Title: Paying the price of naturalness with a supersymmetric twin Higgs

Date: Jan 21, 2014 01:00 PM

URL: http://pirsa.org/14010105

Abstract: What is the price of naturalness? In minimal extensions of the standard model, stringent limits on new colored particles and measurements of Higgs properties from the LHC severely challenge the hypothesis of naturalness of the electroweak scale. However, these measurements also provide unprecedented guidance in exploring non-minimal models of new electroweak physics. The supersymmetric twin Higgs provides a concrete example where few-percent level tuning remains compatible with superpartner limits and Higgs physics as well as gauge coupling unification and other successes of the MSSM. Studying such models in detail is crucial to understanding the role naturalness will play as a motivating principle for future searches at the 13 TeV LHC and beyond.

Paying the price of naturalness with a SUSY twin Higgs

Kiel Howe, Stanford Institute for Theoretical Physics & SLAC

Perimeter Institute 1/21/14

based on work in:
(N. Craig and K.H., arXiv:1312.1341)

Outline

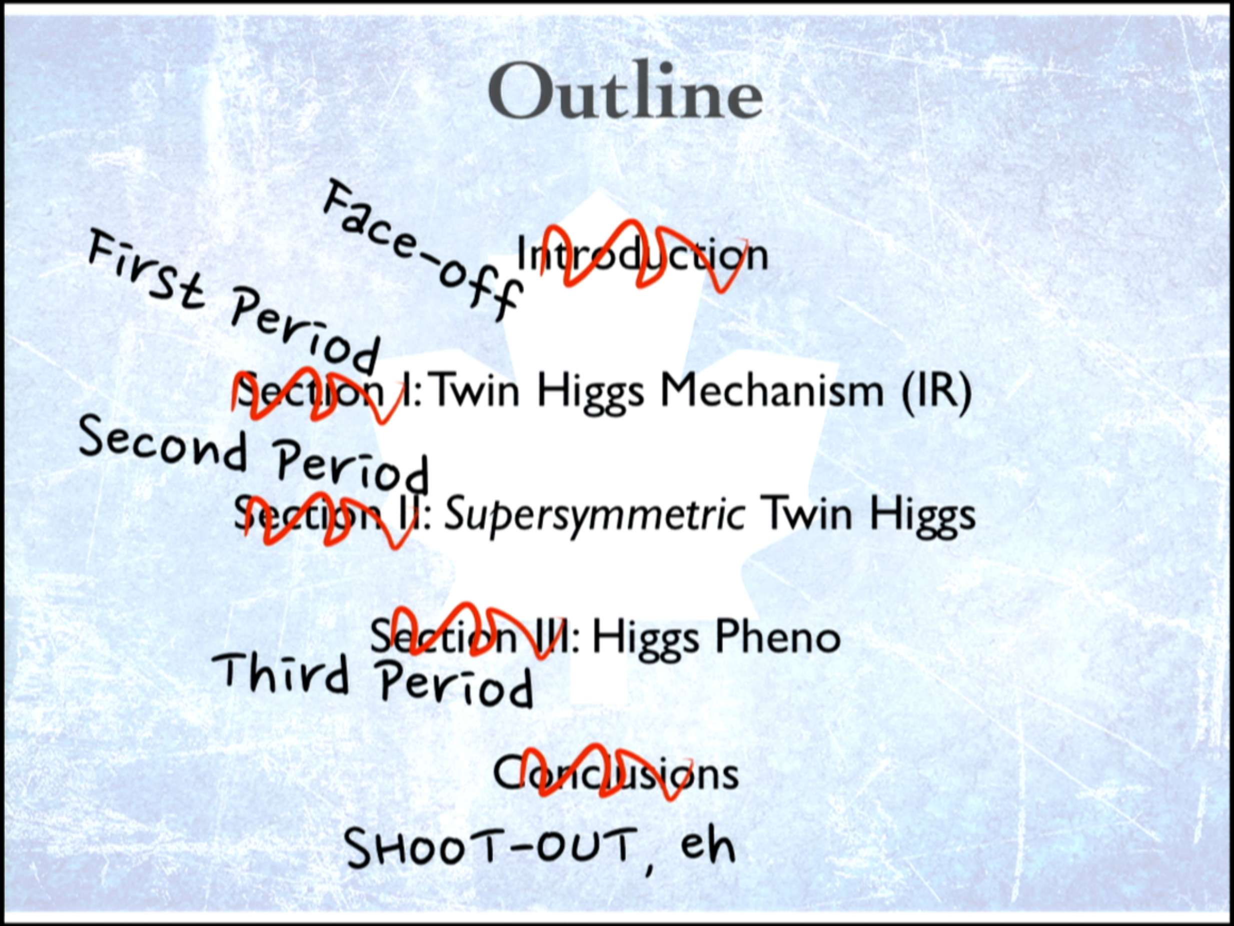
Introduction

Section I: Twin Higgs Mechanism (IR)

Section II: *Supersymmetric* Twin Higgs

Section III: Higgs Pheno

Conclusions



Outline

Face-off

Introduction

First Period

Section I: Twin Higgs Mechanism (IR)

Second Period

Section II: *Supersymmetric* Twin Higgs

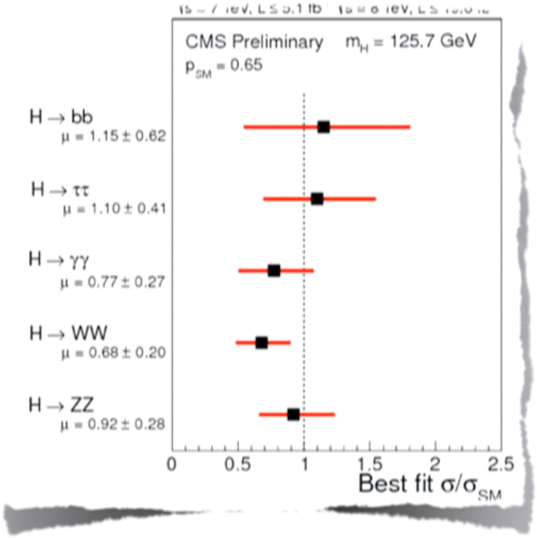
Section III: Higgs Pheno

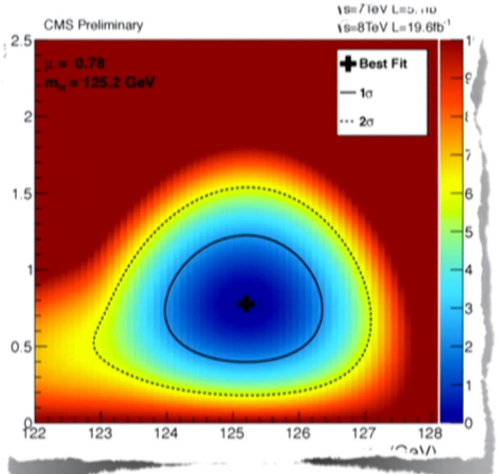
Third Period

Conclusions

SHOOT-OUT, eh

Naturalness of Higgs Properties





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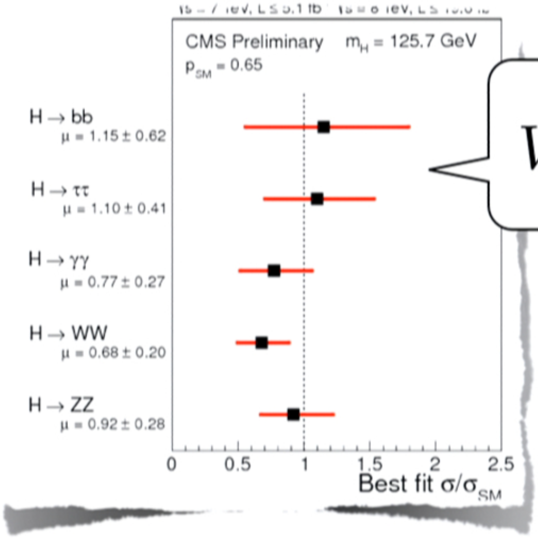
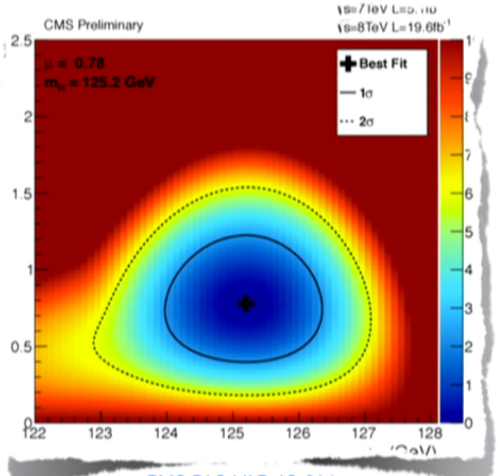
Naturalness of Higgs Properties



$$V(h) \approx \lambda(|h|^2 - \frac{v^2}{2})^2$$



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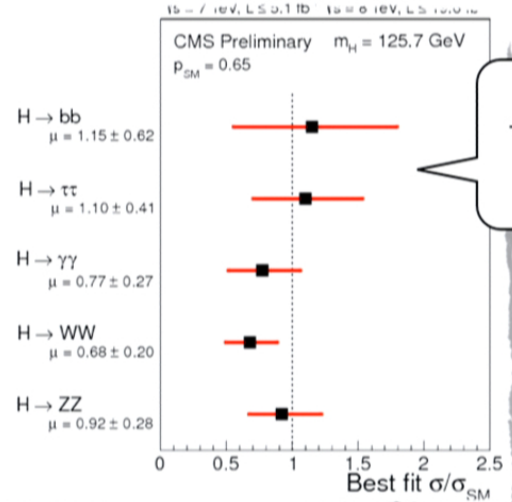
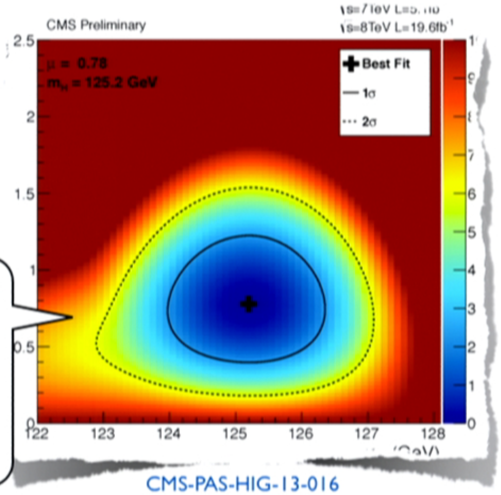


$$V(h) \approx \lambda(|h|^2 - \frac{v^2}{2})^2$$

MSSM ??? composite

λ small λ large

$$m^2_{h^0} = 2\lambda v^2 \approx (125\ \mathrm{GeV})^2$$



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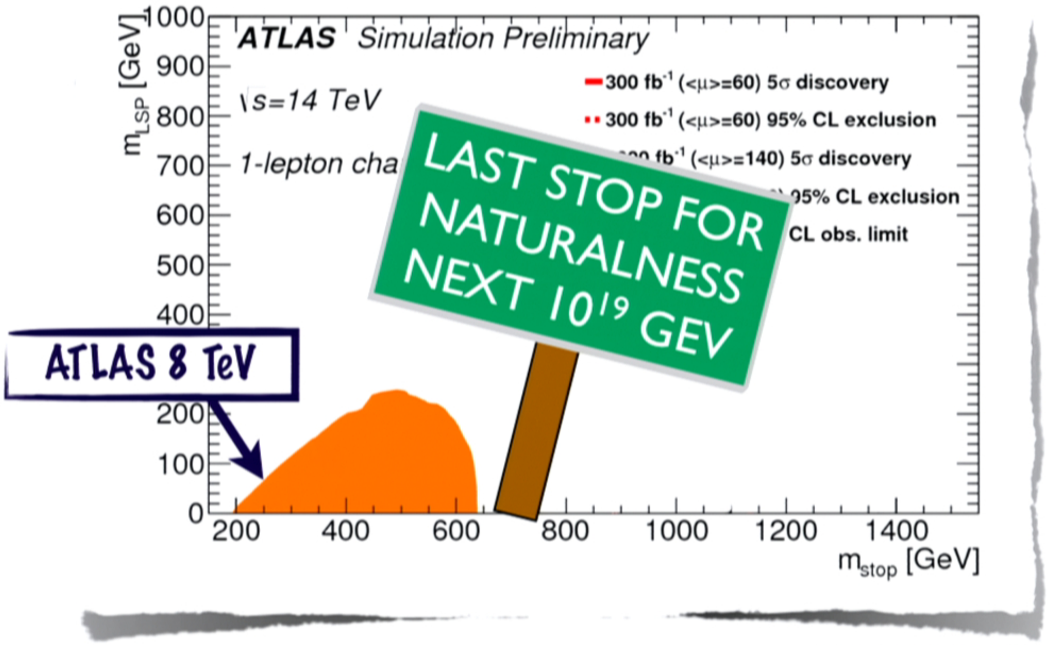
Naturalness of weak Scale



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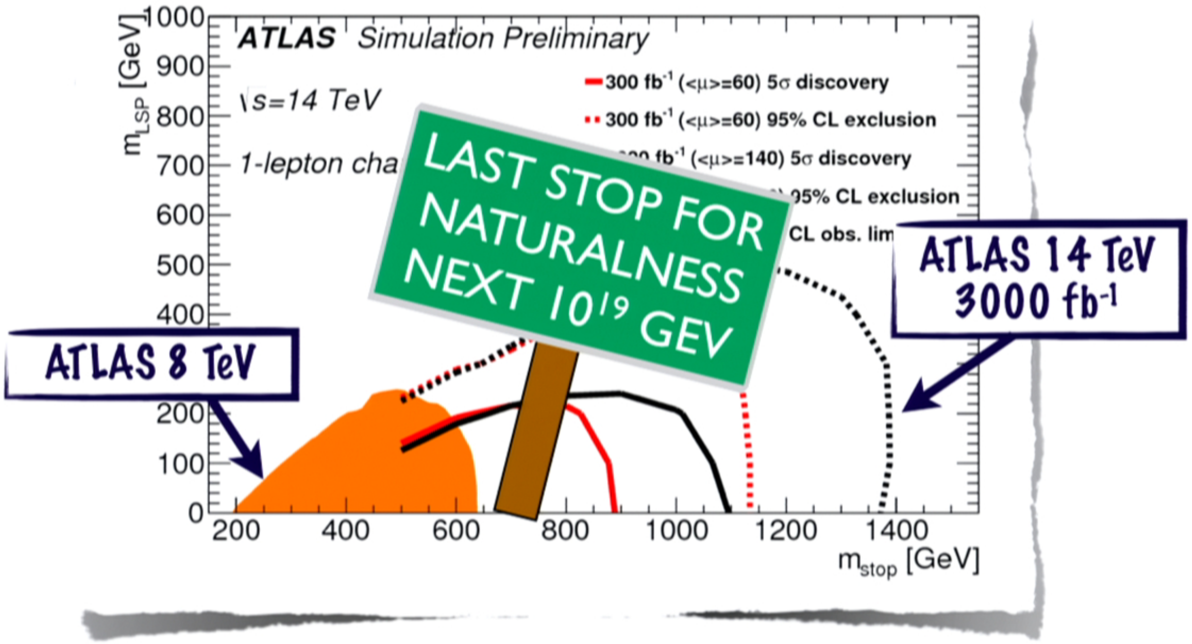
Naturalness of weak Scale



