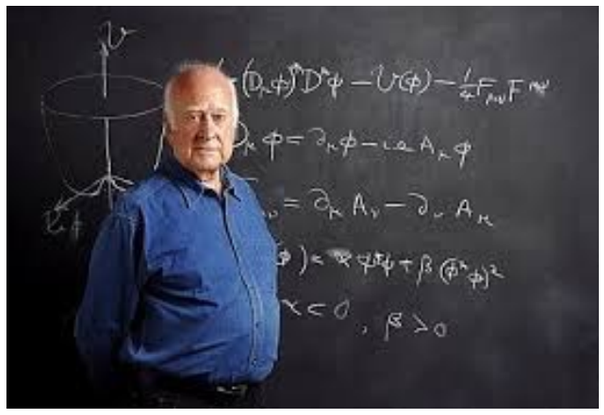
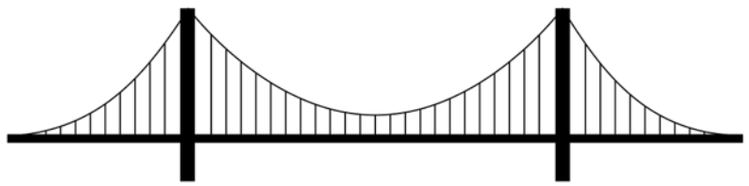
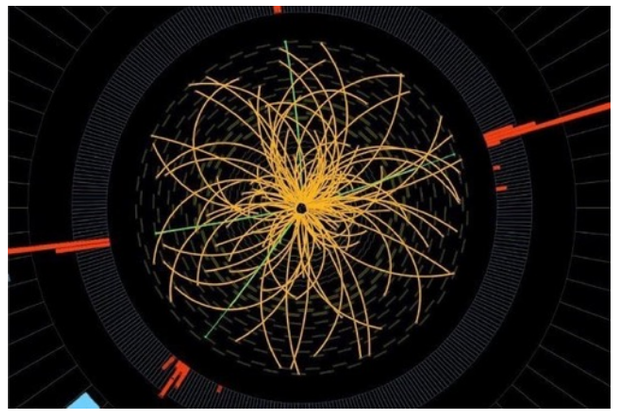
Higgs theory for LHC run-2

Filippo Sala

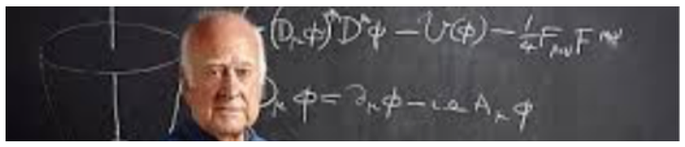
LPTHE Univ. Paris 6 and CNRS



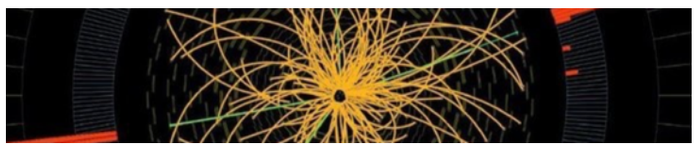




LHCpp Meeting, Università di Pisa, Tue 17 May 2016



Could new Higgs bosons be the first new particles seen?



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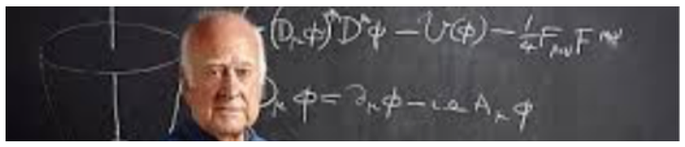

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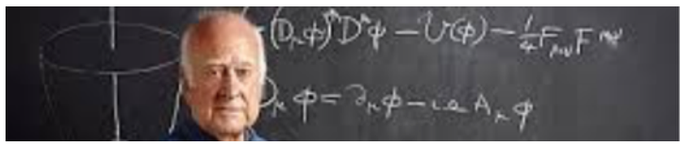

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Here *Higgs* = scalar with “a relation” to EW symmetry breaking

Extra Higgses are ubiquitous, for example in

- Supersymmetry
- Twin and composite Higgs
- Electroweak Baryogengesis (independent of naturalness)

Twin Higgs

Chacko Goh Harnik 2005, Barbieri Gregoire Hall 2005,...

Could a “Twin" Higgs be the first new particle seen?

- Radial mode Buttazzo FS Tesi 2015
- Scalars from SUSY UV completion Redigolo Ziegler et al, to appear
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Why TH interesting? Solves **little** hierarchy problem, without coloured top partners

If nothing new at the LHC14, TH models still quite natural!

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- Add a Z_2 symmetric copy of the SM
  [only copy of top strictly necessary see e.g. J Serra @ MIAPP 2015]
- 8 “Higgs” degrees of freedom - vs 4 in the SM

  7 are massless Goldstone bosons

  one, σ = radial mode of symmetry breaking = SM singlet

  $\langle\sigma\rangle = f,\ m_\sigma \sim f$ conceivable if UV completion is weakly coupled

Other particles? Either $M \gtrsim 4\pi f$ or very weakly coupled

Extra Higgses in Supersymmetry

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	Higgs mass (125 GeV)	Fine tuning
MSSM	Prefers $m_{\tilde{t}} \gtrsim 1.5$ TeV $(m_h^2 \leq m_Z^2 \cos^2 2\beta + \Delta_{\text{loops}})$	worse than 1% (v sensitivity to $m_{\tilde{t}}$ fixed by $SU(2)_w$)
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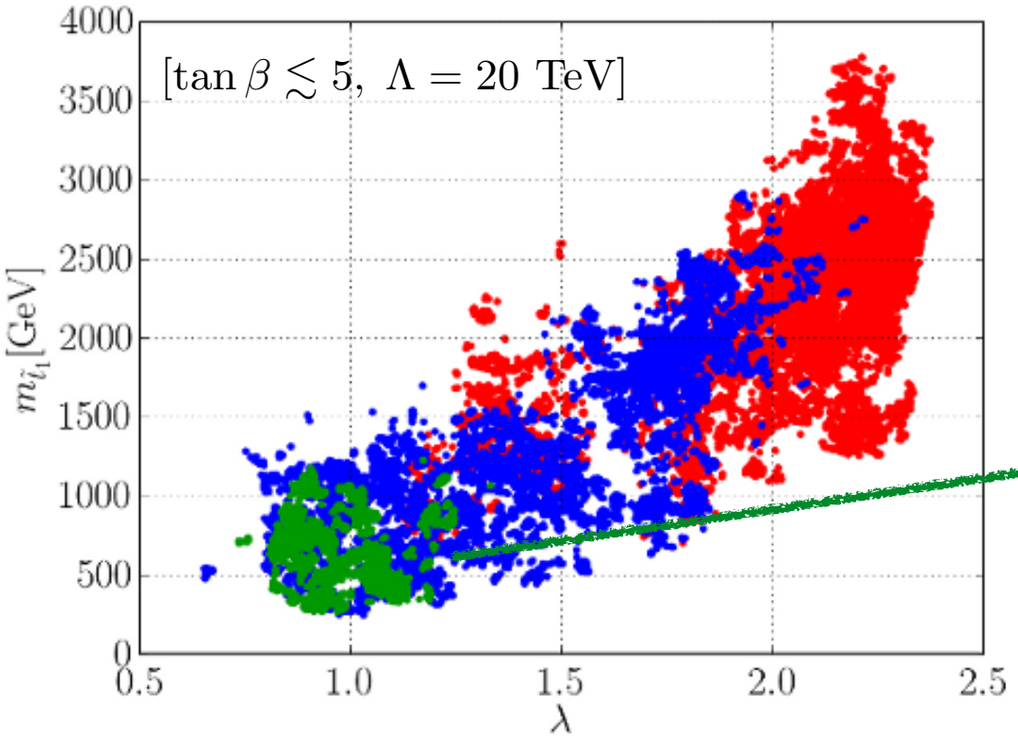
NMSSM	$m_h^2 \leq m_Z^2 c_{2\beta}^2 + \Delta_{\rm loops} + \lambda^2 v^2 s_{2\beta}^2$	$\tilde{t}$ and $\tilde{g}$ heavier by $\sim \lambda/g$ than in MSSM (given a fixed tuning)



NMSSM = MSSM + singlet S

$$W = W_{MSSM} + \lambda S H_u H_d + f(S)$$

Fine tuning better than 5%

Gherghetta et al. 1212.5243

see also Gherghetta et al. 1401.8291
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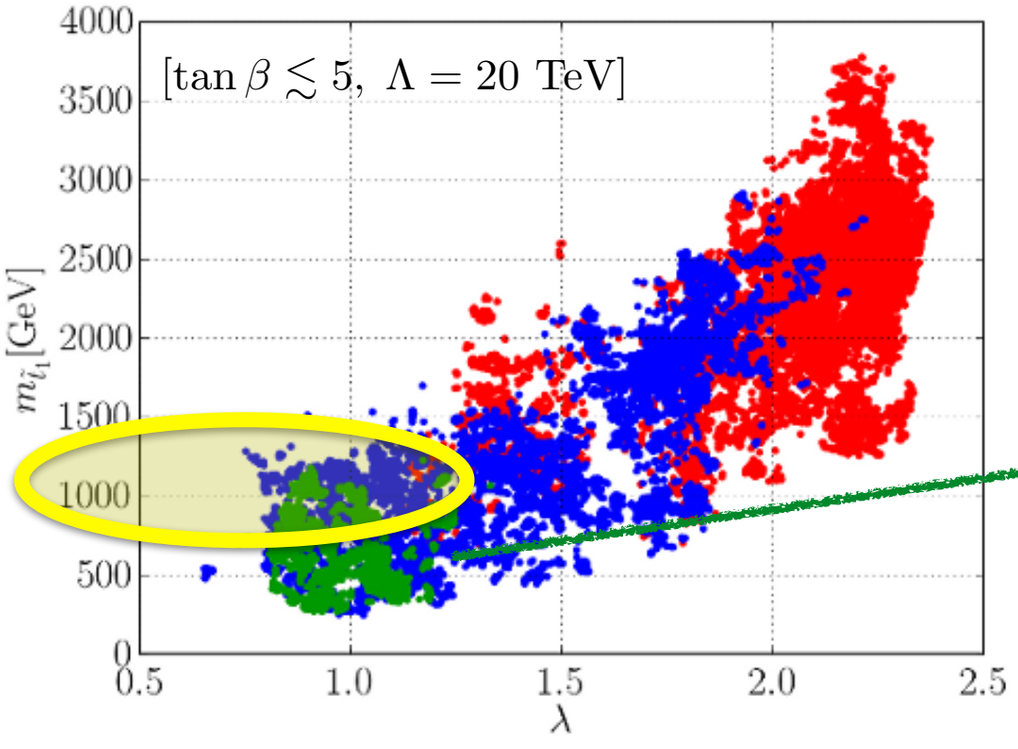

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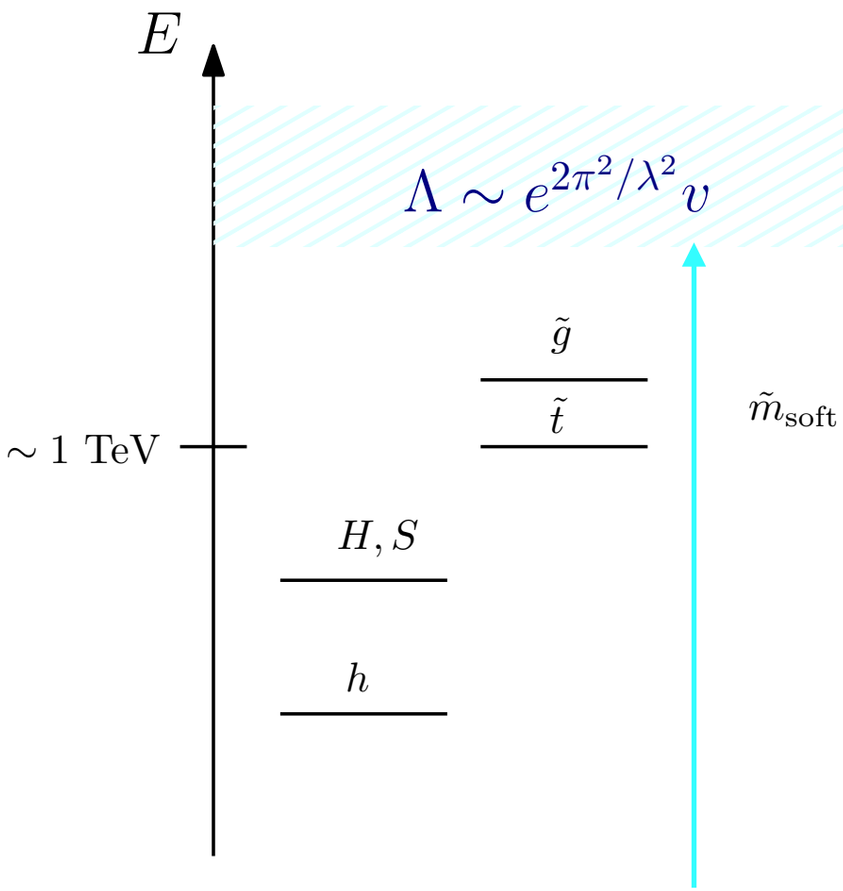
SUSY Higgs spectra

Extra Higgses *could* be seen before stops and gluinos, in both MSSM and NMSSM



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needs UV completion before GUT
see e.g. Harnik et al hep-ph/0311349,
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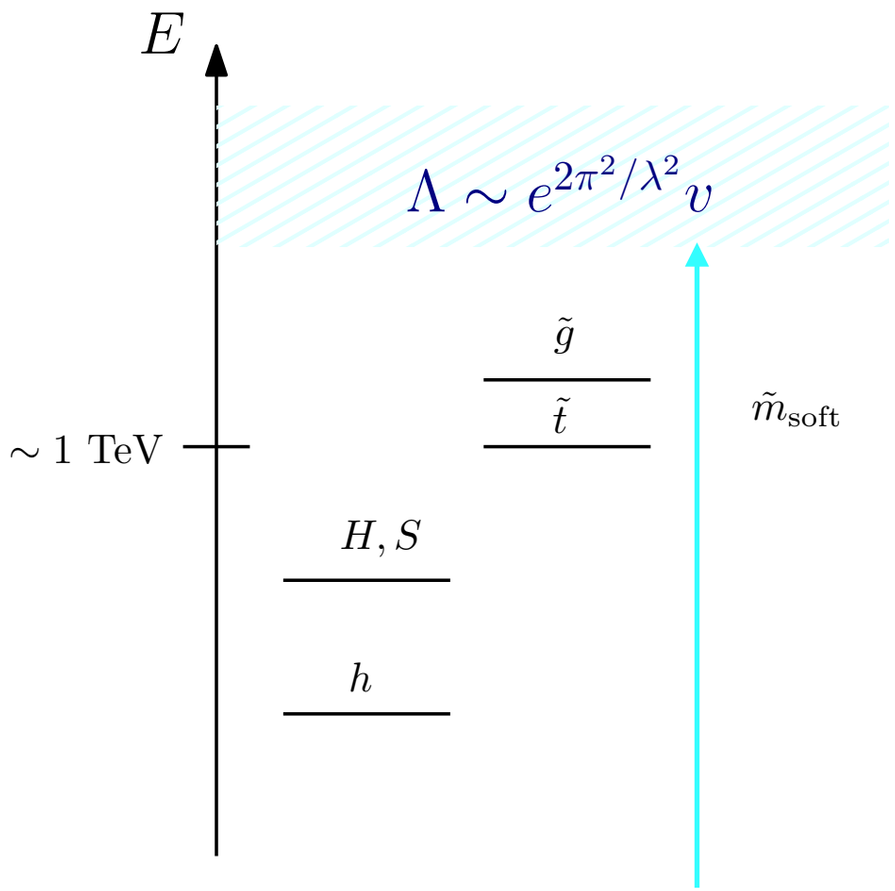

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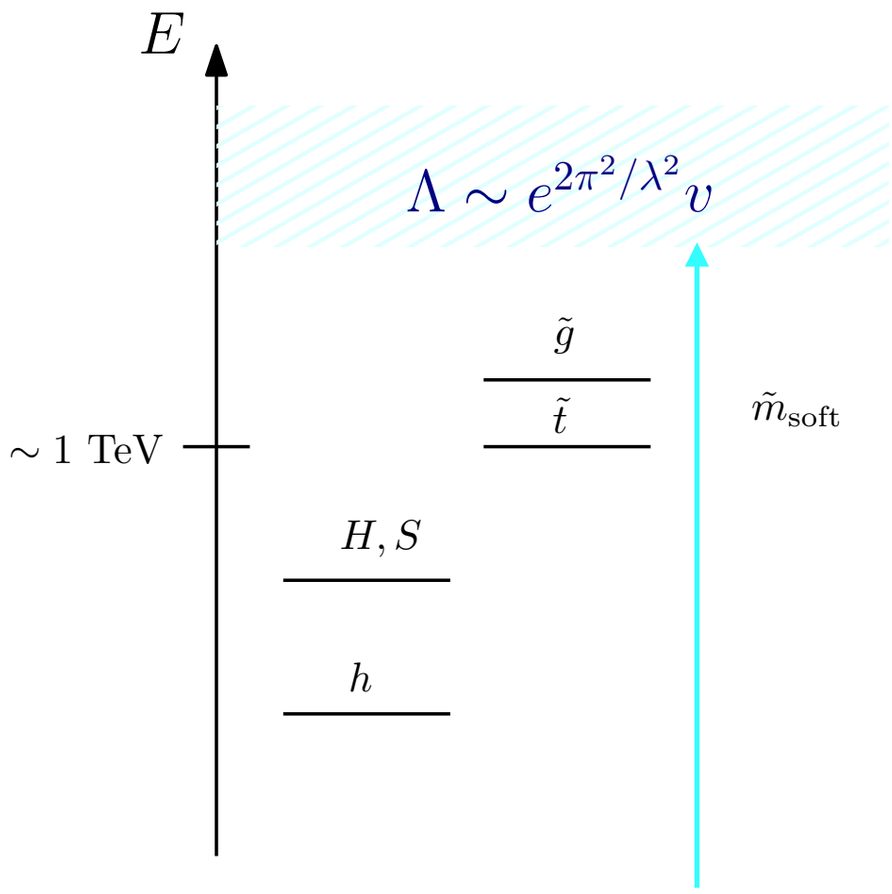

