Flavor, Compositeness & Supersymmetry

"La Grande Bouffe"

- A. Glioti, RR, L. Ricci, L. Vecchi 2024
- K. Agashe, G. Giudice, RR, R. Sundrum in progress

Hierarchy Paradox

$$\mathcal{L}_{SM} = \underbrace{\mathcal{L}^{(d\leq 4)}}_{\text{seen}} + \underbrace{\frac{1}{m_*}\mathcal{L}^{(5)} + \frac{1}{m_*^2}\mathcal{L}^{(6)} + \dots}_{\text{unseen or tiny}}$$

p-decay ... ν-mass

- $m_* \gg m_{weak}$

· B, L, GIM	☺	Simple yet unNatural
· m_H^2	☹	

- $m_* \sim m_{weak}$

· m_H^2	☺	Natural yet "not so simple"
· B, L, GIM	☹	

"Not so simple": but how much?

Λ_{UV}

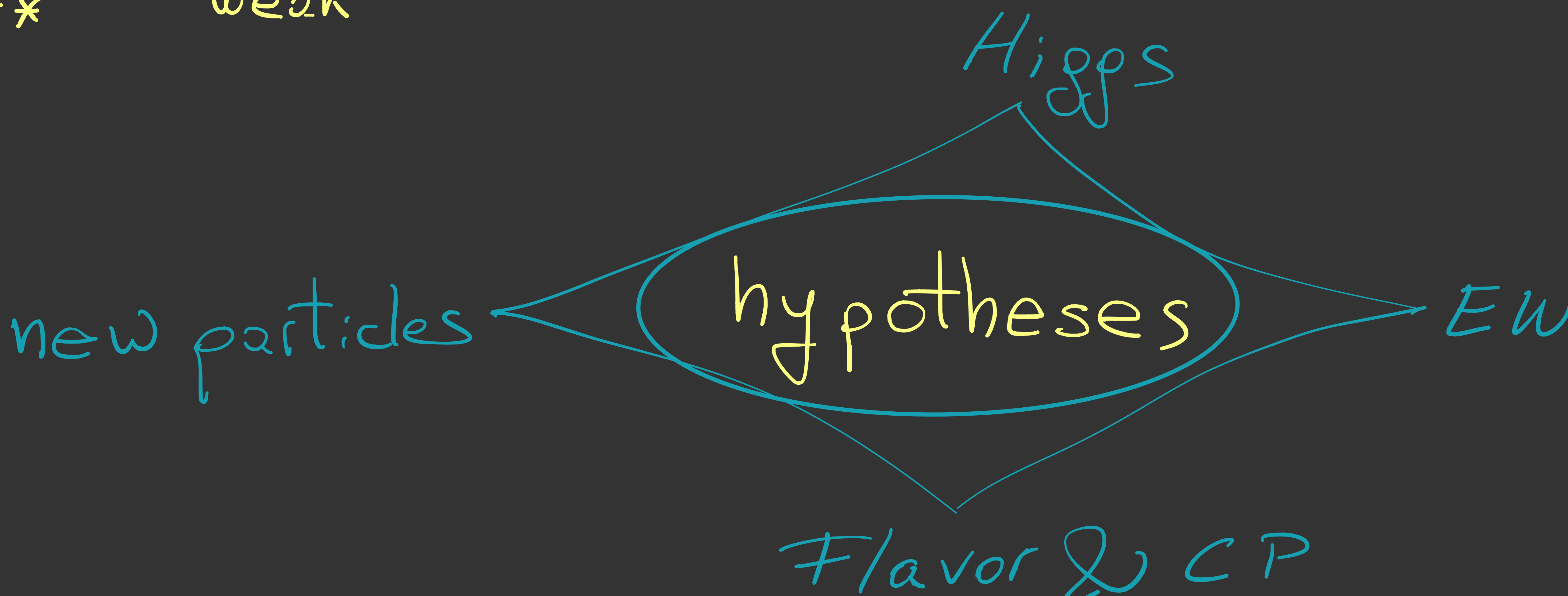
natural

$m_* \sim m_{weak}$

$\Rightarrow$

- explain $V(H)$
- deal with Flavor

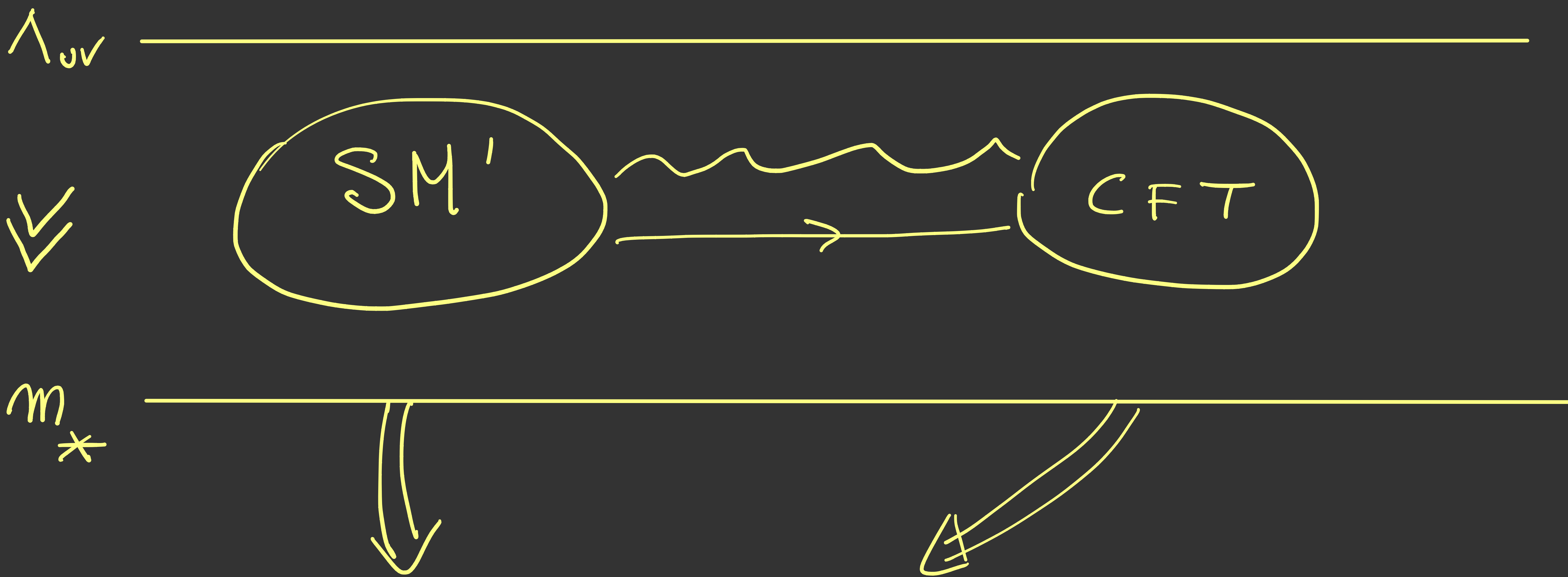
} Model Building: Exploration of structured hypotheses



