Jura, 1975

About flavour, once again

Zoltan fest

ETH, Zurich, May 24, 2024

R. Barbieri
SNS, Pisa

Participating in the November Revolution

Mixing of p Wave Axial Vector Resonances #1

Riccardo Barbieri (CERN), Raoul Gatto (CERN), Z. Kunszt (Eotvos U.) (Dec, 1976)

Published in: *Phys.Lett.B* 66 (1977) 349-352

pdf DOI cite claim reference search 11 citations

Meson Masses and Widths in a Gauge Theory with Linear Binding Potential #2

Riccardo Barbieri (CERN), R. Kogerler (CERN), Z. Kunszt (CERN), Raoul Gatto (Rome U.) (Jun, 1975)

Published in: *Nucl.Phys.B* 105 (1976) 125-138

DOI cite claim reference search 243 citations

Electron-Positron Annihilation Above Charm Threshold #3

Riccardo Barbieri (CERN), R. Kogerler (CERN), Z. Kunszt (CERN), Raoul Gatto (Rome U. and INFN, Rome) (Jun, 1975)

Published in: *Phys.Lett.B* 56 (1975) 477-481

pdf DOI cite claim reference search 17 citations

Meson hyperfine splittings and leptonic decays #4

Riccardo Barbieri (CERN), Raoul Gatto (INFN, Rome), R. Kogerler (CERN), Z. Kunszt (CERN) (May, 1975)

Published in: *Phys.Lett.B* 57 (1975) 455-459

DOI cite claim reference search 264 citations

More to say at the end ...

The SM Lagrangian
(since 1973 in its full content)

$$\mathcal{L}_{\sim SM} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{\psi}\, \not{D} \psi$$ (∿1975-2000)

$$+ |D_\mu h|^2 - V(h)$$ (∿1990-2012-now)

$$+ \psi_i \lambda_{ij} \psi_j h + h.c.$$ (∿2000- now)

In () the approximate dates of the experimental confirmation of the various lines (at different levels)

The synthetic nature of the SM exhibited

Observational

Questions from (problems for) the SM

Structural

0. Which rationale for matter quantum numbers?

E.g.: $|Q_n - Q_p - Q_e| < 10^{-21} e$

1. Phenomena unaccounted for

neutrino masses — matter-antimatter asymmetry

Dark matter — inflation?

2. Why $\theta \lesssim 10^{-10}$? $\theta G_{\mu\nu} \tilde{G}^{\mu\nu}$

Axions? A discrete space-time symmetry?

3. $\mathcal{O}_i : d(\mathcal{O}_i) \leq 4$ only?

neutrino masses — Are the protons forever?

Gravity — What about individual L_i conservations?

4. Lack of calculability

$\Rightarrow$ the hierarchy problem, the flavour puzzle $\Leftarrow$ none of the 15 masses predicted in the SM

Where could some light come from?

1.A theory breakthrough →
- 1a BSM
- 1b Foundations (FT, QM in curved space)

On 1a, not that one hasn't tried, sometimes with great ideas (GUT, susy, axion,…)

2.Astrophysics, Cosmology →
- 2a DM, Dark Energy, B-asymmetry
- 2b Early Universe, Inflation
- 2c Black Holes, Grav. waves

Fundamental questions. Related to the structure of the SM of PP?

3.An experimental deviation from the SM →
- 3a New particles
- 3b Precision

Focus on 3b, assuming (which requires) new physics in the MultiTeV,
(as made likely by the hierarchy problem, still pending)

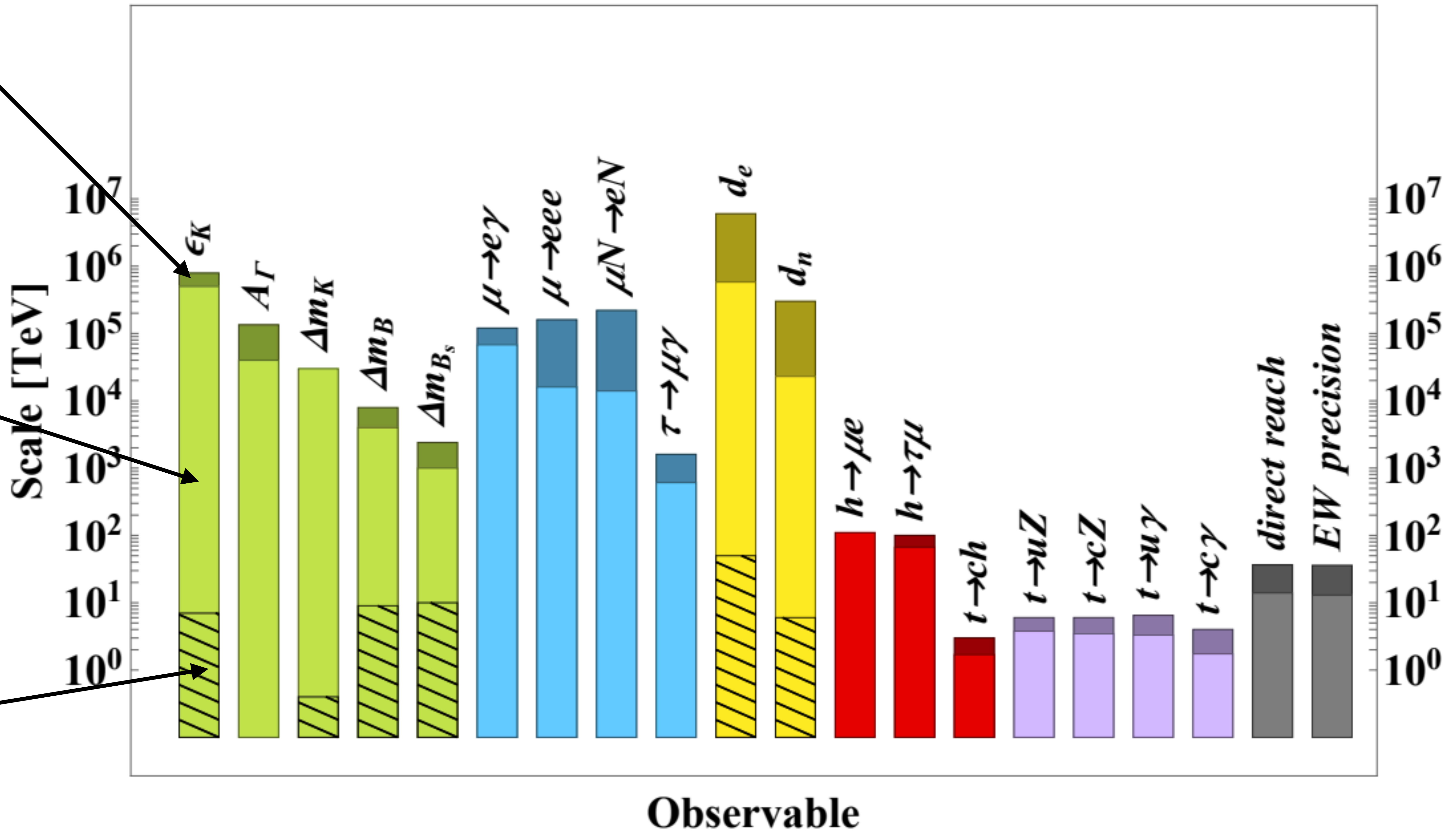
An extreme summary in precision measurements

(European Strategy for PP, 2020)

"Mid-term" prospects:
All approved exp.s + LHCb II

current
$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{1}{\Lambda_i^2}\mathcal{O}_i$$

current
$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{F_i^{SM}}{\Lambda_i^2}\mathcal{O}_i$$



Flavour and EDMs (CPV) dominate

A more detailed plot

(from actually measured flavour quantities only)

$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{C_i}{\Lambda_i^2} \mathcal{O}_i$$

$$Q_1^{q_i q_j} = \bar{q}_{jL}^{\alpha} \gamma_\mu q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} \gamma^\mu q_{iL}^{\beta} ,$$

$$Q_2^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jR}^{\beta} q_{iL}^{\beta} , \qquad Q_4^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} q_{iR}^{\beta} ,$$

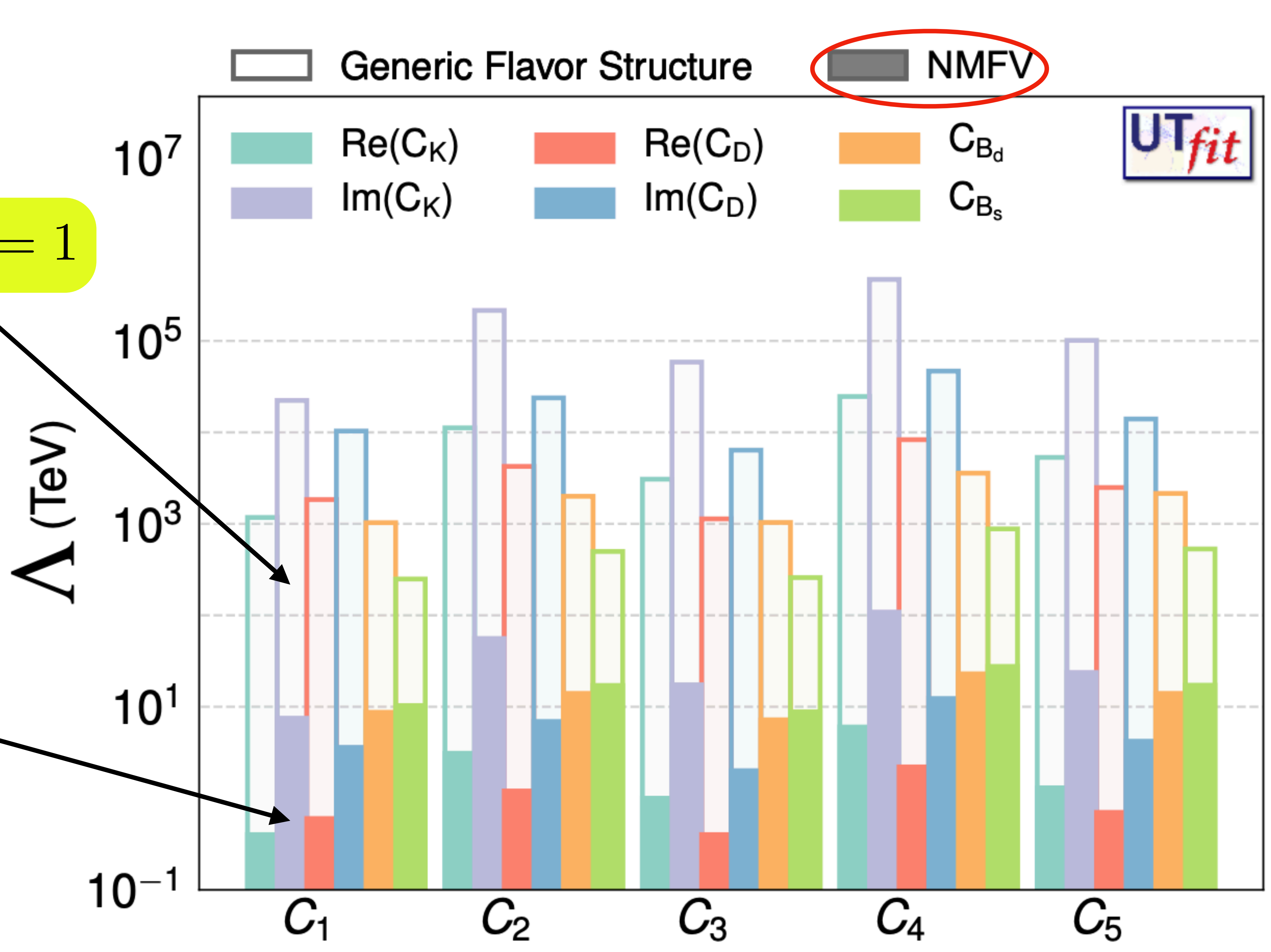
$$Q_3^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jR}^{\beta} q_{iL}^{\alpha} , \qquad Q_5^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jL}^{\beta} q_{iR}^{\alpha} .$$

