Flavor, Compositeness & Supersymmetry

"La Grande Bouffe"

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Physics $\Longleftrightarrow$ Separation of Scales

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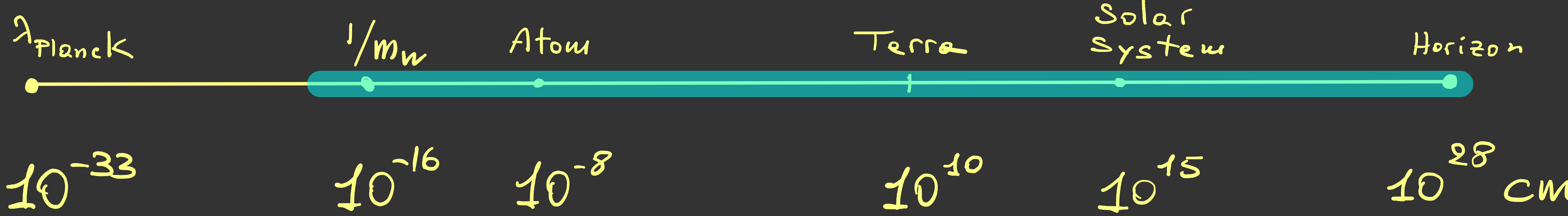


- Standard Model + General Relativity
  - Dark Matter ?
  - Dark Energy "?"
  - Why the hierarchies ?

The SM as an EFT

$$\mathcal{L} = \underbrace{F_{\mu\nu}^2 + \bar{\psi} \not{D} \psi + |DH|^2 + V(H) + Y\bar{\psi}H\psi}_{d \leq 4} + \underbrace{\cdots}_{d>4}$$

$|DH|^2 + V(H)$: $m_{W,Z,h}$, $G_F = \frac{1}{v^2}$

$Y\bar{\psi}H\psi$: m_q, m_e, V_{CKM}, $m_\nu = 0$

$d > 4$:

- $\lambda_L \frac{\ell\ell HH}{M} \longrightarrow m_\nu \sim 0.1\,\text{eV} \Longrightarrow \frac{M}{\lambda_L} \sim 10^{14}\,\text{GeV}$
- $\lambda_B \frac{uude}{M^2} \longrightarrow \tau_p > 10^{34}\,\text{yrs} \Longrightarrow \frac{M}{\lambda_B} \gtrsim 10^{15}\,\text{GeV}$
- $y_e \frac{\ell H \sigma_{\mu\nu} e B^{\mu\nu}}{M^2} \longrightarrow d_e \leq 10^{-30}\,e\,\text{cm} \Longrightarrow M \gtrsim 2 \cdot 10^{6}\,\text{GeV}$

A hierarchy $M \gg m_W$ seems to neatly distinguish the things we observe from those we do not

... but things are actually more subtle

The <u>Misfits</u> : θ_{QCD} , m_h^2 , Λ_{cc}^4

☆ The electroweak hierarchy Paradox

$$m_h^2 = \# \frac{3 y_t^2}{8\pi^2} M^2 - \# \frac{9 g_2^2}{32\pi^2} M^2 + \cdots + [\,?\,] = (125\ \mathrm{GeV})^2$$

- barring cancelations : $M \lesssim 500$ GeV
- $M \gg 500$ GeV : <u>Uncanny Cleverness</u>

Hierarchy Paradox

- $M \lesssim TeV$: Natural, but we loose attractive explanation of : GIM, B, L, ν_{mass} ...

- $M \gg TeV$: attractive explanation of GIM, etc but unNatural

⚠ Of CFTs and of Natural Hierarchies

M_{UV}

⟶ $\sim$ scale invariance $\Rightarrow$ $\sim$ CFT

M_{IR}

Natural $M_{UV} \gg M_{IR}$:

- "Marginality": lowest scalar primary $\Delta_{\mathcal{O}} = 4 - \varepsilon$

$$\mathcal{L}_{mass} = c\, M_{UV}^{\varepsilon}\, \mathcal{O} \Rightarrow M_{IR} = M_{UV}\, c^{1/\varepsilon}$$

$c \sim \varepsilon \sim 0.1 \longrightarrow 10^{-10}$

- "Symmetry Protected Marginality"

  - Ex: Chiral Symmetry, Supersymmetry, ...

▲ Example : Technicolor World

$$\frac{1}{g_{TC}^2}\left(G_{\mu\nu}^{TC}\right)^2 + \frac{1}{g_W^2} W_{\mu\nu}^2 + \frac{1}{g_s^2} G_{\mu\nu}^2 + \bar{T}\not{D}T + \bar{q}\not{D}q + \frac{g_*^2}{M^2}\bar{T}T\bar{q}q$$

- $\Lambda_{TC} \sim M e^{-16\pi^2/g_{TC}^2} \Longrightarrow \begin{cases} \cdot\ m_W \sim \frac{g_W}{4\pi}\Lambda_{TC} \\ \cdot\ m_q \sim \left(\frac{g_*}{4\pi}\right)^2 \frac{\Lambda_{TC}^3}{M^2} \end{cases}$

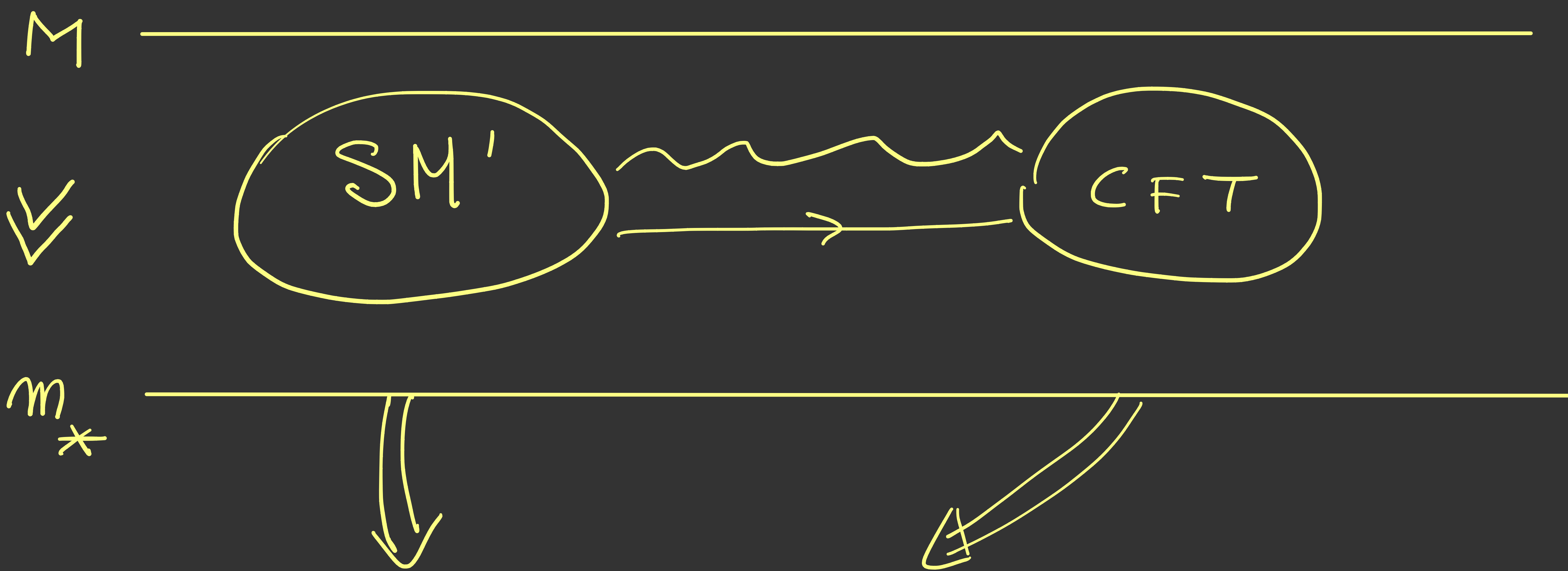
- $\Lambda_{QCD} \sim M e^{-16\pi^2/g_s^2}$

