Higgs measurements and searches as a portal to new physics

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based on work in collaboration with F. Sala and A. Tesi

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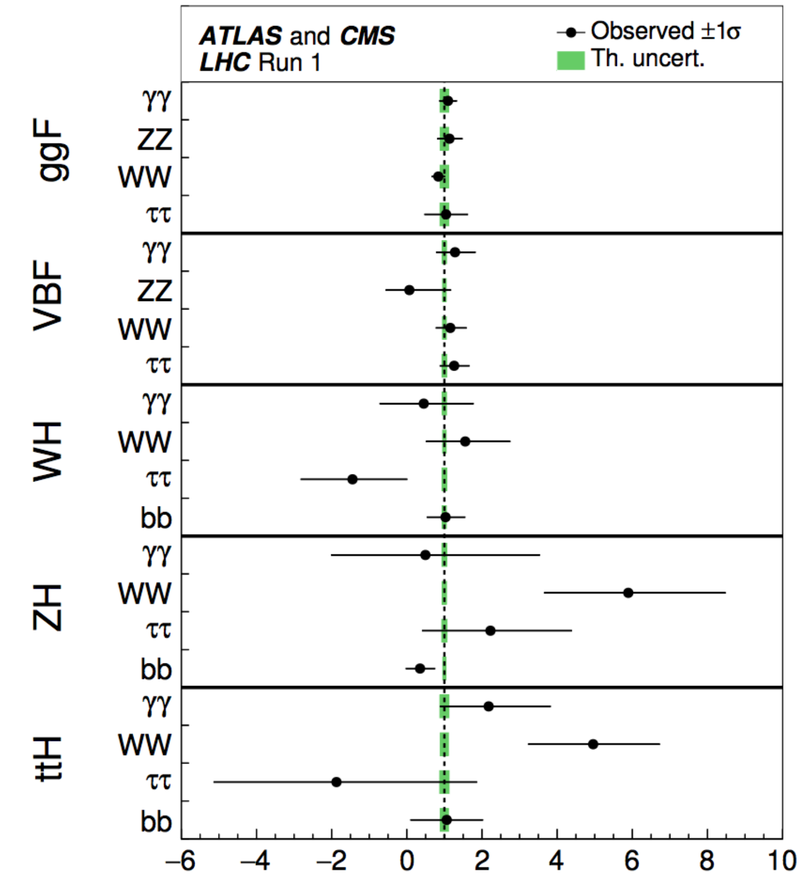
Higgs properties

- Higgs couplings currently measured with ~ 10% precision
- HL-LHC will be able to reach a precision of a few %
- differential measurements start to be possible, more than just Higgs signal strenghts…



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- ‣ What are the implications for motivated models of new physics?
- ‣ How do direct searches compare with these results?

➡ see talks by E. Vryonidou, V. Sanz, L. Silvestrini + ATLAS, CMS

Composite Higgs: a typical example

- Strong coupled physics generates operators of higher dimension that modify Higgs interactions

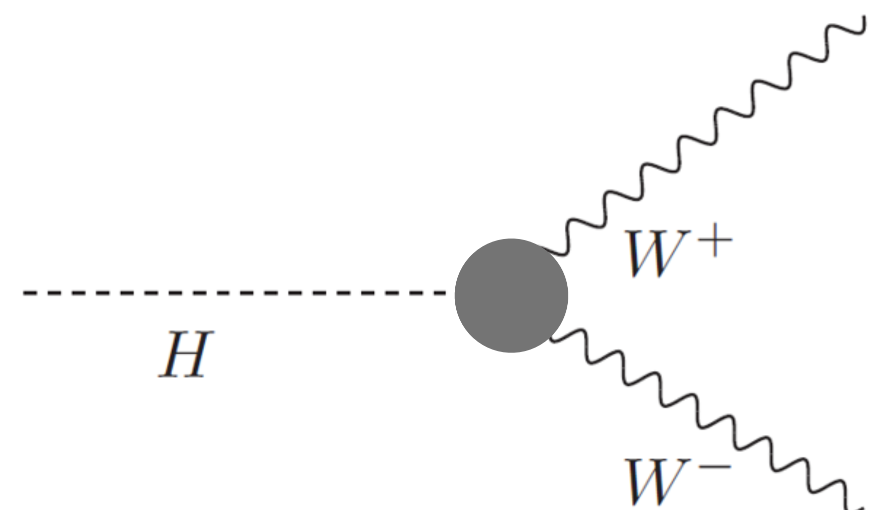
$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \cdots$$

(see talk by L. Silvestrini)

- **Model-independent predictions**, from symmetry arguments:

  symmetry that controls the size of coefficients c_i, broken at a scale f, Higgs is a (pseudo) Goldstone

coupling to vectors $\quad \kappa_V \sim \sqrt{1 - \frac{v^2}{f^2}}$



(coupling to fermions more model-dependent)

- In general, $\delta g_{hXX} \sim v^2/f^2 \sim 1/\Delta_{\text{f.t.}}$

direct connection with tuning of the EW scale

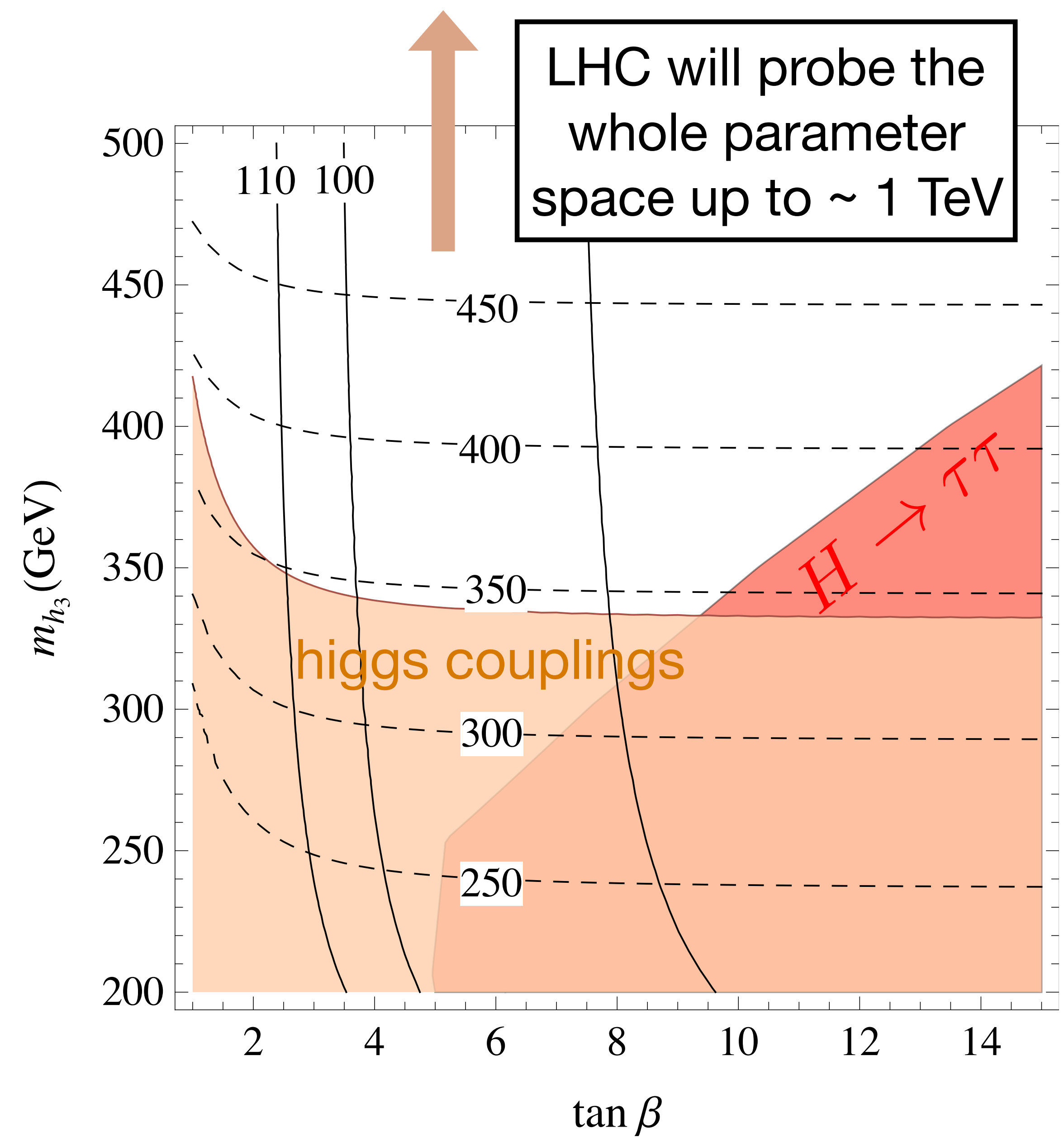
Extended Higgs sectors

Higgs couplings can be modified at tree-level, from mixing with another state

mass eigenstates:
$$h \sim H_1 \cos\theta + H_2 \sin\theta$$
$$\phi \sim -H_1 \sin\theta + H_2 \cos\theta$$

$$g_{hXX} \sim g_{H_1XX} \cos\theta + g_{H_2XX} \sin\theta$$

- **<u>Example:</u> the MSSM**
  (more in general, 2HDM)
  - A light state is excluded by the Higgs fit
  - Large tuning required by m_h = 125 GeV independent from coupling modification!



Less minimal SUSY

Add a scalar singlet: $\mathcal{W} = \mathcal{W}_{\rm MSSM} + \lambda S H_u H_d + f(S)$

- Extra tree-level contribution to the Higgs mass

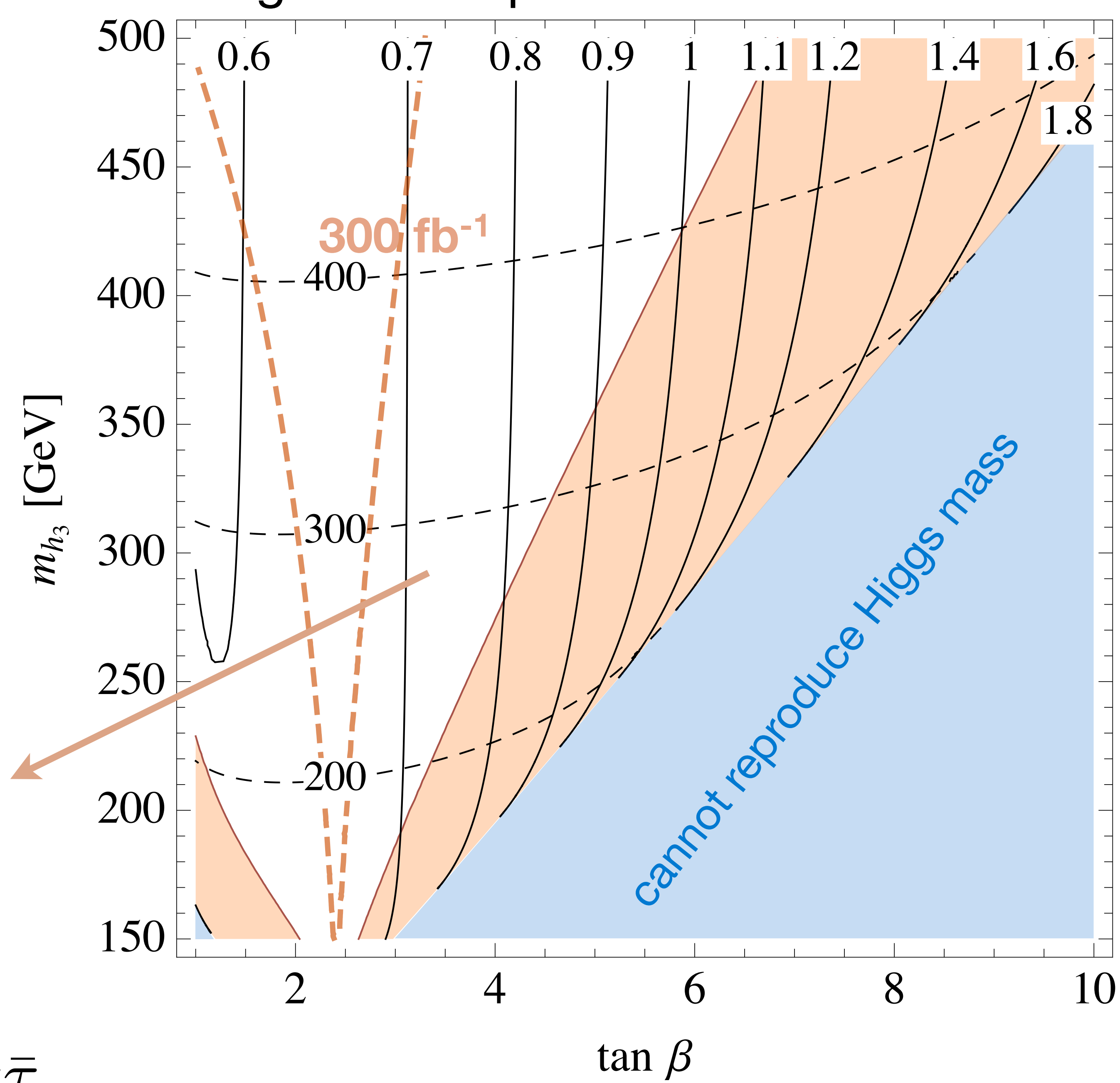
$$M_{hh}^2 = m_Z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2 + \Delta^2$$

