NEW MODELS OF ELECTROWEAK SYMMETRY BREAKING

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What is EW Symmetry Breaking?

We observe from experiment that quarks and leptons obey the gauge symmetries:

$SU(3)_c$ - QCD "strong force" (quarks only)

binds quarks into protons and neutrons

$U(1)_{em} \rightarrow$ electromagnetism (charged only)

forms atomic bound states, etc.

and an approximate $SU(2)_L$ symmetry:

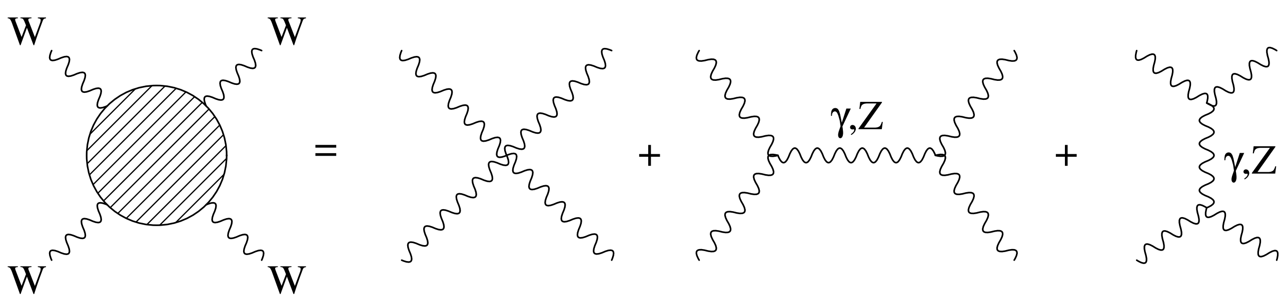
$\rightarrow$ observe massive W, Z; short-range force

$\rightarrow$ Z has some right-handed coupling

Problem 1: $M_{W,Z}$ wreck gauge invariance!

Theory needs something else...

Problem 2: $WW \rightarrow WW$ unitarity violation



$\mathcal{A} \propto G_F E_{CM}^2$ - unitarity violation (at LHC!)

What does the SM say about this?

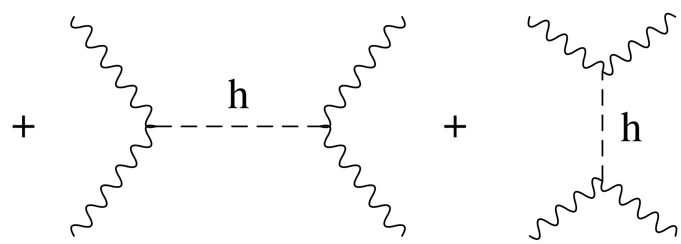
Postulate new particle, must be scalar (S=0)

▶ use to break $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$

simple potential:

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$\mu^2 \to < 0$ breaks $SU(2)_L$ spontaneously, generates $M_{W,Z}$, leaves photon massless; and add'tl diagrams



cancel $G_F E_{CM}^2$ terms IFF coupling = gM_W <u>*and*</u> $M_h \lesssim 1$ TeV (otherwise M_h arbitrary)

▶ Even Yukawa and self-couplings determined by unitarity!

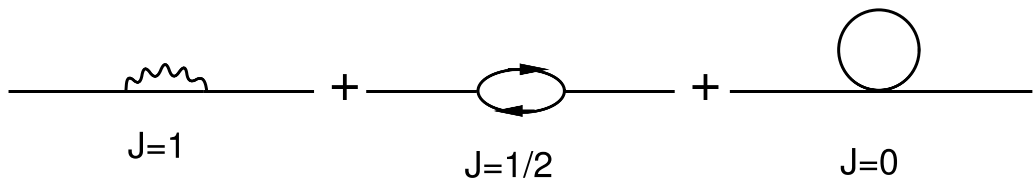
• This is the MINIMAL theory of EWSB

But note: never seen a fundamental scalar

Theoretical problem #1: M_h stability

Quantum corrections drive M_h to M_{Pl}

$m^2(p^2) = m_0^2 +$



$$\delta M_h^2 \propto G_F \left(2M_W^2 + M_Z^2 + M_h^2 - 4m_t^2\right) \Lambda^2$$

Λ is new physics scale $\rightarrow M_{Pl}$? M_{GUT}? M_{DM}?

1. SM can't explain stable, EW-scale M_h
   $\rightarrow$ Veltman condition? M_h tuned so $\delta M_h^2 = 0$:
   hard to believe; doesn't work for if new physics

2. expect new physics! (dark matter, flavor, ν_R, ...)
   $\twoheadrightarrow$ destabilizes M_h even worse!

Theoretical problem #2: flavor (Yukawas)

Theoretical problem #3: ν oscillations

Theoretical problem #4: dark matter

Theoretical problem #5: CP violation

Theoretical problem #6: gauge unification

Possible old solutions:

- supersymmetry (SUSY)
- strong dynamics
  (TC/ETC/WTC, TC2, ...)

Possible new solutions:

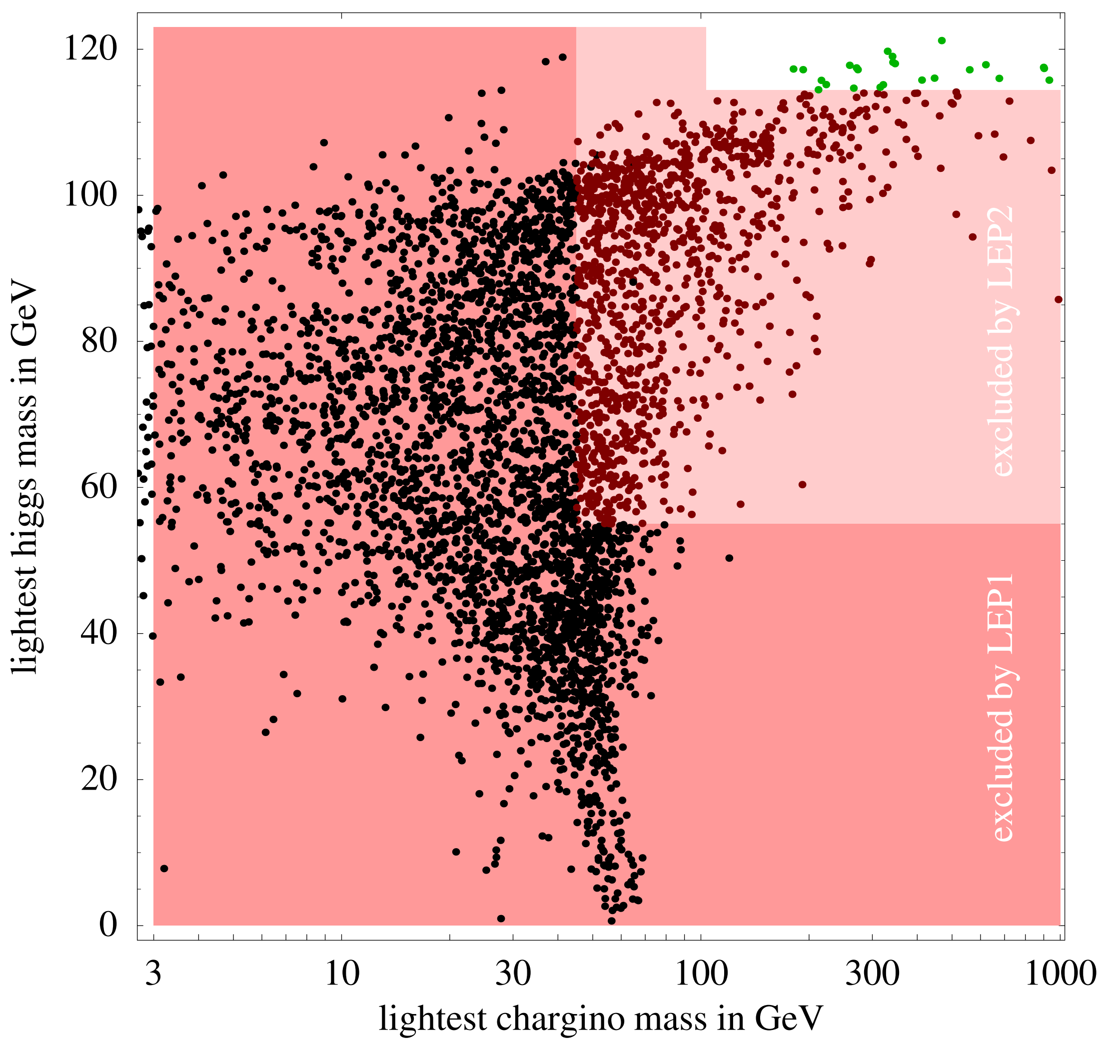
- Fat Higgs
- Little Higgs
- no Higgs

OLD SOLUTION #1: SUSY

- spartners cancel quadratic divergences:

$$\delta M_h^2 \propto \Lambda^2 \longrightarrow \delta M_h^2 \propto \ln(\Lambda)$$

- radiative EWSB (Y_t evol. drives $\mu^2 < 0$)
- DM, gauge coup unif'n, add'tl CP viol.
- minimal 120 parameters! ("MSSM")
- no flavor, very broken, fine-tuned



[Strumia '04]

New approaches in SUSY

Problem? exp. limit on M_h getting large

Examine M_h dependence in MSSM:

$$M_h^2 \propto \frac{1}{4}[g^2 + g\prime^2] + (\text{stuff}) \cdot \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

$\rightarrow$ M_h partly driven by top sector

$m_{\tilde{t}} \uparrow$ to avoid LEP M_h bound

$m_{\tilde{t}} \downarrow$ to avoid fine-tuning

$\therefore$ tension! ("SUSY Little hierarchy")

$\rightarrow$ M_h also driven by gauge sector

Poss. alternative soln: new gauge structure

[Batra, Delgado, Kaplan, Tait, JHEP(0402:043)2004]

e.g. $SU(2)_1 \times SU(2)_2 \longrightarrow SU(2)_L$:

$$M_h^2 \propto \frac{1}{4}[g^2 + g\prime^2 + a g_x^2] + \cdots \quad (a \sim O(1))$$

Phenomenological predictions:

· $M_h = 120 - 350$ GeV

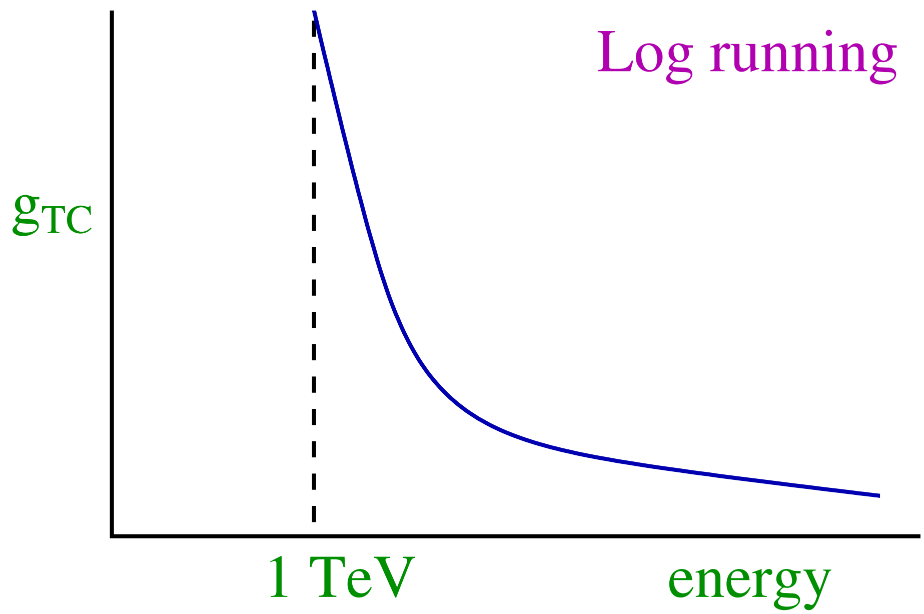
· new gauge bosons: $M_{W',Z'} \approx 2 - 5$ TeV

Old solution #2: strong dynamics

$\Longrightarrow$ no scalars, no stabilization problem!

"Extended Technicolor"; inspired by QCD:

new force is large @ $\Lambda \sim 4\pi v \sim O\,(\text{TeV})$



techniquarks condense as $g_{TC} \to 4\pi$:

$$M_{W,Z} \propto \Lambda_{TC} \sim \langle \bar{T}_L T_R \rangle^{1/3}$$

Problems:

1. needs multiple scales
2. can't (easily) accommodate large m_t
3. many unseen heavy Goldstone bosons
4. easy to violate precision EW data
5. generally predicts FCNCs
6. difficult to calculate precisely

