Flavour non-universality vs Naturalness

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JD, Isidori 2303.01520

JD, Stefanek 2305.16280

JD, Gosnay, Miller, Renner (work in progress)

KCL, 22nd June

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)

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I will discuss:

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

Outline

1. Introduction: flavour BSM, naturalness, LHC

2. Solving the flavour puzzle at the TeV scale: non-universal gauge interactions

3. Implications for naturalness

4. Some phenomenological consequences

1. Introduction:
Flavour BSM, naturalness, LHC

Flavour puzzle

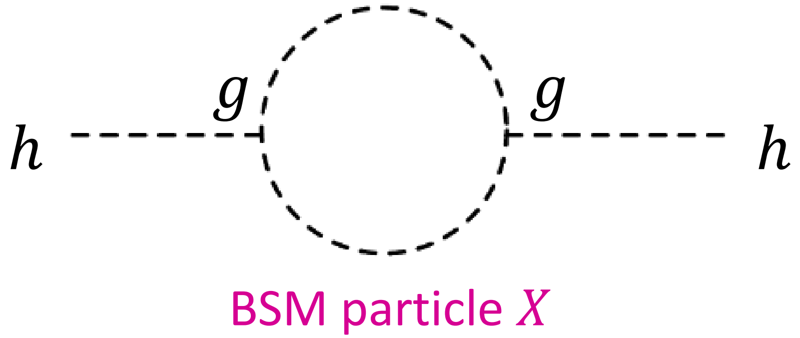
Huge (technically natural) hierarchies in SM Yukawa couplings $y\,\bar{\Psi}_L H \Psi_R$:

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

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

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



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

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

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

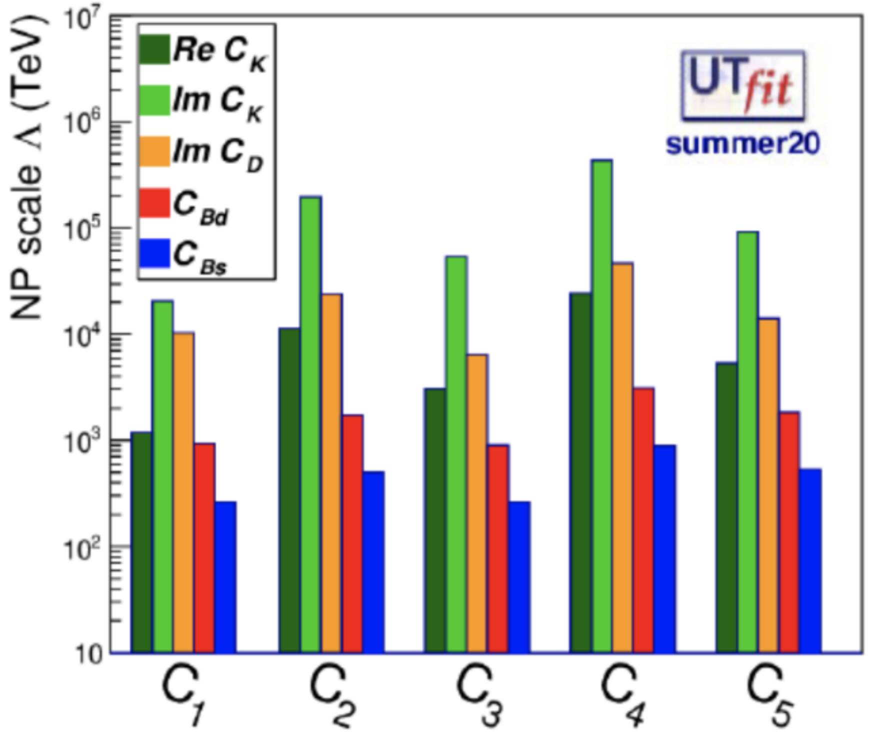
This sensitivity of M_h^2 to flavour-puzzle-solving-BSM appears severe:

1. Trying to explain structure of Higgs couplings $y\ \bar{\Psi}_L H \Psi_R$, 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

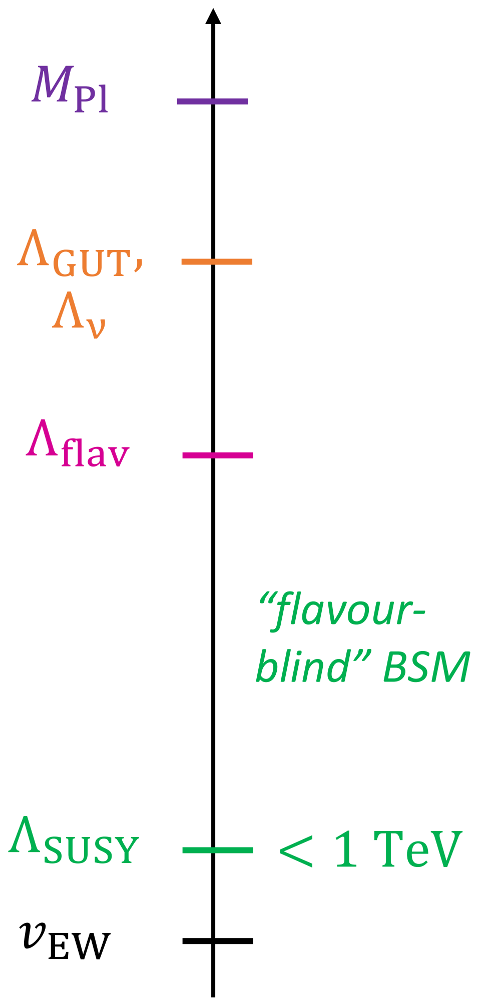
These mechanisms would protect M_h from **all** higher NP scales up to $M_{\rm Pl}$;

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
Kagan, Perez, Volansky, Zupan, 0903.1794
…



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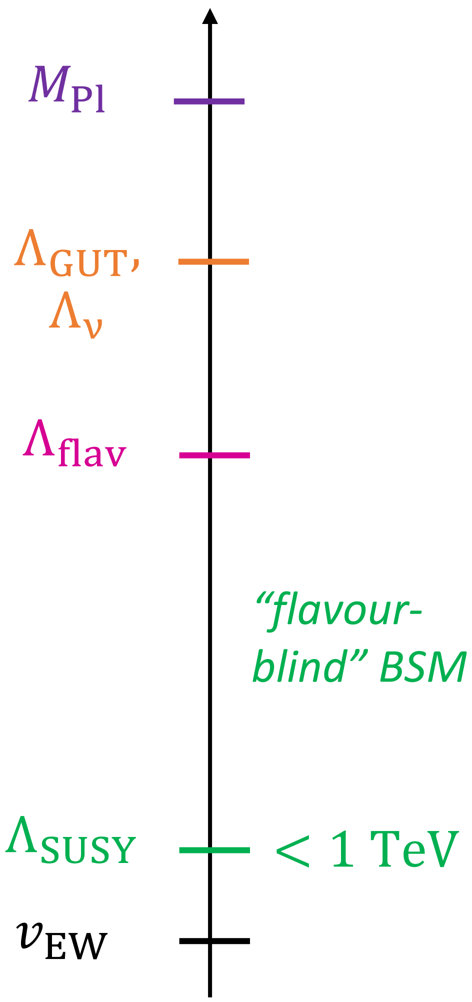
…

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

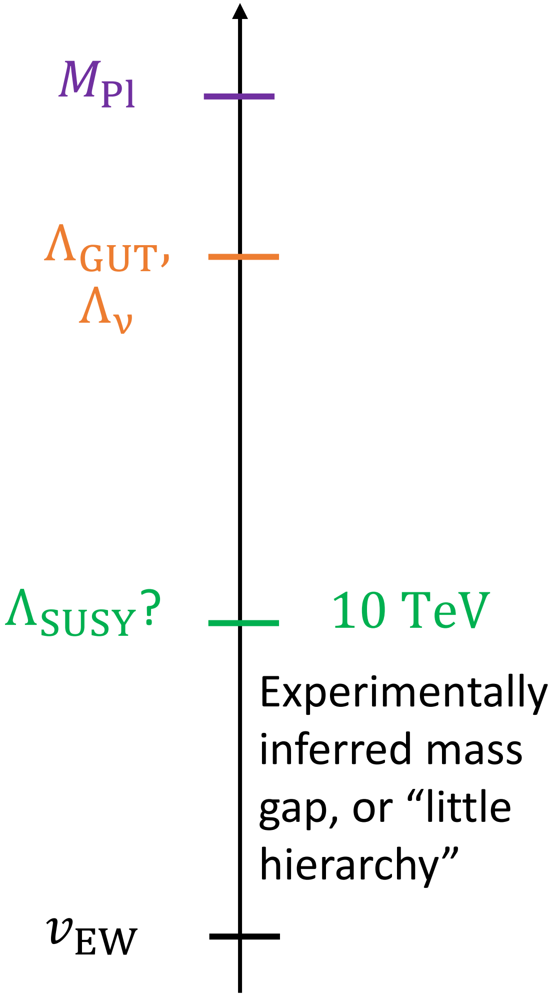
- Traditionally done using *horizontal gauge* symmetries that commute with $G_{\rm SM}$

