New Developments in Physics of Electroweak Symmetry Breaking

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What do we expect to see at TeV?

→ Physics of electroweak symmetry breaking

Is there New Physics at TeV?

→ We don't know

Possible hints

- Problem of Naturalness
- Existence of the Dark Matter

Good motivations for Physics beyond the SM

May also be responsible for weak-Planck hierarchy

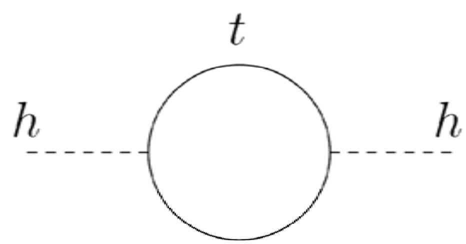
… e.g. theory of radiative EWSB

→ Target of Next Experiments (LHC, LC, …)

Naturalness Problem of the SM

The SM Lagrangian is not stable under quantum corrections:

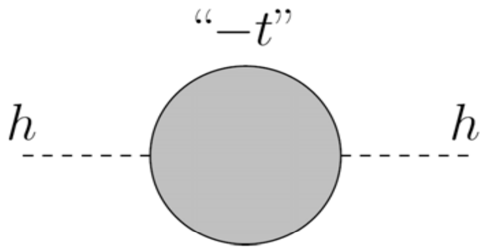
$V_{Higgs} = m_h^2 |h|^2 + \lambda |h|^4/4$



$$\delta m_h^2 \approx -\frac{y_t^2}{16\pi^2}\Lambda^2$$

We need

$$\Longrightarrow \quad \delta m_h^2 \approx -\frac{y_t^2}{16\pi^2} m^2$$



$$\delta m_h^2 \approx \frac{y_t^2}{16\pi^2}(\Lambda^2 - m^2)$$

"Experimentally" $m_h^2 < O(100\ \text{GeV})^2$ ($v = 2m_h^2/\lambda = 174$ GeV)

Naturalness: $m_h^2 < O(100\ \text{GeV})^2$ → $m < O(\text{TeV})$

What do we know about New Physics?

→ The SM describes physics at < *O*(100 GeV) extremely well

Contributions from New Physics:

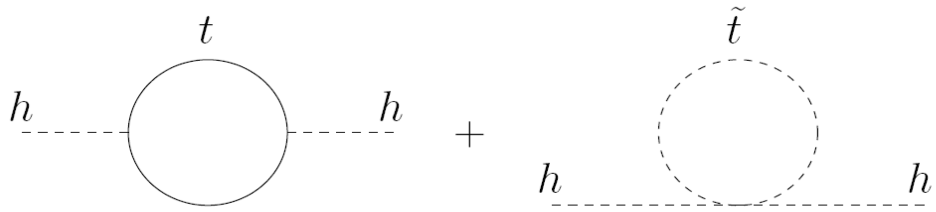
$$\mathcal{L} = \frac{1}{M^2}\mathcal{O}^{(6)}$$

M > a few TeV

$$\left(\frac{1}{M^2} \simeq \frac{1}{16\pi^2 m^2} \longrightarrow M \simeq 4\pi m\right)$$

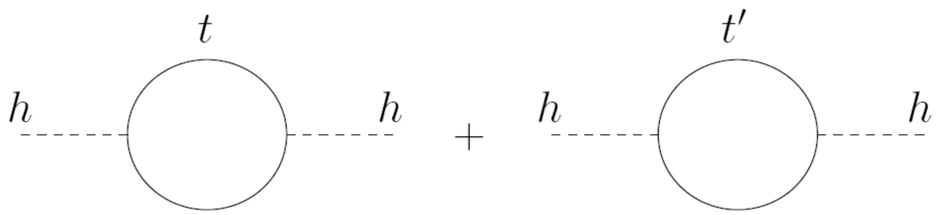
→ New Physics is (most likely) weakly coupled

Weak scale supersymmetry



… opposite statistics

Higgs as a pseudo Nambu-Goldstone boson



… same statistics

Weak Scale Supersymmetry

Superparticle at the TeV scale

Bosons	Fermions
A_μ	λ
$\tilde{q}$	q
$\tilde{l}$	l
h	$\tilde{h}$

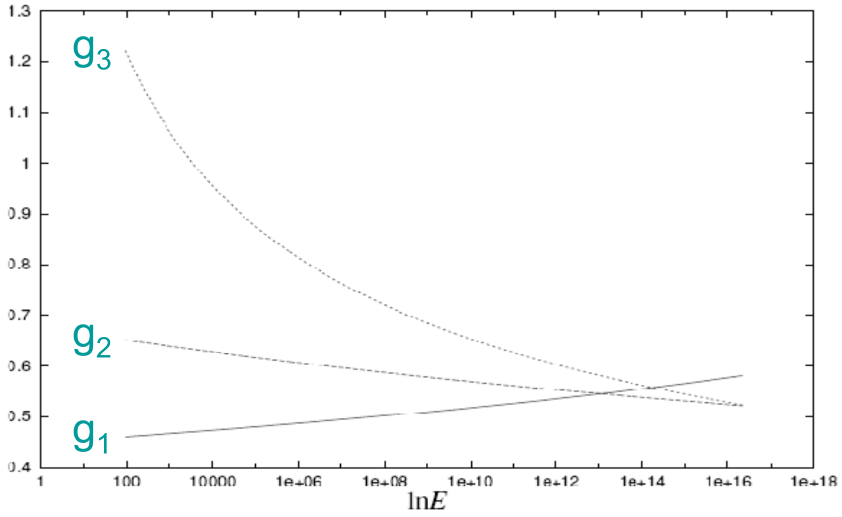
After SUSY breaking, λ, $\tilde{q}$, $\tilde{l}$ and $\tilde{h}$ obtain masses of O(TeV)

