What and Why

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What would we learn?

What could we discover?

Problems vs Mysteries

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

Plausible EFT solutions exist

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

Challenge or outside EFT paradigm

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Challenge or outside EFT paradigm

Simplicity vs Naturalness: The Hierarchy Paradox

SM is EFT valid below physical cut-off Λ_{UV}

$$\mathcal{L}_{SM} = \mathcal{L}^{d\leq 4} + \frac{1}{\Lambda_{UV}}\mathcal{L}^{d=5} + \frac{1}{\Lambda_{UV}^2}\mathcal{L}^{d=6} + \dots$$

Observations speak for Simplicity: $\Lambda_{UV} \gg m_{weak}$

- $\mathcal{L}_{SM} \to \mathcal{L}^{d\leq 4}$ B, L, "GIM suppression", custodial symm, ...
- $m_\nu \ll m_{weak}$ beautifully explained

Theory expects Naturalness: $\delta m_h^2 \sim \frac{y_t^2}{4\pi^2}\Lambda_{UV}^2 + \dots$ ⇒ $\Lambda_{UV} \lesssim 500\,\mathrm{GeV}$

Clash between Simplicity and Naturalness

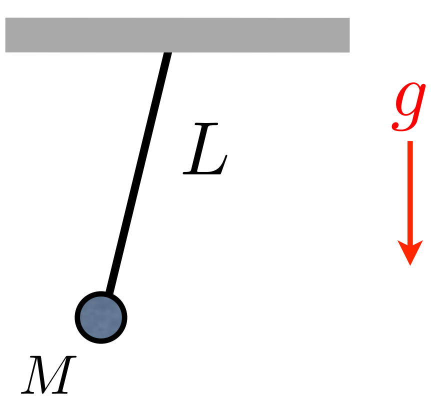
Made concrete by all available Natural models (SUSY, Comp Higgs,...)

$$m_h^2 = c\,\frac{y_t^2}{4\pi^2}\Lambda_{UV}^2 + \dots$$

high spin symm

dilatation symm

As good as dimensional analys in mechanics



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

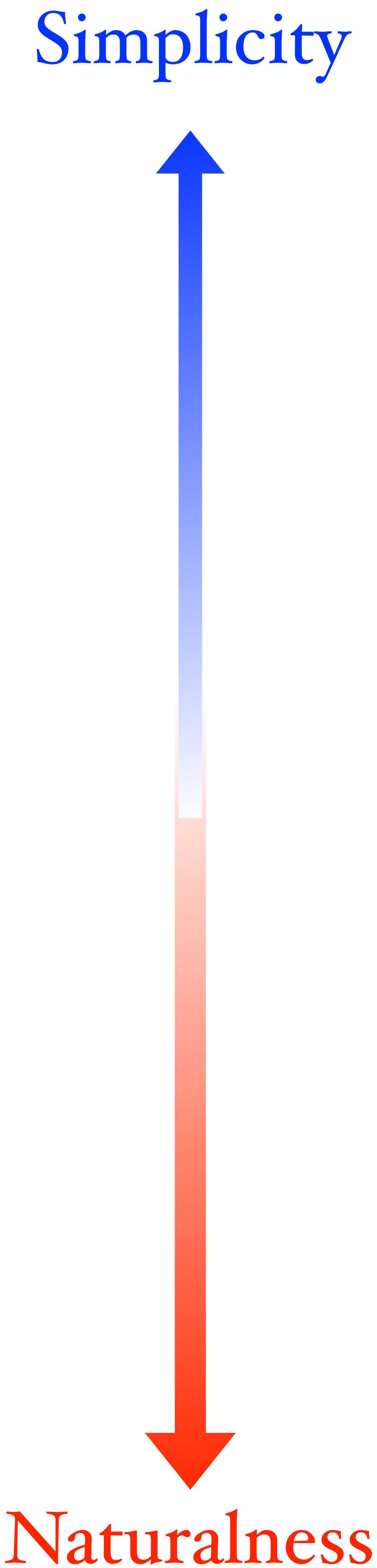
The two Chief Systems

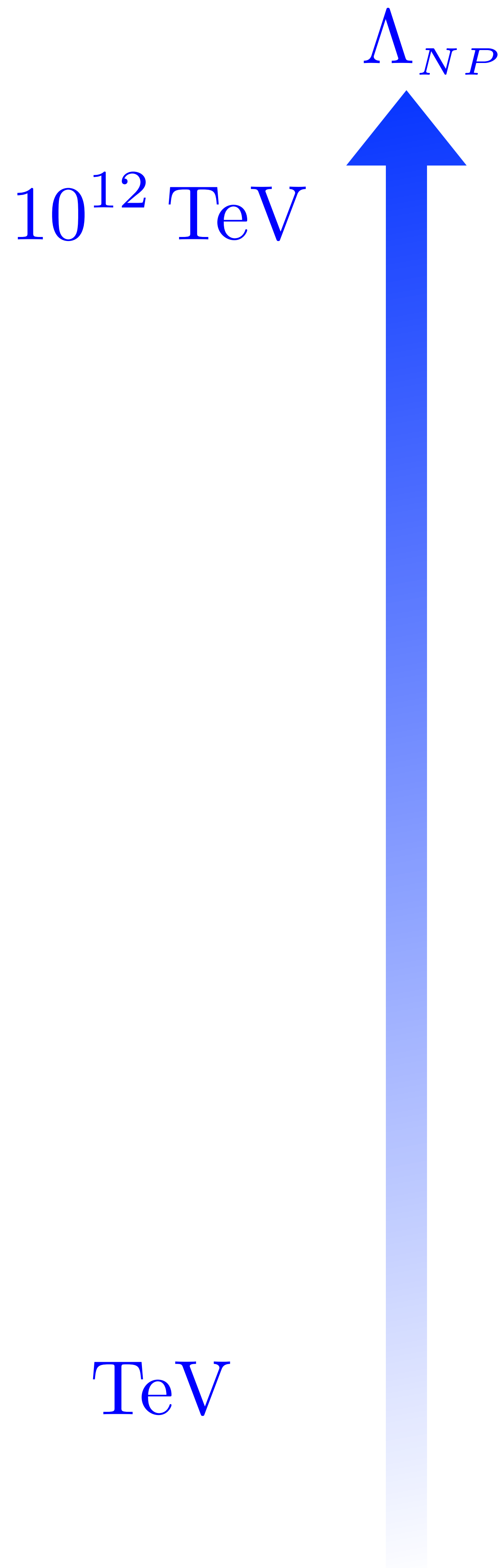
I. The SM is valid up to $\Lambda_{UV} \gg TeV$