loop correction from top-stop

- Alleviates fine-tuning in v for $\lambda > 1$ and moderate tan β

Mixing with doublet, singlet decoupled: Higgs couplings will cover most of the parameter space

singlet decoupled



Coupling to fermions: $H \to t\bar{t}, b\bar{b}, \tau\bar{\tau}$

Less minimal SUSY

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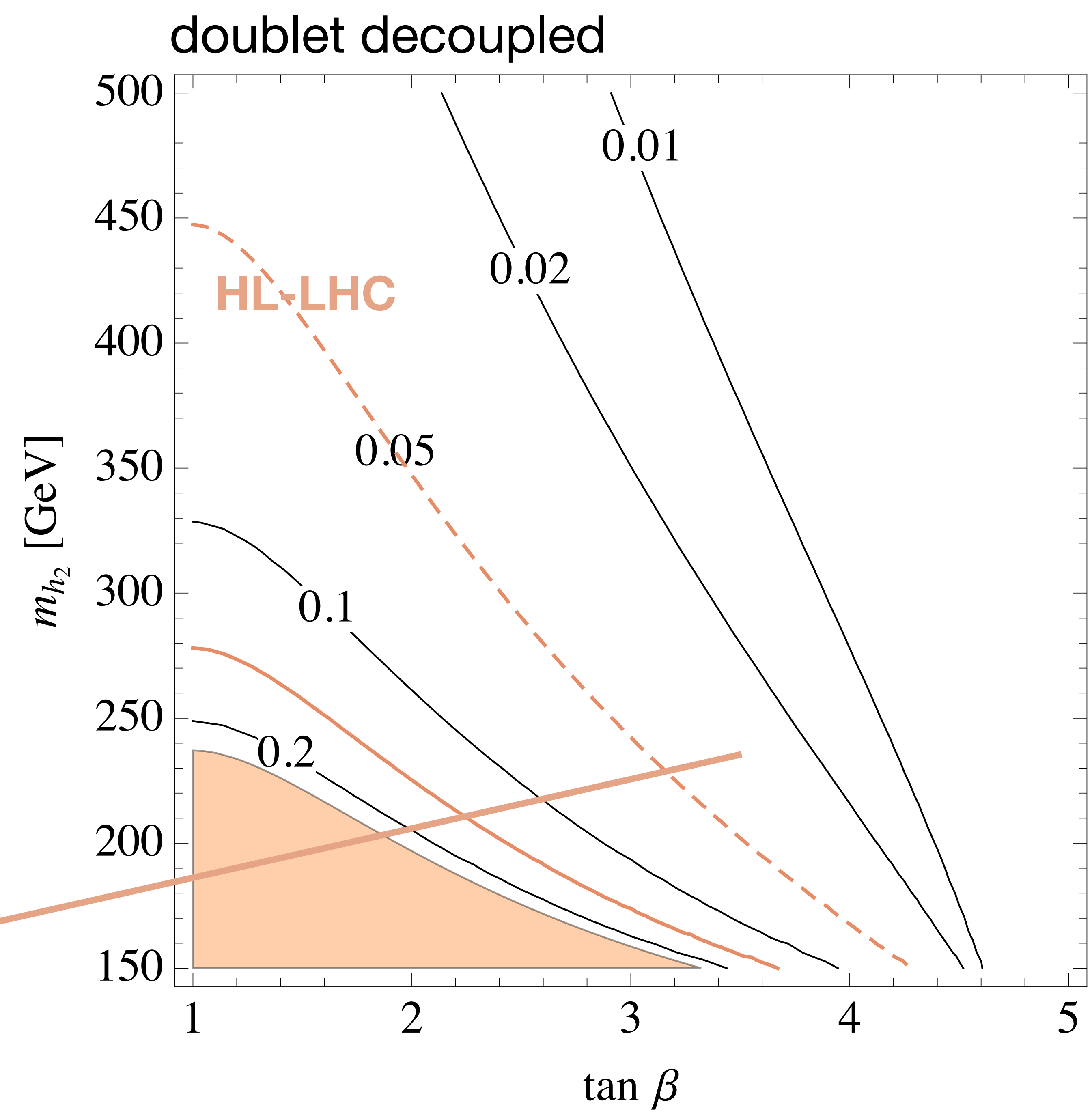
loop correction
to Higgs mass
from top-stop

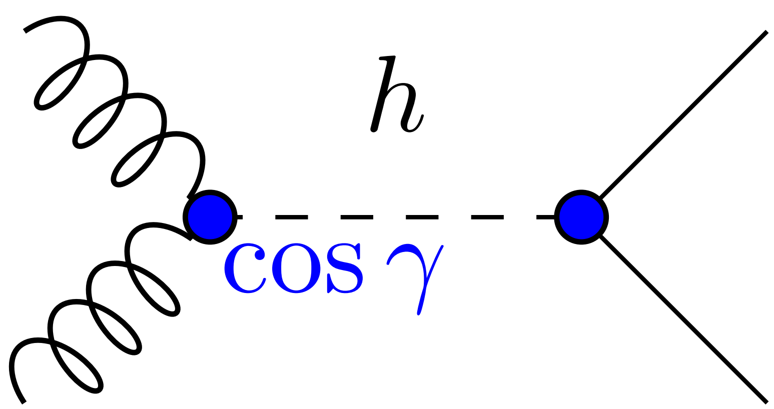
- Alleviates fine-tuning in v for $\lambda > 1$ and moderate tan β



Mixing with singlet:
Higgs couplings less effective

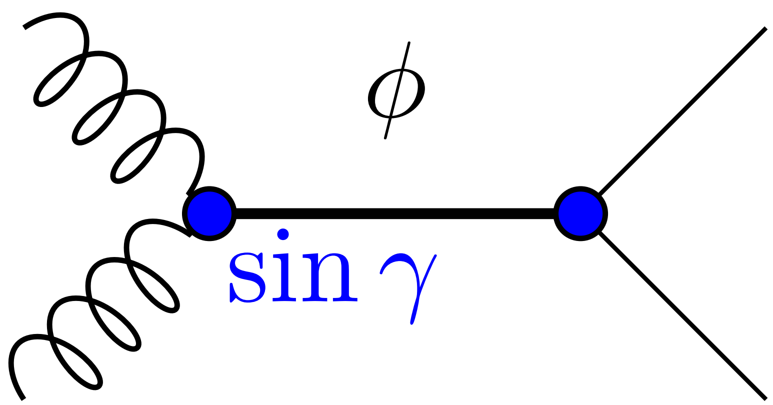
Two complementary ways to look for the extra Higgs:

Higgs signal strengths



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

Direct searches



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

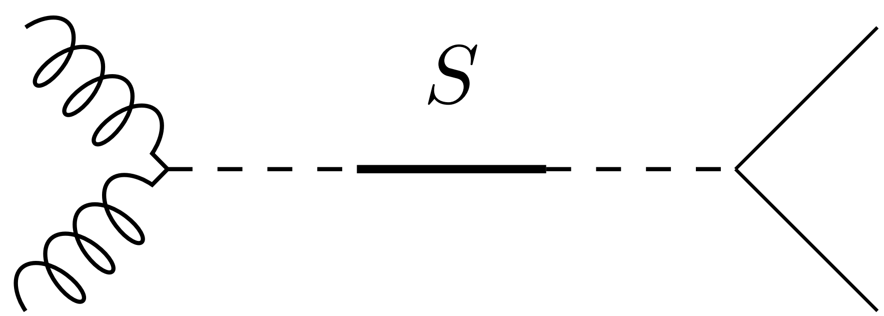
➡ Direct reach of LHC vs Higgs measurements?

A simple reference case

At the risk of being trivial… Take just the SM + scalar singlet

- Realised in the NMSSM
- Low energy effective theory of Twin Higgs models
- Paradigm for 1st order ElectroWeak phase transition
- "Higgs portal", DM, …

$\lambda |H|^2 S$ →



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

✓ easy enough to test capabilities of LHC and future colliders with just a few meaningful parameters

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

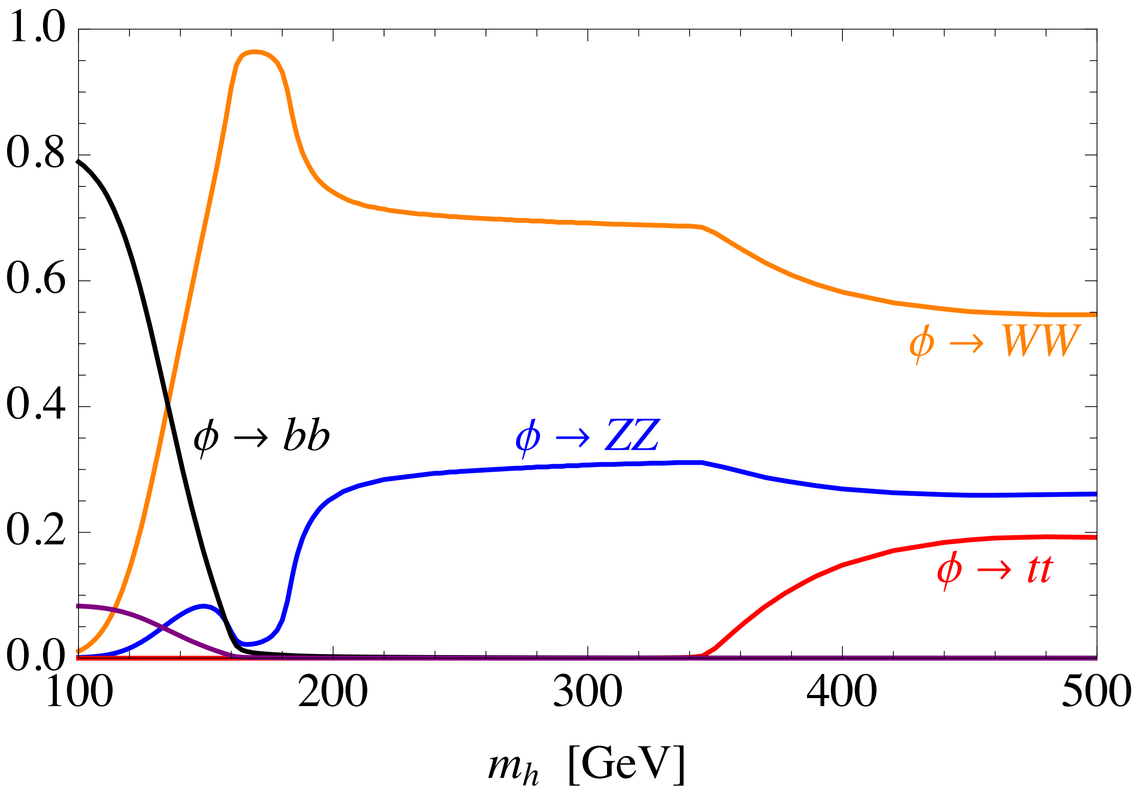
At high mass the equivalence theorem relates the decay widths

