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Quark and lepton flavour theory

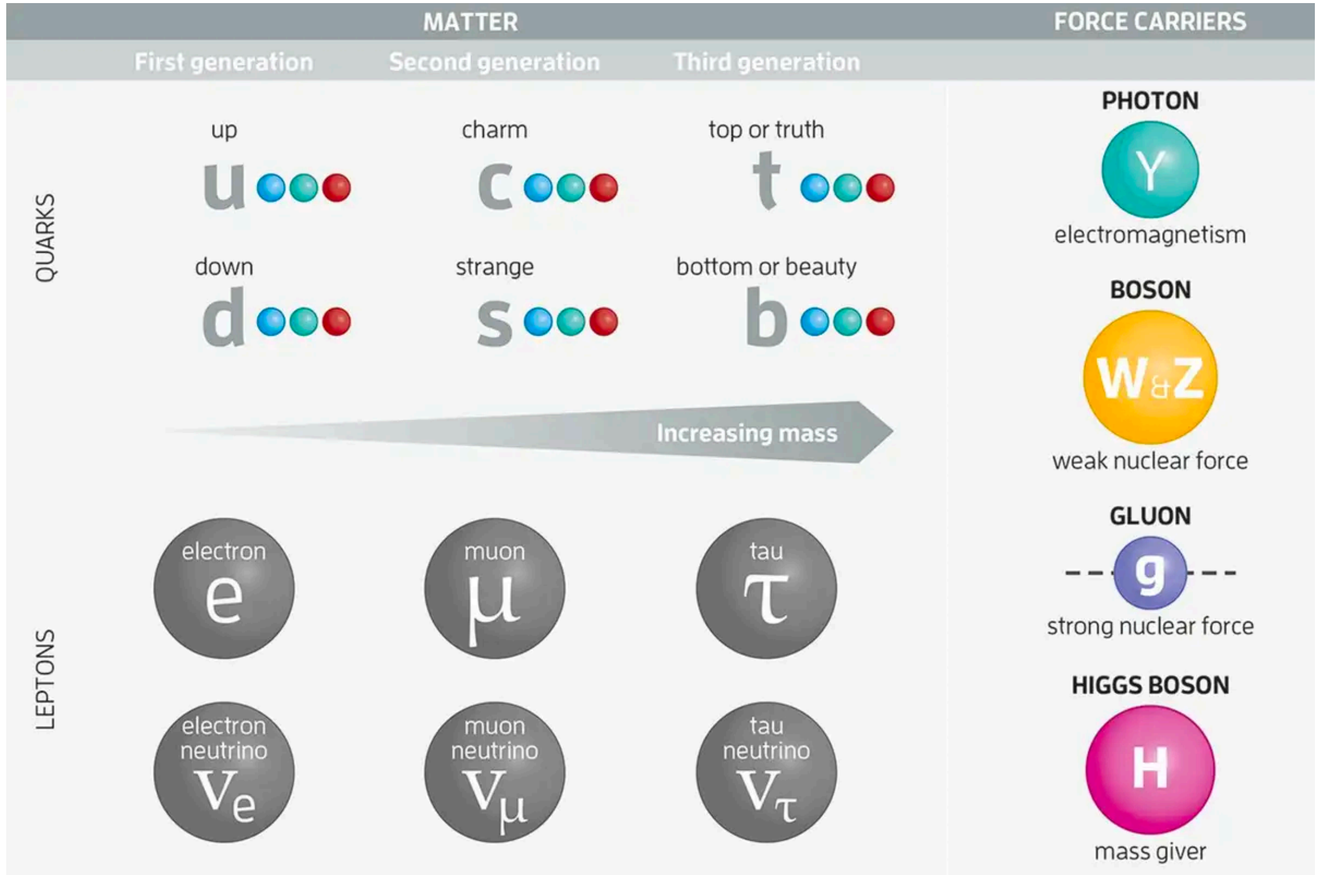
Sophie Renner, University of Glasgow

EPS-HEP Marseille 2025

Who ordered that?

Why are there three copies of each fermion?

What determines their very hierarchical masses and mixings?



Parameters

3 free parameters

3 gauge couplings

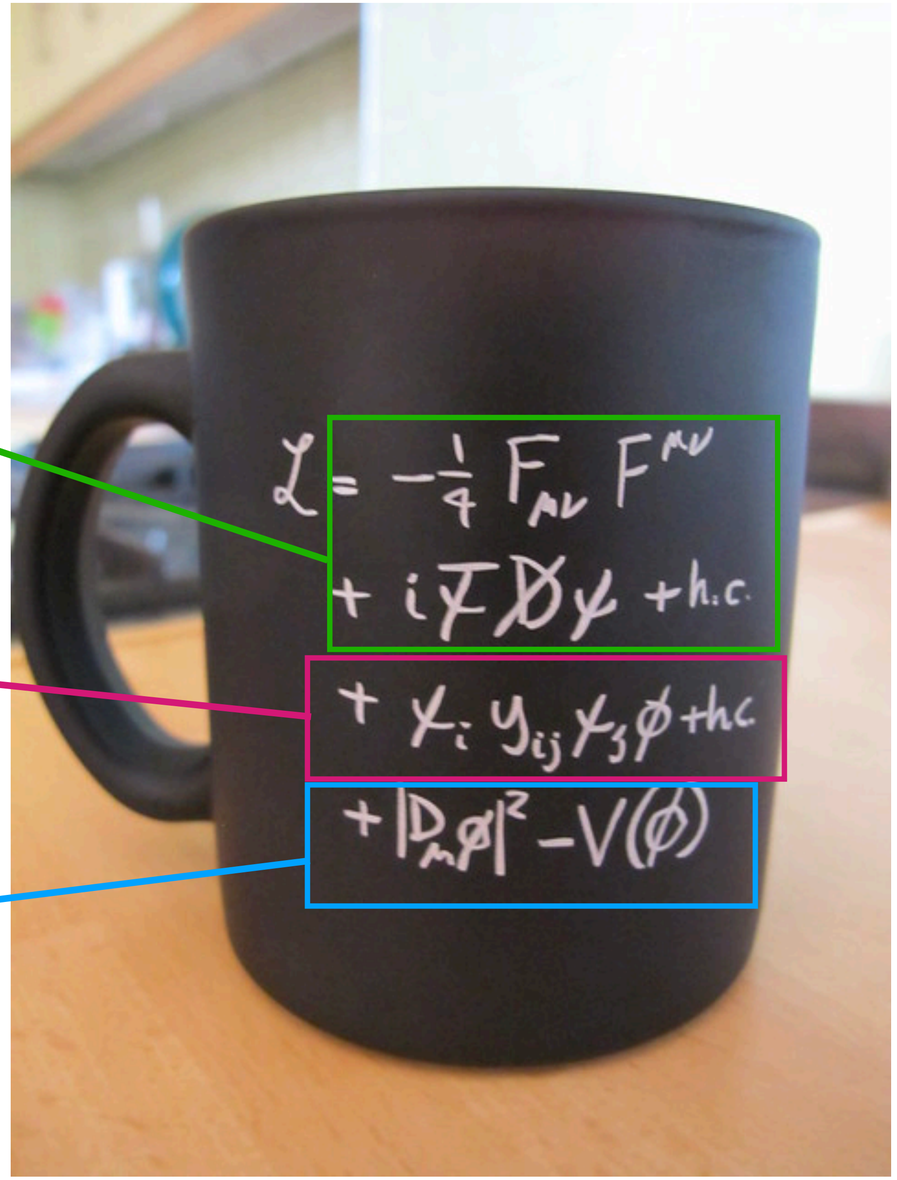
13 (+7) free parameters

9 fermion masses (+ 3 neutrino masses)

4 CKM parameters (+ ≥4 PMNS parameters)

2 free parameters

Higgs mass, vev



Flavour accounts for many of the free parameters of the SM

Flavour in the Standard Model

Gauge and kinetic terms $i \sum \bar{\psi} \gamma^\mu D_\mu \psi$

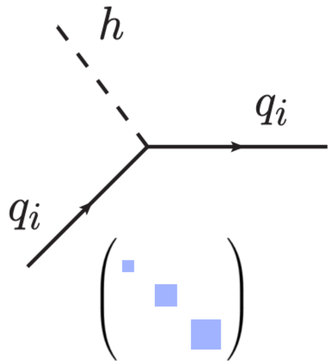
$\psi = \{Q, u, d, L, e\}$

Symmetric under $\psi \to U\psi$

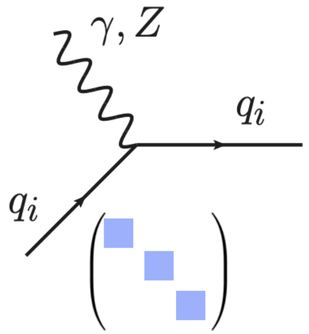
Yukawa terms $Y_u \tilde{H} \bar{Q} u + Y_d H \bar{Q} d + Y_e H \bar{L} e$

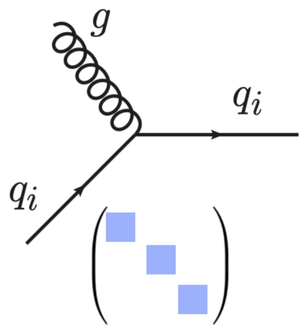
Under $\psi \to U\psi$, Yukawa matrices rotate, e.g. $U_Q^\dagger Y_u U_u$ and can be diagonalised

Diagonalise the Yukawa matrices to find physical mass basis… then:



