Singlet-like scalars at HL and HE LHC

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Higgs physics at HL and HE LHC

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

Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 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

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

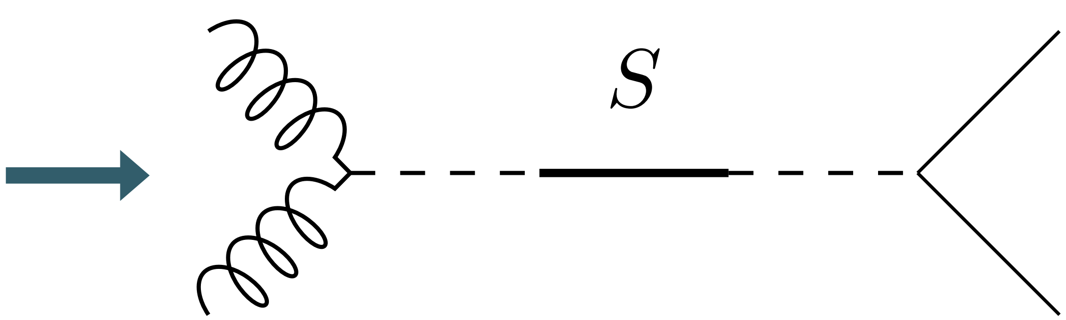
How do direct searches compare with these results?

A simple reference case

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

- Low energy effective theory of Mirror/Twin Higgs models
- Realised in the NMSSM
- Paradigm for 1st order ElectroWeak phase transition
- …

$\lambda |H|^2 S$



- 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

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At high mass the equivalence theorem relates the decay widths

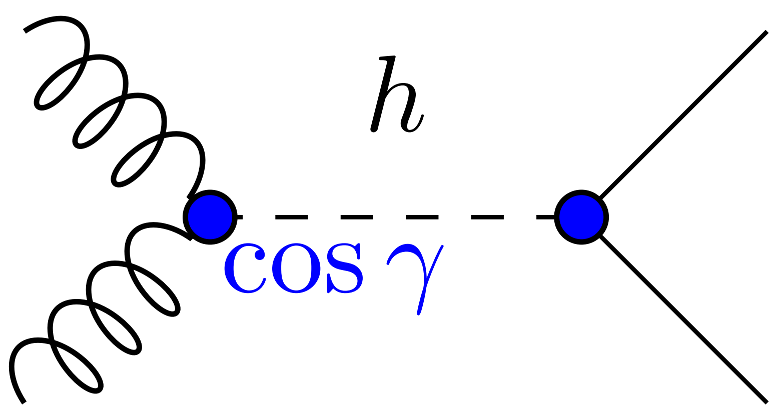
$${\rm BR}_{\phi\to hh} = {\rm BR}_{\phi\to ZZ} = \frac{1}{2}{\rm BR}_{\phi\to WW} \simeq \frac{1}{4}, \qquad m_\phi \gg m_h$$

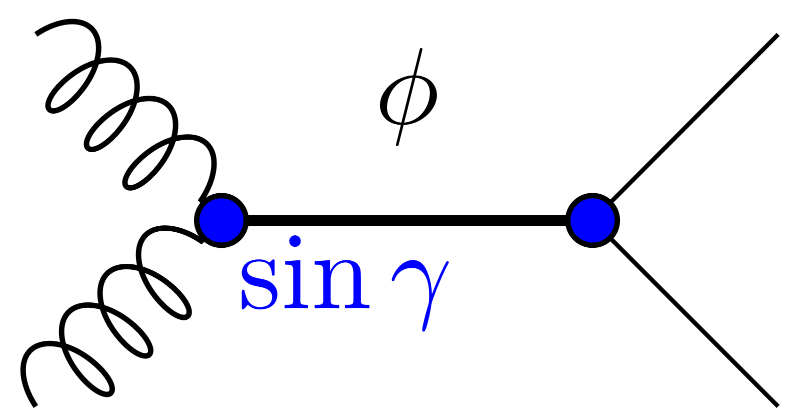
(these are the dominant channels, fermionic modes suppressed)

Two complementary ways to look for the extra Higgs:

Higgs signal strengths

Direct searches





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

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

➡ Direct reach of HL and HE LHC vs Higgs measurements?