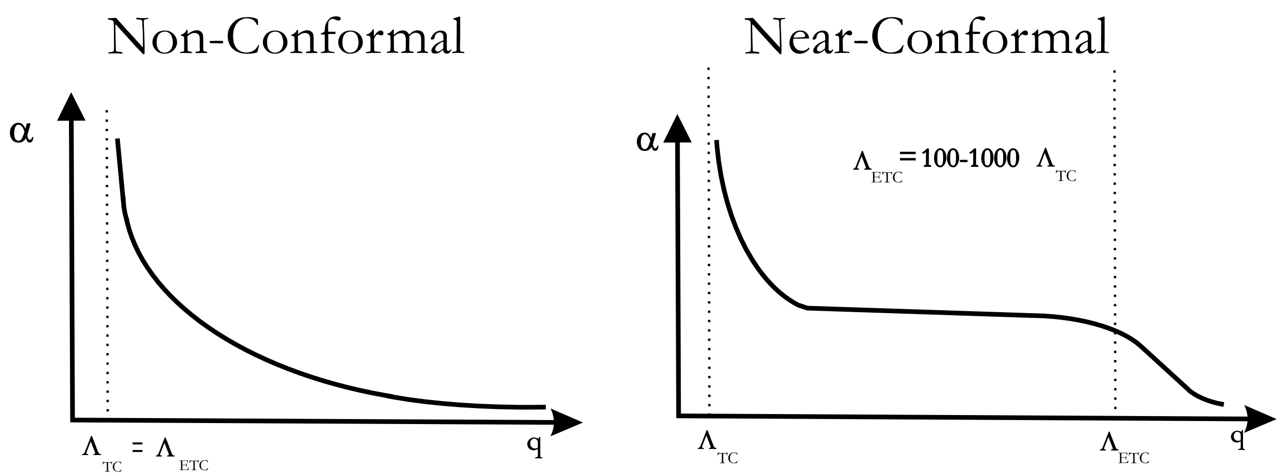
New idea for strong dynamics

conflict: $m_f \sim \frac{\Lambda_{TC}^3}{\Lambda_{ETC}^2}$ with $\Lambda_{TC} = 4\pi v$

but FCNC $\propto \frac{1}{\Lambda_{ETC}^2}$, need $\Lambda_{ETC} \gg \Lambda_{TC}$

Trick: allow larger Λ_{ETC} by slowing running of g_{ETC}

("conformal behavior")



Obtained with larger N_{Tf}; yields larger $\triangle S$ – oops!

New strategy: T-fermions in higher representations -

"counts" more in g_{ETC} running, $N_{Tf} \downarrow \therefore \triangle S \downarrow$

[Hong, Hsu, Sannino, PLB(597)2004]

Estimate: M_h = 170-500 GeV, $\Lambda_{TC} \sim$ 250 GeV

New solution #1: Fat Higgs

[Harnik, Kribs, Larson, Murayama, PRD(70)015002]

Goal: solve SUSY little hierarchy
without fine-tuning

Try: SUSY + composite Higgs; strong EWSB

Ingredients:

· extra gauge symmetry $SU(2)_H$

· extra global symmetries $SU(2)_R$, $SU(2)_g$, $U(1)_R$

· 6 top quark doublets, $T^1, T^2, T^3, T^4, T^5, T^6$,
careful symmetry assignments, mass m for 1 pair

► T^i condensation to meson states M_{ij} at scale $\Lambda_H > M_{SUSY}$ yields an NMSSM-like superpotential:

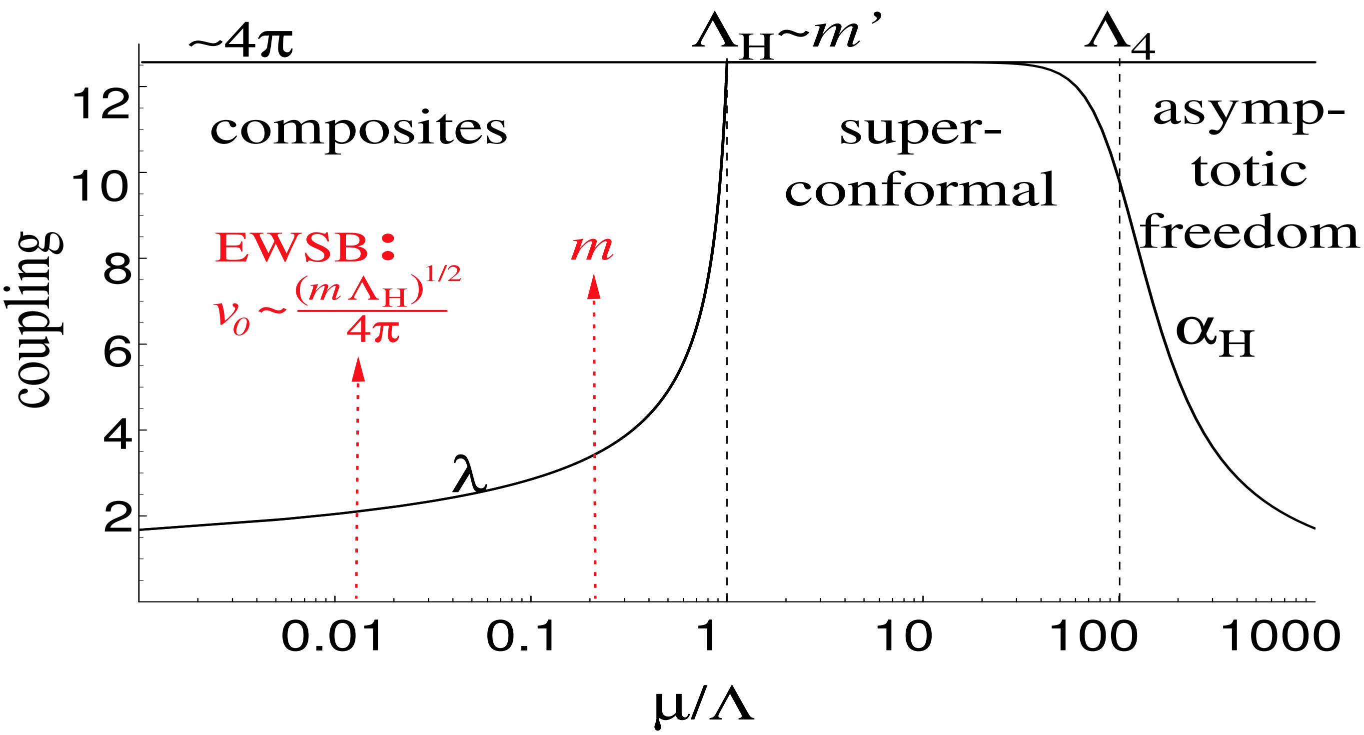
$$W = \lambda M_{56} \left(\begin{pmatrix} M_{14} \\ M_{24} \end{pmatrix} \begin{pmatrix} M_{13} \\ M_{23} \end{pmatrix} - v_0^2 \right)$$

$$W = \lambda S \left(\quad H_d \quad H_u \quad - v_0^2 \right)$$

$$v_0^2 \sim \frac{m\Lambda_H}{(4\pi)^2}$$

Fat Higgs: noteworthy features

→ $SU(2)_H$ forces <u>*weak*</u> λ below scale Λ_H



→ no fine-tuning

→ no domain wall problem like in NMSSM

→ gauge coupling unification works

→ no bound on M_h (typically heavy)

