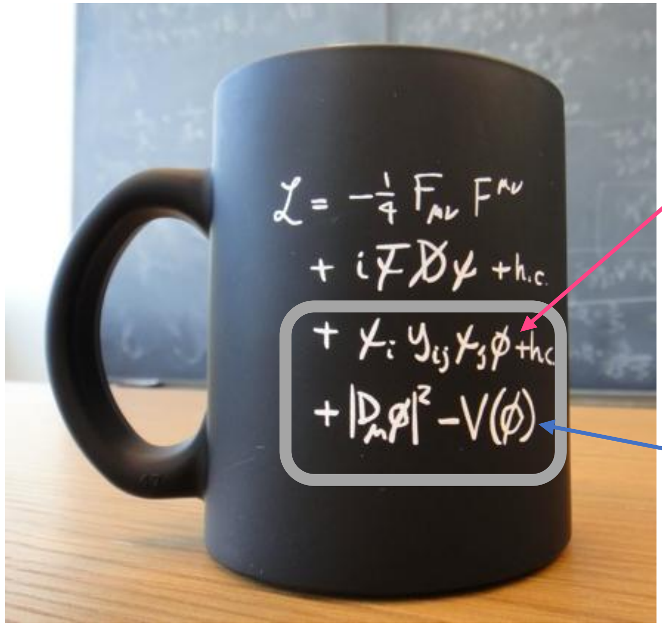
New Physics for the Flavour Puzzle

Joe Davighi, CERN

MITP, June 18th 2025

Our Guide to New Physics (Ideology)



Flavour puzzle: $y_{ij} \ll y_t \sim 1$

Hierarchy problem: $m_h^2 \ll M_{\mathrm{NP}}^2$

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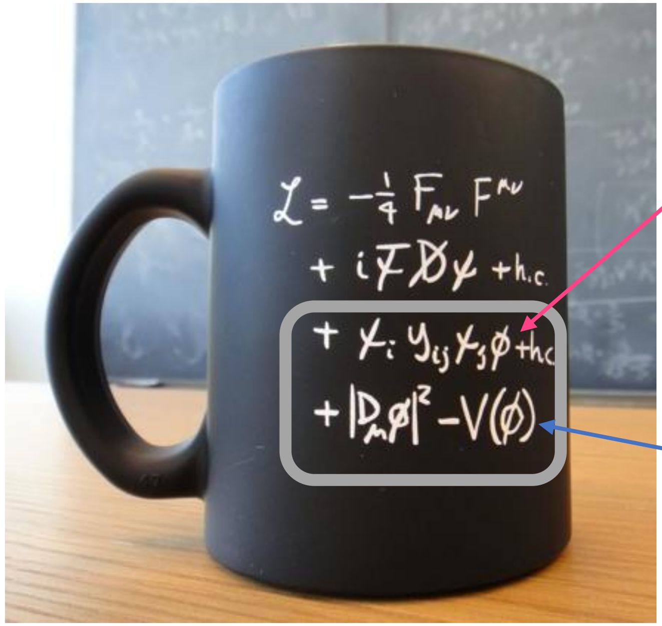

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Radiative corrections to y_{ij}^f are logarithmic in M_{NP}

$\Longrightarrow$ New physics **somewhere**

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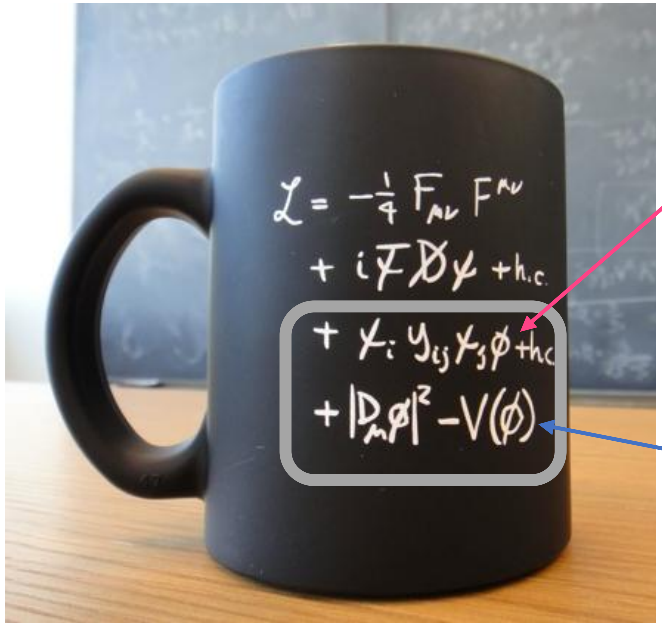

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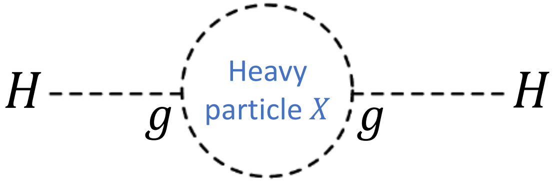

$$\Longrightarrow \delta M_h^2 \Big|_{\text{from } X} \sim \left(\frac{g^2}{16\pi^2}\right)^n M_{\rm NP}^2$$

Hierarchy problem: $m_h^2 \ll M_{\rm NP}^2$

Radiative corrections to m_h^2 are **quadratic** in $M_{\rm NP}$

$\Longrightarrow$ Cut-off UV loops by new physics $\lesssim 4\pi m_h \approx$ **TeV**

E.g. SUSY, compositeness

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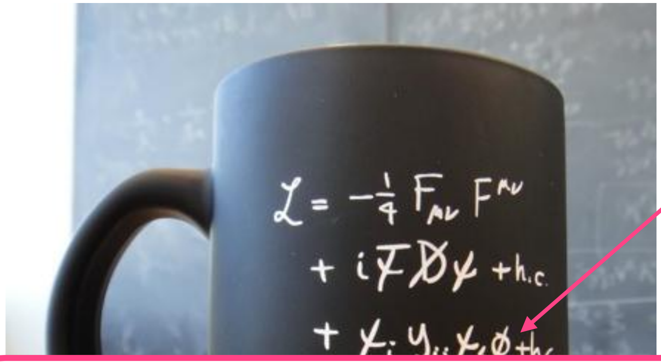

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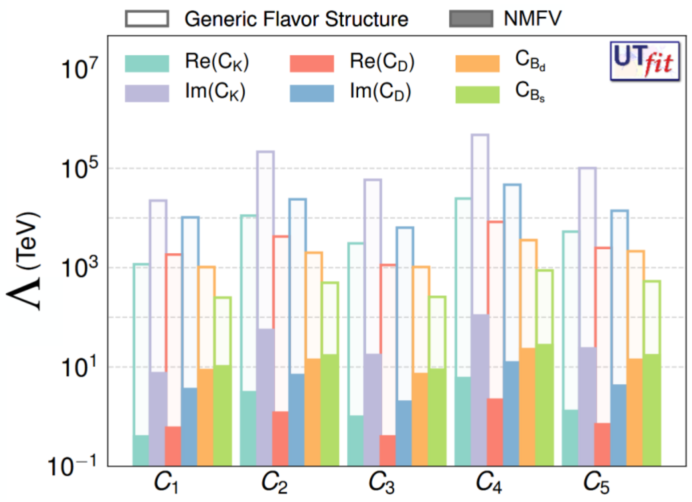

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Precision flavour tests $\Longrightarrow$ NP flavour structure $\approx$ SM

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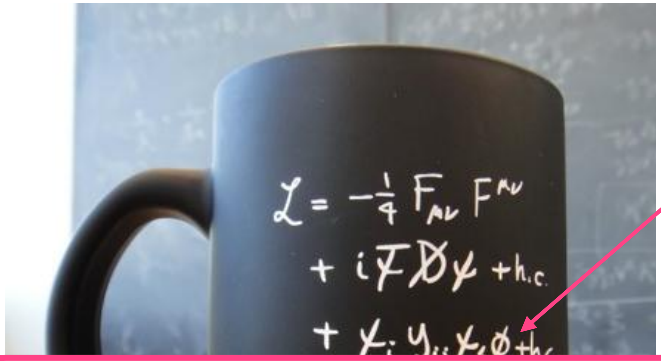

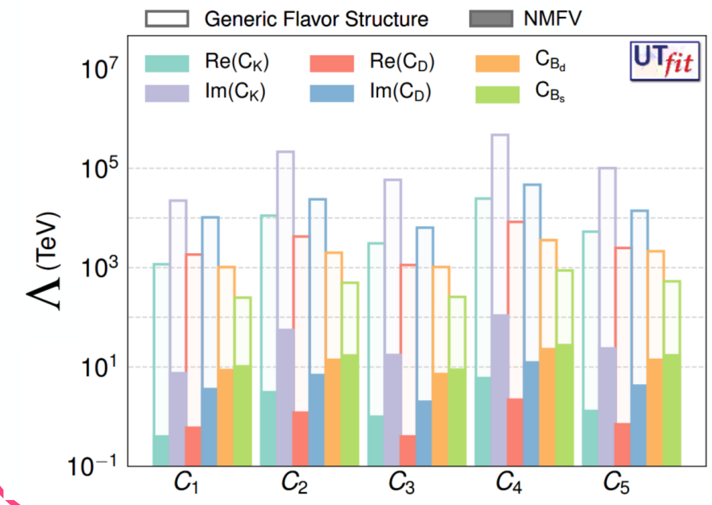

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Precision flavour tests $\Longrightarrow$ NP flavour structure $\approx$ SM

Hypothesis: SM flavour structure also generated at a low scale?

