

SUSY 2015 – Lake Tahoe 23-29 July 2015

Singlet-like Higgs bosons

Andrea Tesi
University of Chicago



Thanks to



Dario Buttazzo

(TUM, Munich / U. Zurich)



Filippo Sala

(Saclay, Paris)

and to **Matthew Low** (U. Chicago → IAS) and **LianTao Wang**

Introduction

Why are you talking about singlets? (I)

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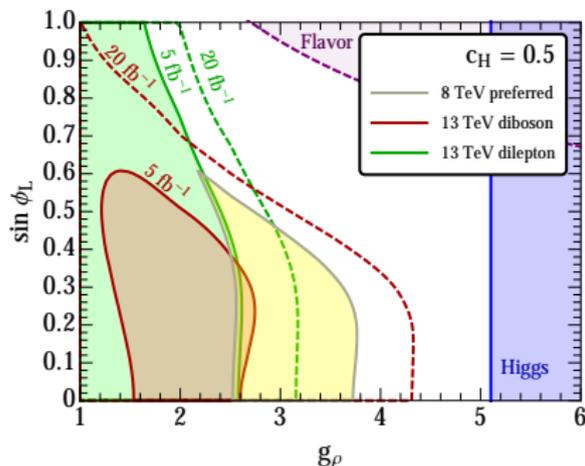
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ATLAS excess: 7-8 events close to 2 TeV, $WZ \rightarrow JJ$

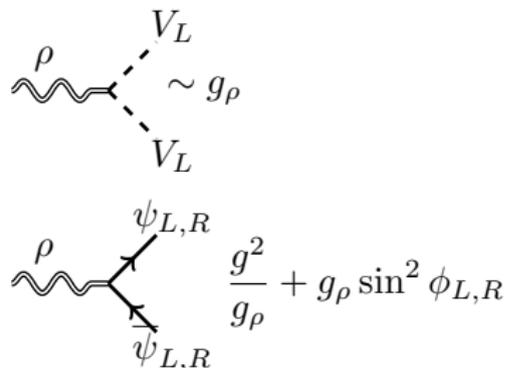
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ATLAS excess: 7-8 events close to 2 TeV, $WZ \rightarrow JJ$



Composite vectors, SU(2) triplet



w/ Matthew Low and LianTao Wang – excess lifetime ~ 1 year

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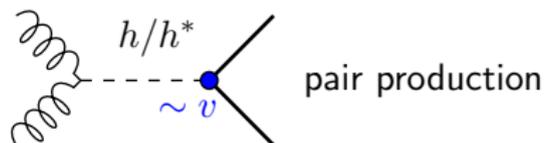
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Produced via EWSB effects, non trivial test of the Higgs sector!



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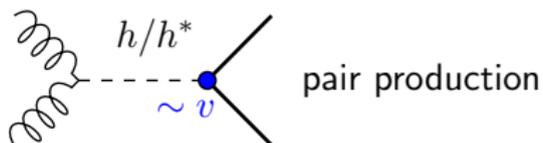
$$\frac{|H|^2}{\Lambda} \bar{S}S, \quad |H|^2 S^2, \quad \dots$$

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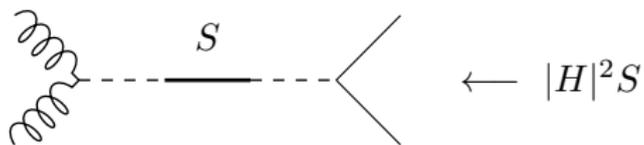
If singlets are collider-stable need an extra j [Craig, Lou, McCullough, Thalapillil]

Generally low cross sections, so why are you interested at all?

Singlet-like Higgs boson

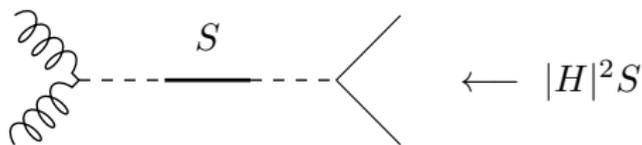
Singlet-like Higgs boson

If the singlet S is a CP-even scalar, it can be **singly** produced



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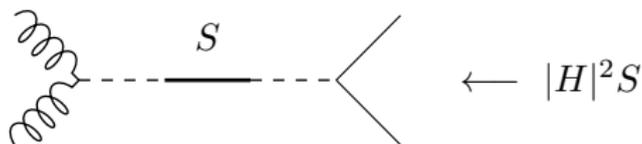
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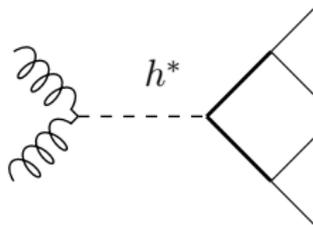
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This might also help to avoid the jet-tag



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

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7 parameters - m_h - v = 5 free parameters!

