Universität Zürich[UZH]

Radiative Electroweak Symmetry Breaking in the 4321 model

Higgs Hunting 2021, Young Scientist Forum, 20 September 2021

Julie Pagès

University of Zurich (UZH)

In collaboration with

R. Houtz (Durham U., IPPP) and *S. Trifinopoulos (SISSA, Trieste)*

B anomalies

Lepton Flavour Universality (LFU)
is an accidental symmetry of the Standard Model (SM) in the limit of vanishing lepton Yukawa couplings

$$\boxed{U(3)_\ell \times U(3)_e} \xrightarrow[Y_e \neq 0]{} U(1)_e \times U(1)_\mu \times U(1)_\tau$$

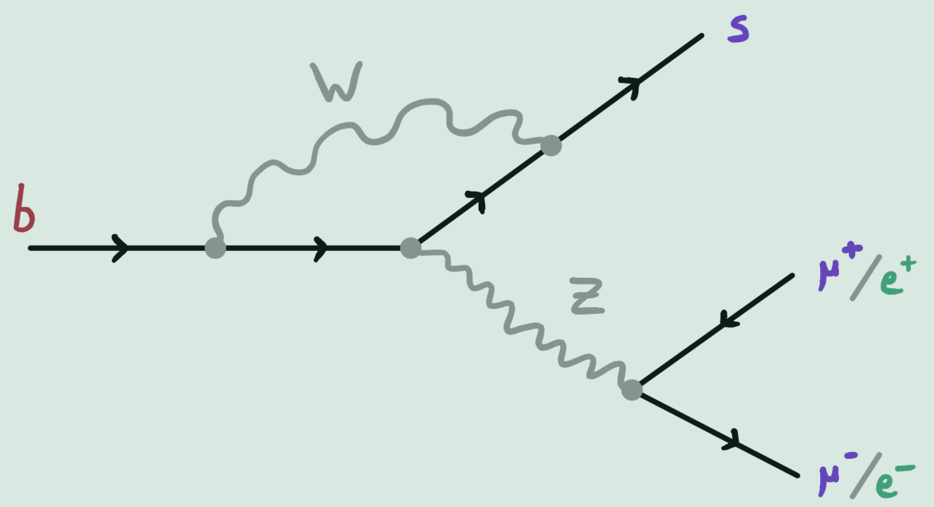
$y_e \sim 3 \cdot 10^{-6}\,, \quad y_\mu \sim 6 \cdot 10^{-4}\,, \quad y_\tau \sim 10^{-2}$

soft breaking $y_\ell \ll g_i$ ⟹ approximate LFU

Results since 2013 in semi-leptonic B decays hint towards a new type of interaction violating LFU more

