Determining the properties of the observed state at 126 GeV

Georg Weiglein

DESY

Santander, 09 / 2012

- Introduction
- Mass, spin, $\mathcal{CP}$ properties
- Couplings
- Conclusions and outlook

Introduction

Interpretation of the observed signal at $\sim 126\ \mathrm{GeV}$:

SM, SUSY, . . .

Introduction

Interpretation of the observed signal at ~ 126 GeV:
SM, SUSY, ...

Interpretation in SUSY possible in terms of the lightest (MSSM: h, NMSSM: $h_1, \ldots$; has SM-like behaviour in the decoupling limit, $M_A \gg M_Z$) and the next-to-lightest (MSSM: H, NMSSM: $h_2, \ldots$) neutral Higgs

Introduction

Interpretation of the observed signal at ~ 126 GeV:
SM, SUSY, . . .

Interpretation in SUSY possible in terms of the lightest (MSSM: h, NMSSM: h_1, . . . ; has SM-like behaviour in the decoupling limit, $M_A \gg M_Z$) and the next-to-lightest (MSSM: H, NMSSM: h_2, . . .) neutral Higgs

Latter possibility would imply an additional non-SM like light Higgs, often has mass below the LEP limit of $M_{H_{SM}} > 114.4$ GeV (with reduced couplings to gauge bosons, in agreement with LEP bounds)

$\Rightarrow$ It is important to extend the LHC Higgs searches to the region below 114 GeV!

Not only the observed signal at $\sim 126\ \mathrm{GeV}$ but also the latest limits have important impact on MSSM Higgs searches

Limits in M_A–$\tan\beta$ plane of the MSSM:

- LEP limits: highest sensitivity for small M_A and / or small $\tan\beta$
- LHC limits from $H, A \to \tau^+\tau^-$ search: highest sensitivity for small M_A and / or large $\tan\beta$

Not only the observed signal at ~ 126 GeV *but also the latest limits have important impact on MSSM Higgs searches*

Limits in M_A–$\tan\beta$ plane of the MSSM:

- LEP limits: highest sensitivity for small M_A and / or small $\tan\beta$
- LHC limits from $H, A \to \tau^+\tau^-$ search: highest sensitivity for small M_A and / or large $\tan\beta$
- LHC limits from SM Higgs search: rules out region outside of $123 \text{ GeV} \lesssim M_{H_{SM}} \lesssim 127 \text{ GeV}$

  $\Rightarrow$ Depending on the mixing in the $\tilde{t}$ sector, limits can lead to exclusion in decoupling region, $M_A \gg M_Z$

HiggsBounds: ***determination of 95% C.L. exclusion region from given cross section limits***

[*P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., K. Williams '08, '12*]

In order to obtain an exclusion limit having the correct statistical interpretation as a 95% C.L.:

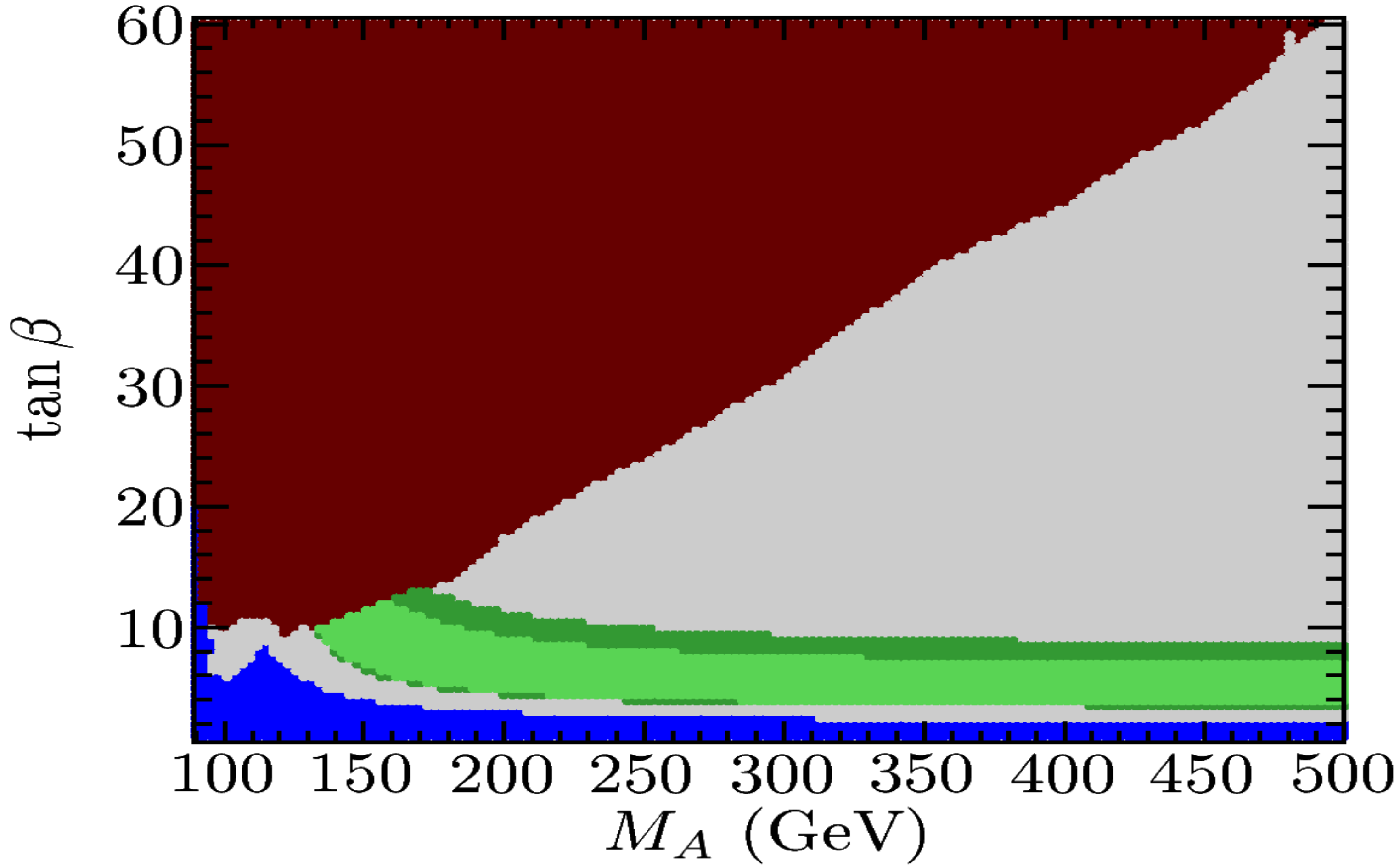
- On the basis of the expected search limits for different channels in a given model one needs to determine for every parameter point the search channel having the highest statistical sensitivity for setting an exclusion limit

- For this single channel only one needs to compare the observed limit with the theory prediction for the Higgs production cross section times decay branching ratio to determine whether or not the considered parameter point of the model is excluded at 95% C.L.

m_h^{max} benchmark scenario: situation in December 2011

Red: LHC limits from $H, A \to \tau^+\tau^-$ search; Blue: LEP limits
Green: compatible with interpreting signal at ~ 126 GeV as light MSSM Higgs h (+ m_t variation)

