Singlet-like Higgs production

Dario Buttazzo

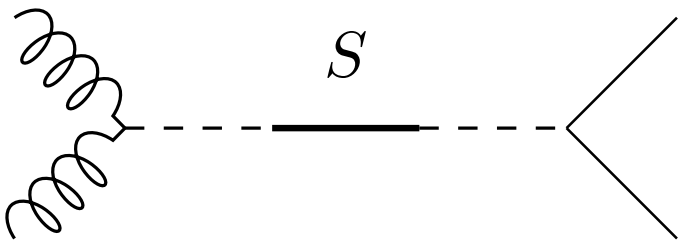
Physik-Institut - Universität Zürich

1st FCC Physics Workshop – CERN, 18.1.2017

1505.05488 with F. Sala, A. Tesi – Physics at the FCC-hh report 1606.09408

Why scalar singlets?

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

Higgs-singlet mixing: main features

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

Mass eigenstates: $\begin{cases} h = h^0 \cos\gamma + s^0 \sin\gamma, \\ \phi = s^0 \cos\gamma - h^0 \sin\gamma. \end{cases}$

The phenomenology mainly depends on 3 parameters only:

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

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

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}, \qquad M_{hh}^2 \propto v^2 \text{ depends only on EW physics}$$

Singlet decays

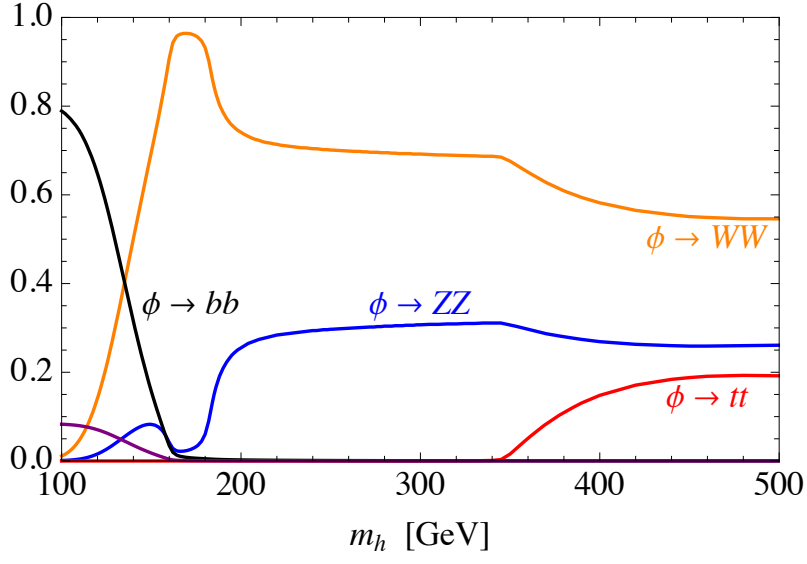
At high mass the equivalence theorem relates the decay widths

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

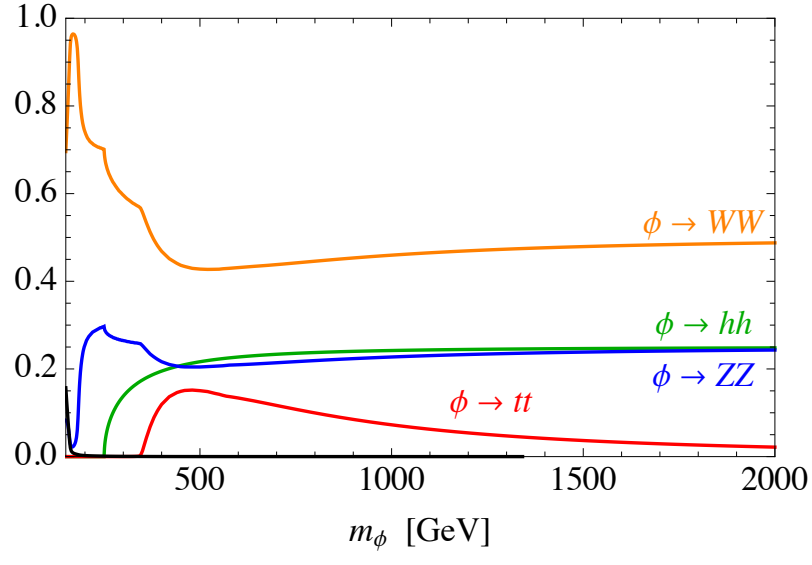
(these are the dominant channels, fermionic modes suppressed)

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

h branching ratios



ϕ branching ratios



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

Singlet decays

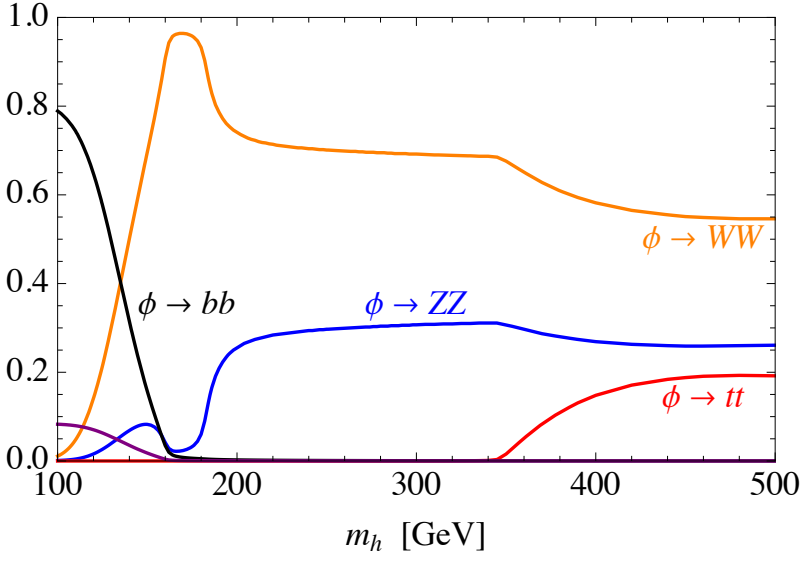
At high mass the equivalence theorem relates the decay widths

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

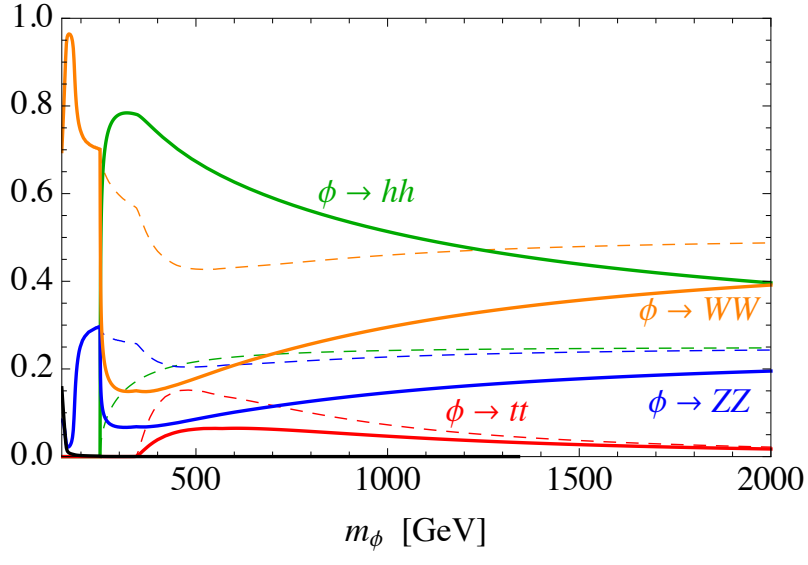
(these are the dominant channels, fermionic modes suppressed)

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

h branching ratios



ϕ branching ratios



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

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 hhh coupling

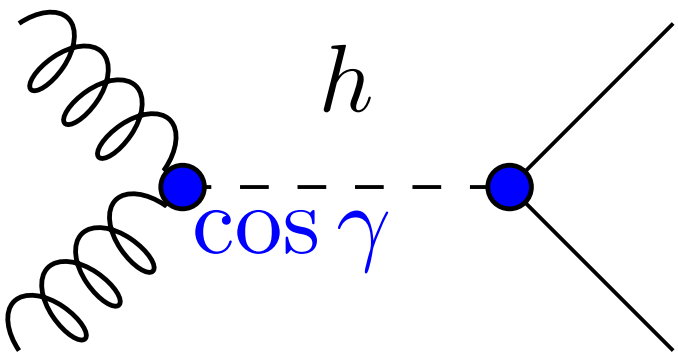
$$\mathrm{BR}_{\phi\to hh} = \frac{1}{4} - \frac{3}{4}\frac{v}{v_s}\frac{\sqrt{M_{hh}^2 - m_h^2}}{m_\phi} + \mathcal{O}(v^2/m_\phi^2),$$