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

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

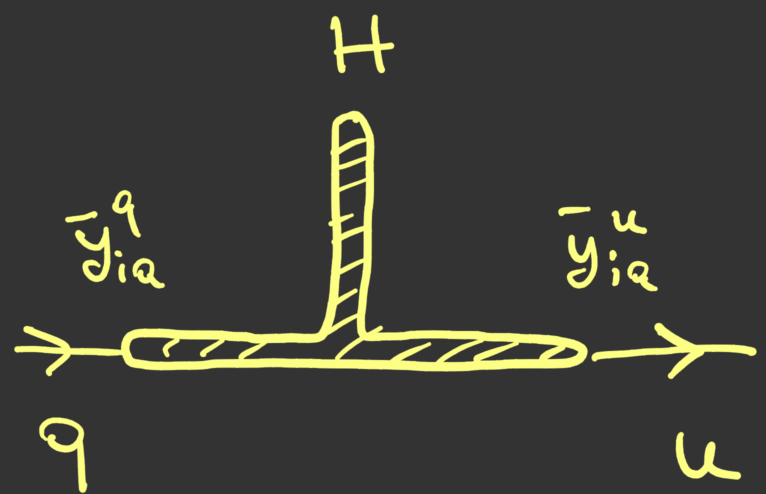
$$\underset{3/2}{q_i} \qquad \Delta^q_a = \frac{5}{2} + \gamma^q_a \qquad \text{etc}$$