Froggatt, Nielsen, Nucl Phys B (1979)
…

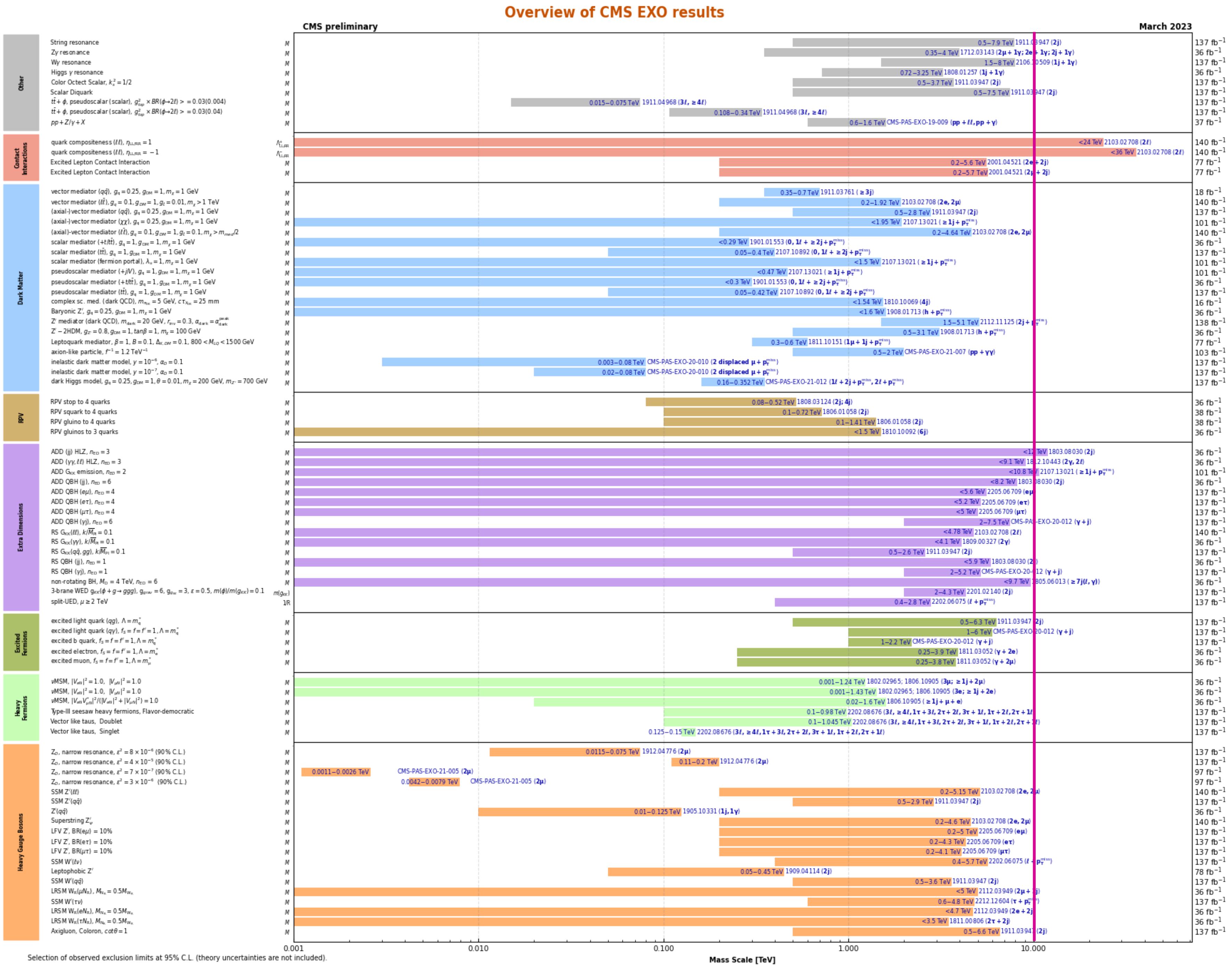


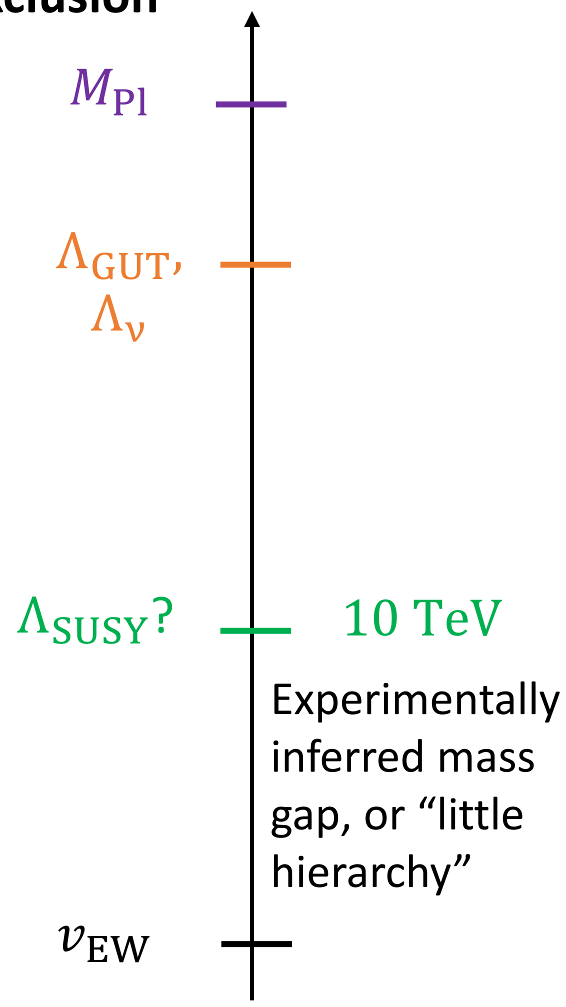
In 2020s, we know a lot more from the LHC + other experiments