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

Hunting the singlet Higgs bosons

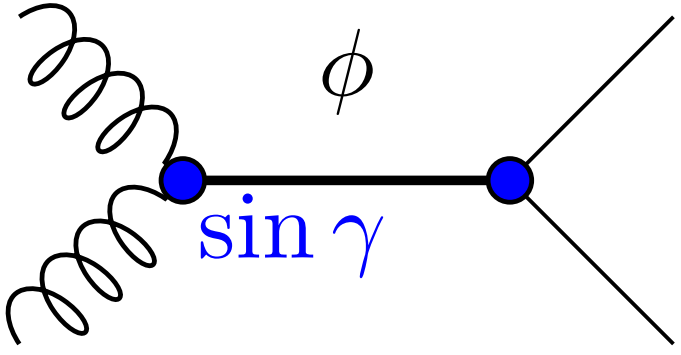
Two complementary ways to look for the extra Higgs:

Higgs signal strengths



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

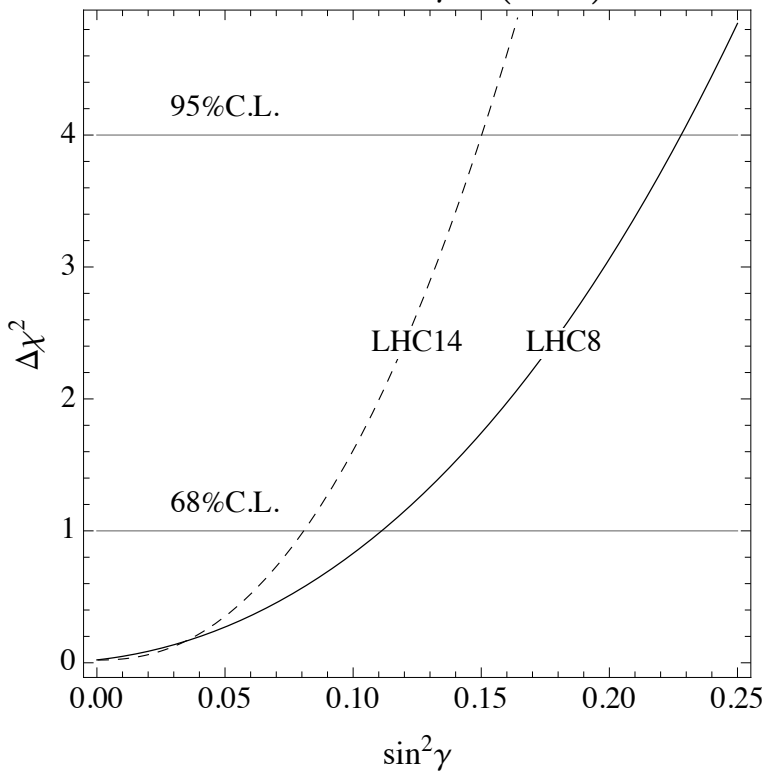
Direct searches



$\mu_\phi \sim s_\gamma^2 \times \mu_{\rm SM}$

Higgs couplings

Fit to all rates $\mu_h(125)$:



compare with 2HDM: $\sin^2\gamma \lesssim 0.02$

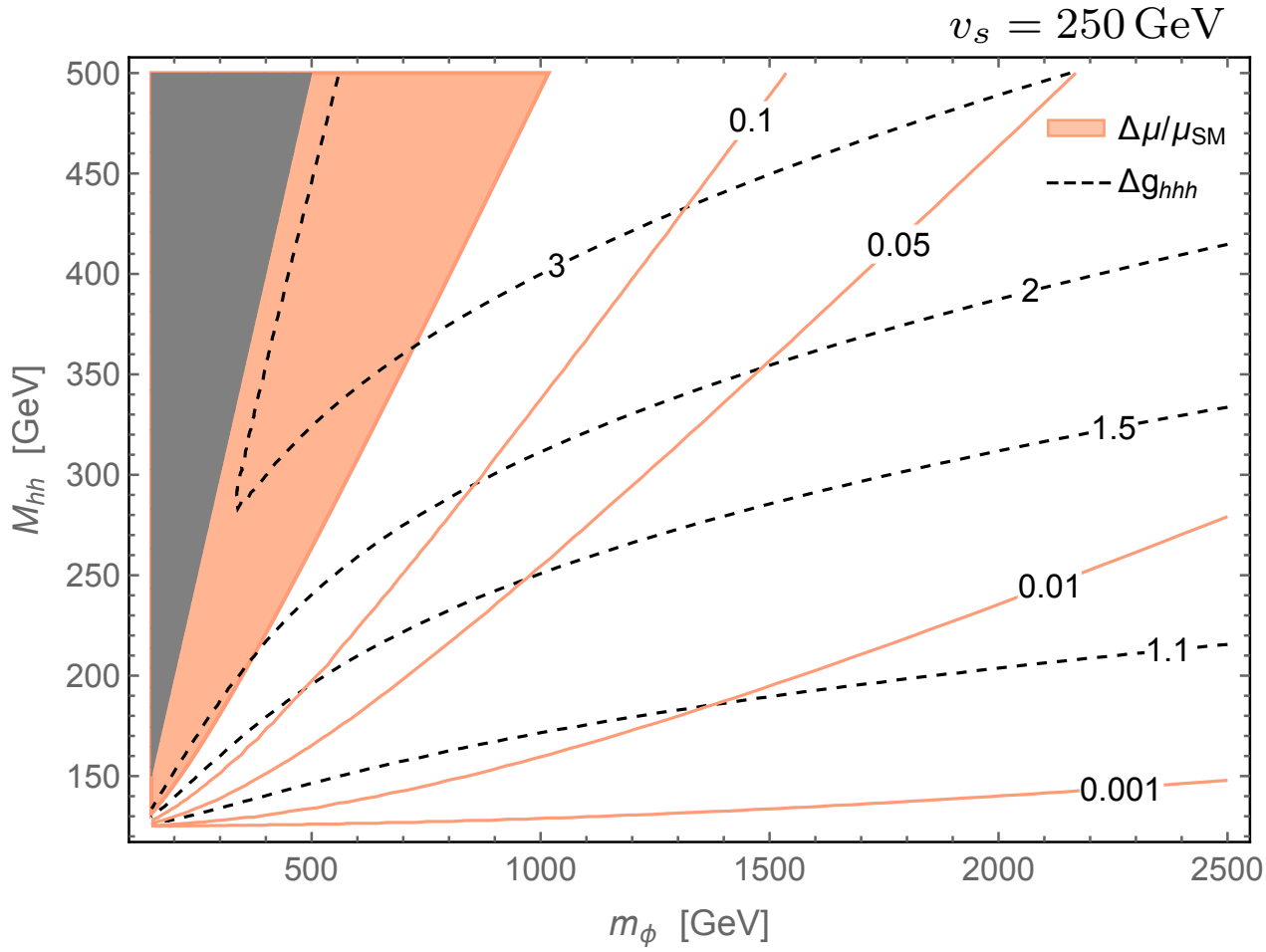
1σ reach	$s_\gamma^{2\,*}$	Δg_{hhh}
LHC8	0.2	-
LHC14	0.08 - 0.12	-
HL-LHC	0.04 - 0.08	0.5
HE-LHC	"	0.2
FCC-hh	"	0.08
ILC	2×10^{-2}	0.2 - 0.8
ILC-up	4×10^{-3}	0.1 - 0.5
CLIC	2×10^{-3}	-
FCC-ee	10^{-3}	-

(* projections for most precise coupling)

[Snowmass '13]