→ Beautiful cancellation of δm_h^2 between contributions from the SM and superparticles

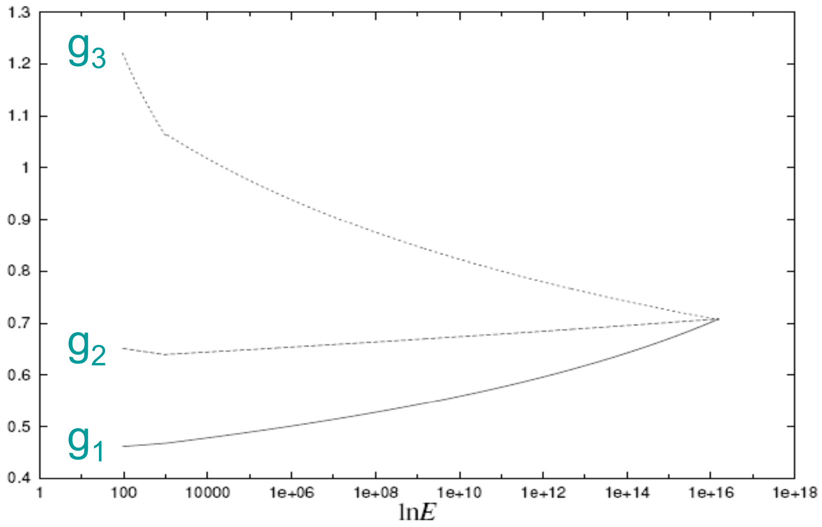
R parity → the existence of Dark Matter

Gauge coupling unification at a high scale:

- nonSUSY



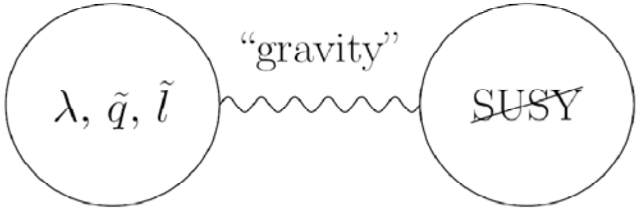
- SUSY



$M_{unif} \sim 10^{16}$ GeV

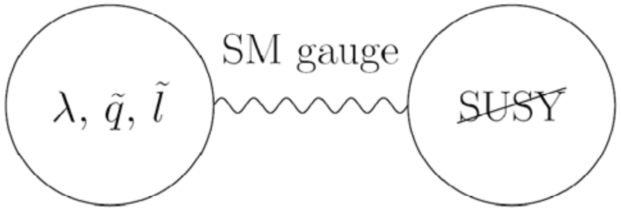
Superparticle spectrum provides a window for a deeper level of physical theory

- “Gravity” mediation



(Gaugino mediation, Moduli mediation, …)

- Gauge mediation



- Anomaly mediation
- …

→ Distinct spectra

Combination of LHC and LC important

LSP ~ DM: weakly interacting --- Exploration at LC

Supersymmetry after the LEPII

- "Minimal" Supersymmetry is fine-tuned

… Supersymmetric fine-tuning problem

– Minimization condition

$$\frac{M_{\rm Higgs}^2}{2} \simeq -m_h^2 - |\mu|^2$$

Natural EWSB requires

$$\frac{M_{\rm Higgs}^2}{2} \sim |m_h^2| \sim |\mu|^2$$

In the MSSM,

$$M_{\rm Higgs} \lesssim 130 \text{ GeV} \underset{\Delta^{-1} \geq 20\%}{\longrightarrow} |m_h^2|,\ |\mu|^2 \lesssim (200 \text{ GeV})^2$$

m_h^2 receives contribution from top-stop loop

$$\delta m_h^2 \simeq -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\left(\frac{M_{\rm mess}}{m_{\tilde{t}}}\right)$$

M_{mess}: the scale where suerparticle masses are generated

What's wrong?

