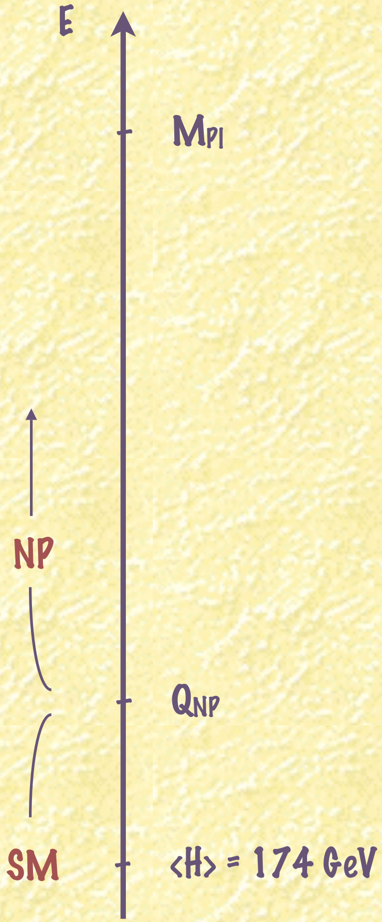
# Scenarios for LHC physics

Andrea Romanino
SISSA

# Indirect information on NP




- The SM holds up to $Q_{NP}$
- At $E < Q_{NP}$, new physics is parameterized in terms of D>4 interactions suppressed by powers of $E/Q_{NP}$, in analogy to Fermi's effective description of weak interactions
  - general parameterization of the physics above Q
  - the experimental identification of D>4 interactions at $E < Q_{NP}$ would provide information on the physics above $Q_{NP}$ (as in the case of weak interactions); no clear evidence so far (except neutrinos) → lower limit on $Q_{NP}$

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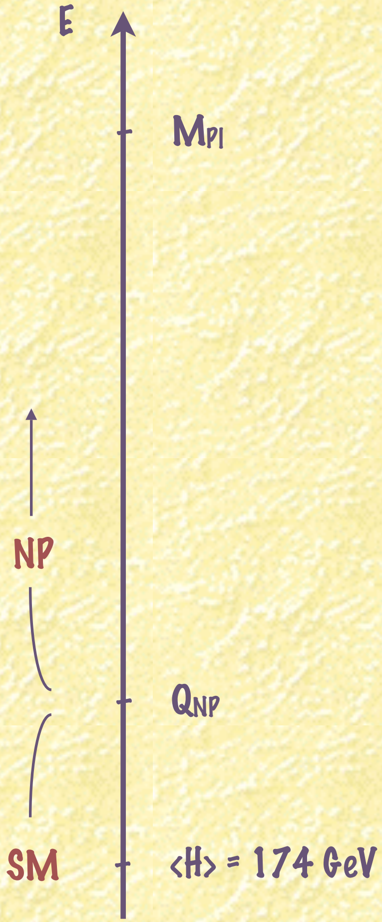


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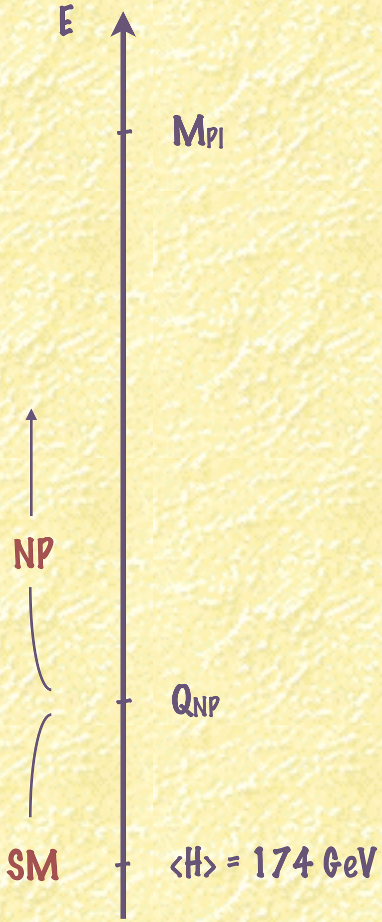


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$$\frac{g^2}{2M_W^2}\bar{\psi}_1\Gamma^A\psi_2\,\bar{\psi}_3\Gamma_A\psi_4 \quad \Rightarrow \quad \frac{g^2}{8M_W^2}\bar{\psi}_1\gamma^\mu(1-\gamma_5)\psi_2\,\bar{\psi}_3\gamma_\mu(1-\gamma_5)\psi_4$$

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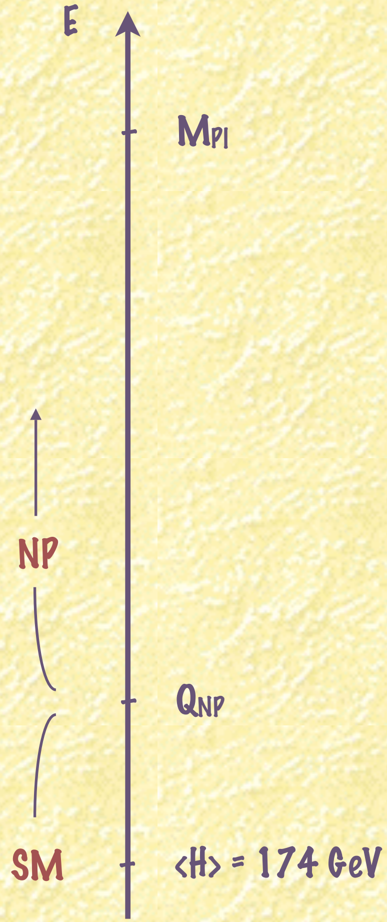


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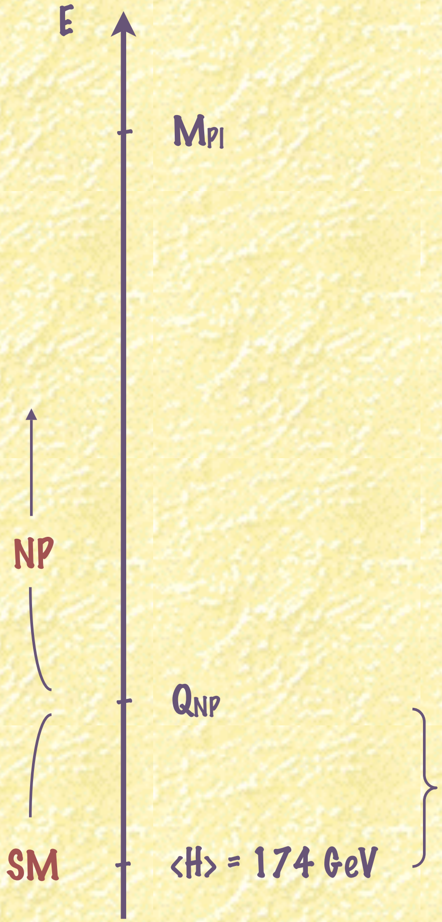
- Leading theoretical guideline on the physics at $Q_{NP}$: a natural solution of the hierarchy problem

# LEP and the residual hierarchy

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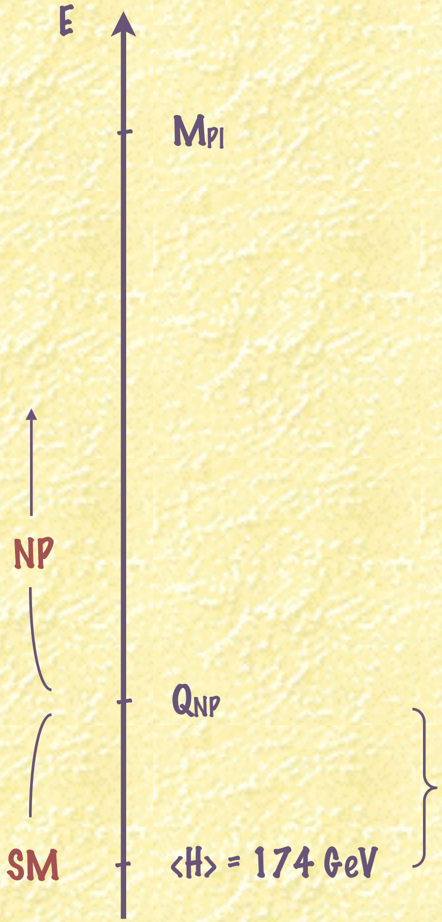