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$$\begin{pmatrix} H \\ h \\ \phi \end{pmatrix} = R \begin{pmatrix} H_0 \\ h_v \\ S \end{pmatrix}, \qquad R = R_\sigma^{HS}\, R_\gamma^{hS}\, R_\delta^{hH}$$

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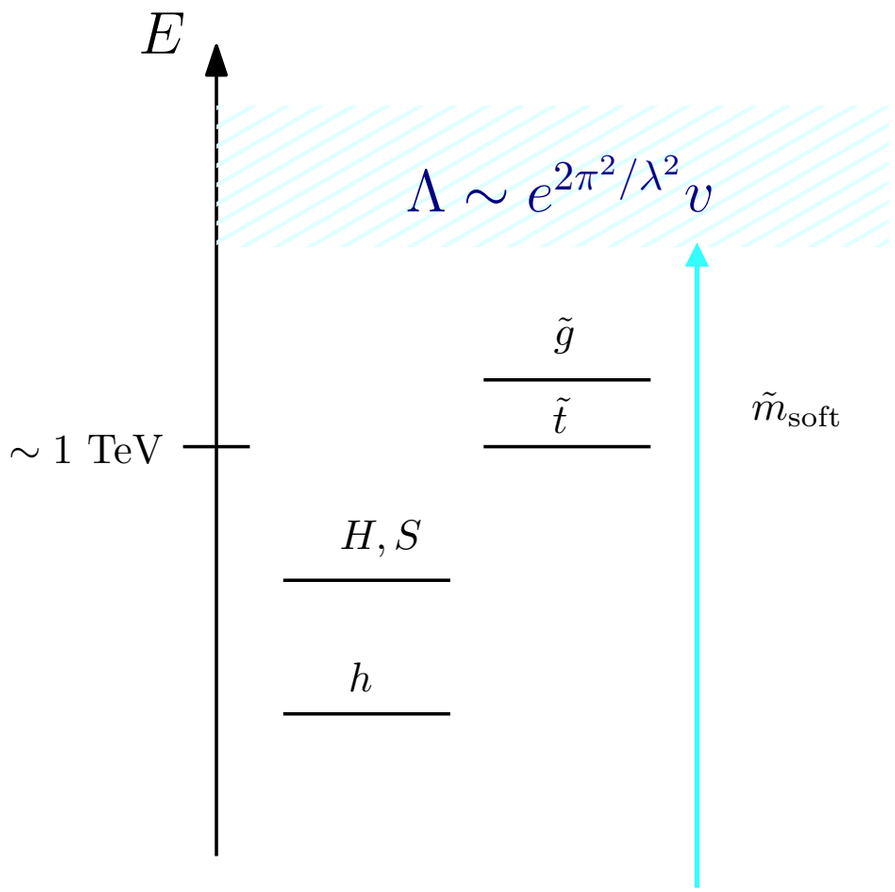

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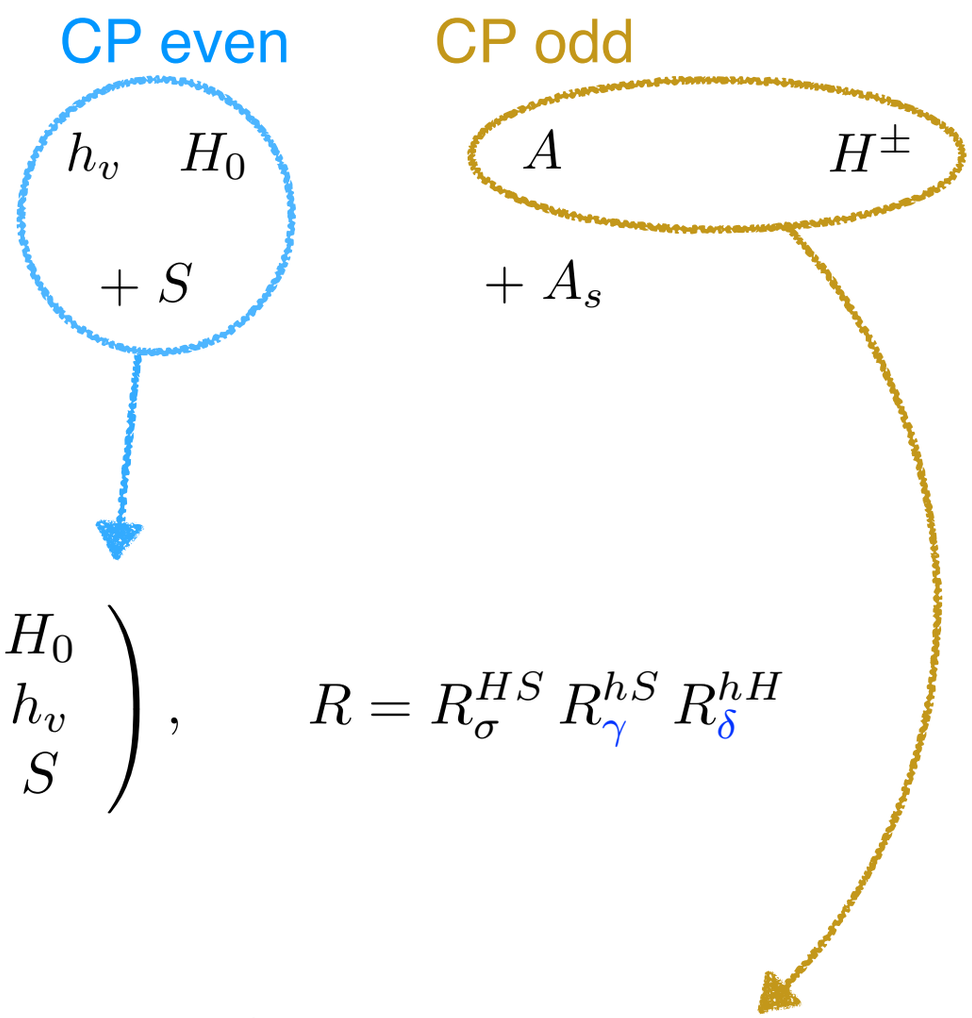

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Masses of A $H^\pm$ H are within a few GeV

$$m_A^2 = m_{H^\pm}^2 - m_W^2 + \lambda^2 v^2/2$$

A “simplified” Higgs model

A reasonable approach for two reasons:

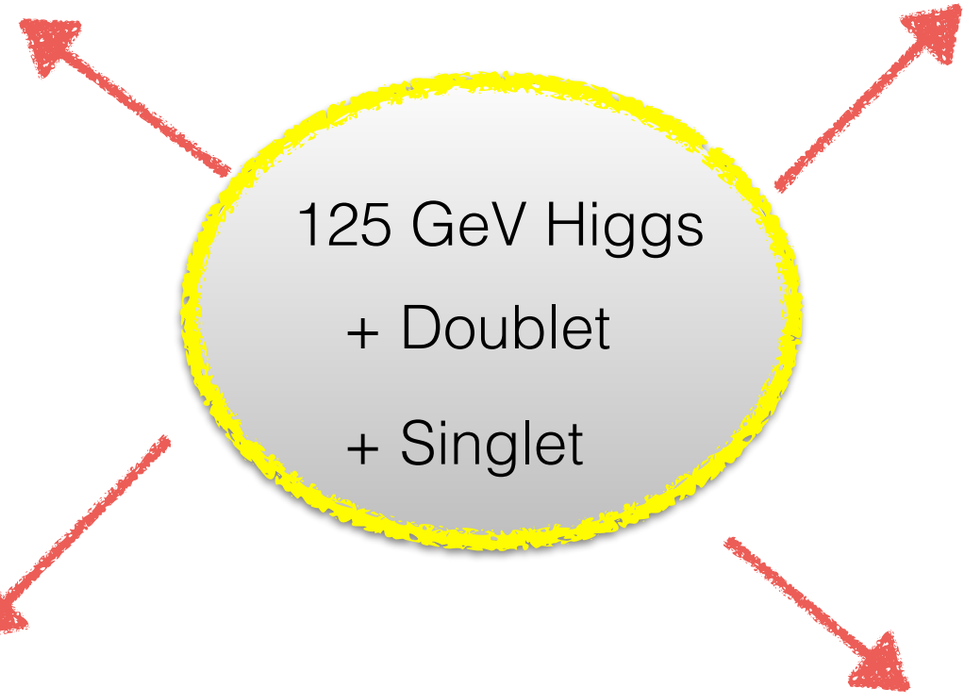
- Allows to define an “exploration strategy”
- Good description of several models!

MSSM (= constrained 2HDM type-II)

$h + H$

Twin Higgs

$h + S$



NMSSM

$h + H + S$

.....

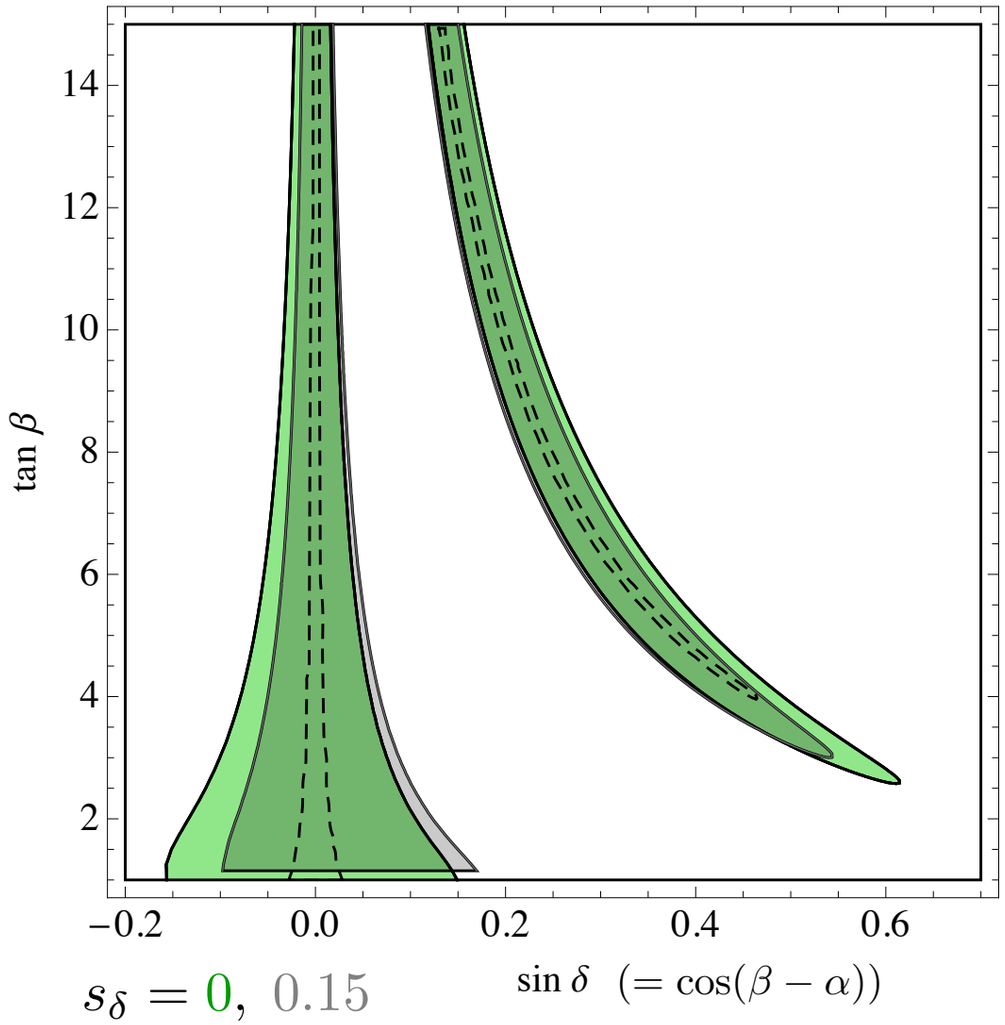
Bottom-up look at extra Higgses

$$h_{\rm LHC} = h = c_\gamma (c_\delta h_v - s_\delta H_0) + s_\gamma S$$

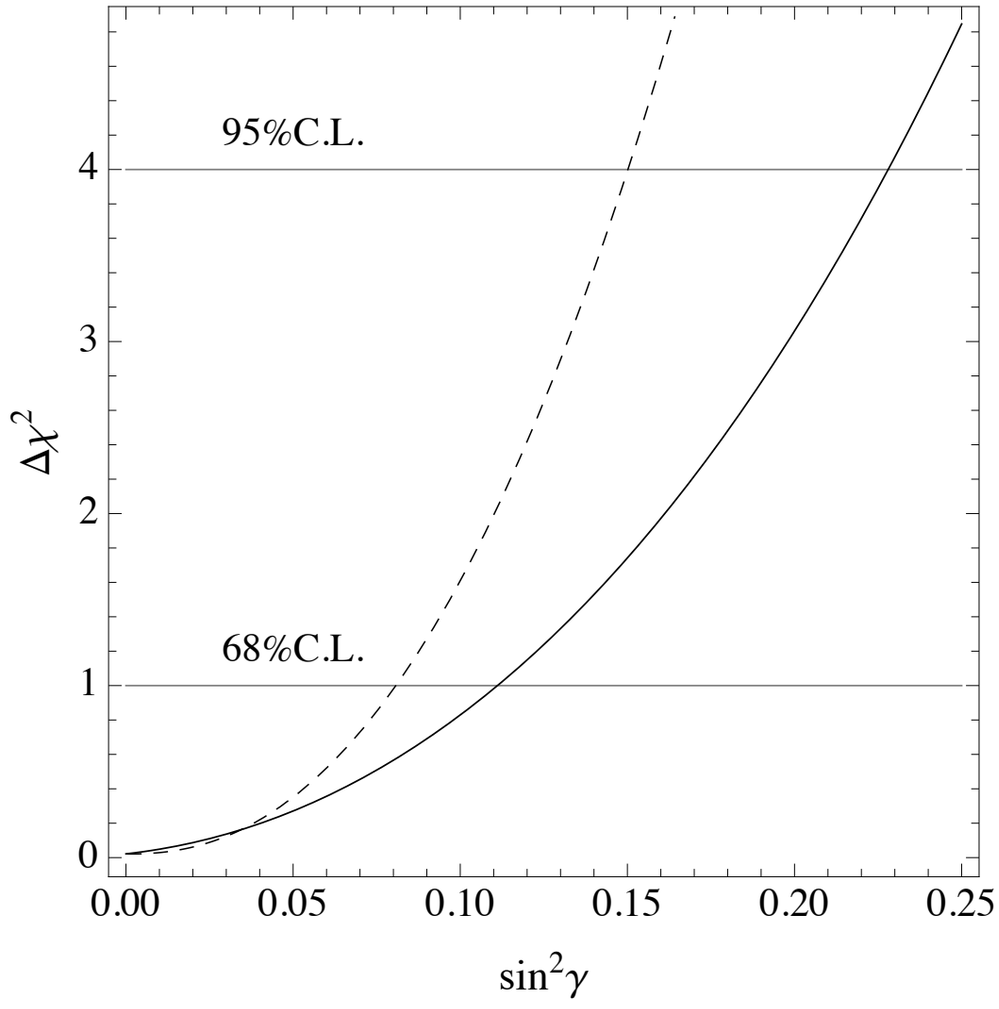
$$\left[\frac{g_{hu\bar{u}}}{g^{\rm SM}_{hu\bar{u}}} = c_\gamma (c_\delta + \frac{s_\delta}{\tan\beta}), \qquad \frac{g_{hd\bar{d}}}{g^{\rm SM}_{hd\bar{d}}} = \frac{g_{h\ell\bar{\ell}}}{g^{\rm SM}_{h\ell\bar{\ell}}} = c_\gamma (c_\delta - s_\delta \tan\beta), \qquad \frac{g_{hVV}}{g^{\rm SM}_{hVV}} = c_\gamma c_\delta \right]$$

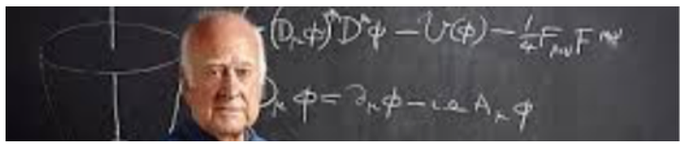
Cont: LHC8 status

Dashed: LHC 14 projections ($300\ \mathrm{fb}^{-1}$)



$s_\delta = 0,\ 0.15$





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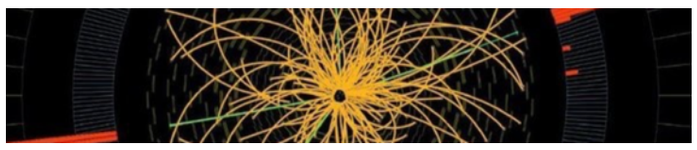

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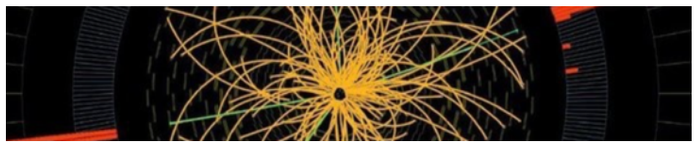
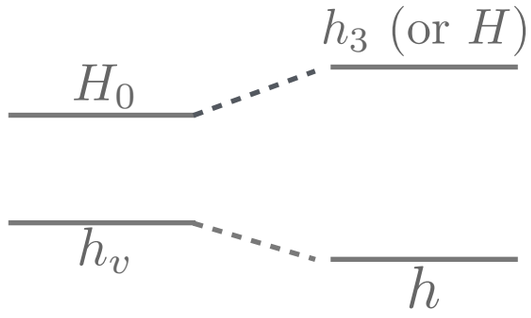


How to look for them?