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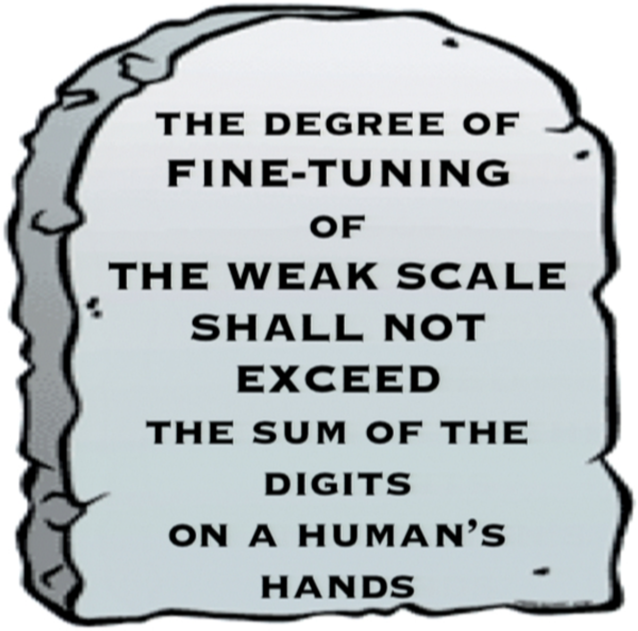
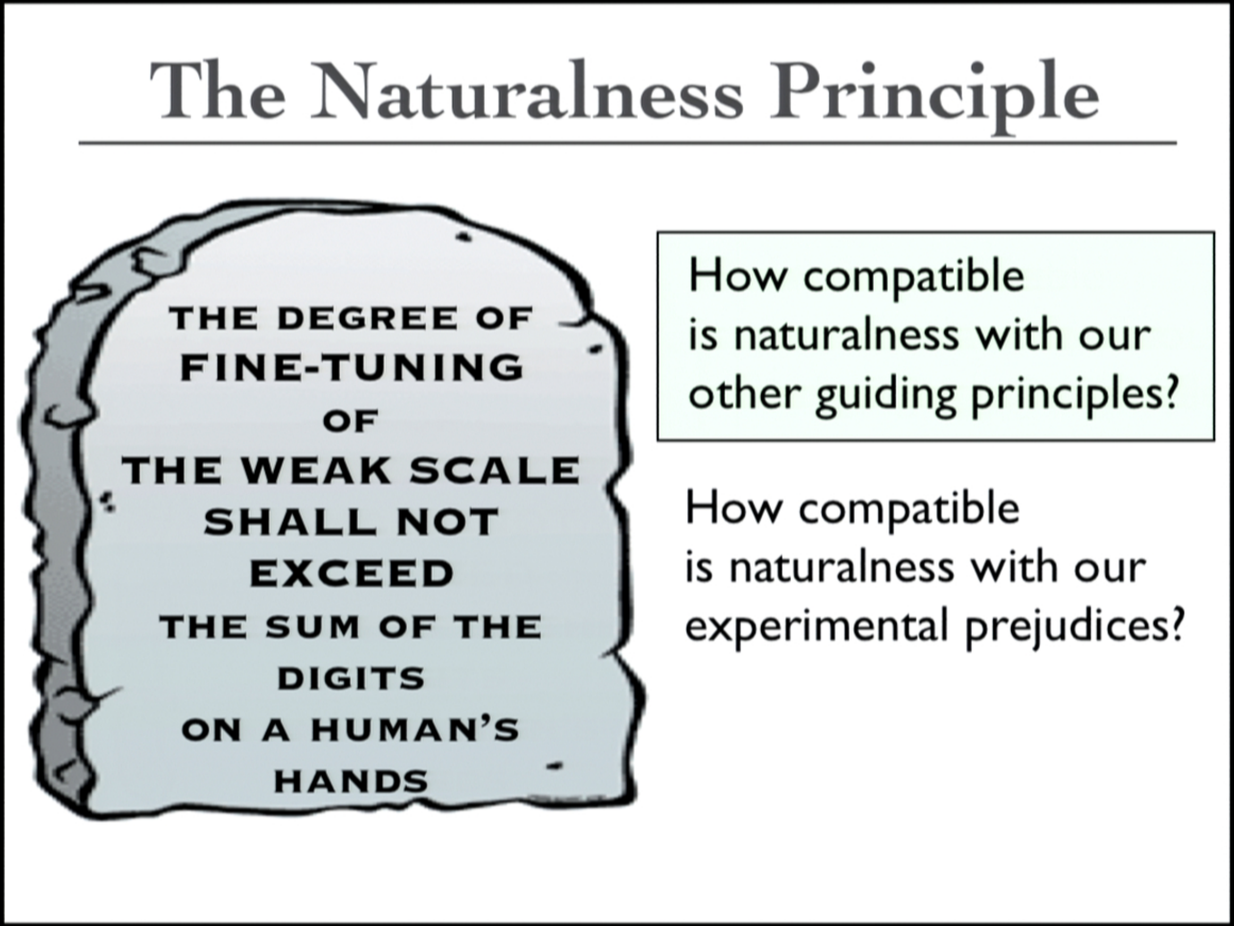
The Naturalness Principle



THE DEGREE OF FINE-TUNING OF THE WEAK SCALE SHALL NOT EXCEED THE SUM OF THE DIGITS ON A HUMAN'S HANDS

How compatible
is naturalness with our
other guiding principles?

How compatible
is naturalness with our
experimental prejudices?



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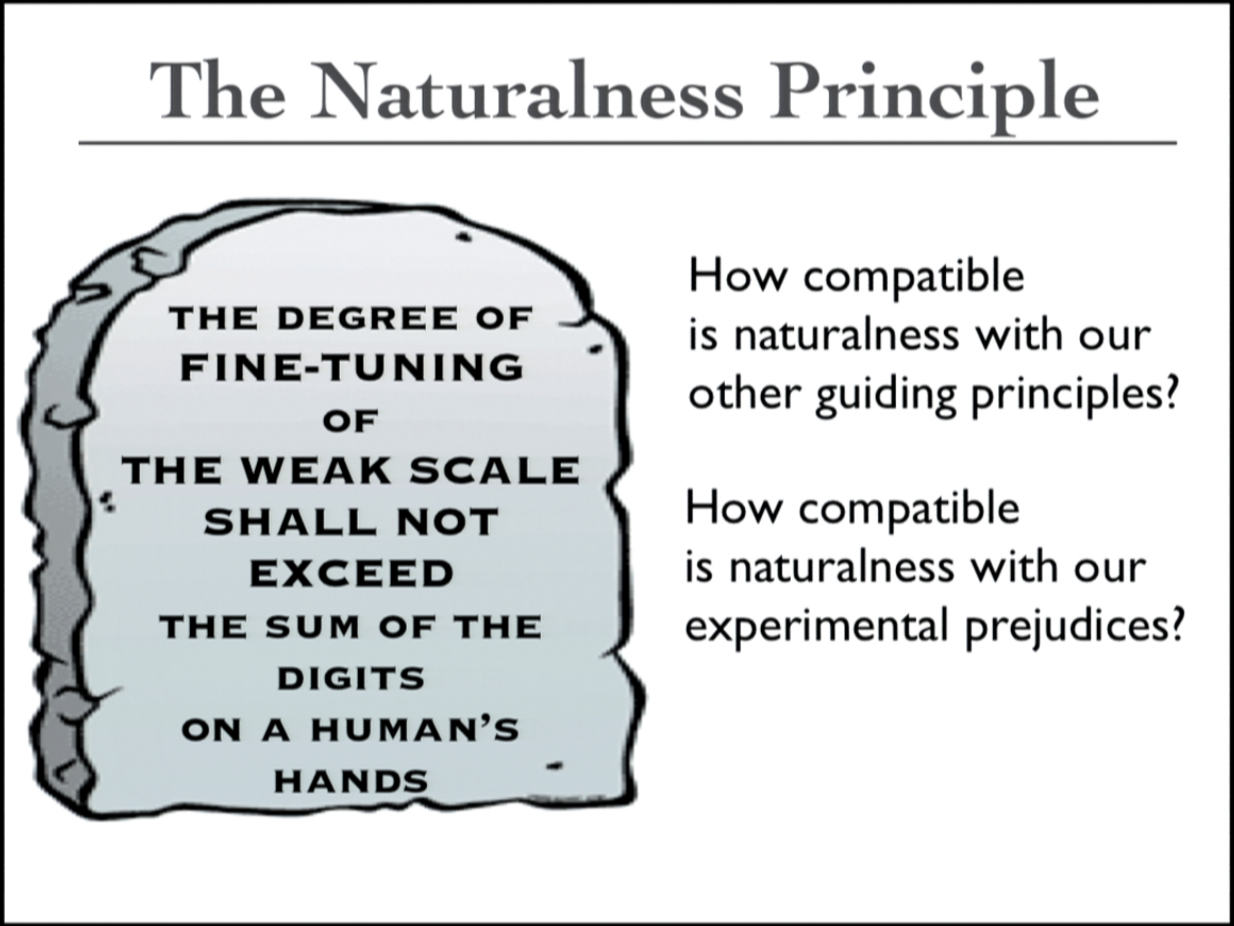

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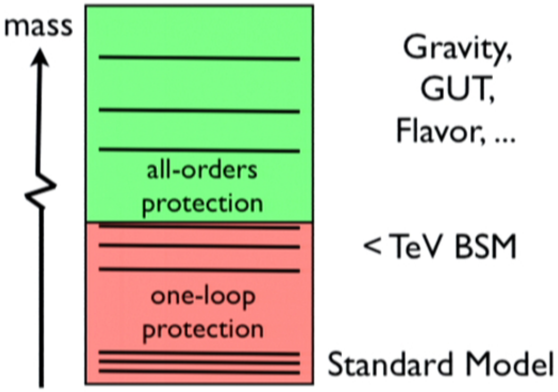
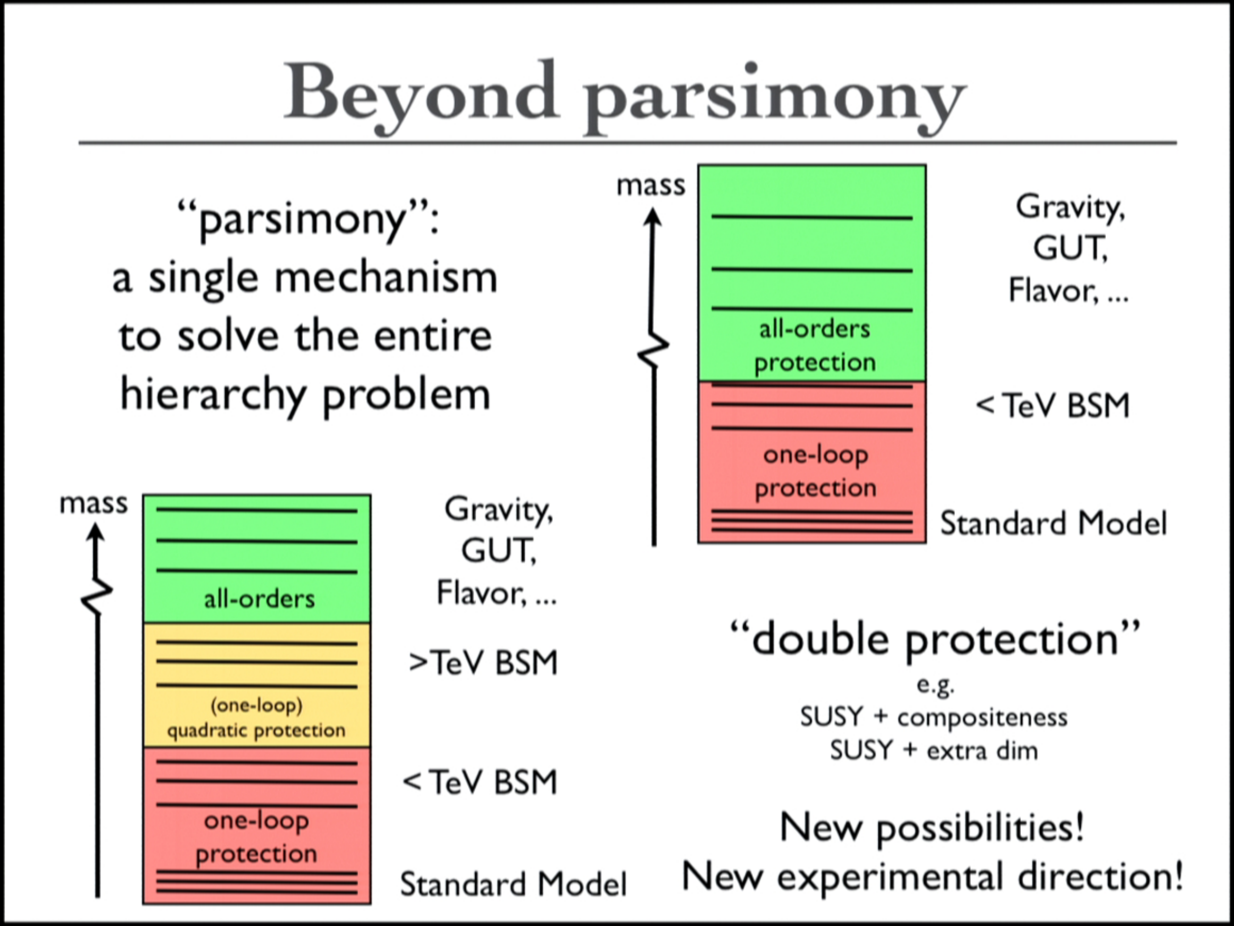
Beyond parsimony

“parsimony”:
a single mechanism
to solve the entire
hierarchy problem





Beyond parsimony

"parsimony":
a single mechanism
to solve the entire
hierarchy problem

"double protection"
e.g.
SUSY + compositeness
SUSY + extra dim

New possibilities!
New experimental direction!

Beyond parsimony

"parsimony":
a single mechanism
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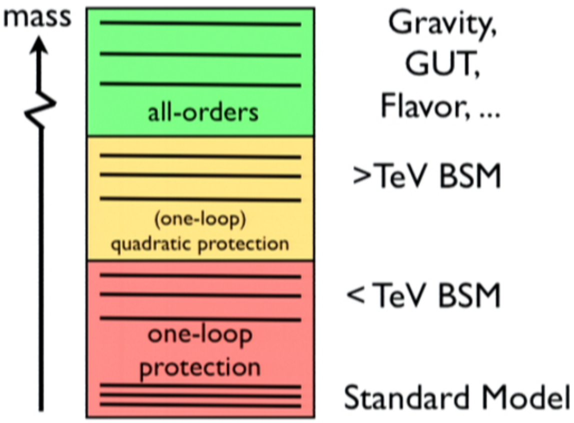
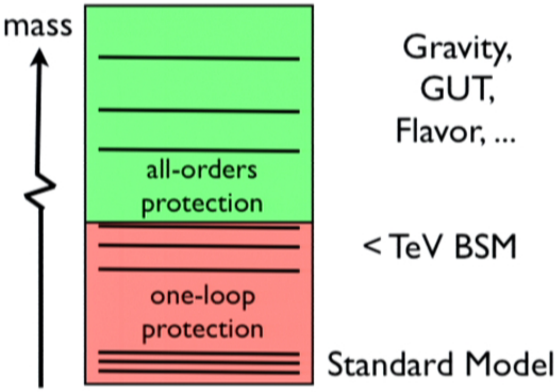


Gravity,
GUT,
Flavor, ...

>TeV BSM

< TeV BSM

Standard Model



Gravity,
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Flavor, ...

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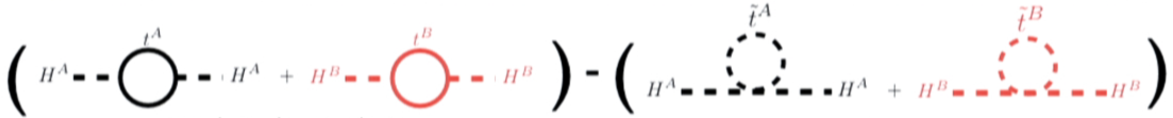
Standard Model

"double protection"
e.g.
SUSY + compositeness
SUSY + extra dim

New possibilities!
New experimental direction!