However the main phenomenology depends on 3 parameters

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

$$\mu_{\phi \rightarrow VV, ff} = s_\gamma^2 \times \mu_{\text{SM}}(m_\phi) \times (1 - \text{BR}_{\phi \rightarrow hh})$$

$$\mu_{\phi \rightarrow hh} = s_\gamma^2 \times \sigma_{\text{SM}}(m_\phi) \times \text{BR}_{\phi \rightarrow hh}$$

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

$$M_{hh}^2 = \lambda_H v^2$$

ϕ is the mass eigenstate

Two parameters: mass and mixing

At high mass **equivalence theorem** relates the decay widths

$$\Gamma(\phi \rightarrow WW) = 2\Gamma(\phi \rightarrow ZZ) = 2\Gamma(\phi \rightarrow hh), \quad m_\phi \gg m_h$$

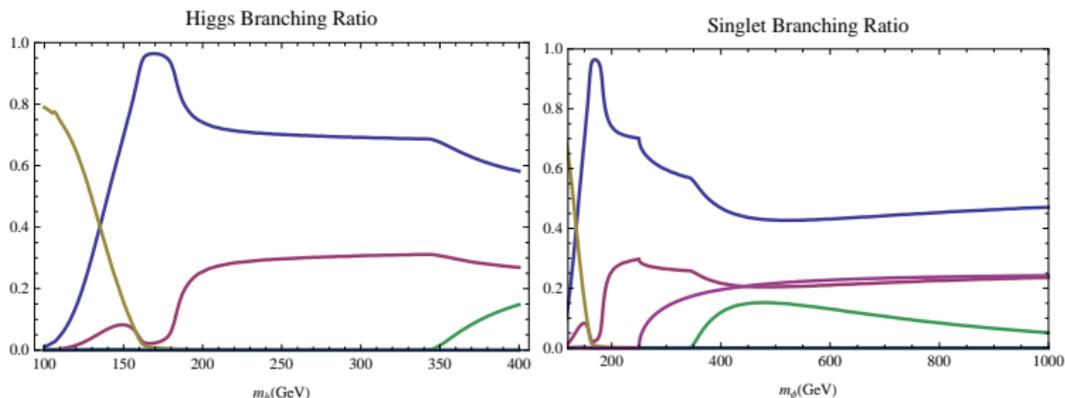
These are the dominant BR's, fermionic channels suppressed

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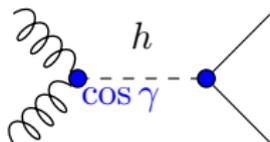
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[Memo: ϕ is like a heavy SM Higgs, with a narrow width and hh channel]

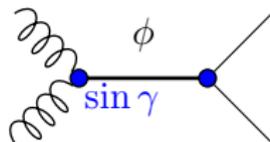
Hunting the singlet Higgs bosons

Higgs couplings



universal tree-level shift

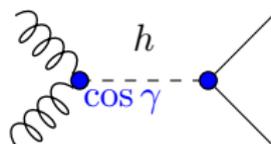
Direct searches



same h -BR (below $2m_h$)

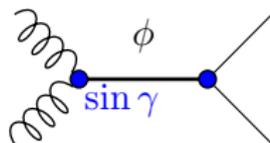
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Parametrization is simple enough to make simple "projections":
 $\sin \gamma$ and m_ϕ

[in EFT approach the comparison with direct searches is lost]

Higgs couplings & Direct Searches

Higgs couplings

1σ reach in	s_γ^2	$\left 1 - \frac{g_{hhh}}{g_{hhh}^{\text{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}	–

Snowmass '13
pre-CDR CEPC

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At present a determination of 20%
This still allows for *sizeable* deviations

Direct searches

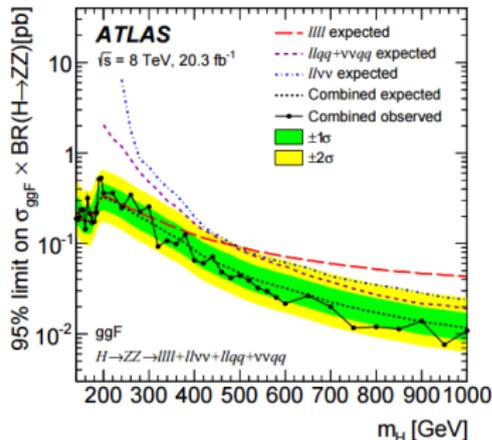
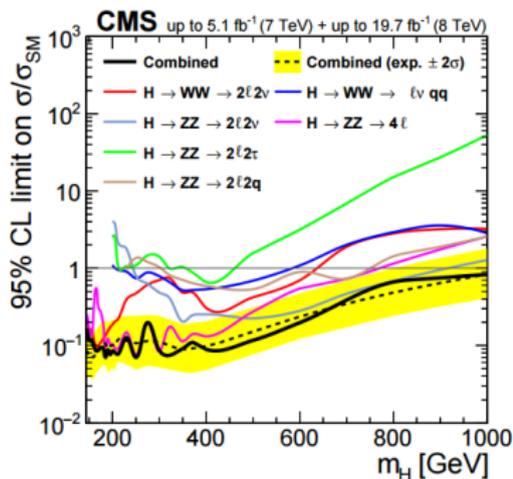
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Direct searches

