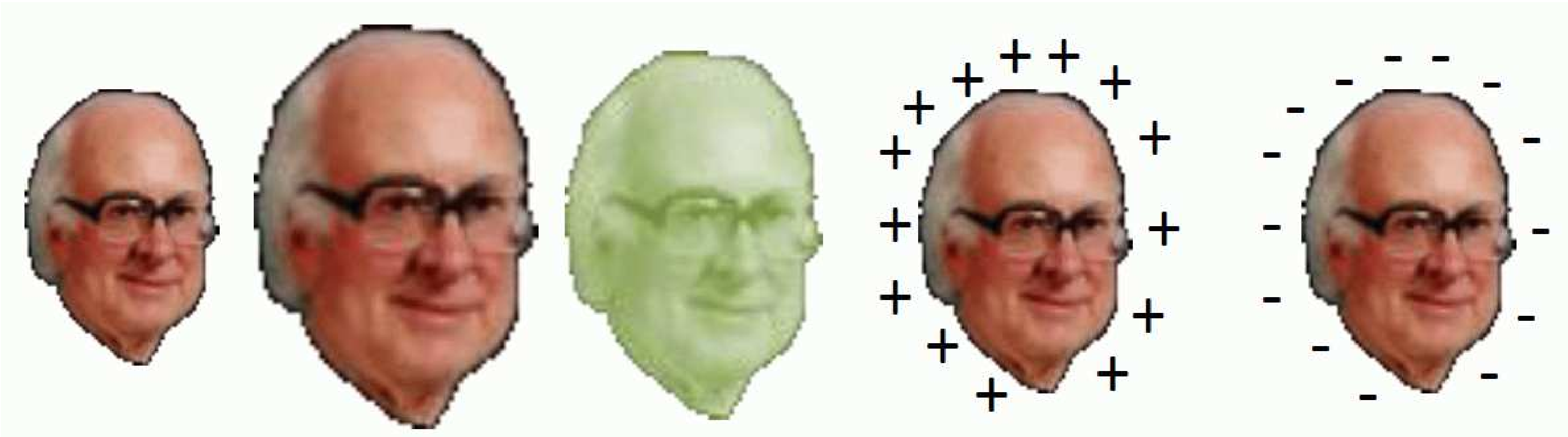


New Developments for SUSY Higgses

Sven Heinemeyer, IFCA (CSIC, Santander)

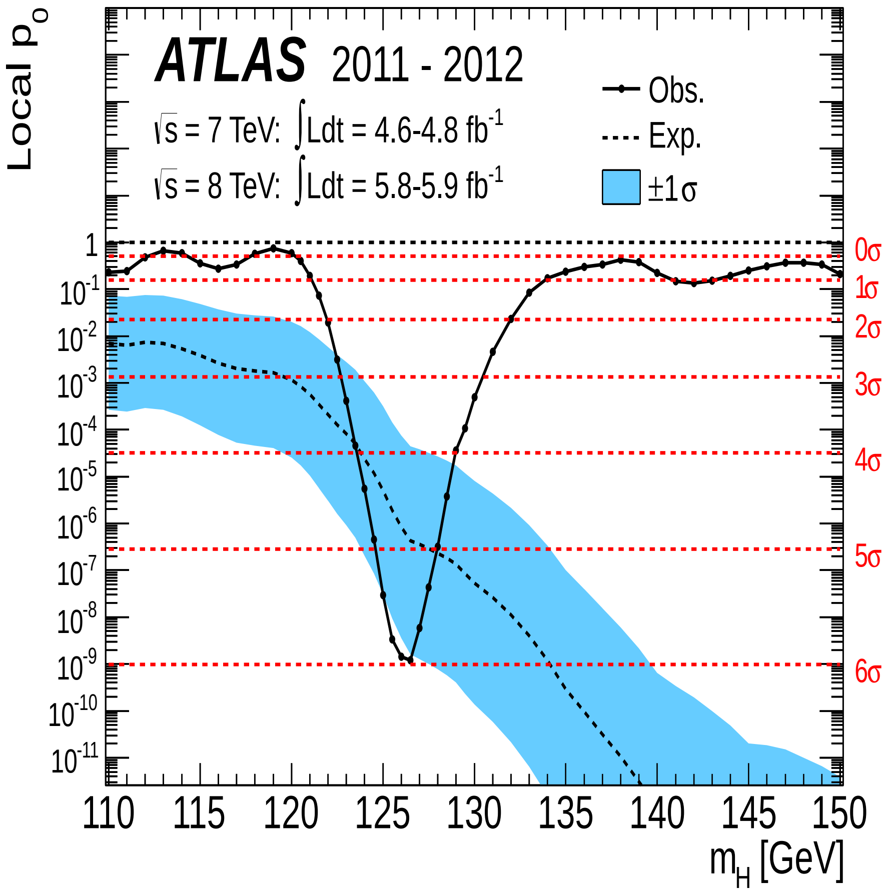
Heidelberg, 06/2015

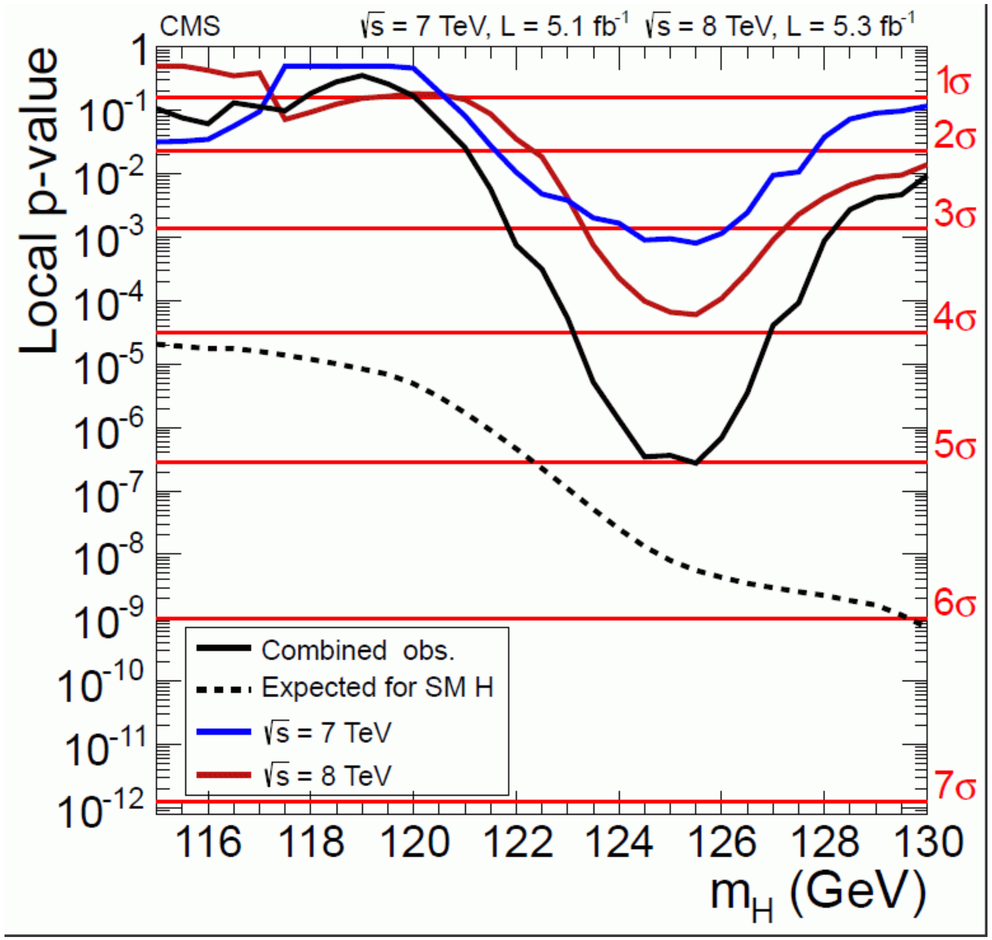
1. Why it is not the SM Higgs
2. Higgs bosons in the MSSM
3. . . . at the LHC and Beyond
4. Conclusions

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:

We have a discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be "the SM Higgs"!

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A: check changed properties

A: check for additional Higgs bosons

Which model should we focus on?

Some “recent” measurements:

– top quark mass
– Higgs boson mass
– Higgs boson “couplings”
– Dark Matter (properties)

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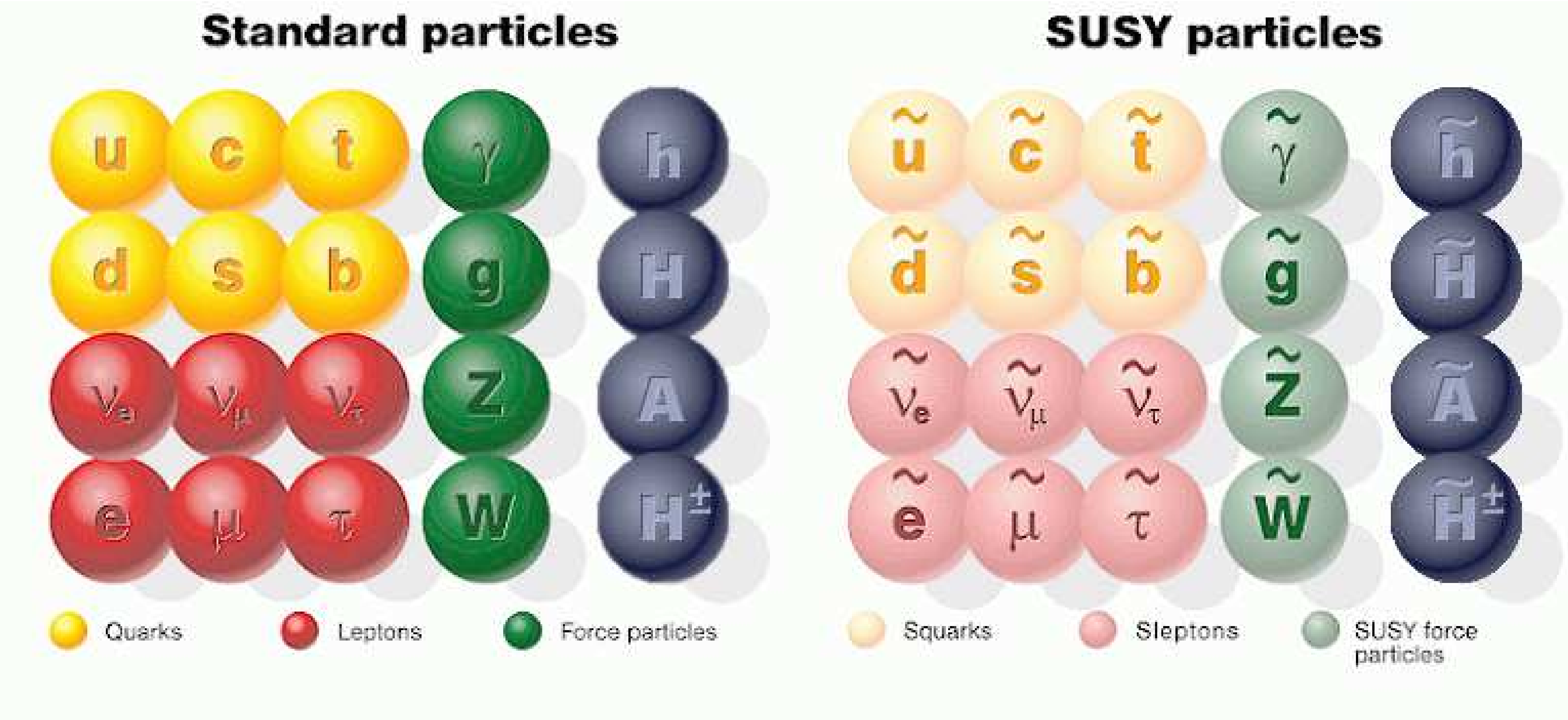
⇒ **good motivation to look at SUSY! :-)**

2. Higgs bosons in the 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: $\frac{e\, m_t}{2 M_W s_W}$, $\frac{e\, m_t^2}{M_W s_W}$, ...

$\Rightarrow$ 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, ...

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

Stop mass matrix

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

with

$$X_t = A_t - \mu / \tan\beta$$

$\Rightarrow$ mixing important in stop sector!

Simplifying abbreviation:

$$M_{\text{SUSY}}, M_S := M_{\tilde{t}_L} = M_{\tilde{t}_R}$$

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 – '15*]

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

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Experiment:

ATLAS:	$M_h^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18$ GeV
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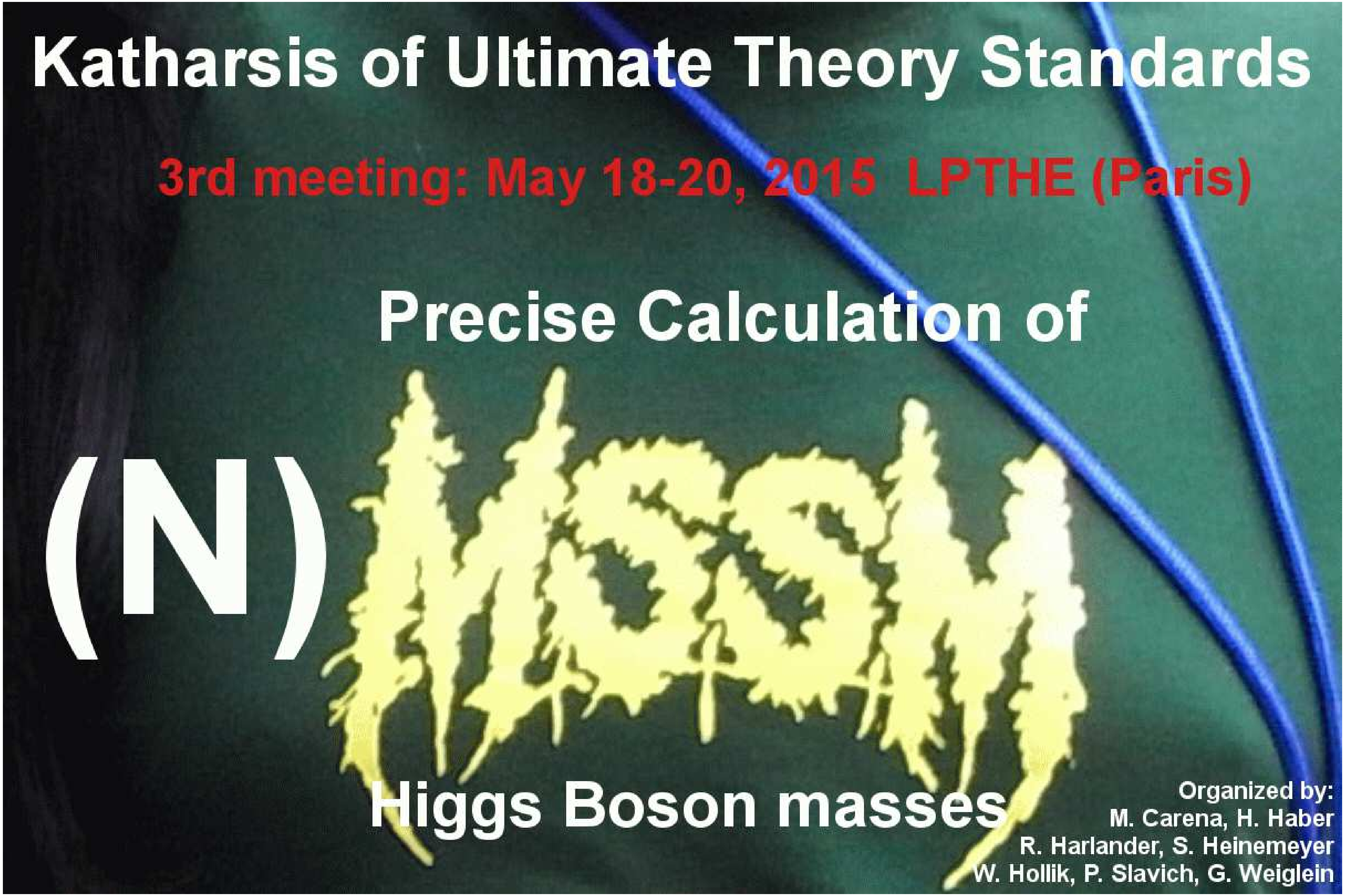
$\Rightarrow$ Theory prediction must be improved
to match the experimental accuracy!

