Singlet-like Higgs bosons at present and future colliders

Filippo Sala

LPTHE Univ. Paris 6 and CNRS

mainly based on Buttazzo S Tesi 1505.05488

GDR Terascale, Grenoble, 24 Nov 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)

Twin Higgs

Chacko Goh Harnik 2005, Barbieri Gregoire Hall 2005,...

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Why TH interesting? Solves little hierarchy, without coloured top partners

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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, σ = radial mode of $\mathcal{G} \to \mathcal{H}$

$\langle\sigma\rangle = f$, $m_\sigma \sim f$ 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

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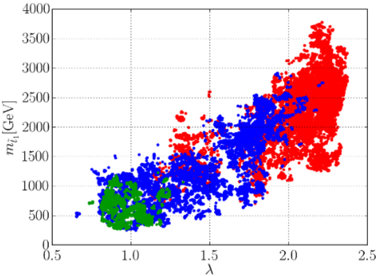
NMSSM $=$ MSSM $+$ singlet S

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

Fine tuning better than 5% $\longrightarrow$

[green points, $\tan\beta \lesssim 5$, $\Lambda = 20$ TeV]



Gherghetta et al. 1212.5243

see also Gherghetta et al. 1401.8291

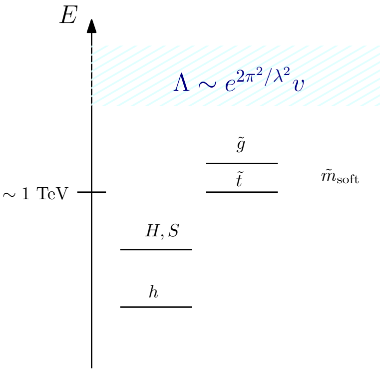
Cao et al. 1409.8431

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

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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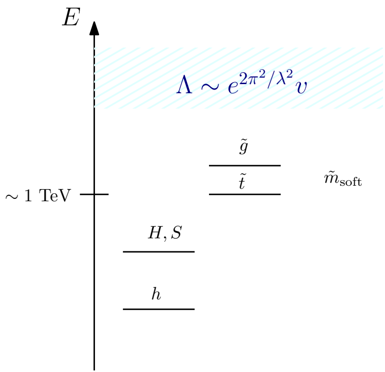
The scalars are:

CP-even h, h_3, ϕ (from h_v, H, S)

CP-odd A, A_s

$H^\pm$



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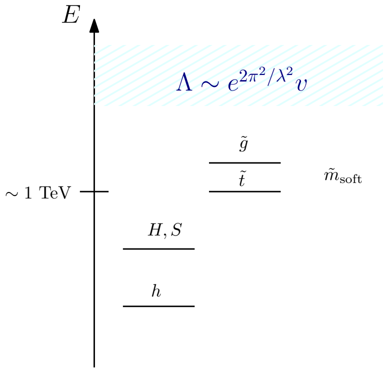
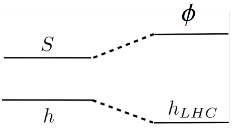
CP-even h, h_3, ϕ (from h_v, H, S)

$$\mathcal{H}_{\rm ph} \equiv \begin{pmatrix} h_3 \\ h \\ \phi \end{pmatrix} = R^T \begin{pmatrix} H \\ h_v \\ S \end{pmatrix}, \qquad R = R^{12}_{\delta} R^{23}_{\gamma} R^{13}_{\sigma}$$





$\gamma = h_v - S$ mixing

A motivated limiting case

$m_{h_3} \gg m_{h,\phi}$ and $\sigma, \delta \to 0$

Bottom-up motivation for a Singlet: Higgs couplings fit

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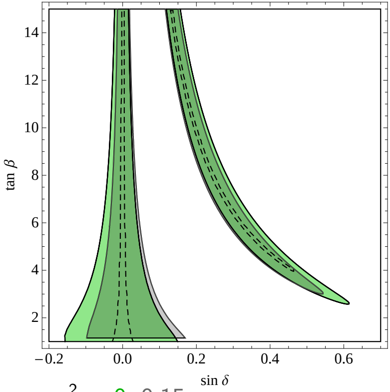
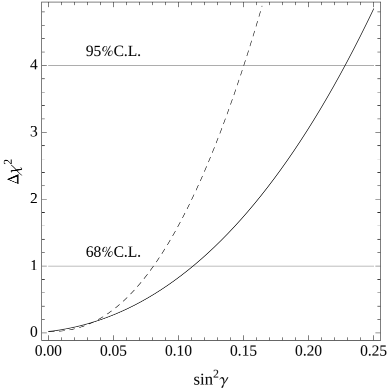
$$h_{\rm LHC} = h = c_\gamma(c_\delta h_v - s_\delta H) + s_\gamma S$$