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$$\phi \rightarrow VV$$

[ATLAS 1507.05930; CMS, 1504.00936]



exclusion dominated by $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$

Direct searches

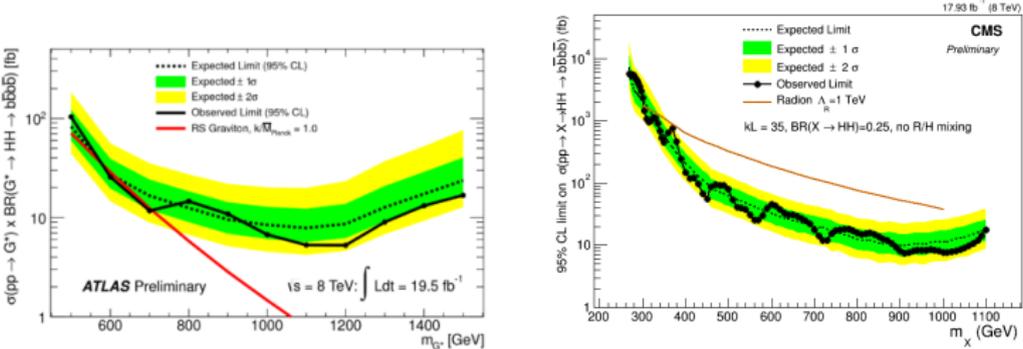
Remember, ϕ is like a heavy SM Higgs + hh channel

Direct searches

Remember, ϕ is like a heavy SM Higgs + hh channel

$\phi \rightarrow hh(4b)$

[ATLAS 2014-005; CMS, 1503.04114]



searches for resonant hh

From the data to the future

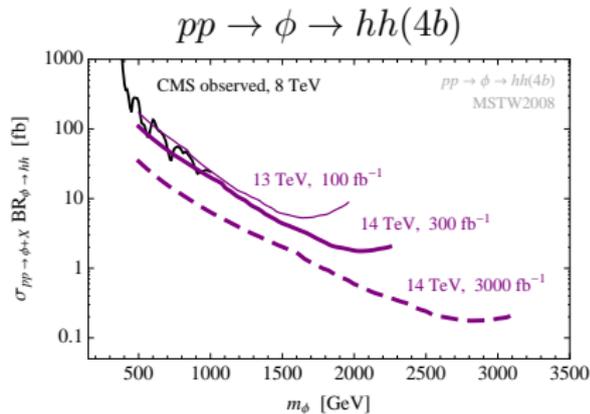
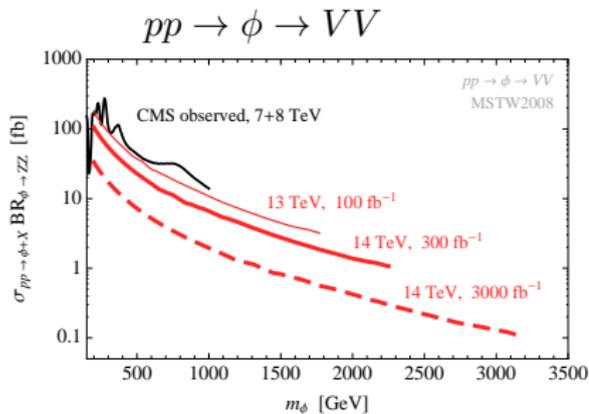
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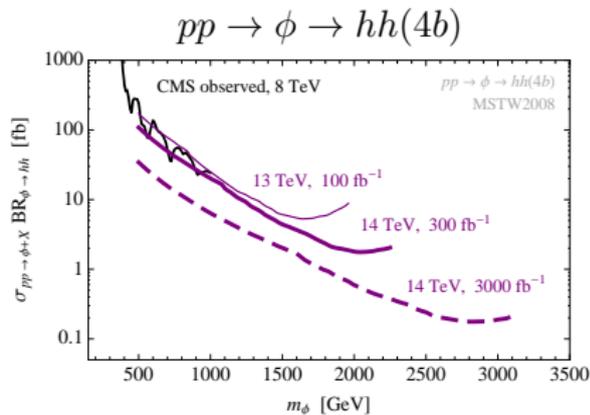
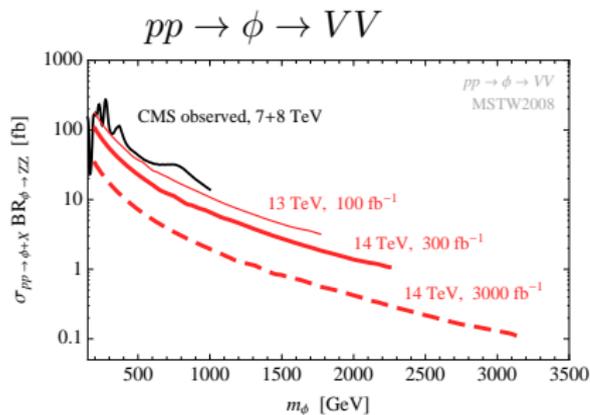
Use 8 TeV data and rescale them, driven by $B(s_0, L_0, m_0) = B(s, L, m)$



