Extra Higgs bosons in SUSY and beyond

based on 1505.05488 with F. Sala and A. Tesi
and 1304.3670 ,1307.4937 with R. Barbieri, K. Kannike, F. Sala and A. Tesi

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Intent and motivation

- One or more Higgs bosons?
  May the extra Higgs bosons be the lightest new particles?

- Identify a few most natural, motivated SUSY scenarios,
  in light of present and future experimental searches

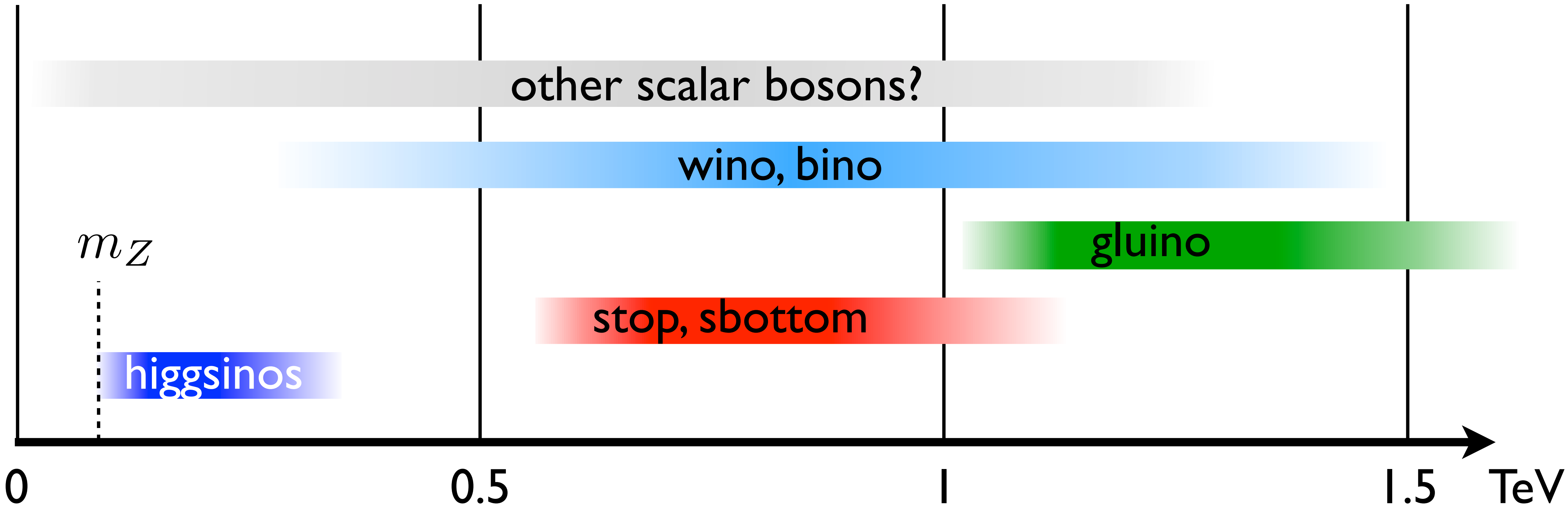
- Sketch a search strategy for the extra scalar states

1. Precision measurements of the couplings of the 125 GeV (standard-like) Higgs boson h_{LHC}

2. Direct searches: $pp \to h_{\cancel{LHC}} + X$

   decay products

An “almost natural” SUSY spectrum

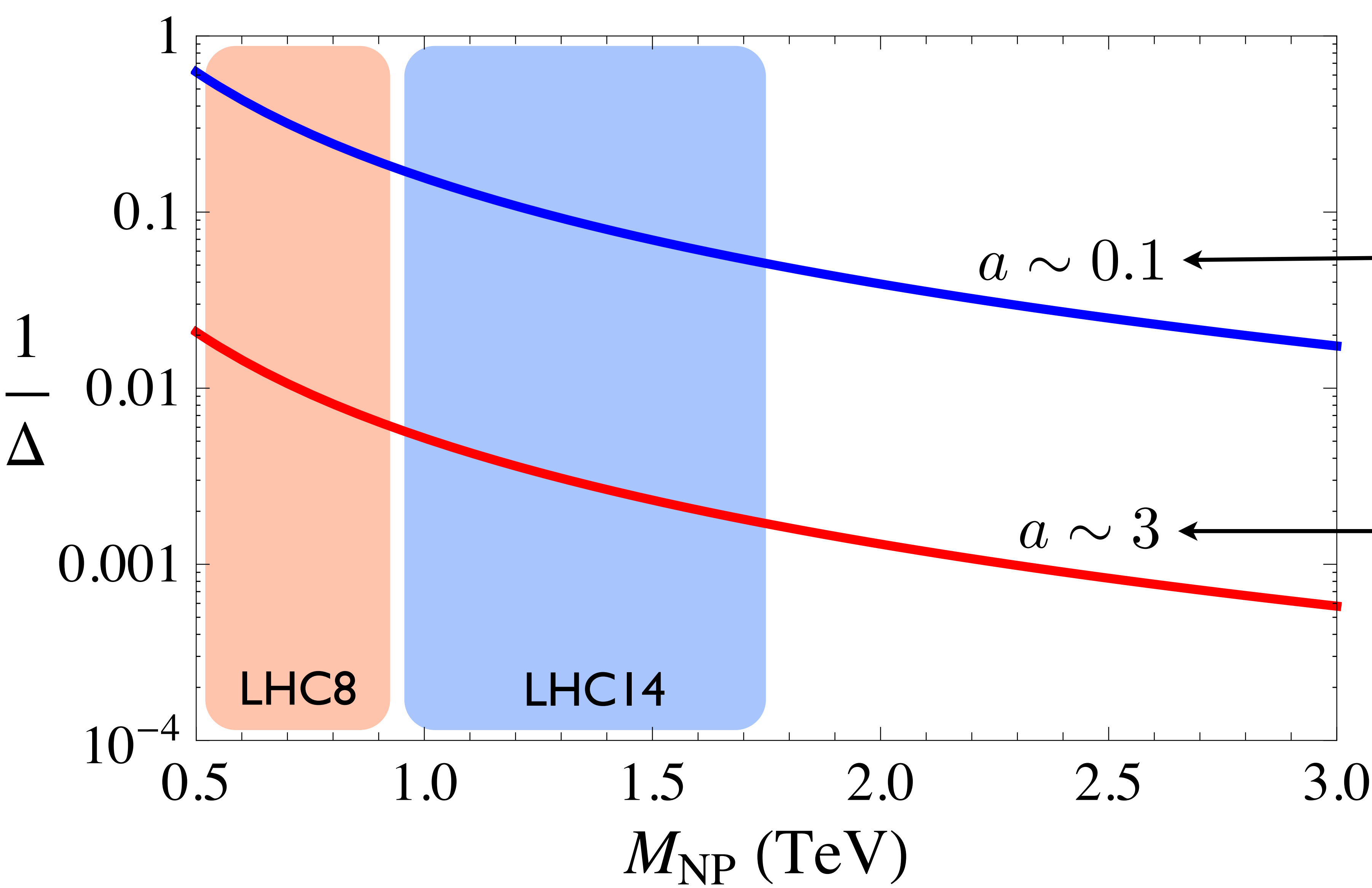


- Light top squarks: most strongly coupled to the Higgs boson
- Light gluino: affects the stop mass, and Higgs at two loops
- Light higgsinos: experimentally not very constrained

Where do we stand?

- A measure of fine-tuning: $\delta m_h^2 = a M_{\rm NP}^2 < \Delta \cdot m_h^2$

model dependent



hard to achieve (some NMSSM)

a typical MSSM

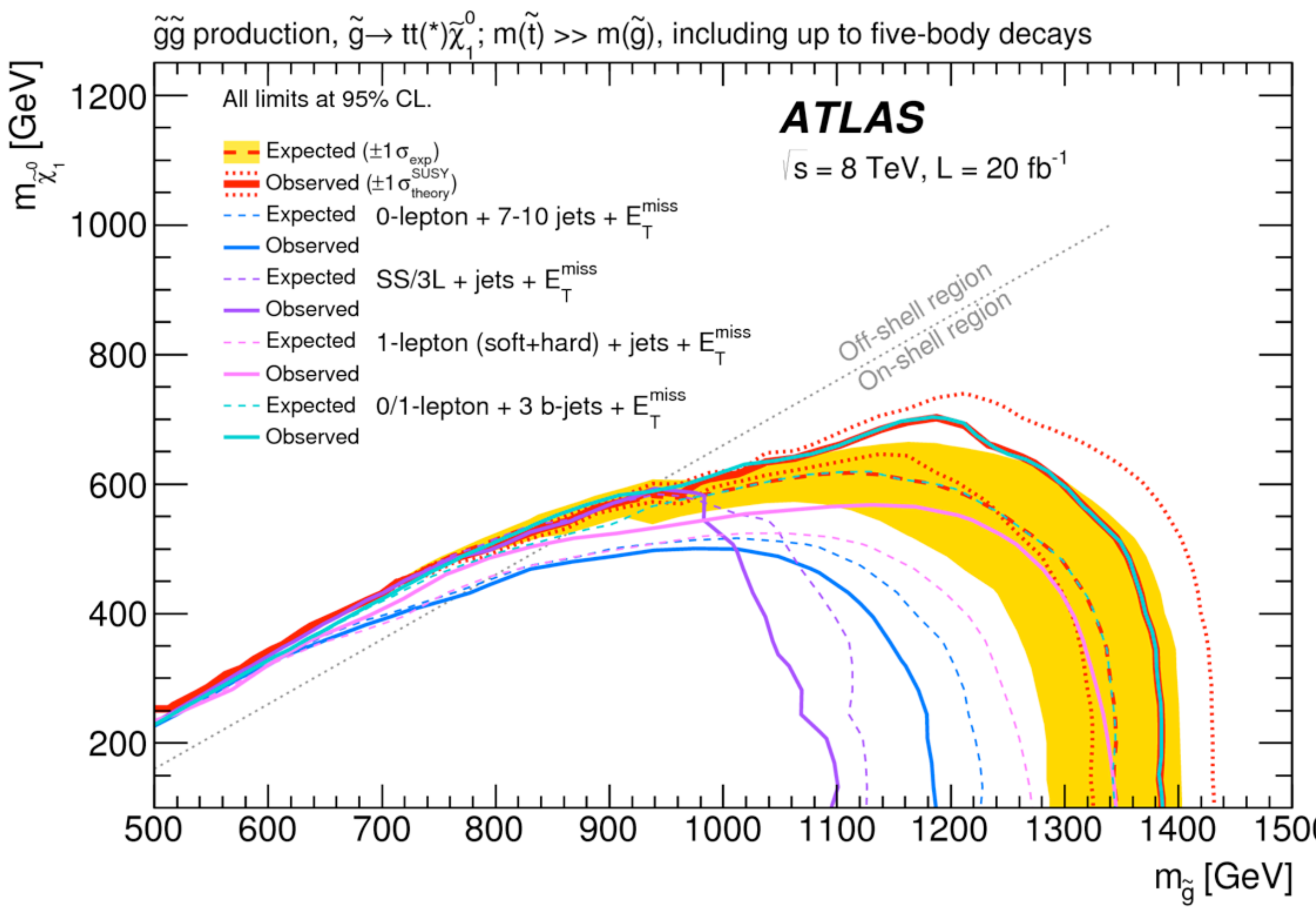
Where do we stand?

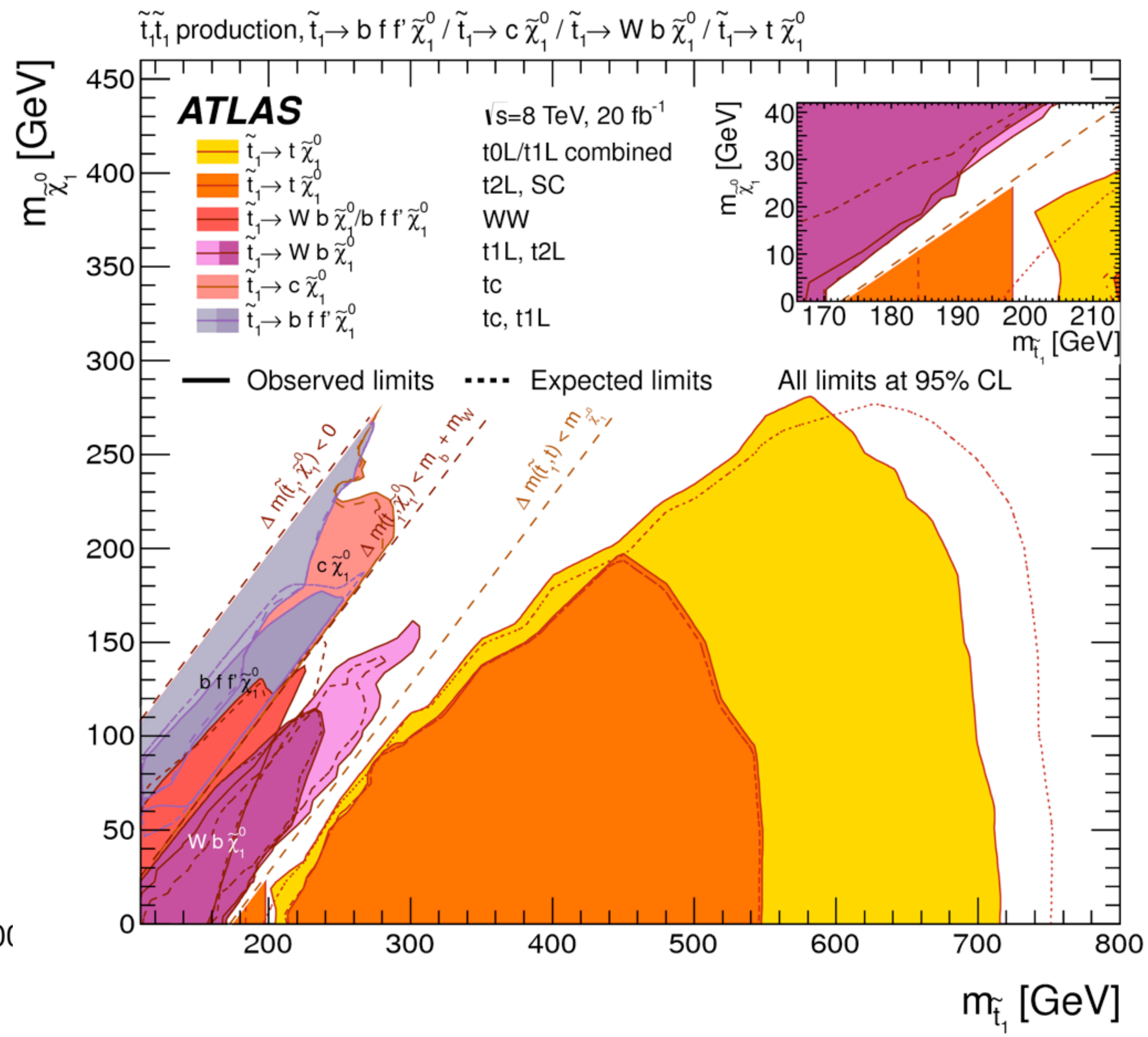
- A measure of fine-tuning: $\delta m_h^2 = a M_{\rm NP}^2 < \Delta \cdot m_h^2$

model dependent

$m_{\tilde{t}} \gtrsim 700\,\mathrm{GeV}$

$m_{\tilde{g}} \gtrsim 1.4\,\mathrm{TeV}$





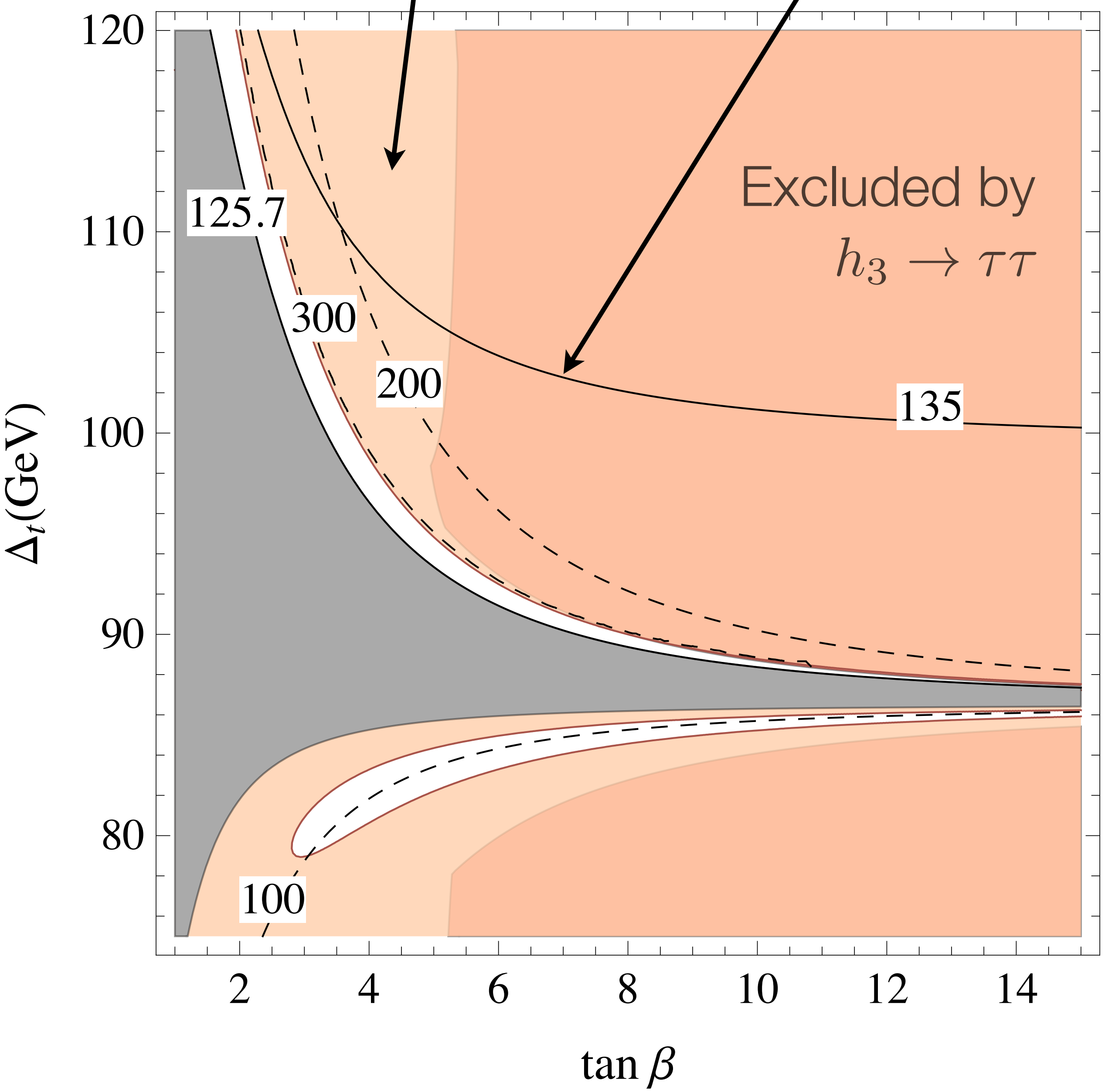
Higgs mass in the MSSM

$$m_h^2 < m_{hh}^2 = m_Z^2 c_{2\beta}^2 + \Delta_t^2$$ Δ_t is the top-stop contribution to m_h

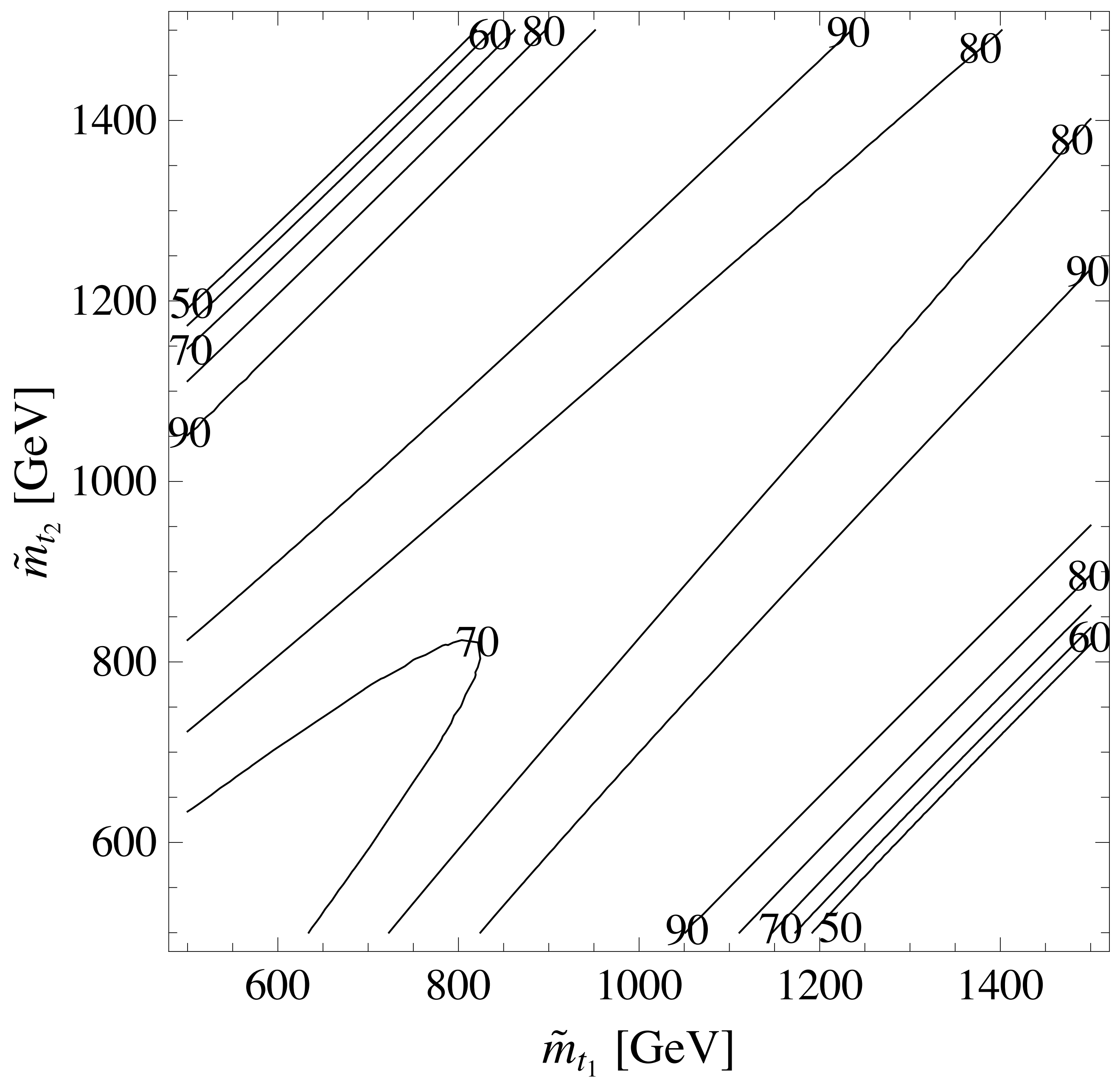
Excluded by h_{LHC} signal strengths

[see also Diego's talk...]

Isolines of m_{hh}

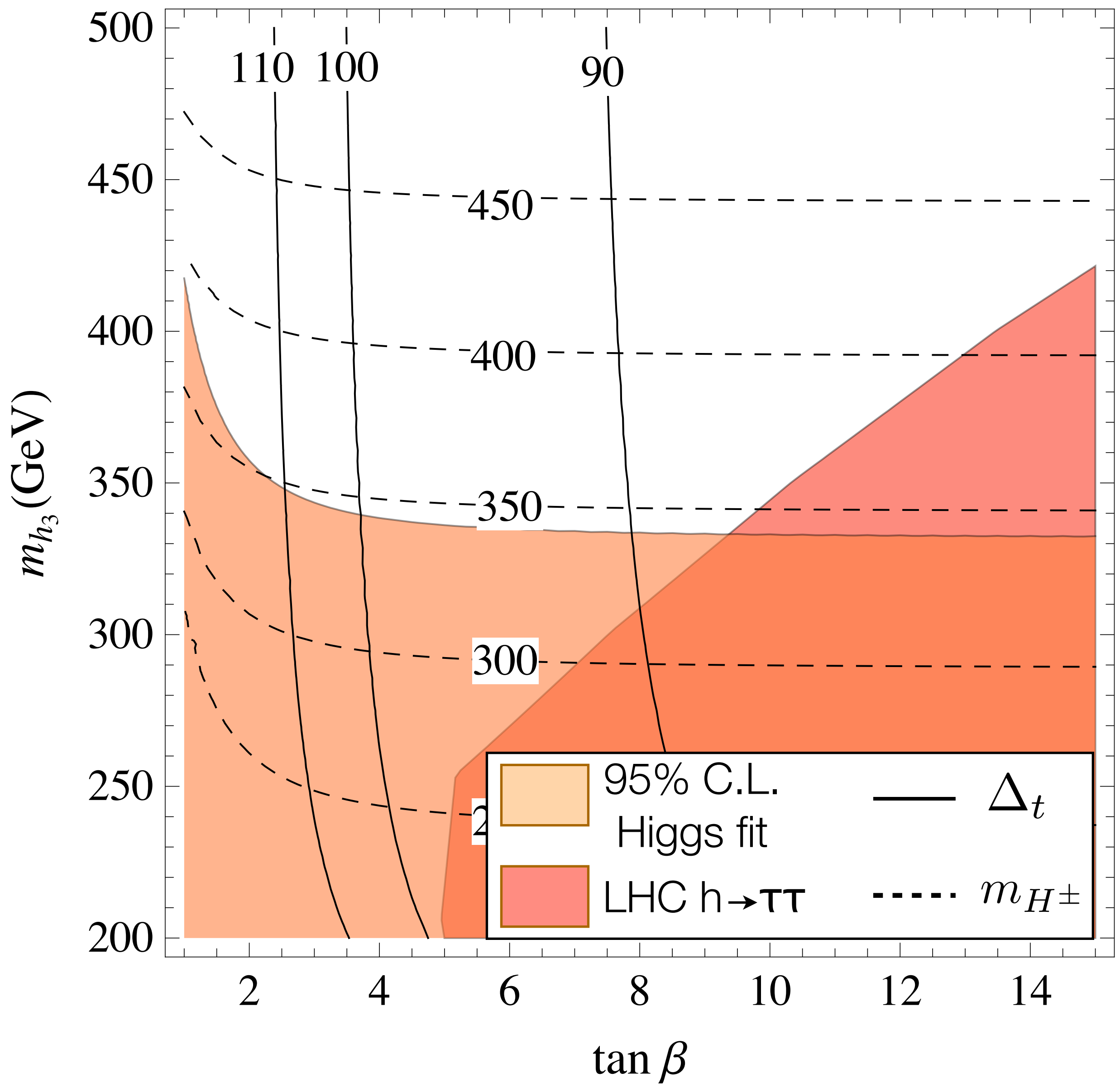


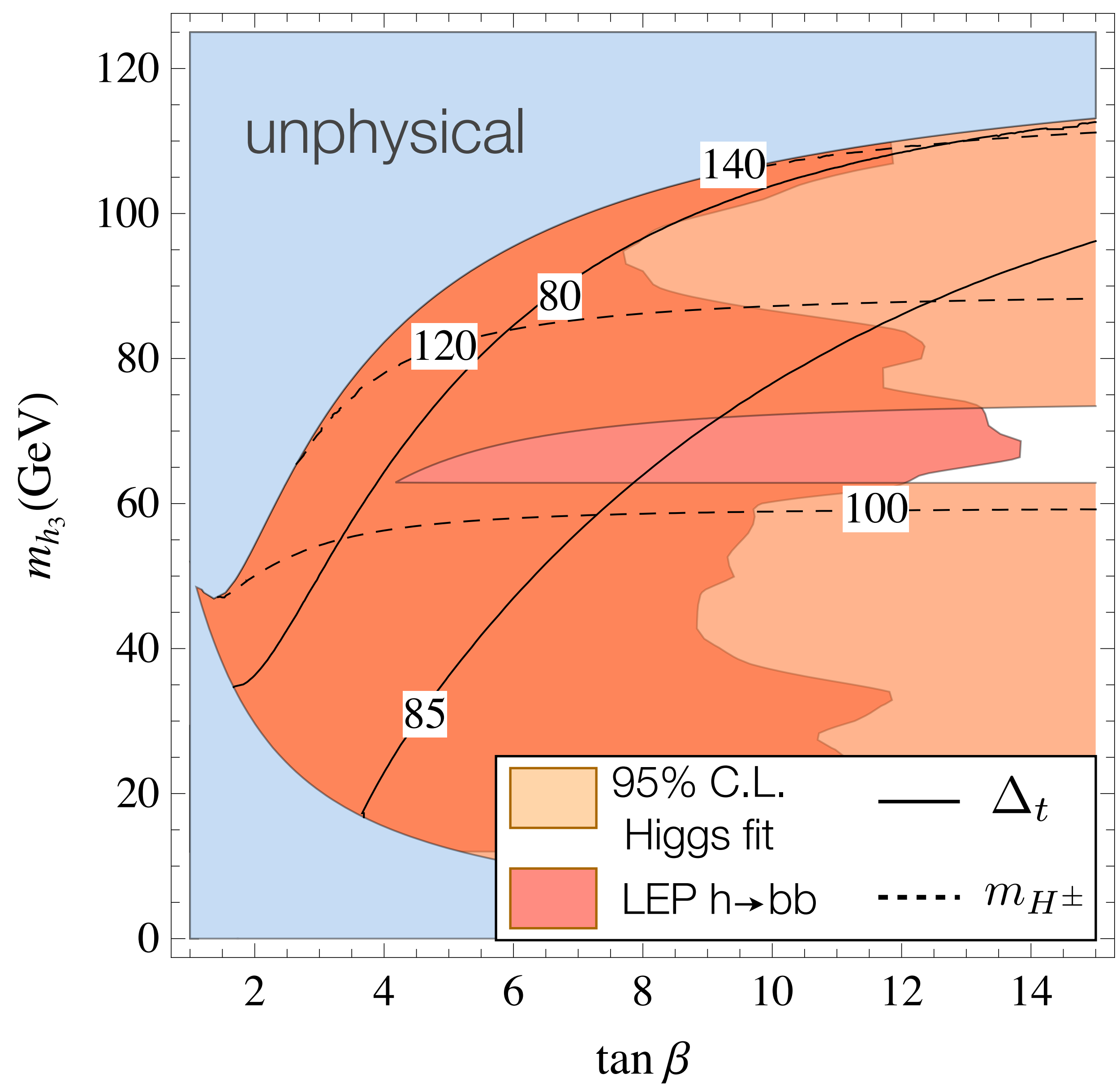
Isolines of Δ_t $(\theta_t = 45^\circ, \tan\beta = 5)$



