A TeV Scale Origin for Higgs and Flavour?

Joe Davighi, CERN

UCL particle physics seminar, 22nd November, 2024

Outline of the Talk

1. Introduction: the mysteries of Higgs and Flavour

2. Flavour symmetries: from MFV to U2

3. Flavour deconstruction: solving the flavour puzzle near the TeV

4. Flavour deconstructing the Composite Higgs: solving flavour + hierarchy problem near the TeV

If you remove the Higgs, the Standard Model is a gauge theory with x3 $g_i = O(1)$.

This Higgs-less SM is completely natural!

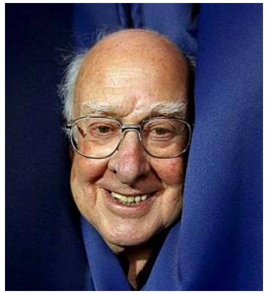
~~Hierarchy problem~~

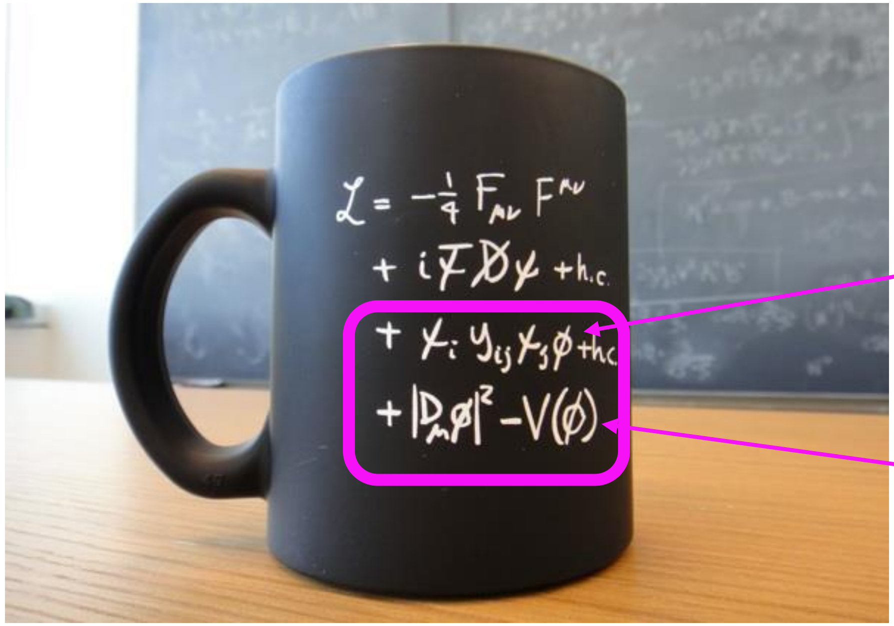
~~Flavour puzzle~~

~~Strong CP problem~~ [massless quarks]

Higgs = key to BSM, both theoretically & experimentally

(modulo dark sectors)

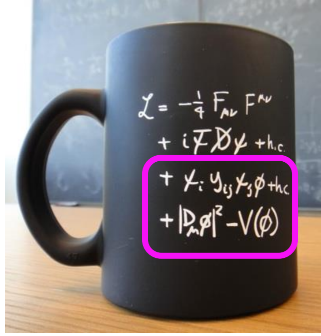




Flavour puzzle!

Hierarchy problem!

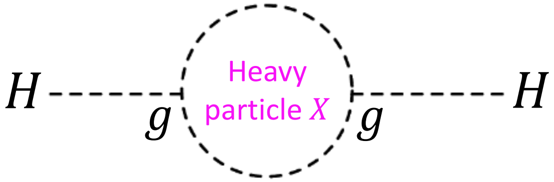
The Hierarchy Problem



*The Higgs has an unnaturally small **mass** parameter:

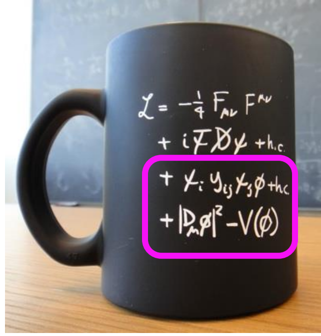
Large hierarchy: $\mu^2 \ll \Lambda^2_{\text{high scales}}$

[Λ could be new particles at GUT scale, flavour scale, PQ scale, neutrino see-saw scale, Planck scale…]



$$\Longrightarrow \quad \delta M_h^2 \Big|_{\text{from } X} = \frac{\mathcal{O}(1)}{16\pi^2} g^2 M_X^2$$

The Hierarchy Problem



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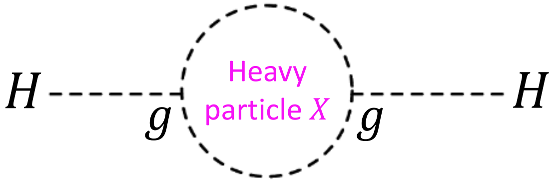


$$\Longrightarrow \quad \delta M_h^2 \Big|_{\text{from } X} = \frac{\mathcal{O}(1)}{16\pi^2} g^2 M_X^2$$

Two well-understood solutions: **Higgs' compositeness** or **supersymmetry** as low scale as possible

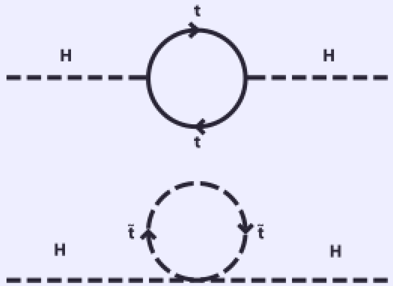
Composite Higgs

- Loops cut off by composite resonances
- To get $m_h \ll m_{\text{res}}$, need Higgs to be pseudo-Goldstone bosons ($\sim$ QCD pions)
- Explicit breaking by top Yukawa and EW gauging generates m_h^2 at 1-loop

$$\delta m_h^2 \sim \frac{1}{16\pi^2}\left(\# n_c y_t^2 M_T^2 - \# g_1^2 M_\rho^2\right)$$

Supersymmetry

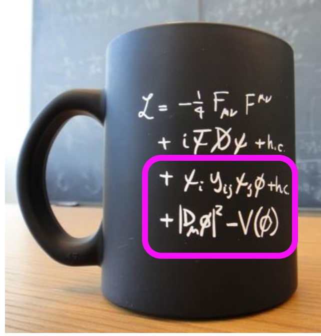
Inclusion of superpartner loops removes quadratic sensitivity to UV cut-off due to bose vs fermi cancellation



$$\Rightarrow \delta m_h^2 \approx \frac{3}{2\pi^2}\frac{m_t^2}{v^2} M_T^2 \log\frac{\Lambda^2}{M_T^2}$$

vs $\delta m_h^2 \approx \frac{3}{2\pi^2}\frac{m_t^2}{v^2}\Lambda^2$ for top alone

The Hierarchy Problem



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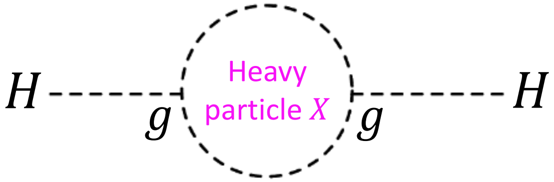

$$\Longrightarrow \quad \delta M_h^2 \Big|_{\text{from } X} = \frac{\mathcal{O}(1)}{16\pi^2} g^2 M_X^2$$

Two well-und…

Most natural (i.e. least tuned) expectation:
New particle masses $M_* \lesssim (\text{loop factor})^{-1/2}\, m_h \sim$ few TeV

- Loops cu… composite resonances
- To get $m_h \ll m_{\text{res}}$, need Higgs to be pseudo-Goldstone bosons ($\sim$ QCD pions)
- Explicit breaking by top Yukawa and EW gauging generates m_h^2 at 1-loop

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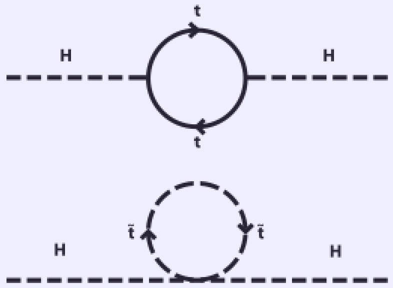

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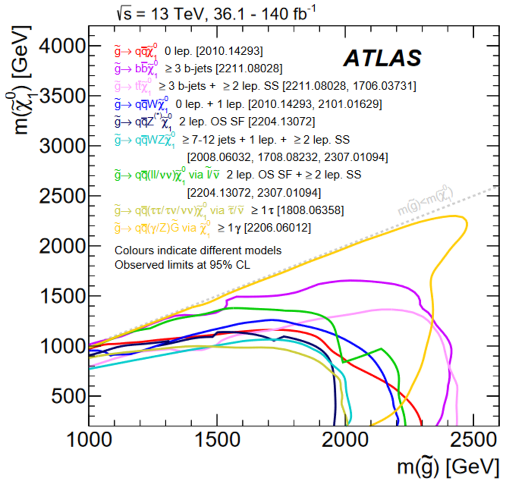
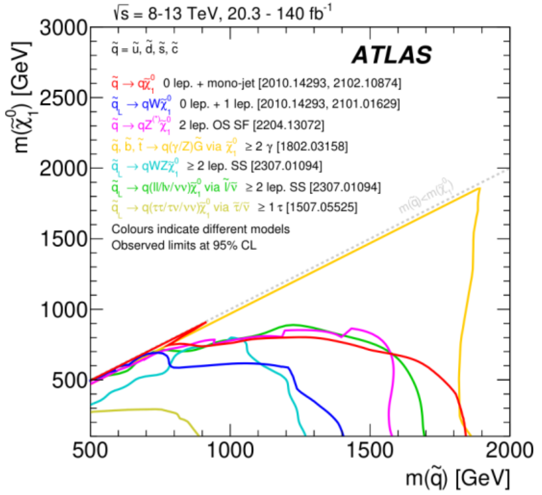
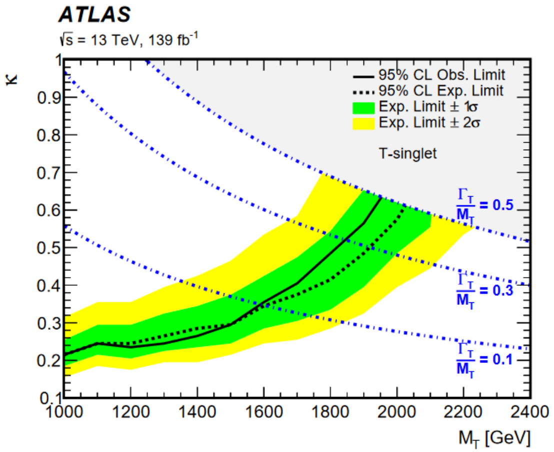
We are now probing natural M_* directly at the LHC

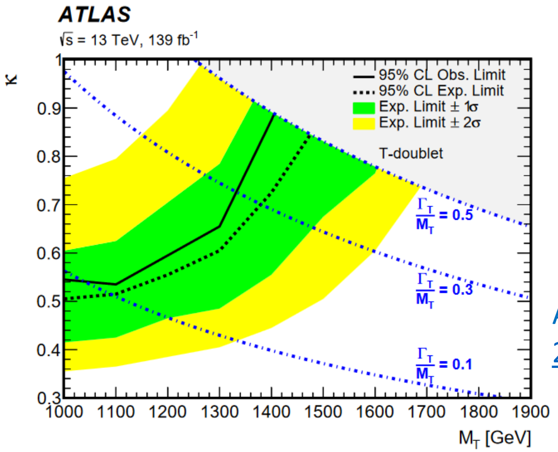
Few TeV limits on SUSY particles, top partners!





ATLAS, [2403.02455](https://arxiv.org/abs/2403.02455)



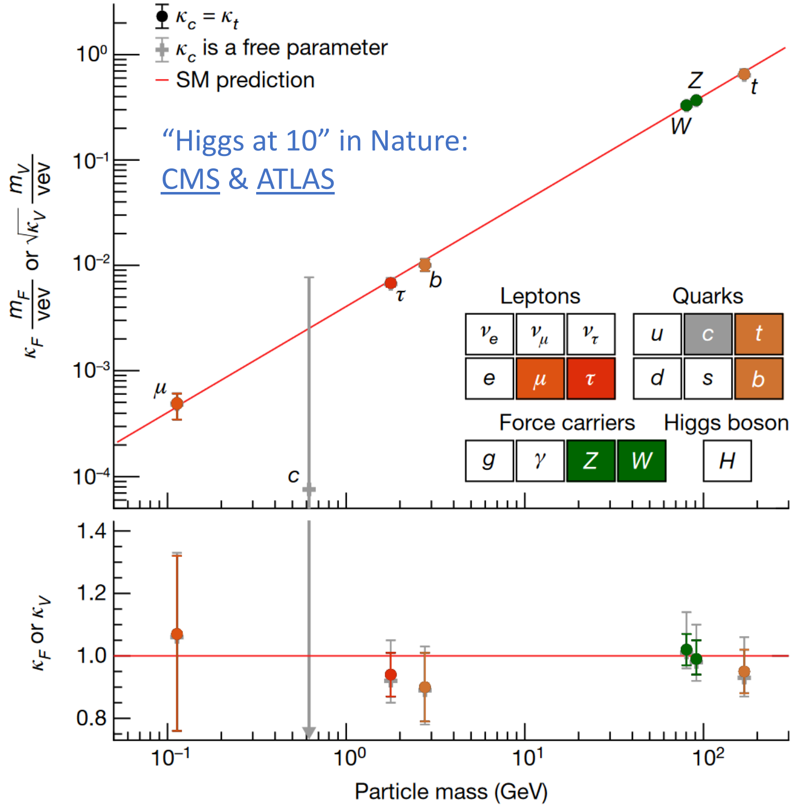


ATLAS, [2307.07584](https://arxiv.org/abs/2307.07584)

$$\Rightarrow \frac{\delta m_h^2}{m_h^2} \sim \left(\frac{M_T}{500\ \text{GeV}}\right)^2$$

+ No sign of compositeness in Higgs couplings!

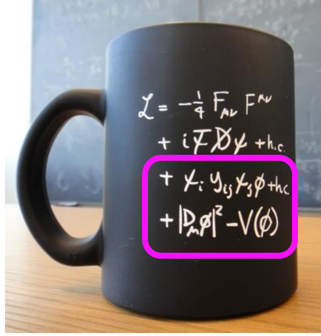
HWW, HZZ at LHC agree with SM to 3%



$$\Rightarrow \frac{v^2}{f^2} \lesssim 5\%$$

where f is compositeness scale

The Hierarchy Problem(s)



*The Higgs has an unnaturally small **mass** parameter:

Large hierarchy: $\mu^2 \ll \Lambda^2_{\text{high scales}}$ $\Longrightarrow$ **compositeness** or **SUSY** as low scale as possible

Little hierarchy: $\mu^2 \ll \Lambda^2_{\text{SM}} \sim \text{TeV}^2$ $\Longrightarrow$ accept it! or try even clever-er model-building

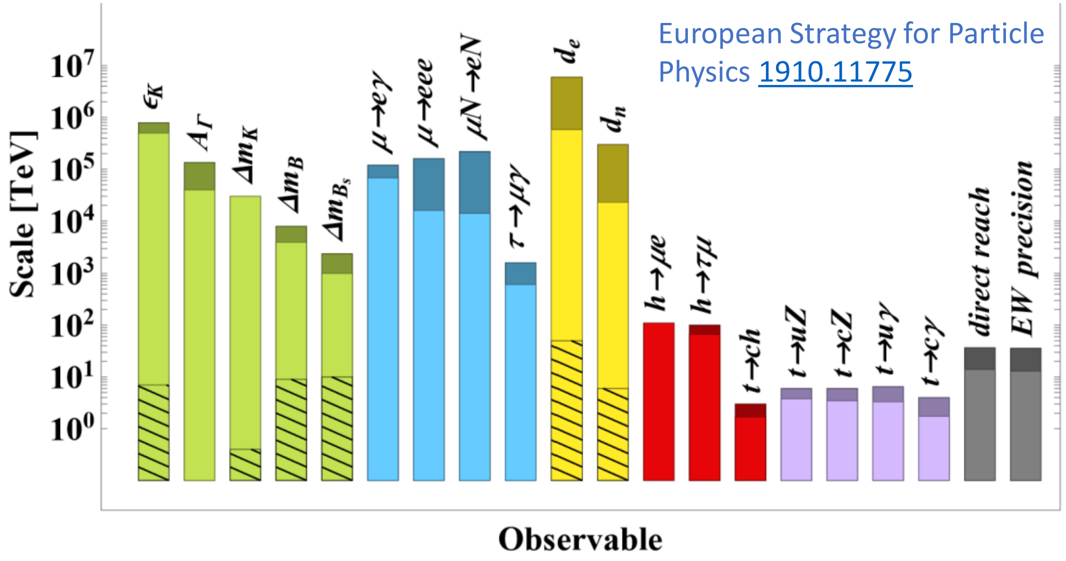
E.g. “Gegenbauer Goldstones”
Durieux, McCullough, Salvioni 2110.06941, 2202.01228

Will return to the little hierarchy at the end of the talk…

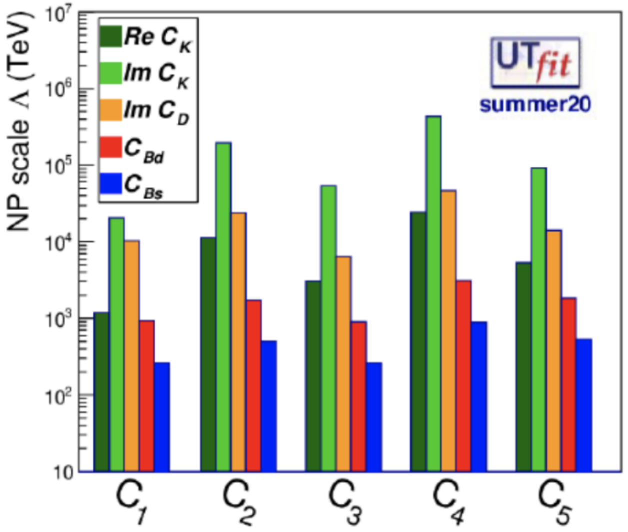
When trying to solve the (large or little) hierarchy problem, we **cannot** ignore flavour!