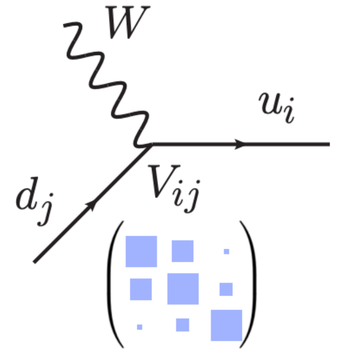
Higgs couplings diagonal by construction





Gauge boson couplings diagonal by symmetry

EXCEPT



Charged gauge bosons which are sensitive to V_{CKM}

$$V_{CKM} = U_Q^{(u)} U_Q^{(d)\dagger}$$

where $U_Q^{(u)}$ diagonalizes Y_u and $U_Q^{(d)}$ diagonalizes Y_d

Standard Model flavour phenomenology

This particular interplay between the gauge and Yukawa interactions makes strong and successful predictions

Quark FCNCs are loop- and GIM-suppressed

see talks by R. Salerno, A. Boletti, A. Romano, S. Neshatpour, L. Carus, F. Dettori, L. Vittorio, C. Kar

e.g. $\mathrm{Br}(D \to \mu\mu)_{\mathrm{SM}} \approx 3 \times 10^{-13}$ $\mathrm{Br}(D \to \mu\mu)_{\mathrm{CMS}} < 2.4 \times 10^{-9}$

$\mathrm{Br}(B_s \to \mu\mu)_{\mathrm{SM}} = (3.67 \pm 0.15) \times 10^{-9}$ $\mathrm{Br}(B_s \to \mu\mu)_{\mathrm{PDG}} = (3.34 \pm 0.27) \times 10^{-9}$

No charged lepton flavour violation

see talks by A. Oya, V. Bertacchi, L. Zani, C. Basile, V. Duk

e.g. $\mathrm{Br}(\mu \to e\gamma)_{\mathrm{SM}} < 10^{-54}$ $\mathrm{Br}(\mu \to e\gamma)_{\mathrm{MEGII}} < 1.5 \times 10^{-13}$

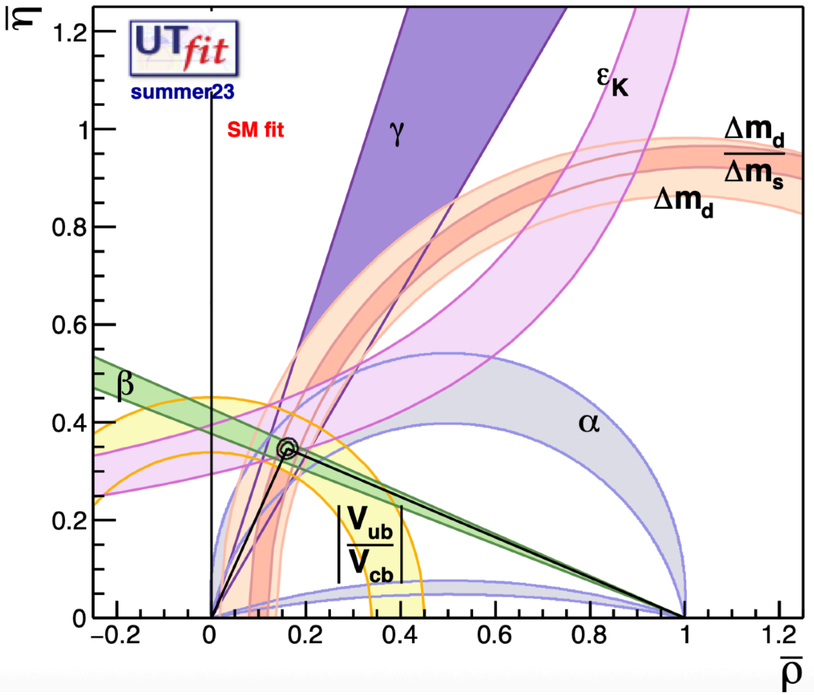
Lepton flavour universality

see talks by A. Boletti, C. Basile, A. Lusiani, M. Mantovano, D. Lancierini

e.g. $\mu - e$ universality in pion decay $\left(\frac{g_\mu}{g_e}\right)_{\mathrm{SM}} = 1$ $\left(\frac{g_\mu}{g_e}\right)_{R^{\pi}_{e/\mu}} = 1.0010 \pm 0.0009$ PIENU, 1506.05845

Unitarity of the CKM matrix

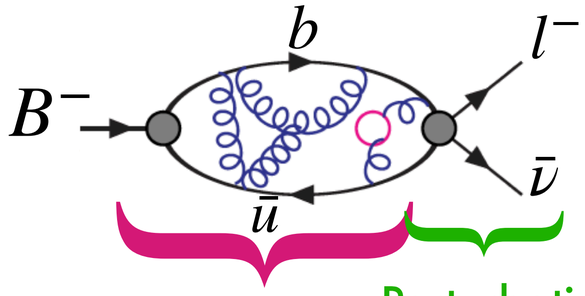
see talk by L. Vittorio



Hadronic inputs and lattice QCD

Flavour measurements are done at a scale where quarks are bound into hadrons
Need model independent way to calculate non-perturbative QCD (+QED) contributions

EXAMPLE: leptonic B decay

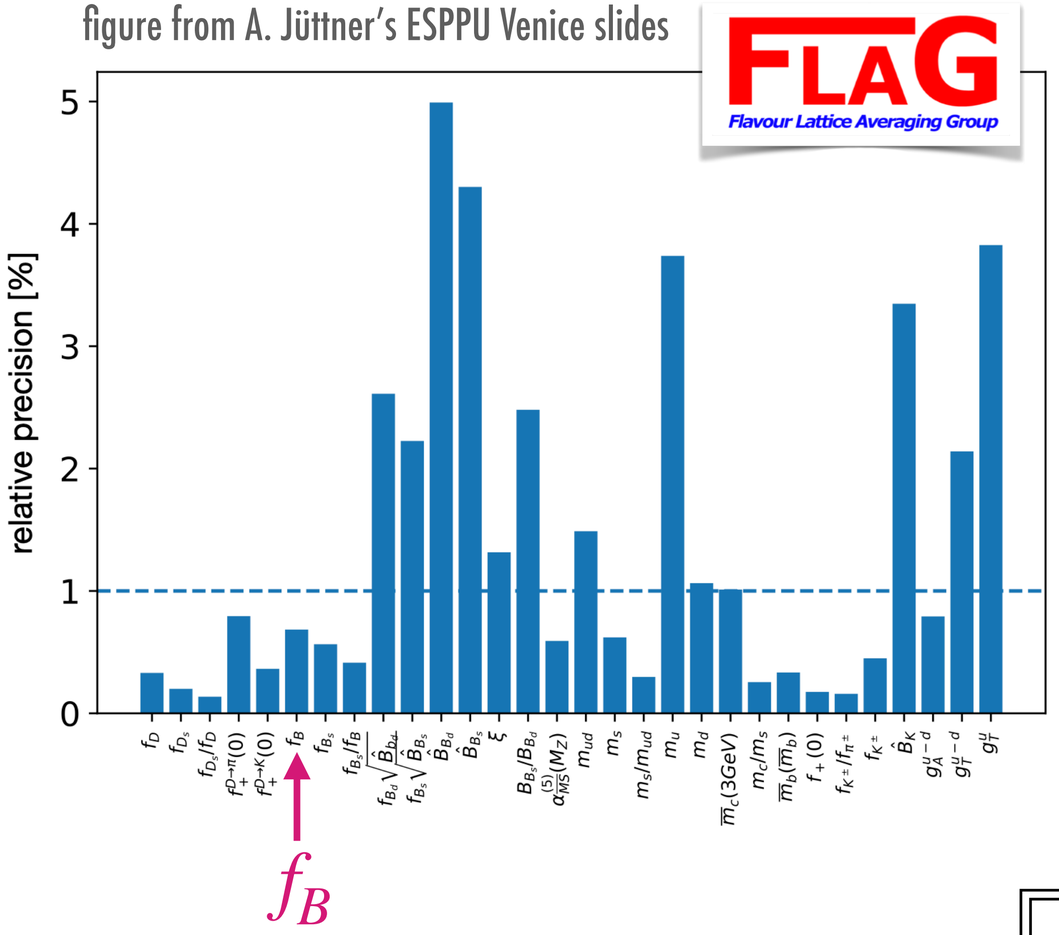


kinematics

$$\Gamma(B^- \to l^- \bar{\nu}) = \frac{m_B}{8\pi}\left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 \; |V_{ub}|^2 G_F^2$$