Extrapolation of the limits

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

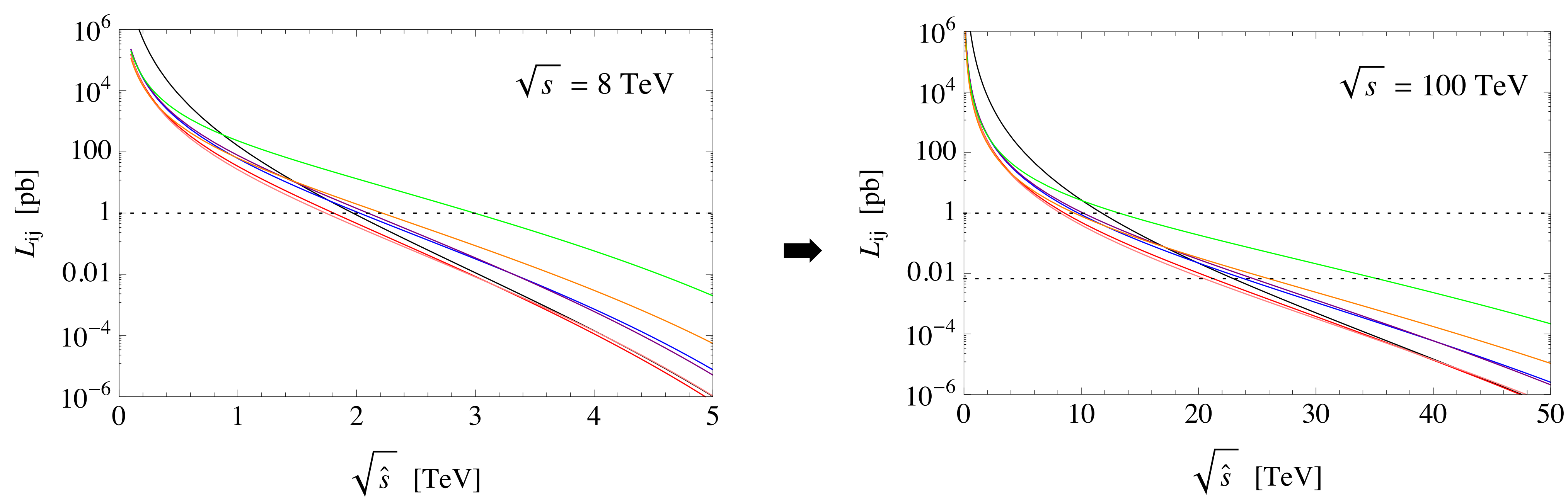
$$S_{95\%} \approx 2\sqrt{B + \alpha_{\rm sys}^2 B^2}$$

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

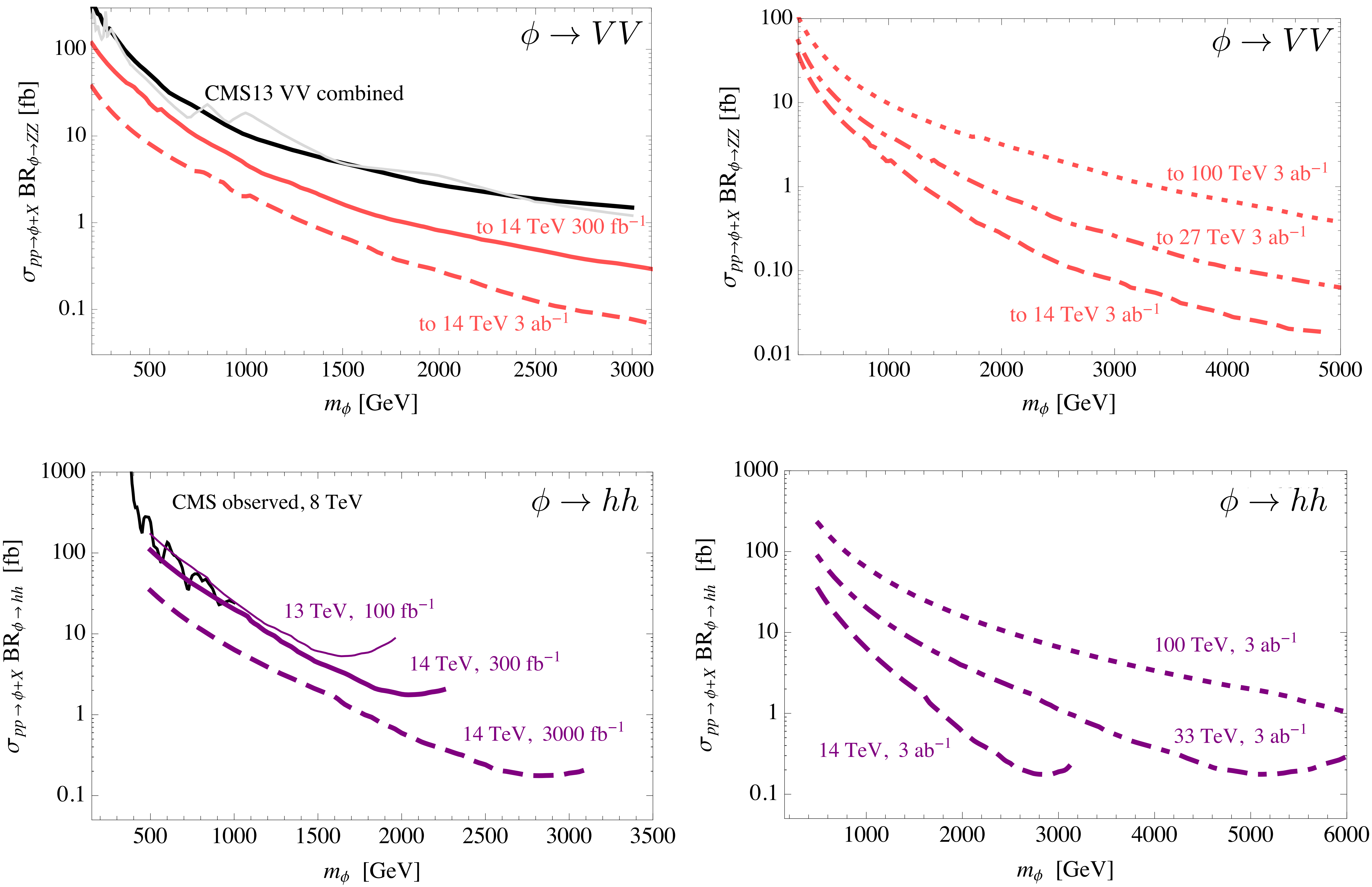
- Rescale LHC data with the parton luminosity of the bkg

