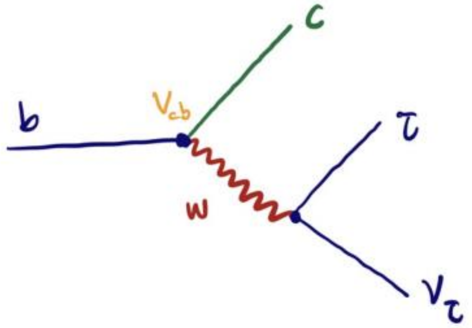






Charged current $b \to cl\nu$





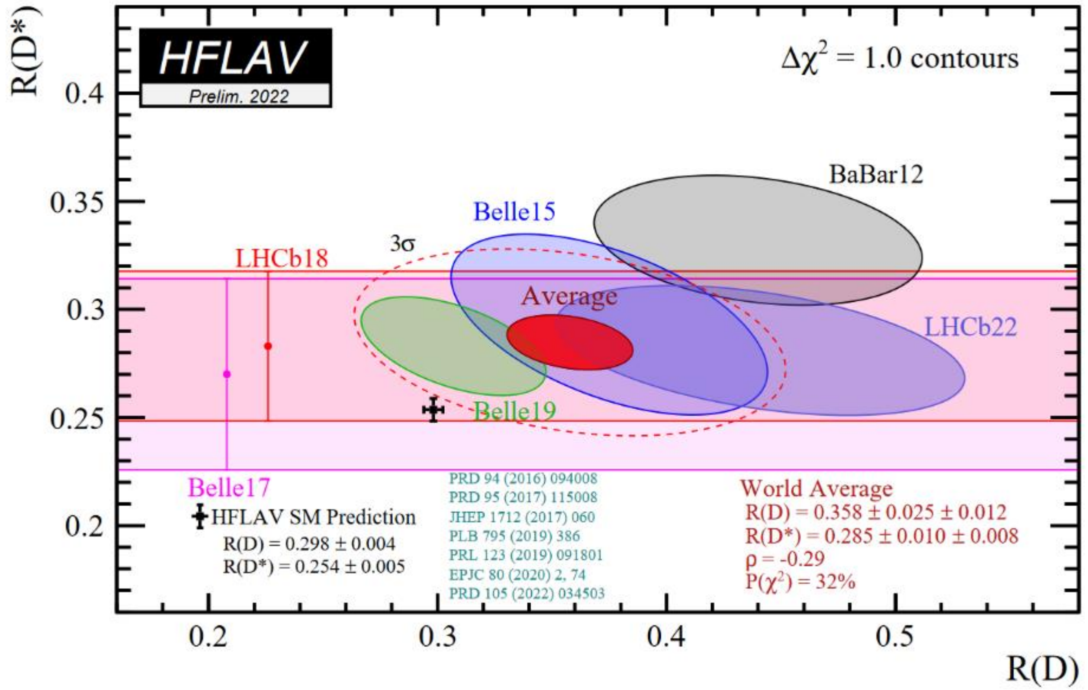
Here, LFUV ratios are

$$R_H = \frac{\mathrm{BR}(B \to H\tau\nu)}{\mathrm{BR}(B \to H\mu\nu)}$$

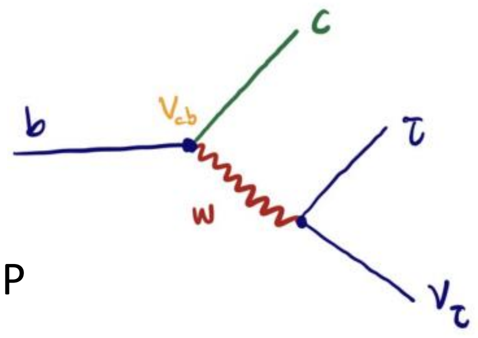
2022 update from LHCb:
First measurement of R_D at a collider!

- Measurements continue to show good agreement
- Significance remains just above 3σ after LHCb 2022

Charged current $b \to cl\nu$

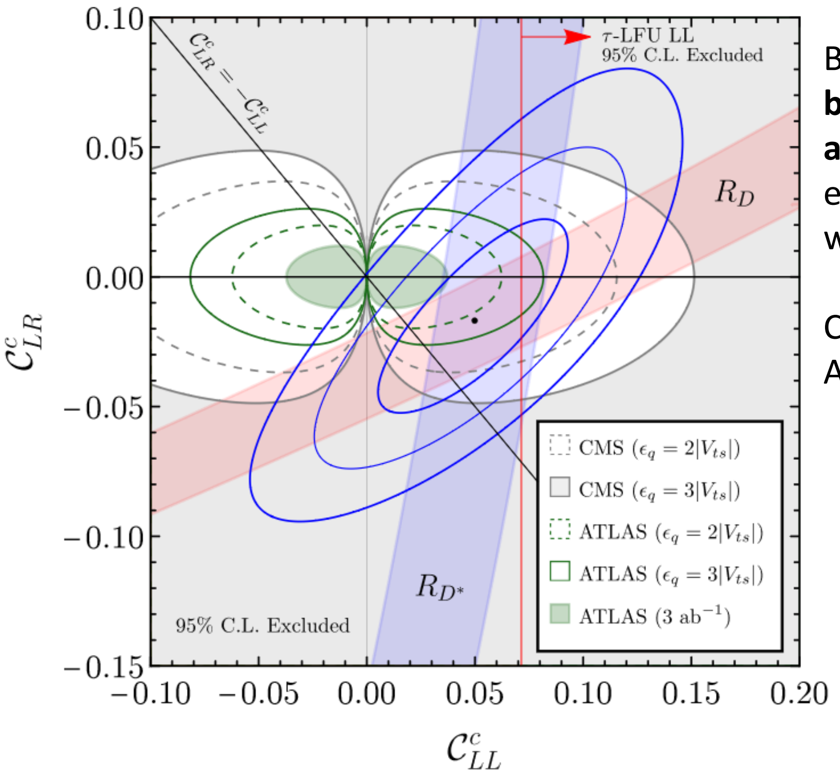


- Measurements continue to show good agreement
- Significance remains just above 3σ after LHCb 2022



New physics explanations:

- SM process here is tree-level, so the NP effect is BIG! Mass/g ~ 3 TeV/1
- The W'/charged Higgs explanations ruled out by LHC high p_T & B_c lifetime
- **Leptoquark** is best explanation



