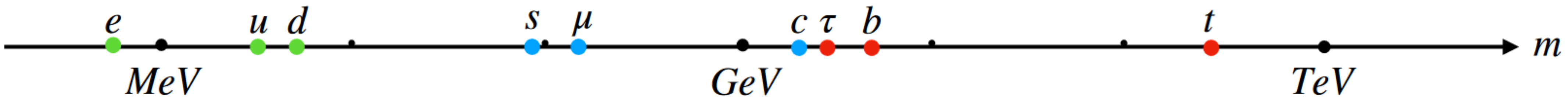
A Unified Approach to the Flavour Puzzle

Joe Davighi, University of Zurich

Particle Physics Seminar @ University of Birmingham, 9th November 2022



Outline

1. Review of the flavour puzzle(s)

2. Flavour model building in the LHC era: the appeal of **TeV** scale **flavour non-universal** New Physics
   a) Horizontal symmetries
   b) Deconstructed symmetries
   c) Unified symmetries

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

2201.07245 with Joseph Tooby-Smith (Cornell)

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:

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

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

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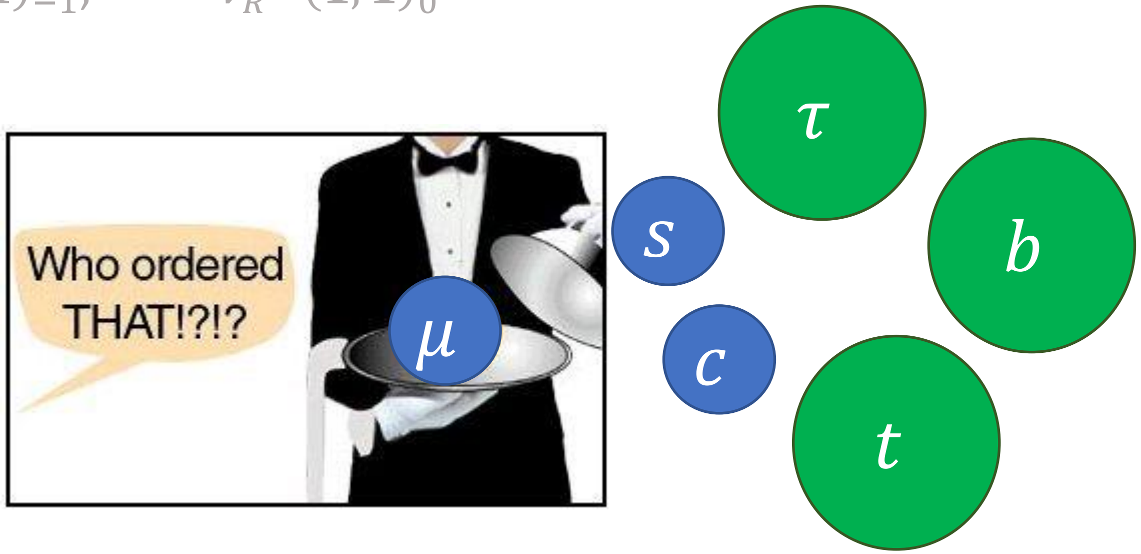

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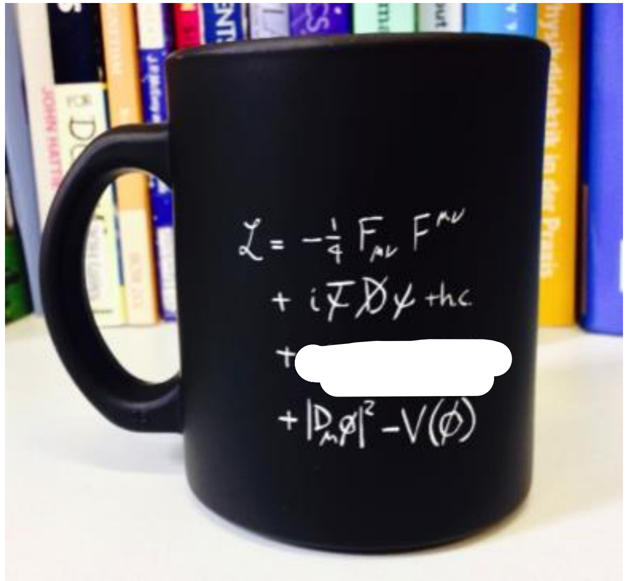
Puzzle 3: SM without Yukawa couplings has a big global symmetry

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



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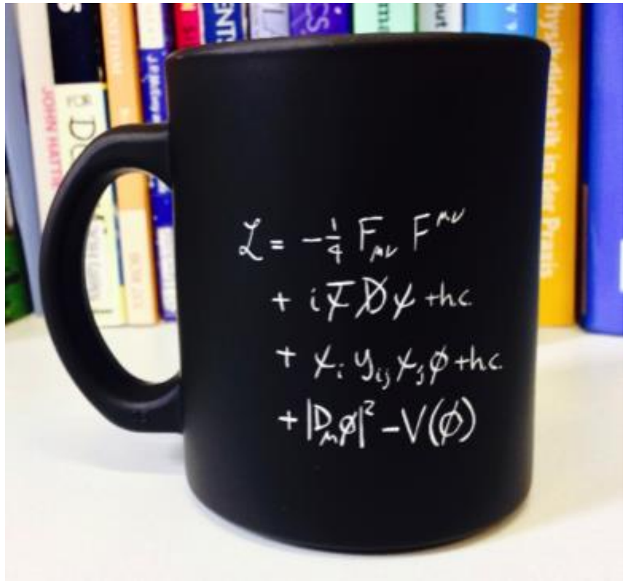
$$U(3)^5 \to G_{\text{acc}} \coloneqq U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$



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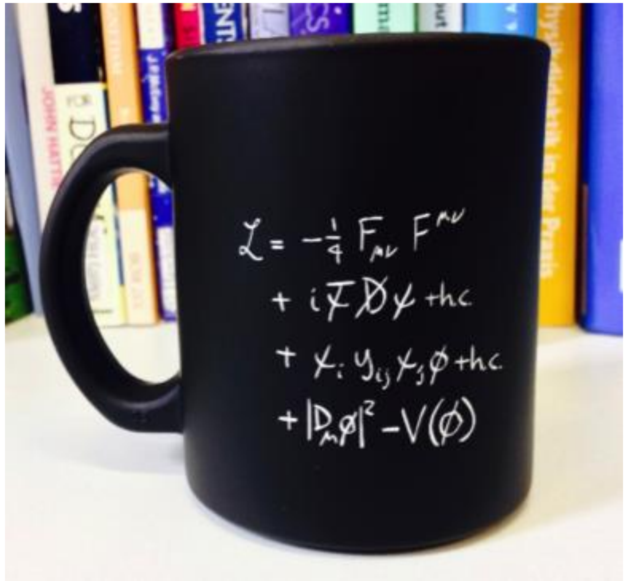

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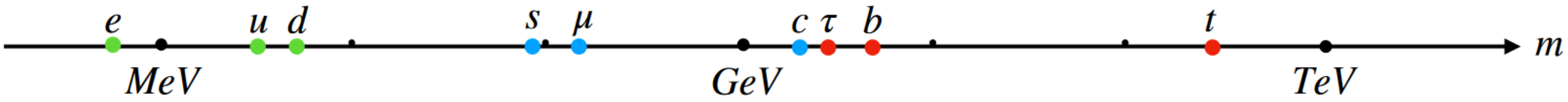
The breaking by **Y** to G_{acc} is not "random", but very structured:

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**!*

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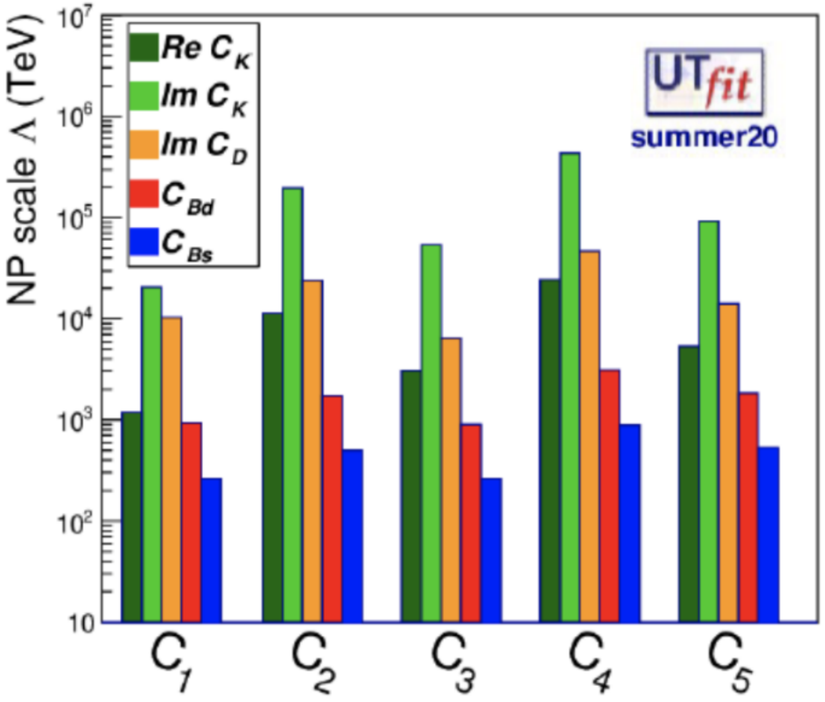
Neutral meson mixing constraints