$\mathcal{C}_i = 1$

NMFV $$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{F_i^{SM}}{\Lambda_i^2} \mathcal{O}_i$$

$$F^{SM}(C_{K,D}) = (V_{td} V_{ts}^*)^2 e^{i\phi_{K,D}}$$

$$F^{SM}(C_{B_q}) = (V_{tq} V_{tb}^*)^2 e^{i\phi_{B_q}}$$



Pierini, 2023

Where is the actual scale of flavour physics Λ^f ? Must Λ^f be "low"?

How low can Λ^f be? Can one "make sense" of "NMFV"?

Must Λ^f be "low"?

Is the hierarchy problem related to the flavour puzzle?

A difference in the two sectors of the SM?

$$\mathcal{L}_{SM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\Psi}\not{D}\Psi$$

The "gauge sector"

$$+|D_\mu\phi|^2 + M^2|\phi|^2 - \lambda|\phi|^4 + \Lambda + \lambda_{ij}\phi\bar{\Psi}_i\Psi_j$$

The "Higgs sector"

(where the Fermi scale originates)

the hierarchy problem | the CC problem | the flavour problem

In EFT they look much the same

No particle mass calculable (15=17-2)

To me: the relatively best motivation for BSM in the MultiTeV

(and a strong motivation for the next HE collider)

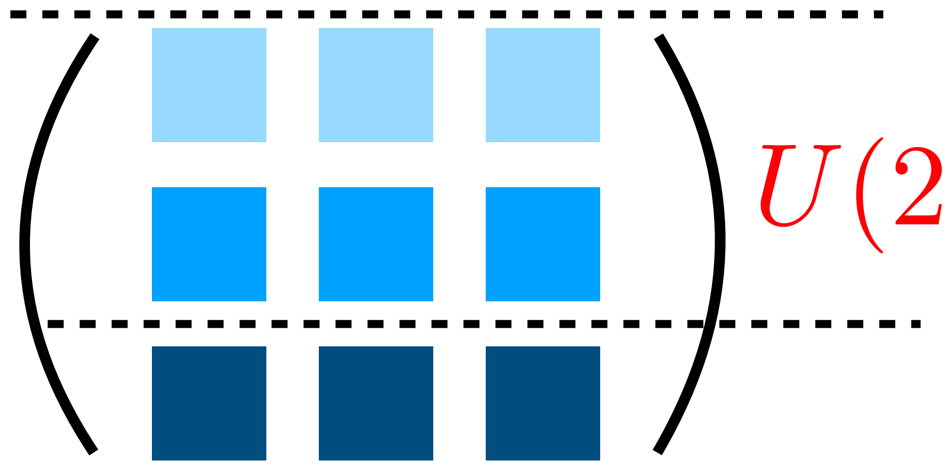
(Approximate) symmetries of the Yukawa couplings

Charged fermion Yukawa couplings

$$Y \propto U_L^+ \begin{pmatrix} m_1/m_3 & 0 & 0 \\ 0 & m_2/m_3 & 0 \\ 0 & 0 & 1 \end{pmatrix} U_R \qquad m_1/m_3 << m_2/m_3 << 1 \qquad U_L^u (U_L^d)^+ = V_{CKM} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

1 IF $[U_L^{u,d}]_{i\neq j} \lesssim [V_{CKM}]_{i\neq j}$

$Y^{u,d} \approx$



$U(2)_q$

$\Rightarrow U(2)_q$

(approximate) symmetries of the Yukawa couplings

Charged fermion Yukawa couplings

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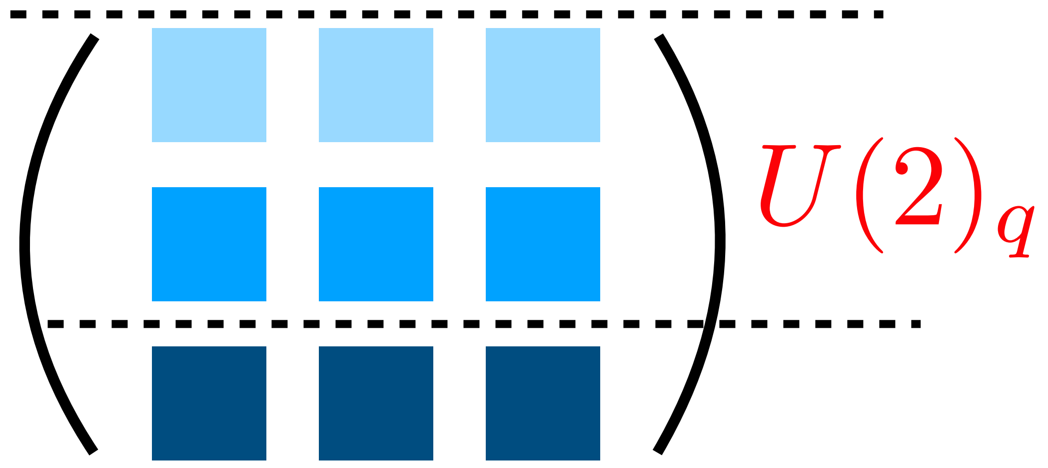
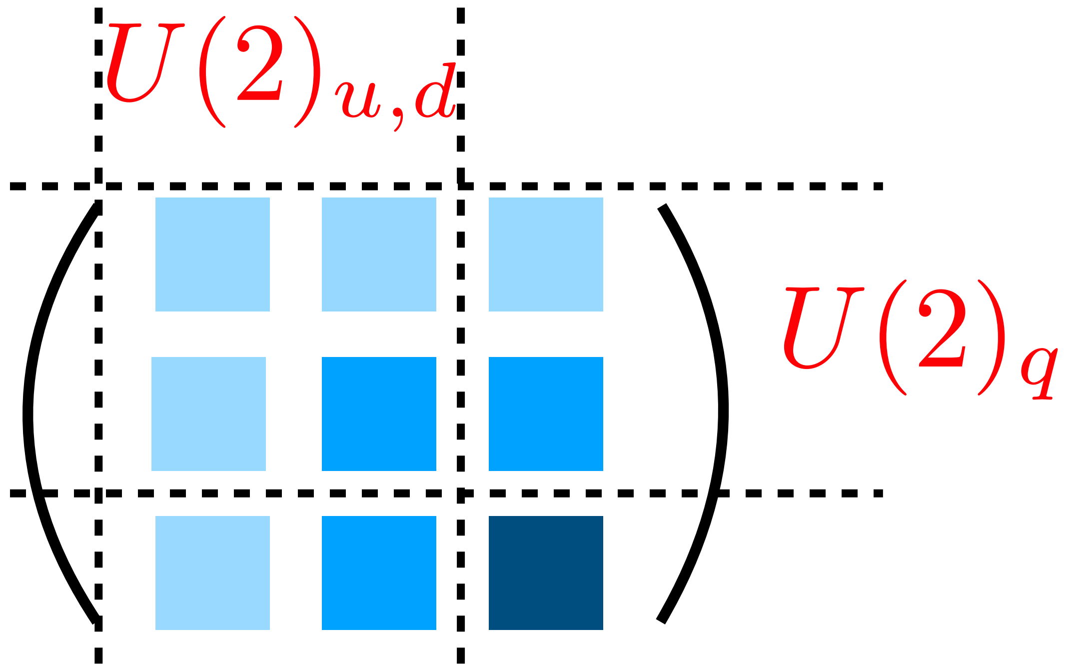


$\Rightarrow U(2)_q$

2 IF 1 + $[U_R^{u,d}]_{i\neq j} \lesssim [U_L^{u,d}]_{i\neq j}$

$Y^{u,d} \approx$



$\Rightarrow U(2)_q \times U(2)_u \times U(2)_d$

(approximate) symmetries of the Yukawa couplings

Charged fermion Yukawa couplings

$$Y \propto U_L^+ \begin{pmatrix} m_1/m_3 & 0 & 0 \\ 0 & m_2/m_3 & 0 \\ 0 & 0 & 1 \end{pmatrix} U_R \qquad m_1/m_3 << m_2/m_3 << 1 \qquad U_L^u (U_L^d)^+ = V_{CKM} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

