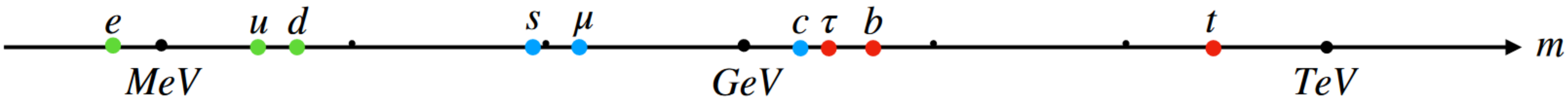
What is the most natural theory of flavour?

Joe Davighi, University of Zurich

Work with Gino Isidori 2303.01520

La Thuile 2023



The fermion sector of the SM holds many mysteries, including:

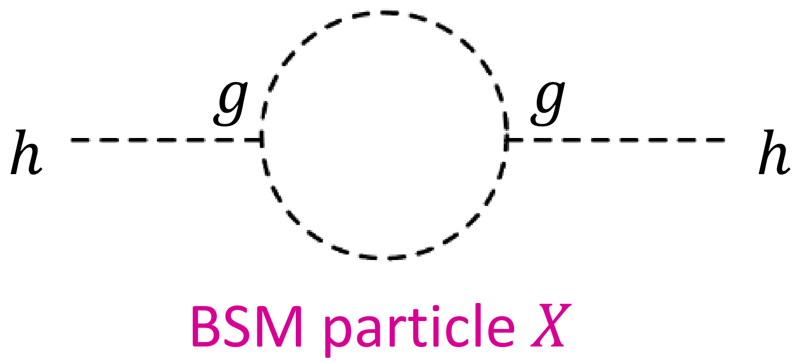
- Hypercharge quantization
- Flavour puzzle: $1 \approx y_3 \gg y_2 \gg y_1$ (quarks & charged leptons); $V_{us} \gg V_{cb} \gg V_{ub}$

These mysteries strongly suggest there is heavy BSM physics

(new gauge symmetries at higher scales), that couples strongly to Higgs and/or top

Heavy BSM physics that couples to Higgs means the physical Higgs mass is tuned

See e.g. Farina, Strumia, Pappadopulo, 1303.7244



$$\delta M_h^2 \sim \frac{1}{16\pi^2} g^2 M_X^2$$

[Contrast with e.g. dark matter, strong-CP problem, which *could* be explained with light NP

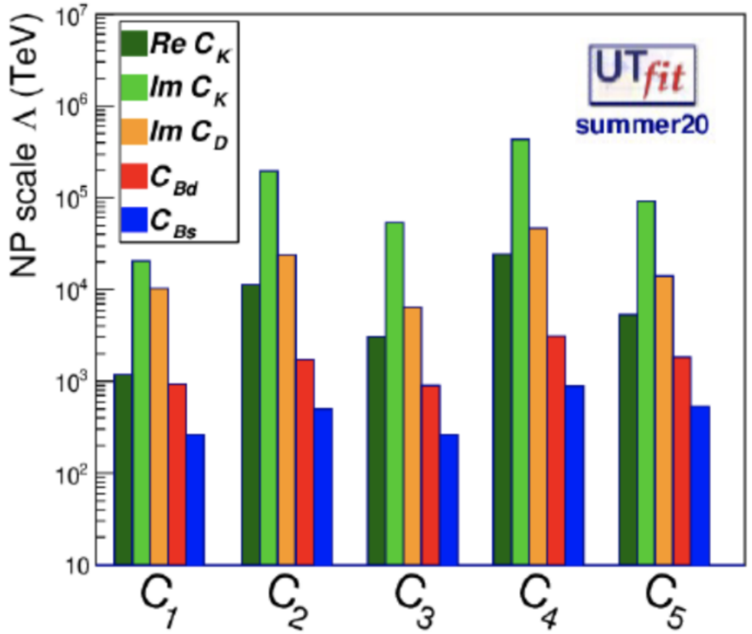
see E. Fuch's talk]

$$\delta M_h^2 \sim \frac{1}{16\pi^2} g^2 M_X^2$$

For the flavour puzzle this sensitivity of M_h^2 is (naively) severe:

- Directly concerns Higgs couplings $y\overline{\Psi}_L H \Psi_R$
- Flavour models typically feature many extra states, with large couplings to 3rd generation (top)
- Consistency with precision flavour data means some flavour-violating NP states need to be very heavy

Neutral meson mixing constraints



Barbieri, 2103.15635


IT'S A LITTLE TOO HOT FOR 125 GeV...
HIGGS

The natural view from the 2000s (Pre-LHC)

Higgs is surely stabilized by new physics near the TeV scale.

Q: How to reconcile with constraints on flavour-violation, which probe $\mathcal{O}(10^{4-5})$ TeV?

A: NP resolving the hierarchy problem is *minimally flavour violating* (MFV): nearly flavour-blind, with flavour violating effects set by SM Yukawas.

Flavour puzzle is probably then solved at much higher scales (M_h^2 now shielded from it)

D'Ambrosio, Giudice, Isidori, Strumia, hep-ph/0207036

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In 2020s, we know a lot more from the LHC!

No signs of TeV scale SUSY partners or composite resonances that would stabilize the Higgs.

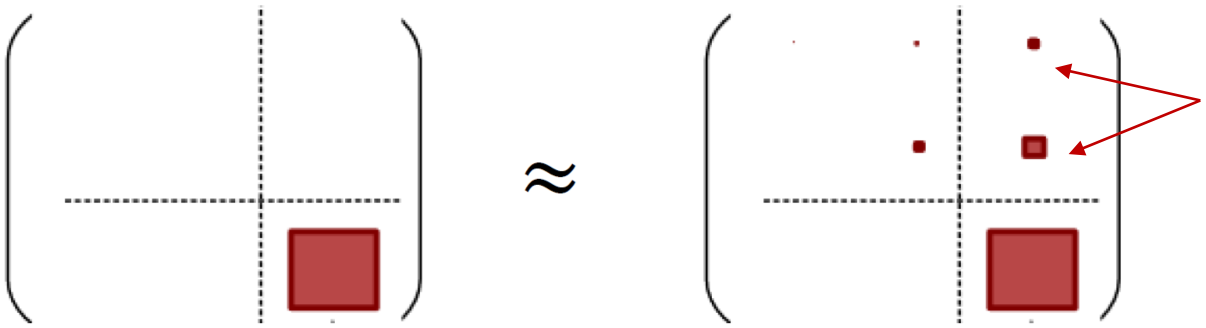
Under MFV hypothesis, ATLAS & CMS searches push back NP scales to $\sim$10 TeV (driven by contributions from light-flavour operators due mainly to PDF enhancement in pp)

But collider + flavour constraints still rather weak for 3rd family: TeV scale NP that is *very flavoured* remains viable. Maybe *flavour* is explained at *low* scales?

Q: Can we simultaneously preserve naturalness of EW scale?

Beyond MFV:
From $U(2)$ global symmetries to non-universal gauge symmetry

Yukawa matrices have approximate $U(2)^5 \subset U(3)^5$ global symmetries acting on light families



$U(2)$-breaking effects
Barbieri et al, 1105.2296
Isidori, Straub, 1202.0464
Fuentes-Martin et al, 1909.02519

Exact $U(2)$ limit | Observed Yukawa

- Naturally explained via NP that only allows 3rd family Yukawas, which must therefore be non-universal
- All NP in light generations can come from subleading $U(2)^5$-breaking effects
- Enables TeV scale NP to remain consistent both with precision flavour bounds + LHC searches