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

cont: LHC8 status dashed: LHC14 projections (300 fb^{-1})



$s_\gamma^2 = 0, 0.15$



✓ Can new Higgses be the lightest new particles around?

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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! $+ \, \text{BR}_{\phi\to hh}$ $(= \text{BR}_{\phi\to ZZ}$ at $m_\phi \gg m_W)$

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

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

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

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

Generic singlet: Higgs couplings

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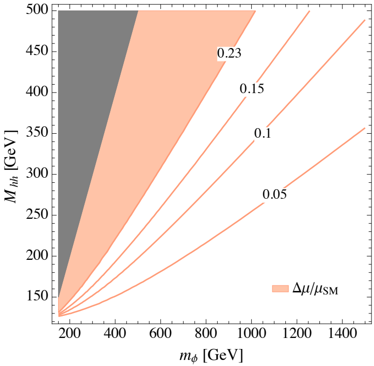
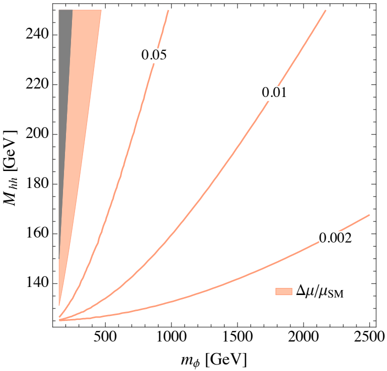


1σ reach in	s_γ^2	$\left\|1 - \frac{g_{hhh}}{g_{hhh}^{\rm SM}}\right\|$
LHC8	0.2	–
LHC14	0.08-0.12	–
HL-LHC	$4\text{-}8\times10^{-2}$	0.5
HE-LHC	–	0.2
FCC-hh	–	0.08
ILC	2×10^{-2}	0.21-0.83
ILC-up	4×10^{-3}	0.13-0.46
CLIC	$2\text{-}3\times10^{-3}$	0.1-0.21
CEPC	2×10^{-3}	–
FCC-ee	1×10^{-3}	–

Snowmass 2013



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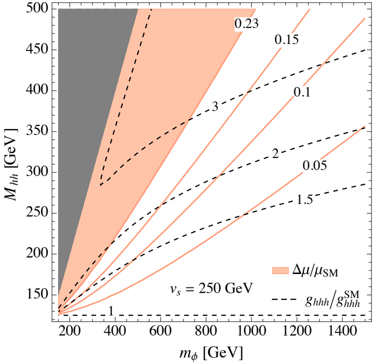
h: signal strengths $\mu = c_\gamma^2 \times \mu_{\rm SM}$ Add g_{hhh}: could be first deviation seen!



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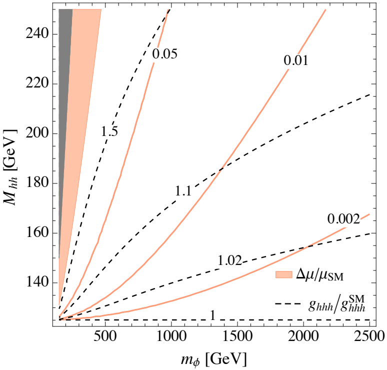

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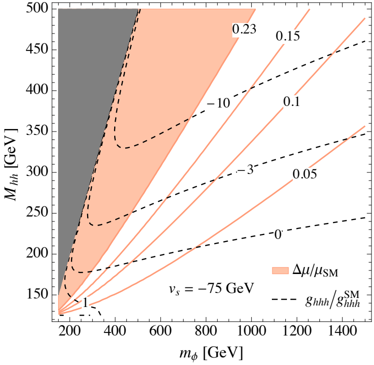

