Electroweak Symmetry Breaking

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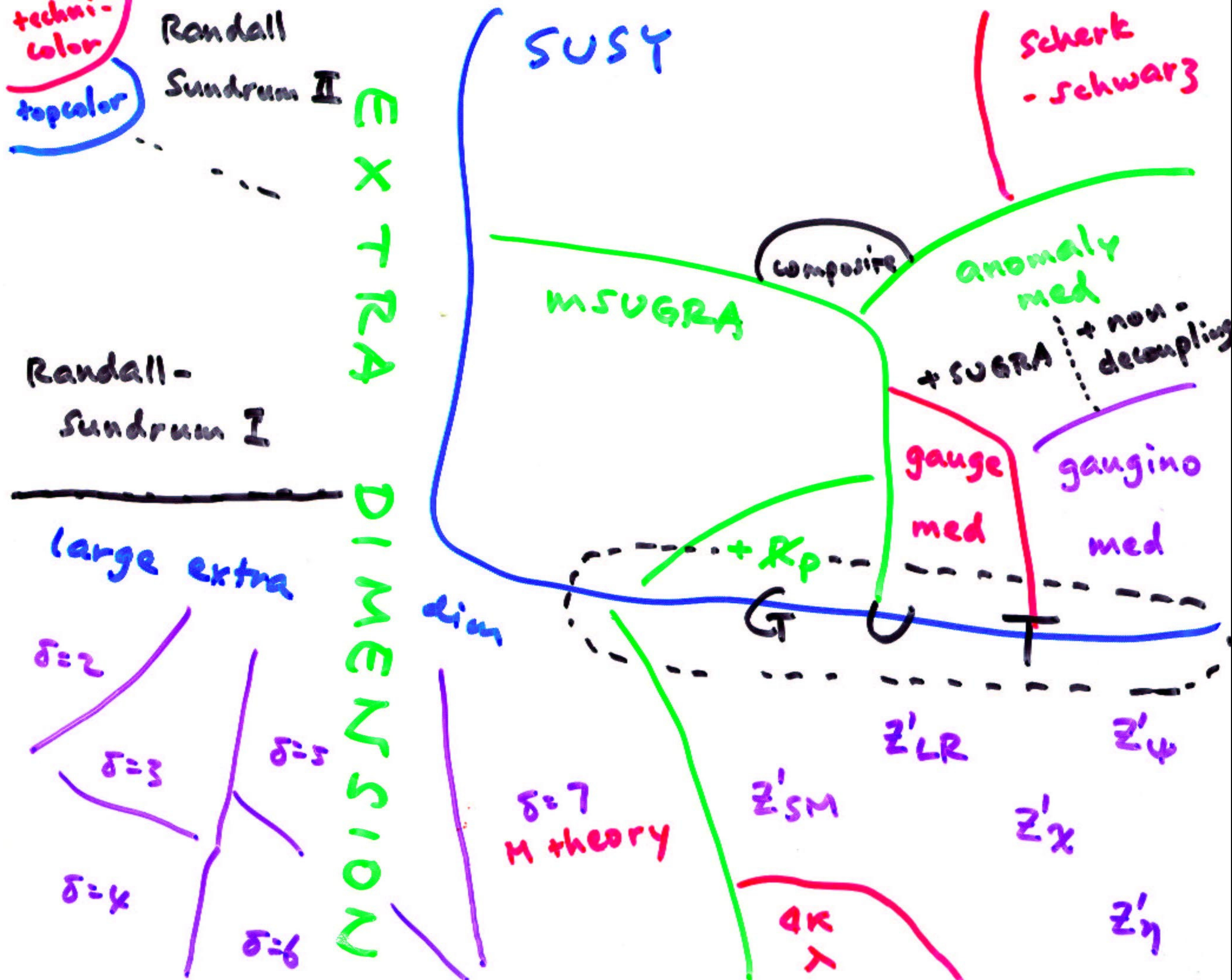
SLAC, Jan 7, 2003



techni-color
topcolor
Randall Sundrum II
SUSY
Scherk - Schwarz
EXTRA DIMENSION
composite
anomaly med
mSUGRA
+ SUGRA
+ non-decoupling
Randall-Sundrum I
gauge med
gaugino med
large extra dim
+ R_p
GUT
δ=2
δ=3
δ=5
δ=4
δ=6
δ=7
M theory
Z'LR
Z'ψ
Z'SM
Z'χ
Z'η
4K
λ


bosonic TC
composite Higgs
TC-TC
hypercolor
supercolor
techni-GIM
extended TC
pseudo NGB
NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
effective SUSY
SUSY
NMSSM
MSSM +νR
ununified SM
axigluon
sterile ν
heavy Majorana
6th gen
5th gen
4th gen
lepto quark
vector-like family
fractionally charged
milli-charged
mono-pole
S,T,U
X Y
shadow matter
mirror symmetry
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
spontaneous CP
superweak
milli-weak
Weinberg's 3HD
Majoron
axion
familon
NGB
saxion
axino
worm-hole
Extra dim
quintessence
k-essence
composite W,Z
γ,g
contact int.
string
hetero tic
matrix M
IIB
F
IIA
I
N=2
N=4
N=8

Task

- Find physics responsible for EWSB
- We can eliminate many possibilities at LHC
- But new interpretations necessarily emerge
- Race will be on:
  - theorists coming up with new interpretations
  - experimentalists excluding new interpretations

  $\Rightarrow$ A *loooong* process of elimination
- Crucial information is in *details*
- Elucidate what that physics is
  - Reconstruct the Lagrangian from measurements
- *That is why I want a LC in addition to the LHC*

Absolute confidence is crucial for a major discovery

- As an example, supersymmetry
- "New York Times" level confidence

  "The other half of the world discovered"

  still a long way to

- "Halliday-Resnick" level confidence

  "We have learned that all particles we observe have unique partners of different spin and statistics, called superpartners, that make our theory of elementary particles valid to small distances."