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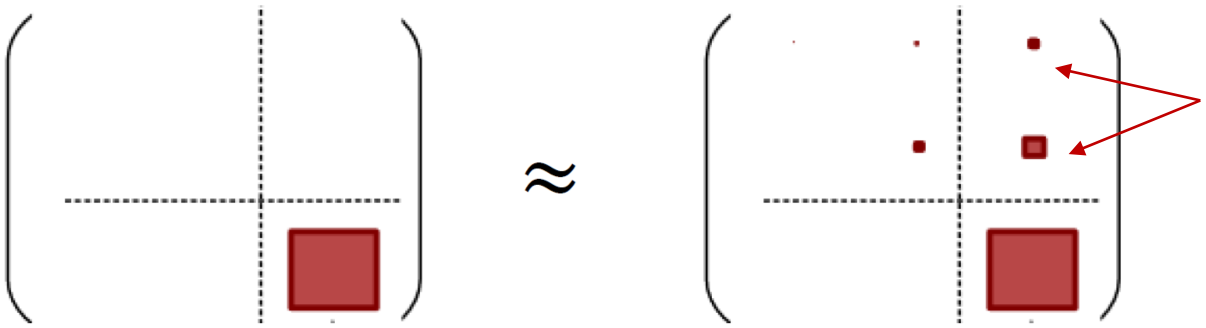

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This idea has is at the heart of much recent flavour models, all inspired by the ***B-anomalies***. E.g:

Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368; Greljo, Stefanek, 1802.04274; Fuentes-Martin, Stangl, 2004.11376; Davighi, 2105.06918; Fuentes-Martin, Isidori, Lizana, Selimovic, Stefanek, 2203.01952; Navarro, King, 2209.00276; Davighi, Isidori, Pesut, 2212.06163

Our goal:

Use *stability of Higgs mass* as a guide in the vast space of non-universal gauge models, to identify the *most natural models of flavour* consistent with current data

Our main hypotheses

Davighi, Isidori 2303.01520
See also Allwicher, Isidori, Thomsen, 2011.01946

1. TeV scale dynamics is a (weakly interacting) flavour non-universal gauge theory, which gives $U(2)^5$ emerging as accidental symmetry
2. Higgs is a fundamental scalar up to at least this energy scale (then e.g. SUSY or compositeness could screen from even higher scales)
3. Model has semi-simple embedding in the UV i.e. no fundamental $U(1)$ gauge symmetries (explains hypercharge quantisation; has a shot at being asymptotically free)
4. Quasi-naturalness of Higgs mass; identify models for which finite corrections from each NP sector satisfy $\delta M_h^2 \lesssim (100 \text{ GeV})^2$ as a rule of thumb

Assumption 3 (+ experiment) already cuts down the options:

Semi-simple embeddings of the SM are classified*; surprisingly few possibilities!

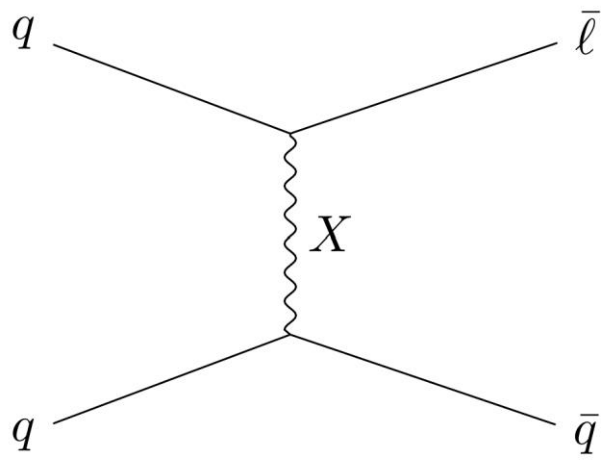
Allanach, Gripaios, Tooby-Smith, 2104.14555

All options use the basic unification patterns:

- Pati—Salam $SU(4) \times SU(2) \times SU(2)$ Pati, Salam, 1974
- $SU(5)$ Georgi, Glashow, 1974
- $SO(10)$ Georgi, 1975 and Fritzsch, Minkowski, 1975

BUT $SU(5)$ & $SO(10)$ feature **LQs that give tree-level proton decay!**
Experimental bound ⇒ $M_X \gtrsim$ GUT scale