$\Rightarrow$ dedicated working group has been formed to take care . . . (KUTS)


Katharsis of Ultimate Theory Standards
3rd meeting: May 18-20, 2015 LPTHE (Paris)
Precise Calculation of
(N)
Higgs Boson masses
Organized by:
M. Carena, H. Haber
R. Harlander, S. Heinemeyer
W. Hollik, P. Slavich, G. Weiglein

Possible (likely?) omplication:

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

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

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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:

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

with

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

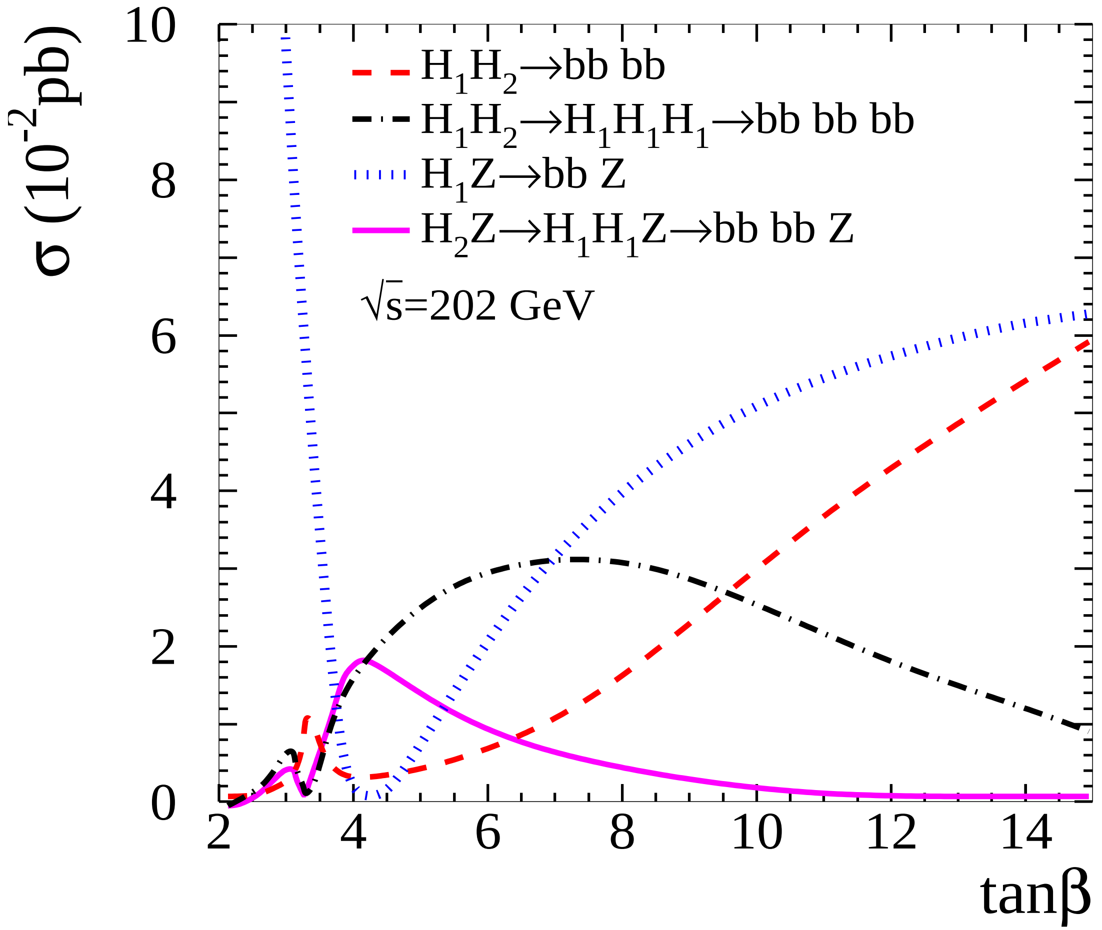
$\Rightarrow$ strong changes in Higgs couplings to SM gauge bosons and fermions

$\Rightarrow$ see Sebastian Paßehr's talk this afternoon!

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

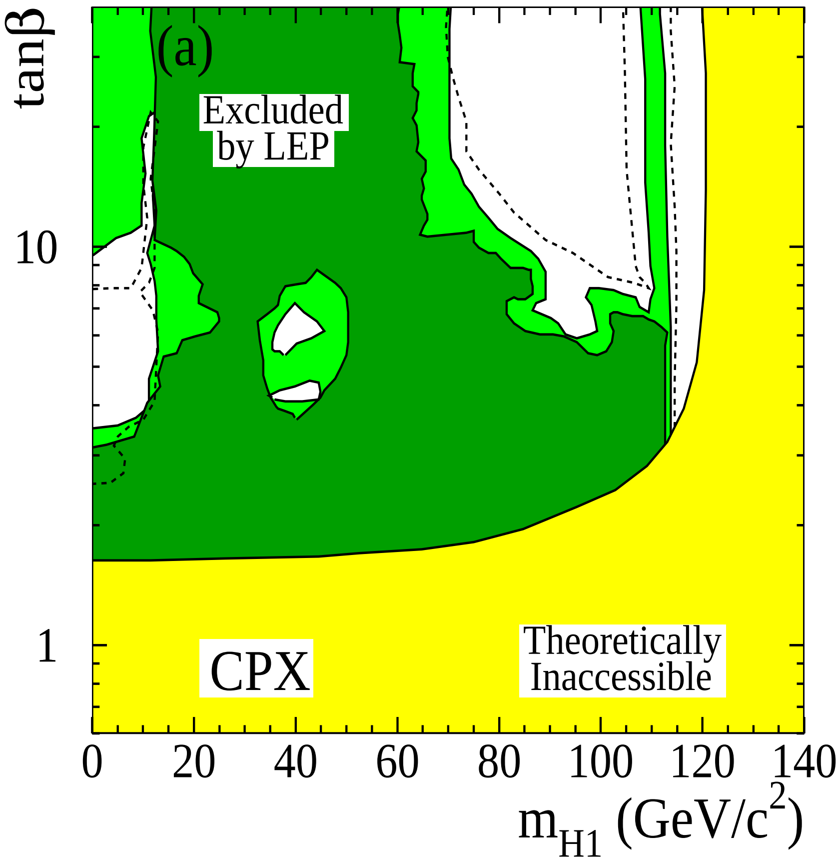
CPX: benchmark scenario in the cMSSM
[*M. Carena, J. Ellis, A. Pilaftsis, C. Wagner '00*]

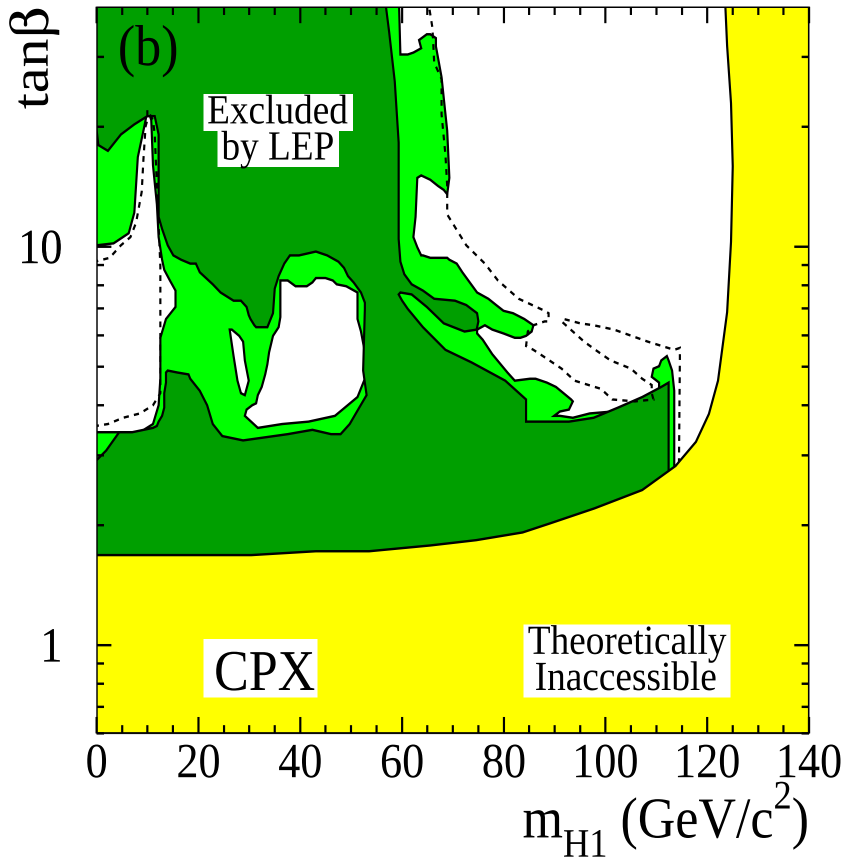
LEP Higgs production cross sections: [*LEPHiggsWG '06*]



Results of LEP searches in CPX scenario: [*LEPHiggsWG '06*]

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





The LEP analysis showed unexcluded holes in the m_{h_1}–$\tan\beta$ plane

$\Rightarrow$ masses below ~ 62 GeV ruled out, but above . . . ?

3. . . . at the LHC and beyond

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

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A simple exercise on stop masses:

⇒ 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
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⇒ only certain combinations of stop parameters are compatible with the Higgs discovery.

⇒ clear prediction for the LHC?

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For this exercise make sure:

⇒ use the best available Higgs mass calculation!

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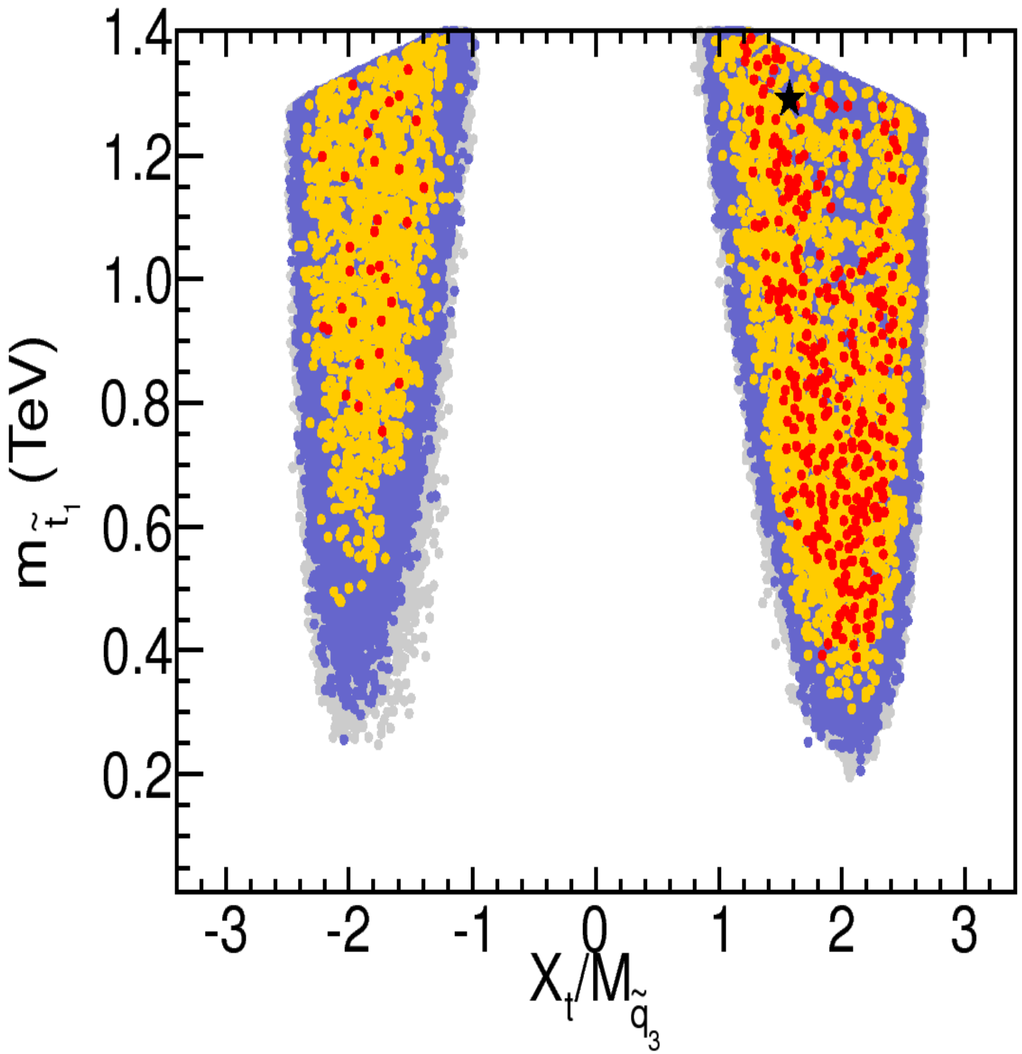
Stop masses: [P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein, L. Zeune '15 – PRELIMINARY]



$M_h = 125 \pm 3$ 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}

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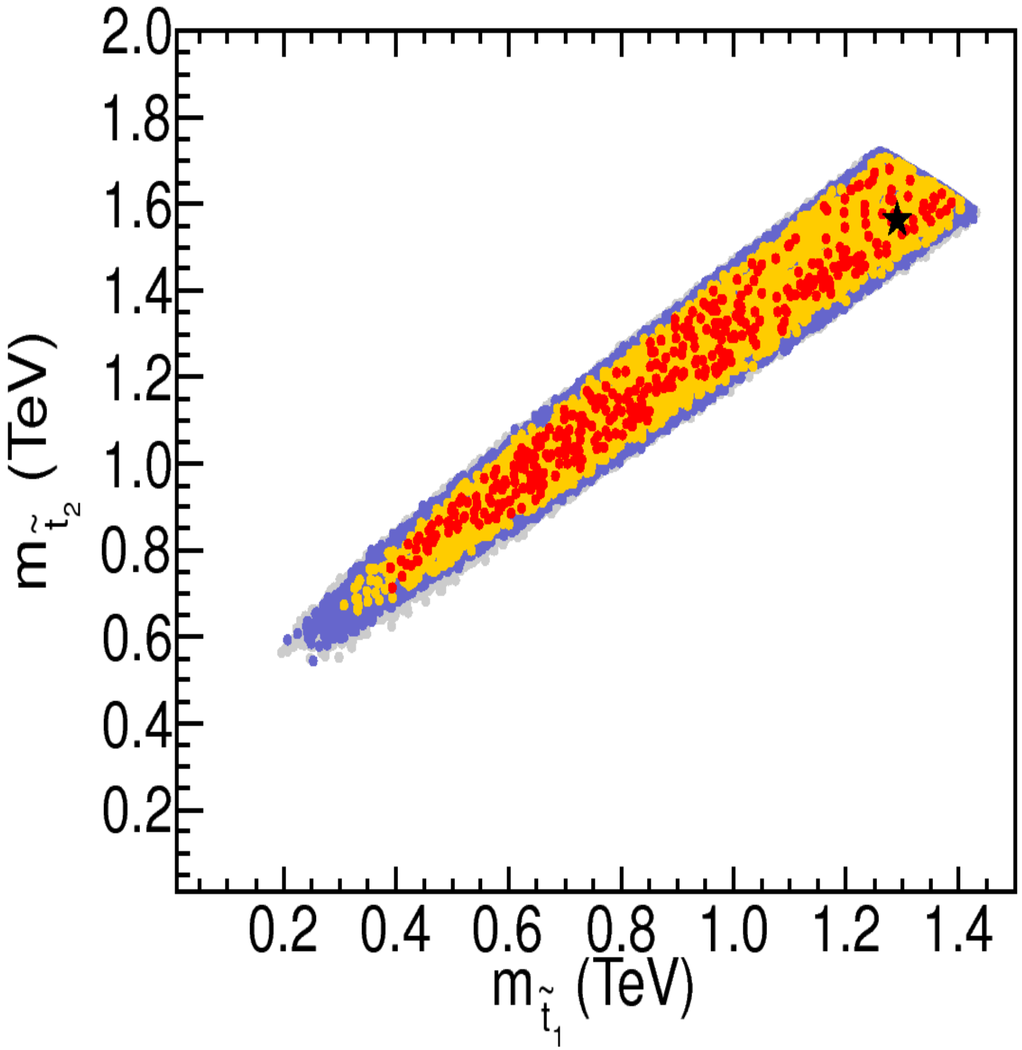