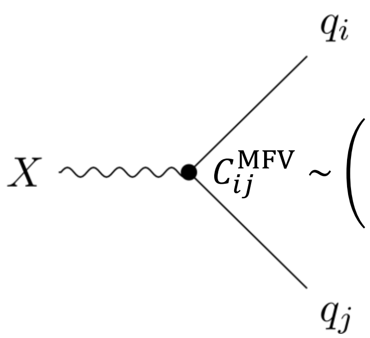
2. Non-Universal New Physics

Flavour Universal New Physics

Minimal Flavour Violation:

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

- Yukawa interactions $y_{ij}\bar{\psi}_i H \psi_j$ are the *only* couplings that distinguish flavour



$$C_{ij}^{\mathrm{MFV}} \sim \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} + h_{ij}(y_{u,d,e})$$

- Designed pre-LHC to protect flavour observables from SUSY / Composite Higgs near 1 TeV

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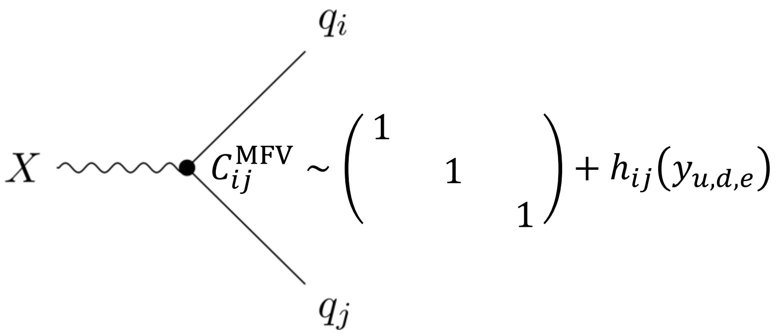

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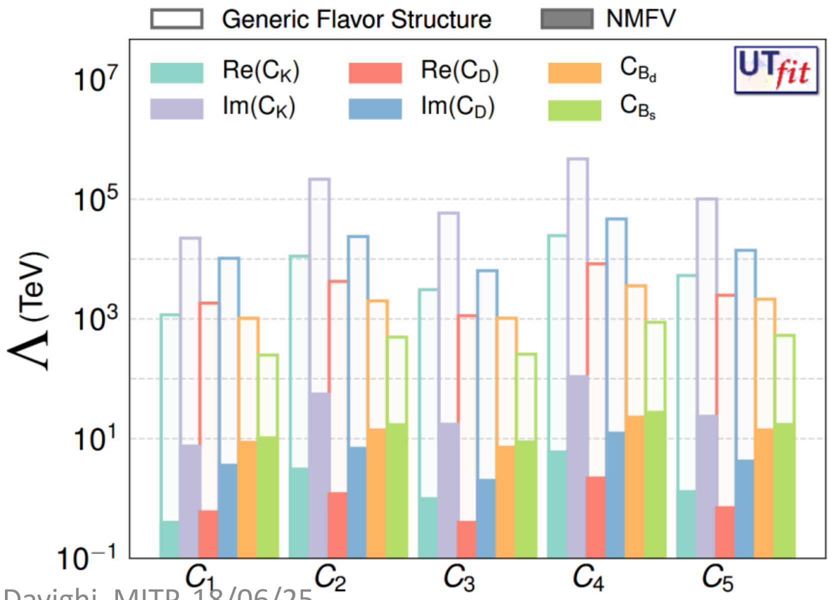
Example: Kaon mixing with MFV:

$$\frac{1}{\Lambda_{sd}^2} \sim y_t^4 (V_{31}V_{32}^*)^2 \frac{1}{\Lambda_{\mathrm{NP}}^2} \sim \left(\frac{10^{-5}}{\Lambda_{\mathrm{NP}}}\right)^2$$



NMFV:
C(Λ) = $\alpha \times |F_{SM}|/\Lambda^2$, $F_i \sim |F_{SM}|$, arbitrary phase

$\alpha \sim 1$ for strongly coupled NP

$\Lambda > 108$ TeV

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions

$\Lambda > 3.2$ TeV

M. Bona @ ICHEP 24

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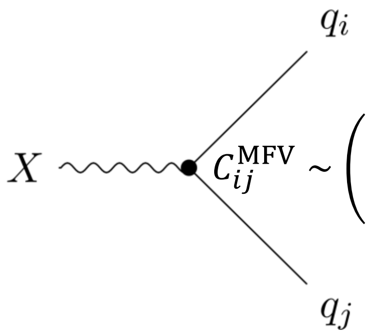

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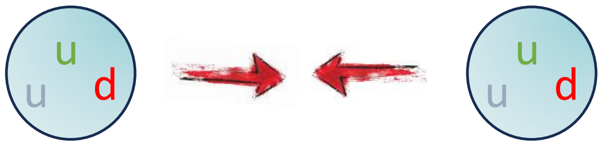
- Designed pre-LHC to protect flavour observables from SUSY / Composite Higgs near 1 TeV
- **LHC** constraints circa 2025: $\Lambda_{\mathrm{MFV}} \approx 5 \div 10\ \mathrm{TeV}$



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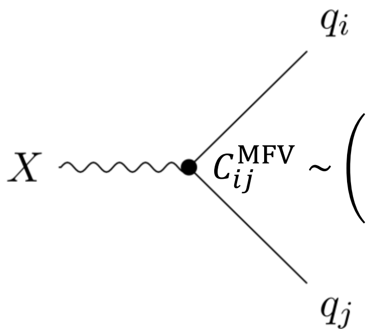

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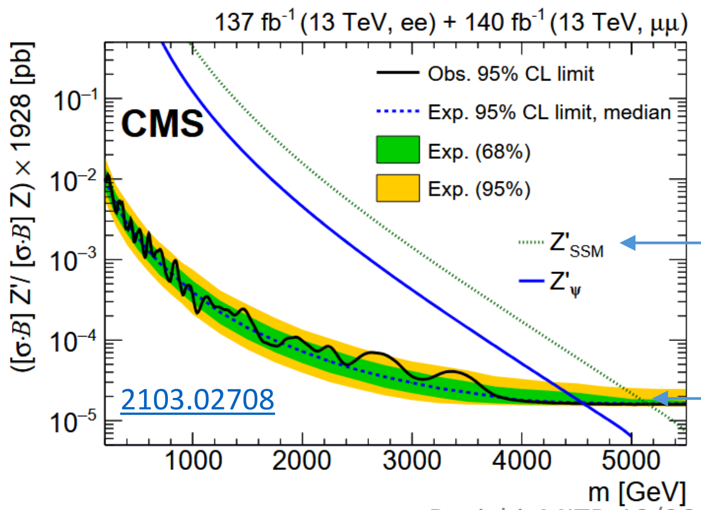
For composite Higgs
$M_*^{\mathrm{MFV}} \approx 7 \div 8\ \mathrm{TeV}$

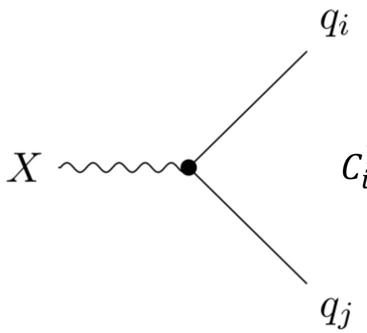
Glioti, Rattazzi, Ricci, Vecchi, 2402.09503



"Sequential SM"

$M_{\mathrm{MFV}\ Z'} > 5\ \mathrm{TeV}$

Flavour Non-Universal New Physics



$$C_{ij}^{\mathrm{MFV}} \sim \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} \longrightarrow C_{ij}^{\mathrm{U2}} \sim \begin{pmatrix} a & & \\ & a & \\ & & b \end{pmatrix}$$

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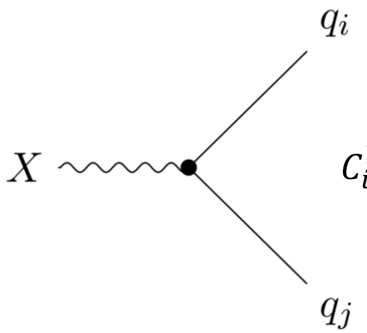

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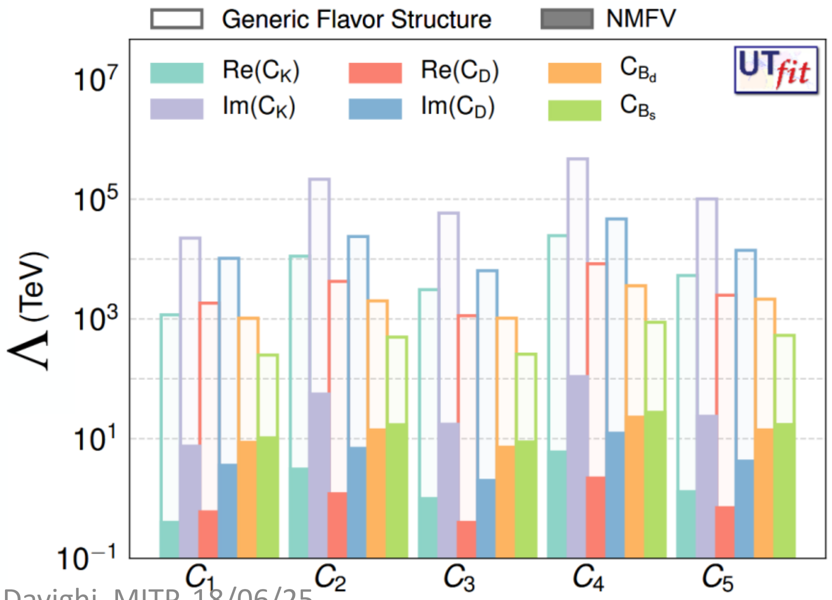
Just as good flavour protection as MFV ☑

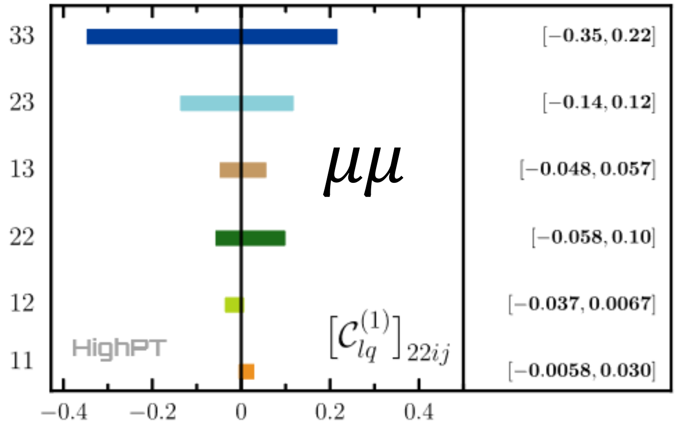
Example: Kaon mixing with ~~MFV~~ U2

$$\frac{1}{\Lambda_{sd}^2} \sim y_t^4 (V_{31} V_{32}^*)^2 \frac{1}{\Lambda_{\mathrm{NP}}^2} \sim \left(\frac{10^{-5}}{\Lambda_{\mathrm{NP}}}\right)^2$$



Flavour Non-Universal New Physics

$$y^u_{ij} \approx \begin{pmatrix} & <0.01 & 0.04 \\ & & \\ & & 1 \end{pmatrix} \quad C^{\mathrm{MFV}}_{ij} \sim \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} \quad \longrightarrow \quad C^{\mathrm{U2}}_{ij} \sim \begin{pmatrix} a & & \\ & a & \\ & & b \end{pmatrix}$$



Allwicher et al, 2207.10714; 2207.10756

Two reasons to prefer U2 over MFV:

1. Lowering Λ

- Limit $a \ll b$ can **reduce little hierarchy** by a factor a few → $\Lambda_{\mathrm{U(2)}} \approx 1 \div 2\ \mathrm{TeV}$

2. Solving the SM flavour puzzle!

- The *same* $U(2)$-like non-universal BSM could explain SM *and* BSM flavour puzzles

$$y^u_{ij} \approx \begin{pmatrix} & <0.01 & 0.04 \\ & & 1 \end{pmatrix} \leftarrow y_t$$

For composite Higgs
$M^{\mathrm{U(2)}}_* \approx 1 \div 2\ \mathrm{TeV}$

Glioti, Rattazzi, Ricci, Vecchi, 2402.09503
Stefanek, 2407.09593

U2 decouples strong bounds:
- $pp \to jj$,
- Modified W-couplings

Dynamical origin of $U(2)^n$?

