Higgs & Flavour

Joe Davighi, CERN

24th October, Rencontres de Blois 2024

If you remove the Higgs, the Standard Model is a gauge theory with x3 $g_i = O(1)$.
The Higgs-less SM is completely natural!

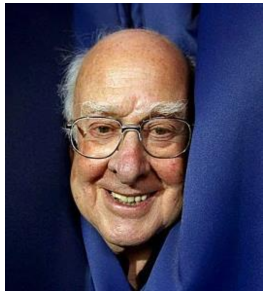
~~Hierarchy problem~~

~~Flavour puzzle~~

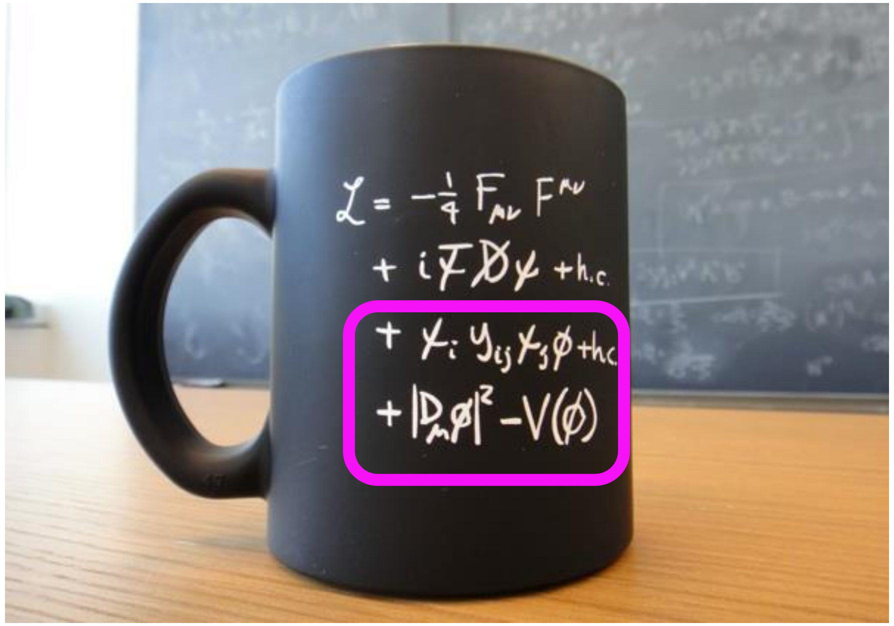
~~Strong CP problem~~ [massless quarks]

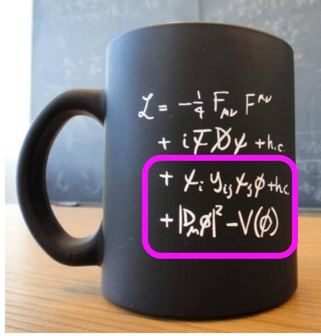
Higgs = key to BSM, both theoretically & experimentally

(modulo dark sectors)



The Higgs-centric view of BSM



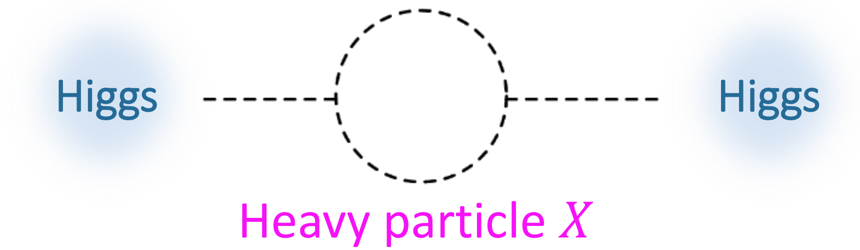


The Higgs-centric view of BSM

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

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

[e.g. GUT scale, flavour scale, neutrinos, Planck…]



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

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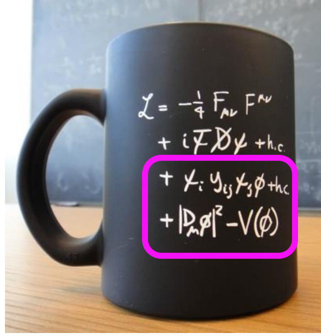

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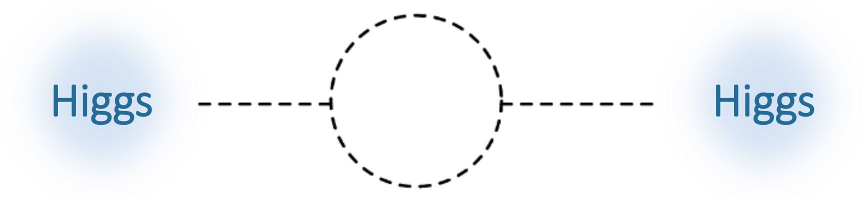

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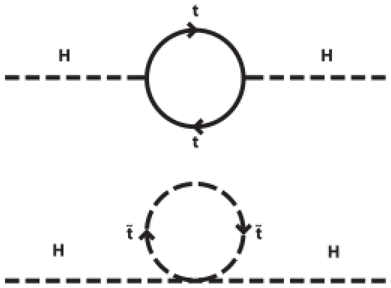
Compositeness:

- Loops cut off by compositeness scale f
- To get $m_h \ll m_{\text{res}}$, need Higgs = pNGB associated with global symmetry breaking
- E.g. $SO(5) \to SO(4)$
- Explicit breaking by y_t & $g_{1,2}$ generates m_h^2 at 1-loop

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

Supersymmetry:

Inclusion of superpartner loops removes quadratic sensitivity to UV cut-off



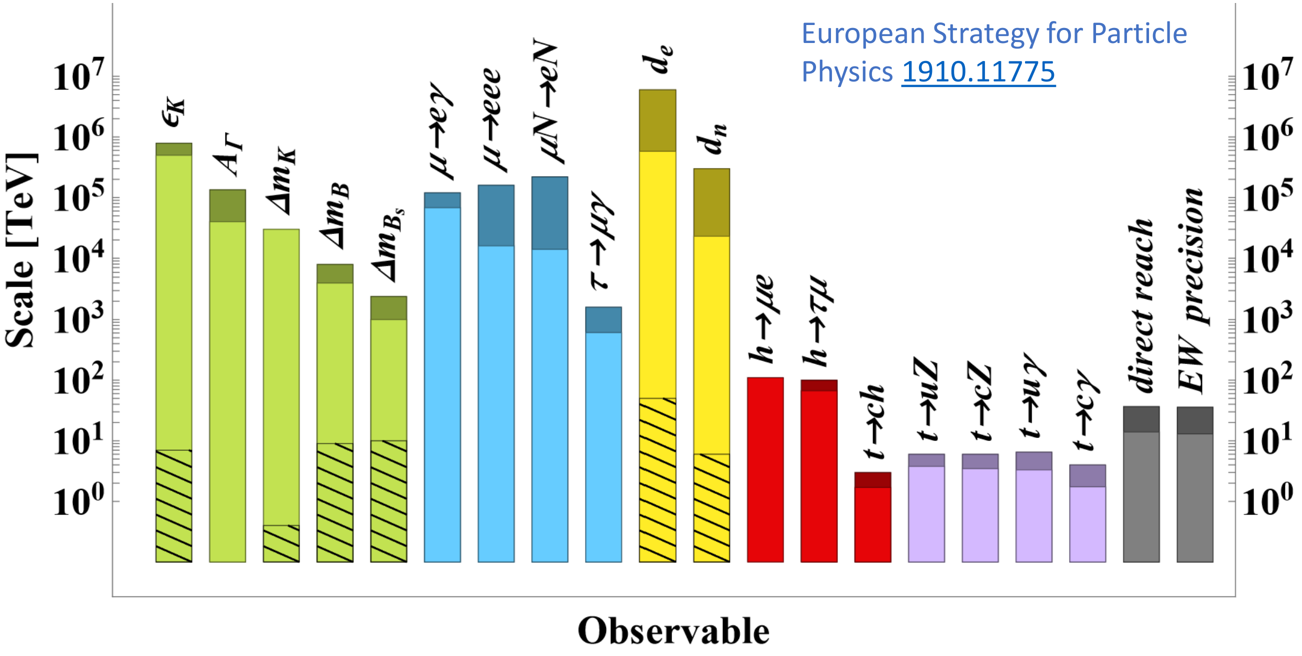
$$\Rightarrow \delta m_h^2 \approx \frac{3}{2\pi^2}\frac{m_t^2}{v^2} M_T^2 \log\frac{\Lambda^2}{M_T^2}$$