Outline

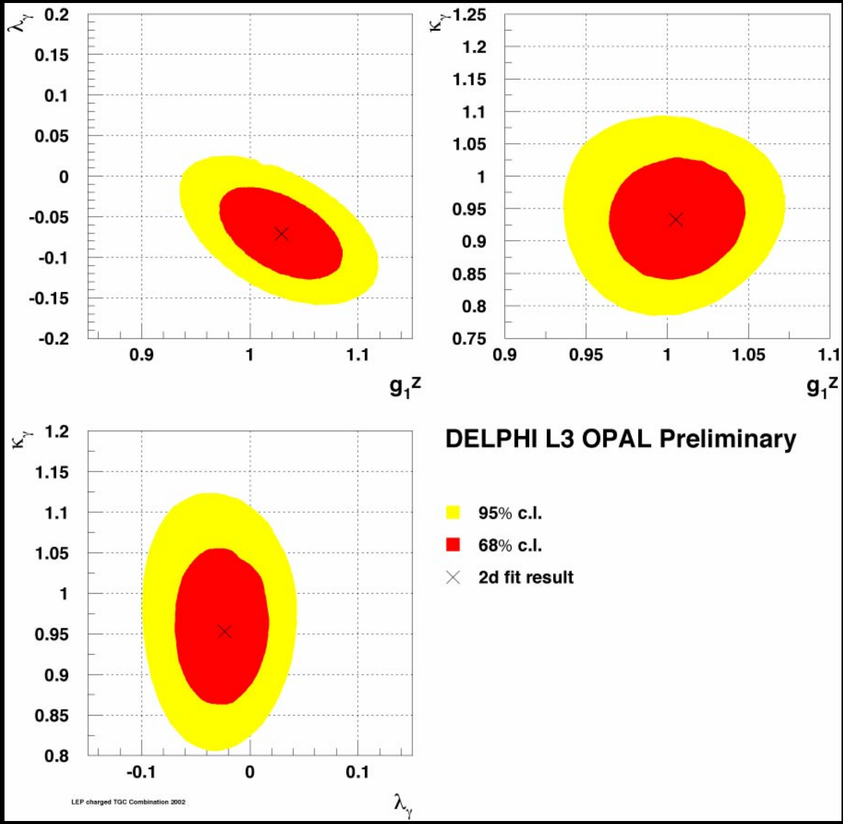
- Why Higgs?
- MSSM is fine-tuned
- Little Higgs
- Fat Higgs
- No Higgs Boson
- No Higgs Mechanism

Why Higgs?

Textbook

- *W* and *Z* are massive vector bosons
- Only known consistent (renormalizable) quantum field theory of massive vectors is gauge theory with Higgs mechanism
- Therefore, *W* and *Z* bosons must be gauge bosons, broken by a Higgs

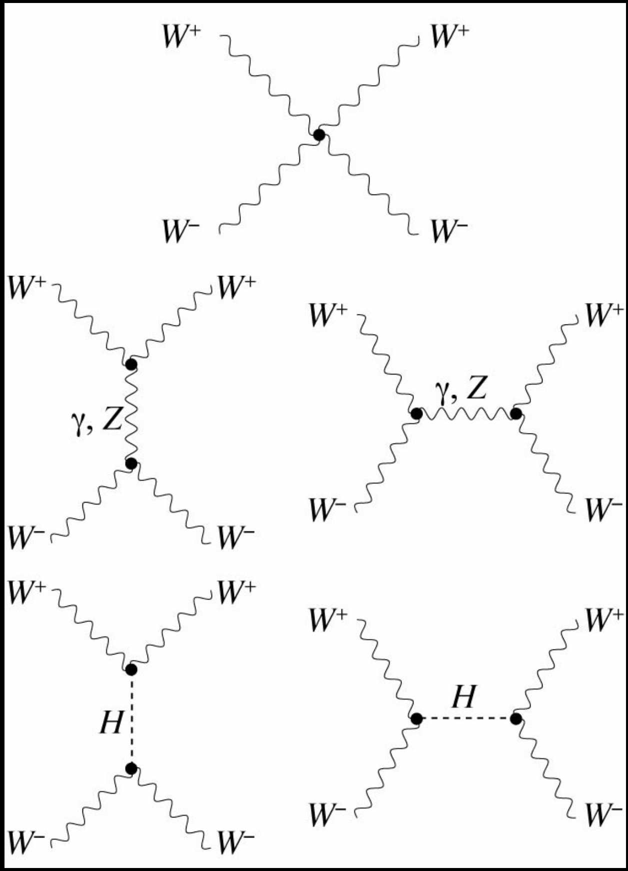
S. Weinberg



Now added evidence of vector boson self-couplings

unitarity

- *W*-boson scattering grows with energy $A \sim G_F E^2$ and violates unitarity at 1.8TeV
- If you allow only one extra particle beyond what we know to restore unitarity, the only possibility is to add a spin zero particle whose couplings are precisely those of the SM Higgs