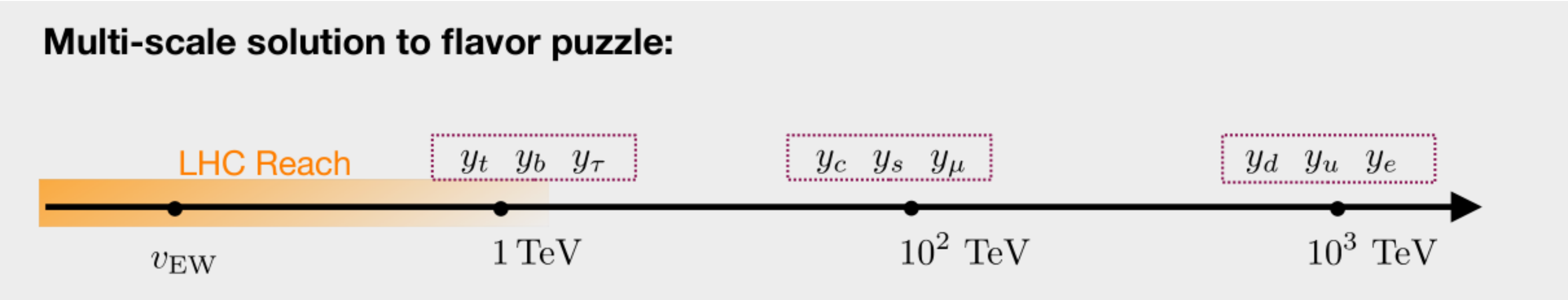
Best-fit region is **already being squeezed by ATLAS and CMS**. Here are 95% exclusion from $pp \to \tau\tau$ with b-tag

CMS: 2208.02717
ATLAS: 2002.12223

These anomalies are, for now, only hints of BSM.

But if they are real, they are the kind of thing we would expect at the LHC, if taking flavour puzzle seriously. Moreover, the anomalies **anchor the lowest scale** in a BSM theory of flavour ~TeV:

Gripaios, 0910.1789



From D. Faroughy

This is one reason why the B anomalies are so interesting to theorists – they could be a **window onto the flavour puzzle**

With this in mind, let's return to model building for the flavour puzzle.

Three routes for solving the flavour puzzle

1. Horizontal flavour symmetries

2. Deconstructed gauge symmetries

3. Unified (gauge & flavour) symmetries

1: Horizontal flavour symmetries

A horizontal symmetry *commutes with the SM gauge symmetry*

Froggatt, Nielsen, 1979
+many more
Grinstein et al, 1009.2049

$$G = G_{\mathrm{SM}} \times G_F$$

Flavour symmetry G_F can be continuous or discrete, abelian or non-abelian.

Gauging G_F enforces selection rules on Yukawa couplings e.g. only allowing Y_{33}.

1: Horizontal flavour symmetries

A horizontal symmetry *commutes with the SM gauge symmetry*

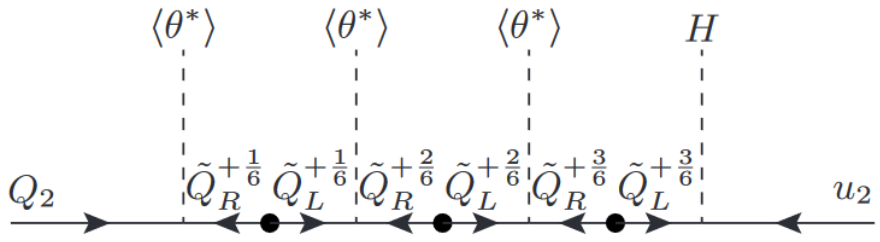
Froggatt, Nielsen, [1979]
+many more
Grinstein et al, [1009.2049]

$$G = G_{\mathrm{SM}} \times G_F$$

Flavour symmetry G_F can be continuous or discrete, abelian or non-abelian.

Gauging G_F enforces selection rules on Yukawa couplings e.g. only allowing Y_{33}.

Example: **Froggatt—Nielsen mechanism**, where $G_F = U(1)_F$ with appropriate non-universal charges



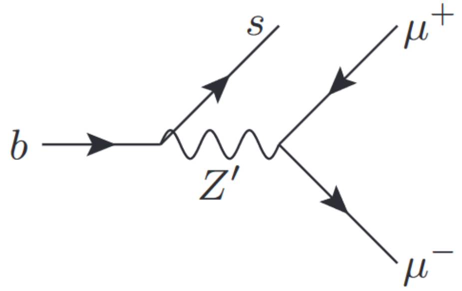
Allanach, Davighi, [1905.10327]

Here, the **hierarchies** come from **operator dimensions** in the low energy EFT

The heavy gauge bosons from breaking G_F will all be SM singlets $\longrightarrow$ heavy Z's

1: Horizontal flavour symmetries

$$G = G_{\mathrm{SM}} \times G_F$$

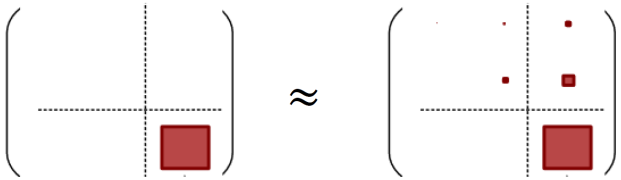


Example 2: Simple Z' models connecting flavour puzzle with the $b \to sll$ anomalies

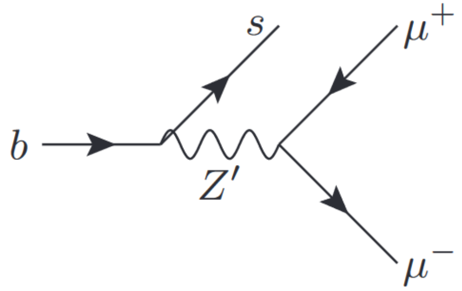
- Gauge $G_F = U(1)_X;\ X = Y_3$. Breaking $U(1)_X \to$ the Z'

Allanach, Davighi, 1809.01158; 2103.12056; 2205.12252

Only Y_{33} renormalizable:



1: Horizontal flavour symmetries



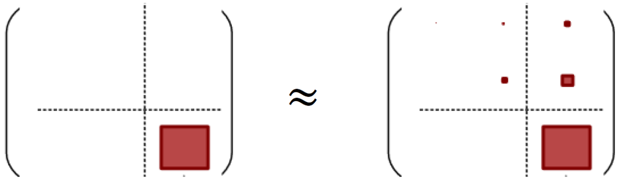
$$G = G_{\mathrm{SM}} \times G_F$$

Example 2: Simple Z' models connecting flavour puzzle with the $b \to sll$ anomalies