Ingredients for “double protection”



cancels one-loop quadratic

cuts off one-loop log

IR “Mirror” Twin Higgs

Higgs as (weakly coupled) PNGB

Light *uncharged* mirror states partially restore global symmetry

Novel Higgs Physics

Extremely low tuning

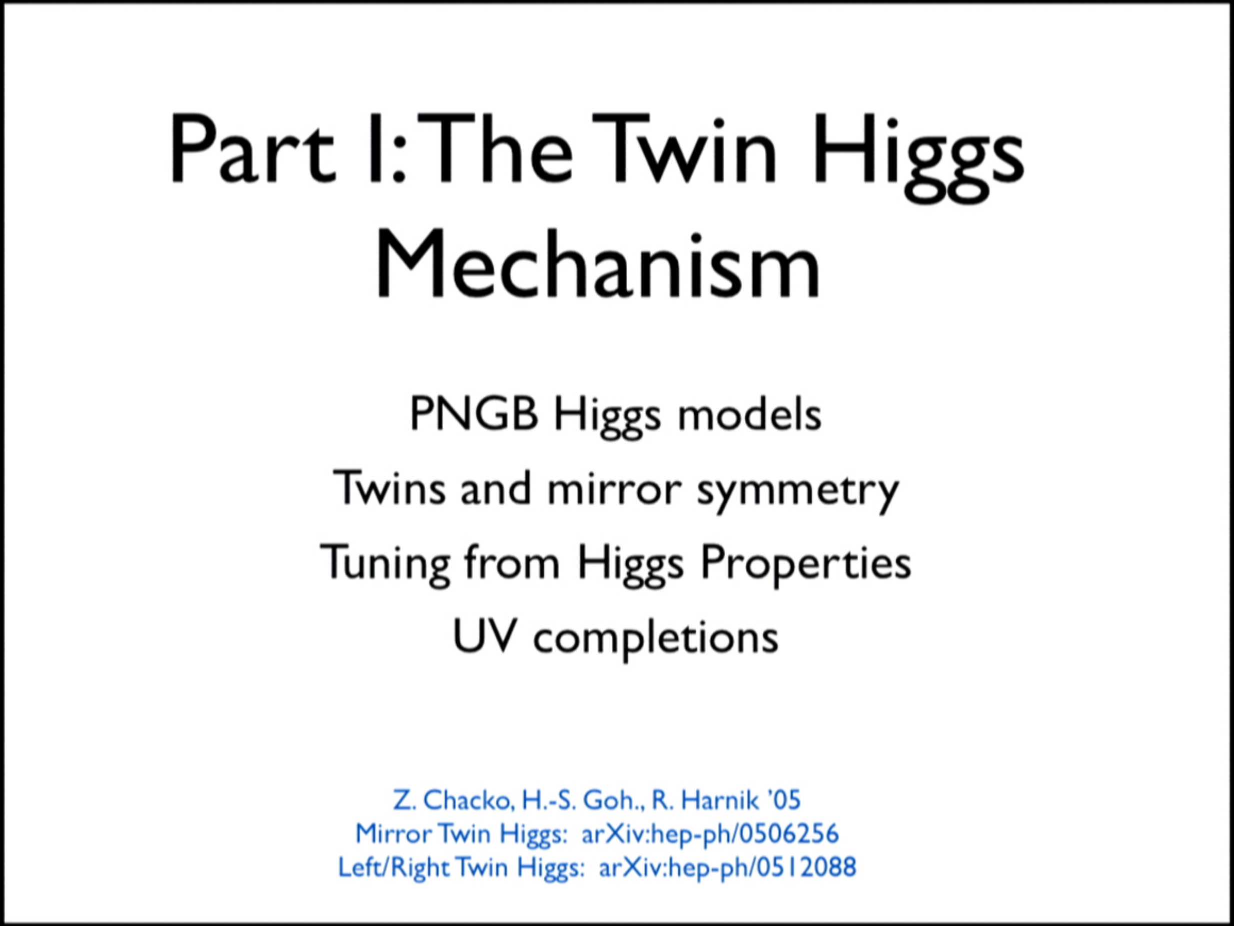
UV Supersymmetry

Gauge coupling unification*

Squarks/gluinos pushed beyond 14 TeV reach*

Protection against EWPT and Flavor

“natural” Higgs mass



Part I: The Twin Higgs Mechanism

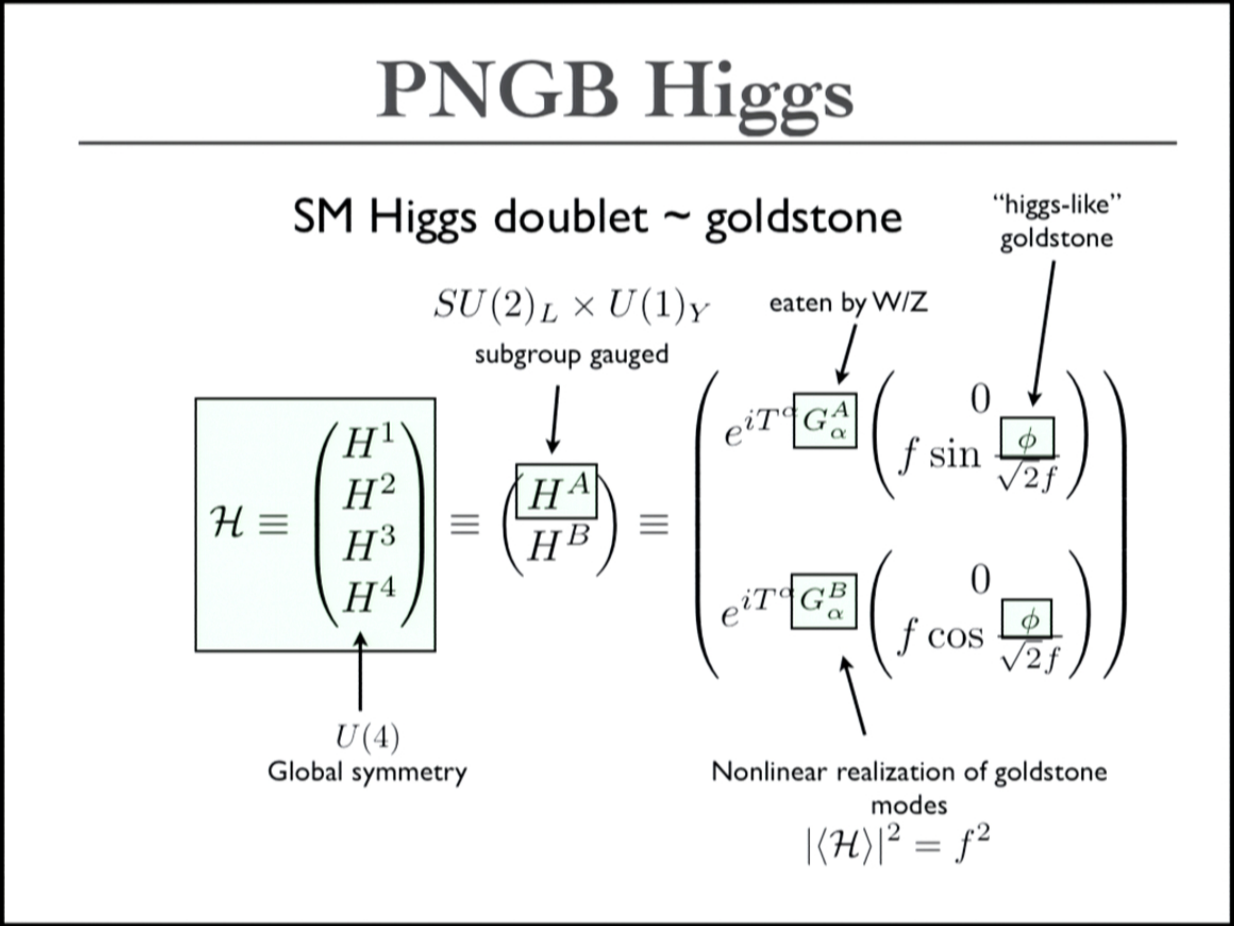
PNGB Higgs models

Twins and mirror symmetry

Tuning from Higgs Properties

UV completions

Z. Chacko, H.-S. Goh., R. Harnik '05
Mirror Twin Higgs: arXiv:hep-ph/0506256
Left/Right Twin Higgs: arXiv:hep-ph/0512088



PNGB Higgs

SM Higgs doublet ~ goldstone

“higgs-like” goldstone

$SU(2)_L \times U(1)_Y$

subgroup gauged

eaten by W/Z

$$\boxed{\mathcal{H} \equiv \begin{pmatrix} H^1 \\ H^2 \\ H^3 \\ H^4 \end{pmatrix}} \equiv \begin{pmatrix} \boxed{H^A} \\ H^B \end{pmatrix} \equiv \begin{pmatrix} e^{iT^\alpha \boxed{G^A_\alpha}} \begin{pmatrix} 0 \\ f \sin \frac{\boxed{\phi}}{\sqrt{2} f} \end{pmatrix} \\ e^{iT^\alpha \boxed{G^B_\alpha}} \begin{pmatrix} 0 \\ f \cos \frac{\boxed{\phi}}{\sqrt{2} f} \end{pmatrix} \end{pmatrix}$$

$U(4)$

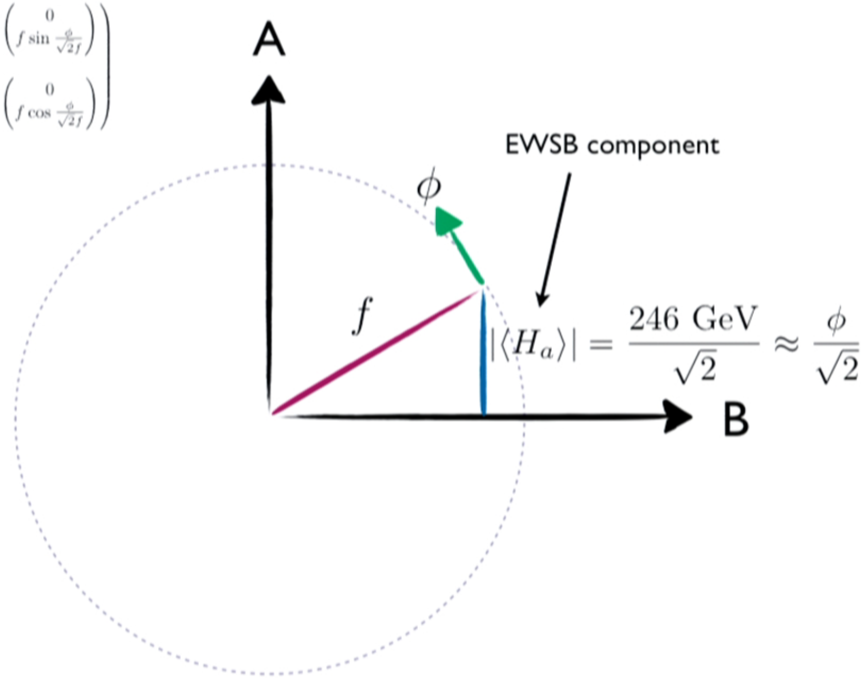
Global symmetry

Nonlinear realization of goldstone modes

$|\langle\mathcal{H}\rangle|^2 = f^2$

PNGB Higgs

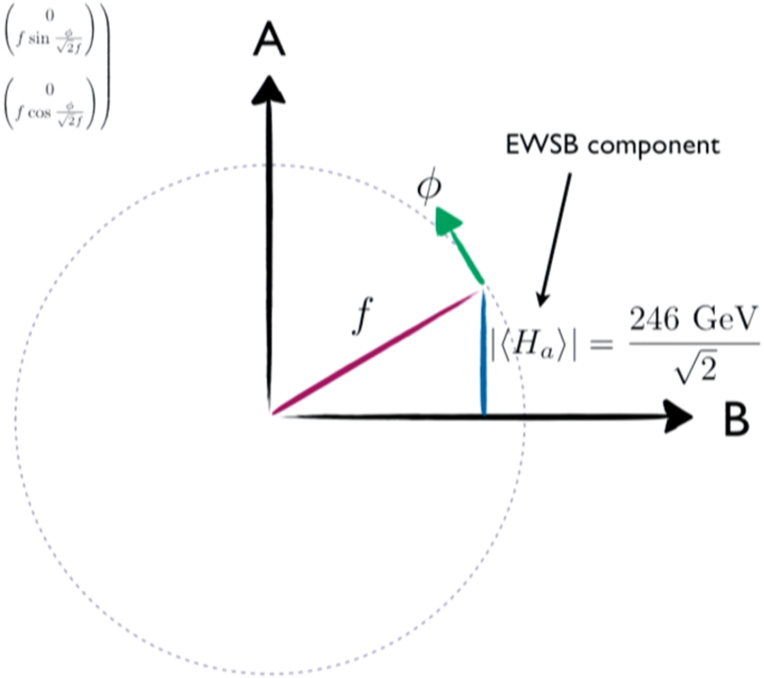
$$\mathcal{H} \equiv \begin{pmatrix} H^1 \\ H^2 \\ H^3 \\ H^4 \end{pmatrix} \equiv \begin{pmatrix} H^A \\ H^B \end{pmatrix} \equiv \begin{pmatrix} e^{iT^a G^A_a} \begin{pmatrix} 0 \\ f \sin \frac{\phi}{\sqrt{2} f} \end{pmatrix} \\ \\ e^{iT^a G^B_a} \begin{pmatrix} 0 \\ f \cos \frac{\phi}{\sqrt{2} f} \end{pmatrix} \end{pmatrix}$$



$$|\langle H_a \rangle| = \frac{246\ \text{GeV}}{\sqrt{2}} \approx \frac{\phi}{\sqrt{2}}$$

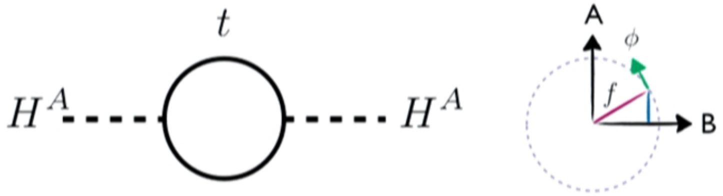
PNGB Higgs

$$\mathcal{H} \equiv \begin{pmatrix} H^1 \\ H^2 \\ H^3 \\ H^4 \end{pmatrix} \equiv \begin{pmatrix} H^A \\ H^B \end{pmatrix} \equiv \begin{pmatrix} e^{iT^a G_a^A} \begin{pmatrix} 0 \\ f \sin \frac{\phi}{\sqrt{2} f} \end{pmatrix} \\ e^{iT^a G_a^B} \begin{pmatrix} 0 \\ f \cos \frac{\phi}{\sqrt{2} f} \end{pmatrix} \end{pmatrix}$$



$$|\langle H_a \rangle| = \frac{246 \text{ GeV}}{\sqrt{2}} \approx \frac{\phi}{\sqrt{2}}$$

one-loop protection?



$$\delta V_{1-\mathrm{loop}} \approx -\frac{3y_t^2\boxed{\Lambda_t^2}}{16\pi^2}|H^A|^2 = -\boxed{\frac{3y_t^2\Lambda_t^2 f^2}{16\pi^2}}\boxed{\sin^2(\frac{\phi}{\sqrt{2}f})}$$

$$\delta V_{1-\mathrm{loop}} \sim \boxed{0.02\frac{\Lambda_t^2}{f^2}} \times \boxed{(c_1\frac{\phi^2}{2} - c_2 f^2)^2} + \ldots$$

$$\frac{m_{h^0}^2}{(125\ \mathrm{GeV})^2} \sim \frac{\Lambda_t^2}{(2f)^2}$$

Tension with Higgs mass & colored partner searches

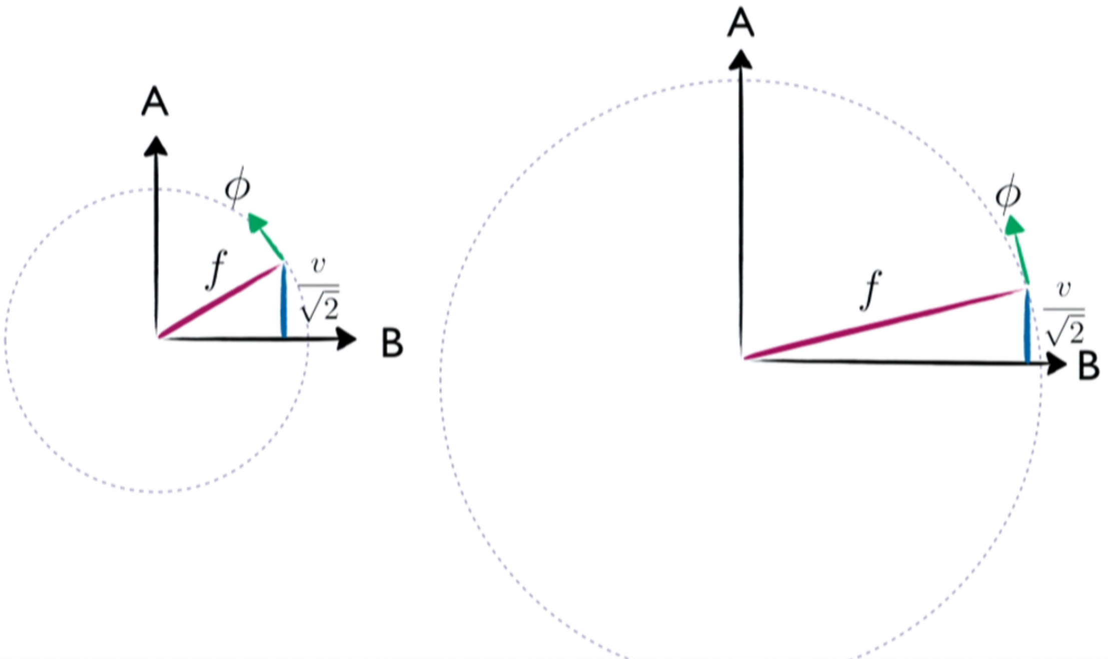
$$f \sim v$$

Tension with Higgs couplings

Generic problems for PNGB Higgs models! (see e.g. Bellazzini et. al.)

