SUSY MEETS ITS TWIN

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based on work w/ A. Mariotti, S. Pokorski, D. Redigolo and R. Ziegler

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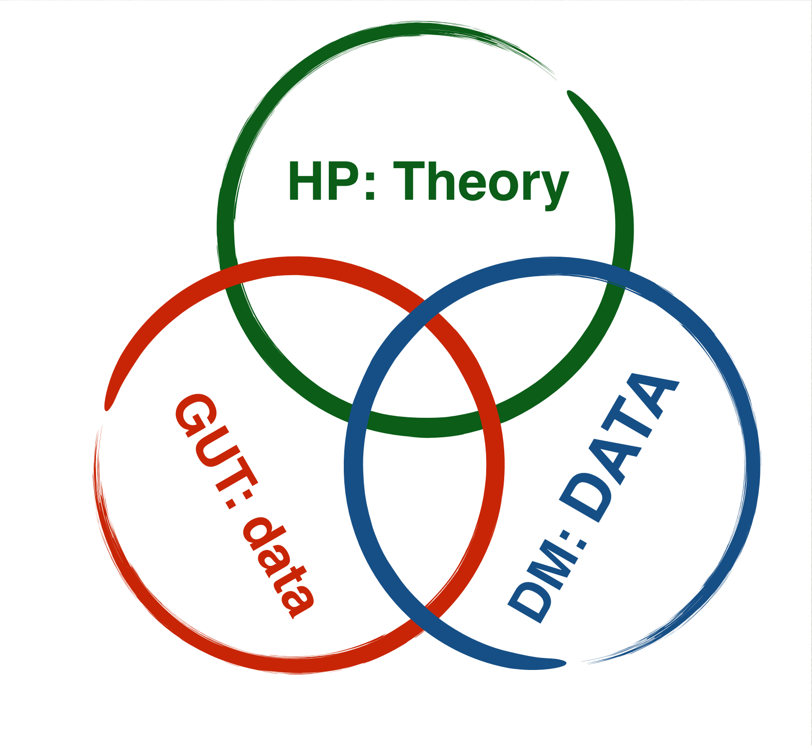
Little About the Main Question.

Is SUSY alive and doing well??

What kind of SUSY are we talking about?

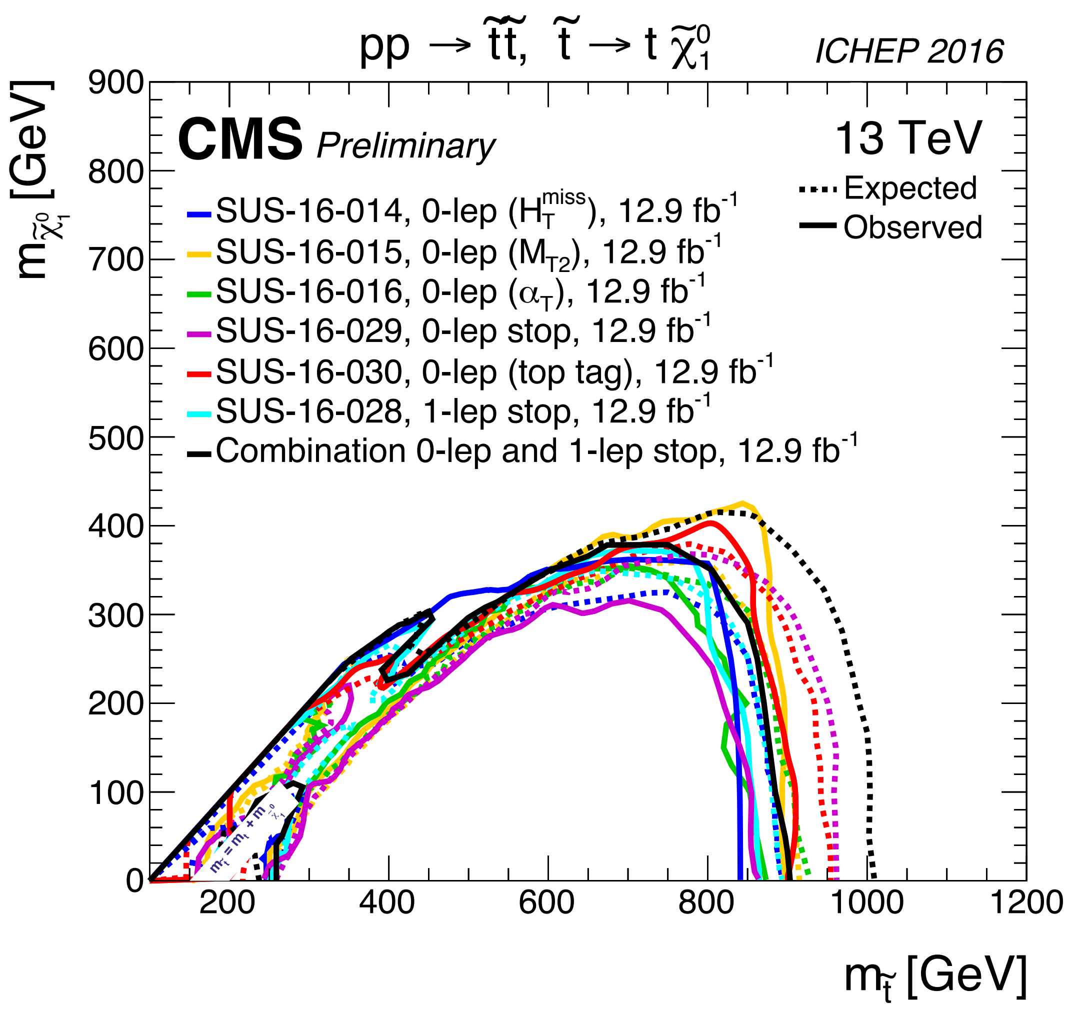
Original idea of 80's and 90's?



The LHC is finally here. What do we know about the FT in garden-variety SUSY

$$m_h^2 \propto \frac{3y_t^2}{4\pi^2} M_{stops}^2 \log\left(\frac{\Lambda^2}{M_{stops}^2}\right)$$