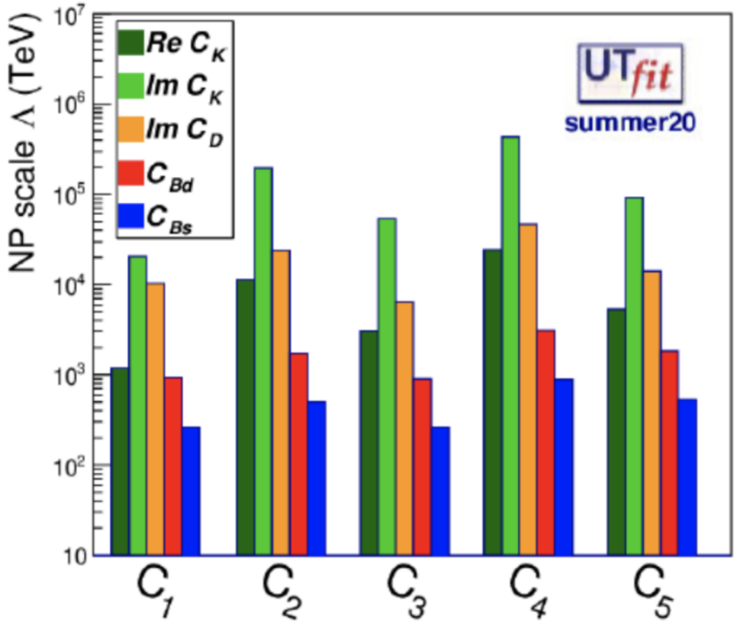
vs $\delta m_h^2 \approx \frac{3}{2\pi^2}\frac{m_t^2}{v^2}\Lambda^2$ for top alone

Most natural expectation: $M_* \lesssim (\text{loop factor})\, m_h \sim \text{few TeV}$

The BSM Flavour Puzzle

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





E.g. kaon mixing: $L \supset \frac{(\bar{d}s)^2}{\Lambda_{sd}^2} \implies \Lambda_{sd} \gtrsim 10^{5\div6}\ \mathrm{TeV}$

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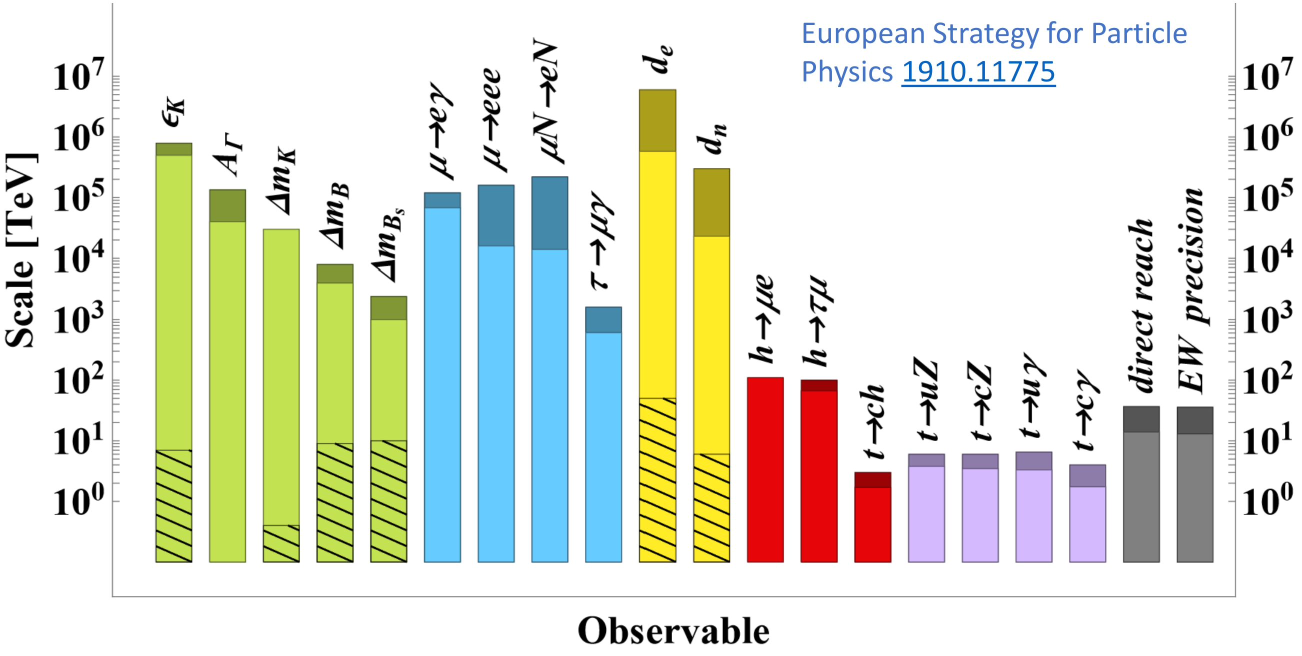

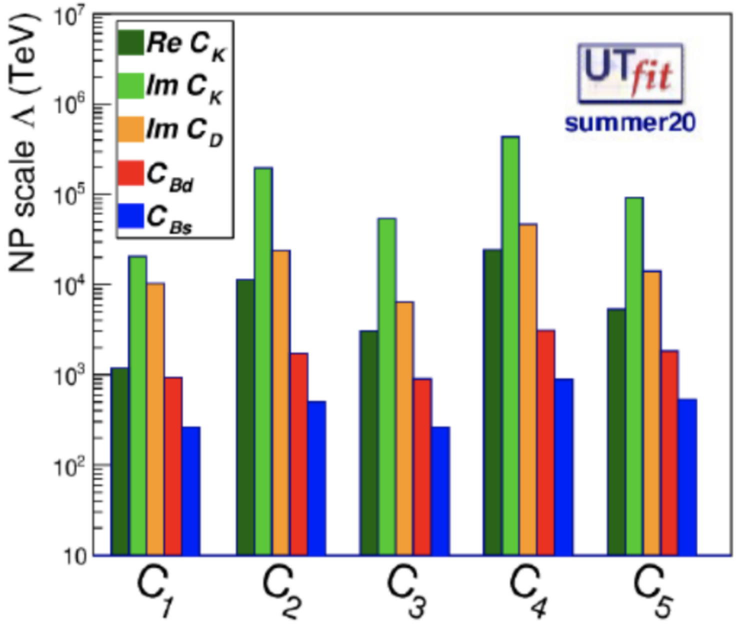

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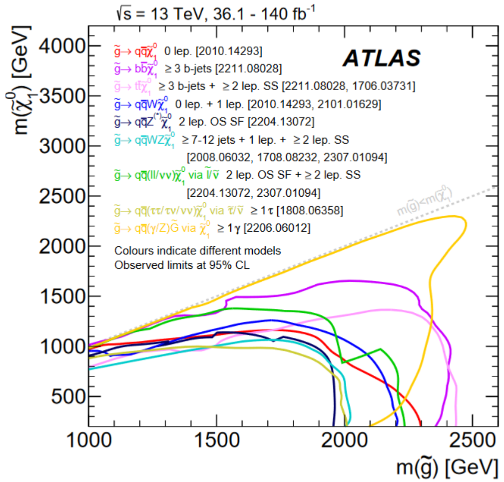
Therefore *any* solution to hierarchy problem **needs** non-trivial **flavour structure**

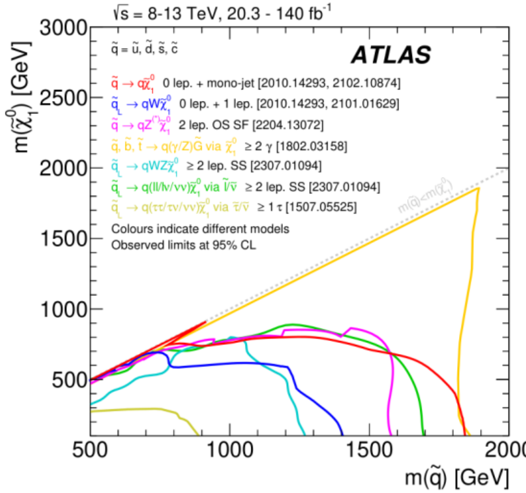
E.g. **Minimal Flavour Violation (MFV):** BSM couplings $C_{ij} \sim \delta_{ij} + \cdots$, with … built from SM Yukawas

MFV: $\frac{1}{\Lambda_{sd}^2} \sim y_t^4 (V_{31} V_{32}^*)^2 \frac{1}{\Lambda_{\mathrm{NP}}^2} \sim \left(\frac{10^{-5}}{\Lambda_{\mathrm{NP}}}\right)^2$ is good enough flavour protection!

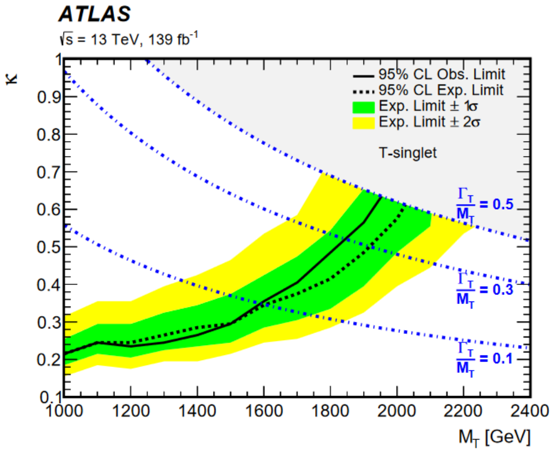
We are now probing M_* directly at the LHC

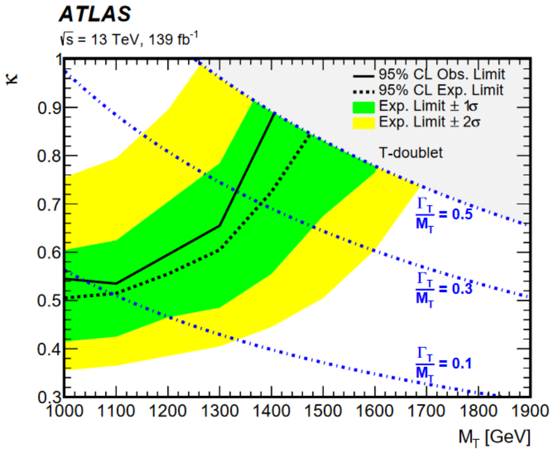
Few TeV limits on SUSY particles, top partners!