PNGB Higgs Couplings

$f \sim v$ $\qquad$ $f \gg v$



PNGB Higgs Couplings

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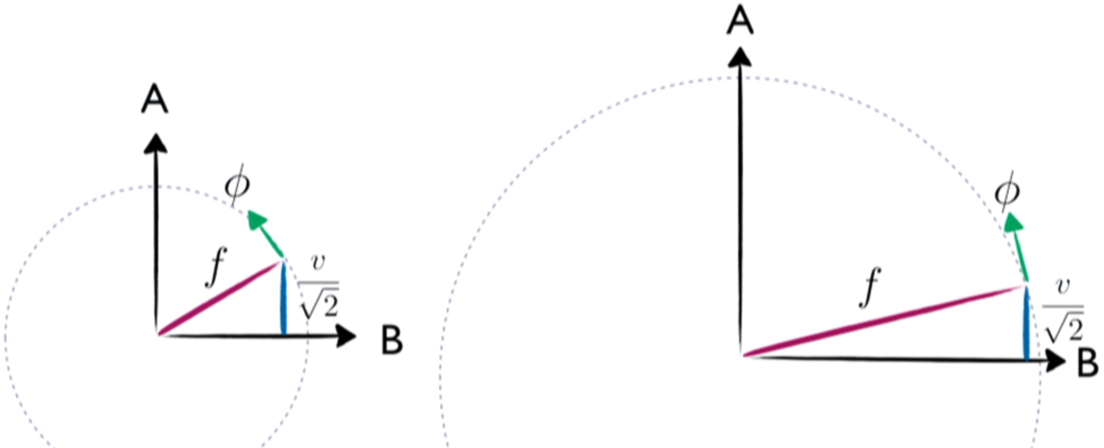
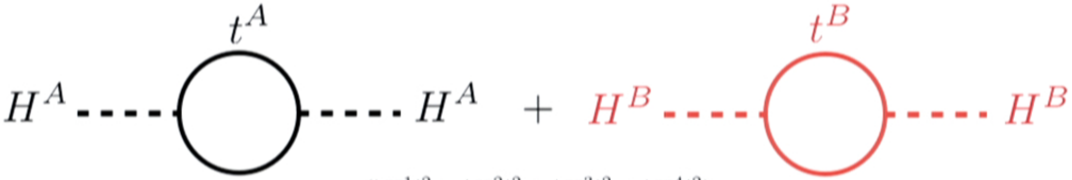


$$\frac{g^2_{\phi XX}}{g^2_{h^0_{\rm SM} XX}} = (1 - \frac{v^2}{2f^2})$$ → $f \gtrsim$ 500GeV

Mirror symmetry

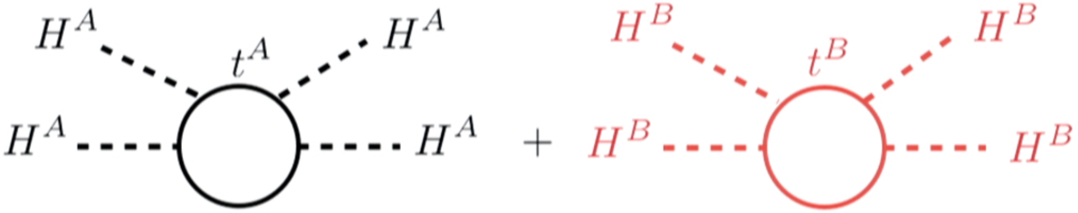


$$\delta V = -\frac{3y_t^2\Lambda_t^2}{16\pi^2}\Big(\underbrace{\overbrace{|H^A|^2 + |H^B|^2}^{(|H^1|^2+|H^2|^2+|H^3|^2+|H^4|^2)}}_{}\Big)$$

$$\sin^2(\frac{\phi}{\sqrt{2}}) + \cos^2(\frac{\phi}{\sqrt{2}}) = 1!!!$$

Mirror Z_2 → Accidental $U(4)$ for all quadratic diagrams!

Mirror symmetry

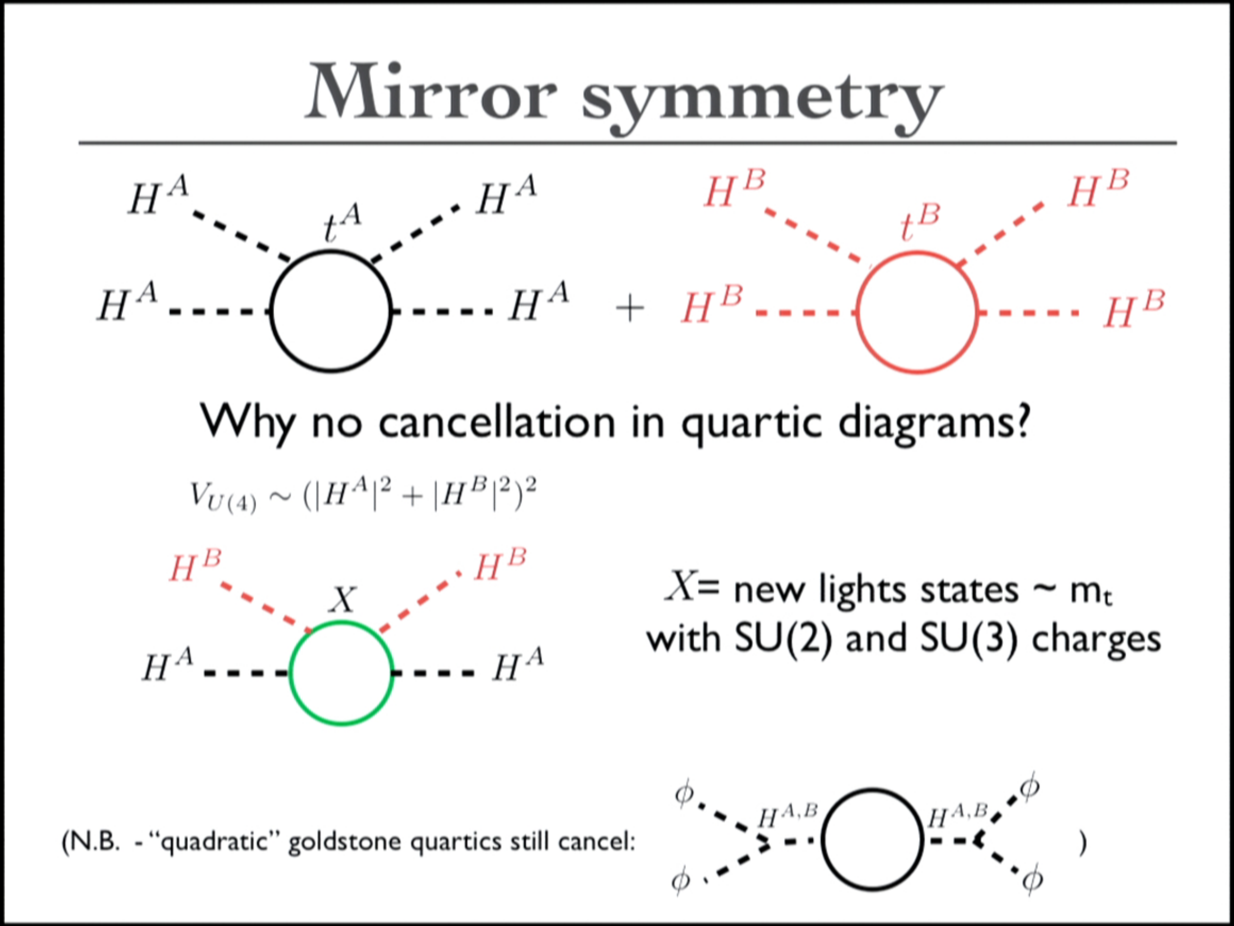


$$\delta V = \frac{3y_t^4 \cancel{\Lambda_t^2}}{16\pi^2} \log\left(\frac{\Lambda_t^2}{m_t^2}\right) \underbrace{\left(|H^A|^4 + |H^B|^4\right)}_{\sin^4(\frac{\phi}{\sqrt{2}}) + \cos^4(\frac{\phi}{\sqrt{2}})}$$

symmetric minimum: $|H^B| = |H^A| = f\sin(\frac{\phi}{\sqrt{2}}) = \frac{f}{\sqrt{2}}$

log sensitivity of higgs pole mass:

$m_{h^0} = 125$ GeV for $\Lambda_t \sim 5 - 10$ TeV



Mirror symmetry

Why no cancellation in quartic diagrams?

$$V_{U(4)} \sim (|H^A|^2 + |H^B|^2)^2$$

X= new lights states ~ m_t
with SU(2) and SU(3) charges

(N.B. - "quadratic" goldstone quartics still cancel:

)

Full mirror symmetry?

Standard Model (A) **Mirror Sector (B)**

$y_t^A H^A Q_3^A t^A$ → $y_t^B H^B Q_3^B t^B$

cancellation for $N(t^A) = N(t^B)$ & $y_t^A \approx y_t^B$ & $\Lambda_t^A \approx \Lambda_t^B$

$SU(2)^A \times U(1)^A$ → $SU(2)^B \times U(1)^B$

cancellation of quadratic EW for $g_{1,2}^A \approx g_{1,2}^B$ (and eat extra goldstones)

$SU(3)^A$ → $SU(3)^B$ (left/right models?)

two-loop cancellation (e.g. running of y_t) for $g_3^A \approx g_3^B$

1st & 2nd generations, tau, b → light mirror fermions?

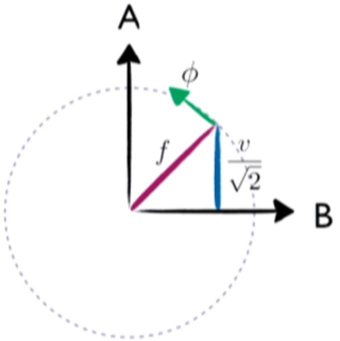
running of couplings needs only $N_f(A) = N_f(B)$ ($y_{ij}^A \neq y_{ij}^B$)

Z_2 Breaking

Obligatory radiative potential:

$$V(\phi)_{Z2} \sim \cos^4(\frac{\phi}{\sqrt{2}}) + \sin^4(\frac{\phi}{\sqrt{2}})$$

$$|H^A| = |H^B|$$



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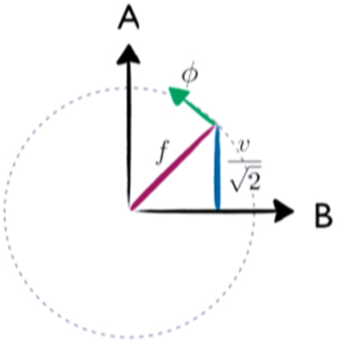
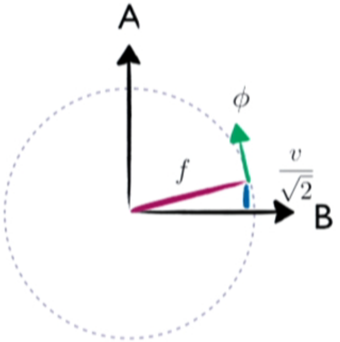


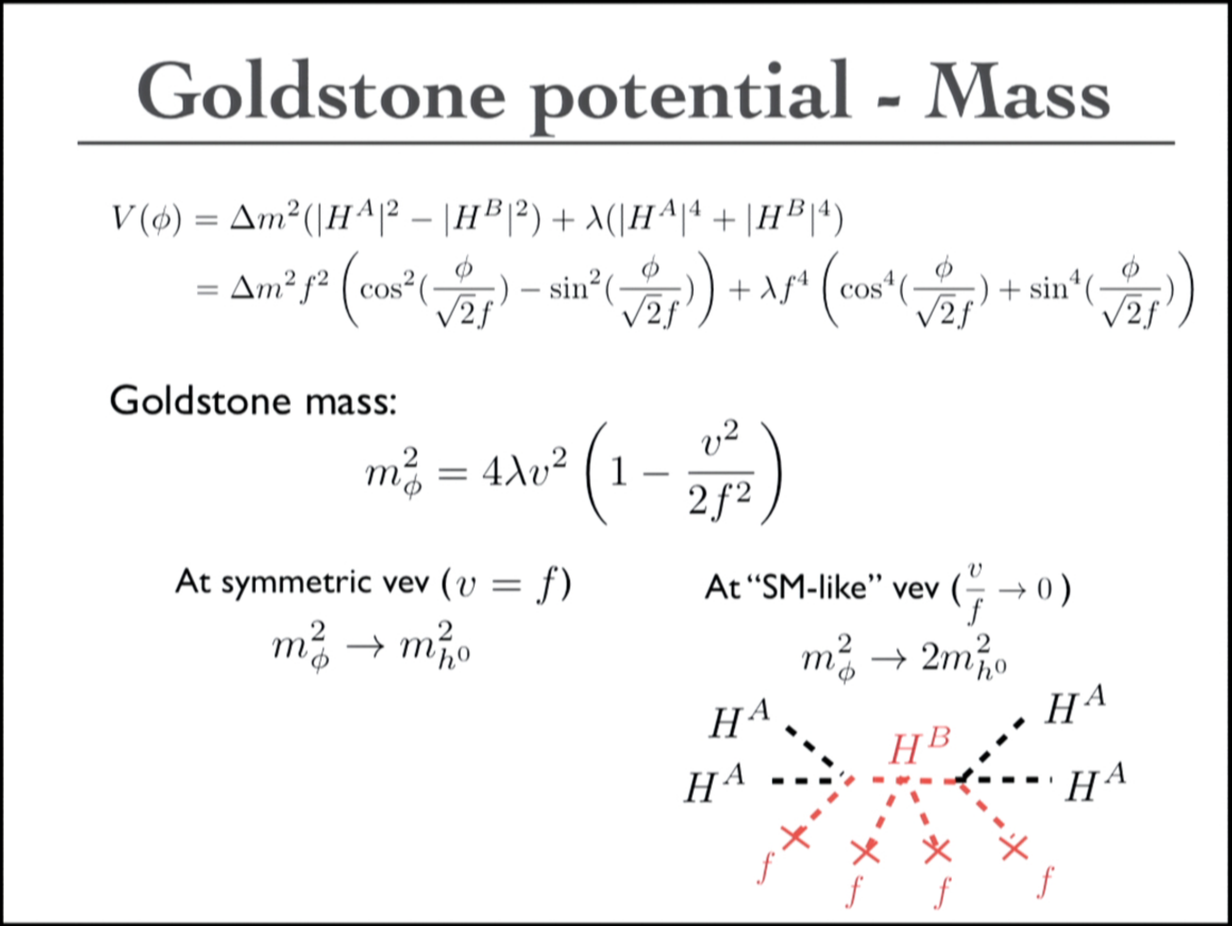
“by hand” Z_2 breaking

“Soft breaking”

$$V(\phi)_{\cancel{Z_2}} \sim \begin{array}{l} \Delta m^2(|H^A|^2 - |H^B|^2) \sim \cos^2(\frac{\phi}{\sqrt{2}f}) - \sin^2(\frac{\phi}{\sqrt{2}f}) \\ \Delta\lambda(|H^A|^4 - |H^B|^4) \sim \cos^4(\frac{\phi}{\sqrt{2}f}) - \sin^4(\frac{\phi}{\sqrt{2}f}) \end{array}$$

