University of Glasgow

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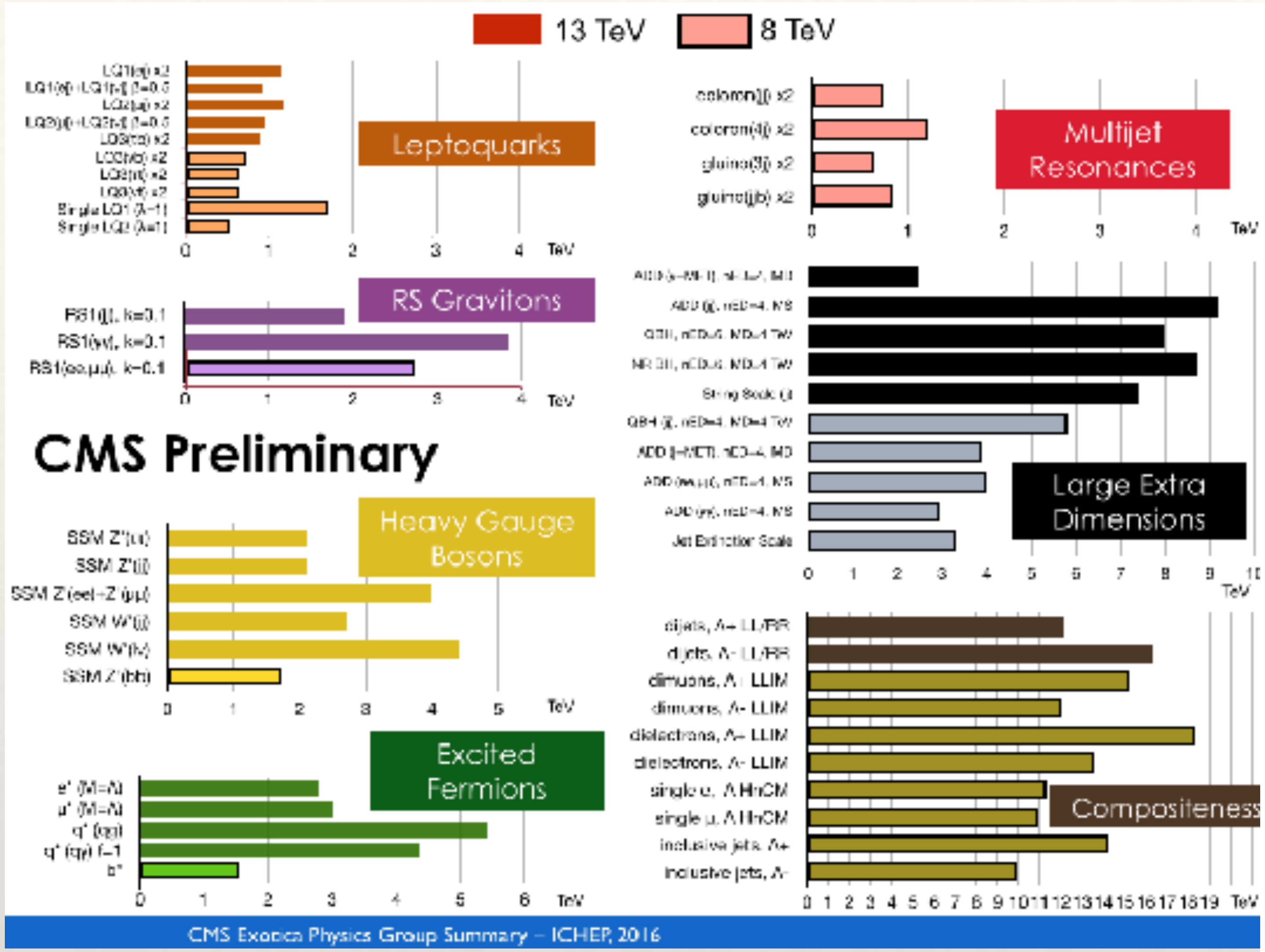
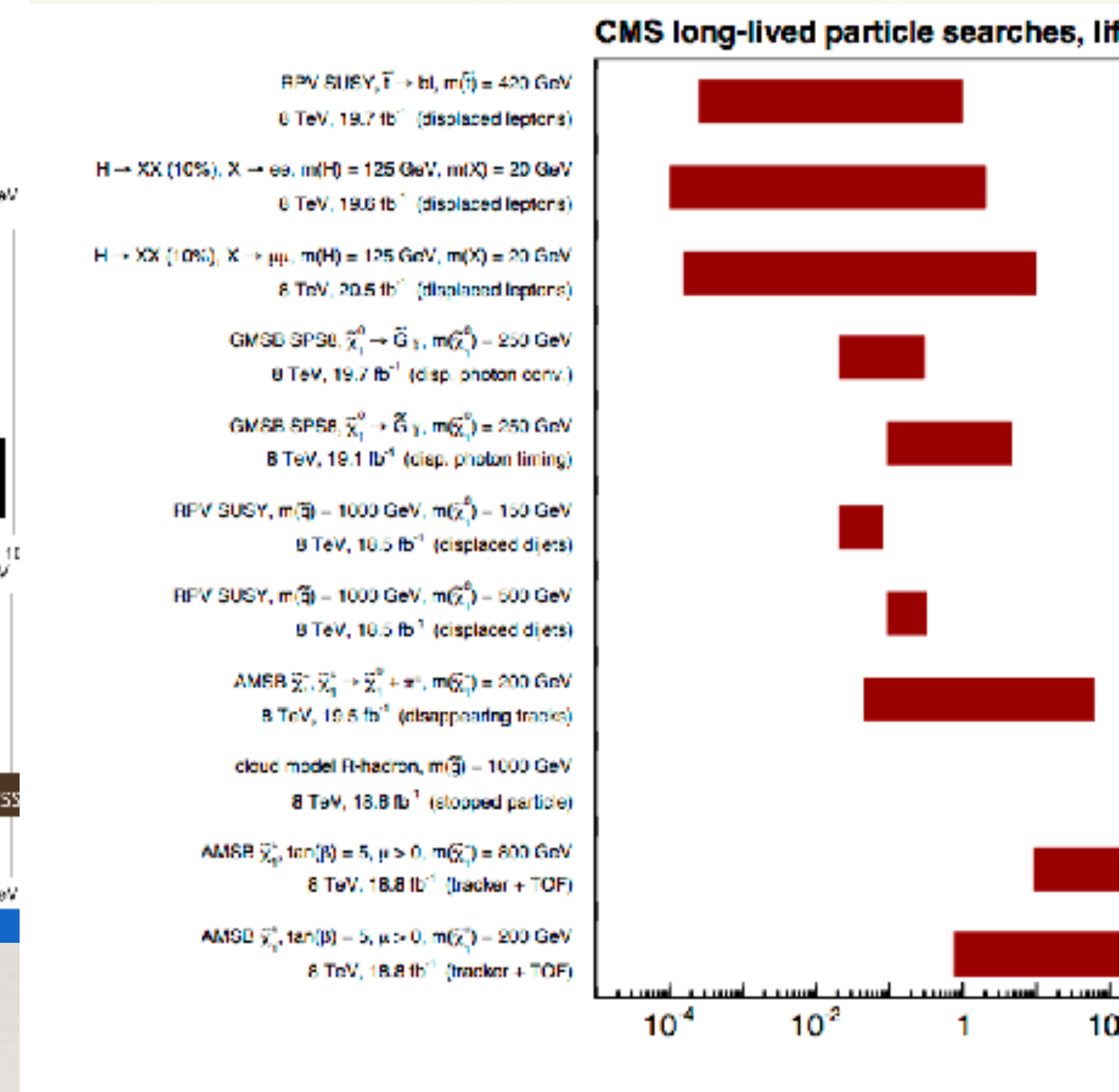
Theories killed by the LHC

YETI Durham, 10/01/2018

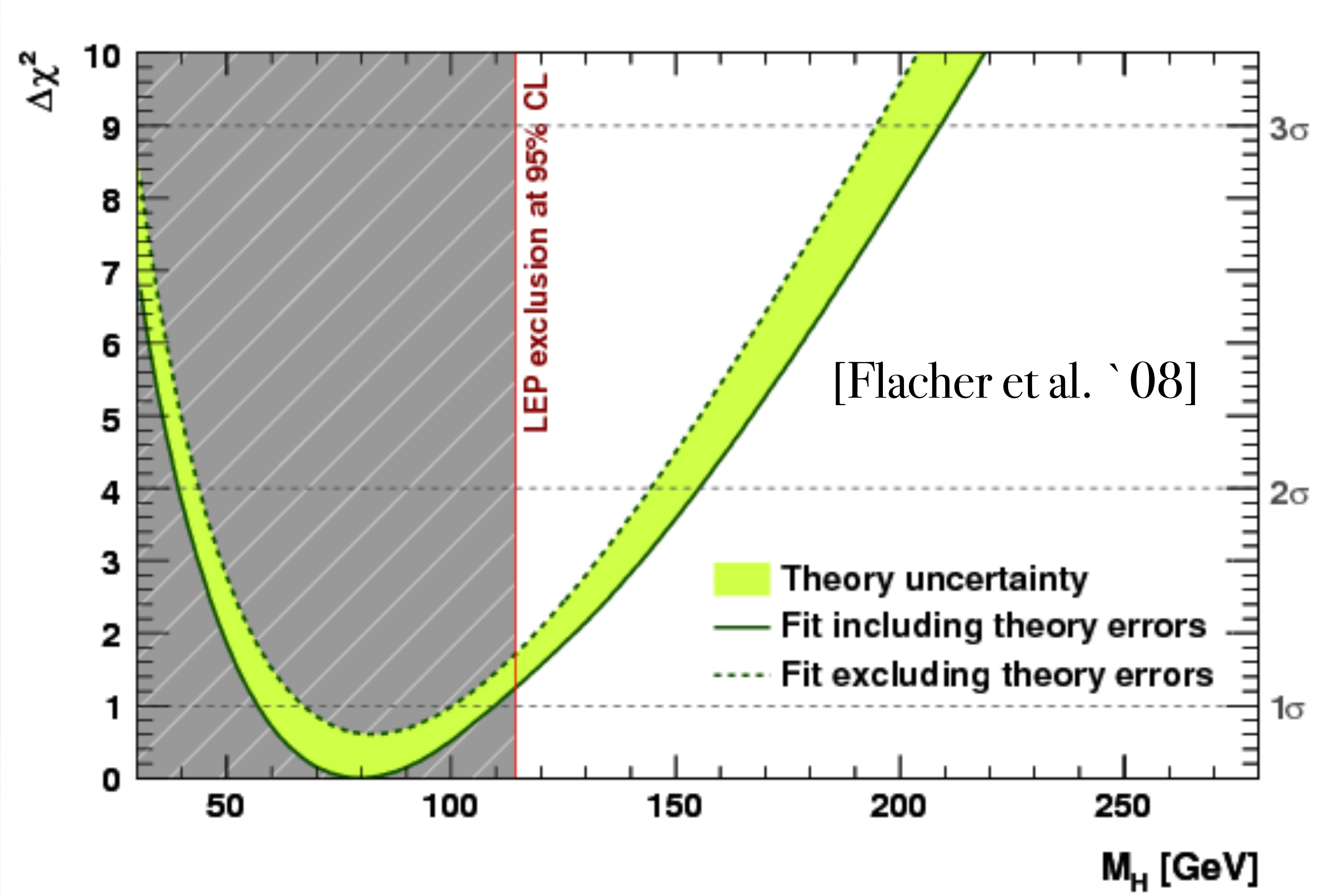
LHC...