ATLAS, [2403.02455](2403.02455)



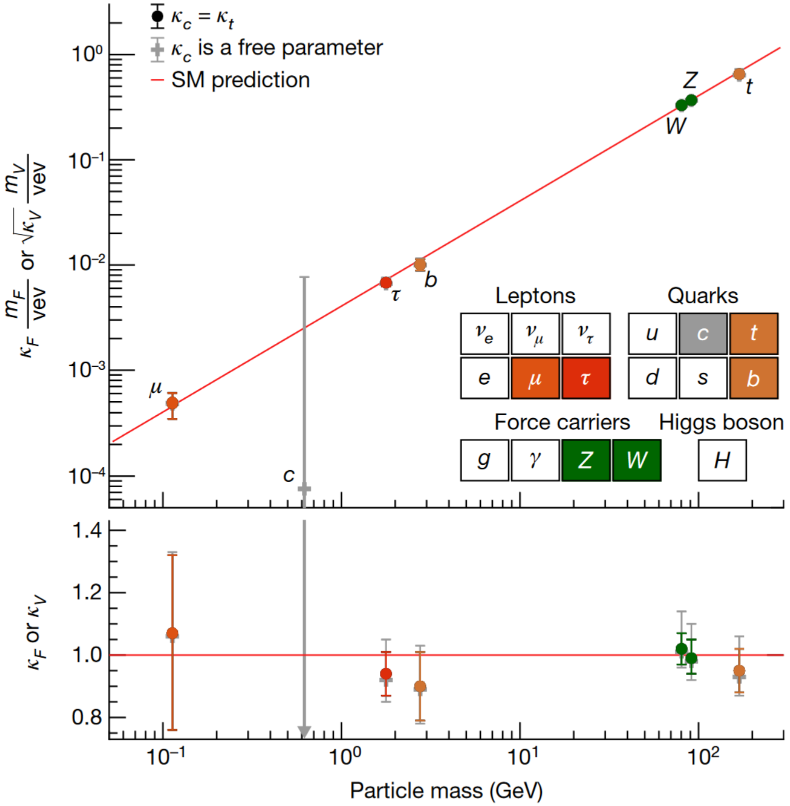


ATLAS, [2307.07584](2307.07584)

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

+ No sign of compositeness in Higgs couplings!

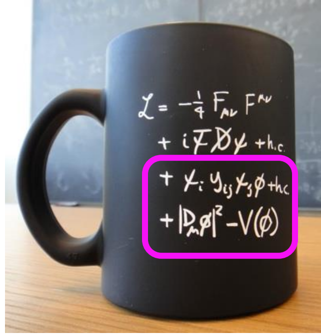
HWW, HZZ at LHC agree with SM to 3%



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

Davighi, Blois 2024

The Higgs-centric view of BSM



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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. Durieux, McCullough, Salvioni 2110.06941, 2202.01228

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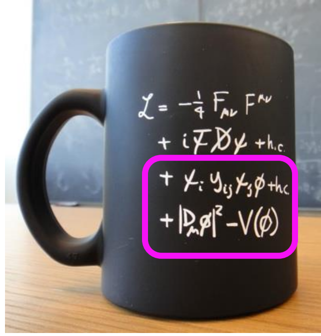

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*Most of the Higgs couplings are generating **flavour**:

$y_{q_3 t_3} \sim 1$; all other x12 physical $y_{ij} \ll 1$

$\Longrightarrow \mathcal{L}_{\text{SM}}$ has approx. $\boldsymbol{U(2)^n}$ **flavour symmetry**

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

V_{cb} provides largest $U(2)$-breaking spurion
Then y_2/y_3 is next largest

Is there a dynamical explanation? = “SM flavour puzzle”

y_{ij} = marginal couplings: do not clearly point to a scale, unlike μ^2

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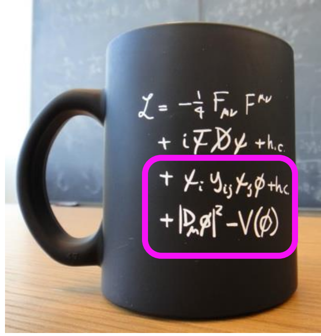

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BUT since Higgs is origin of hierarchy problem & flavour puzzle: maybe they have a **joint solution** near TeV?

Rest of the Talk

1. Introduction: Higgs-centric BSM

2. Higgs into Flavour
    - Which flavour symmetry? The appeal of $U(2)$s over MFV
    - Case study: partial compositeness solutions to hierarchy problem, MFV vs U(2)
    - Future prospects esp. FCC-ee

3. Flavour into Higgs
    - Flavour non-universal gauge interactions as origin of U(2), solving SM + BSM flavour puzzles
    - Testing these flavour models via electroweak precision
    - General Lessons from SMEFT regarding EW precision, and FCC-ee

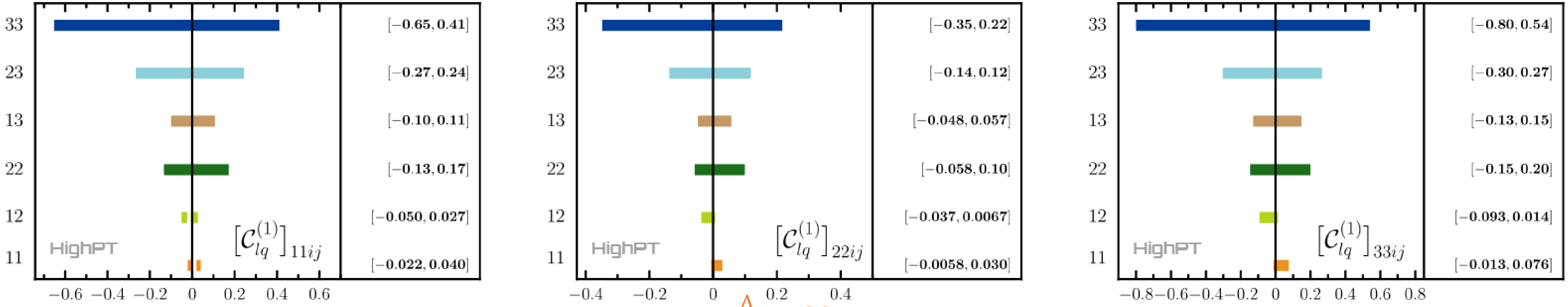
2. Higgs into Flavour

BSM Flavour Puzzle: **Beyond MFV**

- MFV $[C_{ij} \sim \delta_{ij} + \cdots]$ now probed to 10 TeV by LHC direct searches: driven by valence quarks

Example: High-p_T Drell-Yan tails $pp \to ll$ $\quad \frac{\Lambda}{c_{33}} \gtrsim 3$ TeV

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



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

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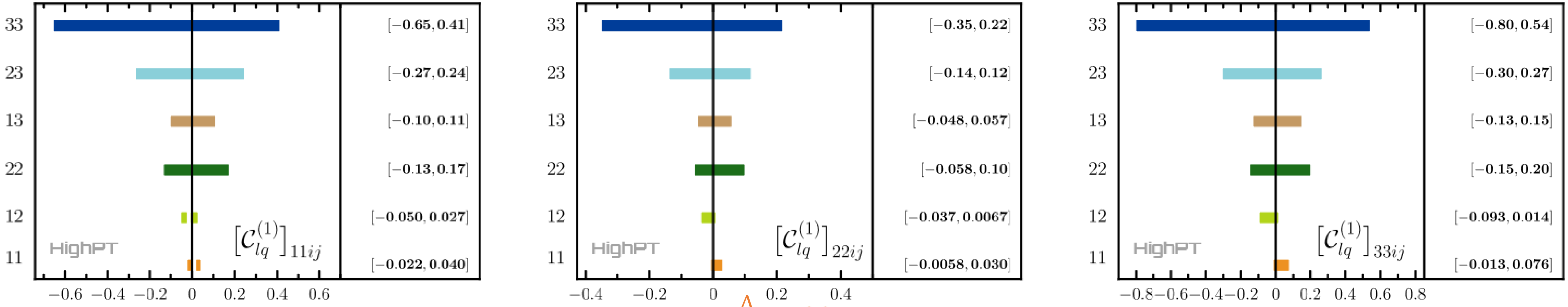

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From MFV to $U(2)$: the **flavour *non-universal* path** to BSM…

$$C_{ij} \sim \begin{pmatrix} \epsilon & & \\ & \epsilon & \\ & & 1 \end{pmatrix} + \cdots$$

1. Just as good flavour protection as MFV ☺
2. Direct search bounds weaker: $\Lambda_{U(2)} \sim 1$ TeV vs $\Lambda_{\rm MFV} \sim 10$ TeV ☺
3. Same global symmetry as Yukawa! Also explain SM flavour puzzle? ☺

The $U(2)$ vs MFV advantages are totally general; not just for semi-leptonic operators

(we'll return to theories that solve the flavour puzzle later)

But how does the phenomenology play out in "explicit" solutions to the hierarchy problem?