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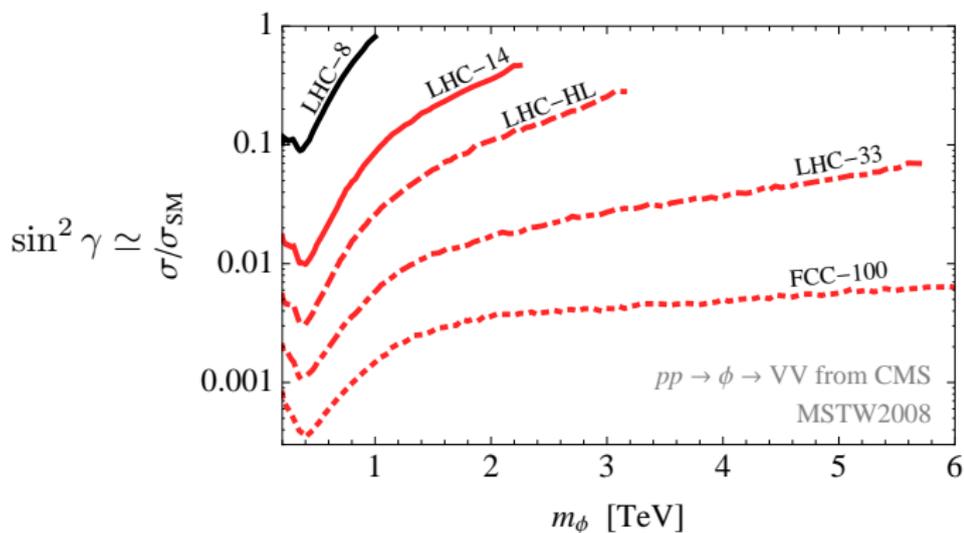
Rescaling is subject to a number of assumptions, satisfied in these cases

[Salam, Weiler; Thamm, Torre, Wulzer]

[we have plots also for 33 and 100 TeV (see later)]

Who dominate?

We can now compare direct and indirect searches

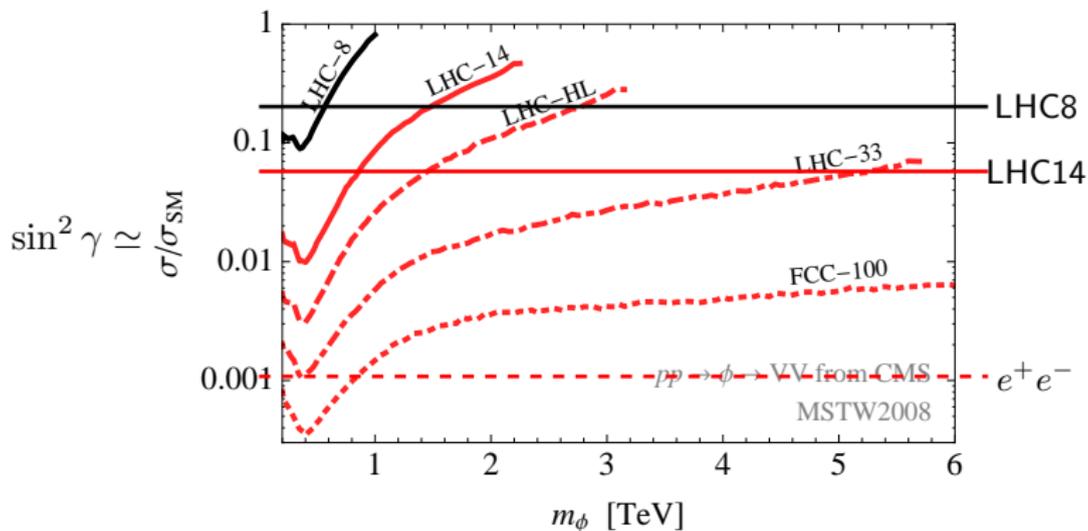


Direct searches dominate at low masses
(at each phase of the experimental program)

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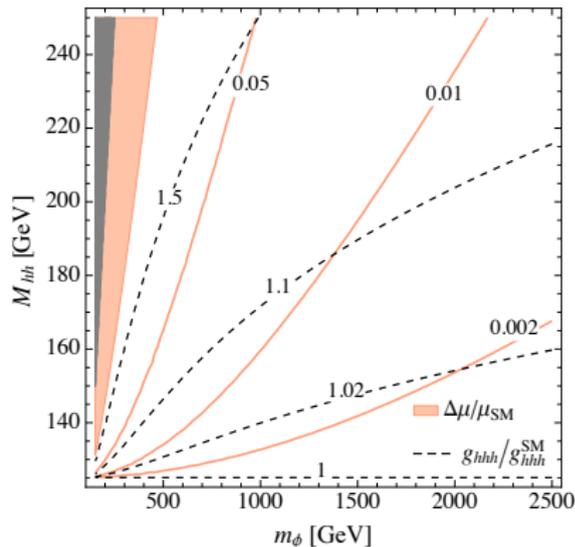
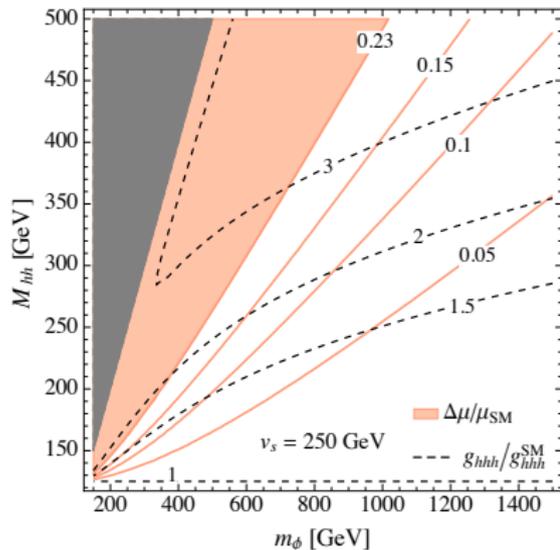
Models