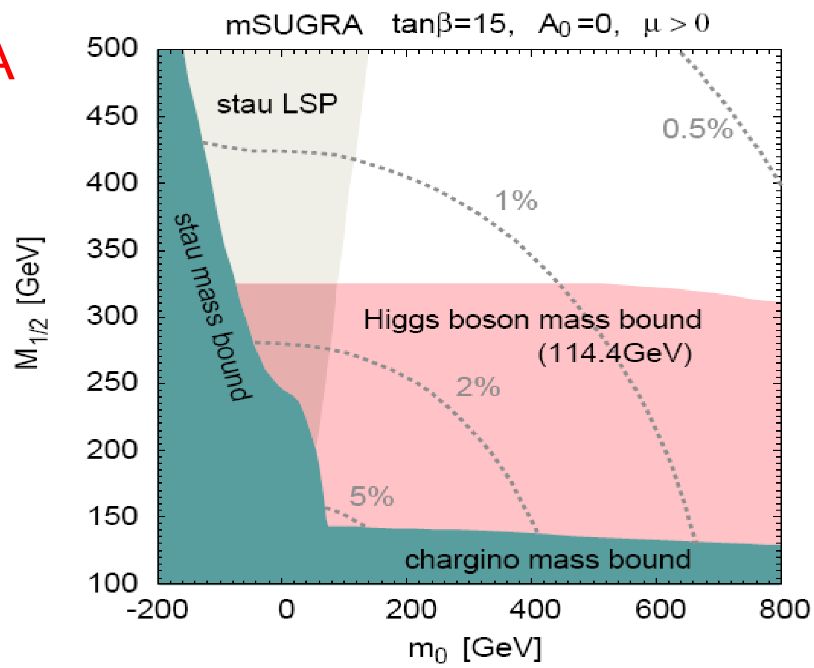
- $M_{\text{Higgs}} < M_Z$ at tree level
  - need radiative corrections from top-stop loop

$$M_{\text{Higgs}} \gtrsim 114\ \text{GeV} \quad \Rightarrow \quad m_{\tilde{t}} \gtrsim 1\ \text{TeV} \qquad (\text{for small } A_t)$$

- Tension with the other superparticle mass bounds
  - e.g. mediation by the SM gauge interactions

$$\frac{m_{\tilde{t}}}{m_{\tilde{e}}} \simeq \frac{(4/3)g_3^4 + \delta}{(3/5)g_1^4} \simeq (7\sim 8) \quad \Rightarrow \quad m_{\tilde{t}} \gtrsim 700\ \text{GeV} \ \text{ for } \ m_{\tilde{e}} \gtrsim 100\ \text{GeV}$$

e.g. mSUGRA



Possible approaches

- We don't care
- Higgs boson may be lighter Dermisek, Gunion; Chang, Fox, Weiner; …

  → LEPII may have missed the Higgs h^0 because h^0 decays into final states that are hard to detect
- Higgs boson may be heavier Barbieri, Hall, Y.N., Rychkov; …

  … alleviates fine-tuning (in the most straightforward way)

  → We may have been misled in interpreting EWPT
- Problem of SUSY breaking mechanism? Kitano, Y.N.; …

  → Some mechanism may be preferred over others
- Environmental
  - Split SUSY Arkani-Hamed, Dimopoulos; Giudice, Romanino; …
  - Living dangerously Giudice, Rattazzi; …

SUSY without a light Higgs boson

- Heavier Higgs boson alleviates tuning

$V_{Higgs} = m_h^2\,|h|^2 + \lambda|h|^4/4$

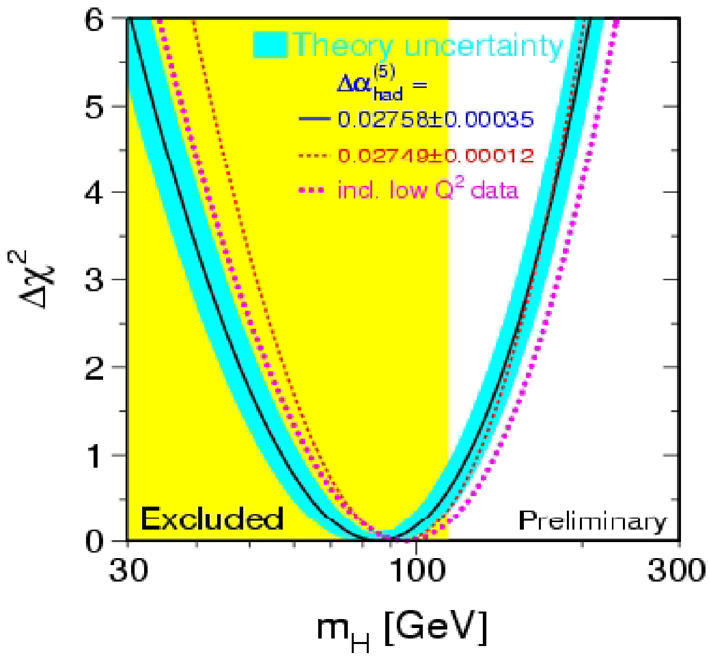
→ $v^2 = |h|^2 = -2m_h^2/\lambda,\ \ M_{Higgs}^2 = \lambda v^2$

