Probing Flavour Models with Electroweak Precision

Joe Davighi, University of Zurich

FCC Phenomenology Workshop, 5th July 2023, CERN

Key message:

An EW precision machine like *FCC-ee has power to completely exclude natural* flavour models* based on "deconstructed" gauge interactions

* Natural means:

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

Outline

1. Flavour puzzles $\rightarrow$ accidental $U(2)$ flavour symmetries

2. Natural gauge explanations by deconstructing the SM near the TeV

3. UV?

4. Phenomenology: flavour + high pT + EW precision

1. Flavour and accidental symmetries

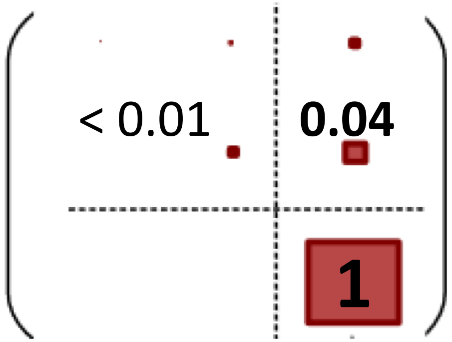
The Flavour Puzzle(s)

Fermion sector of SM looks ad hoc:

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

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



See Gino's talk

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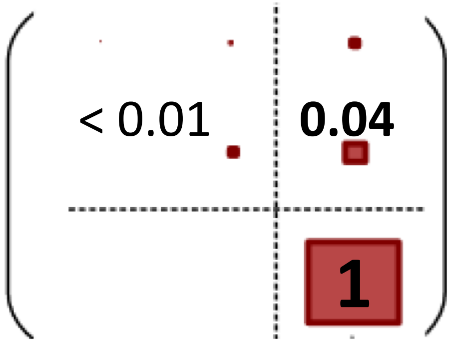

See Gino's talk

Yukawa matrices exhibit approximate $U(2)_L \times U(2)_R$ flavour symmetry

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

Kagan, Perez, Volansky, Zupan, 0903.1794
Barbieri et al, 1105.2296
Isidori, Straub, 1202.0464
Fuentes-Martin et al, 1909.02519

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

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

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Tempting hypothesis: *common dynamical origin!*

These $U(2)$ flavour symmetries emerge as accidental symmetries from a gauge symmetry (broken < 10 TeV) that is flavour non-universal (acts differently on 3rd family, same on 1st and 2nd families)

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

Pre-LHC, when $< \mathrm{TeV}$ SUSY or compositeness was anticipated, Minimal Flavour Violation (MFV) was an attractive way to pass flavour bounds. MFV now ruled out to $10\ \mathrm{TeV}$

European Strategy for Particle Physics, 2020 Briefing Book 1910.11775

Recall "Traditional MFV": New Physics has approximate $U(3)$ (flavour blind), broken only by $Y_{u,d,e}$

D'Ambrosio, Giudice, Isidori, Strumia, hep-ph/0207036
Kagan, Perez, Volansky, Zupan, 0903.1794
…

Reasons to prefer $U(3)$:

- No extra input spurions (predictive)

Reasons to prefer $U(2)$:

- $U(3)$ cannot explain the flavour hierarchies! Yukawas are just an "input"
- Extra spurions is reasonable from a UV perspective
- $U(3)$ unnecessarily aggressive; NP could couple differently to 3rd family
- E.g. if NP is "heavy-flavoured", LHC search bounds are weaker

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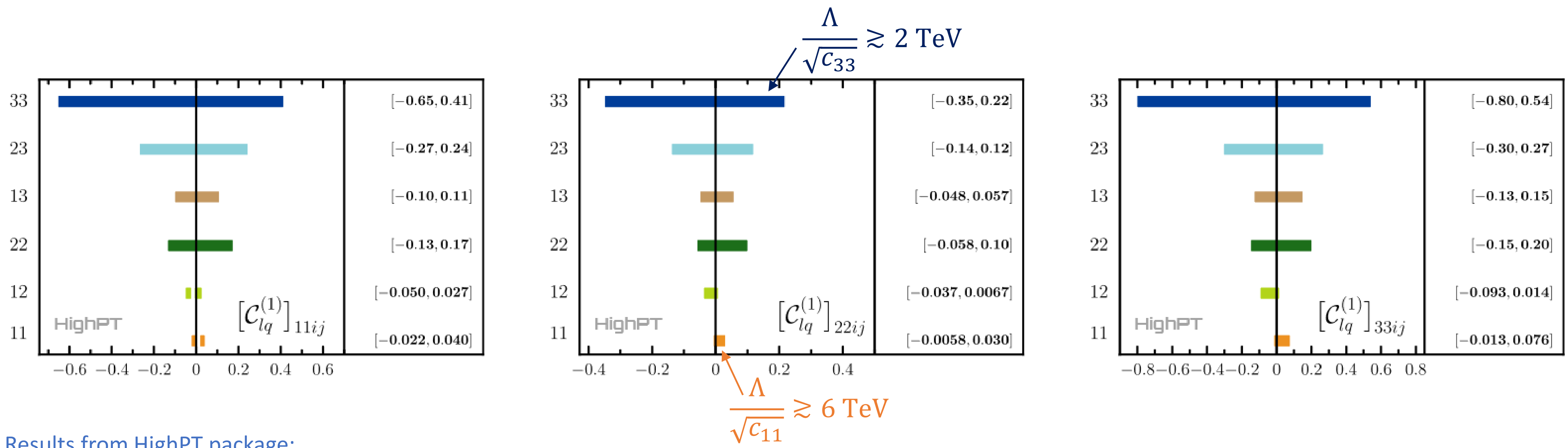
Example: High-p_T Drell-Yan tail constraints on semi-leptonic SMEFT operators $\quad \mathcal{L} \sim \frac{C}{\Lambda^2} QQLL$

