Twin Higgs, Naturalness and SUSY

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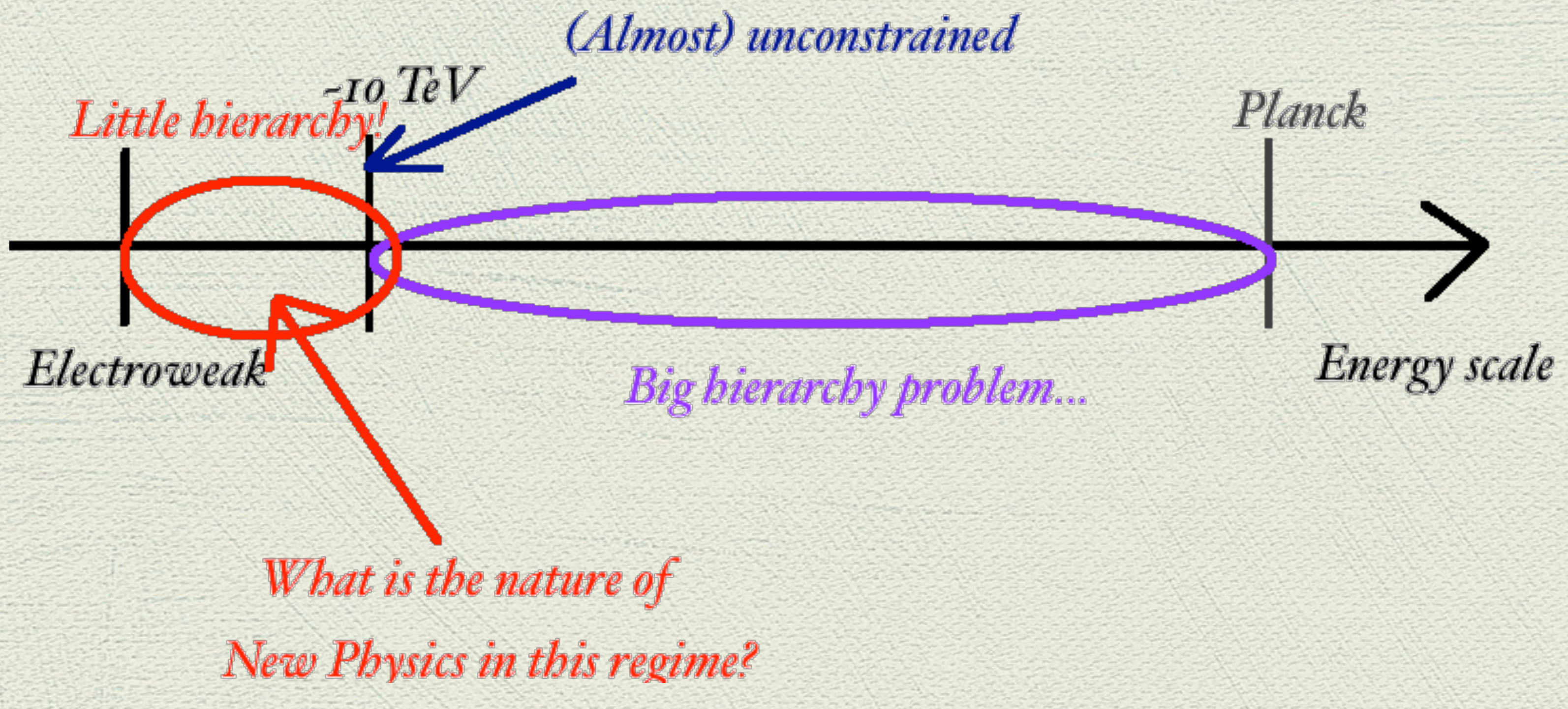
Outline

- 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

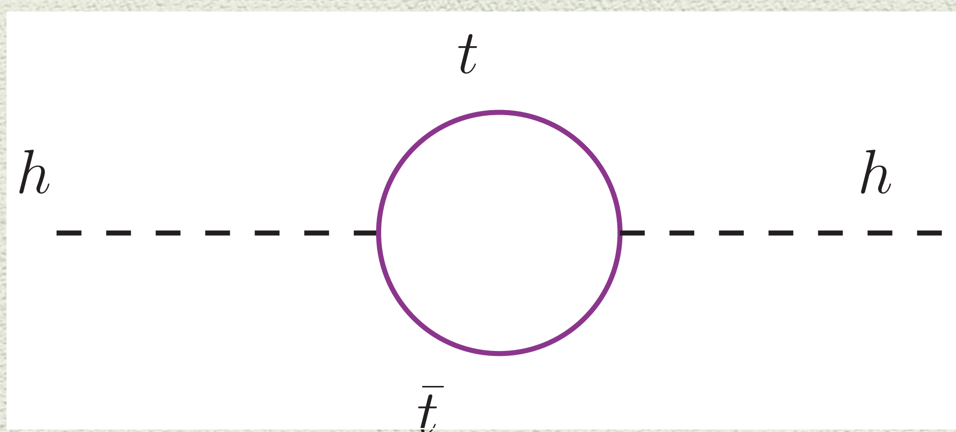


There is no guarantee that the world is absolutely natural. If it is — why no signatures at the EW scale? What is the nature of physics at 0.1…10 TeV scale?

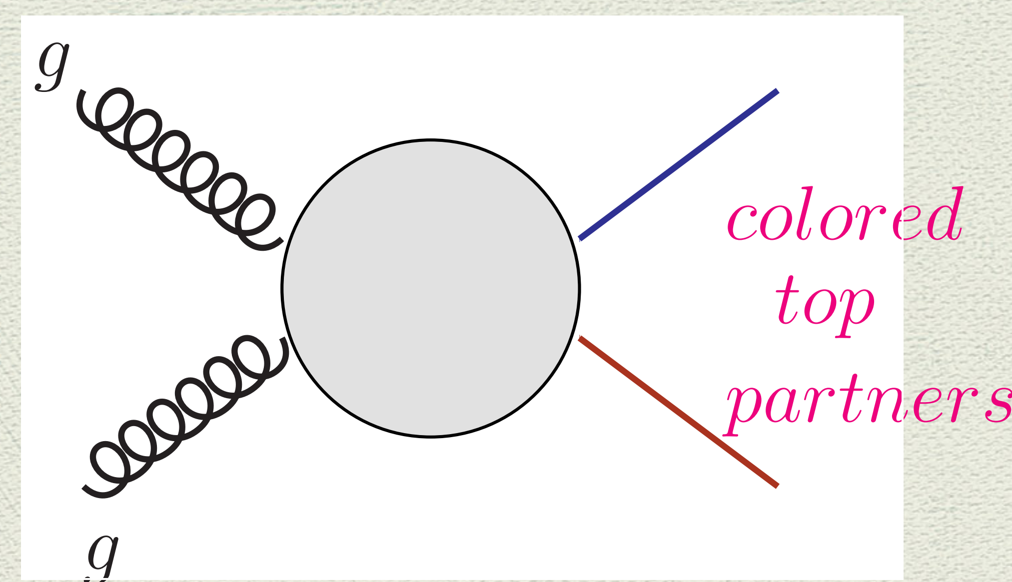
If we would like to solve the naturalness problem all the way to the Planck scale, there are essentially two options: SUSY and compositeness. But we also know that the NP is almost unconstrained above ~10 TeV scale

Why Neutral Naturalness?