▲ Easily : $M \gg m_W \gg \Lambda_{QCD} \gg m_q$

Modern Composite Higgs

(Agashe, Contino, Pomarol '04)

$$\mathcal{L} = \mathcal{L}_{SM'} + \mathcal{L}_{CFT} + g A_\mu J^\mu_{CFT} + y_{ia} \psi_i \mathcal{O}_a$$



$$\mathcal{L}_{SM'} + \mathcal{L}(H) + Y H \bar{\psi} \psi$$

D.B. Kaplan '91

Fermion Mass Spectrum from RG flow

$$y^q_{ia}\, q_i\, \mathcal{O}^q_a + y^d_{ia}\, d_i\, \mathcal{O}^d_a + y^u_{ia}\, u_i\, \mathcal{O}^u_a + y^\ell_{ia}\, \ell_i\, \mathcal{O}^\ell_a + y^e_{ia}\, e_i\, \mathcal{O}^e_a$$

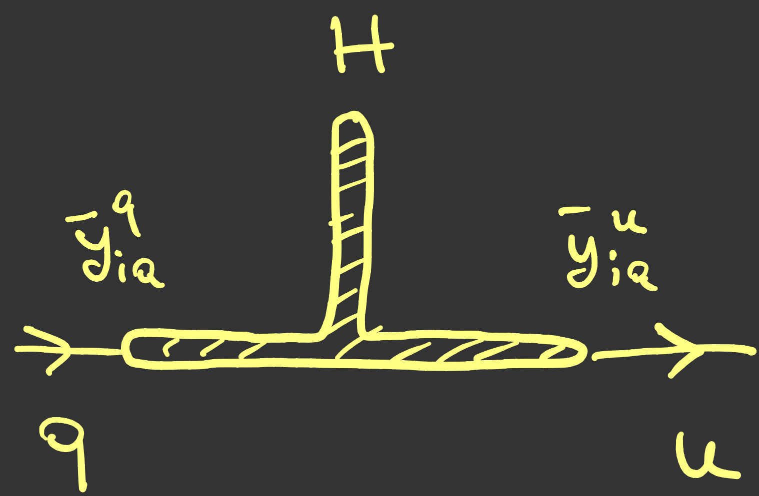
$q_i \downarrow 3/2$, $\quad \mathcal{O}^q_a \downarrow \Delta^q_a = \frac{5}{2} + \gamma^q_a \qquad$ etc

$$\Rightarrow y^F_{ia}(\mu) = y^F_{ia}(M)\left(\frac{\mu}{M}\right)^{\gamma^F_a} \xrightarrow{m_*} \bar{y}^F_{ia} = y^F_{ia}(M)\left(\frac{m_*}{M}\right)^{\gamma^q_a}$$

- Imagine $\gamma^F_1 \gtrsim \gamma^F_2 \gtrsim \gamma^F_3$ [Ex $\gamma_1 = 0.6$, $\gamma_2 = 0.4$, $\gamma_3 = 0.2$]

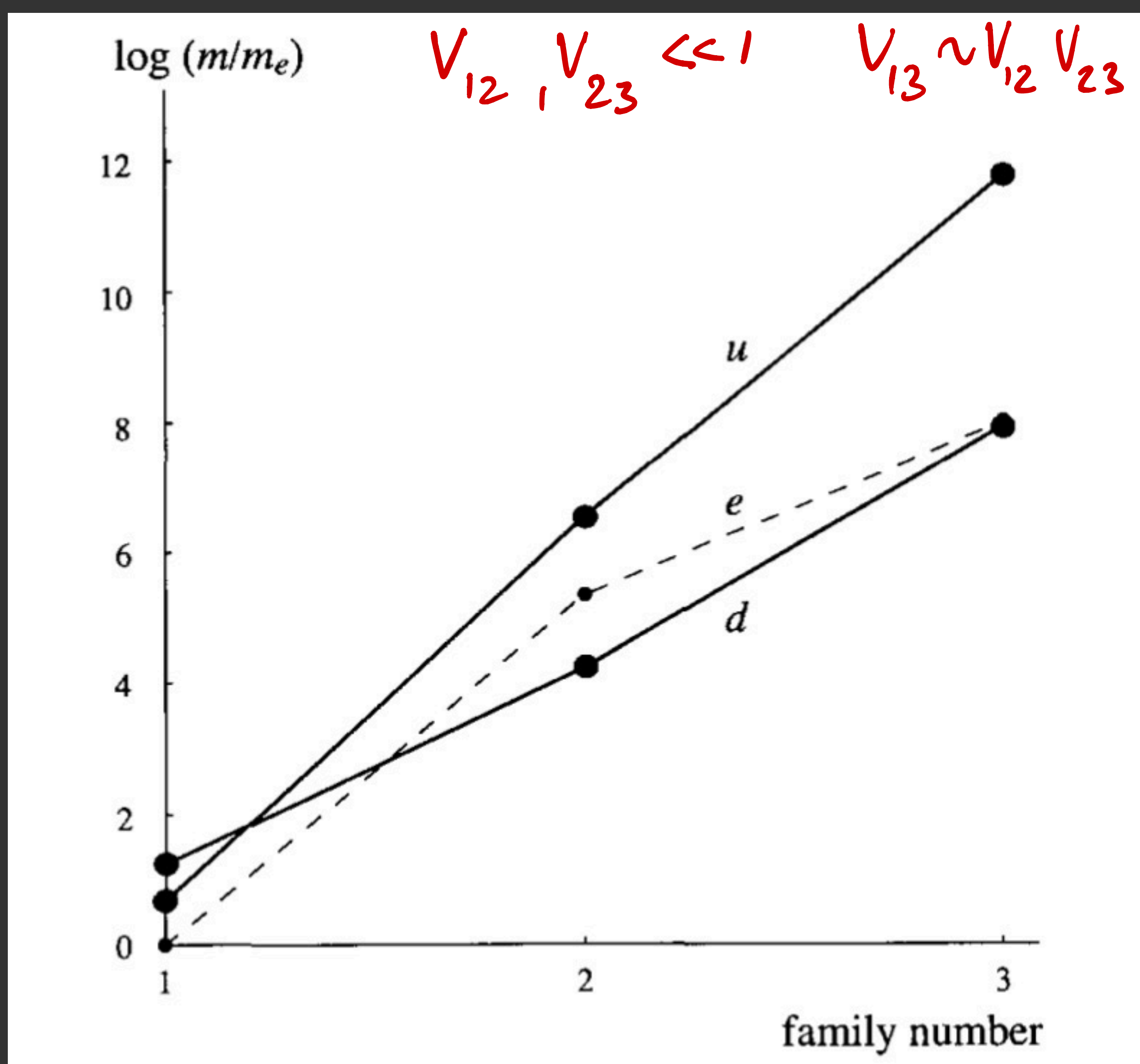
$$|y_{i1}| \sim \left(\frac{m_*}{M}\right)^{0.6} \sim \left(10^{-6}\right)^{0.6} \sim 10^{-3}, \quad |y_{i2}| \sim 10^{-2}, \quad |y_{i3}| \sim 10^{-1}$$

