A TeV Scale Origin for Higgs and Flavour

Joe Davighi, CERN

Uni Siegen Theoretical Physics Seminar, 12th May 2025

Outline of the Talk

1. Motivation: hierarchy problem & flavour puzzles
2. Flavour symmetries to lower Λ_{NP}: from MFV to U2
3. Flavour deconstructed gauge interactions: solving the flavour puzzle near the TeV
4. Phenomenology of flavour deconstruction
5. Flavour deconstructing the Composite Higgs: solving flavour + hierarchy problem near the TeV

If you remove the Higgs, the Standard Model reduces to

$$L_{\mathrm{SM}\setminus\mathrm{H}} = -\frac{1}{4}\left(\frac{F^2}{g_1^2} + \frac{\mathrm{tr}\, W^2}{g_2^2} + \frac{\mathrm{tr}\, G^2}{g_3^2}\right) + i \sum_{\psi,i} \bar{\psi}\,(\partial + A)\psi$$

This Higgs-less SM is a completely natural gauge theory (modulo CC):

Couplings $g_i = O(1)$ at weak scale

~~Hierarchy problem~~

~~Flavour puzzle~~

~~Strong CP problem~~ [massless quarks]

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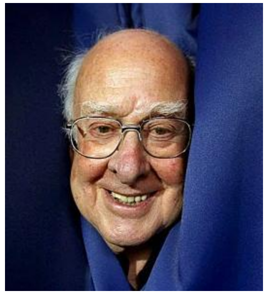
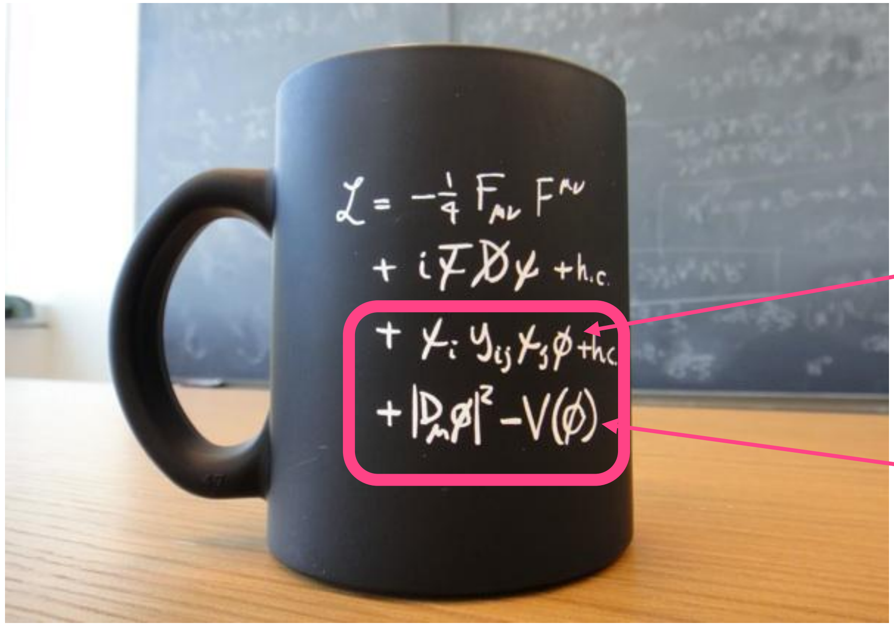
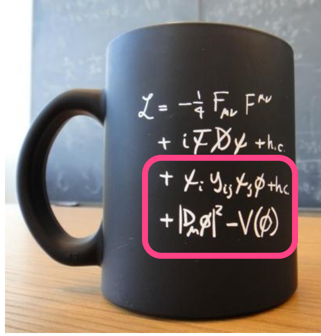


∴ Higgs = key to BSM, both theoretically & experimentally (modulo dark sectors)



Flavour puzzle!

Hierarchy problem!

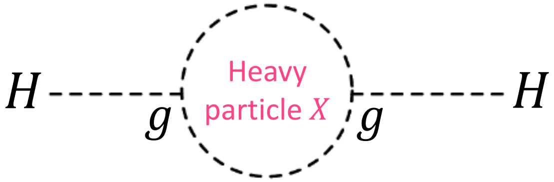


The Hierarchy Problem

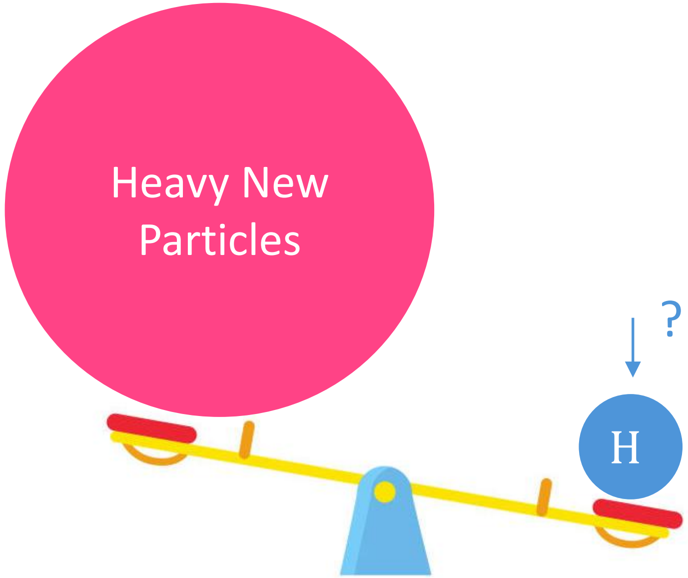
The Higgs has an unnaturally small **mass** parameter:

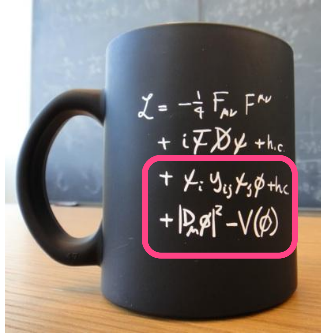
Large hierarchy: $\mu^2 \ll \Lambda^2_{\text{high scales}}$

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



$$\Longrightarrow \quad \delta M_h^2 \Big|_{\text{from } X} \sim \left(\frac{g^2}{16\pi^2}\right)^n M_X^2$$





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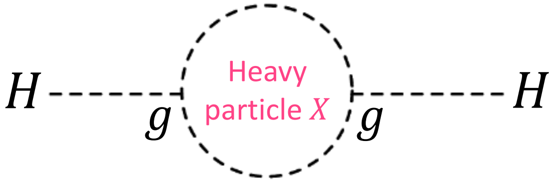


$$\Longrightarrow \quad \delta M_h^2\Big|_{\text{from } X} \sim \left(\frac{g^2}{16\pi^2}\right)^n M_X^2$$

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

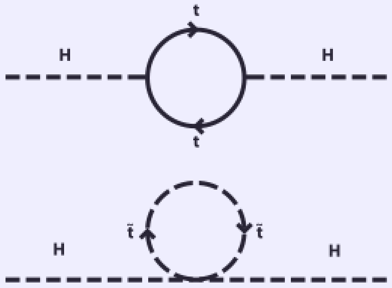
Composite Higgs

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

$$\delta m_h^2 \sim \frac{1}{16\pi^2}\left(4n_c y_t^2 M_T^2 - \frac{9}{2} g_1^2 M_\rho^2\right)$$

Supersymmetry

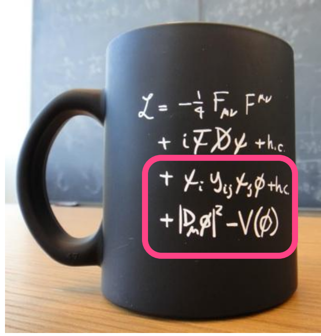
Inclusion of superpartner loops removes quadratic sensitivity to UV cut-off due to bose vs fermi cancellation



$$\Rightarrow \delta m_h^2 \approx \frac{1}{16\pi^2} 4n_c y_t^2 M_T^2 \log\frac{\Lambda^2}{M_T^2}$$

v. $\delta m_h^2 \approx \frac{1}{16\pi^2} 4n_c y_t^2 \Lambda^2$ for top alone

The Hierarchy Problem



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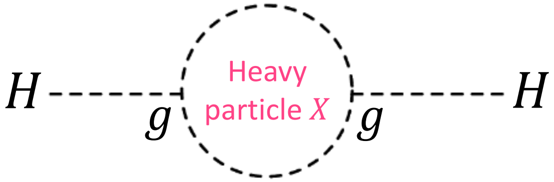

$$\Longrightarrow \quad \delta M_h^2 \Big|_{\text{from } X} \sim \left(\frac{g^2}{16\pi^2}\right)^n M_X^2$$

Two well-un…

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

- Loops cut off by composite resonances
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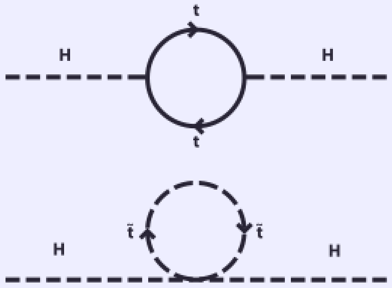

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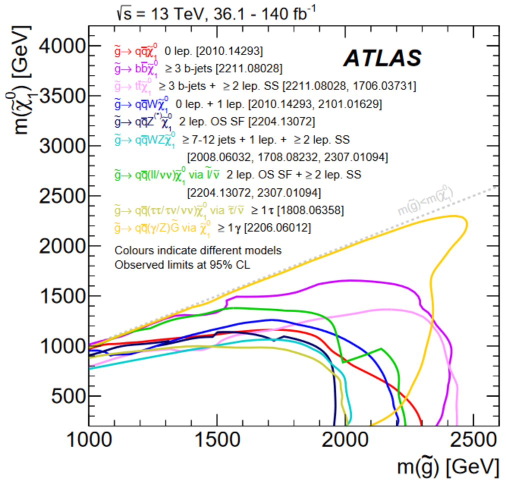
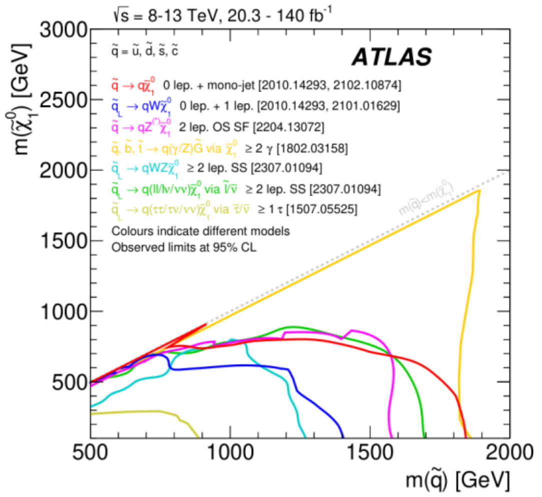
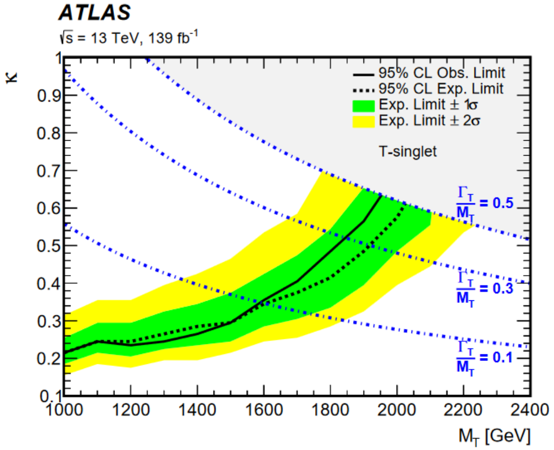
We are now probing natural M_* directly at the LHC

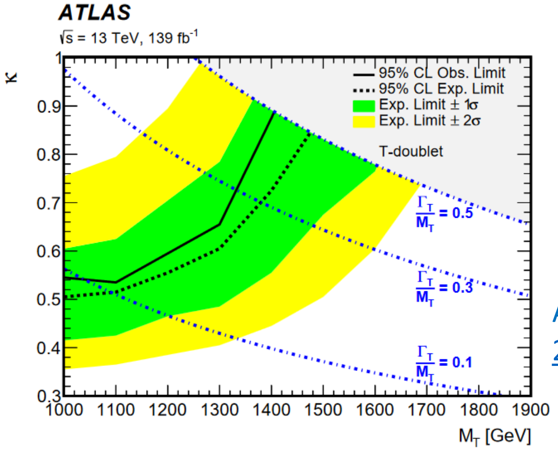
Few TeV limits on SUSY particles, top partners!





ATLAS, [2403.02455]



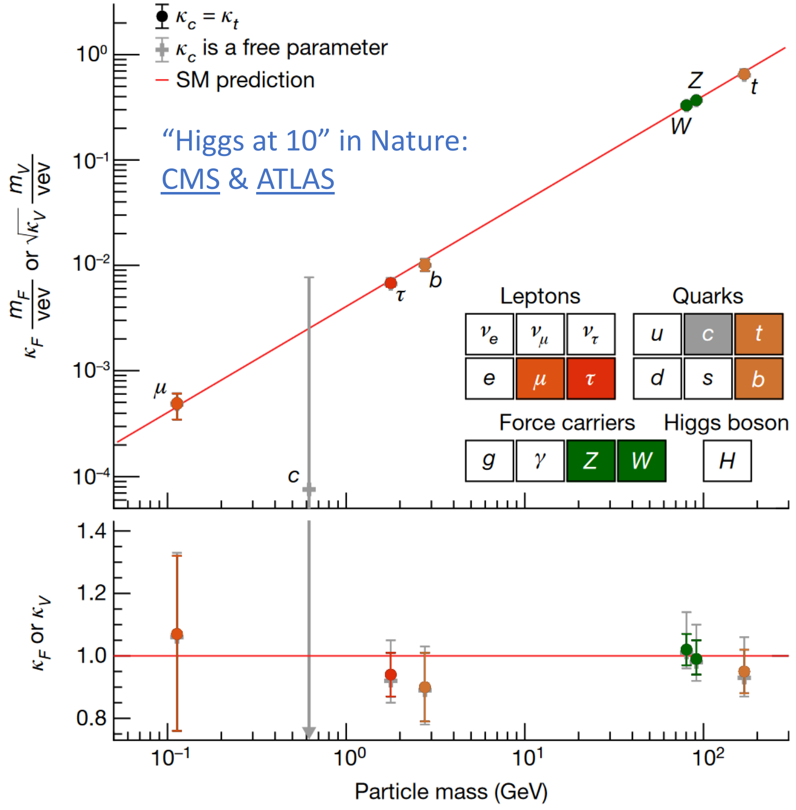


ATLAS, [2307.07584]

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

+ No sign of compositeness in Higgs couplings!

HWW, HZZ at LHC agree with SM to 3%

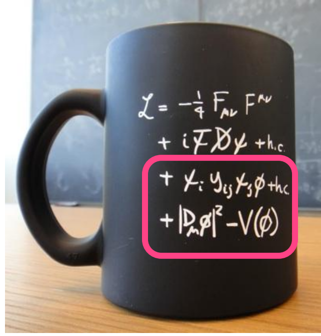


"Higgs at 10" in Nature: [CMS] & [ATLAS]

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

where f is compositeness scale

The Hierarchy Problem(s)



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

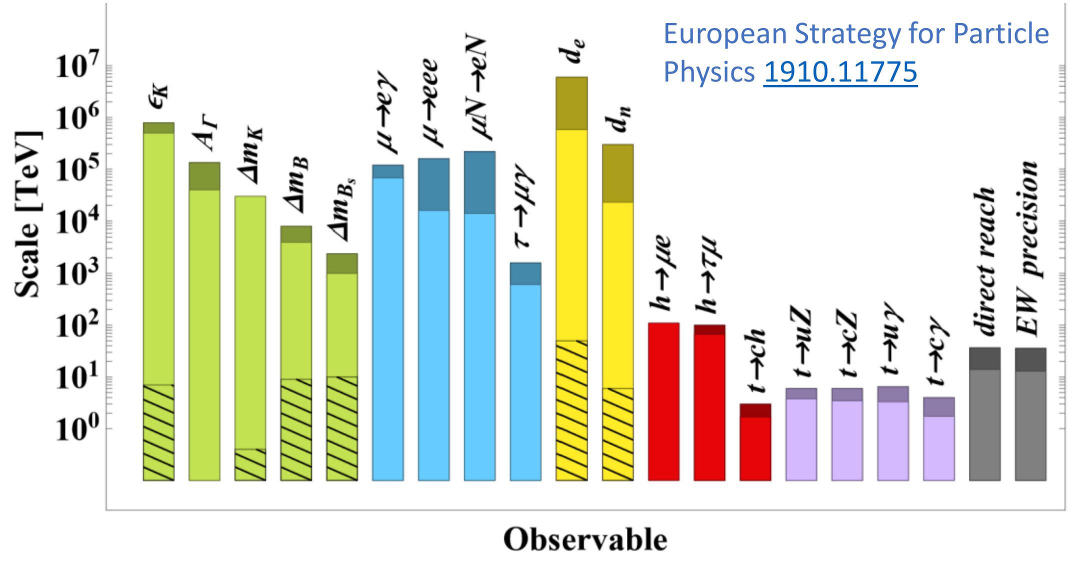
LHC data $\Longrightarrow$ (+ LEP…) Little hierarchy: $\mu^2 \ll \Lambda^2_{\text{SM}} \sim \text{TeV}^2$ $\Longrightarrow$ accept it! or try even clever-er EW model-building

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

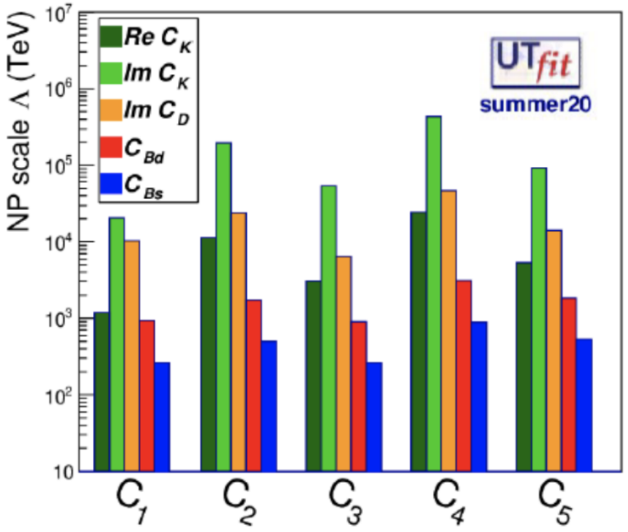
When trying to solve the (large or little) hierarchy problem, we cannot ignore flavour!