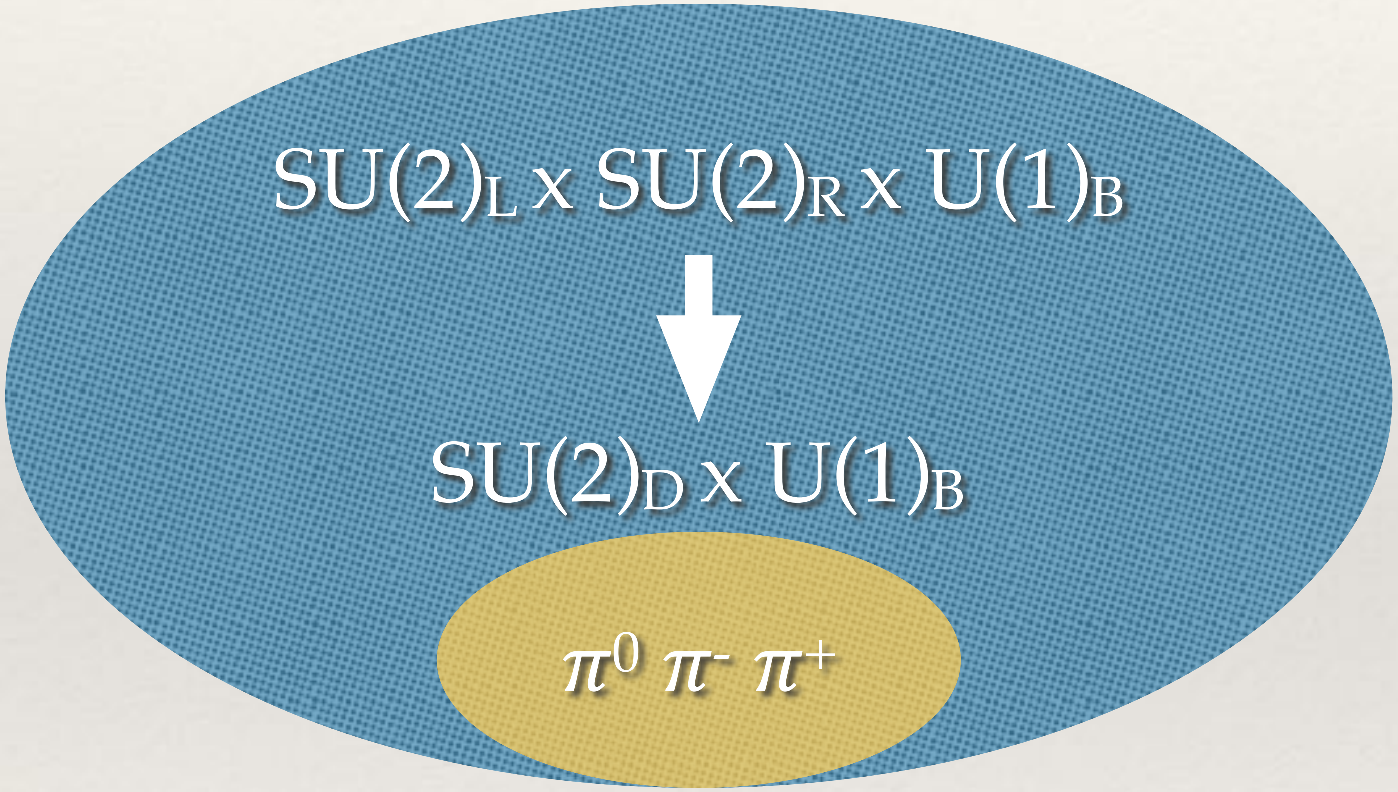
- left lots of theories constrained
- some constrained with little comeback options
- **this talk:** focus on concepts (and tensions) rather than quoting results
- put this in context with motivations for new experiments

- EWSB in the SM minimal yet ad-hoc $V(\Phi^\dagger\Phi) = \underbrace{\mu^2}_{<0}\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$
- the fact that we can understand the SM as a perturbative QFT allowed us to make self-consistent predictions



- however, is perturbativity really a necessary for EWSB?

- not at all: can interpret the electroweak scale as a radiative phenomenon
- strong dynamics of QCD in chiral limit breaks global symmetries



three massless NGBs with quantum numbers of broken generators

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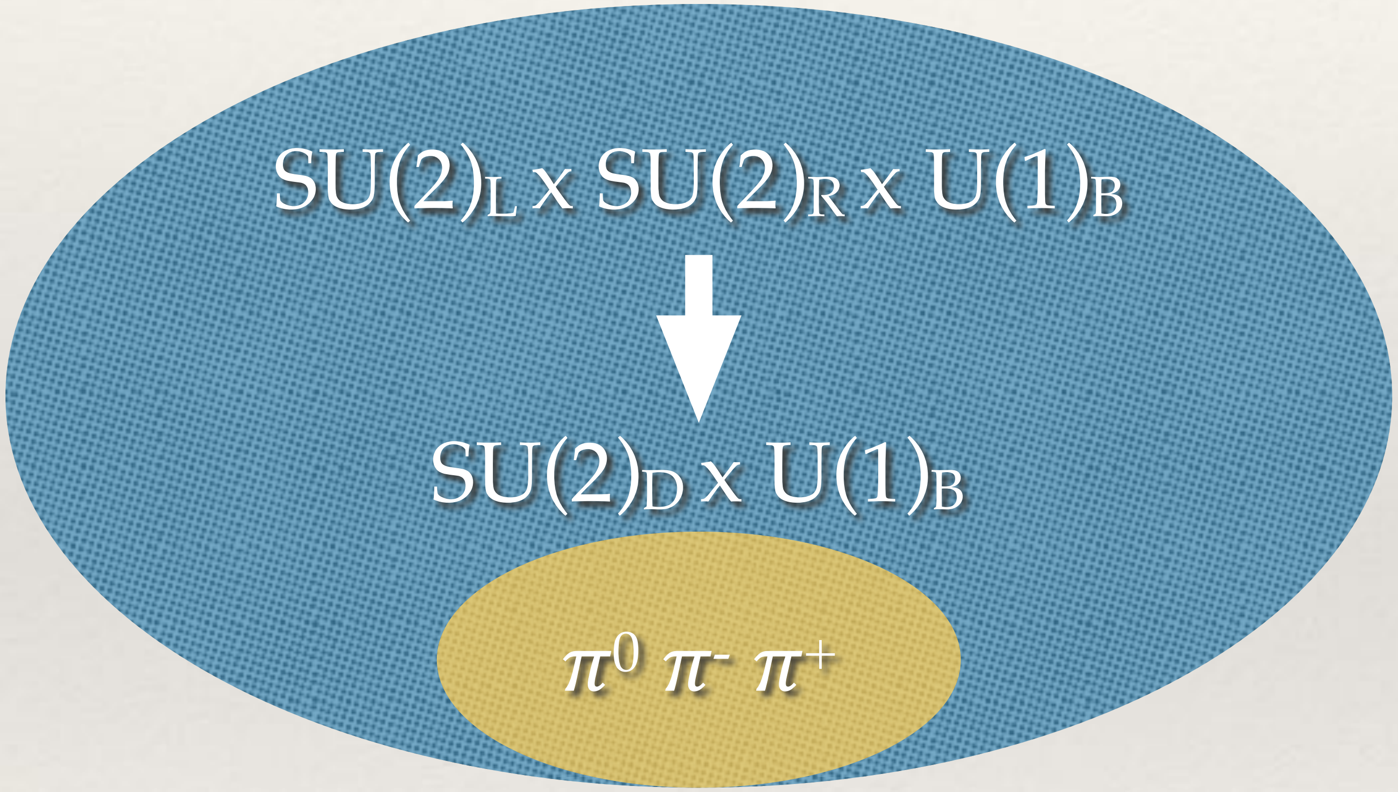

three massless NGBs with quantum numbers of broken generators

$$< 0|j_\mu^{a5}|\pi^b >= i f_\pi p_\mu \delta_{ab}$$

$$j_\mu^{a5} = \overline{\psi}\gamma_\mu\gamma^5\frac{\tau^a}{2}\psi \text{ where } \psi = (u, d)$$

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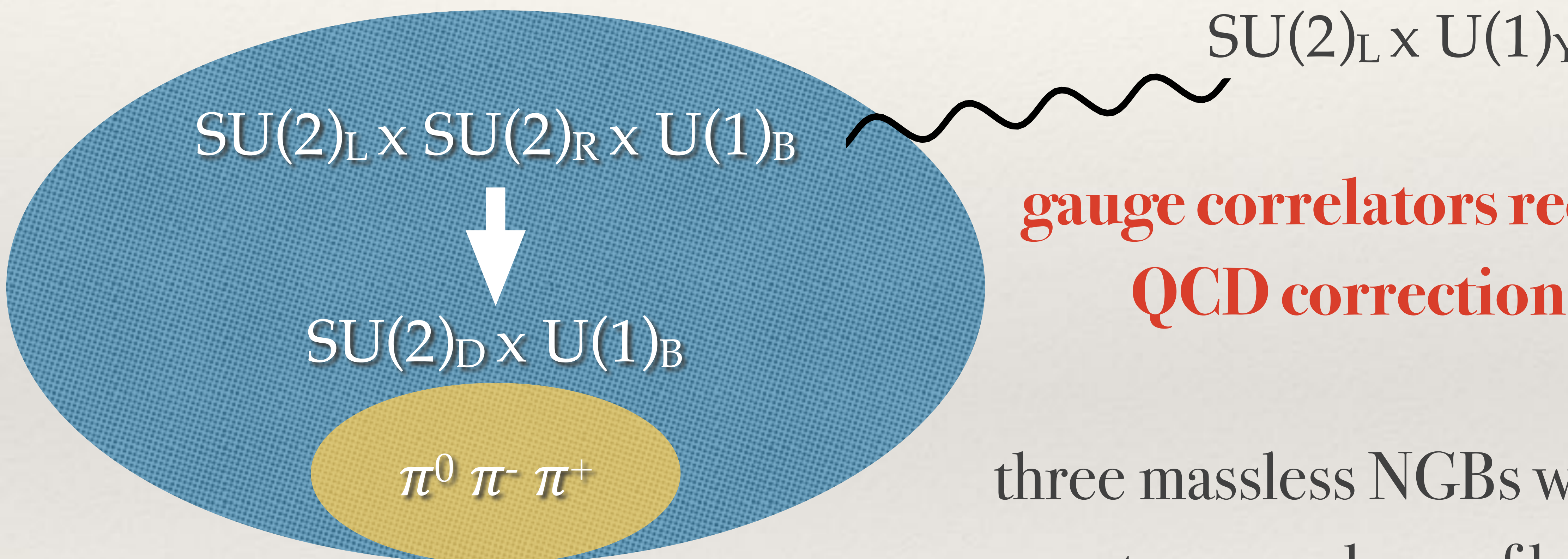

