## Twin Higgs, Naturalness and SUSY

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## **Outline**

- Introduction, motivation, the Twin Higgs
- Tuning in the Twin Higgs scenarios
- Why SUSY has anything to do with the Twin Higgs?
- SUSY Twin Higgs: natural and non-minimal
- One slide pheno overview
- Conclusions

# The Little Hierarchy Problem



There is no guarantee that the world is **the unconstrained about**  $\sim$  10 TeV scale absolutely natural. If it is — why no signatures at the EW scale? What is the nature of physics at 0.1…10 TeV scale?

**If we would like to solve the naturalness problem all the way to the Planck scale, there are essentially two options: SUSY and compositeness. But we also know that the NP is almost unconstrained above** 

# Why Neutral Naturalness?

### Why are we some of us so sceptic about the NP at the EW scale?



**Neutral Naturalness — top partners are uncolored. If realized — candidate to solve the little hierarchy problem. NN also cannot really help with the big hierarchy problem — UV completion is needed** 



# The Twin Higgs Overview

*Chacko, Goh, Harnik; 2006*

**Higgs is a pGB of a global SU(4) [ often enhanced to SO(8)], spontaneously broken down to SU(3). This approximate symmetry is protected by a more fundamental one:**



Cancellation of top divergencies:



EW gauge boson contribution cancels out similarly. Leading order: only mirror symmetry is needed to maintain the cancellation. Miracle: 1-loop level respects the approximate global symmetry

#### Higgs Potential of the Twin Higgs **Ö** ˇ ˇ ˇ *m*<sup>2</sup> *h* 2*m*<sup>2</sup> *h* ˇ ˇ ˇ ˇ tial of the Twin Higg  $\frac{1}{2}$   $\frac{1}{2}$  ˇ 2*m*<sup>2</sup> *h* ˇ « 1*.*4% (84) ˇ 2*m*<sup>2</sup> *h* ˇ « 1*.*4% (84)

ˆ ⇤<sup>2</sup>

˙

#### Break the approximate SU(4) at scale  $f \gg v$ : *h h*  $\ln$  $\overline{1}$ **k** the ap<sub>l</sub>  $\ddot{\phantom{a}}$  $\overline{M}$ **Break the annu** ⇡<sup>3</sup> *<sup>M</sup>g*˜ log<sup>2</sup> *Mg*˜

$$
V = m^{2} (|A|^{2} + |B|^{2}) + \lambda (|A|^{2} + |B|^{2})^{2}
$$
 SU(4) symmetric  
+  $\kappa (|A|^{4} + |B|^{4})$    
mirror symmetric, not not  
SU(4) symmetric

$$
+ \sigma f^2 |A|^2 + \rho |A|^4
$$
  
soft

5.7 Martin 1994 - 1994 - 1994 B

ˇ ˇ

*m*<sup>2</sup>

*y*2

*<sup>h</sup>* «

*<sup>t</sup>* ↵*<sup>s</sup>*

*<sup>t</sup>* ↵*<sup>s</sup>*

*m*<sup>2</sup>

*m*<sup>2</sup>

Mirror symmetry cannot be exactle <sup>4</sup> Mirror symmetry cannot be exact exactly as SUSY cannot be exact. **Breaking:** 

(85)

(85)<br><mark>(1953)</mark>

### Tuning in the Twin Higgs `p|*A*| <sup>4</sup> ` |*B*<sup>|</sup> q (87)  $455°$

q

**Figure of merit of most of the Twin Higgs models: v/f** too small — excluded by the higgs precision data<br>  $\frac{1}{2}$  and  $\frac{1}{2}$  **FT too big — FT** <sup>2</sup> ` ⇢|*A*<sup>|</sup>



q ` p|*A*|

*<sup>V</sup>* " *<sup>m</sup>*<sup>2</sup>

 $2\kappa$  another leads to an inevitable FT ~ tuning two quartics one against another leads to an inevitable  $FT \sim$  $({\bf v}/{\bf f})^2$ evi  $\mathbf{a}$  $\overline{\text{FT}}$   $\sim$ 