- 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

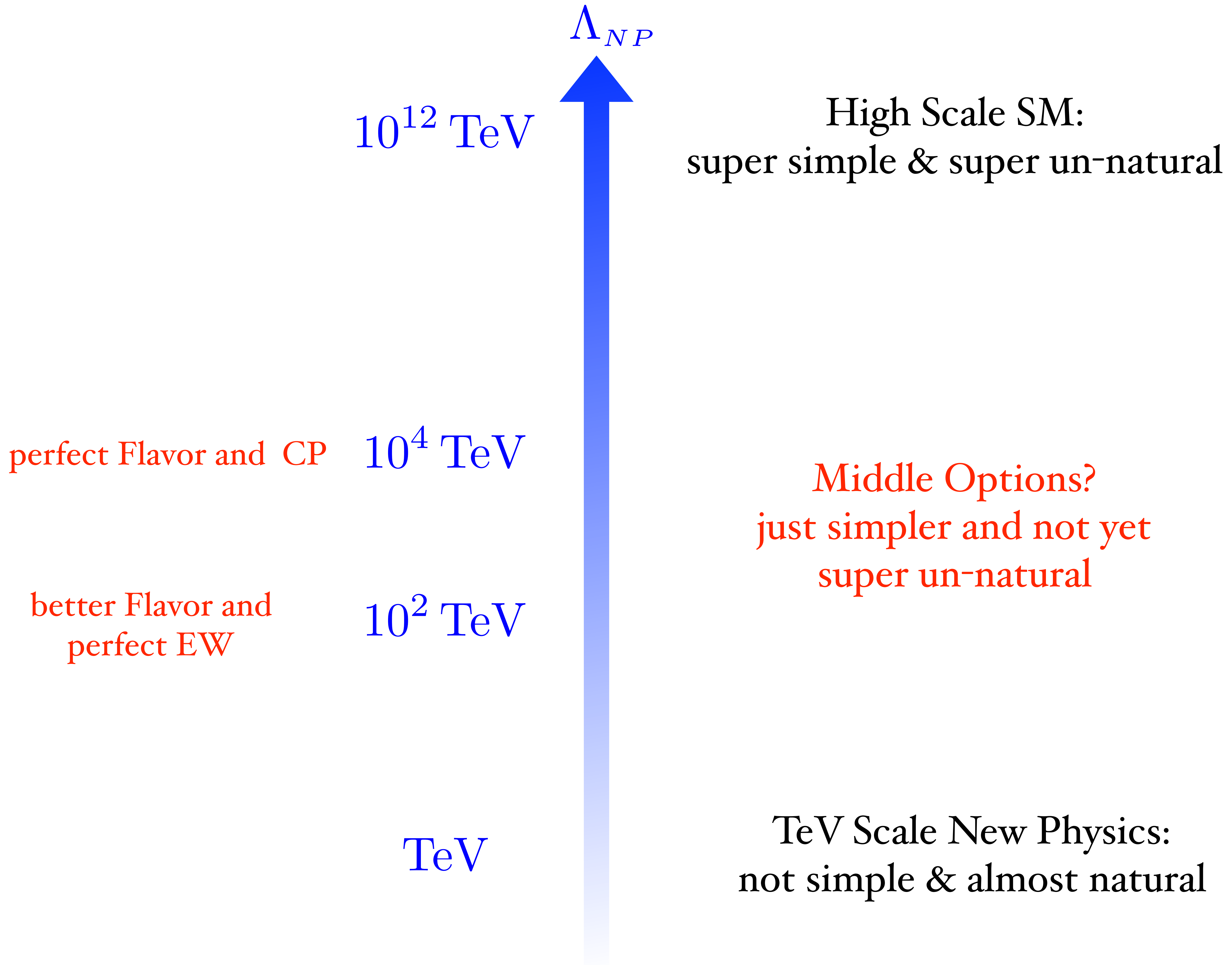




High Scale SM:
super simple & super un-natural

TeV Scale New Physics:
not simple & almost natural

See also talk by R. Sundrum HEFT 2016



See also talk by R. Sundrum HEFT 2016

Hierarchy Paradox → ***unavoidable*** and ***global*** perspective on energy frontier exploration

In any model with calculable m_h:

$$m_h^2 = \sum_i \Delta m_i^2$$

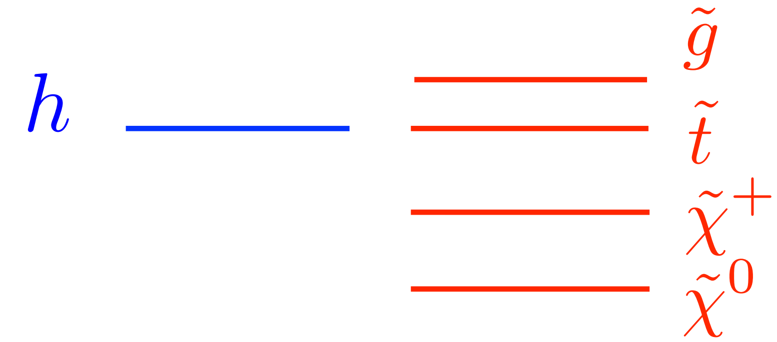
fine tuning $$\epsilon \equiv \frac{m_h^2|_{exp}}{\Delta m_h^2|_{max}}$$

offers a measure of where Nature stands in the negotiation between Simplicity and Naturalness

- direct searches
- Higgs couplings
- EWPT

▲ ***Soft Models*** (SUSY with high scale mediation)

$$\Delta m_h^2 \sim \frac{3y_t^2}{4\pi^2} \times m_{\tilde{t}}^2 \times \ln(\Lambda_S/m_{\tilde{t}}) \xrightarrow{\Lambda_S \gtrsim 10\,\text{TeV}} m_{\tilde{t}}^2$$

