Twin Higgs meets SUSY

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Based on work in progress with:

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Introduction

Many fundamental questions after the first LHC run …

Is SUSY still alive?

What about Naturalness?

(Little) Hierarchy problem?

Exotic naturalness realization?

What is the status of naturalness?

FT and Top partner lore

Paradigm: symmetry protecting Higgs mass

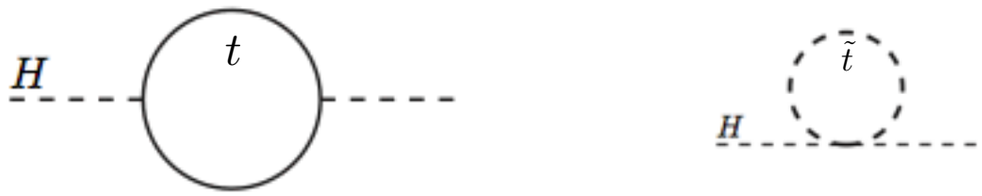
Largest coupling with the Higgs is top $\mathcal{L} \supset y_t H Q_3 t_R$

→ Symmetry implies existence of light top partner

Prototype: Supersymmetry and the stop

Stop main responsible for naturalness in SUSY!

Also Gluino, Higgsino enters significantly



Stop Mass

$$\delta m_h^2 \simeq \frac{3y_t^2}{8\pi^2} M_S^2 \log \frac{\Lambda_{UV}^2}{M_S^2}$$

SUSY Fine Tuning: $\Delta \simeq \frac{3y_t^2}{8\pi^2} \frac{M_S^2}{m_h^2} \log \frac{\Lambda_{GUT}^2}{M_S^2}$

FT and Top partner lore

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Prototype: Supersymmetry → stop

Stop main responsible for ... ss in SUSY!

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Where is the stop???

Stop Mass

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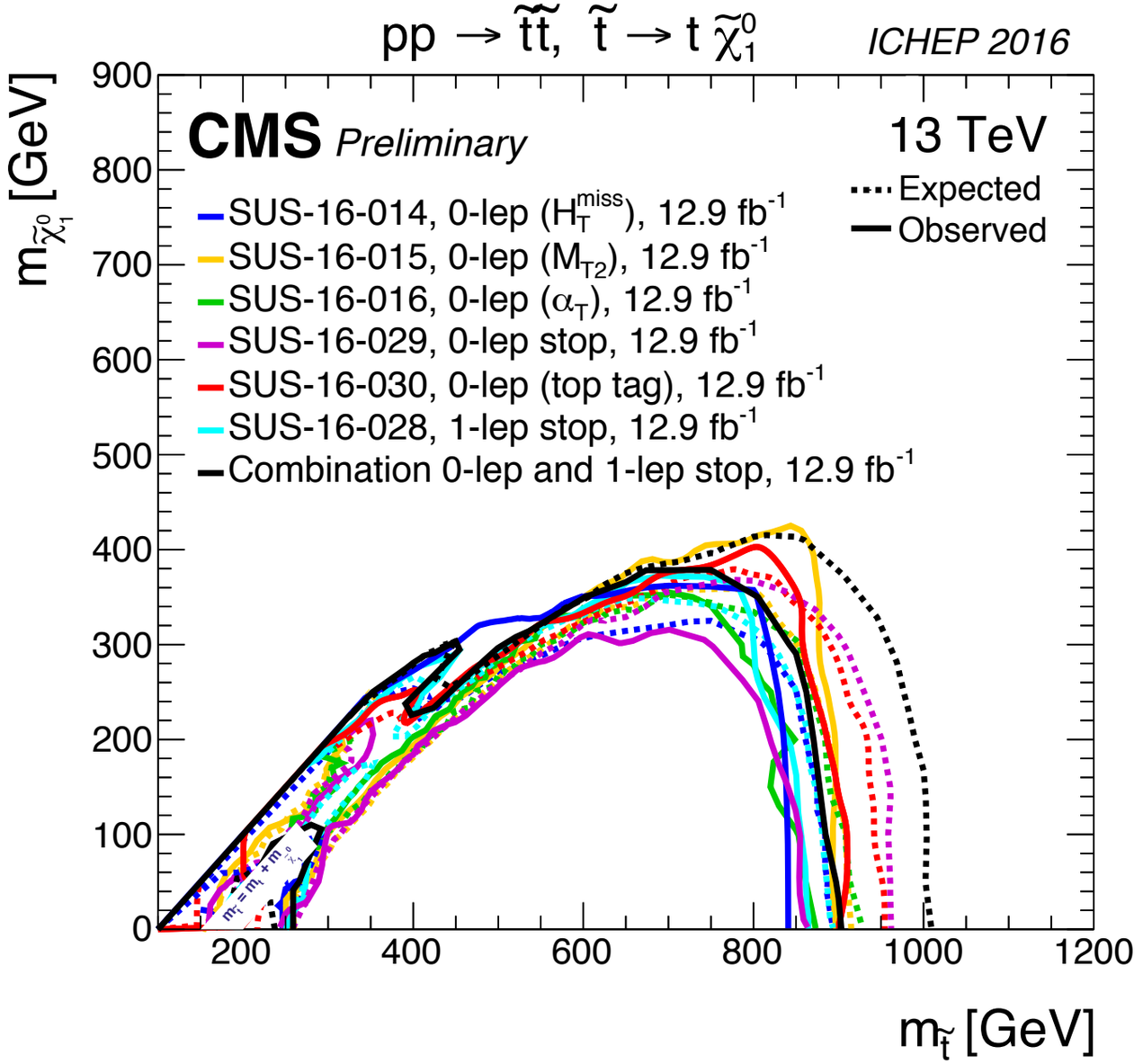
Stop vs LHC searches

Stop excluded up to ~ 1 TeV

FT: $\Delta \sim 100$

Gluino limits lead to similar conclusions

If HL-LHC do not find anything tuning will be ~ 500



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Little Fine Tuning problem of SUSY