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



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

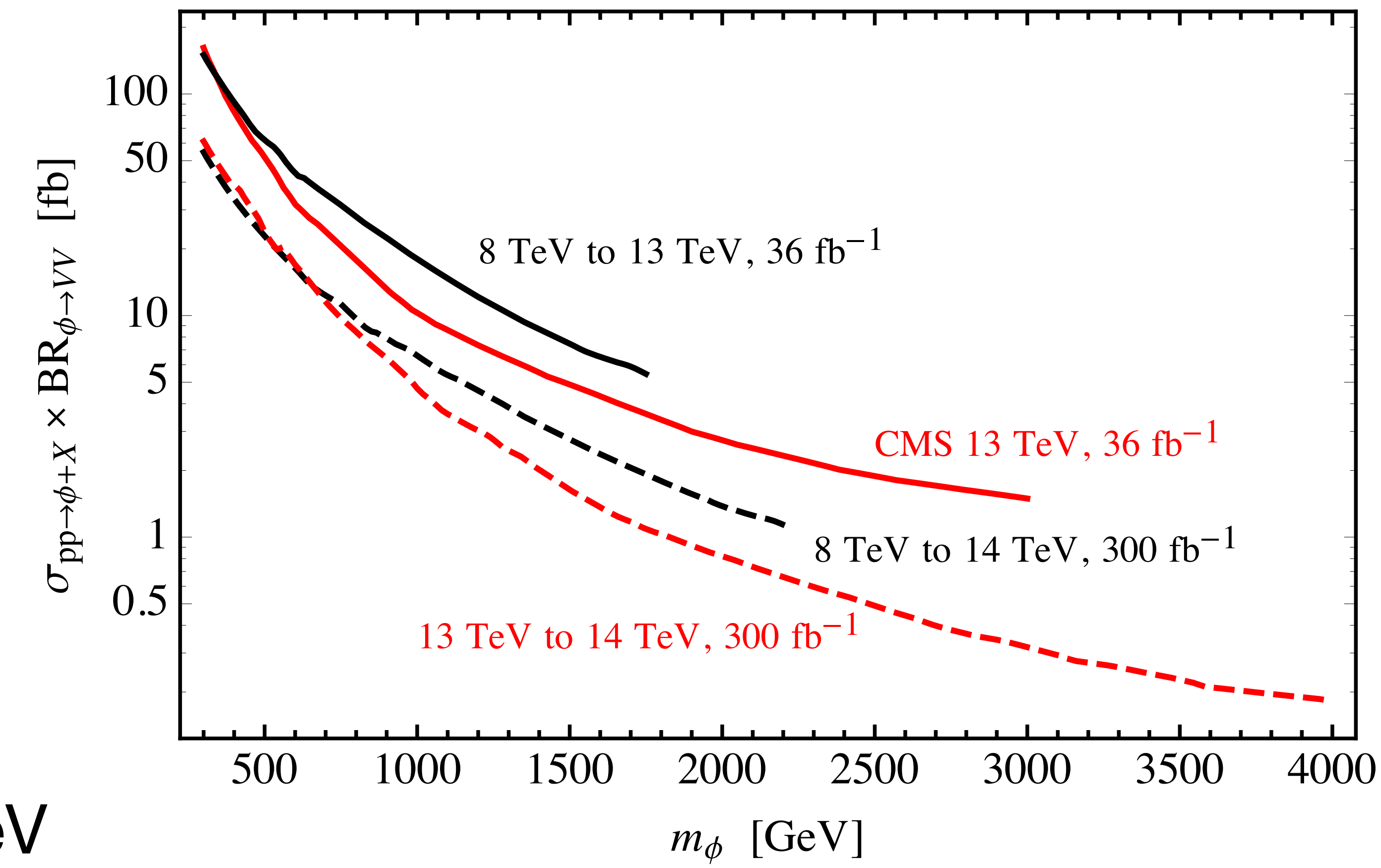
- Agreement – up to O(1) factors – with other studies at 13, 14, 27 TeV