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

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

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

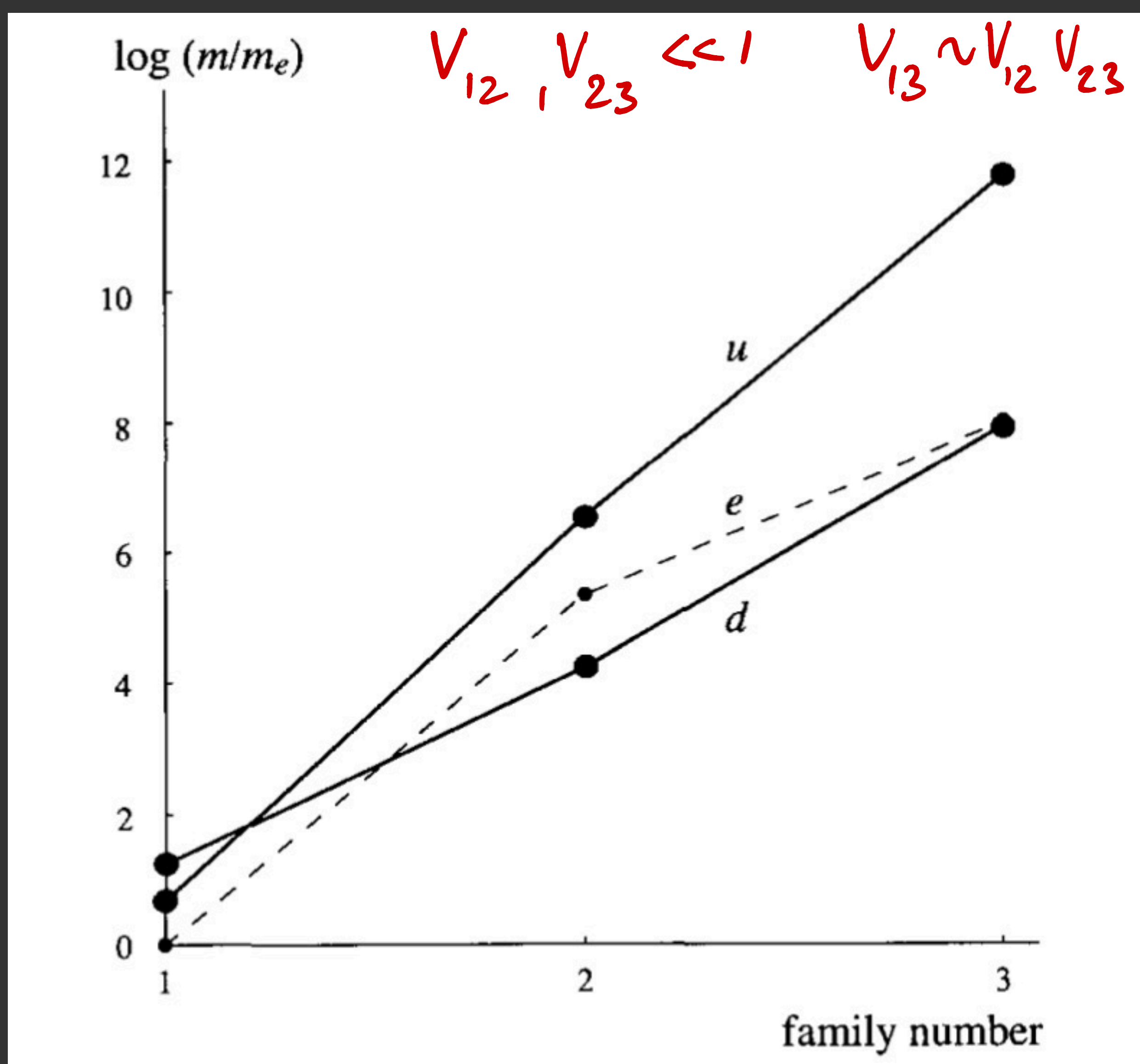
Yukawa Couplings



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

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

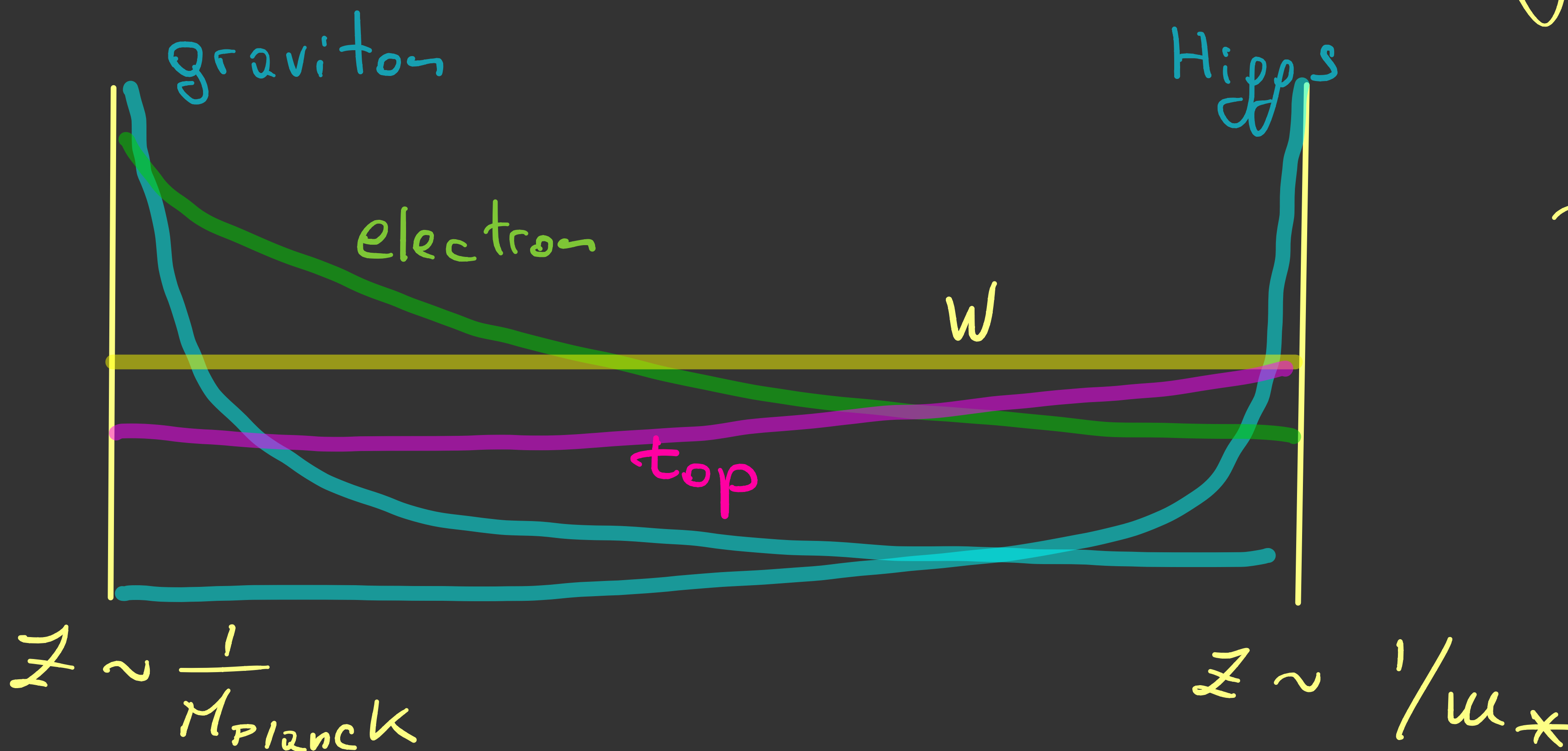
$$\left\{ \begin{array}{l} y_{a3} \longrightarrow \text{rank} = 1 \\ \oplus\; y_{a2} \longrightarrow \text{rank} = 2 \\ \oplus\; y_{a1} \longrightarrow \text{rank} = 3 \end{array} \right.$$



A full fledged CFT realizing all that ?

... of course not

- but we have at least "holographic realizations"



Randall-Sundrum's slice of AdS5

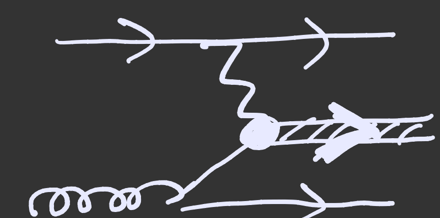
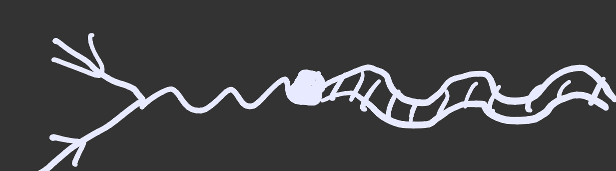
$$\boxed{m_* \sim m_{KK}\ ,\ g_* \sim g_{KK} \sim \frac{4\pi}{\sqrt{N}}\ ,\ \varepsilon\text{'s} \equiv \text{wave function overlap}}$$