1. Only extra doublet
2. Only extra singlet
3. Mixed situation

An extra Doublet: MSSM



Pheno controlled by only two parameters

(unless $\frac{\mu A_t}{m_{\tilde{t}}^2} \gtrsim 1$, i.e. extremely large loops)

$m_{h3} \quad \tan\beta$

$$m_{h3}^2 \simeq m_A^2 = m_{H^\pm}^2 - m_W^2$$

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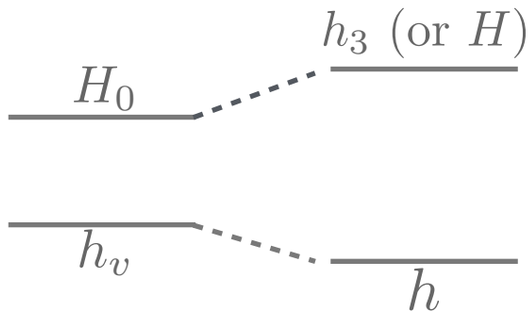

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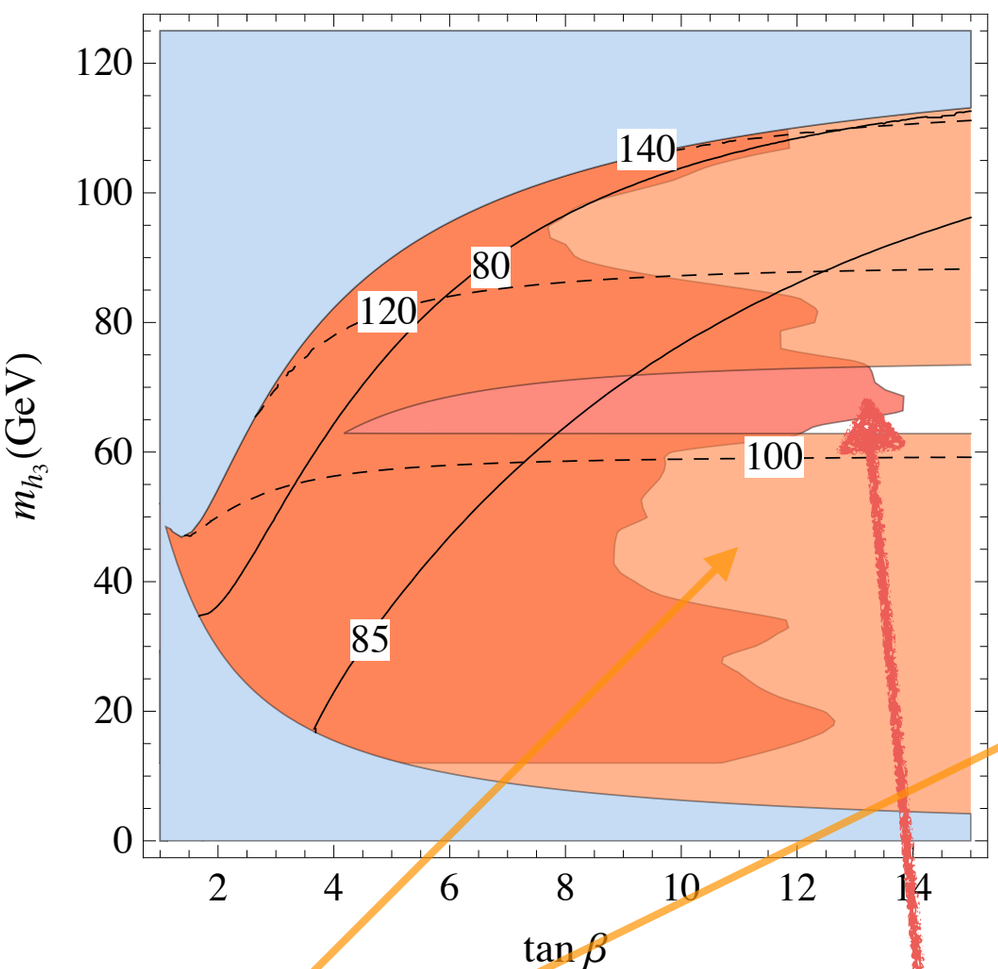

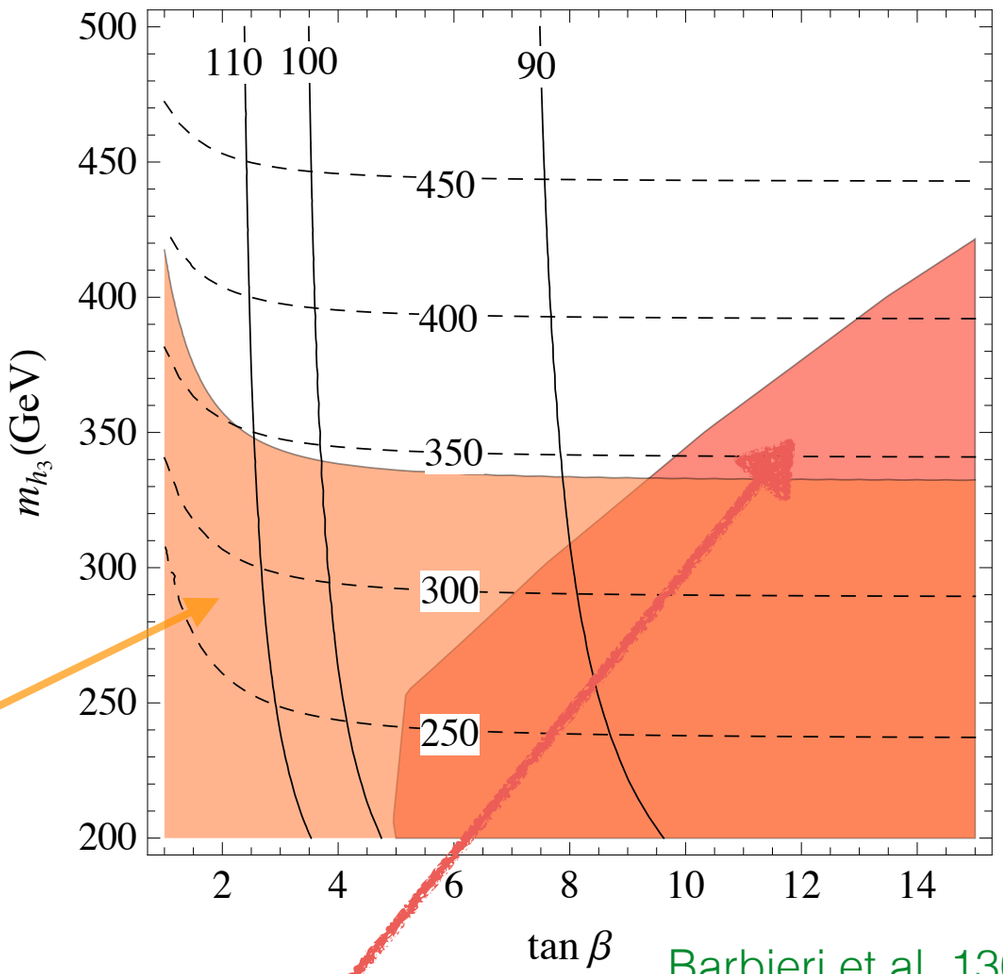

Higgs coupling fit

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Djouadi et al. 1307.5205 (hMSSM)

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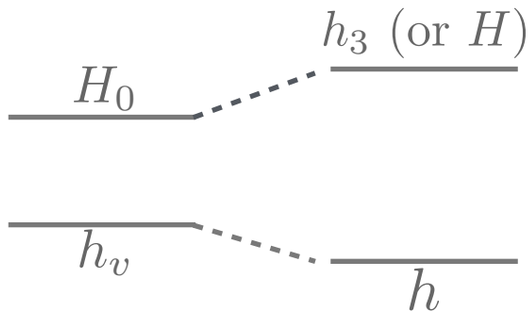

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dashed: $m_{H^\pm}$ cont: $\Delta_{\rm loop}$

$(\Delta_{\rm loop} \lesssim 85\ {\rm GeV}\ \ {\rm for}\ \ m_{\tilde{t}} \lesssim 1 - 1.5\ {\rm TeV})$

$m_{H^\pm} > 480$ GeV from BR$(B \to X_s\gamma)$
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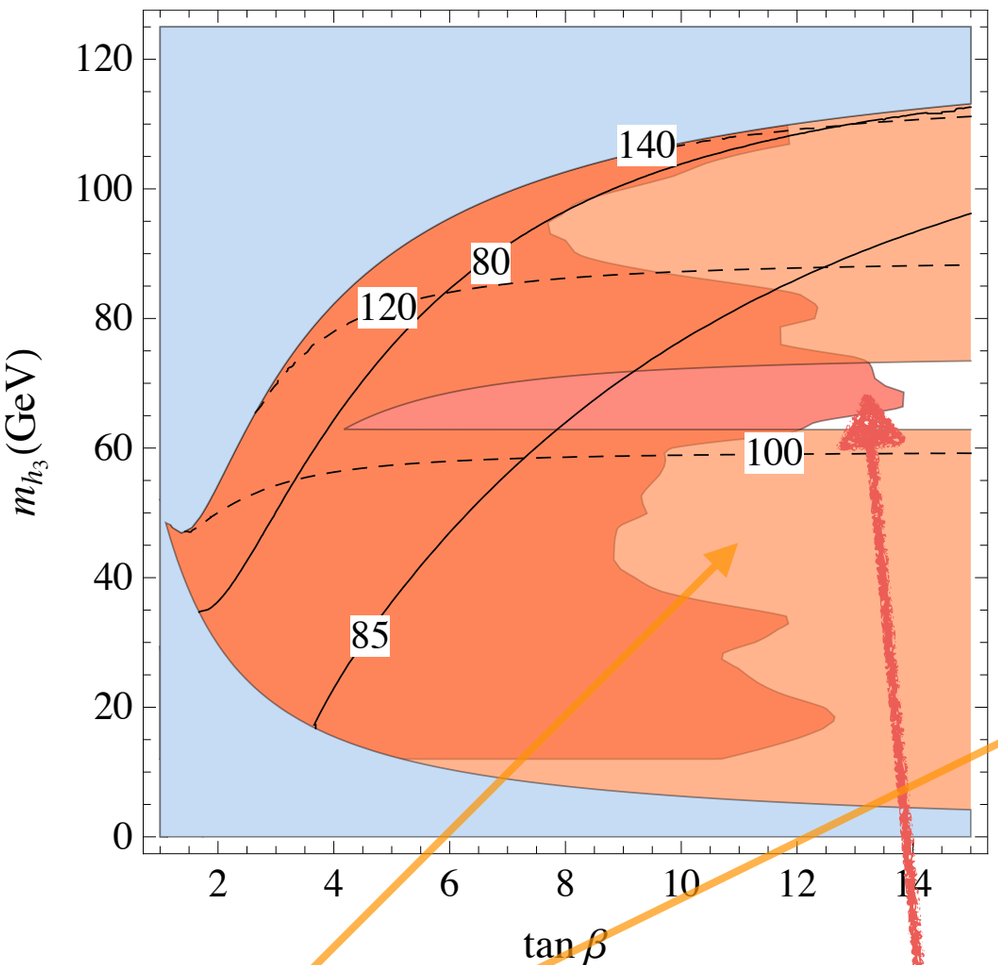

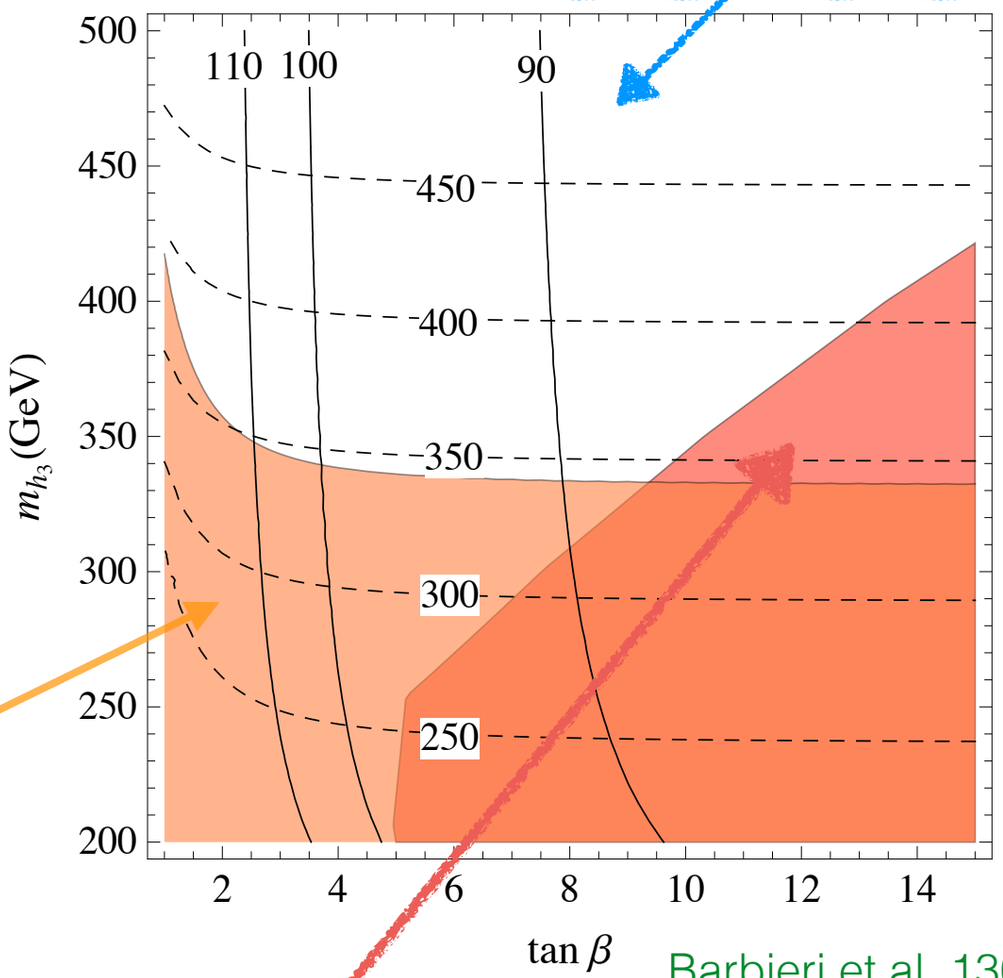

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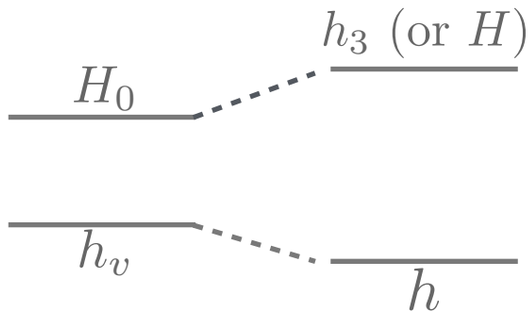