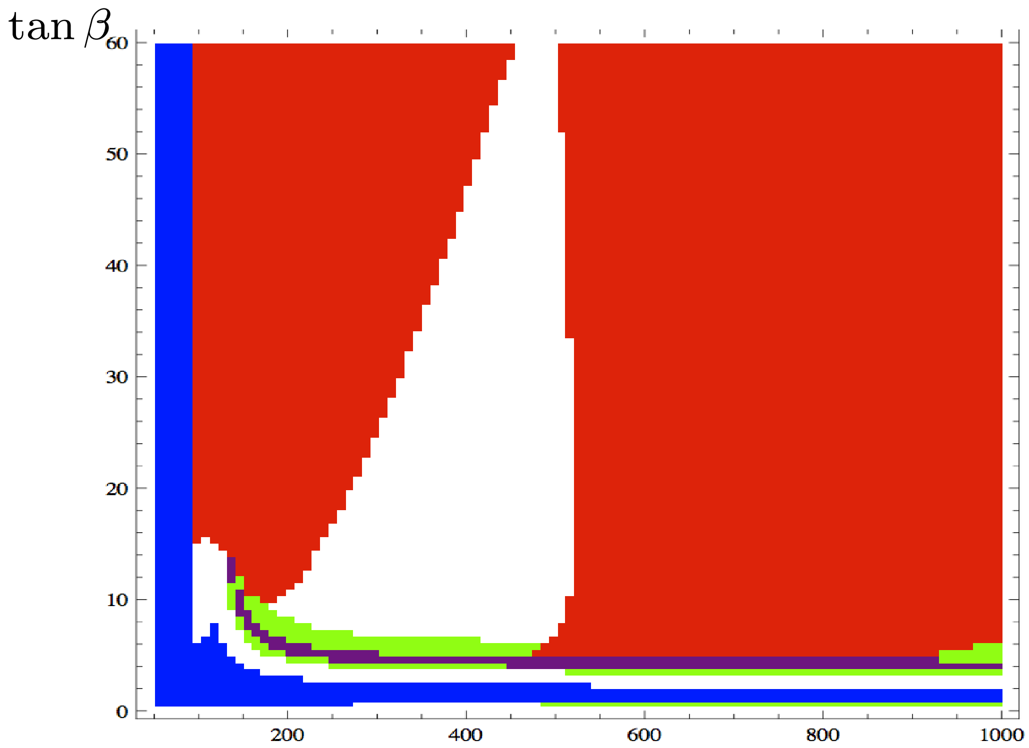
[S. Heinemeyer, O. Stål, G. W. '11]



m_h^{max} *benchmark scenario: situation now*

(no theo. uncertainty imposed on SM Higgs search limit)

[Y. Linke, G. W. '12]



M_A [GeV]

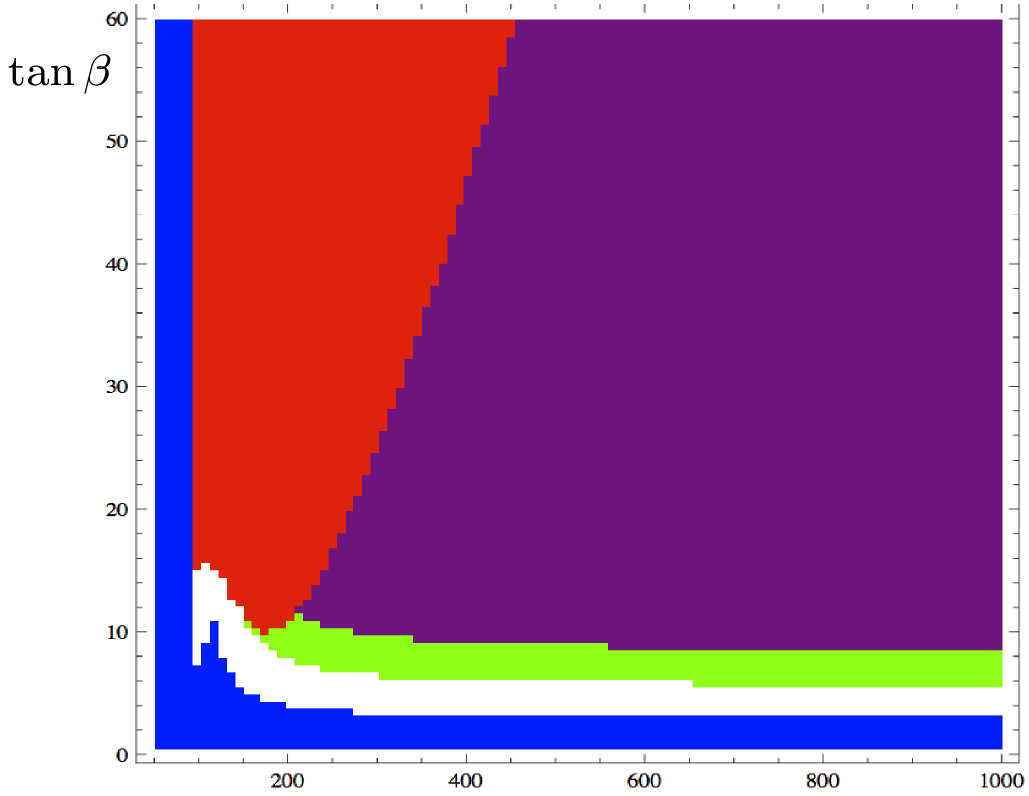
(■) : Excluded by LHC, (■) : Excluded by LEP

