Flavor from the hierarchy standpoint

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Keren-Zur, Lodone, Nardecchia, Pappadopulo,RR, Vecchi in progress

The Hierarchy Paradox

The Stardard Model as an Effective Theory

with fundamental scale $\Lambda_{UV}^2 \gg 1\,\mathrm{TeV}$

The Stardard Model as an Effective Theory

with fundamental scale $\Lambda^2_{UV} \gg 1\,\text{TeV}$

$$\mathcal{L}_{SM} \;=\; \mathcal{L}_{kin} + g A_\mu \bar{F} \gamma_\mu F + Y_{ij} \bar{F}_i H F_j$$

d=4

The Stardard Model as an Effective Theory

with fundamental scale $\Lambda_{UV}^2 \gg 1\,\mathrm{TeV}$

$$\mathcal{L}_{SM} = \mathcal{L}_{kin} + gA_\mu \bar{F}\gamma_\mu F + Y_{ij}\bar{F}_i H F_j$$

d=4

$$+ \frac{b_{ij}}{\Lambda_{UV}} L_i L_j H H$$

$$+ \frac{c_{ijkl}}{\Lambda_{UV}^2} \bar{F}_i F_j \bar{F}_k F_\ell + \frac{c_{ij}}{\Lambda_{UV}} \bar{F}_i \sigma_{\mu\nu} F_j G^{\mu\nu} + \ldots$$

$$+ \ldots$$

d>4

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$$+ \ldots$$

d>4

$\Lambda_{UV} \to \infty$ (pointlike limit) nicely accounts for ‘what we see’

The Stardard Model as an Effective Theory

with fundamental scale $\Lambda^2_{UV} \gg 1\,\text{TeV}$

$$+ c\Lambda^2_{UV}\, H^\dagger H$$

d<4

$$\mathcal{L}_{SM} = \mathcal{L}_{kin} + gA_\mu \bar{F}\gamma_\mu F + Y_{ij}\bar{F}_i H F_j$$

d=4

$$+ \frac{b_{ij}}{\Lambda_{UV}} L_i L_j H H$$

$$+ \frac{c_{ijkl}}{\Lambda^2_{UV}} \bar{F}_i F_j \bar{F}_k F_\ell + \frac{c_{ij}}{\Lambda_{UV}} \bar{F}_i \sigma_{\mu\nu} F_j G^{\mu\nu} + \ldots$$

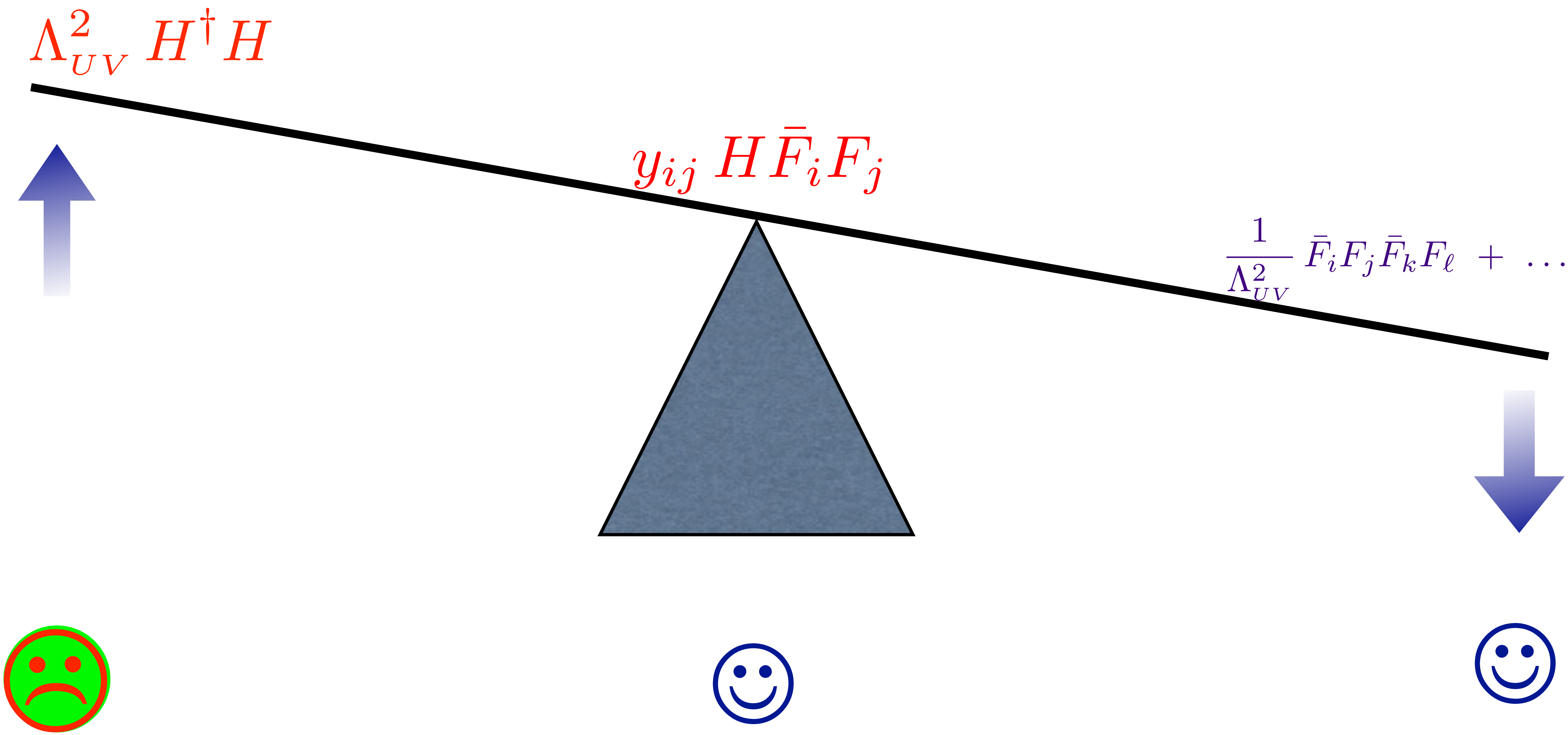
$$+ \quad \ldots$$

d>4

$\Lambda_{UV} \to \infty$ (pointlike limit) nicely accounts for 'what we see'

