A LITTLE HIGGS FOR A HUGE COLLIDER

GRAHAM KRIBS

IAS PRINCETON

FERMILAB

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HOW IS ELECTROWEAK SYMMETRY BROKEN?

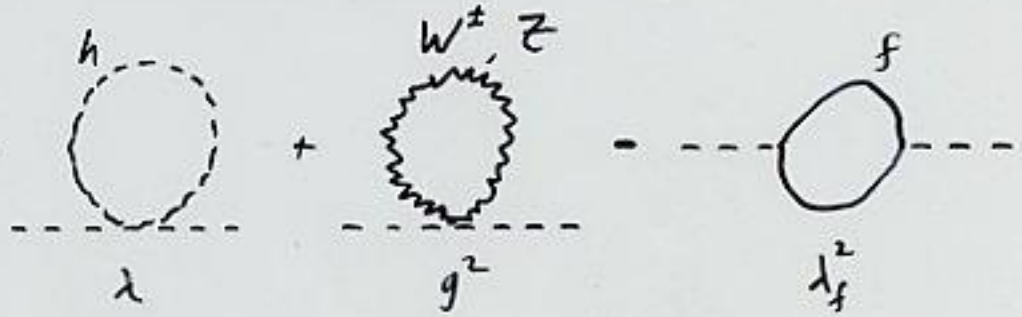
$$\Updownarrow$$

WHAT STABILIZES THE HIGGS MASS?

HIGGS MASS IN SM

A FUNDAMENTAL SCALAR'S MASS IS INFAMOUSLY UNSTABLE TO RADIATIVE CORRECTIONS. IN THE SM:

$m_h^2 =$



THE NATURAL EXPECTATION FOR THE EFFECTIVE THEORY CUTOFF SCALE FOR THE SM IS THUS:

$$\Lambda^2 \sim 16\pi^2 \cdot m_h^2$$

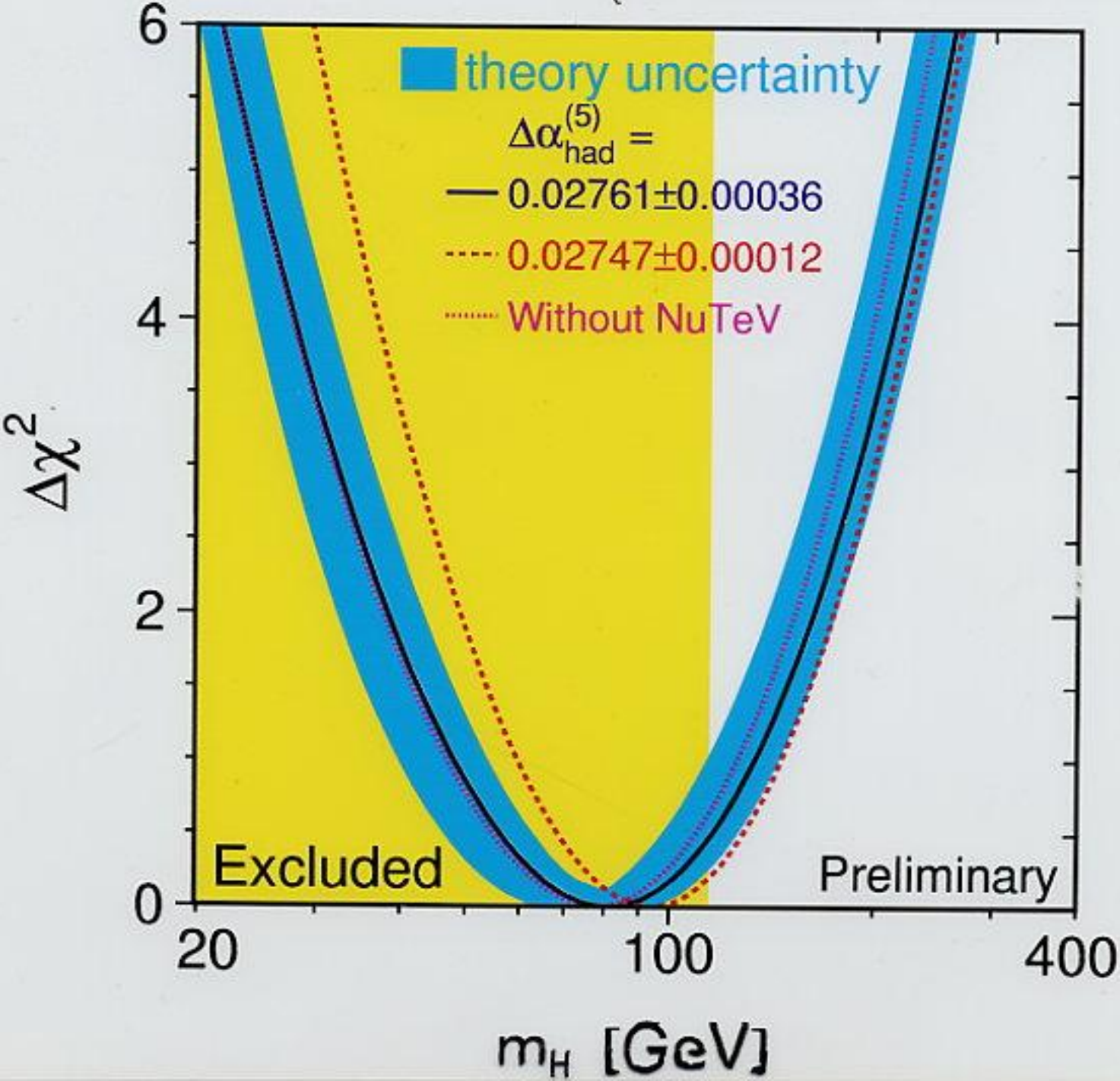
(WHEN THE QUADRATICALLY DIVERGENT LOOP DIAGRAMS ARE COMPARABLE TO TREE-LEVEL MASS)

OR: $\Lambda \sim 4\pi \cdot m_h$

A LIGHT HIGGS MASS IMPLIES A LOW CUTOFF SCALE.

FIT TO ELECTROWEAK PRECISION DATA

(SUMMER 2002
LEP ELECTROWEAK WORKING GROUP)



