The precision frontier from the hierarchy standpoint

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partly based on
Keren-Zur, Lodone, Nardecchia, Pappadopulo,RR, Vecchi

arXiv:1205.5803

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

$$\mathcal{L}_{SM} = \mathcal{L}_{kin} + gA_\mu \bar{F}\gamma_\mu F + Y_{ij}\bar{F}_i H F_j + \lambda(H^\dagger H)^2$$

d=4

The Stardard Model as an Effective Theory

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

$$\mathcal{L}_{SM} = \mathcal{L}_{kin} + g A_\mu \bar{F}\gamma_\mu F + Y_{ij}\bar{F}_i H F_j + \lambda(H^\dagger H)^2$$

d=4

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

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

$$+ \quad \ldots$$

d>4

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$$\mathcal{L}_{SM} = \mathcal{L}_{kin} + gA_\mu \bar{F}\gamma_\mu F + Y_{ij}\bar{F}_i H F_j + \lambda(H^\dagger H)^2$$

d=4

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

$$+ \ \ldots$$

d>4

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

The Stardard Model as an Effective Theory

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

$$+ c\Lambda_{UV}^2 H^\dagger H$$

d<4

$$\mathcal{L}_{SM} = \mathcal{L}_{kin} + gA_\mu \bar{F}\gamma_\mu F + Y_{ij}\bar{F}_i H F_j + \lambda(H^\dagger H)^2$$

d=4

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

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

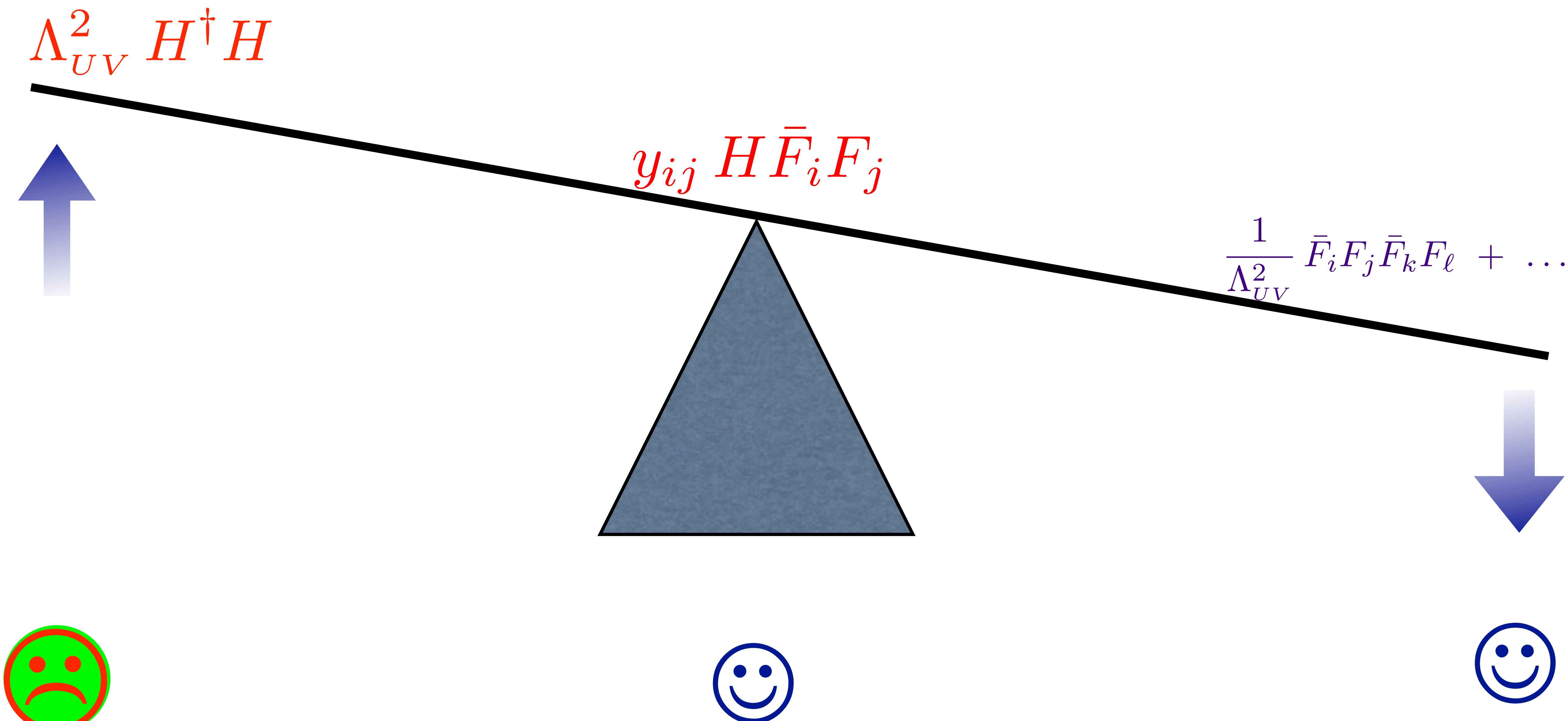
$$+ \ldots$$

d>4

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

Hierarchy see-saw

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



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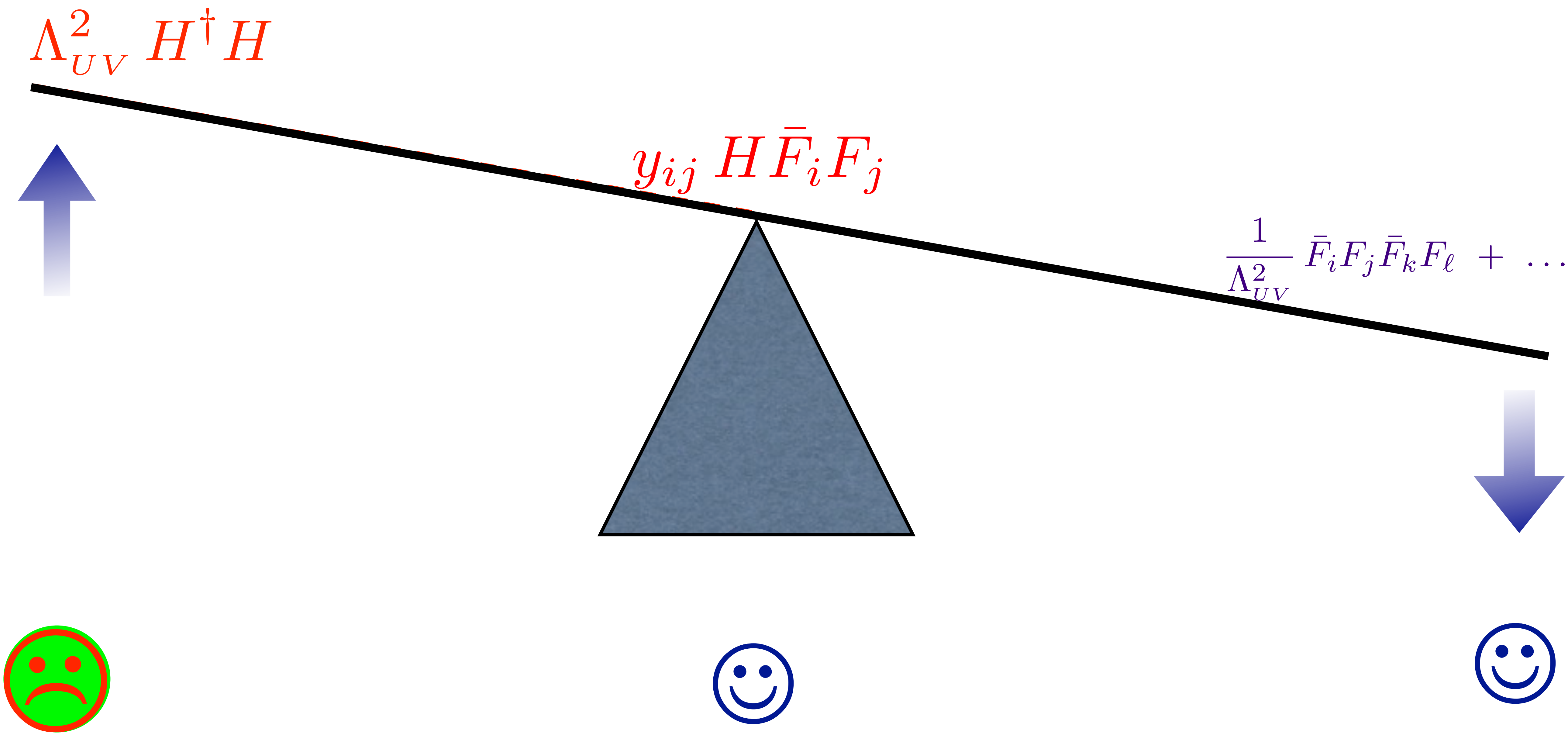