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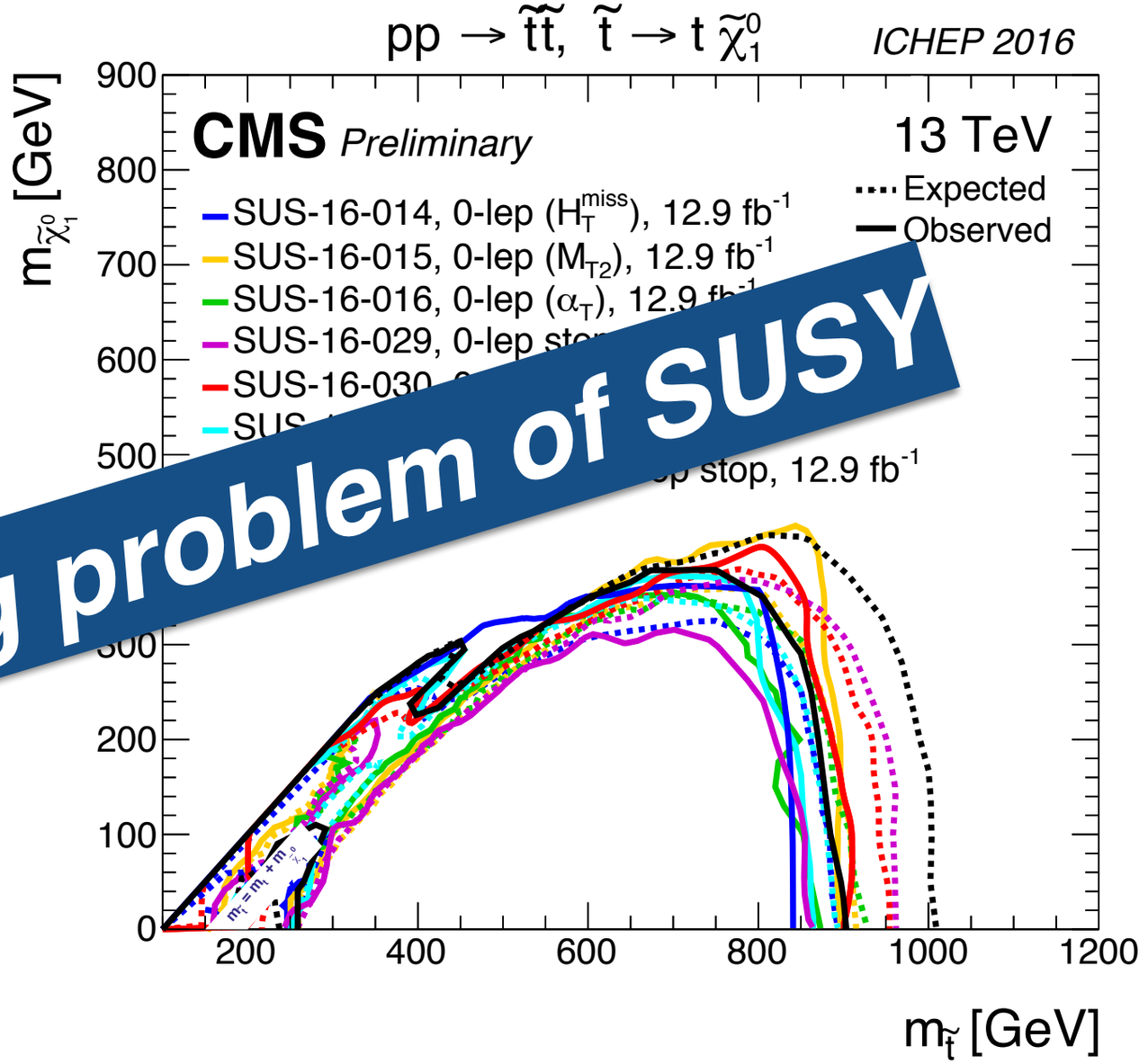


Naturalness status

Little hierarchy problem

Negative LHC results brings in a minimal amount of fine tuning

Same argument applies to standard SUSY and composite Higgs models

Top Partner searches

What next options?

A. *Accept Little Fine Tuning and aim at 100 TeV collider*

B. *Give up some further assumption (e.g. RPV SUSY)*

C. *Investigate alternative natural models and their signatures*

Maybe just a bridge over the little fine-tuning

Neutral naturalness in a nutshell

Usual strategy

- New symmetry G to protect Higgs mass
- New symmetry commutes with SM gauge groups

SUSY $\quad [G, \mathrm{SM}_{\mathrm{gauge}}] = 0\,,\; G \sim Q_\alpha$

Top partner (stop) is charged under QCD

Neutral strategy

- New symmetry G to protect Higgs mass
- New symmetry NOT commute with SM gauge groups

$$[G, \mathrm{SM}_{\mathrm{gauge}}] \sim \mathrm{SM}'_{gauge}\,,\; G \sim \mathbb{Z}_2$$

Top partner is neutral under QCD

Can escape detection at LHC !

Outline of rest of the talk

★Fresh look on Twin Higgs and fine tuning

★Twin Higgs marries SUSY

★Phenomenology at LHC

Twin Higgs setup

Double SM gauge fields, Higgs and tops

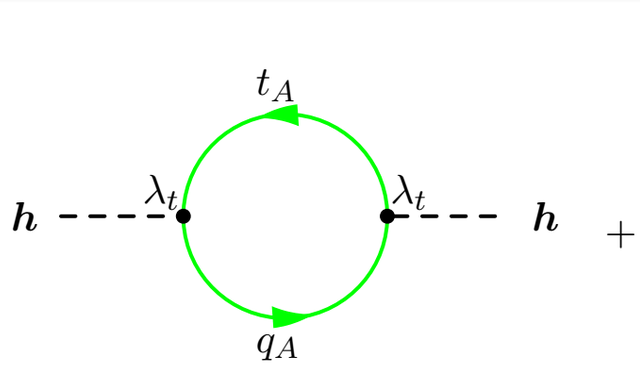
$$G_{\rm SM} \longrightarrow G^A_{\rm SM} \times G^B_{\rm SM}$$

$$H, Q_3, U_3 \longrightarrow \underbrace{H_A, Q_{3A}, U_{3A}}_{\text{visible sector}} + \underbrace{H_B, Q_{3B}, U_{3B}}_{\text{“dark” sector: neutral under SM!}}$$

Mirror sector

$\mathbb{Z}_2$ symmetry exchange sector A and B

Accidental SU(4) symmetry in quadratic potential will protect Higgs mass



Neutral top partner

Twin Higgs potential

Most general potential compatible with symmetries

$$V = \lambda\left(|H_A^2| + |H_B|^2 - f^2\right)^2 + \kappa\left(|H_A|^4 + |H_B|^4\right) + \tilde{\mu}^2|H_A|^2 + \rho|H_A|^4$$

SU(4) and Z2 invariant

f **spontaneously breaks**

$$SU(4) \to SU(3)$$

7 Nambu Goldstone bosons

6 NGB eaten in BEH mechanism

Radial Mode $\longleftrightarrow$ $m_H \sim \lambda f$

One NGB massless scalar! It's the SM Higgs!