- For 33 vs 11 quark indices, bound on C/Λ^2 weaker by factor$\sim$10



Results from HighPT package:

Allwicher, Faroughy, Jaffredo, Sumensari, Wilsch, 2207.10714

Allwicher, Faroughy, Jaffredo, Sumensari, Wilsch, 2207.10756

2. Explaining the accidents: Deconstructing the SM

Flavour non-universality, non-horizontally

- Want $U(2)^n$ to emerge as accidental from a flavour non-universal gauge symmetry
- One approach is to "factorize the flavour problem" by gauging a horizontal symmetry e.g. $U(1)_X$

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

Froggatt, Nielsen, Nucl Phys B (1979)
…

Deconstruction approach:

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

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

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

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- Embedding of SM gauge interactions intrinsically non-universal in UV
- This breaking is generic for simple G: for any choice of gauge couplings, and any scalar rep $(R_1 \neq 1, R_2 \neq 1)$, you *always* breaks this to the diagonal (flavour universal) subgroup!

Craig, Garcia-Garcia, Sutherland, 1704.07831

- So universality of SM really pops out "accidentally" from deconstructed G_{SM}
  - whereas maybe it's "reduced" to ad hoc charges in FN approach?
- Easy to find semi-simple UV completions with deconstruction approach
  - whereas 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

With Higgs charged under $G_{\text{SM},3}$, we can explain Yukawa hierarchies with accidental $U(2)^n$

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

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

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

Explains $V_{cb} \ll 1$

Doesn't explain $m_2 \ll m_3$

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

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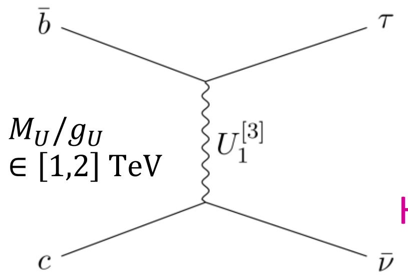
If we enlarge $SU(3)^{[3]} \to SU(4)^{[3]}$, can also explain $b \to c\tau\nu$ anomalies



Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368; Greljo, Stefanek, 1802.04274; Di Luzio, Fuentes-Martin, Greljo, Nardecchia, Renner, 1808.00942

Hint for deconstruction near TeV

See Gino's talk

The new particles: flavoured SM gauge bosons

Symmetry breaking pattern

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

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

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

What of Naturalness?

Flavour deconstructed models all predict heavy gauge bosons X with big couplings to Higgs or top

Unavoidable finite corrections to Higgs mass squared

$$\delta M_h^2 \sim \left(\frac{1}{16\pi^2}\right)^{\#\text{loops}} g_X^2 \, M_X^2$$

Farina, Strumia, Pappadopulo, 1303.7244

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If these corrections are $\gg M_h^2$ then the physical Higgs mass is *fine-tuned* (regardless of higher-scale stabilization), in absence of SUSY or compositeness in interim scales to soften/cancel δM_h^2

Absence of NP in colliders means a "little hierarchy" $\delta M_h^2|_{\text{SUSY}} \sim \text{TeV}^2$ is ~ observational fact

c.f. Giudice, 1710.07663

But we do not want to make the δM_h^2 fine-tuning *worse* with our flavoured New Physics!

→ Use naturalness as a guide in the space of deconstructed flavour models

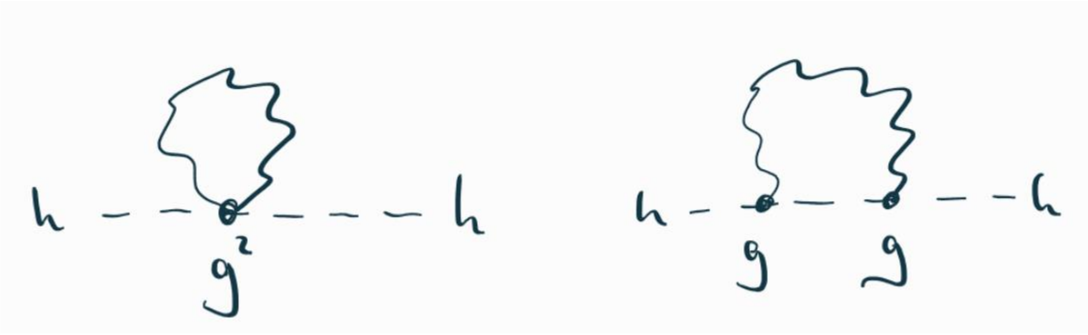
Naturalness of electroweak scale

Davighi, Isidori 2303.01520
Davighi, Stefanek 2305.16280
See also Allwicher, Isidori, Thomsen 2011.01946

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

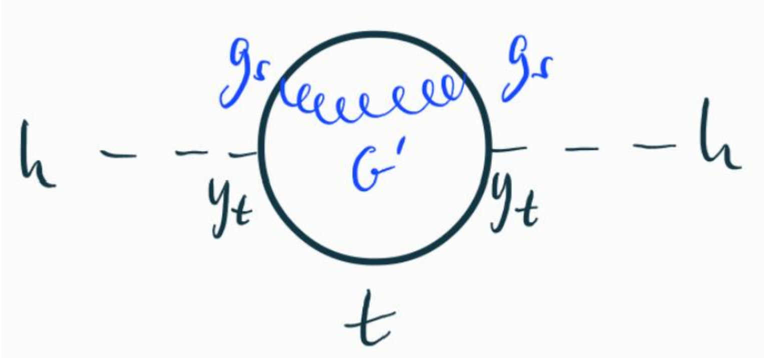
Deconstructing EW symmetries give 1-loop Higgs mass corrections:

(recall we need this to explain $m_2 \ll m_3$)



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

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



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

Natural mass ranges remain viable:

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

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

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

3. UV completion?

Semi-simple UV

Nice UV requirement: $\exists$ 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

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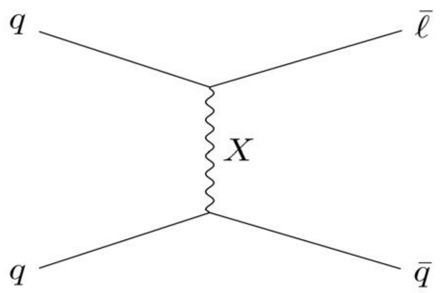
$SU(5)$ & $SO(10)$ feature LQs that give tree-level proton decay! $\Rightarrow$ $M_X \gtrsim$ GUT scale
So $SU(5)$ & $SO(10)$-based options cannot appear in low-scale natural models



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

Semi-simple UV

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

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

Higgs and ψ_3, dominate M_h^2

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

Davighi, Isidori 2303.01520

Deeper into the UV

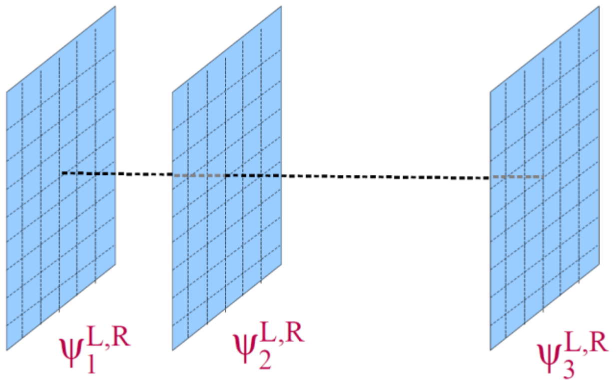
What is the origin of the flavour deconstruction?

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

Dvali, Shifman hep-ph/0001072
Craig, Green, Katz 1103.3708
Cacciapaglia et al, 1501.03818
Panico, Pomarol 1603.06609
Bordone et al, 1712.01368
Navarro, King 2209.00276
Davighi, Isidori, Pesut 2212.06163

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”; approaching “model 1”)

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Example origin 2: 4d gauge flavour unification

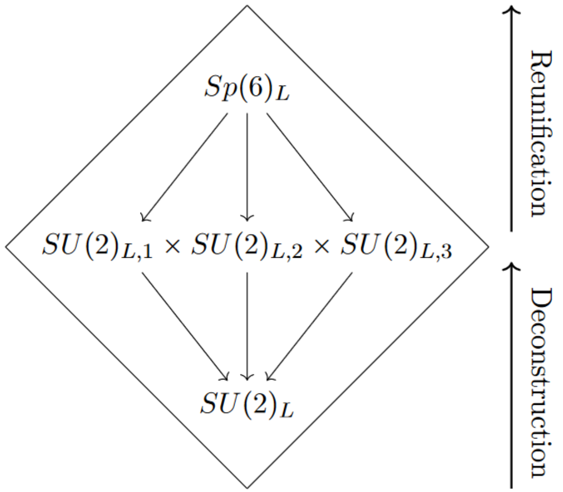
Complete UV unification of matter into two Weyls $\psi_L \oplus \psi_R$; implies one of 3 gauge groups

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

- $\mathbf{2}^{\oplus \mathbf{3}} \hookrightarrow \mathbf{6}$: 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

Allanach, Gripaios, Tooby-Smith, 2104.14555

Davighi, Tooby-Smith, 2201.07245
Davighi, 2206.04482



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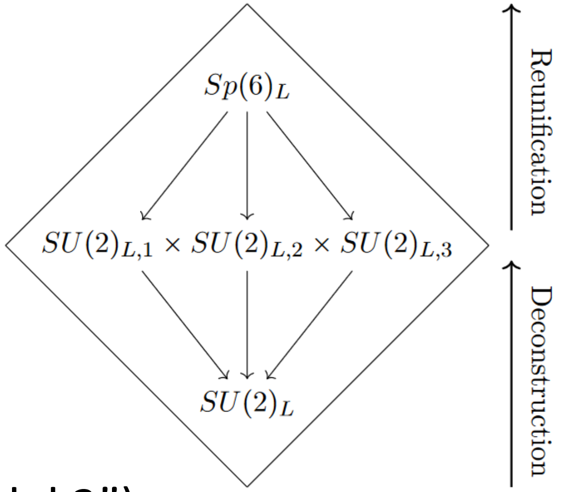

BUT: flavour-universal $SU(4)$ breaking must be $\gtrsim 200$ TeV due to $K_L \to e^+\mu^-$ vs. natural scale for $SU(4)$ breaking is 10 (80) TeV

A natural realisation could require e.g. SUSY < 80 TeV (same for any "model 3")

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Example origin 3:

"Hybrid" approach prioritizing flavour and naturalness:

$$G = SU(2)_L \times SU(4)^3 \times SU(4)^{12} \times SU(2)_R^3 \times Sp(4)_R^{12}$$