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

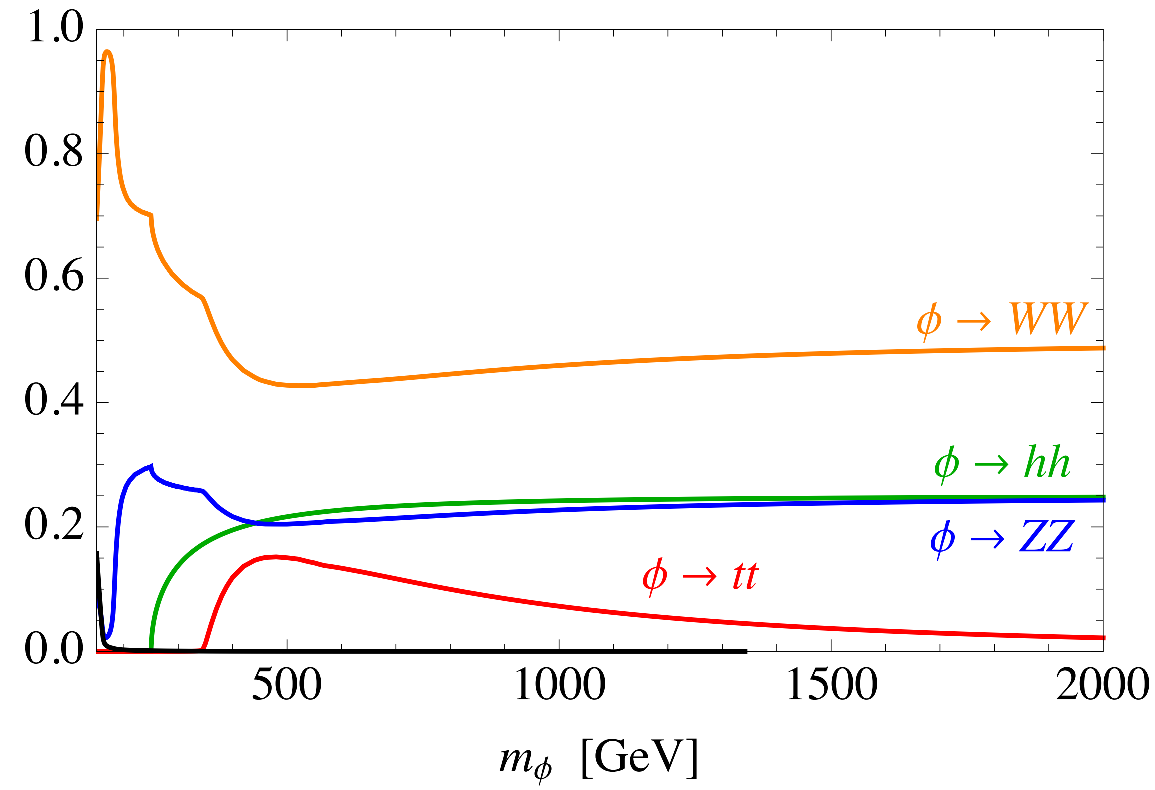
(these are the dominant channels, fermionic modes suppressed)

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

h branching ratios



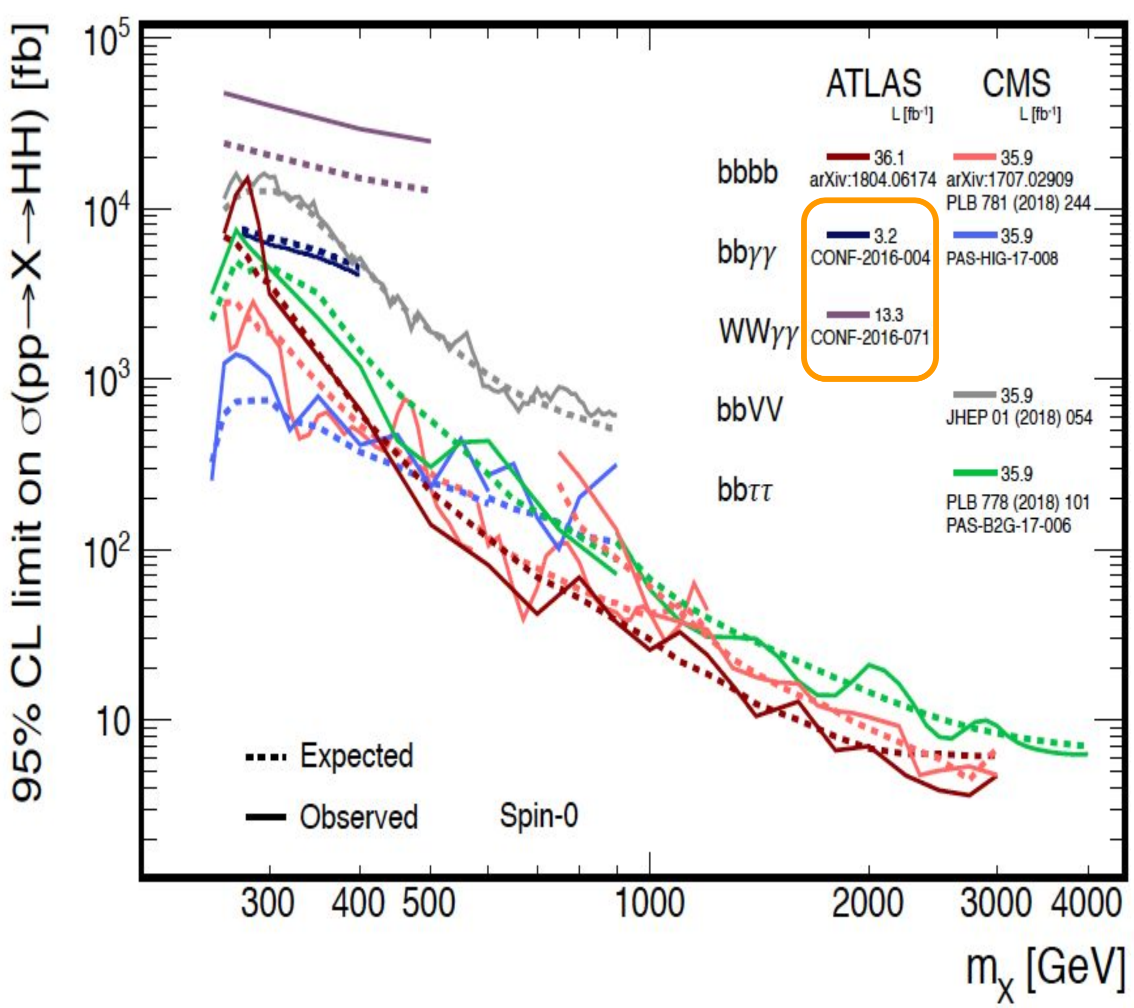
ϕ branching ratios

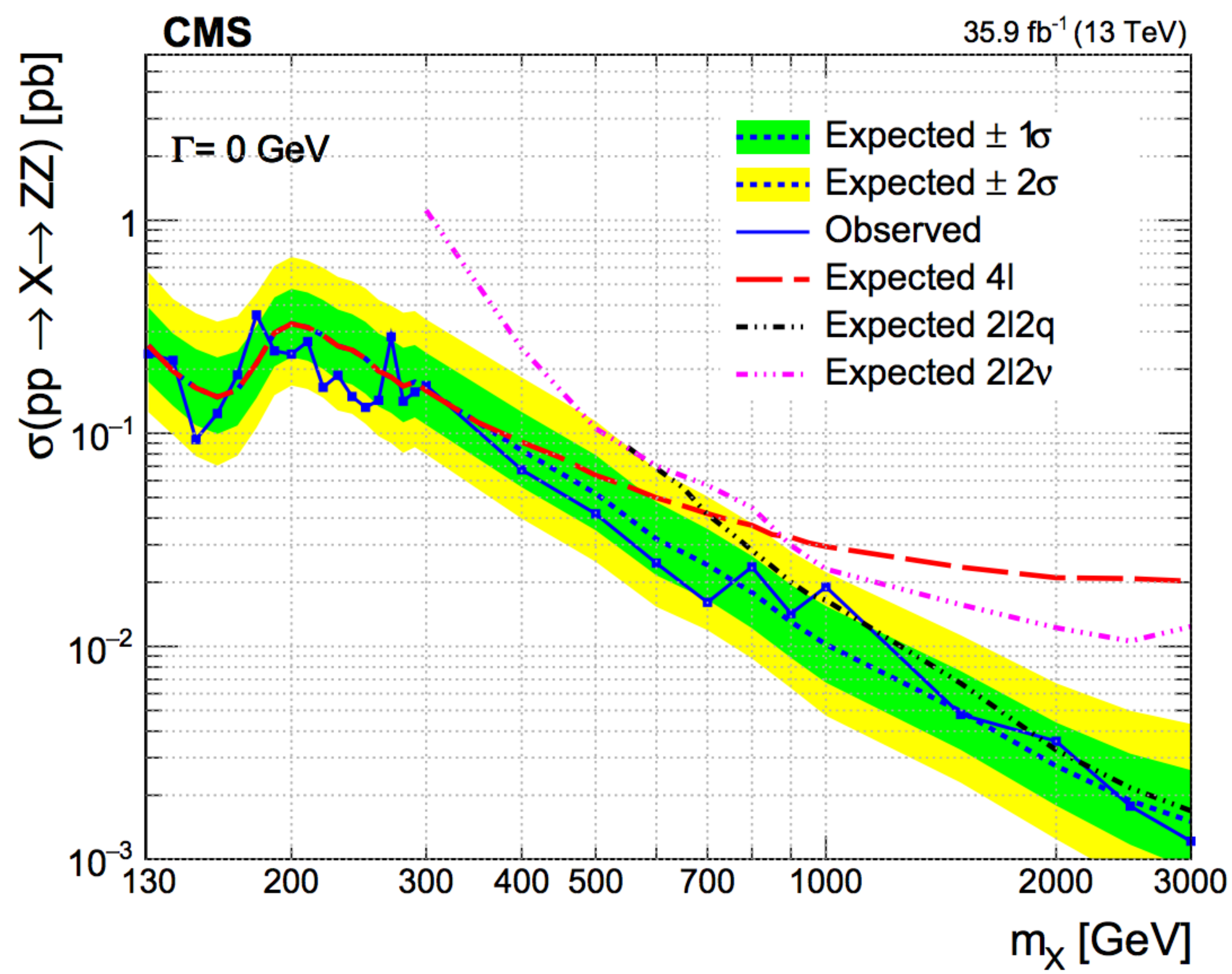


ϕ is like a heavy SM Higgs + $\mathrm{BR}_{\phi\to hh}$

Direct searches

- Searches in diboson final states (WW, ZZ, hh) at ATLAS and CMS, in many different channels
- Already more sensitive than Higgs couplings at low masses!





