LITTLE HIERARCHY PROBLEM:

FROM LITTLE HIGGS TO FAT HIGGS MODELS

GRAHAM KRIBS

IAS PRINCETON

ASPEN '04 WINTER

WHERE WERE WE?

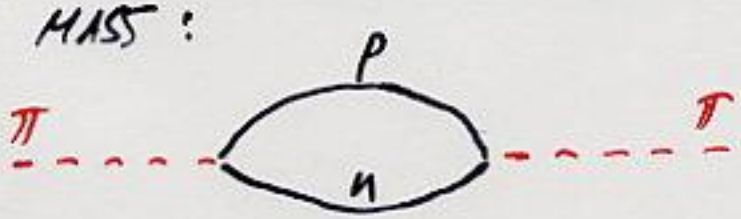
1950's

- QED
- STRONG FORCE (PIONS)
- WEAK FORCE (FERMI INTERACTION)

$$\mathcal{L} = \pi p n + \frac{p n e \nu_e}{\Lambda^2} + m_\pi^2 \pi^+ \pi^-$$

THIS HAS ALL THE INGREDIENTS OF A LITTLE HIERARCHY

- FUNDAMENTAL SCALARS $m_\pi \ll \Lambda$
  FOR STRONG FORCE
- CUTOFF-SUPPRESSED INTERACTION
  FOR WEAK FORCE
- QUADRATICALLY DIVERGENT RADIATIVE CORRECTION TO PION MASS:



$$m_\pi^2\Big|_{physical} = m_\pi^2\Big|_{bare} + \sim \Lambda^2$$

AS WE ALL KNOW, THIS WAS RESOLVED THROUGH

SYMMETRIES & DYNAMICS

A THEME THAT RECURS FOR BEYOND-THE-SM PHYSICS.

SYMMETRY:

- PION UNDERSTOOD TO BE A PSEUDO-GOLDSTONE BOSON OF SPONTANEOUSLY BROKEN $SU(2)_{ISOSPIN}$

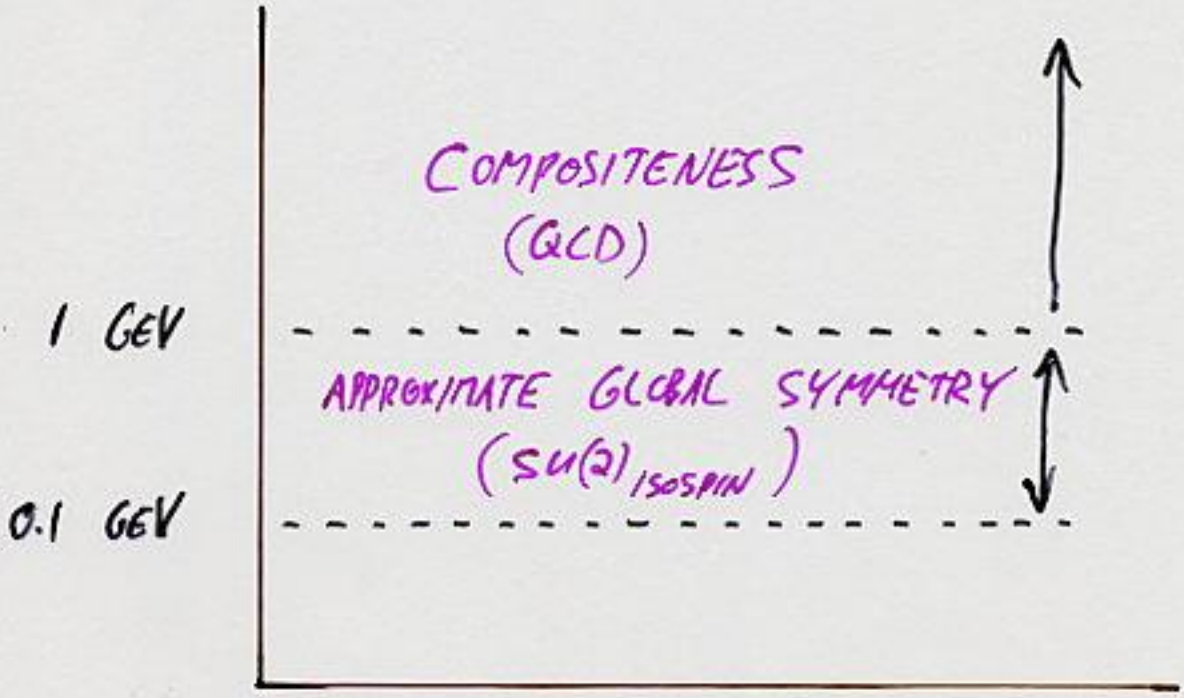
- REPRESENTED AS A NON-LINEAR σ-MODEL WITH CUTOFF $\Lambda \sim 4\pi f_\pi \sim 1$ GeV

DYNAMICS

- THEORY ABOVE Λ IS "UV COMPLETED" INTO QCD:

  PIONS ARE COMPOSITE!

PROTECTING THE PION MASS



WHERE ARE WE NOW?

STANDARD MODEL

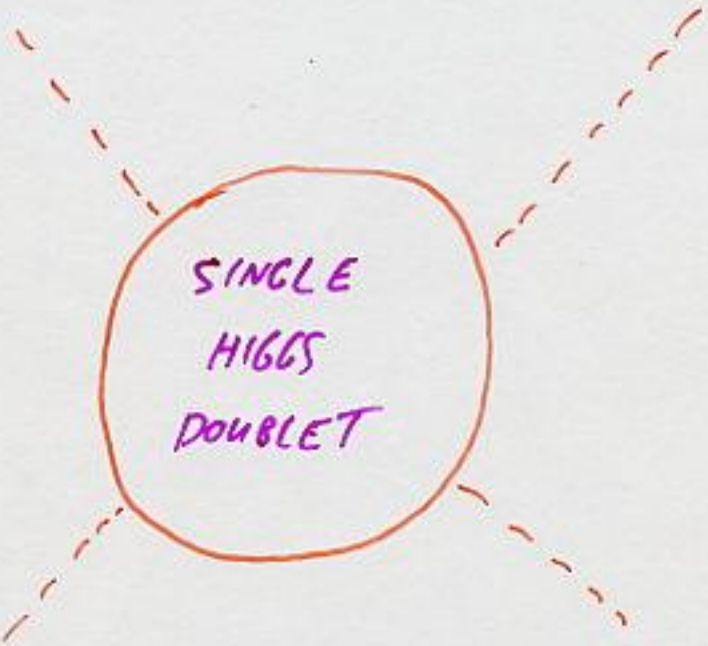
SINGLE COMPLEX SCALAR DOUBLET H

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

ACOMPLISHES SEVERAL THINGS AT ONCE:

$W^\pm, Z$ MASSES

FERMION MASSES



UNITARIZE W SCATTERING

PRECISION EW EXCELLENT
(IF $m_h \lesssim 200$-250 GeV)
AGREEMENT W/ EXPERIMENT

WHAT'S PUZZLING ABOUT FUNDAMENTAL H?