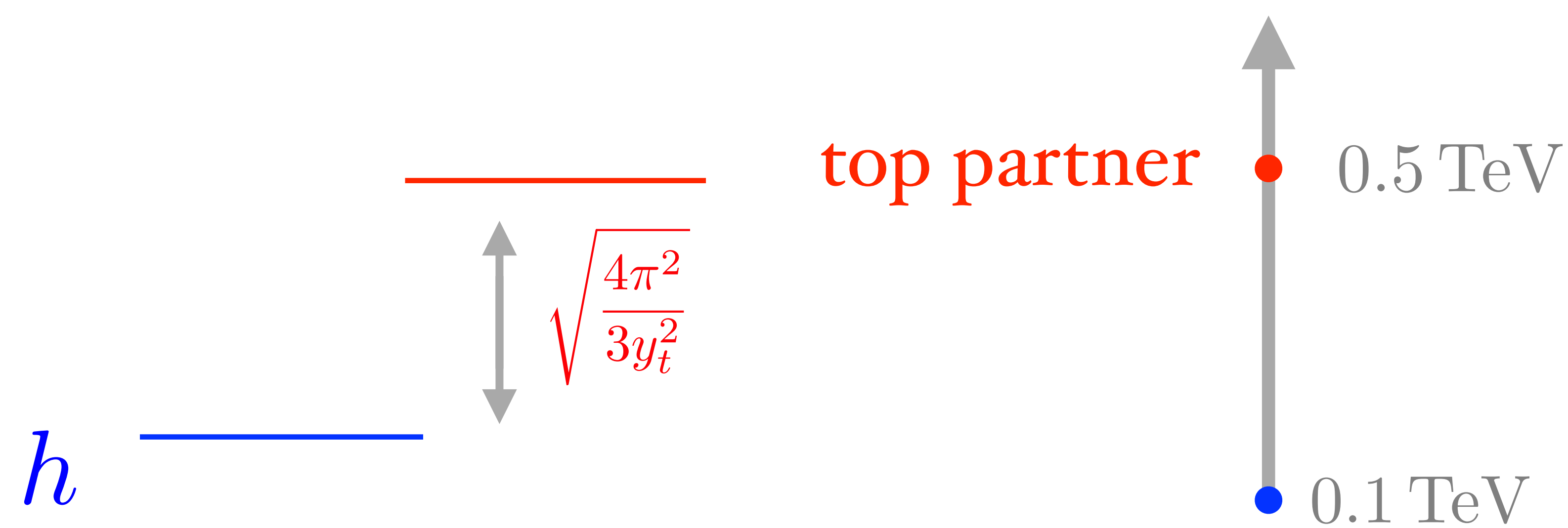


Natural range: LEP/Tevatron

LHC: $\epsilon \lesssim 10^{-2}$ $m_{\tilde{t}} \gtrsim 1$ TeV

▲ ***SuperSoft Models*** (SUSY with low scale mediation & Composite Higgs)

$$\Delta m_h^2 \sim \frac{3y_t^2}{4\pi^2} \times m_T^2$$

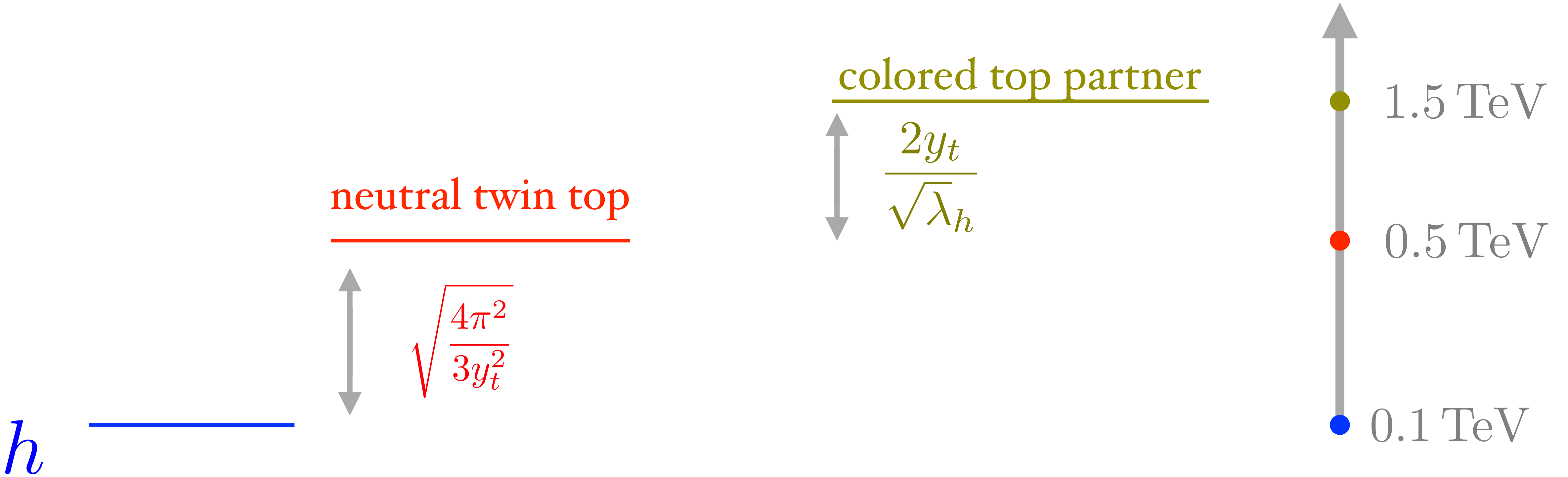


LHC just got into the relevant grounds: $\epsilon \lesssim 10^{-1}$

▲ ***HyperSoft Models*** (Twin Higgs & Folded SUSY)