Yukawa Couplings



$$\Longrightarrow \quad Y^u_{ij} \sim \frac{\bar{y}^q_{ia}\,\bar{y}^u_{jb}}{g_*}\, m_{ab}$$

$$\approx \varepsilon^q_{ia}\, \varepsilon^u_{jb}\, m_{ab} \cdot g_*$$

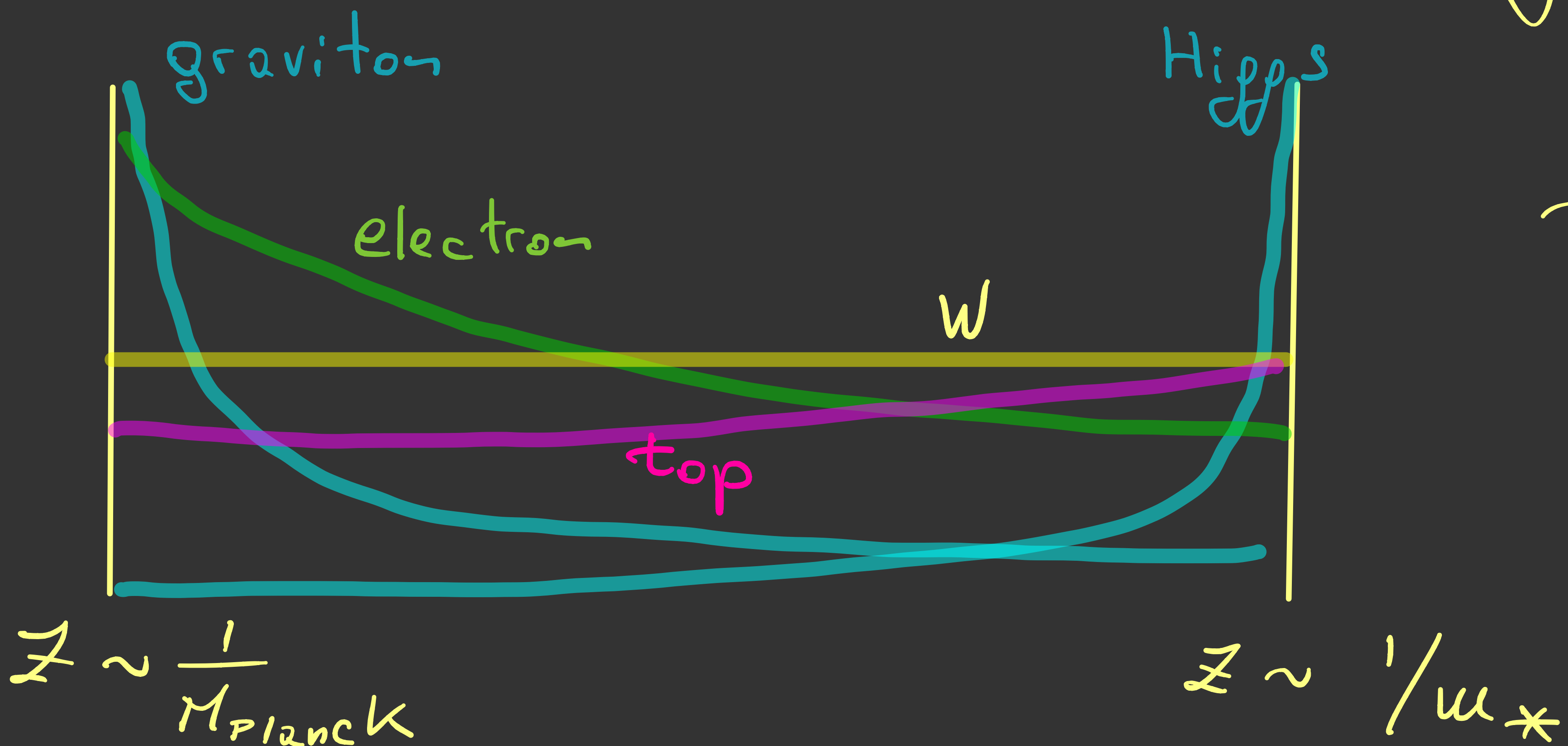


$$\begin{cases} y_{a3} \longrightarrow \text{rank} = 1 \\ \oplus\; y_{a2} \longrightarrow \text{rank} = 2 \\ \oplus\; y_{a1} \longrightarrow \text{rank} = 3 \end{cases}$$

A full fledged CFT realizing all that ?

... of course not

• but we have at least "holographic realizations"



Randall-Sundrum's slice of AdS5

$$m_* \sim m_{KK} \;,\; g_* \sim g_{KK} \sim \frac{4\pi}{\sqrt{N}} \;,\; \varepsilon\text{'s} \equiv \text{wave function overlap}$$

△ Ordinary composite Higgs (~ Technicolor)

$\Rightarrow$ $m_h \sim \Gamma_h \sim m_*$, not what we observe

☆ Solution: pseudo-Nambu-Goldstone Higgs

- $m_h^2 \sim \frac{1}{8\pi^2}\left(\# y_t^2 + \# g^2\right) m_*^2$
- $v^2 \sim \frac{m_*^2}{g_*^2} \equiv f^2$

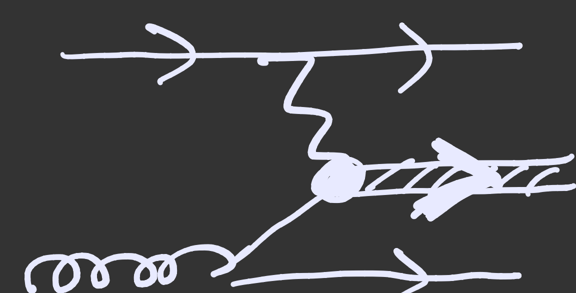
Naturalness $\Rightarrow$
- $m_* \lesssim 1$ TeV
- $\left(\frac{v}{f}\right)^2 \sim 1$