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



Many ATLAS and CMS direct search limits approach 10 TeV exclusion





https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

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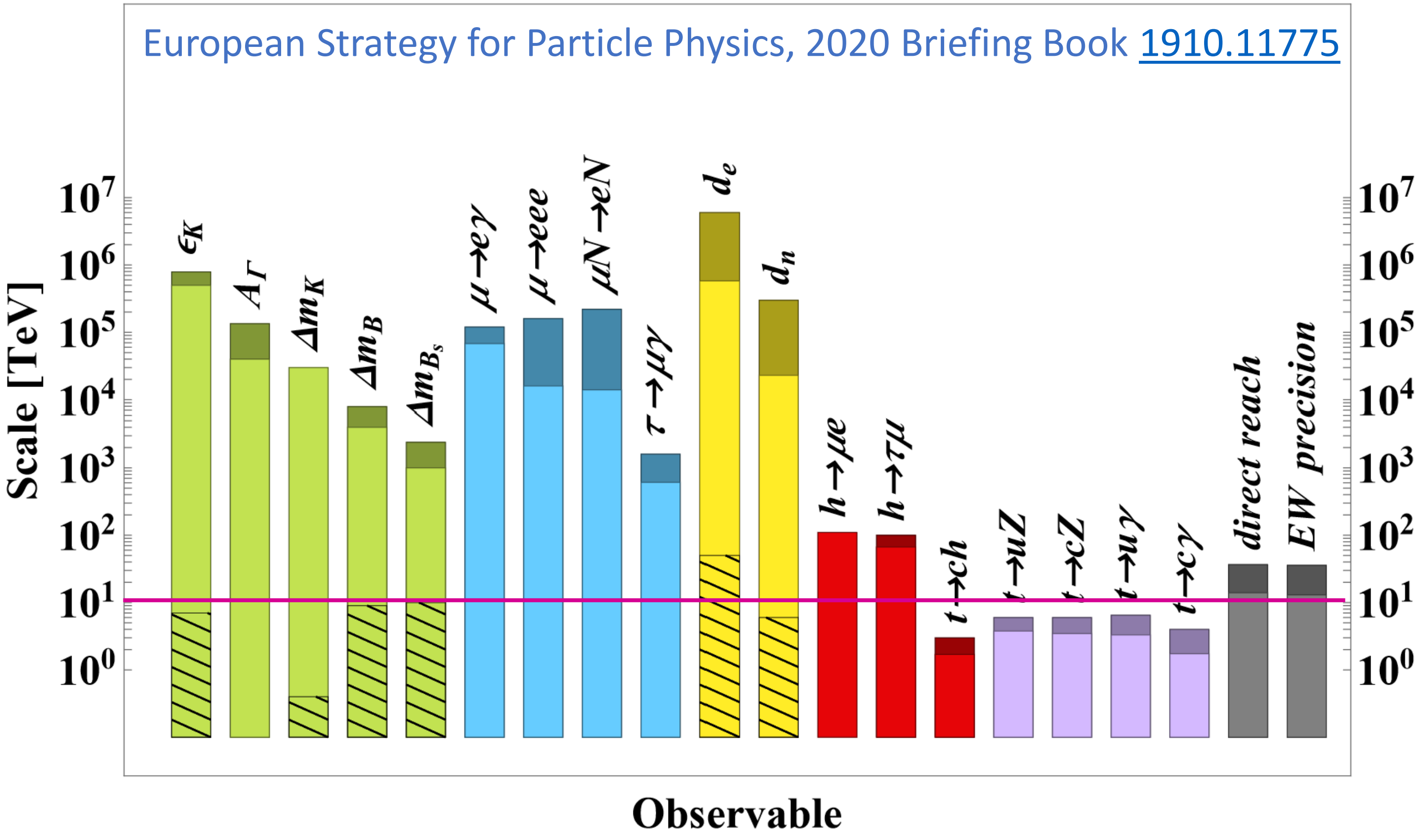
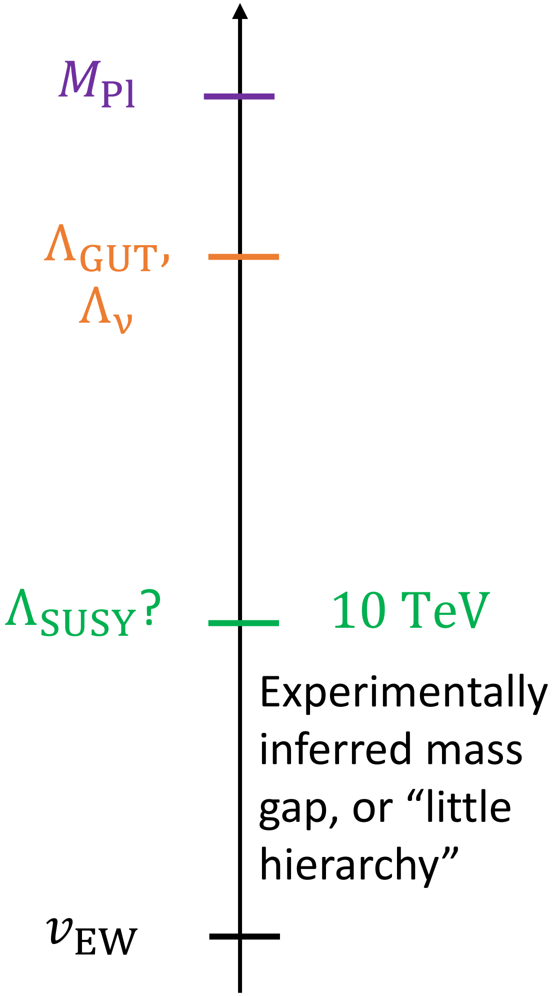




With **MFV**, the effective scale of NP as constrained by flavour + EWPO + direct searches is in similar ballpark: currently around **10 TeV**

Percent level tuning on M_h^2 in MFV SUSY / compositeness = "little hierarchy problem"

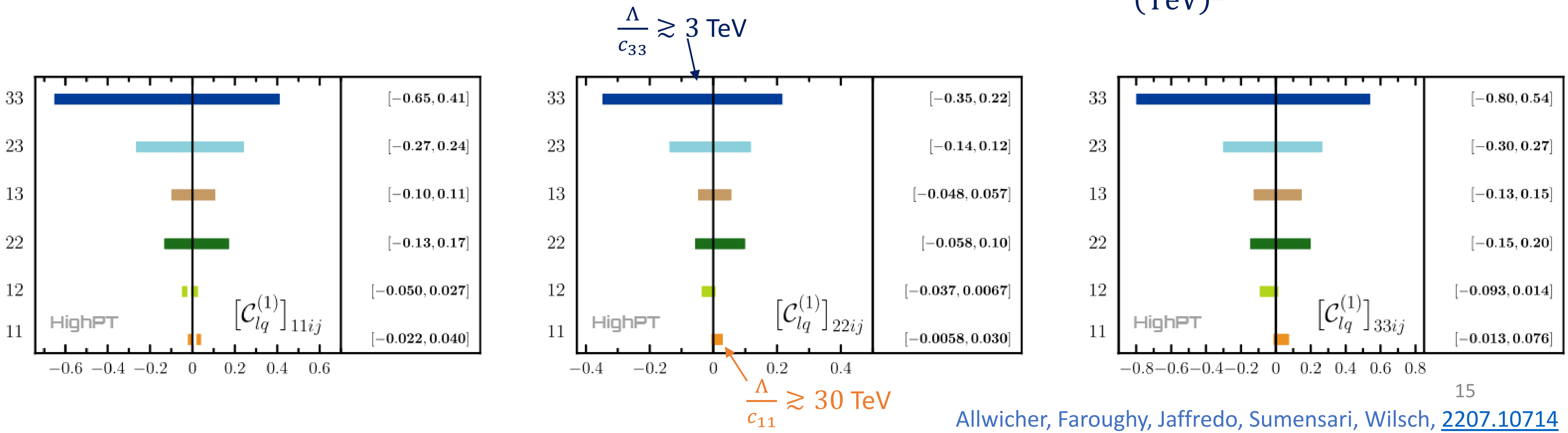
Beyond MFV: *very flavoured* NP can be lighter!

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**

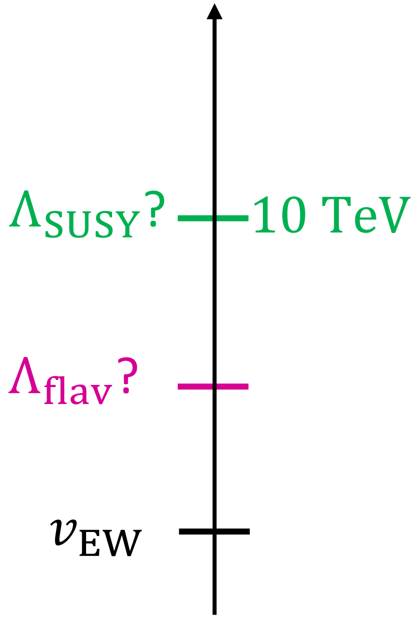
Example: high-p_T Drell-Yan tail constraints on semi-leptonic SMEFT operators

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



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

2. Solving the flavour puzzle at the TeV scale



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:

$(\psi_1 \quad \psi_2)$ = doublets of $U(2)$, ψ_3 = 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

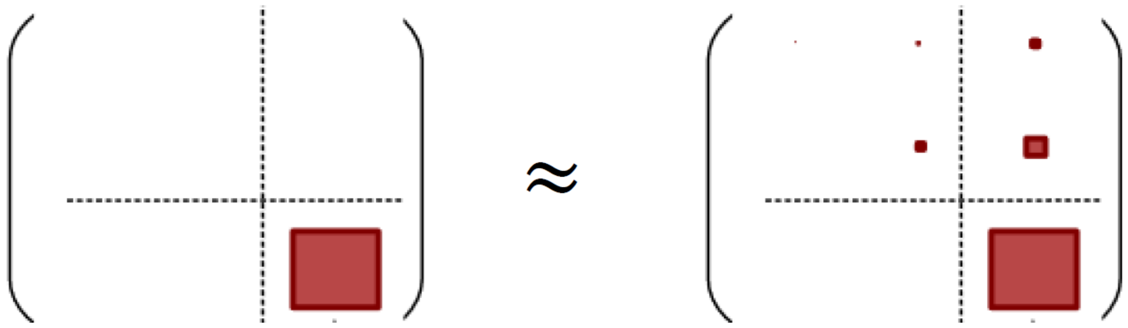
Barbieri et al, 1105.2296;
Isidori, Straub, 1202.0464;
Fuentes-Martin et al, 1909.02519