Chacko, Goh, Harnik 2005
+ Burdman 2006

$$\Delta m_h^2 \sim \frac{3\lambda_h}{16\pi^2} \times m_T^2$$

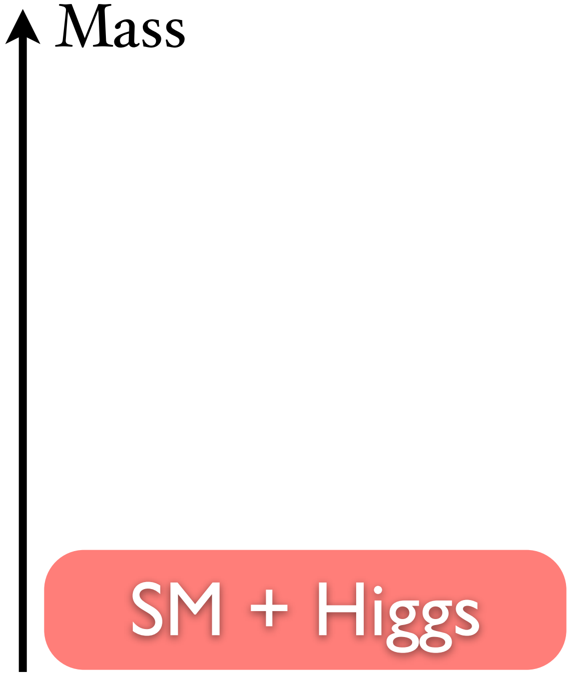


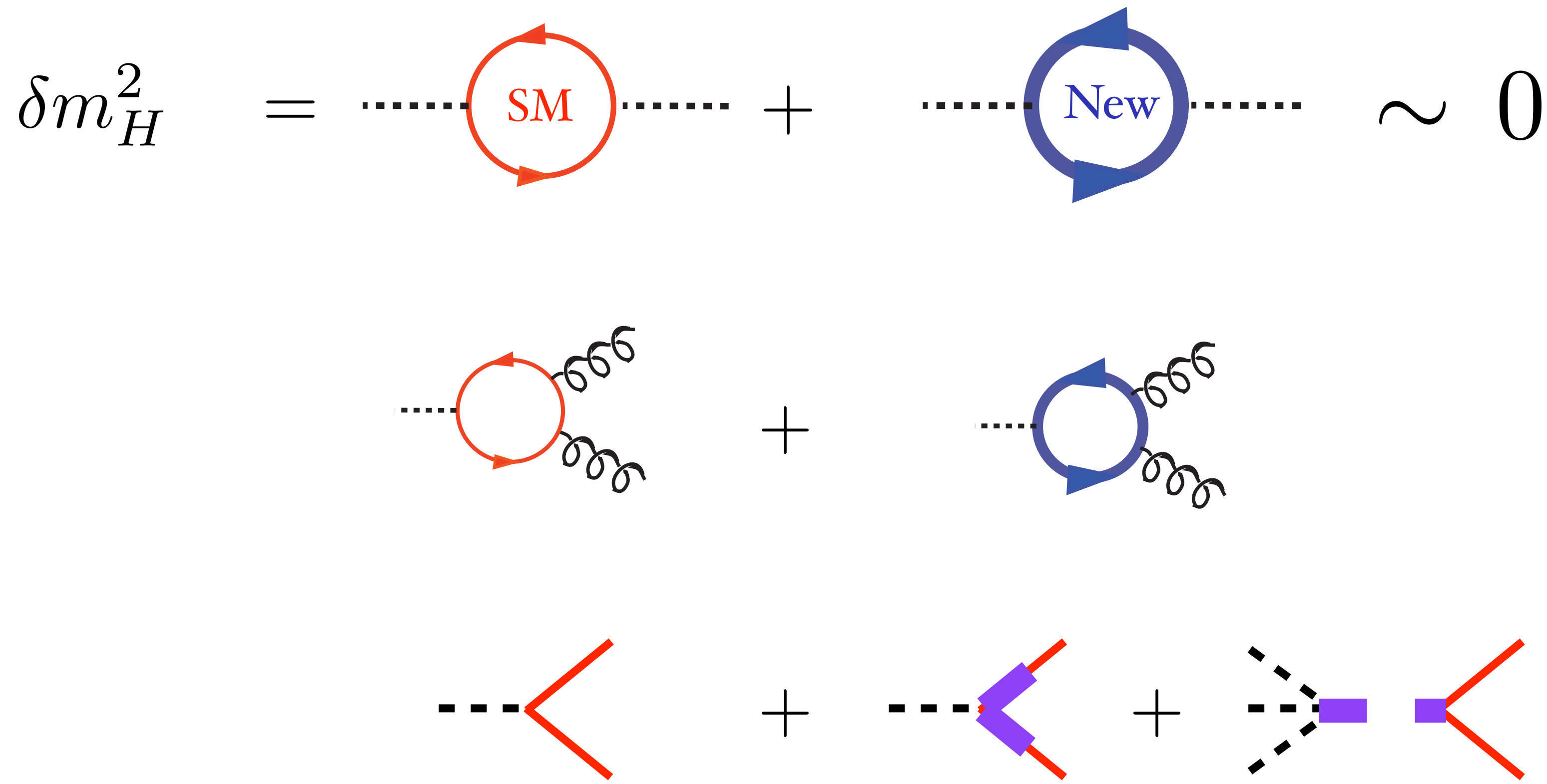
- colored top partners out of LHC reach
- still tuning required by Higgs coupling data

FCChh

Soft	$\epsilon \lesssim 10^{-4}$	
SuperSoft	$\epsilon \lesssim 10^{-3}$	$m_T \gtrsim 10 \text{ TeV}$
HyperSoft	$\epsilon \lesssim 10^{-2}$	

