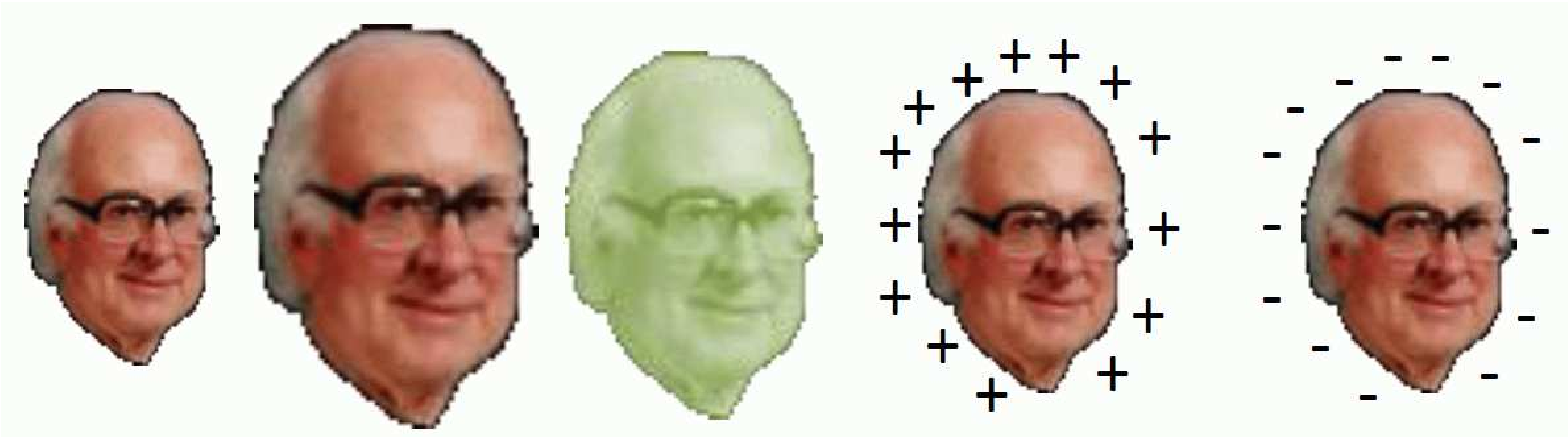


SUSY and 2HDM

Sven Heinemeyer, IFCA (CSIC, Santander)

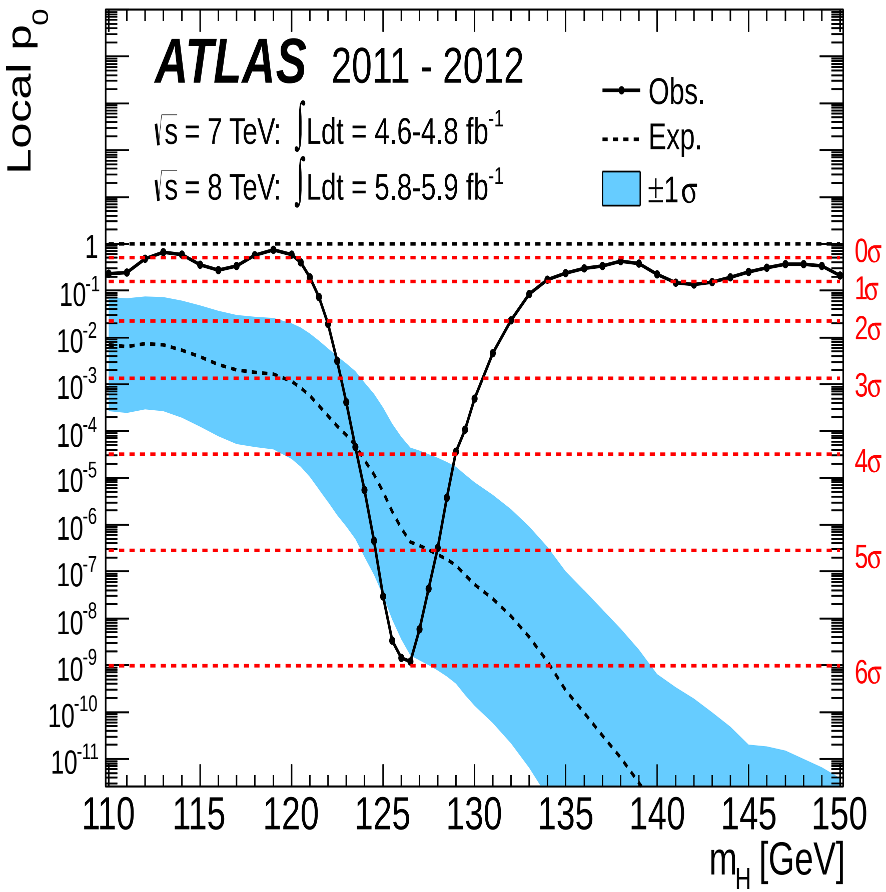
Hamburg, 10/2014

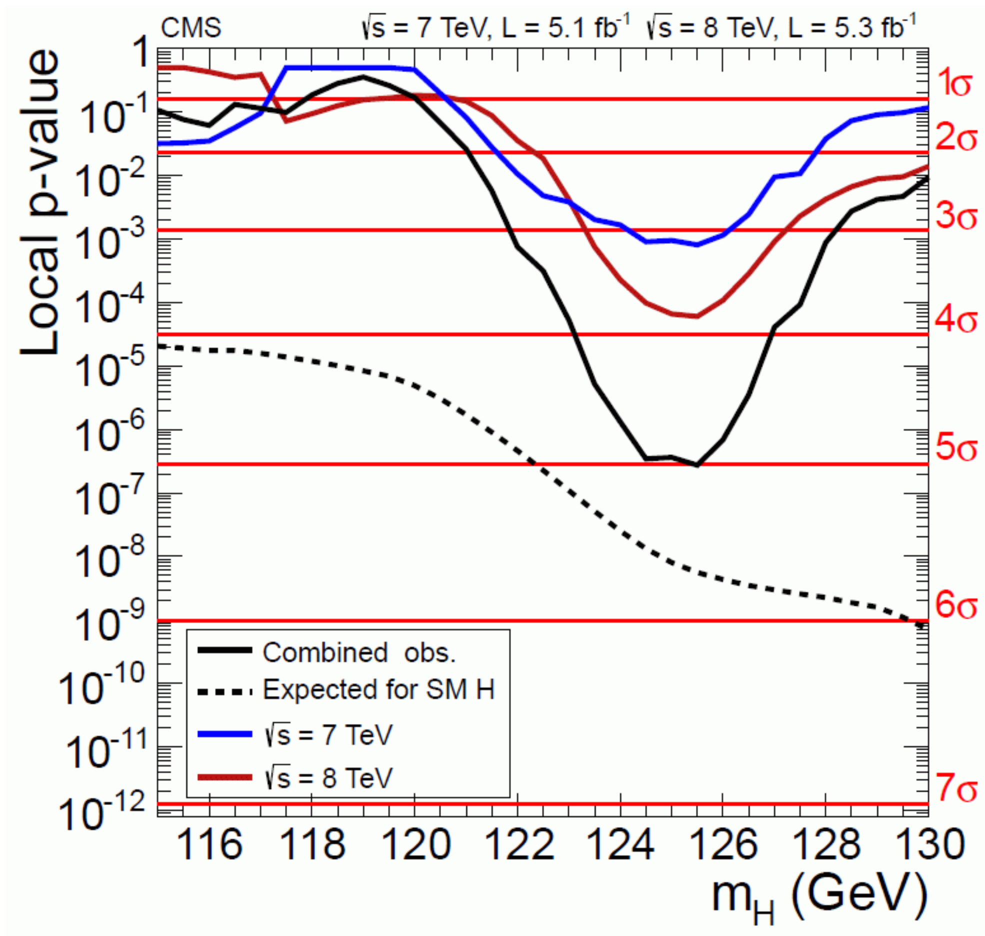
1. Why it is not the SM Higgs
2. Higgs bosons in the 2HDM
3. Higgs bosons in the (N)MSSM
4. What to look out for?
5. Conclusions

1. Why it is not the SM Higgs

Fact I:

We have a discovery!





Fact II:

The SM cannot be the ultimate theory!

Some facts:

1. gravity is not included

2. the hierarchy problem

3. Dark Matter is not included

4. neutrino masses are not included

5. anomalous magnetic moment of the muon shows a $\sim 4\,\sigma$ discrepancy

Fact I & II:

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The SM cannot be the ultimate theory!

Q: Does the BSM physics have any (relevant) impact on the Higgs?

Fact I & II:

We have a discovery!

The SM cannot be the ultimate theory!

Q: Does the BSM physics have any (relevant) impact on the Higgs?

A: check changed properties

A: check for additional Higgs bosons

We have a discovery!

But what is it?

Q: Is it a Higgs boson?

Q: Is it the Higgs boson of the SM?

Q: Is it an MSSM Higgs boson?

Q: Is it a Higgs boson of a different model?

Q: Is it an impostor?

We have a discovery!

But what is it?

Q: Is it a Higgs boson? $\Rightarrow$ yes according to CERN!

Q: Is it the Higgs boson of the SM? $\Rightarrow$ no according to me!

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How can we decide?

A: Measure all its characteristics

A: Compare to the predictions of the various models

A: Search for BSM / other Higgses at the LHC

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$\Rightarrow$ Some more details on 2HDM/SUSY Higgses here

Physics beyond the SM:

Interesting (new) physics models :

- 2HDM:
  - two Higgs doublets more natural than one
- MSSM:
  - solves hierarchy problem, goes towards gravity
  - automatic electroweak symmetry breaking
  - gauge coupling unification
  - cold dark matter candidate
  - $(g-2)_\mu$ solved easily
- Little Higgs:
  - (partially) solves the hierarchy problem
  - cold dark matter candidate
- Extra dimensions:
  - solves the hierarchy problem
  - cold dark matter candidate
- ...

⇒ pick your favorite model now - I pick the 2HDM, (N)MSSM

2. Higgs bosons in the 2HDM

[*taken from H. Haber, HDays14*]

The CP-conserving 2HDM—a brief review

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c.}\right) + \tfrac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \tfrac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2$$
$$+\lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \left[\tfrac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + [\lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2]\Phi_1^\dagger \Phi_2 + \mathrm{h.c.}\right],$$

such that $\langle \Phi_a^0 \rangle = v_a/\sqrt{2}$ (for $a = 1, 2$), and $v^2 \equiv v_1^2 + v_2^2 = (246\ \mathrm{GeV})^2$. For simplicity, assume a CP-conserving Higgs potential and vacuum where v_1, v_2, m_{12}^2, λ_5, λ_6 and λ_7 are real. We define Higgs basis fields, $H_1 \equiv (v_1\Phi_1 + v_2\Phi_2)/v$ and $H_2 \equiv (v_1\Phi_2 - v_2\Phi_1)/v$, so that $\langle H_1^0 \rangle = v/\sqrt{2}$ and $\langle H_2^0 \rangle = 0$.

$$\mathcal{V} \ni \ldots + \tfrac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \ldots + \left[\tfrac{1}{2} Z_5 (H_1^\dagger H_2)^2 + Z_6 (H_1^\dagger H_1) H_1^\dagger H_2 + \mathrm{h.c.}\right] + \ldots\,,$$

where $\tan\beta \equiv v_2/v_1$ with e.g.,

$$Z_1 \equiv \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + \tfrac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5) s_{2\beta}^2 + 2 s_{2\beta}\left[c_\beta^2 \lambda_6 + s_\beta^2 \lambda_7\right],$$
$$Z_6 \equiv -\tfrac{1}{2} s_{2\beta}\left[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - (\lambda_3 + \lambda_4 + \lambda_5) c_{2\beta}\right] + c_\beta c_{3\beta} \lambda_6 + s_\beta s_{3\beta} \lambda_7\,,$$

and the shorthand notation, $s_\beta \equiv \sin\beta$, $c_\beta \equiv \cos\beta$, etc., has been employed.

The alignment and decoupling limits of the CP-conserving 2HDM

In the $\{\Phi_1, \Phi_2\}$ basis, when the CP-even neutral Higgs squared-mass matrix is diagonalized, the resulting mixing angle is called α. In the Higgs basis, the CP-even neutral Higgs squared-mass matrix is

$$\mathcal{M}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix},$$

where $\alpha - \beta$ is the corresponding mixing angle. The neutral mass-eigenstates are the CP-even h and H (with $m_h < m_H$) and CP-odd A. It follows that $m_h^2 \leq Z_1 v^2$, and the off-diagonal element, $Z_6 v^2$, governs the H_1^0—H_2^0 mixing.

- If $Z_6 = 0$ and $Z_1 < Z_5 + m_A^2/v^2$, then $c_{\beta-\alpha} = 0$ and $m_h^2 = Z_1 v^2$. In this case $h = \sqrt{2} H_1^0 - v$ and h behaves precisely as the SM Higgs boson.

- If $Z_6 = 0$ and $Z_1 > Z_5 + m_A^2/v^2$, then $s_{\beta-\alpha} = 0$ and $m_H^2 = Z_1 v^2$. In this case $H = \sqrt{2} H_1^0 - v$ and H behaves precisely as the SM Higgs boson.

That is, $Z_6 = 0$ is the alignment limit of the 2HDM.

Given the CP-even neutral Higgs squared-mass matrix in the Higgs basis,

$$\mathcal{M}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix} ,$$

consider the limit where $m_A^2 \gg Z_i v^2$. In this case, standard perturbation theory shows that $m_h^2 \simeq Z_1 v^2$ and $|c_{\beta-\alpha}| \ll 1$. That is, $h \simeq \sqrt{2} H_1^0 - v$ (approximate alignment) and the properties of h approach that of the SM Higgs boson. This is the well-known decoupling limit of the 2HDM.

The normalized φVV couplings ($\varphi = h$ or H and $VV = W^+W^-$ or ZZ) are

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} = s_{\beta-\alpha} , \qquad \frac{g_{HVV}}{g_{h_{\rm SM}VV}} = c_{\beta-\alpha} .$$

• If h is SM-like then it follows that $|c_{\beta-\alpha}| \ll 1$, which implies that the 2HDM is close to either the decoupling and/or alignment limits.

• If H is SM-like then it follows that $|s_{\beta-\alpha}| \ll 1$, which implies that the 2HDM is close to the alignment limit.

Overview of benchmark scenarios

- Scenario A
  "Standard" scenario searching for heavy second Higgs boson, H
  $M_h = 125 \text{ GeV} < M_H < M_A = M_{H+}$
- Scenario B
  "Inverted" scenario with lightest Higgs below 125 GeV
  $M_h < M_H = 125 \text{ GeV} < M_A = M_{H+}$
- Scenario C
  Overlapping CP-even and CP-odd Higgses @ 125 GeV
  $M_h = M_A = 125 \text{ GeV} < M_H = M_{H+}$

 [taken from O. Stål, HDays14]

Overview of benchmark scenarios

- Scenario D

  Heavy CP-even Higgs with non-SM decays, e.g. H -> A Z, H -> H^+W^-

  M_h = 125 GeV < M_A/M_{H+} < M_H

- Scenario E

  Scenario for heavy CP-odd / charged Higgs with

  A -> H^+ W^- or H^+ -> A W^+

- Scenario F

  h with SM-like couplings to up-type fermions and vector bosons, but flipped sign of coupling to down-type fermions

- Scenario G

  "MSSM"-like (mass-degenerate) scenario for heavy Higgs bosons

  M_h = 125 GeV < M_H = M_A = M_{H+} (type II Yukawa couplings)

Latest (interim) recommendation: XS, BR in the 2HDM: [*LHCHXSWG '13*]

LHCHXSWG-2013-001

KA–TP–41–2013
LU TP 13–44
PSI–PR–13–17
WUB/13-19

LHC Higgs Cross Section Working Group

Interim recommendations for the evaluation of Higgs production cross sections and branching ratios at the LHC in the Two-Higgs-Doublet Model

R. Harlander[1], M. Mühlleitner[2], J. Rathsman[3], M. Spira[4], O. Stål[5]

– SusHi & 2HDMC
– Higlu & Hdecay
– updates/improvements expected (Powheg, MadGraph5, . . .)

- **2HDM cross sections ($gg \to \phi$, $b\bar{b} \to \phi$):** HIGLU [Spira] and SUSHI [Harlander,Liebler,Mantler]

$$\sigma^{2HDM}(gg \to \phi) = \left(\frac{g_t^{2HDM}}{g_t^{SM}}\right)^2 \sigma_{tt}(gg \to \phi) + \left(\frac{g_b^{2HDM}}{g_b^{SM}}\right)^2 \sigma_{bb}(gg \to \phi) + \frac{g_t^{2HDM}}{g_t^{SM}} \frac{g_b^{2HDM}}{g_b^{SM}} \sigma_{tb}(gg \to \phi)$$

$$\Delta\sigma_{tt}^{NNLO}(gg \to \phi) = \Delta K_{NNLO}\, \sigma_{tt}^{LO}(gg \to \phi), \qquad \Delta K_{NNLO} = \frac{\sigma_{NNLO} - \sigma_{NLO}}{\sigma_{LO}}$$

$\sqrt{s}$ /TeV	$\sigma(gg \to h)$/pb			$\sigma(gg \to H)$/pb			$\sigma(gg \to A)$/pb		
	SusHi	HIGLU	%	SusHi	HIGLU	%	SusHi	HIGLU	%
7	21.99	21.25	3.4	0.07199	0.06996	2.9	4.061	4.063	0.06
8	28.02	27.07	3.5	0.09895	0.09617	2.9	5.639	5.642	0.06
13	63.94	61.79	3.4	0.2845	0.2766	2.8	16.69	16.70	0.06
14	72.03	69.60	3.4	0.3303	0.3212	2.8	19.45	19.46	0.06

- **2HDM branching ratios:** type I-IV:
  2HDMC [Eriksson,Rathsman,Støal] and
  HDECAY [Djouadi,Kalinowski,MMM,Spira]
  both include higher-order (QCD) corrections

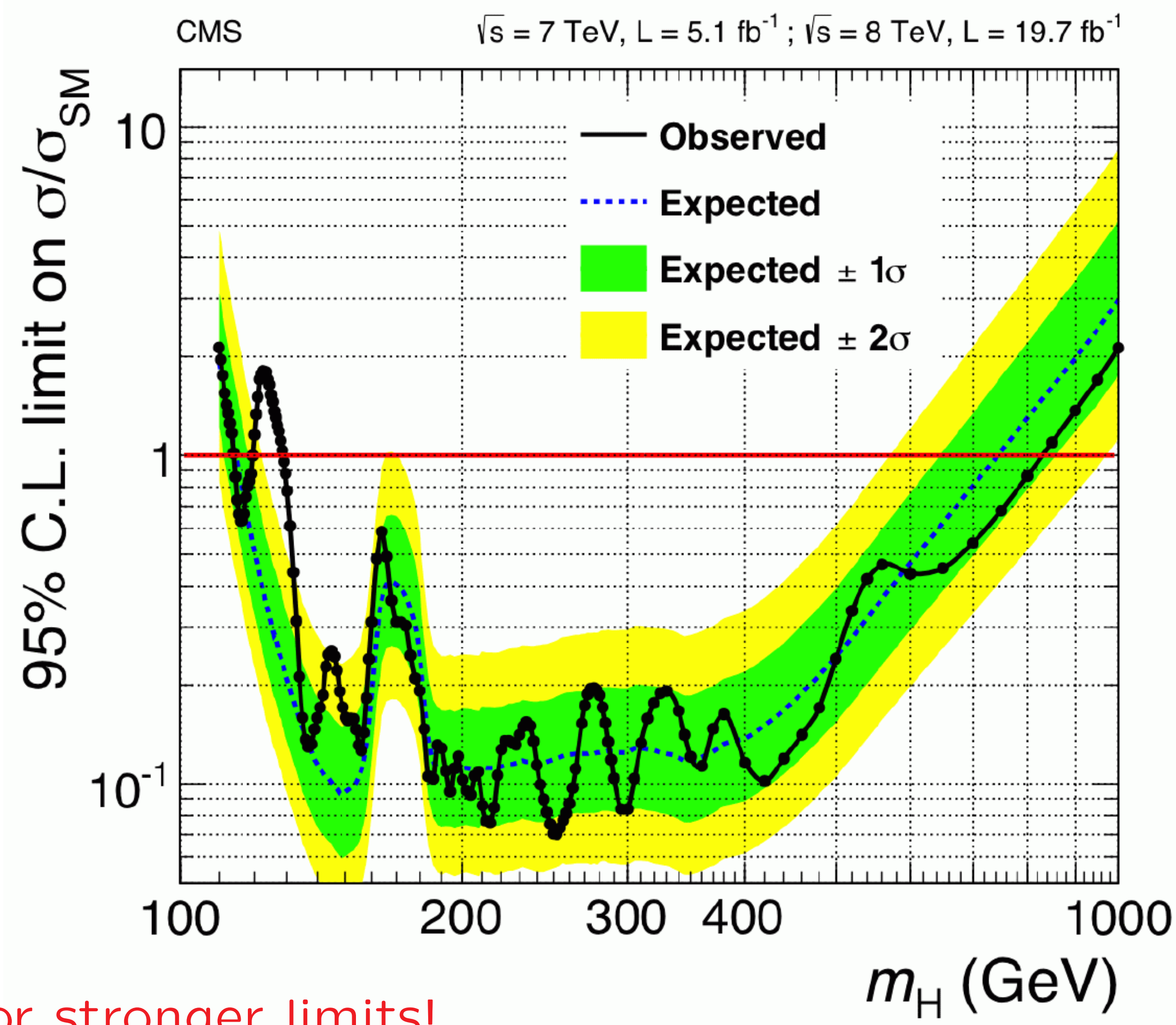
- **Recommendation: Use**
  2HDMC, HDECAY for BRs, Sushi, HIGLU for cxn;
  links Sushi/2HDMC and HIGLU/HDECAY

taken from [*M. Mühlleitner '13*]

Re-interpretation of SM Higgs search results:

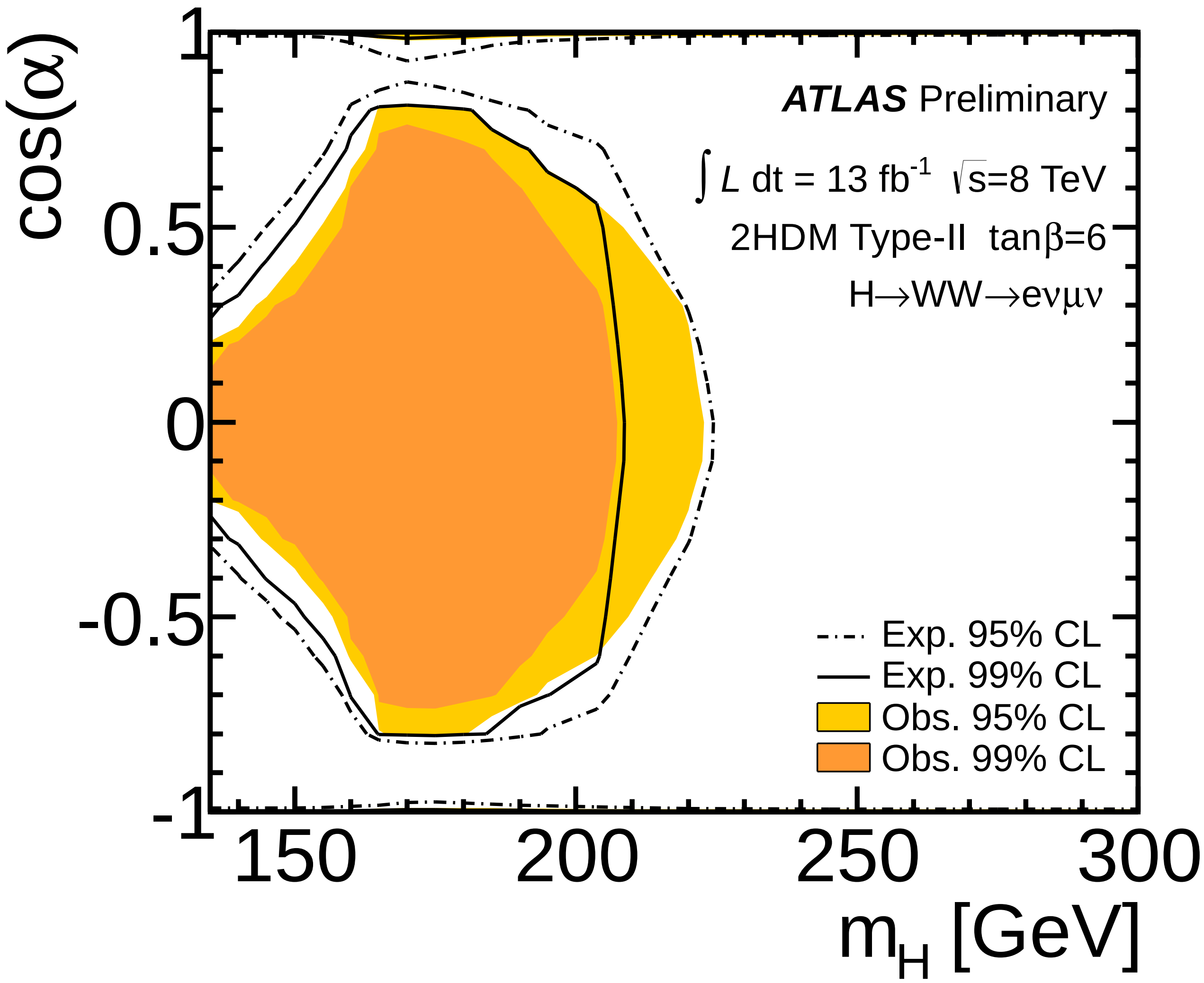
$g^2_{hVV} = \sin^2(\beta - \alpha)\, g^2_{HVV,\text{SM}}, \quad g^2_{HVV} = \cos^2(\beta - \alpha)\, g^2_{HVV,\text{SM}}$

$\Rightarrow$ some coupling strength could remain for the heavy Higgs



$\Rightarrow$ go ahead for stronger limits!

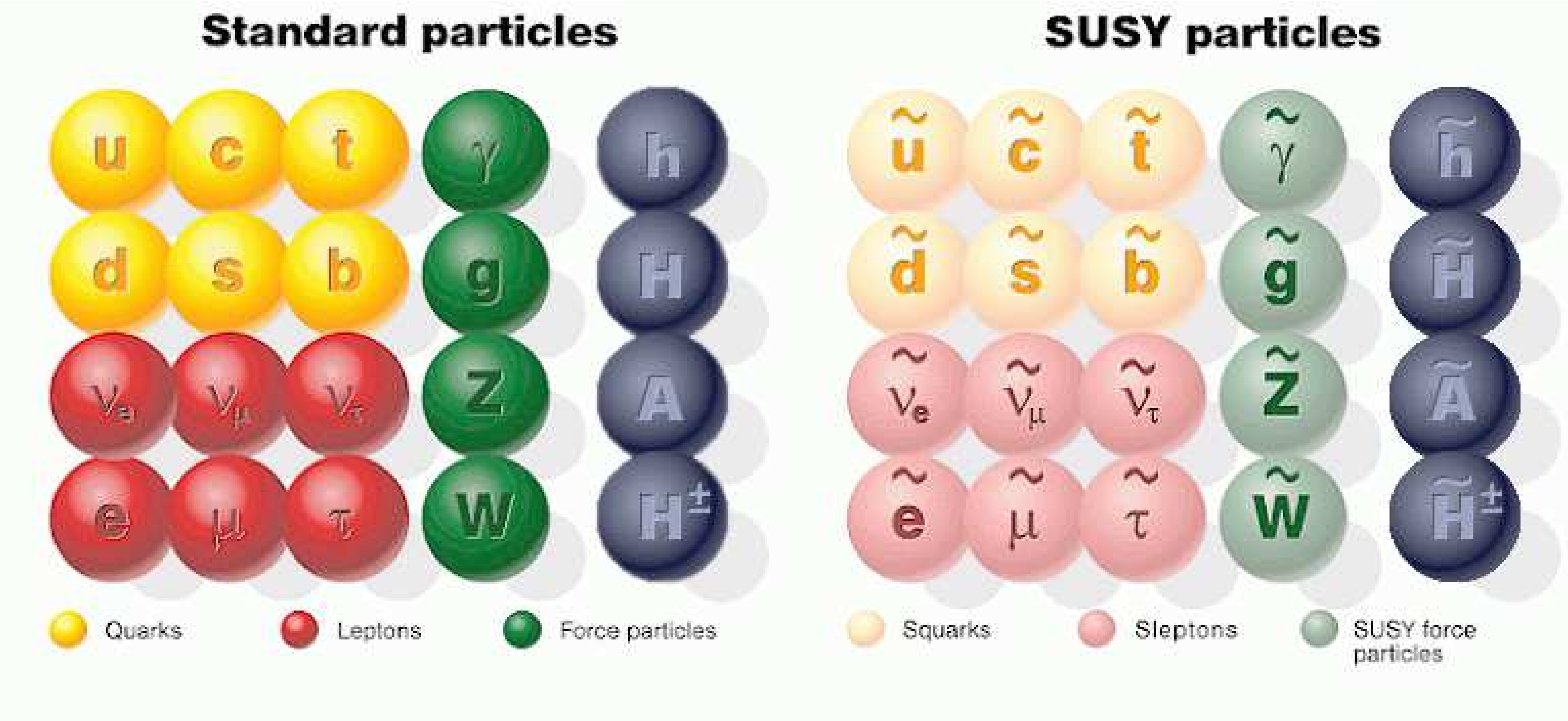
2HDM type II analysis by ATLAS, $H \to WW^{(*)}$ [ATLAS-CONF-2013-027]



$\Rightarrow$ analysis is most sensitive in the parameter space, where the model is least compatible with $M_h \sim 125.5$ GeV

3. Higgs bosons in the (N)MSSM:

⇒ Superpartners for Standard Model particles



The simplest case: **MSSM with real paremeters**

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2(\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}(H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM $\Rightarrow m_h \leq M_Z$

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

The lightest MSSM Higgs boson

MSSM predicts upper bound on M_h:

tree-level bound: $m_h < M_Z$, excluded by LEP Higgs searches!

Large radiative corrections:

Yukawa couplings: $\frac{\mathrm{e}\, m_t}{2 M_W s_\mathrm{W}}, \frac{\mathrm{e}\, m_t^2}{M_W s_\mathrm{W}}, \ldots$

$\Rightarrow$ Dominant one-loop corrections: $\Delta M_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

> The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

Present status of M_h prediction in the MSSM:

Complete 1L, 'almost complete' 2L available, LL+NLL resummed, . . .

$\tilde{t}/\tilde{b}$ sector of the MSSM:

Stop, sbottom mass matrices ($X_t = A_t - \mu/\tan\beta$, $X_b = A_b - \mu\tan\beta$):

$$\mathbf{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathbf{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$

mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

$SU(2)$ relation $\Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$

$\Rightarrow$ relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

Upper bound on M_h in the MSSM:

"Unconstrained MSSM":

M_A, $\tan\beta$, 5 parameters in $\tilde{t}$–$\tilde{b}$ sector, μ, $m_{\tilde{g}}$, M_2

$$M_h \lesssim 135 \text{ GeV}$$

for $m_t = 173.2 \pm 0.9\,\text{GeV}$ and $m_{\tilde{t}} \lesssim \mathcal{O}\,(\text{few TeV})$

(including theoretical uncertainties from unknown higher orders)

$\Rightarrow$ clear prediction for the LHC

Obtained with:

FeynHiggs

`www.feynhiggs.de`

[*T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '98 – '14*]

$\rightarrow$ all Higgs masses, couplings, BRs, XSs (easy to link, easy to use :-)

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The decoupling limit:

For $M_A \gtrsim 150$ GeV:

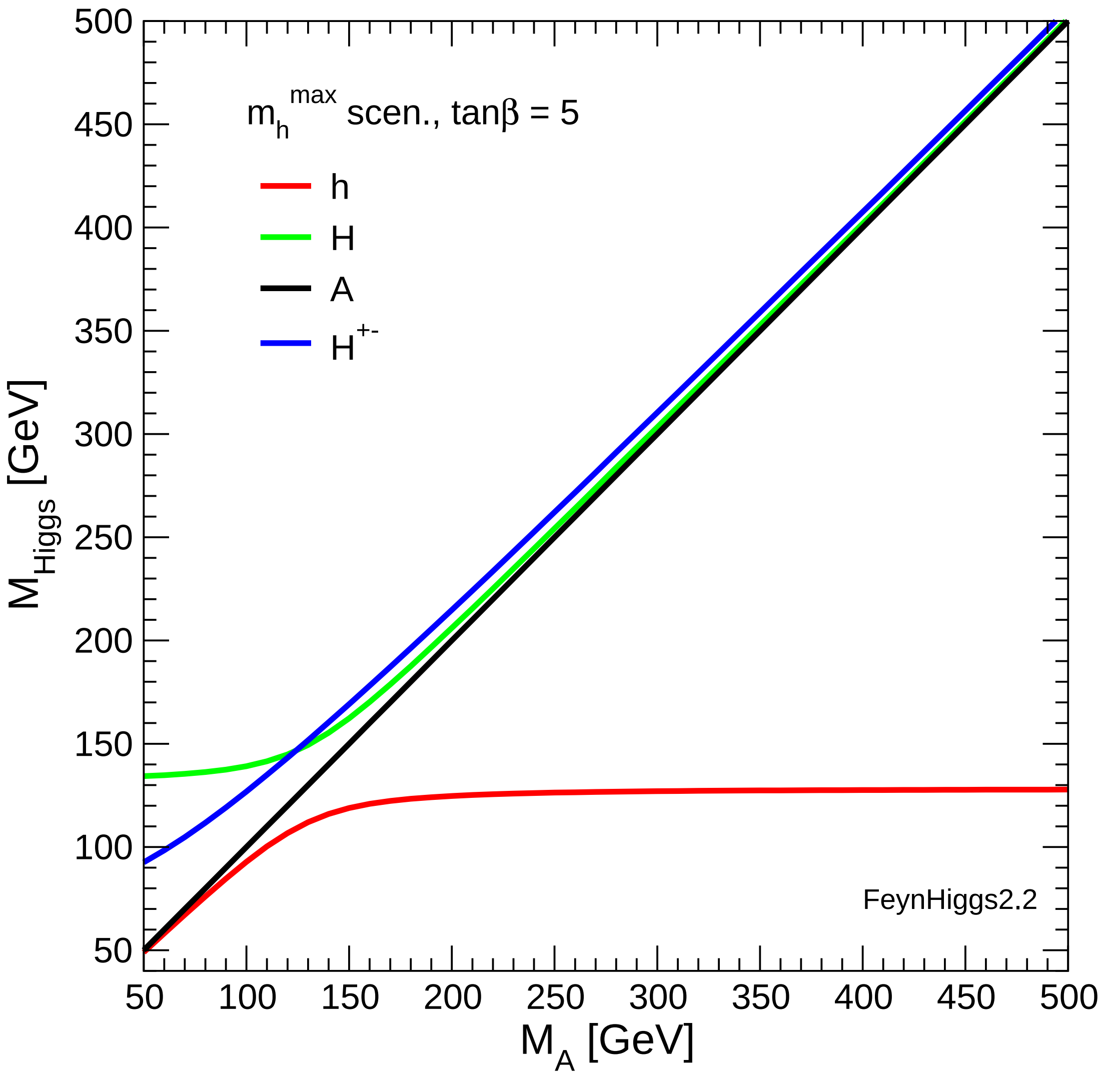
The lightest MSSM Higgs
is SM-like

$\Rightarrow$ SM analysis applies!

The heavy MSSM Higgses:
$M_A \approx M_H \approx M_{H^\pm}$

$\rightarrow$ coupling to gauge bosons ~ 0

$\Rightarrow$ no decay $H \rightarrow WW^{(*)}$, ...



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ATLAS:	$M_h^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18$ GeV
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$\Rightarrow$ dedicated working group has been formed to take care . . . (KUTS)

Can we learn something on SUSY from the Higgs mass measurement?

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A simple exercise on stop masses:

$\Rightarrow$ Dominant one-loop corrections: $\Delta M_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

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For this exercise make sure:
$\Rightarrow$ use the best available Higgs mass calculation!

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For this exercise make sure:
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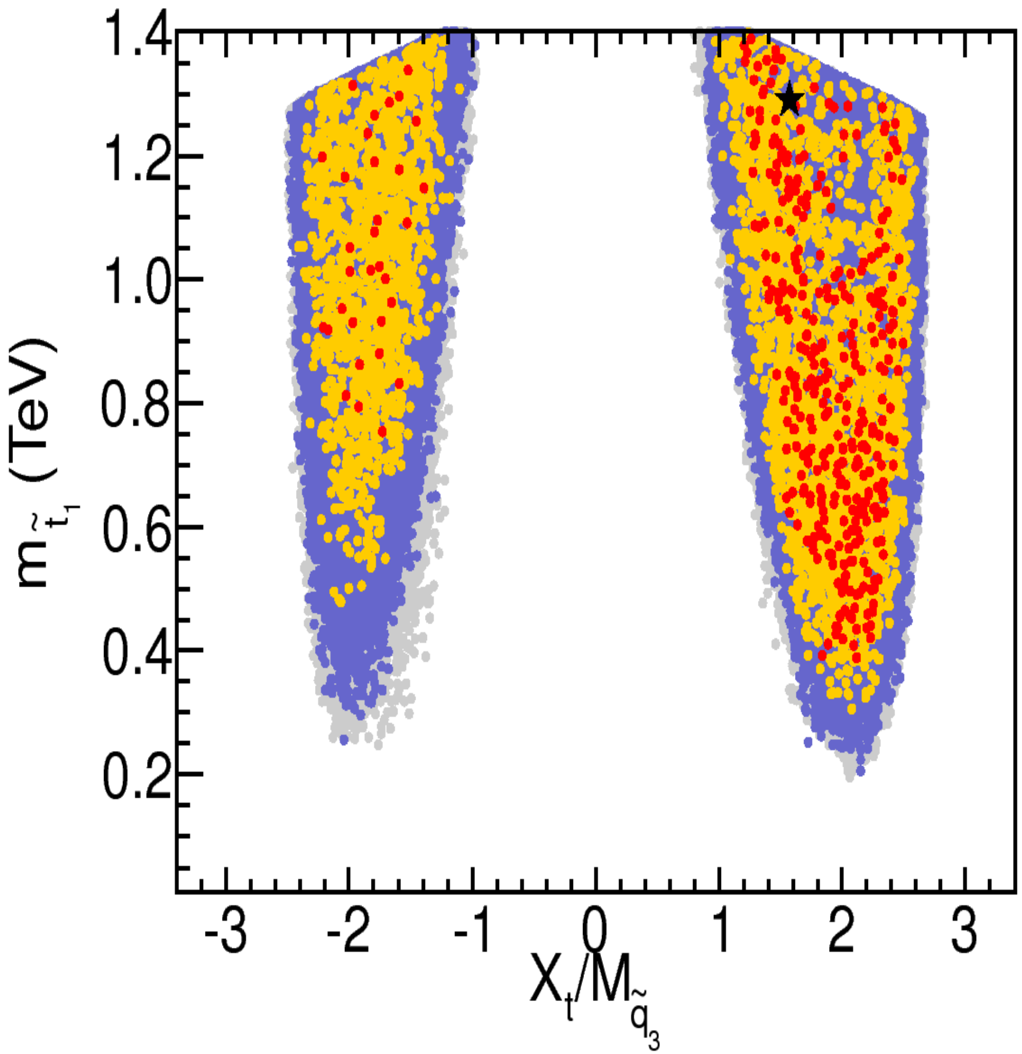


$M_h = 125 \pm 3$ GeV

$\star$: best-fit point

red: $\Delta\chi^2 < 2.3$

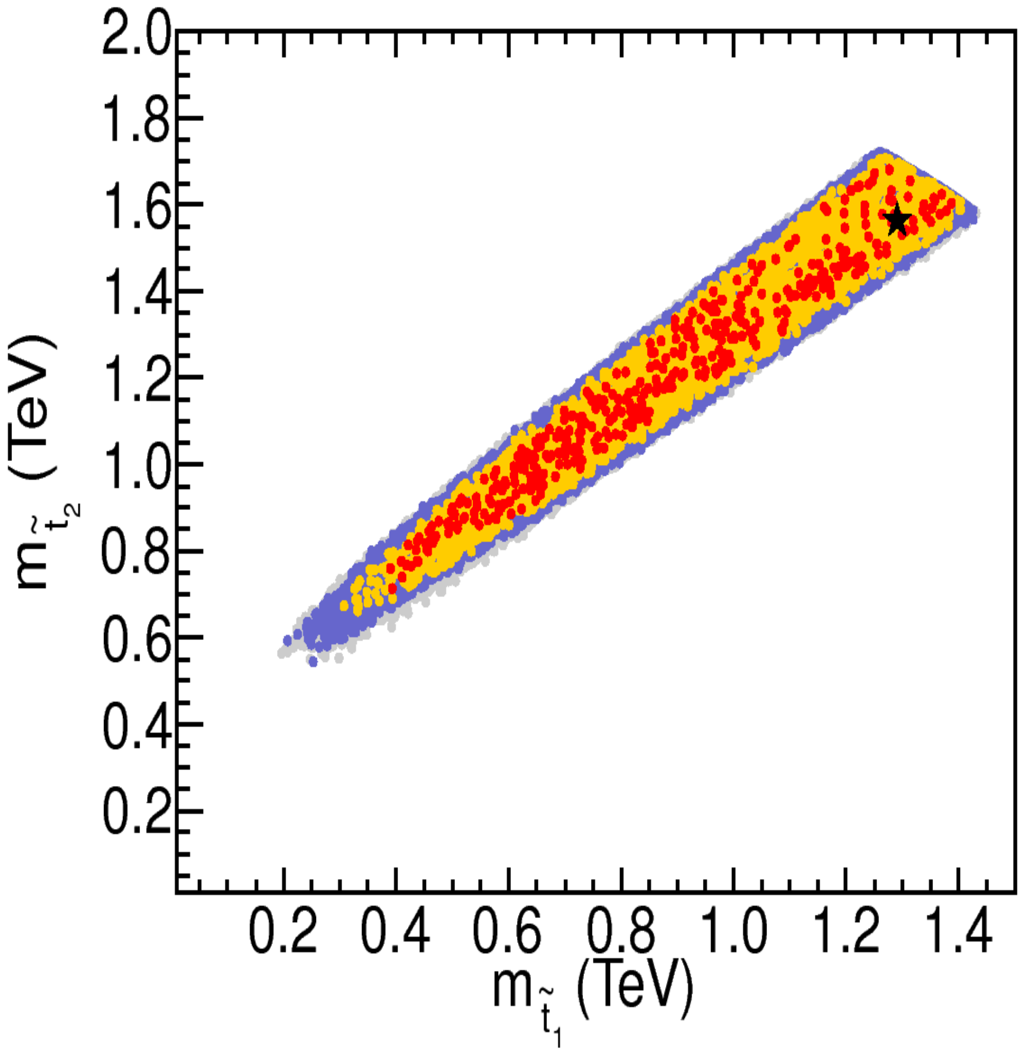
orange: $\Delta\chi^2 < 5.99$

blue: all points HiggsBounds allowed

gray: all scan points

$\Rightarrow M_h \sim 125$ GeV requires large X_t and/or large M_{SUSY}

Stop masses: [P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein, L. Zeune '14 – PRELIMINARY]