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

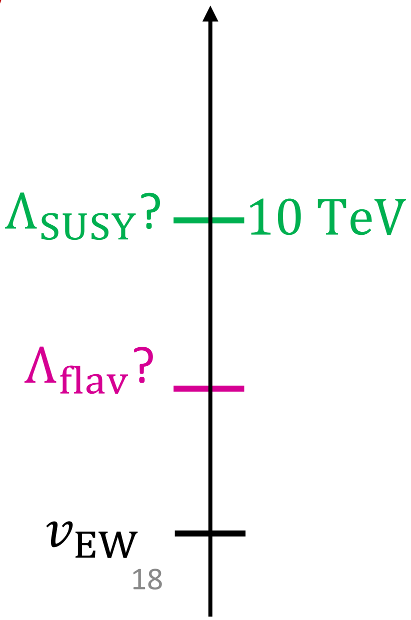
The non-universal gauge symmetry, and the $U(2)^5$ it delivers, could be the origin of **flavour hierarchies**, because it will also restrict the Yukawa couplings:



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

$U(2)$ accidental symmetries from **deconstructed** SM 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 $m_2 \ll m_3$

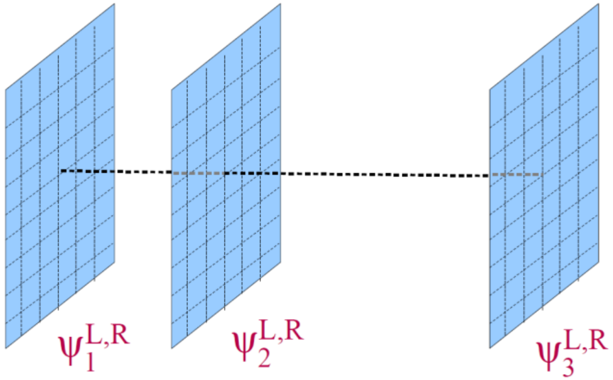
Towards the UV: possible origin of deconstructed gauge symmetry [digression]

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
Cacciapaglia et al, 1501.03818
Panico, Pomarol, 1603.06609

Example origin 1:

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

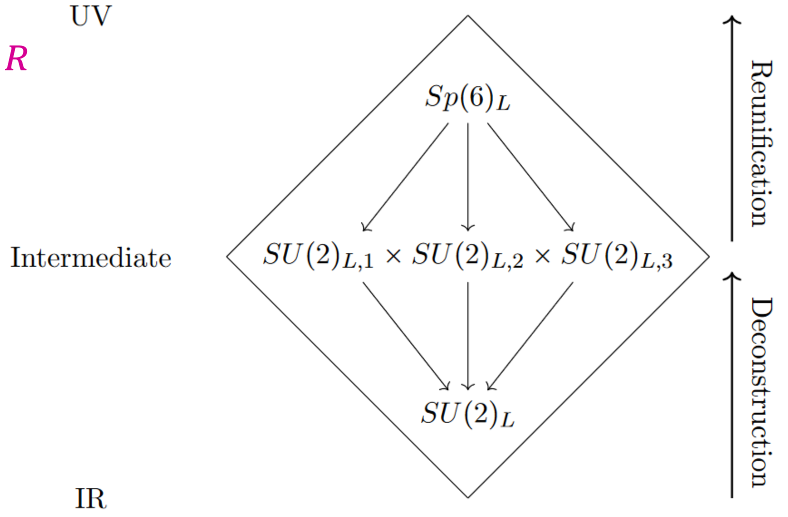


Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368
Fuentes-Martin, Isidori, Lizana, Selimovic, Stefanek, 2203.01952

Example origin 2:

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

- $\mathbf{2}^{\oplus 3} \hookrightarrow \mathbf{6}$: all SM fermions in just 2 fields Ψ_L and Ψ_R
- Offers a "gauge answer" to "why 3 generations?"
- Higgs $\hookrightarrow (\mathbf{6}, \mathbf{6})$; EW-breaking vev also breaks flavour symmetry



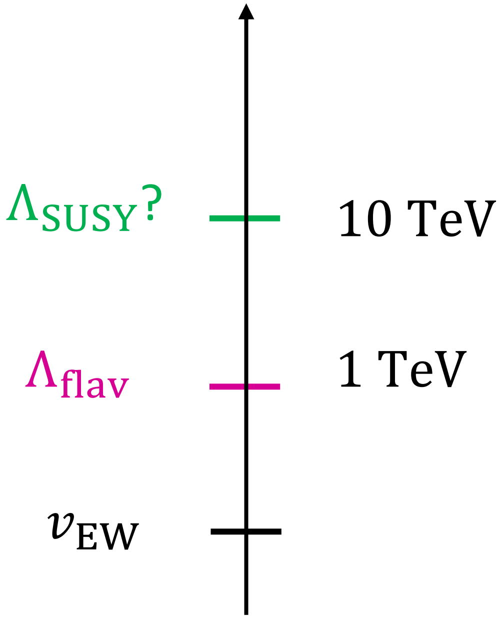
Davighi, Tooby-Smith, 2201.07245
Davighi, 2206.04482

3. Deconstructed flavour symmetry vs Naturalness

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

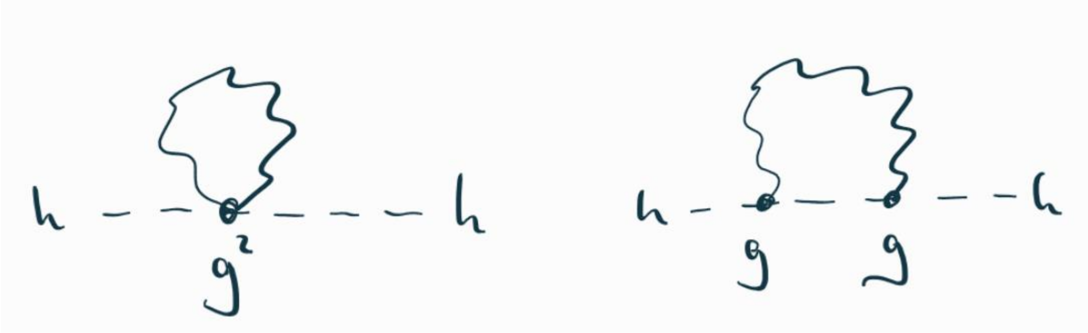
Davighi, Isidori, Pesut, 2212.06163
Davighi, Isidori 2303.01520
Davighi, Stefanek 2305.16280
Davighi, Gosnay, Miller, Renner (work in progress)

Flavour non-universality vs. Naturalness

Allwicher, Isidori 2011.01946
Davighi, Isidori 2303.01520

Naturalness criteria: $\delta M_h^2 \lesssim (125\ \text{GeV})^2$ (aggressive), $\delta M_h^2 \lesssim (\text{TeV})^2$ (little hierarchy)

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



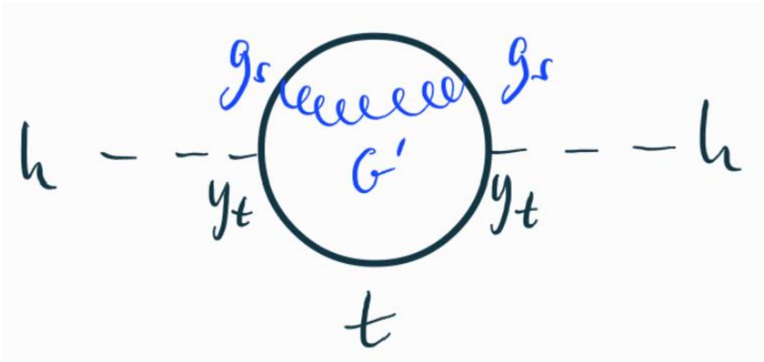
$$\Longrightarrow \delta M_h^2 \sim \frac{1}{16\pi^2} g_{L/Y}^2 M_{L/Y}^2$$

Natural mass ranges:

$M_{W_L'} \lesssim 2.5\ (20)\text{TeV}$
$M_{Z_Y'} \lesssim 5\ (40)\ \text{TeV}$

Since $g_Y \sim \frac{1}{2} g_L$, which *also* gives safer pheno (more later…)

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



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

$M_{G'} \lesssim 10\ (80)\ \text{TeV}$

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

Allanach, Gripaios, Tooby-Smith, 2104.14555

All options use one of the basic "vertical" 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

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

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

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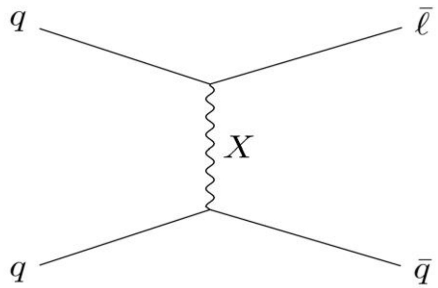
BUT $SU(5)$ & $SO(10)$ feature **LQs that give tree-level proton decay!** $\Rightarrow$ $M_X \gtrsim$ GUT scale
So $SU(5)$ & $SO(10)$ -based options **cannot appear** in our low-scale, natural models