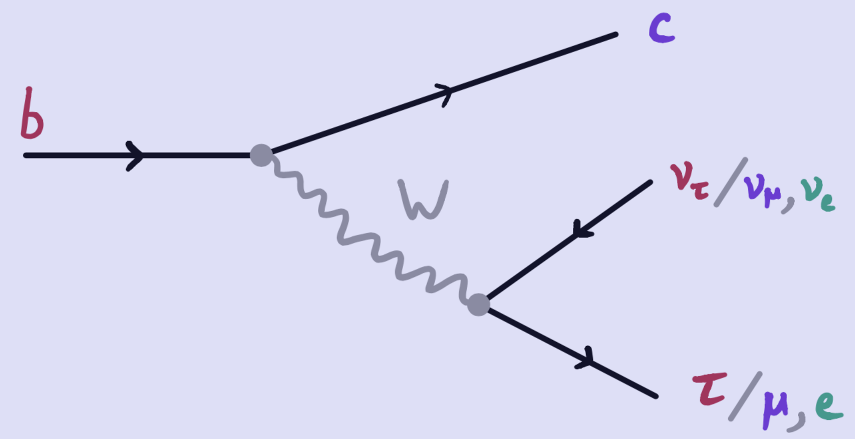
Neutral currents

$b \to s\ell^+\ell^-$: universality in μ vs. e



Charged currents

$b \to c\ell\nu$: universality in τ vs. μ,e



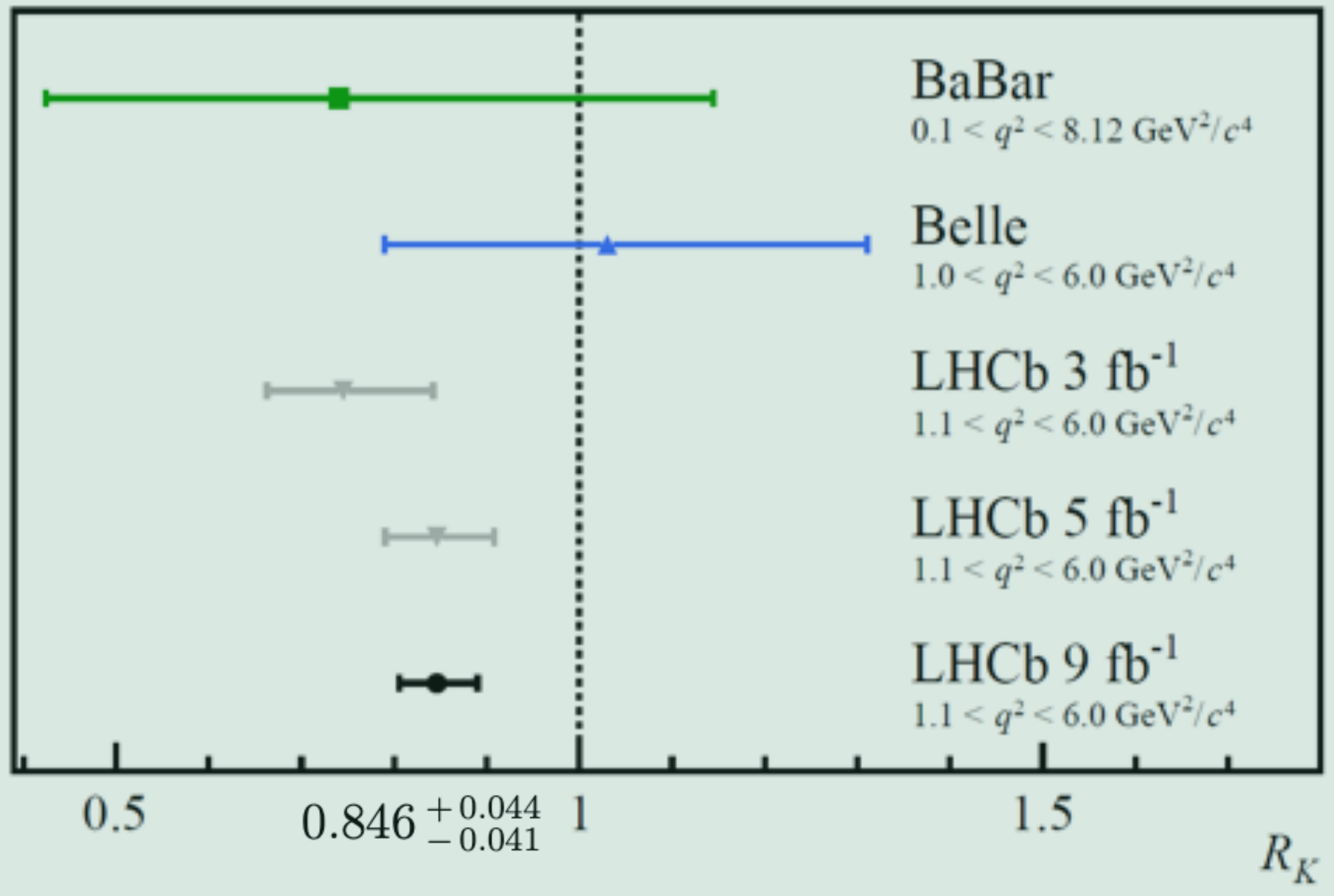
B anomalies

Neutral currents

$b \to s\ell^+\ell^-$: universality in μ vs. e

$$R_K = \frac{\Gamma(B \to K\mu^+\mu^-)}{\Gamma(B \to Ke^+e^-)}$$

3.1 σ



+ other observables:

$R_{K^{(*)}}$, P_5', $B \to K^{(*)}\mu^+\mu^-$,
$B_s \to \mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, …