The BSM Flavour Puzzle

While the hierarchy problem points to scale $M_* \sim \mathrm{TeV}$, flavour points to much higher scales!



European Strategy for Particle Physics 1910.11775



E.g. kaon mixing: $L \supset \frac{e^{i\alpha}(\bar{d}s)^2}{\Lambda_{sd}^2} \implies \Lambda_{sd} \gtrsim 10^{5\div 6}\ \mathrm{TeV}$

Therefore *any* solution to hierarchy problem **needs** non-trivial **flavour structure**

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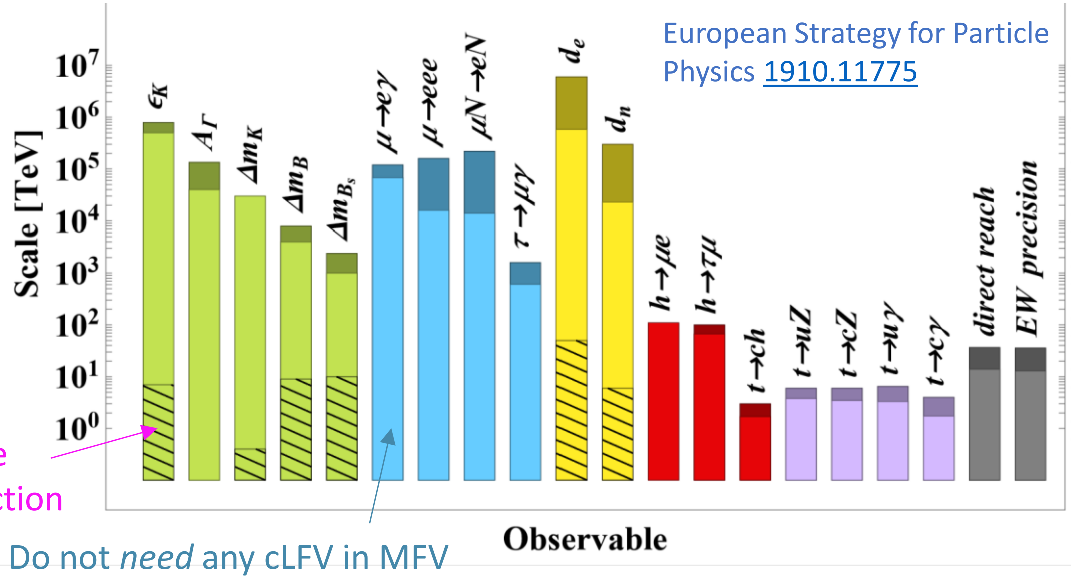
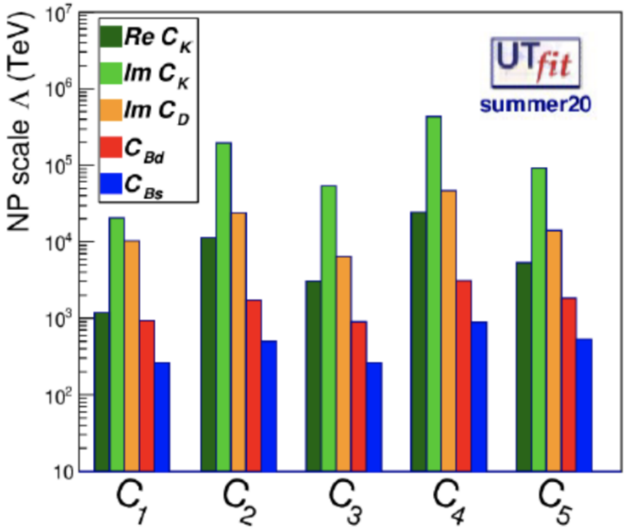


Hatched bars are with MFV protection

Do not *need* any cLFV in MFV



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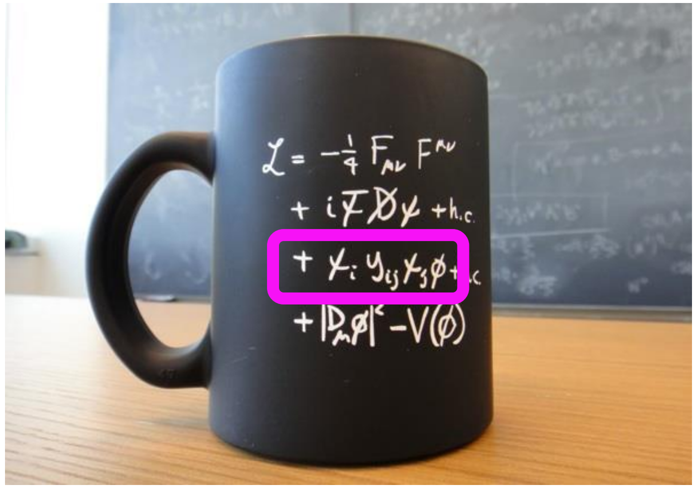
Example = **Minimal Flavour Violation:** BSM couplings $C_{ij} \sim \delta_{ij} + \cdots$, with … built from SM Yukawas

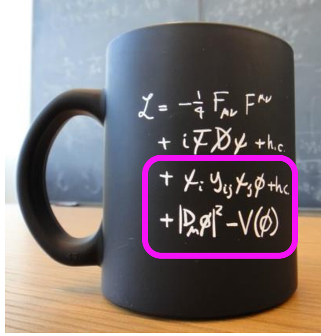
Kaon mixing with MFV: $\dfrac{1}{\Lambda_{sd}^2} \sim y_t^4 (V_{31}V_{32}^*)^2 \dfrac{1}{\Lambda_{\mathrm{NP}}^2} \sim \left(\dfrac{10^{-5}}{\Lambda_{\mathrm{NP}}}\right)^2$ is sufficient flavour protection!

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

Flavour is already a rich source of mysteries within the SM

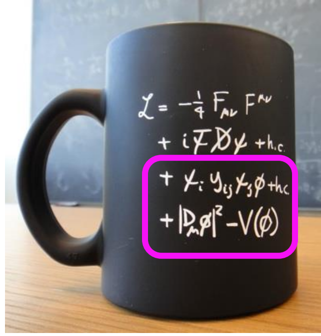


The SM Flavour Puzzle(s)



Fermion sector of SM contains many mysteries:

1. Why those (chiral) representations / hypercharges?



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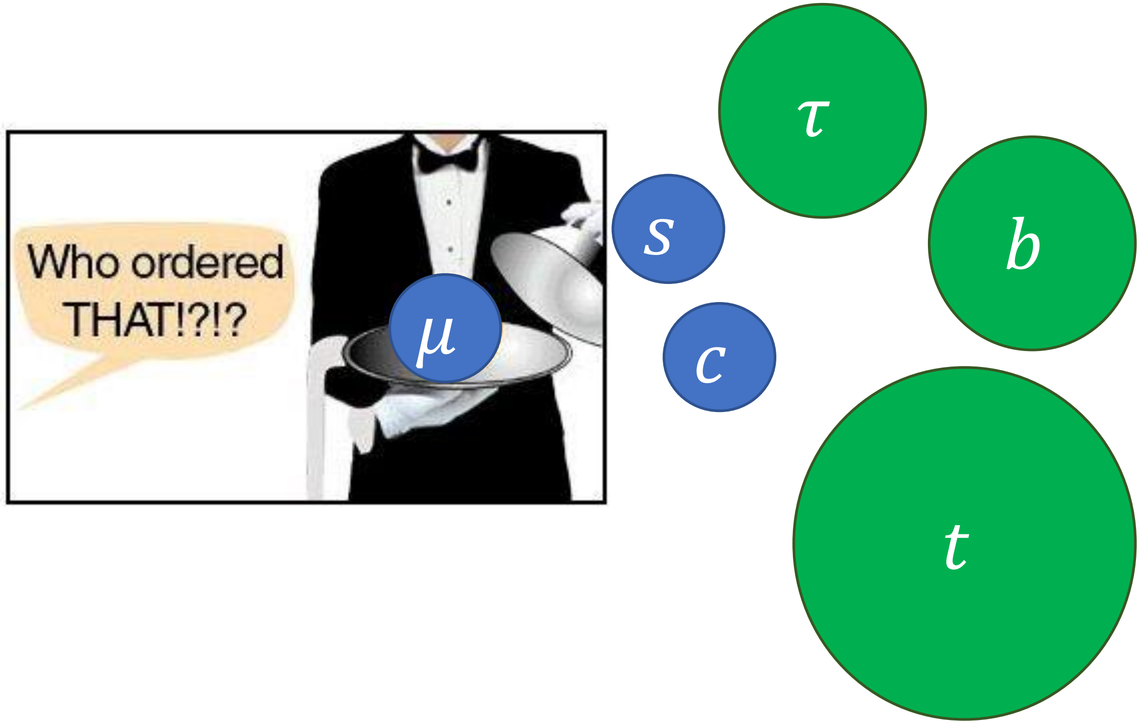

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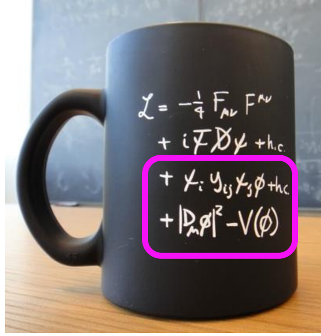

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3. Why huge (technically natural) hierarchies in SM Yukawa couplings $y^f_{ij}\, \bar{f}_{L,i} H f_{R,j}$?

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

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

Most of the Higgs' couplings in the SM are generating **flavour**! Higgs is the origin also of the flavour puzzle

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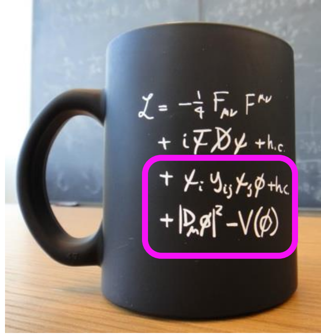

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Does puzzle (3) have a dynamical explanation?

- y_{ij}^f are marginal (dimension-4) interactions: do not clearly point to a particular scale for NP explanation, unlike μ^2
- BUT since Higgs is origin of hierarchy problem & flavour puzzle: maybe they have a **joint solution** near TeV?

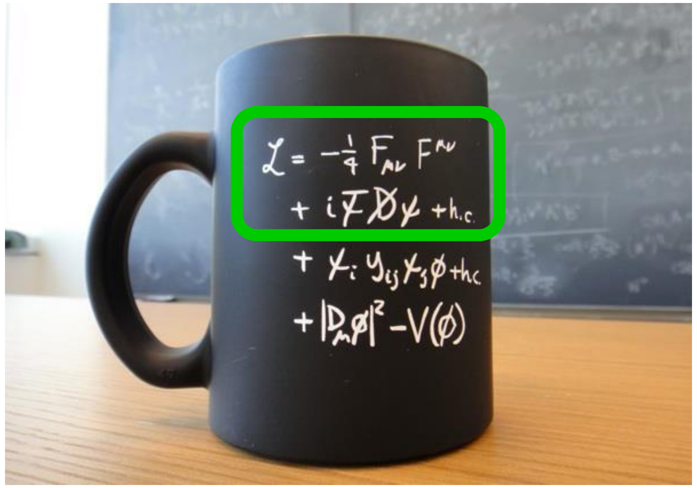
2. From MFV to U2

The case for flavour ***non***-universal New Physics

U2: Global Symmetries of the SM

SM without Yukawas has a large $U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$ global symmetry

[SM gauge interactions are flavour-universal]



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[SM gauge interactions are flavour-universal]

SM Yukawas y_{ij}^f are a weak breaking of this $U(3)^5 \to U(1)_B \times \prod_{i=1}^3 U(1)_{L_i}$; but only y_{33}^u is order−1

$$y_{ij}^u \approx \begin{pmatrix} & < 0.01 & 0.04 \\ & & 1 \end{pmatrix}$$

Top Yukawa

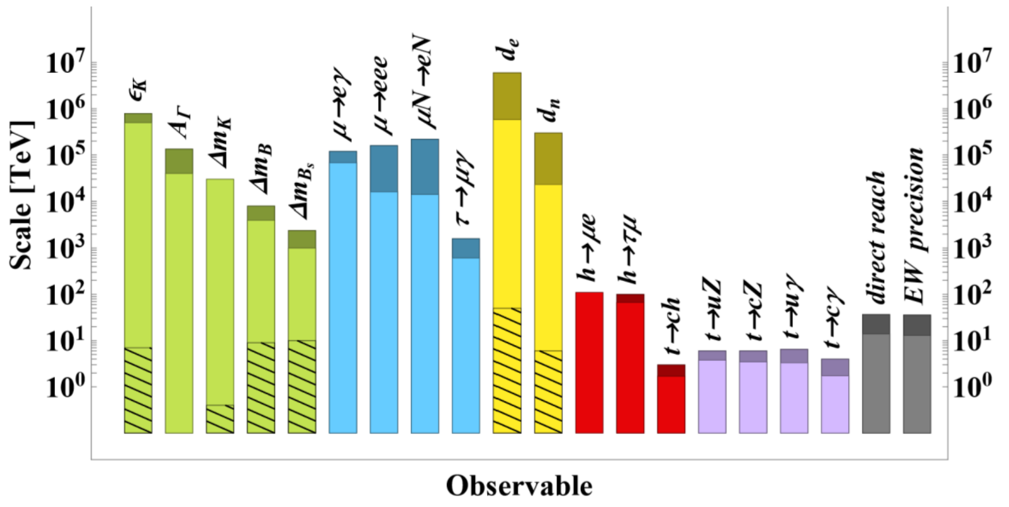
Leaves unbroken an approximate $U(2)_q \times U(2)_u$ flavour symmetry, with $(q_1, q_2) \sim \mathbf{2}$, $q_3 \sim \mathbf{1}$ of $U(2)_q$ etc

Leading "spurions" needed to populate y_{ij}^f are:

- $V_q \sim \mathbf{2}$ of $U(2)_q \longrightarrow V_{cb} \sim 0.04$
- $\Delta_u \sim (\mathbf{2}, \mathbf{2})$ of $U(2)_q \times U(2)_u \longrightarrow y_c/y_t \sim 0.01$

U2: Global Symmetry of New Physics?

We saw that TeV scale NP needs a special flavour structure e.g. MFV



U2 is just as good as MFV for evading flavour bounds

[spurions used to build flavour-violating operators are now V_q and Δ_u etc, rather than y^f themselves as in MFV]

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

MFV:
$(q_1, q_2, q_3) \sim \mathbf{3}$ of $U(3)_q$
Spurions = y^f (most predictive)

U2 is a **weaker assumption** on NP than MFV: can decouple 3rd generation from light generations

U2:
$(q_1, q_2) \sim \mathbf{2}$, $q_3 \sim \mathbf{1}$ of $U(3)_q$
Spurions = V_q, Δ_u etc

$$C_{ij} \sim \begin{pmatrix} a & & \\ & a & \\ & & b \end{pmatrix} + \cdots$$

Two big reasons to prefer U2 over MFV

$$C_{ij}^{\mathrm{U2}} \sim \begin{pmatrix} a & & \\ & a & \\ & & b \end{pmatrix} + \cdots \quad \text{vs} \qquad C_{ij}^{\mathrm{MFV}} \sim \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} + \cdots$$

1. Theoretical: same global symmetry as the SM Yukawas $\Longrightarrow$ can **explain SM flavour puzzle** at same time!

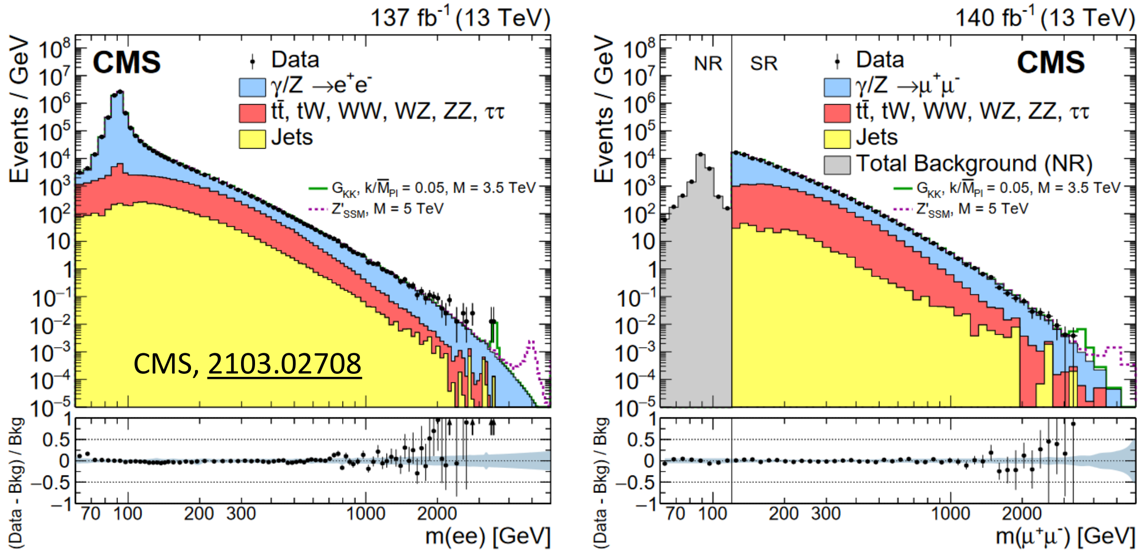
2. Phenomenological: weaker collider bounds!

