

Searching for the Higgs bosons of the NMSSM

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IPhT, CEA/Saclay and CNRS



based on: Barbieri, Buttazzo, Kannike, S, Tesi, 1304.3670 and 1307.4937
Buttazzo, S, Tesi, BSM working group, "What Next" initiative of INFN

RPP 2015, Institut Henri Poincaré Paris, 16 Jan 2015

Can new scalars be the lightest particles around?

Motivation for that: a natural solution to hierarchy problem, like SUSY

MSSM

$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \Delta_t^2 \Rightarrow \Delta_t \gtrsim 85 \text{ GeV} \Rightarrow \text{stops above a TeV}$$

Fine tuning worse than 1%!

$$\frac{dv^2}{dm_{H_u}^2} \simeq \frac{4}{g^2} \quad \delta m_{H_u}^2 \sim -\frac{3y_t^2}{4\pi^2} \cancel{m_t^2} \log \frac{\Lambda}{m_{\tilde{t}}}$$

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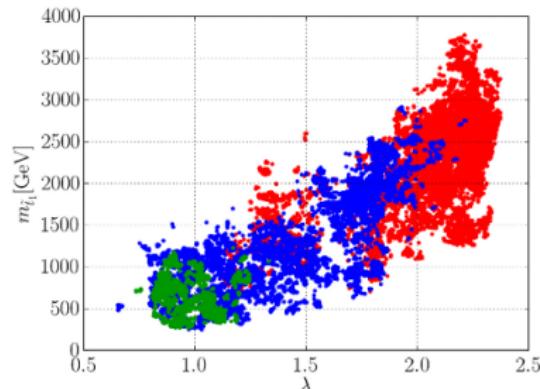
NMSSM

Add singlet $S \quad \Delta W = \lambda S H_u H_d + f(S)$

$$m_h^2 \leq m_Z^2 c_{2\beta}^2 + \Delta_t^2 + \cancel{\lambda}^2 v^2 s_{2\beta}^2$$

Fine tuning better than 5%!
[green points, $\tan \beta \lesssim 5$]

$$\frac{dv^2}{dm_{H_u}^2} \simeq \frac{\kappa}{\cancel{\lambda}^3} \frac{1}{t_{2\beta}}$$

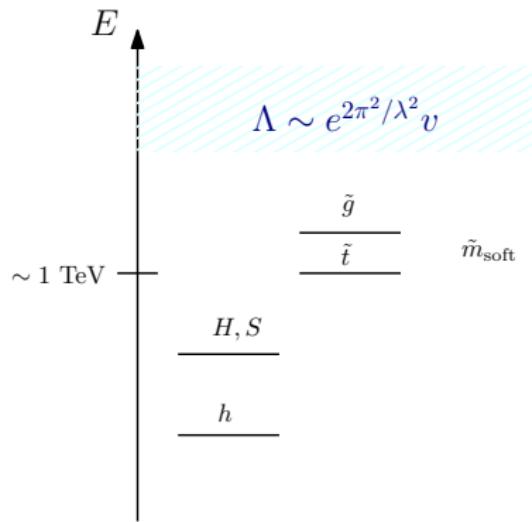


Model and plan

NMSSM with $\lambda \sim 1$ and heavy stops & gluinos

[$\lambda \gtrsim 0.7$ needs completion before GUT scale]

Goal = strategy to look for extra scalars



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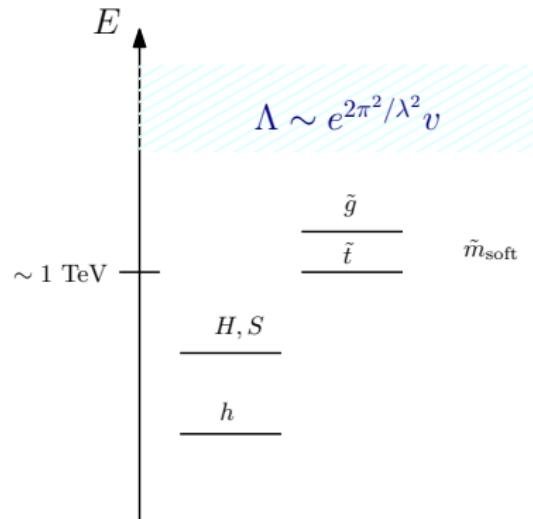
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Scalars are:

CP-even h_1, h_2, h_3 (from h, S, H)