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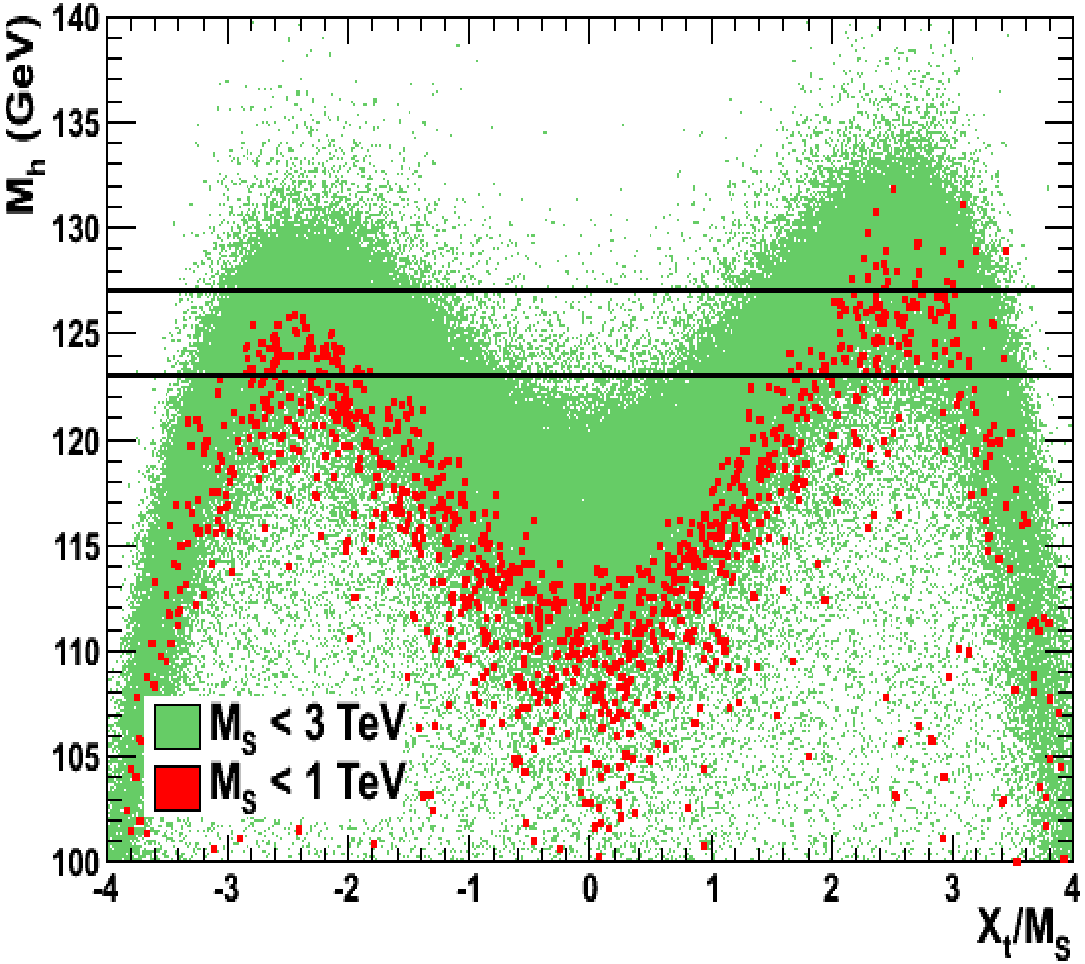
gray: all scan points

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

Stop masses for $M_h = 125$ GeV

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



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

$\Rightarrow$ no clear prediction for the LHC!

(MSSM) Higgs limit setting at the LHC and beyond

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

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

– measure its couplings, any deviation from the SM?

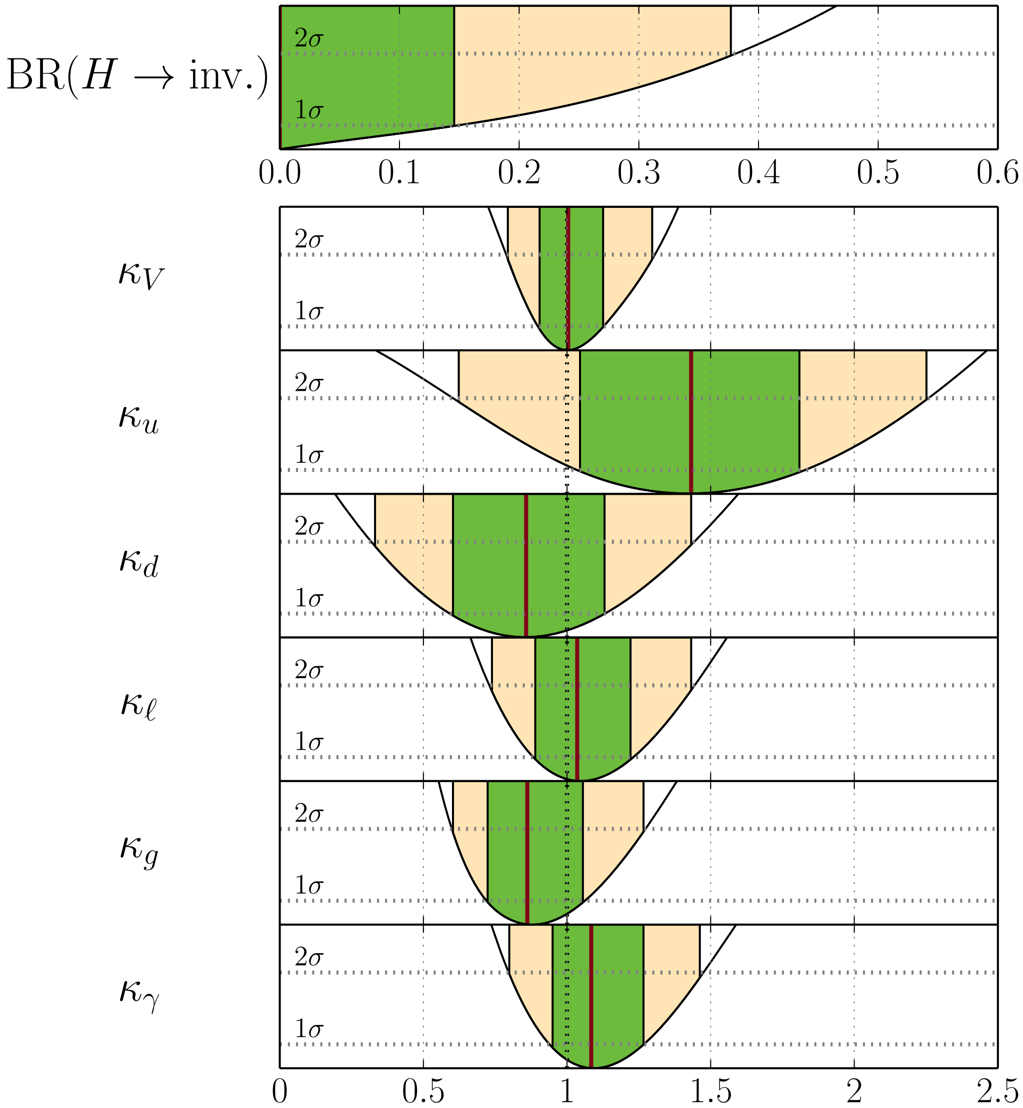
– search for additional heavier Higgs bosons
re-interpretation of SM Higgs searches?

– special issues for heavy Higgs phenomenology

– Higgs $\to$ SUSY decays?

– Higgs production from SUSY decays?

Coupling measurement: [P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14]



Very general model:

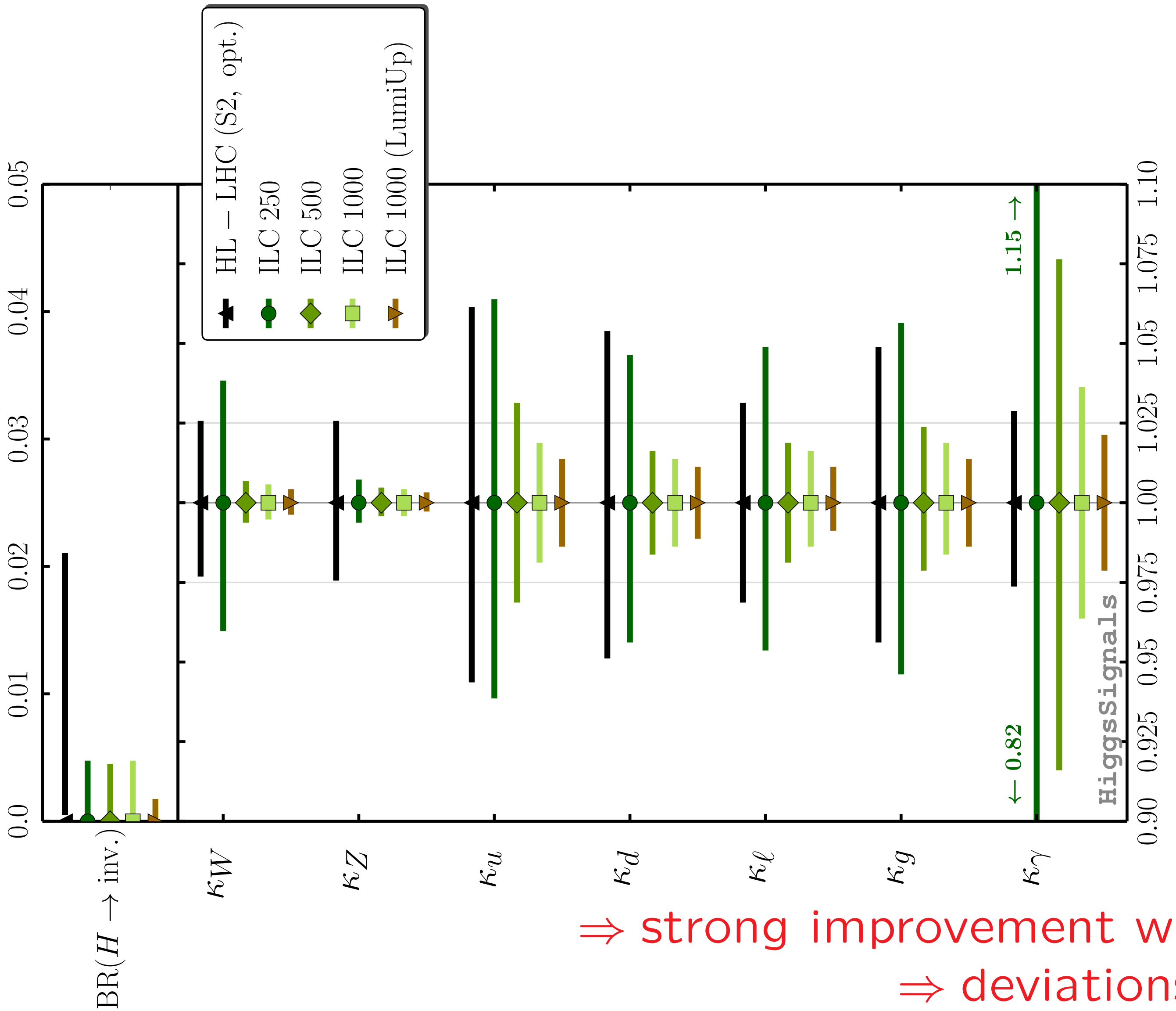
$\kappa_V, \kappa_u, \kappa_d, \kappa_l, \kappa_g, \kappa_\gamma$, BR($H \to$ inv.)

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

Beyond LHC: HL-LHC vs. ILC in the most general κ framework:

[P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14]

assumption: $\text{BR}(H \to \text{NP}) = \text{BR}(H \to \text{inv.})$



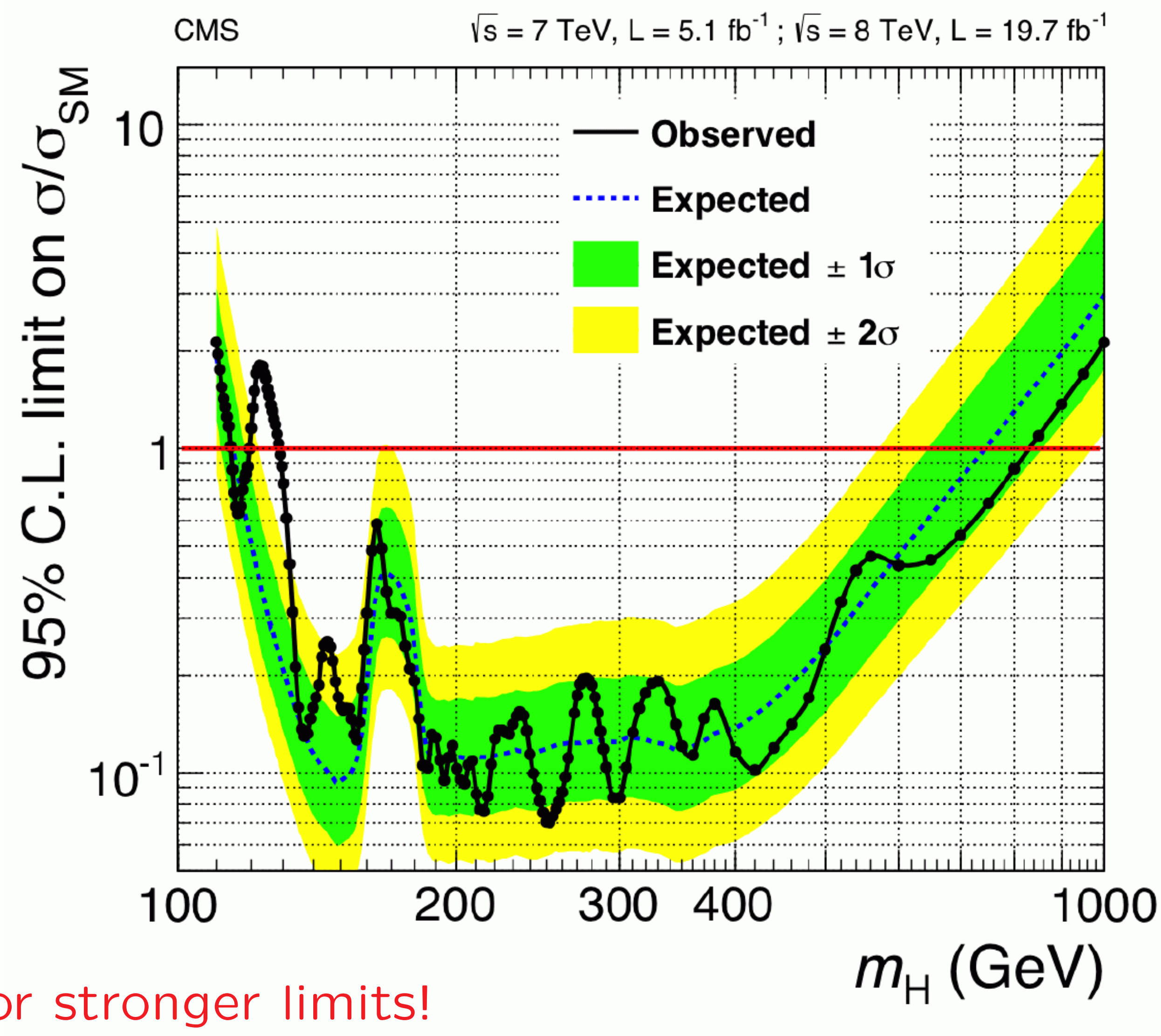
⇒ strong improvement with the ILC!

⇒ deviations from SM?

Re-interpretation of SM Higgs search results:

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

⇒ some coupling strength could remain for the heavy Higgs



⇒ go ahead for stronger limits!