A general hypothesis:

- Accidental symmetries emerging from a non-universal [3 vs 1+2] **gauge** symmetry

Froggatt, Nielsen, Nucl Phys B (1979)
+ ...

A more specific hypothesis:

- Flavour Deconstruction

3. Flavour Deconstruction

Non-Universality from Flavour Deconstruction

$$G_1 \times G_2 \times G_{3+\mathrm{H}} \xrightarrow{\langle \phi_{12} \rangle \sim 10^{2\div 3}\ \mathrm{TeV}} G_{12} \times G_{3+\mathrm{Higgs}} \xrightarrow{\langle \phi_{23} \rangle \sim 1\ \mathrm{TeV}} G_{123}$$

$U(2)$ violation

Delivers $U(2)$ flavour symmetry

E.g. $G = SU(2)_L$ or $U(1)_Y$ or …

Li, Ma, 1981, …
Arkani-Hamed, Cohen, Georgi hep-th/0104005 …
Craig, Green, Katz 1103.3708 …
Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368 …
Davighi, Isidori, 2303.01520…

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Davighi, Isidori, 2303.01520…

Some top-down motivations

1. Breaking pattern $G_A \times G_B \to G_{A+B}$, given scalar condensate ϕ, is **generic** for simple G
   - … because there is no other non-trivial subgroup embedding

Goursat, 1889
Craig, Garcia-Garcia, Sutherland, 1704.07831

2. Easy to find semi-simple UV completions with deconstruction approach
   - In contrast most $G_{\mathrm{SM}} \times U(1)_{\mathrm{horizontal}}$, even anomaly-free, have no semi-simple completion

Davighi, Tooby-Smith, 2206.11271

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Delivers $U(2)$ flavour symmetry

$$\psi_1 H \psi_3 \frac{\phi_{23}\phi_{12}}{\Lambda_{23}\Lambda_{12}} \to V_{ub} \ll V_{cb} \ll 1$$

etc

$$\psi_2 H \psi_3 \frac{\phi_{23}}{\Lambda_{23}} \to V_{cb} \ll 1$$

etc

SM Flavour Puzzle ☑

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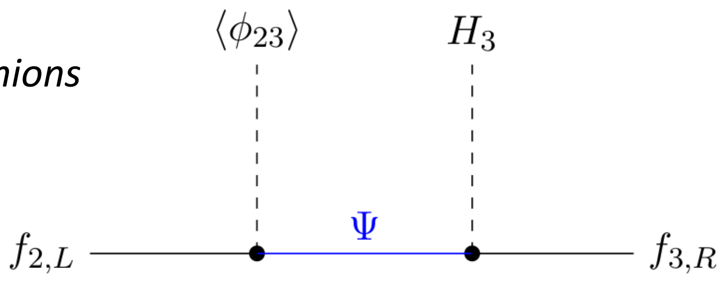
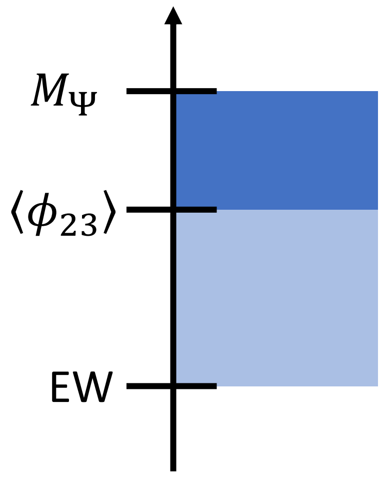
SM Flavour Puzzle ☑

Example UV:
Vector-like fermions



$$\Lambda_{23} \sim M_\Psi / g$$



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$U(2)$ violation

Delivers $U(2)$ flavour symmetry

Vector bosons in adj G, w **flavour diagonal** BUT **non-universal** couplings

$$C_{ij} \sim g_{\mathrm{SM}} \begin{pmatrix} g_{12}/g_3 & & \\ & g_{12}/g_3 & \\ & & g_3/g_{12} \end{pmatrix}, \qquad g_{12}, g_3 \geq g_{\mathrm{SM}}.$$

Define $\tan\theta = g_3/g_{12}$

Non-Universality from Flavour Deconstruction

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$G_{12} \times G_{3+H} \to G_{\mathrm{SM}}$ **can** occur near TeV because **no flavour violation** + $g_3 \gg g_{1,2}$ **U2 limit** possible

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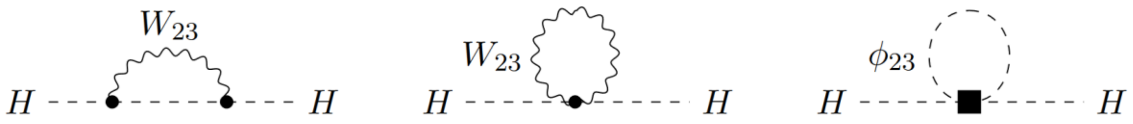
$G_{12} \times G_{3+H} \to G_{\mathrm{SM}}$ **can** occur near TeV because **no flavour violation** + $g_3 \gg g_{1,2}$ **U2 limit** possible

$G_{12} \times G_{3+H} \to G_{\mathrm{SM}}$ **should** occur near TeV to not worsen the little hierarchy problem

Davighi, Isidori 2303.01520



$$\delta m_h^2 \sim \frac{g_{\mathrm{SM}}^2 \tan^2\theta\, M^2}{16\pi^2}$$

Flavour Deconstruction = a finite *class* of models

Which SM gauge interaction should we deconstruct?

- What can we explain?
- What is the phenomenology, and at what scale?

What to Deconstruct?

Davighi, Isidori 2303.01520

	Deconstructed force	$SU(3)$	$SU(2)_L$	$SU(2)_R$	$U(1)_Y$	$U(1)_{B-L}$
Flavour	$\lvert V_{cb}\rvert \ll 1$	✓	✓	×	✓	✓
	$y_i \ll y_3$	×	✓	✓	✓	×

$$Y \sim \begin{pmatrix} \times & \times & \\ \times & \times & \\ & & \times \end{pmatrix} \quad \begin{pmatrix} & & \\ & & \\ \times & \times & \times \end{pmatrix} \quad \begin{pmatrix} & & \times \\ & & \times \\ & & \times \end{pmatrix} \quad \begin{pmatrix} & & \\ & & \\ & & \times \end{pmatrix} \quad \begin{pmatrix} \times & \times & \\ \times & \times & \\ & & \times \end{pmatrix}$$

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Davighi, Isidori 2303.01520

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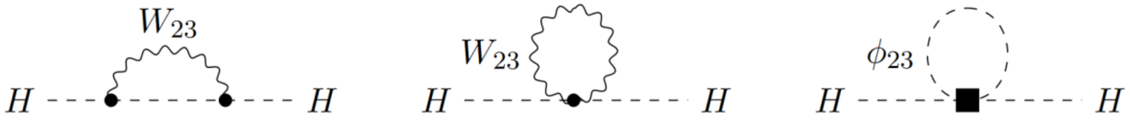
Flavour	$\lvert V_{cb}\rvert \ll 1$ $y_i \ll y_3$	$\checkmark$ $\times$	$\checkmark$ $\checkmark$	$\times$ $\checkmark$	$\checkmark$ $\checkmark$	$\checkmark$ $\times$
EW	Natural upper limit of $\lvert\tan\theta\rvert M$ EWPOs order	90 TeV 1-loop	20 TeV Tree	40 TeV Tree	40 TeV Tree	500 TeV 1-loop

$Y \sim \begin{pmatrix} \times & \times & \\ \times & \times & \\ & & \times \end{pmatrix}$ $\begin{pmatrix} & & \\ & & \\ \times & \times & \times \end{pmatrix}$ $\begin{pmatrix} & & \times \\ & & \times \\ & & \times \end{pmatrix}$ $\begin{pmatrix} & & \\ & & \\ & & \times \end{pmatrix}$ $\begin{pmatrix} \times & \times & \\ \times & \times & \\ & & \times \end{pmatrix}$

"Finite naturalness" limits on M_X from requiring the finite part of $\delta m_h^2 \lesssim 1\ \mathrm{TeV}^2$



General Lesson

- Need to deconstruct part of the EW symmetry to explain the flavour puzzle
- Unavoidable tree-level δ EWPOs
- Unavoidable 1-loop δm_h^2

A UV scenario: from Deconstruction to Unification

Davighi, Tooby-Smith, 2201.07245, Davighi, 2206.04482

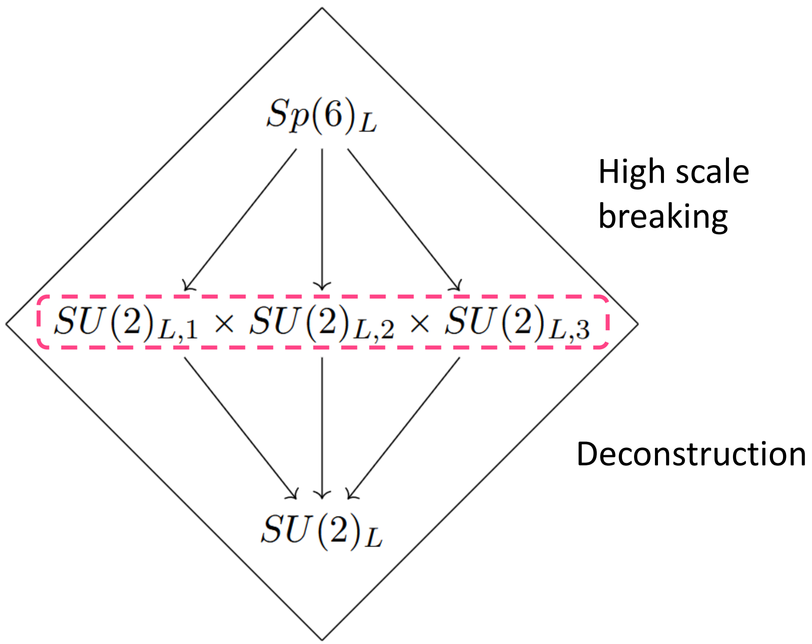
Whence $G_1 \times G_2 \times G_{3+\mathrm{H}}$? One path is to **reunify** in the UV! Using e.g. $SU(2)^{n_f} \cong Sp(2)^{n_f} \hookrightarrow Sp(2n_f)$

Electroweak flavour unification: $\mathrm{G}_{\mathrm{UV}} = SU(4) \times Sp(6)_L \times Sp(6)_R$

- **All SM matter unified*** into $\Psi_L \sim (\mathbf{4}, \mathbf{6}, \mathbf{1})$ + $\Psi_R \sim (\mathbf{4}, \mathbf{1}, \mathbf{6})$

Reminder:

$Sp(6) = \{U \in SU(6) | U^T \Omega U = \Omega\}$ where $\Omega = \begin{pmatrix} 0 & I_3 \\ -I_3 & 0 \end{pmatrix}$



*Very few anomaly-free options that do this!

