Flavour non-universality
vs
Naturalness

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NPKI, 9th June 2023

DISCLAIMER

I will not say anything new about the large hierarchy problem (TeV^2 vs M_{Pl}^2)

I will not say anything new about reducing the little hierarchy problem (M_{h}^2 vs TeV^2)

I will discuss:

- recent ideas for solving the flavour puzzle at low scales (TeV),
- their consequences for the (little) hierarchy problem,
- phenomenology in flavour observables, direct searches, & EW precision

Flavour puzzle

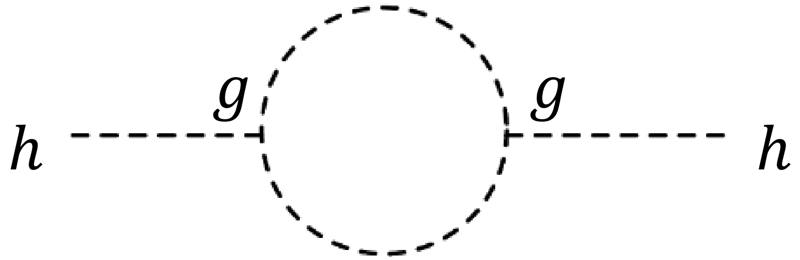
Huge (technically natural) hierarchies in SM Yukawa couplings $y\,\bar{\Psi}_L H \Psi_R$:

$$1 \approx y_t \gg y_c \gg y_u \sim 10^{-5}$$

$$V_{us} \gg V_{cb} \gg V_{ub}$$

Highly suggestive of accidental symmetries due to heavy BSM physics, e.g. 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, unless we have e.g. SUSY or compositeness at a lower scale to protect M_h



BSM particle X

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

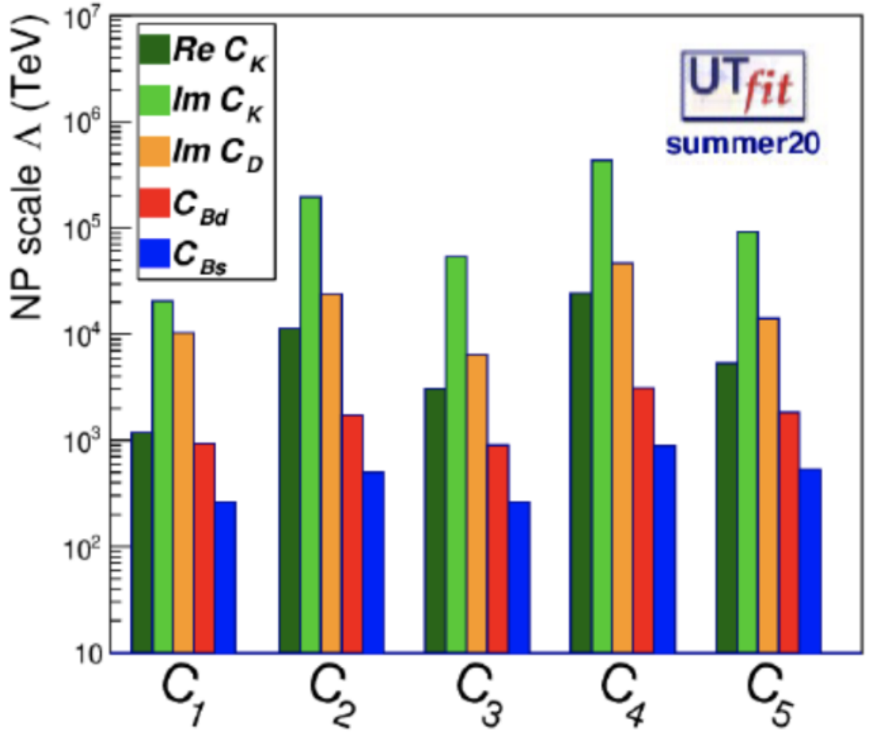
See e.g. Farina, Strumia, Pappadopulo, 1303.7244

Contrast with dark matter & strong-CP problem, which *could* be explained with *light* NP that has no direct impact on EW stability

This sensitivity of M_h^2 to flavour-puzzle-solving-BSM appears severe:

1. Trying to explain structure of Higgs couplings $y\,\overline{\Psi}_L H \Psi_R$, so the NP probably couples to Higgs
2. Typically many extra states, probably with large couplings to top (even 2-loop δM_h^2 can be big)
3. Precision flavour data means that flavour-violation naively probes very heavy scales

Neutral meson mixing constraints: probe effective scales $> \ 10^5$ TeV



$$\mathcal{L} \supset \frac{C}{\Lambda^2} QQQQ$$

Flavour-ful BSM:

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

To avoid this fine-tuning, Higgs surely stabilized by SUSY or compositeness near TeV

These mechanisms would protect M_h from **all** higher NP scales up to M_{Pl};

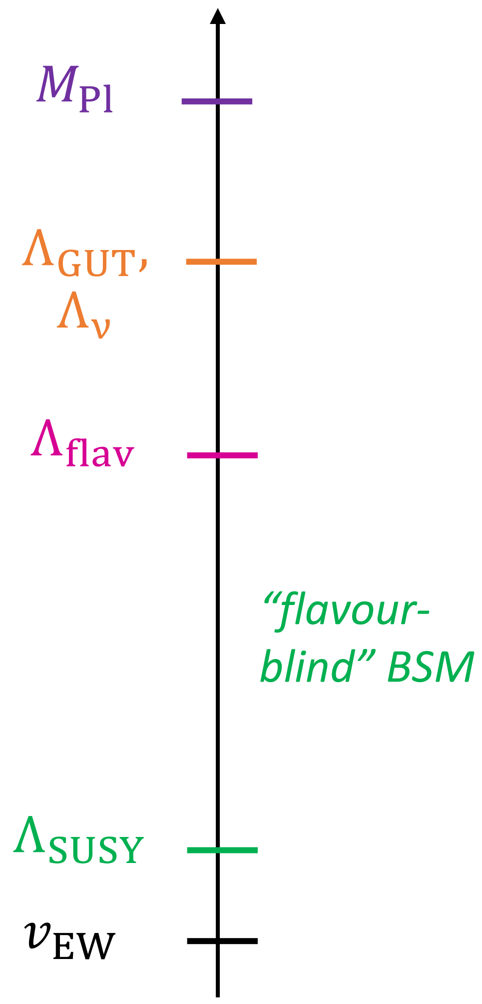
NP explaining flavour, gauge unification, neutrino masses, QG …

Old Q: how to reconcile with flavour-violation constraints probing $\mathcal{O}(10^{4-5})$ TeV?