Bounds and Fine Tunings



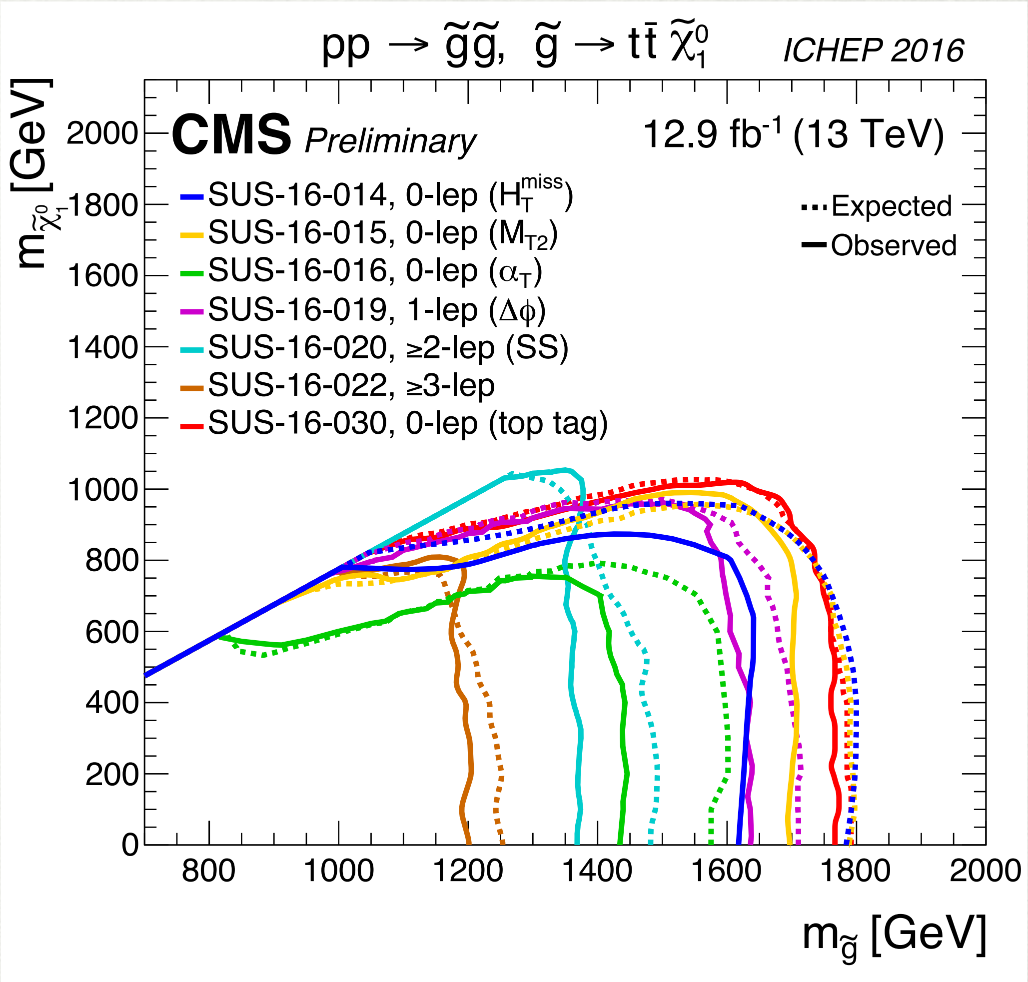
Generic bound on stops ~900 GeV

$$\Delta^{-1} \approx \left|\frac{m_h^2}{2\delta m_h^2}\right| \approx 1.4\%$$

Comparable result from gluino bounds

$$\delta m_h^2 \approx \frac{y_t^2\alpha_s}{\pi^3} M_{\tilde{g}} \log^2\left(\frac{\Lambda^2}{M_{\tilde{g}}}\right)$$

FT ~ 2%

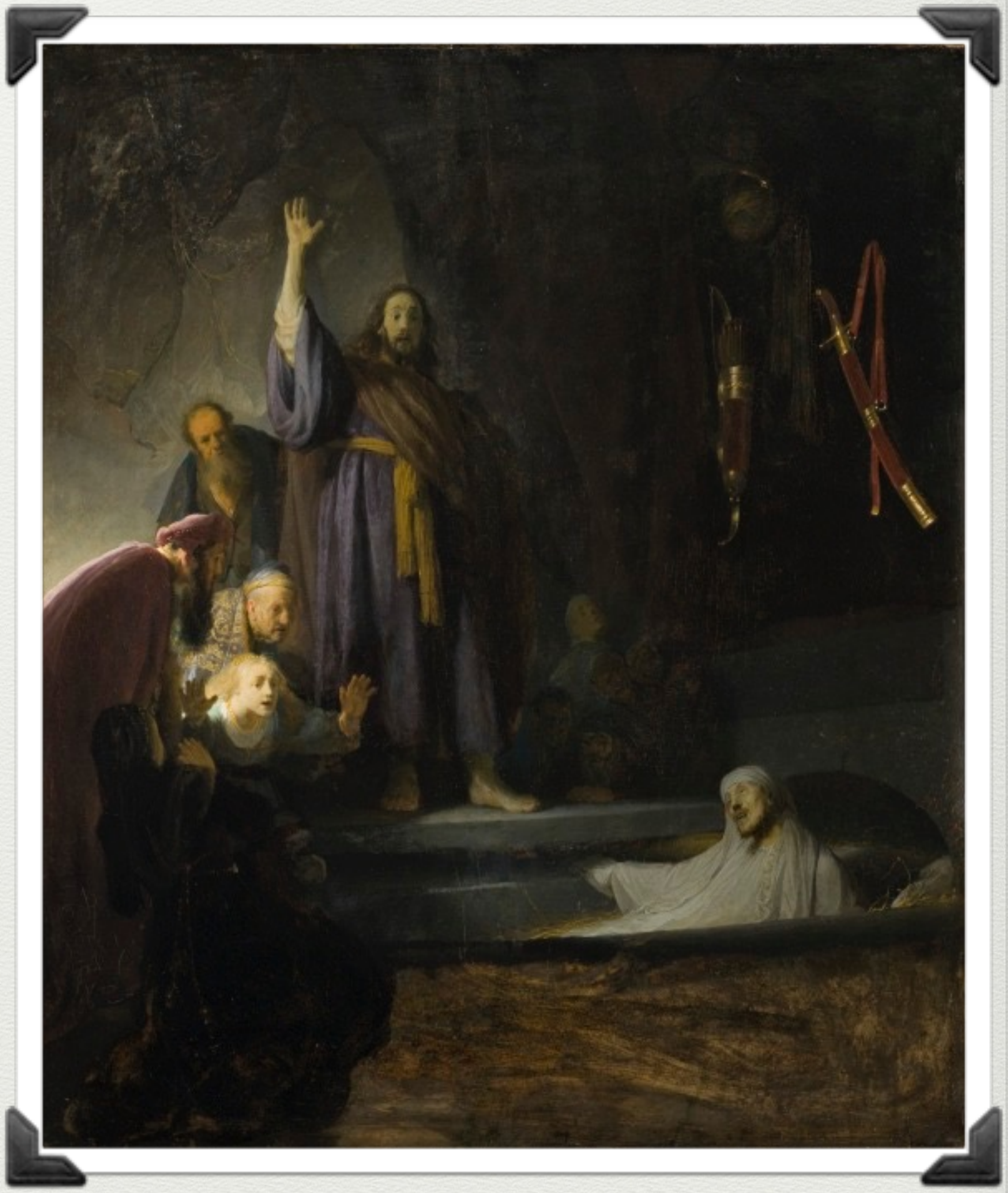


Ways Out?

Pick the two:

- *Keep naturalness and Unification — RPV (also cornered , but in better shape). Give up on the DM.*
- *Choose a mechanism to bridge over the little hierarchy (NN ?). Usually screws unification.*
- *Mini-split — perfectly addresses unification + DM. OK w. 125 GeV higgs. Just give up on the little (?) hierarchy*