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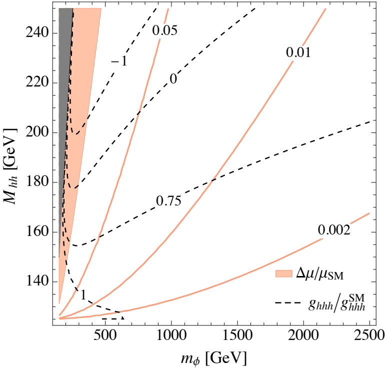
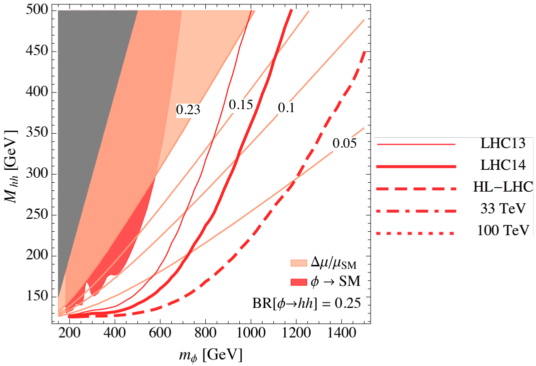
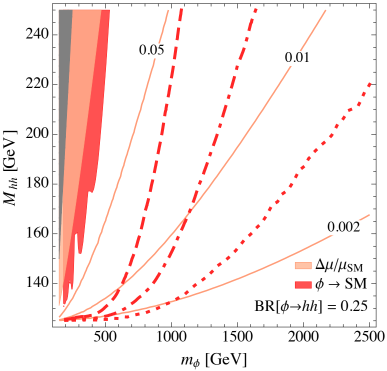


$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

[$\phi \to VV$ dominates over $\phi \to hh$, unless $v_s < 0$ and small]

h: signal strengths $\mu = c_\gamma^2 \times \mu_{\text{SM}}$ ϕ: $\mu(m_\phi) = s_\gamma^2 \times \mu_{\text{SM}}(m_\phi)$ [barring $\phi \to hh$]





Twin Higgs and the NMSSM

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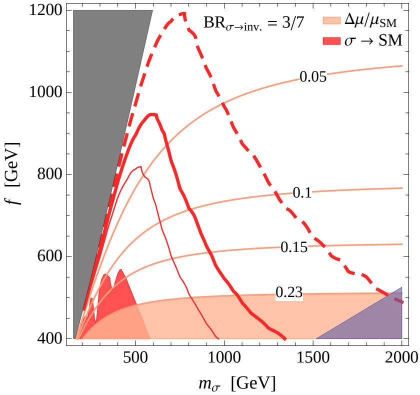
Twin Higgs: $M_{hh}^2 = (m_h^2 + m_\phi^2)\, v^2/f^2$

Take-home messages

Twin Higgs:

- → Signal strengths μ_h more effective than direct ϕ searches, unless $m_\phi \sim f$
- → no significant deviations in g_{hhh}



...more in back up slides

Twin Higgs and the NMSSM

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Twin Higgs: $M_{hh}^2 = (m_h^2 + m_\phi^2)\, v^2/f^2$

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

Take-home messages

Twin Higgs:

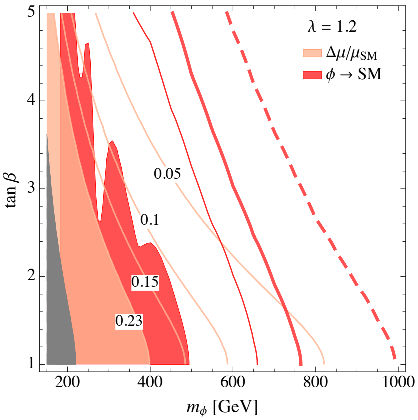
→ Signal strengths μ_h more effective than direct ϕ searches, unless $m_\phi \sim f$

→ no significant deviations in g_{hhh}

NMSSM:

→ For μ_h to do better than direct ϕ searches, per-mille precision needed

→ g_{hhh} could show significant deviations

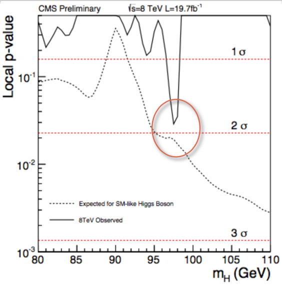


...more in back up slides

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

Singlet-like state lighter than 125 GeV

Hard to see, could it explain this hint?