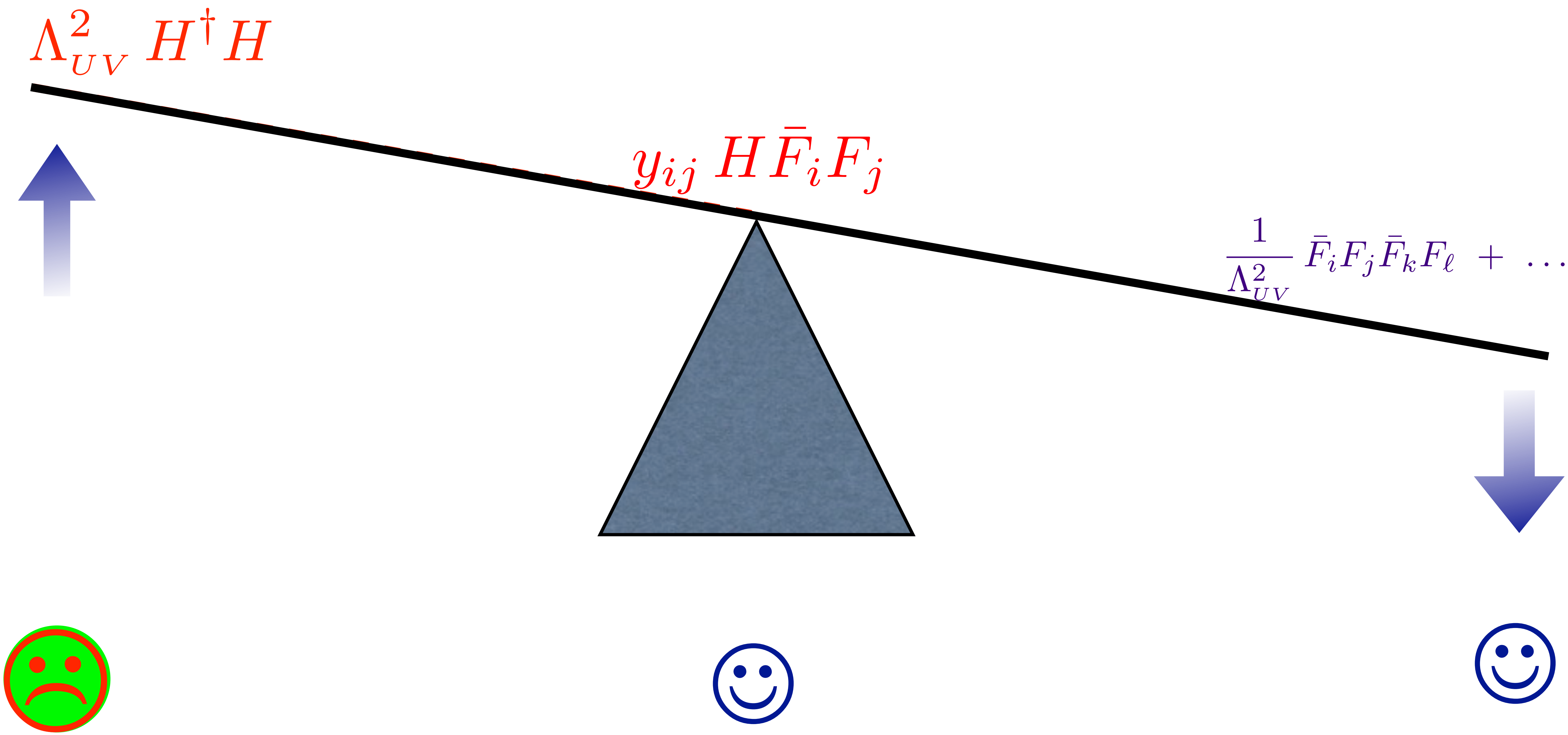
Hierarchy see-saw

Standard Model up to some $\Lambda_{UV}^2 \gg 1\,\text{TeV}$



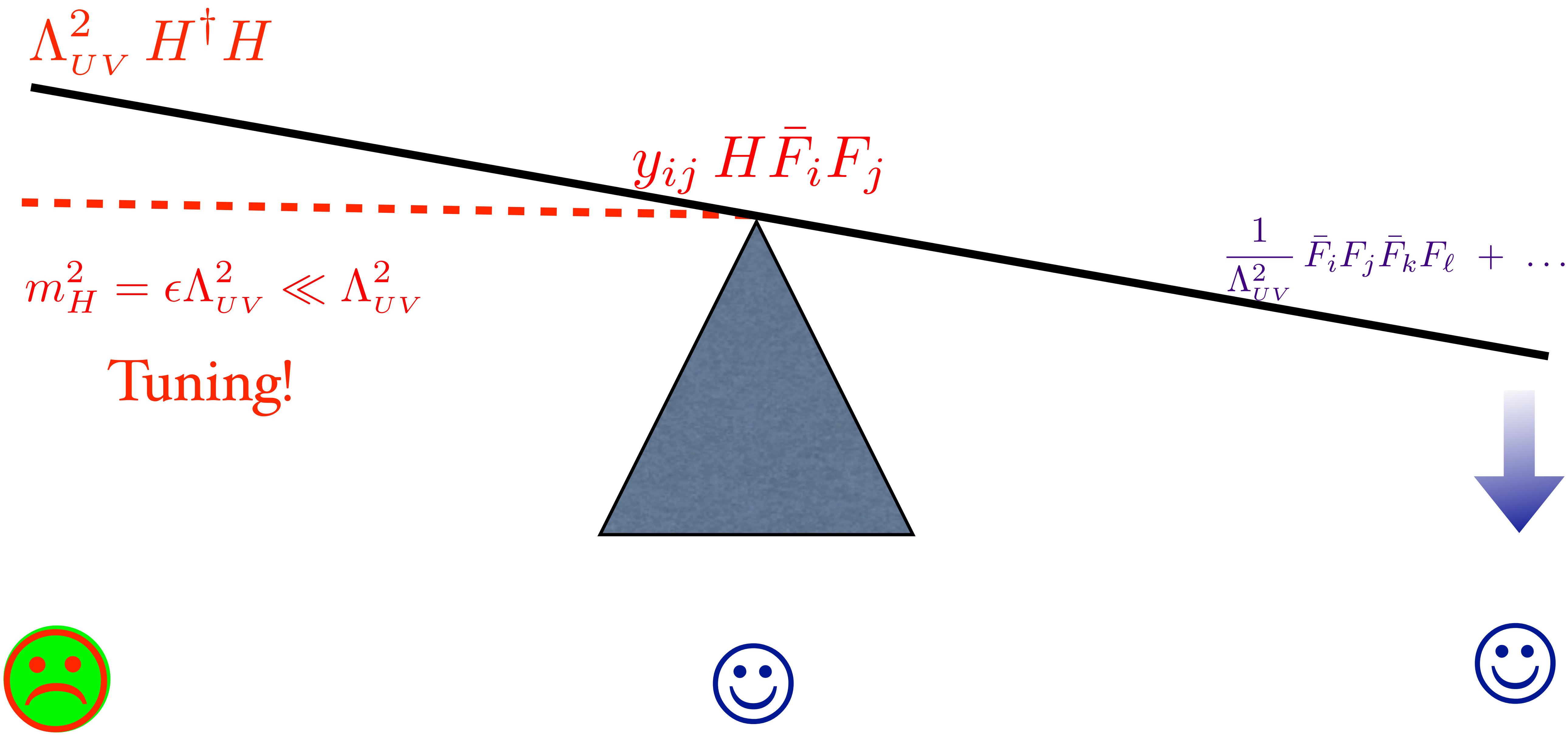
Hierarchy see-saw

Standard Model up to some $\Lambda_{UV}^2 \gg 1\,\mathrm{TeV}$



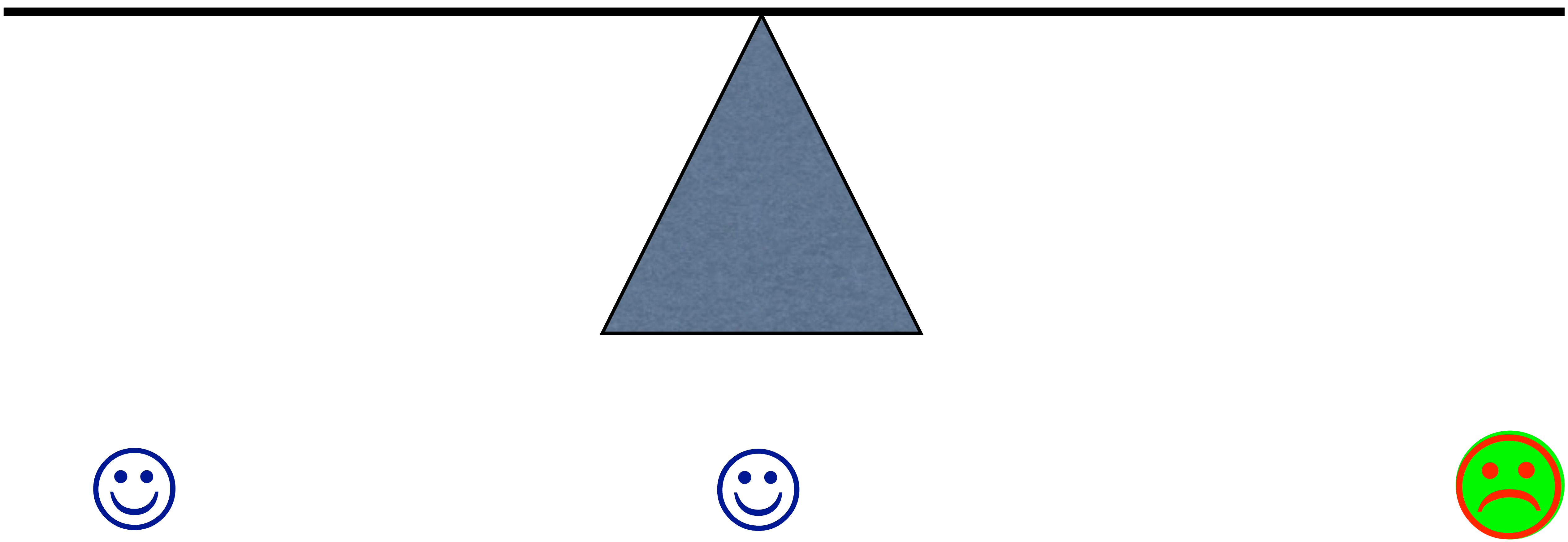
Hierarchy see-saw

Standard Model up to some $\Lambda^2_{UV} \gg 1\,\mathrm{TeV}$



Natural SM : $\Lambda^2_{UV} \lesssim 1\,\mathrm{TeV}$

$\Lambda^2_{UV}\, H^\dagger H$ $\quad$ $y_{ij}\, H \bar{F}_i F_j$ $\quad$ $\frac{1}{\Lambda^2_{UV}} \bar{F}_i F_j \bar{F}_k F_\ell \ + \ \ldots$

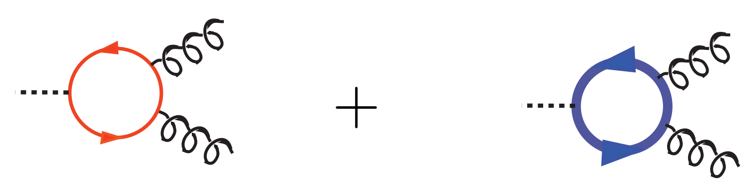


Un-natural SM

Flavor and approx B & L
are theoretically appealing

... and experimentally boring

new states



Higgs is
NOT
SM Higgs

Natural SM

$$\frac{c_{ijk\ell}}{\Lambda_{UV}^2}\bar{F}_i F_j \bar{F}_k F_\ell$$

Flavor
NOT
just CKM

Flavor & the Hierarchy & the hint from Δa_{CP}^{dir}

- ✦ Strongly coupled EWSB (Composite Higgs)