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](https://arxiv.org/abs/1910.11775)



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

Therefore *any* solution to hierarchy problem (or anything at all at TeV) **needs** non-trivial **flavour structure**

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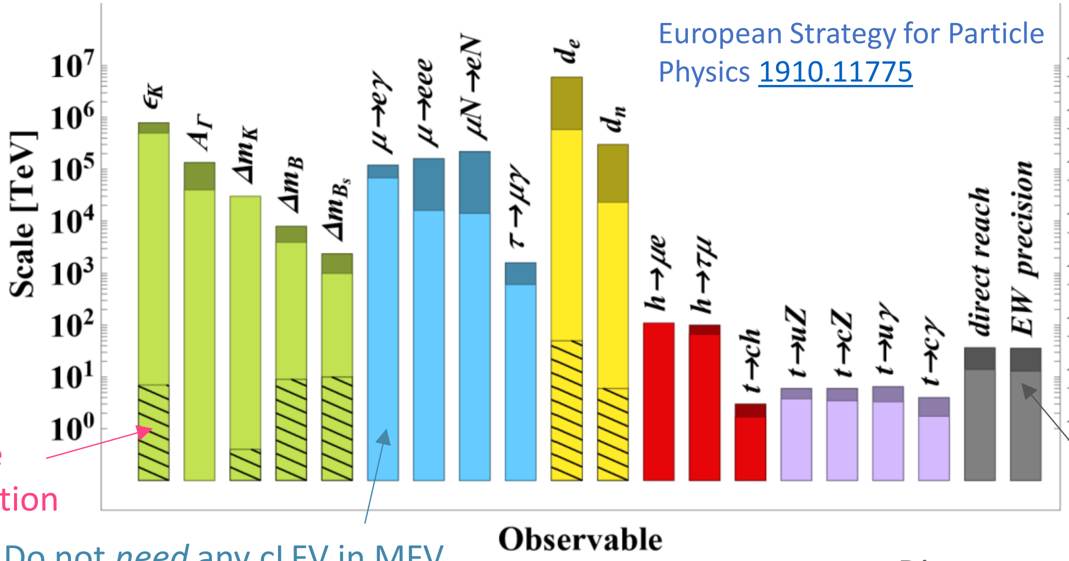

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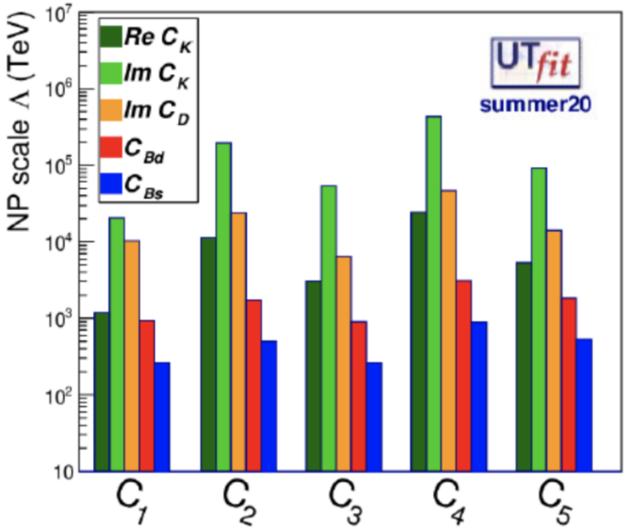

Hatched bars are with MFV protection

Do not *need* any cLFV in MFV

Direct searches probe MFV up to $5 - 10$ TeV

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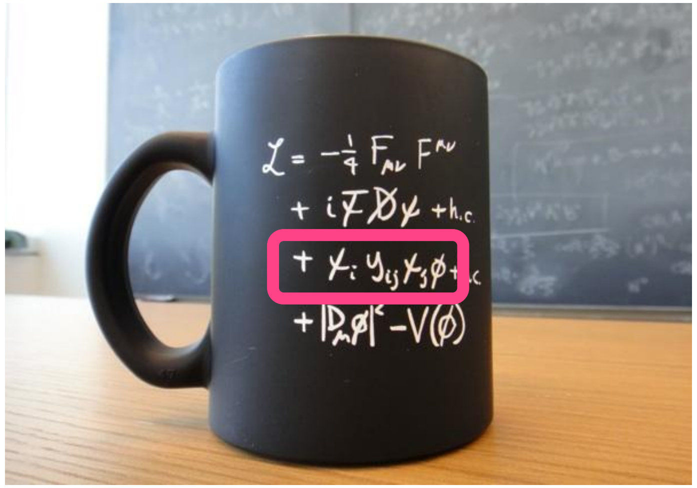
Example = **Minimal Flavour Violation** (MFV): SM Yukawas are **only** source of flavour violation in SM + BSM theory

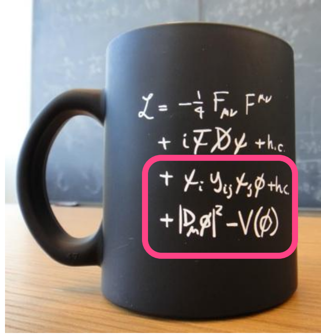
Kaon mixing with MFV: $\frac{1}{\Lambda_{sd}^2} \sim y_t^4 (V_{31}V_{32}^*)^2 \frac{1}{\Lambda_{\mathrm{NP}}^2} \sim \left(\frac{10^{-5}}{\Lambda_{\mathrm{NP}}}\right)^2$ is sufficient flavour protection!

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

Flavour is already a rich source of mysteries within the SM

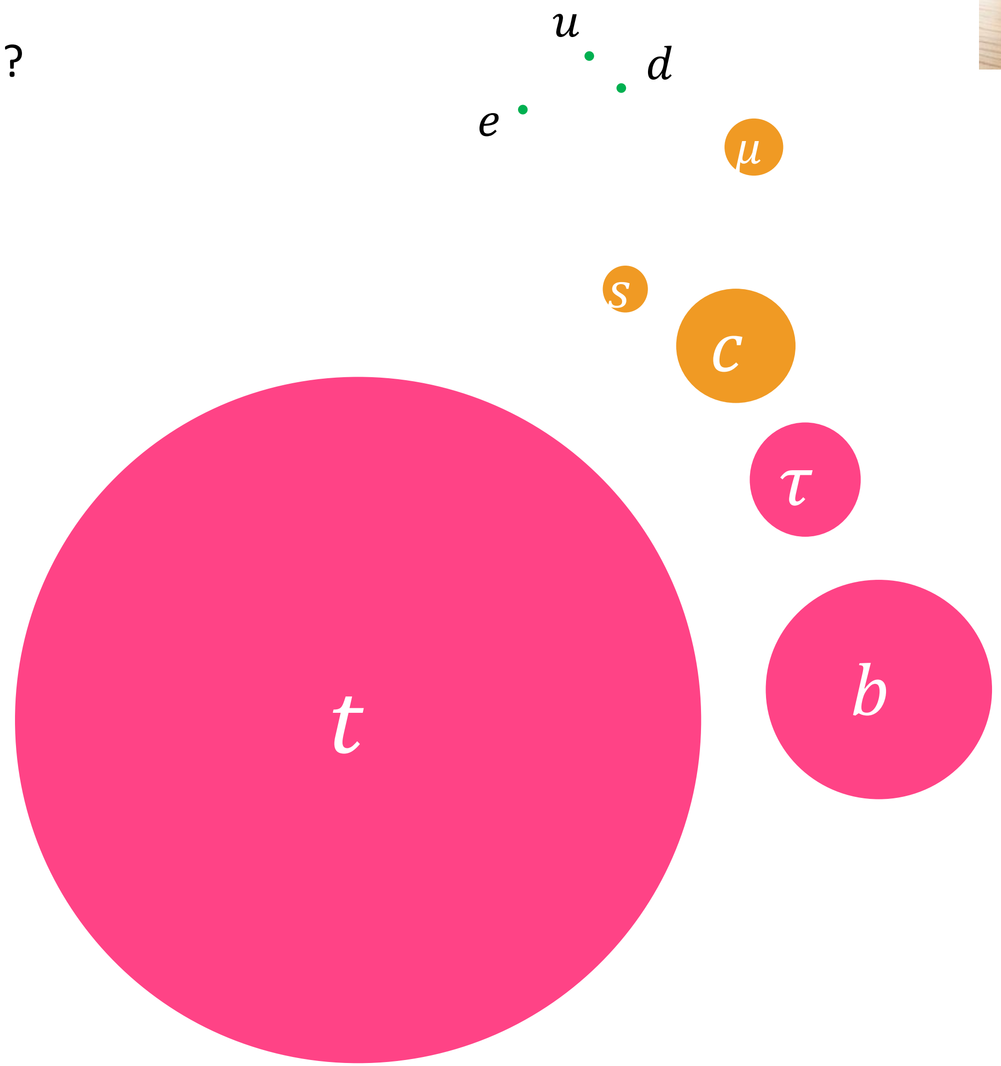


The SM Flavour Puzzle(s)



Fermion sector of SM contains many mysteries:

1. Why those (chiral) representations / hypercharges?
2. Why 3 generations?



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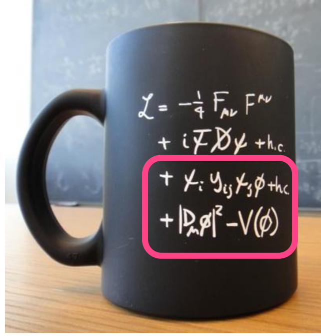

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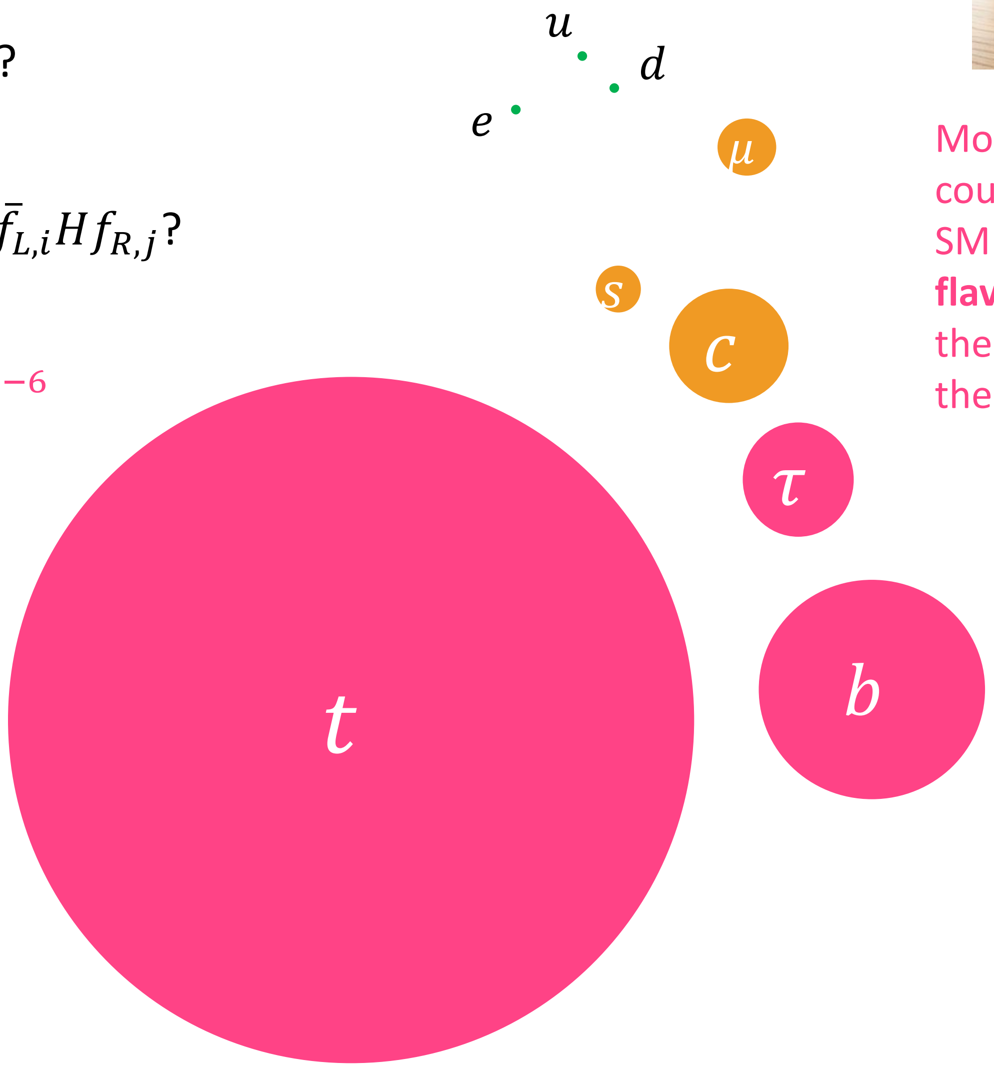
Masses: $1 \approx y_t \gg y_c \gg y_u \sim 10^{-5},\, y_e \sim 10^{-6}$

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



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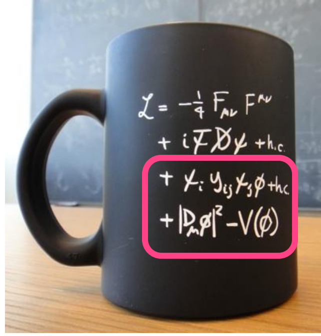

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Does puzzle (3) have a dynamical explanation?

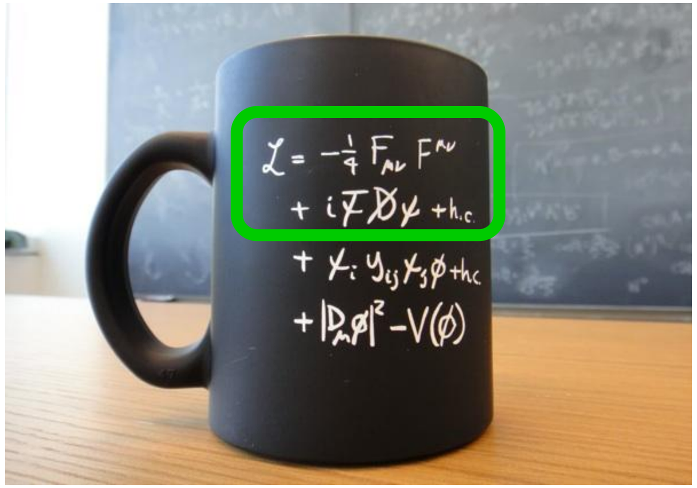
- y_{ij}^{f} are marginal (dimension-4) interactions: do not clearly point to a particular scale for NP explanation, unlike μ^2
- BUT since Higgs is origin of hierarchy problem & flavour puzzle: maybe they have a **joint solution** near TeV?

2. From MFV to U2

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

BSM Beyond MFV

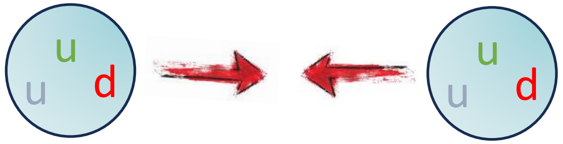
SM without Yukawas has a large $U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$ global symmetry



MFV: $U(3)^5$ broken only by $\bar{q}_{L,i}\, y^u_{ij}\, H u_{R,j} + \cdots$

- E.g. neutral spin-1 X_μ couples as $L \supset X_\mu\big(\delta_{ij} + \cdots\big)\bar{u}_i \gamma^\mu u_j$
- Bounds $\Lambda_{\rm MFV} \approx 5 \div 10\ \text{TeV}$ driven by couplings to valence quarks

e.g. $M_{W'\,\rm SSM} \gtrsim 6\ \text{TeV}$



BSM Beyond MFV

SM Yukawas $y^f_{ij}\,\bar{f}_{L,i} H f_{R,j}$ break this $U(3)^5 \to U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$;

- But only y^u_{33} is order−1

$$y^u_{ij} \approx \begin{pmatrix} & < 0.01 & 0.04 \\ & & 1 \end{pmatrix}$$

Top Yukawa

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

Imposing $U(2) \subset U(3)$ on the NP sector provides enough flavour protection to reconcile flavour bounds at the TeV: strongest constraints come from $1 \leftrightarrow 2$ flavour change (**kaon mixing**)

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

BSM Beyond MFV

Reasons for $U(2)$ part 1: Lowering Λ

- $U(2)$ is a **weaker assumption** on NP than MFV

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

- 3[rd]-family alignment $a \ll b$ can **reduce little hierarchy** → $\Lambda_{\mathrm{U(2)}} \approx 1 \div 2\ \mathrm{TeV}$
- In the LHC era this allows for **more natural models** than with MFV

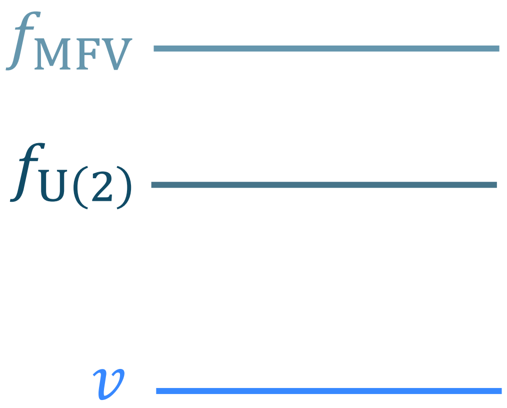
Reasons for $U(2)$ part 2: Solving the flavour puzzle!