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

- ELECTROWEAK SYMMETRY BROKEN "BY HAND"

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

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

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

IF Λ_{CUTOFF} IS NOT FAR FROM $m_H^2 \sim v_{EW}^2$,

NO PROBLEM.

BUT WE KNOW NUMEROUS CUTOFF - SUPPRESSED OPERATORS THAT ARE EXPERIMENTALLY FORBIDDEN UNLESS

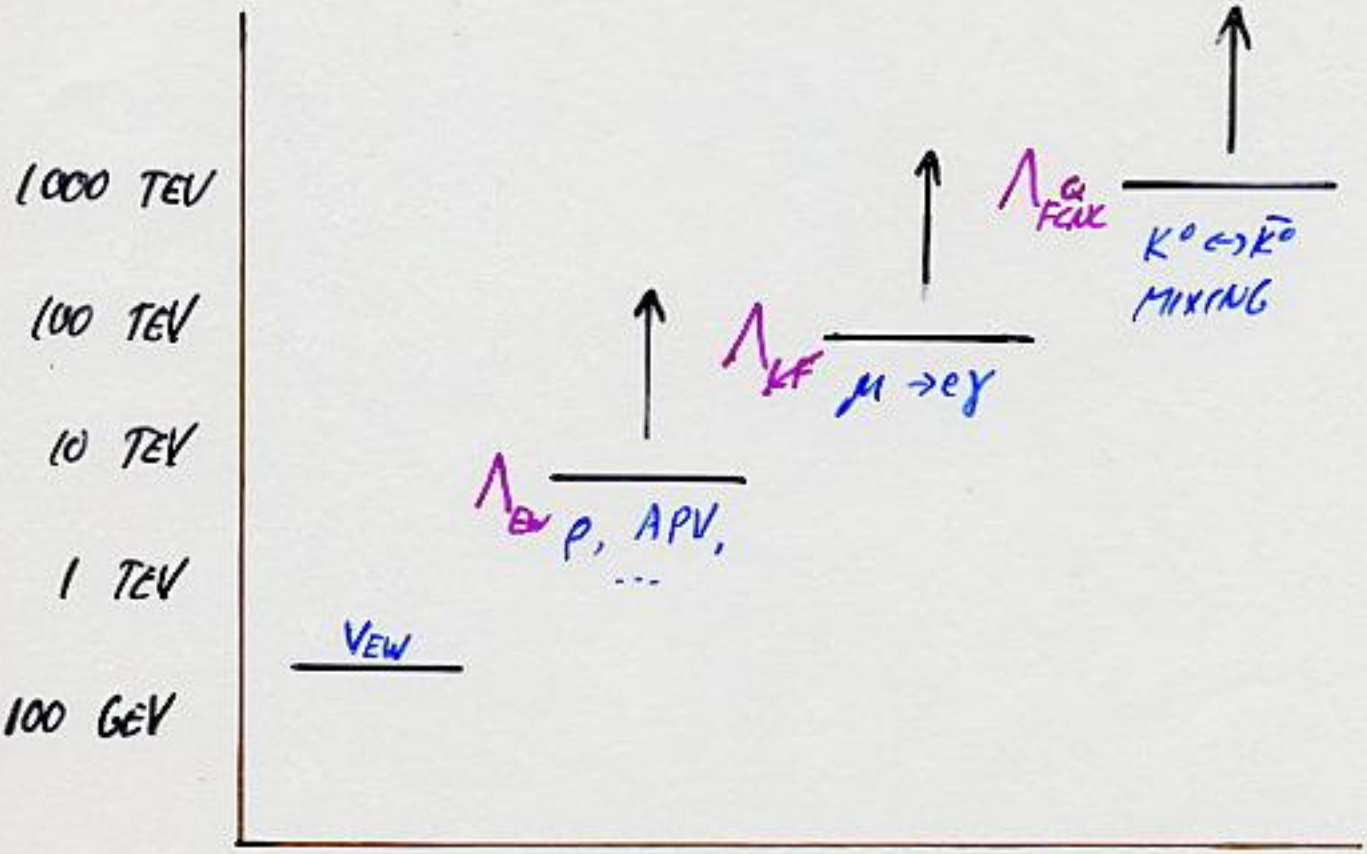
$$\Lambda_{CUTOFF} \gg v_{EW}$$

ELECTROWEAK OPERATORS INVOLVING THE HIGGS, FOR EXAMPLE

$$\propto T = \rho \sim \frac{(H^+ D_\mu H)^2}{\Lambda_{EW}^2}$$

MUST BE SUPPRESSED BY $\Lambda_{EW} \sim 5$ TeV

LITTLE HIERARCHY PROBLEM(S)



IN MODELS THAT EXPLAIN EWSB:

WHY IS $m_H \sim v_{EW} \ll \Lambda$?

NEW PHYSICS

NATURALNESS SUGGESTS NEW PHYSICS $\lesssim$ TEV, BUT USUALLY RUNS AFOUL AT 1 TEV DUE TO

- TOO LARGE CONTRIBUTIONS TO EW PRECISION
- TOO LARGE CONTRIBUTIONS TO FCNC

YOUR FAVORITE IDEA	THE PROBLEM
WEAK SCALE SUSY @ 1 TEV	SUPERSYMMETRIC FLAVOR PROBLEM
TECHNICOLOR @ 1 TEV	EW, FCNC
LARGE EXTRA DIMENSIONS @ 1 TEV	EW, FCNC, PROTON DECAY

⋮

THERE ARE OF COURSE SOLUTIONS, BUT THEY USUALLY COMPLICATE THE MODEL FURTHER.