Barbieri, 2103.15635

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

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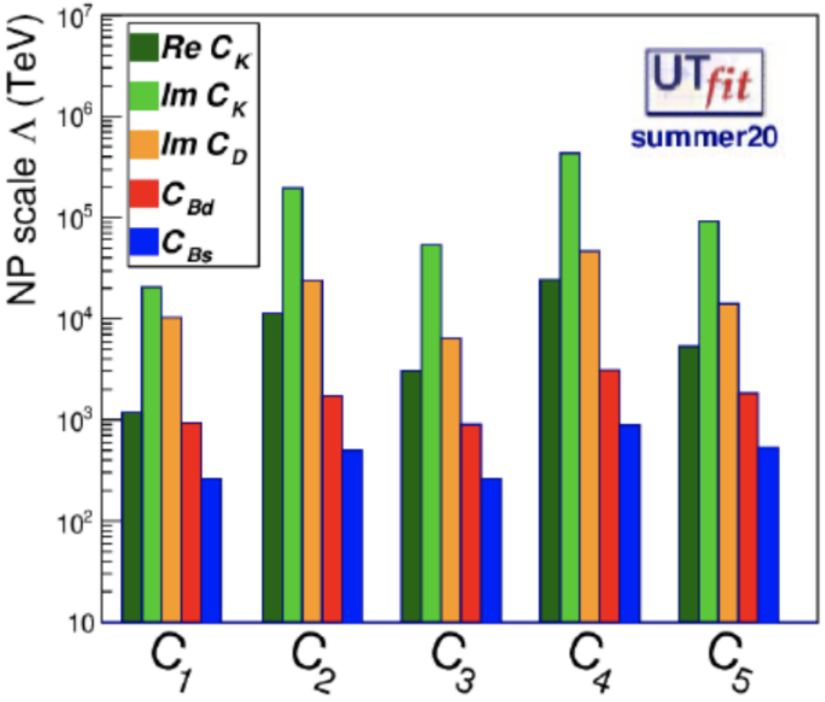

Barbieri, 2103.15635

Flavour model building
(in the LHC era)

Global symmetries: a big clue for model building

Puzzle 3

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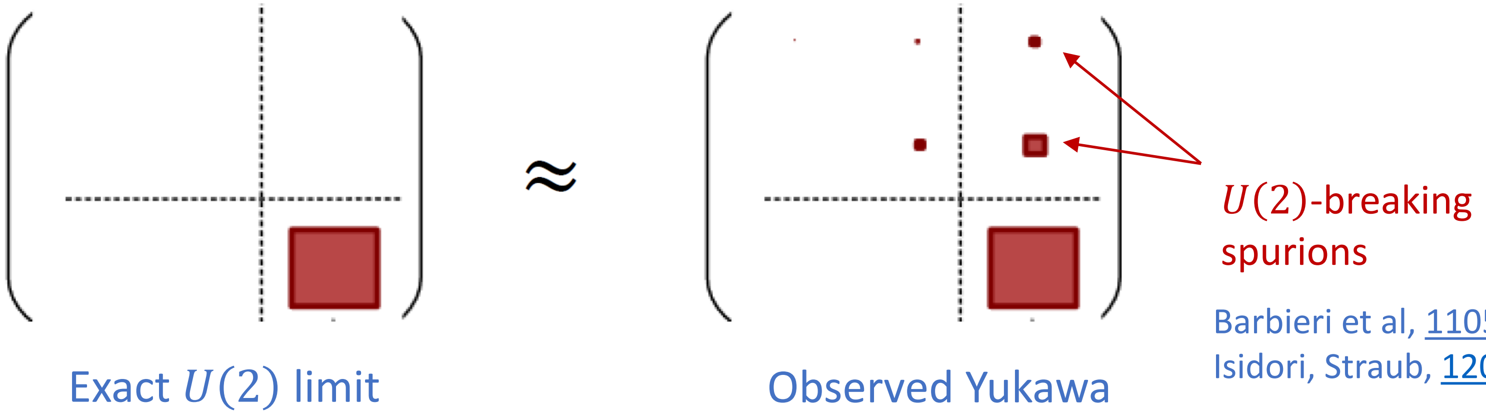
Yukawa matrices have approximate global symmetries e.g. $U(2)^5$ acting on light families



Barbieri et al, 1105.2296
Isidori, Straub, 1202.0464

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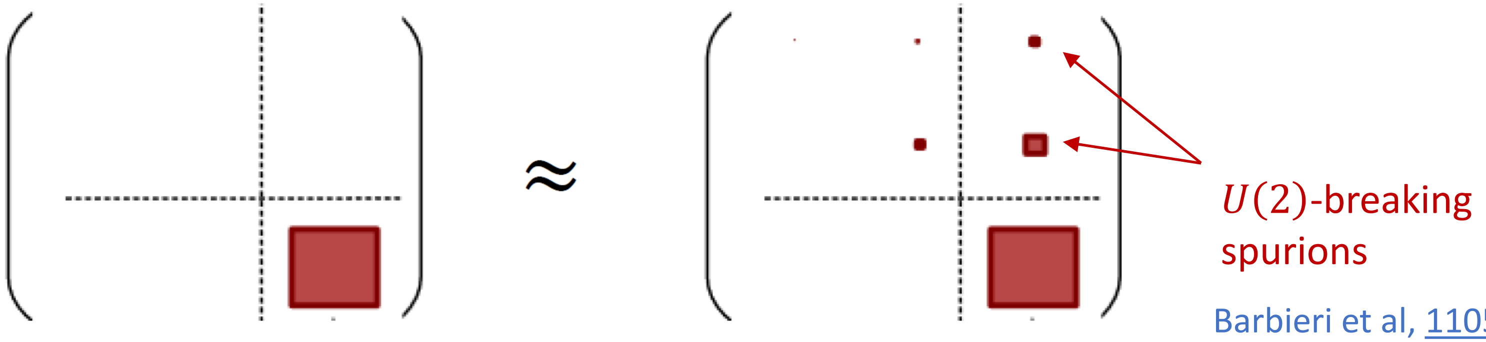

Exact $U(2)$ limit

Observed Yukawa

Barbieri et al, 1105.2296
Isidori, Straub, 1202.0464

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:

$$\mathcal{L} \supset \bar{\psi}_3 H \psi_3 + \frac{1}{\Lambda^n} \bar{\psi}_i H \psi_j$$

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

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→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:

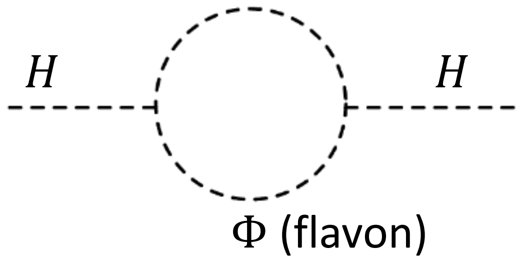
$$\mathcal{L} \supset \bar{\psi}_3 H \psi_3 + \left(\frac{w}{\Lambda}\right)^{n_{ij}} \bar{\psi}_i H \psi_j$$

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)

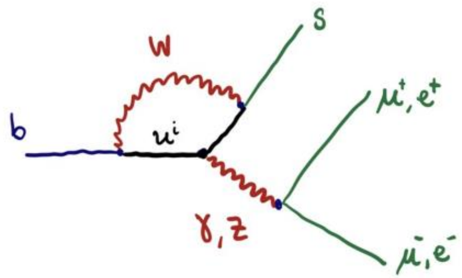
BUT, there are two good reasons for anchoring the scale not too far off:

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



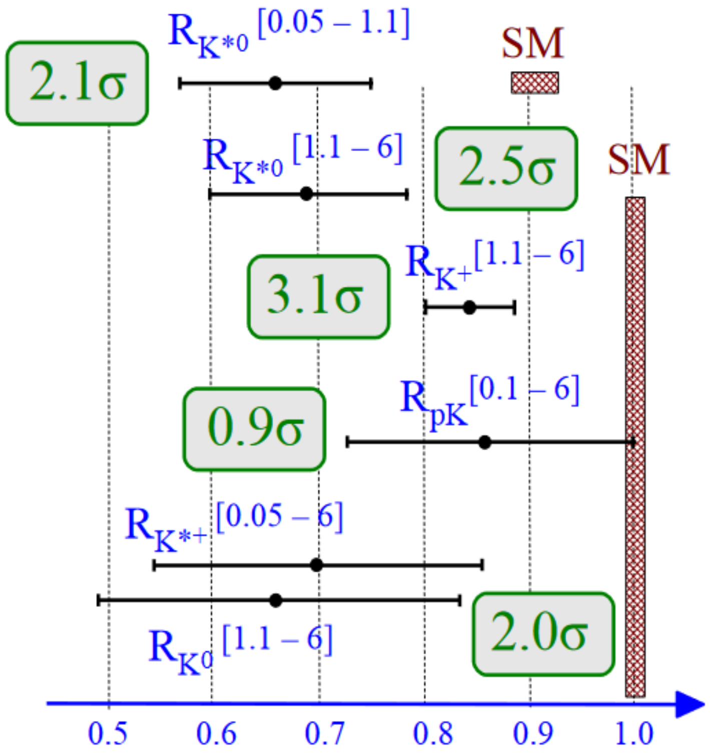
Digression: a quick review of the flavour anomalies…

Neutral current $b \to sll$



LFUV ratios (clean) @ LHCb

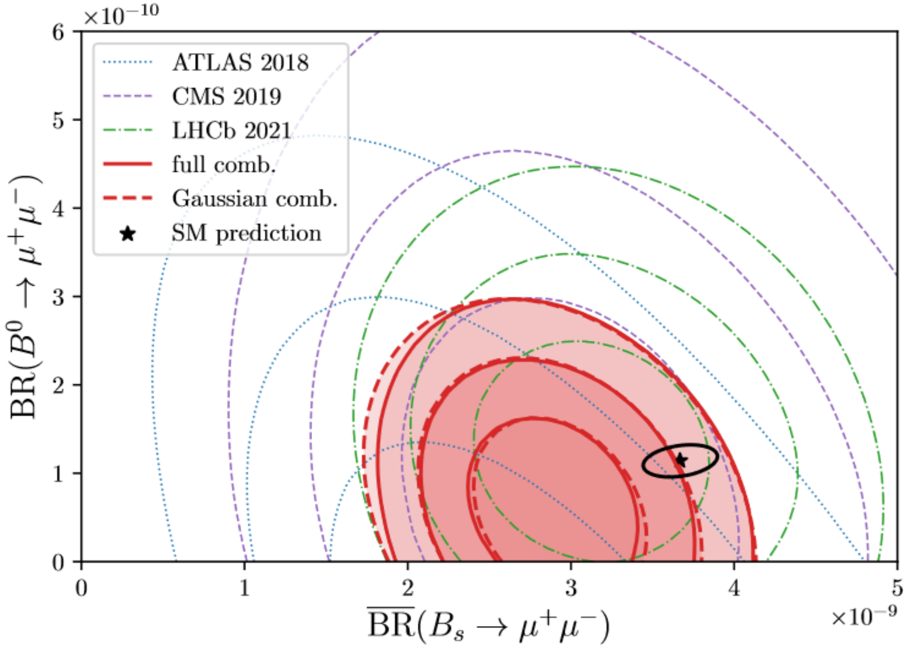
$$R_H = \frac{\text{BR}(B \to H\mu\mu)}{\text{BR}(B \to Hee)}$$



Summary from G. Isidori @ Planck 22

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

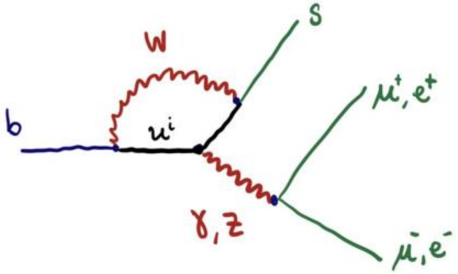
In 2021



Pull = $2.3\ \sigma$

Altmannshofer, Stangl 2103.13370

Neutral current $b \to sll$



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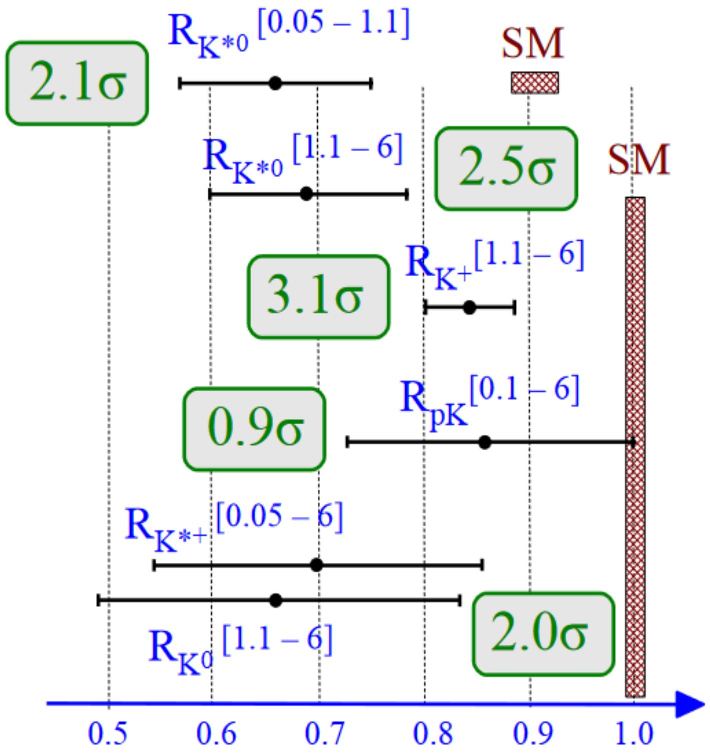

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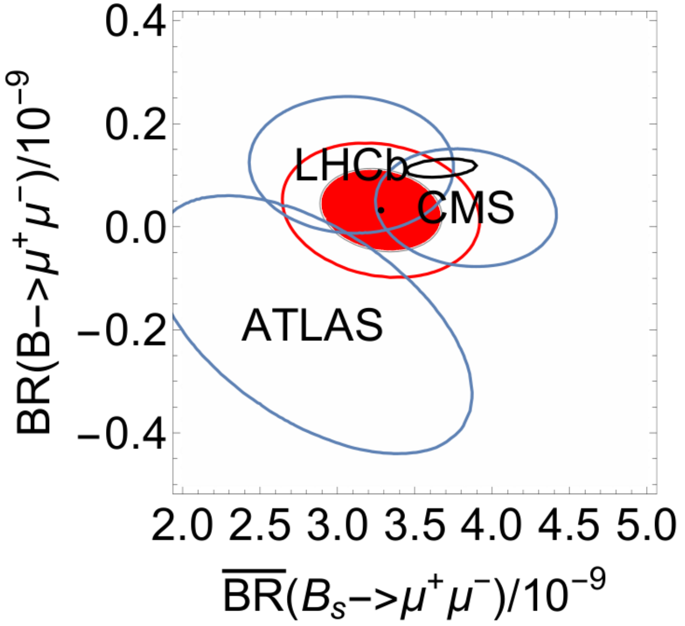
$\text{BR}(B_s \to \mu\mu)$ (clean)

In 2022



Pull = 1.6 σ (agrees with SM now)

Allanach, Davighi (in progress)

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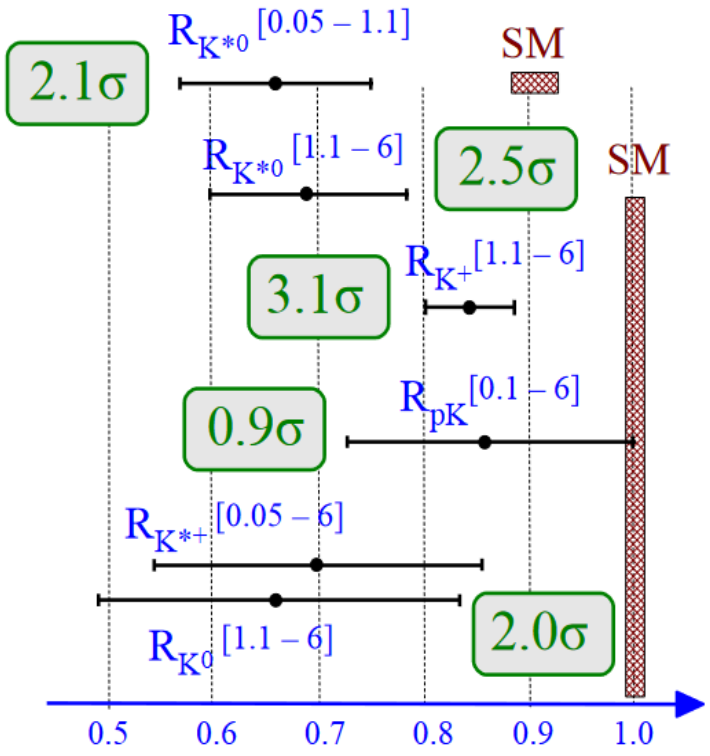