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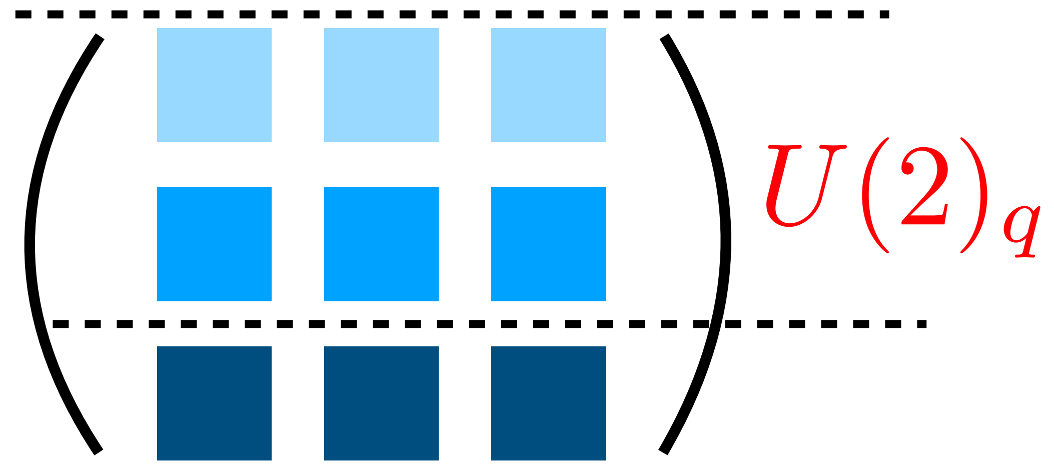
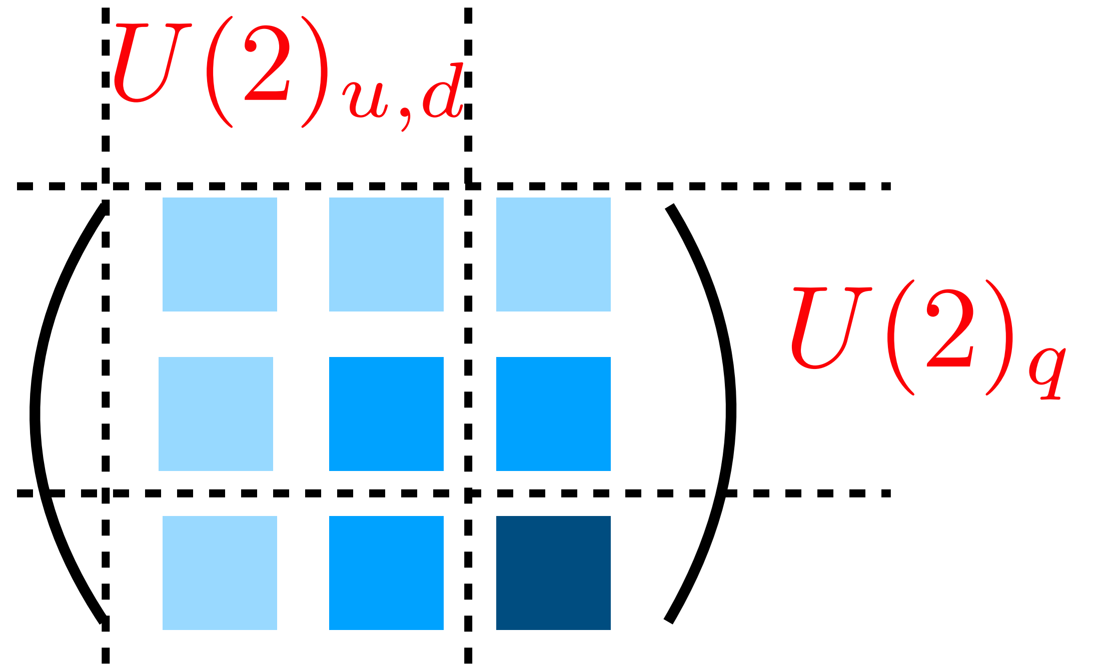


$\Rightarrow U(2)_q$

2 IF 1 + $[U_R^{u,d}]_{i\neq j} \lesssim [U_L^{u,d}]_{i\neq j}$

$Y^{u,d} \approx$



$\Rightarrow U(2)_q \times U(2)_u \times U(2)_d$

3 IF 2 + $[U_{L,R}^e]_{i\neq j} \lesssim [U_{L,R}^{u,d}]_{i\neq j}$

$\Rightarrow U(2)_q \times U(2)_u \times U(2)_d \times U(2)_l \times U(2)_e$

Can $U(2)^n$ emerge as an accidental symmetry?
What breaks it?

B, Isidori et al, 2011

A definite goal: Precision in composite Higgs

What is the radius of Higgs compositeness, if any? $l_H = 1/m_*$

A two-parameter "theory"

$m_* = g_* f$

f

m_H

Giudice et al, 2007

H = pNGB

f = scale of symmetry breaking

m_* = scale of Higgs compositeness

Fine tuning = $(\frac{v}{f})^2$ $\quad v = 175 GeV$

An EFT approach

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{m_*^4}{g_*^2}\mathcal{L}_{res}\left(\frac{g_*\Phi^d}{m_*^d}, \frac{d_\mu}{m_*}, \frac{gA_\mu}{m_*}, \frac{\lambda_\Psi^i \Psi^i}{m_*^{3/2}}\right)$$

Giudice et al, 2007

Φ^d = Strong resonances of dim d (J=0,1/2,1,...) including H

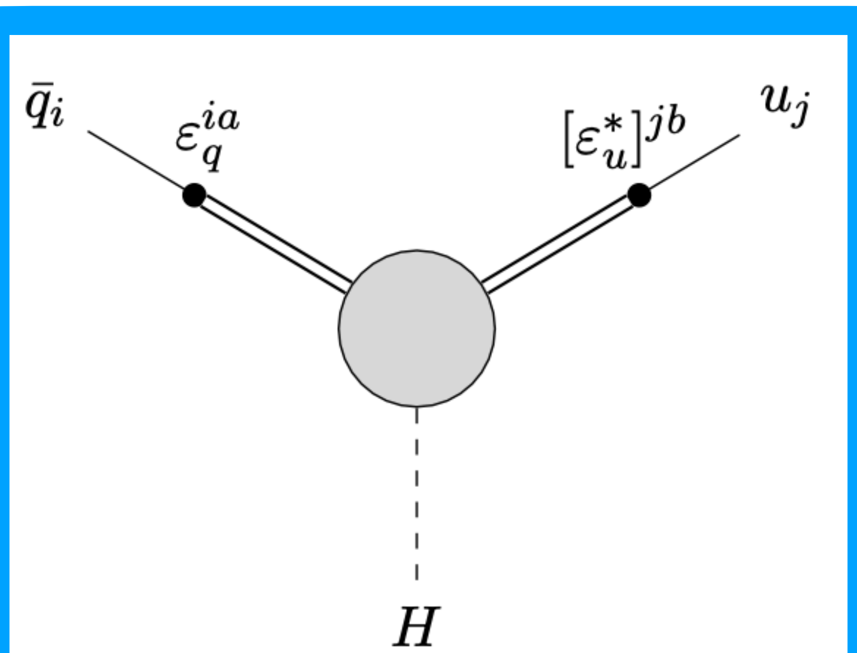
Ψ^i, A_μ = SM fields

λ_Ψ^i = flavour par.s, subject to suitable symmetries

Redi, Wyler 2011

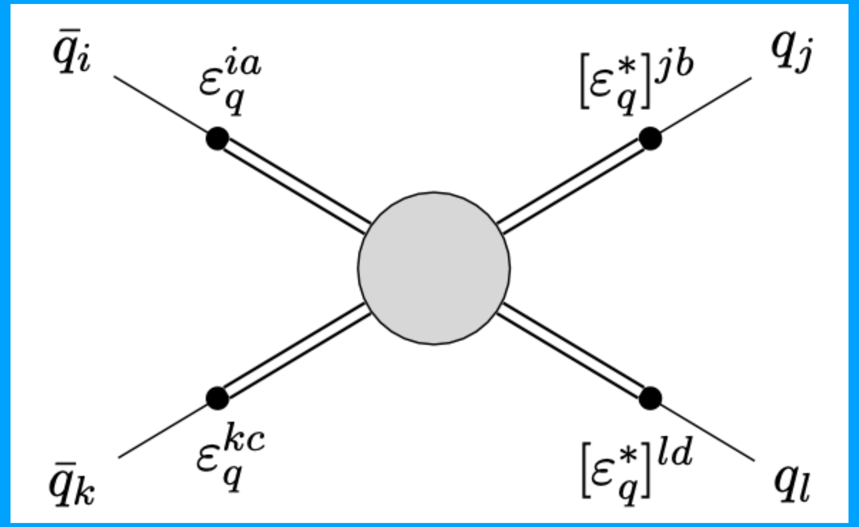
B, Buttazzo et al, 2013

Glioti et al, 2024



$$Y^u_{ij} = g_*\varepsilon_q^{ia} c_{ab}[\varepsilon_u^*]^{jb}$$

E.g.



$$\mathcal{L}^{4q} = \frac{g_*^2}{m_*^2} c_{abcd}\varepsilon_q^{ia}[\varepsilon_q^*]^{jb}\varepsilon_q^{kc}[\varepsilon_q^*]^{ld}\bar{q}^i\gamma_\mu q^j \bar{q}^k\gamma^\mu q^l$$

$$\epsilon_f^{ia} = \frac{\lambda_f^{ia}}{g_*}$$

$$c_{ab}, c_{abcd} = \mathcal{O}(1)$$

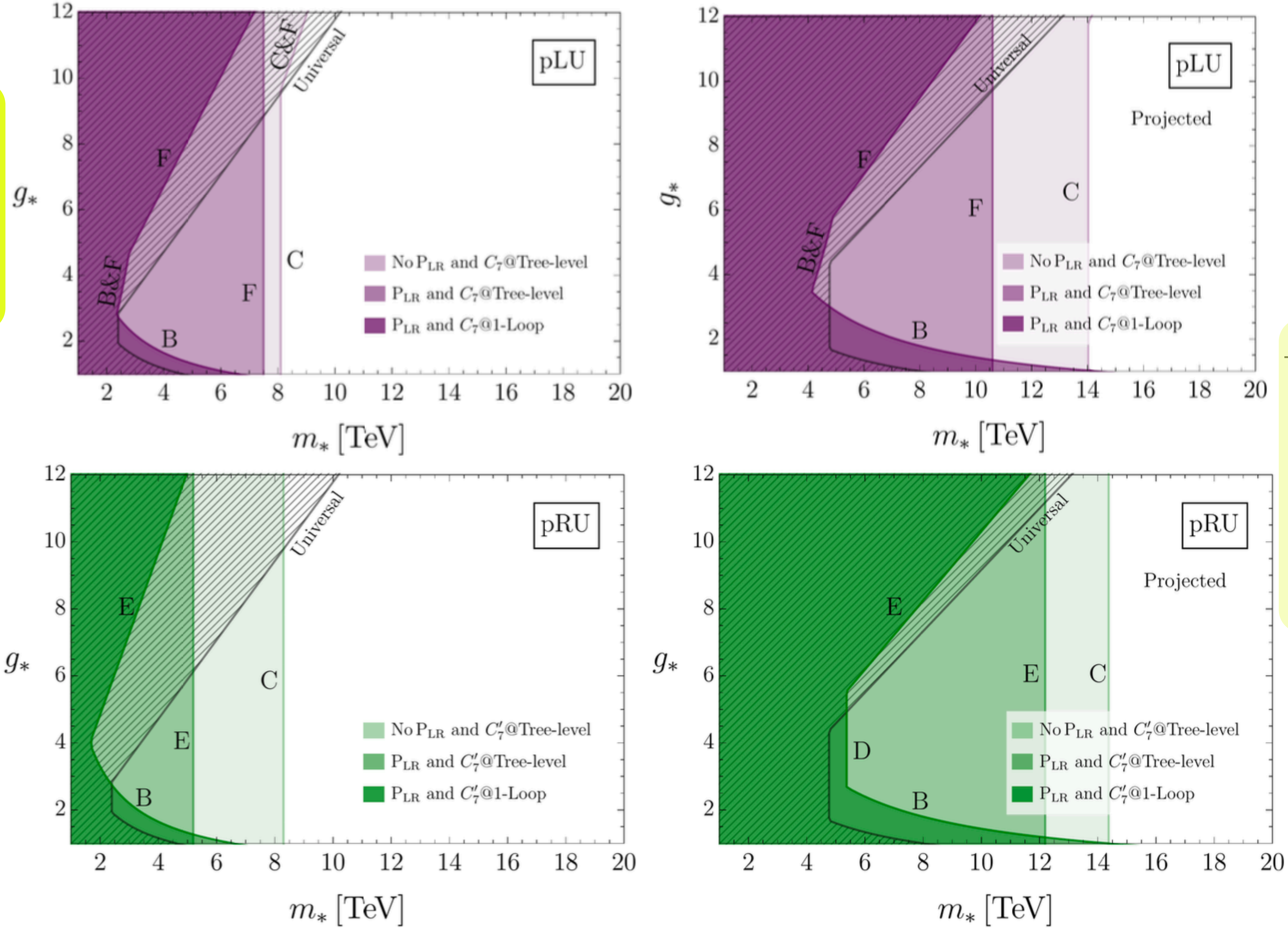
If $\epsilon_{11} << \epsilon_{22} << \epsilon_{33}$ "anarchy" $\Rightarrow m_* \gtrsim 10^{2\div3} TeV(g_*/4\pi)$

