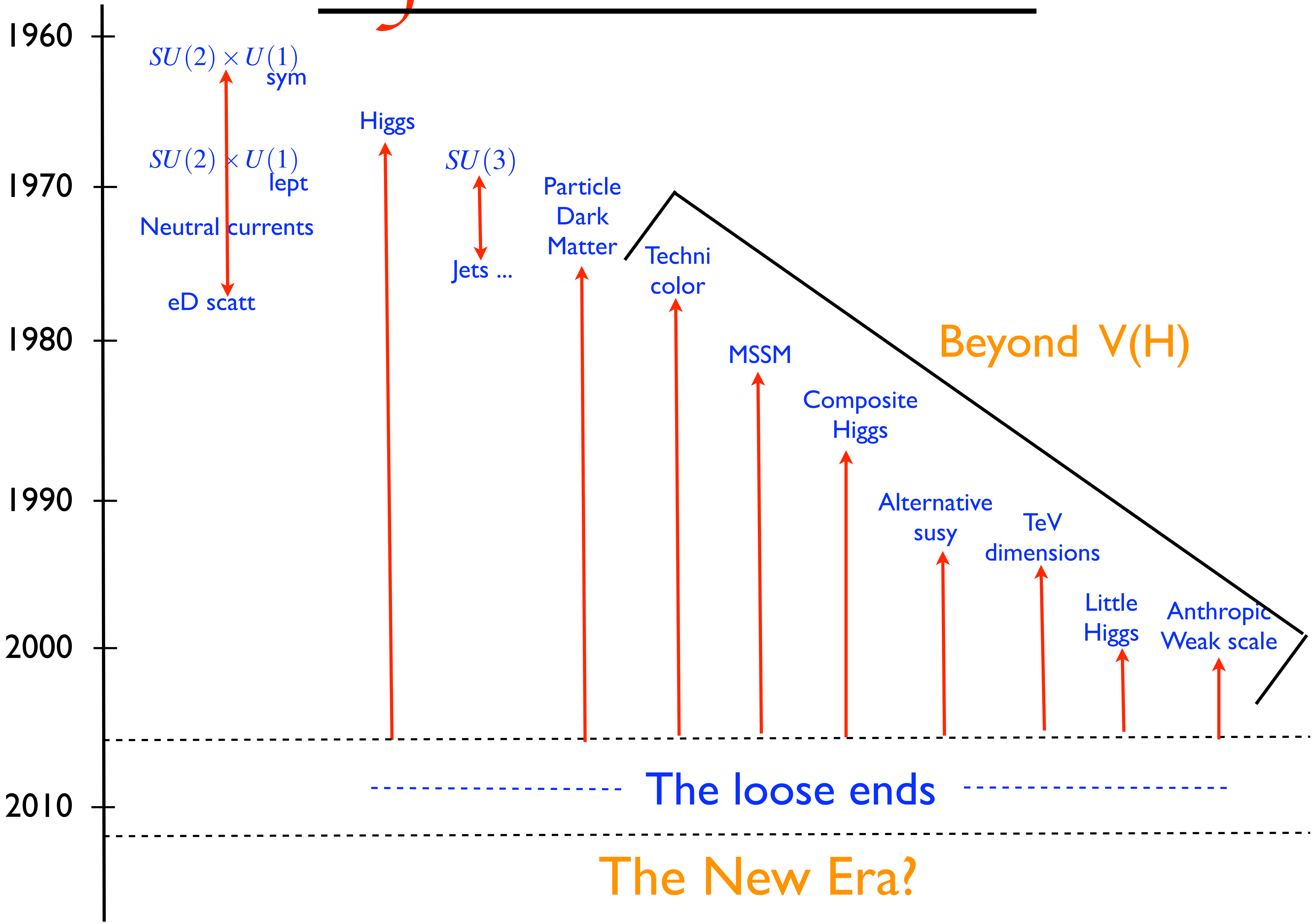
A More Natural Higgs Sector at LHC

Lawrence Hall UC Berkeley

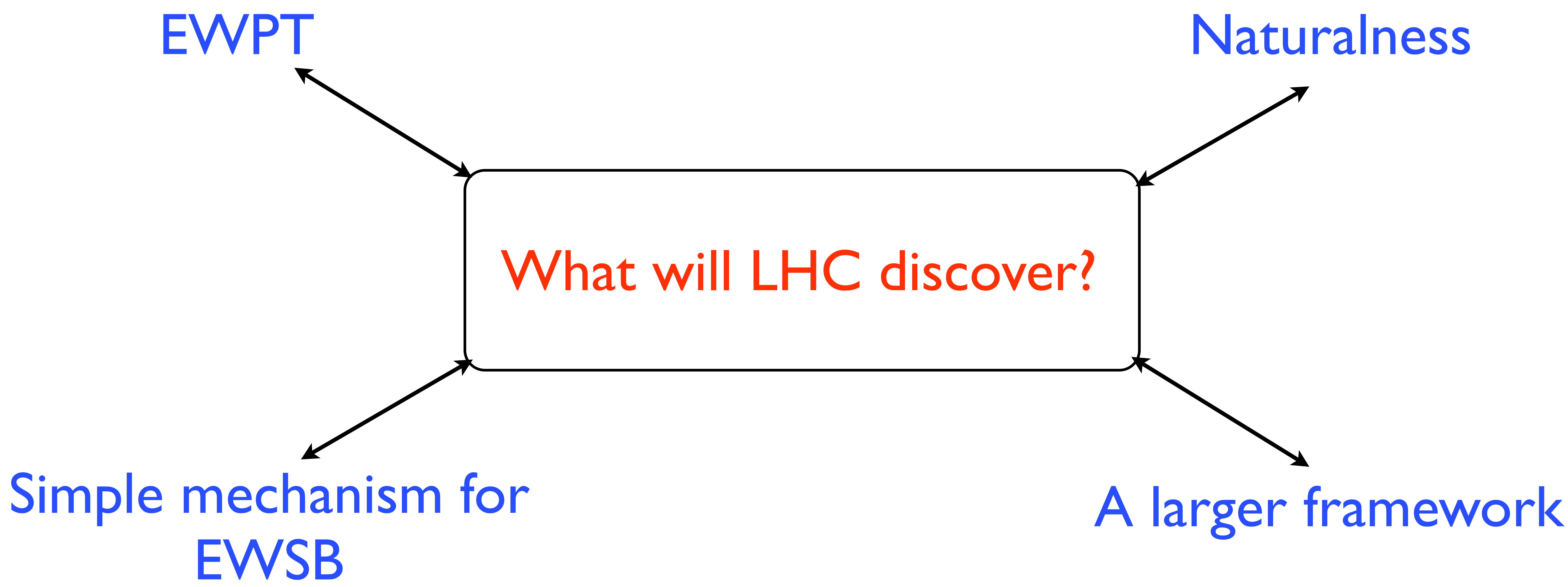
Based on

R. Barbieri, T. Gregoire and LJH, hep-ph/0509242
R. Barbieri and LJH, hep-ph/0510243
R. Barbieri, S. Rychkov and LJH, hep-ph/0603188

After the SM ... ?


1960
1970
1980
1990
2000
2010
$SU(2) \times U(1)$ sym
$SU(2) \times U(1)$ lept
Neutral currents
eD scatt
Higgs
$SU(3)$
Jets ...
Particle Dark Matter
Techni color
MSSM
Composite Higgs
Alternative susy
TeV dimensions
Little Higgs
Anthropic Weak scale
Beyond V(H)
The loose ends
The New Era?

Four Signposts



Supersymmetry is very successful on all four, and hard to beat on any one!

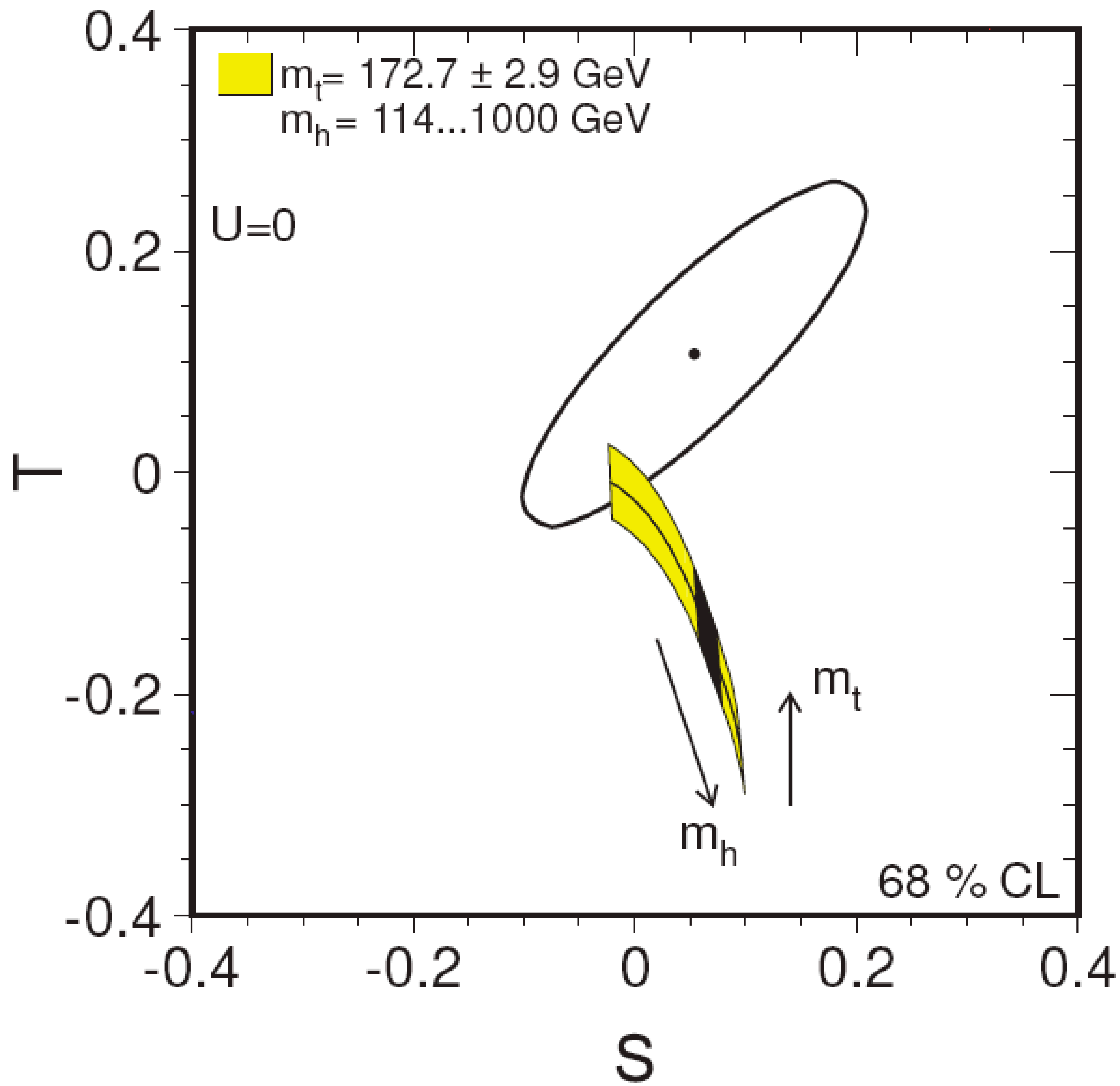
But:

- -superpartners
- -exotic flavor/CP
- -light Higgs
- -p decay

If not susy: What?

Ultra Bottom Up approach: EWPT & Naturalness

EWPT and SM



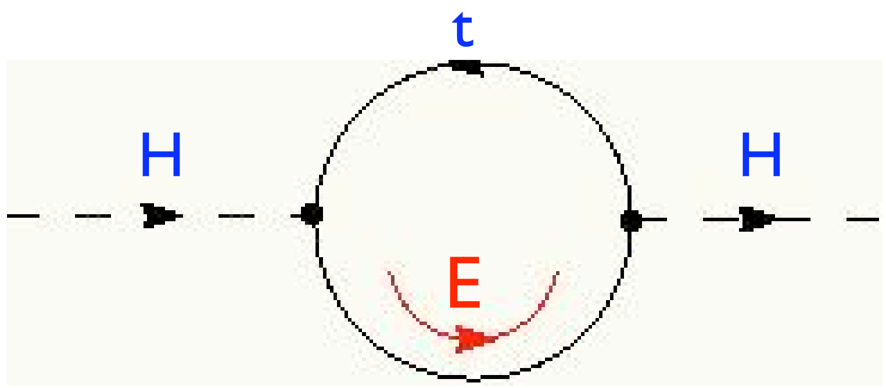
adapted from http://lepewwg.web.cern.cg/LEPEWWG/plots

SM Higgs is light!