gauge correlators receive QCD corrections

three massless NGBs with quantum numbers of broken generators

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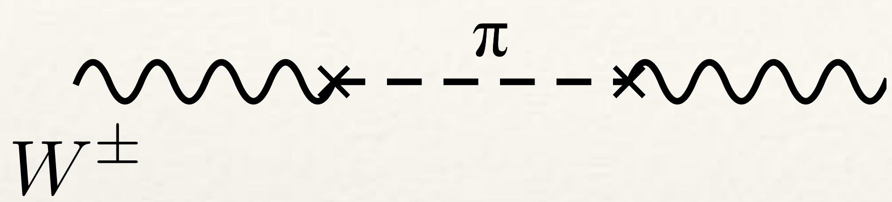
- non-perturbative QCD effects break electroweak symmetry



$$\sim \frac{i}{p^2 - g^2 f_\pi^2/4}$$

$$m_W = \frac{g f_\pi}{2} \simeq 29\,\mathrm{MeV}$$

- **Technicolor:** ”scale up” QCD by adding new confining gauge interactions SU(N). The electroweak scale becomes a dimensional transmutation effect (like the QCD scale)

$$\mu \frac{d}{d\mu} \frac{1}{g_{TC}^2}(\mu) = -\frac{\beta_0}{8\pi^2} \quad \Longrightarrow \quad v = M_{Pl} \exp\left(-\frac{8\pi^2}{g_{TC}^2(M_{Pl})(-\beta_0)} \right)$$

- implications:
    1. **no Higgs boson**
    2. additional strongly interacting bound states (rho-like etc.)
    3. trouble with EWPD: $S \sim N_C/\pi$, but $S < 0.3$ from LEP
    4. trouble with fermion masses: (walking) extended technicolor.

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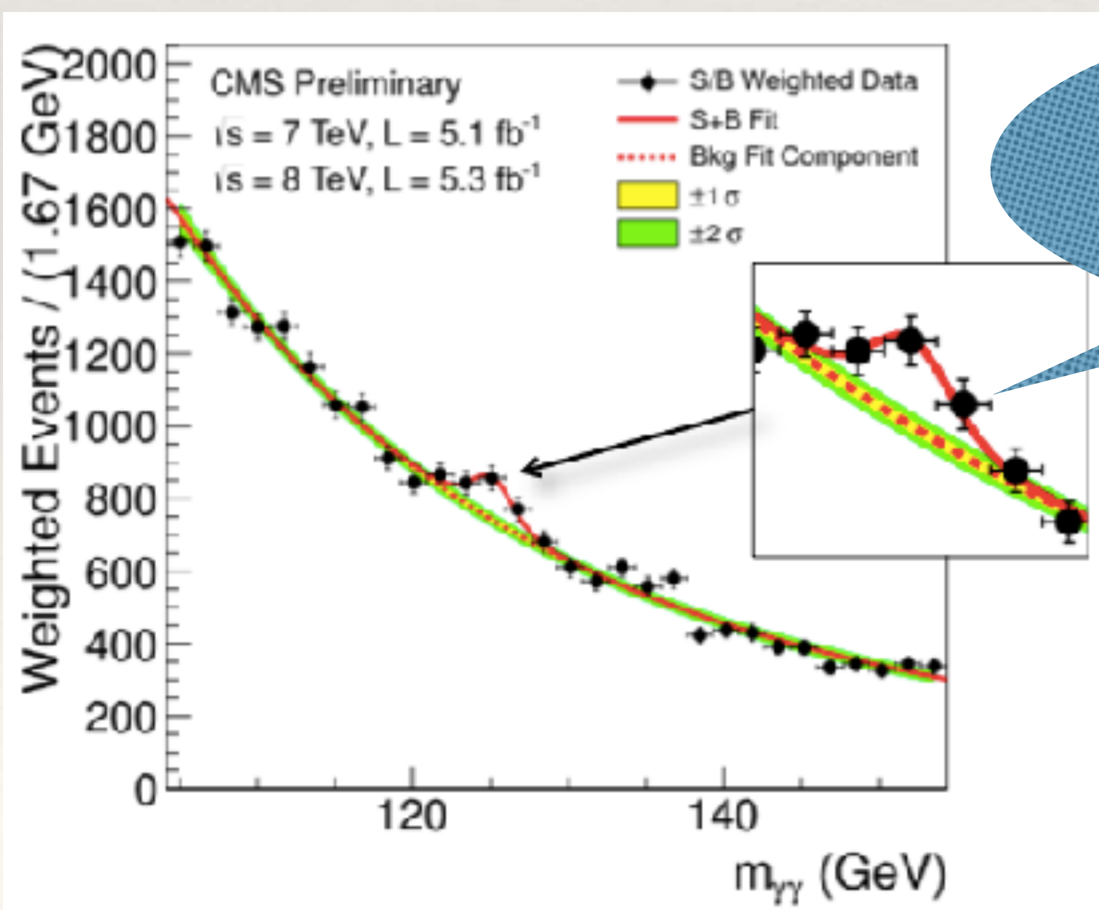
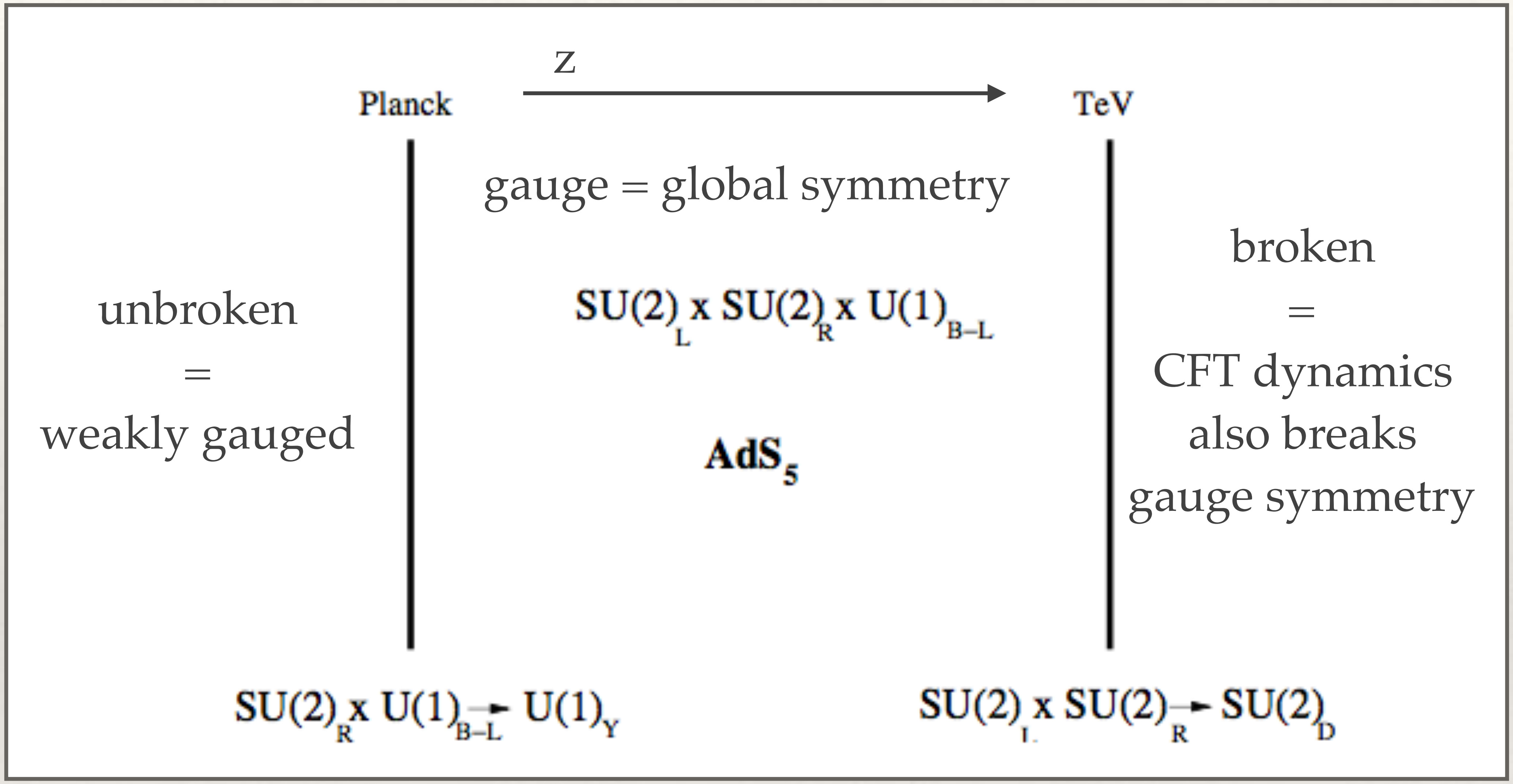


vanilla technicolor is **ruled out** by the LHC

- AdS/CFT dictionary

[Arkani-Hamed, Porrati, Randall `00]
[Rattazzi, Zaffaroni `01]



- Planck brane = UV cutoff of CFT
- bulk z = CFT energy scale, TeV brane = CFT breaks spontaneously due to strong interactions