CP-odd A, A_s

H^\pm



Model and plan

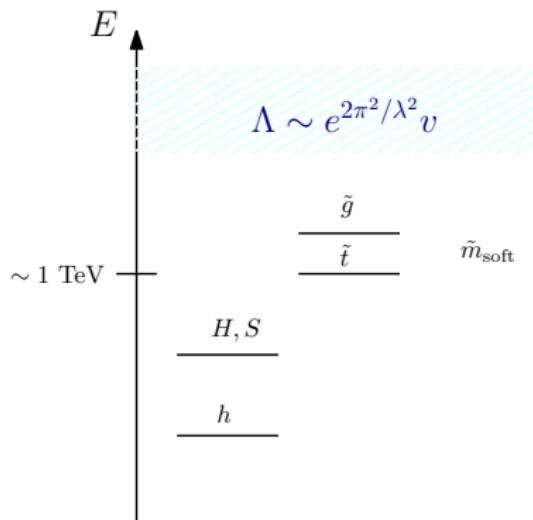
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Assumptions

Only loop contribution = top-stop Δ_t

No invisible decays $h_1, h_2 \rightarrow \chi\chi, \dots$

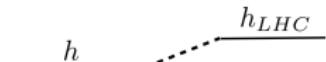
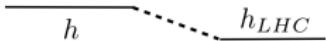
A useful parametrisation

(no specific NMSSM, no scatter plots..)

$$\mathcal{H}_{\text{ph}} \equiv \begin{pmatrix} h_3 \\ h_1 \\ h_2 \end{pmatrix} = R^T \begin{pmatrix} H \\ h \\ S \end{pmatrix}, \quad R = \boxed{R_\delta^{12} R_\gamma^{23} R_\sigma^{13}}$$

$m_{h_1} = 125 \text{ GeV}$

$$\mathcal{M}^2 = \begin{pmatrix} \widetilde{\mathcal{M}}^2(m_{H^\pm}^2, \lambda, t_\beta, \Delta_t) & & \\ v M_1 & v M_2 & M_3^2 \end{pmatrix} = R^T \text{diag}(m_{h_3}^2, m_{h_1}^2, m_{h_2}^2) R$$



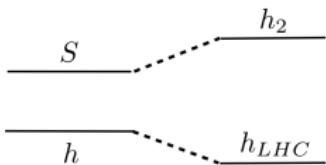
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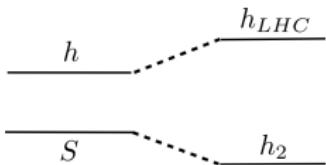
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Analytical relations!

$\delta, \gamma, \sigma(m_{h_2}, m_{h_3}, m_{H^\pm}, \lambda, t_\beta, \Delta_t)$



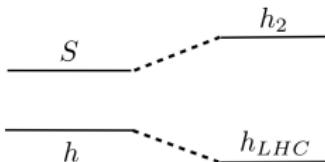
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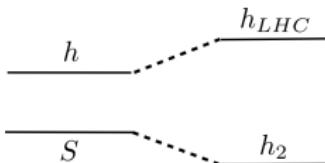
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Analytical relations!

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A motivated limiting case

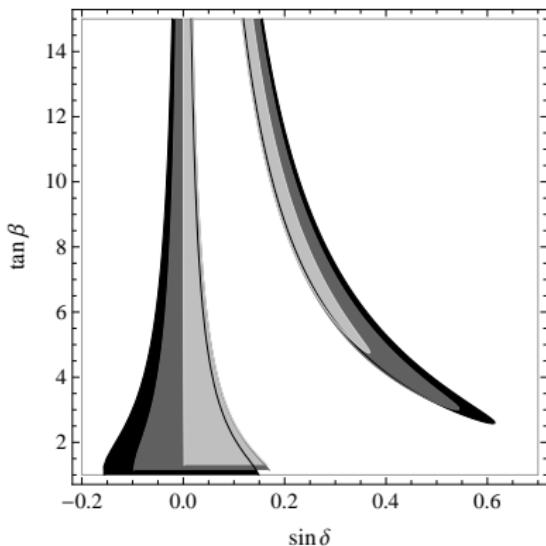
$m_{h_3} \gg m_{h_{1,2}}$ and $\sigma, \delta \rightarrow 0$ [free pars: $m_{h_2}, t_\beta, \Delta_t, \lambda$]