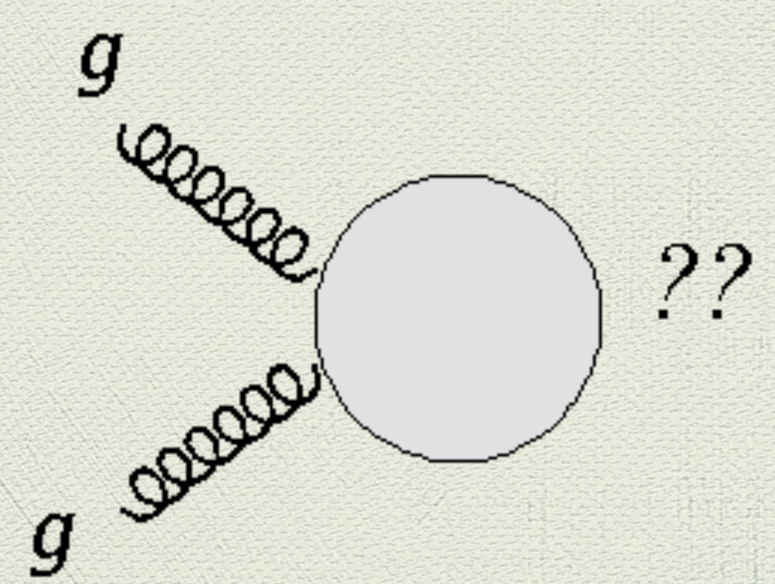
Why are ~~we~~ some of us so sceptic about the NP at the EW scale?



Naturalness



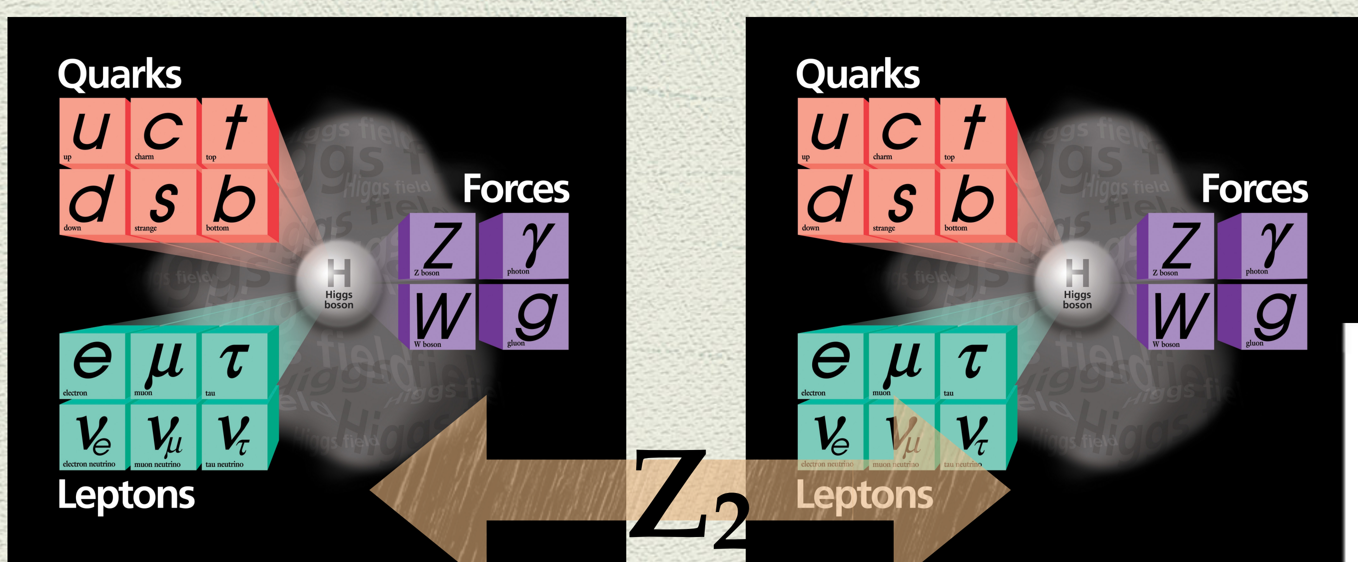
Neutral Naturalness — top partners are uncolored. If realized — candidate to solve the little hierarchy problem. NN also cannot really help with the big hierarchy problem — UV completion is needed



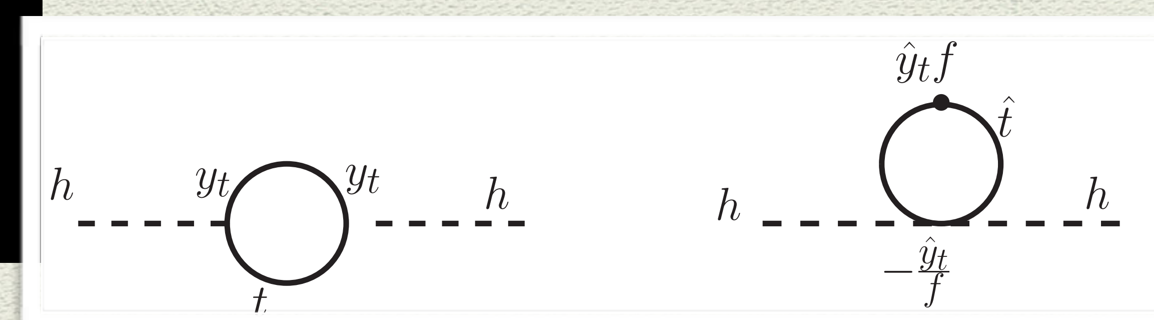
The Twin Higgs Overview

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

Break the approximate SU(4) at scale f » v:

$$V = m^2(|A|^2 + |B|^2) + \lambda(|A|^2 + |B|^2)^2$$

SU(4) symmetric

$$+\kappa(|A|^4 + |B|^4)$$

Mirror symmetric, not not SU(4) symmetric

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

soft

hard

Mirror symmetry cannot be exact exactly as SUSY cannot be exact. Breaking:

Tuning in the Twin Higgs

Figure of merit of most of the Twin Higgs models: v/f
too small — excluded by the higgs precision data
too big — FT

$$\frac{v^2}{f^2} \approx \frac{1}{2}\frac{2\kappa - \sigma}{2\kappa}$$

tuning two quartics one against another leads to an inevitable FT ~ $(v/f)^2$

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

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

TH Fine Tuning, One Step Further

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?

