THE SUPERSYMMETRIC COMPOSITE "FAT HIGGS" MODEL

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FERMILAB

8 JAN 04

HOW IS ELECTROWEAK SYMMETRY BROKEN?

IS THERE A HIGGS?

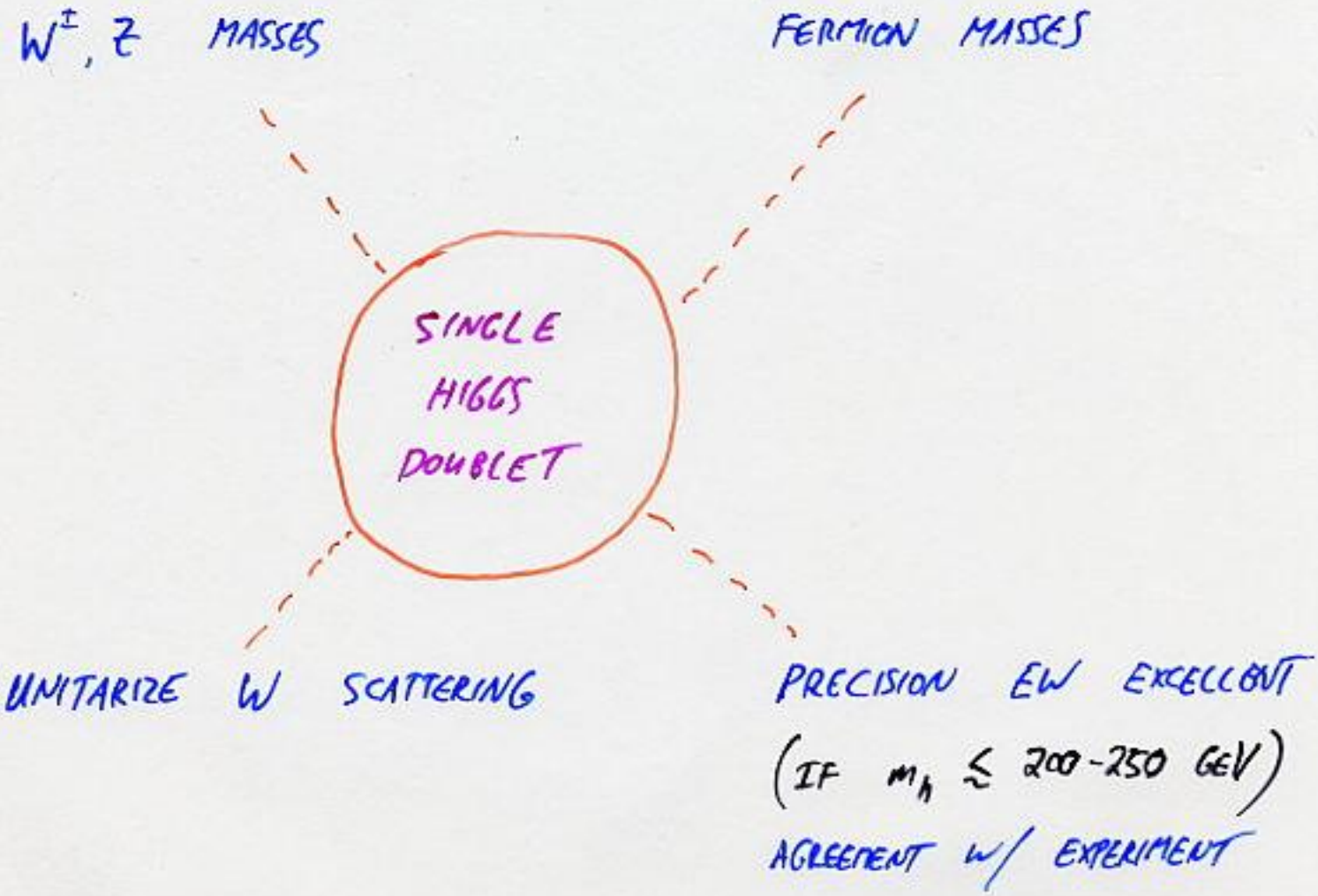
IS THE HIGGS FUNDAMENTAL?

STANDARD MODEL

SINGLE COMPLEX SCALAR DOUBLET H

$$\mathcal{L} = (D_\mu H)^\dagger D^\mu H - \underbrace{\left(-m^2 H^\dagger H + \lambda (H^\dagger H)^2 \right)}_{V(H)}$$

ACOMPLISHES SEVERAL THINGS AT ONCE:



WHAT'S PUZZLING ABOUT FUNDAMENTAL H?

- HIGGS $(\text{MASS})^2$ QUADRATICALLY DIVERGENT $\sim \frac{\Lambda^2_{\text{CUTOFF}}}{16\pi^2}$

- ELECTROWEAK SYMMETRY BROKEN "BY HAND"

$$V(H) = -m^2 H^\dagger H + \dots$$

- FUNDAMENTAL (UNEATEN) SCALARS NEVER SEEN BEFORE IN STANDARD MODEL

(YET WE HAVE A PLETHORA OF EXPERIMENTALLY OBSERVED COMPOSITE SCALARS)

TECHNICOLOR

A NEW STRONG GAUGE INTERACTION DYNAMICALLY BREAKS EW SYMMETRY, PROVIDING COMPOSITE GOLDSTONE BOSONS FOR $W^{\pm}, Z$

PROBLEMS ARE WELL-KNOWN:

- STRONG SCALE $\lesssim$ 2 TEV TO UNITARIZE W SCATTERING, BUT EW PRECISION DATA IS A TIGHT NOOSE

- FERMION MASSES ARISE FROM ETC INTERACTIONS $\frac{f f_{TC} f_{TC}}{\Lambda_{ETC}^2}$

$$m_f \sim \frac{\Lambda_{TC}^3}{\Lambda_{ETC}^2}$$

BUT AVOIDING FCNC FORCES $\Lambda_{ETC} \gtrsim 100 \to 1000$ TEV

- CALCULABILITY @ STRONG COUPLING IS DIFFICULT

→ VACUUM ALIGNMENT

COMPOSITE HIGGS

GEORGI-KAPLAN CONSTRUCTED A MODEL WITH A FULL $SU(2)_L \times U(1)_Y$ DOUBLET OF COMPOSITE SCALARS THAT SURVIVE BELOW Λ_{TC}

- W SCATTERING IS UNITARIZED WITHOUT Λ_{TC} HELD TO 2 TEV
- Λ_{TC} COULD BE PUSHED UP CLOSER TO Λ_{ETC} TO RESOLVE FERMION MASS / FCNC TENSION
- EW PRECISION AUTOMATICALLY BETTER

  → (COMPOSITE) HIGGS h $\lesssim$ IN SPECTRUM

  → Λ_{TC}-SUPPRESSED EW OPERATORS SAFE ($\Lambda_{TC} \gtrsim 5$ TEV)

  (BUT, LARGE N_F, N_C STILL POTENTIAL PROBLEM → TOO LARGE S PARAMETER)

WHAT'S THE CATCH?