A few possibilities

- Generic singlet
- Scalar singlet in the NMSSM
- Scalar singlet in the (weakly-coupled) Twin Higgs

Generic Singlet

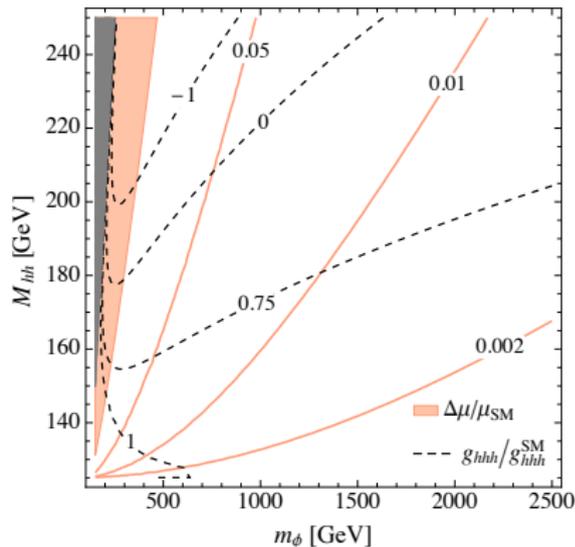
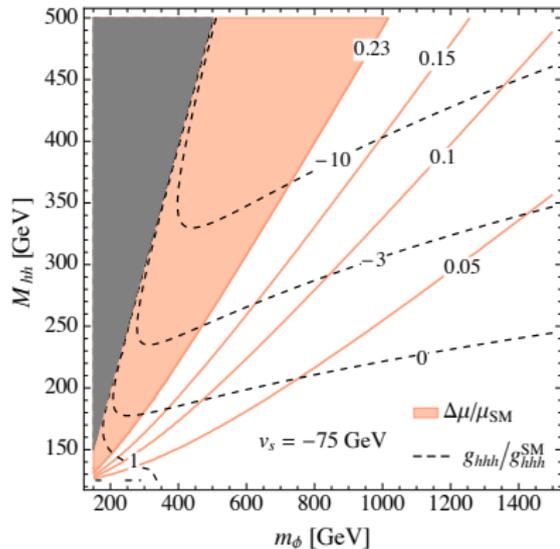
Higgs couplings and trilinear



Triple Higgs coupling is sensitive to v_s (and to quartic couplings)

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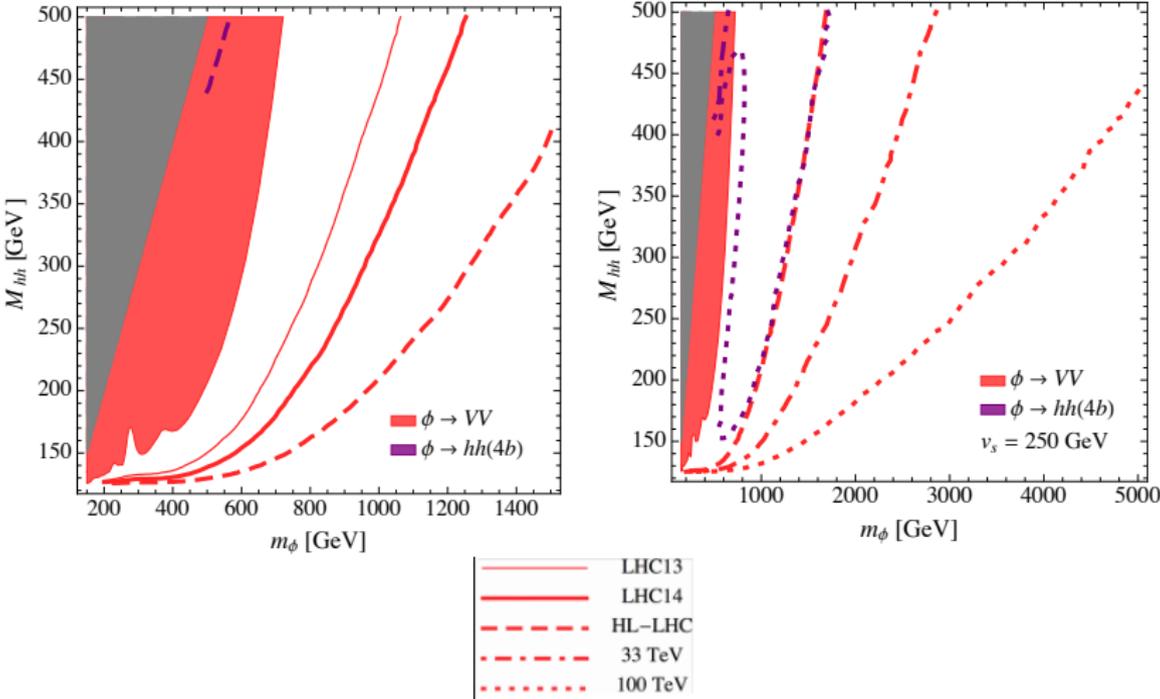
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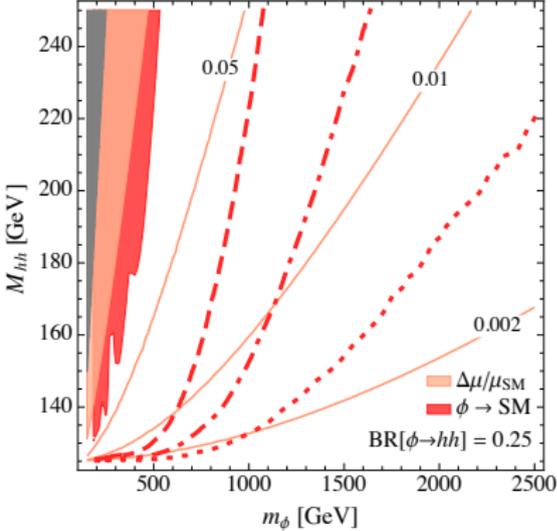
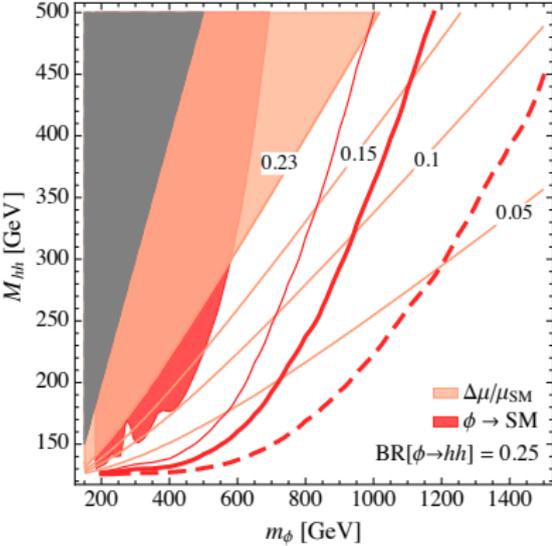
Impact of direct searches