*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

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3	$\mathrm{SU}(4)$	$\mathrm{SU}(2)_L^{[3]} \times \mathrm{SU}(2)_R^{[3]}$	$\mathrm{SU}(2)_L^{[12]} \times \mathrm{U}(1)_R^{[12]}$
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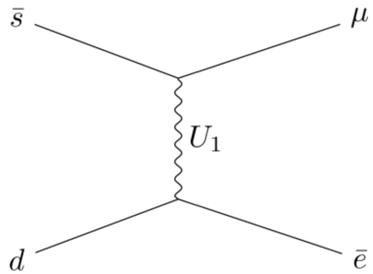
Option 1 is **new**, and has naturally suppressed RH fermion mixing ☑ ☑

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

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

4. Flavour deconstruction (at natural scale) gives rich phenomenology

$M_{G'} \lesssim 10\ (80)\text{TeV}$

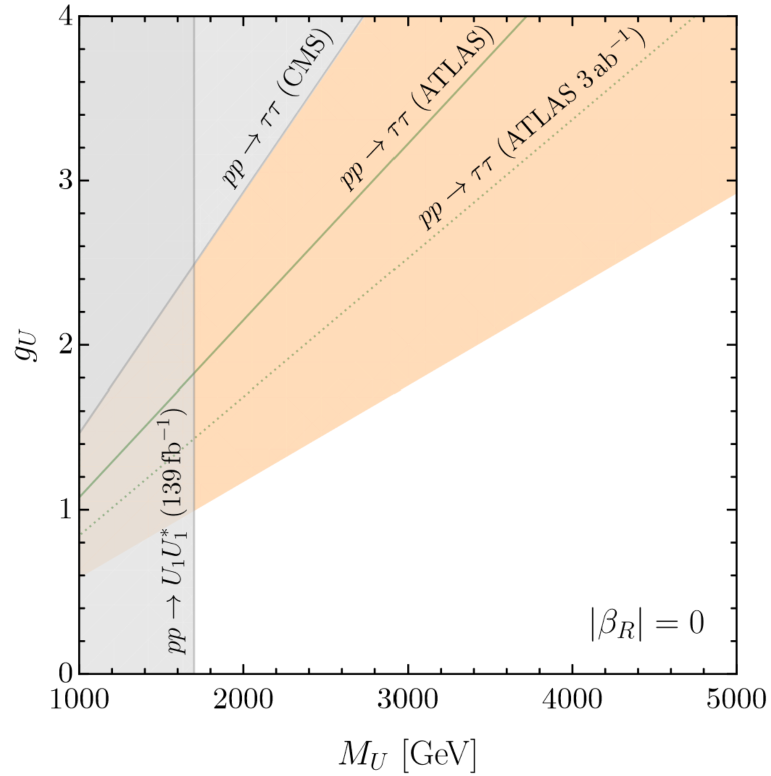
$M_{W_L'} \lesssim 2.5\ (20)\ \text{TeV}$

$M_{Z_Y'} \lesssim 5\ (40)\ \text{TeV}$

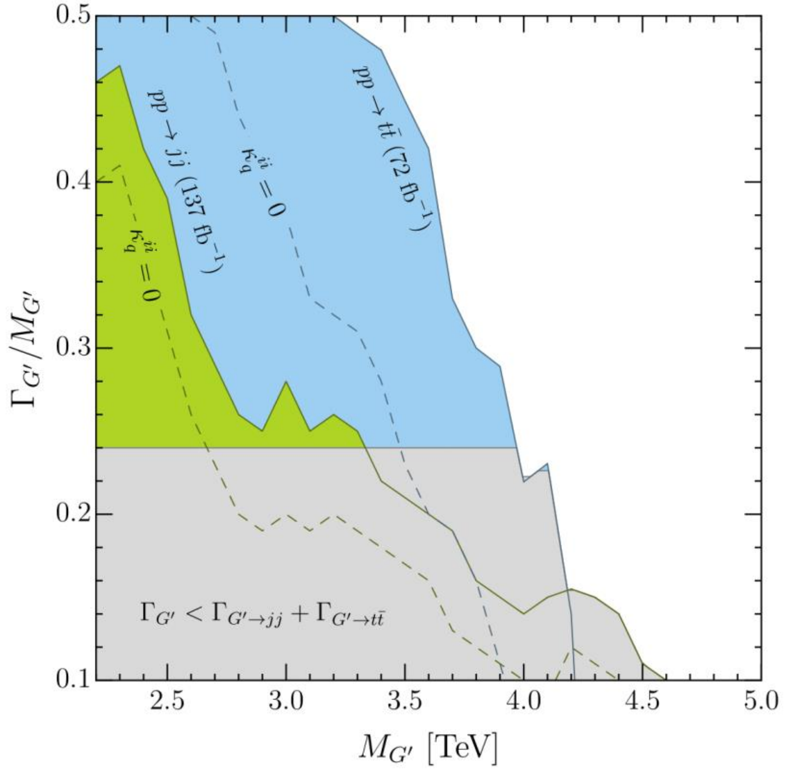
Deconstructed $SU(3)$ gives 'coloron' $G \sim (\mathbf{8},\mathbf{1})_0$
Deconstructed $SU(4)$ also gives vector leptoquark $U_1 \sim (\mathbf{3},\mathbf{1})_{2/3}$ + Z', $M < 10$ TeV

$M_{G'} \lesssim 10\ (80)\text{TeV}$

- 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

(but remember this option does not explain m_2/m_3 hierarchy)

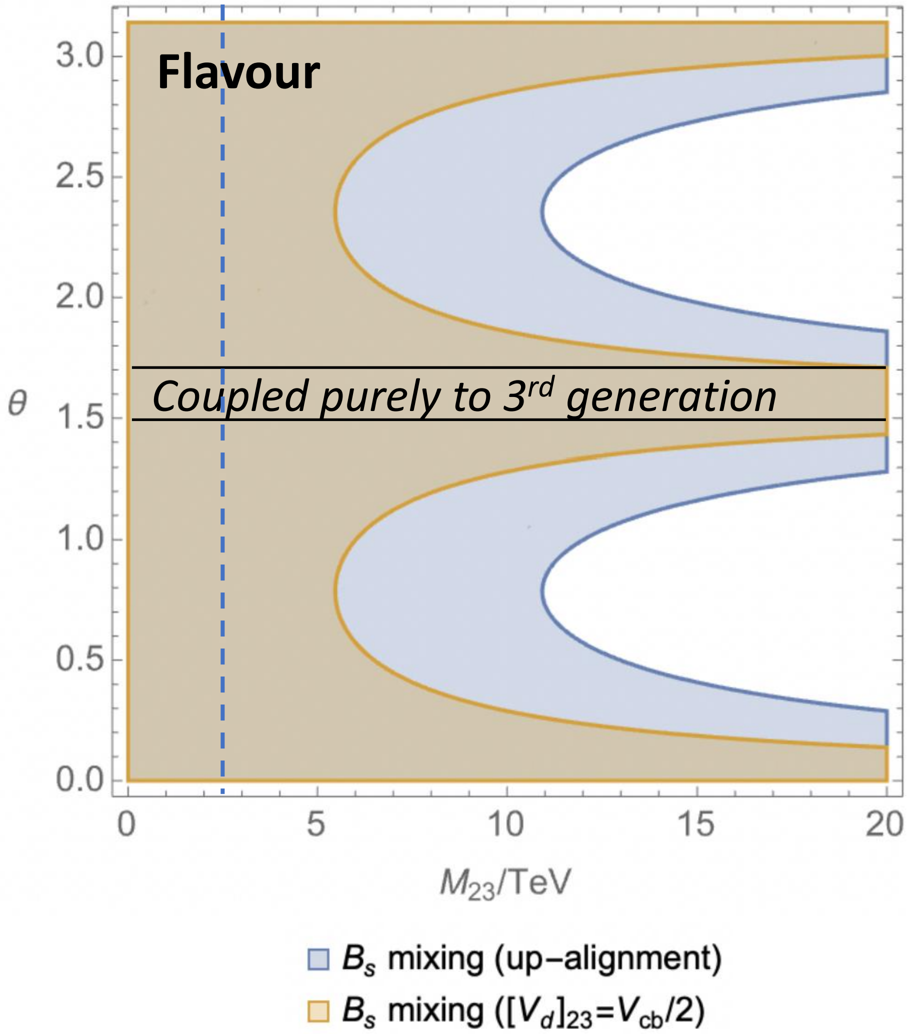
No clear "prediction" for an anomaly in $R_{D^{(*)}}$; if $M \approx 10$ TeV, $\Delta R_{D^{(*)}} \sim 10^{-3} R_{D^{(*)}}^{\text{SM}}$ (undetectable)