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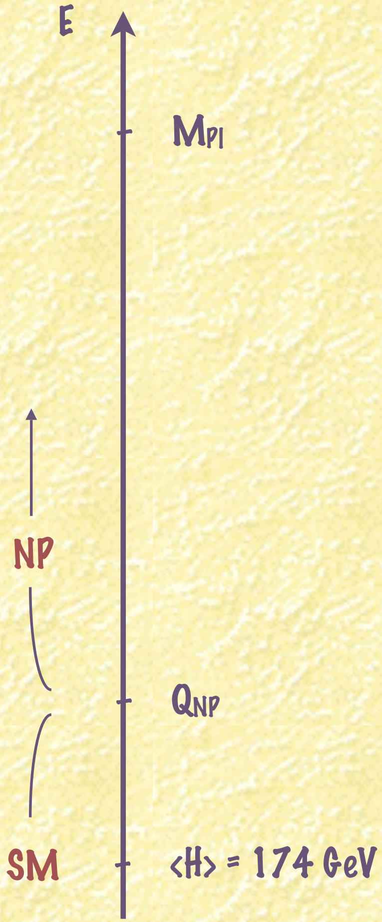


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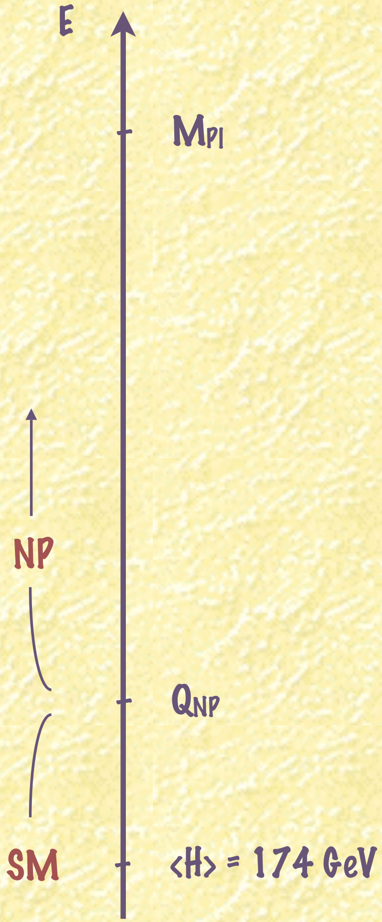


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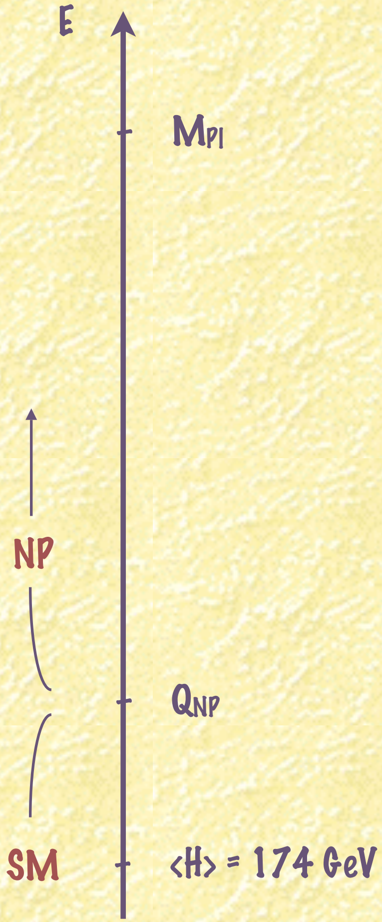


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$$Q_{\rm NP} \gtrsim \sqrt{c_i}\cdot 5\,{\rm TeV} \approx \begin{cases} 50\,{\rm TeV} & \text{composite SM fermions} \\ 5\,{\rm TeV} & \text{composite Higgs} \\ 0.5\,{\rm TeV} & \text{1-loop perturbative} \end{cases}$$

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# Scenarios

# MSSM

Higgs mass protected by scalar $\leftrightarrow$ fermion

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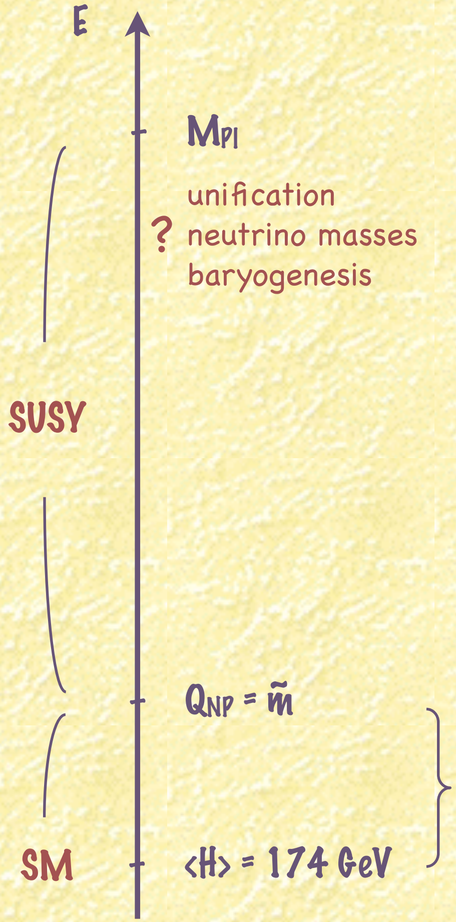


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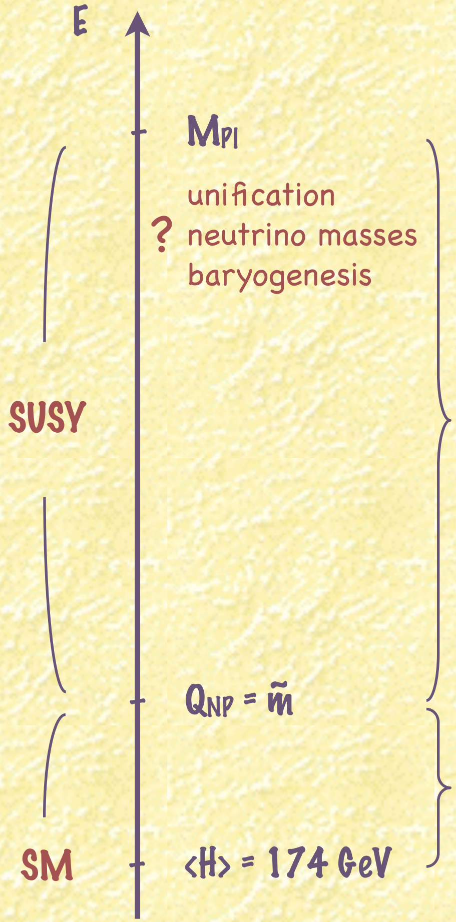
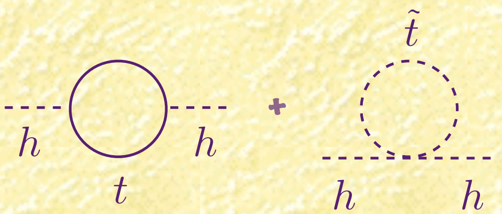



$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2 \log\frac{M_{\rm Pl}^2}{Q_{\rm NP}^2}$$

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# Fine tuning in the MSSM

$$M_Z^2 \approx (91\,\mathrm{GeV})^2 \left[ \frac{\tilde m_Q^2}{(70\,\mathrm{GeV})^2} - \frac{\tilde m_H^2}{(80\,\mathrm{GeV})^2} + \frac{M_{1/2}^2}{(40\,\mathrm{GeV})^2} - \frac{\mu^2}{(70\,\mathrm{GeV})^2} \right]$$

- FT ≈ maximum contribution in [...] (+ possibly in tanβ and $m_t$)
- Benchmark points:

$$M_{1/2} = (250 \div 1840)\,\mathrm{GeV}: \quad \mathrm{FT} \simeq 40 \div 2000$$

[De Roeck, Ellis, Gianotti, Moortgat, Olive, Pape]

$$\tilde m_Q = (1500 \div 4300)\,\mathrm{GeV}: \quad \mathrm{FT} \simeq 430 \div 3700 \quad \text{or} \quad M_{1/2} = 500\,\mathrm{GeV}: \quad \mathrm{FT} \simeq 150$$

[Lykken, Mrenna, Nelson, Wang, Wang]