(■) : $M_h = 125.5 \pm 1$ GeV, (■) : $M_h = 125.5 \pm 3$ GeV

$\Rightarrow$ Additional LHC-excluded region from SM Higgs searches, $M_h \gtrsim 127$ GeV, very sensitive to SUSY parameters

Modified $m_{\rm h}^{\rm max}$ *scenario:* $X_{\rm t} = 1300$ GeV

[Y. Linke, G. W. '12]



$M_{\rm A}$ [GeV]

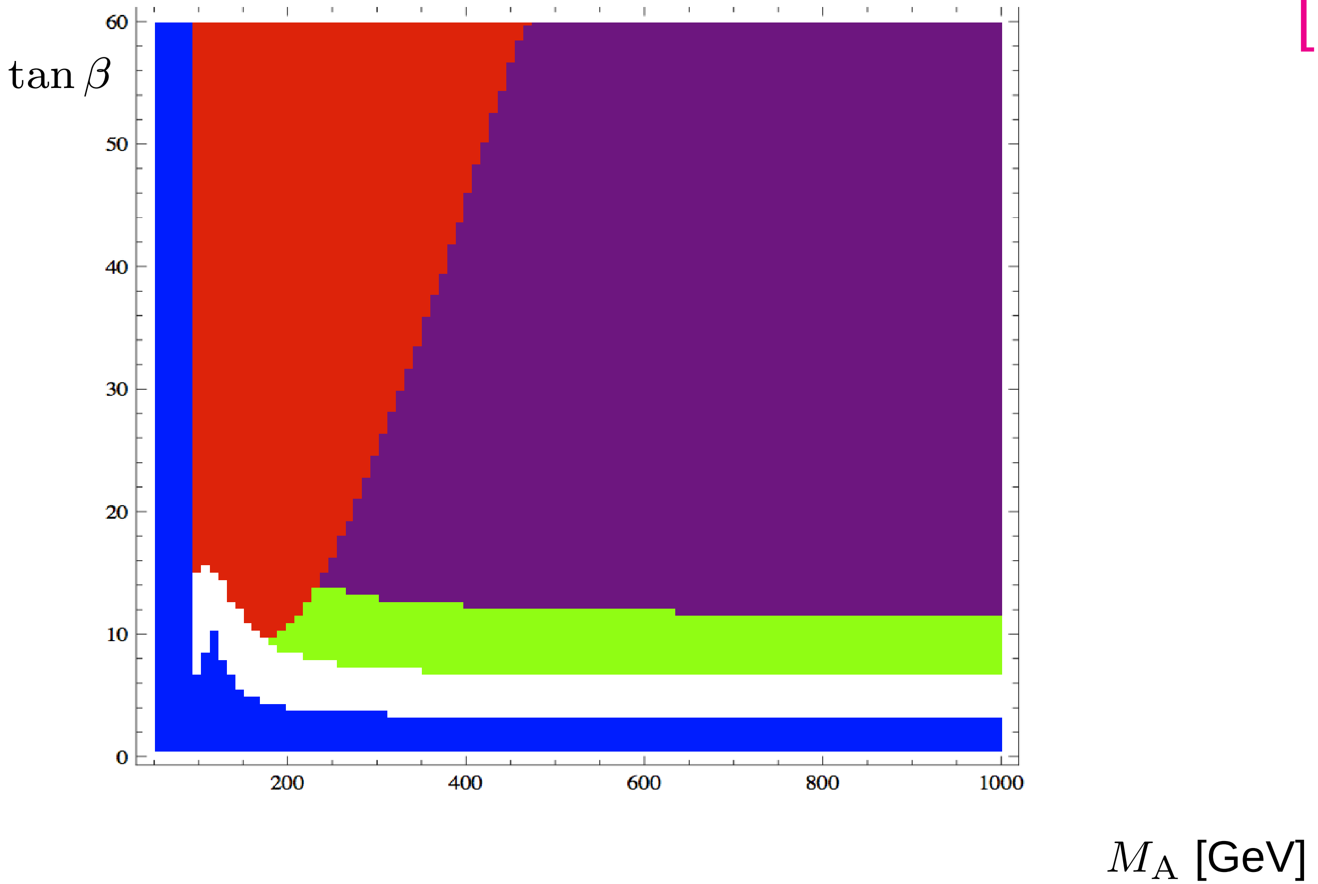
(■) : Excluded by LHC, (■) : Excluded by LEP