IS THERE AN ALTERNATIVE?

WHERE ARE WE GOING?

LITTLE HIGGS THEORIES

A NEW APPROXIMATE GLOBAL SYMMETRY PROTECTS HIGGS MASS AGAINST ONE LOOP QUADRATIC DIVERGENCES

OR

$$\boxed{m_h^2 \sim \frac{\Lambda^2}{(16\pi^2)^2}}$$

THIS SOLVES (MOST) OF THE LITTLE HIERARCHY PROBLEM BY PUSHING $\Lambda \to 10 \to 20$ TEV WITHOUT ANY MORE FINE-TUNING THAN THE SM WITH $\Lambda_{SM} \to 1 \to 2$ TEV

TO IMPLEMENT A NEW APPROXIMATE GLOBAL SYMMETRY THAT IS USEFUL, NEED:

→ LARGEST COUPLINGS OF SM HIGGS PRESERVE ENOUGH OF THE GLOBAL SYMMETRY THAT THE HIGGS IS MASSLESS @ ONE-LOOP

→ THIS REQUIRES INTRODUCING NEW PARTICLES THAT HAVE THE EFFECT OF CANCELING LARGEST ONE-LOOP QUADRATIC DIVERGENCES

e.g. LITTLEST HIGGS THEORY

$$SU(5)_{GLOBAL} \xrightarrow{\langle \Sigma \rangle} SO(5)$$

$$\langle \Sigma \rangle = \begin{pmatrix} & & \mathbb{I} \\ & 1 & \\ \mathbb{I} & & \end{pmatrix}$$

AND $[SU(2) \times U(1)]^2$ SUBGROUP OF $SU(5)_{GLOBAL}$ IS GAUGED.

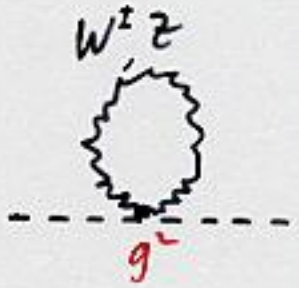
ANY PAIR $\begin{matrix} (g_1, g_2) \\ (g_1', g_2') \end{matrix}$ OF GAUGE COUPLINGS PRESERVES $SU(3)_{GLOBAL}$ THAT SPONTANEOUSLY BROKEN LEADS TO 8 GOLDSTONE BOSONS

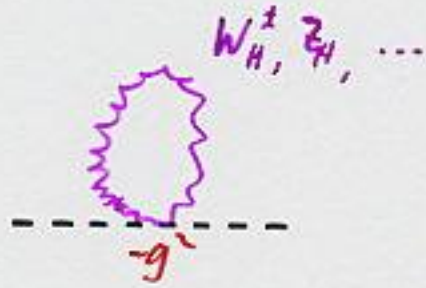
4 ARE THE HIGGS

ONE-LOOP CANCELLATIONS

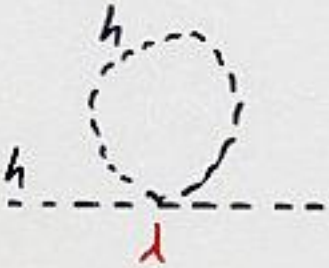
THE SLICK SYMMETRY ARGUMENT CAN BE VERIFIED [redacted]

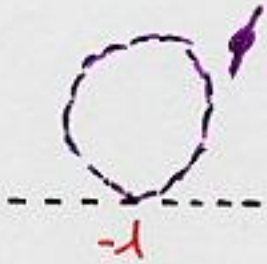
DIAGRAMMATICALLY:



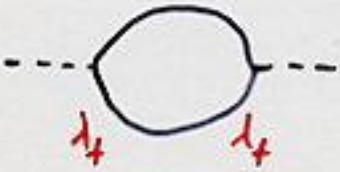


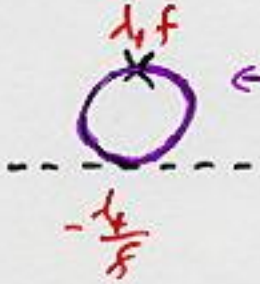
A SIMILAR ANALYSIS SHOWS THAT: (ROUGHLY):