▲ Higgs non-linearities : $\frac{H^\dagger H}{f^2}$

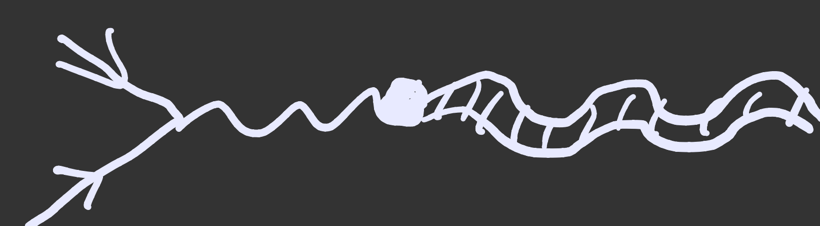
$$\Rightarrow \frac{\delta g_h}{g_h|_{SM}} \sim \left(\frac{v}{f}\right)^2 \sim \text{tuning}$$

▲ Composite resonances

- top partners



- W partners



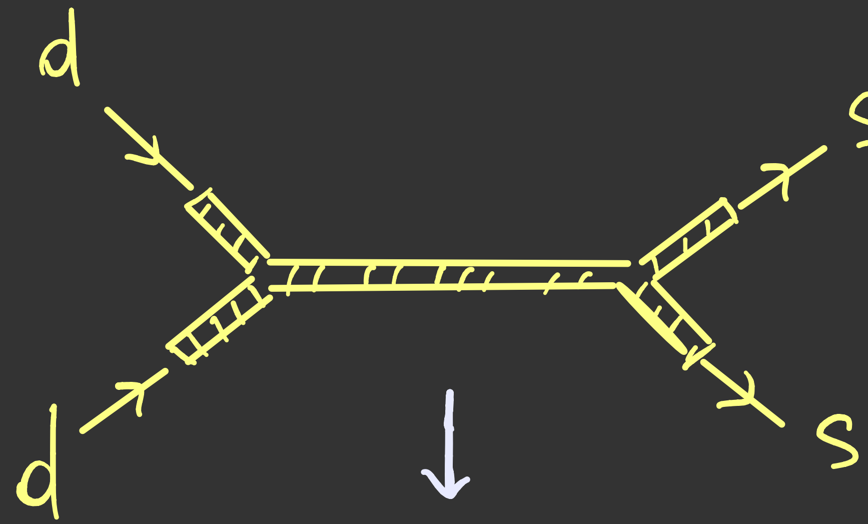
LHC

$$\left(\frac{v}{f}\right)^2 \lesssim 0.1 \div 0.2$$

$$m_* \gtrsim 1.5\ \text{TeV}$$

$$m_* \gtrsim 4.5\ \text{TeV}$$

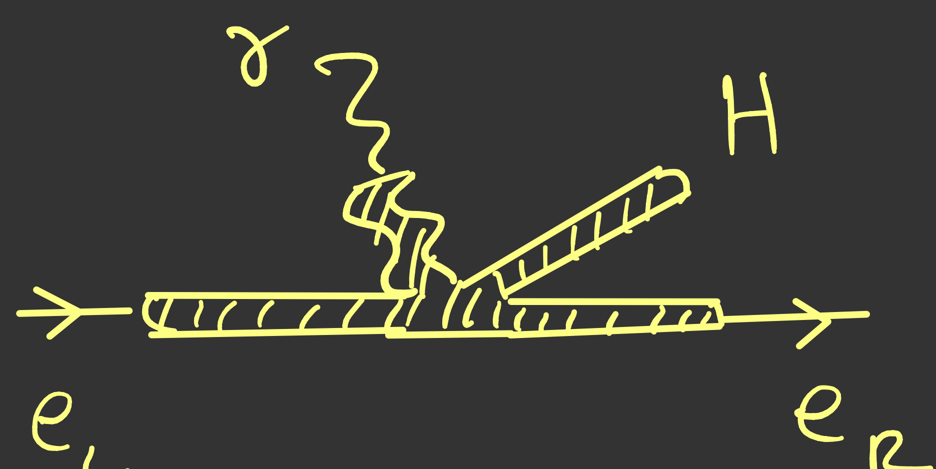
⚠ The Flavor Catastrophe



$$\downarrow \quad \sim \frac{y_d y_s}{m_*^2}$$

$+ \ldots$

$$\left\{ \begin{array}{l} \varepsilon_K \\ b \to s\gamma \\ c \to u\gamma \\ \text{edm}_{u,d} \end{array} \right. \Longrightarrow m_* \gtrsim 20 \div 50 \text{ TeV}$$



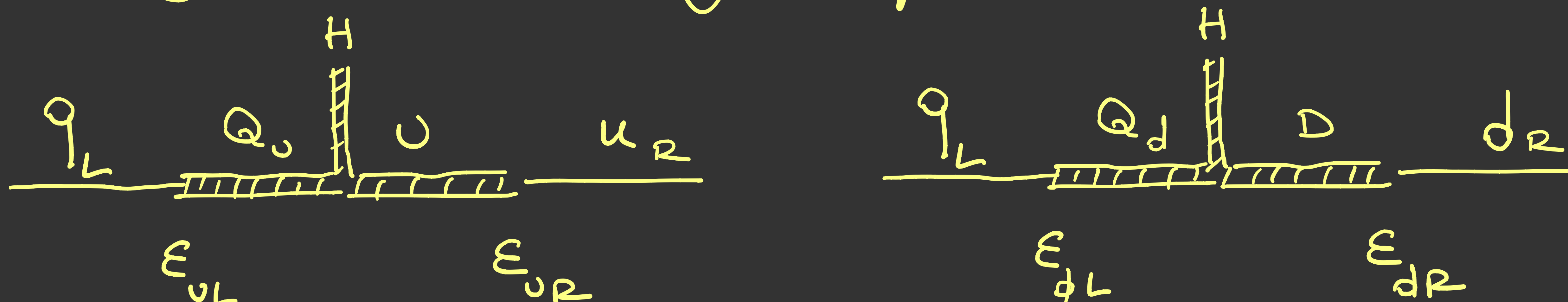
$$\Rightarrow d_e \sim \frac{m_e e}{m_*^2} \Longrightarrow m_* \gtrsim 2\cdot 10^3 \text{ TeV}$$

⚠ Not only unNatural, but out of FCChh reach!!