- SEPARATION $v_{EW} \leftrightarrow \Lambda_{TC}$ REQUIRES FINE-TUNING

  1 PART IN $\left(\frac{v_{EW}}{\Lambda_{TC}}\right)^{\sim}$

- STILL FACE CALCULABILITY, ISSUES @ STRONG COUPLING

  VACUUM ALIGNMENT

SUPERSYMMETRY

- HIGGS MASS: $m_h \lesssim$ 130 MSSM
  150 NMSSM
  200 crazy-not-minimal-SSM

- AND, SUFFICIENTLY HEAVY SPARTICLES YIELD NO NOTICABLE DEVIATIONS FROM PRECISION EW.

BUT!

$$m_h^2 \simeq M_Z^2 + \frac{3}{4\pi^2} h_t^4 v^2 \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

TO EVADE THE LEP BOUND ($m_h \gtrsim 115$ GeV) MUST RAISE TOP SQUARK MASSES TO AT LEAST $\gtrsim$ 500-700 GeV, AND THIS CAUSES A LARGE RENORMALIZATION OF

$$\Delta m_{H_u}^2 \sim -\frac{3 h_t^2}{4\pi^2} m_{\tilde{t}}^2 \log \frac{M_{UV}}{M_{IR}}$$

THAT IMPLIES SIGNIFICANT FINE-TUNING IS REQUIRED TO SATISFY

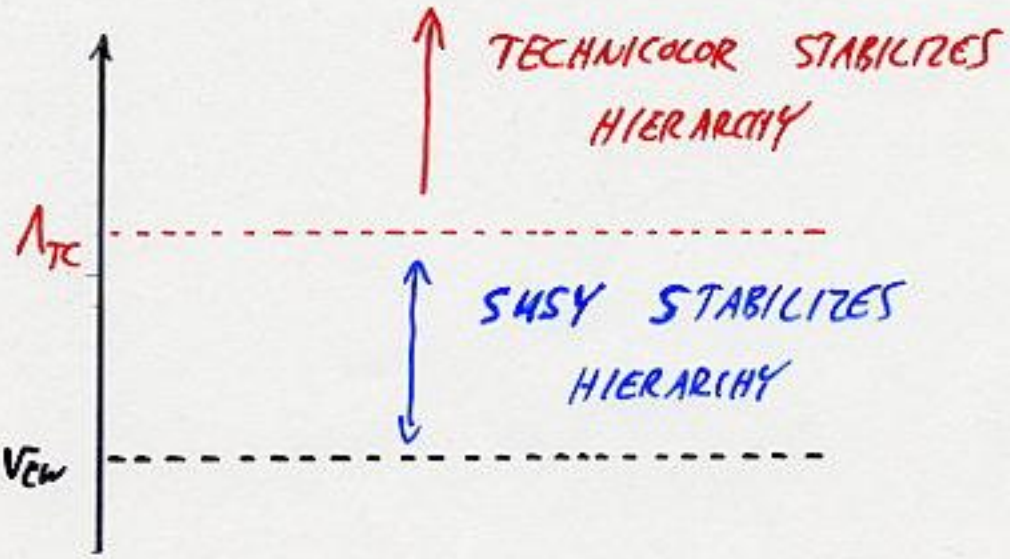
$$\frac{1}{2} M_Z^2 \simeq -\mu^2 - m_{H_u}^2$$

CANCELLATION!

IN THIS TALK, A HYBRID APPROACH WILL BE PURSUED:

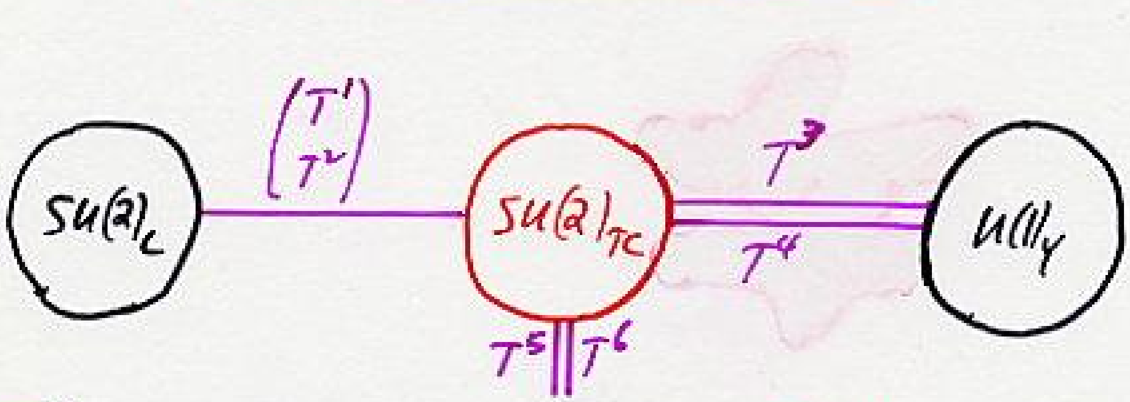
SUPERSYMMETRIC COMPOSITE HIGGS

"FAT HIGGS"



LET'S SEE WHERE THIS LEADS US!

THE FAT HIGGS MODEL



- T^i's ARE DOUBLETS OF $SU(2)_{TC}$ THAT TRANSFORM AS

$\begin{pmatrix} T^1 \\ T^2 \end{pmatrix}$ $(2, 2, 0)$ UNDER $(SU(2)_L, SU(2)_{TC}, U(1)_Y)$

T^3, T^4 $(1, 2, \pm\frac{1}{2})$

T^5, T^6 $(1, 2, 0)$

- $SU(2)_{TC}$ "TECHNICOLOR GROUP" GETS STRONG AT Λ_{TC}

⇒ THIS IS AN $N_f = N_c + 1$ ($N_f = 3$, $N_c = 2$) STRONGLY COUPLED SUPERSYMMETRIC THEORY THAT SEIBERG SHOWED GENERATES A DYNAMICAL SUPERPOTENTIAL:

$$W = \frac{\mathrm{Pf}\, M}{\Lambda^3} \quad \text{WHERE} \quad \mathrm{Pf}\, M = \varepsilon_{ijklmn} M^{ij} M^{kl} M^{mn}$$

$$M^{ij} = (T^i T^j)$$

FOR THE MESON COMPOSITES.

WE ADD THE SUPERPOTENTIAL TERMS:

1) $-m\, T^5 T^6$

$\Rightarrow$ A SUPERSYMMETRIC MASS FOR THE 3rd FLAVOR

THIS WILL CONTROL THE SCALE SEPARATION

$$v_{EW} \longleftrightarrow \Lambda_{TC}$$

2) $S\, T^1 T^2 + S'\, T^3 T^4$

$\Rightarrow$ SINGLET FIELDS THAT FORCE

$$\langle T^1 T^2 \rangle = \langle T^3 T^4 \rangle = 0$$

BY F-FLATNESS OF SUSY.