Higgs couplings and fit

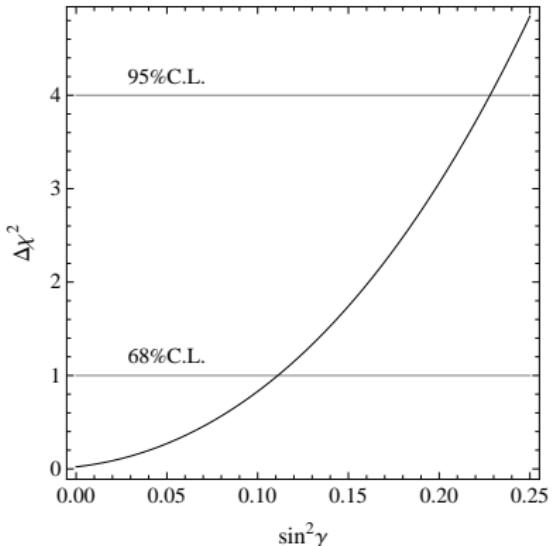
$$[h_{\text{LHC}} = h_1 = c_\gamma(c_\delta h - s_\delta H) + s_\gamma S]$$

$$\frac{g_{h_1 tt}^{} }{g_{htt}^{\text{SM}}} = c_\gamma \left(c_\delta + \frac{s_\delta}{\tan \beta} \right), \quad \frac{g_{h_1 bb}^{} }{g_{hbb}^{\text{SM}}} = c_\gamma \left(c_\delta - s_\delta \tan \beta \right), \quad \frac{g_{h_1 VV}^{} }{g_{hVV}^{\text{SM}}} = c_\gamma c_\delta$$

LHC8 status



$$s_\gamma^2 = 0, 0.15, 0.3$$

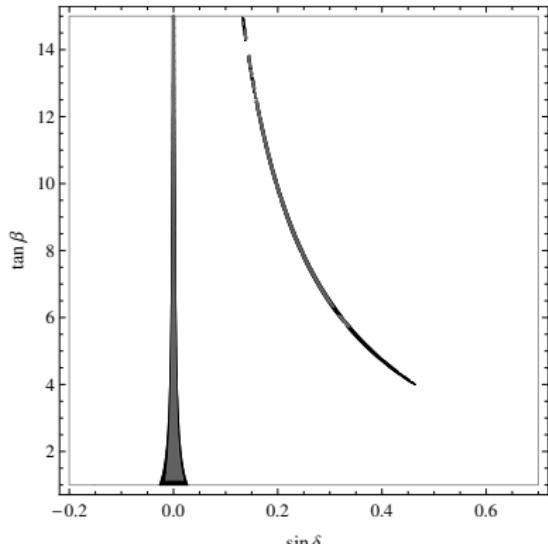


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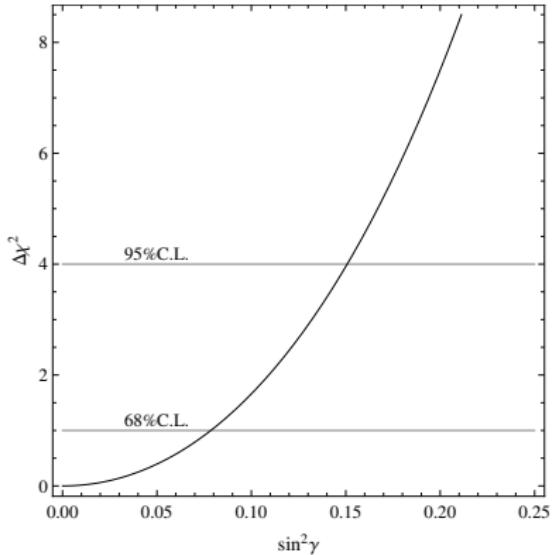
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LHC14 projections (300 fb⁻¹)



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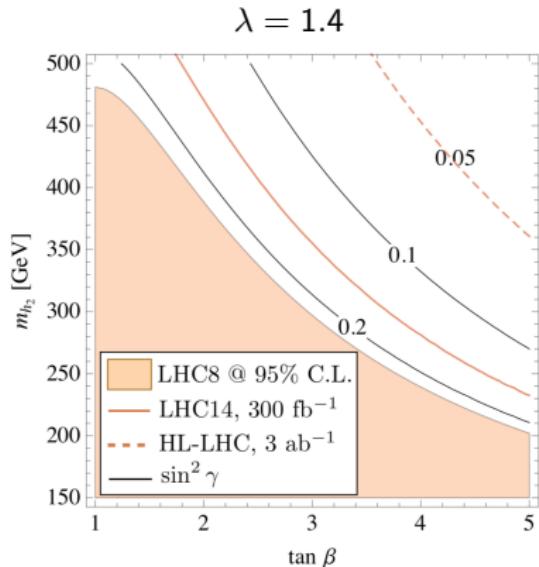
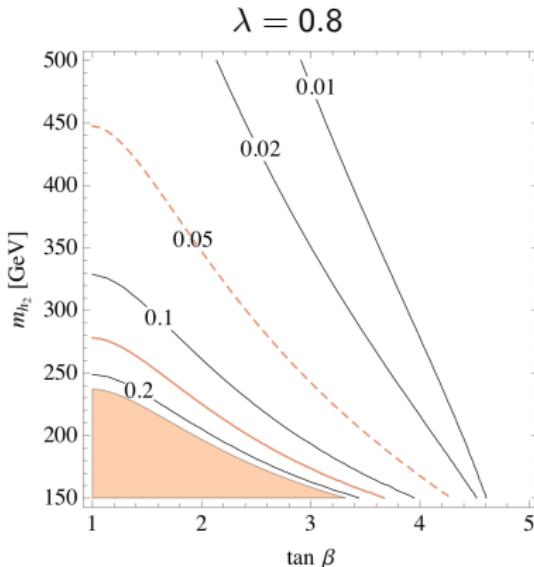
Doublet H decoupled