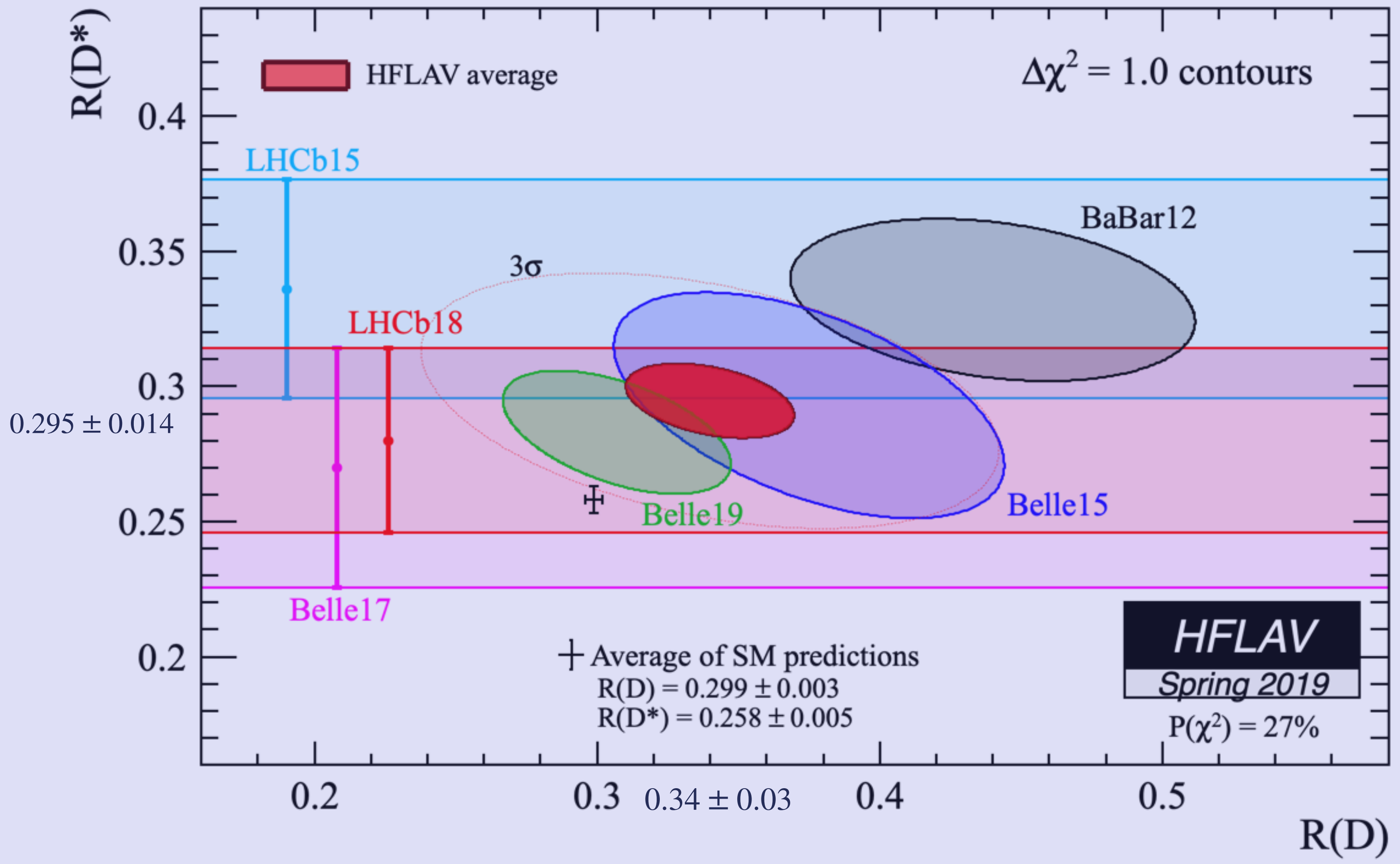
$> 4\ \sigma$

Charged currents

$b \to c\ell\nu$: universality in τ vs. μ,e

$$R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$$

3.1 σ



4321 - Gauge sector

$$U(1)_Y$$

$$\underset{g_4}{SU(4)} \times \underset{g_3}{SU(3)'} \times SU(2)_L \times \underset{g_1}{U(1)_X} \longrightarrow \underset{g_s}{SU(3)_c} \times SU(2)_L \times \underset{g_Y}{U(1)_Y}$$

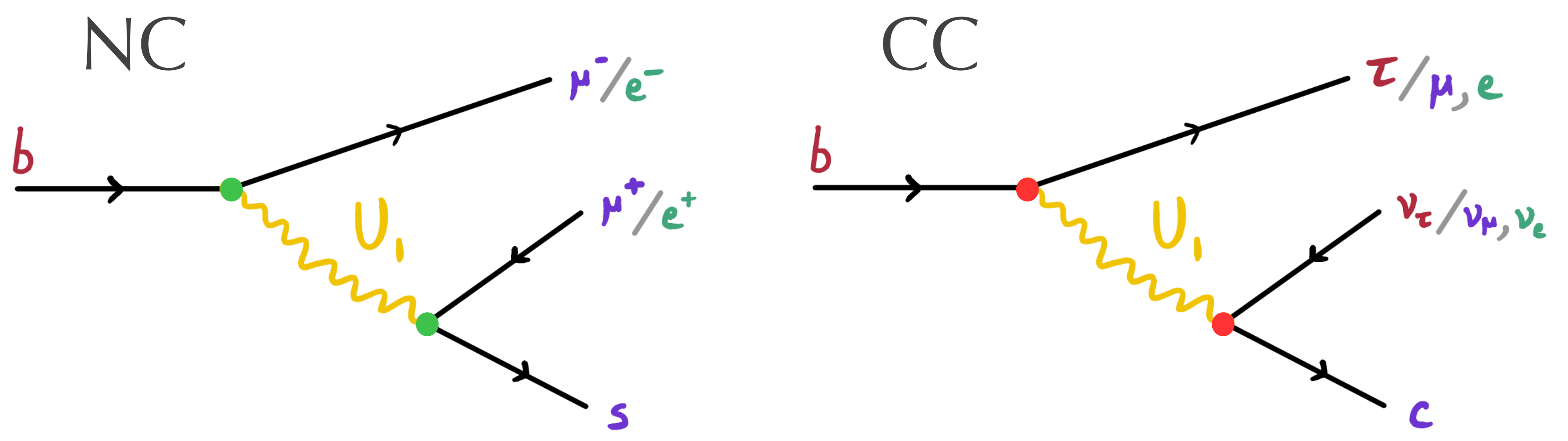
$$SU(3)_c \qquad\qquad + U_1, G', Z'$$

[Di Luzio et al., 1708.08450; Bordone et al., 1712.01368; Greljo, Stefanek, 1802.04274]

Why an additional $SU(4)$?

- Contains the $U_1 \sim (3,1)_{2/3}$ leptoquark
  - only <u>single mediator solution</u> to both B anomalies

[Buttazzo, Greljo, Isidori, Marzocca, 1706.07808]



  - no tree-level $\Delta F = 2$ (4-quark or 4-lepton)
  - no resonant production at high-p_T
- no proton decay (protected by accidental $U(1)_B$)

$$SU(4) \sim \begin{pmatrix} G' & U_1 \\ U_1^\dagger & Z' \end{pmatrix}$$

Why not 421, with $SU(3)_c \supset SU(4)$?