Case study: **Composite Higgs from strongly dynamics; $U(2)$ vs MFV**

Main reference here:
Glioti, Rattazzi, Ricci, Vecchi, 2402.09503; see also Stefanek, 2407.09593

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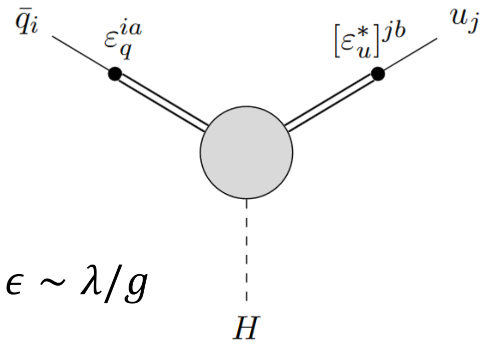
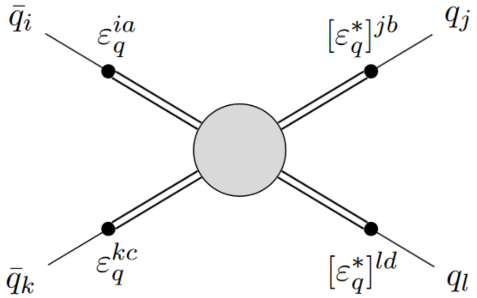
Partial Compositeness is a solution: $L \supset \lambda_q^{ia} \bar{q}_i O_a^q + \lambda_u^{ia} \bar{u}_i O_a^u + \bar{O}_a^q O_H O_b^u$

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 Λ_{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 $\Rightarrow M_* \gtrsim 20 \div 25\ \text{TeV}$

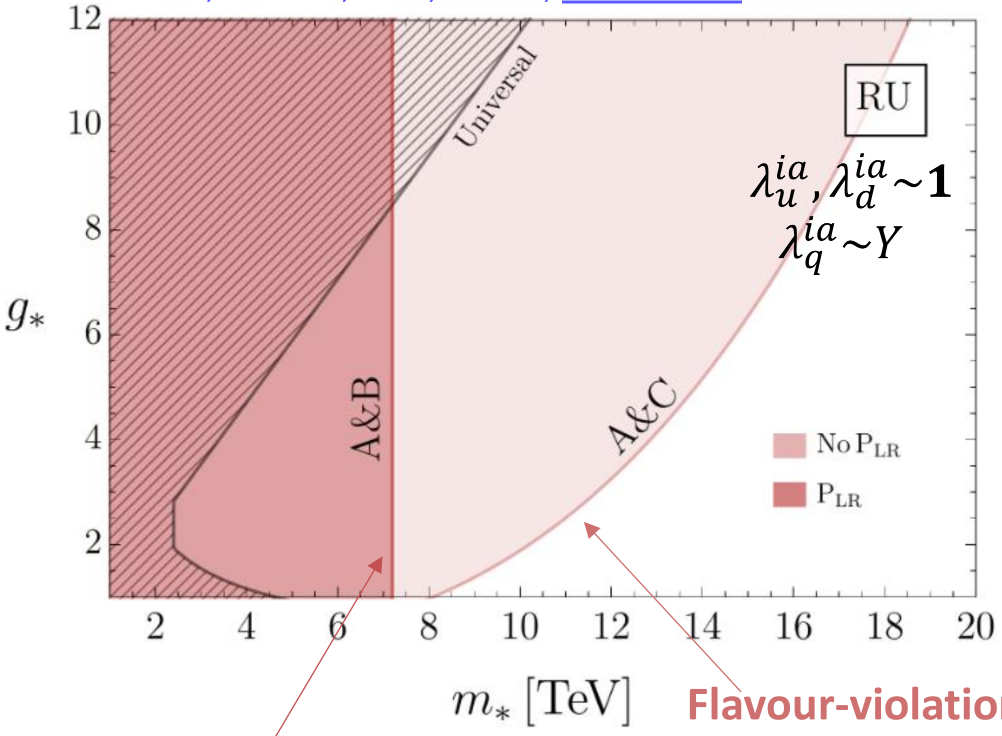
[Even assuming 1-loop suppressed quark dipole operators]

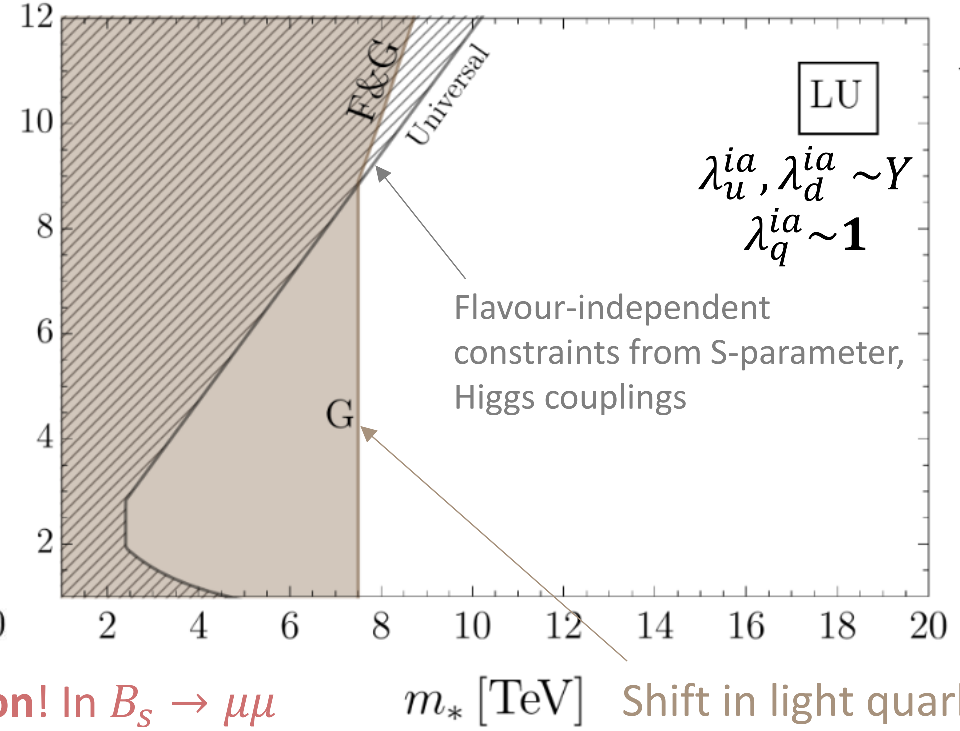
- Such a high scale degrades this as a solution to the hierarchy problem AND is untestable in colliders
- We **need** a flavour symmetry to bring down m_*. Let's compare MFV vs. $U(2)$-like

Partial Compositeness with MFV: $M_* \gtrsim 7 \div 8$ TeV

MFV-like flavour symmetry [+ custodial $SU(2)_L \times SU(2)_R$ symmetry to protect m_W/m_Z]

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

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

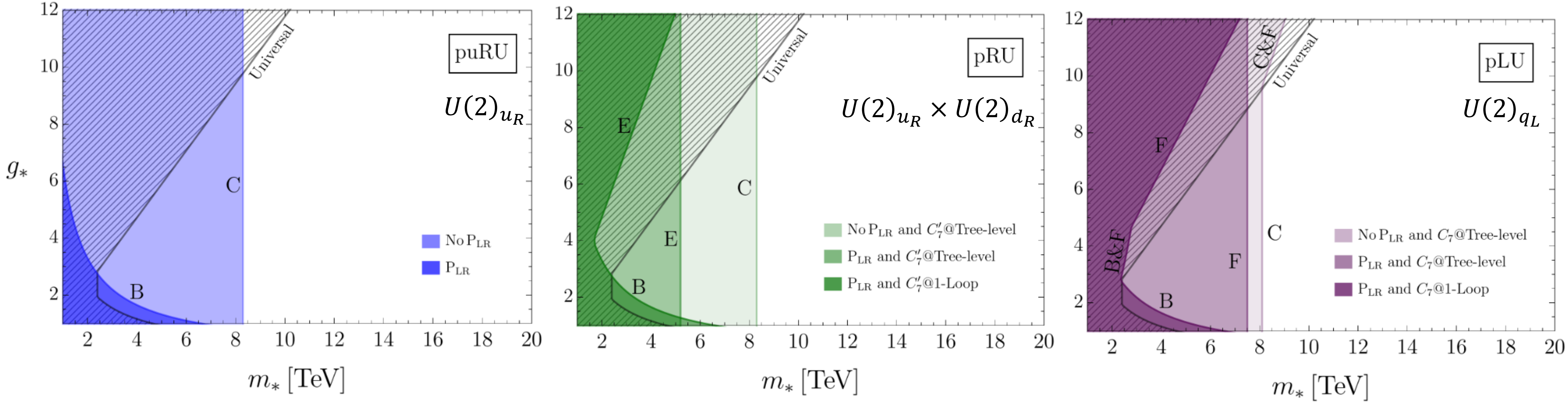
Di-jet constraints from **LHC**, driven by light quark couplings

P_{LR} denotes an extensional of custodial by a `left-right' exchange symmetry [kills corrections to Zb_Lb_L vertices]

Key point: strongest current bounds are driven by couplings to **light generation fermions** OR **flavour violation**, not EW constraints