- Direct lower limits on squark and gluinos

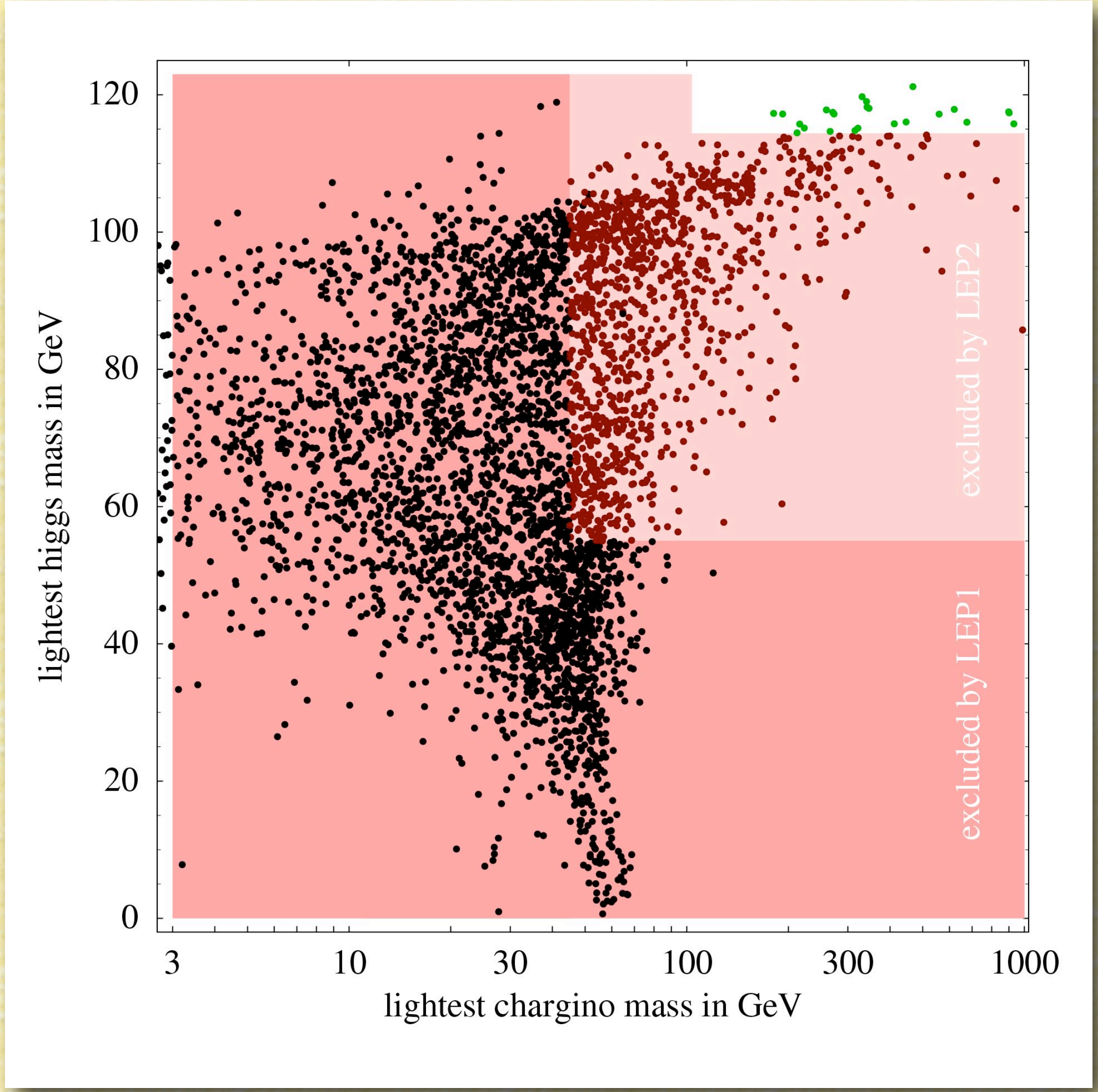
$$M_{\tilde g} \gtrsim \begin{cases} 195\,\mathrm{GeV} \\ 260\,\mathrm{GeV} \\ 500\,\mathrm{GeV} \end{cases} \Rightarrow \mathrm{FT} \gtrsim \begin{cases} 3 \\ 6 \\ 20 \end{cases} \qquad m_{\tilde t} \gtrsim \begin{cases} 300\,\mathrm{GeV} \\ 260\,\mathrm{GeV} \\ 100\,\mathrm{GeV} \end{cases} \Rightarrow \begin{cases} 25 \\ 10 \\ 50 \end{cases}$$

- Indirect lower limit on the stop mass

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

# What is left?

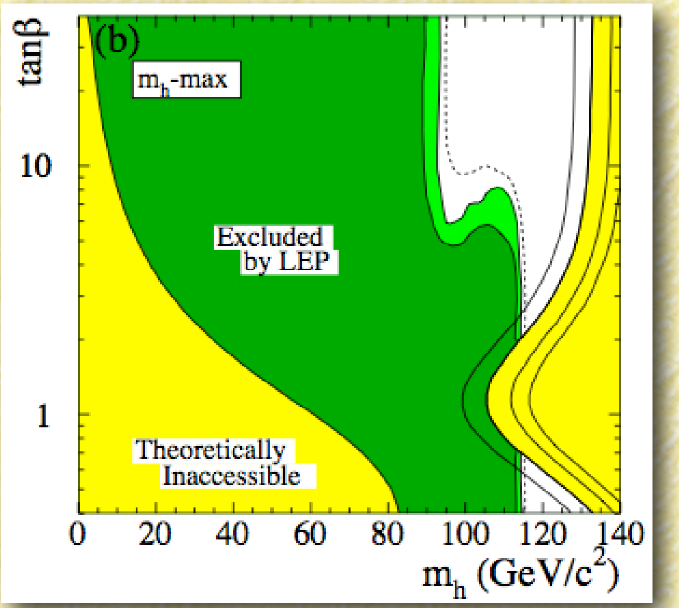
- Quantitative measure of naturalness nicely taking into account and combining all the considerations above
  - Scan the relative sizes of SUSY parameters and the SM parameters in their ranges
  - Set the overall scale of SUSY parameters from <H> = 174 GeV
  - Calculate SUSY spectrum and compare with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

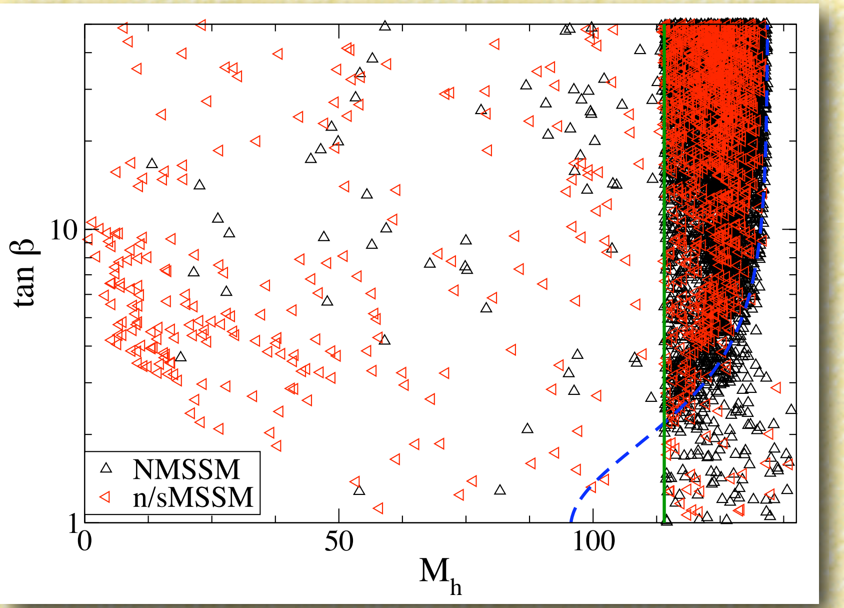



[Giusti R Strumia]

# Beyond MSSM: xMSSM

* Minimal extension: $\lambda S H_u H_d$ (with no $\mu H_u H_d$ because of symmetries)
  - 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 $(114\,\mathrm{GeV})^2 < m_h^2 < M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} h_t^2 m_t^2 \log \frac{\tilde{m}_t^2}{m_t^2}$ :
  - $\lambda_H = \frac{g^2 + g'^2}{4} \cos^2 2\beta + \frac{\lambda^2}{2} \sin^2 2\beta + \text{loops}$ (λ bound by Landau poles)
  - $m_h^2 < (114\,\mathrm{GeV})^2$ through invisible decays h → aa ($m_a$ protected by PQ, R)
* Persistent FT from
  - direct bounds on SUSY partners
  - arranging the invisible decay [Shuster Toro hep-ph/0512189]
* Signatures:



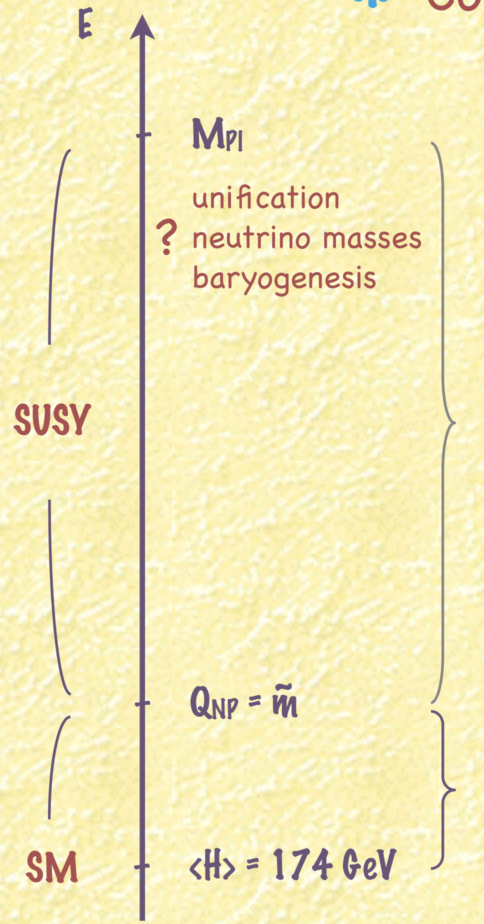

[Barger Langacker Lee Shaughnessy hep-ph/0603247]

