Singlet-like Higgs bosons

at present and future colliders

Dario Buttazzo

Institute for Advanced Study, TU Munich

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Based on arXiv:1505.05488 in collaboration with

Filippo Sala
(CEA/Saclay, Paris)

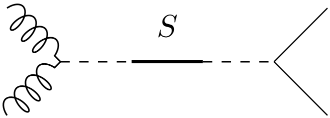
Andrea Tesi
(University of Chicago)

Why scalar singlets?

◇ Total singlets: not coloured, no EW interactions... challenging?

◇ Can be part of a hidden sector: neutral naturalness, DM...

◇ If CP-even scalar, mixing with the Higgs boson can be sizeable:



- can be singly produced
- decays to SM particles
- modified Higgs couplings

... a useful probe of the Higgs sector.

◇ A very simple model – but not trivial: appears in many interesting scenarios (NMSSM, Twin Higgs, EW baryogenesis, etc.)

◇ Study the sensitivity of future colliders to extra Higgses

Outline

1. Higgs-Singlet mixing: general features
2. Constraints: present and future
    - Indirect bounds: Higgs couplings
    - Direct searches: $pp \to \phi$
3. Concrete models
    - SUSY: the NMSSM
    - Twin Higgs (& Composite Higgs)

Higgs-singlet mixing: main features

SM + 1 real singlet: $H = (i\pi^+, \frac{v+h^0+\pi^0}{\sqrt{2}})$, $S = v_s + s^0$.

Mass eigenstates: $h = h^0 \cos\gamma + s^0 \sin\gamma$, $\phi = s^0 \cos\gamma - h^0 \sin\gamma$.

The phenomenology mainly depends on only 3 parameters:

$$\mu_h = c_\gamma^2 \times \mu_{\rm SM},$$
$$\mu_{\phi\to VV,ff} = s_\gamma^2 \times \mu_{\rm SM}(m_\phi) \times (1 - {\rm BR}_{\phi\to hh}),$$
$$\mu_{\phi\to hh} = s_\gamma^2 \times \sigma_{\rm SM}(m_\phi) \times {\rm BR}_{\phi\to hh},$$

ϕ is like a heavy SM Higgs, with narrow width + hh channel

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

$M_{hh}^2 \propto v^2$ depends only on EW physics

Decays of ϕ

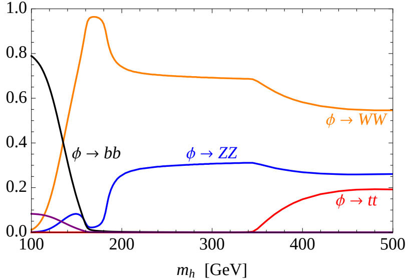
At high mass the equivalence theorem relates the decay widths

$$\mathrm{BR}_{\phi\to hh} = \mathrm{BR}_{\phi\to ZZ} = \frac{1}{2}\mathrm{BR}_{\phi\to WW} \simeq \frac{1}{4}, \qquad m_\phi \gg m_h$$

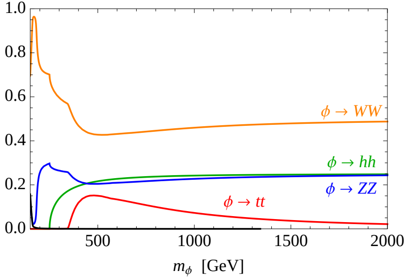
(these are the dominant channels, fermionic modes suppressed)

- Phenomenology roughly determined just by m_ϕ and M_{hh}!

h branching ratios



ϕ branching ratios



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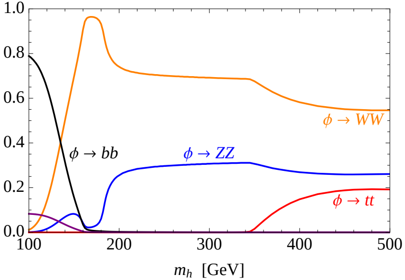

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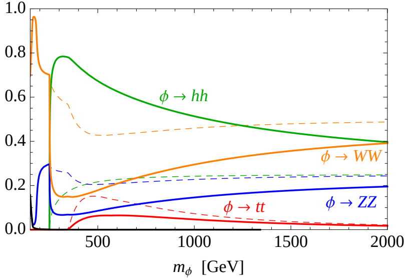


ϕ is like a heavy SM Higgs + $\mathrm{BR}_{\phi\to hh}$

Triple Higgs couplings

The triple couplings depend on the details of the potential

$$V = \mu_H^2|H|^2 + \lambda_H|H|^4 + \lambda_{HS}|H|^2S^2 + a_H|H|^2S + \mu_S^2S^2 + a_SS^3 + \lambda_SS^4$$