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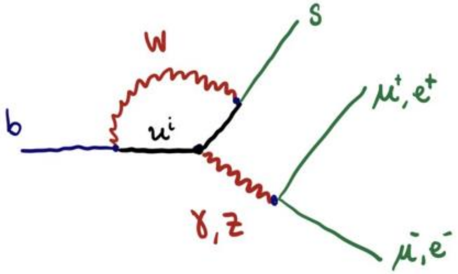
Also tensions in muon-only observables where hadronic uncertainties in TH predictions could be unexpectedly big. E.g. angular distributions for

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

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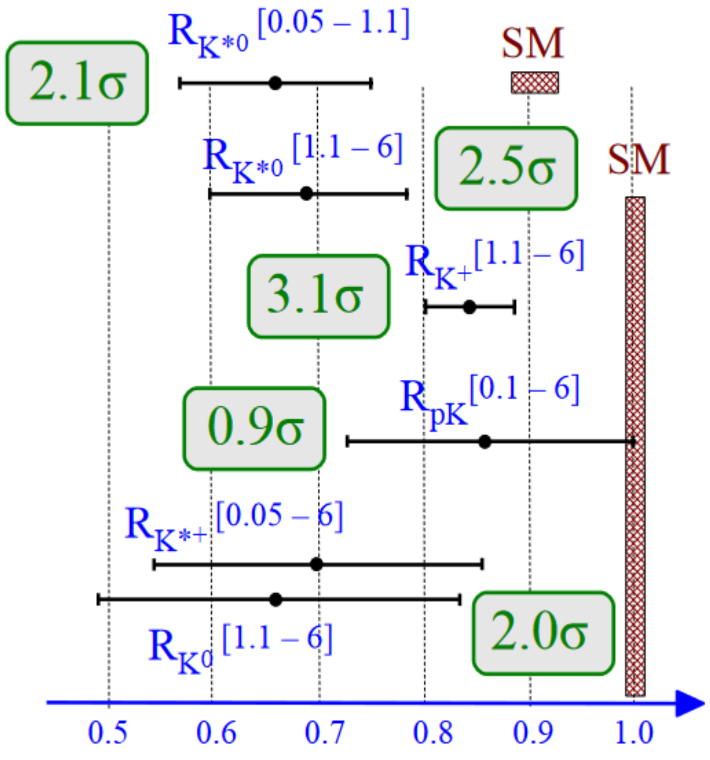

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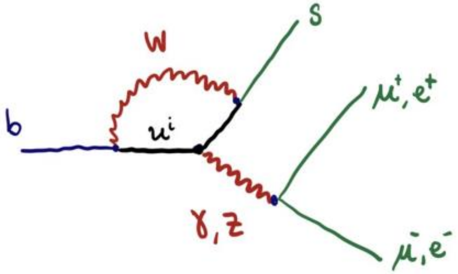

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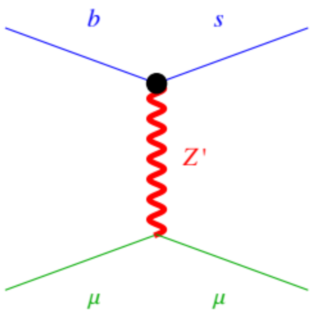
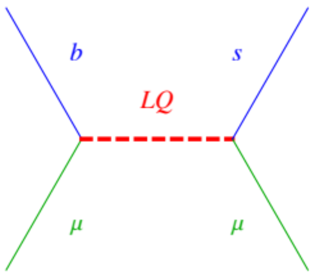
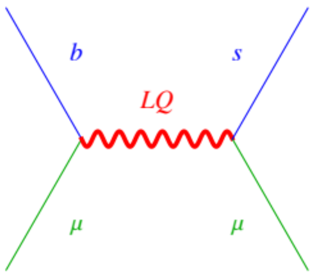
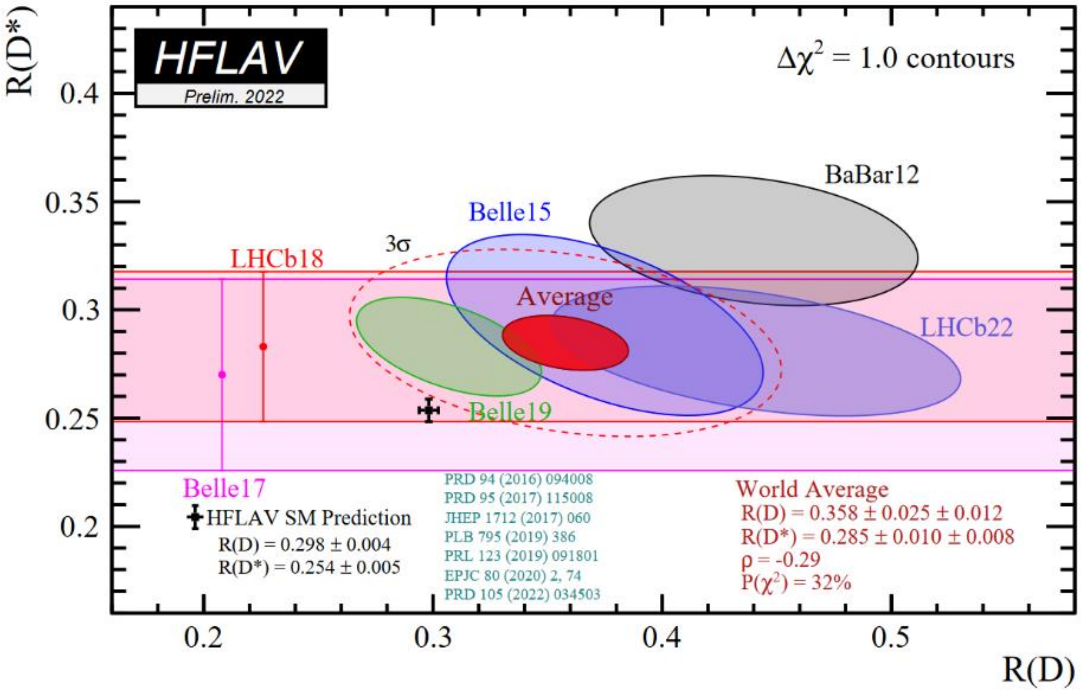
New particle explanations. Mass/g ~ 3 TeV/0.1 (weak effect)





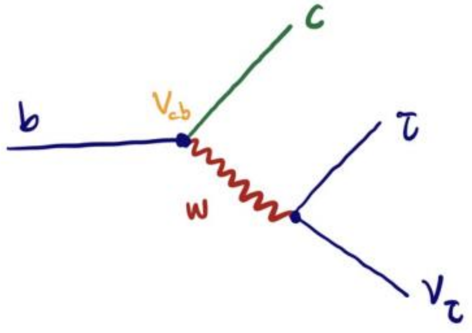


Charged current $b \to cl\nu$



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

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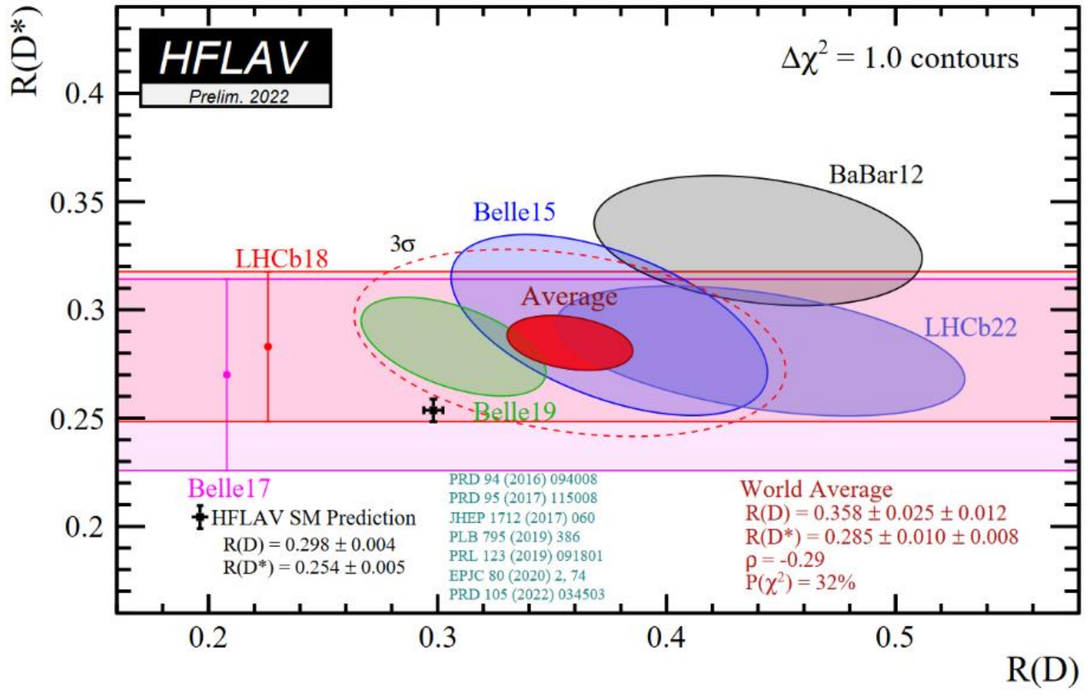

