The Flavour of BSM: from LHC to Future Experiments

Joe Davighi, CERN

Zurich Phenomenology Workshop, 9th January 2024, University of Zurich

Key message:

1. “Deconstructing” SM gauge interactions $[G_{12} \times G_3 \to G]$ offers well-motivated solutions to flavour puzzle; current measurements allow significant natural* parameter space

2. Future experiments, especially EW precision programme of **FCC-ee** but also HL-LHC, Belle II, Mu3e…, will cover this natural parameter space

* Natural means:
  1. Electroweak stability: $\delta M_h^2 \lesssim (\mathrm{TeV})^2$
  2. Order-1 marginal couplings in UV model

This Talk

1. SM & BSM Flavour Puzzles → accidental $U(2)$ flavour symmetries

2. Natural gauge explanations by deconstructing the SM near the TeV
   - $G_{12}^{EW} \times G_3^{EW} \to G^{EW}$, Higgs charged under G_3^{EW}
   - Generic consequences: large δm_h^2 (naturalness?), large deviations in EWPO

3. Sketches of the UV

4. Phenomenological Case Studies
   - Deconstructed $U(1)_Y$, $m_{Z'} \gtrsim 4.5\ \mathrm{TeV}$; deconstructed $\mathrm{SU}(2)_L$, $m_{W',Z'} \gtrsim 9.5\ \mathrm{TeV}$
   - Flavour + high pT + EW precision all provide complementary constraints
   - FCC-ee will push back scales by a (significant!) order of magnitude: natural → unnatural

1. Flavour and accidental symmetries

The Flavour Puzzle(s)

Fermion sector of SM contains many mysteries:

1. Why those (chiral) representations / hypercharges?
2. Why 3 generations?
3. Why huge (technically natural) hierarchies in SM Yukawa couplings $y\,\bar{\Psi}_L H \Psi_R$?

Masses: $1 \approx y_t \gg y_c \gg y_u \sim 10^{-5},\, y_e \sim 10^{-6}$

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

The Flavour Puzzle(s)

See Claudia's talk

SM Lagrangian exhibits approximate $U(2)_L \times U(2)_R$ flavour symmetry

SM flavour puzzle

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

$$Y_u \sim \begin{pmatrix} & < 0.01 & 0.04 \\ & & 1 \end{pmatrix};$$

origin of $U(2)$s and $U(2)$-breaking spurions?

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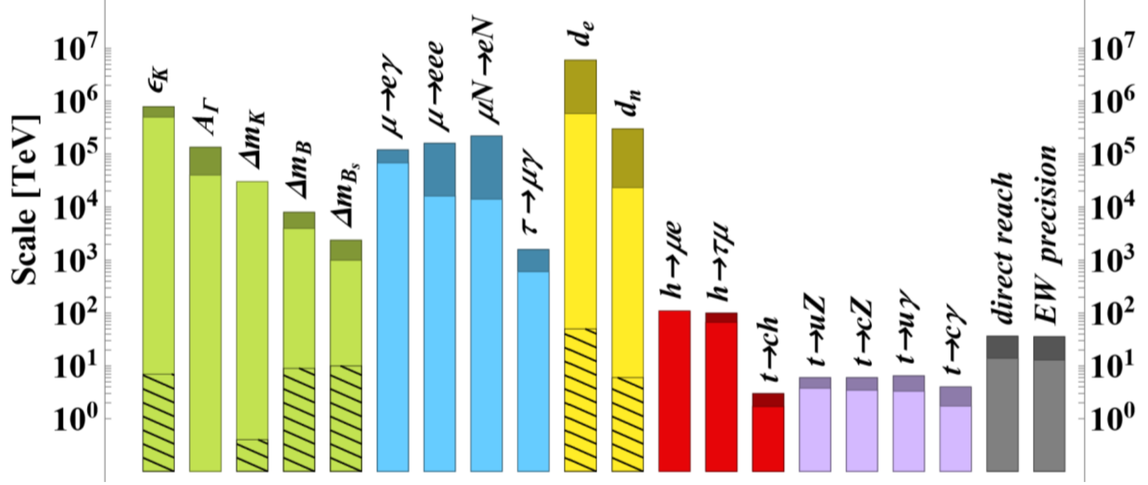
origin of $U(2)$s and $U(2)$-breaking spurions?

If New Physics is light ($\Lambda < 10$ TeV), it also exhibits $U(2)$ flavour symmetries

BSM flavour puzzle

Need to suppress e.g. kaon mixing, which probes effective scale $\sim 10^{5-6}$ TeV

European Strategy for Particle Physics 1910.11775



Aside: $U(2)$ or $U(3)$?

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

Traditional MFV: New Physics has approximate $U(3)$ i.e. flavour-universal, broken only by $Y_{u,d,e}$

- $U(3)$ and $U(2)$ equally good for evading flavour bounds (BSM flavour puzzle);
- $U(3)$ more predictive (fixed spurions)

Reasons to prefer $U(2)$

- $U(2)$ can **also explain SM flavour puzzle**; $U(3)$ cannot!
- $U(3)$ unnecessarily aggressive; ties 3rd family couplings (most important for **naturalness**) to valence quark couplings, which are strongly bound by LHC
- With $U(2)$, NP can couple most to 3rd generation; it can be lighter, and so more natural

For 33 vs 11 quark indices in $\mathcal{L} \sim \frac{C_{ij}}{\Lambda^2} Q^i Q^j L^a L^b$, bounds on C_{ij}/Λ^2 from LHC Drell—Yan weaker by factor ~ 10, see e.g. [Allwicher et al 2207.10714; Allwicher et al 2207.10756]

2. Explaining the accidents: Deconstructing the SM forces

Hypothesis: $U(2)$s manifest in Yukawas and NP couplings have *common dynamical origin!*

Emerge as accidental symmetries from spontaneously-broken non-universal gauge symmetry that acts differently on 3rd family, same on 1st and 2nd

Flavour non-universality

- Want $U(2)^n$ to emerge as accidental from a flavour non-universal gauge symmetry

Horizontal approach

- One approach is to "factorize the flavour problem" by gauging a horizontal symmetry

$$G = G_{\mathrm{SM}} \times G_{\mathrm{hor}} \to G_{\mathrm{SM}}$$

Froggatt, Nielsen, Nucl Phys B (1979)

- All heavy gauge bosons are SM singlet Z's. Examples:

  - Gauge $G_{\mathrm{hor}} = U(2)^n$ symmetries directly

  - Gauge a particular $G_{\mathrm{hor}} = U(1)_X$ a la Froggatt—Nielsen

Recent examples:
Greljo, Thomsen, 2309.11547
Antusch, Greljo, Stefanek, Thomsen, 2311.09288

… Cornella et al 2306.08026

Flavour non-universality, non-horizontally

- Want $U(2)^n$ to emerge as accidental from a flavour non-universal gauge symmetry

Deconstruction approach:

- A more intricate approach is to split apart (or "deconstruct") SM gauge symmetry by flavour:

$$G = G_{\text{SM},12} \times G_{\text{SM},3} \rightarrow G_{\text{SM}}$$

Arkani-Hamed, Cohen, Georgi hep-th/0104005; … Craig, Green, Katz 1103.3708; … Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368 …

- Heavy gauge bosons in adjoint of G_{SM}, e.g. if $G_{\text{SM}} = SU(2)_L$ we get a heavy electroweak triplet, coupled to a flavour-non-universal fermion current

Gauge Model of Generation Nonuniversality

Xiao-yuan Li[a] and Ernest Ma

Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822

(Received 13 October 1981)

An electroweak gauge model is discussed, where generations are associated with separate gauge groups with different couplings. The observed μ-e universality is the result of a mass-scale inequality, $v_{03} \ll v_{12}$, in much the same way as strong isospin is the result of $m_u, m_d \ll 1$ GeV. However, in contrast to the standard model, it is now possible to have (1) a longer τ lifetime, (2) an observable B^0-$\bar{B}^0$ mixing, and (3) many gauge bosons W_i, Z_i in place of W, Z with $M_{W_i} > M_W$ and $M_{Z_i} > M_Z$.