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

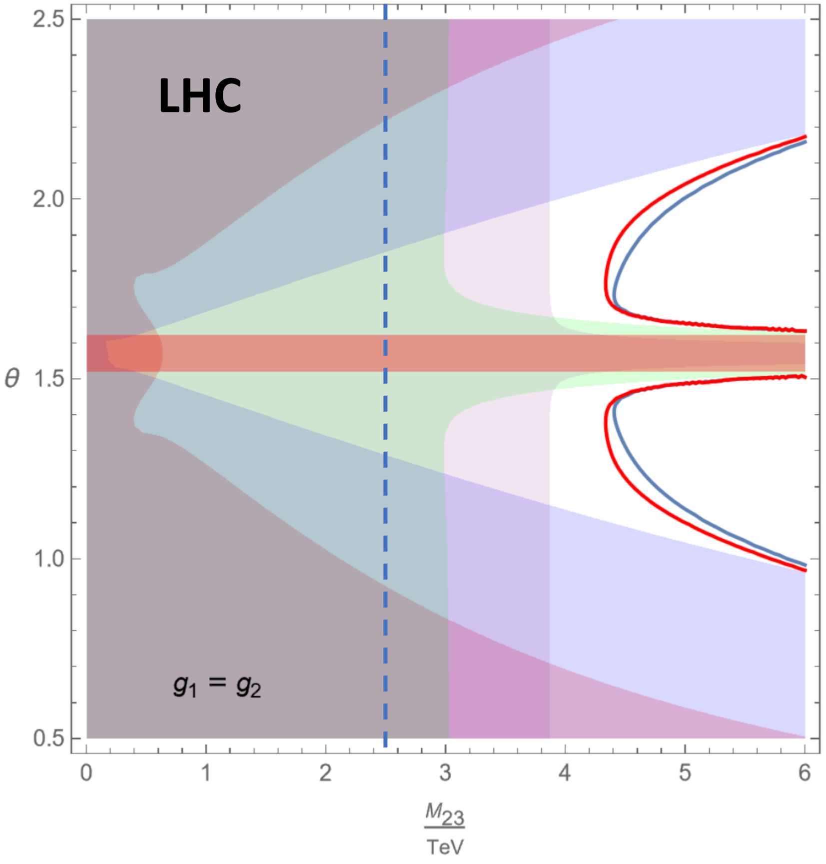
$M_{W_L'} \lesssim 2.5\ (20)$ TeV

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

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



(If down-alignment, there is no constraint)



$$\theta = \arctan\left(\frac{g_3}{\sqrt{g_1^2 + g_2^2}}\right)$$

- CMS di–muon exclusion
- ATLAS single muon exclusion
- ATLAS di–tau exclusion
- ATLAS single tau exclusion
- Combination: muon and tau channels only
- Combination: electron, muon and tau channels
- Non – perturbative g_3

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

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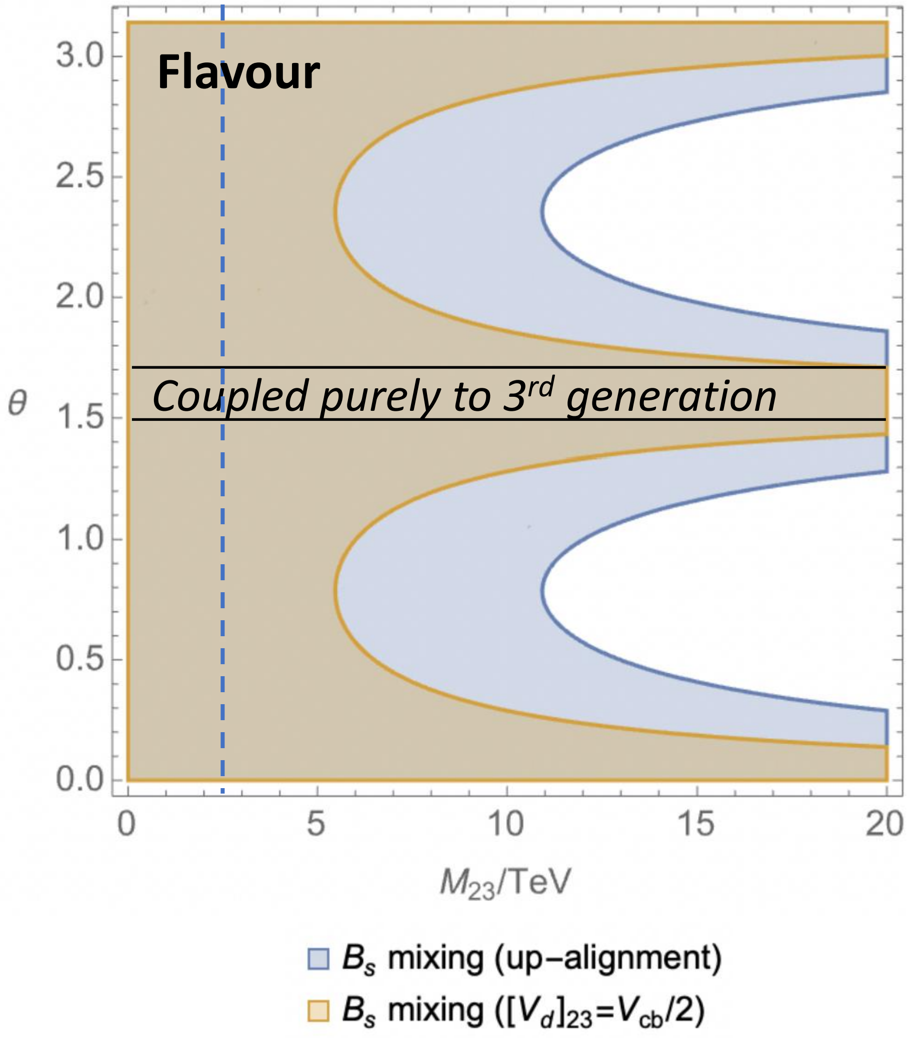

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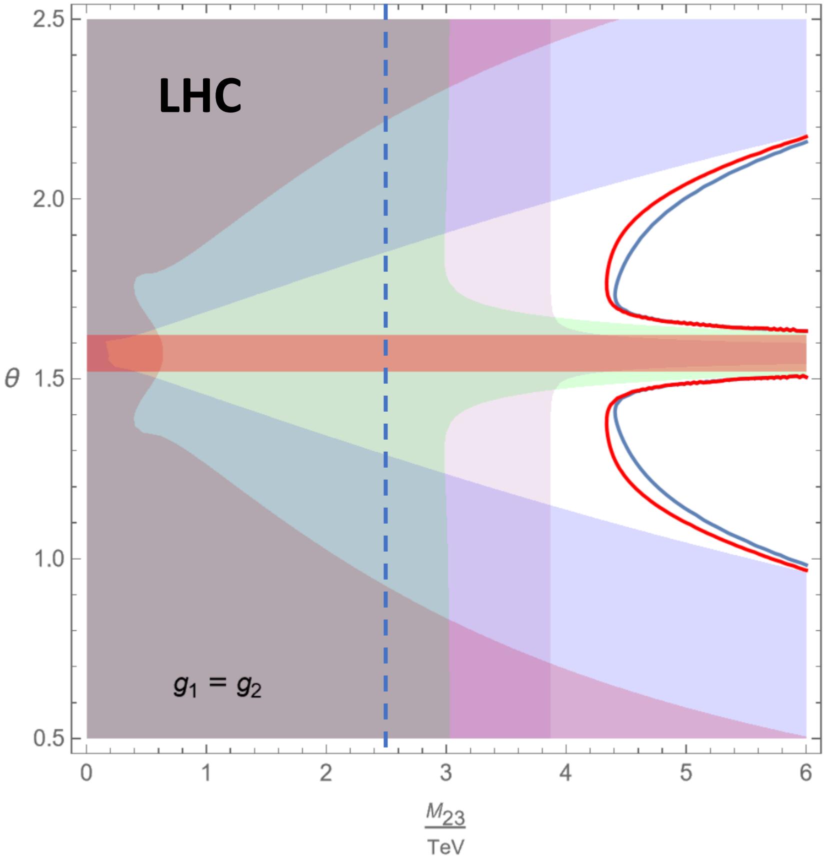