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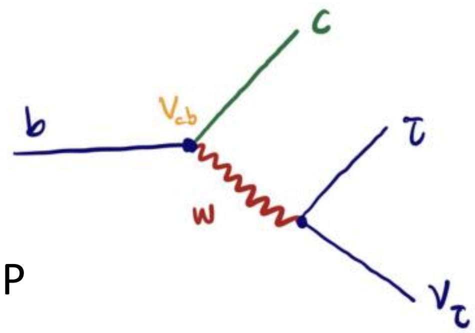
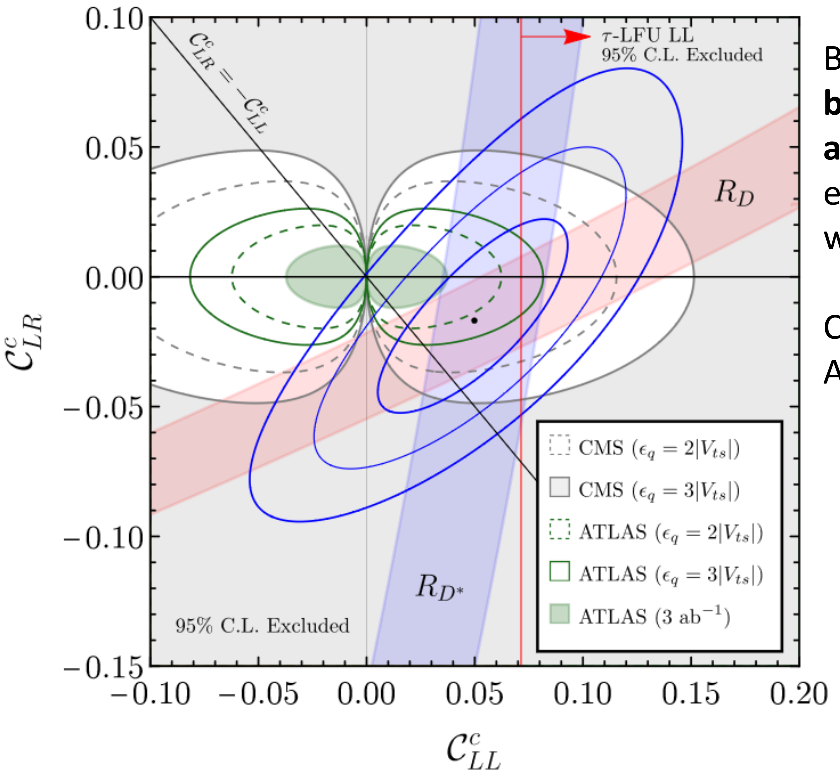


New physics explanations:

- 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

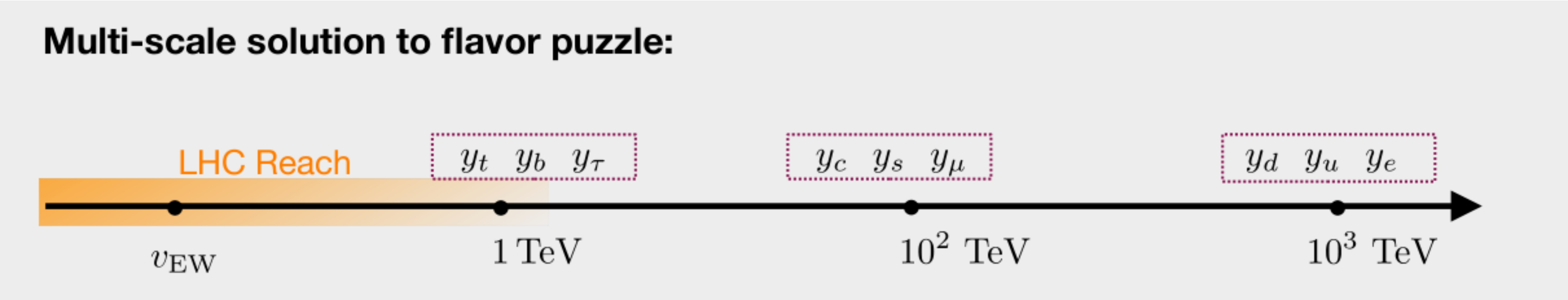


Best-fit region is **already being squeezed by ATLAS and CMS**. Here are 95% exclusion from $pp \to \tau\tau$ with b-tag

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 the flavour puzzle seriously. Moreover, they can **anchor the lowest scale** in a BSM theory of flavour ~TeV:



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 flavour non-universal NP

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

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

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

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Froggatt, Nielsen, 1979

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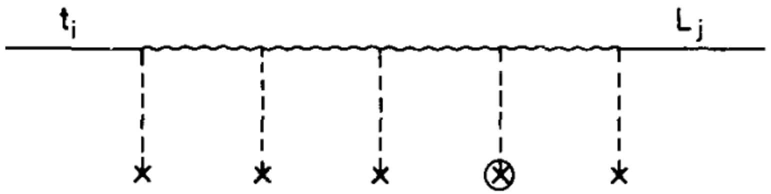
Example: **Froggatt—Nielsen mechanism**, where $G_F = U(1)_F$ with appropriate non-universal charges



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 a.k.a. heavy Z's

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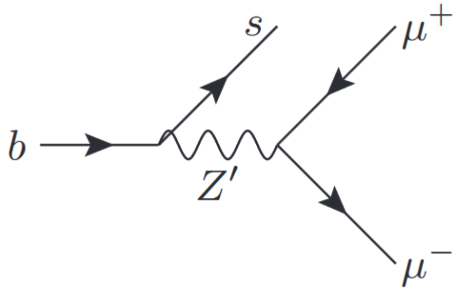
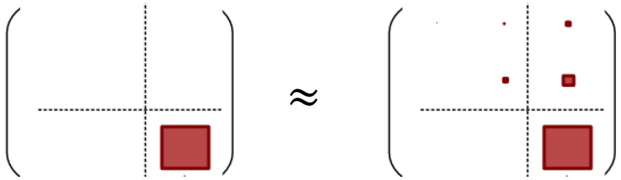


Example 2: Simple Z' models for the $b \to sll$ anomalies

Allanach, Davighi, 1809.01158; 2103.12056; 2205.12252

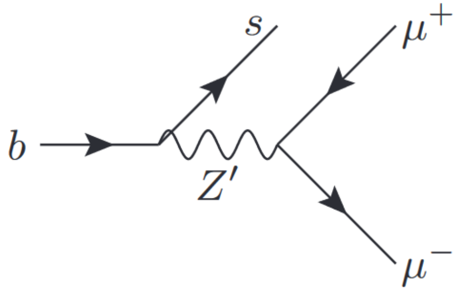
- Gauge $G_F = U(1)_X$; $X = Y_3$

  Only Y_{33} renormalizable:



1: Horizontal flavour symmetries

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



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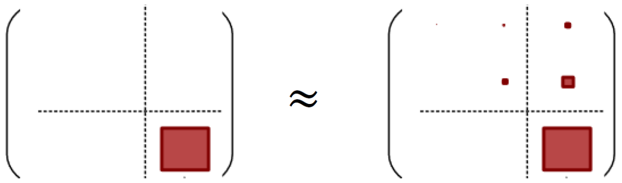
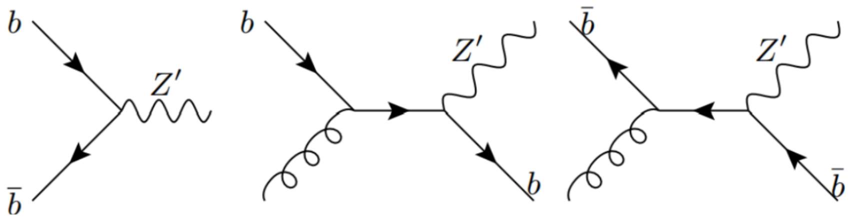


LHC Z' production:

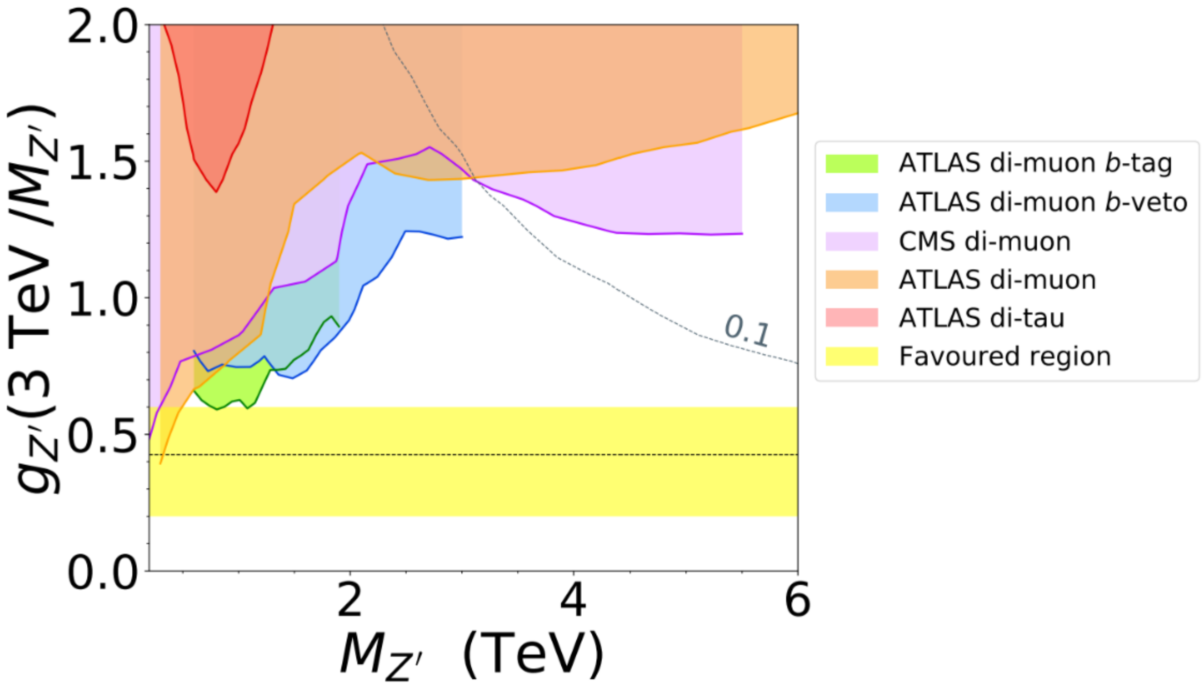


Z' decay modes:

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!

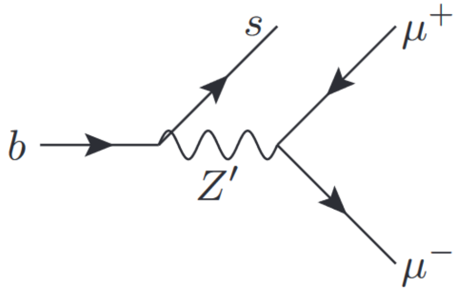
LHC Z' searches:



Allanach, Banks, 2111.06691

1: Horizontal flavour symmetries

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



Example 2: Simple Z' models for the $b \to sll$ anomalies

- Gauge $G_F = U(1)_X;\ X = Y_3 + a(L_2 - L_3)$

Davighi, 2105.06918

$$Y_u = y_t \begin{pmatrix} \frac{\Delta_u^{ab}\Phi}{\Lambda^2} & \frac{V_q^a}{\Lambda} \\ 0 & 1 \end{pmatrix} + \text{ dim } 9$$

$$Y_d = y_b \begin{pmatrix} \frac{\Delta_d^{a\dot{b}}\Phi}{\Lambda^2} & \frac{V_q^a}{\Lambda} \\ 0 & 1 \end{pmatrix} + \text{ dim } 7$$

$$Y_e = \begin{pmatrix} c_e \frac{\epsilon_\Phi^3}{\Lambda^3} & 0 & 0 \\ 0 & c_\mu \frac{\epsilon_\Phi^3}{\Lambda^3} & 0 \\ 0 & 0 & y_\tau \end{pmatrix} + \text{ dim } > 10$$

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

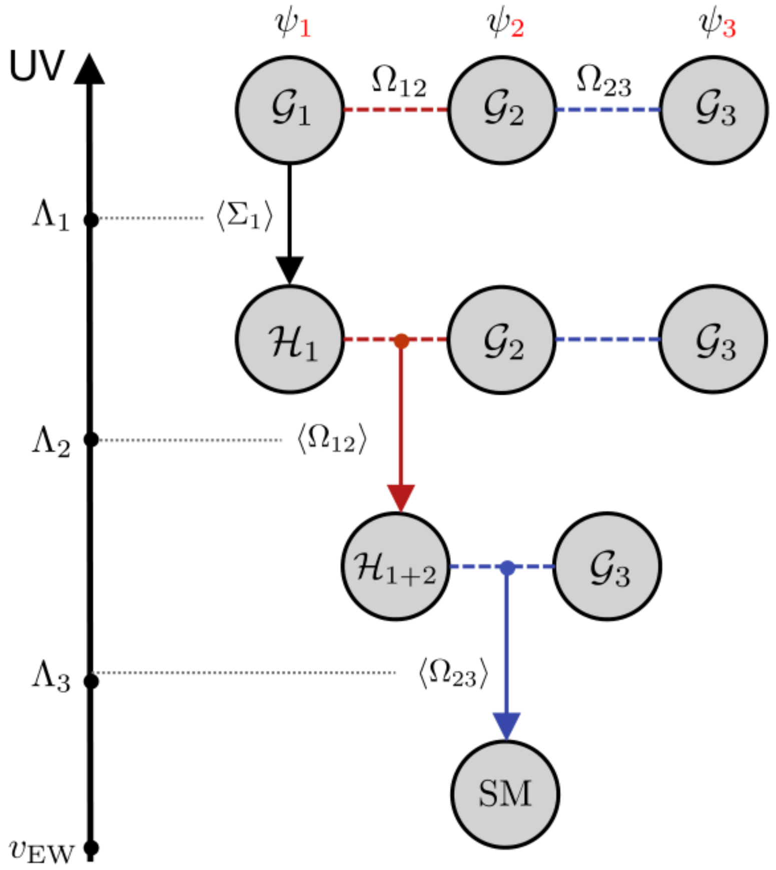
2: Deconstructed gauge symmetries

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:

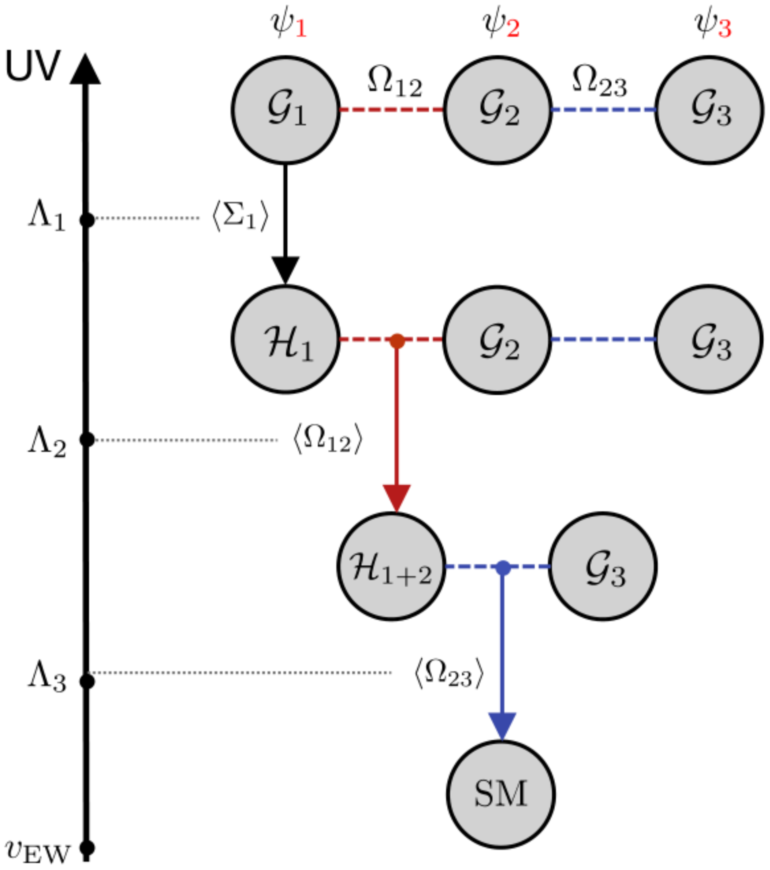
The **hierarchies** can come from different operator dimensions, and/or from **different scales associated with each family**

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

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



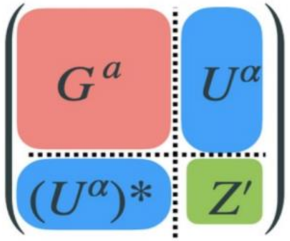
$$G = G_1 \times G_2 \times G_3$$

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

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

$SU(4)$ also **unifies quarks and leptons** (puzzle 1!)