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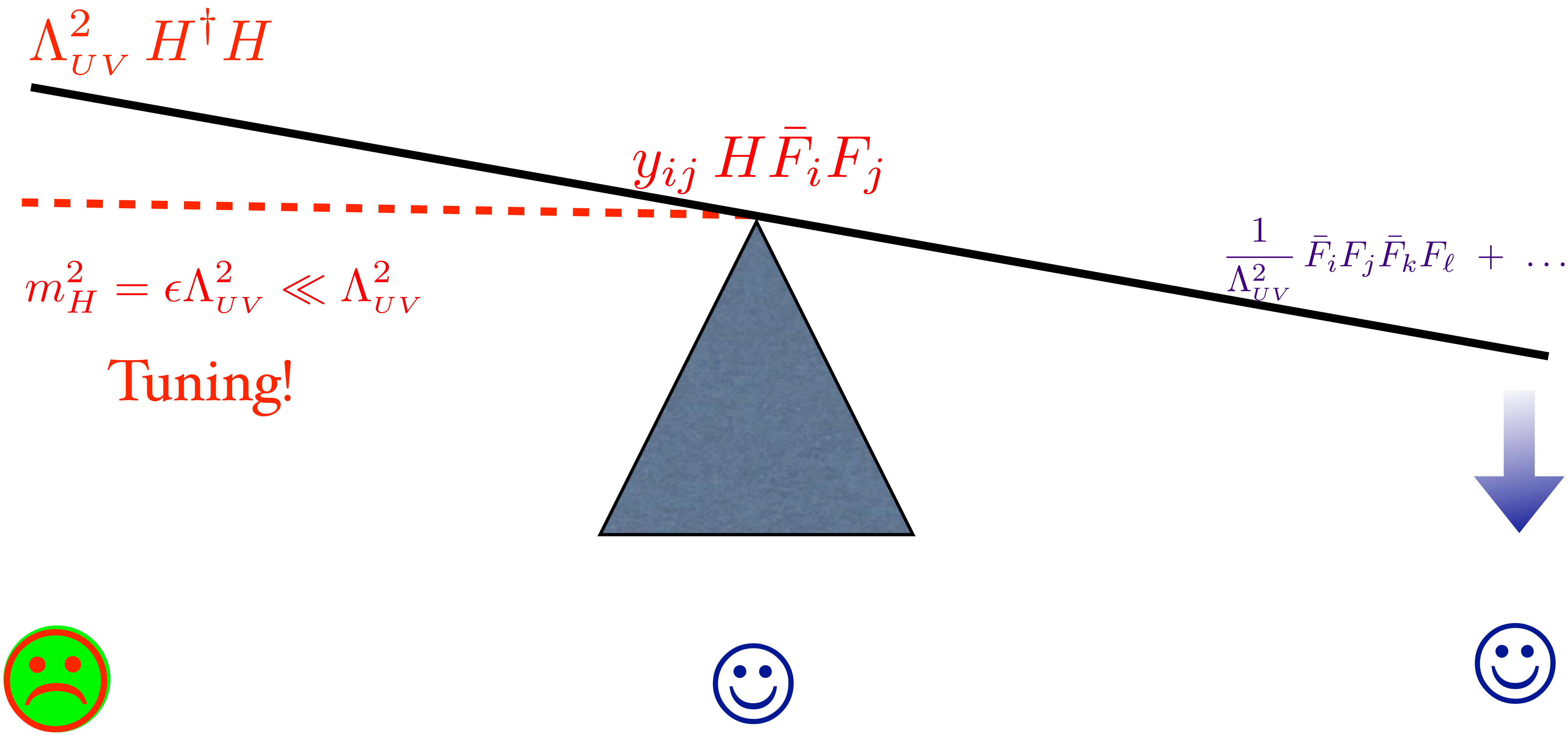
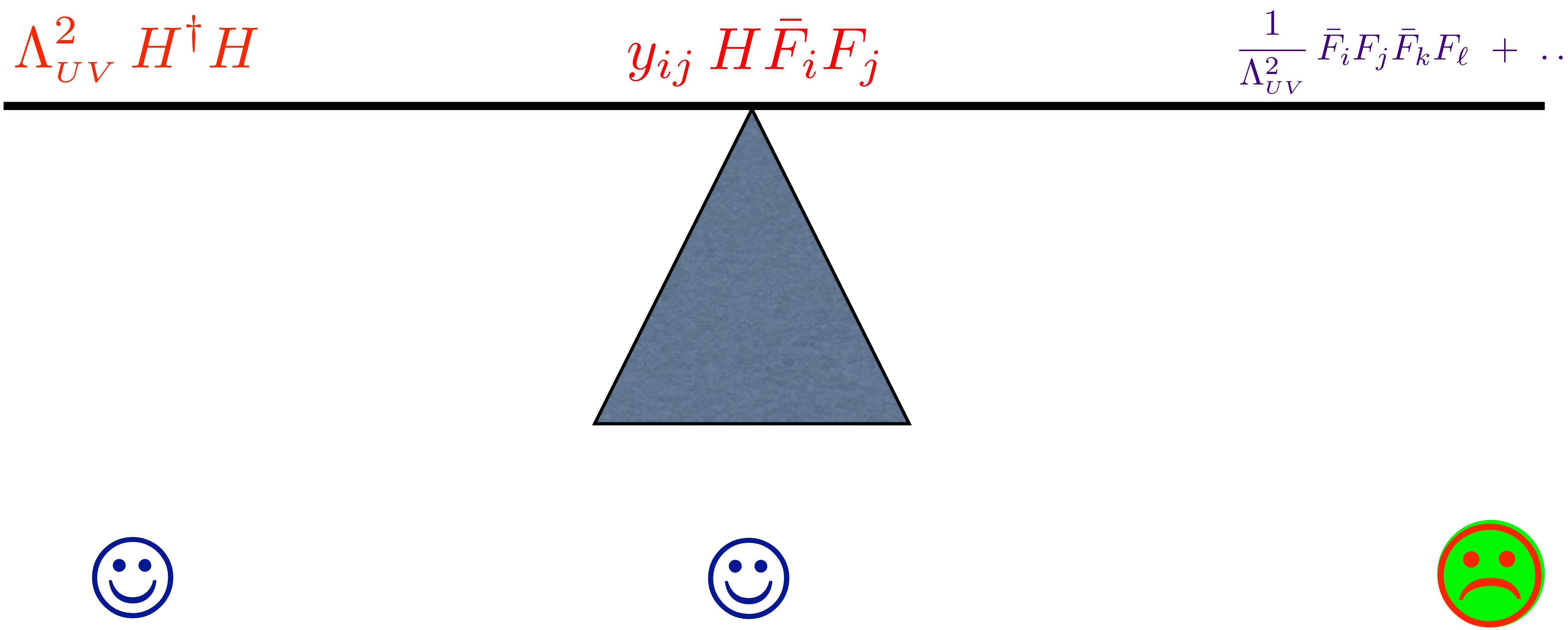
Standard Model up to some $\Lambda_{UV}^2 \gg 1\,\mathrm{TeV}$



Natural SM : $\Lambda_{UV}^2 \lesssim 1\,\text{TeV}$



Supersymmetry: the existence of scalar matter fields introduces a myriad of ***relevant couplings*** violating F, B and L

$$\mathcal{L}^{d\leq 4} = m^2_{ij}\tilde{Q}^\dagger_i\tilde{Q}_j + A_{ij}Y^D_{ij}\tilde{Q}_i\tilde{D}_j H_d + \lambda_{ijk}\tilde{U}_i D_j D_k + \dots$$

Naive Composite Higgs (TC) : the Yukawa themselves are ***irrelevant couplings***

$$Y_{ij}\, H\, \bar{Q}^i_L Q^j_R \;\to\; Y_{ij}\,\frac{1}{\Lambda^2_F}\,(\bar{\Psi}\Psi)Q^i_L Q^j_R \qquad\qquad m_{ij} = Y_{ij}\,\frac{v^3_F}{\Lambda^2_F}$$