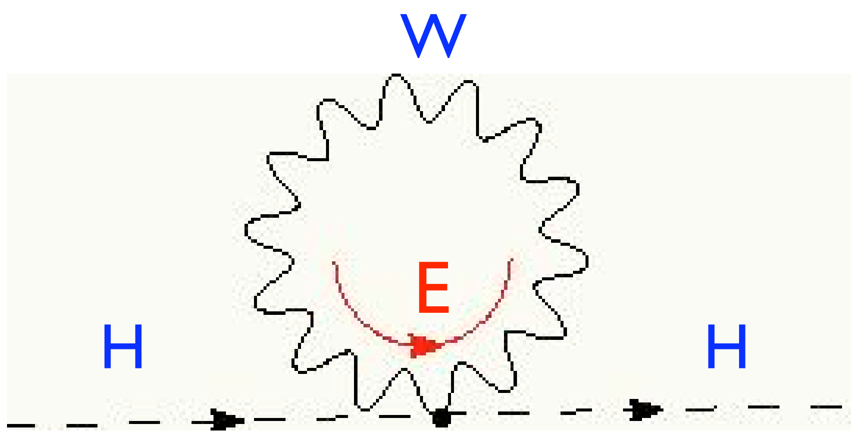
Especially as TeVatron Run II finds a lower top mass.

Light SM Higgs → Low SM Cutoff

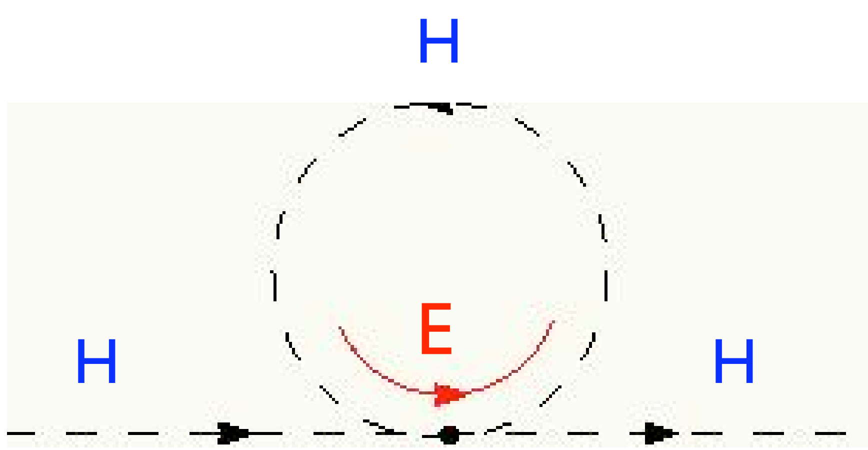
$E_{max} \longrightarrow \Lambda_{t,W,H}$



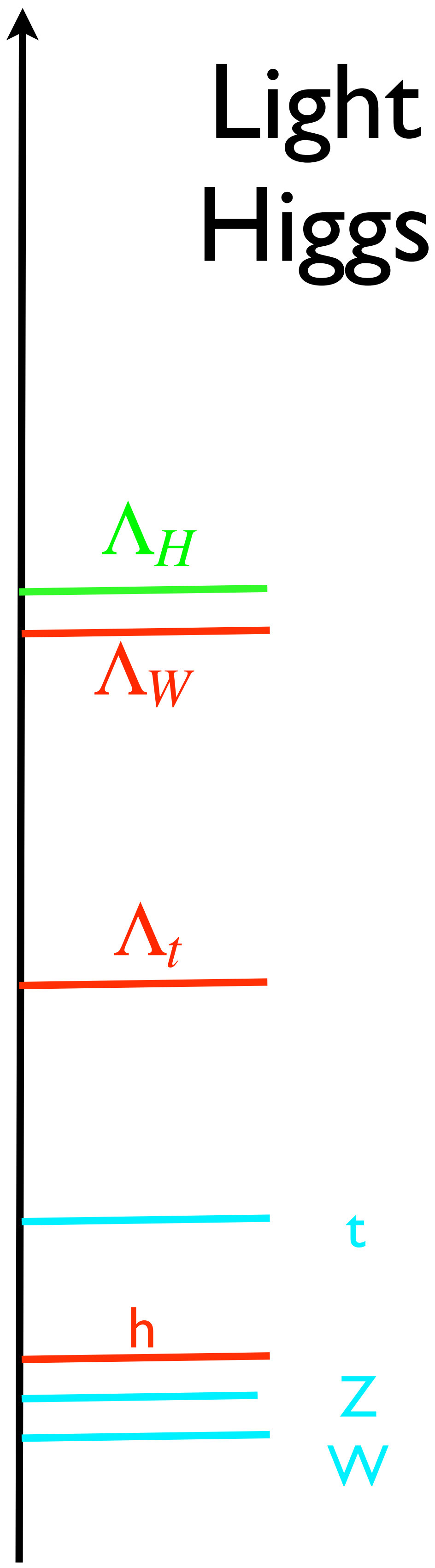
$$\Lambda_t = 400 \text{ GeV} \left(\frac{m_h}{115\text{GeV}}\right) D_t^{1/2}$$



$$\Lambda_W = 1.1 \text{ TeV} \left(\frac{m_h}{115\text{GeV}}\right) D_W^{1/2}$$



$$\Lambda_H = 1.3 \text{ TeV}\ D_H^{1/2}$$



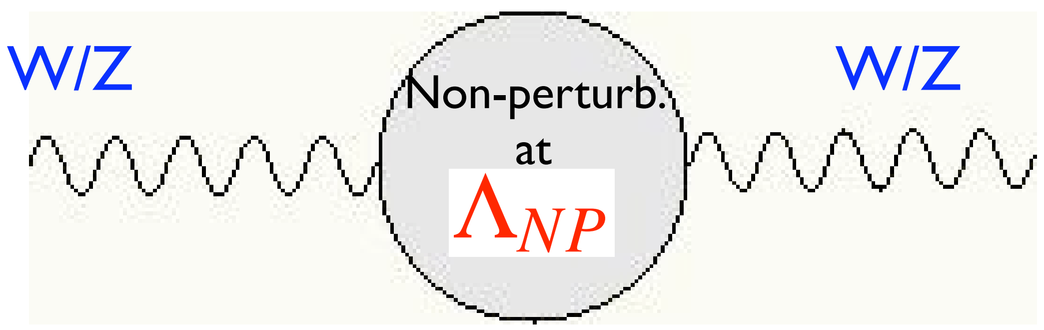
We expect to find "canceling" physics at $\Lambda_{t,W,H}$

TeV Scale Non-Perturbative Physics

No susy → non-perturbative physics at the TeV scale

(eg technicolor, composite Higgs, KK EWSB, BC EWSB, ...)

Expectations from EWPT for Λ_{NP}



$$\Lambda_{NP} \geq 5\text{–}10\ \mathrm{TeV}$$

$$(S,T) = (S,T)_{SM}\left(1 + \frac{16\pi^2 v^2}{\Lambda_{NP}^2}\right)$$

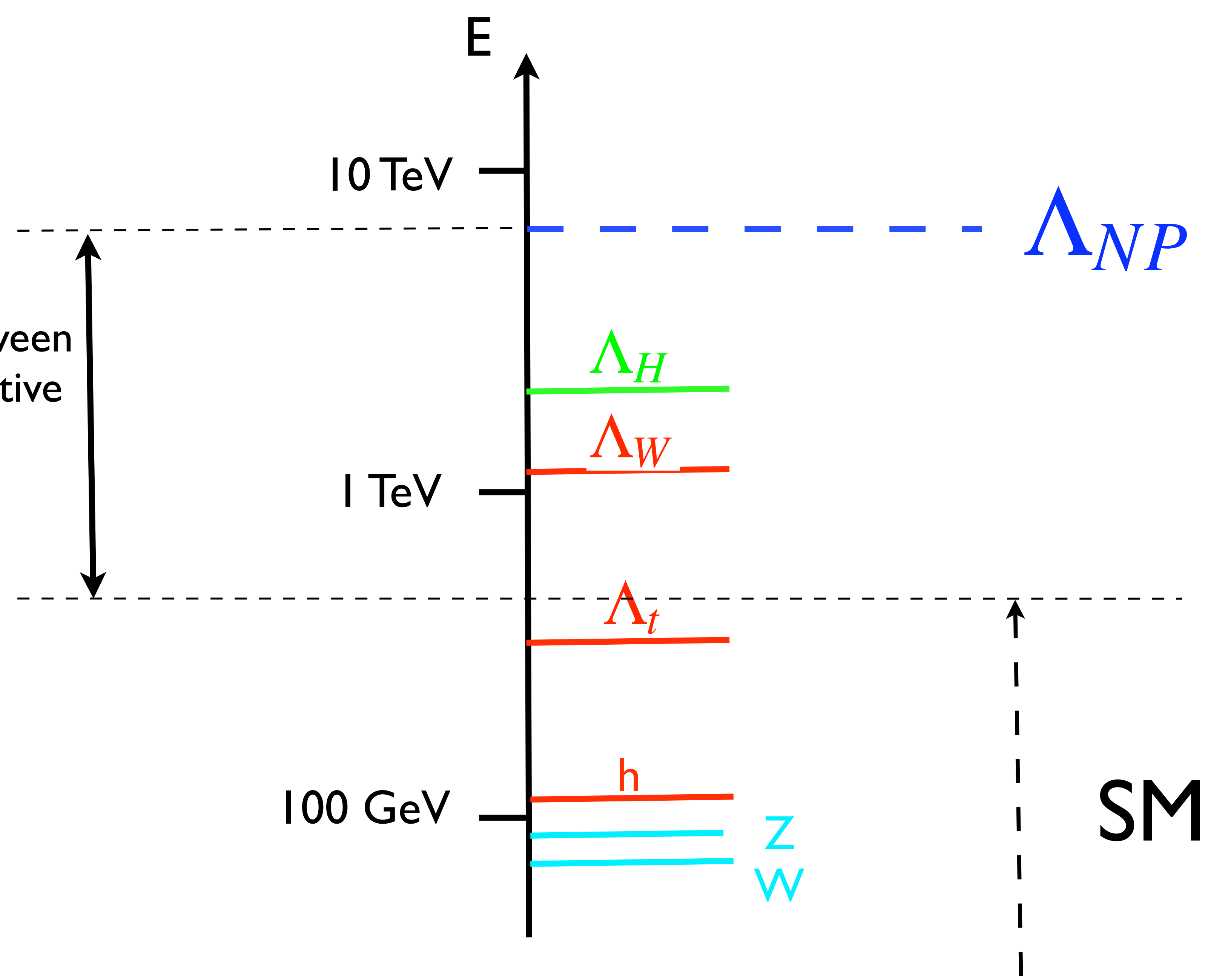
Contribution from light Higgs works well!

The Little Hierarchy Problem

Barbieri, Strumia hep-ph/0007265

Applies to theories with low Λ_{NP}

An energy interval of a factor of 10 between "cancellation" physics and non-perturbative physics.



1% fine-tune

In non-susy theories, what is the perturbative "cancellation" physics?

- How does it delay strong interactions?
- Does it satisfy EWPT?
- What are LHC signals?

Beautiful Ideas for EWSB that have LHP

Technicolor

The first and best BSM idea for EWSB

Strong interactions at TeV scale, but perturbative to Planck scale

Supersymmetric SM in 5D

Boundary Conditions break supersymmetry at TeV scale

Higgs mass calculable

Higgsless

EWSB directly by boundary conditions in extra dimensions

LHP Hard to Solve

Perhaps susy is right after all!