Summary of excluded/sensitivity regions

Glioti et al, 2024

partial Left Univ = λ_Ψ^i respecting $U(2)_q$

part. Right Univ = λ_Ψ^i respecting $U(2)_u \times U(2)_d$



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

Universal = flavour-less EW observables

Projected = "mid-term"

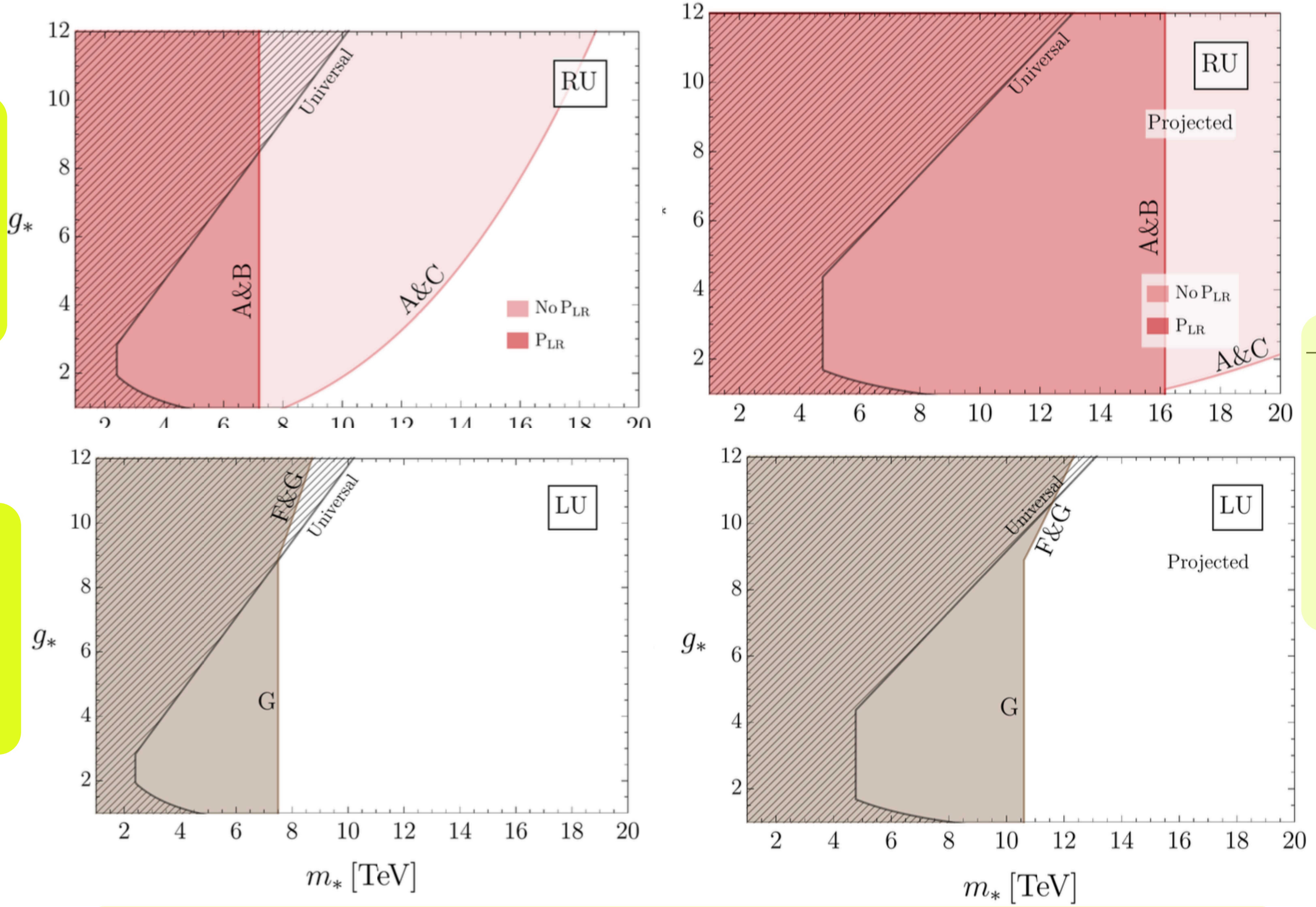
(Quarks only)

Summary of excluded/sensitivity regions

Glioti et al, 2024

Right Univ = λ^i_Ψ respecting $U(3)_u \times U(3)_d$

Left Univ = λ^i_Ψ respecting $U(3)_q$



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

Mid-term prospect: $m_* > (11 \div 20) TeV$ for any g_*

(Quarks only)

Can one "make sense" of "NMFV"?

(or of the symmetries respected by λ_Ψ^i in the previous case?)

$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{F_i^{SM}}{\Lambda_i^2} \mathcal{O}_i$$

$$F^{SM}(C_{K,D}) = (V_{td} V_{ts}^*)^2 e^{i\phi_{K,D}}$$

$$F^{SM}(C_{B_q}) = (V_{tq} V_{tb}^*)^2 e^{i\phi_{B_q}}$$

Can one relate the F_i^{SM} to the structure of $Y^{u,d}$?

All the SM in 1 page

1. Symmetry group $L \times \mathcal{G}$

L = Lorentz (space-time)

$\mathcal{G} = SU(3) \times SU(2) \times U(1)$ (local)

2. Particle content (rep.s of $L \times \mathcal{G}$)

	h	Q	L	u	d	e
Lorentz	0	$1/2_L$	$1/2_L$	$1/2_R$	$1/2_R$	$1/2_R$
$SU(3)$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$
$SU(2)$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)$	$-1/2$	$1/6$	$-1/2$	$2/3$	$-1/3$	-1

3. All "operators" (products of $\Phi, \partial_\mu \Phi$) in $\mathcal{L}$ of dimension ≤ 4

$$\hbar = c = 1 \Rightarrow [A_\mu] = [\phi] = [\partial_\mu] = M, \quad [\Psi] = M^{3/2}, \quad [\mathcal{L}] = M^4$$

Minimal Flavour Deconstruction

B, Isidori, 2023

$$SU(3) \times SU(2) \times G_Y$$

$$G_Y = U(1)_Y^{[3]} \times U(1)_{B-L}^{[12]} \times U(1)_{T_{3R}}^{[2]} \times U(1)_{T_{3R}}^{[1]} \qquad H \overset{G_Y}{=} (-1/2, 0, 0, 0)$$

$$G_Y \xrightarrow{\sigma} U(1)_Y^{[3]} \times U(1)_{B-L}^{[12]} \times U(1)_{T_{3R}}^{[12]} \xrightarrow{\phi,\chi} U(1)_Y$$

$$\epsilon_\sigma = \frac{\langle \sigma \rangle}{\Lambda_{[12]}}, \qquad \epsilon_\phi = \frac{\langle \phi \rangle}{\Lambda_{[23]}}, \qquad \epsilon_\chi = \frac{\langle \chi^{q,l} \rangle}{\Lambda_{[23]}}$$

$$\begin{array}{cc} & \overbrace{U(1)_{T_{3R}}^{[1]} \quad U(1)_{T_{3R}}^{[2]}}^{U(1)_{B-L}^{[12]}} \\ Y \sim & \left(\begin{array}{cc|c} \mathcal{O}(\epsilon_\sigma \epsilon_\phi) & \mathcal{O}(\epsilon_\phi) & \mathcal{O}(\epsilon_\chi) \\ \hline \mathcal{O}(\epsilon_\sigma \epsilon_\phi \epsilon_\chi) & \mathcal{O}(\epsilon_\phi \epsilon_\chi) & \mathcal{O}(1) \end{array} \right) \begin{array}{c} U(1)_{B-L}^{[12]} \\ \\ \end{array} \end{array}$$

(Still EFT)

Can one construct an explicit 4d gauge theory without small Yukawa couplings?

(Where do the Λ's come from?)