(see talk by M. D'Alfonso)

Projections for the future

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

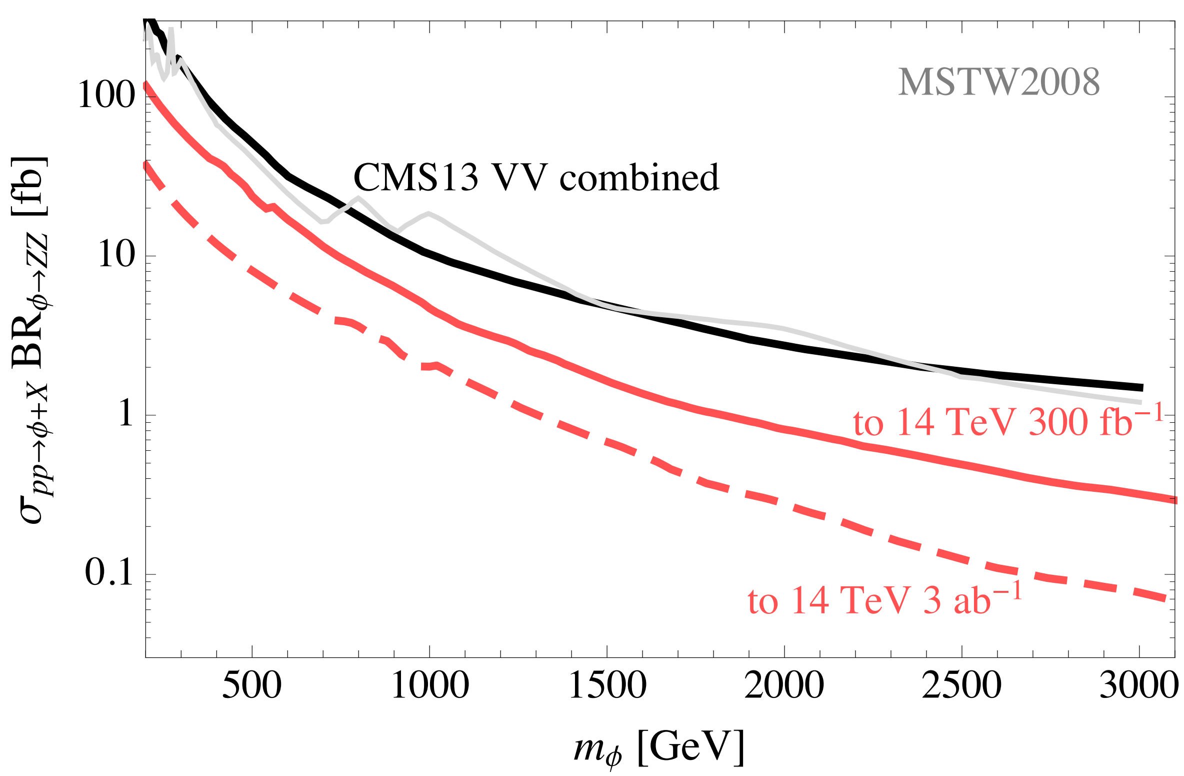
- Rescale 8 TeV LHC data with the parton luminosity of the bkg

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

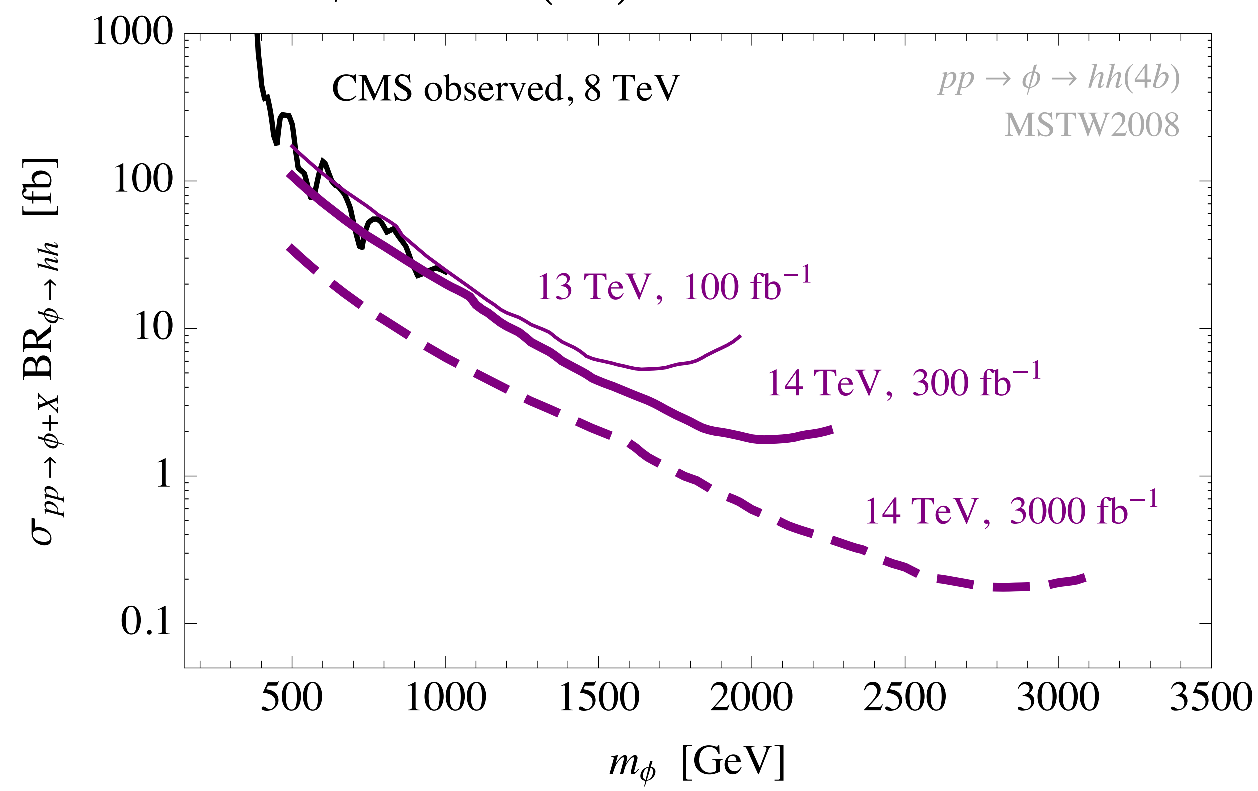
The limit on the cross-section is mainly determined by the number of background events around the resonance peak

B, Sala, Tesi '15

$\phi \to VV$ channel



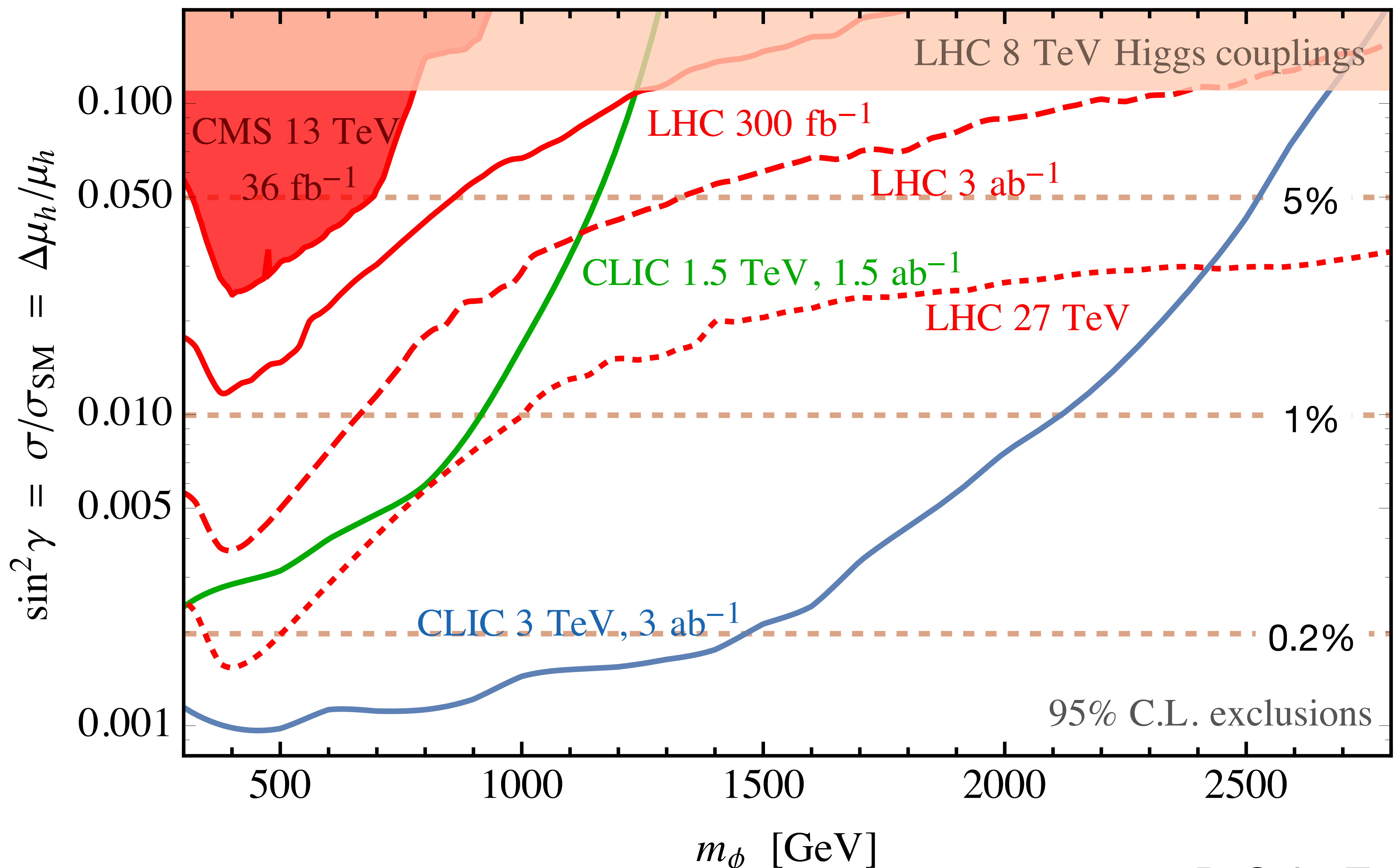
$\phi \to hh(4b)$ channel



These results are valid for any scalar resonance decaying to VV, hh

Direct vs indirect

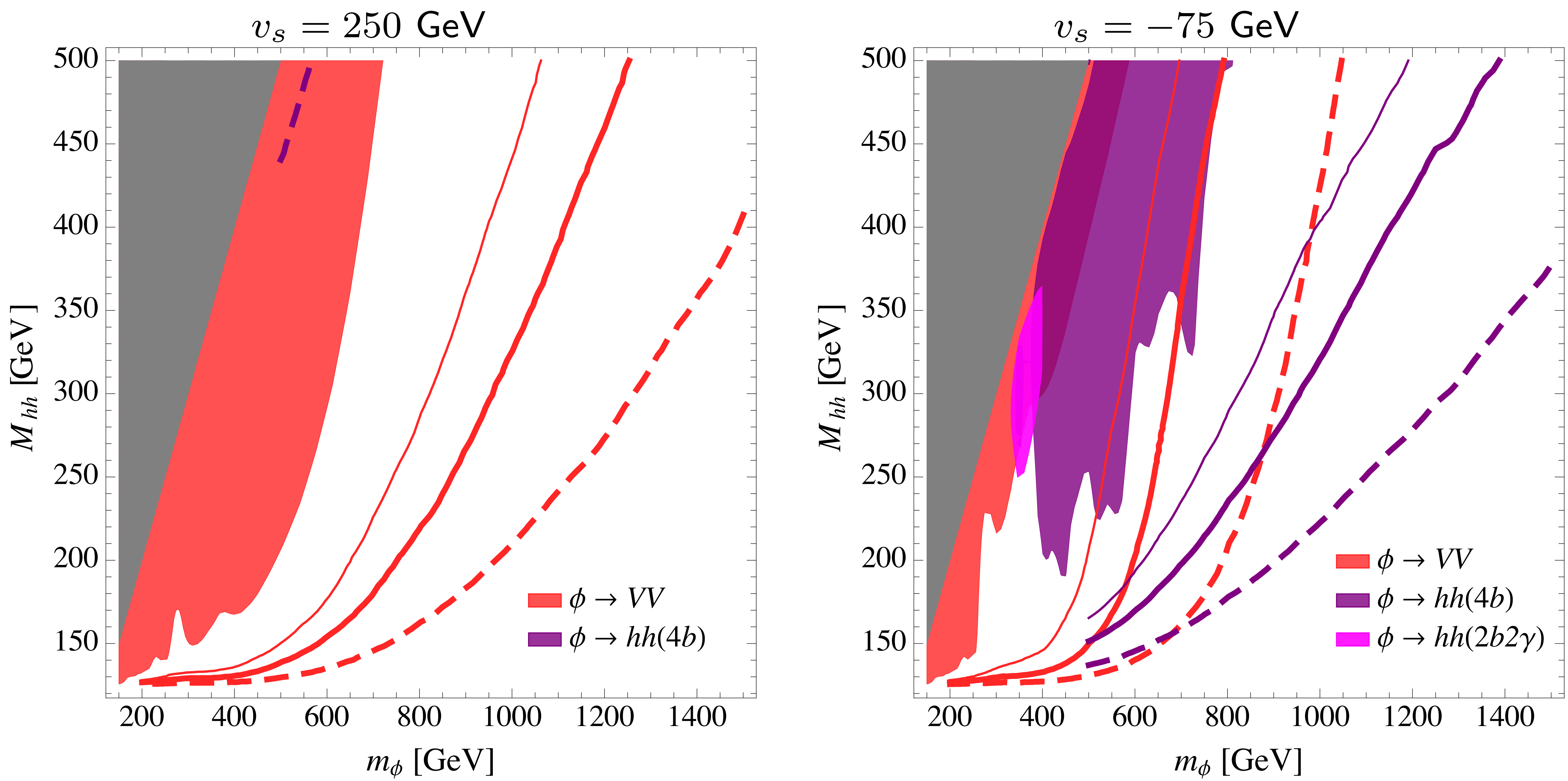
- Easy to compare the limits with indirect bounds from Higgs couplings