Higgs couplings and naturalness

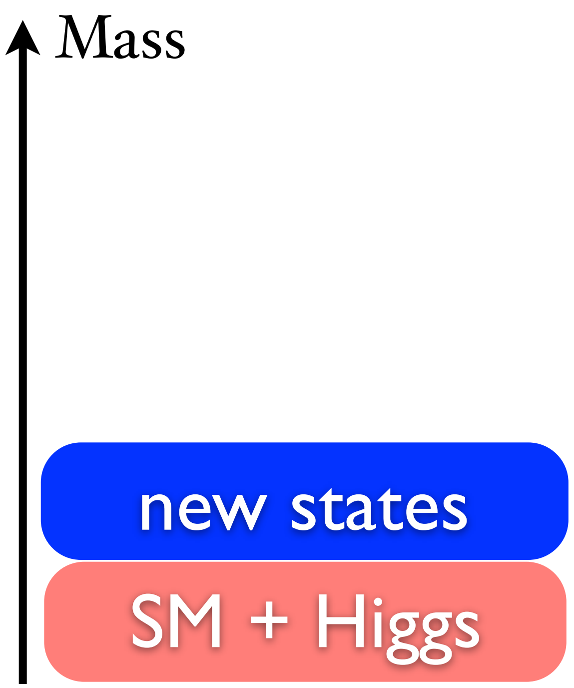


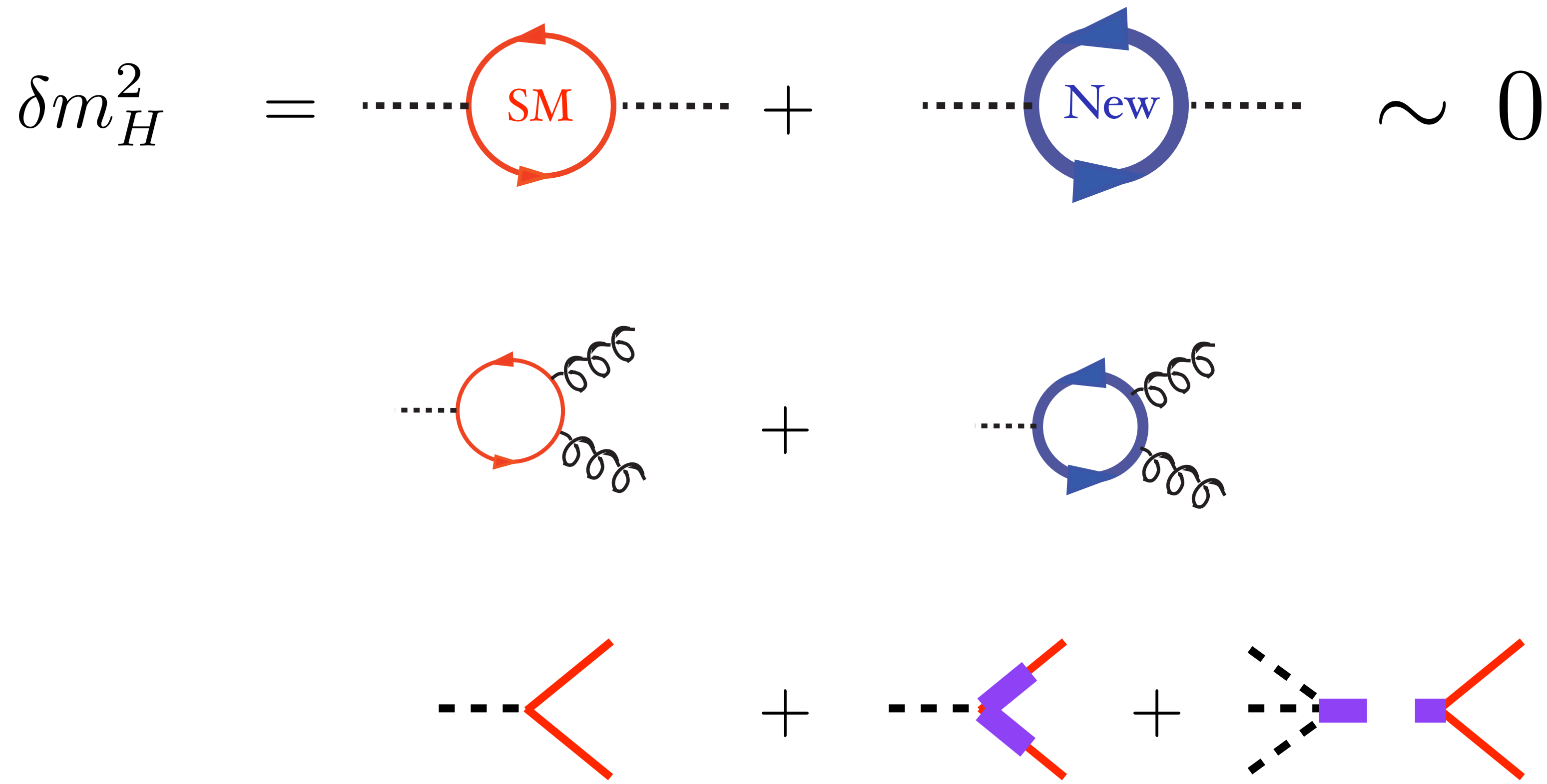


Higgs coupling deviations measure Naturalness

$$\frac{\delta g_h}{g_h} \sim \frac{m_h^2}{\Delta m_h^2} \equiv \epsilon \equiv \text{fine tuning}$$

Higgs couplings and naturalness





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ILC, CEPC, CLIC, FCC

1-**σ** sensitivity: $\epsilon = 1 \div 2 \times 10^{-3}$ dominated by g_{hZZ}

Comparison with direct searches

- Soft : not competitive
- SuperSoft : comparable, but 5-**σ** slightly weaker
- HyperSoft : stronger

Electroweak Precision quantities

$$\hat{S} \sim \frac{\alpha_w}{8\pi} \times \frac{g_*^2 v^2}{m_*^2} \times N \lesssim \frac{m_W^2}{m_*^2}$$

In all cases $\quad \hat{S} \sim 10^{-2\div 3} \times \epsilon$

- few $\times\ 10^{-2} \times \epsilon$ Comp Higgs
- few $\times\ 10^{-3} \times \epsilon$ SUSY

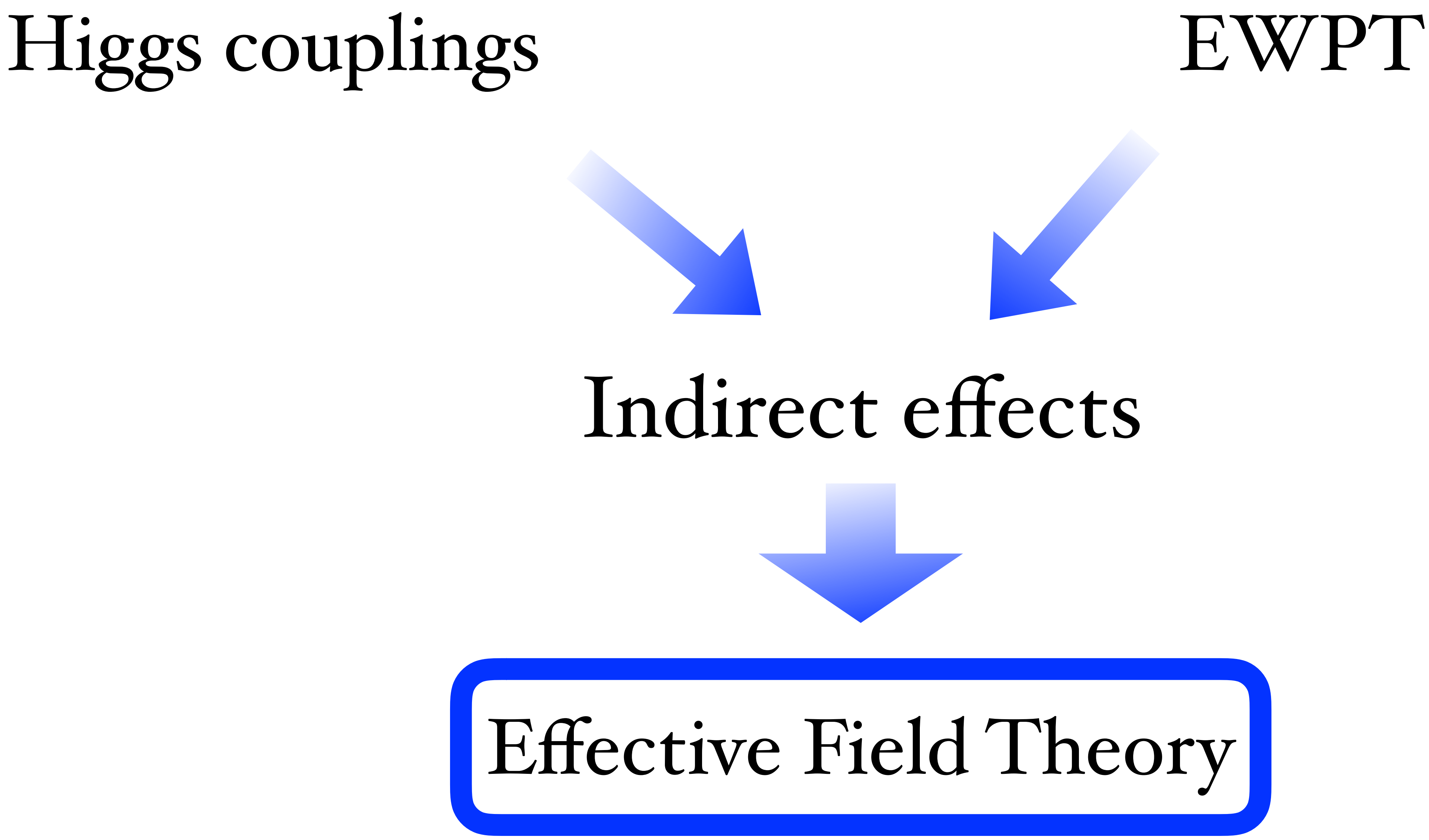
$$\frac{\hat{S}}{m_W^2} i \left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H \right) (D^\nu W_{\mu\nu})^a$$

→ need high energy/huge precision

- dibosons at CLIC $< 1 \times 10^{-5}$
- EWPT at FCCee, dibosons at Fcchh $< 2.5 \times 10^{-5}$

Comp Higgs

$$\epsilon \lesssim \frac{1}{\text{few}} \times 10^{-3}$$



Beware of general analyses

Know your own assumptions!