▲ To allow low m_* **must** assume Flavor + CP Symms

⇒ explanation of fermion spectrum is lost

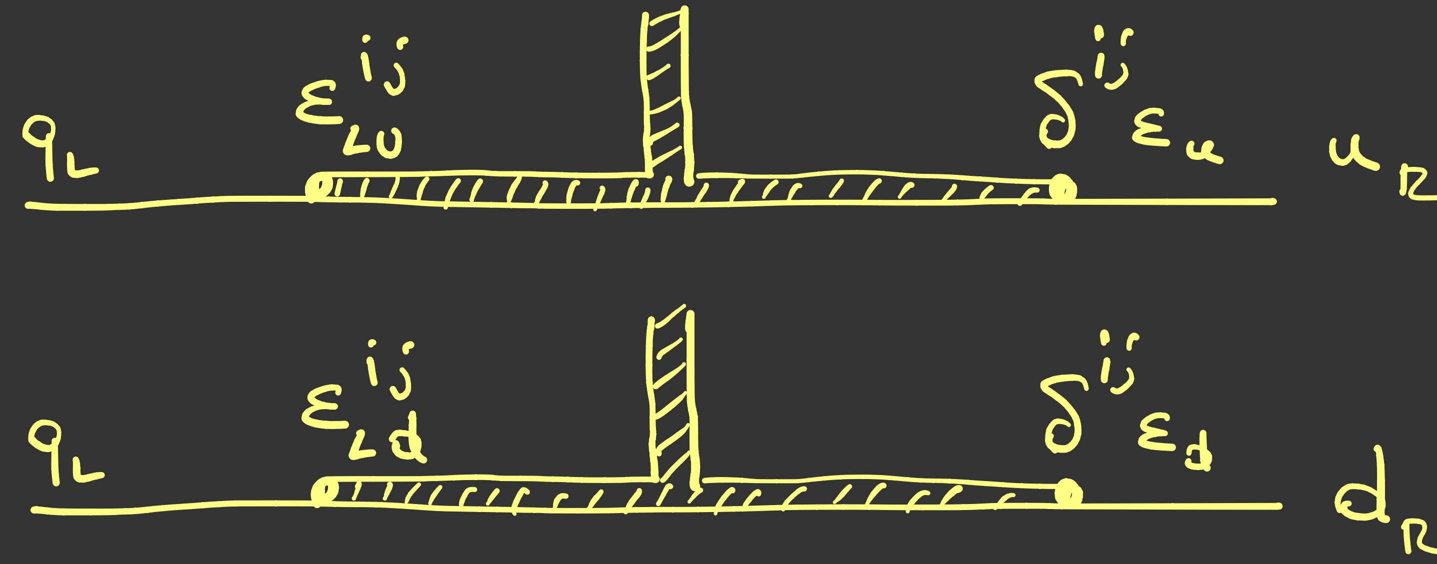
▲ Largest Symmetry Group at play



$$U(3)_q \times U(3)_u \times U(3)_d \times U(3)_U \times U(3)_D$$

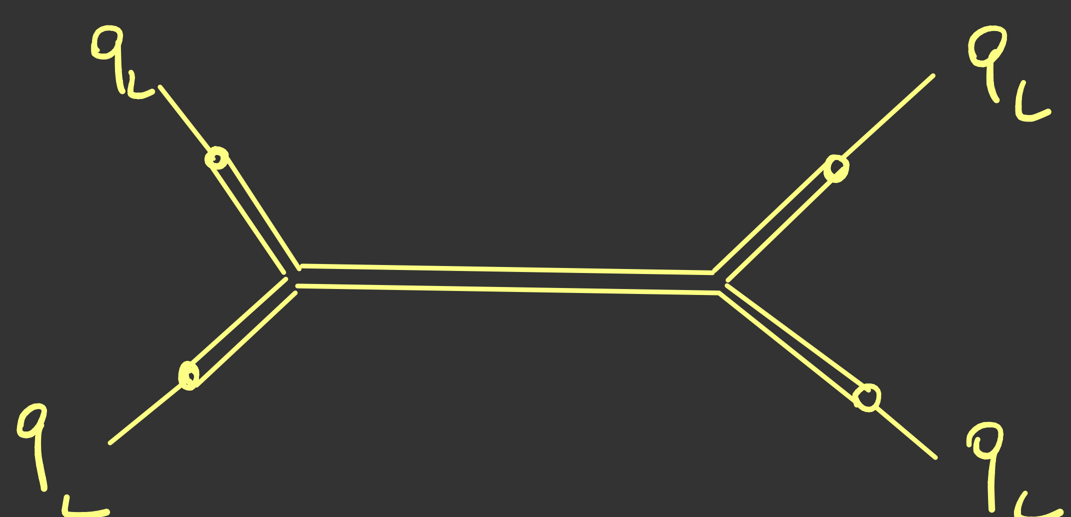
• scenarios ⟺ ϵ-induced breaking patterns

Ex "Right Universality"

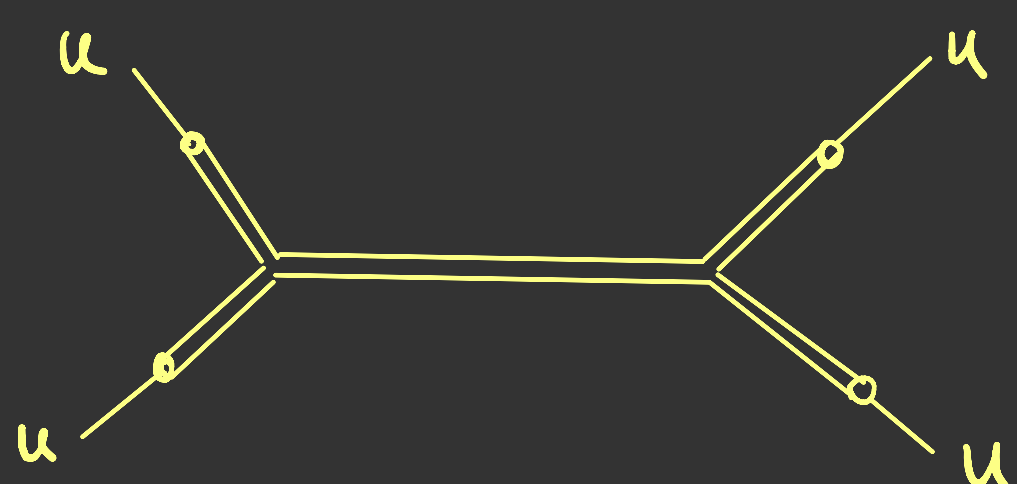


$$Y_u^{ij} = \varepsilon_{Lu}^{ij}\,\varepsilon_u\, g_*$$

$$Y_d^{ij} = \varepsilon_{Ld}^{ij}\,\varepsilon_d\, g_*$$



$$\sim \frac{(Y_u^\dagger Y_u)^2}{g_*^2\,\varepsilon_u^4}\,\frac{1}{m_*^2} \Longrightarrow m_* \gtrsim \frac{6.6\ \text{TeV}}{g_*\,\varepsilon_u^2}$$