- Invisible Higgs decays: $h \to aa \to 4X$ [No loose theorem? Ellwanger Gunion Hugonie Moretti hep-ph/0401228, ...]
- 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

[Pomarol Quiros hep-ph/9806263
Barbieri Hall Nomura hep-ph/0011311]

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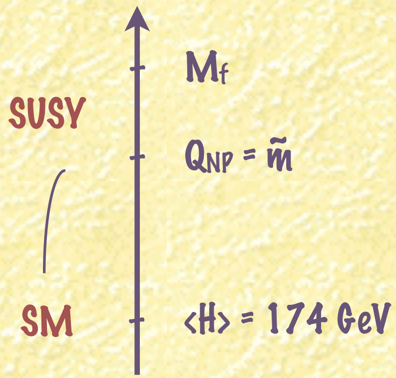


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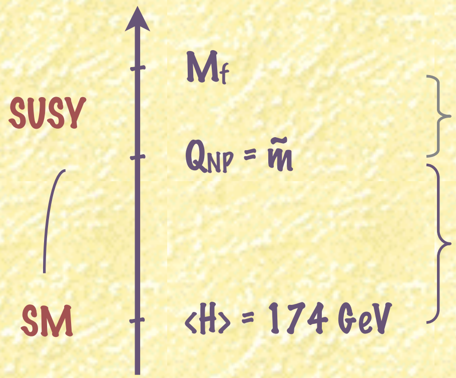


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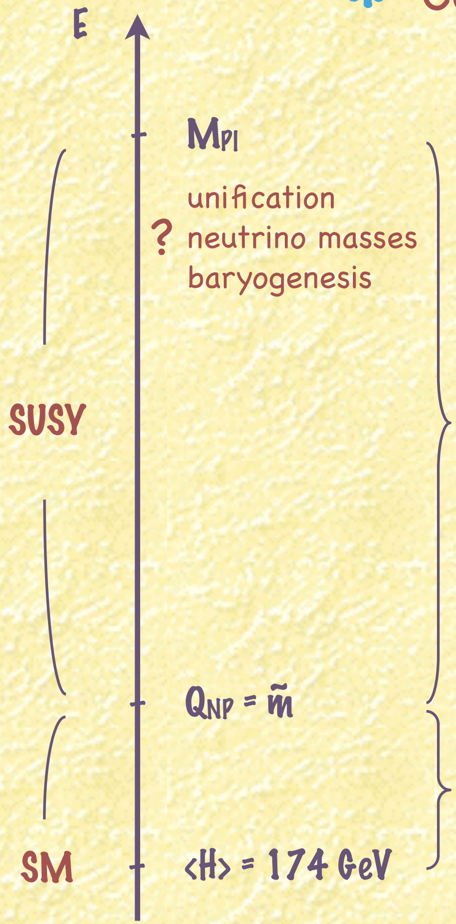
[Berezhiani Chankowski Falkovski Pokorski hep-ph/0509311
Roy Schmaltz hep-ph/0509357]

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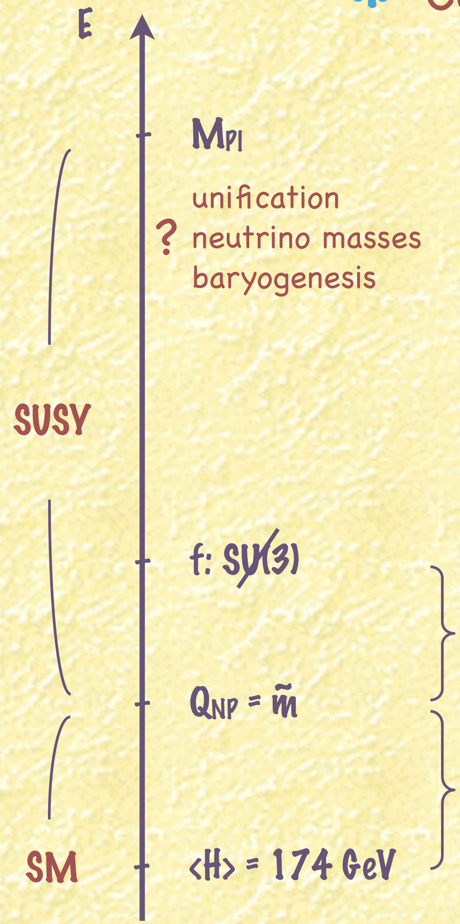


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  $H(x) \to H(x) + c$. Explicit breaking by $\lambda_t$ $\lambda_H$ $g$: [Georgi Kaplan 84]

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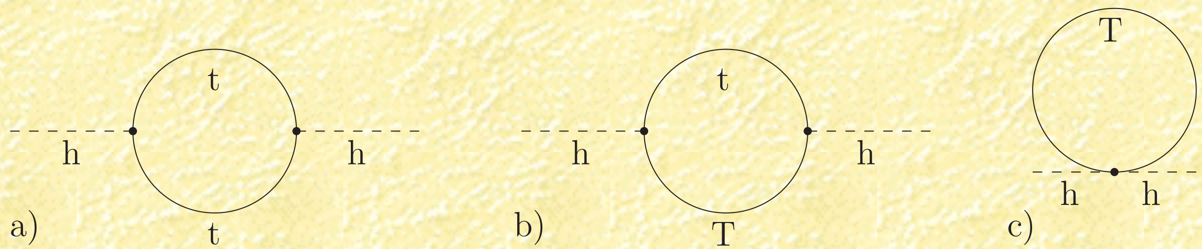
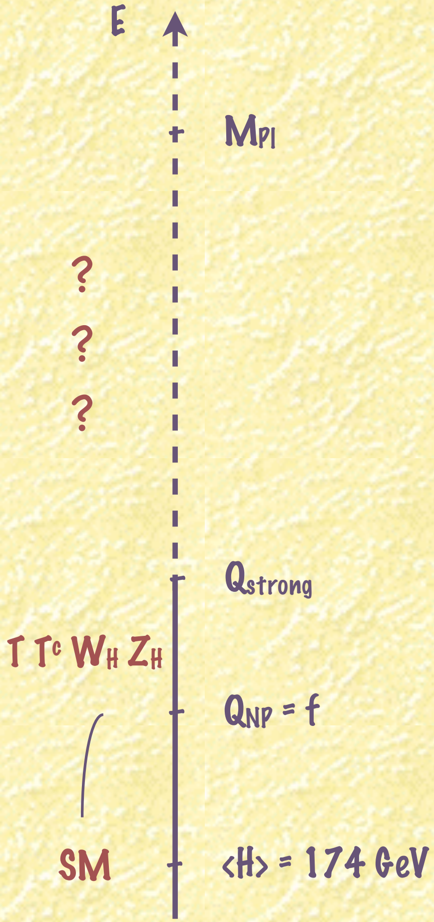
* More clever explicit breaking ("collective breaking"): **Little Higgs**
  - no 1-loop $Q_{\rm NP}^2$ terms (exact-NGB unless 2+ non-vanishing couplings)
  - the top (gauge, Higgs) loop **must** be cancelled at a lower scale (= global symmetry breaking scale $f \ll Q_{strong}$) by same statistics partners



# Little Higgs

Higgs mass protected by H(x) → H(x) + c

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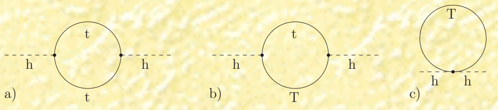


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[Arkani-Hamed Cohen Georgi 01, Arkani-Hamed Cohen Katz Nelson 02, Arkani-Hamed Cohen Katz 02, Nelson Gregoire Wacker 02]

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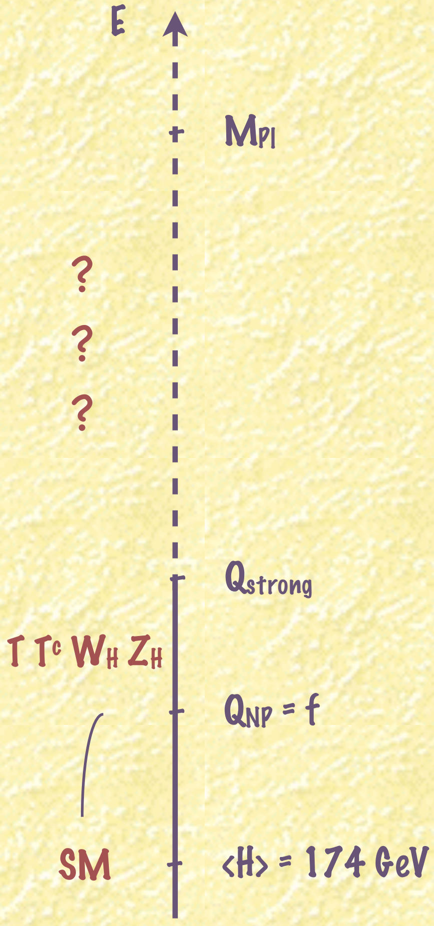