THERE IS QUIBBLING OVER DETAILS, BUT THE BROAD PICTURE IS:

$$m_h \lesssim 200 \to 250 \text{ GeV} \quad \text{to } 95\% \text{ C.L.}$$

FROM ELECTROWEAK DATA, WHICH IMPLIES

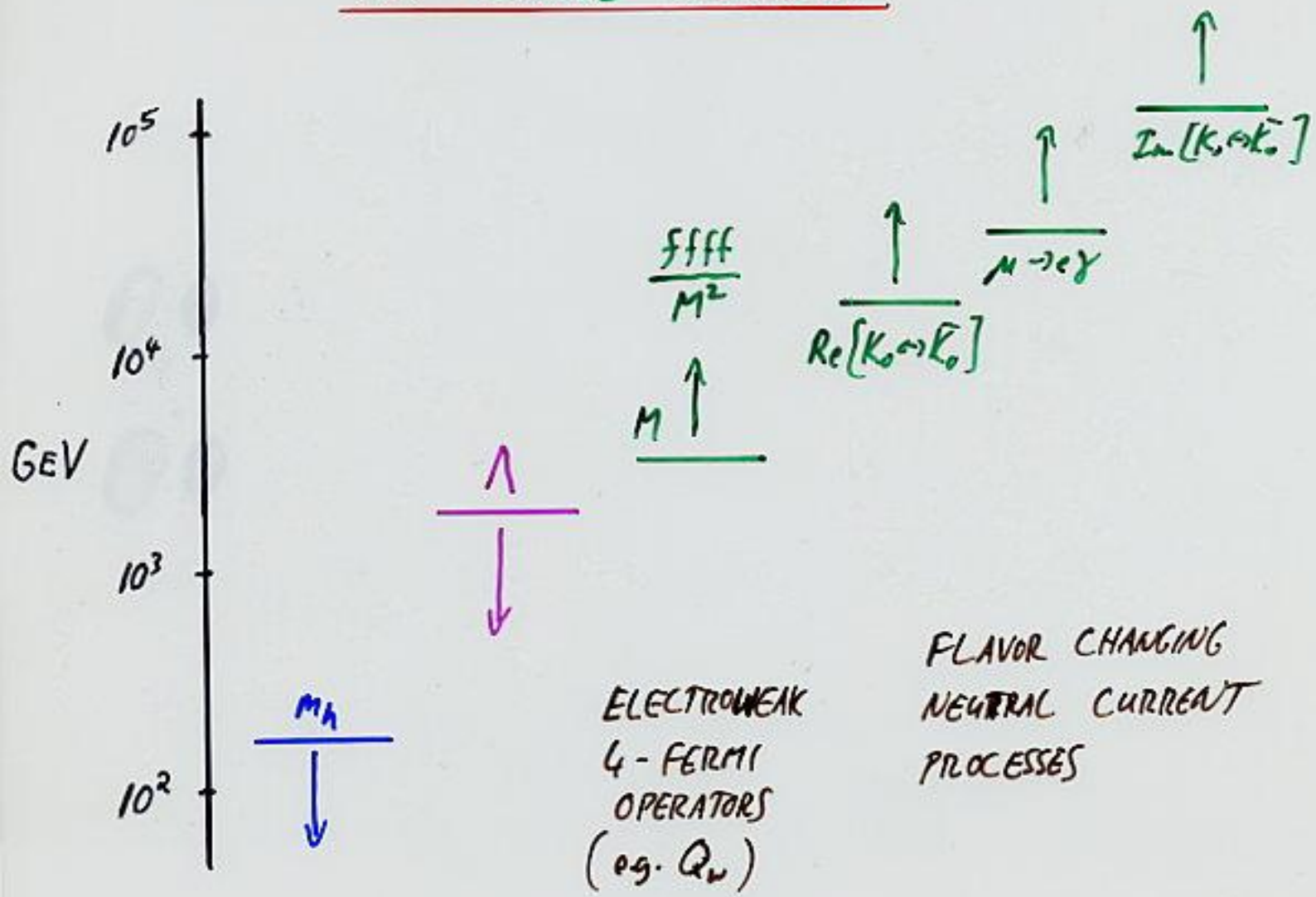
$$\boxed{\Lambda \lesssim 2 \to 3 \text{ TeV}}$$

PHYSICS BEYOND THE SM THAT PURPORTS TO EXPLAIN ELECTROWEAK SYMMETRY BREAKING SHOULD BE MANIFEST AT THIS SCALE

BUT, THERE IS A PUZZLE:

"LITTLE HIERARCHY PROBLEM"

THE LITTLE HIERARCHY



A LIGHT HIGGS IMPLIES A LOW CUTOFF SCALE, YET SEVERAL INDIRECT PROBES GO WELL BEYOND Λ.

$\Rightarrow$ THIS SUGGESTS THERE ARE TIGHT RESTRICTIONS ON THE FORM OF PHYSICS BEYOND THE SM THAT EXPLAINS EWSB.

NEW PHYSICS

USUALLY RUNS AFOUL AT 2 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?

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

BASIC IDEA

- THE HIGGS BECOMES ONE COMPONENT OF A LARGER MULTIPLET OF SCALARS Σ (OR $\Sigma_1, \Sigma_2, \ldots \Sigma_n$)

- $\Sigma_{(i)}$ TRANSFORMS NON-LINEARLY UNDER A NEW GLOBAL SYMMETRY

- NEW GLOBAL SYMMETRY IS SPONTANEOUSLY BROKEN, LEAVING THE HIGGS AS A GOLDSTONE

- GAUGING SOME OF THE GLOBAL SYMMETRY IMPLIES HIGGS IS NOT EXACT GOLDSTONE ("PSEUDO-GOLDSTONE")

- CAREFULLY GAUGING CAN ARRANGE THAT HIGGS DOES NOT ACQUIRE ONE-LOOP DIVERGENCE

(THUS, $\delta m_H^2 \sim \dfrac{\Lambda^2}{(16\pi^2)^2}$ IMPLYING $\Lambda \gtrsim 10 \to 20$ TeV)

TWO LOOP !!

AND THUS SOLVES LITTLE HIERARCHY PROBLEM!

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.

ANALOGY WITH CUSTODIAL SU(2) IN SM

- SM COMPLEX HIGGS DOUBLET $H = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$ TRANSFORMS

  AS A $4 = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{pmatrix}$ OF $SO(4)_{GLOBAL} \sim \underbrace{SU(2)_L}_{\text{GAUGED}} \times SU(2)$

- WHEN THE HIGGS ACQUIRES A VEV $\begin{pmatrix} 0 \\ 0 \\ v \\ 0 \end{pmatrix}$, THIS BREAKS

  $SO(4) \xrightarrow{v} SO(3) \sim SU(2)_{custodial}$ GLOBAL SYMMETRY

- IF THIS $SU(2)_{custodial}$ WERE EXACT, IT WOULD IMPLY

$$\frac{M_W}{M_Z} = 1$$

- BUT, GAUGING HYPERCHARGE BREAKS CUSTOPIAL SU(2)

$$\frac{M_W^2}{M_Z^2} = \frac{g^2}{g^2 + (g')^2}$$

NEVERTHELESS THERE IS A SMOOTH TRANSITION $g' \to 0$

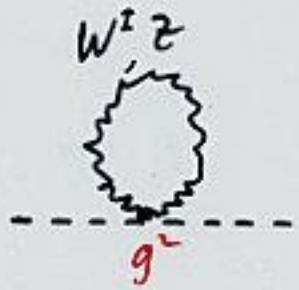
IN WHICH THE GLOBAL SYMMETRY IS RESTORED.