In SUSY

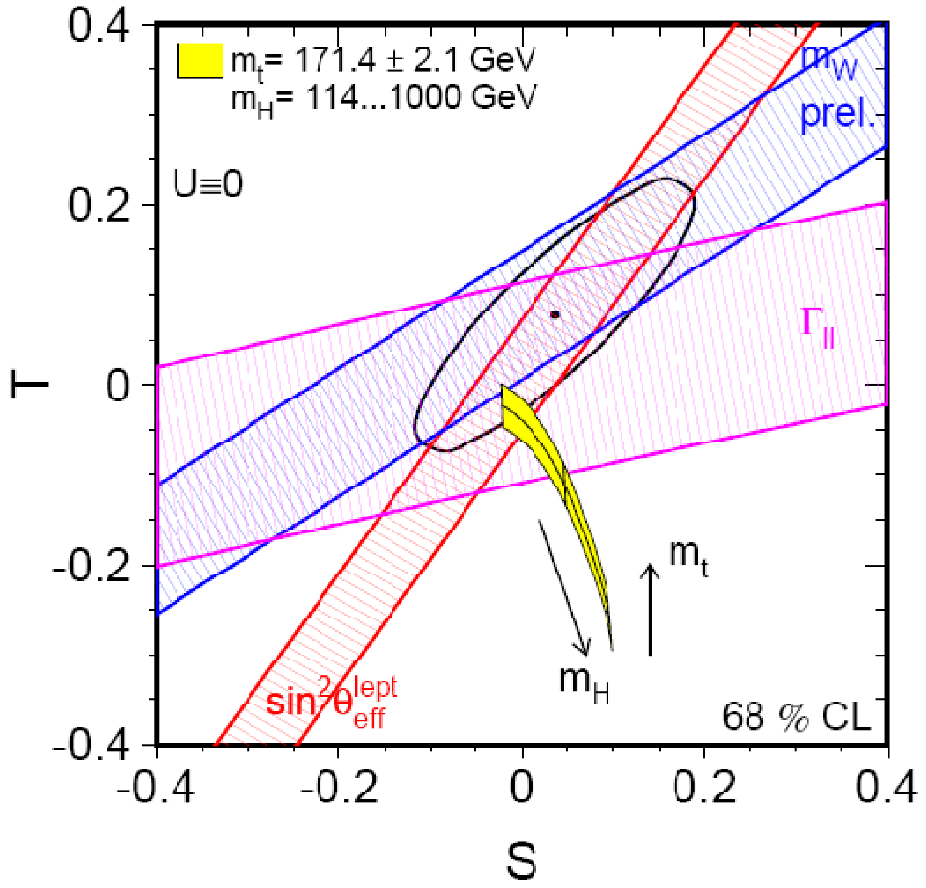
$$\frac{M^2_{\rm Higgs}}{2} \simeq -m_h^2 - |\mu|^2$$

- Allowed by EWPT?

(We imagine e.g. M_{Higgs} ~ 200-300 GeV)



Constraint on M_{Higgs} on the S-T plane



LEP EWWG

→ easy to have large M_{Higgs} if additional ΔT exist

Maybe we are being fooled by $\Delta T|_{New\ Physics}$

λSUSY framework

Barbieri, Hall, Y.N., Rychkov, hep-ph/0607332

- Higgs boson can be made heavy in SUSY by

$$W = \lambda S H_u H_d$$

with $\lambda \approx (1 \sim 2)$ (λ perturbative up to ~10TeV)

- Large λ makes M_{Higgs} heavy and **at the same time** induces sizable ΔT from singlet-doublet mixings!

Parameter of the model:

Scalar sector

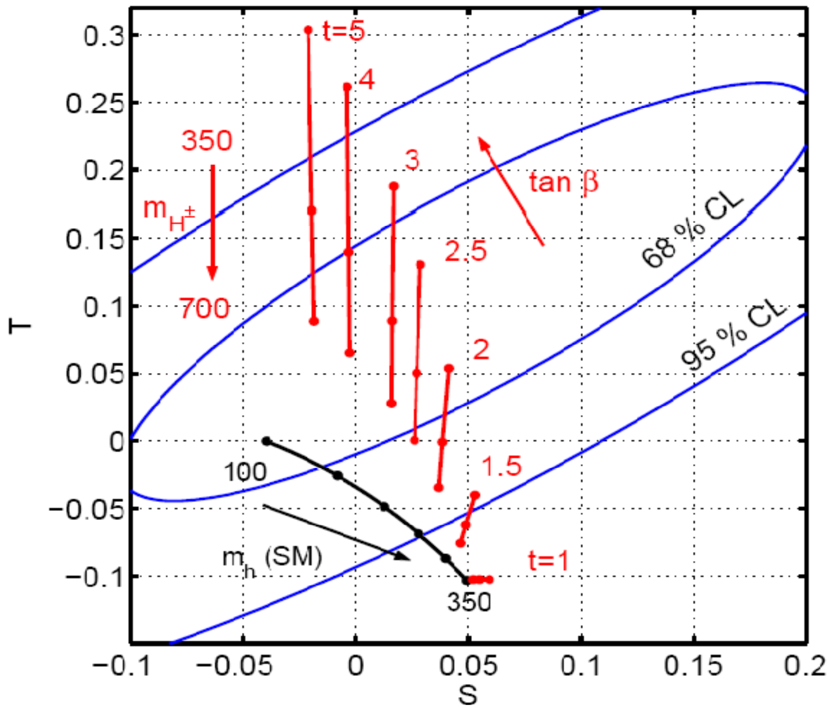
$\mu_1^2, \mu_2^2, \mu_3^2 \rightarrow \tan\beta, m_{H^+}, v$