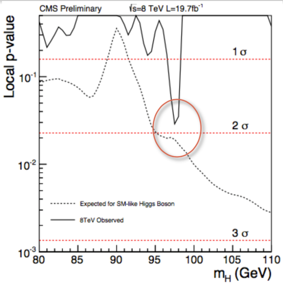


Singlet-like state lighter than 125 GeV

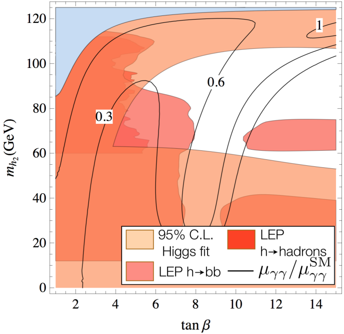
Hard to see, could it explain this hint?

[see also Badziak et al. 1304.5437,...]

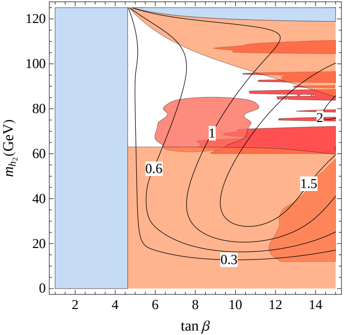
$[m_{h_3} = 500 \text{ GeV},\ s_\sigma^2 = 10^{-3},\ v_s = v]$



$\lambda = 0.1, \Delta_t = 85$ GeV

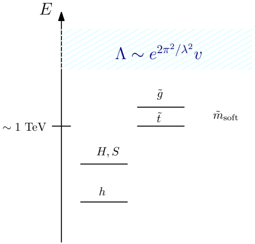


$\lambda = 0.8, \Delta_t = 75$GeV



A (necessary) input to plan future HEP strategy

$\phi \to VV, hh,\quad h$ couplings, $\quad g_{hhh}, \dots$



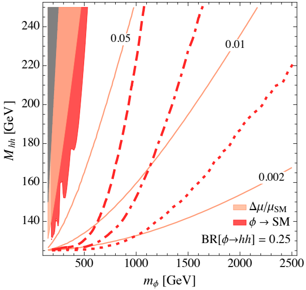
Very relevant for natural theories

NMSSM with $\lambda \sim 1$

singlet-like ϕ 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 σ

for extra Higgses see also F.S. 1509.08655

Back up

Generic singlet: direct searches

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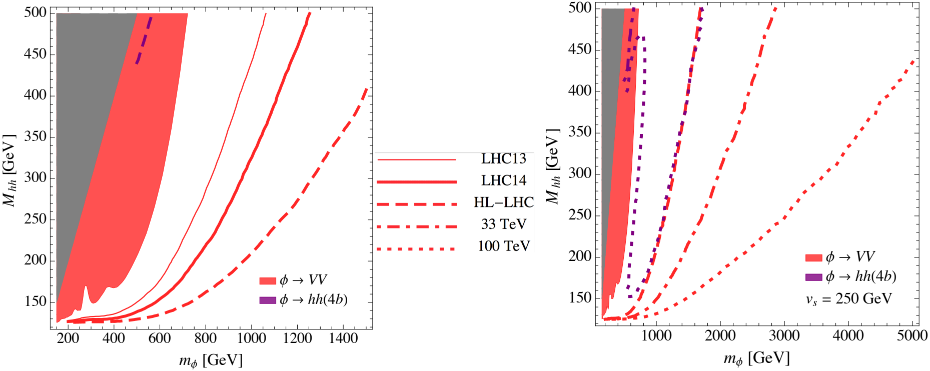
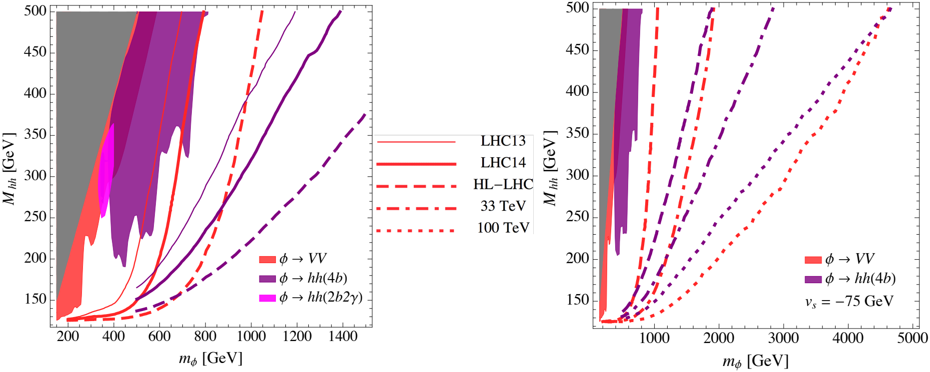
ϕ: $\mu(m_\phi) = s_\gamma^2 \times \mu_{\rm SM}(m_\phi)$ [barring $\phi \to hh$]