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

Higgs couplings



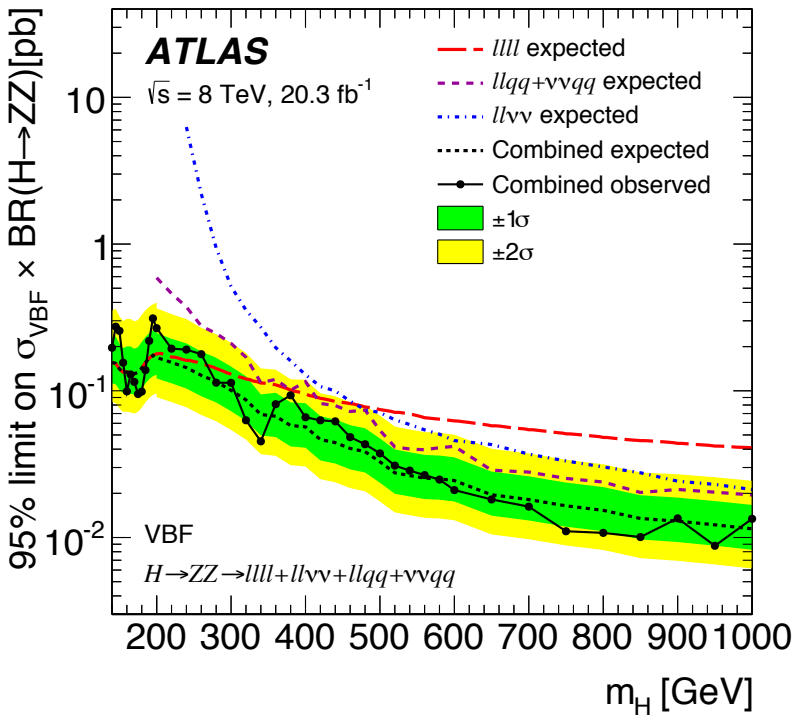
Very large modifications of the triple Higgs coupling are possible: in principle observable at the LHC. Whole region covered by FCC-ee.

Direct searches

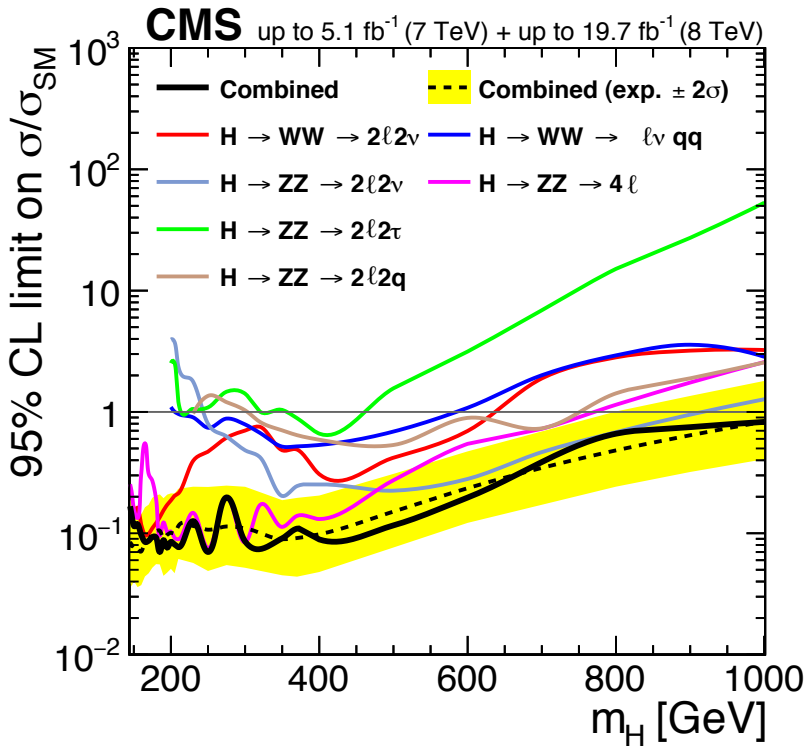
ϕ is like a heavy SM Higgs boson: $\phi \to VV$ dominant decay mode

- Combination of ZZ and WW final states:

ATLAS [1507.05930]



CMS [1504.00936]



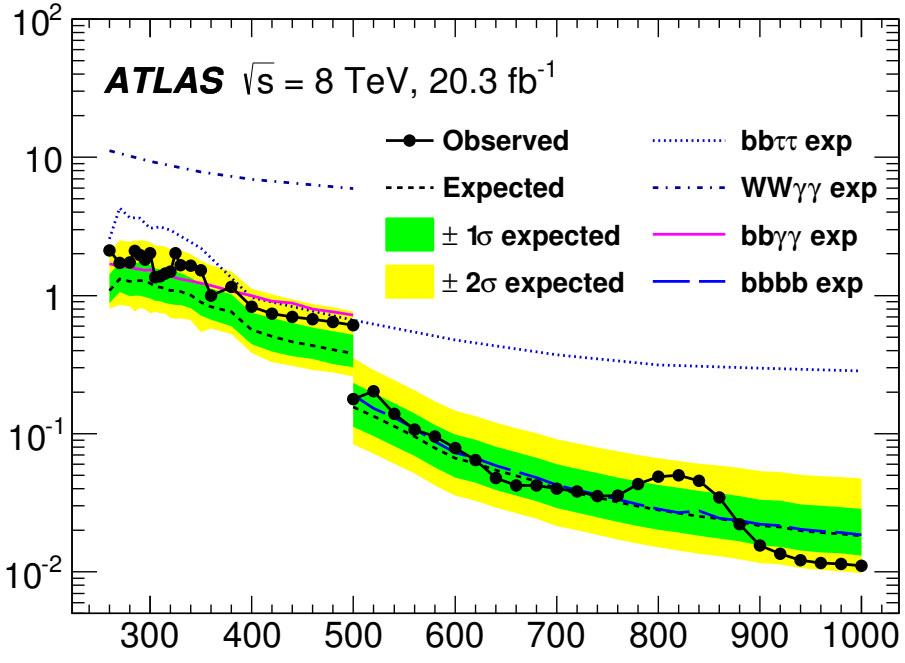
Already more sensitive / comparable to Higgs couplings

Direct searches

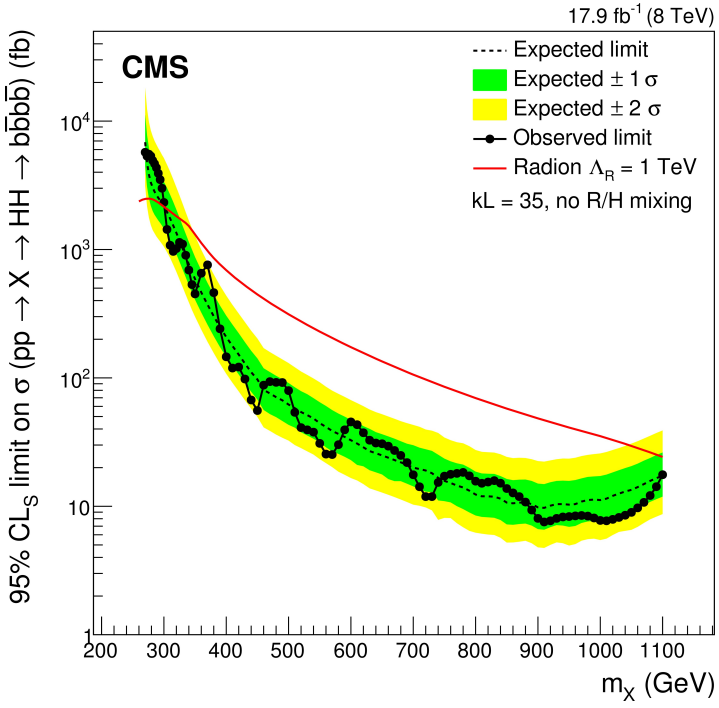
ϕ is like a heavy SM Higgs boson + $\phi \to hh$ decay channel

- Mainly $\phi \to hh \to 4b$ final state at high masses:

ATLAS [1509.04670]



CMS [1503.04114]



- $hh \to 2b2\gamma$ dominates at low m_ϕ
- Also other decay channels: $hh \to 2b2\tau$, $hh \to 4\tau$, $hh \to 2b2W$

[No et al., Kotwal et al., Martin-Lozano et al.]

Projections for the future

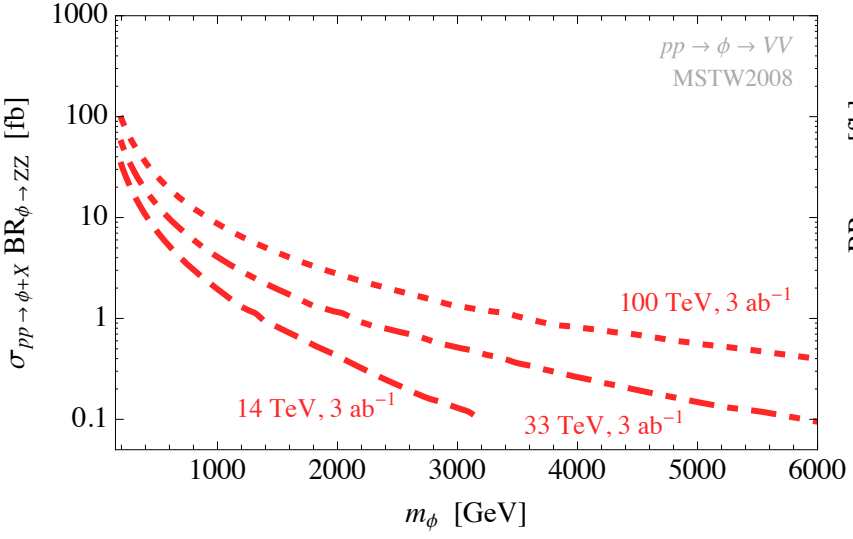
How to get fast estimates of the reach of future machines?