The scale of the SU(4) breaking is not stable w/o a UV completion:

$$\Delta f^2 = \frac{1}{32\pi^2}\left(\frac{3y_t^2}{\lambda}\Lambda_t^2 - 5\,\Lambda_\lambda^2\right)$$

top-stop threshold

scalar threshold

Let us be very naïve and assume that IR and UV FTs factorize

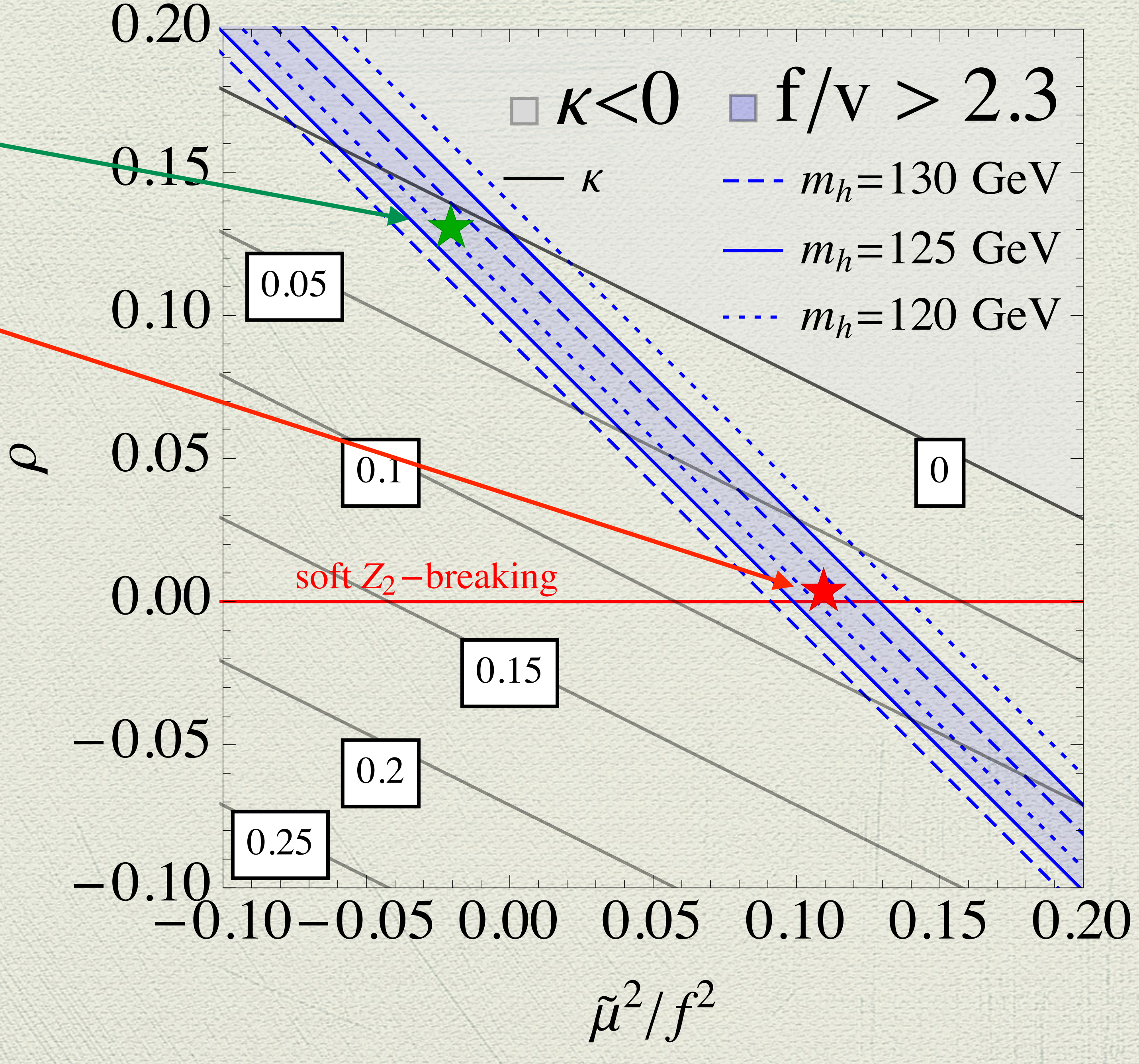
$$\frac{\mathrm{FT}_{twin+SUSY}}{\mathrm{FT}_{SUSY}} \sim \frac{\lambda_{SM}}{\lambda}$$

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

IR Fine Tuning, Soft vs Hard

pure hard breaking

pure soft breaking



Higgs mass measurement ☛ confined to a narrow strip

Intermediate conclusion: κ is always small.

Radiative corrections?

Fine Tuning and Hard Breaking

The improvement of FT in softly broken TH is not great: cannot exceed λ_{SM}/λ independent on the FT structure.

Hard breaking: a priori no need to fine one parameter against another to get v/f small

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

But expect ϱ to be quadratically sensitive to σ:

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

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

Without a proper UV completion we even do not know the sign!

