

# Direct searches for scalar singlets

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mainly based on Buttazzo S Tesi 1505.05488

FCC-hh BSM group informal meeting, CERN, 5 Oct 2015

- ◊ Can new scalar singlets be the lightest new particles around?
- ◊ How to look for them?

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Extra **Singlet** scalars are ubiquitous, for example in

- Twin Higgs
- Supersymmetry
- Electroweak Baryogenesis (independent of naturalness)

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- Add a  $Z_2$ -symmetric copy of the SM
  - [only copy of top strictly necessary see e.g. J Serra @ MIAPP 2015]
- 8 "Higgs" degrees of freedom - vs 4 in the SM
  - 7 are massless Goldstone bosons
  - one,  $\sigma$  = radial mode of  $\mathcal{G} \rightarrow \mathcal{H}$
  - $\langle \sigma \rangle = f$ ,  $m_\sigma \sim f$  conceivable if UV completion is weakly coupled

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Other particles? Either  $M \gtrsim 4\pi f$  or very weakly coupled

# Singlet scalars in Supersymmetry

Could the singlet-like scalar be the first new particle seen?

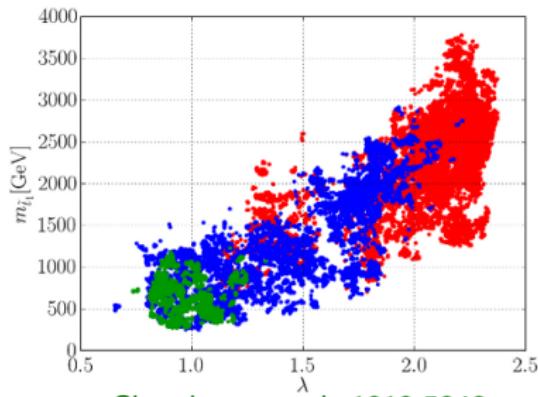
# Singlet scalars in Supersymmetry

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NMSSM = MSSM + singlet  $S$

$$W = W_{\text{MSSM}} + \lambda S H_u H_d + f(S)$$

Fine tuning better than 5%  
[green points,  $\tan \beta \lesssim 5$ ,  $\Lambda = 20$  TeV]



Gherghetta et al. 1212.5243  
see also Gherghetta et al. 1401.8291  
Cao et al. 1409.8431

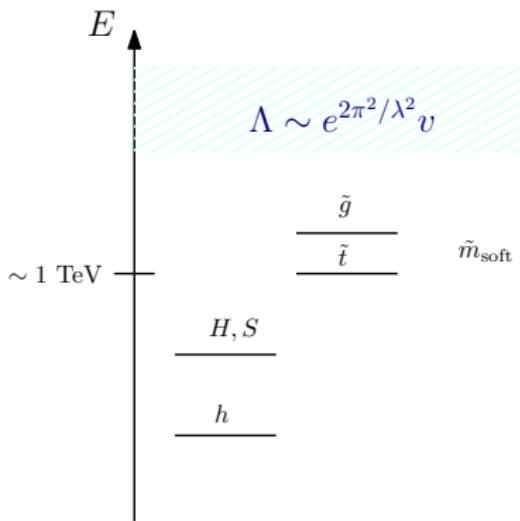
Given a fixed tuning,  $\tilde{t}$  and  $\tilde{g}$  heavier by  $\sim \lambda/g$  than in MSSM

I would find interesting to have a reach in tuning of  $\tilde{t}$  and  $\tilde{g}$  vs singlet searches

# NMSSM spectrum

NMSSM with  $\lambda \sim 1$  and heavy stops & gluinos

[ $\lambda \gtrsim 0.7$  needs a completion before GUT scale]



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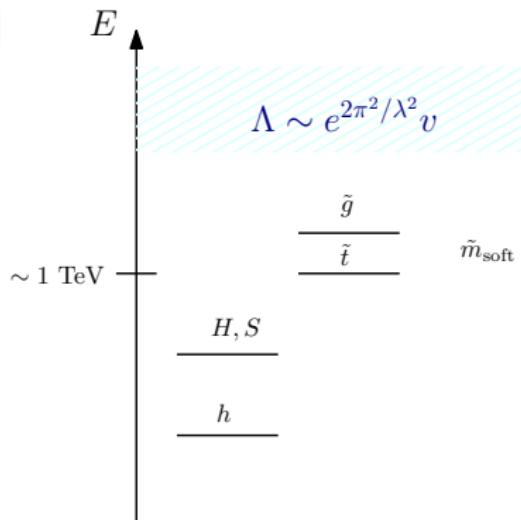
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The scalars are:

CP-even  $h, h_3, \phi$  (from  $h_\nu, H, S$ )

CP-odd  $A, A_s$

$H^\pm$



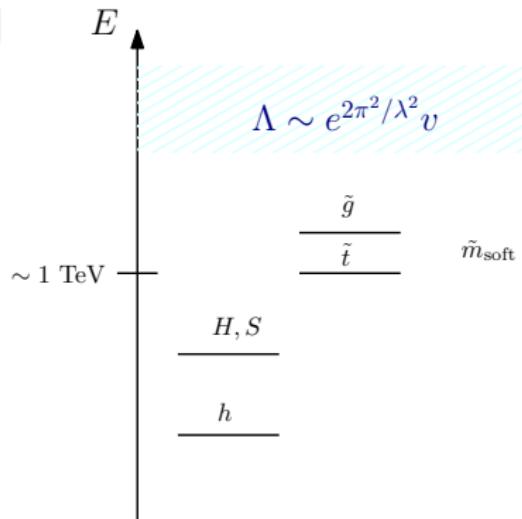
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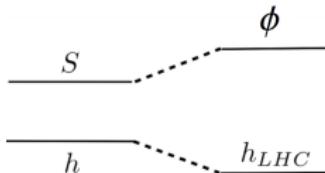
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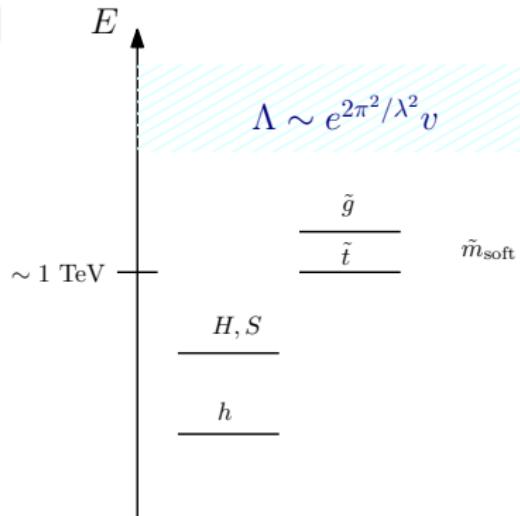
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$$\gamma = h_\nu - S \text{ mixing}$$