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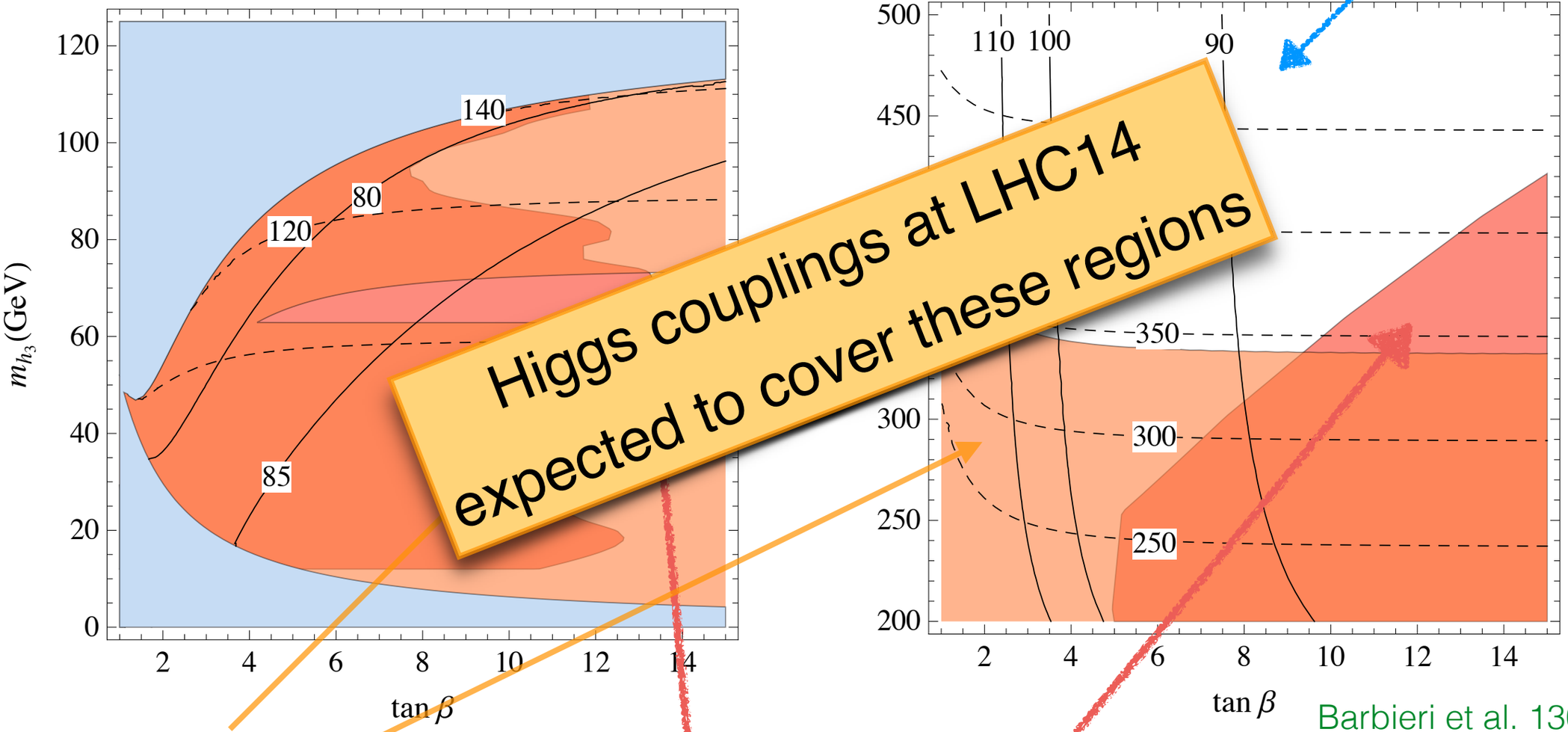

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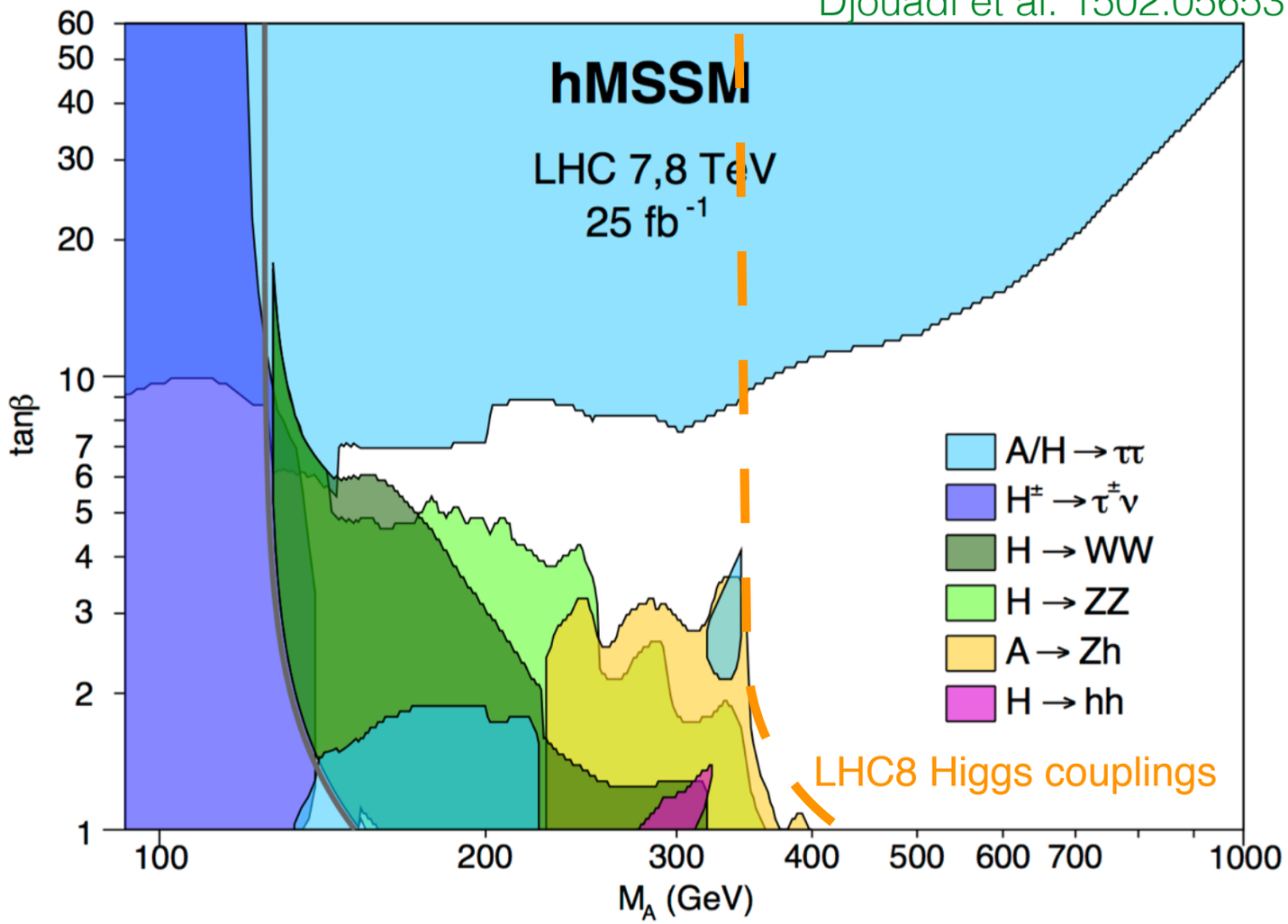
Djouadi et al. 1502.05653



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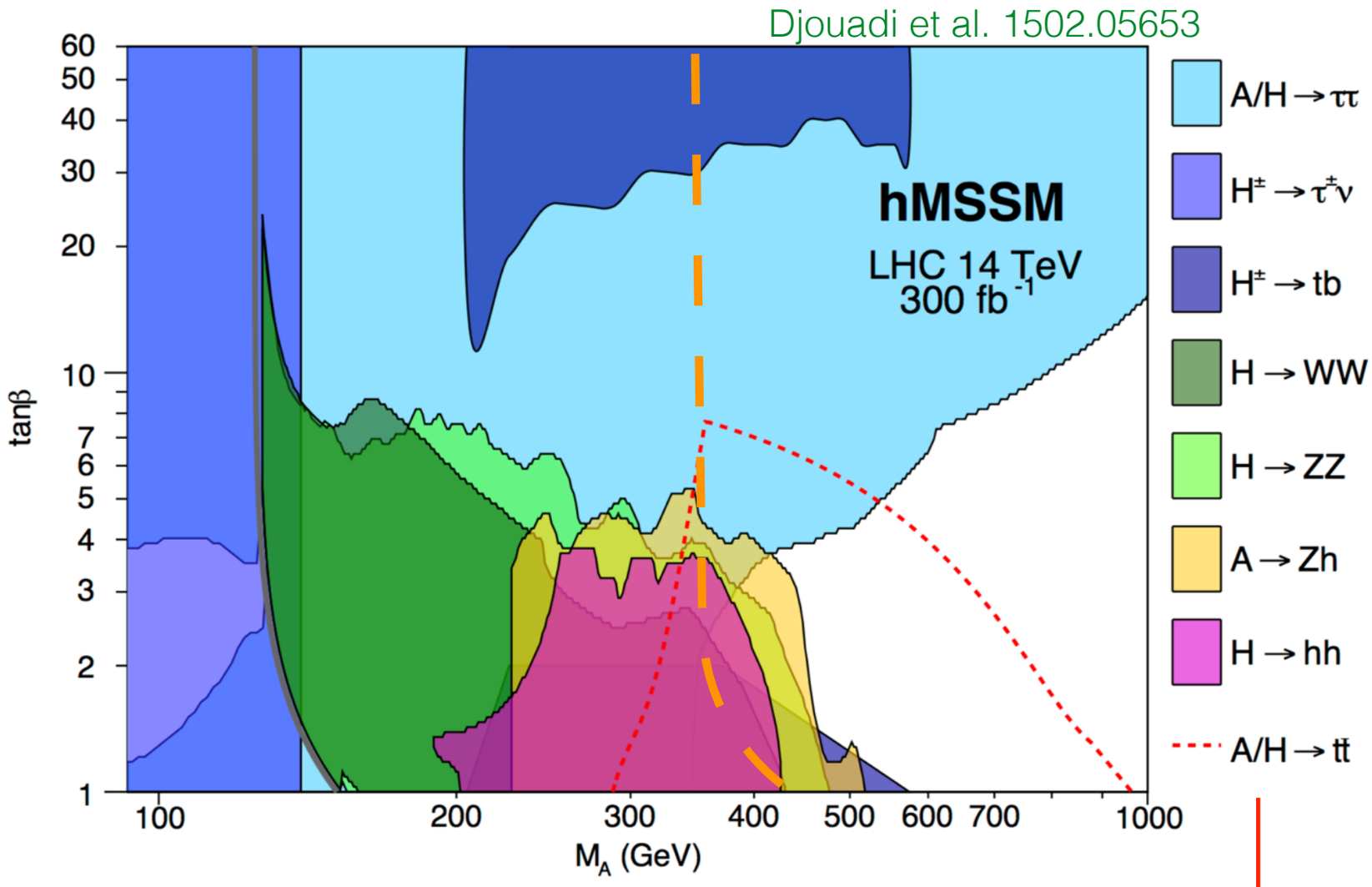

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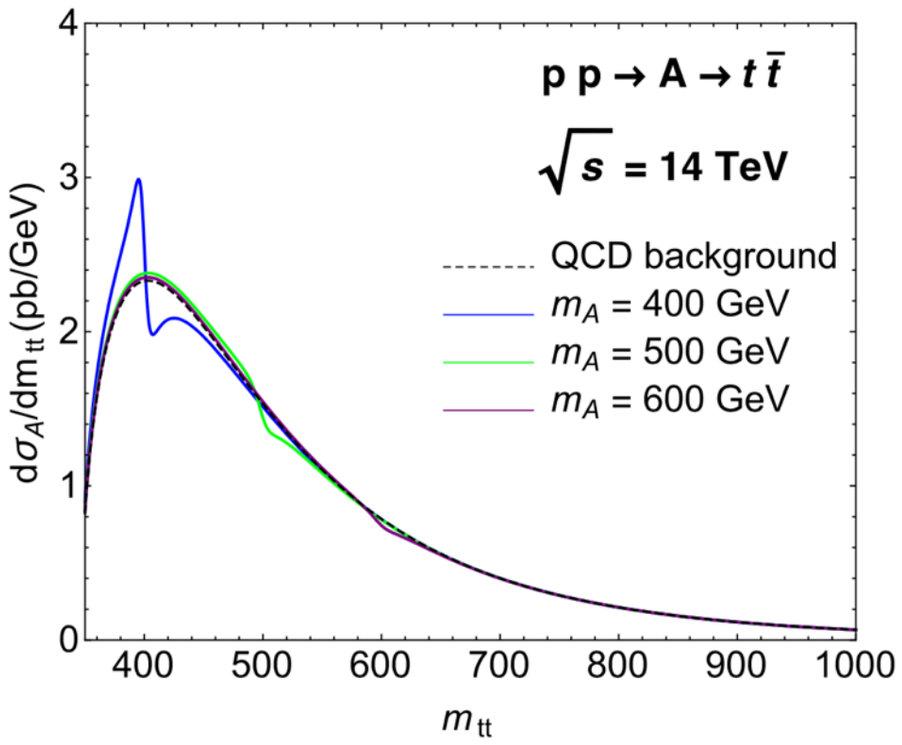
$pp \to A/H \to t\bar{t}$ has the potential to fill low $\tan\beta$ gap, but….

Shortcoming of tt searches

Craig et al. 1504.04630



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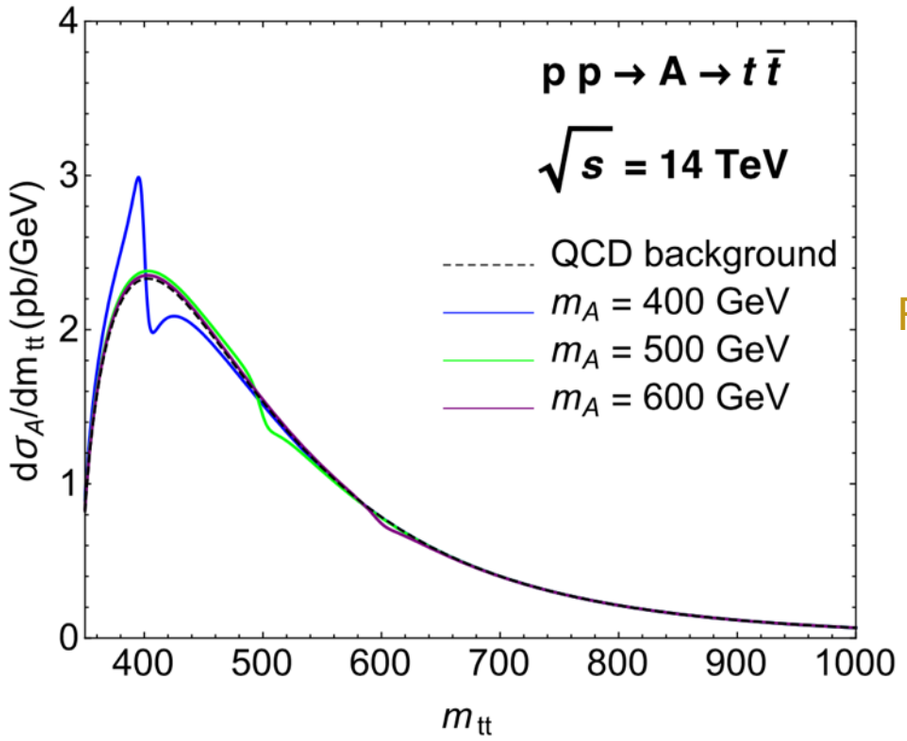
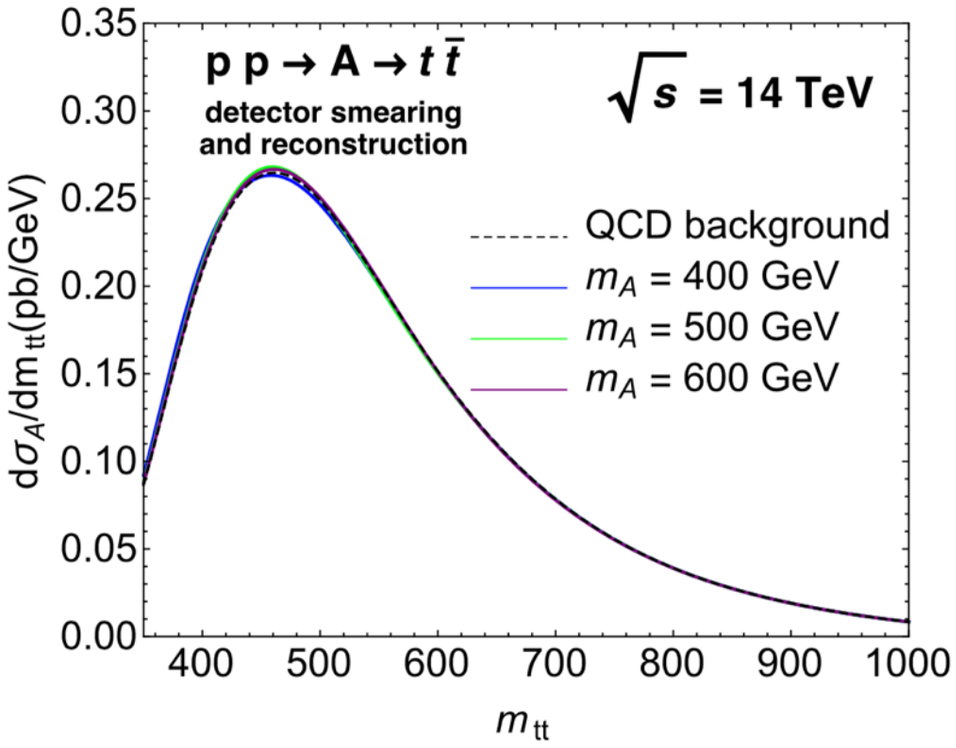


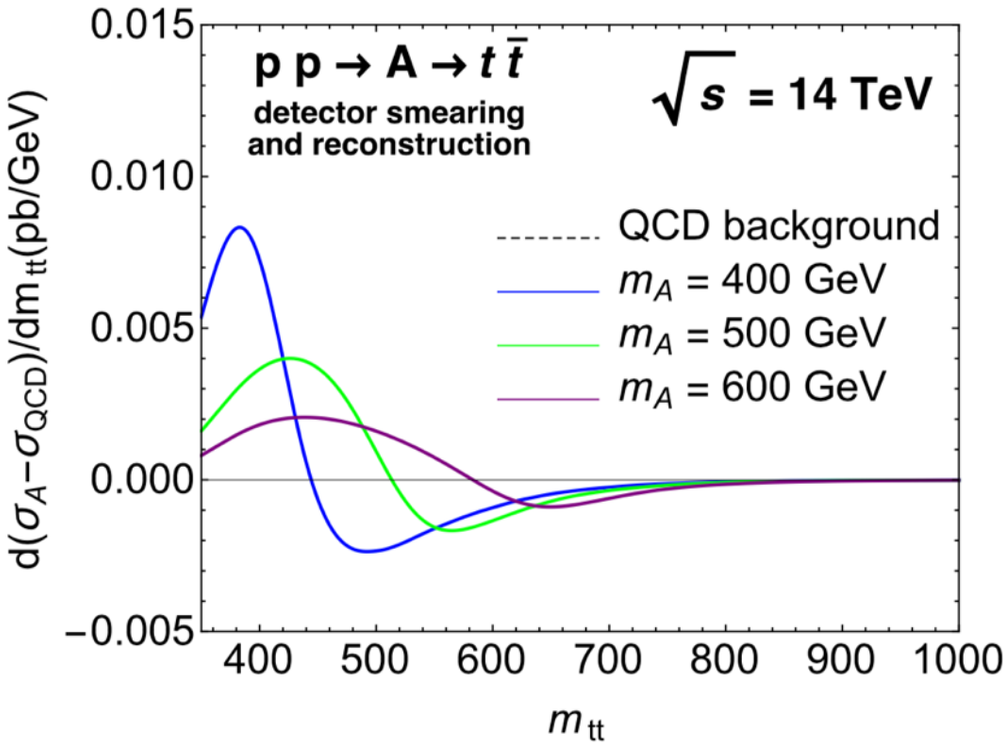
Pythia 6.4 + Delphes3 +…
details in App C
of 1504.04630



Conclusion of 1504.04630:

"Systematic uncertainties (even at the percent level) will almost certainly prevent any significant detection."