  TC, ConformalTC, Randall Sundrum,... with or without a light Higgslike scalar

- ✦ Supersymmetry

Strongly coupled EWSB: basic picture

Λ_{UV}^{II}

TeV$\equiv \Lambda_{UV}^{I}$

Strongly coupled EWSB: basic picture

Λ_{UV}^{II}

TeV$\equiv \Lambda_{UV}^{I}$

Strongly coupled EWSB: basic picture

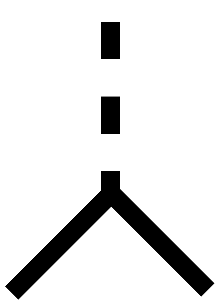
Use $\Lambda_{UV}^{II} \gg$ TeV to filter out unwanted effects and produce a realistic Flavor story

Scale (conformal) invariant theories are thus an essential ingredient of model building

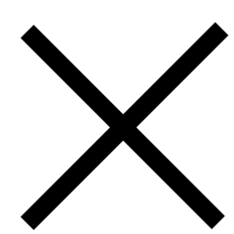
Composite sector is *broadly* described by:

✦ one mass scale m_ρ (of order TeV)

✦ one coupling g_ρ $g_\rho \sim g_{KK}$ $g_\rho \sim \frac{4\pi}{\sqrt{N}}$



$$= g_\rho \, \bar{\Psi}\Psi\Phi$$

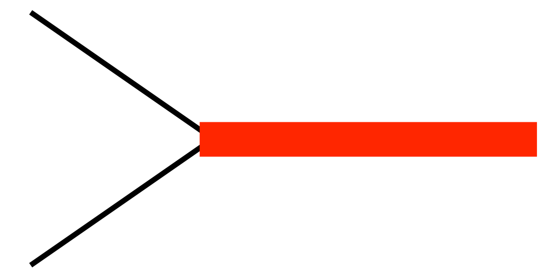


$$= \frac{g_\rho^2}{m_\rho^2} \, \bar{\Psi}\Psi\bar{\Psi}\Psi$$

Three Ways to Flavor

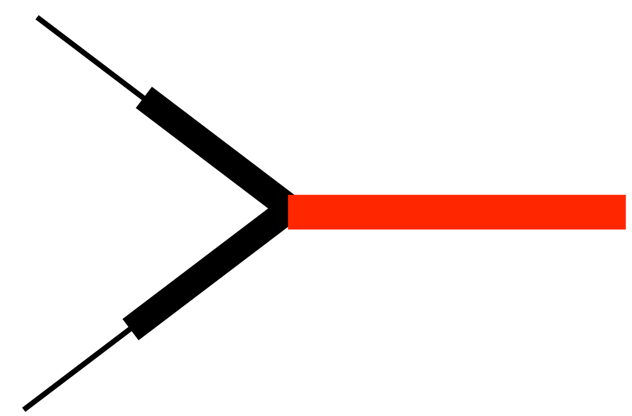
Bilinear: ETC, conformalTC

Dimopoulos, Susskind
Holdom
....
Luty, Okui



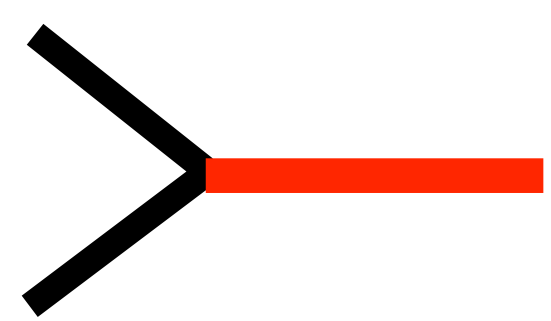
Linear: partial compositeness

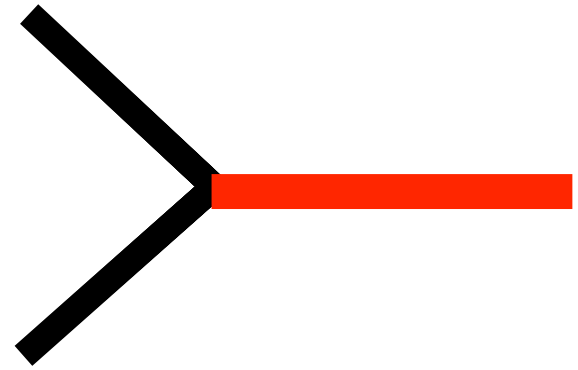
D.B. Kaplan
....
Huber
RS with bulk fermions



Total compositeness

ex: minimal RS
Rattazzi-Zaffaroni





$$\frac{g_\rho^2}{m_\rho^2}\ \bar{\ell}\ell\bar{\ell}\ell \quad \xrightarrow{\text{LEP}} \quad m_\rho > g_\rho \times 5\,\text{TeV} \sim \frac{50\,\text{TeV}}{\sqrt{N}}$$

$$\frac{g_\rho^2}{m_\rho^2}\ \bar{q}q\bar{q}q \quad \xrightarrow{\text{LHC}} \quad m_\rho > g_\rho \times 3\,\text{TeV} \sim \frac{30\,\text{TeV}}{\sqrt{N}}$$

...and we haven't even broken flavor yet
let us move on!

Wishes ...

