The little hierarchy problem at the LHC

Andrea Romanino
SISSA/ISAS

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- Experimental "problems" of the SM:
  - Gravity
  - Dark matter
  - Baryon asymmetry
- Experimental "hints" of physics beyond the SM
  - Neutrino masses
  - Quantum number unification
- Theoretical puzzles of the SM:
  - $\langle H \rangle \ll M_{Pl}$
  - Family replication
  - Small Yukawa couplings, pattern of masses and mixings
  - Gauge group, no anomaly, charge quantization, quantum numbers
- Theoretical problems of the SM:
  - Naturalness / unitarity problem
  - Cosmological constant problem
  - Strong CP problem

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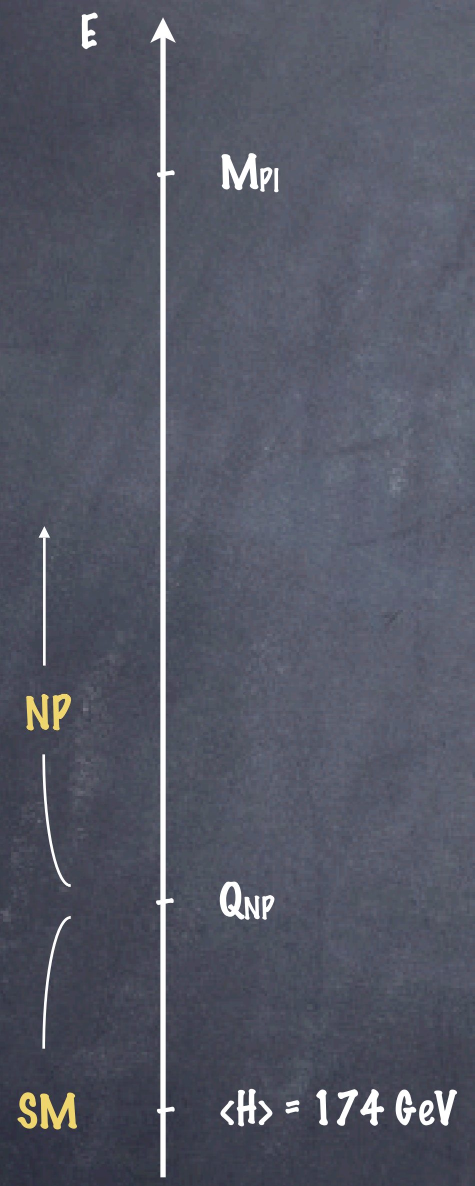
  $G_a \leftrightarrow h$, with $\delta m^2_h/m^2_h \approx (Q_{NP}/\text{TeV})^2$
- Many options; how do they confront the Little Hierarchy problem?

The little residual hierarchy (e.g. with h)



$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2 = \begin{cases} m_h^2 \left(\dfrac{Q_{\rm NP}}{0.5\,{\rm TeV}}\right)^2 & \text{if } m_h = 115\,{\rm GeV} \\ m_h^2 \left(\dfrac{Q_{\rm NP}}{2\,{\rm TeV}}\right)^2 & \text{if } m_h = 250\,{\rm GeV} \end{cases}$$

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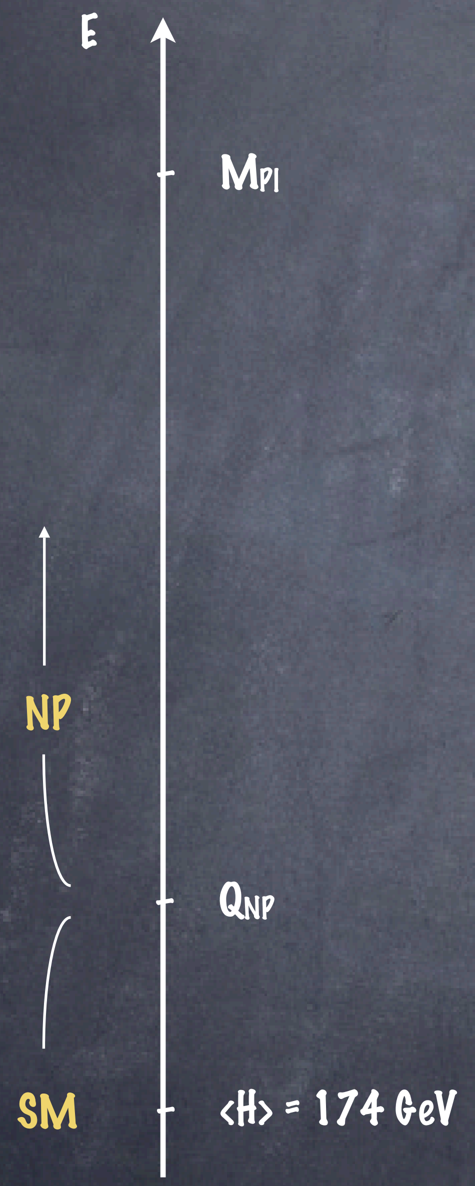

No hint of physics at Q_{NP}:

$$\mathcal{L}^{\rm eff}_{\rm SM}(E < Q_{\rm NP}) = \mathcal{L}^{\rm ren}_{\rm SM} + \sum_i \frac{c_i}{Q^2_{\rm NP}} \mathcal{O}_i + \ldots \qquad \frac{c_i}{Q^2_{\rm NP}} \lesssim \frac{1}{(5\,{\rm TeV})^2}$$

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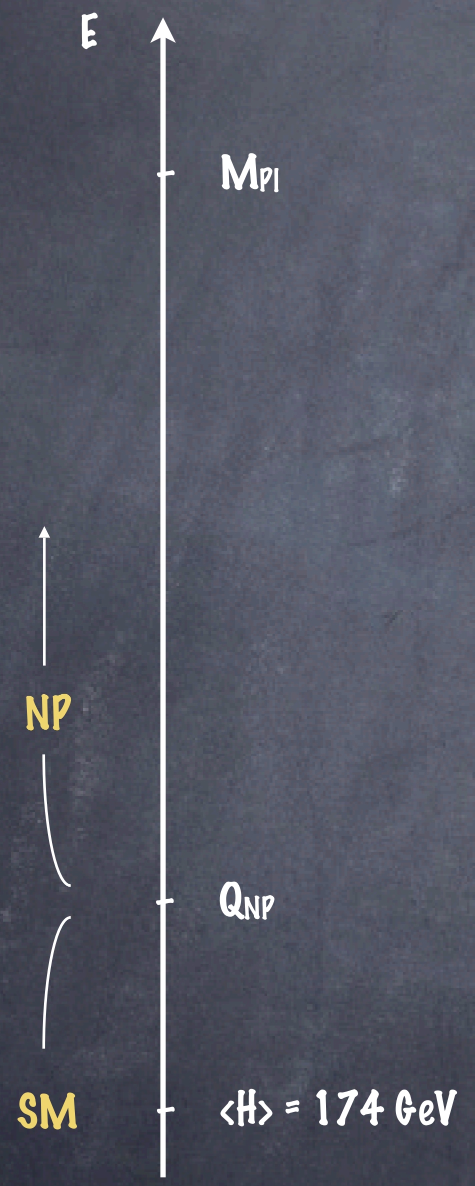

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$$Q_{\rm NP} \gtrsim \sqrt{c_i}\cdot 5\,{\rm TeV} \approx \begin{cases} 50\,{\rm TeV} & \text{composite } e \\ 5\,{\rm TeV} & \text{composite } G_a,\, h \\ 0.5\,{\rm TeV} & \text{1-loop perturbative} \end{cases}$$

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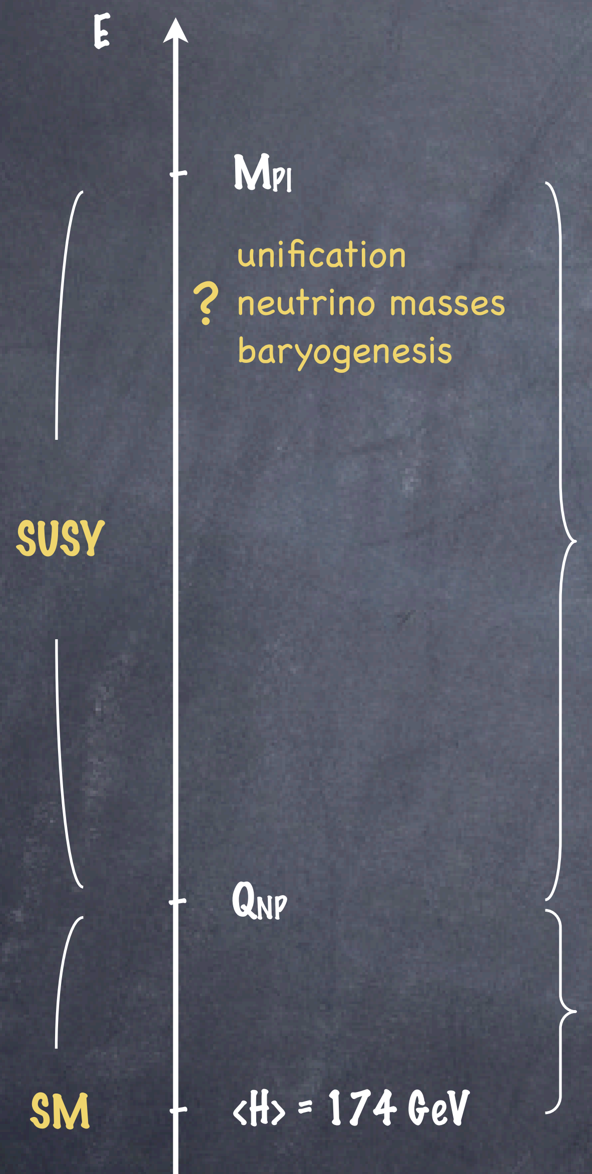