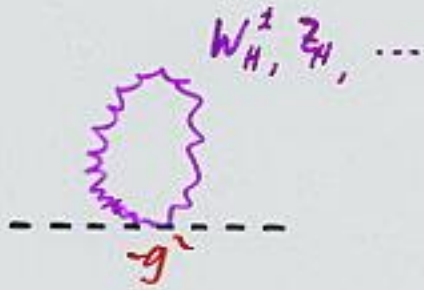
	CUSTODIAL SU(2)	LITTLEST HIGGS MODEL
global symmetry	$SO(4)$	$SU(5)$
realized	linearly	non-linearly
scalar field	$\phi = (H, H^+)$	$\Sigma = \exp \frac{i}{f}\begin{pmatrix} G_i & H^+ & \phi^\dagger \\ H & G_0 & H^* \\ \phi & H^T & G_i \end{pmatrix}$ $\downarrow$ (15 $\equiv$ SYMMETRIC TENSOR REP)
acquires VEV	$v\begin{pmatrix}0\\0\\1\\1\\0\end{pmatrix}$ breaks $SO(4)\to SU(2)$	$f\begin{pmatrix} & & \mathbb{1}_{2\times2} \\ & 1 & \\ \mathbb{1}_{2\times2} & & \end{pmatrix}$ breaks $SU(5)\to SO(5)$
gauged subgroup	$SU(2)_L \times U(1)_Y$	$[SU(2)\times U(1)]^2$
broken to	$U(1)_{EM}$	$SU(2)_L \times U(1)_Y$
	as $g'\to 0$ restore $\underbrace{SU(2)_{CUSTODIAL}}_{\text{GLOBAL!}}$	as $g_1, g_1' \to 0$ restore $\underbrace{SU(3)_1}_{\text{GLOBAL!}}$ as $g_2, g_2' \to 0$ restore $\underbrace{SU(3)_2}_{\text{GLOBAL!}}$
VEV breaks global symmetry?	no	yes
effect of symmetry restoration?	$\frac{M_W}{M_Z}\to 1$	$m_H \to 0$ H, G_i, G_0 ARE EXACT GOLDSTONES OF SPONTANEOUSLY BROKEN $SU(3)_{GLOBAL}$

ONE-LOOP CANCELLATIONS

THE SLICK SYMMETRY ARGUMENT CAN BE VERIFIED [redacted]

DIAGRAMMATICALLY:

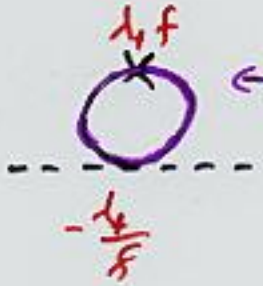




NEW GAUGE BOSONS

A SIMILAR ANALYSIS SHOWS THAT: (ROUGHLY):

SCALAR ASSOCIATED WITH GLOBAL SHIFT SYMMETRY



← NEW (VECTOR-LIKE) TOP QUARKS $\tilde{t}, \tilde{t}^c$

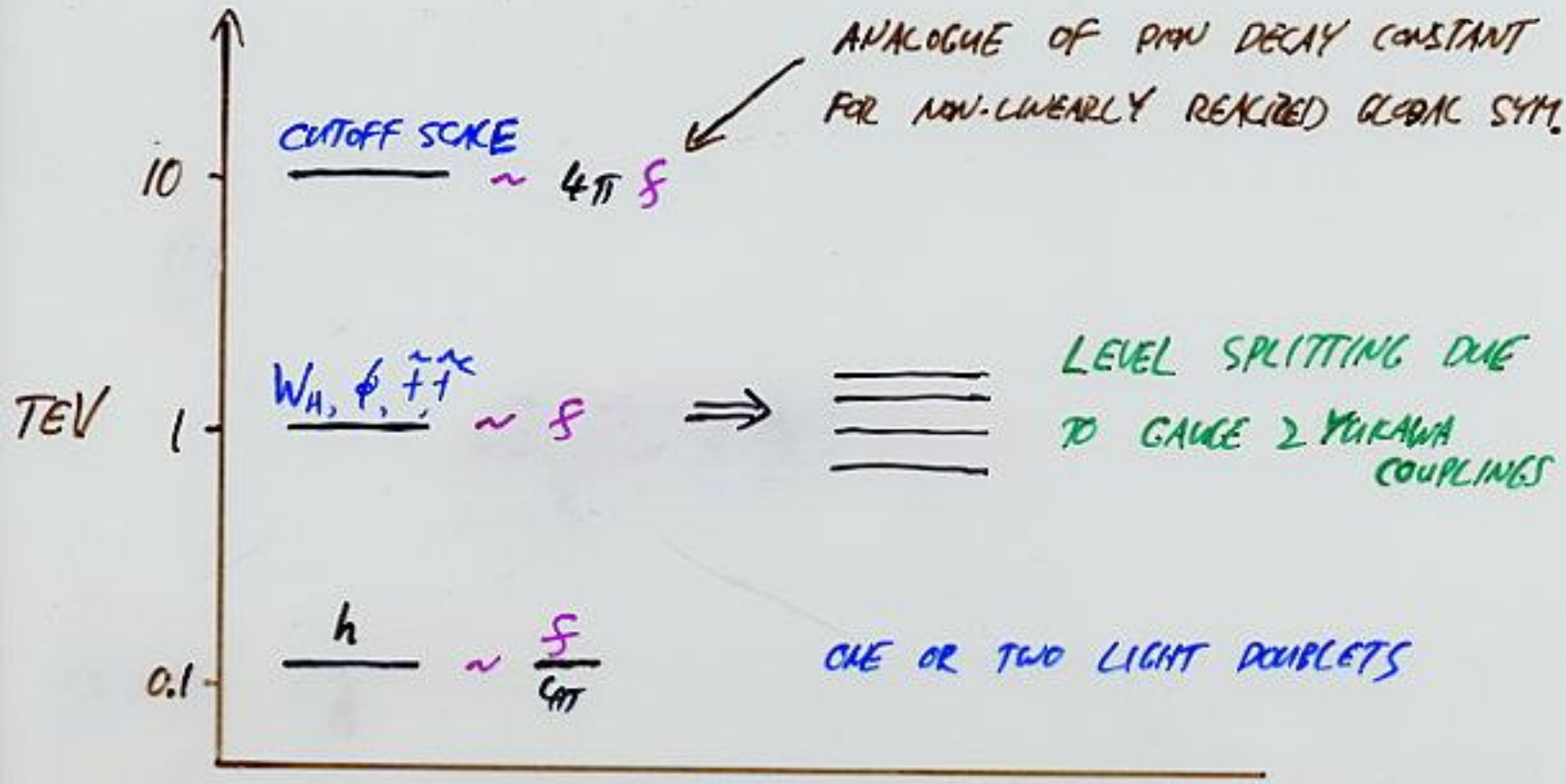
THESE NEW PARTICLES ARE REQUIRED TO IMPLEMENT THE GLOBAL SYMMETRY SO THAT ALL DANGEROUS QUADRATIC DIVERGENCES (PROPORTIONAL TO $\mathcal{O}(1)$ COUPLINGS) ARE CANCELED.

PHENOMENOLOGY

SEVERAL NEW PARTICLES MUST APPEAR NEAR ~ 1 TEV TO CANCEL QUADRATIC DIVERGENCES:

- NEW GAUGE BOSONS
- NEW SCALARS
- NEW (VECTOR-LIKE) QUARKS

AND MANY MODELS HAVE TWO (LIGHT) HIGGS DOUBLETS.