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

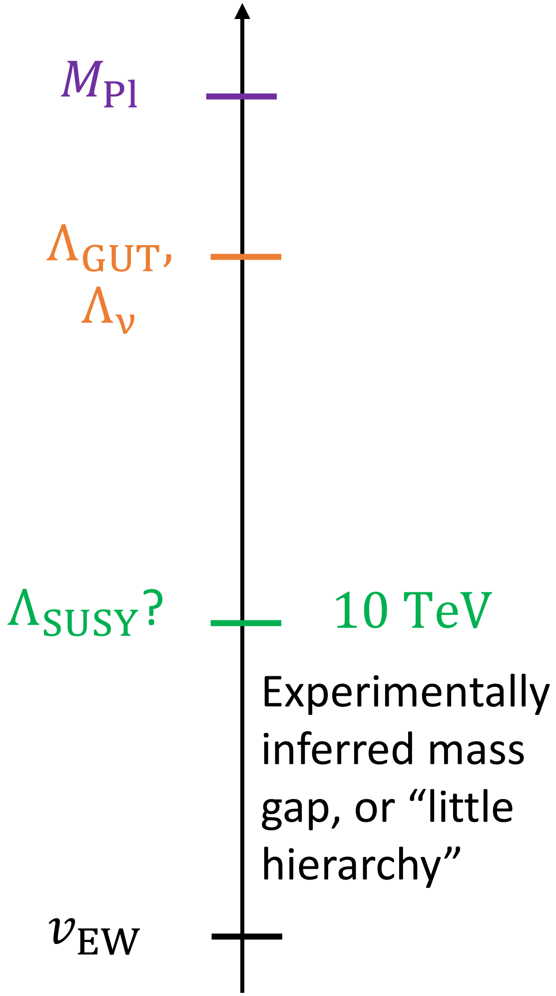
D'Ambrosio, Giudice, Isidori, Strumia, hep-ph/0207036

Flavour puzzle can then be solved at much higher scales without destabilising M_h^2



In 2020s, we know a lot more from the LHC + other experiments

No sign (yet) of TeV scale SUSY partners or composite resonances that would stabilize the Higgs.



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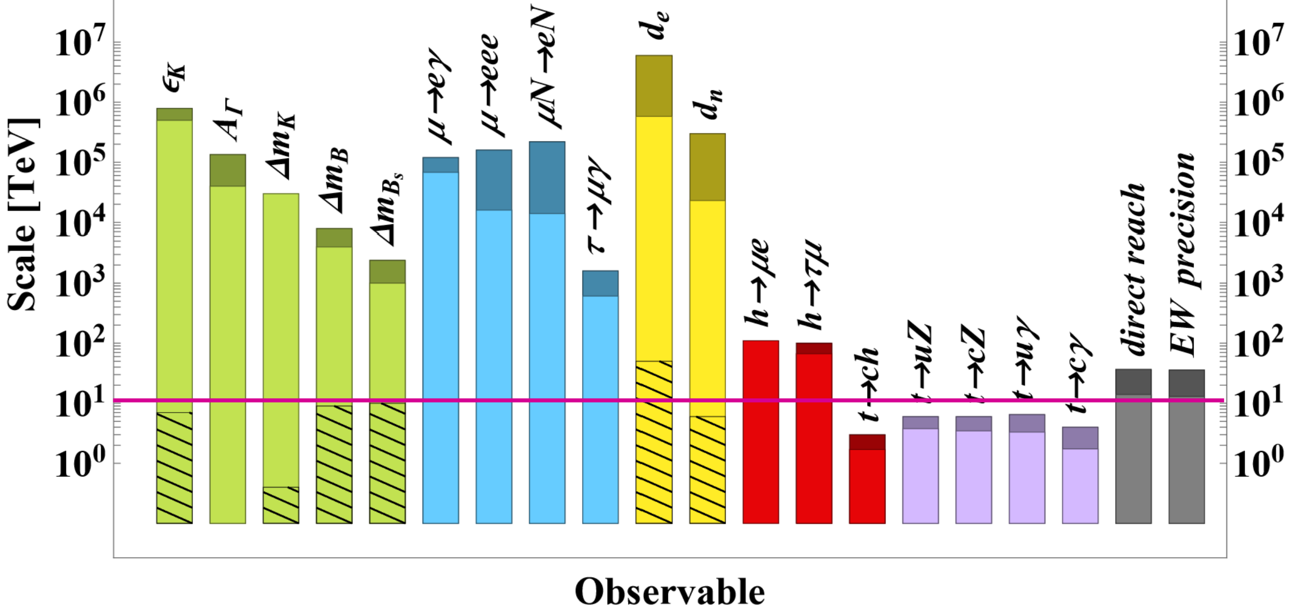
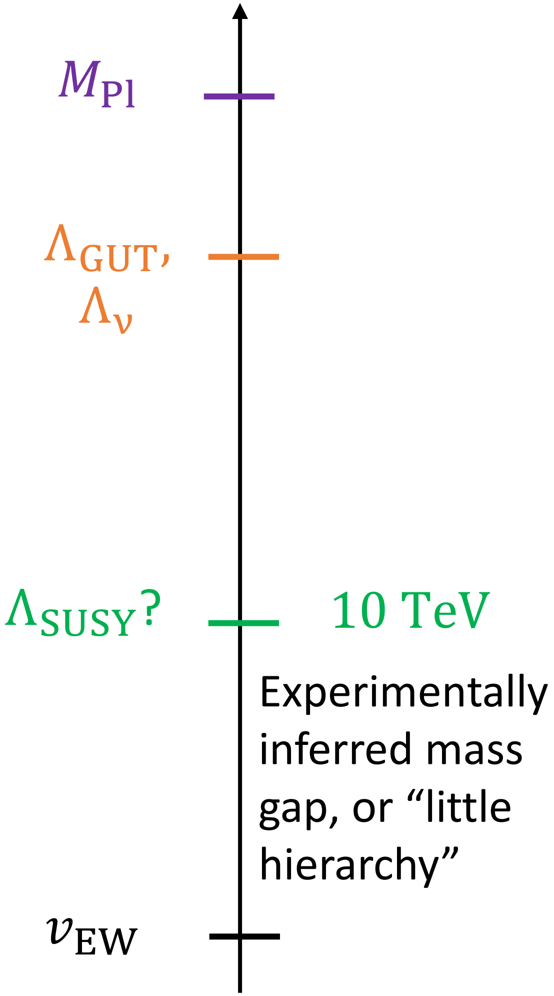
European Strategy for Particle Physics, 2020 Briefing Book
1910.11775

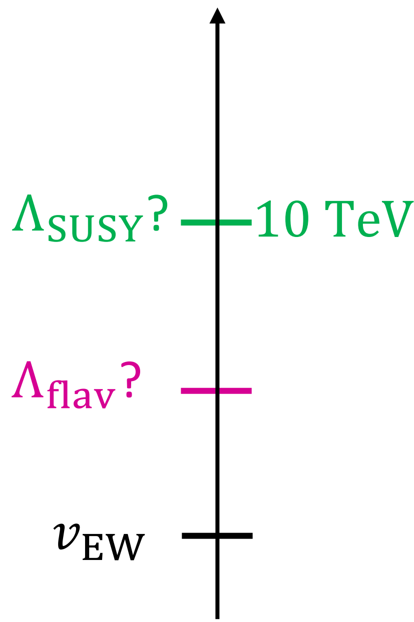




With MFV, the effective scale of NP as constrained by flavour + EWPO + direct searches is in similar ballpark: currently around **10 TeV**

Percent level tuning on M_h^2 in MFV SUSY / compositeness = "little hierarchy problem" See Gauthier's talk

Beyond MFV: *very flavoured* NP can be lighter!