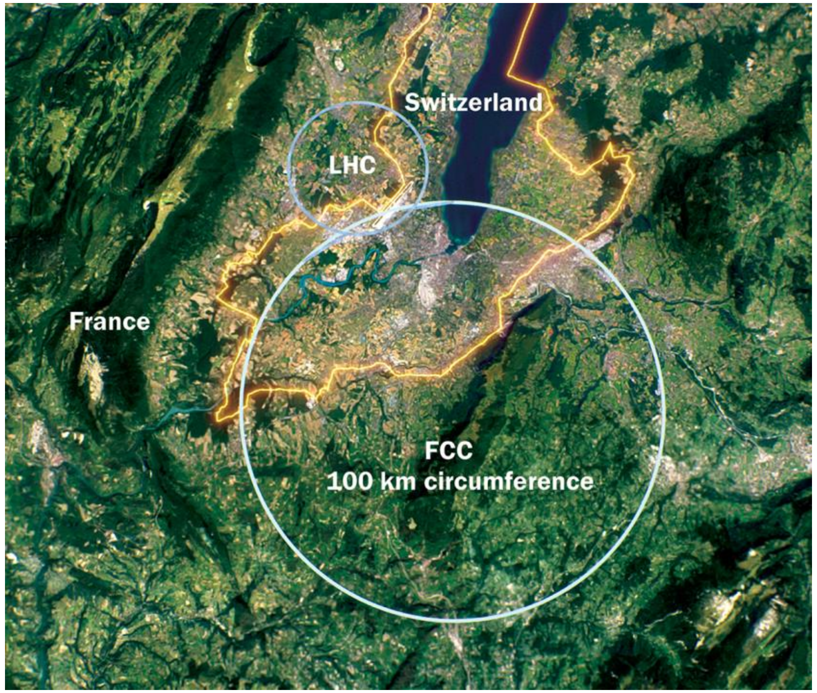
Davighi, Isidori 2303.01520

V_{cb} $\quad m_2/m_3 \quad m_1/m_2$

✓ 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



4. Phenomenology

… and the power of FCC-ee for probing flavour

Flavoured SM gauge bosons

Low-energy pheno of all these models dominated by the low-scale breaking

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

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

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 (contrast with G_{hor}):

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

Flavoured SM gauge bosons

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

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

for some $SU(4)_3 \times SU(3)_{12}$ pheno, see Gino's talk

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 $l\nu$)	$O_{Hq}^{(3)}, O_{Hl}^{(3)}$
$U(1)_{Y,12} \times U(1)_{Y,3}$	$O_{qq}^{(1)}, O_{dd}$ …, $O_{lq}^{(1)}, O_{qe}, \ldots$	$O_{lq}^{(1)}, O_{qe}, O_{eu}, O_{ed}, \ldots$	$O_{Hq}^{(1)}, O_{Hl}^{(1)}, O_{He}, \ldots, O_{HD}$

(assuming flavour aligned charged lepton Yukawa)

(+ve) shift in M_W only in deconstructed hypercharge case (custodial violating)

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

Deconstructed $SU(2)_L$ triplet

Naïve naturalness:

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

Work in progress with Sophie Renner, Alastair Gosnay, David Miller

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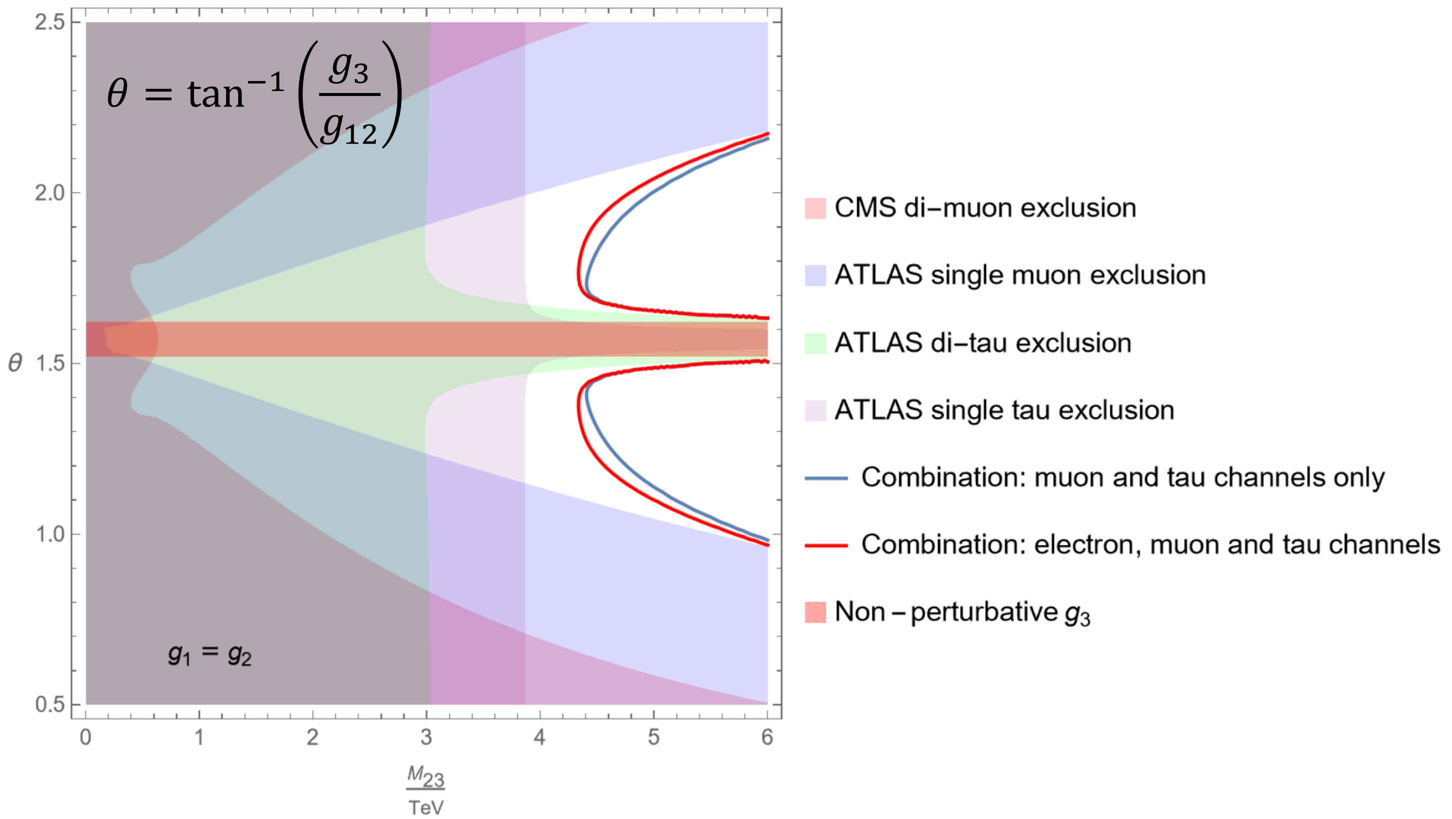
Current bounds e.g. High pT