Or one can keep believing in miracles



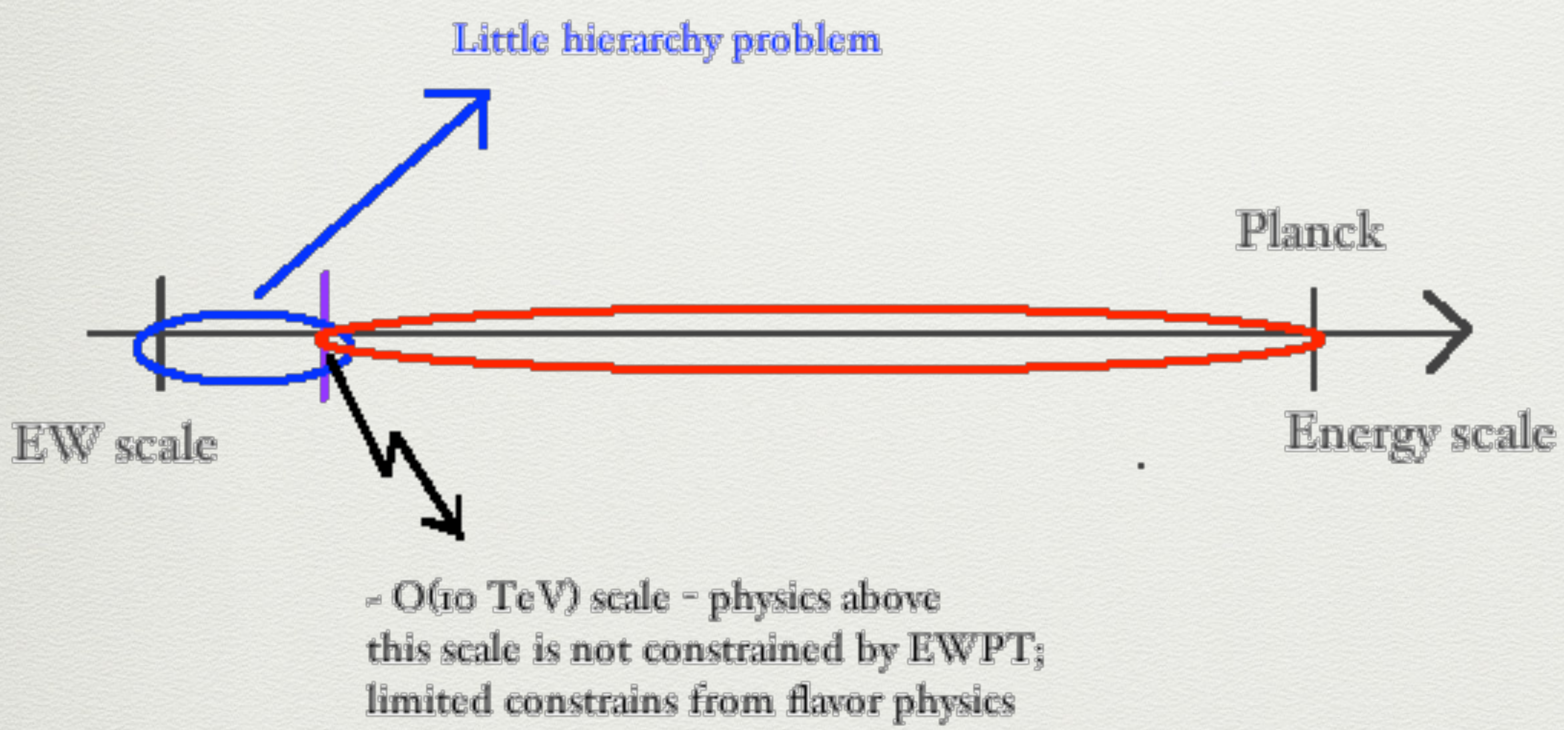
Outline

Logic: we can neither confirm nor rule out perturbative unification at the LHC.
DM is also a long shot.
Let us see if we can bridge over the little hierarchy problem.

- Twin Higgs: Basic Idea and Fine Tuning
- Why marrying the Twin Higgs with SUSY?
- SUSY Twin Higgs: Natural, Non-Minimal
- Comments on Phenomenology — there is still a (weak) hope for the LHC
- Conclusions and Outlook

Twin Higgs (Still Alive and Well!!)

The idea fits into the paradigm of neutral naturalness (NN) solutions to the little hierarchy problem.



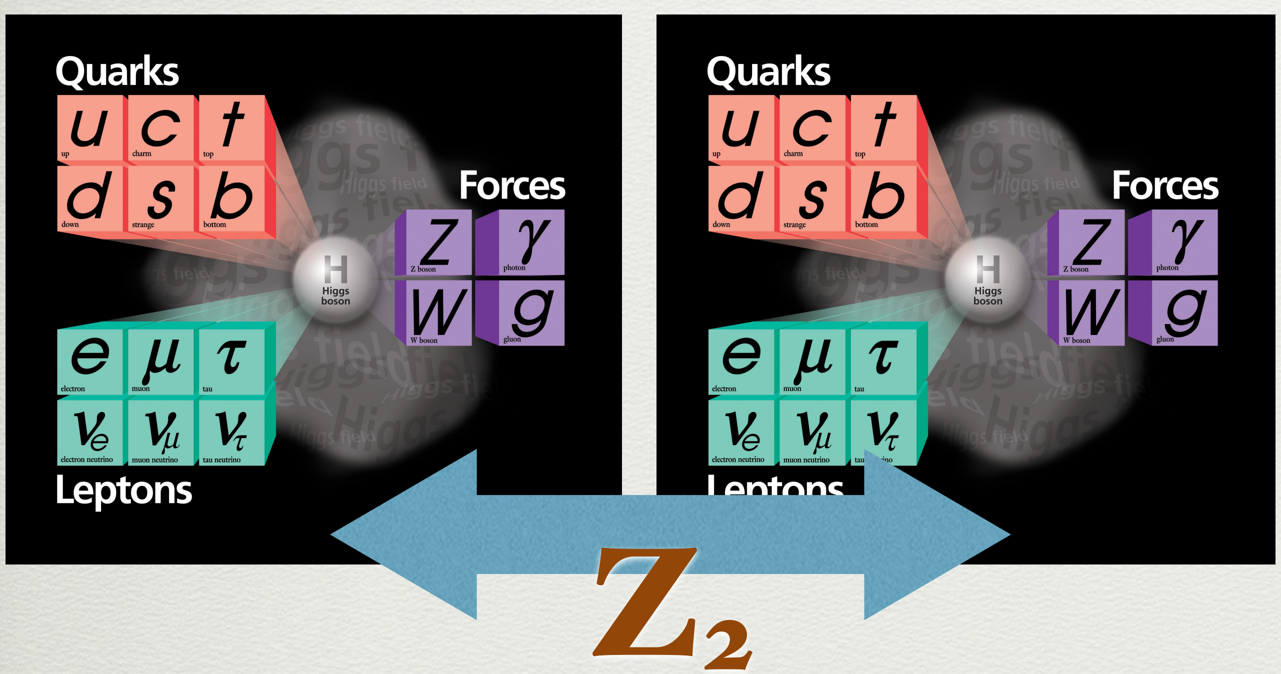
Why neutral?

Expect to get a natural model without light colored particles — mild constraints from the LHC

The Twin Higgs

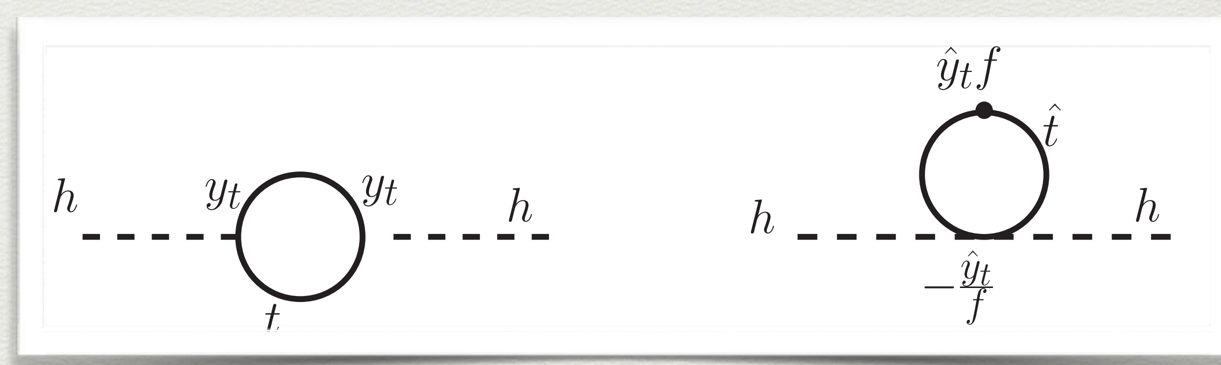
Chacko, Goh, Harnik; 2005

In the Twin Higgs the lightness of the EW scale is explained by the fact, that the SM like higgs is a pGB of an approximate SU(4) [enhanced to SO(8)] symmetry of the Lagrangian. This symmetry is not exact, but holds up to good approximation due to a mirror symmetry of the Lagrangian



At the leading order only Z_2 is needed

Cancellation of the leading divergencies:



The Twin Higgs Potential

Break SU(4) at a scale f ≫ v

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

Standard SU(4) conserving and mirror symmetric term — massless higgs

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

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

Mirror symmetric, but breaks SU(4). We expect the SM higgs mass to come from this term

Need to break the mirror symmetry, otherwise the SM higgs would be an equal mixture of our higgs and the twin higgs. The correct alignment can be achieved via σ or ρ

Mirror Symmetry Breaking by the Higgs Potential

Most of the works until now considered soft mirror symmetry breaking — relative radiative safety.
Why bothering with the hard mirror symmetry?