In conclusion, we have put forward in this paper a radical, if not heretical, point of view that both the observed μ-e universality and the known suppression of flavor-changing neutral-current kaon processes are in fact accidents, in much the same way that strong isospin is an accident. We thus predict a hierarchy of generations, in analogy with strong SU(2), SU(3), SU(4), etc., in which each succeeding generation breaks the universality of weak interactions more and more

Li, Ma, 1981

Flavour non-universality, non-horizontally

$$G = G_{\mathrm{SM},12} \times G_{\mathrm{SM},3} \to G_{\mathrm{SM}}$$

Deconstruction of SM gauge interactions is a theoretically appealing approach:

1. Charge assignment and anomaly-freedom inherited from SM (no *ad hoc* choices)

2. Breaking pattern, assuming scalar condensate ϕ, is **generic** for simple G
   - for any choice of gauge couplings, and any scalar rep $\phi \sim (\boldsymbol{R}_{12} \neq 1, \boldsymbol{R}_3 \neq 1)$, you *always* break to the diagonal (ergo flavour-universal) subgroup
   - … because there is no other non-trivial subgroup embedding, by *Goursat's lemma*
   - i.e. flavour universality of SM emerges almost **inevitably** from deconstructed G_{SM}

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

3. Easy to find semi-simple UV completions with deconstruction approach
   - e.g. Pati—Salam cubed [Bordone et al 1712.01368], $SU(5)$ cubed [Fernandez-Navarro, King, 2311.05683]
   - In contrast most $G_{\mathrm{SM}} \times U(1)_X$, even anomaly-free, have no semi-simple completion

Davighi, Tooby-Smith, 2206.11271

Flavour non-universality, non-horizontally

Davighi, Isidori 2303.01520

With Higgs charged under $G_{\mathrm{SM},3}$, deconstruction can explain Yukawa hierarchies via accidental $U(2)^n$:

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

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

Allows 2 x 2 matrix of light Yukawas (Higgs colourless)

Explains $V_{cb} \ll 1$

Doesn't explain $m_2 \ll m_3$

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

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Rank-1 matrix, can be diagonalised by a RH-rotation that is unphysical (as in SM)

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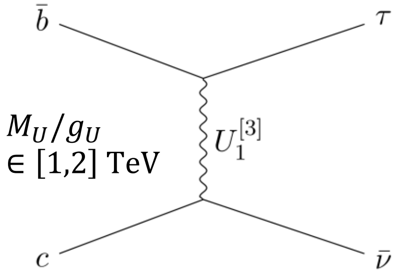
If we enlarge $SU(3)^{[3]} \to SU(4)^{[3]}$, can also explain $b \to c\tau\nu$ anomalies in $R_{D^{(*)}}$ via '4-3-2-1' models



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 …

Hint for deconstruction near TeV?

Flavour non-universality, non-horizontally

Davighi, Isidori 2303.01520

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⊛ What of Naturalness?

See also Allwicher, Isidori, Thomsen 2011.01946

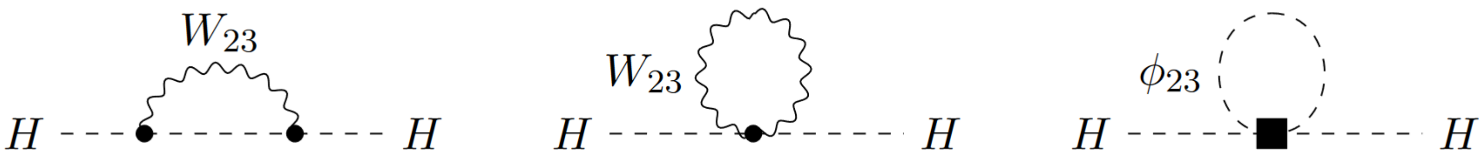
c.f. Farina, Strumia, Pappadopulo, 1303.7244

Unavoidable finite corrections to Higgs mass squared:

$$\delta m_h^2 \sim \left(\frac{1}{16\pi^2}\right)^2 g_s^2 y_t^2 N_c M_X^2 \qquad \delta m_h^2 \sim \frac{1}{16\pi^2} g_L^2 M_X^2 \qquad \delta m_h^2 \sim \frac{1}{16\pi^2} g_Y^2 M_X^2$$

Requiring $\delta M_h^2 \lesssim (125\ \mathrm{GeV})^2$ (aggressive), $\delta M_h^2 \lesssim (\mathrm{TeV})^2$ (little hierarchy) gives naturalness ‘bounds’:

$M_{G'} \lesssim 10\ (80)\ \mathrm{TeV}$ $\qquad$ $M_{W_L'} \lesssim 2.5\ (20)\mathrm{TeV}$ $\qquad$ $M_{Z_Y'} \lesssim 5\ (40)\ \mathrm{TeV}$



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⊛ Electroweak Precision

Deconstructing $SU(2)_L$ and/or $U(1)_Y$ gives tree-level effects in EWPOs: strong constraints ~ 5 TeV or so

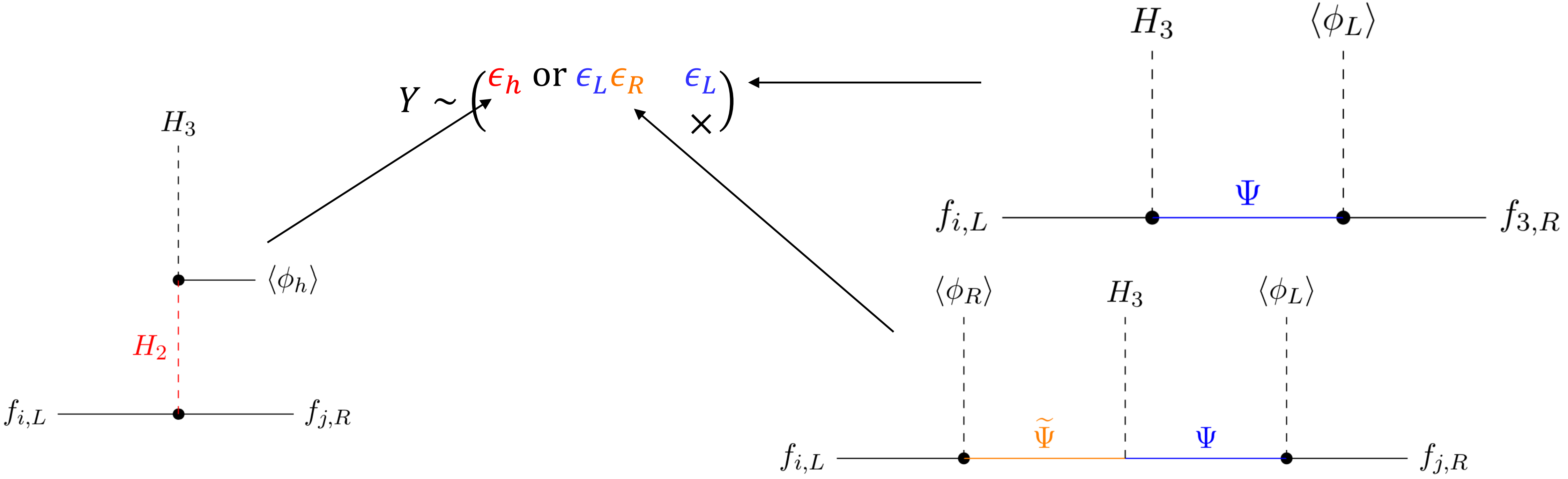
For deconstructed colour (e.g. '4-3-2-1'), EWPO much milder [Allwicher, Isidori, Lizana, Selimovic, Stefanek 2302.11584]

3. UV completion?

General Ingredients

Integrate out vector-like fermions Ψ or heavy Higgs-like scalars H_i to generate effective higher-dimensional Yukawa interactions, suppressed by ratios of scales $\epsilon \sim \langle\phi\rangle / M_{\Psi/H}$

Link fields ϕ typically in bi-fundamental of $G_{12} \times G_3$; condensate breaks to diagonal



These ingredients give extra Higgs mass contributions (and phenomenological effects); but these are more model-dependent than the gauge sector contributions

See e.g. Davighi, Isidori 2303.01520 for naturalness implications

Resolving the 1-2 sector

Bordone et al, 1712.01368
Fernandez-Navarro, King 2209.00276
Davighi, Isidori, Pesut 2212.06163
Davighi, Isidori 2303.01520
Fernandez-Navarro, King 2305.07690
Davighi, Gosnay, Miller, Renner, 2312.13346