Partial Compositeness with $U(2)$: $M_* \gtrsim 1 \div 2$ TeV

Glioti, Rattazzi, Ricci, Vecchi, 2402.09503



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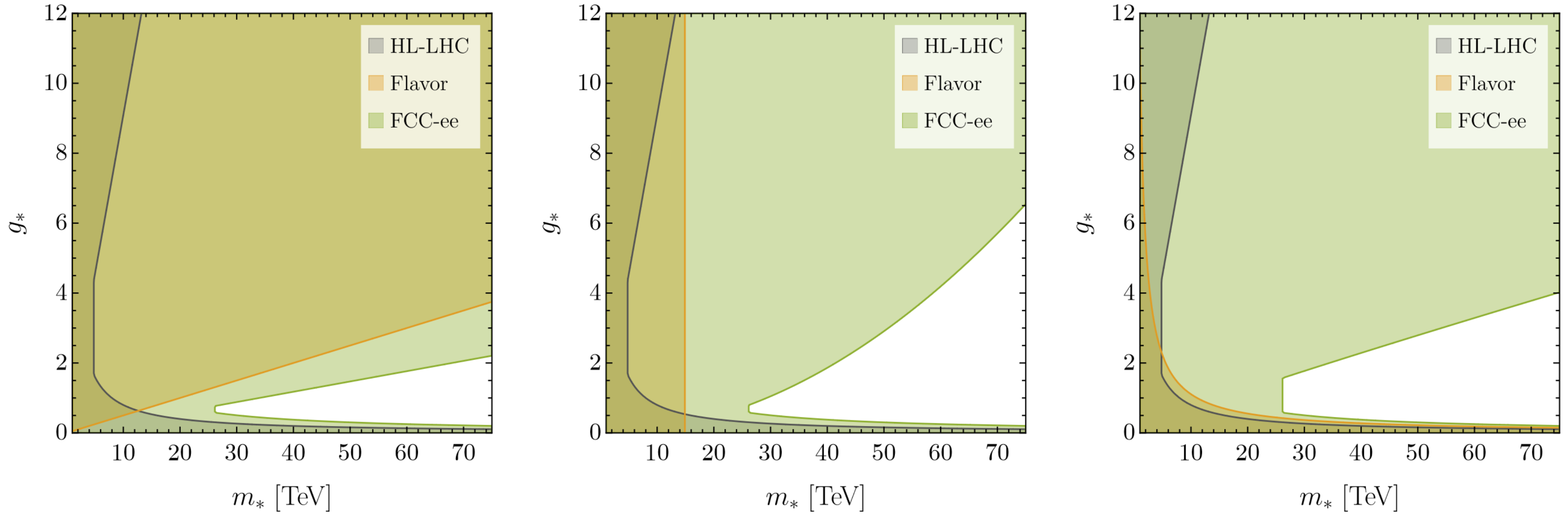
Going from MFV to U(2), we decouple the strong LHC constraints: dominant bounds now heavy-to-light quark flavour-violation + universal EW constraints

Future Prospects: HL-LHC, FCC-ee

Stefanek, 2407.09593

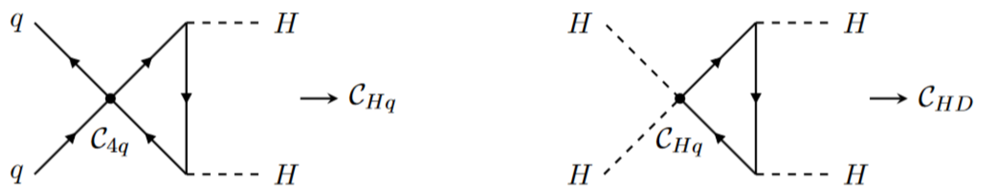
- FCC-ee “tera-Z” run: approx. 10^5 times LEP dataset on Z-pole
- With this precision, RG-running into EWPOs at 1-loop (and even 2-loop) is crucially important



(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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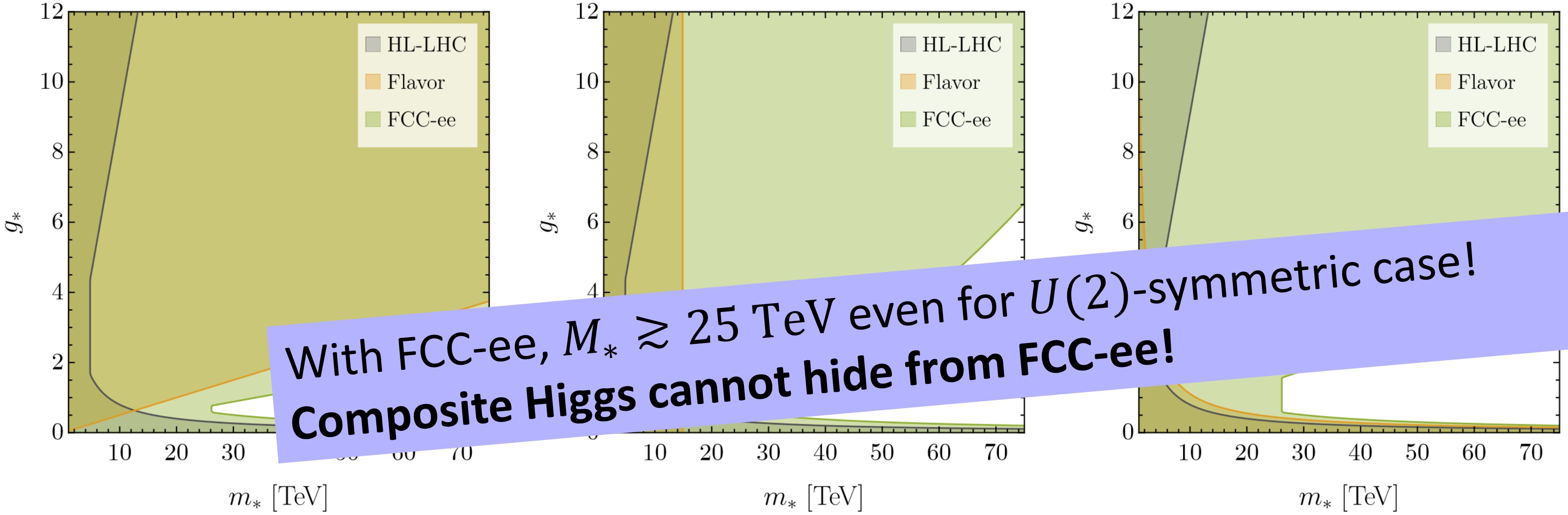

With FCC-ee, $M_* \gtrsim 25$ TeV even for $U(2)$-symmetric case!
Composite Higgs cannot hide from FCC-ee!

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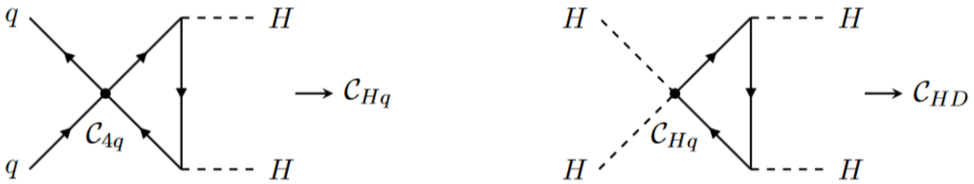

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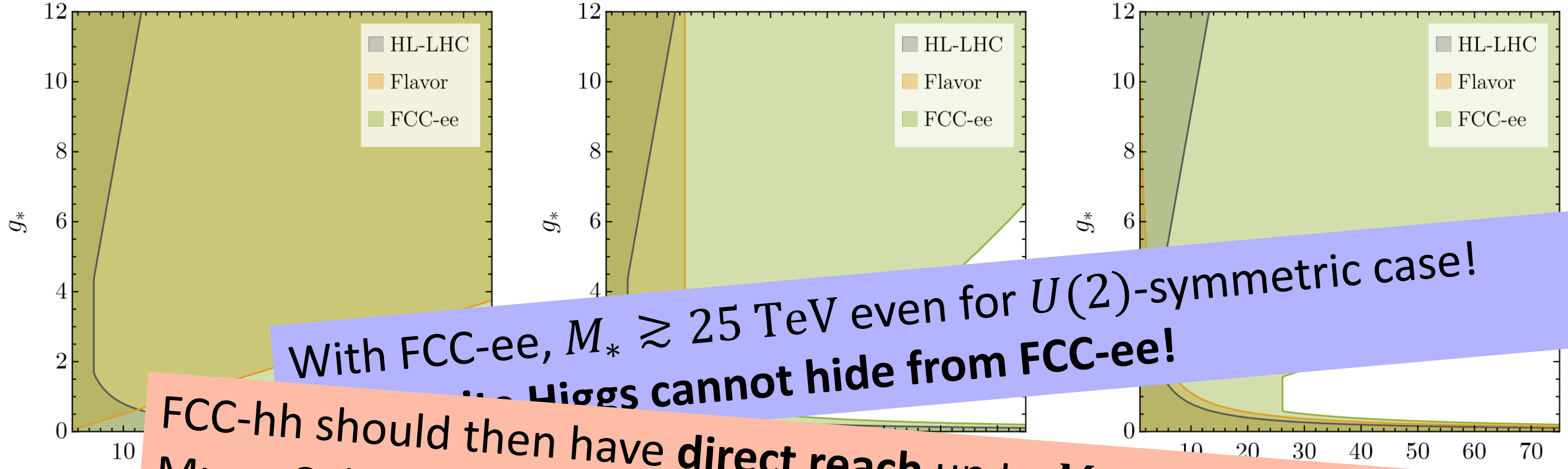

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... Higgs cannot hide from FCC-ee!