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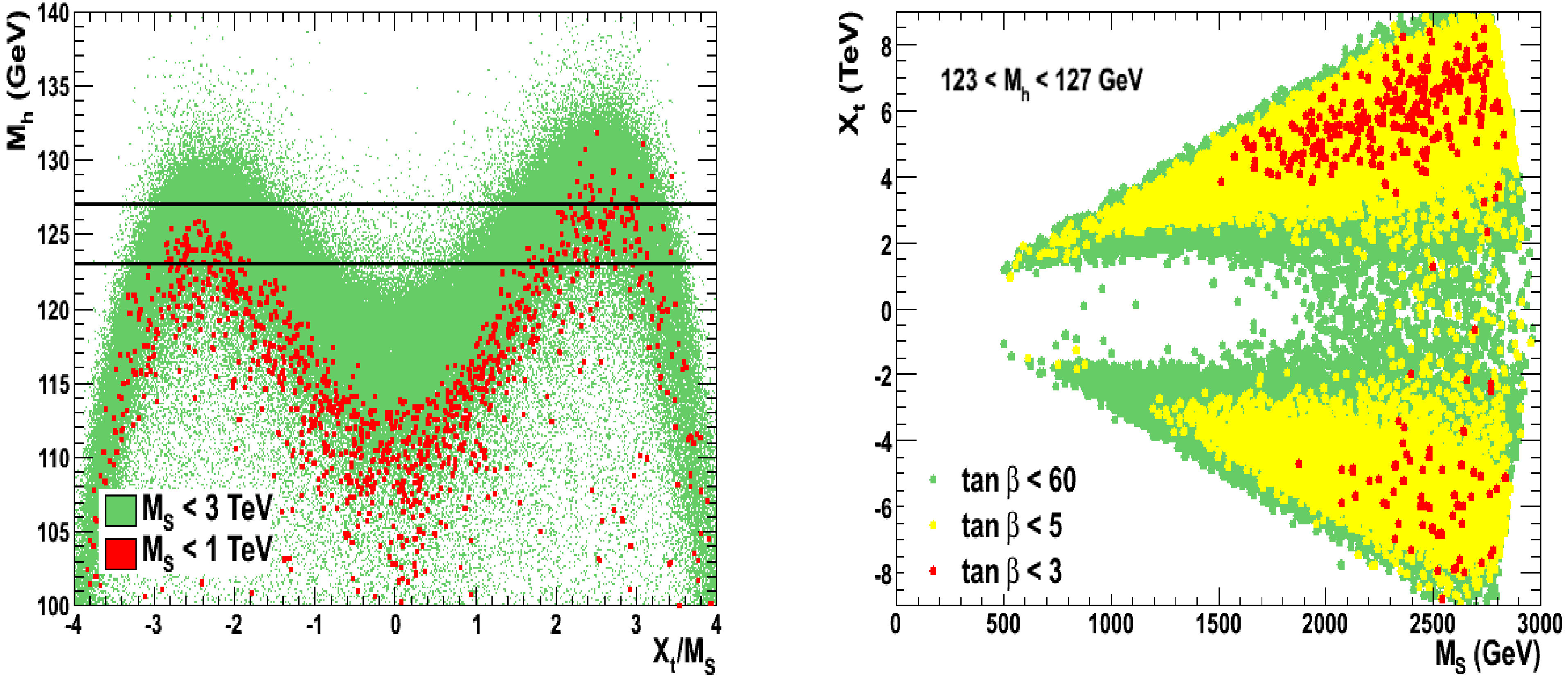
gray: all scan points

$\Rightarrow$ light and heavy stops compatible with $M_h \simeq 125$ GeV

Stop masses for $M_h = 125.5$ GeV

[*A. Arbey et al., '11*]



$\Rightarrow M_h \sim 125$ GeV requires large X_t and/or large M_{SUSY}

$\Rightarrow$ watch out: FeynHiggs was not used! ;-)

Complication I:

The MSSM Higgs sector with $\mathcal{CP}$ violation

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \underbrace{\frac{g'^2 + g^2}{8}}(H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

2 $\mathcal{CP}$-violating phases: ξ, arg(m_{12}) $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2$$

The Higgs sector of the cMSSM at the loop-level:

Complex parameters enter via loop corrections:

- μ : Higgsino mass parameter
- $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b,\tau} - \mu^* \{\cot\beta\,, \tan\beta\}$ complex
- $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)
- M_3 : gluino mass parameter

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

Result:

$$(A, H, h) \to (h_3, h_2, h_1)$$

with

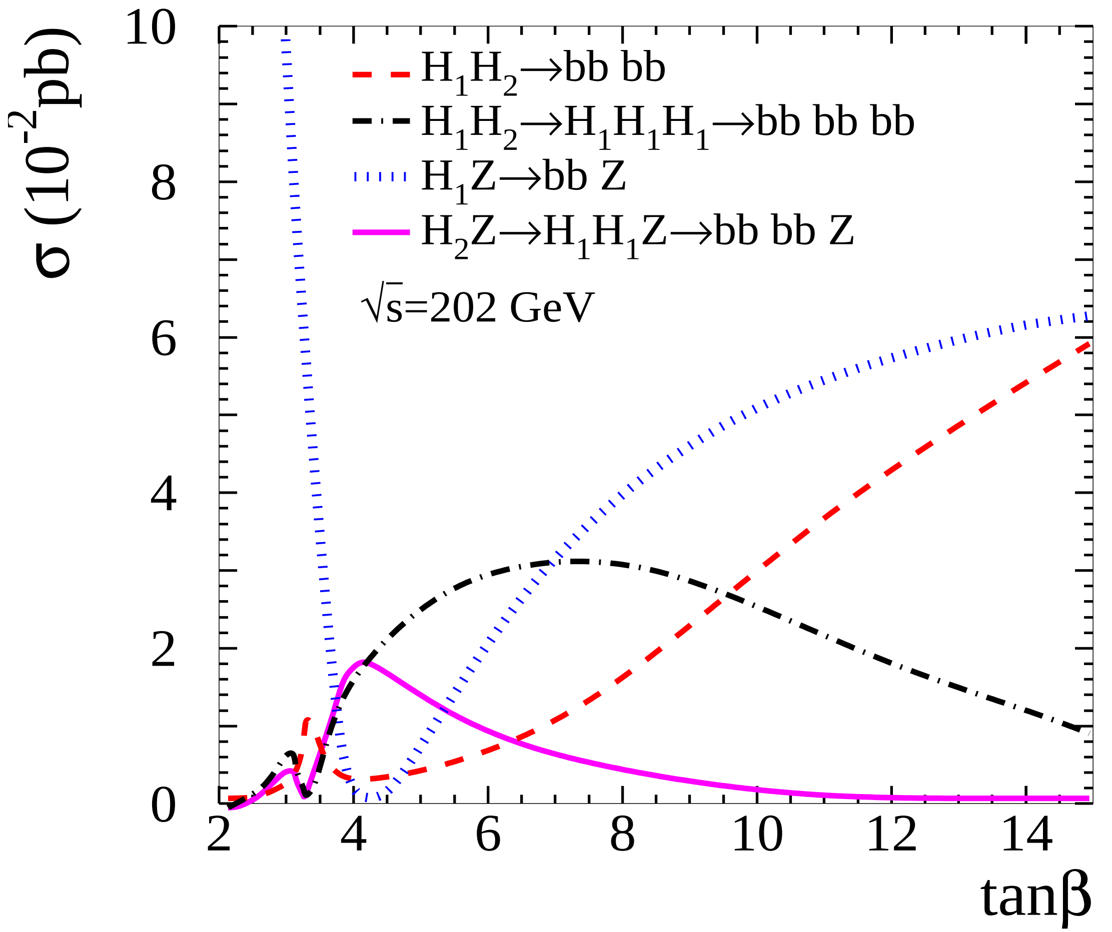
$$m_{h_3} > m_{h_2} > m_{h_1}$$

$\Rightarrow$ strong changes in Higgs couplings to SM gauge bosons and fermions

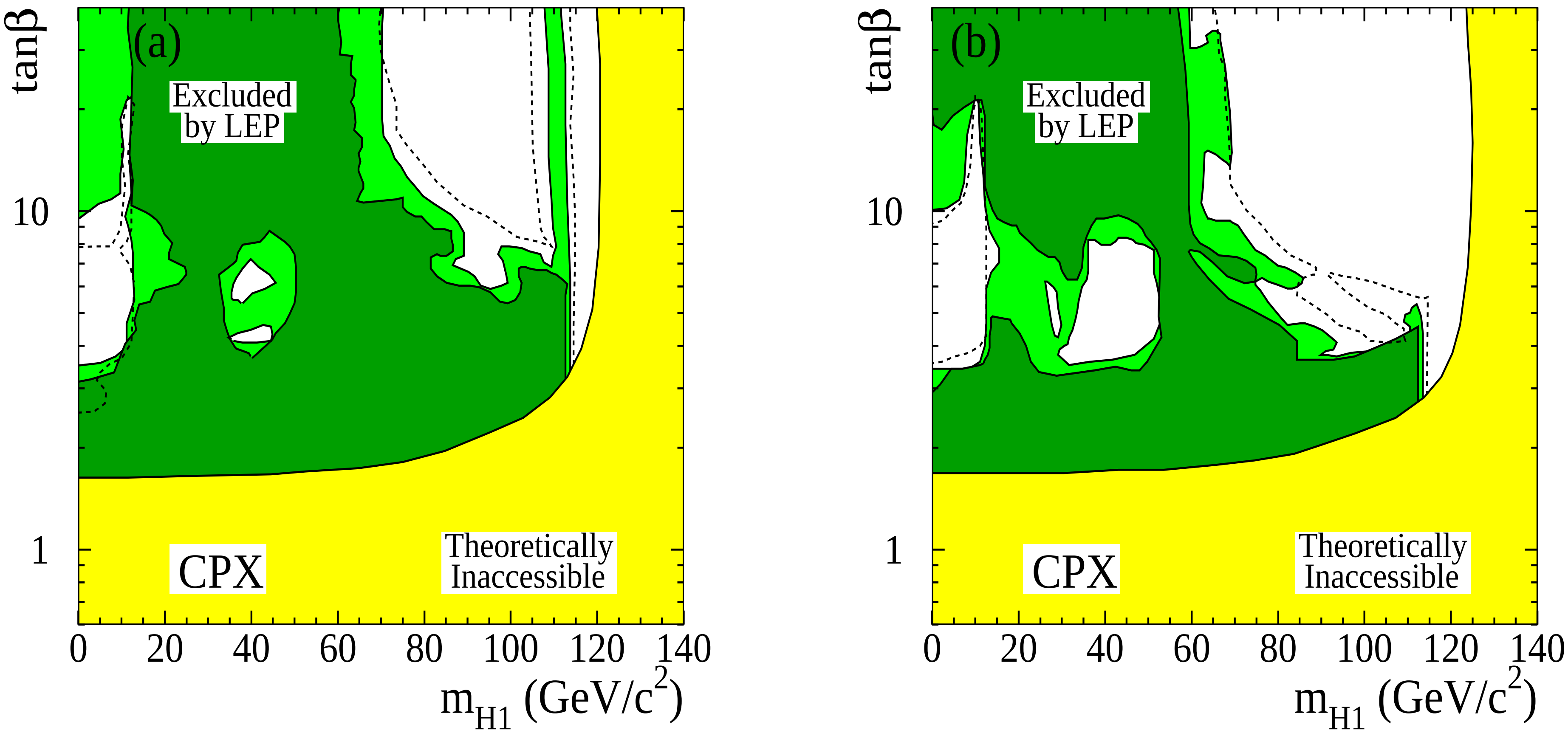
$\mathcal{CP}$V effects on Higgs boson searches:

CPX: benchmark scenario in the cMSSM
[*M. Carena, J. Ellis, A. Pilaftsis, C. Wagner '00*]

LEP Higgs production cross sections: [*LEPHiggsWG '06*]



$m_t = 169.3$ GeV $m_t = 174.3$ GeV



The LEP analysis showed an unexcluded hole in the m_{h_1}–$\tan\beta$ plane at $m_{h_1} \approx 45$ GeV, $\tan\beta \approx 8$

$\Rightarrow$ still persists

Complication II:
The NMSSM Higgs sector   (Z_3 invariant NMSSM)

MSSM Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = (\tilde{m}_1^2 + |\mu \quad |^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\mu \quad |^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2$$

Complication II:

The NMSSM Higgs sector (Z_3 invariant NMSSM)

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} \\
S &= v_s + S_R + I S_I
\end{aligned}
$$

$$
\begin{aligned}
V = & (\tilde{m}_1^2 + |\not{\mu}\lambda S|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\not{\mu}\lambda S|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
& + \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2 \\
& + |\lambda(\epsilon_{ab} H_1^a H_2^b) + \kappa S^2|^2 + m_S^2 |S|^2 + (\lambda A_\lambda (\epsilon_{ab} H_1^a H_2^b) S + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.})
\end{aligned}
$$

Free parameters:

$$\lambda,\ \kappa,\ A_\kappa,\ M_{H^\pm},\ \tan\beta,\ \mu_{\text{eff}} = \lambda v_s$$

Higgs spectrum:

$$\mathcal{CP}\text{−even} : h_1, h_2, h_3$$
$$\mathcal{CP}\text{−odd} : a_1, a_2$$
$$\text{charged} : H^+, H^-$$
$$\text{Goldstones} : G^0, G^+, G^-$$

Neutralinos:

$$\mu \to \mu_{\text{eff}}$$

compared to the MSSM: one singlino more

$$\to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0$$

Mass of the lightest $\mathcal{CP}$-even Higgs:

$$m^2_{h,\text{tree,NMSSM}} = m^2_{h,\text{tree,MSSM}} + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

Mass of the $\mathcal{CP}$-odd Higgs:

$$\text{MSSM}: M_A^2 = -m_{12}^2(\tan\beta + \cot\beta) = \mu B(\tan\beta + \cot\beta)$$

$$\text{NMSSM}: "M_A^2" = \mu_{\text{eff}} B_{\text{eff}}(\tan\beta + \cot\beta)$$

with $B_{\text{eff}} = A_\lambda + \kappa\, s,\ \mu_{\text{eff}} = \lambda\, s$ $\Rightarrow$ one very light a_1

Mass of the charged Higgs:

$$\text{MSSM}: M_{H^\pm}^2 = M_A^2 + M_W^2 = M_A^2 + \frac{1}{2} v^2 g^2$$

$$\text{NMSSM}: M_{H^\pm}^2 = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2 \right)$$

Mass of the lightest $\mathcal{CP}$-even Higgs:

$$m^2_{h,\text{tree,NMSSM}} = m^2_{h,\text{tree,MSSM}} + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

Mass of the $\mathcal{CP}$-odd Higgs:

$$\text{MSSM}: M_A^2 = -m_{12}^2(\tan\beta + \cot\beta) = \mu B(\tan\beta + \cot\beta)$$

$$\text{NMSSM}: \text{"}M_A^2\text{"} = \mu_{\text{eff}} B_{\text{eff}}(\tan\beta + \cot\beta)$$

with $B_{\text{eff}} = A_\lambda + \kappa\, s,\ \mu_{\text{eff}} = \lambda\, s$ $\Rightarrow$ one very light a_1

Mass of the charged Higgs:

$$\text{MSSM}: M_{H^\pm}^2 = M_A^2 + M_W^2 = M_A^2 + \frac{1}{2} v^2 g^2$$

$$\text{NMSSM}: M_{H^\pm}^2 = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2 \right)$$

$\Rightarrow M_{h_1}^{\text{MSSM,tree}} \le M_{h_1}^{\text{NMSSM,tree}}$, one light a_1, $M_{H^\pm}^{\text{MSSM,tree}} \ge M_{H^\pm}^{\text{NMSSM,tree}}$

4. What to look out for?

Two complementary methods for searches and limits:

1. obtain model independent limits on cross sections and branching ratios
   - What is interesting to look out for?
   - How to take the Higgs discovery into account?

2. obtain limits in representative benchmark scenarios
   - Which constraints should be taken into account?
   - Which not? And why?

⇒ some (representative?) examples

Possible interpretations of the observed signal:

- The light $\mathcal{CP}$-even MSSM Higgs with $M_h \sim 125.5$ GeV
- The heavy $\mathcal{CP}$-even MSSM Higgs with $M_H \sim 125.5$ GeV
- The light Higgs in the cMSSM with $M_{h_1} \sim 125.5$ GeV
- The second-lightest Higgs in the cMSSM with $M_{h_2} \sim 125.5$ GeV
- The lightest NMSSM Higgs with $M_{h_1} \sim 125.5$ GeV
- The second-lightest NMSSM Higgs with $M_{h_2} \sim 125.5$ GeV
- ...

$\Rightarrow$ each option has its own implications!

The Vanilla solution:
the discovery is interpreted as the light $\mathcal{CP}$-even Higgs

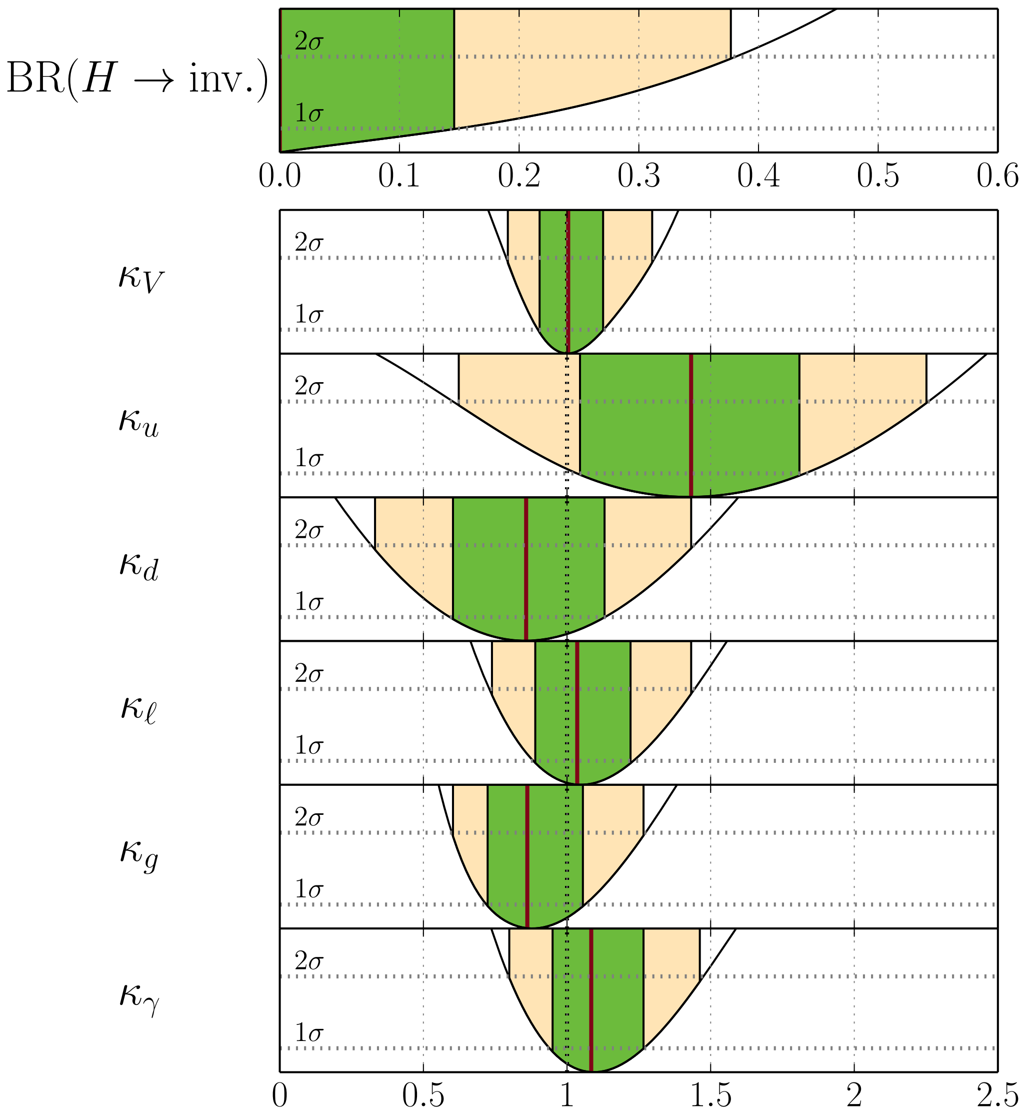
– measure its couplings, any deviation from the SM?

– search for additional heavier Higgs bosons
re-interpretation of SM Higgs searches?

– special issues for heavy Higgs phenomenology

– Higgs $\rightarrow$ SUSY decays?

– Higgs production from SUSY decays?