- $G_{\mathrm{SM},12} \times G_{\mathrm{SM},3} \to G_{\mathrm{SM}}$ could be last step in a multi-scale breaking from fully deconstructed $G_1 \times G_2 \times G_3$
- Scale hierarchy $\Lambda_{12} > \Lambda_{23}$; the higher breaking step $G_1 \times G_2 \to G_{12}$ resolves 1-2 substructure i.e. explains the y_1/y_2 hierarchy
  - ➢ Λ_{12} *must* be higher (100s TeV), because it will induce 1-2 flavour violation e.g. kaon mixing
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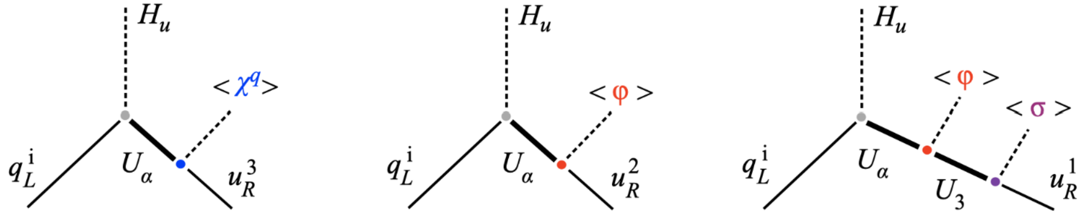
Abelian Example: '**Minimal Flavour Deconstruction**' Barbieri, Isidori, 2312.14004

vev scale	Field	$U(1)_Y^{[3]}$	$U(1)_{B-L}^{[12]}$	$U(2)_{T3R}^{[2]}$	$U(1)_{T3R}^{[1]}$	$SU(3) \times SU(2)$
v	$H_{u,d}$	$-1/2$	0	0	0	$(\mathbf{1},\mathbf{2})$
$O(10^{-1}) \times \Lambda_{[23]}$	χ^q	$-1/6$	$1/3$	0	0	$(\mathbf{1},\mathbf{1})$
	χ^l	$1/2$	-1	0	0	$(\mathbf{1},\mathbf{1})$
	ϕ	$1/2$	0	$-1/2$	0	$(\mathbf{1},\mathbf{1})$
$O(10^{-1}) \times \Lambda_{[12]}$	σ	0	0	$1/2$	$-1/2$	$(\mathbf{1},\mathbf{1})$

$$\begin{array}{c|cc|c|c} & \multicolumn{2}{c|}{U(1)^{[12]}_{B-L}} & & \\ & U(1)^{[1]}_{T3R} & U(1)^{[2]}_{T3R} & & \\ \hline Y \sim & O(\epsilon_\sigma \epsilon_\phi) & O(\epsilon_\phi) & O(\epsilon_\chi) & U(1)^{[12]}_{B-L} \\ \hline & O(\epsilon_\sigma \epsilon_\phi \epsilon_\chi) & O(\epsilon_\phi \epsilon_\chi) & O(1) & \end{array}$$

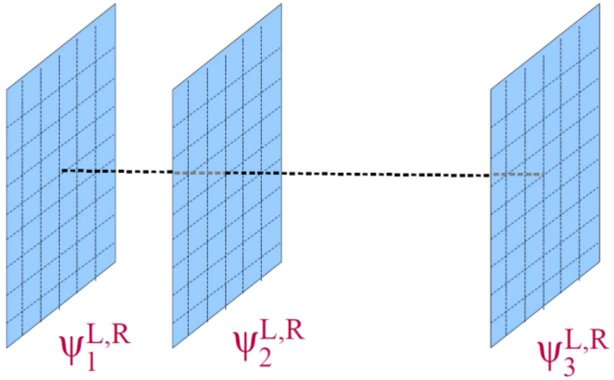
Example generation of light Yukawa EFT operators:



What is the origin of the flavour deconstruction?

Example origin 1: Fifth dimension

Realise multiple flavour sites via multiple stable branes in 5d bulk



Fuentes-Martin, Isidori, Lizana, Selimovic, Stefanek, 2203.01952

One bulk electroweak $SO(5) \supset SU(2)_L \times SU(2)_R$ gauge symmetry

- Holographic Higgs as light pNGB
- Fermions localised on 3 branes → $\prod_{i=1}^{3} SU(2)_{L,i} \times SU(2)_{R,i}$ in effective 4d description
- $SU(2)_R$ more sharply localised on branes ($SU(2)_L$ is "more universal")

What is the origin of the flavour deconstruction?

Example origin 2: 4d gauge flavour unification

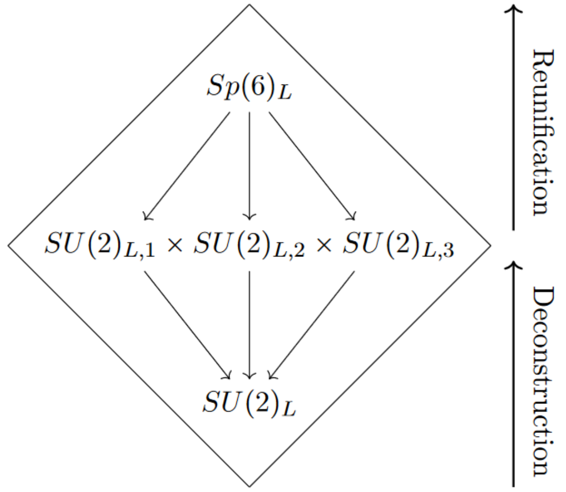
Allanach, Gripaios, Tooby-Smith, 2104.14555

Complete UV unification of matter into two Weyls $\psi_L \oplus \psi_R$; implies one of only 3 gauge groups

E.g. $SU(4) \times \prod_{i=1}^{3}(SU(2)_{L,i} \times SU(2)_{R,i}) \hookrightarrow SU(4) \times Sp(6)_L \times Sp(6)_R$

Davighi, Tooby-Smith, 2201.07245
Davighi, 2206.04482

- $\mathbf{2}^{\oplus 3} \hookrightarrow \mathbf{6}$: all SM fermions in just one pair of chiral fields $\Psi_{L/R}$
- Offers a "gauge answer" to "why 3 generations?"
- Higgs $\hookrightarrow (\mathbf{6}, \mathbf{6})$; EW-breaking vev also breaks flavour symmetry
- The "extra ingredients" here come for free, as the extra Higgs-like scalars!



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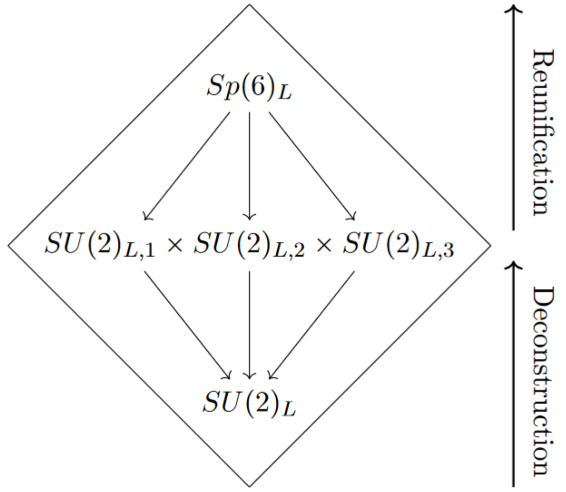
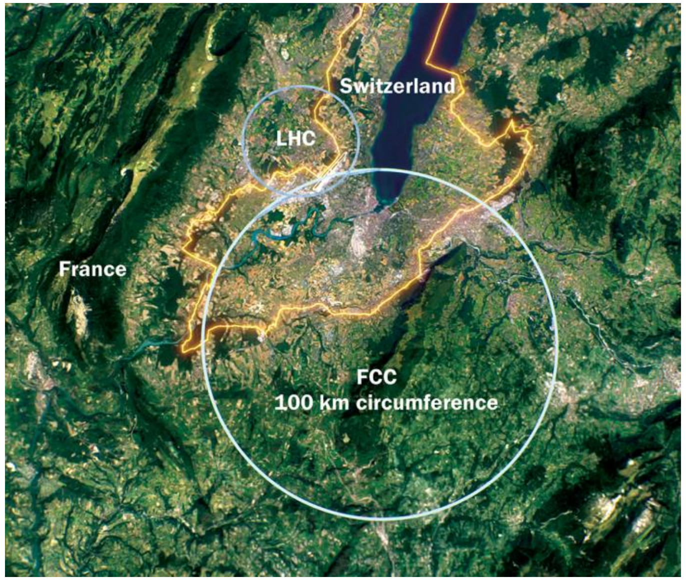


BUT: flavour-universal $SU(4)$ breaking must be $\gtrsim 200$ TeV due to $K_L \to e^+\mu^-$
vs. natural scale for $SU(4)$ breaking is $10\ (80)$ TeV

A natural realisation could require e.g. SUSY < 80 TeV

4. Phenomenology: Present & Future



Flavoured SM gauge bosons

- High-scale breaking $G_{\mathrm{SM},1} \times G_{\mathrm{SM},2} \to G_{\mathrm{SM},12}$ gives $U(2)$-violation; typically there is **one dominant meson mixing constraint** e.g. kaon, D-meson mixing
- **Low-energy** pheno of all these models dominated by the low-scale breaking $G_{\mathrm{SM},12} \times G_{\mathrm{SM},3} \to G_{\mathrm{SM}}$
- Gives heavy gauge bosons in adjoint, coupled to flavour-non-universal fermion current:

$$J^\mu \sim g_{12}^2 (J_1^\mu + J_2^\mu) - 2 g_3^2 J_3^\mu \,, \qquad J_3^\mu \supset D_{\mathrm{SM}}^\mu H$$