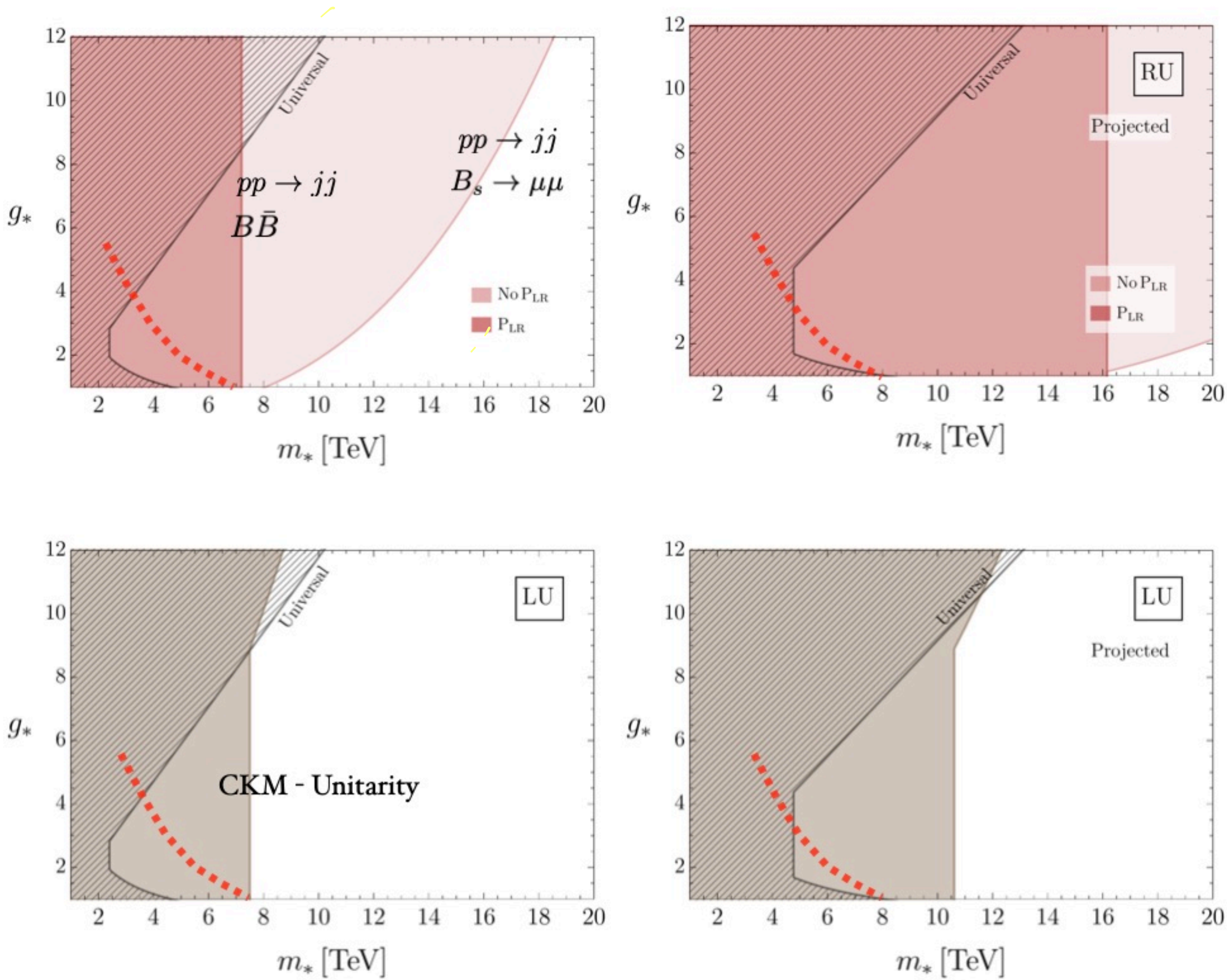


$$\sim \frac{g_*^2\,\varepsilon_u^4}{m_*^2} \Longrightarrow m_* \gtrsim (5\div 8)\ \text{TeV}\cdot g_*\,\varepsilon_u^2$$

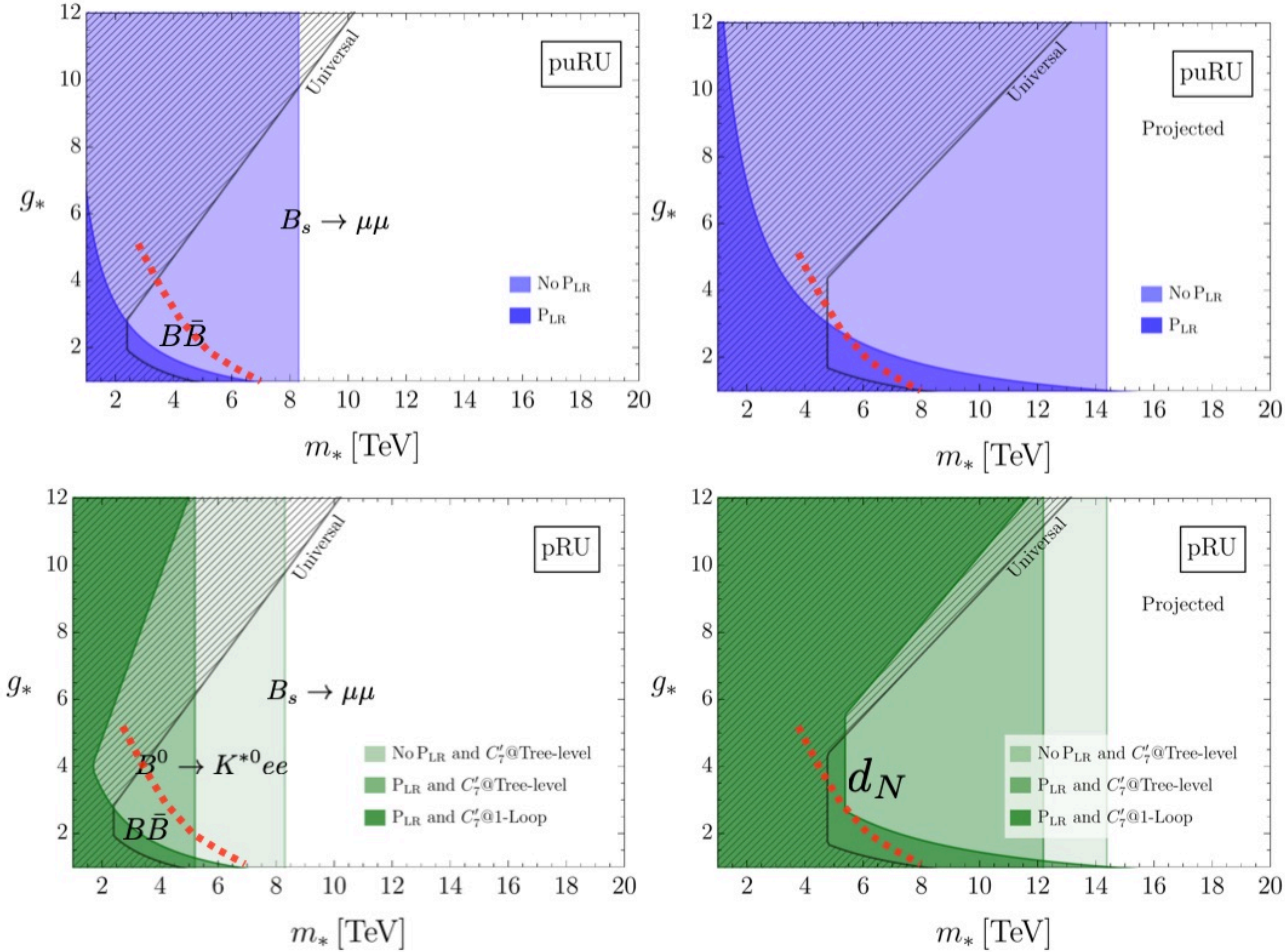
△ Broad Scenarios

- R.U. $\quad U(3)_q \times U(3)_{U+u} \times U(3)_{D+d}$
- partial up R.U. $\quad U(3)_q \times [U(2)\times U(1)]_{U+u} \times U(3)_{D+d}$
- partial R.U. $\quad U(3)_q \times [U(2)\times U(1)]_{U+u} \times [U(2)\times U(1)]_{D+d}$
- L.U. $\quad U(3)_{q+Q} \times U(3)_u \times U(3)_d$
- partial L.U. $\quad [U(2)\times U(1)]_{q+Q} \times U(3)_u \times U(3)_d$