And they are referring to the HL-LHC!



Where to look other than tt?

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$pp \to b\bar{b}\,H \to b\bar{b}\,t\bar{t}$ not that promising

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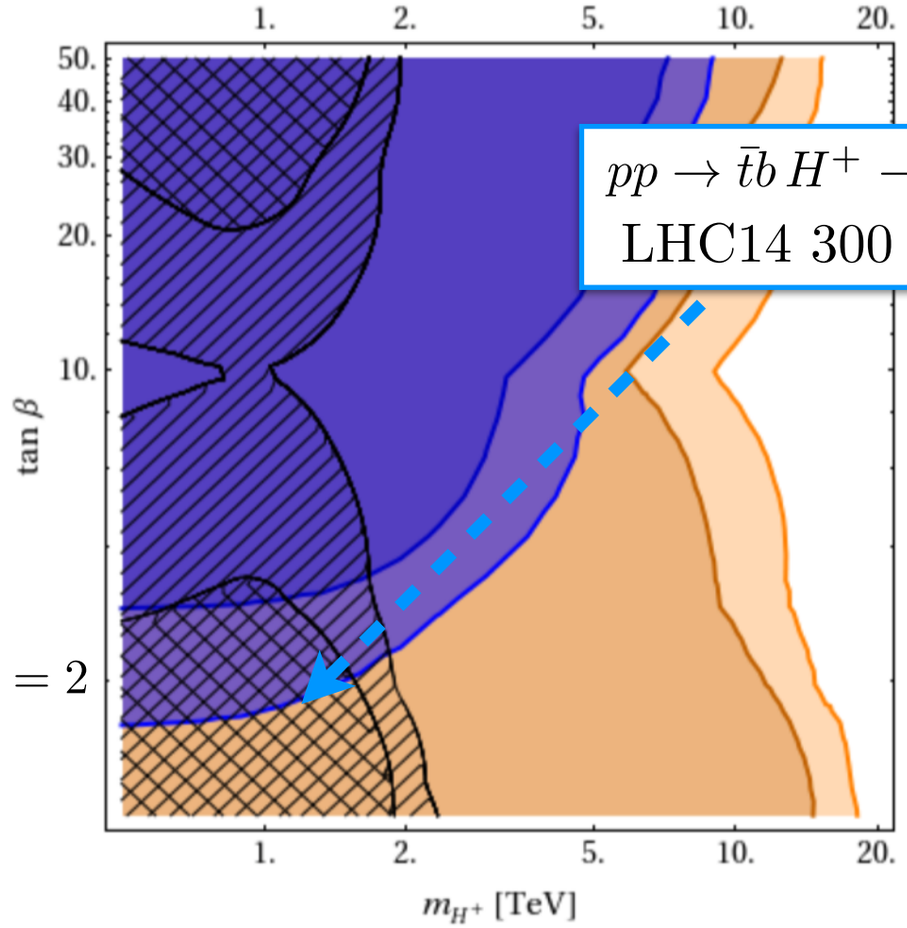
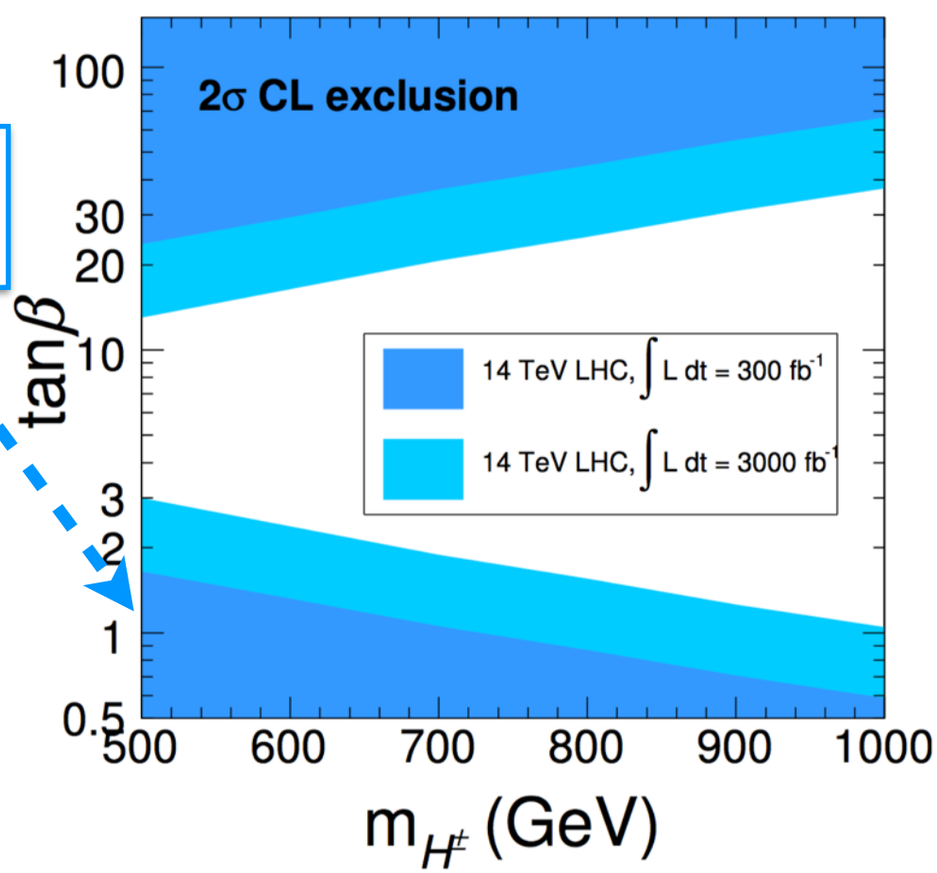
Charged Higgs searches

$$g_{H^+\bar{u}d} = y_d\, t_\beta\, P_R + \frac{y_u}{t_\beta}\, P_L \qquad g_{H^+\bar{\nu}\ell} = y_\ell\, t_\beta\, P_R$$



Hajer et al 1504.07617



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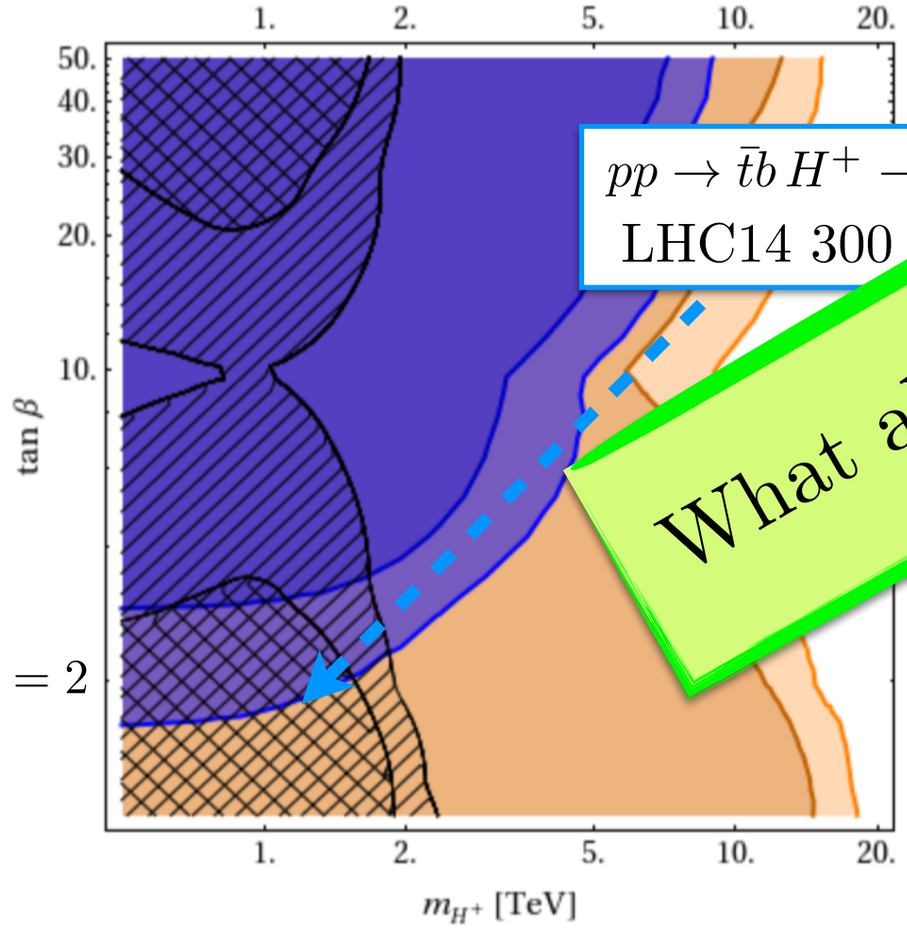

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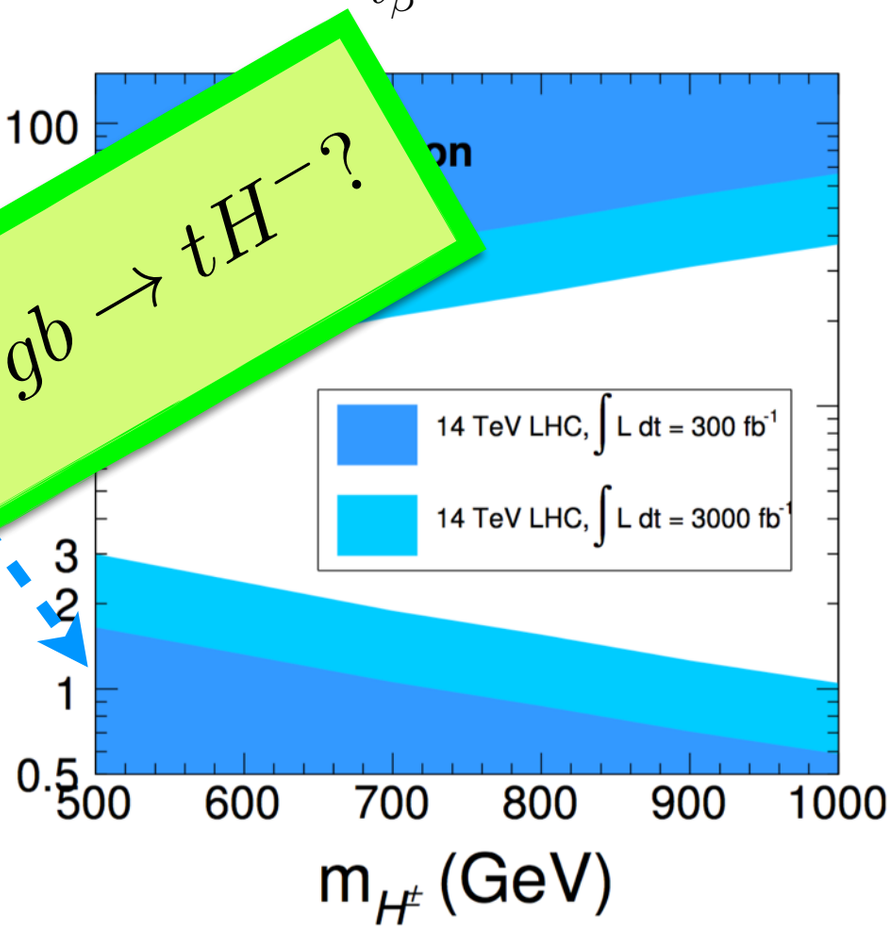

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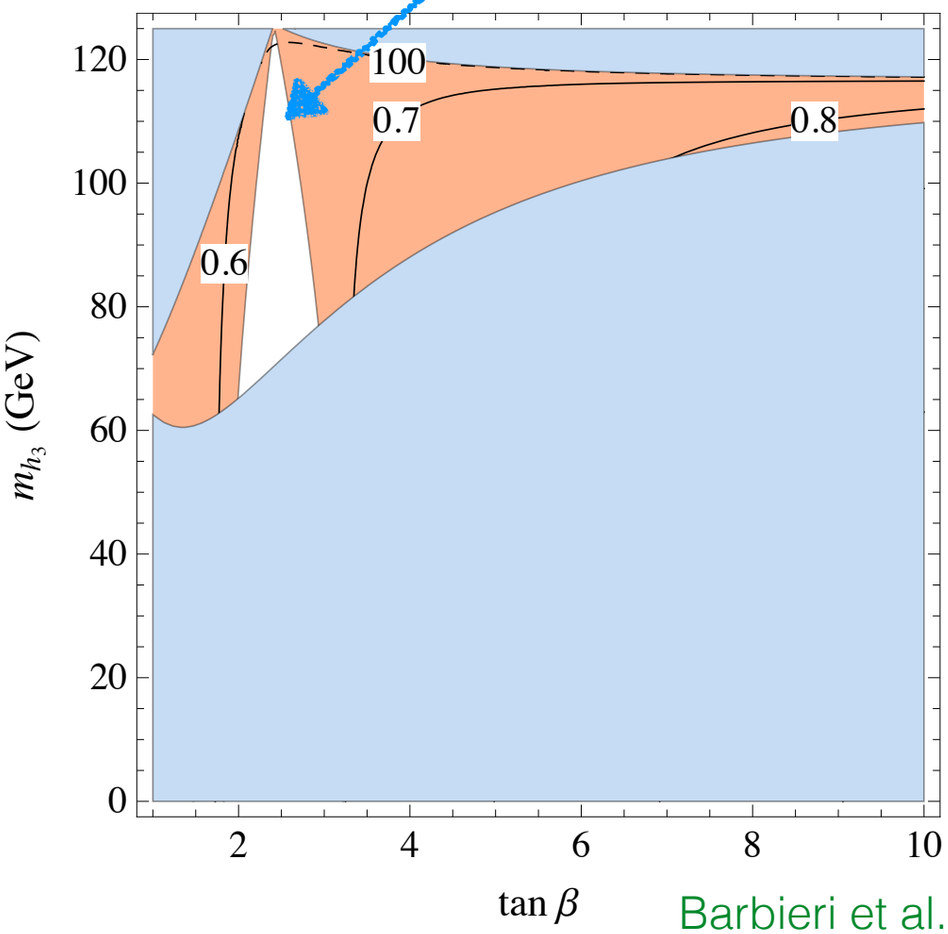
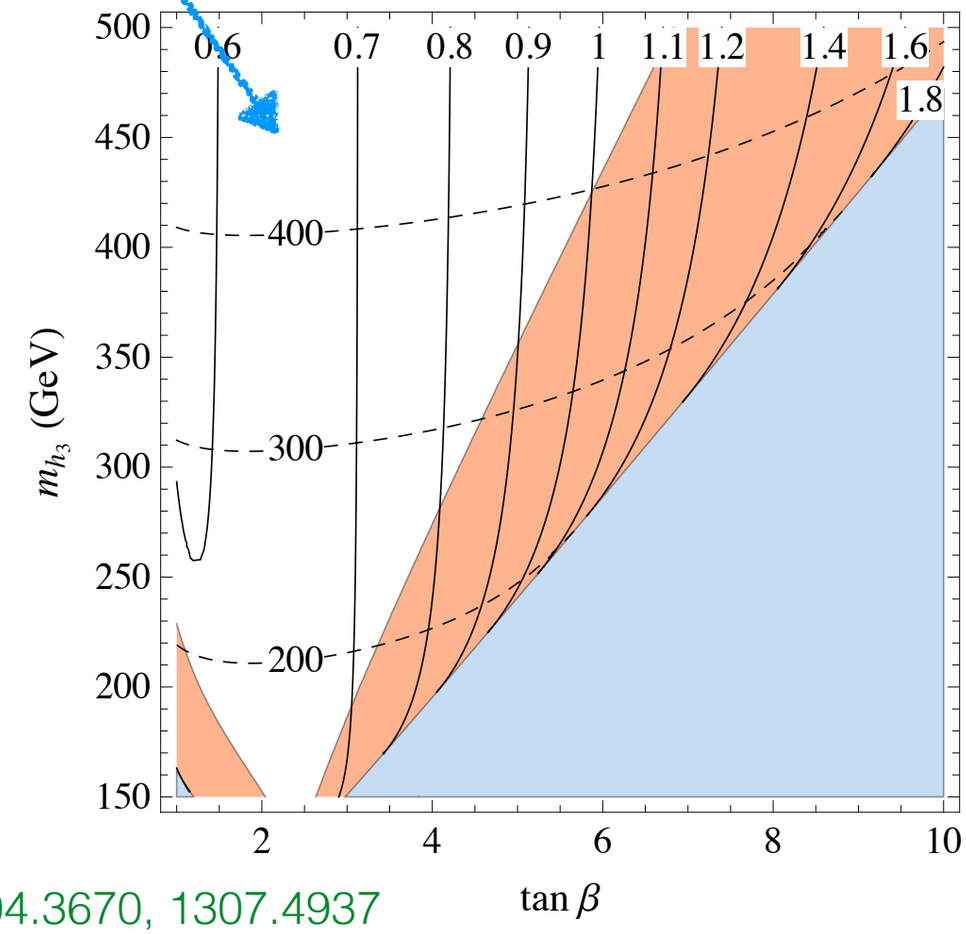
More reasons to care: NMSSM Doublet