- to disentangle the SM color group from $SU(4)$

  ↪ in the limit $g_4 \gg g_1, g_3$, suppressed G′ and Z' coupling to valence quarks
- to <u>break</u> flavour universality (see next slide)

4321 - Fermion content

$$\underset{g_4}{SU(4)} \times \underset{g_3}{SU(3)'} \times SU(2)_L \times \underset{g_1}{U(1)_X} \longrightarrow \underset{g_s}{SU(3)_c} \times SU(2)_L \times \underset{g_Y}{U(1)_Y}$$

$$\begin{pmatrix} q_L \\ q_L \\ q_L \\ \ell_L \end{pmatrix}$$

Quark-Lepton unification

Lepton number as "the fourth color"

[Pati, Salam, Phys. Rev. D10 (1974) 275]

but not for all families !

Only 3rd family is charged under $SU(4)$ leading to

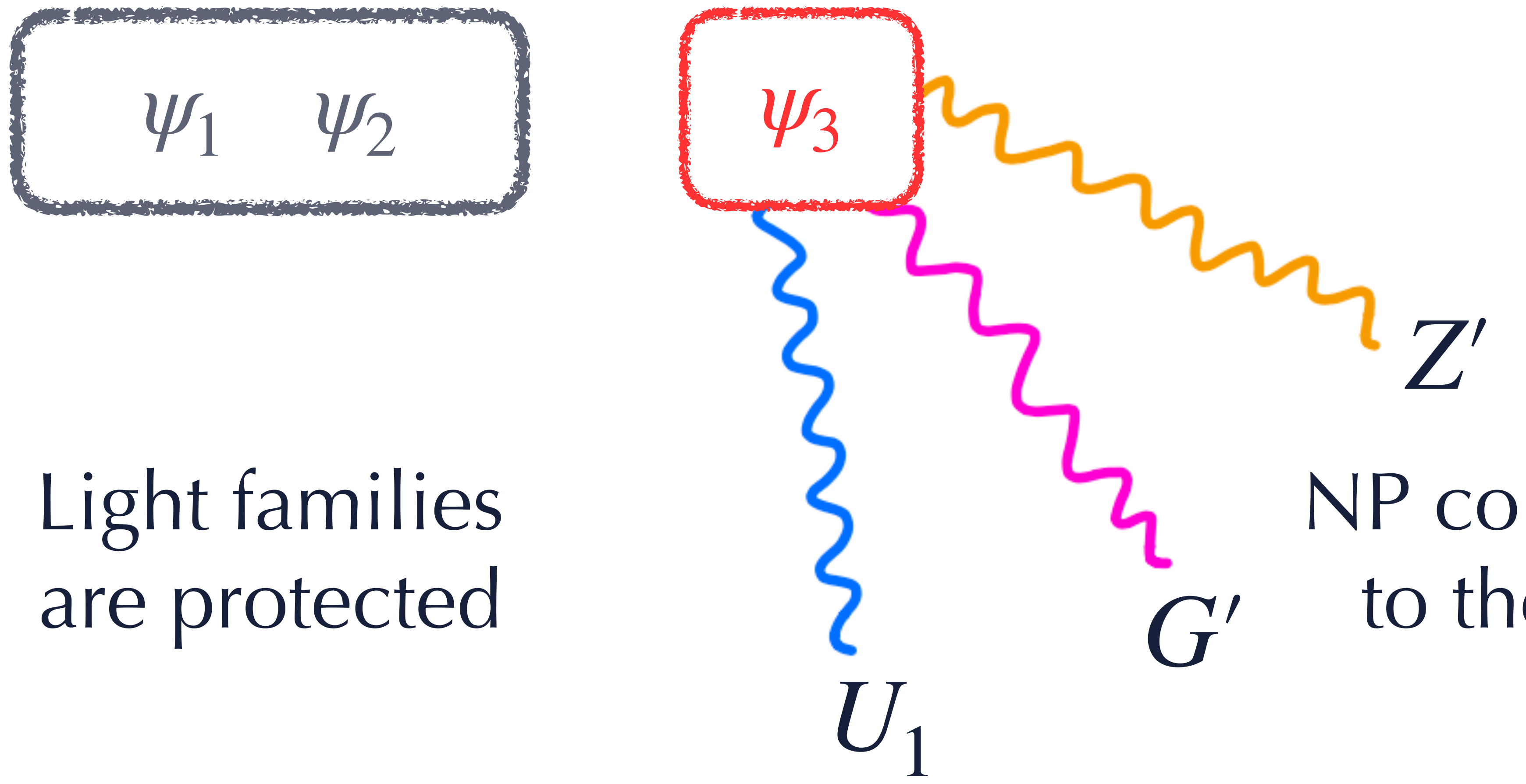
$$U(2)^5 = U(2)_q \times U(2)_u \times U(2)_d \times U(2)_\ell \times U(2)_e$$

as approximate accidental symmetry

$U(2)^5$ flavour symmetry

[Barbieri, Isidori, Pattori, Senia, 1512.01560]

- New Physics (NP) scale (quark-lepton unification for 3rd family) can be as low as a few TeV



Light families are protected

NP couples mainly to the 3rd family

- same as observed in Yukawa couplings: $y_t \gg y_{c,u}$
- broken by spurions generated by scalar vevs