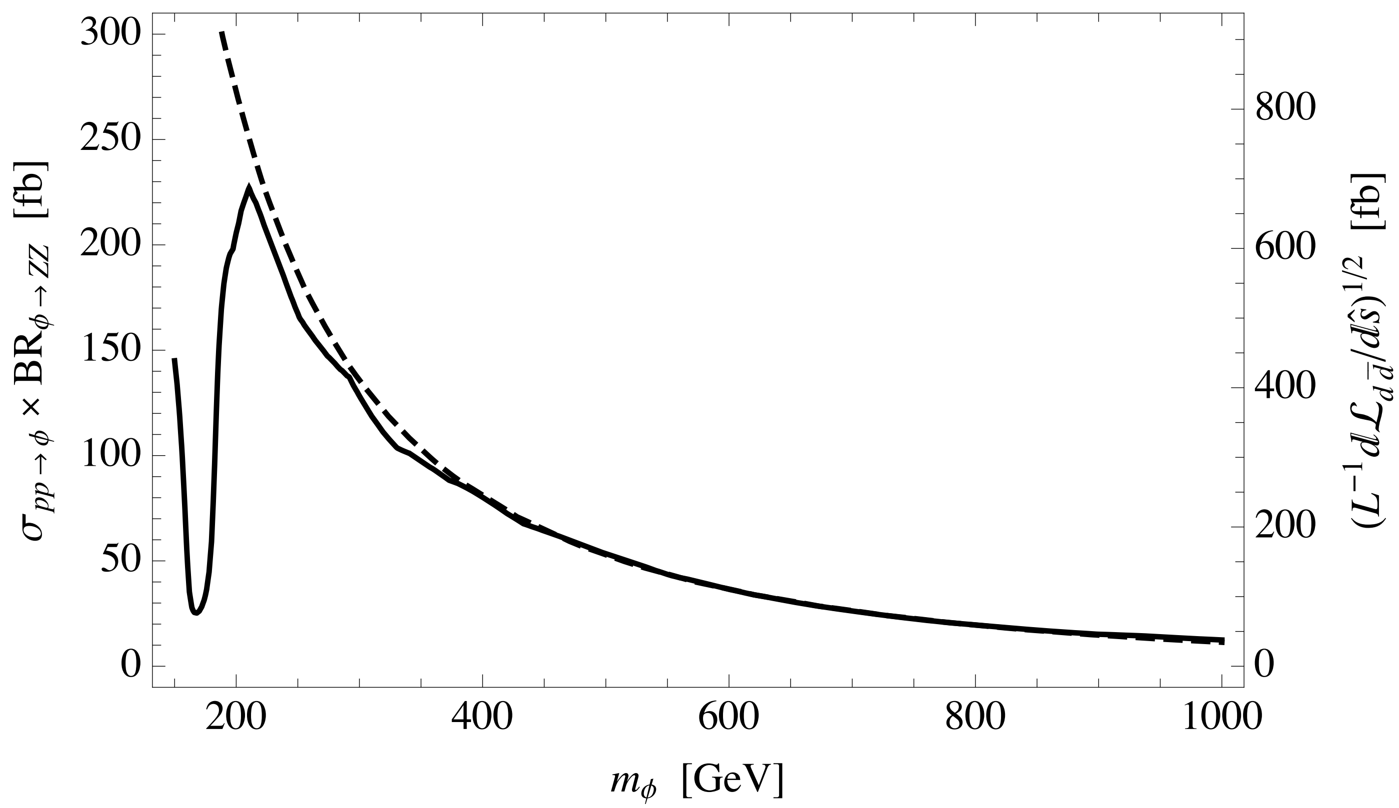
Brownson et al. '13

Gouzevich et al '13

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

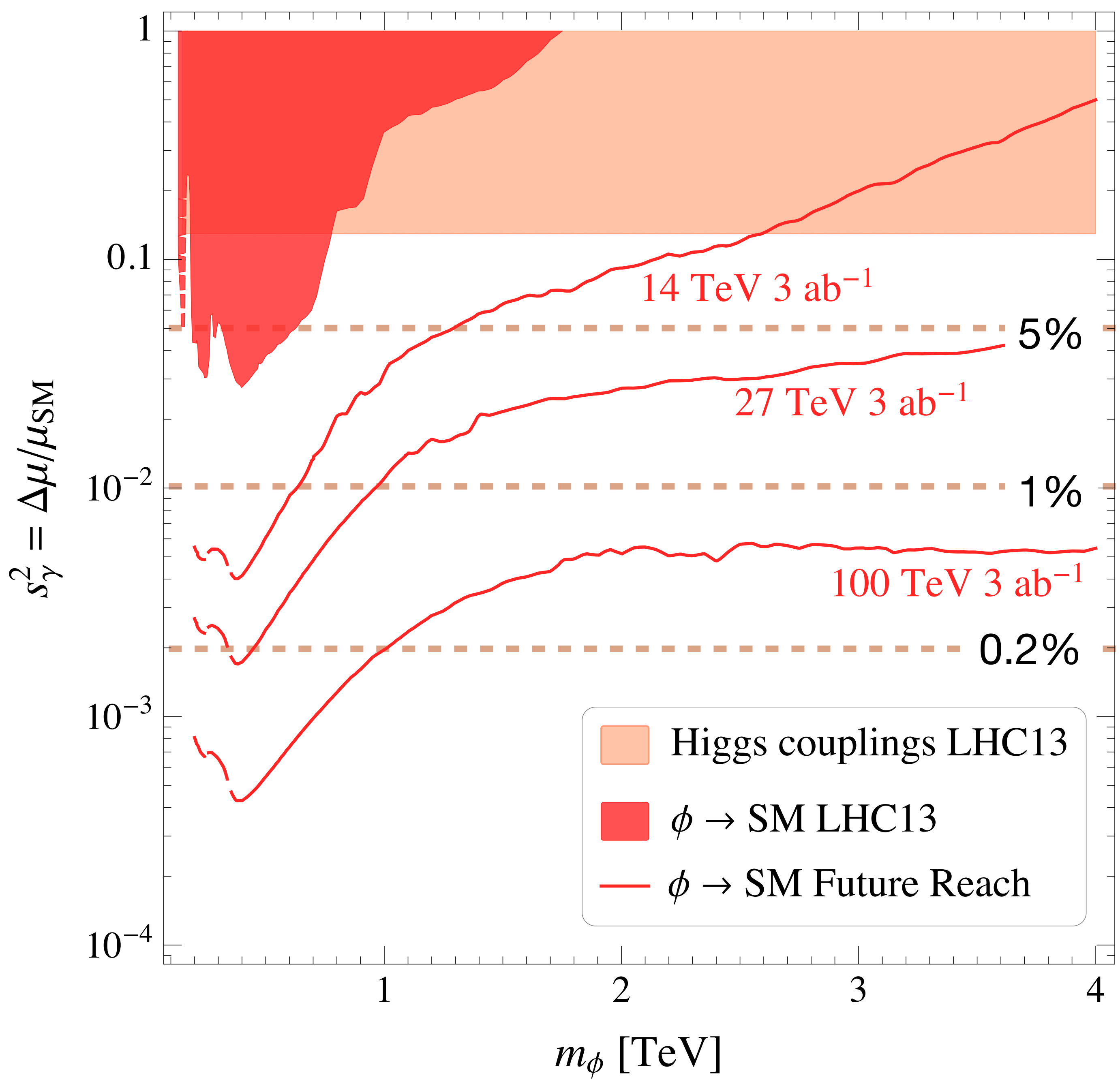
(below a certain mass SM thresholds become important: we don't extrapolate the limits beyond that point)





Direct vs indirect

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



direct searches dominate at low mass (at each stage of the experimental program)