→ MSSM spectrum relatively light

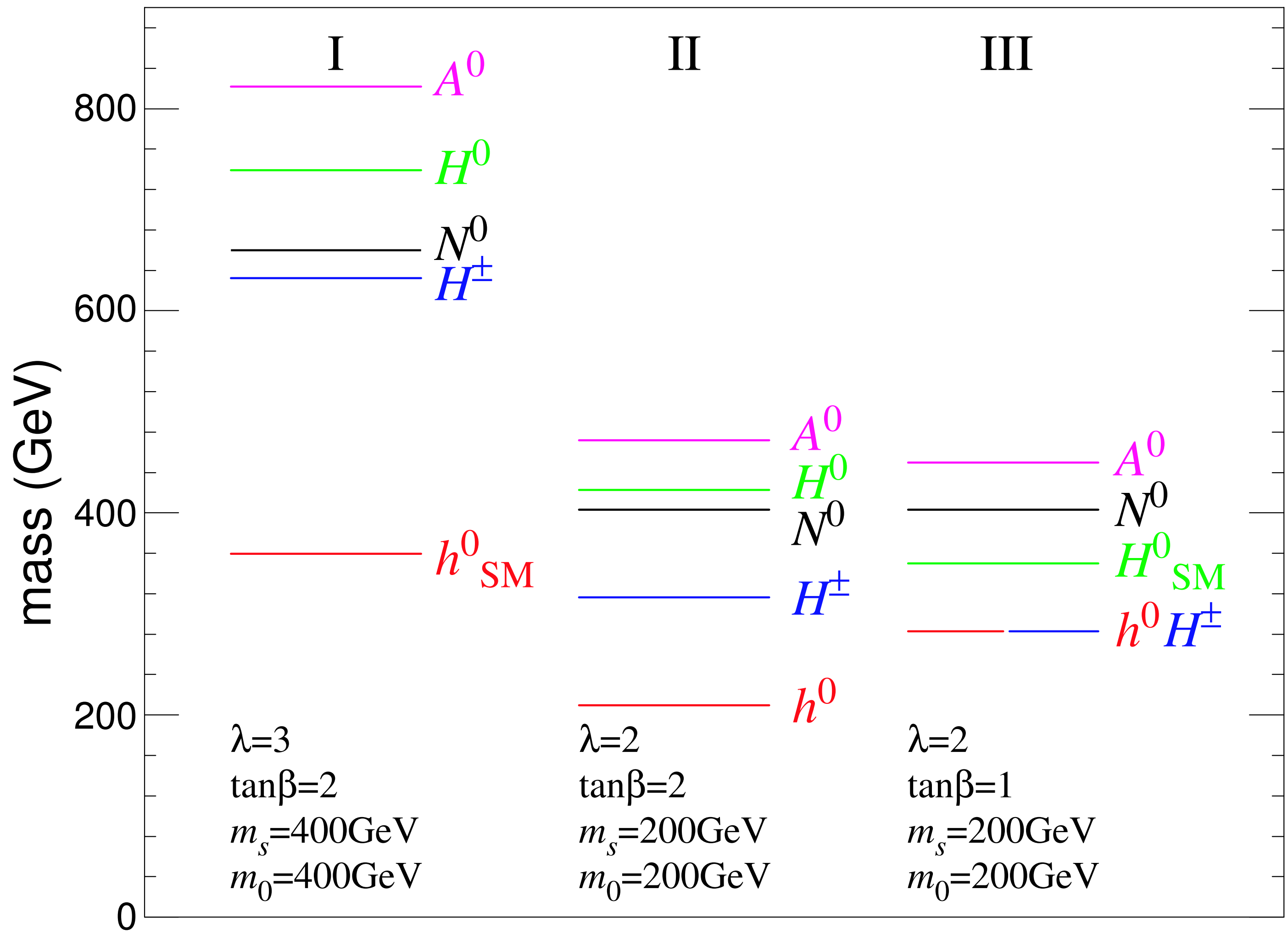
Drawbacks

→ contains awful lot of new model content

→ no obvious GUT scheme

Fat Higgs: scalar spectrum

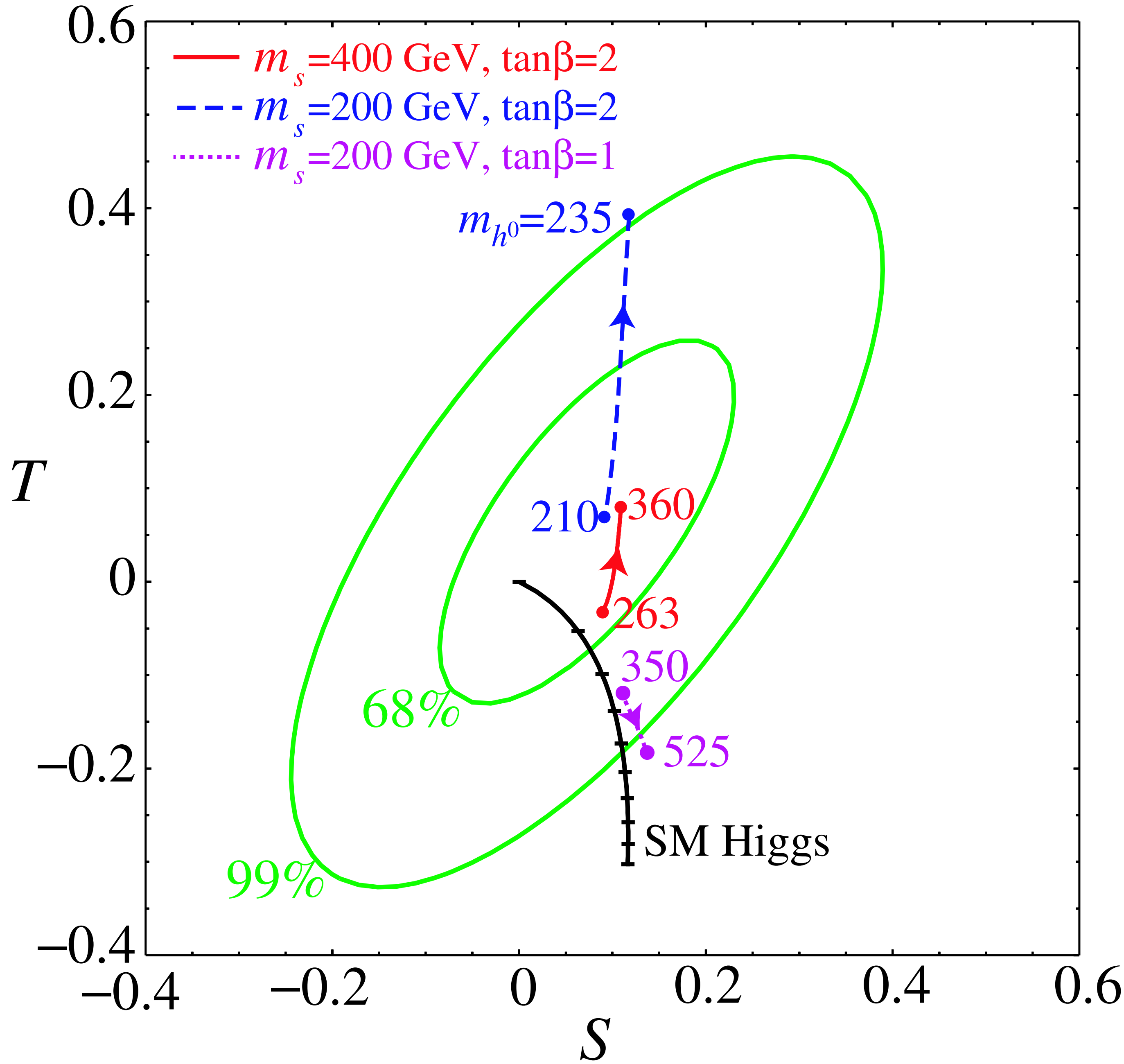
3 models presented:



► *NOT* MSSM/NMSSM-like!
(h^0 heavy, N^0 very heavy,
$H^0/A^0/H^\pm$ not degenerate)

Fat Higgs confronts precision EW data

Model I Model II Model III



Note: $\triangle T \sim$ 0.1-0.5 expected in Model III

► no problem with precision EW data

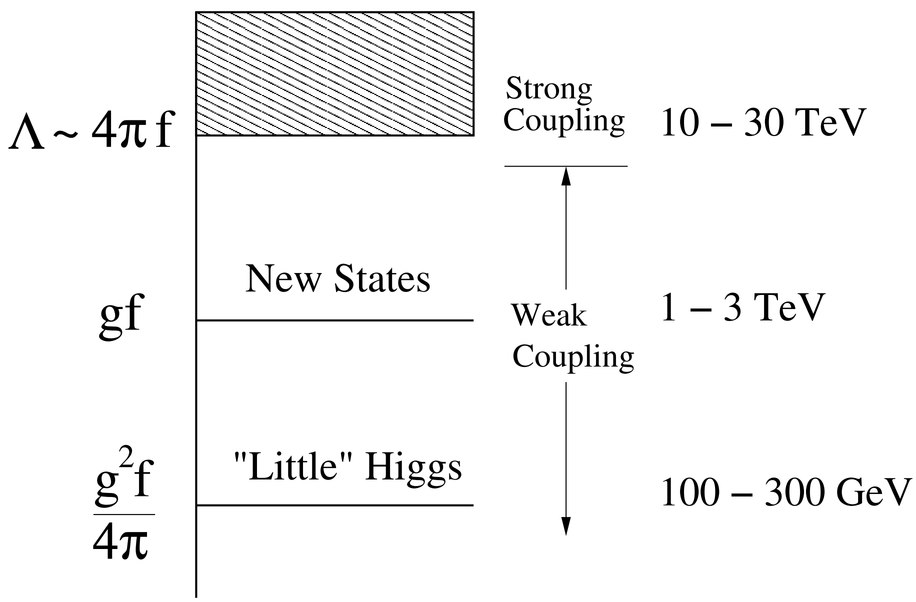
NEW SOLUTION #2: LITTLE HIGGS

Motivation:

precision data constrains new flavor physics to 5-10 TeV: Little Hierarchy

$\rightarrow$ solve this without SUSY

▶ 3-scale symmetry breaking to yield SM



▶ 3 essential ingredients:

1. extended gauge sector, ≥ 2 new gauge coups
2. enlarged global symmetry
3. extended top sector: vector-like $t'_{L,R}$
   (but this is a bit cooked up)

Note: full theory probably strong dynamics!

How Little Higgs works

"Littlest Higgs" as example:

[Arkani-Hamed, Cohen, Katz, Nelson, JHEP(0207)034]

- Global sym. broken spontan'ly via $\langle\Sigma\rangle$: $\Lambda \sim 4\pi f$

$SU(5) \to SO(5) \quad \Rightarrow$ 14 Goldstone bosons

and at the same time:

- Gauge sym. broken spontan'ly via $\langle\Sigma\rangle$: $f \sim 4\pi\text{v}$

$[SU(2)\otimes U(1)]_1 \otimes [SU(2)\otimes U(1)]_2 \to SU(2)_L \otimes U(1)_Y$

4 GB's eaten for $W'^{\pm}, Z', A'$

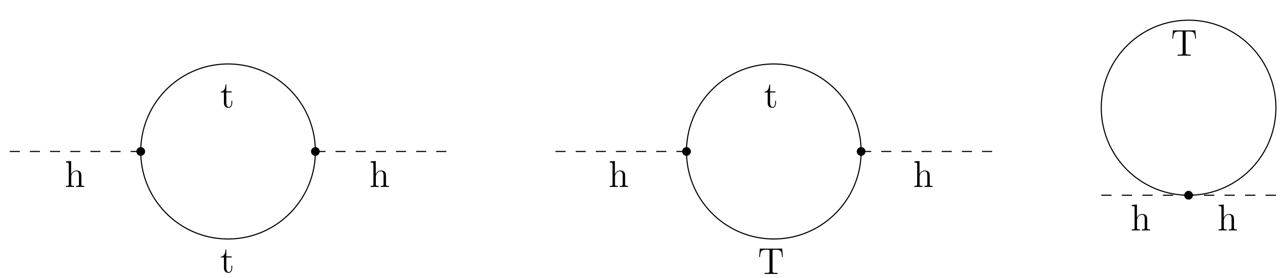
$W^{\pm,0}, B^0$ still massless

- EWSB happens: $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$, $\text{v} \sim 250$ GeV

$\to$ yields complex heavy triplet ϕ, Higgs doublet h

($m_\phi > f$ expected)

M_h stabilized up to scale Λ by *1-loop* quadratic divergence cancellations due to carefully-arranged gauge structure and hand-massaged top sector



Little Higgs phenomenology

Model variations: diff. groups (couple dozen):

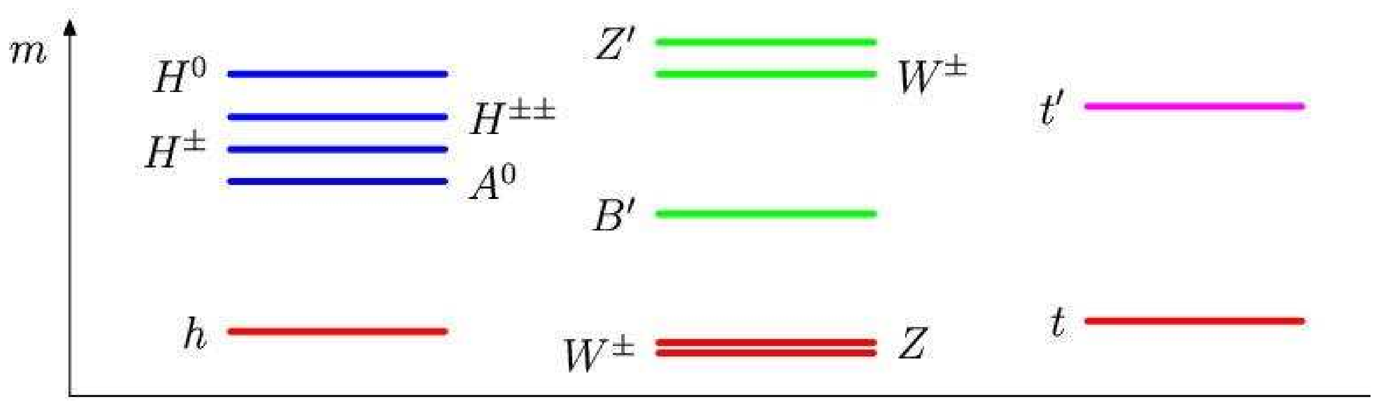
· scalars: 1-2 doublets, 0-1 triplets, 0-3 singlets

· vectors: W', Z', A'; can have even more Z's

Obvious and mostly easy exp. task:

observe t', $W'^{\pm}$, Z', A', ϕ, ...