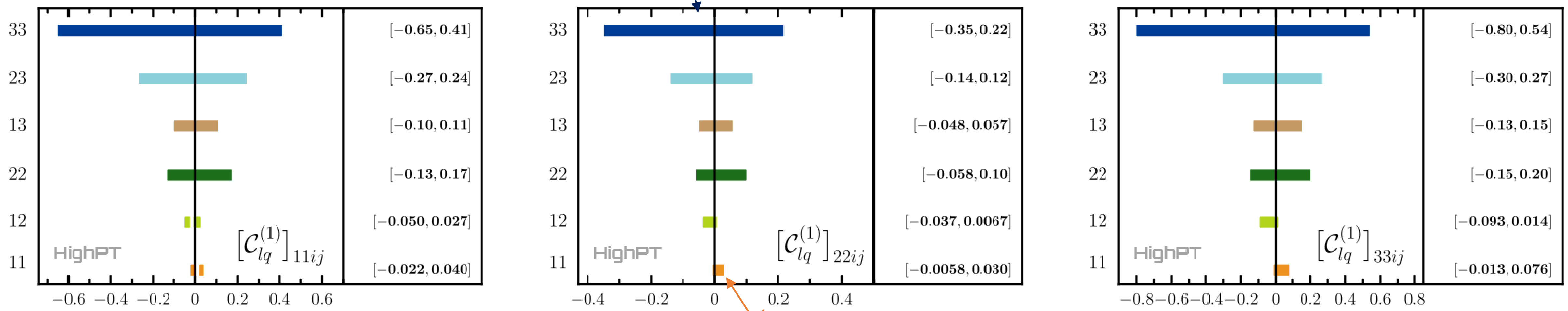
MFV is unnecessarily aggressive: LHC direct search limits driven by contributions from light-flavour operators (PDF enhanced in pp).

LHC bounds roughly **10 times weaker** for **NP coupled mostly to 3rd family**, for which **TeV scale remains viable**

Example: high-p_T Drell-Yan tail constraints on semi-leptonic SMEFT operators

$$\mathcal{L} \sim \frac{C}{(\mathrm{TeV})^2} QQLL$$

$\frac{\Lambda}{c_{33}} \gtrsim 3$ TeV



$\frac{\Lambda}{c_{11}} \gtrsim 30$ TeV

Allwicher, Faroughy, Jaffredo, Sumensari, Wilsch, 2207.10714
Allwicher, Faroughy, Jaffredo, Sumensari, Wilsch, 2207.10756

Beyond MFV:
From $U(3)$ global symmetries to $U(2)$

NP that couples differently to 3rd family, but universally (e.g. zero) to light families, has some $U(2)^n$ flavour symmetry:

$$(\psi_1 \quad \psi_2) = \text{doublets of } U(2), \qquad \psi_3 = \text{singlets of of } U(2)$$

Imposing $U(2)^5$ flavour symmetry on NP is a weaker assumption than the $U(3)^5$ of MFV

- It allows NP coupled mostly to 3rd family, giving much weaker direct search constraints
- With a choice of minimal $U(2)^5$-breaking spurions, one also avoids flavour bounds with NP scale around 1 TeV

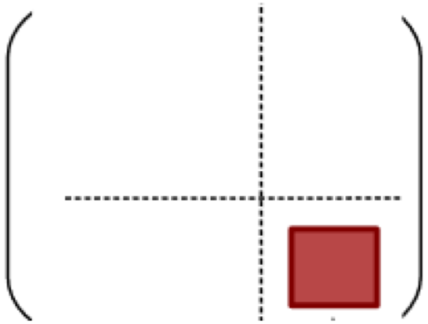
Barbieri et al, 1105.2296; Isidori, Straub, 1202.0464; Fuentes-Martin et al, 1909.02519

What would be the UV origin of such $U(2)^n$ flavour symmetries?

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

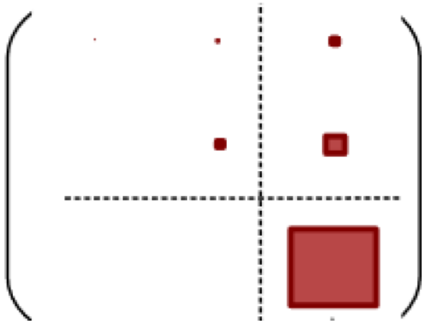
The $U(2)^5$ flavour symmetry can be realised **accidentally**, from a flavour non-universal **gauge symmetry** that couples differently to 3rd family

The non-universal gauge symmetry, and the $U(2)^5$ it delivers, could be the origin of **flavour hierarchies**, because it will also restrict the Yukawa couplings:



Exact $U(2)$ limit

$\approx$



Observed Yukawa

Light Yukawas (and $U(2)$ breaking) from **higher-dimension operators**; originate from NP at higher scales

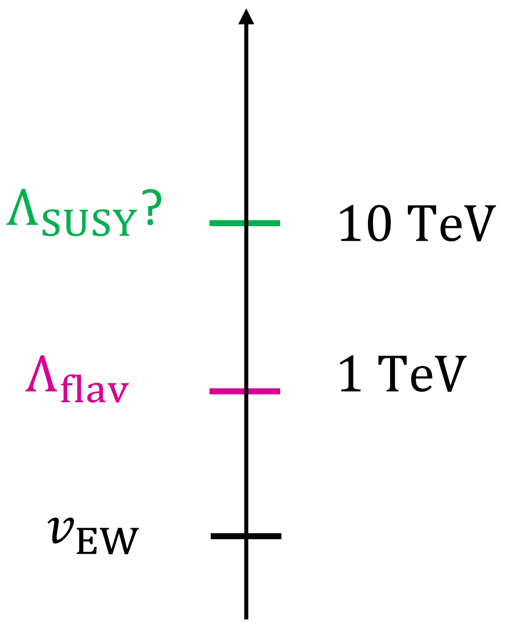
Barbieri et al, 1105.2296
Isidori, Straub, 1202.0464
Fuentes-Martin et al, 1909.02519

The associated heavy gauge bosons inherit the $U(2)^5$ symmetric couplings to SM fermions and so can be a few TeV. Flavour could still be explained at low scale – an inversion of the MFV paradigm

TeV scale solution to flavour puzzle, via non-universal gauge interactions, is a phenomenologically viable possibility

If SUSY / compositeness doesn't kick in until 10 TeV (to resolve the large hierarchy problem), we should ask:

Have we made the little hierarchy problem (% tuning in M_h^2) worse?