SUSY: the NMSSM

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

- Extra tree-level contribution to the Higgs mass

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

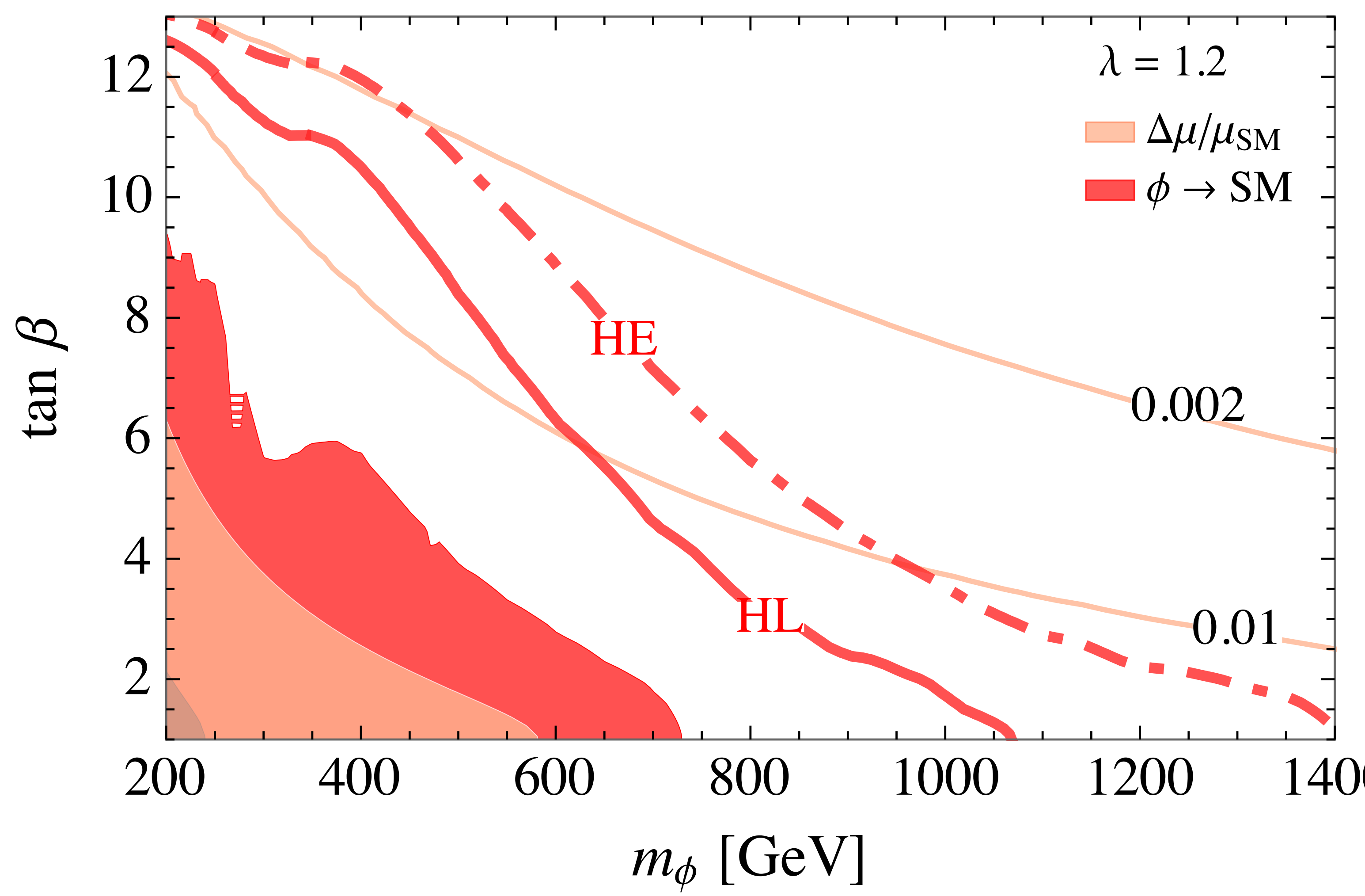
- Alleviates fine-tuning in v for $\lambda \gtrsim 1$ and moderate $\tan\beta$

Recast the previous bounds:

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

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

loop correction to Higgs mass from top-stop



already now direct searches more stringent than Higgs fit

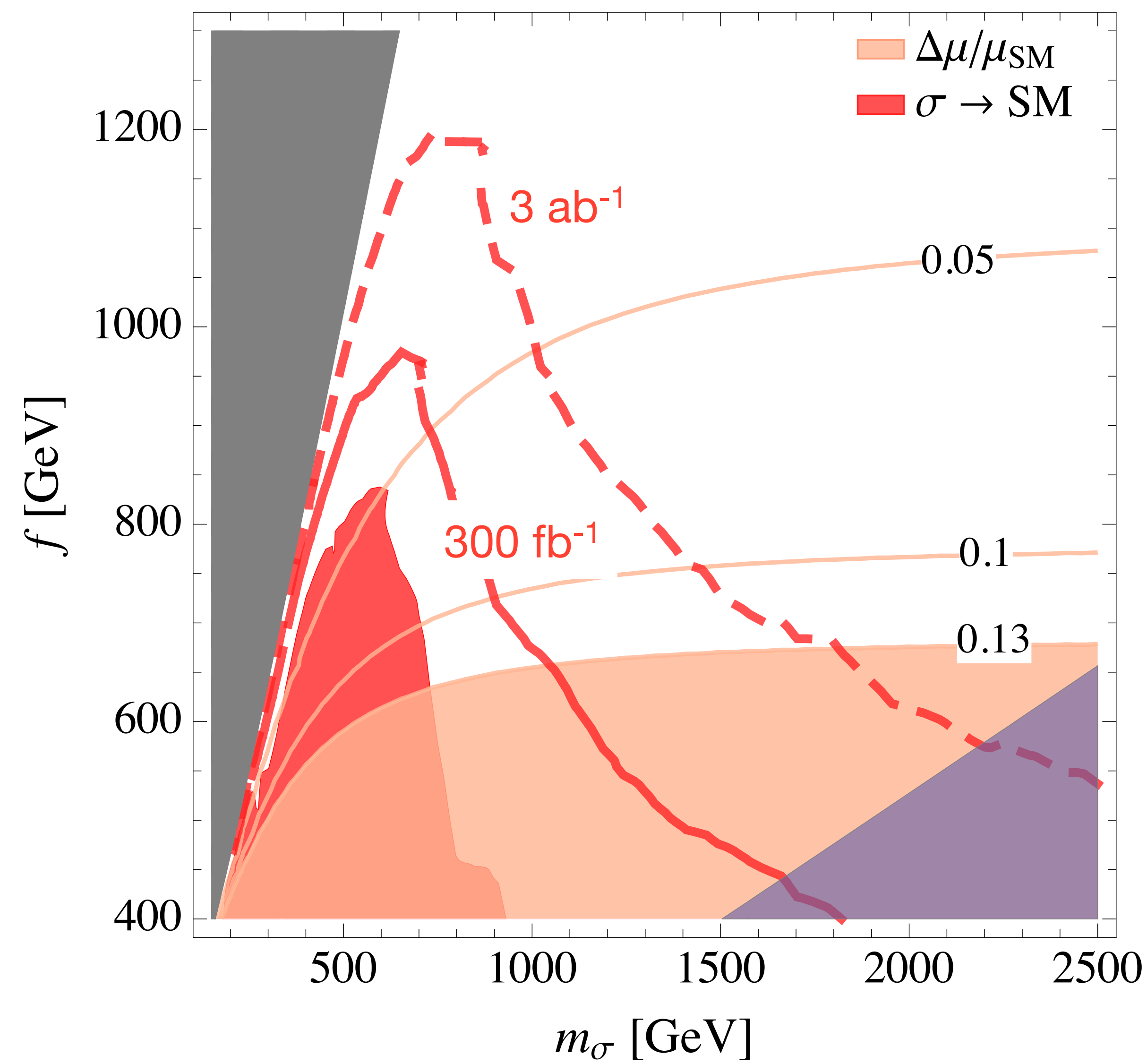
Twin Higgs

- 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.

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

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

If not too strongly coupled the