$[\delta, \sigma \rightarrow 0]$

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$$\frac{g_{h_2 ff}}{g_{hff}^{\text{SM}}} = \frac{g_{h_2 VV}}{g_{hVV}^{\text{SM}}} = -s_\gamma$$

$[\Delta_t = 75 \text{ GeV}]$



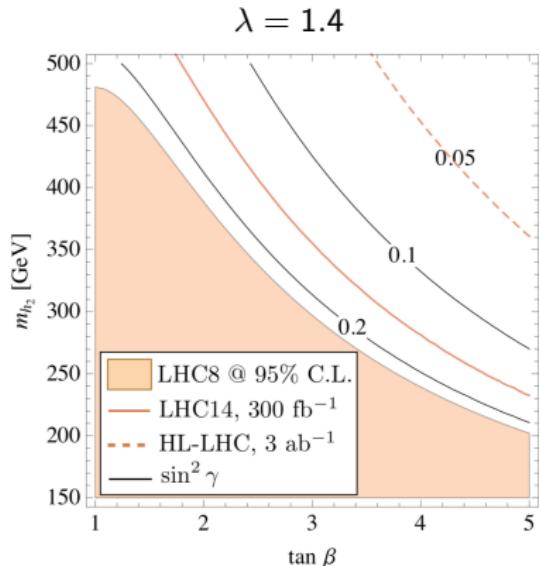
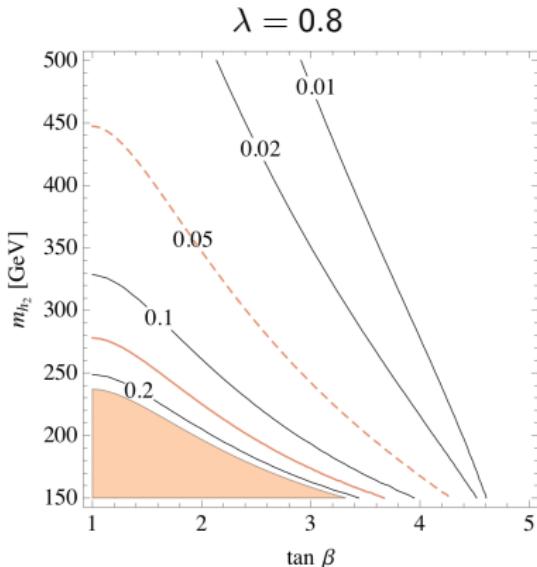
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Direct detection of h_2 : $m_{h_2} > 250 \text{ GeV}$: hh dominant decay [depends on v_s]

$m_{h_2} < 250 \text{ GeV}$: signal strengths = $s_\gamma^2 \times \text{SM}$

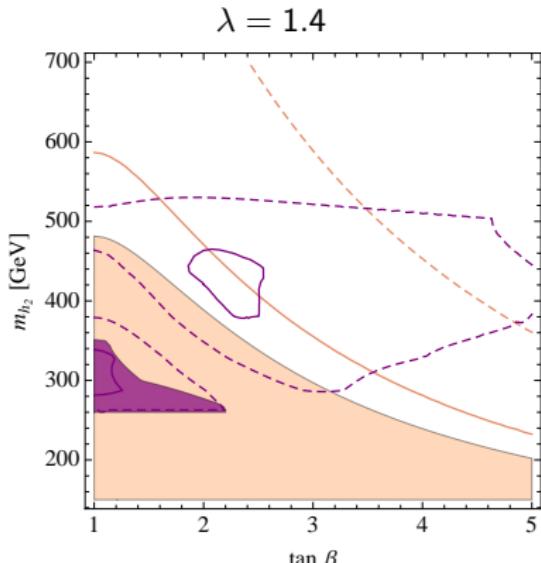
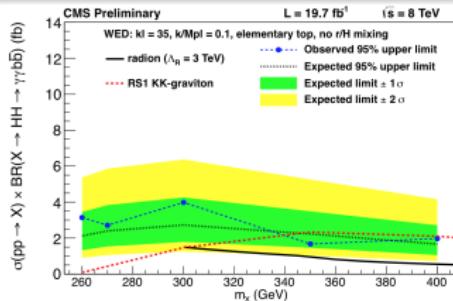
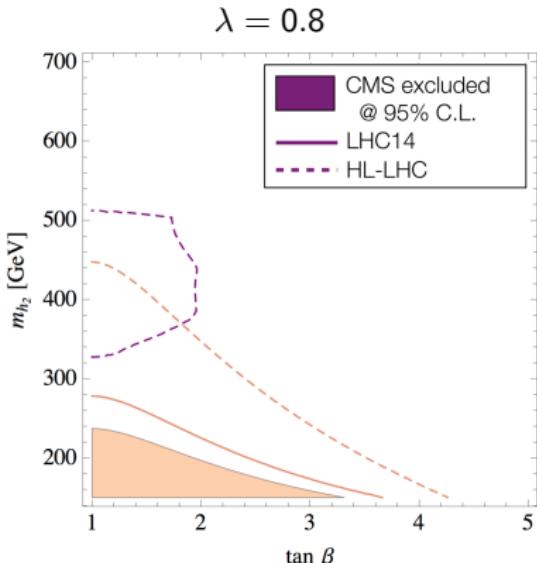
Looking for the singlet: $h_2 \rightarrow hh$