→ count states, measure spectrum



Obvious but hard exp. task - prec. coupl's:

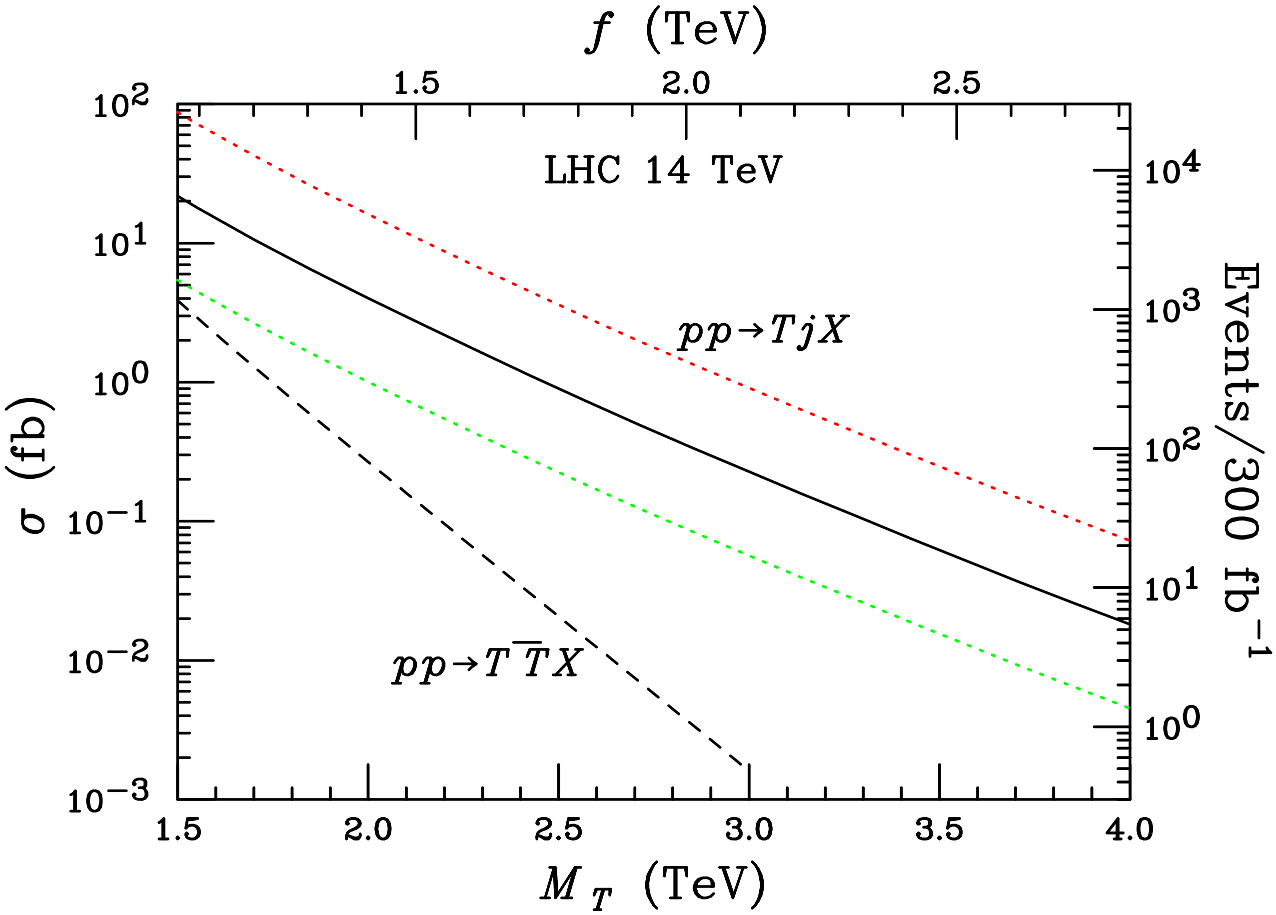
$t\bar{t}h$, $t\bar{t}Z$, $Z'Zh$, $W'Wh$, $A'Zh$, ...

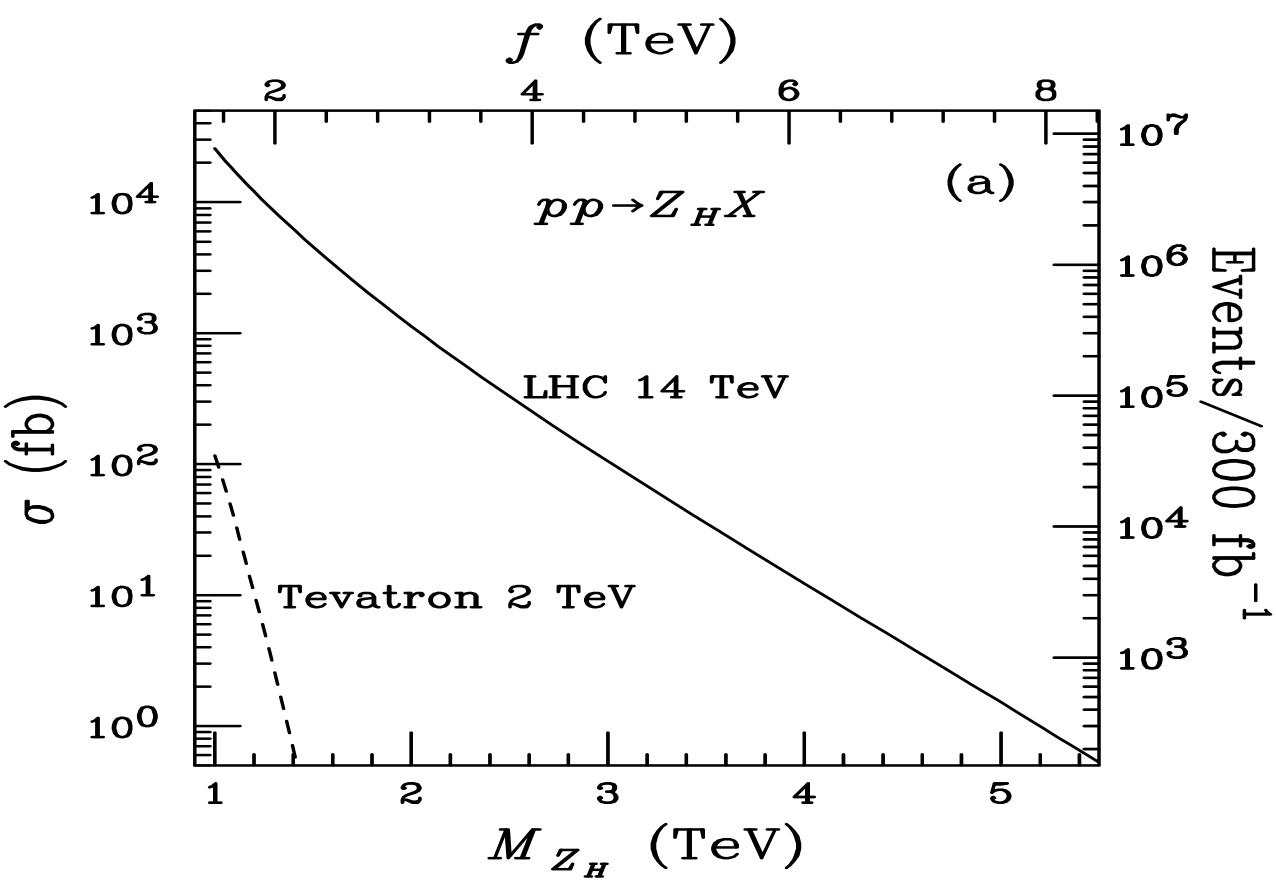
► some models' coups are free parameters!