Fermion sector

μ, M

in the limit of decoupling the S scalar and gauginos

- Contribution from the scalar Higgs sector



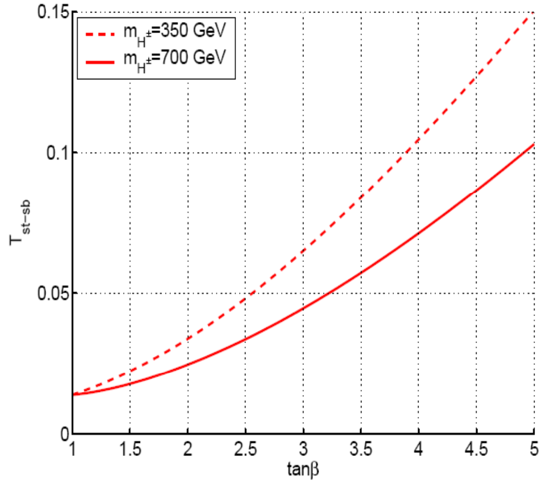
λ=2

m_{H+}=350,500,750 GeV

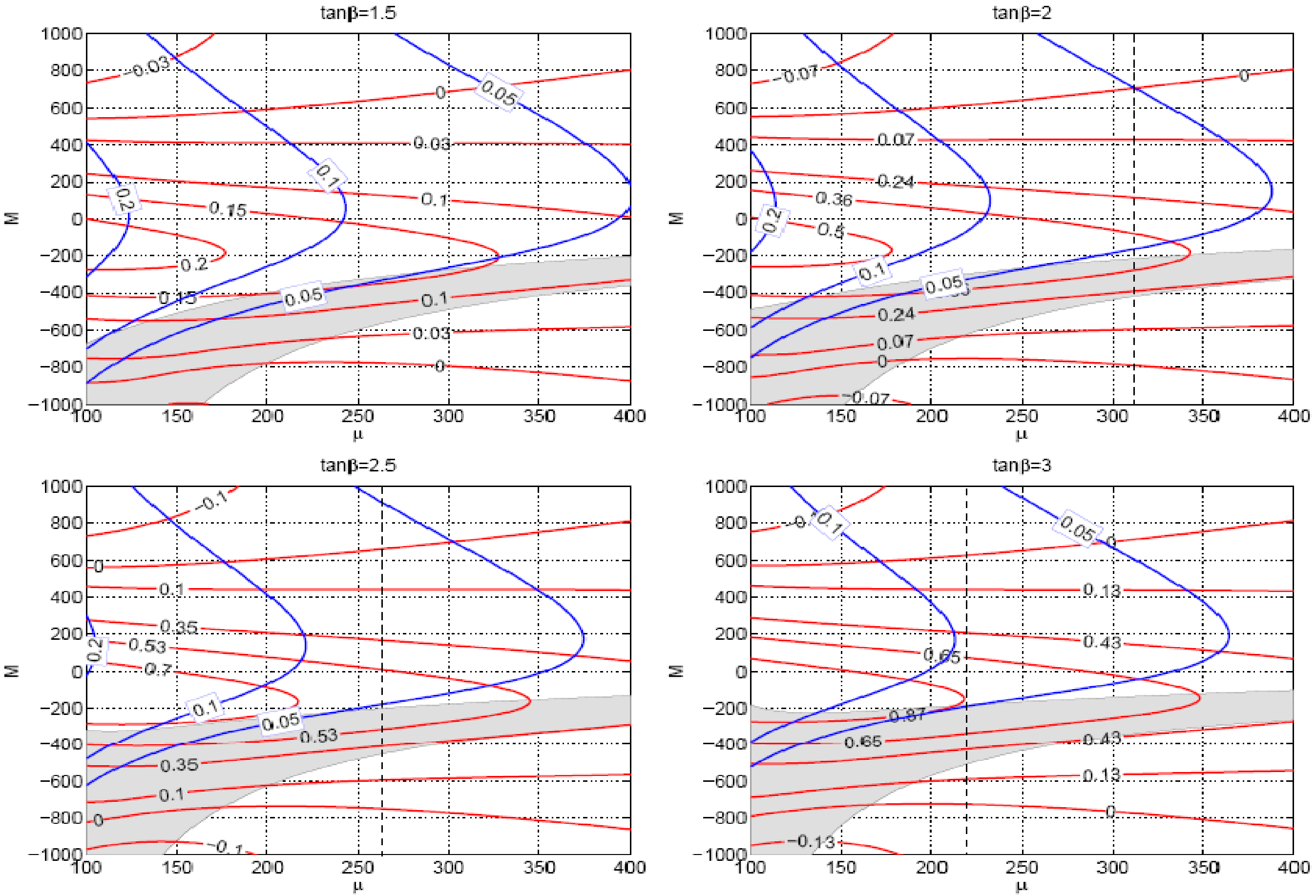
  - ΔT→0 for tanβ→1 (custodial symmetry)
  - ΔT>0 can make large M_{Higgs} consistent

