HCP 2006
Duke University

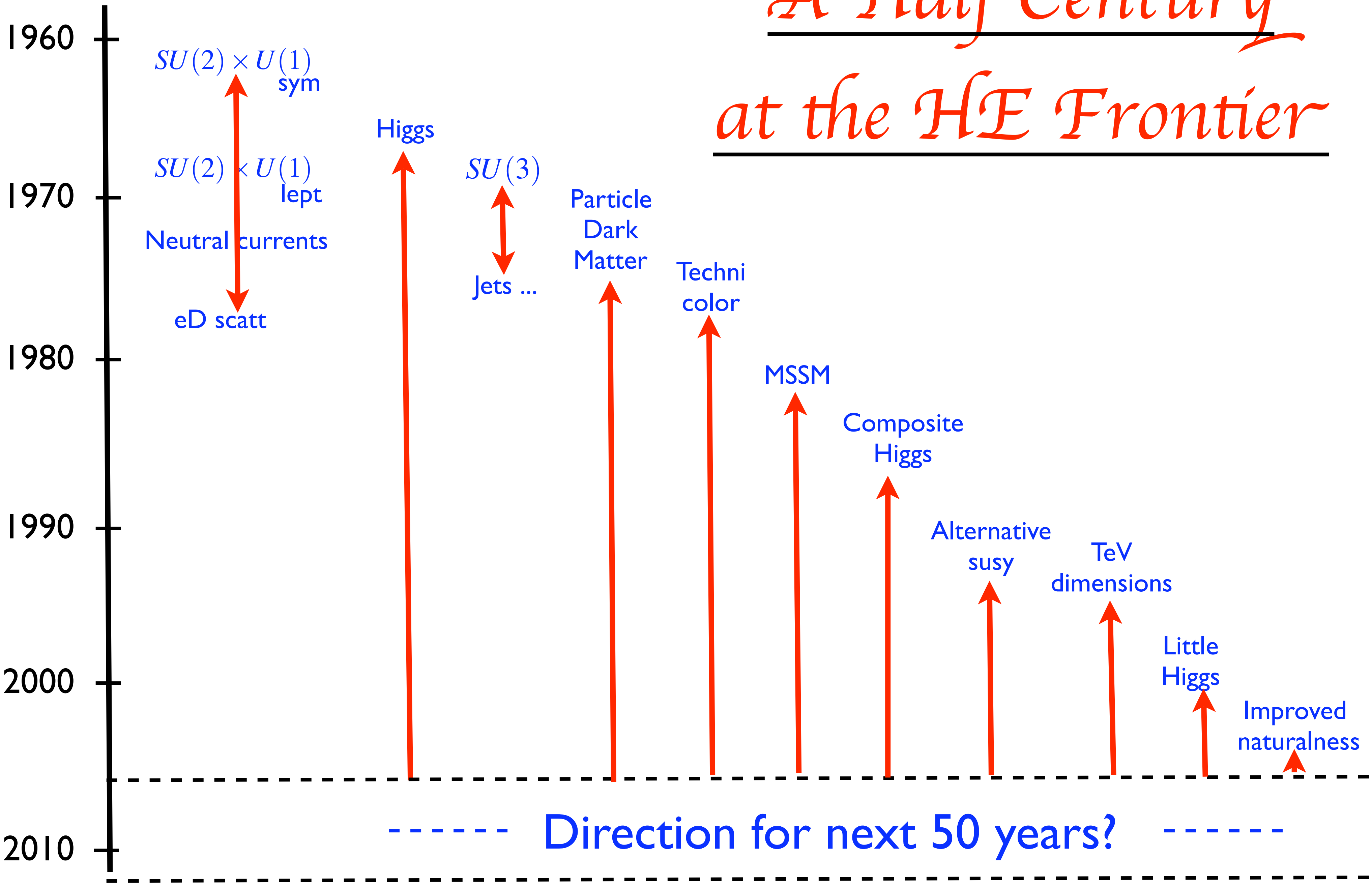
# Where will Hadron Collider Data Lead Us?

Lawrence Hall
UC Berkeley

# Outline

- Overview
- Supersymmetry
- New strong interactions
- Improved Naturalness

# A Half Century at the HE Frontier




The New Era?

# *Four Signposts*

EWPT

Naturalness

What will HC discover?

Simple mechanism for EWSB

A larger framework

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?

EWPT & Naturalness

# *SM and Naturalness*

## Potential

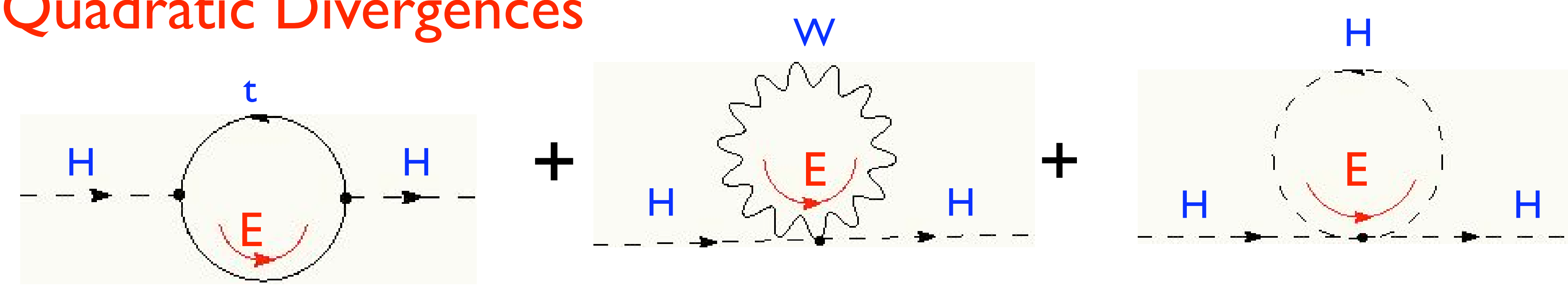
$$m_h^2 = 2\mu^2 = 4\lambda v^2$$

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

Light Higgs ⟷ $\lambda, \frac{\mu^2}{v^2}$ small

Heavy Higgs ⟷ $\lambda, \frac{\mu^2}{v^2}$ large

## Quadratic Divergences

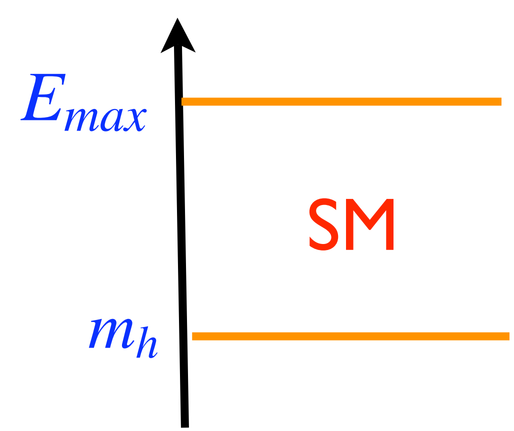



$$\Delta \mu^2 = \frac{3}{16\pi^2}\frac{m_t^2}{v^2}E^2 - \frac{1}{16\pi^2} g^2 E^2 - \frac{1}{16\pi^2}\lambda E^2$$