B, Sala, Tesi to appear

direct searches dominate at low mass (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 $\mathrm{BR}_{\phi\to hh}$

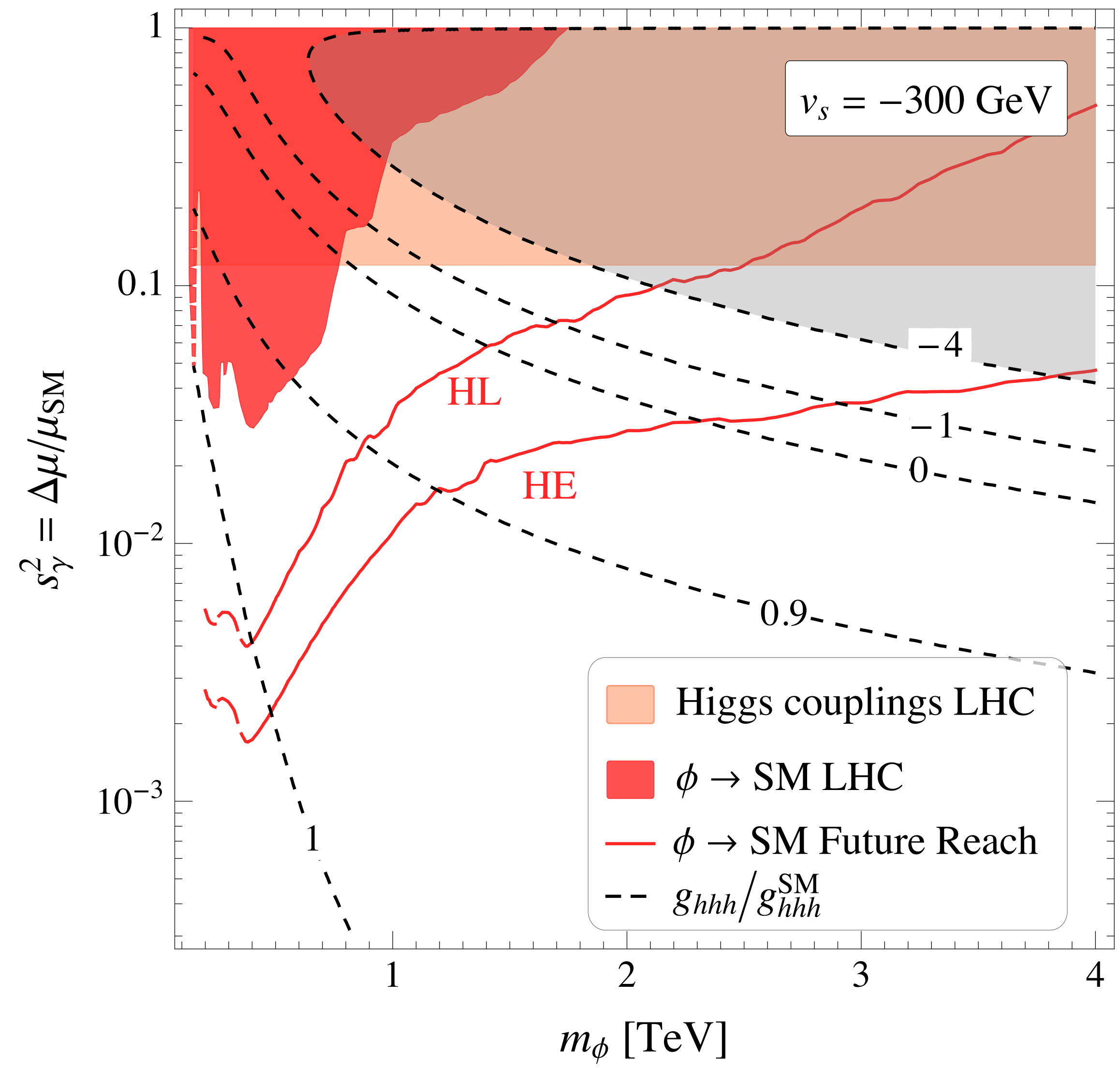
Double Higgs production

- The triple interactions *ϕhh* and *hhh* are sensitive to the parameters of the scalar potential

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

$$g_{hhh} \simeq g_{hhh}^{\mathrm{SM}}\left(1 + \frac{2}{3}\frac{v}{v_s}\sin\gamma\right) + \mathcal{O}(m_h^2/m_\phi^2)$$

both quantities mainly depend on v_s only (not on the quartic couplings)



➡ Very large modifications of triple Higgs coupling are possible: in principle observable even at LHC!

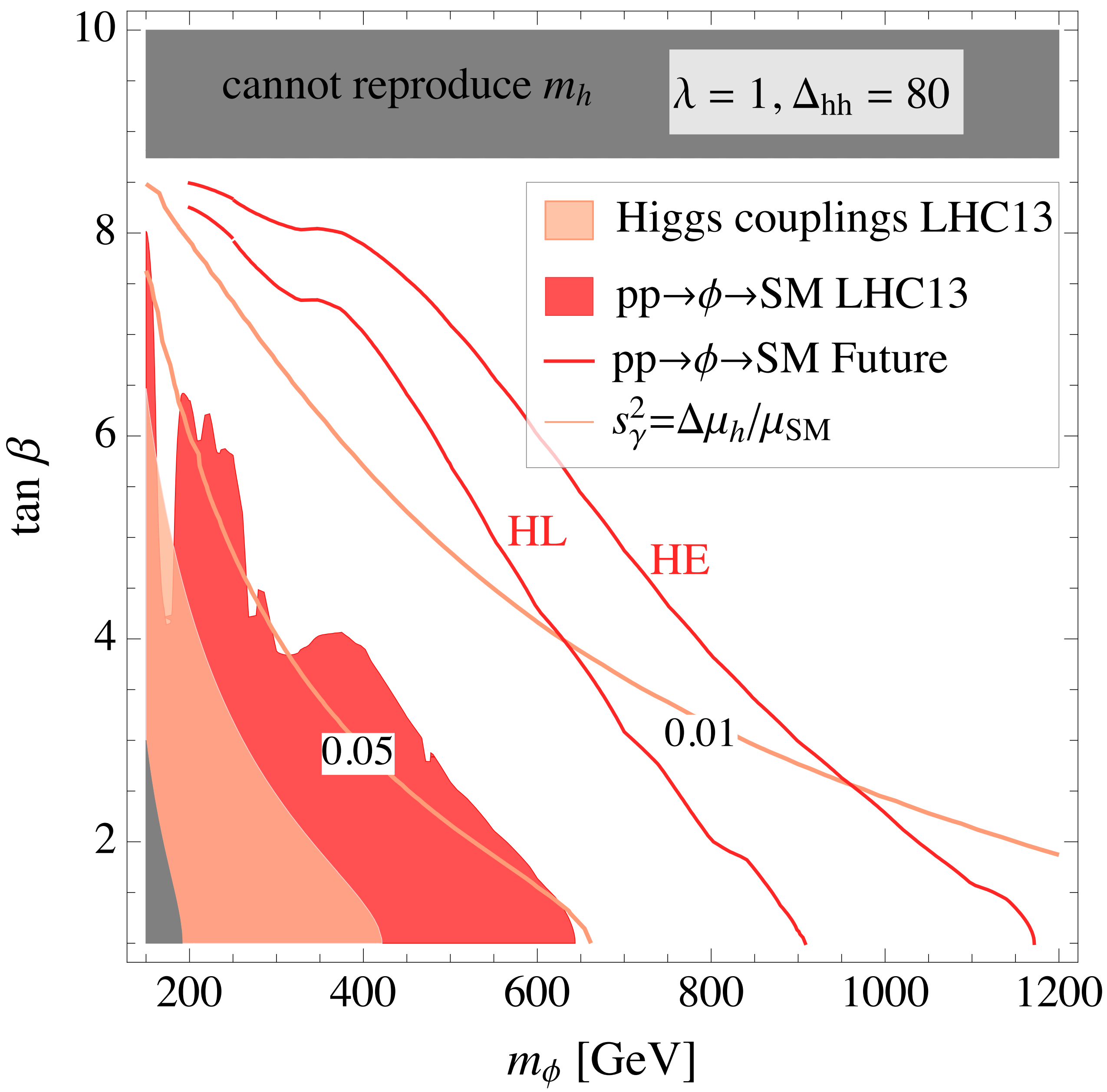
SUSY: the NMSSM

$\lambda S H_u H_d$

◇ Extra tree-level contribution to the Higgs mass

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

easy to recast the previous bounds



- Already now, searches for ϕ –> ZZ comparable with reach of HL-LHC in Higgs couplings
- Weakly coupled model, low masses: Direct searches always dominate

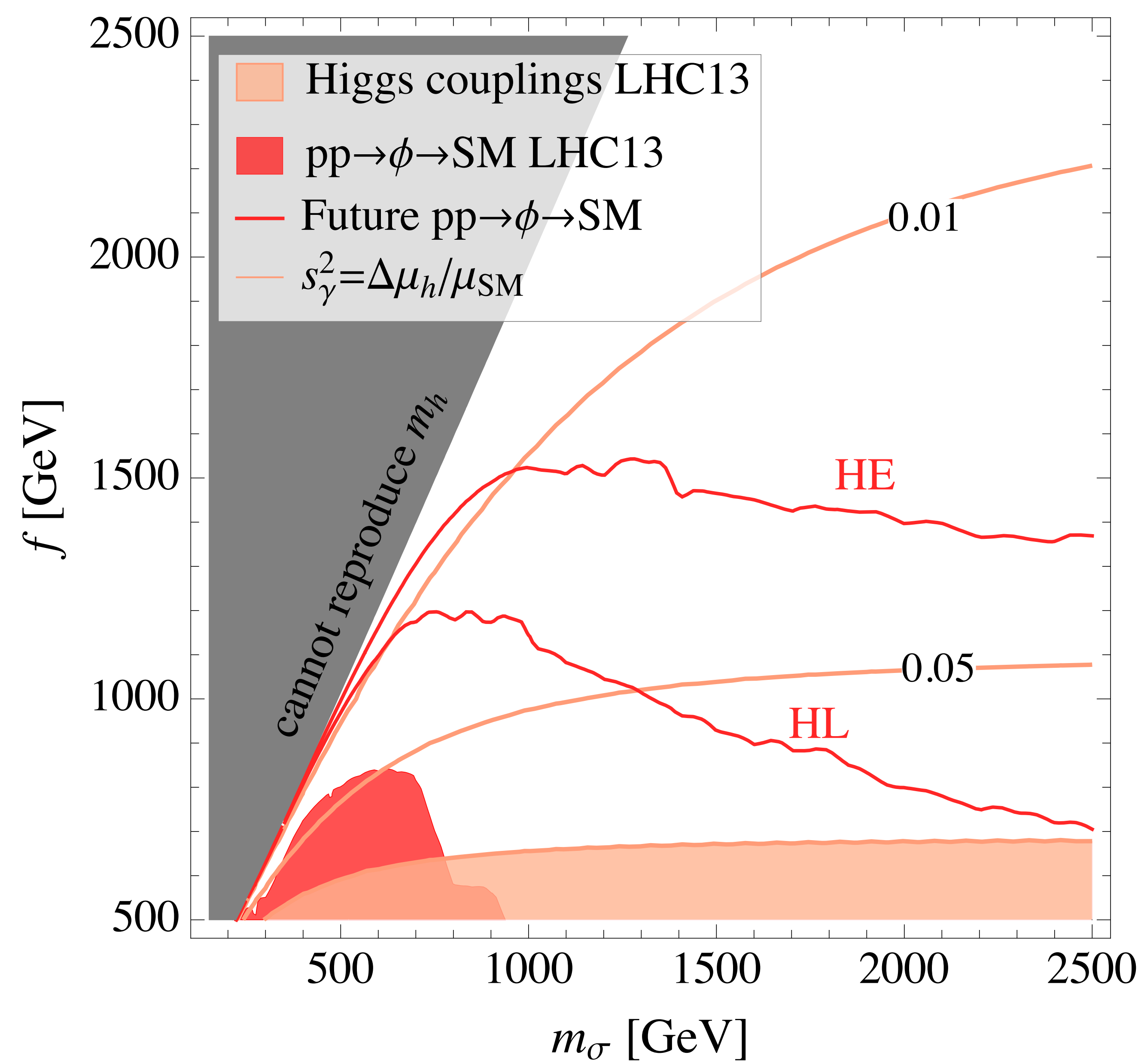
Twin/Composite Higgs

- Linear sigma-model $V = \lambda_*(\Phi^2 - f^2)^2 + m^2|H|^2 + \kappa|H|^4, \qquad \Phi = (H, S).$
- If not too strongly coupled, light singlet in the spectrum $m_\sigma \approx \lambda_* f$
- Describes a generic pNGB Higgs, symmetry breaking at the scale *f*

$$\sin^2\gamma \sim v^2/f^2$$

- **<u>Twin Higgs:</u>** natural without light colored states…
  effects only through Higgs portal