IR Fine Tuning and Hard Breaking

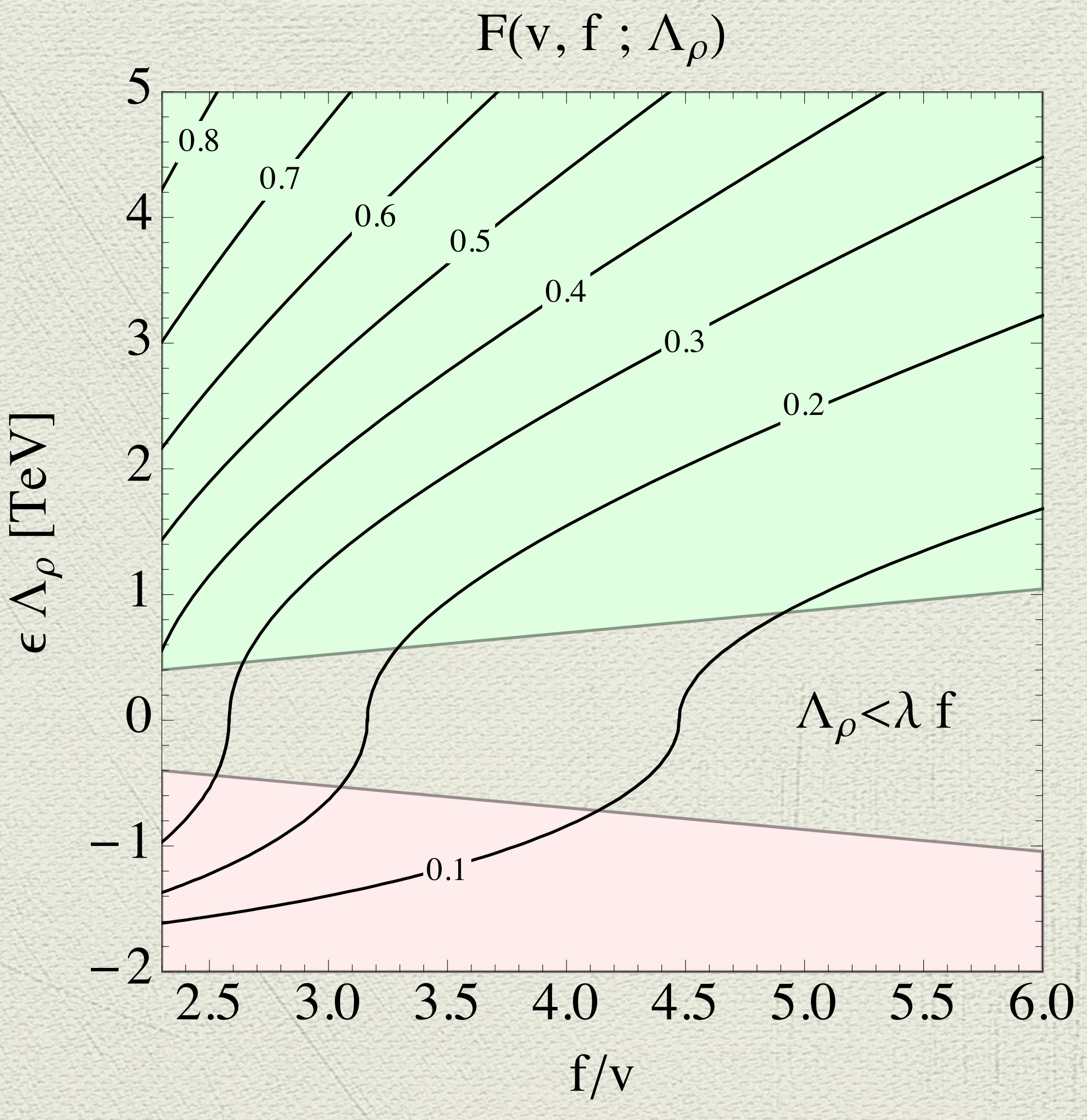
Simplification assumption: only hard breaking at the cutoff scale

Full FT in the hard model:

$$\Delta^{\rm hard}_{v/f} = \frac{f^2 - 2v^2}{2v^2} \times F(v, f; \Lambda_\rho)$$

- As $\Lambda \to \infty$, F goes to 1 and there is no real gain in FT
- If $\Lambda \ll 4\pi f$, the function F reduces to $(f/v)^2$ and the IR FT is effectively erased

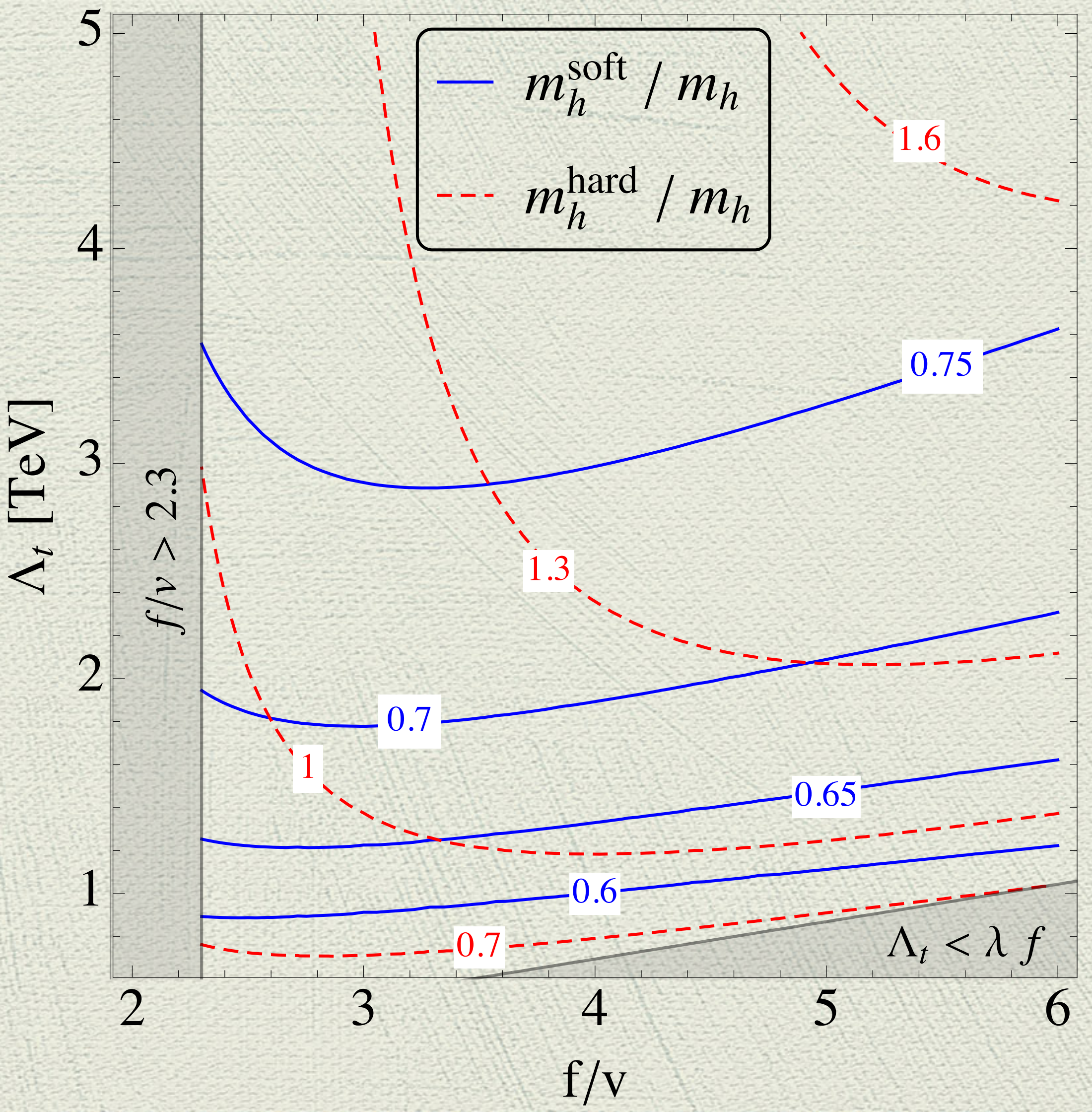
Real gain in IR!