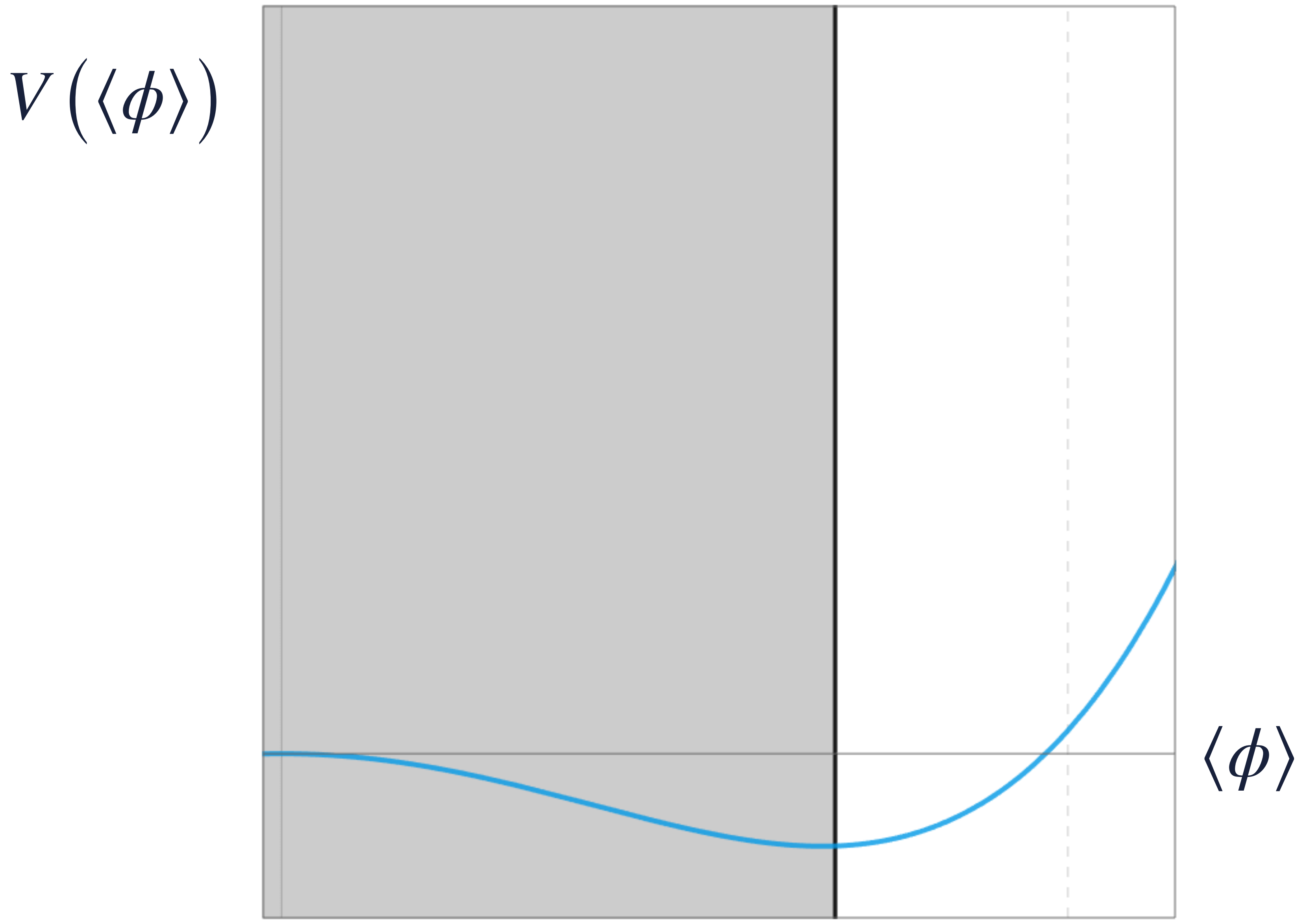
More about why in general $U(2)^5$ is a powerful flavour symmetry in this video from WIN2021: [https://www.youtube.com/watch?v=OA6AZbLmEqw]

REWSB

Radiative electroweak symmetry breaking:

Electroweak symmetry is conserved at the classical level,
but loop corrections to the mass parameter of the Higgs boson trigger its spontaneous breaking.

$\Rightarrow$ A positive Higgs mass parameter at high field value can turn negative at lower scale via the renormalization group flow.



Examples:

[Babu, Gogoladze, Khan, 1512.05185]

- Standard Model $\quad \beta_H^{\mathrm{SM}} \propto m_H^2$ ✗
- Type-I seesaw model $\quad \beta_H^{\mathrm{SS1}} = \beta_H^{\mathrm{SM}} - 4|y_\nu|^2|m_R|^2$ ✗
- Scalar singlet dark matter model $\quad \beta_H^{\mathrm{sDM}} = \beta_H^{\mathrm{SM}} + \lambda_3 m_s^2$ ✓

Necessary ingredients:

new states

positive contribution

-

$\Rightarrow$ TeV-scale new scalars

4321 - Scalar sector

This is precisely what we have in the 4321 model !

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
Ω_1	$\bar{4}$	1	1	$-1/2$
Ω_3	$\bar{4}$	3	1	$1/6$

TeV-scale new scalar states!