Under the assumption that this is dominated by SM, can then compare with measured decay rate to extract V_{ub}

figure from A. Jüttner's ESPPU Venice slides



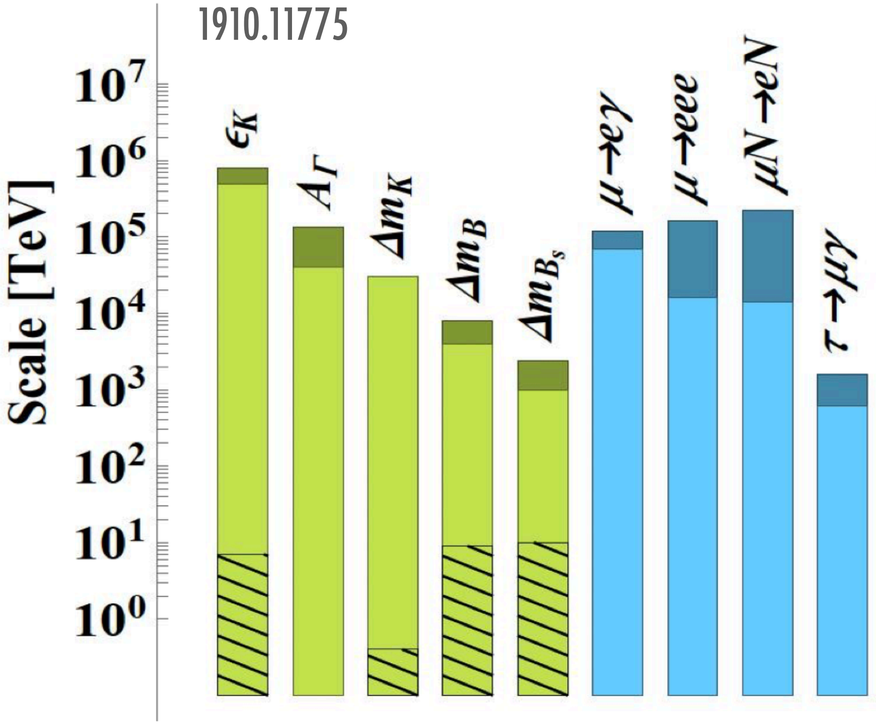
Flavour beyond the SM

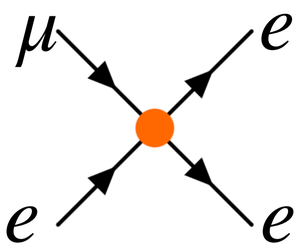
In general, expect BSM physics to break this delicate picture

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{C_i}{\Lambda^2}\mathcal{O}_i + \dots$$

BSM induces new contact interactions

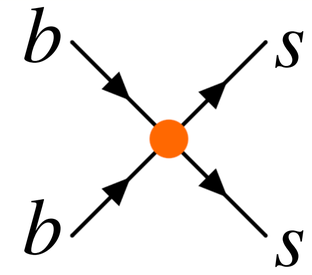
Λ is the scale of new physics



e.g. 

Breaks exact lepton flavour symmetry

Contributes to $\mu \to 3e$

e.g. 

Breaks approximate quark flavour symmetry

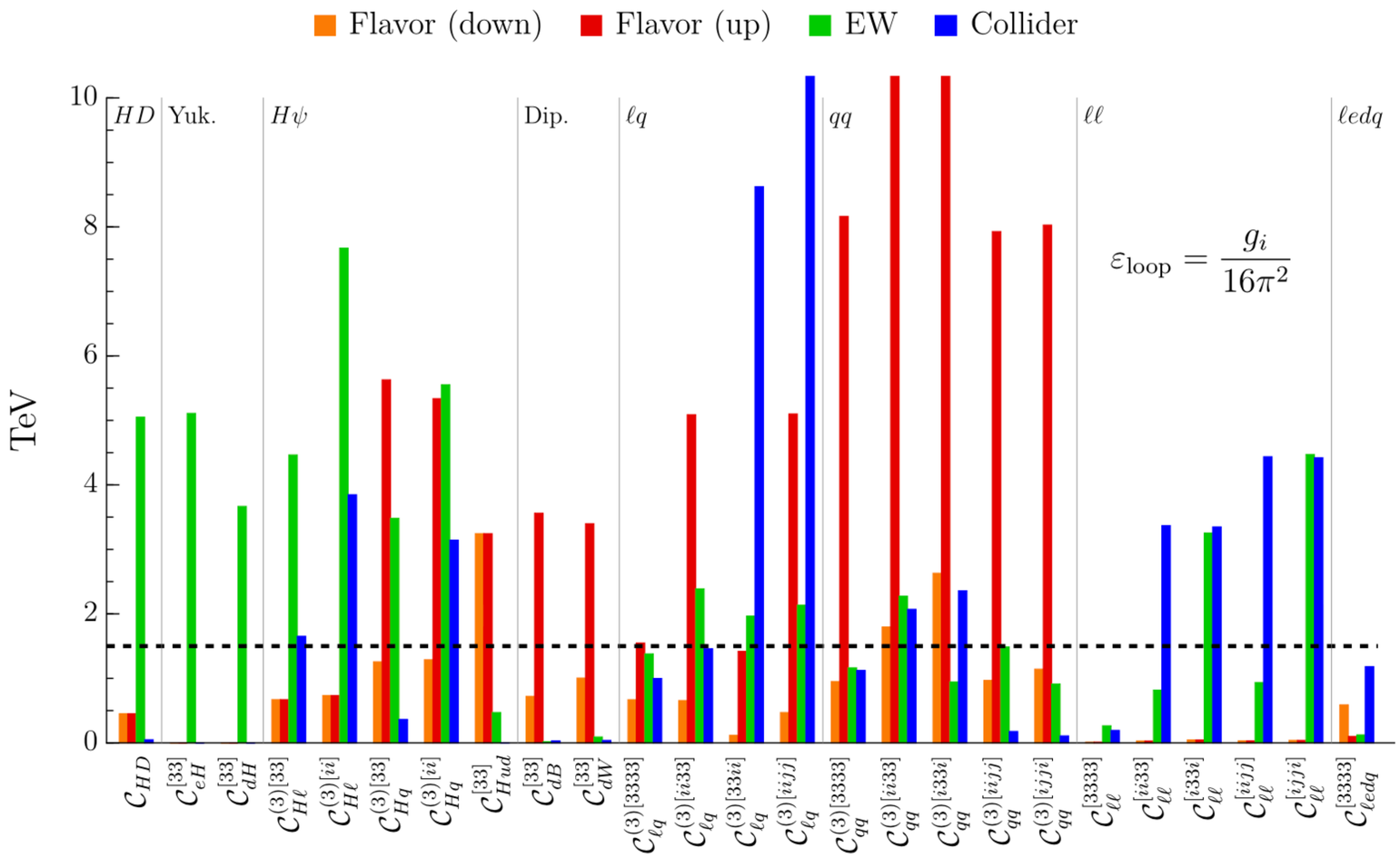
Contributes to $B_s - \bar{B}_s$ mixing

<u>Extremely</u> strong constraints but assuming $O(1)$ flavour-breaking couplings

Need to understand what flavour structure we expect!

Flavourful physics at the TeV scale

Unsuppressed couplings to light generations:

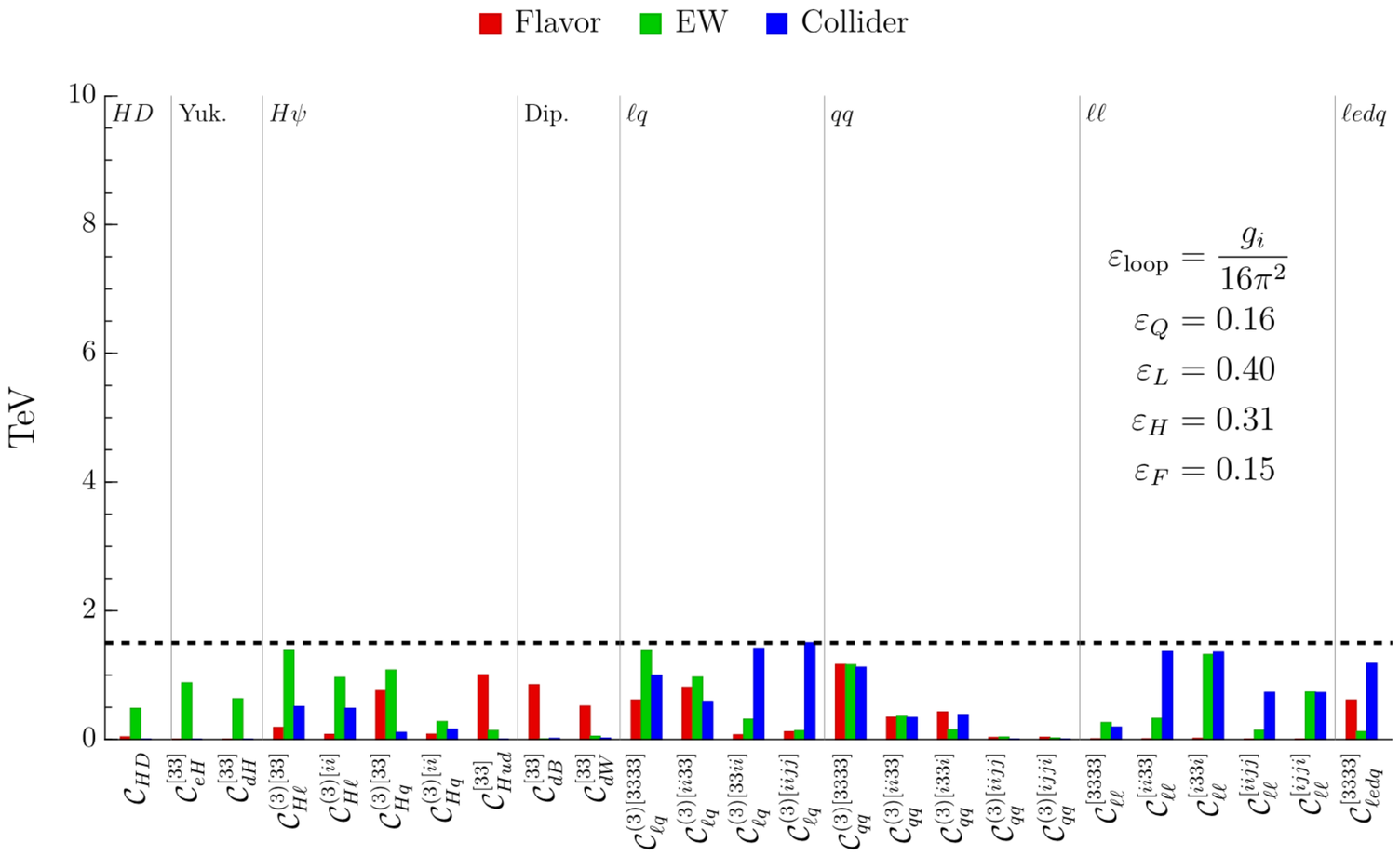


Allwicher et al, 2311.00020

If BSM physics couples differently to different flavours, bounds change

Flavourful physics at the TeV scale

Suppressed couplings to light generations:



Allwicher et al, 2311.00020

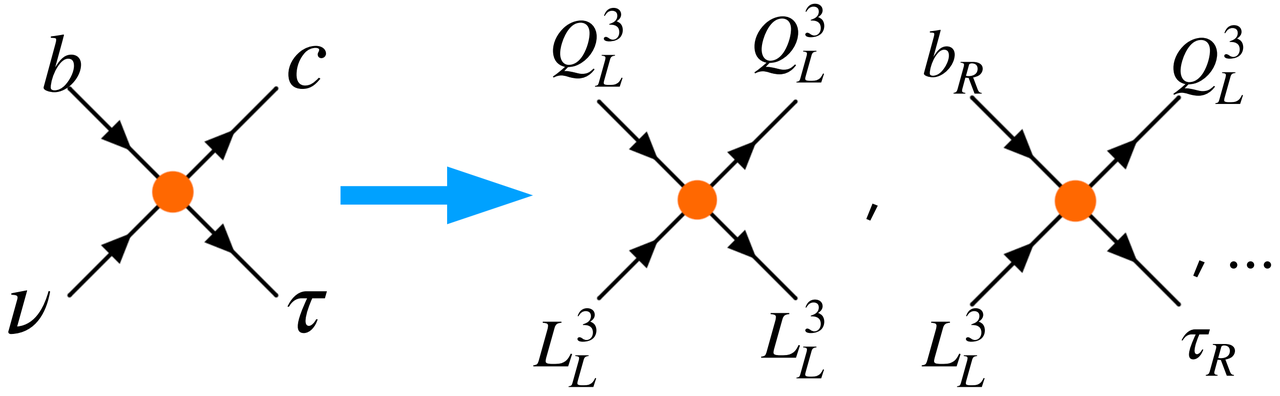
If BSM physics couples differently to different flavours, bounds change

In particular, reduced bounds if NP couples mostly to 3rd family

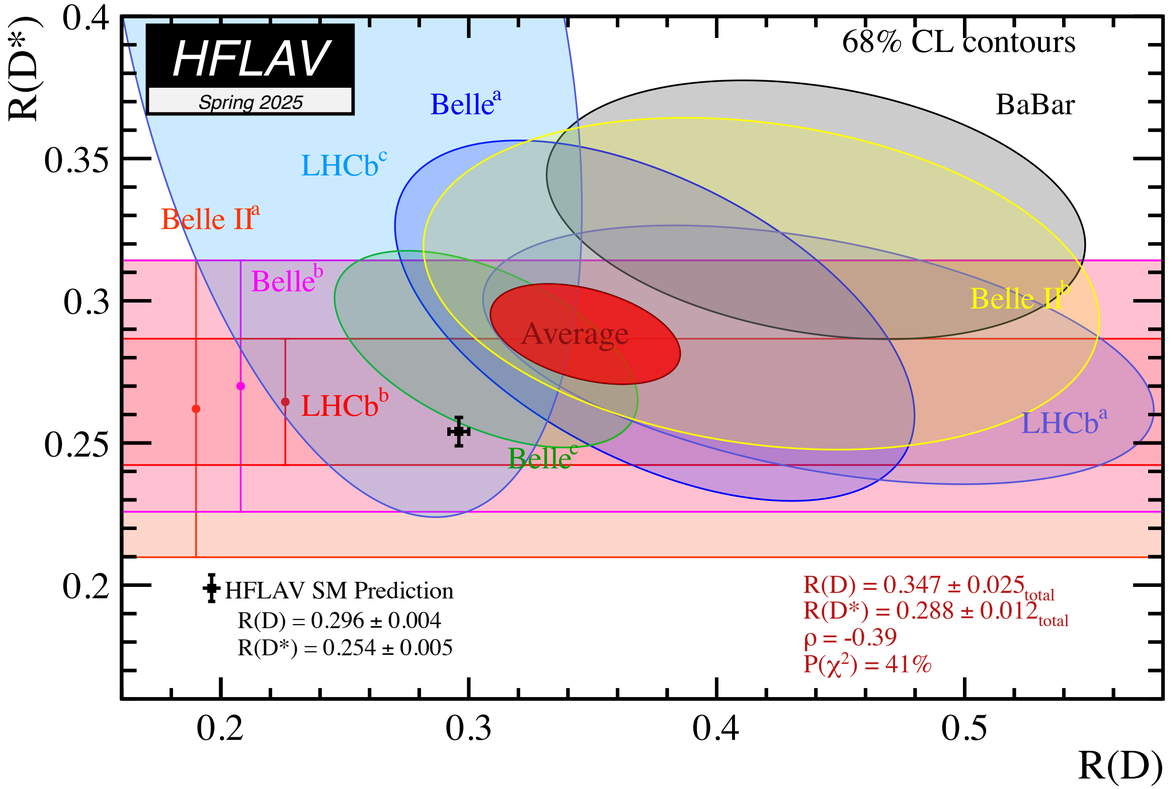
<u>At LHC</u>: PDF suppression
<u>Low energy/electroweak</u>: 3rd generations less precisely measured

Hints of lepton flavour non-universal new physics

$$R(D^{(*)}) = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}l\nu)}$$



Well described by heavy new physics coupling only or mostly to 3rd generation



Same quark-level process:

$$R(J/\psi) = \frac{\mathrm{Br}(B_c \to J/\psi\,\tau\nu)}{\mathrm{Br}(B_c \to J/\psi\,l\nu)}$$

$$R(J/\psi)_{\mathrm{SM}} = 0.2582 \pm 0.0038$$ Harrison et al, 2007.06956

$$R(J/\psi)_{\mathrm{LHCb}} = 0.71 \pm 0.17(\mathrm{stat}) + 0.18(\mathrm{syst})$$ LHCb, 1711.05623

$$R(J/\psi)_{\mathrm{CMS}} = 0.49 \pm 0.25(\mathrm{syst}) \pm 0.09(\mathrm{stat})$$ CMS-PAS-BPH-23-001

+ see talk by C. Basile

Hints of lepton flavour non-universal new physics

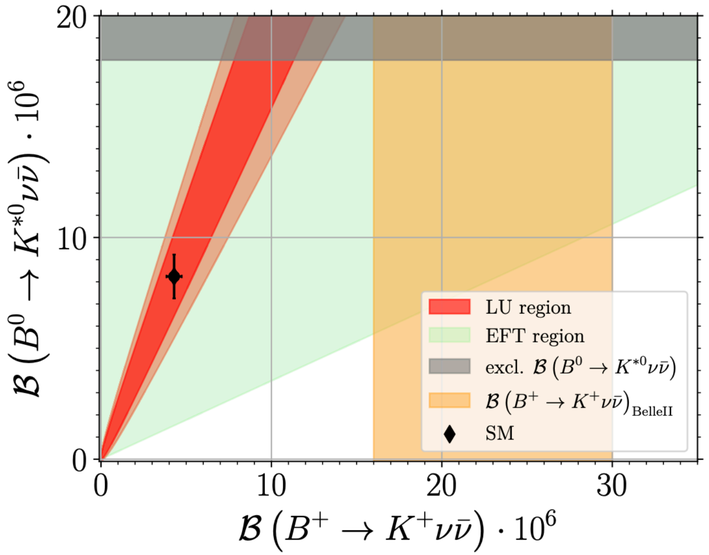
Third generation leptons can also be neutrinos

$\mathrm{Br}(B^+ \to K^+\bar{\nu}\nu) = \left(2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})\right) \times 10^{-5}$ 2.7σ above SM prediction

Belle II 2311.14647
+ see talk by V. Bertacchi

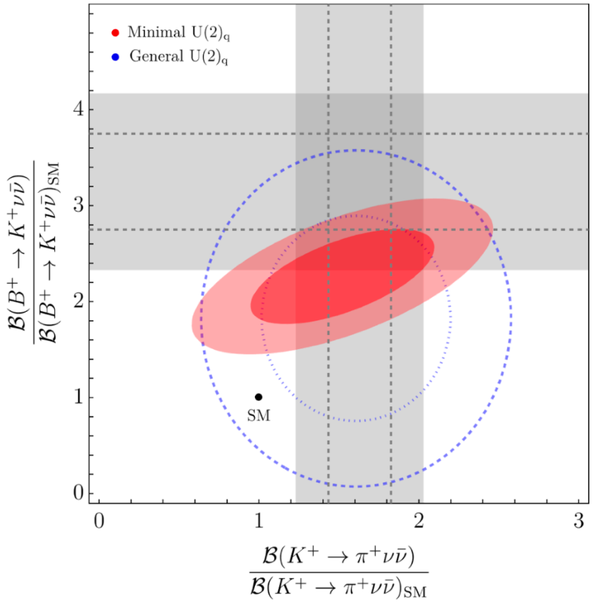
$\mathrm{Br}(K^+ \to \pi^+\bar{\nu}\nu) = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11}$ 1.7σ above SM prediction

NA62 2412.12015 + see talk by A. Romano



Excess in $B^+ \to K^+\bar{\nu}\nu$ cannot be due to lepton flavour universal BSM