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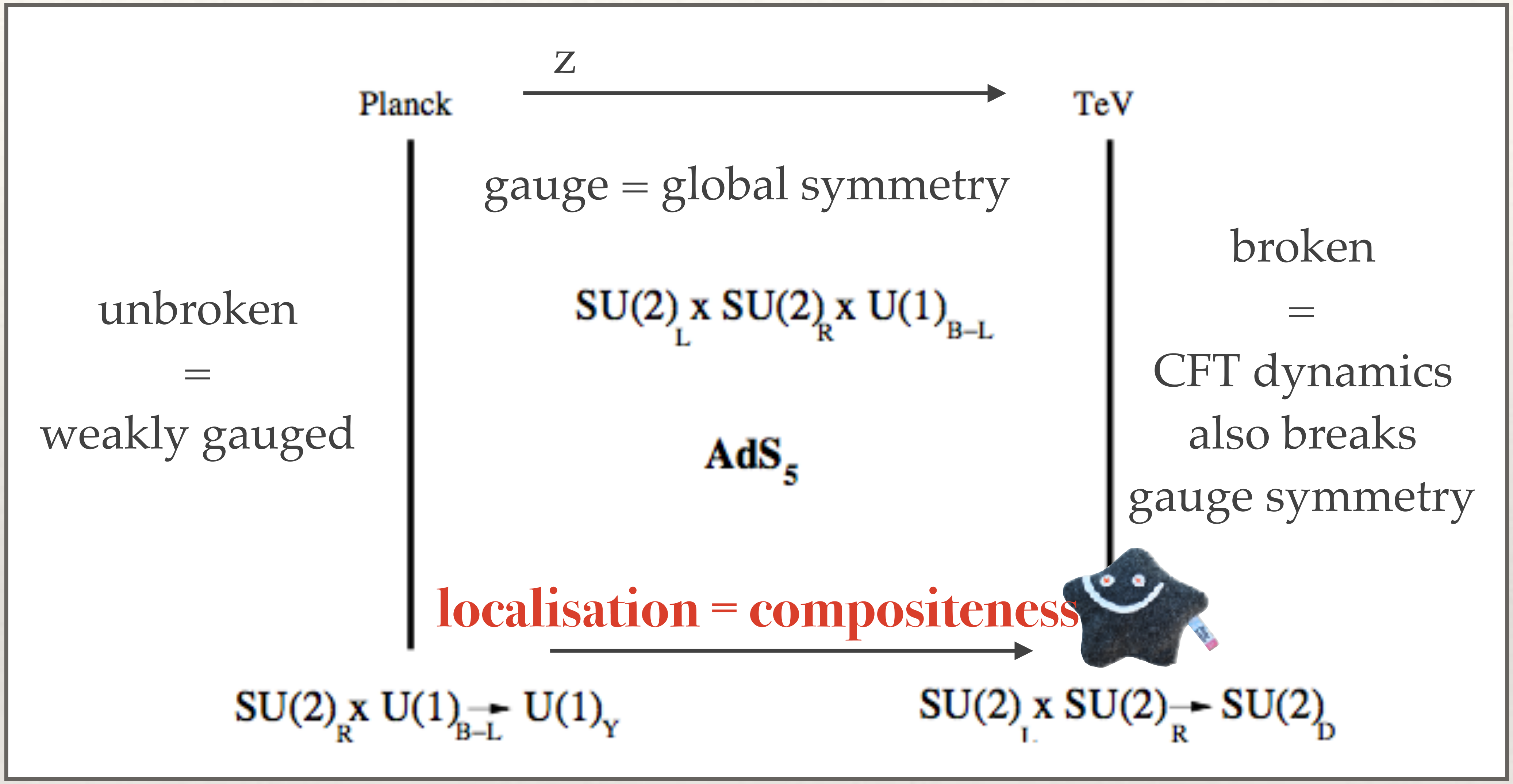

- Planck brane = UV cutoff of CFT
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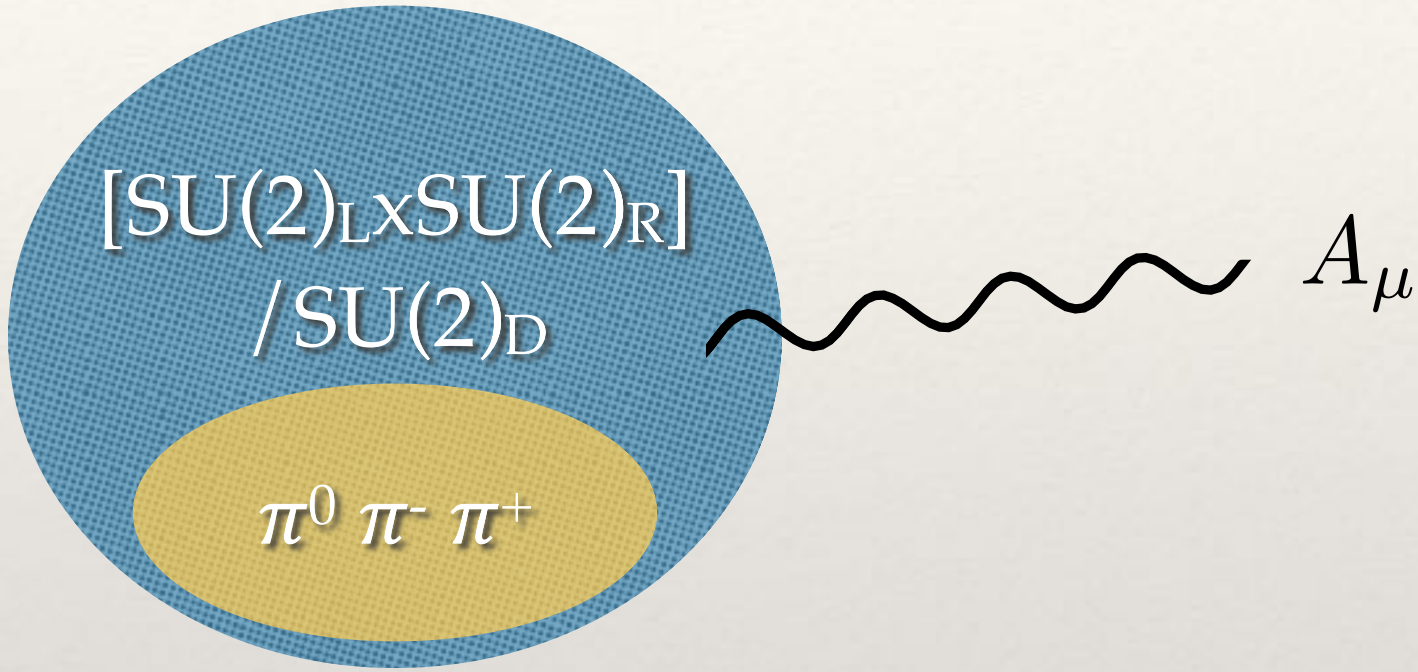
- back to interpreting the electroweak scale as a radiative phenomenon, **but this time look at the pion mass splitting**



Compositeness in a nutshell

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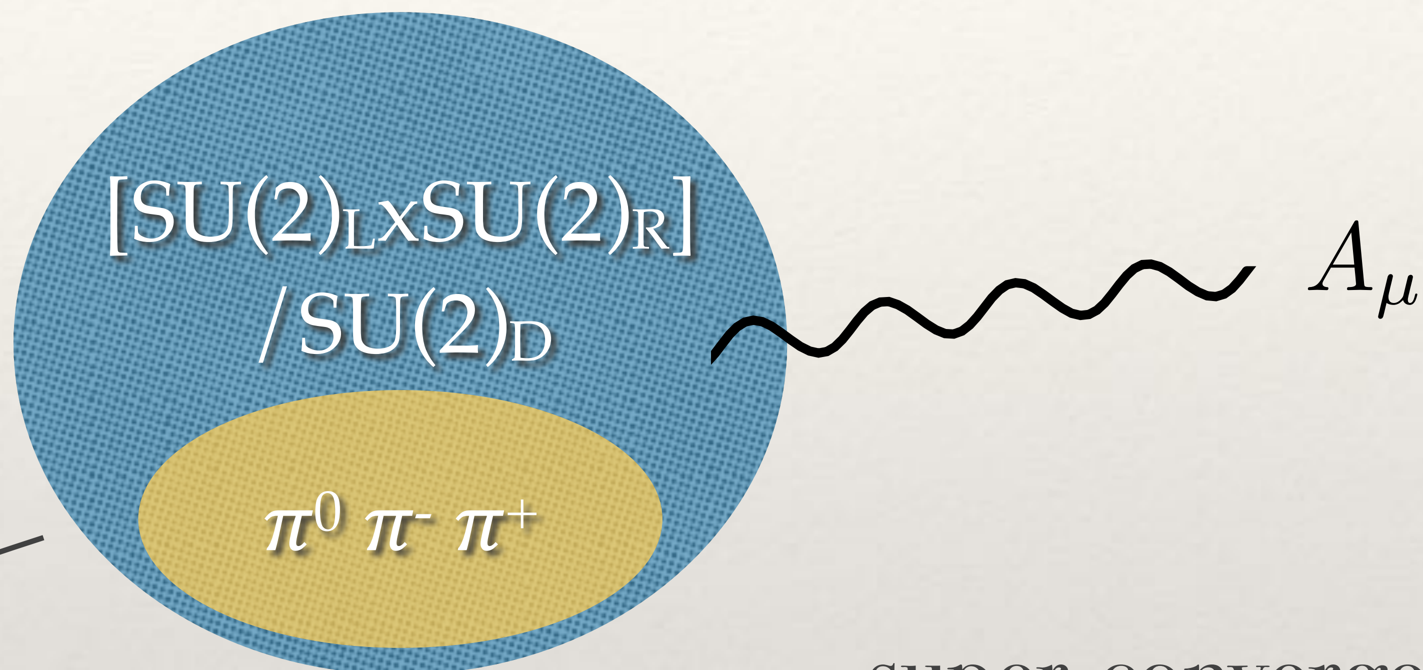

effective potential
[Coleman, Weinberg `73]...

super-convergent
[Weinberg `67]
[Witten `83]
...

$$V(\pi) \simeq \frac{3}{8\pi^2}\alpha_{em}\frac{\sin^2(\pi/f_\pi)}{\pi^2}(\pi^+\pi^-)\int_0^\infty dQ^2\,\Pi_{LR}(Q^2)\,.$$

$$(m_{\pi^\pm} - m_{\pi_0})|_{\text{TH}} \simeq 5.8\,\text{MeV} \quad \text{vs} \quad (m_{\pi^\pm} - m_{\pi_0})|_{\text{EXP}} \simeq 4.6\,\text{MeV}$$

Compositeness in a nutshell

- not straightforward to this adapt to the Higgs case   e.g. [Contino ` 10]

trigger
ELW symmetry
breaking not just
CW masses

respect global
symmetries in the
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LEP precision
measurements

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- **complete vacuum mis-alignement** from $SU(2)_L$ x $U(1)_Y$ direction requires the presence of heavy fermions

in units of *f*

$$\hat{V}(\hat{h}) = \alpha \cos(2\hat{h}) - \beta \sin^2(2\hat{h})$$

gauge + fermions

fermions

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gauge + fermions

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Higgs mass $\hat{m}_h^2 = \hat{V}''(\langle \hat{h} \rangle) = 32\beta\xi(1-\xi) = 8\beta - 2\alpha^2/\beta$