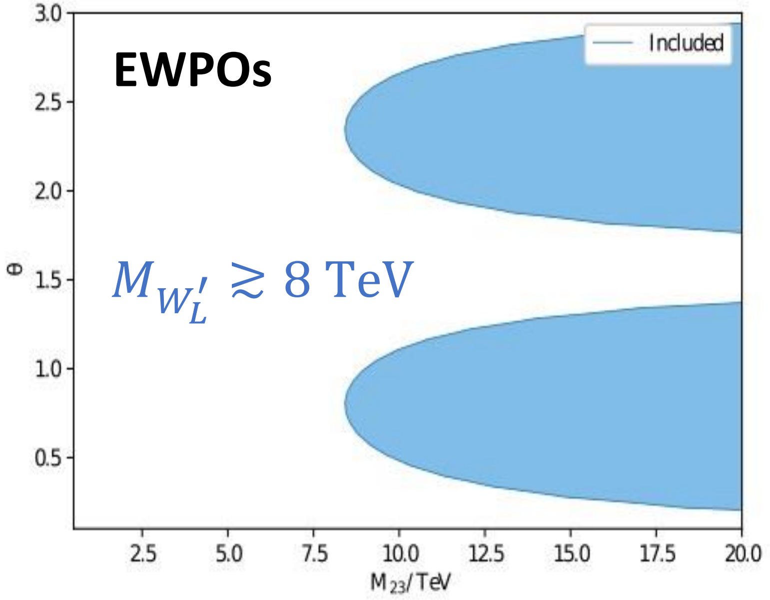

Computed using **smelli** package:
Aebischer, Kumar, Stangl, Straub
1810.07698

Built on **Wilson** and **flavio**
Aebischer, Kumar, Straub 1804.05033
Straub 1810.08132

Deconstructed $U(1)_Y$ gives Z': arguably **most natural** possibility, double benefit from $g_Y < g_L$

1. smaller Higgs mass correction
2. smaller NP effects

$M_{Z'_Y} \lesssim 5\ (40)\text{TeV}$

We built an explicit model in 2305.16280 (JD, Stefanek)

- TeV SSB $U(1)_{Y_{12}} \times U(1)_{Y_3} \rightarrow U(1)_Y$ by two scalars $\Phi_{q,H}$, Higgs charged under $U(1)_{Y_3}$

$$y_{u,d} \sim \begin{pmatrix} \frac{\langle\Phi_H\rangle}{\Lambda_H} & \frac{\langle\Phi_q\rangle}{\Lambda_q} \\ \frac{\langle\Phi_H\rangle\langle\Phi_q\rangle}{\Lambda_H\Lambda_q} & 1 \end{pmatrix}, \qquad y_e \sim \begin{pmatrix} \frac{\langle\Phi_H\rangle}{\Lambda_H} & \frac{\langle\Phi_H\rangle}{\Lambda_\ell} \\ \frac{\langle\Phi_H\rangle\langle\Phi_q\rangle}{\Lambda_H\Lambda_\ell} & 1 \end{pmatrix}$$

- Light Yukawa couplings generated by UV states at $\sim$10 TeV (provide $U(2)$-breaking spurions):

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_3$	$U(1)_{12}$	Generates:
H_{12}	**1**	**2**	0	1/2	$y_{c,s,\mu,u,d,e}$, V_{us}
$Q_{L,R}$	**3**	**2**	1/6	0	V_{cb}, V_{ub}

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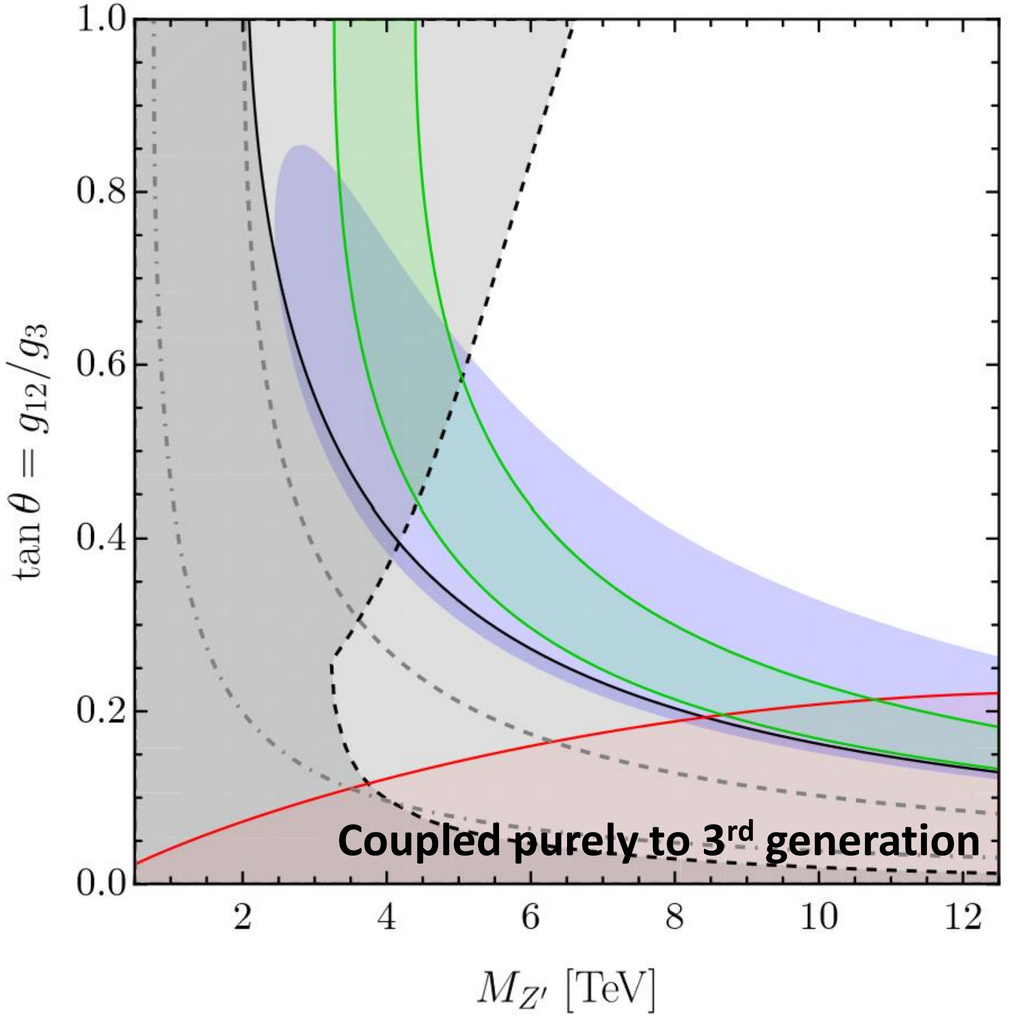


B_s mixing (with up-alignment! Suppressed by $Y_Q g_Y$)