  If not too heavy (i.e. not too strongly coupled) the singlet can be directly visible



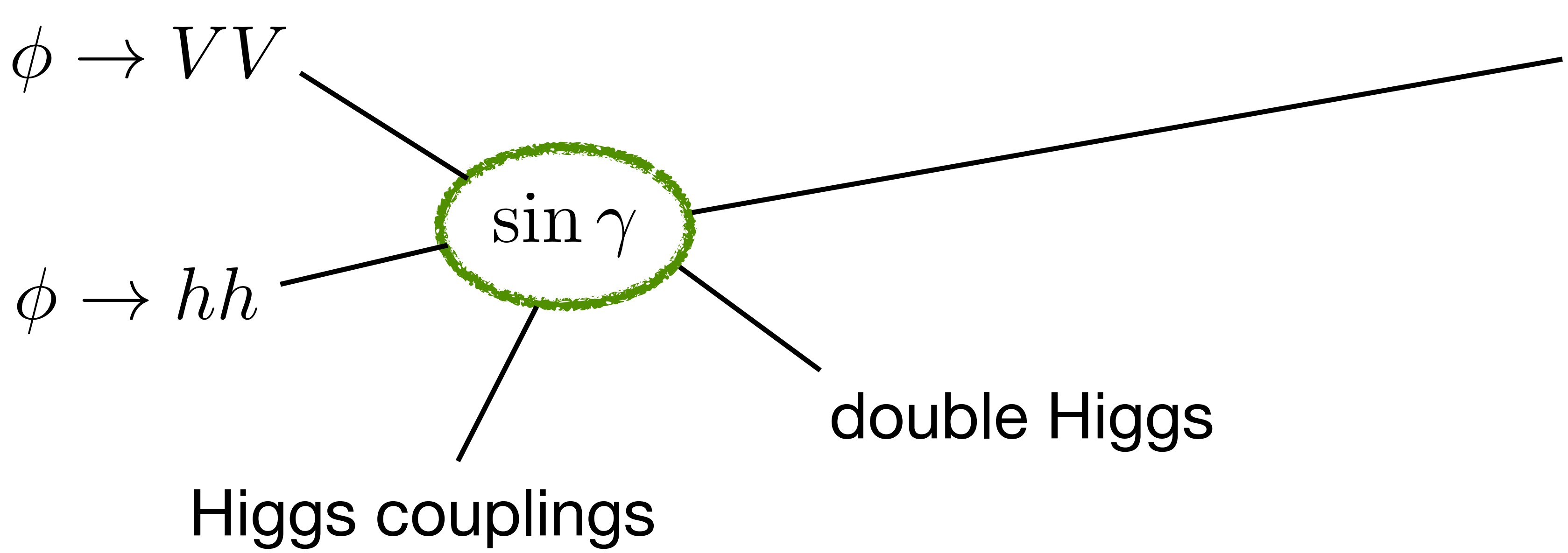
Conclusions & outlook

Higgs couplings
(moderate improvement at LHC)

Resonance searches
(very powerful at 'low' masses)

combine to fully probe NP models

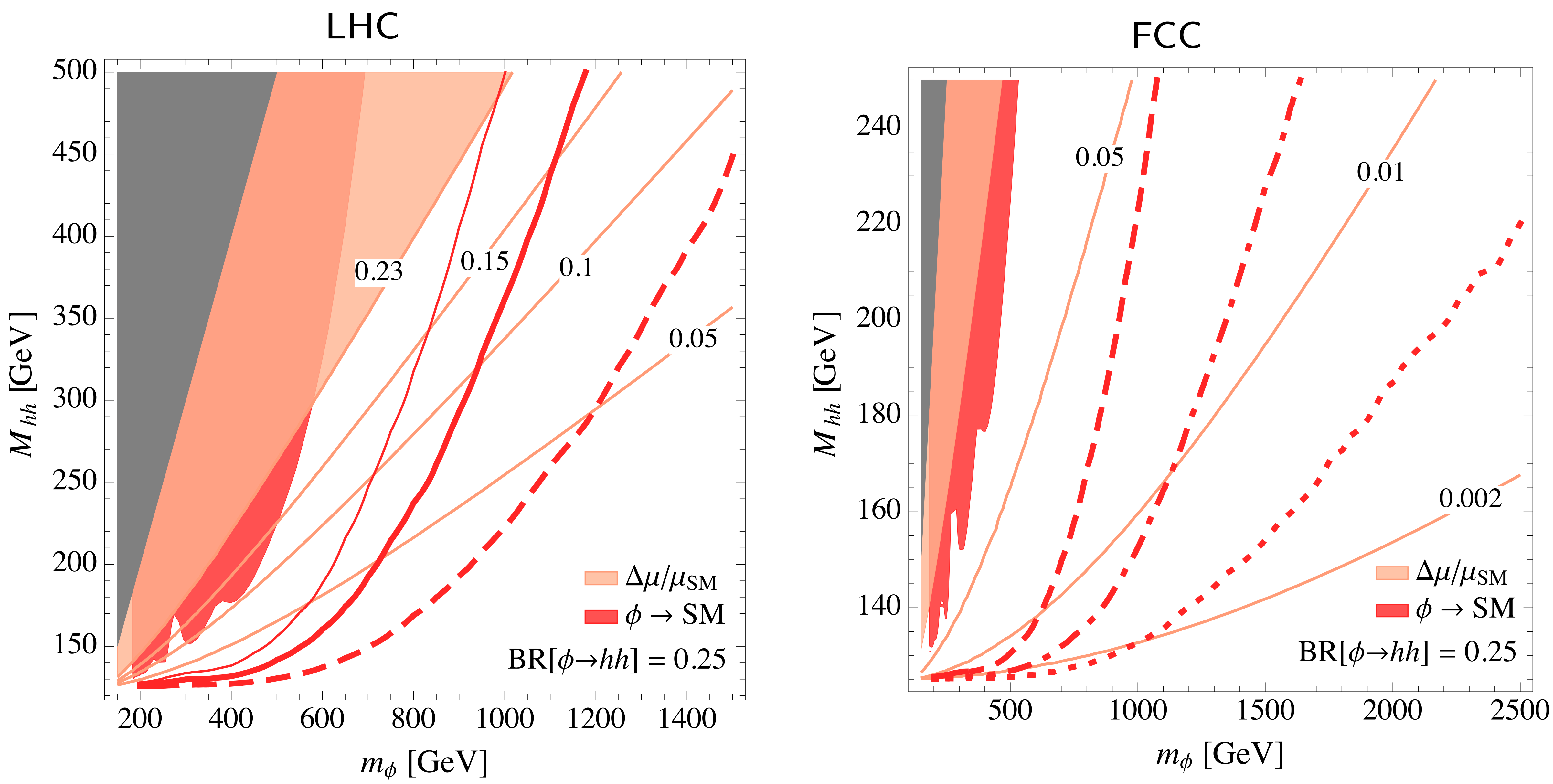
Scalar singlets: simple but interesting example