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

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



Deconstructed $SU(2)_L$ triplet

Naïve naturalness:

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

Work in progress with Sophie Renner, Alastair Gosnay, David Miller

	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 $l\nu$)	$O_{Hq}^{(3)}, O_{Hl}^{(3)}$

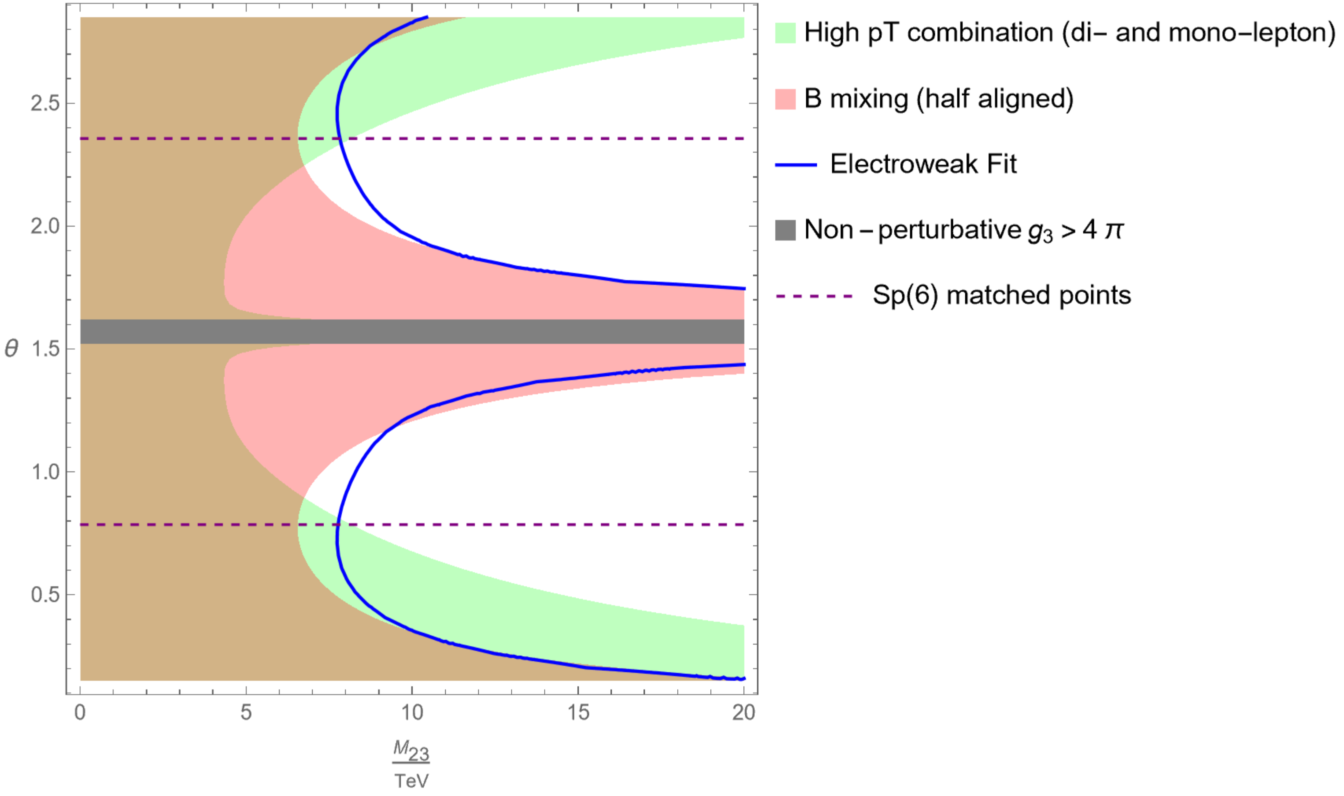
Current bounds, combined:

High pT

Flavour (B_s mixing)

EW fit

Based on (flavour-general) method and likelihood function of Bresó-Pla, Falkowski, González-Alonso 2103.12074