Task that needs the ILC: EW prec. meas.

Little Higgs t',Z' cross sections at LHC

[Han, Logan, McElrath, Wang, PRD(67)095004]





Little Higgs and EW precision constraints

Corrections typically $\sim \frac{v^2}{f^2}$

ALL L.H. models reduce to prec. EW tests!

2 cases: [Kilian and Reuter, PRD(70)015004]

1. no extra gauged $U(1)$'s:

   S, T plus $4f$ contact interactions

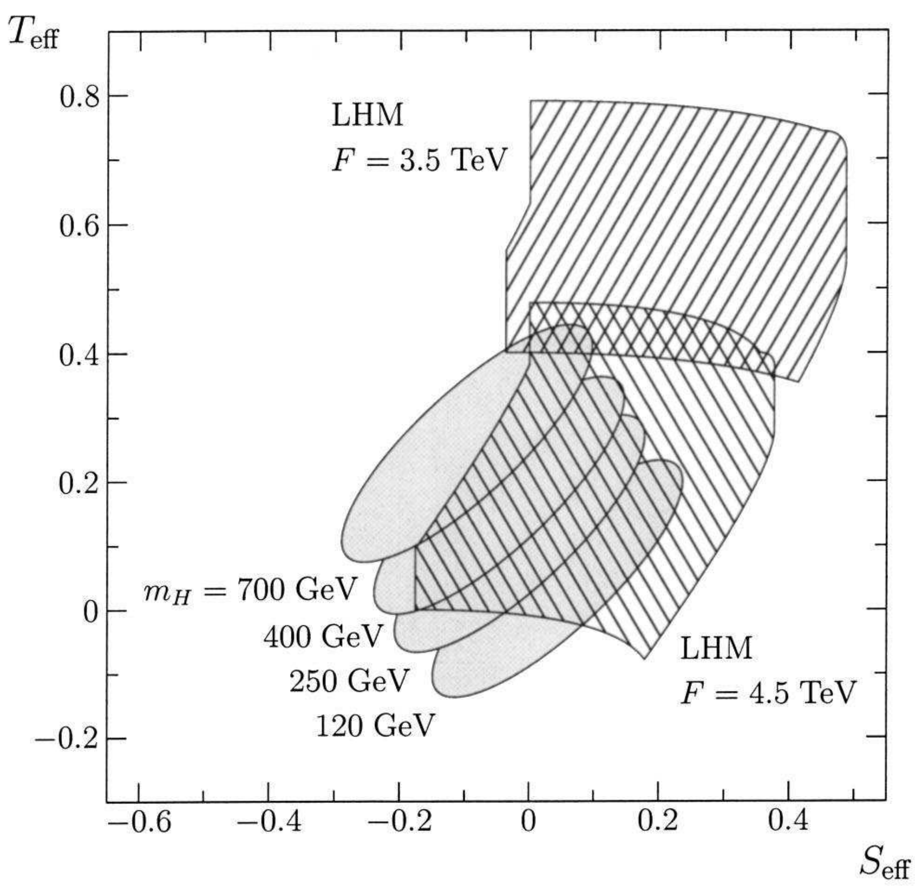
2. extra gauged $U(1)$'s:

   $Zf\bar{f}$ coups shifted so adapt EW fits

"Littlest Higgs" already limited:

$\rightarrow f \gtrsim 4$ TeV, $m_{t'} \gtrsim 14$ TeV

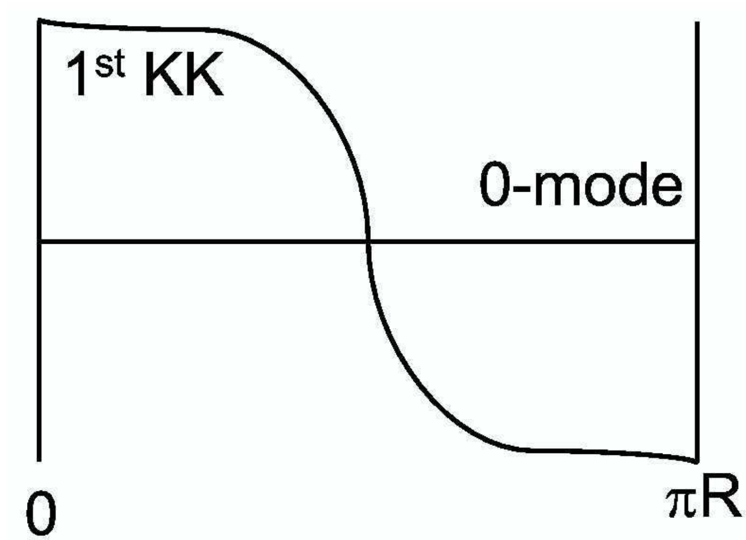
► implies large fine-tuning!