NMSSM allows for alignment without decoupling = $\delta \to 0$ without $m_{h3} \to \infty$

answering question by Andrea on Monday





Barbieri et al. 1304.3670, 1307.4937

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$$\delta = 0 \implies {\rm BR}_{H\to VV} = {\rm BR}_{H\to hh} = 0 \; (= {\rm BR}_{A\to Zh} = {\rm BR}_{H^\pm \to W^\pm h})$$

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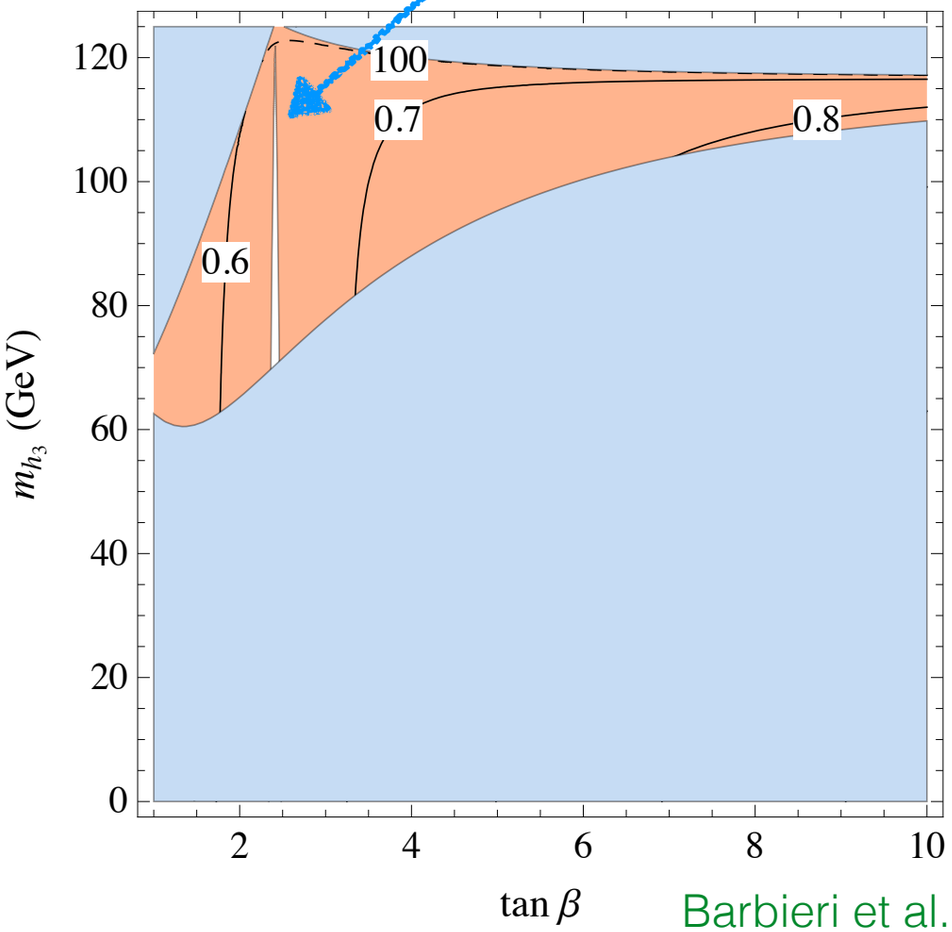

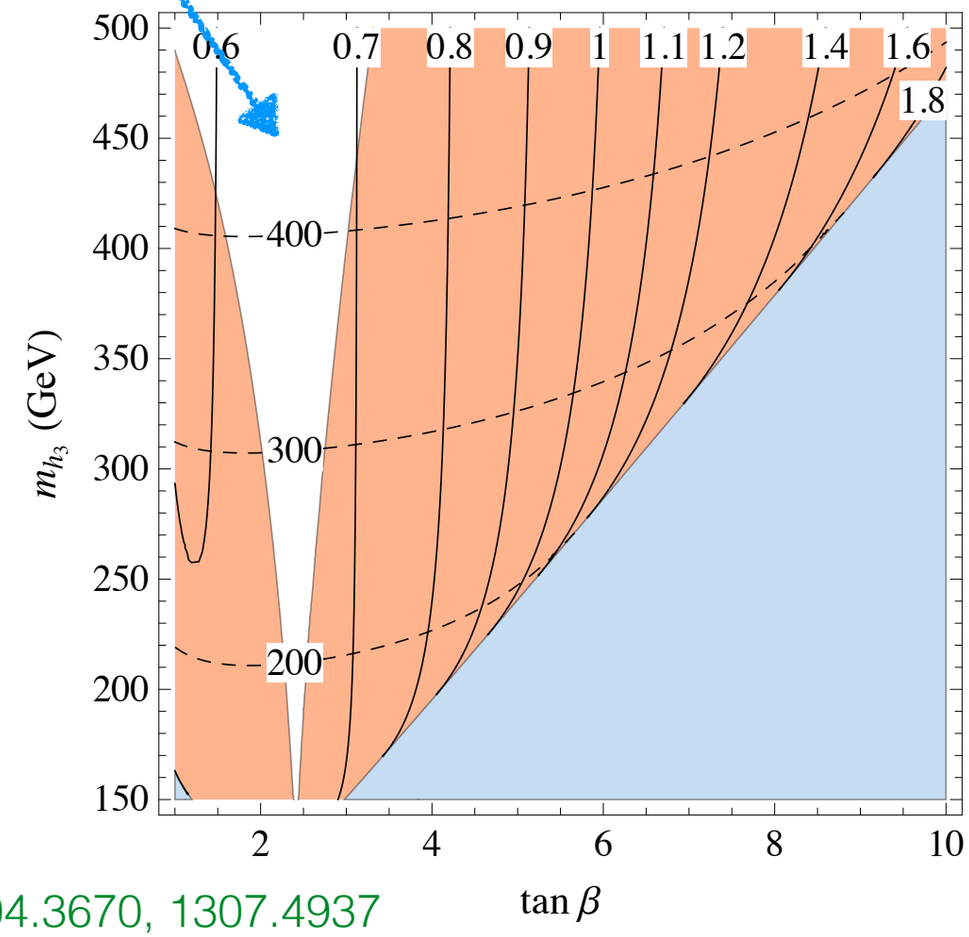

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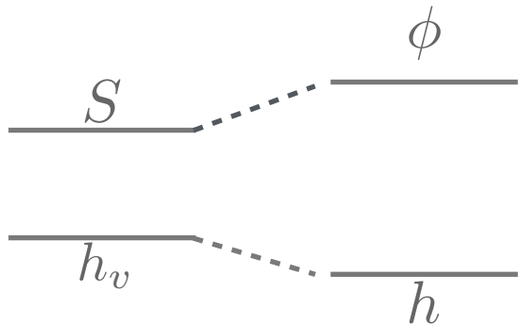
An extra Singlet



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

Master formula, valid for ***any*** model

Two free parameters control all pheno! $+\ \mathrm{BR}_{\phi\to hh}\ (= \mathrm{BR}_{\phi\to ZZ}\ \text{at}\ m_\phi \gg m_W)$

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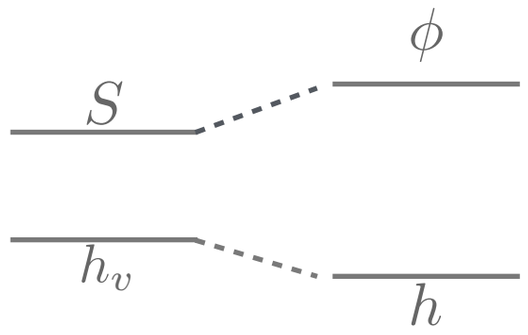

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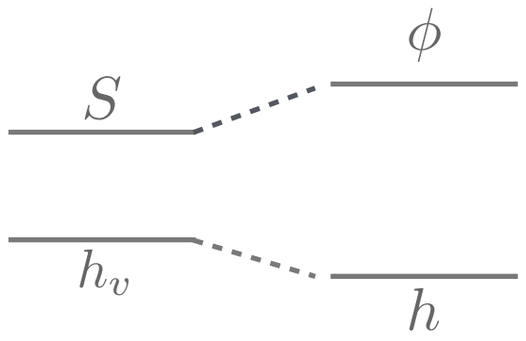

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What do we learn from the potential $f(S)$?

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

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

Valid for ***any*** potential! v_s leading new parameter

Buttazzo Sala Tesi 1505.05488

An extra Singlet: Higgs couplings

Buttazzo Sala Tesi 1505.05488

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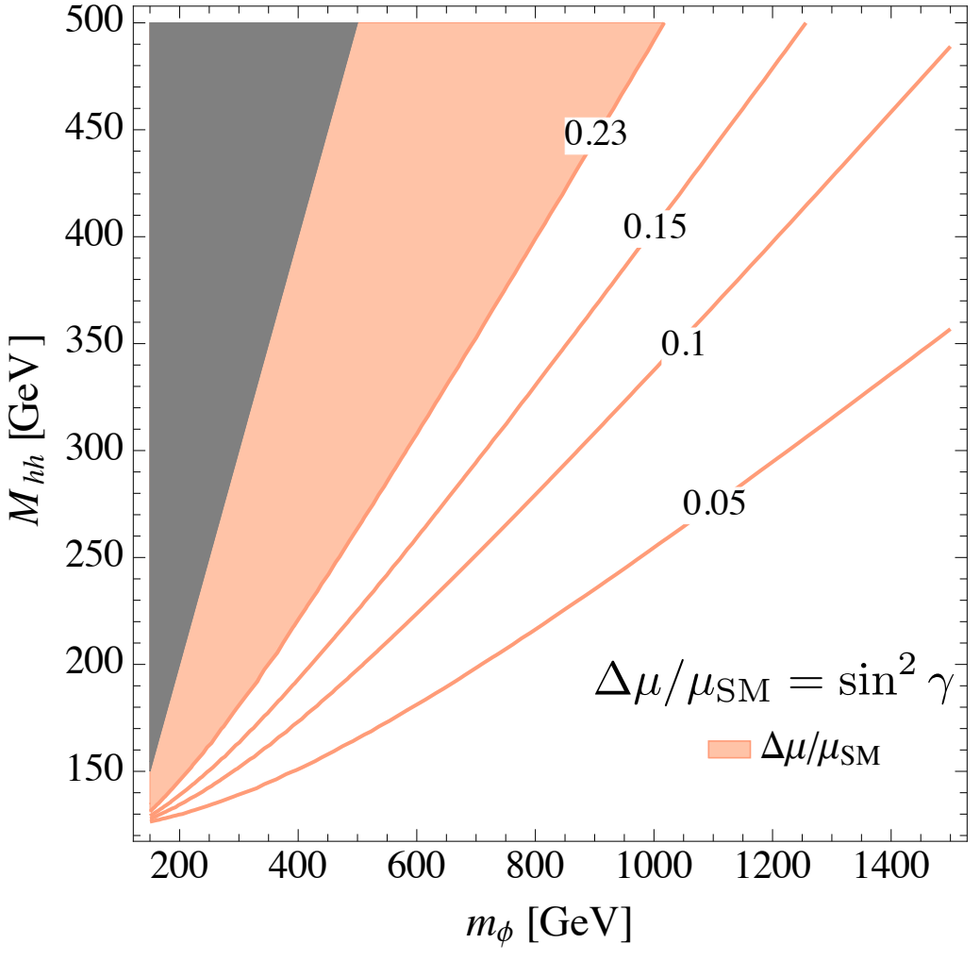


Facility	LHC	HL-LHC
$\sqrt{s}$ (GeV)	14,000	14,000
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt
κ_γ	$5-7\%$	$2-5\%$
κ_g	$6-8\%$	$3-5\%$
κ_W	$4-6\%$	$2-5\%$
κ_Z	$4-6\%$	$2-4\%$
κ_ℓ	$6-8\%$	$2-5\%$
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$

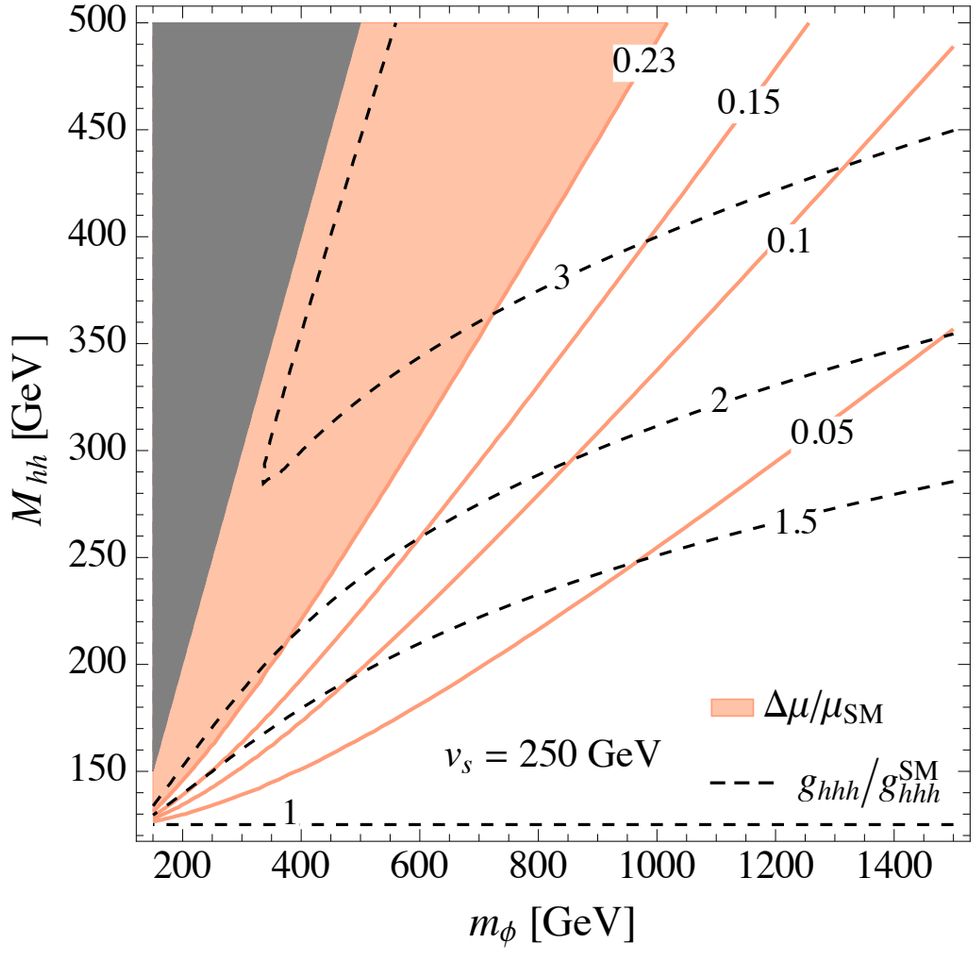
WhatNext 2014

An extra Singlet: Higgs couplings

Buttazzo Sala Tesi 1505.05488

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

h: signal strengths $\mu = c_\gamma^2 \times \mu_{\rm SM}$ (Add g_{hhh}: seeable at HL-LHC)



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Snowmass 2013

	HL-LHC
$\sqrt{s}$ (TeV)	14
$\int \mathcal{L}dt$ (fb^{-1})	3000
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089
$S/\sqrt{B}$	2.3
λ (stat)	50%