- *Same* $U(2)$-like non-universal BSM could explain SM *and* BSM flavour puzzles at same time!

$$Y^u \sim y_t \begin{pmatrix} \epsilon_c & \epsilon_{23} \\ & 1 \end{pmatrix} \quad C_X \sim \begin{pmatrix} \delta & \\ & 1 \end{pmatrix}$$

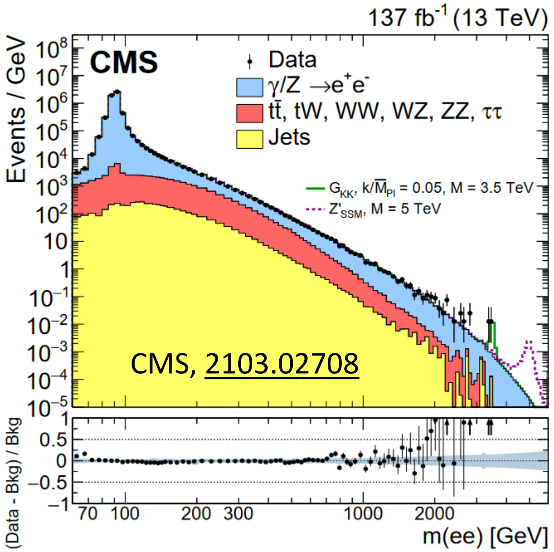
Reasons for $U(2)$ part 1: Lowering Λ

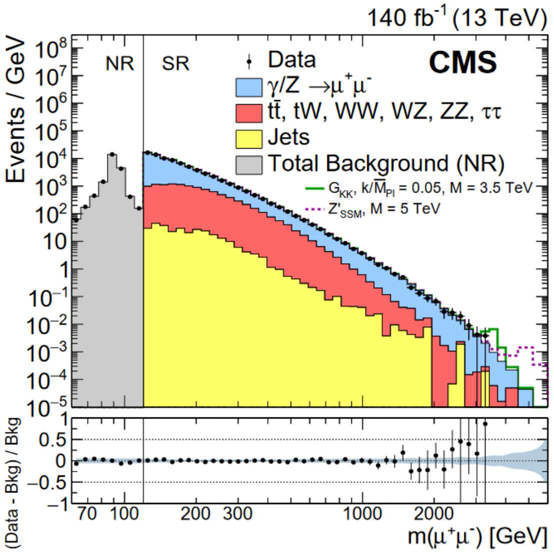
Let's review some evidence.



Lowering Λ_{NP} with U2

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

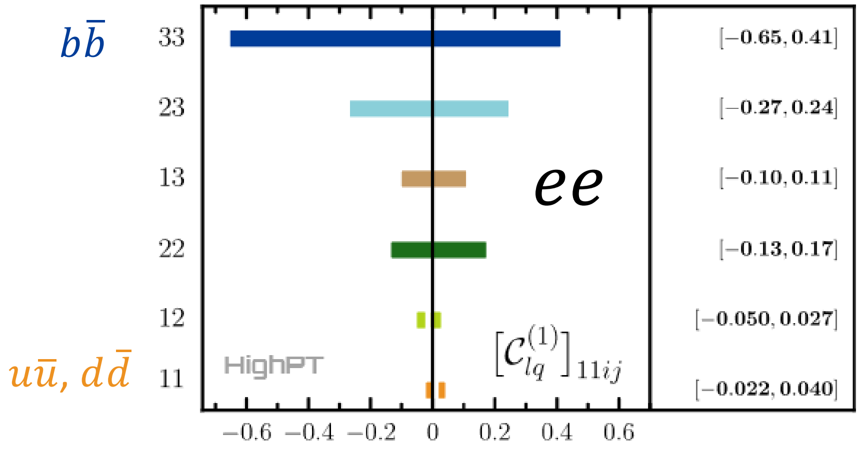


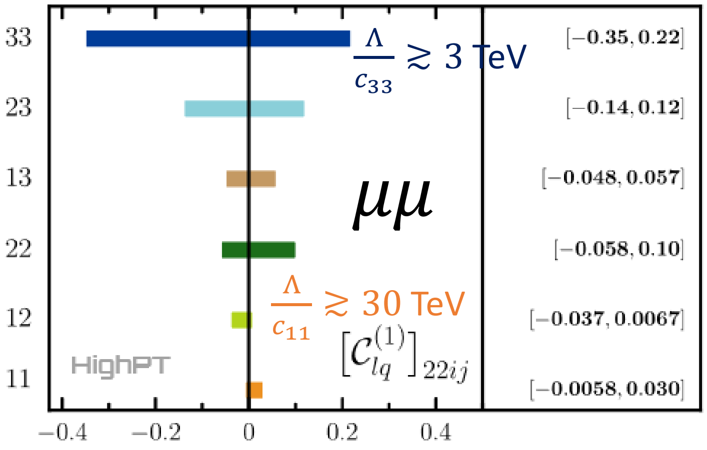


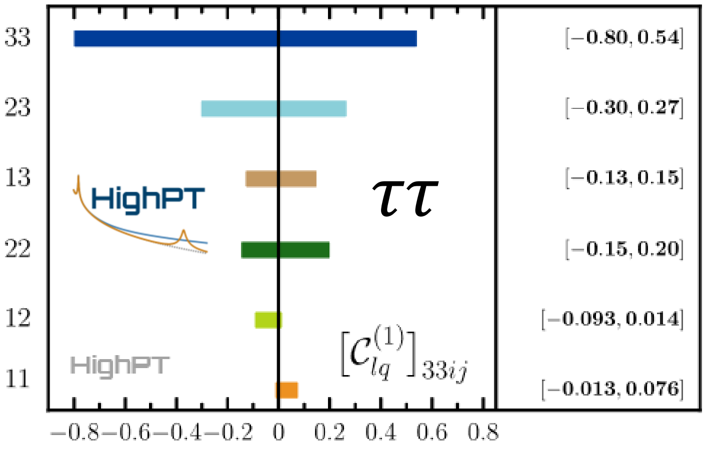
Bounds on dim-6 semi-leptonic operators:

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

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

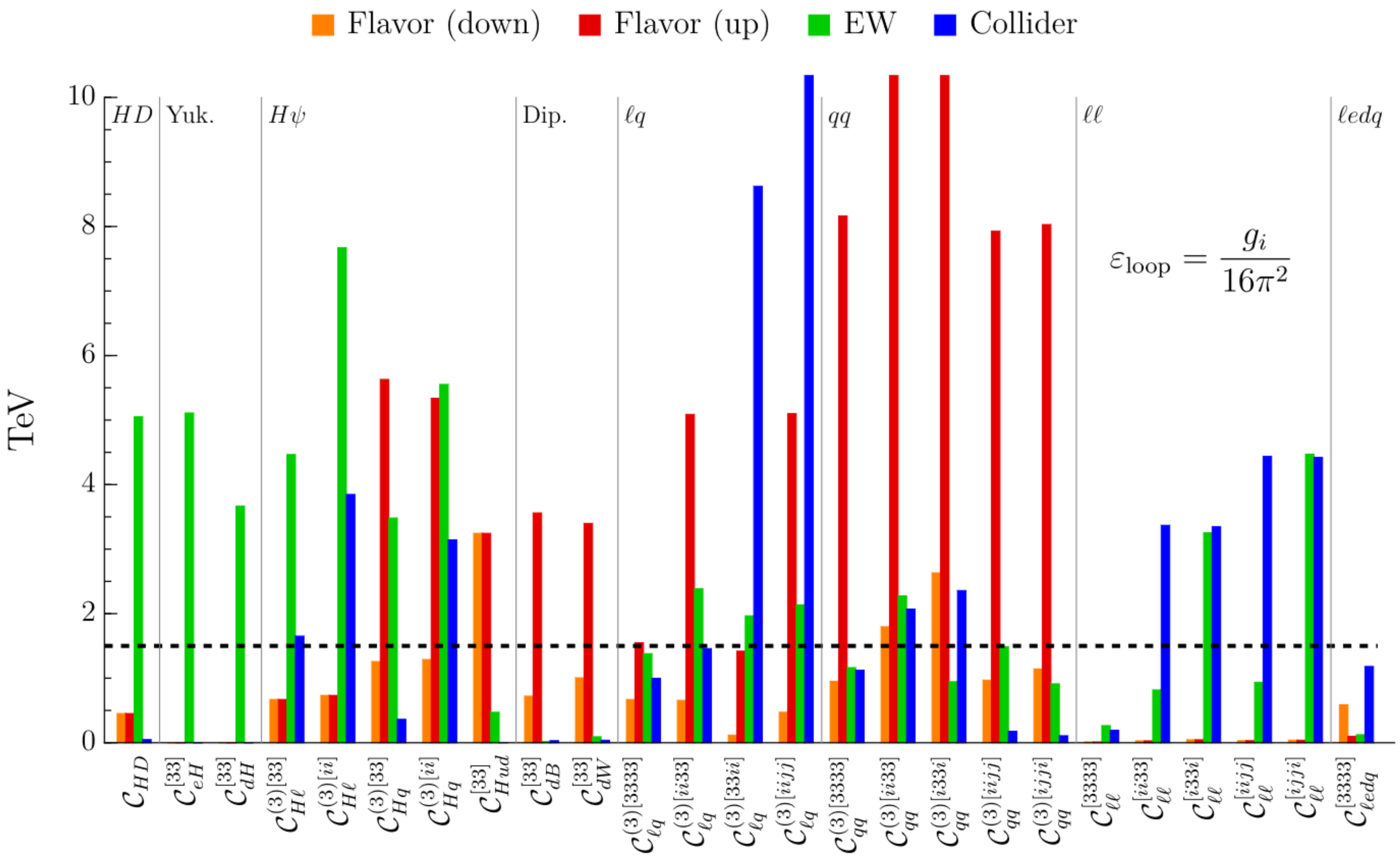






Lowering Λ_{NP} with U2

Exhibit B: global lessons from SMEFT likelihoods



MFV-like

Allwicher, Cornella, Isidori, Stefanek, 2311.00020

Lowering Λ_{NP} with U2

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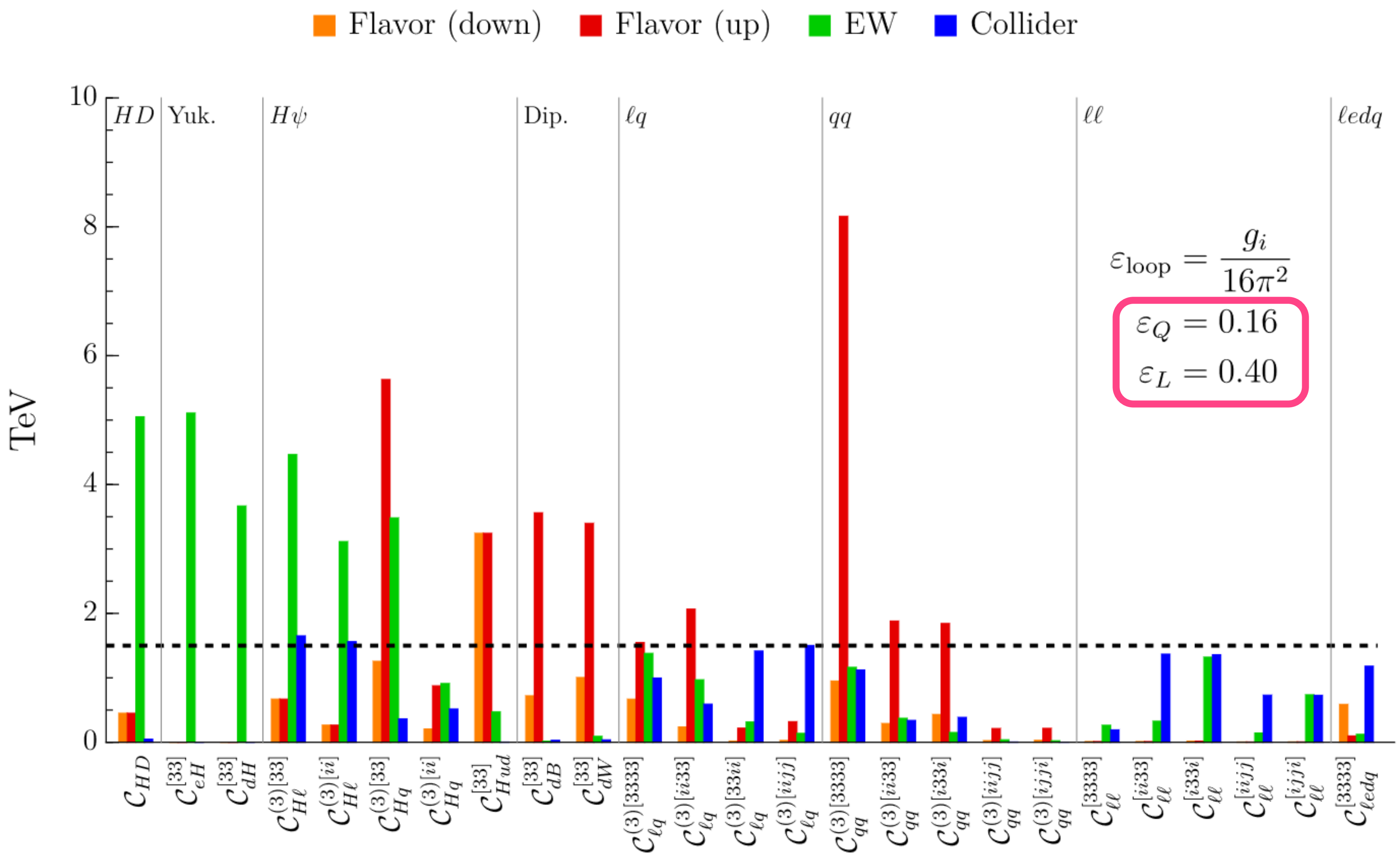

U2-like

Allwicher, Cornella, Isidori, Stefanek, [2311.00020]

Mild suppression of operators with light-generation quarks and leptons

Lowering Λ_{NP} with U2

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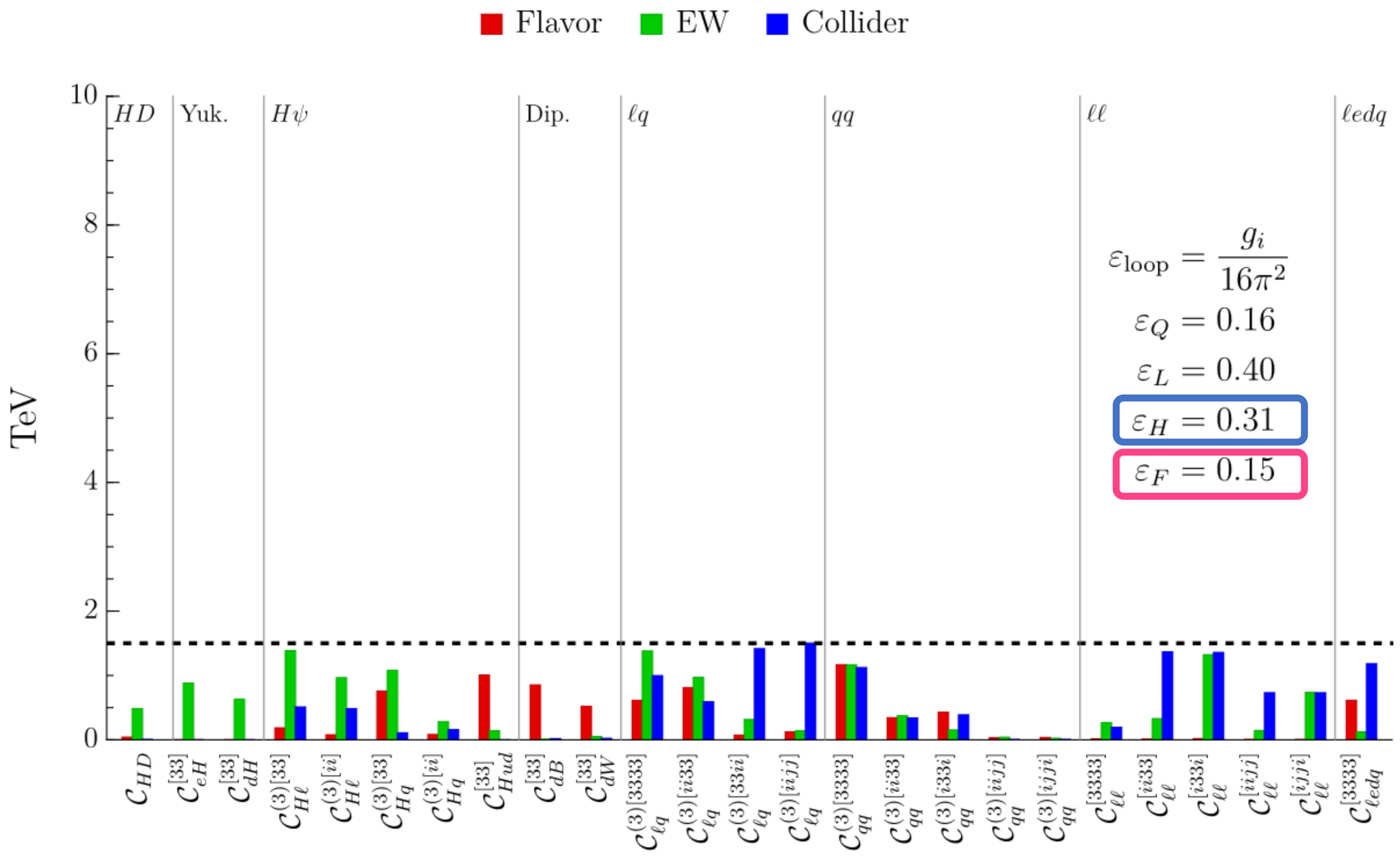