Current best limit: $hh \rightarrow b\bar{b}\gamma\gamma$ CMS

LHC14 reach only for $hh \rightarrow 4b$

Gouzevitch et al. 1303.6636

$hh \rightarrow b\bar{b}\gamma\gamma$ will likely do better!



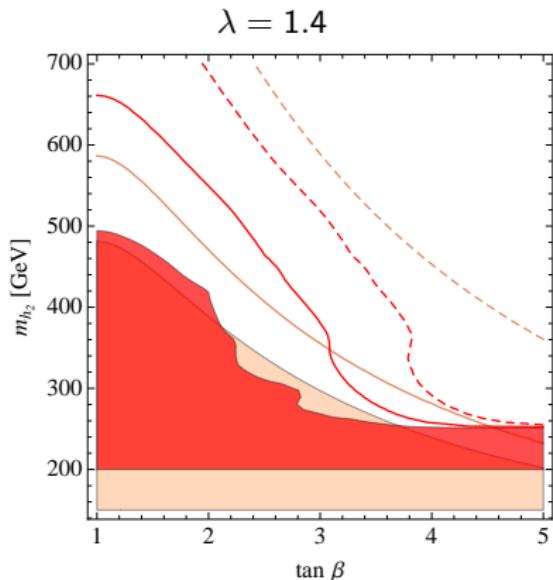
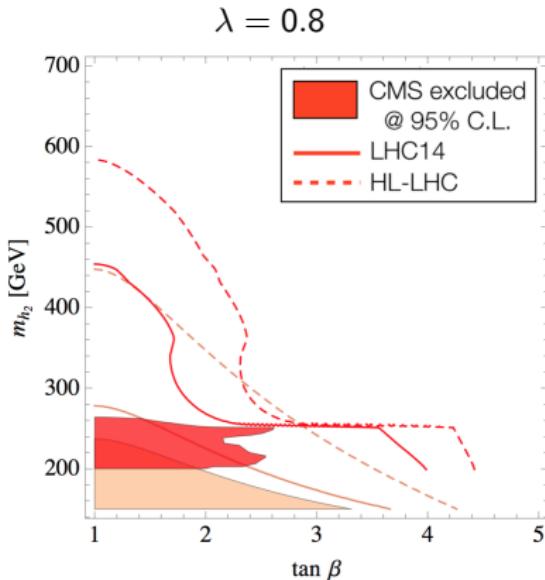
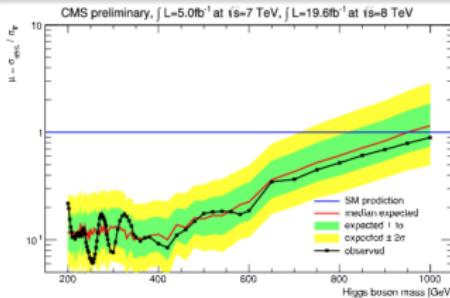
Looking for the singlet: $h_2 \rightarrow VV$

Current best limit: $ZZ \rightarrow 2\ell 2q, 4\ell, \dots$ CMS

LHC14 reach for $ZZ \rightarrow 4\ell$

Brownson et al. 1308.6334

already a good assessment?