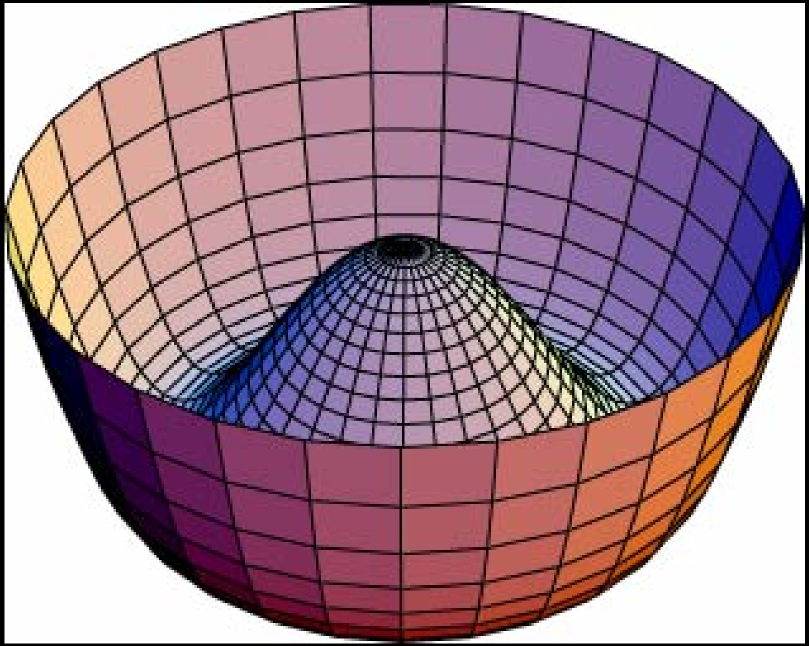
C. H. Llewellyn Smith; D. A. Dicus and V. S. Mathur;
J. M. Cornwall, D. N. Levin and G. Tiktopoulos

UGLY

- $V = \lambda |H|^4 - m^2 |H|^2$
- Why negative mass-squred?
- Why only one scalar in the SM?
- Hierarchy problem because of its quadratic divergence,

$$\Delta m^2 = \frac{3\Lambda^2}{32\pi^2 v^2}(2m_W^2 + m_Z^2 + m_h^2 - 4m_t^2)$$

  need $\Lambda <$ TeV
- Ginzburg-Landau rather than BCS



Many attempts

- Many attempts to make the Higgs look more natural
- Hierarchy must be stabilized somehow
- SUSY
  - Higgs only one of many scalars that happen to acquire negative mass-squared
  - SUSY stabilizes the hierarchy
- technicolor
  - Higgs fermion-pair bound state à la BCS
  - form factor stabilizes the hierarchy
- Extra dimension
  - there is no hierarchy (???)

SUSY: the dominant paradigm

- soft SUSY mass-squared of H_u driven naturally negative by top/stop loop: "radiative breaking"
- easily consistent with the EW precision observables because it is "decoupling" physics
- FCNC is a concern, but OK if special mediation mechanism for SUSY breaking employed
  - gauge mediation, anomaly mediation, gaugino mediation, ...
- can be connected to GUT, string, etc

Outline

- Why Higgs?
- Little Higgs
- Fat Higgs Boson
- No Higgs Boson
- No Higgs Mechanism
- Conclusions

Little Higgs

(Arkani-Hamed, Cohen, Georgi
+ Gregoire, Katz, Nelson, Wacker)

Little Higgs

- The basic idea: Higgs boson is a composite pseudo-Nambu-Goldstone boson akin to pions in the QCD
- If $m_u = m_d = 0$, π^0 massless, but $\pi^\pm$ massive @ 1-loop

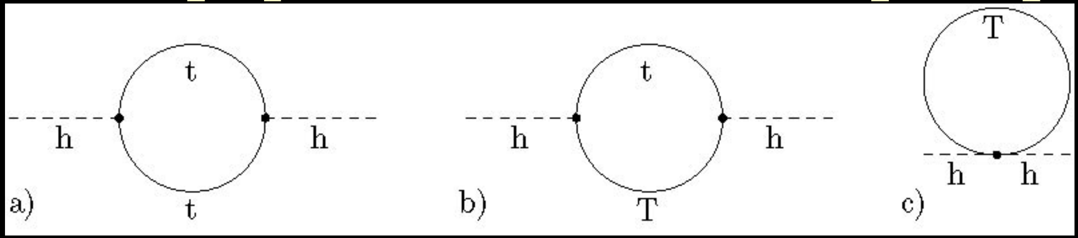
  $$\Delta m_\pi^2 = m_{\pi^\pm}^2 - m_{\pi^0}^2 \simeq \frac{\alpha}{4\pi}\Lambda^2 \simeq e^2 f_\pi^2 \qquad \Lambda \sim 1 \text{ GeV}$$
- Similarly, m_h^2 is quadratically divergent with $\Lambda \sim 1$TeV
- *Can we postpone the problem to 10 TeV?*
- Make sure that no single interaction induces one-loop divergence
- Only two-loop quadratic divergence

The Littlest Higgs

- SU(5)/SO(5): 14 NGB
- Gauge SU(5)⊃SU(2)×SU(2)×U(1)⊃$SU(2)_L \times U(1)_Y$
- $14 = 1_0 + 3_0 + 2_{+1/2} + 2_{-1/2} + 3_{+1} + 3_{-1}$
- 3_0 eaten by the broken SU(2)
- Higgs: $2_{+1/2} + 2_{-1/2}$ the mass protected against quadratic divergence at the one-loop because neither SU(2) breaks the global symmetry
- Two-loop divergence allows Λ~10TeV
- Many variants: SU(6)/Sp(6), $SU(4)^4/SU(3)^4$