Search (interpretation) in new benchmark scenarios:

[*LHCHXSWG – M. Carena, S.H., O. Stål, C. Wagner, G. Weiglein, '13*]

⇒ designed to have $M_h \sim 125 \pm 3$ GeV
and to reproduce rate measurements

⇒ designed to exhibit certain features of Higgs phenomenology

– light Higgs phenomenlogy
– heavy Higgs phenomenology

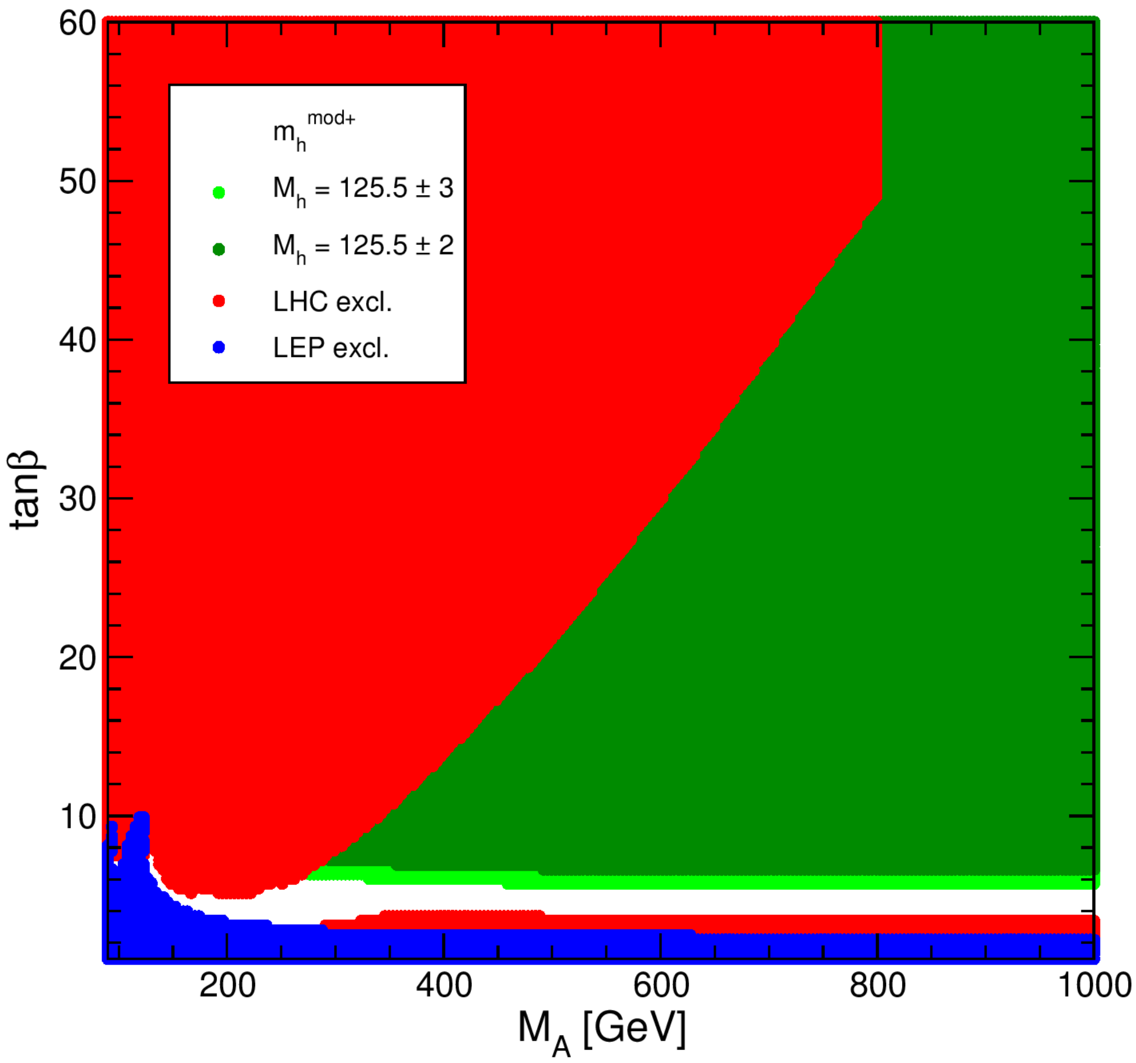
Not taken into account on purpose:

– 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:

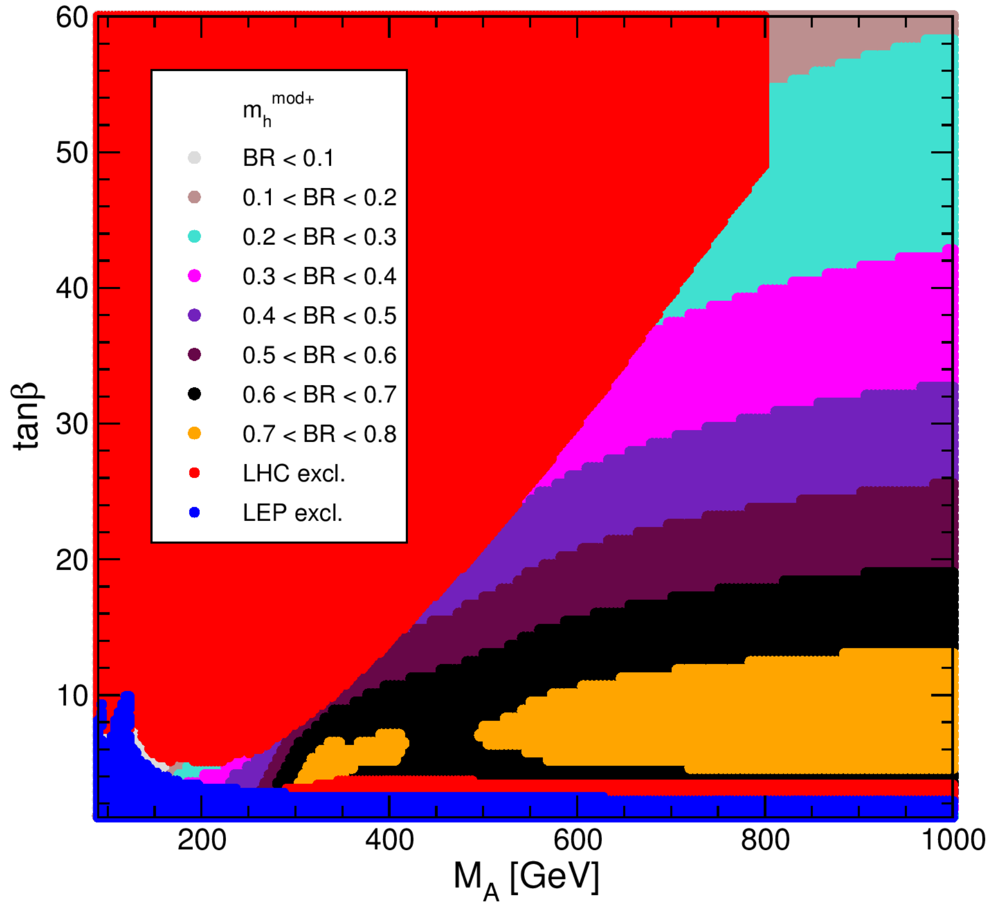


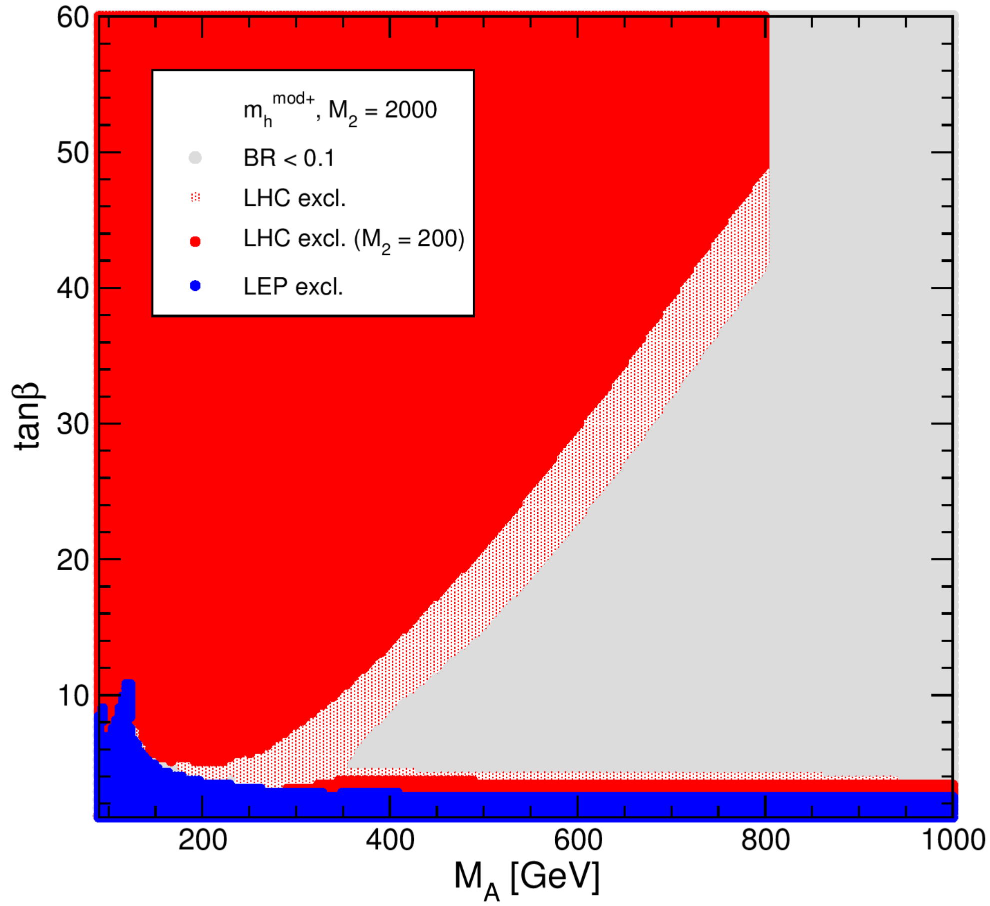
$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= 1.5\, M_{\text{SUSY}} \\
A_b = A_\tau &= A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
m_{\tilde{l}_3} &= 1000 \text{ GeV}\ .
\end{aligned}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

$\Rightarrow M_h \approx 125$ GeV nearly “everywhere”

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

⇒ effect of non-SM Higgs decays:





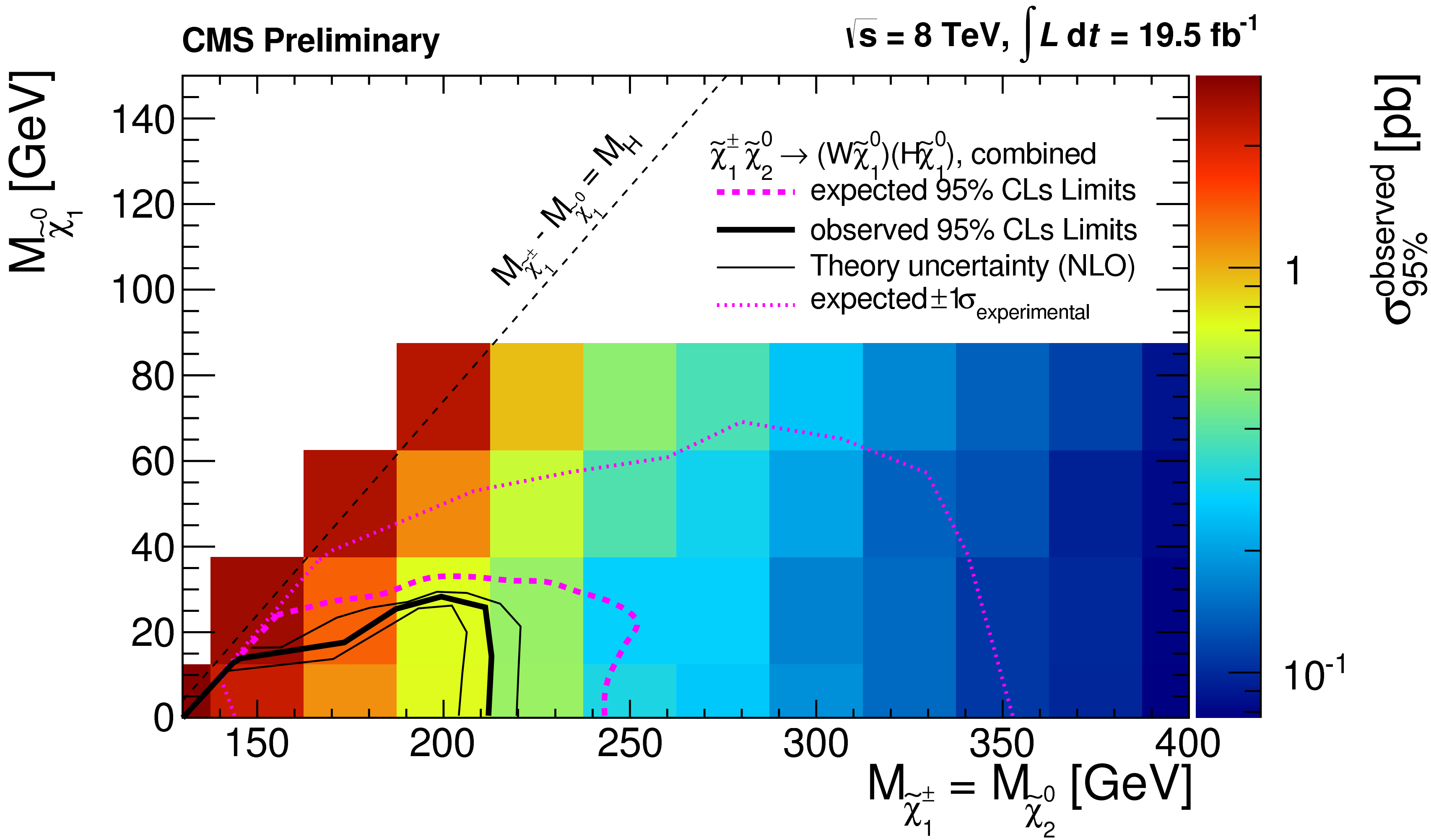
⇒ strong impact from $H/A \to \tilde{\chi}_i^0 \tilde{\chi}_j^0, \tilde{\chi}_k^\pm \tilde{\chi}_l^\mp$

⇒ disover heavy Higgses and SUSY at the same time!

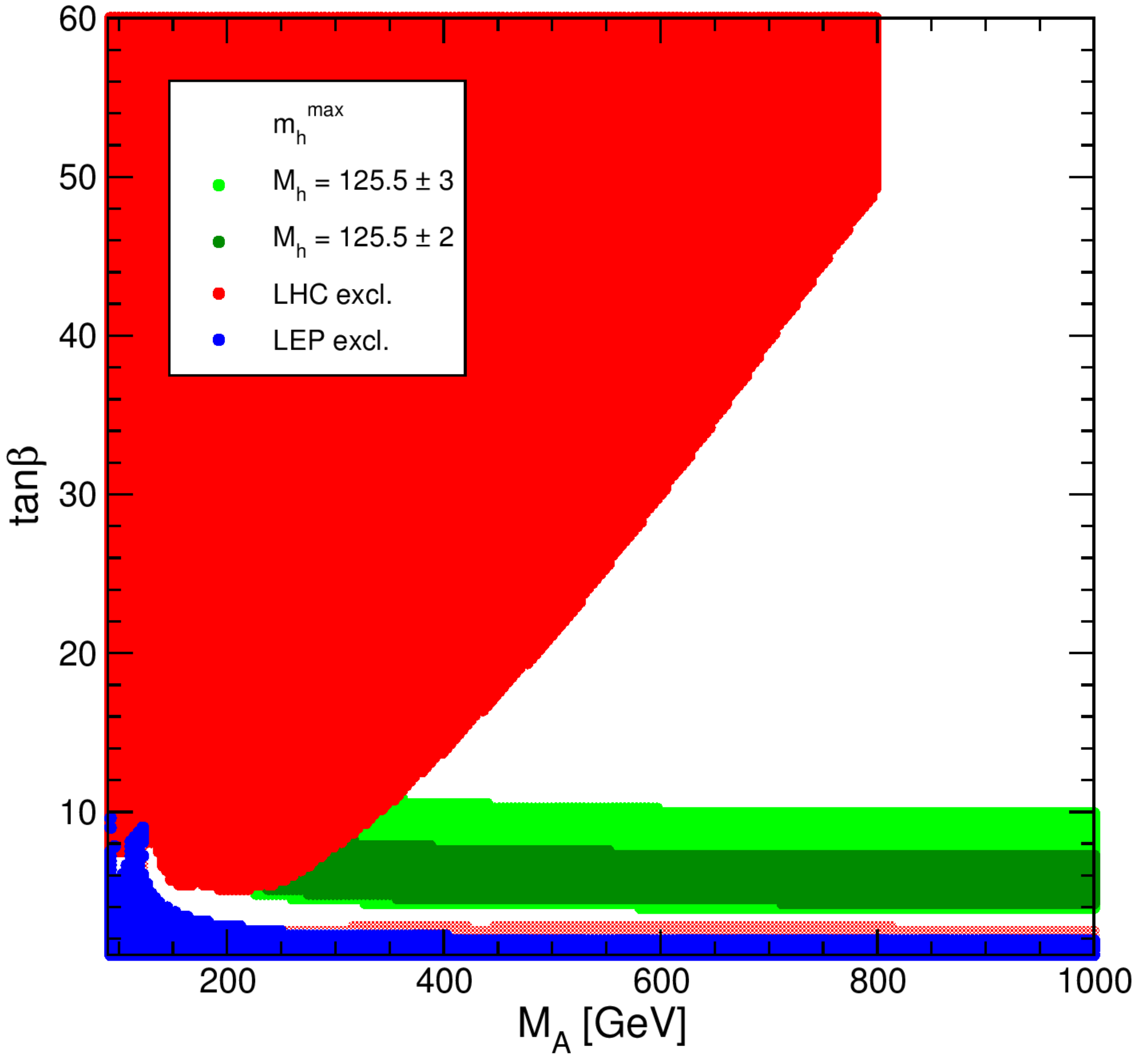
Higgs production from SUSY decays:

ATLAS and CMS are now also searching for

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



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



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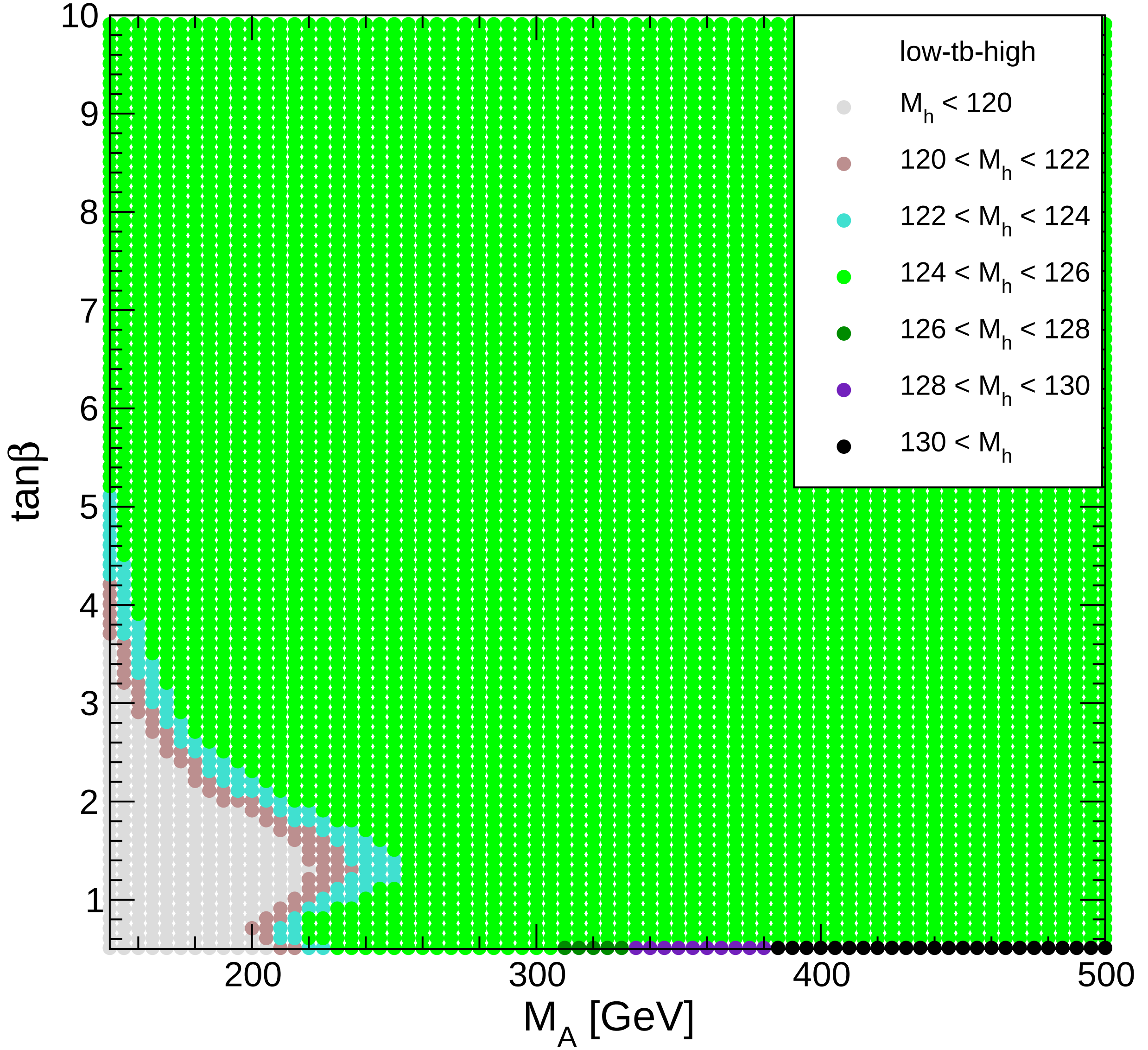
$$A_b = A_\tau = A_t,$$
$$m_{\tilde g} = 1500 \text{ GeV},$$
$$m_{\tilde l_3} = 1000 \text{ GeV} .$$

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

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

Example scenario: “low-tb-high” [S.H. (LHCHXSWG??) '14]

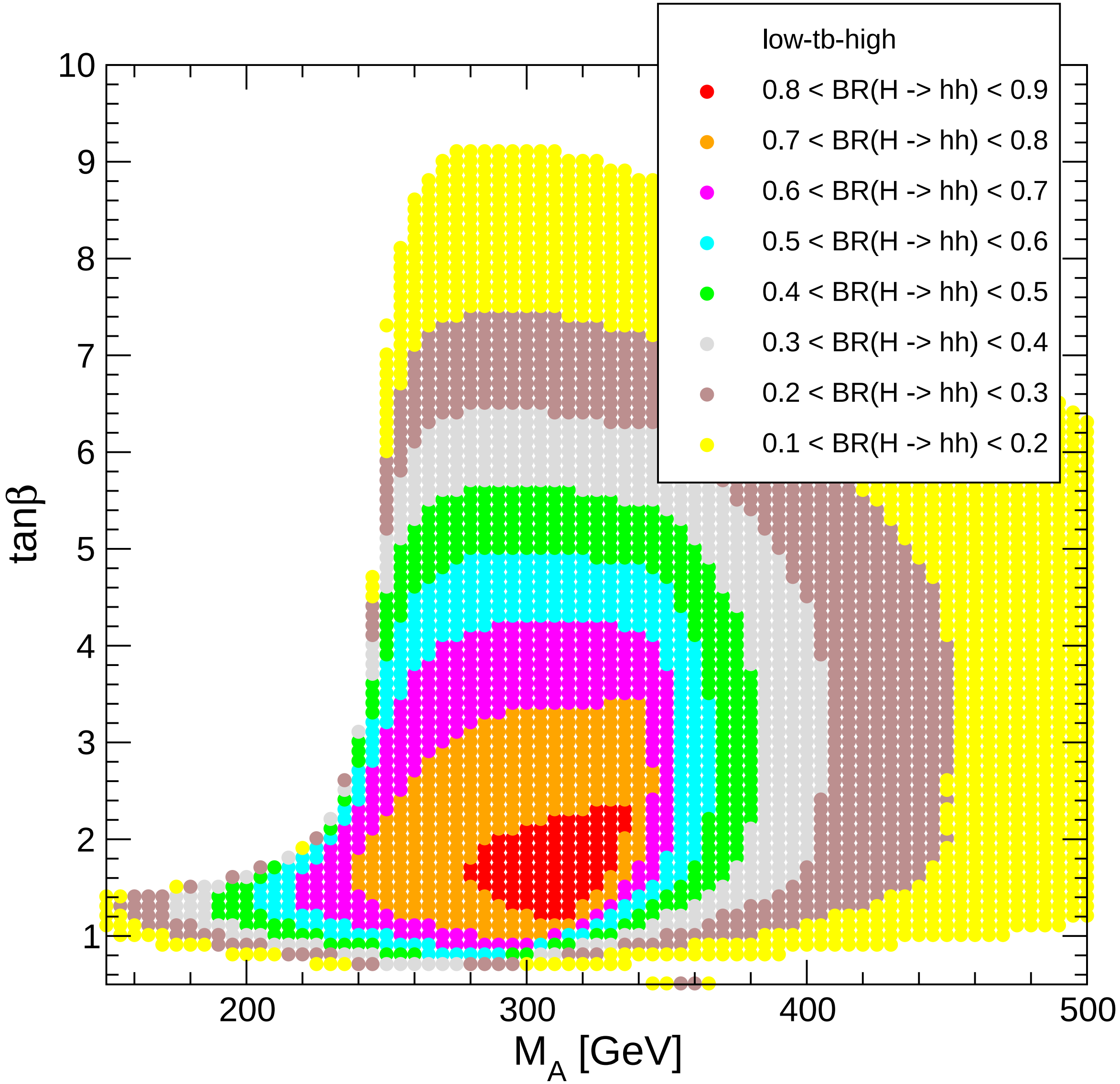
$M_{\rm SUSY}$ and X_t adjusted to give $M_h \sim 125$ GeV “everywhere”



⇒ lower $\tan\beta$ values possible! Relevant? ⇒ “new” relevant decay channels!

Example scenario: "low-tb-high" : $H \to hh$ [S.H. (LHCHXSWG??) '15]

M_{SUSY} and X_t adjusted to give $M_h \sim 125$ GeV "everywhere"



$\Rightarrow$ important at low $\tan\beta$

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

In principle also possilbe:

$$M_h < 125 \text{ GeV}$$
$$M_H \approx 125 \text{ GeV}$$

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.)

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- 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.)

$\Rightarrow$ original scenario: low-M_H

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

In principle also possilbe:

$$M_h < 125 \text{ GeV}$$
$$M_H \approx 125 \text{ GeV}$$

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.)

⇒ original scenario: low-M_H ⇒ ruled out by charged Higgs searches

⇒ stay tuned for updated scenario! :-)

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

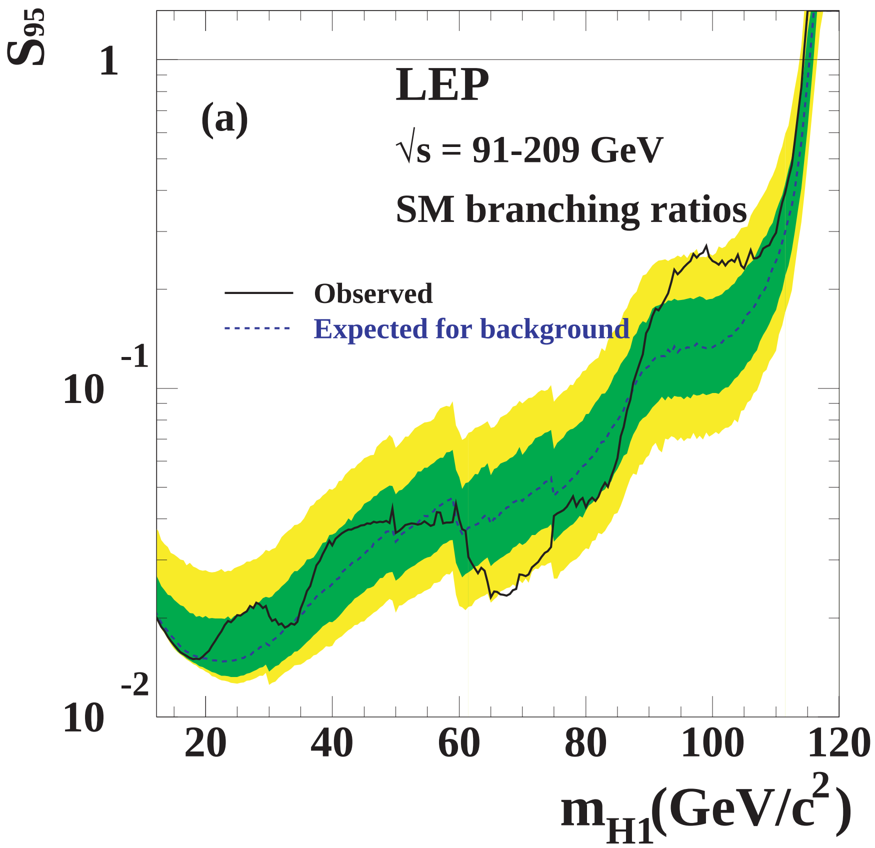
Is such a light Higgs detectable at the LHC?

– $h_2 \to h_1 h_1$ possible, but strongly suppressed for $M_{h_1} \gtrsim 63$ GeV
– so far few (and "weak") LHC searches for a Higgs with $M_{h_1} \lesssim 100$ GeV
– Possible: SUSY $\to$ SUSY h_1 , e.g. $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h_1$

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/only channel? $h_1 \to \gamma\gamma$??

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

4. 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 (cMSSM, NMSSM, . . .)
  $\Rightarrow$ search for new states above and below 125 GeV

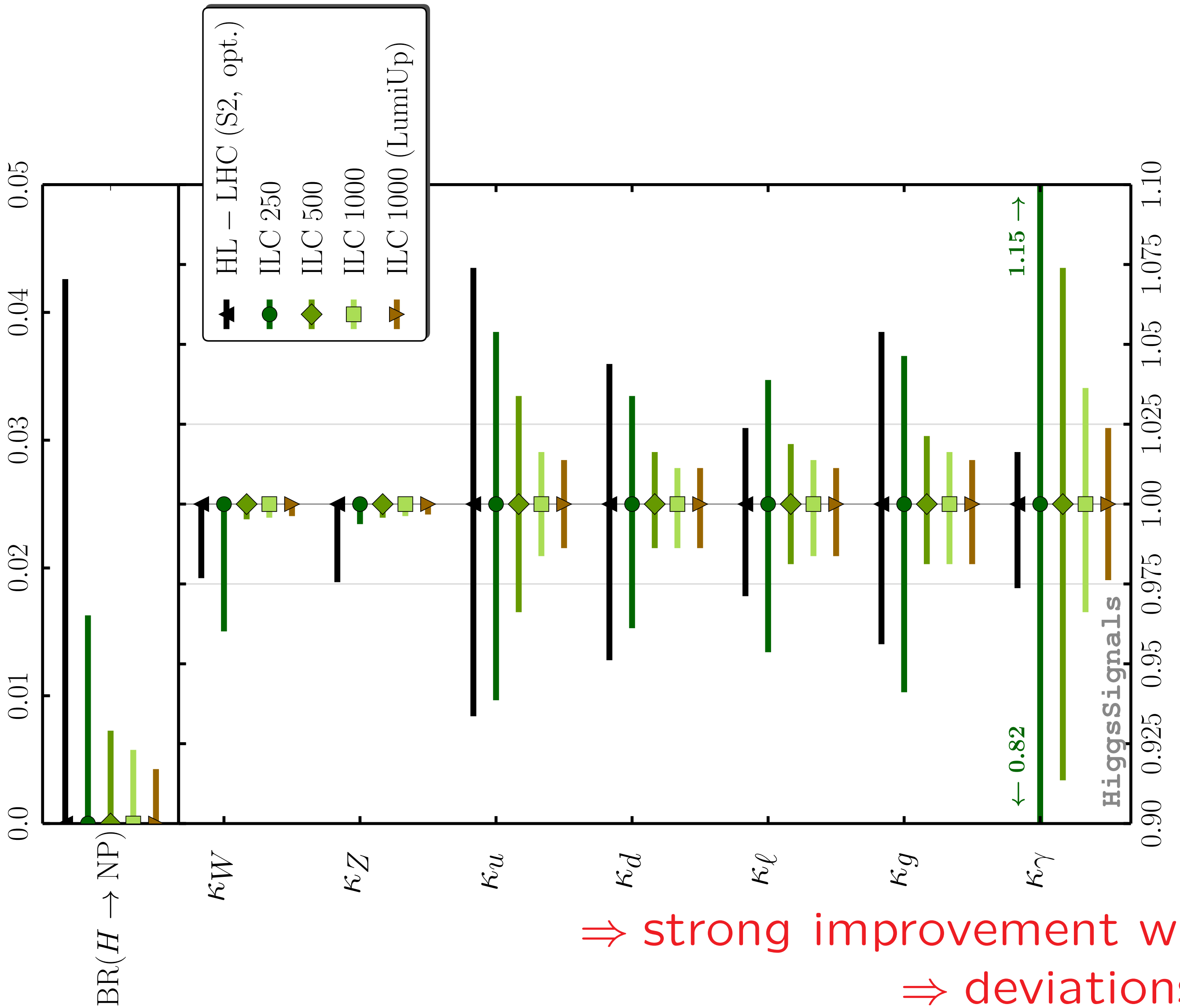

Higgs Days at Santander 2015
Theory meets Experiment
14.-18. September
contact: Sven.Heinemeyer@cern.ch
http://www.ifca.es/HDays15
IFCA
Instituto de Física de Cantabria
CSIC
UC
UNIVERSIDAD DE CANTABRIA
MultiDark
Multimessenger Approach for Dark Matter Detection

Back-up

Beyond LHC: HL-LHC vs. ILC in the most general κ framework:

[P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14]

assumption: $\kappa_V \leq 1$



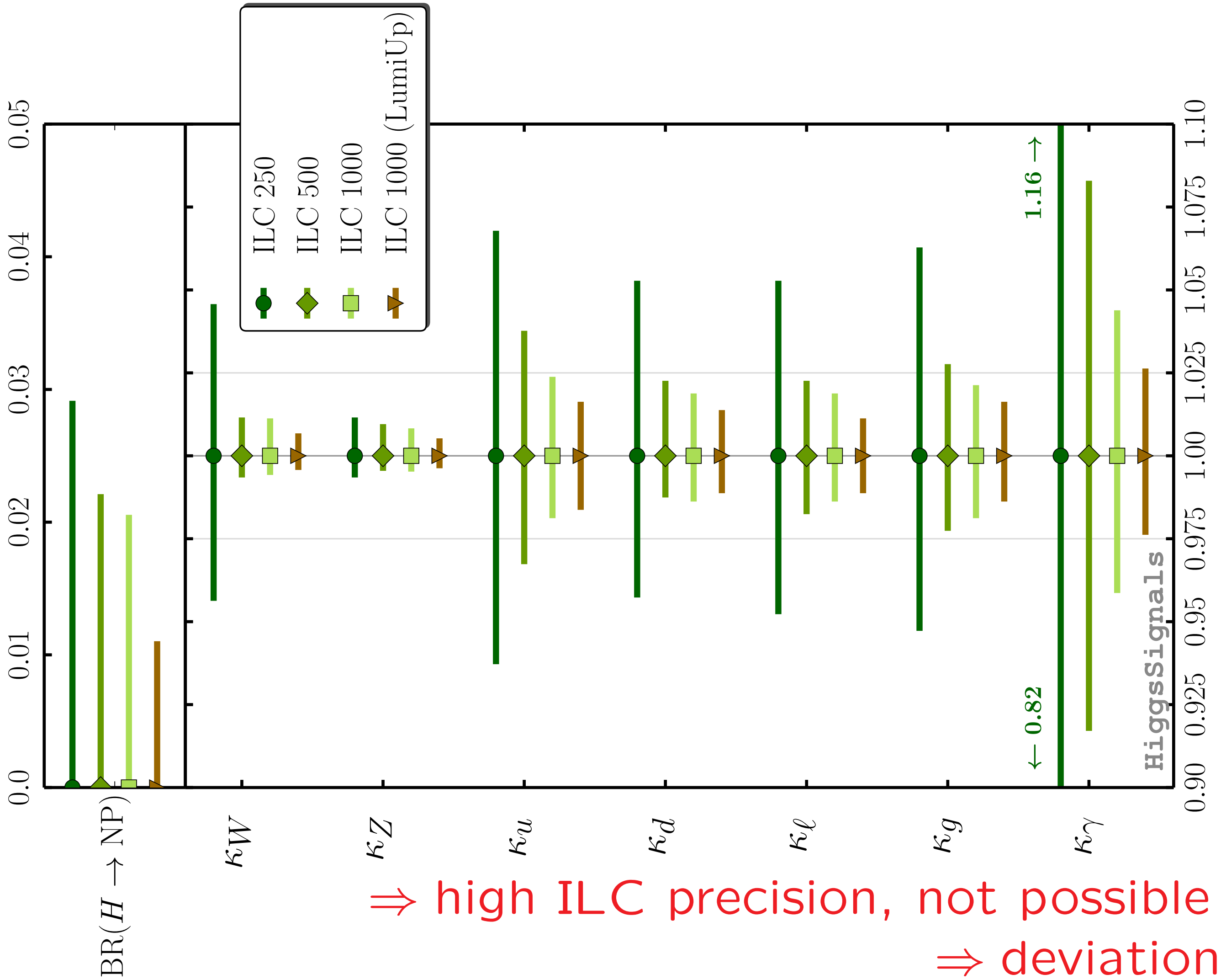
⇒ strong improvement with the ILC!