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

The experimental bound is ~0.4, we have to fine tune σ against to make it small

leads to inevitable FT ≈ v^2/f^2

In fact, in the soft-broken mirror symmetry scenario is not a free parameter:

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

It is simply a SM quartic!

On the FT, More Carefully

multiple talks by Riccardo Rattazzi; 2015-2016

What is our real gain in the FT due to the little Higgs?

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

Sources:

1. IR effective theory — v/f FT
2. Is the scale f is stable??

Up to the denominator it is the SUSY FT

Can be cancelled by higgsinos, mild LHC bounds

Let us now be very naive, assume that these two sources perfectly factorize and neglect other caveats:

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

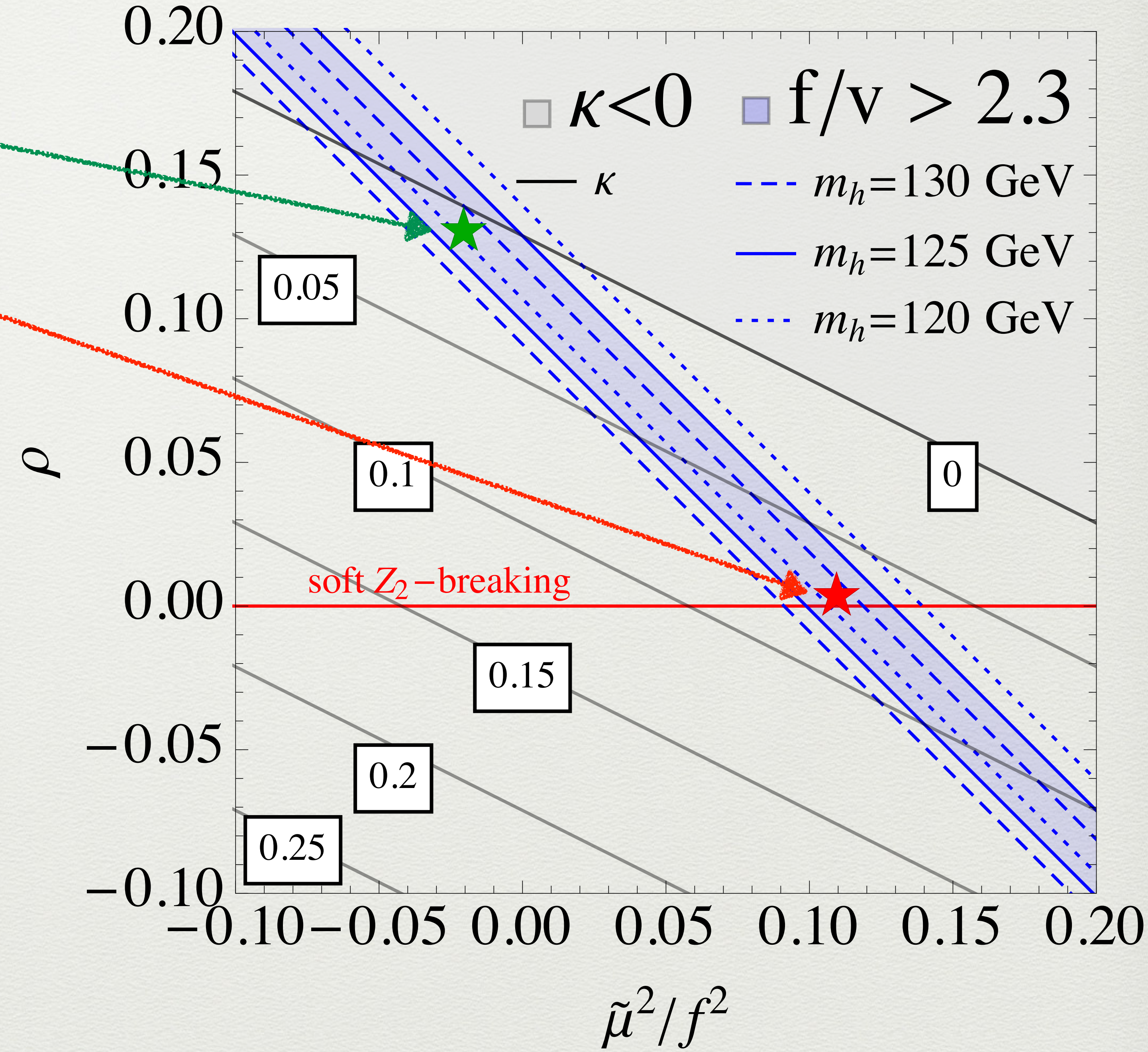
This coupling is measured to be ~0.06, the effect cannot be moderate at best

What is the Full Parameter Space?

pure hard breaking

pure soft breaking

With the given measurement of the higgs mass we are always constrained to a narrow strip



Always need small κ.
Radiative corrections?

On the FT, Hard Breaking

Can we do a better job if we allow the hard symmetry breaking?

Simple answer: YES

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

There is a-priori no need to fine-tune σ against κ. But…

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

ρ is a hard breaking term, we expect σ to be quadratically sensitive to it

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

And w/o UV completion we even do not know the sign of this term

FT, Hard Breaking

Let us assume for simplicity that we have only hard mirror symmetry breaking at the "cutoff" scale. Of course in the real theory we will have soft + hard.