New particles

- New gauge bosons cancel the *W/Z* loop
- New "top quark" cancels the top loop

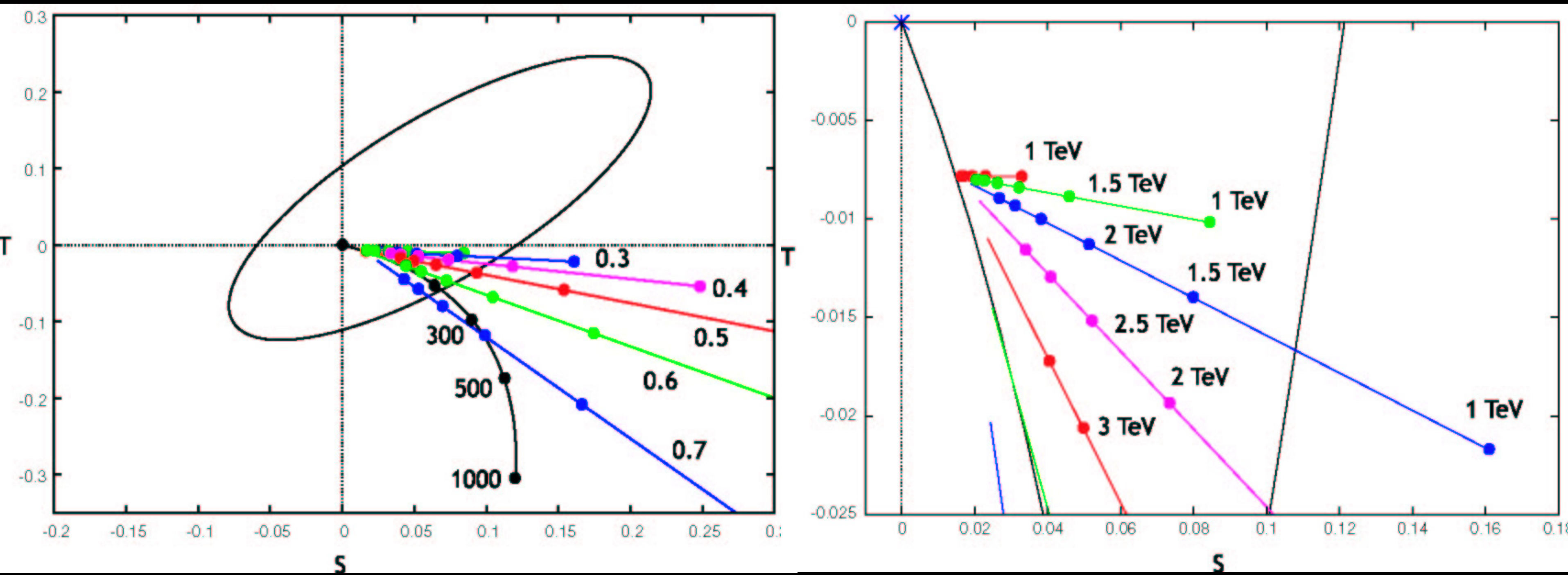


$$\Delta m_h^2 = -3\frac{\lambda_t^2 m_T^2}{8\pi^2}\log\frac{\Lambda^2}{m_T^2} + \frac{9g^2 m_{W'}^2}{64\pi^2}\log\frac{\Lambda^2}{m_{W'}^2}$$

- To avoid fine-tuning more than 10%, the new "top quark" must be lighter than ~2TeV
- *W'* also expected around the same mass range
- Tension with precision EW constraint >7 TeV?

Precision EW

- The "best version" looks OK



Perelstein, Peskin, Pierce

Fat Higgs Boson

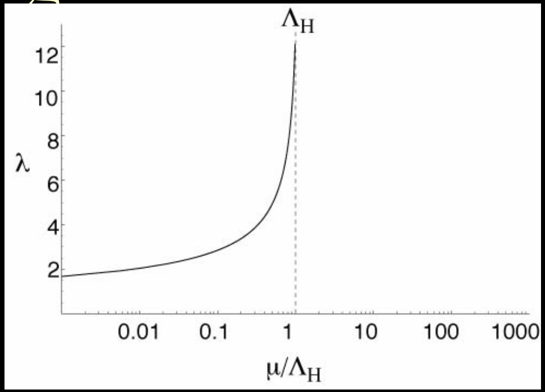
R. Harnik, G. Kribs, D. Larson, HM

The MSSM

- The Higgs self-coupling is given by the gauge coupling $\lambda=(g^2+g'^2)/8$
- That is why $m_h < m_Z$ @ tree-level
- soft SUSY mass-squared of H_u driven naturally negative by top/stop loop: "radiative breaking"
- EWSB a consequence of SUSY breakng
- Requires $m_{\rm SUSY} \sim m_Z$
- LEP-II didn't find Higgs nor SUSY
- Getting fine-tuned at a few percent level

Making Higgs Heavier

- Make λ independent of gauge couping
  - $W = \lambda N (H_u H_d - v^2)$
  - $V = \lambda^2 |H_u H_d - v^2|^2$
- $m_h \sim \lambda v$ instead of m_Z
- But λ gets bigger at higher energies
- To keep it finite up to the GUT-scale, it still requires $m_h < 150$ GeV
- *What if it blows up?*
- Higgs is composite at that energy scale Λ_H