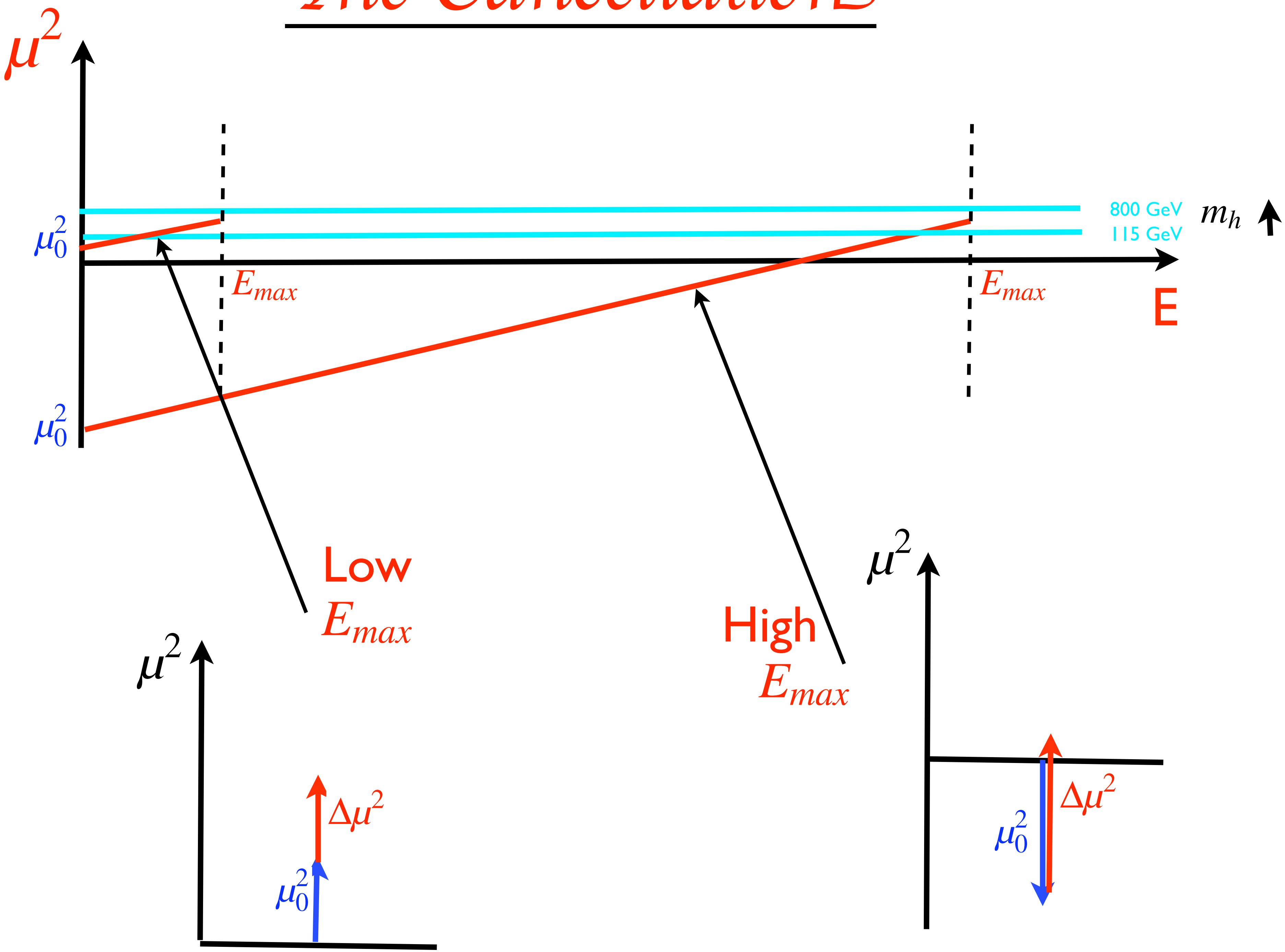
## Fine Tuning

$$\mu^2 = \mu_0^2 + \frac{3}{16\pi^2}\frac{m_t^2}{v^2}E_{max}^2$$

Fine tuning increases as $E_{max}$ increases

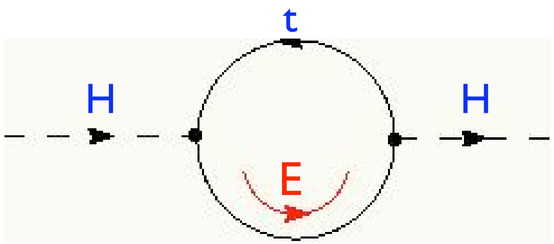


# The Cancellation

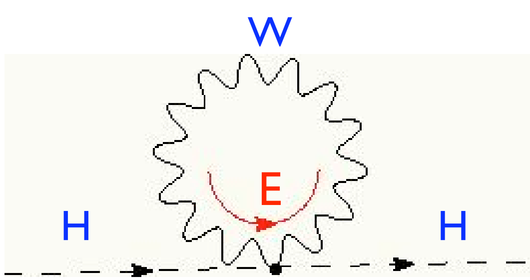


# Light SM Higgs → Low SM Cutoff

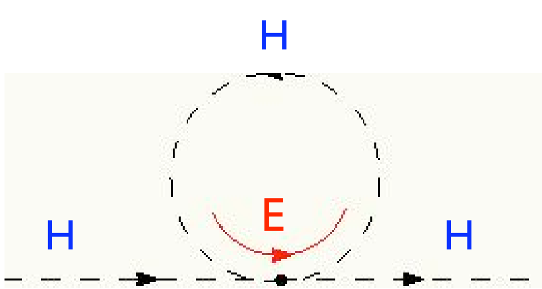
## $E_{max} \rightarrow \Lambda_{t,W,H}$