- Rescale LHC data with the parton luminosities of the bkg

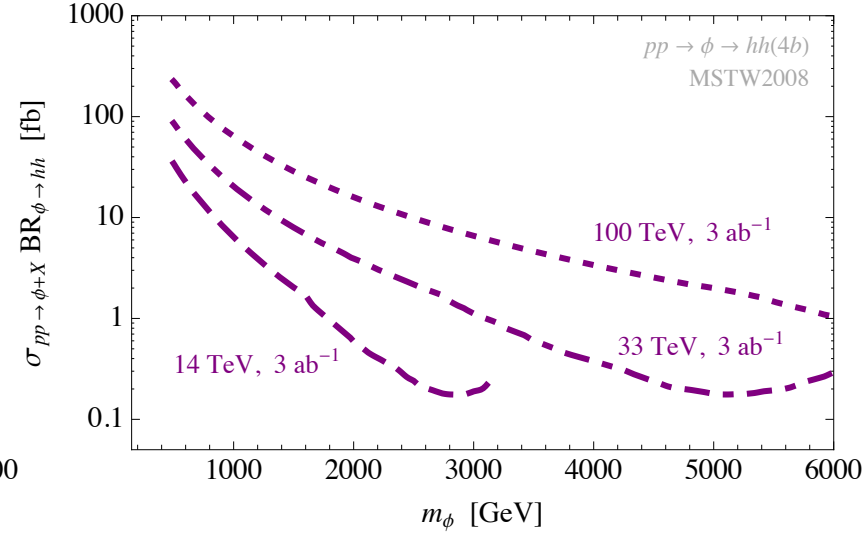
see also Salam, Weiler '14; Thamm, Torre, Wulzer '15

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



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

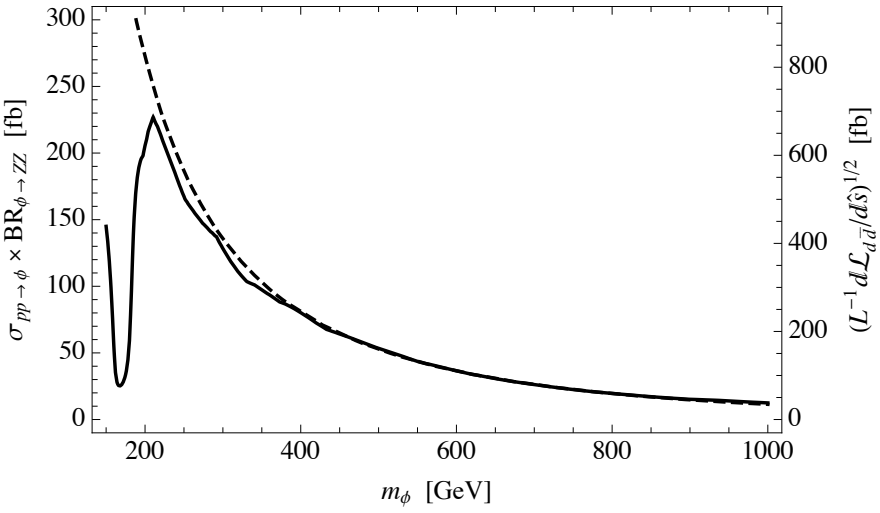
Extrapolation procedure

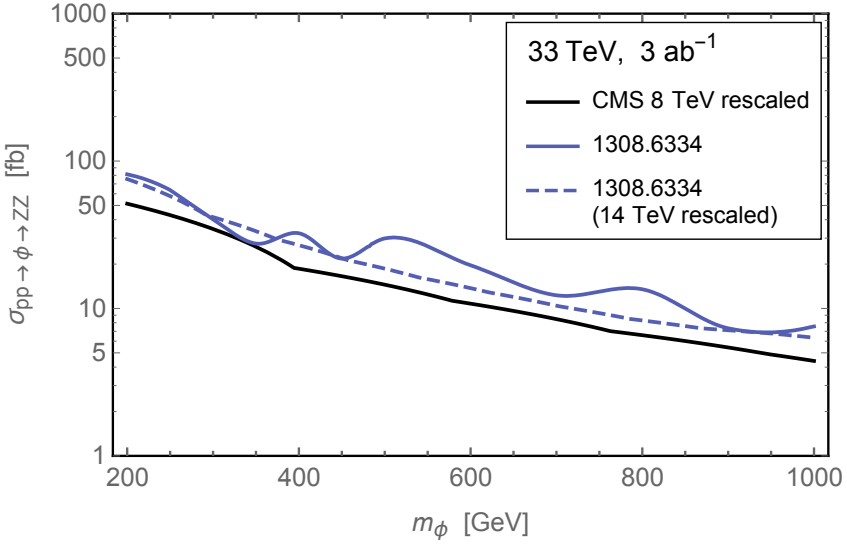
This method is subject to a number of rather strong assumtions!

- ◇ 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 & cout experiment for narrow resonances
- ◇ SM bkg scale as $\sigma(\hat{s}) \sim \hat{s}^{-1}$: 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 $(\text{parton luminosity})^{1/2}$

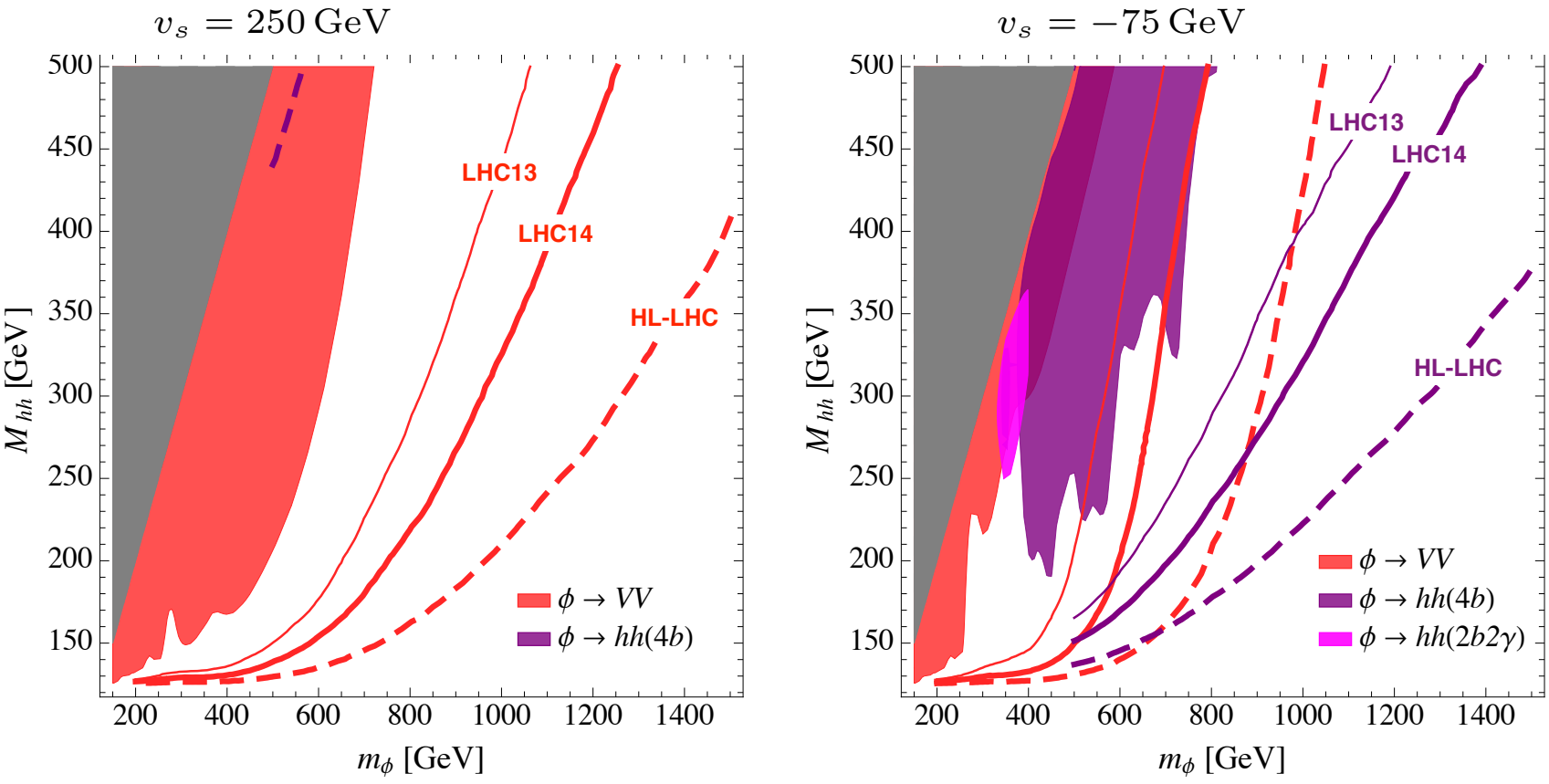
  Below a certain mass SM thresholds become relevant: we do not extrapolate the exclusions beyond that point.