The Minimal SUSY Fat Higgs

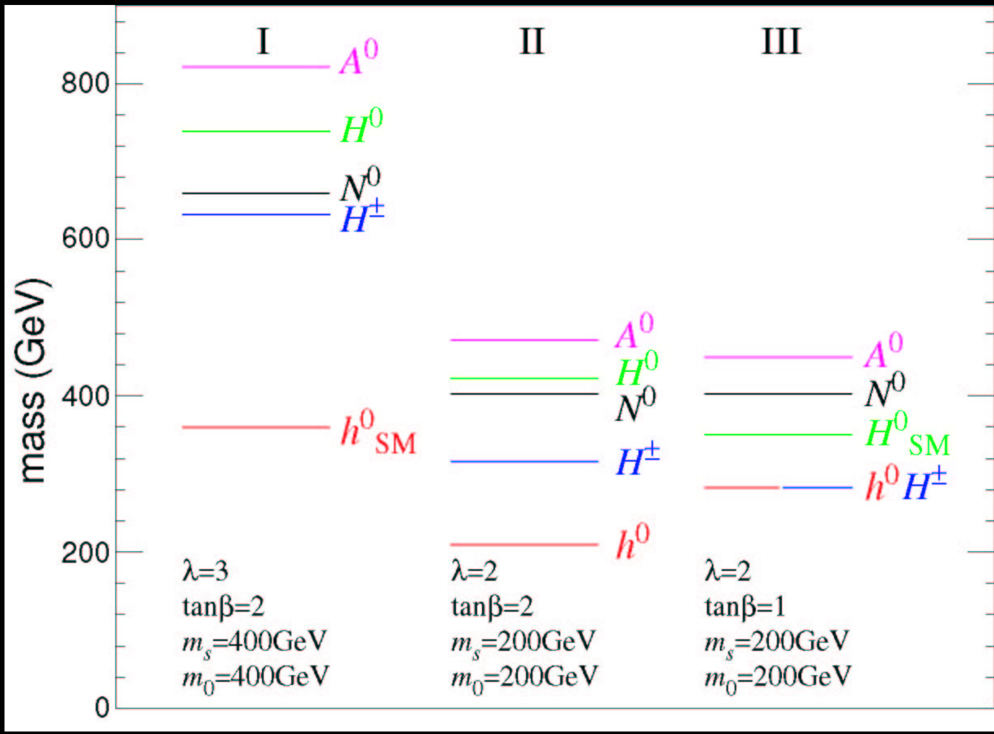
- $SU(2)_H$ with N_f=3 (6 doublets)
  - $T^{1,2}$: $SU(2)_L$ doublet
  - $T^{3,4}$: $U(1)_Y$ $\pm 1/2$
  - $T^{5,6}$: electroweak neutral
- 6*5/2=15 mesons M_{ij}: $W_{\rm dyn} = \mathrm{Pf}\,(M)/\Lambda^3$ (Seiberg)
- 5 of them look good:
  - $H_u=(T^1, T^2)T^3$, $H_d=(T^1, T^2)T^4$, $N= T^5 T^6$
- $W_{\rm dyn}=\lambda\, N\, H_u\, H_d$ with $\lambda \sim 4\pi$
- Add mass term for $T^{5,6}$: $W=m\, T^5\, T^6$
- $W_{eff}=\lambda\, N\, (H_u\, H_d - v^2)$

No fine-tuning

- Electroweak symmetry breaking *without* relying on SUSY breaking
- Higgs mass $m_h = \lambda v$, not tied to m_Z
- SUSY breaking scale $\leq m_h$ because of naturalness, but can be higher than m_Z
- Couplings can also unify by adding suitable extra particles
- However, some fields have quantum numbers not embeddable into SU(5)
- Orbifold GUT, string unification
- Uses superconformal dynamics to accommodate large enough top Yukawa without FCNC