- One can pump up the (relative) coupling to the heavy or light families by varying g_{12}/g_3.
- BUT we cannot decouple either completely, because there is a matching condition

$$\frac{1}{g^2} = \frac{1}{g_{12}^2} + \frac{1}{g_3^2} \quad \Rightarrow \quad g_{12}, g_3 > g$$

Parametrization: $g_{SM} = g_3 \cos\theta = g_2 \sin\theta \cos\phi = g_1 \sin\theta \sin\phi$

Contrast these explicit models with simplified $U(2)$-based SMEFT analysis, in which the light generations can be decoupled – see Claudia's talk

Flavoured SM gauge bosons

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Focus on deconstructed EW bosons, $SU(2)_{L,12} \times SU(2)_{L,3}$ and $U(1)_{Y,12} \times U(1)_{Y,3}$

[The $SU(4)_3 \times SU(3)_{12}$ phenomenology is well-explored in B-anomaly context]

Important SMEFT operators:

	Flavour (mixing, $bs\mu\mu$)	LHC Drell-Yan $pp \to ll \ (l\nu)$	Electroweak Precision
$SU(2)_{L,12} \times SU(2)_{L,3}$	$O_{qq}^{(3)}, O_{lq}^{(3)}$	$O_{lq}^{(3)}$ (ll and $l\nu$)	$O_{Hq}^{(3)}, O_{Hl}^{(3)}$
$U(1)_{Y,12} \times U(1)_{Y,3}$	$O_{qq}^{(1)}, O_{dd}$ …, $O_{lq}^{(1)}, O_{qe}$, …	$O_{lq}^{(1)}, O_{qe}, O_{eu}, O_{ed}$, …	$O_{Hq}^{(1)}, O_{Hl}^{(1)}, O_{He}$, …, O_{HD}

Current bounds: all 3 observable classes give very complementary constraints!

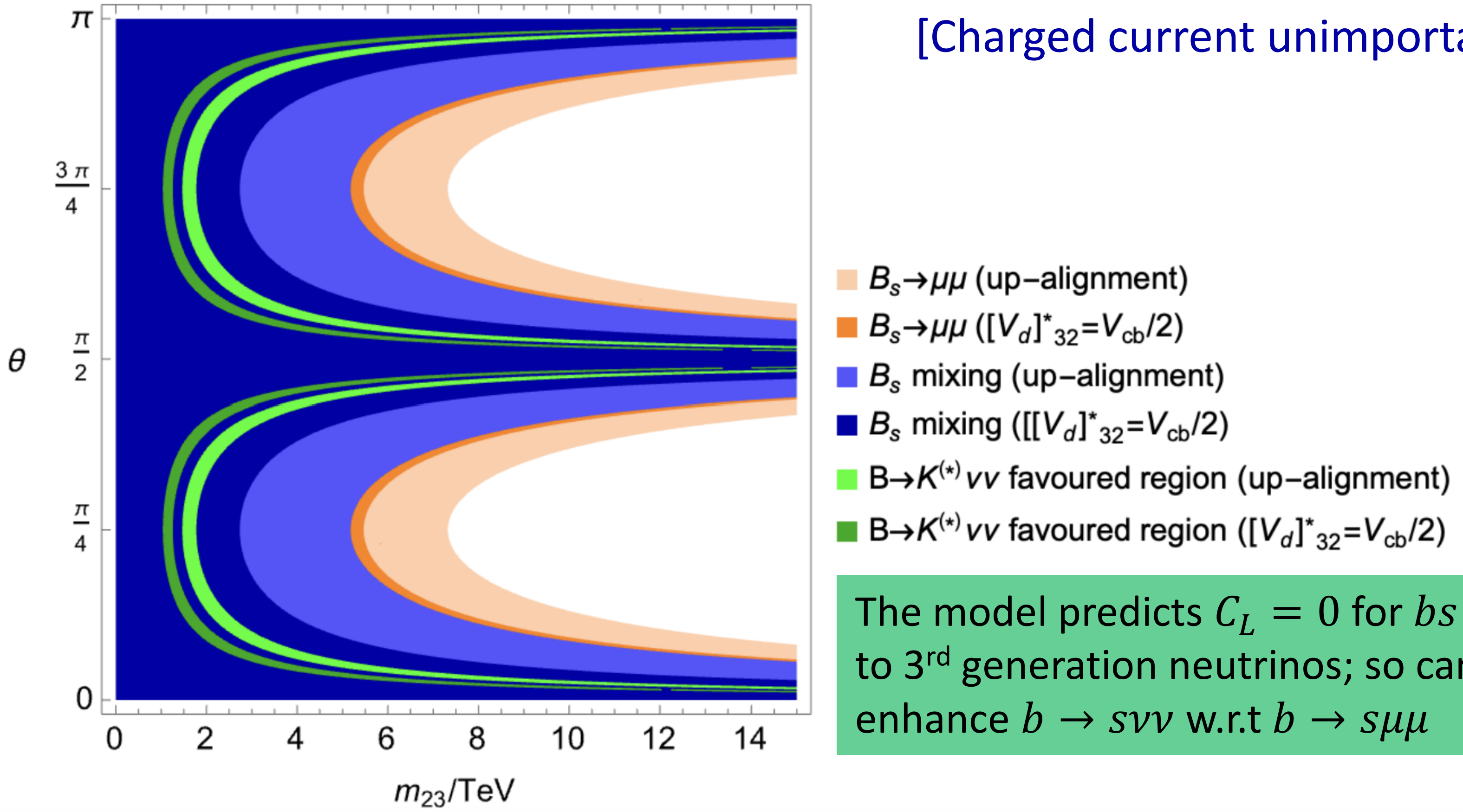
Deconstructed $SU(2)_L$

Davighi, Gosnay, Miller, Renner 2312.13346
See also Capdevila, Crivellin, Lizana, Pokorski 2401.00848

	Quark Flavour bounds (meson mixing, $bs\mu\mu$)	LHC Drell-Yan $pp \to ll\ (l\nu)$	Electroweak Precision, LFUV in τ decays
$SU(2)_{L,12} \times SU(2)_{L,3}$	$O_{qq}^{(3)}, O_{lq}^{(3)}$	$O_{lq}^{(3)}$ (ll and $l\nu$)	$O_{Hq}^{(3)}, O_{Hl}^{(3)}$

Quark Flavour

[Charged current unimportant]



The model predicts $C_L = 0$ for bs coupling to 3rd generation neutrinos; so cannot enhance $b \to s\nu\nu$ w.r.t $b \to s\mu\mu$

Deconstructed $SU(2)_L$

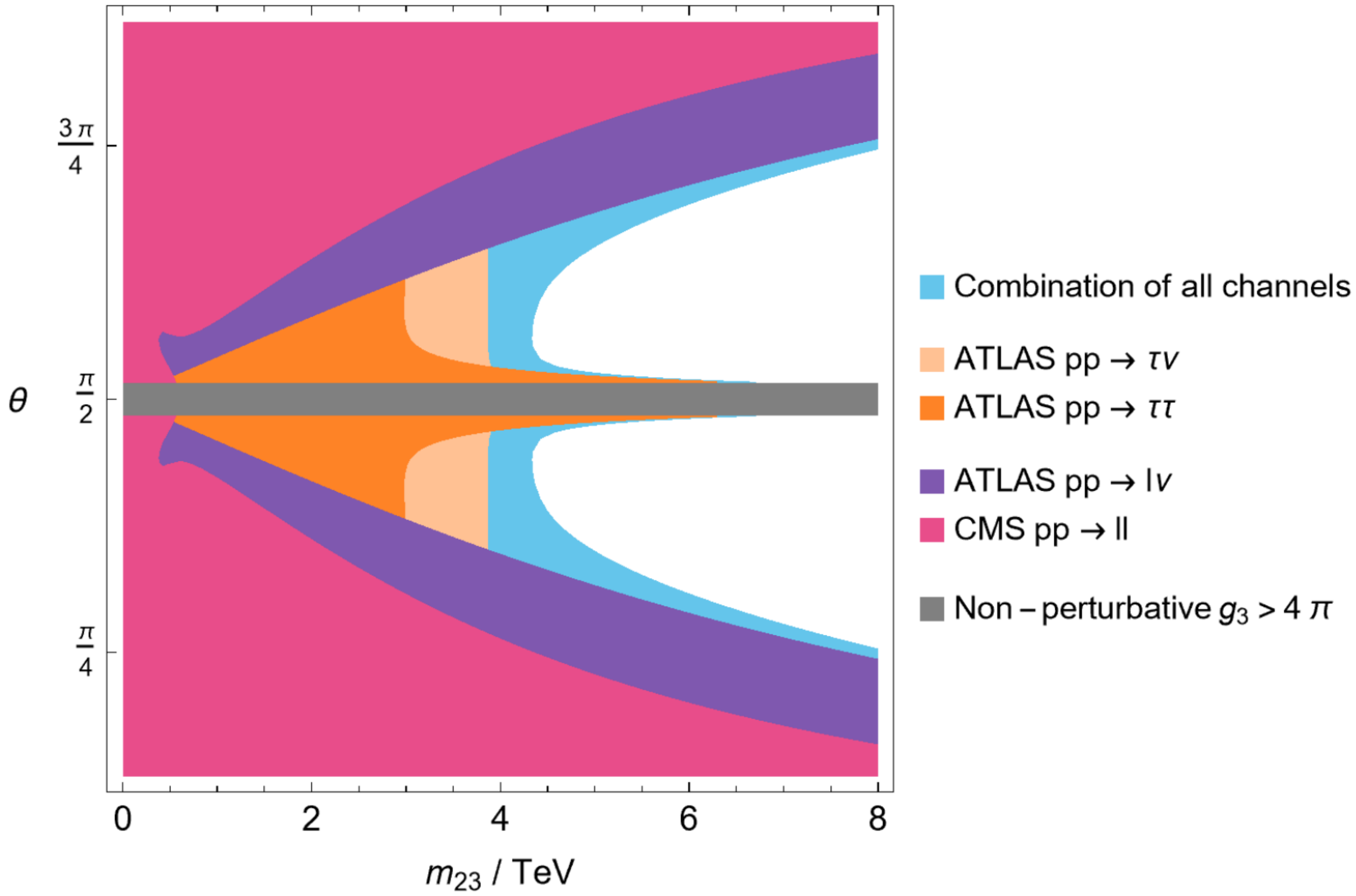
Davighi, Gosnay, Miller, Renner 2312.13346
See also Capdevila, Crivellin, Lizana, Pokorski 2401.00848