- Extrapolations consistent – up to O(1) factors – with other results at 13, 14, 33 TeV.

[Gouzevich et al. '13]

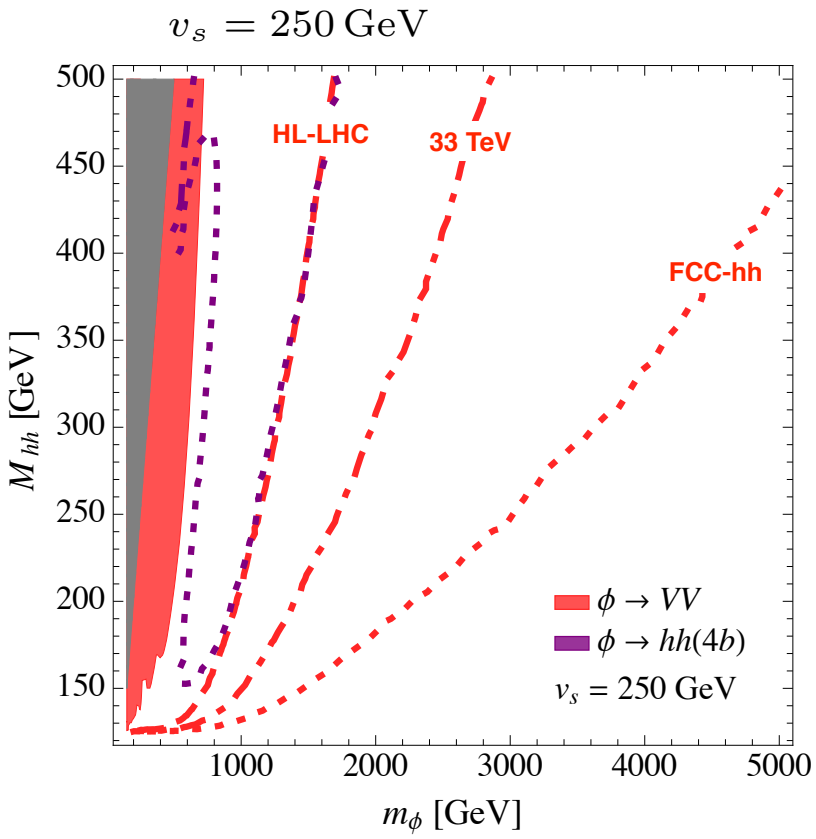
[Brownoson et al. '13]

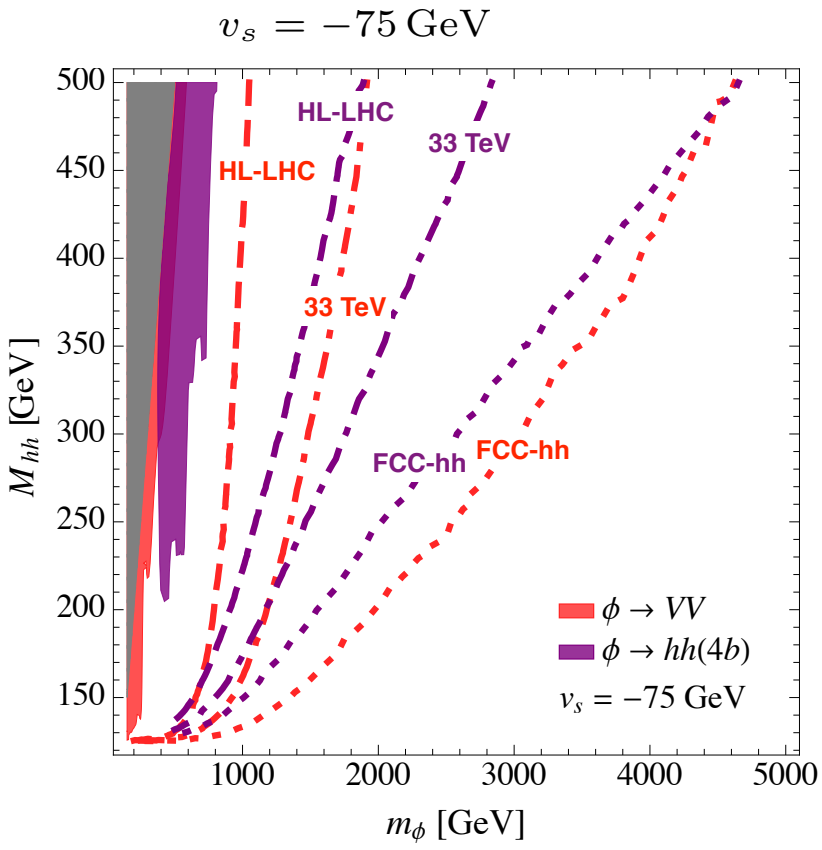
Direct searches: comparison of bounds



- Combining the VV and hh channels, the total reach does not strongly depend on $\mathrm{BR}_{\phi \to hh}$
- At high masses relevant for FCC, VV dominant (equivalence theorem)