+ two-Higgs-doublet model (2HDM)

(singlets under $SU(4)$)

- Ω_3 break $SU(4) \times SU(3)' \times U(1)_X \to SU(3)_c \times U(1)_Y$

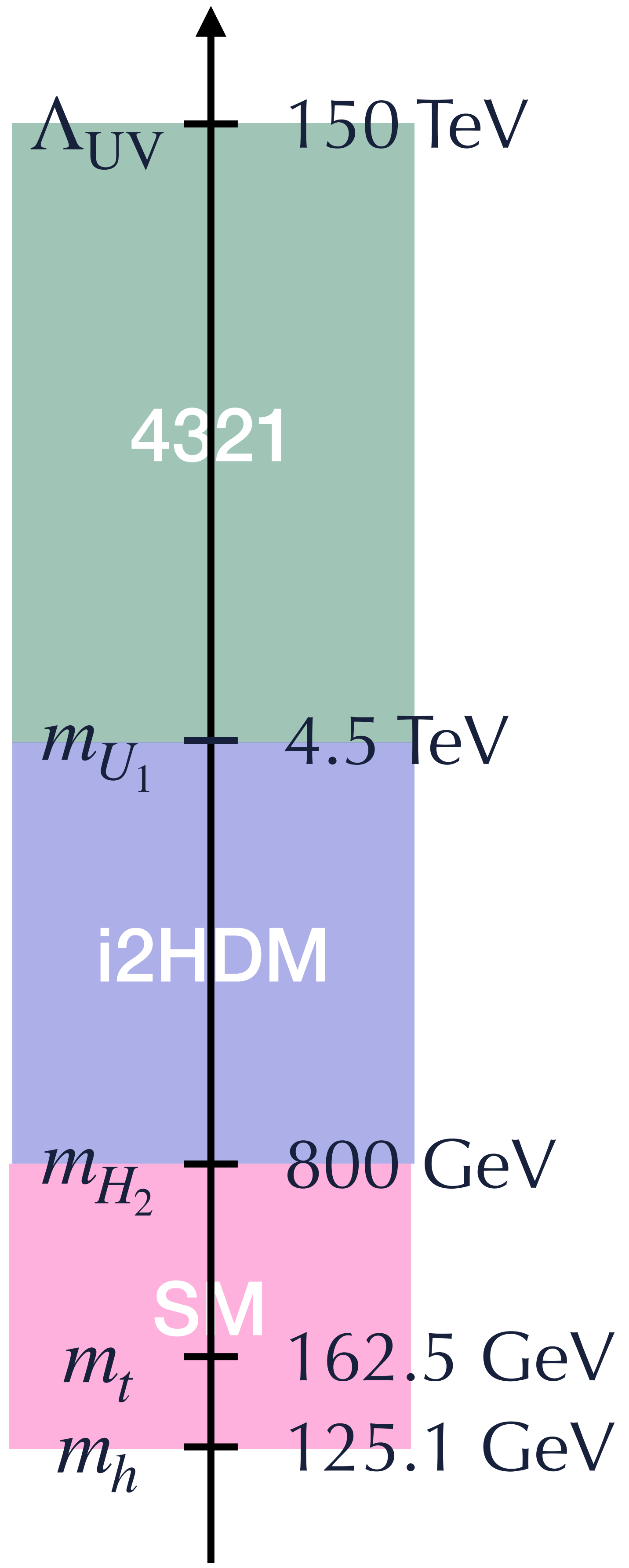
  vacuum expectation values: $\langle \Omega_3 \rangle \propto \frac{\omega_3}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$ and $\langle \Omega_1 \rangle = \frac{\omega_1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$

- $\Omega_{3,1}$ connect light family, resp., quarks and leptons to the 3rd site

- $H_{1,2}$ couple only to 3rd family (ignoring vector-like fermions mixing)

  $\hookrightarrow$ $U(2)^5$ in the Yukawa couplings

Scalar potential and RGE



$$V \;=\; \underset{\{\rho_i\},\, m_{\Omega_{1,3}}}{V_\Omega} \;+\; \underset{\{\lambda_i\},\, m_{H_{1,2}}}{V_{\rm 2HDM}} \;+\; \underset{\{\eta_i\}}{V_{\Omega H}}$$

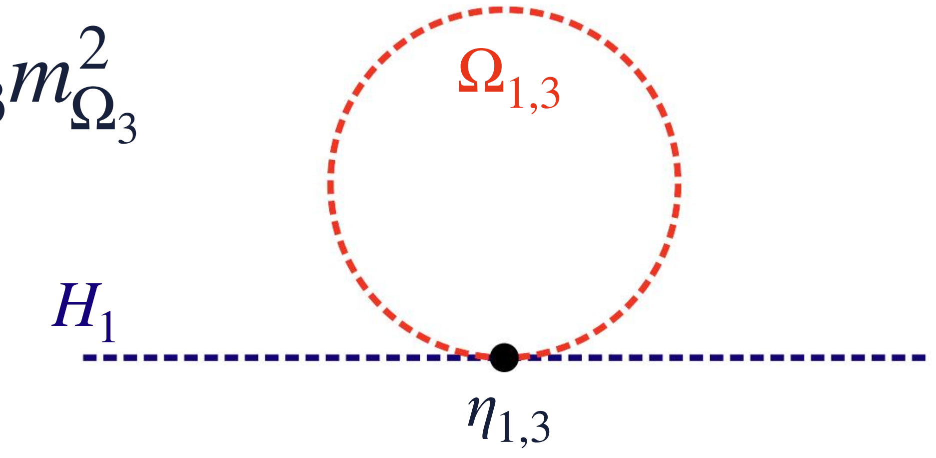
- $V_{\rm 2HDM}$ as in [Branco et al., 1106.0034]
- V_Ω as in [Di Luzio et al., 1808.00942]
- $V_{\Omega H} \supset \eta_i\, H_i^\dagger H_i \Omega_1^\dagger \Omega_1 + \eta_{i+2}\, H_i^\dagger H_i \mathrm{Tr}[\Omega_3^\dagger \Omega_3],\ i = 1{,}2$