Redi–Weiler '11 | Barbieri et al '13 | ... Barbieri '23

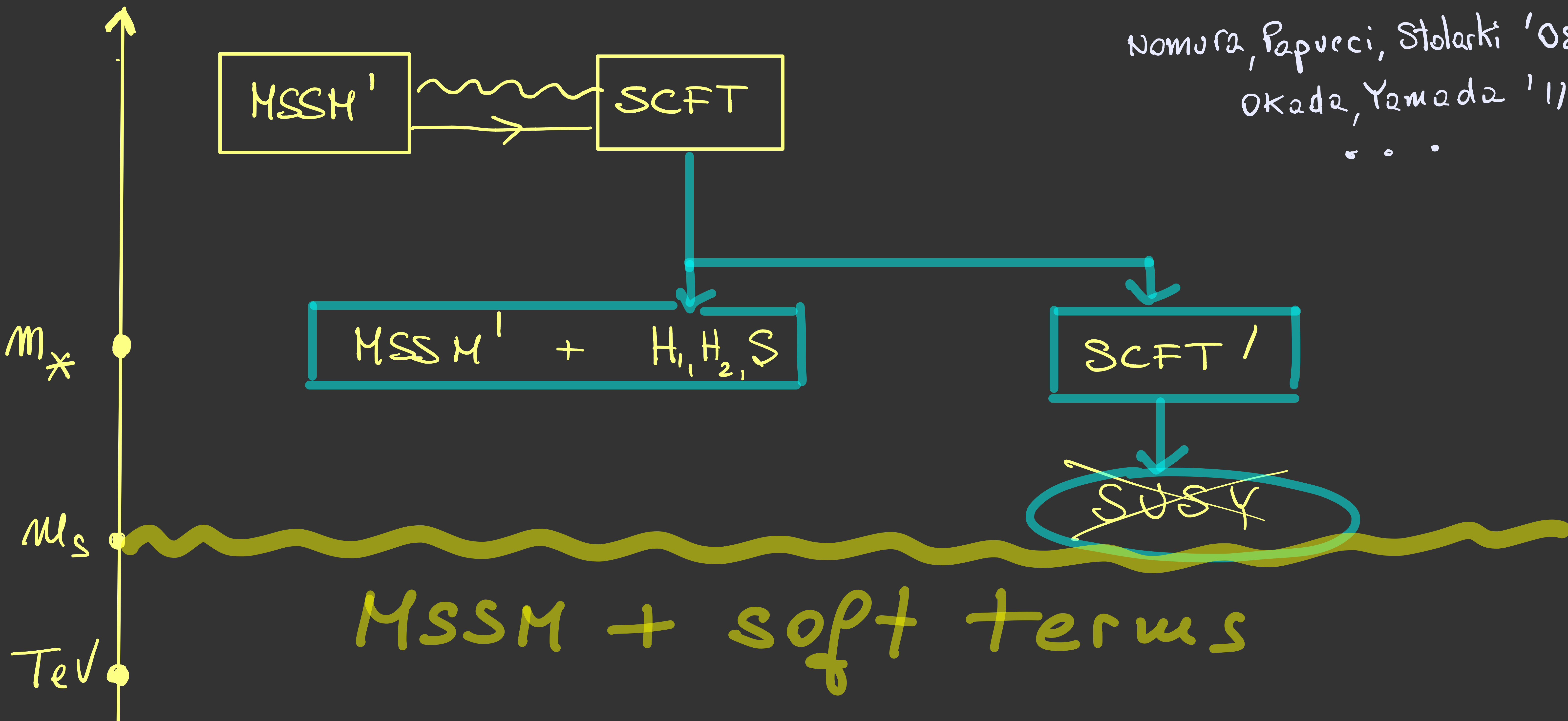


g_*
m_* [TeV]
Universal
$pp \to jj$
$B\bar{B}$
$pp \to jj$
$B_s \to \mu\mu$
No P_{LR}
P_{LR}
RU
Projected
No P_{LR}
P_{LR}
LU
CKM - Unitarity
LU
Projected

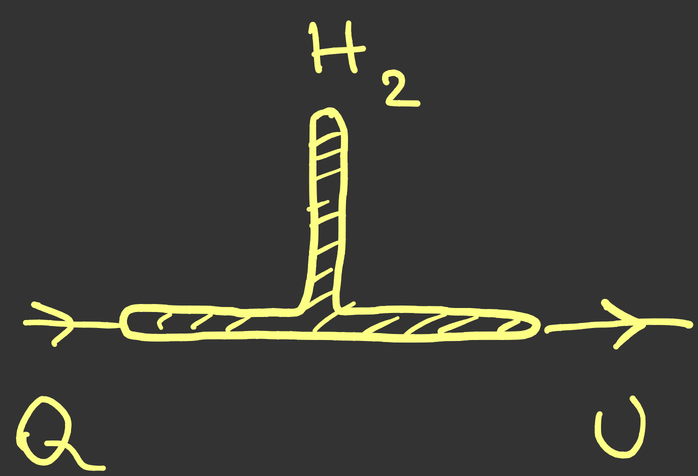

puRU
Universal
$B_s \to \mu\mu$
$B\bar{B}$
No P_{LR}
P_{LR}
g_*
m_* [TeV]
puRU
Projected
Universal
No P_{LR}
P_{LR}
g_*
m_* [TeV]
pRU
Universal
$B_s \to \mu\mu$
$B^0 \to K^{*0}ee$
$B\bar{B}$
No P_{LR} and C_7'@Tree-level
P_{LR} and C_7'@Tree-level
P_{LR} and C_7'@1-Loop
g_*
m_* [TeV]
pRU
Projected
Universal
d_N
No P_{LR} and C_7'@Tree-level
P_{LR} and C_7'@Tree-level
P_{LR} and C_7'@1-Loop
g_*
m_* [TeV]