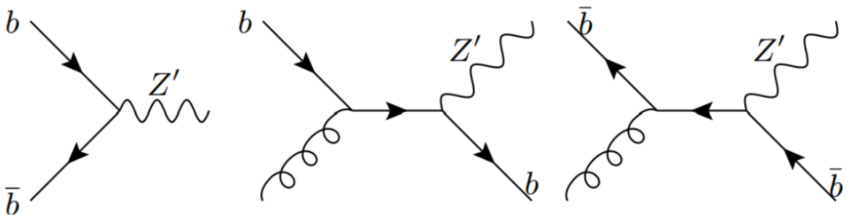
- Gauge $G_F = U(1)_X$; $X = Y_3$. Breaking $U(1)_X \to$ the Z'

Allanach, Davighi, 1809.01158; 2103.12056; 2205.12252

Only Y_{33} renormalizable:



LHC Z' production:

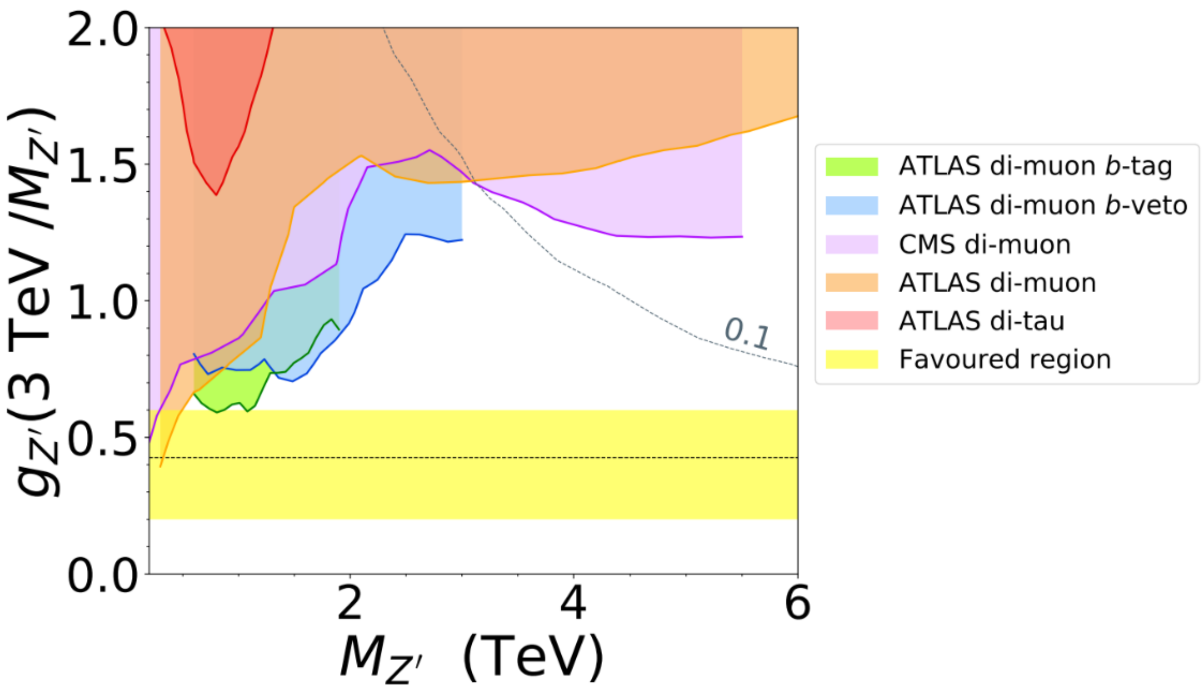


Z' decay modes:

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 $f_i f_j$	$\sim \mathcal{O}(10^{-4})$

*Mostly heavy flavours!

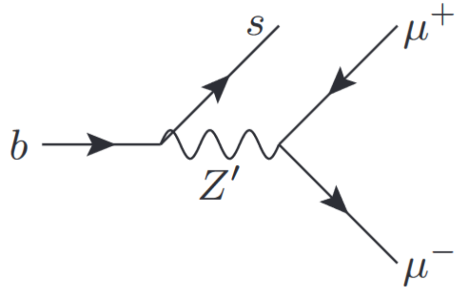
LHC Z' searches:



Allanach, Banks, 2111.06691

1: Horizontal flavour symmetries

$$G = G_{\rm SM} \times G_F$$



Example 3: Simple Z' models connecting flavour puzzle with the $b \to sll$ anomalies + absence of LFV!

- Gauge $G_F = U(1)_X$; $X = Y_3 + a(L_2 - L_3)$. Breaking $U(1)_X \to$ the Z'

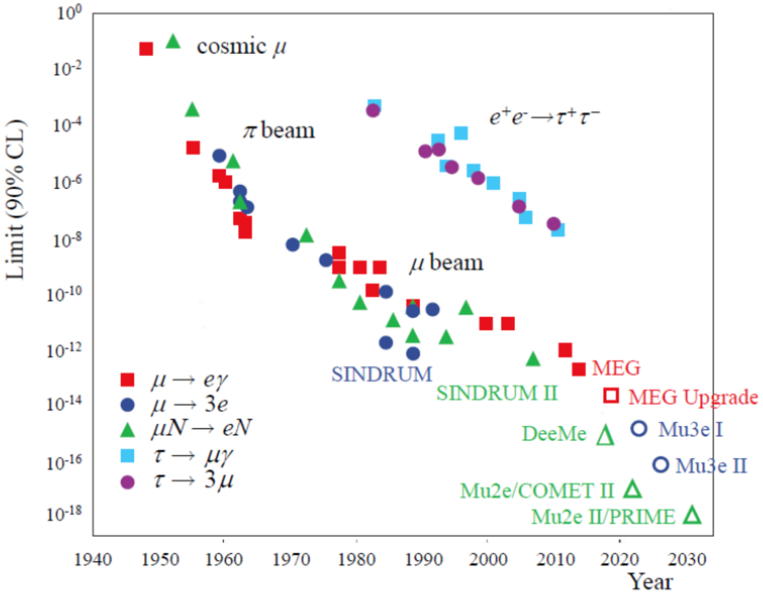
Davighi, 2105.06918

$$Y_u = y_t \begin{pmatrix} \frac{\Delta_u^{ab}\Phi}{\Lambda^2} & \frac{V_q^a}{\Lambda} \\ 0 & 1 \end{pmatrix} \qquad Y_e = \begin{pmatrix} c_e \frac{\epsilon_\Phi^3}{\Lambda^3} & 0 & 0 \\ 0 & c_\mu \frac{\epsilon_\Phi^3}{\Lambda^3} & 0 \\ 0 & 0 & y_\tau \end{pmatrix}$$

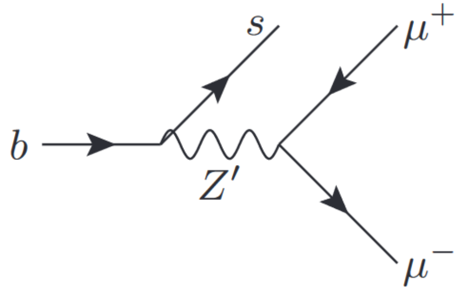
$$Y_d = y_b \begin{pmatrix} \frac{\Delta_d^{ab}\Phi}{\Lambda^2} & \frac{V_q^a}{\Lambda} \\ 0 & 1 \end{pmatrix}$$

Quark masses + $b \to sll$

$\Lambda \sim 100$ TeV



1: Horizontal flavour symmetries



$$G = G_{\mathrm{SM}} \times G_F$$

Example 3: Simple Z' models connecting flavour puzzle with the $b \to sll$ anomalies + absence of LFV!