Little Higgs: considerable new physics; partial progress

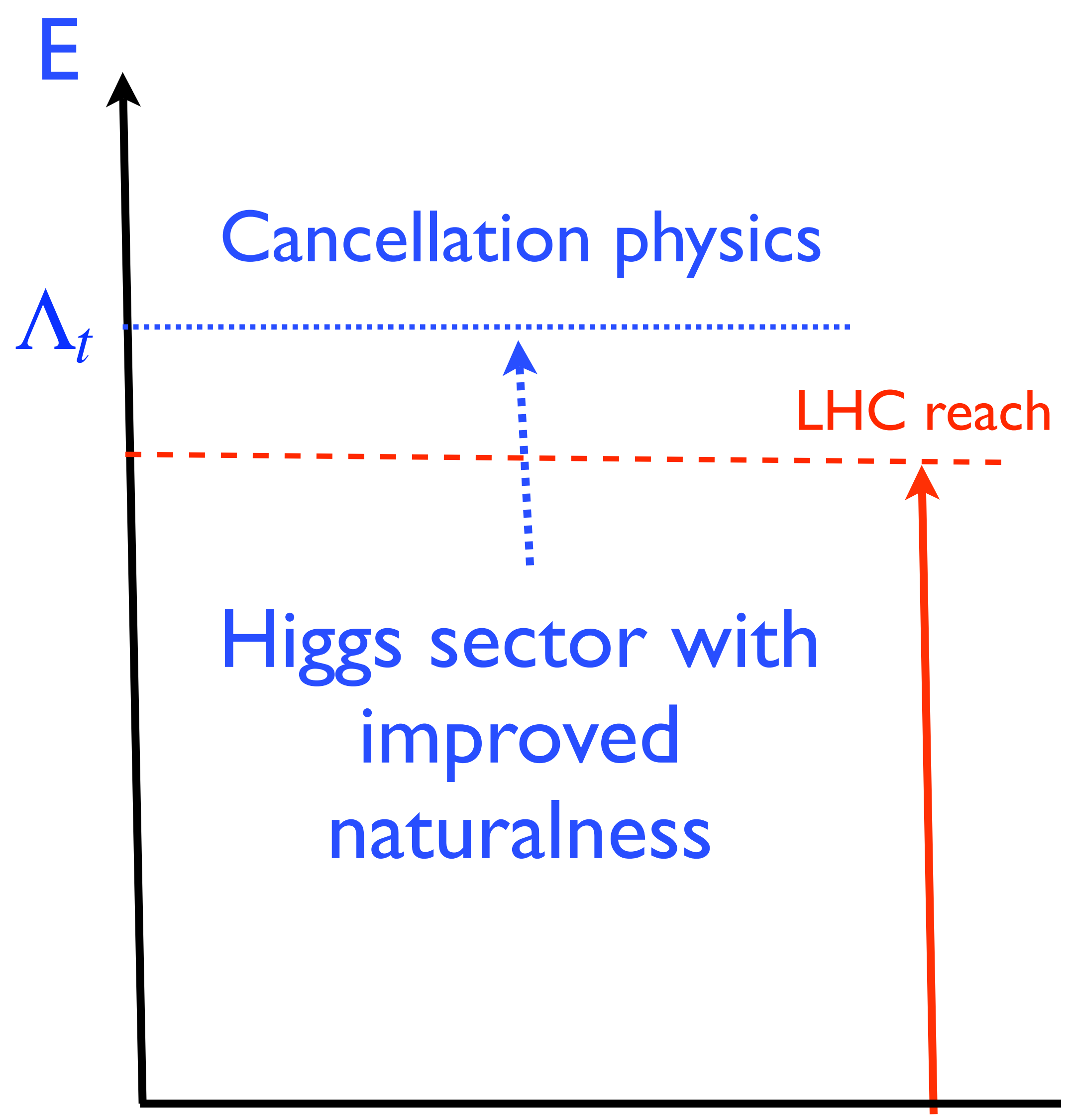
Improved Naturalness

Seek simple Higgs sector that

1) agrees with all data (especially EWPT)

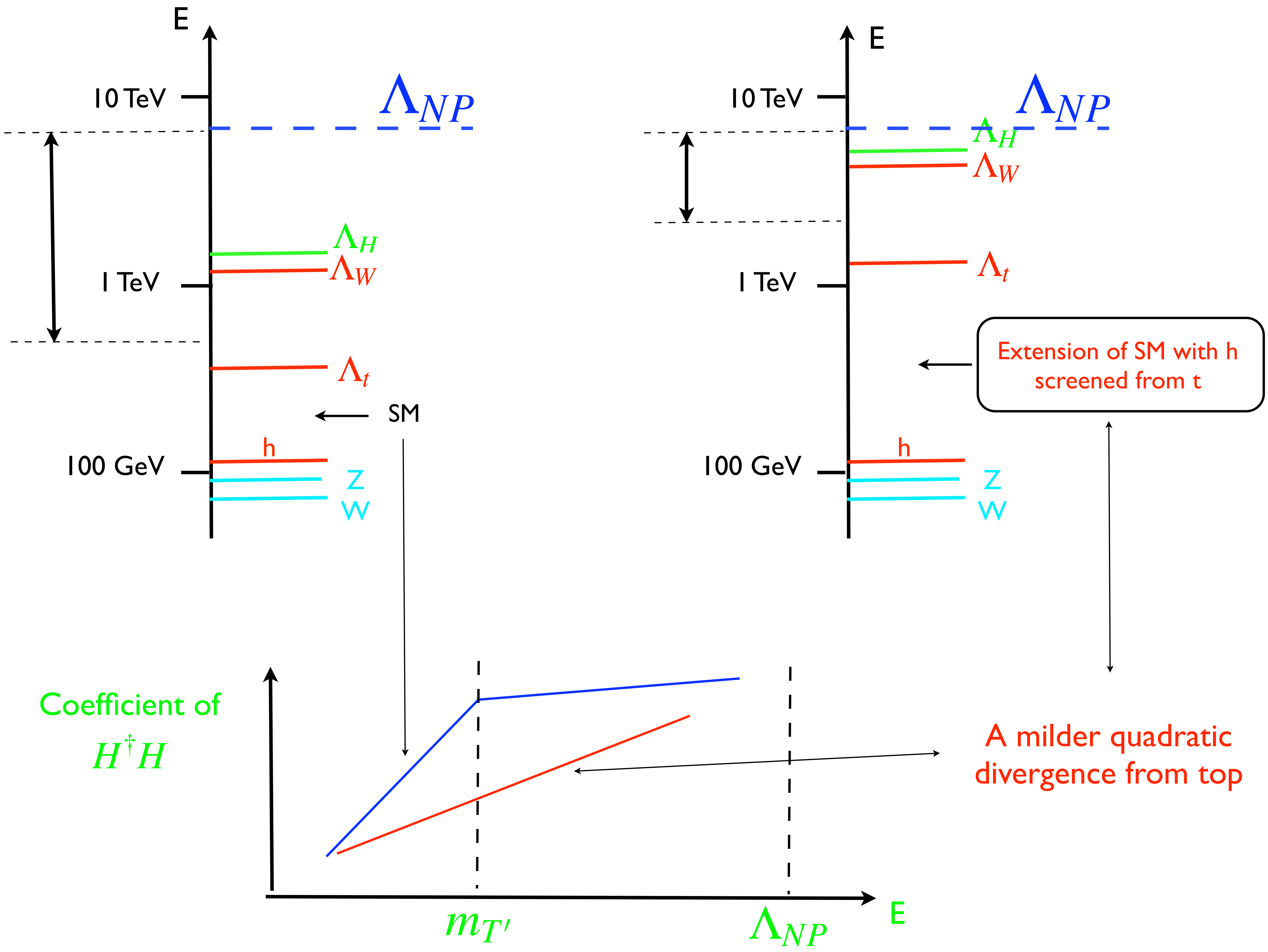
2) is completely natural up to 1.5 TeV

ie
cutoff is factor 3 higher
fine tuning is a factor 10 less } than SM with light Higgs



A modest "ultra bottom up" approach, with crucial consequences for the LHC

Improving Naturalness: a Light Higgs

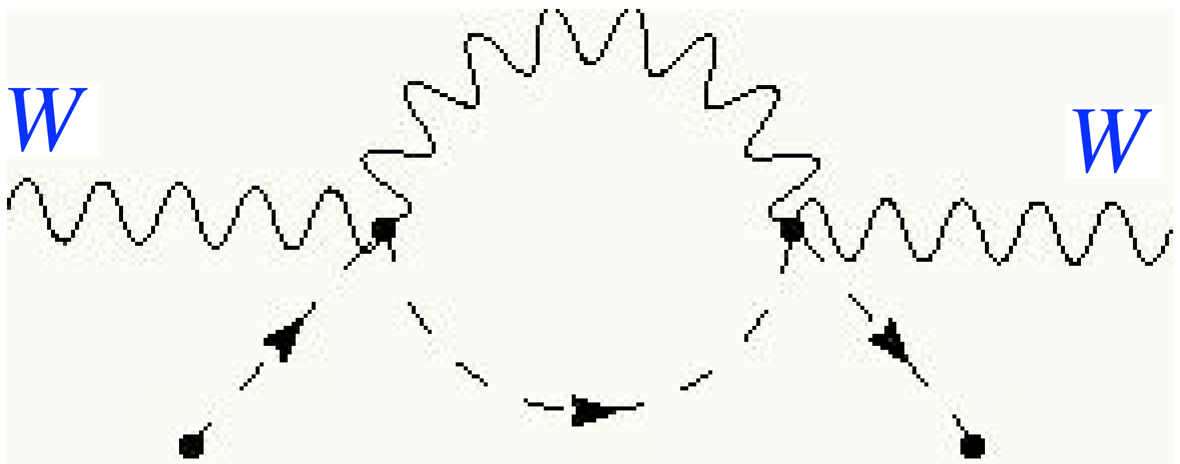


Two scalars: one heavy, one light

$h_{1,2}$ mix to $h_\pm$

Top couples to h_2 which mainly h_+ so $\Lambda_t \propto m_+$

For EWPT, contribution to T from



$h_\pm$

$$\ln m_h \rightarrow \frac{v_1^2}{v^2} \ln m_- + \frac{v_2^2}{v^2} \ln m_+$$

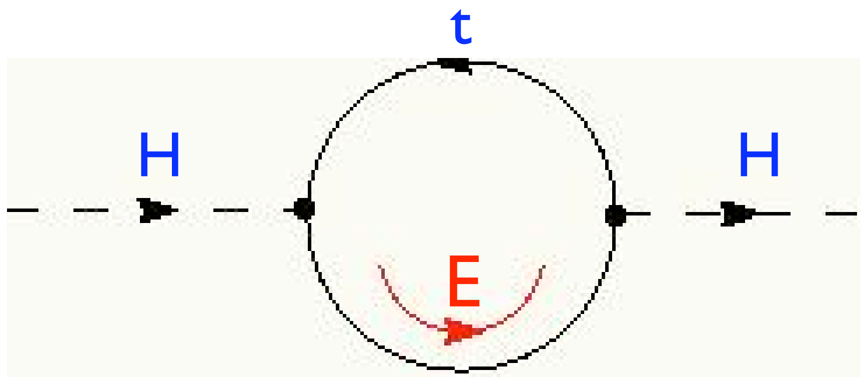
$$m_+ < m_- \left(\frac{m_{EWPT}}{m_-} \right)^{1+v_1^2/v_2^2}$$

Two models → Mirror world — R. Barbieri, T. Gregoire and LJH, hep-ph/0509242

→ Usual 2 Higgs doublet — R. Barbieri and LJH, hep-ph/0510243

Improving Naturalness with a Heavy Higgs

Recall SM:



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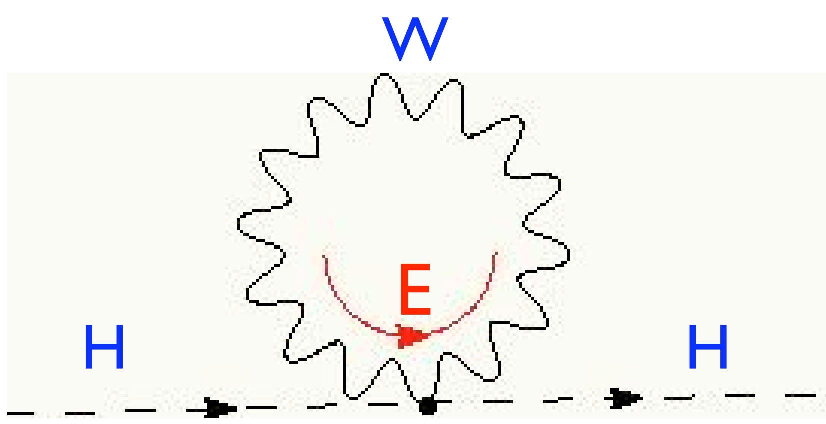