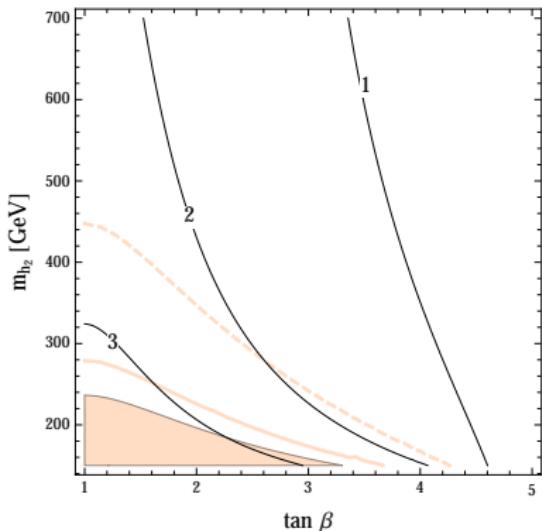


Looking for the singlet: hhh coupling

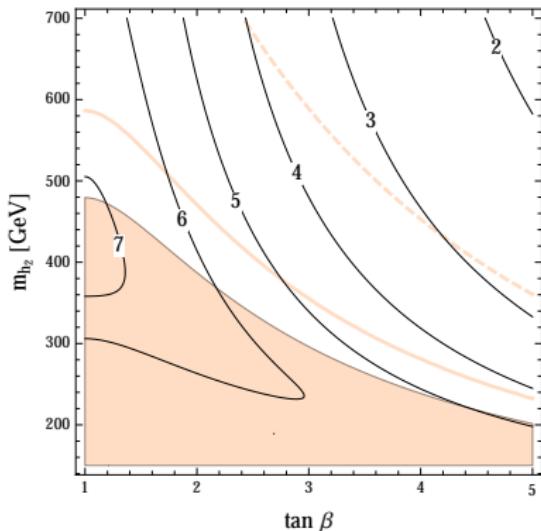
Trilinear Higgs coupling could be first place where we observe deviations

Isolines of $g_{hhh}/g_{hhh}^{\text{SM}}$:

$$\lambda = 0.8, v_s = 2v$$



$$\lambda = 1.4, v_s = v$$



HL-LHC sensitivity: $\sim 50\%$

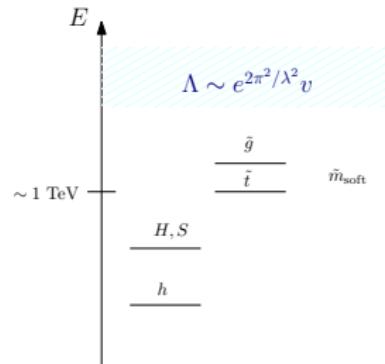
[see Snowmass report Dawson et al 1310.8361]

Summary and outlook

Looking for extra scalars

NMSSM with $\lambda \sim 1$ as a most natural scenario

Focus on CP-even sector



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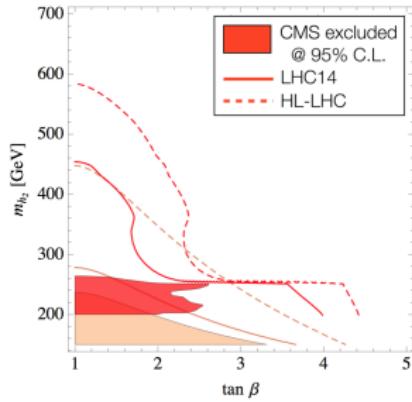
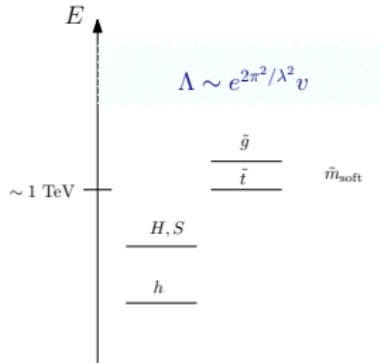
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Results:

Parametrization in terms of only physical quantities, no need to specify potential

Current status and future reaches
at the LHC for singlet-like scalar
direct vs indirect prospects



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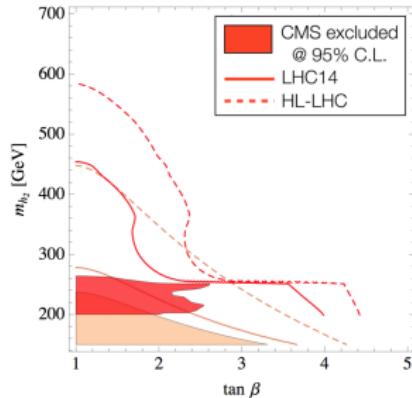
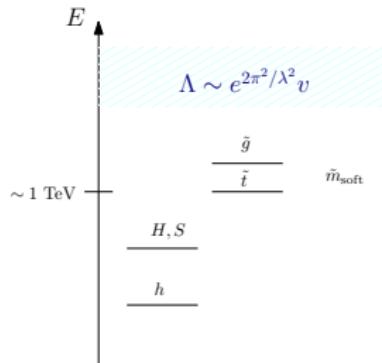
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Future: lot of space to be covered!