A motivated limiting case

$$m_{h_3} \gg m_{h,\phi} \quad \text{and} \quad \sigma, \delta \rightarrow 0$$

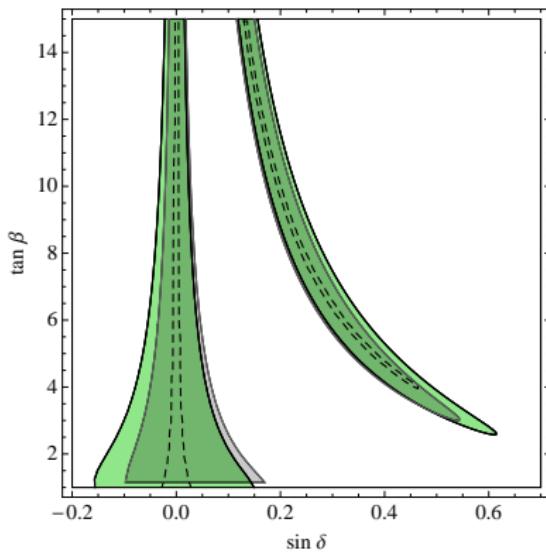
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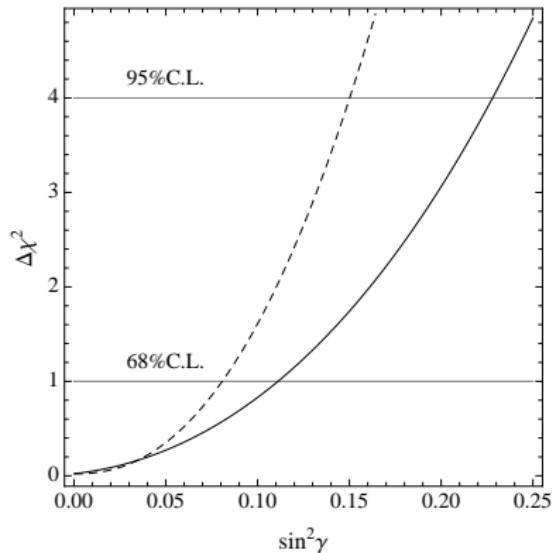
$$[ h_{\text{LHC}} = h = c_\gamma (c_\delta h_v - s_\delta H) + s_\gamma S ]$$

$$\frac{g_{htt}^{\text{SM}}}{g_{htt}} = c_\gamma \left( c_\delta + \frac{s_\delta}{\tan \beta} \right), \quad \frac{g_{hbb}^{\text{SM}}}{g_{hbb}} = c_\gamma \left( c_\delta - s_\delta \tan \beta \right), \quad \frac{g_{hVV}^{\text{SM}}}{g_{hVV}} = c_\gamma c_\delta$$

cont: LHC8 status      dashed: LHC14 projections (300 fb<sup>-1</sup>)



$$s_\gamma^2 = 0, 0.15$$



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# Extrapolation of direct searches

We started from

- i) Collider Reach ( $\beta$ ) Salam Weiler 2014
- ii) Thamm Torre Wulzer 1502.01701

$m_0$  excluded at LHC8, obtain  $m_1$  at future collider via

$$B(s_1, L_1, m_1) = B(s_0, L_0, m_0)$$

$$B(s, L, m) \propto L \times \int d\hat{s} \frac{1}{\hat{s}} \hat{s} \hat{\sigma}(\hat{s}) \frac{d\mathcal{L}}{d\hat{s}}(s)$$

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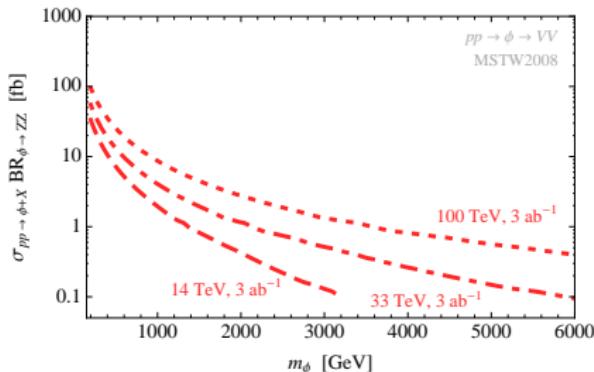
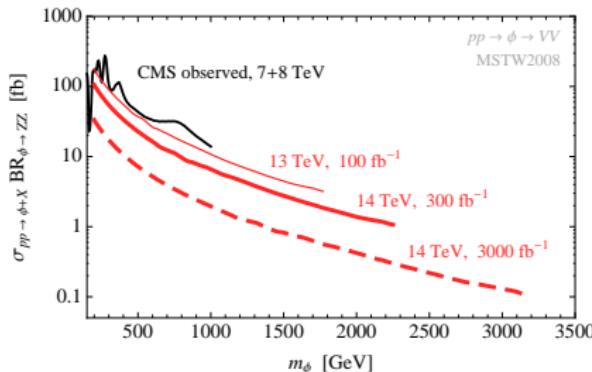
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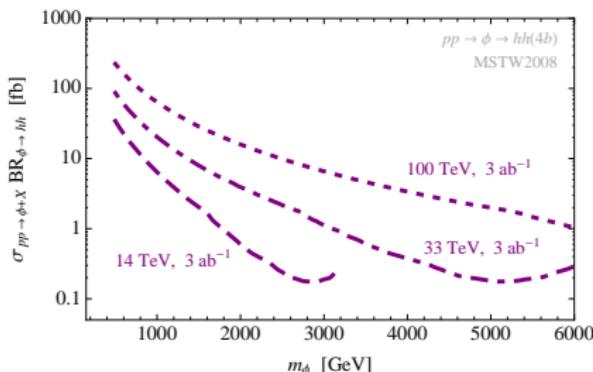
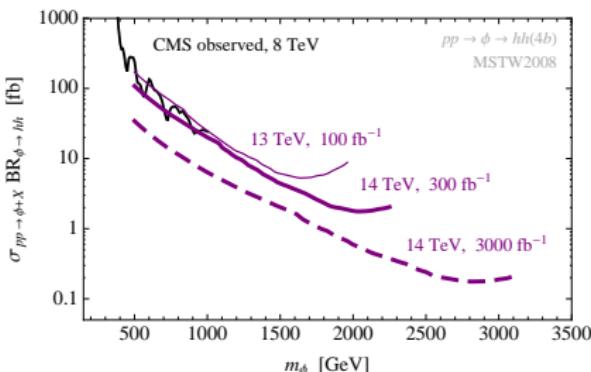
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# Generic singlet

$$\sin^2 \gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

Master formula, valid for **any** model

2 free parameters control all pheno! +  $\text{BR}_{\phi \rightarrow hh}$  ( $= \text{BR}_{\phi \rightarrow ZZ}$  at  $m_\phi \gg m_W$ )