So $SU(5)$ & $SO(10)$ -based options **cannot appear** in our low-scale, natural models



*Caveat: assuming no extra chiral fermions

$U(2)$ accidental symmetries from non-universal gauge interactions

Starting point: minimal extension of SM to $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
Then 'deconstructing' each factor only allows a subset of Yukawa couplings:

$$\mathrm{U}(1)^{[12]}_{B-L} \times \mathrm{U}(1)^{[3]}_{B-L} \qquad Y^F_{ij} \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$\mathrm{SU}(2)^{[12]}_{L} \times \mathrm{SU}(2)^{[3]}_{L} \qquad Y^F_{ij} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}$$

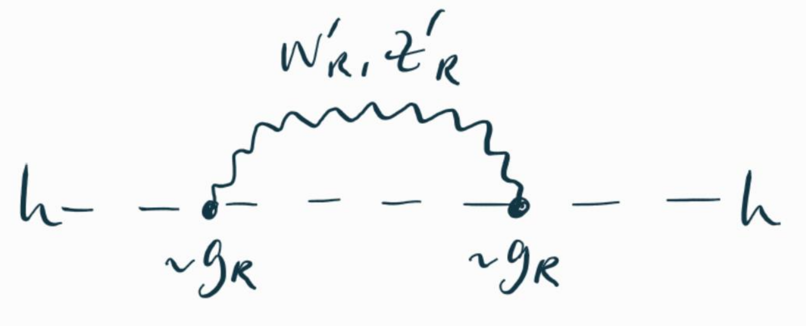
$$\mathrm{U}(1)^{[12]}_{R} \times \mathrm{U}(1)^{[3]}_{R} \qquad Y^F_{ij} \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & 0 & \times \\ 0 & 0 & \times \end{pmatrix}$$

Deconstructing any pair of these (or all three), with the Higgs charged only under the 3rd family groups, is enough to restrict to just Y_{33} renormalizable coupling

This gives 4 options to study:
one of $\{U(1)_{B-L}, SU(2)_L, U(1)_R, \text{nothing}\}$ is kept universal

Naturalness of electroweak gauge bosons

Because $SU(2)_L$ and $U(1)_R$ couple directly to Higgs, breaking deconstructed $SU(2)_L$ / $U(1)_R$ gives 1-loop Higgs mass corrections:



$$\Longrightarrow \quad \delta M_h^2 \sim \frac{1}{16\pi^2} g_{L/R}^2 M_X^2$$

Naturalness: $\delta M_h^2 \lesssim (100\ \mathrm{GeV})^2 \;\Rightarrow\; M_X \lesssim$ few TeV

Semi-simple completion: also embed $U(1)_R^{U/3} \hookrightarrow SU(2)_R^{U/3}$ at TeV scale

$$u_R, d_R \to q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

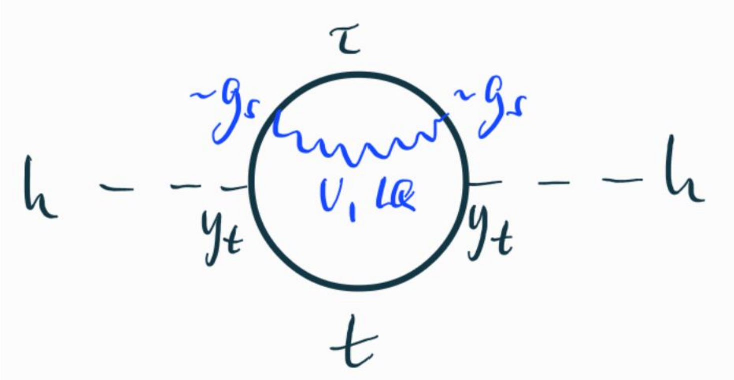
Naturalness of strong gauge bosons

What about $U(1)_{B-L}^{U/3}$?