Twin Higgs could be directly visible



Summary & Outlook

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

✓ General description in terms of a few physical parameters: a simple reference case for the study of extended Higgs sectors

✓ Direct searches are a powerful probe: assess reach of HL and HE LHC

Higgs couplings become more important for NP above ~ a TeV

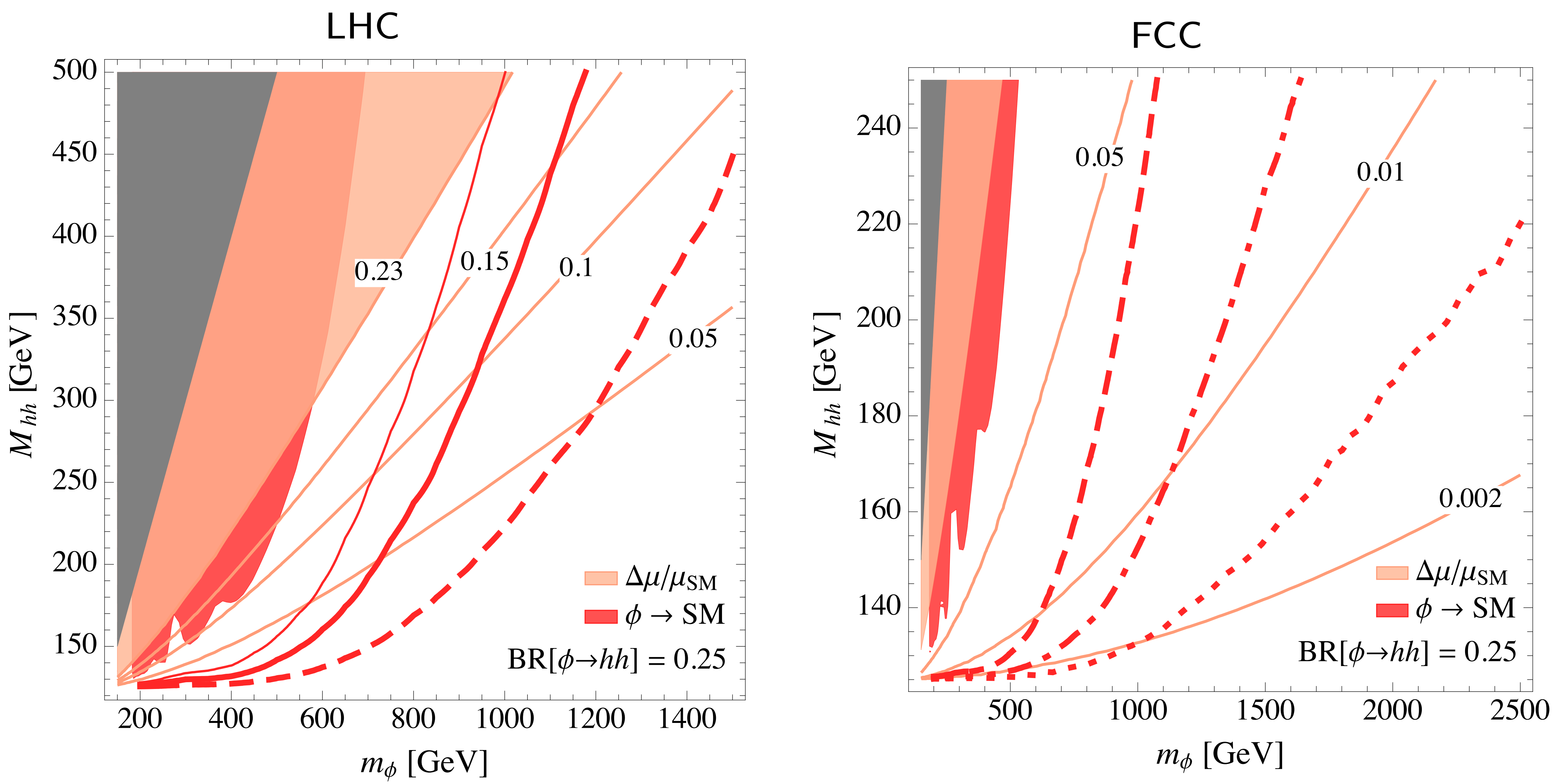
➡ For the report: update all the bounds with most recent data, PDF, etc…