- Gauge $G_F = U(1)_X;\ X = Y_3 + a(L_2 - L_3)$. Breaking $U(1)_X \to$ the Z'

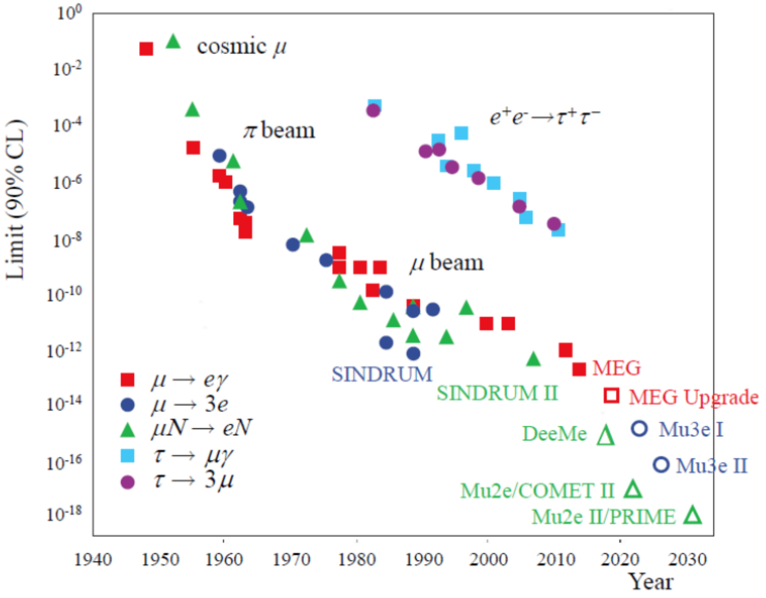
Davighi, 2105.06918

$$Y_u = y_t \begin{pmatrix} \frac{\Delta_u^{ab}\Phi}{\Lambda^2} & \frac{V_q^a}{\Lambda} \\ 0 & 1 \end{pmatrix} \qquad Y_e = \begin{pmatrix} c_e \frac{\epsilon_\Phi^3}{\Lambda^3} & 0 & 0 \\ 0 & c_\mu \frac{\epsilon_\Phi^3}{\Lambda^3} & 0 \\ 0 & 0 & y_\tau \end{pmatrix}$$

$$Y_d = y_b \begin{pmatrix} \frac{\Delta_d^{ab}\Phi}{\Lambda^2} & \frac{V_q^a}{\Lambda} \\ 0 & 1 \end{pmatrix}$$

Quark masses + $b \to sll$

$\Lambda \sim 100$ TeV



By gauging a combination of lepton numbers, we have **excellent protection against LFV**, despite LFUV!

$\mu \to e\gamma$, due to dim >12 operators. Need

$$\frac{\Lambda}{\sqrt{\tilde{c}}}\epsilon_\Phi^{-\frac{a-3}{2}} \gtrsim 58\,000 \text{ TeV}$$ (Satisfied for order-1 WCs)

$l_j \to 3l_i$, due to dim >15 operators.

$$\Delta BR(\mu \to 3e) \sim \frac{m_\mu^5}{768\pi^3\Gamma_\mu}\frac{1}{\Lambda^4}\epsilon^{2a} \lesssim 10^{-29}$$

etc

tiny!!

Dvali, Shiffman, hep-ph/0001072
Panico, Pomarol, 1603.06609
Barbieri, 2103.15635

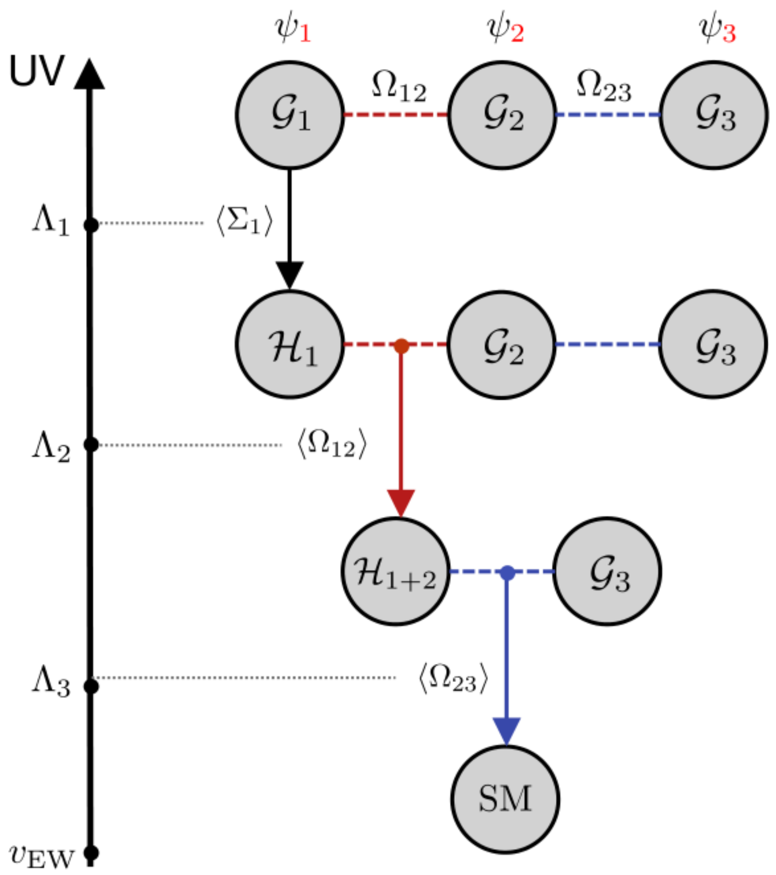
2: Deconstructed gauge symmetries

The SM gauge symmetry, which is flavour-universal, could be *deconstructed* in the UV:

$$G = G_1 \times G_2 \times G_3$$

SM Fermions:

$$\psi_1 \sim (\boldsymbol{R}, 1, 1)$$
$$\psi_2 \sim (1, \boldsymbol{R}, 1)$$
$$\psi_3 \sim (1, 1, \boldsymbol{R})$$