Direct searches: comparison of bounds

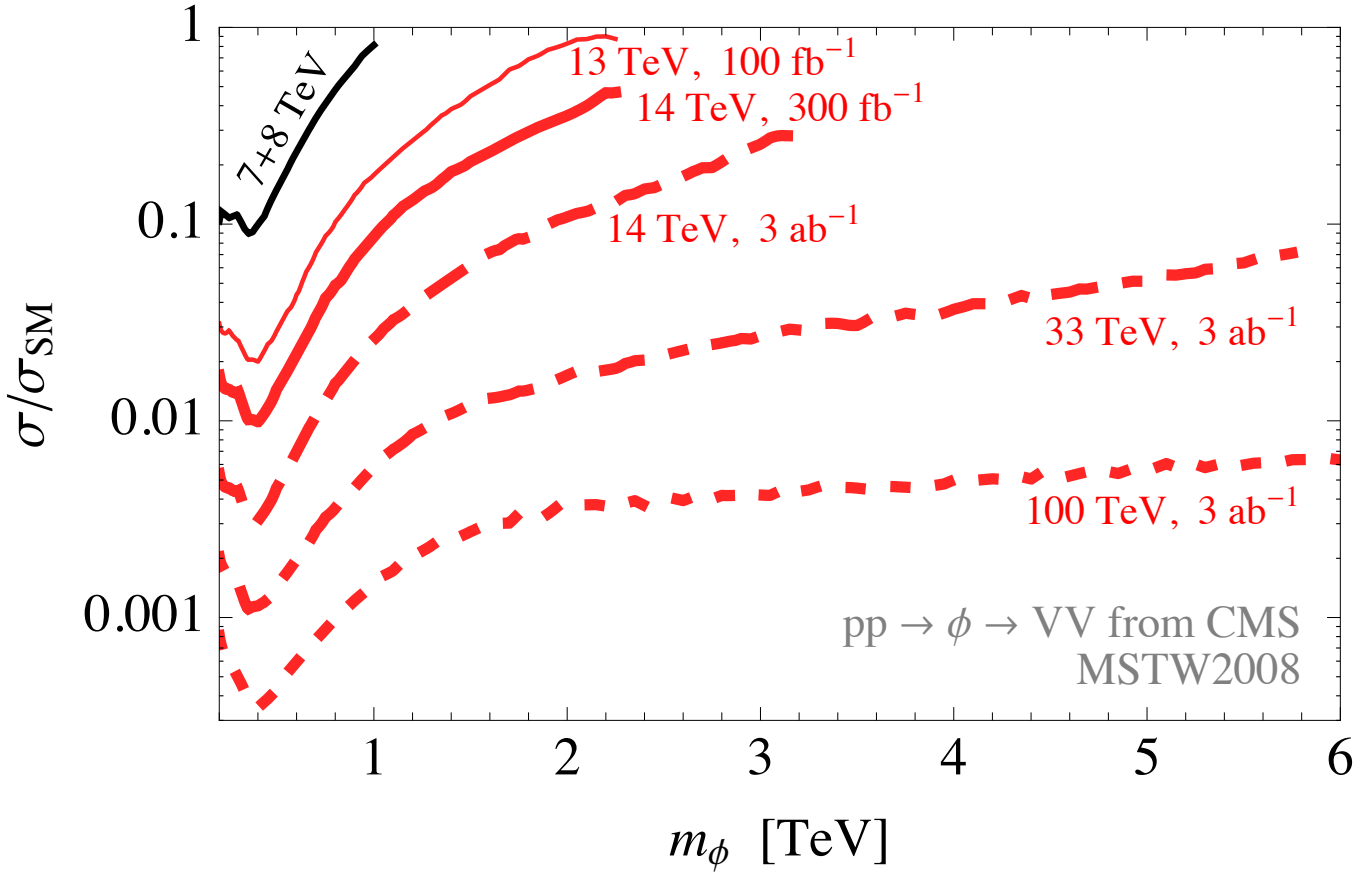




- Combining the VV and hh channels, the total reach does not strongly depend on $\mathrm{BR}_{\phi \to hh}$
- At high masses relevant for FCC, VV dominant (equivalence theorem)

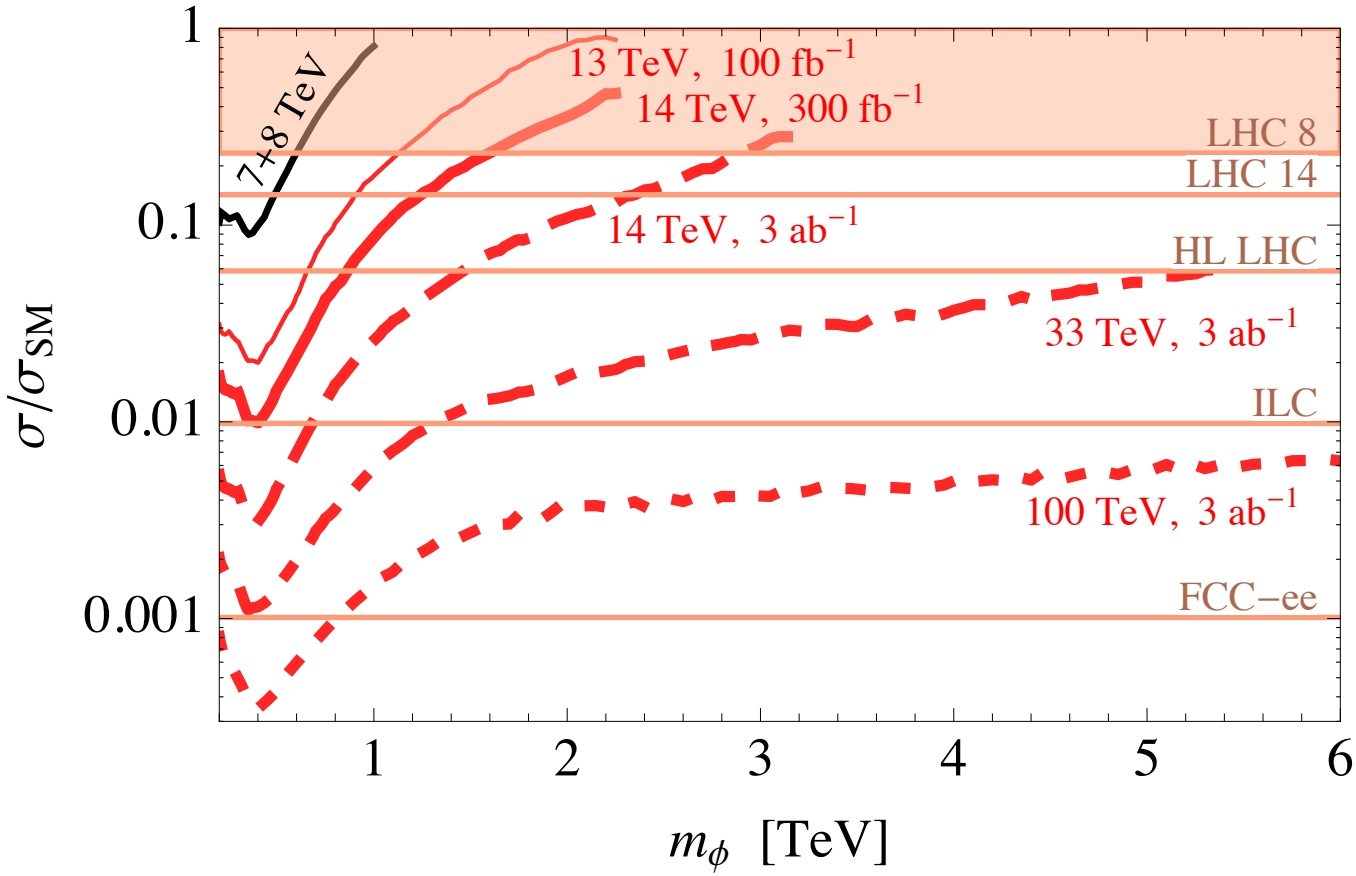
Direct vs indirect

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...)



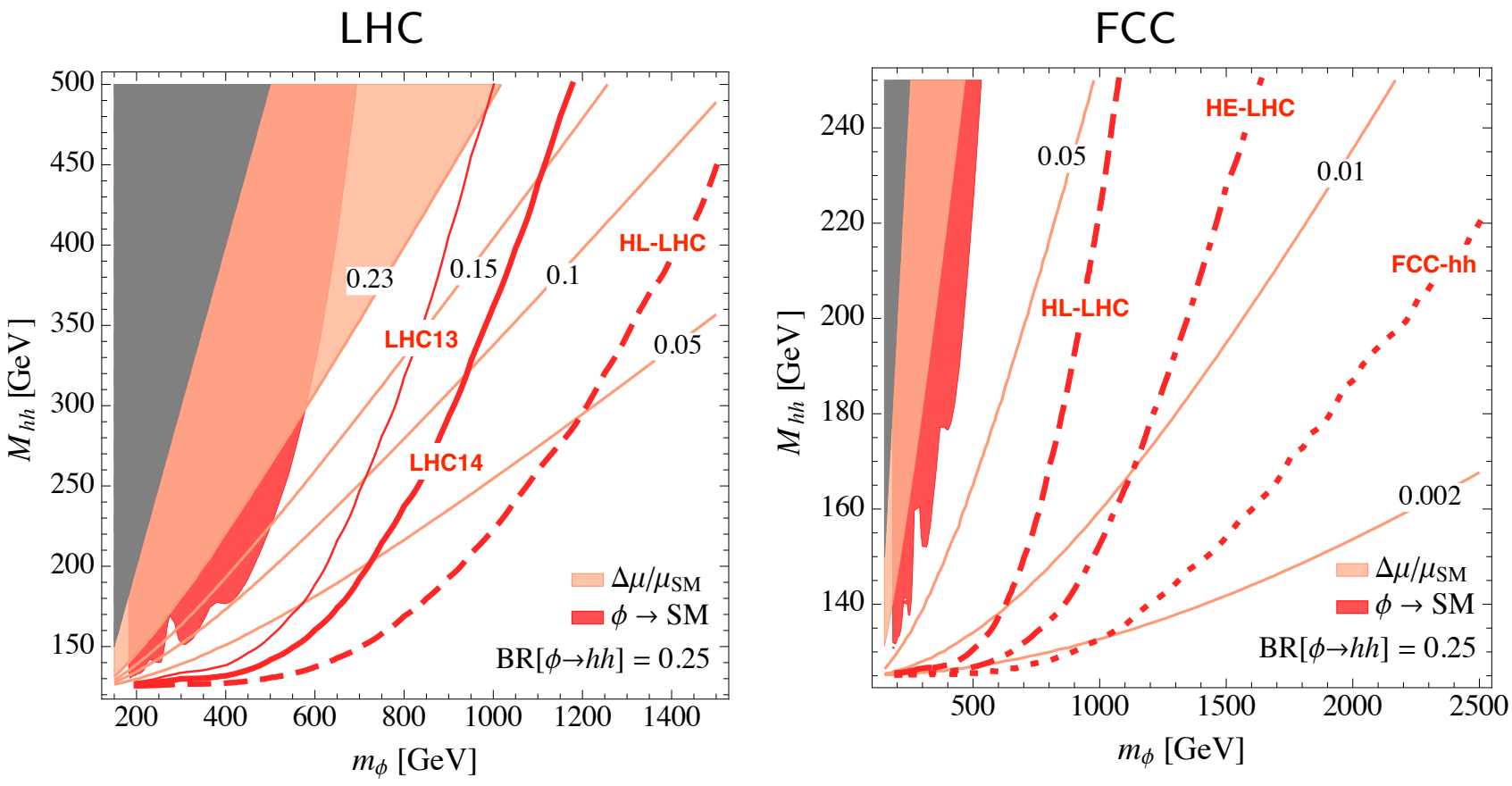
Direct vs indirect

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...)