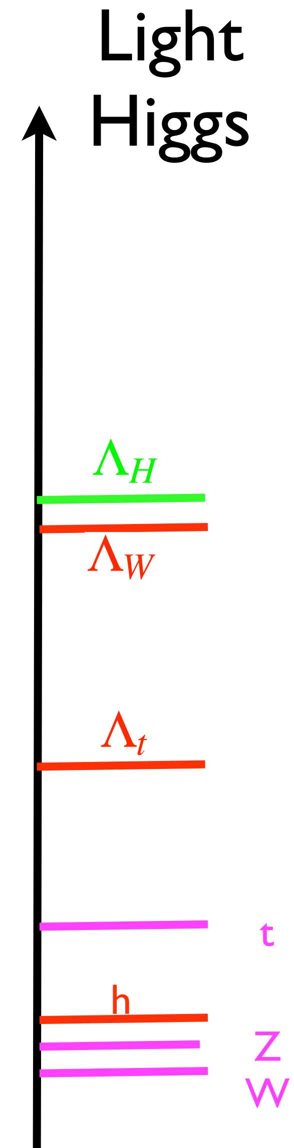

$$\Lambda_t = 400\ \text{GeV}\left(\frac{m_h}{115\text{GeV}}\right) D_t^{1/2}$$




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



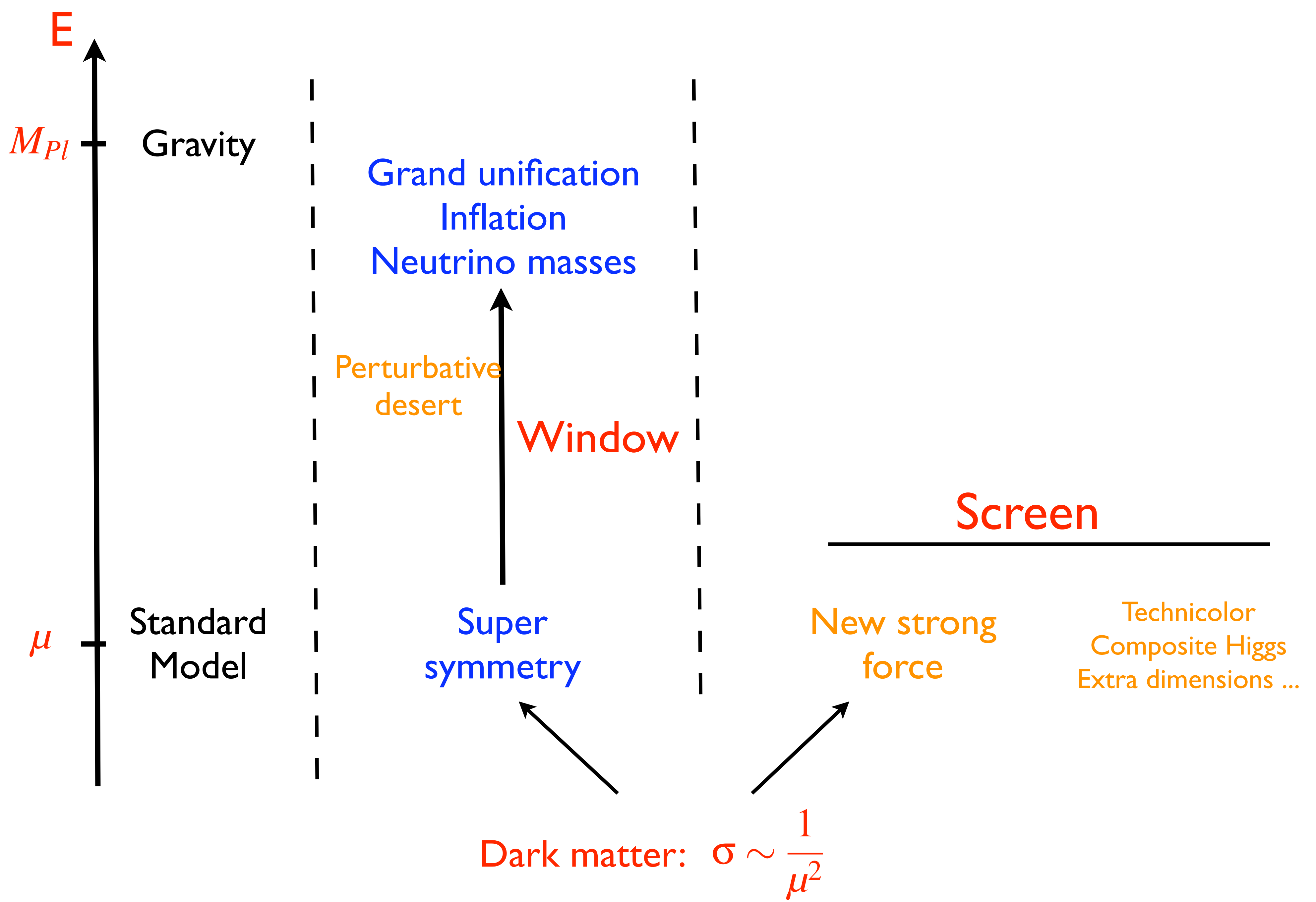

$$\Lambda_H = 1.3\ \text{TeV}\ D_H^{1/2}$$




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

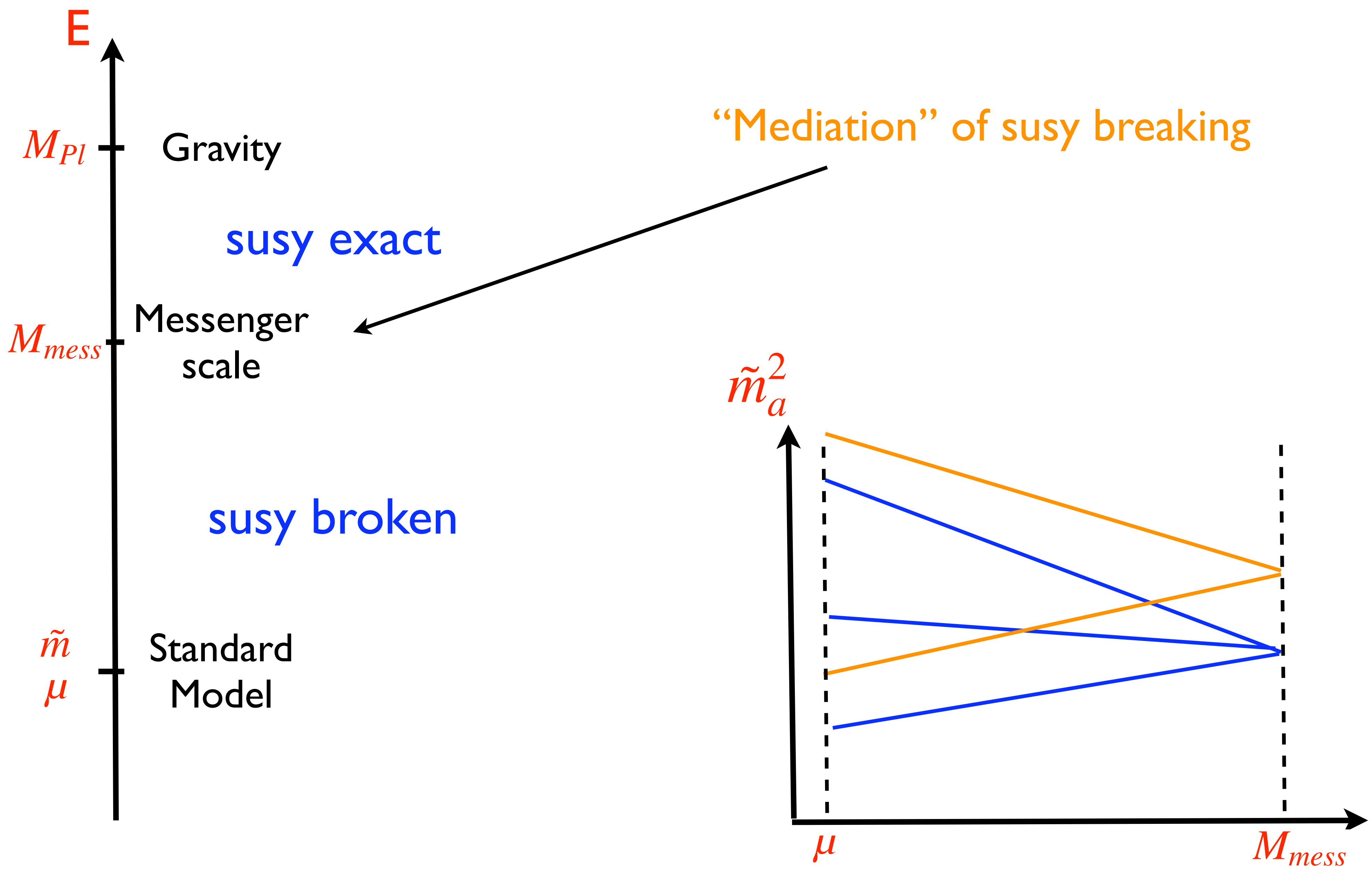
# What is the Cancellation Physics?