SCALAR ASSOCIATED WITH GLOBAL SHIFT SYMMETRY





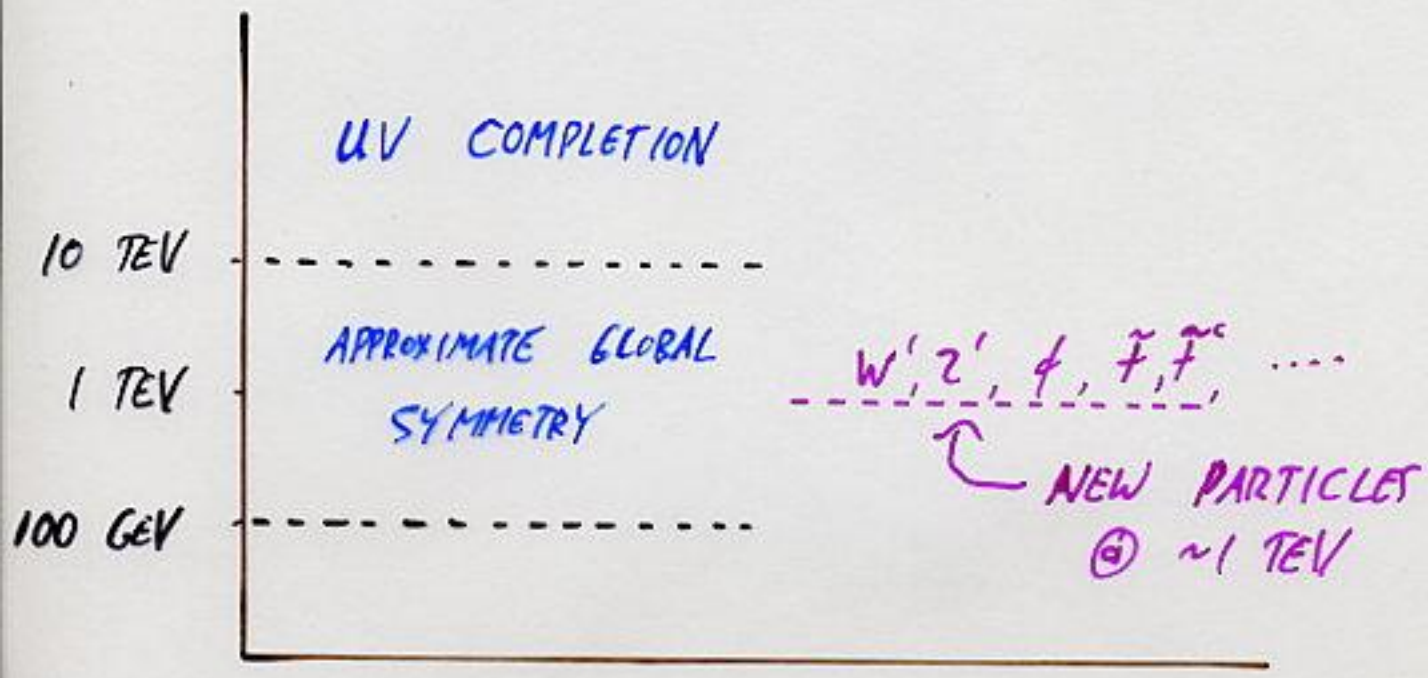
← NEW (VECTOR-LIKE) TOP QUARKS

$\tilde{t}, \tilde{t}^c$

THESE NEW PARTICLES ARE REQUIRED TO IMPLEMENT THE GLOBAL SYMMETRY SO THAT ALL DANGEROUS QUADRATIC DIVERGENCES (PROPORTIONAL TO $\mathcal{O}(1)$ COUPLINGS) ARE CANCELED.

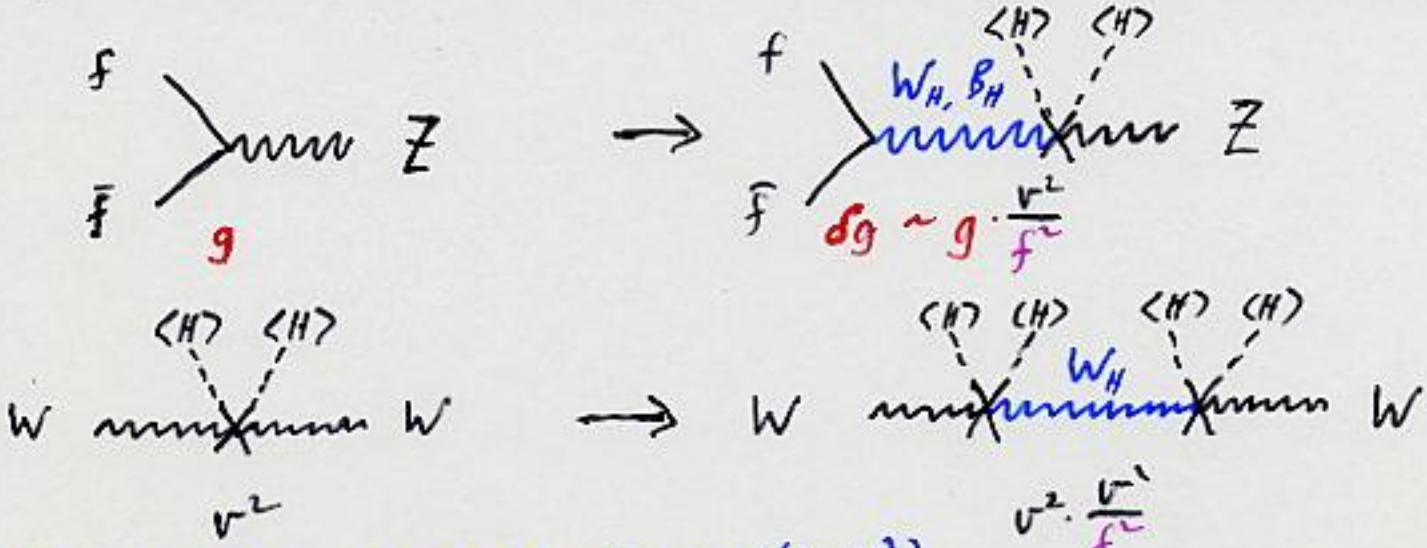
LITTLE HIGGS MODELS

Name	Global Symmetry	Gauge Symmetry	# of light Higgs doublets	Higgs triplet? VEV
Littlest Higgs [ACKN]	$SU(5)$	$[SU(2)\times U(1)]^2$	1	yes!
Minimal Moose [ACGKNW]	$[SU(3)]^8$	$SU(3)\times SU(2)\times U(1)$	2	yes!
Antisymmetric condensate [LSS]	$SU(6)$	$[SU(2)\times U(1)]^2$	2	no.
Simple Group [KS]	$[SU(4)]^4$	$SU(4)\times U(1)$	2	no.
Minimal Moose Variant [CW]	$[SO(5)]^8$	$SO(5)\times SU(2)\times U(1)$	2	yes!
Two Little Higgs [ST]	$SU(9)$	$SU(3)\times U(1)$	2	no.
Custodial SU(2) [C]	$SO(9)$	$[SU(2)]^3\times U(1)$	1	yes*
T-parity LH [CL]	$[SO(5)]^{10}$	$[SU(2)\times U(1)]^3$	2	no.