* $Q_{NP}$: $Q_{strong} \to f$ = global symmetry breaking scale (separate the top loop cutoff from $Q_{strong} > 5$ TeV)
* Bounds on $Q_{NP}$ from EWPT still worse than MSSM (unless T-parity is used), FT similar
* No dramatic gain but interesting alternative

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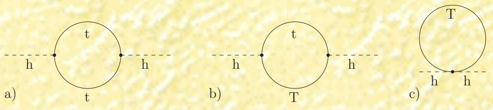


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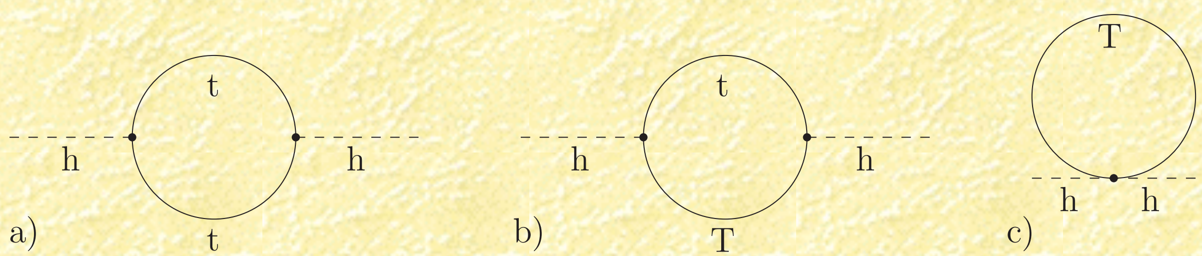
[Arkani-Hamed Cohen Georgi 01, Arkani-Hamed Cohen Katz Nelson 02, Arkani-Hamed Cohen Katz 02, Nelson Gregoire Wacker 02]

# LH @ LHC

* Observe the partners responsible for the divergence cancellation
  - $q\bar{q} \to Z_H \to l^+l^-$ up to few TeV (standard); in general $\to$ ff, VV, Vh
  - T, $T^c$: single production via Wb fusion dominates (b pdf up to $x \approx 0.2$)
    - $\Gamma(T \to th) = \Gamma(T \to tZ) = \Gamma(T \to bW)/2$ all identifiable: $tZ \to bWl^+l^-$ ($m_T$), $th \to bWb\bar{b}$ ($m_h$, $m_T$), $bW \to bl\nu$
  - additional (++) Higgs states

[Burdman Perelstein Pierce hep-ph/0212228
Han Logan Wang hep-ph/0301040
Azuelos et al hep-ph/0402037]

* Observe the divergence cancellation




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

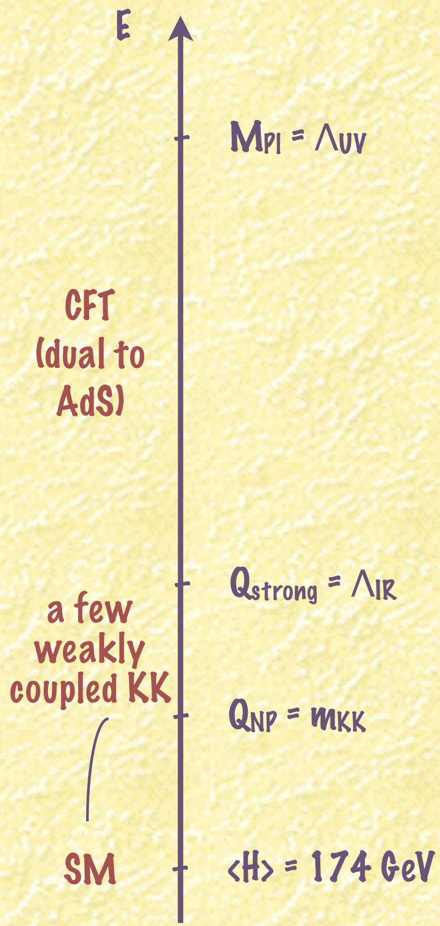
$$b) = -6\lambda_T^2 \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m_T^2},$$

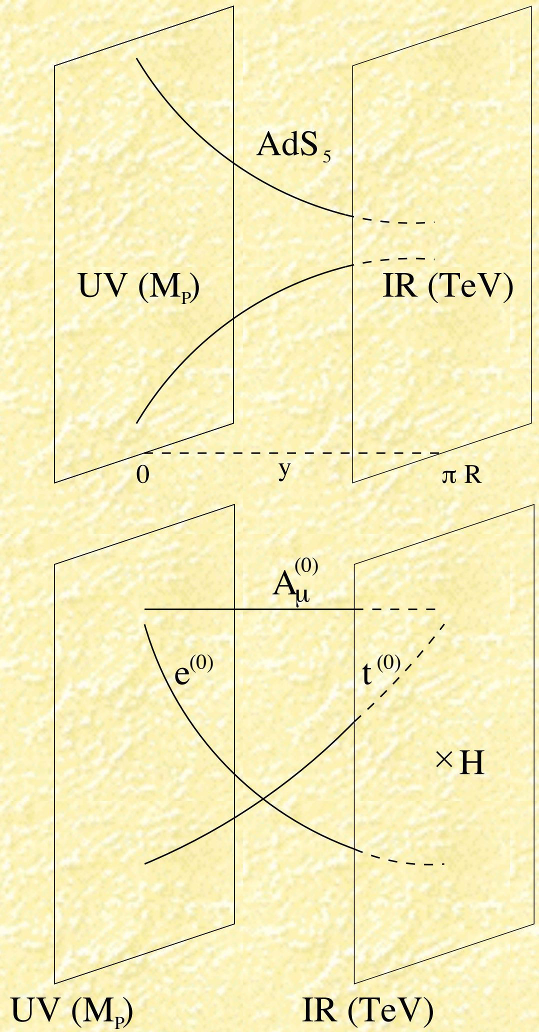
$$c) = +6\frac{\lambda_T}{f} \int \frac{d^4k}{(2\pi)^4} \frac{m_T}{k^2 - m_T^2}$$

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

[Perelstein Peskin Pierce hep-ph/0310039]

# Warping and composite Higgs




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

$$k = \text{curvature}$$

- Breaking of $G_{bulk}$ by bc's: $H = (A_5)_0$, or Little Higgs + UV completion and solution of the hierarchy problem
- $m_H$ protected from $Q_{strong}$ by 5D gauge symmetry, or collective breaking
- 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)


[Contino Nomura Pomarol hep-ph/0306259
Agashe Contino Pomarol hep-ph/0412089
hep-ph/0605341]

# @LHC (a first look)

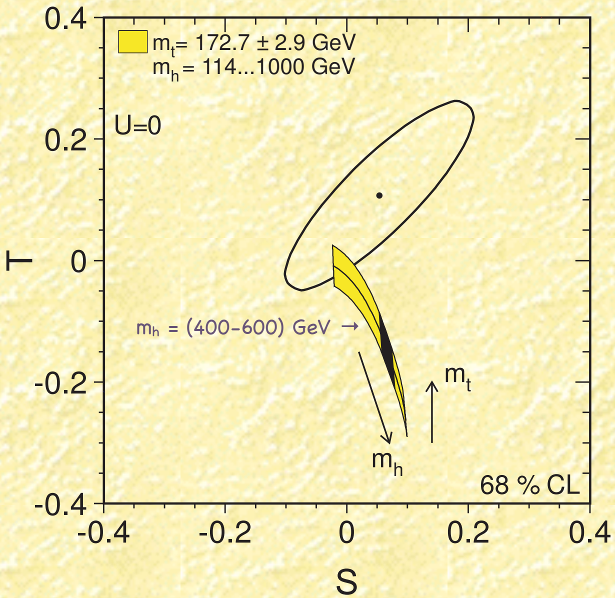
* Production:
  * $A(SM_1\ SM_2 \to KK_3)$
  * $SM_3$ needs to be substantially composite: $t_R$ (bW fusion) or $V_{long}$ (DY) (analogous to LH)
* Decay
  * into $V_{long}$ and heavier particles ($t_R\ b_R$, $\tau$ if non negligible) dominates
  * also: $(\text{gluon})_{KK} \to t_R \bar{t}_R$
  * possibly lepton excitations (if open)

# Back to the residual hierarchy

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

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

- $m_h$ = 500 GeV would help ($Q_{NP}$ up to 2 TeV); disfavoured by EWPTs only within the SM
- Cancel SM heavy Higgs contributions to EWPT with NP (good SM + light H fit accidental); does not require a large FT
- Generic prediction of NP giving ΔT = 0.25±0.1
- UV completion?