THIS IS NECESSARY TO ENSURE CONFINEMENT OF $SU(2)_{TC}$ RESULTS IN AN EW BREAKING VACUUM

3) $(T^1\ T^2)\, P \begin{pmatrix} T^5 \\ T^6 \end{pmatrix} \qquad (T^3\ T^4)\, Q \begin{pmatrix} T^5 \\ T^6 \end{pmatrix}$

$\Rightarrow$ ADDITIONAL $SU(2)_L$ DOUBLETS (P_1, P_2) AND SINGLETS $(Q_{1..4})$ WITH HYPERCHARGE ARE ADDED TO MARRY OFF CERTAIN "SPECTATOR COMPOSITES"

THE FULL SUPERPOTENTIAL (AFTER CANONICALLY NORMALIZING THE COMPOSITES)

$$W = \lambda \left(Pf\, M - v_0^2 M_{56} \right) + m_{spect} \left(S M_{12} + S' M_{34} + P \cdot M + Q \cdot M \right)$$

WHERE

$$\lambda(\Lambda_{TC}) \sim 4\pi$$

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

$$m_{spect} \sim \frac{\Lambda_{TC}}{4\pi}$$

NOW WE IDENTIFY

$M_{i3} \equiv (T^i T^3)$ HAS EW QUANTUM NUMBERS $(2, +\frac{1}{2})$ NEW LABEL H_u

$M_{i4} \equiv (T^i T^4)$ $(2, -\frac{1}{2})$ H_d

$M_{56} \equiv (T^5 T^6)$ $(1, 0)$ N

LOW ENERGY EFF THEORY (AFTER INTEGRATING OUT SPECTATORS)

$$\boxed{W = \lambda N \left(H_d H_u - v_0^2 \right)}$$

INCREDIBLE!

OUR THREE-FLAVOR s-CONFINING SUPERSYMMETRIC THEORY

HAS A DYNAMICALLY GENERATED NMSSM(-like) SUPERPOTENTIAL!

- H_u AND H_d ARE (COMPOSITE) HIGGS DOUBLET (SUPER)FIELDS
- N IS A (COMPOSITE) SINGLET UNDER SM GAUGE SYMMETRIES

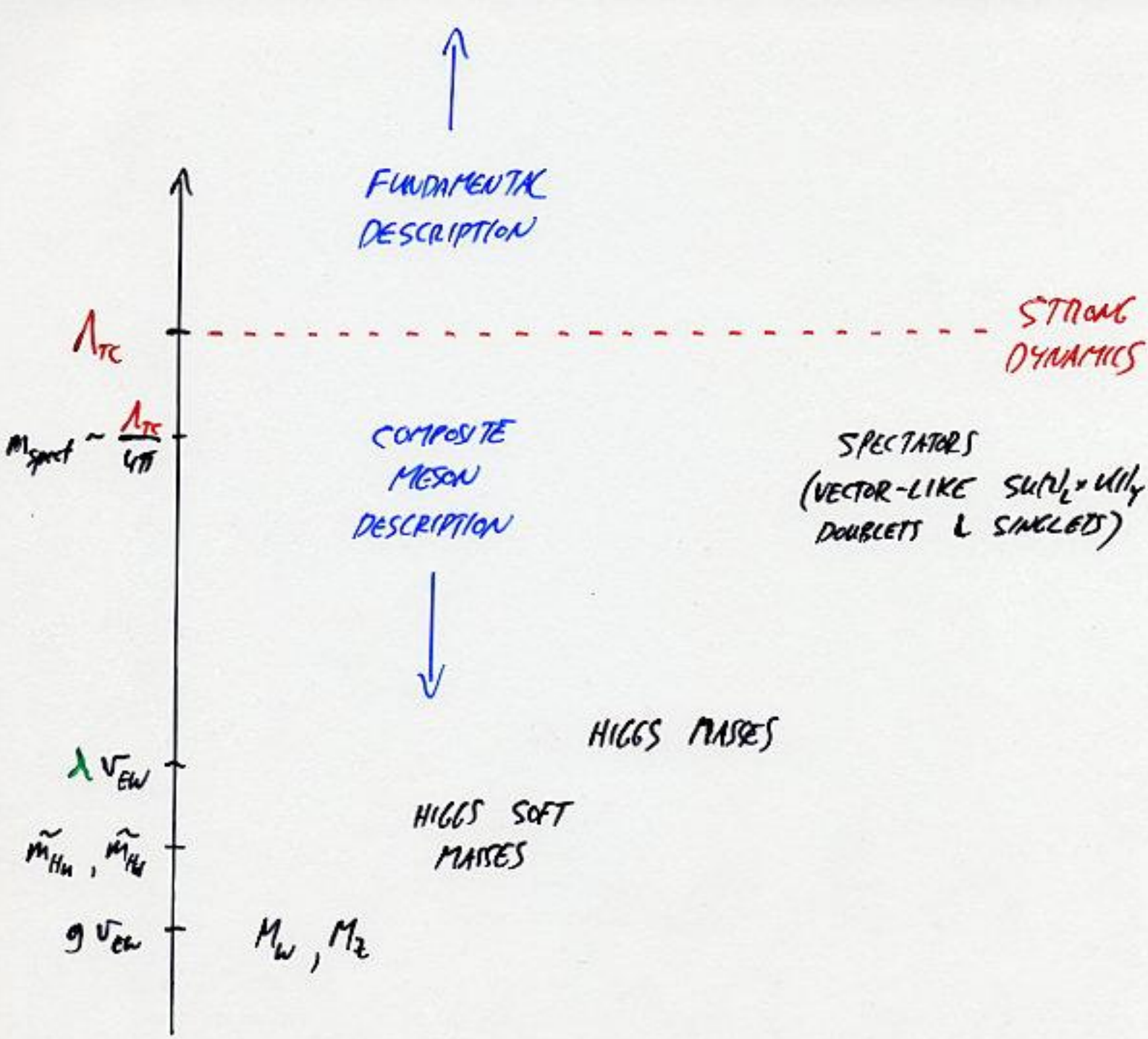
EW SYMMETRY BREAKING IS FORCED BY

$$\frac{\partial W}{\partial \tilde{N}} = \hat{H}_d \hat{H}_u - v_0^2 = 0$$

$$\Rightarrow \langle \hat{H}_d \hat{H}_u \rangle = v_0^2$$

AND IS TUNABLE VIA THE HOLOMORPHIC MASS m:

$$v_0 \sim \frac{\sqrt{m \Lambda_{TC}}}{4\pi}$$


FUNDAMENTAL DESCRIPTION
Λ_{TC}
STRONG DYNAMICS
$M_{spect} \sim \frac{\Lambda_{TC}}{4\pi}$
COMPOSITE MESON DESCRIPTION
SPECTATORS (VECTOR-LIKE $SU(2)_L \times U(1)_Y$ DOUBLETS & SINGLETS)
HIGGS MASSES
λv_{EW}
HIGGS SOFT MASSES
$\tilde{m}_{H_u}$, $\tilde{m}_{H_d}$
$g v_{EW}$
M_W , M_Z