UV COMPLETION
10 TEV
APPROXIMATE GLOBAL SYMMETRY
1 TEV
W', Z', ϕ, F̃, F̃^c ....
NEW PARTICLES @ ~1 TEV
100 GEV

ELECTROWEAK CONTRIBUTION: BACK OF THE ENVELOPE

NEW CONTRIBUTIONS ARISE DUE TO MODIFICATIONS TO SM RELATIONS, E.G.:



EXPECT CONTRIBUTIONS TO OBSERVABLES $\sim \left(1 + \frac{v^2}{f^2}\right)$

$$\Gamma_Z = 2.4952 \pm \underbrace{0.0023}_{1\sigma} \text{ GEV}$$

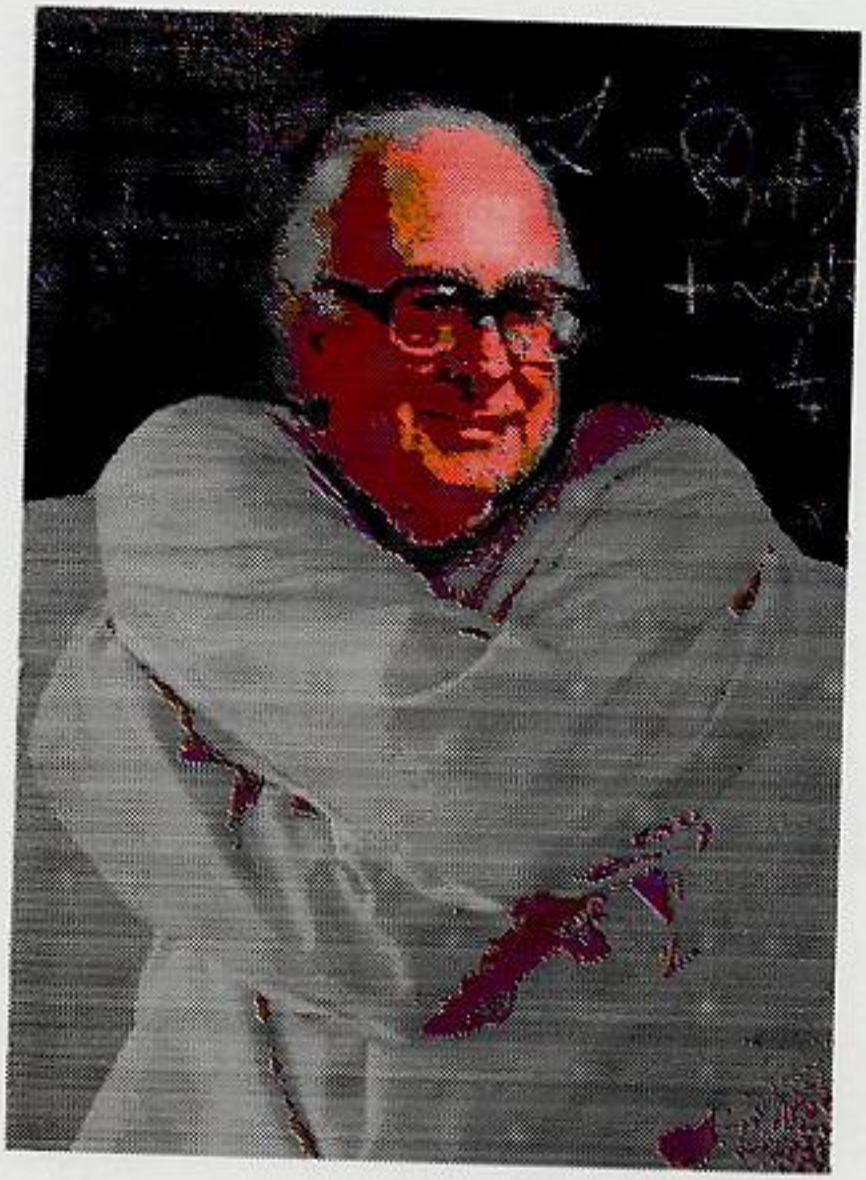
$$M_W = 80.449 \pm \underbrace{0.034}_{1\sigma} \text{ GEV}$$

$$\frac{\delta \Gamma_Z}{\Gamma_Z} \lesssim 0.2\% \quad , \quad \frac{\delta M_W^2}{M_W^2} \lesssim 0.2\% \quad \text{to } 95\% \text{ C.L.}$$

$$\Rightarrow \quad \frac{v^2}{f^2} \lesssim 0.002$$

$$\Rightarrow \quad f \gtrsim 5 \text{ TEV} \quad \text{to } 95\% \text{ C.L.}$$

STRONG BOUNDS ON f SHOULD BE EXPECTED !



BOUNDS ON LH MODELS: VERY CRUDE!

Model	Custodial SU(2) violation	Bound on symmetry breaking scale f
Littlest Higgs	gauge bosons, triplet vev	4 TEV
LH variants	gauge bosons, triplet vev	1→2 TEV (tuned)
Minimal Moose	gauge bosons, triplet vev, $\tan\beta$	SEVERAL TEV
Antisymmetric condensate	gauge bosons, $\tan\beta$	3 TEV (VARIANTS: 1 TEV)
Simple Group	gauge bosons	4 TEV
Minimal Moose variant	~~gauge bosons~~ triplet vev, $\tan\beta$	1→3 TEV (tuned?)
Two Little Higgs	gauge bosons, $\tan\beta$	3.4 TEV
Custodial SU(2)	~~gauge bosons~~, triplet vev	1 TEV
T-parity LH	~~gauge bosons~~, ~~$\tan\beta$~~	1 TEV

PRODUCTION OF HEAVY W'S @ LHC

(LITTLEST HIGGS MODEL)