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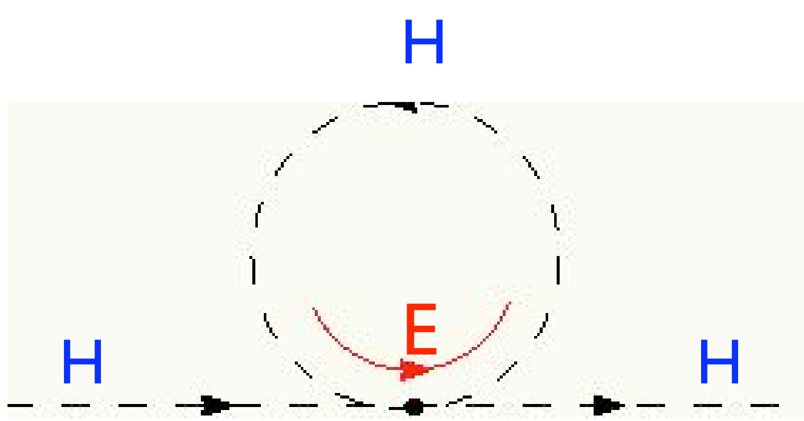
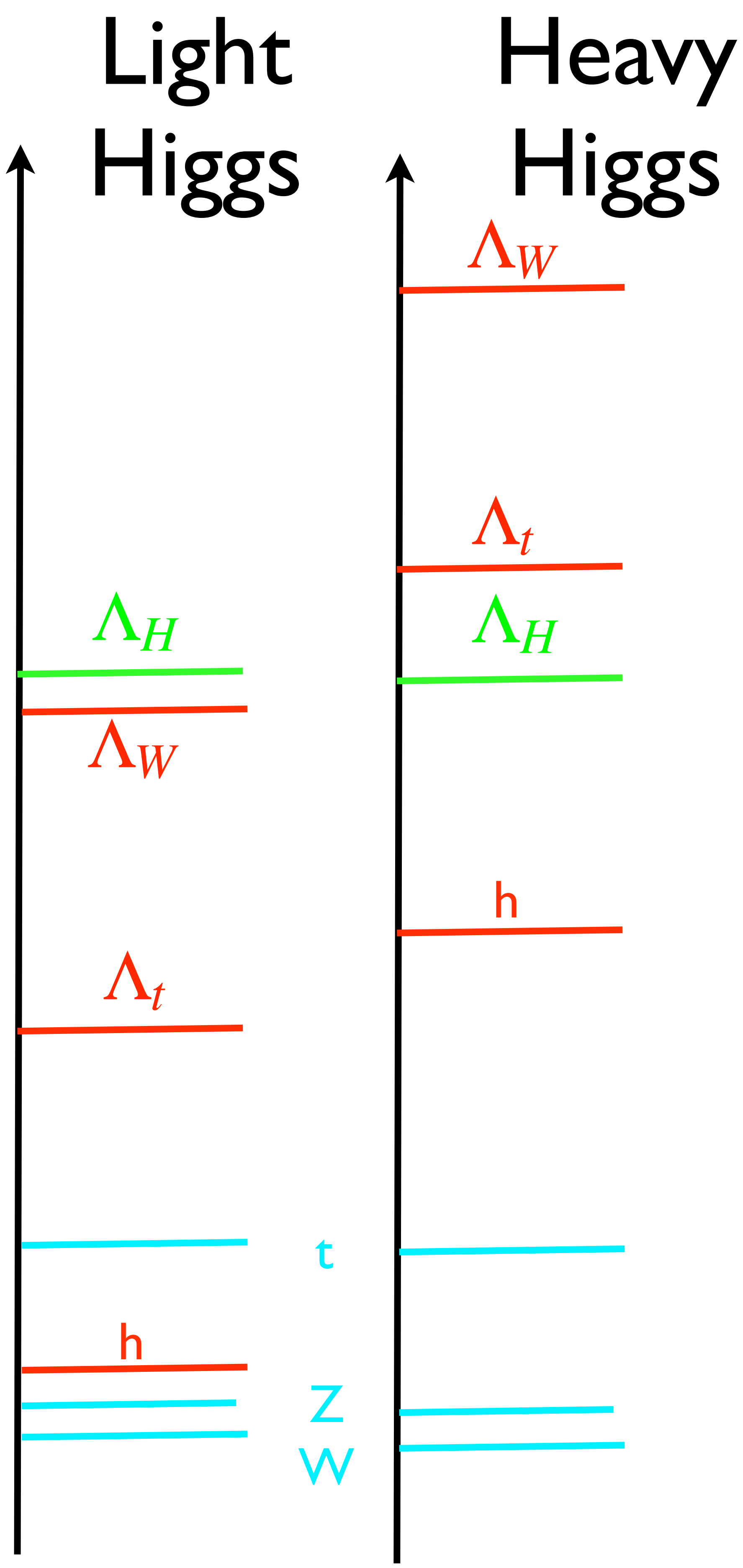
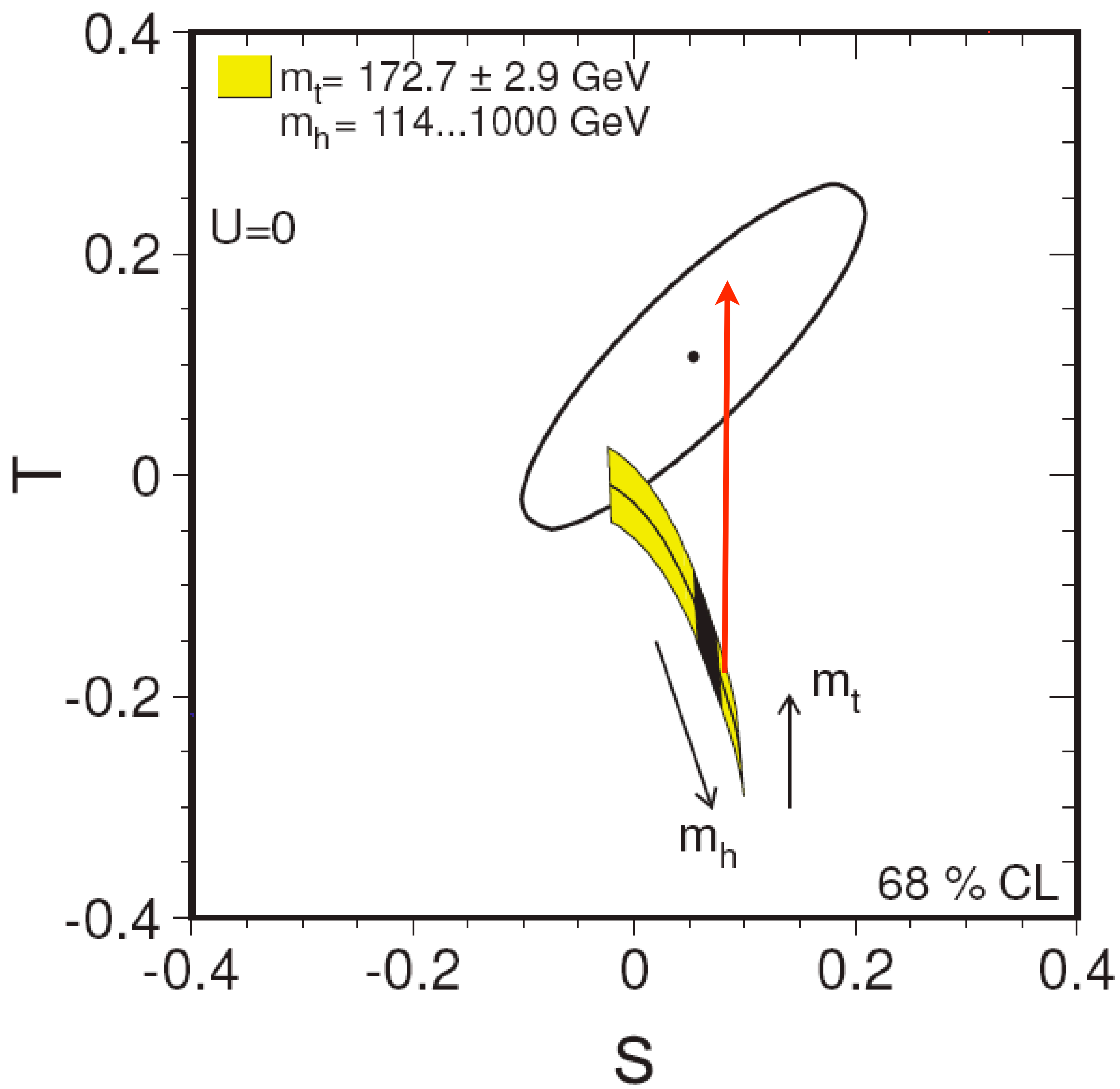


$$\Lambda_H = 1.3\text{ TeV } D_H^{1/2}$$



A Heavy SM Higgs and EWPT



Heavy Higgs with positive ΔT

No fine tuning!!!

Origin of ΔT (Peskin, Wells hep-ph/0101342)

SM + heavy triplet scalars

New gauge interaction - but often get trouble from 4 fermion operators

2 Higgs Doublets - both with vevs $\Lambda_{H_i} = 1.3\,\text{TeV}\ (\cos\beta, \sin\beta)$

2 HDM in an Alternative Phase

Barbieri, Hall, Rychkov, hep-ph/0603188

$$V = -\mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 + \text{ quartics}$$

For natural flavor conservation impose

$H_2 \to -H_2$

Only H_1 couples to matter

$$H_2 = \begin{pmatrix} H^+ \\ H + iA \end{pmatrix}$$

is "inert"

$v_2 = 0$

This is not the usual phase in the fine-tuned limit of

$v_2 \ll v_1$

1. $H_1 = \begin{pmatrix} 0 \\ v + h \end{pmatrix}$ similar to SM Higgs

2. H_2 mass splittings lead to $\Delta T > 0$

3. $H_2 \to -H_2$ is exact, and not spontaneously broken

Lightest Inert Particle (LIP) is stable and could be Dark Matter

SM-like Doublet + Inert Doublet

Higgs sector

$$H_1 = \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

Couples to fermions and is much like SM doublet; h heavy

$$\Lambda_t = 1.5\,\mathrm{TeV}\left(\frac{m_h}{400\,\mathrm{GeV}}\right) D_t^{1/2} \qquad \Lambda_H = 1.3\ \mathrm{TeV}\ D_H^{1/2}$$