- Prospects for more channels/other colliders
- Tuning,...



Back up

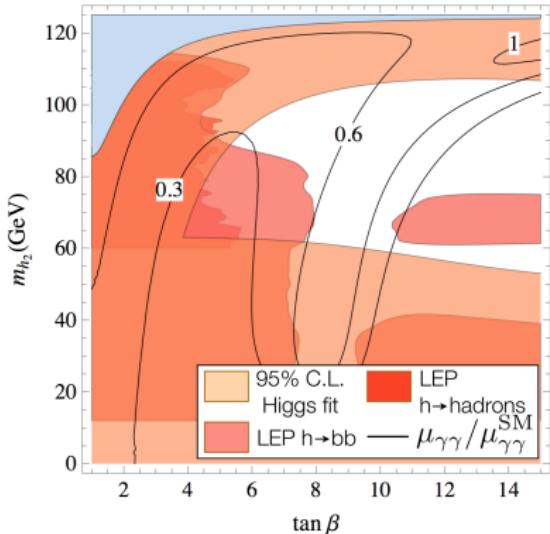
Fully mixed case and a $\gamma\gamma$ signal

Singlet-like state lighter than 125 GeV

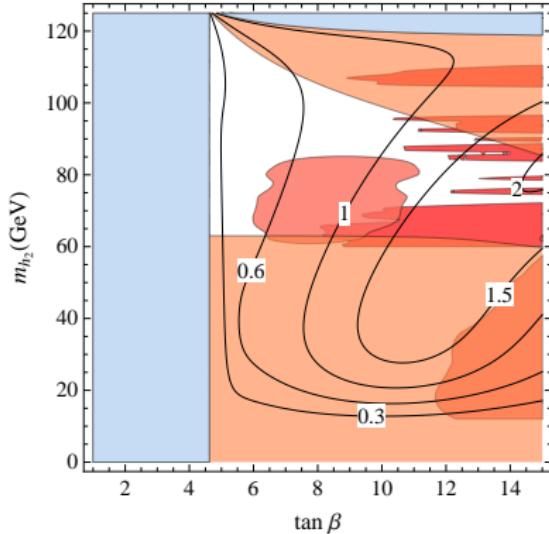
[see also R. Ziegler talk]

still allowed, hard to see

$$\lambda = 0.1, \Delta_t = 85 \text{ GeV}$$



$$\lambda = 0.8, \Delta_t = 75 \text{ GeV}$$

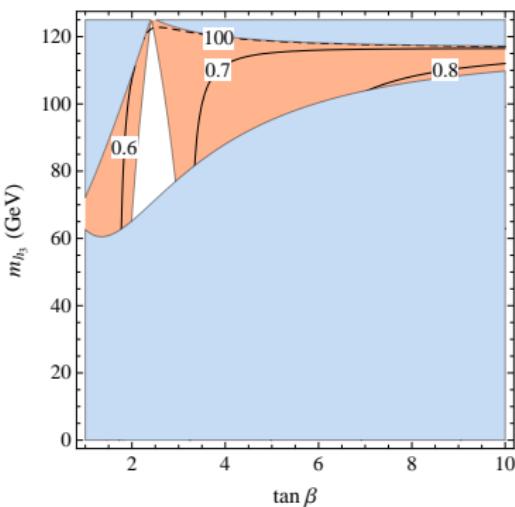
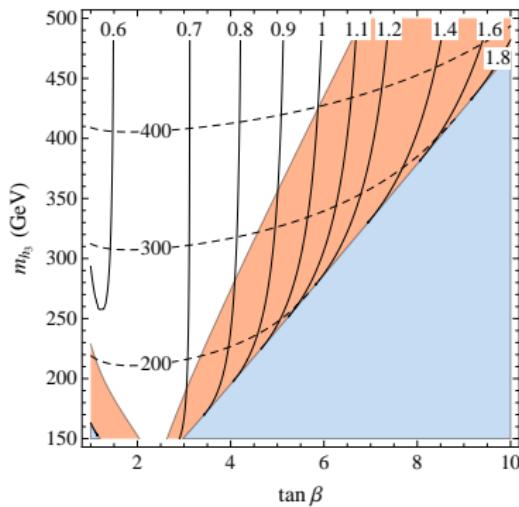