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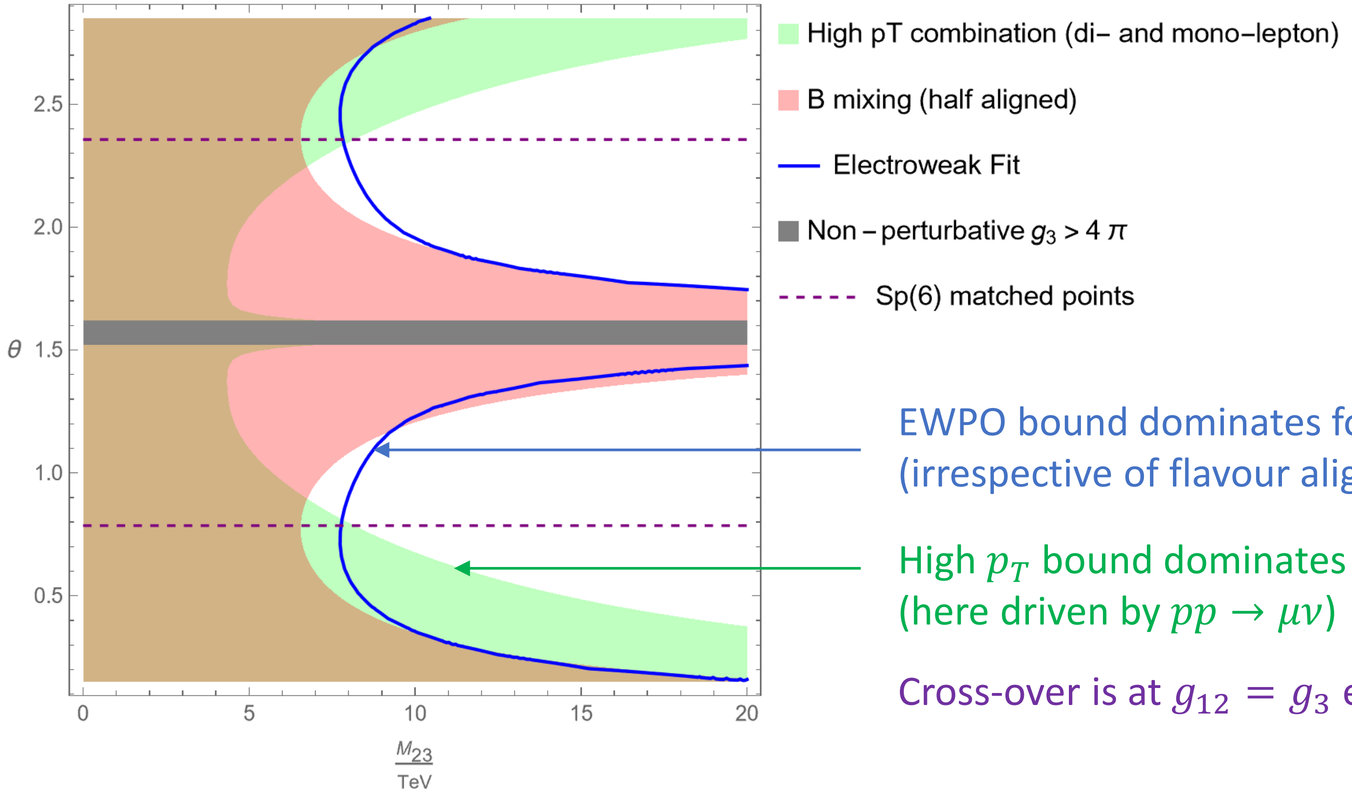
Flavour (B_s mixing)

EW fit

All are important!

$M_{W_L'} > 8\ \text{TeV}$



EWPO bound dominates for $g_3 \gg g_{12}$ (irrespective of flavour alignment)

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

Cross-over is at $g_{12} = g_3$ e.g. from $Sp(6)_L$

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Current bounds, combined:

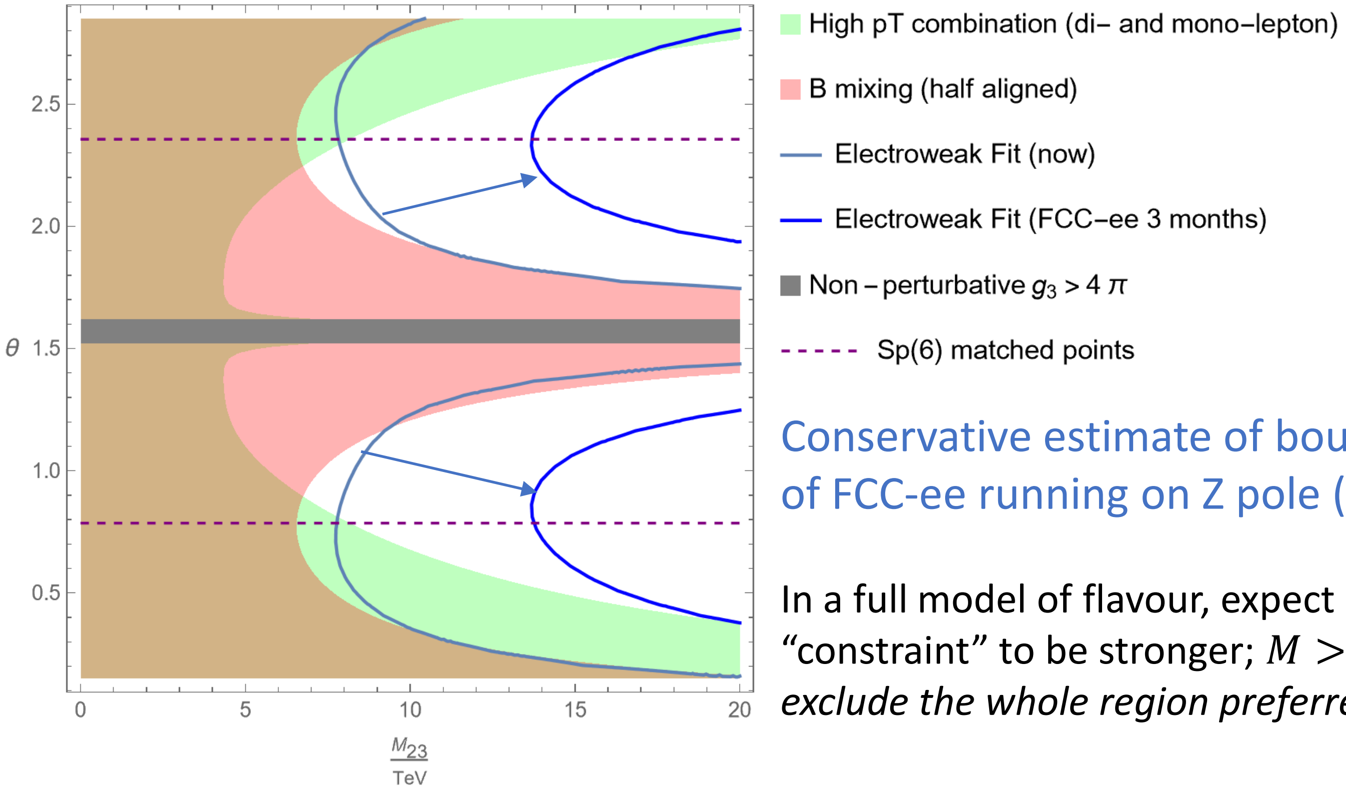
High pT

Flavour (B_s mixing)

EW fit

Future:

$M_{W'_L} > 14\ \mathrm{TeV}$



Conservative estimate of bound after ~3 months of FCC-ee running on Z pole ($10^4 \times$ LEP dataset)

In a full model of flavour, expect naturalness "constraint" to be stronger; $M > 14\ \mathrm{TeV}$ *will typically exclude the whole region preferred by naturalness*

Deconstructed $U(1)_Y$ Z' boson

Naïve naturalness:

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

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

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)

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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)

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):

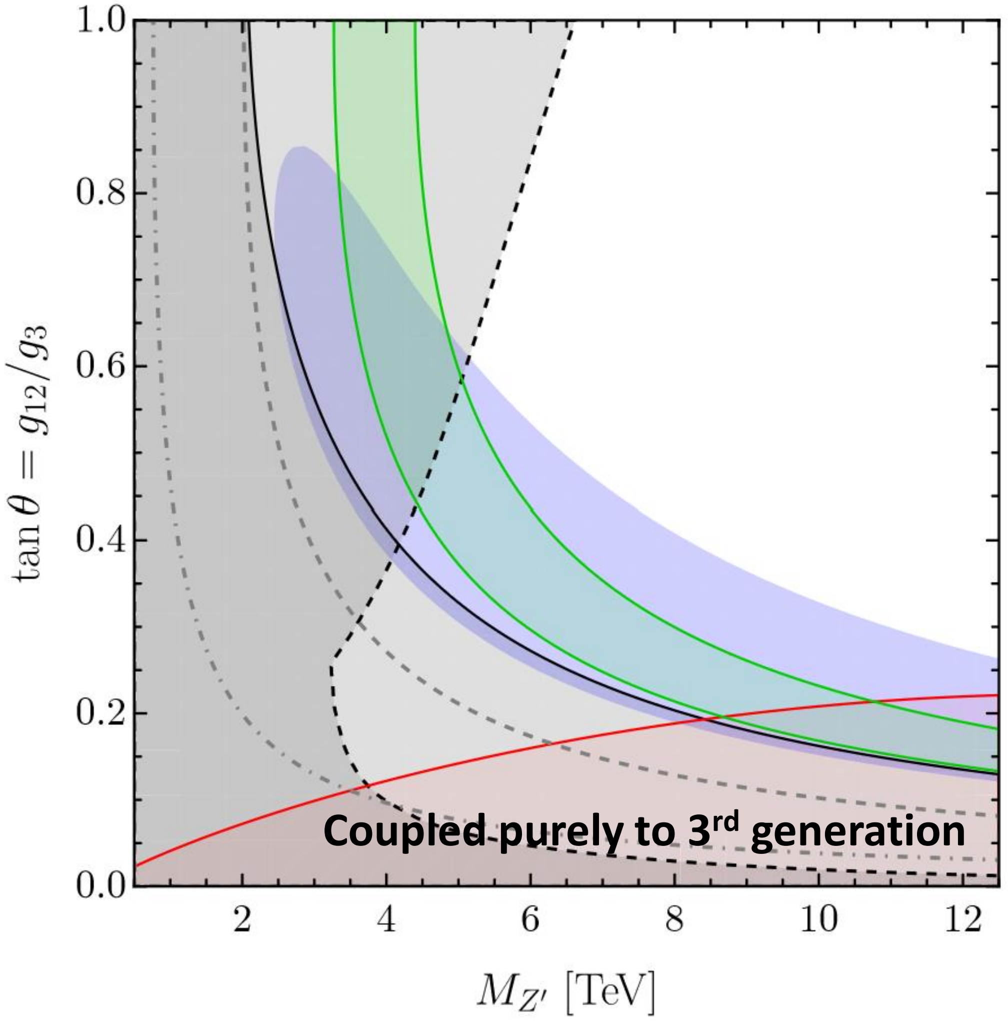
Field	$SU(3)_c$	$SU(2)_L$	$U(1)_3$	$U(1)_{12}$	Generates:
H_{12}	**1**	**2**	0	1/2	$y_{c,s,\mu,u,d,e}$, V_{us}
$Q_{L,R}$	**3**	**2**	1/6	0	V_{cb}, V_{ub}

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

- 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)