Λ_F must be not too far above weak scale: expect unwanted FCNC

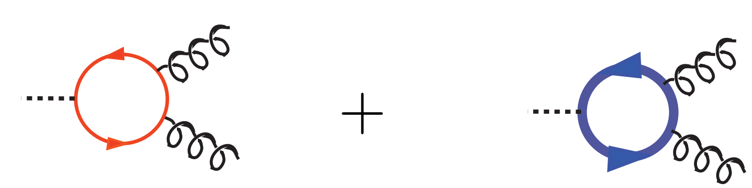
Un-natural SM

Flavor and approx B & L
are theoretically appealing

... and, possibly, experimentally boring

Natural SM

new states



Higgs is
NOT
SM Higgs

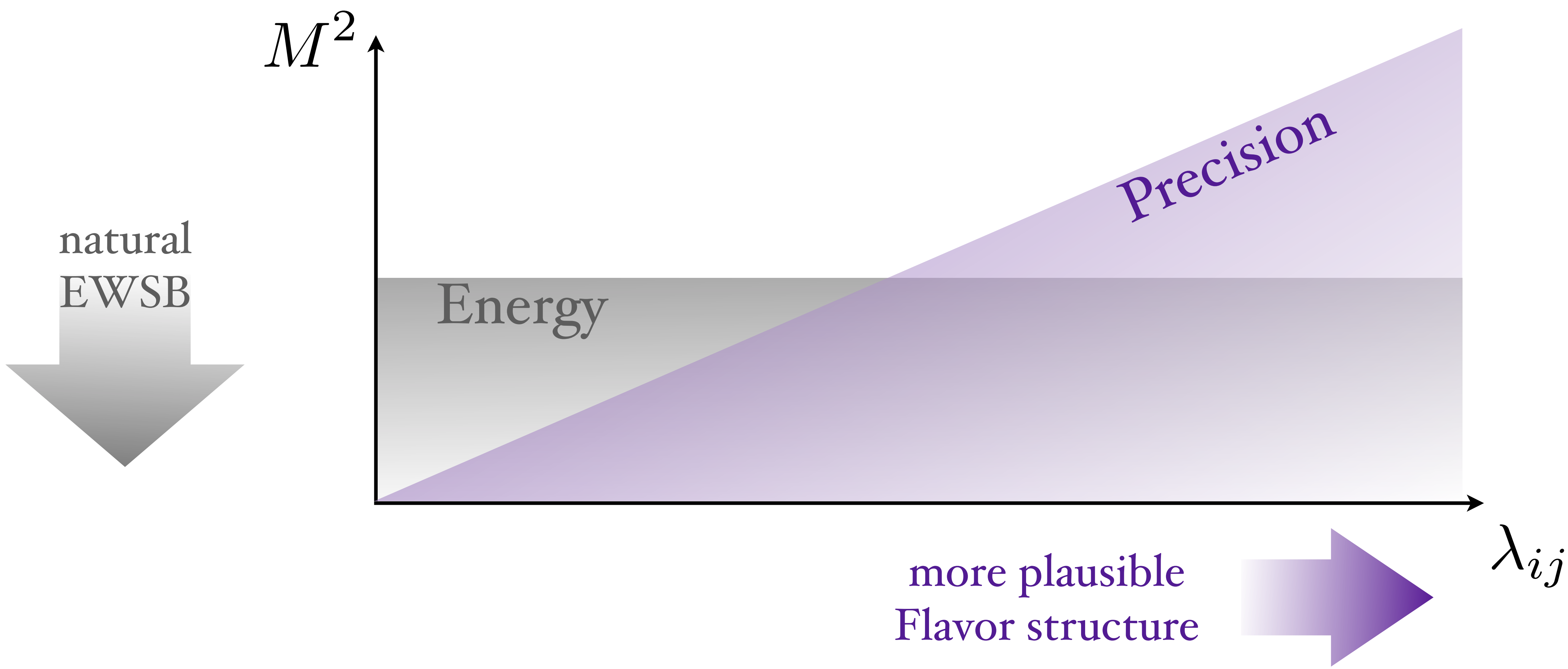
$$\frac{c_{ijk\ell}}{\Lambda_{UV}^2}\bar{F}_i F_j \bar{F}_k F_\ell$$

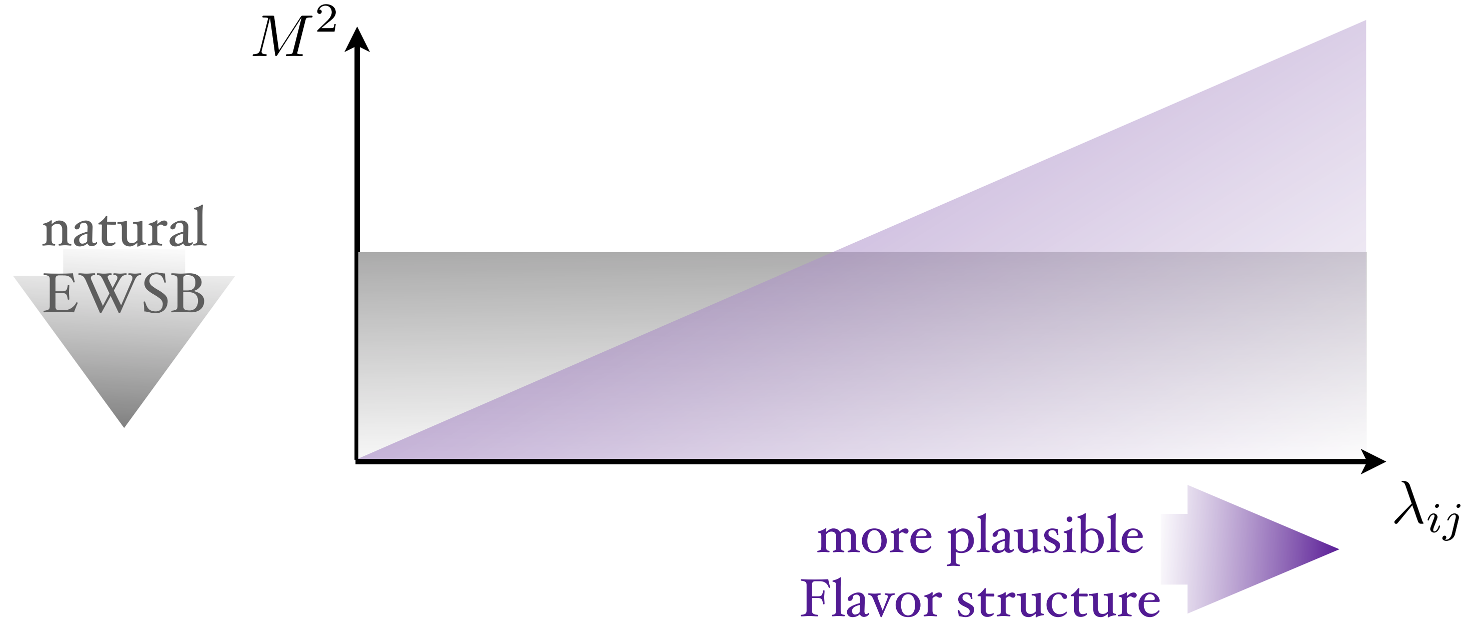
Flavor
NOT
just CKM

The energy and precision frontiers on a cartoon

New physics at scale M with couplings describing flavor structure

$$\frac{\lambda_{ijkl}}{M^2}\,\bar{q}_i q_j \bar{q}_k q_l \;+\; m_i\,\frac{\lambda_{ij}}{M^2}\,\bar{\ell}_i \sigma_{\mu\nu} \ell_j F^{\mu\nu} \;+\; \ldots$$





- LHC is stuck with testing more or less natural theories of EWSB
- Precision experiments probe also deep into the space of theories with un-natural EWSB but with perhaps more plausible Flavor structure

Approaches to Flavor

Symmetry

pick a subgroup of $U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$
pick a set of spurions to break it
construct a lagrangian using the selection rules

Dynamics

mass mixing hierarchy from radiative corrections
flavor from geography in extra-dim
flavor from partial compositeness
↕ holography

Partial compositeness is a broad paradigm useful to illustrate theoretical aspects of searches at the precision frontier

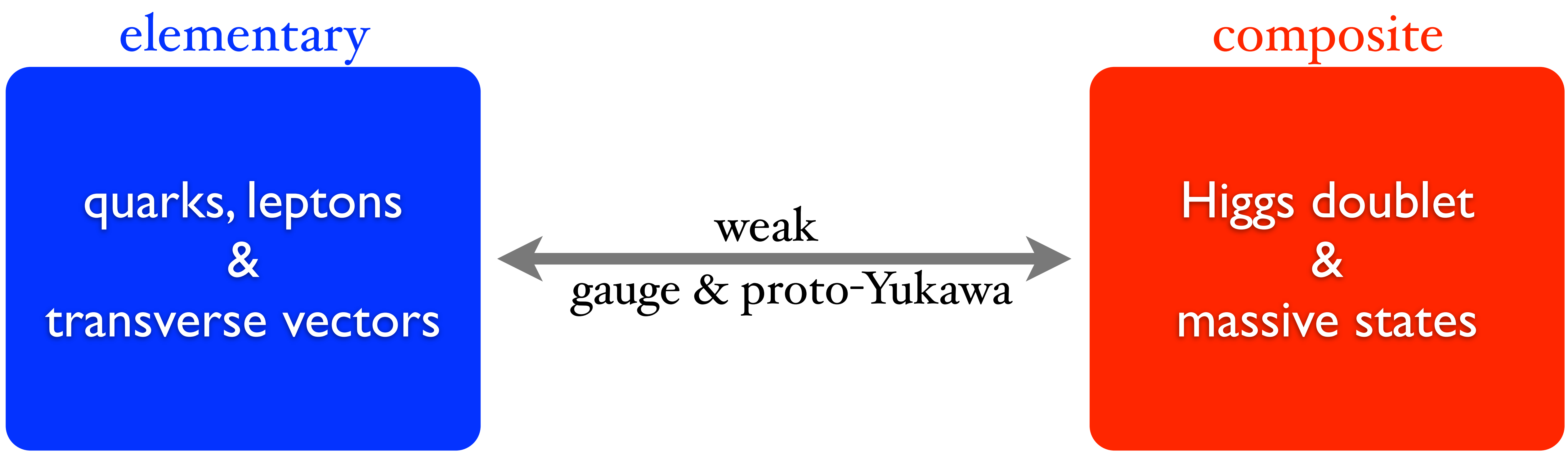
It applies to both supersymmetry and composite Higgs, but it is basically the only available option in the latter scenario

- ✦ Strongly coupled EWSB (Composite Higgs)