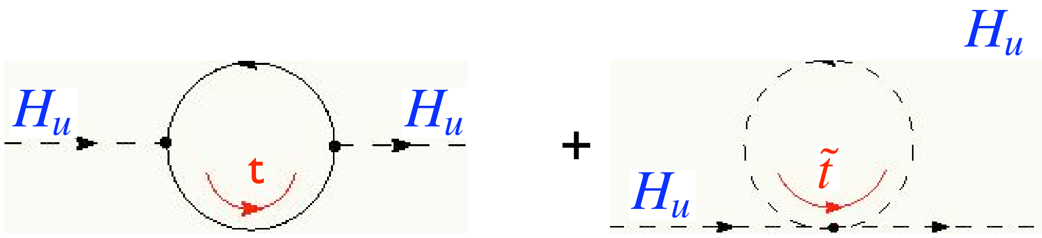
# (II) Supersymmetry

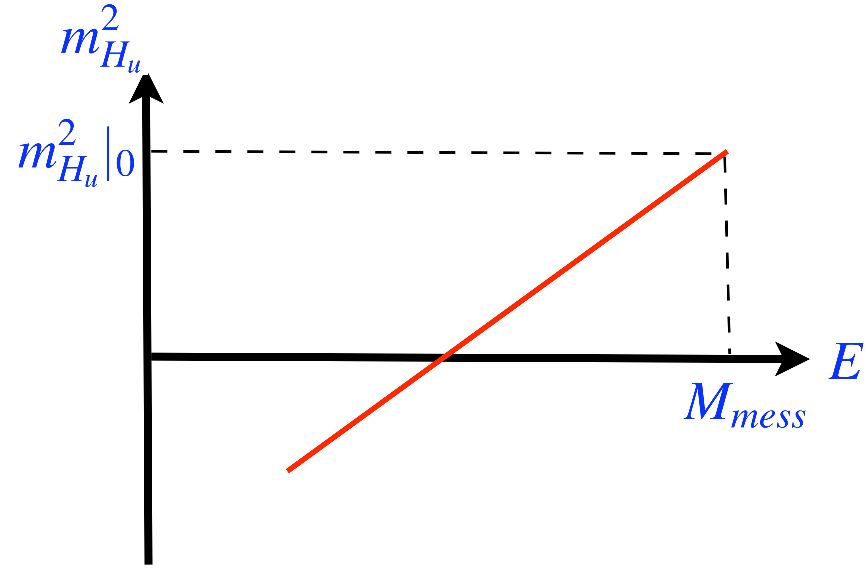
# The Messenger Scale



# Radiative EWSB

$$V \approx (\mu^2 + m_{H_u}^2) H_u^\dagger H_u + \frac{g^2}{8}(H_u^\dagger H_u)^2$$




$$\frac{M_Z^2}{2} \approx \mu^2 + m_{H_u}^2$$

How heavy is the top squark?

What is the messenger scale?

$$-\delta m_{H_u}^2 \approx \frac{3}{4\pi^2} y_t^2 m_{\tilde{m}_t}^2 \ \ln \frac{M_{mess}}{\tilde{m}_t} \approx \tilde{m}_t^2 \left( \frac{\ln(M_{mess}/\tilde{m}_t)}{12} \right)$$

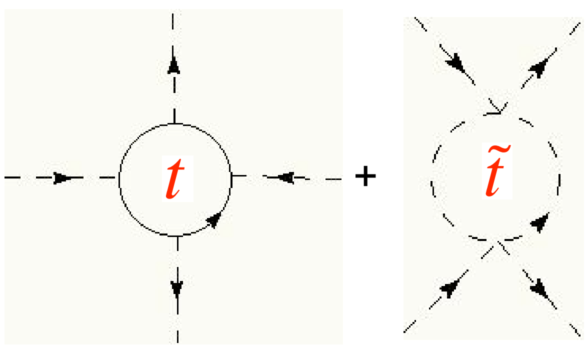
# Supersymmetric Fine-Tuning Problem

$$\frac{M_Z^2}{2} \approx \mu^2 + m_{H_u}^2$$

LEP bound on Higgs mass

$$m_h^2 \propto \lambda \approx g^2$$

large radiative correction to quartic




Heavy $\tilde{t}$

Direct Higgs searches

Problem with $V(H_u, H_d)_{MSSM}$

New gauge interactions?
Large A parameter?

Origin of supersymmetry breaking

Gravity Mediation

$$M_{mess} \approx M_{Pl} \qquad \ln\left(\frac{M_{mess}}{\tilde{m}_t}\right) \approx 35$$

Gauge Mediation

Gauge origin $$\frac{\tilde{m}_t}{\tilde{m}_{e_R}} \approx \frac{g_3^2}{g_1^2} \approx 8$$

Direct searches for $\tilde{t}, \tilde{e}_R$

Problem with Gravity med. & Gauge med.

Modified gauge mediation?

# "Non-Decoupling" D Terms

Batra, Delgado, Kaplan, Tait hep-ph/0309149

Ex: $U(1)_{T_{3R}}$

$$V_4 = \frac{g^2+g'^2}{8}(H_u^\dagger H_u - H_d^\dagger H_d)^2 + \frac{g_R^2}{8}(H_u^\dagger H_u - H_d^\dagger H_d + \phi^\dagger\phi - \phi'^\dagger\phi')^2$$

$$m_h^2 \approx M_Z^2 \cos 2\beta \left(1 + \frac{g_R^2}{g^2}\frac{m_\phi^2}{M_{Z'}^2}\right)$$

Even with $M_{Z'} \geq 3\text{TeV}$ can assume large susy breaking in $\phi$

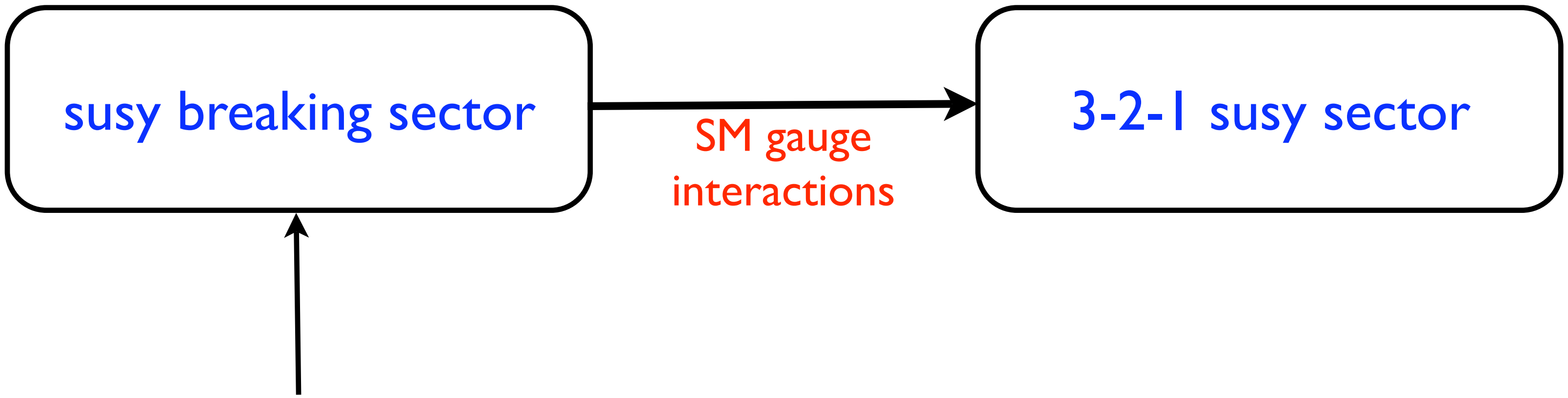
Running of couplings makes $g_R$ small ➡ modest gain

Non-Abelian, eg SU(2)' ➡ gauge coupling unification not automatic!