(■) : $M_{\rm h} = 125.5 \pm 1$ GeV, (■) : $M_{\rm h} = 125.5 \pm 3$ GeV

$\Rightarrow$ Large region compatible with signal at $M_{\rm h} \approx 126$ GeV

Modified m_h^{max} *scenario:* $X_t = -1500$ GeV

[*Y. Linke, G. W. '12*]



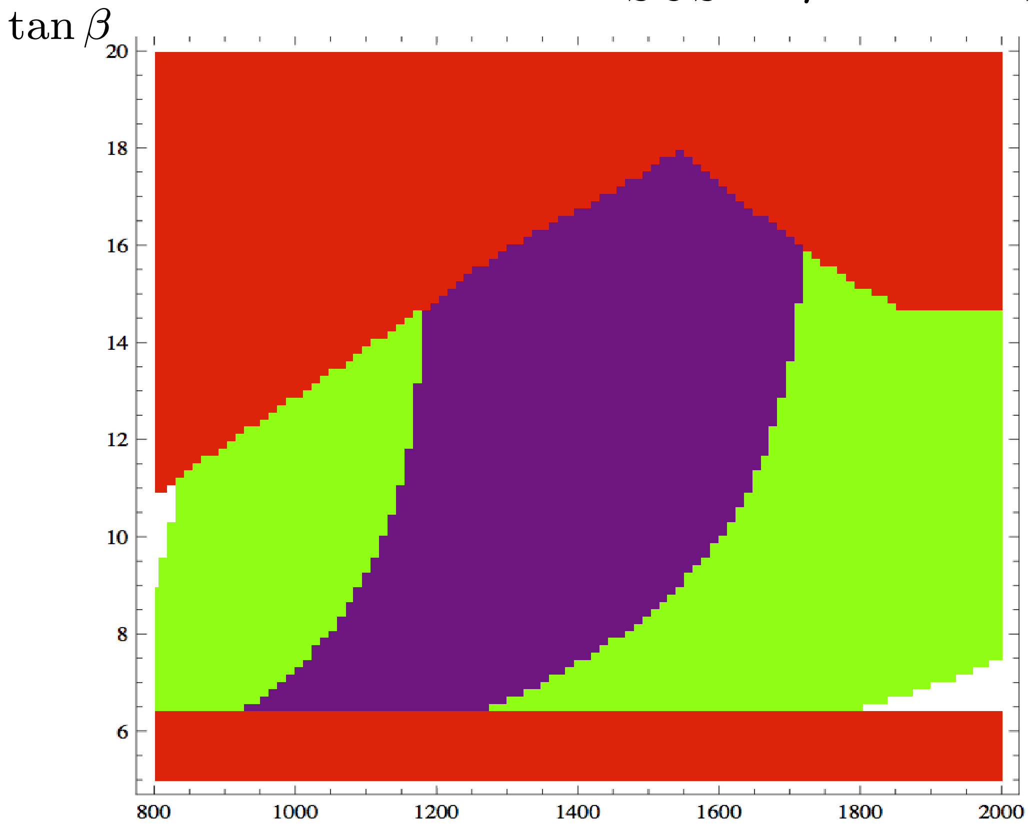
(■) : Excluded by LHC, (■) : Excluded by LEP