Very general model:

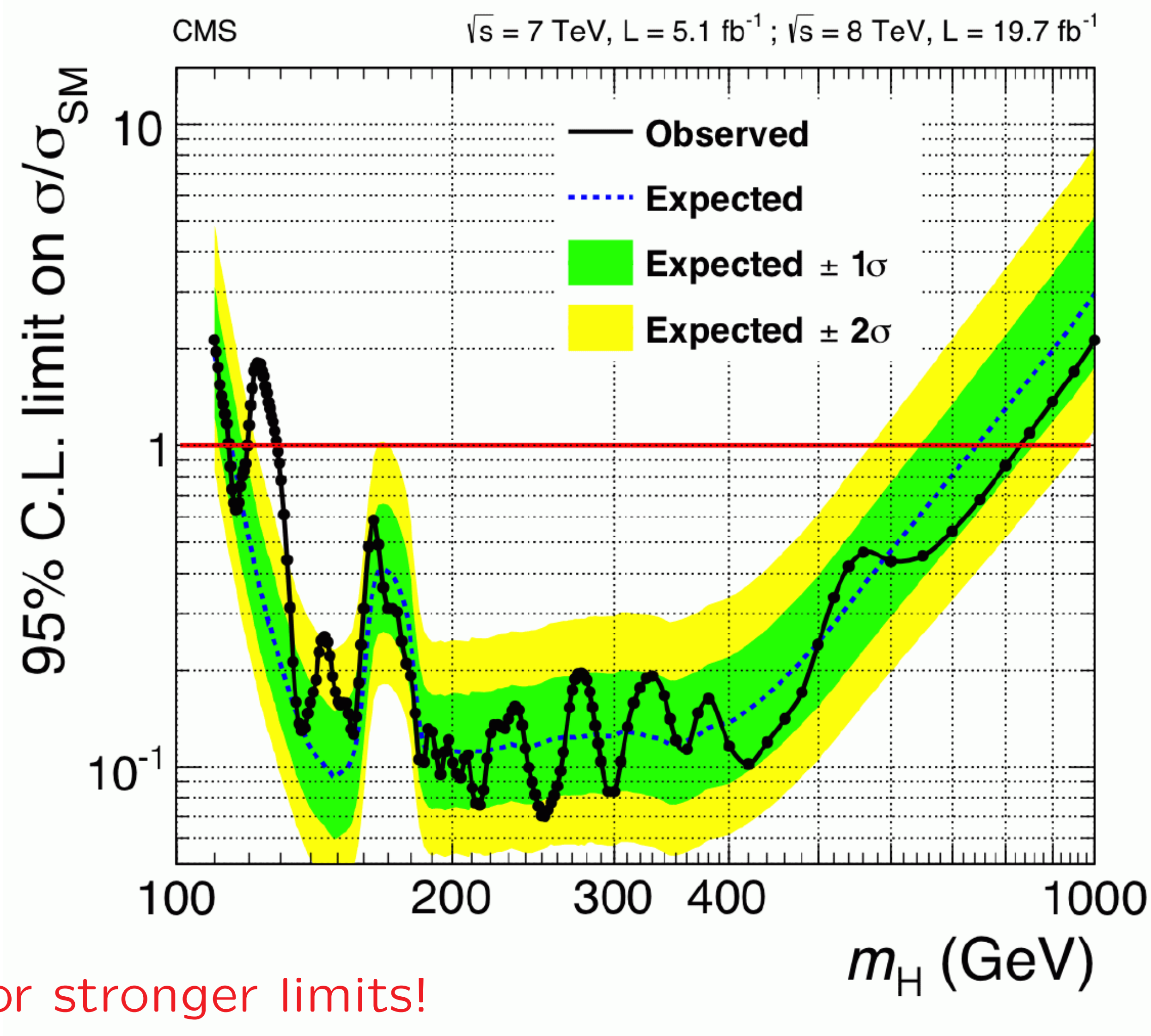
$\kappa_V, \kappa_u, \kappa_d, \kappa_l, \kappa_g, \kappa_\gamma$, BR($H \to$ inv.)

using HiggsSignals with
80 channels from
ATLAS, CMS, CDF, DØ

Re-interpretation of SM Higgs search results:

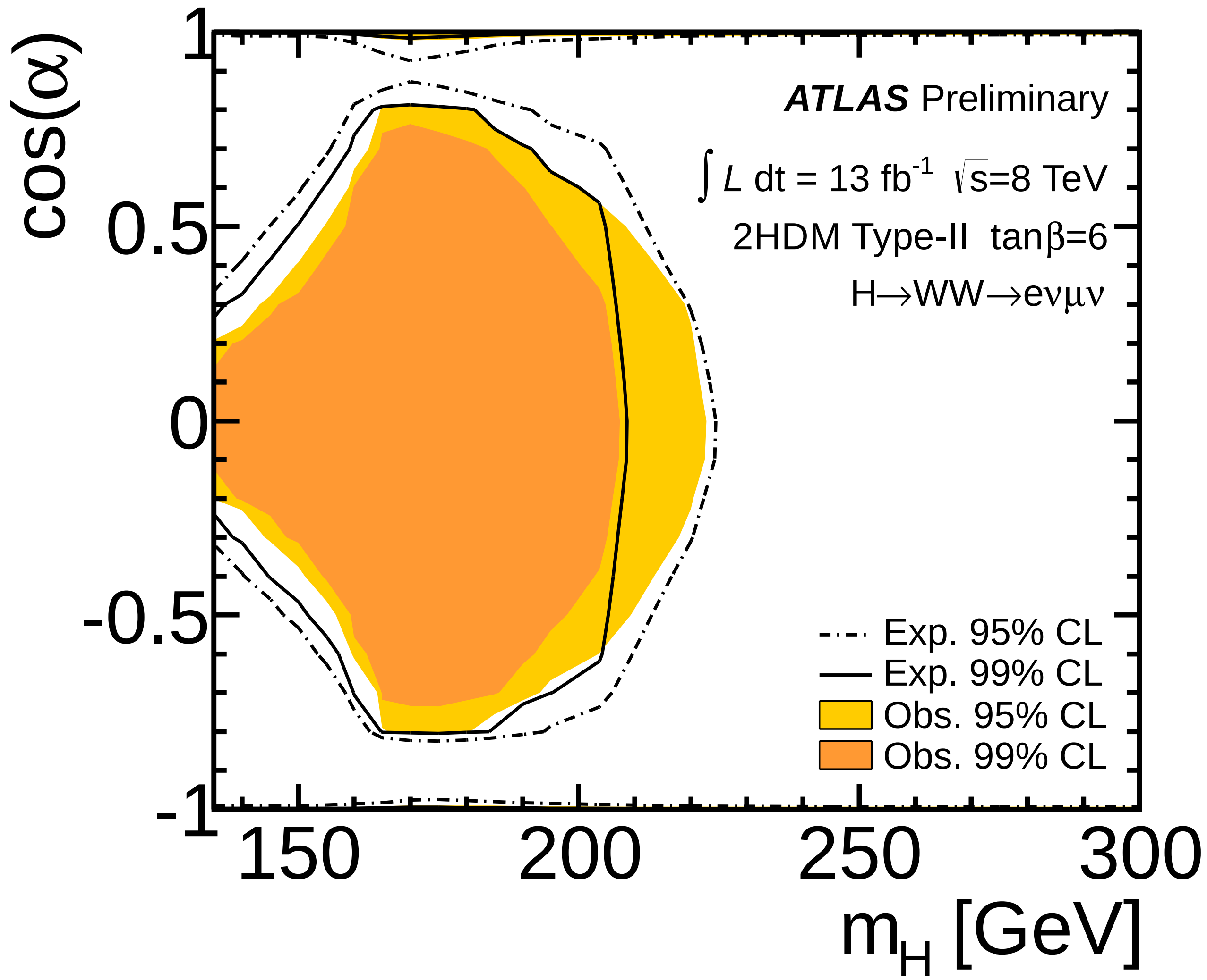
$g^2_{hVV} = \sin^2(\beta - \alpha)\, g^2_{HVV,\mathrm{SM}}, \quad g^2_{HVV} = \cos^2(\beta - \alpha)\, g^2_{HVV,\mathrm{SM}}$

$\Rightarrow$ some coupling strength could remain for the heavy Higgs



$\Rightarrow$ go ahead for stronger limits!

2HDM type II analysis by ATLAS, $H \to WW^{(*)}$ [ATLAS-CONF-2013-027]



⇒ analysis is most senstive in the parameter space,
where the model is least compatible with $M_h \sim 125.5$ GeV

Search (interpretation) in new benchmark scenarios:

[*M. Carena, S.H., O. Stål, C. Wagner, G. Weiglein, arXiv:1302:7033*]

⇒ designed to have $M_h \sim 125.5 \pm 3$ GeV
and to reproduce rate measurements

⇒ designed to exhibit certain features of Higgs phenomenology

– light Higgs phenomenlogy
– heavy Higgs phenomenology

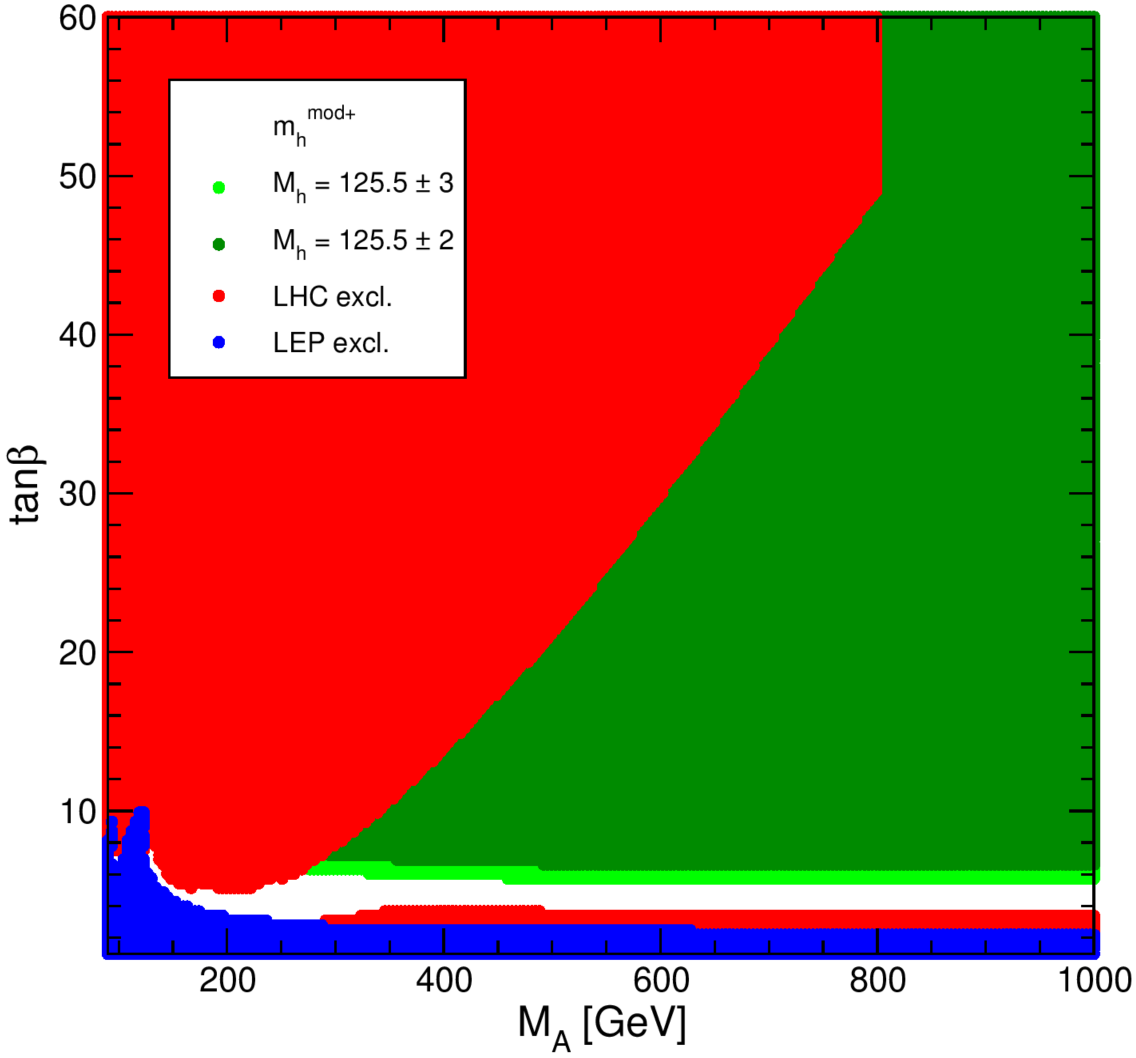
Not taken into account on purpose:

– Flavor contraints
– Precision observables
– Dark Matter
– ...

⇒ can all be avoided easily by small model modification
that do not change the Higgs phenomenology

⇒ do not overconstrain yourself!

$m_h^{\text{mod}+}$ scenario:

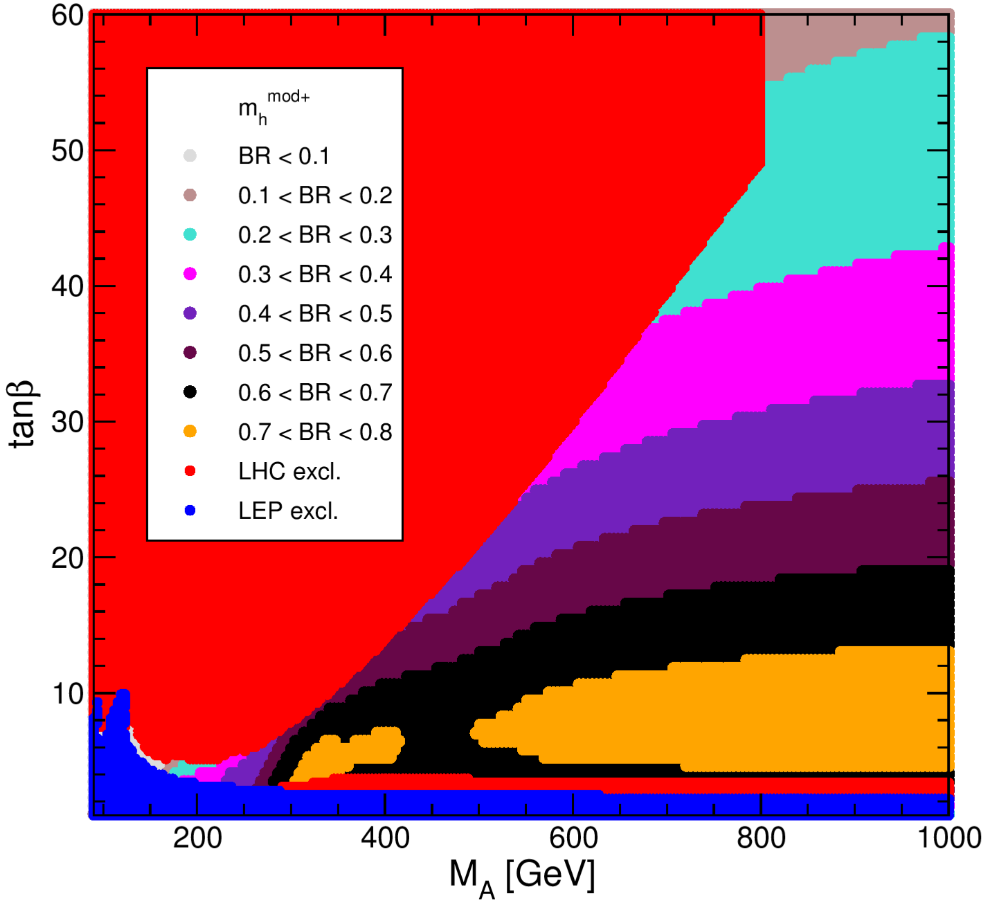


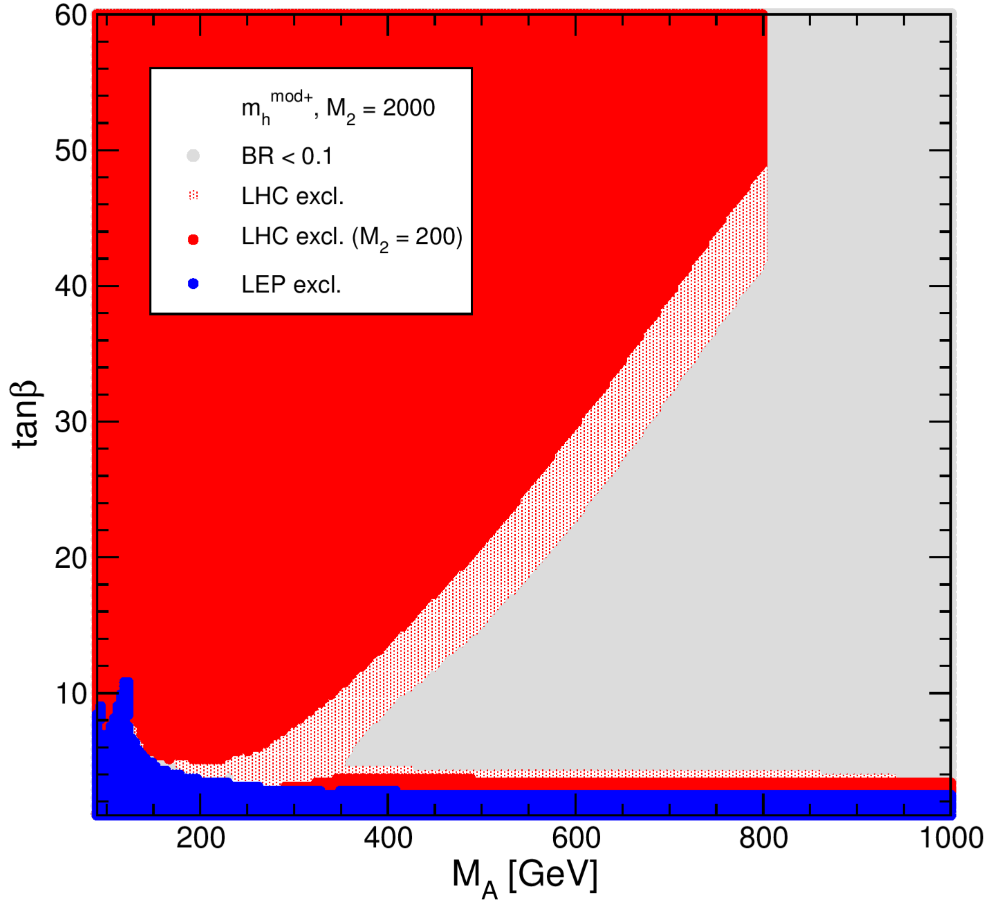
$$m_t = 173.2 \text{ GeV},$$
$$M_{\text{SUSY}} = 1000 \text{ GeV},$$
$$\mu = 200 \text{ GeV},$$
$$M_2 = 200 \text{ GeV},$$
$$X_t^{\text{OS}} = 1.5\, M_{\text{SUSY}}$$
$$A_b = A_\tau = A_t,$$
$$m_{\tilde{g}} = 1500 \text{ GeV},$$
$$M_{\tilde{l}_3} = 1000 \text{ GeV} \;.$$

$\Rightarrow M_h \approx 125.5$ GeV nearly "everywhere"

$m_h^{\text{mod}+}$ scenario:

$\Rightarrow$ effect of non-SM Higgs decays:





$\Rightarrow$ strong impact from $H/A \to \tilde{\chi}_i^0 \tilde{\chi}_j^0, \tilde{\chi}_k^{\pm} \tilde{\chi}_l^{\mp}$

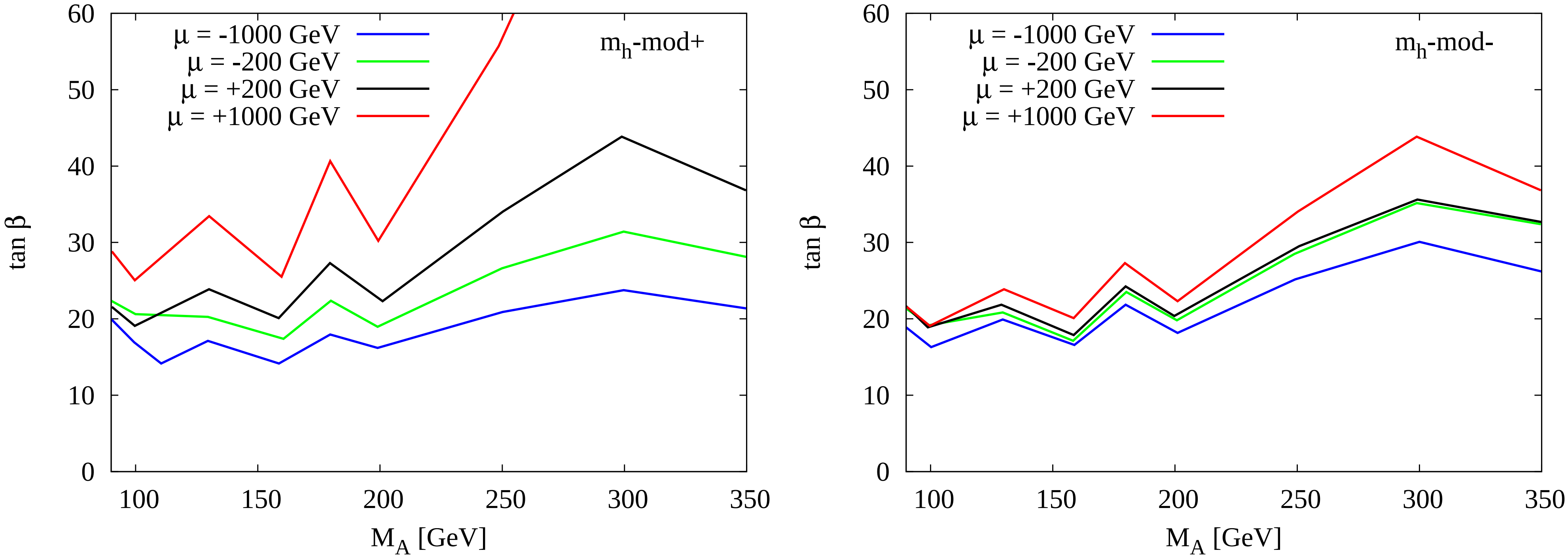
$\Rightarrow$ disover heavy Higgses and SUSY at the same time!