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 $E_{\mathrm{CoM}}/2$ [Accettura et al 2303.08533]

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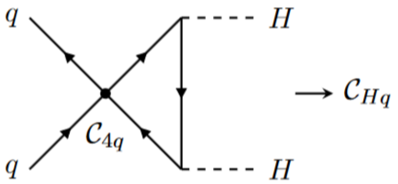

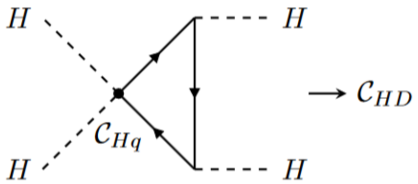

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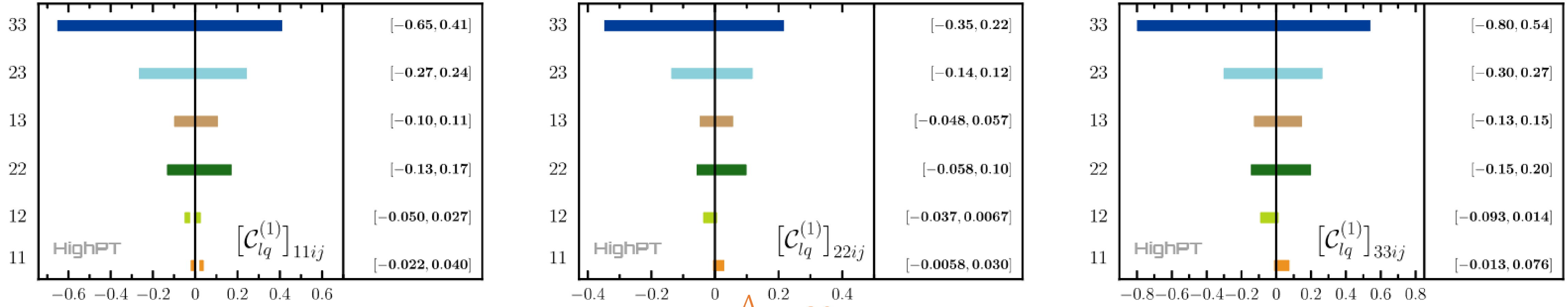
Allwicher, Faroughy, Jaffredo, Sumensari, Wilsch, 2207.10756

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

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



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

From MFV to $U(2)$: the **flavour *non-universal* path** to BSM…

$$C_{ij} \sim \begin{pmatrix} \epsilon & & \\ & \epsilon & \\ & & 1 \end{pmatrix} + \cdots$$

1. Just as good flavour protection as MFV ☺
2. Direct search bounds weaker: $\Lambda_{U(2)} \sim 1\text{ TeV}$ vs $\Lambda_{\text{MFV}} \sim 10\text{ TeV}$ ☺
3. Same global symmetry as Yukawa! Also explain SM flavour puzzle? ☺

So far $U(2)$ has been imposed. What could be its origin?

Flavour non-universal [3 vs 1+2] **gauge** symmetry!

A finite class of models is provided by **flavour deconstruction**

$$G_1 \times G_2 \times G_{3+\mathrm{H}} \to G_{12} \times G_{3+\mathrm{H}} \qquad \langle\phi_{12}\rangle \sim 100(0\ldots)\ \mathrm{TeV}$$
$$\to G_{\mathrm{SM}} \qquad \langle\phi_{23}\rangle \sim 1(0\ldots)\ \mathrm{TeV}$$

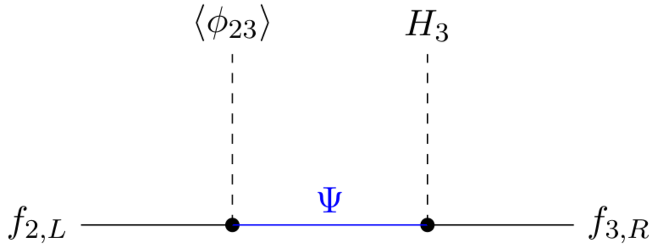
Original example: Li, Ma, 1981

Breaking pattern $G_A \times G_B \to G_{A+B}$, given scalar ϕ, is **generic** for simple G!

Goursat, 1889

Craig, Garcia-Garcia, Sutherland, 1704.07831

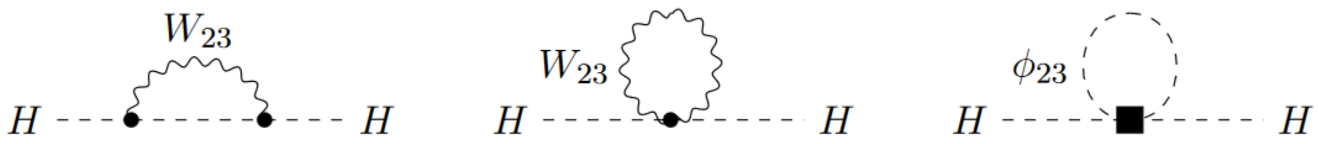
Solves the SM flavour puzzle



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

Non-decoupling phenomenology

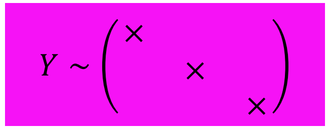
- Predicts non-universal, charged heavy gauge bosons in adj G, gauge couplings $\gtrsim\ g_i = O(1)$
- Cannot be decoupled $[M \to \infty]$ without creating a hierarchy problem $\delta m_h^2 \sim g^2 M^2/16\pi^2$



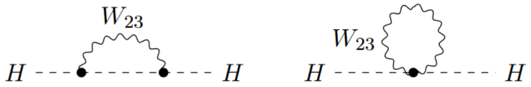
Survey of Flavour Deconstruction models

	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

Davighi, Isidori 2303.01520




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



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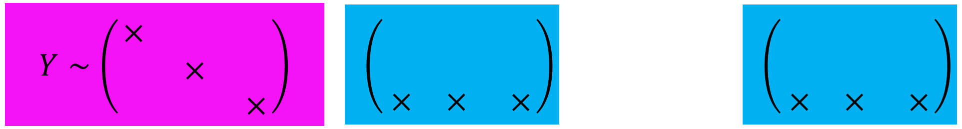
Davighi, Isidori 2303.01520



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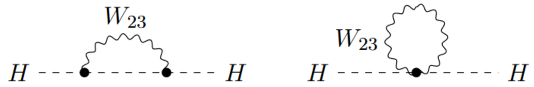

Motivates a **joint solution** with the **hierarchy problem.** Example: **flavour deconstructed compositeness**

Covone, Davighi, Isidori, Pesut, 2407.10950 *See Marko Pesut's parallel talk*

- Delivers a **gauge explanation** for the $U(2)$ protection that we saw can lower compositeness scale
- More freedom for tuning in minimal composite Higgs $m_h^2 \sim \frac{1}{16\pi^2}[\#y_t^2 M_T^2 - \#g_{R,3}^2 M_\rho^2 + \#g_{R,3}^4 v_\phi^2]$
- To explain $y_2 \ll y_3$, the heavy fermion is 100s of TeV – but gives no radiative contribution to Higgs mass thanks to compositeness near TeV!

Phenomenology of Flavour Deconstructed Gauge Bosons

	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

Tree-level shifts in Z-pole observables & m_W means EW constraints often stronger than flavour!

Key observable given current data is e.g. the W mass (+ Z-pole measurements from LEP *etc*)

- Deconstructing $SU(2)_L$ gives $\delta m_W < 0$
- Deconstructing $U(1)_Y$ gives $\delta m_W > 0$

Phenomenology of Deconstructed $SU(2)_L$ gauge bosons

	Deconstructed $SU(2)_L$	Deconstructed $U(1)_Y$
Electroweak: Z-pole & W-pole	9 TeV (5 TeV if exc. m_W)	2 TeV
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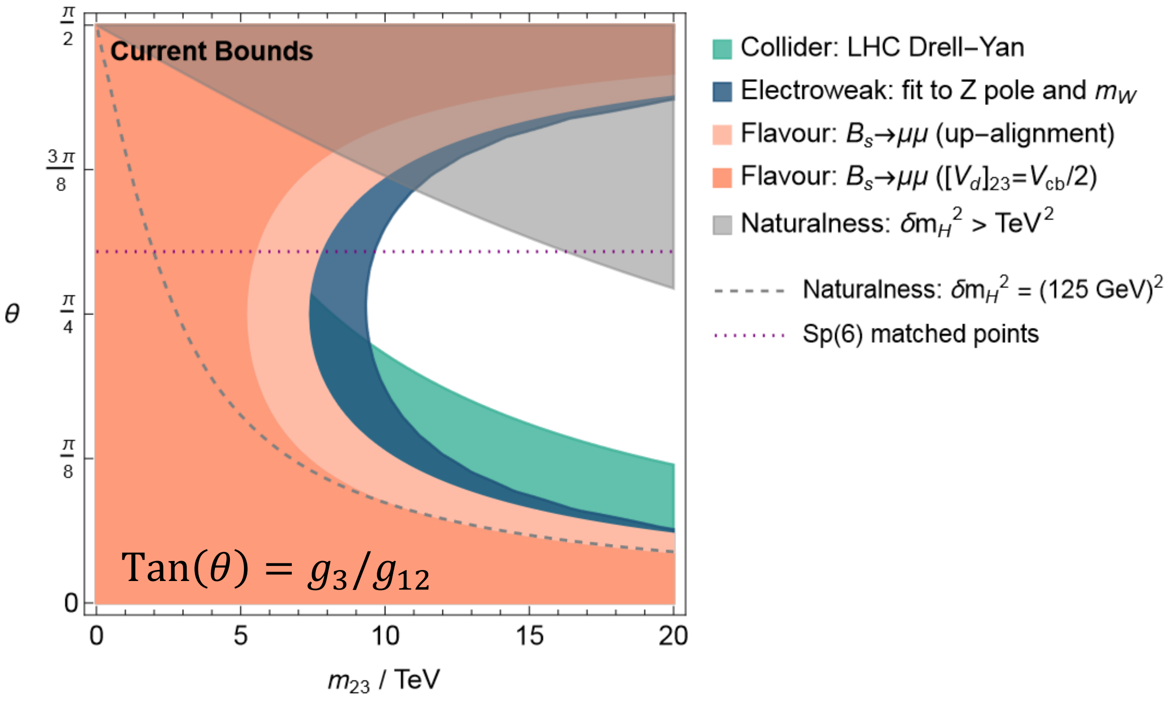