Pseudo NG-Higgs

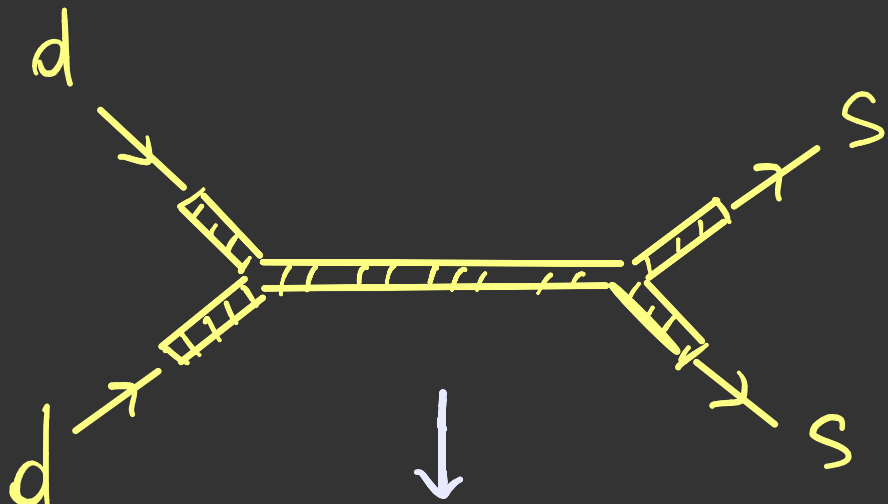
$$m_*$$

$$m_h$$

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

Naturalness	LHC
$\left(\frac{v}{f}\right)^2 \sim 1$	$\frac{\delta g_h}{g_h\big\vert_{SM}} \sim \left(\frac{v}{f}\right)^2 \leq 0.1 \div 0.2$
	 $m_* \gtrsim 1.5\,\mathrm{TeV}$
$m_* \sim 0.5\,\mathrm{TeV}$	 $m_* \gtrsim 4.5\,\mathrm{TeV}$

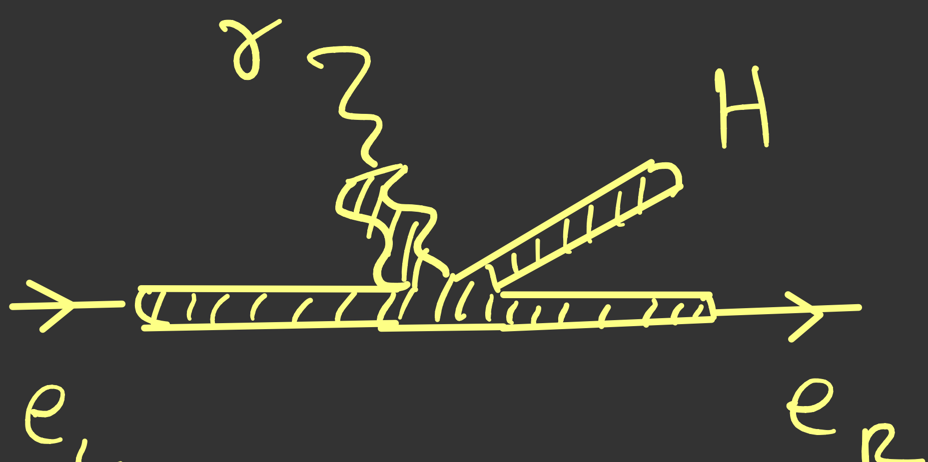
The Flavor Catastrophe



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

$+ \ldots$

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



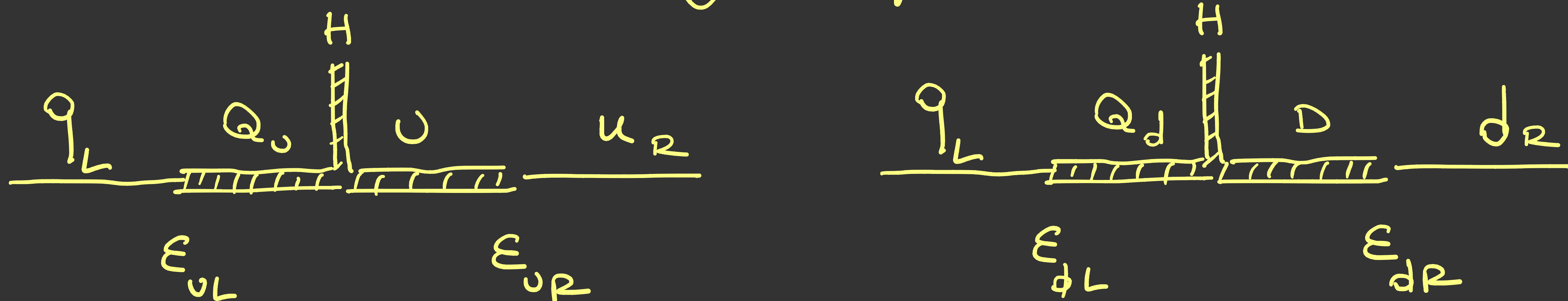
$$\Longrightarrow d_e \sim \frac{m_e\, e}{m_*^2} \Longrightarrow m_* \gtrsim 2\cdot 10^3\ \text{TeV}$$

Not only unNatural, but out of FCChh reach!!

