Discussion. Not a Talk

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The Standard Model is a Quantum-EFT valid below a physical cut-off

$$\Lambda_{UV} \gg 1\,\text{TeV}$$

Dimensional Analysis
&
Symmetry Selection Rules

Hierarchy Paradox

Naturalness

the three troubles

$$+\,\Lambda_{UV}^4\,\sqrt{g}$$ d=0

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

$$+\,\theta\,\tilde{G}_{\mu\nu}\tilde{G}^{\mu\nu}$$ 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

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

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

$$+ \quad \ldots$$ d>4

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

The Issue of Naturalness

Reductionism:

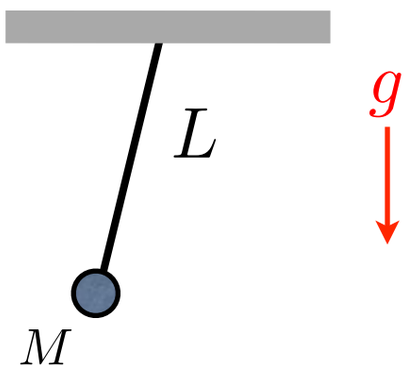
m_H^2 is a calculable quantity : $\quad m_H^2 \;=\; c\,\Lambda_{UV}^2$

In all cases, and not by chance
(Symmetries!)

$$m_H^2 \;=\; c_t\;\frac{y_t^2}{16\pi^2}\;\Lambda_{UV}^2 \;+\; \dots$$

high spin symm

dilatation symm



$$\omega \;=\; c\sqrt{\frac{g}{L}}$$

Galileo would surely have gasped had he found $\quad c = 10^{-20}$

The Issue of Simplicity

- SUSY: a myriad of new ***d ≤ 4 operators*** violating Flavor, B and L

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

- Old Composite Higgs (TC) : Yukawa themselves are ***d > 4 operators***

$$\mathcal{L}^{d>4} = Y_{ij}\,\frac{1}{\Lambda^2_F}\,(\bar{T}T)Q^i_LQ^j_R + \frac{Y_{ijkl}}{\Lambda^2_F}\bar{Q}^i_LQ^j_R\bar{Q}^k_LQ^\ell_R + \dots$$

$$m_{ij} = Y_{ij}\,\frac{v^3_F}{\Lambda^2_F}$$

seen!

FCNC

not seen!

The epicyclic Flavor of natural models

- The **more natural** the models, the **more clever** they must be in order to account for the lack of FCNC and CP violation in excess of observation