SU(4) breaking and Z2 invariant

- *top loop corrections have this form*

Higgs is PNGB

$$\kappa \ll \lambda$$

$$m_h \ll m_H$$

- *PGNB mass log sensitive to the cutoff*

$$v_A = v_B$$

Maximal mixing, excluded by Higgs coupling

Z2 breaking

$\tilde{\mu} \equiv \sigma f$ — ***Soft breaking***

ρ — ***Hard breaking***

allows for hierarchy

$$v \equiv v_A \ll v_B \sim f$$

Controls Higgs mixing angle

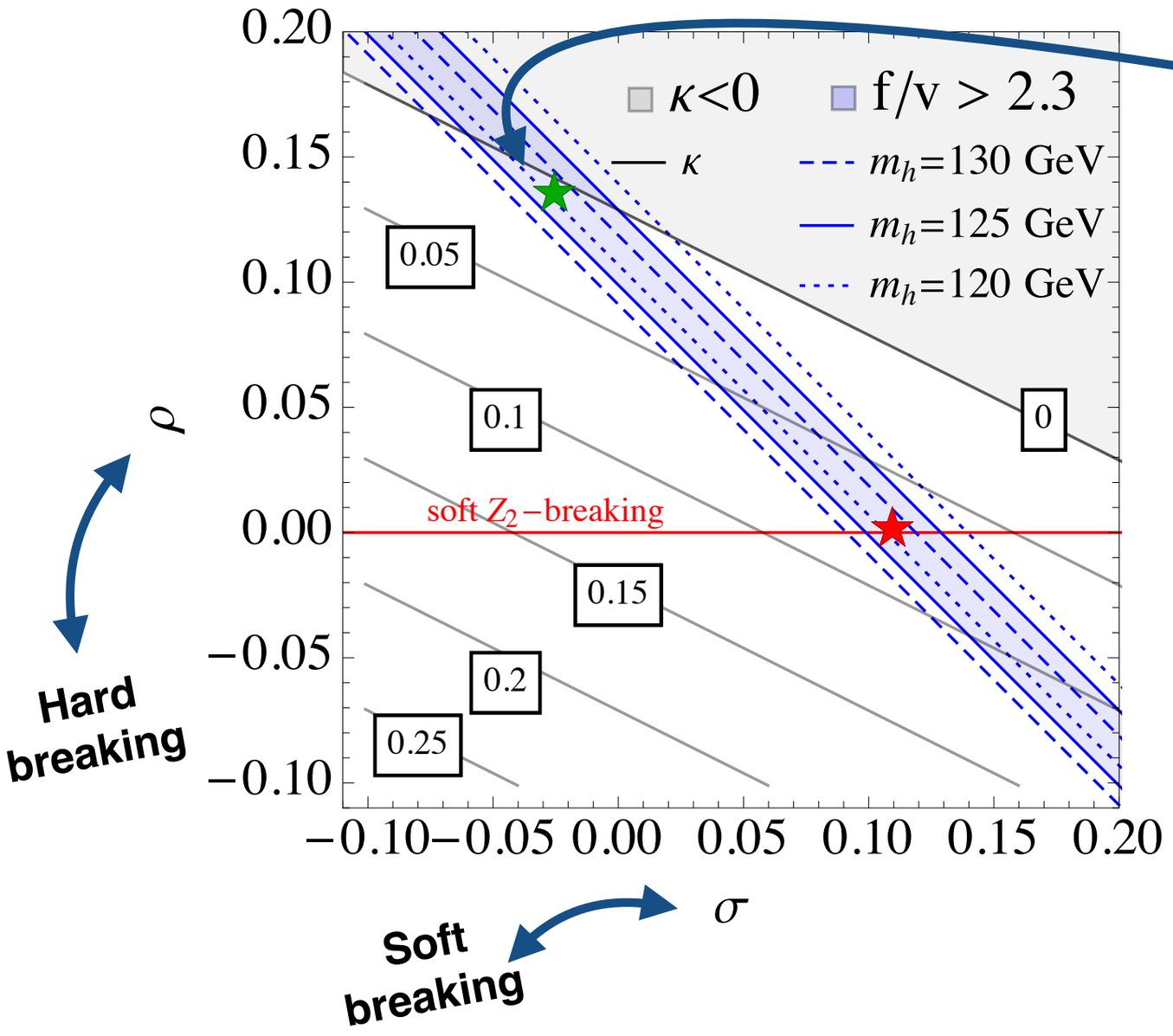
$$s_\theta \sim \frac{v}{f}$$

$$\frac{f}{v} > 2.3$$

The Twin on a Plane

EWSB condition

$$\frac{v^2}{f^2} = \frac{1}{2}\left(\frac{\kappa - \sigma/2}{\kappa + \rho/2}\right) \qquad m_h^2 \approx 4f^2\left(\kappa - \frac{\sigma}{2}\right) \approx 8v^2\left(\kappa + \frac{\rho}{2}\right)$$



Viable strip

4 parameters $\{f, \kappa, \sigma, \rho\}$

- 2 observables $\{v, m_h\}$

and constraint $f/v > 2.3$

★ soft-breaking: $\rho \ll \sigma$

tuning $\sigma \approx 2\kappa$ to get $f/v > 2.3$

★ hard-breaking: $\rho \gg \sigma$

tuning $\kappa \ll \rho$ to get m_h

Twin Higgs: summary

Higgs mass log sensitive → ***Cut-off of the Twin Higgs*** $\Lambda_{\rm Twin}$

Possible mixed with the Higgs -> signatures → ***Neutral States*** f

EW scale v

The Twin Higgs is a bridge over the little hierarchy problem

Candidate UV completions

SUSY

- *Weakly coupled*

Composite

- *Strongly coupled*

Twin SUSY

Twin Higgs

Higgs is a PNGB of accidental global symmetry

Top partners are neutral under SM gauge

Improve Fine-Tuning

Provide UV completion

Supersymmetry

To Do's:

Only few existing models

Chang Hall Weiner 2006
Falkowski, Pokorski, Schmaltz 2006
Craig Howe 2013

Explore general structure and identify phenomenology

Twin SUSY

$$\mathrm{MSSM}_A \xleftrightarrow{\mathbb{Z}_2} \mathrm{MSSM}_B$$

- Two copy of Two Higgs doublet model $\mathcal{H}_u = \begin{pmatrix} h_u^A \\ h_u^B \end{pmatrix} \quad \mathcal{H}_d = \begin{pmatrix} h_d^A \\ h_d^B \end{pmatrix}$

SU(4) inv. combinations

- Match SUSY potential to Twin Higgs using $h_u^A = H_A \sin\beta_A \quad h_u^B = H_B \sin\beta_B$

$h_d^A = H_A \cos\beta_A \quad h_d^A = H_B \cos\beta_B$

$$V = \lambda\left(|H_A^2| + |H_B|^2 - f^2\right)^2 + \kappa\left(|H_A|^4 + |H_B|^4\right) + \tilde{\mu}^2|H_A|^2 + \rho|H_A|^4$$

Parameters set by SUSY

SU(4) and Z2 invariant

- *Generated by SU(4) preserving soft masses*
- *f-tuning is calculable*

SU(4) breaking and Z2 invariant

- *top-stop loop contribution*
- *D-term tree level contribution*

Z2 breaking

- *hard Z2 breaking can be radiatively stable in SUSY*

Twin SUSY Tuning

Now we can estimate the tuning using SUSY UV completion and compare to standard SUSY

Z2 breaking v/f $\times$ ***UV sensitivity f/Ms***

$$\Delta_{f^2/M_S^2} \approx \frac{3y_t^2}{8\pi^2}\frac{M_S^2}{2\lambda_{SU(4)}v^2}\log\frac{\Lambda_{UV}^2}{M_S^2}$$

Soft

$$\Delta_{v^2/f^2} \approx \frac{f^2}{2v^2}$$

Hard

$$\Delta_{v^2/f^2} \approx \frac{f^2}{2v^2}F(m_{S_A}, f)$$

★***Soft: Gain is*** $\sim \frac{\lambda_{SU(4)}}{\lambda_{SM}}$

Vanilla SUSY

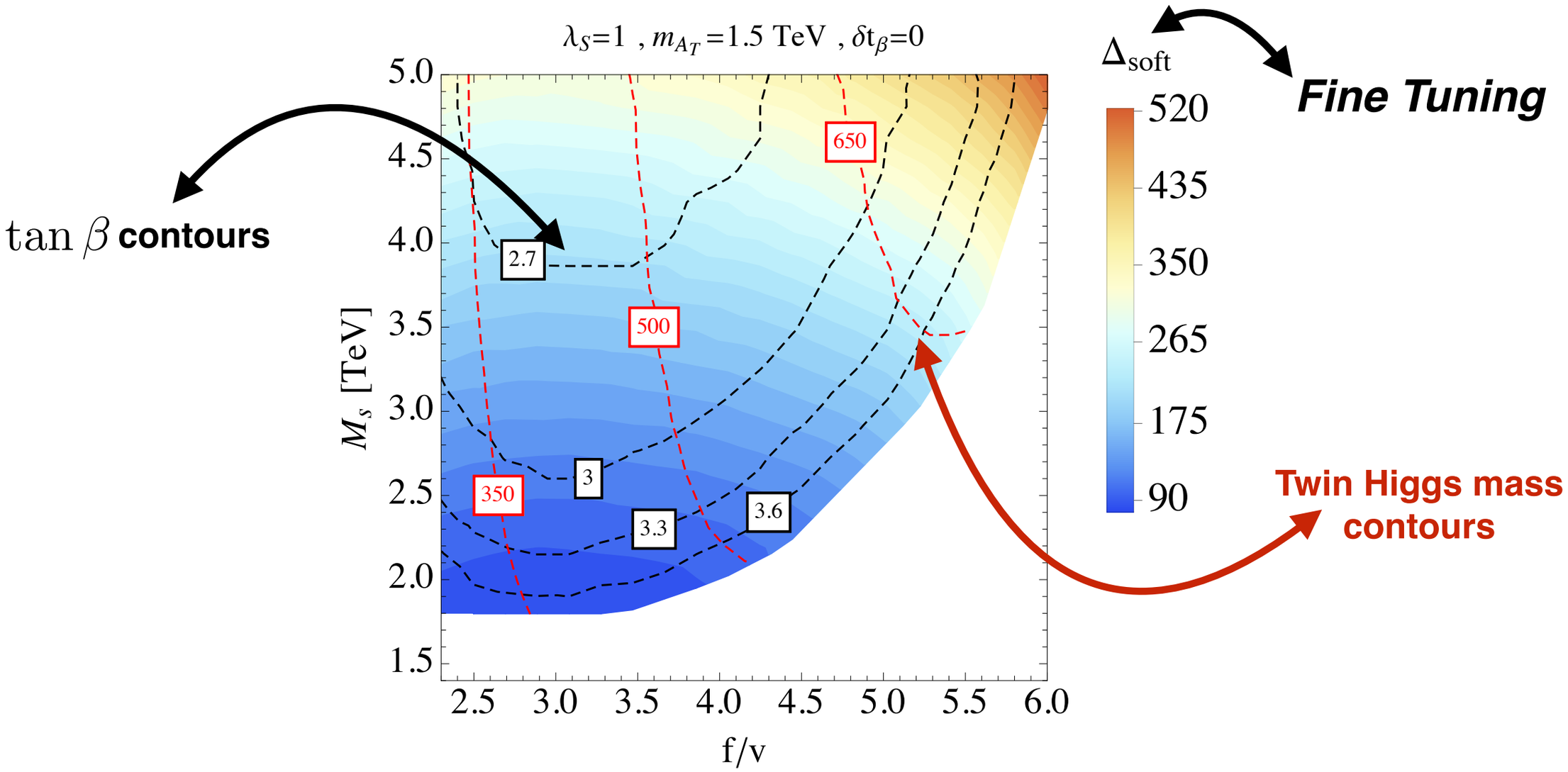
$$\Delta \simeq \frac{3y_t^2}{8\pi^2}\frac{M_S^2}{2\lambda_{SM}v^2}\log\frac{\Lambda_{UV}^2}{M_S^2}$$

★***Hard: we can gain more with low*** m_{S_A}***:*** $F(m_{S_A}, f) \lesssim 1$

Formula and factorization is approximation

Q: Does the gain robust in proper quantitative estimate?