The Higgs Mass

Desired: κ ~10^{-2}

$$m_h^2 \approx 4\kappa f^2$$



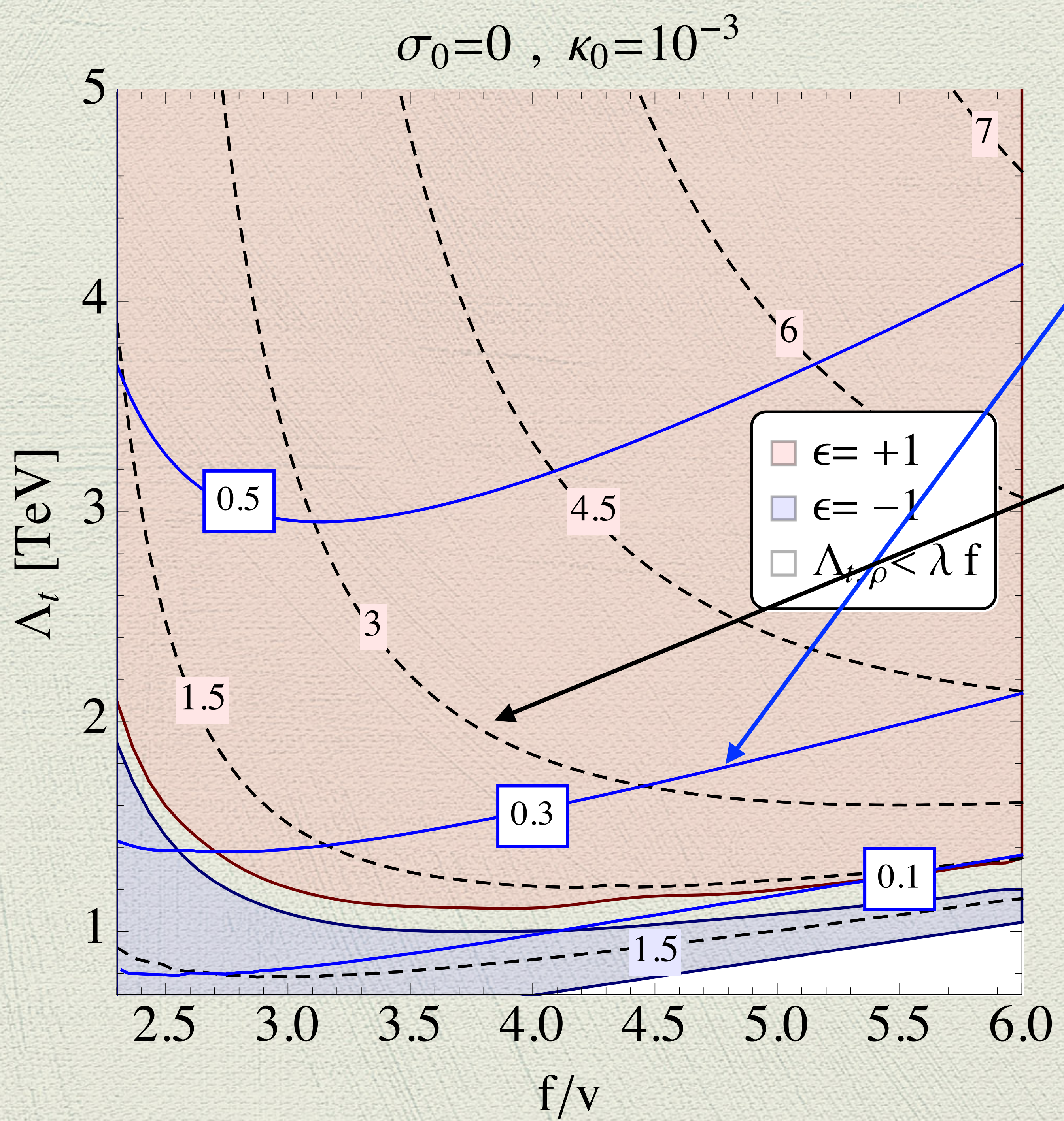
Radiative corrections:

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

Radiative corrections to the higgs mass with Λ = 1 TeV

Clearly we pay some (relatively minor) price for adjusting the higgs mass. We are slightly overshooting for the higg mass.

The Sign of the Threshold Matters



Improvement in FT with respect to the soft model

Required Λ_ϱ to get the right higgs mass

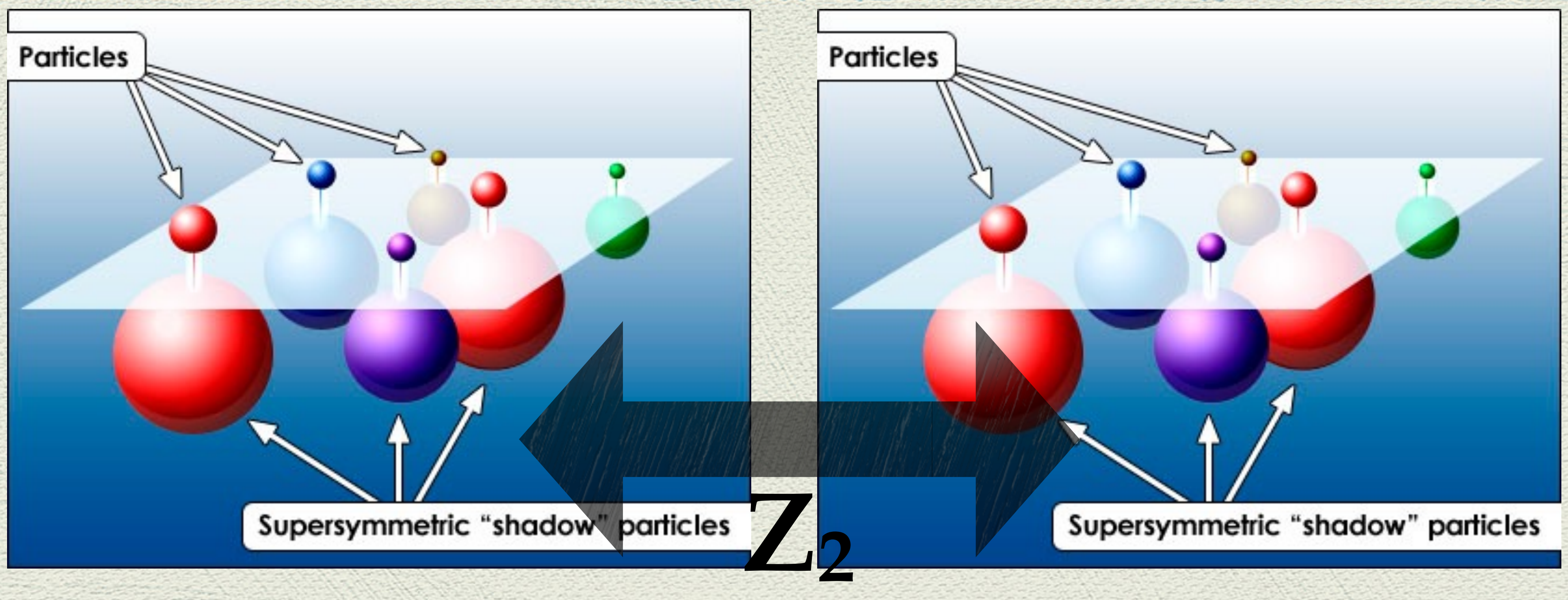
Knowing the sign of the quadratic correction to the soft breaking term is crucial. Negative threshold demands extremely low stops threshold, or simply overshoots for the higgs mass