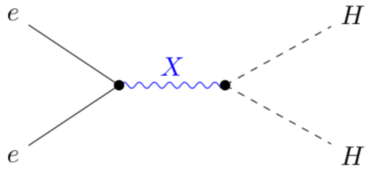
4. Phenomenology of Flavour Deconstruction

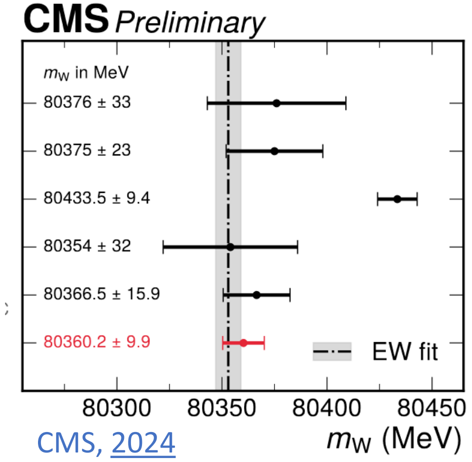
Phenomenology of Electroweak Deconstruction

$DU(1)_Y$: Davighi, Stefanek 2305.16280; Fernández Navarro, King 2305.07690
$DSU(2)_L$: Davighi, Gosnay, Miller, Renner 2312.13346; Capdevila, Crivellin, Lizana, Pokorski 2401.00848

EWPOs: tree-level shifts in Z/W-pole means EW constraints often strongest!

- A key observable is m_W: $\mathrm{DSU}(2)_L \Rightarrow \delta m_W < 0$; $DU(1)_Y \Rightarrow \delta m_W > 0$

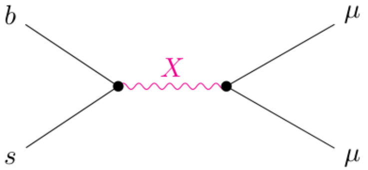




CMS, 2024

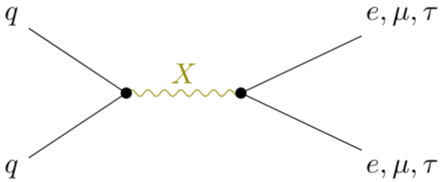
Flavour: key observable is $BR(B_s \to \mu^+\mu^-)$, measured precisely at LHC

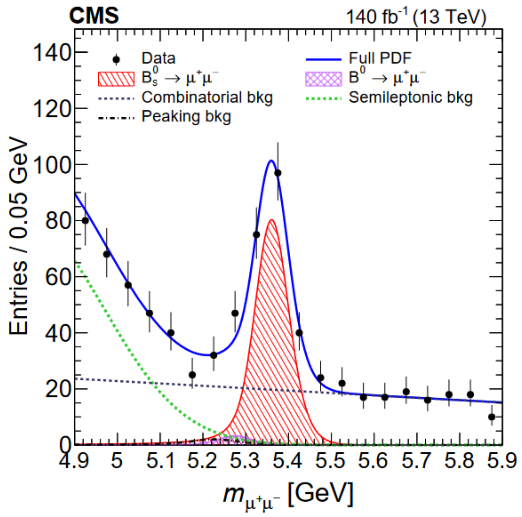
- B_s mixing strictly subleading in these models
- Power-suppressed by $y_Q = 1/6$ for $DU(1)_Y$



LHC high p_T: driven by valence-quark couplings

- Favours $g_3 \gg g_{12}$ region i.e. $\theta \to \pi/2$



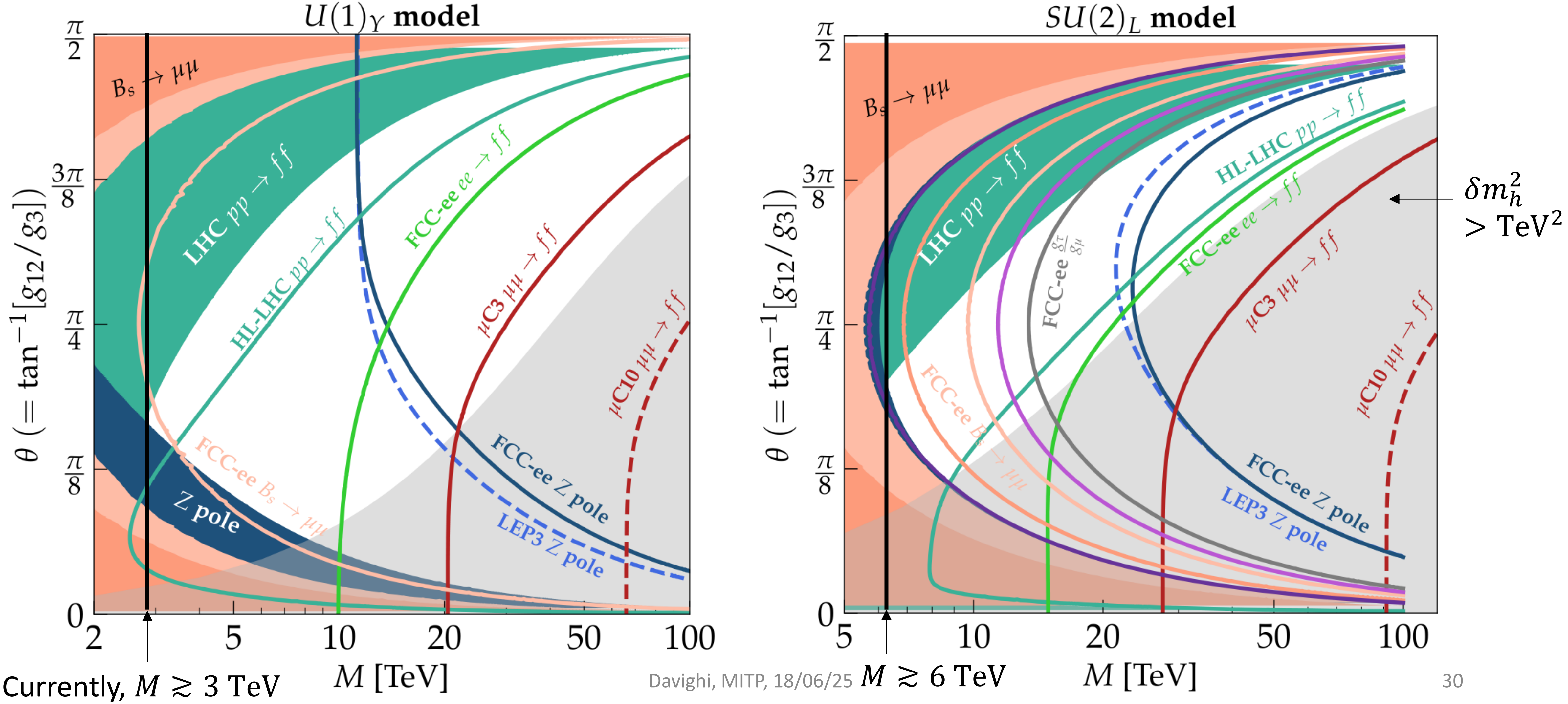


CMS, 2212.10311

Phenomenology of Electroweak Deconstruction

$DU(1)_Y$: Davighi, Stefanek 2305.16280; Fernández Navarro, King 2305.07690
$DSU(2)_L$: Davighi, Gosnay, Miller, Renner 2312.13346; Capdevila, Crivellin, Lizana, Pokorski 2401.00848

Updated plots courtesy of Sophie Renner 🙏



Currently, $M \gtrsim 3$ TeV $\quad M \gtrsim 6$ TeV

There is much more to learn…

FCC-ee will test these models not only through EWPOs and $\sigma(e^+e^- \to ff)$, but also low-energy flavour probes

- FCC-ee flavour studies well-developed for processes with τ, ν

Kamenik, Monteil, Semkiv, Vale Silva 1705.11106
Miralles, Thesis 2024
Amhis, Hartmann, Helsens, Hill, Sumensari, 2105.13330
Zuo, Fedele, Helsens, Hill, Iguro, Klute, 2305.02998
Amhis, Kenzie, Reboud, Wiederhold, 2309.11353