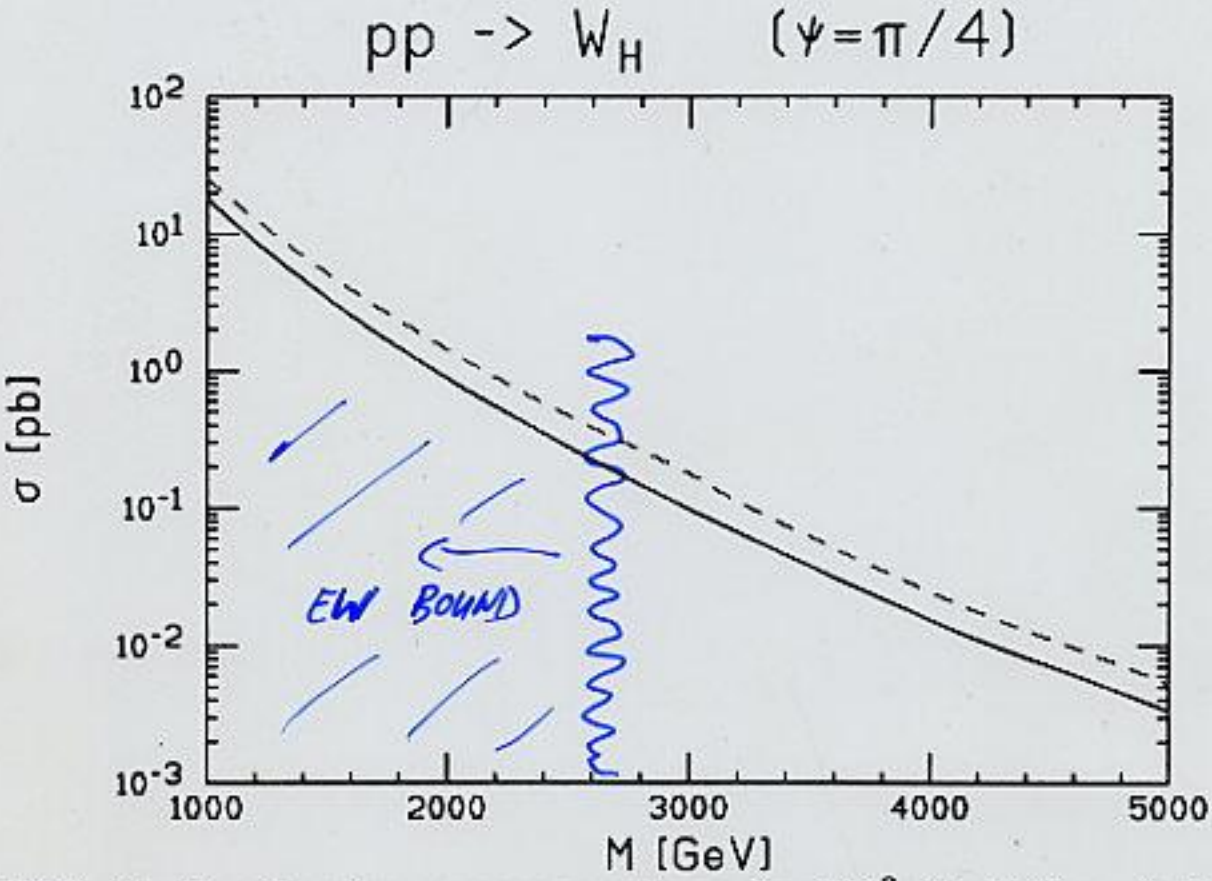
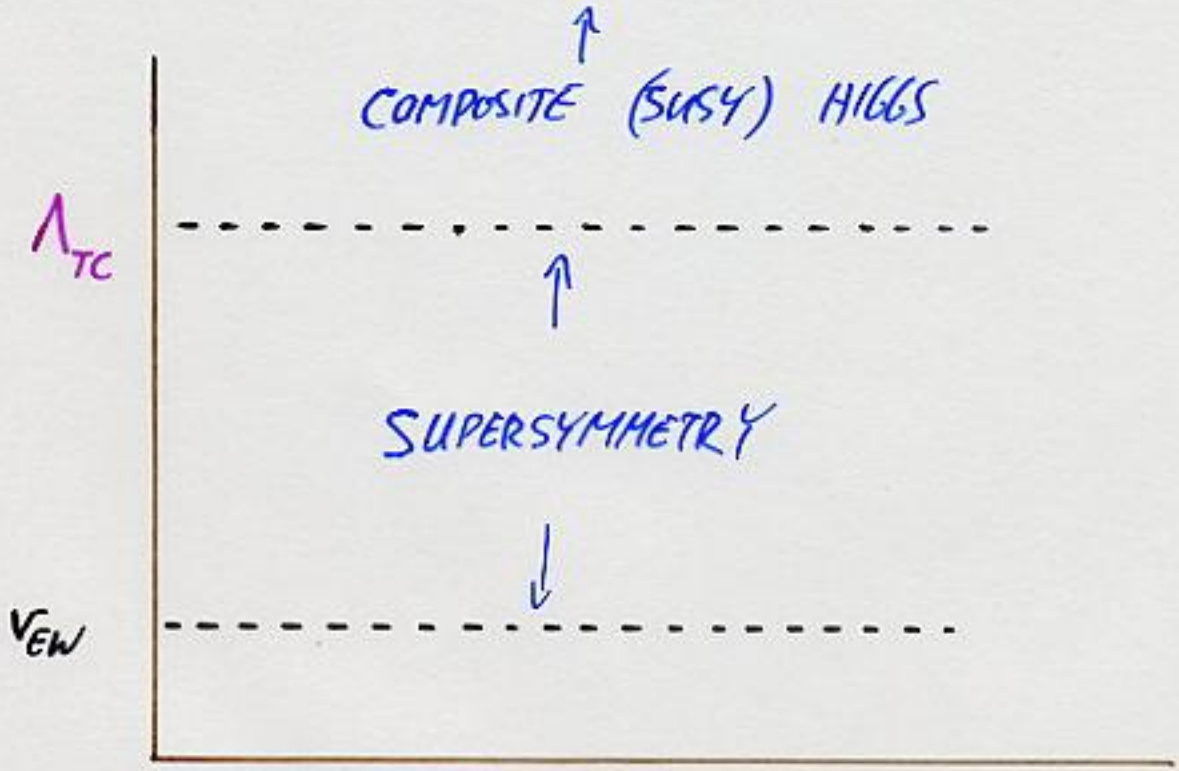


FIG. 3. Production cross sections for W_H^3 (solid) and $W_H^\pm$ (dashed) at the LHC, for $\psi = \pi/4$. We use the CTEQ5L parton distribution function.

[BURDMAN, PERELSTEIN, PIERCE]

IS THERE ANOTHER WAY?

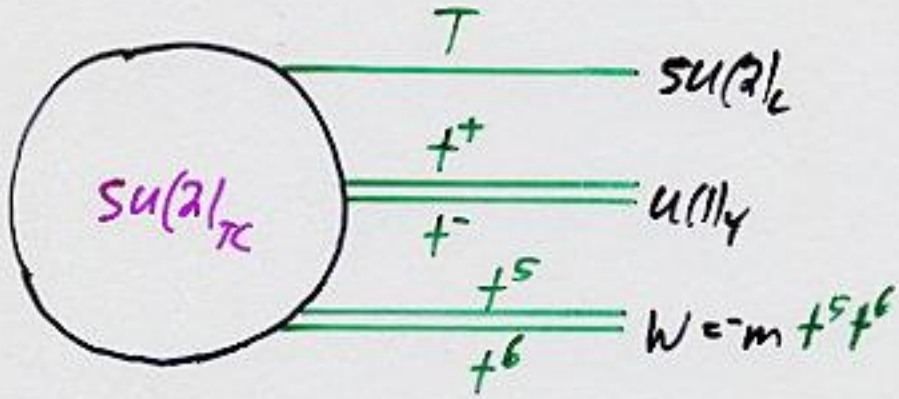
FAT HIGGS MODEL!