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

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



How do we get the right Higgs potential?

The SU(4) conserving Higgs quartic: NMSSM ``trick"

$$W = \lambda S \mathcal{H}_u \mathcal{H}_d$$

full multplets of the accidental SU(4)

To get the standard TH structure, we integrate out S non-SUSically.

SUSY Soft TH — Higgs potential

Immediate worry: to maximize the FT gain we need λ as big as possible, but:

$$\lambda \approx \frac{\lambda_S^2}{4} s_{2\beta}^2$$

Clearly the model will not perform great.

Where do we get the rest of the terms from?

Parity symmetric, SU(4) - breaking quartic κ, practically it is the higgs quartic.

D-terms:

$$V_{\not{U}(4)}^D = \frac{g_{\text{ew}}^2}{8}\left[\left(|h_u^A|^2 - |h_d^A|^2\right)^2 + \left(|h_u^B|^2 - |h_d^B|^2\right)^2\right]$$

+ top radiative corrections

The expression for the SM quartic practically forces tan β ~ 1.

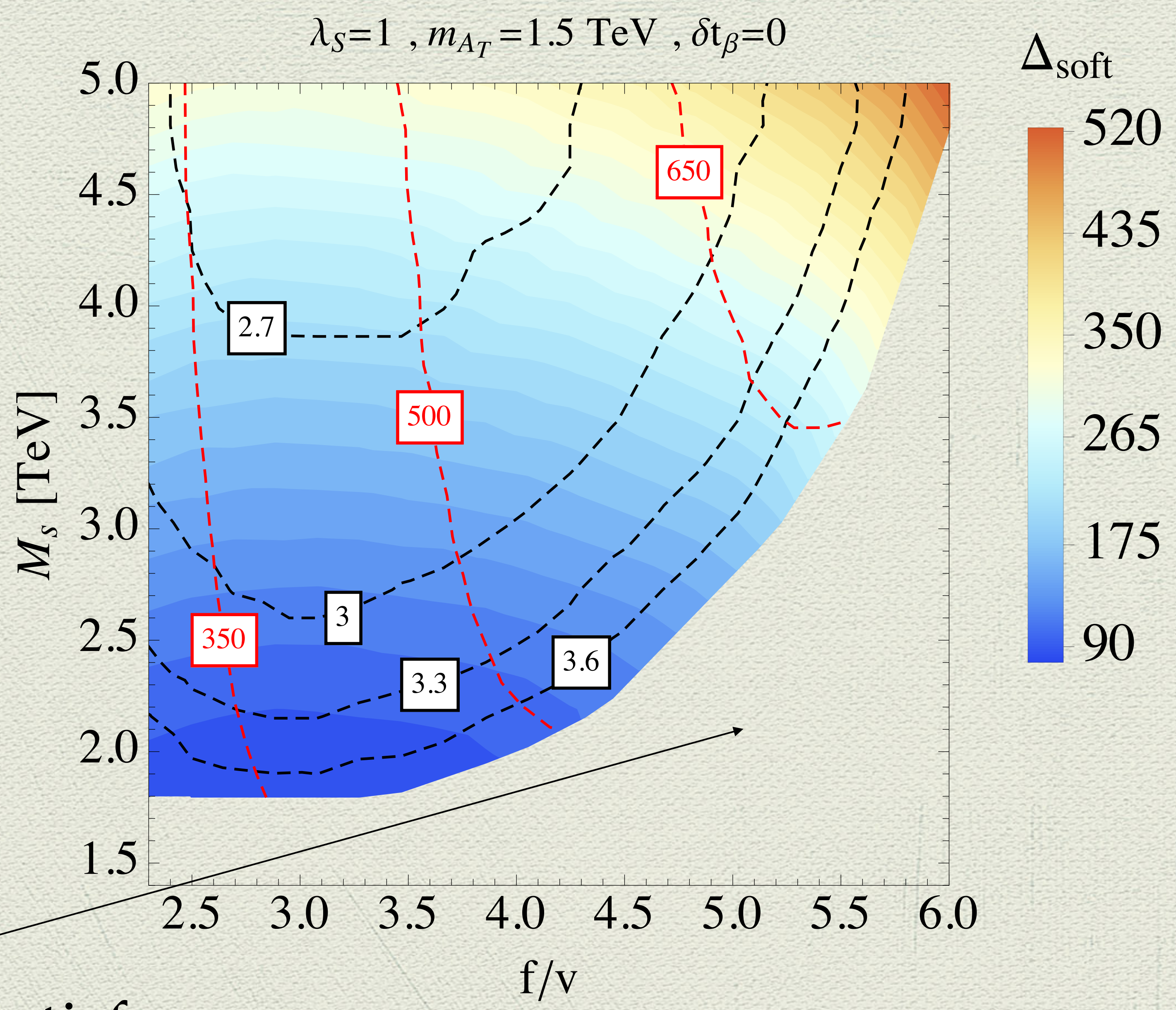
$$\kappa \approx \frac{g_{\text{ew}}^2}{8} c_{2\beta}^2 + \frac{3m_t^4}{16\pi^2 v^4} \log\left(\frac{M_s^2}{m_t^2}\frac{v^2}{f^2}\right)$$

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.