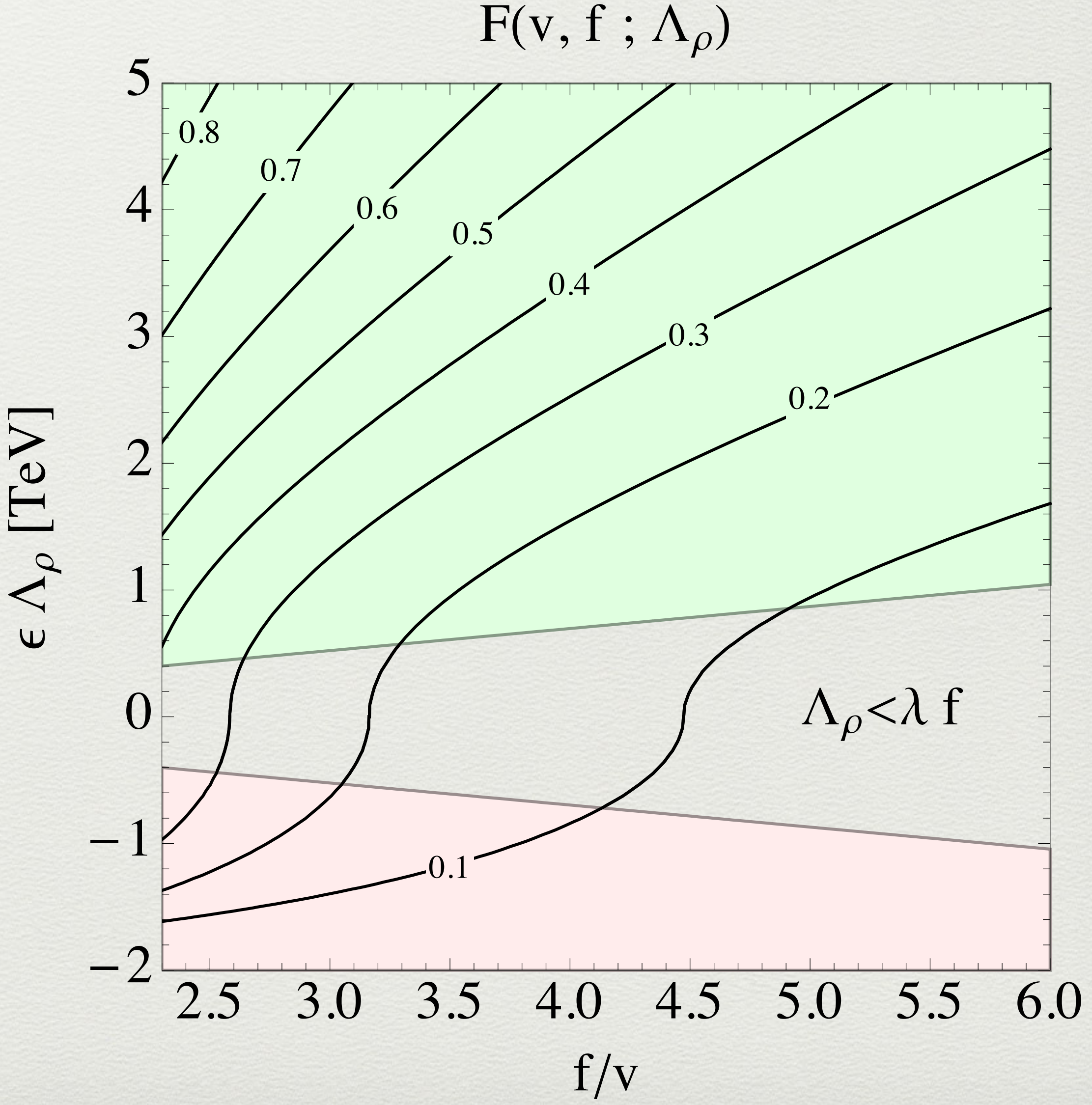
In the IR:

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

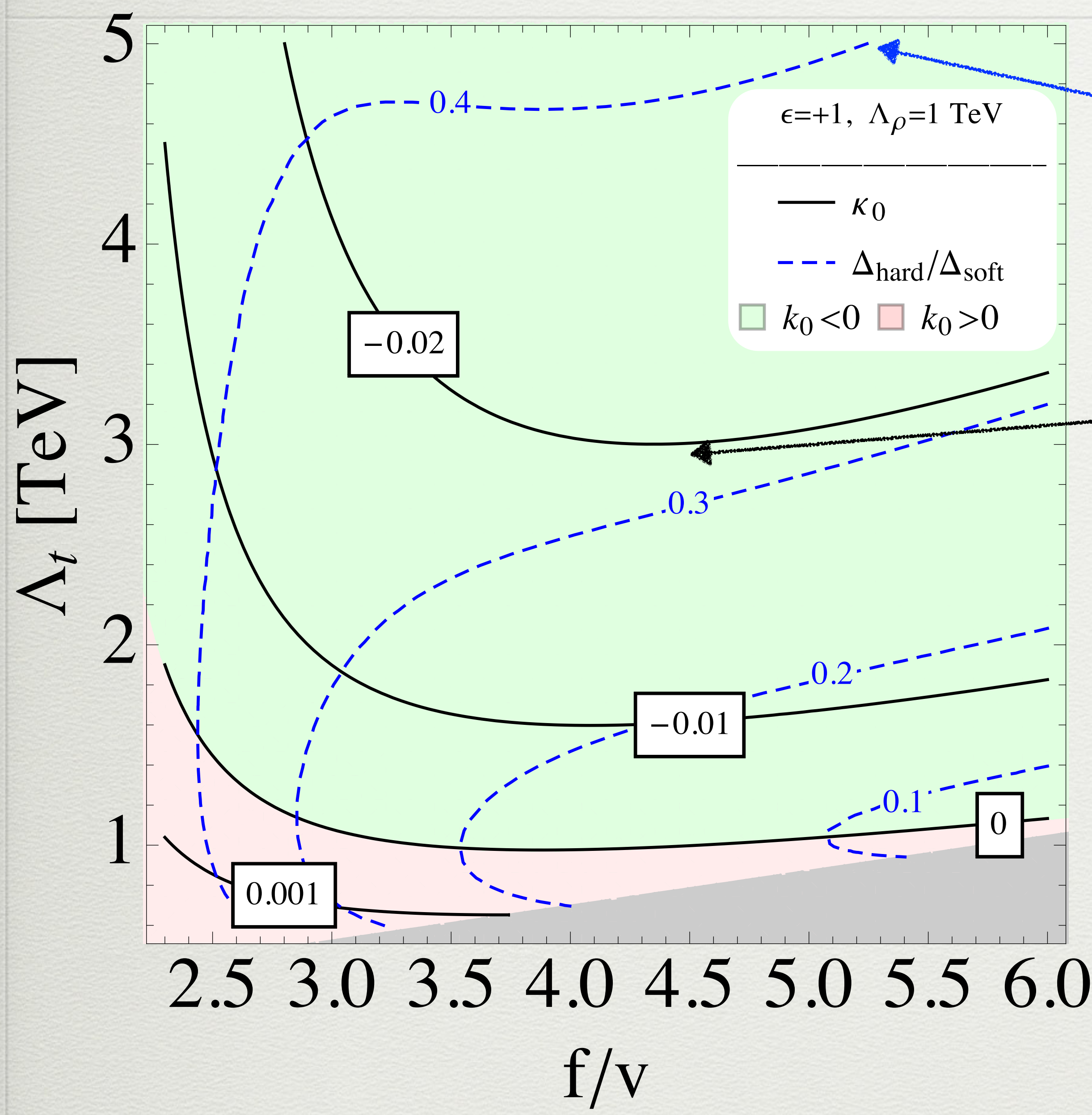
Limits:

- Λ goes to infinity ☛ the function F reduces to 1, no gain
- Λ ≪ 4πf ☛ the function F ~ v^2/f^2

There is a true gain if the "cutoff" is low enough



Caveats



Gains in the FT

Desired values of quartic at the "cutoff" scale

The desired values of the quartic are of order 10^{-2}, but…

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

Should we FT the higgs mass?