Multi-scale symmetry breaking pattern generates structure:

The **hierarchies** can come from different operator dimensions, and/or from **different scales associated with each family**

$$\Lambda_1 > \Lambda_2 > \Lambda_3$$

The “ladder of scales” does not destabilize Higgs mass! Allwicher, Isidori, Thomsen, 2011.01946

Dvali, Shiffman, hep-ph/0001072
Panico, Pomarol, 1603.06609
Barbieri, 2103.15635

2: Deconstructed gauge symmetries

$$G = G_1 \times G_2 \times G_3$$

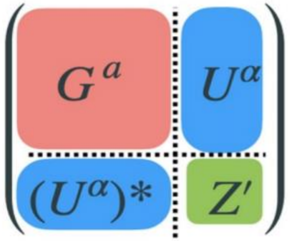
Example: `Pati—Salam cubed' model: Bordone et al. 1712.01368, 1805.09328

$$G_i = [SU(4) \times SU(2)_L \times SU(2)_R]_i$$

The Pati-Salam $SU(4)$ also **unifies quarks and leptons** (puzzle 1!)

Pati, Salam, 1974

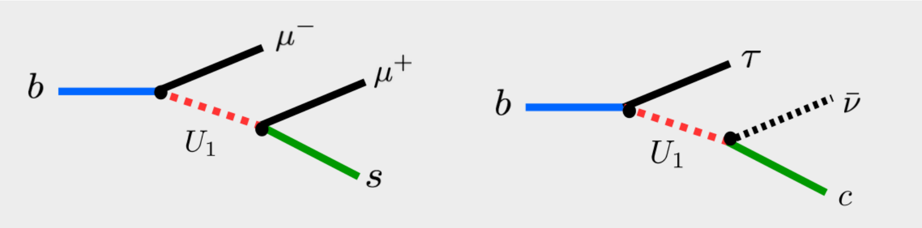
Symmetry breaking via the `4-3-2-1 model':

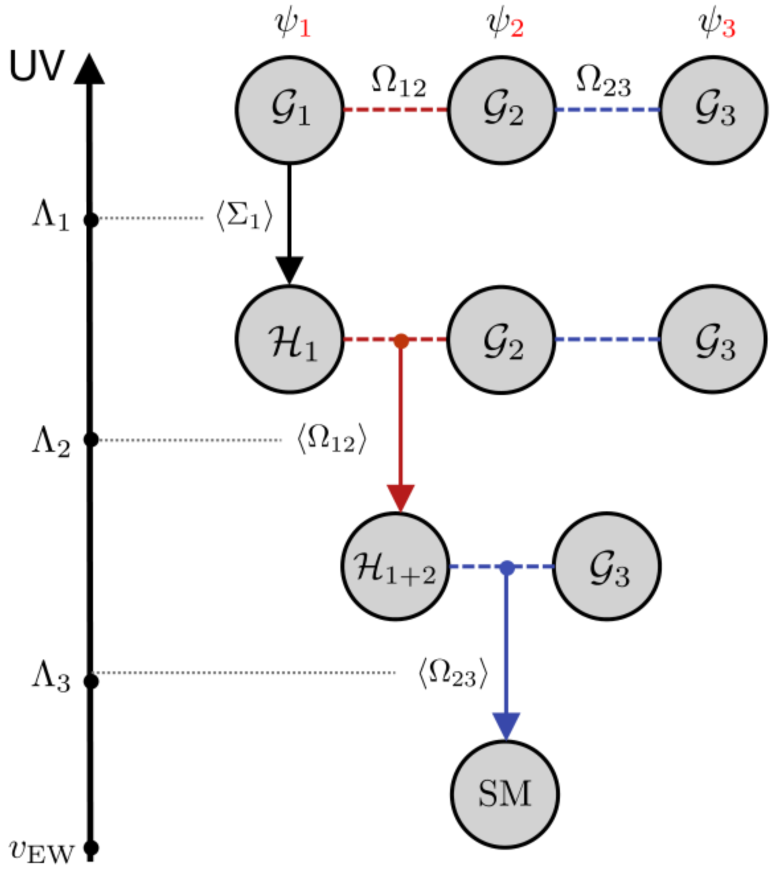


$$G \to SU(4)_3 \times SU(3)_{1+2} \times SU(2)_L \times U(1)_{Y'} \to G_{SM}$$

gives U_1 leptoquark coupled mostly to 3rd family

→ *only* single mediator for both $b \to sll$ and $b \to c\tau\nu$ anomalies!





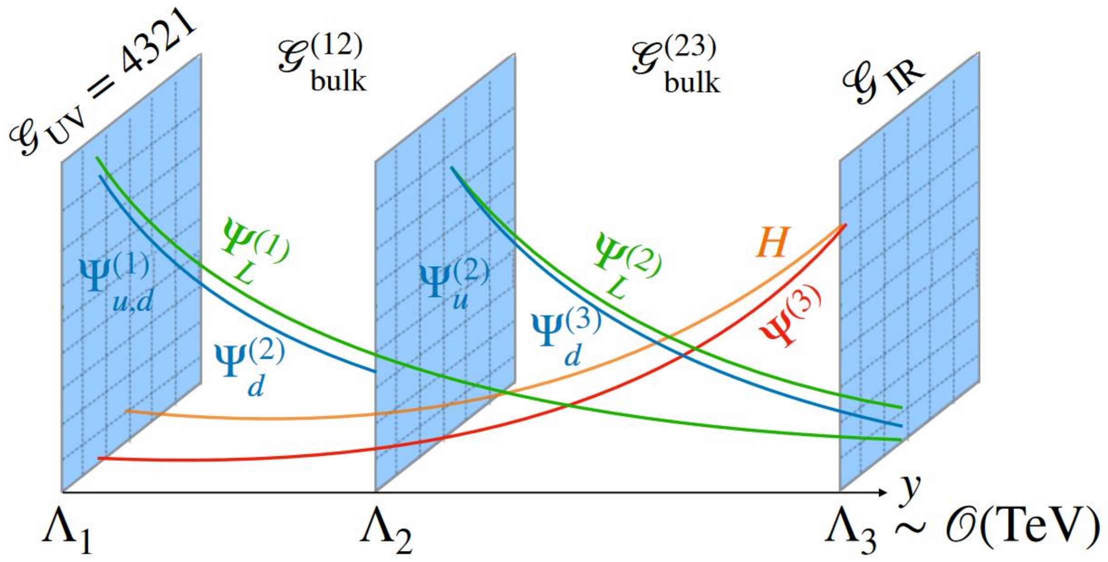
Butazzo et al, 1706.07808
Angelescu et al, 1808.08179