Generic singlet: direct searches

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

Large $\mathrm{BR}_{\phi\to hh}$ easier for $v_s < 0$ $\qquad$ ϕ: $\mu(m_\phi) = s_\gamma^2 \times \mu_{\mathrm{SM}}(m_\phi)$ [barring $\phi \to hh$]



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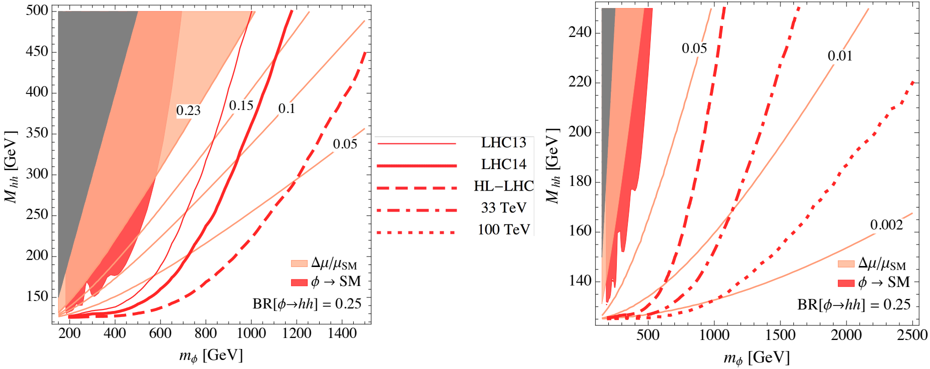
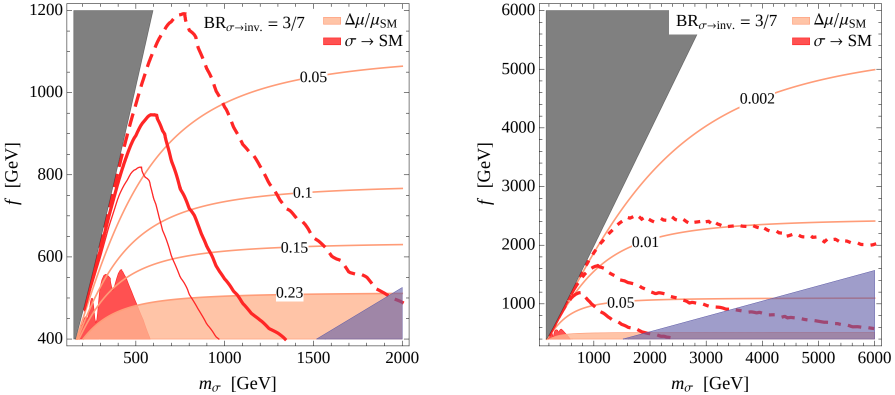


Higgs as a PNG boson: Twin Higgs

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\sigma^2 - m_h^2} \qquad M_{hh}^2 = (m_h^2 + m_\sigma^2)\, v^2/f^2$$