⇒ deviations from SM?

Beyond LHC: HL-LHC vs. ILC in the most general κ framework:

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]

no theory assumptions, full fit



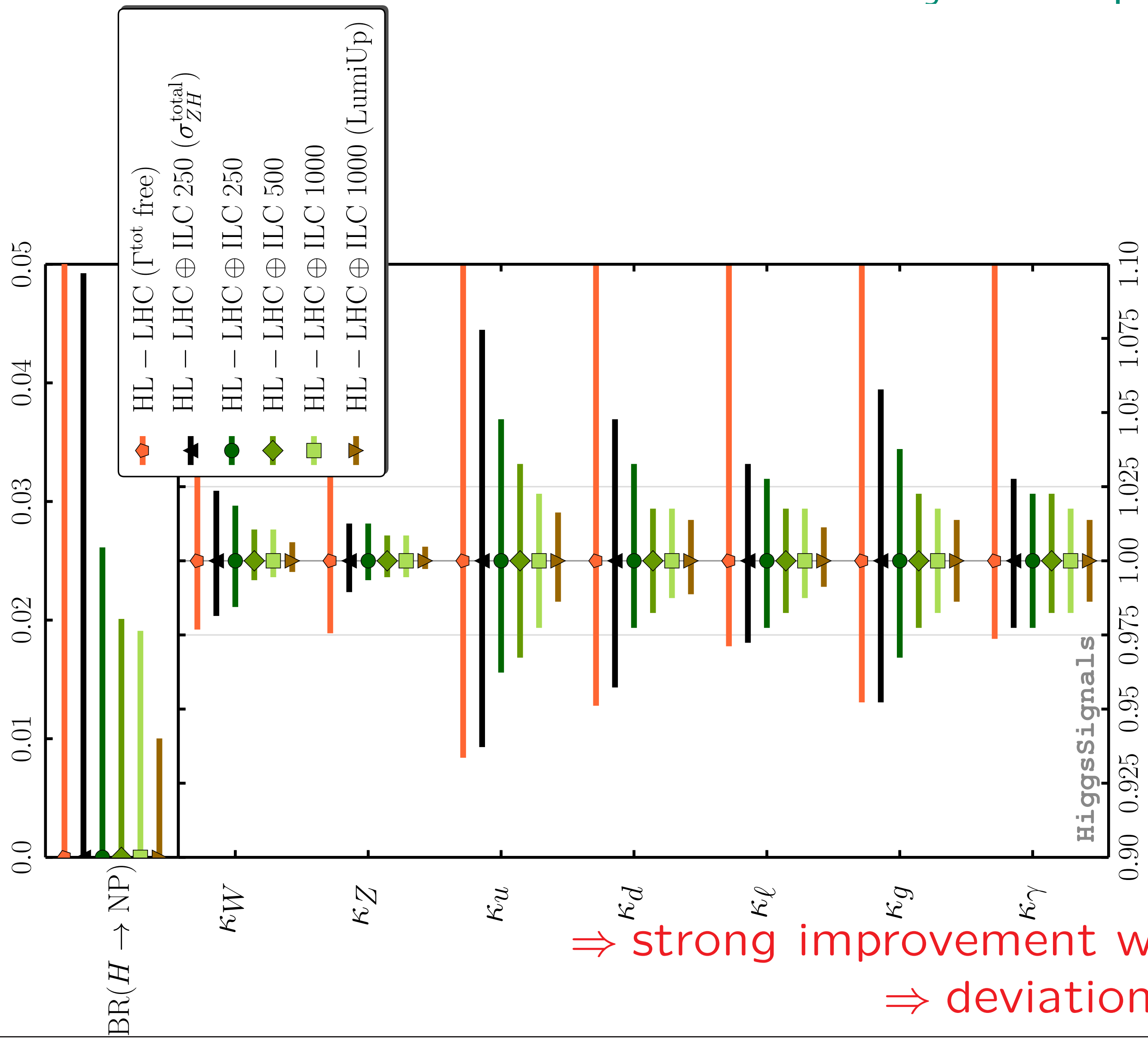
⇒ high ILC precision, not possible at the LHC

⇒ deviations from SM?

Beyond LHC: HL-LHC vs. ILC in the most general κ framework:

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]

no theory assumptions, full fit



⇒ strong improvement with the ILC!

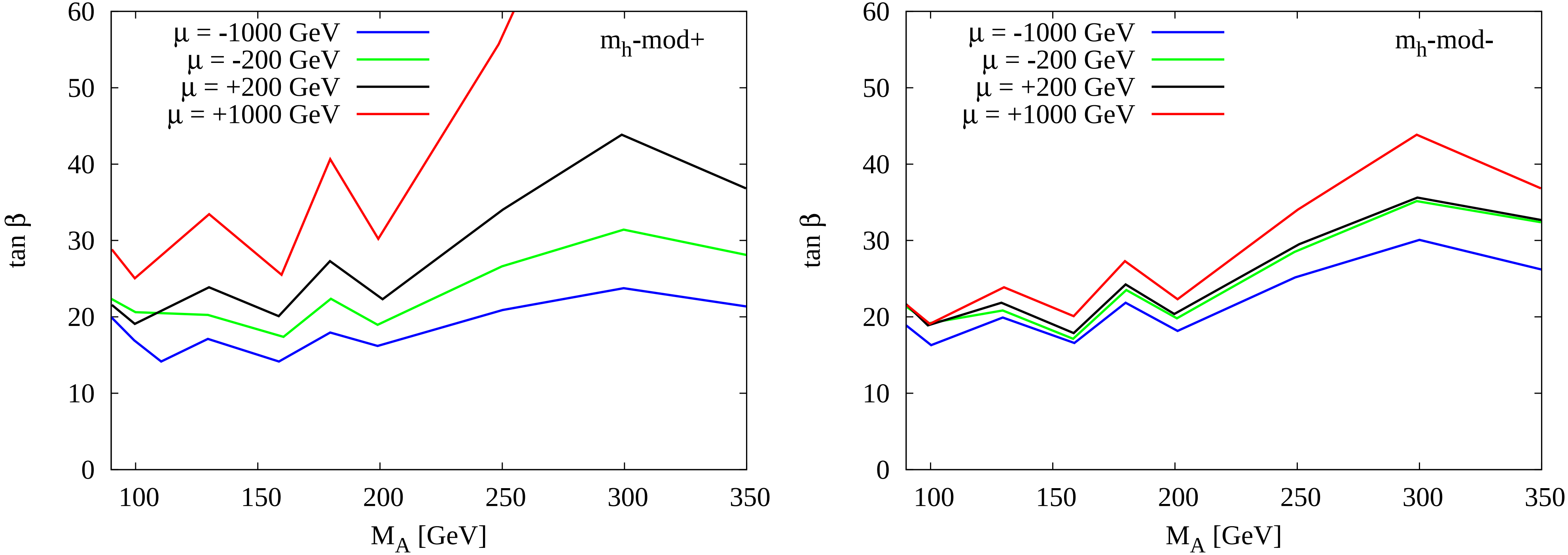
⇒ deviations from SM?

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

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

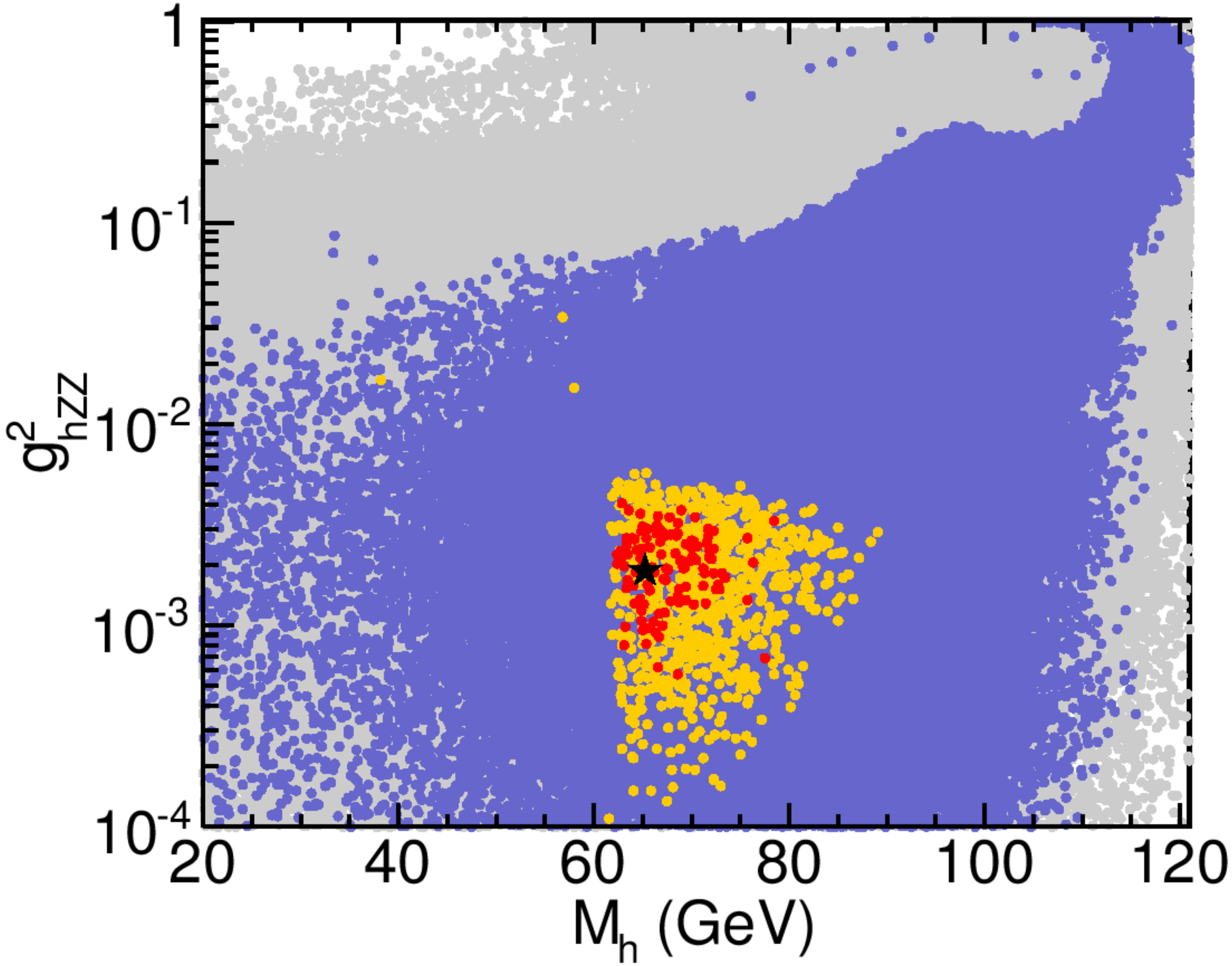
Additional factors wrt. the SM:

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



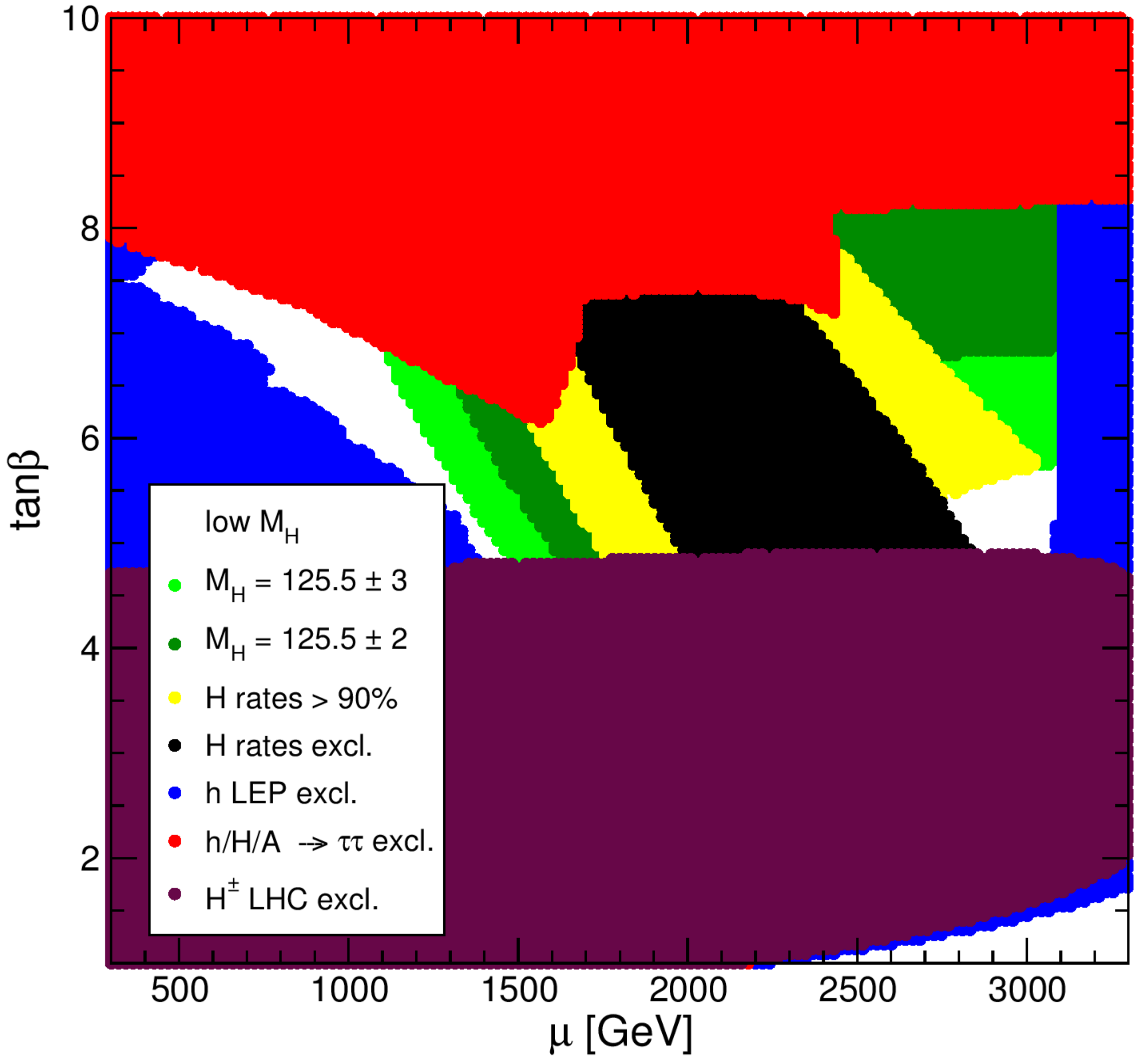
⇒ phenomenology can depend on "new" parameters!