U2-like

Allwicher, Cornella, Isidori, Stefanek, 2311.00020

Mild suppression of operators with light-generation quarks and leptons

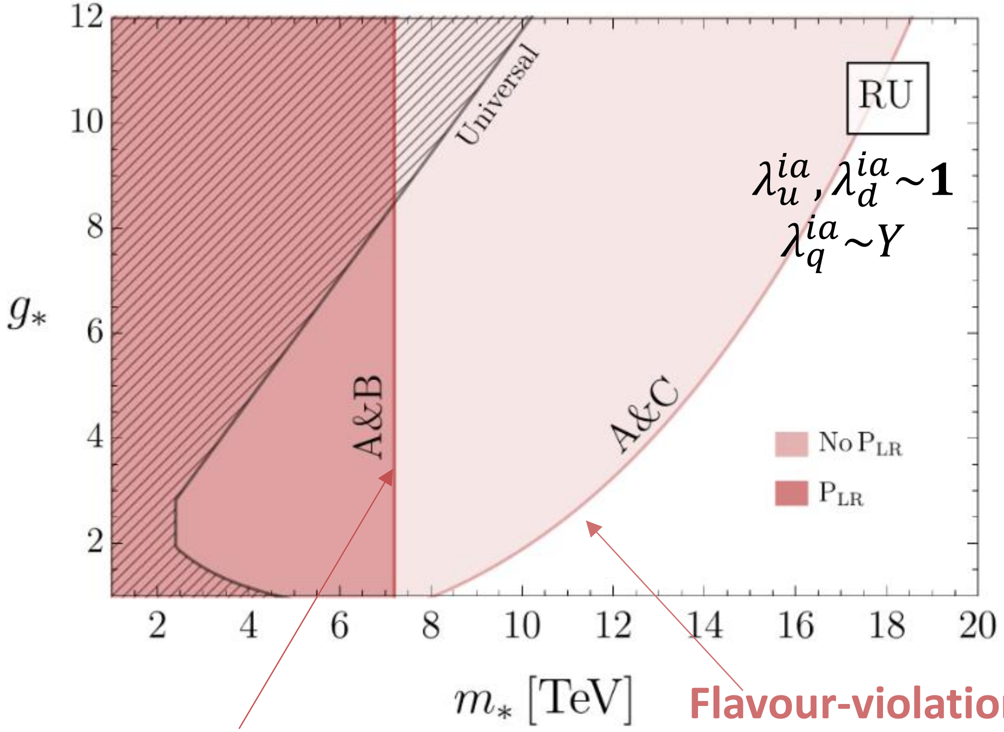
+ suppression of Higgs insertions
+ approximate down-alignment

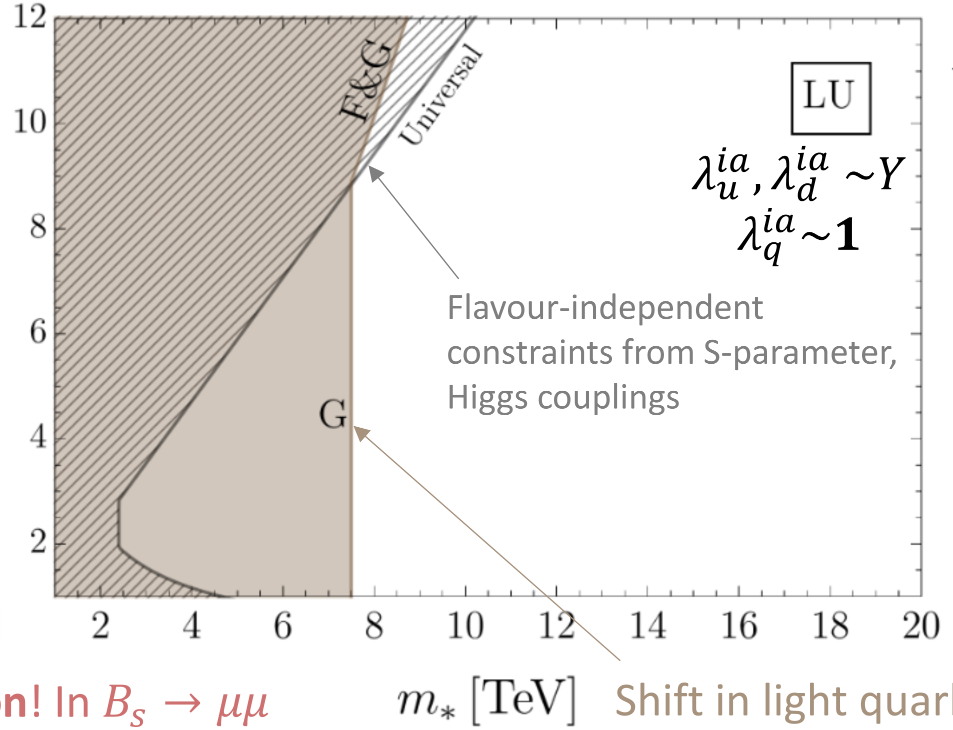
Lowering Λ_{NP} with U2

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-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

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

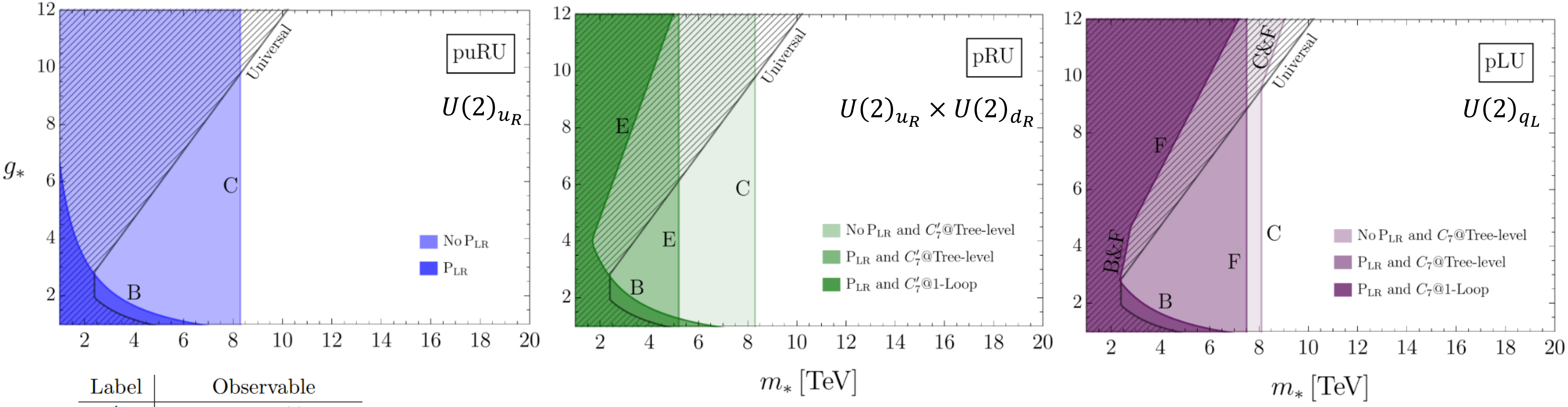
Strongest current bounds are driven by couplings to **light generation fermions** OR **flavour violation**, not EW constraints

Lowering Λ_{NP} with U2

Exhibit C: composite Higgs solutions to hierarchy problem

With U2 + P_{LR}: $M_* \gtrsim 1 \div 2$ TeV

Glioti, Rattazzi, Ricci, Vecchi, 2402.09503



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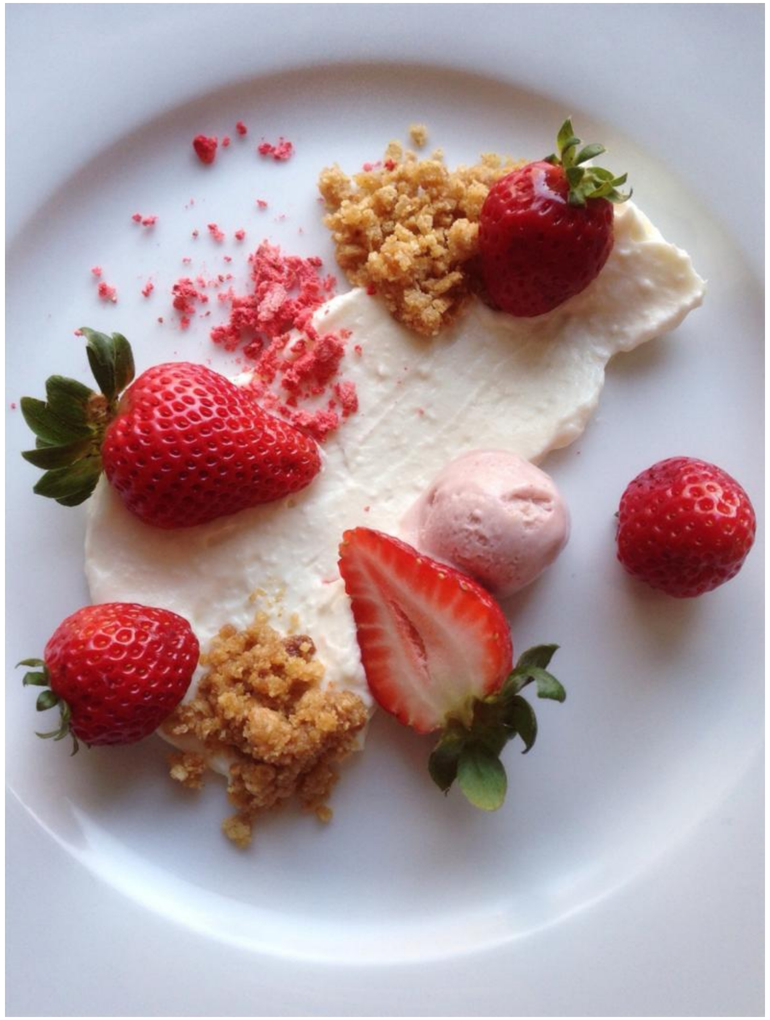
F	$B \to X_s \gamma$ (C_7)
~~G~~	~~W-coupling~~

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

So far we have considered the pheno consequences of $U(2)^n$ imposed as a global symmetry

What might be the origin of this $U(2)^n$?

3. On the Origin of U2: Flavour Deconstruction



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

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

But what symmetry to gauge? There are many options…

Flavour non-universal gauge interactions

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

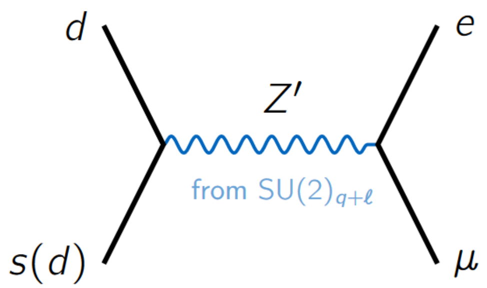
Froggatt, Nielsen, Nucl Phys B (1979)

Gauge some $H \subset U(2)^n \times U(1)_3^m$ directly, and break to nothing

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

But typically **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

Li, Ma, 1981, …
Arkani-Hamed, Cohen, Georgi hep-th/0104005 …
Craig, Green, Katz 1103.3708 …
Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368 …
Davighi, Isidori, 2303.01520

$$G_1 \times G_2 \times G_{3+\mathrm{H}} \xrightarrow{\langle \phi_{12} \rangle \sim 10^{2\div 3}\ \mathrm{TeV}} G_{12} \times G_{3+\mathrm{Higgs}} \xrightarrow{\langle \phi_{12} \rangle \sim 1\ \mathrm{TeV}} G_{123} = G_{\mathrm{SM}}$$

$y_1 \ll y_2$
$U(2)$ violation

$y_{12} \ll y_3$
Universality violation

Can reside near 1 TeV because no direct flavour violation at the low scale (more later…)

Flavour non-universality, non-horizontally

Deconstruction Approach

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$y_{12} \ll y_3$
Universality violation

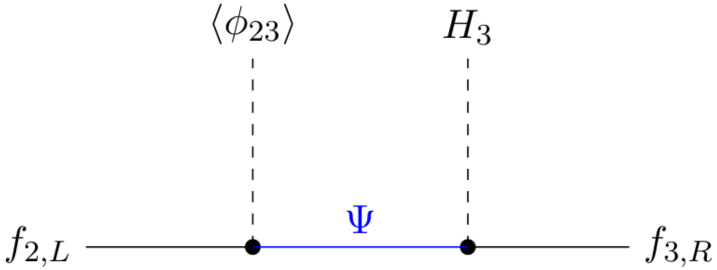
How it explains SM flavour:

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

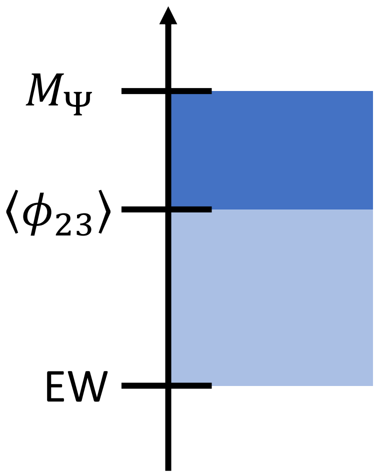
To connect 3rd family / Higgs to 1st family, $\phi_{12}\phi_{23}$ insertion $\Longrightarrow \frac{v_{12}}{\Lambda_{12}}\frac{v_{23}}{\Lambda_{23}}$ suppression

Example UV:

Vector-like fermions



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



Flavour non-universality, non-horizontally

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$$G_1 \times G_2 \times G_{3+\mathrm{H}} \xrightarrow{\langle\phi_{12}\rangle \sim 10^{2\div3}\,\mathrm{TeV}} G_{12} \times G_{3+\mathrm{Higgs}} \xrightarrow{\langle\phi_{12}\rangle \sim 1\,\mathrm{TeV}} G_{123} = G_{\mathrm{SM}}$$

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Davighi, Isidori, 2303.01520

Further theoretical appeal:

1. Charge assignment and anomaly-freedom inherited from SM – no *ad hoc* choices
2. Breaking pattern $G_A \times G_B \to G_{A+B}$, 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 (flavour-universal) subgroup
   - … because there is no other non-trivial subgroup embedding, by *Goursat's lemma*
3. Easy to find semi-simple UV completions with deconstruction approach
   - In contrast most $G_{\mathrm{SM}} \times U(1)_X$, even anomaly-free, have no semi-simple completion

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

Davighi, Tooby-Smith, 2206.11271

From Deconstruction to Unification

Davighi, Tooby-Smith, 2201.07245, Davighi, 2206.04482

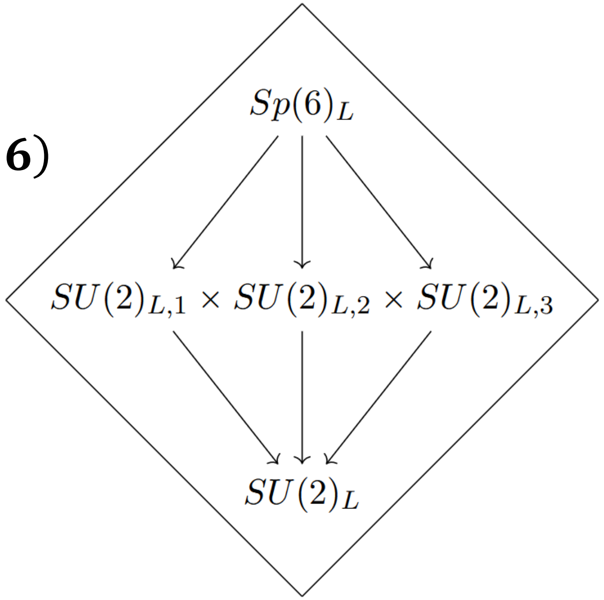
Whence $G_1 \times G_2 \times G_{3+\mathrm{H}}$? One path is to **reunify** in the UV! Using e.g. $SU(2)^{n_f} \cong Sp(2)^{n_f} \hookrightarrow Sp(2n_f)$

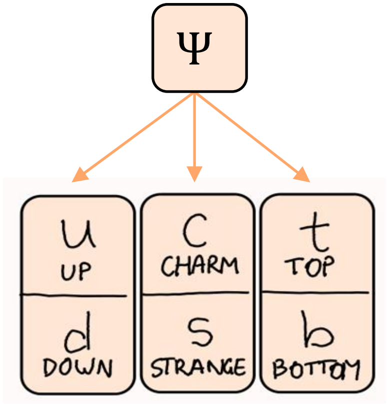
Electroweak flavour unification: $\mathrm{G}_{\mathrm{UV}} = SU(4) \times Sp(6)_L \times Sp(6)_R$

- **All SM matter unified*** into a single pair $\Psi_L \sim (\mathbf{4}, \mathbf{6}, \mathbf{1}) + \Psi_R \sim (\mathbf{4}, \mathbf{1}, \mathbf{6})$

Reminder:

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





*Very few anomaly-free options that do this!
See the classification of all embeddings of 3-flavour SM gauge algebra: Allanach, Gripaios, Tooby-Smith, 2104.14555

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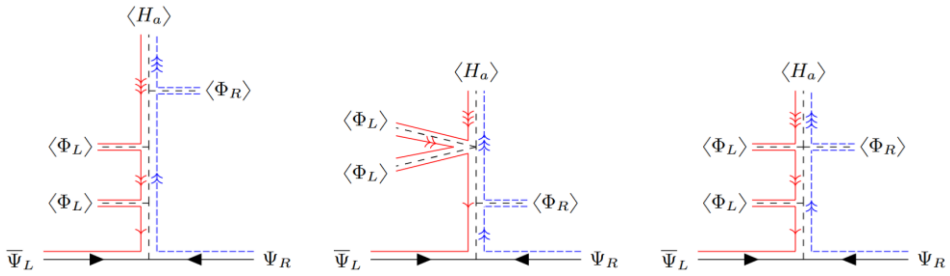
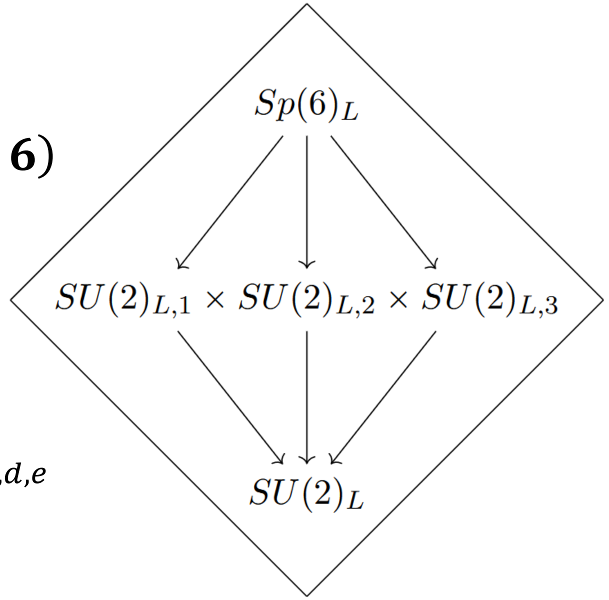
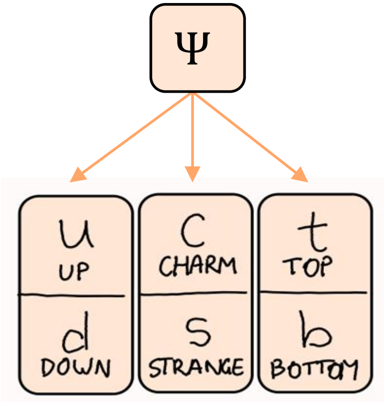
- **All SM matter unified*** into a single pair $\Psi_L \sim (\mathbf{4}, \mathbf{6}, \mathbf{1}) + \Psi_R \sim (\mathbf{4}, \mathbf{1}, \mathbf{6})$
- Offers a "gauge answer" to "why 3 generations?"
- Solves flavour puzzle with the minimal ingredients

E.g.