$m_h$ ⬌ $g_i$ unification

# Modified Gauge Mediation

Nomura, Tweedie hep-ph/0504246




Matter content is SU(5) invariant for gauge coupling unification, hence:

$$\frac{\tilde{m}_t}{\tilde{m}_{e_R}} \approx \frac{g_3^2}{g_1^2} \approx 8$$

Spontaneously break this global SU(5) along with susy:

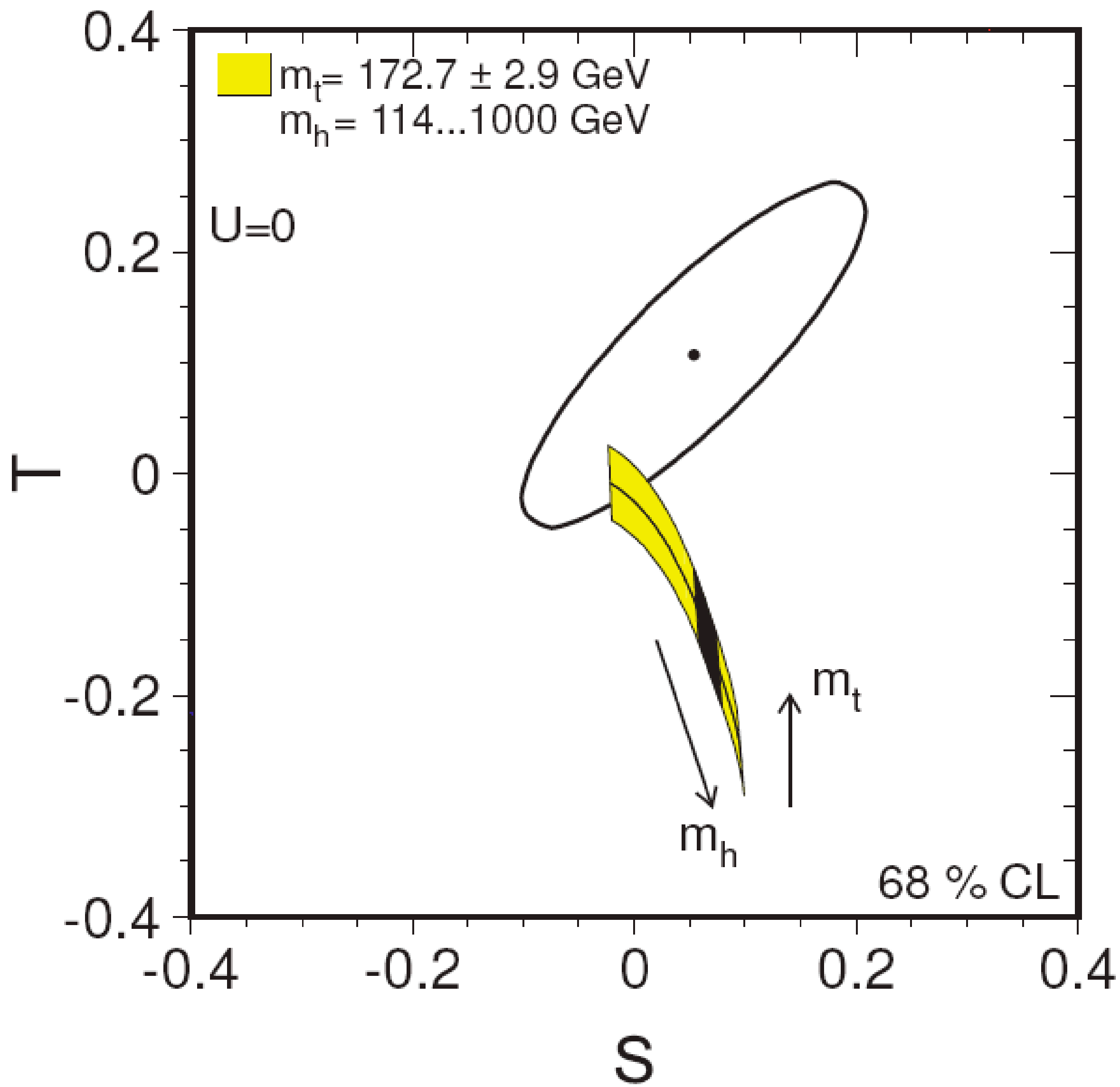
$$\frac{\tilde{m}_t}{\tilde{e}_R} \approx \left(\frac{g_3^2}{g_1^2}\right)\left(\frac{M_{color}^2}{M_{weak}^2}\right)$$

Spontaneously breaking of SU(5) leads to colored scalars X(1/3) and Y(4/3) with masses 1-3 TeV

Superpartners are the leading candidate for the "Cancellation Physics" --- but, the devil is in the details.

# (III) New Strong Forces

# *EWPT and SM*




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

## SM Higgs is light!

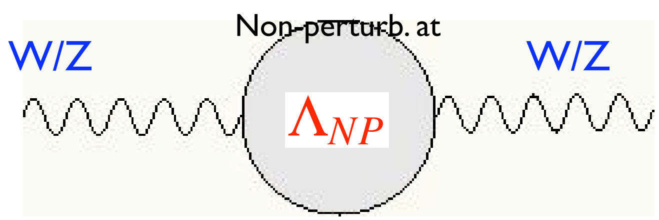
Especially as TeVatron Run II finds a lower top mass.

# 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 $\Lambda_{NP}$




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

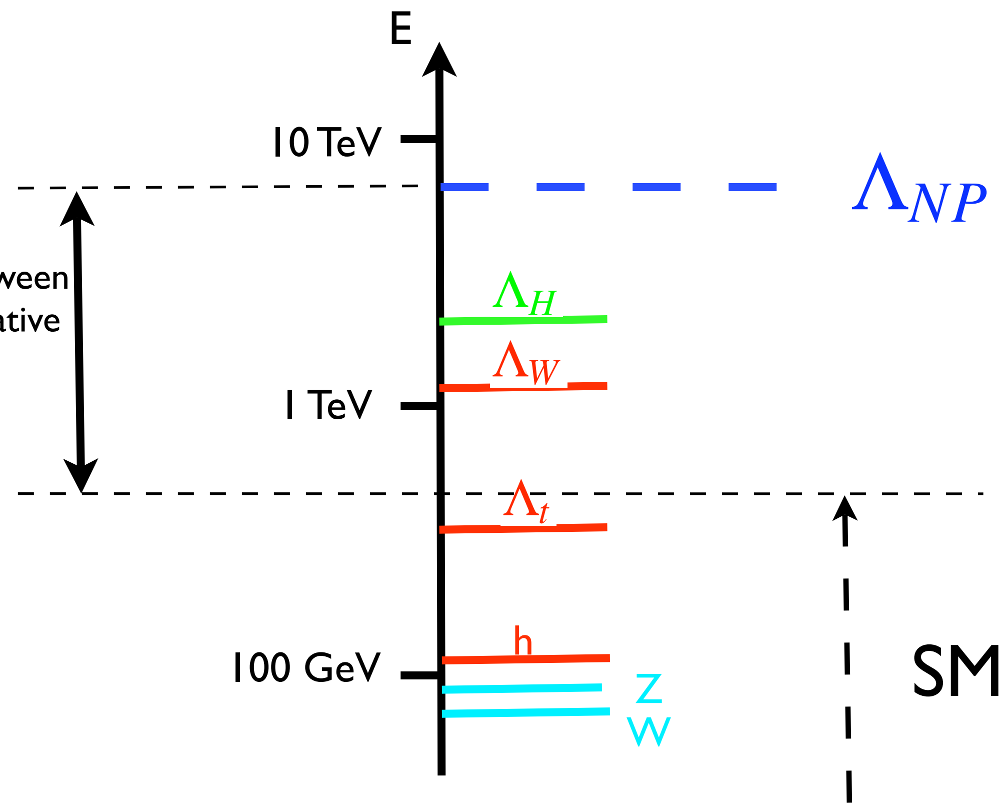
$$\Lambda_{NP} \geq 5\text{–}10 \text{ TeV}$$

# The Little Hierarchy Problem

Barbieri, Strumia hep-ph/0007265

Applies to theories with low $\Lambda_{NP}$

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 HC signals ?