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

Direct vs indirect



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

Twin Higgs

◇ Neutral naturalness: Higgs mass is protected from radiative corrections without coloured states at the weak scale

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

Higgs potential with approximate $\mathrm{SO}(8)$ symmetry.

Global symmetry broken by m, κ to reproduce $m_h, v \neq 0$.

◇ Linear σ-model: there is a "radial mode" with mass $m_\sigma^2 \approx \lambda_* f^2$.

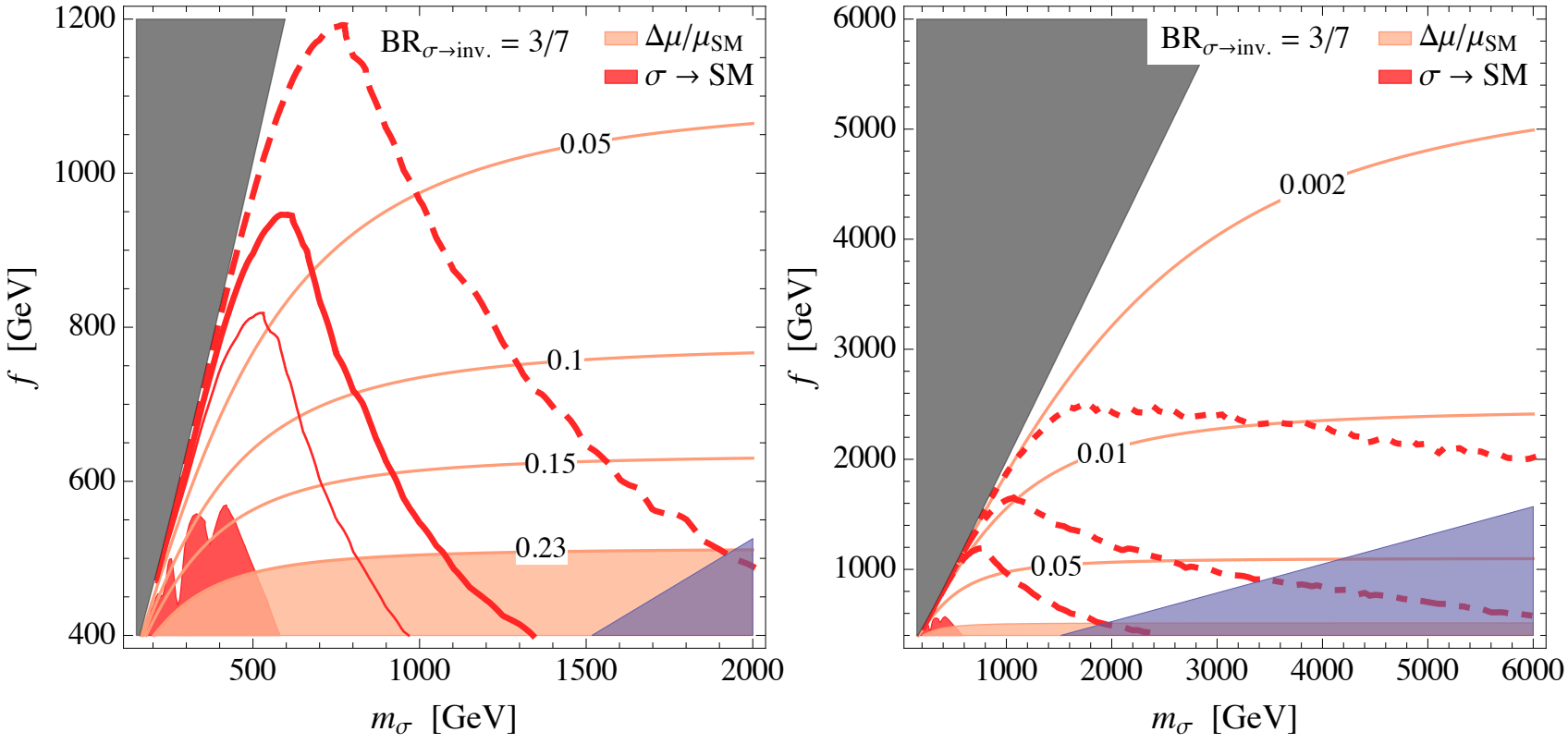
◇ The model is fully determined by 4 parameters: m_σ, f, m_h, v.

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

- recast the generic singlet bounds

Twin Higgs

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



- If not too strongly coupled, the Twin Higgs could be directly visible!
- Model-independent probe of the Twin scenario, with Higgs couplings

SUSY: the NMSSM

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

- Extra treel-level contribution to the Higgs mass $\Rightarrow$ lighter stops:

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

- Parametrically lower fine-tuning of v, for same values of the soft masses

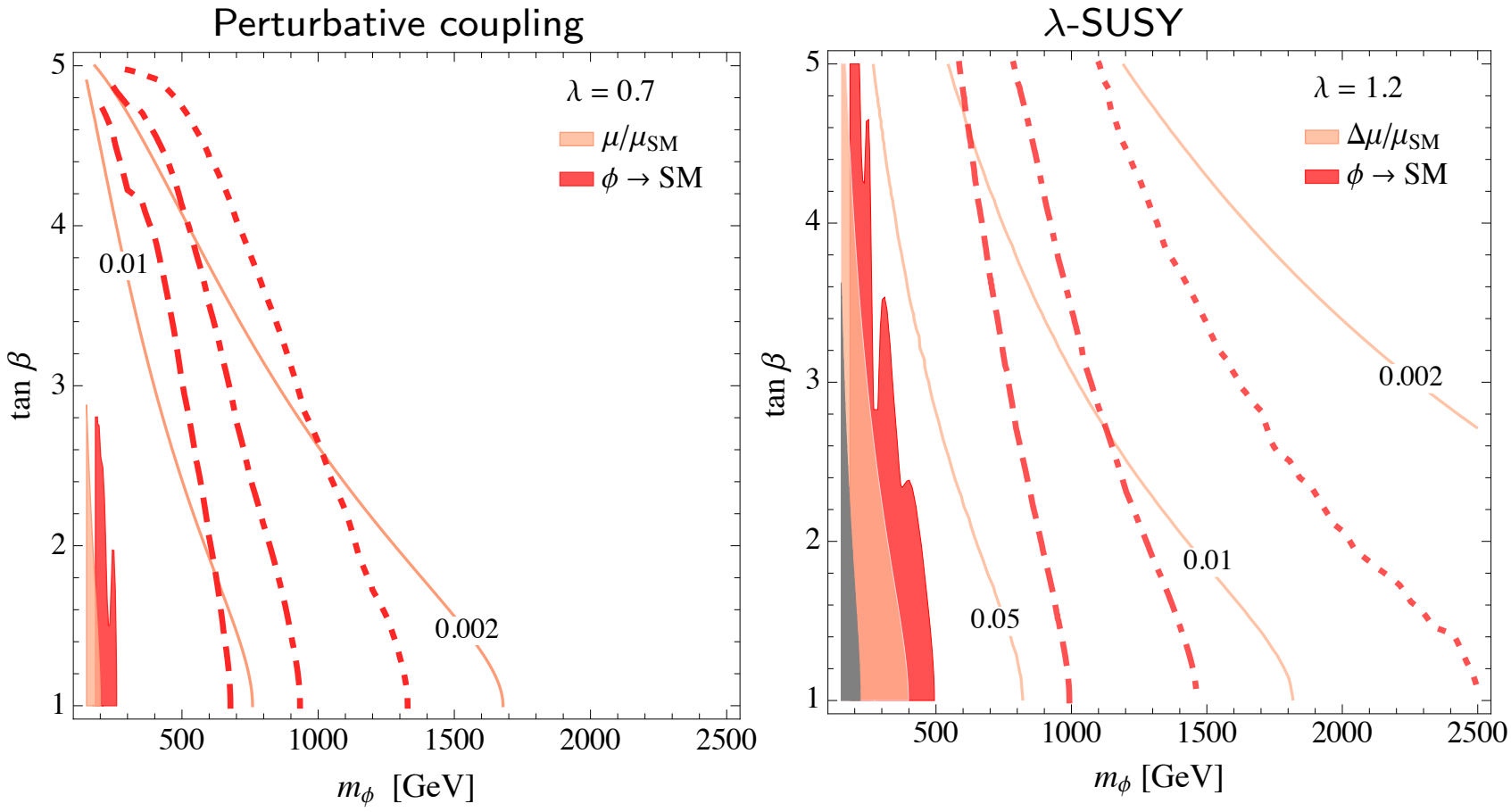
$$\delta v^2|_{\rm NMSSM} \sim \frac{\cot 2\beta}{\lambda^3} \times \tilde{m}^2, \qquad \delta v^2|_{\rm MSSM} \sim \frac{4}{g^2} \times \tilde{m}^2$$