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

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



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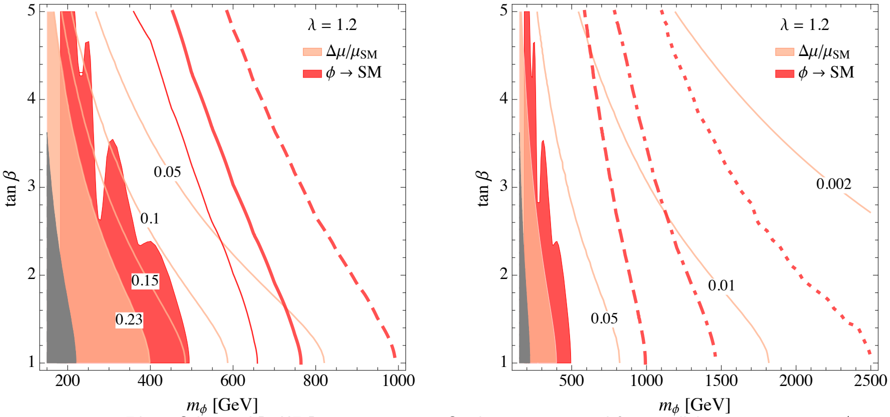
$$M_{hh}^2 = m_Z^2\, c_{2\beta}^2 + \lambda^2 v^2\, s_{2\beta}^2 + \Delta^2$$

Δ = all loop effects, e.g. top-stop

Here $\lambda = 1.2$ $\Delta = 70$ GeV $\tan\beta$ "small" otherwise EWPT



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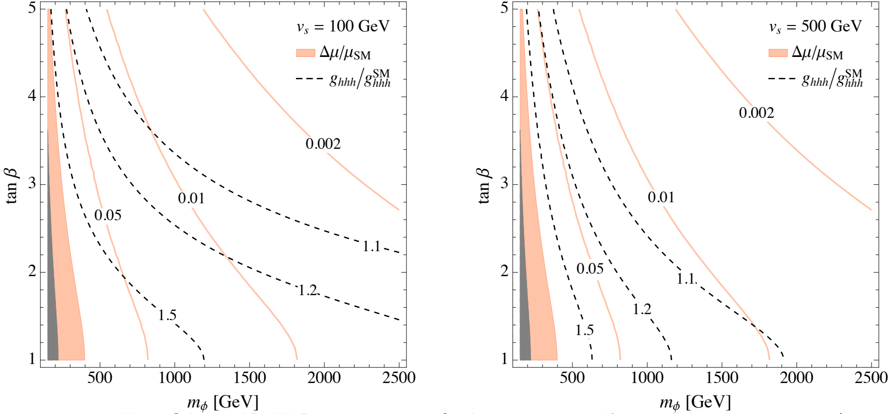

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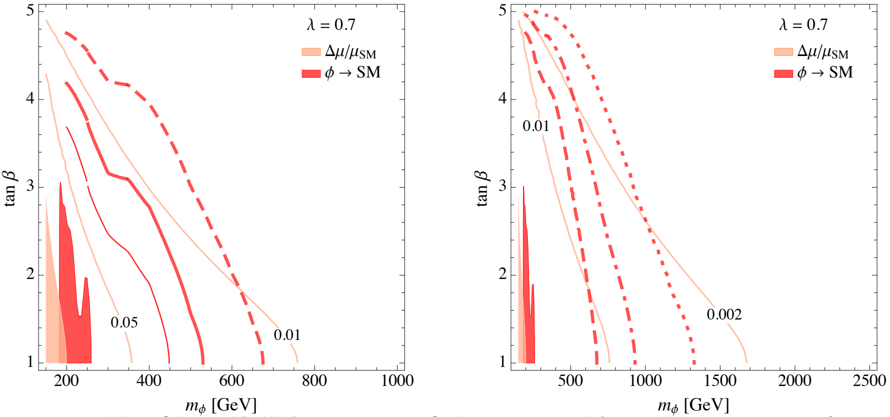
Here $\lambda = 0.7$ $\quad \Delta = 80$ GeV $\qquad \tan\beta$ "small" otherwise EWPT



Extrapolation of direct searches I

We started from

i) Collider Reach (β) 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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$B(s, L, m) \propto L \times \quad \frac{\Delta \hat{s}}{m^2}\, c\, \frac{d\mathcal{L}}{d\hat{s}}(s)\Big|_{\hat{s}=m^2} \qquad \hat{s}\hat{\sigma}(\hat{s}) = c \;\Rightarrow\; \frac{d\mathcal{L}}{d\hat{s}}$ drives the reach