“Hard breaking”





Goldstone potential - Mass

$$V(\phi) = \Delta m^2(|H^A|^2 - |H^B|^2) + \lambda(|H^A|^4 + |H^B|^4)$$
$$= \Delta m^2 f^2 \left(\cos^2(\frac{\phi}{\sqrt{2}f}) - \sin^2(\frac{\phi}{\sqrt{2}f})\right) + \lambda f^4 \left(\cos^4(\frac{\phi}{\sqrt{2}f}) + \sin^4(\frac{\phi}{\sqrt{2}f})\right)$$

Goldstone mass:

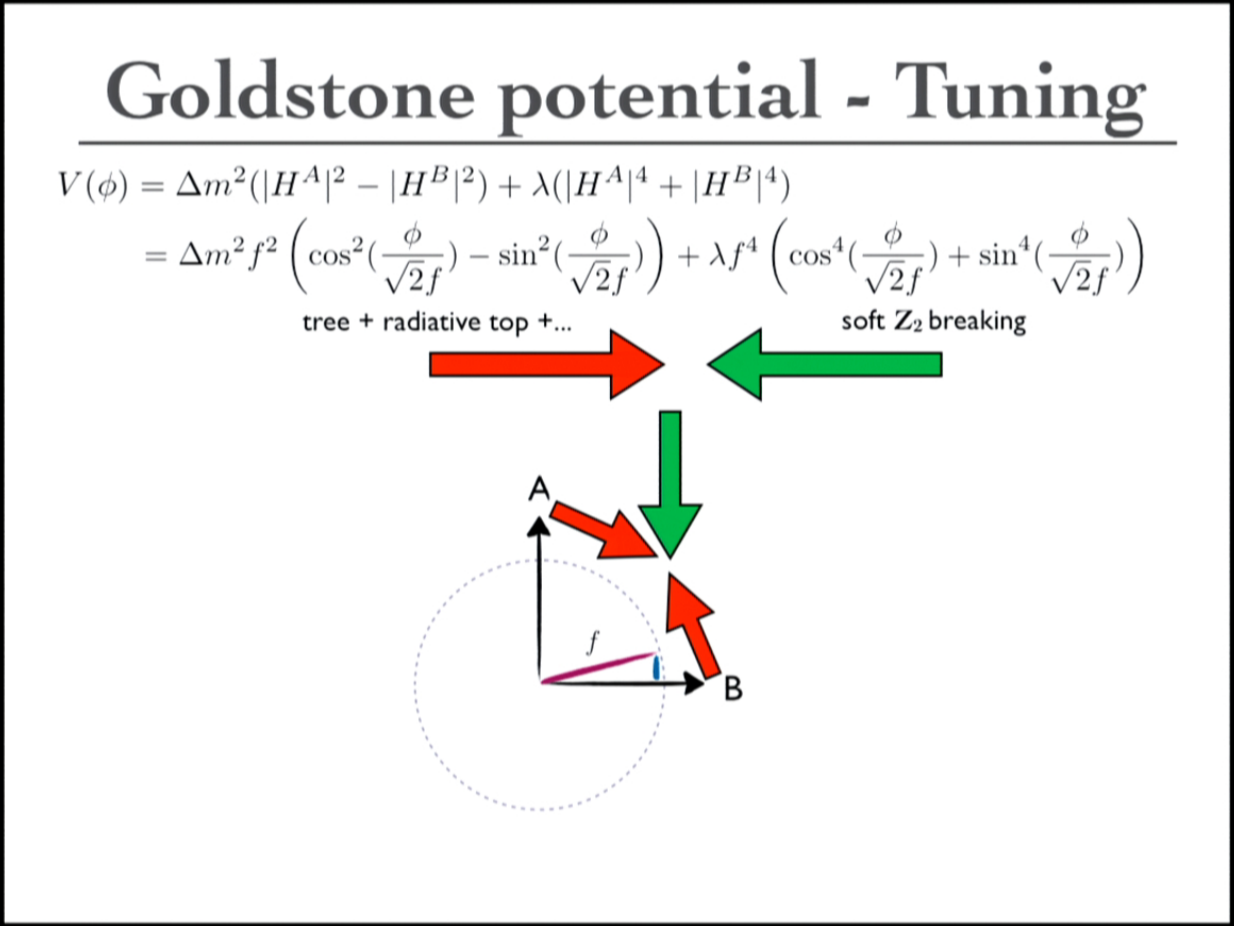
$$m_\phi^2 = 4\lambda v^2 \left(1 - \frac{v^2}{2f^2}\right)$$

At symmetric vev $(v = f)$

$$m_\phi^2 \to m_{h^0}^2$$

At "SM-like" vev ($\frac{v}{f} \to 0$)

$$m_\phi^2 \to 2m_{h^0}^2$$



Goldstone potential - Tuning

$$V(\phi) = \Delta m^2(|H^A|^2 - |H^B|^2) + \lambda(|H^A|^4 + |H^B|^4)$$

$$= \Delta m^2 f^2 \left(\cos^2(\frac{\phi}{\sqrt{2}f}) - \sin^2(\frac{\phi}{\sqrt{2}f})\right) + \lambda f^4 \left(\cos^4(\frac{\phi}{\sqrt{2}f}) + \sin^4(\frac{\phi}{\sqrt{2}f})\right)$$

tree + radiative top +...

soft Z_2 breaking

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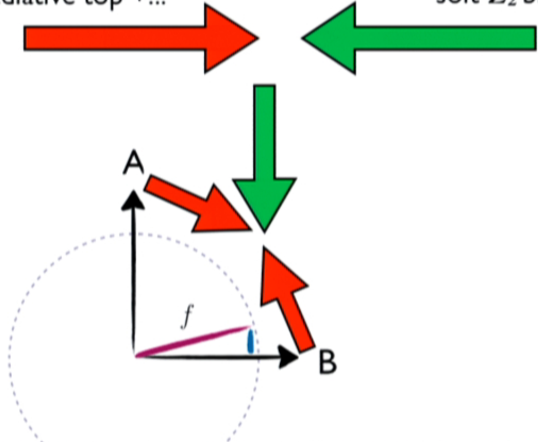
tree + radiative top +...

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Tuning: $\Delta_{v/f} = \frac{\partial \ln(v^2/f^2)}{\partial \ln \Delta m^2} = \left(\frac{f^2}{v^2} - 1\right)$

Tuning?

Mirror, mirror of the arXiv--
Who is the least tuned model of them all?

Tuning?

Mirror, mirror of the arXiv--
Who is the least tuned model of them all?

Composite twin higgs? $\Lambda_t \sim \Lambda_{\mathcal{H}} \sim 4\pi f$

Λ (TeV)	f (GeV)	M (TeV)	M_B (TeV)	μ (GeV)	m_h (GeV)	Tuning
10	800	6	1	239	122	0.134
6	500	5.5	1	145	121	0.378
10	800	—	0	355	166	0.112
6	500	—	0	203	153	0.307

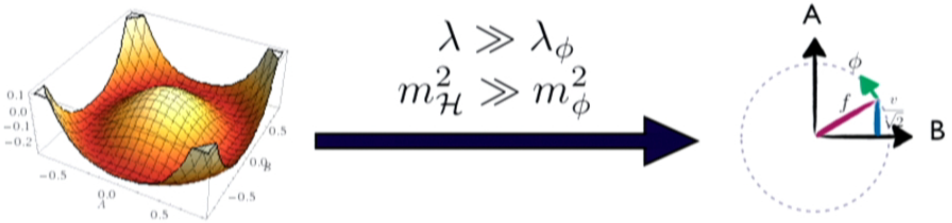
Z. Chacko, H.-S. Goh., R. Harnik '05

Goldstone UV completion

Perturbative Goldstone: $V(\mathcal{H}) = -m_{\mathcal{H}}^2|\mathcal{H}|^2 + \lambda|\mathcal{H}|^4$

(R. Barbieri, T. Gregoire, L. J. Hall '05 arXiv: hep-ph/0509242)

(U(4) Symmetric!)



$$\lambda \gg \lambda_\phi$$
$$m_{\mathcal{H}}^2 \gg m_\phi^2$$

Quadratic sensitivity re-enters! $\delta m_{\mathcal{H}}^2 \sim -\frac{3y_t^2\Lambda_t^2}{16\pi^2}$

Protection due to large U(4) symmetric quartic coupling $\langle\mathcal{H}\rangle \equiv f \sim \frac{m_{\mathcal{H}}^2}{\lambda}$

Not constrained by $m_h = 125$ GeV $\rightarrow \lambda \gg \lambda_{\rm SM}$ possible

Strongly coupled goldstone: $\sim \lambda \rightarrow (4\pi)^2 \quad m_{\mathcal{H}}^2 \rightarrow \Lambda_S^2$

Goldstone UV completion

Perturbative Goldstone: $V(\mathcal{H}) = -m_{\mathcal{H}}^2|\mathcal{H}|^2 + \lambda|\mathcal{H}|^4$

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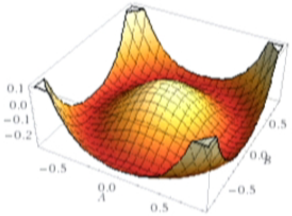
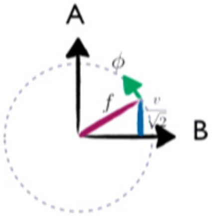


$$\lambda \gg \lambda_\phi$$
$$m_{\mathcal{H}}^2 \gg m_\phi^2$$



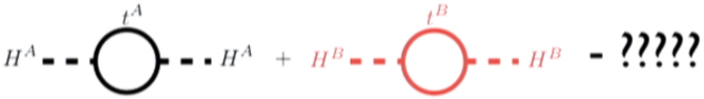
Quadratic sensitivity re-enters! $\delta m_{\mathcal{H}}^2 \sim -\frac{3y_t^2\Lambda_t^2}{16\pi^2}$

Protection due to large U(4) symmetric quartic coupling $\langle\mathcal{H}\rangle \equiv f \sim \frac{m_{\mathcal{H}}^2}{\lambda}$

Not constrained by $m_h = 125\ \mathrm{GeV}$ $\rightarrow \lambda \gg \lambda_{\mathrm{SM}}$ possible

Strongly coupled goldstone: $\sim \lambda \rightarrow (4\pi)^2 \quad m_{\mathcal{H}}^2 \rightarrow \Lambda_S^2$

Full* UV completion?



Composite PNGB Higgs w/top + gauge partners

Natural completion for
"strongly coupled goldstone"

Less constrained pheno

Fine-tuning

SUSY

Natural completion for
"perturbative goldstone"

MSSM-like gauge coupling unification

Avoid introducing mixed U(1) charged matter

EWPT & Flavor*

Precise determination of Higgs mass & "honest" tuning

Unusual Higgs pheno

So far...

PNGB Higgs generally suffer from:

-v/f tuning (higgs couplings)

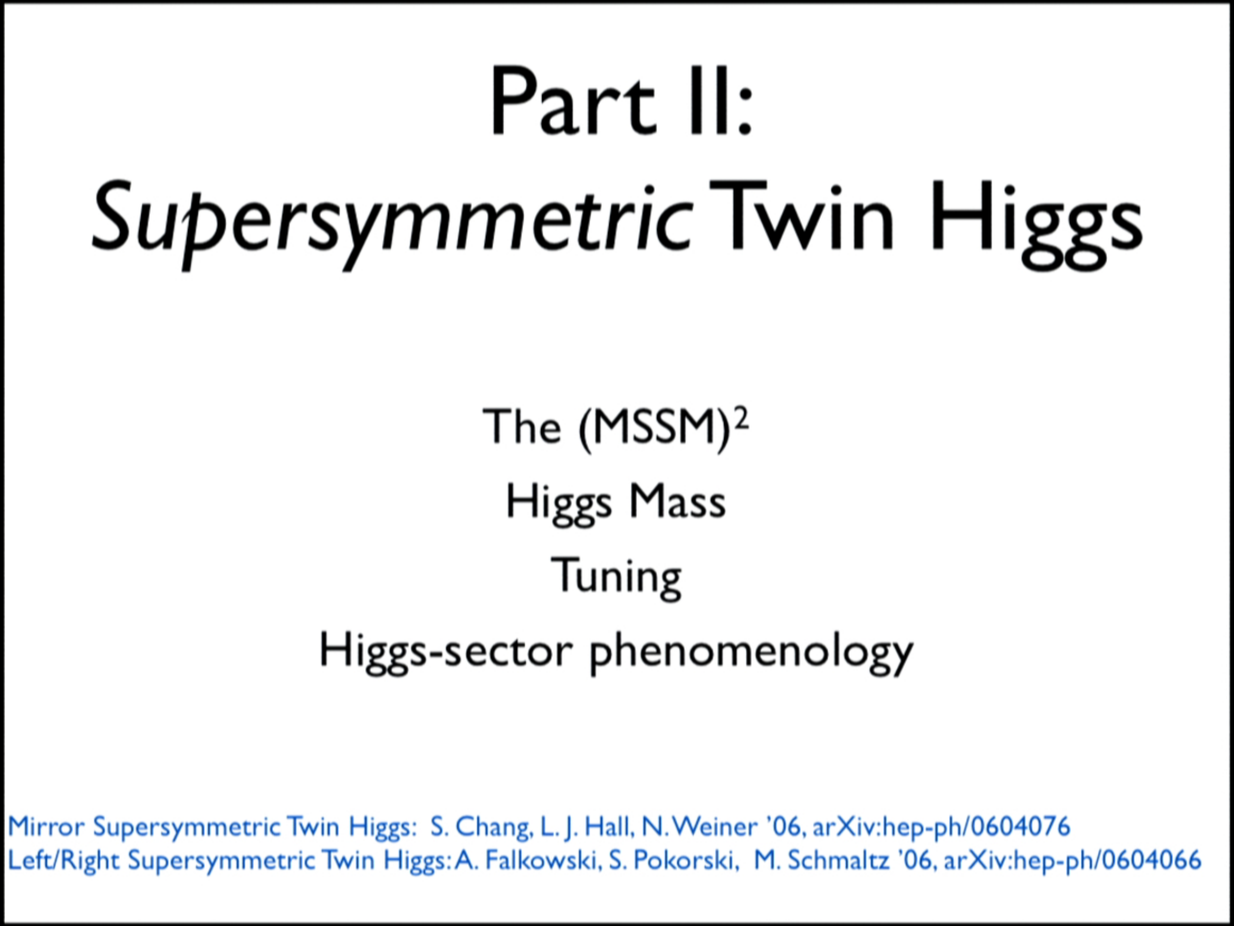
-Higgs mass tuning (colored partners)

Twin Higgs mechanism:

-removes quadratic top partner contributions to Higgs mass

-introduces no new light colored particles (mirror sector)

-reintroduces tuning from top partners in f, but suppressed by quartic potential



Part II:

Supersymmetric Twin Higgs

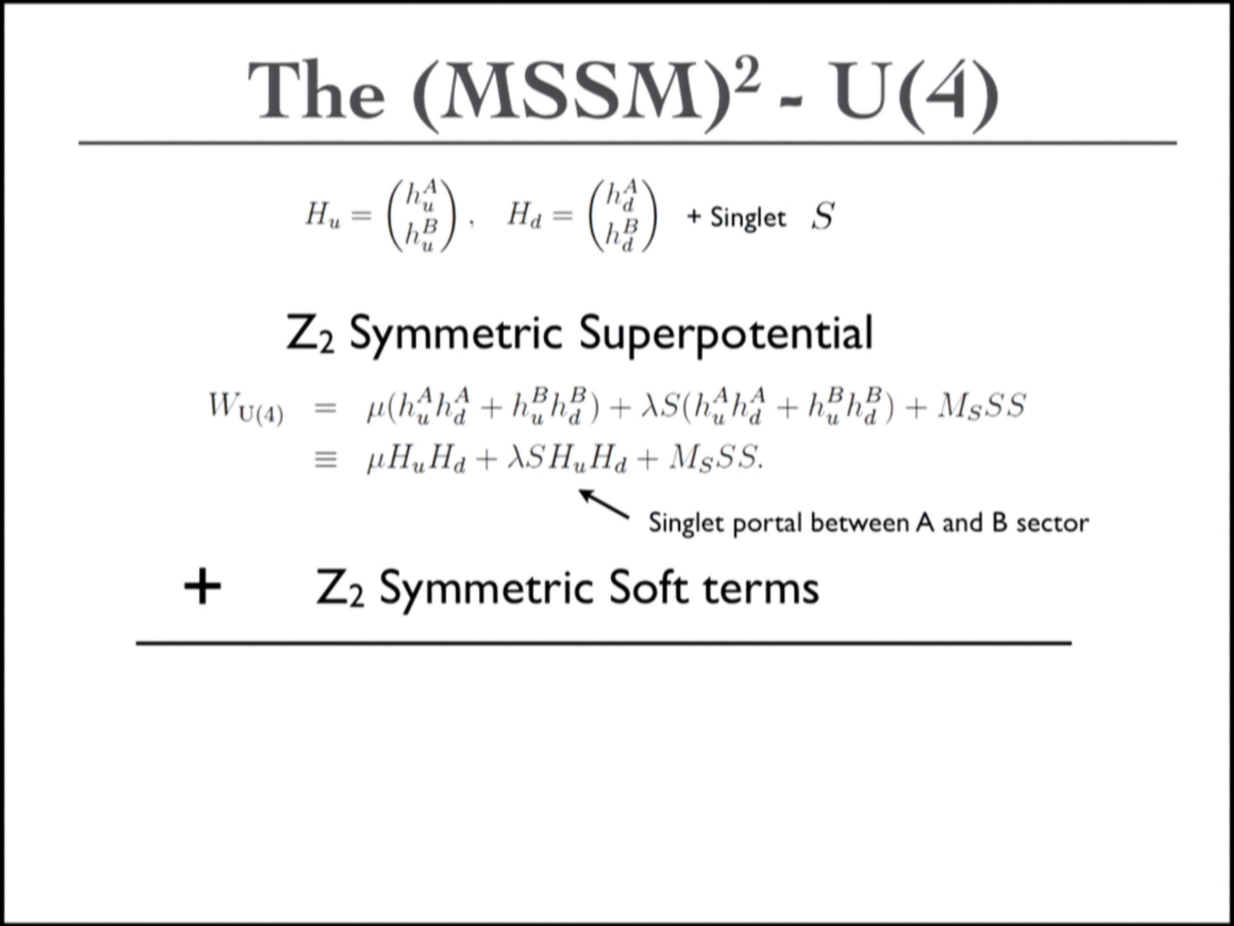
The (MSSM)^2

Higgs Mass

Tuning

Higgs-sector phenomenology

Mirror Supersymmetric Twin Higgs: S. Chang, L. J. Hall, N. Weiner '06, arXiv:hep-ph/0604076
Left/Right Supersymmetric Twin Higgs: A. Falkowski, S. Pokorski, M. Schmaltz '06, arXiv:hep-ph/0604066



The (MSSM)^2 - U(4)

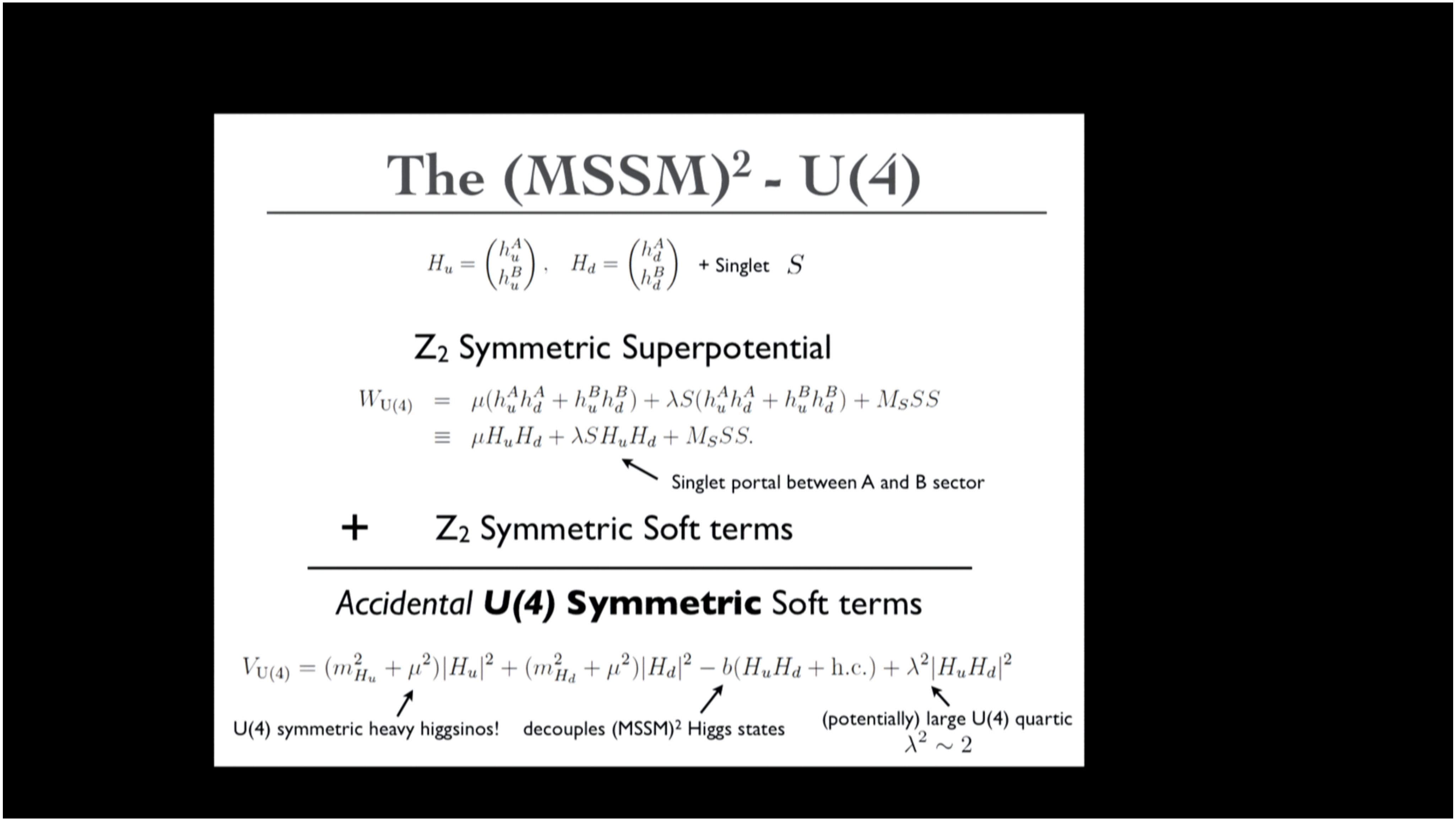
$$H_u = \begin{pmatrix} h_u^A \\ h_u^B \end{pmatrix}, \quad H_d = \begin{pmatrix} h_d^A \\ h_d^B \end{pmatrix}$$ + Singlet S

Z_2 Symmetric Superpotential

$$\begin{aligned} W_{\mathrm{U(4)}} &= \mu(h_u^A h_d^A + h_u^B h_d^B) + \lambda S(h_u^A h_d^A + h_u^B h_d^B) + M_S SS \\ &\equiv \mu H_u H_d + \lambda S H_u H_d + M_S SS. \end{aligned}$$

↖ Singlet portal between A and B sector

+ Z_2 Symmetric Soft terms



The (MSSM)^2 - U(4)

$$H_u = \begin{pmatrix} h_u^A \\ h_u^B \end{pmatrix}, \quad H_d = \begin{pmatrix} h_d^A \\ h_d^B \end{pmatrix}$$ + Singlet S

Z$_2$ Symmetric Superpotential

$$\begin{aligned} W_{\mathrm{U(4)}} &= \mu(h_u^A h_d^A + h_u^B h_d^B) + \lambda S(h_u^A h_d^A + h_u^B h_d^B) + M_S SS \\ &\equiv \mu H_u H_d + \lambda S H_u H_d + M_S SS. \end{aligned}$$

Singlet portal between A and B sector

+ Z$_2$ Symmetric Soft terms

Accidental **U(4) Symmetric** Soft terms

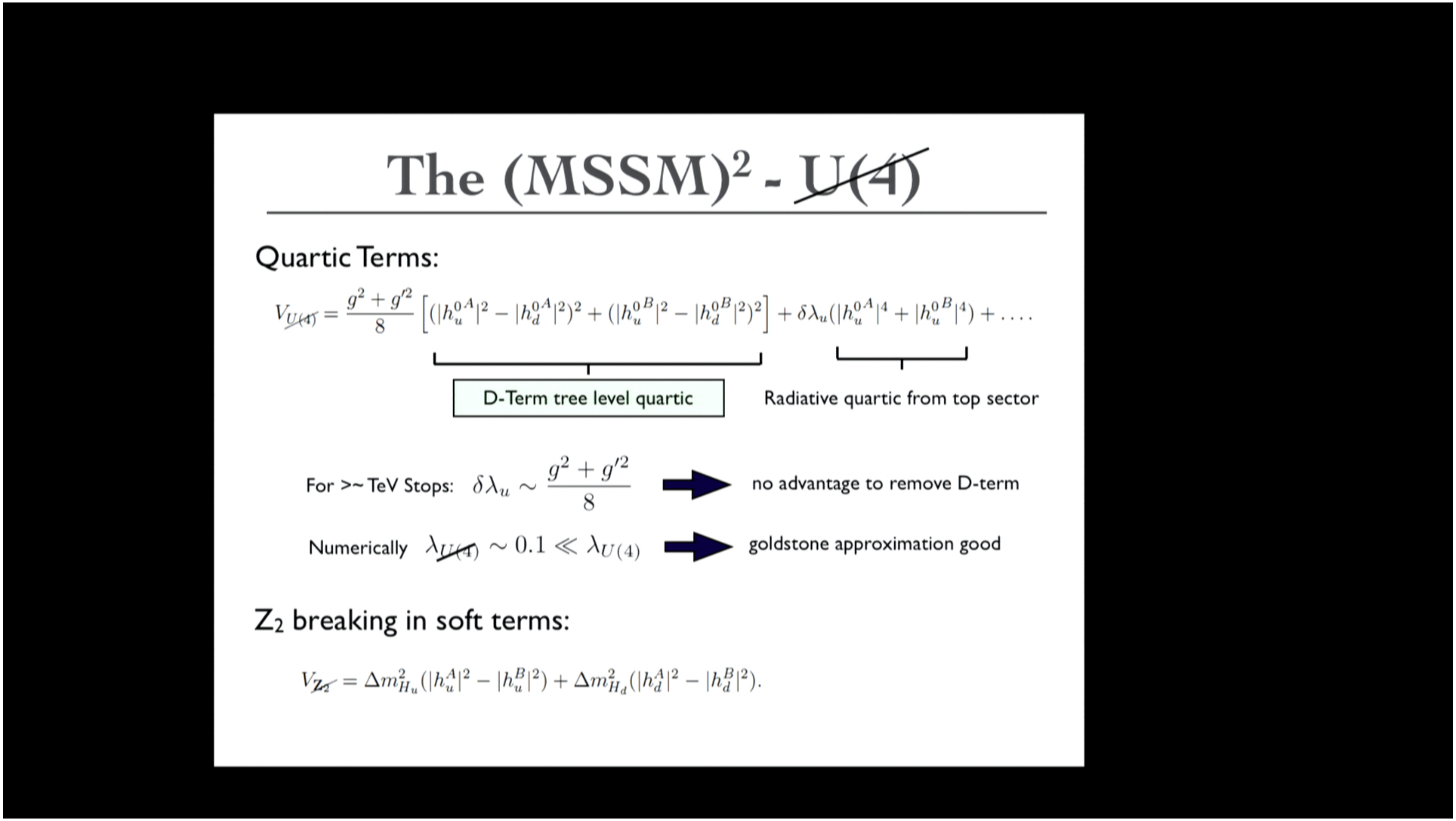
$$V_{\mathrm{U(4)}} = (m_{H_u}^2 + \mu^2)|H_u|^2 + (m_{H_d}^2 + \mu^2)|H_d|^2 - b(H_u H_d + \mathrm{h.c.}) + \lambda^2 |H_u H_d|^2$$

U(4) symmetric heavy higgsinos!

decouples (MSSM)^2 Higgs states

(potentially) large U(4) quartic

$\lambda^2 \sim 2$



The (MSSM)^2 - ~~U(4)~~

Quartic Terms:

$$V_{\cancel{U(4)}} = \frac{g^2+g'^2}{8}\underbrace{\Big[(|h_u^{0\,A}|^2 - |h_d^{0\,A}|^2)^2 + (|h_u^{0\,B}|^2 - |h_d^{0\,B}|^2)^2\Big]}_{\boxed{\text{D-Term tree level quartic}}} + \underbrace{\delta\lambda_u(|h_u^{0\,A}|^4 + |h_u^{0\,B}|^4)}_{\text{Radiative quartic from top sector}} + \ldots.$$

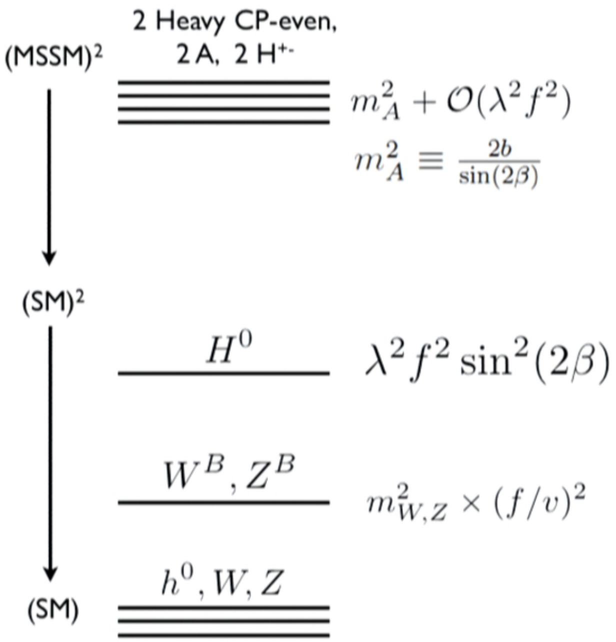
For >~ TeV Stops: $\delta\lambda_u \sim \dfrac{g^2+g'^2}{8}$ → no advantage to remove D-term

Numerically $\lambda_{\cancel{U(4)}} \sim 0.1 \ll \lambda_{U(4)}$ → goldstone approximation good

Z_2 breaking in soft terms:

$$V_{\cancel{Z_2}} = \Delta m^2_{H_u}(|h_u^A|^2 - |h_u^B|^2) + \Delta m^2_{H_d}(|h_d^A|^2 - |h_d^B|^2).$$