MSSM

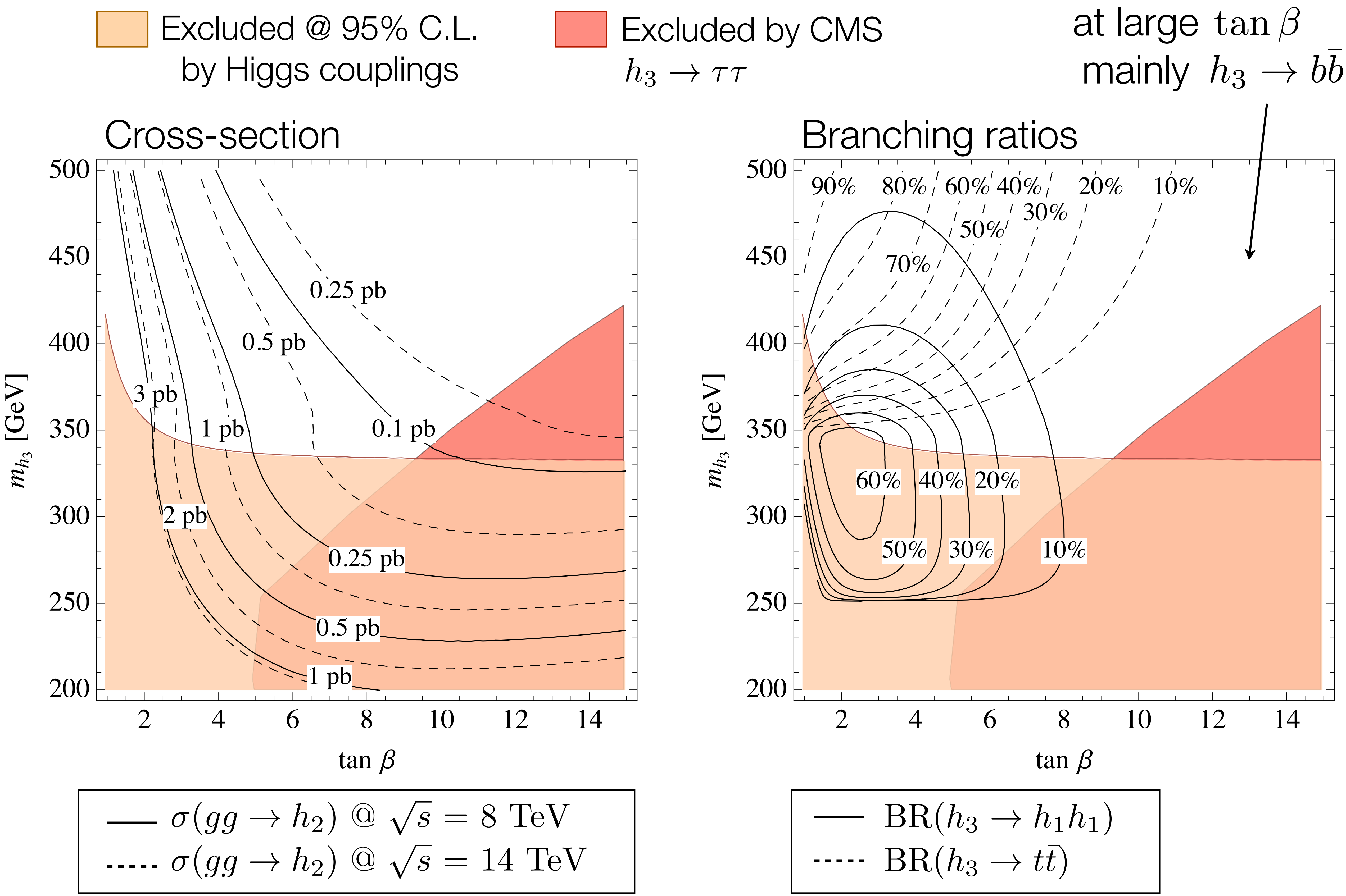
- A second scalar lighter than 350 GeV is excluded (except a small window)





- Whole parameter space up to ~ 1 TeV will be tested by Higgs fit @ LHC14

MSSM


Excluded @ 95% C.L. by Higgs couplings
Excluded by CMS $h_3 \to \tau\tau$
at large $\tan\beta$ mainly $h_3 \to b\bar{b}$
Cross-section
Branching ratios
3 pb
2 pb
1 pb
0.5 pb
0.25 pb
0.1 pb
90%
80%
70%
60%
50%
40%
30%
20%
10%
m_{h_3} [GeV]
$\tan\beta$
$\sigma(gg \to h_2)$ @ $\sqrt{s} = 8$ TeV
$\sigma(gg \to h_2)$ @ $\sqrt{s} = 14$ TeV
$\mathrm{BR}(h_3 \to h_1 h_1)$
$\mathrm{BR}(h_3 \to t\bar{t})$

Higgs mass in the NMSSM $\quad W \supset \lambda S H_u H_d$

- Extra contribution to the tree-level Higgs mass
$$m_{hh}^2 = m_Z^2 c_{2\beta}^2 + \Delta_t^2 + \boxed{\lambda^2 v^2 s_{2\beta}^2} \Rightarrow \text{allows for lighter stops}$$

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

$$\left.\frac{dv^2}{dm_{H_u}^2}\right|_{NMSSM} \simeq \frac{\kappa}{\lambda^3}\cot 2\beta, \qquad \left.\frac{dv^2}{dm_{H_u}^2}\right|_{MSSM} \simeq \frac{4}{g^2}$$

Hall et al. '11

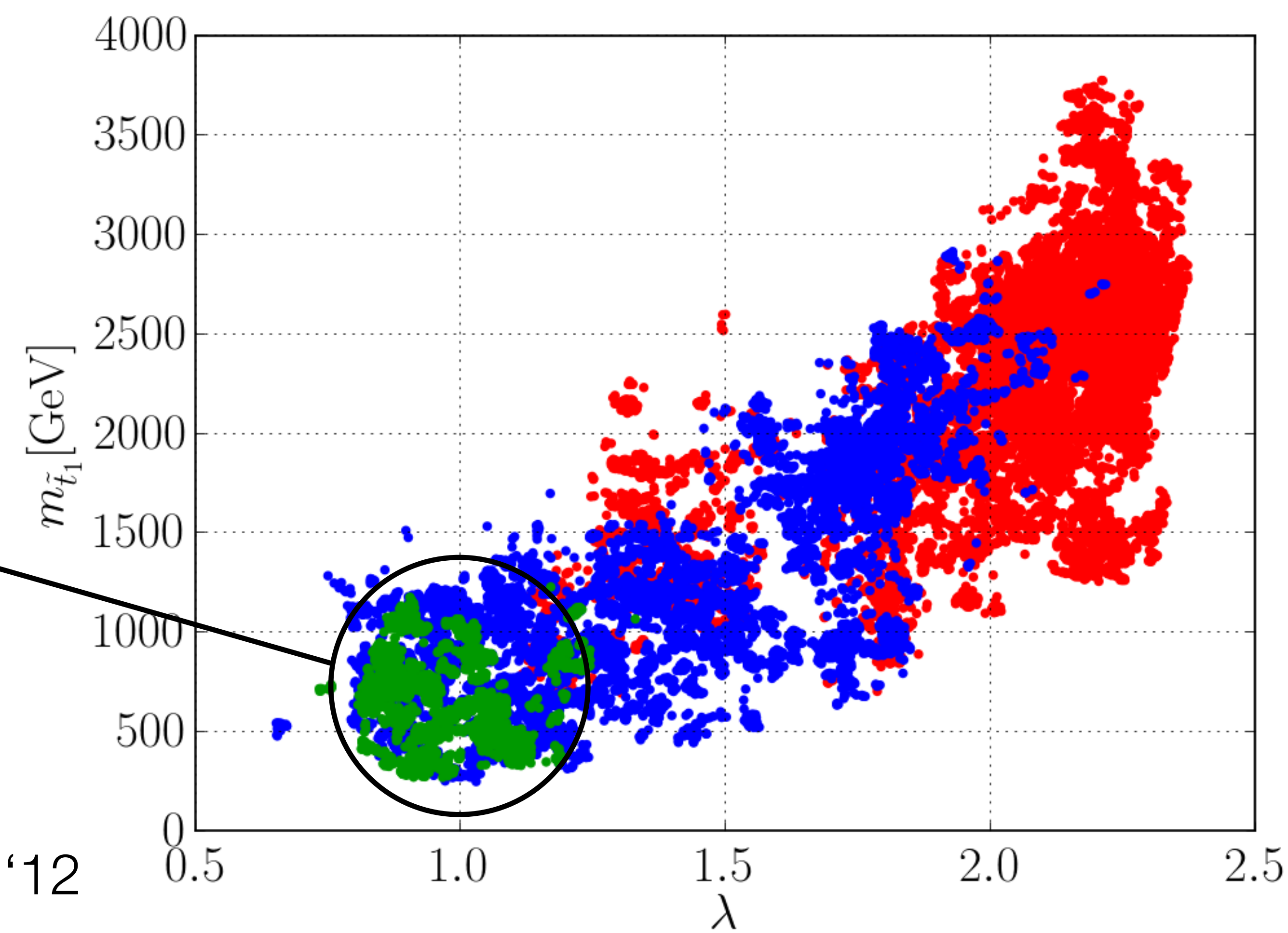
coefficient of quadratic correction to v

Example:

better than 5% combined fine-tuning and $\Lambda_{\rm mess} \approx 20\,\mathrm{TeV}$ in the scale-invariant NMSSM

$$m_{\tilde t_1} \lesssim 1.2\,\mathrm{TeV}$$
$$m_{\tilde g} \lesssim 3\,\mathrm{TeV}$$

Gherghetta et al. '12



Assumptions

- General NMSSM: no specific singlet potential
- No CP violation in the Higgs sector

- No SUSY loops or invisible decays, e.g. $h_1 \to \chi\chi$
- Only loop contribution (from top-stop) Δ_t ~ 75 GeV
- Naturalness: light stops, gluinos, Higgsinos; $\mu A_t \lesssim \langle m_{\tilde{t}}^2 \rangle$

- Description in terms of physical parameters

Higgs sector of a general NMSSM

CP-even states: $\mathcal{H} = (H, h, S)^T = R^{12}_\delta R^{23}_\gamma R^{13}_\sigma (h_3, h_1, h_2)^T \equiv R\,\mathcal{H}_{\rm phys}$

Mass matrix:

$$\mathcal{M} = R \cdot \mathrm{diag}\left(m_{h_3}, m_{h_1}, m_{h_2}\right) \cdot R^T$$

$$= \begin{pmatrix} m_A^2 + s_{2\beta}^2(m_Z^2 - \lambda^2 v^2) + \frac{\Delta_t^2}{t_\beta^2} & \frac{s_{4\beta}}{2}(m_Z^2 - \lambda^2 v^2) - \frac{\Delta_t^2}{t_\beta^2} & \lambda v M_1 \\ \frac{s_{4\beta}}{2}(m_Z^2 - \lambda^2 v^2) - \frac{\Delta_t^2}{t_\beta^2} & m_Z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2 + \Delta_t^2 & \lambda v M_2 \\ \lambda v M_1 & \lambda v M_2 & M_3^2 \end{pmatrix}$$

3 relations

$\delta, \gamma, \sigma = \delta, \gamma, \sigma\left(m_{h_i}^2, m_{H^\pm}^2, \lambda, \tan\beta, \Delta_t\right)$

3 mixing angles, 6 independent parameters

3 unknown parameters
$M_i[V(S), \mu_{\rm eff}]$

$m_A^2 = m_{H^\pm}^2 - m_W^2 + \lambda^2 v^2$ (not the physical pseudoscalar mass)

Higgs sector of a general NMSSM

CP-even states: $\mathcal{H} = (H, h, S)^T = R_\delta^{12} R_\gamma^{23} R_\sigma^{13} (h_3, h_1, h_2)^T \equiv R\,\mathcal{H}_{\rm phys}$

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3 relations

1 relation

$\delta, \lambda, m_{H^\pm} = \delta, \lambda, m_{H^\pm}(m_{h_3}^2, \tan\beta, \Delta_t)$

3 independent parameters

$\gamma = \gamma(m_{h_2}^2, \lambda, \tan\beta, \Delta_t)$

4 independent parameters

$m_A^2 = m_{H^\pm}^2 - m_W^2 + \lambda^2 v^2$ (not the physical pseudoscalar mass)

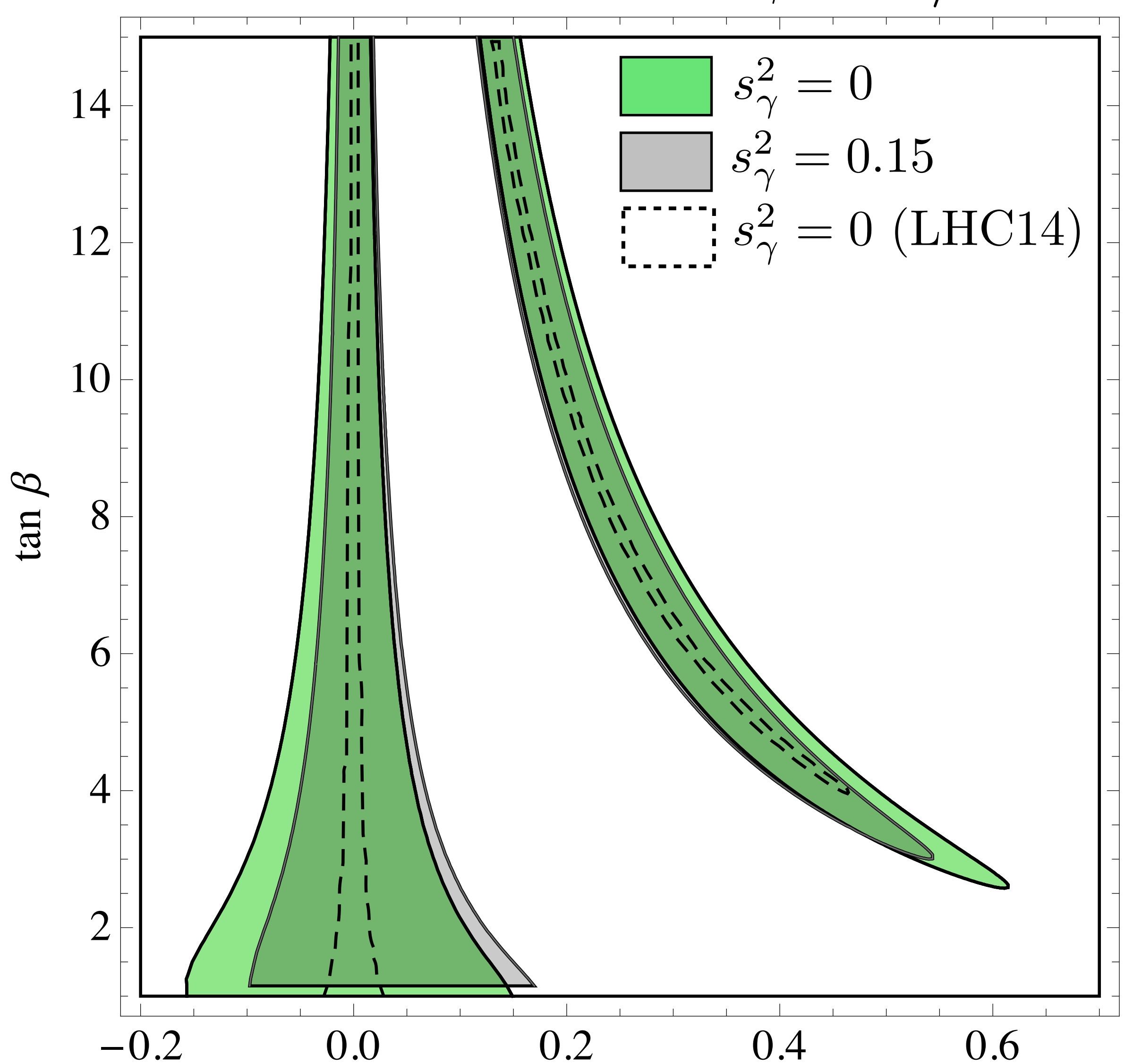
Decoupling limits: $m_A \to \infty$ or $M_3 \to \infty$

Modified Higgs couplings

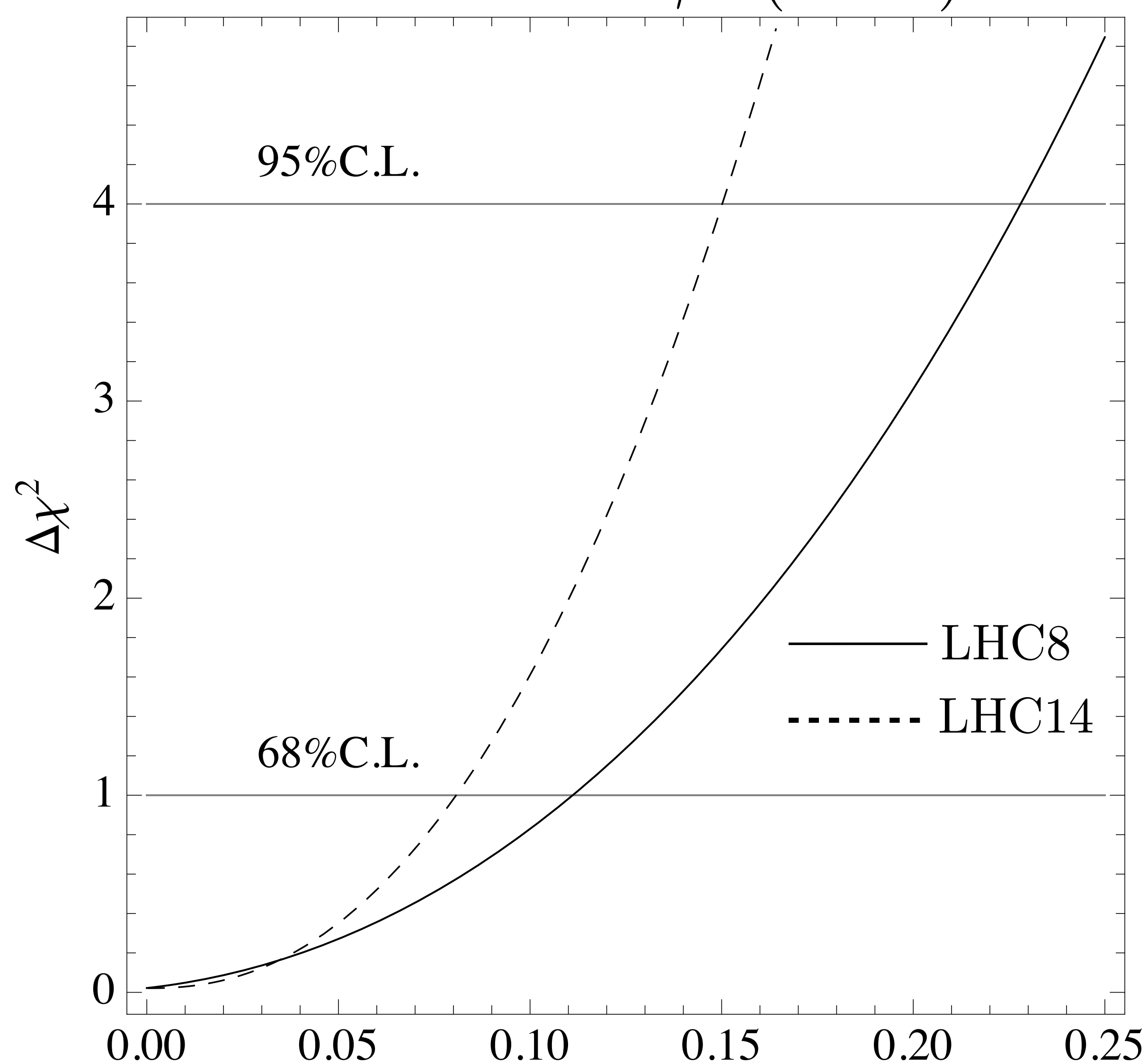
- Take $h_1 = c_\gamma(c_\alpha H_u - s_\alpha H_d) + s_\gamma S = c_\gamma(c_\delta h - s_\delta H) + s_\gamma S \equiv h_{\rm LHC}$

$$\frac{g_{h_1tt}}{g_{htt}^{\rm SM}} = c_\gamma\left(c_\delta + \frac{s_\delta}{\tan\beta}\right), \qquad \frac{g_{h_1bb}}{g_{hbb}^{\rm SM}} = c_\gamma\left(c_\delta - s_\delta \tan\beta\right), \qquad \frac{g_{h_1VV}}{g_{hVV}^{\rm SM}} = c_\gamma c_\delta$$

95% C.L. on $\delta = \alpha - \beta + \pi/2$



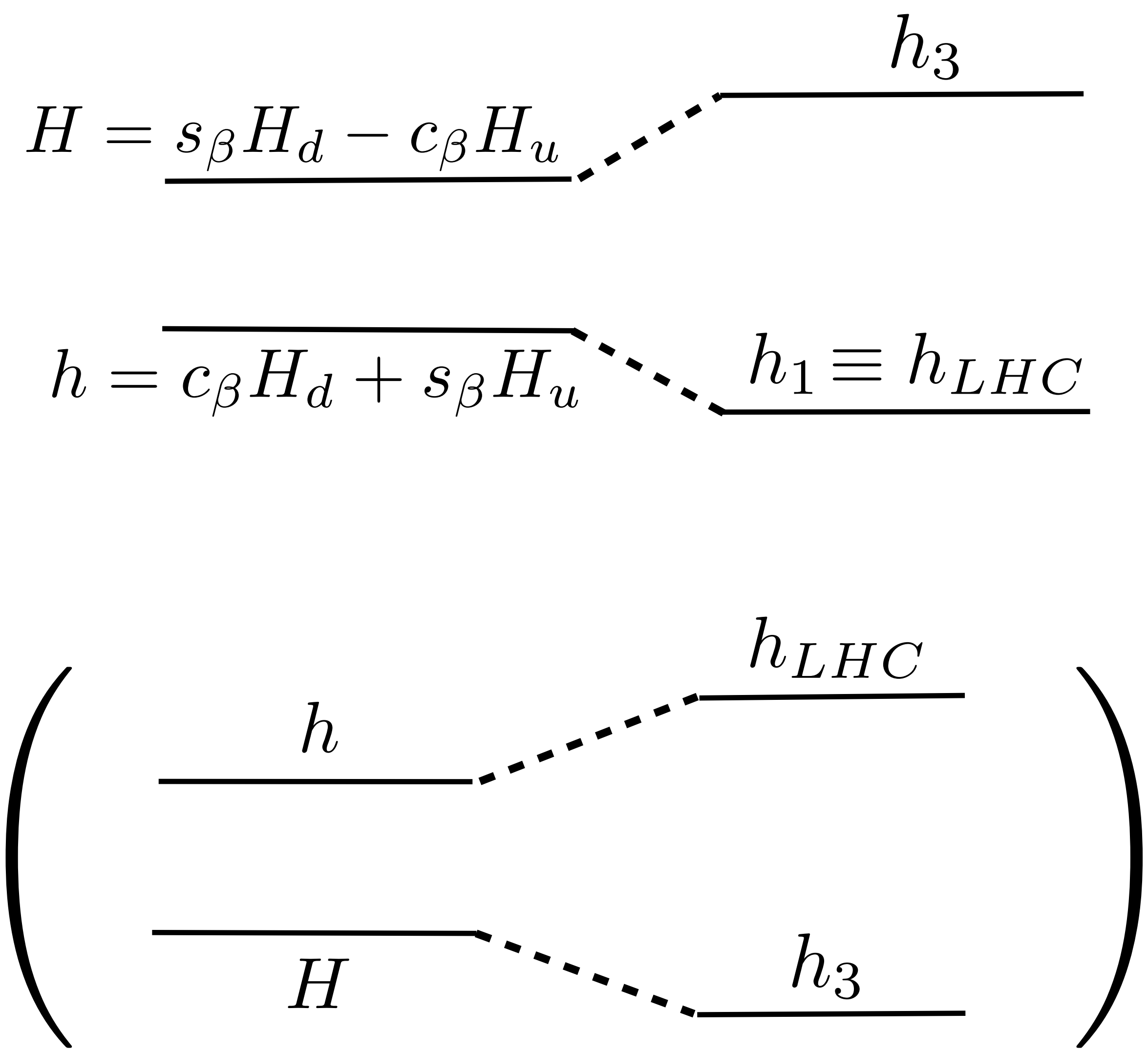
95% C.L. on $\sin^2\gamma \quad (\delta = 0)$



Two limiting cases

S decoupled

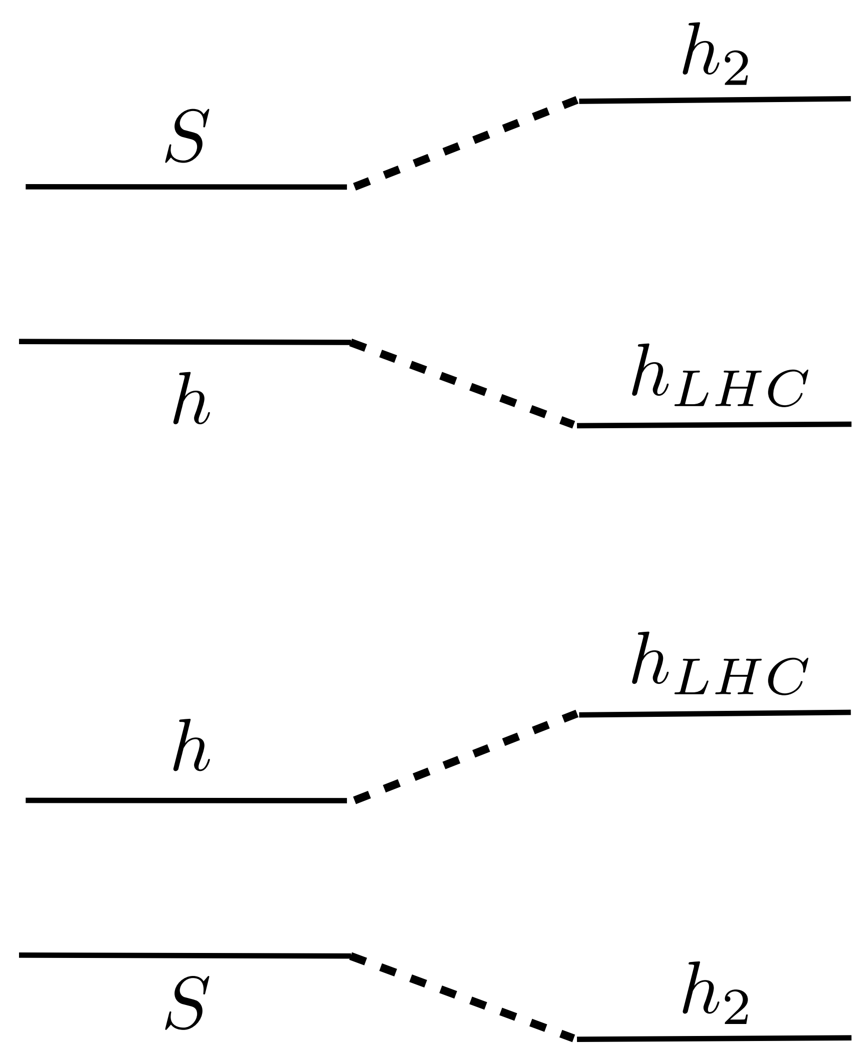
(both MSSM and NMSSM)