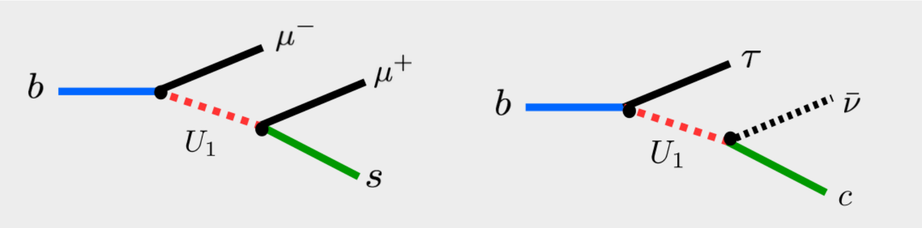
Symmetry breaking:



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

gives U_1 leptoquark coupled mostly to 3rd family

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



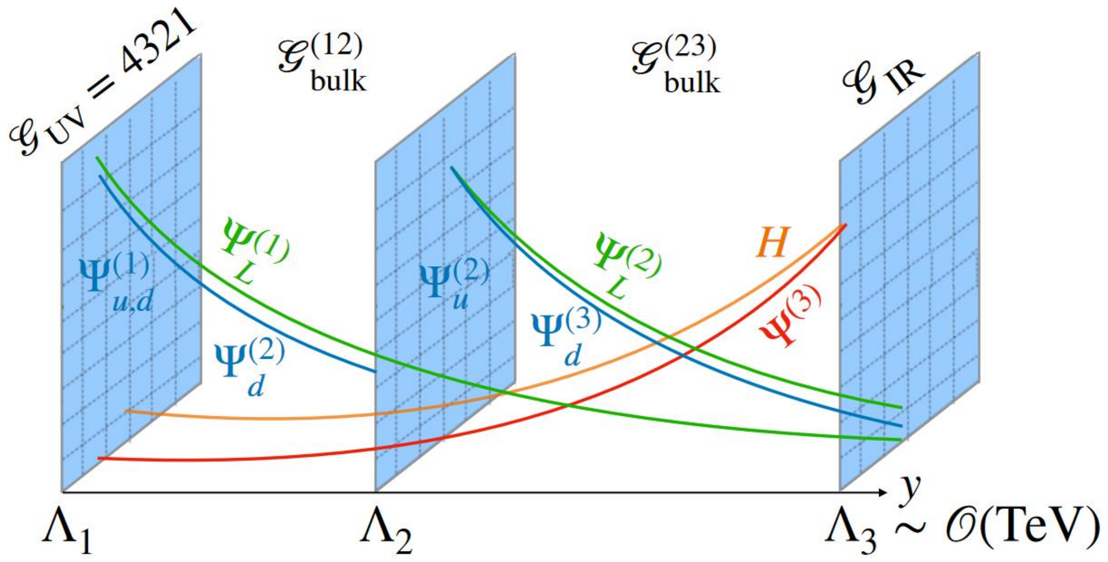
Butazzo et al, 1706.07808
Angelescu et al, 1808.08179

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



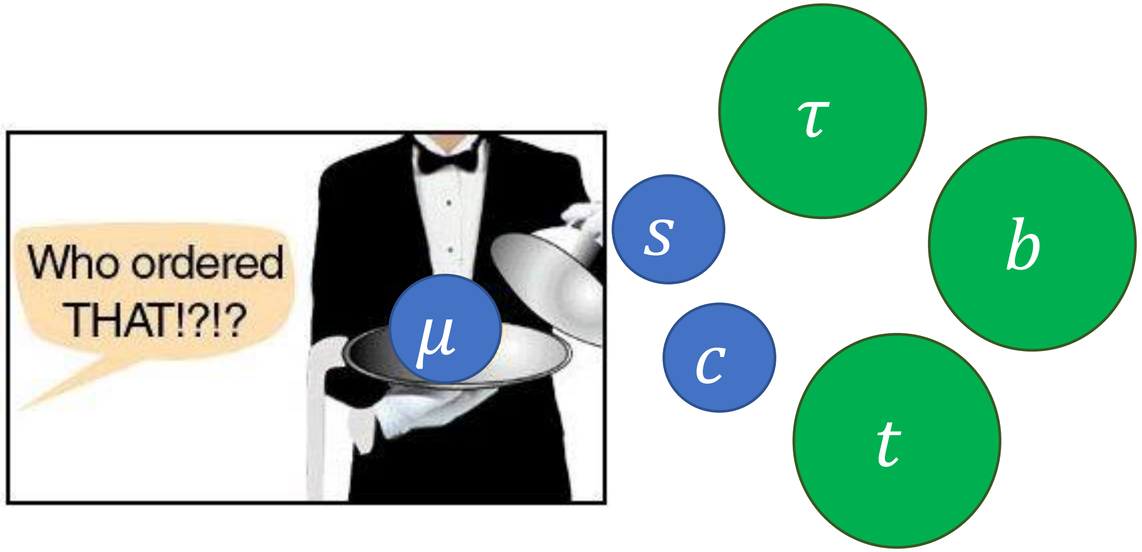
Higgs embedded as a composite pNGB:

→ 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?

<u>Gauge-flavour unification</u>

- **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 energy scales, G_{123} is spontaneously broken and flavour emerges as a low-energy remnant

Electroweak Flavour Unification

Davighi, Tooby-Smith, 2201.07245

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

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

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

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

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:

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

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

$\langle S_{L,R}\rangle$ ↓

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

$\langle\Phi_{L,R}\rangle$ ↓

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

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

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

EWFU: generating the Yukawa structure

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↓

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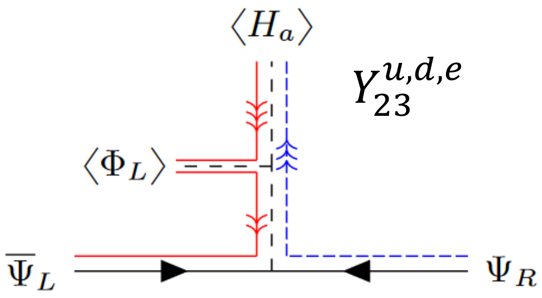

$$V \supset \Lambda_H \mathrm{Tr}\left(\Omega^T H_1^\dagger \Omega \Phi_L \Omega H_1\right)$$

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: generating the Yukawa structure

<u>The upshot</u>: all Yukawa matrices have the hierarchical structure

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

for $f \in u, d, e$.

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:

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

Extract observables in our model using matrix perturbation theory:

$$m_1 \sim \epsilon_L^{12}\epsilon_R^{12}\epsilon_L^{23}\epsilon_R^{23}, \qquad V_{ub} \sim \epsilon_L^{12}\epsilon_L^{23}$$
$$m_2 \sim \epsilon_L^{23}\epsilon_R^{23}, \qquad V_{cb} \sim \epsilon_L^{23}$$
$$m_3 \sim 1, \qquad V_{us} \sim \epsilon_L^{12}$$

Quark masses and mixings

Puzzle 3

Mass hierarchies:	$m_3 \gg m_2 \gg m_1$
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$$\frac{M^f}{v} \sim \begin{pmatrix} \epsilon_L^{12}\epsilon_L^{23}\epsilon_R^{12}\epsilon_R^{23} & \epsilon_L^{12}\epsilon_L^{23}\epsilon_R^{23} & \epsilon_L^{12}\epsilon_L^{23} \\ \epsilon_L^{23}\epsilon_R^{12}\epsilon_R^{23} & \epsilon_L^{23}\epsilon_R^{23} & \epsilon_L^{23} \\ \epsilon_R^{12}\epsilon_R^{23} & \epsilon_R^{23} & 1 \end{pmatrix}$$

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$$m_2 \sim \epsilon_L^{23}\epsilon_R^{23}, \qquad V_{cb} \sim \epsilon_L^{23}$$
$$m_3 \sim 1, \qquad V_{us} \sim \epsilon_L^{12}$$

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 ☑

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

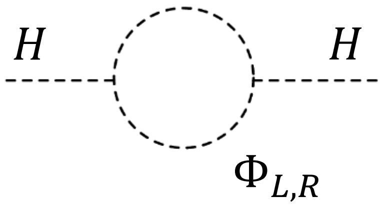
$$SU(3) \times SU(2)_L \times U(1)_Y$$

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



Work in progress

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

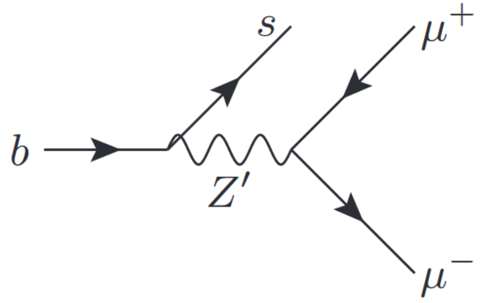
Gauge bosons (LIGHTER):
$\langle\Phi_L\rangle$: (W', Z') triplets x2
$\langle\Phi_R\rangle$: $Z^{\pm} \sim (\mathbf{1}, \mathbf{1})_1$ x3
$Z' \sim (\mathbf{1}, \mathbf{1})_0$ x4

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? Thorough investigation of flavour + high p_T pheno



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 NP 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

A key message:

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

Thank you!