… But these deconstruction models give **cancellations** in most tau observables

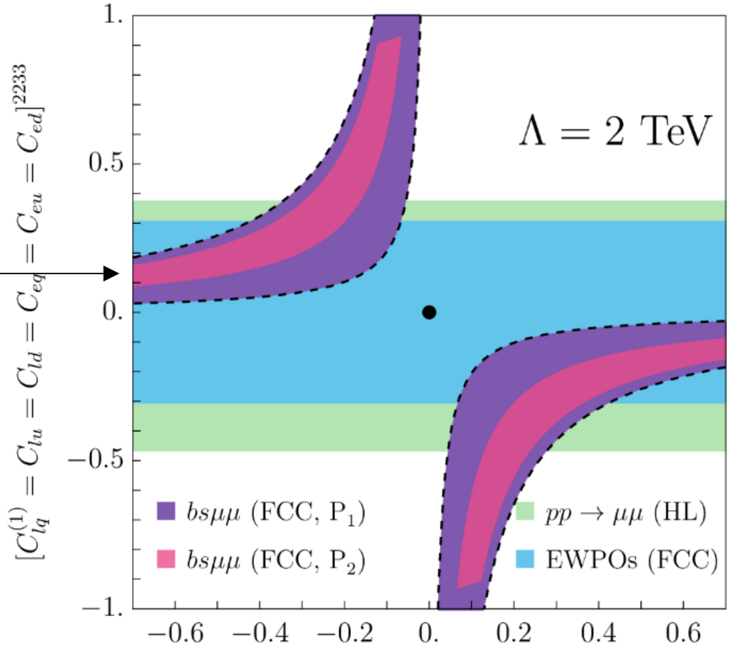
- Prospects in e.g. $\boldsymbol{bs\mu\mu}$ and $\boldsymbol{bsee}$ are very little explored so far

$$BR(B \to K^*\mu\mu) + BR(B_s \to \mu\mu)$$

Bordone, Cornella, Davighi, 2503.22635

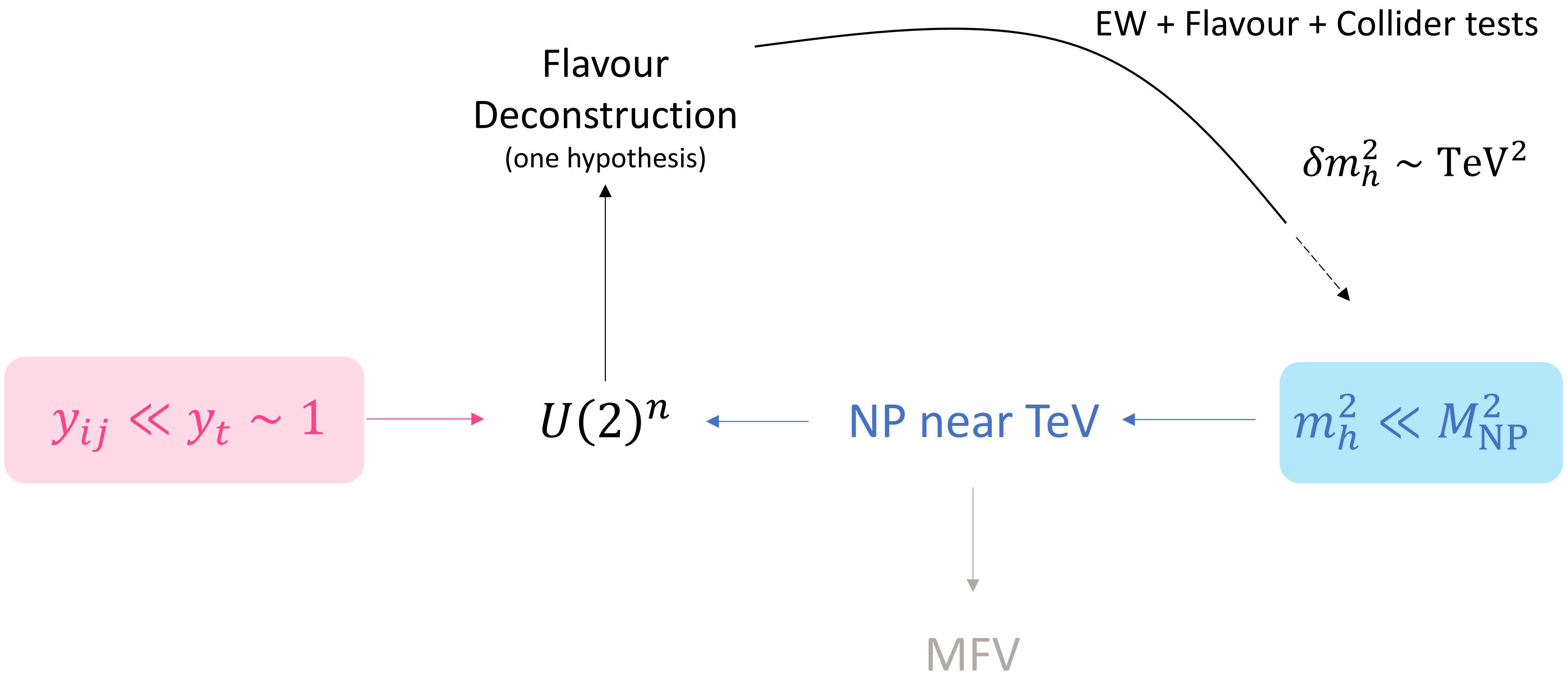
To make the most of FCC-ee statistics requires significant improvement in theory uncertainties

"P2": $\sigma_{\rm FF} \to \sigma_{\rm FF}/5; \quad \sigma_{V_{cb}} \to 0.5\%$



* For NP coupled **vectorially** to 3rd generation quarks and muons

5. Higgs and Flavour – Together


EW + Flavour + Collider tests
Flavour
Deconstruction
(one hypothesis)
$\delta m_h^2 \sim \mathrm{TeV}^2$
$y_{ij} \ll y_t \sim 1$
$U(2)^n$
NP near TeV
$m_h^2 \ll M_{\mathrm{NP}}^2$
MFV

EW + Flavour + Collider tests

Flavour
Deconstruction
(one hypothesis)

$\delta m_h^2 \sim \text{TeV}^2$

$y_{ij} \ll y_t \sim 1$ $\rightarrow$ $U(2)^n$ $\leftarrow$ NP near TeV $\leftarrow$ $m_h^2 \ll M_{\text{NP}}^2$

MFV

… Motivates trying to solve the hierarchy problem at the same time

Flavour Deconstructing the Composite Higgs

Covone, **Davighi**, Isidori, Pesut, 2407.10950

Flavour deconstruction can (should?) be combined with Composite Higgs at ~ 2 TeV:

$\longrightarrow$ Solves flavour puzzle

$\longrightarrow$ Gauge protected $M_*^{\mathrm{U}(2)} \approx 1 \div 2\ \mathrm{TeV}$

$\longrightarrow$ Cures large hierarchy problem

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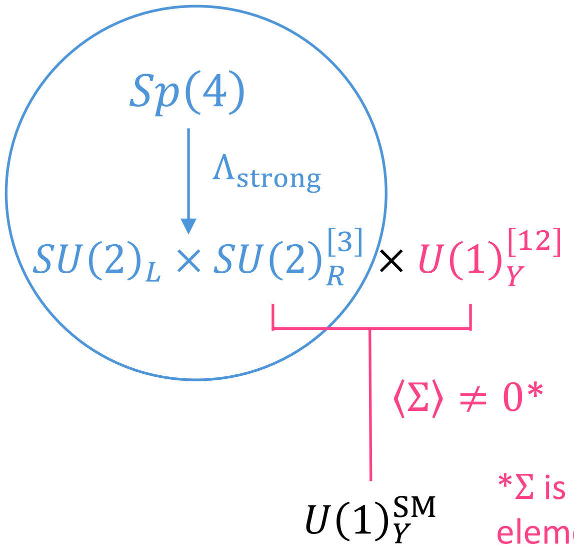
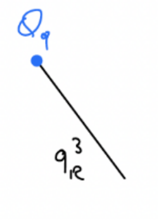
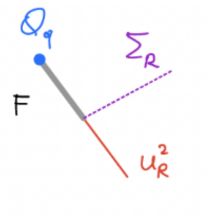


*Σ is for now elementary…



3rd gen ~ partial composite

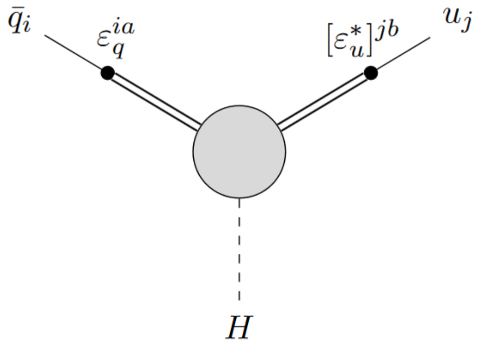


1st /2nd gens ~ elementary

Minimal Composite Higgs

Global symmetry breaking $Sp(4) \to SU(2)_L \times SU(2)_R$ delivers pNGBs $\sim (\mathbf{2},\mathbf{2})$

Partial Compositeness



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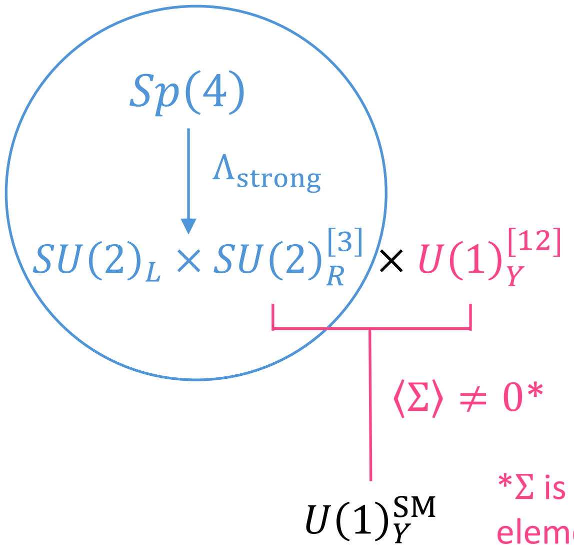
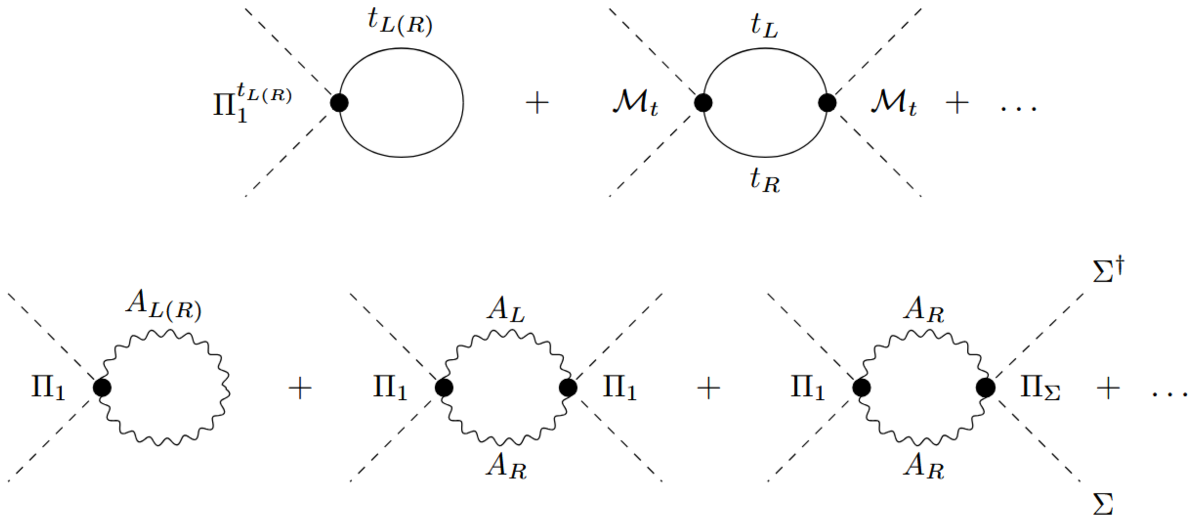