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

$\Rightarrow$ explanation of fermion spectrum is lost

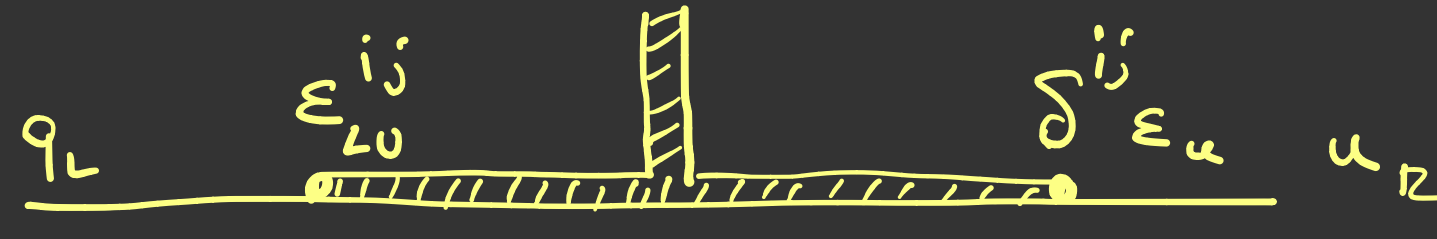
△ Largest Symmetry Group at play



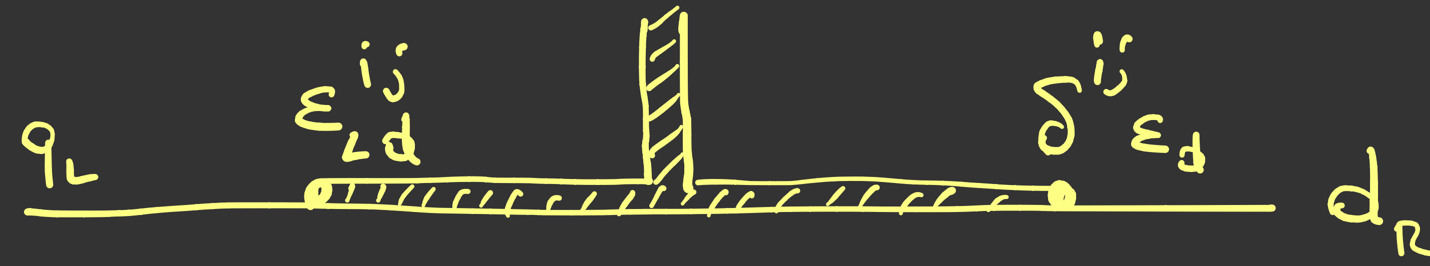
$$U(3)_q \times U(3)_u \times U(3)_d \times U(3)_U \times U(3)_D$$

- scenarios $\Longleftrightarrow$ ϵ-induced breaking patterns

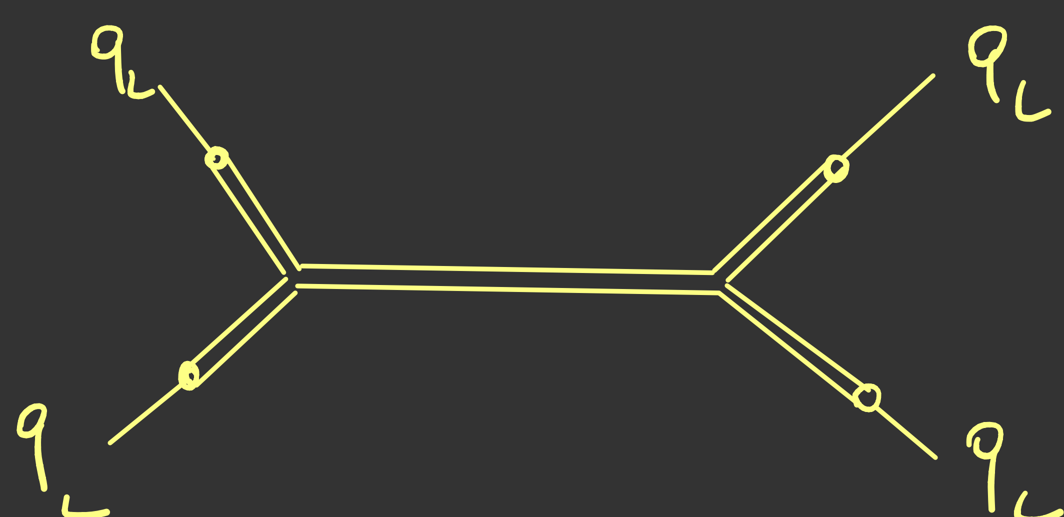
Ex "Right Universality"



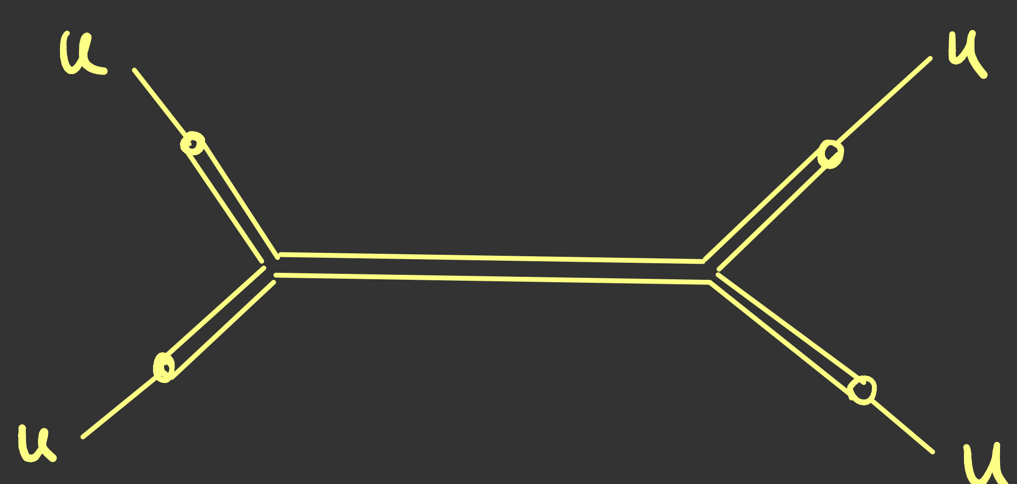
$$Y_u^{ij} = \varepsilon_{Lu}^{ij}\,\varepsilon_u\, g_*$$