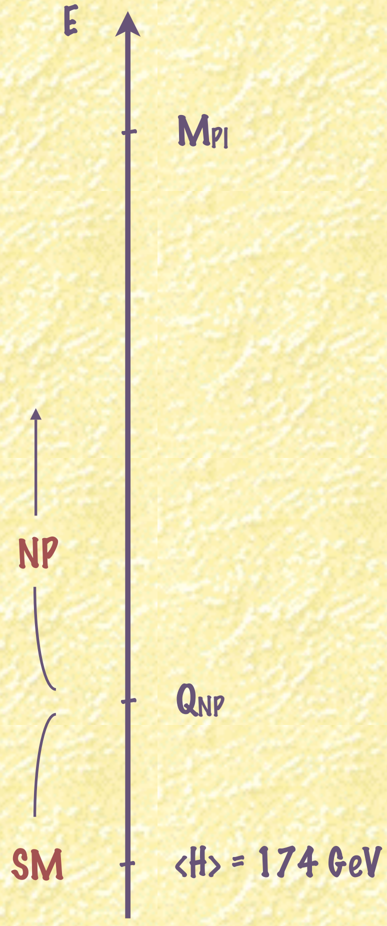

[Barbieri Hall hep-ph/0510243]

# 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

[Barbieri Hall Rychkov hep-ph/0603188]

# Is a natural $m_H$ unavoidable?



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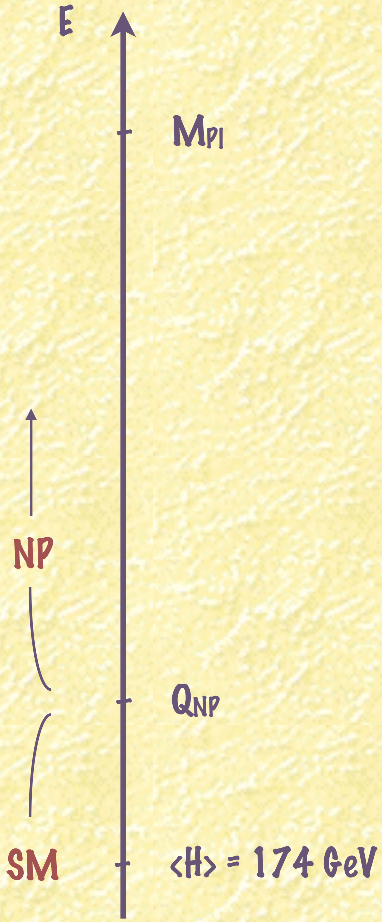
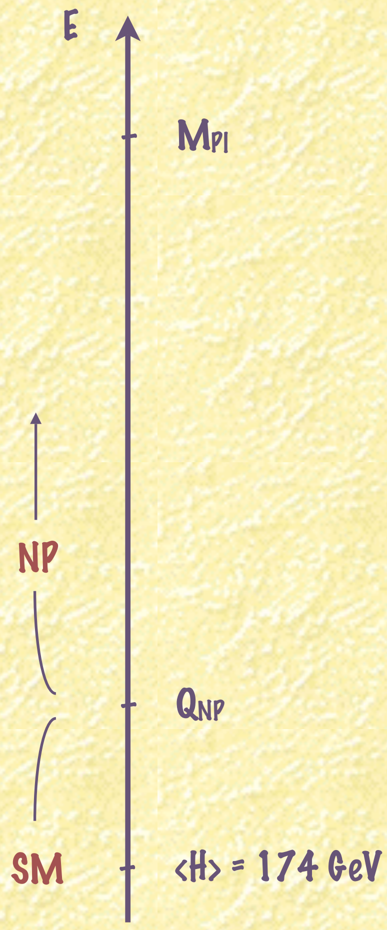



* What about the cosmological constant?

# Is a natural $m_H$ unavoidable?




* What about the cosmological constant?
* If the $m_h$ naturalness criterium is irrelevant, what are the observable consequences?

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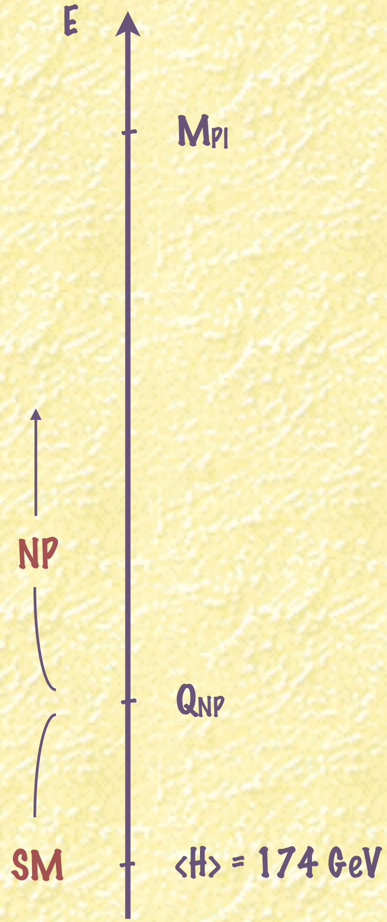


- What about the cosmological constant?
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- LHC..?

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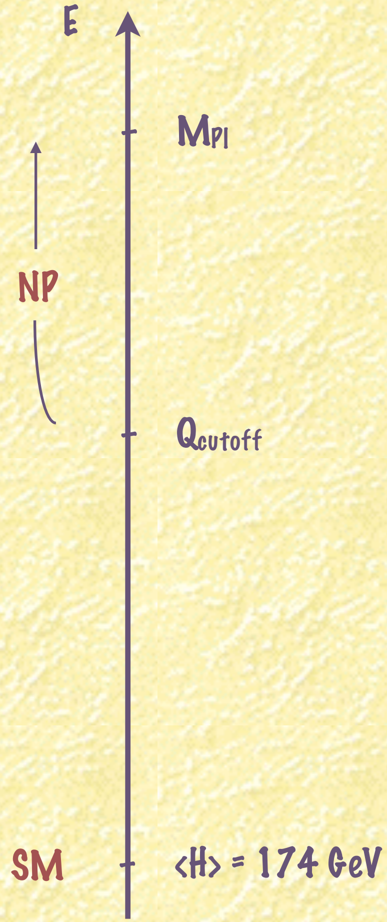


* What about the cosmological constant?
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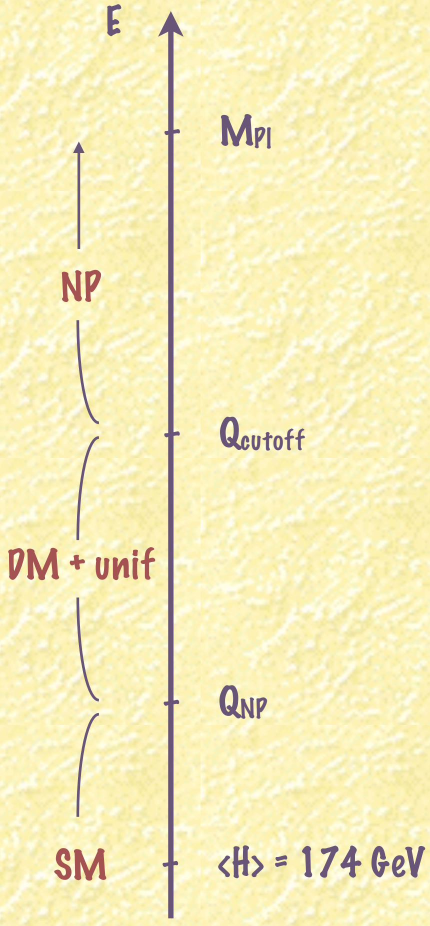
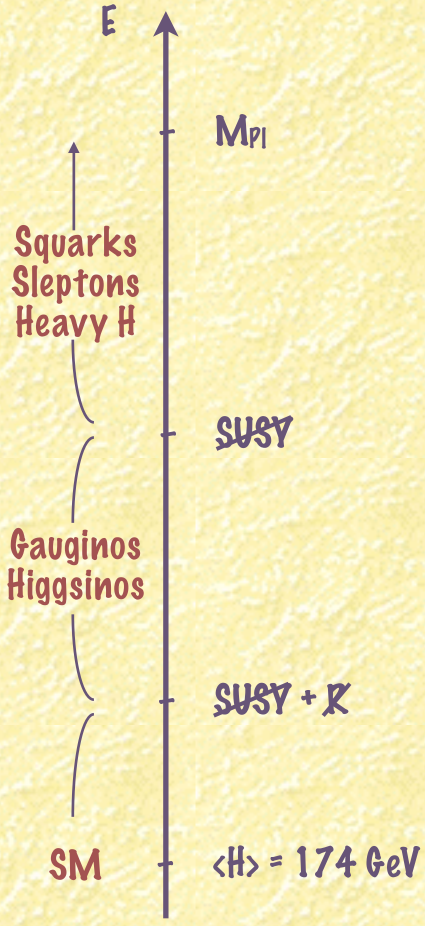