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

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

SUSY: the NMSSM

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



- Direct searches generically dominate over Higgs couplings
- Direct reach at 100 TeV comparable with FCC-ee sensitivity

Conclusions

- Looking for singlets is easy, and motivated by many (natural) models
  - Direct searches are a powerful probe
  - Higgs precision measurements more effective at high masses
- General description in terms of few physical parameters
- Projections for the reach of FCC in diboson channels
- Twin Higgs & NMSSM: two prime examples of most natural models that contain a singlet

Backup

Extrapolation procedure

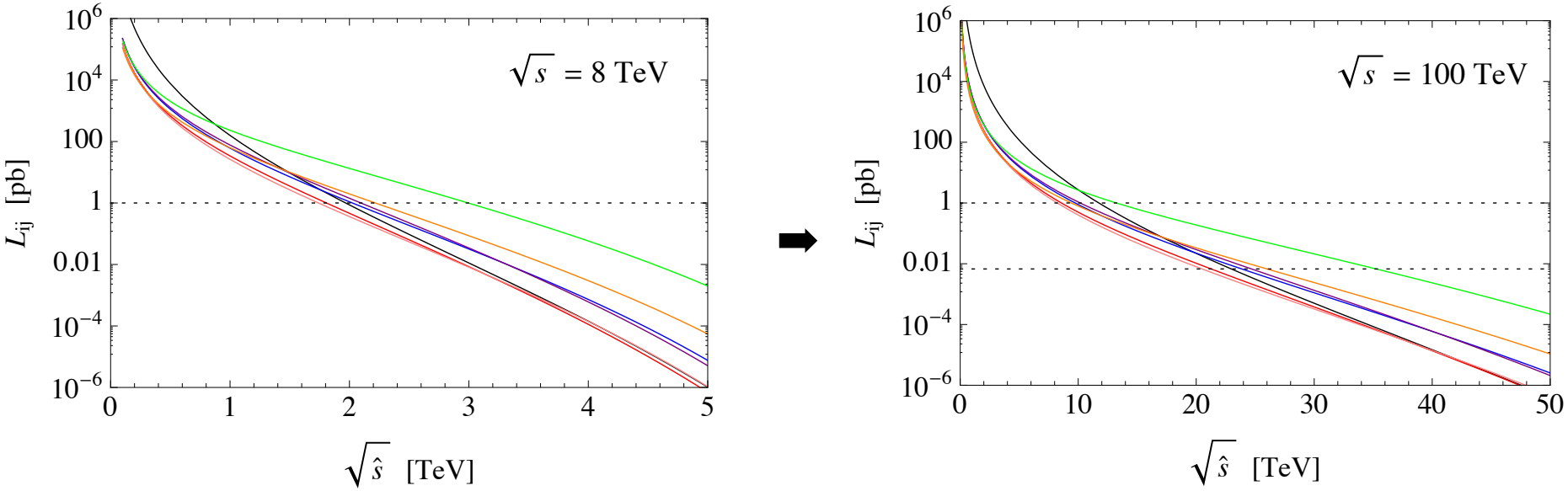
- # of bkg events:

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

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

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

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



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'.

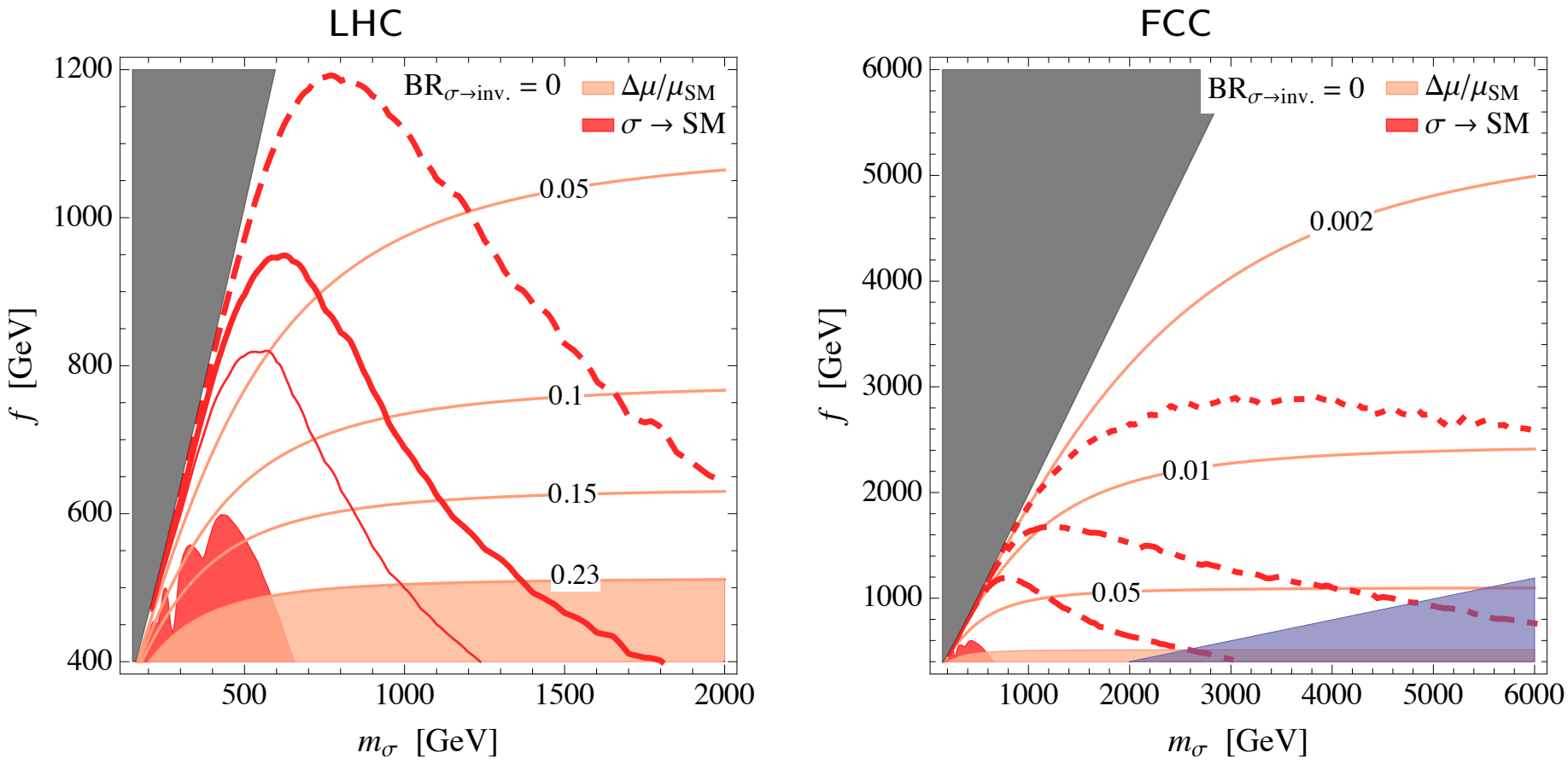
For each m, $L_0 \leq L' \leq L$ is chosen as to maximise the exclusion

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

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

(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

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

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

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:

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