Δ_b effects on $b\bar{b} \to H/A \to b\bar{b}$:

$$\Delta_b = \frac{2\alpha_s}{3\,\pi}\, m_{\tilde{g}}\,\mu\,\tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\,\pi}\, A_t\,\mu\,\tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)$$

Additional factors wrt. the SM:

$$\sigma(b\bar{b}\,H/A) \times \mathrm{BR}(H/A \to b\bar{b}) \sim \frac{\tan\beta^2}{(1+\Delta_b)^2}$$

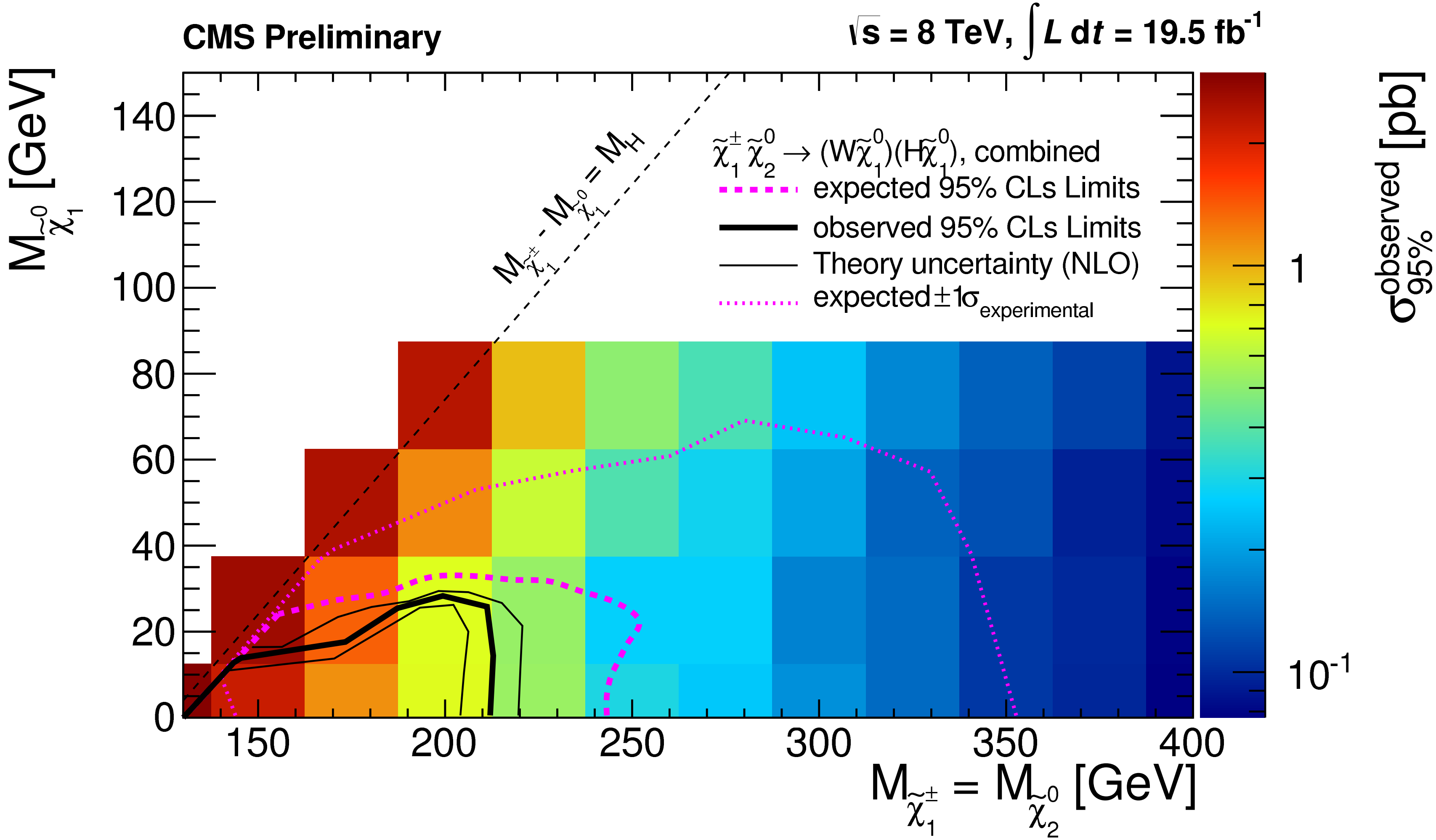


⇒ phenomenology can depend on “new” parameters!

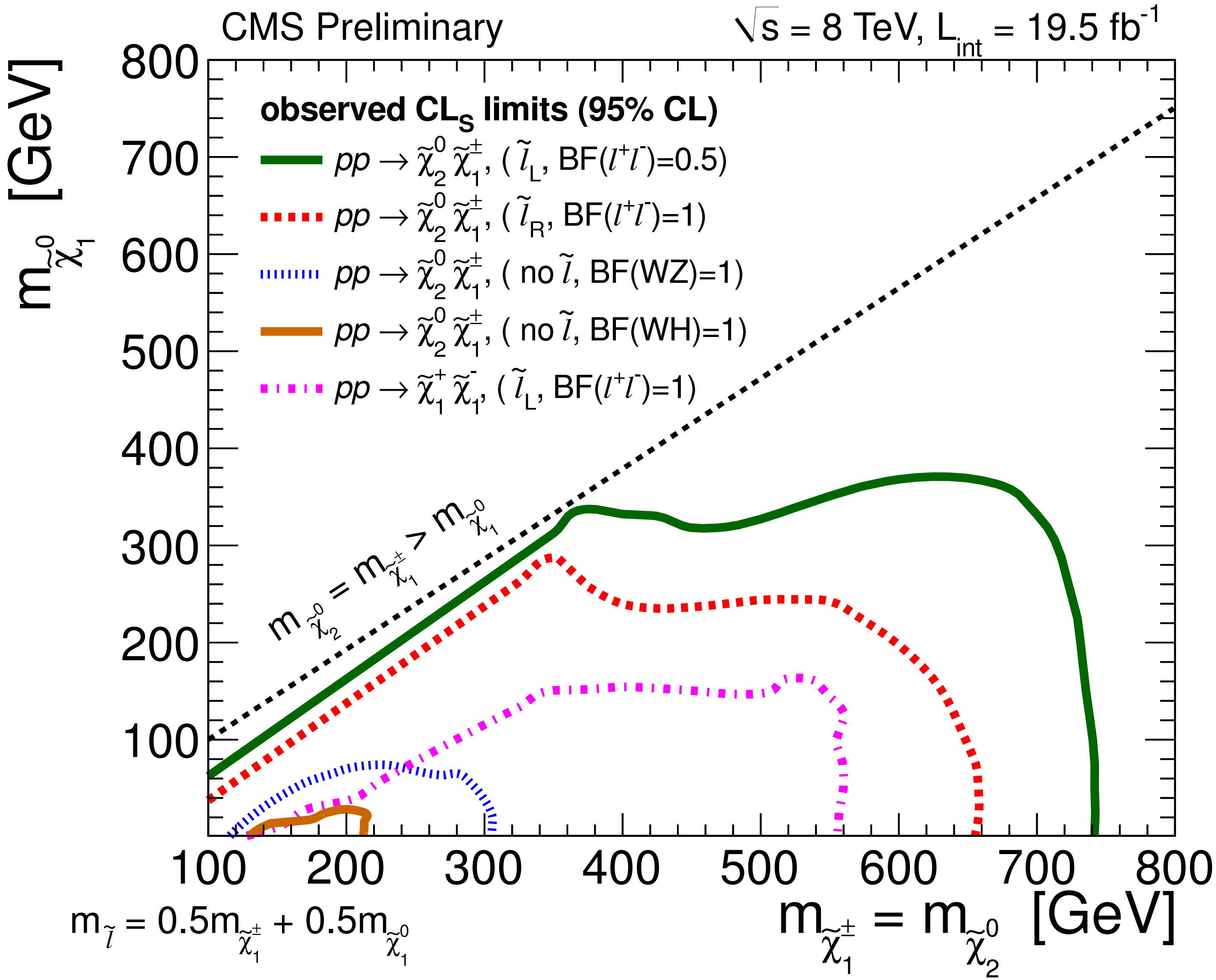
Higgs production from SUSY decays:

ATLAS and CMS are now also searching for

$$pp \to \tilde{\chi}_1^{\pm}\,\tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0\,\tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0\,h\tilde{\chi}_1^0 \to W^{\pm}\tilde{\chi}_1^0\,b\bar{b}\tilde{\chi}_1^0$$

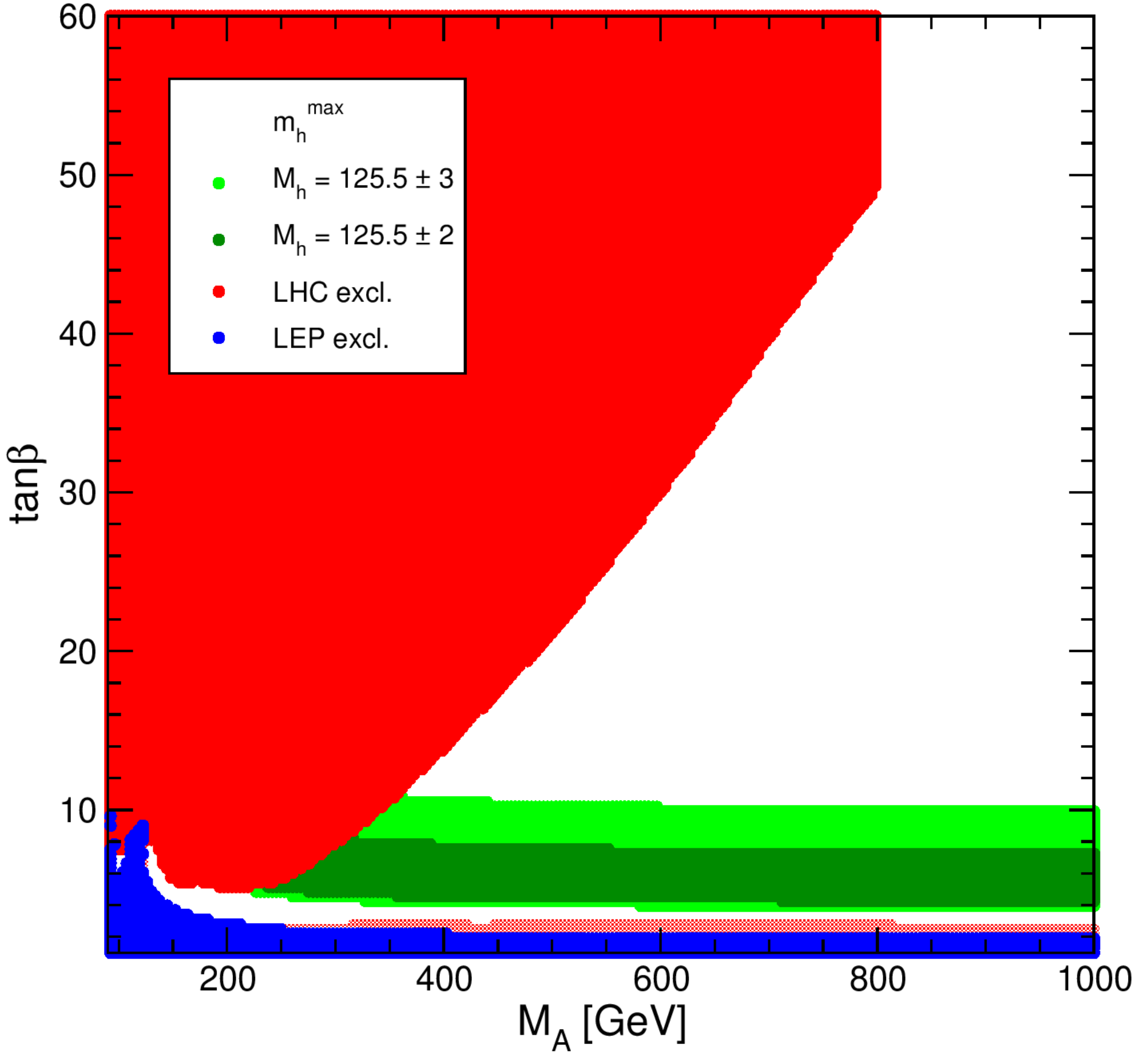


Exclusion bounds from $h \to b\bar{b}$:



⇒ rather small exclusion regions . . .

Phenomenology at very low $\tan\beta$: look at the $m_h^{\rm max}$ scenario:



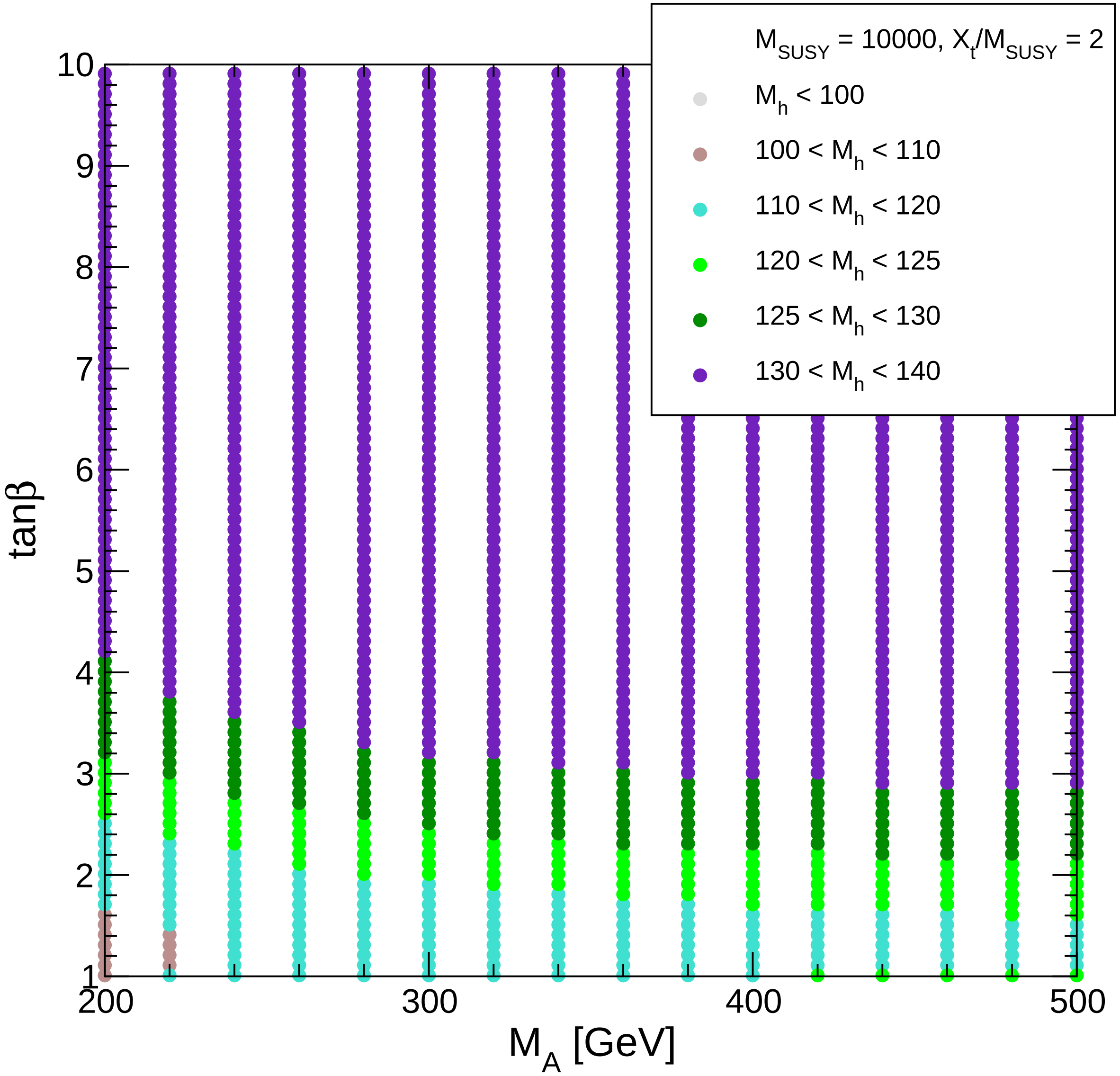
$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\rm SUSY} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\rm OS} &= 2\, M_{\rm SUSY} \\
A_b &= A_\tau = A_t, \\
m_{\tilde g} &= 1500 \text{ GeV}, \\
M_{\tilde l_3} &= 1000 \text{ GeV} \; .
\end{aligned}
$$

$\Rightarrow \tan\beta \gtrsim 4$ for $M_{\rm SUSY} \lesssim$ few TeV

But what happens for $M_{\rm SUSY} \gtrsim 10$ TeV?

Just one first example:

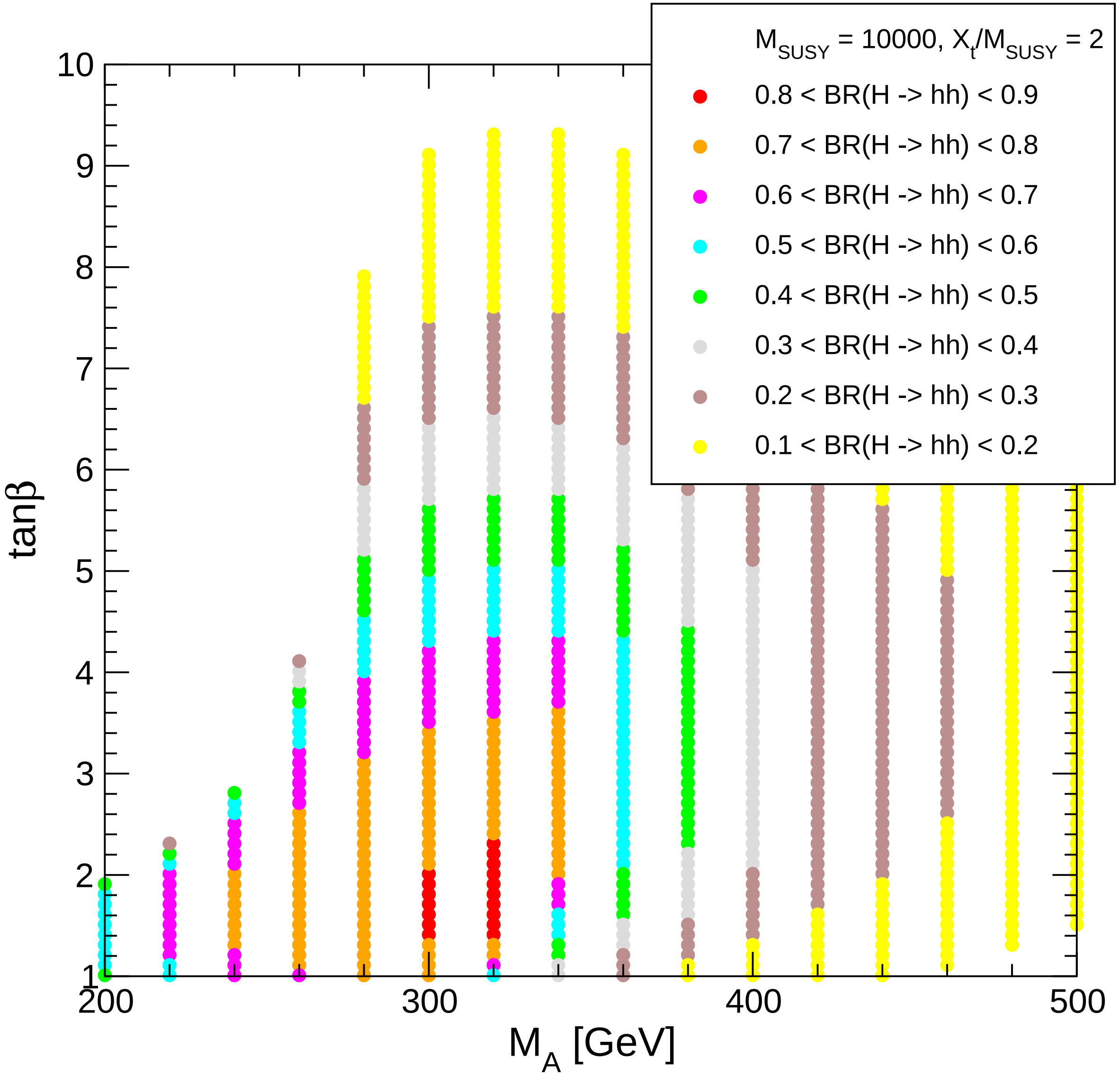
$M_{\rm SUSY} = m_{\tilde{g}} = 10$ TeV, $X_t/M_{\rm SUSY} = 2$, $M_2 = \mu = 1$ TeV



$\Rightarrow$ lower $\tan\beta$ values possible! Relevant? $\Rightarrow$ "new" relevant decay channels!

$\underline{H \to hh}$:

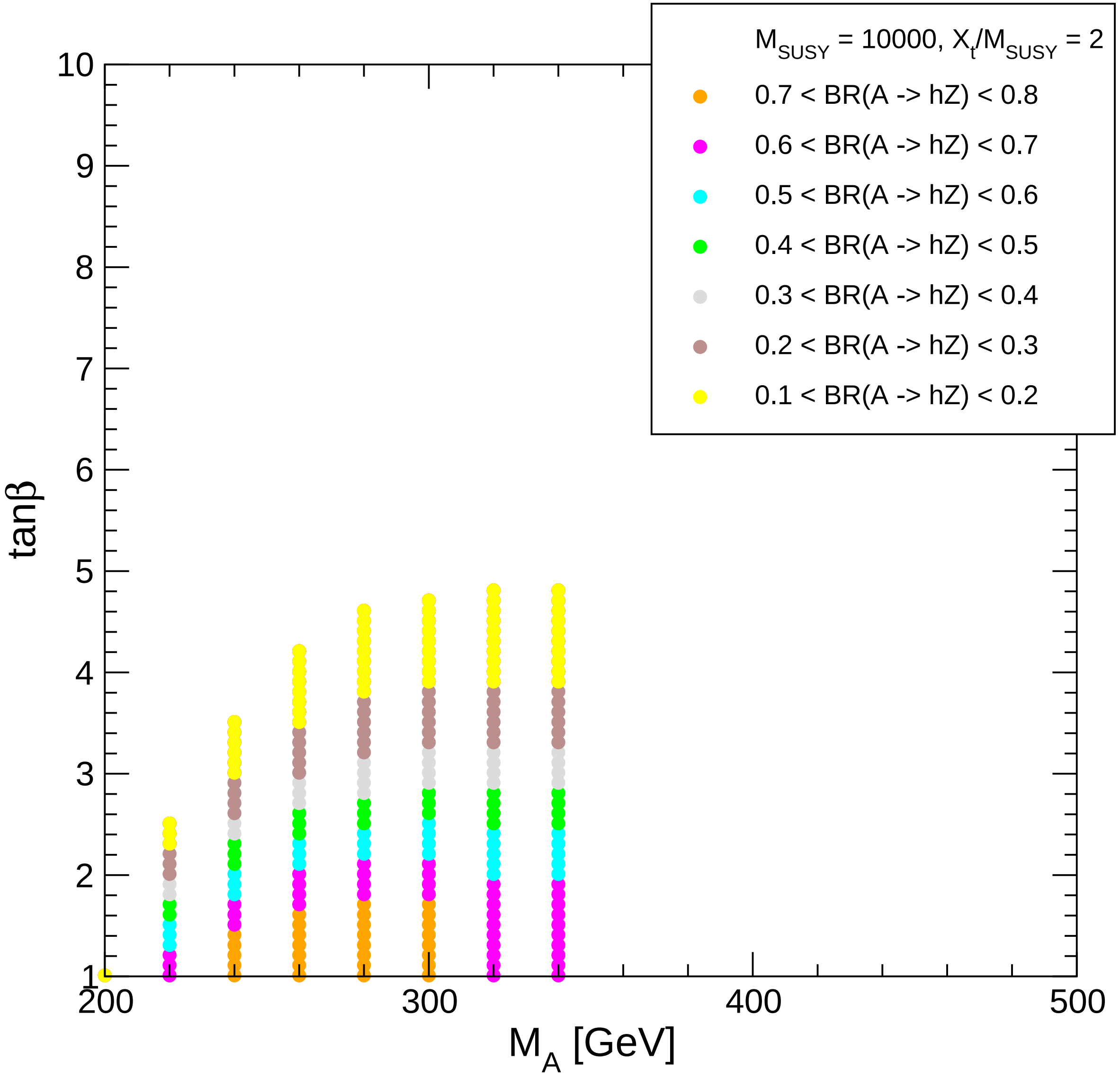
$M_{\rm SUSY} = m_{\tilde g} = 10$ TeV, $X_t/M_{\rm SUSY} = 2$, $M_2 = \mu = 1$ TeV



$\Rightarrow$ important at low $\tan\beta$ $\Rightarrow$ new benchmarks necessary . . .