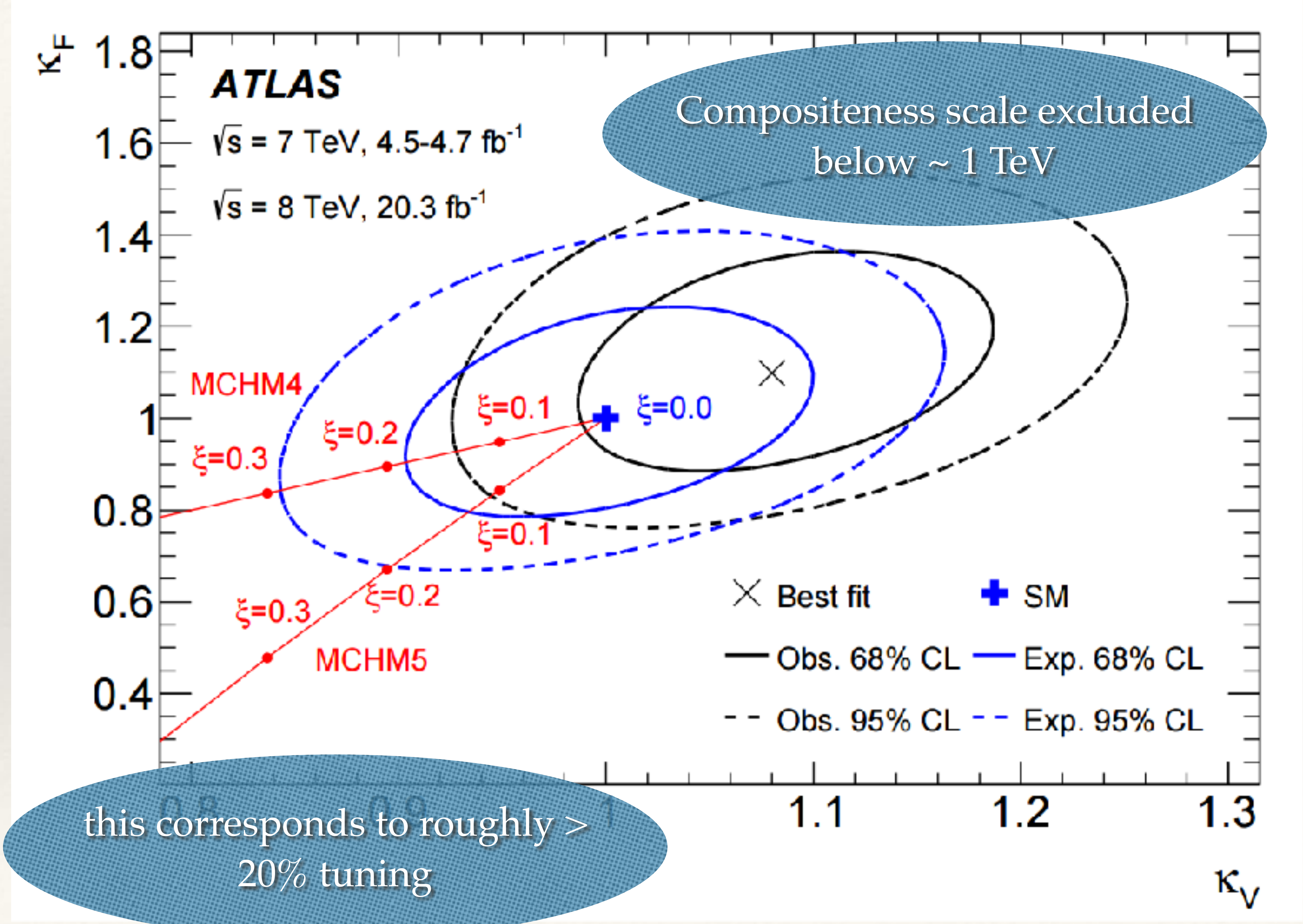
➡ **tuning required to have** $m_h \ll f$

Higgs coupling modifier $\xi \equiv \dfrac{v^2}{f^2} = \sin^2(\langle \hat{h} \rangle) = \dfrac{\alpha + 2\beta}{4\beta}$.

e.g.

$g_{VVh} = \sqrt{1-\xi}\, g_{VVh}^{SM}$

➡ **tuning not visible in couplings** $\xi \sim 0$



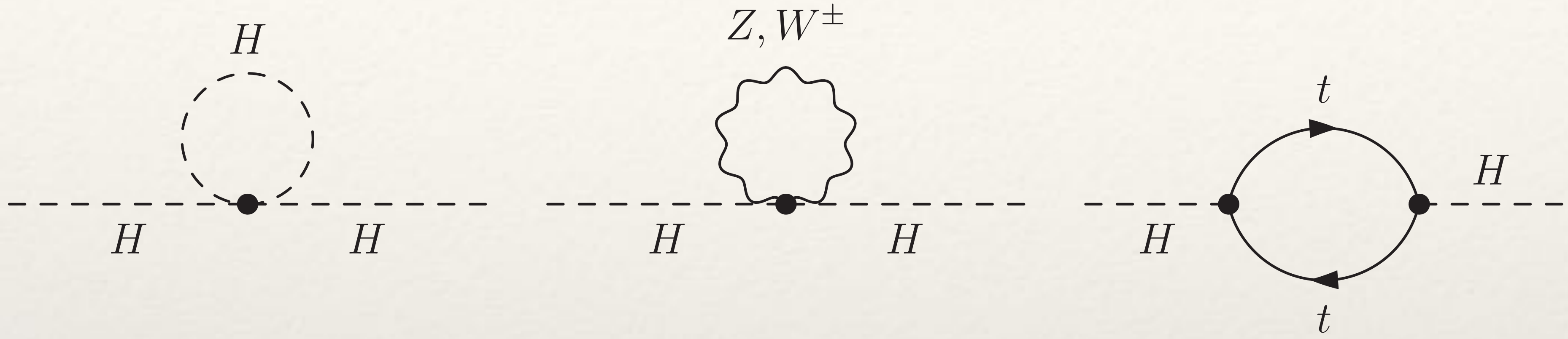
Compositeness scale excluded below ~ 1 TeV

this corresponds to roughly > 20% tuning

- then SUSY is not far (super well-motivated, but no clue of its scale)

THE SM

[Veltman `81]



$$\delta m_H^2 \sim \text{UV cutoff/threshold(s)}$$
$$\sim \underbrace{(m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2)}_{=\,0\ ?} \times \frac{\Lambda^2}{\langle H \rangle^2}$$

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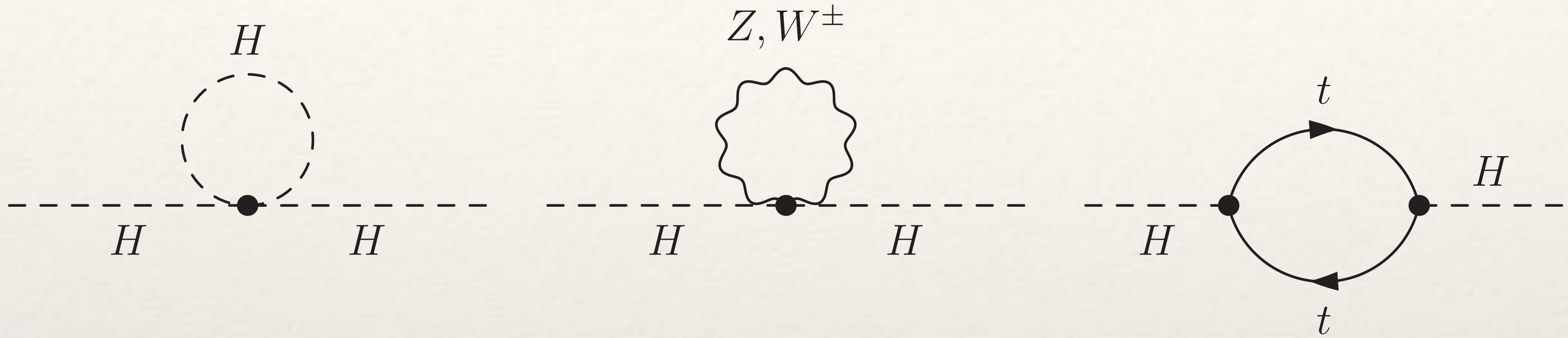

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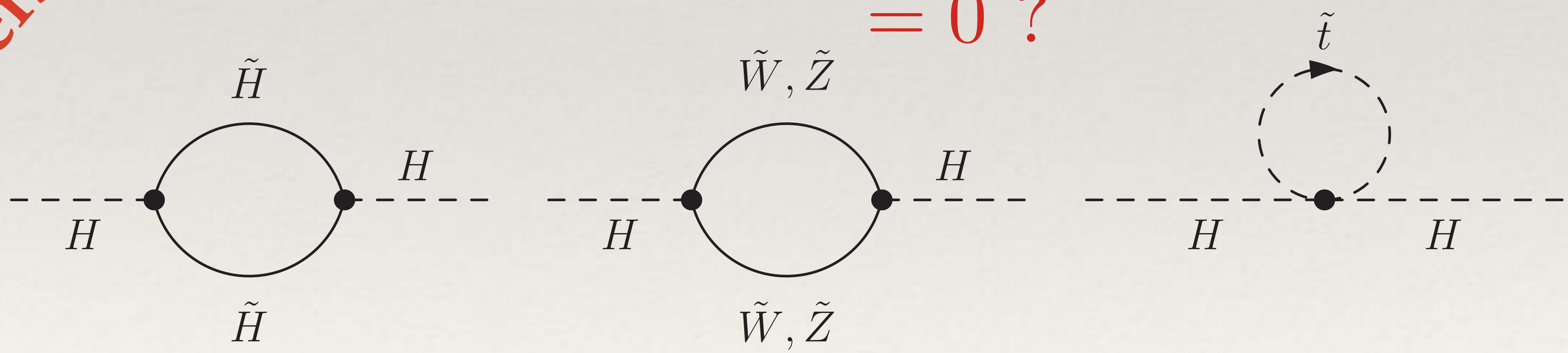
SUSY Partners



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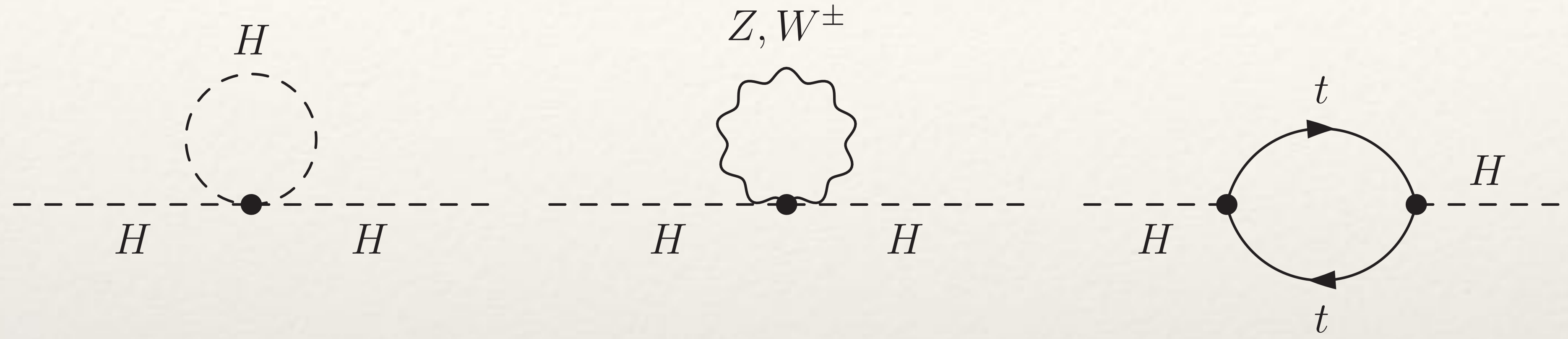