DETAILS

THE LEVEL SPLITTINGS AMONG THE $\sim f$ MASS HEAVY PARTICLES DEPENDS ON THE DETAILS OF THE MODEL.

e.g. FOR THE LITTLEST HIGGS MODEL

$W_H^\pm$, Z_H	$\frac{gf}{2sc}$
B_H	$\frac{g'f}{2\sqrt{5}\,s'c'}$
ϕ (SU(2) TRIPLET SCALAR)	$\sqrt{a}\,f$
$\tilde{t}, \tilde{t}^c$	$\sqrt{\lambda_1^2+\lambda_2^2}\,f$ $\qquad \lambda_t = \frac{\sqrt{2}\lambda_1\lambda_2}{\sqrt{\lambda_1^2+\lambda_2^2}}$

I WILL USE THE SU(5)/SO(5) LITTLEST HIGGS MODEL AS AN EXAMPLE FOR MOST OF THE REMAINDER.

PHENOMENOLOGY II

WHAT ARE THE EXPERIMENTAL IMPLICATIONS OF THE NEW PARTICLES NEEDED TO IMPLEMENT A LITTLE HIGGS MODEL?

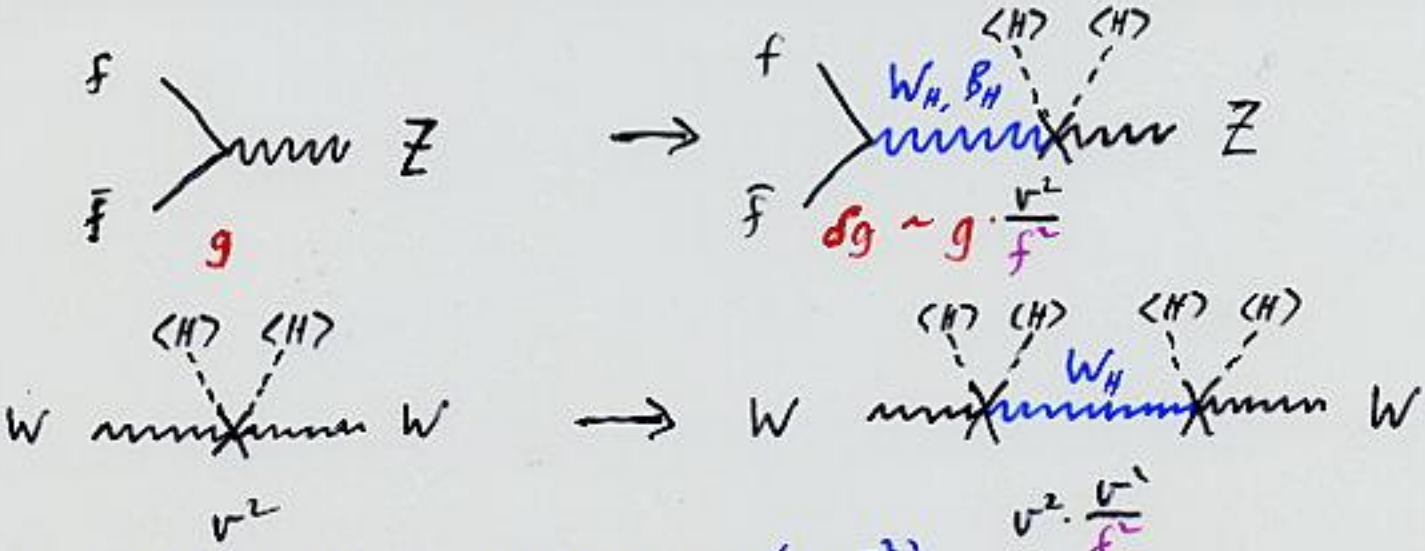
- INDIRECT EFFECTS ON EW PRECISION OBSERVABLES
  - NEW GAUGE BOSONS THAT $\begin{cases} \text{MIX WITH SM GAUGE BOSONS} \\ \text{COUPLE TO LIGHT FERMIONS} \end{cases}$
  - SCALAR SU(2) TRIPLET ACQUIRES VEV $\sim \frac{v_{EW}^2}{f}$ (IN SOME MODELS)
  - $\tan\beta \neq 1$ LEADS TO A FINAL SOURCE OF CONCERN (CUSTODIAL SU(2)) (IN 2HDMS) [CHKMT1, CHKMT2, HPR, GSW]
- DIRECT PRODUCTION AT FUTURE HADRON COLLIDER
  - HEAVY $W^\pm$, Z
  - HEAVY $\tilde{t}$, $\tilde{t}^c$

  $\left\{ \right.$ [HPR, BPP, HLMW ...]
  - MODIFIED $h \to gg$, $h \to \gamma\gamma$ [HLMW, DRZ]

    $b \to s\gamma$ [HZ]
- VERIFY COLLECTIVE BREAKING [PPP]
- DARK MATTER CANDIDATE [BW, Q, BHKW]

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!

CALCULATE SHIFTS IN EW OBSERVABLES

⇒ IN LITTLEST HIGGS MODEL WITH MATTER COUPLING TO $SU(2)_1 \times U(1)_1$

$$
\begin{aligned}
\Gamma_Z &= (\Gamma_Z)_{SM}\left[1+\Delta(1.7-0.23c^2-0.89c^4-3.8c'^2+0.83c'^4)-5.4\Delta'\right]\\
R_e &= (R_e)_{SM}\left[1+\Delta(0.34-0.18c^2+0.08c^4-3.0c'^2+4.6c'^4)-1.1\Delta'\right]\\
R_\mu &= (R_\mu)_{SM}\left[1+\Delta(0.34-0.18c^2+0.08c^4-3.0c'^2+4.6c'^4)-1.1\Delta'\right]\\
R_\tau &= (R_\tau)_{SM}\left[1+\Delta(0.34-0.18c^2+0.08c^4-3.0c'^2+4.6c'^4)-1.1\Delta'\right]\\
\sigma_h &= (\sigma_h)_{SM}\left[1+\Delta(-0.04+0.02c^2+0.01c^4+0.31c'^2-0.48c'^4)+0.12\Delta'\right]\\
R_b &= (R_b)_{SM}\left[1+\Delta(-0.08+0.04c^2-0.02c^4+0.66c'^2-1.0c'^4)+0.24\Delta'\right]\\
R_c &= (R_c)_{SM}\left[1+\Delta(0.15-0.08c^2+0.04c^4-1.3c'^2+1.9c'^4)-0.47\Delta'\right]\\
A^e_{FB} &= (A^e_{FB})_{SM}+\Delta(0.73-0.38c^2+0.18c^4-6.4c'^2+9.8c'^4)-2.3\Delta'\\
A^\mu_{FB} &= (A^\mu_{FB})_{SM}+\Delta(0.73-0.38c^2+0.18c^4-6.4c'^2+9.8c'^4)-2.3\Delta'\\
A^\tau_{FB} &= (A^\tau_{FB})_{SM}+\Delta(0.73-0.38c^2+0.18c^4-6.4c'^2+9.8c'^4)-2.3\Delta'\\
A_\tau(P_\tau) &= (A_\tau(P_\tau))_{SM}+\Delta(3.2-1.7c^2+0.78c^4-28c'^2+43c'^4)-10\Delta'\\
A_e(P_\tau) &= (A_e(P_\tau))_{SM}+\Delta(3.2-1.7c^2+0.78c^4-28c'^2+43c'^4)-10\Delta'\\
A^b_{FB} &= (A^b_{FB})_{SM}+\Delta(2.3-1.2c^2+0.54c^4-20c'^2+30c'^4)-7.2\Delta'\\
A^c_{FB} &= (A^c_{FB})_{SM}+\Delta(1.8-0.91c^2+0.42c^4-15c'^2+23c'^4)-5.6\Delta'\\
A_{LR} &= (A_{LR})_{SM}+\Delta(3.2-1.7c^2+0.78c^4-28c'^2+43c'^4)-10\Delta'\\
M_W &= (M_W)_{SM}\left[1+\Delta(0.89-0.21c^2+0.21c^4-2.6c'^2+3.6c'^4)-2.9\Delta'\right]\\
g^2_L(\nu N\to\nu X) &= \left(g^2_L(\nu N\to\nu X)\right)_{SM}+\Delta(1.1-0.16c^2+0.25c^4-2.7c'^2+1.2c'^4)\\
&\quad -3.4\Delta'\\
g^2_R(\nu N\to\nu X) &= \left(g^2_R(\nu N\to\nu X)\right)_{SM}+\Delta(-0.032+0.055c^2-0.085c^4+0.92c'^2\\
&\quad -0.42c'^4)+0.10\Delta'\\
g_{eV}(\nu e\to\nu e) &= (g_{eV}(\nu e\to\nu e))_{SM}+\Delta(-0.87+0.43c^2-0.66c^4+7.1c'^2-3.3c'^4)\\
&\quad +2.8\Delta'\\
g_{eA}(\nu e\to\nu e) &= (g_{eA}(\nu e\to\nu e))_{SM}-\frac{5\Delta}{8}+2\Delta'\\
Q_W(Cs) &= (Q_W(Cs))_{SM}+\Delta(-1.5-47c^2+73c^4-786c'^2+363c'^4)+4.7\Delta'
\end{aligned}
\tag{A.1}
$$