Goal for rest of talk:

Use *stability of Higgs mass* to identify *natural TeV scale models of flavour* consistent with current data. We will see these models have rich pheno

Davighi, Isidori, Pesut, 2212.06163
Davighi, Isidori 2303.01520
Davighi, Stefanek 2305.16280
Davighi, Gosnay, Miller, Renner (work in progress)

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

Let's work from the bottom up. SM gauge symmetry: $SU(3) \times SU(2)_L \times U(1)_Y$
Consider 'deconstructing' each factor into a separate "light family" and "third family + Higgs" part:

TeV gauge symmetry contains:

$SU(3)^{[12]} \times SU(3)^{[3]}$

$$Y_{ij}^F \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

Allows 2 x 2 matrix of light Yukawas (Higgs colourless)
Explains $V_{cb} \ll 1$
Doesn't explain $m_2 \ll m_3$

$SU(2)_L^{[12]} \times SU(2)_L^{[3]}$

$$Y_{ij}^F \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}$$

Rank-1 matrix, can be diagonalised by a RH-rotation that is unphysical (as in SM)
Explains $V_{cb} \ll 1$
Explains $m_2 \ll m_3$

$U(1)_Y^{[12]} \times U(1)_Y^{[3]}$

$$Y_{ij}^F \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

Explains $V_{cb} \ll 1$
Explains $m_2 \ll m_3$

Need to deconstruct EW gauge symmetry to explain $m_2 \ll m_3$

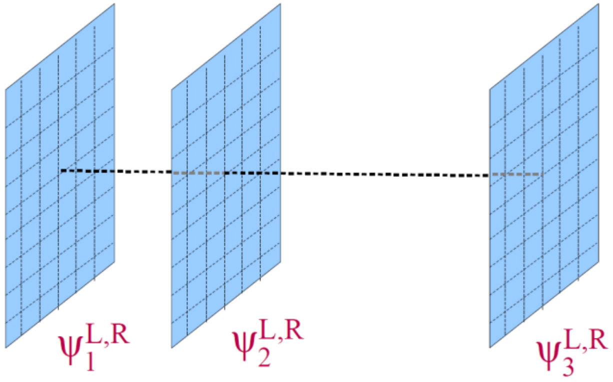
UV speculation: possible origin of deconstructed gauge symmetry [digression]

Could be the last step in a multi-scale symmetry breaking pattern from fully deconstructed $G = G_1 \times G_2 \times G_3$; scale hierarchy $\Lambda_1 > \Lambda_2 > \Lambda_3$

Dvali, Shifman, hep-ph/0001072
Panico, Pomarol, 1603.06609

Example origin 1:

Can embed multi-site picture in a stable multi-brane model in 5d

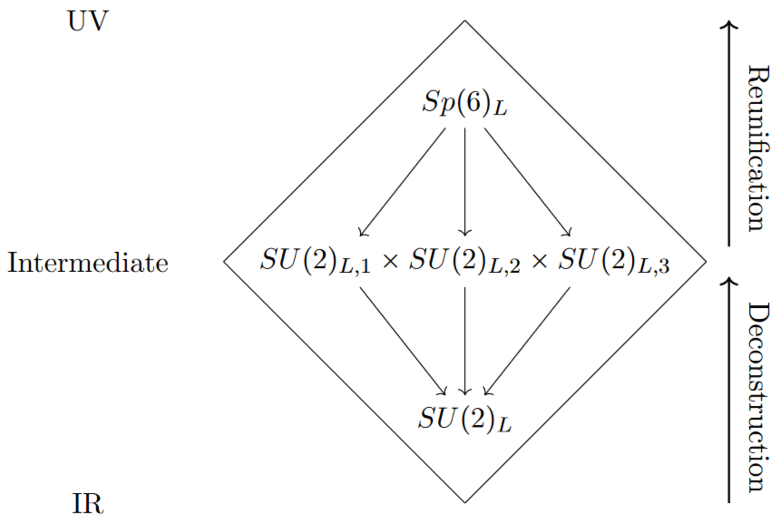


Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368
Fuentes-Martin, Isidori, Lizana, Selimovic, Stefanek, 2203.01952

Example origin 2:

"Gauge flavour unification": eg $\prod_{i=1}^{3} SU(2)_{L,i} \hookrightarrow Sp(6)_L$

[offers a "gauge answer" to "why 3 generations?"]



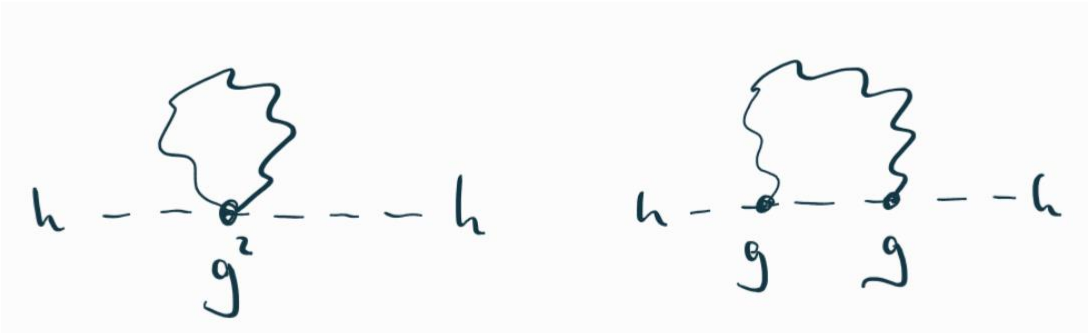
Davighi, Tooby-Smith, 2201.07245
Davighi, 2206.04482

See also the $SU(9)$ of Sungwoo's talk

Flavour non-universality vs. Naturalness

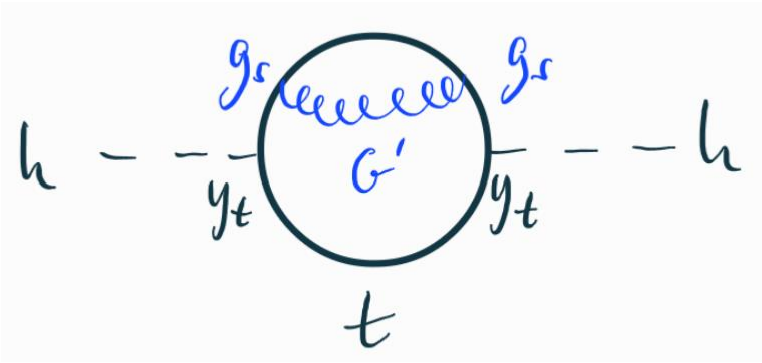
An aggressive naturalness condition: $\delta M_h^2 \lesssim (125\ \text{GeV})^2$