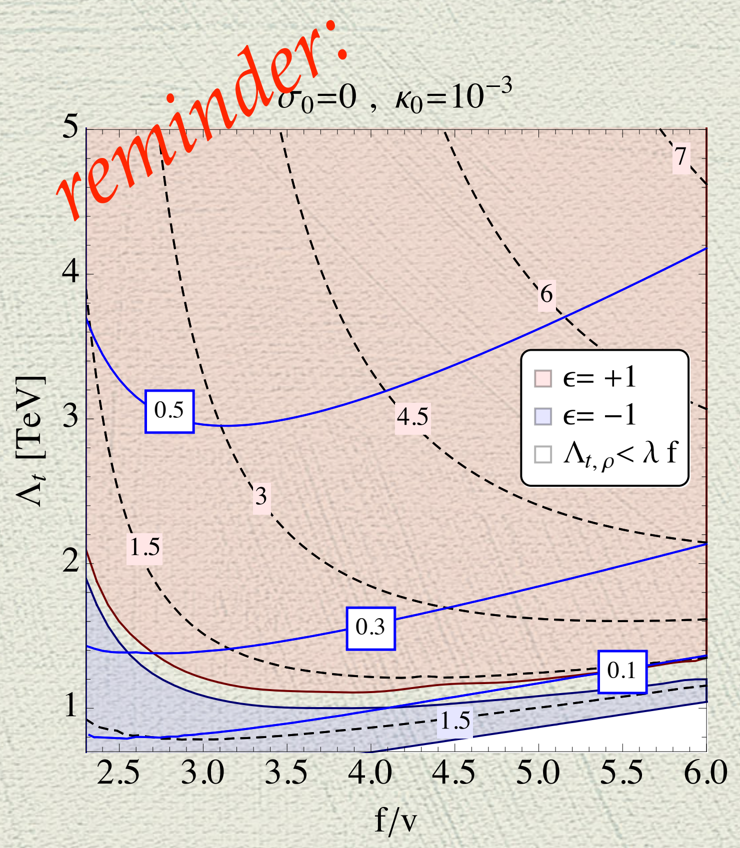


No tan β can be found to satisfy the higgs constraints here

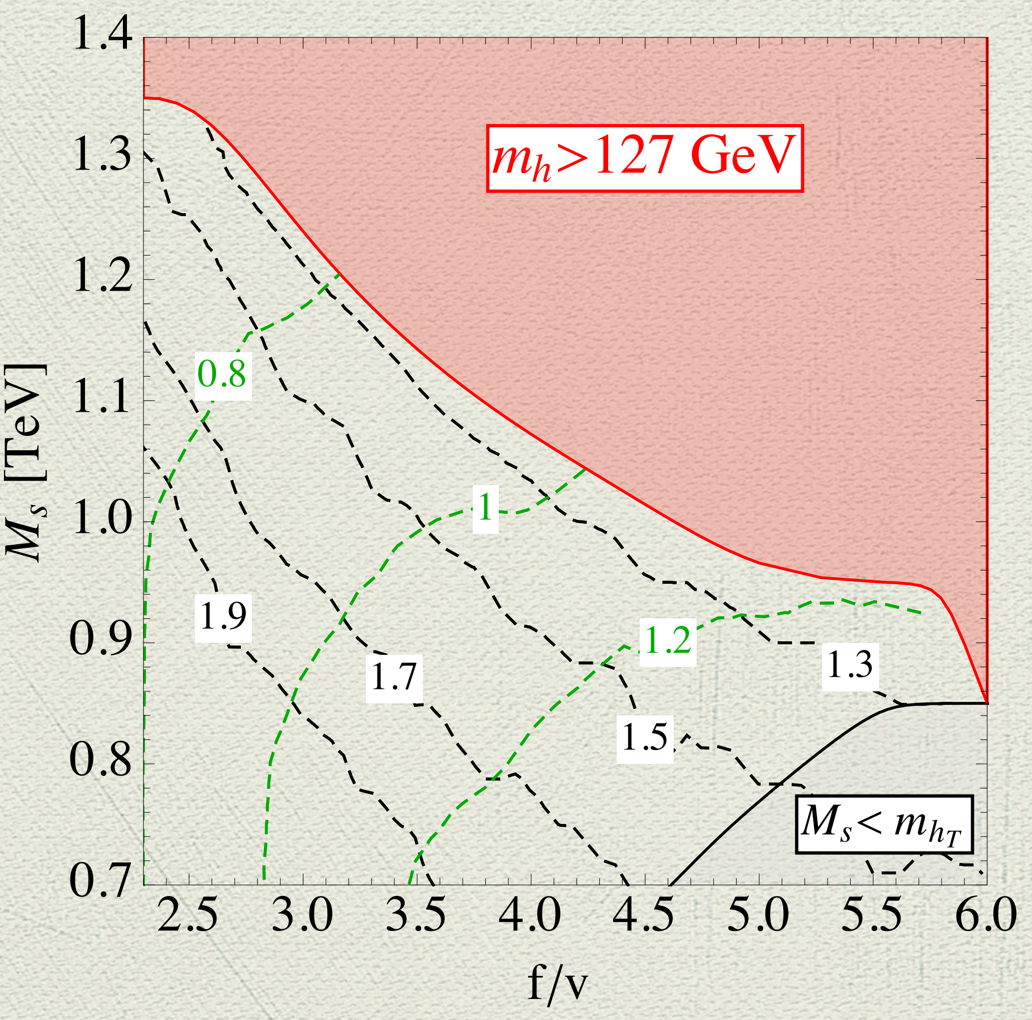
Hard Breaking in SUSY: First Attempt

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

$$W = \lambda' H_u^A H_d^A$$



The threshold correction < 0 ☛ very constrained



Hard Breaking: the Bidoublets

Potential way out: negative κ at the mediation scale, compensating for a positive D-terms contribution