Bause et al 2309.00075
Athron et al 2308.13426



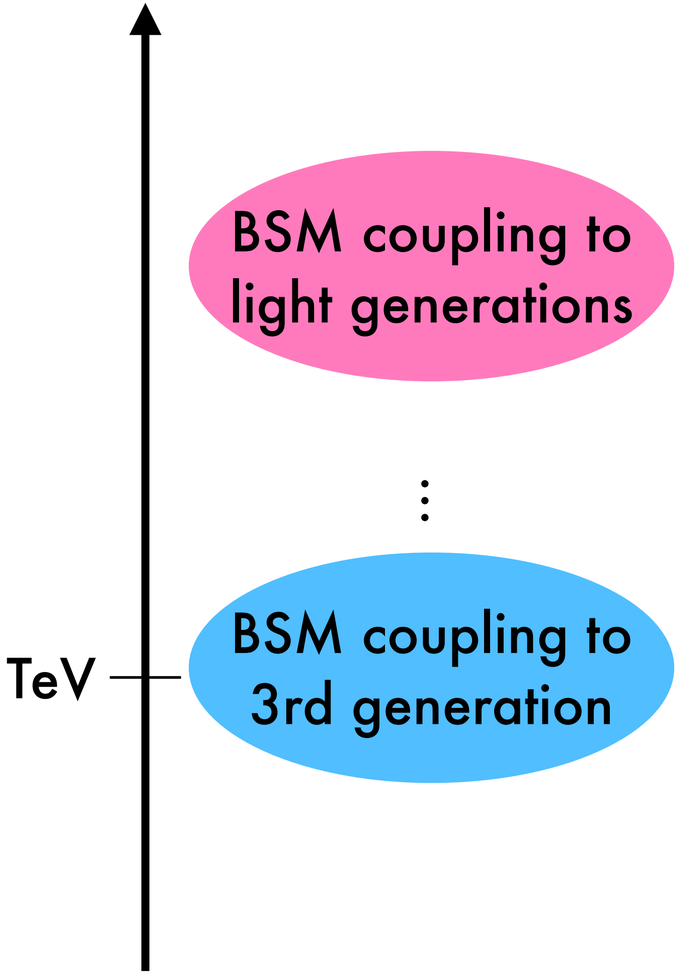
Both measurements can be well described by BSM coupling (predominantly) to the third generation of quarks and leptons

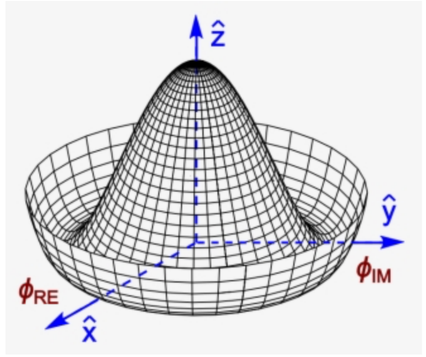
Allwicher et al 2410.21444

Note that these require a smaller absolute excess than $R(D^{(*)})$: *models to fit* $R(D^{(*)})$ *still need suppression in the neutrino modes compared to the semileptonic*

Is the third generation special?

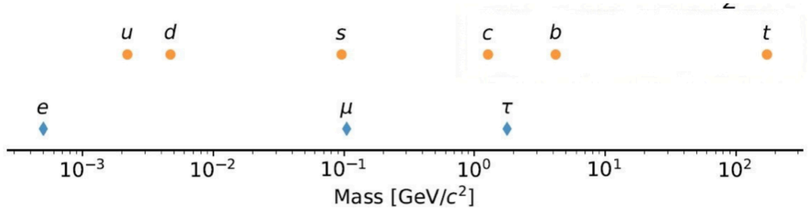
Some puzzles of the SM are strongly connected to the 3rd generation





Higgs potential

Light top partners/stops



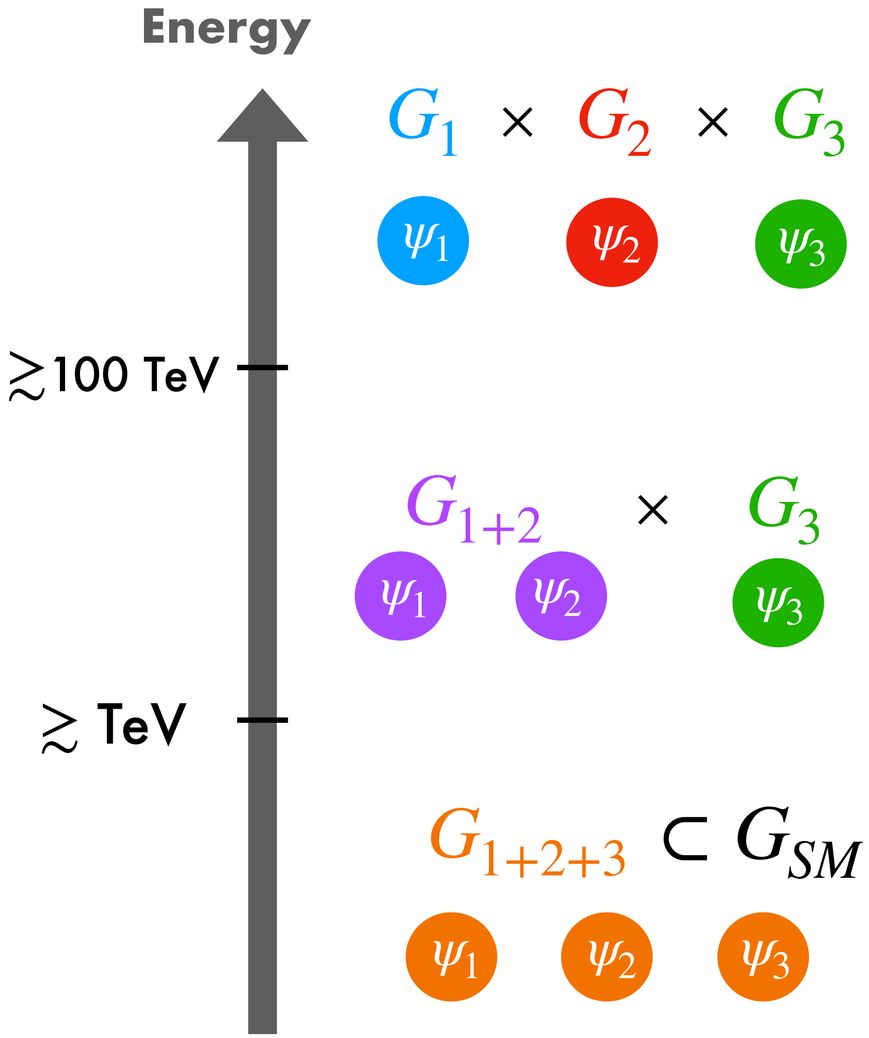
SM flavour structure

Origin of Yukawas

Partial compositeness

Flavour-deconstructed gauge theories

see talks by J. Lizana, S. Covone



What if the generations are genuinely different particles above some scale?

At very high scales, each generation is charged under its own copy of gauge group G

symmetry ⇩ breaking

At lower scales, light generations are both charged under the same subgroup, but 3rd generation still has its own group

symmetry ⇩ breaking

At the electroweak scale, all generations are charged under the same subgroup, which is part of the SM group

Full catalogue of semisimple extensions of the SM: Allanach, Gripaios, Tooby-Smith 2104.14555

New gauge bosons

Each breaking step produces new <u>heavy gauge bosons</u>...

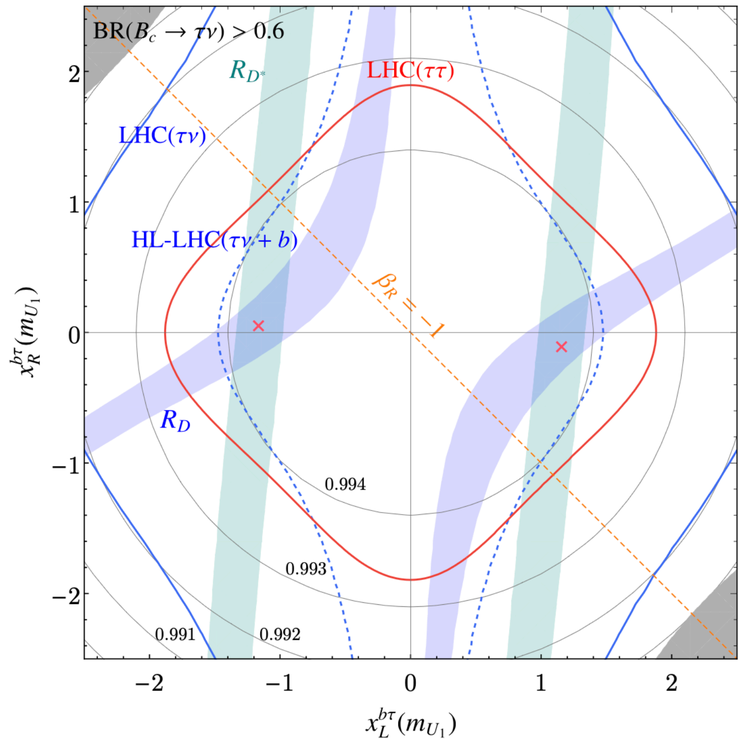
...the deconstructed group G determines their charges

e.g. deconstructions involving the colour group $SU(3)_c$ can give rise to *vector leptoquarks*