   The scale Λ_{NP} can be reduced by taking $a \ll b$, allowing $\Lambda_{U(2)} \sim 1\ \mathrm{TeV}$ vs $\Lambda_{\mathrm{MFV}} \sim 10\ \mathrm{TeV}$;

   in the LHC era this allows for **more natural models** than with MFV

Lowering $\Lambda_{\rm NP}$ with U2

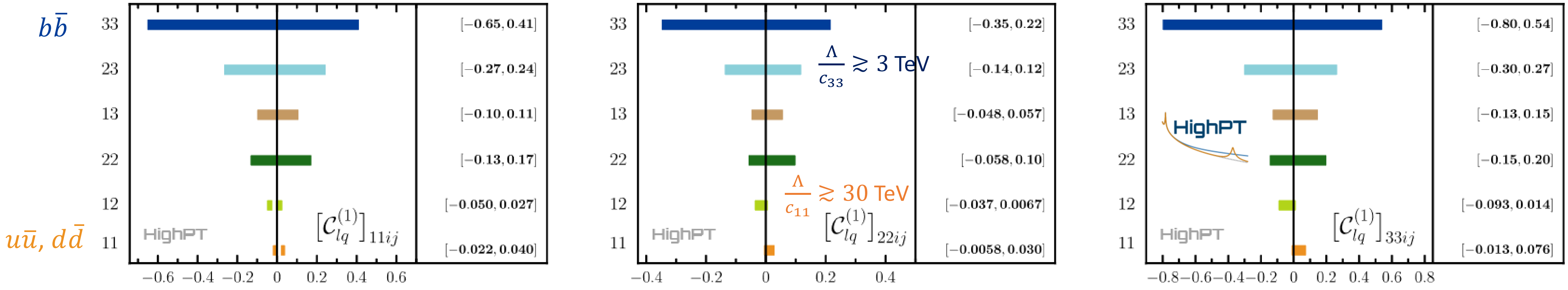
Exhibit A: High-p_T Drell-Yan tails $pp \to ll$



Bounds on dim-6 semi-leptonic operators:

$$L_{\rm SMEFT} \supset \frac{C_{lq}^{(1)}}{1\ {\rm TeV}^2}\,\bar{l}\gamma^\mu l\,\bar{q}\gamma_\mu q$$

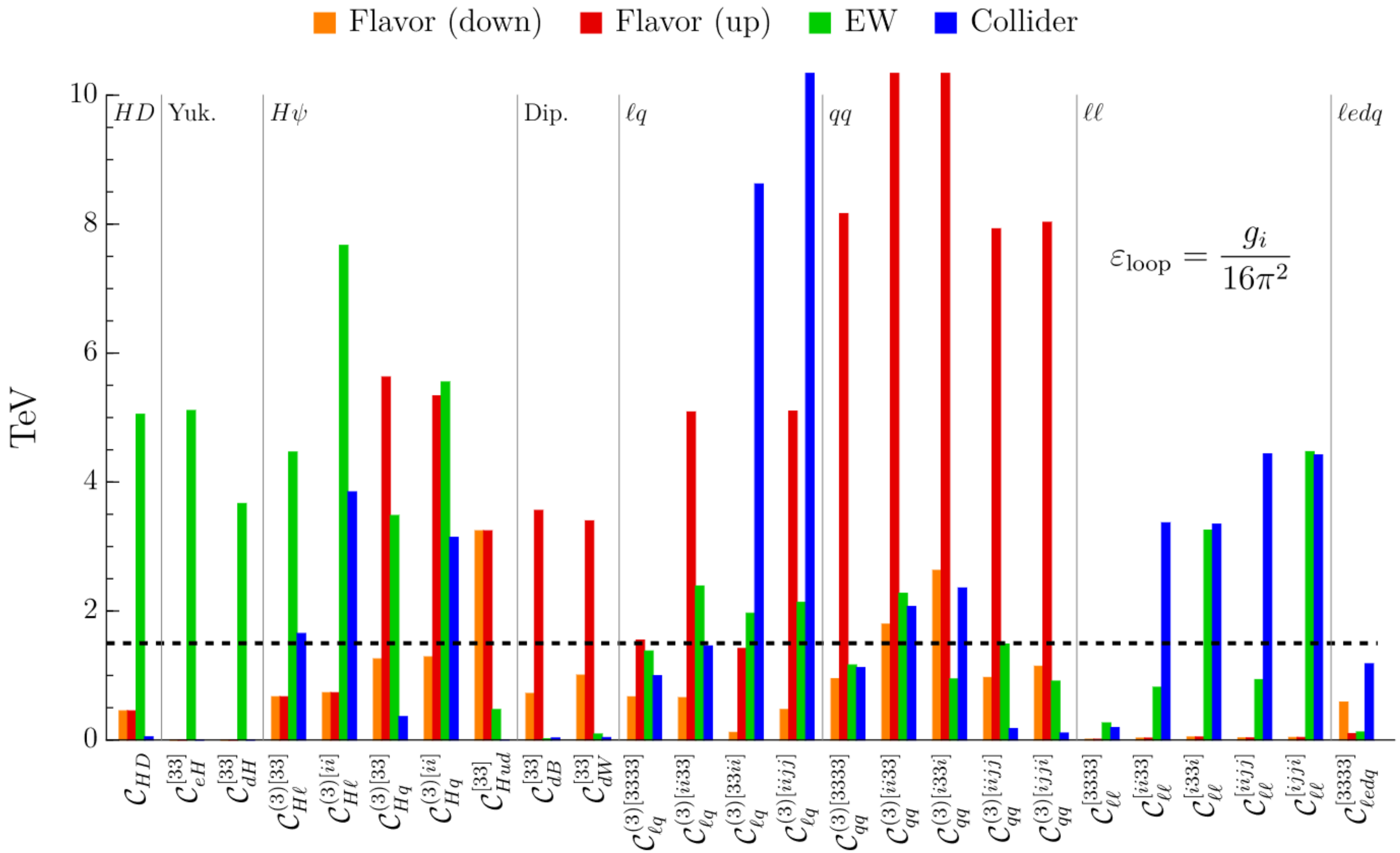
Allwicher, Faroughy, Jaffredo, Sumensari, Wilsch, 2207.10714
Allwicher, Faroughy, Jaffredo, Sumensari, Wilsch, 2207.10756



Lowering Λ_{NP} with U2

Exhibit B: global lessons from SMEFT likelihoods

Allwicher, Cornella, Isidori, Stefanek, 2311.00020



MFV-like

Lowering Λ_{NP} with U2

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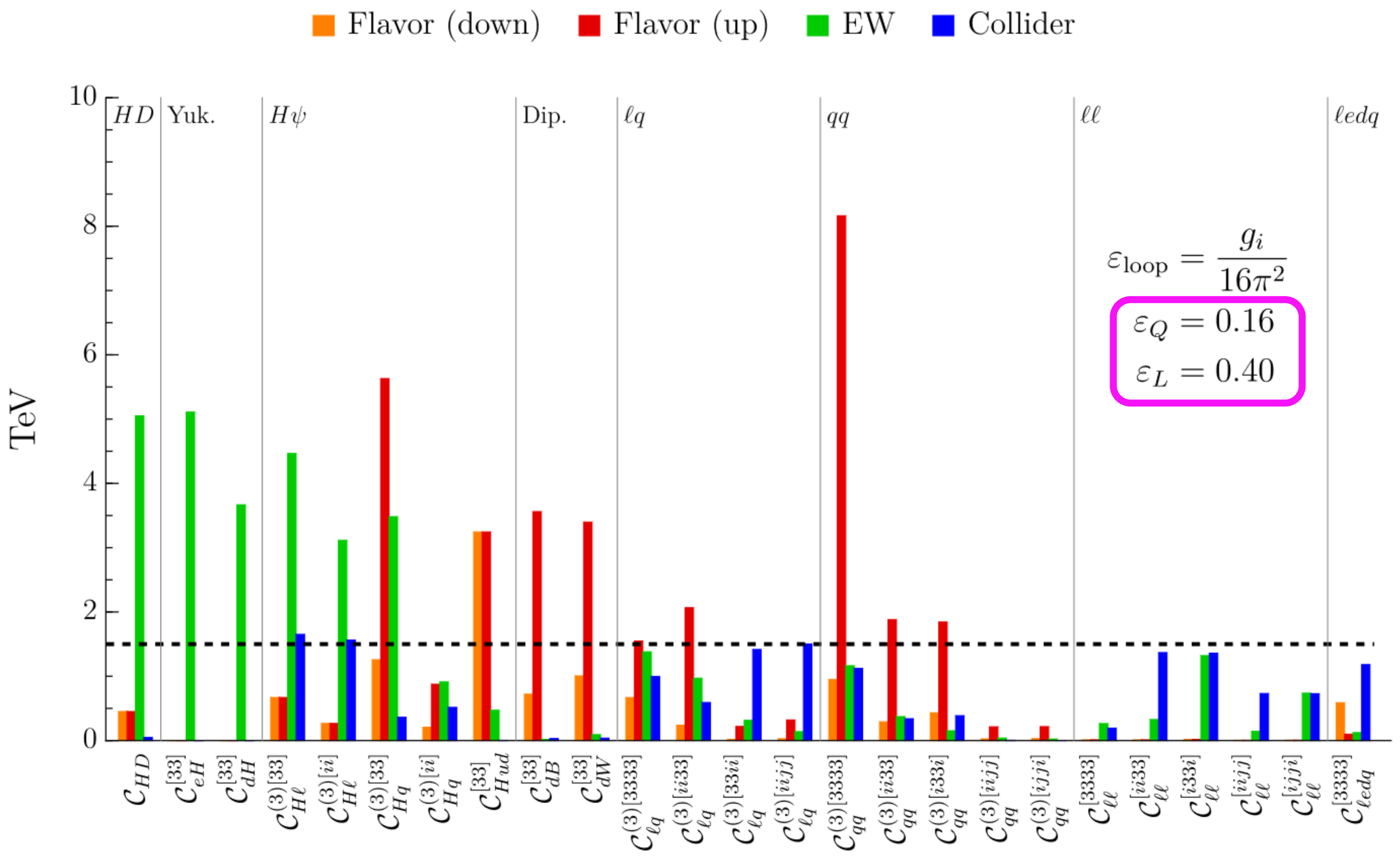
Allwicher, Cornella, Isidori, Stefanek, 2311.00020



U2-like

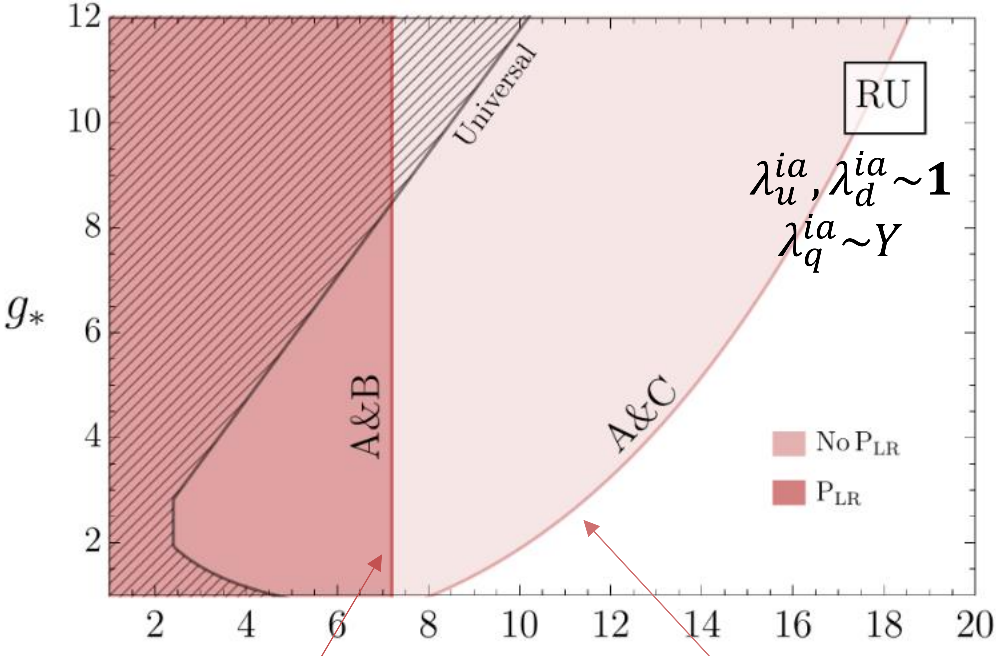
Mild suppression of operators with light-generation quarks and leptons

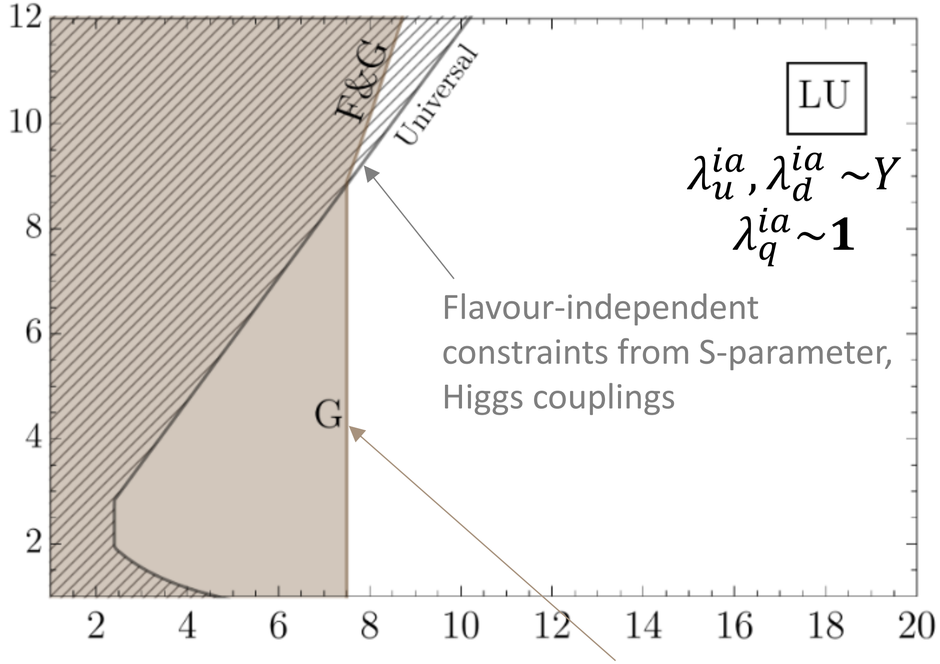
Lowering Λ_{NP} with U2

Exhibit C: composite Higgs solutions to hierarchy problem

With MFV: $M_* \gtrsim 7 \div 8$ TeV

Glioti, Rattazzi, Ricci, Vecchi, 2402.09503





Label	Observable
A	$pp \to jj$
B	$\Delta F = 2\,(B_d)$
C	$B_s \to \mu^+\mu^-$
D	nEDM
E	$B^0 \to K^{*0} e^+ e^-\ (C_7')$
F	$B \to X_s \gamma\ (C_7)$
G	W-coupling

Flavour-independent constraints from S-parameter, Higgs couplings

Flavour-violation! In $B_s \to \mu\mu$

Shift in light quark **couplings to W boson**

Di-jet constraints from **LHC**, driven by light quark couplings

P_{LR} is an extension of custodial by a `left-right' exchange symmetry [kills $Z b_L b_L$ correction]

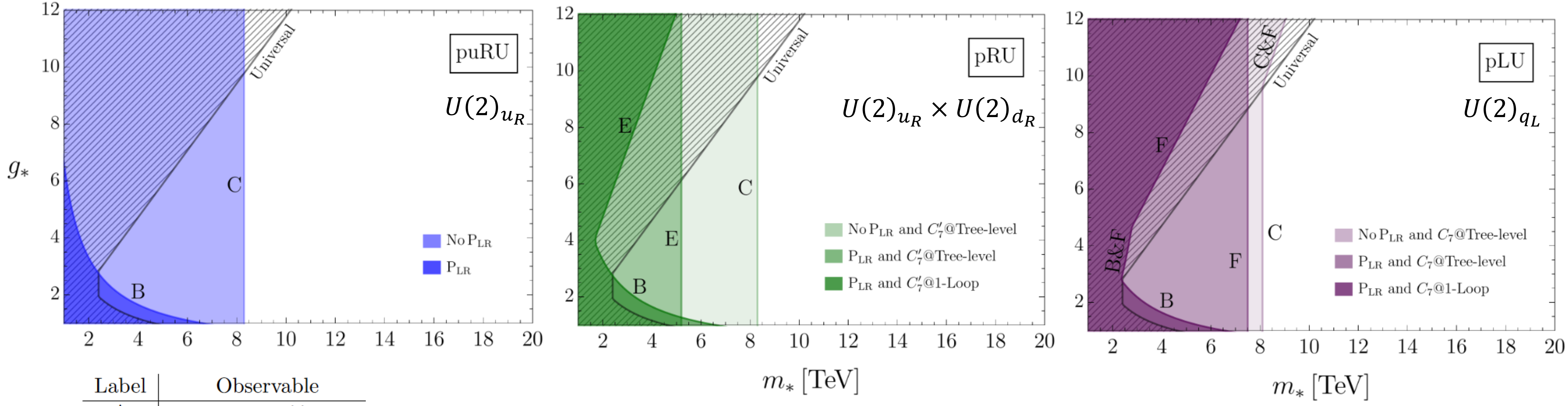
Strongest current bounds are driven by couplings to **light generation fermions** OR **flavour violation**, not EW constraints

Lowering Λ_{NP} with U2

Exhibit C: composite Higgs solutions to hierarchy problem

With U2: $M_* \gtrsim 1 \div 2$ TeV

Glioti, Rattazzi, Ricci, Vecchi, 2402.09503



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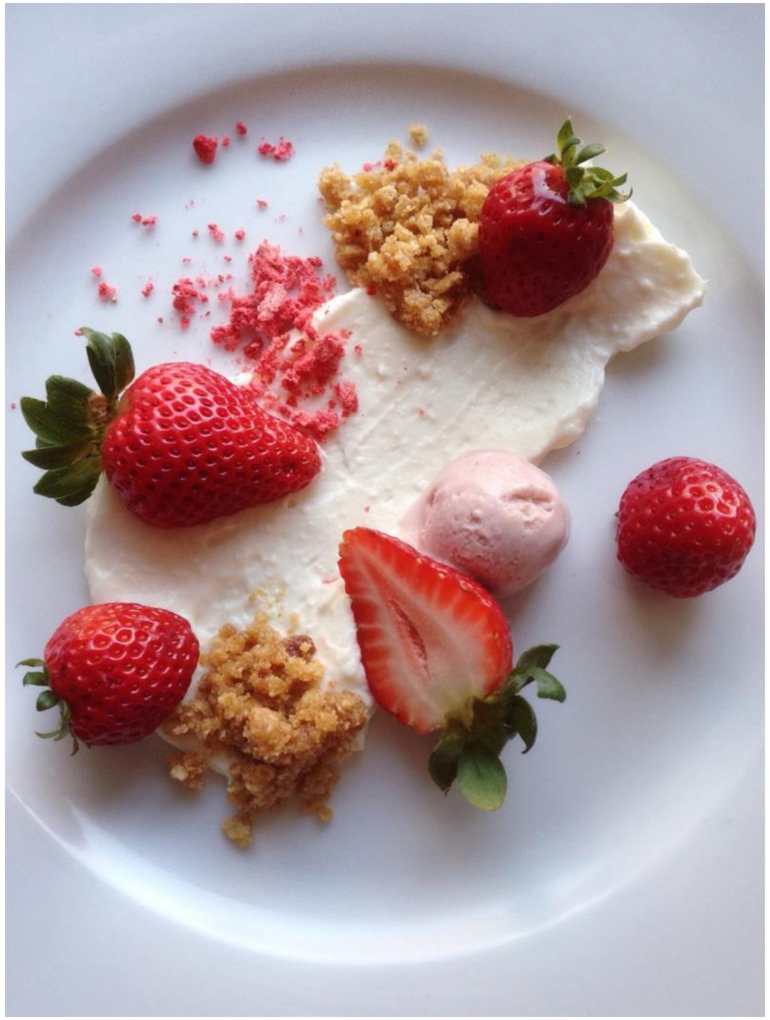
Going from MFV to U(2), we decouple the strong LHC constraints: dominant bounds now heavy-to-light quark flavour-violation + universal EW constraints

3. On the Origin of U2: Flavour Deconstruction



So far we have considered the phenomenological consequences of $U(2)^n$ as an imposed global symmetry of NP. What might be the origin of this $U(2)^n$?