*Σ is for now elementary…

Higgs potential generated by explicit $Sp(4)$ breaking: y_t and $g_{L,R}$



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⟶ Cures large hierarchy problem

$$Sp(4) \xrightarrow{\Lambda_{\text{strong}}} SU(2)_L \times SU(2)_R^{[3]} \times U(1)_Y^{[12]}$$

$$\underbrace{SU(2)_R^{[3]} \times U(1)_Y^{[12]}}_{\langle \Sigma \rangle \neq 0^*} \to U(1)_Y^{\mathrm{SM}}$$

*Σ is for now elementary...

$$\Longrightarrow \quad m_h^2 = \frac{1}{16\pi^2}\left[4 n_c y_t^2 M_T^2 - \frac{9}{2} g_{R,3}^2 M_\rho^2 \left(1 - \frac{2M_{W_R}^2}{M_\rho^2}\right)\right]$$

Realising the Higgs mass
- $\boldsymbol{g_{R,3}^2}$ **can be pumped up** to better cancel top contribution
- Allows top partner to be heavier ($M_T > 1.5$ TeV), **better compatibility with direct searches**

Enhanced predictivity
- Require $\boldsymbol{2M_{W_R}^2 < M_\rho^2}$ to avoid sign flip in m_h^2

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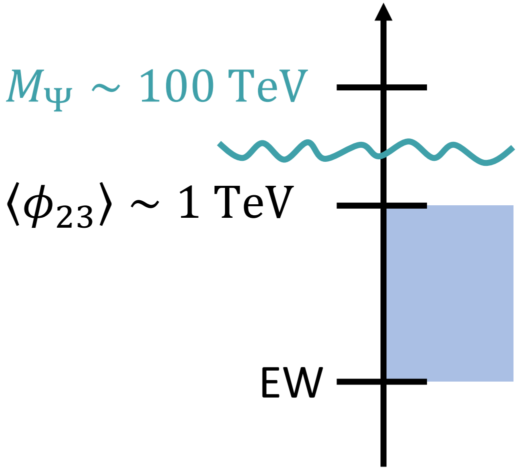

$Sp(4)$

$\downarrow \Lambda_{\mathrm{strong}}$

$\underbrace{SU(2)_L \times SU(2)_R^{[3]} \times U(1)_Y^{[12]}}$

$\langle \Sigma \rangle \neq 0^*$

$U(1)_Y^{\mathrm{SM}}$

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Enhanced predictivity

- Require $2M_{W_R}^2 < M_\rho^2$ to avoid sign flip in m_h^2

- $y_2 \ll y_3 \Rightarrow M_\Psi >$ few 100 TeV
Now this gives **no radiative** δm_h^2 contribution thanks to compositeness at lower scale ☺

Flavour Deconstructing the Composite Higgs

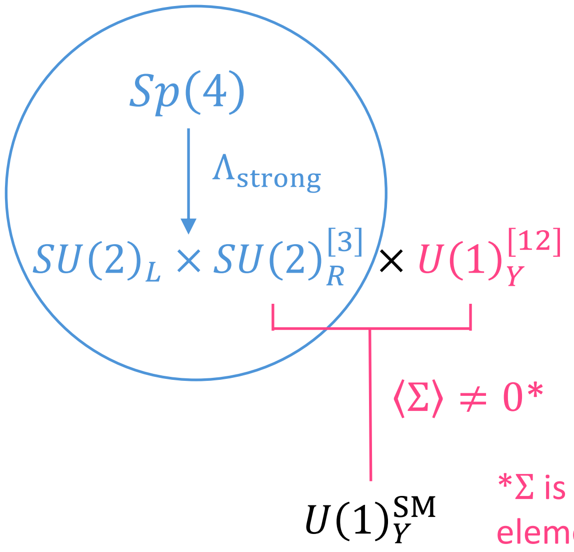
Covone, **Davighi**, Isidori, Pesut, 2407.10950

Flavour deconstruction can (should?) be combined with Composite Higgs at $\sim 2\ \mathrm{TeV}$:

⟶ Solves flavour puzzle

⟶ Gauge protected $M_*^{\mathrm{U}(2)} \approx 1 \div 2\ \mathrm{TeV}$

⟶ Cures large hierarchy problem



*Σ is for now elementary…

Phenomenologically viable benchmark:

- Large $g_{R,3} \sim 1$
- Light top partner $M_T \approx 2\ \mathrm{TeV}$; spin-1 resonance $M_\rho \approx 10\ \mathrm{TeV}$
- Deconstruction scale $v_\Sigma \approx 3\ \mathrm{TeV}$
- Order 5% tuning in Higgs mass

Needs to be explored in more detail…

Deconstruction without fundamental scalars

Work in progress…

An elementary scalar Σ introduces a second hierarchy problem

A more complete proposal:

Global breaking $Sp(6)_{\text{global}} \to SU(2)_L \times SU(2)_R^3 \times SU(2)_R^{12}$

Delivers x12 pNGBs:

$$\begin{array}{rcccccl} & (& \mathbf{2} & , & \mathbf{2} & &) \\ \oplus & (& \mathbf{2} & , & & \mathbf{2} &) \\ \oplus & (& & & \mathbf{2} \;,& \mathbf{2} &) \end{array}$$

SM Higgs (tuned mass)

$H_{12} \to$ light Yukawas

Link field Σ (natural mass)

Deconstruction without fundamental scalars

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	$(\mathbf{2}$	, $\mathbf{2}$		$)$	SM Higgs (tuned mass)
$\oplus$	$(\mathbf{2}$	,	$\mathbf{2}$	$)$	$H_{12} \to$ light Yukawas
$\oplus$	$($	$\mathbf{2}$	, $\mathbf{2}$	$)$	Link field Σ (natural mass)

UV model? Here's a sketch:

Start from $Sp(n_c)$ gauge theory with 6 $i\mathbb{R}$ Ψs. Chiral symmetry breaking $SU(6) \to Sp(6)$

Include large *explicit* breaking $SU(6) \to Sp(6)'$

Lifts x2 pNGBs to give effective coset $\frac{Sp(6)'}{Sp(6) \cap Sp(6)'} = \frac{Sp(6)'}{SU(2)^3}$

Q: origin of top partners? No QCD analogue...

Deconstruction without fundamental scalars II

An elementary scalar Σ introduces a second hierarchy problem

Alternative approach: Lizana, 2412.14243; Fuentes-Martin, Lizana 2402.09507

Realise deconstruction breaking pattern via **strong condensate** itself: $\zeta_{L,R}^{(L,R)} \sim \square$ of $SU(n_c)$

	Site 1	Site 2
$SU(2)_L$	$\zeta_L^{(L)}, q_L^{1,2}, l_L^{1,2,3}$	$\zeta_R^{(L)}, q_L^3$
$SU(2)_R$	$\zeta_L^{(R)}, q_R^{1,2,3}, e_R^{1,2}$	$\zeta_R^{(R)}, l_R^3$

Approximate global breaking $SU(4)_1 \times SU(4)_2 \to SU(4)_{1+2} \supset SU(2)_L \times SU(2)_R$

15 pNGBs of which 6 are eaten $\to$ $(\mathbf{2},\mathbf{2}) \oplus (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1})$

Similar scalar spectrum, but different phenomenology (e.g. this singlet $\to \gamma\gamma$ via WZW)

Conclusions

The Higgs remains a central motivation for high-energy BSM. Flavour cannot be overlooked.

Pre-LHC: postpone flavour and solve the hierarchy problem with MFV

Alternatively, an intrinsically flavour non-universal approach can

1. Emerge from interesting new gauge-flavour unified theories
2. Render m_h more natural e.g. in composite Higgs framework
3. Simultaneously unlock the flavour puzzle e.g. by flavour deconstruction
4. … and has rich phenomenology: great potential at HL-LHC and FCC-ee is just beginning to be explored

Thank you!

Backup

How to generate flavour in Composite Higgs Models?

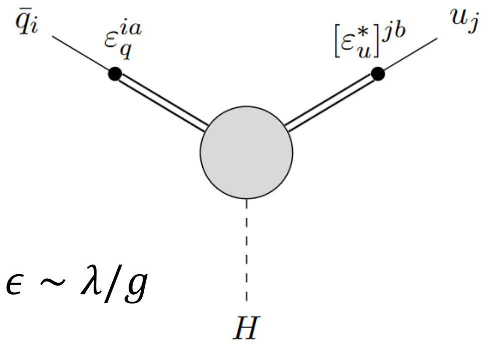
The problem with elementary fermions: $L_{\text{strong}} \supset \frac{1}{\Lambda^{d-1}} \bar{q} O_H u + \Lambda^{4-d'} O_H O_H^\dagger + \frac{1}{\Lambda^2} (\bar{q} q)^2$ Cannot have Λ low due to flavour bounds

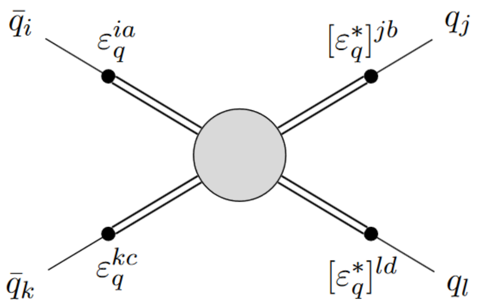
O_H is a composite scalar operator with quantum numbers of Higgs.
Want $d \approx 1$ to get large top Yukawa

Want $O_H O_H^\dagger$ to be irrelevant!
But $d \approx 1$ (quasi-free) implies $d' \approx 2d \approx 2$

Partial Compositeness is a solution: $L \supset \lambda_q^{ia} \bar{q}_i O_a^q + \lambda_u^{ia} \bar{u}_i O_a^u + \bar{O}_a^q O_H O_b^u$

Kaplan, 1991
Review: Panico, Wulzer, 1506.01961





Yukawa couplings now generated by **relevant** operators

Flavour from Anarchy?