FERMION MASSES

EASY AT DIMENSION-5:

$$W = \frac{1}{\Lambda_f}\left[Y_u\, Q u^c (T^\dagger T^3) + Y_d\, Q d^c (T^\dagger T^4) + Y_L\, L e^c (T T^4)\right]$$

CANONICALLY NORMALIZING GIVES

$$m_f \sim Y_f v \frac{\Lambda_{TC}}{4\pi \Lambda_f}$$

NOTE ALSO THAT FCNC EFFECTS ARE GIM SUPPRESSED

(Λ_f COULD BE ~ 2 TEV)

THESE INTERACTIONS CAN BE UV-COMPLETED INTO RENORMALIZABLE ONES BY ADDING FUNDAMENTAL FIELDS

$\Phi_u, \bar{\Phi}_u$	$(2, \frac{1}{2}), (2, -\frac{1}{2})$
$\Phi_d, \bar{\Phi}_d$	$(2, -\frac{1}{2}), (2, \frac{1}{2})$

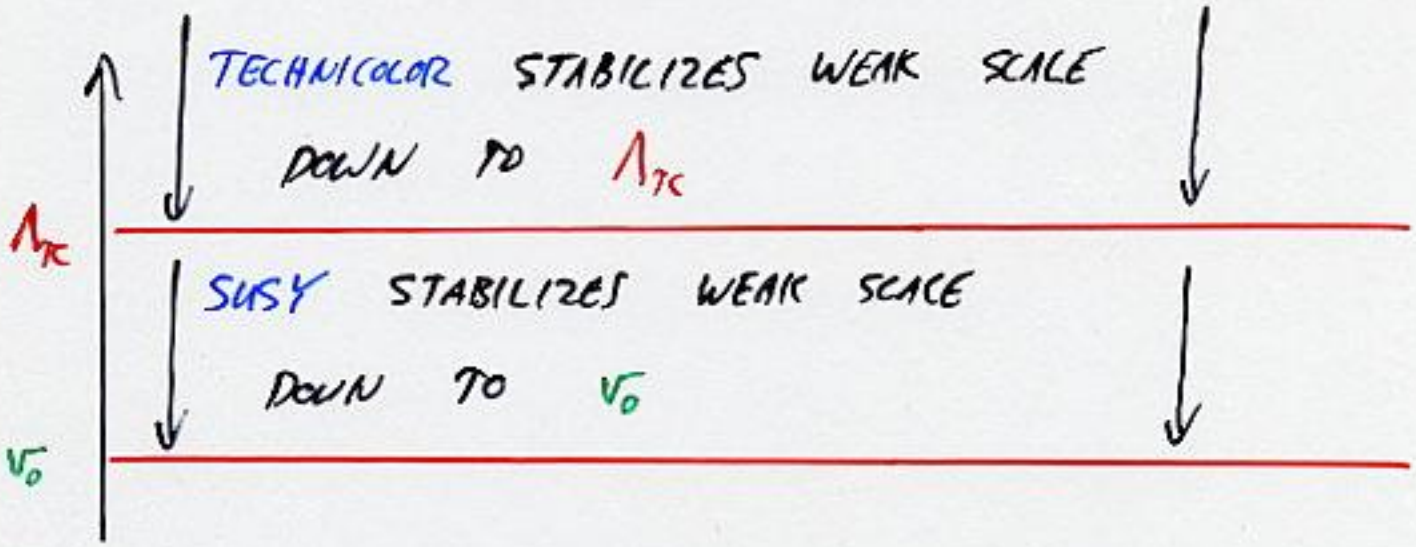
AND THE SUPERPOTENTIAL

$$W = \Lambda_f\left(\Phi_u \bar{\Phi}_u + \Phi_d \bar{\Phi}_d\right) + \bar{\Phi}_d (T T^4) + \bar{\Phi}_u (T T^3)$$

$$+ Y_u\, Q u^c \Phi_u + Y_d\, Q d^c \Phi_d + Y_L\, L e^c \Phi_d$$

$\Rightarrow$ EFF THEORY BELOW Λ_f IS THE ABOVE DIM-5 W.

SCALES



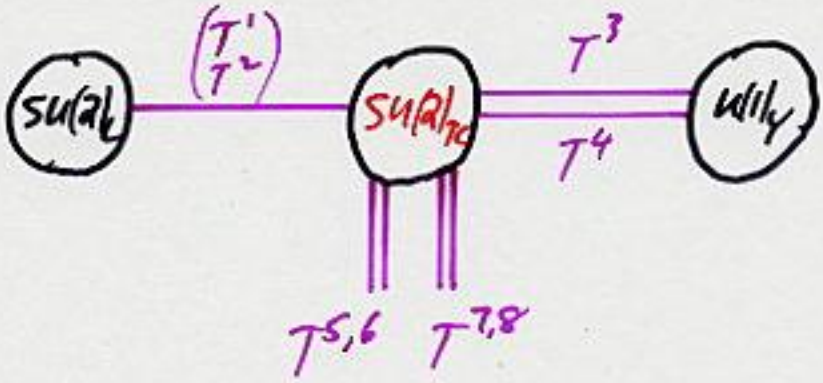
THIS REQUIRES $v_0 \sim m_{SUSY}$.

THIS IS A TECHNICALLY NATURAL TUNING (JUST LIKE RELATING $\mu \sim m_{SUSY}$ IN MSSM), BUT CAN WE DO BETTER?

YES!

WE CAN EMPLOY A COMBINATION OF FLAVOR SYMMETRY (AMONG TC-DOUBLETS) AND GIUDICE-MASIERO MECHANISM.

FOUR FLAVOR FAT HIGGS MODEL



ADDITIONAL $T^{7,8}$ CAUSE THE THEORY TO BECOME SUPERCONFORMAL. IMAGINE A U(1) FLAVOR SYMMETRY

WHERE	$T^{5,6}$	$+1$	
	$T^{7,8}$	-1	
	χ	$+2$	FLAVOR BREAKING FIELD $\langle \chi \rangle = m'$