Flavor

$$\frac{1}{\Lambda_{UV}^{d_H-1}} H\bar{F}F \;+\; \frac{c}{\Lambda_{UV}^2}\bar{F}F\bar{F}F$$

wish d_H as close to 1 as possible

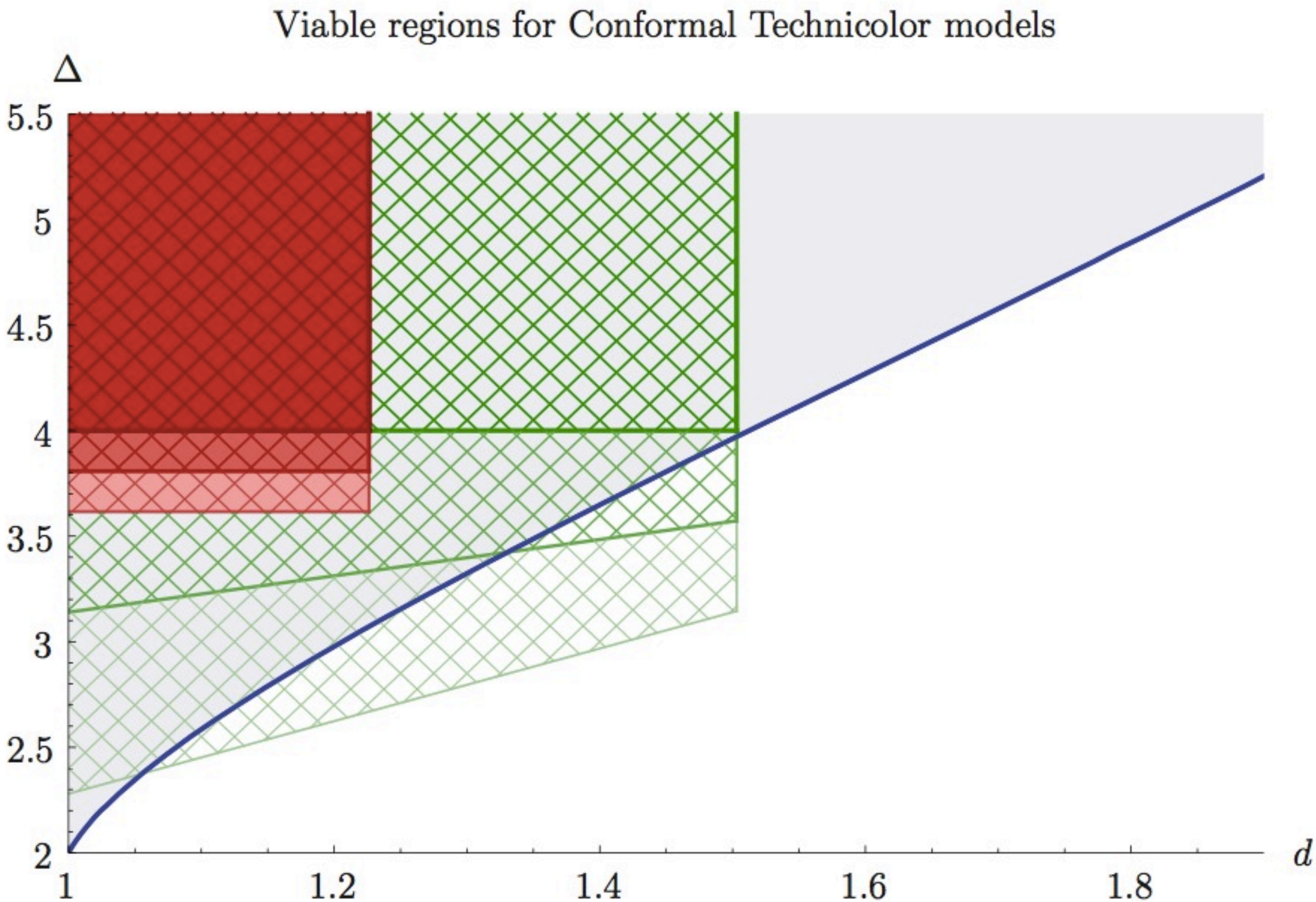
Hierarchy

$$(\Lambda_{UV})^{\Delta-4}\, H^\dagger H \qquad\qquad \Delta \equiv \dim(H^\dagger H)$$

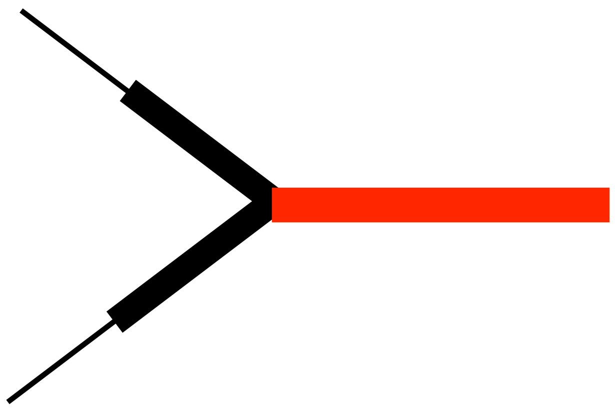
wish $\Delta > 4 - \varepsilon$

... Constraints

RR, Rychkov, Tonni, Vichi '08



Poland, Simmons-Duffin, Vichi '11



$$\mathcal{L}_{Yukawa} = \epsilon_q^i q_L^i \mathcal{O}_q^i + \epsilon_u^i u_L^i \mathcal{O}_u^i + \epsilon_d^i d_L^i \mathcal{O}_d^i$$

Yukawas

$$Y_u^{ij} \sim \epsilon_q^i \epsilon_u^j g_\rho$$

$$Y_d^{ij} \sim \epsilon_q^i \epsilon_d^j g_\rho$$

ΔF=1

$$\epsilon_q^i \epsilon_u^j g_\rho \times \frac{v}{m_\rho^2} \times \frac{g_\rho^2}{16\pi^2} \quad \bar{q}^i \sigma_{\mu\nu} u^j G_{\mu\nu}$$

ΔF=2

$$\epsilon_q^i \epsilon_d^j \epsilon_q^k \epsilon_d^\ell \times \frac{g_\rho^2}{m_\rho^2} \quad (\bar{q}^i \gamma^\mu d^j)(\bar{q}^l \gamma_\mu d^\ell)$$

Bounds & an intriguing hint

Davidson, Isidori, Uhlig '07

Keren-Zur, Lodone, Nardecchia, Pappadopulo, RR, Vecchi

ϵ_k	$m_\rho \gtrsim 10 \text{ TeV}$
$\epsilon'/\epsilon, \quad b \to s\gamma$	$m_\rho \gtrsim \frac{g_\rho}{4\pi} \times (10-15) \text{ TeV}$
d_n	$m_\rho \gtrsim \frac{g_\rho}{4\pi} \times (20-40) \text{ TeV}$
CP violation in D decays $\Delta a_{CP} = a_{KK} - a_{\pi\pi} = -(0.67 \pm 0.16)\%$	$m_\rho \simeq \frac{g_\rho}{4\pi} \times 10 \text{ TeV}$