7 parameters $= \underbrace{m_\phi, M_{hh}, v_s, \lambda_{HS}, \lambda_S}_{\text{5 free parameters}} + m_h,\, v$

The dependence on λ_{HS}, λ_S is very weak: v_s is the only relevant additional parameter that determines $\mathrm{BR}_{\phi\to hh}$ and the h^3 coupling

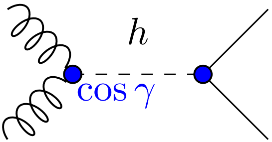
$$\mathrm{BR}_{\phi\to hh} = \frac{1}{4} - \frac{3}{4}\frac{v}{v_s}\frac{\sqrt{M_{hh}^2 - m_h^2}}{m_\phi} + \mathcal{O}(v^2/m_\phi^2)$$

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

Hunting the singlet Higgs bosons

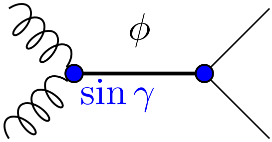
Two complementary ways to look for the extra Higgs:

Higgs signal strengths



$$\mu_h = c_\gamma^2 \mu_{\rm SM}$$

Direct searches



$$\mu_\phi = s_\gamma^2 \mu_{\rm SM} \times (1 - {\rm BR}_{\phi\to hh})$$

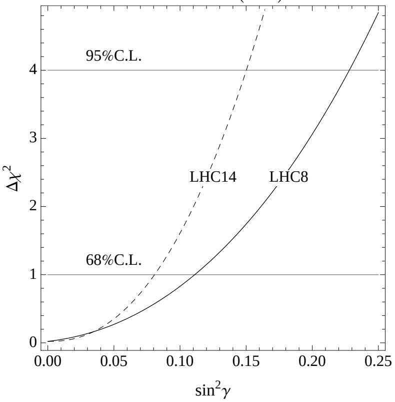
Higgs signal strengths

1σ reach in	$s_\gamma^{2\,*}$	$\left\|1 - \frac{g_{hhh}}{g_{hhh}^{\rm SM}}\right\|$
LHC8	0.2	–
LHC14	0.08-0.12	–
HL-LHC	4-8$\times 10^{-2}$	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	2-3$\times 10^{-3}$	0.1-0.21
CEPC	2×10^{-3}	–
FCC-ee	1×10^{-3}	–

* projections for most precise coupling

Snowmass '13

Fit to all rates $\mu_{h(125)}$



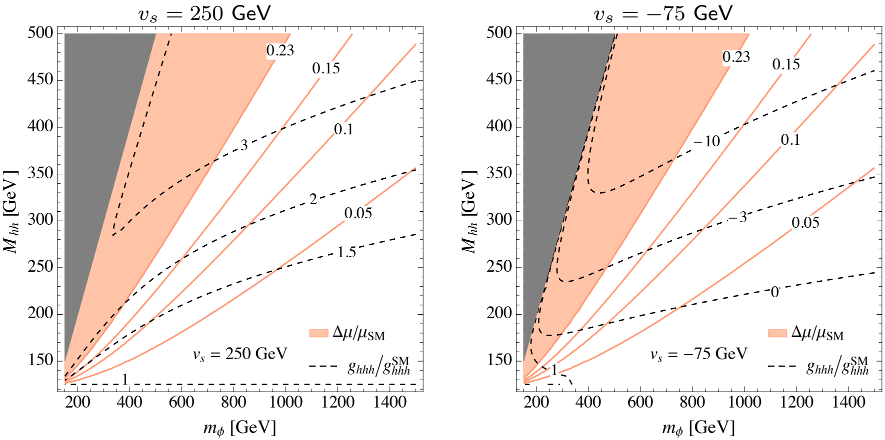
Barbieri, B, Kannike, Sala, Tesi '13

compare with 2HDM:

$\sin^2\gamma \lesssim 0.02$

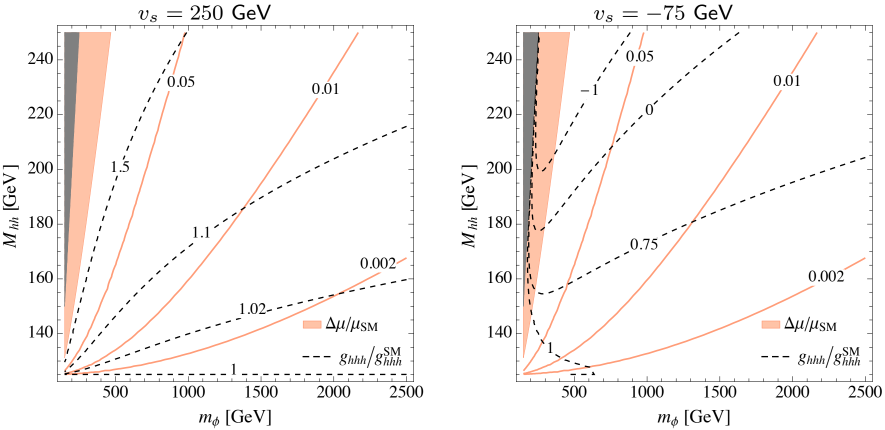
At present a precision of 20%: still room for sizeable deviations!