We also give in Table (1) the experimental data [22, 26] and the SM predictions used for our fit.

EVERYTHING DETERMINED IN TERMS OF*

$\Delta \equiv \frac{v_{EW}^2}{f^2}$, $c \equiv \cos\theta$ AMOUNT OF $SU(2)_L$ IN $SU(2)_1$ VS. $SU(2)_2$

$c' \equiv \cos\theta'$ AMOUNT OF $U(1)_Y$ IN $U(1)_1$ VS. $U(1)_2$

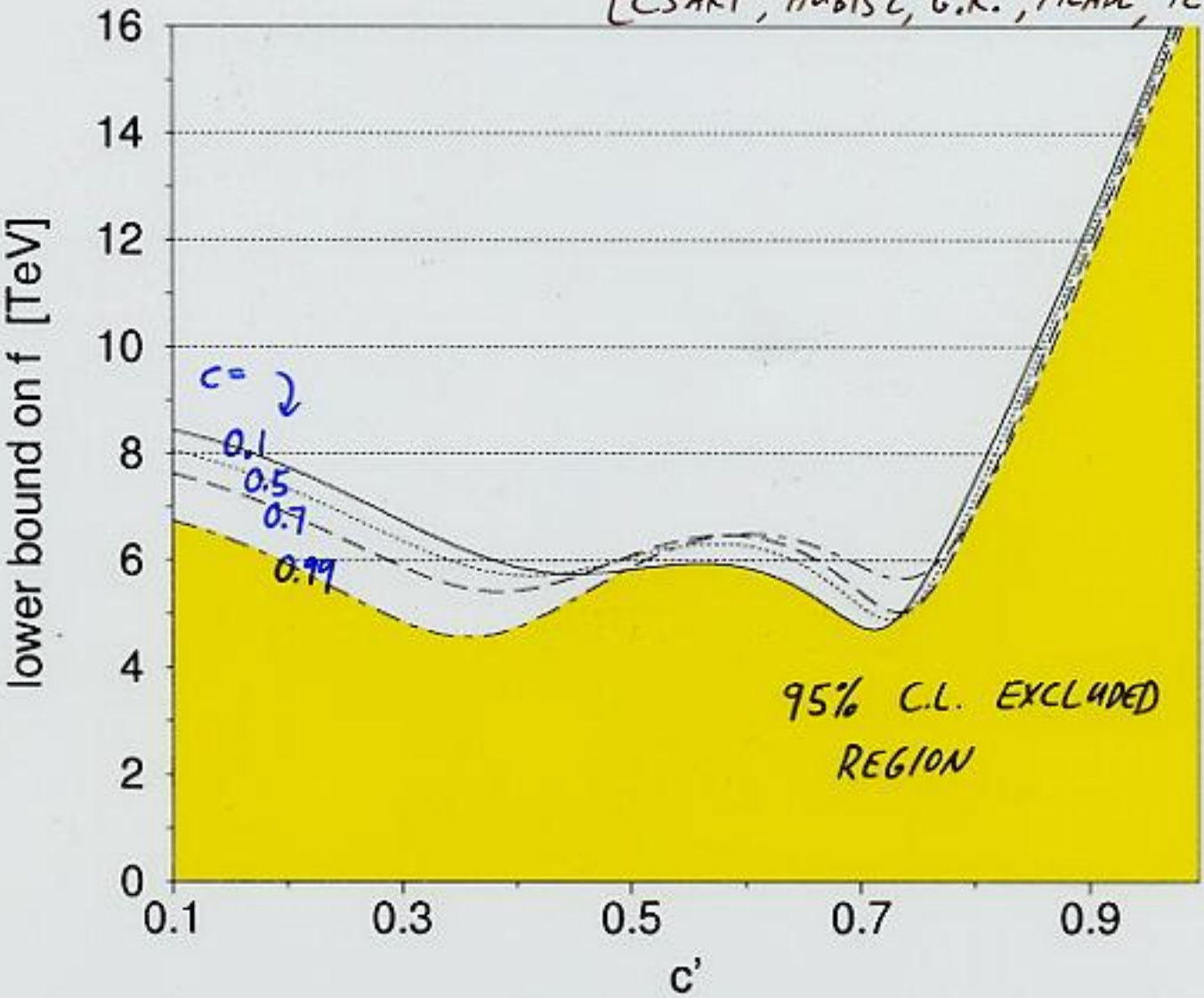
$\Delta' \equiv \frac{v'^2}{v_{EW}^2}$ TRIPLET VEV

* ONE CAVEAT

95% C.L. BOUND USING GLOBAL FIT

$\Delta' = 0$ (NO TRIPLET VEV)

[CSÁKI, HUBISZ, G.K., MEADE, TERNING]



LIGHT FERMIONS COUPLE TO $SU(2)_1 \times U(1)_1$

BOUND ON LITTLEST HIGGS MODEL WITH LIGHT FERMIONS COUPLING TO $SU(2)_1 \times U(1)_1$ IS $\gtrsim 4$ TEV

CAN THIS BE RELAXED BY ALTERING THE MODEL?

YES!