<sup>2</sup> (86)

<sup>2</sup> ` |*B*<sup>|</sup>

q ` p|*A*|

<sup>2</sup> ` |*B*<sup>|</sup>

q (87)

<sup>4</sup> (88)

p|*A*|

*Interestingly, κ is not a free parameter:*  $m_h^2 \approx 8 \kappa v^2$ 

 $m_h^2 \approx 8 \kappa v^2$ 

Softly broken mirror symmetry ☞ κ is determined by the measured higgs mass (SM quartic)

#### TH Fine Tuning, One Step Further  $p_{11}$   $p_{21}$   $p_{12}$   $p_{21}$   $p_{22}$   $p_{12}$   $p_{21}$   $p_{22}$  $\mathcal{G}$  tuning, One dedituning  $\mathcal{G}$ of *v*<sup>2</sup> with respect to : soft *v/f* <sup>=</sup> *<sup>f</sup>*22*v*<sup>2</sup> <sup>2</sup>*v*<sup>2</sup> . Of course, this is just a part of the total fine-tuning *<sup>V</sup>* " *<sup>m</sup>*<sup>2</sup> p|*A*| <sup>2</sup> ` |*B*<sup>|</sup> 2 q ` p|*A*| <sup>2</sup> ` |*B*<sup>|</sup> 2 <sup>2</sup> (86)

**TH solves the little hierarchy problem, therefore its cutoff cannot be too high. It needs a UV completion at ~ 5 TeV scale (this is where SUSY will come in). What kind of FT does this threshold introduce?**  fittle biomenshy nuch lem the wefous its sutoff sennet he fine-tuning showld be computed in the full UV theory, but it turns out that  $\frac{1}{\sqrt{2}}$ reasonable estimate by analyzing the threshold corrections to threshold corrections to the earth. the major and funta variative corrections in convenience.  $\beta$  solves the little hierarchy problem, therefore its cutoff c `*<sup>f</sup>* <sup>2</sup> 2 **A 2 A 2 A 2 A 2 A 2 A 2 A 2 A** 4 MEDIANA LAN ENGELHANG ETA GANGANG SEMBORAN PERTAMBANG TILAMAN DENGAN DENGAN PERTAMBANG TERRAPA TILAMAN DENG<br>A

are a control of the control of the<br>The control of the c The scale of the SU(4) breaking is not stable w/o a UV completion: «

ੇ ∂ੇ ਇਹ ਦੇ ਪ੍ਰੋਗਟਾ ਪ੍ਰੋਗਟ<br>ਸਮਾਨ

*Mg*˜

˙

$$
\Delta f^2 = \frac{1}{32\pi^2} \left(\frac{3y_t^2}{\lambda}\right) \left(\frac{\lambda^2}{\lambda^2}\right)
$$

and show that if hard Z2-breaking is involved, one in fact expects to improve on the fine-

tuning compared to the soft breaking case. For illustration purposes let us start from the soft breaking purpo<br>The soft breaking case in the soft breaking case in the soft breaking cases in the soft breaking the social pu

(85)<br>Kalendari<br>Kalendari

that one estimates in the IR e20e equal that one should also consider a considerable that one should also consider

 $\text{top-stop threshold}$ top-stop threshold scalar threshold z a continued to the stop threshold

scalar threshold

–9–

●

*.* (2.8)

the sensitivity to the thresholds ⇤*<sup>t</sup>* and ⇤ are equally dangerous and, unlike in the SM, ery naive and assume that ik and  $\cup$  v F is factorize Let us be very naïve and assume that IR and UV FTs factorize