(unlikely: $H^\pm$ too light)

H decoupled

(NMSSM only)



Singlet decoupled

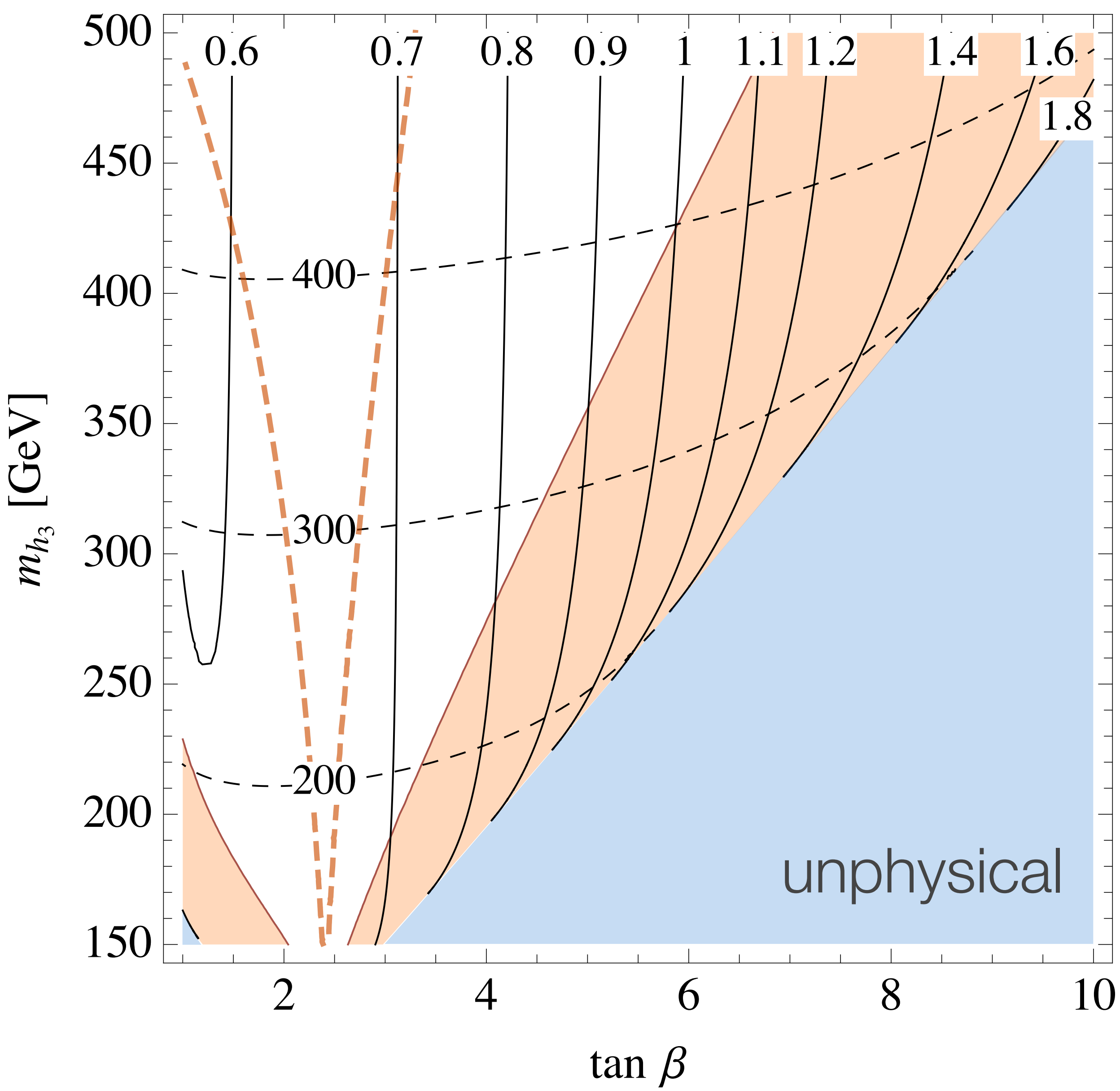
$M_3^2 \gg M_{1,2} v$ and $\gamma, \sigma \to 0$

3 independent parameters: $\delta, \lambda, m_{H^\pm} (m_{h_3}, \tan\beta, \Delta_t)$

$$\boxed{\begin{aligned} \Delta_t &\approx 75\,\mathrm{GeV} \\ \mu A_t &\lesssim \langle m_{\tilde{t}}^2 \rangle \end{aligned}}$$

$$\sin^2\delta = \frac{M_{hh}^2 - m_{h_1}^2}{m_{h_3}^2 - m_{h_1}^2} \quad \text{where } M_{hh}^2 = m_Z^2 c_{2\beta}^2 + v^2 \lambda^2 s_{2\beta}^2 + \Delta_t^2$$

$m_{h_3} > m_{h_1}$



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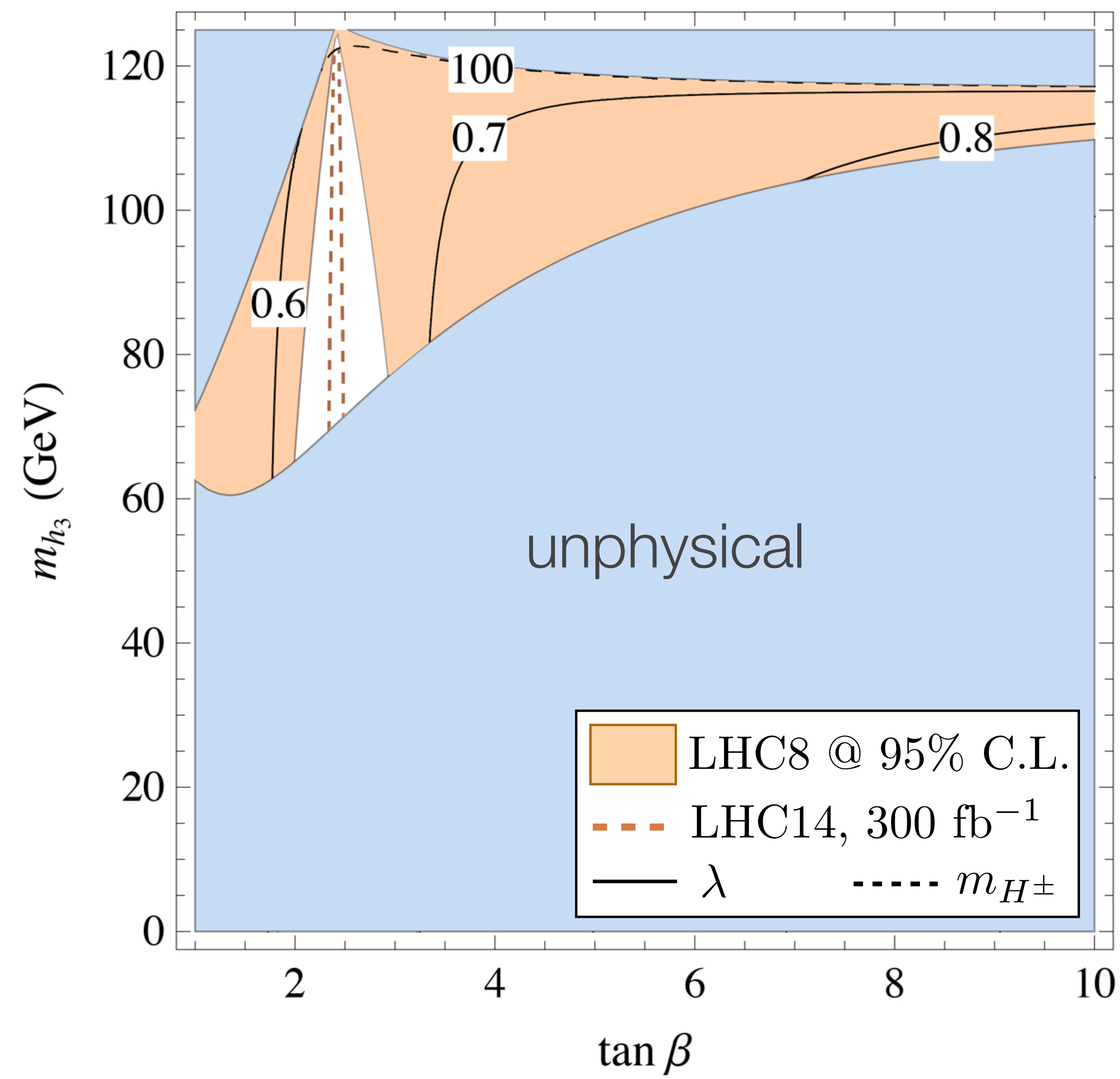
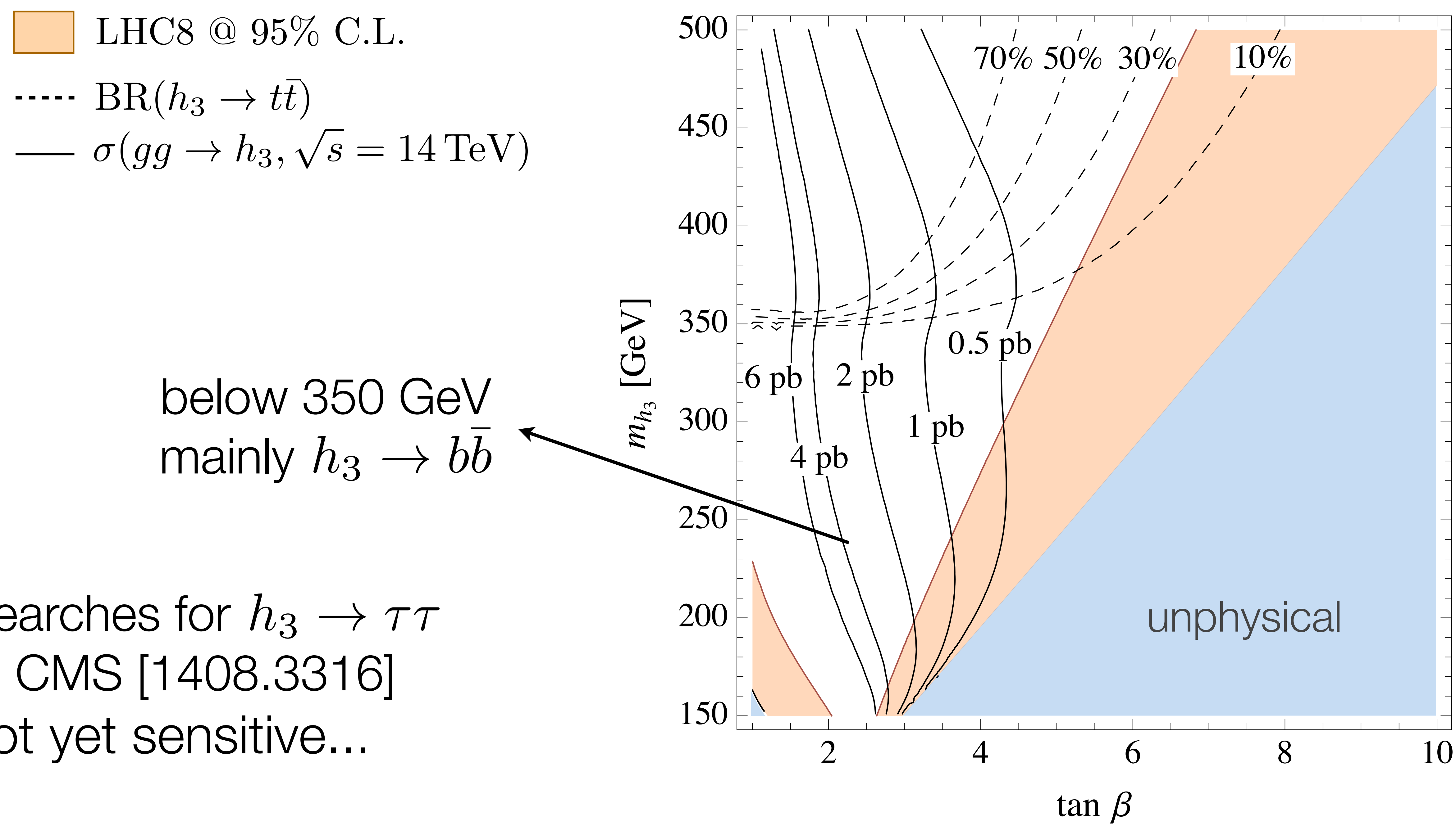


Singlet decoupled: h_3 production and decays

- Small values of λ: h_3 decays mainly into fermions ~ MSSM



below 350 GeV
mainly $h_3 \to b\bar{b}$

Searches for $h_3 \to \tau\tau$
at CMS [1408.3316]
not yet sensitive...

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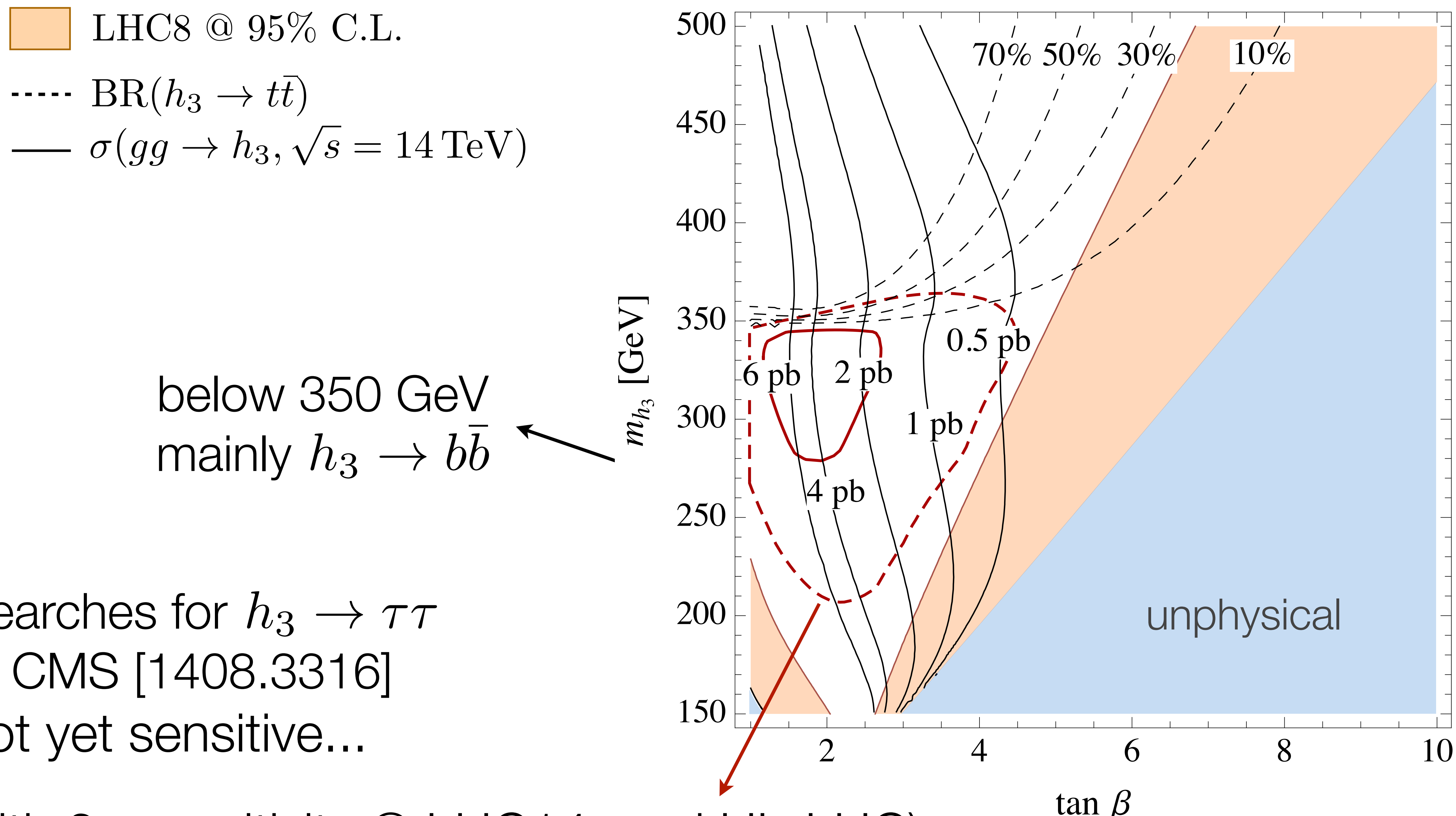

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Searches for $h_3 \to \tau\tau$
at CMS [1408.3316]
not yet sensitive...

(with 3x sensitivity @ LHC14, and HL-LHC)

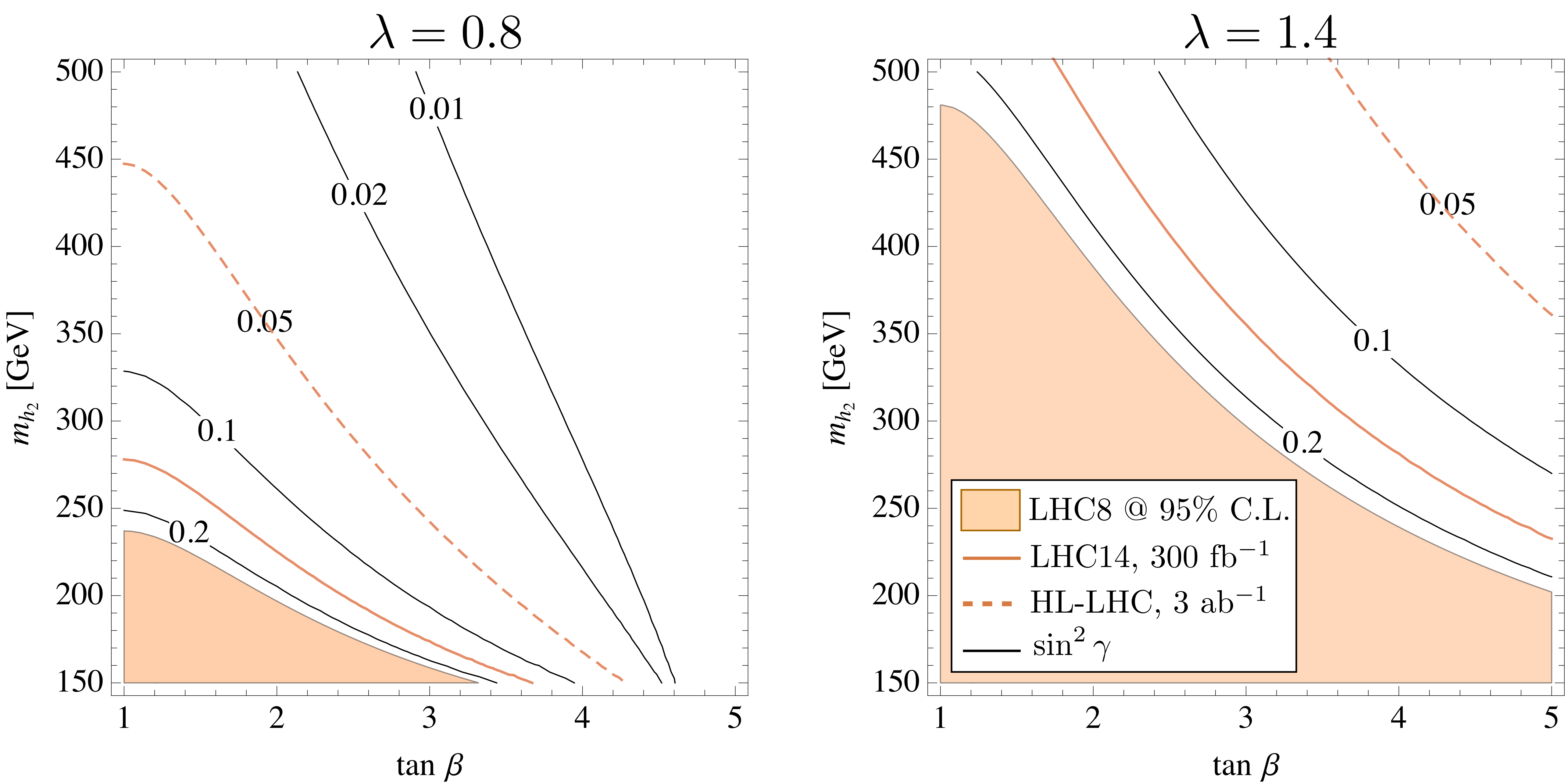
Doublet decoupled

$m_A^2 \gg \lambda^2 v^2$ and $\delta, \sigma \to 0$

$$\sin^2\gamma = \frac{M_{hh}^2 - m_{h_1}^2}{m_{h_2}^2 - m_{h_1}^2} \quad \text{where} \quad M_{hh}^2 = m_Z^2 c_{2\beta}^2 + v^2\lambda^2 s_{2\beta}^2 + \Delta_t^2$$

4 independent parameters: $\gamma = \gamma(m_{h_2}, \lambda, \tan\beta, \Delta_t)$

$\boxed{\Delta_t \approx 75\,\mathrm{GeV}}$

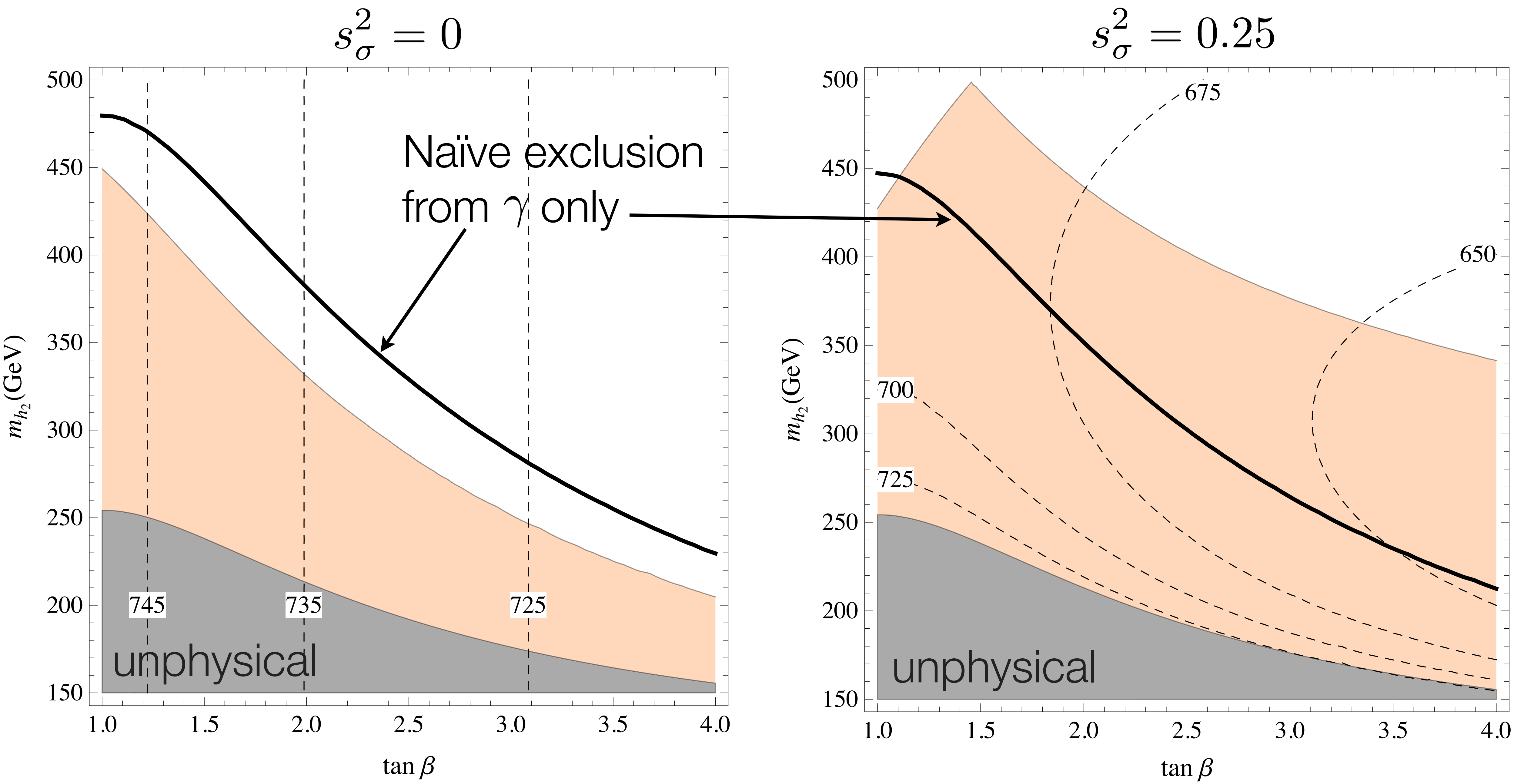


General case: 3-state mixing

6 independent parameters, $\delta, \gamma, \sigma \neq 0$

Not all combinations of $m_{h_1}, m_{h_2}, m_{h_3}, m_{H^\pm}$ and of $\lambda, \tan\beta, \Delta_t$ are viable

$m_{h_3} = 750$ GeV, $\lambda = 1.4$, $\Delta_t = 75$ GeV



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

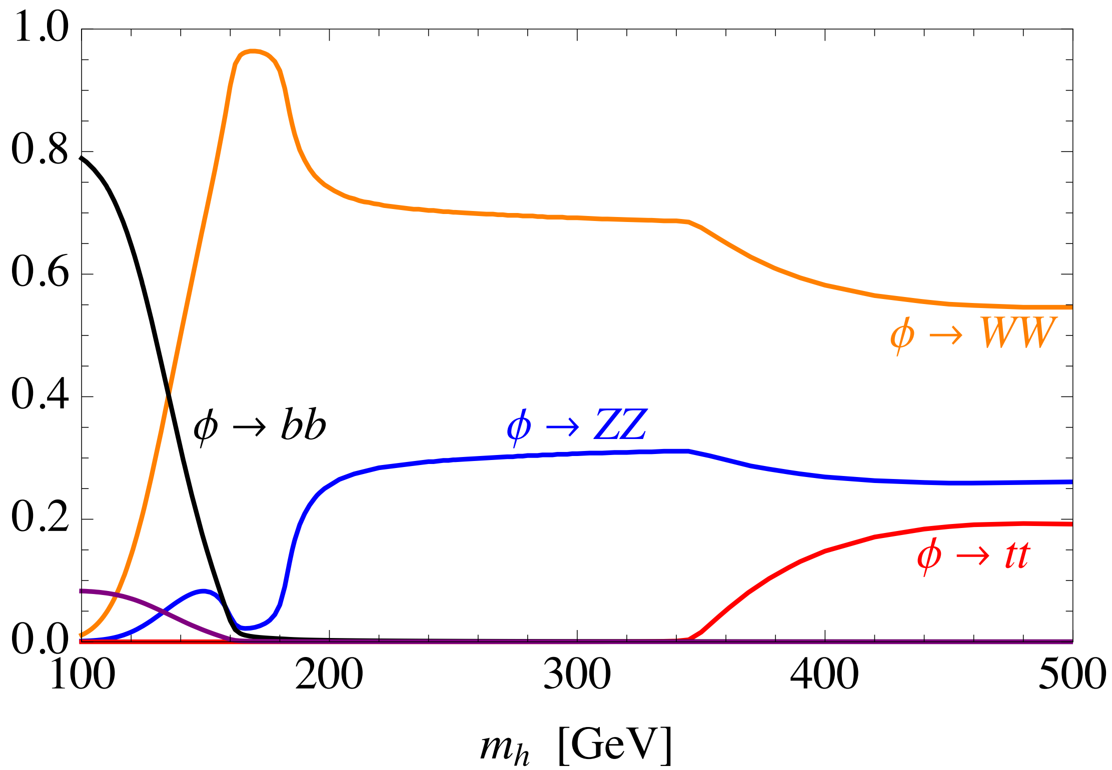
At high mass the equivalence theorem relates the decay widths