- Not crazy at all to see deviation in D's first !
- d_n should be next
- connection with weak scale not perfect

tuning

$$0.25\% \left(\frac{m_h}{125\,\text{GeV}}\right)^2 \left(\frac{10\,\text{TeV}}{m_\rho}\right)^2$$

$$\mu \rightarrow e\gamma \qquad \frac{\sqrt{m_\mu m_e}}{m_\rho^2}\,\bar{\mu}\sigma_{\alpha\beta}e\,F^{\alpha\beta}$$

MEG: $Br(\mu \rightarrow e\,\gamma) < 2.4 \times 10^{-12}$ $\qquad m_\rho \gtrsim 150$ TeV

Partial compositeness clearly cannot be the full story

Must assume strong sector possesses some flavor symmetry

$U(1)_e \times U(1)_\mu \times (1)_\tau$

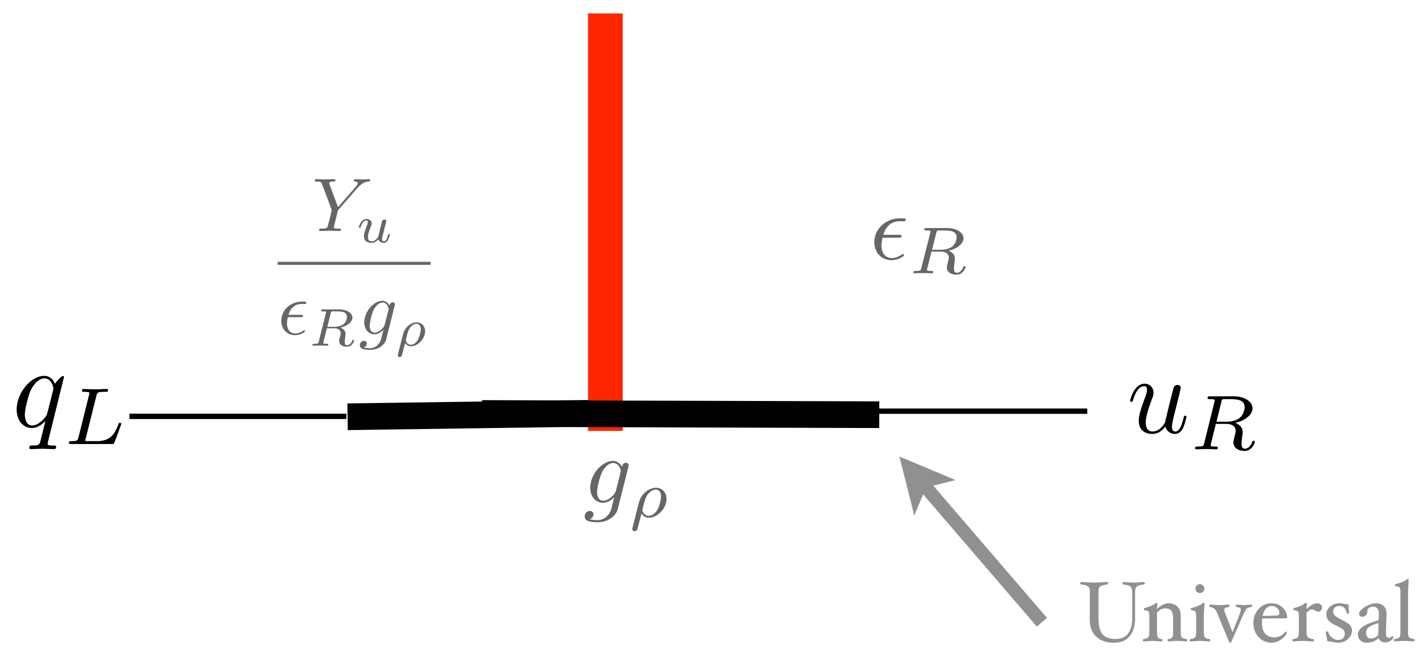
Range of possibilities

. . . .

SU(3) x SU(3) x ...

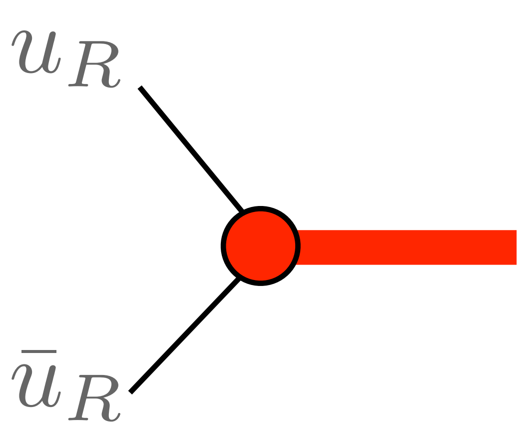
Basically the only case where it makes sense to invoke MFV