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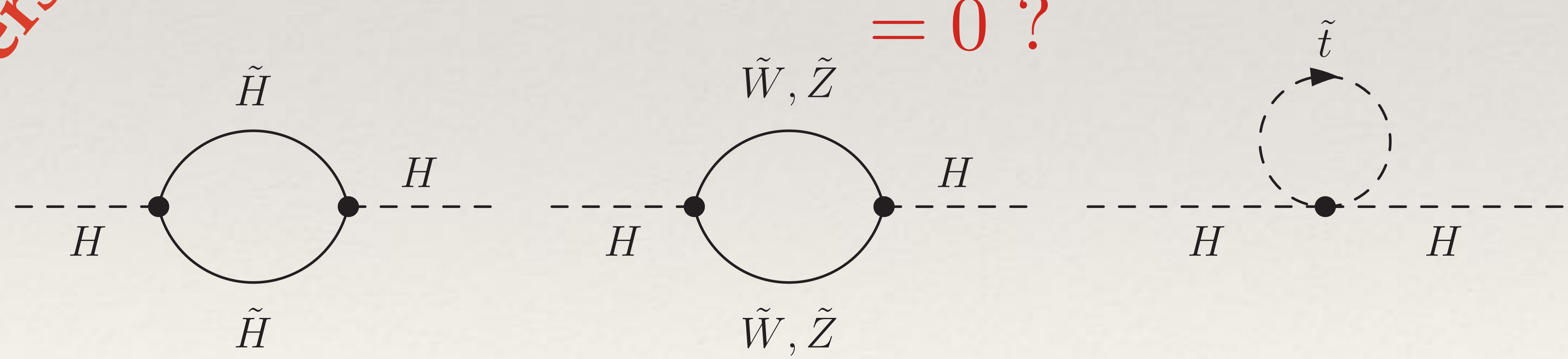
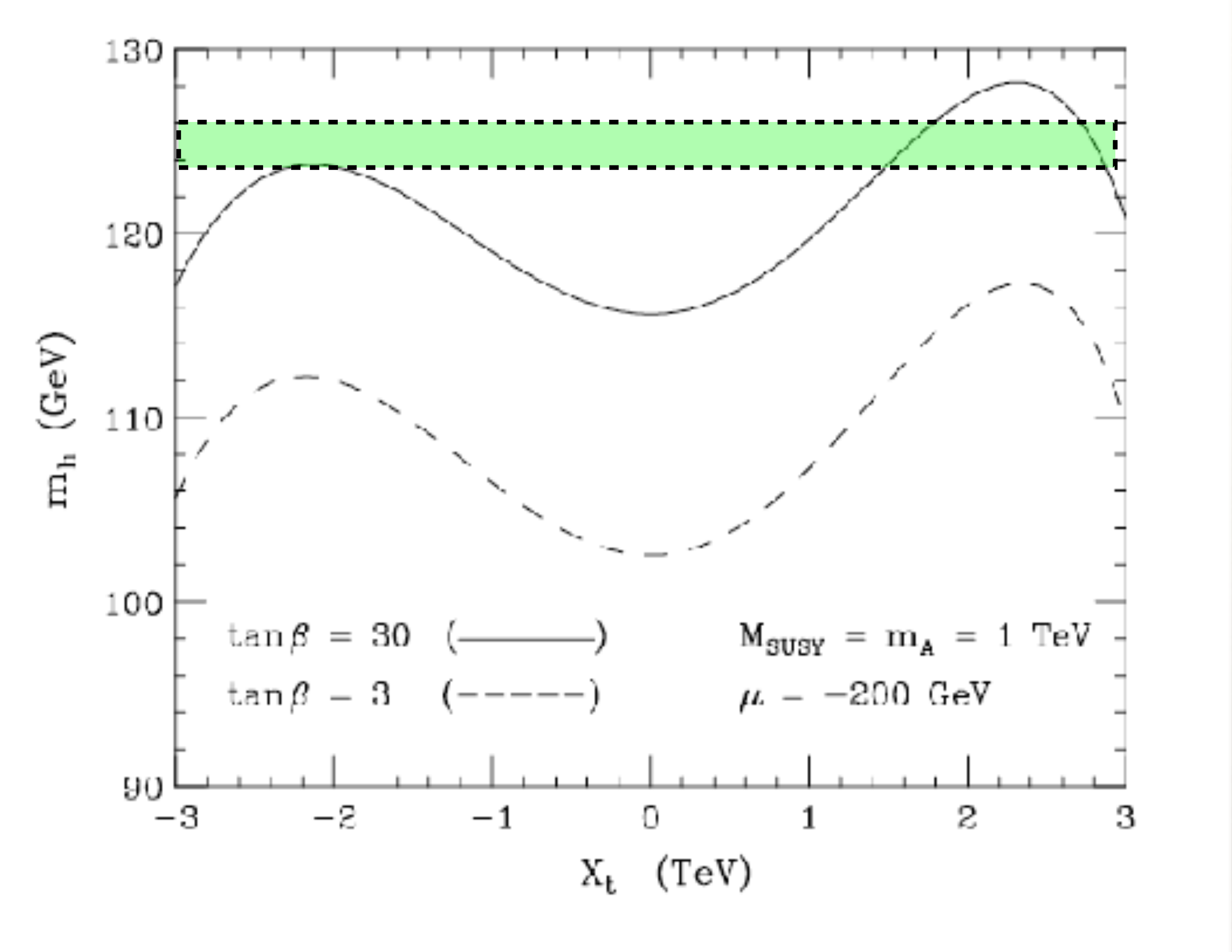


$$\delta m_H^2 = 0$$

Talking about naturalness….

- no degeneracy is observed so SUSY must be softly broken

- expressions for the CP-even Higgs mass



tree-level: $m_h \leq m_Z$

corrections: $$m_h^2 \lesssim m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{m_S^2}{m_t^2}\right) + \frac{X_t^2}{m_S^2}\left(1 - \frac{X_t^2}{12 m_S^2}\right)\right]$$

$X_t = A_t - \mu\cot\beta$ governs stop mixing and m_S^2 is average stop squared-mass

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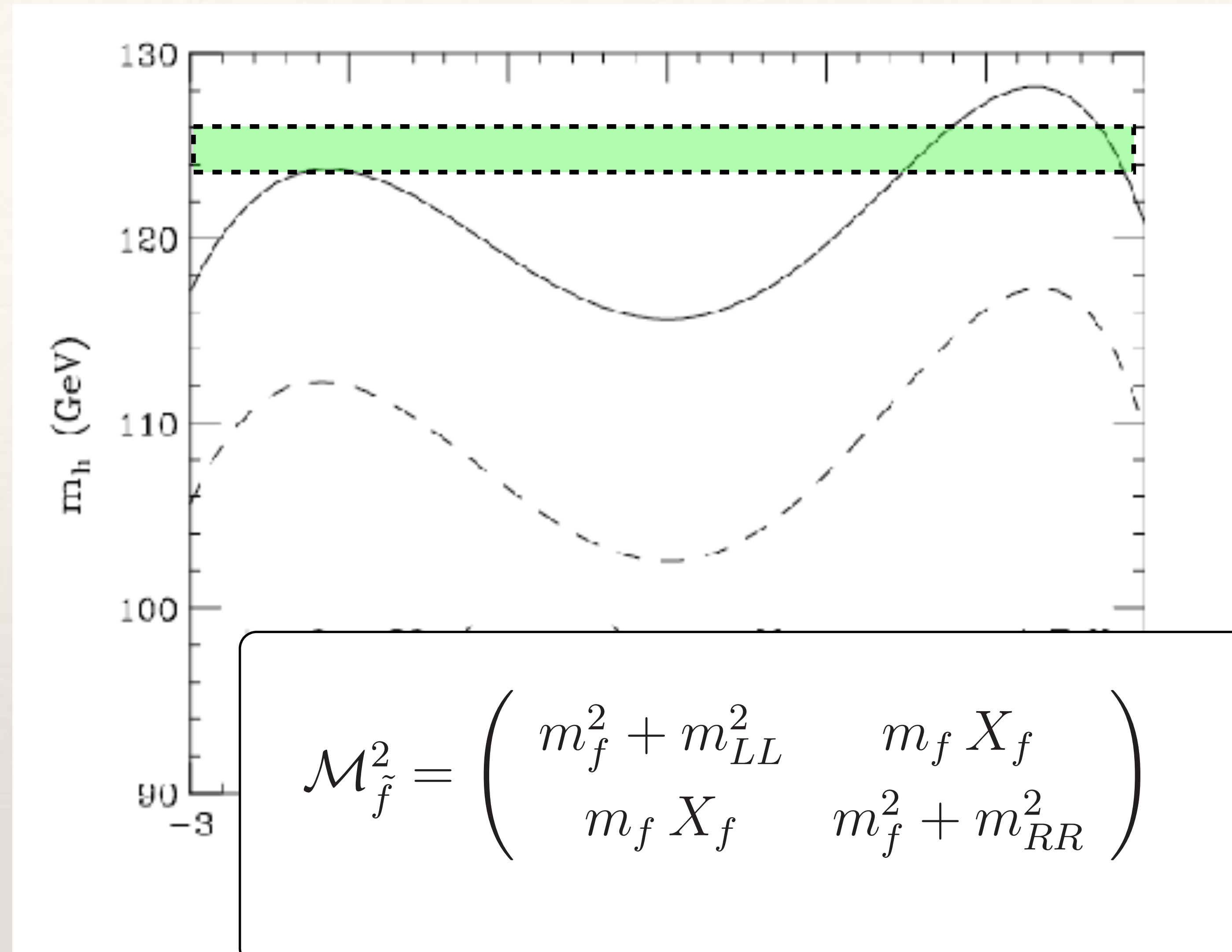

$$\mathcal{M}^2_{\tilde{f}} = \begin{pmatrix} m_f^2 + m_{LL}^2 & m_f X_f \\ m_f X_f & m_f^2 + m_{RR}^2 \end{pmatrix}$$