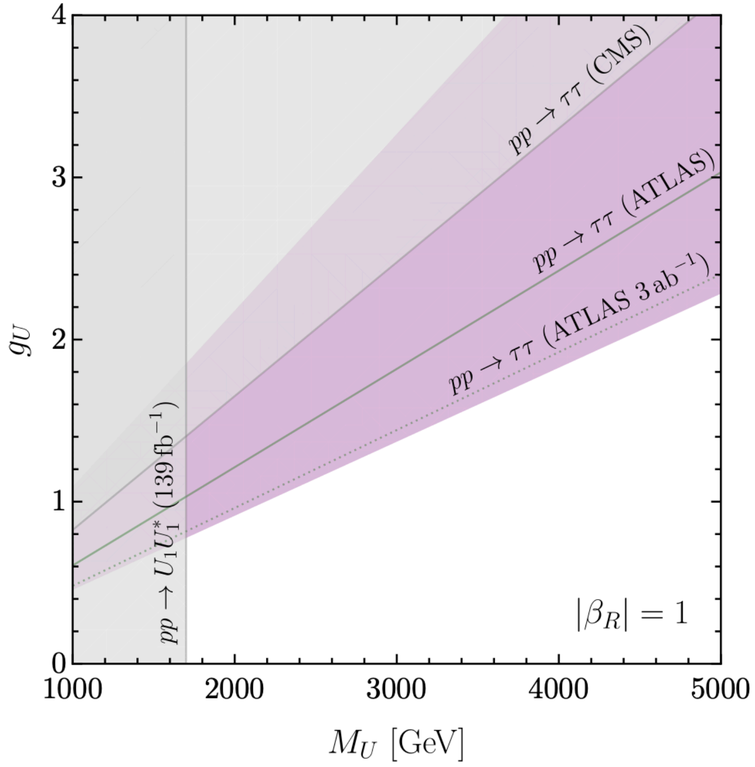
Bordone et al 1712.01368

These can provide explanations for the hints of flavour non-universality in B decays

Sakaki et al, 1309.0301
Freytsis et al, 1506.08896
Buttazzo et al, 1706.07808,
many more...



Iguro et al 2405.06062



Aebischer et al 2210.13422

Electroweak deconstructions

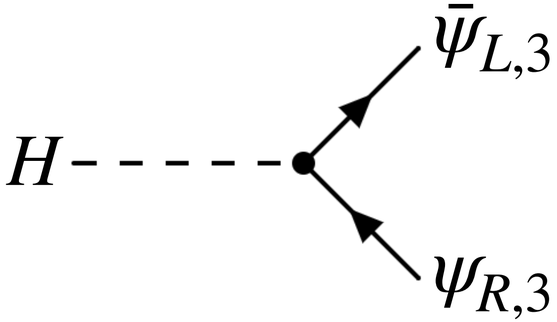
Deconstructing the electroweak groups can explain Yukawa hierarchies

	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

Table from Davighi 2501.16064

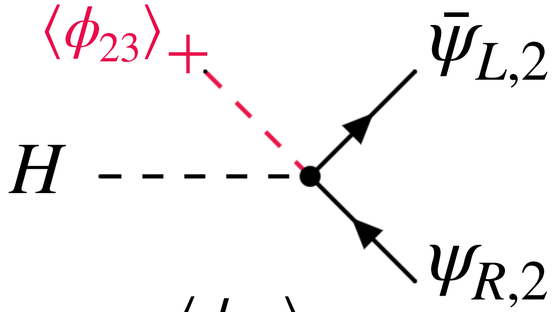
Davighi, Isidori 2303.01520
Fernandez Navarro, King, 2305.07690
Davighi, Stefanek, 2305.16280
Barbieri, Isidori 2312.14004
Ma, Li 1982
Davighi et al 2312.13346
Capdevila et al 2401.00848, ...

Higgs is charged only under the **third family** gauge symmetry

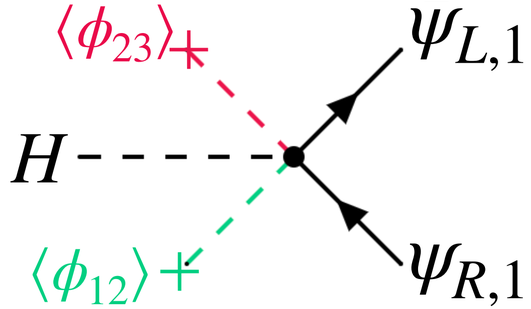


$\Longrightarrow$ Only third family Yukawas are allowed at the renormalisable level

Light family Yukawas are generated at **higher dimension**



$$\sim \frac{\langle\phi_{23}\rangle}{\Lambda_{23}}$$



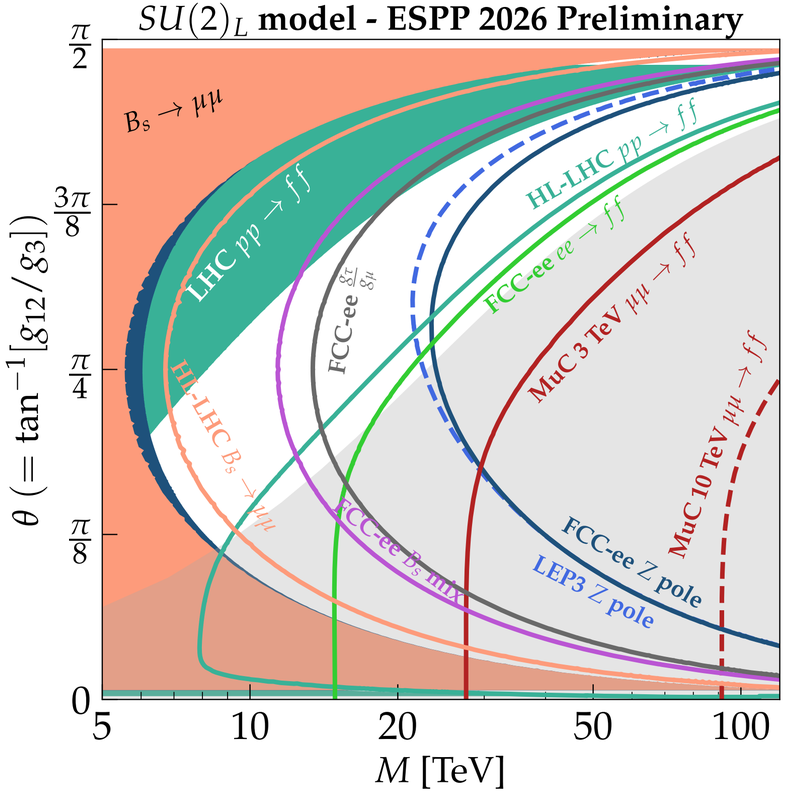
$$\sim \frac{\langle\phi_{23}\rangle\langle\phi_{12}\rangle}{\Lambda_{23}\Lambda_{12}}$$

Electroweak deconstructions

Deconstructing the electroweak groups can explain Yukawa hierarchies

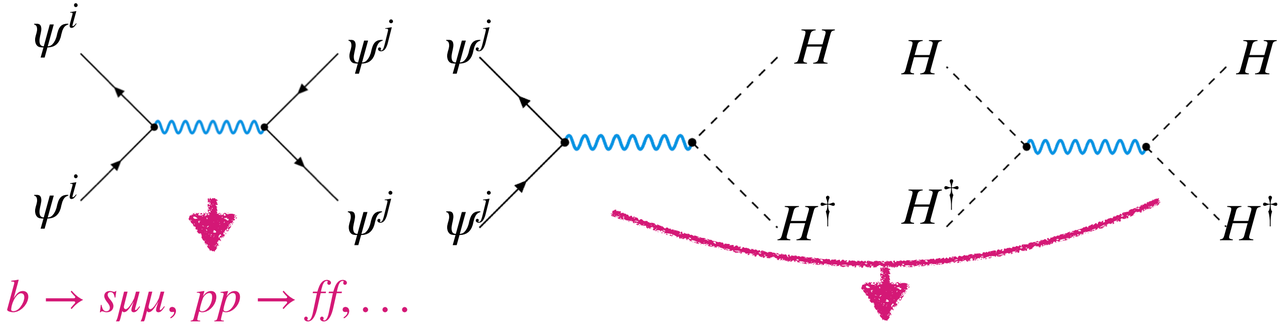
	Deconstructed force	$SU(3)$	$SU(2)_L$	$SU(2)_R$	$U(1)_Y$	$U(1)_{B-L}$
Flavour	$\|V_{cb}\| \ll 1$	✓	✓	×	✓	✓
	$y_i \ll y_3$	×	✓	✓	✓	×
EW	Natural upper limit of $\|\tan\theta\|M$	90 TeV	20 TeV	40 TeV	40 TeV	500 TeV
	EWPOs order	1-loop	Tree	Tree	Tree	1-loop

Ma, Li 1982
Davighi et al 2312.13346
Capdevila et al 2401.00848



Breaking to SM produces <u>electroweak triplet W'</u> gauge boson

$$g^{ij}_{W'} = g_L\,\mathrm{diag}(-\tan\theta, -\tan\theta, \cot\theta) \qquad g^{H}_{W'} = g_L \cot\theta$$



$b \to s\mu\mu,\ pp \to ff, \ldots$

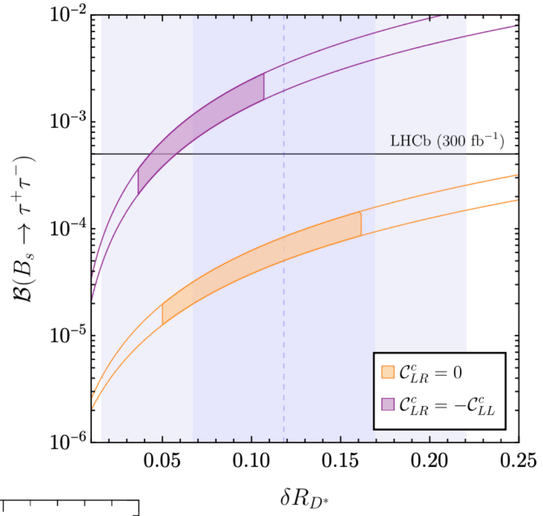
Z pole observables

Light grey shaded region is where $\delta m_h^2 > 1\,\mathrm{TeV}^2$ (i.e. naturalness-disfavoured)