Embedding into semi-simple G $\Longrightarrow$ *quark-lepton unification* via Pati—Salam $SU(4)$

$$q_{L/R}^a, l_{L/R} \to \begin{pmatrix} q_{L/R}^a \\ l_{L/R} \end{pmatrix}$$

The extra gauge bosons give 2-loop Higgs mass corrections:

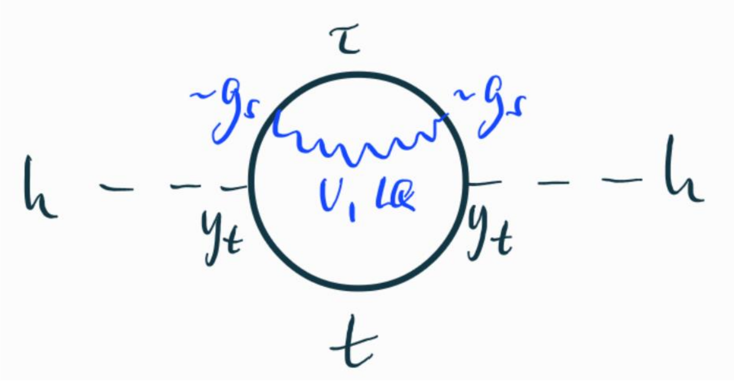


$$\Longrightarrow \quad \delta M_h^2 \sim \left(\frac{1}{16\pi^2}\right)^2 g_s^2 y_t^2 M_U^2$$

Naturalness: $\delta M_h^2 \lesssim (100\text{ GeV})^2 \Rightarrow M_U \lesssim 10$ TeV

[even though 2-loops, couplings are big]

Flavour universal $SU(4)$ is unnatural

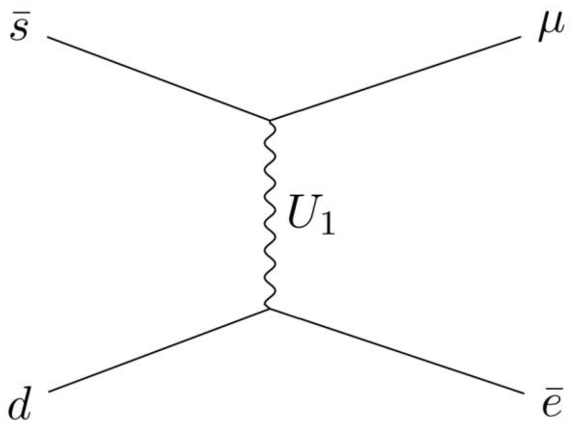


$\Rightarrow \; M_U \lesssim 10$ TeV

For universal $SU(4)$, *experimental flavour bounds* e.g., $K_L \to e^+\mu^-$ mediated by the U_1 gauge leptoquark, require $M_U \gtrsim 200$ TeV

Giudice et al., 1412.2769

$\Rightarrow$ discard universal $SU(4)$ options as unnatural



The TeV scale layer

End up with a very small class of natural models at the TeV scale:

$G_U \times G_3 \times H_{12}$			
	G_U	G_3	H_{12}
1	$SU(2)_L$	$SU(4)^{[3]} \times SU(2)_R^{[3]}$	$SU(3)^{[12]} \times U(1)_{B-L}^{[12]} \times U(1)_R^{[12]}$
2	$SU(2)_R$	$SU(4)^{[3]} \times SU(2)_L^{[3]}$	$SU(3)^{[12]} \times SU(2)_L^{[12]} \times U(1)_{B-L}^{[12]}$
3	$SU(4)$	$SU(2)_L^{[3]} \times SU(2)_R^{[3]}$	$SU(2)_L^{[12]} \times U(1)_R^{[12]}$
4	$\emptyset$	$SU(4)^{[3]} \times SU(2)_L^{[3]} \times SU(2)_R^{[3]}$	$SU(3)^{[12]} \times SU(2)_L^{[12]} \times U(1)_{B-L}^{[12]} \times U(1)_R^{[12]}$