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$$B(s, L, m) \propto L \times \quad \frac{\Delta \hat{s}}{m^2}\, c\, \frac{d\mathcal{L}}{d\hat{s}}(s)\Big|_{\hat{s}=m^2} \qquad \hat{s}\hat{\sigma}(\hat{s}) = c \;\Rightarrow\; \frac{d\mathcal{L}}{d\hat{s}} \text{ drives the reach}$$

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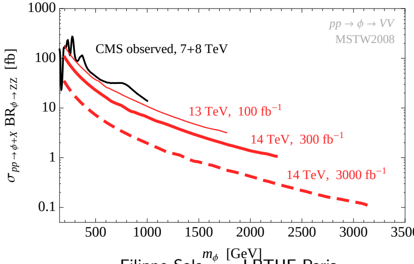

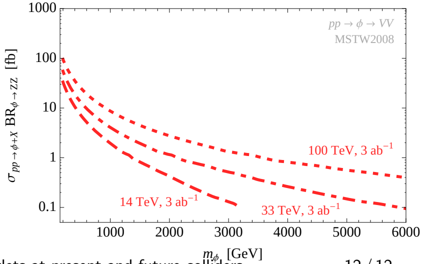

Extrapolation of direct searches I

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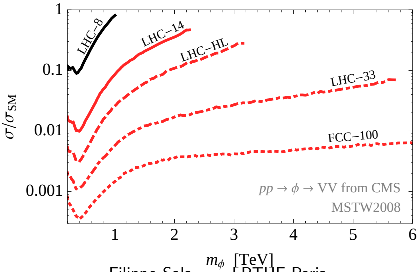

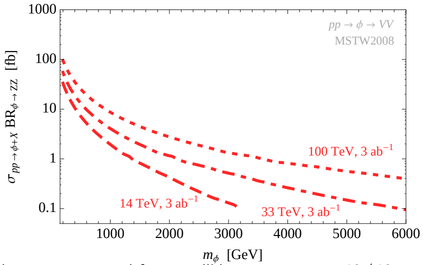

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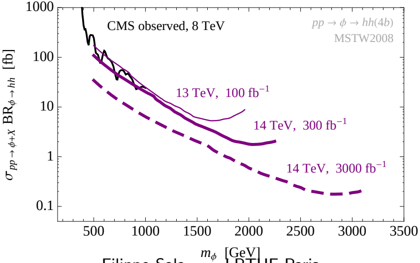
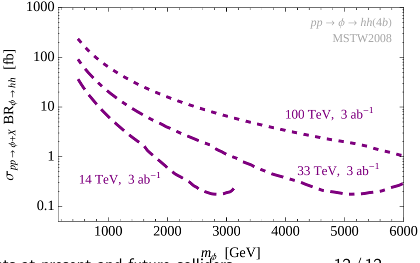
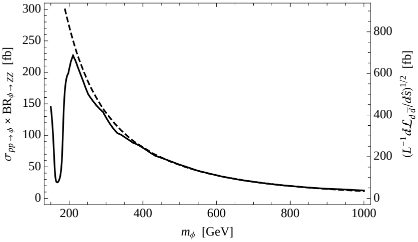
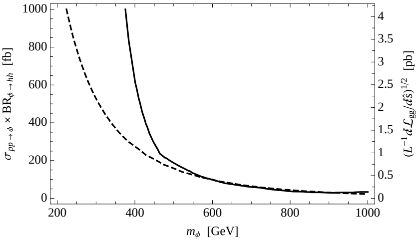