Soft breaking in Twin SUSY



We can get to 1% tuning with colored states decoupled from LHC

Reproduce findings of *Craig Howe 2013*

Hard breaking in Twin SUSY

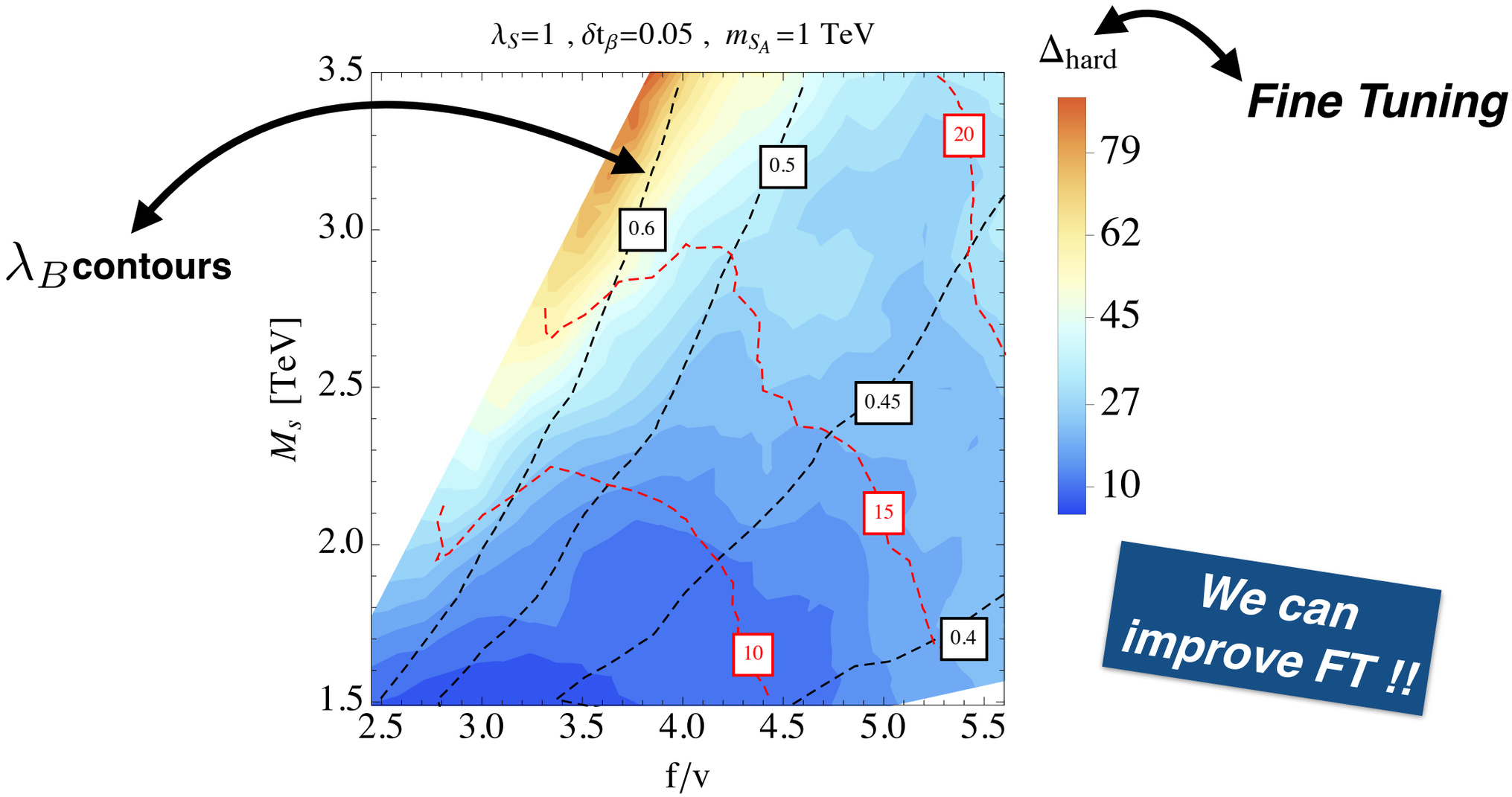
Generate extra quartic couplings with non decoupling F-terms

$$W = \lambda_A S_A H_u^A H_d^A \qquad m_{S_A}^{soft} \gg m_{S_A}^{susy}$$

→ **Z2 breaking quartic**

$$W = \lambda_B \Phi^{AB} H_u^A H_u^B \qquad m_{\Phi}^{soft} \gg m_{\Phi}^{susy}$$

→ **Extra negative contribution to k**



We can improve FT !!

10% fine tuning with stops at 2 TeV

Twin SUSY @ LHC

Neutral naturalness → ***Extended Higgs sector***

Twin SUSY → ***4 Higgs doublet model***

2 CP-odd higgses | *4 CP-even higgses* | *2 Charged higgses*

Expected scalar spectrum controlled by two parameters

- m_A → ***MSSM-like scalars***
- f → ***Twin-Higgs***

Q: Can we probe these extra scalars @ LHC?