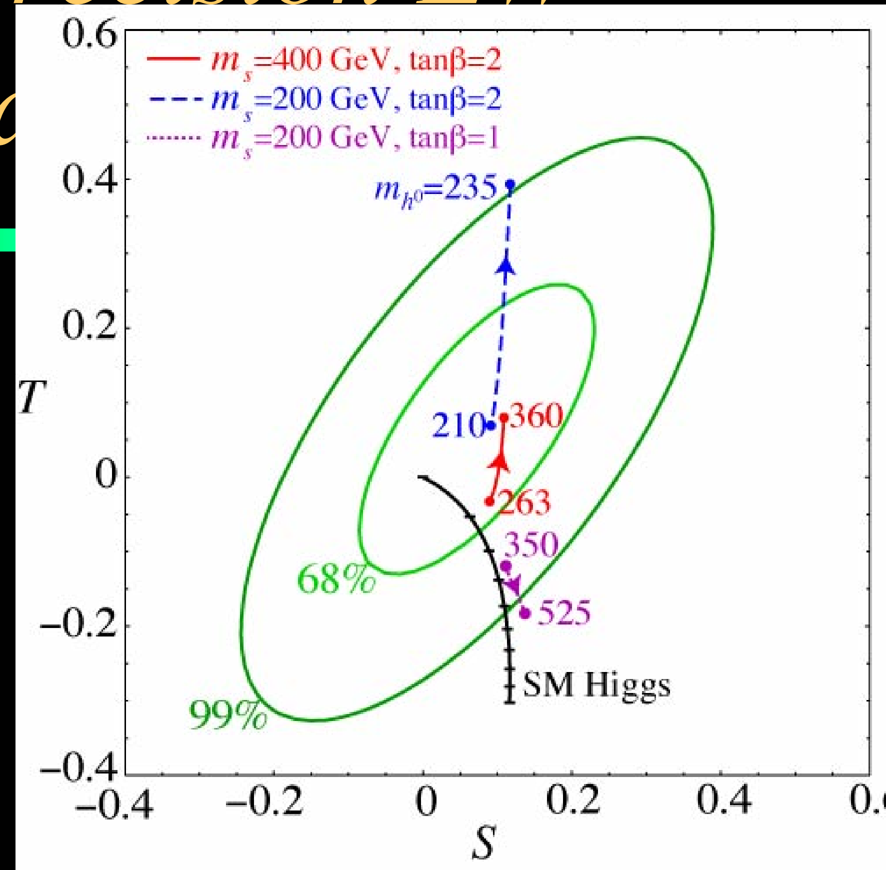
Higgs spectrum

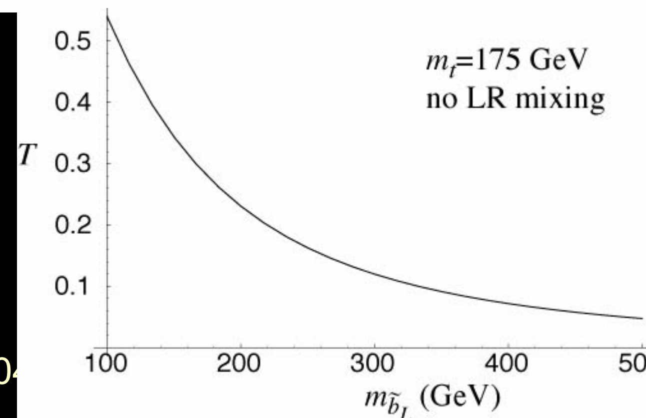
- Higgs mass spectrum can be unusual, quite different from the MSSM
- Combine LHC+LC
- Completely calculable despite the composite nature of Higgs



What about precision EW constr

- Heavier Higgs gives positive *S*, negative *T*
- Can be easily compensated by an additional positive *T*
- Higgs sector itself may provide positive *T*
- Stop/sbottom sector also gives positive *T*





No Higgs Boson

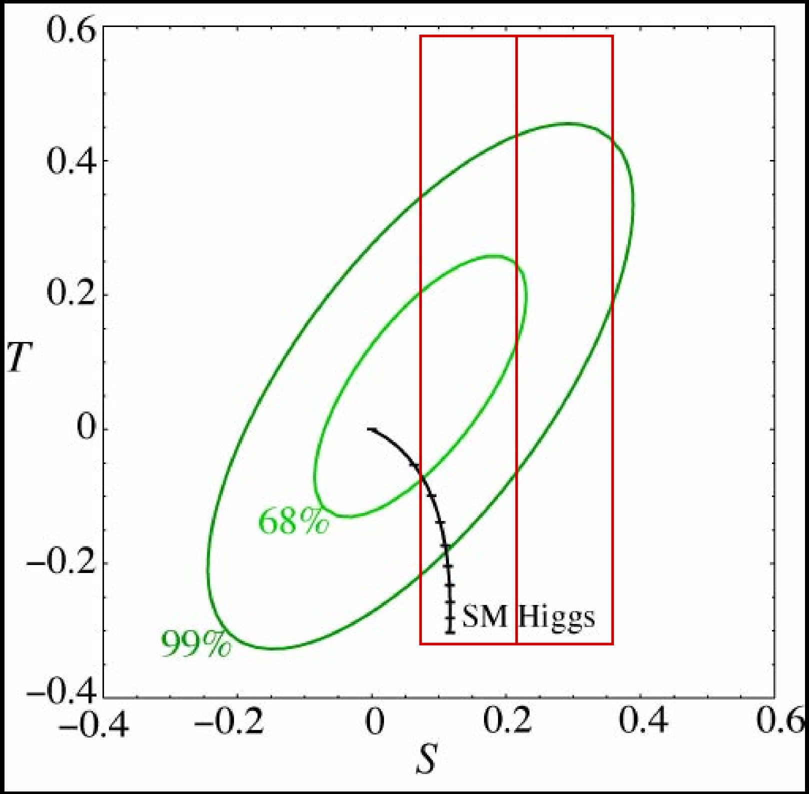
HM, hep-ph/0307293

Technicolorful Supersymmetry

- Seiberg and Witten: SUSY gauge theories do not exhibit phase transitions as parameters are varied continuously
- What about the limit $m \to \Lambda_H$ of fat Higgs?
- Decouple $T^{5,6}$, giving $SU(2)_H$ with $N_f=2$
- Quantum modified moduli space: $H_u H_d = v^2$
- "Higgs" becomes as heavy as TeV, broadens and disappears from the spectrum
- Yet, the fermion masses are generated consistently without dangerous FCNC
- First demonstrable example of walking technicolor theory!