Minimal Flavour Deconstruction in 4d

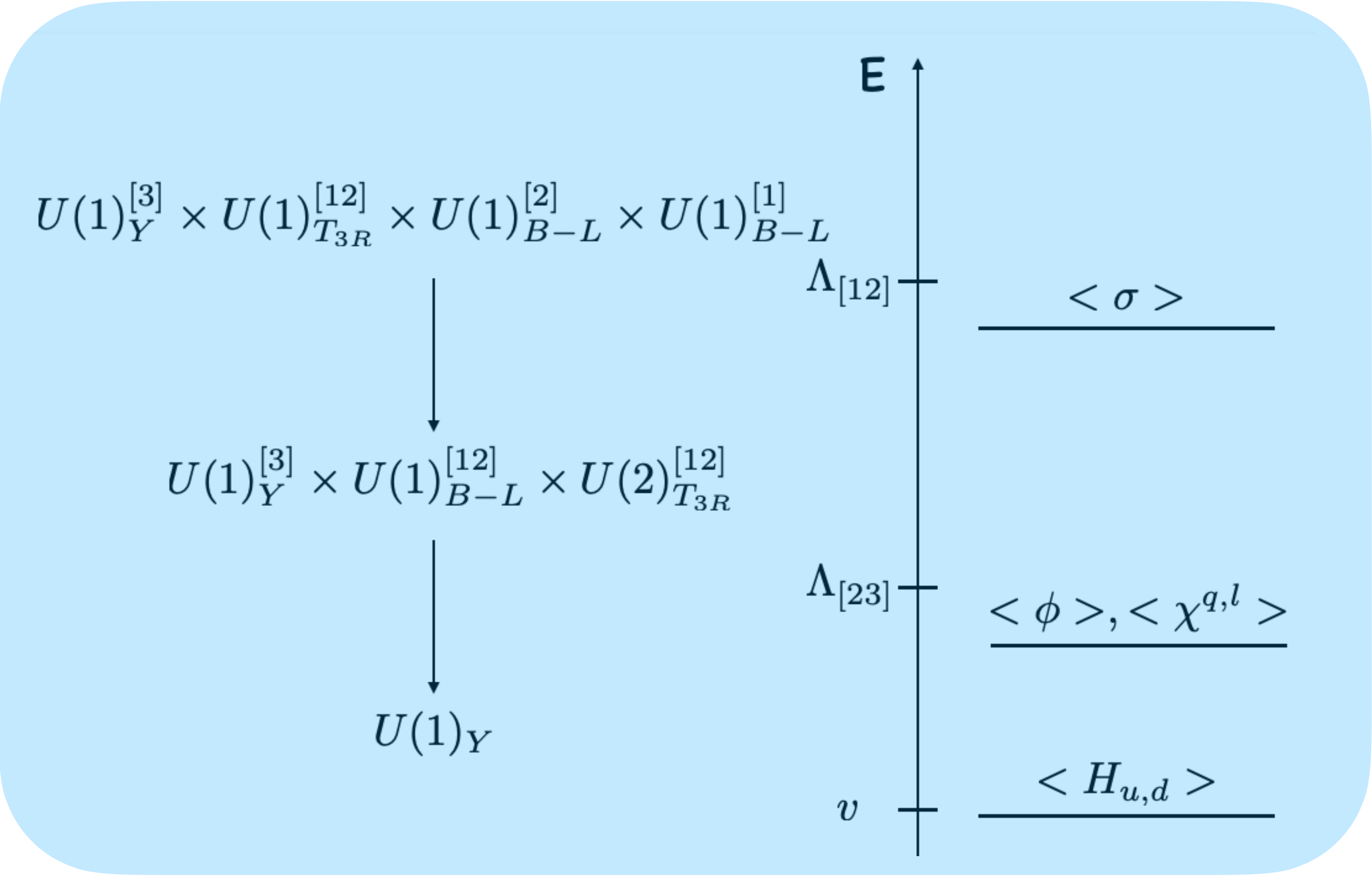
vev scale	Field	$U(1)_Y^{[3]}$	$U(1)_{B-L}^{[12]}$	$U(1)_{T_{3R}}^{[2]}$	$U(1)_{T_{3R}}^{[1]}$	$SU(3)\times SU(2)$
v	$H_{u,d}$	$-1/2$	0	0	0	$(\mathbf{1},\mathbf{2})$
$O(10^{-1})\times\Lambda_{[23]}$	χ^q	$-1/6$	$1/3$	0	0	$(\mathbf{1},\mathbf{1})$
	χ^l	$1/2$	-1	0	0	$(\mathbf{1},\mathbf{1})$
	ϕ	$1/2$	0	$-1/2$	0	$(\mathbf{1},\mathbf{1})$
$O(10^{-1})\times\Lambda_{[12]}$	σ	0	0	$1/2$	$-1/2$	$(\mathbf{1},\mathbf{1})$

$$Z_2: \quad H_u \to u, H_d \to d, e$$

$$tan\beta = v_u/v_d = 10 \div 30$$

$$V = \lambda(\chi^q)^3\chi^l$$

Universal breaking of the gauge group



$$\epsilon_\sigma = \frac{\langle\sigma\rangle}{\Lambda_{[12]}}$$

$$\epsilon_\phi = \frac{\langle\phi\rangle}{\Lambda_{[23]}}, \qquad \epsilon_\chi = \frac{\langle\chi^{q,l}\rangle}{\Lambda_{[23]}}$$

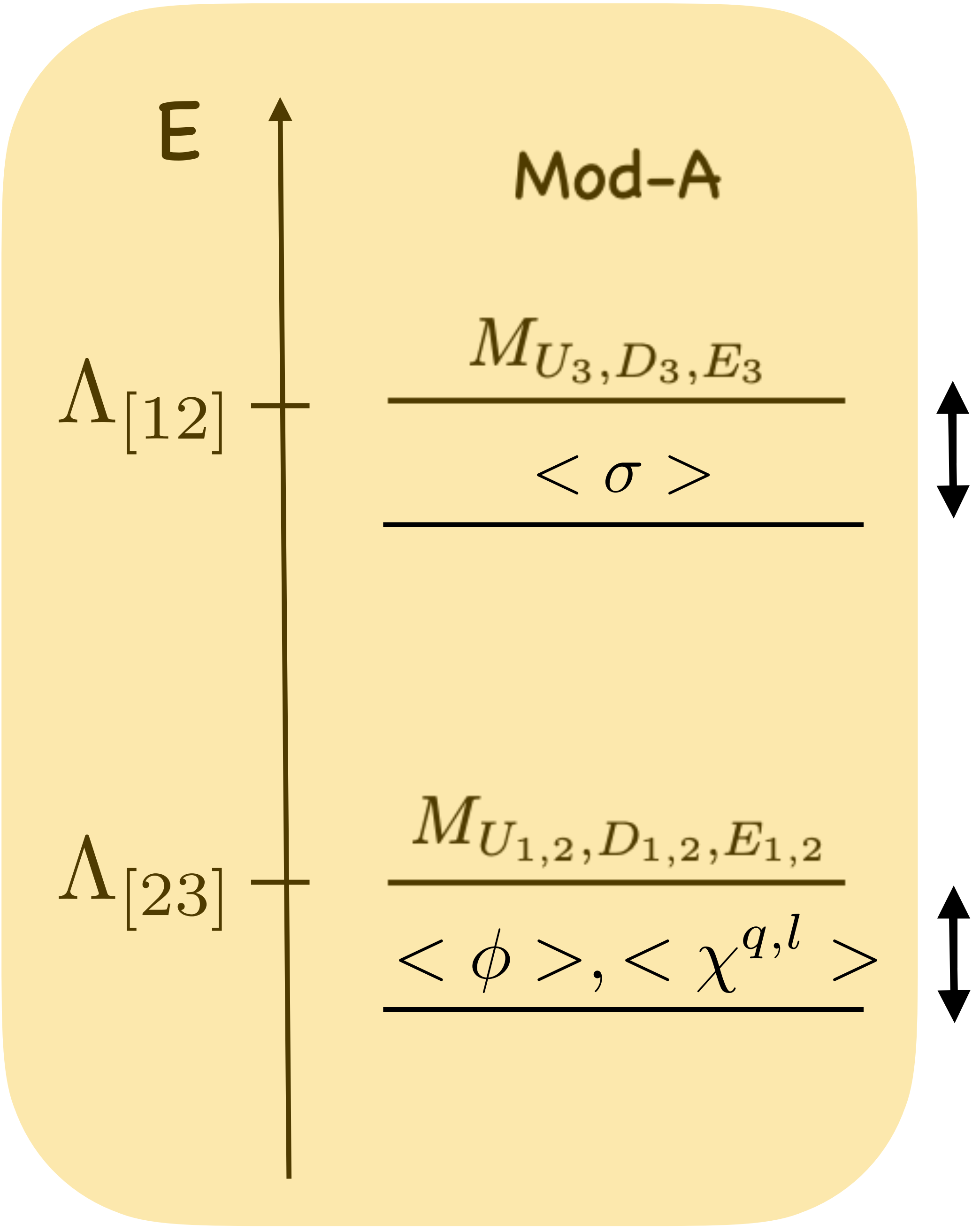
(Where do the Λ's come from?)

Model A

1st way for the Λ's

Vector-like fermions

		$U(1)_Y^{[3]}$	$U(1)_{B-L}^{[12]}$	$U(1)_{T_{3R}}^{[2]}$	$U(1)_{T_{3R}}^{[1]}$	$SU(3)\times SU(2)$
light VL ($\alpha=1,2$)	U_α	$1/2$	$1/3$	0	0	$(\mathbf{3},\mathbf{1})$
	D_α	$-1/2$	$1/3$	0	0	$(\mathbf{3},\mathbf{1})$
	E_α	$-1/2$	-1	0	0	$(\mathbf{1},\mathbf{1})$
heavy VL	U_3	0	$1/3$	$1/2$	0	$(\mathbf{3},\mathbf{1})$
	D_3	0	$1/3$	$-1/2$	0	$(\mathbf{3},\mathbf{1})$
	E_3	0	-1	$-1/2$	0	$(\mathbf{1},\mathbf{1})$