$\rightarrow Y_{12}^{u,d,e}$





- Low-energy pheno matches that of deconstruction…

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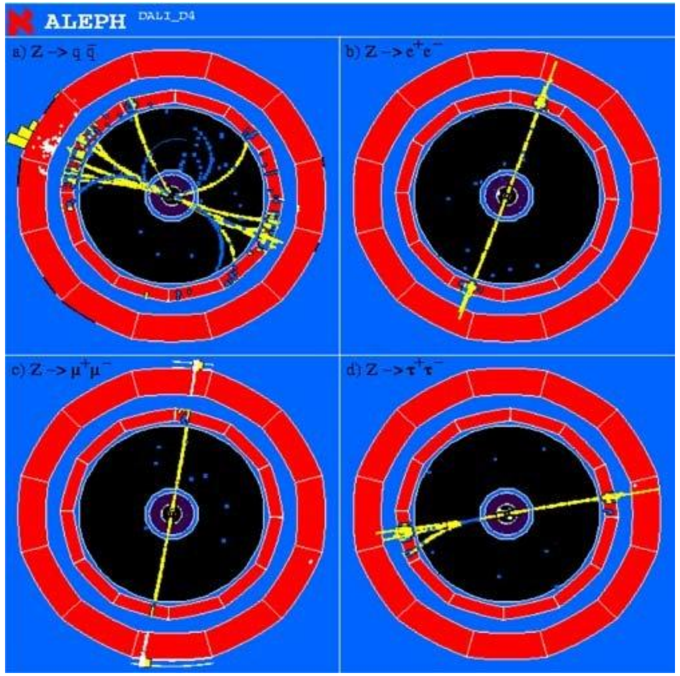
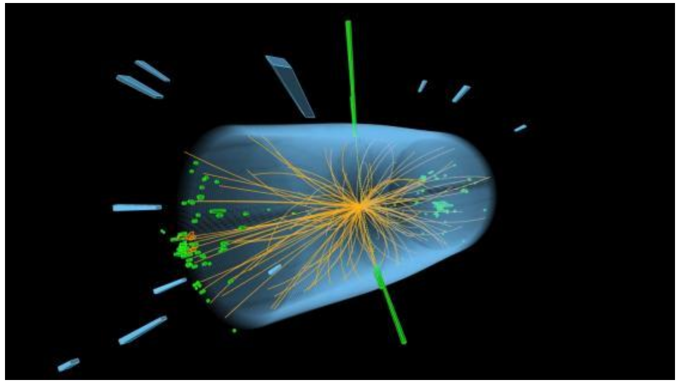
4. Phenomenology of Flavour Deconstruction





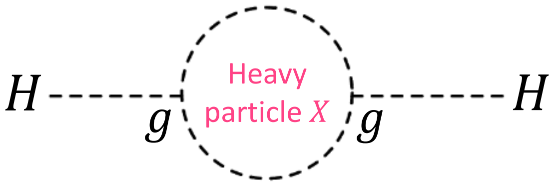
Phenomenology of Flavour Deconstruction

Deconstruction approach has much richer phenomenology than the horizontal approach

$G_{12} \times G_{3+\mathrm{Higgs}} \to G_{123}$ gives vectors in adj G, w flavour diagonal BUT non-universal couplings

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

- $G_{12} \times G_{3+H} \to G_{\mathrm{SM}}$ **can** occur near TeV because **no flavour violation**, + $g_3 \gg g_{1,2}$ **U2 limit** possible
- $G_{12} \times G_{3+H} \to G_{\mathrm{SM}}$ **should** occur near TeV to not worsen the little hierarchy problem



$$\delta m_h^2 \sim \frac{g_{\mathrm{SM}}^2 \tan^2\theta \, M^2}{16\pi^2}$$

Davighi, Isidori 2303.01520
Davighi, Gosnay, Miller, Renner 2312.13346 + …

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

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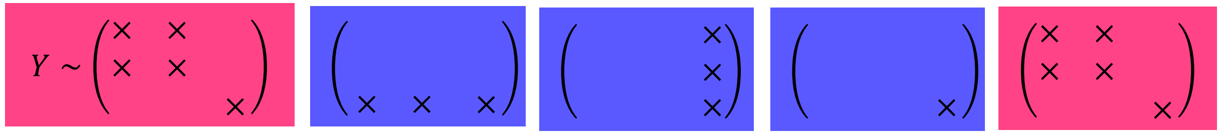

"EWPO"s:

	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

Survey of Flavour Deconstruction models

Davighi, Isidori 2303.01520

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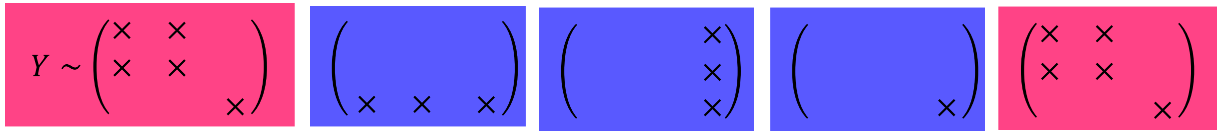
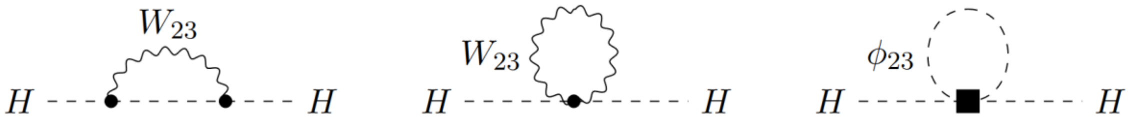
Flavour	$\lvert V_{cb}\rvert \ll 1$ $y_i \ll y_3$	✓ ×	✓ ✓	× ✓	✓ ✓	✓ ×
EW	Natural upper limit of $\lvert \tan\theta \rvert M$ EWPOs order	90 TeV 1-loop	20 TeV Tree	40 TeV Tree	40 TeV Tree	500 TeV 1-loop



"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

Survey of Flavour Deconstruction models

Davighi, Isidori 2303.01520

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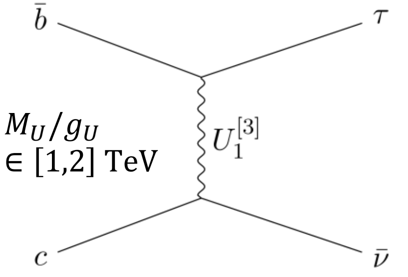
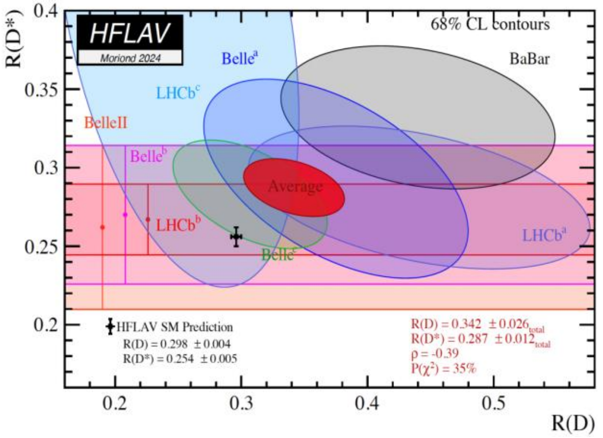
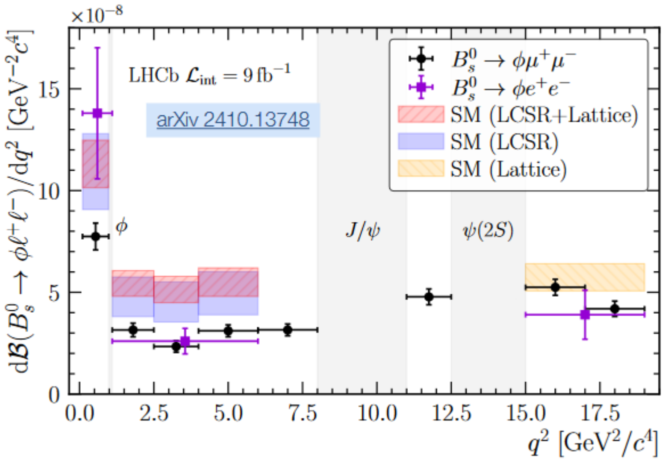
	EWPOs order	1-loop	Tree	Tree	Tree	1-loop

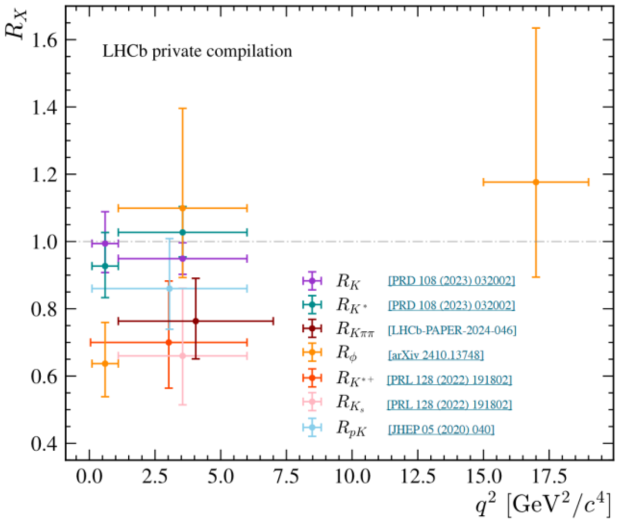
Aside: If enlarge $SU(3)^{[3]} \to SU(4)^{[3]}$, can also explain $b \to c\tau\nu$ anomalies in $R_{D^{(*)}}$ & $bs\mu\mu$ via '4-3-2-1' models



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 ...







Experimental hints for deconstruction near TeV?

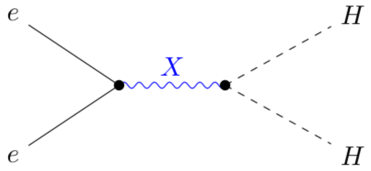
LHCb Implications 2024

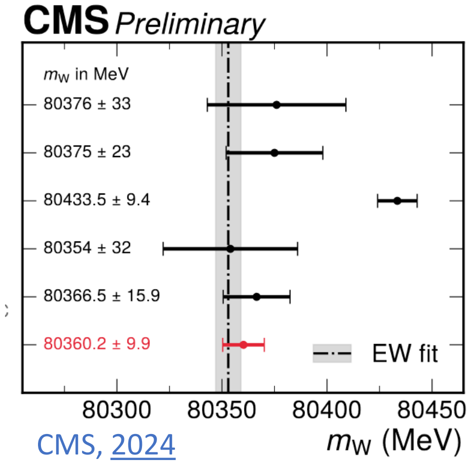
Phenomenology of Deconstructed EW Forces

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

EWPOs: tree-level shifts in Z/W-pole means EW constraints often strongest!

- A key observable is m_W: $\mathrm{D}SU(2)_L \Rightarrow \delta m_W < 0$; $DU(1)_Y \Rightarrow \delta m_W > 0$

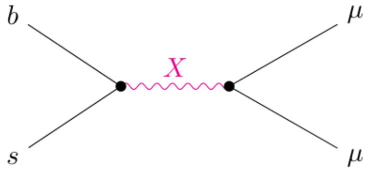


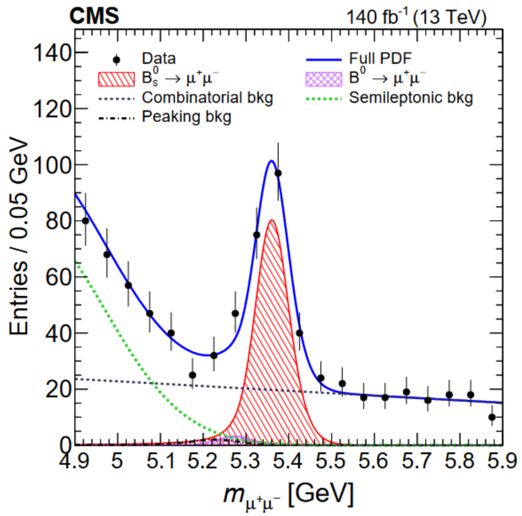


CMS, 2024

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

- B_s mixing strictly subleading in these models

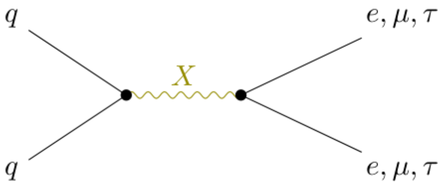




CMS, 2212.10311

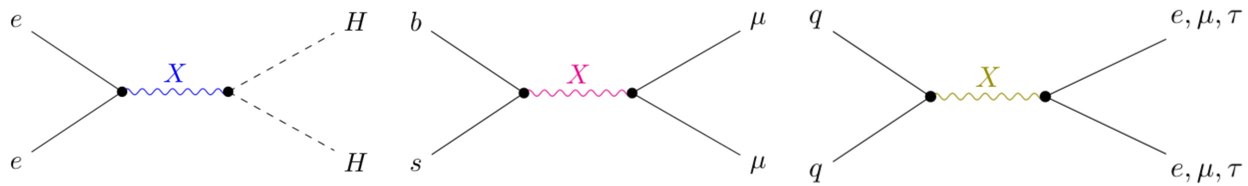
LHC high p_T: driven by valence-quark couplings

- Favours $g_3 \gg g_{12}$ region i.e. $\theta \to \pi/2$



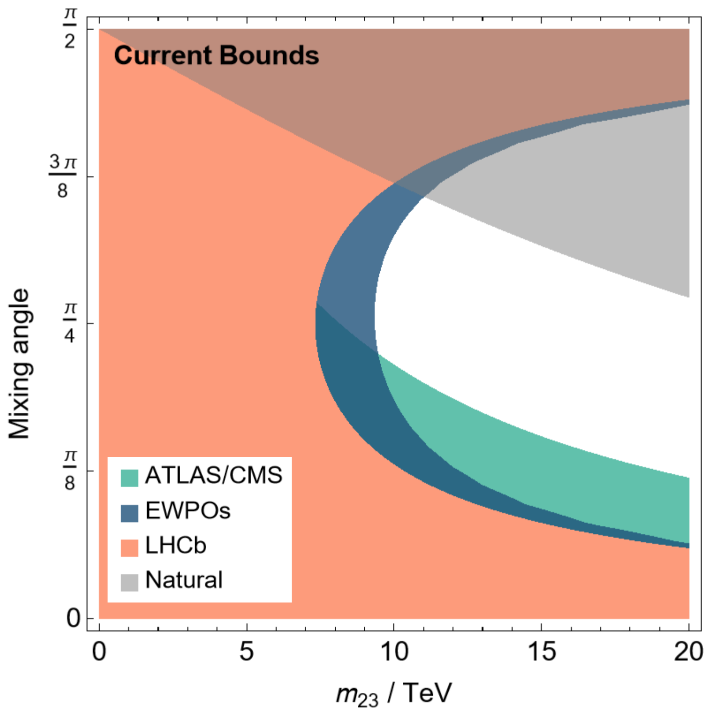
Phenomenology of Deconstructed EW Forces

Davighi, Gosnay, Miller, Renner 2312.13346 + …



See also Capdevila, Crivellin, Lizana, Pokorski 2401.00848

Ex: $Sp(6)_L \to SU(2)_L^3 \to SU(2)_L$ [pheno of Electroweak Flavour Unification]



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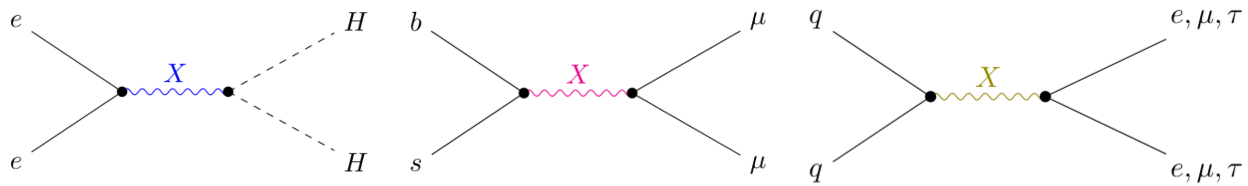