Davighi, Gosnay, Miller, Renner 2312.13346
See also Capdevila, Crivellin, Lizana, Pokorski 2401.00848

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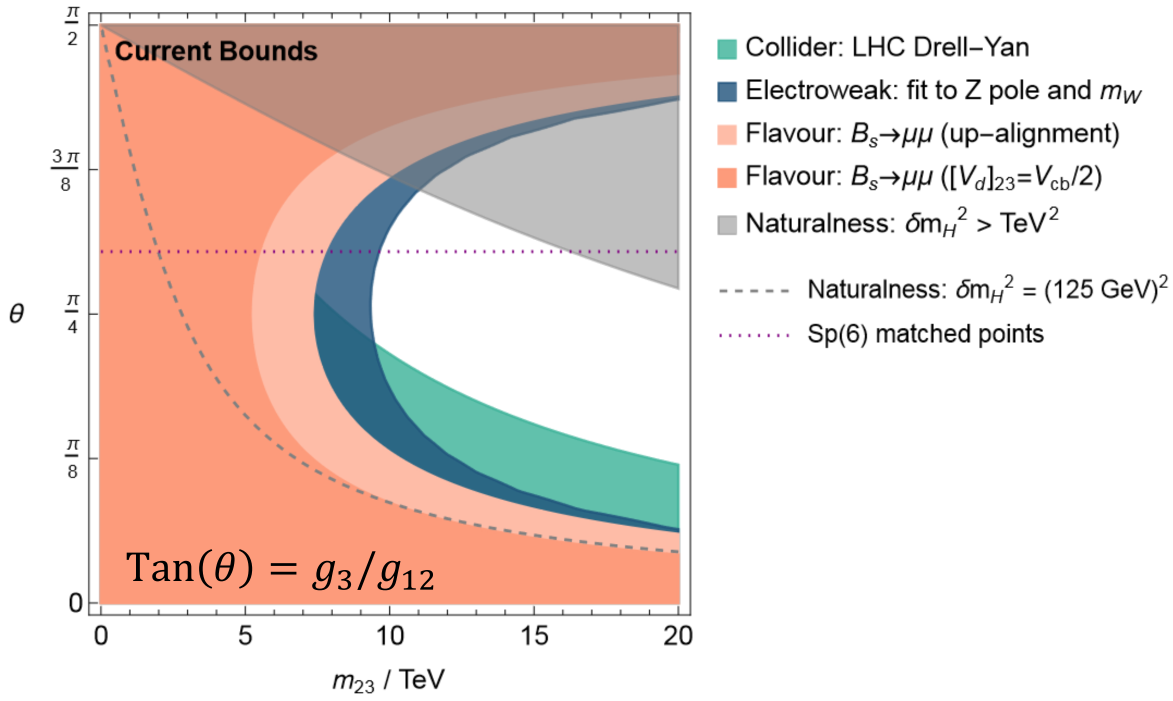
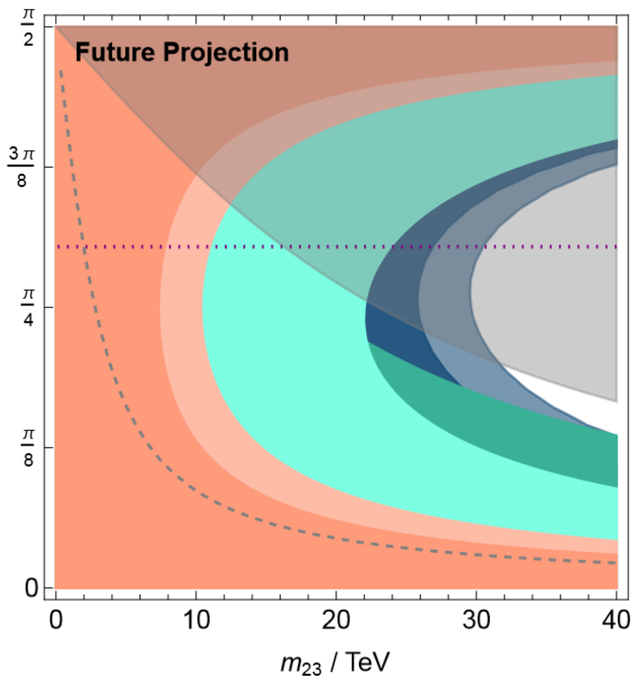




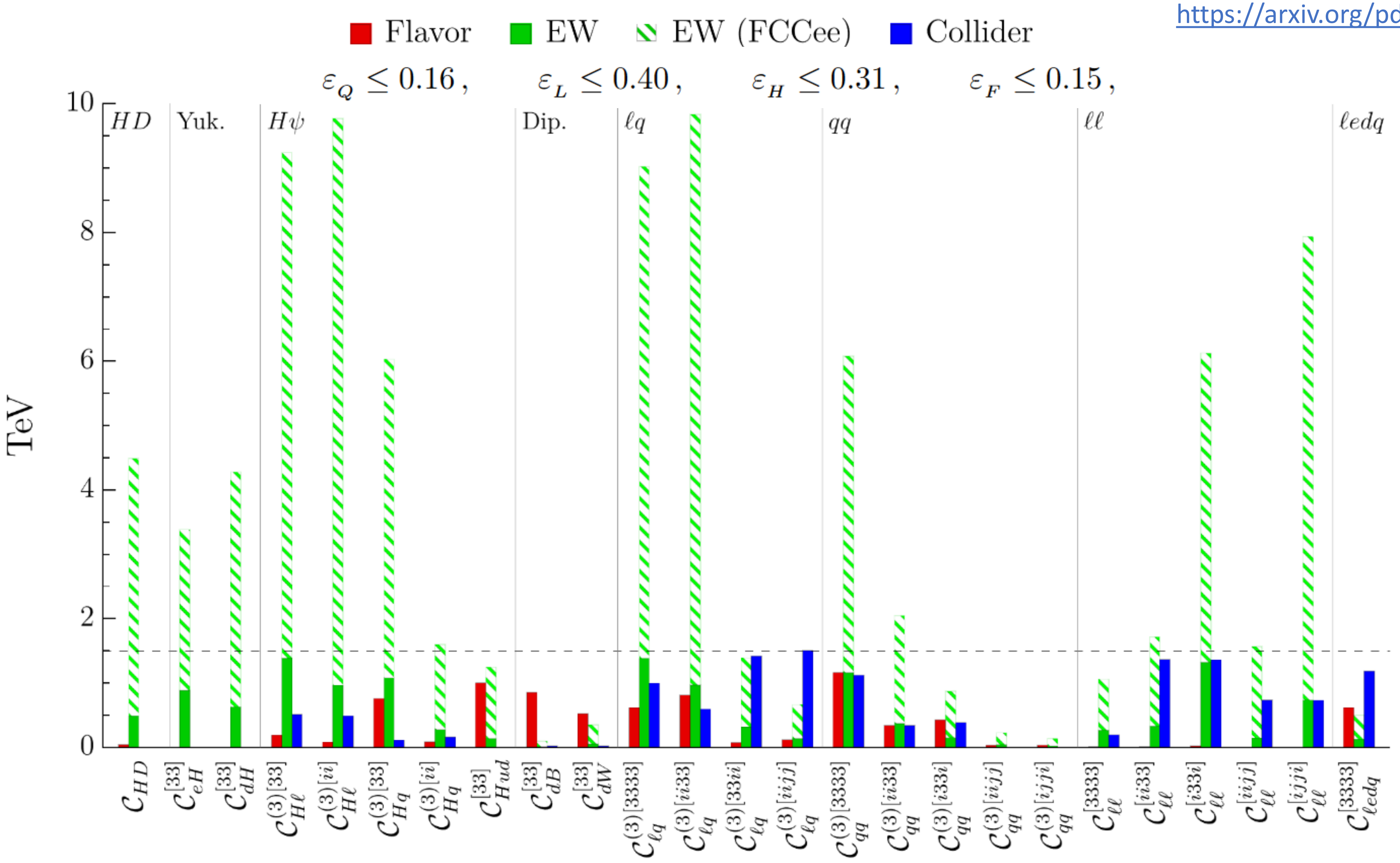
+ key flavour probe at FCC-ee!
- $B \to K\nu\nu$ to 1% at FCC-ee, synergy with $B_s \to \mu\mu$ at HL-LHC
- Tau LFUV measurements at FCC-ee improve by x13, probe 11 TeV
- $bs\tau\tau$ prospects at FCC-ee