SuperSymmetric Composite Higgs

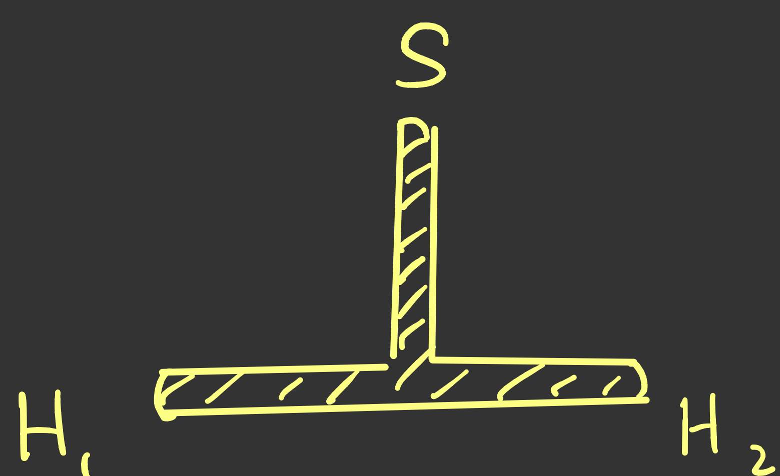
$$\mathcal{L} = \mathcal{L}_{MSSM'} + \mathcal{L}_{SCFT} + \int d^4\theta \; g V_{SM} \, J_{CFT} + \int d^2\theta \; y_{ia} F_i \, O_a$$



At m_*



$$\Longrightarrow \quad Y^u_{ij} \sim \varepsilon^Q_{ia}\, \varepsilon^U_{jb}\, w_{ab} \cdot g_*$$

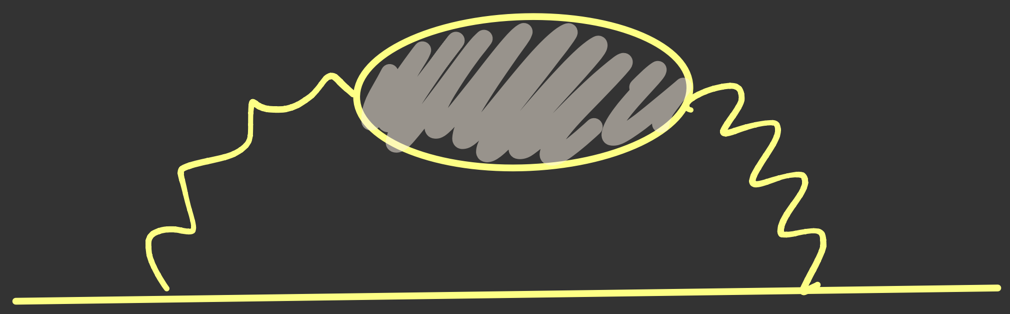


$$\Longrightarrow \quad \int d^2\theta \; g_* \, H_1 H_2 S$$

$g_* \sim 2 \div 4 \Longrightarrow m_h = 125$ GeV even with "light stops"

At m_s

$$m_{1/2} \sim \frac{g^2}{g_*^2} m_s \sim \frac{\alpha N}{4\pi} m_s$$



$$m^2_{\text{sfermions}} \sim \frac{m^2_{1/2}}{N} + \text{RG.}$$

Flavor universal masses mediated by gauge fields

$\equiv$ Gauge Mediated Supersymmetry Breaking

The $\mu - B\mu$ conundrom

- μ $\quad \int d^4\theta \, \frac{H_1 H_2 \mathcal{O}^+}{M_*^{\Delta_O}} \longrightarrow \mu \sim \frac{m_S^{\Delta_O+1}}{M_*^{\Delta_O}}$

Giudice–Masiero '88

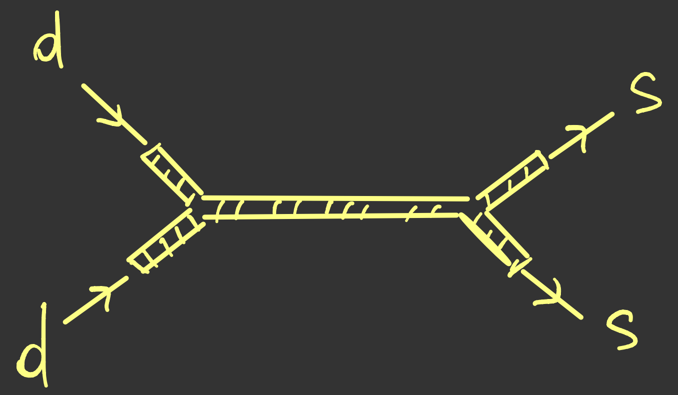
$$\mu \sim m_{1/2} \Longrightarrow \boxed{100\,\text{TeV} \lesssim M_* \lesssim 2000\,\text{TeV}}$$

$N=10 \quad \Delta_O = 2 \qquad\qquad N=5 \quad \Delta_O = 1$

- $B\mu$ $\quad \int d^4\theta \, \frac{H_1 H_2 \mathcal{R}}{M_*^{\Delta_R}} \longrightarrow$ suppressed if $\Delta_R > 2\Delta_O$

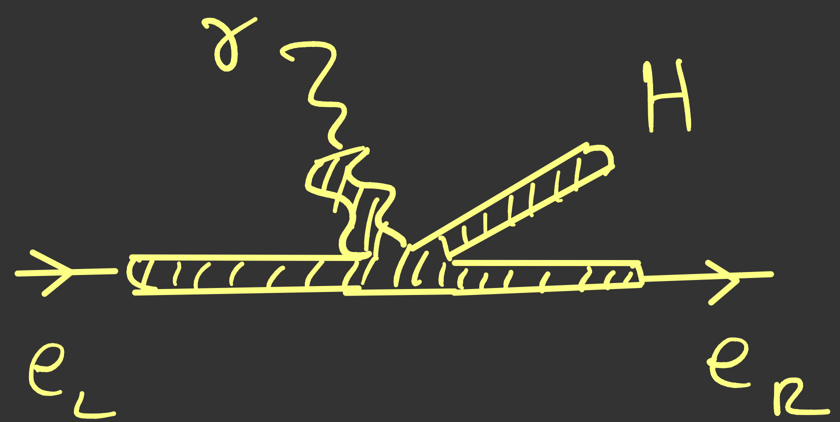
Ferrara-Remiddi '74

SUSY saves Flavor and edms



$\longrightarrow \quad \frac{y_d y_s}{m_*^2} e^{i\varphi} \, d d \bar{s} \bar{s} \qquad \frac{m_*}{\tan\beta} \gtrsim 30 \text{ TeV}$

OK



$\longrightarrow$ "0" in SUSY limit $\Rightarrow$ bound relaxed!

$$d_e \lesssim 4 \cdot 10^{-30} \, e \cdot cm \Longrightarrow m_* \gtrsim 120 \text{ TeV}$$

- compatible with Flavor physics at FCC edge
- d_e expected to improve $2 \div 3$ orders

Many details to work out

- Supersymmetric SILH-EFT : g_*, m_*, $H_{1,2}$, S

  ⊕ constrained ⟶
  - X, $X^2 = 0$ Goldstino
  - Π, $X(\Pi - \Pi^\dagger) = 0$ PQ-Goldstone

- EWSB and m_h, with and without S or $U(1)_{PQ}$

- Cosmology : light gravitino affects LSS & DM if in thermal equilibrium $m_S \lesssim 100\,\text{TeV}$

- "Subdominant" short/long distance Flavor effects

Outlook

I. Higgs mass scale
II. Fermion spectrum

no explanation within SM

- I. forces us to deal with II.
- Easiest and dullest $\Rightarrow$ Flavor Symmetries
- SUSY & Compositeness if allied allow to explain I., II. at "testable" energy