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Fine-tuning in the MSSM

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$$\approx -2\left(m_{h_u}^2(M_0) + |\mu|^2\right) + 2\,\delta m_{h_u}^2$$
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- Indirect bound on stop mass stronger (but direct one is also relevant)

$$(114\,\mathrm{GeV})^2 < m_h^2 < M_Z^2\cos^2 2\beta + \frac{3}{4\pi^2}h_t^2 m_t^2 \log\frac{\tilde{m}_t^2}{m_t^2} \Rightarrow \mathrm{FT} \sim 50 \div 100$$

A comment on scanning procedures

- Numerical procedures typically trade |μ| for M_Z: do not "see" FT

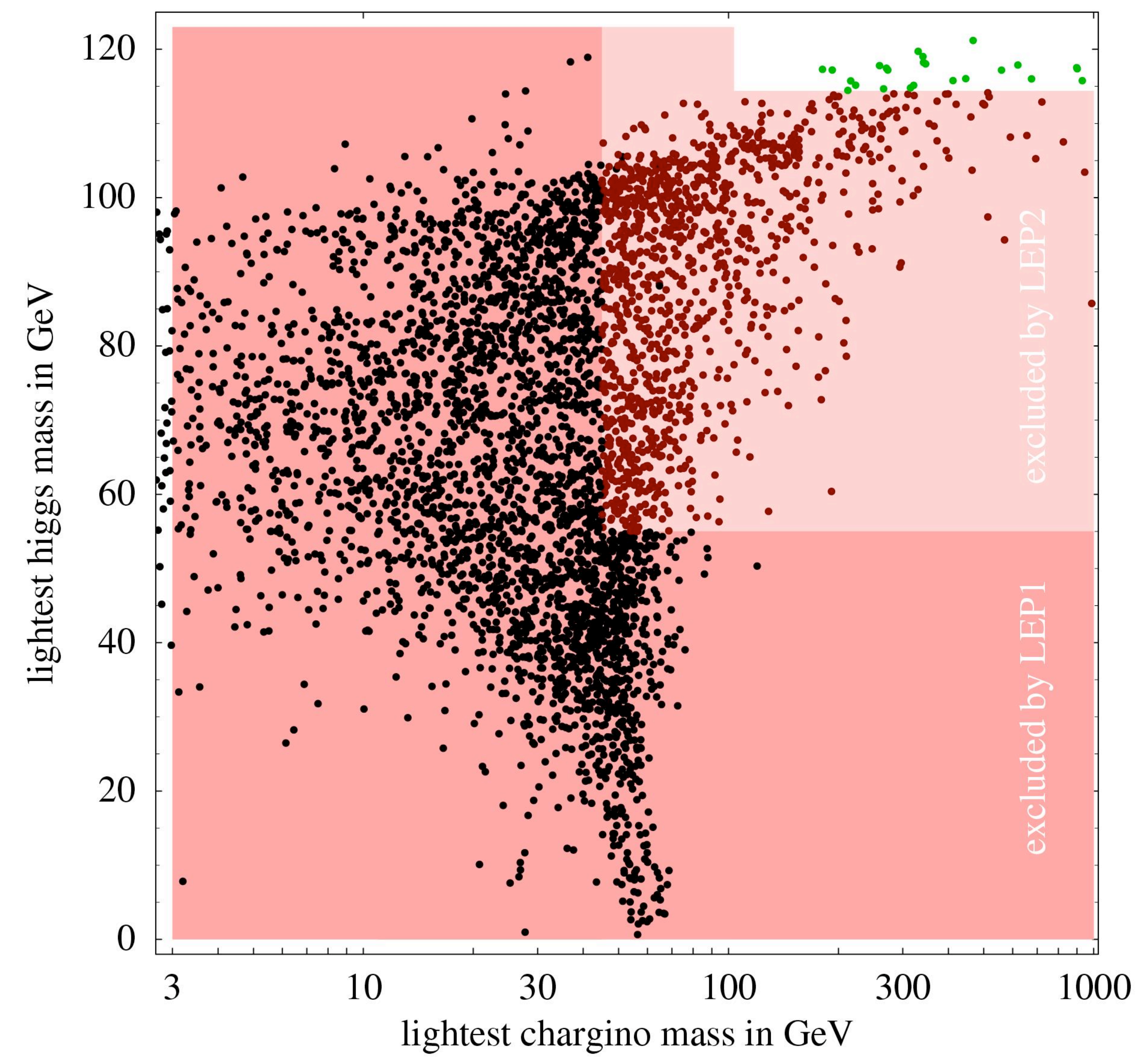
$$M_Z^2 \approx -2\left(m_{h_u}^2(M_0) + |\mu|^2\right) + 2\,\delta m_{h_u}^2$$

- The FT problem then may introduce a bias in numerical scans of the MSSM parameter space: the (necessary) cancellation is forced to take place between μ^2 and all the rest

- Example: LSP is rarely an Higgsino (work in progress)

What is left?

- Quantitative measure of naturalness nicely taking into account and combining all the considerations above
  - Scan the relative sizes of SUSY parameters and the SM parameters in their ranges
  - Set the overall scale of SUSY parameters from <H> = 174 GeV
  - Calculate SUSY spectrum and compare with experiment
- Few O(1%) of points satisfy all experimental constraints



[Giusti R Strumia]

Beyond MSSM: xMSSM

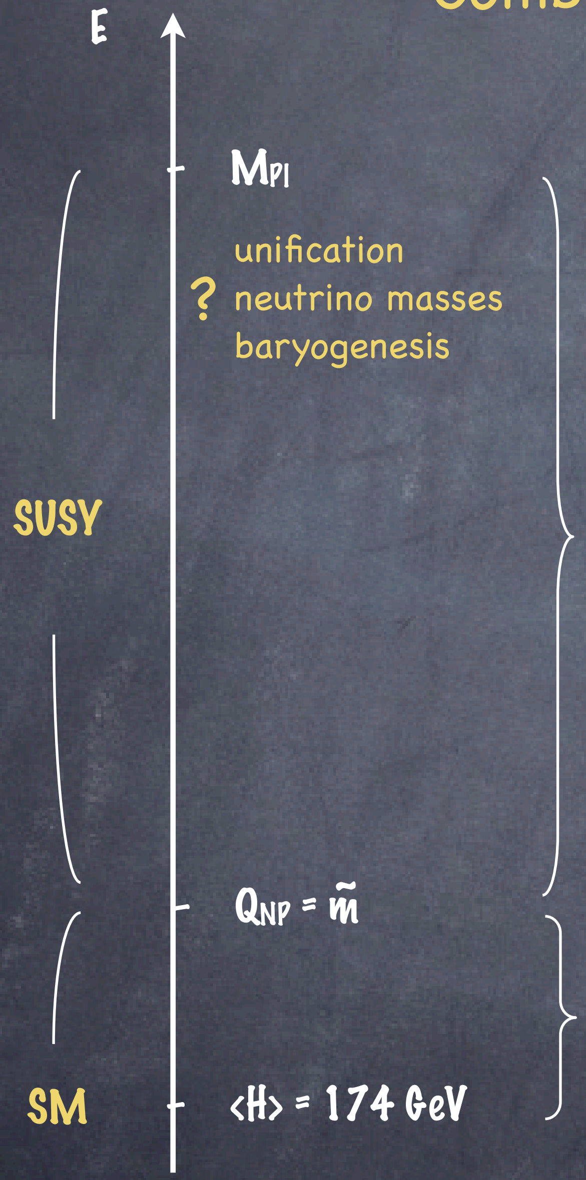
- Minimal extension: $\lambda S H_u H_d$ (symmetries forbid $\mu H_u H_d$)
  - harmless (unification OK)
  - welcome ($\mu = \lambda\langle S\rangle \approx$ susy scale)
- Spectrum: h H → h_1 h_2 h_3, A → a_1 a_2, $N_1 \ldots N_4$ → N_0 $N_1 \ldots N_4$
- Help with FT from $(114\,\mathrm{GeV})^2 < m_h^2 < M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} h_t^2 m_t^2 \log \frac{\tilde{m}_t^2}{m_t^2}$:
  - $\lambda_h = \frac{g^2 + g'^2}{4} \cos^2 2\beta + \frac{\lambda^2}{2} \sin^2 2\beta + \mathrm{loops}$ gain limited by poles