$A \to hZ$:

$M_{\text{SUSY}} = m_{\tilde{g}} = 10$ TeV, $X_t/M_{\text{SUSY}} = 2$, $M_2 = \mu = 1$ TeV



$\Rightarrow$ important at low $\tan\beta$ $\Rightarrow$ new benchmarks necessary . . .

The "exotic" solution:
the discovery is interpreted as the heavy $\mathcal{CP}$-even Higgs

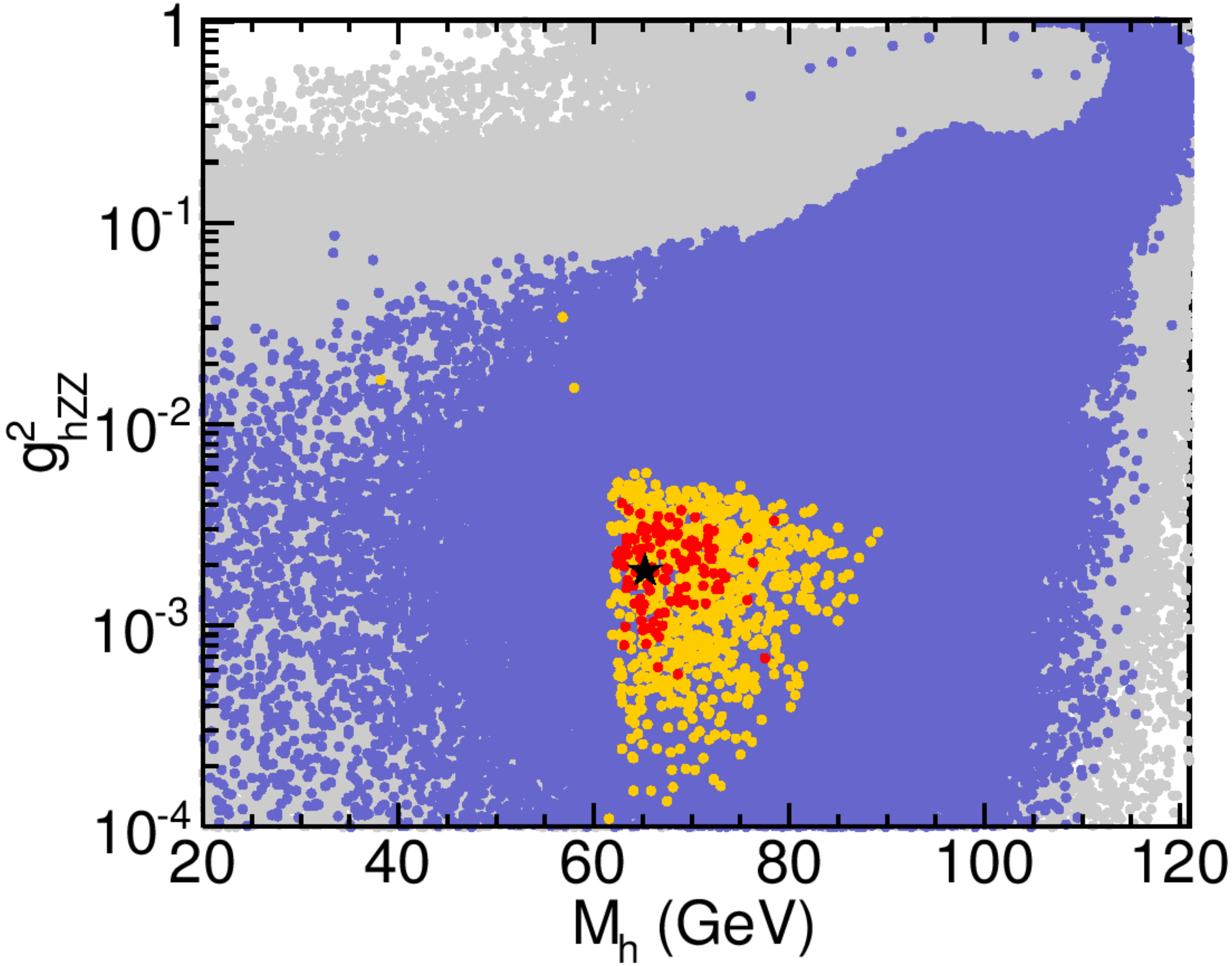
In principle also possilbe:

$$M_h < 125.5 \text{ GeV}$$
$$M_H \approx 125.5 \text{ GeV}$$

Consequences:
- all Higgs bosons very light
- easy(?) discovery of additional Higgs bosons at the LHC

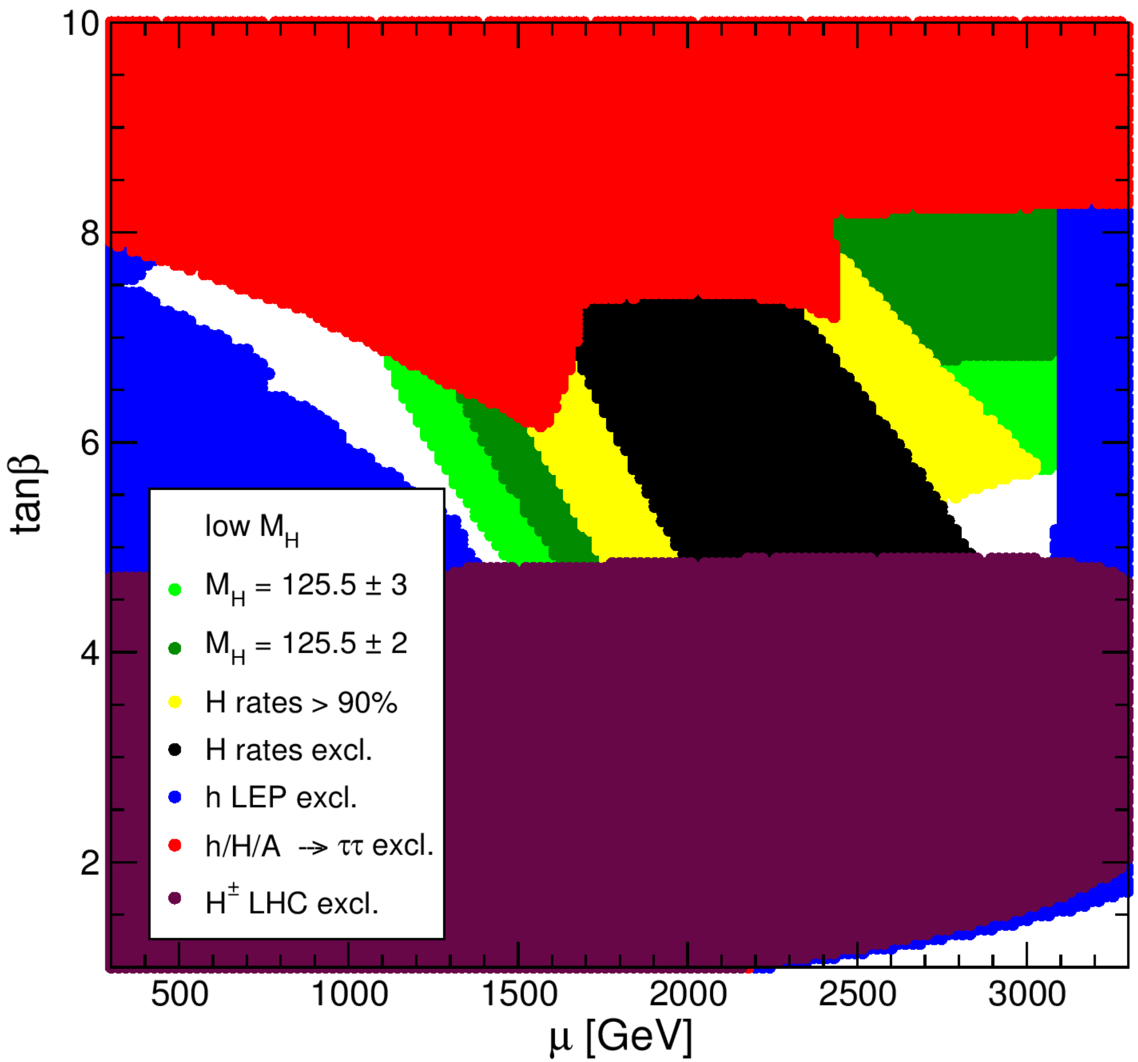
Constraints:
- direct searches for the lightest $\mathcal{CP}$-even Higgs
- direct searches for the heavy neutral Higgses
- direct searches for the charged Higgses
- flavor constraints (BR($B_s \to \mu^+\mu^-$) etc.)

Where is the light Higgs in the “heavy Higgs case”?



$\Rightarrow$ low M_h values, strongly reduced couplings

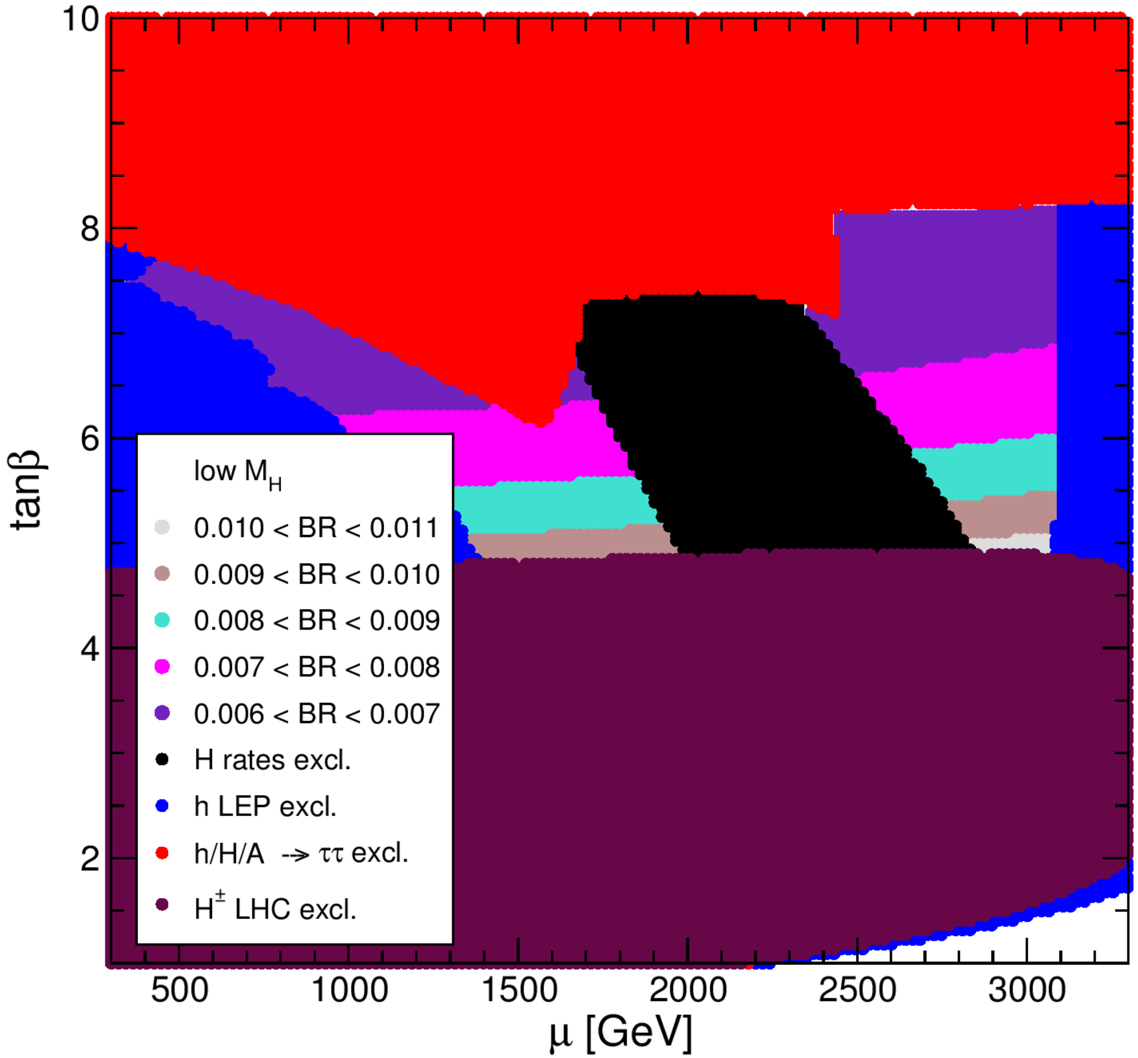
low-M_H scenario:



$$m_t = 173.2 \text{ GeV},$$
$$M_A = 110 \text{ GeV},$$
$$M_{\text{SUSY}} = 1500 \text{ GeV},$$
$$M_2 = 200 \text{ GeV},$$
$$X_t^{\text{OS}} 2.45 M_{\text{SUSY}}$$
$$A_b = A_\tau = A_t,$$
$$m_{\tilde{g}} = 1500 \text{ GeV},$$
$$M_{\tilde{l}_3} = 1000 \text{ GeV} .$$

$\Rightarrow M_H \approx 125.5$ GeV can in principle be realized

low-M_H scenario:



$$m_t = 173.2 \text{ GeV},$$
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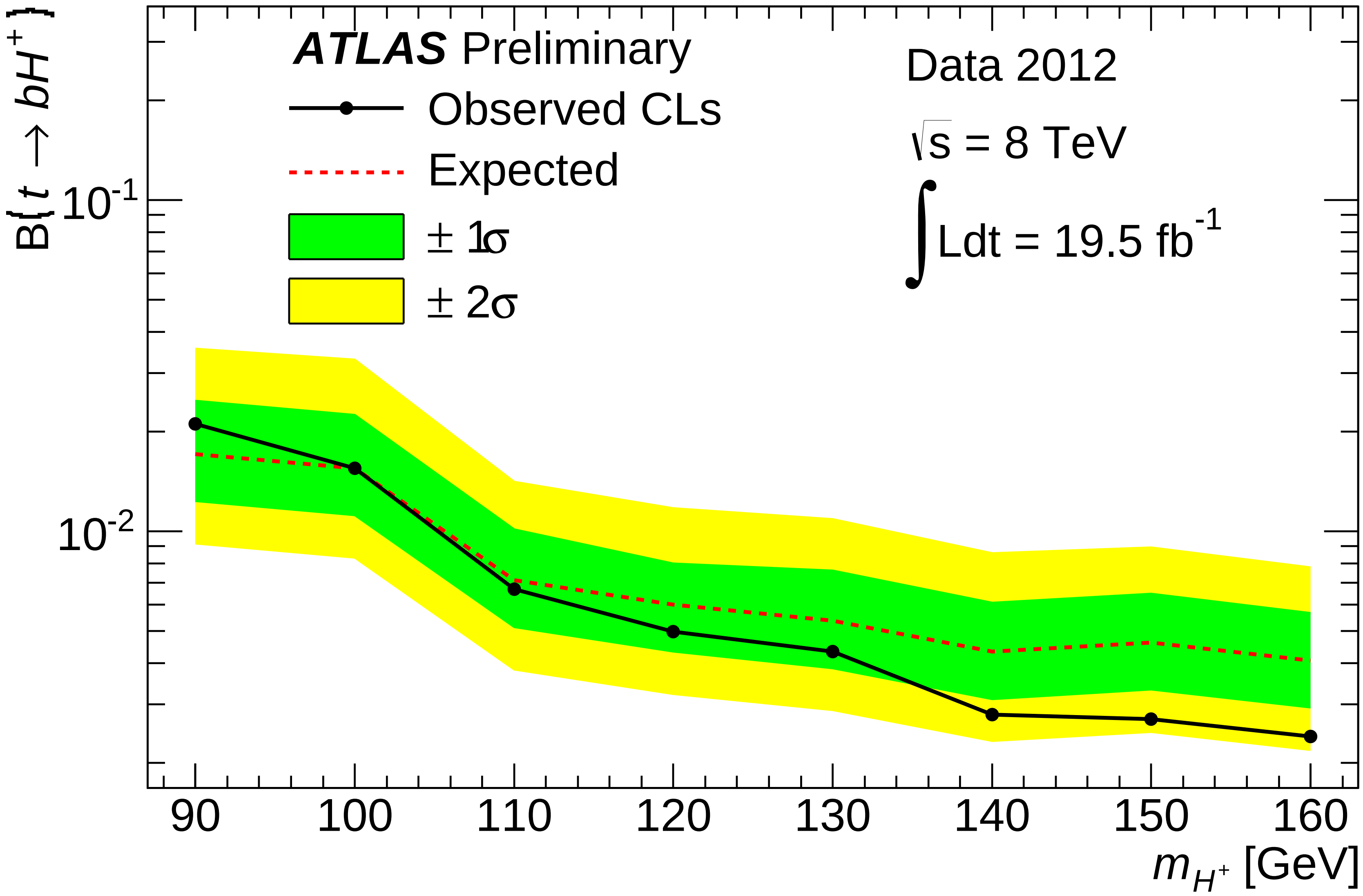
$$M_{\text{SUSY}} = 1500 \text{ GeV},$$
$$M_2 = 200 \text{ GeV},$$
$$X_t^{\text{OS}} 2.45 M_{\text{SUSY}}$$
$$A_b = A_\tau = A_t,$$
$$m_{\tilde{g}} = 1500 \text{ GeV},$$
$$M_{\tilde{l}_3} = 1000 \text{ GeV} .$$

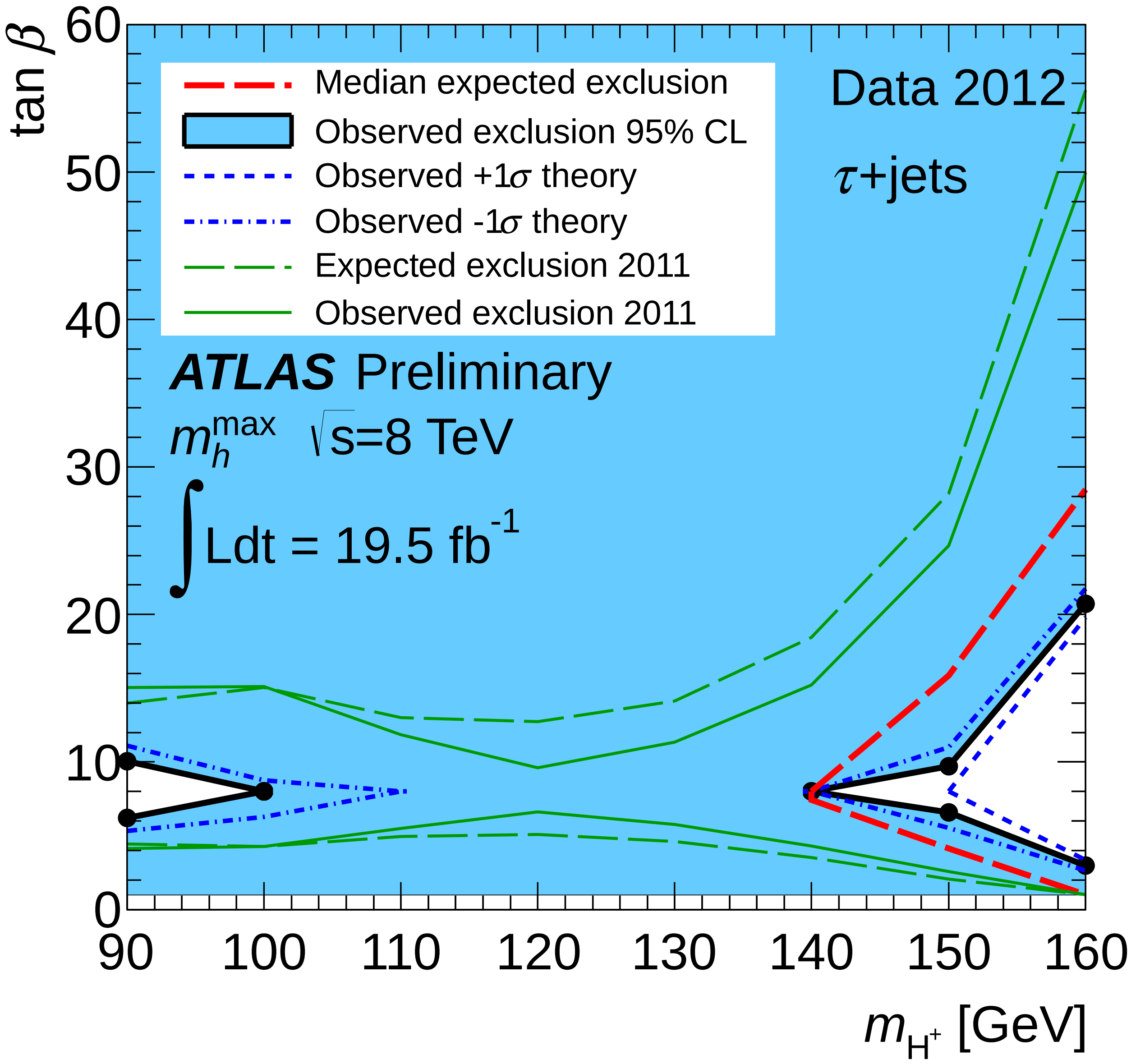
⇒ Interesting prospects also for the charged Higgs searches

Latest ATLAS results for charged Higgs searches: [ATLAS '13]



⇒ model independent limits!