→ tanβ cannot be large

also reinforced by the stop-sbottom contributions



• Contribution from the Higgsino sector



Blue – S
Red – T

Shaded region indicates $m_\chi < m_Z/2$

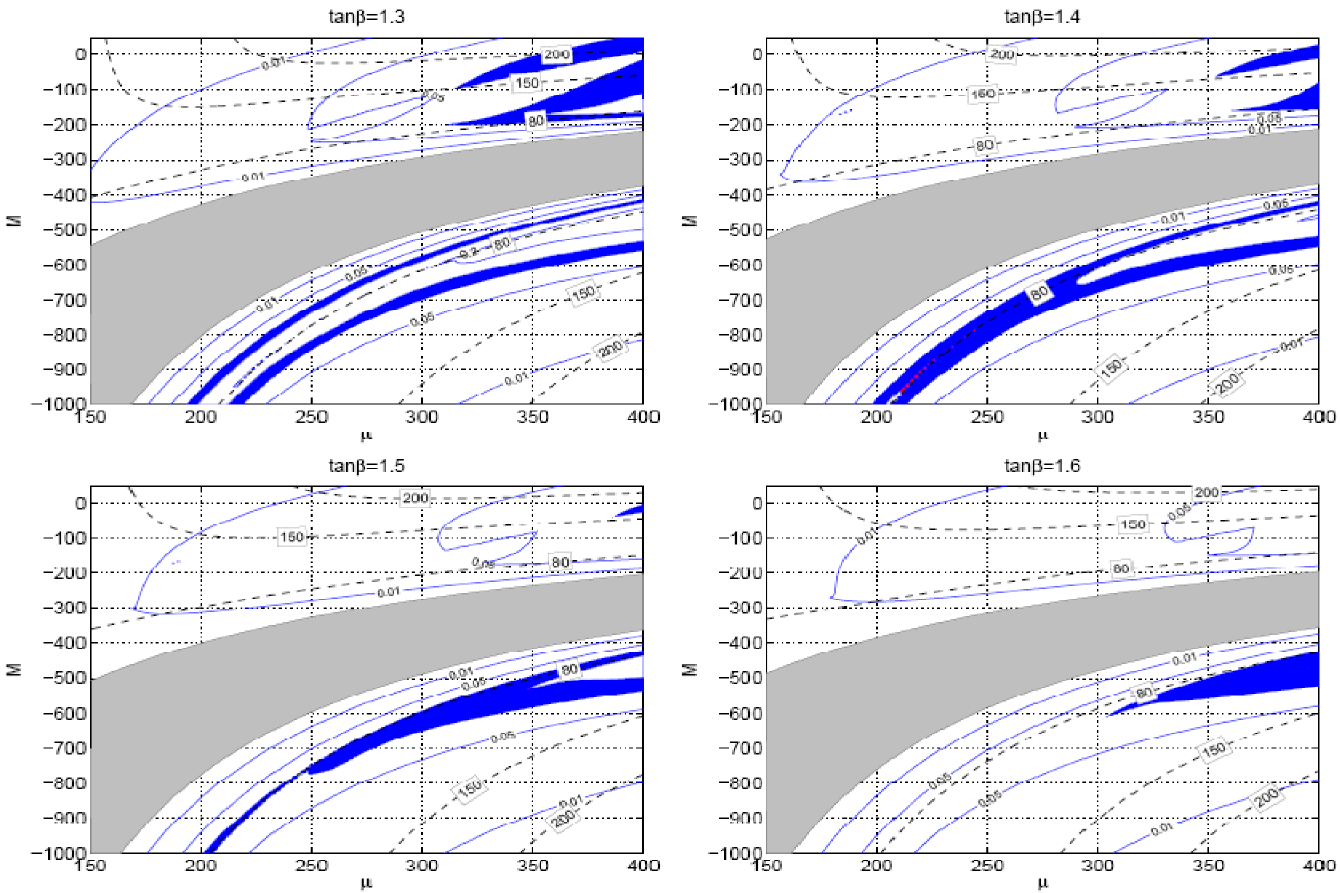
tanβ < 3 preferred in λSUSY

→ rich Higgs physics at ~*O*(200-700 GeV)

- New Possibility for Dark Matter

In the limit of heavy gauginos, $\chi = \{\psi_S, \psi_{Hu}, \psi_{Hd}\}$

$\chi\chi \rightarrow Z \rightarrow ff$ suppressed ➔ χ can be the dark matter



Blue:
WMAP region

tanβ ~ 1.4 (detection promising: $\sigma_{SI} > 10^{-44}$ cm^2)

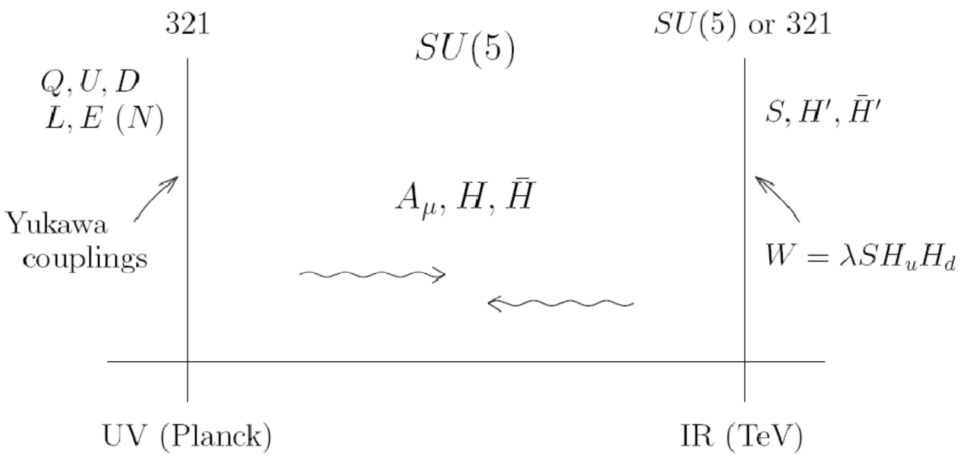
- # Gauge Coupling Unification

Compositeness of S, H_u, H_d and/or top can induce large λ, keeping the desert

Harnik, Kribs, Larson, Murayama; Chang, Kilic, Mahbubani; Birkedal, Chacko, Y.N.; Delgado, Tait; …

– 5D realization/modeling

Birkedal, Chacko, Y.N.