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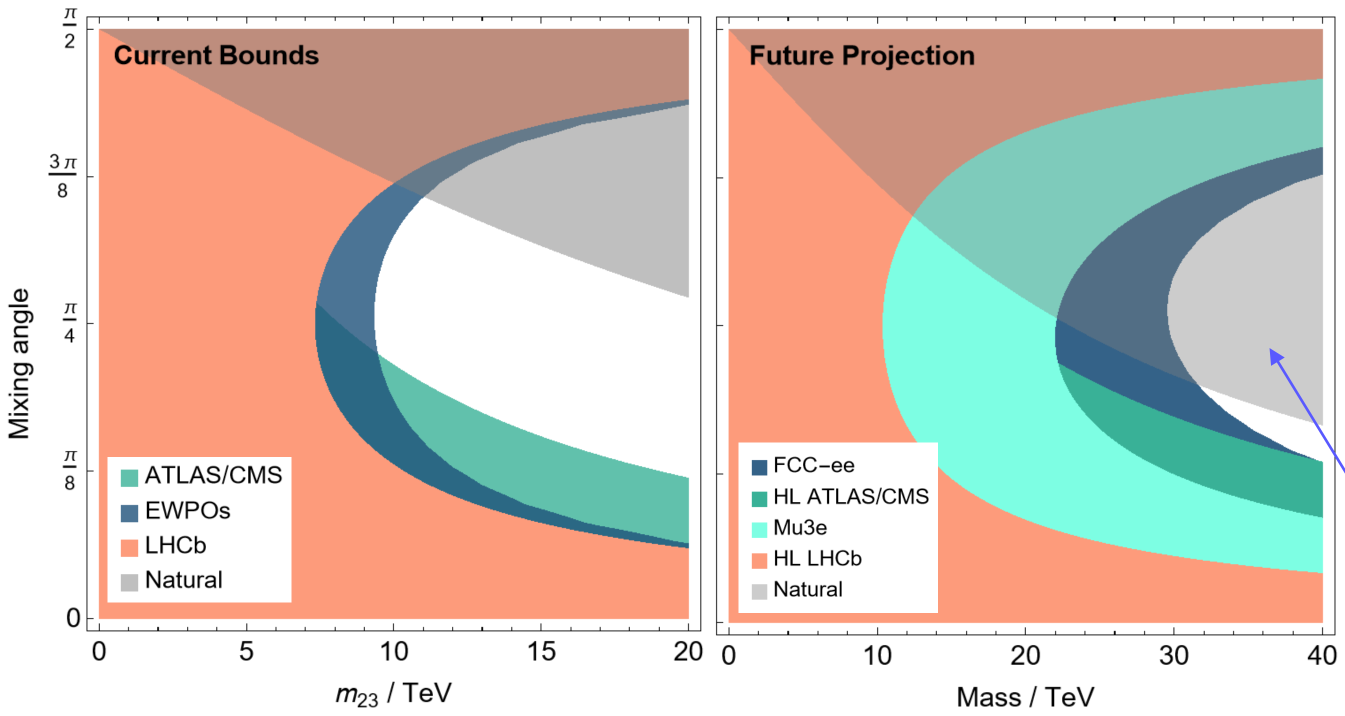
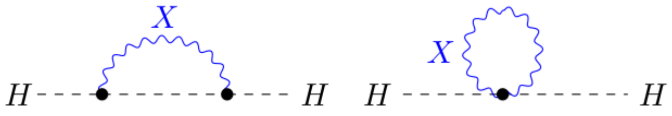


Showcases complementarity of **FCC** and **HL**

- HL-LHC Drell—Yan and Mu3e rule out impressive parameter space in the medium term before FCC-ee
- Tera-Z EW precision programme can cover entire natural parameter space
- Tau LFUV alone at FCC-ee probes 11 TeV

$$\delta m_h^2 \sim \frac{g_{SM}^2 \tan^2\theta \, M^2}{16\pi^2} > \text{TeV}^2$$

worsens hierarchy problem…



Aside: Flavour Opportunities at FCC-ee

Monteil, Wilkinson, 2106.01259

Particle production (10^9)	$B^0/\overline{B}^0$	B^+/B^-	$B_s^0/\overline{B}_s^0$	$B_c^+/\overline{B}_c^-$	$\Lambda_b/\overline{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	n/a	65	45
FCC-ee	620	620	150	4	130	600	170

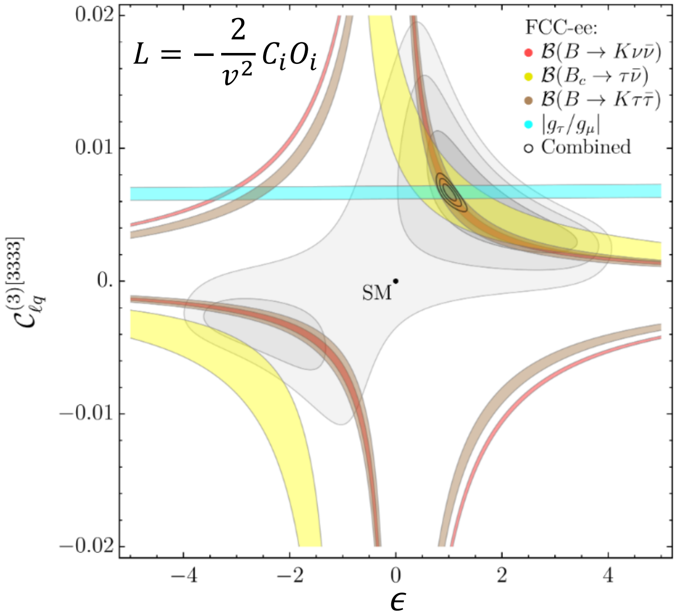
- Vs. B factories: tera-Z statistics → 15x (at least…) more $b\bar{b}$ pairs than Belle II + BOOSTED!
- Vs. LHC: clean environment → precision measurements with neutrinos (taus)

FCC-ee flagships

1. $B \to K^*\tau\tau$ new frontier!
2. $B_c \to \tau\nu$ new frontier!
3. $b \to s\bar{\nu}\nu$ 10% to 1% precision

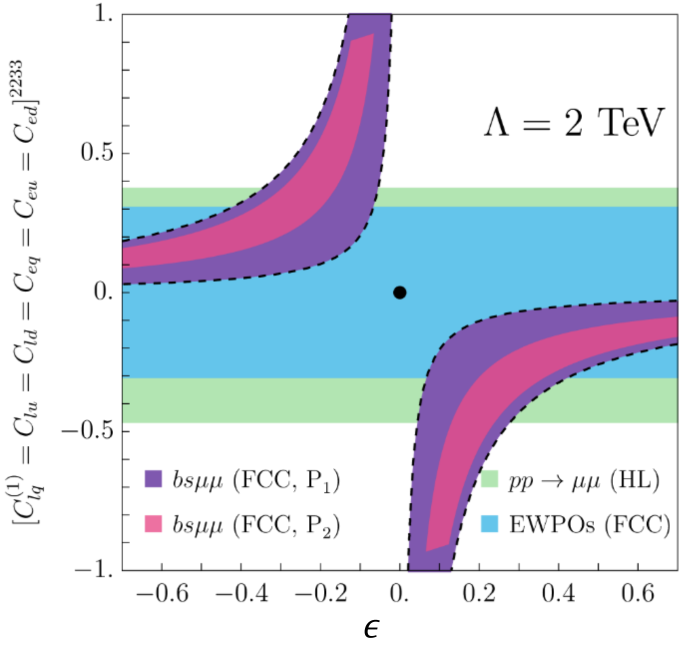
Kamenik, Monteil, Semkiv, Vale Silva 1705.11106
Miralles, Thesis 2024
Amhis, Hartmann, Helsens, Hill, Sumensari, 2105.13330
Zuo, Fedele, Helsens, Hill, Iguro, Klute, 2305.02998
Amhis, Kenzie, Reboud, Wiederhold, 2309.11353

$b \to s\tau\tau$



Allwicher, Isidori, Pesut, 2503.17019

$b \to s\mu\mu$



Bordone, Cornella, Davighi, 2503.22635

Phenomenology of EW Flavour Deconstruction

Summary $DU(1)_Y$ vs. $DSU(2)_L$:

	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

5. Deconstructing the Composite Higgs

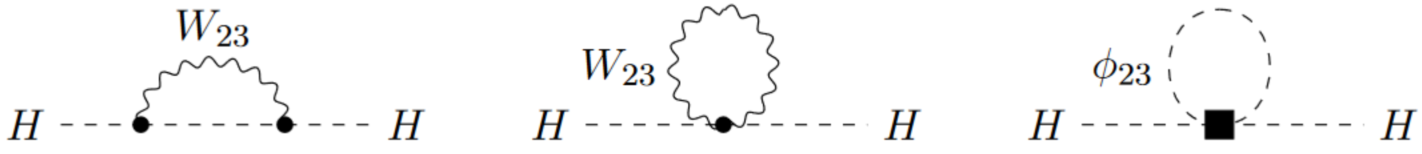
Covone, Davighi, Isidori, Pesut, 2407.10950

Back to the Hierarchy Problem

We saw that U2 is needed for $1 \div 2$ TeV comp Higgs solution to hierarchy problem

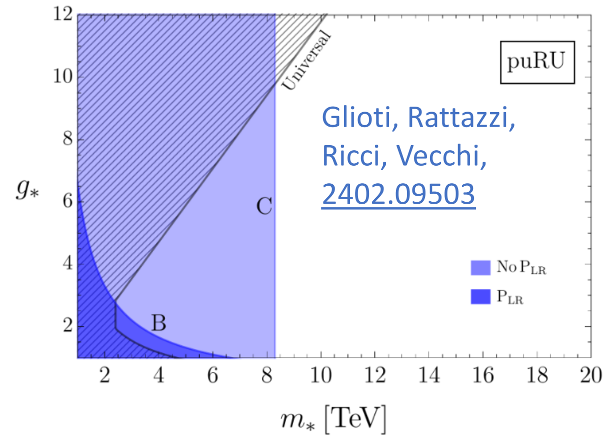
We also saw that flavour deconstruction can deliver U2 + solve flavour puzzle near TeV

- … but EWPOs + flavour + high pT push us to regions with large finite δm_h^2
- Motivates us to solve the hierarchy problem simultaneously

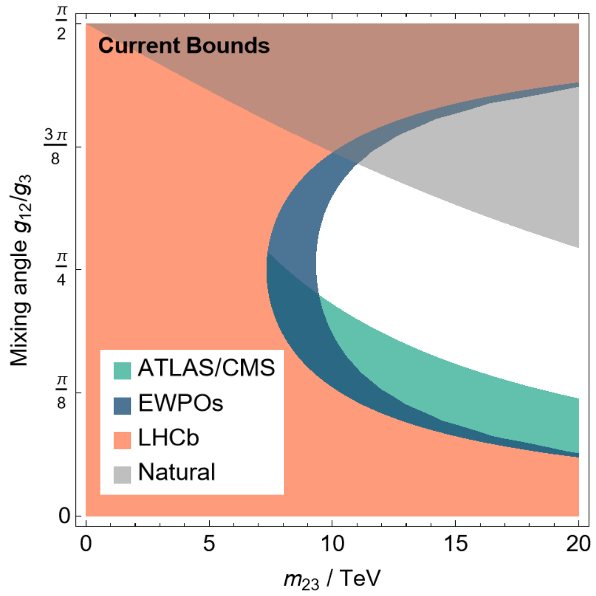


⟶ **Joint solution** near TeV of hierarchy problem & flavour puzzle?

Maybe the flavour deconstruction can even help *reduce* little hierarchy in CH?



Glioti, Rattazzi, Ricci, Vecchi, 2402.09503

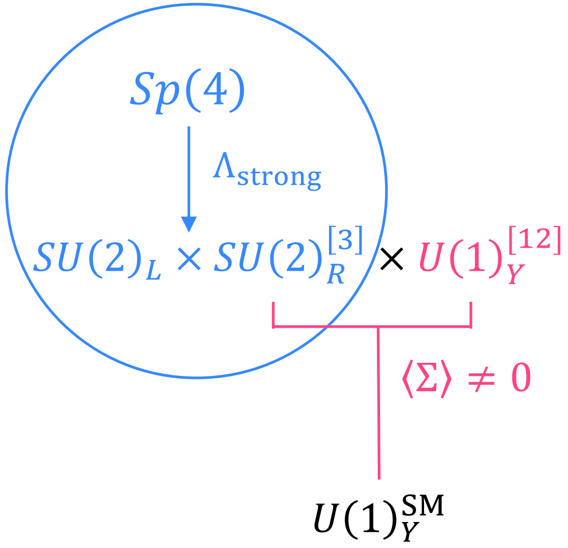


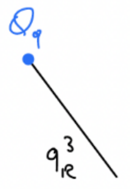
Higgs and Flavour – Together

Covone, Davighi, Isidori, Pesut, 2407.10950

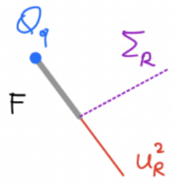
Flavour deconstruction can be combined with Comp Higgs at $\sim 2\ \mathrm{TeV}$:

- Delivers **gauge explanation** for $U(2)$ needed to reduce little hierarchy
- Compositeness cures large hierarchy problem
- Explains SM flavour puzzle in same dynamical step(s)!





3[rd] gen ~
partial
composite



1[st] /2[nd] gens ~
elementary

Higgs and Flavour – Together

Covone, Davighi, Isidori, Pesut, 2407.10950

Flavour deconstruction can be combined with Comp Higgs at ~ 2 TeV:

- Delivers **gauge explanation** for $U(2)$ needed to reduce little hierarchy
- Compositeness cures large hierarchy problem
- Explains SM flavour puzzle in same dynamical step(s)!
- Higgs potential:

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

Deconstruction helps the CHM be more natural!

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

CH makes deconstruction more predictive! (+ natural)

- Require $\boldsymbol{2M_{W_R}^2 < M_\rho^2}$ to avoid sign flip in m_h^2, i.e. deconstruction bosons must be sufficiently light
- Experiment dictates $M_{W_R} >$ few TeV. **Squeezed**!

Higgs and Flavour – Together

Covone, Davighi, Isidori, Pesut, 2407.10950

Flavour deconstruction can be combined with Comp Higgs at ~ 2 TeV:

- Delivers **gauge explanation** for $U(2)$ needed to reduce little hierarchy
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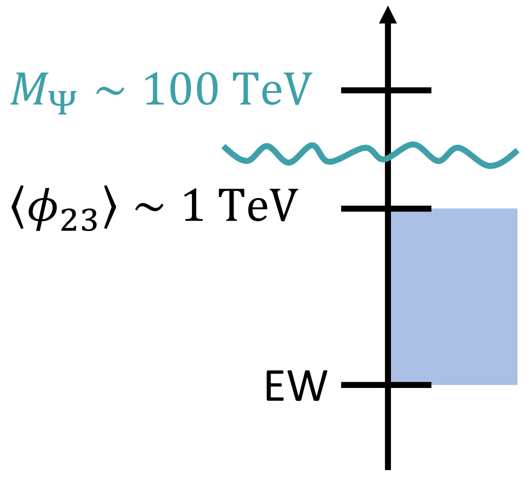

Deconstruction helps the CHM be more natural!