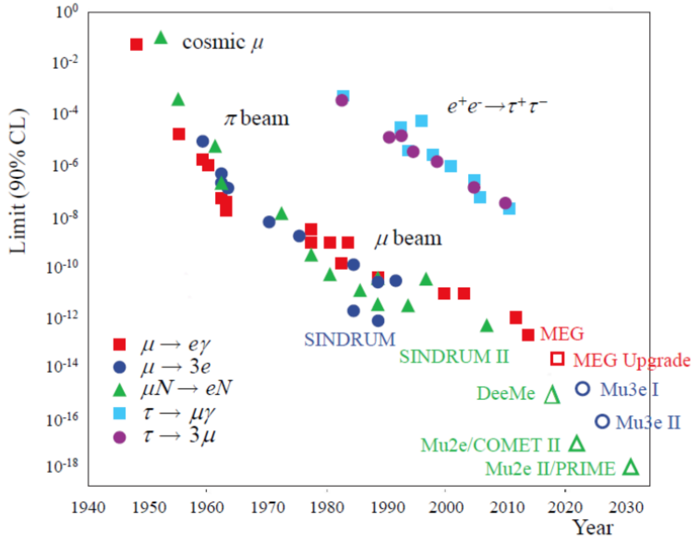
Backup slides

Guiding principles for BSM theory of flavour

1. Yukawa couplings have *approximate* global symmetries e.g. $U(2)^5$
2. Recall the SM has *exact* global symmetries: $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

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

- Example: half-life $\tau(p \to \pi^0 e^+) \gtrsim 10^{34}$ yr, $\tau(p \to \bar{\nu} K^+) \gtrsim 10^{34}$ yr
- LFV:



From F. Cei @ KAON2019

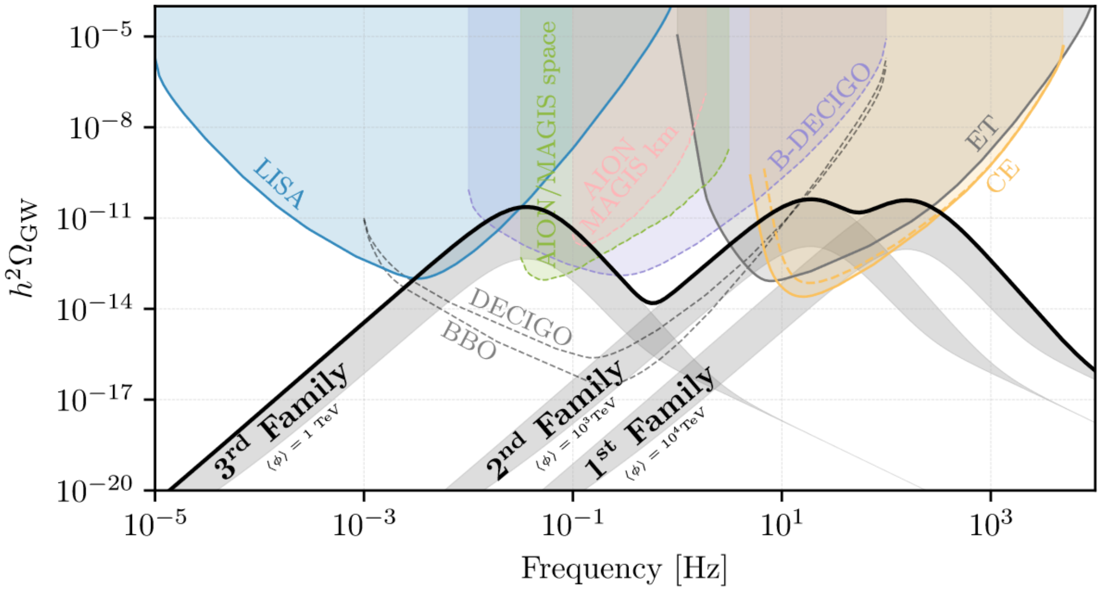
If there is **new physics at the TeV scale**, it cannot be "generic", because the inferred scale associated with violating the SM accidental symmetries is $\Lambda_{\text{acc}} \gg \text{TeV}$

Example: if p-decay due to dimension-6 operators $\mathcal{L} \sim \frac{1}{\Lambda^2} QQQL$ as in "generic" SMEFT, then $\Lambda \gtrsim 10^{13}\ \text{TeV}$. Essentially the **strongest bound we have on NP**

Some future directions

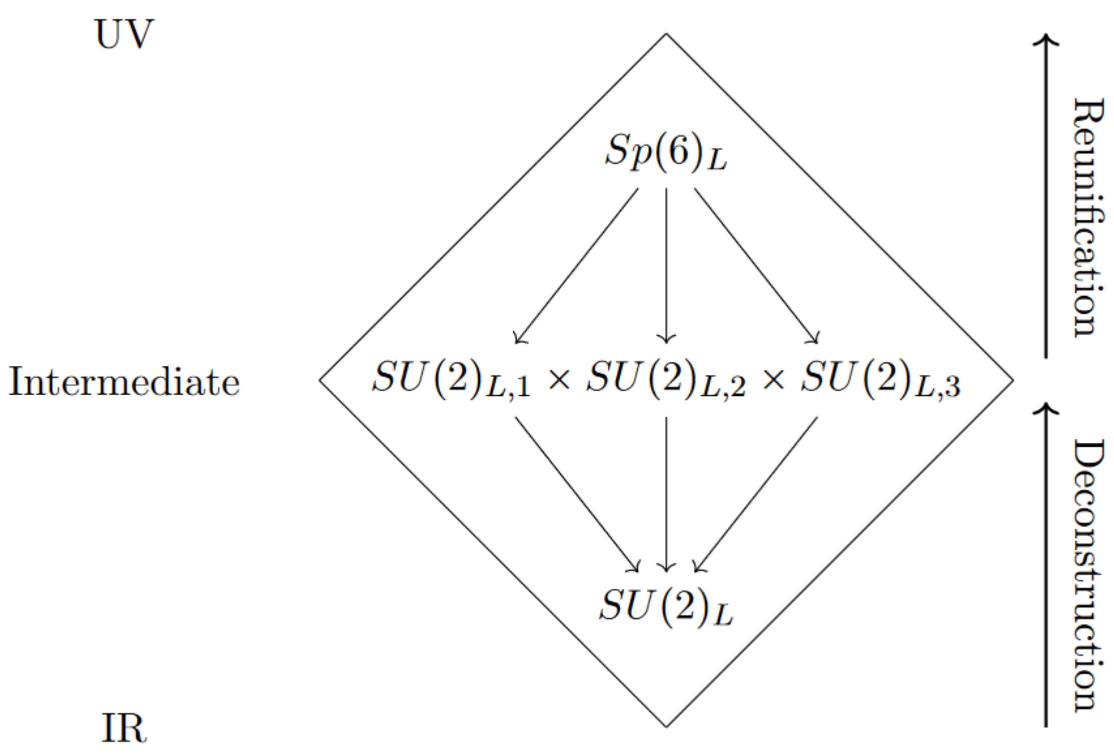
- Neutrino masses

- Cosmology
  - EWFU predicts **monopole** production, since $\pi_2(SU(4) \times Sp(6)_L \times Sp(6)_R/SM) = \mathbb{Z}$. Dilute by taking $\Lambda_R > \Lambda_{\text{inflation}}$
  - **Gravitational wave** production in early Universe: stochastic multi-peaked GW signal. An alternative probe of EWFU, even if the SSB scales are very high



Greljo, Opferkuch, Stefanek, 2019

Deconstructed flavour symmetries



Deconstructed gauge groups have been used in flavour model building e.g. $G = \prod_i^3 PS_i$ for B-anomalies + fermion masses.

Here, "gauge-flavour unification" provides a natural 4d explanation of such a flavour-deconstructed gauge symmetry.