Deconstructing EW symmetries give 1-loop Higgs mass corrections:
(recall we need this to explain $m_2 \ll m_3$)



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

Deconstructing colour gives 2-loop correction, but with big couplings:



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

Most natural mass ranges:

$M_{W_L'} \lesssim 2.5$ TeV
$M_{Z_Y'} \lesssim 5$ TeV

Since $g_Y \sim \frac{1}{2} g_L$, which *also* gives safer pheno

$M_{G'} \lesssim 10$ TeV

Semi-simple completions

In 2303.01520 (JD, Isidori), we made an additional assumption:

> 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)

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> 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)

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

Allanach, Gripaios, Tooby-Smith, 2104.14555

3 generation subalgebra 339
Algebra: $\mathfrak{so}(10) \oplus \mathfrak{su}(2)$
$(\mathbf{16}, \mathbf{1}),\ (0,0,0,0,1,0) \mapsto (D,E,L,N,Q,U)$
$(\mathbf{16}, \mathbf{2}),\ (0,0,0,0,1,1) \mapsto (D,D,E,E,L,L,N,N,Q,Q,U,U)$
Projection matrix for α:

$$\begin{pmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 3 & 6 & 4 & 0 & 2 & 0 \end{pmatrix}$$

3 generation subalgebra 340
Algebra: $\mathfrak{so}(10)$
$(\mathbf{16}),\ (0,0,0,0,1) \mapsto (D,E,L,N,Q,U)$
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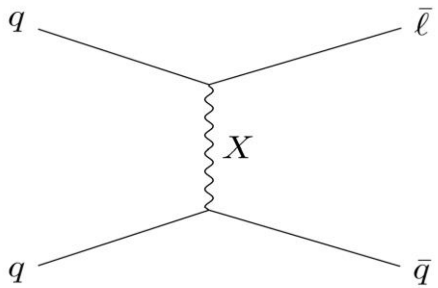
All options use one of the basic unification patterns:

- 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!** $\Rightarrow$ $M_X \gtrsim$ GUT scale
So $SU(5)$ & $SO(10)$ -based options **cannot appear** in our low-scale, natural models



*Caveat: assuming no extra chiral fermions

End up with a small class of natural models at the TeV scale; all feature 3rd family quark-lepton unification

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

Higgs and ψ_3

$\psi_{1,2}$, small impact on M_h^2 , can be UV completed at higher E

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2	$\mathrm{SU}(2)_R$	$\mathrm{SU}(4)^{[3]} \times \mathrm{SU}(2)_L^{[3]}$	$\mathrm{SU}(3)^{[12]} \times \mathrm{SU}(2)_L^{[12]} \times \mathrm{U}(1)_{B-L}^{[12]}$
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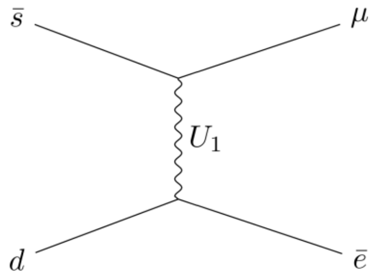
Higgs and ψ_3

$\psi_{1,2}$, small impact on M_h^2 , can be UV completed at higher E

Option 1 is **new**, and has naturally suppressed RH fermion mixing ☑ ☑ $Y^F \sim \begin{pmatrix} \epsilon_R & \epsilon_\Omega \\ \epsilon_\Omega \epsilon_R & 1 \end{pmatrix}$

Option 2 **needs large tuning** due to large RH mixing × × $Y^F \sim \begin{pmatrix} \epsilon_L & \epsilon_\Omega \epsilon_L \\ \epsilon_\Omega & 1 \end{pmatrix}$



Option 3 is **unnatural**: flavour-universal $SU(4)$ breaking must be $\gtrsim$ **200 TeV** due to $K_L \to e^+\mu^-$