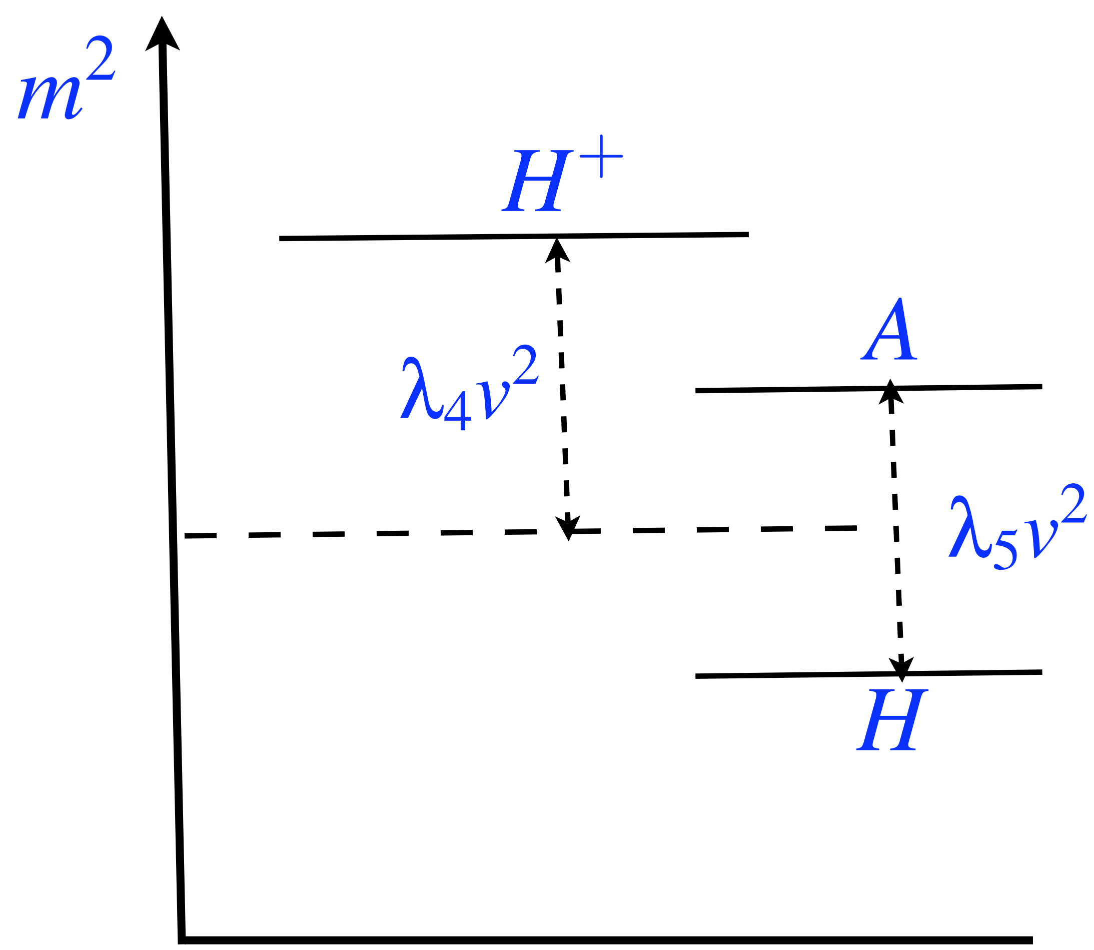
Perturbative up to 2 TeV

Inert sector

$$H_2 = \begin{pmatrix} H^+ \\ H+iA \end{pmatrix}$$

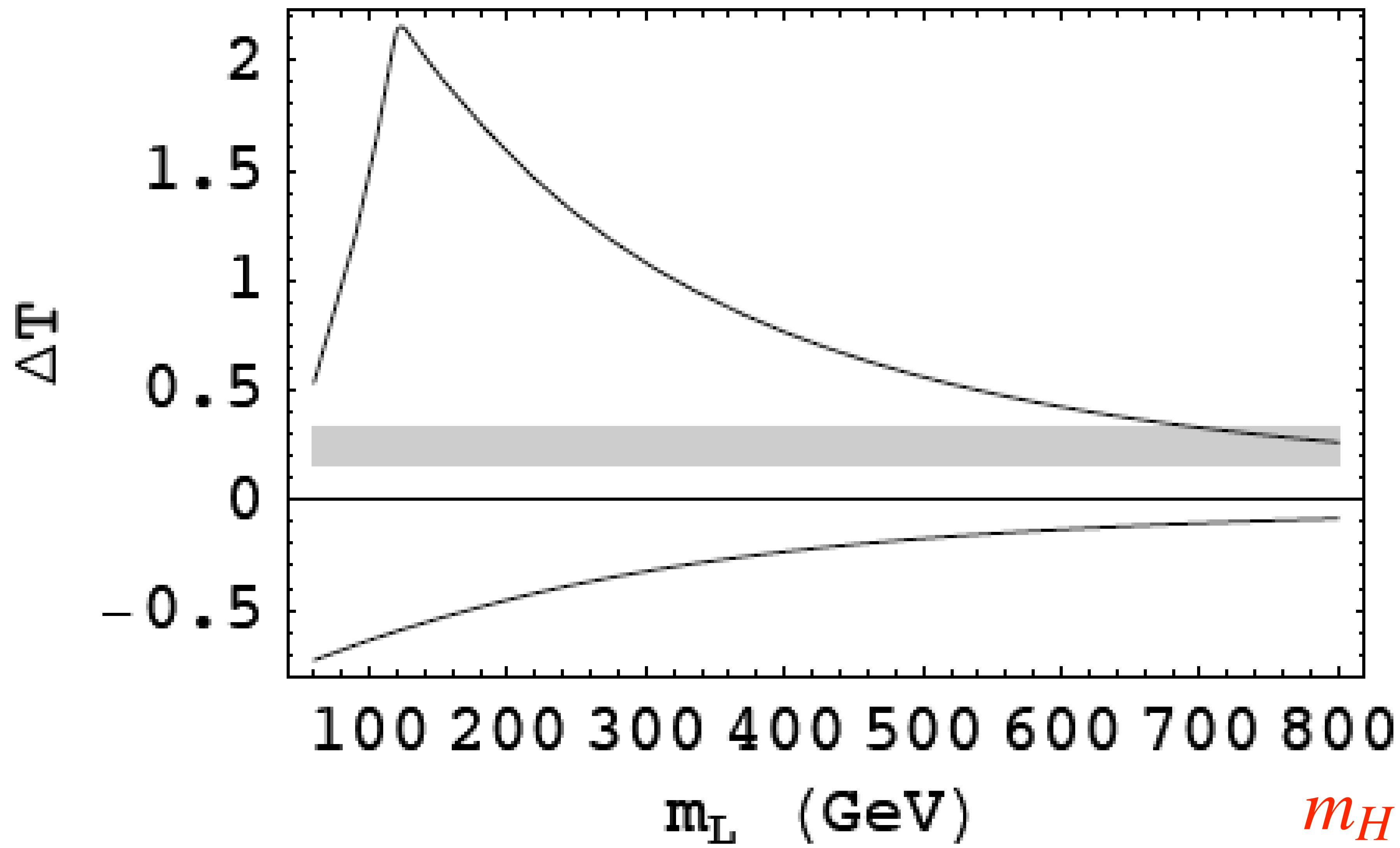
Custodial breaking masses for ΔT

$$(m_{H^+} - m_A)(m_{H^+} - m_H) \approx (120\,\mathrm{GeV})^2$$



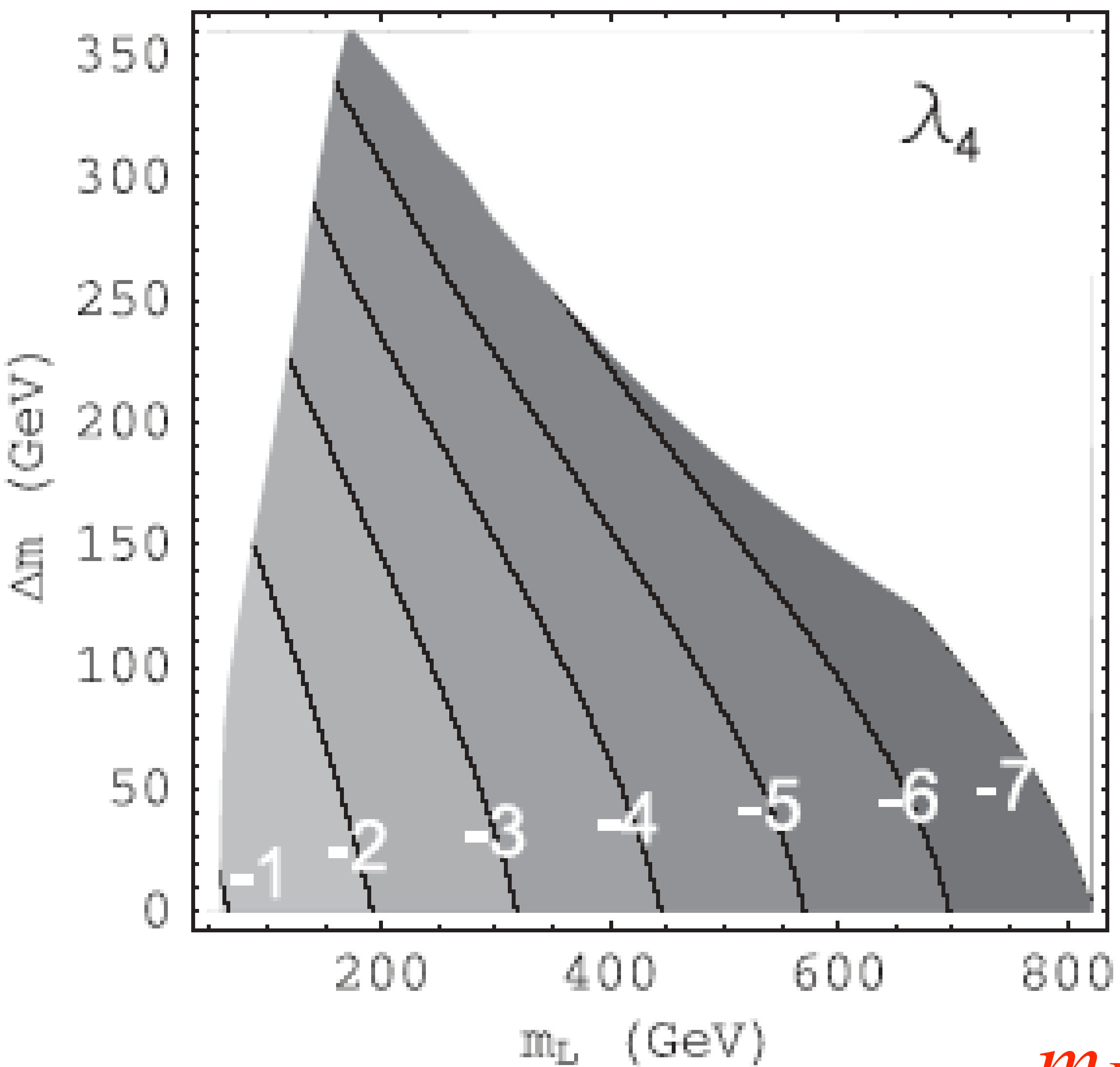
Ranges for:

$\Delta T, m_H, m_A - m_H$

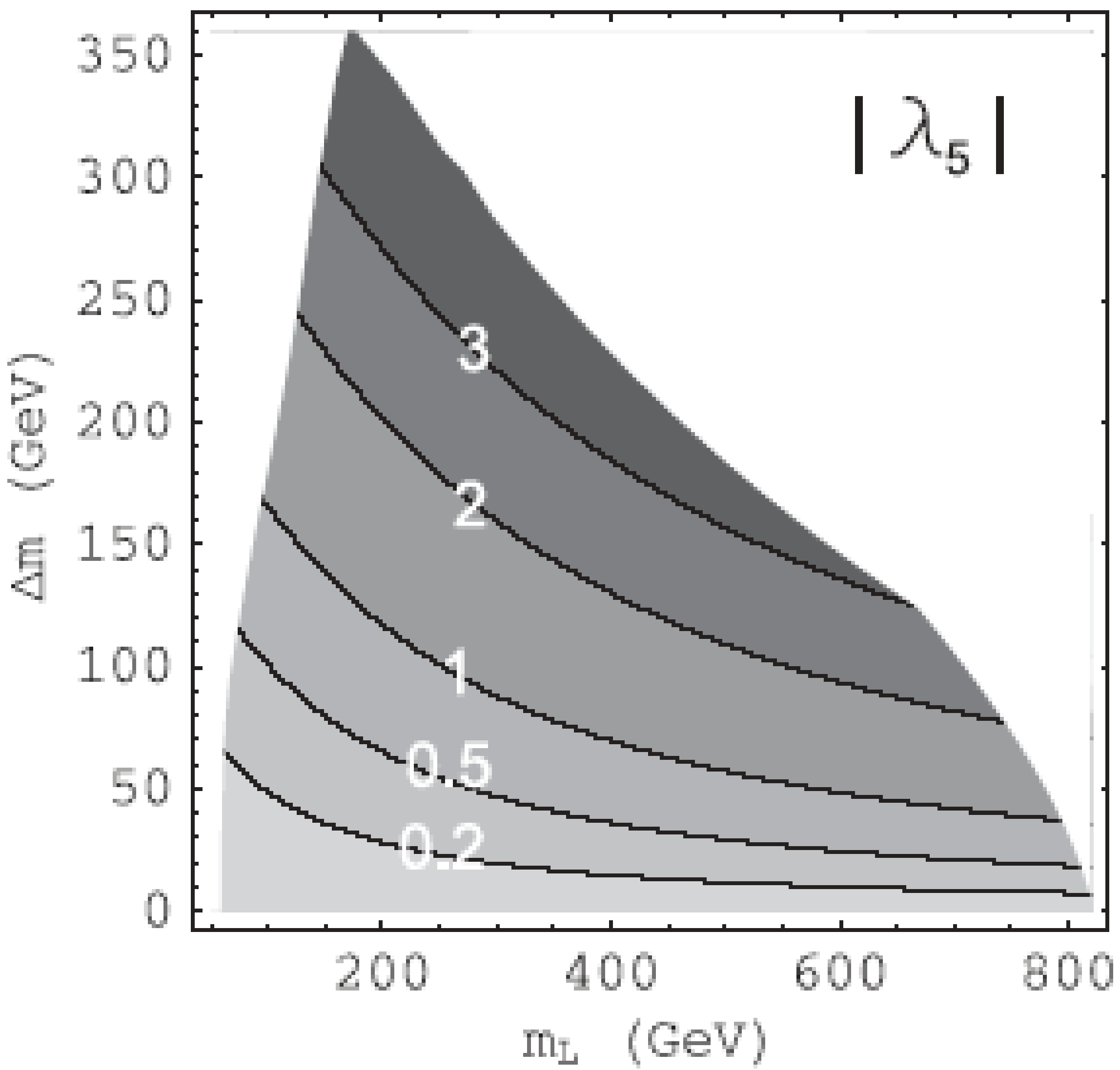


m_H

$m_A - m_H$



m_H



m_H

LIP Dark Matter

$m_H > m_W$

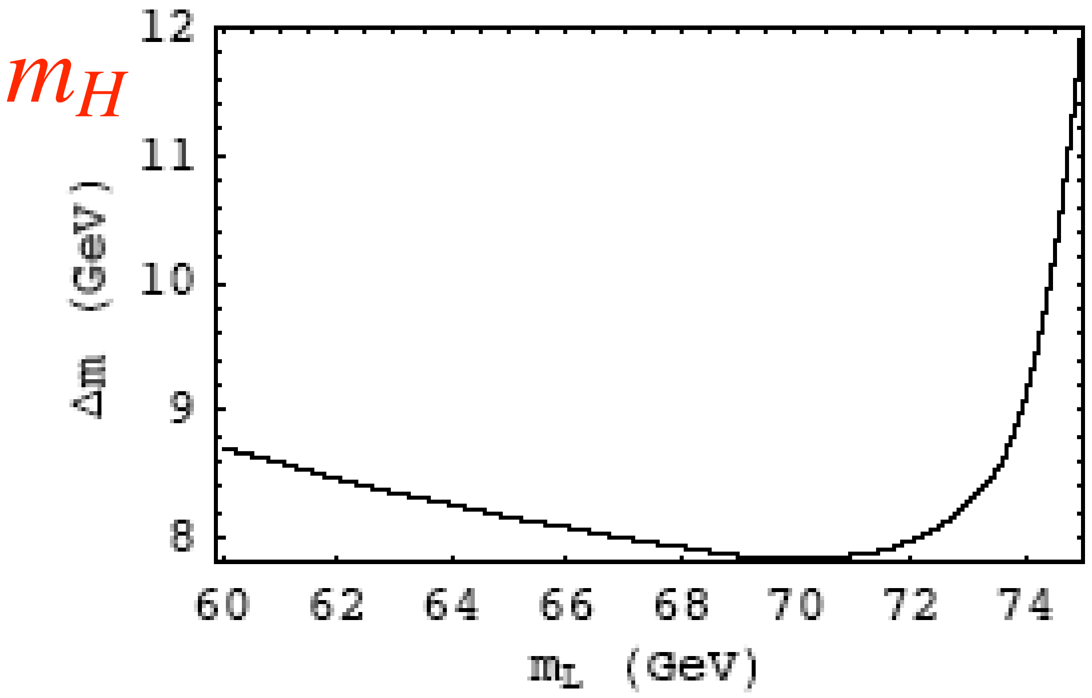
$HH \to W^+W^-$ Depletes H to a small fraction of the observed Dark Matter

$m_H < m_W$

If A and H degenerate, then $AH \to Z^* \to \bar{f}f$ over-depletes by about a factor 10

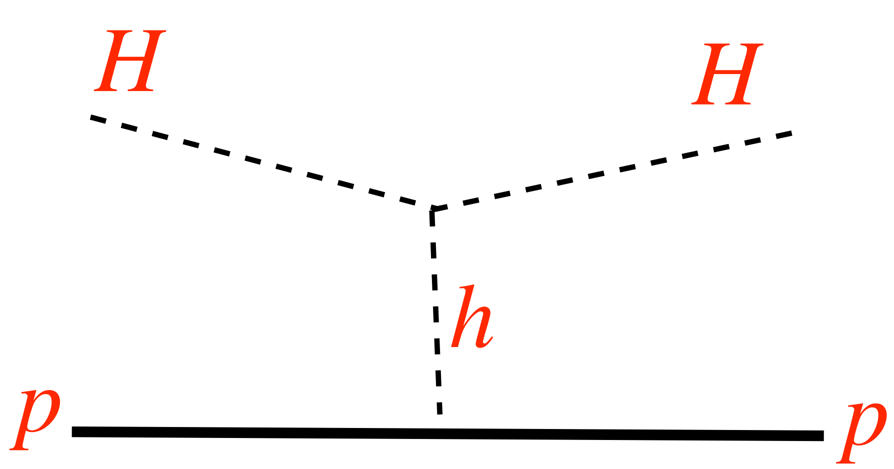
AH co-annihilation gives observed Dark Matter if:

$m_A - m_H$



m_H

Direct detection



$$\sigma(Hp \to Hp) \approx 2 \times 10^{-9}\,\mathrm{pb} \left(\frac{70\,\mathrm{GeV}}{m_H}\right)^2 \left(\frac{500\,\mathrm{GeV}}{m_h}\right)^2 \left(\frac{\lambda_H}{0.5}\right)^2$$

About 2 orders of magnitude below the present Ge limit from CDMS

LHC Signals of the Inert Doublet

Pair Production of inert particles: $pp \to AH,\ H^+H^-,\ AH^+,\ HH^+$

followed by cascade decays: $H^+ \to W^+(A,H)$ $\qquad A \to Z^* H$

Events with leptons, jets, missing transverse energy

Tri-leptons in Dark Matter region

$$pp \to W^* \to AH^+ \to (H,Z^*) + (W^+H)$$

with Z* and W decaying to leptons

$$\sigma \approx (0.25\,\mathrm{pb})(0.015) \approx 3.5\,\mathrm{fb}$$

Pythia lept. BR

with $\Delta m_{l^+l^-} < 10\,\mathrm{GeV}$

Background $\sigma_{WZ} \approx 20\,\mathrm{fb}$

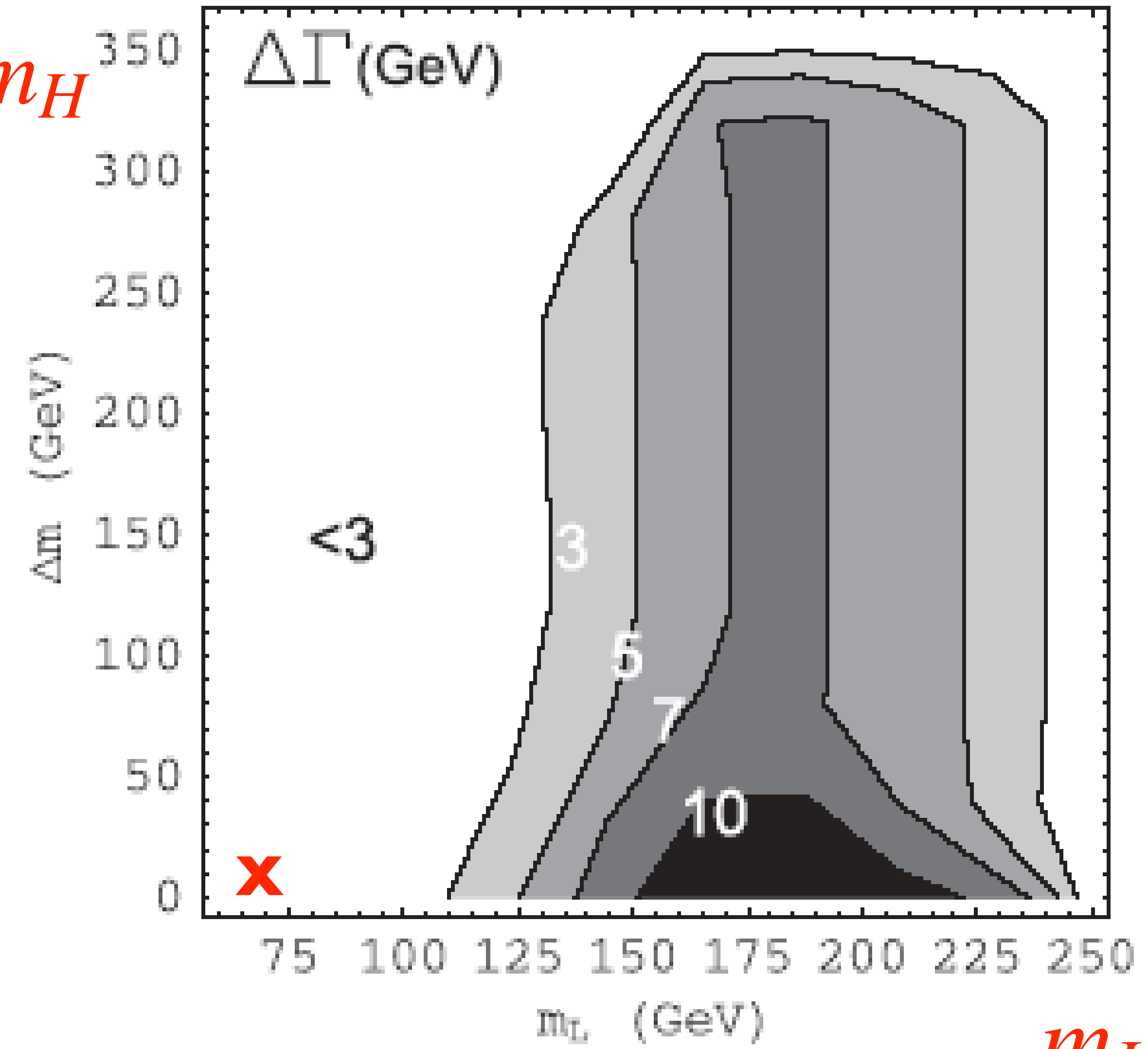
Signal may be detected with $30\,\mathrm{fb}^{-1}$

but other backgrounds $\bar{t}t,\ W\gamma^*$

Increase in h width

$$h \to AA, HH, H^+H^-$$

$m_A - m_H$



m_H

Conclusions

Suppose no susy at the weak scale: use naturalness and EWPT as guides

1) Alternative Higgs sectors, natural up to 1.5 TeV

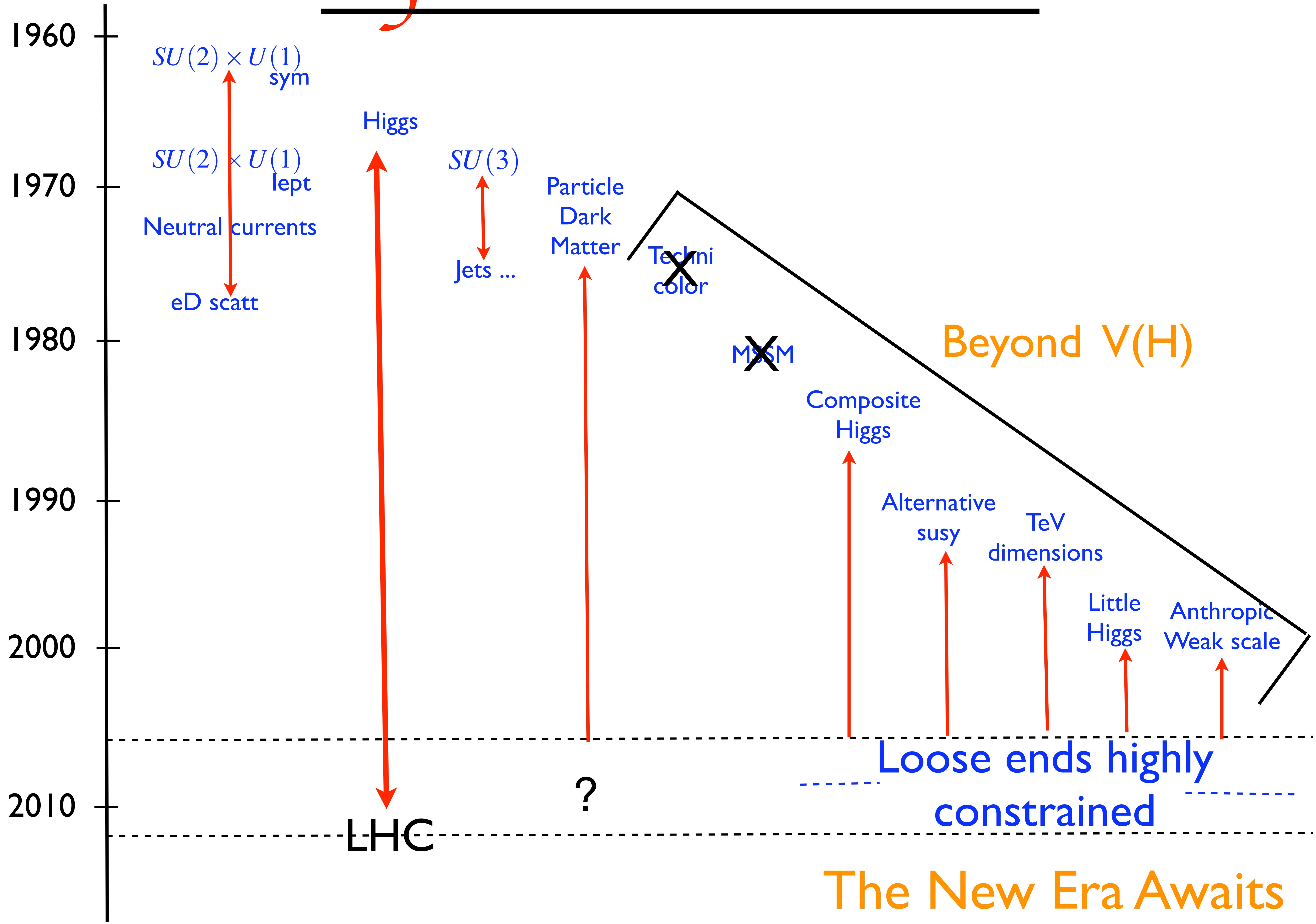
Little Hierarchy Problem ameliorated, but not solved

eg: $H_1 = \begin{pmatrix} 0 \\ v+h \end{pmatrix}$ SM-like Higgs for EWSB

$H_2 = \begin{pmatrix} H^+ \\ H+iA \end{pmatrix}$ Inert Doublet for EWPT and for DM

2) The cancellation physics may be out of the reach of LHC, which will probe the alternative Higgs sector.