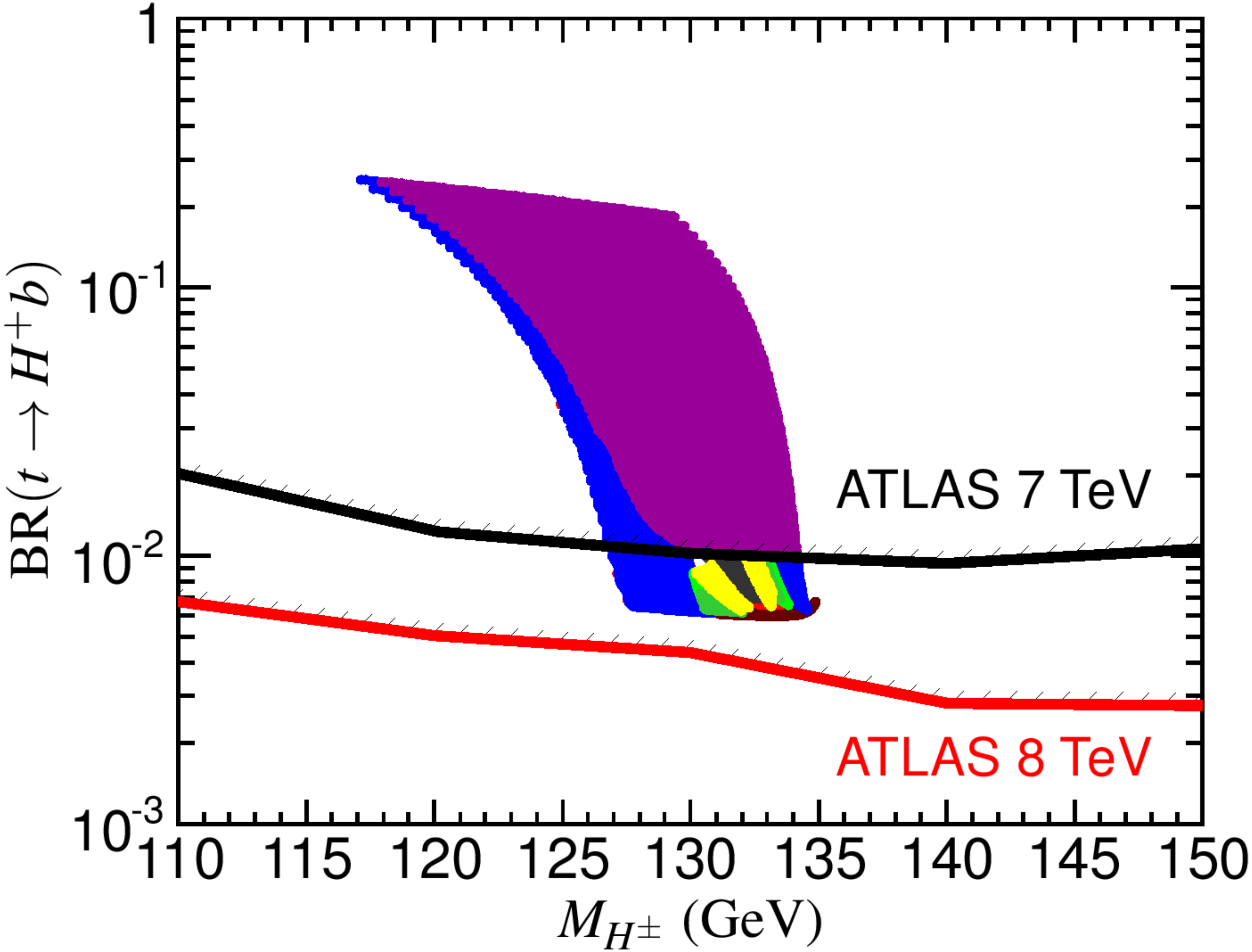
Latest ATLAS results for charged Higgs searches: [ATLAS '13]



$\Rightarrow$ exclusion of light $M_{H^\pm}$ in the m_h^{max} scenario! . . . low-M_H?

Application of charged Higgs limits on low-M_H scenario:

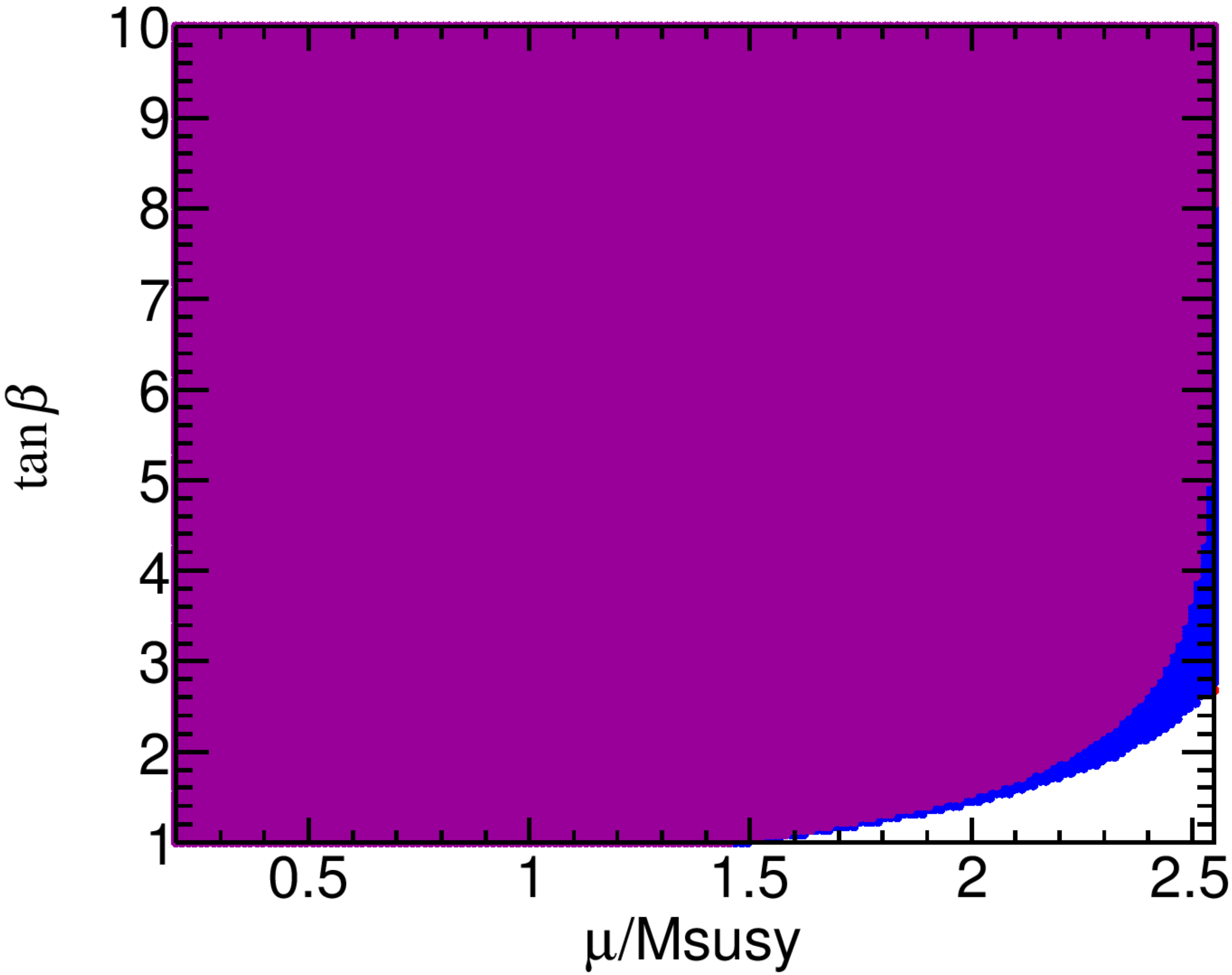
[*HiggsBounds 4.1*]



$\Rightarrow$ that (particular incarnation of the) low-M_H scenario is excluded?

Application of charged Higgs limits on low-M_H scenario:

[*HiggsBounds 4.1*]



$\Rightarrow$ that (particular incarnation of the) low-M_H scenario is excluded?

The general possibility:
the discovered Higgs is the second-lightest one

– more contrived in the MSSM with real parameters

– "easier" (?) possible in the MSSM with complex parameters

– "easier" (!) possible in the NMSSM
$\Rightarrow$ light Higgs can be singlet like
can more easily escape detection

Is such a light Higgs detectable at the LHC?

– $h_2 \to h_1 h_1$ possible, but strongly suppressed for $M_{h_1} \gtrsim 63$ GeV
– so far no LHC searches for a Higgs with $M_{h_1} \lesssim 100$ GeV
– Possible: SUSY $\to$ SUSY h_1 , e.g. $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h_1$

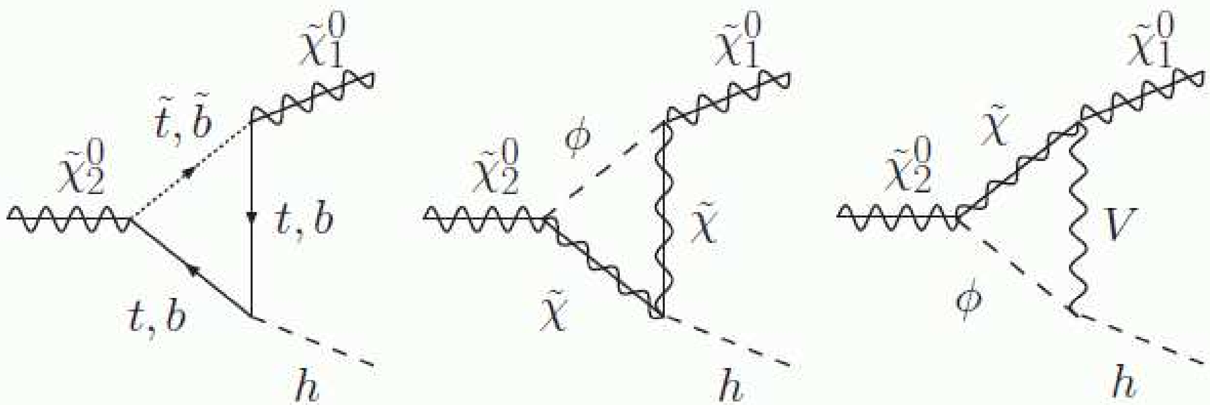
Higgs production in SUSY cascade decays

SUSY cascade decays could be a promising Higgs source

E.g. $\mathcal{CP}$-violating scenario: very light Higgs, $M_{h_1} \approx 40$ GeV not excluded by LEP, difficult to cover with standard search channels at the LHC

$\Rightarrow$ $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h$ can dominate over $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 l\bar{l}$

[*A. Fowler, G. W. '09*]



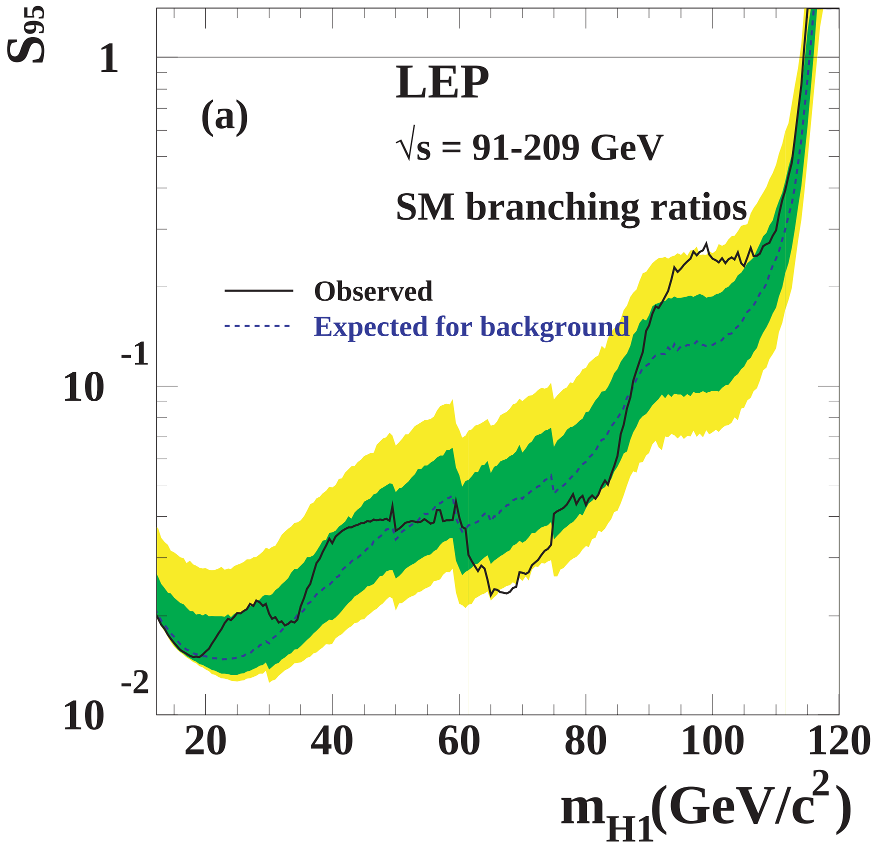
$\Rightarrow$ CPX scenario: 13% of the gluinos decay into h_1

SUSY Higgs Production and Decays at the LHC, Georg Weiglein, Higgs Days at Santander 2010, Santander, 10 / 2010 – p.27

LHC Higgs searches below 100 GeV:

– crucial to cover extended Higgs sectors

– needed to re-check LEP exclusions ($\sim 2.x\,\sigma$ "excess" around 98 GeV)



Best channel? $h_1 \to \gamma\gamma$??

You tell me!

$\Rightarrow$ we cannot encourage you enough to perform this search!

5. Conclusinos

- LHC: **we have a HIGGS DISCOVERY !!!** $\Rightarrow M_H \simeq 125.1 \pm 0.2$ GeV
- It is impossible that it is SM Higgs
  Impact of BSM physics on Higgs sector??
  – impact on couplings of the discovered Higgs
  – search for additional Higgs bosons

- Implications in the rMSSM, cMSSM, NMSSM

- The discovered Higgs could be the lightest or second-lightest Higgs of each model $\Rightarrow$ various, different implications

- Searches/interpretation via
  – general limits
  – benchmark scenarios
  $\Rightarrow$ always take into account the discovery (mass, properties)

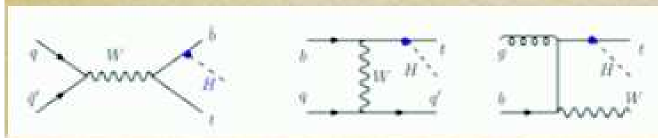
- rMSSM, $M_H \sim 125$ GeV: disfavored by charged Higgs searches
  but well possible in other models
  $\Rightarrow$ search for new states above and below 125 GeV

Back-up

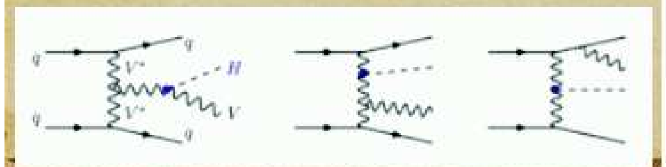
Additional Higgs decay modes?

(taken from *[R. Tanaka, talk at ATLAS HSG1 meeting]*)

- Surveyed [H, qqH, VH], [ttH/bbH/ccH], [tH+V/q], [HH, qqHH, VHH, HHH], [VVH], [qqHV].
- Perhaps we are not missing important process.
- bq→tHq' (14% of ttH) generated in HSG8 for $k_F=\pm1$.



- qq→HWqq (2% of VBF, 5% of WH) interest for HL-LHC to measure Y_b.



A. Djouadi, Physics Reports 457 (2008) 1

Class	14 TeV MH=125GeV		
I	Major production processes at LHC (H, qqH, VH)		
	gg→ggF	60.35 pb *	
	qq→VBF	4.172 pb *	
	qq→WH	1.504 pb *	
	qq→ZH	0.883 pb *	
II	Associated Higgs production with heavy quarks (ffH)		
	gg/qq→bbH	0.8-0.9 pb	A. Djouadi, Phys. Rep. 457 (2008), Fig. 3.30
	gg/qq→ttH	0.611 pb *	
	gg/qq→ccH	O(100fb)	ccH should be about 1/9 of bbH due to Yukawa and PDF
III	Associated Higgs production with a single top quark (TH+V/HF)		
	bq→tHq'	88.2 fb	M. Farina et al. JHEP 05 (2013) 022, Table 2
	bg→WtH	~20 fb	F. Maltoni et al., Phys. Rev. D 64 (2001) 094023, Fig. 4
	qq→btH	~2-3 fb	idem.
IV	Higgs boson pair/triple production (HH, qqHH, VHH, HHH)		
	gg→HH	33.86 fb *	
	qq→HH	<0.1 fb	D. Dicus, Z. Phys. C 39 (1988) 583, Fig. 2 @17TeV
	gg/qq→ttHH	~1 fb	F. Gianotti et al., Eur. Phys. J. C 39 (2005) 293, Table 7 by C. G. Papadopoulos
	qq→qqHH	1.807 fb *	
	qq→WHH	0.43 fb *	
	qq→ZHH	0.27 fb *	
	gg→HHH	0.044 fb *	
V	Higgs production in association with gauge bosons (VVHH)		
	qq→WWH	~8-9 fb	A. Djouadi, Phys. Rep. 457 (2008), Fig. 3.42
	qq→ZZH	~2 fb	pT_γ>10GeV, |y_γ|<2.5
	qq→WZH	~3-4 fb	
	qq→γZH	~3-4 fb	
	qq→γWH	~5 fb	
VI	Higgs production in association with a gauge boson and two jets (HVqq)		
	qq→HWqq	78 fb	D. Rainwater, Phys. Lett. B 503 (2001) 320, Table 1 → 5% of WH !?
	qq→HZqq	-	
	qq→Hγqq	-	
VII	Rare processes		
	qq→Hγ	O(1fb)	A. Djouadi, Phys. Rep. 457 (2008), Section 3.6.3.1 (gg→Hγ forbidden by Furry's theorem)
	t→cH	BR~4E-14	B. Mele, S. Petrarca, A. Soddu, Phys. Lett. B 435 (1998) 401, Table 1
	Diffractive	?	