SUCH THAT

$m T^5 T^6$ FORBIDDEN

$\chi T^7 T^8 \to m' T^7 T^8$ ALLOWED

NO χ IN SUPERPOTENTIAL, WHILE KÄHLER POTENTIAL HAS

$$\frac{S^\dagger T^6 T^7}{M_{Pl}}, \quad \frac{S^\dagger T^5 T^8}{M_{Pl}}$$

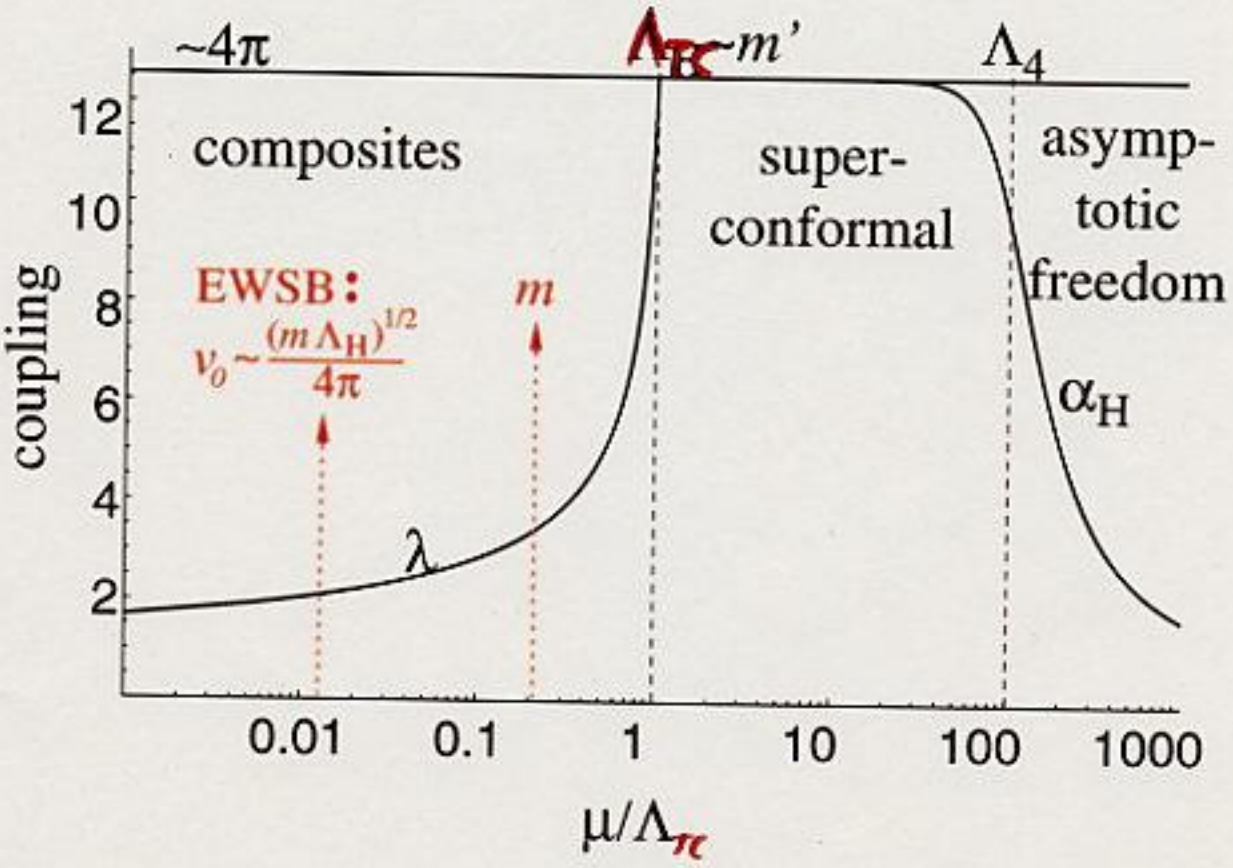
LEADING TO

$$\begin{array}{c} \\ T^6 \\ T^8 \end{array} \begin{array}{c} \begin{array}{cc} T^5 & T^7 \end{array} \\ \begin{pmatrix} & m_{SM\,SM} \\ m_{SM\,SM} & m' \end{pmatrix} \end{array}$$

HAS EIGENVALUES (SEE-SAW!) $m_- = \frac{m_{SM\,SM}^2}{m'}$, $\sim m'$

RECALL THAT

$$v_0 \sim (m \Lambda_{TC})^{\frac{1}{2}} \sim \left(\frac{m_{SUSY}^2}{m'} m'\right)^{\frac{1}{2}} \sim m_{SUSY}$$



ELECTROWEAK BREAKING VACUUM

LIMIT #1 NO SUPERSYMMETRY BREAKING

$$\langle H_u^0 \rangle = \langle H_d^0 \rangle = v_0$$

LIMIT #2: EQUAL SOFT $(\text{MASS})^2$ FOR H_u, H_d, N: $\tilde{m}^2$

$$\langle H_u^0 \rangle = \langle H_d^0 \rangle = v_0 \left(1 - \frac{\tilde{m}^2}{\lambda v_0^2}\right)^{\frac{1}{2}}$$

$\Rightarrow$ EWSB REQUIRES $\lambda v_0^2 > \tilde{m}^2$

LIMIT #3 GENERAL SOFT BREAKING INCLUDING TRILINEAR SCALAR COUPLINGS

$$\mathcal{L} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_N^2 |N|^2 + A\lambda N H_u H_d - C\lambda v_0^2 N + \text{h.c.}$$

IN THE LIMIT $\lambda v_0^2 \sim \hat{m}^2 \gg g^2 v^2$

$$\tilde{m} \equiv (m_1, m_2)^{\frac{1}{2}}$$

$$\langle H_u^0 \rangle = v_0 \left(1 - \frac{\tilde{m}^2}{\lambda v_0^2}\right)^{\frac{1}{2}} (\tan\beta)^{\frac{1}{2}}$$

$$\langle H_d^0 \rangle = v_0 \left(1 - \frac{\tilde{m}^2}{\lambda v_0^2}\right)^{\frac{1}{2}} \left(\frac{1}{\tan\beta}\right)^{\frac{1}{2}}$$

$$\tan\beta = \frac{m_1}{m_2}$$

$$\langle N \rangle \propto (C - A)\lambda v_0^2 + A\hat{m}^2 \sin 2\beta$$

FINE - TUNING

THE ELECTROWEAK VEV $v = 174$ GeV IS DETERMINED B

$$v^2 = \langle H_u^0 \rangle^2 + \langle H_d^0 \rangle^2 = 2 \frac{\lambda^2 v_0^2 - \tilde{m}^2}{\lambda^2 \sin 2\beta}$$