Model A

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light VL ($\alpha = 1,2$)	U_α	$1/2$	$1/3$	0	0	$(\mathbf{3},\mathbf{1})$
	D_α	$-1/2$	$1/3$	0	0	$(\mathbf{3},\mathbf{1})$
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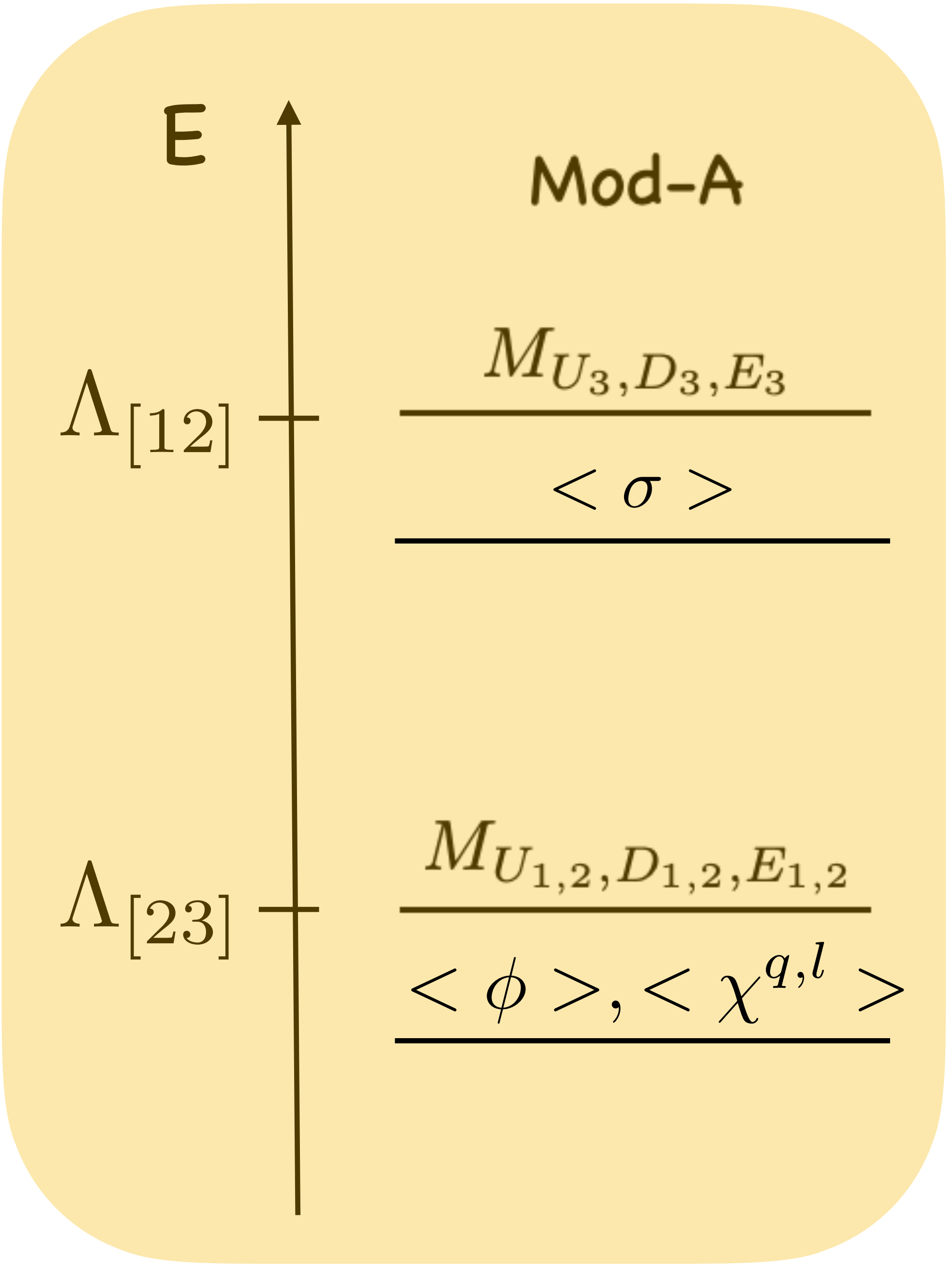
	E_3	0	-1	$-1/2$	0	$(\mathbf{1},\mathbf{1})$



Most general $d \leq 4$

$$\mathcal{L}_Y^u = (y_3^u\, \bar q_3 u_3 H_u + y_{i\alpha}^u\, \bar q_i U_\alpha H_u + y_\alpha^{\chi_u}\, \bar U_\alpha u_3 \chi^q + y_{\alpha 2}^{\phi_u}\, \bar U_\alpha u_2 \phi + y_{\alpha 3}^{\phi_u}\, \bar U_{R\alpha} U_{L3} \phi + \hat y_{\alpha 3}^{\phi_u}\, \bar U_{L\alpha} U_{R3} \phi + y_1^{\sigma_u}\, \bar U_3 u_1 \sigma + \text{h.c.}) + M_{U_3}\, \bar U_3 U_3 + M_{U_\alpha}\, \bar U_\alpha U_\alpha$$

Model A

1st way for the Λ's

Vector-like fermions

		$U(1)_Y^{[3]}$	$U(1)_{B-L}^{[12]}$	$U(1)_{T_{3R}}^{[2]}$	$U(1)_{T_{3R}}^{[1]}$	$SU(3)\times SU(2)$
light VL ($\alpha=1,2$)	U_α	$1/2$	$1/3$	0	0	$(\mathbf{3},\mathbf{1})$
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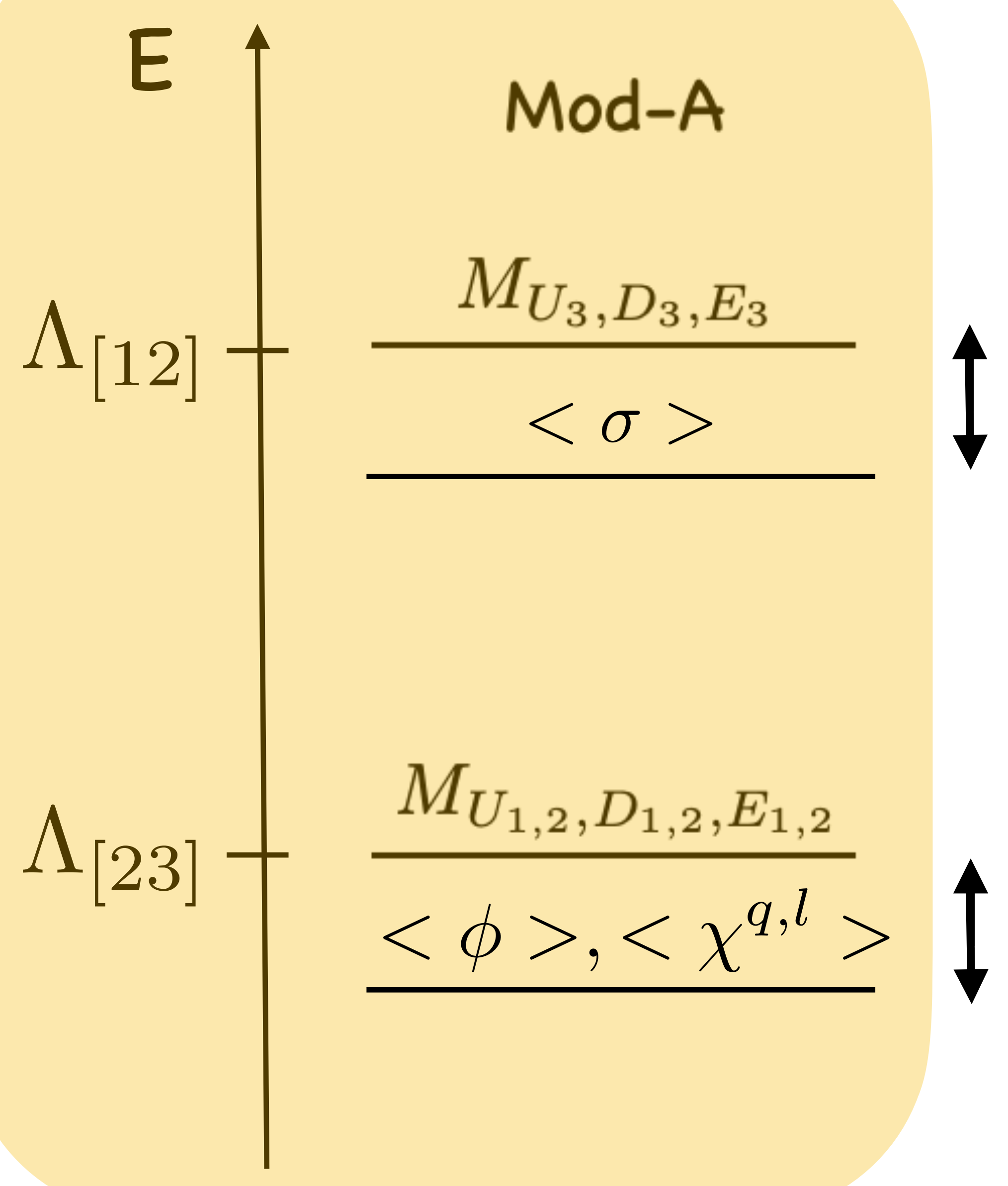
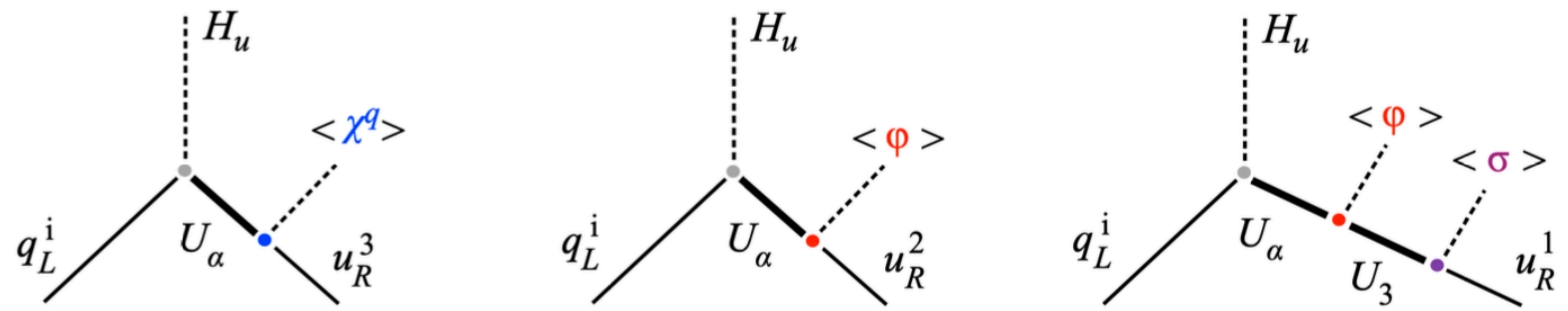
heavy VL	U_3	0	$1/3$	$1/2$	0	$(\mathbf{3},\mathbf{1})$
	D_3	0	$1/3$	$-1/2$	0	$(\mathbf{3},\mathbf{1})$
	E_3	0	-1	$-1/2$	0	$(\mathbf{1},\mathbf{1})$



Most general $d\leq 4$

$$\mathcal{L}_Y^u = (y_3^u\,\bar{q}_3 u_3 H_u + y_{i\alpha}^u\,\bar{q}_i U_\alpha H_u + y_\alpha^{\chi_u}\,\bar{U}_\alpha u_3 \chi^q + y_{\alpha 2}^{\phi_u}\,\bar{U}_\alpha u_2 \phi + y_{\alpha 3}^{\phi_u}\,\bar{U}_{R\alpha} U_{L3}\phi + \hat{y}_{\alpha 3}^{\phi_u}\,\bar{U}_{L\alpha} U_{R3}\phi + y_1^{\sigma_u}\,\bar{U}_3 u_1 \sigma + \text{h.c.}) + M_{U_3}\,\bar{U}_3 U_3 + M_{U_\alpha}\,\bar{U}_\alpha U_\alpha$$