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

- ✦ Supersymmetry

Composite Higgs scenario



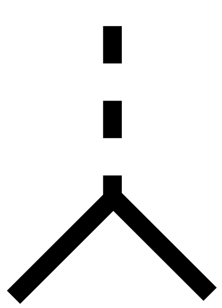
Georgi, Kaplan '84
Banks '84
Arkani-Hamed, Cohen, Katz, Nelson '02
Agashe, Contino, Pomarol '04

Composite sector is *broadly* described by:

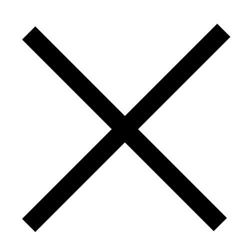
Giudice, Grojean, Pomarol, RR, '07

- one mass scale m_ρ (of order TeV)

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



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

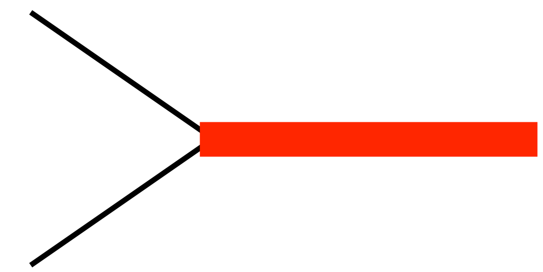


$$= \frac{g_\rho^2}{m_\rho^2} \, \bar{\Psi}\Psi\bar{\Psi}\Psi$$

Three Ways to Flavor

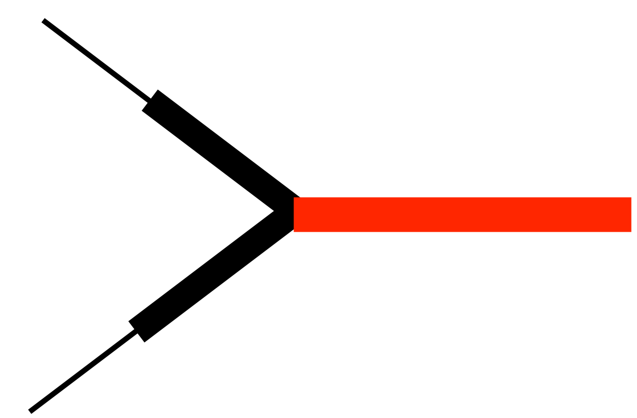
Bilinear: ETC, conformalTC

Dimopoulos, Susskind
Holdom
....
Luty, Okui



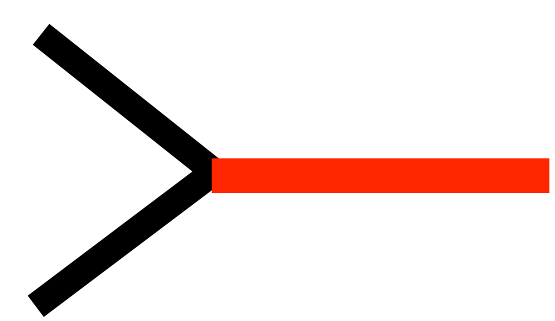
Linear: partial compositeness

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



Total compositeness

ex: minimal RS
Rattazzi-Zaffaroni



Three Ways to Flavor

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disfavored by CFT ‘theorems’
Rychkov, Rattazzi, Tonni, Vichi 2008

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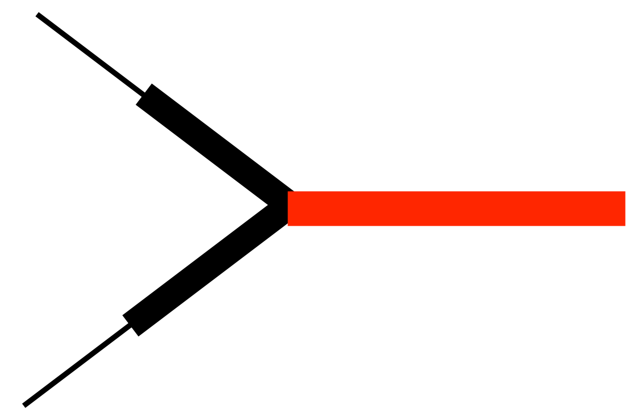

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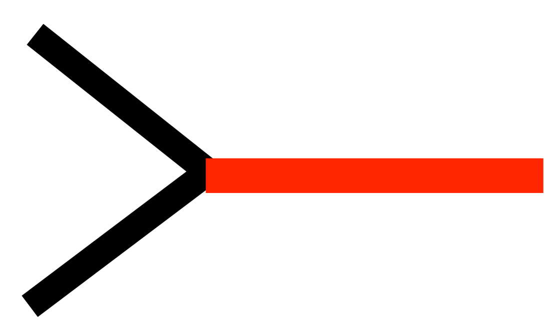

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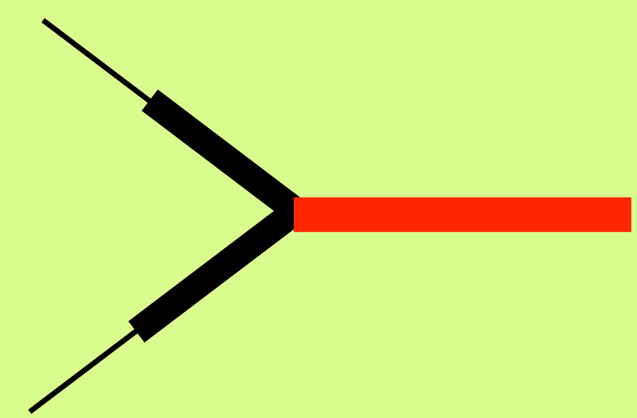
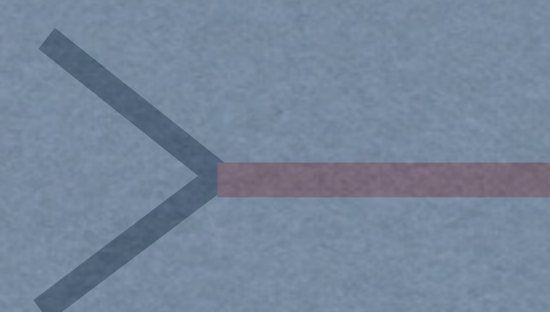
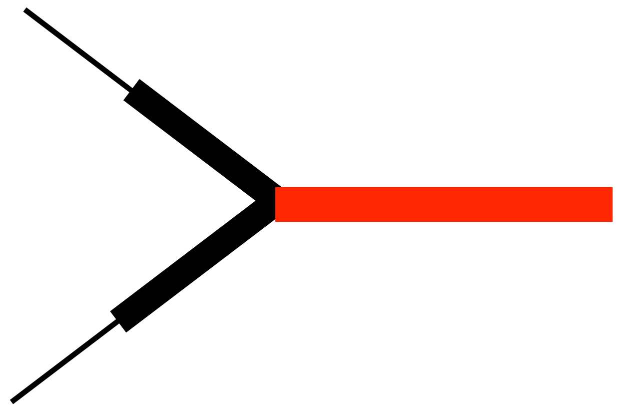


Total compositeness

ex: minimal RS
Rattazzi-Zaffaroni

~ ruled out by LEP bounds
on lepton compositeness





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

Hypothesis

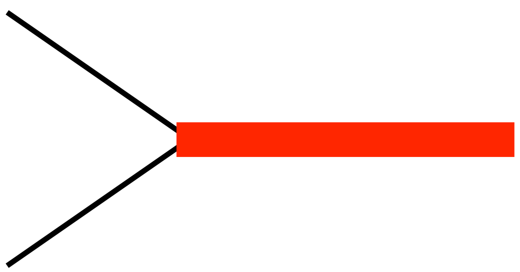
∃ at least 3 families of composite fermionic operators with same gauge quantum numbers as elementary ones

small difference in dimension among $\mathcal{O}^i$ generates appreciable hierarchy in ϵ^i via RG flow

Yukawas

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

Neutrino masses



$$\frac{y_{ij}}{\Lambda^{\Delta-1}}\ \ell_i \ell_j\, \mathcal{O}$$

bosonic field of dimension Δ

Just one source associated with higher dimensional operator

$$m_\nu^{ij} \sim y_{ij} v_F \left(\frac{v_F}{\Lambda}\right)^{\Delta-1}$$

very small
non-hierarchical

play no significant role in charged lepton flavor violation

Flavor transitions controlled by selection rules

(accidental non-compact $U(1)^9$ flavor symmetry)

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

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

electron edm

$$\left(\frac{g_\rho}{4\pi}\right)^2 \frac{m_e}{m_\rho^2}\, \bar{\psi}_e \sigma_{\mu\nu}\gamma_5 \psi_e\, F^{\mu\nu}$$

$$m_\rho > \frac{g_\rho}{4\pi}\, 100 \text{ TeV} \left(\frac{1.6\times 10^{-27}\, e\cdot\text{cm}}{d_e^{\text{exp}}}\right)^{1/2}$$

^{205}Tl
Regan et al '02

$\mu \to e\gamma$

most favorable choice $$\frac{\epsilon_1^\ell}{\epsilon_2^\ell} \sim \frac{\epsilon_1^e}{\epsilon_2^e} \sim \sqrt{\frac{m_e}{m_\mu}}$$

$$\left(\frac{g_\rho}{4\pi}\right)^2 \frac{\sqrt{m_\mu m_e}}{m_\rho^2}\, \bar{\psi}_\mu \sigma_{\alpha\beta} \psi_e\, F^{\alpha\beta}$$

$$m_\rho > \frac{g_\rho}{4\pi}\, 150 \text{ TeV} \left(\frac{2.4\times 10^{-12}}{Br^{\text{exp}}}\right)^{1/2}$$

MEG '11

In a natural theory of EWSB
Partial compositeness clearly cannot be the full story

Either g_ρ is very weak in the lepton sector

or

Must assume strong sector possesses some flavor symmetry and CP

Range of possibilities

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

. . . .