- Cleverness mostly appears in the form of ad hoc symmetries

The two Chief Systems

Simplicity

Naturalness

I. The SM is valid up to $\Lambda_{UV} \gg TeV$

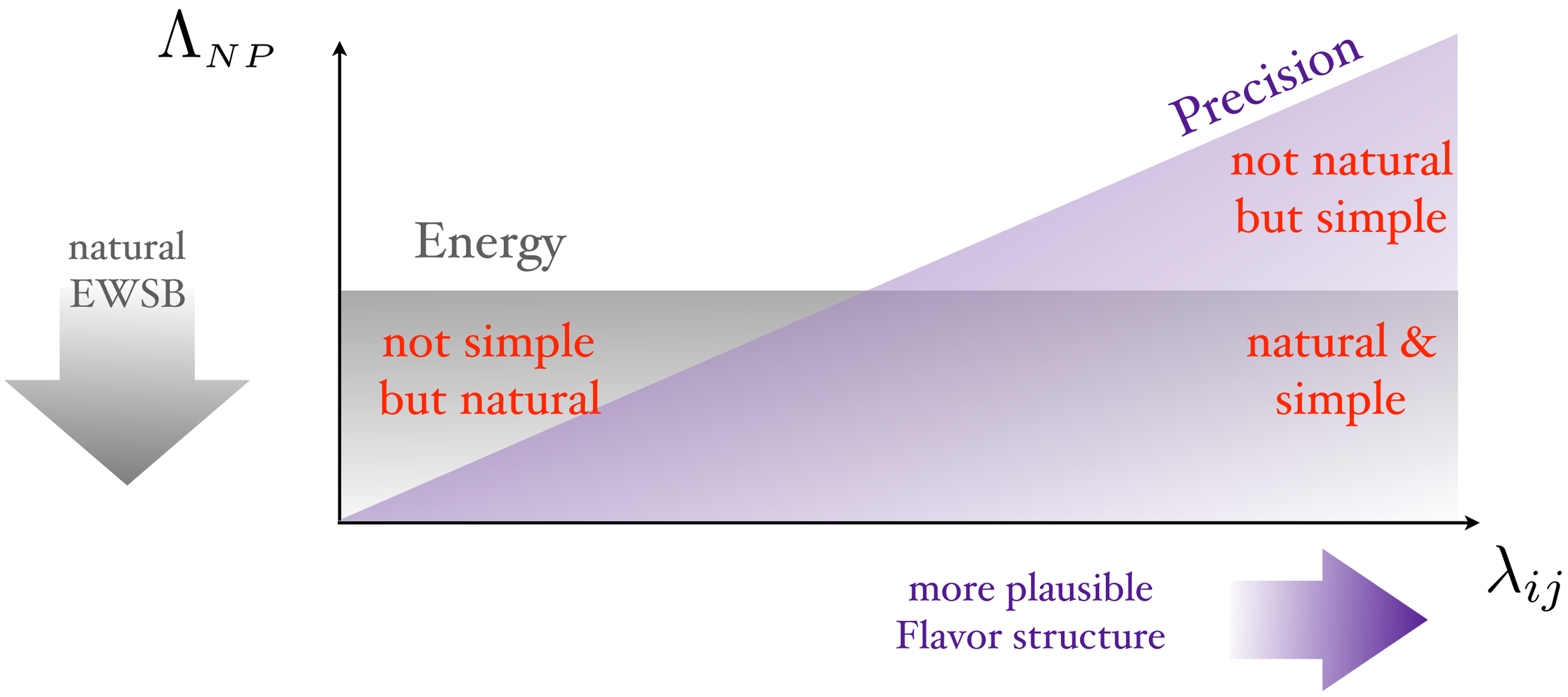
- B, L and Flavor: beautifully in accord with observation
- Higgs mass & C.C. hierarchy point beyond naturalness
  - multiverse
  - cosmological relaxation, Nnaturalness
  - failure of EFT ideology (UV/IR connection)

II. Naturalizing New Physics appears at $\Lambda_{UV} \sim 1\,\mathrm{TeV}$

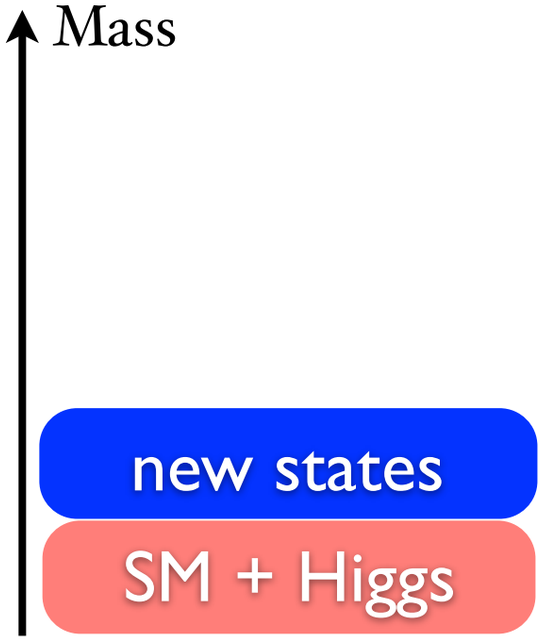
- Constraints on B, L, Flavor & CP met by clever model building

Complementarity of Energy and Precision

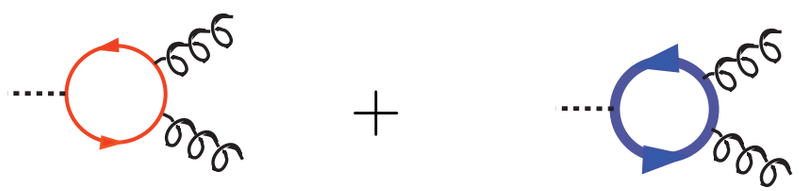
$$\mathcal{L}_{eff} = \frac{y_{ijk\ell}}{\Lambda_{NP}^2}\,\bar{q}_i q_j \bar{q}_k q_\ell + m_i \frac{y_{ij}}{\Lambda_{NP}^2}\,\bar{q}_i \sigma_{\mu\nu} q_j F^{\mu\nu} + \ldots$$