yes, but the extra FT is of order 1

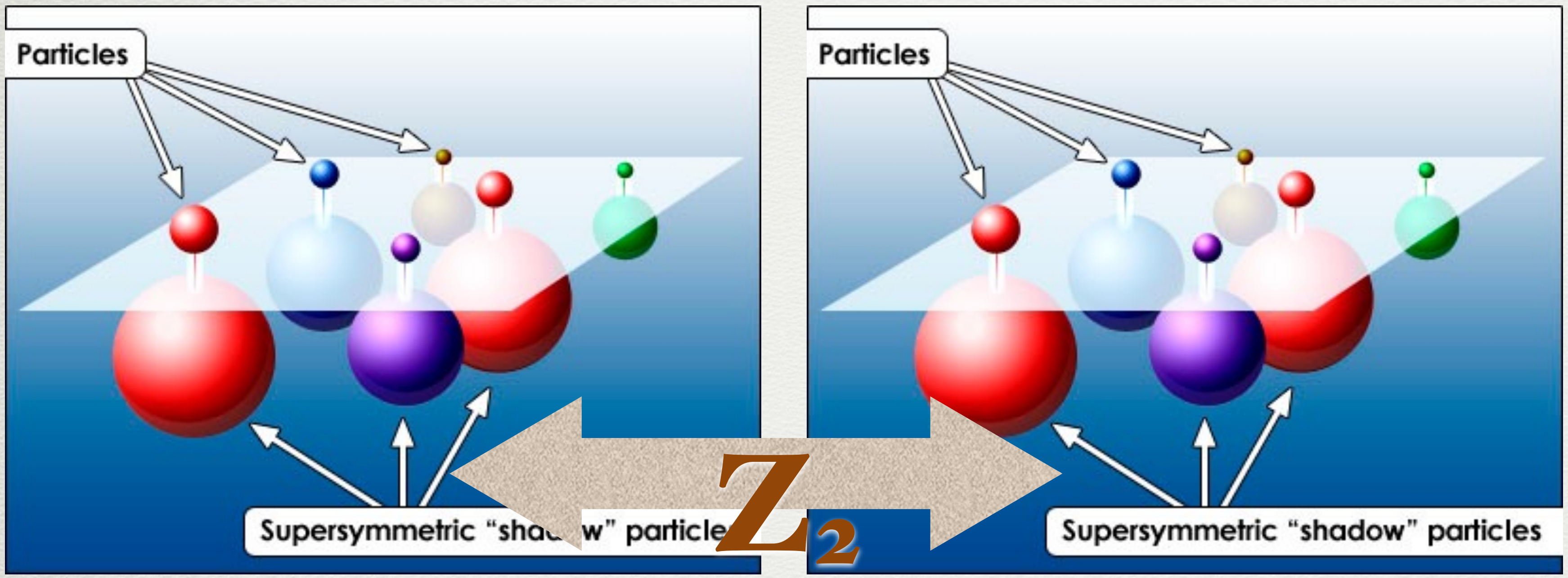
Typically full models with hard breaking will slightly overshoot for the Higgs mass, and will lack perfect factorization, but these caveats turn to be minor.

UV Completion. Why Do We Prefer SUSY?

- The scale f is unstable by itself and requires a natural UV completion. Known options: strong coupling, SUSY or “turtles all the way down”.
- Examples of the latest version are not know in the Twin Higgs context.
- Strongly coupled Twin Higgs has its own problems, e.g. precisions EW. In the strongly coupled models all the mass scales should come out similar.
- We would like to have some moderate separation between the top partners mass scale and the higgs partners mass scale — hard in a strongly coupled theory
- SUSY can naturally explain why various mass scales that we have introduced are slightly different from one another — technically natural, moderately small couplings.

SUSY Meets Its Twin

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



How do we get the necessary couplings?

Getting SU(4) conserving quartic: **NMSSM** (well, almost)

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

$\mathcal{H}_u \mathcal{H}_d$ → *full multiplets of the approximate SU(4)*

λ → assume to be order-1

The singlet should be integrated out non-supersymmetrically (soft mass ≫ SUSY mass)

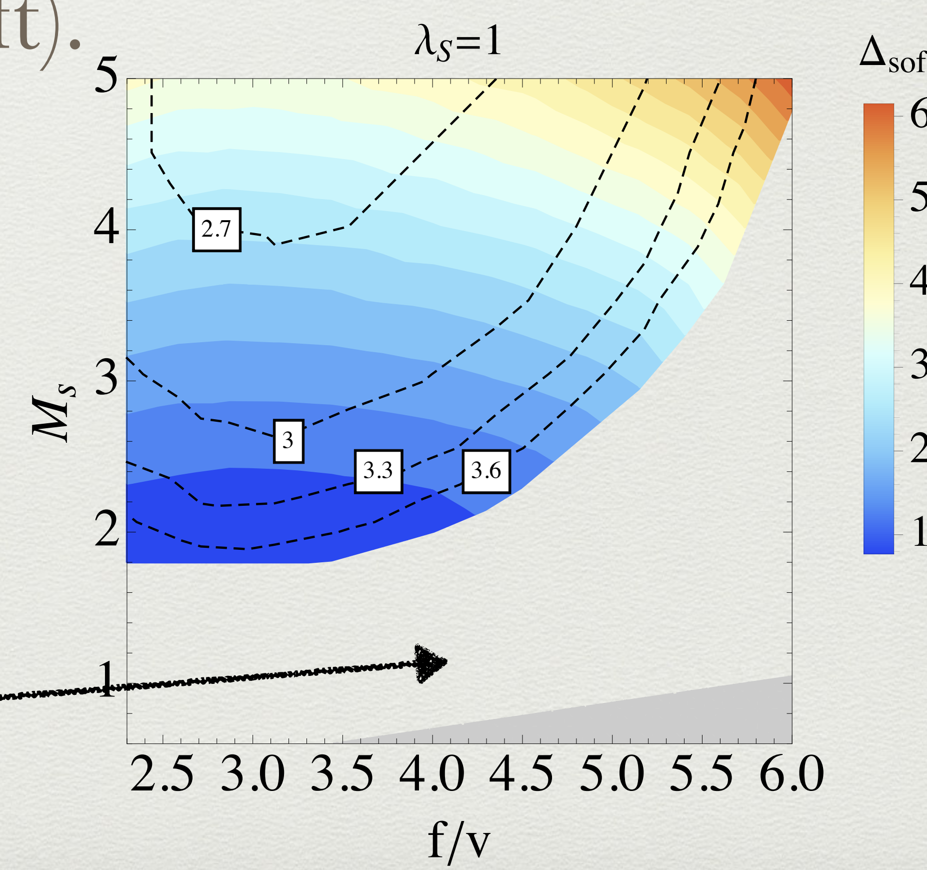
The Soft SUSY Model

Straightforward, but do not expect big gains in the FT!

- κ — comes out from the D-terms. Given that the SM higgs mass ~ κ, it very similar to the MSSM (but factor of 2 helps!)
- Mirror symmetry breaking terms — simply assume asymmetric soft masses (definitely soft).

Rattazzi's logic clearly works — no FT better than 1% (in agreement with Craig & Howe)

Higgs mass condition cannot be satisfied for any tan β.



The Hard SUSY Model — Wrong Way

Very naive way to break the mirror symmetry:

Just introduce a mirror symmetry breaking W:

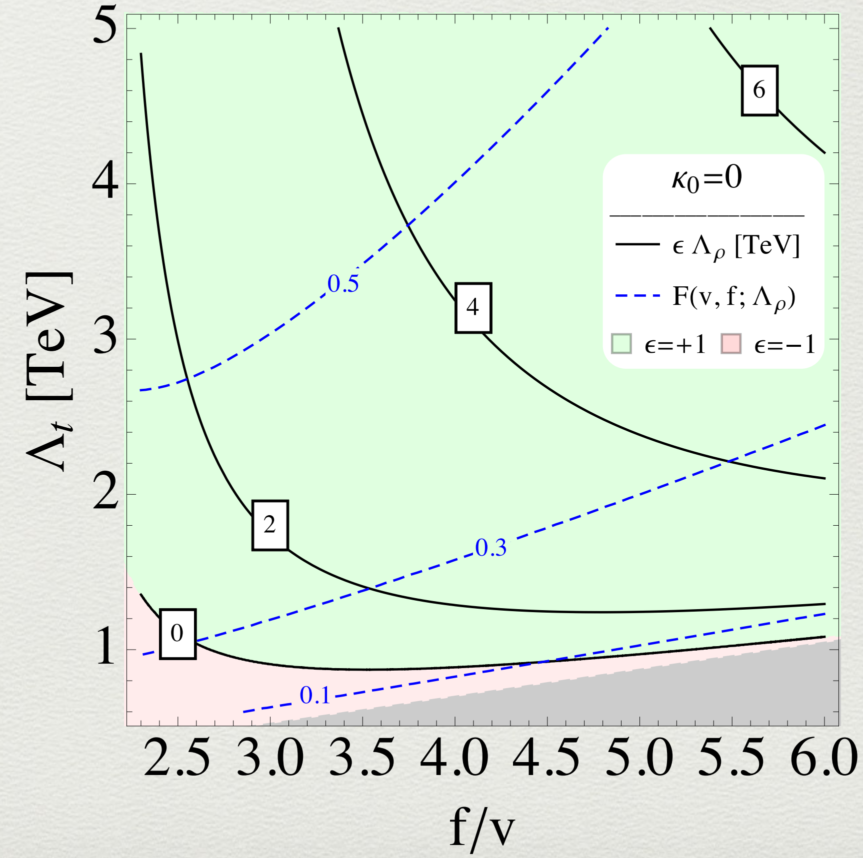
$$W = \lambda' H_u^A H_d^A$$

Perfectly maps on a ρ-term. Small problem:

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

Now we can really calculate the sign, and it turns out to be negative

This negative threshold drags the soft mass negative, allows only low values of the stop masses.



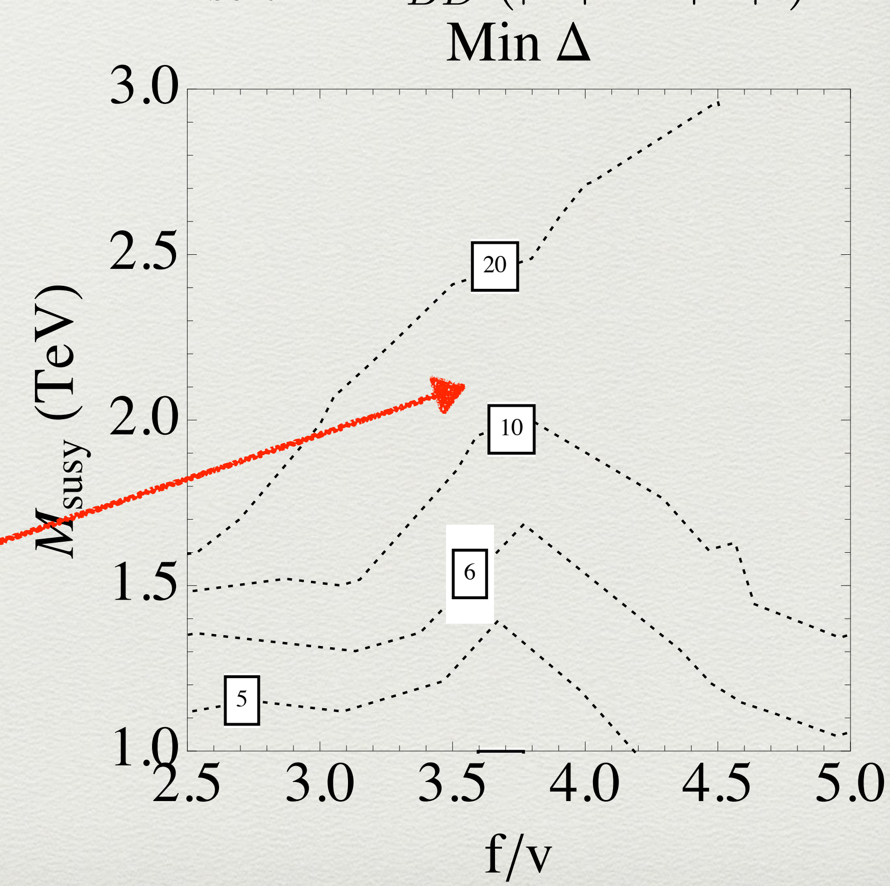
Way out — negative κ.

The Bi-Doublets

Desiderata: negative mirror symmetry preserving quartic, hard mirror symmetry breaking terms. Any way to get this?

Trick: introduce vectorlike bidoublets:

$$\Delta W = \lambda_B B h_u^A h_u^B + M_{BD} \overline{B} B \,, \qquad V_{\text{soft}} = m_{BD}^2 \left(|B|^2 + |\overline{B}|^2 \right) \,.$$



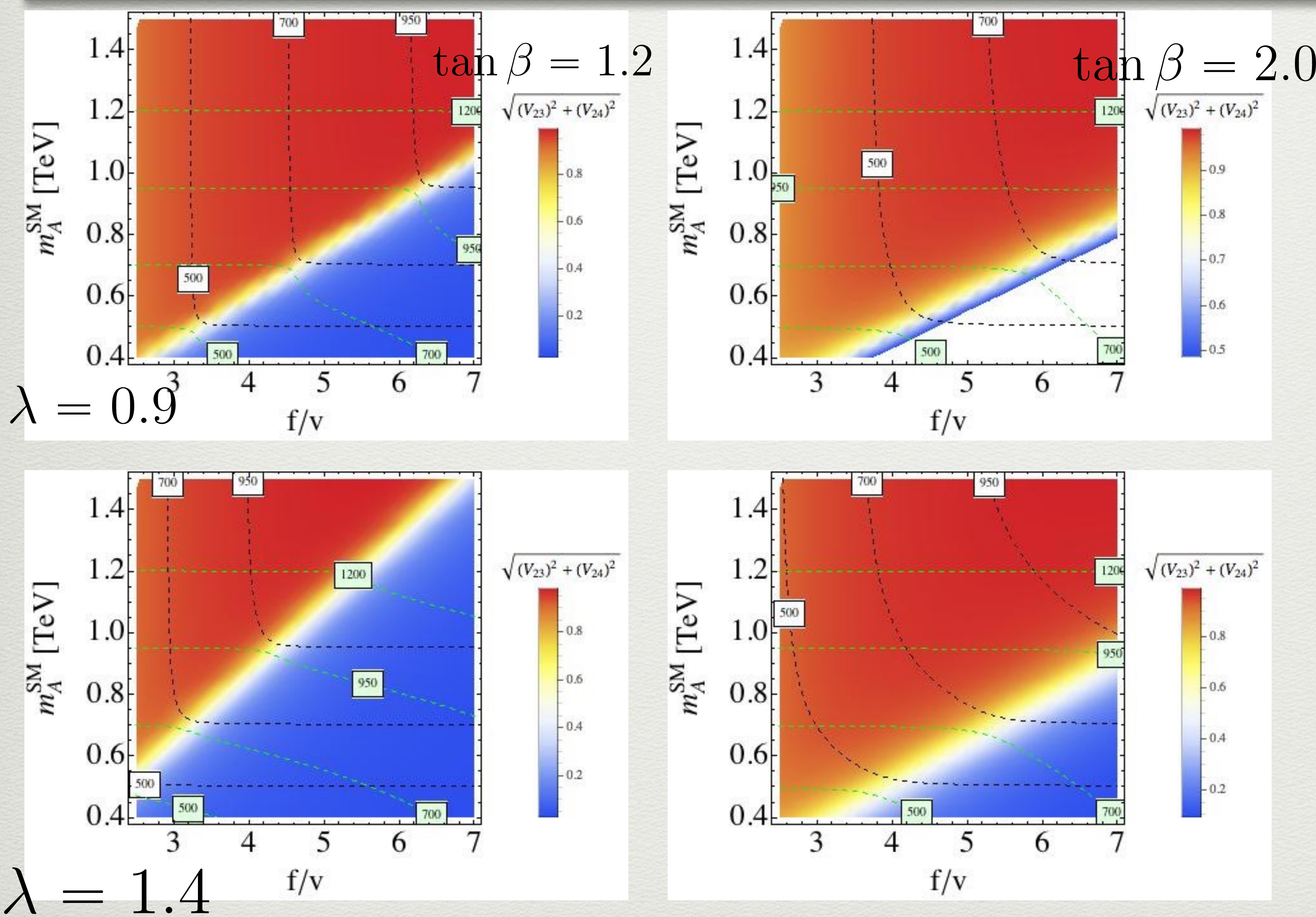
Automatically get negative quartic which can outweigh the D-terms

Contours of the FT (scan!!)