$Y_u \Rightarrow$



And similarly for $Y_{d,e}$

$$Y_u \approx \begin{pmatrix} y_{1\alpha}^u \hat{y}_{\alpha 3}^{\phi_u} y_1^{\sigma_u}\epsilon_\sigma\epsilon_\phi & y_{1\alpha}^u y_{\alpha 2}^{\phi_u}\epsilon_\phi & y_{12}^u y_2^{\chi_u}\epsilon_\chi \\ y_{2\alpha}^u \hat{y}_{\alpha 3}^{\phi_u} y_1^{\sigma_u}\epsilon_\sigma\epsilon_\phi & y_{2\alpha}^u y_{\alpha 2}^{\phi_u}\epsilon_\phi & y_{22}^u y_2^{\chi_u}\epsilon_\chi \\ \approx 0 & \approx 0 & y_3^u \end{pmatrix}$$

$\frac{v_2}{v_1}\approx 10 \quad \epsilon_\chi \approx \epsilon_\phi \approx 5\cdot 10^{-2}$

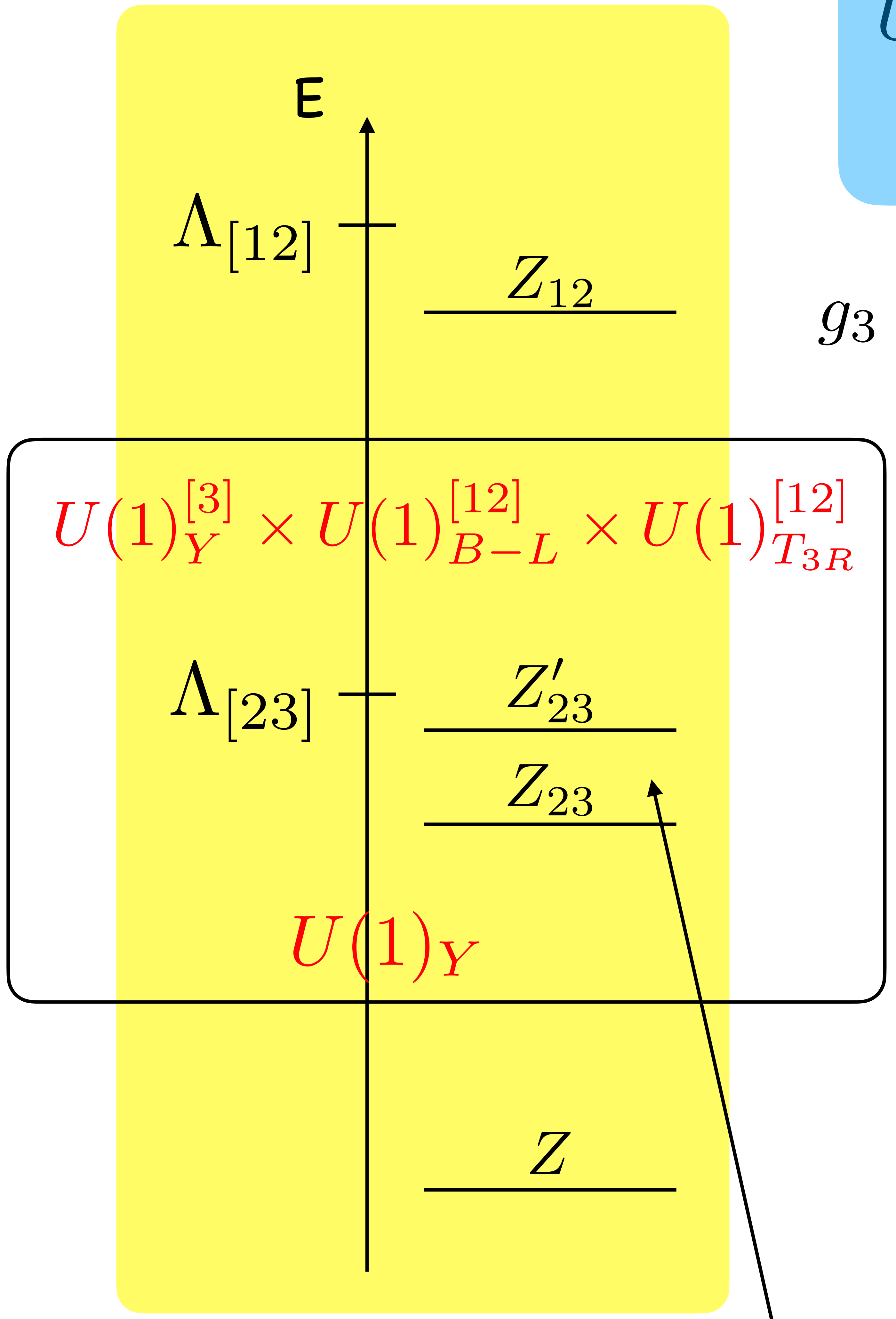
$y's = 0.1 \div 1 \quad \epsilon_\sigma \approx 2\cdot 10^{-2}$

Phenomenology at $\Lambda_{[23]}$ (universal)

$$U(1)_Y^{[3]} \times U(1)_{(B-L)/2}^{[12]} \times U(1)_{T_{3R}}^{[2]} \times U(1)_{T_{3R}}^{[1]}$$

g_3 $\quad g_B$ $\quad g_T$ $\quad g_T$

$g_3 >> g_B, g_T \qquad g_B = g'/sin\alpha \qquad g_T = g'/cos\alpha$



For every tree level effect at $\Lambda_{[23]}$, 4 parameters: $m_{Z_{23}}, \alpha, b$ and $(\theta_L^d)_{23}$

$B_{s,d} \to \mu\mu$

$b \to s + ll$

$\Delta B = 2$

EWPT

$pp \to ll$

$\Rightarrow$

$1/4 < b < 4, \quad 1/2 < t_\alpha < 2$

$$m_{Z_{23}} \gtrsim 4 \div 5 \quad TeV$$

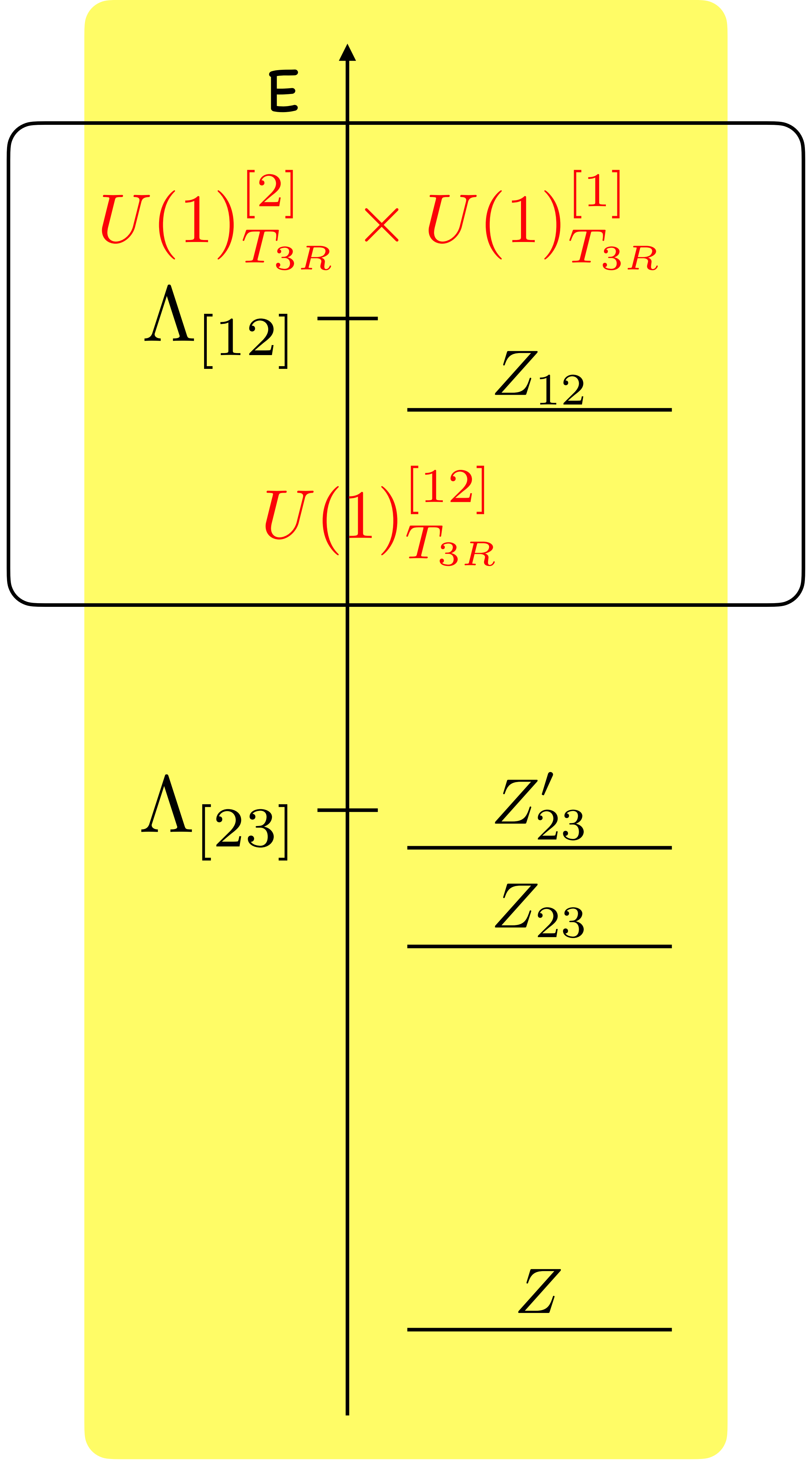
Near MFV in the b,t, τ - sector

E.g. $\mathcal{L} \approx \frac{g'^2}{m_{Z_{23}}^2} (U_{L3b} U_{L3q}^*)^2 \mathcal{O}_1^{bq} \quad q = s, d$

$$\frac{m_{Z'_{23}}}{m_{Z_{23}}} = \frac{g_3}{g'} \frac{(1+b)t_\alpha}{\sqrt{b}(1+t_\alpha^2)} \qquad b = \frac{|\phi|^2}{|\chi^l|^2 + |\chi^q|^2/9}$$

(an overall fit still lacking)