(■) : $M_h = 125.5 \pm 1$ GeV, (■) : $M_h = 125.5 \pm 3$ GeV

$\Rightarrow$ Large region compatible with signal at $M_h \approx 126$ GeV

Benchmark scenario where signal at $126\ \mathrm{GeV}$ is interpreted as the heavy $\mathcal{CP}$-even MSSM Higgs

M_{SUSY} varied, $X_{\mathrm{t}} = -1.5 M_{\mathrm{SUSY}}$, $\mu = 2 M_{\mathrm{SUSY}}$ [*Y. Linke, G. W. '12*]



M_{SUSY} [GeV]

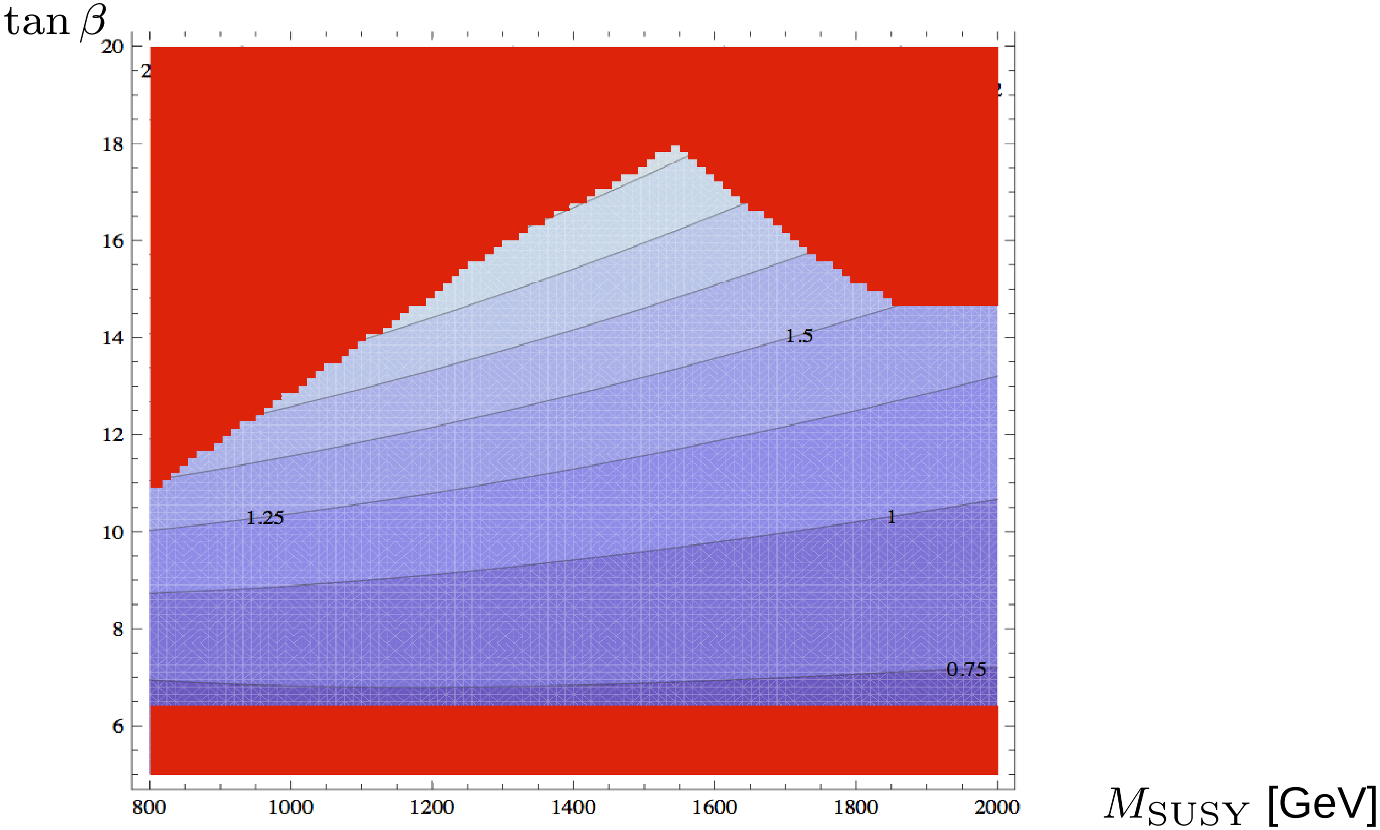
(■) : Excluded by LHC, (■) : Excluded by LEP