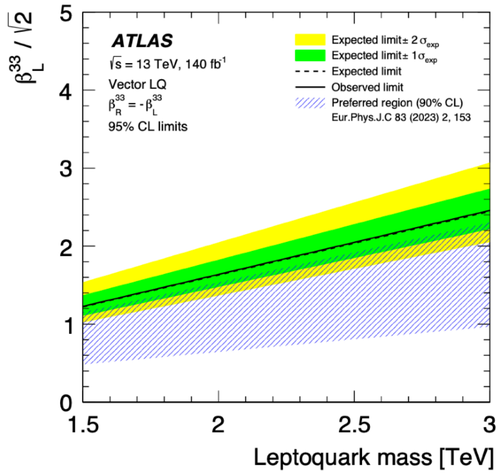
Future tests

Non-flavour universal NP implies a few targets

Continued exploration/more observables in LFU ratios and neutrino and tau modes



Aebischer et al 2210.13422

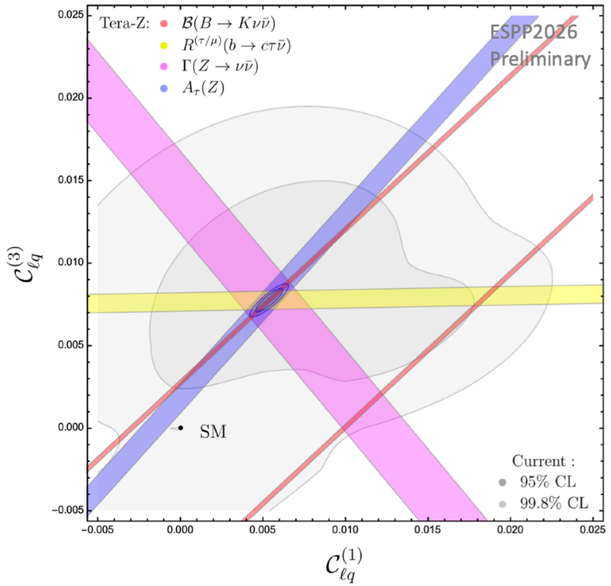


ATLAS 2503.19836

High p_T

$pp \to \tau\tau, \tau\nu$, measurements of top couplings, …

From G. Isidori slides, ESPPU Venice



Future colliders

- generally expect effects in *electroweak precision*
- Tera-Z flavour programme would allow *precision tau studies*

Summary

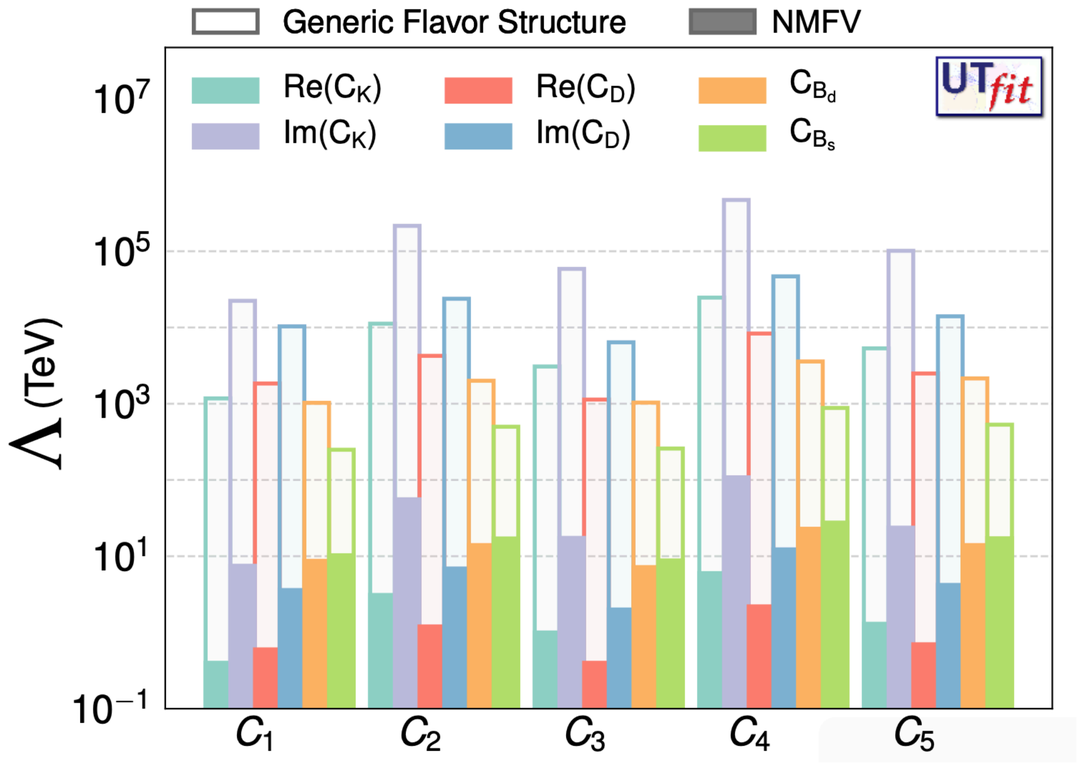
- Flavour sector of SM is incredibly rich, but lacks explanation
- Theory and experiment working together provide very strong constraints on a wide variety of flavour-changing interactions beyond SM
- If NP is around the TeV scale, must have a particular structure which is somewhat aligned with that of the SM
- Data and theoretical arguments could be pointing us towards NP aligned towards the third generations of quarks and leptons
- If so, further tests at current and proposed experiments will tell us more

Backup

Minimal flavour violation

D'Ambrosio et al, hep-ph/0207036

Meson mixing bounds:



from talk by M. Pierini, EPS-HEP 2023

Can assume that new physics is entirely flavour universal and that all flavour violation comes with the same suppressions as in the SM

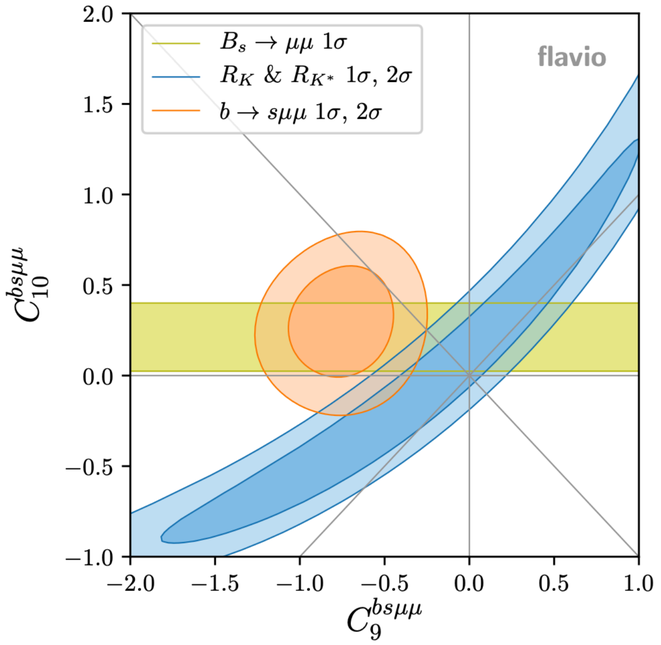
Drastically weakens bounds, and makes predictions about expected patterns of flavour breaking

Is this the best choice, theoretically and experimentally?

Rare neutral current decays to light leptons

There are also discrepancies in various $b \to s\mu\mu$ observables

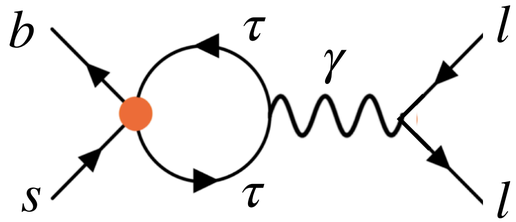
Greljo et al 2212.10497



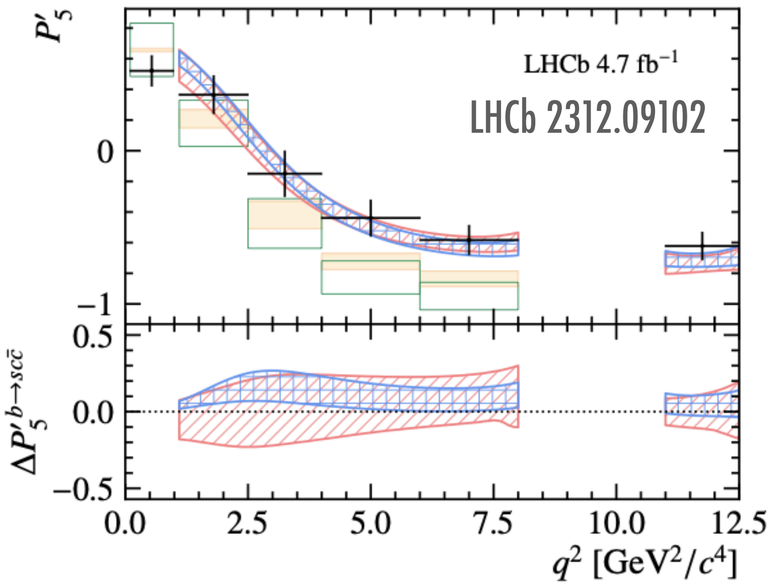
Global fits favour contribution to operator with a vectorial lepton current: $O_9^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$

Could be due to $bs\tau\tau$ operators at one loop:

Crivellin et al 1807.02068,
Cornella et al 2103.16558



Still consistent with third generation BSM!