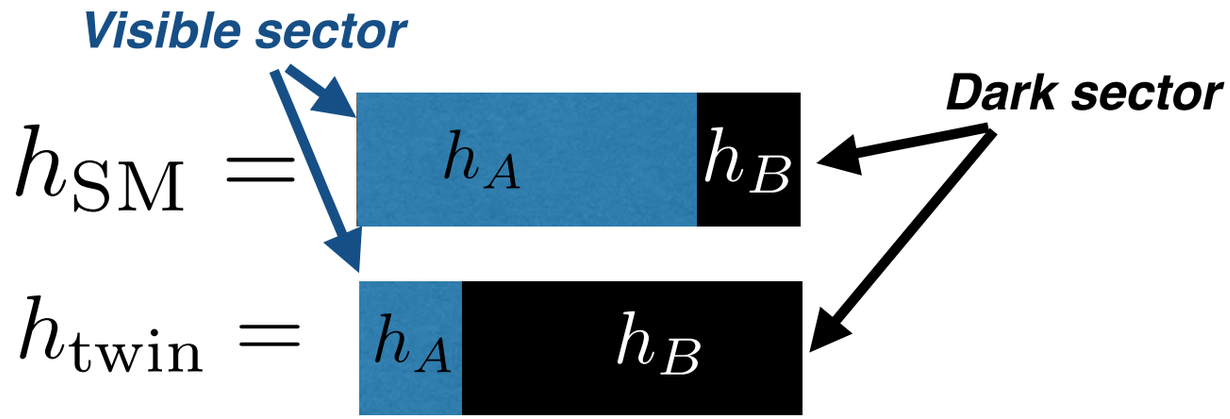
- ***Usual MSSM scalar searches***
  Possibly augmented with MET signature
- ***Twin Higgs mixes with SM Higgs***
- ***Resonance in di-bosons*** *Buttazzo Sala Tesi '15*

Searching the Twin Higgs

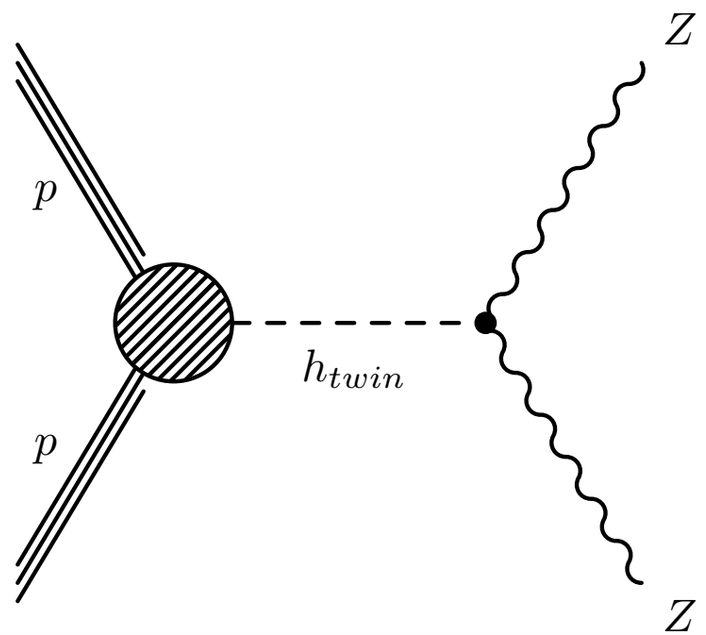
Two important scalars in the spectrum

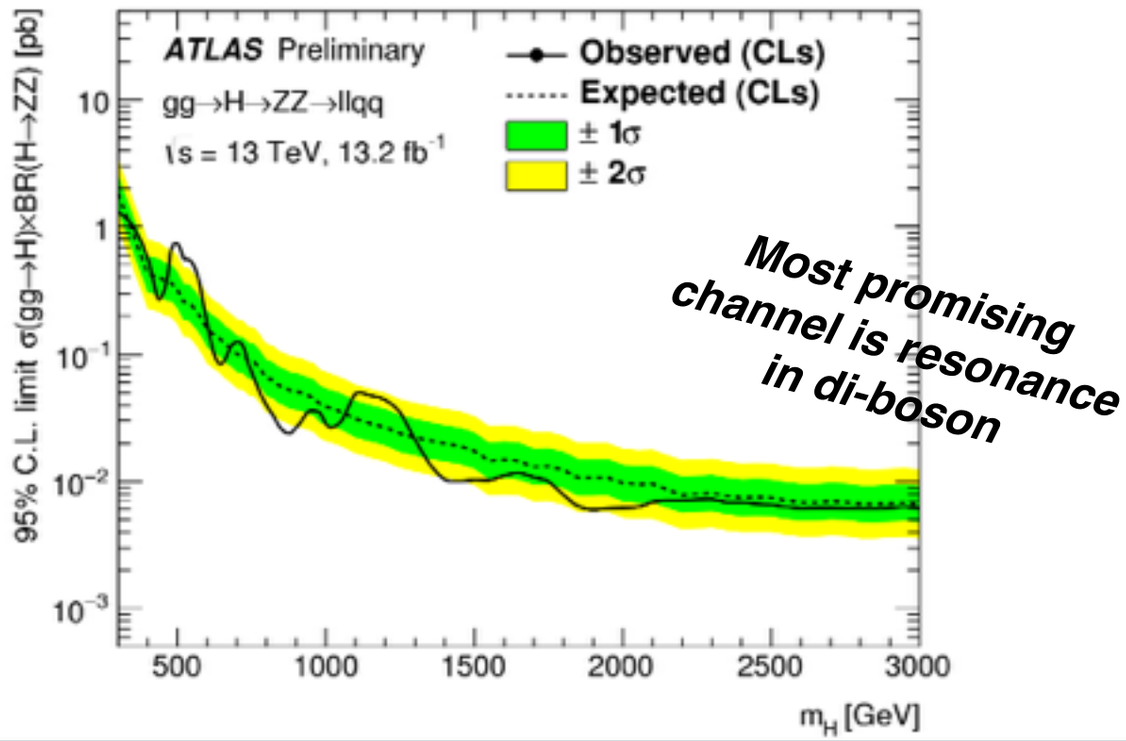
1. Higgs is PNGB of accidental continuos SU(4) symmetry
2. The Twin Higgs is the massive scalar associated to the SU(4) breaking

The two scalars will mix !!!