An extra Singlet: direct searches

Buttazzo Sala Tesi 1505.05488

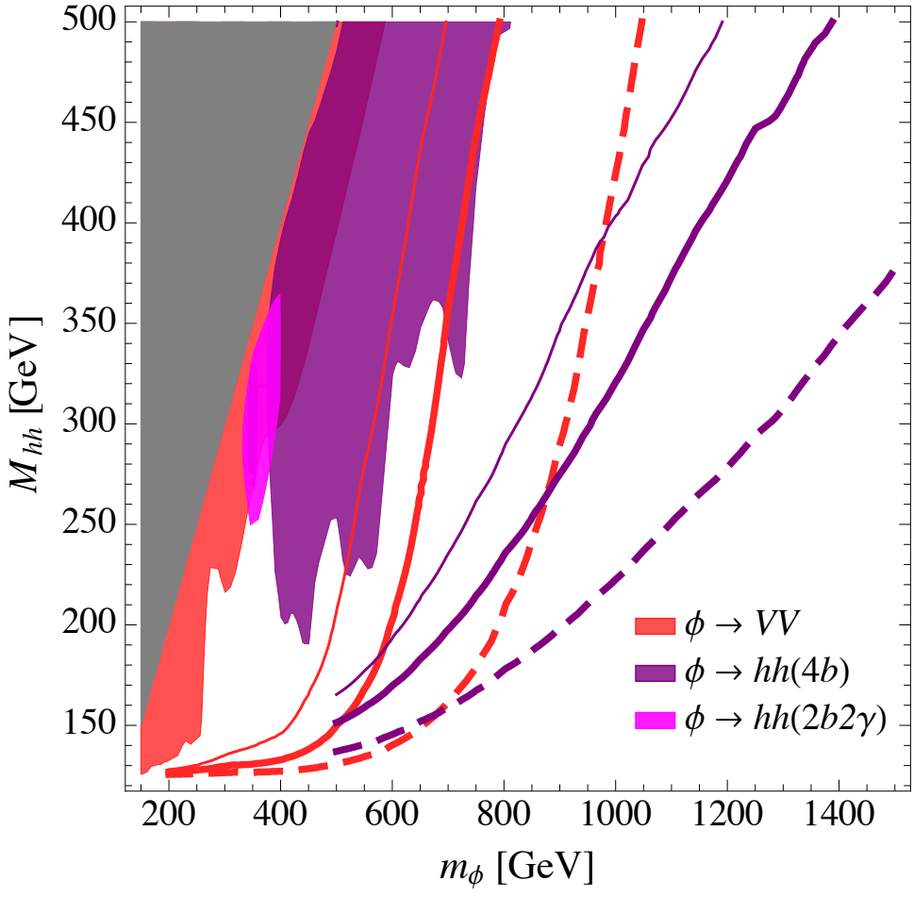
$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

LHC bounds scaled with parton luminosities

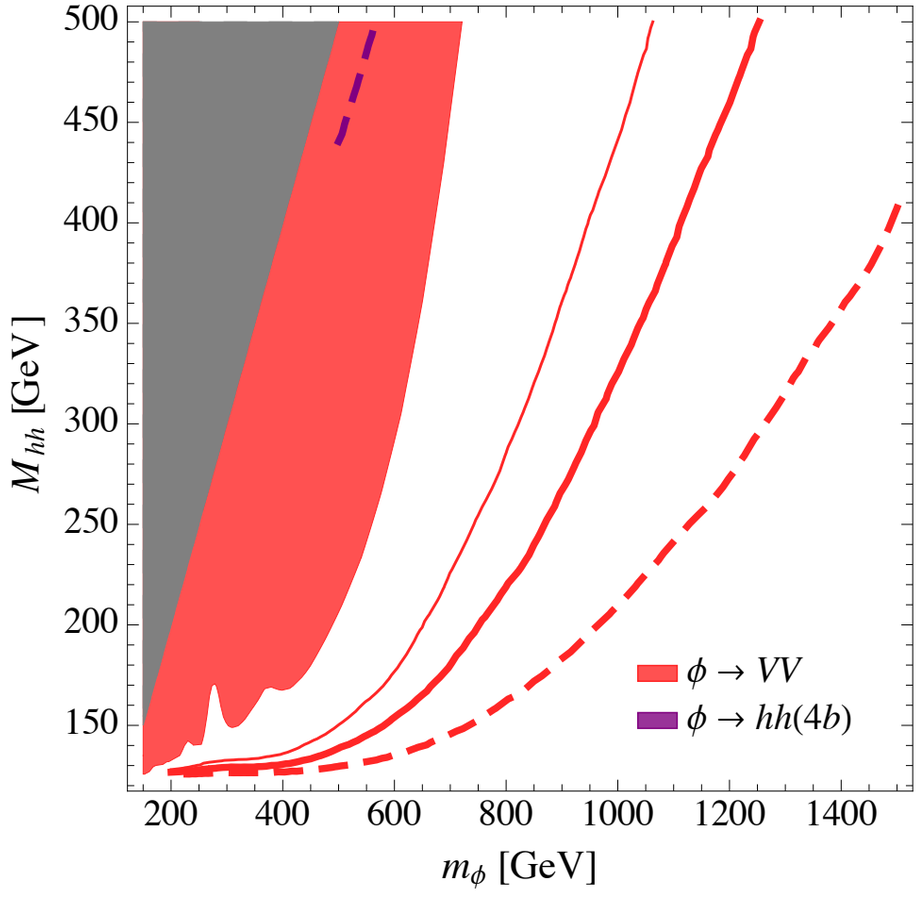
$[\phi \to VV$ dominates over $\phi \to hh$, unless $v_s < 0$ and small$]$

ϕ: $\mu(m_\phi) = s_\gamma^2 \times \mu_{\rm SM}(m_\phi)$ [barring $\phi \to hh$]

$v_s = -75$ GeV



$v_s = 250$ GeV



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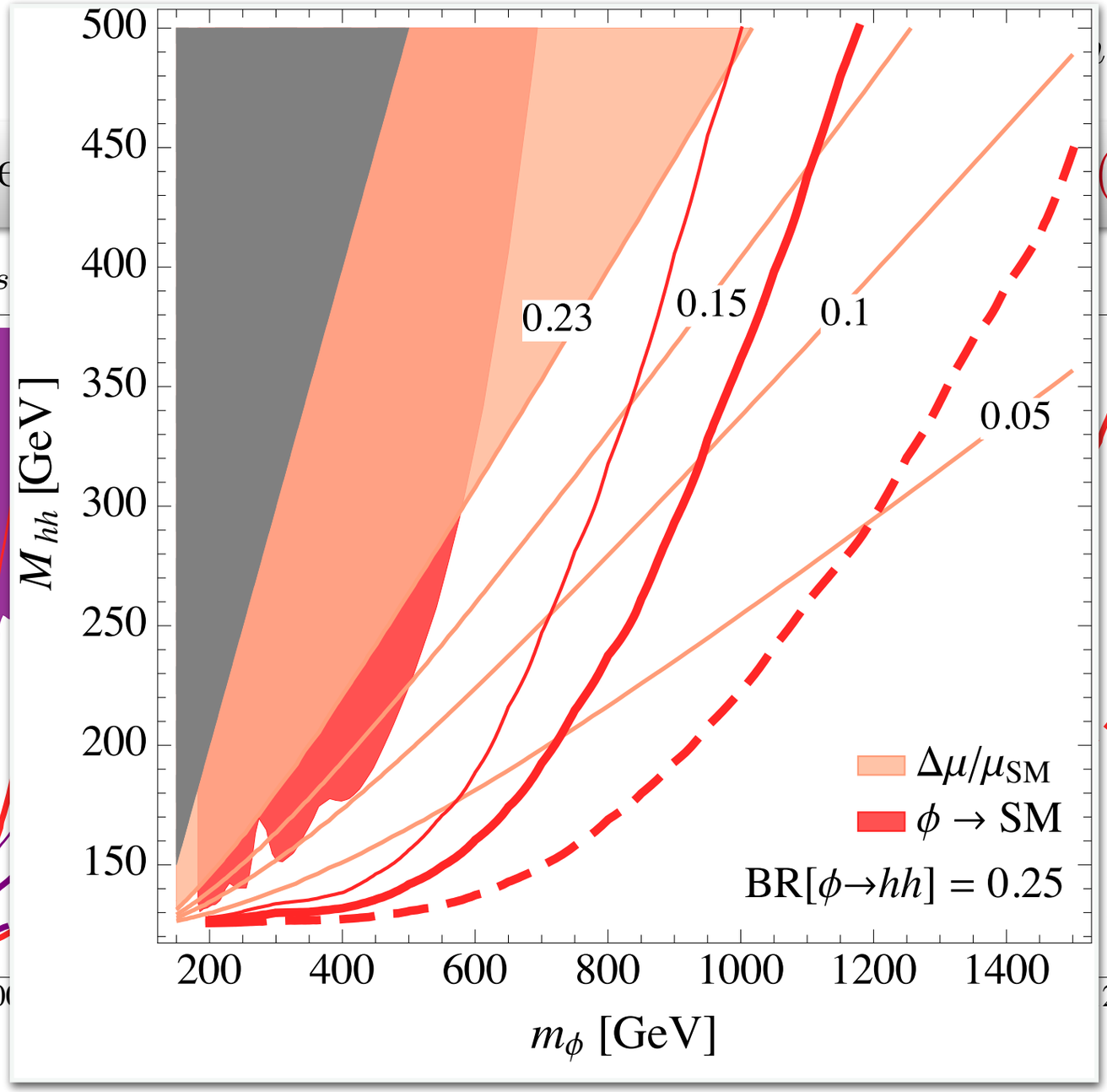
(m_ϕ) [barring $\phi \to hh$]

v_s



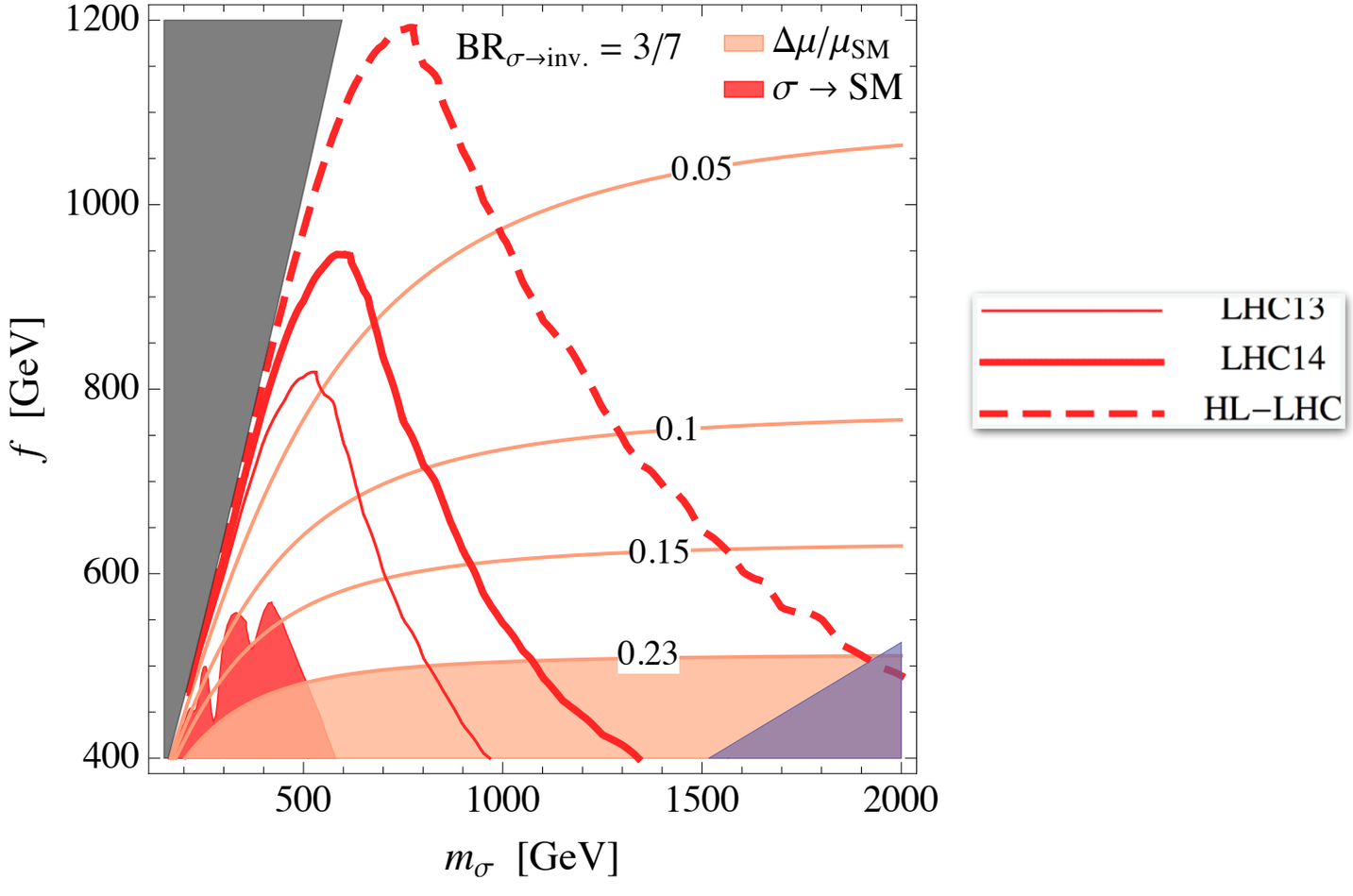
Twin Higgs and the NMSSM

Buttazzo Sala Tesi 1505.05488

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

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

Twin Higgs Signal strengths μ_h more effective than direct ϕ searches, unless $m_\phi \sim f$



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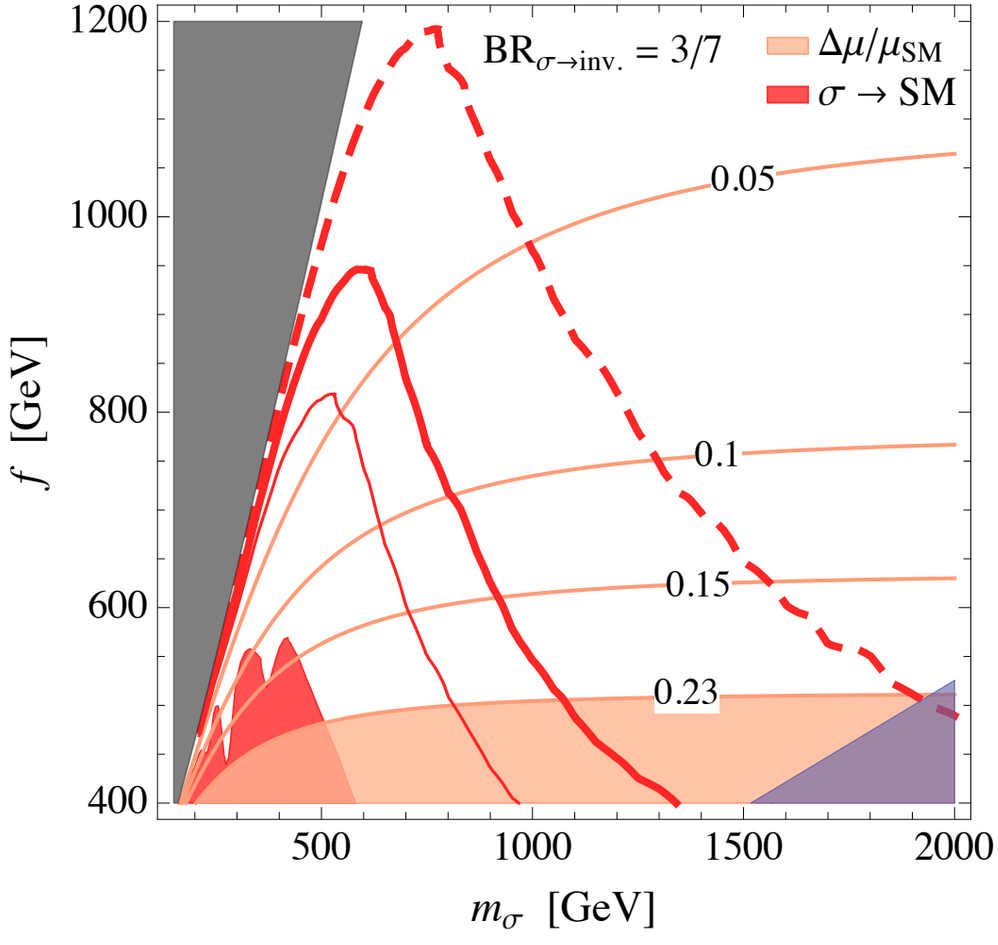
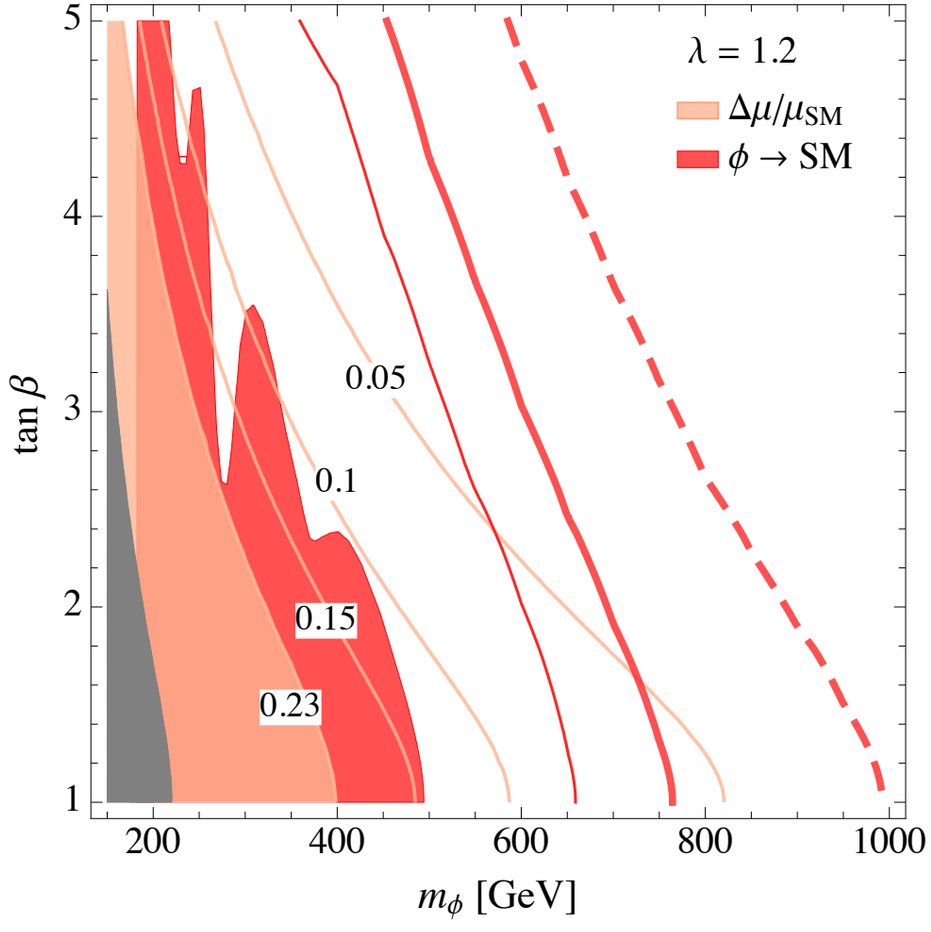
Twin Higgs $M_{hh}^2 = (m_h^2 + m_\phi^2)\, v^2/f^2$