2: Deconstructed gauge symmetries

$$G = G_1 \times G_2 \times G_3$$

The origin of deconstruction? Flavour as a **5th dimension**, with a 4D brane for each family

Fuentes-Martín, Isidori, Lizana, Selimovic, Stefanek, 2203.01952



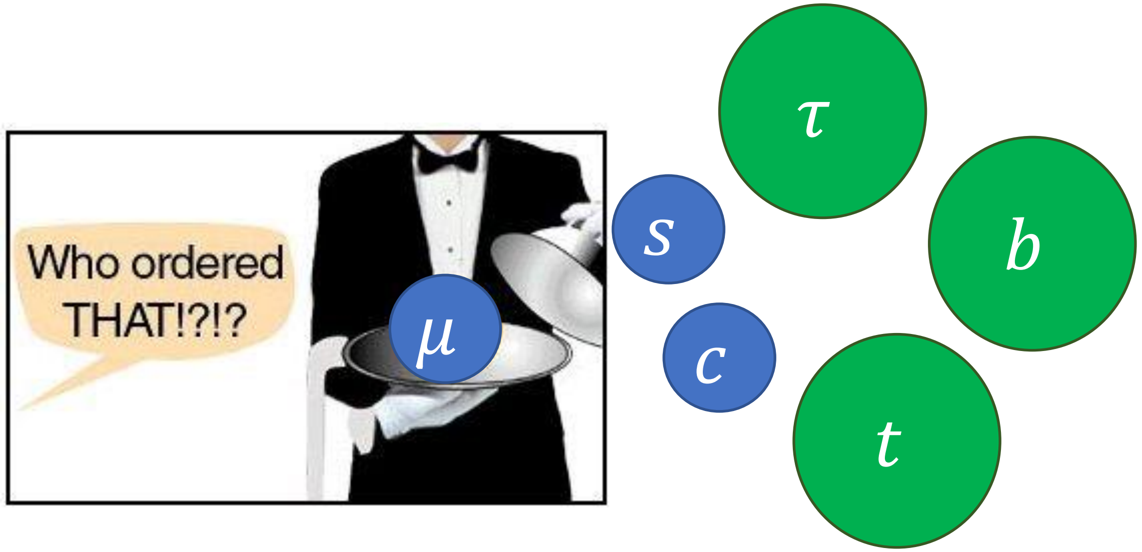
Higgs embedded as a composite pNGB!

→ Flavour puzzle & hierarchy problem solved together at TeV scale, while unifying quarks and leptons, consistent with all LHC constraints: Puzzles 1, 3 and 4 ☑

3: Unifying gauge and flavour symmetries

None of the previous approaches address Puzzle 2: why 3 families in the first place?

(In the 5d model, "why 3 families?" becomes "why 3 branes?")



3: Unifying gauge and flavour symmetries

None of the previous approaches address Puzzle 2: why 3 families in the first place?

Gauge-flavour unification

- **3 generations** of SM fermions start life as **one particle** in the UV
- This UV fermion is acted on by a **large gauge symmetry** G_{123}
- So in the UV, different generations are indistinguishable – **opposite to deconstruction** approach!
- At intermediate energies, G_{123} spontaneously broken: flavour emerges as a low-energy remnant

Electroweak Flavour Unification

Davighi, Tooby-Smith, 2201.07245
Davighi, 2206.04482

Gauge Flavour Unification

First challenge: embed the SM in an **anomaly-free gauge theory** that unifies the generations

$$G_{123} = ??$$

Gauge Flavour Unification

First challenge: embed the SM in an **anomaly-free gauge theory** that unifies the generations

A comprehensive analysis of Lie algebras reveals it is not possible to unify either $SU(5)$ or $SO(10)$ GUT with flavour.

Allanach, Gripaios, Tooby-Smith, 2104.14555

To unify gauge and flavour symmetries, we should start from **Pati-Salam** gauge group:

Pati, Salam, 1974

$$SU(4) \times SU(2)_L \times SU(2)_R$$

$$\Psi_L \sim (\mathbf{4}, \mathbf{2}, \mathbf{1})^{\oplus 3}, \quad \Psi_R \sim (\mathbf{4}, \mathbf{1}, \mathbf{2})^{\oplus 3}$$

Gauge Flavour Unification

First challenge: embed the SM in an **anomaly-free gauge theory** that unifies the generations

A comprehensive analysis of Lie algebras reveals it is not possible to unify either $SU(5)$ or $SO(10)$ GUT with flavour.

Allanach, Gripaios, Tooby-Smith, 2104.14555

To unify gauge and flavour symmetries, we should start from **Pati-Salam** gauge group:

Pati, Salam, 1974

$$SU(4) \times SU(2)_L \times SU(2)_R$$
$$\Psi_L \sim (\mathbf{4}, \mathbf{2}, \mathbf{1})^{\oplus 3}, \quad \Psi_R \sim (\mathbf{4}, \mathbf{1}, \mathbf{2})^{\oplus 3}$$

Two options:

1. Unify colour and flavour: $SU(4) \to SU(12)$: $\Psi_L \sim (\mathbf{12}, \mathbf{2}, \mathbf{1}), \Psi_R \sim (\mathbf{12}, \mathbf{1}, \mathbf{2})$
2. Unify electroweak and flavour: $SU(2)_L \times SU(2)_R \to Sp(6)_L \times Sp(6)_R$: $\Psi_L \sim (\mathbf{4}, \mathbf{6}, \mathbf{1}), \Psi_R \sim (\mathbf{4}, \mathbf{1}, \mathbf{6})$

Gauge Flavour Unification

Reminder:
The Lie group $Sp(6)$ is a subgroup of $SU(6)$:
$Sp(6) = \{U \in SU(6) | U^T \Omega U = \Omega\}$, where $\Omega = \begin{pmatrix} 0 & I_3 \\ -I_3 & 0 \end{pmatrix}$

<ins>First challenge</ins>: embed the SM in an **anomaly-free gauge theory** that unifies the generations

A comprehensive analysis of Lie algebras reveals it is not possible to unify either $SU(5)$ or $SO(10)$ GUT with flavour.