Twin Higgs production at LHC

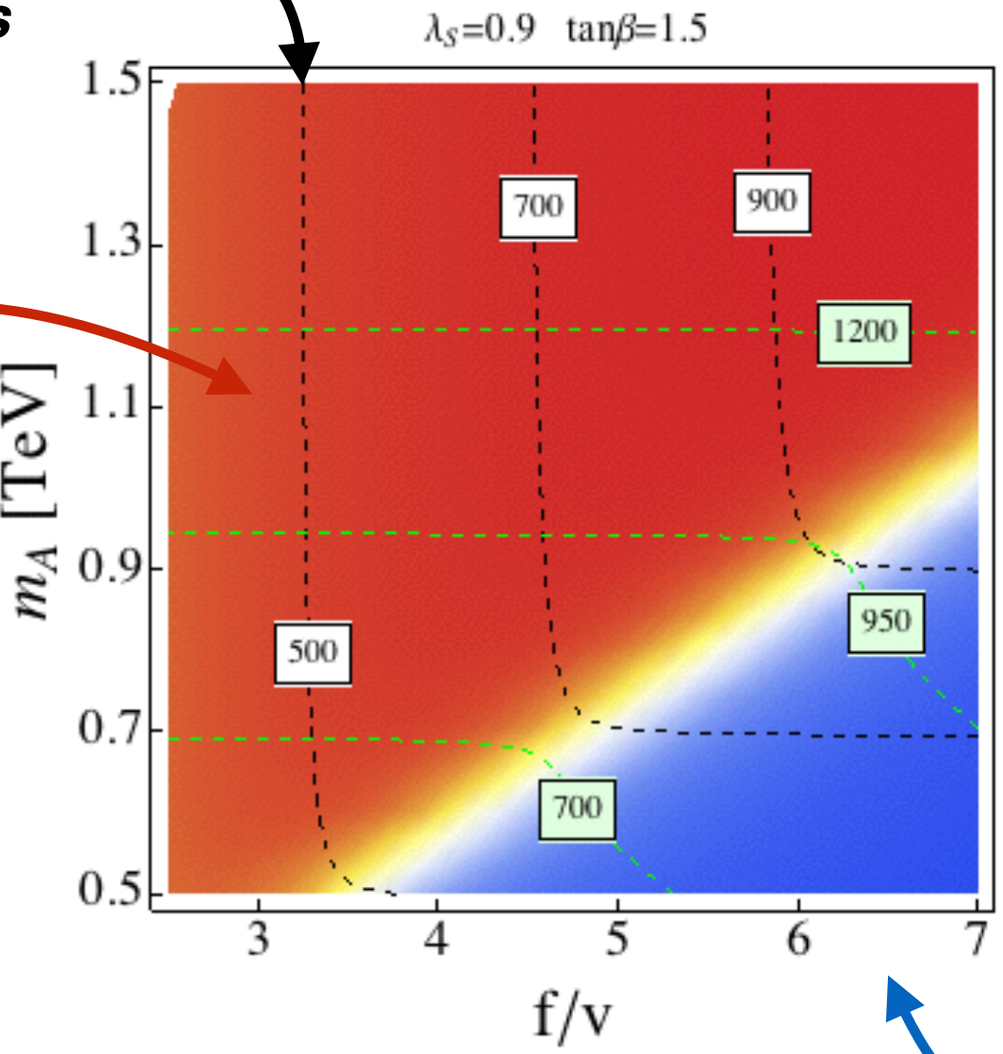




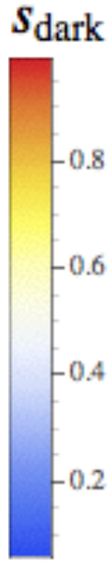
Most promising channel is resonance in di-boson

CP-even spectrum

Next to lightest state mass contours



Measure how much the state is Dark



$m_A \gg \lambda f$

Lightest state is Twin Higgs

Light scalar that mixes with the Higgs

$m_A \ll \lambda f$

Lightest state is MSSM-like

All MSSM-like scalars at similar mass

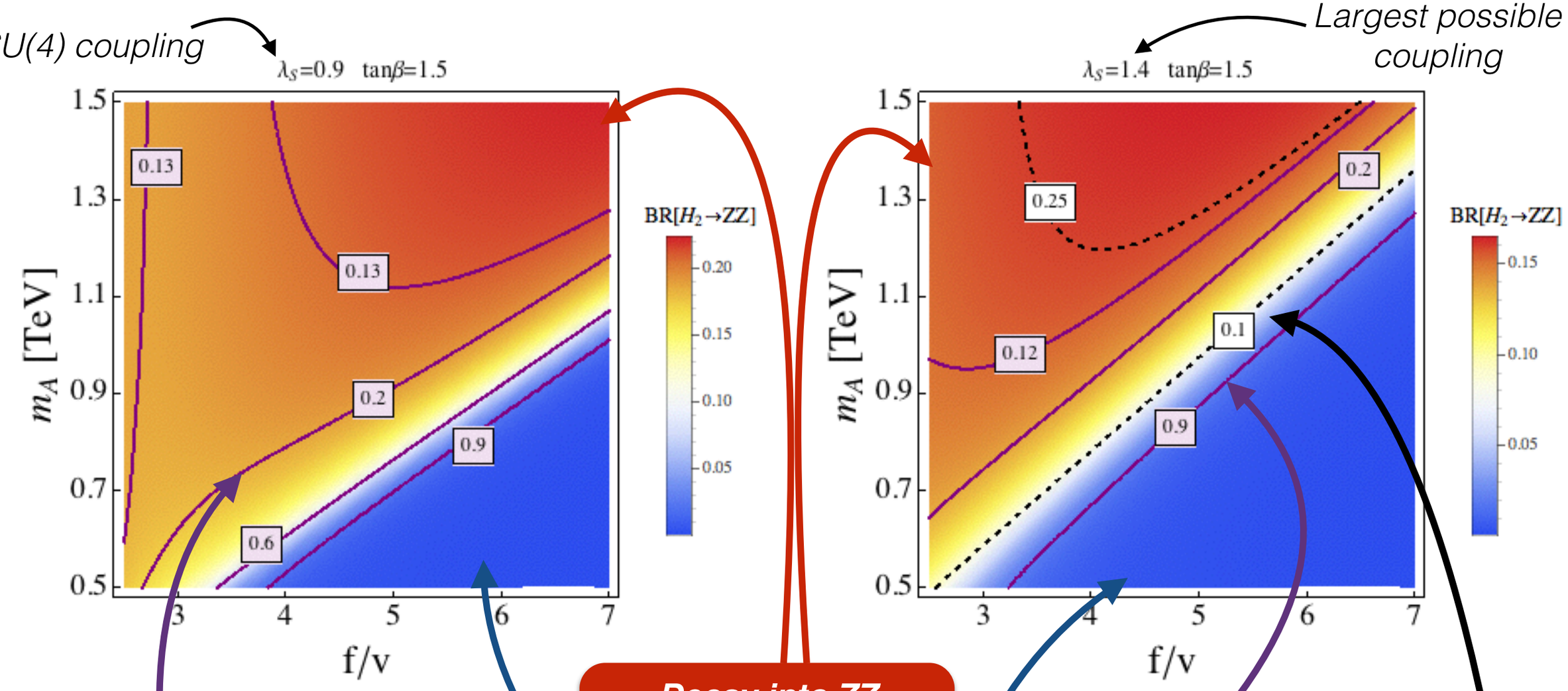
Low lying spectrum interpolates between (non-SUSY) Twin Higgs and MSSM