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

Flavour deconstruction (at natural scale) gives rich phenomenology

$M_{G'} \lesssim 10\ \text{TeV}$

$M_{W_L'} \lesssim 2.5\ \text{TeV}$

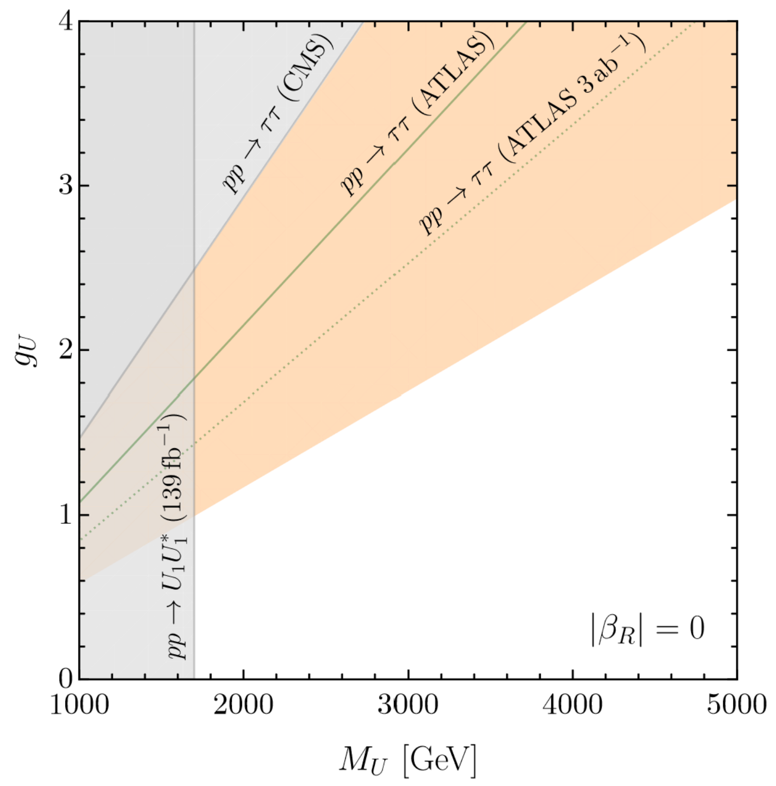
$M_{Z_Y'} \lesssim 5\ \text{TeV}$

Deconstructed $SU(3)$ gives 'coloron' $G \sim (\mathbf{8}, \mathbf{1})_0$

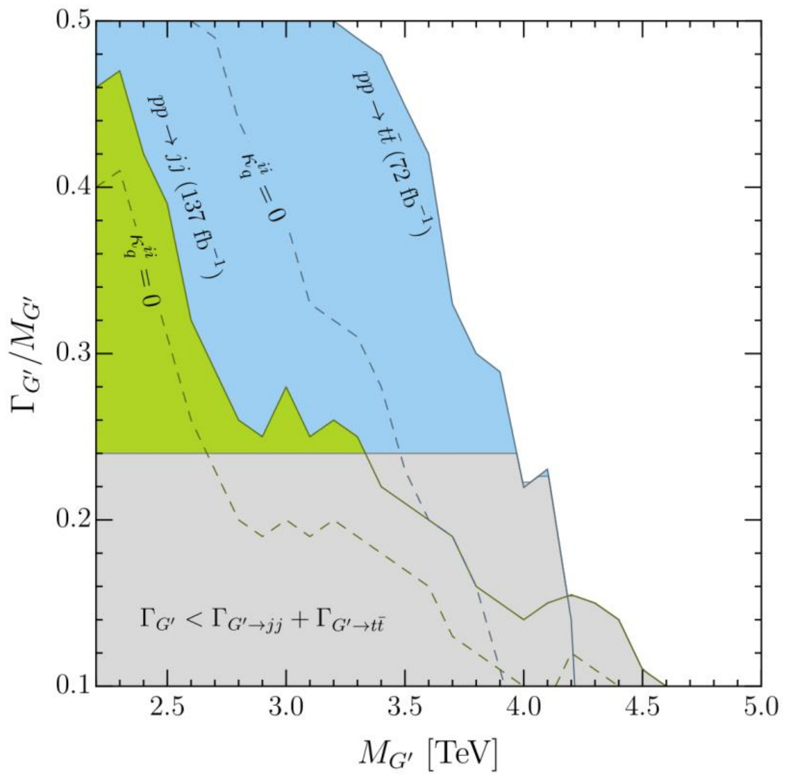
Deconstructed $SU(4)$ also gives vector leptoquark $U_1 \sim (\mathbf{3}, \mathbf{1})_{2/3}$ + Z', $M < 10$ TeV

$M_{G'} \lesssim 10$ TeV

- Pheno of these particles has been well-studied in connection to *B*-anomalies



Aebischer, Isidori, Pesut, Stefanek, Wilsch 2210.13422



Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert 2210.13422

Plenty of natural parameter space not yet probed

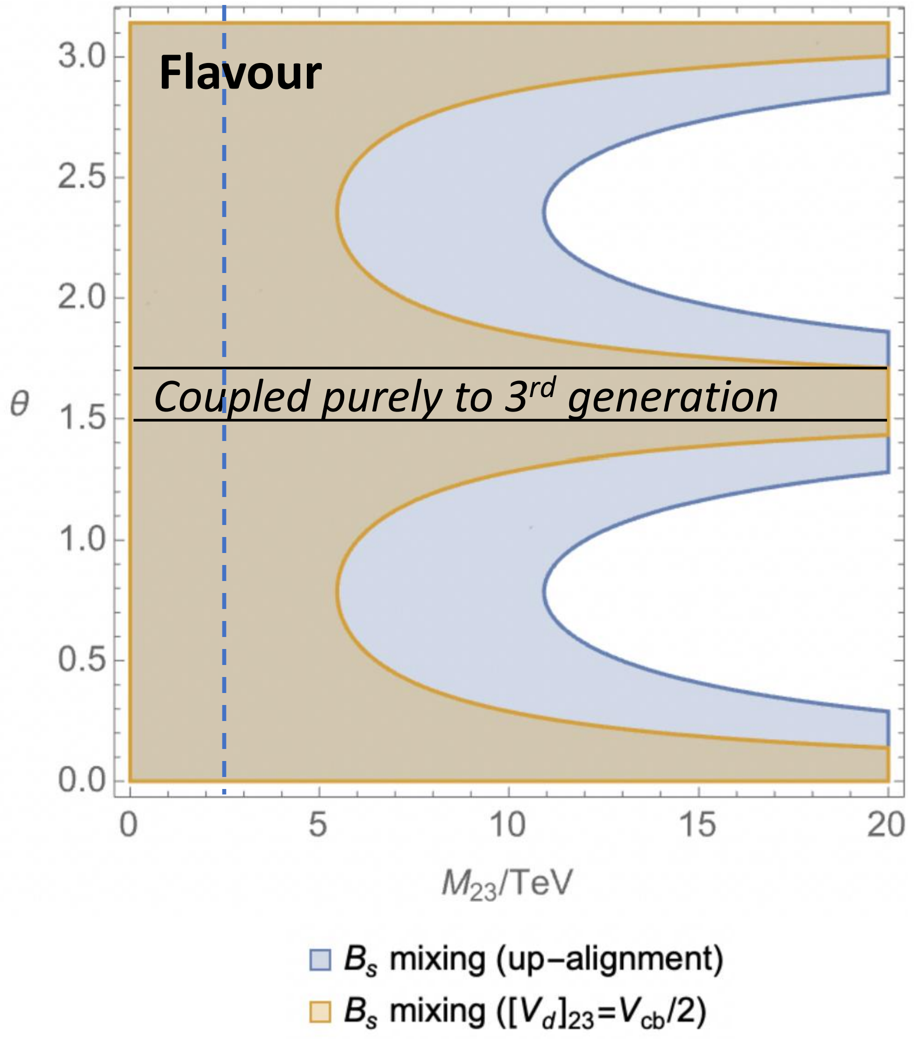
No clear "prediction" for an anomaly in $R_{D^{(*)}}$; if $M \approx 10$ TeV, $\Delta R_{D^{(*)}} \sim 10^{-3} R_{D^{(*)}}^{\rm SM}$ (undetectable)

- Still, a sizeable (up to 10%) deviation is a plausible signature of these models