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

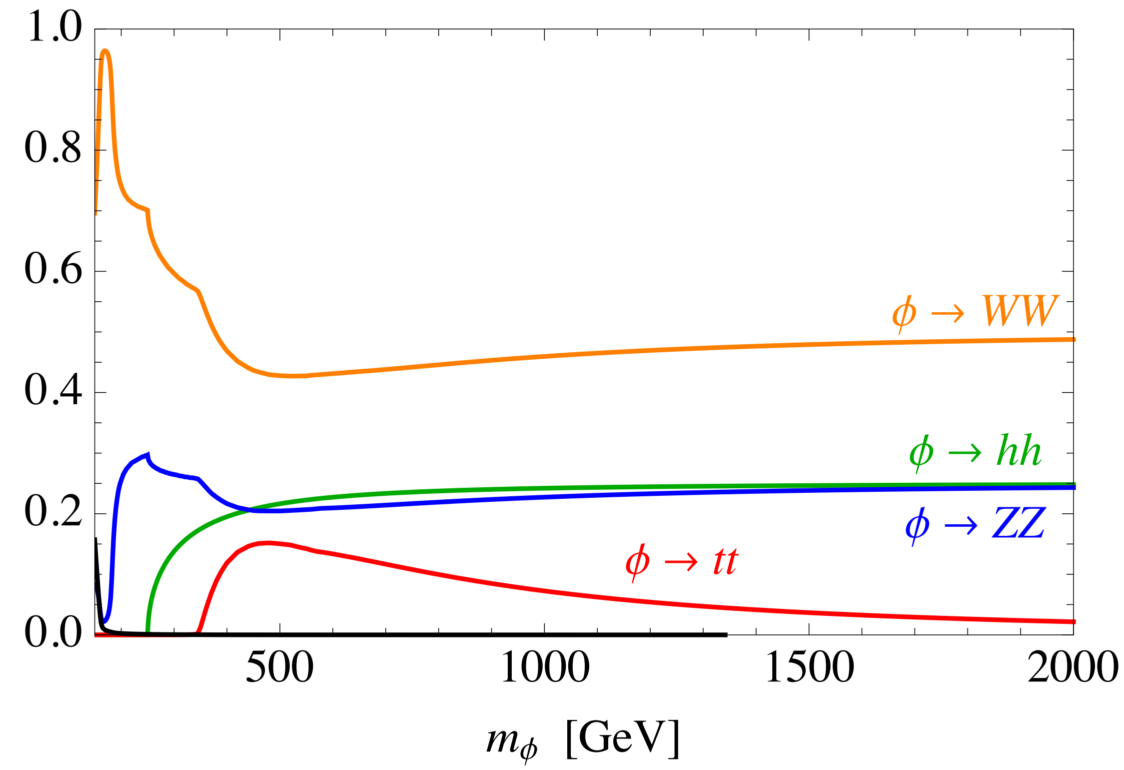
(these are the dominant channels, fermionic modes suppressed)

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

h branching ratios



ϕ branching ratios



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

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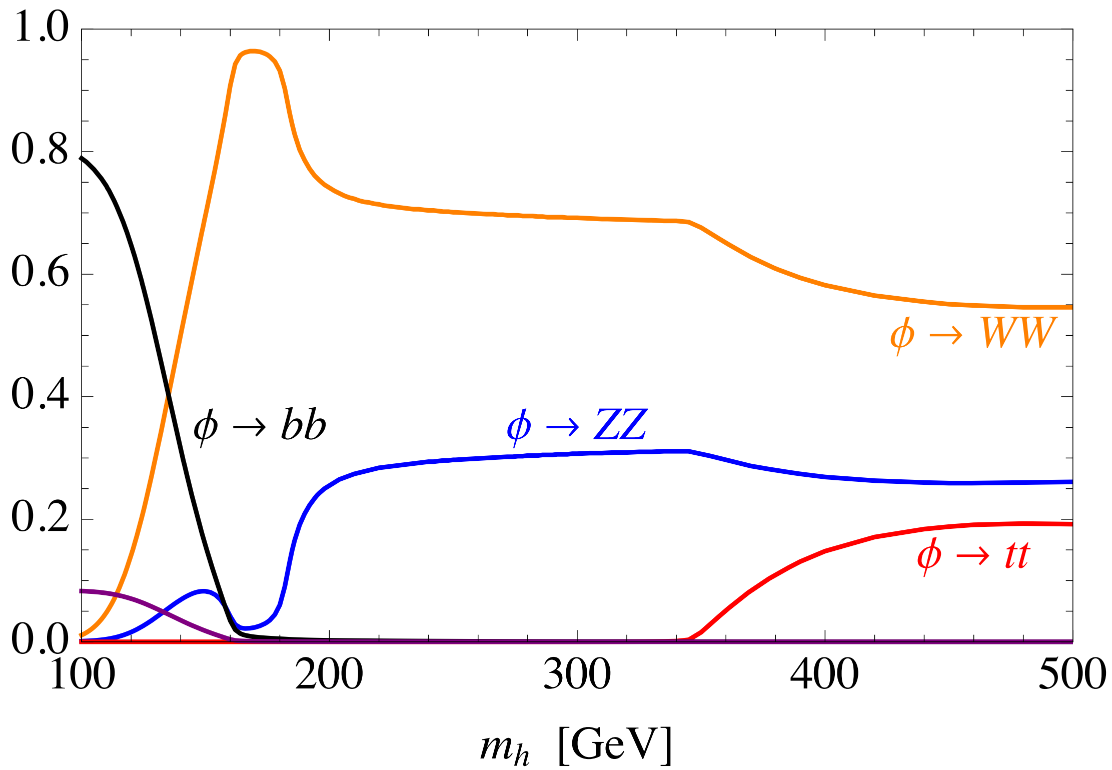

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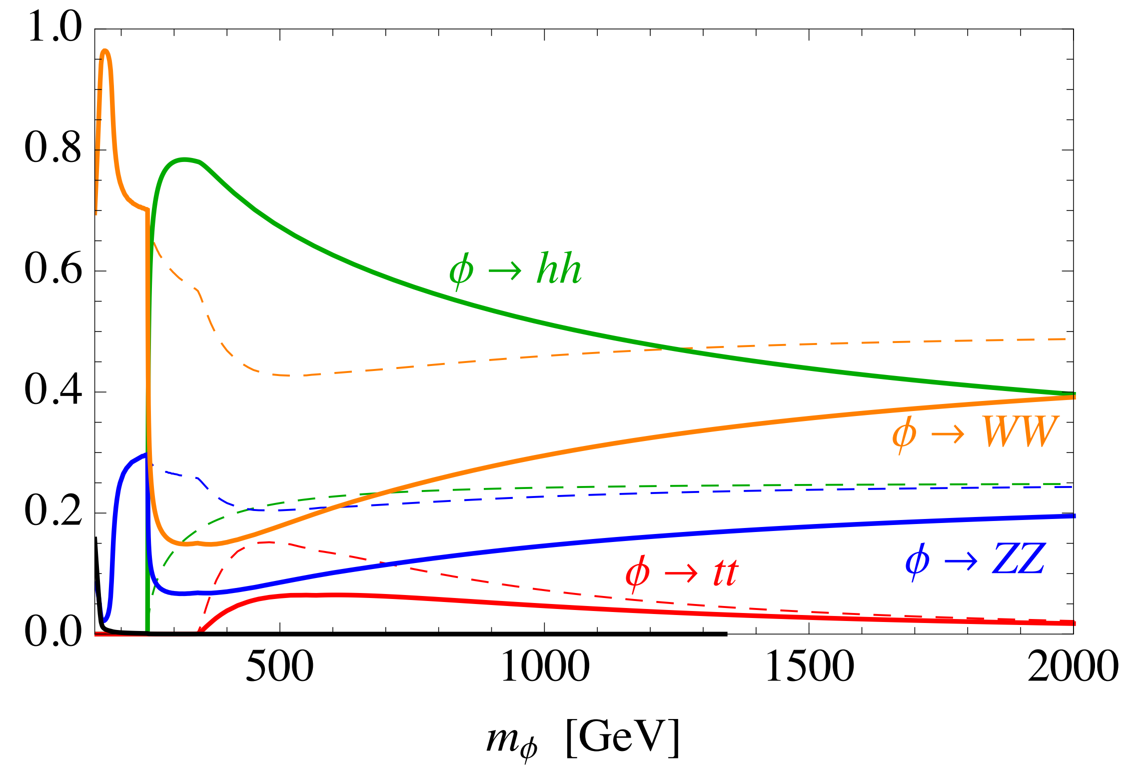


ϕ is like a heavy SM Higgs + $\mathrm{BR}_{\phi\to hh}$

Triple couplings

The triple couplings depend on the details of the potential

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

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

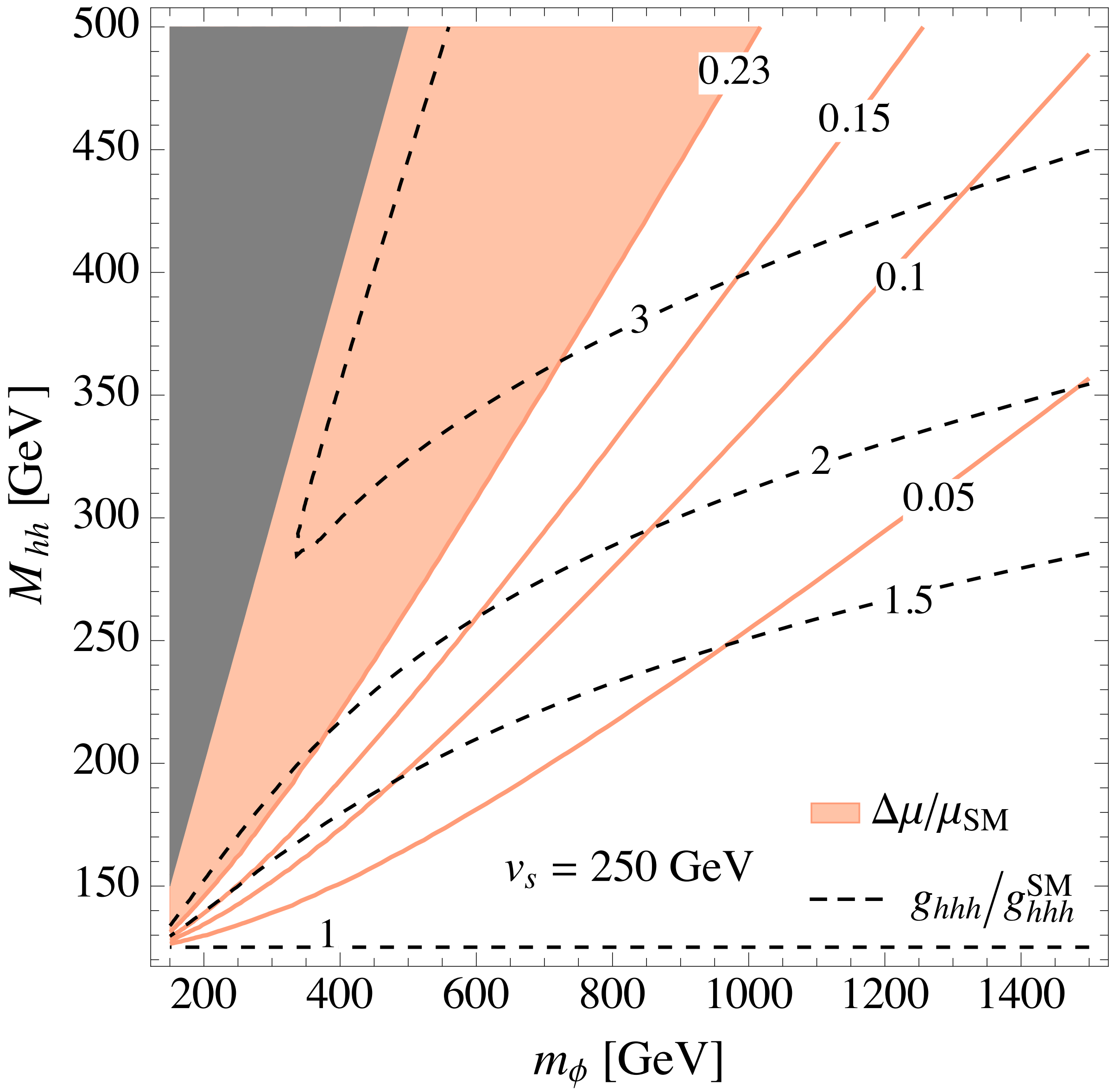
The dependence on λ_{HS}, λ_S is very weak: v_s is the only relevant additional parameter that determines $\mathrm{BR}_{\phi\to hh}$ and the h^3 coupling

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

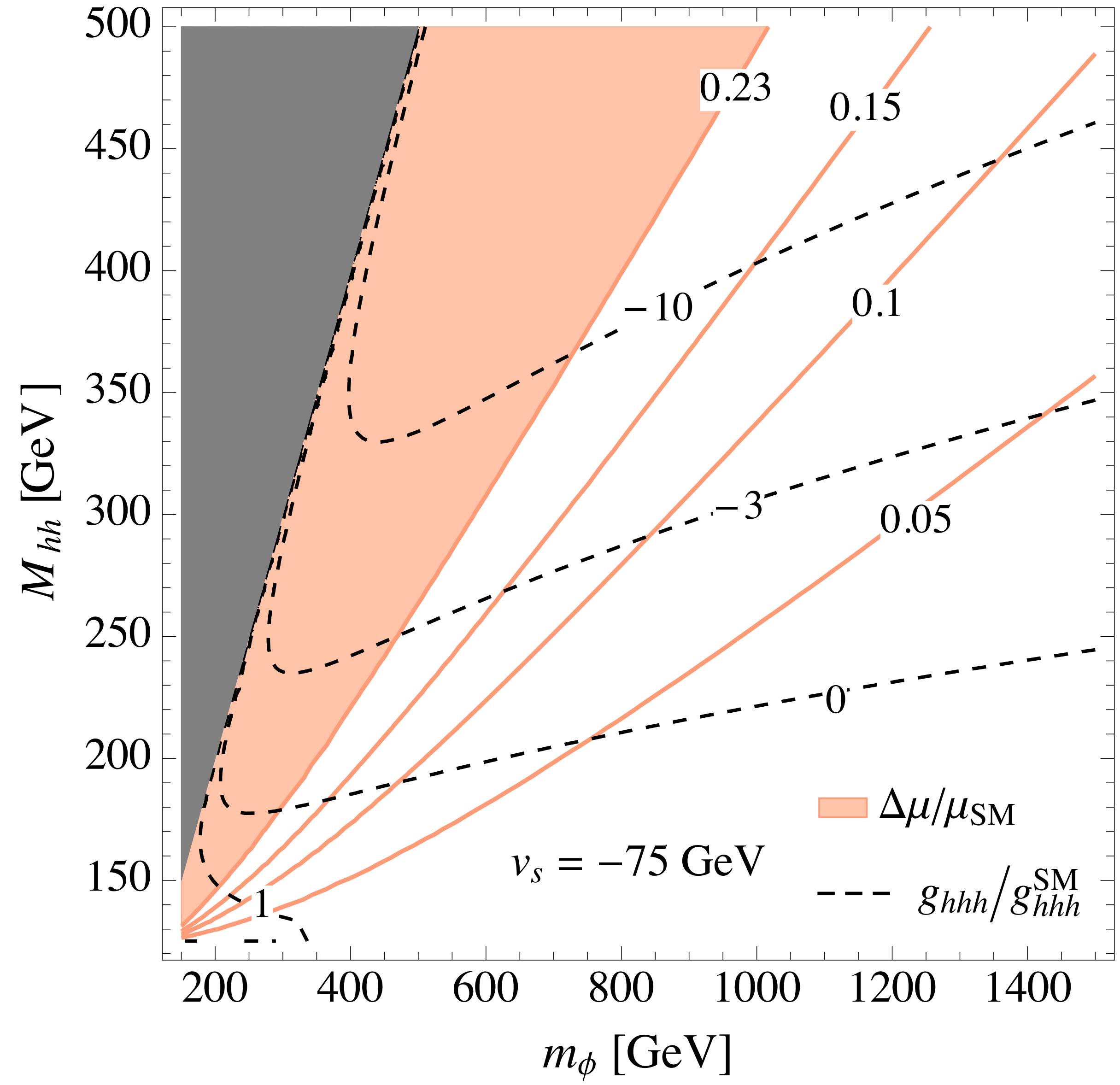
$$g_{hhh} = g_{hhh}^{\mathrm{SM}}\left(1 + \frac{2}{3}\frac{v}{v_s}\frac{\sqrt{M_{hh}^2 - m_h^2}}{m_\phi}\left(\frac{M_{hh}^2}{m_h^2} - 1\right) + \mathcal{O}(v^2/m_\phi^2)\right)$$

Higgs couplings

v_S = 250 GeV

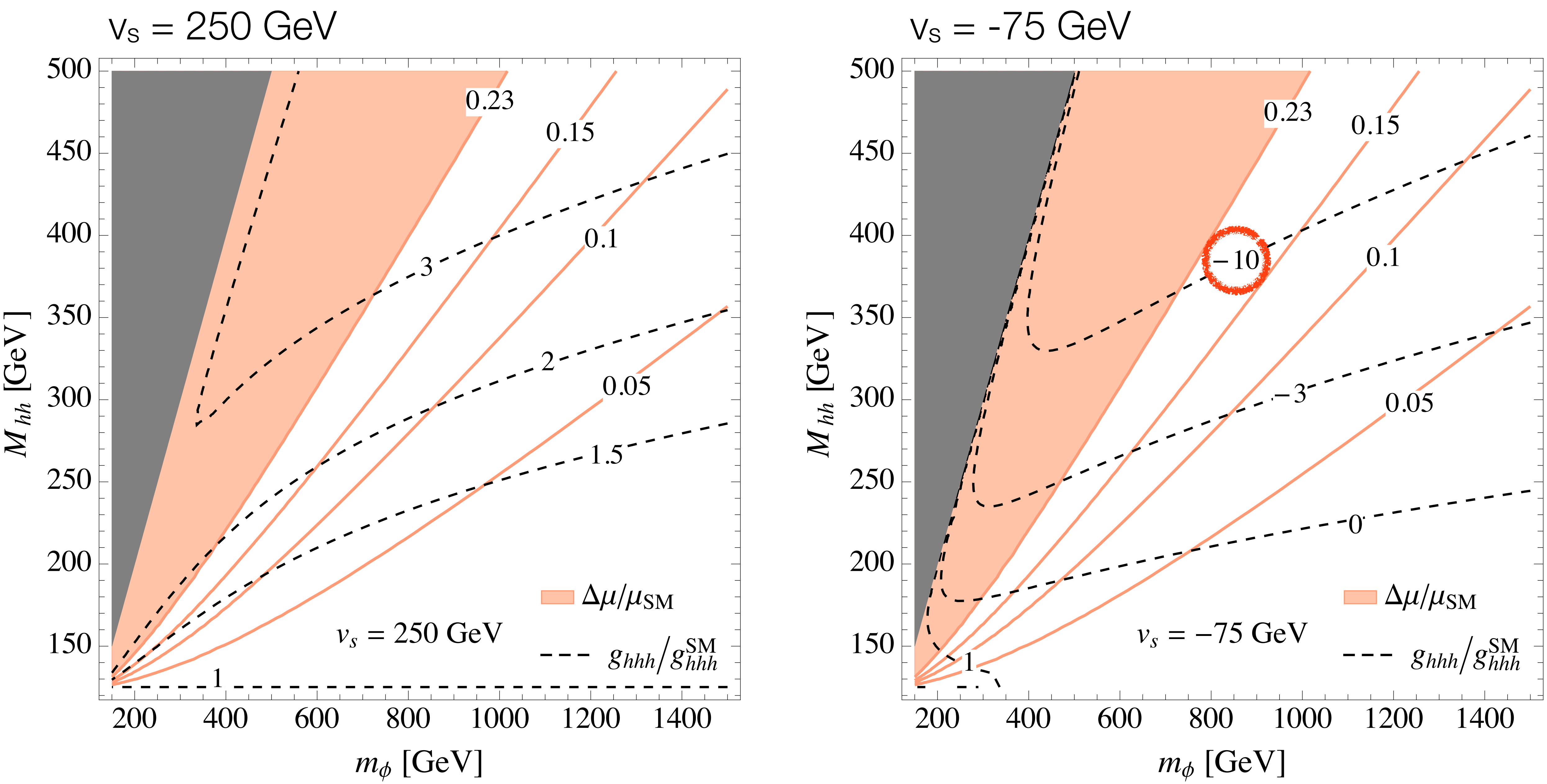


v_S = -75 GeV



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

Higgs couplings



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

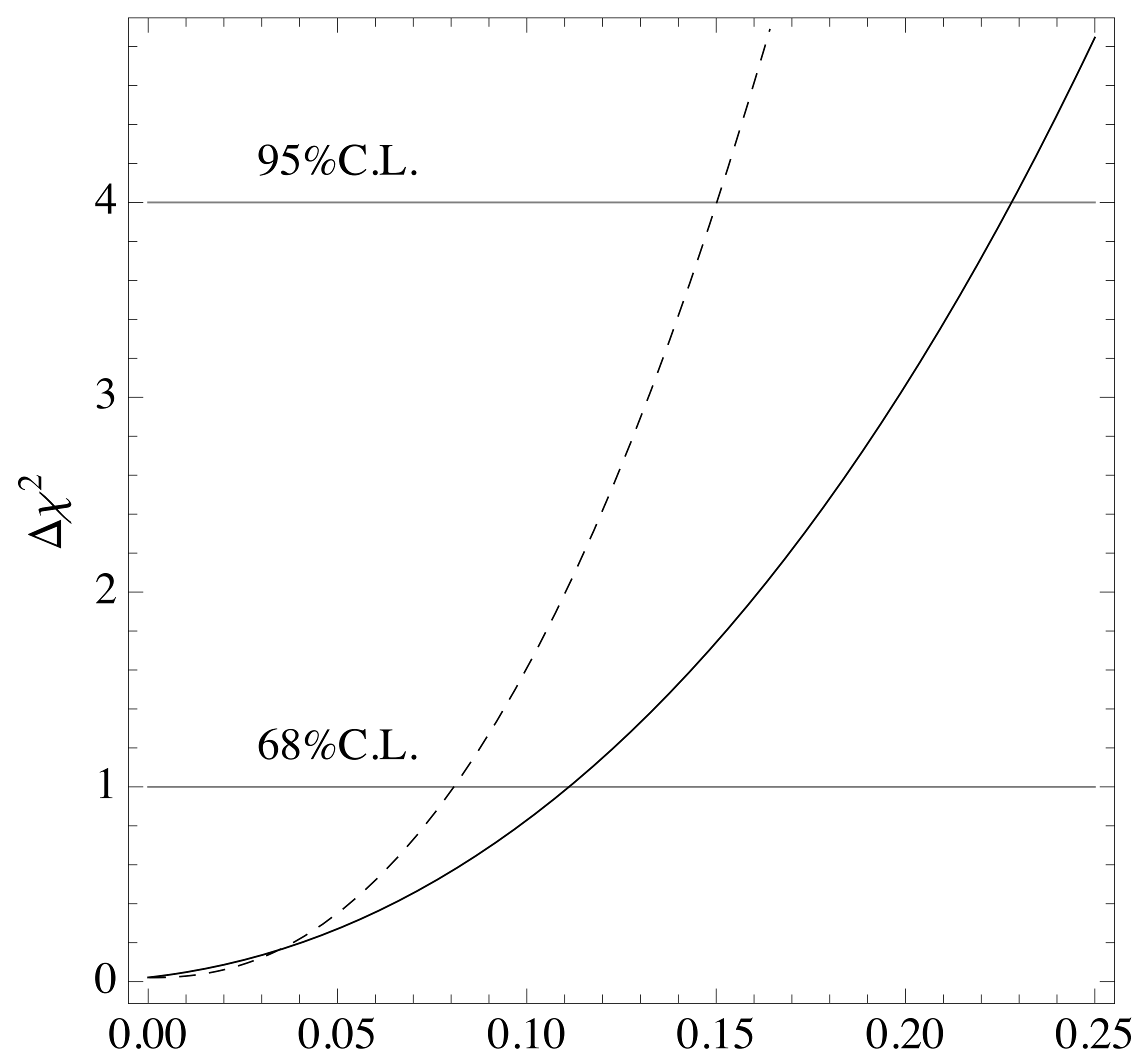
Higgs couplings: projections for the future

[Snowmass '13]

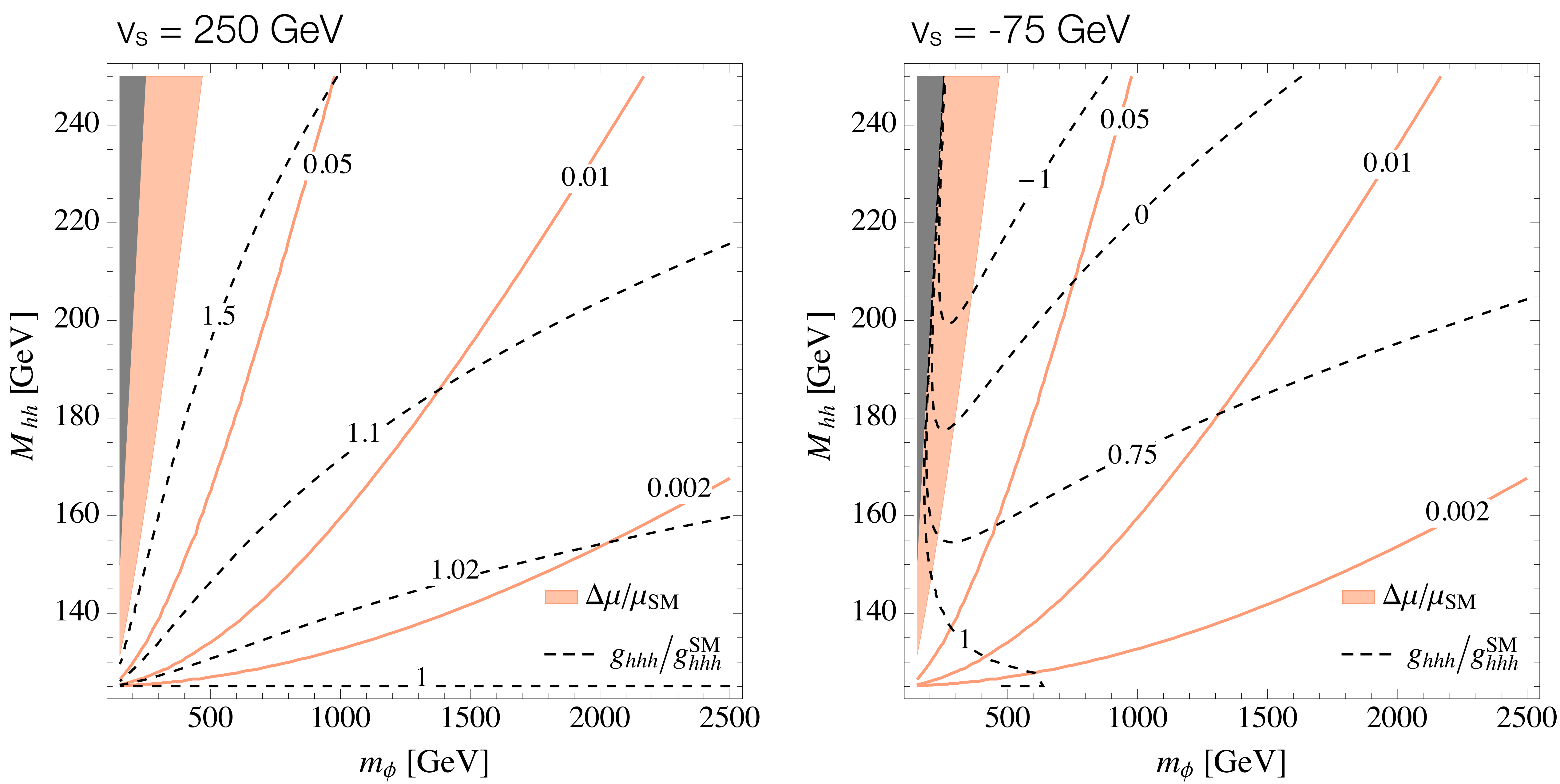
1σ reach in	$s_\gamma^{2\,*}$	$\left\lvert 1 - \frac{g_{hhh}}{g_{hhh}^{\rm SM}} \right\rvert$
LHC8	0.2	–
LHC14	0.08-0.12	–
HL-LHC	4-8$\times 10^{-2}$	0.5
HE-LHC	–	0.2
FCC-hh	–	0.08
ILC	2×10^{-2}	0.21-0.83
ILC-up	4×10^{-3}	0.13-0.46
CLIC	2-3$\times 10^{-3}$	0.1-0.21
CEPC	2×10^{-3}	–
FCC-ee	1×10^{-3}	–