After the SM ... ?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Loose ends highly constrained
?
LHC
The New Era Awaits

Is DM Region Excluded by LEP2

Outline

Going 1 step beyond the SM

(I) Little Hierarchy Problem and "Improved Naturalness"

(II) Light Higgs
- using Twin Higgs
- using 2 HDM

(III) Heavy Higgs
- Inert Doublet Model

A) Twin Higgs

Chacko, Goh, Harnik hep-ph/0506256

$L_{SM}(H)$ $\quad$ $H^\dagger H H'^\dagger H'$ $\quad$ $L_{SM'}(H')$

Approx SU(4)

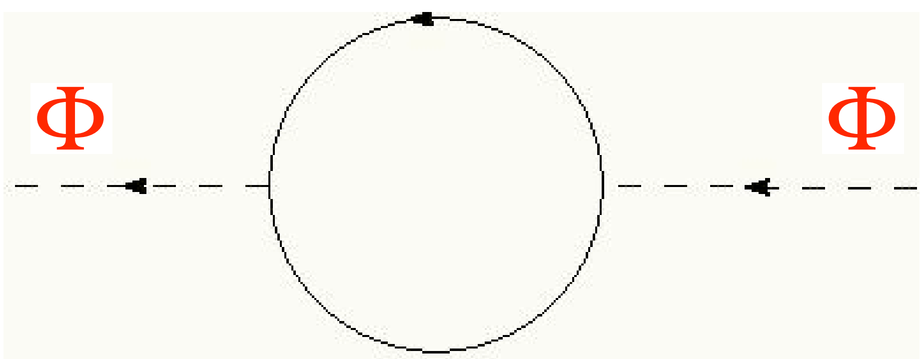
$$\Phi = \begin{pmatrix} H \\ H' \end{pmatrix}$$

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

$$< \Phi >= \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix} \qquad f^2 = \frac{\mu^2}{2\lambda}$$

H is a Goldstone Boson

t, t'



does not contribute to $V(H)$

Bottom Up Analysis

Barbieri, Gregoire, Hall hep-ph/0509242

Radiative quartics don't respect SU(4), hence add

$$\Delta V = \delta\left[\left(H^\dagger H\right)^2 + \left(H'^\dagger H'\right)^2\right]$$

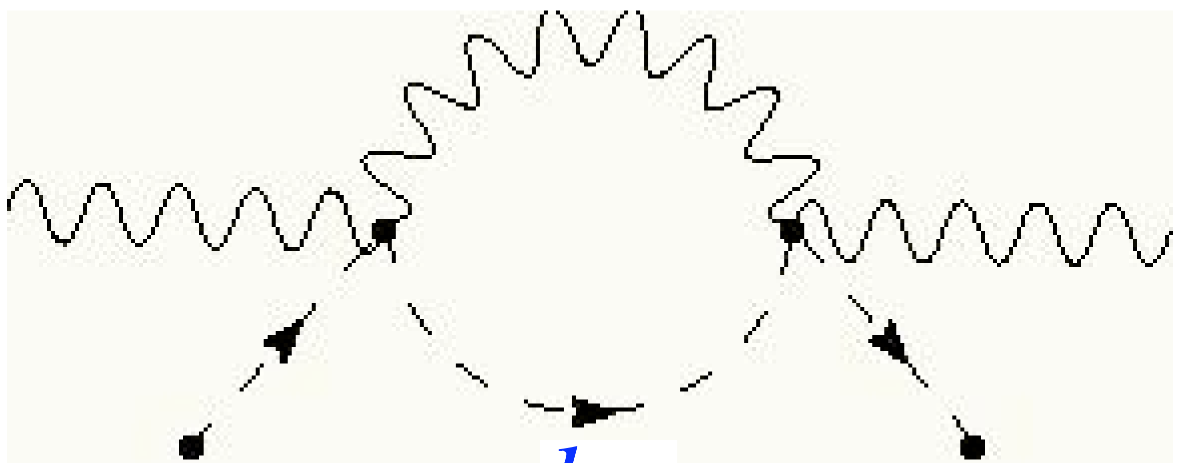
Aligns vacuum to $H = H' = \begin{pmatrix} 0 \\ v \end{pmatrix}$

so that Higgs mass eigenstates are

$$h_+ = \frac{h+h'}{\sqrt{2}} \qquad m_+^2 = 2\mu^2$$

$$h_- = \frac{h-h'}{\sqrt{2}} \qquad m_-^2 = \mu^2\frac{\delta}{\lambda}$$

Make μ^2 large and $\frac{\delta}{\lambda}$ small? No: EWPT!



$h_\pm$

$$\ln m_h \to \frac{1}{2}\ln m_+ + \frac{1}{2}\ln m_-$$

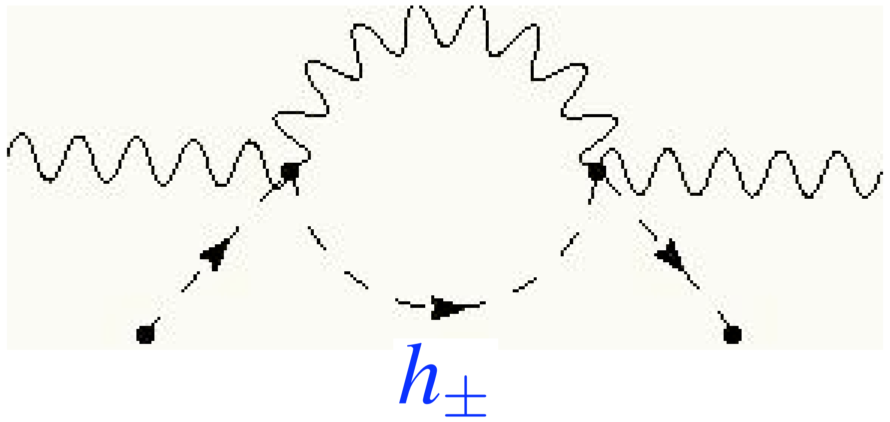
Only a modest improvement

Unequal vevs

Add Z_2 breaking $\Delta V = m^2(H^\dagger H - H'^\dagger H')$

$$\frac{v'}{v} = \frac{\cos\theta}{\sin\theta}$$

(but large ratio is still a fine tune)



$h = \cos\theta\, h_- + \sin\theta\, h_+$ so $\ln m_h \to \cos^2\theta\, \ln m_- + \sin^2\theta\, \ln m_+$

$$m_+ < m_- \left(\frac{m_{EWPT}}{m_-}\right)^{1+v'^2/v^2}$$

For example: $\frac{v'}{v} = 1.5, \quad m_- = 120\,\mathrm{GeV}, \quad m_{EWPT} = 180\,\mathrm{GeV}, \quad m_+ = 450\,\mathrm{GeV}$

allowing

$$\Lambda_t = 1.5\,\mathrm{TeV}$$

$$\Lambda_H = 1.4\,\mathrm{TeV}$$

Twin Higgs: LHC Signals

h_-

$$\Gamma_{prod} = \cos^2\theta\,\Gamma_{SM}(m_-)$$

$$BR(h_- \to X) = \cos^2\theta\, BR_{SM}(h \to X)$$

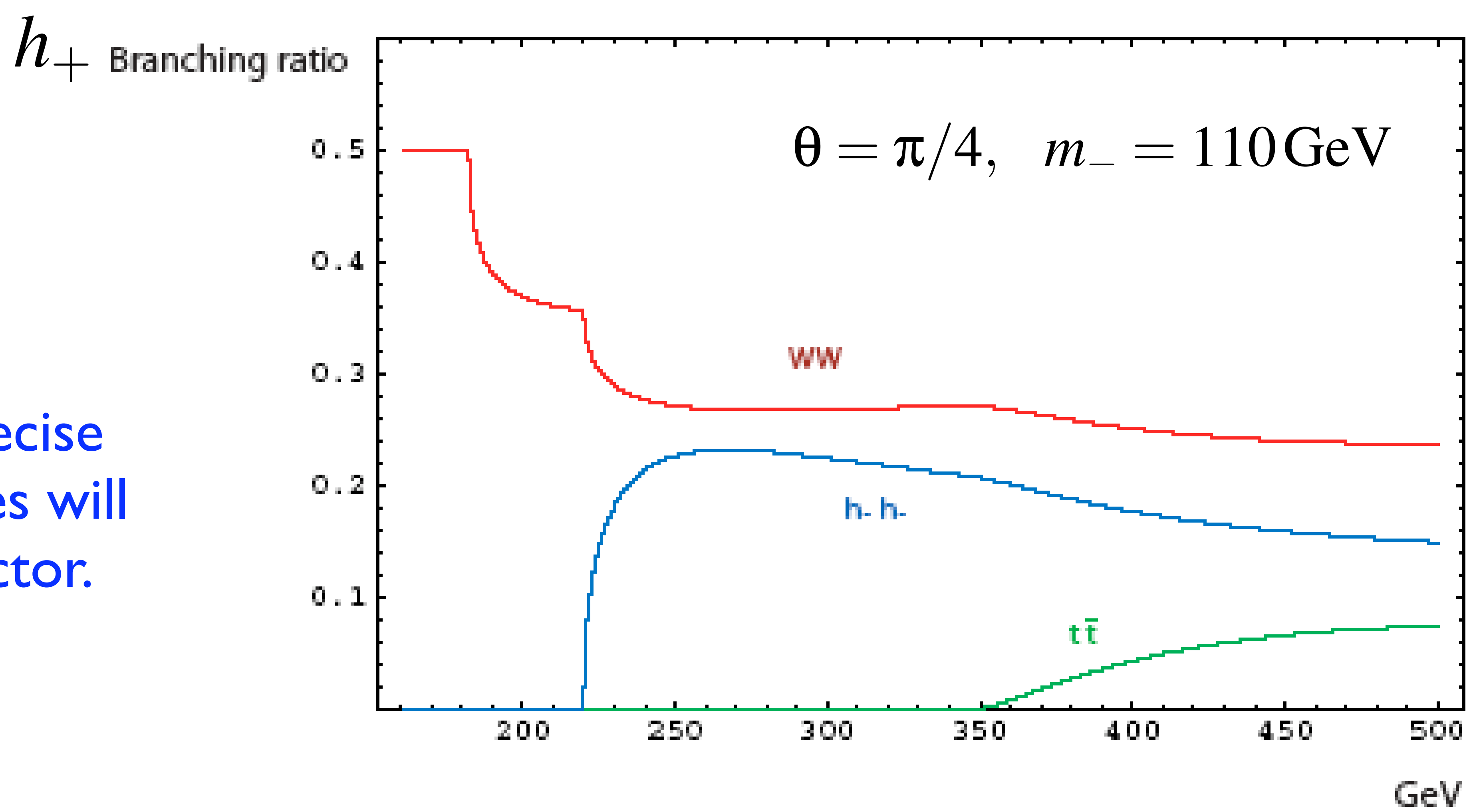
All event rates of light Higgs are reduced relative to SM by

$$\cos^4\theta \qquad (0.48 \text{ for } \frac{v'}{v} = 1.5)$$

h_+

$$\Gamma_{prod} = \sin^2\theta\,\Gamma_{SM}(m_+)$$

Will be first discovery at LHC; a precise measurement of the signal event rates will provide evidence for the mirror sector.