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

A lesson on $\mu \to e\gamma$ versus $\mu \to eee$ & $\mu N \to eN$

$$\mathcal{L}_{eff} = \frac{1}{\Lambda^2}\left[e\, m_\mu \bar{\psi}_\mu \sigma_{\alpha\beta} \psi_e\, F^{\alpha\beta} \;+\; \bar{\psi}_\mu \gamma_\alpha \psi_e \left(\kappa_e \bar{\psi}_e \gamma^\alpha \psi_e \,+\, \kappa_q \bar{\psi}_q \gamma^\alpha \psi_q\right)\right]$$

$\kappa_e,\, \kappa_q, \lesssim\, e^2 \equiv \sqrt{4\pi\alpha_{EM}}$

dipole operator dominates

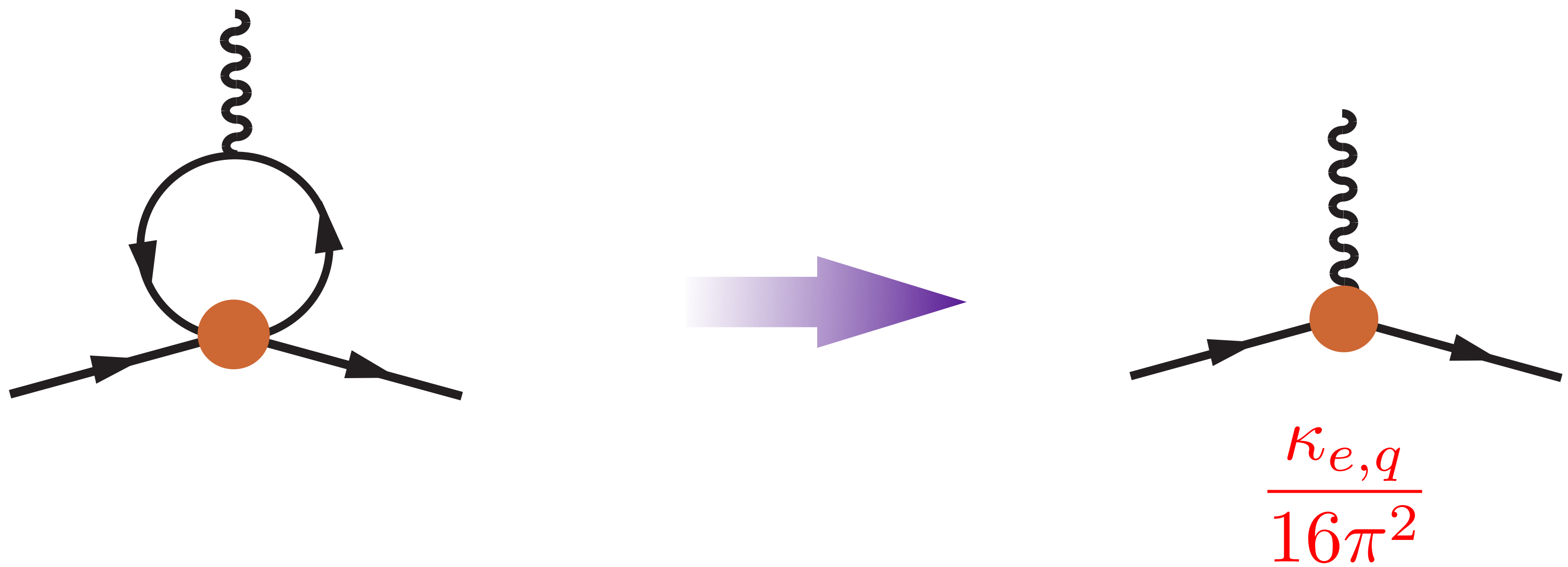
$$Br(\mu \to eee) \,\simeq\, 6.7 \times 10^{-3}\, Br(\mu \to e\gamma)$$

$$Br(\mu\, \mathrm{T}i \to e\, \mathrm{T}i) \,\simeq\, 4 \times 10^{-3}\, Br(\mu \to e\gamma)$$

10^{-14} in $\mu \to e\gamma$ conservatively matches 10^{-16} in the other two processes

but in principle they could be enhanced because $\kappa_e,\, \kappa_q, \gg\, e^2$

what are the possible ranges of κ_e, κ_q ?



$$\kappa_e, \kappa_q \lesssim 16\pi^2$$

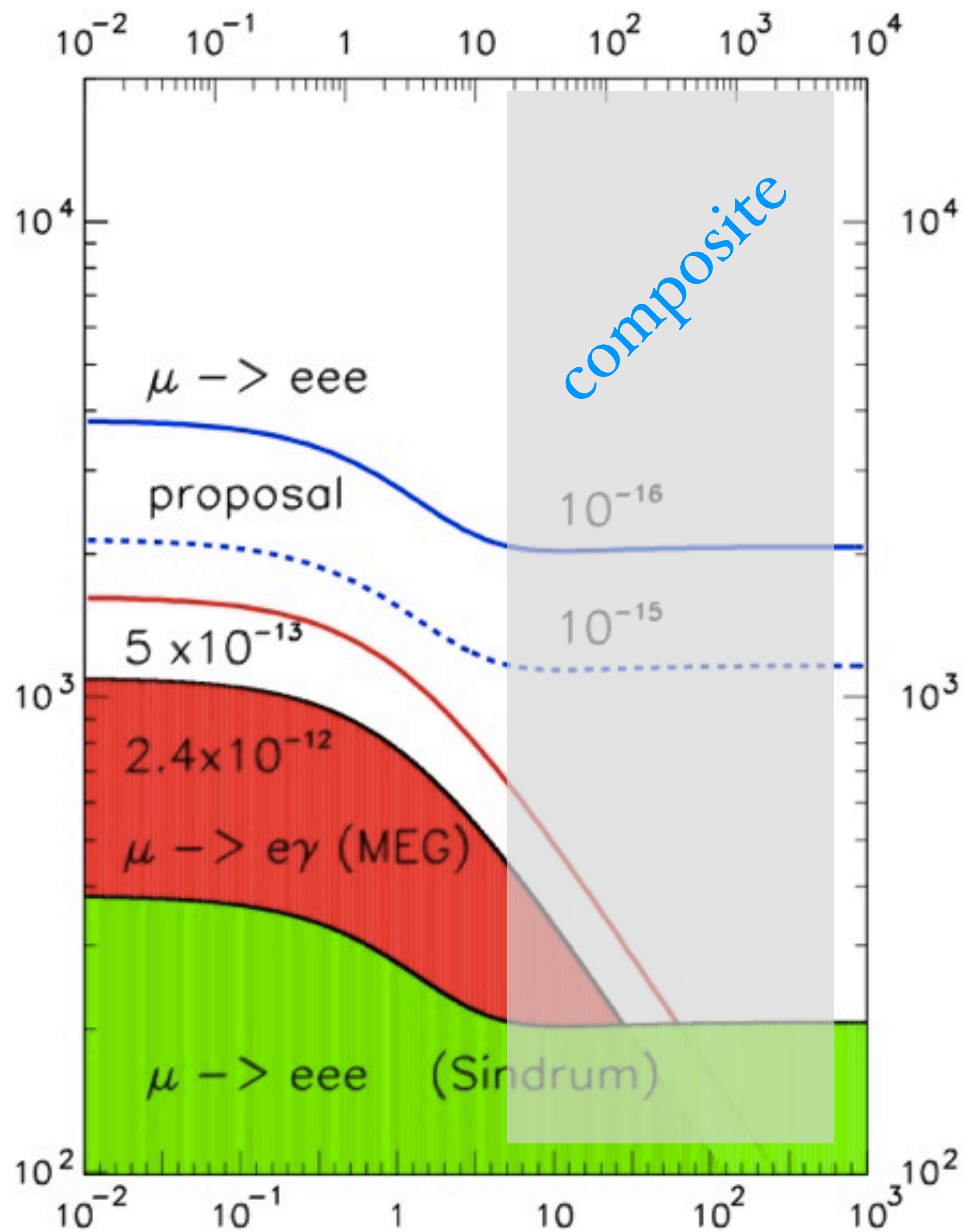
In partial compositeness

$$e^2 > 16\pi^2 \frac{\lambda_\mu}{g_\rho} \lesssim \kappa_{e,q} \lesssim 16\pi^2$$