SINCE $\lambda^2 v_0^2 > \tilde{m}^2$ FOR AN EW BREAKING VACUUM,

THERE IS NO FINE-TUNING TO OBTAIN CORRECT v,

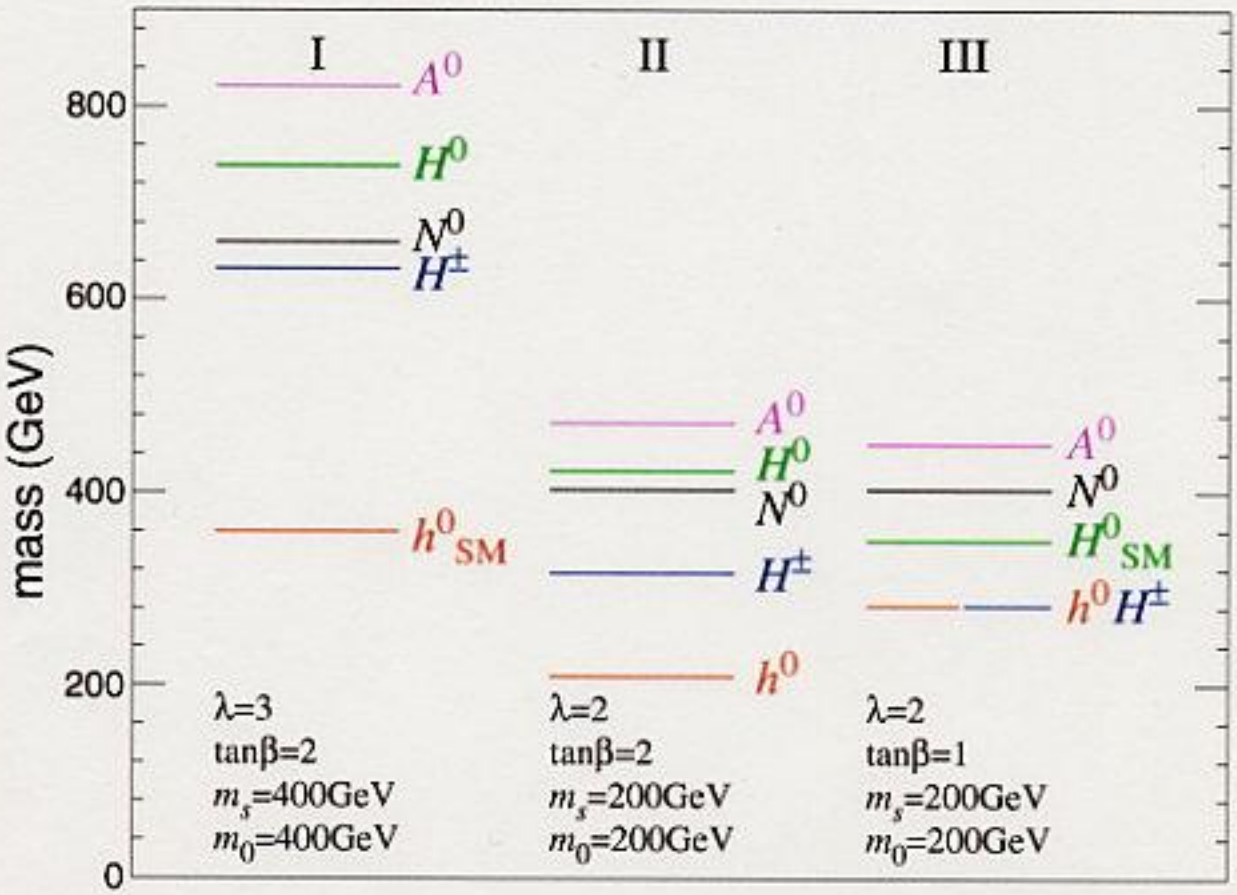
(OR M_Z).

THIS IS MUCH BETTER THAN MSSM!

HIGGS MASS SPECTRUM

CONSISTS OF FIELD CONTENT OF NMSSM

(BUT NO CUBIC TERM ~~kN^3~~ ; LINEAR TERM $\lambda v_0^2 N$ INSTEAD)



UNUSUAL FEATURES

- LIGHTEST HIGGS MASS CAN BE MUCH HEAVIER THAN MSSM BOUND
- PSEUDO-SCALAR (A^0) ALWAYS HEAVIER THAN CHARGED HIGGS ($H^\pm$)

FAT HIGGS: $m_A^2 = \lambda^2 v^2 + m_{H^\pm}^2$ MSSM: $m_A^2 = -M_W^2 + m_{H^\pm}^2$

IT IS WORTH EMPHASIZING ...

! THERE IS NO UPPER BOUND ON LIGHTEST HIGGS MASS !

WHY?

THE QUARTIC COUPLING OF THE HIGGS

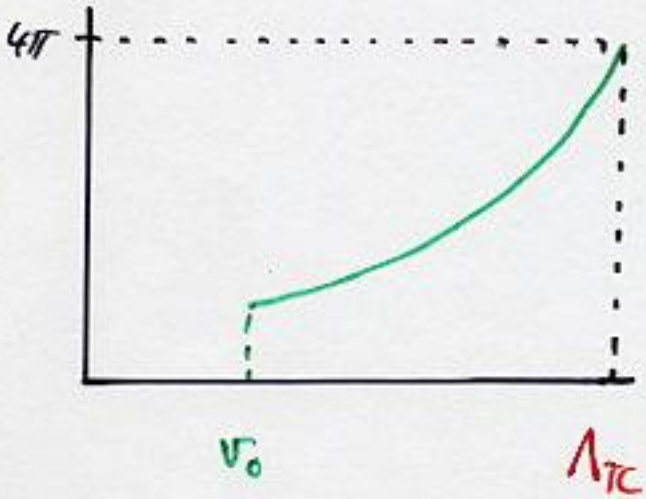
IS DOMINATED BY λ IN THE POTENTIAL

$$V = \lambda^2 \left(H_d H_u - v_0^2 \right)^2$$

AND NOT THE USUAL D-TERMS.

HOW BIG IS λ?