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



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

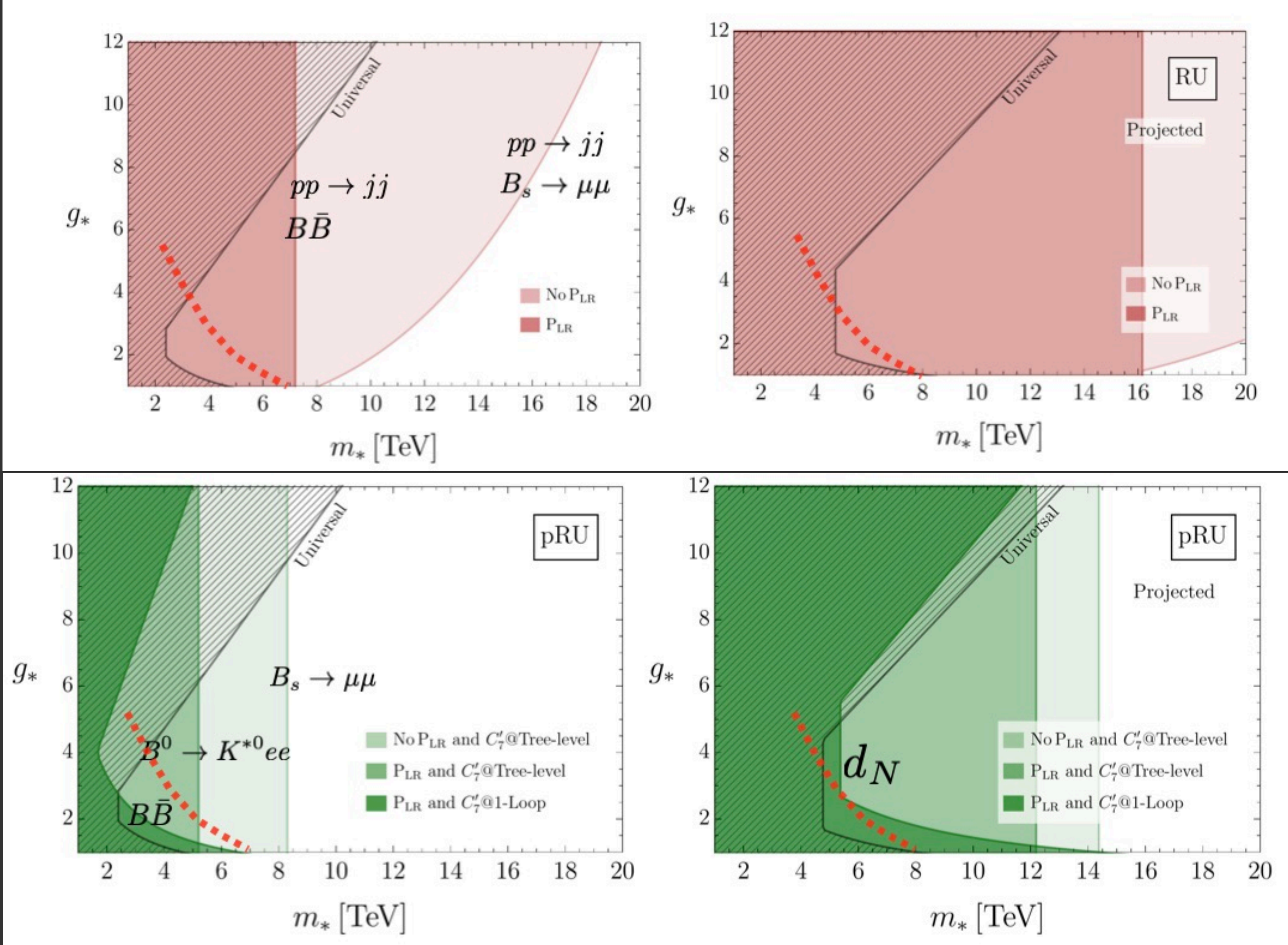


$$\sim \frac{g_*^2\,\varepsilon_u^4}{m_*^2} \Longrightarrow m_* \gtrsim (5\div 8)\ \text{TeV}\cdot g_*\,\varepsilon_u^2$$

Redi-Weiler '11 | Barbieri et al. '13
Matsedonskyi '13 | Barbieri '23

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. $\quad [U(2)\times U(1)]_{q+Q} \times U(3)_u \times U(3)_d$