# Beautiful Ideas for EWSB that have LHP

## Technicolor

"Cancellation" Physics

The first and best BSM idea for EWSB

Strong interactions at TeV scale, but perturbative to Planck scale. → Technipions

## Supersymmetric SM in 5D

Boundary Conditions break supersymmetry at TeV scale

Higgs mass calculable

## Higgsless

EWSB directly by boundary conditions in extra dimensions

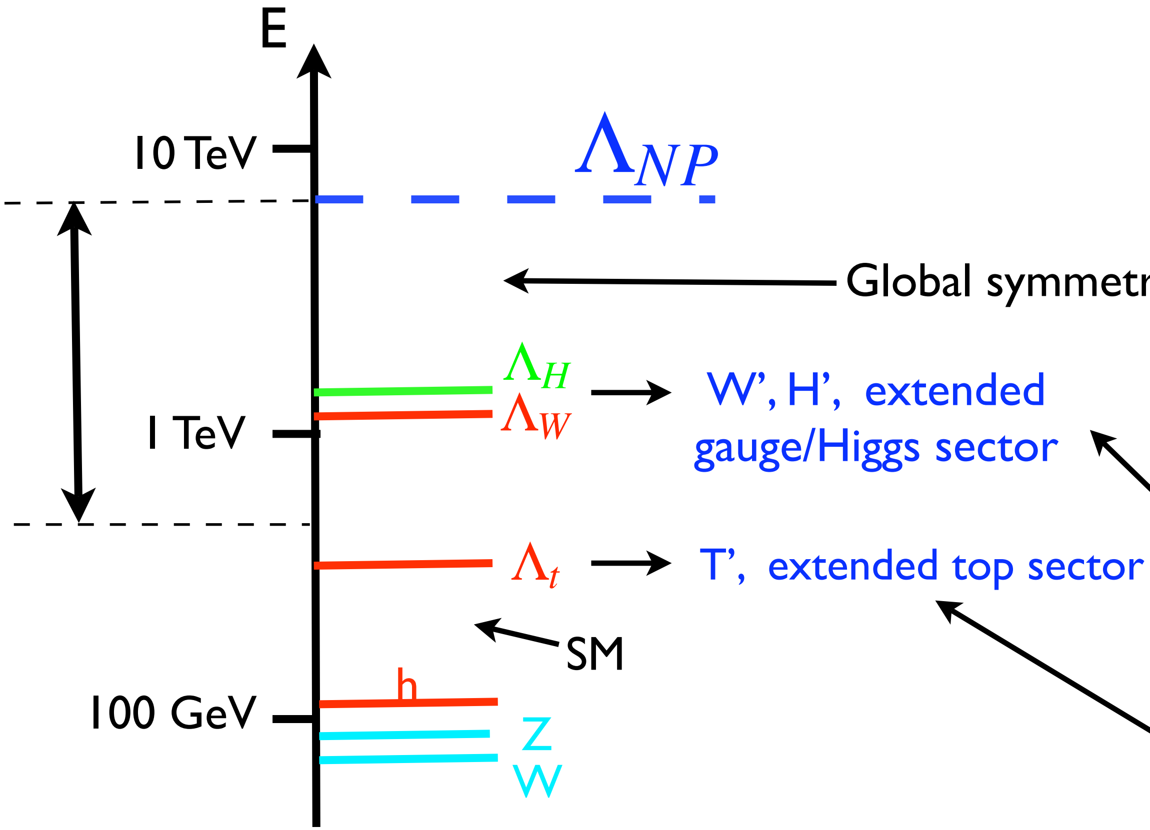
→ Characteristic set of KK resonances for all SM particles

These theories have $\Lambda_{NP} \approx \mathrm{TeV}$ LHP Hard to Solve

Perhaps susy is right after all!

# "Little Higgs" for LHP

Arkani-Hamed, Cohen, Georgi
hep-ph/0105239




Global symmetry structure allowing

$$m_h^2 = 0 + 0 + \left(\frac{\lambda_1}{16\pi^2}\frac{\lambda_2}{16\pi^2}\right)\Lambda_{NP}^2$$

Beautiful idea!

LHC discovers
cancellation physics
T', W', H'

Implementation complex;
need to avoid EWPT problems from W'

Only a factor 3 of LHP understood

# *(IV) Improved Naturalness*

# The Idea

Barbieri, Hall hep-ph/0510243

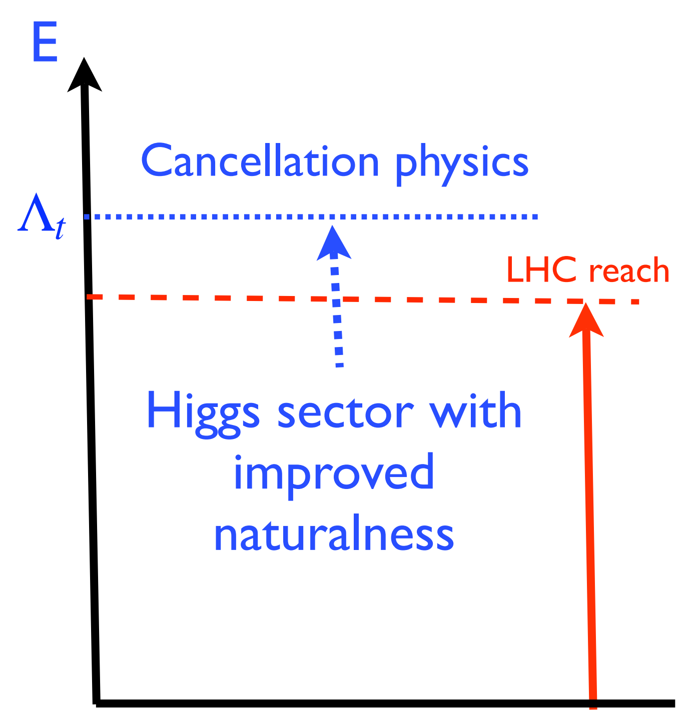
Seek simple Higgs sector that

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

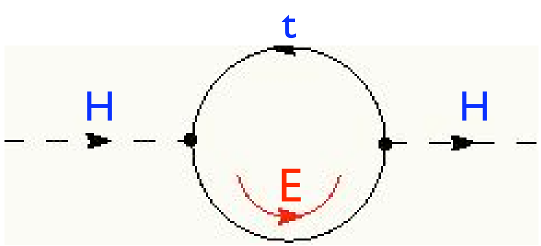
(Same as Little Higgs)