The two EFT classes

Chang, Luty, '19
Falkowski, RR, '19

▲ Mass Λ of new states indipendent of v_F ➡ SMEFT

$\mathcal{L}_{SMEFT} \equiv$ polynomial in SM fields

effects decouple like Λ^{-p}

▲ $\Lambda \propto v_F$ ➡ HEFT

$\mathcal{L}_{HEFT} \equiv$ non-polynomial in Higgs doublet

$\frac{\delta g_h}{g_h} = O(1)$ by now very implausible

$$\mathcal{L} = \mathcal{L}^{d\leq 4} + \frac{1}{\Lambda}\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\mathcal{L}^{d=6} + \dots$$

- tremendous un-Simplicity (Ex. 2499 operators at d=6)
- reduced in motivated models because of necessary symmetry structure (B,L, Flavor, CP) and because of peculiar dynamics
- is the truncation to a most general $\mathcal{L}^{d=6}$ valuable? I fear not...
- as long as $\Lambda \lesssim 10\,\mathrm{TeV}$, more likely that some term of dim 8 beats some terms of dim 6 in importance
- with a lot of of good data it may not hurt to be slightly redundant, but beware not to get lost in parameter space...

The oft-mistreated kappa-framework

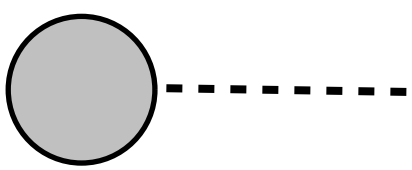
THOU SHALL ONLY USE IT TO DESCRIBE SINGLE HIGGS PRODUCTION AND DECAY AROUND THRESHOLD

- faithfully captures leading effects in SUSY, CH and various portal scenarios
- beyond that (high energy, hh,..) need assumptions: EFT

EFT illustration: legs and derivatives in CH

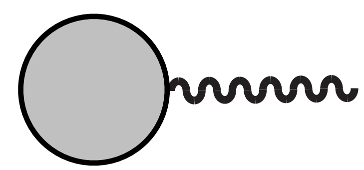
$$m_W = g_W v \qquad\qquad m_* = g_* f \qquad g_* \lesssim 4\pi$$

H-leg



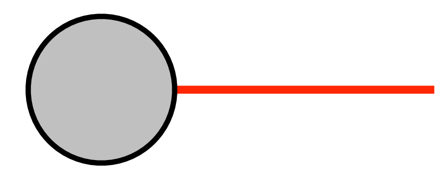
$$\frac{g_*}{m_*}$$

V-leg

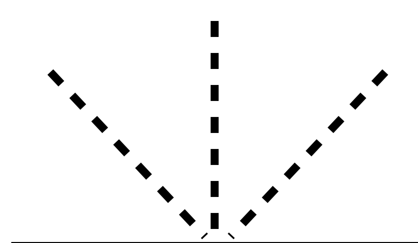


$$\frac{g}{m_*}$$

derivative

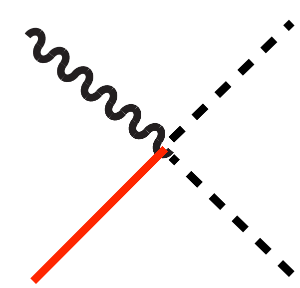


$$\frac{1}{m_*}$$



$$y_f \frac{g_*^2}{m_*^2} (\bar{f} H f)\, H^\dagger H$$

sensitivity on m_* enhanced
at strong coupling



$$\frac{g}{m_*^2} i \left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H \right) (D^\nu W_{\mu\nu})^a$$

for $g_* > g$ need either
more precision or more energy

▲ Higgs legs $\frac{g_*^2|H|^2}{m_*^2}\left\{c_H\frac{(\partial|H|^2)^2}{|H|^2}+c_f Y_f^{ij}\bar{f}_i H f_j + c_6\lambda_h|H|^4 + c_g\frac{G_{\mu\nu}^2}{(4\pi)^2}+c_\gamma\frac{B_{\mu\nu}^2}{(4\pi)^2}\right\}$

$$\frac{\delta g_h}{g_h}\sim\frac{g_*^2 v^2}{m_*^2}\equiv\frac{v^2}{f^2}\sim\epsilon \qquad \epsilon\lesssim 10^{-3}$$

at a Higgs factory

▲ Derivatives and vectors $\frac{i}{m_*^2}\left\{c_W g\left(H^\dagger\sigma^a\overleftrightarrow{D^\mu}H\right)(D^\nu W_{\mu\nu})^a + c_B g'\left(H^\dagger\overleftrightarrow{D^\mu}H\right)(D^\nu B_{\mu\nu})\right\}$