* projections on most precise coupling

The result of the Higgs fit is approximated well by the precision on g_{hVV}



Higgs couplings

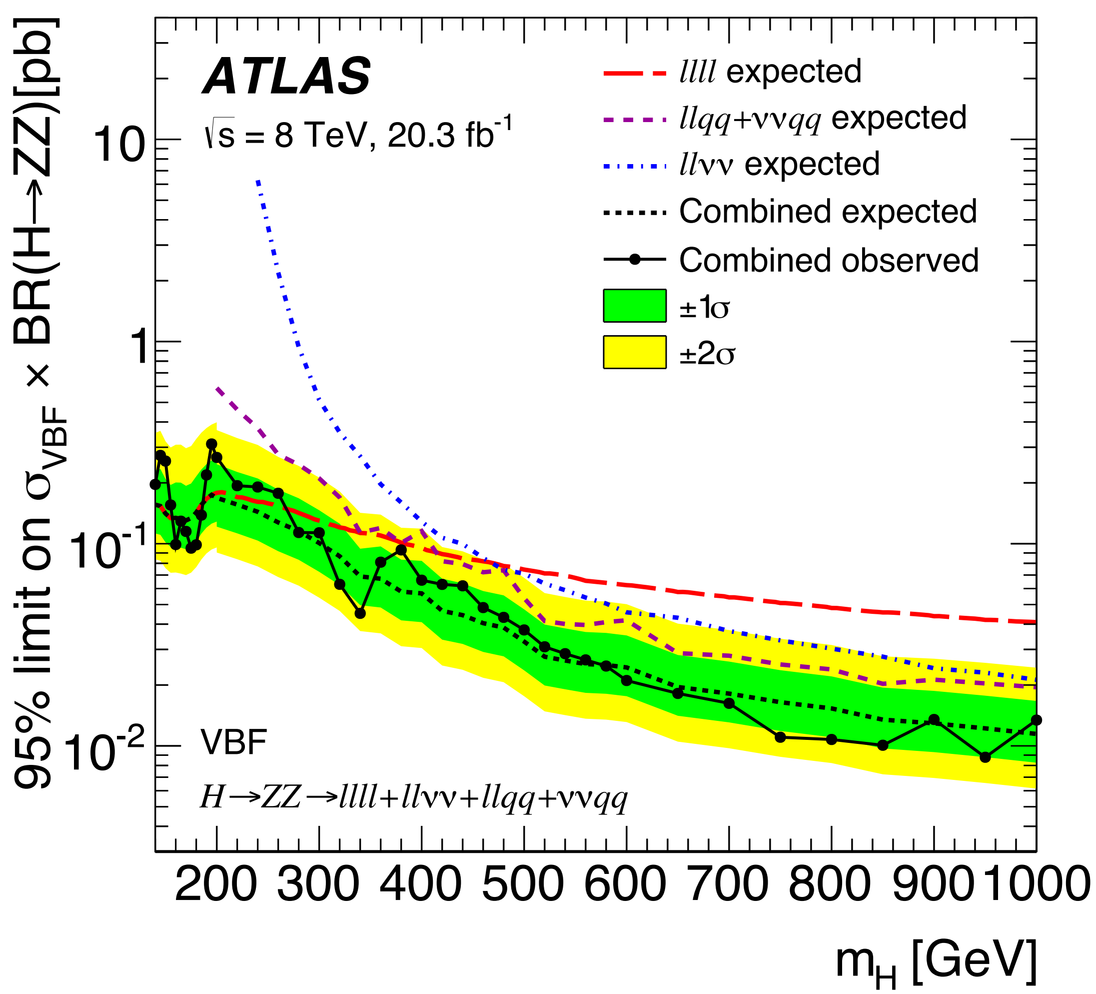


Region relevant for an e^+e^- collider

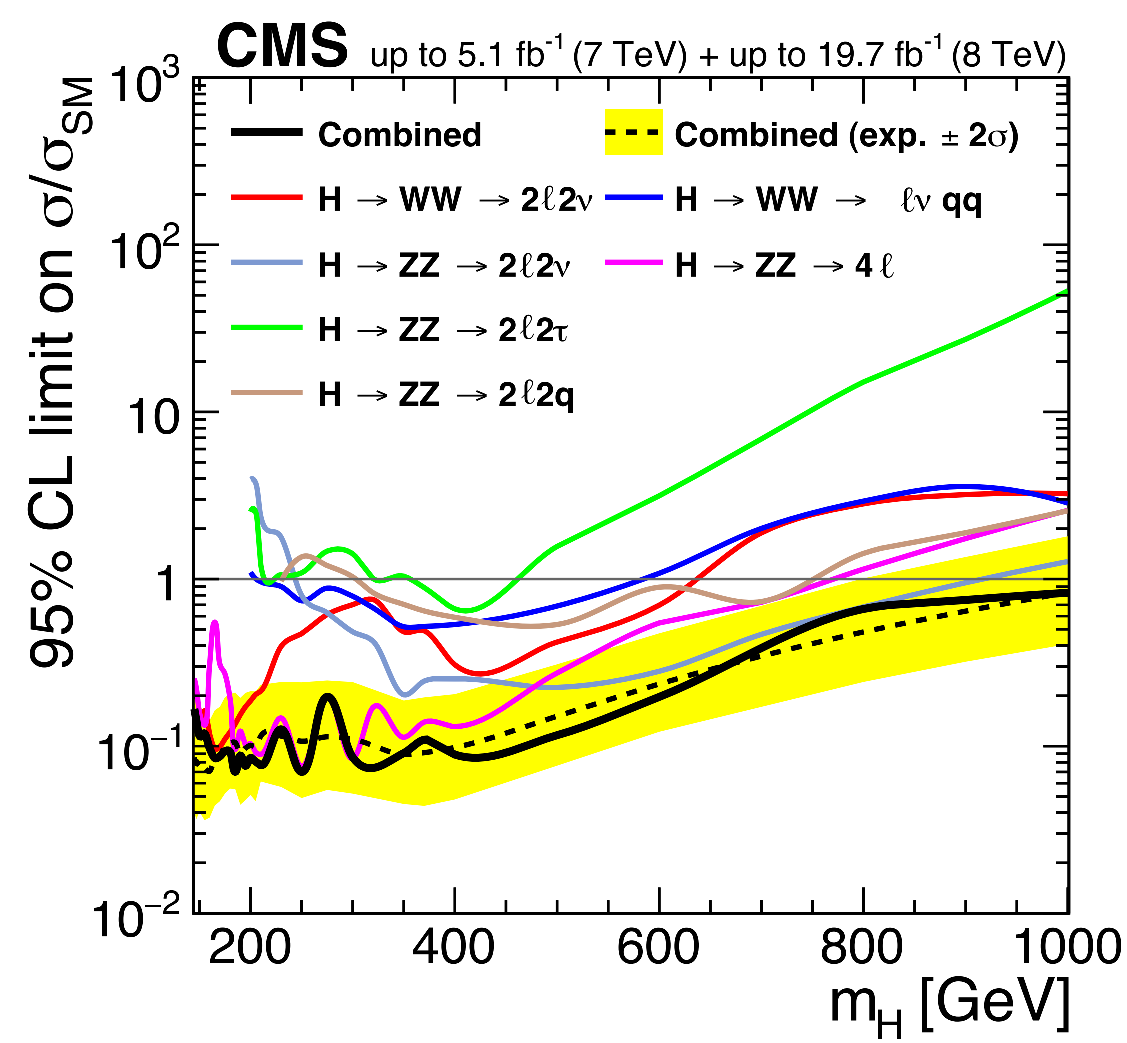
Direct searches

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

ATLAS [1507.05930]



CMS [1504.00936]

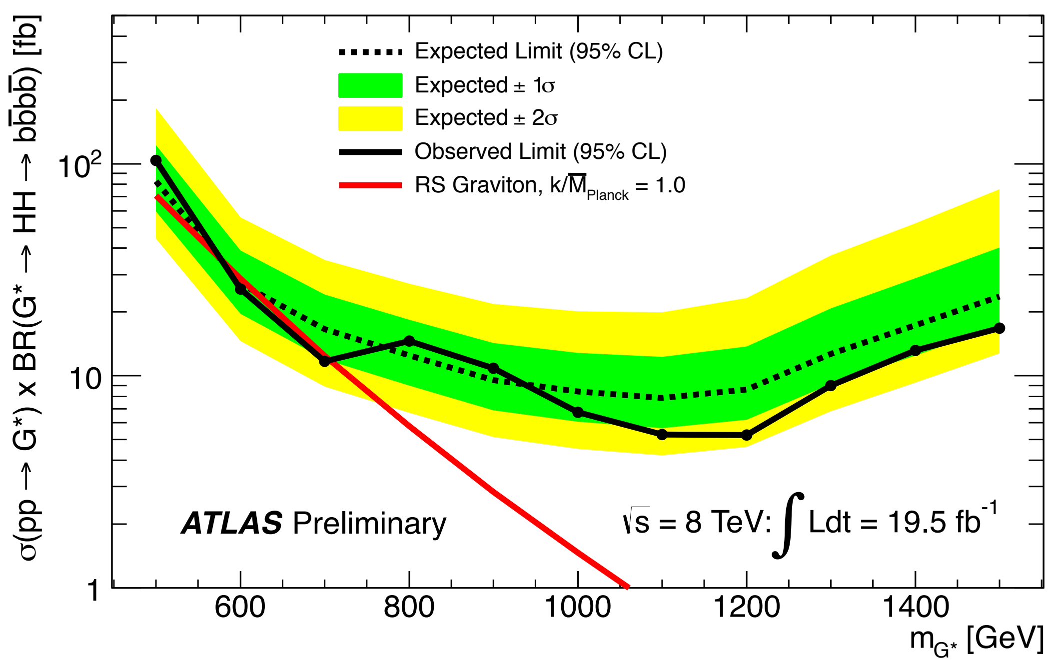


Already more sensitive than Higgs couplings at low masses!

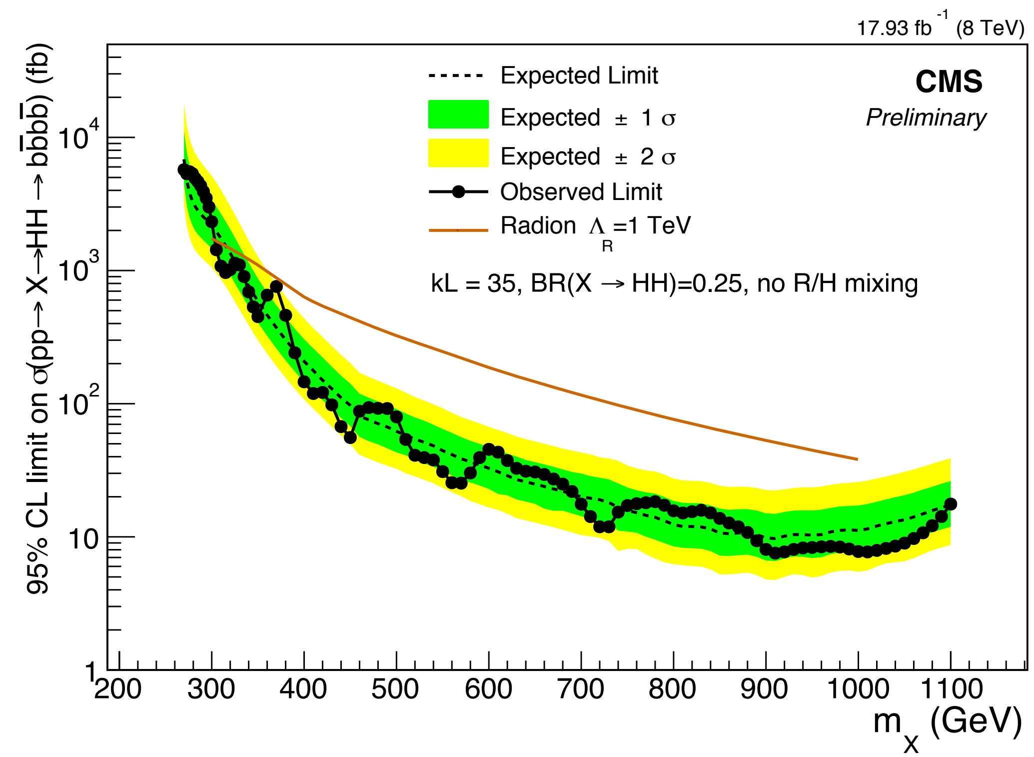
Direct searches

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

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?

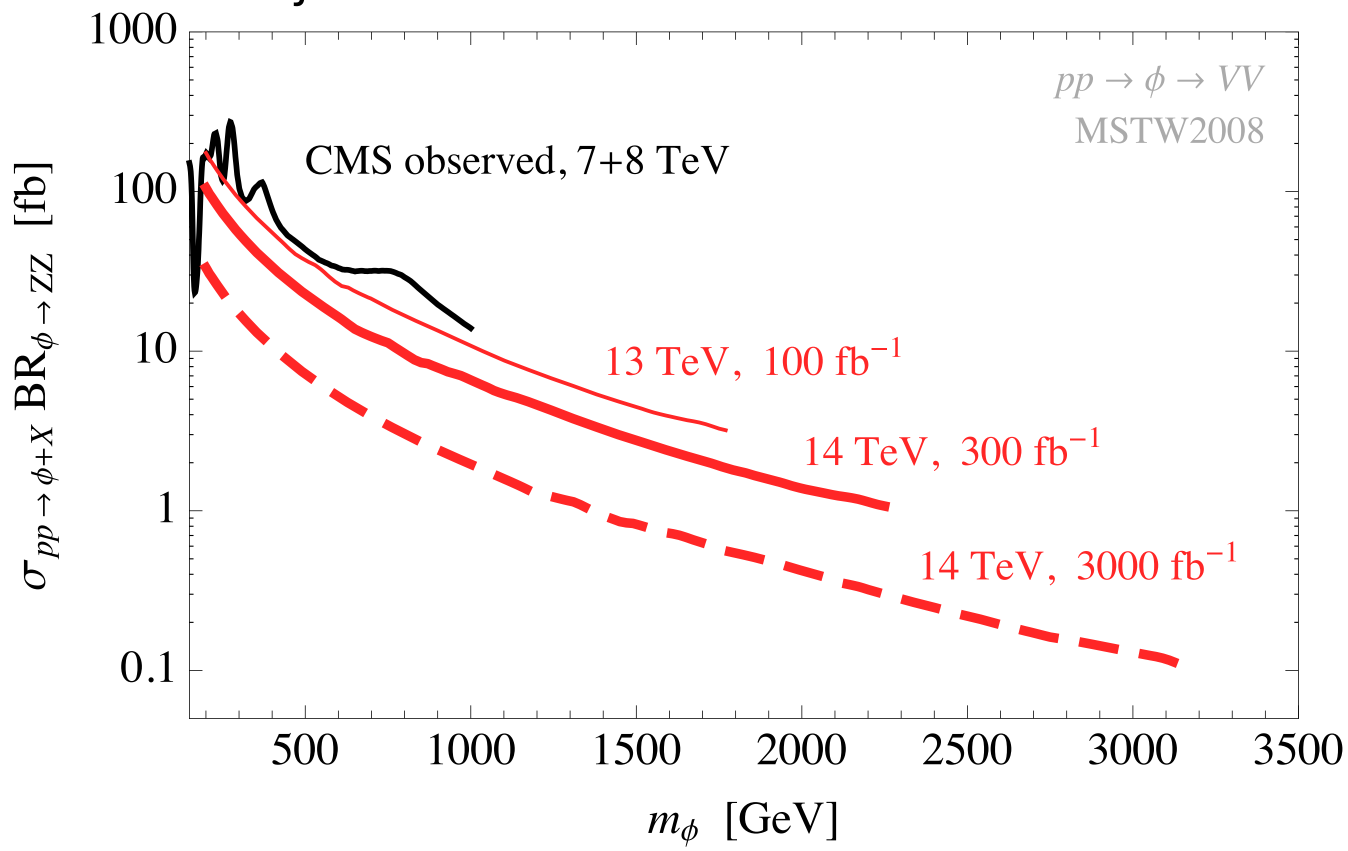
Projections for the future

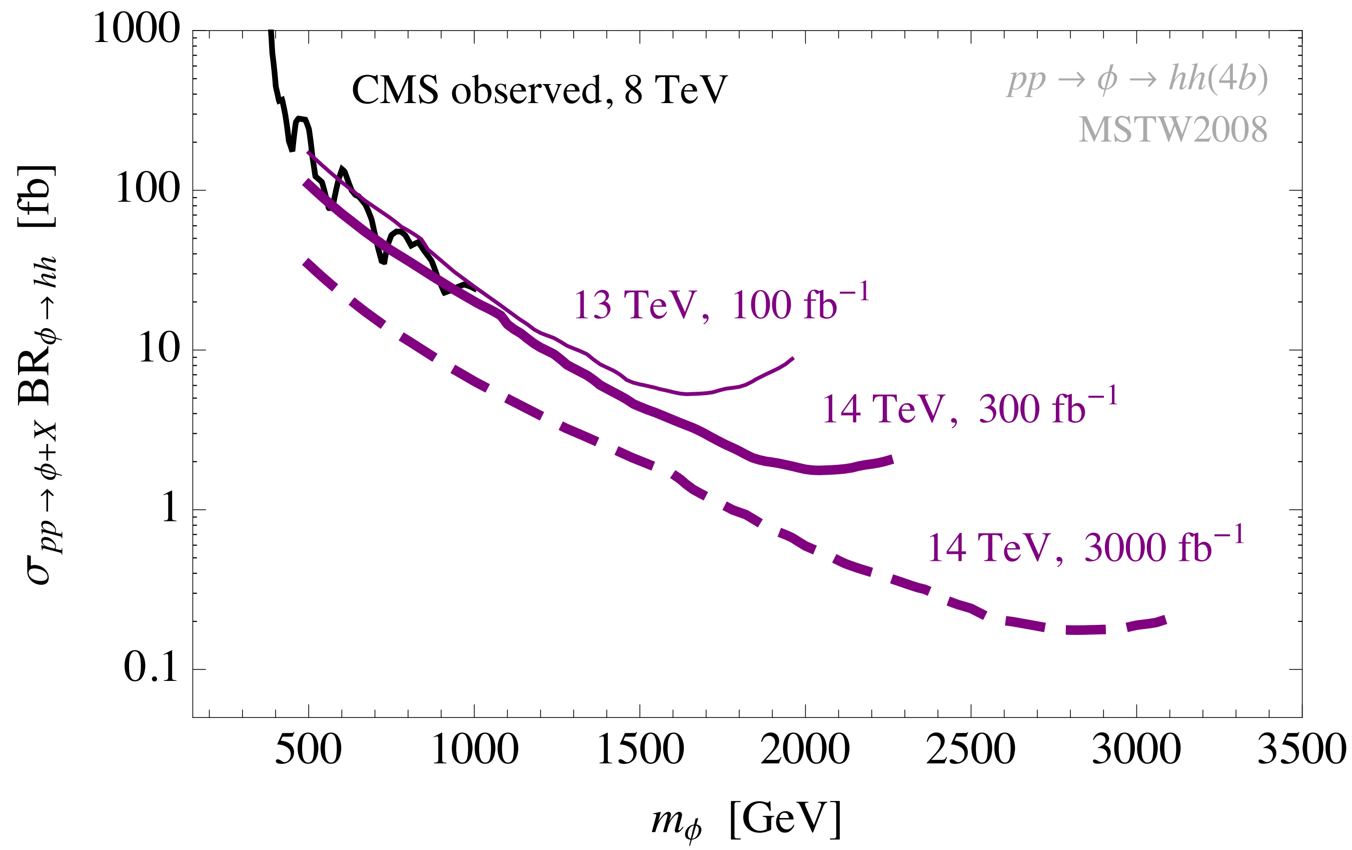
How to get fast estimates of the reach of future machines?

➡ rescale 8 TeV LHC data with the parton luminosity of the bkg

[see also Salam, Weiler ’14 and Thamm, Torre, Wulzer ’15]

Projections for LHC:





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

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

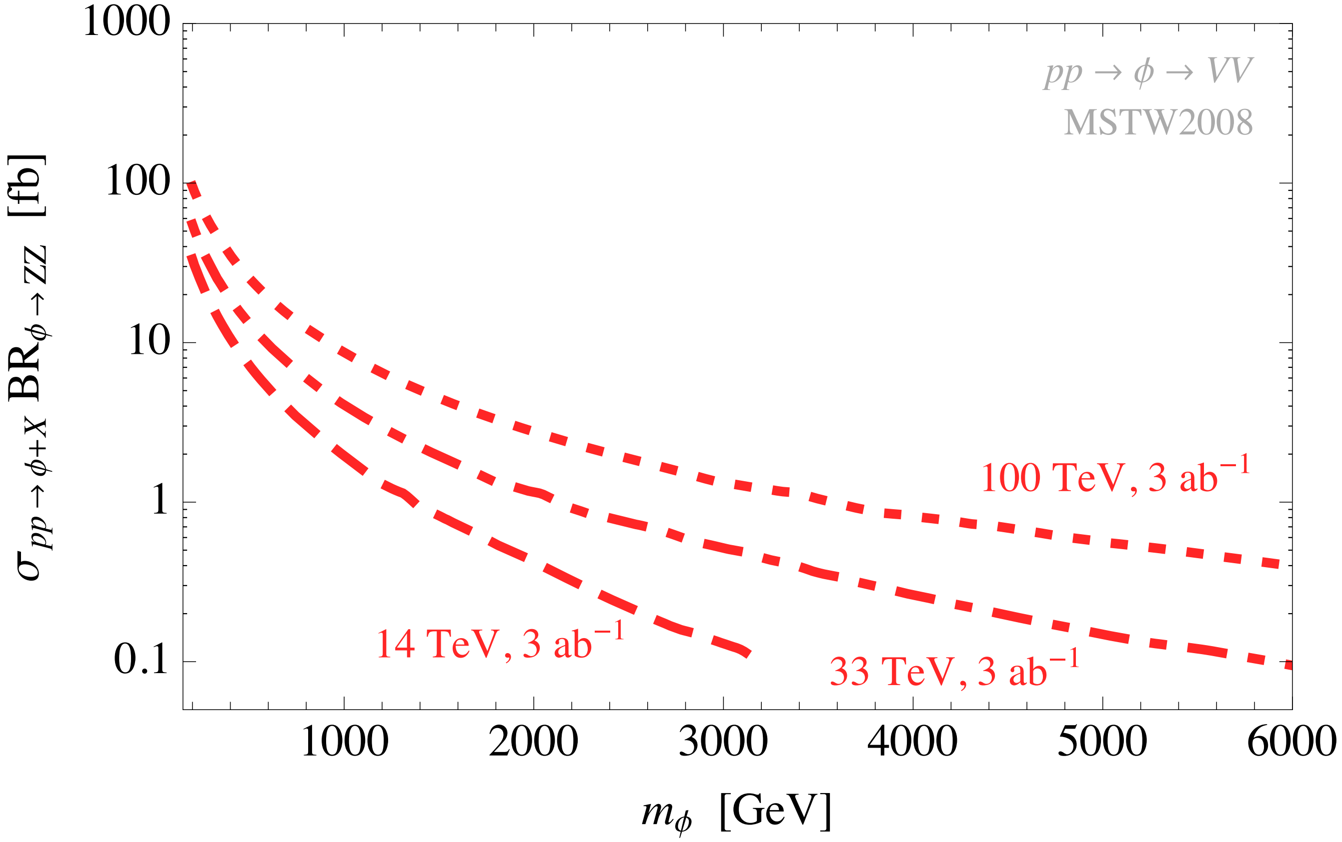
Projections for the future

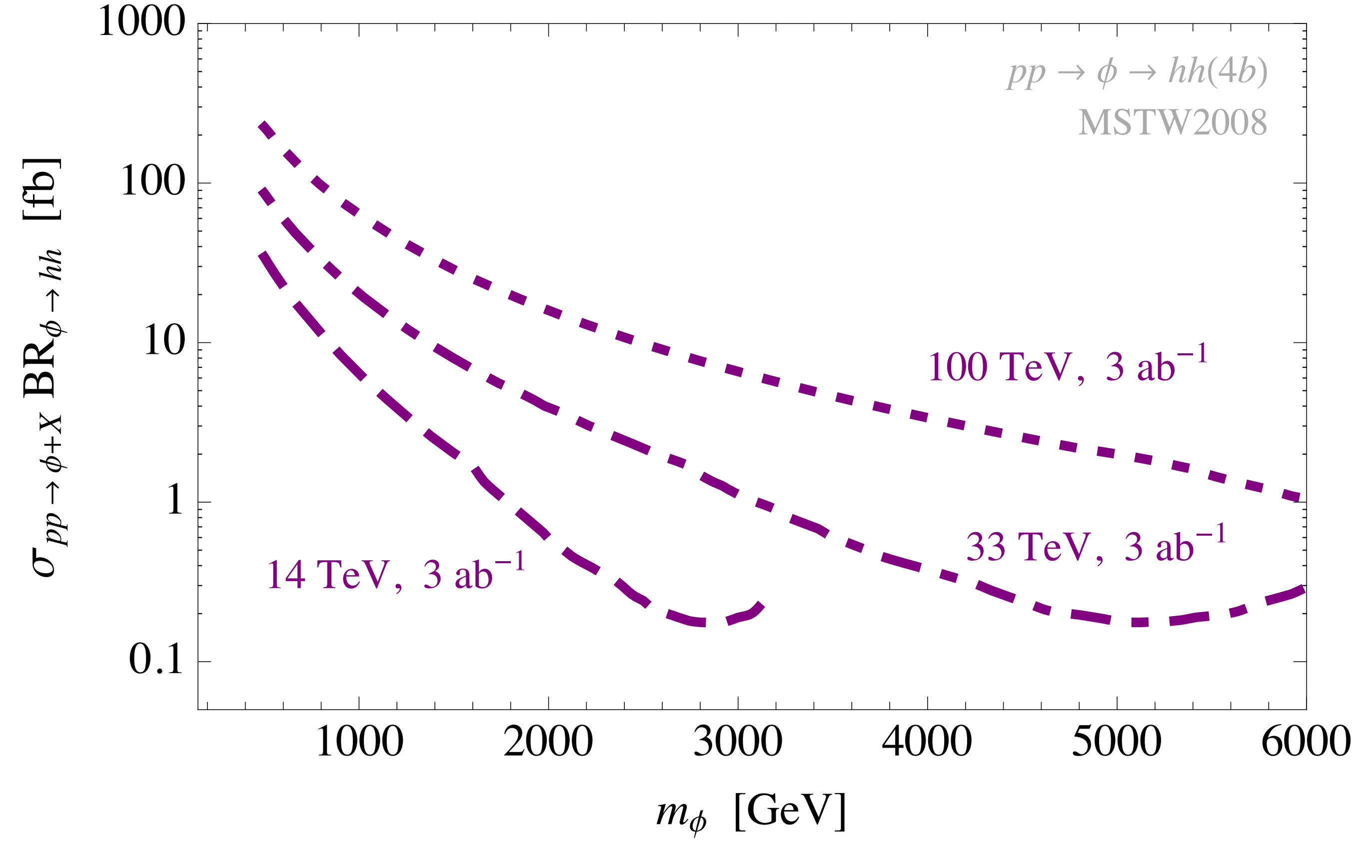
How to get fast estimates of the reach of future machines?