* What about the cosmological constant?
* If the $m_h$ naturalness criterium is irrelevant, what are the observable consequences?
* LHC..?
* Dark matter still motivates NP at the TeV scale

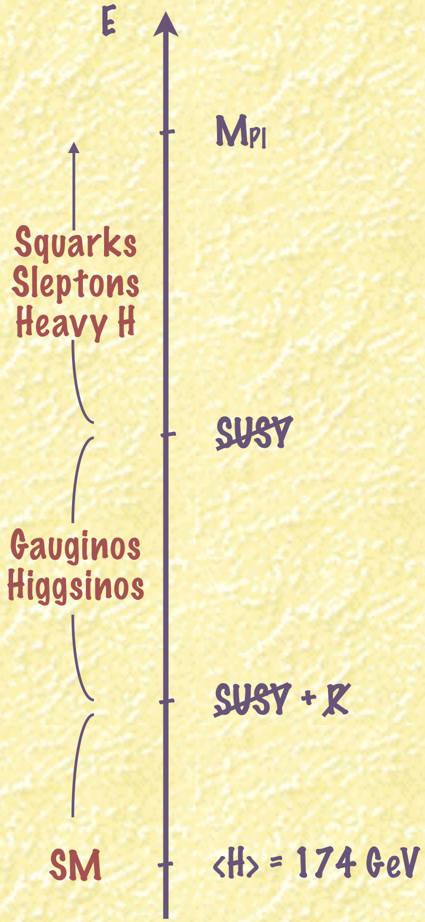
[Arkani-Hamed Dimopoulos 04,
Giudice R 04,
Arkani-Hamed Dimopoulos Giudice R 04]

# Split Supersymmetry



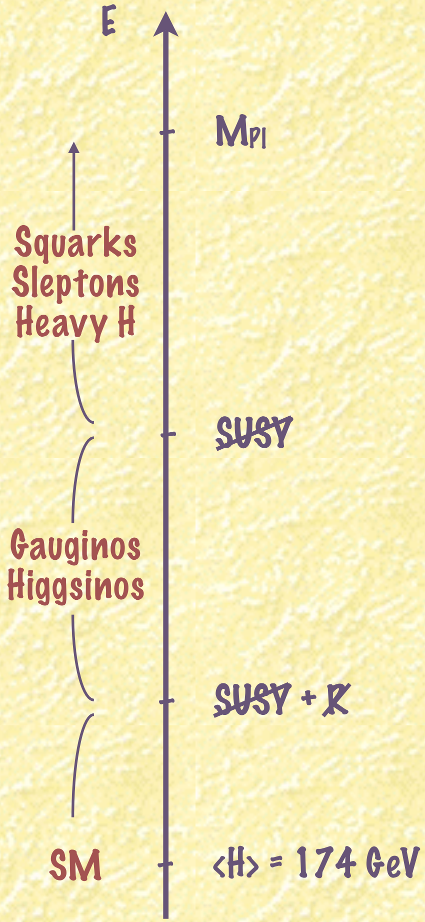
# Split Supersymmetry

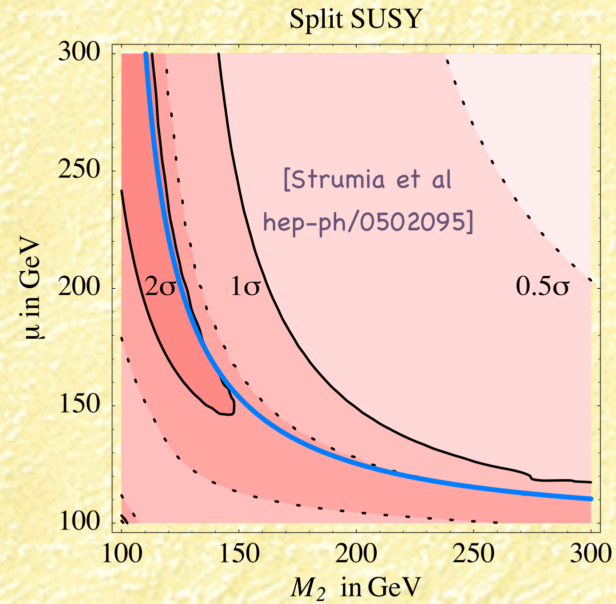
* DM: $\mu$ < 1.2 TeV ($M_1 < M_2$), mostly Bino favourable for LHC



# Split Supersymmetry

- DM: μ < 1.2 TeV ($M_1 < M_2$), mostly Bino favourable for LHC
- No bounds from EWPTs



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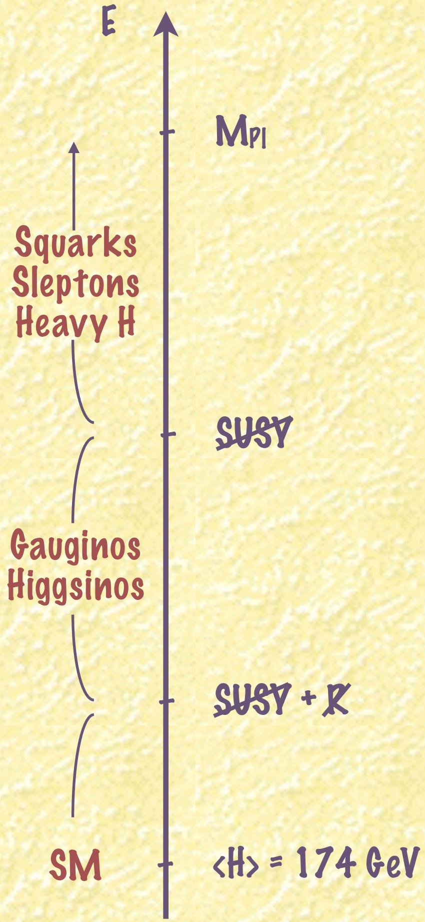


* DM: $\mu$ < 1.2 TeV ($M_1 < M_2$), mostly Bino favourable for LHC
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* $m_H$ < 170 GeV, in terms of of $\tilde{m}$, $\tan\beta$

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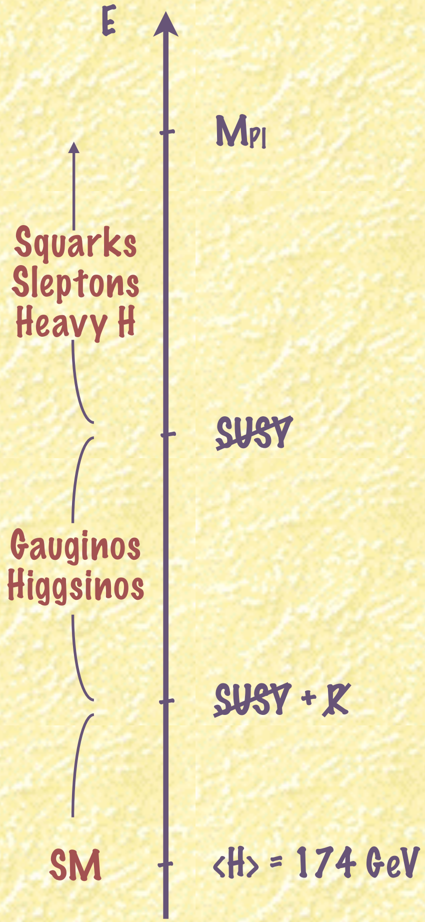


- DM: $\mu$ < 1.2 TeV ($M_1 < M_2$), mostly Bino favourable for LHC
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- $m_H$ < 170 GeV, in terms of of $\tilde{m}$, tan$\beta$
- Long-lived gluino R-hadrons (charged: slow, highly ionizing track; neutral: missing energy, mild hadronic activity; actually: Energy, charge, Baryon-number exchange)
  LHC sensitivity up to (1-2.5) TeV [Kilian Plehn Richardson Schmidt hep-ph/0408088, Hewett Lillie Masip Rizzo hep-ph/0408248, Kraan Hansen Nevski hep-ex/0511014]

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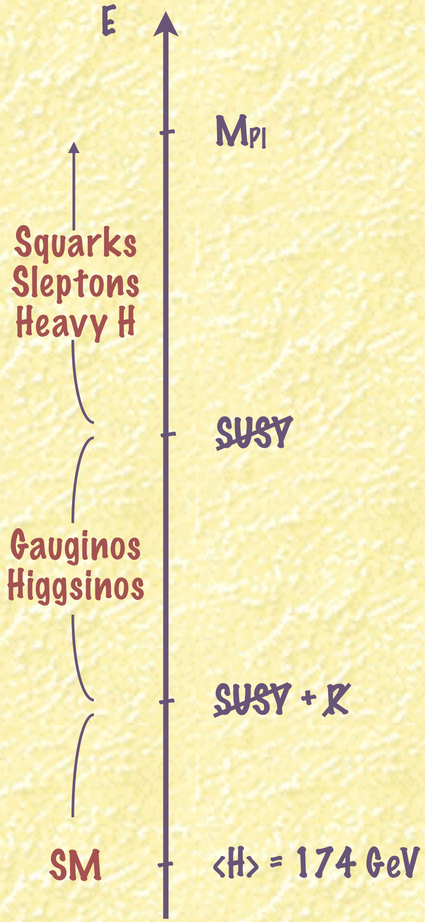