Higgs couplings



Very large modifications of the triple Higgs coupling are possible: in principle observable at the LHC

Higgs couplings



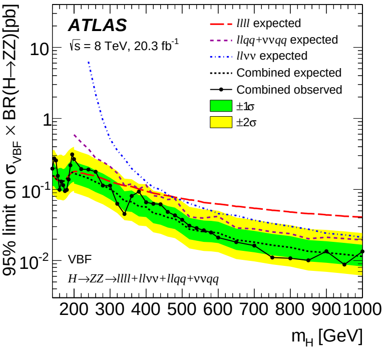
(Region relevant for an e^+e^- collider)

Direct searches

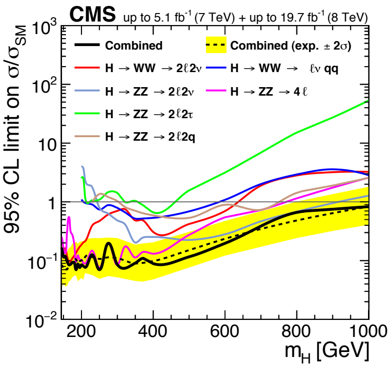
ϕ is like a heavy SM Higgs boson: $\phi \to VV$ dominant decay mode

- Combination of ZZ & W^+W^- final states:

ATLAS [1507.05930]



CMS [1504.00936]



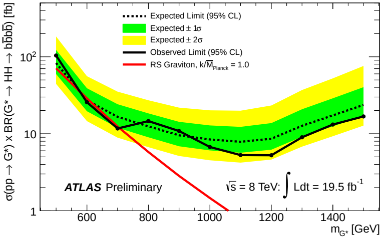
Already more sensitive than Higgs couplings at low masses!

Direct searches

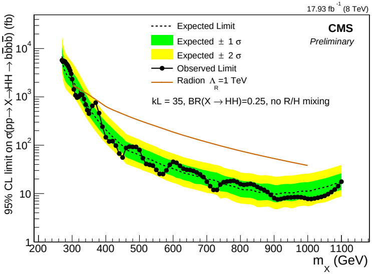
ϕ is like a heavy SM Higgs boson + $\phi \to hh$ decay width

- $hh \to 4b$ final state:

ATLAS [CONF-2014-005]



CMS [1503.04114]



Other decay channels can also be relevant:

- ◇ $hh \to 2b\,2\gamma$ dominates only at low $m_\phi \lesssim 400$ GeV [1406.5053] [CMS-HIG-13-032]
- ◇ $hh \to 2b\,2\tau$, $hh \to 4\tau$, $hh \to 2b\,2W$

No et al. '13, Kotwal et al. '15, Martin-Lozano et al. '15

Projections for the future

How to get fast estimates of the reach of future machines?

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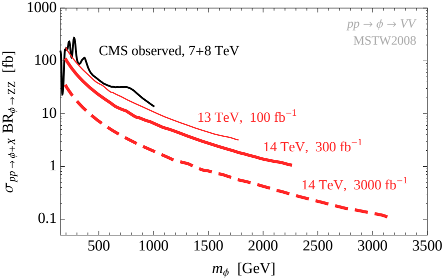
- Rescale 8 TeV LHC data with the parton luminosity of the bkg

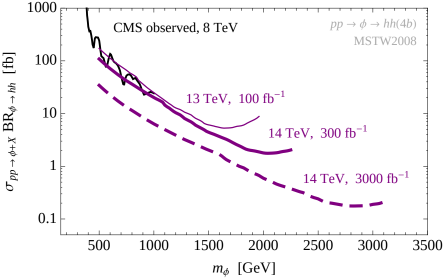
see also Salam, Weiler '14; Thamm, Torre, Wulzer '15

The limit on the cross-section is mainly determined by the number of background events around the resonance peak