λ QUICKLY RENORMALIZES FROM STRONG COUPLING TO $O(\text{few})$

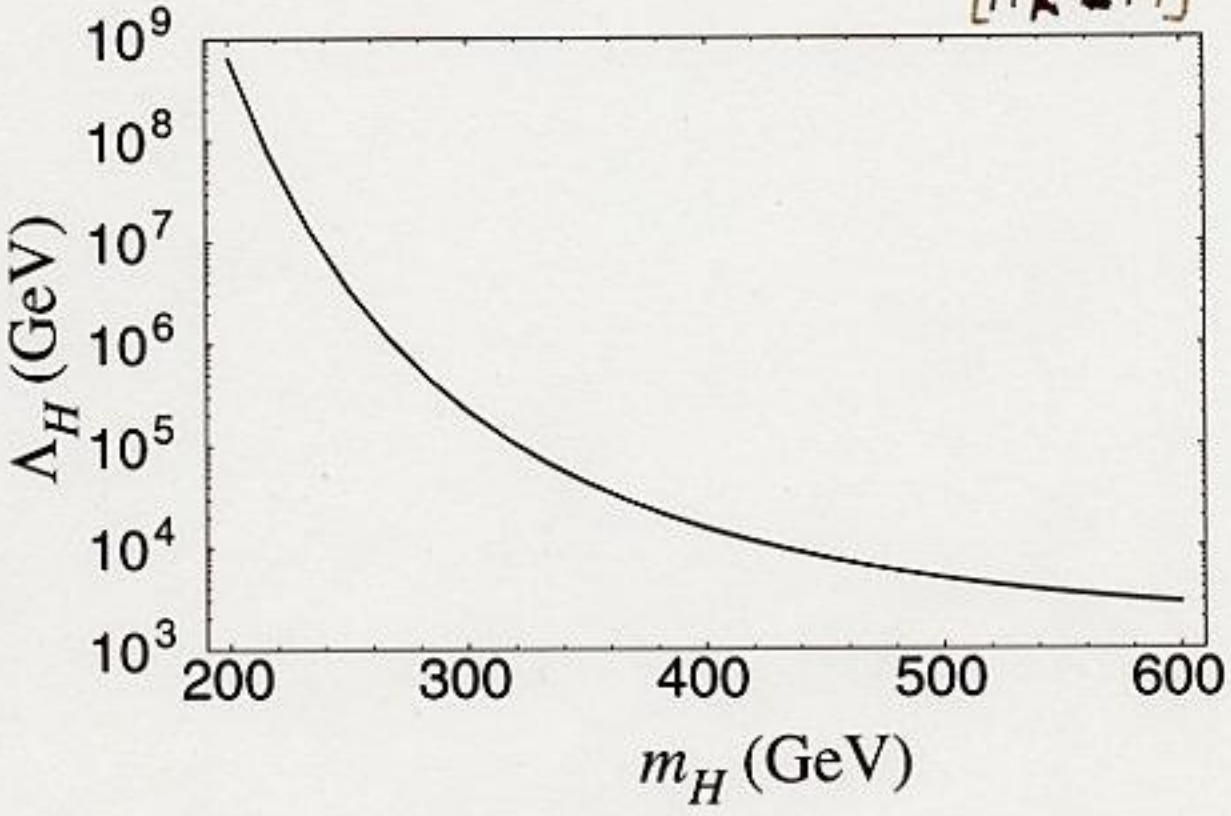


BUT SINCE λ [redacted] ONLY RUNS FROM AN INTERMEDIATE SCALE (THAT COULD BE AS LOW AS 5→10 TEV)

λ IS MUCH LARGER THAN GAUGE COUPLINGS.

HIGGS MASS AS A FUNCTION OF Λ_{TC}

[HKEM]



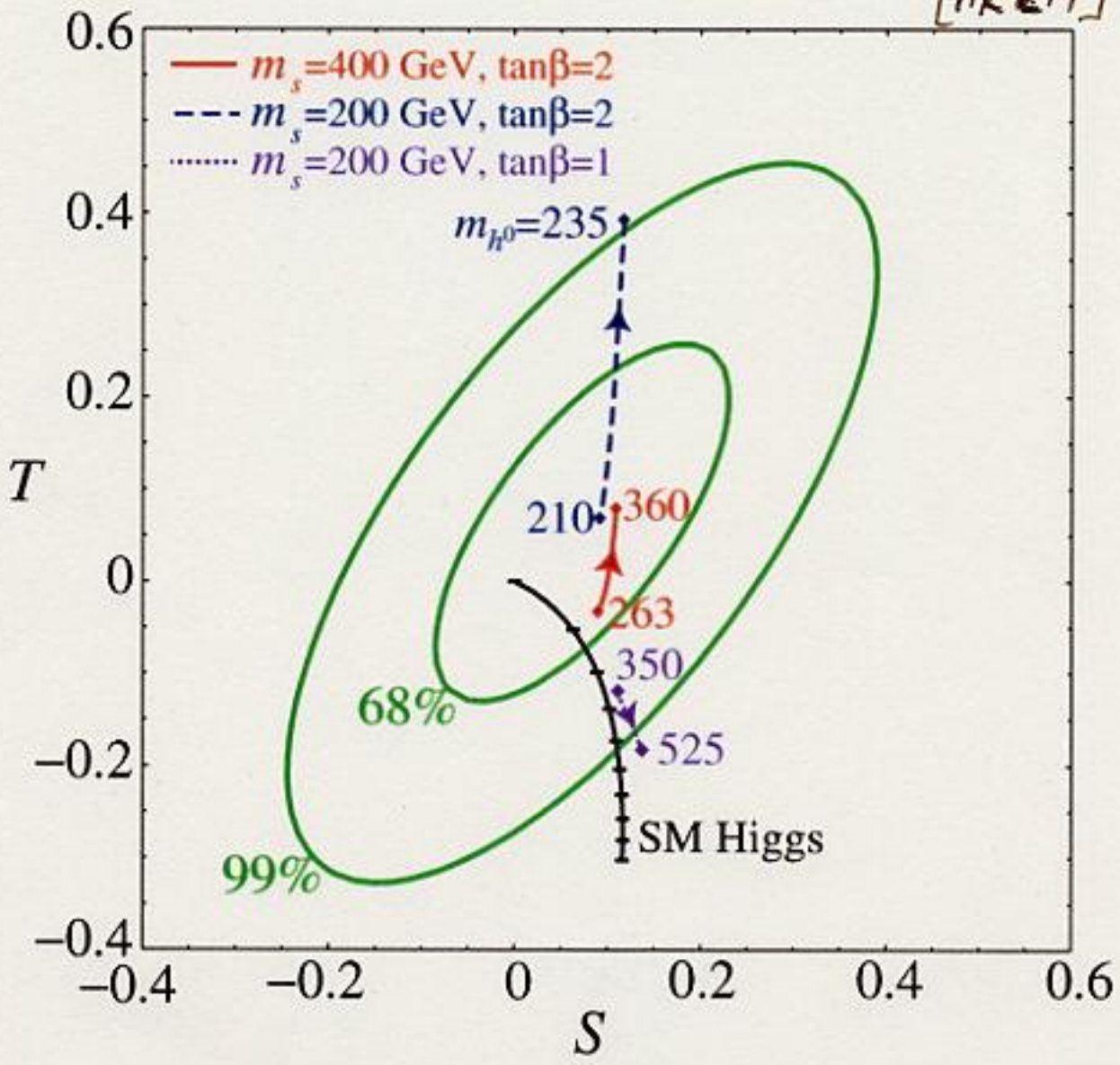
PRECISION ELECTROWEAK?

THERE ARE POSITIVE CONTRIBUTIONS TO T FOR $\tan\beta \neq 1$

$\Rightarrow$ WE CALCULATED THE HIGGS CONTRIBUTIONS TO S,T, FINDING

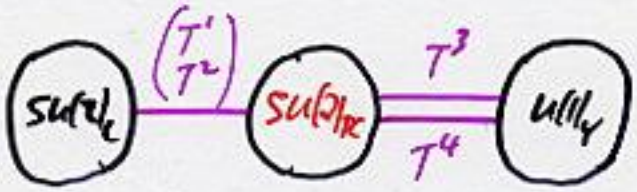
HEAVIER SM-like HIGGS IS TOTALLY COMPATIBLE WITH EW DATA.

[HKCM]



GAUGE COUPLING UNIFICATION?