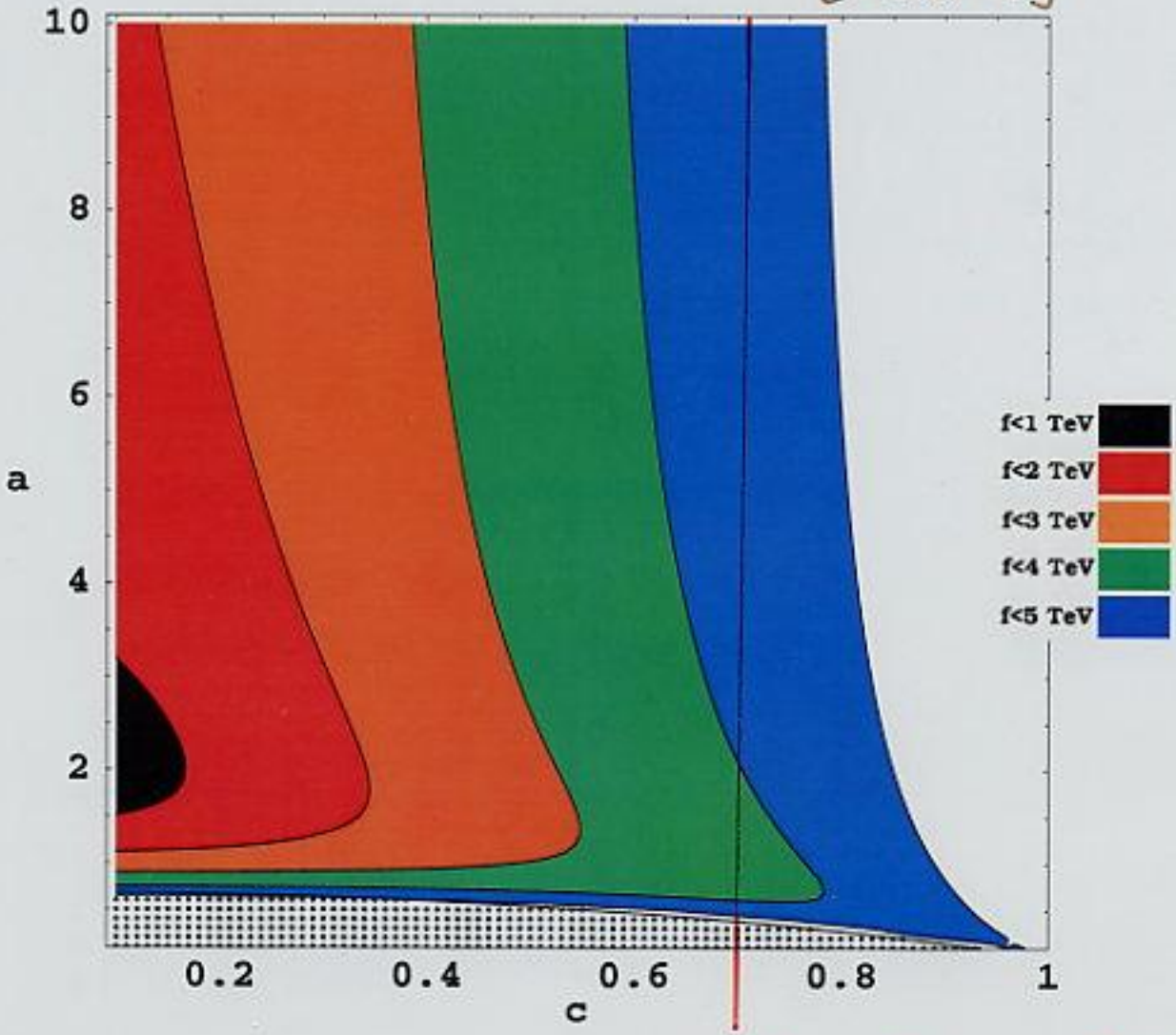
(BUT PARAMETER SPACE IS TYPICALLY SMALL)

ALTERATIONS

- LITTLEST HIGGS: $\begin{cases} \cdot \text{ CHANGE FERMION COUPLINGS} \\ \cdot \text{ GAUGE ONLY } U(1)_Y \end{cases}$
- $SU(6)/Sp(6)$ $\begin{cases} \text{(FERMION COUPLINGS CAN'T BE EASILY CHANGED)} \\ \text{GAUGE ONLY } U(1)_Y \end{cases}$
- $SU(4)^4/SU(3)^4$. $[SO(5)]^8$. $SO(9)/SO(4)/SO(5)$. $SU(9)/SU(8)$. $[SO(5)]^{10}$

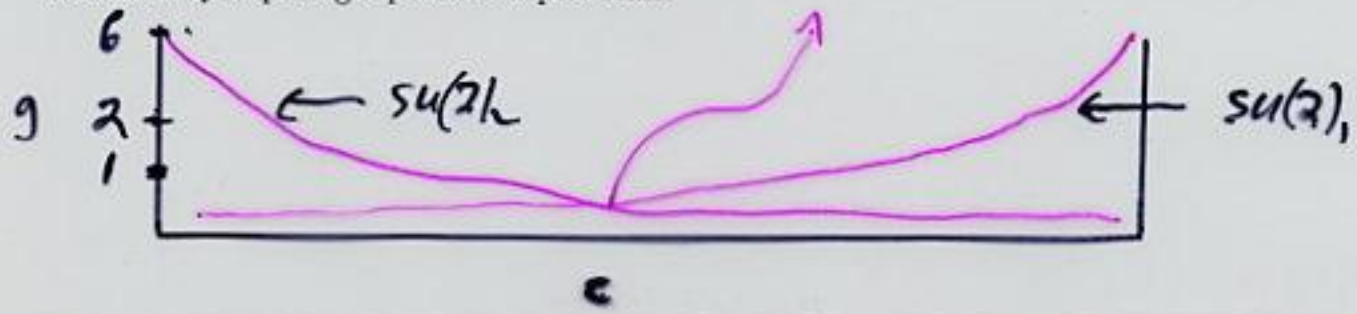
LITTLEST HIGGS: GAUGE ONLY $U(1)_Y$

[CHKMT]



$SU(2)_L$ EMBEDDED EQUALLY IN $SU(2)_1 \times SU(2)_2$

Figure 6: Contour plot of the allowed values of f as a function of a and c. The x-axis is c and the y-axis is a. The grey shaded region at the bottom corresponds to the region excluded by requiring a positive triplet mass.



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

HOW IS A $\left\{ \begin{array}{c} \text{LARGE} \\ \text{VERY LARGE} \end{array} \right\}$ COLLIDER USEFUL?