B) General 2 Higgs Doublet ModeL

Barbieri, Hall hep-ph/0510243

Impose a discrete symmetry for natural flavor conservation; most general potential is

$$V = -\mu_1^2 H_1^\dagger H_1 - \mu_2^2 H_2^\dagger H_2 + \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger H_2 H_2^\dagger H_1 + \frac{\lambda_5}{2}[(H_1^\dagger H_2)^2 + h.c.]$$

Neutral Higgs mass matrix

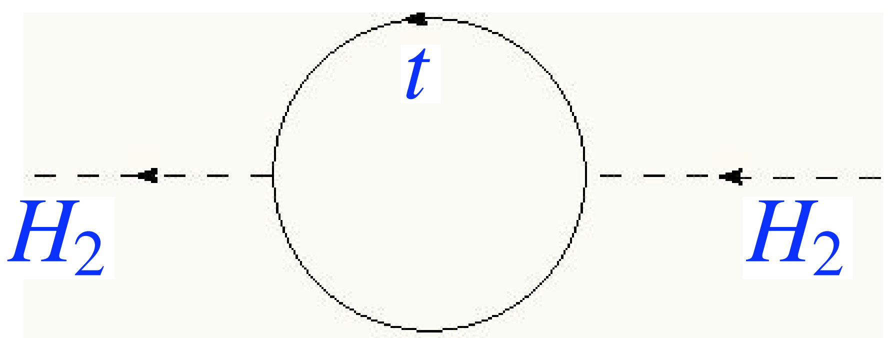
$$\begin{pmatrix} h_1 & h_2 \end{pmatrix} \begin{pmatrix} 4\lambda_1 v_1^2 & 2\delta v_1 v_2 \\ 2\delta v_1 v_2 & 4\lambda_2 v_2^2 \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

Naturalness

$$\delta = \lambda_3 + \lambda_4 + \lambda_5$$

H_2 couples to top

λ_2 largest, so $h_+ \sim h_2$ $\quad m_+^2 \approx 4\lambda_2 v_2^2$



$$\boxed{\Lambda_t \propto m_+}$$

Problems

1) Distributing the vev hurts $\Lambda_{H_i} = 1.3\,\mathrm{TeV}\,(\cos\beta, \sin\beta)$

Conflict

2) To increase Λ_t $\begin{cases} \sin\beta \text{ small} \\ m_{EWPT} \text{ large} \end{cases}$

TeVatron Run II

3) Λ_t from m_-^2 $\longrightarrow$ m_{H^+} relatively low

Since top Yukawa increased, $Z\bar{b}b,\ \ b \to s\gamma$

Only a factor 2 increase in natural cutoff compared to SM

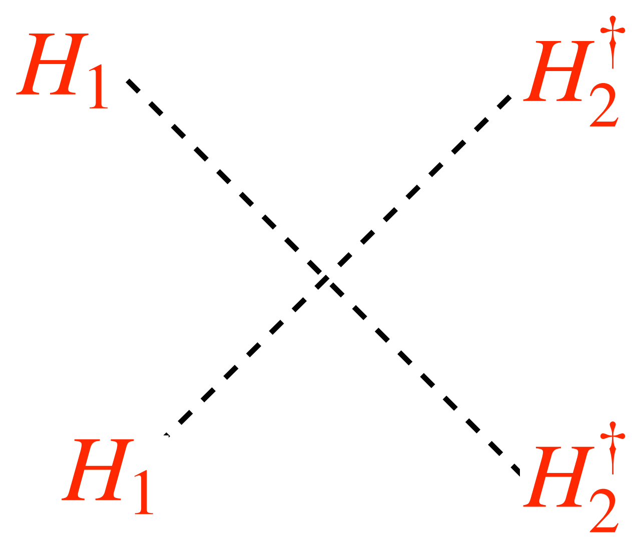
The "Charged" 2 HDM

Suppose the quartics are dominated by λ_5

$$V = \mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 - \mu^2 (H_1^\dagger H_2 + h.c.) + \frac{\lambda_5}{2}[(H_1^\dagger H_2)^2 + h.c.]$$

A local minimum with $\frac{v_1}{v_2} = \frac{\mu_2}{\mu_1}$

Cannot close quartic into loop!



$\Lambda_H \approx 10$ TeV !

Problem

Tunnel to runaway vacuum: $H_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}$ $H_2 = \begin{pmatrix} 0 \\ iv_2 \end{pmatrix}$

2-Higgs Doublets: An Alternative Phase

Work in progress with R. Barbieri and V. Rychkov

$H_2 \to -H_2$ ⟹ $V = \mu_1^2 H_1^\dagger H_1 + \mu_1^2 H_1^\dagger H_1 + \ldots$

$\mu_1^2 < 0,\ \mu_2^2 > 0$ ⟹ $v_2 = 0$ H_2 Inert

$$H_1 = \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

Couples to fermions and is much like SM doublet; H heavy

$$H_2 = \begin{pmatrix} H^+ \\ h + iA \end{pmatrix}$$

Custodial breaking masses for ΔT

$$(m_{H^+} - m_A)(m_{H^+} - m_h) \approx (120\ \mathrm{GeV})^2$$

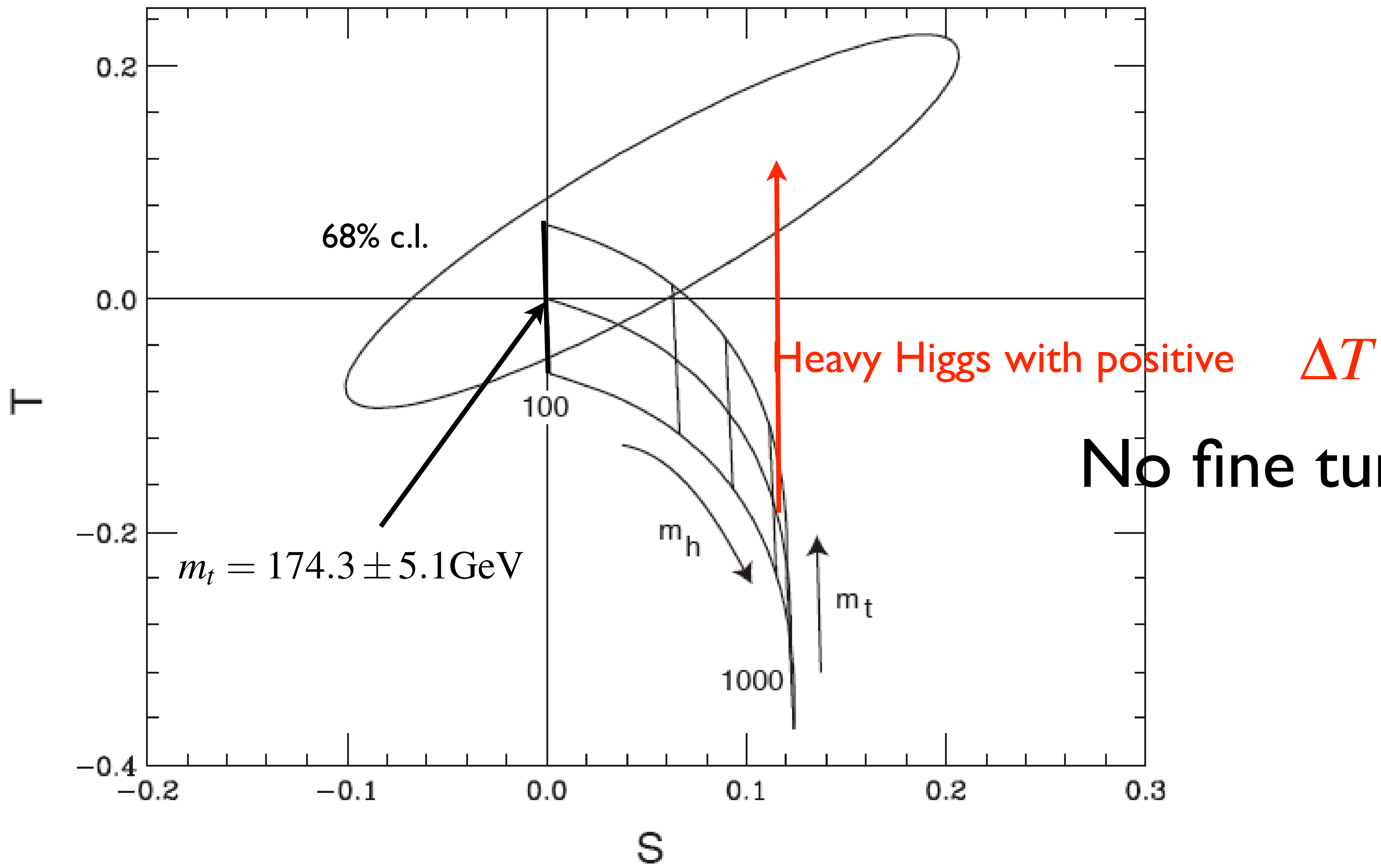
Λ_t increased to 1.5 TeV $D_t^{1/2}$

LHC signals could be just those of H^+, h, A

Lightest of h, A is stable and could be DM

A Heavy SM Higgs and EWPT

Peskin, Wells hep-ph/0101342



No fine tuning!!!

Origin of ΔT

SM + heavy triplet scalars

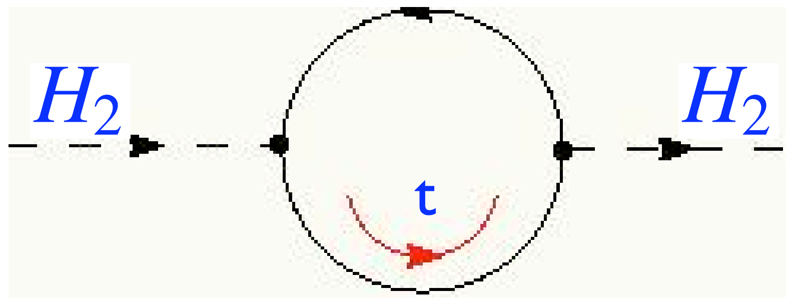
New gauge interaction - but often get trouble from 4 fermion operators

2 Higgs Doublets - both Higgs heavy $\Lambda_{H_i} = 1.3\ \mathrm{TeV}(\sin\beta, \cos\beta)$

1 Heavy Higgs and 1 Light Higgs

(H_2, t)

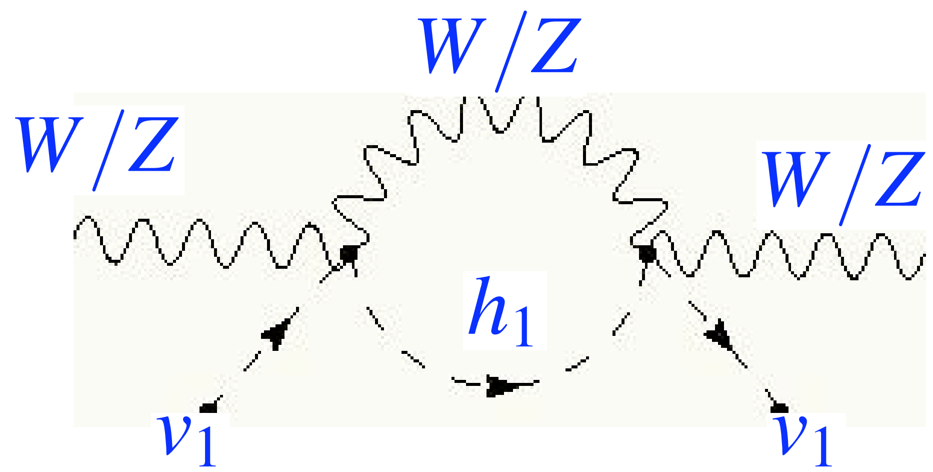
Top couples to a heavy Higgs



$$\Lambda_t \approx 2\ TeV \left(\frac{m_{H_2}}{600\ \mathrm{GeV}}\right) \sin\beta\, D_t^{1/2}$$

(h_1, W)

Light Higgs dominates EWPT



$$\frac{g^4}{16\pi^2} v_1^2 \ln \frac{m_{h_1}}{M_W}$$

What is EWPT limit on m_{H_2} ?

$$m_{H_2} < m_{h_1} \left(\frac{m_{max}}{m_{h_1}}\right)^{\frac{1}{\sin^2\beta}}$$

"Cancellation" physics may be out of LHC reach. Discover 2 Higgs with:

$\tan\beta \approx 0.8\text{–}1$

$\alpha \leq 0.3$

$m_{h_1} \approx 115\text{–}150$ GeV

$m_{H_2} \approx 500\text{–}800$ GeV

Low top mass?

2 Higgs Doublets

Most general model with a discrete symmetry for natural flavor conservation

$$V = \mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2$$

$$+\lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger H_2 H_2^\dagger H_1 + \lambda_5 [(H_1^\dagger H_2)^2 + h.c.]$$

Standard Phase

$$\mu_{1,2}^2 < 0 \quad \Longrightarrow \quad v_{1,2} \neq 0$$

Mass Constraints from T