$\phi \to VV$ channel



$\phi \to hh(4b)$ channel



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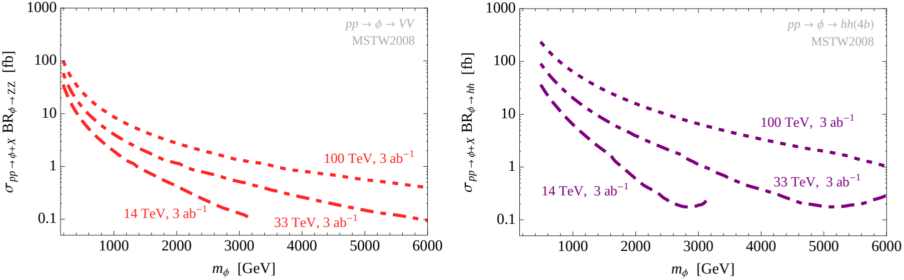
$\phi \to VV$ channel | $\phi \to hh(4b)$ channel



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Extrapolation procedure

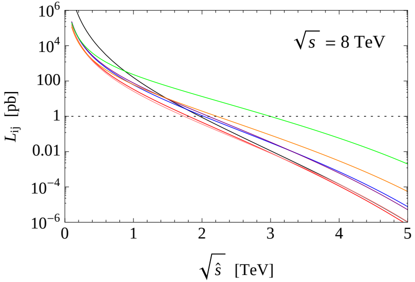
- # of bkg events:

$$N_B = L \cdot \sum_{i,j} \int d\hat{s} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(\sqrt{\hat{s}}, \sqrt{s}) \cdot \hat{\sigma}_{ij}(\hat{s}) \approx L \cdot \sum_{i,j} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}},$$

where $\hat{\sigma}_{ij} \sim c_{ij}/\hat{s}$ is the partonic cross-section $ij \to$ final state

- # of signal events: $N_S = L \cdot \sigma$.

$$\begin{cases} N_B(s_0, L_0, m_0) = N_B(s, L, m) & \to \quad m = m(m_0) \\ N_S(s_0, L_0, m_0) = N_S(s, L, m) & \to \quad \sigma(m) = (L_0/L)\, \sigma_0(m_0) \end{cases}$$



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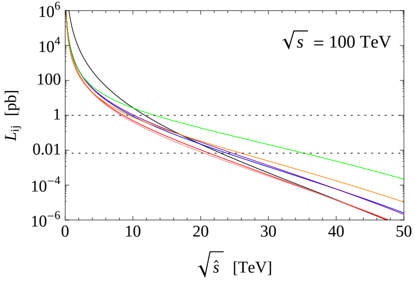


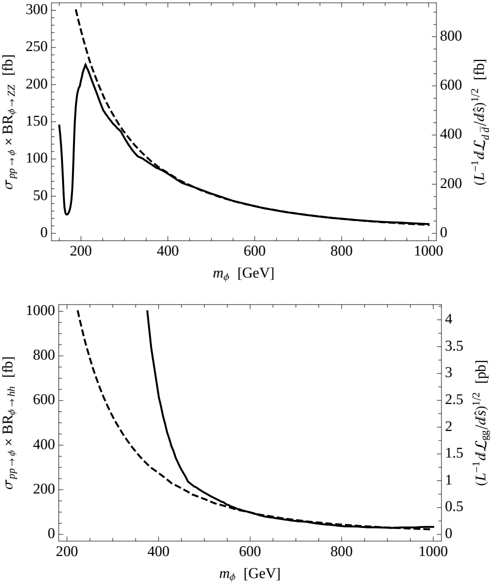
Extrapolation procedure

This method is subject to a number of rather strong assumptions!

- ◇ The composition of the background must not change radically at higher energies
- ◇ Acceptances and efficiencies at the new collider roughly the same as at the LHC
- ◇ Cut & count experiment for narrow resonances
- ◇ SM backgrounds scale as $\sigma_{ij}(\hat{s}) \sim c_{ij}/\hat{s}$: true above the SM thresholds
- ◇ Systematics are not large (significance $\propto N_S$ for fixed N_B)

Still, predictions accurate up to O(1) factors...

Checks of our assumptions



- The excluded cross-sections scale as (parton luminosity)$^{1/2}$

  Below a certain mass SM thresholds become relevant: we do not extrapolate the exclusions beyond that point.