(■) : $M_{\mathrm{H}} = 125.5 \pm 1\ \mathrm{GeV}$, (■) : $M_{\mathrm{H}} = 125.5 \pm 3\ \mathrm{GeV}$

$\Rightarrow$ Large region compatible with signal at $M_{\mathrm{H}} \approx 126\ \mathrm{GeV}$

Benchmark scenario where signal at* $126\ \mathrm{GeV}$ *is interpreted as the heavy* $\mathcal{CP}$*-even MSSM Higgs

$\gamma\gamma$ rate relative to SM: $R_{\gamma\gamma}$ [*Y. Linke, G. W. '12*]



(■) : Excluded by LHC, (■) : Excluded by LEP

(■) : $M_h = 125.5 \pm 1\ \mathrm{GeV}$, (■) : $M_h = 125.5 \pm 3\ \mathrm{GeV}$

$\Rightarrow R_{\gamma\gamma} \gtrsim 1$ possible

Mass, spin, $\mathcal{CP}$ properties

Mass determination, assumptions currently made (according to my understanding):

- Single resonance: no overlapping signals

- Finite width effects neglected
  $\Rightarrow$ interference of signal and background neglected
  $\Rightarrow$ These effects will have to be taken into account for future high-precision mass measurements

Higgs spin and $\mathcal{CP}$ properties

Spin: need to discriminate between hypotheses for spin 0, (1), 2

Higgs spin and $\mathcal{CP}$ properties

Spin: need to discriminate between hypotheses for spin 0, (1), 2

At which level of significance can the hypothesis spin $= 1$ be excluded (2 τ's vs. 4 τ's)?

Higgs spin and $\mathcal{CP}$ properties

Spin: need to discriminate between hypotheses for spin 0, (1), 2

At which level of significance can the hypothesis spin $= 1$ be excluded (2 τ's vs. 4 τ's)?

$\mathcal{CP}$-properties: Observed state can be any admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components

Observables investigated at the LHC ($H \to ZZ^*, WW^*$ and H production in weak boson fusion) involve HVV coupling

$\Rightarrow$ little sensitivity to $\mathcal{CP}$-odd components:
would be loop-induced and heavily suppressed in most BSM models

$\Rightarrow$ Observables involving the HVV coupling "project" to the $\mathcal{CP}$-even component of the observed state

$\mathcal{CP}$ properties

General structure of HVV coupling (from Lorentz invariance):

$$a_1(q_1, q_2) g^{\mu\nu} + a_2(q_1, q_2) \left[(q_1 q_2)\, g^{\mu\nu} - q_1^\mu q_2^\nu \right] + a_3(q_1, q_2) \epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

Pure $\mathcal{CP}$-even state: $a_1 = 1, a_2 = 0, a_3 = 0$,

Pure $\mathcal{CP}$-odd state: $a_1 = 0, a_2 = 0, a_3 = 1$

Do loop effects give rise to a sizable contribution to a_3?