$$\hat{S}\sim\frac{g^2v^2}{m_*^2}\equiv\frac{g^2}{g_*^2}\frac{v^2}{f^2}$$

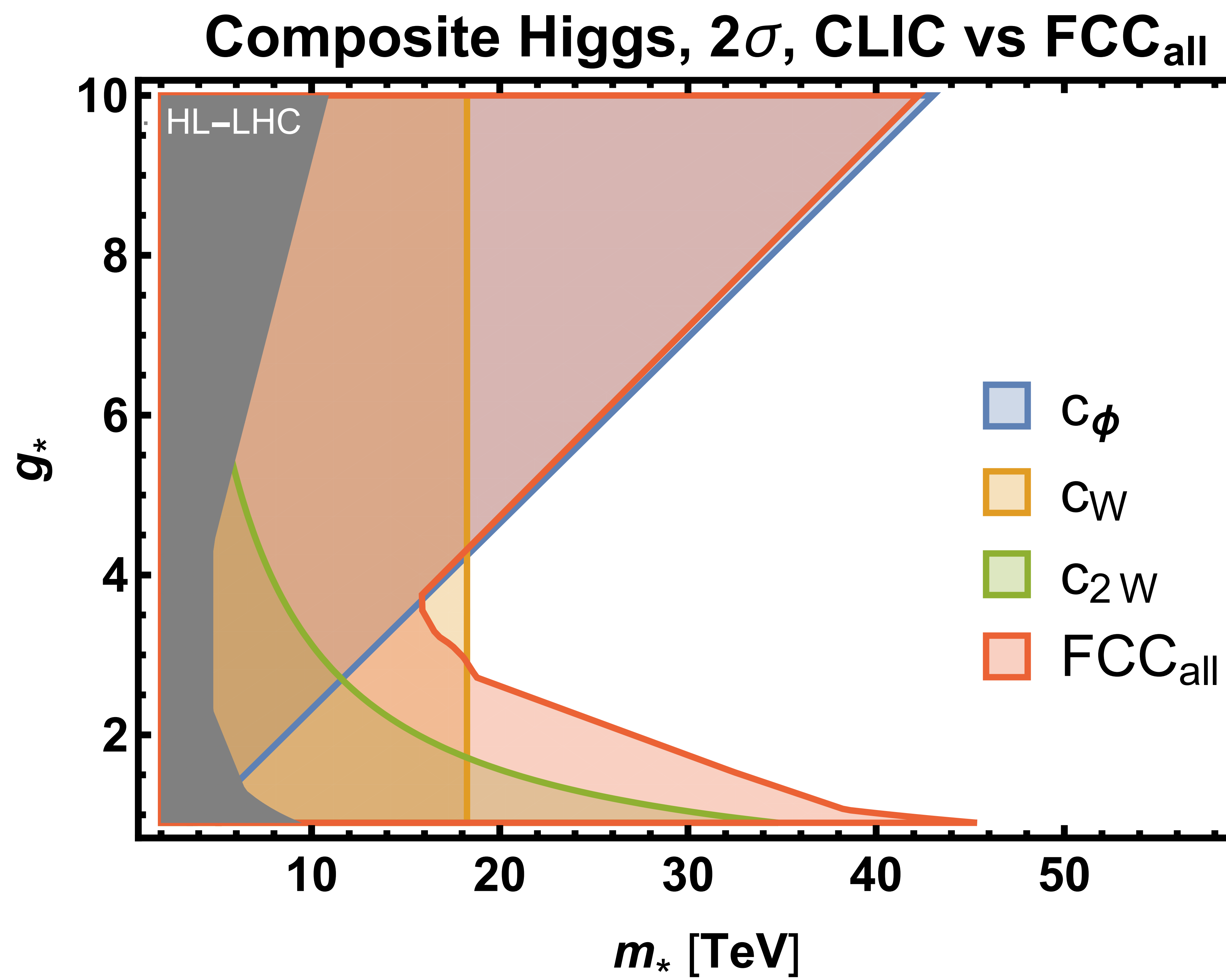
$\lesssim 10^{-5}$ CLIC

$\lesssim 2.5\times 10^{-5}$ FCC

$$\epsilon\lesssim 0.5\times 10^{-3}\times\left(\frac{g_*}{4}\right)^2$$

A Composite Higgs?

Results: FCC-hh vs CLIC



The irresistible fascination for the Higgs trilinear

▲ In the simplest motivated models of EWSB λ_3 is unspecial:

$$\frac{\delta\lambda_3}{\lambda_3} \sim \epsilon \qquad \text{not competitive}$$

▲ Accidentally Light Higgs: both quartic and VEV are tuned small

Falkowski, RR, '19

$$V(H) = -m_H^2|H|^2 + \lambda_h|H|^4 + a_6\frac{g_*^4}{m_*^2}|H|^6 + a_8\frac{g_*^6}{m_*^4}|H|^8 + \dots$$

$$m_H \ll m_*^2$$

$$\lambda_h \ll g_*^2$$

remarkably: $\dfrac{\delta\lambda_3}{\lambda_3} \sim 2 \div 3$ for $\left[\begin{array}{l} g_* \ \text{strong} \\ m_* \lesssim 5\,\text{TeV} \end{array}\right.$

Grojean, Servant, Wells

less plausible than CH but could be motivated by EW baryogenesis

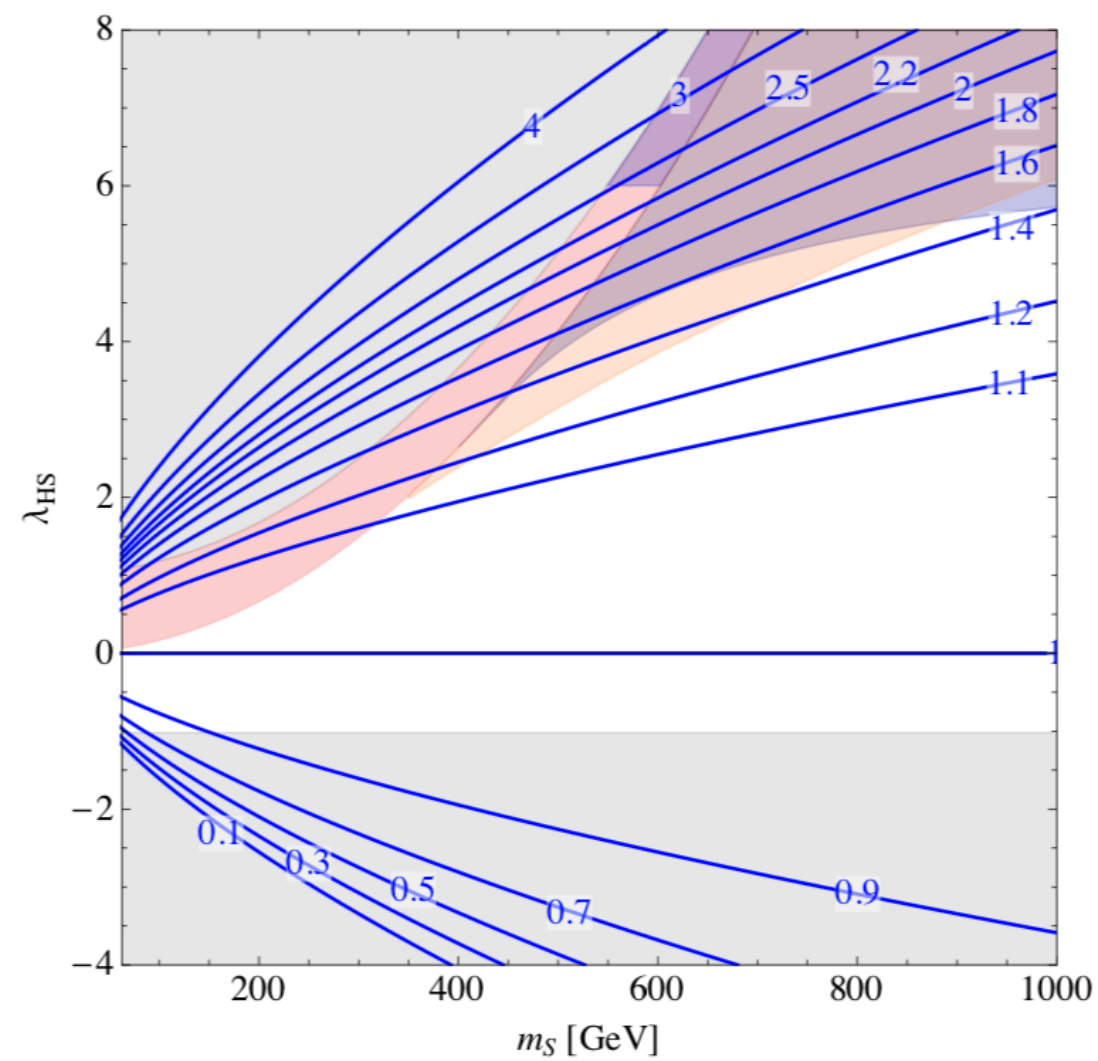
▲ Yeah… EW Baryogenesis:
need 1st order phase transition + extra CP violation