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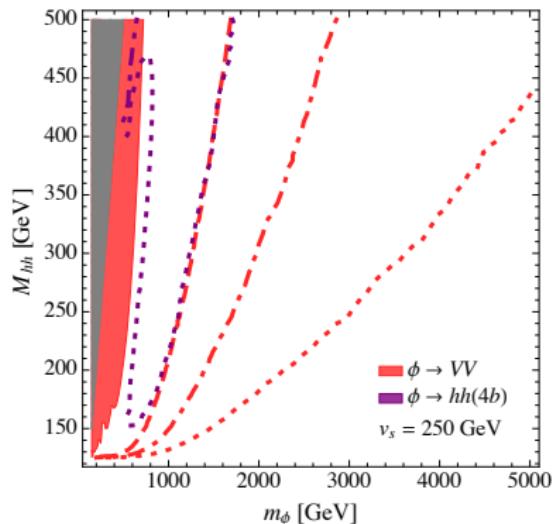
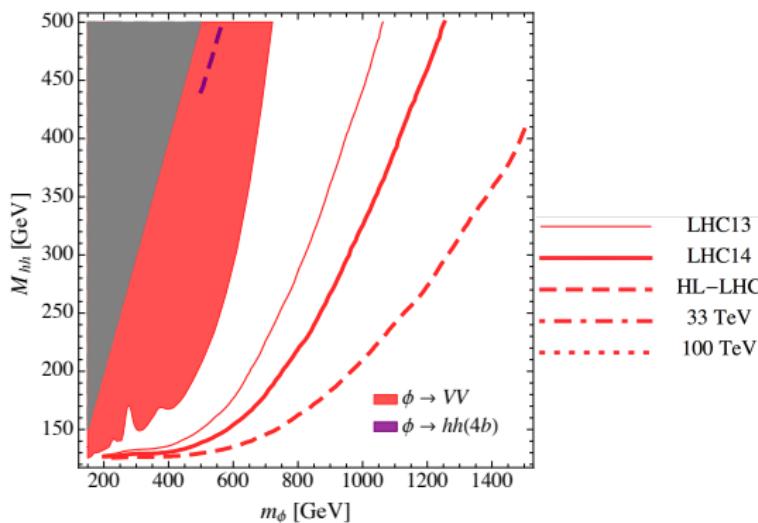
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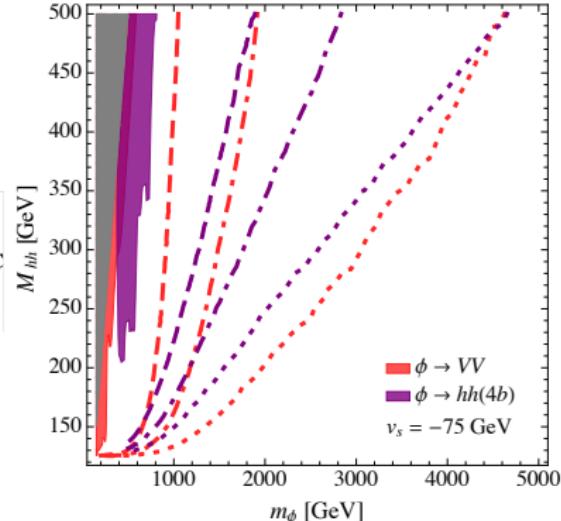
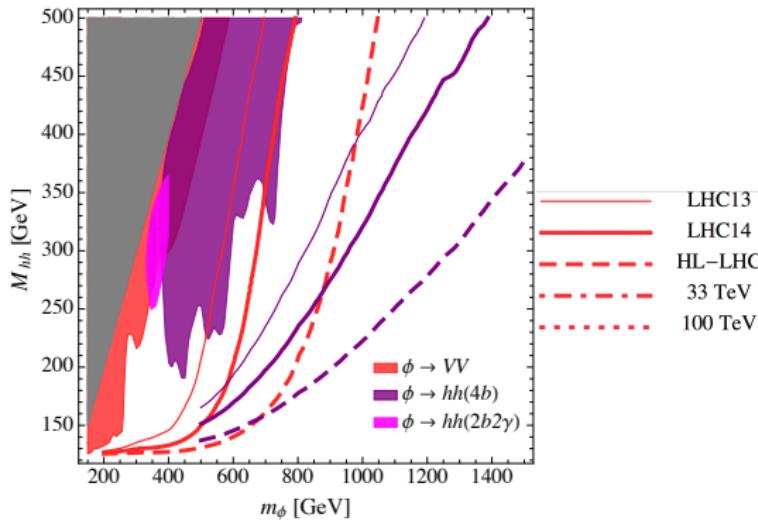
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Large  $\text{BR}_{\phi \rightarrow hh}$  easier for  $v_s < 0$

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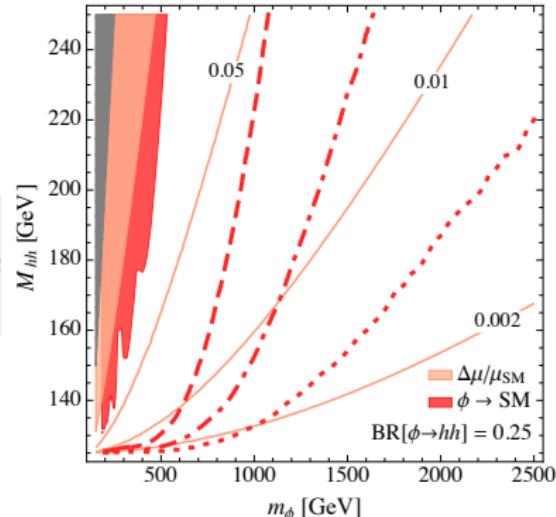
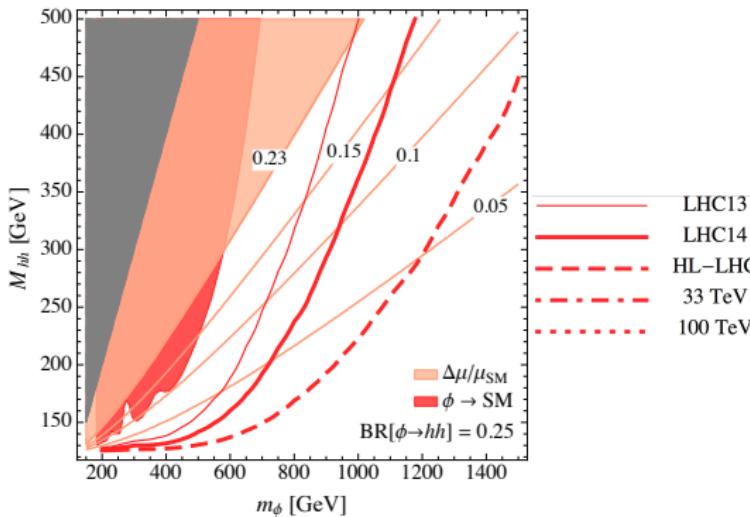
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Take-home message:

Mixing angle  $\sin \gamma \simeq \frac{v}{f}$



Direct searches of the singlet can be promising!

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$$M_{hh}^2 = (m_h^2 + m_\sigma^2) v^2 / f^2$$

Only two free parameters  $f$  and  $m_\sigma$   $\Rightarrow$   $\text{BR}_{\sigma \rightarrow hh}$  fixed everywhere

Twin SM  $\Rightarrow$   $\text{BR}_{\sigma \rightarrow \text{inv.}} \neq 0$  [equivalence theorem:  $\text{BR}_{\sigma \rightarrow \text{inv.}} \rightarrow 3/7$  for  $m_\sigma > m_Z \times f/v$ ]

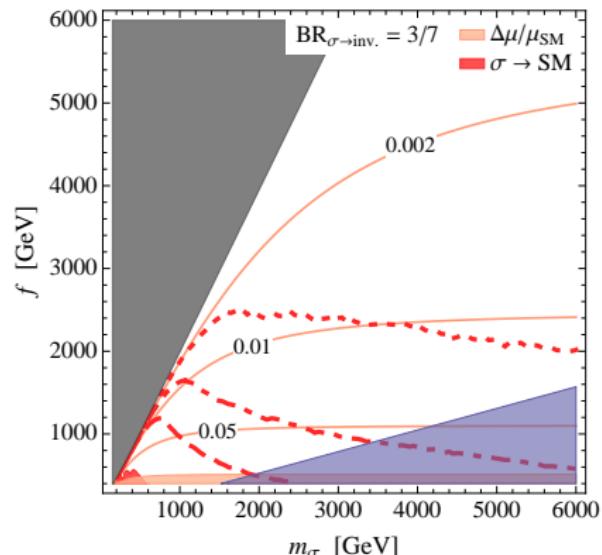
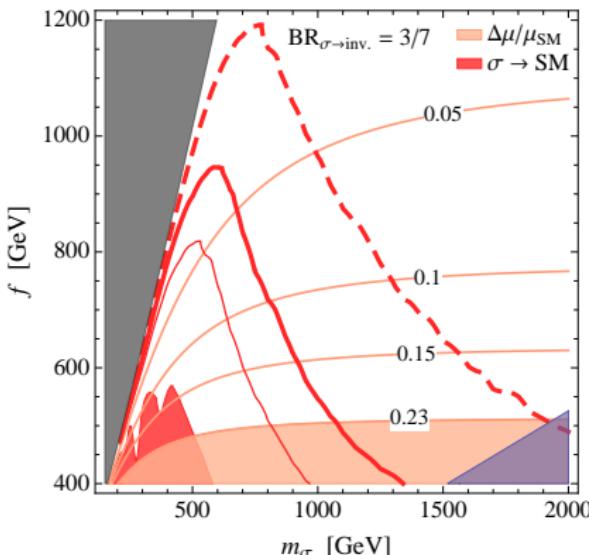
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$$M_{hh}^2 = m_Z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2 + \Delta^2$$

$\Delta$  = all loop effects, e.g. top-stop

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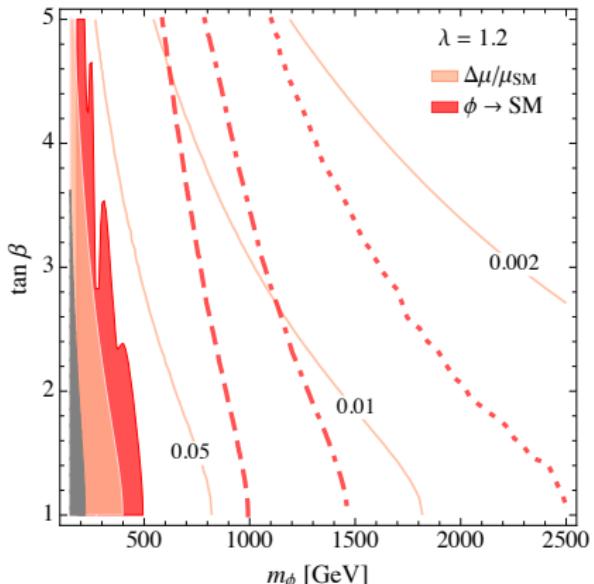
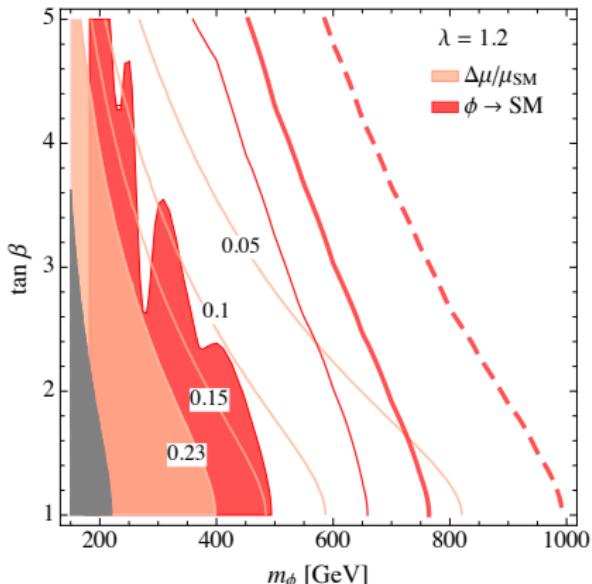
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Here  $\lambda = 1.2$      $\Delta = 70$  GeV