$(\text{Higgs Decoupling})^2$



2 Heavy CP-even, 2 A, 2 H^{+-}

$(\text{MSSM})^2$

$m_A^2 + \mathcal{O}(\lambda^2 f^2)$

$m_A^2 \equiv \frac{2b}{\sin(2\beta)}$

$(\text{SM})^2$

H^0 $\lambda^2 f^2 \sin^2(2\beta)$

W^B, Z^B $m_{W,Z}^2 \times (f/v)^2$

h^0, W, Z

(SM)

SUSY Decoupling:

$$b(H_u H_d + \text{h.c.})$$
$$U(4)_u \times U(4)_d \to U(4)_{\mathcal{H}}$$

$$\tan\beta_A \approx \tan\beta_B$$

$$\lambda^2 f^2 \ll m_A^2$$

Goldstone Decoupling:

$$H_u = f\sin\beta \begin{pmatrix} 0 \\ \sin\frac{\phi}{\sqrt{2}f} \\ 0 \\ \cos\frac{\phi}{\sqrt{2}f} \end{pmatrix}, \quad H_d = f\cos\beta \begin{pmatrix} 0 \\ \sin\frac{\phi}{\sqrt{2}f} \\ 0 \\ \cos\frac{\phi}{\sqrt{2}f} \end{pmatrix}$$

Higgs Mass

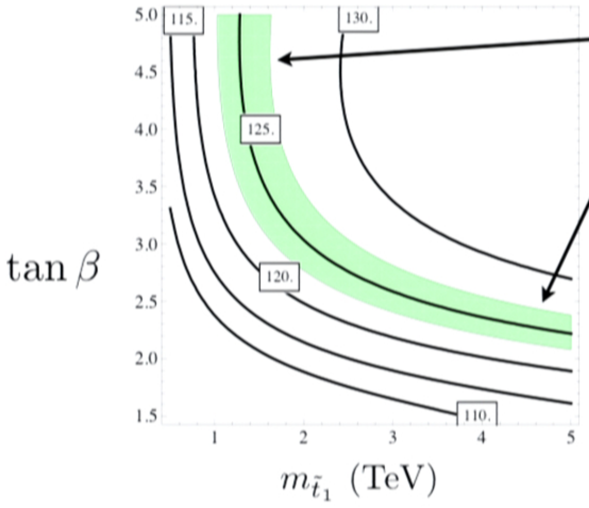
Goldstone Limit: $m_\phi^2 = (m_Z^2 \cos^2 2\beta + 4\delta\lambda_u v^2 \sin^4 \beta)\left(2 - \frac{2v^2}{f^2}\right)$

D-Term: O(1)

1L top/stop: O(1)

BONUS factor of 2

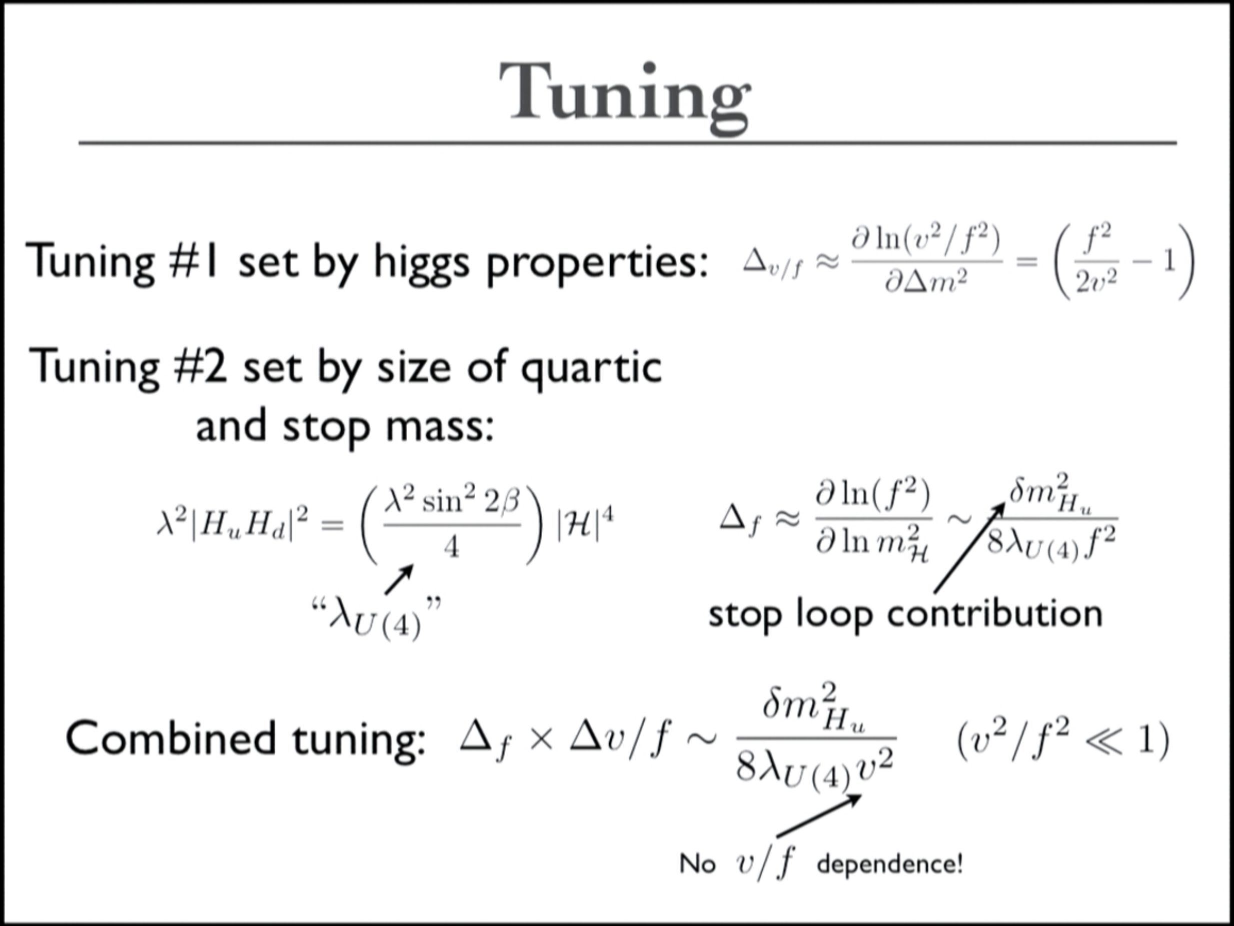
1L Electroweak: ~10%, Full LL top/stop: ~10%, higher order $\frac{v^2}{f^2}$: ~10%



radiative small: large $\tan\beta$

radiative large: small $\tan\beta$

$v^2/f^2 = 2/9$
$\lambda = 1.4$
$m_A^2 = 1.5$ TeV
$(m_{\tilde{t}_1} = m_{\tilde{t}_2} \quad A_t = 0)$



Tuning

Tuning #1 set by higgs properties: $\Delta_{v/f} \approx \frac{\partial \ln(v^2/f^2)}{\partial \Delta m^2} = \left(\frac{f^2}{2v^2} - 1\right)$

Tuning #2 set by size of quartic
and stop mass:

$$\lambda^2|H_u H_d|^2 = \left(\frac{\lambda^2 \sin^2 2\beta}{4}\right)|\mathcal{H}|^4$$

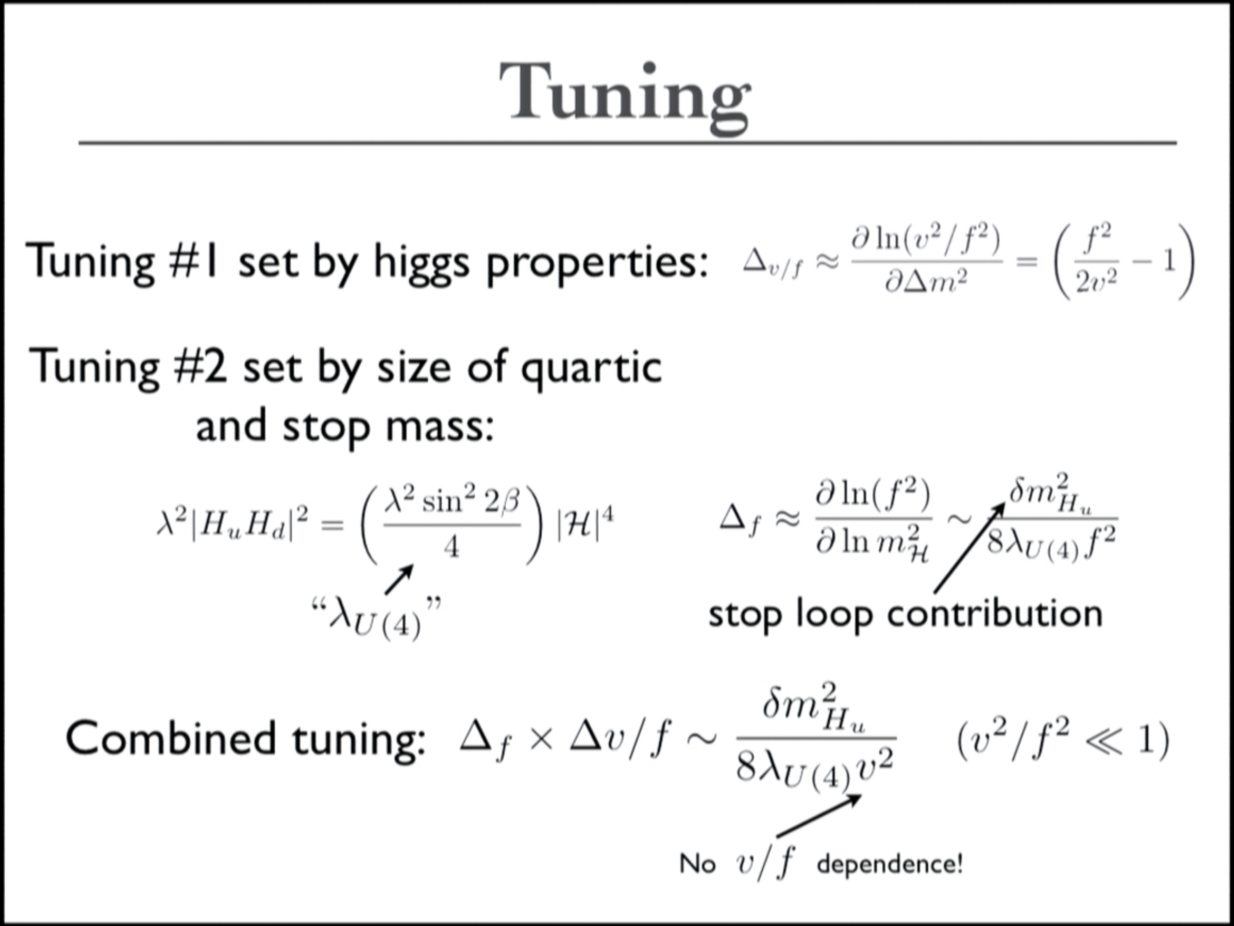
“$\lambda_{U(4)}$”

$$\Delta_f \approx \frac{\partial \ln(f^2)}{\partial \ln m^2_{\mathcal{H}}} \sim \frac{\delta m^2_{H_u}}{8\lambda_{U(4)} f^2}$$

stop loop contribution

Combined tuning: $\Delta_f \times \Delta v/f \sim \frac{\delta m^2_{H_u}}{8\lambda_{U(4)} v^2} \quad (v^2/f^2 \ll 1)$

No v/f dependence!



Tuning

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"$\lambda_{U(4)}$"

stop loop contribution

Combined tuning: $\Delta_f \times \Delta v/f \sim \frac{\delta m_{H_u}^2}{8\lambda_{U(4)} v^2} \quad (v^2/f^2 \ll 1)$

No v/f dependence!

Tuning (Carefully)

$$\Delta_f \;=\; \left[\sum_{x=\{m^2_{\tilde t_L},m^2_{\tilde t_R},M_3,m^2_{H_u},m^2_{H_d},\mu,m^2_{\tilde S}\}} \left(\frac{\partial \ln f^2|_{m_{\rm soft}}}{\partial \ln x|_{\Lambda_{\rm mess}}}\right)^2\right]^{\frac{1}{2}}$$

$$\Delta_{\frac{v}{f}} \;=\; \left[\sum_{x=\{\Delta m^2_{H_u},\Delta m^2_{H_d}\}} \left(\frac{\partial \ln v^2/f^2|_{m_{\rm soft}}}{\partial \ln x|_{\Lambda_{\rm mess}}}\right)^2\right]^{\frac{1}{2}}$$

$$\Delta_v \times \Delta v/f$$

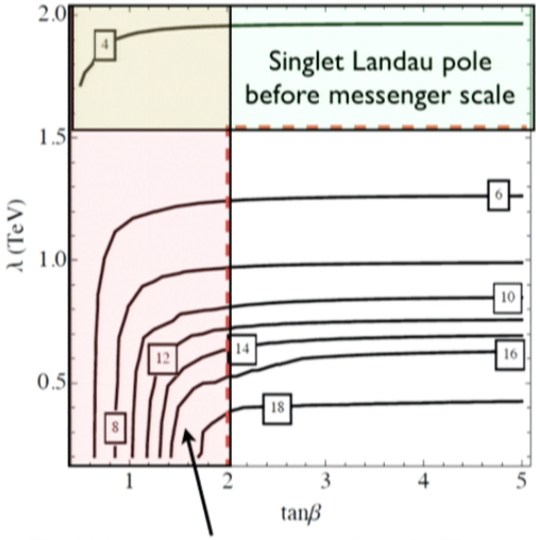
Compare to suitable NMSSM

$$\Delta^{\rm NMSSM} = \left[\sum_{x=\{m^2_{\tilde t_L},m^2_{\tilde t_R},M_3,m^2_{H_u},m^2_{H_d},\mu,m^2_{\tilde S}\}} \left(\frac{\partial \ln v^2|_{m_{\rm soft}}}{\partial \ln x|_{\Lambda_{\rm mess}}}\right)^2\right]^{\frac{1}{2}}$$

$$\Lambda_{\rm mess} = 100 m_{\tilde t}$$

Tuning - Perturbativity

How large can singlet coupling be?