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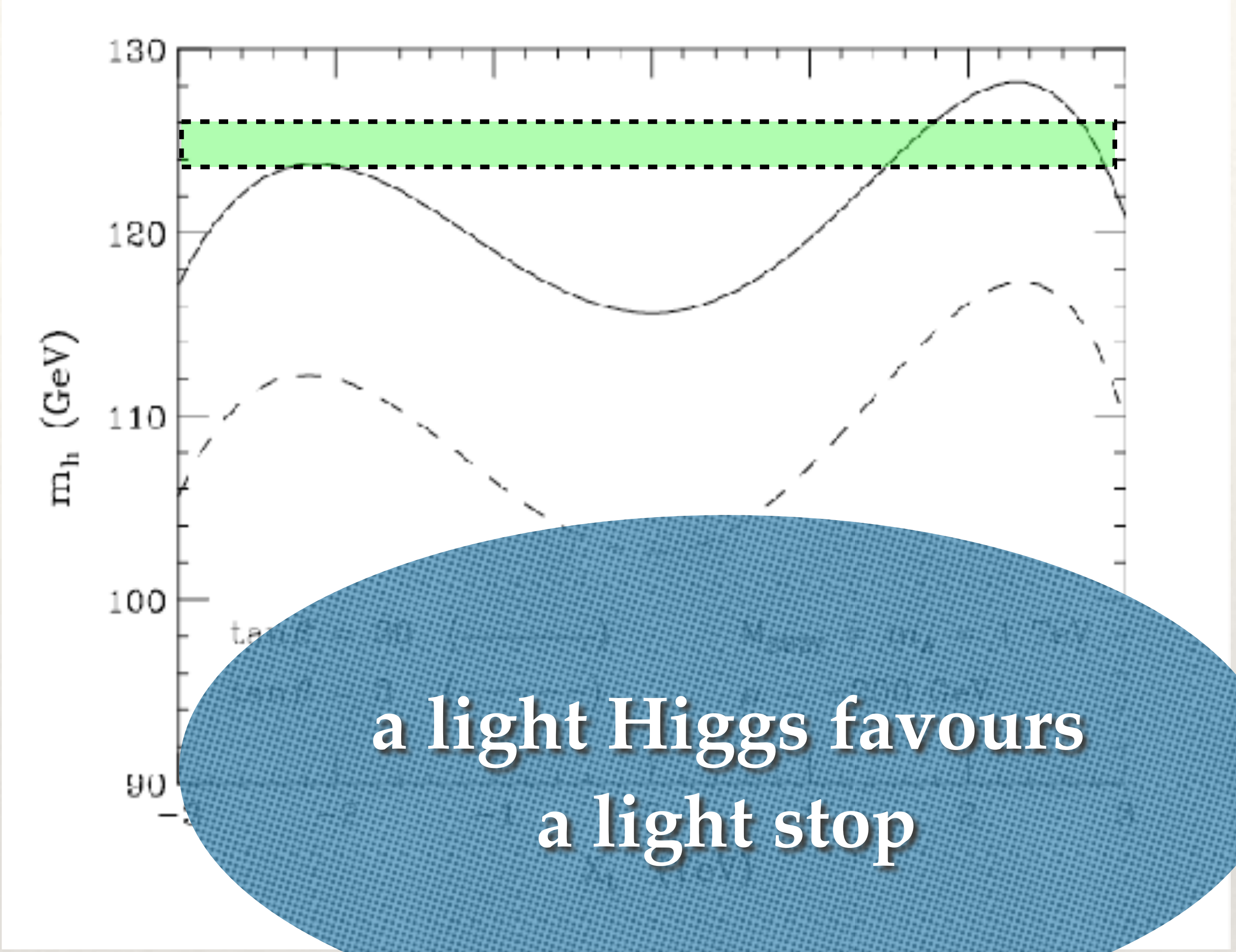

a light Higgs favours a light stop

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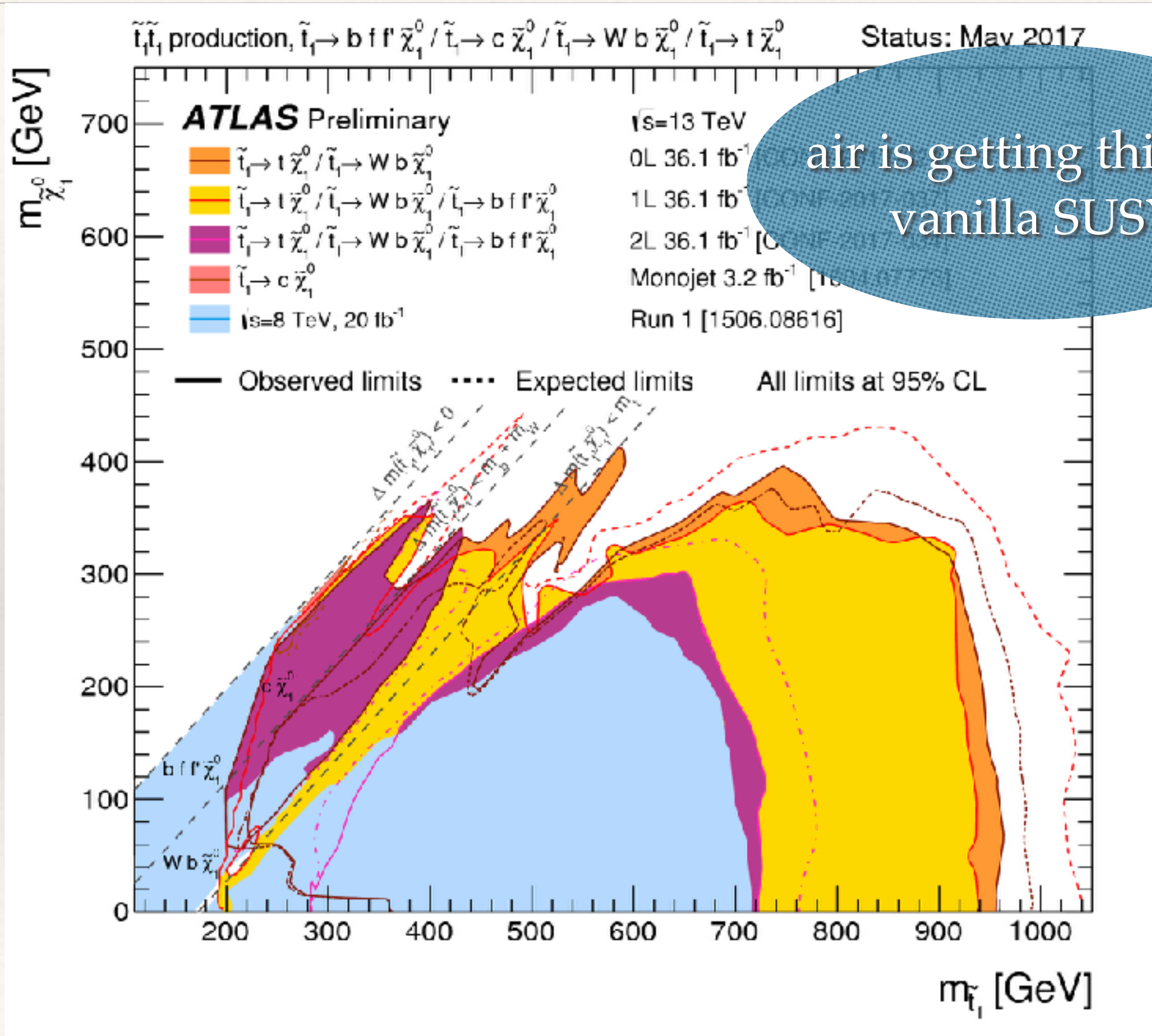
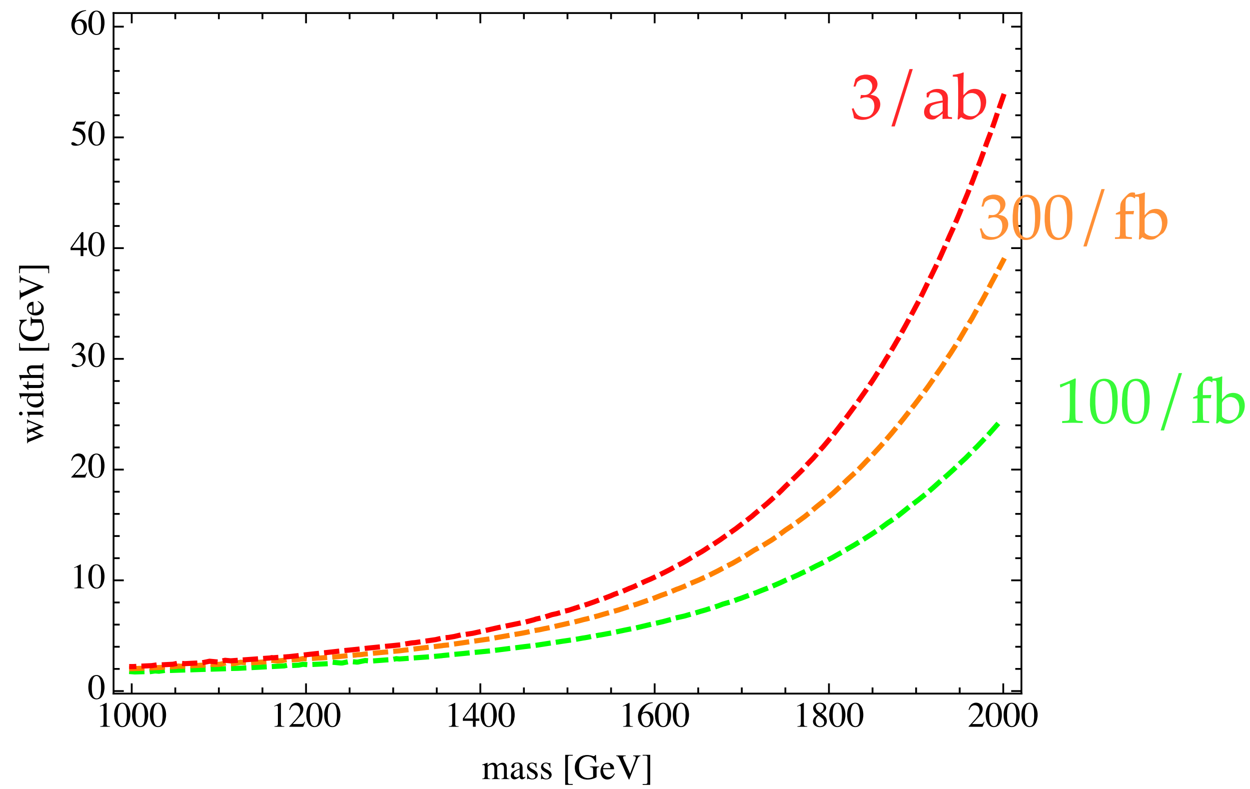


air is getting thin for vanilla SUSY

What are the options?

- any deviation of the SM coupling pattern induces perturbative unitarity violation $g_{VVh} = \sqrt{1-\xi}\, g_{VVh}^{\mathrm{SM}}$
- Composite scenarios have **extra stuff** that compensate this
  - ☛ fermiophobic = WBF
  - ☛ fermiophilic = Drell-Yan
  - ☛ LHC run 2 will zero in on those states
  - ☛ realistic spectra require lattice input

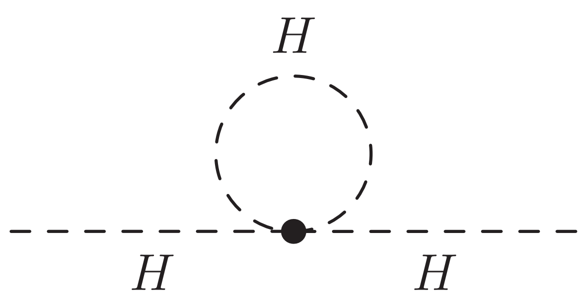


[CE, Harris, Spannowsky, Takeuchi ` 15]

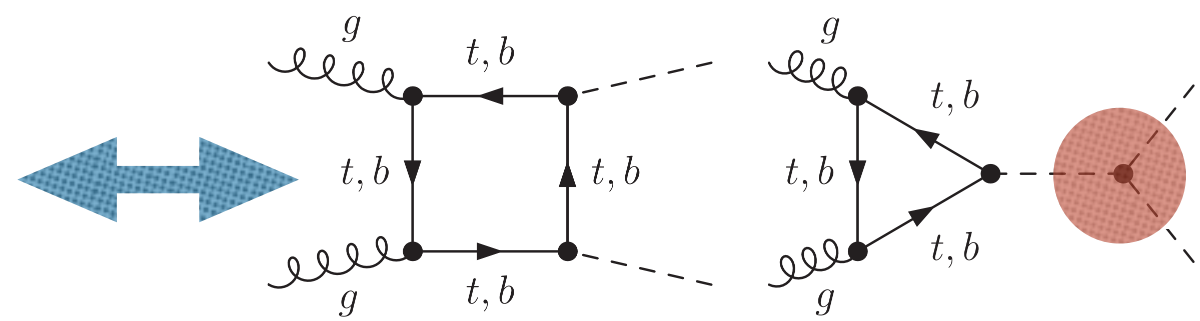
- Stops and other exotica searches scale with kinematic endpoints: 33 TeV / 100 TeV machines?