 $FT_{twin+SUSY}$  $\mathrm{FT}_{SUSY}$  $\sim$  $\lambda_{SM}$ 

|*A*|

*f* 2

*m*<sup>2</sup>

*y*2

⇡<sup>3</sup> *<sup>M</sup>g*˜ log<sup>2</sup>

 $\frac{SM}{\lambda}$  realistic UV completions  $\lambda$  is hard to  $\lambda_{\rm SM} \approx 0.06 \Rightarrow$  the effect is moderate. Also in maximize

## IR Fine Tuning, Soft vs Hard



#### Fine Tuning and Hard Breaking ˇ 2*m*<sup>2</sup> *h* ˇ ↵<sup>8</sup> " 24<br>2€ *<sup>a</sup>*p'q <u>nir</u> (82)

*<sup>H</sup><sup>A</sup>* <sup>=</sup> *<sup>f</sup>* sin

<sup>p</sup>2*<sup>f</sup>*

*m*<sup>2</sup>

*<sup>h</sup>* «

p|*A*|

ˇ

*<sup>t</sup>* ↵*<sup>s</sup>*

**The improvement of FT in softly broken TH is not great: cannot exceed**   $\lambda_{\rm SM}/\lambda$  independent on the FT structure. *k* The improvement of FT in softly broken TH is not great: cannot exceed  $\lambda_{\rm SM}/\lambda$  independent on the FT structure. *Mg*˜ *<sup>V</sup>* " *<sup>m</sup>*<sup>2</sup> <sup>2</sup> ` |*B*<sup>|</sup> 2 <sup>2</sup> ` |*B*<sup>|</sup> improv ي<br>Extempt of FT ir *FT* in sof  $\overline{\phantom{a}}$ 

Hard breaking: a priori no need to fine one parameter against another to get v/f small ˇ  $\overline{\mathbf{)}$ ˇ e one  $a^{\frac{1}{2}}$ ˇ ˇ ˇ  $\bigcup$ 

ˆ ⇤<sup>2</sup>

*cam*<sup>2</sup>

*m*<sup>2</sup>

*m*<sup>2</sup>

3*y*<sup>2</sup> *t*

*y*2

g: a priori no need  
parameter against  

$$
\frac{2v^2}{f^2} = \left(\frac{2\kappa - \sigma}{2\kappa + \rho}\right)
$$

sions into Eq. (?) and obtain the e2. (?) and obtain the e2. (?) and obtain the low energy eq. (?) and obtain<br>The election of the election state state of the low energy eq. (?) and in the low energy eq. (?) and in the lo

⇡<sup>3</sup> *<sup>M</sup>g*˜ log<sup>2</sup>

*m*<sup>2</sup> *h* ˇ

ˇ

q ` p|*A*|

*, H<sup>B</sup>* = *f* cos

 $\mathcal{L}$ 

 $(1)^4$ 

*,* (2.3)

« 1*.*4% (84)

 $\frac{4}{\sqrt{8}}$ 

 $\frac{1}{2}$  he quadratically  $+\sigma f^2$  $f^2|_4$  $\int_0^4 f(x) dx$  $+ \sigma f^2 |A|^2 + \rho |A|$ But expect  $\rho$  to be quadratically sensitive to σ:  $Bu$ *<sup>t</sup>* ↵*<sup>s</sup>* expect  $\varrho$  to be qu

$$
\Delta\sigma\sim\frac{3\rho}{16\pi^2}\frac{\Lambda_\rho^2}{f^2}
$$

Without a proper UV  $\Delta \sigma \sim \frac{3\rho}{18.3} \frac{\Lambda_p^2}{r^2}$  completion we even do not  $\ln w$  die sign.  $\frac{p}{f^2}$  know the sign! completion we even do not

### IR Fine Tuning and Hard Breaking  $2.5$  3.0 3.5 4.0 4.5 5.0 5.5 6.0  $f/v$ Figure 3. Contours of *F*(*v, f*;⇤⇢). The two di↵erent colors correspond to to the two di↵erent signs