Partial compositeness even promised a *dynamical solution* to *flavour puzzle:*

- The $\lambda_q^{ia}\bar{q}_i O_a^q$ mixing operators run with scale
- If λ_q^{ia} anarchic at high scale Λ_{high}, slight differences in anomalous dimensions of O_a^q transmute to *exponential hierarchies* in the resulting "proto-Yukawas" at scale m_*

$$\lambda_\psi^{ia}(m_*) \simeq \lambda_\psi^{ia}(\Lambda)\left(\frac{m_*}{\Lambda}\right)^{\gamma_\psi^a} \equiv \lambda_\psi^{ia}(\Lambda)e^{-\gamma_\psi^a L}\,, \qquad L \equiv \ln \Lambda/m_*$$

- BUT this entails large flavour violation also at m_*
- Strongest bound from neutron EDM $\Rightarrow M_* \gtrsim 20 \div 25\ \text{TeV}$

[Even assuming 1-loop suppressed quark dipole operators]

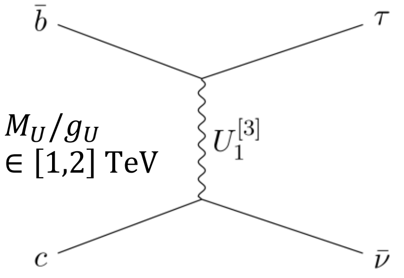
- Such a high scale degrades this as a solution to the hierarchy problem AND is untestable in colliders
- We **need** a flavour symmetry to bring down m_*

Non-Universality from Flavour Deconstruction

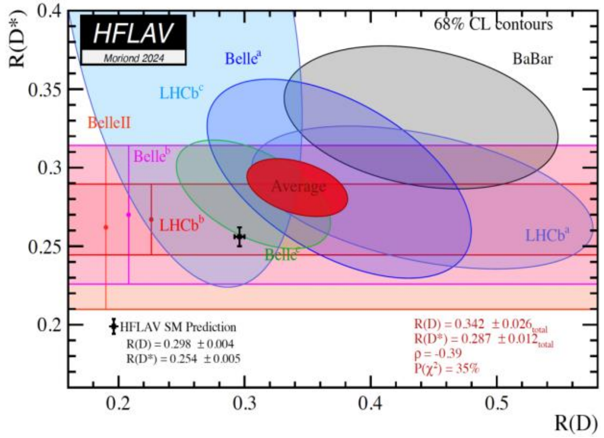
Davighi, Isidori 2303.01520

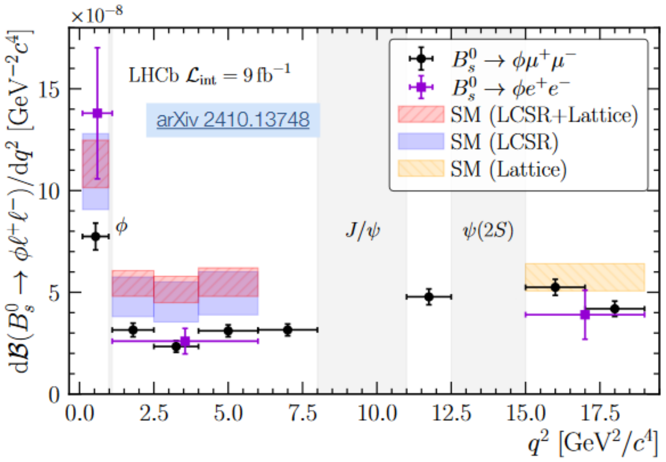
	Deconstructed force	$SU(3)$	$SU(2)_L$	$SU(2)_R$	$U(1)_Y$	$U(1)_{B-L}$
Flavour	$\lvert V_{cb}\rvert \ll 1$ $y_i \ll y_3$	✓ ×	✓ ✓	× ✓	✓ ✓	✓ ×
EW	Natural upper limit of $\lvert\tan\theta\rvert M$ EWPOs order	90 TeV 1-loop	20 TeV Tree	40 TeV Tree	40 TeV Tree	500 TeV 1-loop

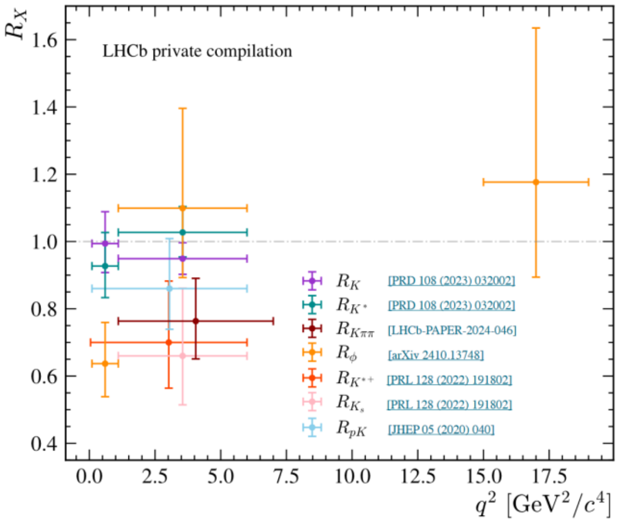
Aside: If enlarge $SU(3)^{[3]} \to SU(4)^{[3]}$, can also explain $b \to c\tau\nu$ anomalies in $R_{D^{(*)}}$ & $bs\mu\mu$ via '4-3-2-1' models



Buttazzo, Greljo, Isidori, Marzocca, 1706.07808; Di Luzio, Greljo, Nardecchia, 1708.08450; Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368; Greljo, Stefanek, 1802.04274; Di Luzio, Fuentes-Martin, Greljo, Nardecchia, Renner, 1808.00942; Fuentes-Martin, Stangl, 2004.11376 …







Experimental hints for deconstruction near TeV?

LHCb Implications 2024

From Deconstruction to Unification

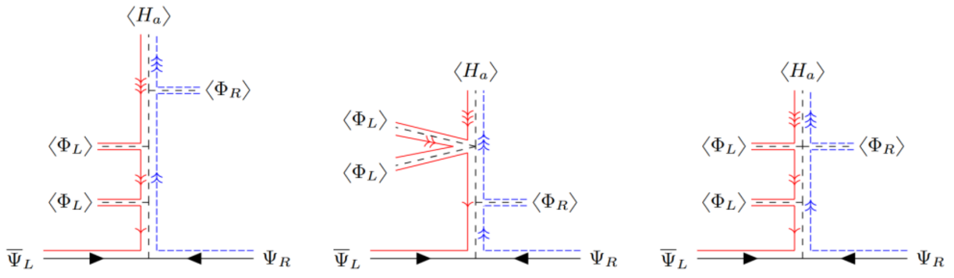
Davighi, Tooby-Smith, 2201.07245, Davighi, 2206.04482

Whence $G_1 \times G_2 \times G_{3+\mathrm{H}}$? One path is to **reunify** in the UV! Using e.g. $SU(2)^{n_f} \cong Sp(2)^{n_f} \hookrightarrow Sp(2n_f)$

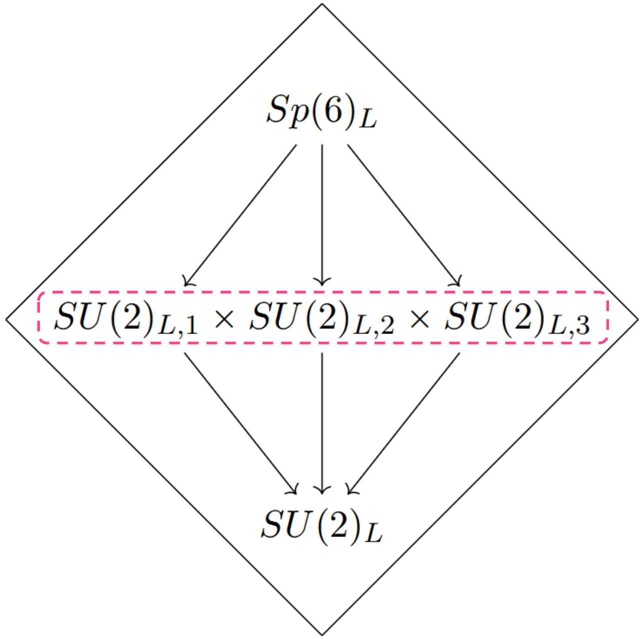
Electroweak flavour unification: $\mathrm{G}_{\mathrm{UV}} = SU(4) \times Sp(6)_L \times Sp(6)_R$

- **All SM matter unified*** into $\Psi_L \sim (\mathbf{4}, \mathbf{6}, \mathbf{1})$ + $\Psi_R \sim (\mathbf{4}, \mathbf{1}, \mathbf{6})$
- Offers a “gauge answer” to “why 3 generations?”
- Solves flavour puzzle with the minimal ingredients

E.g.



$\rightarrow Y_{12}^{u,d,e}$

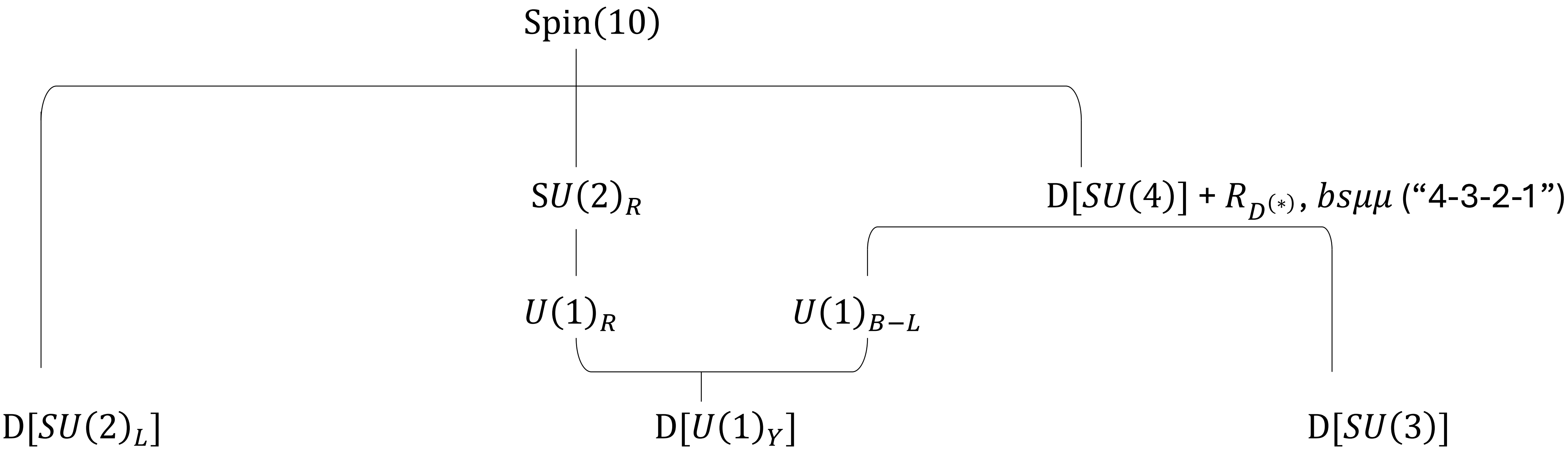


- Low-energy pheno matches that of deconstructed $SU(2)_L \times U(1)_Y$

*Very few anomaly-free options that do this!
See the classification of all embeddings of 3-flavour SM gauge algebra: Allanach, Gripaios, Tooby-Smith, 2104.14555

What about **neutrinos**? Can we explain anarchic mixing angles?