$\phi \rightarrow VV$ usually dominant

Generic Singlet

All constraints together



- LHC13
- LHC14
- - - HL-LHC
- - - 33 TeV
- ⋯ 100 TeV

Strong complementarity between direct and indirect

NMSSM

$$\mathcal{W}_{\text{NMSSM}} \supset \lambda S H_u H_d + f(S) \rightarrow \lambda^2 |H_u H_d|^2$$

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$$m_h^2 \simeq \lambda^2 v^2 \sin^2(2\beta) + m_Z^2 c_{2\beta}^2 + \Delta^2$$

- ElectroWeak scale less-sensitive to soft masses

$$v^2 \sim \frac{\tilde{m}^2}{\lambda^2} \quad \tilde{m} \sim \frac{2\lambda}{g} \tilde{m}_{\text{MSSM}}$$

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$\lambda \lesssim 1$ complies with the above issues...

... and minimizes the tuning (for moderate $\tan\beta$) [\[Gherghetta et al\]](#)

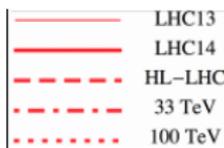
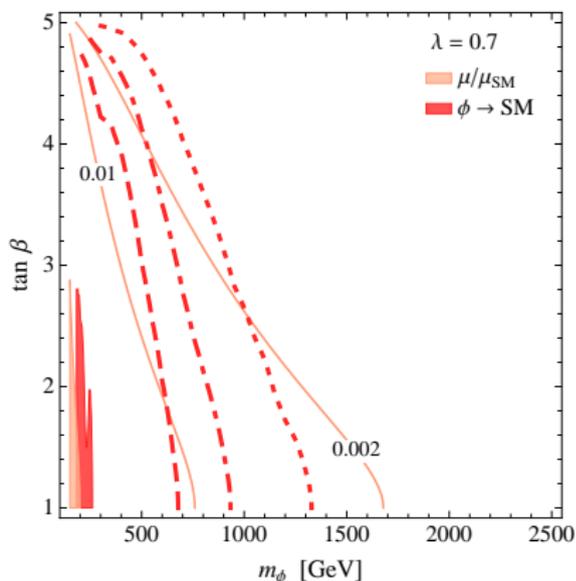
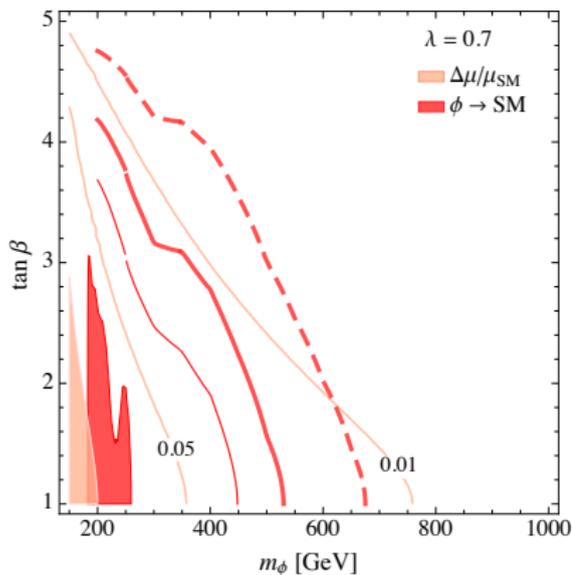
NMSSM