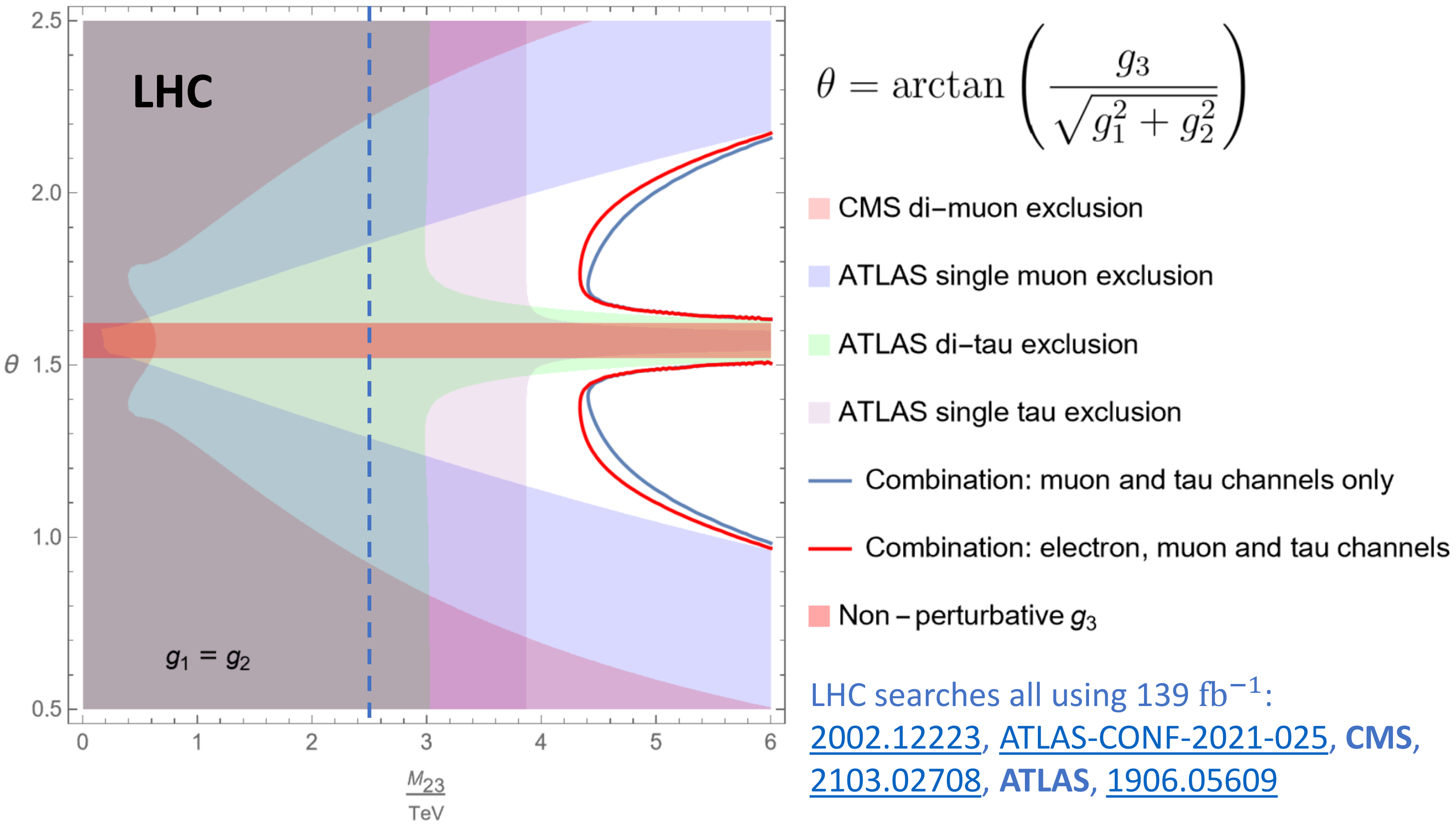
Deconstructed $SU(2)_L$ gives weak triplet: dominant constraints from B_s mixing + LHC

No tuning:
$M_{W_L'} \lesssim 2.5$ TeV

w.i.p. with Sophie Renner, Alastair Gosnay, David Miller



(If down-alignment, there is no constraint)



LHC searches all using 139 fb^{-1}:
2002.12223, ATLAS-CONF-2021-025, **CMS**, 2103.02708, **ATLAS**, 1906.05609

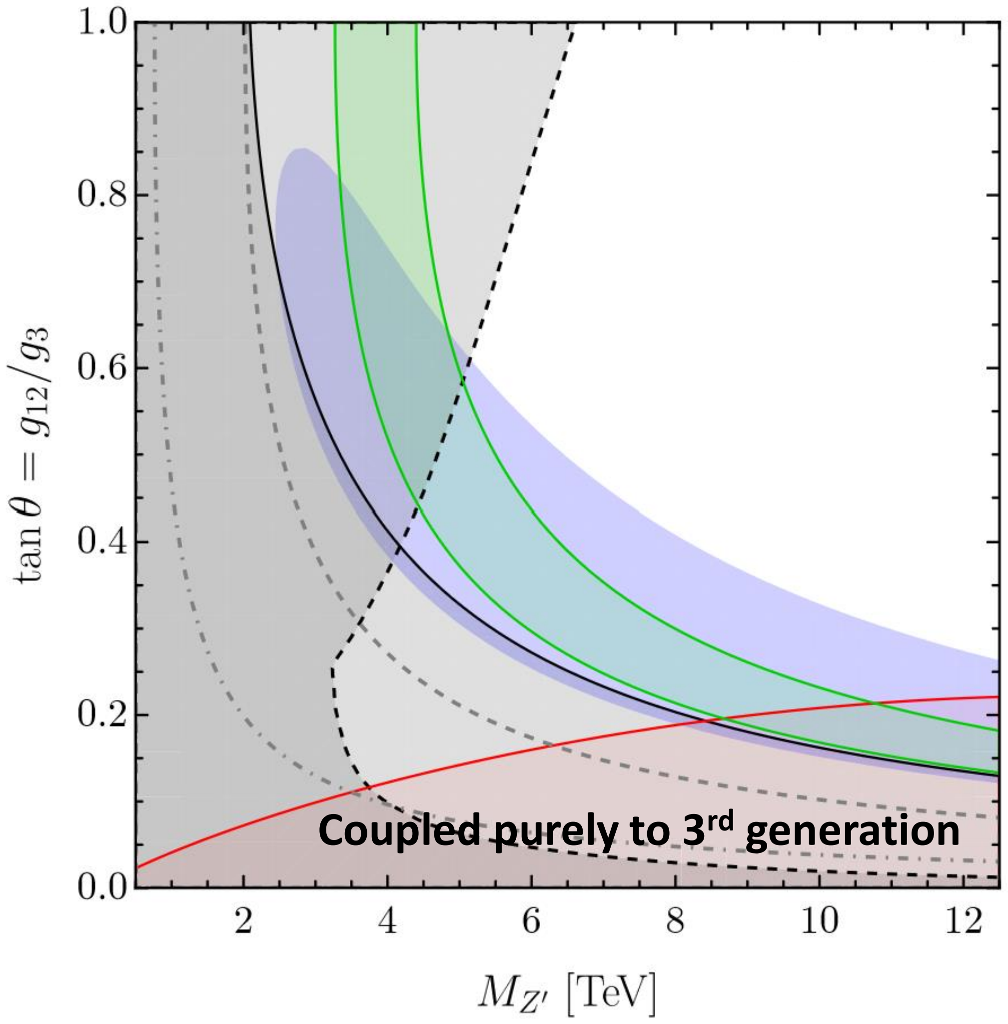
Computed using **HighPT** package:
Allwicher et al, 2207.10756

LHC Drell-Yan: $M_{W_L} > 4.5$ TeV, so $\delta M_h^2 \sim 4 M_h^2$

Deconstructed $U(1)_Y$ gives Z': viable at **lower mass**
(Double benefit from $g_Y < g_L$: smaller Higgs mass correction, and smaller NP effects)

No tuning:
$M_{Z'_Y} \lesssim 5$ TeV

We built an explicit model in 2305.16280 (JD, Stefanek). Main constraints now **EWPOs**