$\tan \beta$  “small” otherwise EWPT



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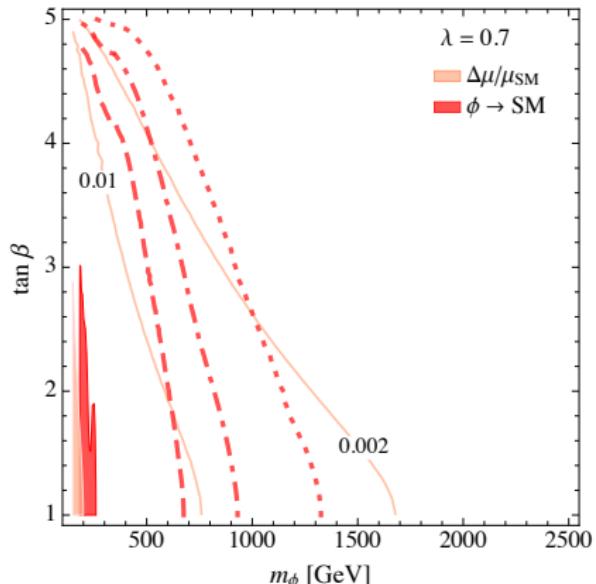
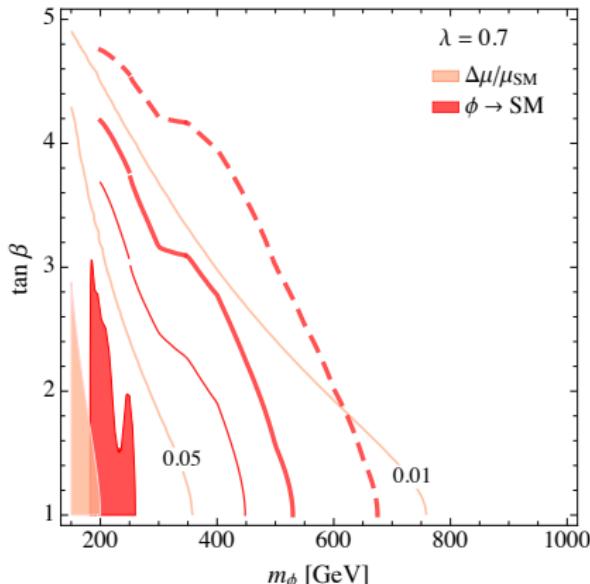
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Here  $\lambda = 0.7$      $\Delta = 80$  GeV

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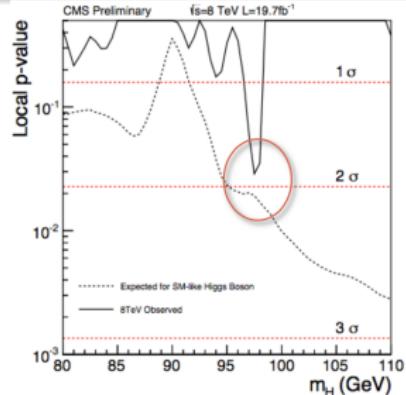


# Fully mixed case and a $\gamma\gamma$ signal

**Singlet-like state lighter than 125 GeV**

Hard to see, could it explain this hint?

SUSY 2015, Tristan du Pree



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Barbieri et al 1304.3670, 1307.4937

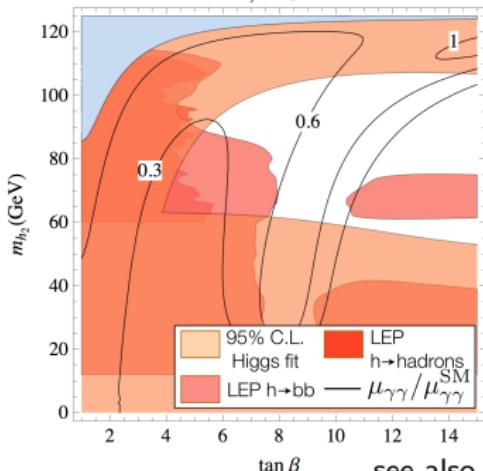
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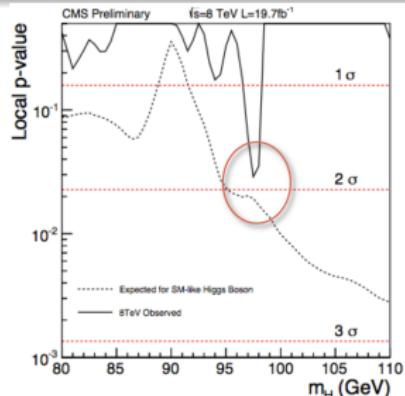
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$$[m_{h_3} = 500 \text{ GeV}, s_\sigma^2 = 10^{-3}, v_s = v]$$

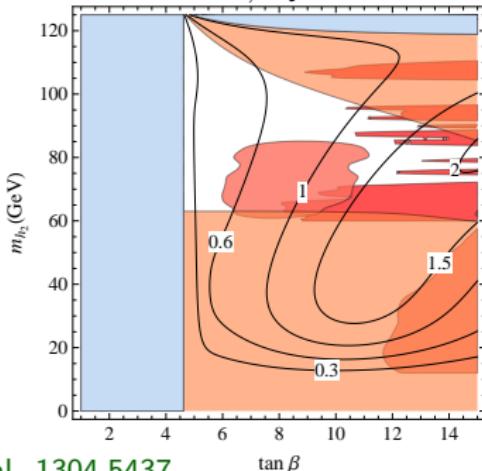
$$\lambda = 0.1, \Delta_t = 85 \text{ GeV}$$



see also Badziak et al. 1304.5437, ...



$$\lambda = 0.8, \Delta_t = 75 \text{ GeV}$$



A (necessary) input to plan future HEP strategy

$\phi \rightarrow VV, hh, h$  couplings, ...