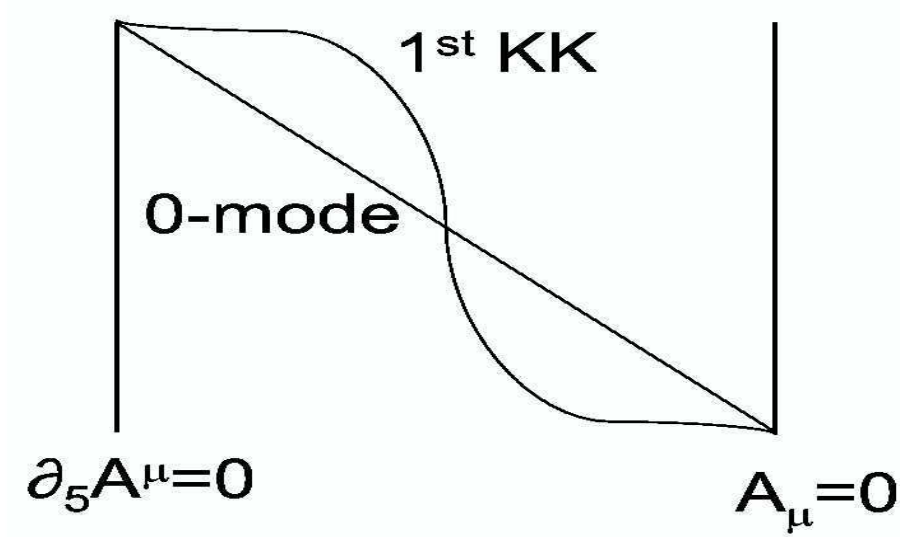
New solution #3: no Higgs ("Higgsless" models)

Goal: NO fundamental or composite scalar

Simple observation: in finite-sized "flat space" extra dim.'s, MIXED boundary conditions (BC) can give mass



zero-mode unchanged: $m_0 = 0$



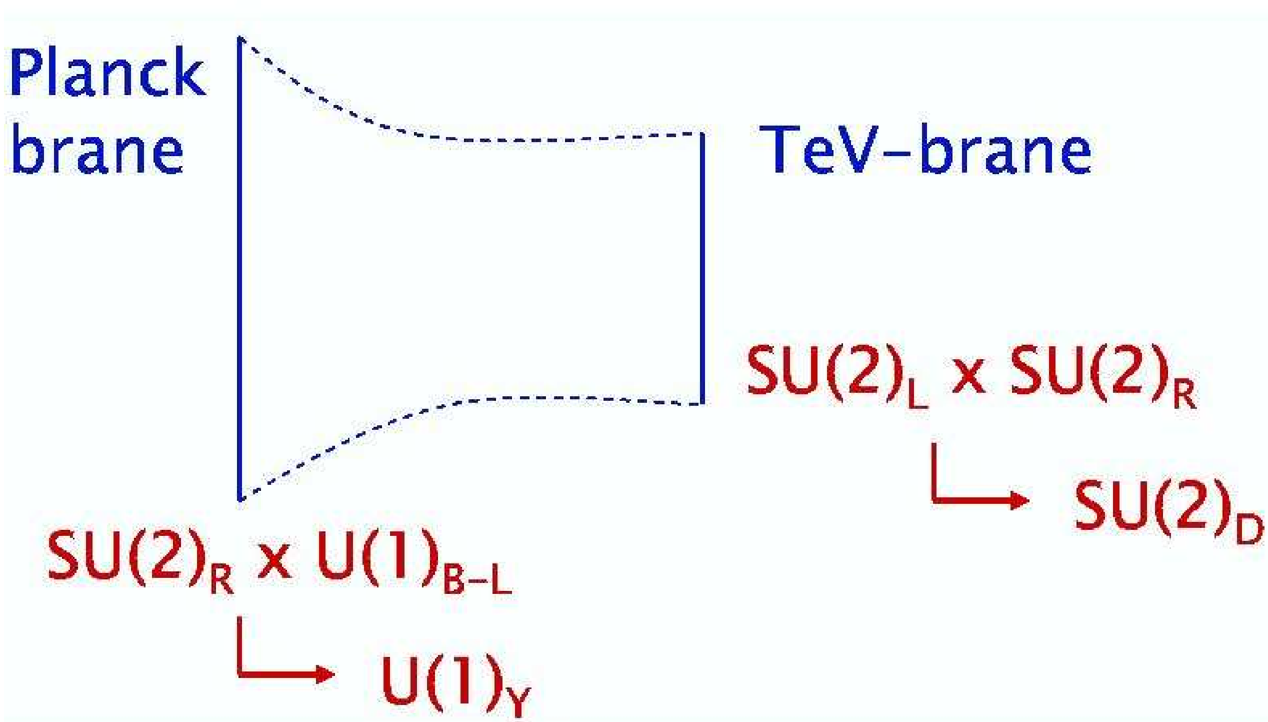
zero-mode lifted: $m_n = (n+\frac{1}{2})/R$

But this is not enough!

brane-localized Higgs still necessary,
massive custodial $SU(2)$ violation
($T \neq 0$ by lots)

Way out: [Csáki, Grojean, Pilo, Terning, PRL(92)101802]

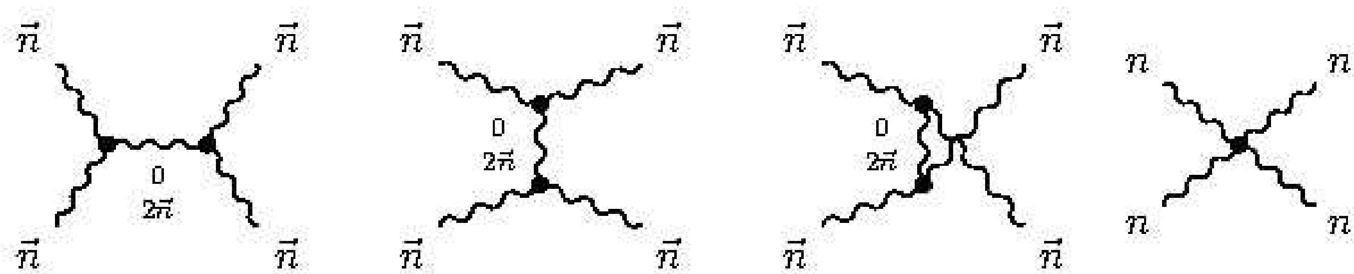
- AdS (warped) space preserves custodial $SU(2)$, no Higgs on brane required



- presence of TeV brane breaks EW symm.
- model is dual to walking TC

Do Higgsless models preserve $WW \to WW$ unitarity?

► Yes! preserved by gauge boson KK tower
(cancellation between all tower modes)



$\to$ exact relations between gauge couplings of various tower states; from 5-d gauge theory

$\to$ however, tree unitarity breaks down at 5-d cutoff scale due to finite terms (E^0)

$\to$ expect first Z' around few hundred GeV, second around 1 TeV

Do viable Higgsless models agree with precision EW data?

Default theory predicts:

$$S \approx 1.15 \qquad S_{\text{data}} = -0.03 \pm 0.11$$
$$T = 0 \qquad T_{\text{data}} = -0.02 \pm 0.13$$
$$U = 0 \qquad U_{\text{data}} = +0.24 \pm 0.13$$

3 possible modifications to fix S. Implications:

1. S reduced, but $M_{Z'}$ too large to fix unitarity, theory becomes strong, calc. unreliable

2. S reduced, but tachyon appears

3. $S \approx 0$, $M_{Z'} \approx 300$ GeV, unknown if ruled out

Other issue: fermion sector not understood

Summary of new EWSB models

- nearly all models have SM-like Higgs
  LHC *can* see this and measure it
- new model SM-like Higgs often heavy
- most interesting physics is NOT Higgs
- Higgsless: *WW* excitation curve crucial
- all paths lead to strong dynamics