In SM phase transition is smooth cross-over ➡ 'light' new physics

- sizeable corrections to V(H) if PT in H direction $\frac{\delta\lambda_3}{\lambda_3} \gtrsim 0.2$
- smaller corrections if extra symms involved in PT

Ex: extra scalar singlet S

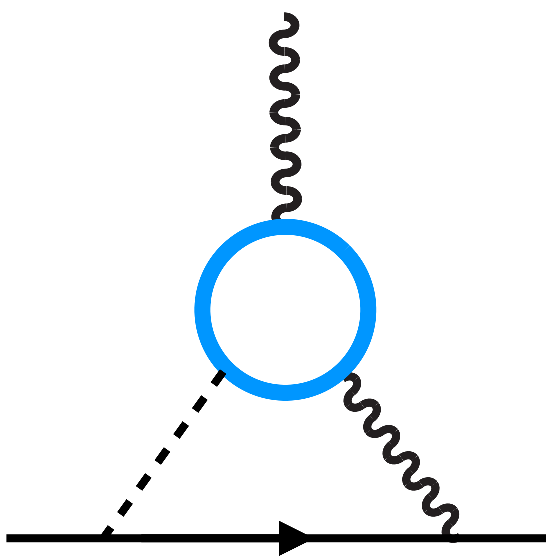
Curtin, Meade, Yu '15



What about extra CP violaton?

Need: EW charged fermions coupled to H and breaking CP

Barr-Zee contributions to edms



$$\frac{|d_e|}{e} \sim \sin\phi_{\rm CP}\left(\frac{g^2}{16\pi^2}\right)^2\frac{m_e}{m_*^2} \sim 10^{-29}{\rm cm}\times\sin\phi_{\rm CP}\left(\frac{2.5\ {\rm TeV}}{m_*}\right)^2$$

ACME bound

plan to go down to 10^{-34} !!!

Cesarotti et al '18

Dark Matter

Weak interactions remarkably admit minimal DM options: neutral components of radiatively split SU(2) multiplets

see table in 1303.7244 (Farina, Pappadopulo, Strumia)

Ex: pure higgsino (I=1/2), pure wino (I=1), pentino (I=2), …

mass range: 1-10 TeV

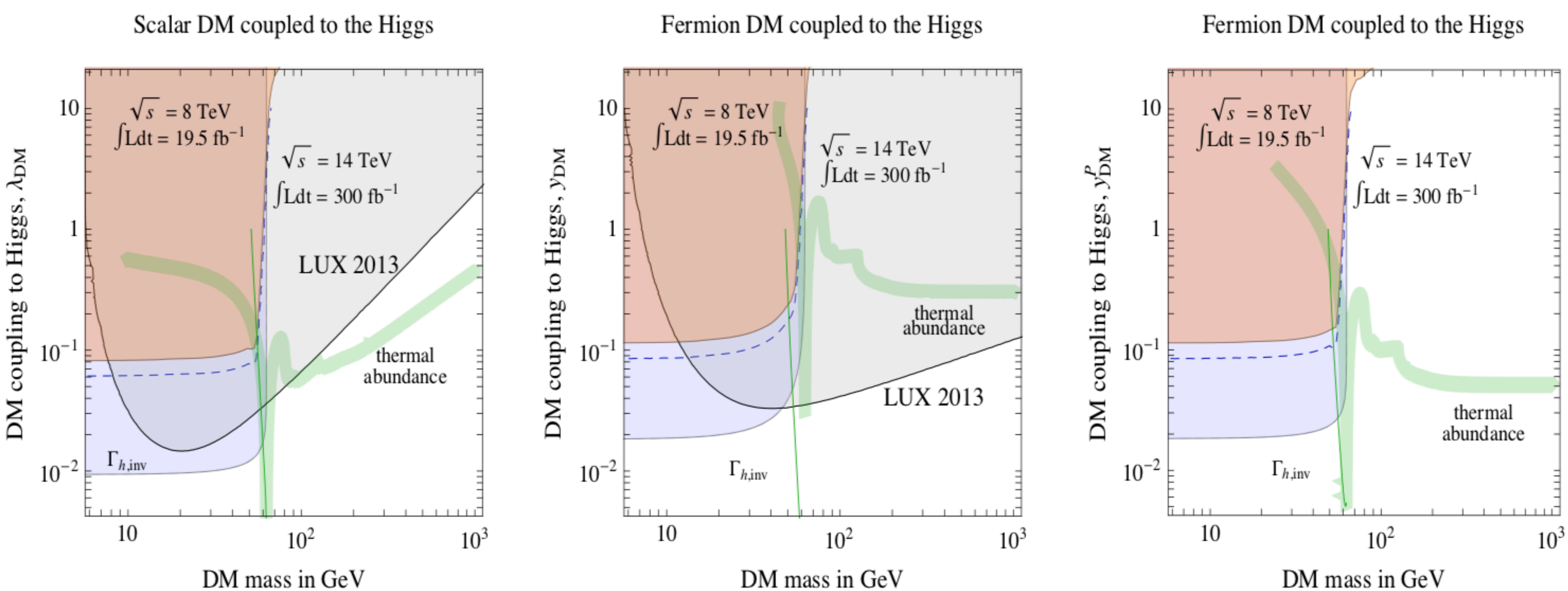
$$\Omega \sim \Omega_{obs} \left(\frac{I(I+1)\,\mathrm{TeV}}{m_I} \right)^2$$

direct detection cross section loop suppressed

CLIC and FCChh will make very significant exploration

Higgs invisible width

- Would give us access to some Dark Sector
- more plausibly only indirectly related to DM
- only in a small window around $m_{DM} \simeq m_h/2$ could this correspond to decay into DM pairs



DeSimone, Giudice, Strumia, '14

Summary

Simplicity vs. Naturalness: outstanding paradox of modern physics

The future of experimental particle physics can be read in this vein

as quantified by
'Fine Tuning Theorems'

$$\frac{\delta g_h}{g_h} \sim \epsilon$$

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

$$O_{EW} \sim 10^{-2} \div 10^{-3} \times \epsilon$$

$\epsilon \sim 10^{-3}$ is sufficiently far from Naturalness and sufficiently close to Simplicity to make me want to live (much) longer