Features

- Hierarchy generated and stabilized by the technicolor gauge dynamics
- Despite SUSY, no Higgs
- EW precision constraint tighter, need a small conspiracy between positive S and positive T
- Need Giga-Z to sort it out
- Expect strong WW scattering ($e^+e^- \to W^+W^-$)

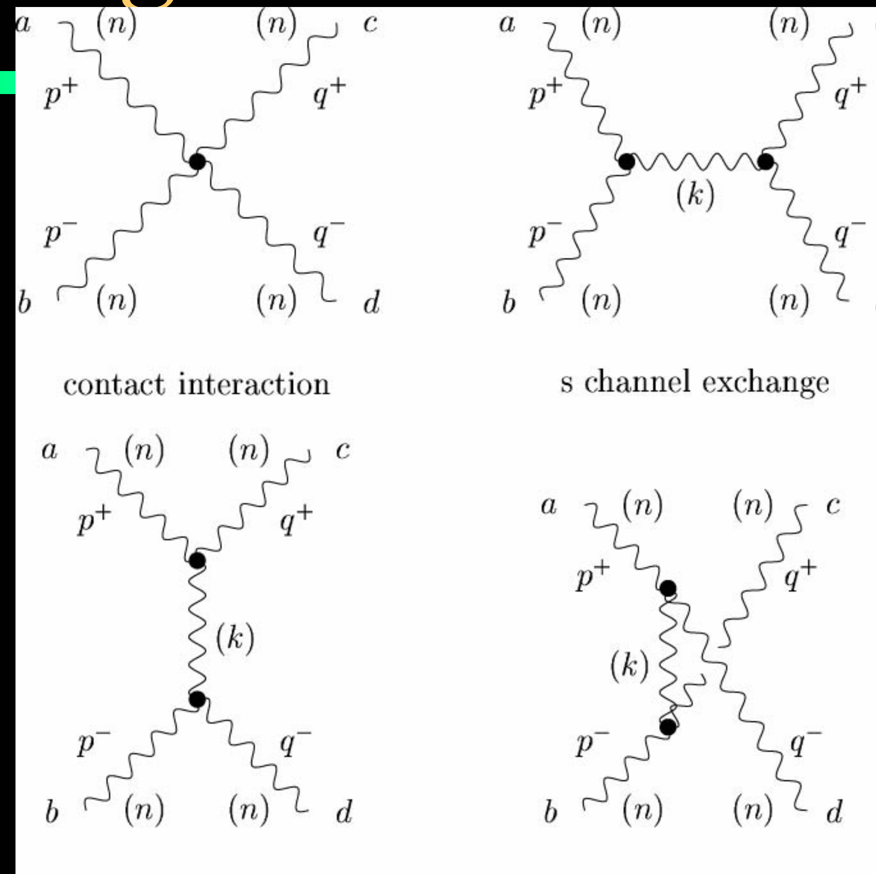


No Higgs Mechanism

C. Csáki, C. Grojean, HM, J. Terning, L. Pilo
C. Csáki, C. Grojean, J. Terning, L. Pilo
Y. Nomura
C. Csáki, C. Grojean, J. Hubisz, Y. Shirman, J. Terning
G. Burdman and Y. Nomura

unitarity again

- The only way to restore unitarity in WW scattering is to add Higgs boson
- True, if only one (or finite) particle
- *What about an infinite tower of particles?*
- extra dimensions give an infinite tower of Kaluza-Klein states
- Maybe another way to restore unitarity?
- need cancellations both in E^4 and E^2 terms



contact interaction
s channel exchange
t channel exchange
u channel exchange

$$g_{nnnn}^2 = \sum_k g_{nnk}^2 \qquad 4 g_{nnnn}^2 M_n^2 = 3 \sum_k g_{nnk}^2 M_k^2$$

Toy model

- SU(2) in the 5D bulk
- boundary conditions break SU(2)→U(1)
  - $A_\mu^{1,2}(0)=0$, $\partial_5 A_\mu^{1,2}(0)=0$
  - $\partial_5 A_\mu^{1,2,3}(\pi R)=0$

- $m_\gamma=0$, $2/R$, $4/R$, ...
- $m_W=1/R$, $3/R$, $5/R$, ...
- scattering of the lowest W unitarized by the exchange of KK photons