$B_s \to \mu\mu$ 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

$M_{Z'_Y} \gtrsim 4\ \mathrm{TeV}$

More natural than the W'_L option as anticipated

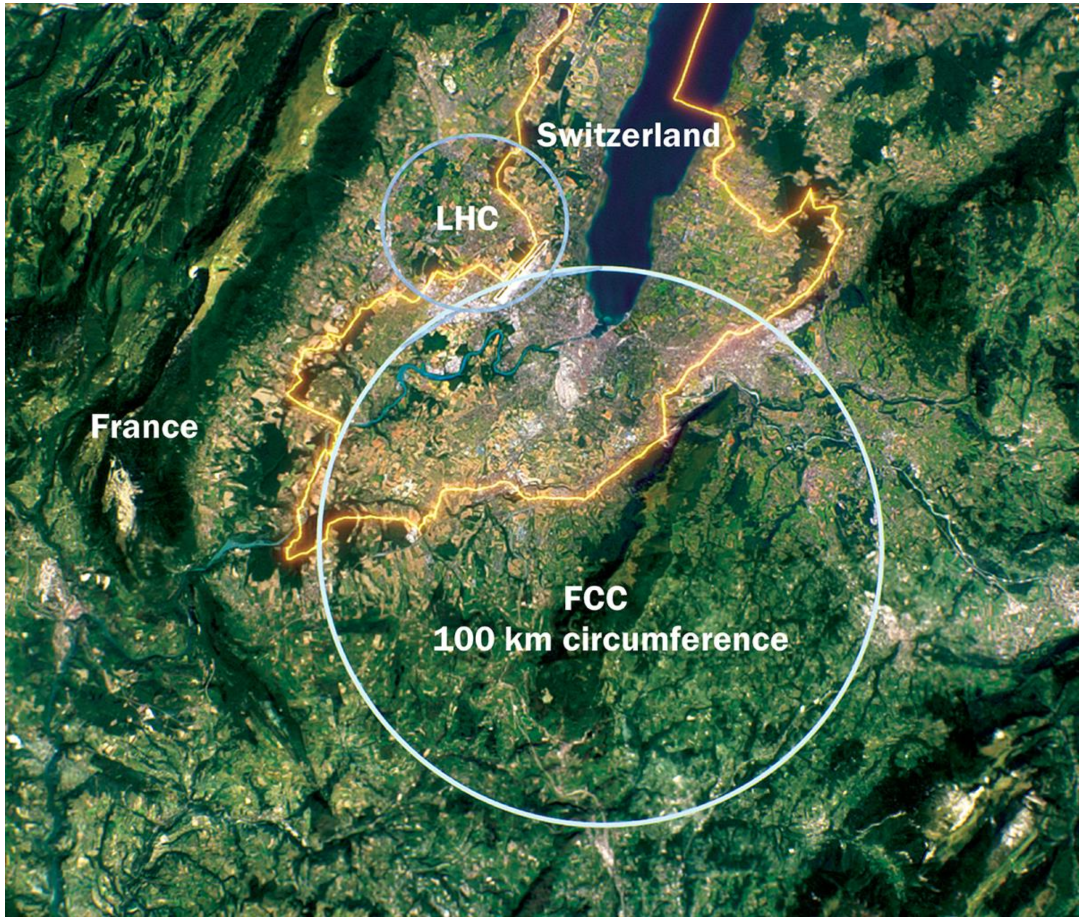
Future prospects: **FCC-ee**

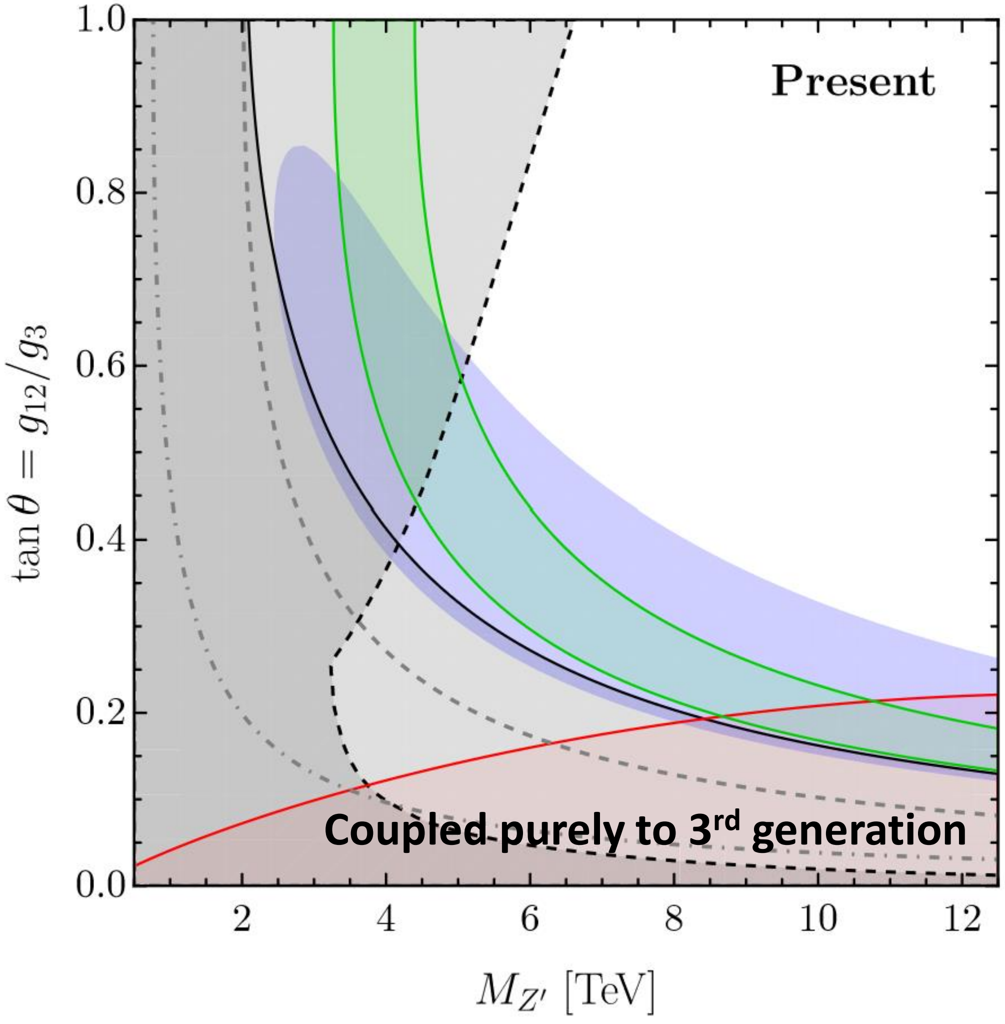
- Huge luminosity compared to LEP (1 LEP worth of Z boson events few minutes)
- Plan: 4 years running on Z pole

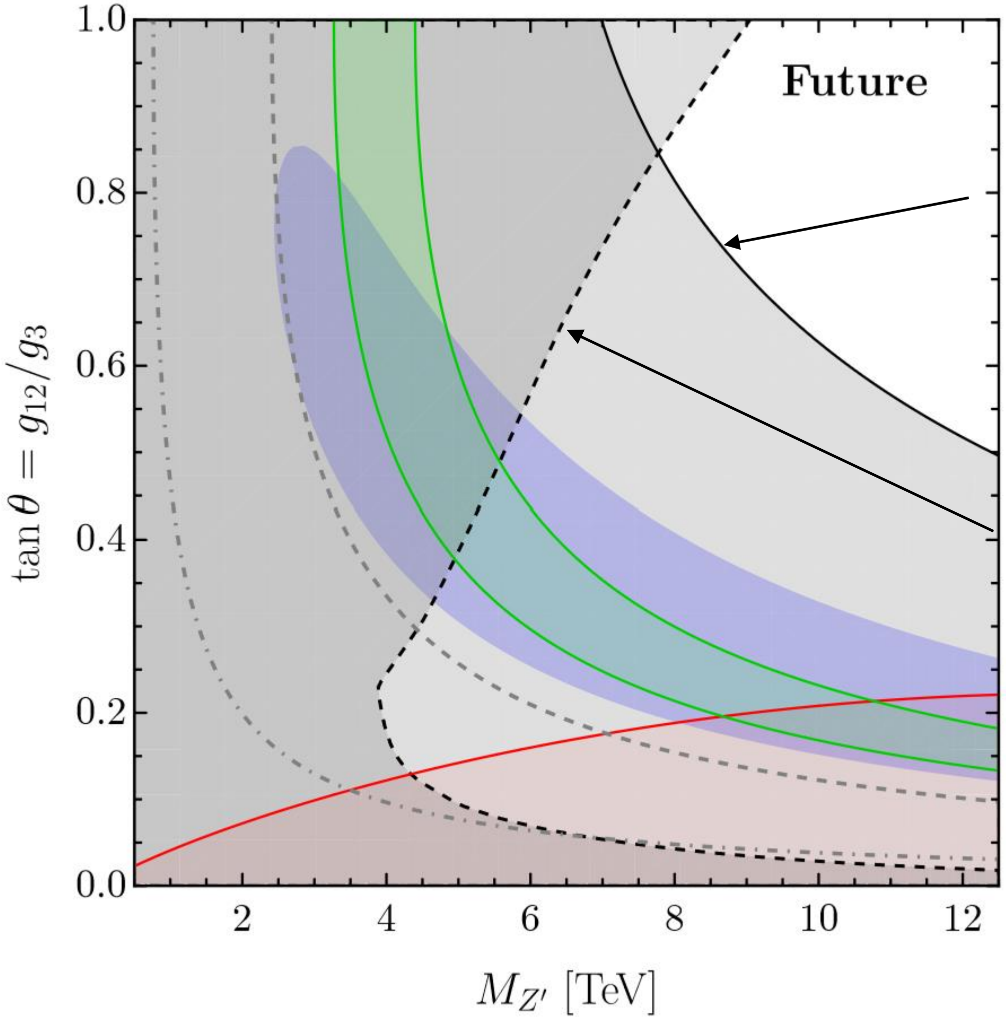
Outcome:

- Huge leap forward in EW precision (“Z pole”) observables

See e.g. FCC report for Snowmass [2203.06520]







Estimated exclusion from EWPOs after 3 months of FCC-ee ($10^4 \times$ LEP dataset)

Hi-Lumi LHC estimated bound (3 ab^{-1}) for $pp \to ll$ also improves significantly

FCC-ee also has great potential in important flavour observables e.g. $BR(B \to K\tau^+\tau^-)$

Li & Liu, 2012.00665

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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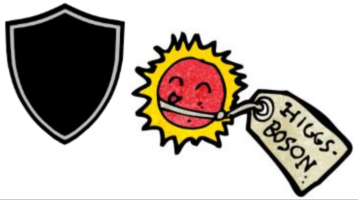
…

Higher physical scales

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



Compositeness or SUSY

10 TeV

U_1, G, Z'

1 TeV — W'_R, Z'_R — VLFs

100 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, expect 3^{rd} 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!