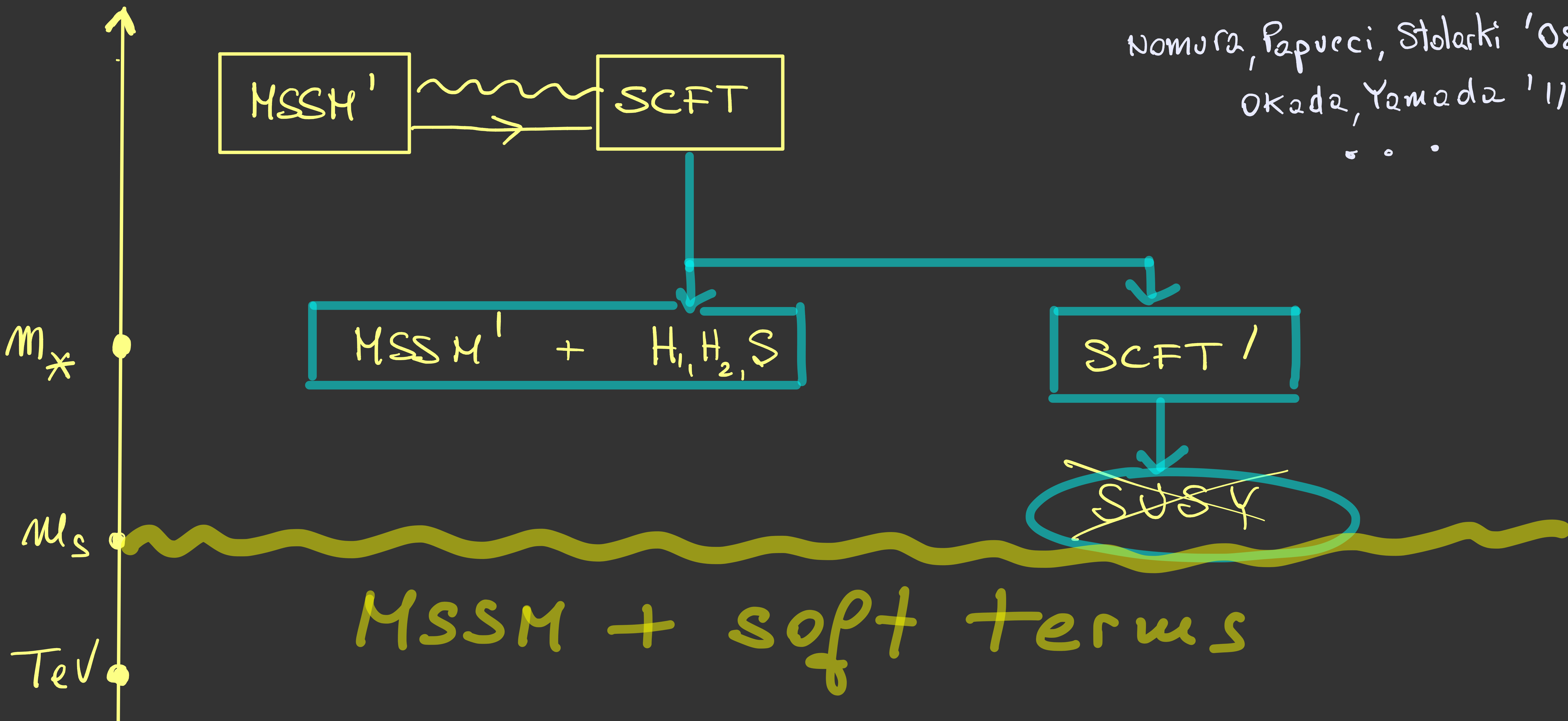


Universal
$pp \to jj$
$B\bar{B}$
$pp \to jj$
$B_s \to \mu\mu$
No P_{LR}
P_{LR}
g_*
m_* [TeV]
RU
Projected
Universal
No P_{LR}
P_{LR}
g_*
m_* [TeV]
pRU
Universal
$B_s \to \mu\mu$
$B^0 \to K^{*0}ee$
$B\bar{B}$
No P_{LR} and C_7'@Tree-level
P_{LR} and C_7'@Tree-level
P_{LR} and C_7'@1-Loop
g_*
m_* [TeV]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

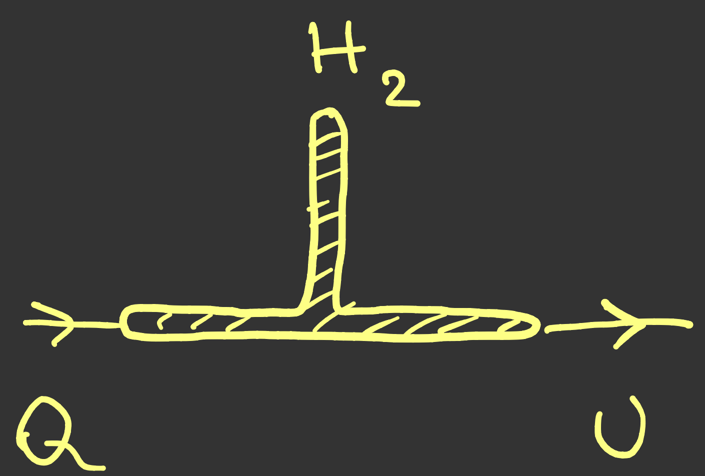
SuperSymmetric Composite Higgs

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

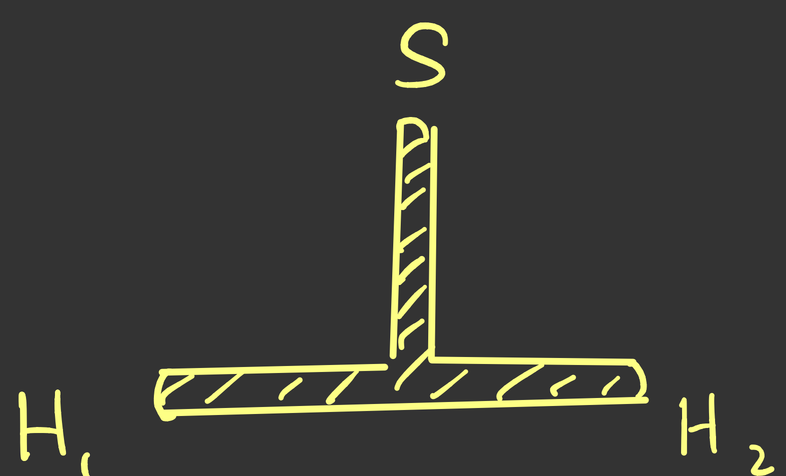
Nomura, Papucci, Stolarski '08
Okada, Yamada '11
...



At m_*



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

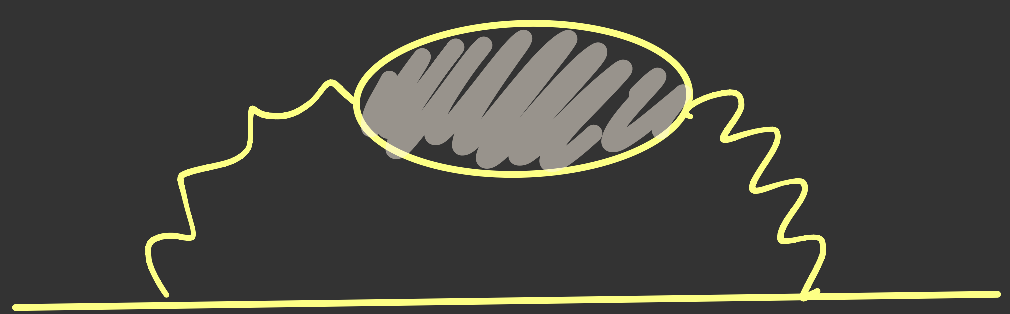


$$\Longrightarrow \int d^2\theta \; g_* \, H_1 H_2 S$$

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

At m_s

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



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

Flavor universal masses mediated by gauge fields

$\equiv$ Gauge Mediated Supersymmetry Breaking

The $\mu - B\mu - A$ Situation

Giudice-Masiero '88

- $\mathcal{O}$ chiral, $R \sim \mathcal{O} \times \mathcal{O}^\dagger$ vector $\Longrightarrow \Delta_R = 2\Delta_{\mathcal{O}} + O(\frac{1}{N})$
- ~~SUSY~~ $\Longrightarrow \langle \mathcal{O} \rangle = m^{\Delta_{\mathcal{O}}} \theta_s^2 \qquad \langle R \rangle = \cdots$