    λ(10 TeV) < 3 (EWPTs) best, $\lambda(M_{GUT})$ < 3 (unification) OK
  - $m_h^2 < (114\,\mathrm{GeV})^2$ hidden Higgs: h → aa → 4X (m_a protected by PQ, R)
- Persistent FT from
  - direct bounds on SUSY partners
  - arranging the invisible decay [Shuster Toro hep-ph/0512189]

- Invisible Higgs decays: $h \to aa \to 4X$
- 3leptons → multileptons from additional steps in chargino/neutralino decays
  - C_1+N_2 and then
  - $N_2 \to N_1+2l \to N_0+4l$ (if N_0 is lightest and mainly singlino)
  - $C_1 \to N_0+l+\nu$ (5l overall) or even $C_1 \to N_1+l+\nu \to N_0+3l+\nu$ (7l overall)
- Deviation from MSSM coupling relations: $VVh = VHA = \sin^2(\alpha-\beta)$, $VVH = VhA = \cos^2(\alpha-\beta)$ (optimistic)
- Z′ if μ is protected by a gauge symmetry

Other variations on the MSSM

Combine MSSM with extra-dimensions not far from TeV



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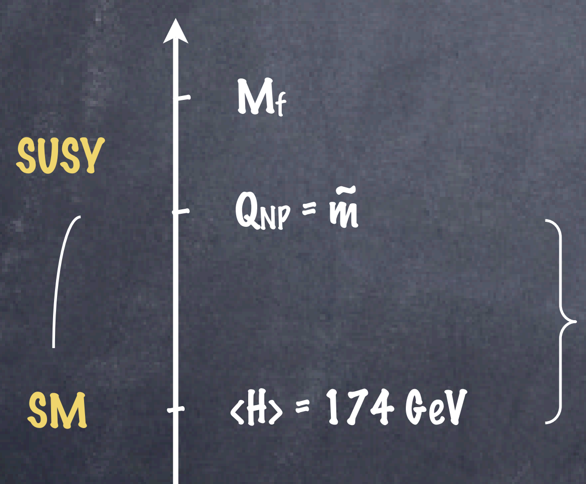

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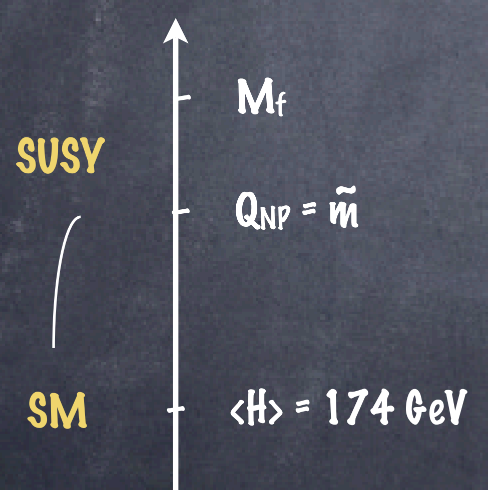

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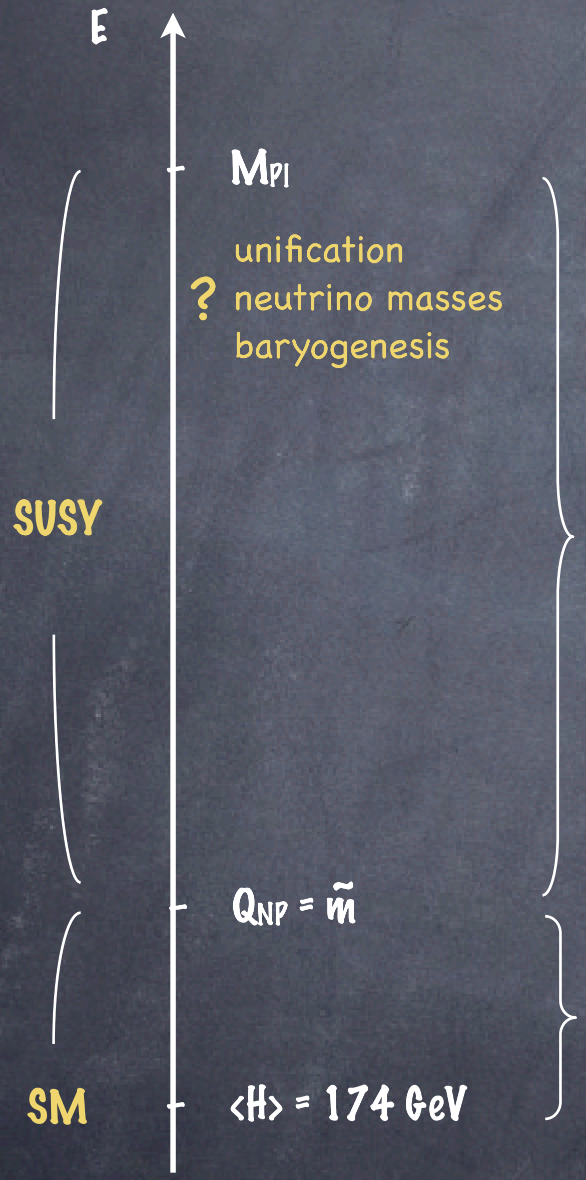

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SSM with $Q_3 = (t_L\ b_L)$ = gaugino

- $G = SU(5) \times G'_{SM}$ broken to the diagonal G_{SM} [Cai Cheng Terning, arXiv:0806.0386]
- Extra vector superfields ≈ $Q+\bar{Q}$, g′ W′ B′
- $H_5 \approx (5,1) \approx H_d + T^c$
- $g A_i^\dagger T_A^{ij} \lambda_A \psi_j \to \lambda_t H_d^\dagger Q T^c$

Strongly coupled models

- Higgsless (technicolor & C): G_a Goldstones of global $SU(2)_L \times SU(2)_R$
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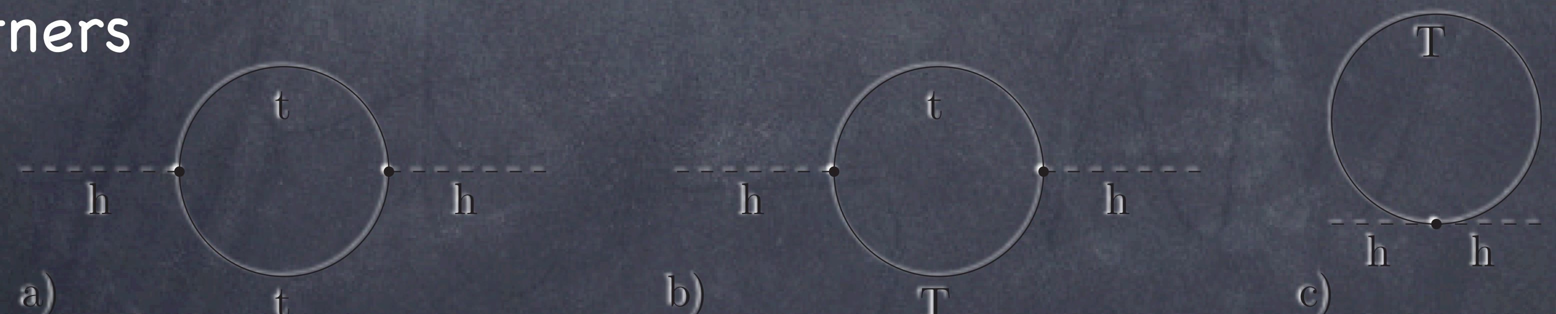
- More clever explicit breaking ("collective breaking"): **Little Higgs**
    - no 1-loop $Q_{\rm NP}^2$ terms (exact-NGB unless 2+ non-vanishing couplings)
    - the top (gauge, Higgs) loop **must** be cancelled at a lower scale (= global symmetry breaking scale f « Q_{strong}) by same statistics partners



Little Higgs

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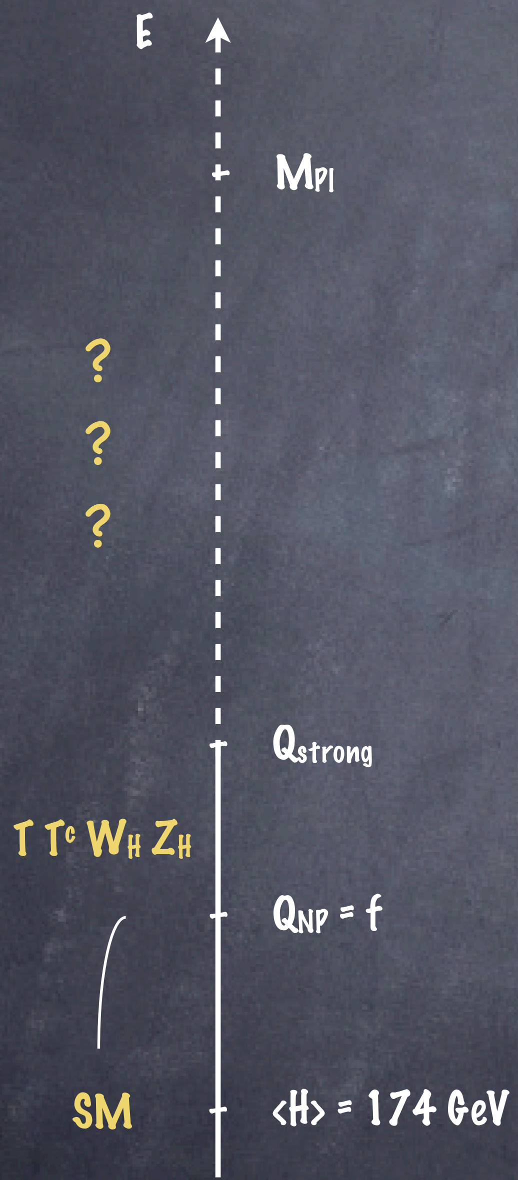