comparable (small) compositeness in left and right sector

one of the two chiralities is fully composite

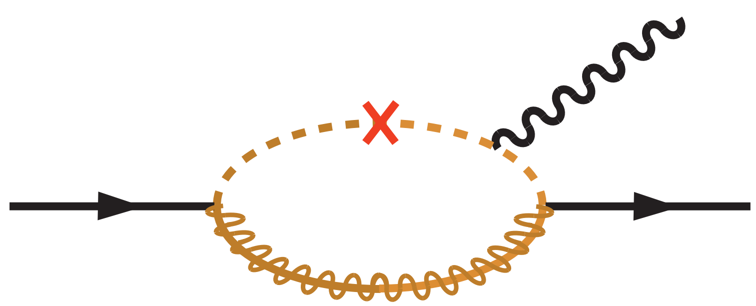
$\Lambda/\sqrt{1+\kappa_e}$



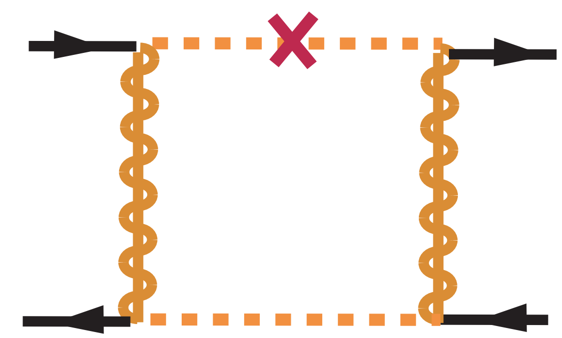
κ_e

Dipole vs boxes in Supersymmetry

$$\delta_{LL} = \frac{\tilde{m}^2_{12}}{\tilde{m}^2}, \quad \delta_{LL} = \dots$$



$$e\,\frac{\alpha_W}{4\pi}\frac{m_\mu}{\tilde{m}_L^2}\,\left[\delta_{LL}F_L + \delta_{RR}F_R + \delta_{LR}F_{LR}\right]$$



$$g_W^2\,\frac{\alpha_W}{4\pi}\frac{1}{\tilde{m}_L^2}\,\left[\delta_{LL}G_L + \delta_{RR}G_R\right]$$

$$\kappa_{e,q} \sim g_W^2\,\frac{\max(\delta_{LL},\delta_{RR})}{\max(\delta_{LL},\delta_{RR},\delta_{LR})} \lesssim g_W^2$$

4-fermion interactions are never dominating dipole term and are indeed often subleading

A taste of $\mu \to e\gamma$ in supersymmetry

LL mixing

wino-higgsino loop

$$Br(\mu \to e\gamma) \sim 10^{-13} \left(\frac{\tan\beta}{10}\right)^2 \left(\frac{0.5\ \text{TeV}}{\tilde{m}_L}\right)^4 \left(\frac{\delta_{LL}}{10^{-4}}\right)^2$$

$$\sim 10^{-14} \left(\frac{\tan\beta}{10}\right)^2 \left(\frac{100\ \text{TeV}}{\tilde{m}_L}\right)^4 (\delta_{LL})^2$$

LR or RR mixing

bino loop

$$Br(\mu \to e\gamma) \sim 10^{-13} \left(\frac{5\ \text{TeV}}{\tilde{m}_L}\right)^4 \left(\frac{\delta_{LR}}{\sqrt{m_e/m_\mu}}\right)^2$$

Flavor in 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}

Flavor universal soft mass generation

Ex: gauge mediation or friendly string vacuum

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

Λ_{Flavor}

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

Soft masses universal up to ε^i effects

Expected form of soft terms

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

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

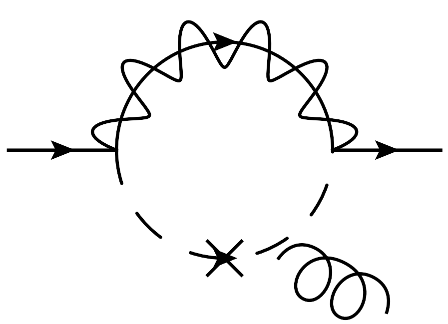
- LL and RR are approximately universal and aligned
- LR are O(1) non-universal but aligned
- Structure of $\Delta F = 1$ and $\Delta F = 2$ analogous to non-SUSY partial compositeness
- concretely realizes scenario invoked to explain a_{CP} by Giudice, Isidori, Paradisi '12

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

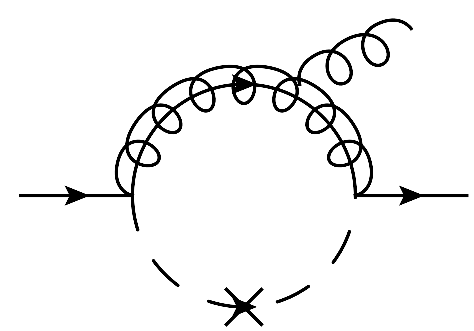
$$\begin{matrix} d_n,\, d_e \\ \text{Br}(\mu \to e\gamma) \end{matrix} \quad = \quad \text{(exp bound)} \times \left(\frac{A/\tilde{m}}{6}\right) \times \left(\frac{\text{TeV}}{\tilde{m}}\right)^2 \times O(5-10)$$

with all other Flavor observables well under control

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



$= g_Y^2 F_1$



$= g_s^2 F_2$

$\tau \to \mu\gamma$ versus $\mu \to e\gamma$

$$\mathcal{L} = \frac{1}{\Lambda^2}\left[m_\mu a_\mu \mathcal{O}^{\mu\to e\gamma} + m_\tau a_\tau \mathcal{O}^{\tau\to\mu\gamma}\right]$$

$$\frac{Br(\mu \to e\gamma)}{Br(\tau \to \mu\gamma)} = 5.6\left(\frac{a_\mu}{a_\tau}\right)^2$$

$\tau \to \mu\gamma$ can compete only for rather large a_τ/a_μ

most favorable scenario

$Br(\mu \to e\gamma) \sim 10^{-12}$

$Br(\tau \to \mu\gamma) > 10^{-9}$

$a_\tau/a_\mu \gtrsim 75$

inequality satisfied only marginally in a few cases

Ex: in partial compositness $\max(a_\tau/a_\mu) \sim 10$

Electric dipole moments vs $\mu \to e$ transitions

roughly

$$d_n \sim \phi_q \frac{A}{\tilde{m}_q} \left(\frac{2\,\mathrm{TeV}}{\tilde{m}_q} \right)^2 \times 2.9 \times 10^{-26}\, e\, cm$$

$$d_e \sim \phi_\ell \frac{A}{\tilde{m}_\ell} \left(\frac{1.5\,\mathrm{TeV}}{\tilde{m}_\ell} \right)^2 \times 1.6 \times 10^{-27}\, e\, cm$$

$$d_{n,e} \sim \frac{1}{\tilde{m}^2} \qquad\qquad Br(\mu \to e) \sim \frac{1}{\tilde{m}^4}$$

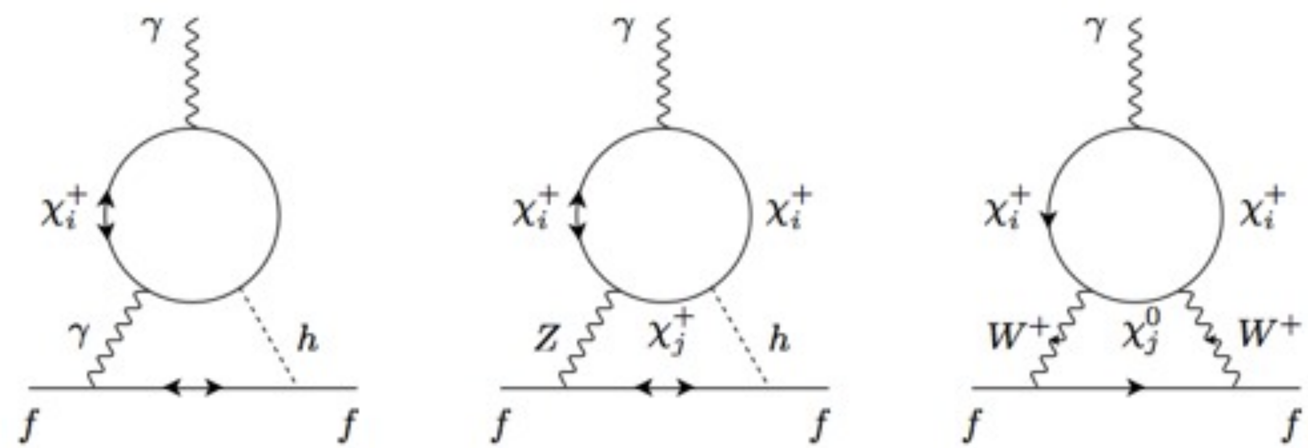
$Br(\mu\,\mathrm{Ti} \to e\,\mathrm{Ti})$		$Br(\mu \to e\gamma)$		d_n		d_e
10^{-18}	$\sim$	10^{-16}	$\sim$	$10^{-28}\, e\, cm$	$\sim$	$10^{-29}\, e\, cm$