Redi, Weiler '11



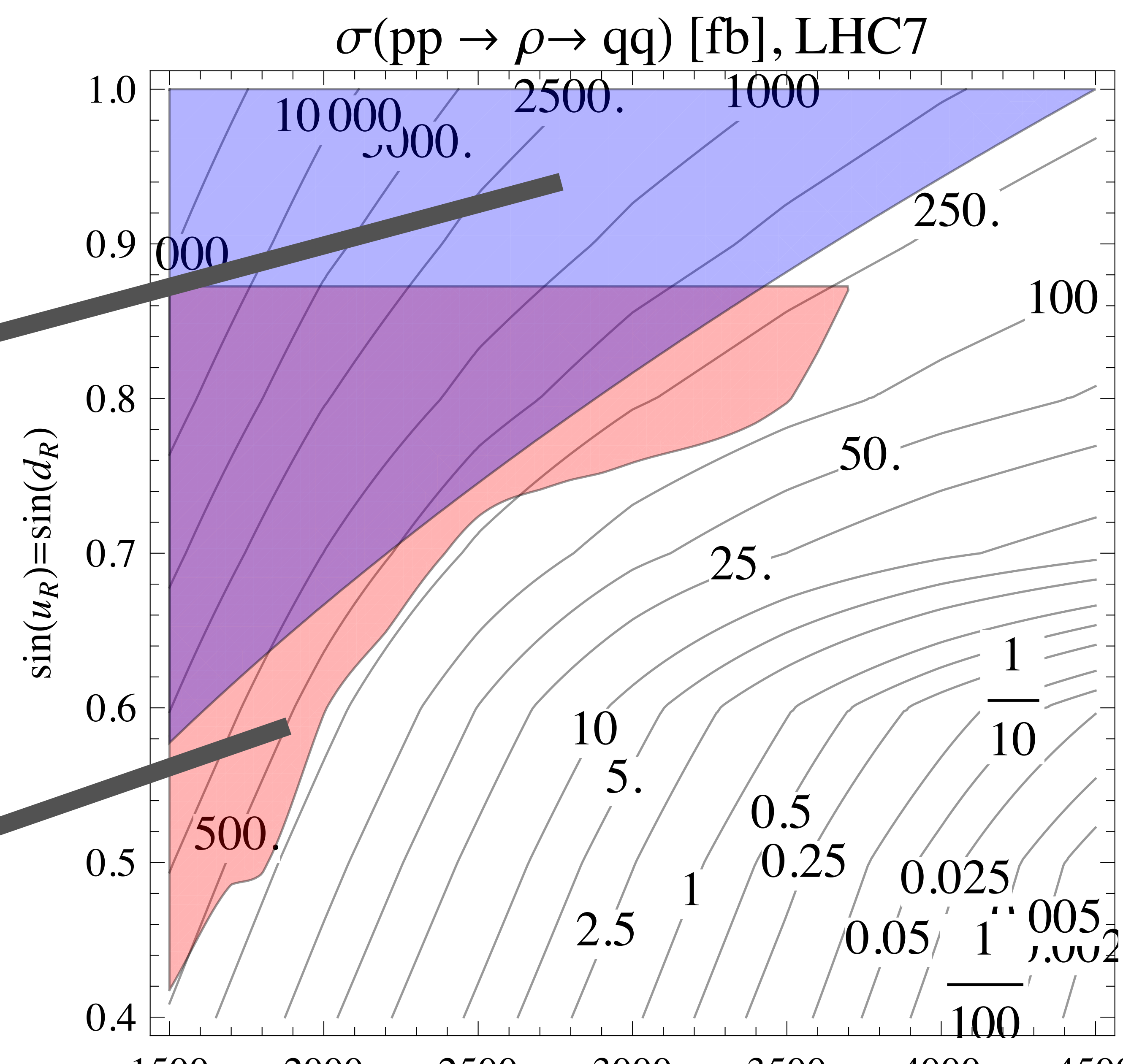
Observed m_t → $\epsilon_R \gtrsim \frac{1}{g_\rho} > 0.1$

Predict sizeable effects in right handed quarks



all possible resonances (Ex. massive gluon)

LHC7 bounds already relevant:



Di-jet bounds 35/pb

CMS-EXO-11-015
1/fb

$g_\rho = 3$

Expected signals in di-jet.

Flavor & the Hierarchy & the hint from Δa_{CP}^{dir}

✦ Strongly coupled EWSB（Composite Higgs）

✦ Supersymmetry

Two broad cases

Λ_{SUSY}

Λ_{Flavor}

Flavor dynamics will necessarily introduce new sources of mixing in soft masses

Λ_{Flavor}

Λ_{SUSY}

Minimal Flavor Violation:
Ex Gauge Mediation

Flavor from Partial Compositeness in SUSY

Flavorful SUSY: Nomura, Papucci, Stolarski '07

Λ_{SUSY}

$$W = \epsilon_q^i Q_L^i \mathcal{O}_Q^i + \epsilon_u^i U_L^i \mathcal{O}_U^i + \epsilon_d^i D_L^i \mathcal{O}_D^i$$

Λ_{Flavor}

Flavor universal soft mass generation

Ex: gauge mediation or friendly string vacuum

$$Y_u^{ij} \sim \epsilon_q^i \epsilon_u^j g_\rho \qquad Y_d^{ij} \sim \epsilon_q^i \epsilon_d^j g_\rho$$

Soft masses universal up to ε^i effects

Expected form of soft terms

$$
\begin{aligned}
(m_Q^2)_{ij} &= \tilde{m}_Q^2 \delta^{ij} + \tilde{m}_0^2 c_Q^{ij}\, \epsilon_Q^i \epsilon_Q^j \sim \delta^{ij} + \epsilon_Q^i \times \epsilon_Q^j \\
(m_U^2)_{ij} &= \tilde{m}_U^2 \delta^{ij} + \tilde{m}_0^2 c_U^{ij}\, \epsilon_U^i \epsilon_U^j \sim \delta^{ij} + \epsilon_U^i \times \epsilon_U^j \\
(m_D^2)_{ij} &= \tilde{m}_D^2 \delta^{ij} + \tilde{m}_0^2 c_D^{ij}\, \epsilon_D^i \epsilon_D^j \sim \delta^{ij} + \epsilon_D^i \times \epsilon_D^j
\end{aligned}
$$

$$
\begin{aligned}
A_U^{ij} &= \epsilon_Q^i \epsilon_U^j g_\rho\, a_U^{ij} \tilde{m}_0 \sim Y_U^{ij} \tilde{m}_0 \\
A_D^{ij} &= \epsilon_Q^i \epsilon_D^j g_\rho\, a_D^{ij} \tilde{m}_0 \sim Y_D^{ij} \tilde{m}_0
\end{aligned}
$$