	Quark Flavour bounds (meson mixing, $bs\mu\mu$)	LHC Drell-Yan $pp \to ll\ (l\nu)$	Electroweak Precision, LFUV in τ decays
$SU(2)_{L,12} \times SU(2)_{L,3}$	$O_{qq}^{(3)}, O_{lq}^{(3)}$	$O_{lq}^{(3)}$ (ll and $l\nu$)	$O_{Hq}^{(3)}, O_{Hl}^{(3)}, O_{ll}$

LHC Drell—Yan

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

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



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Electroweak

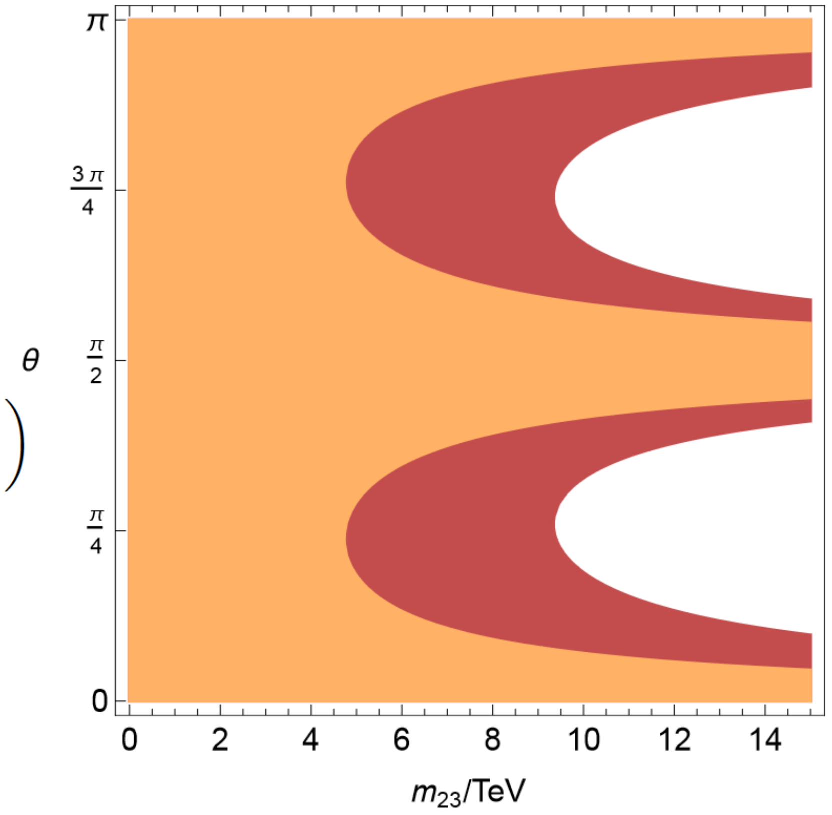
EW fit (with $m_{W\,(2017)}$)
EW fit (without m_W)

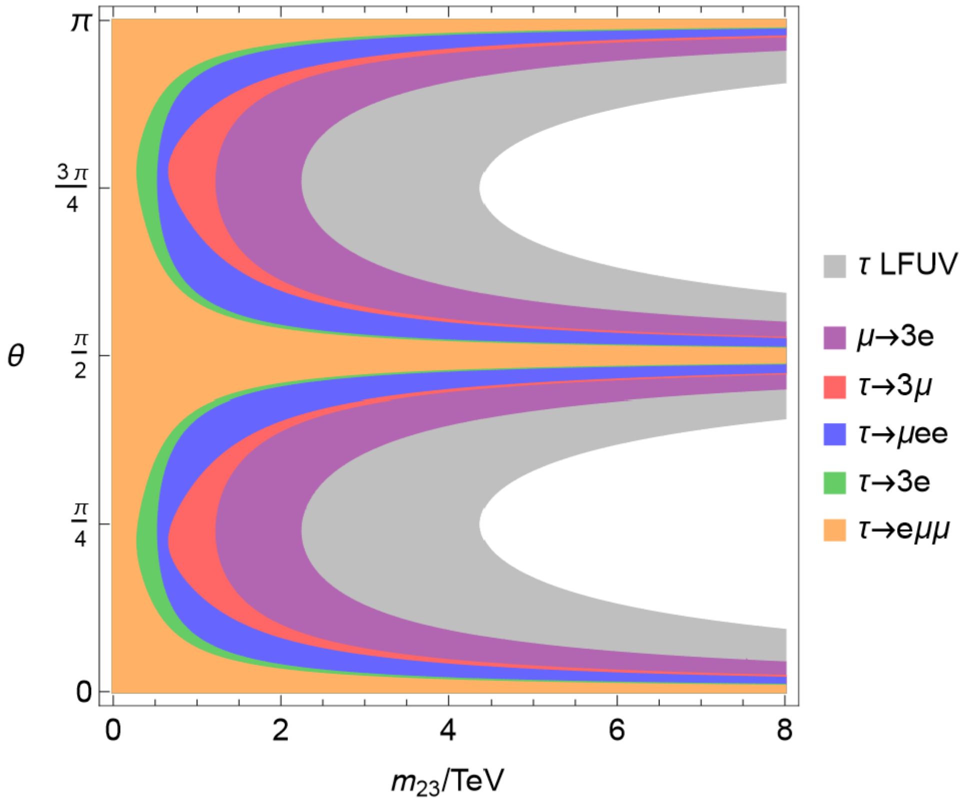
Model predicts negative shift in m_W

$$\delta m_W^2 = (m_W^2)_{\rm SM}\, \Delta\, \frac{s_W}{c_W} g_{\rm SM}^2 \left(\frac{2+\cot^2\theta}{2m_{23}^2}\right)$$

$$\Delta = 2\sqrt{2} G_F c_W s_W / (c_W^2 - s_W^2)$$

Due to observed positive shift (excluding CDF'2022), m_W has huge effect on EW fit