NMSSM
Twin Higgs
Composite Higgs
Higgs portal
EW baryogenesis

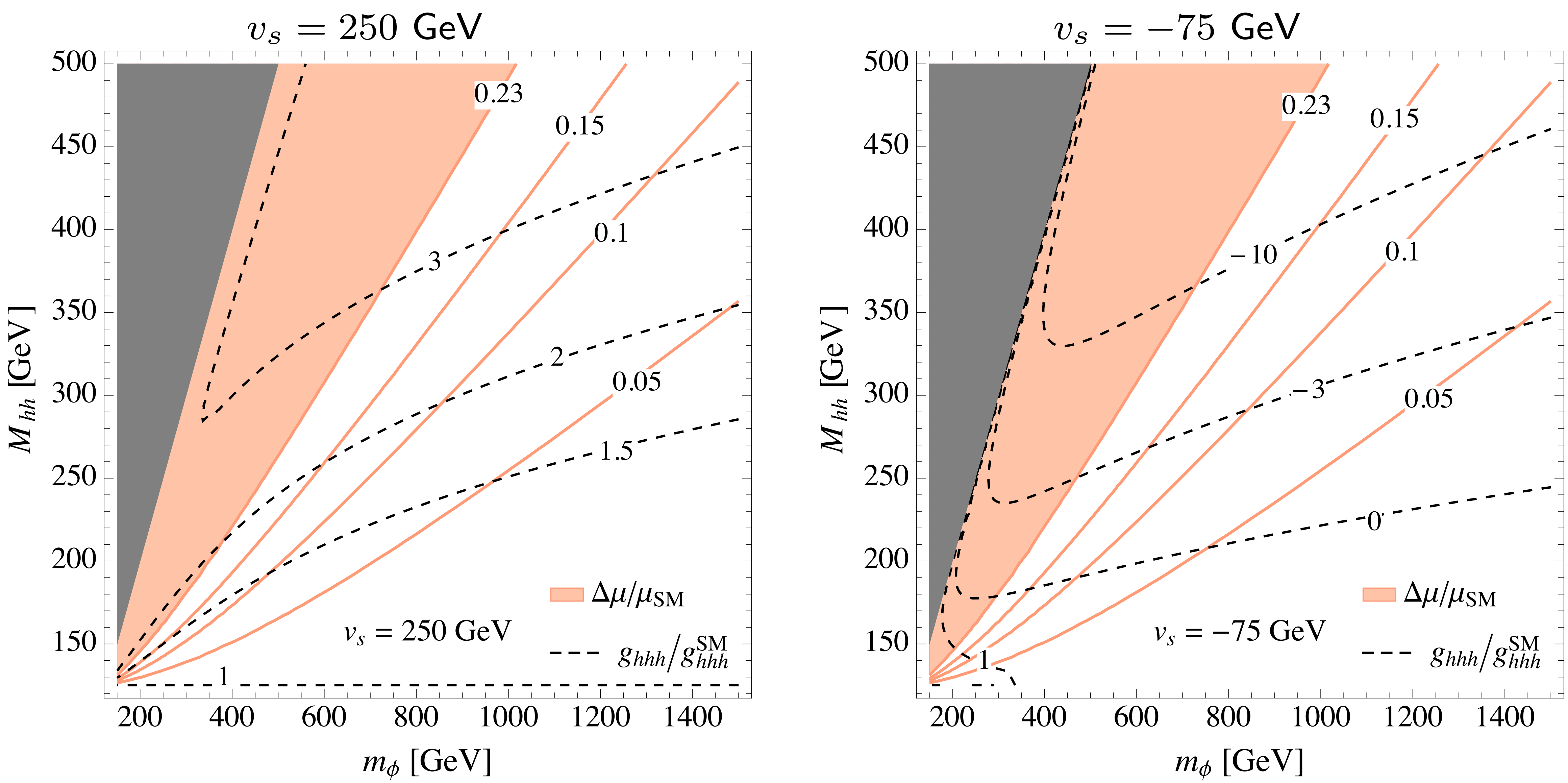
Backup

Generic singlet: comparison of bounds



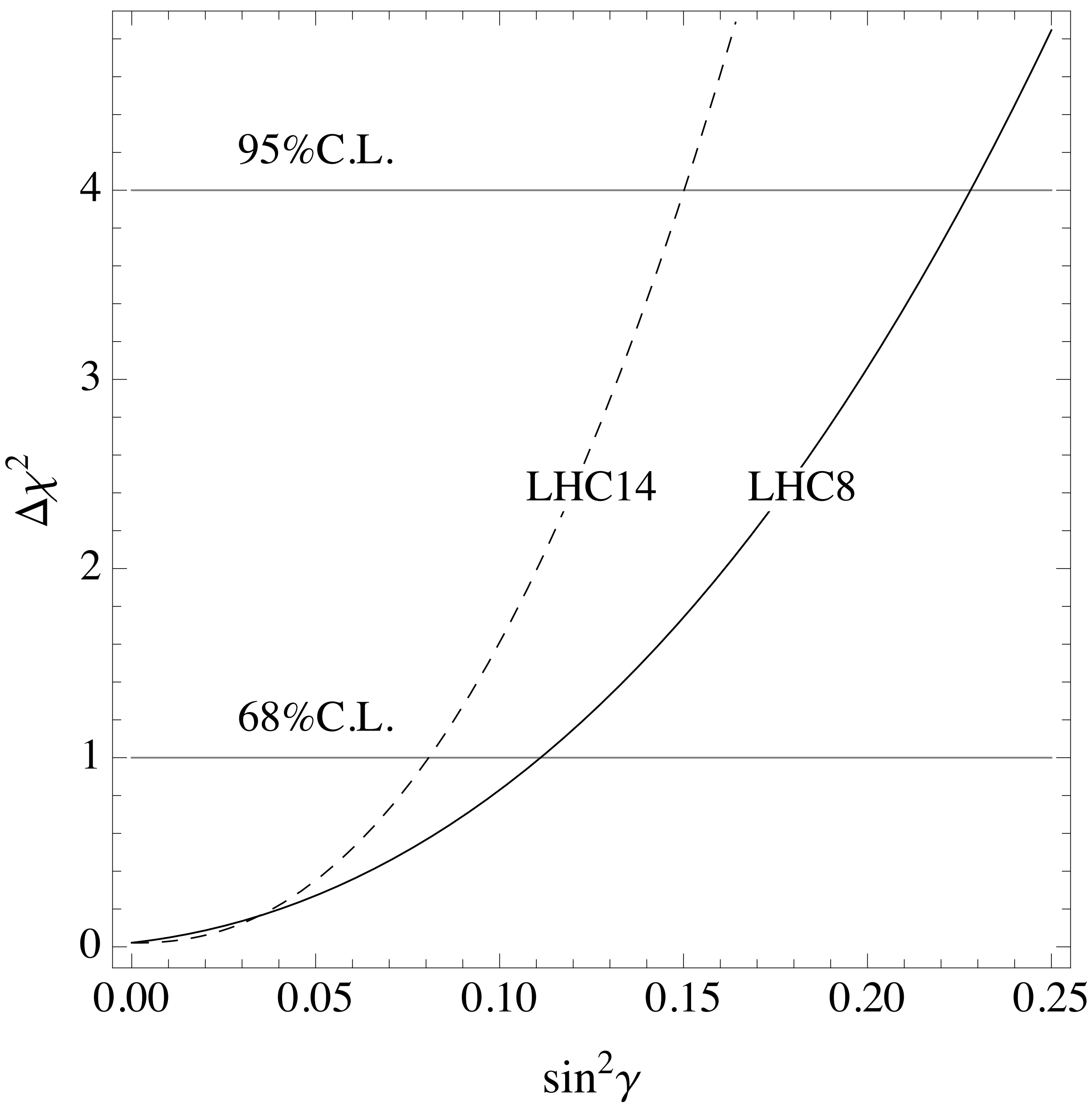
Direct searches dominate for low m_ϕ, M_{hh}: look for the singlet!

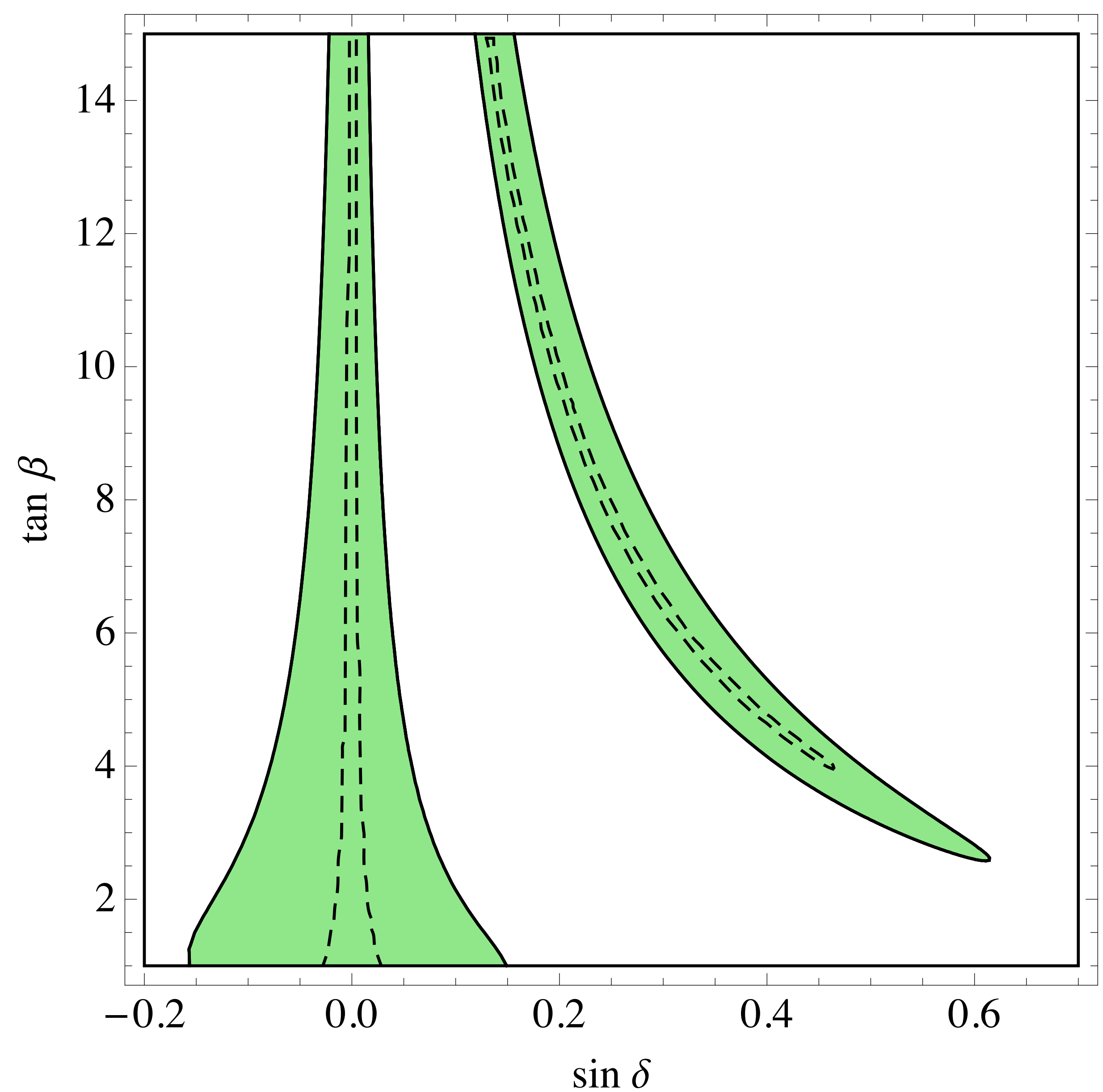
Higgs couplings



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

Higgs couplings





Motivation

LHC will be able to measure Higgs couplings with a precision of a few %

Coupling	Uncertainty (%)			
	$300\ \mathrm{fb}^{-1}$		$3000\ \mathrm{fb}^{-1}$	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

CMS-NOTE-2012-006

Extended Higgs sectors: take a simple scenario w/ large effects due to tree-level mixing with new states

How do direct searches compare with these results?

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).

Extrapolation of the limits

Estimate the bounds as follows: $\text{significance} = \dfrac{S}{\sqrt{S + B + \alpha_{\rm sys}^2 B^2}} \lesssim 2$

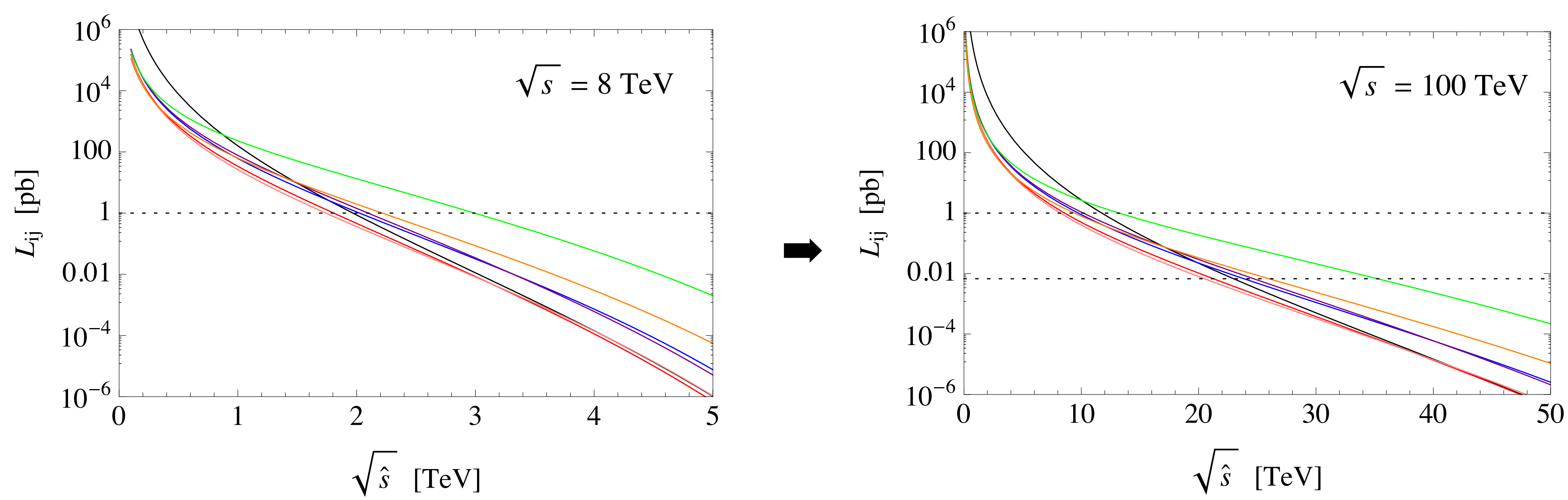
$$S_{95\%} \approx 2\sqrt{B + \alpha_{\rm sys}^2 B^2}$$

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

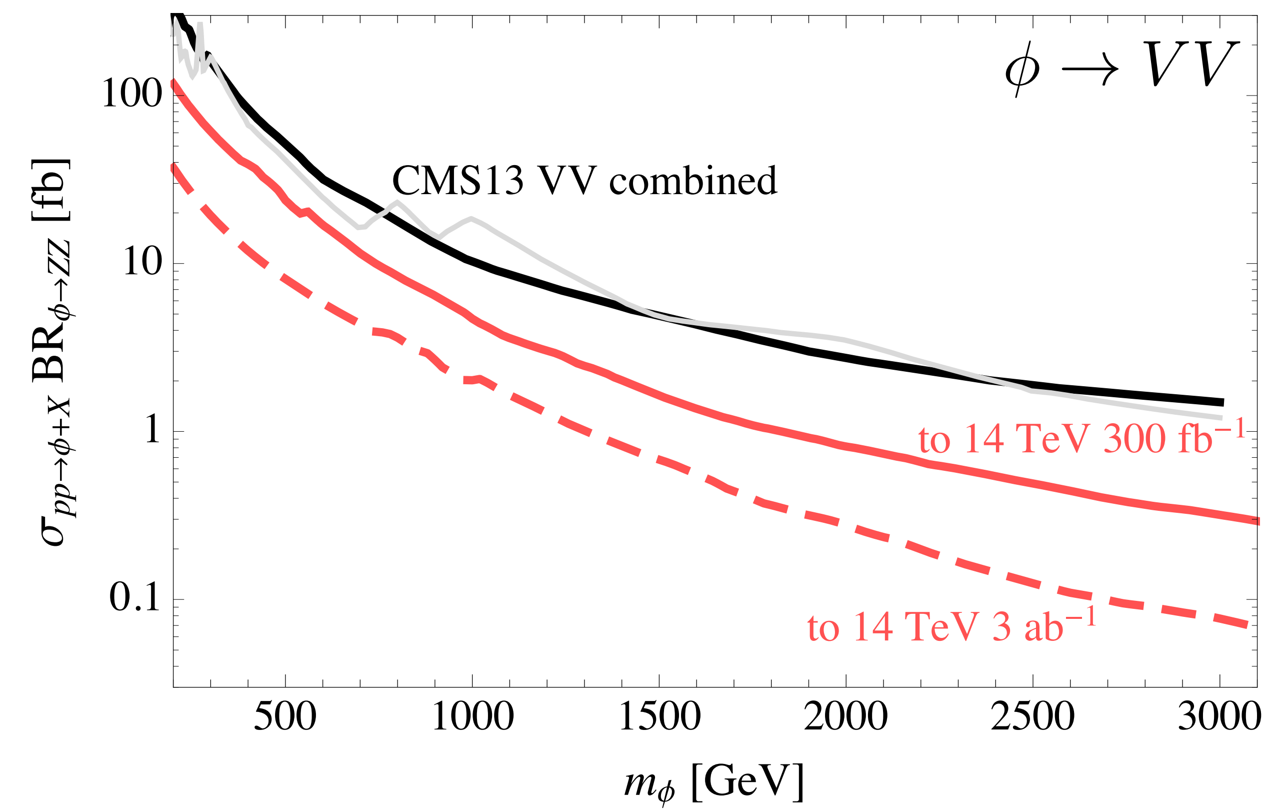
- Rescale LHC data with the parton luminosity of the bkg