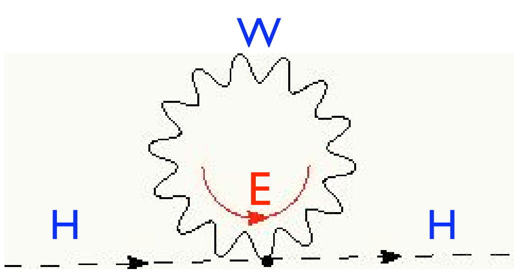

A modest "ultra bottom up" approach, with crucial consequences for the LHC

# A Helpful Ingredient: A Heavy Higgs

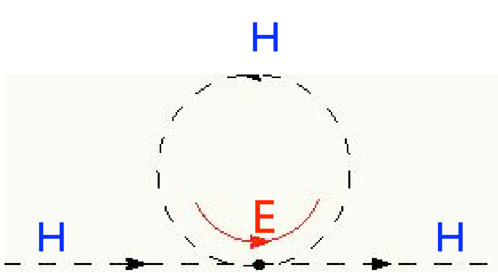
Recall SM:



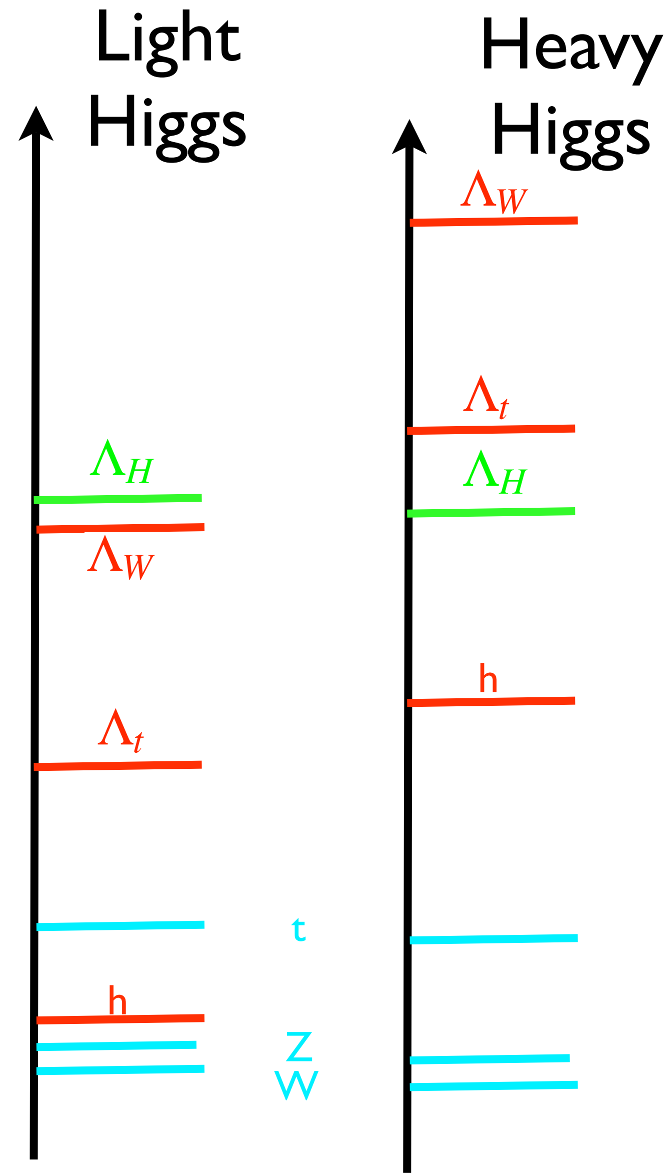

$$\Lambda_t = 400 \text{ GeV} \left(\frac{m_h}{115\text{GeV}}\right) D_t^{1/2}$$



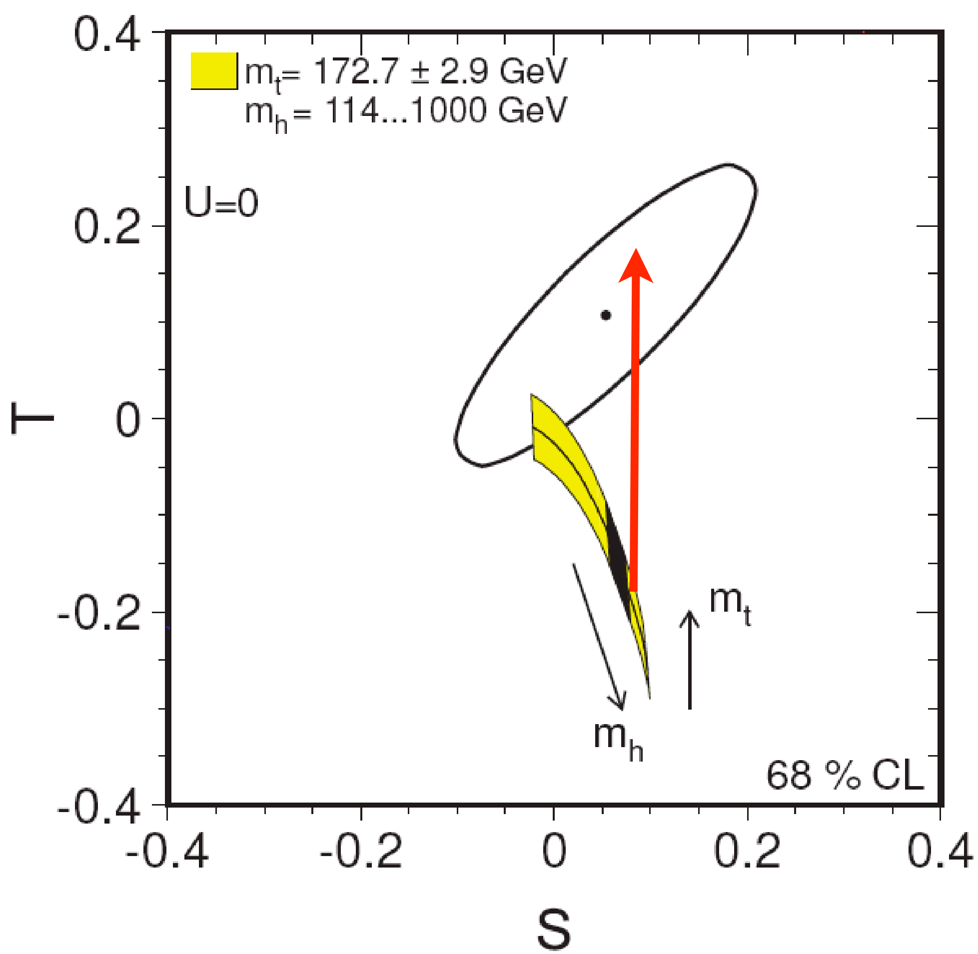

$$\Lambda_W = 1.1 \text{ TeV} \left(\frac{m_h}{115\text{GeV}}\right) D_W^{1/2}$$




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



# A Heavy SM Higgs and EWPT




Heavy Higgs with positive $\Delta T$

No fine tuning!!!