Theory status of $B \to K^{(*)}ll$ observables not completely clear. Lots of theory and experimental activity to understand impact of charm loops

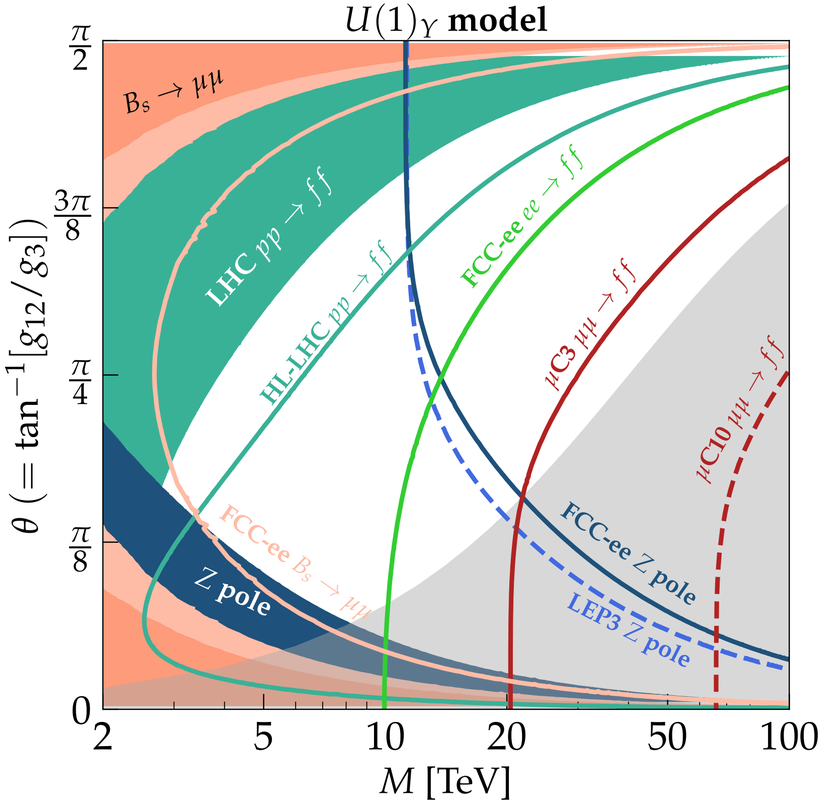
Algueró et al 2205.15212
Gubernari et al 2206.03797
Bordone et al 2401.18007
Isidori et al 2405.17551, ...

Electroweak deconstructions

Deconstructing the electroweak groups can explain Yukawa hierarchies

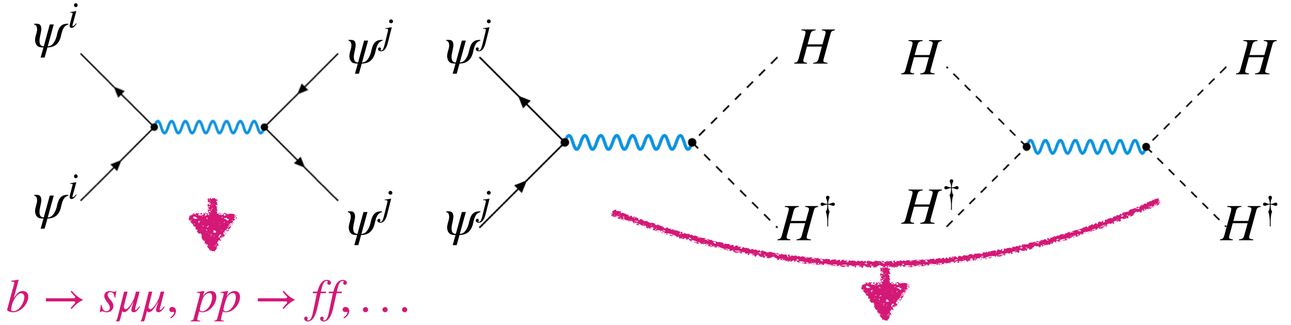
	Deconstructed force	$SU(3)$	$SU(2)_L$	$SU(2)_R$	$U(1)_Y$	$U(1)_{B-L}$
Flavour	$\lvert V_{cb}\rvert \ll 1$	✓	✓	×	✓	✓
	$y_i \ll y_3$	×	✓	✓	✓	×
EW	Natural upper limit of $\lvert\tan\theta\rvert M$	90 TeV	20 TeV	40 TeV	40 TeV	500 TeV
	EWPOs order	1-loop	Tree	Tree	Tree	1-loop

Davighi, Isidori 2303.01520
Davighi 2501.16064



Breaking to SM produces <u>electroweak singlet Z'</u> gauge boson

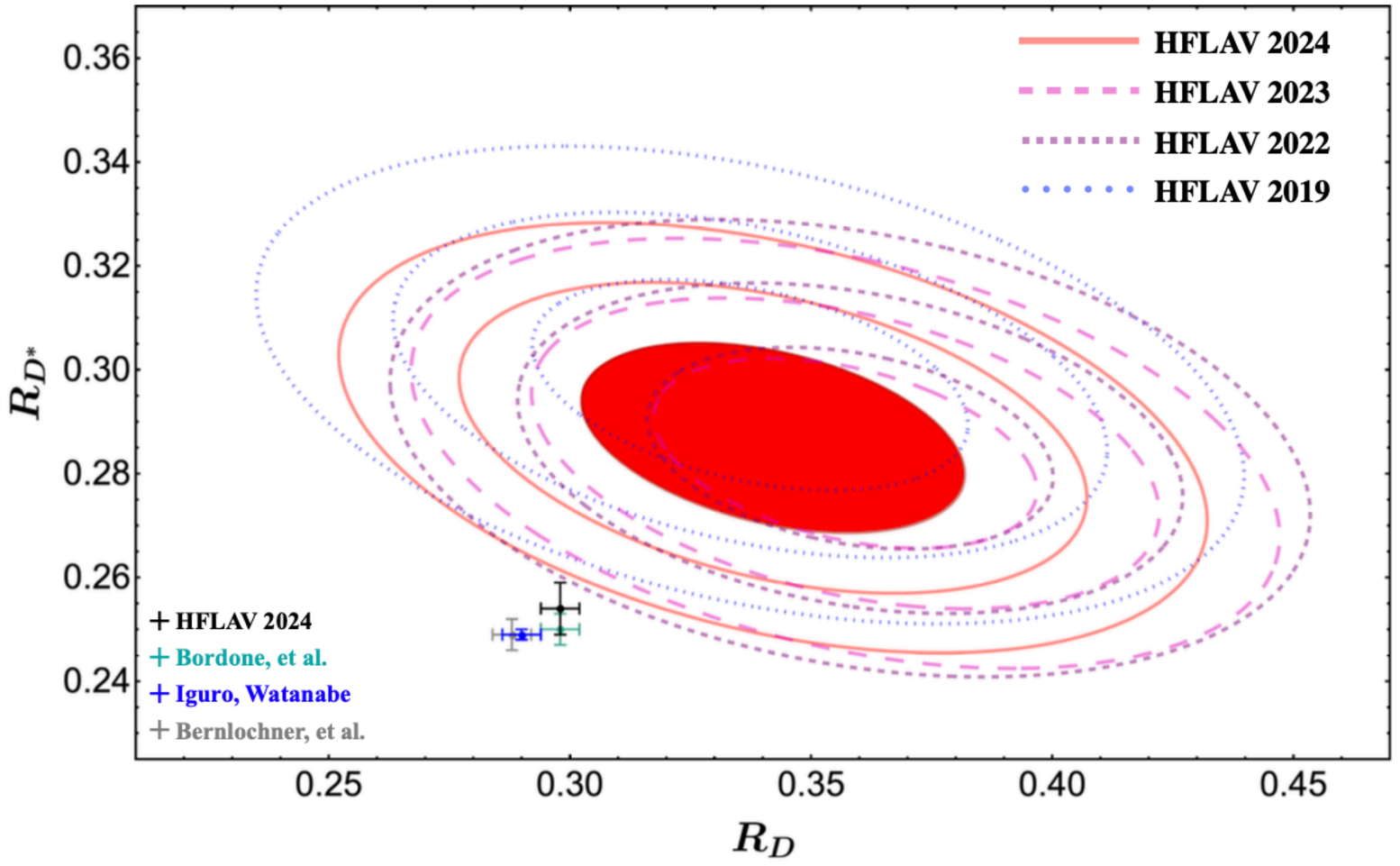
$$g^{ij}_{Z'} = g_Y \,\mathrm{diag}(-\tan\theta, -\tan\theta, \cot\theta) \qquad g^H_{Z'} = g_Y \cot\theta$$



$b \to s\mu\mu,\ pp \to ff, \ldots$

Z pole observables

Light grey shaded region is where $\delta m_h^2 > 1$ TeV (i.e. naturalness-disfavoured)


HFLAV 2024
HFLAV 2023
HFLAV 2022
HFLAV 2019
HFLAV 2024
Bordone, et al.
Iguro, Watanabe
Bernlochner, et al.
0.36
0.34
0.32
0.30
0.28
0.26
0.24
R_{D^*}
0.25
0.30
0.35
0.40
0.45
R_D

2405.06062