PRODUCTION OF HEAVY $\tilde{f}, \tilde{f}^c$ @ LHC

EW BOUND

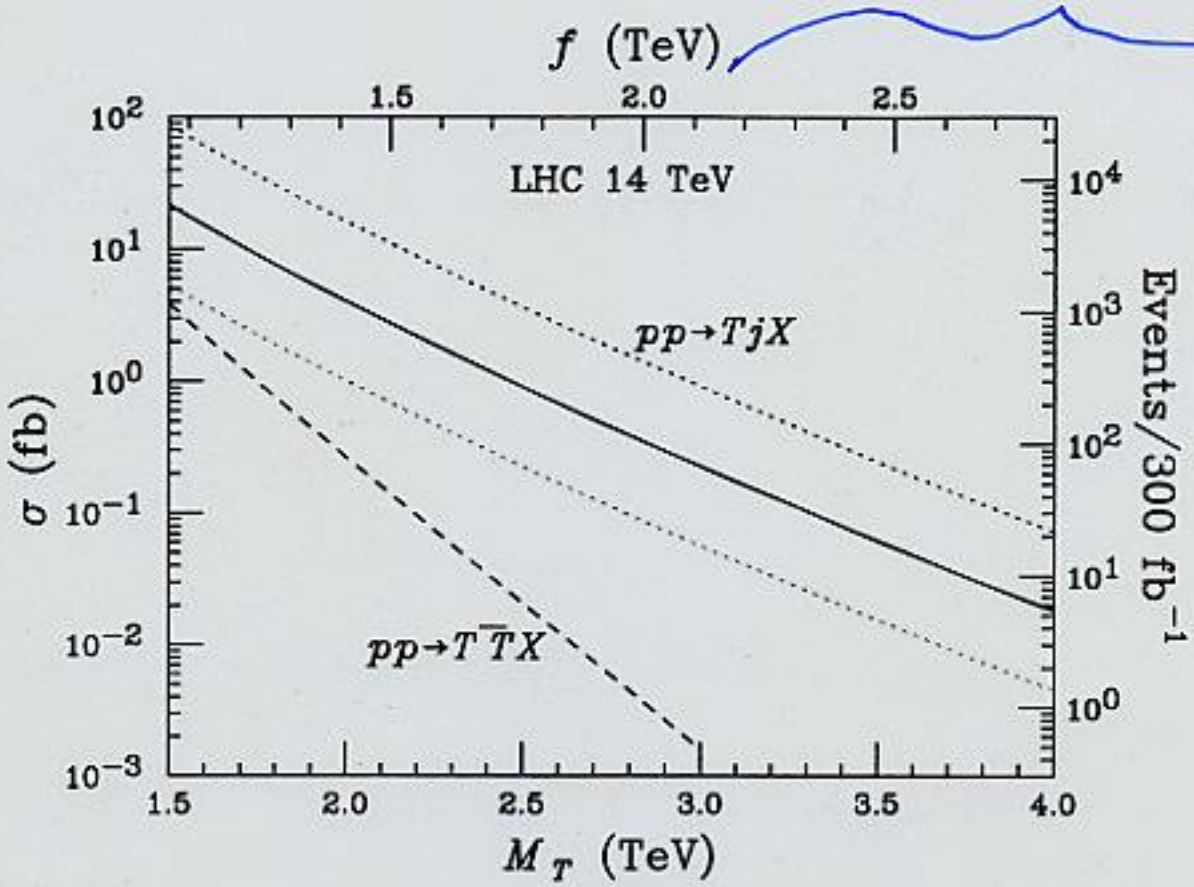


FIG. 5: Total cross sections for $T\bar{T}$ production (dashed) and T+jet production (solid and dotted) vi t-channel W-exchange versus mass M_T at the LHC. The solid line is for the couplings $\lambda_1 = \lambda_2$; th dotted are for $\lambda_1/\lambda_2 = 2$ and $1/2$. The number of events expected per 300 fb^{-1} luminosity is indicate on the right-hand axis. The scale f corresponding to $\lambda_1 = \lambda_2$ is given on the top axis.

[HAN, LOGAN, MCELRATH, WANG]

(LITTLEST HIGGS MODEL)

SINGLE T:

PRODUCTION OF HEAVY W'S @ LHC

(LITTLEST HIGGS MODEL)

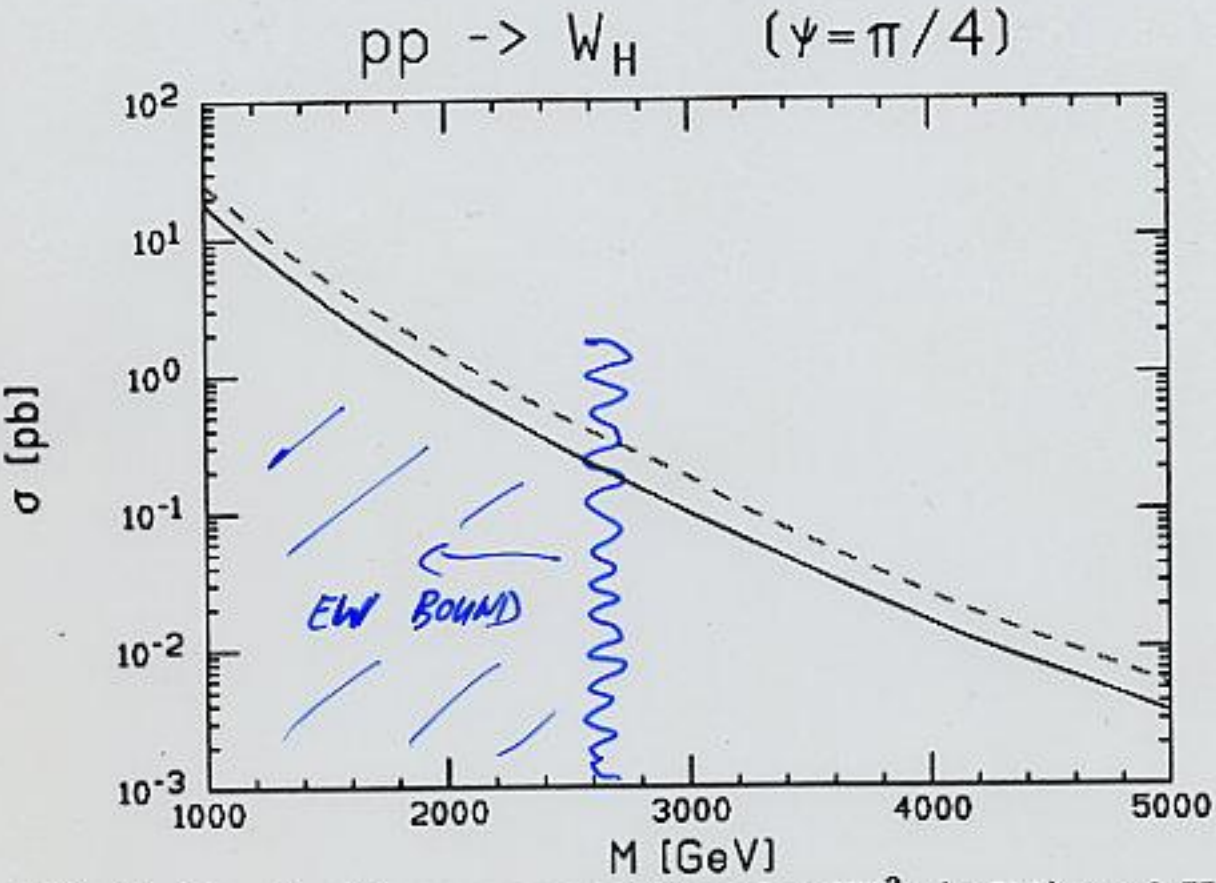
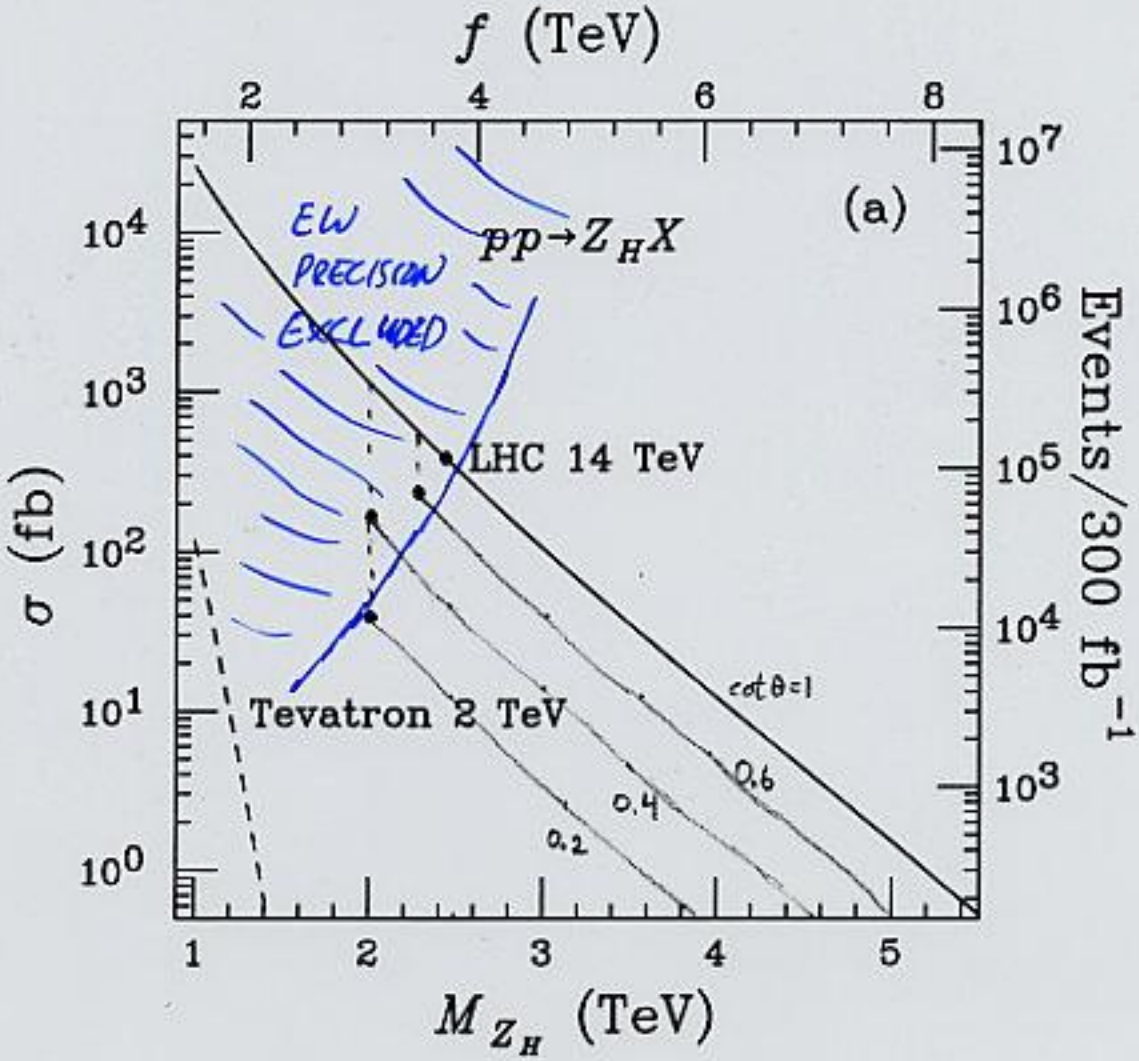