Branching Ratio

Decay modes of next to lightest state determines phenomenology

SU(4) coupling

Largest possible coupling



Decay into tops via mixing

Decay into ZZ through mixing

Decay into ZZ suppressed

Decay into tops

Invisible Decay into Dark gauge bosons

Twin SUSY @ LHC

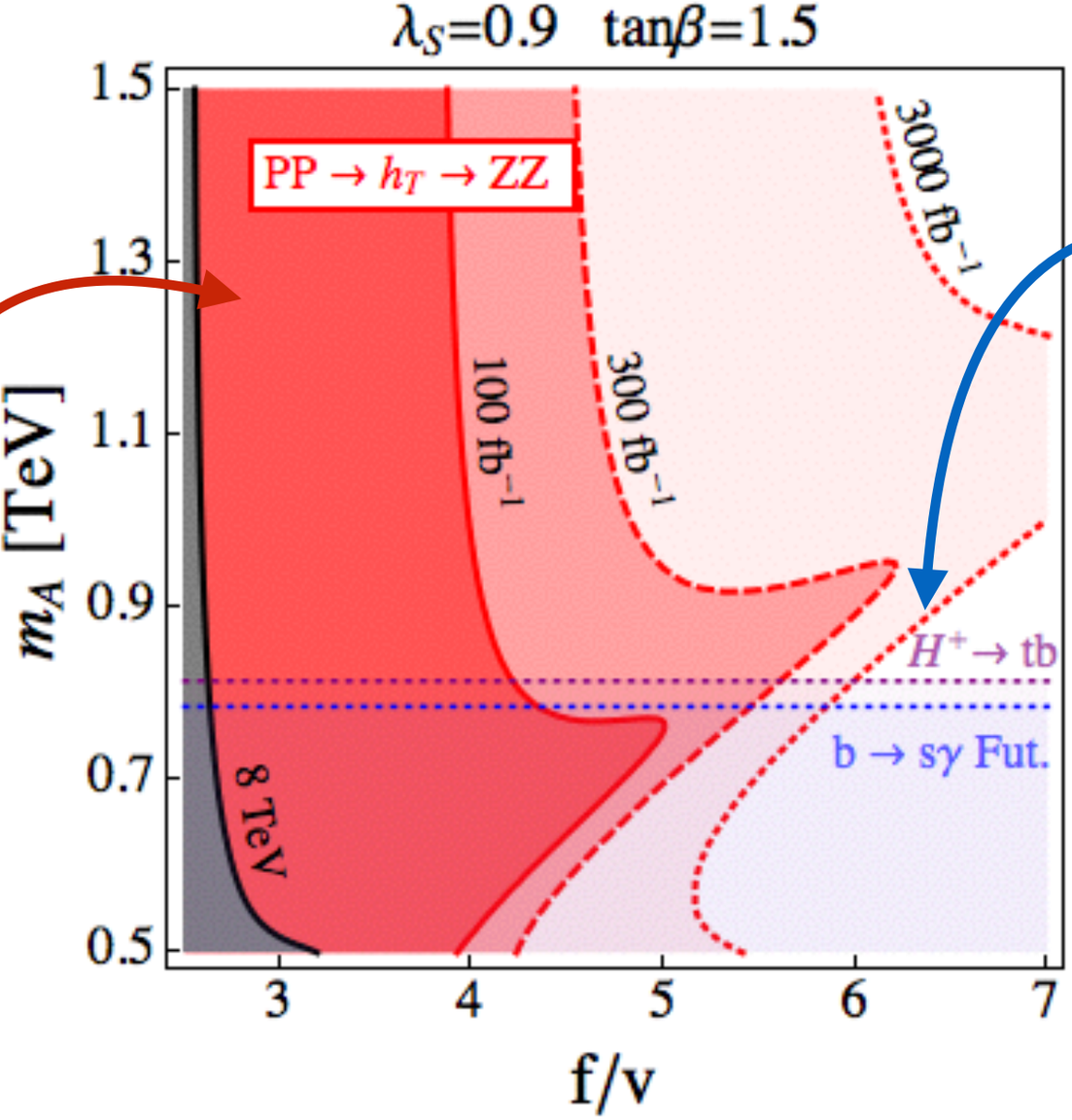
Prospects for Twin SUSY

Twin Higgs decay mainly in di-bosons and ttbar

Exclusion and prospects for ZZ searches

Direct searches stronger than Higgs couplings

Di-boson searches vs Neutral Naturalness



MSSM Higgses searches probe other region

$H^+ \to tb$ *up to 800 but with high luminosity*

$b \to s\gamma$ *will also probe MSSM-like region*

CP-odd Higgs searches less promising …

Almost all parameter space with small tuning will be covered combining LHC direct searches and indirect limits

Conclusions

★BSM under pressure given negative results of LHC

★Neutral naturalness possibility

- *could have evaded current searches and improve FT*

★Twin Higgs bridge over Little fine tuning

- *Soft and Hard breaking of Z2 symmetry*

★Twin Higgs meets SUSY

- *Soft and Hard breaking of Z2 symmetry realizable*
- *Hard show moderate gain in fine tuning*

★Rich phenomenology accessible at LHC in different channels

- *Interpolates between (non SUSY)-Twin and MSSM*
- *Different final states and searches will cover the parameter space*

...

Thanks for the attention