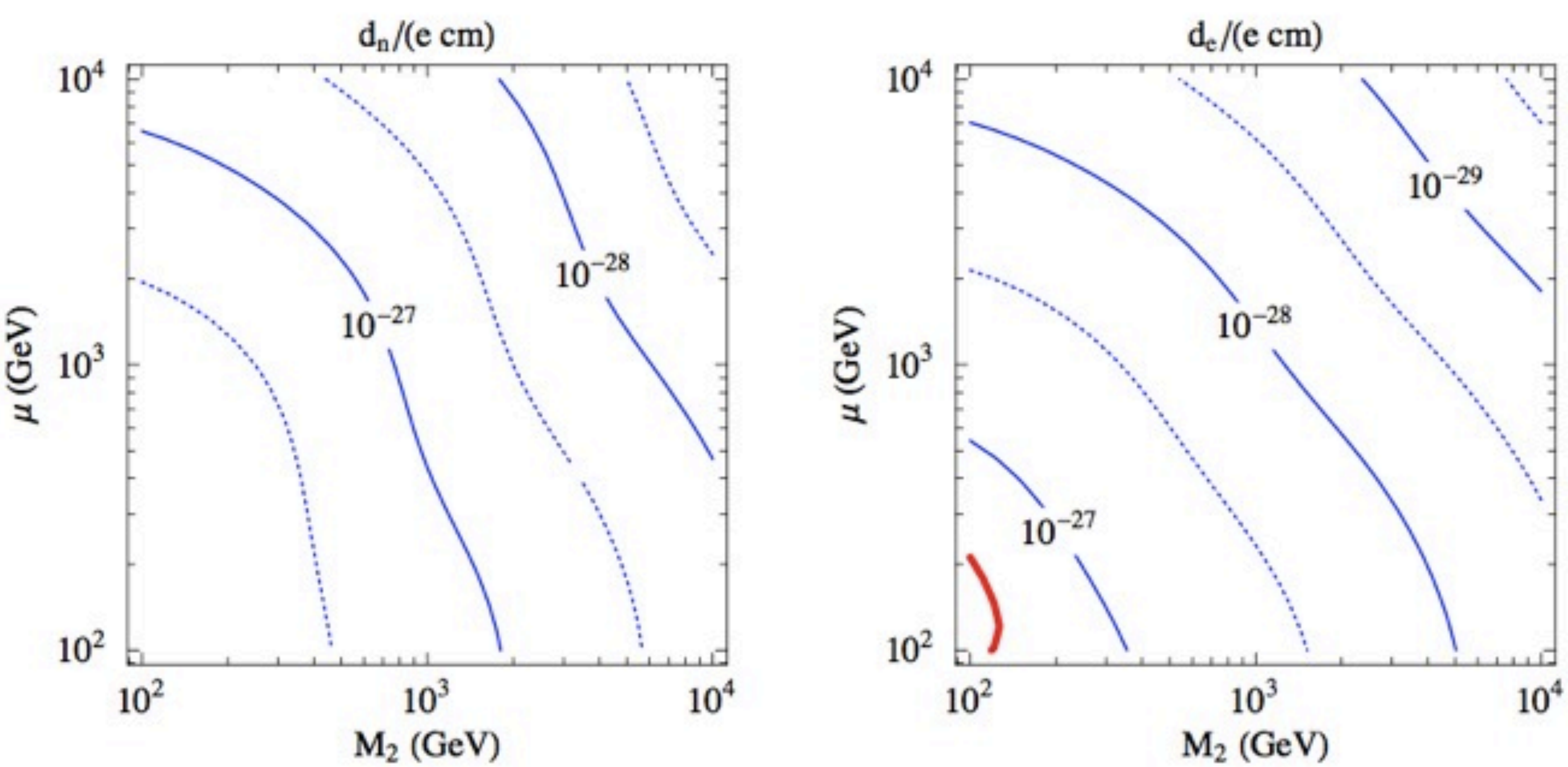
probe comparably far in mass in wide class of models

EDM in un-natural theories: split supersymmetry

Giudice, Romanino '06

squarks and sleptons
beyond the horizon
...but still
edms from 2-loops
involving charginos





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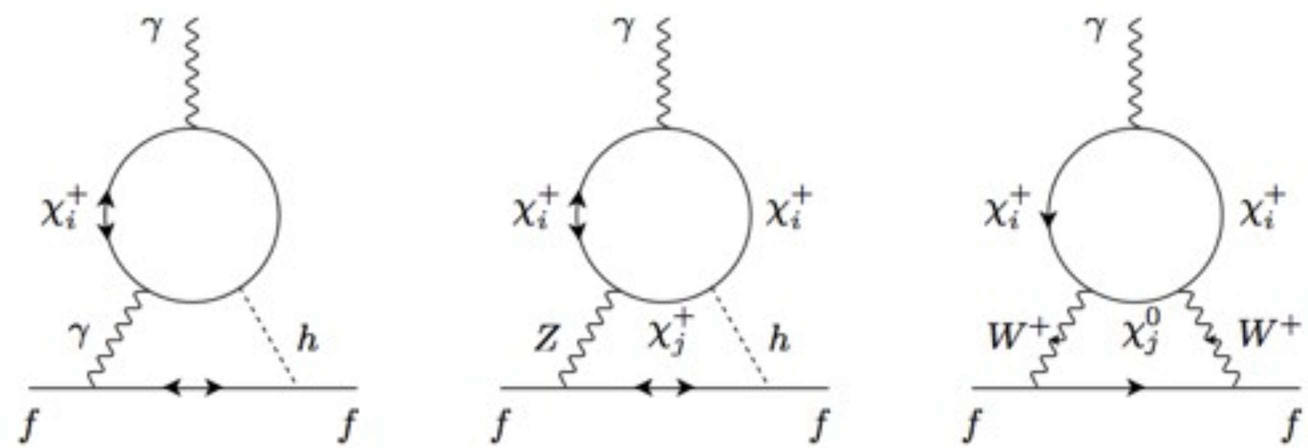
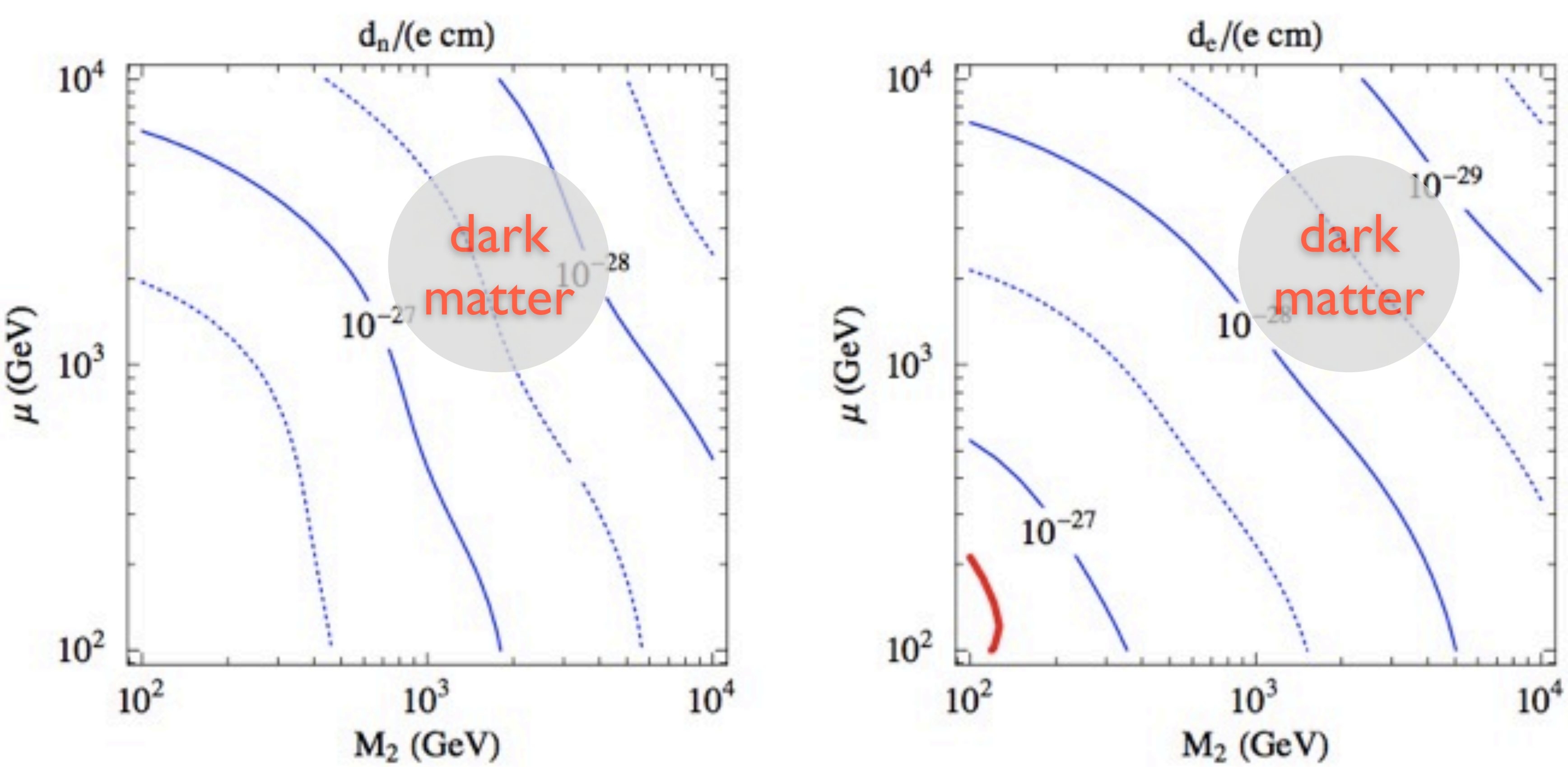
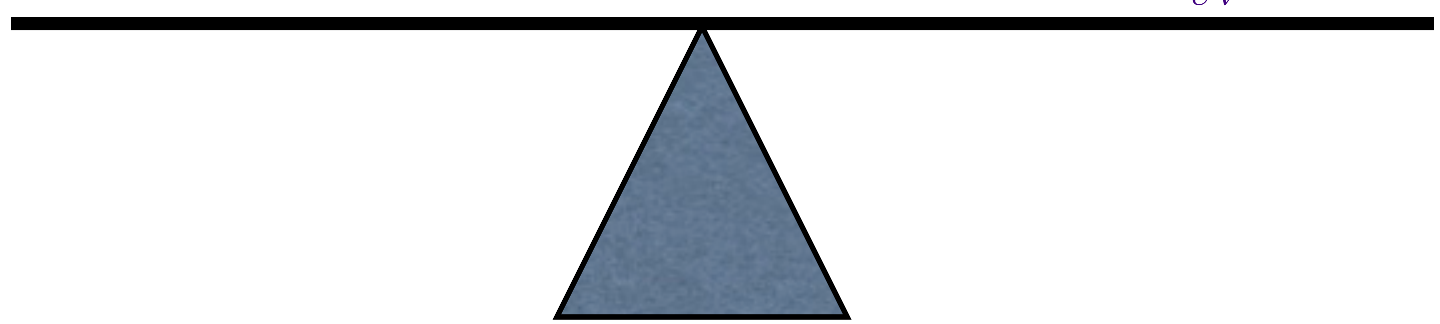