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

The power of tera-Z: general lessons from the SMEFT

Approach 1: bounds on the $U(2)$-symmetric SMEFT, including RGE running

Allwicher, Cornella, Isidori, Stefanek, https://arxiv.org/pdf/2311.00020



The power of tera-Z: general lessons from the SMEFT

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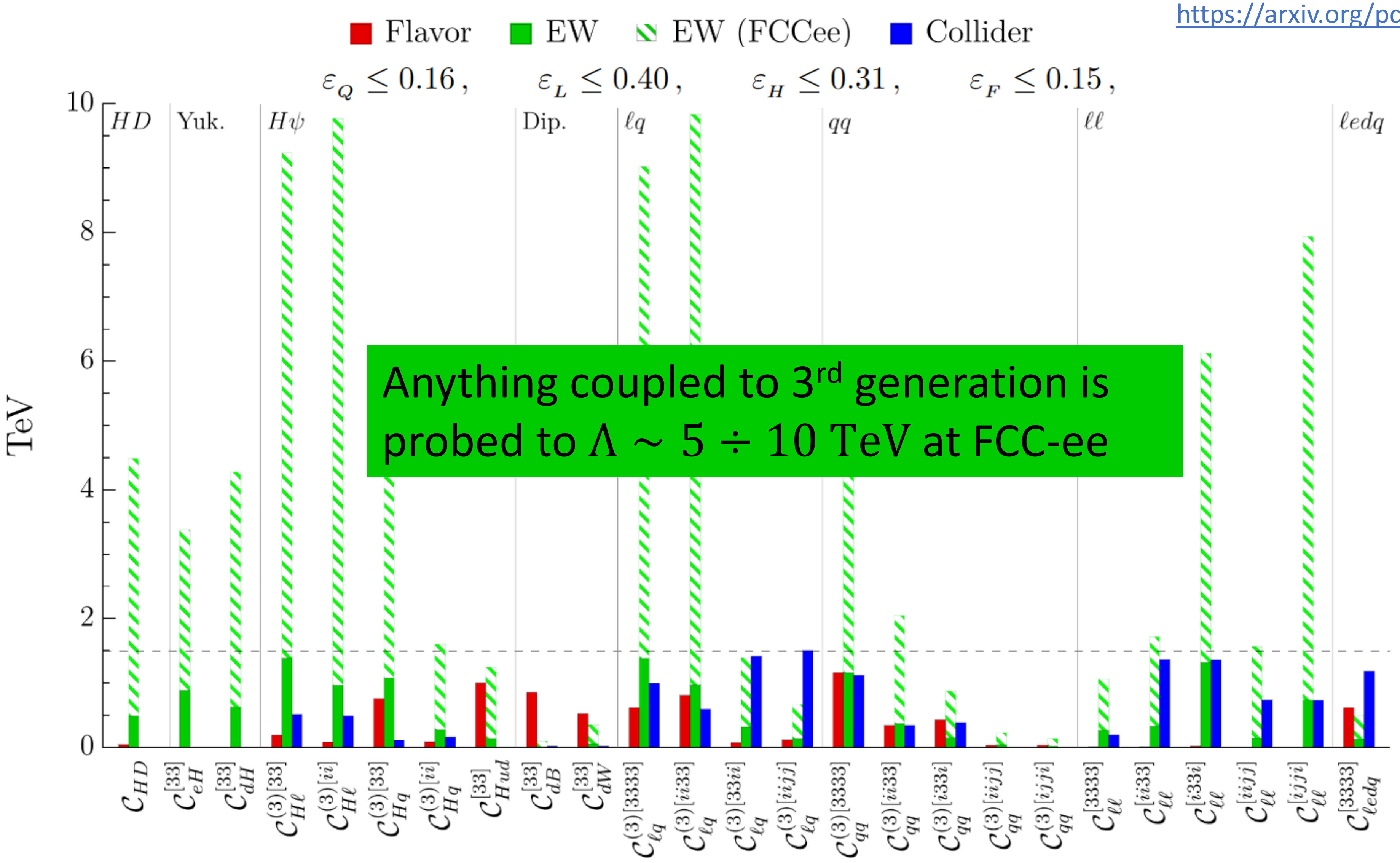
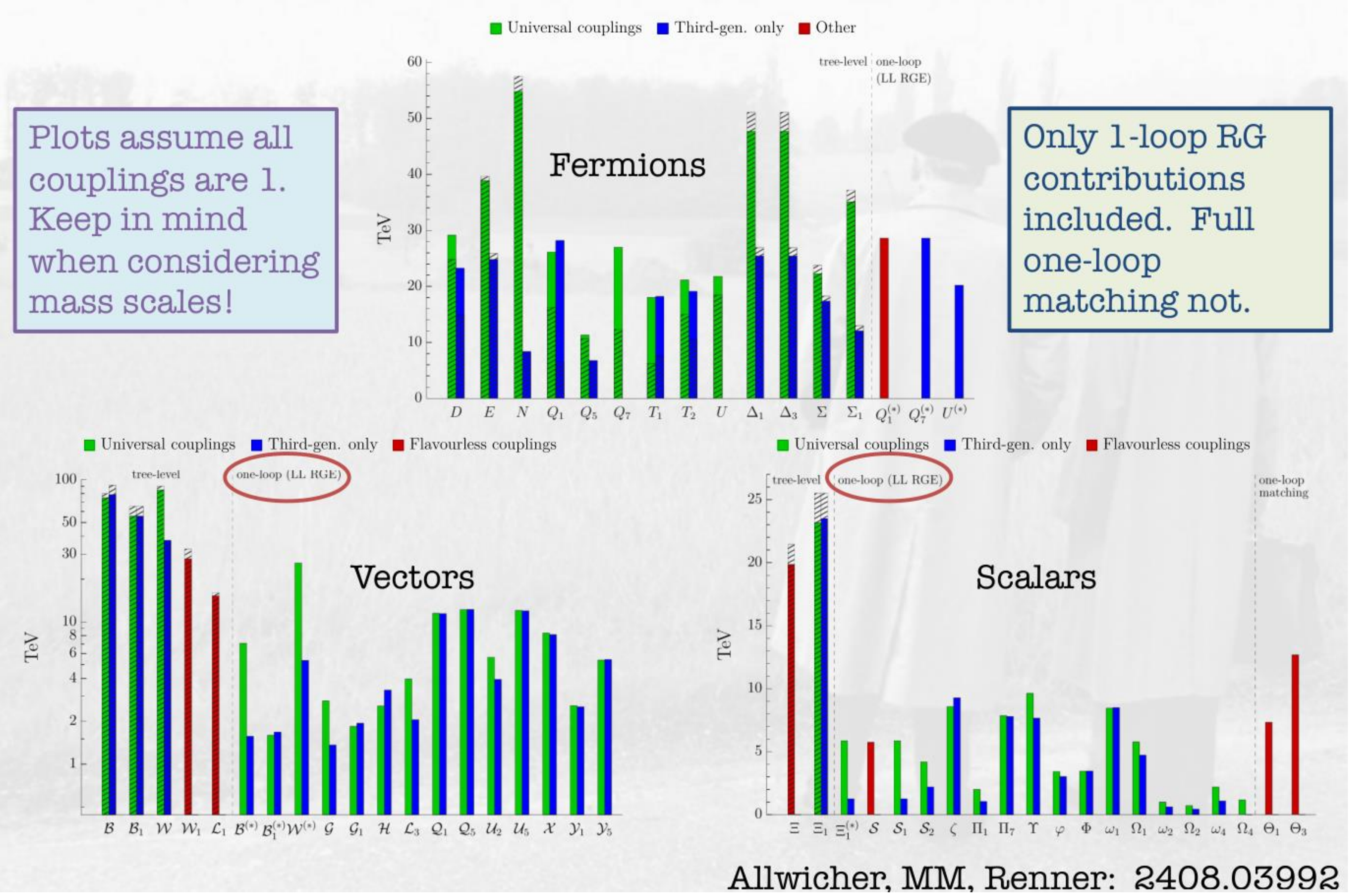


Anything coupled to 3[rd] generation is probed to $\Lambda \sim 5 \div 10$ TeV at FCC-ee

The power of tera-Z: general lessons from the SMEFT

Approach 2: integrate out *any* particle that gives dimension-6 SMEFT operators, and it runs into EWPOs



Allwicher, McCullough, Renner, 2408.03992

Slide from Matthew McCullough @ CERN EP/TH Faculty Meeting, Sep 2024

Conclusions

1. The Higgs remains central motivation for high-energy BSM
2. Flavour and Higgs/EW physics are inextricably connected
3. Flavour provides key experimental probes of Composite Higgs solutions to hierarchy problem
4. EWPOs provide key experimental tests of "deconstruction" theories for the flavour puzzle
5. Fruitful to pursue flavour non-universal models that solve flavour puzzle and hierarchy problem simultaneously, even if they appear complicated…
6. Tera-Z run at FCC-ee will tie together Higgs and flavour like never before!