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- 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 ☺

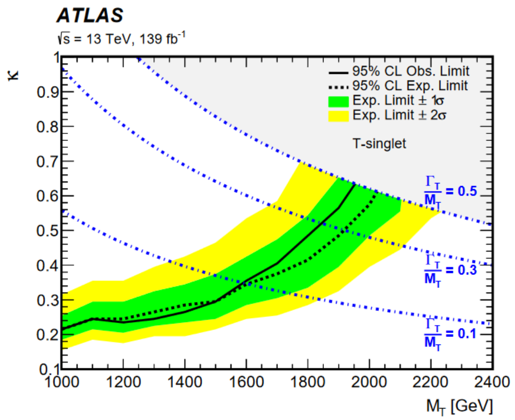
Higgs and Flavour – Together

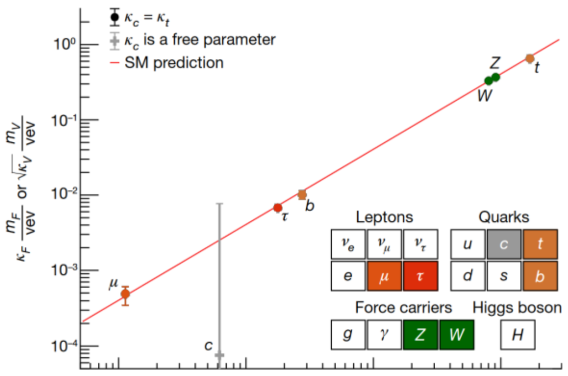
Covone, Davighi, Isidori, Pesut, 2407.10950

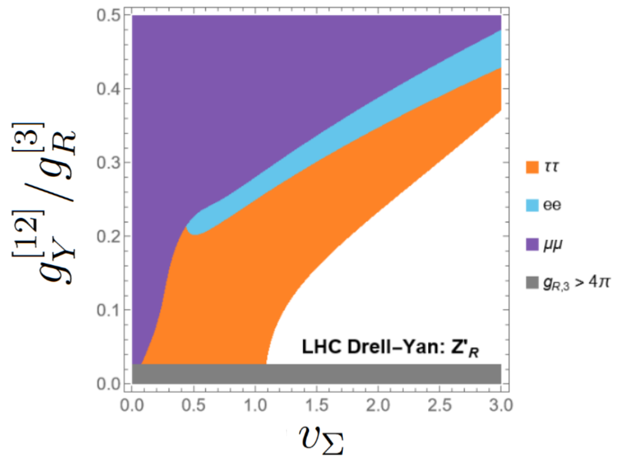
Phenomenology resembles that of minimal CHM with U2 x deconstructed gauge bosons

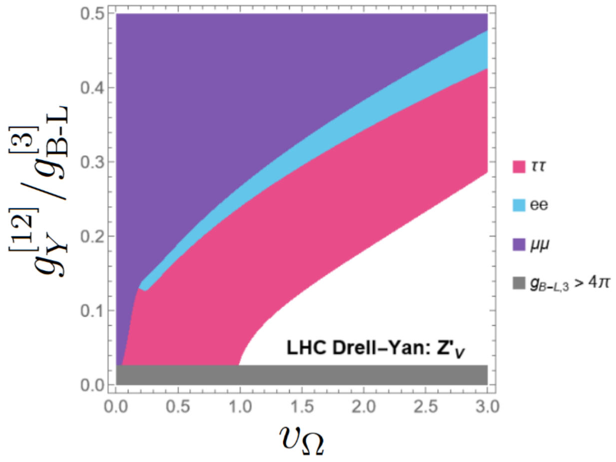
- Modified HWW and HZZ
- Top partners et al
- Universal shifts in EWPOs

- Flavour e.g. $B \to X_s\gamma$ particularly strong
- LHC Drell—Yan
- Non-universal shifts in EWPOs









Viable benchmark:

- 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

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

Pre-LHC: postpone flavour and solve the hierarchy problem with MFV

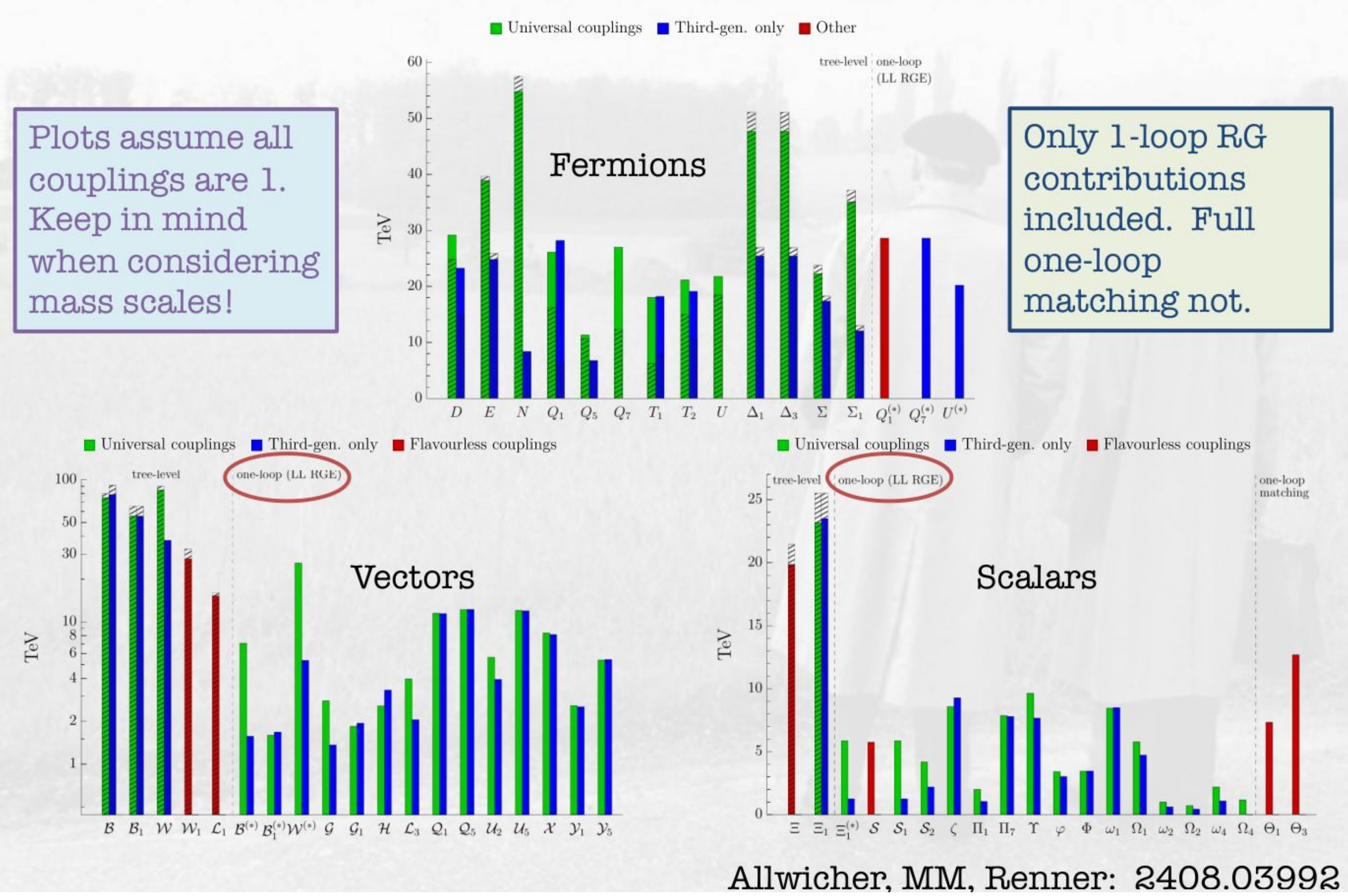
New vision: an intrinsically flavour non-universal approach can

1. Emerge from interesting new gauge-flavour unified theories
2. Render m_h more natural e.g. in composite Higgs framework
3. Simultaneously unlock the flavour puzzle e.g. by flavour deconstruction
4. … and has rich phenomenology: great potential at HL-LHC and FCC-ee is just beginning to be explored

Thank you!

Backup

EWPOs at tera Z probe most BSM to few TeV



Allwicher, McCullough, Renner, 2408.03992

Celada, Hoeve, Mantani, Rojo, Rossia, Thomas, Vryonidou, 2404.12809;

Hoeve, Mantani, Rojo, Rossia, Vryonidou, 2502.20453

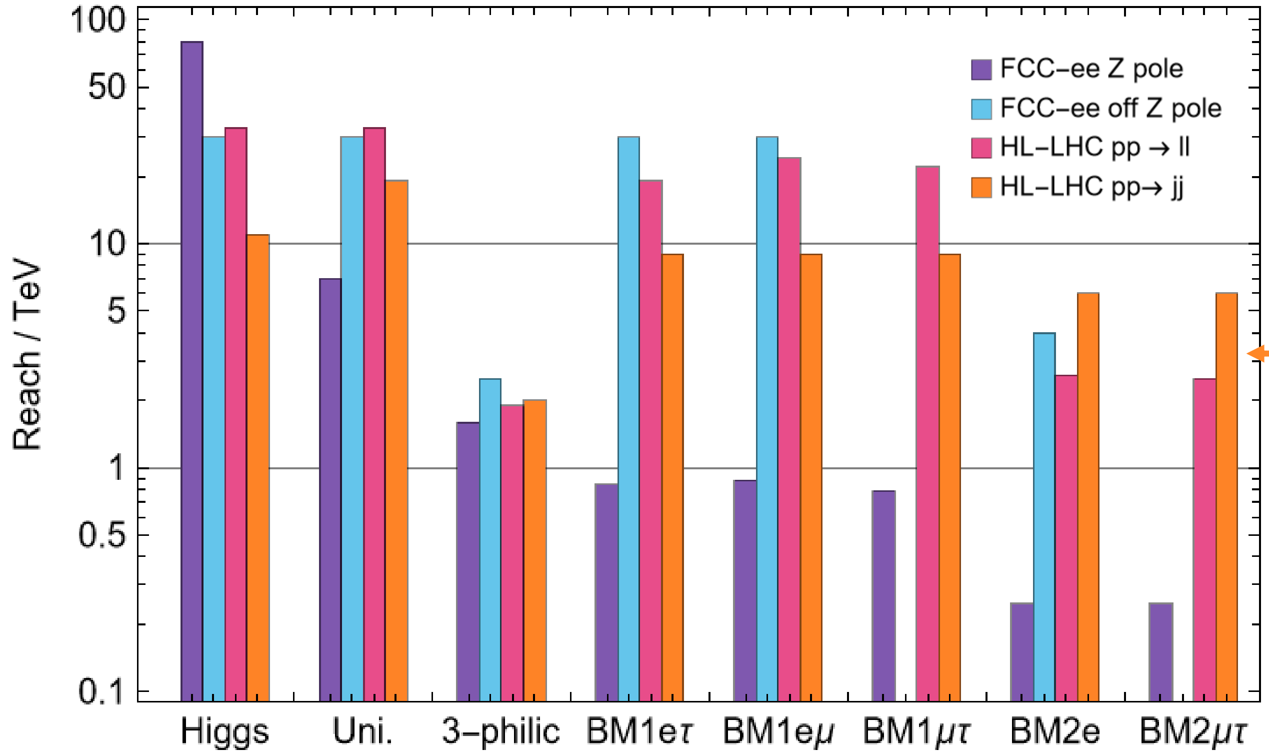
Slide from Matthew McCullough @ CERN EP/TH Faculty Meeting, Sep 2024

… with ≈ 1 exception

Davighi, 2412.07694

$\boldsymbol{Z'}$ **extension**, from a gauged $U(1)$**,** avoids running into EWPOs at 1-loop for the anomaly-free charges:

- $(U_1, U_2, U_3) = (X_u, -X_u, 0),$ $X_u = p^2 + q^2$
- $(D_1, D_2, D_3) = (X_d, -X_d, 0),$ $X_d = p^2 + 2pq - q^2$
- $(E_1, E_2, E_3) = (X_e, -X_e, 0),$ $X_e = -p^2 + 2pq + q^2$



Models that are "invisible" on the Z pole are very visible at LHC!

How to generate flavour in Composite Higgs Models?

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

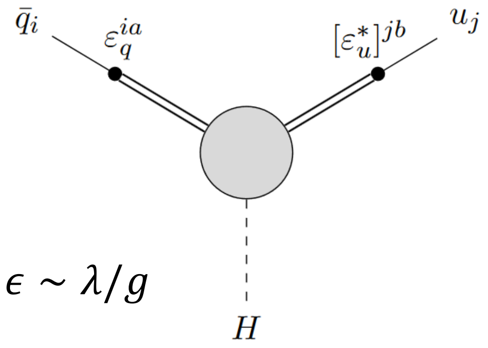
Cannot have Λ low due to flavour bounds

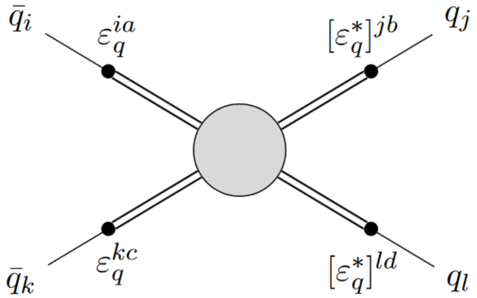
O_H is a composite scalar operator with quantum numbers of Higgs.
Want $d \approx 1$ to get large top Yukawa

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

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

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

[Even assuming 1-loop suppressed quark dipole operators]

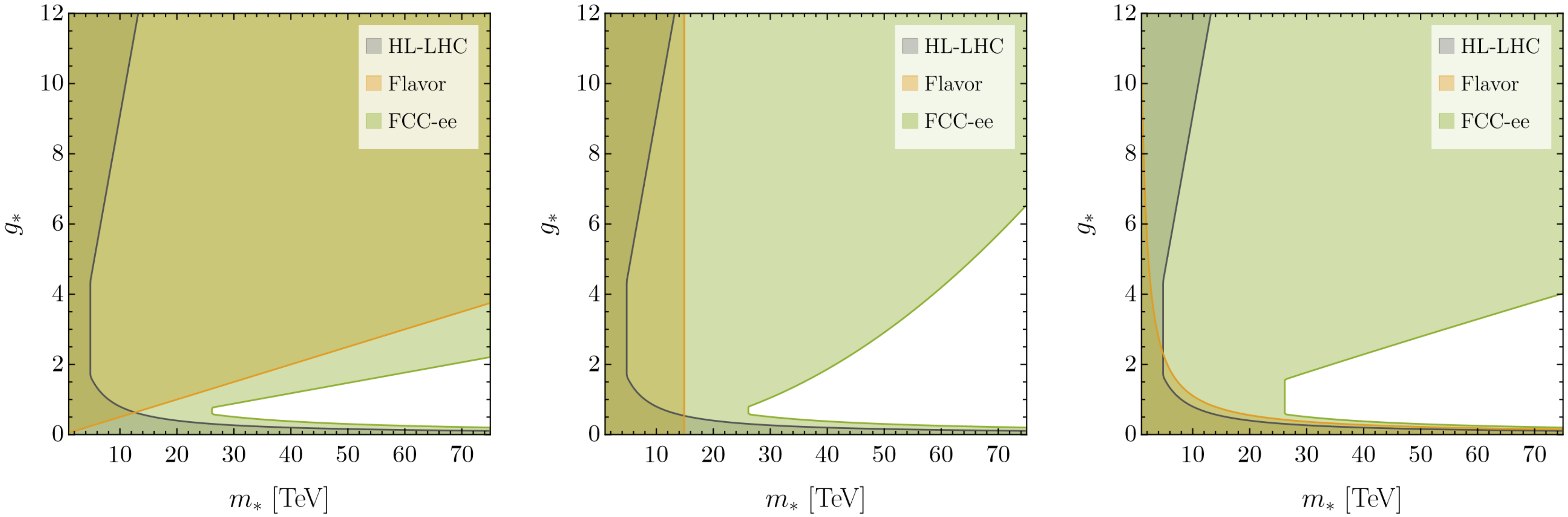
- Such a high scale degrades this as a solution to the hierarchy problem AND is untestable in colliders
- We **need** a flavour symmetry to bring down m_*

Composite Higgs @ HL-LHC, FCC-ee

- FCC-ee "tera-Z" run: approx. 10^5 times LEP dataset on Z-pole

Stefanek, 2407.09593

- 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

Composite Higgs @ HL-LHC, FCC-ee

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Stefanek, 2407.09593

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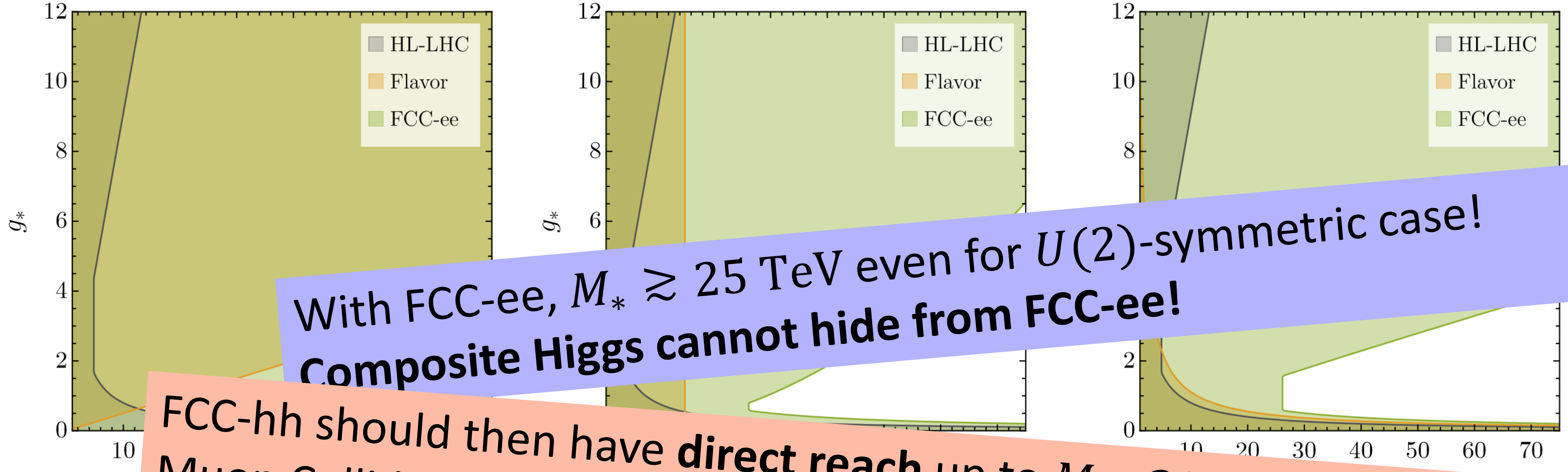


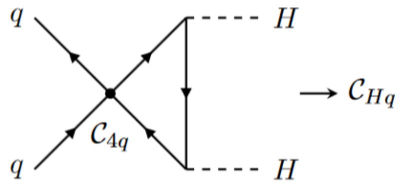
All 3 scenarios have $U(2)_{u_R} \times U(2)_{q_L}$

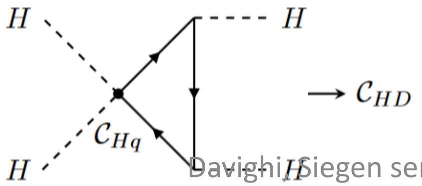
With FCC-ee, $M_* \gtrsim 25$ TeV even for $U(2)$-symmetric case!
Composite Higgs cannot hide from FCC-ee!