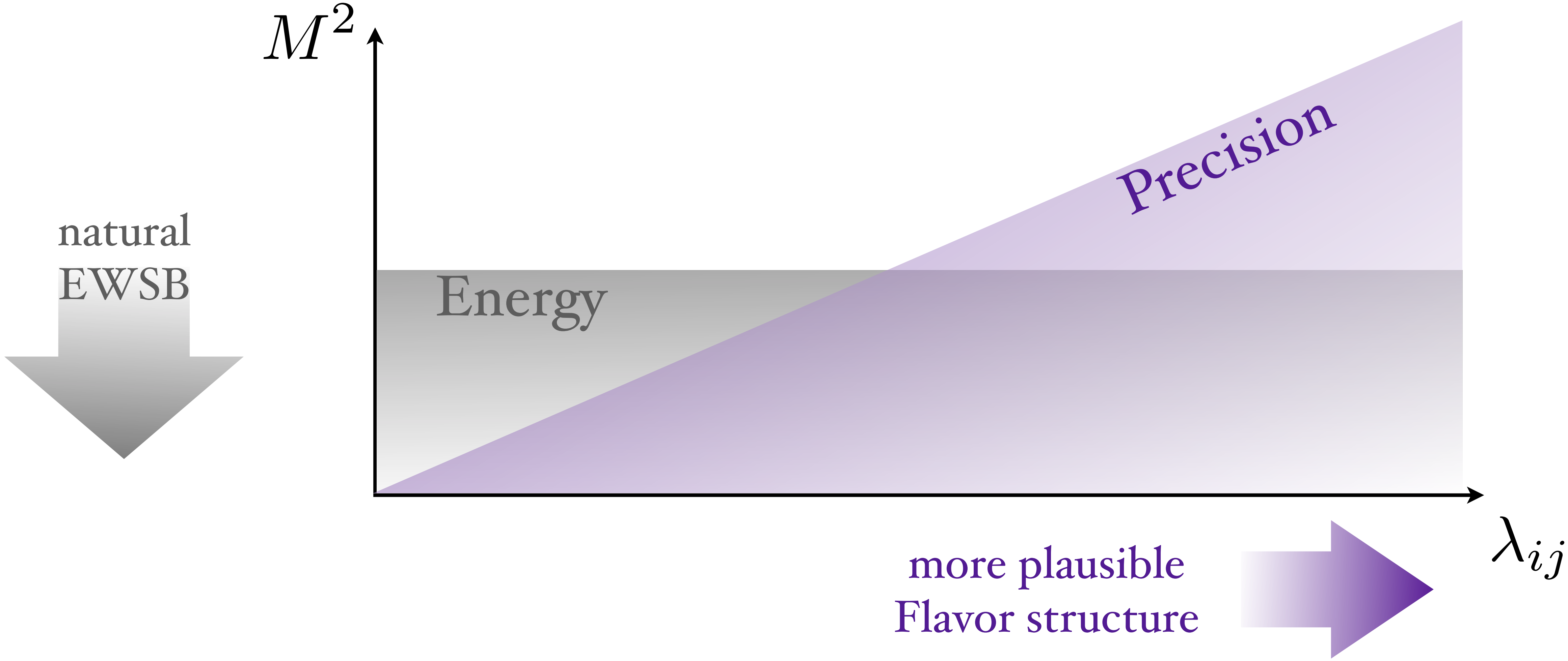


Summary

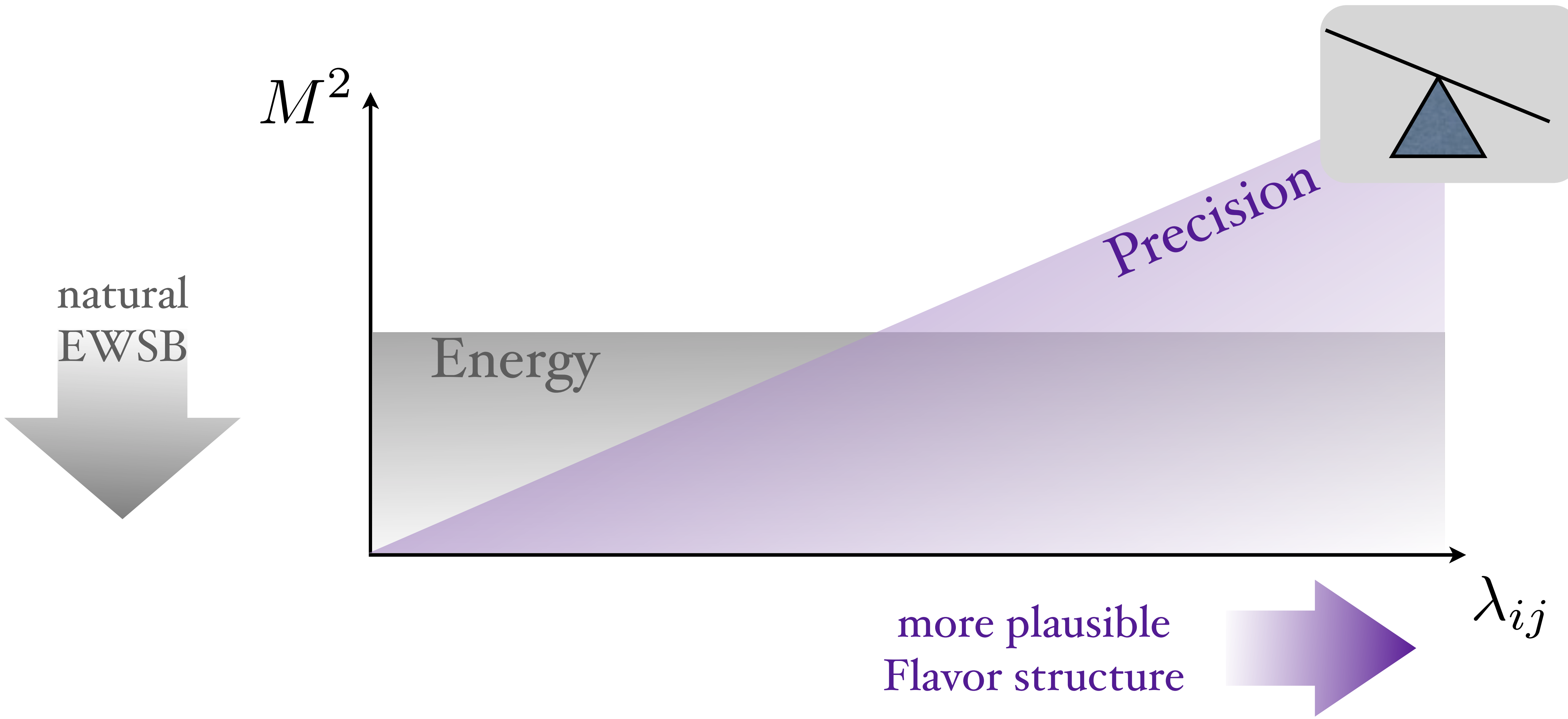
$\Lambda^2_{UV}\, H^\dagger H$ $\qquad$ $y_{ij}\, H \bar{F}_i F_j$ $\qquad$ $\frac{1}{\Lambda^2_{UV}}\, \bar{F}_i F_j \bar{F}_k F_\ell \;+\; \ldots$



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



But precision physics probes also a good portion of theory space where electroweak symmetry breaking looks fine tuned



But precision physics probes also a good portion of theory space where electroweak symmetry breaking looks fine tuned

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