### **Simplification assumption: only hard breaking at the cutoff scale**

 $\Delta_{v/f}^{\rm hard} =$  $f^2 - 2v^2$ Full FT in the hard model:

of ✏. maybe we can shaded in gray the region where ⇤⇢ *< f*? - DR

for further convenience

and in the limit 3⇤<sup>2</sup>

As  $\Lambda \rightarrow \infty$ , F goes to 1 and  $\frac{1}{\sqrt{2}}$ there is no real gain in FT  $\left( \frac{1}{2} \right)$ If  $\Lambda \ll 4\pi$ f, the function F 3✏⇤<sup>2</sup> ⇢ + 32⇡2*v*<sup>2</sup> reduces to  $(f/v)^2$  and the IR  $\qquad \qquad ^0$ *<u>F</u> F</del>* FT is effectively erased

### **Real gain in IR!**



### The Higgs Mass <sup>ˆ</sup> " *ytf* (110)

dimr*H*:



Radiative corrections:

*H*s " 2 ùñ dimr*Ocomp*s ° 4 (109)

3⇢

16⇡<sup>2</sup>

$$
m_h^2 \approx 4\kappa f^2 \qquad \Delta \kappa = \frac{3y_t^4}{16\pi^2} \log \frac{\Lambda_t^2}{m_{t_B}^2} + \frac{3\lambda \rho}{32\pi^2} \left( \log \frac{\Lambda_\rho^2}{m_{rad}^2} + \log \frac{\Lambda_\rho^2}{m_h^2} \right)
$$

*Padiative corrections to the* Radiative corrections to the  $\mathbf{i}$  $\frac{1}{2}$ ggs mass </sup> *m*<sup>2</sup> higgs mass with  $\Lambda = 1$  TeV

*,* (2.5)

**∴**<br>← <del>Utally</del> we pay some (relatively  $\sum_{\text{o.7}}$  -  $\sum_{\text{e.8}}$  -  $\sum_{\text{e.9}}$  e $\sum_{\text{e.9}}$  minor) price for adjusting the <u>**Example 2.65**</u> **higgs mass. We are slightly**  $\frac{0.6}{\Lambda_t < \lambda}$  overshooting for the higg mass. Clearly we pay some (relatively

coupled UV completions, *e.g.* SUSY, one might expect appreciable di↵erences between

### The Sign of the Threshold Matters

2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 1  $\overline{\phantom{0}}$ 3 4 5  $f/v$  $\blacktriangle$ *t* TeV]  $\sigma_0=0$ ,  $\kappa_0=10^{-3}$ 1.5 3 4.5 6 7 1.5 0.1 0.3 0.5  $\Box \epsilon= +1$  $\epsilon$ = - $\gamma$  $\Delta t \approx \lambda f$ 

Improvement in FT with respect to the soft model

Required  $\Lambda$ <sub>o</sub> to get the right higgs mass

**Knowing the sign of the quadratic correction to the soft breaking term is crucial. Negative threshold demands extremely low stops threshold, or simply overshoots for the higgs mass** 

# UV Completion: Why SUSY?

- The scale of the global symmetry breaking is unstable. Candidates to stabilize it: SUSY or compositeness (turtles?)
- Problems with the strongly coupled UV completions: 1) not easy to generate moderate mass splittings 2) EWPM
- We would prefer to have moderate separations between the top partners and the scalar partners. Easy in SUSY, not that easy in composite models
- SUSY naturally explains different masses in UV completions: small and technically natural couplings

### SUSY Meets Its Twin: 10 Years Ago *<sup>h</sup>* «  $2V$  $M$  $g$  $h$ (85)

*<sup>t</sup>* ↵*<sup>s</sup>*

 $\mathcal{L}(\mathcal{D})$ 

˙

*Falkowski, Pokorski, Schamltz; Chang, Hall, Weiner; 2006*



The SU(4) conserving Higgs quartic: NMSSM ``trick" tan " 2<sup>2</sup>.0 (88)  $\frac{1}{2}$  (88)  $\frac{1}{2}$ 

 $W = \lambda S \mathcal{H}_u \mathcal{H}_d$  ) full multplets of the accidental SU(4) To get the standard TH structure, we integrate out S non-SUSically.