➡ rescale 8 TeV LHC data with the parton luminosity of the bkg

[see also Salam, Weiler '14 and Thamm, Torre, Wulzer '15]

Projections for FCC:





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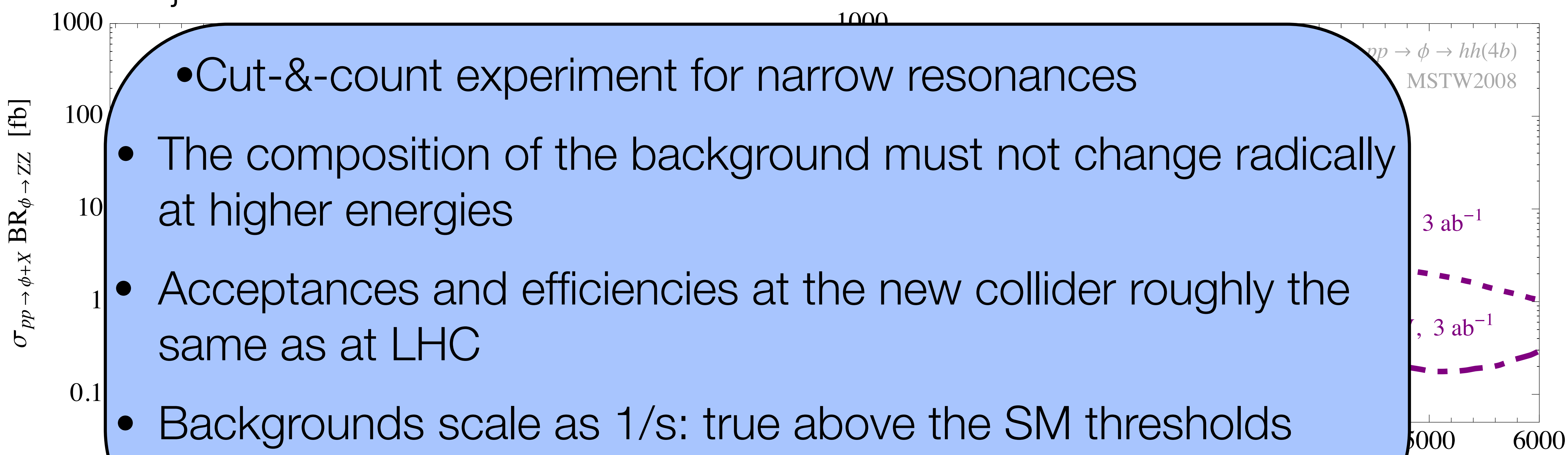


- Cut-&-count experiment for narrow resonances
- The composition of the background must not change radically at higher energies
- Acceptances and efficiencies at the new collider roughly the same as at LHC
- Backgrounds scale as 1/s: true above the SM thresholds
- Systematic errors are not too large

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

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

Extrapolation of the limits

- # of background events:

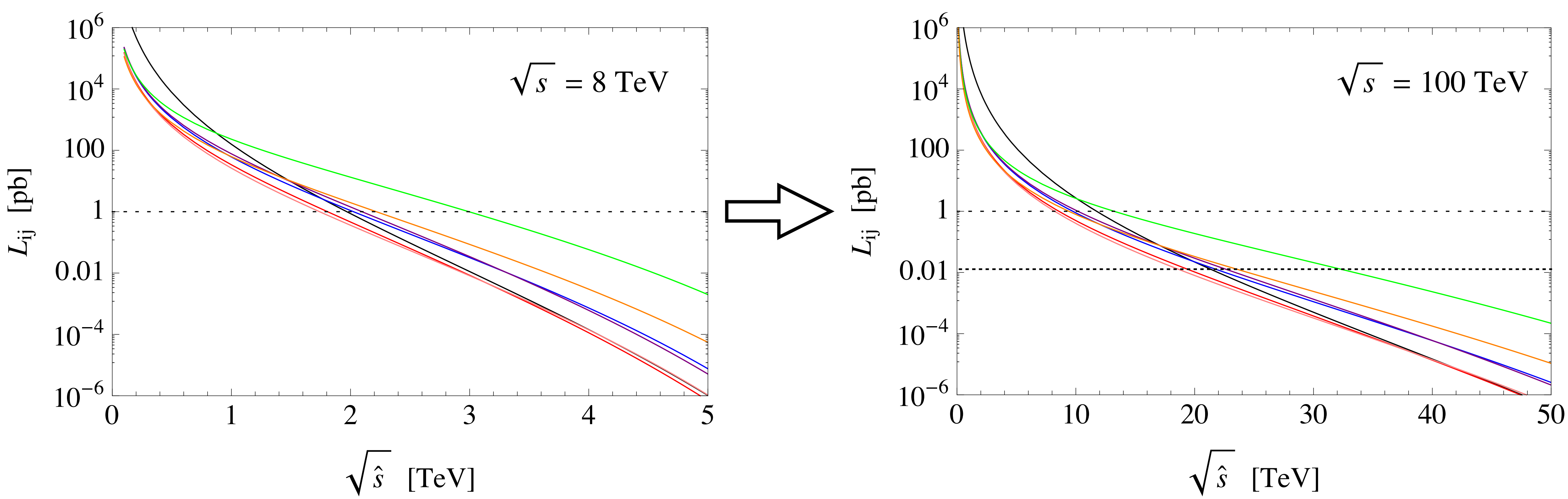
$$B \propto L \cdot \sum_{i,j} \int d\hat{s} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(\sqrt{\hat{s}}, \sqrt{s}) \cdot \hat{\sigma}_{ij}(\hat{s}) \approx L \cdot \frac{\Delta \hat{s}}{m} \cdot \sum_{i,j} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}}$$

parton luminosity

$\hat{\sigma}_{ij} \sim c_{ij}/\hat{s}$ partonic cross-section $ij \to h_2$

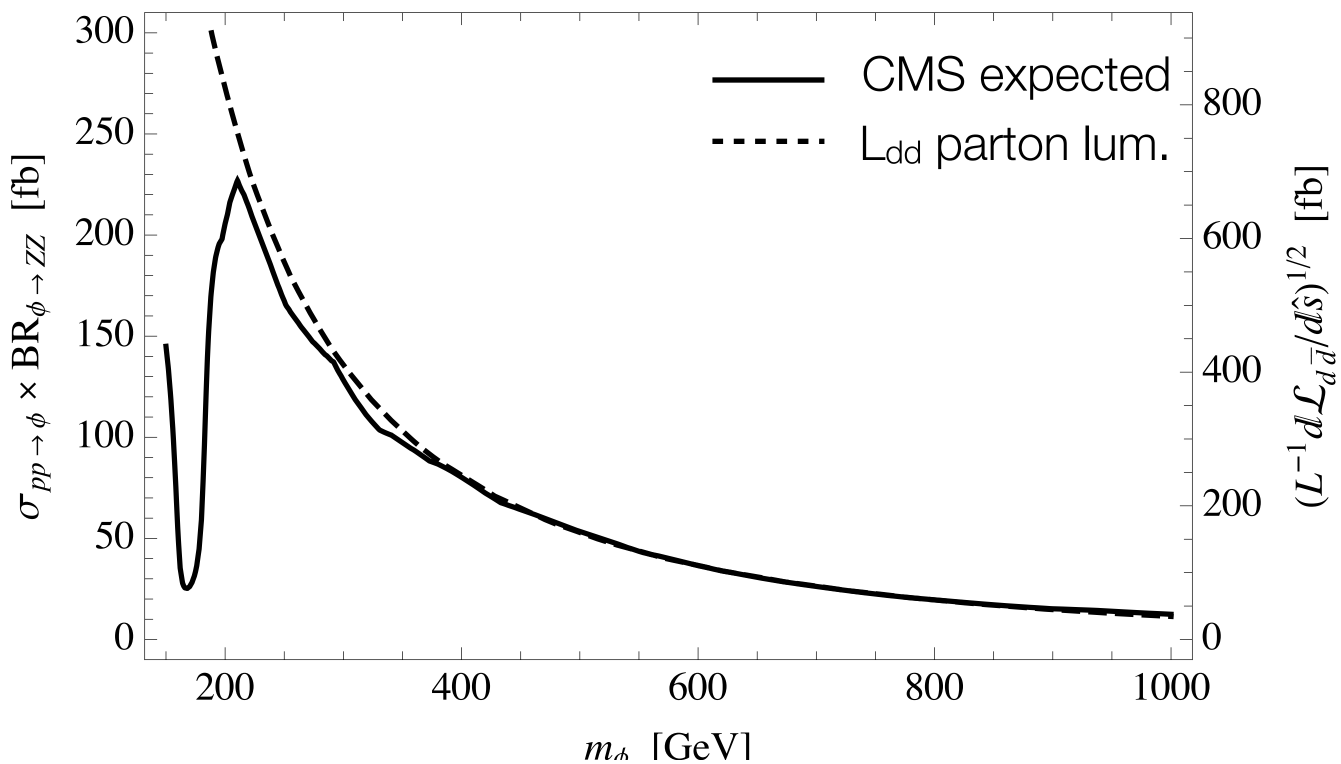
- # of signal events: $S = \sigma \cdot L$

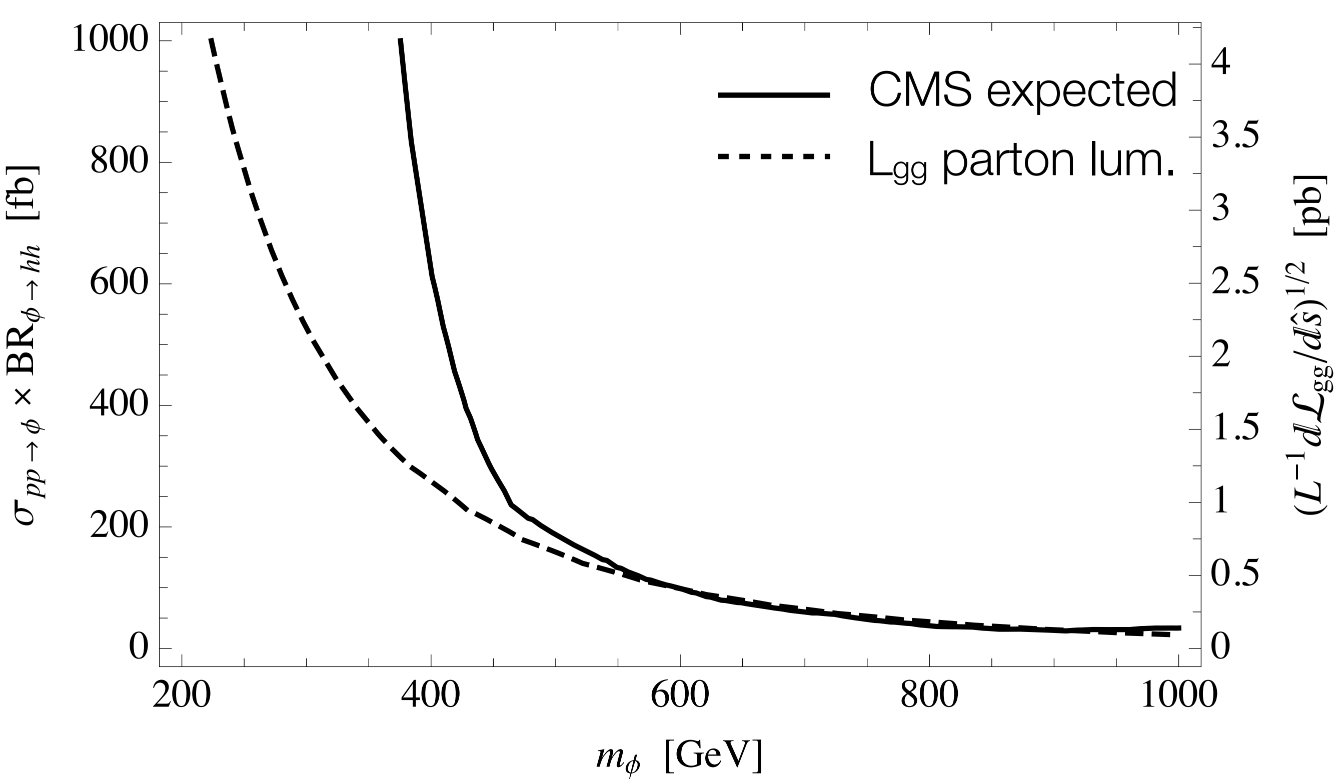
$$B(s, L, m) = B(s', L', m') \Rightarrow \sum_{i,j} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(m', \sqrt{s'}) = \frac{L}{L'} \sum_{i,j} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(m, \sqrt{s})$$



Extrapolation of the limits

Some check of our assumptions...





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

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

Extrapolation of the limits

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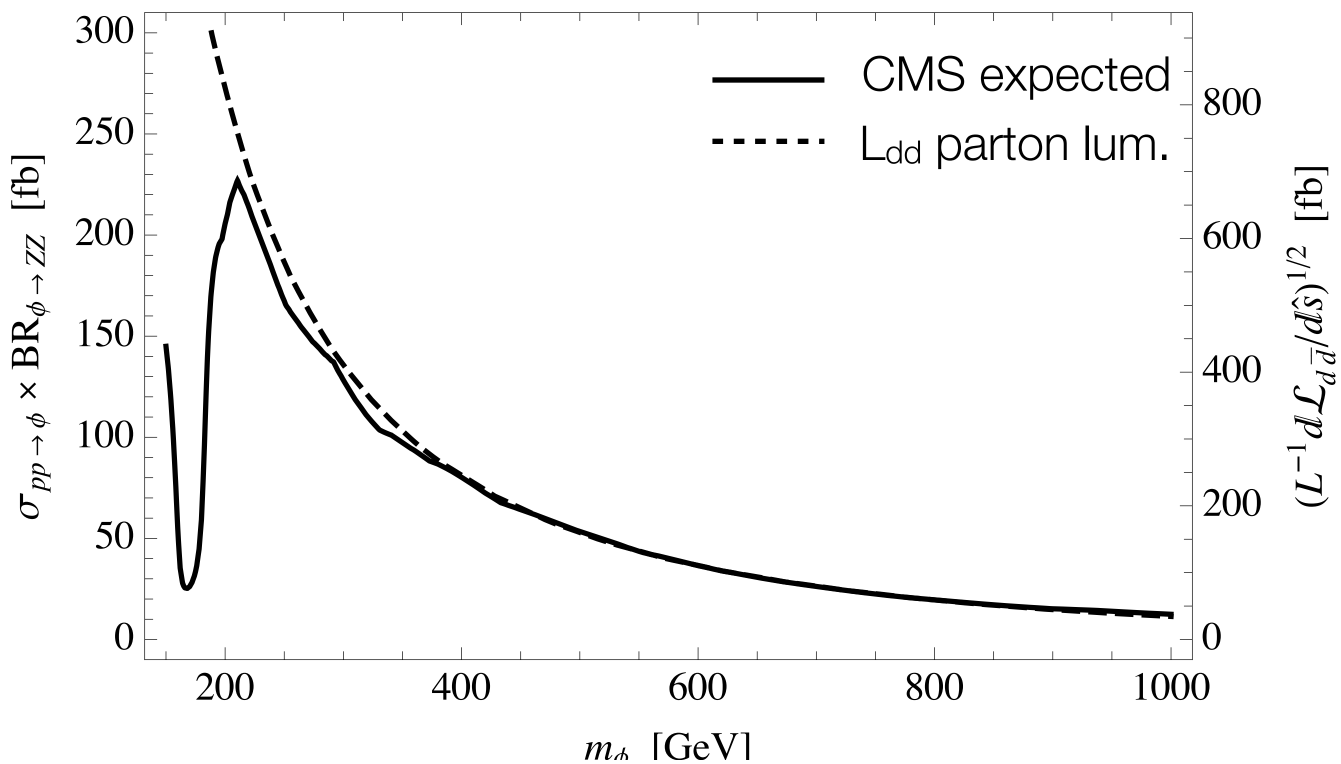
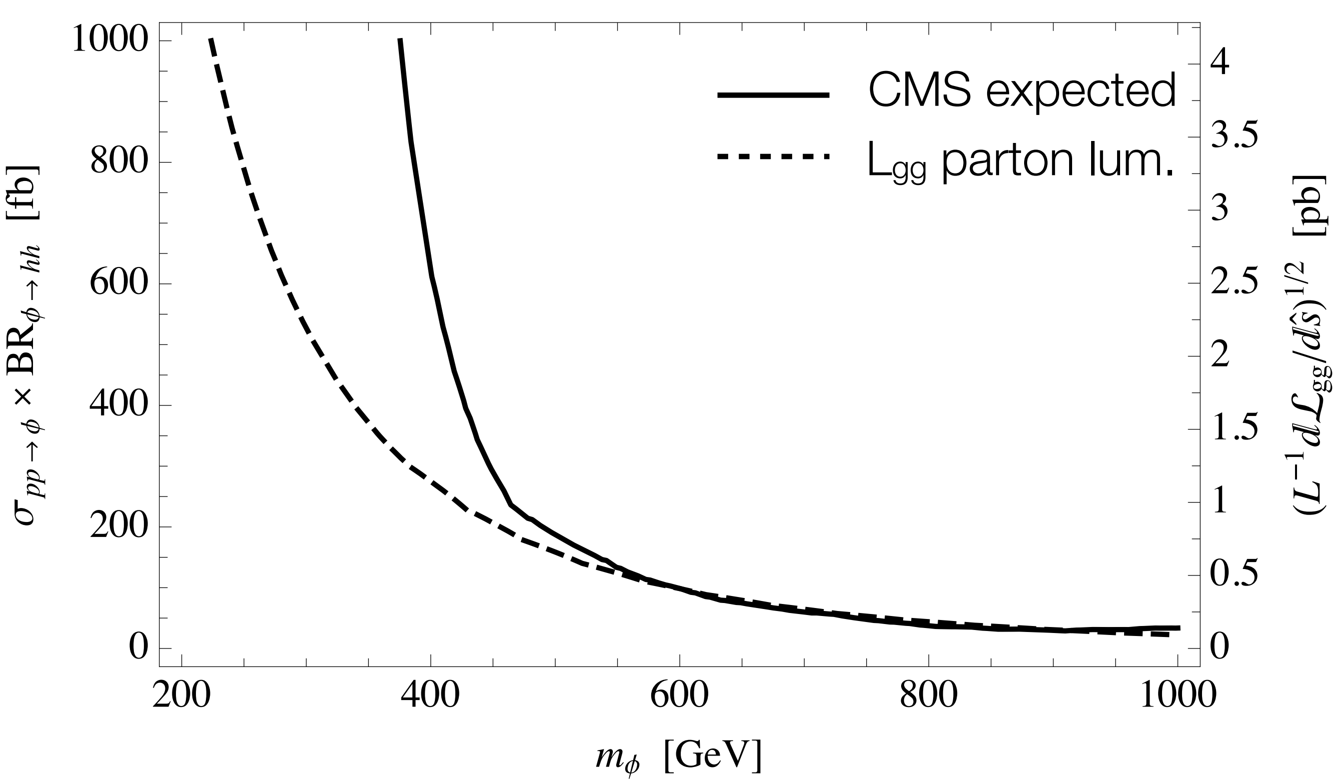




- The excluded cross-sections scale as (parton luminosity)$^{1/2}$

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

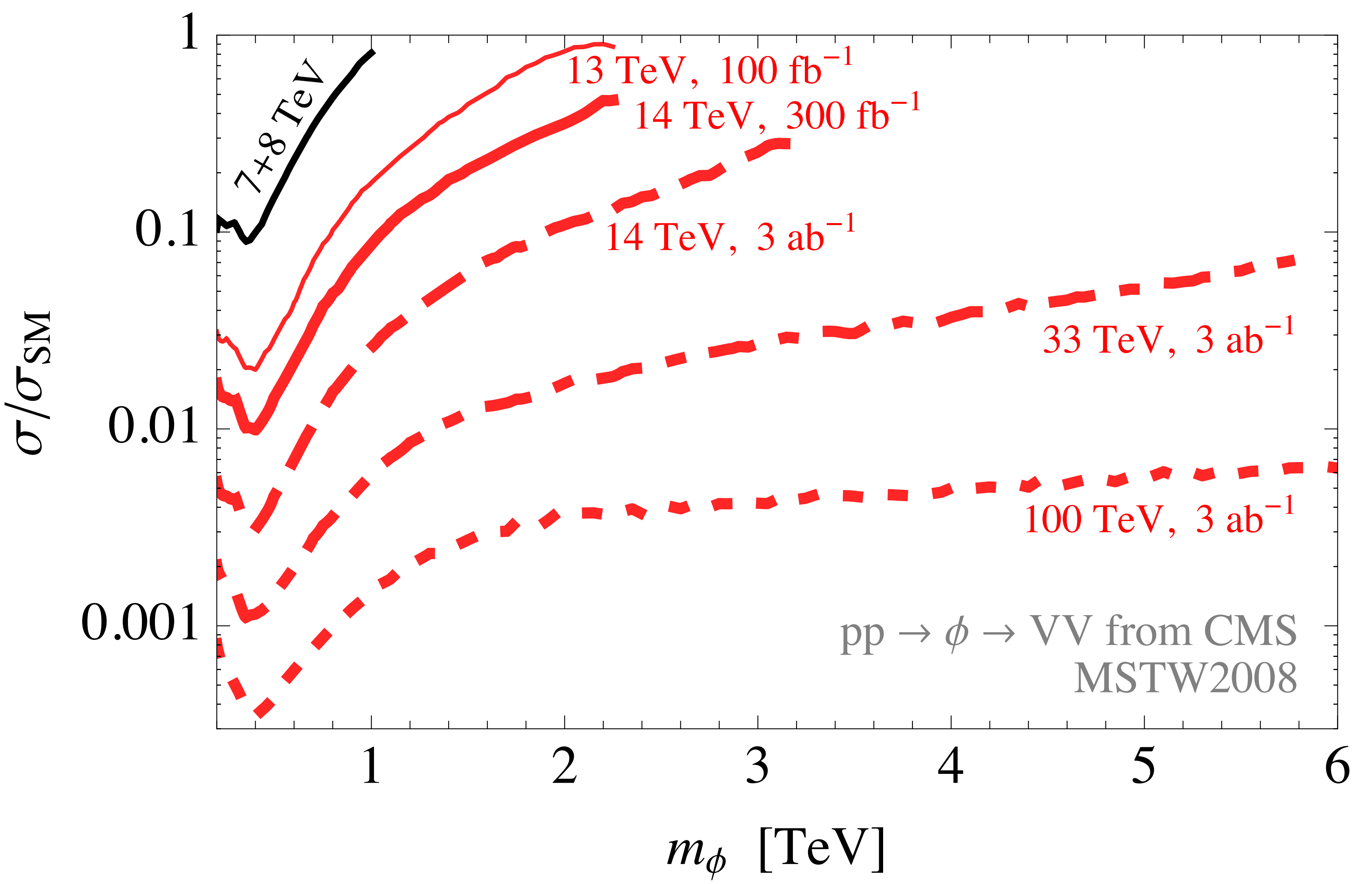
- Our extrapolations are consistent – within a factor of O(1) – with several other studies at 13, 14, 33 TeV...

Brownson et al. ’13
Gouzevich et al. ’13

Direct vs. indirect

One can now compare the reach of direct and indirect searches

$\sigma/\sigma_{\rm SM} \propto \sin^2\gamma$ (ignore for the moment the hh branching ratio)



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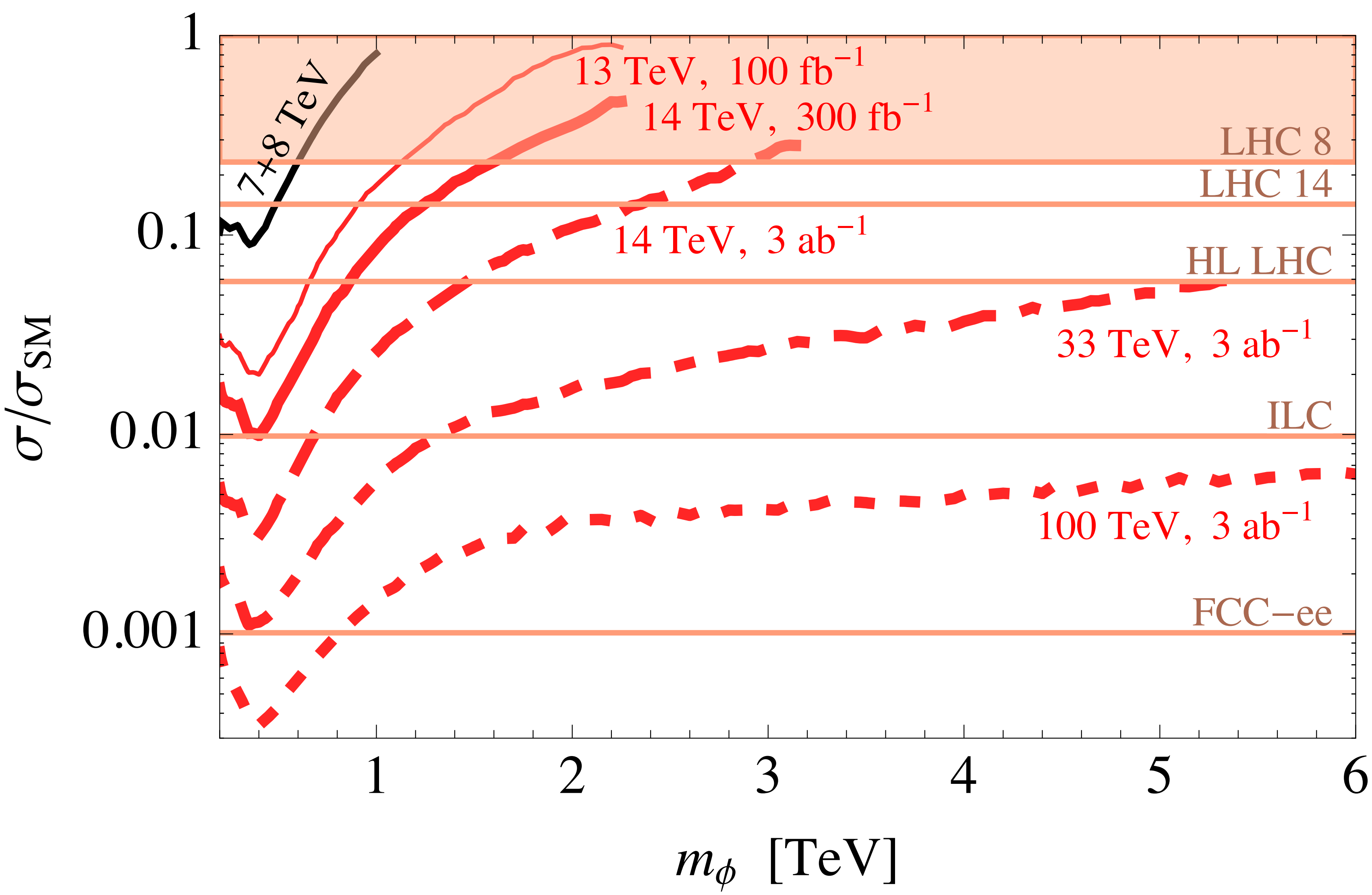
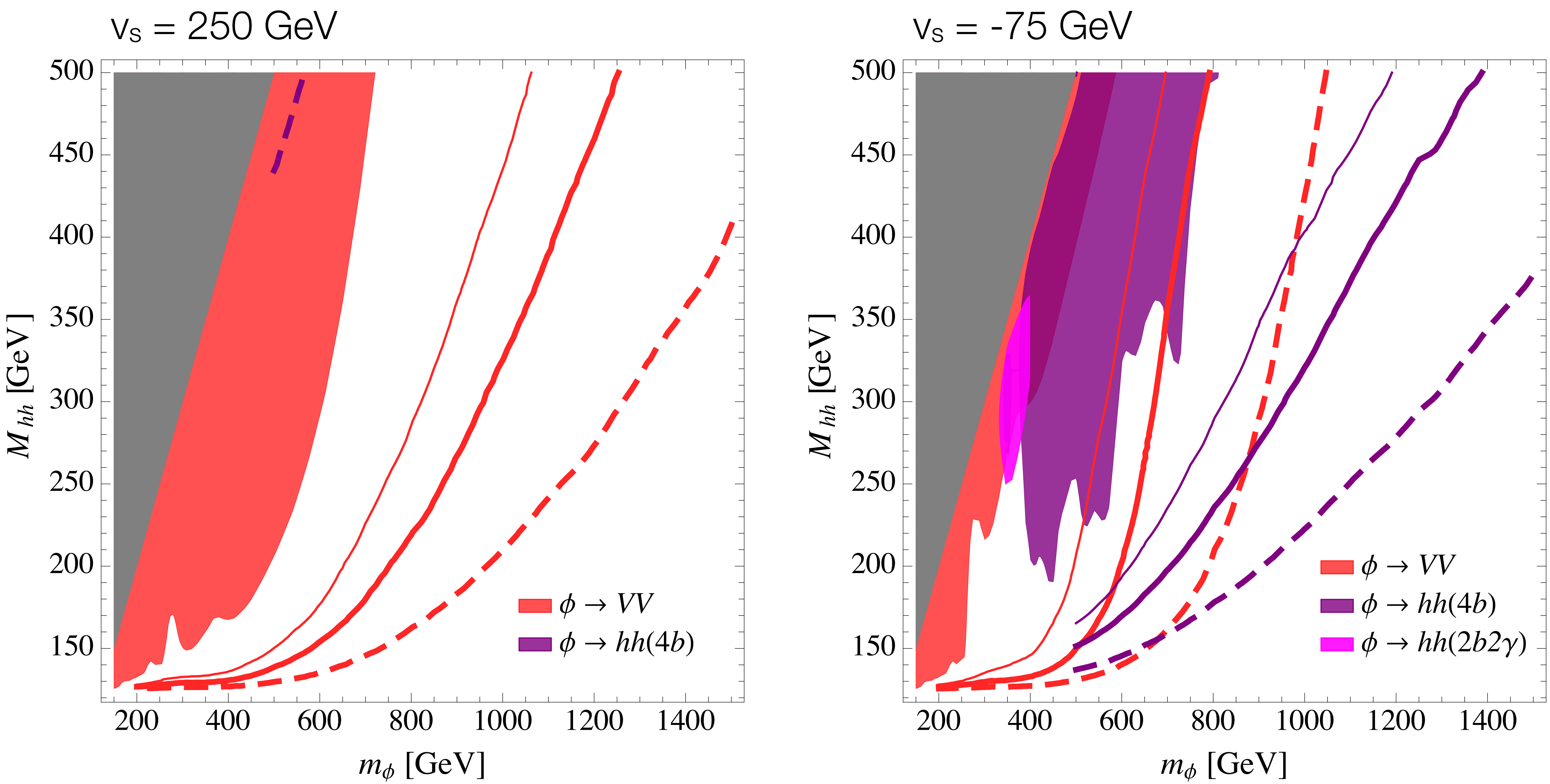