Allanach, Gripaios, Tooby-Smith, 2104.14555

To unify gauge and flavour symmetries, we should start from **Pati-Salam** gauge group:

$$SU(4) \times SU(2)_L \times SU(2)_R$$

Pati, Salam, 1974

$$\Psi_L \sim (\mathbf{4}, \mathbf{2}, \mathbf{1})^{\oplus 3}, \quad \Psi_R \sim (\mathbf{4}, \mathbf{1}, \mathbf{2})^{\oplus 3}$$

Two options:

1. Unify colour and flavour: $SU(4) \to SU(12)$: $\Psi_L \sim (\mathbf{12}, \mathbf{2}, \mathbf{1})$, $\Psi_R \sim (\mathbf{12}, \mathbf{1}, \mathbf{2})$
2. Unify electroweak and flavour: $SU(2)_L \times SU(2)_R \to Sp(6)_L \times Sp(6)_R$: $\Psi_L \sim (\mathbf{4}, \mathbf{6}, \mathbf{1})$, $\Psi_R \sim (\mathbf{4}, \mathbf{1}, \mathbf{6})$

Electroweak Flavour Unification (EWFU)

- Gauge group: $G_{123} = SU(4) \times Sp(6)_L \times Sp(6)_R$

- SM fermions:

$$\Psi_L \sim (\mathbf{4}, \mathbf{6}, \mathbf{1}) \sim \begin{pmatrix} u_1^r & u_2^r & u_3^r & d_1^r & d_2^r & d_3^r \\ u_1^g & u_2^g & u_3^g & d_1^g & d_2^g & d_3^g \\ u_1^b & u_2^b & u_3^b & d_1^b & d_2^b & d_3^b \\ \nu_1 & \nu_2 & \nu_3 & e_1 & e_2 & e_3 \end{pmatrix}, \qquad \Psi_R \sim (\mathbf{4}, \mathbf{1}, \mathbf{6}) \sim \text{ similar}$$

Electroweak Flavour Unification (EWFU)

By unifying all matter, such a gauge theory explains puzzles 1 and 2 “out of the box”.

But with so much unification, can we also explain puzzle 3?

Puzzle 3		
	Mass hierarchies:	$m_3 \gg m_2 \gg m_1$
	Small mixing angles:	$V_{us} \sim \lambda \sim 0.2, \quad V_{cb} \sim \lambda^2, \quad V_{ub} \sim \lambda^3$

EWFU: generating the Yukawa structure

Two steps:

1. Flavour **deconstruction** of G_{123} at very high scale

2. Break the flavour non-universal intermediate symmetry to G_{SM}

$\langle \Phi_{L,R} \rangle$ have components that *link* families together. 4 independent vevs:

$\epsilon_L^{12}, \epsilon_L^{23}, \epsilon_R^{12}, \epsilon_R^{23}$

$$SU(4) \times Sp(6)_L \times Sp(6)_R$$

$$\downarrow \langle S_{L,R} \rangle$$

$$SU(3) \times SU(2)_{L,1} \times SU(2)_{L,2} \times SU(2)_{L,3} \times Sp(4)_{R,1+2} \times U(1)_R$$

$$\downarrow \langle \Phi_{L,R} \rangle$$

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

Integrate out heavy stuff (Higgs components)

↓

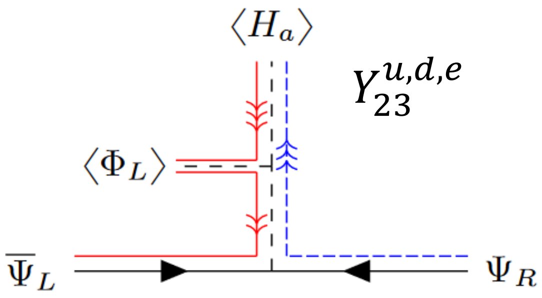
High-dimension operators

$$\mathcal{O}^{4+n} \sim \left(\frac{\Phi_{L/R}}{\Lambda_H}\right)^n \overline{\psi_L} H \psi_R$$

↓

Match onto SM Yukawas

$$\epsilon_{L/R}^n \, \overline{\psi_L} H \psi_R$$



$$V \supset \Lambda_H \mathrm{Tr}\left(\Omega^T H_1^\dagger \Omega \Phi_L \Omega H_1\right)$$

The scalar sector is almost minimal:

$S_L \sim (\mathbf{1}, \mathbf{14}, \mathbf{1})$, $S_R \sim (\overline{\mathbf{4}}, \mathbf{1}, \mathbf{6})$, $\Phi_L \sim (\mathbf{1}, \mathbf{14}, \mathbf{1})$, $\Phi_R \sim (\mathbf{1}, \mathbf{1}, \mathbf{14})$

EWFU: quark masses and mixings

Puzzle 3

Mass hierarchies:	$m_3 \gg m_2 \gg m_1$
Small mixing angles:	$V_{us} \sim \lambda \sim 0.2, \quad V_{cb} \sim \lambda^2, \quad V_{ub} \sim \lambda^3$

EWFU model generates Yukawa structures:

$$\frac{M^f}{v} \sim \begin{pmatrix} \epsilon_L^{12}\epsilon_L^{23}\epsilon_R^{12}\epsilon_R^{23} & \epsilon_L^{12}\epsilon_L^{23}\epsilon_R^{23} & \epsilon_L^{12}\epsilon_L^{23} \\ \epsilon_L^{23}\epsilon_R^{12}\epsilon_R^{23} & \epsilon_L^{23}\epsilon_R^{23} & \epsilon_L^{23} \\ \epsilon_R^{12}\epsilon_R^{23} & \epsilon_R^{23} & 1 \end{pmatrix}$$

Extract observables using perturbation theory:

$m_1 \sim \epsilon_L^{12}\epsilon_R^{12}\epsilon_L^{23}\epsilon_R^{23}$, $\quad V_{ub} \sim \epsilon_L^{12}\epsilon_L^{23}$

$m_2 \sim \epsilon_L^{23}\epsilon_R^{23}$, $\quad V_{cb} \sim \epsilon_L^{23}$

$m_3 \sim 1$, $\quad V_{us} \sim \epsilon_L^{12}$

EWFU: quark masses and mixings

Puzzle 3

Mass hierarchies:	$m_3 \gg m_2 \gg m_1$
Small mixing angles:	$V_{us} \sim \lambda \sim 0.2, \quad V_{cb} \sim \lambda^2, \quad V_{ub} \sim \lambda^3$

EWFU model generates Yukawa structures:

$$\frac{M^f}{v} \sim \begin{pmatrix} \epsilon_L^{12}\epsilon_L^{23}\epsilon_R^{12}\epsilon_R^{23} & \epsilon_L^{12}\epsilon_L^{23}\epsilon_R^{23} & \epsilon_L^{12}\epsilon_L^{23} \\ \epsilon_L^{23}\epsilon_R^{12}\epsilon_R^{23} & \epsilon_L^{23}\epsilon_R^{23} & \epsilon_L^{23} \\ \epsilon_R^{12}\epsilon_R^{23} & \epsilon_R^{23} & 1 \end{pmatrix}$$