$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2 \log \frac{Q_{\rm strong}^2}{Q_{\rm NP}^2} + 2 \text{ loops}$$

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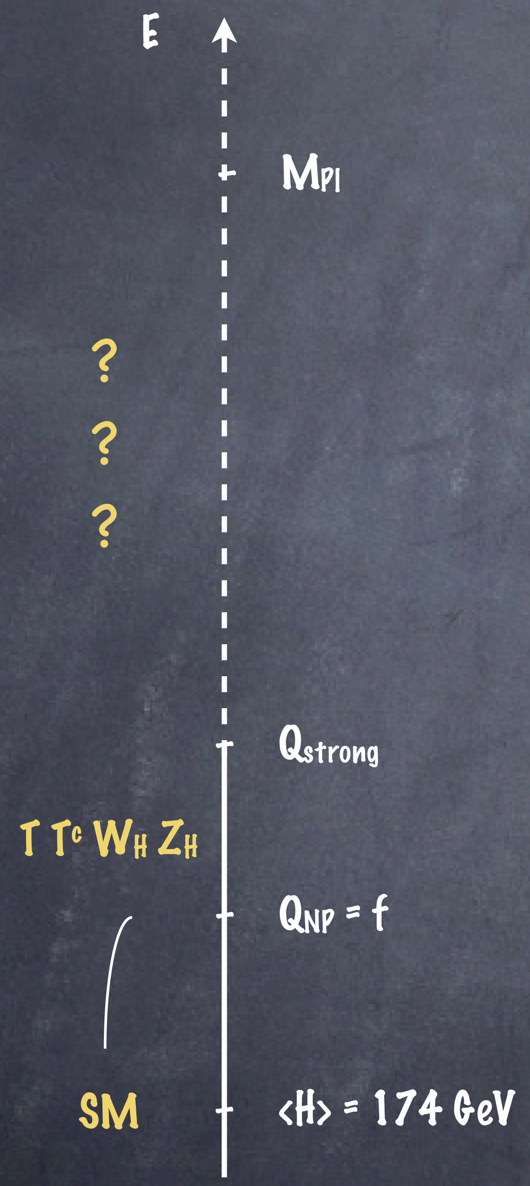

- Q_{NP}: Q_{strong} → f = global symmetry breaking scale (separate the top loop cutoff from Q_{strong} > 5 TeV)
- Bounds on Q_{NP} from EWPT still worse than MSSM (unless T-parity is used), FT similar
- No dramatic gain but interesting alternative

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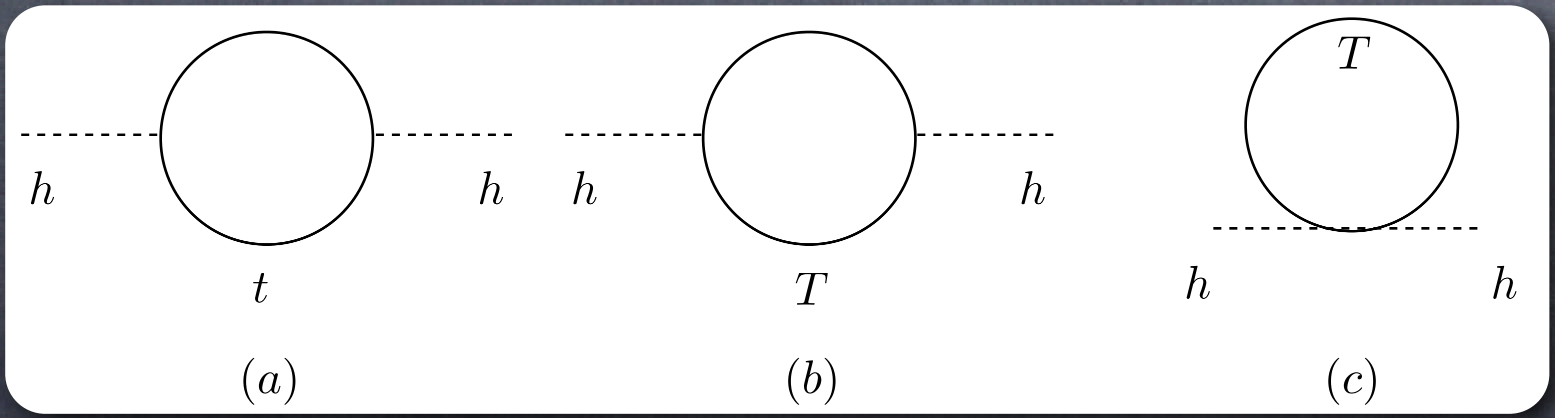
LH @ LHC

- Observe the partners responsible for the divergence cancellation
  - $qq \to Z_H \to l^+l^-$ up to few TeV (standard); also → ff, VV, Vh
  - T, T^c: single production (bWT) dominates (b pdf up to ≈0.2)
    - $\Gamma(T\to th) = \Gamma(T\to tZ) = \Gamma(T\to bW)/2$ all identifiable: $tZ \to bWl^+l^-$ (m_T), $th \to bWbb$ (m_h, m_T), $bW \to bl\nu$
  - additional (++) Higgs states
- Observe the divergence cancellation



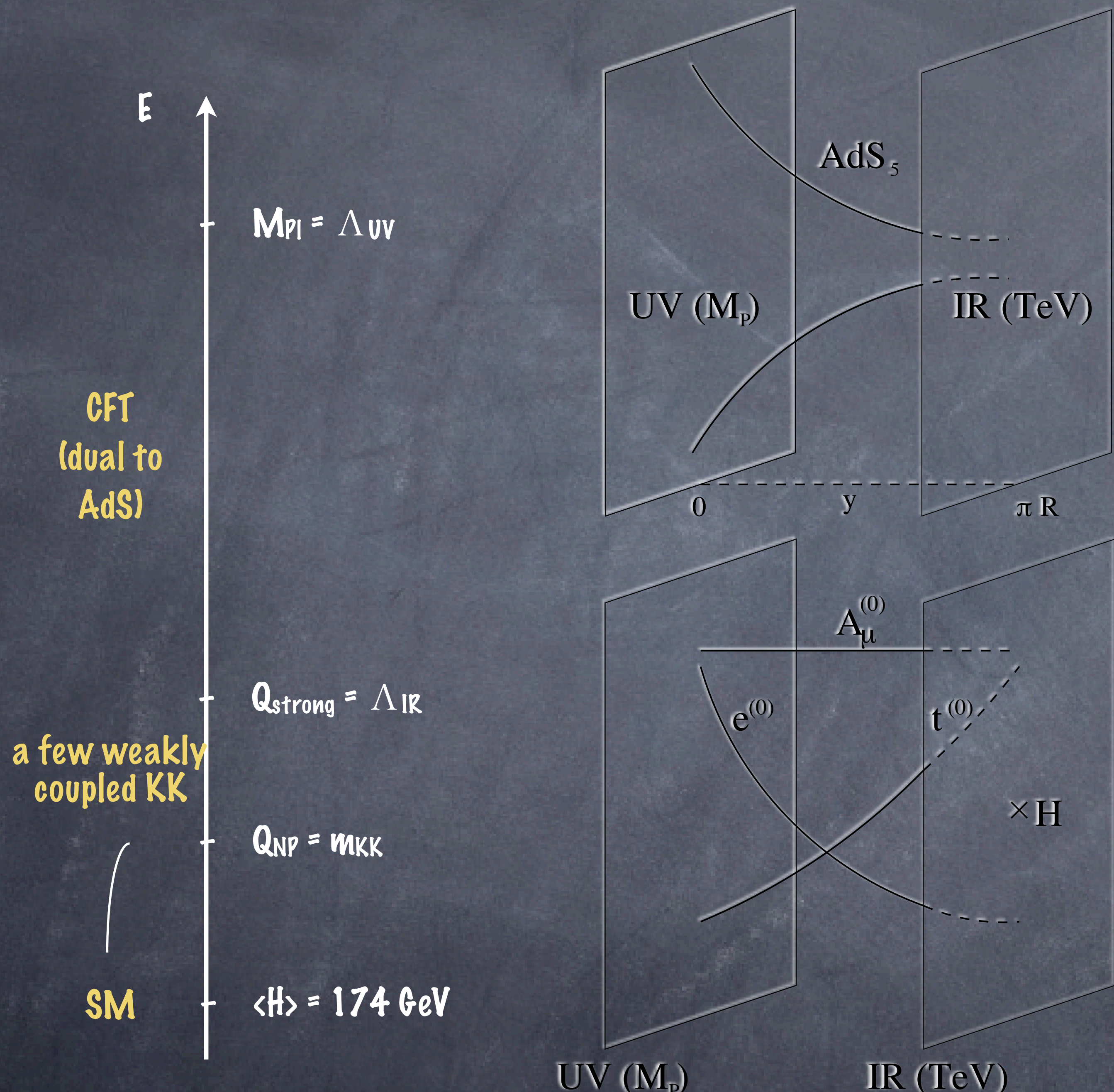
$$(a) = -6\lambda_t^2 \int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2},$$

$$(b) = -6\lambda_T^2 \int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2 - m_T^2},$$

$$(c) = +6\frac{\lambda_T}{f} \int \frac{d^4k}{(2\pi)^4}\frac{m_T}{k^2 - m_T^2}$$

$$-\lambda_t^2 \qquad -\lambda_T^2 \qquad +\lambda_T\frac{m_T}{f} \qquad = 0$$

Warping and composite Higgs



$$m_h \sim M_5 e^{-\pi k R}$$

$$k = \text{curvature}$$

- RS + bulk fermions + H as $(A_5)_0$ + deconstruction = Little Higgs + UV completion
- m_H protection: collective breaking = bc breaking of 5D gauge symmetry
- 4D dual: UV brane: elementary
  IR brane: composite (H, t_R)
- Q_{strong} > 5 TeV as usual
  m_{KK} > TeV, watch $Z \to b\bar{b}$
- Gauge coupling unification in a novel way (but limited calculability)