* https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy

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Some numerical results

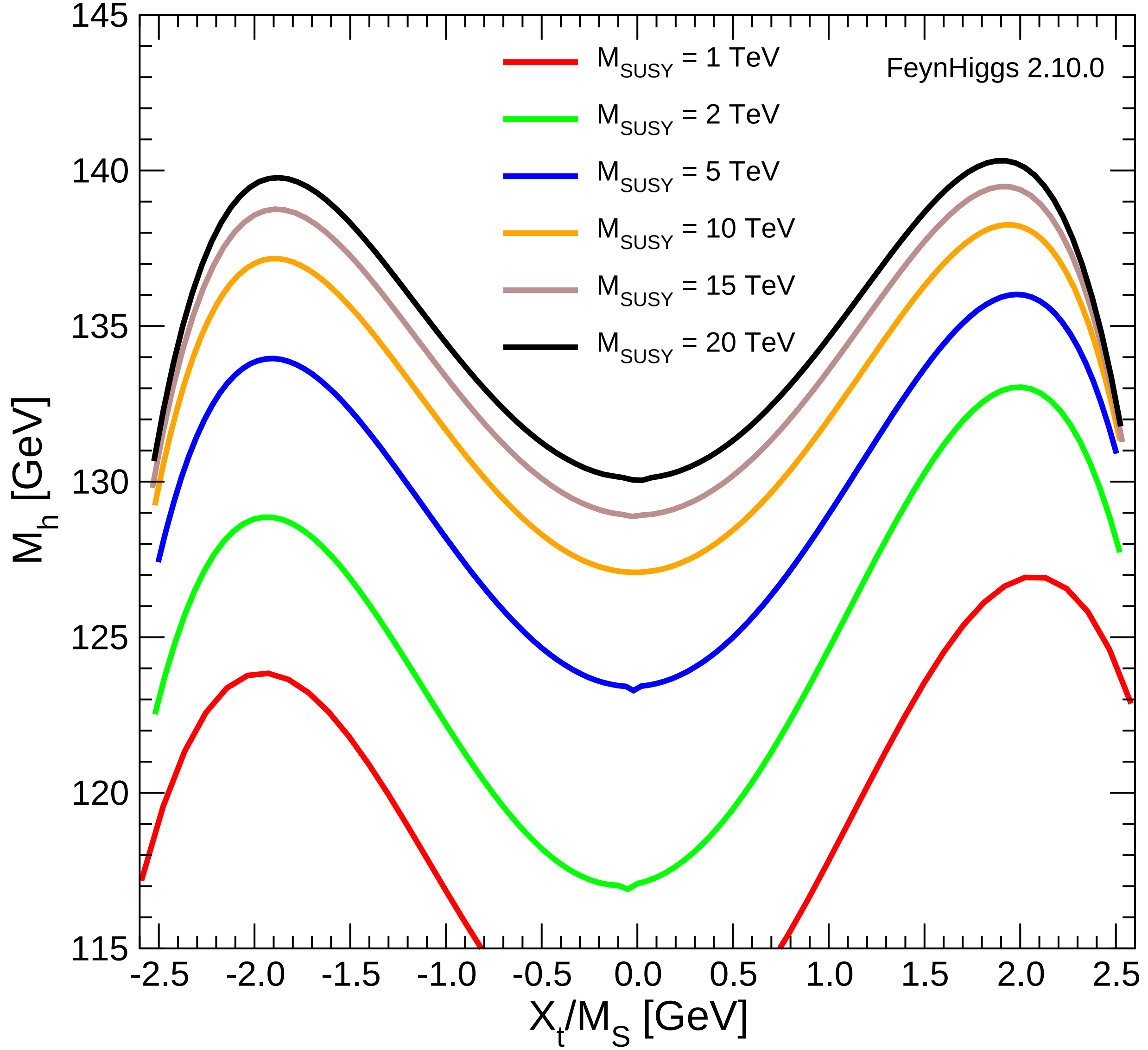
[*FeynHiggs 2.10.0*]

Parameters:

$$M_{\mathrm{S}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$
$$M_A = 1000 \text{ GeV}$$
$$\mu = 1000 \text{ GeV}$$
$$M_2 = 1000 \text{ GeV}$$
$$m_{\tilde{g}} = 1600 \text{ GeV}$$
$$\tan\beta = 10$$

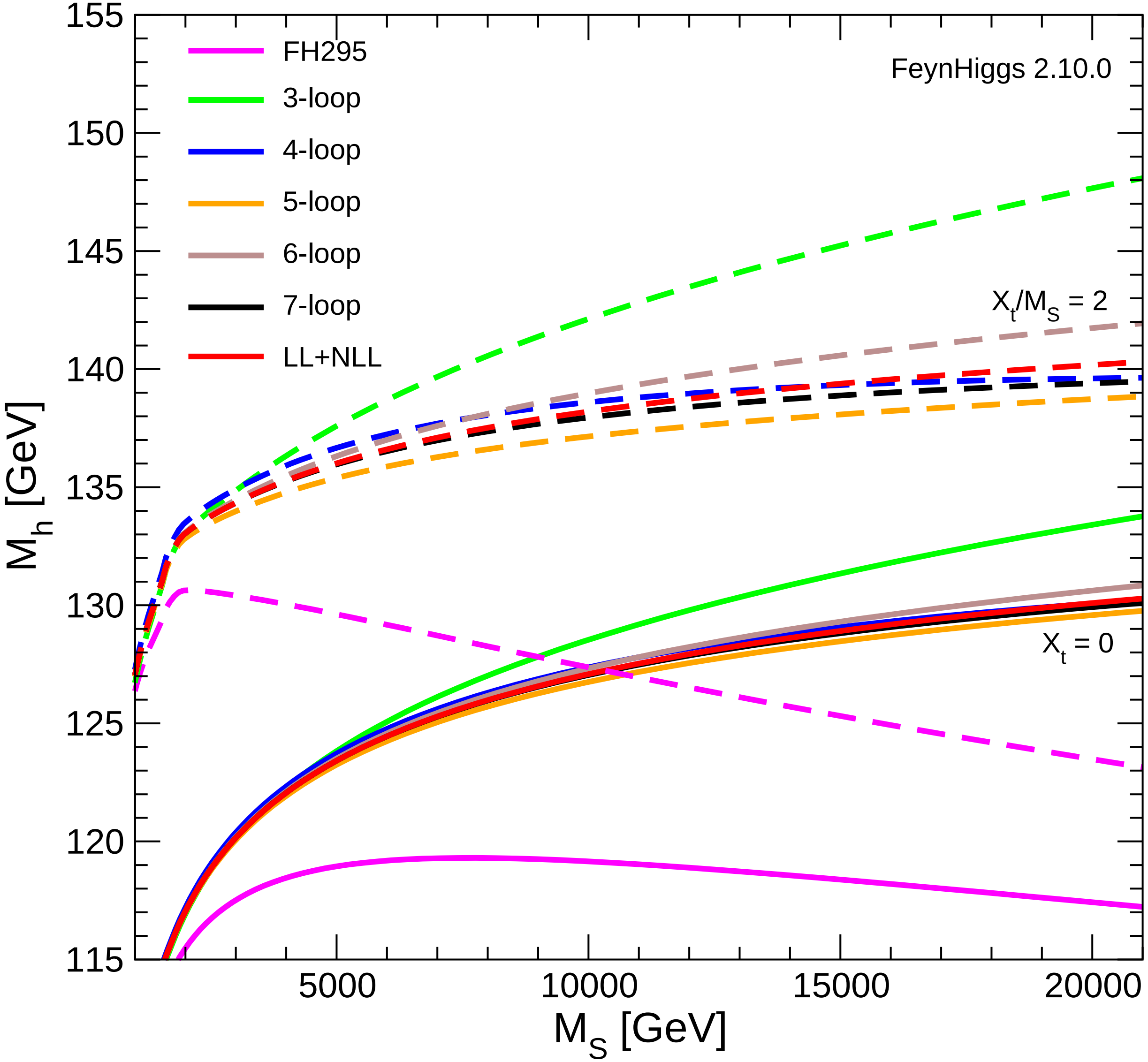
Vary M_{S}, X_t to analyze effects

$M_h(X_t/M_S)$: [*FeynHiggs 2.10.0*]



$\Rightarrow$ increase with M_S, maxima at $X_t/M_S = \pm 2$

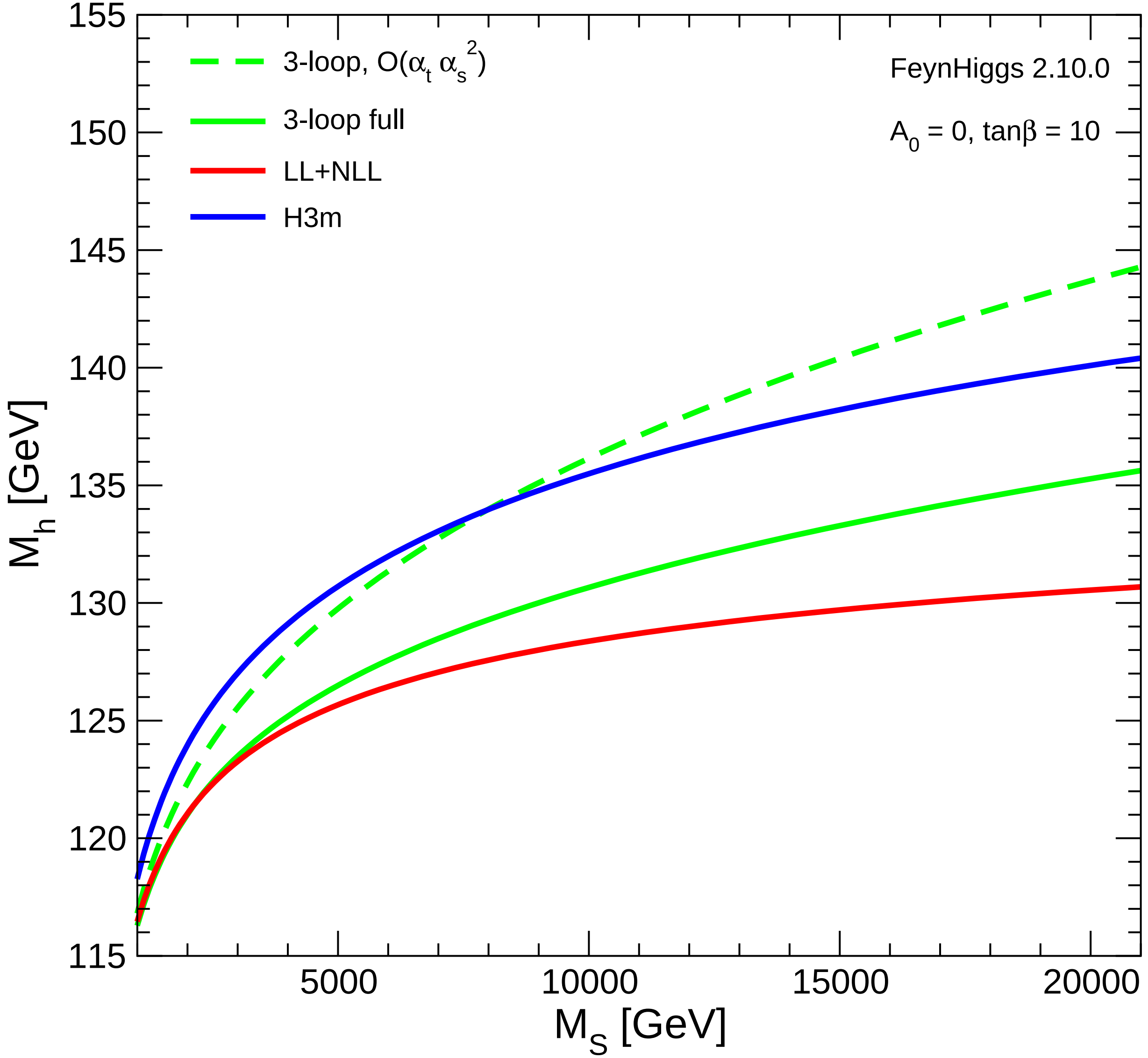
$M_h(M_S)$ for various approximations: [*FeynHiggs 2.10.0*]



$\Rightarrow$ 3-loop good for $M_S \lesssim 2$ TeV, 7-loop: $\Delta \sim 1$ GeV for $M_S = 20$ TeV

$M_h(M_S)$ compared with H3m:

[FeynHiggs 2.10.0]



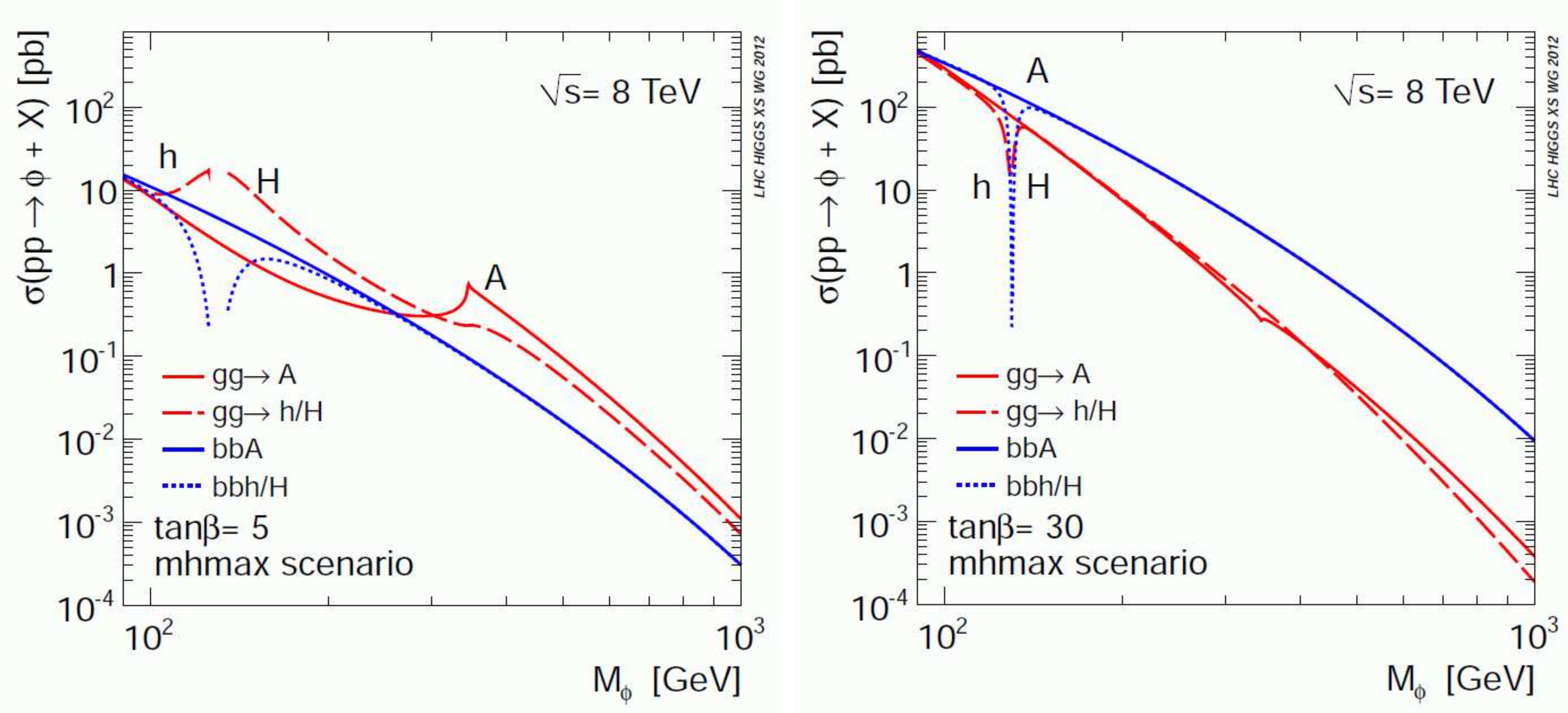
$\Rightarrow$ 3-loop $\mathcal{O}\left(\alpha_t^2\alpha_s, \alpha_t^3\right) \oplus$ beyond 3-loop important for precise M_h prediction!

Prediction of SUSY Higgs Cross Sections (and BRs):

"Official" theory predictions for the MSSM Higgs XS: *[LHC Higgs XS WG '12]*

Masses, couplings: FeynHiggs

Cross sections: combination of Higlu, bbh@nnlo, FeynHiggs, . . .



⇒ most relevant cross sections ($bb\Phi$: Santander matching)

⇒ update for $gg \to \Phi$ . . .

The old LHC-HXSWG numbers for gluon fusion

NLO top/bottom contributions from HIGLU + NNLO top bit from ggH@NNLO, rescaled by MSSM Higgs-quark couplings from FeynHiggs:

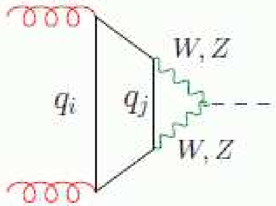
$$\sigma(gg \to \phi) \;=\; (g_t^\phi)^2\,\left(\sigma_{\rm NLO}^{\rm tt} + \Delta\sigma_{\rm NNLO}^{\rm tt}\right) \;+\; (g_b^\phi)^2\,\sigma_{\rm NLO}^{\rm bb} \;+\; g_t^\phi\,g_b^\phi\,\sigma_{\rm NLO}^{\rm tb}$$

e.g., for h :

$$g_t^h \;=\; \frac{\cos\alpha}{\sin\beta}\,, \qquad g_b^h \;=\; -\,\frac{\sin\alpha}{\cos\beta}\,\frac{1}{1+\Delta_b}\left(1 - \frac{\Delta_b}{\tan\alpha\tan\beta}\right)$$

$$\Delta_b \;=\; \frac{2\,\alpha_s}{3\pi}\,m_{\tilde g}\,\mu\,\tan\beta\,I(m^2_{\tilde b_1}, m^2_{\tilde b_2}, m^2_{\tilde g}) \;+\; \ldots$$

- No stop/sbottom contributions (apart from those implicit in Δ_b)
- No electroweak contributions (not even the known SM ones)



From the first "Yellow report": (1101.0593)

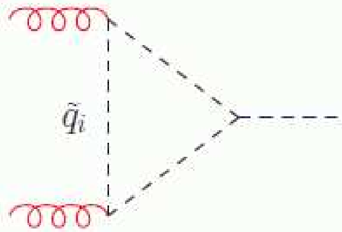
"In further steps we will have to include the full SUSY QCD and SUSY electroweak corrections where available..."

[P. Slavich, talk given at HDays13]

Update for $gg \to \Phi$: [LHCHXSWG - MSSM '13] [E. Bagnaschi et al. '14]

In the MSSM, additional contributions to Higgs production
from loops involving superparticles:

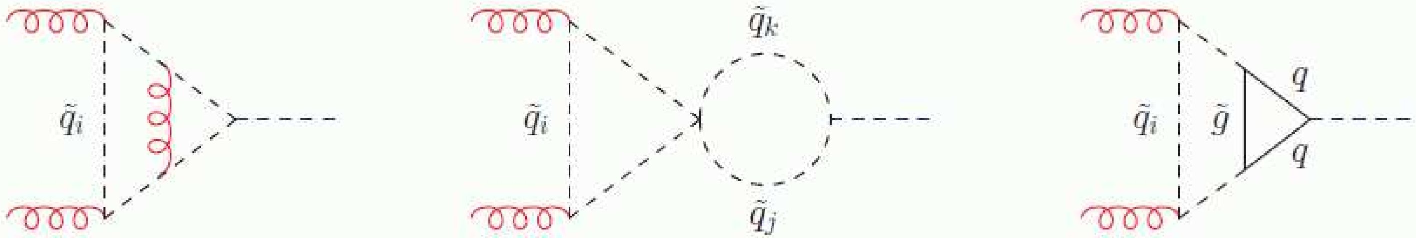
At LO, 1-loop
squark contribution:



$(\tilde{q} = \tilde{t}, \tilde{b})$

At NLO, different classes of 2-loop SUSY contributions:

gluon-squark: quartic squark coupling: gluino-quark-squark:



Also, squark contributions from 1-loop diagrams with real parton emission

[P. Slavich, talk given at HDays13]

Update for $gg \to \Phi$: [LHCHXSWG - MSSM '13] [E. Bagnaschi et al. '14]

Towards a state-of-the-art NLO calculation in the MSSM

A joint effort:

➡ Bagnaschi, Degrassi, Slavich, Vicini

➡ Harlander, Mantler, Liebler (SusHi)

Full NLO top/bottom + expanded NLO stop/sbottom + NNLO top + SM-EW

The road map (HDays'13)

- ✓ Compare the two codes at pure NLO and understand any discrepancies
- ✓ Explore different options for renormalization schemes (esp. large $\tan\beta$)
- ✓ Determine best way to include known NNLO and EW effects
- ✓ Produce new numbers and compare with the "official" LHCHXSWG ones

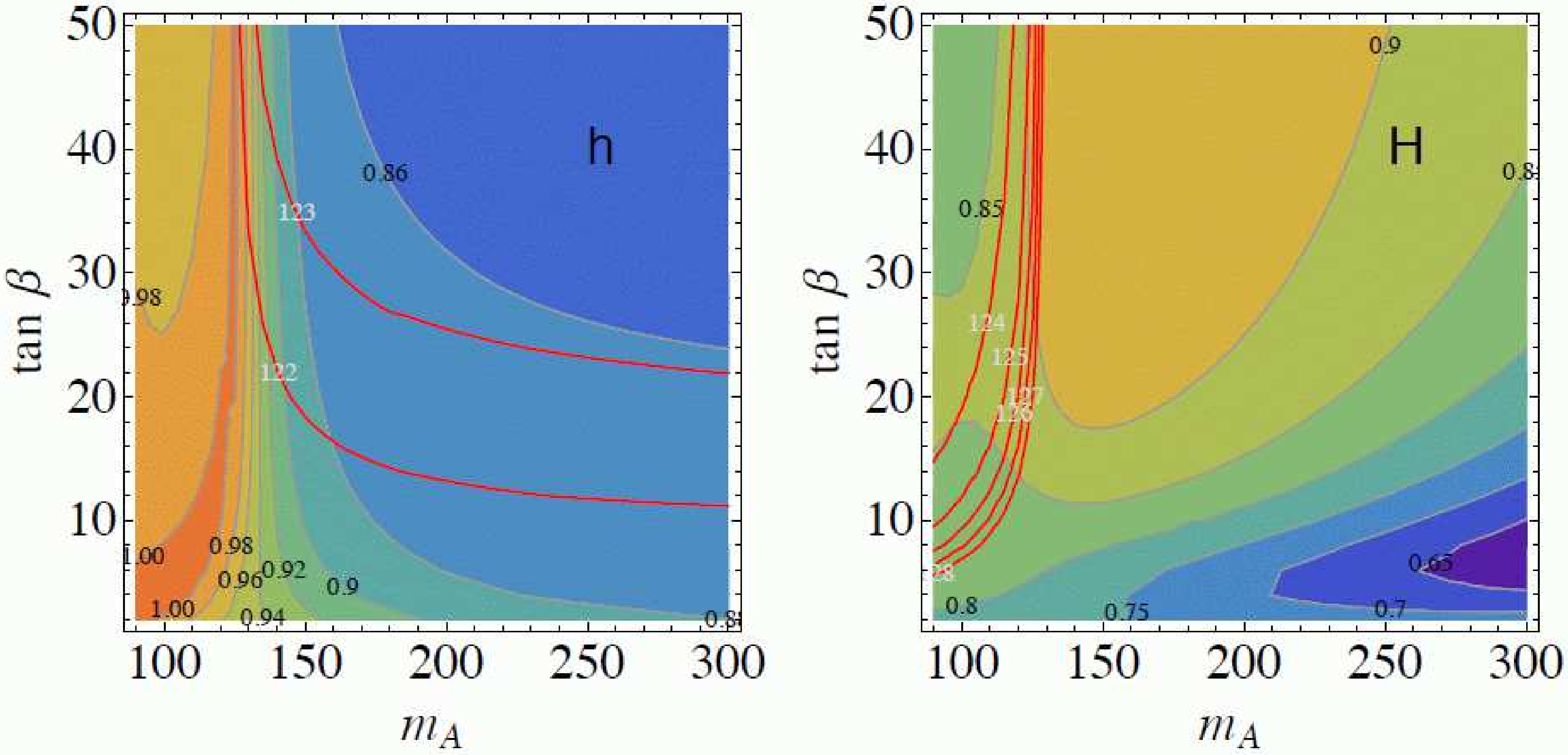
[P. Slavich, talk given at HDays13]

Update for $gg \to \Phi$: [*LHCHXSWG - MSSM '13*] [*E. Bagnaschi et al. '14*]

A benchmark scenario with light stops and large mixing:

$$M_S = 0.5 \text{ TeV}, \quad X_t = 1 \text{ TeV}, \quad \mu = M_2 = 350 \text{ GeV}, \quad m_{\tilde{g}} = 1.5 \text{ TeV}$$

[parameters from Carena *et al.*, arXiv:1302.7033]



$\sigma_{gg}^{q+\tilde{q}} \,/\, \sigma_{gg}^{q}$ [*P. Slavich, talk given at HDays13*]