Deconstructed $U(1)_Y$ Z' boson

Davighi, Stefanek 2305.16280



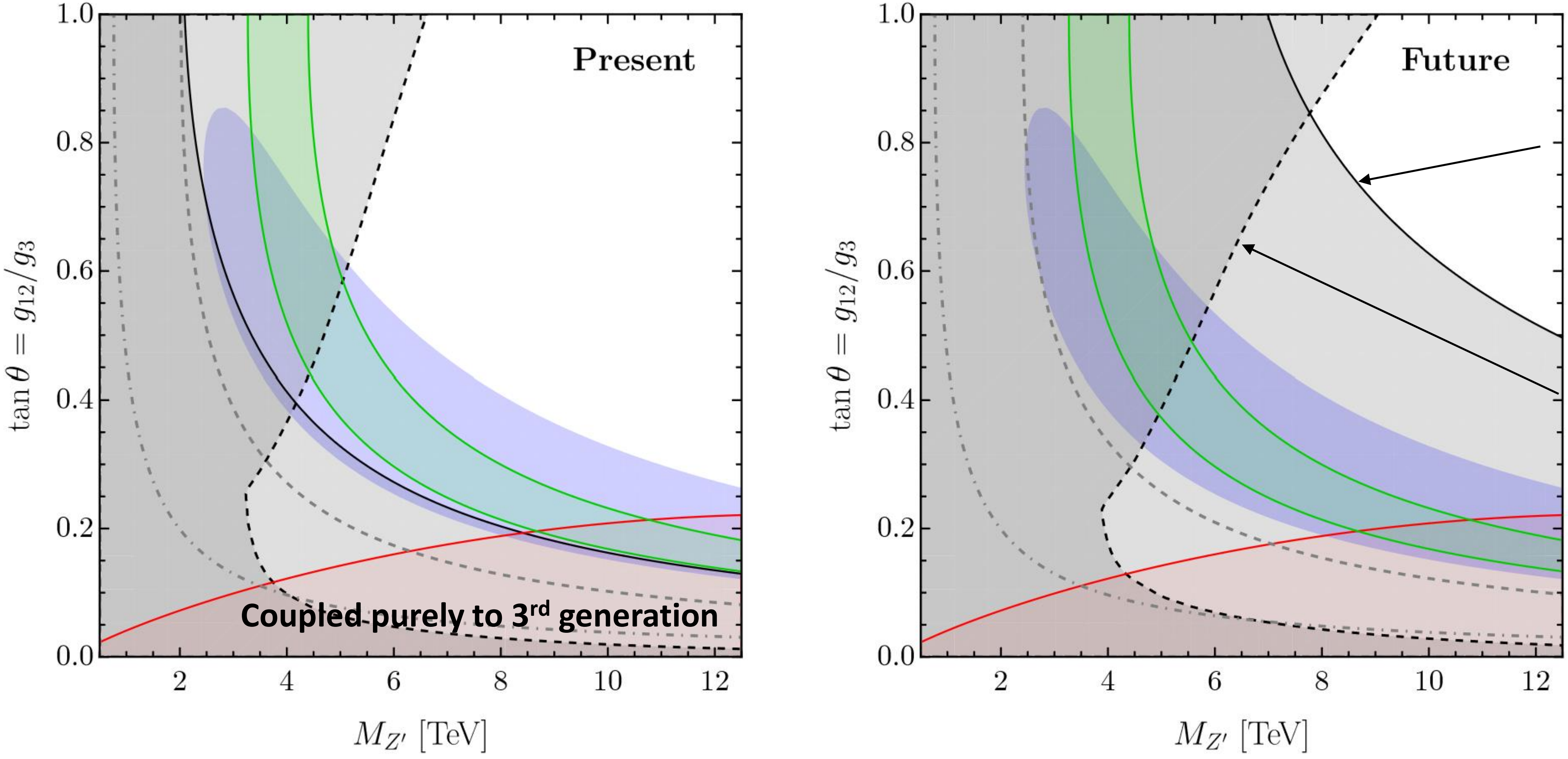
- B_s mixing (with up-alignment! Suppressed by $Y_Q g_Y$)
- $B_s \to \mu\mu$ exclusion (strong-ish because our $bs\mu\mu$ is $\approx C_{10}$)
- Electroweak fit (1 sigma) using a new M_W average
- Electroweak fit (2 sigma exclusion) excluding CDF II M_W
- High p_T exclusion (recast of $pp \to ee, \mu\mu, \tau\tau$ searches)
- Percent tuning in M_h^2 (δM_h^2 now computed exactly in model)
- 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

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

Sins of omission

I only sketched the spectacular gain in EWP from FCC-ee, which has a huge effect shaping the parameter space of these natural flavour models

Many other powerful probes of these models we haven't studied/mentioned. A few important ones:

- Continued High-p_T searches in 3rd family final states at LHC and HL-LHC — CMS 2209.07327
- Pheno of vector-like quarks and leptons (often appear in UV completion) e.g. at LHC — see talks by Gino, Sophie, Michele T
- Flavour itself @ FCC-ee(hh) !
  - Example 1: expect $BR(B \to K\tau^+\tau^-)$ observation at FCC-ee if SM rate [*much enhanced* in these models] — Kamenik, Monteil, Semkiv, Silva, 1705.11106; Li & Liu, 2012.00665
  - Example 2: $BR(B_{s,d} \to \mu\mu)$ expect improvement by $\times$ 10 in precision — see e.g. S. Monteil's slides
- Top and Higgs physics — see talks by Sophie, Michele S, Michele T
- Lepton flavour universality tests — see talks by Gino and Sophie

Key message:

An EW precision machine like *FCC-ee has power to completely exclude natural flavour models* based on "deconstructed" gauge interactions

Thank you!