#### SUSY Soft TH — Higgs potential *<sup>A</sup>* ⇡ *<sup>m</sup>*<sup>2</sup> *<sup>A</sup><sup>T</sup>* <sup>2</sup> *<sup>S</sup>f* <sup>2</sup> (see Appendix B).  $\mu$  *Higgs potential* to the parameters of the parameters of the parameters of the Twin Higgs potential in Eq. (2.1):<br>(2.1): The parameters of the Twin Higgs potential in Eq. (2.1): The parameters of the parameters of the Twin H  $\alpha$  for  $\alpha$   $\alpha$  for the  $\alpha$  $SL(3)$  is the original immediately explains the problem allows the problem all  $SL(2)$ previous section: SUSY UV completion: SUSY UV completions have a hard time to maximize  $\bigcup\bigcup_{i=1}^n\mathcal{C}_i$  and therefore therefore therefore the  $\mathcal{C}_i$ ameliorated by changing the functional dependence of on tan and other fundamental pour la parameter de la parameter We now proceed to discus the leading Z2-even but *SU*(4)-breaking operators in the

be always lighter: *m*<sup>2</sup>

Immediate worry: to maximize the FT gain we need  $\lambda$  as big as possible, but:  $\lambda \approx \frac{\lambda}{4} s_{2\beta}$ showld be perturbative. Moreover, as we will showld showld showld showld showld showld showld  $\Omega$ miniedrate worry, to maximize the FT gain  $\sqrt{S}$   $_{2}$ to recover to maximize the  $ET$  cain  $\frac{1}{2}$ ble h *|hA u |* <sup>2</sup> *<sup>|</sup>h<sup>A</sup>*



<sup>+</sup> *<sup>|</sup>h<sup>A</sup>*

*u |*

<sup>4</sup>) log *<sup>M</sup>*<sup>2</sup>

*m*<sup>2</sup>

i

<sup>4</sup> log *<sup>f</sup>* <sup>2</sup>

*v*2

squared of the *mirror CP-odd Higgs*. The mass of the "visible" CP-odd Higgs turns out to

*,* (3.5)

*.* (3.7)

Clearly the model will not perform great. clearly the model will not perform great ameliorated by changing the functional dependence of the functional dependence of one **V** the d 3*y*<sup>4</sup> *t*  $\overline{O}$ (*|h<sup>A</sup>* <sup>4</sup> <sup>+</sup> *<sup>|</sup>h<sup>B</sup>*

the top mass as *m<sup>t</sup>* = *ytv* sin . In order to get Eq. (3.6) we compute the CW potential

obtained integrating out the twin Higgs and expanding at twin Higgs and expanding at the first non-trivial order in<br>The first non-trivial order in the first non-trivial order in the first non-trivial order in the first non

also the fine-tuning gain, which is SM*/*. In SUSY UV completions *S*, rather than ,

**Where do we get the rest of the terms from?**  $\frac{1}{\sqrt{2}}$  these expected of  $\frac{1}{\sqrt{2}}$  the terms that depends that depends that depends on the disregarded the disregard **parameters**, and the comment of the comme <u>**u** at the terms f</u>

Parity symmetric, SU(4) - breaking quartic κ, practically it is the higgs quartic. D-terms:  $CTI(1)$  be adjoing superiories we oficelly Parity symmetric,  $SU(4)$  - breaking quartic  $\kappa$ , practically  $\frac{1}{\sqrt{2}}$  $g(x)$  symmetric,  $SU(4)$  - breaking quartic  $\kappa$ , practically and the diggs quantie. and  $L$ -terms.  $\Box$ 