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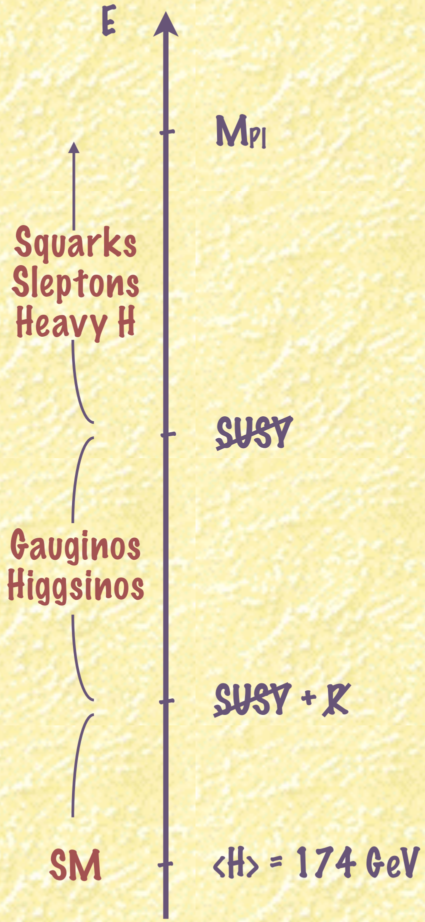


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- (quasi-stable coloured particles also e.g stop in some 5D SUSY models or in MSSM with fine-tuned $\tilde{m}_t \approx M_{N1}$)
- Wilder: stopping gluinos (1-2 jets in any direction from denser parts of the detector + m.e.), displaced vertexes (low 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
* Interpretation might not be unique

# Upper pressure on $Q_{NP}$

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

Depends on the Higgs mass (see below)

# Lower bounds on $Q_{NP}$

* Negative searches
* No evidence of D>4 relics at E < $Q_{NP}$
  - no L-violating operators → $Q_L > 10^{15}$ GeV
  - no flavour violating operators → $Q_{FCNC} > 10^6$ GeV
  - no contribution to EWPT → $Q_{NP} > (0.5\text{-}5)\ 10^3$ GeV (model dependent but unavoidable)

# EWPT and the type of physics at QSM

$$\mathcal{L}_{\rm SM}^{\rm eff}(E < Q_{\rm SM}) = \mathcal{L}_{\rm SM}^{\rm ren} + \sum_i \frac{c_i}{Q_{\rm SM}^2} O_i + \dots$$

$$c_i = \lambda^2 \left(\frac{\lambda^2}{16\pi^2}\right)^n$$

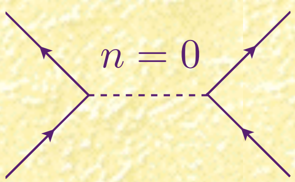
$$\text{EWPT: } \frac{c_i}{Q_{\rm SM}^2} \lesssim \frac{1}{(5\,\text{TeV})^2} \Rightarrow Q_{\rm SM} \gtrsim \sqrt{c_i}\cdot 5\,\text{TeV} \approx \begin{cases} 50\,\text{TeV if NP is strongly interacting} \\ 5\,\text{TeV if NP is perturbative, tree level, } \lambda\sim 1 \\ 0.5\,\text{TeV if NP is perturbative, one loop, } \lambda \sim 1 \end{cases}$$

The hierarchy problem is best solved by perturbative physics

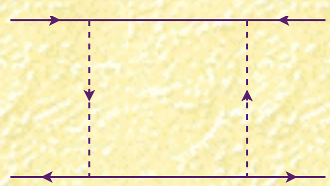
# EWPT and the type of physics at QSM

$$\mathcal{L}^{\text{eff}}_{\text{SM}}(E < Q_{\text{SM}}) = \mathcal{L}^{\text{ren}}_{\text{SM}} + \sum_i \frac{c_i}{Q^2_{\text{SM}}} O_i + \ldots$$

$$c_i = \lambda^2 \left( \frac{\lambda^2}{16\pi^2} \right)^n$$




$n = 1$



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The hierarchy problem is best solved by perturbative physics

# LH at LHC

f, ψ

$$M_{Z_H} = \sqrt{\frac{g_L^2 + g_R^2}{2}}\, f = \frac{\sqrt{2} g}{\sin 2\psi}\, f$$

$$\Gamma = \frac{g^2}{96\pi} \left(\cot^2 2\psi + 24 \tan^2 \psi\right) M_{Z_H}$$

$$\mathrm{Br}(\ell\bar{\ell}) = \frac{1}{3}\mathrm{Br}(q\bar{q}) = \frac{\tan^2\psi}{\cot^2 2\psi + 24\tan^2\psi};$$

$$\mathrm{Br}(W^+W^-) = \mathrm{Br}(Zh) = \frac{1}{2}\,\frac{\cot^2 2\psi}{\cot^2 2\psi + 24\tan^2\psi}.$$

[Burdman Perelstein Pierce hep-ph/0212228]

$m_T$

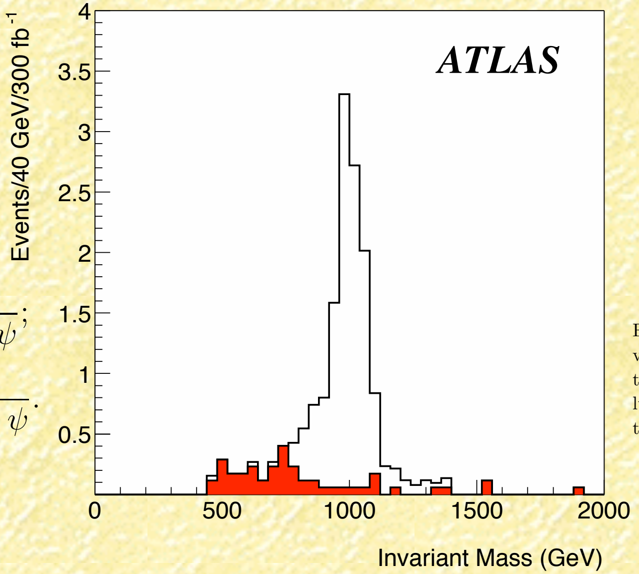


Figure 2: Reconstructed mass of the $Z$ and $t$ (inferred from the measured lepton, $\not{E}_T$, and tagged $b$−jet). The signal $T \to Zt$ is shown for a mass of 1000 GeV. The background, shown as the filled histogram, is dominated by $WZ$ and $tbZ$ (the latter is larger) production. The signal event rates correspond to $\lambda_1/\lambda_2 = 1$ and a $BR(T \to ht)$ of 25%. More details can be found in Ref [17].

[Azuelos et al hep-ph/0402037]

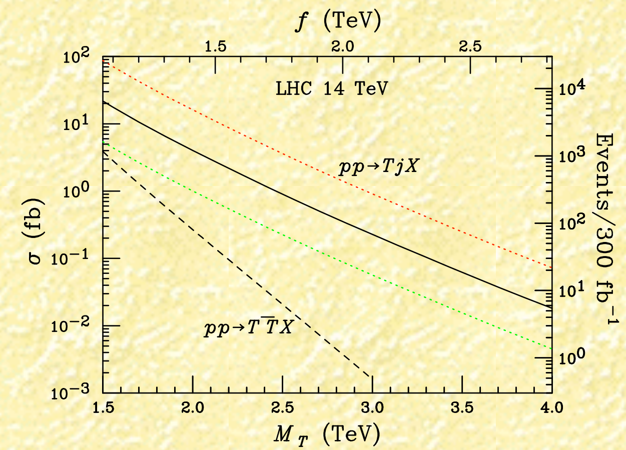


FIG. 5: Total cross sections for $T\bar{T}$ production (dashed) and $T$+jet production (solid and dotted) via $t$-channel $W$-exchange versus mass $M_T$ at the LHC. The solid line is for the couplings $\lambda_1 = \lambda_2$; the dotted are for $\lambda_1/\lambda_2 = 2$ (upper) and 1/2 (lower). The number of events expected per 300 fb$^{-1}$ luminosity is indicated on the right-hand axis. The scale $f$ corresponding to $\lambda_1 = \lambda_2$ is given on the top axis.

$\lambda_T$

[Han Logan Wang hep-ph/0301040]