Option 4 has been used in various models: Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368; Fuentes-Martin, Isidori, Lizana, Selimovic, Stefanek, 2203.01952; Davighi, Isidori, Pesut, 2212.06163

Phenomenological implications:

- All natural models feature $U_1 \sim (\mathbf{3},\mathbf{1})_{2/3}$ vector LQ + coloron $G \sim (\mathbf{8},\mathbf{1})_0$ + Z', $M < 10$ TeV
- Pheno of these particles has been well-studied in connection to *B*-anomalies
- Strengthens motivation to continue searches in $pp \to \tau\tau/tt$ (independent of anomalies!)
- All models also have flavoured EW gauge bosons, $M <$ few TeV – *pheno not as well studied*

See J. Lizana's talk

The TeV scale layer

Mixing between light & third generations
What flavour structures do we get for the different options?

Model 1 ($SU(2)_L$ remains universal): [New!]

$$Y^F \sim \begin{pmatrix} \epsilon_R & \epsilon_\Omega \\ \epsilon_\Omega \epsilon_R & 1 \end{pmatrix} \qquad \epsilon_\Omega \sim |V_{cb}|, \qquad \epsilon_R \sim \frac{y_2}{y_3}$$

RH fermion mixing naturally suppressed ☑ ☑

Model 2 ($SU(2)_R$ remains universal): [Unnatural]

$$Y^F \sim \begin{pmatrix} \epsilon_L & \epsilon_\Omega \epsilon_L \\ \epsilon_\Omega & 1 \end{pmatrix}$$

RH mixing $\gg$ LH mixing. Needs huge tuning to evade bounds from e.g. B_s meson mixing ✗

Model 4 (both $SU(2)_L$ and $SU(2)_R$ deconstructed):

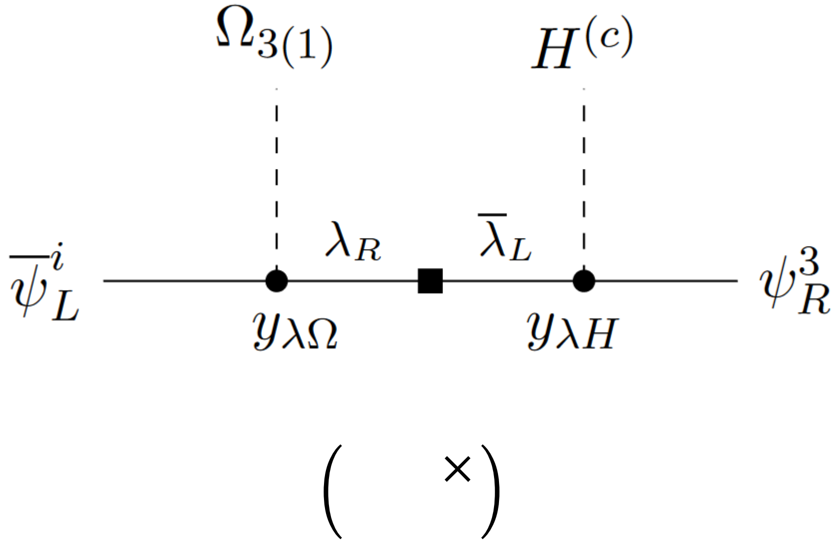
$$Y^F \sim \begin{pmatrix} \epsilon_L \epsilon_R & \epsilon_\Omega \epsilon_L \\ \epsilon_\Omega \epsilon_R & 1 \end{pmatrix}$$