- Our extrapolations are consistent – up to O(1) factors – with other studies at 13, 14, 33 TeV

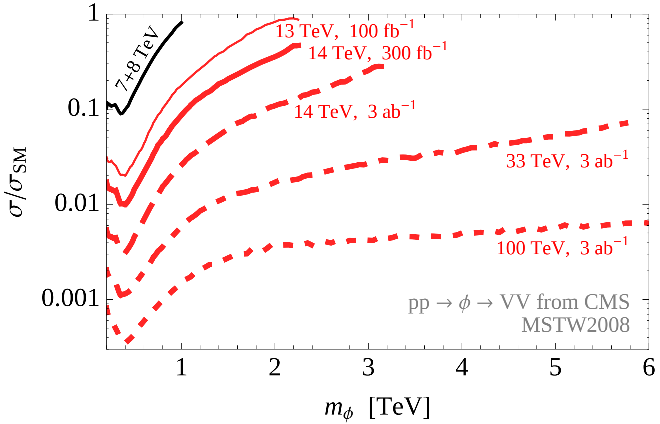
Brownson et al. '13

Gouzevich et al '13

Direct vs. indirect

We can now compare the reach of direct and indirect searches

$\sigma/\sigma_{\rm SM} \propto \sin^2\gamma$ (ignore $\mathrm{BR}_{\phi\to hh}$ for the moment...)



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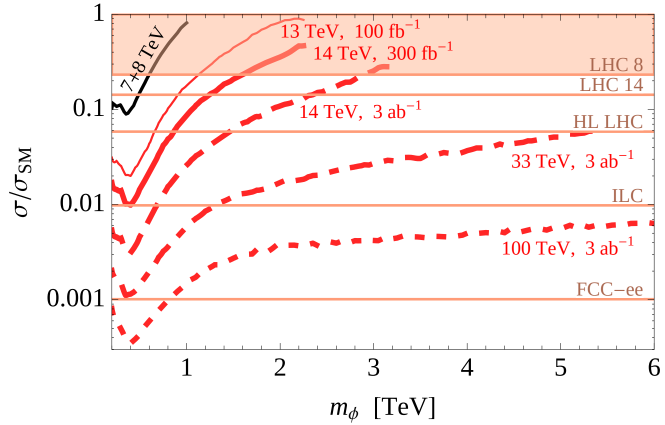
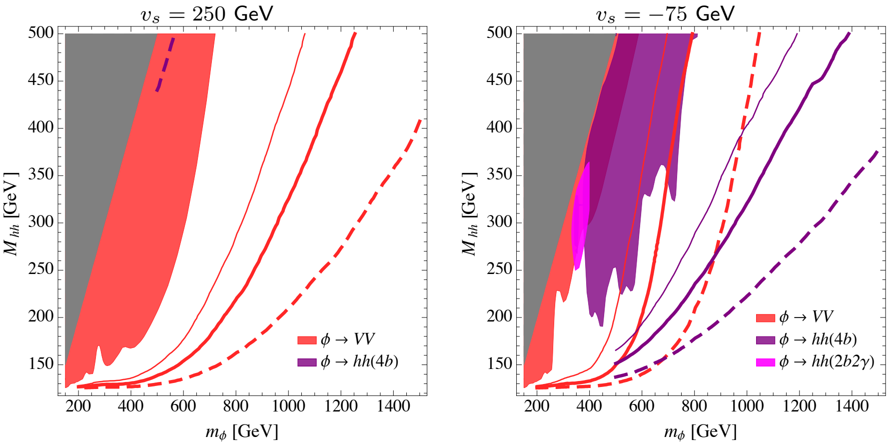


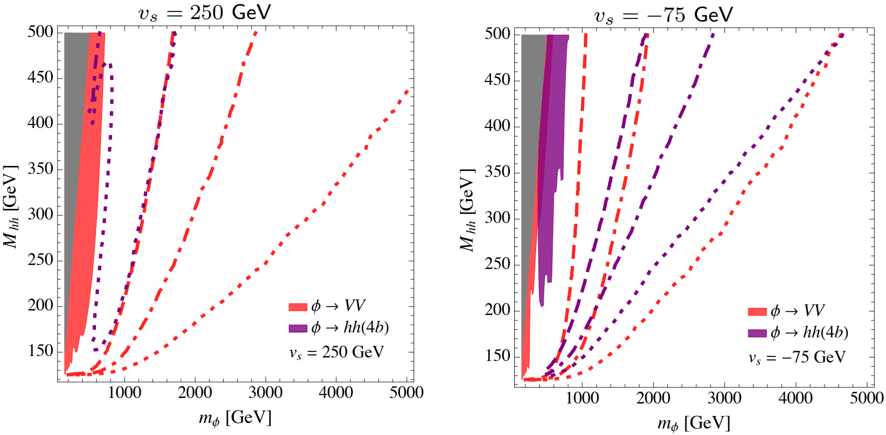
Direct searches dominate for lower masses ($\lesssim 1$ TeV) at each stage of the experimental program