We can improve the situation qualitatively

Hopes for the LHC Pheno?

We have plenty of the Higgses in the story?
Who is the next to the lightest higgs



Red — more radial mode-like

Blue — more MSSM heavy-higgs—like

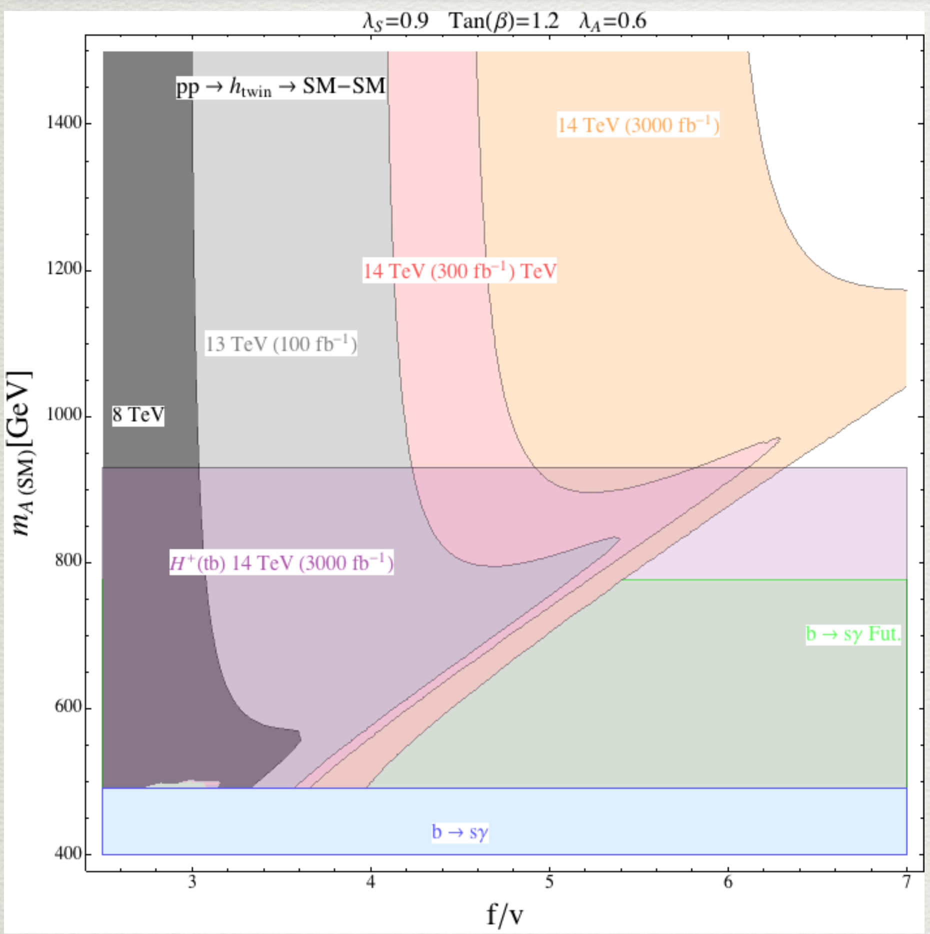
Green, black — contours of the other CP-even higgs masses.

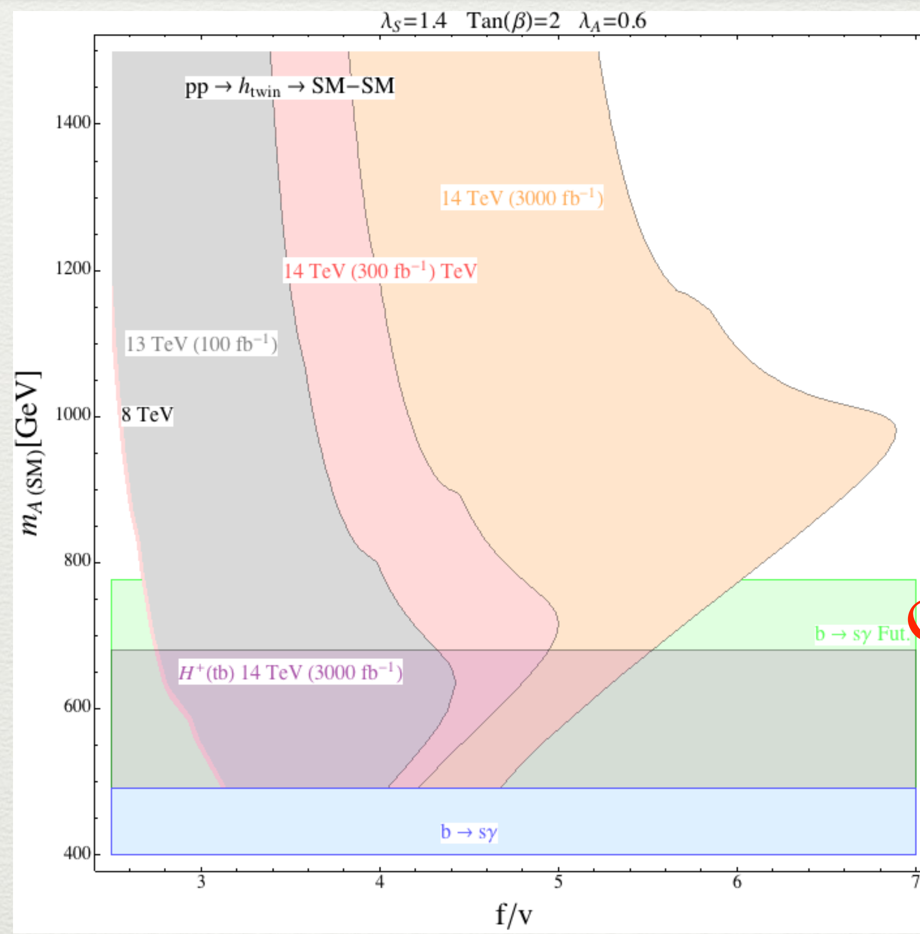
Searches for the New Higgses

What can we search for?

Decays into di-Z and di-h — very promising, BRs are not independent due to the Higgs equivalence theorem.

Decays into tops — very challenging due to the interference with the SM background.





Promising coverage for the HL LHC and future b → sγ

Conclusions

- Twin Higgs is still an alive mechanism to bridge over the looming little hierarchy problem
- Hard mirror symmetry breaking can reduce the FT, with certain caveats
- Twin SUSY is a natural candidate to UV complete the Twin Higgs + hard mirror symmetry breaking
- A model with bidoublets and generic terms in the superpotential can do the job
- LHC signals are possible, both in the searches for the extra higgses and in the precsion measurements of the higgs couplings
- **Where are the stops??**