General hypothesis:

- The $U(2)$s manifest in Yukawas and NP couplings have common dynamical origin:
- = accidental symmetries from a flavour non-universal [3 vs 1+2] **gauge** symmetry, broken $\sim$ TeV

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But what symmetry to gauge? There are many options…

Flavour non-universal gauge interactions

Horizontal Approach: $G = G_{\text{SM}} \times G_{\text{hor}} \to G_{\text{SM}}$

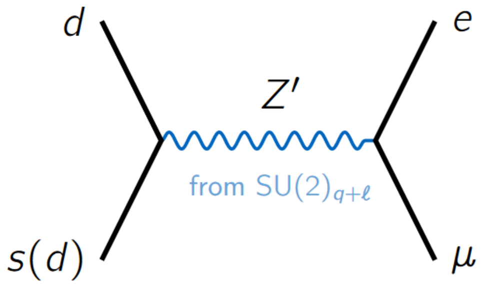
Froggatt, Nielsen, Nucl Phys B (1979)

Gauge some $H \subset U(2)^n$ directly, and break to nothing

Gives a bunch of Z' bosons that can be decoupled from the Higgs (can take $g \ll 1$)

But they are flavour-violating and so **high scale**

- Bounds e.g. from LFV decay $K_L \to \mu^\pm e^\mp \Longrightarrow \frac{M}{g} \gtrsim 10^{2\div 3}\ \text{TeV}$



Recent examples:
Allanach, Davighi, 1809.01158; 1905.10327
Darmé, Deandrea, Mahmoudi, 2307.09595
Greljo, Thomsen, 2309.11547
Antusch, Greljo, Stefanek, Thomsen, 2311.09288
Greljo, Thomsen, Tiblom, 2406.02687

Flavour non-universality, non-horizontally

Deconstruction Approach: $G_{12} \times G_{3+H} \rightarrow G_{SM}$

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

Multi-scale breaking pattern can explain full Yukawa structure:

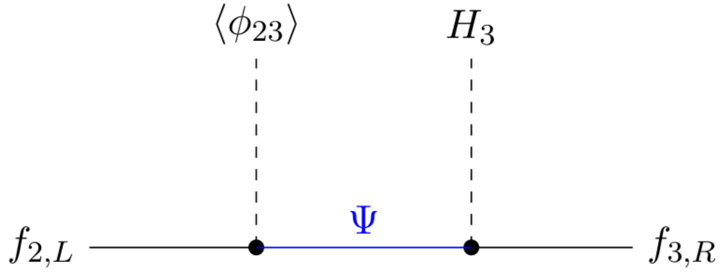
$G_1 \times G_2 \times G_{3+\mathrm{H}}$	$\rightarrow G_{12} \times G_{3+\mathrm{H}}$	by $\langle \phi_{12} \rangle \sim 100(0\ldots)$ TeV	where e.g. $\phi_{12} \sim (\square, \square)$ of $G_1 \times G_2$
	$\rightarrow G_{\mathrm{SM}}$	by $\langle \phi_{23} \rangle \sim 1(0\ldots)$ TeV	where e.g. $\phi_{23} \sim (\square, \square)$ of $G_{12} \times G_{3+\mathrm{H}}$

How it works:

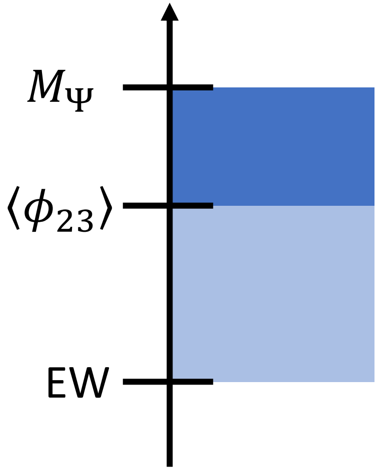
To connect 3rd family / Higgs to 2nd family, need ϕ_{23} insertion $\Longrightarrow \epsilon_{23} \coloneqq \frac{v_{23}}{\Lambda_{23}}$ suppression

To connect 3rd family / Higgs to 1st family, $\phi_{12}\phi_{23}$ insertion $\Longrightarrow \frac{v_{12}}{\Lambda_{12}} \frac{v_{23}}{\Lambda_{23}}$ suppression

Example UV:



$$y_{23} \sim \frac{v_{23}}{M_\Psi} = \epsilon_{23}$$



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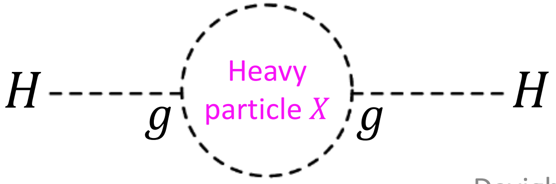
$\to G_{\mathrm{SM}}$ by $\langle\phi_{23}\rangle \sim 1(0\ldots)\ \mathrm{TeV}$ where e.g. $\phi_{23} \sim (\square, \bar{\square})$ of $G_{12} \times G_{3+\mathrm{H}}$

Much richer phenomenology! SM-charged vectors in adj G, w flavour diagonal BUT non-universal couplings

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

- The $G_{12} \times G_{3+H} \to G_{\mathrm{SM}}$ breaking is viable close to TeV because no flavour violation, and $g_3 \gg g_{1,2}$ U2 limit
- Indeed it *cannot* be decoupled from experiment [$M \to \infty$] w/o creating hierarchy problem

Davighi, Isidori 2303.01520



$$\delta m_h^2 \sim g^2 M^2 / 16\pi^2$$

Flavour non-universality, non-horizontally

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$\rightarrow G_{\text{SM}}$ by $\langle \phi_{23} \rangle \sim 1(0\ldots)$ TeV where e.g. $\phi_{23} \sim (\square, \square)$ of $G_{12} \times G_{3+\text{H}}$

Theoretical appeal:

1. Charge assignment and anomaly-freedom inherited from SM – no *ad hoc* choices
2. Breaking pattern $G_A \times G_B \rightarrow G_{A+B}$, given scalar condensate ϕ, is **generic** for simple G
   - for 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*

   Goursat, 1889
   Craig, Garcia-Garcia, Sutherland, 1704.07831
3. Easy to find semi-simple UV completions with deconstruction approach
   - In contrast most $G_{\text{SM}} \times U(1)_X$, even anomaly-free, have no semi-simple completion

   Davighi, Tooby-Smith, 2206.11271

Aside: Electroweak Flavour Unification

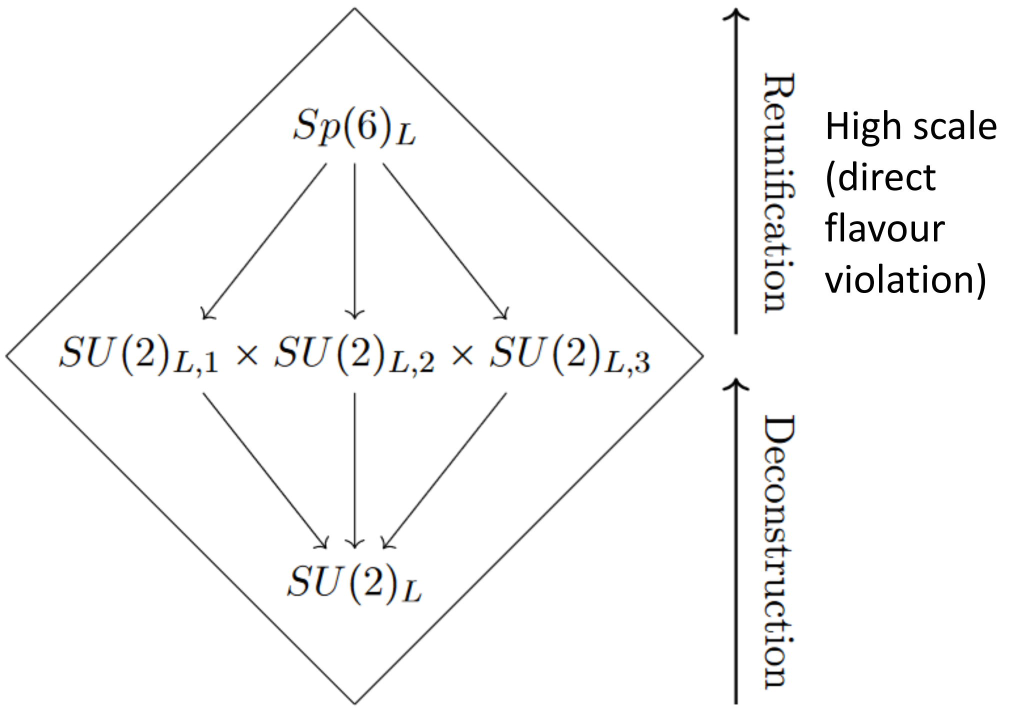
Davighi, Tooby-Smith, 2201.07245
Davighi, 2206.04482

Is there a nice UV origin for flavour deconstruction?

One path is to *reunify* the deconstructed symmetry in the UV

E.g. deconstructed electroweak symmetry $\hookrightarrow Sp(6)_L \times Sp(6)_R$

- Anomaly-free
- New solution to SM flavour puzzle
- Low energy limit (and pheno) is that of flavour deconstruction
- offers a gauge answer to "why 3 generations"?



Reminder:
The Lie group $Sp(6)$ is a subgroup of $SU(6)$:

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

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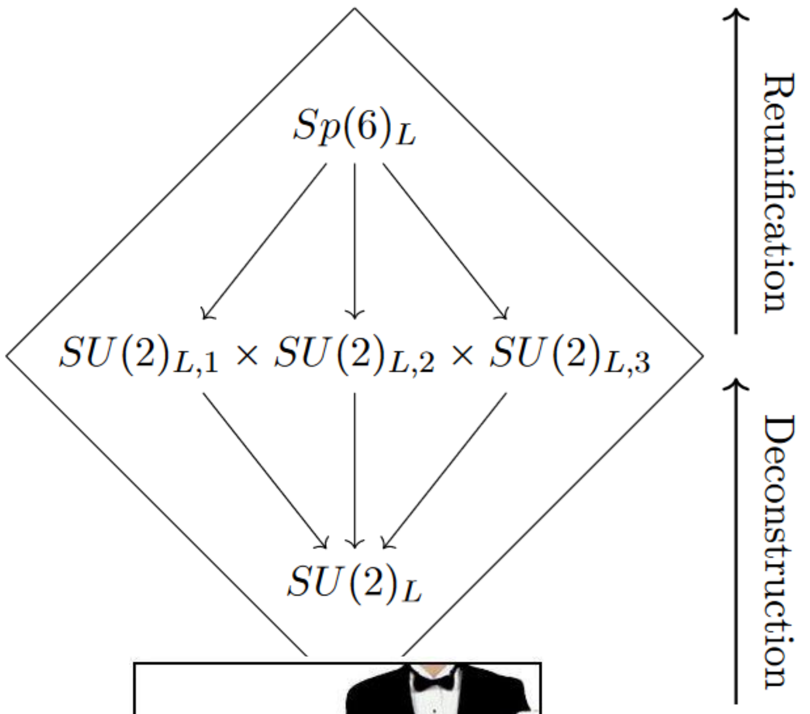


High scale (direct flavour violation)

We arrived at this theory from a different motivation: unification!

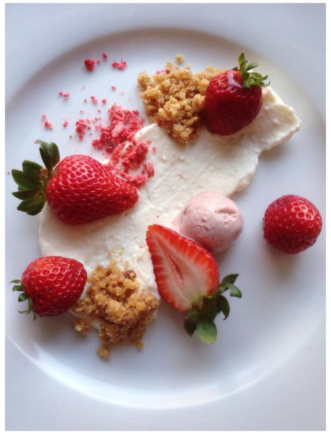
If we want to unify all fermions, the only options are EWFU or "colour flavour unification" via $SU(12)$ - but this "anti-solves" the flavour puzzle by setting $y_u = y_c = y_t$ etc at LO

See the classification of all embeddings of 3-flavour SM gauge algebra: Allanach, Gripaios, Tooby-Smith, 2104.14555

Back to flavour deconstruction

Which SM force should we deconstruct?

And what is the phenomenology?



Survey of Flavour Deconstruction models

Davighi, Isidori 2303.01520

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

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

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"EWPO"s:

	Observable	Definition
Z-pole	Γ_Z	$\sum_f \Gamma(Z\to f\bar f)$
	$\sigma_{\rm had}$	$\frac{12\pi}{m_Z}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar q)}{\Gamma_Z^2}$
	$R_f\ (f=e,\mu,\tau,c,b)$	$\frac{\Gamma(Z\to f\bar f)}{\sum_q \Gamma(Z\to q\bar q)}$
	$A_f\ (f=e,\mu,\tau,s,c,b)$	$\frac{\Gamma(Z\to f_L\bar f_L)-\Gamma(Z\to f_R\bar f_R)}{\Gamma(Z\to f\bar f)}$
	$A_{\rm FB}^{0,\ell}\ (\ell=e,\mu,\tau)$	$\frac{3}{4}A_e A_\ell$
	$A_q^{\rm FB}\ (q=c,b)$	$\frac{3}{4}A_e A_q$
	R_{uc}	$\frac{\Gamma(Z\to u\bar u)+\Gamma(Z\to c\bar c)}{2\sum_q \Gamma(Z\to q\bar q)}$
W-pole	m_W	
	Γ_W	$\sum_{f_1,f_2}\Gamma(W\to f_1 f_2)$
	$\mathrm{Br}(W\to\ell\nu)\ (\ell=e,\mu,\tau)$	
	R_{W_c}	$\frac{\Gamma(W\to cs)}{\Gamma(W\to ud)+\Gamma(W\to cs)}$

LEP-1 and SLC

LEP-2, Tevatron, and LHC

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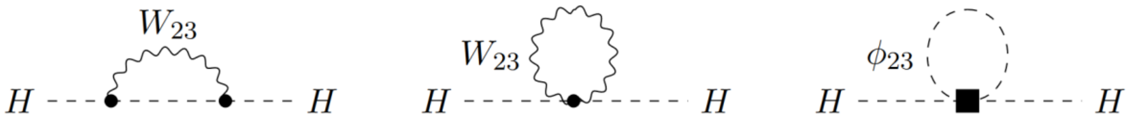
"Finite naturalness" limits on M_X from requiring the finite part of $\delta m_h^2 \lesssim 1\,\mathrm{TeV}^2$



General Lesson

- Need to deconstruct part of the EW symmetry to explain the flavour puzzle (because Higgs is colourless)
- Automatically implies 1-loop δm_h^2 and tree-level δ EWPOs

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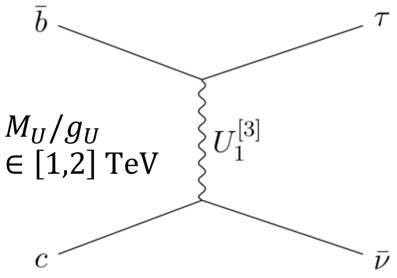
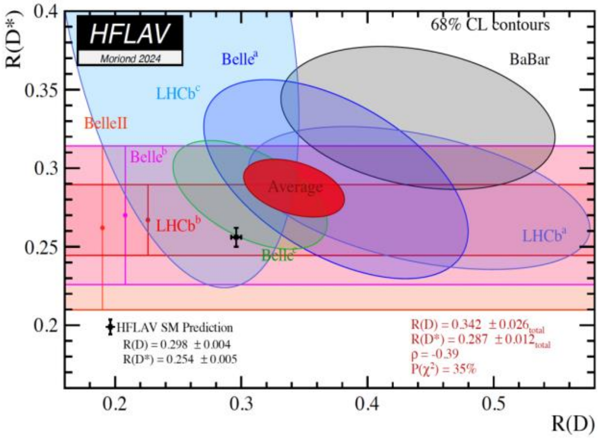
	EWPOs order	1-loop	Tree	Tree	Tree	1-loop

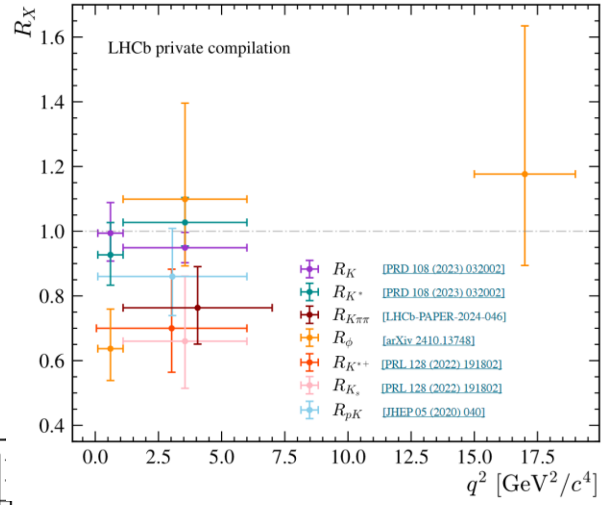
Aside: If we enlarge $SU(3)^{[3]} \to SU(4)^{[3]}$, can also explain $b \to c\tau\nu$ anomalies in $R_{D^{(*)}}$ & $bs\mu\mu$ via '4-3-2-1' models

$M_U/g_U \in [1,2]$ TeV

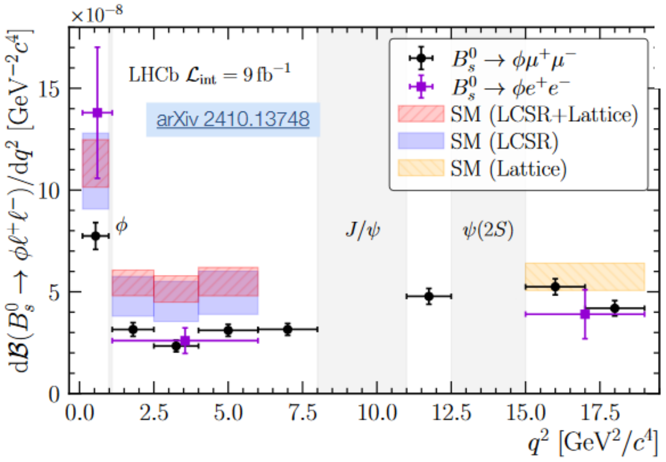


Buttazzo, Greljo, Isidori, Marzocca, 1706.07808; Di Luzio, Greljo, Nardecchia, 1708.08450; Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368; Greljo, Stefanek, 1802.04274; Di Luzio, Fuentes-Martin, Greljo, Nardecchia, Renner, 1808.00942; Fuentes-Martin, Stangl, 2004.11376 …





LHCb Implications 2024



Experimental hints for deconstruction near TeV?