➡ More detailed study of EW phase transitions (case of small mixing)

➡ more suggestions, comments?

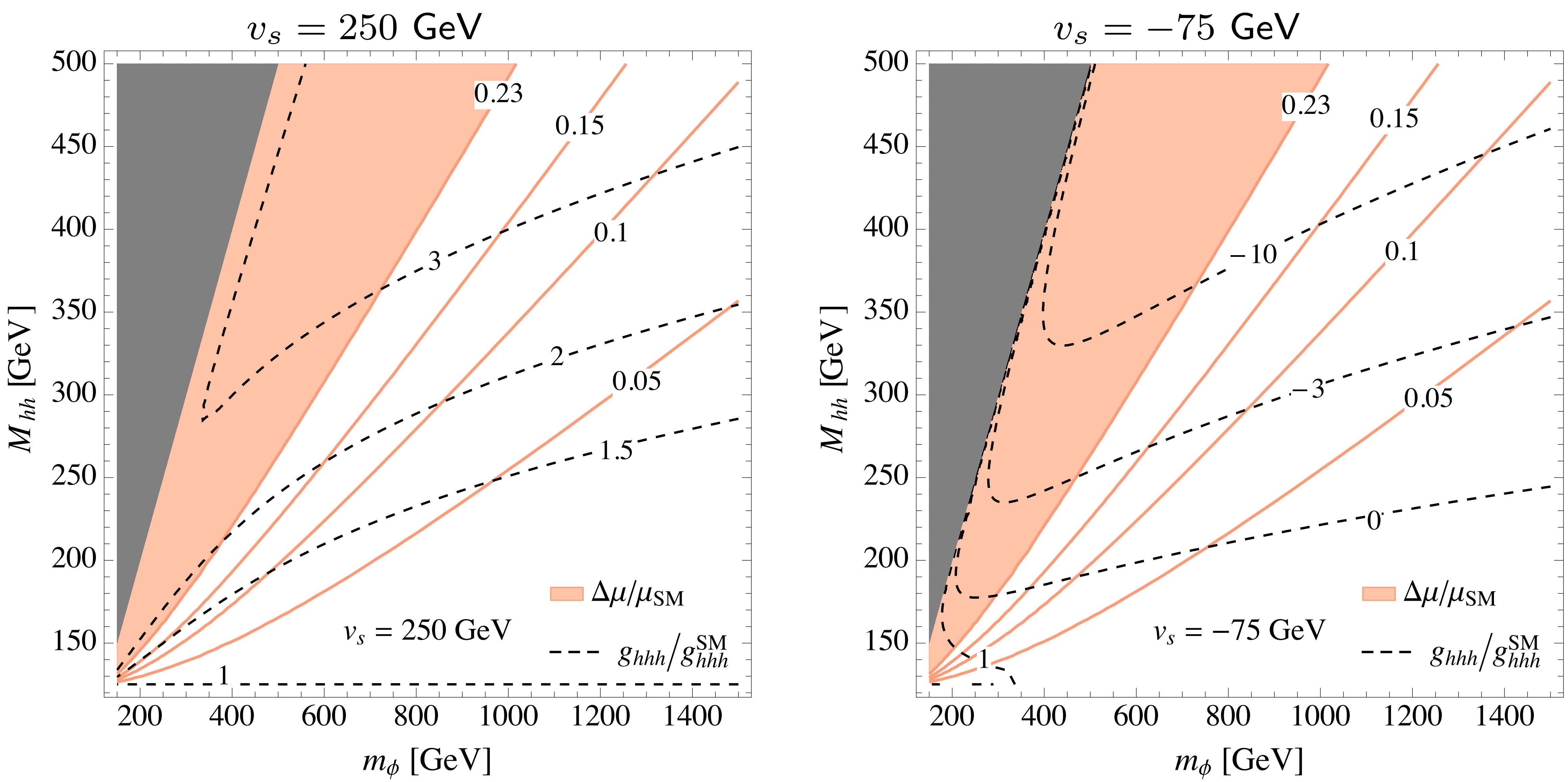
Backup

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

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).