Procedure:

1) Compute all β-functions of the Lagrangian parameters for each energy range

crosschecked with RGBeta [Thomsen, 2101.08265]

$$16\pi^2 \beta(m_{H_1}^2) = \left(6\lambda_1 + 8y_t^2 - \frac{3}{2}g_1^2 - \frac{9}{2}g_2^2\right) m_{H_1}^2 + (4\lambda_3 + 2\lambda_4) m_{H_2}^2 + 8\eta_1 m_{\Omega_1}^2 + 24\eta_3 m_{\Omega_3}^2$$



positive contribution for $\eta_{1,3} < 0$

2) Define quantity that triggers SSB by changing sign

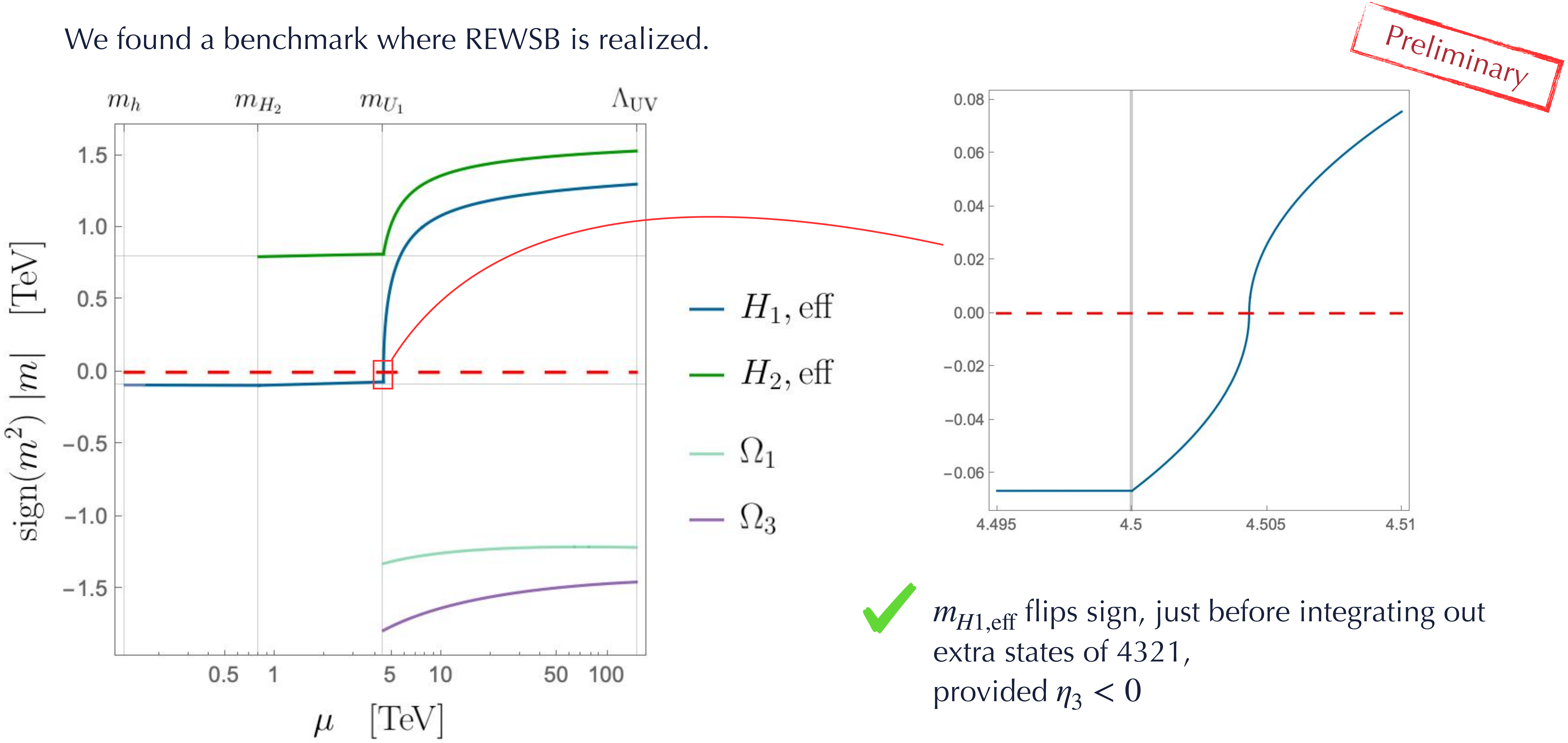
Diagonalization of the Hessian (equivalent to integrating out $\Omega_{1,3}$) gives the effective SM Higgs mass:

$$\boxed{m_{H_1,\rm eff}^2 = m_{H_1}^2 + \frac{\eta_1}{2}\,\omega_1^2 + \frac{3}{2}\eta_3\,\omega_3^2}$$

with $\omega_i = \omega_i\left(m_{\Omega_1}^2, m_{\Omega_3}^2, \{\rho_i\}\right)$