Phenomenology of EW Flavour Deconstruction

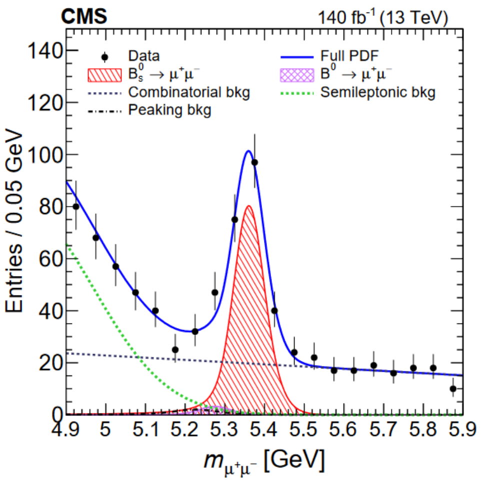
Deconstructing $SU(2)_L$ or $U(1)_Y$ gives a 2-parameter model: M_X and $\tan\theta = g_3/g_{12}$

$DU(1)_Y$: Davighi, Stefanek 2305.16280
$DSU(2)_L$: Davighi, Gosnay, Miller, Renner 2312.13346

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}

$\Longrightarrow$ **Complementary constraints** from (i) flavour observables, (ii) colliders i.e. LHC, (iii) EW precision



CMS, 2212.10311

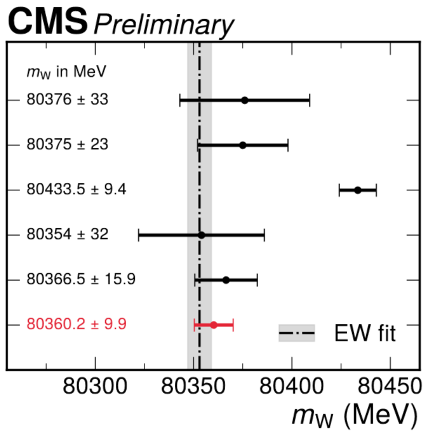
Flavour, key observable is the rare decay $BR(B_s \to \mu^+\mu^-)$, measured precisely at LHC

- Weaker bounds for $DU(1)_Y$ because $Y_Q g_Y \sim 1/18$ vs $t_L^3 g_L \sim 1/3$

LHC Drell-Yan driven by valence-quark couplings: bounds favour $g_3 \gg g_{12}$ region i.e. $\theta \to \pi/2$

EWPOs: tree-level shifts in Z-pole observables & m_W means EW constraints often strongest!

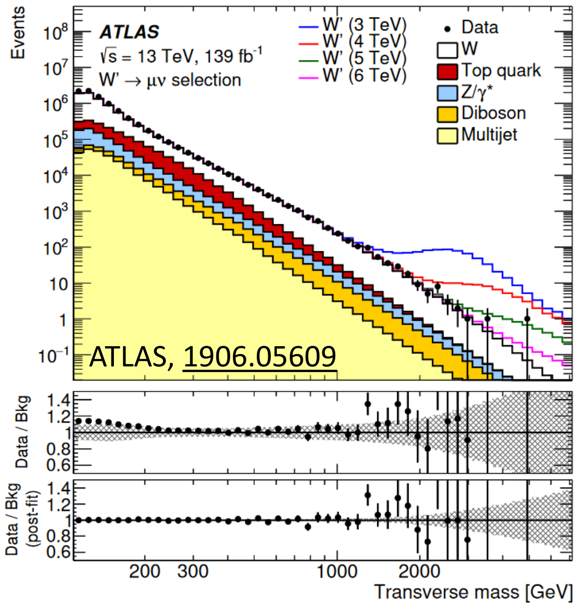
- Key observable given current data is W mass: $DSU(2)_L$ gives $\delta m_W < 0$; $DU(1)_Y$ gives $\delta m_W > 0$

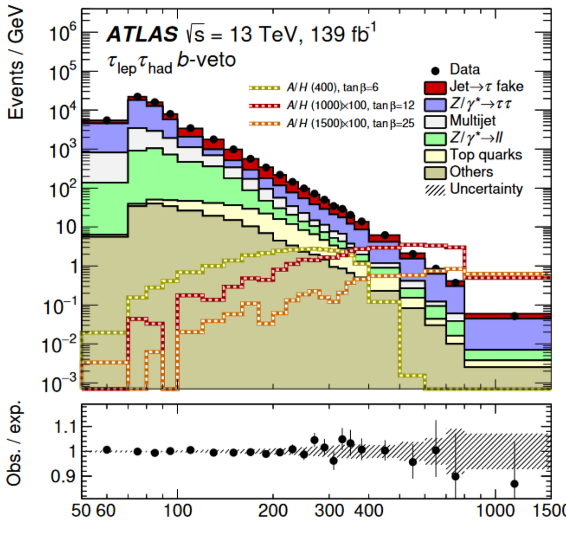


CMS, 2024

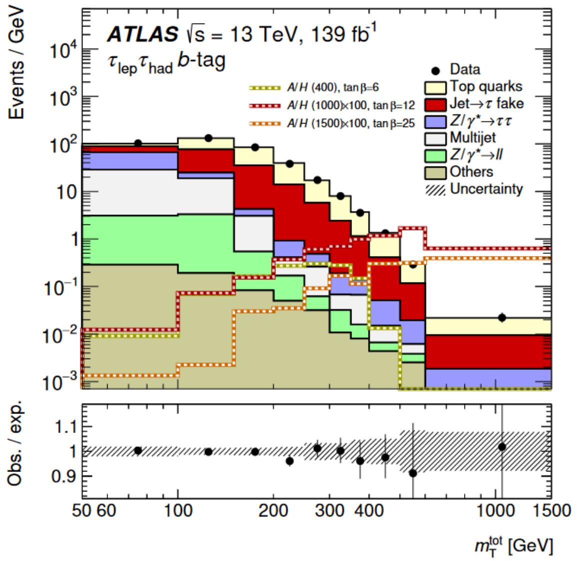
[Sadly not included in our fits yet…]

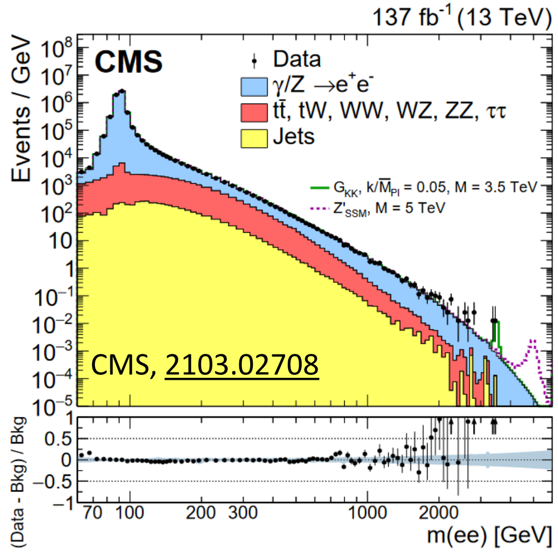
Hight pT LHC constraints

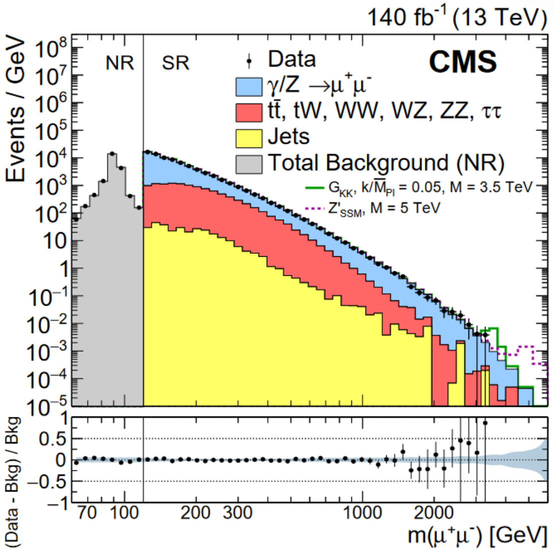


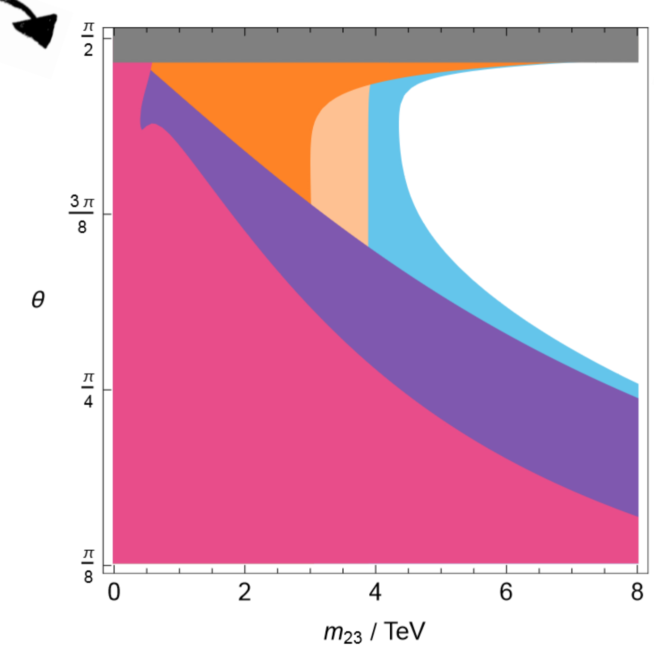


ATLAS, 2002.12223









Combination of all channels

ATLAS pp → τν

ATLAS pp → ττ

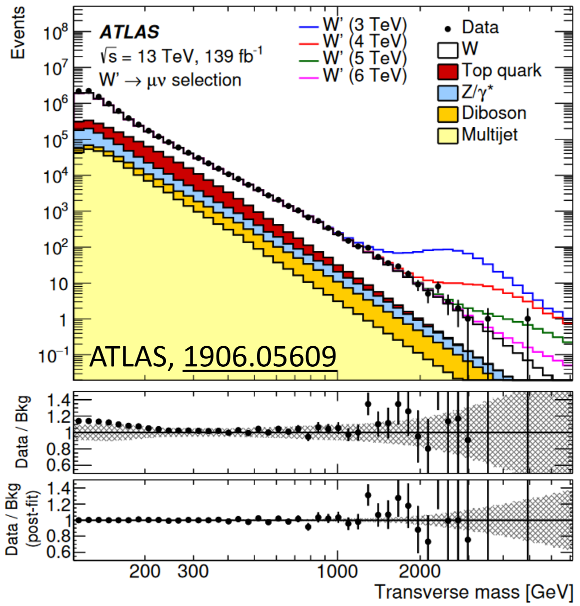
ATLAS pp → lν

CMS pp → ll

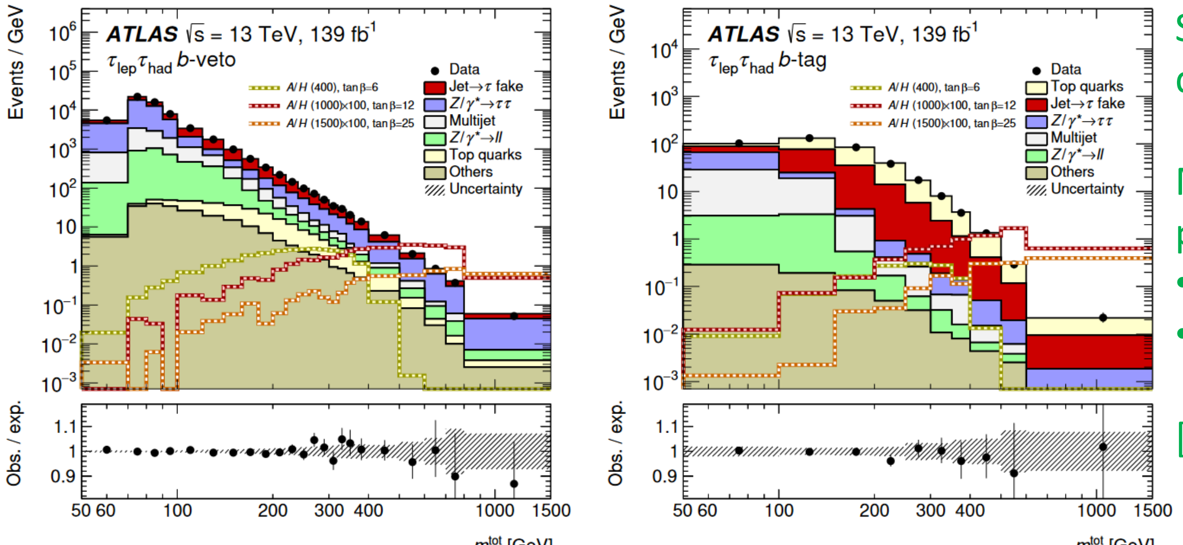
Non – perturbative $g_3 > 4\pi$

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

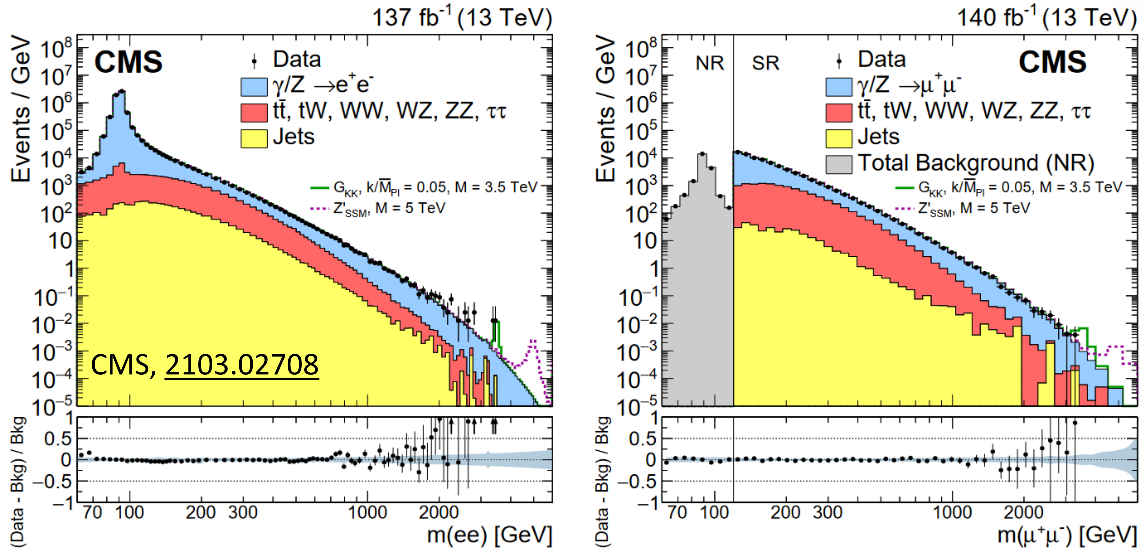
Hight pT LHC constraints



ATLAS, 1906.05609



ATLAS, 2002.12223



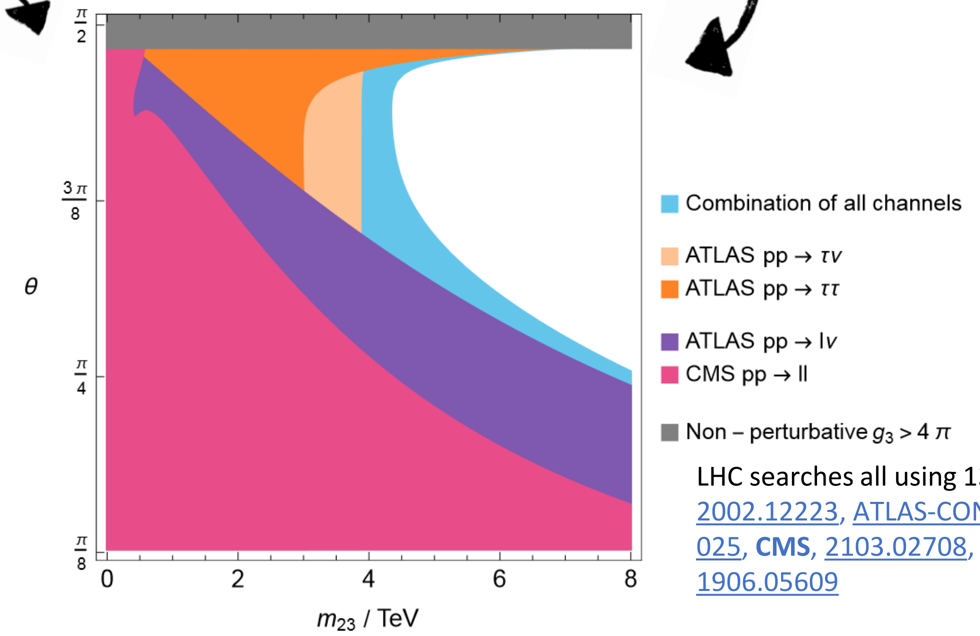
CMS, 2103.02708

So far we just used LHC Drell-Yan data to constrain the models

Many other collider probes are possible!