$$[m_{h_3} = 500 \text{ GeV}, s_\sigma^2 = 10^{-3}, v_s = v]$$

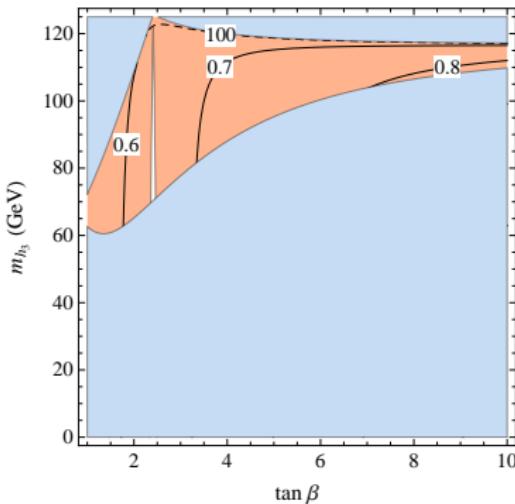
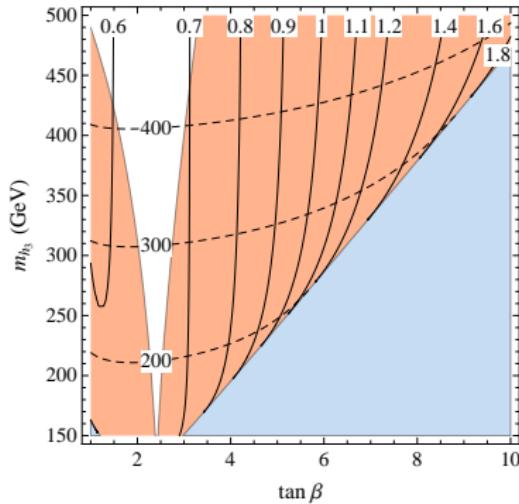
see e.g. Badziak et al. 1304.5437, ...

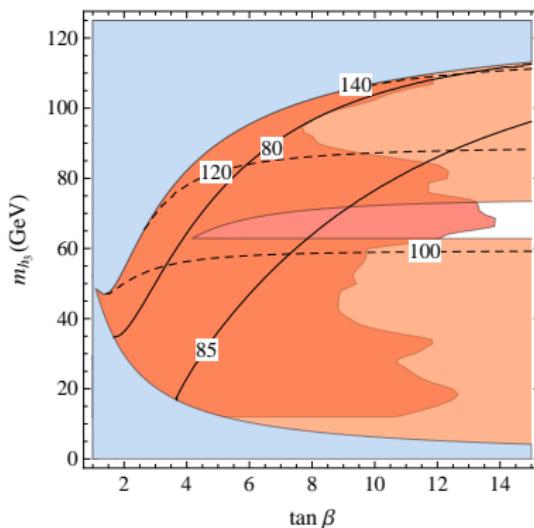
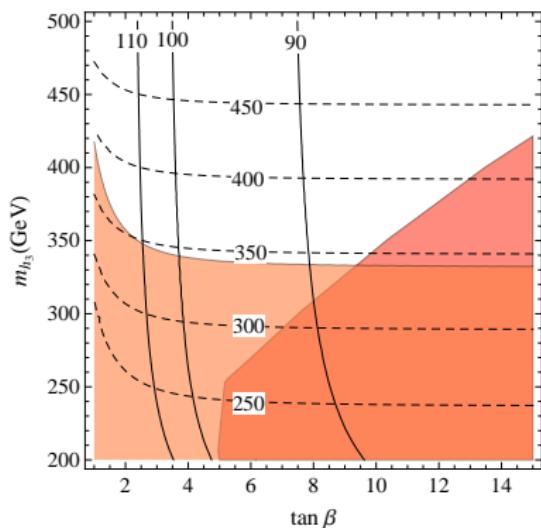
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LHC8 fit status:

dashed: m_{H^\pm} cont: λ Indirect bounds on H^\pm from $B \rightarrow X_s \gamma$! $[\widetilde{\mathcal{M}}_{12}^2(t_\beta, \dots) = 0 \rightarrow \delta = 0]$ h₃ pheno: more similar to MSSM, CMS and ATLAS are looking for it

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LHC14 fit projections (300 fb^{-1}):dashed: m_{H^\pm} cont: λ Indirect bounds on H^\pm from $B \rightarrow X_s \gamma$! $[\widetilde{\mathcal{M}}_{12}^2(t_\beta, \dots) = 0 \rightarrow \delta = 0]$ h₃ pheno: more similar to MSSM, CMS and ATLAS are looking for it

LHC8 fit status:[dashed: m_{H^\pm} cont: Δ_t]

Red regions excluded by LEP and CMS direct searches

LHC14 fit projections: above regions completely filled

[if $\frac{\mu A_t}{m_{\tilde{t}}^2}$ very large this conclusion could change]