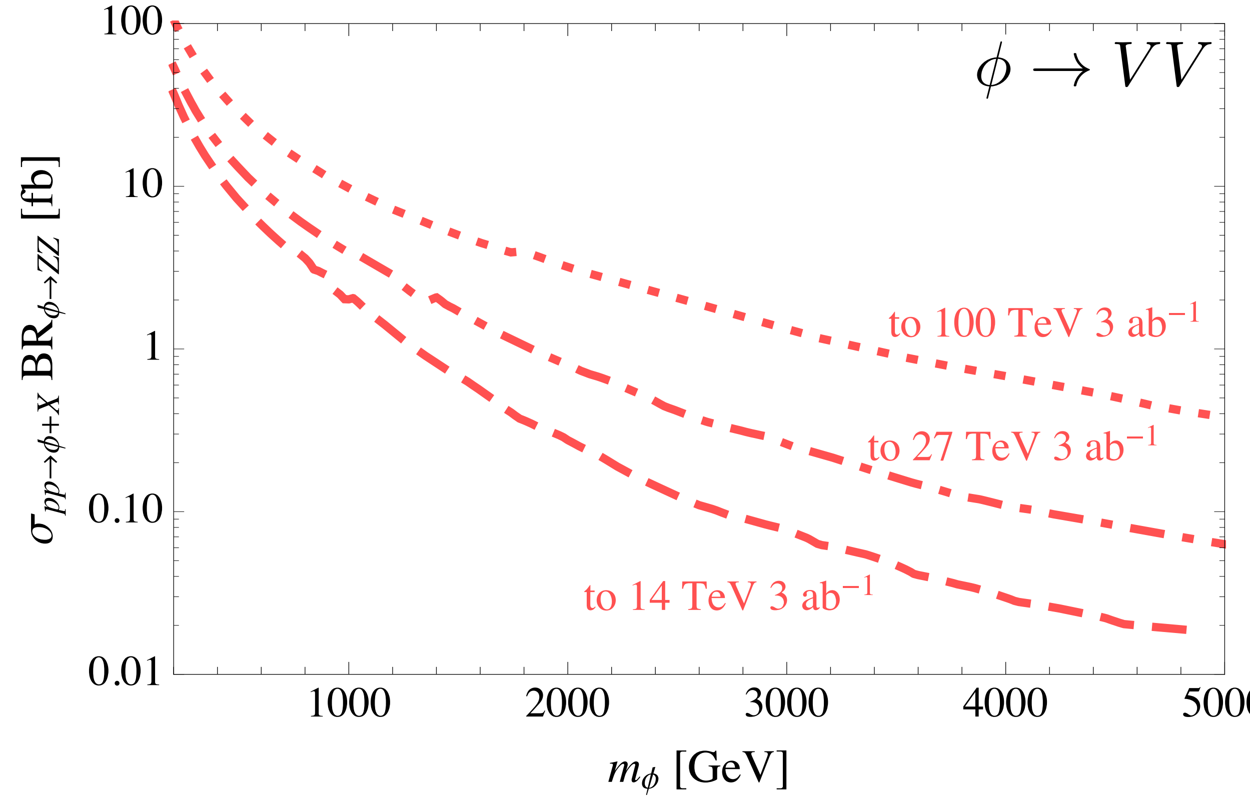
see also Salam, Weiler '14; Thamm, Torre, Wulzer '15

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



Reach of LHC and future upgrades





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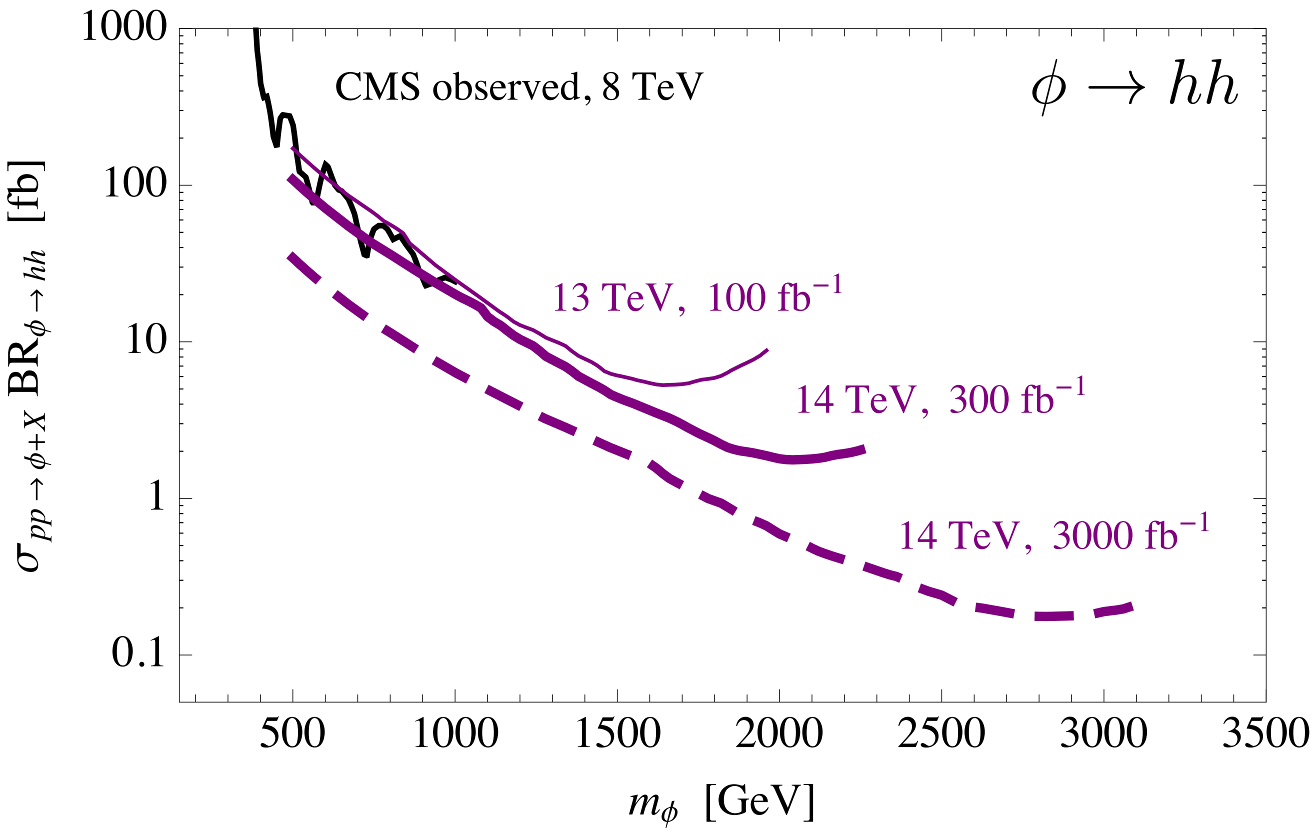

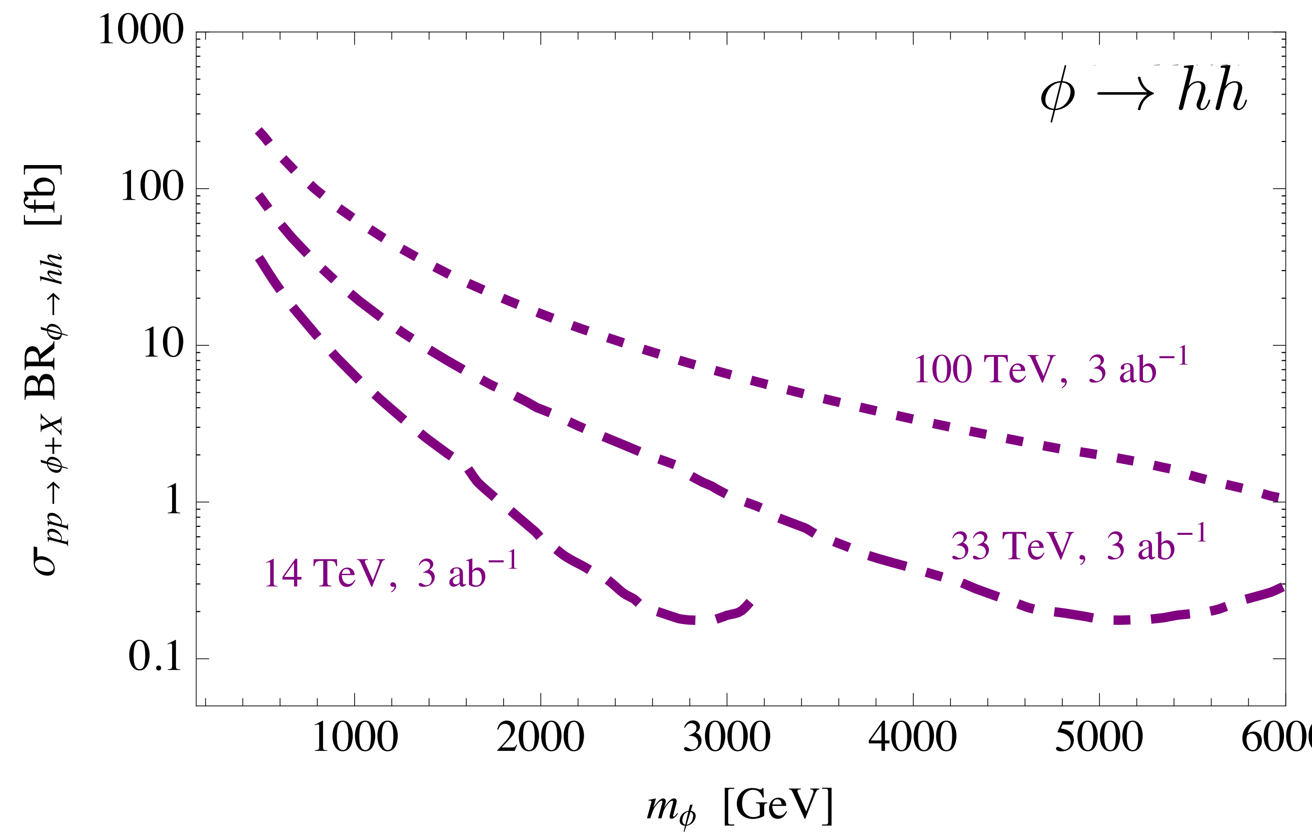

Reach of LHC and future upgrades

- Updated limits using 13 TeV data: good agreement with previous results from 8 TeV

- Extrapolation from 13 to 14 TeV is more robust

- Agreement – up to O(1) factors – with other studies at 13, 14, 27 TeV

Brownson et al. '13

Gouzevich et al '13

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

  (below a certain mass SM thresholds become important: we don't extrapolate the limits beyond that point)