- $X \to HZ \to \cdots$
- $X \to Z\phi \to (\mu\mu)(HH) \to \cdots$

[in brainstorming phase…]



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

Hight pT LHC constraints

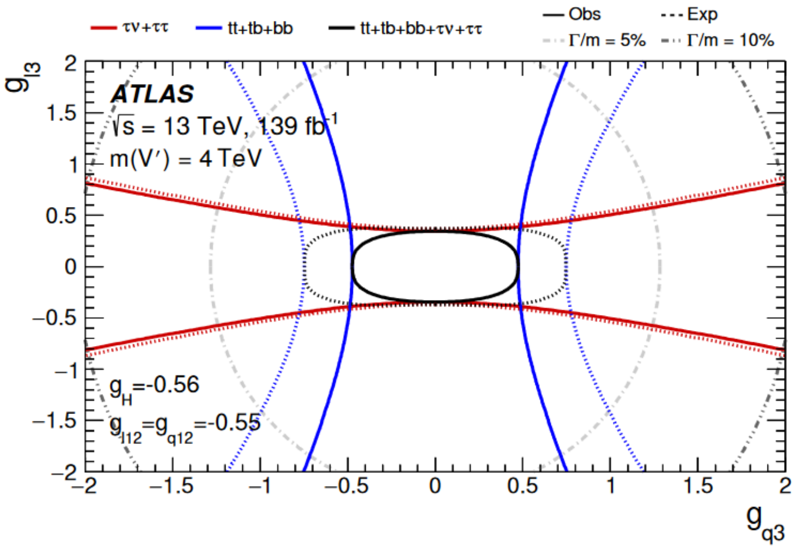
Stronger constraints on the 3rd family aligned $SU(2)_L$ likely already exist! To be explored… ATLAS, 2402.10607

Combination of searches for heavy spin-1 resonances using 139 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: A combination of searches for new heavy spin-1 resonances decaying into different pairings of W, Z, or Higgs bosons, as well as directly into leptons or quarks, is presented. The data sample used corresponds to 139 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV collected during 2015–2018 with the ATLAS detector at the CERN Large Hadron Collider. Analyses selecting quark pairs (qq, bb, $t\bar{t}$, and tb) or third-generation leptons ($\tau\nu$ and $\tau\tau$) are included in this kind of combination for the first time. A simplified model predicting a spin-1 heavy vector-boson triplet is used. Cross-section limits are set at the 95% confidence level and are compared with predictions for the benchmark model. These limits are also expressed in terms of constraints on couplings of the heavy vector-boson triplet to quarks, leptons, and the Higgs boson. The complementarity of the various analyses increases the sensitivity to new physics, and the resulting constraints are stronger than those from any individual analysis considered. The data exclude a heavy vector-boson triplet with mass below 5.8 TeV in a weakly coupled scenario, below 4.4 TeV in a strongly coupled scenario, and up to 1.5 TeV in the case of production via vector-boson fusion.



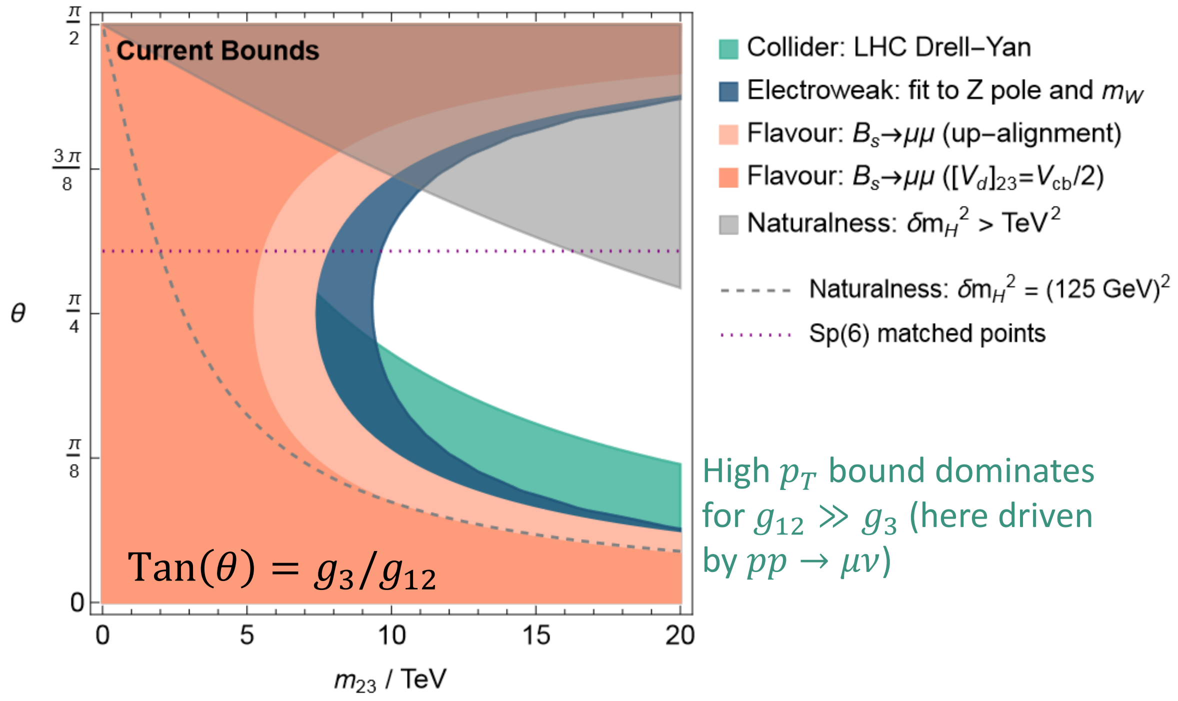
Does not directly map onto deconstruction model

[Assumes Higgs coupling tied to light generations, not third, and assumes fixed light family couplings]

In similar ballpark to the 4-5 TeV exclusion we estimated from Drell-Yan, but looks stronger

Deconstructed $SU(2)_L$ summary

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



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

Current: $M_{W'_L, Z'_L} > 9$ TeV
Driven by EWPOs; flavour and LHC complementary
Plenty of **natural parameter space remains**!

Deconstructed $SU(2)_L$ summary

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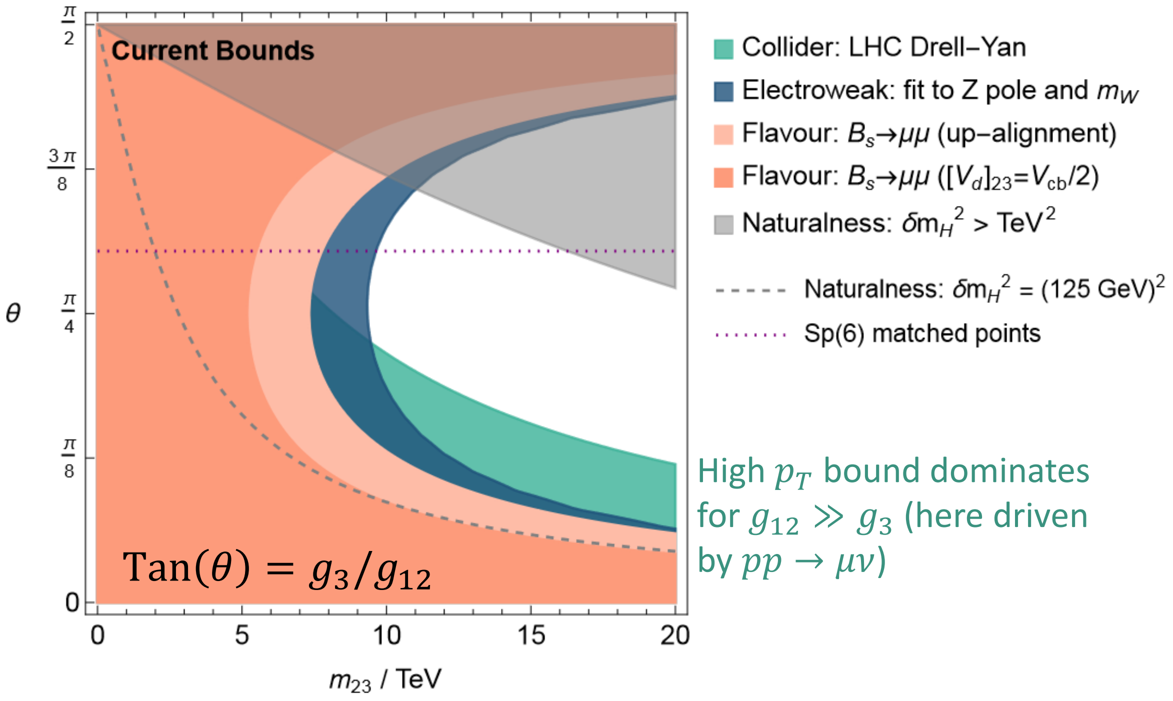

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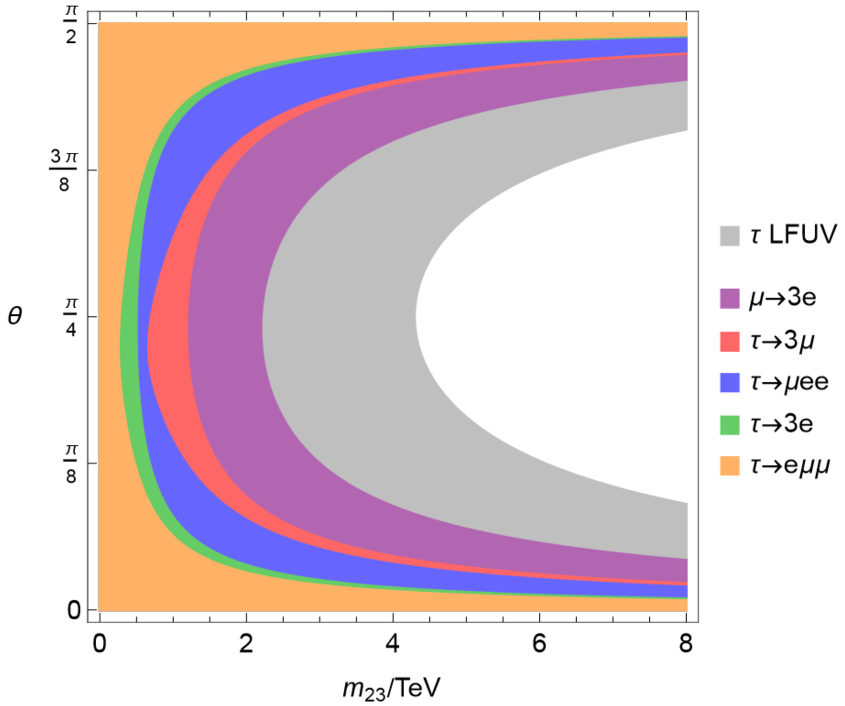
Plenty of **natural parameter space remains**!

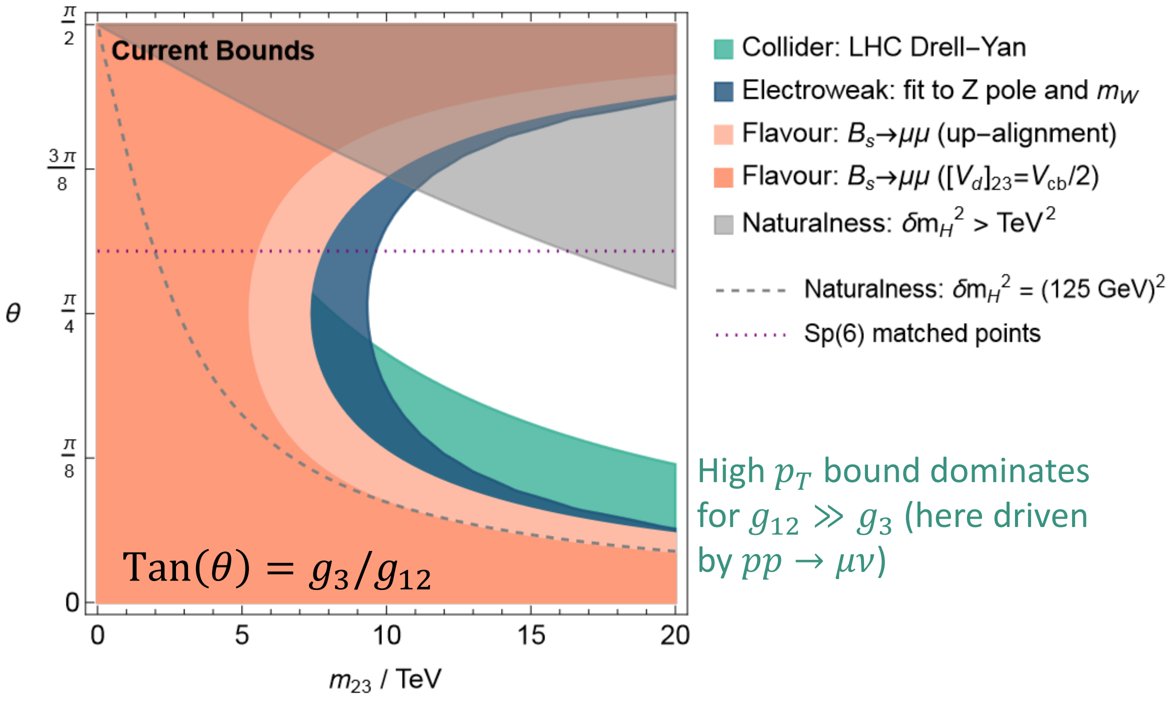
What about Leptons?



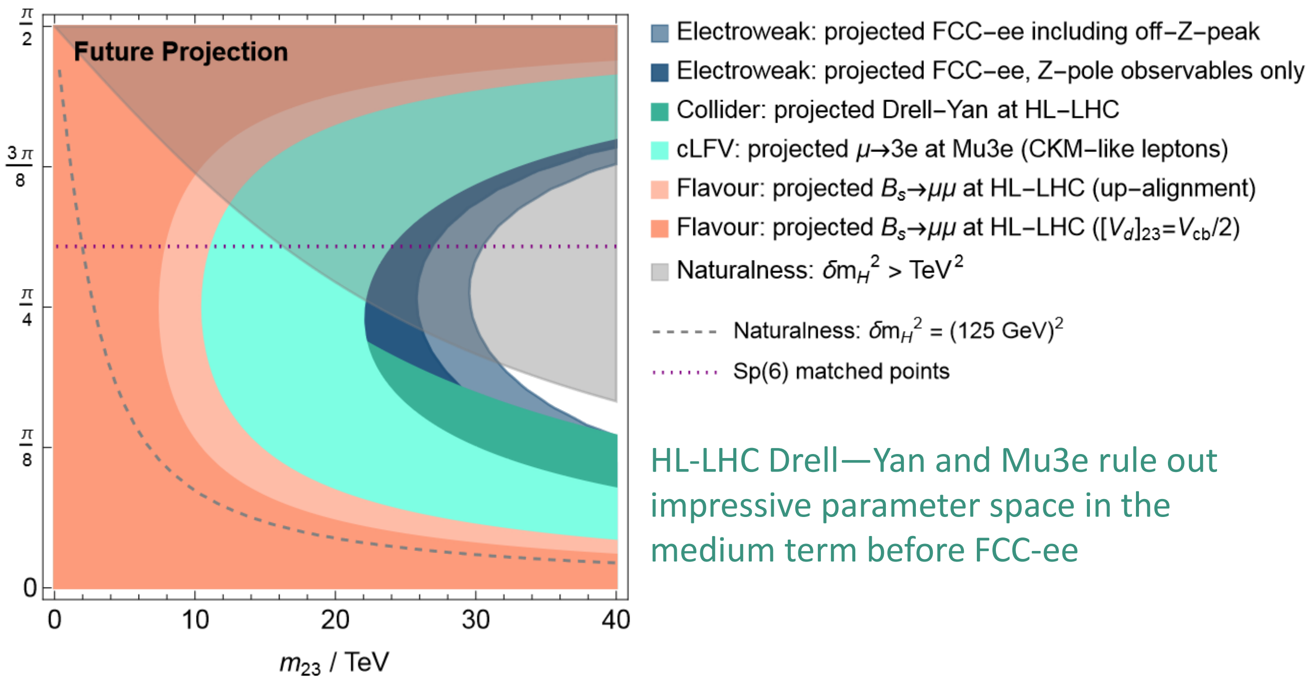
- LFUV (tau vs e/mu) is predicted by the model
- LFV not predicted, but can naturally be CKM-like

Deconstructed $SU(2)_L$ summary

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



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



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

Current: $M_{W'_L,Z'_L} > 9$ TeV
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Plenty of **natural parameter space remains**!