@LHC (a first look)

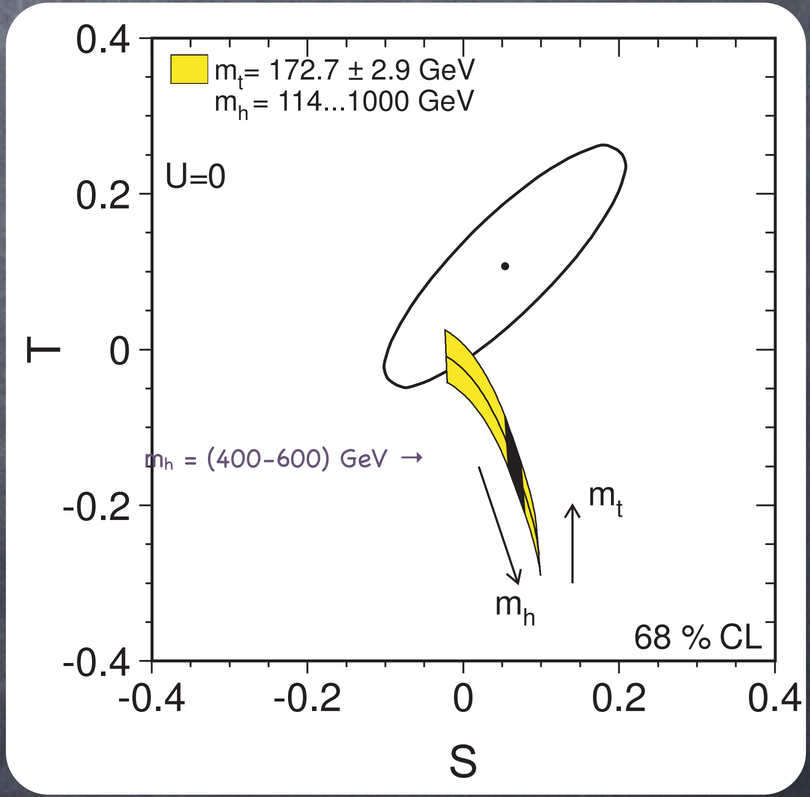
- Keep only first excitation:
  - |SM> = cosφ |elem> + sinφ |comp>
  - |KK> = -sinφ |elem> + cosφ |comp>
- Production:
  - $A(SM_1\ SM_2 \rightarrow KK_3) \propto -g_w \cos\varphi_1 \cos\varphi_2 \sin\varphi_3 + g_s \sin\varphi_1 \sin\varphi_2 \cos\varphi_3$
  - SM_3 needs to be substantially composite:
    t_R (bW fusion) or V_{long} (DY) (analogous to LH)
- Decay:
  - into V_{long} and heavier particles (t_R b_R, τ if non negligible) dominates
  - also: $(\text{gluon})_{KK} \rightarrow t_R \bar{t}_R$
  - possibly lepton excitations (if open)

Back to the residual hierarchy

$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2 = \begin{cases} m_h^2 \left(\frac{Q_{\rm NP}}{0.5\,{\rm TeV}}\right)^2 & \text{if } m_h = 115\,{\rm GeV} \\ m_h^2 \left(\frac{Q_{\rm NP}}{2\,{\rm TeV}}\right)^2 & \text{if } m_h = 250\,{\rm GeV} \end{cases}$$

$$Q_{\rm NP} \gtrsim \sqrt{c_i} \cdot 5\,{\rm TeV} \approx \begin{cases} 50\,{\rm TeV} & \text{composite SM fermions} \\ 5\,{\rm TeV} & \text{composite Higgs} \\ 0.5\,{\rm TeV} & \text{1-loop perturbative} \end{cases}$$

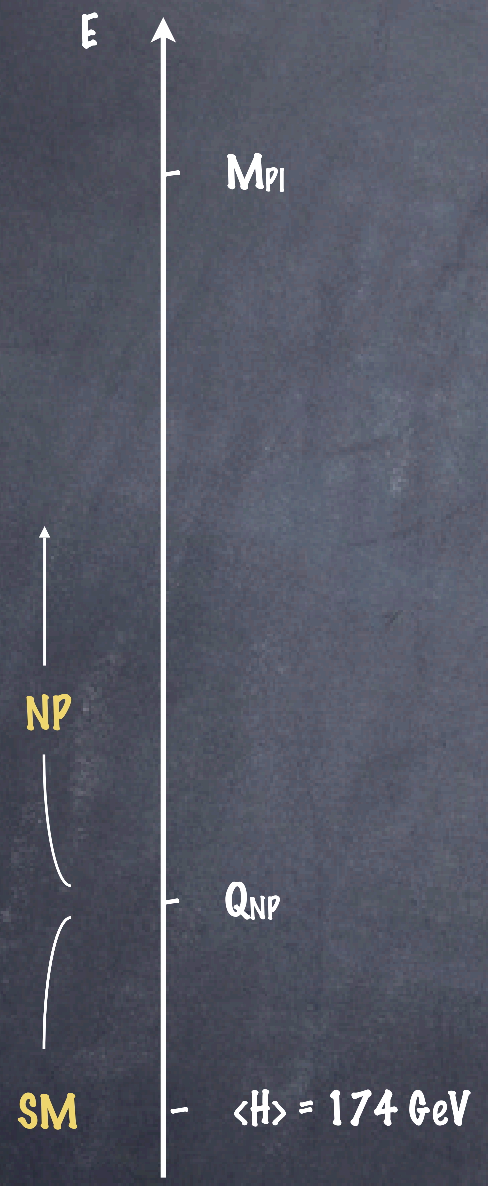
- m_h = 500 GeV would help; disfavoured by EWPTs only within the SM
- Cancel SM heavy Higgs contributions to EWPT with NP (goodness off SM + light H fit accidental but not too much fine-tuned)
- Generic prediction of NP giving ΔT = 0.25±0.1



An inert Higgs

- H_1 (h): usual Higgs (but heavier): EWSB, M_W M_Z, m_f
- H_2 (H, A, $H^\pm$): inert Higgs (60 GeV-1TeV): no vev, no coupling to fermions ($H_2 \to -H_2$), gives $\Delta T = 0.25 \pm 0.1$
- DM candidate for $m_H \approx 70$ GeV (LEP?)
- Pair production: $pp \to W^* \to H^+H$, H^+A or $pp \to Z^* \to H^+H^-$, HA
- Decay into the lightest + gauge bosons (no fermions) → charged leptons in the final states
- UV completion?

Is a natural m_H unavoidable?



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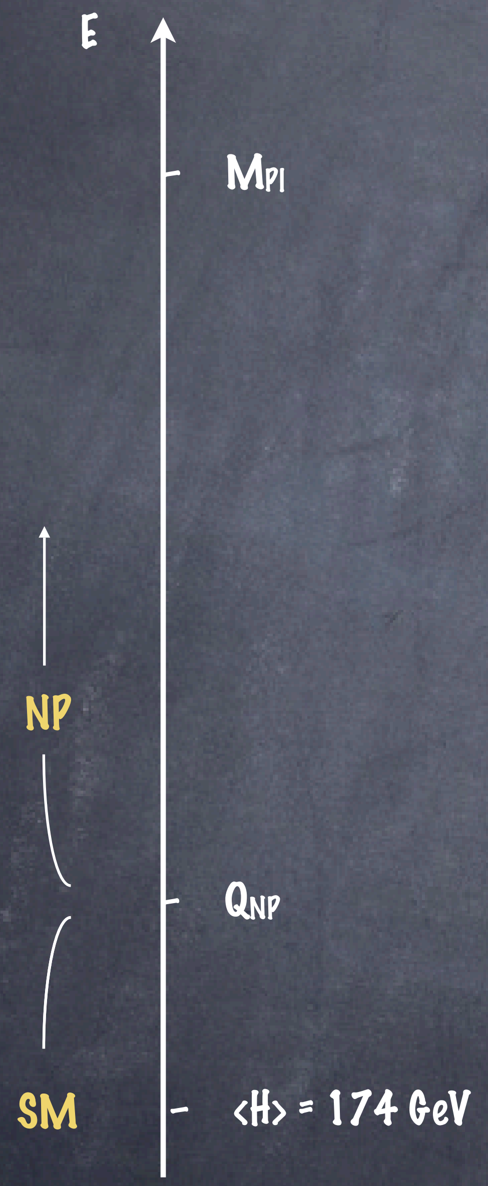