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]

(a) Left compositeness (b) Mixed compositeness

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





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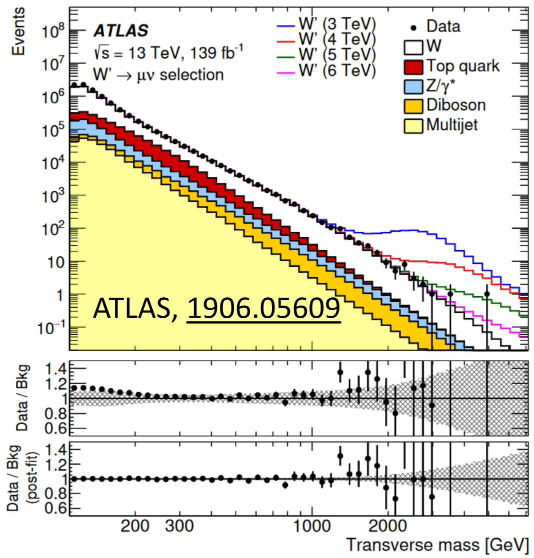
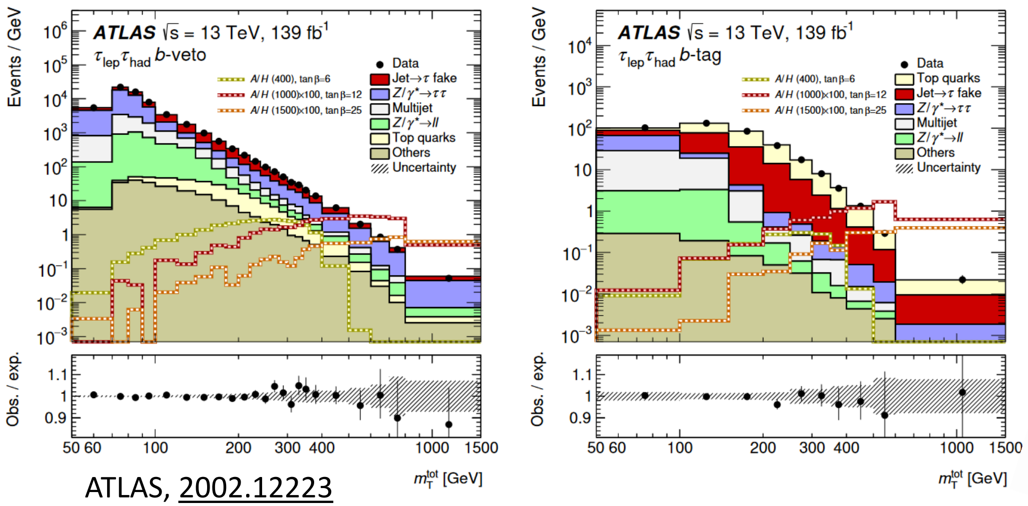
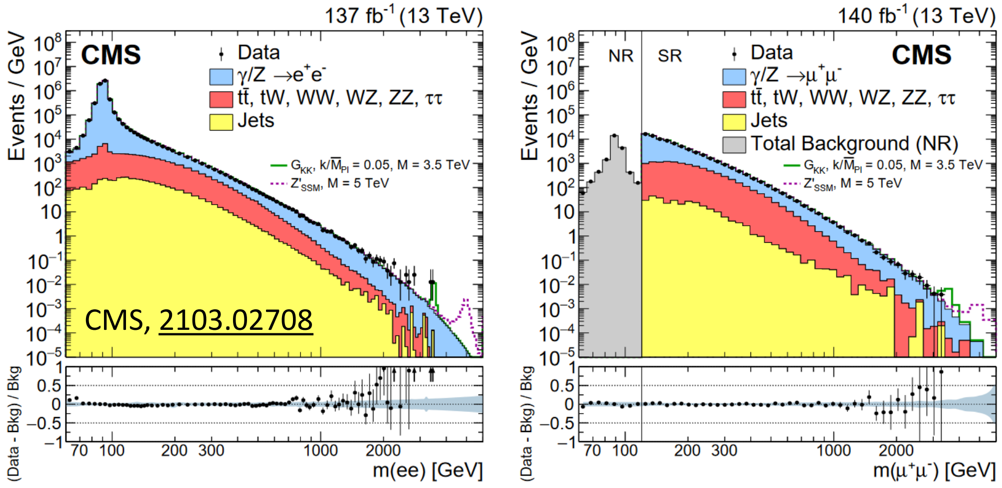
Deconstructed $SU(2)_L$: High mass LHC constraints

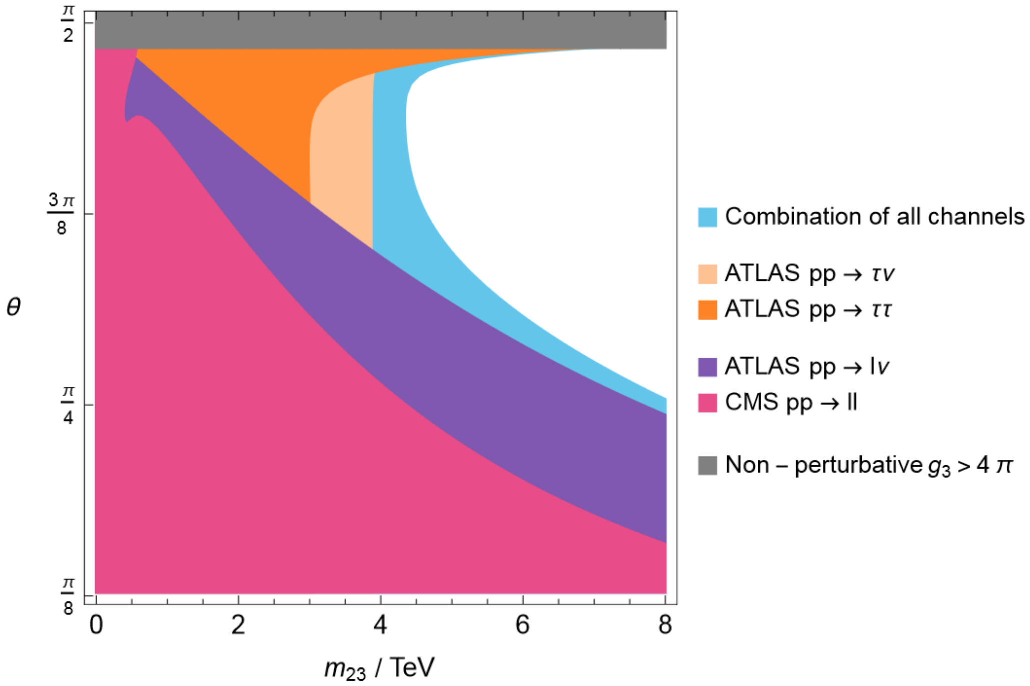




So far we just used LHC Drell-Yan data (139 fb^{-1}) to constrain the models

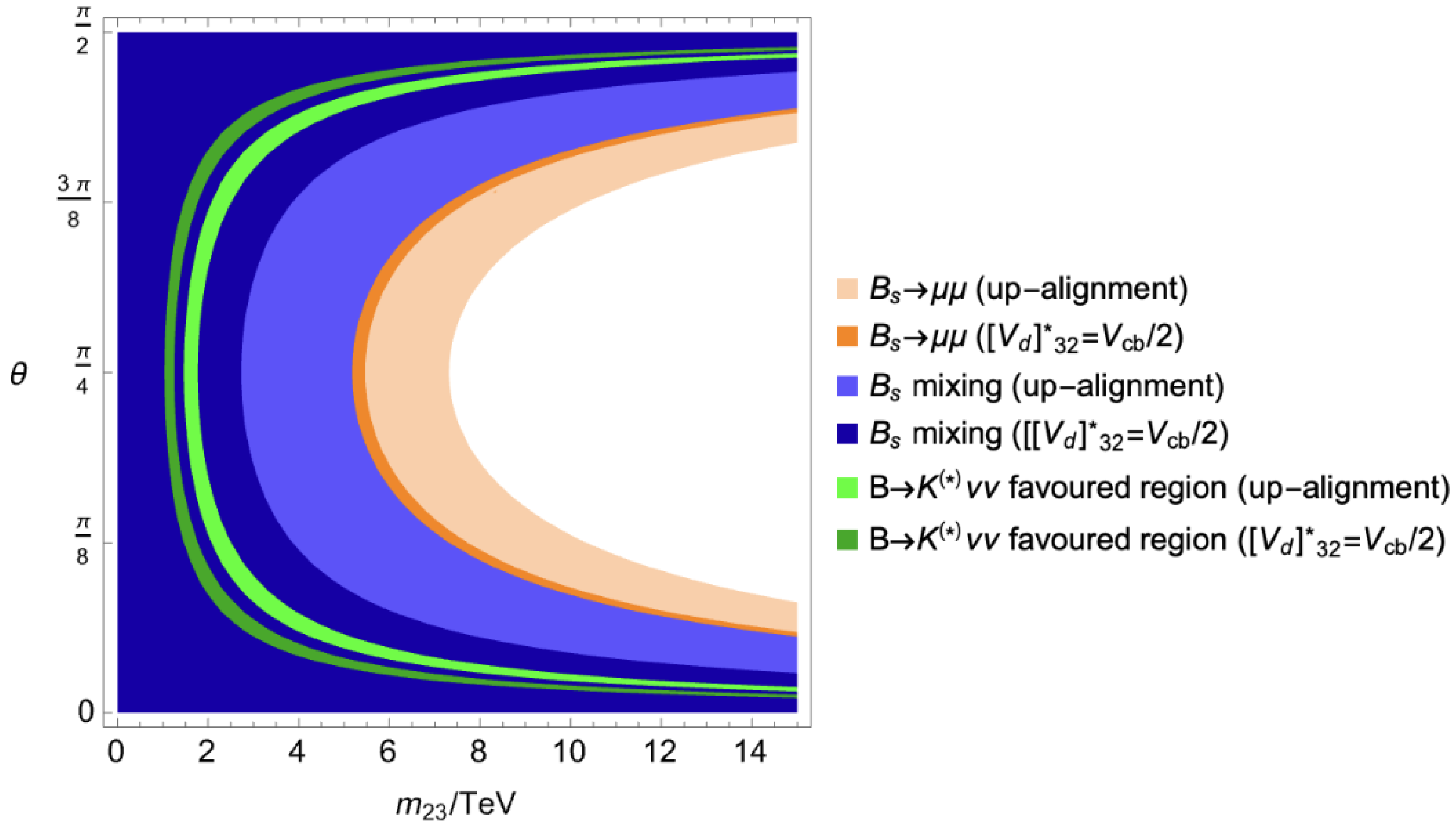
Many other collider probes are possible!



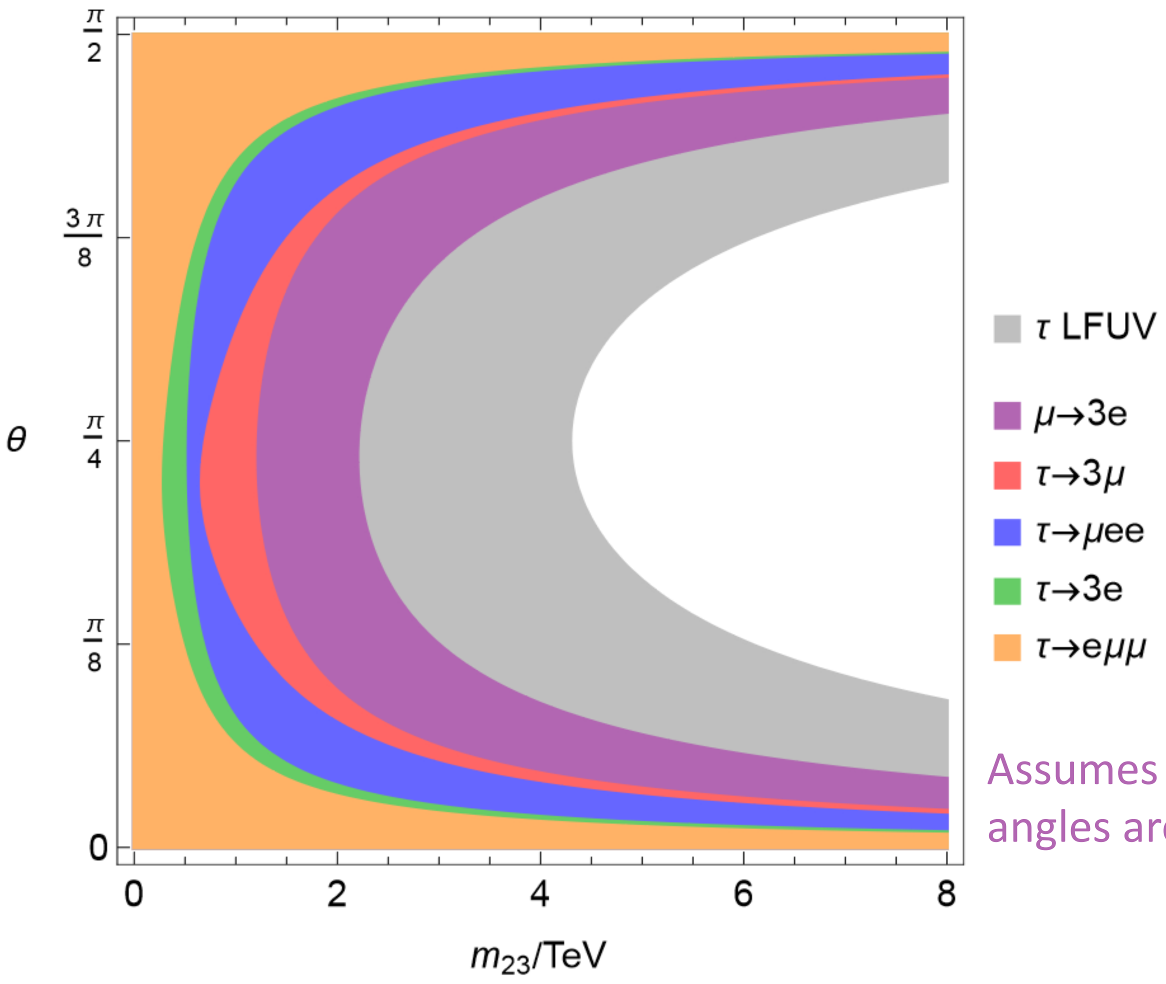


Deconstructed $SU(2)_L$: B-physics constraints

Davighi, Gosnay, Miller, Renner 2312.13346



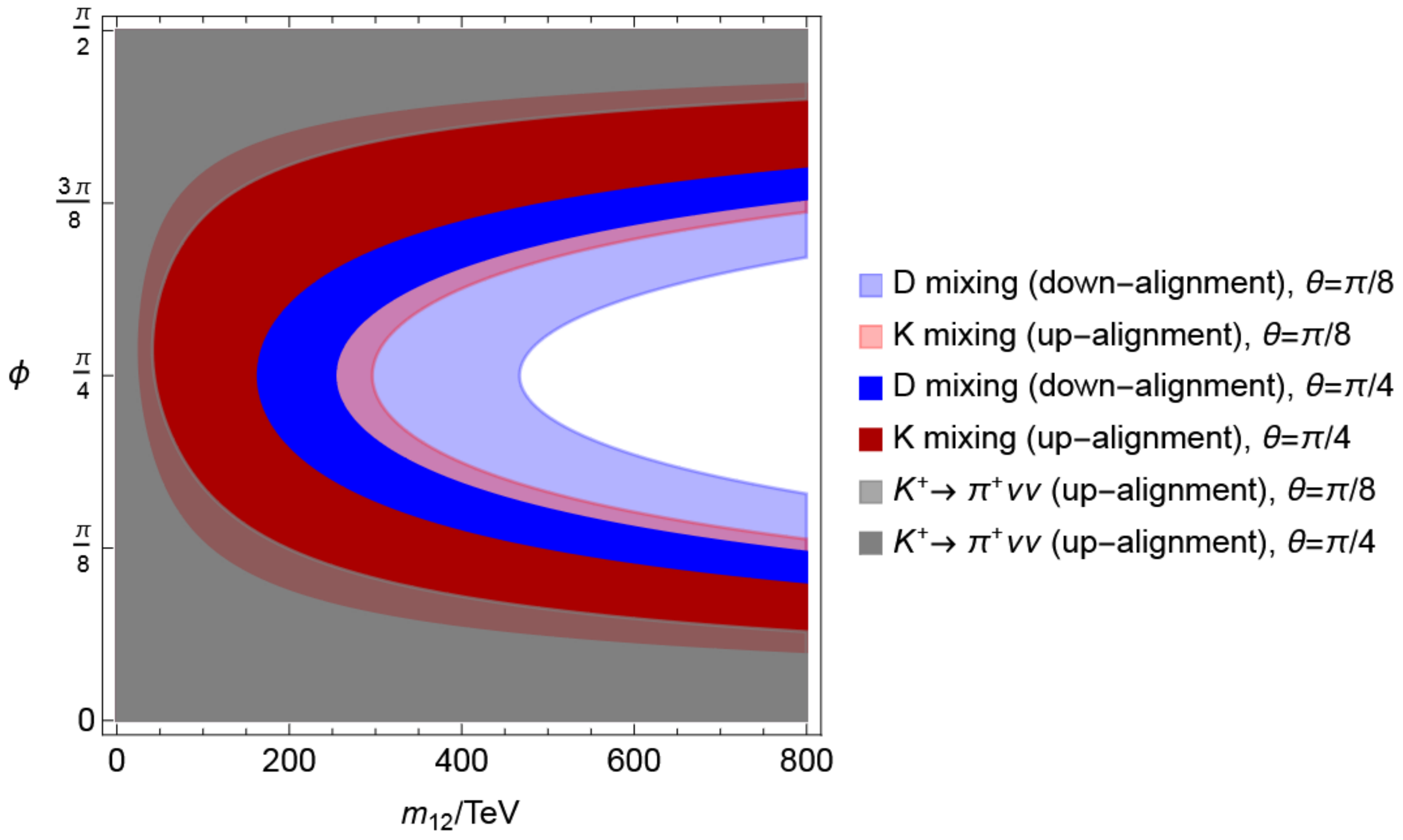
Deconstructed $SU(2)_L$: charged lepton constraints



Assumes LH charged lepton mixing angles are CKM-like

Deconstructed $SU(2)_L$: constraints on the 1-2 breaking

$$G_1 \times G_2 \times G_{3+\mathrm{H}} \xrightarrow{\langle \phi_{12} \rangle \sim 10^{2\div 3}\ \mathrm{TeV}} G_{12} \times G_{3+\mathrm{Higgs}}$$



Deconstructed $U(1)_Y$

See also
Fernández Navarro, King 2305.07690
Allanach, Davighi 1809.01158

Davighi, Stefanek 2305.16280

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)