 $V_{\psi(4)}^{D}=$  $g_{\rm ew}^2$ 8  $\lceil$  $|h_u^A|^2 - |h_d^A|$  $\binom{2}{u}^{2} + (|h_{u}^{B}|^{2} - |h_{d}^{B}|^{2})$  $2\overline{2}$ *coprodions* " + top radiative corrections  $\frac{1}{2}$   $\left(\left|h_{u}^{A}\right|\right)$ Matching again the e $\frac{1}{\sqrt{2}}$ 

The e 1e expr *n*<br> *ssion for the SM qu* ال<br>11<sub>--</sub> The expression for the SM quartic practically forces tan  $\beta \sim 1$ .

where we defined *g*<sup>2</sup>

ew

\n The expression for the SM quartic\n 
$$
\kappa \approx \frac{g_{\text{ew}}^2}{8} c_{2\beta}^2 + \frac{3m_t^4}{16\pi^2 v^4} \log\left(\frac{M_s^2}{m_t^2} \frac{v^2}{f^2}\right)
$$
\n

This expression indicates that the *SU*(4)-breaking Z2-even quartic gets an unavoidable

. As a result, we will generally get *<* 1, such that the gain in fine tuning will never

be large. In passing, we note that the fine tuning in the fine tuning in the fine tuning in the fine tuning in<br>The soft models can be slightly in the soft models can be slightly in the soft models can be slightly in the s

Twin SUSY potential. At leading order the *SU*(4)-breaking originates at tree-level from

# Soft Breaking + SUSY

*also Craig & Howe 2013*

**Finally we get the soft mirror symmetry breaking terms from different soft masses in the visible and the twin sector.**

As expected the gain in the FT is moderate at best. We get slightly better than 1% at best.



No tan  $β$  can be found to satisfy the higgs constraints here

### Hard Breaking in SUSY: First Attempt tan " 1*.*2 tan " 2*.*0 (88)

**Clearly to introduce something that maps onto the soft mirror <b>SA symmetry breaking, we need dim 4, not mirror symmetric operator, and the most natural candidate is** 



#### Hard Breaking: the Bidoublets *yt*{*f* (107) <sup>2</sup> ` |*B*<sup>|</sup> 2 q ` <sup>3</sup>*y*<sup>2</sup> ˆ <sup>)</sup>|CdKII  $8$ . LIC DIUOU!

*<sup>t</sup>* |*B*|

**Potential way out: negative κ at the mediation scale, compensating for a positive D-terms contribution** *<u>designals</u>* and the mediation scale compensating Potential way out: negative  $\kappa$  at the mediation scale, compe

 $\frac{1}{2}$ *negative contribution exacerbates the higgs overshooting problem* 

**Trick introduce bi-doublets:**

+ SUSY masses give negative κ contribution



### What Do We Really Gain After All?

**Here we calculate the FT numerically à la Barbieri Giudice and vary with respect to all free parameters of the model**

SUSY TH might not be as fine-tunes as originally suggested. Price: some model building is needed



## Pheno Remarks

**Parallel <sup>Lac</sup>olo** The stops in this scenario might or might<br>not be reachable at the (HL) LHC.<br>Interesting signals: higgs sector not be reachable at the (HL) LHC. Interesting signals: higgs sector

- Who is the lightest CP even state (radial or 2HDM)?
- Signals in ZZ channel, HL LHC reach,
- Charged higgses signals

See a parallel talk by

 $b \rightarrow sy$  constraints are relevant for high f and relatively light extra higgses

### Conclusions

- Twin Higgs is a promising mechanism to bridge over the little hierarchy problem
- Hard mirror symmetry deserves the second look, it can significantly improve the TH models
- SUSY is a natural candidate to UV complete the TH with hard mirror symmetry breaking (of course no no-goes concerning alternative UV completions)
- A bi-doublet model can clearly do the job
- These models have non trivial collider signatures, to be explored at the HL LHC (to be continued in parallel session)