## Origin of $\Delta T$

(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 $\Lambda_{H_i} = 1.3\,\mathrm{TeV}\,(\cos\beta, \sin\beta)$

# 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

# *LIP Dark Matter*

## $m_H > m_W$

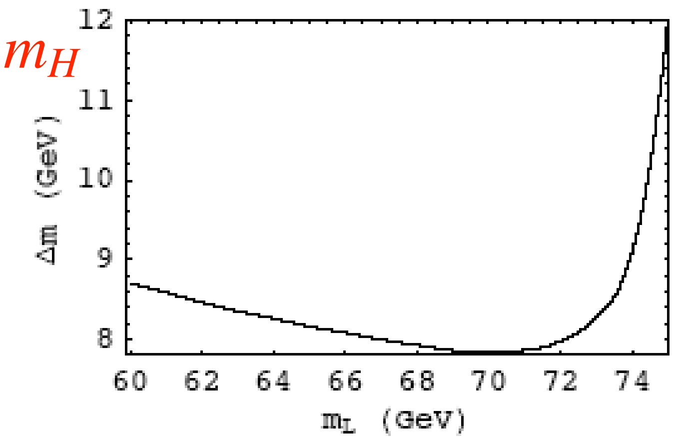
$HH \to W^+W^-$ Depletes H to a small fraction of the observed Dark Matter

## $m_H < m_W$

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

$\Omega_{DM}h^2 \sim 0.1$ if:

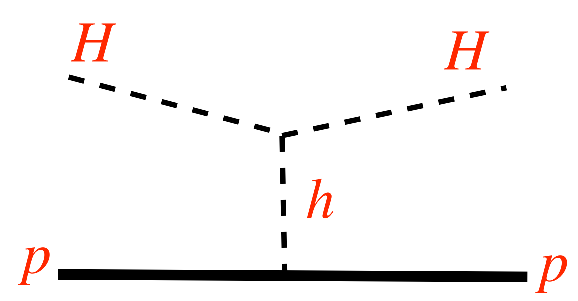
$m_A - m_H$




$m_H$

## 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: $H^+ \to W^+(A,H)$  $A \to Z^* H$

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

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

Pythia  lept. BR

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

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

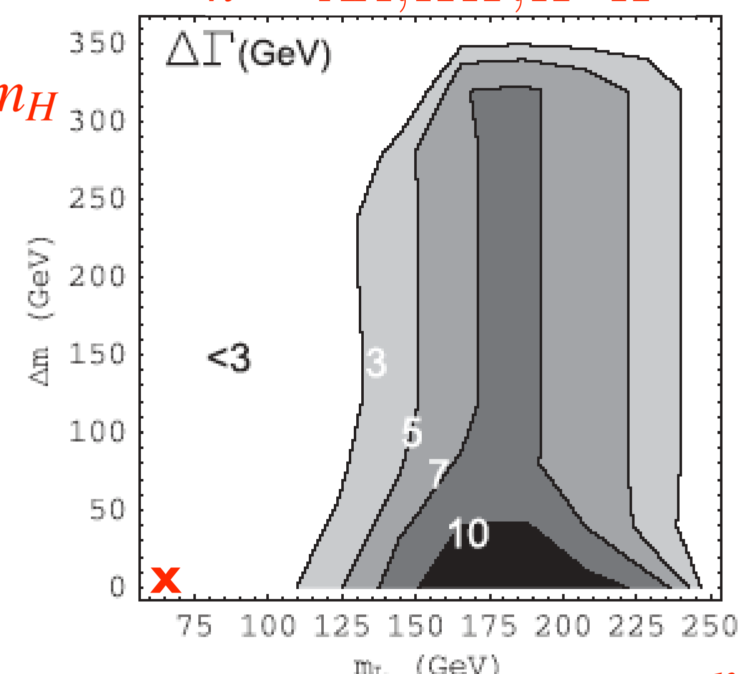
Signal may be detected with $30\,\text{fb}^{-1}$

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

## Increase in h width

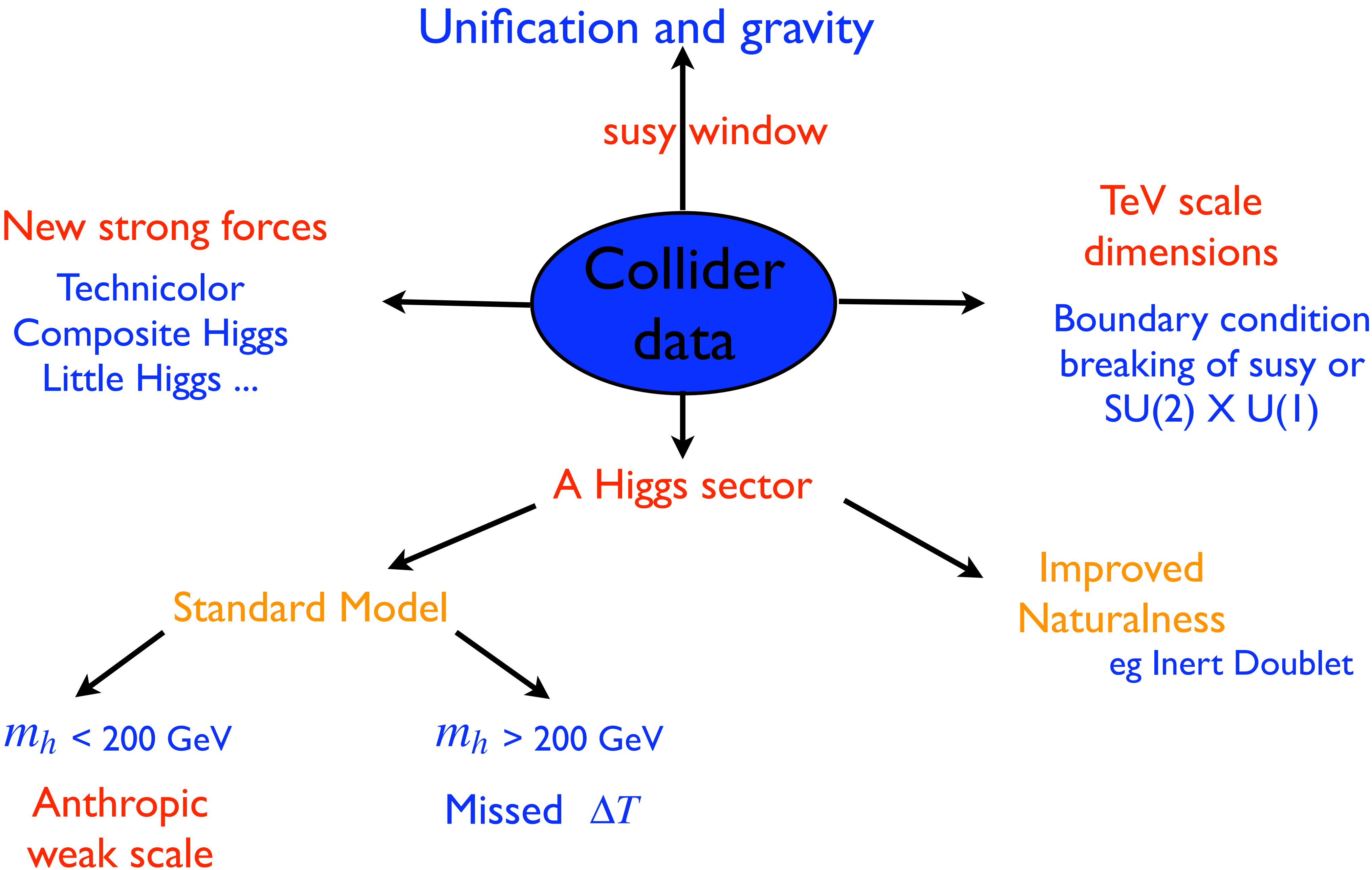
$$h \to AA, HH, H^+H^-$$

$m_A - m_H$




$m_H$

# Conclusions



# Conclusions