Solutions to the RGE

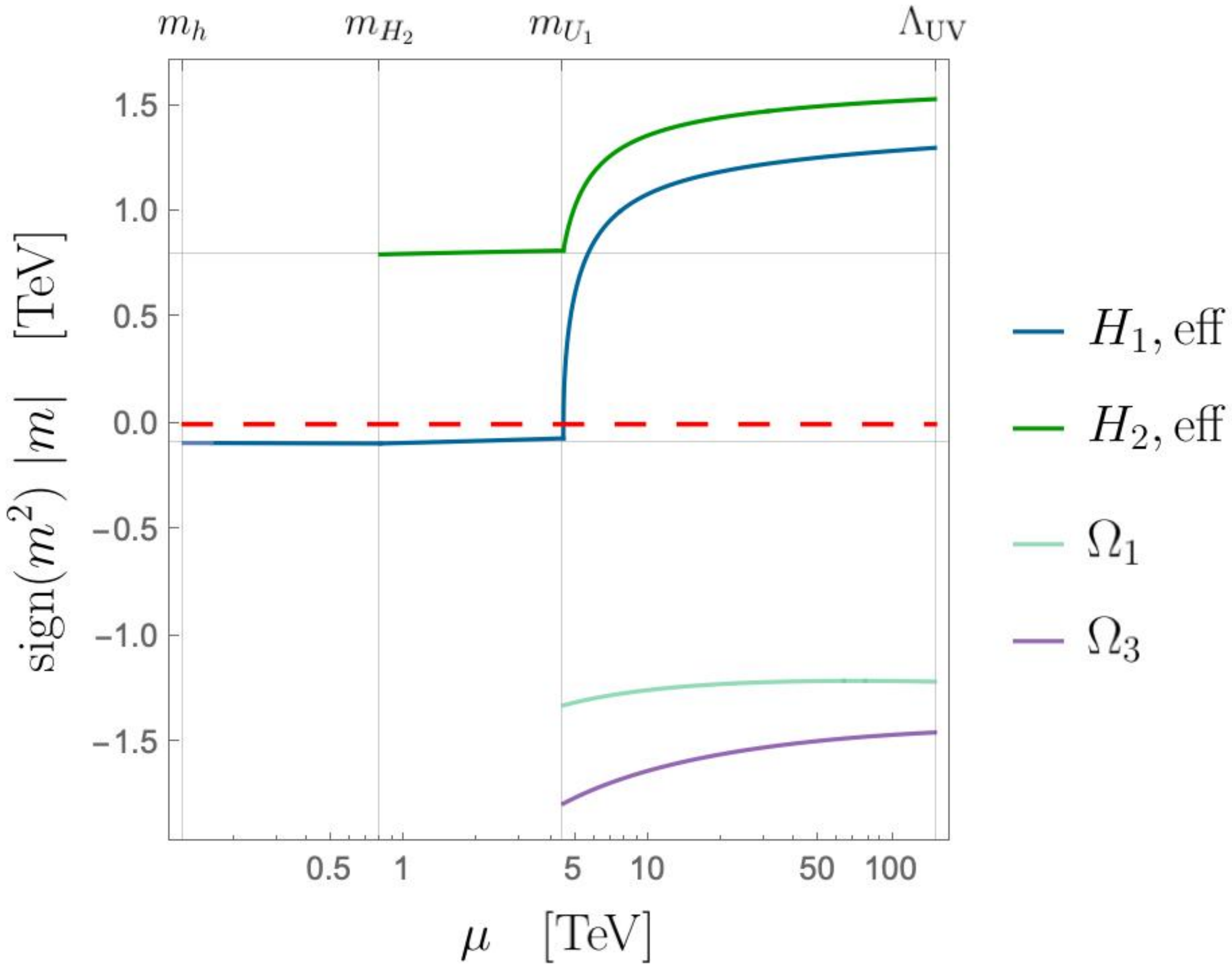
We found a benchmark where REWSB is realized.



✔ $m_{H1,\mathrm{eff}}$ flips sign, just before integrating out extra states of 4321, provided $\eta_3 < 0$

RGE and fine-tuning

We found a benchmark where REWSB is realized.



Checked:

✔ perturbativity until $\sim 10^9$ TeV

✔ bounded from below at all scales

Some observations:

✔ undeniably an RG effect

↪ without running, positive eigenvalues of the hessian will stay positive.

⛔ unavoidable fine-tuning

↪ it generates the strong acceleration near the 4321 breaking scale

Conclusion

The 4321 model

addresses both charge current ($R_{D^{(*)}}$) and neutral current ($R_{K^{(*)}}$) anomalies in semileptonic B-decays.
It features:

- an extended gauge sector containing the U_1 leptoquark
- quark-lepton unification with a $U(2)^5$ flavour symmetry
- a rich scalar sector with TeV-scale new states Ω_1 and Ω_3

Radiative Electroweak Symmetry Breaking

is an interesting mechanism to trigger the breaking of the symmetry by flipping the sign of the electroweak Higgs mass via RGE.

- It can happen in the 4321 model
- But fine-tuning seems ineluctable

Next step:
quantify the fine-tuning precisely and understand if the renormalisation group flow can relax it or not