[HARNIK, GK, LARSON, MURAYAMA]

ABOVE Λ_{TC}

$SU(2)_{TC}$ WITH SIX DOUBLETS



AT Λ_{TC}

$SU(2)_{TC}$ GETS STRONG CONFINING T's, t's INTO MESON COMPOSITES

[SEIBERG]

BELOW Λ_{TC}

NMSSM-like SUPERPOTENTIAL DYNAMICALLY GENERATED:

$$W = \frac{(t^5 t^6)\left[(T t^-)(T t^+)\right]}{\Lambda_{TC}^3} - m(t^5 t^6)$$

$$\boxed{W = \lambda S \left[H_d H_u - v_0^2\right]} \qquad v_0^2 = \frac{m \Lambda_{TC}}{(4\pi)^2}$$

ELECTROWEAK SYMMETRY BROKEN DYNAMICALLY

BENEFITS

- IMPROVES OLD COMPOSITE HIGGS MODEL:

  → SUPERSYMMETRY PROVIDES THEORETICAL CONTROL @ STRONG COUPLING [SEIBERG]

  → $\Lambda_{TC} \leftrightarrow v_{EW}$ LITTLE HIERARCHY STABILIZED BY SUPERSYMMETRY

- IMPROVES ON MSSM:

  → NO FINE-TUNING !!

$$v_{EW}^2 = \frac{2\left(\lambda^2 v_0^2 - m_{susy}^2\right)}{\lambda^2 \sin 2\beta}$$

  → HIGGS MASS DECOUPLED FROM SUSY BREAKING

  NO BOUND ON LIGHTEST HIGGS MASS

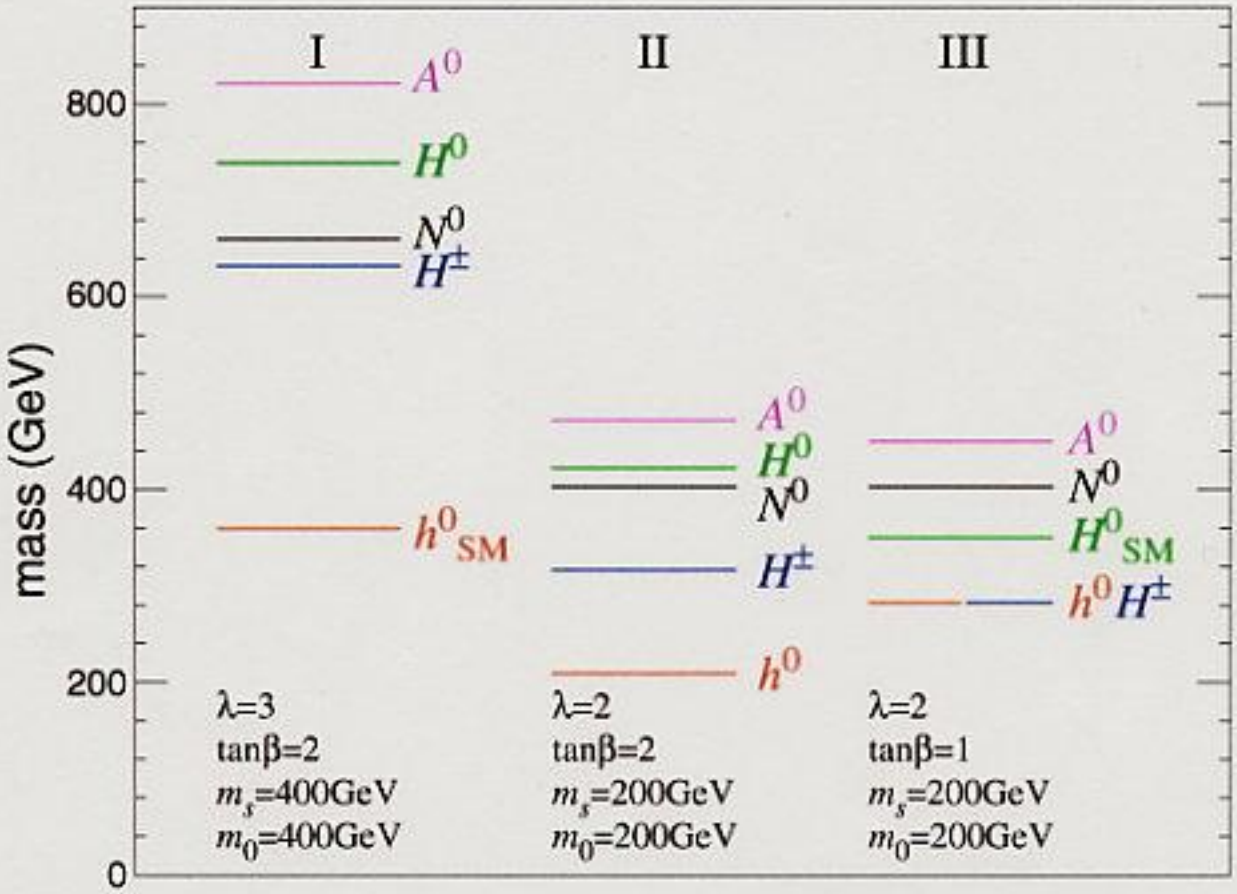
  (QUARTIC COUPLING DETERMINED BY $\lambda \sim 1 \to 4$)

  → SUPERPARTNERS CAN BE AS LIGHT AS COLLIDER BOUNDS WITHOUT VIOLATING HIGGS MASS SEARCH @ LEP.