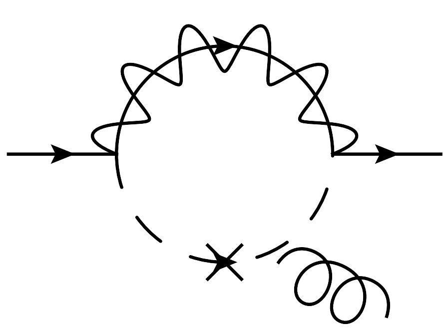
- LL and RR are approximately universal and aligned
- LR are O(1) non-universal but aligned
- Structure of $\Delta F = 1$ and $\Delta F = 2$ analogous to non-SUSY partial compositeness
- concretely realizes scenario invoked to explain a_{CP} by Giudice, Isidori, Paradisi '12

$$\Delta a_{CP}^{dir} = 0.5\% \times \left(\frac{A/\tilde{m}}{6}\right) \times \left(\frac{\mathrm{TeV}}{\tilde{m}}\right)^2 \times \left(\frac{R^{NP}}{0.2}\right)$$

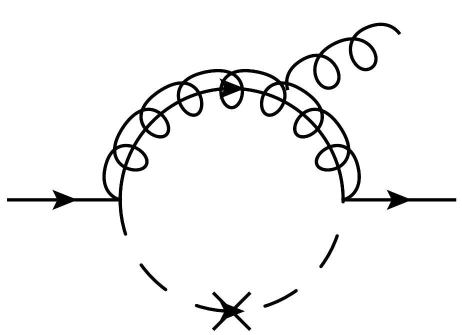
$$\begin{matrix} d_n,\ d_e \\ \mathrm{Br}(\mu \to e\gamma) \end{matrix} = \text{(exp bound)} \times \left(\frac{A/\tilde{m}}{6}\right) \times \left(\frac{\mathrm{TeV}}{\tilde{m}}\right)^2 \times O(5-10)$$

all other observables well under control

leptonic observables fare better in SUSY case because they are purely bino-induced



$= g_Y^2 F_1$



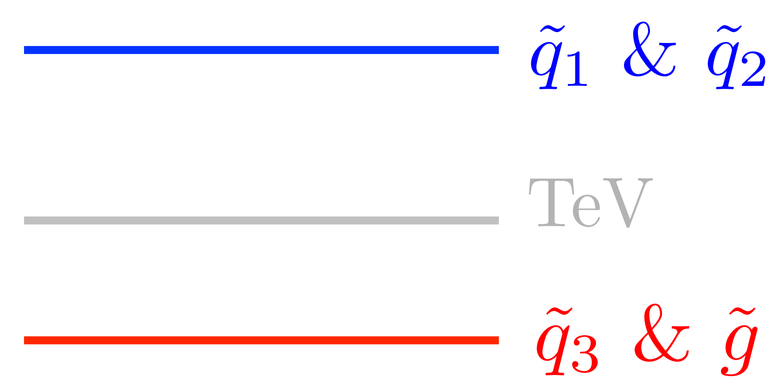
$= g_s^2 F_2$

Sparticle masses at TeV already severely constrained by ATLAS/CMS

however:

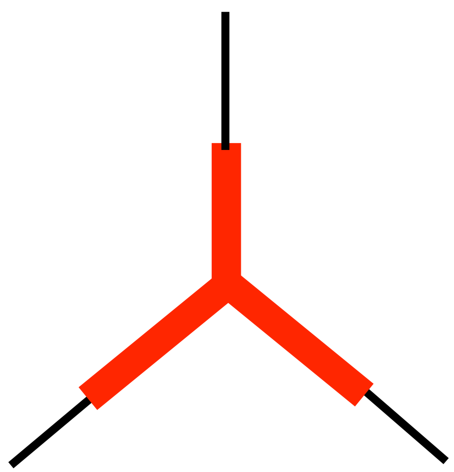
✦ can play with LSP mass to relax bounds (how much?)

✦ a_{CP} still OK with "split" spectrum



✦ Baryonic R-parity violation nicely fits in partial compositeness

- Assume Lepton number conserved by Flavor sector
- Allow maximal B violation

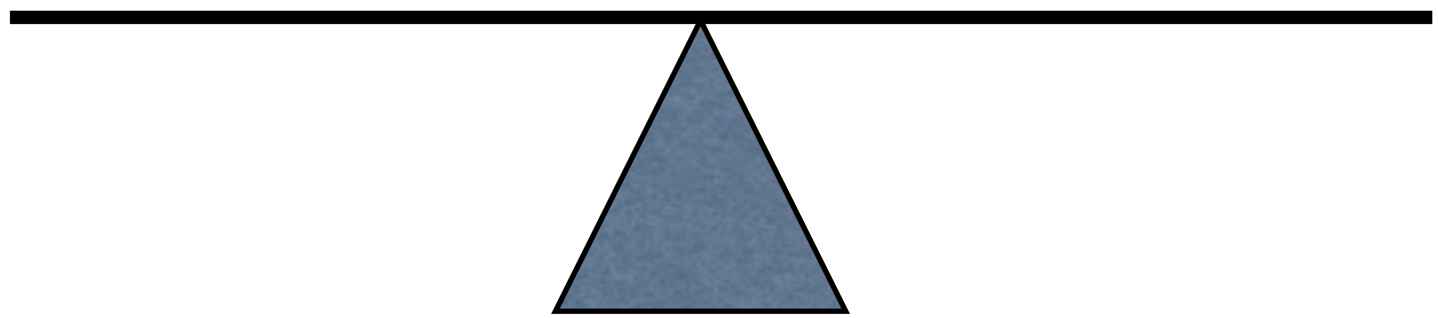


$$\lambda''_{ijk} \sim \epsilon_D^i \epsilon_D^j \epsilon_U^k \, g_\rho$$

Viable scenario with characteristic pattern of B/Flavor violation

Summary

$\Lambda^2_{UV}\, H^\dagger H \qquad y_{ij}\, H \bar{F}_i F_j \qquad \frac{1}{\Lambda^2_{UV}}\, \bar{F}_i F_j \bar{F}_k F_\ell \; + \; \ldots$



The study of Flavor & CP violation
is essential to assess
the riddle of the weak scale

In Partial Compositeness it is not implausible to detect the first major deviation from CKM in the in the D-system

...but expect other mushrooms just under the leaves:

- d_n, d_e, $\mu \to e\,\gamma$
- SUSY case: sparticles in TeV range, conceivably with RPV, should be seen very soon
- composite Higgs case: resonances at around 10 TeV practically out of reach