Generic singlet: direct searches @ LHC



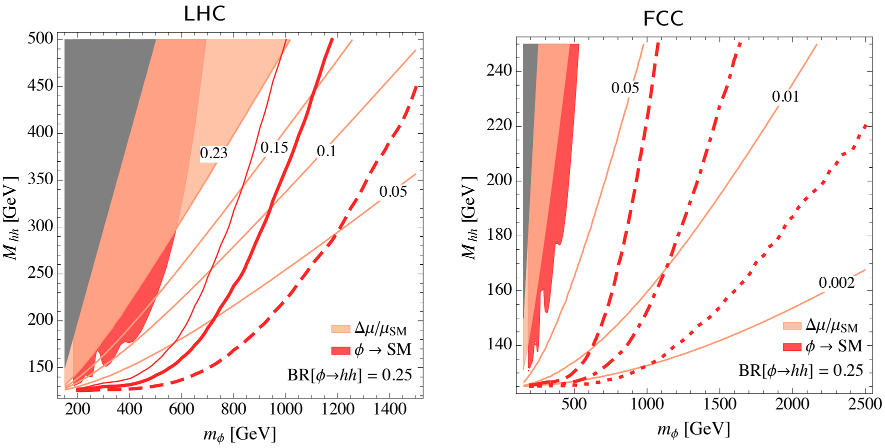
Considering both $\phi \to VV$ and $\phi \to hh$ the combined reach does not strongly depend on $\mathrm{BR}_{\phi \to hh}$

Generic singlet: direct searches @ FCC



At high masses $\phi \to VV$ is always dominant $(\mathrm{BR}_{\phi\to hh} \sim 1/4)$

Generic singlet: comparison of bounds



Direct searches dominate for low m_ϕ, M_{hh}: look for the singlet!

SUSY: the NMSSM

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

Fayet '75

◇ Extra tree-level contribution to the Higgs mass

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

◇ Alleviates fine-tuning in v for $\lambda \gtrsim 1$ and moderate $\tan\beta$

$$\delta v^2\big|_{\text{NMSSM}} \sim \frac{\cot 2\beta}{\lambda^3} \times \tilde{m}^2 \qquad \delta v^2\big|_{\text{MSSM}} \sim \frac{4}{g^2} \times \tilde{m}^2$$

allows for smaller soft masses compared to the MSSM

▶ Combined tuning better than 5% for $\lambda \approx 1$ and stop/gluino masses in reach of LHC

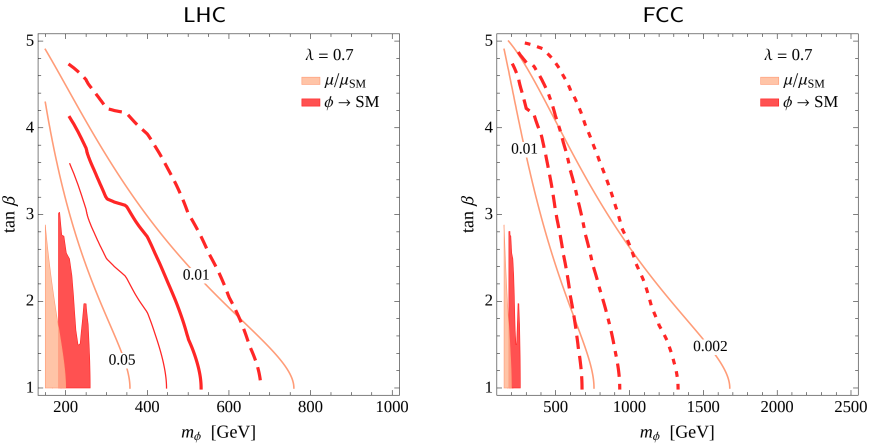
Gherghetta et al. '12 (scale-invariant NMSSM)

◇ Non-perturbative regime at high scales if $\lambda \gtrsim 0.7$

NMSSM

Recast the previous bounds: $M_{hh}^2 = m_Z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2 + \Delta^2$

- Perturbative coupling: $\lambda = 0.7$, $\Delta = 80$ GeV



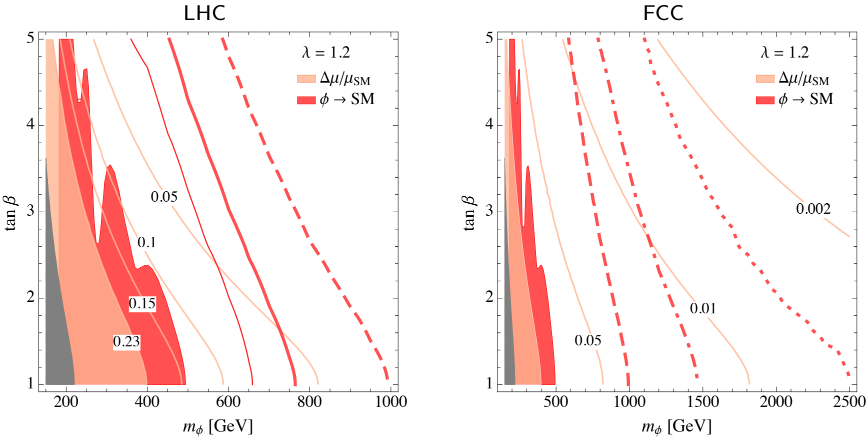
◇ Already w/ 100 fb^{-1} direct searches better than Higgs fit @ HL