Extrapolation of direct searches II

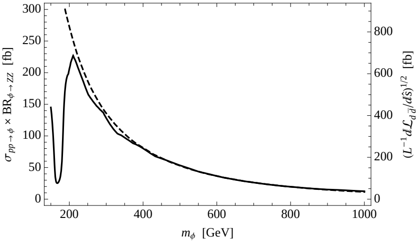


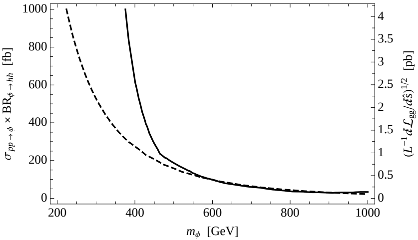


Assumptions/limitations

→ Not valid if systematics dominate and change significantly from s_0 to s_1

Extrapolation of direct searches II





Assumptions/limitations

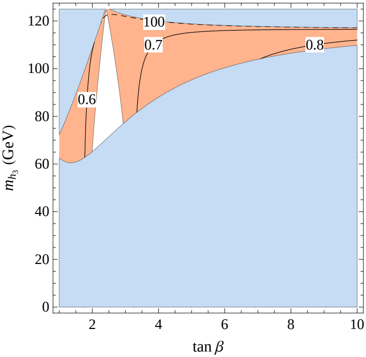
- $\rightarrow$ Not valid if systematics dominate and change significantly from s_0 to s_1
- $\rightarrow$ $\hat{s} \gg m_{\rm bkg}$ [i.e. not valid at $\hat{s} \sim 2m_t$ for $\phi \rightarrow hh(4b)$]
- $\rightarrow$ $\dfrac{\Delta\hat{s}}{m^2} \ll 1$ i.e. not valid if analysis depends a lot on shape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

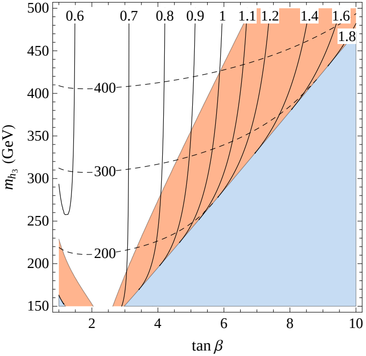
Barbieri Buttazzo Kannike Sala Tesi 1304.3670, 1307.4937

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

Status fit LHC8:

dashed: $m_{H^\pm}$ cont: λ





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

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

h_3 phenomenology: more similar to MSSM

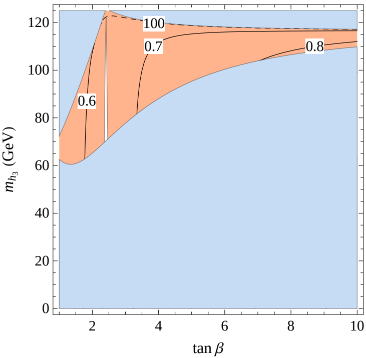
see e.g. Craig et al. 1504.04630

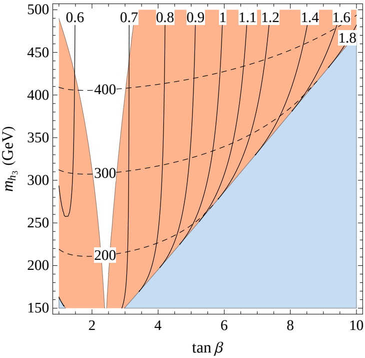
An extra doublet-like state H $[\gamma, \sigma = 0, \quad m_{h_2} \gg m_{h_1}, m_{h_3}]$

Barbieri Buttazzo Kannike Sala Tesi 1304.3670, 1307.4937

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

Projections fit LHC14 (300 fb^{-1}): dashed: $m_{H^\pm}$ cont: λ





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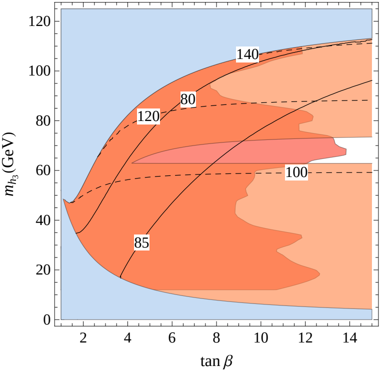
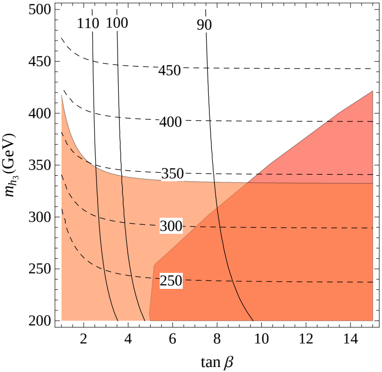
Status fit LHC8: [dashed: $m_{H^\pm}$ cont: Δ_t]





Red regions excluded by direct searches at LEP and CMS

Projections fit LHC14: above regions completely excluded

$\left[\text{if } \frac{\mu A_t}{m_{\tilde{t}}^2} \text{ very large, conclusions could change...}\right]$