FCC-ee: $M_{W'_L,Z'_L} > 30$ TeV
A tera-Z EW precision programme can cover entire natural parameter space

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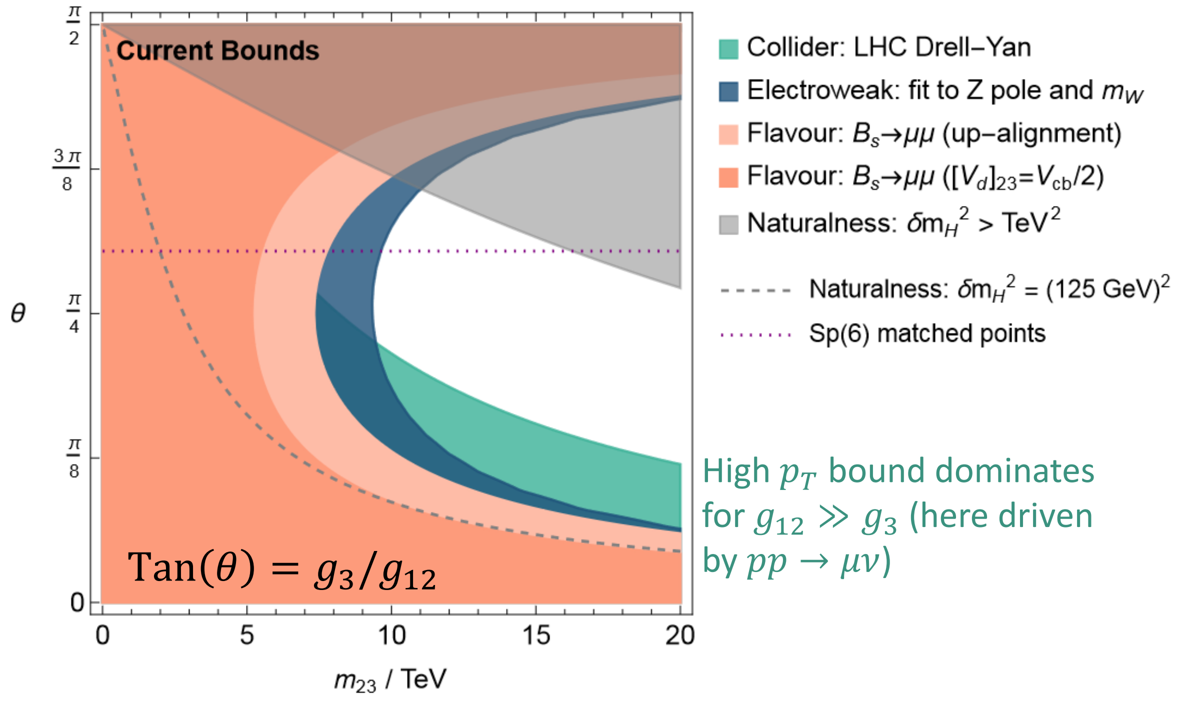

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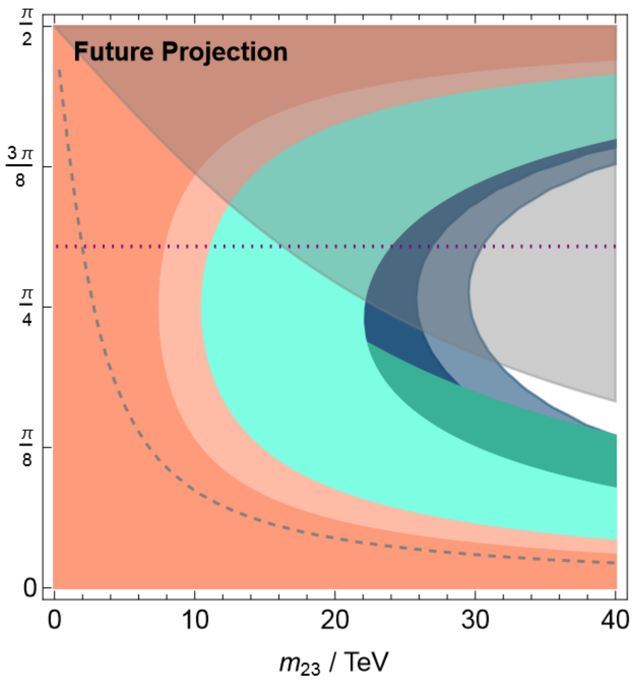

+ key flavour probes at FCC-ee!

- $B \to K\nu\nu$ to 1% at FCC-ee, synergy with $B_s \to \mu\mu$ at HL-LHC
- Tau LFUV measurements at FCC-ee improve by x13, probe 11 TeV
- Excellent $bs\tau\tau$ prospects at FCC-ee

Naturalness: δm_H^2 = (125 GeV)^2
Sp(6) matched points

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Deconstructed $U(1)_Y$

Davighi, Stefanek 2305.16280

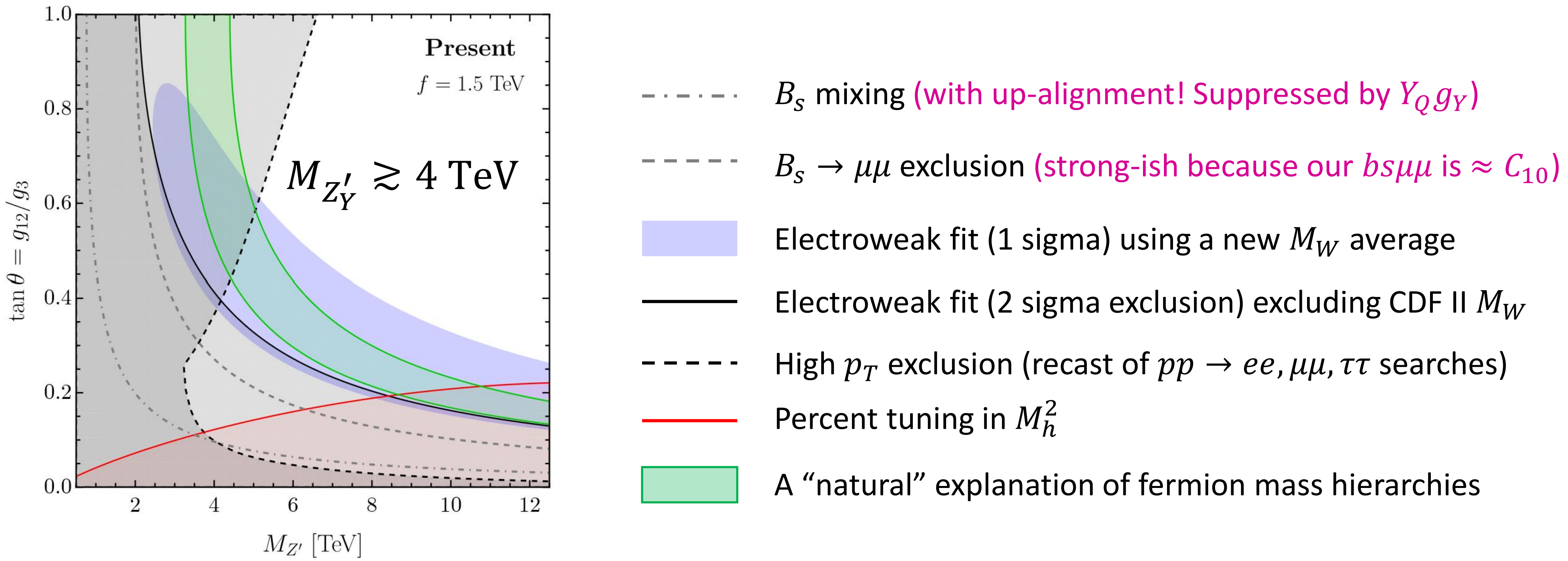
See also
Fernández Navarro, King 2305.07690
Allanach, Davighi 1809.01158

More natural model; double benefit from $g_Y \sim g_L/2$ (roughly x2 smaller δm_h^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}

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)



Phenomenology of EW Flavour Deconstruction

Summary:

	Deconstructed $SU(2)_L$	Deconstructed $U(1)_Y$
Electroweak: Z-pole & W-pole	9 TeV (5 TeV if exc. m_W)	2 TeV
Flavour: $B_s \to \mu\mu$ (up-alignment)	7.5 TeV	2 TeV
High p_T: Drell–Yan $pp \to ee, \mu\mu, \tau\tau$	4.5 TeV	3.5 TeV
EW projection FCC-ee: on and off Z-pole & W-pole	30 TeV	7 TeV

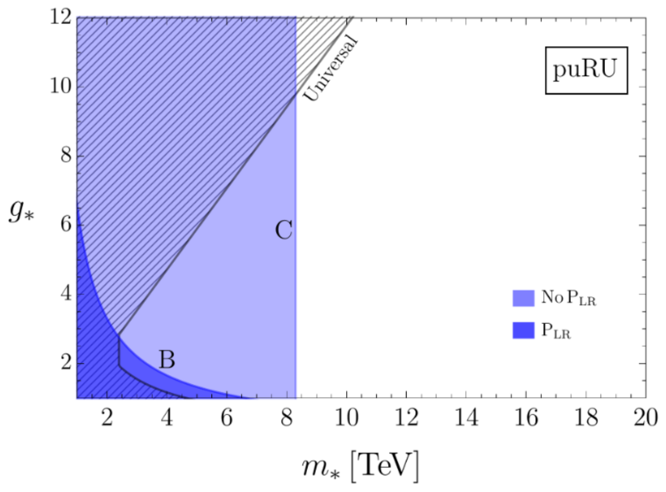
Davighi, Gosnay, Miller, Renner 2312.13346

Davighi, Stefanek 2305.16280

4. Deconstructing the Composite Higgs

Covone, Davighi, Isidori, Pesut, 2407.10950

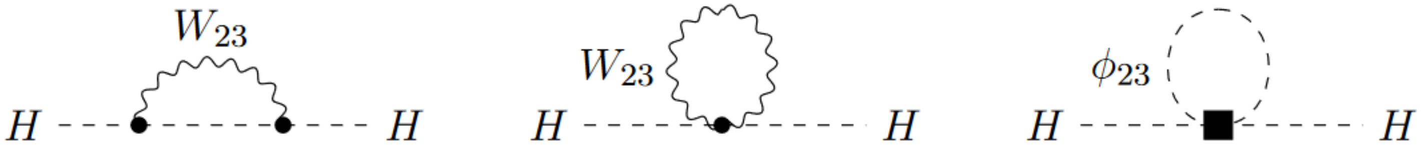
Back to the Hierarchy Problem



We earlier saw that U2 flavour symmetry is needed for a low-scale ($1 \div 2$ TeV) composite Higgs solution to hierarchy problem

We also saw that flavour deconstruction can solve the flavour puzzle near the TeV

- BUT that electroweak precision tests (+ flavour + high pT) are pushing us to regions with large finite δm_h^2
- Motivates us to solve the hierarchy problem simultaneously



$\longrightarrow$ **joint solution** near TeV of hierarchy problem & flavour puzzle?

Maybe the flavour deconstruction can even help *reduce* the little hierarchy in a composite Higgs model?

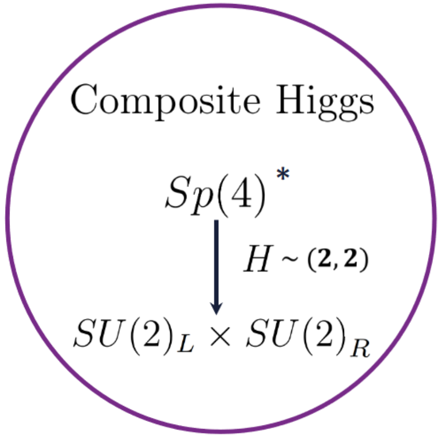
Flavour Deconstructing the Composite Higgs

Covone, Davighi, Isidori, Pesut, 2407.10950

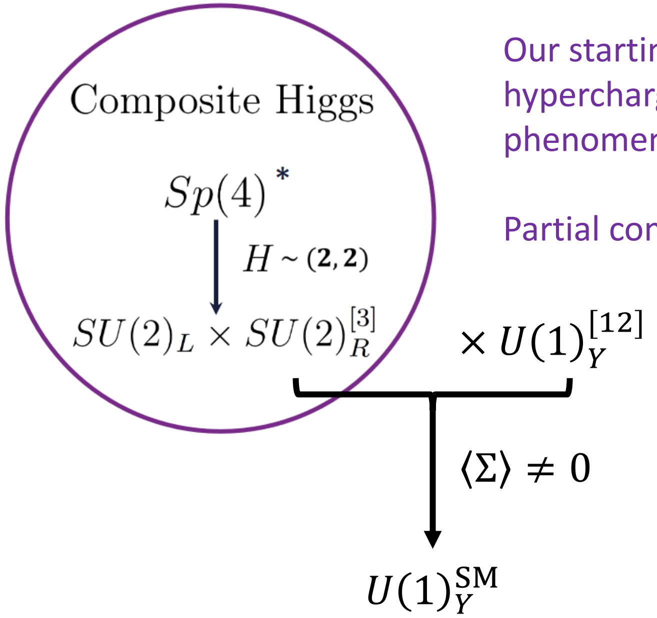
Flavour deconstructed gauge interactions can be elegantly combined with a composite Higgs

Recap: a light composite Higgs = pNGB from global symmetry breaking in a BSM strong sector (like QCD pions)

The usual minimal CHM:



The deconstructed CHM:



Our starting point is deconstructing hypercharge (most natural from phenomenology)

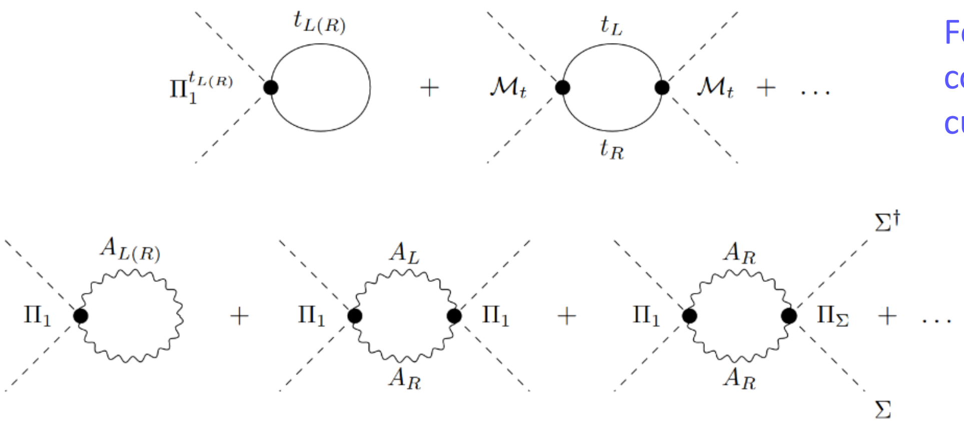
Partial compositeness for 3rd family

- BSM flavour puzzle: delivers **gauge explanation** for the $U(2)$ protection that we saw can lower compositeness scale!
- Explains the SM flavour puzzle in the same dynamical step(s)!

Deconstructing the composite Higgs potential

Covone, Davighi, Isidori, Pesut, [2407.10950](2407.10950)

The Higgs potential is generated at one-loop by top Yukawa and gauging the (deconstructed) EW symmetry:



Fermion (top) contributions, cut off by M_T

EW gauge boson contributions, cut off by M_ρ

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

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Covone, Davighi, Isidori, Pesut, 2407.10950

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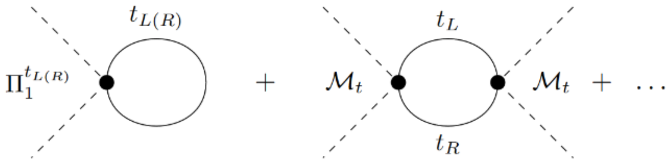

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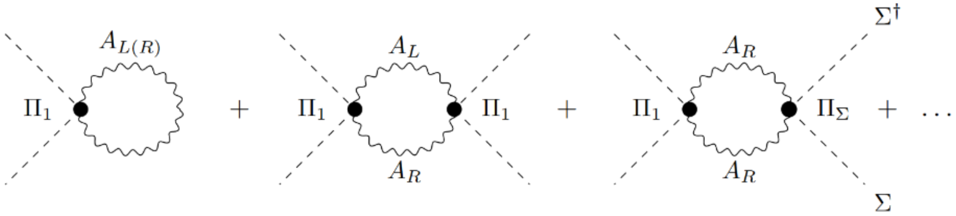

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In addition to solving the SM + BSM flavour puzzles, deconstructing the CH brings further benefits:

Deconstruction helps the CHM be more natural!