## Relevance to BSM working group

NMSSM with  $\lambda \sim 1$

singlet-like  $\phi$  could show up before  $\tilde{t}, \tilde{g}$

Twin Higgs (weakly coupled)

radial mode could be first particle seen

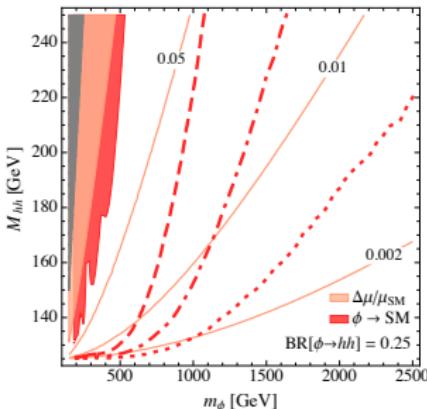
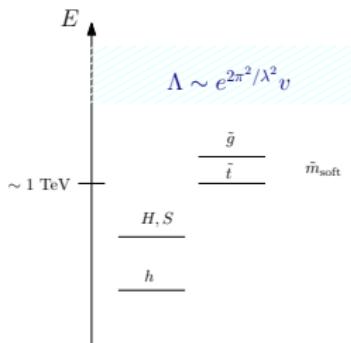
## What Next?

more on extra doublet, e.g.  $f\bar{f}$  prospects

CP-odd scalars

UV model for Twin Higgs with light  $\sigma$

for extra Higgses see also F.S. 1509.08655



Back up

# Generic singlet

$$\sin^2 \gamma = \frac{M_{hh}^2 - m_\phi}{m_\phi^2 - m_h^2}$$

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What does one learn from the potential  $f(S)$ ?

$$\text{BR}_{\phi \rightarrow hh} = \frac{1}{4} - \frac{3}{4} \frac{\nu}{v_s} \frac{\sqrt{M_{hh}^2 - m_h^2}}{m_\phi} + O\left(\frac{\nu^2}{m_\phi^2}\right)$$

$$\frac{g_{h^3}}{g_{h^3}^{\text{SM}}} = 1 + \frac{2}{3} \frac{\nu}{v_s} \frac{\sqrt{M_{hh}^2 - m_h^2}}{m_\phi} \left( \frac{M_{hh}^2}{m_h^2} - 1 \right) + O\left(\frac{\nu^2}{m_\phi^2}\right)$$

Valid for **any** potential!!  $v_s$  leading new parameter

# Generic singlet: Higgs couplings

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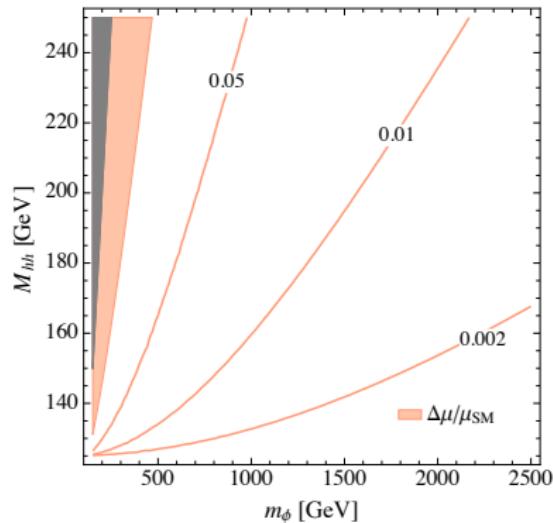
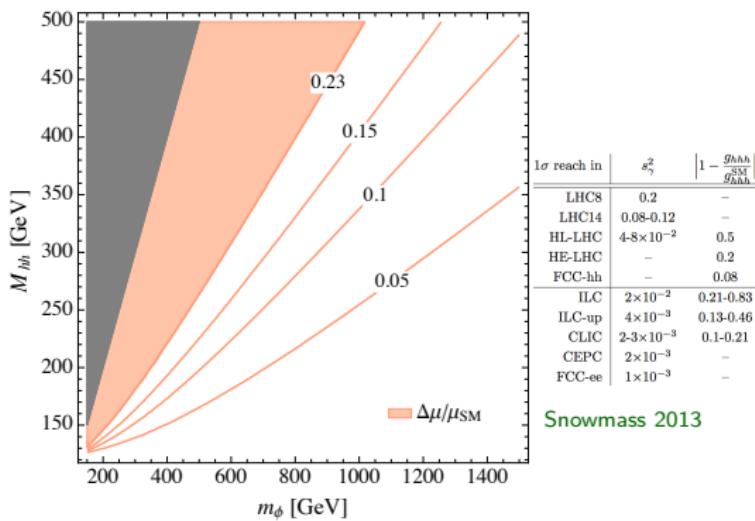
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$$\sin^2 \gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

Master formula, valid for **any** model

2 free parameters control all pheno! +  $\text{BR}_{\phi \rightarrow hh}$  ( $= \text{BR}_{\phi \rightarrow ZZ}$  at  $m_\phi \gg m_W$ )