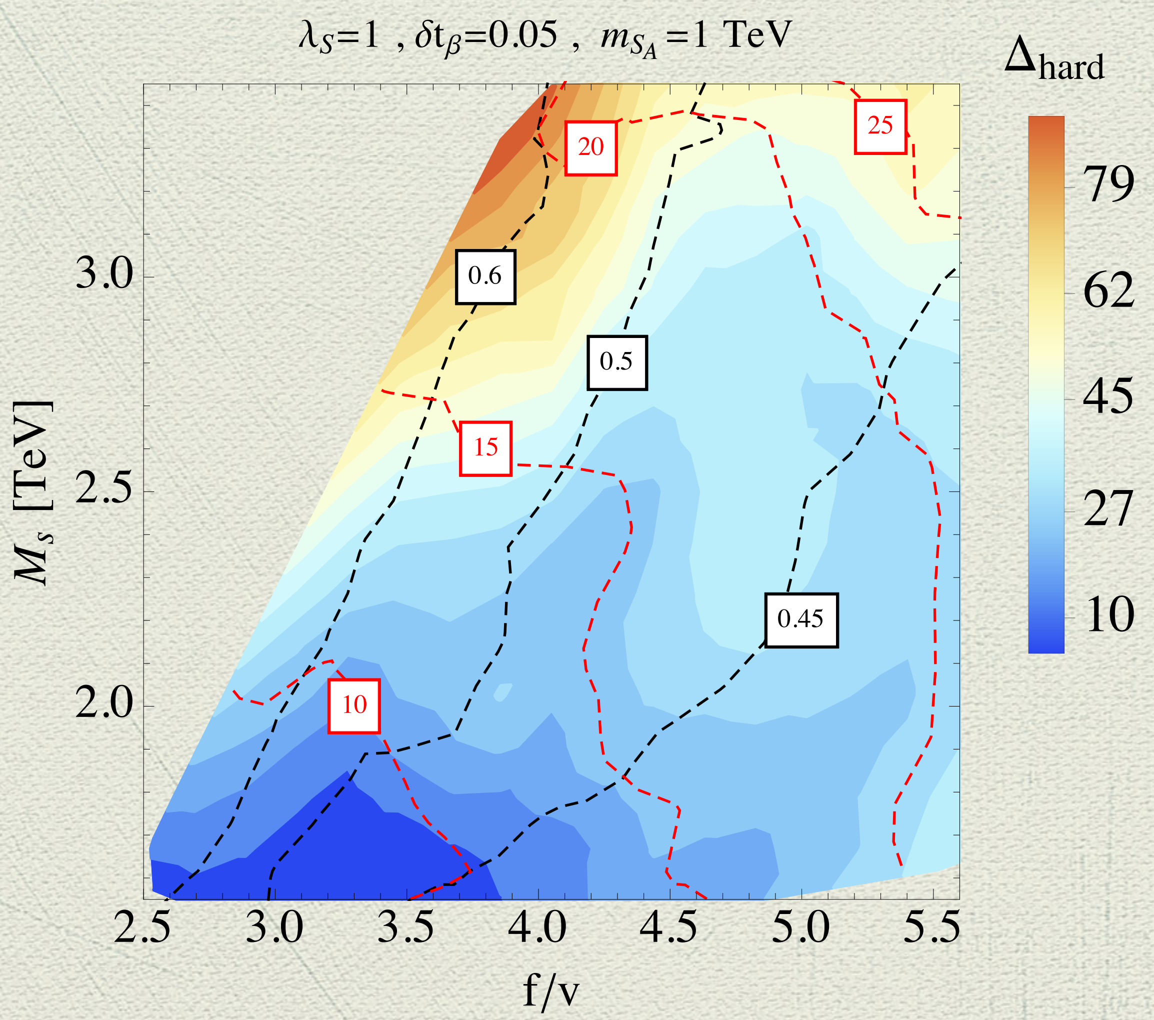
$$m_h^2 \approx 2f^2(2\kappa - \sigma)$$

negative contribution exacerbates the higgs overshooting problem

Trick introduce bi-doublets:

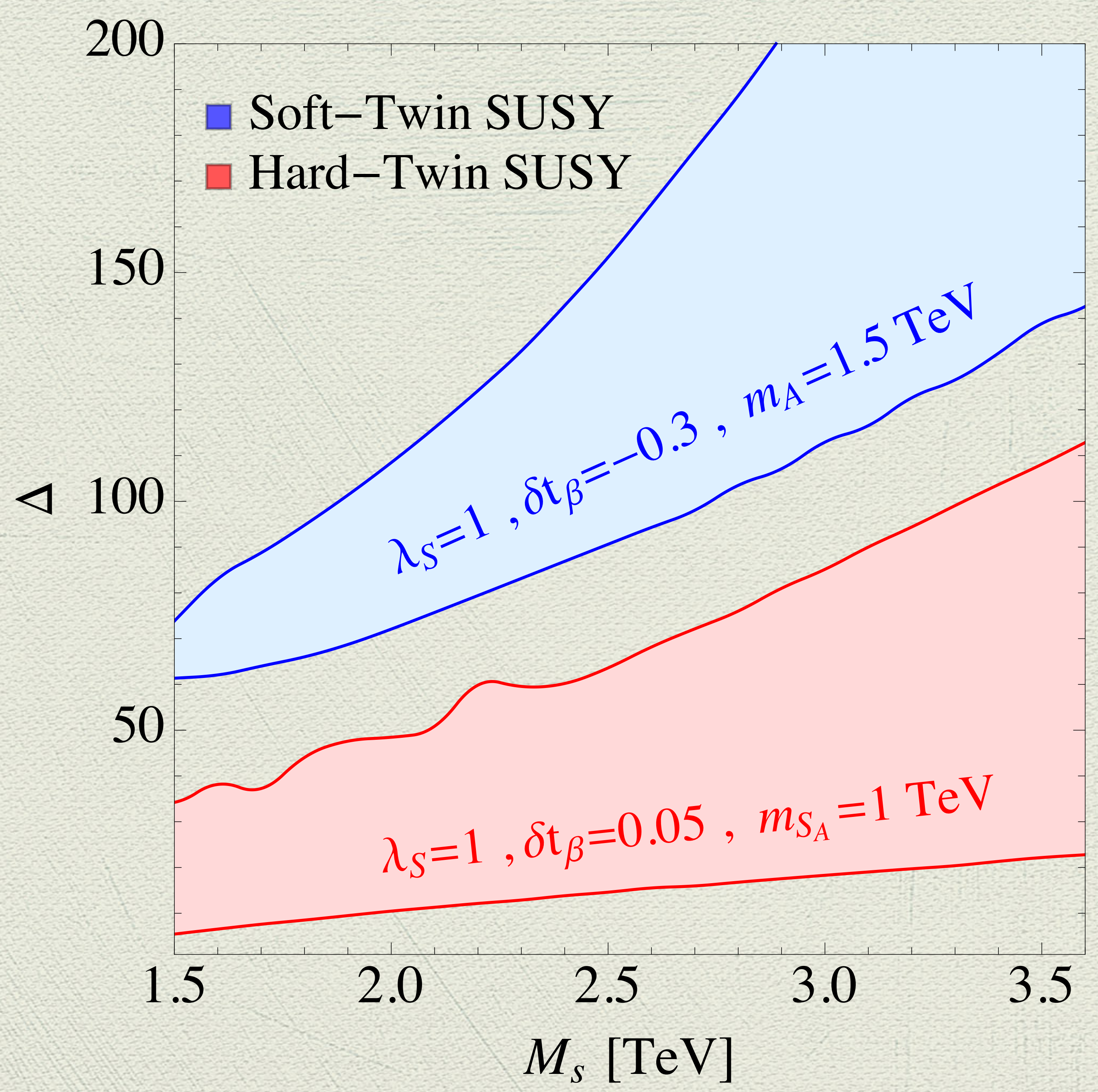
$$W = \lambda_B B h_u^A h_u^B + M_{BD} \bar{B} B$$

+ 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

See a parallel talk by Diego Redigolo

The stops in this scenario might or might 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
- $b \to s\gamma$ 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)