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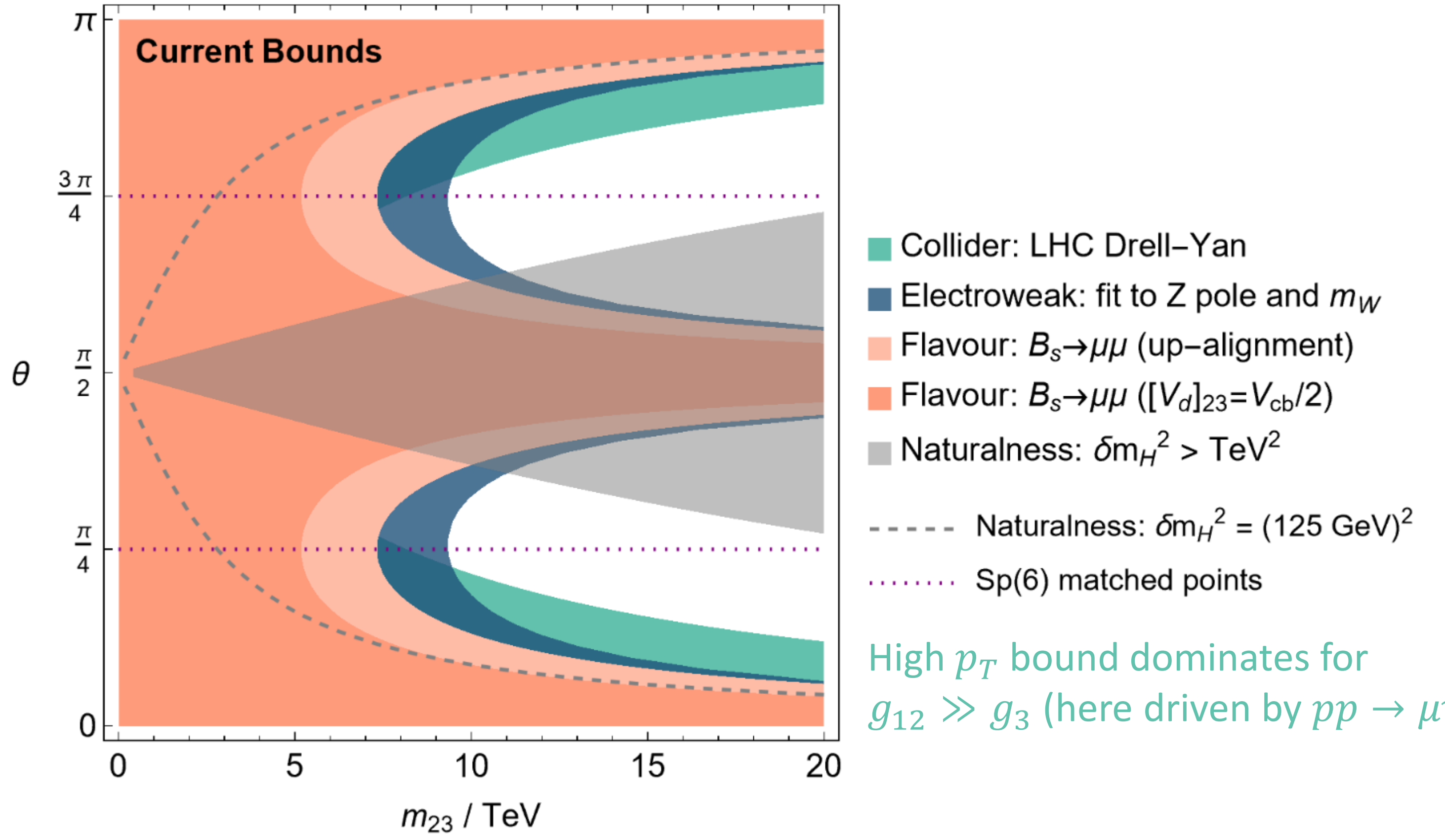
Kaon mixing can be satisfied for m_{12} as light as 160 TeV, for $g_1 = g_2$. For the W_{23} triplet:



High p_T bound dominates for $g_{12} \gg g_3$ (here driven by $pp \to \mu\nu$)

$M_{W'_L, Z'_L} > 9.5$ **TeV**

Driven by EWPOs (LEP II + W mass), with flavour and LHC highly complementary

Plenty of **natural parameter space remains**!

Deconstructed $U(1)_Y$

Davighi, Stefanek 2305.16280

Expect to provide the **most natural** model; double benefit from $g_Y \sim g_L/2$

1. Roughly x2 smaller Higgs mass correction
2. Roughly x2 smaller NP effects

See also
Fernández Navarro, King 2305.07690
Allanach, Davighi 1809.01158

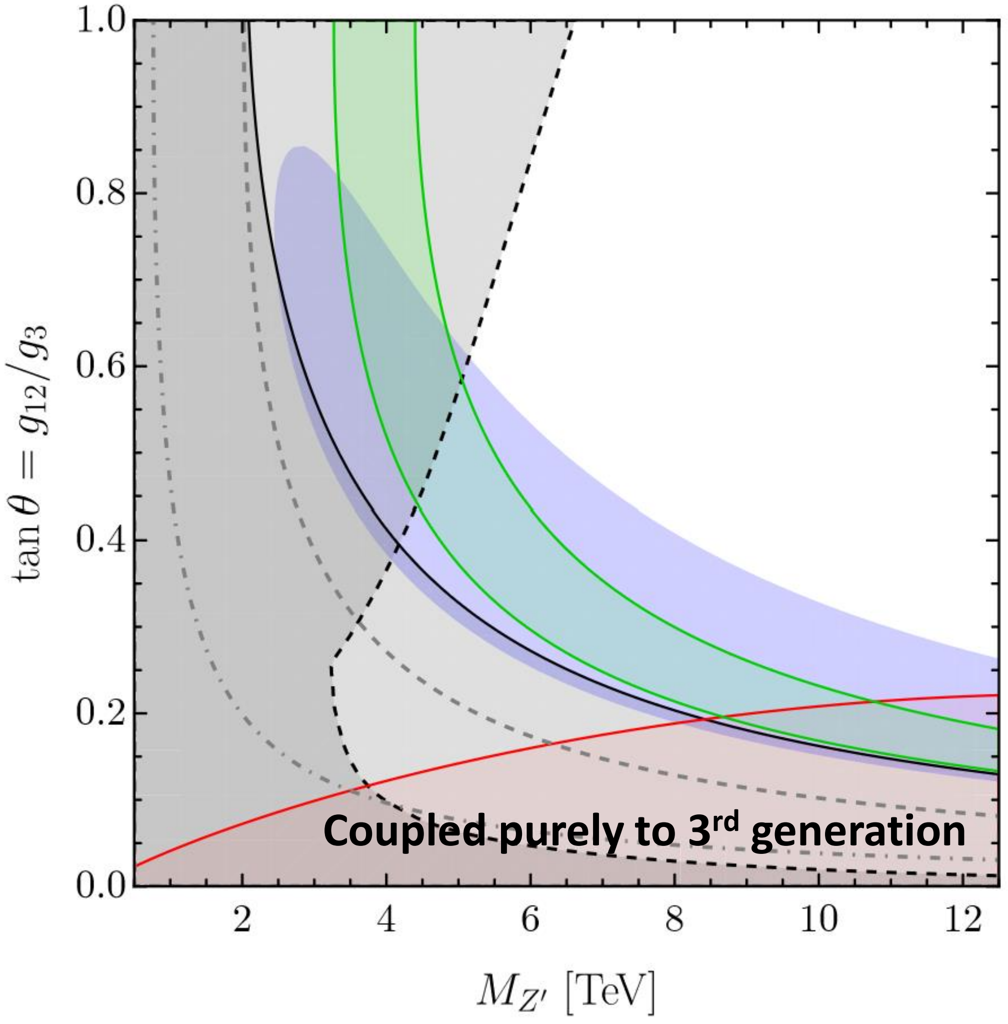
	Flavour (mixing, $bs\mu\mu$)	LHC Drell-Yan $pp \to ll$	Electroweak Precision
$U(1)_{Y,12} \times U(1)_{Y,3}$	$O_{qq}^{(1)}, O_{dd} \ldots, O_{lq}^{(1)}, O_{qe}, \ldots$	$O_{lq}^{(1)}, O_{qe}, O_{eu}, O_{ed}, \ldots$	$O_{Hq}^{(1)}, O_{Hl}^{(1)}, O_{He}, \ldots, O_{HD}$

LL 4-quark operators especially small thanks to $Y_Q g_Y \sim 1/18$

+ve shift in M_W currently preferred by EW fit (even ignoring CDF II measurement)

Deconstructed $U(1)_Y$

Davighi, Stefanek [2305.16280](https://arxiv.org/abs/2305.16280)



- - · - · - B_s mixing (with up-alignment! Suppressed by $Y_Q g_Y$)
- - - - - $B_s \to \mu\mu$ exclusion (strong-ish because our $bs\mu\mu$ is $\approx C_{10}$)
- 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

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

- As for deconstructed $SU(2)_L$, lowest allowed mass from intersection of high p_T + EWPO
- Lighter mass (more natural) allowed, as anticipated

Looking to the Future

We have seen that flavour-deconstructing electroweak gauge interactions, to explain the flavour puzzle, gives big effects in EWPOs.

FCC-ee is an amazing opportunity to probe these models, and cover the parameter space in which they remain natural.