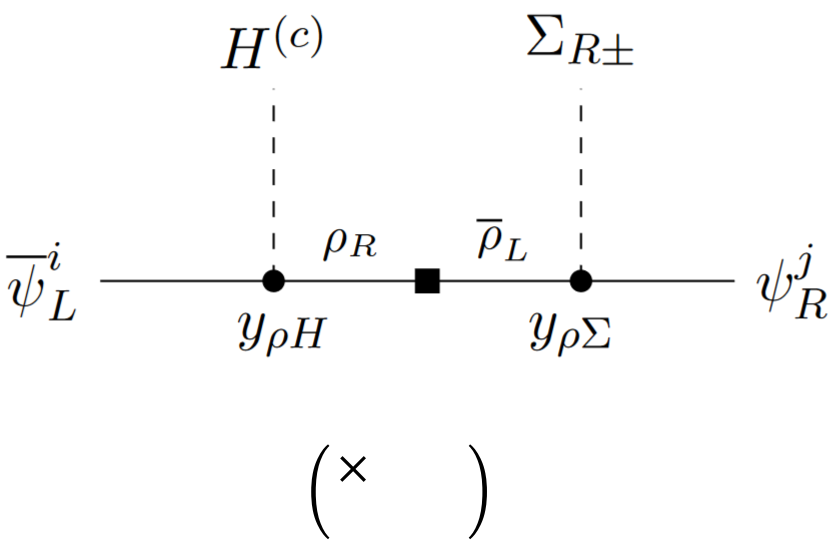
RH mixing can be suppressed by invoking a mild hierarchy of scales: $\epsilon_R \ll \epsilon_L$ ☑

The TeV scale layer

UV completion of the mixing interactions

Completion of EFT via vector-like fermions E.g. for Model 1 ($SU(2)_L$ remains universal):

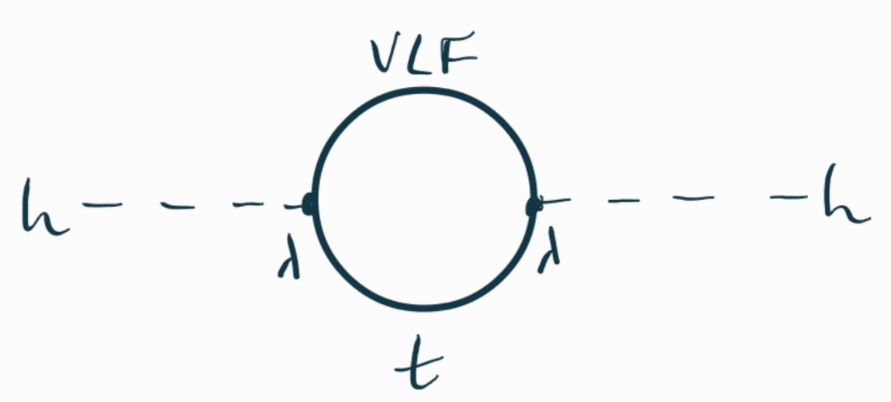




[With these vector-like fermions the bottom row isn't generated even at dimension-6: very safe from RH fermion mixing constraints]

The TeV scale layer

Naturalness of the vector-like fermions



$$\Rightarrow \quad \delta M_h^2 \sim \frac{1}{16\pi^2}\lambda^2 M^2$$

Naturalness: $\delta M_h^2 \lesssim (100\ \mathrm{GeV})^2 \Rightarrow |y|M \lesssim 700$ GeV

Phenomenological implications:

- TeV scale vector-like quarks and leptons
- LHC bounds on VLQs already exclude $M < 1.5$ TeV; just means coupling $< \frac{1}{2}$ or so

CMS Collaboration 2209.07327

Deeper into the UV

Resolving the light generations

Further layer of NP at scale Λ_{12} is needed to resolve the 1^{st} and 2^{nd} generations, such as:

- Further deconstruction of electroweak symmetries by *light-flavour*
- Electroweak-flavour unification via $Sp(4)_{L/R}$ symmetries

Bordone et al 1712.01368
Davighi, Tooby-Smith, 2201.07245
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Flavour bounds require $\Lambda_{12} \gtrsim 100 - 1000$ TeV

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Flavour bounds require $\Lambda_{12} \gtrsim 100 - 1000$ TeV

Model 1 ($SU(2)_L$ universal) again gives efficient account of masses and mixing in light families
Invoking $Sp(4)_R$ + 1 more VLF
[full UV completion, $G = SU(2)_L \times SU(4)^3 \times SU(4)^{12} \times SU(2)_R^3 \times Sp(4)_R^{12}$]