HIGGS MASS SPECTRUM

CONSISTS OF FIELD CONTENT OF NMSSM

(BUT NO CUBIC TERM $\cancel{\kappa N^3}$; LINEAR TERM $\lambda v_0^2 N$ INSTEAD)



UNUSUAL FEATURES

- LIGHTEST HIGGS MASS CAN BE <u>MUCH</u> 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

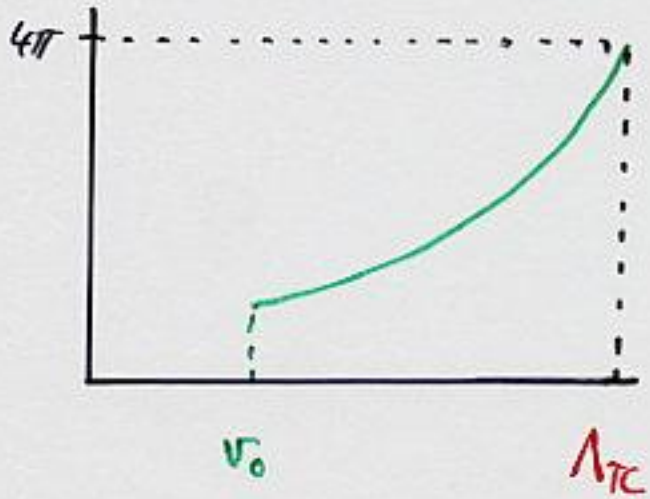
IS DOMINATED BY λ IN THE POTENTIAL

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

AND NOT THE USUAL D-TERMS.

HOW BIG IS λ?

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



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

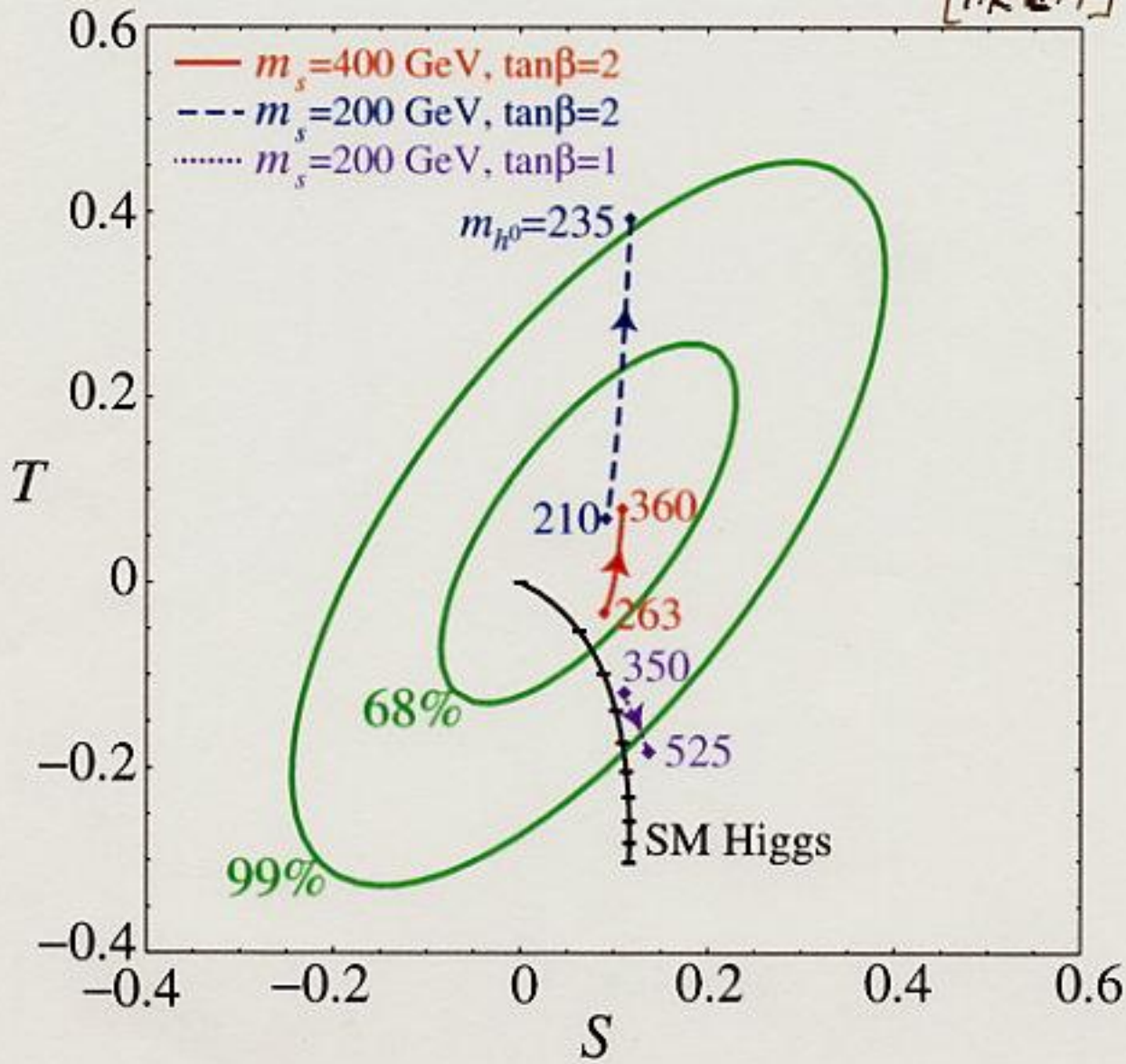
λ IS MUCH LARGER THAN GAUGE COUPLINGS.

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.

[HKLM]



SUMMARY

THERE ARE VIABLE, PREDICTIVE, LESS-FINE-TUNED MODELS OF EWSB THAT RESOLVE $v_{EW} \longleftrightarrow \Lambda_{EW,\,flavor}$ LITTLE HIERARCHY

LITTLE HIGGS PREDICTS NEW GAUGE BOSONS, QUARKS & SCALARS @ 1 → few TeV AND COMPOSITENESS @ 10 TeV

→ TIGHTLY CONSTRAINED BY EW PRECISION;
→ UV COMPLETION TRICKY

FAT HIGGS PREDICTS SUSY:

→ MSSM + DYNAMICALLY GENERATED NMSSM-like SUPERPOTENTIAL

→ HIGGS SPECTRUM DISTINCTLY DIFFERENT THAN MSSM
$(m_A > m_{H^\pm})$

→ LIGHTEST HIGGS MASS DECOUPLED FROM SUSY BREAKING
- m_h CAN BE MUCH HEAVIER 200 → 450 GeV
- SUSY CAN BE AS LIGHT AS COLLIDER BOUNDS