What are the options?

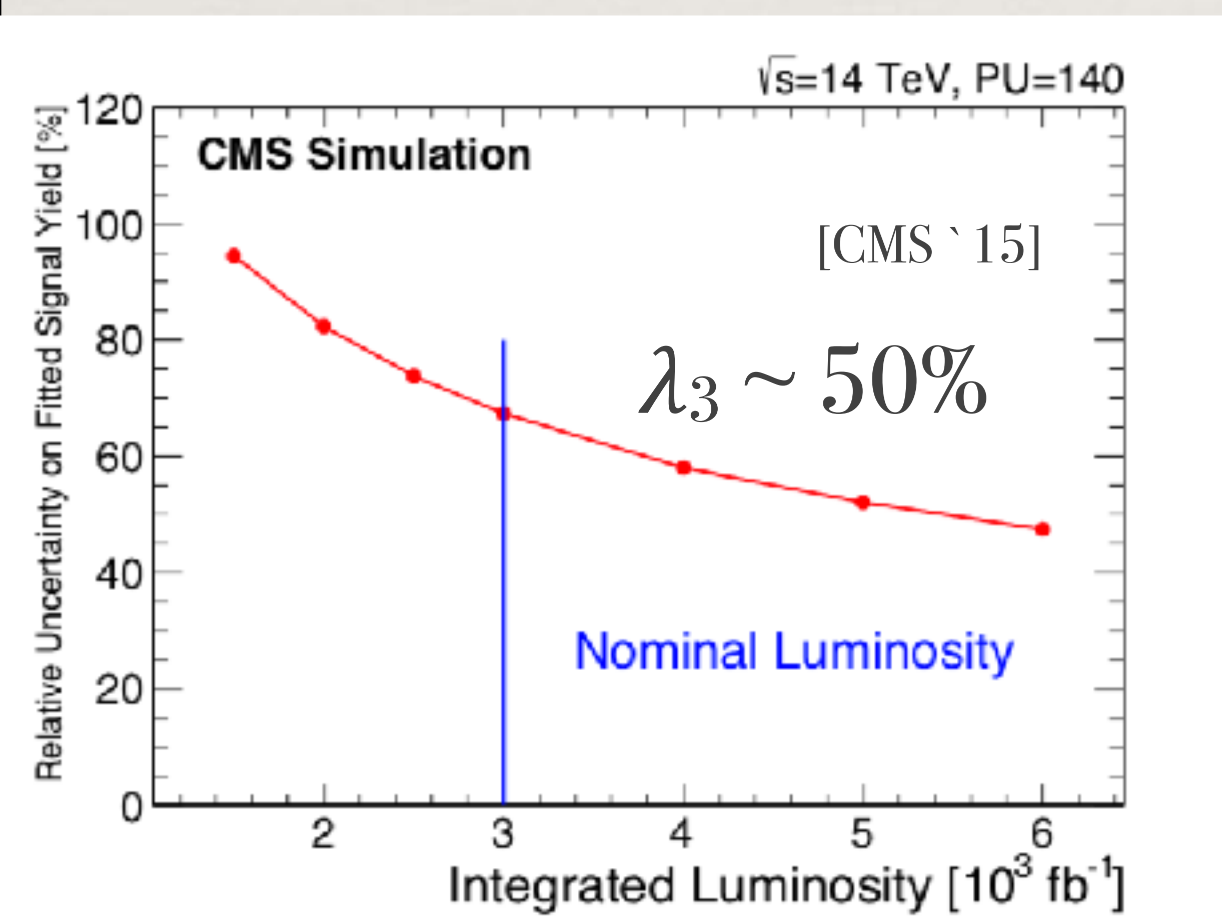
- enhance sensitivity to couplings that might be beyond the reach of the LHC



$$\sim \lambda |H|^4 \supset \lambda_3 H^3$$



$\sigma \sim 30$ fb



signal systematics

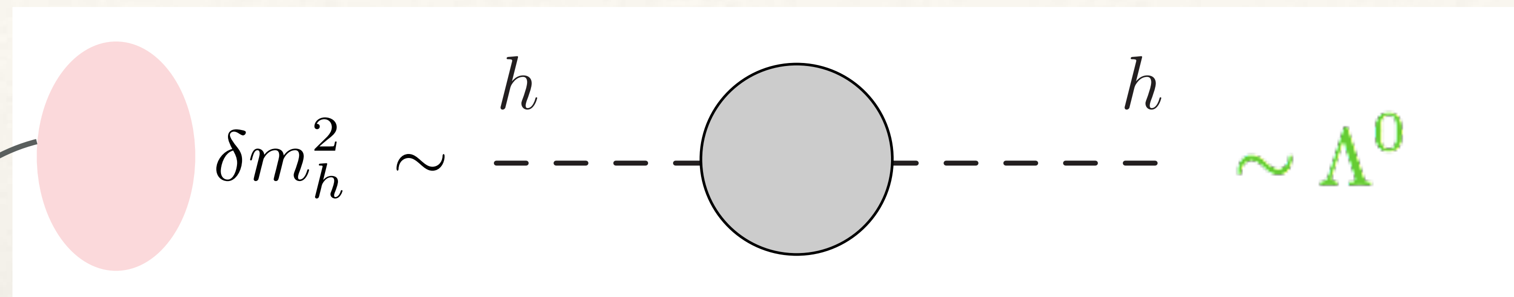
bkg systematics	$\Delta_S = 0.00$	$\Delta_S = 0.01$	$\Delta_S = 0.015$	$\Delta_S = 0.02$
$r_B = 0.5$	2.7%	3.4%	4.1%	4.9%
$r_B = 1.0$	3.4%	3.9%	4.6%	5.3%
$r_B = 1.5$	3.9%	4.4%	5.0%	5.7%
$r_B = 2.0$	4.4%	4.8%	5.4%	6.0%
$r_B = 3.0$	5.2%	5.6%	6.0%	6.6%

precision on λ_3

[Mangano et al. , Physics at a 100 TeV collider ` 16]

What are the options?

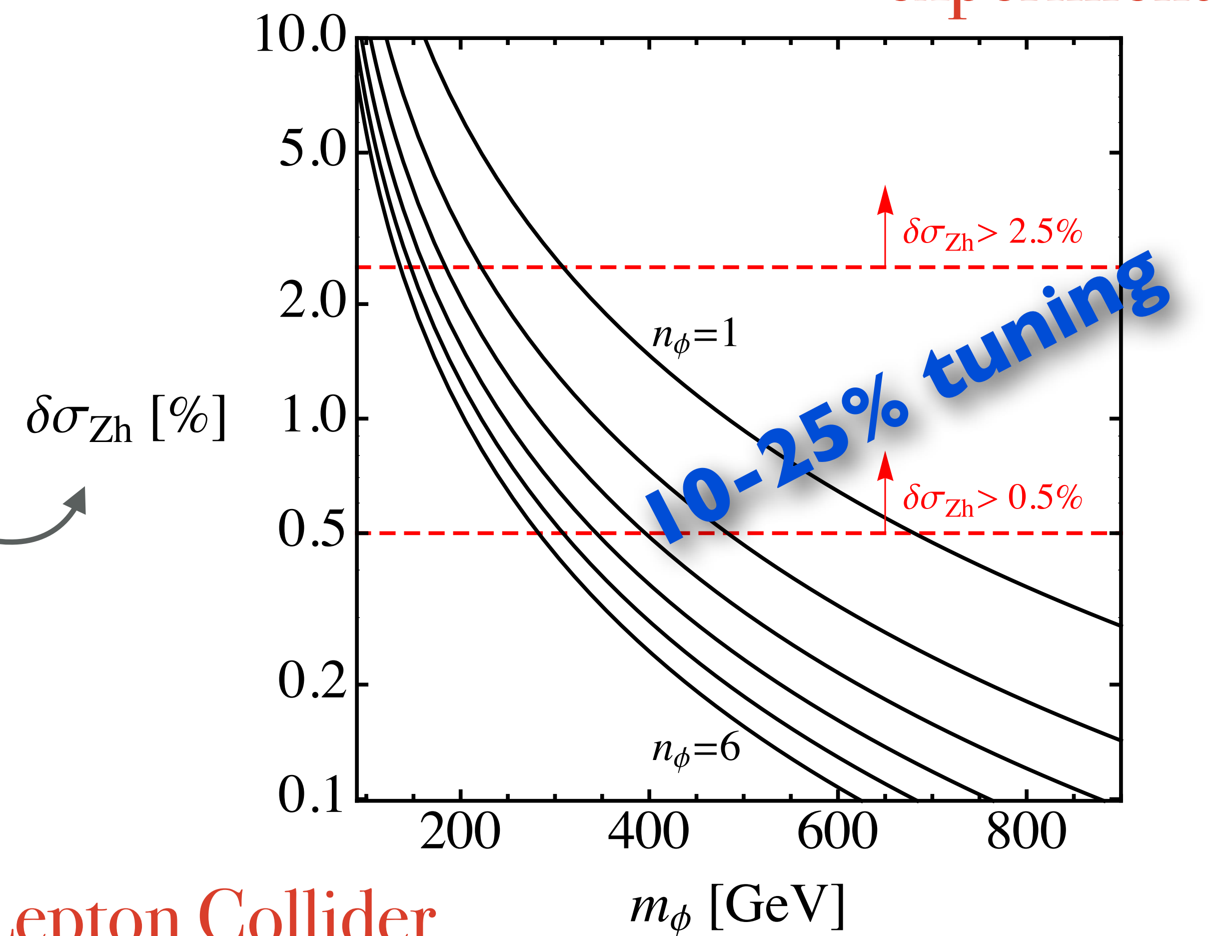
- informed prediction about precision (model-dependent!)



$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\delta Z_h (\partial_\mu h)^2 + \ldots$$

[Craig, CE, McCullough ` 13]
[Goncalves, Han, Mukhopadhyay ` 17]

Cancellations can't always hide at precision experiments



Lepton Collider

Summary

- We have the Higgs and it looks perturbative so far.
- We have nothing else as data keeps pouring in.
- LHC: naturalness might not be such a great guiding principle after all ?
- future colliders: precision vs. energy ?

Any BSM model gets pushed towards their decoupling limit or excluded