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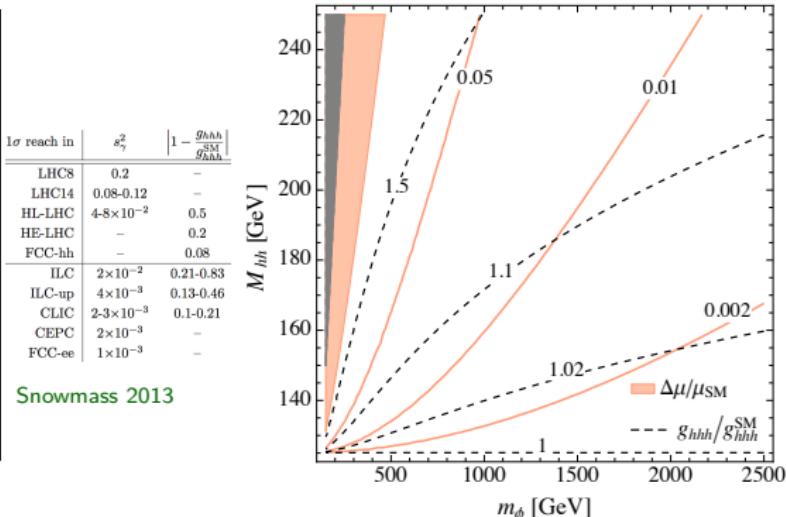
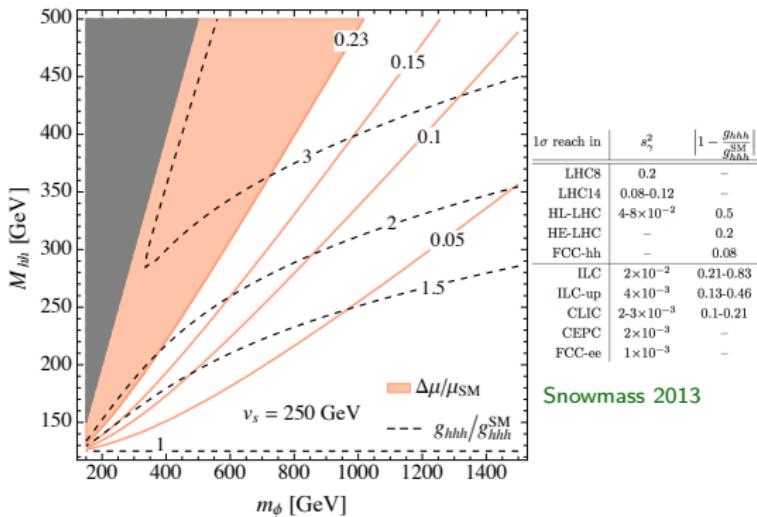
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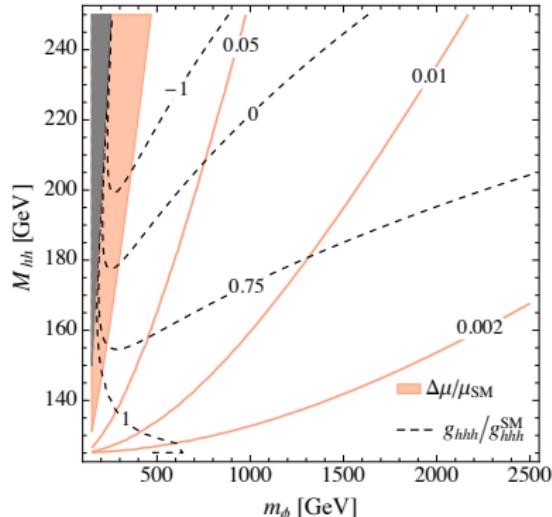
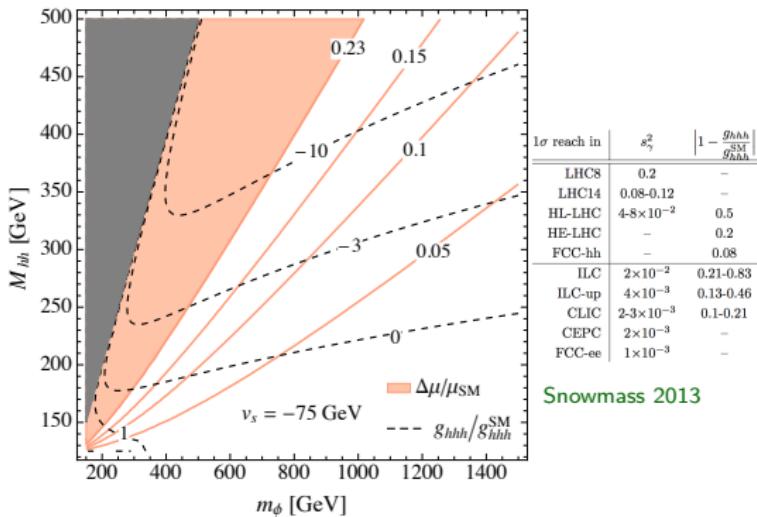
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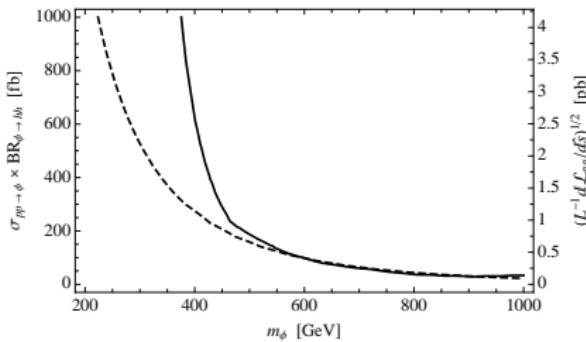
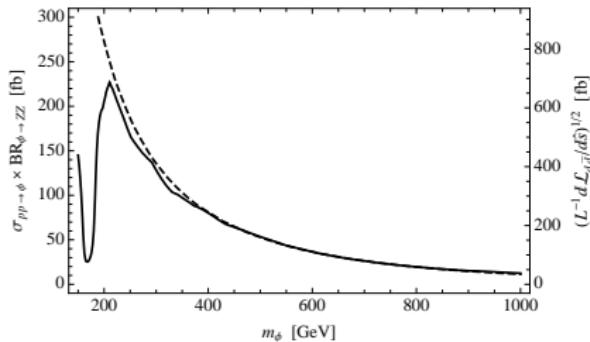
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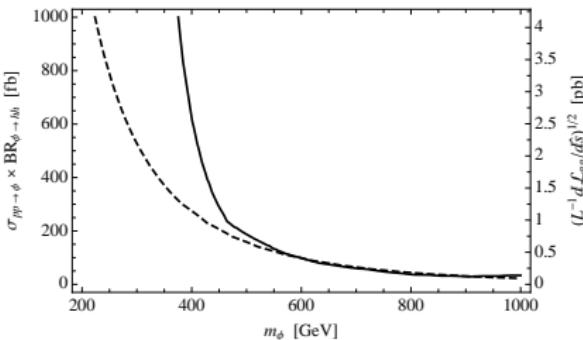
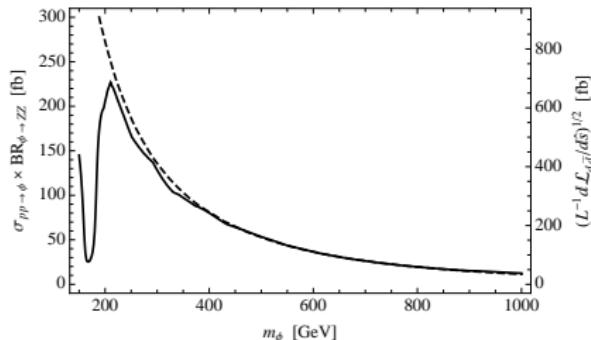
# Extrapolation of direct searches II



## Assumptions/limitations

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- Not valid if systematics dominate and change significantly from  $s_0$  to  $s_1$
- $\hat{s} \gg m_{\text{bkg}}$  [i.e. not valid at  $\hat{s} \sim 2m_t$  for  $\phi \rightarrow hh(4b)$ ]
- $\frac{\Delta\hat{s}}{m^2} \ll 1$  i.e. not valid if analysis depends a lot on shape far from peak