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$$M_{hh}^2 = m_Z^2 \cos^2(2\beta) + \lambda^2 v^2 \sin^2(2\beta) + \Delta^2$$

$$\lambda = 0.7$$

$$\Delta = 80 \text{ GeV}$$



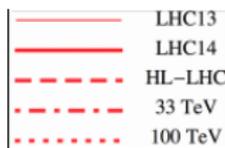
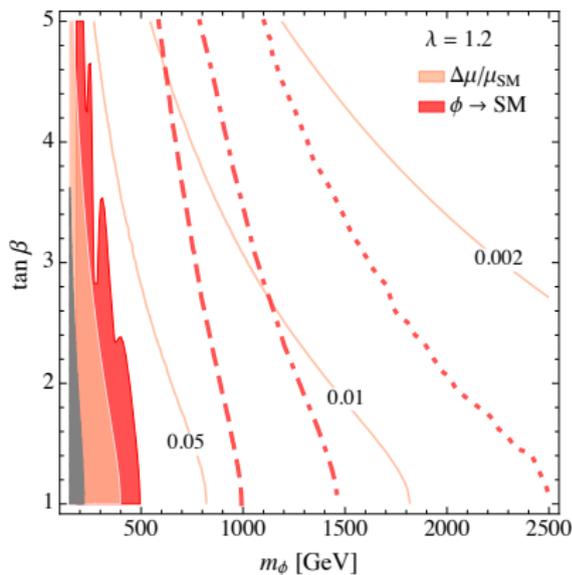
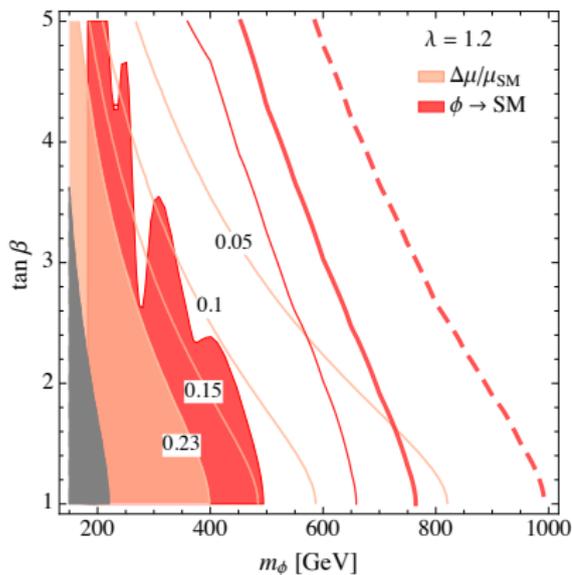
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$$\lambda = 1.2$$

$$\Delta = 70 \text{ GeV}$$



Twin Higgs [Chacko, Goh, Harnik '04]

[Craig's talk and more in the parallel session this afternoon: Curtin, Telem, Salvioni]

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7 GBs - 3 W - 3W = 1 pGB Higgs [+ σ , radial mode **singlet!**]

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The size of λ_* distinguishes between two UV regimes

If $\lambda_* \sim O(1)$

radial mode close to f

look for the singlet!

w/ Dario Buttazzo and Filippo Sala

If $\lambda_* \sim O(16\pi^2)$

radial mode decoupled

Composite Twin Higgs

w/ Matthew Low and Liantao Wang

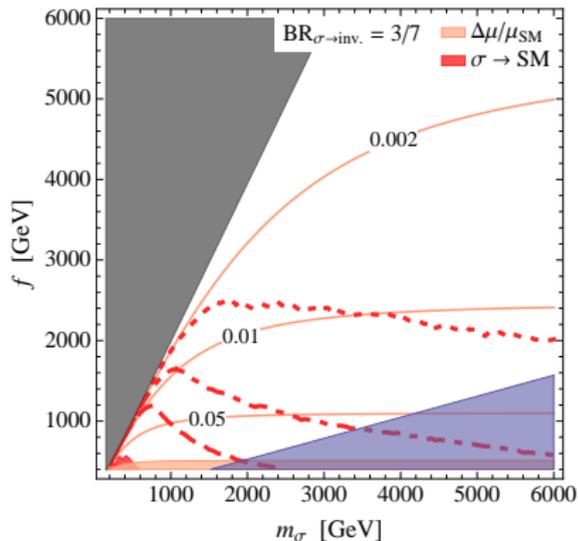
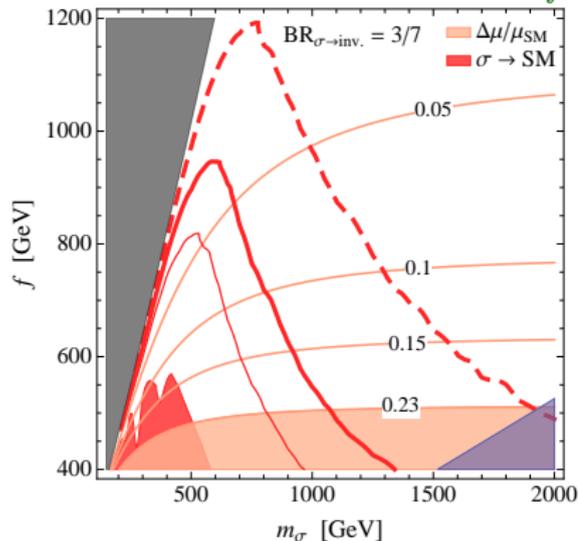
[Geller, Telem; Barbieri, Greco, Rattazzi, Wulzer]

Look for the twin Higgs!