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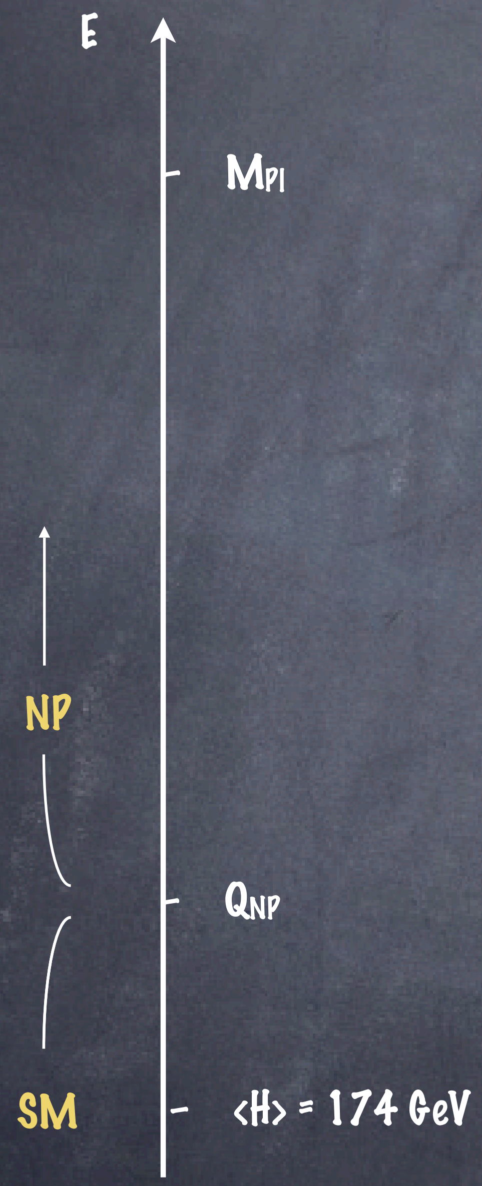

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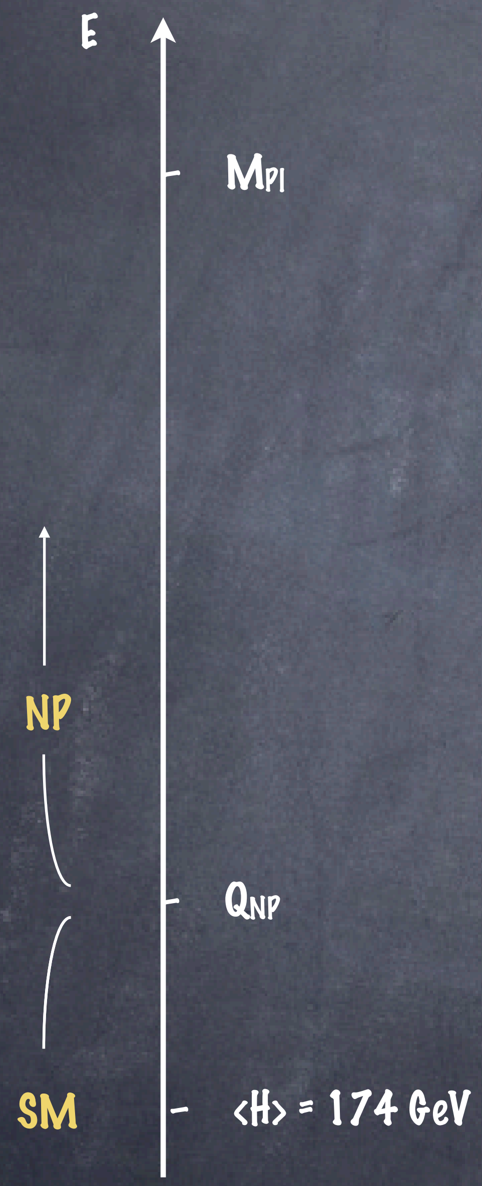

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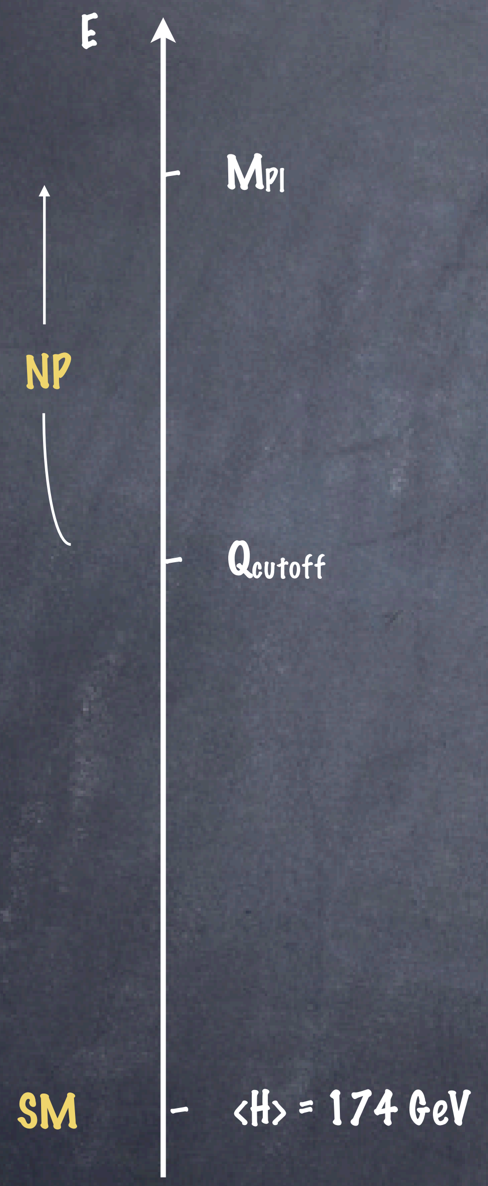

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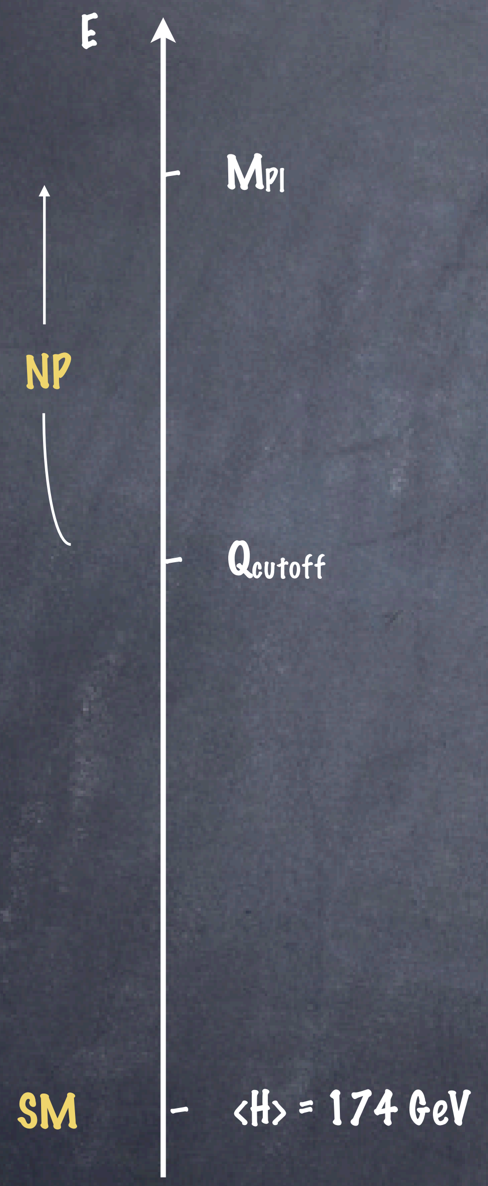