WARMUP: TWO FLAVOR MODEL:



Λ_{TC}

MSSM MATTER + ONE FUNDAMENTAL BIDOUBLET

MSSM MATTER + TWO DOUBLETS WITH $\pm\frac{1}{2}$ HYPERCHARGE

MSSM MATTER + TWO COMPOSITE HIGGSES

$H_u = (T^i T^3)$

$H_d = (T^i T^4)$ $\quad i = 1,2$

BETA FUNCTIONS FOR $SU(2)_L \times U(1)_Y$ IDENTICAL!

(ABOVE AND BELOW Λ_{TC})

$(2,2): \begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$

$b_2^{ABOVE} = b_2^{MATTER} + 2 \cdot \frac{1}{2} = b_2^{MATTER} + 1$ ⟩ SAME!

$b_2^{BELOW} = b_2^{MATTER} + \frac{1}{2} + \frac{1}{2} = b_2^{MATTER} + 1$

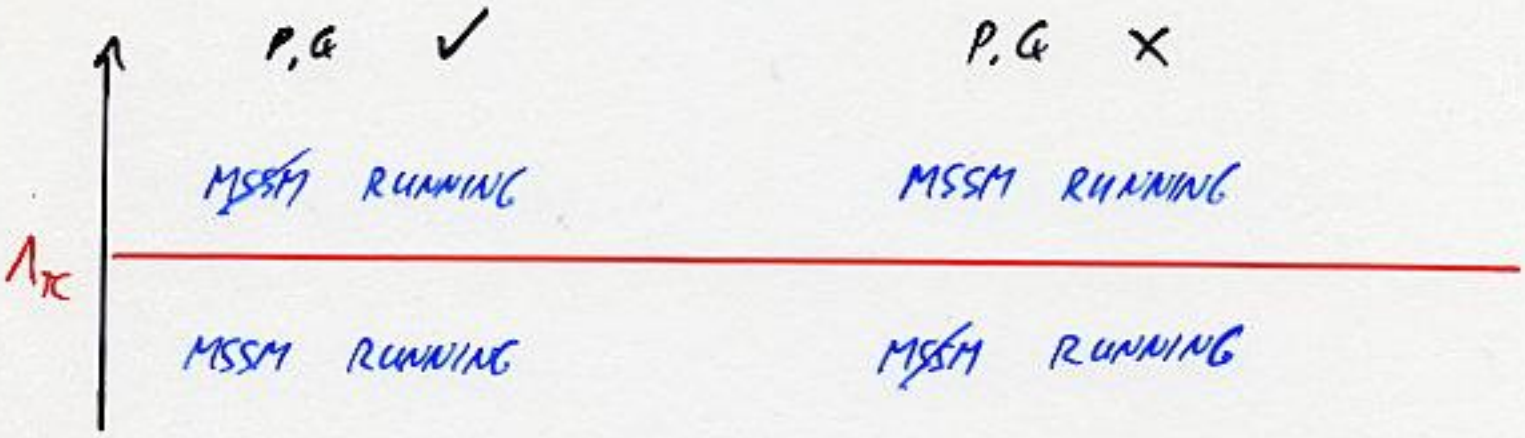
$H_u(2_{\frac{1}{2}})$ $H_d(2_{-\frac{1}{2}})$ — T_3, T_4

$b_Y^{ABOVE} = b_Y^{MATTER} + \left(\frac{1}{2}\right)^2 + \left(-\frac{1}{2}\right)^2$ ⟩ SAME!

$b_Y^{BELOW} = b_Y^{MATTER} + \left(\frac{1}{2}\right)^2 + \left(-\frac{1}{2}\right)^2$ — H_u H_d

FAT HIGGS GAUGE COUPLING RUNNING

ADDING FLAVORS OF $SU(2)_{TC}$ (UNCHARGED UNDER SM) DOES NOT CHANGE THE RUNNING ABOVE Λ_{TC}.



WHETHER P, Q FIELDS ARE ADDED IS A MODEL-BUILDING CHOICE. WITH THEM, WE MUST ADD TWO PAIRS OF COLOR TRIPLETS (FOUR, IF FERMION MASS SECTOR IS MADE RENORMALIZABLE) WITH HYPERCHARGE $\pm\frac{1}{3}$, AND MASS $\sim \Lambda_{TC}$.

THIS IS ANALOGOUS TO GAUGE MEDIATION WITH MESSENGERS JUST IN $(Q, \bar{Q}) \Rightarrow$ QUARK DOUBLET REPRESENTATION. GAUGE COUPLINGS UNIFY ONLY BY COMPLETING $(Q, \bar{Q})$ INTO $(10, \overline{10})$ REPS OF SU(5).

SUSY BREAKING

- CANONICAL FLAVOR-BLIND MECHANISMS SHOULD WORK FINE, BUT THERE ARE SUBTLETIES MATCHING SUSY MASSES ACROSS STRONG COUPLING. [ARKANI-HAMED, RATTAZZI; LUTY, RATTAZZI]

- SIMPLEST, PREDICTIVE MECHANISM WOULD BE ONE THAT COMMUNICATES SUSY IN THE IR: $M_{mess} < \Lambda_{TC}$.

- REMARKABLY WE FOUND THAT UV-INSENSITIVE ANOMALY MEDIATION (AMSB + D-terms) WORKS QUITE WELL HERE! [KITANO, GK, MURAYAMA]

- THIS IS A TOTALLY IR EFFECT AND SO THERE ARE NO STRONG COUPLING THRESHOLD UNCERTAINTIES!

- IT CURIOUSLY REQUIRES $\tan\beta \lesssim 1$. (FOR POSITIVE SLEPTON $(\text{MASS})^2$ AND A PROPER VACUUM SOLUTION)

THE WOULD-BE TOP YUKAWA LANDAU POLE IS RESOLVED BY THE HIGGS COMPOSITENESS.

SUMMARY

- A NEW, CALCULABLE, UV COMPLETE SUPERSYMMETRIC COMPOSITE HIGGS MODEL WAS PRESENTED.
  - → EWSB IS DYNAMICAL
  - → SUSY STRONG DYNAMICS UNDER MUCH BETTER THEORETICAL CONTROL [THANKS TO SEIBERG]
  - → EFFECTIVE SUPERPOTENTIAL OF MESON COMPOSITES KNOWN EXACTLY
- LIGHTEST HIGGS MASS DECOUPLED FROM SUSY BREAKING
  - → SUSY FINE-TUNING PROBLEM SOLVED
  - → NO UPPER BOUND ON LIGHTEST HIGGS MASS
  - → PRECISION EW χ^2 WITH $m_h|^{SUSY} \sim 200 \to 450$ GeV AS GOOD A FIT AS $m_h|^{SM} \sim 100$ GeV
  - → SPARTICLES CAN BE MUCH LIGHTER (THINK STOPS)
- GAUGE COUPLING UNIFICATION CAN WORK AS WELL AS GAUGE MEDIATION
- SUSY BREAKING BY UV INSENSITIVE ANOMALY MEDIATION WORKS WELL → (IT NEVER WORKED IN MSSM WITH $\tan\beta > 1$)