◇ Direct reach @ 100 TeV comparable with sensitivity of FCC-ee

NMSSM

Recast the previous bounds: $M^2_{hh} = m_Z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2 + \Delta^2$

- "Strong" coupling (λ-SUSY): $\lambda = 1.2$, $\Delta = 70$ GeV



◇ Direct searches w/ 300 fb^{-1} better than Higgs fit @ HL-LHC

◇ Direct reach @ 100 TeV close to sensitivity of FCC-ee

Twin Higgs

Chacko et al. '04
Barbieri et al. '05

- Standard Model + a "twin" copy, with an approximate $\mathbb{Z}_2$ symmetry $\mathrm{SM_A} \leftrightarrow \mathrm{SM_B}$. New particles are total singlets.
- The Higgs potential has an approximate $\mathrm{SO}(8)$ symmetry

$$V = \lambda_*(\Phi^2 - f^2)^2 + m^2|H|^2 + \kappa|H|^4, \qquad \Phi = (H, S).$$

(m, κ break both $\mathrm{SO}(8)$ and $\mathbb{Z}_2$ to reproduce $m_h, v \neq 0$)

- The Higgs is a pseudo-Goldstone boson of $\mathrm{SO}(8)/\mathrm{SO}(7)$.
  (7 GB's = 1 light Higgs + (3 + 3) eaten-up)

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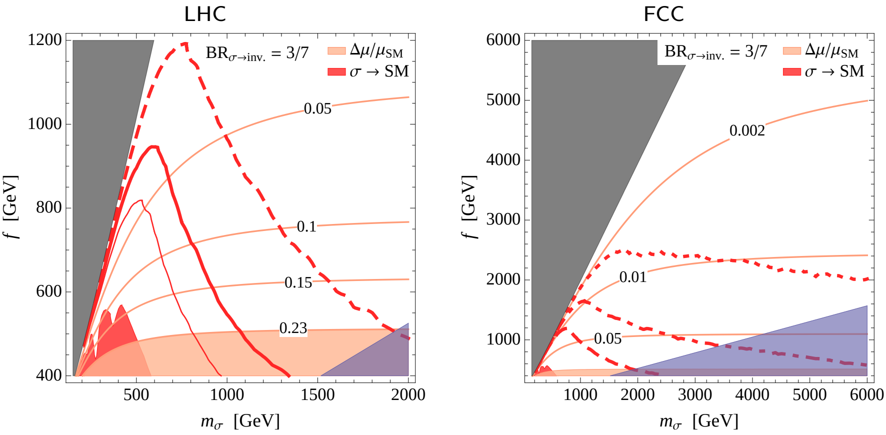
- ◇ The Higgs is a pseudo-Goldstone boson of $\mathrm{SO}(8)/\mathrm{SO}(7)$.
  (7 GB's = 1 light Higgs + (3 + 3) eaten-up)

- ▶ Higgs mass is protected from radiative corrections, without coloured states at the weak scale.
- ▶ Linear σ-model: there is a "radial mode" with mass $m_\sigma^2 \approx \lambda_* f^2$.
- ▶ The model is fully determined by 4 parameters: m_ϕ, m_h, v, f.

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

Look for the twin!

Recast the generic bounds: $M_{hh}^2 = (m_\phi^2 + m_h^2)\dfrac{v^2}{f^2}$



If not too strongly coupled, the twin Higgs could be directly visible!