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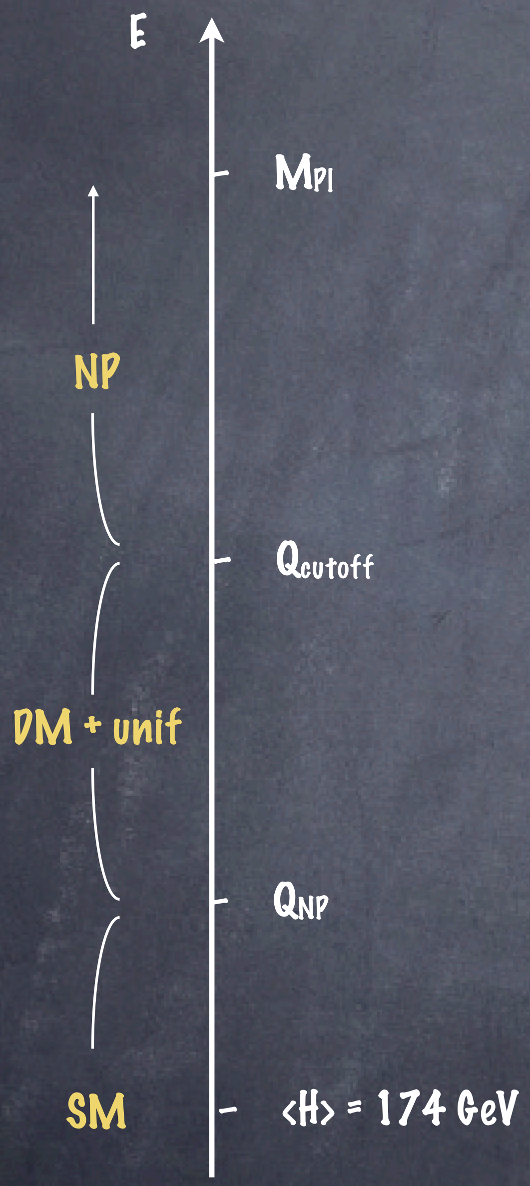

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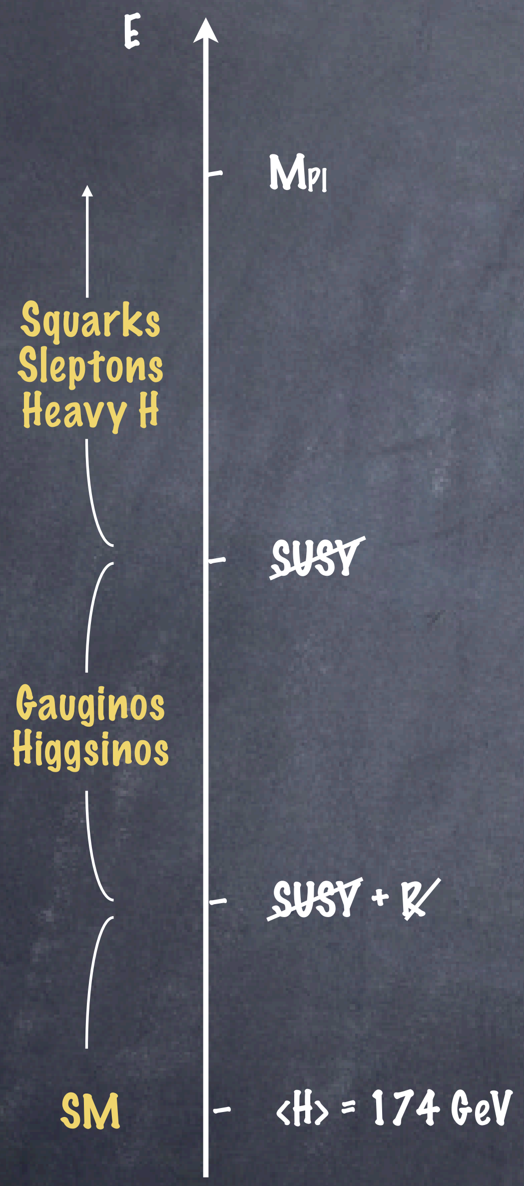

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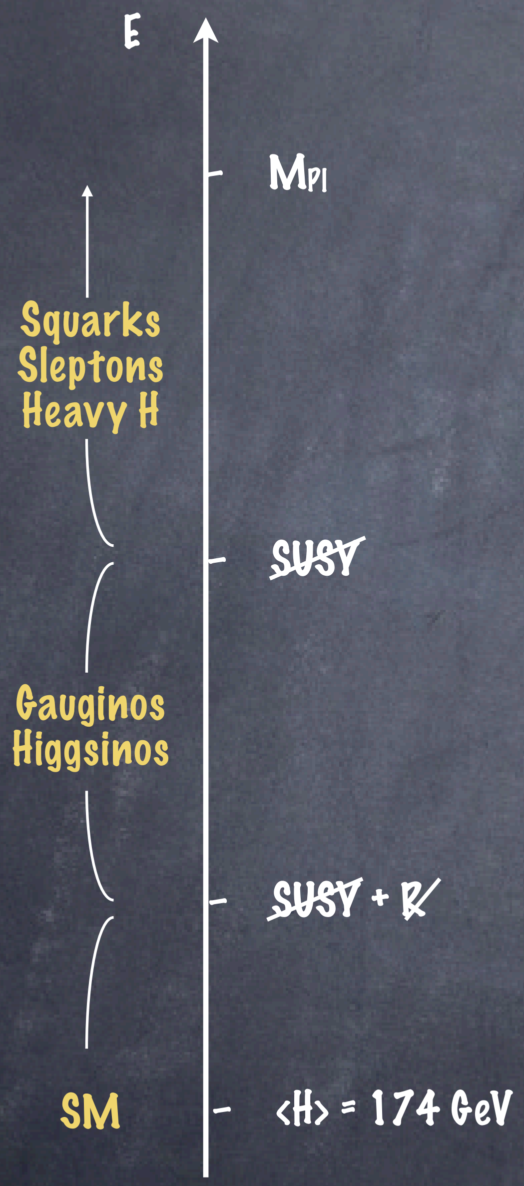

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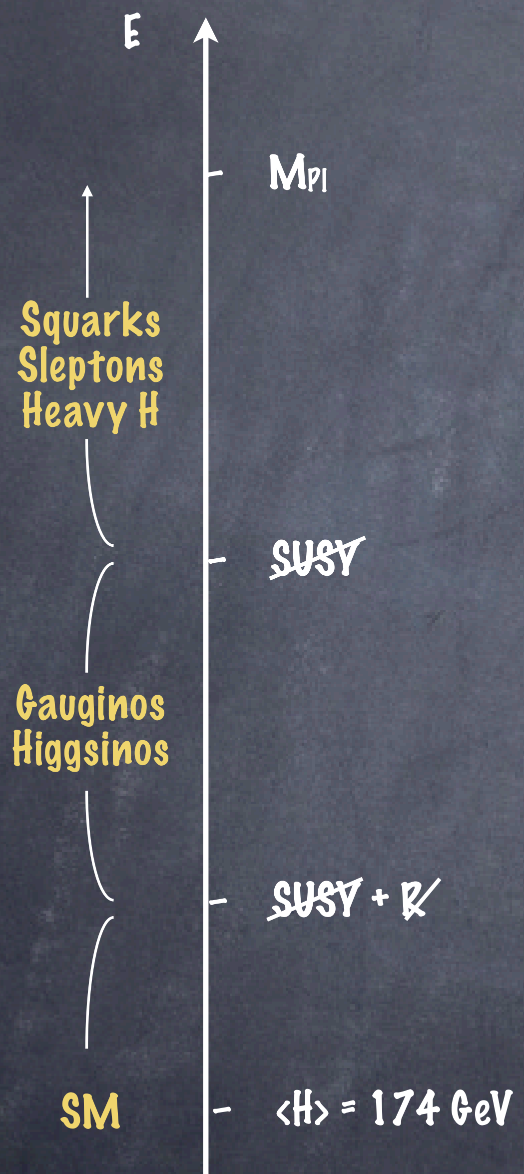