But there are also shorter-term prospects to be excited about…

Deconstructed $SU(2)_L$: Future Prospects

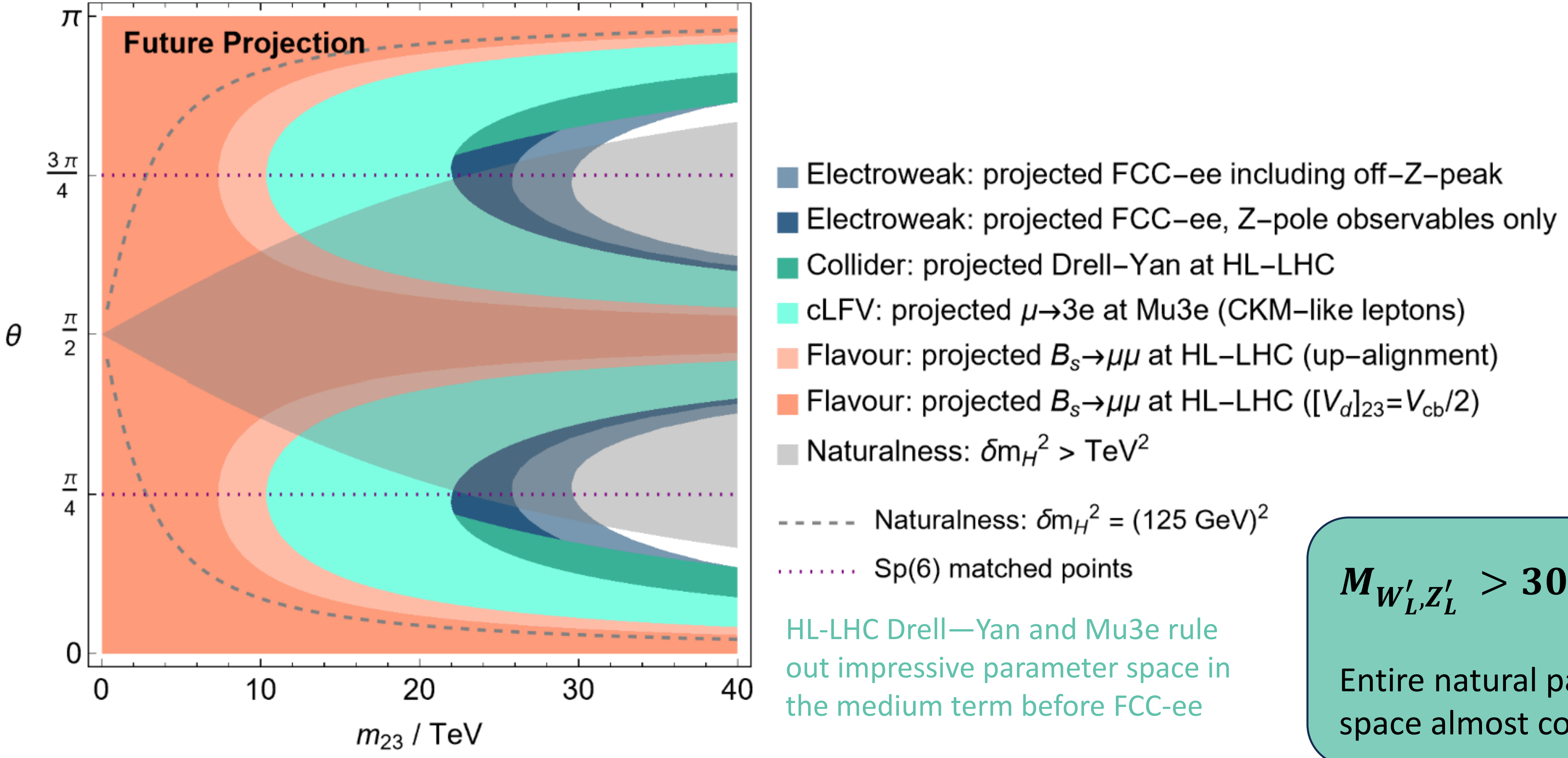
Davighi, Gosnay, Miller, Renner 2312.13346

We perform the following studies of future sensitivities to the W_{23} gauge bosons

- HL-LHC projections for Drell—Yan, assuming 3 ab^{-1} integrated lumi and SM bkg rate in all bins, implemented in *HighPT*
- HL-LHC projection for $BR(B_s \to \mu\mu)$, the most important flavour constraint on the model; use LHCb expected precision of 4.4% HL-LHC Working Group 4 1812.07638
- EWPOs from FCC-ee Z pole run, taking projections from [de Blas et al 2206.08326], plus m_W plus "off-peak" constraints on 4-lepton operators (assuming SM central values)
- Conservative estimate of FCC-ee improvements in τLFUV ratios
- LFV tests from Belle II (tau decays), and huge leap in sensitivity from Mu3e

Deconstructed $SU(2)_L$: Future Prospects

Davighi, Gosnay, Miller, Renner [2312.13346]



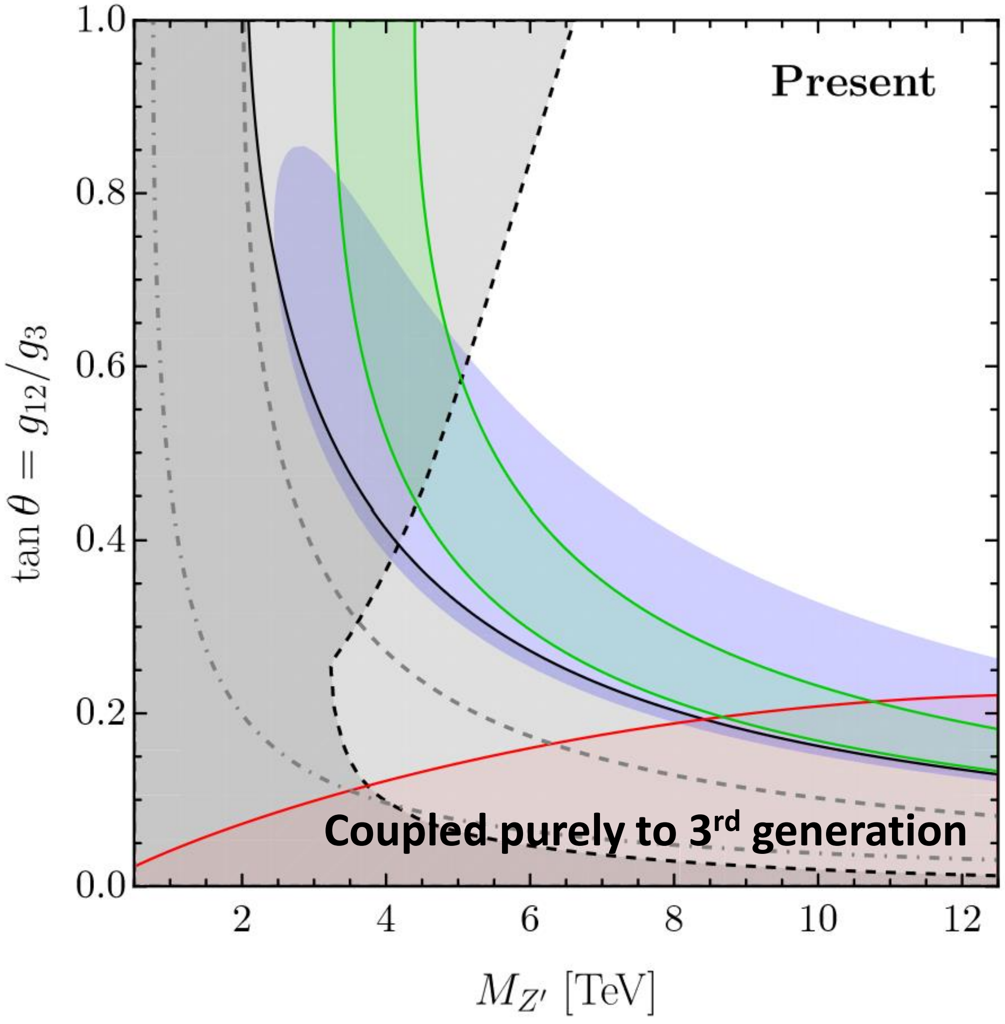
HL-LHC Drell—Yan and Mu3e rule out impressive parameter space in the medium term before FCC-ee