- Gauge coupling $g_{R,3}^2$ **can be pumped up** w.r.t SM g_Y to better cancel top Yukawa contribution to m_h^2
- Numerically, this allows top partner to be heavier ($M_T > 1.5$ TeV), **better compatibility with direct searches**

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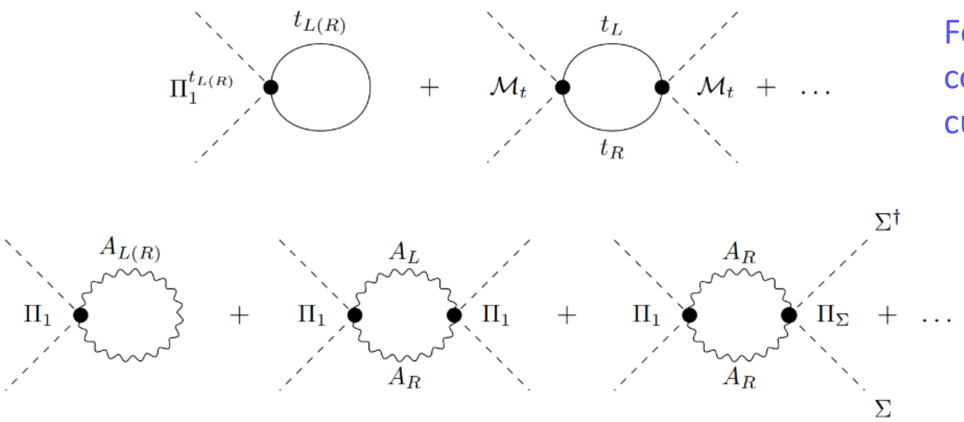

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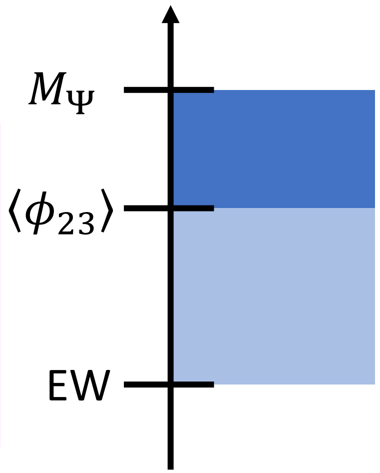
CH makes deconstruction more predictive! (+ natural)

- Require $2M_{W_R}^2 < M_\rho^2$ to avoid sign flip in m_h^2, i.e. deconstruction bosons must be sufficiently light
- Experiment dictates $M_{W_R} >$ few TeV. **Squeezed**!
- To explain $y_2 \ll y_3$, need $M_\Psi >$ few 100 TeV. Now this gives no radiative contribution to Higgs mass thanks to compositeness at lower scale ☺



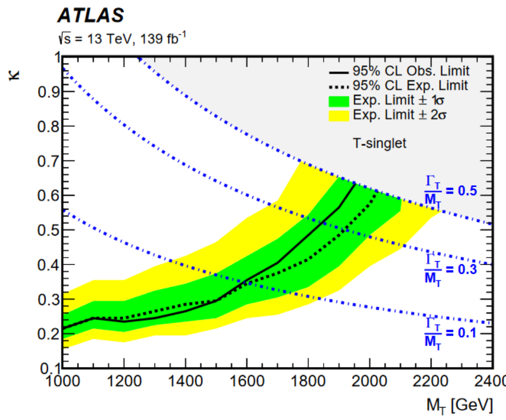
Sketching the Phenomenology

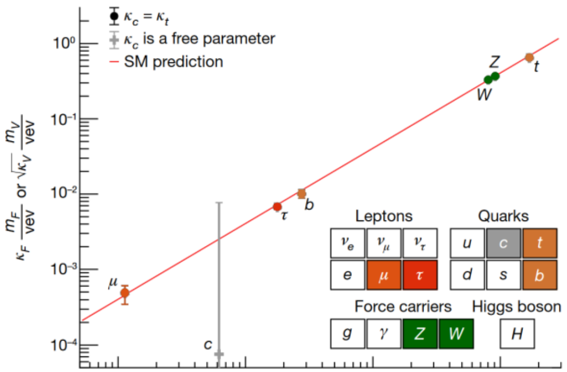
Covone, Davighi, Isidori, Pesut, 2407.10950

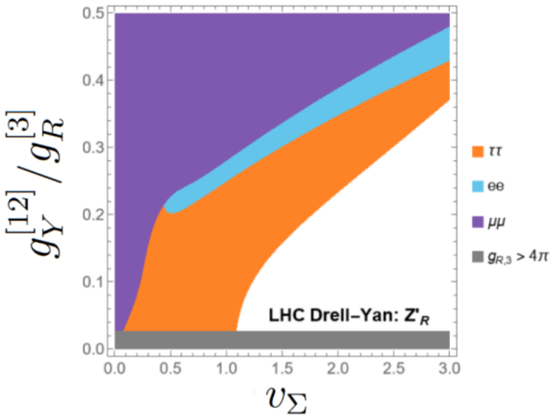
The pheno of this complicated model resembles that of minimal CHM with U2 *SMASH* deconstructed gauge bosons

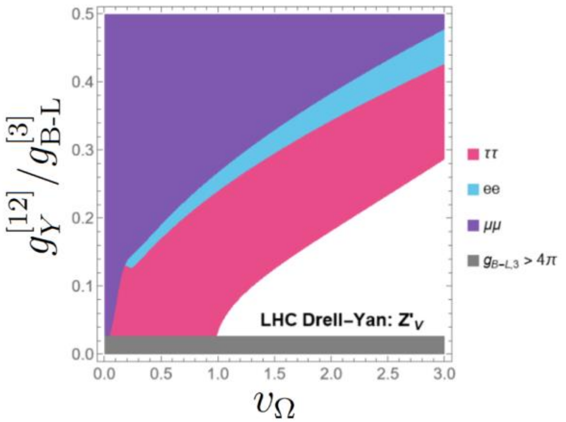
- Modified HWW and HZZ couplings
- Top partners and higher composite resonances
- Universal shifts in EWPOs

- Flavour constraints e.g. $B \to X_s \gamma$ particularly strong
- LHC Drell—Yan bounds on heavy gauge bosons
- Extra shifts in EWPOs









We didn't do a full pheno study of this model, but the following benchmark scenario is viable:

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

Conclusions

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

2. From MFV to U2 flavour symmetries can realise lower Λ_{NP}: more natural BSM solutions to hierarchy problem (or any other problem/puzzle…)

3. U2-like models have the ingredients to also **solve the flavour puzzle** at low-scale: hypothesis of **flavour non-universal gauge interactions** e.g. flavour deconstruction

4. Rich phenomenology across quark and lepton flavour, EWPOs, high pT measurements at LHC

5. Fruitful to pursue flavour non-universal models that solve flavour puzzle **and** hierarchy problem simultaneously, e.g. deconstructed CH, even if they appear complicated…

Thank you!

Backup

How to generate flavour in Composite Higgs Models?

The problem with elementary fermions: $L_{\text{strong}} \supset \frac{1}{\Lambda^{d-1}} \bar{q} O_H u + \Lambda^{4-d'} O_H O_H^\dagger + \frac{1}{\Lambda^2} (\bar{q} q)^2$

Cannot have Λ low due to flavour bounds

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

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

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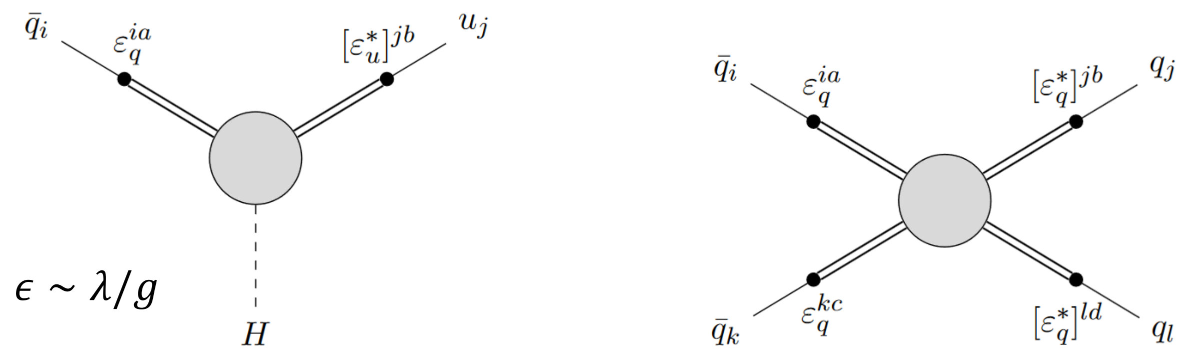
Partial Compositeness is a solution: $L \supset \lambda_q^{ia} \bar{q}_i O_a^q + \lambda_u^{ia} \bar{u}_i O_a^u + \bar{O}_a^q O_H O_b^u$

Kaplan, 1991
Review: Panico, Wulzer, 1506.01961



Yukawa couplings now generated by **relevant** operators

Aside: Flavour from Anarchy?

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

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

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

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

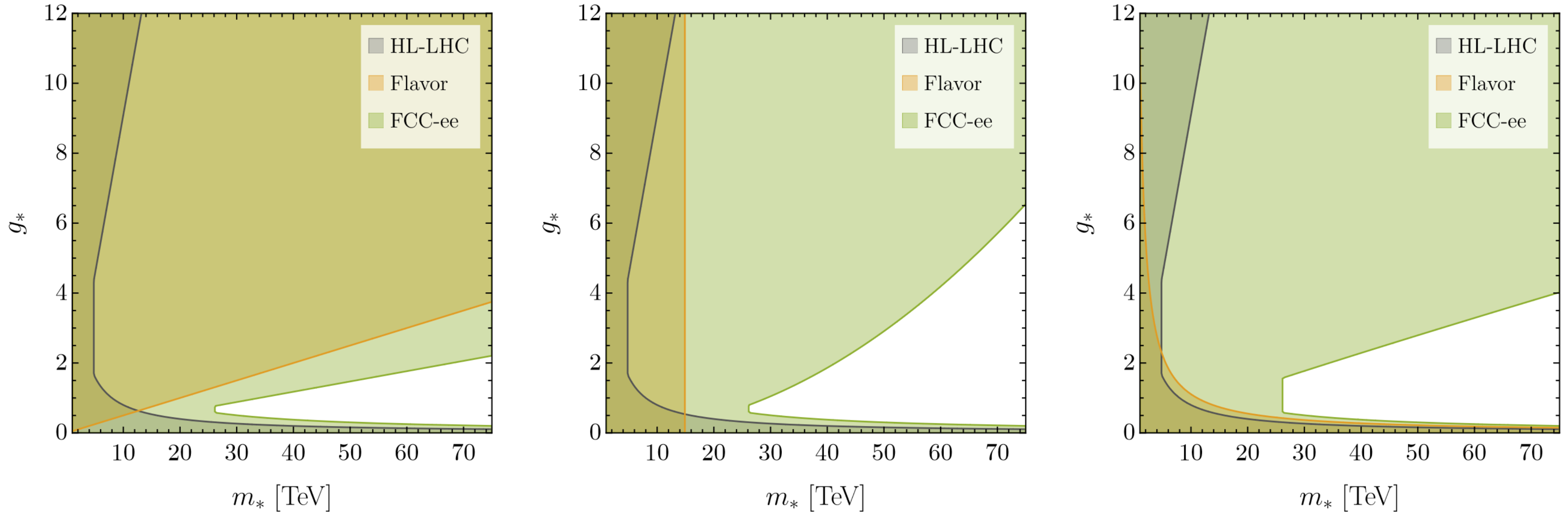
[Even assuming 1-loop suppressed quark dipole operators]

- Such a high scale degrades this as a solution to the hierarchy problem AND is untestable in colliders
- We **need** a flavour symmetry to bring down m_*. Let's compare MFV vs. $U(2)$-like

Future Prospects: HL-LHC, FCC-ee

Stefanek, 2407.09593

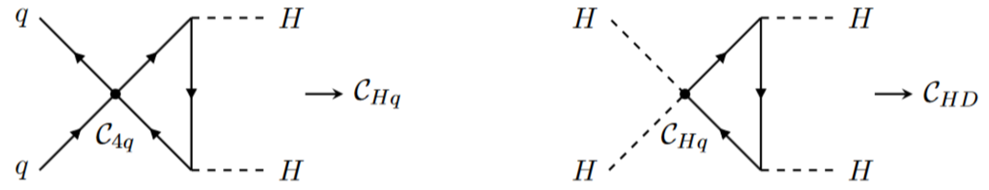
- FCC-ee "tera-Z" run: approx. 10^5 times LEP dataset on Z-pole
- With this precision, RG-running into EWPOs at 1-loop (and even 2-loop) is crucially important



(a) Left compositeness (b) Mixed compositeness (c) Right compositeness

All 3 scenarios have $U(2)_{u_R} \times U(2)_{q_L}$

- All sectors contribute to EWPO bounds at this precision, including e.g. 4 top operators which shift m_W at NLL



Even current EWPOs give stronger constraint on $O_{tt} \sim (t\bar{t})^2$ than LHC $pp \to t\bar{t}$ and $pp \to t\bar{t}t\bar{t}$ measurements!

c.f. also Allwicher et al, 2302.11584

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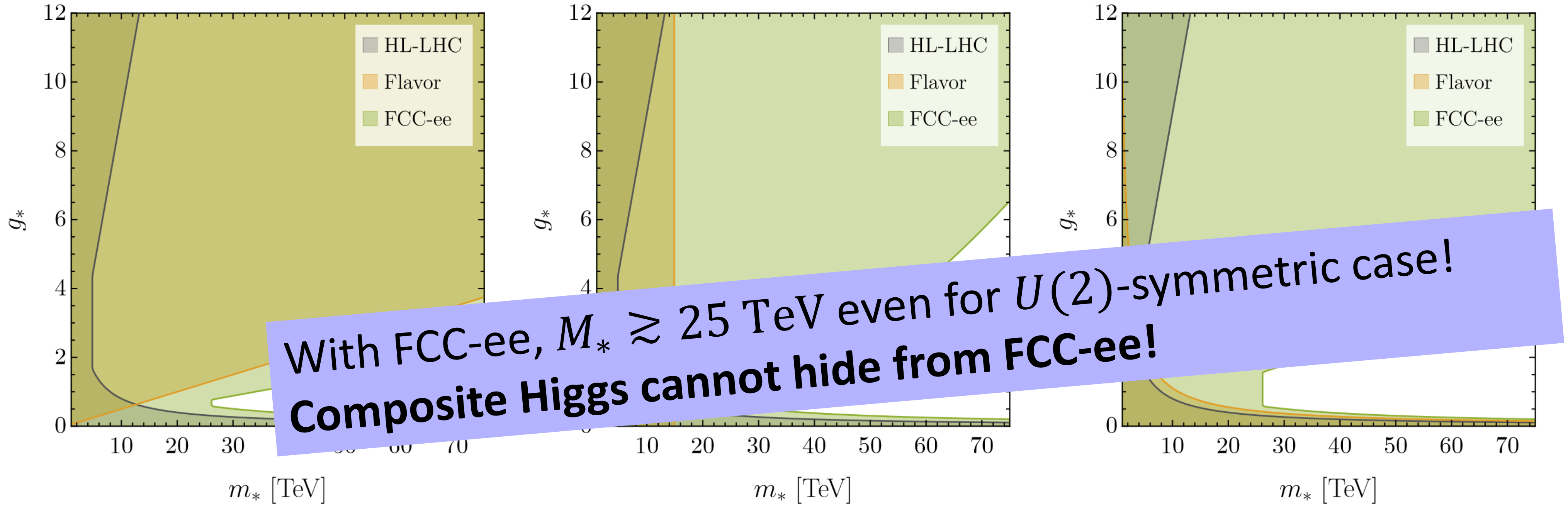

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With FCC-ee, $M_* \gtrsim 25$ TeV even for $U(2)$-symmetric case!
Composite Higgs cannot hide from FCC-ee!

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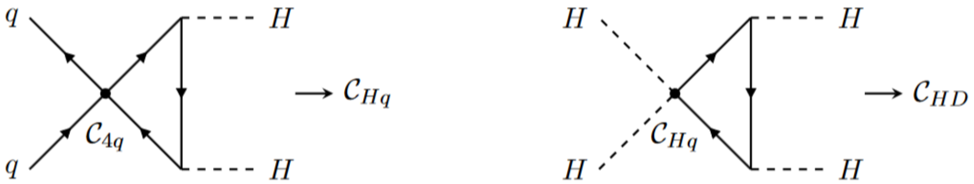

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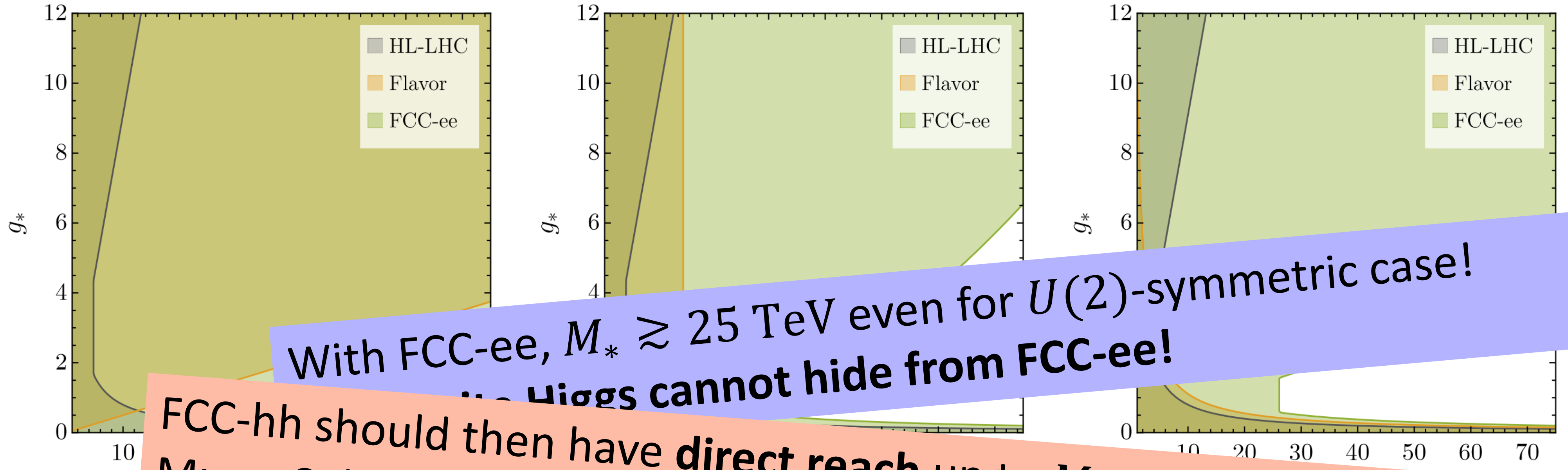

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Higgs cannot hide from FCC-ee!

FCC-hh should then have **direct reach** up to $M_* \sim 20$ TeV [Golling et al 1606.00947]

Muon Collider could have direct reach up to $E_{\text{CoM}}/2$ [Accettura et al 2303.08533]

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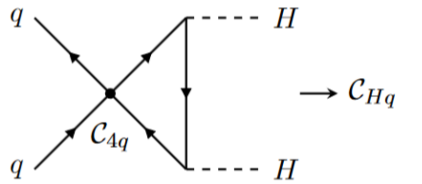

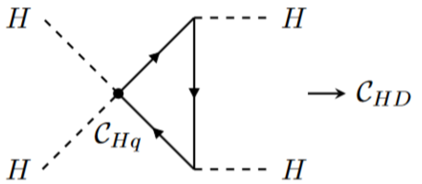

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