→ Gauge coupling unification can be preserved

Higgs sector physics in supersymmetry can be quite rich – potential window for the DM sector

Exploration at LC very useful

Higgs as a pseudo Nambu-Goldstone boson

Why $m_h << M_{Pl}$?

→ Higgs is a pseudo Nambu-Goldstone boson

- Old composite models Georgi, Kaplan; …
- Little Higgs models Arkani-Hamed, Cohen, Georgi; …
- Holographic Higgs models Contino, Y.N., Pomarol; …
- Twin Higgs models Chacko, Goh, Harnik; …
- …

Cancellation of δm_h^2 is between the same statistics fields – e.g. we have t' instead of $\tilde{t}$

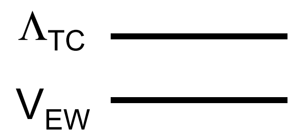
Higgs as a holographic pseudo Nambu-Goldstone boson

Contino, Y.N., Pomarol, hep-ph/0306259
Agashe, Contino, Pomarol, hep-ph/0412089

Technicolor:

(Λ_{QCD} ~ $<q\bar{q}>^{1/3}$ ~ 1 GeV gives f_π ~ m_W ~ 100 MeV)

m_W ~ 100 GeV → Λ_{TC} ~ 1 TeV



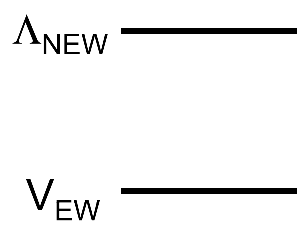
The scale of New Physics too close

--- contradict with the precision electroweak data

Pions in massless QCD:

($m_{\pi\pm}$ ~ 10 MeV with Λ_{QCD} ~ 1 GeV)

m_h ~ 100 GeV → Λ_{NEW} ~ 10 TeV

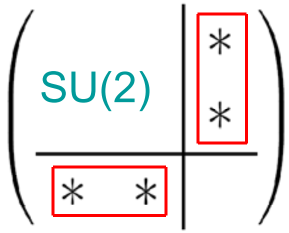


Safer in terms of the precision electroweak data

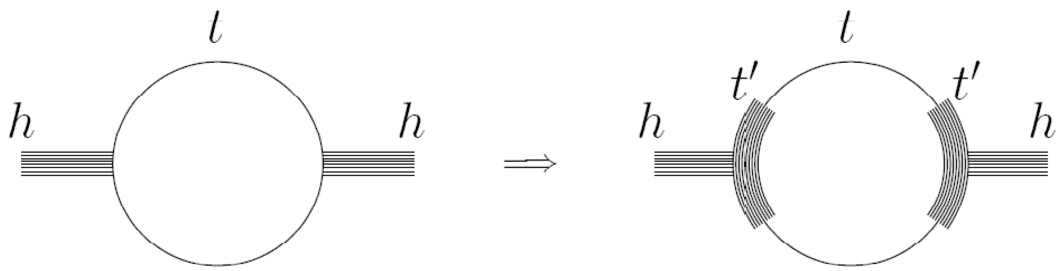
- **Basic structure** (omitting details, e.g. $U(1)_Y$ assignment)

  $SU(3)_{global} \supset SU(2)_L$

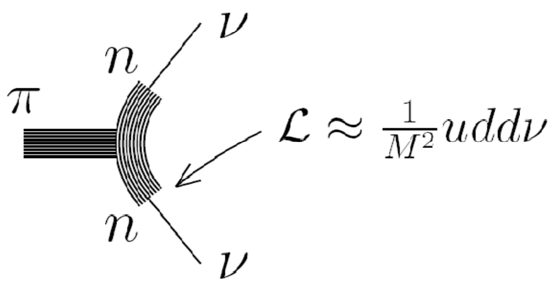
  SSB: $SU(3)_{global} \rightarrow SU(2)$ produces PNGB which is $SU(2)_L$ doublet