NMSSM $M_{hh}^2 = m_Z^2\, c_{2\beta}^2 + \lambda^2 v^2\, s_{2\beta}^2 + \Delta_{\rm loop}^2$

Twin Higgs Signal strengths μ_h more effective than direct ϕ searches, unless $m_\phi \sim f$

NMSSM For μ_h to do better than direct ϕ searches, per-mille precision needed





Mixed case & light Higgses

In fully mixed case higgs to higgs searches relevant $A \to A_s h, \;\; H \to \phi\phi, \; ...$

Analytical treatment increasingly difficult ⟶ approach of scatter plots used so far

see e.g. King et al 1408.1120 (focus on NMSSM prospects at LHC13)
Carena et al 1510.09137 (alignment without decoupling in NMSSM)

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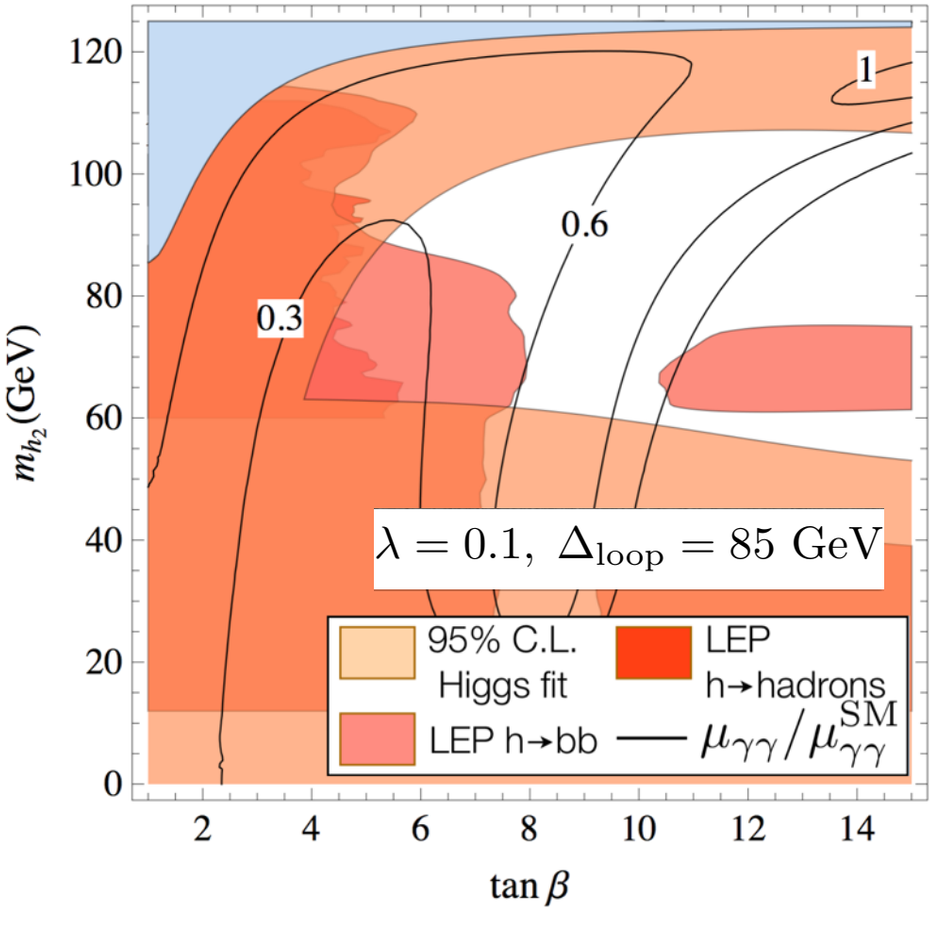
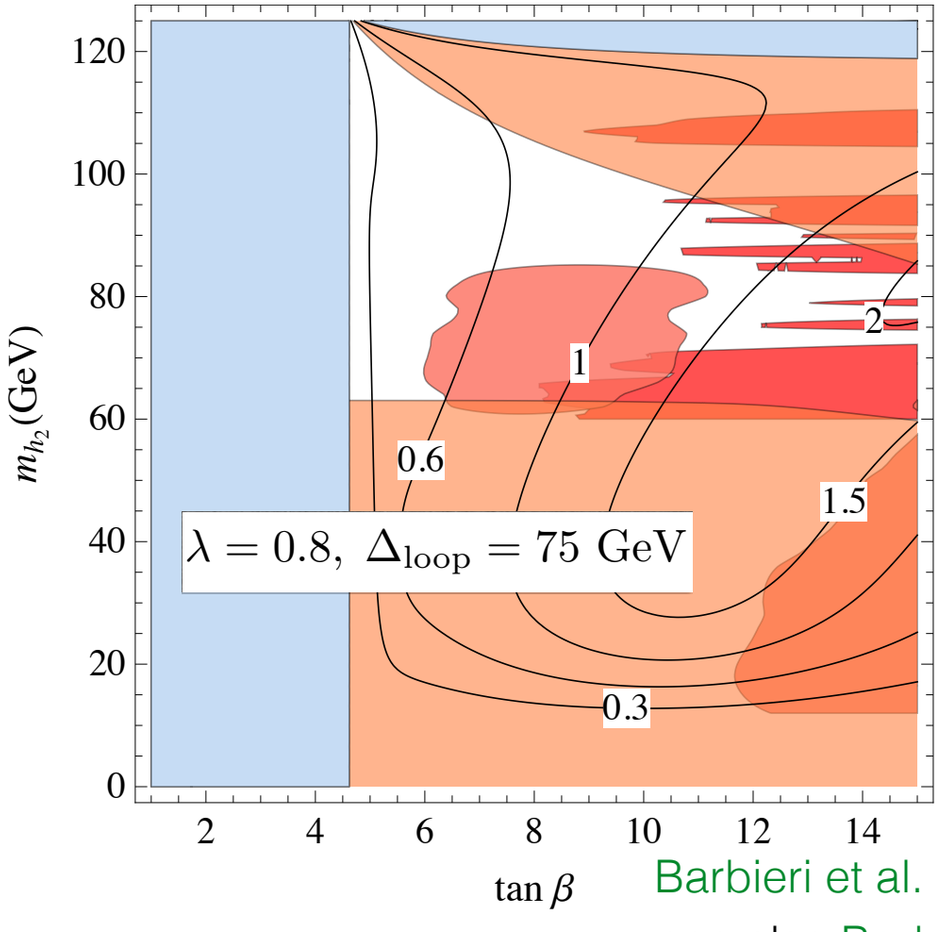
An example: a lighter singlet-like Higgs in $\gamma\gamma$ analytically

$[m_{h3} = 500 \text{ GeV}, \; s_\sigma^2 = 10^{-3}, \; v_s = v]$

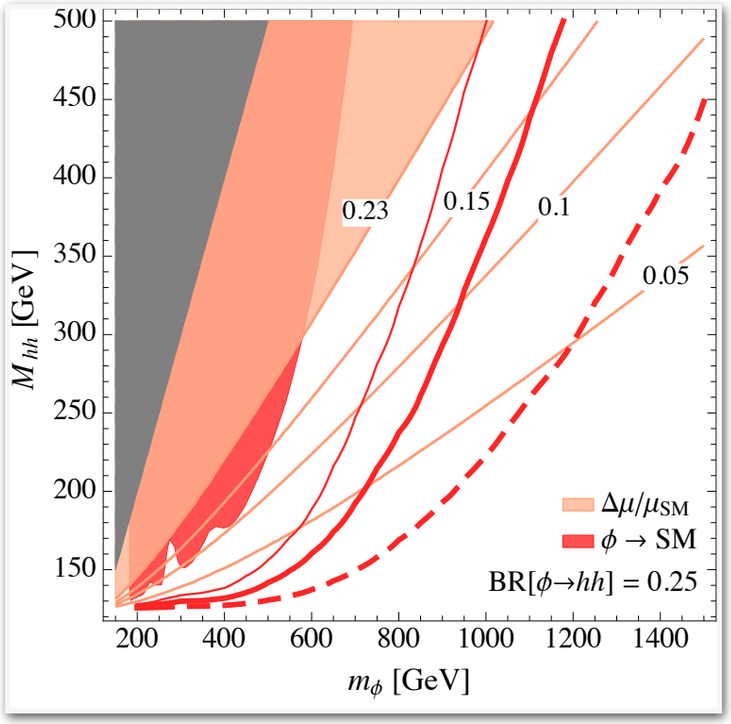


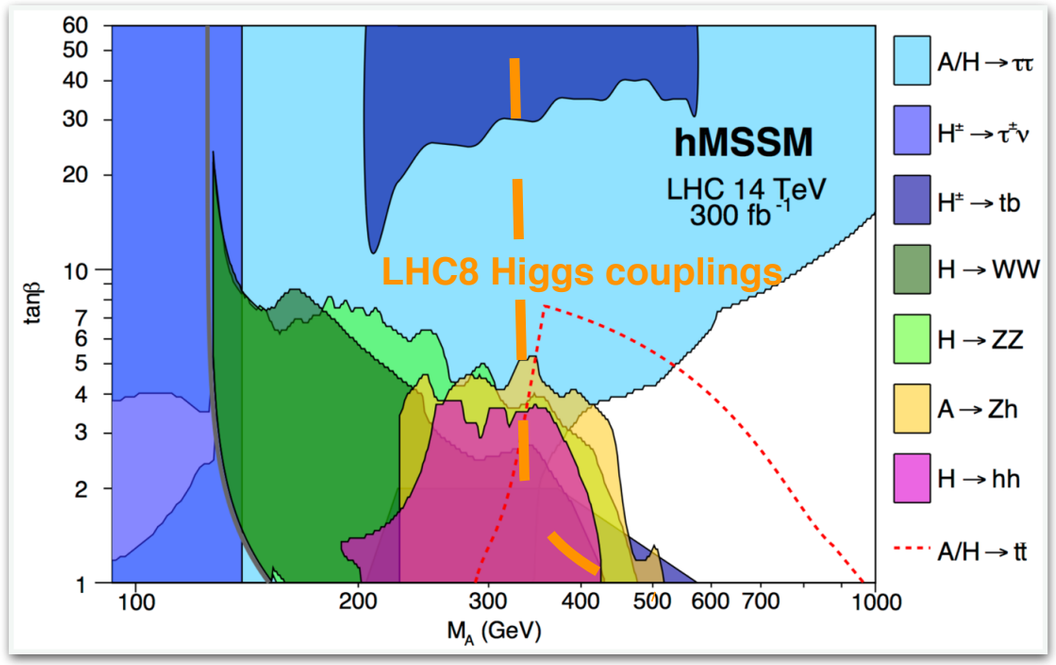


Barbieri et al. 1307.4937
see also Badziak et al 1304.5437

Summary and Outlook

Extra Singlet and Extra Doublet "simplified" benchmark still (very) motivated





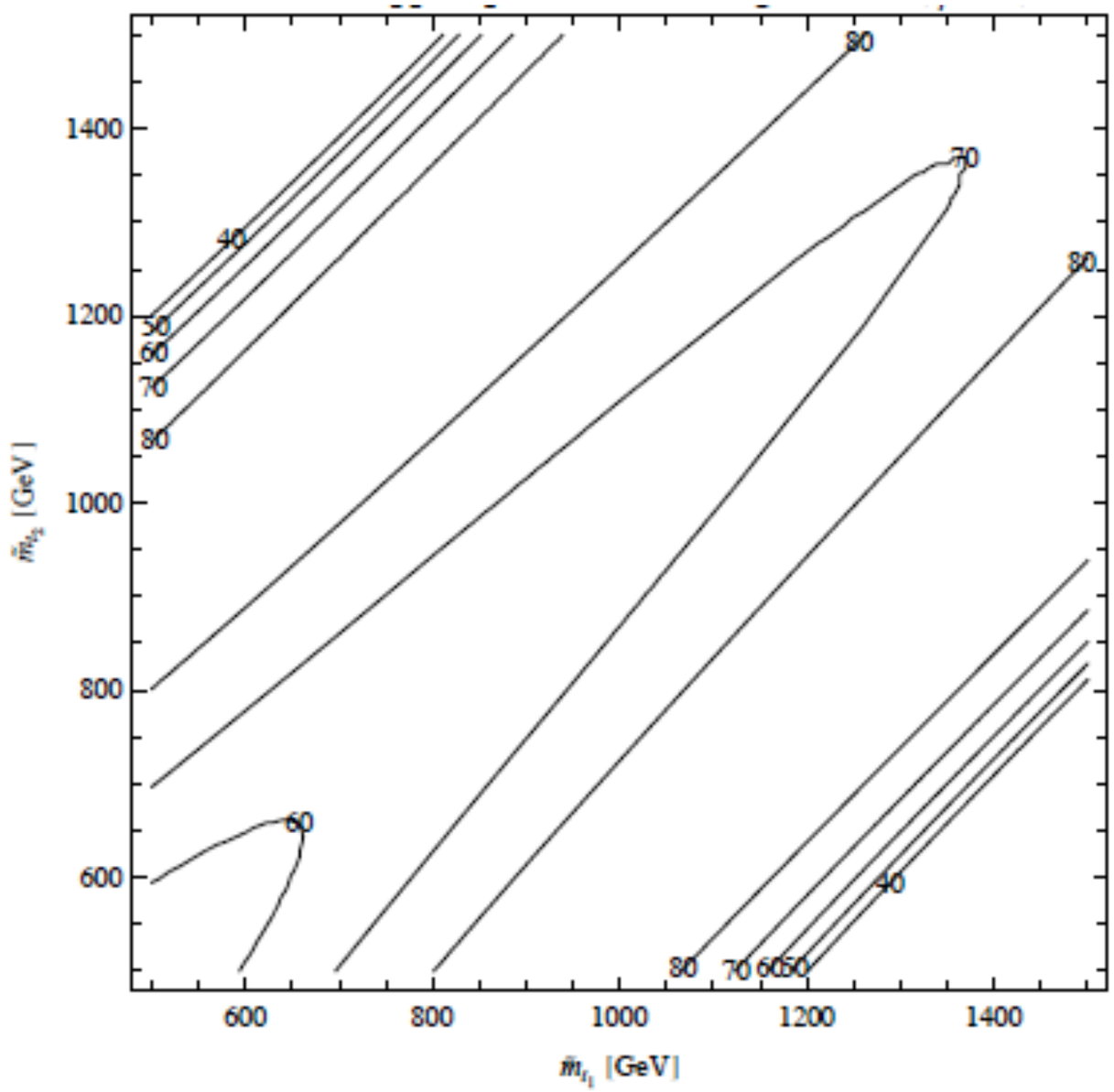
These models can surely inspire more searches (e.g. more charged Higgs?)

But we know little of the TeV scale, keep exploring!

Back up

Top-stop loop corrections

Contours of $\Delta_{\rm loop}$ [GeV] for maximal mixing and $\tan\beta = 4$



$$\Delta^2_{\rm loop} \simeq \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\log\frac{m^2_{\tilde t}}{m_t^2} + \frac{X_t^2}{m^2_{\tilde t}}\left(1 - \frac{X_t^2}{12 m^2_{\tilde t}}\right)\right]$$

$$m^2_{\tilde t} = m_{Q_3} m_{u_3}$$

$$X_t = A_t - \mu\cot\beta$$