Singlet Landau pole before messenger scale

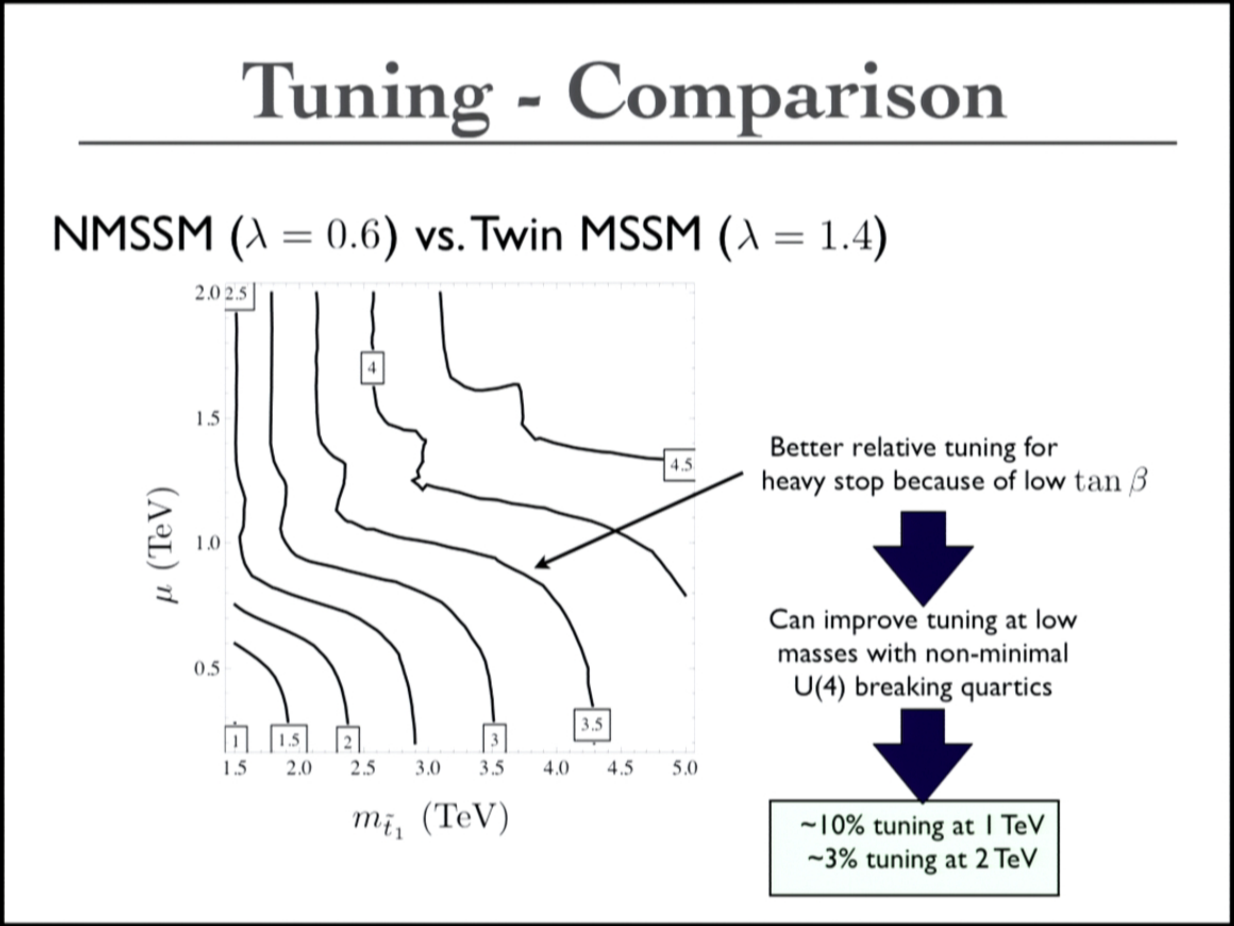
Top Yukawa Landau pole before GUT scale

Tension with
scale of singlet completion

$$\lambda = 1.5, \;\; \Lambda_{\text{singlet}} \approx 100 m_{\tilde{t}_1}$$
$$\lambda = 2.0, \;\; \Lambda_{\text{singlet}} \approx 10 m_{\tilde{t}_1}$$

Tension with
gauge coupling unification

$$\tan\beta \gtrsim 2.0$$



Tuning - Comparison

NMSSM ($\lambda = 0.6$) vs. Twin MSSM ($\lambda = 1.4$)

Better relative tuning for heavy stop because of low $\tan\beta$

Can improve tuning at low masses with non-minimal U(4) breaking quartics

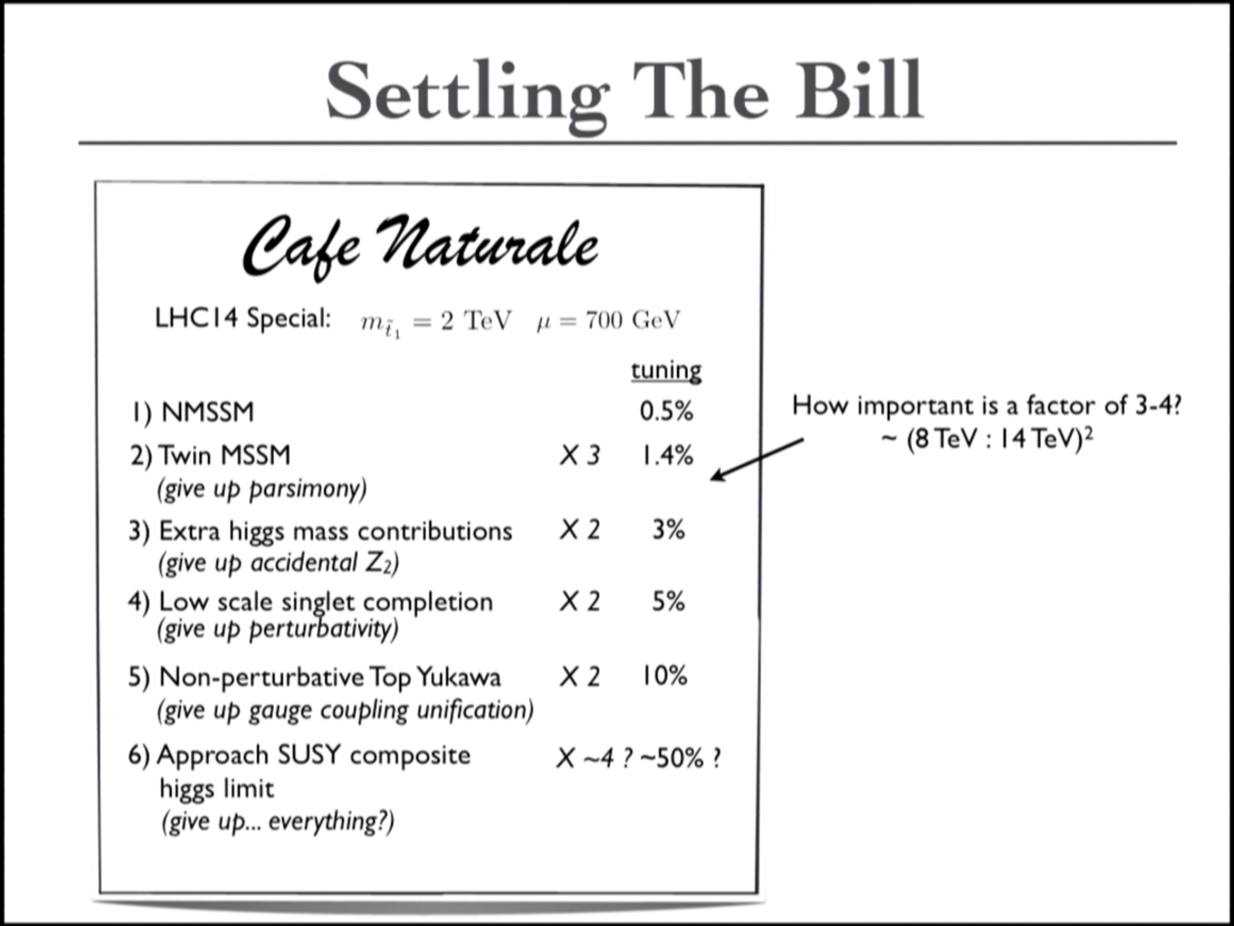
~10% tuning at 1 TeV
~3% tuning at 2 TeV

Settling The Bill

Cafe Naturale

LHC14 Special: $m_{\tilde{t}_1} = 2\ \text{TeV}$ $\mu = 700\ \text{GeV}$

		tuning
1) NMSSM		0.5%
2) Twin MSSM *(give up parsimony)*	*X 3*	1.4%
3) Extra higgs mass contributions *(give up accidental Z_2)*	*X 2*	3%
4) Low scale singlet completion *(give up perturbativity)*	*X 2*	5%
5) Non-perturbative Top Yukawa *(give up gauge coupling unification)*	*X 2*	10%
6) Approach SUSY composite higgs limit *(give up... everything?)*	*X ~4 ?*	~50% ?



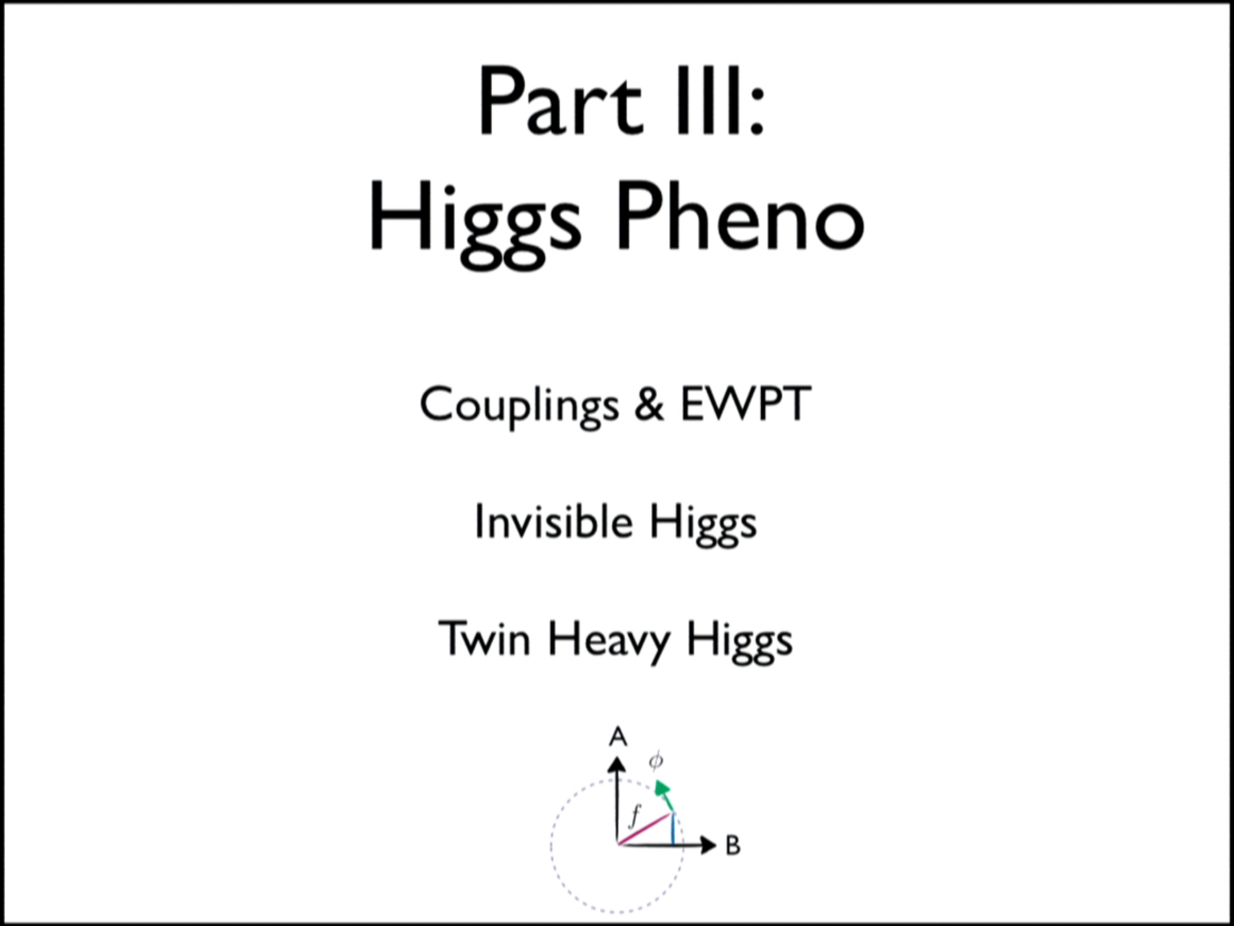
Settling The Bill

Cafe Naturale

LHC14 Special: $m_{\tilde{t}_1} = 2$ TeV $\mu = 700$ GeV

		tuning
1) NMSSM		0.5%
2) Twin MSSM *(give up parsimony)*	*X 3*	1.4%
3) Extra higgs mass contributions *(give up accidental Z_2)*	*X 2*	3%
4) Low scale singlet completion *(give up perturbativity)*	*X 2*	5%
5) Non-perturbative Top Yukawa *(give up gauge coupling unification)*	*X 2*	10%
6) Approach SUSY composite higgs limit *(give up... everything?)*	*X ~4 ?*	~50% ?

How important is a factor of 3-4?
~ (8 TeV : 14 TeV)^2

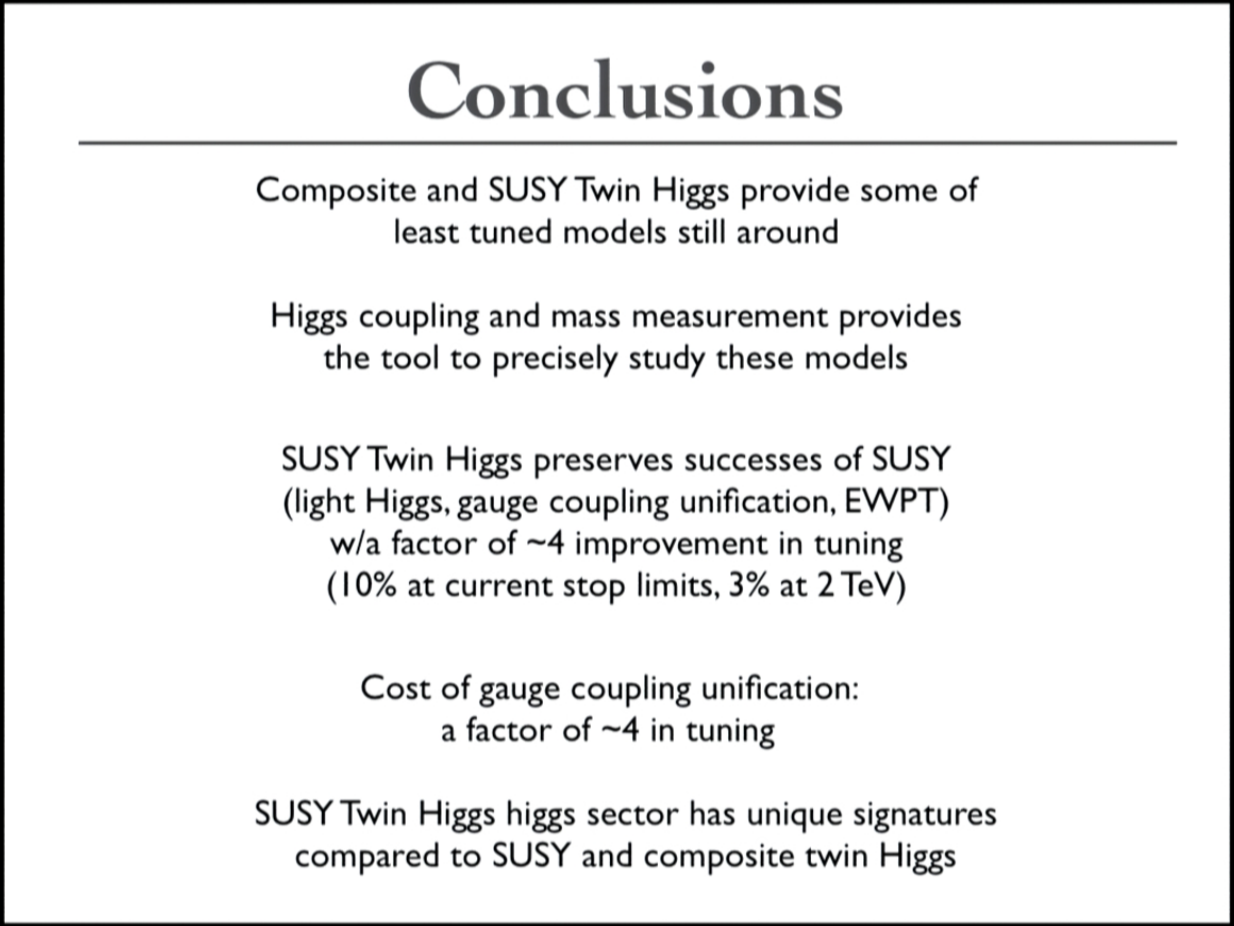


Part III:
Higgs Pheno

Couplings & EWPT

Invisible Higgs

Twin Heavy Higgs



Conclusions

Composite and SUSY Twin Higgs provide some of least tuned models still around

Higgs coupling and mass measurement provides the tool to precisely study these models

SUSY Twin Higgs preserves successes of SUSY (light Higgs, gauge coupling unification, EWPT) w/a factor of ~4 improvement in tuning (10% at current stop limits, 3% at 2 TeV)

Cost of gauge coupling unification: a factor of ~4 in tuning

SUSY Twin Higgs higgs sector has unique signatures compared to SUSY and composite twin Higgs

Back-up