- B_s mixing (with up-alignment! Suppressed by $Y_Q g_Y$)
- $B_s \to \mu\mu$ exclusion
- Electroweak fit (1 sigma) using a new M_W average
- Electroweak fit (2 sigma exclusion) excluding CDF II M_W
- High p_T exclusion (recast of $pp \to ee, \mu\mu, \tau\tau$ searches)
- Percent tuning in M_h^2
- A “natural” explanation of fermion mass hierarchies

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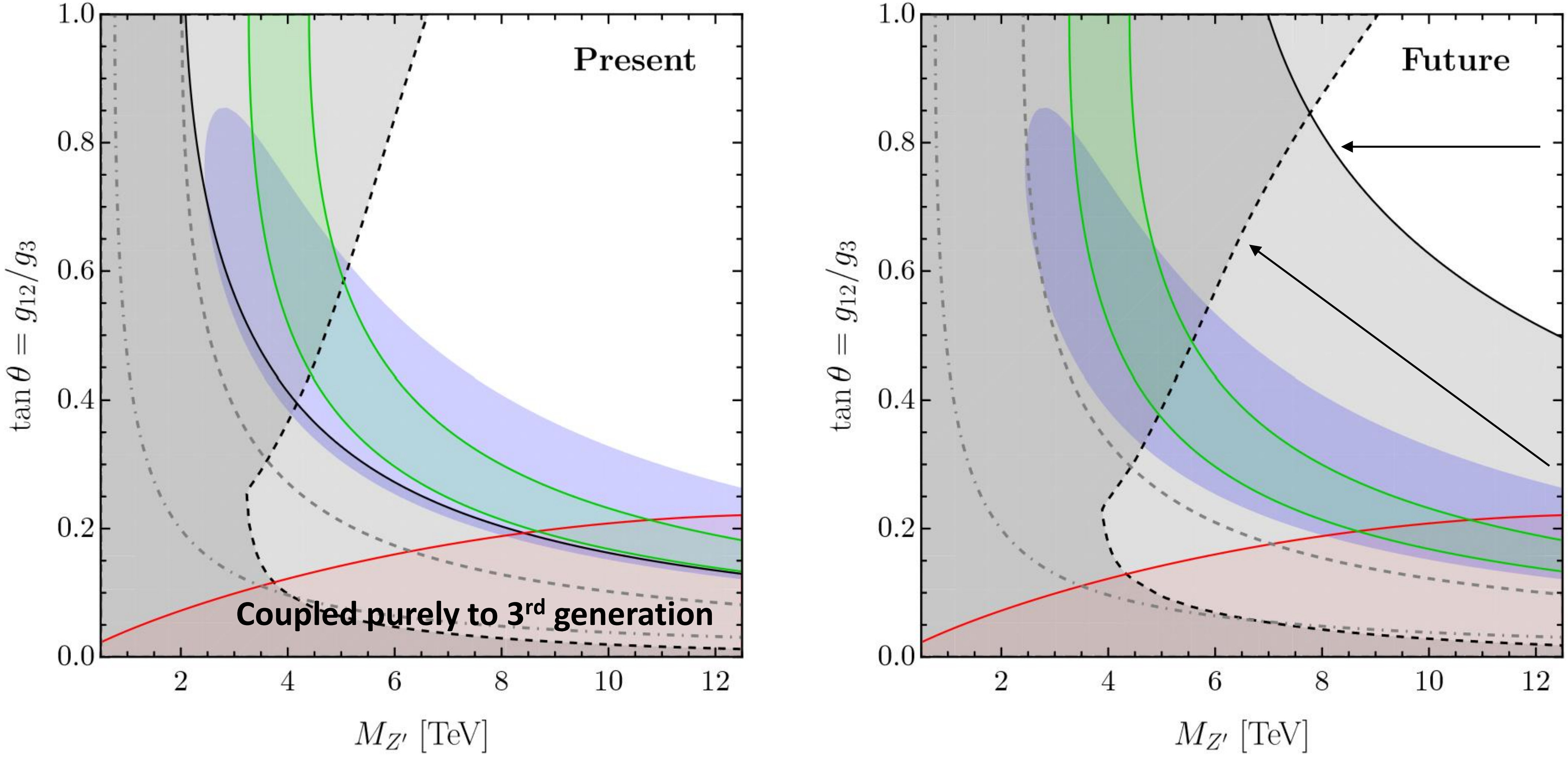

Estimated exclusion from EWPOs after 3 months of FCC-ee (1 LEP worth of Z boson events every 15 minutes!)

Hi-Lumi LHC estimated bound (3 ab^{-1})

A key pheno message:

An EW precision machine like *FCC-ee easily has power to completely exclude natural parameter* space of this deconstructed $U(1)_Y$ model of flavour – which we identified as the *most natural* option in absence of SUSY / compositeness below 10 TeV

… and what of the large hierarchy problem?

"UV problems" that remain:

1. Resolve **1-2 sector** at $\sim 1000\ \mathrm{TeV}$
2. **Neutrino masses**… eg by see-saw from near GUT scale $\sim 10^{12}\ \mathrm{TeV}$
3. Quantum gravity at M_{Pl} (*wave hands*)

We imagine SUSY / compositeness could still enter $\sim 10\ \mathrm{TeV}$, protecting M_h^2 from the deep UV

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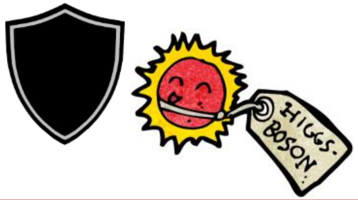
…

Higher physical scales

$\Lambda_{12} \sim 100 - 1000\ \mathrm{TeV}$ — 1-2 sector generated



Compositeness or SUSY

$10\ \mathrm{TeV}$

U_1, G, Z'

W'_R, Z'_R VLFs

$1\ \mathrm{TeV}$

$100\ \mathrm{GeV}$ — *W, Z, h*, 3rd family fermions

Light Yukawas (naturally suppressed)

…

An inversion of MFV paradigm

- Very flavoured physics (non-universal gauge interaction) enters at TeV to explain flavour, but without worsening the little hierarchy problem
- Higgs is properly stabilized at higher scales, say 10 TeV

Summary

1. Flavour could be explained at TeV scale, without worsening the little hierarchy problem
2. Deliver accidental $U(2)$ symmetries by deconstructing SM gauge symmetry; get flavoured heavy versions of the SM gauge bosons
3. Must deconstruct part of EW symmetry to explain fermion mass hierarchies; inevitably gives large-ish 1-loop Higgs mass corrections, so naturalness favours a low scale
4. Most natural option is to just deconstruct hypercharge near TeV scale
5. If also require semi-simple UV gauge group, also require 3rd family quark-lepton unification
6. Rich TeV pheno in colliders, flavour, and EWPOs. FCC-ee has huge potential to probe it.
7. SUSY or compositeness could still kick in at higher scale $\mathcal{O}(10\ \mathrm{TeV})$ to stabilize H from the deep UV

Thanks!