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



⇒ low M_h values, strongly reduced couplings

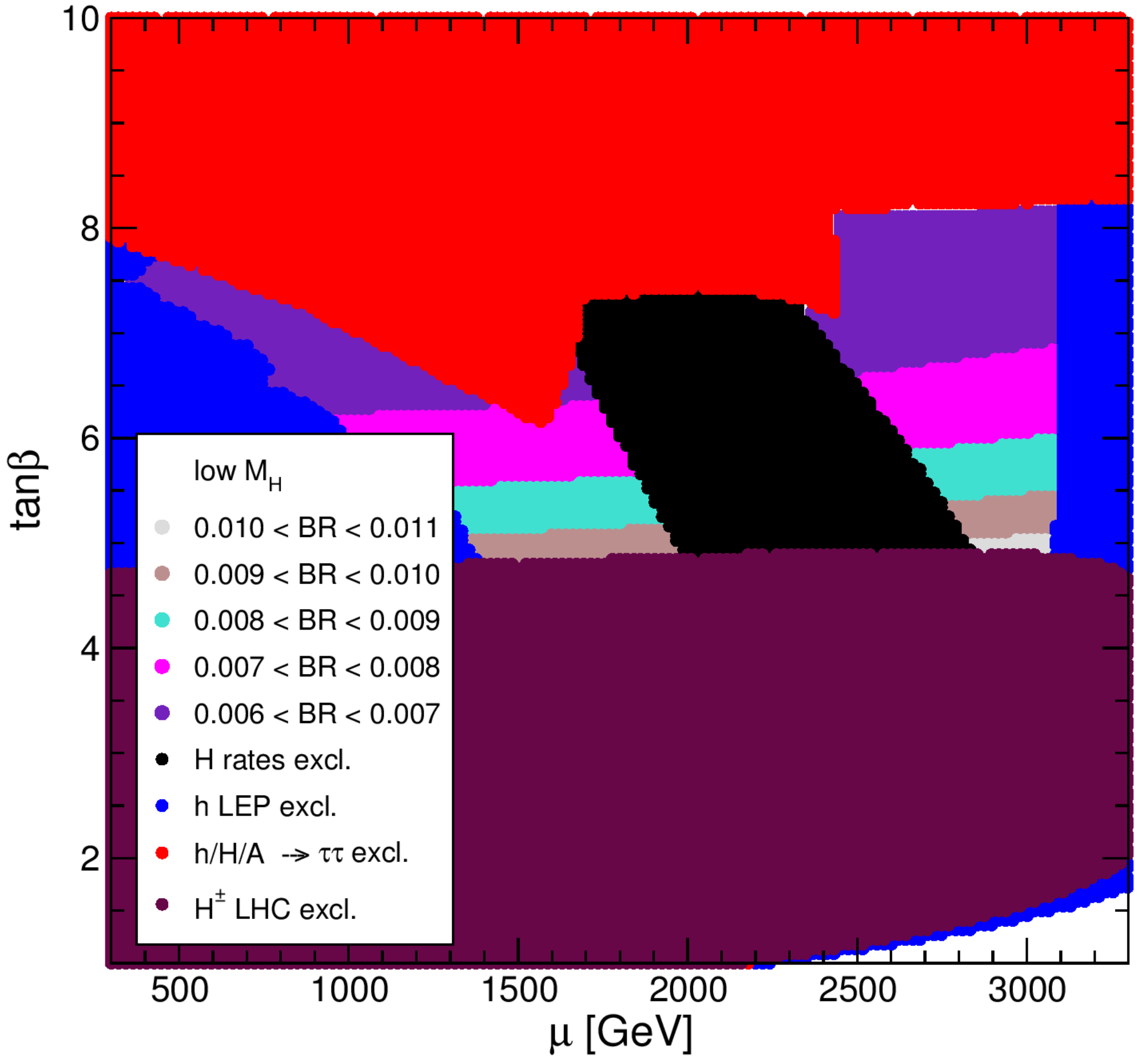
low-M_H scenario:



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

$\Rightarrow M_H \approx 125$ GeV can in principle be realized

low-M_H scenario:



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$$m_{\tilde{g}} = 1500 \text{ GeV},$$
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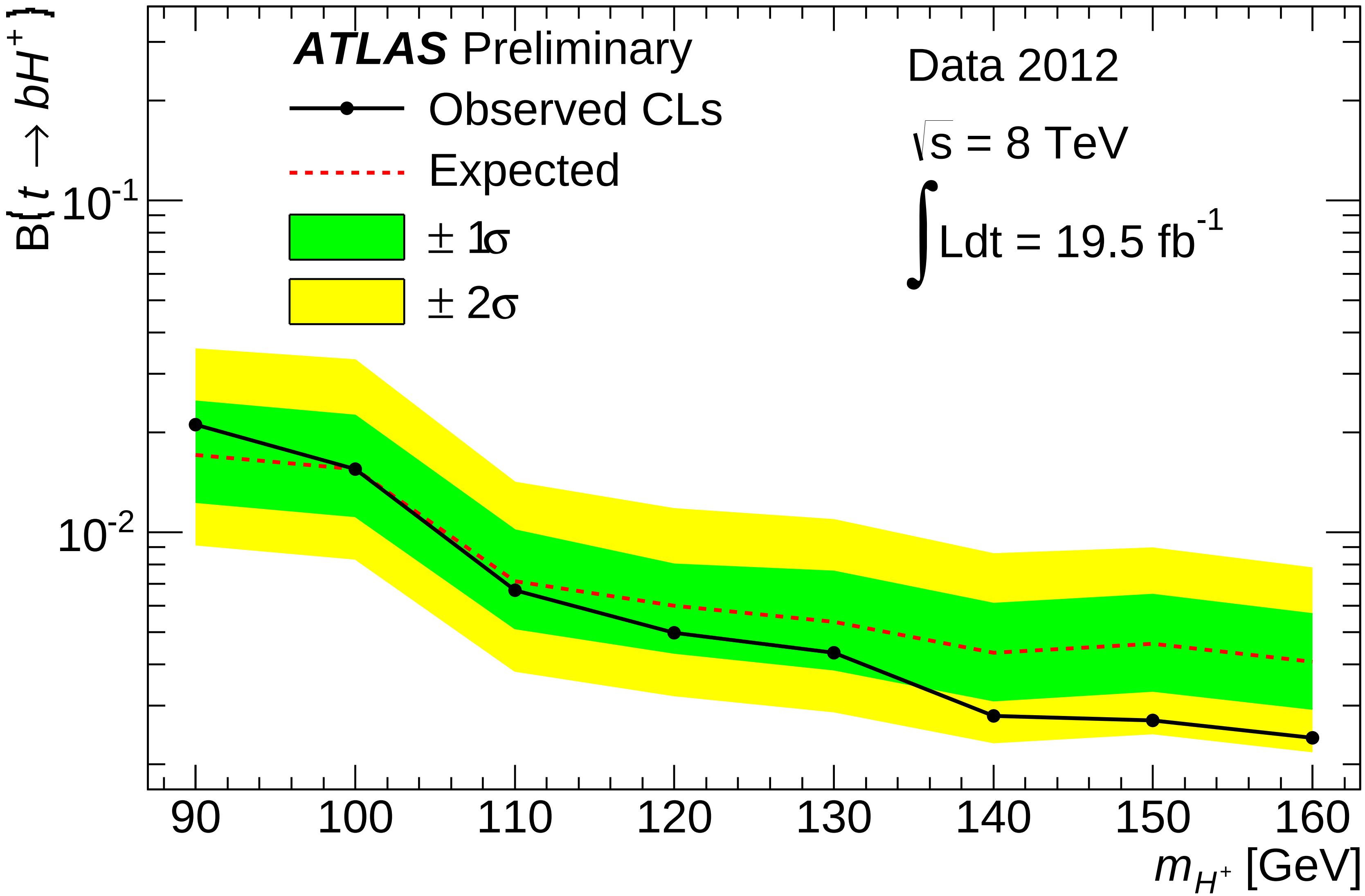
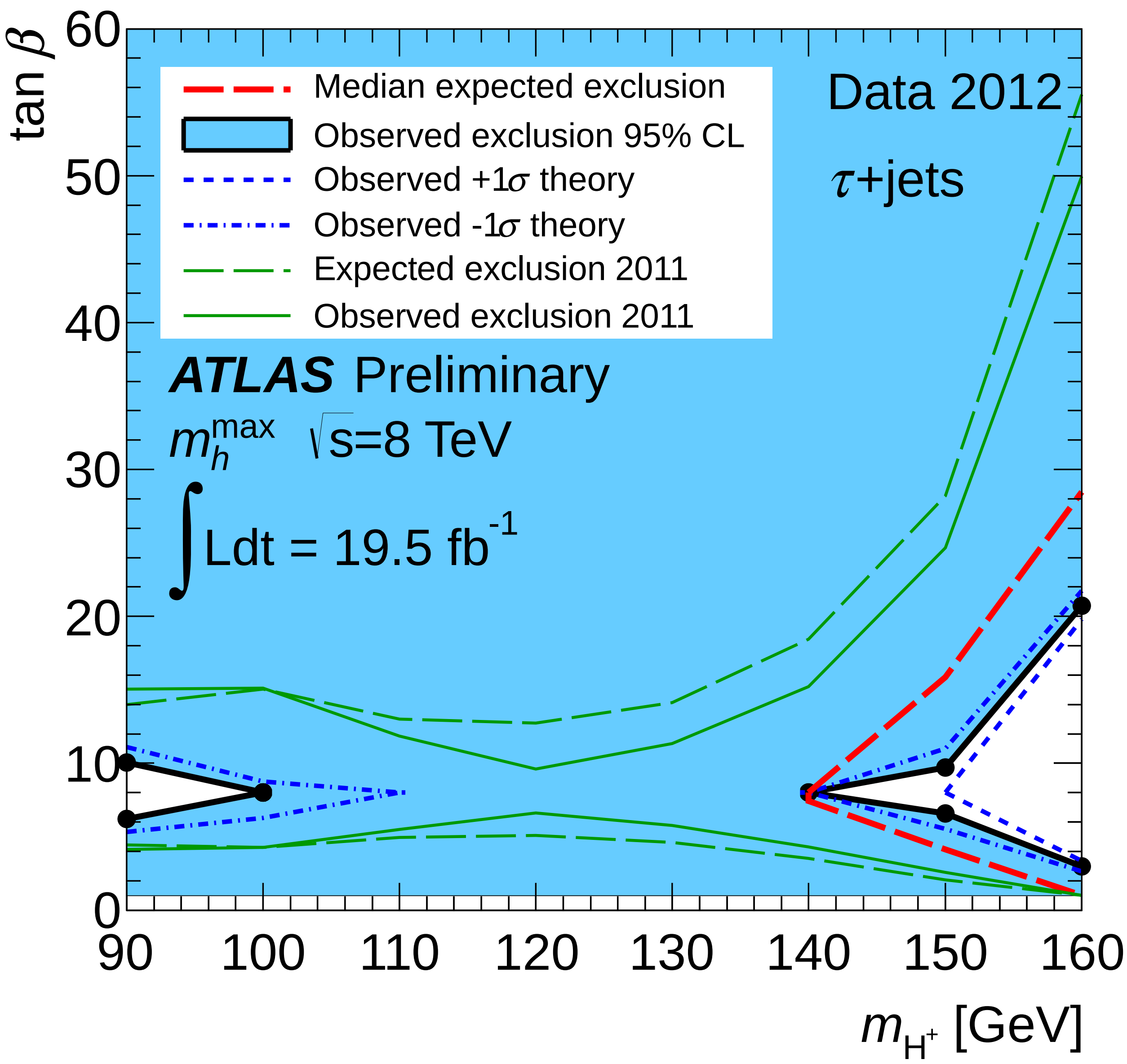
⇒ Interesting prospects also for the charged Higgs searches

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



⇒ model independent limits!

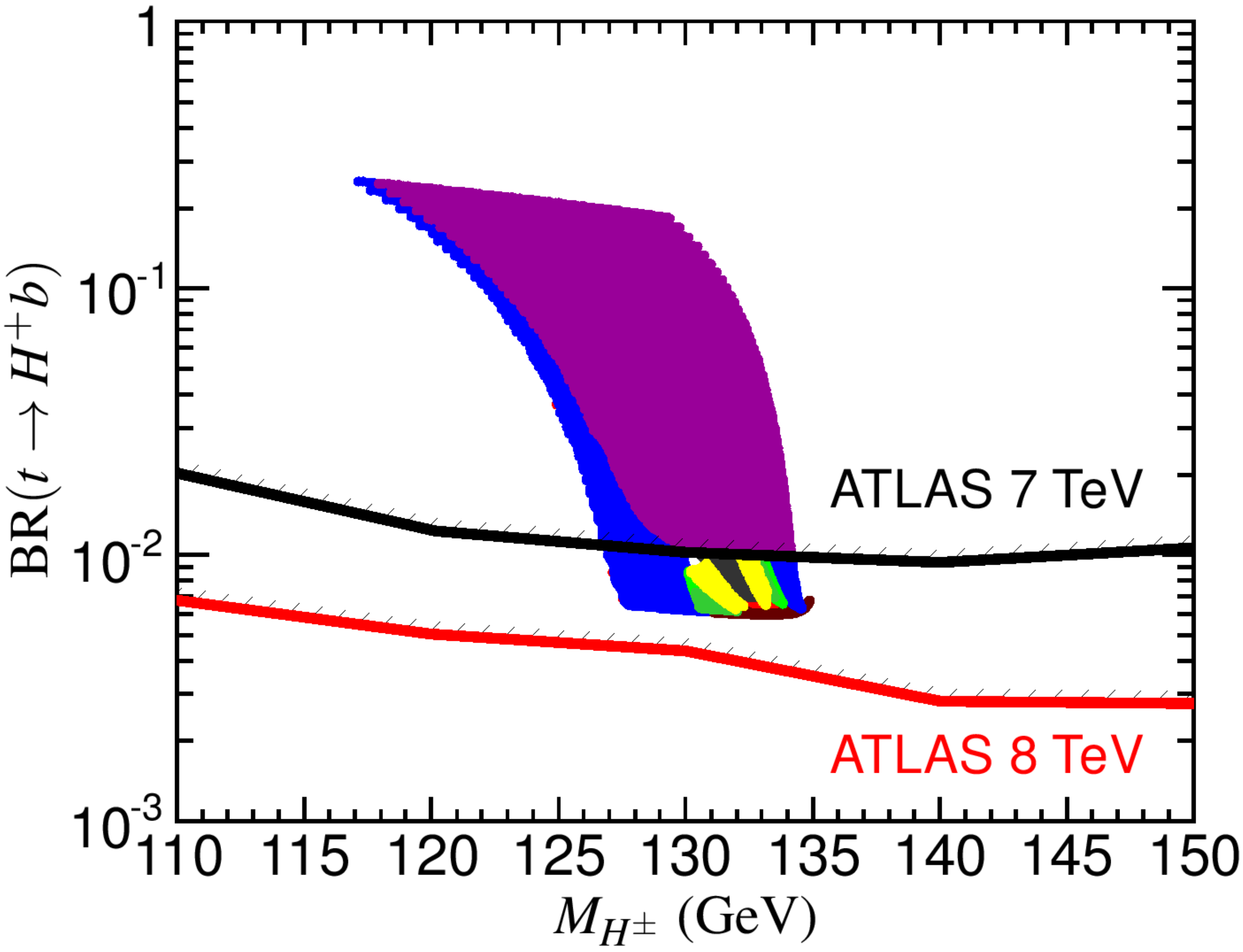
Latest ATLAS results for charged Higgs searches: [ATLAS '13]



$\Rightarrow$ 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:

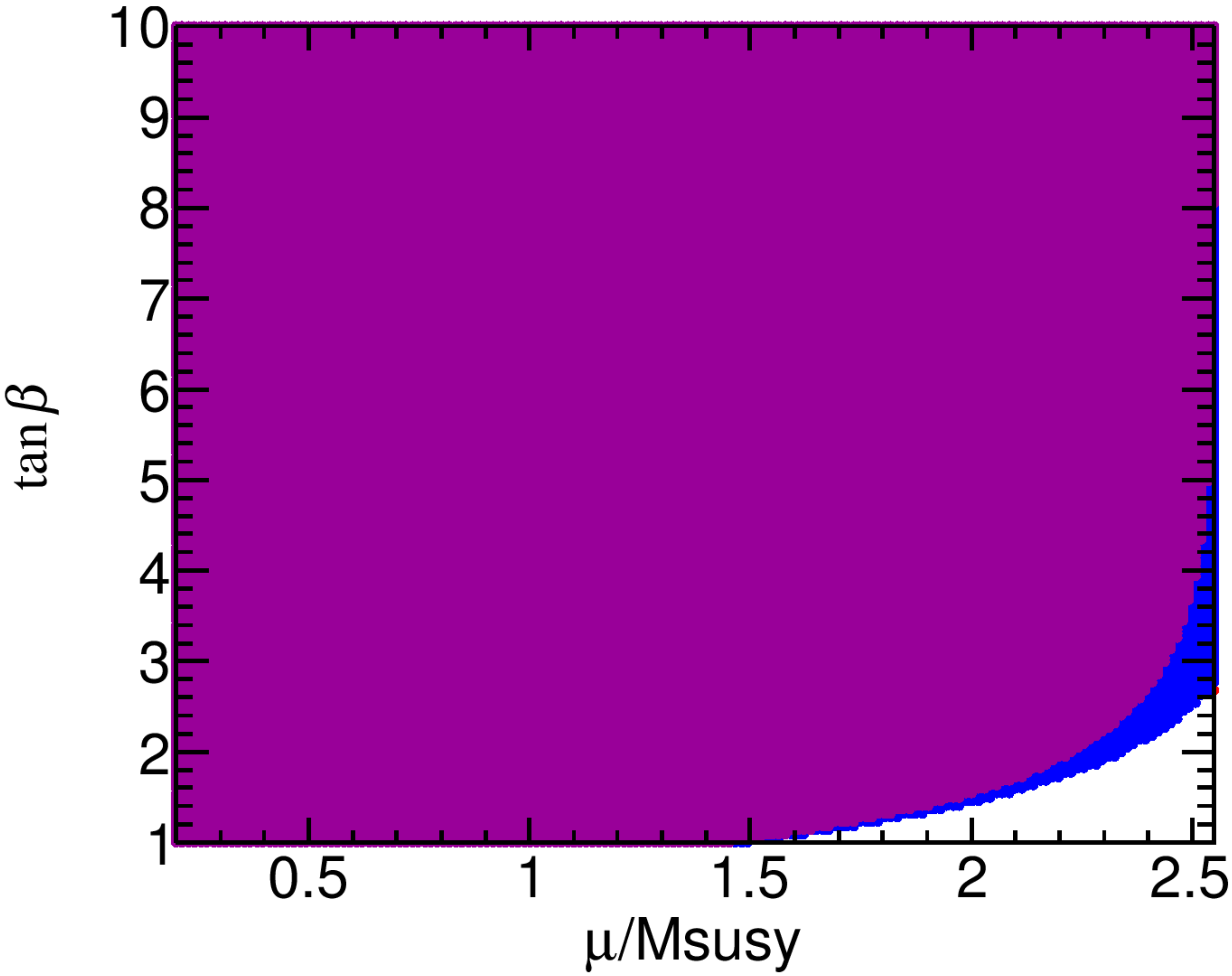
[*HiggsBounds 4.1*]



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

Application of charged Higgs limits on low-M_H scenario:

[*HiggsBounds 4.1*]



⇒ that (particular incarnation of the) low-M_H scenario is excluded?

Analysis of $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h_1$ in the cMSSM:

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

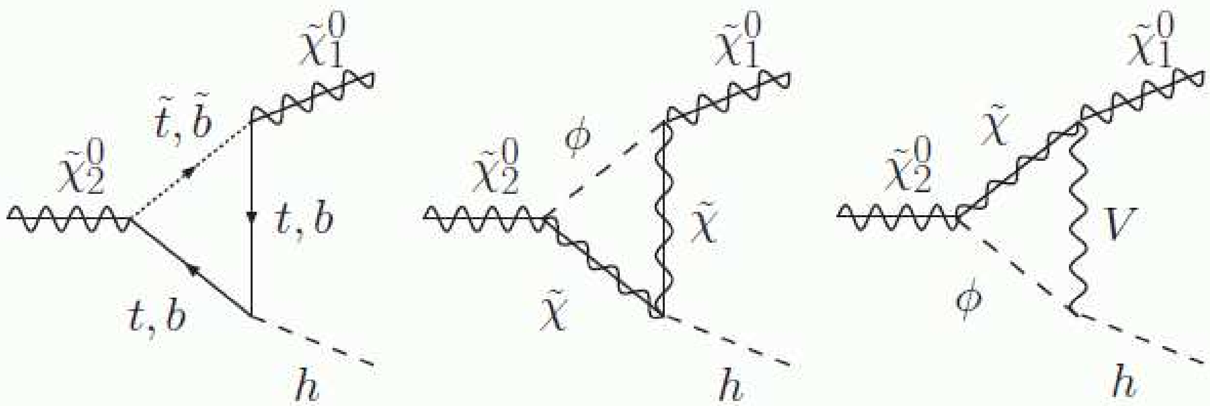
Higgs production in SUSY cascade decays

SUSY cascade decays could be a promising Higgs source

E.g. $\mathcal{CP}$-violating scenario: very light Higgs, $M_{\mathrm{h}_1} \approx 40$ 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

Recent FeynHiggs update: some numerical results

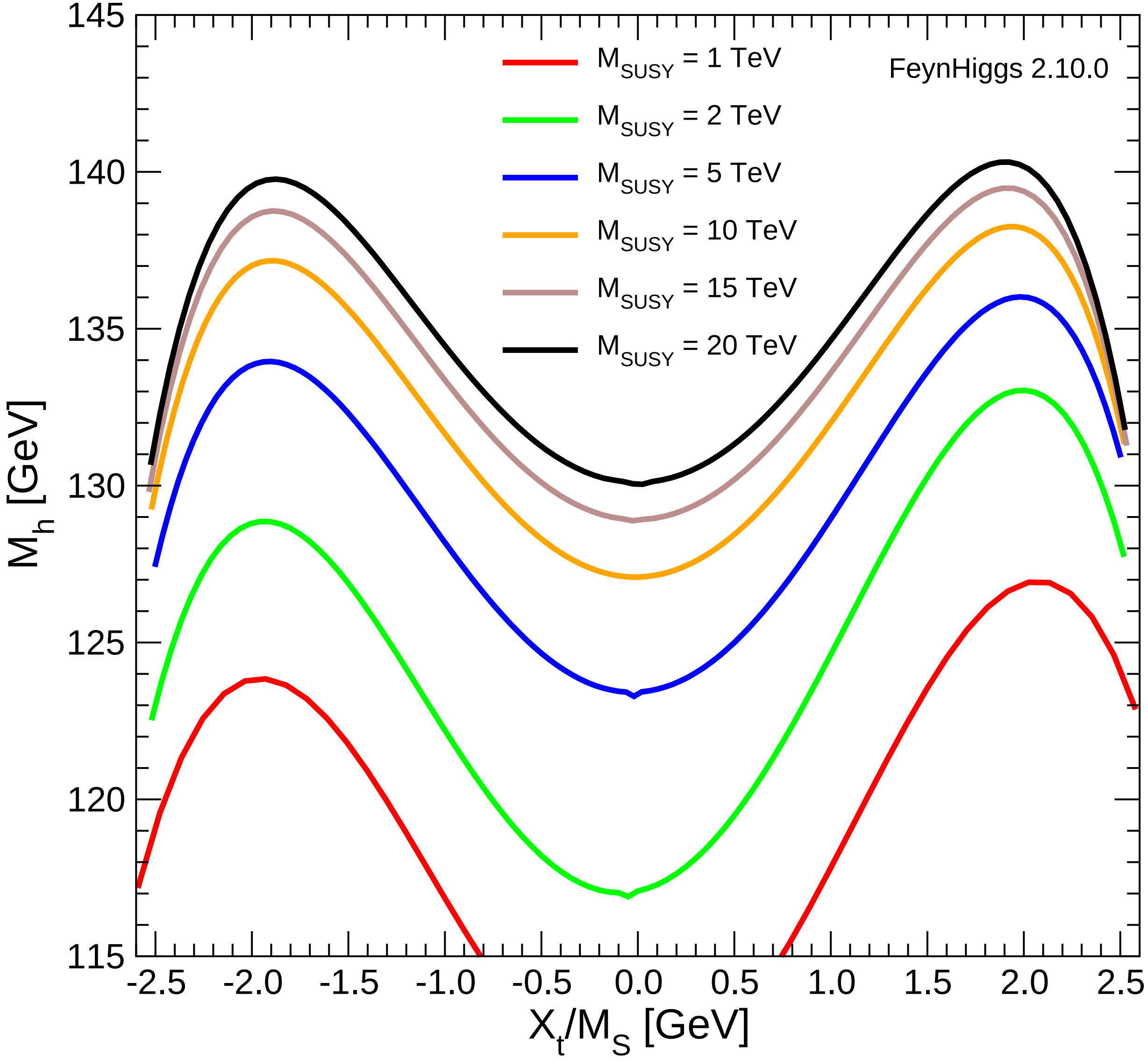
[*FeynHiggs 2.10.0*]

Parameters:

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

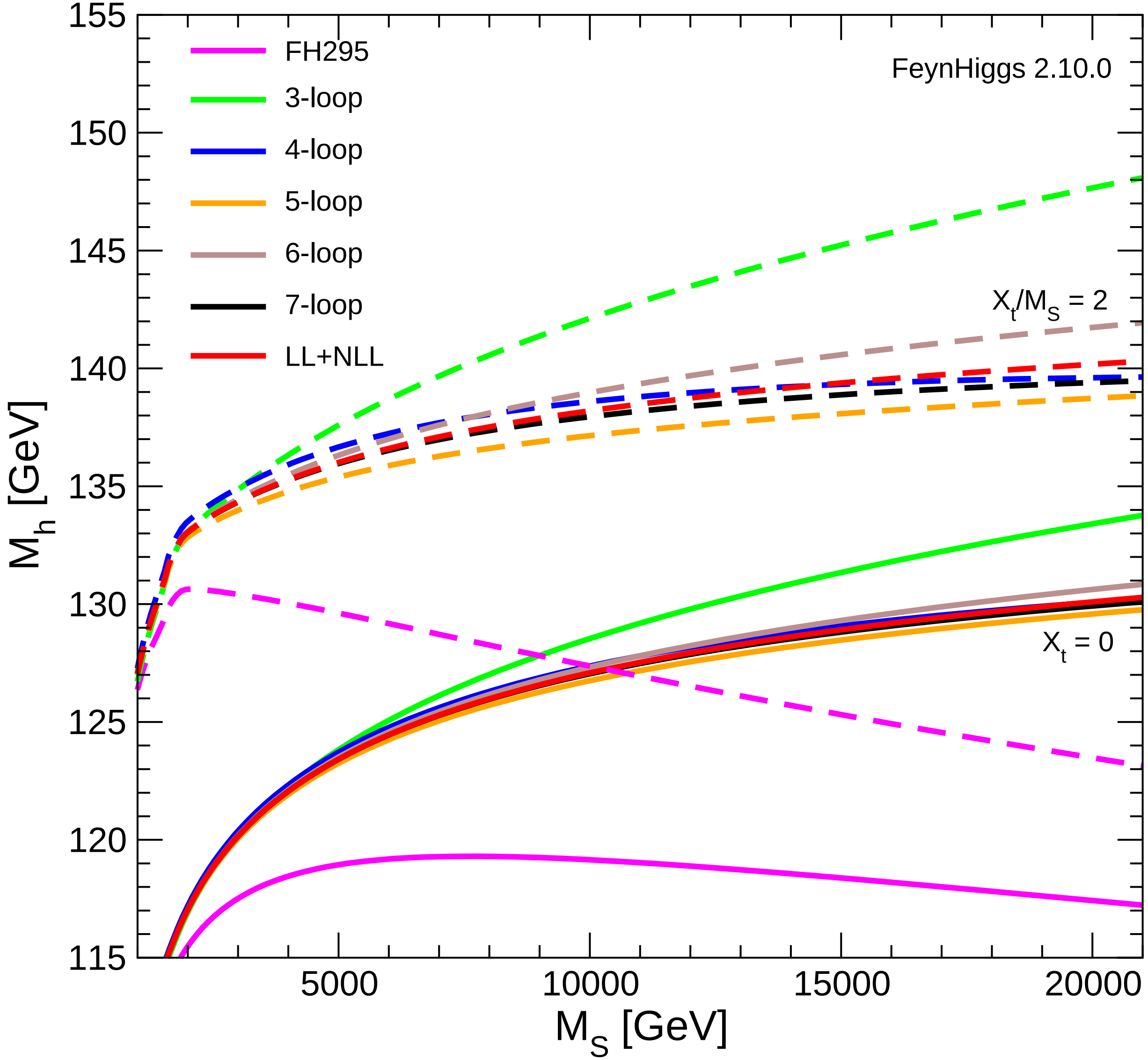
Vary $M_{\rm S}$, X_t to analyze effects

$M_h(X_t/M_S)$:



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

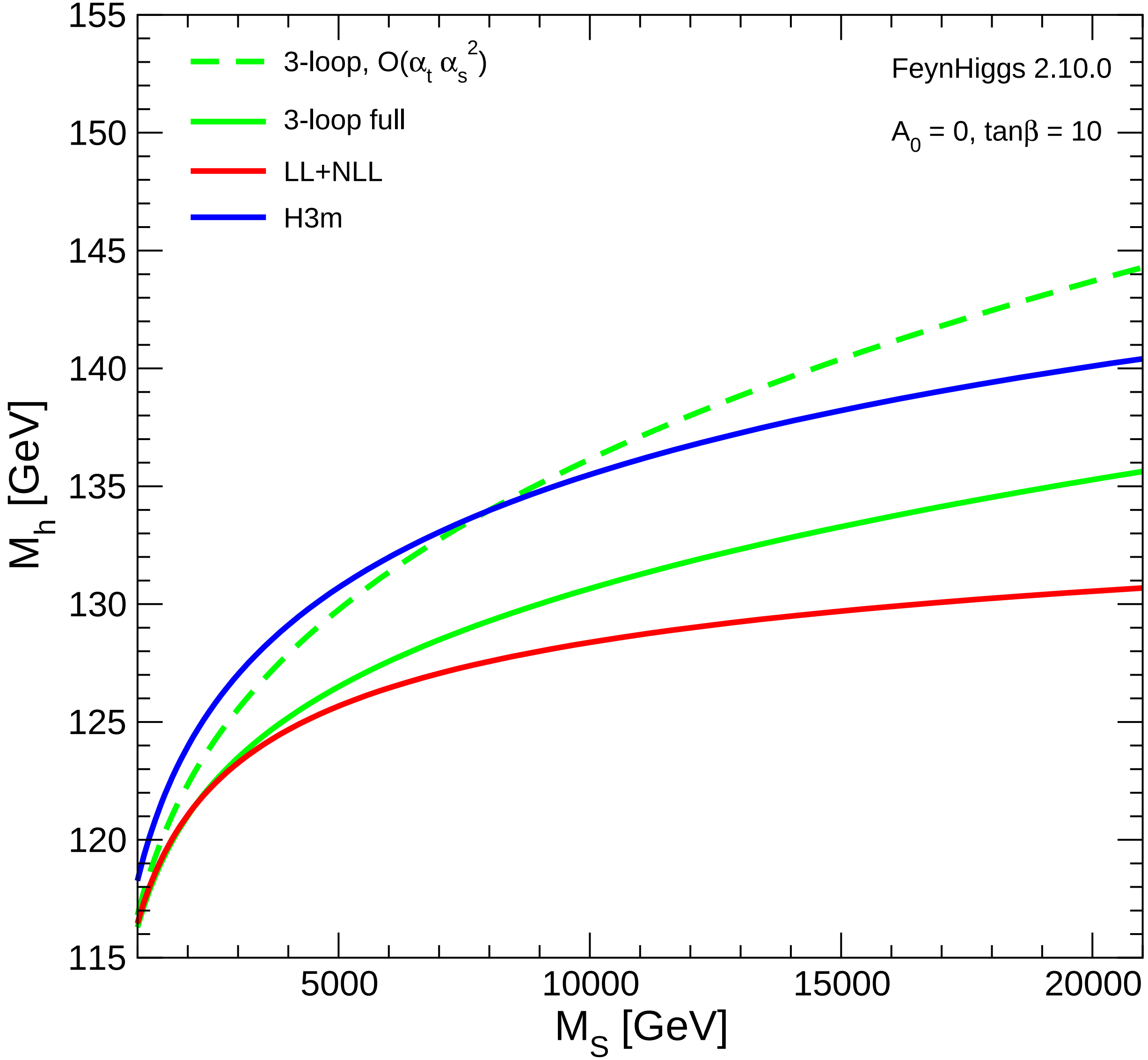
$M_h(M_S)$ for various approximations: [*FeynHiggs 2.10.0*]



⇒ 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*]



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