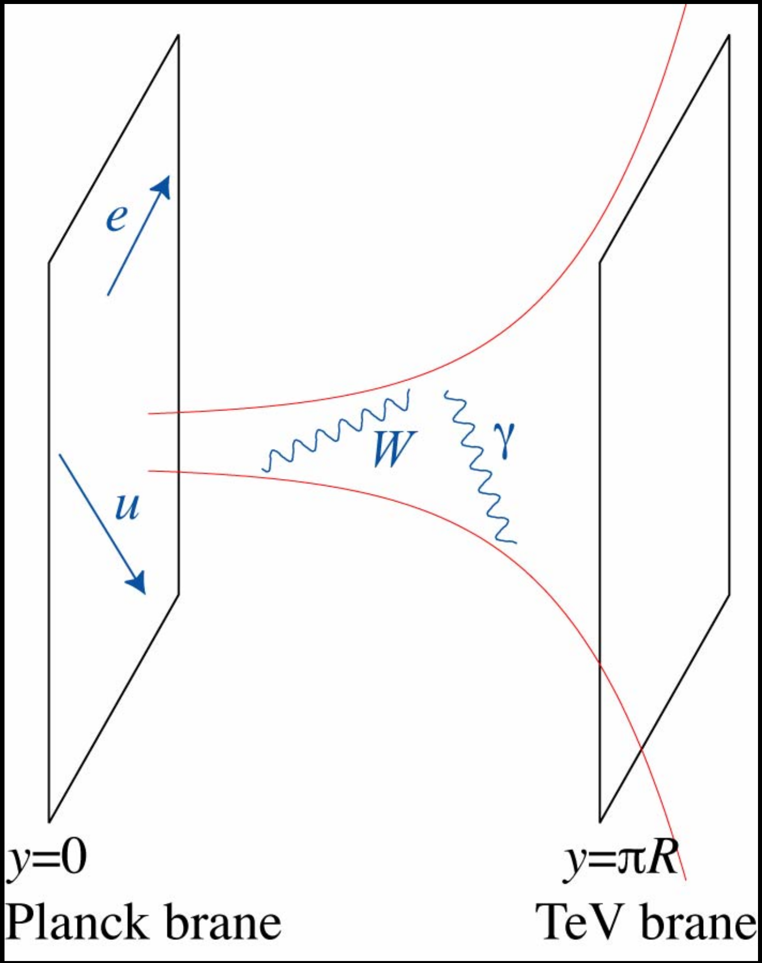
$$g^2_{nnnn} = \sum_k g^2_{nnk}$$

$$4 g^2_{nnnn} M^2_n = 3 \sum_k g^2_{nnk} M^2_k$$

- No Higgs mechanism, no physical scalar bosons: *“Higgsless model”*

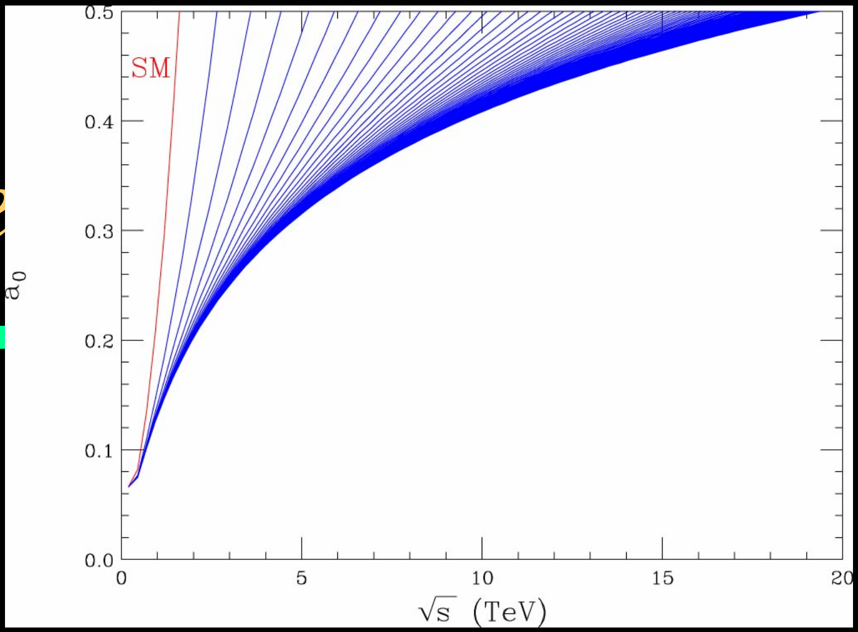
Anti-deSitter

- can reduce the rank by imposing $W_\mu^3(0)+B_\mu(0)=0$
- Use Randall-Sundrum warped extra dimension
- on Plank brane, break $SU(2)_R \times U(1)_X \rightarrow U(1)_Y$
- on TeV brane, break $SU(2)_L \times SU(2)_R \rightarrow SU(2)_D$
- The lowest *W, Z* more or less flat except for near the TeV brane
  - higher KK states >> *W, Z*
  - rho parameter = 1 to 1% level

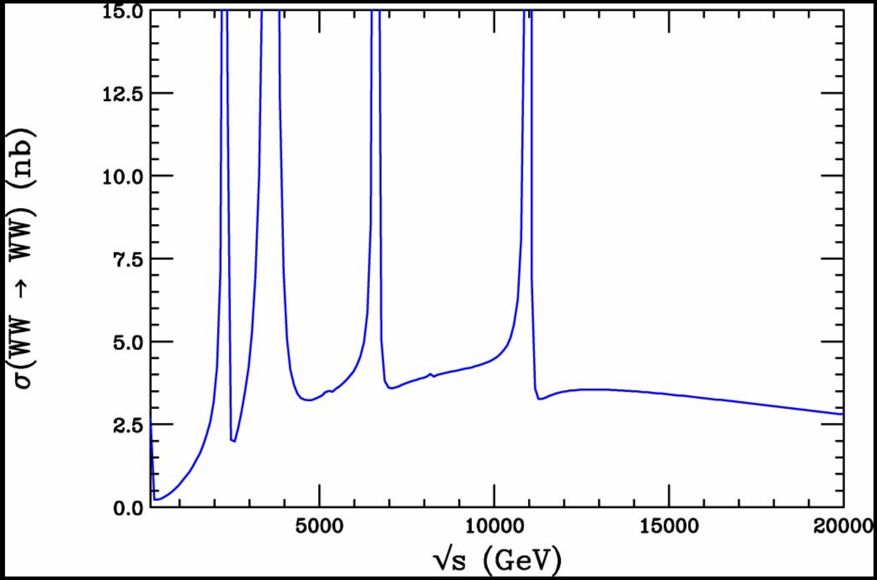


Higgsless phe

- Whole tower of KK vector bosons
  - Can be produced at LHC, on-resonance e^+e^-
  - If on high-end, *WW* scattering becomes quite strong before the first resonance comes in
- may or may not have SUSY
- Tension between:
  - Unitarity wants light KK
  - precision EW wants heavy KK



Foadi, Gopalakrishna, Schmit



Davoudiasl, Hewett, Lillie, Rizzo

Conclusions

- After twenty years of dominance by the MSSM, there are now realistic alternatives
- The MSSM itself is getting fine-tuned
- Little Higgs postpones the hierarchy problem up to ~10TeV
- The Minimal Fat Higgs solves fine-tuning, calculable, viable, unifiable
- Technicolorful SUSY the first demonstrated model of walking technicolor, appears viable
- Higgless models under active development
- Most likely there are more possibilities!