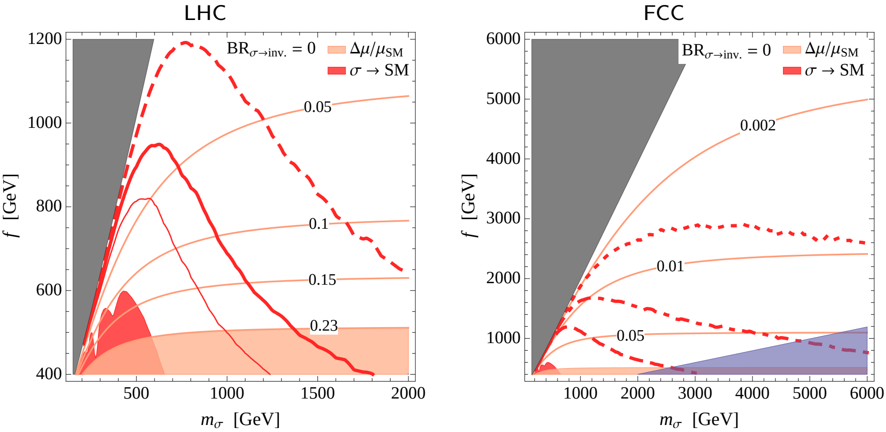
Conclusions

- Looking for singlets is easy, and it is motivated by many (natural) models
  - Direct searches are a very powerful probe
  - Higgs signal strengths needed above the TeV
  - triple Higgs coupling could be large
- General description in terms of few physical parameters
- NMSSM & Twin Higgs: two prime examples of most natural models that contain a singlet

Backup

(Linearised) Composite Higgs

Exactly the same analysis as in Twin Higgs can be applied to the case of a "linearised" Composite Higgs model.



- Only difference: absence of invisible decay width into W', Z'.

Triple Higgs couplings

Exact expressions

$$g_{\phi hh} = s_\gamma \left[\frac{\lambda_{HS}\, v}{2} - \frac{m_\phi^2 + 2m_h^2}{2v} - \frac{v^2}{v_s^2}\frac{m_\phi^2 - m_h^2}{8v} \right.$$
$$+ \frac{s_{2\gamma}}{2}\frac{m_\phi^2 + m_h^2 - \lambda_{HS}\, v^2 + 2\lambda_S\, v_s^2}{v_s} - \frac{c_{2\gamma}}{2}\frac{m_\phi^2 + 2m_h^2 - 3\lambda_{HS}\, v^2}{v}$$
$$\left. + \frac{m_\phi^2 - m_h^2}{4v}\frac{v}{v_s}\left(s_{4\gamma} - \frac{v}{v_s} s_{2\gamma}^2 \right) \right],$$

$$\frac{g_{hhh}}{g_{hhh}^{\mathrm{SM}}} = c_\gamma \left[1 + s_\gamma^2 \left(\frac{\lambda_{HS}\, v^2}{m_h^2} - 1 \right) - \frac{v^2}{v_s^2}\frac{s_\gamma^4}{3}\left(\frac{m_\phi^2}{m_h^2} - 1 \right) \right]$$
$$+ \frac{v}{v_s}\frac{s_\gamma^3}{3}\left[1 + \frac{m_\phi^2 - \lambda_{HS}\, v^2}{m_h^2} + c_{2\gamma}\left(\frac{m_\phi^2}{m_h^2} - 1 \right) + 2\lambda_S \frac{v_s^2}{m_h^2} \right].$$

Electroweak precision tests

$$\hat{S} = \frac{\alpha}{48\,\pi\,s_w^2}\,s_\gamma^2\,\log\frac{m_\phi^2}{m_h^2}, \qquad \hat{T} = -\frac{3\alpha}{16\,\pi\,c_w^2}\,s_\gamma^2\,\log\frac{m_\phi^2}{m_h^2}.$$

- Small mixing angle or small m_ϕ: constraints not relevant

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}, \qquad M_{hh}^2 \propto v^2.$$

- Can become relevant for large masses, if $M_{hh} \propto m_\phi$ as in Composite Higgs & Twin Higgs:

$$\sin^2\gamma \sim \frac{v^2}{f^2}, \qquad m_\phi \propto \sqrt{\lambda_*}f.$$

Extrapolation of bounds

$N_B(m_0, s_0, L_0) = N_B(m, s, L')$ implies

$$\sum_{\{i,j\}} c_{ij} \frac{\mathrm{d}\mathcal{L}_{ij}}{\mathrm{d}\hat{s}}(s, m^2) = \frac{L_0}{L'} \sum_{\{i,j\}} c_{ij} \frac{\mathrm{d}\mathcal{L}_{ij}}{\mathrm{d}\hat{s}}(s_0, m_0^2),$$

which implicitly determines $m(m_0, L')$, for any L'.

For each m, $L_0 \leq L' \leq L$ is chosen as to maximise the exclusion

$$[\sigma \times \mathrm{BR}](m; s, L) = \min_{L' \leq L} \left[\frac{L_0}{\sqrt{LL'}} [\sigma \times \mathrm{BR}]_0(m_0; s_0, L_0) \Big|_{m_0(L')} \right]$$

(we use a $\sqrt{L'/L}$ rescaling from L' to the nominal L).