Phenomenology at $\Lambda_{[12]}$ (universal)



$$U(1)^{[3]}_{Y} \times U(1)^{[12]}_{(B-L)/2} \times U(1)^{[2]}_{T_{3R}} \times U(1)^{[1]}_{T_{3R}}$$

g_3 $\quad g_B$ $\quad g_T$ $\quad g_T$

$g_3 >> g_B, g_T$ $\qquad g_B = g'/sin\alpha$ $\qquad g_T = g'/cos\alpha$

At $\Lambda_{[12]}$ 3 par.s : $m_{Z_{12}}$ and $(\theta^{u,d}_R)_{12}$

$\Delta S = 2$

$\Delta C = 2$

$K \to \pi\nu\nu$

$\mu \to 3e$

$\Rightarrow$

$$\mathcal{L} \approx \frac{g'^2}{m_{Z^2_{12}}}[(U_{R2s}U^*_{R2d})^2\tilde{\mathcal{O}}^{sd}_1 + (U_{R2c}U^*_{R2u})^2\tilde{\mathcal{O}}^{cu}_1]$$

$$m_{Z_{12}} \gtrsim 100 \quad TeV$$

Phenomenology (details)

$$g_3 >> g_B, g_T \qquad g_B = g'/sin\alpha \qquad g_T = g'/cos\alpha$$

Ψ = Standard fermions in interaction basis

$$\mathcal{L}_{Z_{23}} = g' Z_{23\mu} \bar{\Psi} \gamma_\mu \hat{Y}^{[23]} \Psi \qquad \mathcal{L}_{Z'_{23}} = g_3 Z'_{23\mu} \bar{\Psi} \gamma_\mu Y^{[3]} \Psi$$

$$\hat{Y}^{[23]} = a_{12} Y^{[3]} + cot_\alpha (\frac{B-L}{2})^{[12]} + t_\alpha T_{3R}^{[12]} \qquad a_3 = \frac{b}{s_\alpha^2 c_\alpha^2 (1+b)^2} \qquad a_{12} = \frac{cot_\alpha - bt_\alpha}{1+b} \qquad b = \frac{|\phi|^2}{|\chi^l|^2 + |\chi^q|^2/9}$$

$$\mathcal{L}_{Z_{12}} = \frac{g'}{cos\alpha} Z_{12\mu} \bar{\Psi} \gamma_\mu (T_{3R}^{[2]} - T_{3R}^{[1]}) \Psi$$

$$m_Z^2 = m_{Z0}^2 + \delta m_Z^2 \qquad \delta m_Z^2 = -s_W^2 \frac{m_Z^4}{m_{Z_{23}^2}} (a_{12}^2 + a_3)$$

$$\mathcal{L}_Z = \mathcal{L}_Z^{SM} + g' s_W \frac{m_Z^2}{m_{Z_{23}^2}} Z_\mu \bar{\Psi} \gamma_\mu (a_{12} \hat{Y}^{[23]} + a_3 Y^{[3]}) \Psi$$

Back to the “mid-term” prospects of flavour

Flavour precision tests, a partial list (2022)

Input	Reference	Measurement	UTfit Prediction	Pull
$\sin 2\beta$	[22], UTfit	0.688(20)	0.736(28)	−1.4
γ	[22]	66.1(3.5)	64.9(1.4)	+0.29
α	UTfit	94.9(4.7)	92.2(1.6)	+0.6
$\varepsilon \cdot 10^3$	[38]	2.228(1)	2.00(15)	+1.56
$\|V_{ud}\|$	UTfit	0.97433(19)	0.9738(11)	+0.03
$\|V_{ub}\| \cdot 10^3$ •	UTfit	3.77(24)	3.70(11)	+0.25
$\|V_{ub}\| \cdot 10^3$ (excl)	[39]	3.74(17)		
$\|V_{ub}\| \cdot 10^3$ (incl)	[22]	4.32(29)		
$\|V_{cb}\| \cdot 10^3$ •	UTfit	41.25(95)	42.22(51)	−0.59
$\|V_{cb}\| \cdot 10^3$ (excl)	UTfit	39.44(63)		
$\|V_{cb}\| \cdot 10^3$ (incl)	[40]	42.16(50)		
$\|V_{ub}\|/\|V_{cb}\|$	[39]	0.0844(56)		
$\Delta M_d \times 10^{12}\, s^{-1}$	[38]	0.5065(19)	0.519(23)	−0.49
$\Delta M_s \times 10^{12}\, s^{-1}$	[38]	17.741(20)	17.94(69)	−0.30
$BR(B_s \to \mu\mu) \times 10^9$	[38]	3.41(29)	3.47(14)	−0.14
$BR(B \to \tau\nu) \times 10^4$	[38]	1.06(19)	0.869(47)	+0.96
$Re(\varepsilon'/\varepsilon) \times 10^4$	[38]	16.6(3.3)	15.2(4.7)	+0.27
$(\|q/p\|_D - 1) \times 10^2$		0.05(2.50)	0.8(4.0)	−0,15
$BR(B^+ \to K^+\nu\nu)10^6$		23(7)	5.58(37)	+2.5
$BR(K^+ \to \pi^+\nu\nu)10^{11}$		10.6(4.0)	9.31(76)	+0,3
R_D		0.344(26)	0.298(4)	+1.7
R_{D^*}		0.285(12)	0.254(5)	+2.3

UTfit Collaboration
with some little integration

(No EDM's, $\mu \to e\gamma$, etc.)

Current precision

Input	Reference	Measurement	UTfit Prediction	Pull	current
$\sin 2\beta$	[22], **UT***fit*	0.688(20)	0.736(28)	−1.4	4%th/exp
γ	[22]	66.1(3.5)	64.9(1.4)	+0.29	5%exp
α	**UT***fit*	94.9(4.7)	92.2(1.6)	+0.6	5%exp
$\varepsilon \cdot 10^3$	[38]	2.228(1)	2.00(15)	+1.56	8%th
$\lvert V_{ud}\rvert$	**UT***fit*	0.97433(19)	0.9738(11)	+0.03	0.1%th
$\lvert V_{ub}\rvert \cdot 10^3$ •	**UT***fit*	3.77(24)	3.70(11)	+0.25	8%exp/th
$\lvert V_{ub}\rvert \cdot 10^3$ (excl)	[39]	3.74(17)			
$\lvert V_{ub}\rvert \cdot 10^3$ (incl)	[22]	4.32(29)			
$\lvert V_{cb}\rvert \cdot 10^3$ •	**UT***fit*	41.25(95)	42.22(51)	−0.59	2%exp/th
$\lvert V_{cb}\rvert \cdot 10^3$ (excl)	**UT***fit*	39.44(63)	Ciao.		
$\lvert V_{cb}\rvert \cdot 10^3$ (incl)	[40]	42.16(50)			
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	[39]	0.0844(56)			
$\Delta M_d \times 10^{12}\,s^{-1}$	[38]	0.5065(19)	0.519(23)	−0.49	5%th/exp
$\Delta M_s \times 10^{12}\,s^{-1}$	[38]	17.741(20)	17.94(69)	−0.30	4%th
$BR(B_s \to \mu\mu) \times 10^9$	[38]	3.41(29)	3.47(14)	−0.14	9%exp
$BR(B \to \tau\nu) \times 10^4$	[38]	1.06(19)	0.869(47)	+0.96	20%exp
$\mathrm{Re}\,(\varepsilon'/\varepsilon) \times 10^4$	[38]	16.6(3.3)	15.2(4.7)	+0.27	30%th
$(\lvert q/p\rvert_D - 1) \times 10^2$		0.05(2.50)	0.8(4.0)	−0, 15	100%th*
$BR(B^+ \to K^+\nu\nu)10^6$		23(7)	5.58(37)	+2.5	35%exp
$BR(K^+ \to \pi^+\nu\nu)10^{11}$		10.6(4.0)	9.31(76)	+0, 3	40%exp
R_D		0.344(26)	0.298(4)	+1.7	8%exp
R_{D^*}		0.285(12)	0.254(5)	+2.3	4%exp

with strong correlations!

Conceivable progress in the "mid-term" of flavour

Input	Reference	Measurement	UT*fit* Prediction	Pull	current	mid-term
$\sin 2\beta$	[22], **UT*fit***	0.688(20)	0.736(28)	-1.4	4%th/exp	0.6%
γ	[22]	66.1(3.5)	64.9(1.4)	$+0.29$	5%exp	0.8%
α	**UT*fit***	94.9(4.7)	92.2(1.6)	$+0.6$	5%exp	0.4%
$\varepsilon \cdot 10^3$	[38]	2.228(1)	2.00(15)	$+1.56$	8%th	
$\|V_{ud}\|$	**UT*fit***	0.97433(19)	0.9738(11)	$+0.03$	0.1%th	
$\|V_{ub}\| \cdot 10^3$ •	**UT*fit***	3.77(24)	3.70(11)	$+0.25$	8%exp/th	1%
$\|V_{ub}\| \cdot 10^3$ (excl)	[39]	3.74(17)				
$\|V_{ub}\| \cdot 10^3$ (incl)	[22]	4.32(29)				
$\|V_{cb}\| \cdot 10^3$ •	**UT*fit***	41.25(95)	42.22(51)	-0.59	2%exp/th	0.5%
$\|V_{cb}\| \cdot 10^3$ (excl)	**UT*fit***	39.44(63)				
$\|V_{cb}\| \cdot 10^3$ (incl)	[40]	42.16(50)				
$\|V_{ub}\|/\|V_{cb}\|$	[39]	0.0844(56)				
$\Delta M_d \times 10^{12}\,\mathrm{s}^{-1}$	[38]	0.5065(19)	0.519(23)	-0.49	5%th/exp	2%
$\Delta M_s \times 10^{12}\,\mathrm{s}^{-1}$	[38]	17.741(20)	17.94(69)	-0.30	4%th	1.5%
$\mathrm{BR}(B_s \to \mu\mu) \times 10^9$	[38]	3.41(29)	3.47(14)	-0.14	9%exp	4%
$\mathrm{BR}(B \to \tau\nu) \times 10^4$	[38]	1.06(19)	0.869(47)	$+0.96$	20%exp	4%
$\mathrm{Re}\,(\varepsilon'/\varepsilon) \times 10^4$	[38]	16.6(3.3)	15.2(4.7)	$+0.27$	30%th	
$(\|q/p\|_D - 1) \times 10^2$		0.05(2.50)	0.8(4.0)	$-0,15$	100%th*	30%*
$BR(B^+ \to K^+\nu\nu)10^6$		23(7)	5.58(37)	$+2.5$	35%exp	10%
$BR(K^+ \to \pi^+\nu\nu)10^{11}$		10.6(4.0)	9.31(76)	$+0,3$	40%exp	20%
R_D		0.344(26)	0.298(4)	$+1.7$	8%exp	4%
R_{D^*}		0.285(12)	0.254(5)	$+2.3$	4%exp	2.5%

with strong correlations!

(No EDM's, $\mu \to e\gamma$, etc.)

Summary

1. The flavour puzzle and the hierarchy problem are key open issues in BSM
   (and a strong motivation for the next HE collider)

2. Precision offers an indirect discovery potential of NP at MultiTeV, if any, before the next HE collider

3. If the Higgs is composite, Λ^f mast be "low" and subject to flavour symmetries

4. "Deconstructing" SM gauge interactions may be a way to address the flavour puzzle and make sense of NMFV in b,t,τ -physics

...as promised

Engadina, 1997

Zurich, around 2000

Last but not least

where?, 2000

Cheers to Zoltan
and to all his family