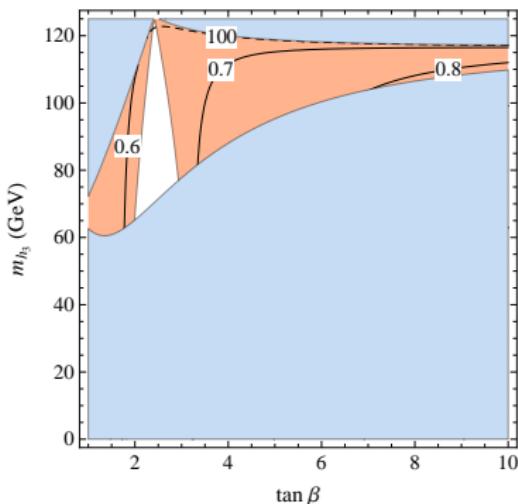
# An extra doublet-like state H

$$[\gamma, \sigma = 0, \quad m_{h_2} \gg m_{h_1}, m_{h_3}]$$

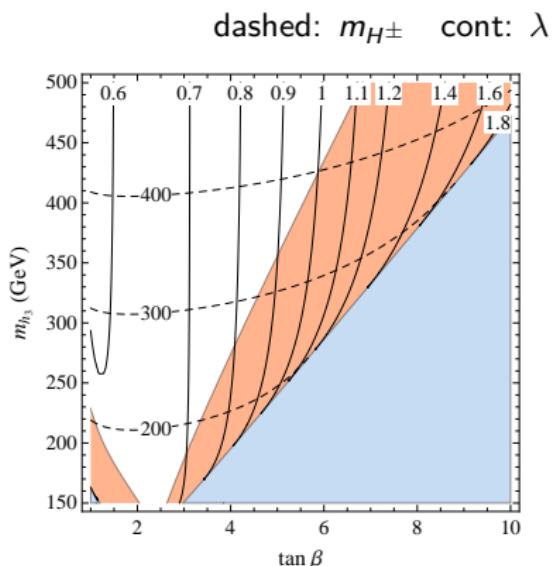
Barbieri Buttazzo Kannike Sala Tesi 1304.3670, 1307.4937

$$\frac{g_{h_3 tt}}{g_{htt}^{\text{SM}}} = s_\delta - \frac{c_\delta}{t_\beta} \quad \frac{g_{h_3 bb}}{g_{hbb}^{\text{SM}}} = s_\delta + t_\beta c_\delta \quad \frac{g_{h_3 VV}}{g_{hVV}^{\text{SM}}} = s_\delta \quad [\Delta_t = 75 \text{ GeV}]$$

Status fit LHC8:



$m_{H^\pm} > 480 \text{ GeV}$  from  $B \rightarrow X_s \gamma$ !



$$[\widetilde{\mathcal{M}}_{12}^2(t_\beta, \dots) = 0 \rightarrow \delta = 0]$$

$h_3$  phenomenology: more similar to MSSM

see e.g. Craig et al. 1504.04630

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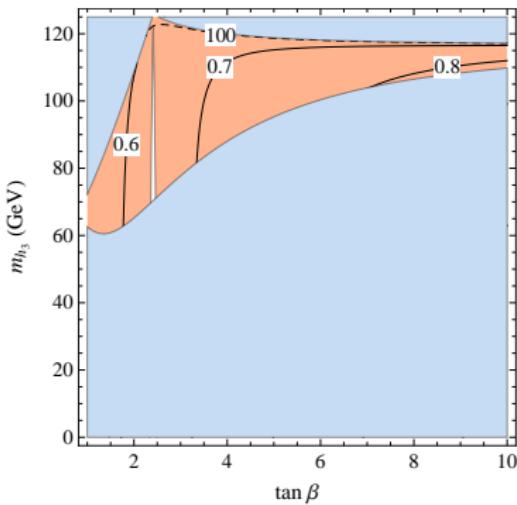
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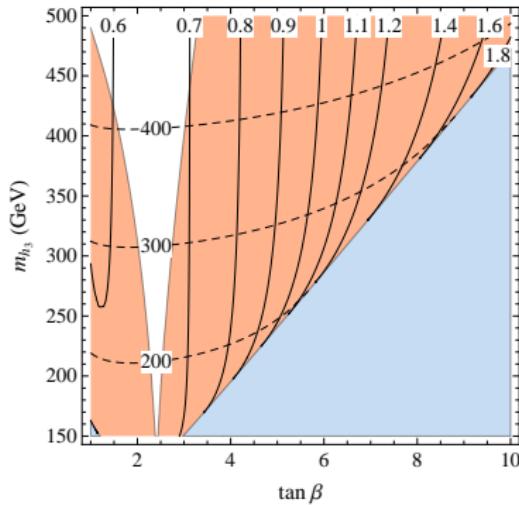
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**Projections fit LHC14 (300 fb<sup>-1</sup>):**

dashed:  $m_{H^\pm}$  cont:  $\lambda$



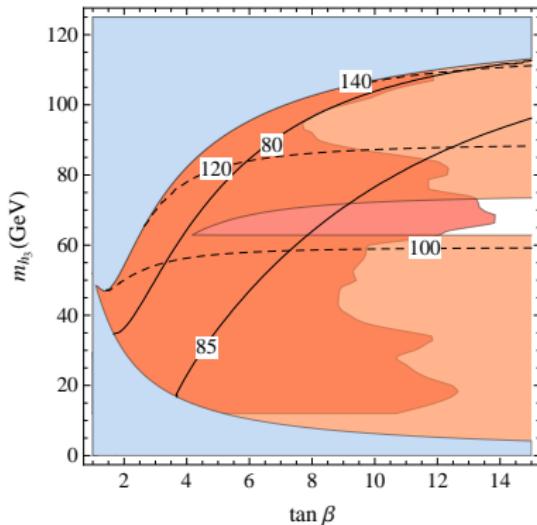
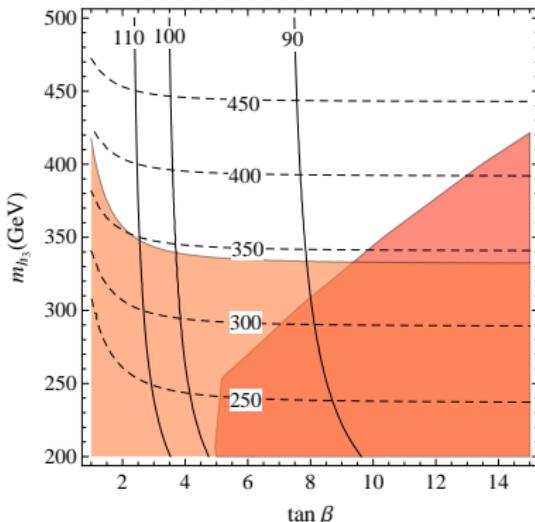
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**Status fit LHC8:**[dashed:  $m_{H^\pm}$  cont:  $\Delta_t$ ]

Red regions excluded by direct searches at LEP and CMS

**Projections fit LHC14:** above regions completely excluded

[if  $\frac{\mu A_t}{m_t^2}$  very large, conclusions could change... ]