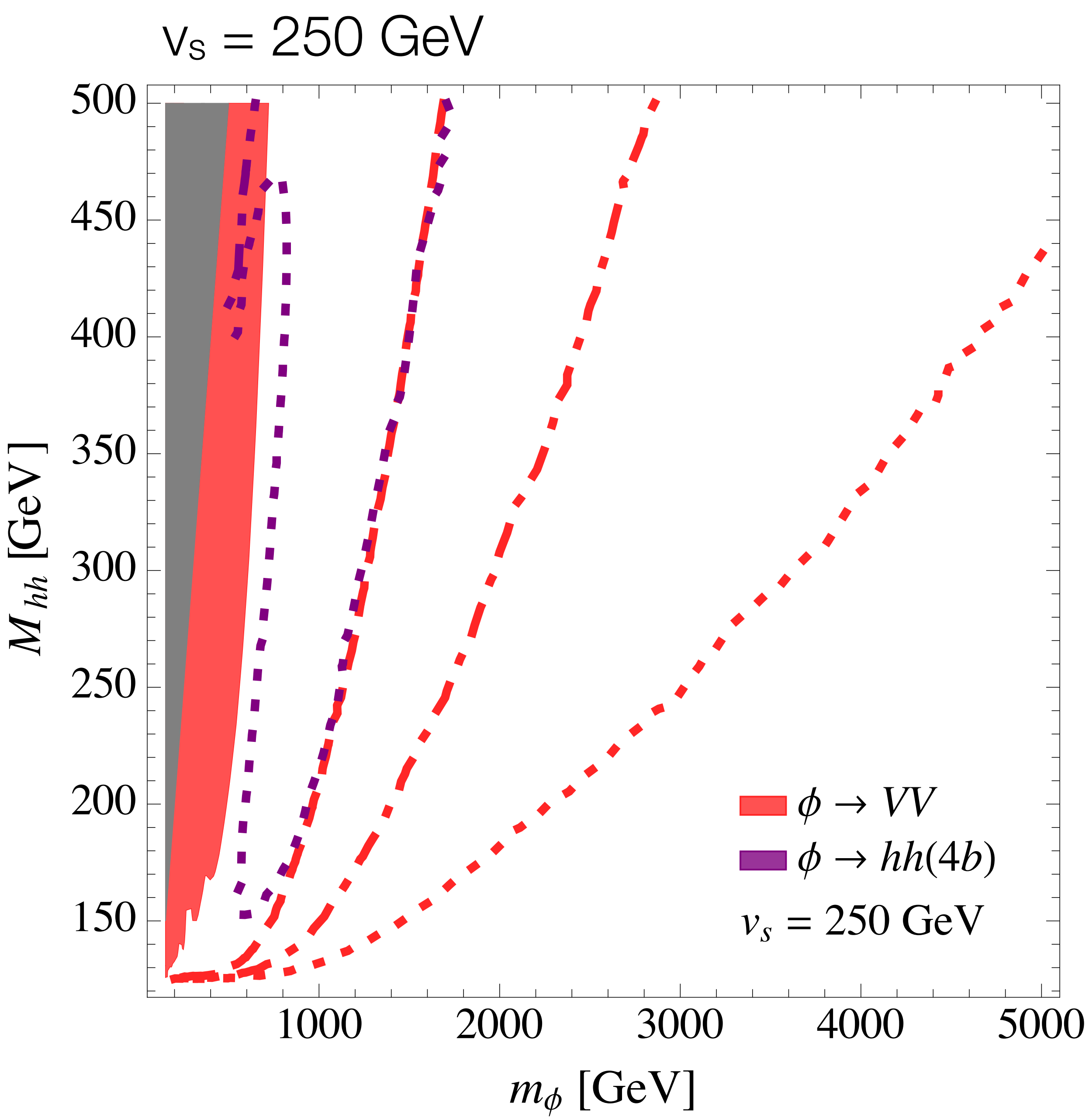
Direct searches always dominate for lower masses (< 1 TeV)

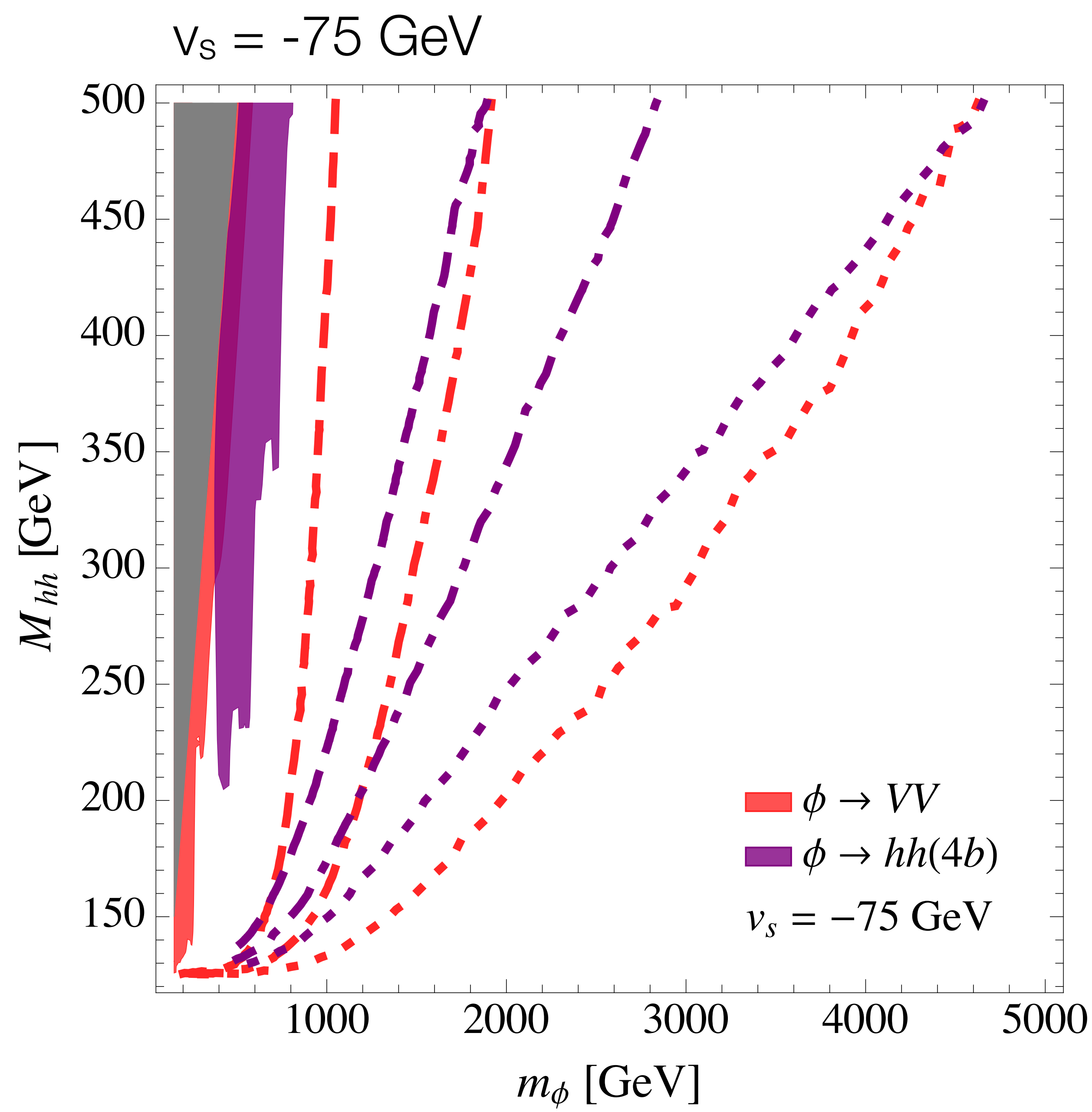
Generic singlet: direct searches @ LHC



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

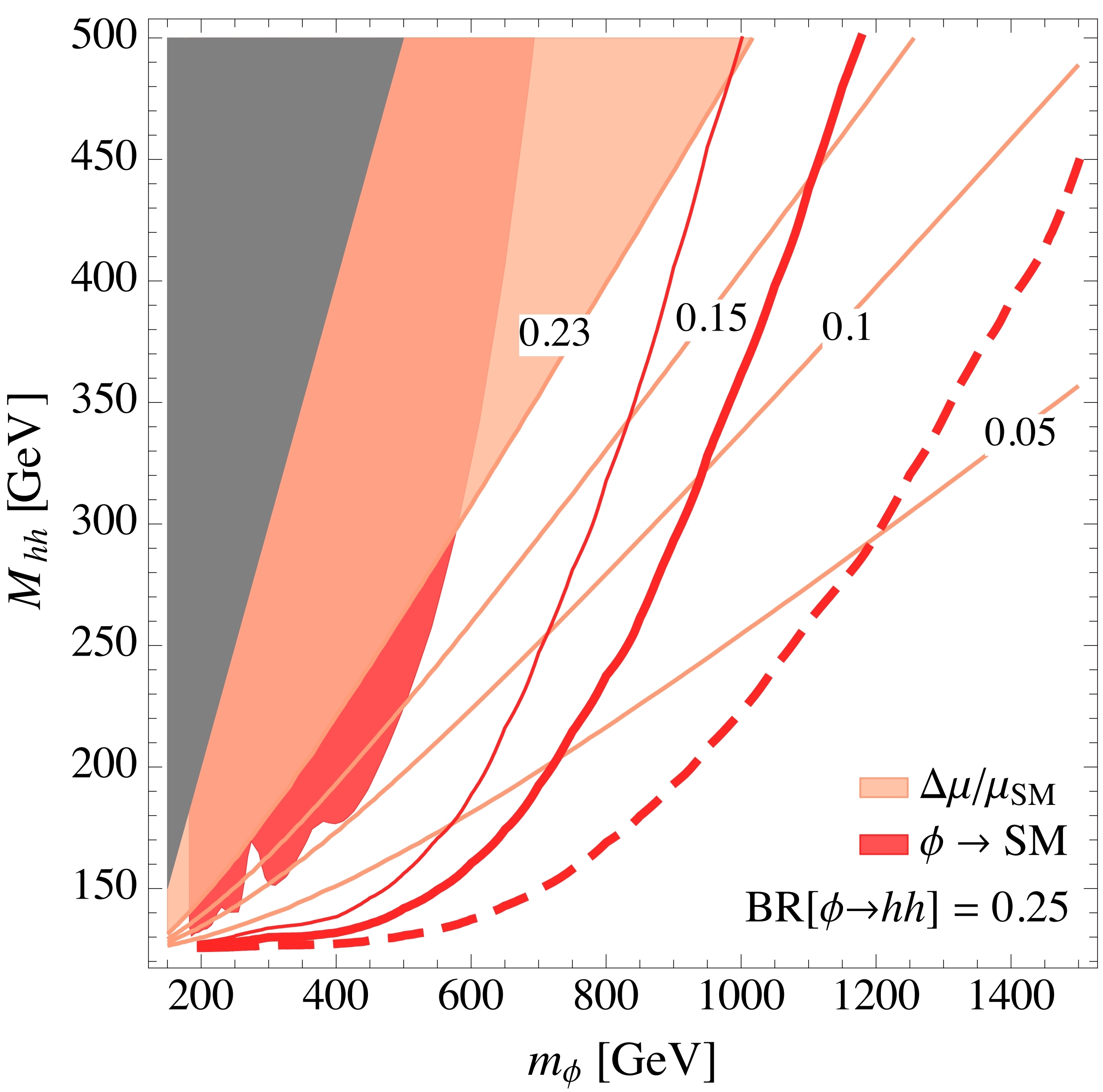
Generic singlet: direct searches @ FCC

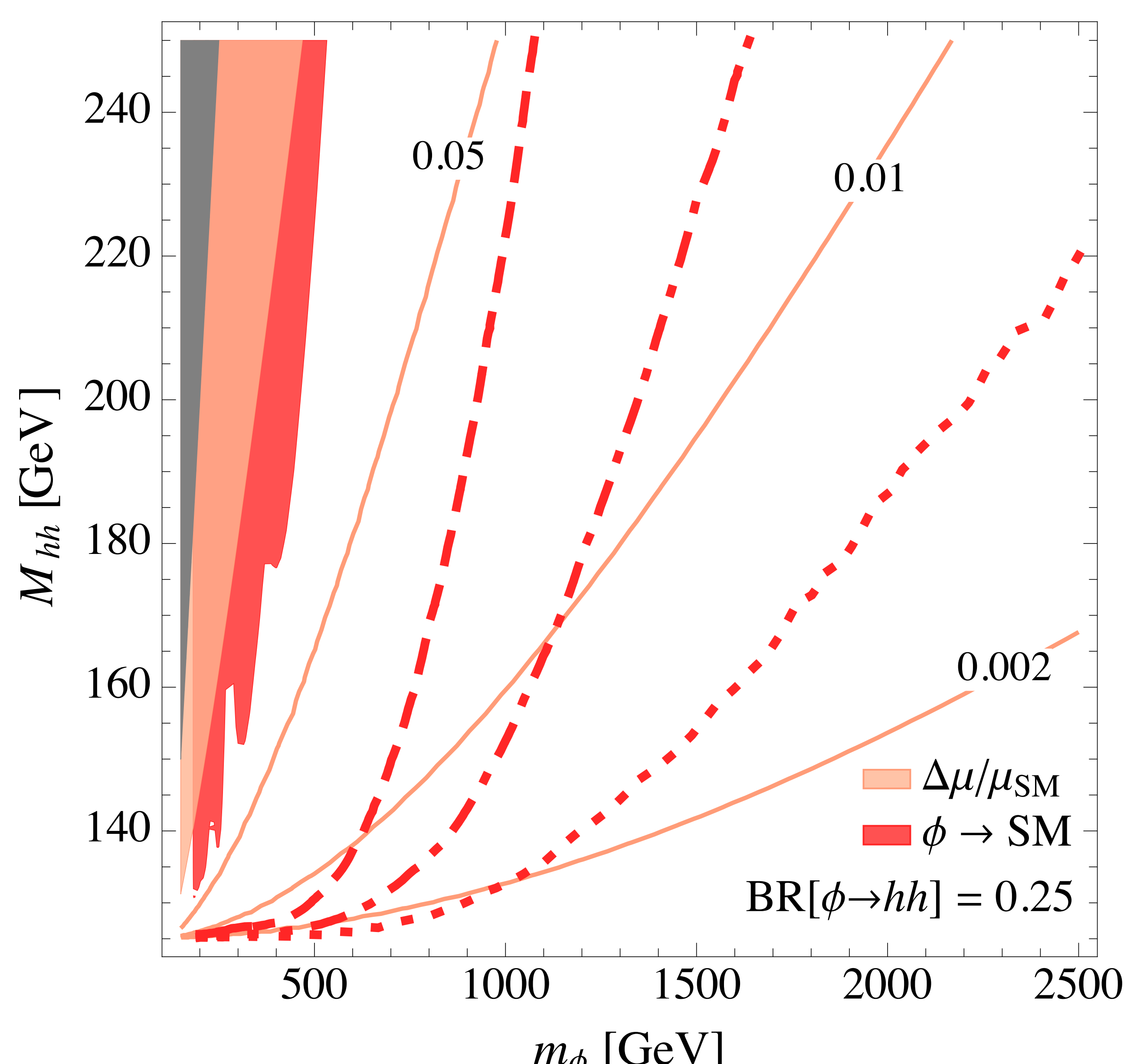




At high masses $\phi \to VV$ is always dominant $(\mathrm{BR}_{\phi\to hh} \sim 1/4)$

Generic singlet: summary of bounds



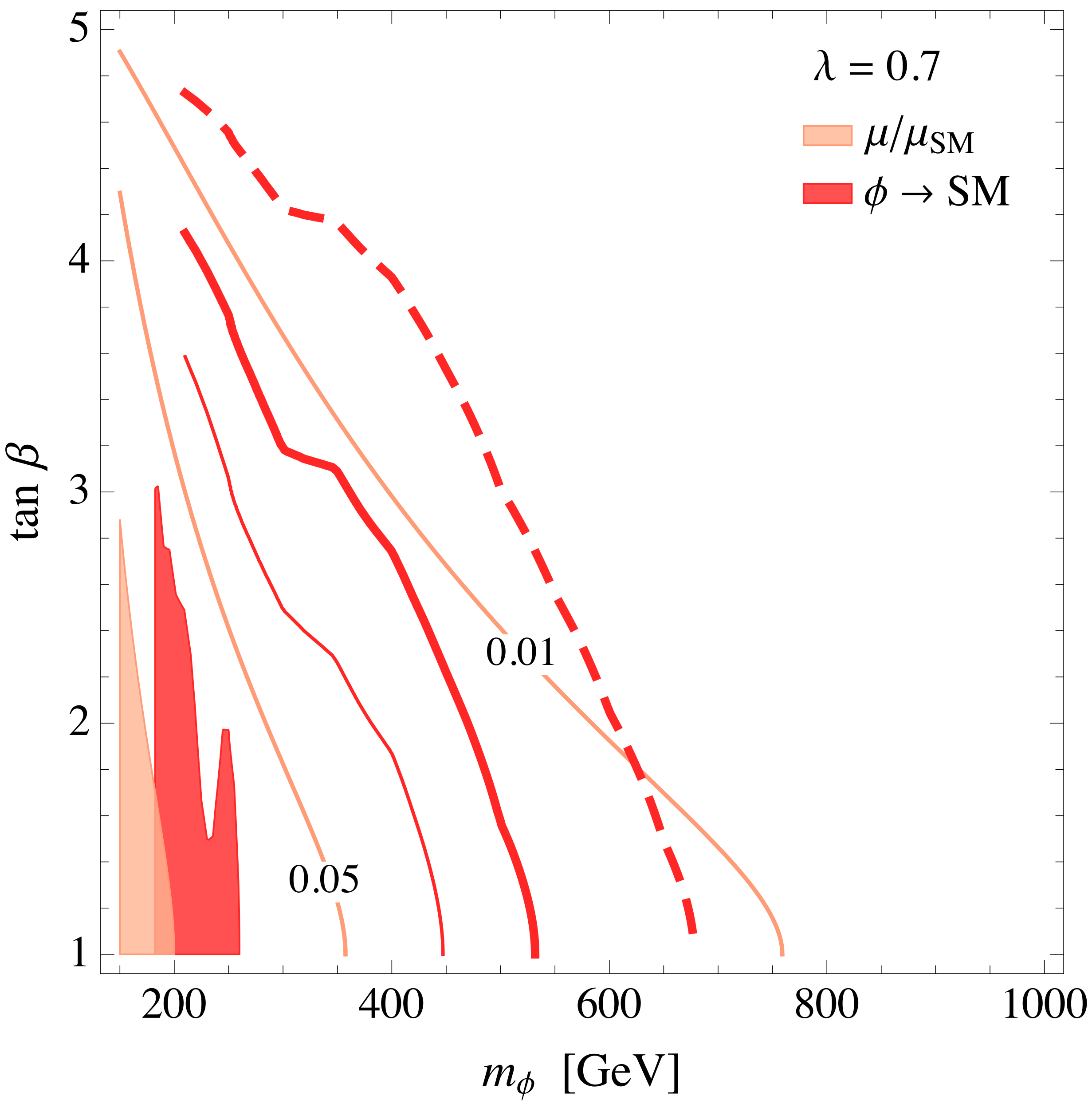


Back to the NMSSM

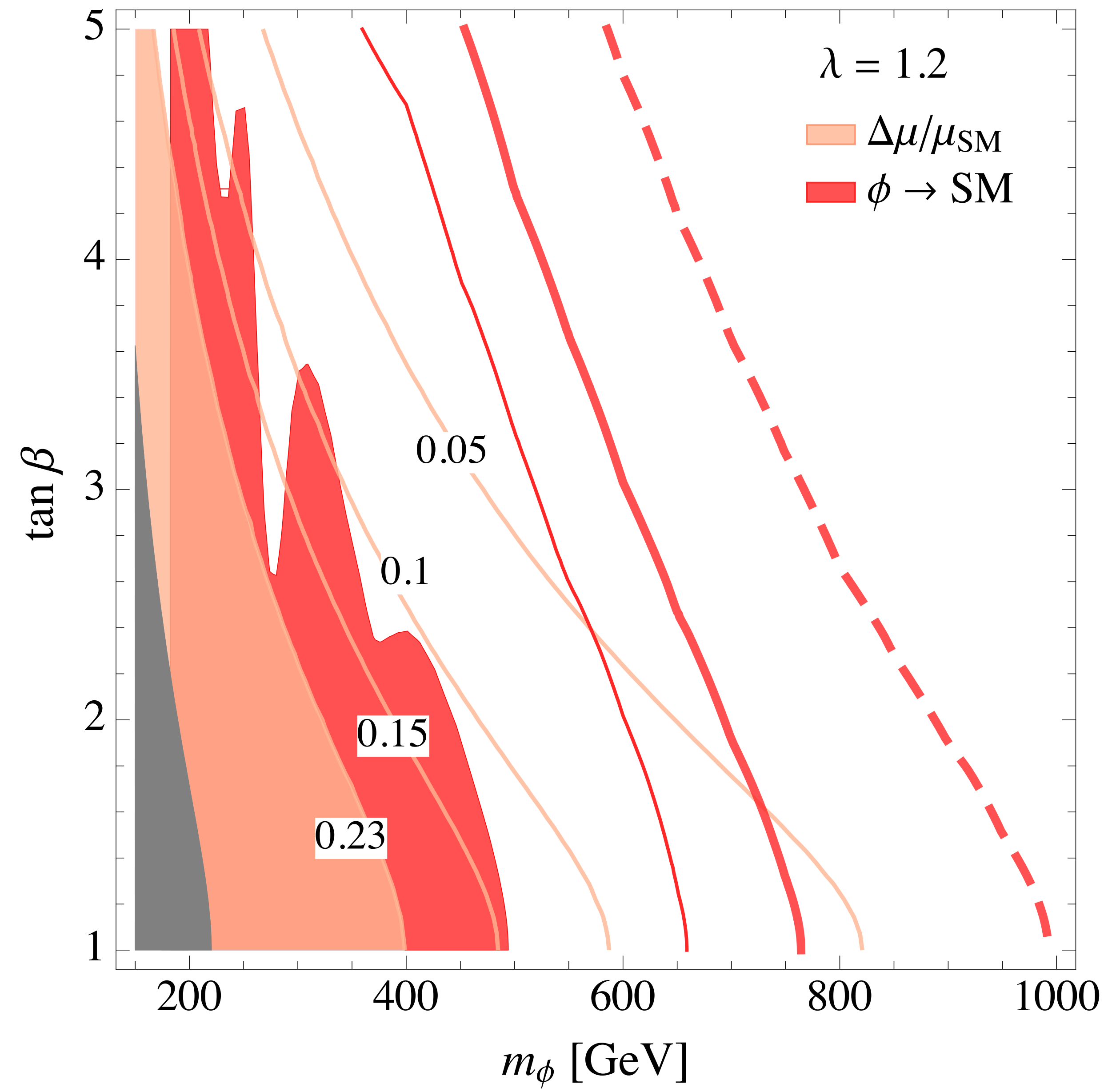
The results for the generic singlet-Higgs are translated to the NMSSM:

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

Perturbative: λ = 0.7, Δ = 80 GeV



Strong coupling: λ = 1.2, Δ = 70 GeV



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

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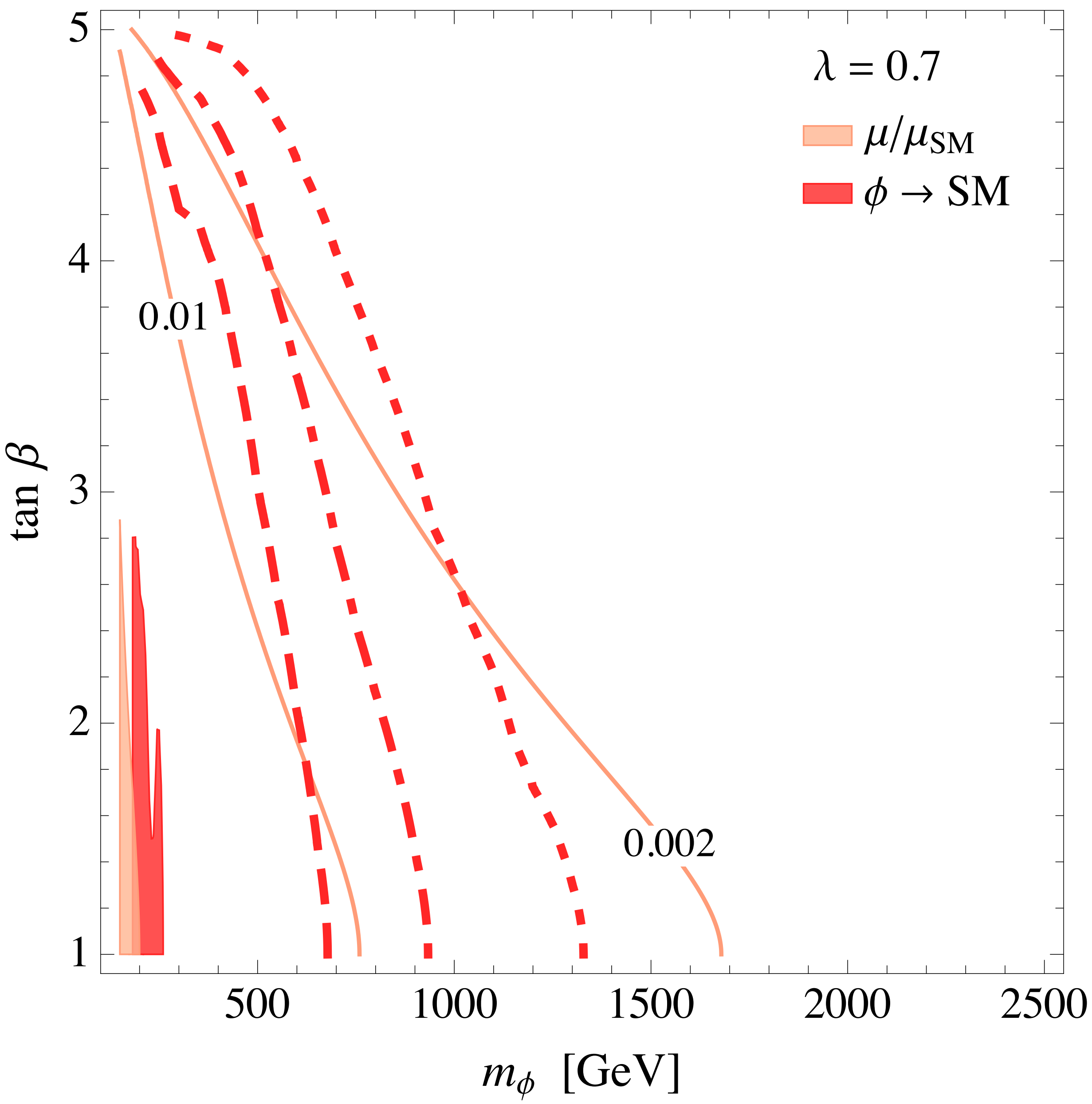