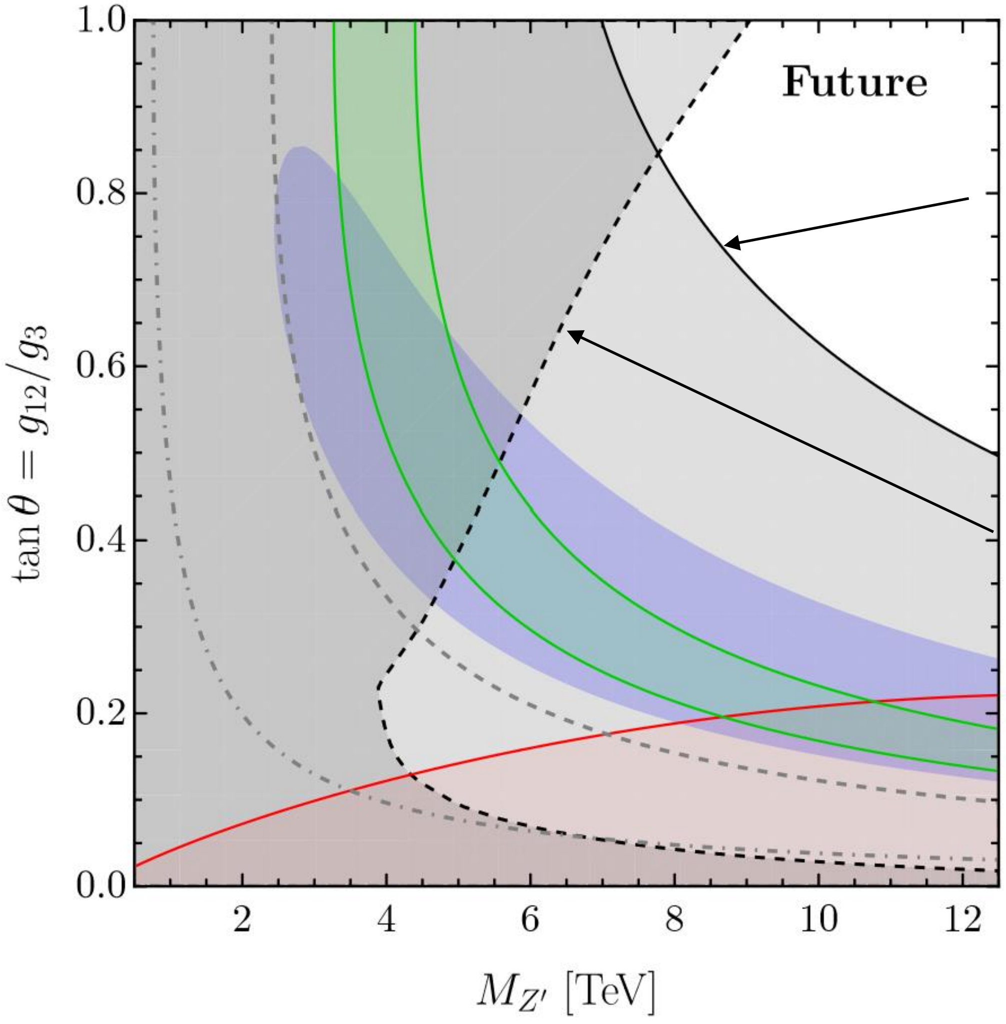
$M_{W'_L,Z'_L} > 30$ **TeV**

Entire natural parameter space almost covered

Deconstructed $U(1)_Y$ Z' boson

Davighi, Stefanek 2305.16280





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

Key message:

1. "Deconstructing" SM gauge interactions offers well-motivated solutions to flavour puzzle; current measurements allow significant natural* parameter space
2. Future experiments, especially an EW precision machine like **FCC-ee** but also HL-LHC, Belle II, Mu3e, …, will cover this natural parameter space

Thank you!

Backup

Semi-simple UV completions

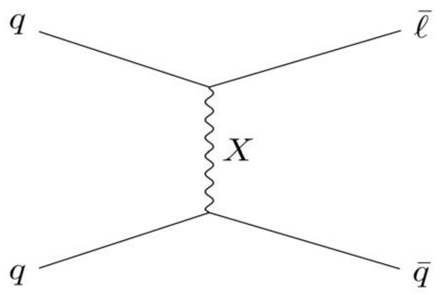
Nice UV requirement: ∃ embedding $G \hookrightarrow$ semi-simple i.e. no fundamental gauged $U(1)$s:

- "Explain" hypercharge quantisation and origin of SM fermion reps
- has a shot at asymptotic freedom (couplings become weaker in UV)

Combined with finite naturalness + assuming no extra fermions, this greatly restricts space of UV models

- All semi-simple extensions of 3-generation SM are classified; Allanach, Gripaios, Tooby-Smith, 2104.14555
- All feature one of the basic "vertical" unification patterns of Pati—Salam $SU(4) \times SU(2)_L \times SU(2)_R$, or $SU(5)$ or $SO(10)$ Pati, Salam, 1974, Georgi, Glashow, 1974, Georgi, 1975, Fritzsch, Minkowski, 1975

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



∴ vertical unification structure requires $SU(4)$s and $SU(2)_R$s

Semi-simple UV completions

From our bottom-up $\mathrm{G_U} \times H_{12} \times G_3$, we have 4 options (up to choices of H_{12})

Davighi, Isidori 2303.01520

	G_U	G_3	H_{12}	Flavour structure
Model 1	$SU(2)_L$	$SU(4)^{[3]} \times SU(2)_R^{[3]}$	$\times$	$\begin{pmatrix} \epsilon_R & \epsilon_\Omega \\ \epsilon_R \epsilon_\Omega & 1 \end{pmatrix}$ ☑ ☑
Model 2	$SU(2)_R$	$SU(4)^{[3]} \times SU(2)_L^{[3]}$	$\times$	$\begin{pmatrix} \epsilon_L & \epsilon_\Omega \epsilon_L \\ \epsilon_\Omega & 1 \end{pmatrix}$ ✗
Model 3	$SU(4)$	$SU(2)_L^{[3]} \times SU(2)_R^{[3]}$	$\times$	$\begin{pmatrix} \epsilon_L \epsilon_R & \epsilon_L \\ \epsilon_R & 1 \end{pmatrix}$ ☑
Model 4	$\emptyset$	$SU(4)^{[3]} \times SU(2)_L^{[3]} \times SU(2)_R^{[3]}$	$\times$	$\begin{pmatrix} \epsilon_L \epsilon_R & \epsilon_\Omega \epsilon_L \\ \epsilon_R \epsilon_\Omega & 1 \end{pmatrix}$ ☑

Higgs and ψ_3, dominate M_h^2

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

Minimal Flavour Deconstruction:

An Abelian model that fits inside model 1 was recently explored in [Barbieri, Isidori, 2312.14004]

What is the origin of the flavour deconstruction?

$G_{\mathrm{SM},12} \times G_{\mathrm{SM},3} \to G_{\mathrm{SM}}$ could be last step in a multi-scale breaking from fully deconstructed $G_1 \times G_2 \times G_3$; scale hierarchy $\Lambda_{12} > \Lambda_3$; $G_1 \times G_2 \to G_{12}$ breaking resolves 1-2 substructure

Example origin 3:

"Hybrid" approach prioritizing flavour and naturalness:

$$G = SU(2)_L \times \underbrace{SU(4)^3 \times SU(4)^{12}}_{V_{cb}} \times \underbrace{SU(2)_R^3 \times Sp(4)_R^{12}}_{m_2/m_3} \quad (Sp(4)_R^{12}: m_1/m_2)$$

Davighi, Isidori 2303.01520

✓ Realises "Model 1" with nicest flavour structure

✓ Keeping $SU(2)_L$ universal helps "seclude" δM_h^2 from large corrections

✓ Complete model has all 1-loop gauge beta functions negative

Deconstructed $U(1)_Y$ Z' boson: model details

Expect to provide the **most natural** model; double benefit from $g_Y \sim g_L/2$

1. Roughly x2 smaller Higgs mass correction — Davighi, Stefanek 2305.16280
2. Roughly x2 smaller NP effects

	Flavour (mixing, $bs\mu\mu$)	LHC Drell-Yan $pp \to ll$	Electroweak Precision
$U(1)_{Y,12} \times U(1)_{Y,3}$	$O_{qq}^{(1)}$, O_{dd} …, $O_{lq}^{(1)}$, O_{qe}, …	$O_{lq}^{(1)}$, O_{qe}, O_{eu}, O_{ed}, …	$O_{Hq}^{(1)}$, $O_{Hl}^{(1)}$, O_{He}, …, O_{HD}

Explicit model:

- TeV: $U(1)_{Y_{12}} \times U(1)_{Y_3} \to U(1)_Y$ by two scalars $\Phi_{q,H}$ (realises "model 1" flavour structure)
- Light Yukawas generated by UV states at ~ 10 TeV (safe choice of $U(2)$-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}

$$\frac{y_c}{y_t} \approx \frac{y_u^2}{y_u^3} \frac{f\langle\Phi_H\rangle}{m_{12}^2}$$

- RH mixing is zero at tree-level
- Semi-simple UV completion? Assume layer of SUSY / compositeness first kicks in around 10 TeV (for "best possible" solution to the *large* hierarchy problem)