Greljo, Isidori [2406.01696]



Consider type 1 see-saw: $m_\nu \sim -Y_D\, M_M^{-1}\, Y_D^T$
RH ν is SM singlet; deconstruction **naively gives doubly hierarchical neutrino texture**
Insight: deconstruct $U(1)_R$ and/or $U(1)_{B-L}$ to get texture in M_M

Conditions for PMNS anarchy: $$M_M \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}, \qquad Y_D \sim \begin{pmatrix} \epsilon^2 & \lesssim \epsilon & \lesssim 1 \\ \lesssim \epsilon^2 & \epsilon & \lesssim 1 \\ \lesssim \epsilon^2 & \lesssim \epsilon & 1 \end{pmatrix}$$

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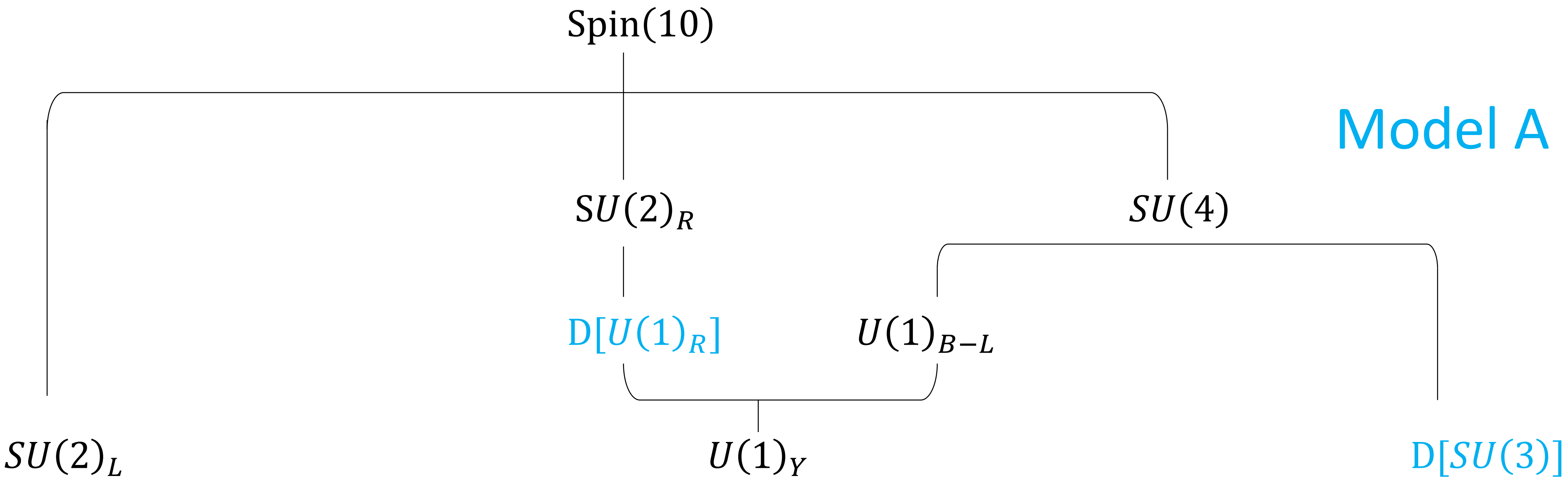
Greljo, Isidori 2406.01696



Model A

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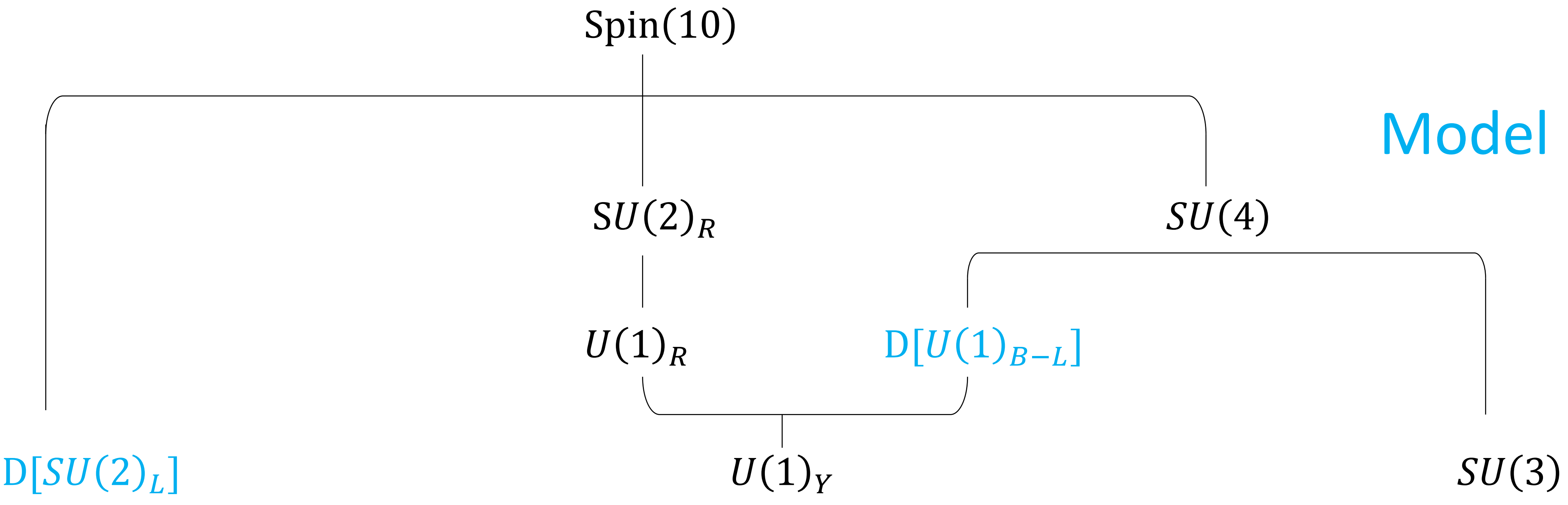
Greljo, Isidori 2406.01696

Model B



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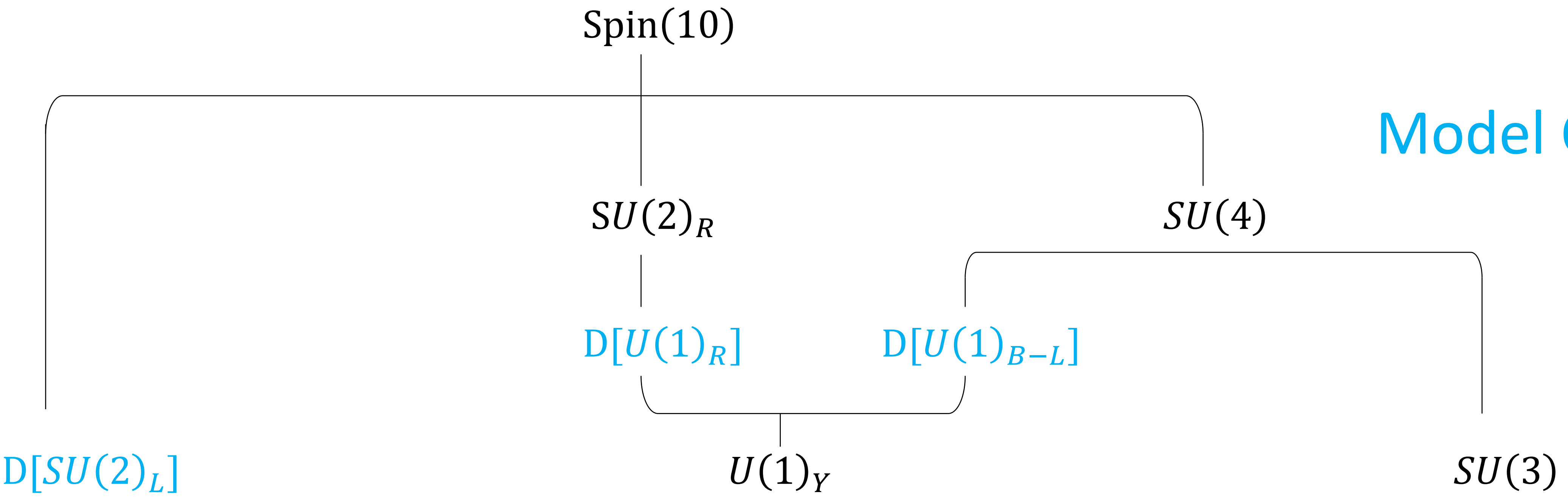
What about **neutrinos**? Can we explain anarchic mixing angles?

Greljo, Isidori 2406.01696



Model C

Consider type 1 see-saw: $m_\nu \sim -Y_D\, M_M^{-1}\, Y_D^T$
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Insight: deconstruct $U(1)_R$ and/or $U(1)_{B-L}$ to get texture in M_M

Conditions for PMNS anarchy: $$M_M \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}, \qquad Y_D \sim \begin{pmatrix} \epsilon^2 & \lesssim \epsilon & \lesssim 1 \\ \lesssim \epsilon^2 & \epsilon & \lesssim 1 \\ \lesssim \epsilon^2 & \lesssim \epsilon & 1 \end{pmatrix}$$