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

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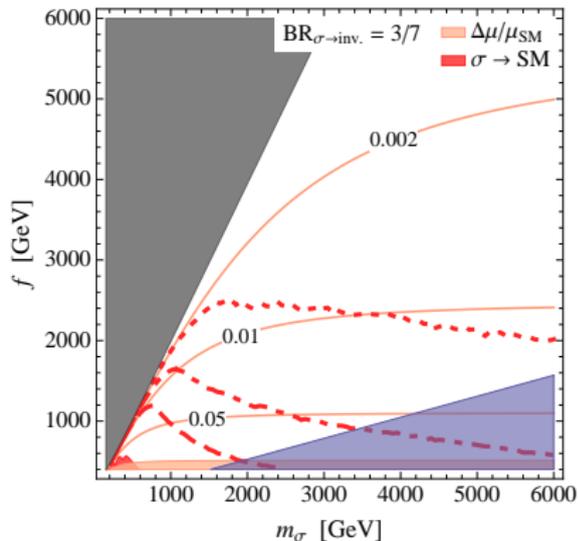
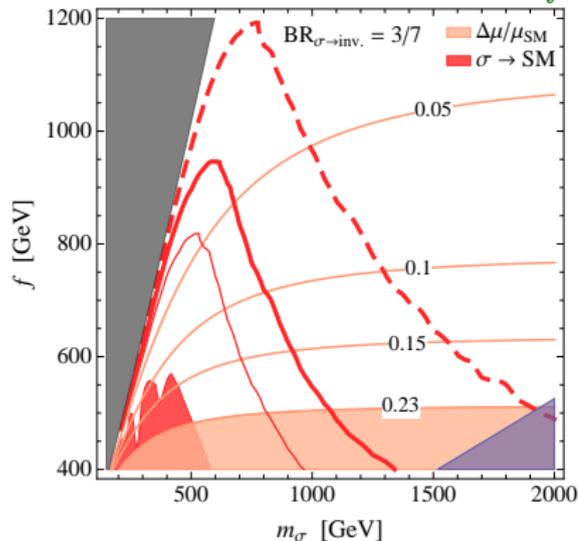


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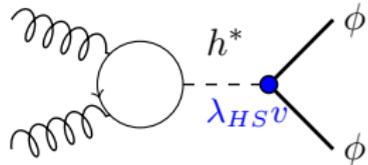
If Twin Higgs is weakly coupled, the twin Higgs (singlet) could be visible!

Double Singlet production*

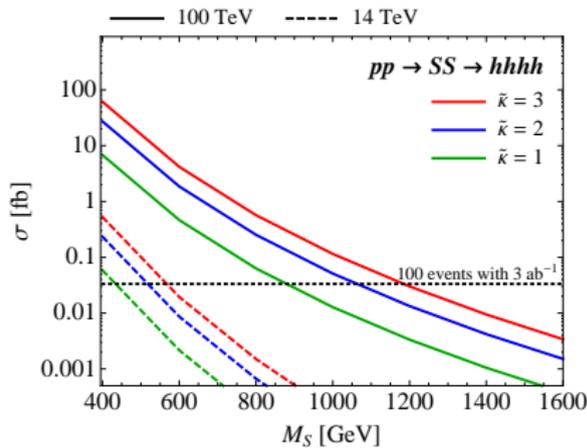
*[aka singlets after a Higgs factory]

Falling like a rock

Pair production drops for $m_\phi > m_t$

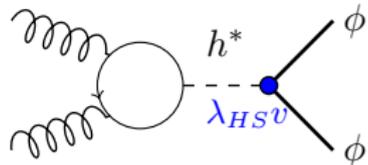


$$\hat{\sigma}_{gg \rightarrow \phi\phi} \simeq \frac{1}{256\pi^3} \frac{m_t^2}{\hat{s}^3} \lambda_{HS}^2 v^2$$

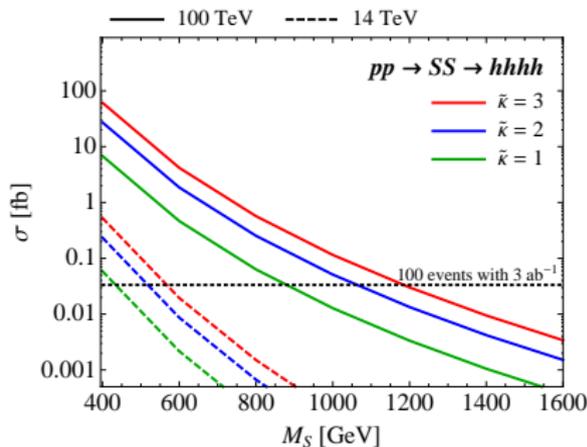


Falling like a rock

Pair production drops for $m_\phi > m_t$



$$\hat{\sigma}_{gg \rightarrow \phi\phi} \simeq \frac{1}{256\pi^3} \frac{m_t^2}{\hat{s}^3} \lambda_{HS}^2 v^2$$



Challenging, but mandatory after the bound from e^+e^- on $\sin^2 \gamma \leq 0.1\%$

Chances for $\phi\phi \rightarrow 4W, 4h$ (many b 's)

Conclusions

Looking for singlets is easy
and it is motivated by many (natural) models

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Thank you!