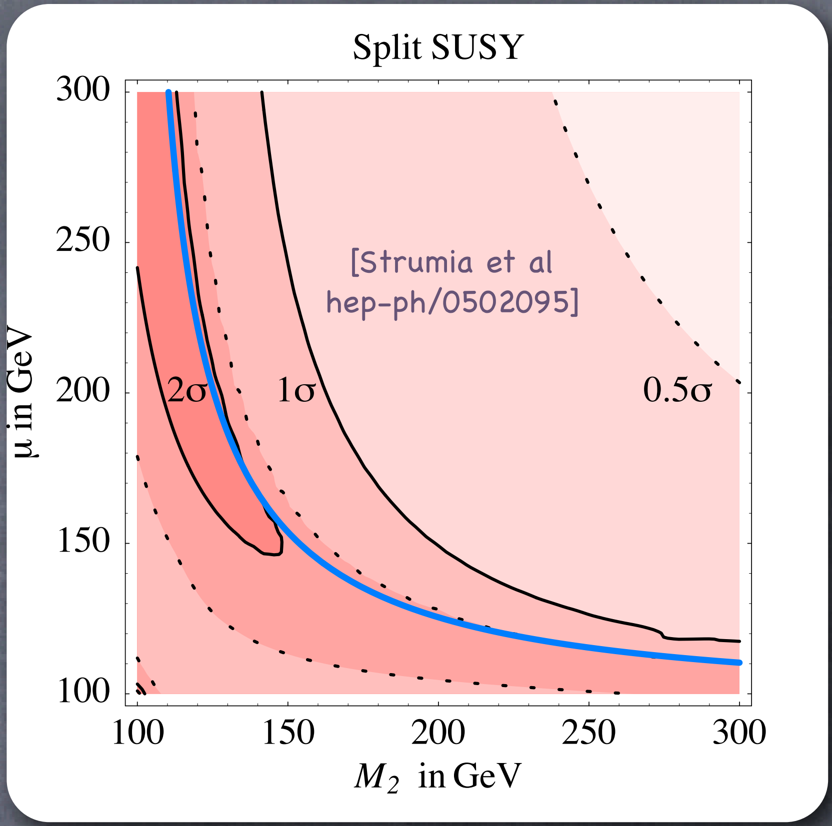

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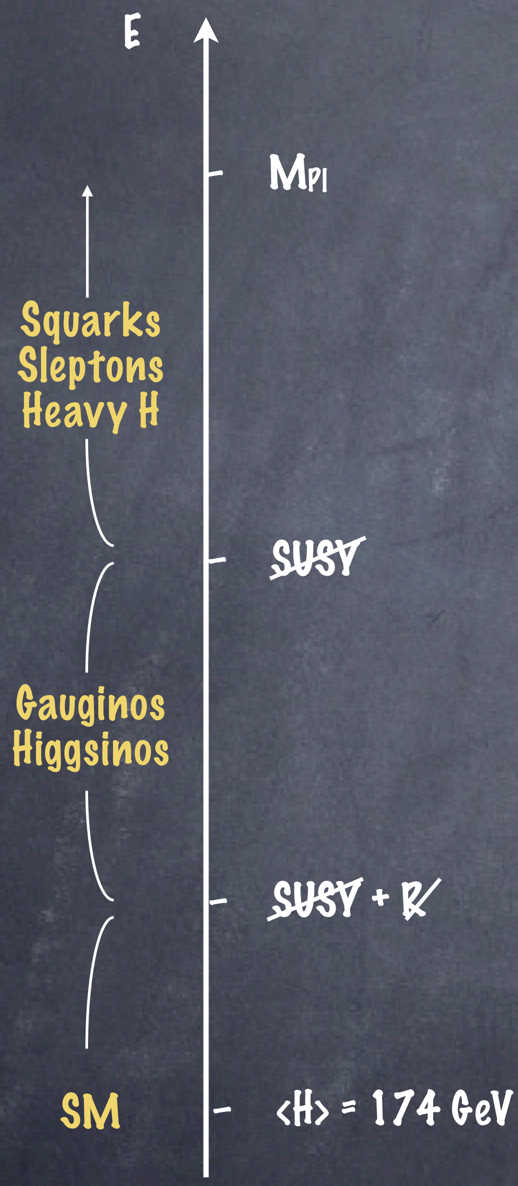

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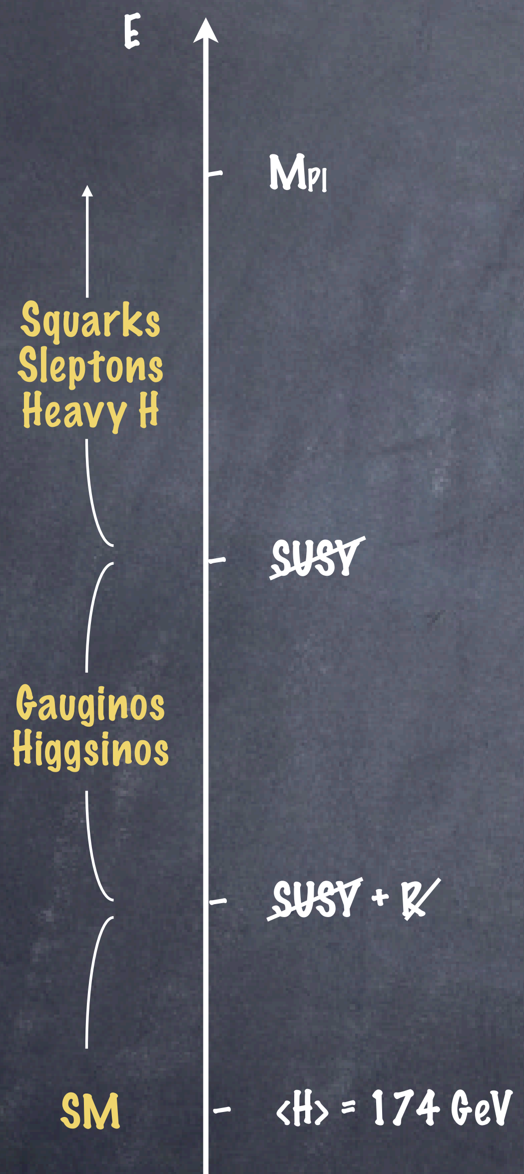

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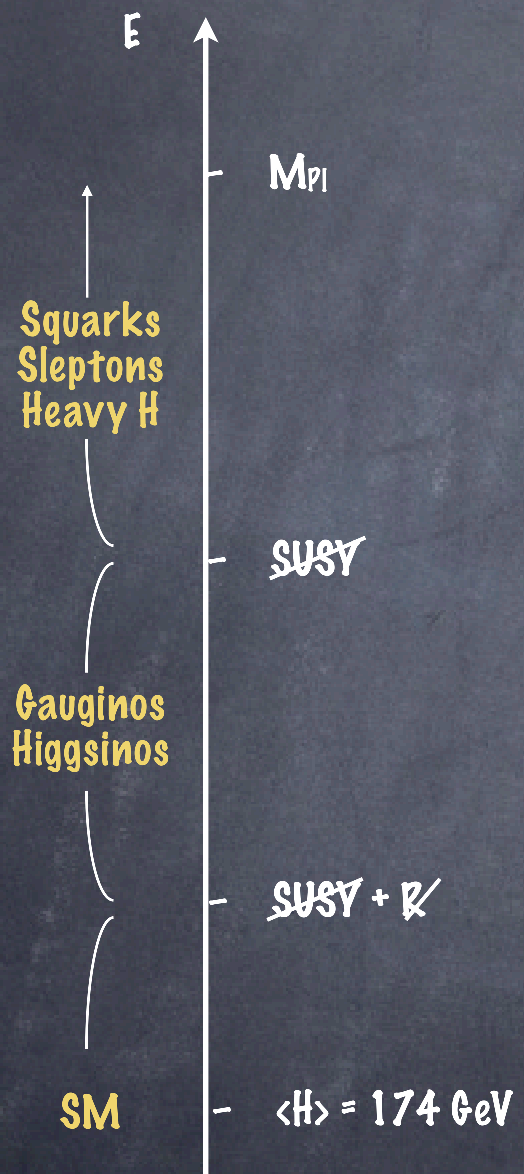

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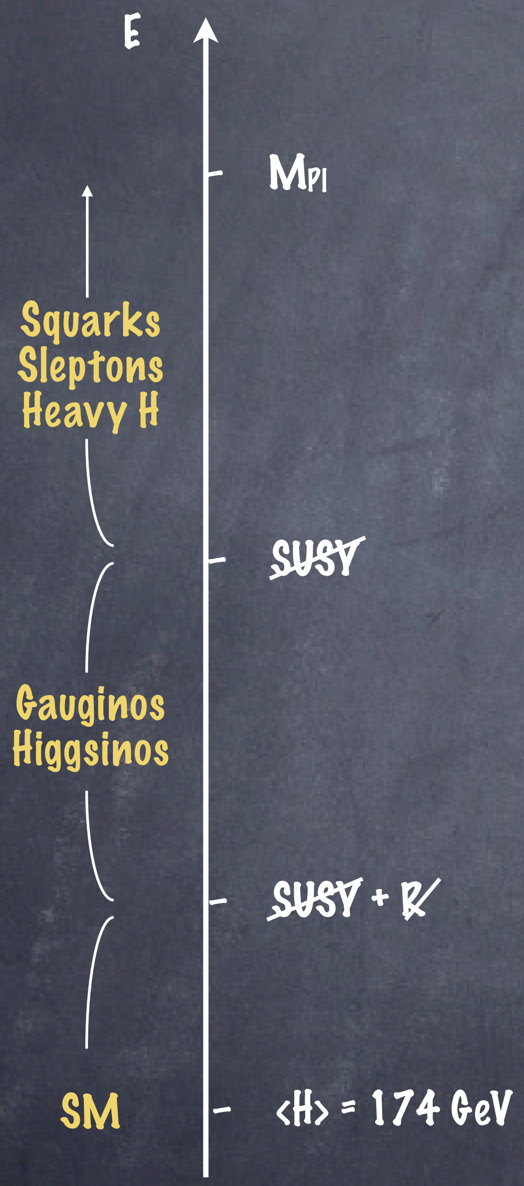

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- Wilder: stopping gluinos (1-2 jets in any direction from denser parts of the detector + m.e.), displaced vertexes (low m), charge flips

Summary

- Is a % tuning really worth worrying?
- If not, NP could as well be out of reach of the LHC
- Barring independent arguments (e.g. DM)
- Useful and fruitful guideline within models addressing the naturalness issue
- Surprises are not unlikely

- Experimental “problems” of the SM:
  - Gravity
  - Dark matter
  - Baryon asymmetry
- Experimental “hints” of physics beyond the SM
  - Neutrino masses
  - Quantum number unification
- Theoretical puzzles of the SM:
  - $\langle H \rangle \ll M_{Pl}$
  - Family replication
  - Small Yukawa couplings, pattern of masses and mixings
  - Gauge group, no anomaly, charge quantization, quantum numbers
- Theoretical problems of the SM:
  - Naturalness / unitarity problem
  - Cosmological constant problem
  - Strong CP problem