FIG. 3. Production cross sections for W_H^3 (solid) and $W_H^\pm$ (dashed) at the LHC, for $\psi = \pi/4$. We use the CTEQ5L parton distribution function.

[BURDMAN, PERELSTEIN, PIERCE]

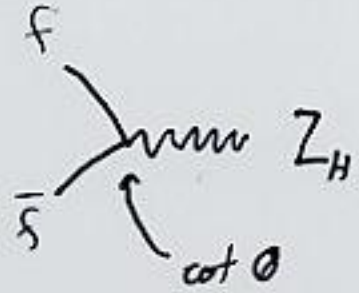
PRODUCTION OF Z_H AT LHC

LITTLEST HIGGS MODEL; GAUGE ONLY $[SU(2)]^2 \times U(1)_Y$



solid line : $\cot\theta = 1$

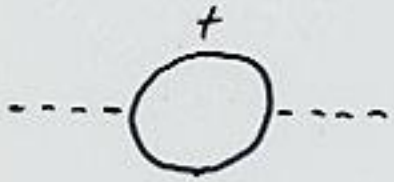
$\sigma \propto \cot^2\theta$



[COURTESY OF HEATHER LOGAN]

CANCELLATION OF QUADRATIC DIVERGENCES

NATURALNESS SUGGESTS ALL QUADRATIC DIVERGENCES NEED NOT BE CANCELED AT ONE SCALE:

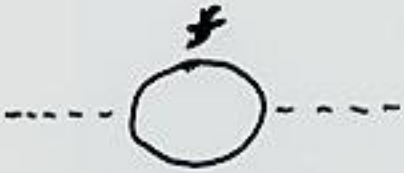


$\Lambda \sim 2$ TEV

$\Lambda \sim 5$ TEV

$\Lambda \sim 15$ TEV

$\Lambda \sim 8$ TEV



$\Lambda \sim (2 \cdot \text{TEV}) \cdot \left(\frac{m_t}{m_f}\right)$

THESE SCALES FOR NEW PARTICLES YIELD ROUGHLY COMPARABLE NEEDED FINE-TUNINGS IN HIGGS MASS

CUTOFF SCALE PHYSICS

ALL LITTLE HIGGS THEORIES ARE EFFECTIVE THEORIES WITH A CUTOFF OF $4\pi f \sim 10 \to 20$ TeV.

AT THIS SCALE A UV COMPLETION MUST TAKE OVER, WHICH COULD BE TECHNICOLOR, SUSY, COMPOSITENESS... BUT WHATEVER IT IS WILL HAVE A RICH SPECTRUM!

(WORK IN PROGRESS BY NELSON & COLLABORATORS SUGGESTS NEW FERMIONS, A STABLE (NEUTRAL) PARTICLE, SUSY... ALL AT SCALES OF ORDER $10 \to 50$ TeV.)

SUMMARY

- LITTLE HIGGS THEORIES ARE A FACINATING NEW IDEA TO STABILIZE THE HIGGS MASS AGAINST ONE-LOOP DIVERGENCES

- WIDE SET OF MODELS WITH VARYING CONSTRAINTS

  "PRE - ELECTROWEAK" $f \gtrsim 3 \to 4$ TeV

  "POST - ELECTROWEAK" $f \gtrsim 1 \to 2$ TeV

(GENERALLY NEED CUSTODIAL SU(2) AND MINIMIZE HEAVY/LIGHT MIXING)

- BEST LHC CANDIDATES
  - HEAVY $\tilde{f}, \tilde{f}^c$ QUARKS
  - HEAVY $Z, W^\pm$ BOSONS
  - TWO HIGGS DOUBLETS

- VLHC EASILY COVERS NATURAL RANGE FOR PARTICLE MASSES ($2 \to 15$ TeV) BUT BEST OF ALL: EXPLORE THE DYNAMICS (THE UV COMPLETION) LEADING TO A LITTLE HIGGS EFFECTIVE THEORY!