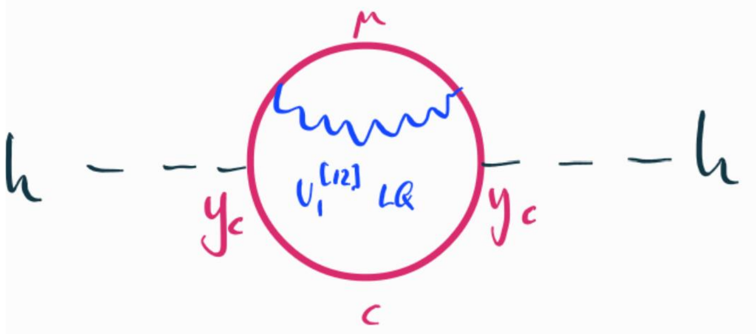
$$\hat{Y}^F \sim \begin{pmatrix} \delta_R y_{11} & y_{12} \\ \delta_R y_{21} & y_{22} \end{pmatrix}$$

Masses: $m_1 \sim \delta_R, m_2 \sim 1$ [both in units of ϵ_R]
LH mixing: Cabibbo $\sim \mathcal{O}(1)$
RH mixing: δ_R - suppresses RH mixing in 1-2 sector

Naturalness of the 1-2 sector

None of the extra states couples directly to Higgs or top
All the associated M_h^2 corrections therefore suppressed by at least 2-loops + small mixings

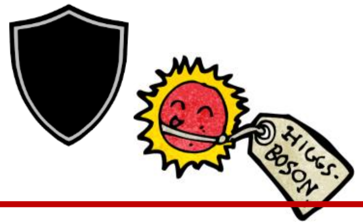
E.g. from $SU(4)^{12}$ breaking



Naturalness of the 1-2 sector

Could even shield M_h^2 completely from Λ_{12} by compositeness/SUSY just above the TeV scale layer:

$\mathcal{O}(100-1000\ \text{TeV})$ — 1-2 sector generated



3rd family compositeness?

$\mathcal{O}(10\ \text{TeV})$ — U_1, G, Z'

W'_R, Z'_R

$\mathcal{O}(1\ \text{TeV})$ — Vector-like fermions

$\mathcal{O}(100\ \text{GeV})$ — *W, Z, h,* 3rd family fermions

Light Yukawas

...

Naturalness of the 1-2 sector

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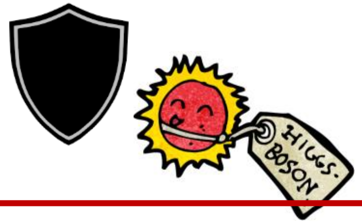
… Higher physical scales

$\mathcal{O}(100-1000\text{ TeV})$ 1-2 sector generated



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$\mathcal{O}(10\text{ TeV})$ U_1, G, Z'

W'_R, Z'_R

$\mathcal{O}(1\text{ TeV})$ Vector-like fermions

$\mathcal{O}(100\text{ GeV})$ *W, Z, h,* 3rd family fermions

Light Yukawas

…

Conclusions

- BSM models of flavour predict heavy particles coupled to Higgs and top quark – threaten electroweak stability

- It appears H isn't stabilized at TeV scale by flavour-blind physics. But data allows TeV NP in 3rd family – such as flavour non-universal gauge bosons that explain the flavour hierarchies

- Requiring that these non-universal gauge symmetries give $\mathcal{O}(100\ \mathrm{GeV})$ Higgs mass corrections, while being compatible with data (e.g., p decay, e/μ violation) selects a small number of models

- Option with $SU(2)_L$ remaining universal, but colour & hypercharge deconstructed at the TeV scale, is most natural (and previously unstudied)

- (Flavoured version of) compositeness could still kick in at higher scales $\mathcal{O}(10\ \mathrm{TeV})$ to stabilize H from whatever lurks in the deep UV…