- **Higgs compositeness is not enough**



- **Analogy with QCD:**

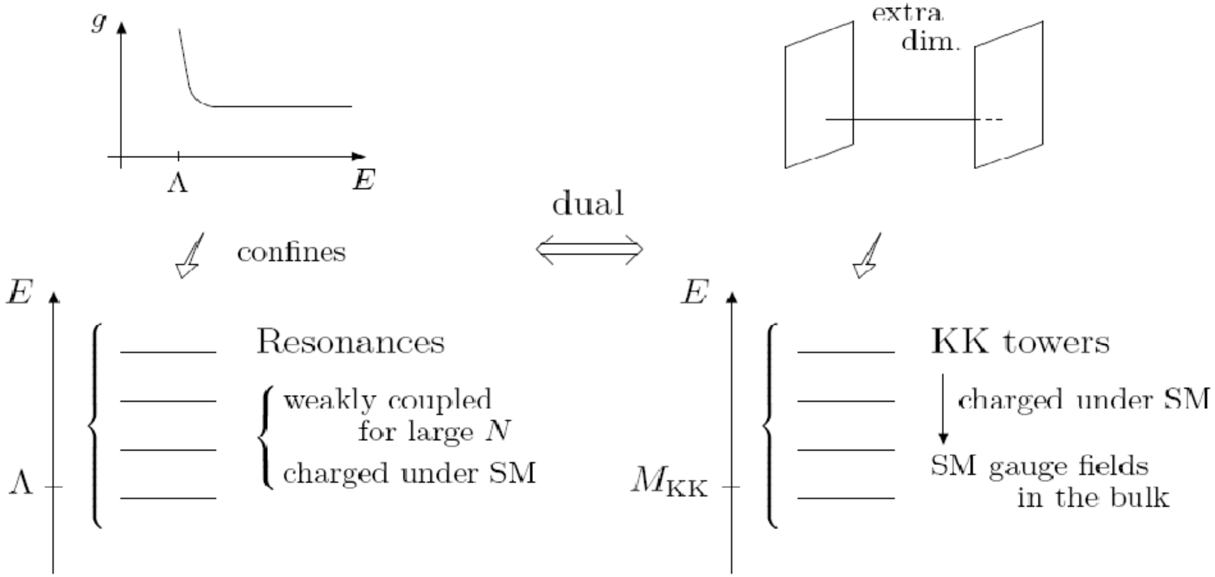


"Yukawa" couplings suppressed because dim[O_n] (O_n=udd) is "large" = 9/2

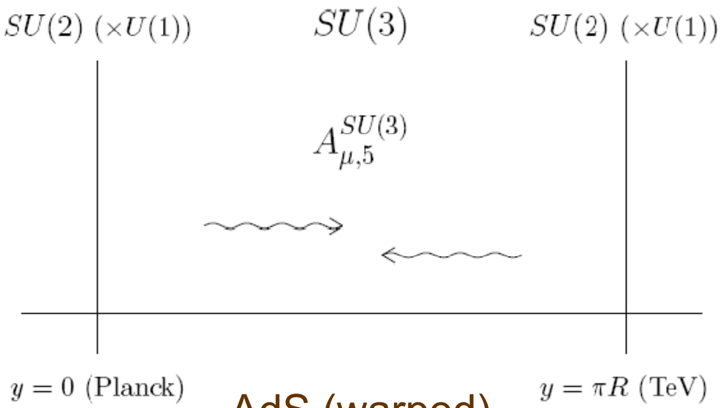
Need interactions strong for a wide energy range to reduce dim[O] → CFT

- How to realize such theories?

--- Gauge theory/gravity correspondence



- Realization in 5D

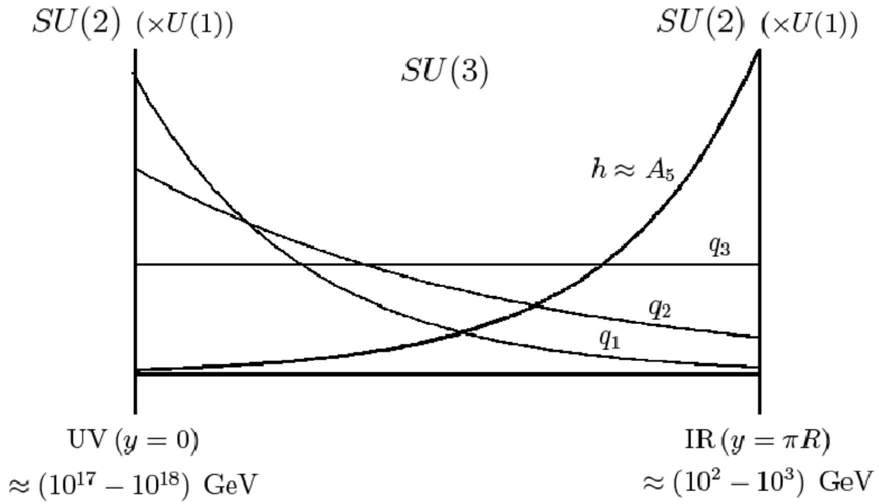


AdS (warped)

$$A_\mu : \left(\begin{array}{cc|c} (+,+) & (+,+) & (-,-) \\ (+,+) & (+,+) & (-,-) \\ \hline (-,-) & (-,-) & (+,+) \end{array}\right) \qquad A_5 : \left(\begin{array}{cc|c} (-,-) & (-,-) & (+,+) \\ (-,-) & (-,-) & (+,+) \\ \hline (+,+) & (+,+) & (-,-) \end{array}\right)$$

Higgs arises as an extra dimensional component of the gauge boson, A_5

- Realistic Yukawa couplings obtained



- Higgs potential is finite and calculable → EWSB

  (due to higher dimensional gauge invariance)

- Existence of resonances (KK towers) for the gauge fields as well as quarks and leptons

  … Physics at the LHC (and LC)

- Nontrivial wavefunctions for W and Z as well as for matter → couplings deviate from the SM

  … Physics at LC

Summary

- We are about to explore physics of EWSB
- New Physics at the TeV scale is well motivated
  - Problem of Naturalness, DM, …
    - Weak scale supersymmetry
    - Higgs as a pseudo Nambu-Goldstone boson
    - …
- Exploration of this New Physics is the prime target of experiments in the next decades

  A variety of possibilities for how New Physics shows up

  → Combination of the LHC and LC very useful
- We hope to understand Nature at a deeper level