I. $$\int d^4\theta \left(H_1 H_2 + H_1^\dagger H_1 + \cdots \right) \left(\frac{\mathcal{O} + \mathcal{O}^\dagger}{m_*^{\Delta_{\mathcal{O}}}} + \frac{R}{m_*^{\Delta_R}} \right) + \cdots$$

$$\mu \sim B \sim A \sim \sqrt{\delta m_H^2} \sim \frac{m_S^{\Delta_{\mathcal{O}}+1}}{m_*^{\Delta_{\mathcal{O}}}}$$

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

$N = 10 \quad \Delta_{\mathcal{O}} = 2 \qquad\qquad N = 5 \quad \Delta_{\mathcal{O}} = 1$

II. $\mathbb{Z}_3^{PQ} \oplus$ singlet

$$\int d^4\theta \left(H_1 H_2 + S^2\right)\frac{\mathcal{O}^\dagger}{m_*^{\Delta_{\mathcal{O}}}} + \left(S^\dagger S + H_1^\dagger H_1 \cdots\right)\frac{R}{m_*^{\Delta_R}}$$

$$+ \int d^2\theta \; g_* \left(H_1 H_2 S + S^3\right) + \cancel{S\mathcal{O}}$$

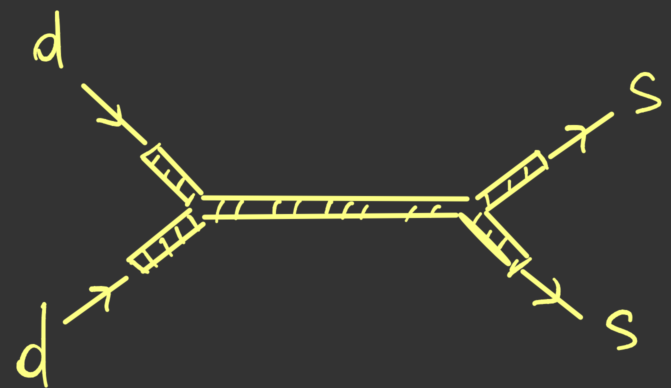
holomorphy

$$\mu \sim \mu_S \sim \sqrt{\delta m_H^2} \sim \sqrt{\delta m_S^2} \gg A, B$$

<u>Study</u> EWSB to fully assess

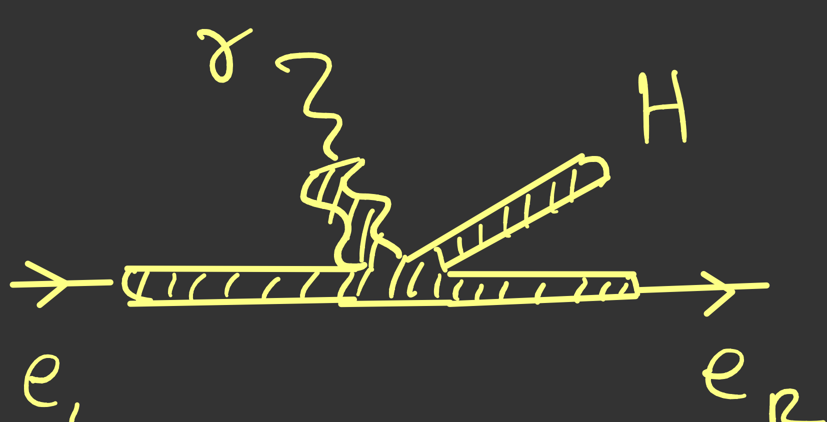
- $m_h = 125$?
- range of $\tan\beta$

SUSY saves Flavor and edms



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

$\Rightarrow$ for $\tan\beta \lesssim 3 \div 5$ $\;m_*$ allowed at FCC edge ✓



$\longrightarrow$ "0" in SUSY limit $\Rightarrow$ can relax bound

Ferrara-Remiddi '74

d_e : pletora of possible effects

- $\int d^4\theta \; y^L_{ia} y^R_{jb} c_{ab} L_i E_j H_1 \dfrac{R}{m_*^{\Delta_R+1}} \Rightarrow \mathrm{Im}\, A_{ee} = \sqrt{\dfrac{y_\mu}{y_\tau}} \dfrac{(\mathrm{TeV})^2}{m_*}$

$$\Downarrow$$

$$\boxed{\begin{array}{c} d_e < 4 \cdot 10^{-30}\, e \cdot cm \\ \Rightarrow m_* \gtrsim 100\,\mathrm{TeV} \end{array}}$$

- $\int d^4\theta \, (\dots) L_i E_j H_1 \overline{W}_{\dot\alpha} \overline{D}^{\dot\alpha} \dfrac{\mathcal{O}^+}{m_*^{\Delta_0+3}} \Rightarrow$

- No PQ $\Rightarrow \int d^4\theta \, (\dots) L_i E_j H_2^+ \Longrightarrow \tilde{e}_i \, \bar{\tilde{h}}_2 \, \bar{\phi} \, e_j \dfrac{1}{m_*}$

$$\boxed{m_* \gtrsim 300 \cdot \tan\beta \;\mathrm{TeV}}$$

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, Z_3^{PQ}, $U(1)_{PQ}$ ...

- Cosmology : light gravitino affects LSS & DM

  if in thermal equilibrium $m_s \lesssim 100\,\text{TeV}$

- edms beyond standard SUSY contributions

$\boxed{\text{I. Higgs mass scale} \quad \text{II. Fermion spectrum}}$ no explanation within SM

- I. forces us to deal with II.
- Easiest and dullest $\Rightarrow$ Flavor Symmetries
- SUSY-Compositeness helps explain I & II at "testable" energy
- electron edm is crucial