Extract observables using perturbation theory:

$m_1 \sim \epsilon_L^{12}\epsilon_R^{12}\epsilon_L^{23}\epsilon_R^{23}$, $\quad V_{ub} \sim \epsilon_L^{12}\epsilon_L^{23}$

$m_2 \sim \epsilon_L^{23}\epsilon_R^{23}$, $\quad V_{cb} \sim \epsilon_L^{23}$

$m_3 \sim 1$, $\quad V_{us} \sim \epsilon_L^{12}$

Mixing angles → $\epsilon_L^{12} \sim \lambda$, $\epsilon_L^{23} \sim \lambda^2$

Mass hierarchies → $\epsilon_R^{12} \sim \lambda^2$, $\epsilon_R^{23} \sim \lambda$

Corresponds to a ladder of symmetry breaking scales separated by steps of $\frac{1}{\lambda} \sim 5 \sim \mathcal{O}(1)$

... And there is **enough freedom** in the EFT coefficients to fit all the data ☑

Work in progress

Phenomenology of EWFU

EWFU offers a new solution to

- Puzzle 1: why the peculiar set of 5+1 SM fermion reps?
- Puzzle 2: why three copies of each?
- Puzzle 3: why is the flavour symmetry broken in such a special way? Mass and mixing angle hierarchies

But what about puzzle 4? TeV scale new physics?

Phenomenology of EWFU

But what about puzzle 4? TeV scale new physics?

$$SU(4) \times Sp(6)_L \times Sp(6)_R$$

$\langle S_{L,R} \rangle$ ↓ Λ_H

$$SU(3) \times SU(2)_{L,1} \times SU(2)_{L,2} \times SU(2)_{L,3} \times Sp(4)_{R,1+2} \times U(1)_R$$

$\langle \Phi_{L,R} \rangle$ ↓ v_Φ

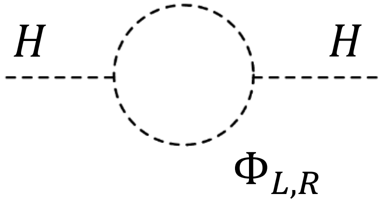
$$SU(3) \times SU(2)_L \times U(1)_Y$$

Small scale separation, $\mathcal{O}(10^{-1} - 10^{-2})$, fixed by Yukawa hierarchy

"Distance to New Physics": can be as low as experimentally allowed by flavour bounds

Recall there are two good reasons for v_Φ to be low (∼TeV):

1. Naturalness
2. Persistent anomalies in low-energy data



Phenomenology of EWFU: the 45 gauge bosons

$$SU(4) \times Sp(6)_L \times Sp(6)_R$$

$\downarrow \langle S_{L,R} \rangle$

$$SU(3) \times SU(2)_{L,1} \times SU(2)_{L,2} \times SU(2)_{L,3} \times Sp(4)_{R,1+2} \times U(1)_R$$

$\downarrow \langle \Phi_{L,R} \rangle$

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

Gauge bosons (VERY HEAVY):

$\langle S_L \rangle$: (W', Z') triplets x3
$Z' \sim (\mathbf{1}, \mathbf{1})_0$ x3

$\langle S_R \rangle$: $U_1 \sim (\mathbf{3}, \mathbf{1})_{2/3}$ leptoquark (flavour universal)
$Z^{\pm} \sim (\mathbf{1}, \mathbf{1})_1$ x3
$Z' \sim (\mathbf{1}, \mathbf{1})_0$ x5

Gauge bosons (LIGHTER):

$\langle \Phi_L \rangle$: (W', Z') triplets x2

$\langle \Phi_R \rangle$: $Z^{\pm} \sim (\mathbf{1}, \mathbf{1})_1$ x3
$Z' \sim (\mathbf{1}, \mathbf{1})_0$ x4

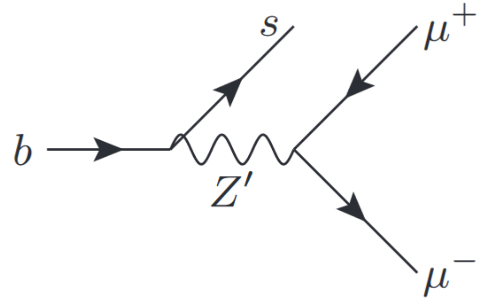
Phenomenology of EWFU: the 45 gauge bosons

Gauge bosons (LIGHTER):
$\langle\Phi_L\rangle$: (W', Z') triplets x2
$\langle\Phi_R\rangle$: $Z^{\pm}\sim(\mathbf{1},\mathbf{1})_1$ x3
$Z'\sim(\mathbf{1},\mathbf{1})_0$ x4

The lightest gauge bosons are **flavoured versions of EW gauge bosons, LH and RH.** For example, LH:

- one triplet coupled to 1st and 2nd families with opposite sign, mass $m_{12}\sim g_L\epsilon_L^{12}\Lambda_H$
- one triplet coupled to 2nd and 3rd families with opposite sign, mass $m_{23}\sim g_L\epsilon_L^{23}\Lambda_H$

New sources of quark flavour violation and LF(U)V!



What's next for me?

Characterise the flavour + high p_T pheno of these flavoured EW gauge bosons.

Conclusions

- The existence of 3 generations and the rich Yukawa structure are fascinating puzzles that beg for a BSM explanation

- Points to **new physics coupled predominantly to heavy generations**. Reasons for a TeV scale “anchor”: (a) **Naturalness** of EW sector, (b) hints of new physics in the **B anomalies**

- 3 approaches to flavour puzzle, all with TeV scale flavoured new physics:
  1. Horizontal flavour symmetry → flavoured Z's
  2. Deconstructed Pati—Salam model → flavoured U_1 LQ
  3. Electroweak flavour unification → flavoured EW gauge bosons

Conclusions

- The existence of 3 generations and the rich Yukawa structure are fascinating puzzles that beg for a BSM explanation

- Points to **new physics coupled predominantly to heavy generations**. Reasons for a TeV scale "anchor": (a) **Naturalness** of EW sector, (b) hints of new physics in the **B anomalies**

- 3 approaches to flavour puzzle, all with TeV scale flavoured new physics:
  1. Horizontal flavour symmetry → flavoured Z's
  2. Deconstructed Pati—Salam model → flavoured U_1 LQ
  3. Electroweak flavour unification → flavoured EW gauge bosons

<u>A key message:</u>

Continued **high p_T searches** with **heavy flavour** final states + continued **precision measurements** of **rare decays** will probe all these solutions to the flavour puzzle!

Thank you!