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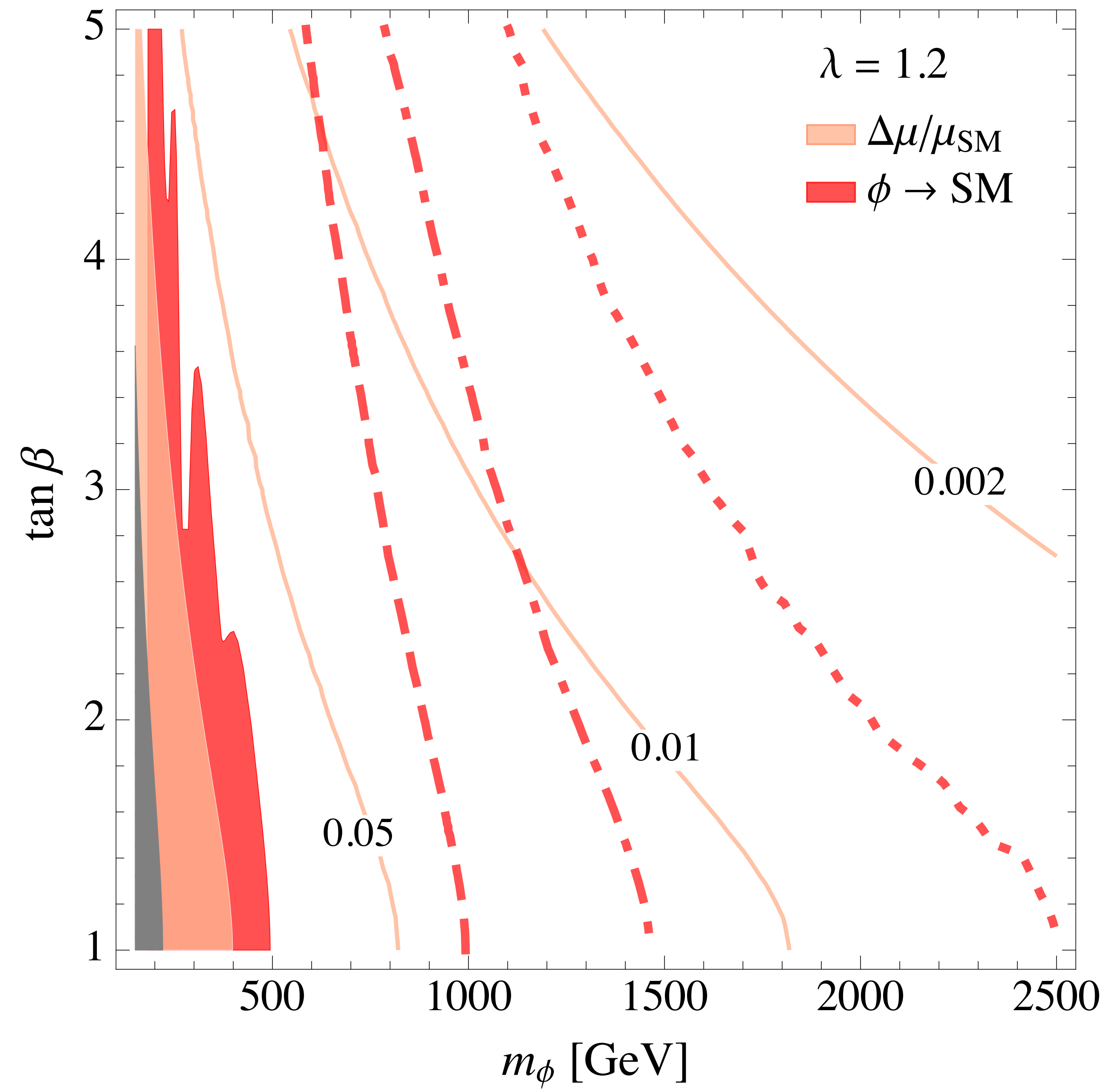
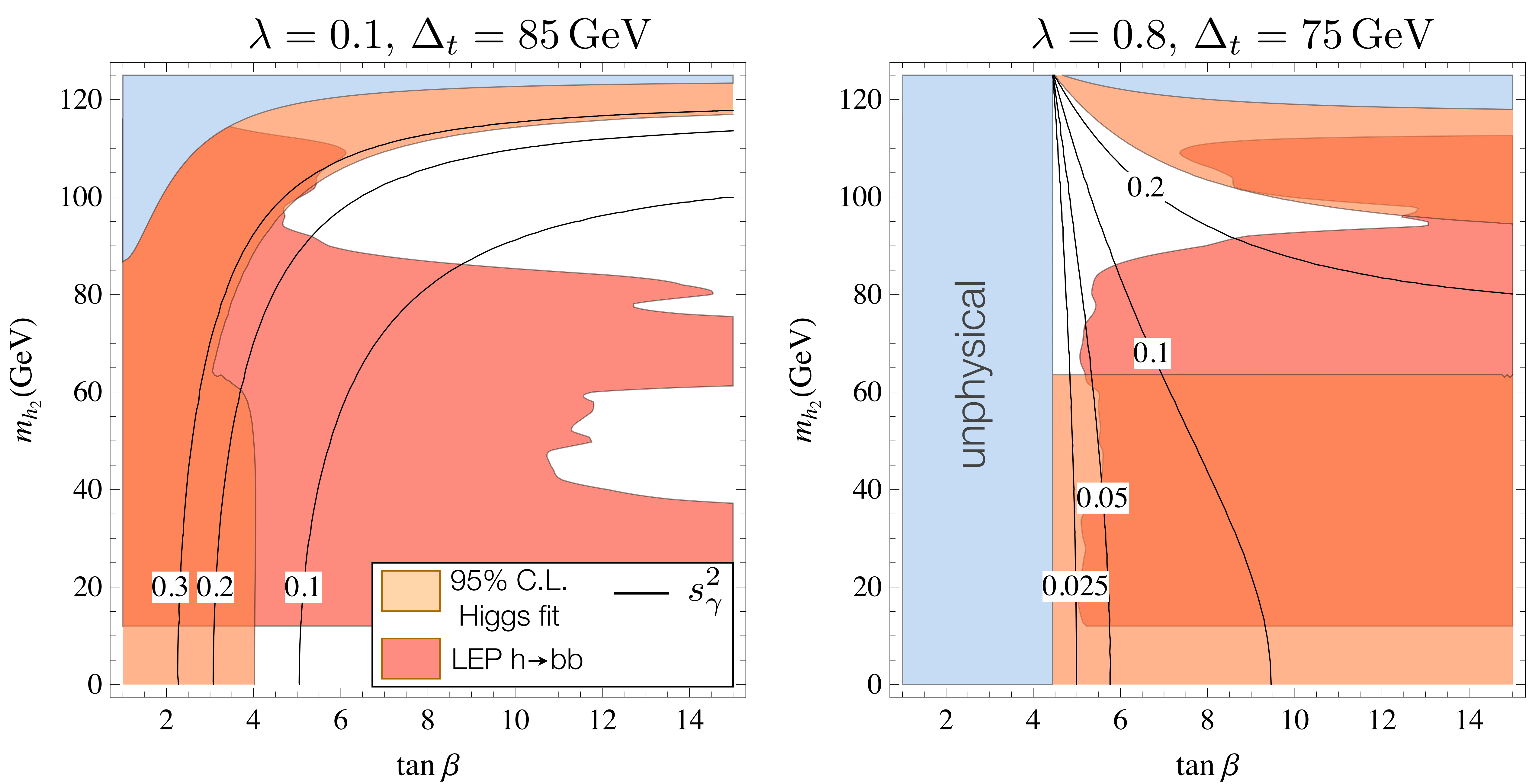


Direct reach @ 100 TeV comparable with sensitivity of FCC-ee

What if h_{LHC} is not the lightest one?

- Still room for a singlet-like state lighter than 125 GeV, compatibly with LEP.
- Regions of parameter space difficult to probe... $\mu_{h_2} = \sin^2\gamma \times \mu_h^{SM}$

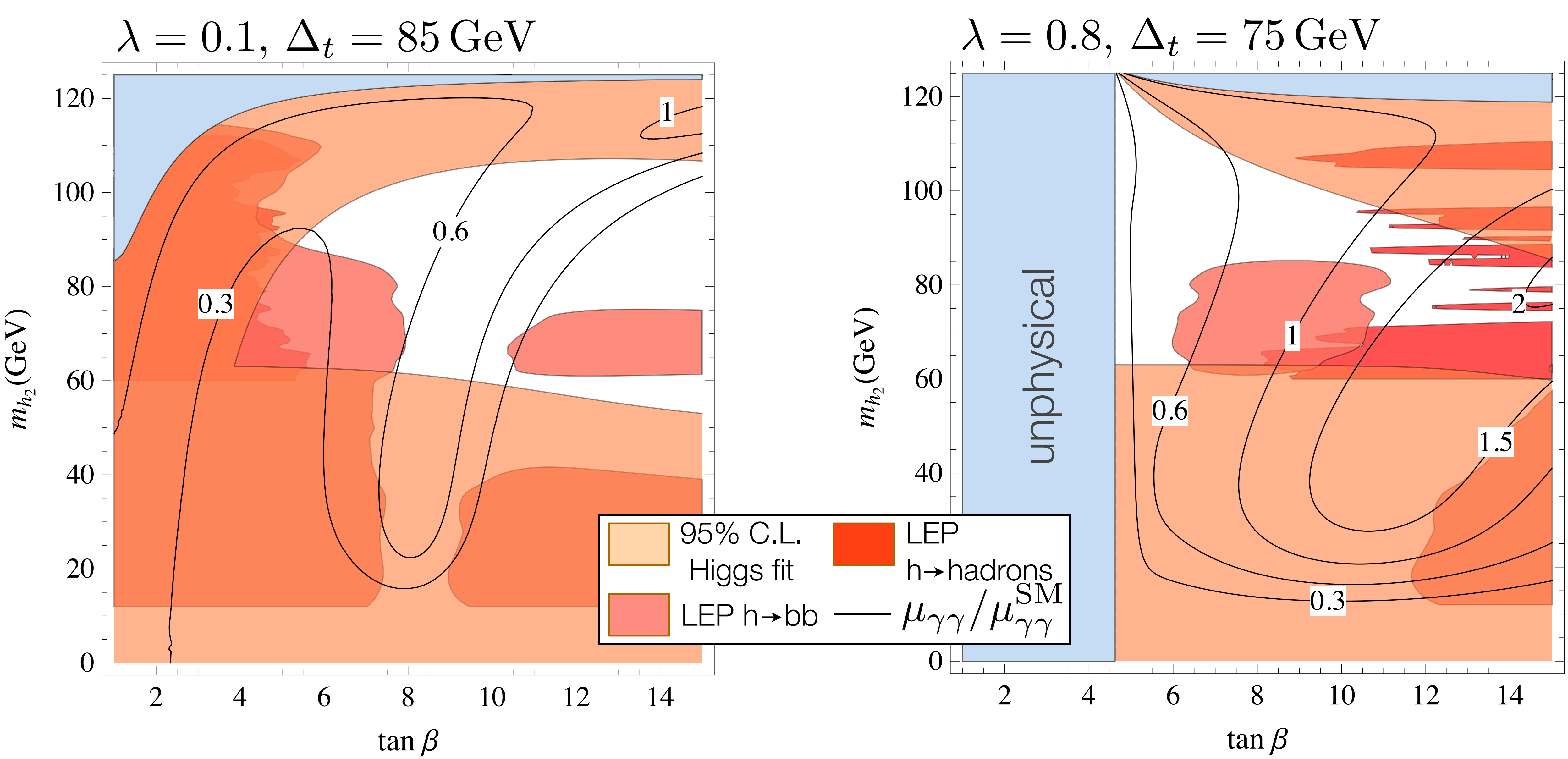


What if h_{LHC} is not the lightest one?

- Still room for a singlet-like state lighter than 125 GeV
- Signal strengths are modified in the 3-state mixing case

Badziak et al. '13
Barbieri, B, Kannike, S, T '13
Ellwanger et al. '14
King et al. '14
Jeong et al. '14
....

Example: $h_2 \to \gamma\gamma \quad (m_{h_3} = 500\,\mathrm{GeV}, \quad s_\sigma^2 = 10^{-3})$



CP-odd states

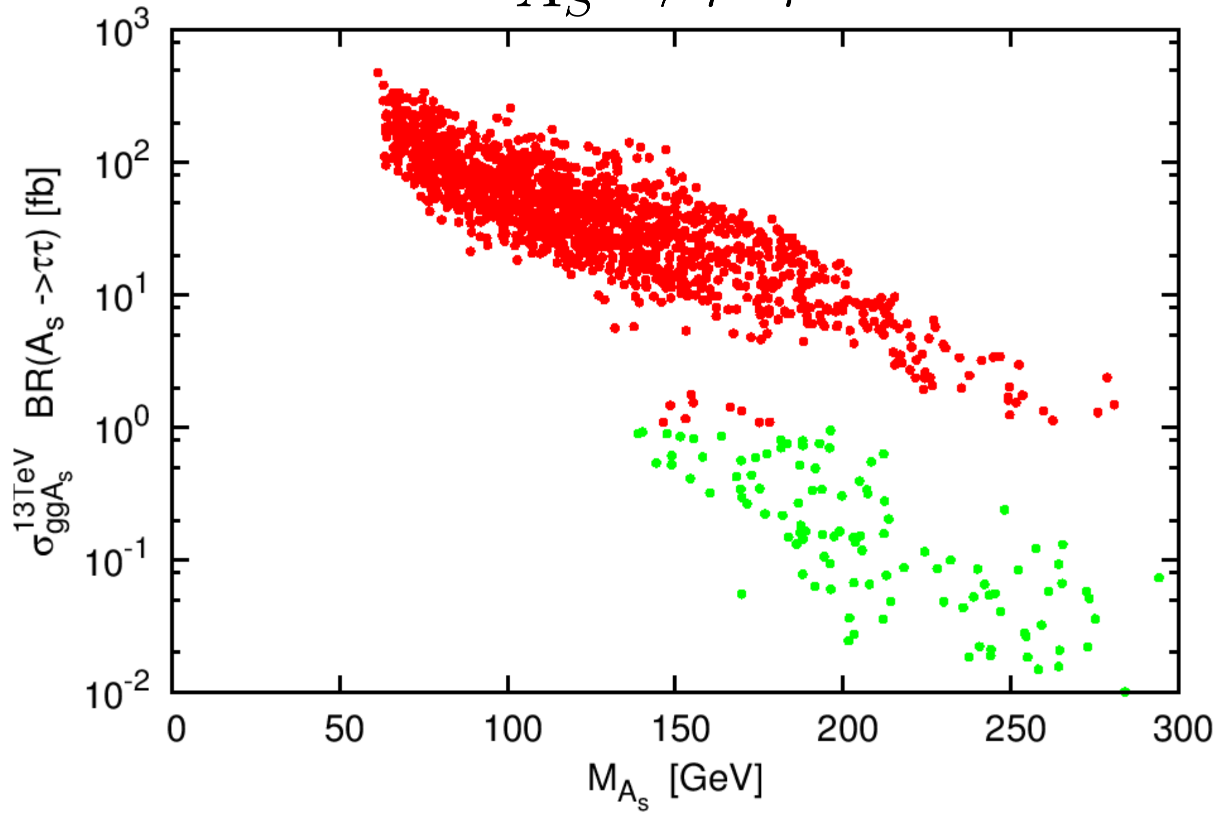
- Two pseudoscalar states A, A_S that mix. Their mass matrix contains additional parameters...

- The singlet-like state can be light: discovery challenging

Example: [King et al. 1408.1120] Scale-invariant NMSSM

$$0.6 \leq \lambda \leq 0.7, \qquad -0.3 \leq \kappa \leq 0.3,$$
$$1.5 \leq \tan\beta \leq 2.5, \quad 100\,\mathrm{GeV} \leq |\mu_{\mathrm{eff}}| \leq 185\,\mathrm{GeV}$$

$A_S \to \tau^+\tau^-$



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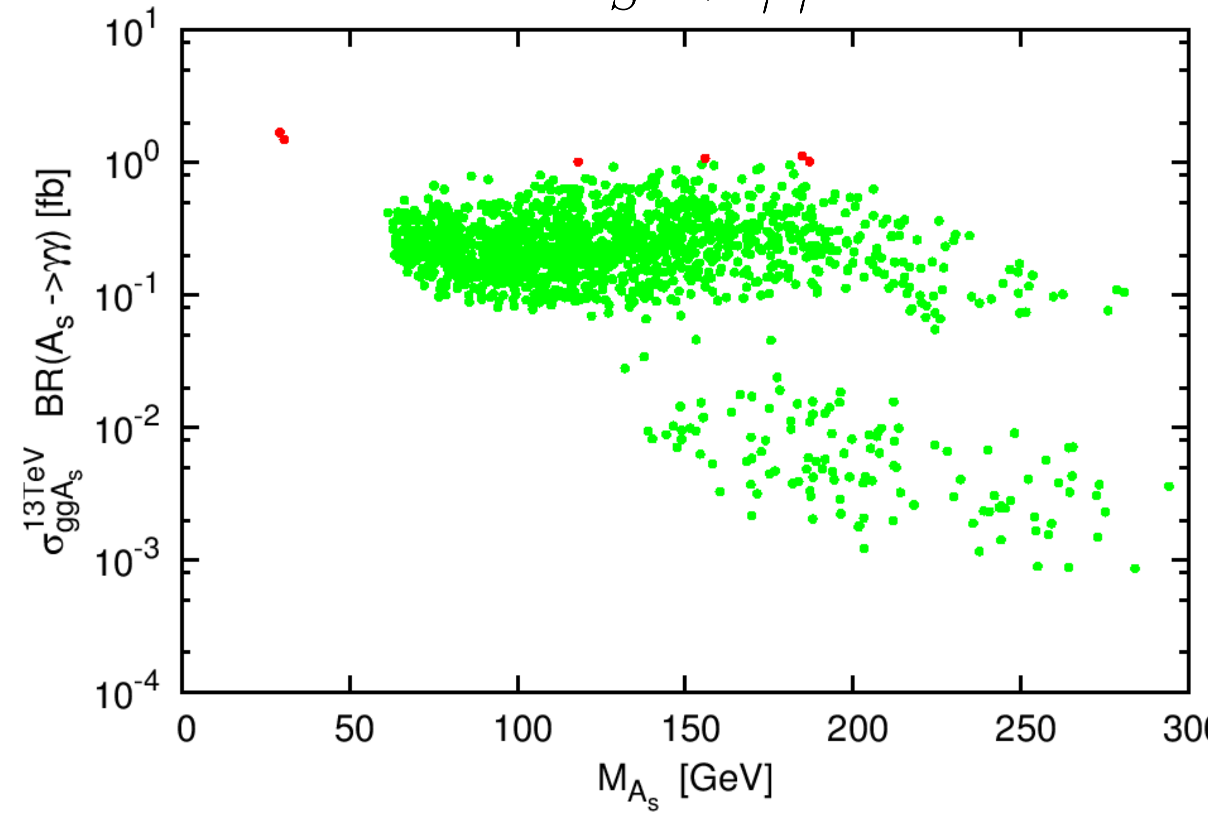


Beyond SUSY: “neutral naturalness”

- Insisting with naturalness, the s-particles cannot be pushed to too high masses (even in the NMSSM)... Where are they?
- Twin Higgs: consider the SM + a “twin” copy SM’:

Chacko et al. ’04
Barbieri et al. ’05

  - Higgs potential SO(8) invariant + Z_2 symmetry SM $\leftrightarrow$ SM’
  - The Higgs is a Goldstone boson of SO(8)/SO(7)
  - The Higgs mass is protected from radiative corrections, without coloured states at the weak scale;
all other particles are heavy or very weakly coupled

$$V = \lambda(\Phi^2 - f_0^2)^2 + \delta V$$

$$\Phi = (h, S)$$

explicitly breaks G in order to generate Higgs mass and potential

$$\delta V = m^2 h^2 + \kappa h^4$$

$$\begin{cases} \langle h^2 \rangle = v^2 \\ \langle \Phi^2 \rangle = f^2 \end{cases}$$

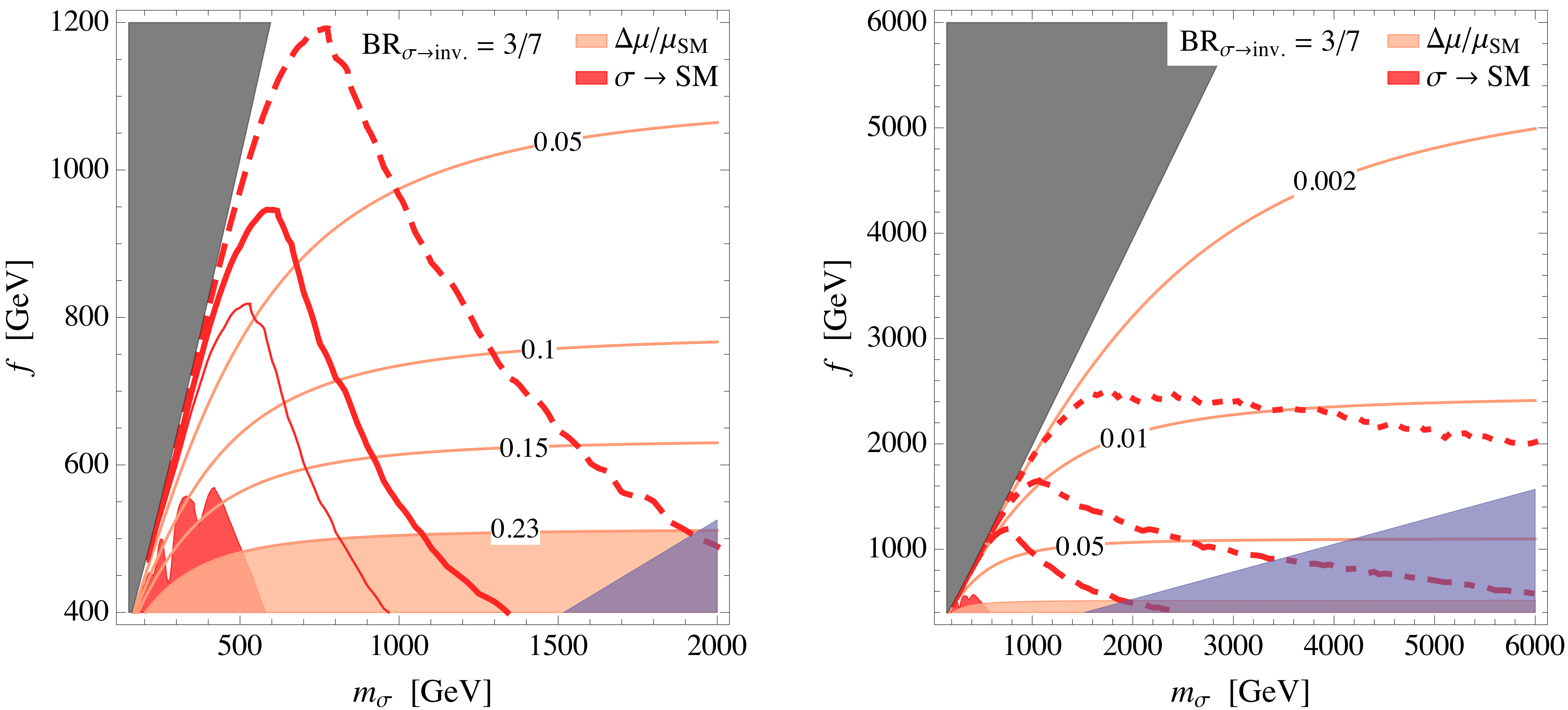
  - 8 d.o.f.: 1 light Higgs + 1 “radial mode” + 6 eaten Goldstones

Twin Higgs

- There is at least one singlet state σ with mass $m_\sigma^2 \approx \lambda f^2$
- Higgs-singlet mixing: exactly the same situation as before!

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

- The model is fully determined by 2 parameters: m_σ, f (and m_h, v)



Summary & conclusions

- Simplified NMSSM scenarios provide “almost natural” new physics cases with extra scalars that can be studied at the LHC

- **Higgs signal strengths:** strong bound in MSSM and NMSSM w/ singlet decoupled: almost whole parameter space covered by LHC14

- **Direct searches:** already the strongest constraint in NMSSM w/ doublet decoupled; significant improvement expected: already with 100 fb^{-1} sensitivity comparable to Higgs couplings with 3000 fb^{-1}.

- **Triple Higgs**: large deviations from SM possible, unlike in MSSM

- **Looking for singlets is easy and motivated by many natural models, in SUSY and beyond!**

- A state lighter than 125 GeV is still allowed: discovery challenging

Backup

Electroweak Precision Tests

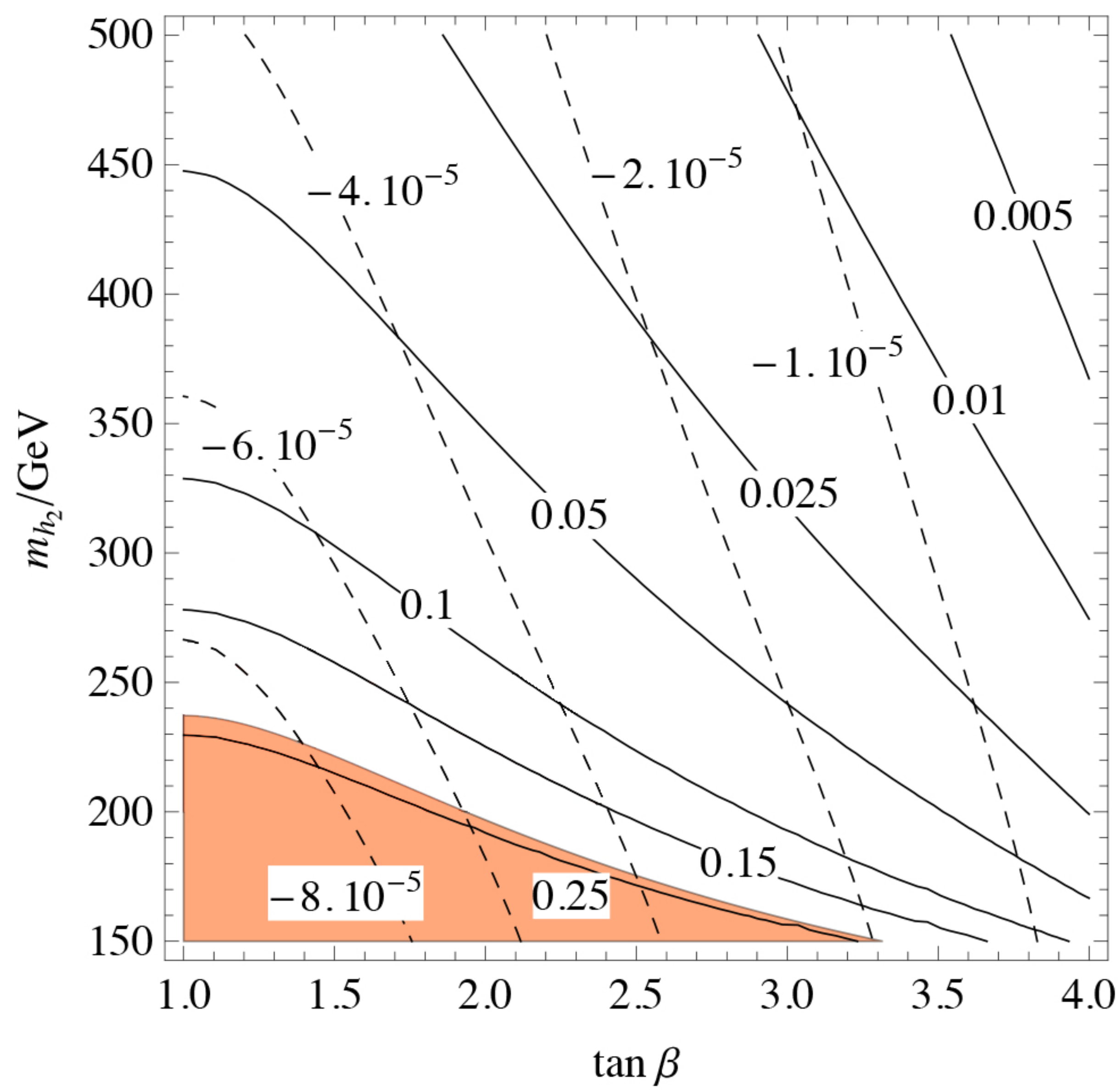
Relevant contribution from loops of the new Higgses? NO ✓

- H decoupled: couplings scale as $\sin^2\gamma\ (\cos^2\gamma)$

$$\Delta\hat{S} = \frac{\alpha}{48\pi s_w^2}\sin^2\gamma\log\frac{m_{h_2}^2}{m_{h_{\rm LHC}}^2},$$

$$\Delta\hat{T} = -\frac{3\alpha}{16\pi c_w^2}\sin^2\gamma\log\frac{m_{h_2}^2}{m_{h_{\rm LHC}}^2}$$

Barbieri, Tesi '13



- S decoupled: larger effects possible in general, but limits on the mixing angle $\delta \simeq 0 \ \Rightarrow$ no new constraint

General solutions for the mixing angles

$$s_\gamma^2 = \frac{\det M^2 + m_{h_1}^2(m_{h_1}^2 - \mathrm{tr} M^2)}{(m_{h_1}^2 - m_{h_2}^2)(m_{h_1}^2 - m_{h_3}^2)},$$

$$s_\sigma^2 = \frac{m_{h_2}^2 - m_{h_1}^2}{m_{h_2}^2 - m_{h_3}^2}\,\frac{\det M^2 + m_{h_3}^2(m_{h_3}^2 - \mathrm{tr} M^2)}{\det M^2 - m_{h_2}^2 m_{h_3}^2 + m_{h_1}^2(m_{h_2}^2 + m_{h_3}^2 - \mathrm{tr} M^2)},$$

$$\begin{aligned}\sin 2\alpha = \Big(& \pm 2|s_\gamma s_\sigma|\sqrt{1-s_\sigma^2}\sqrt{1-\sin^2 2\xi}(m_{h_3}^2 - m_{h_2}^2) \\ & + \left[m_{h_3}^2 - m_{h_2}^2 s_\gamma^2 + s_\sigma^2(1+s_\gamma^2)(m_{h_2}^2 - m_{h_3}^2) - (1-s_\gamma^2)m_{h_1}^2\right]\sin 2\xi\Big) \\ & \times \Big(\left[m_{h_3}^2 - m_{h_1}^2 + s_\gamma^2(m_{h_1}^2 - m_{h_2}^2)\right]^2 + (m_{h_3}^2 - m_{h_2}^2)(1-s_\gamma^2)s_\sigma^2 \\ & \times \left[2m_{h_1}^2(1+s_\gamma^2) - 2(m_{h_3}^2 + s_\gamma^2 m_{h_2}^2) + s_\sigma^2(m_{h_3}^2 - m_{h_2}^2)(1-s_\gamma^2)\right]\Big)^{-1/2}\end{aligned}$$

where M is the 2x2 submatrix of $\mathcal{M}$ in the 1-2 sector, and ξ its mixing angle (contains the dependence on λ and Δ_t)