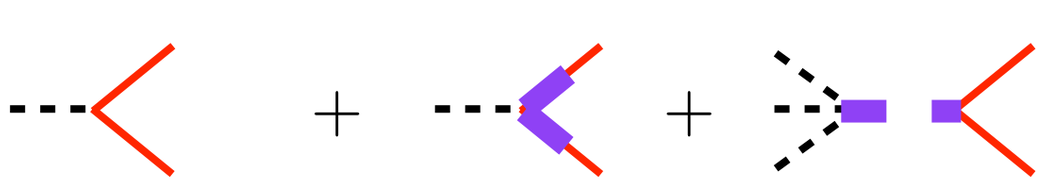


Higgs couplings and naturalness



$$\delta m_H^2 \quad = \quad \text{SM} \quad + \quad \text{New} \quad \sim \; 0$$





Higgs couplings effects measure Naturalness $\dfrac{\delta g_h}{g_h} \sim \epsilon_T \equiv$ fine tuning

'Fine tuning theorems'

- Higgs Couplings $\qquad \dfrac{\delta g_h}{g_h} \sim \epsilon_T \equiv \text{fine tuning}$

- Search for Naturalizing New Physics: top partners

$$\epsilon_T \sim \left(\frac{m_h}{m_{NP}}\right)^2 \div \left(\frac{500\,\text{GeV}}{m_{NP}}\right)^2$$

- EWPT $\qquad \delta\mathcal{O}_{EW} \gtrsim 10^{-2\div 3} \times \epsilon_T \qquad\qquad \delta\rho \sim 10^{-2}\left(\frac{m_t}{m_{NP}}\right)^2$

10^{-5} precision corresponds to a tuning of $10^{-2\div 3}$

Problems vs Mysteries

- Dark Matter
- Baryogenesis
- Strong CP
- Fermion mass spectrum & mixing

- Cosmological Constant
- EW hierarchy
- Black Hole information paradox
- very Early Universe

Plausible EFT-solutions exist

Challenge EFT paradigm

- Experimental priorities set by other crucial element: feasibility
- How to decide?
- Which experiments have a better chance to address multiple questions?
- Which ones have a chance to surprise us?
- Which are going to be valuable even for negative results? (ex Michelson-Morley with aether, LEP/Tevatron/LHC with *strict* naturalness)

The next three slides are meant to illustrate some structurally motivated mesotuned scenarios

Λ_{NP}

10^{10} TeV

High Scale SM: super simple & super un-natural

Middle Options? just simple and un-natural

maybe forced on us by

- Dark Matter
- Baryon density

TeV

TeV Scale New Physics: not simple & not un-natural

See also talk by R. Sundrum HEFT 2016

Ex.: Mesotuned Composite Higgs

Suppose the only option for DM is a strongly coupled composite

$$\Omega_{DM} \propto \frac{1}{\sigma} \propto \frac{\Lambda_{Comp}^2}{g_{Comp}^4}, \quad \longrightarrow \text{heavy}, \quad \longrightarrow \text{large}$$

$$g_c \sim (5 \div 10)\, g_W \quad \Longrightarrow \quad \Lambda_{Comp} \sim 50 \div 200 \text{ TeV}$$

- ✦ Tuning is O(10^{-5})
- ✦ Not necessarily any visible signal at SppC & FCC
- ✦ Flavor and CP effects largely eliminated & on the verge of discovery

Ex.: Mini-Split Supersymmetry (arguably the simplest SUGRA scenario)

Arkani-Hamed, Dimopoulos '04

$10^2 \div 10^3$ TeV —— $m_{scalars} \sim m_{3/2}$

higgsino

$1 \div 10$ TeV —— $m_{gauginos} \sim \frac{\alpha}{4\pi} m_{3/2}$

- ✦ One combination of fermions could be DM
- ✦ For heavy $\tilde{h}$, bino could parent baryogenesis via RPV
- ✦ Flavor, CP and B could be at the edge of discovery
- ✦ gauginos within reach, even at LHC in principle

Cui, Sundrum '12
Cui '13
Rompineve '13