$\mathcal{CP}$ ***properties***

Example: MSSM, CPX scenario: maximally $\mathcal{CP}$-violating benchmark scenario:

[*T. Figy, S. Palmer, G. W. '10*]

$$a_1 \approx 50, \quad a_3 \approx 10^{-10}$$

$\Rightarrow$ Even in such an "extreme" case the contribution to a_3 remains tiny

$\Rightarrow$ Experimental sensitivity of HVV coupling to $\mathcal{CP}$-violating effects is small

$\Rightarrow$ Discrimination between the hypotheses of a pure $\mathcal{CP}$-even and a pure $\mathcal{CP}$-odd state is not sufficient to determine the $\mathcal{CP}$ properties of the new state

$\mathcal{CP}$ ***properties***

The fact that we have observed the new state in the ZZ^* and WW^* channels (at a certain level of significance) already tells us that it is most likely not a pure $\mathcal{CP}$-odd state

$\mathcal{CP}$ properties

The fact that we have observed the new state in the ZZ^* and WW^* channels (at a certain level of significance) already tells us that it is most likely not a pure $\mathcal{CP}$-odd state

How much more will we learn from the dedicated analyses of the $\mathcal{CP}$ properties in the channels involving the HVV coupling (from angular distributions, etc.)?

$\mathcal{CP}$ properties

The fact that we have observed the new state in the ZZ^* and WW^* channels (at a certain level of significance) already tells us that it is most likely not a pure $\mathcal{CP}$-odd state

How much more will we learn from the dedicated analyses of the $\mathcal{CP}$ properties in the channels involving the HVV coupling (from angular distributions, etc.)?

$\Rightarrow$ Need to exploit channels involving only Higgs couplings to fermions

Couplings

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data:

Assumptions:

- Signal corresponds to only one state, no overlapping resonances, etc.
- Zero-width approximation
- Only modifications of coupling strenghts (absolute values of the couplings) are considered, no modification of the tensor structure as compared to the SM case

  $\Rightarrow$ Assume that the observed state is a $\mathcal{CP}$-even scalar

What is actually meant by a Higgs coupling measurement?

A coupling is not a directly measurable quantity

$\Rightarrow$ Need "unfolding" procedure to extract information on the couplings from the actually measured quantities, i.e. $\sigma \times \mathrm{BR}$

$\Rightarrow$ Gives rise in general to a model dependence (in particular through higher-order corrections)

What is actually meant by a Higgs coupling measurement?

A coupling is not a directly measurable quantity

$\Rightarrow$ Need "unfolding" procedure to extract information on the couplings from the actually measured quantities, i.e. $\sigma \times \mathrm{BR}$

$\Rightarrow$ Gives rise in general to a model dependence (in particular through higher-order corrections)

Should one simply use the lowest-order relations?

$\Rightarrow$ Determination of "effective lowest-order couplings"

$\Rightarrow$ Misses large higher-order corrections

Compatibility of the results with the SM would be difficult to assess

Single channel results vs. simultaneous information from several channels

Single channel results: signal strength parameters μ_i for separate search channels

$\Rightarrow$ Most robust information for testing different models

Very useful for confronting theory predictions with experimental results

Adding information from different channels increases sensitivity

But: interpretation of the results is in general more difficult

Analysis in the long run

As long as the SM continues to be (roughly) compatible with the data:

$\Rightarrow$ Use full SM predictions including all available higher-order corrections $+$ anomalous couplings

$\Rightarrow$ Appropriate tools needed

Anomalous couplings would in general change kinematic distributions

$\Rightarrow$ No simple rescaling of MC predictions possible

$\Rightarrow$ Not feasible for analysis of 2012 data set

$\Rightarrow$ Proposal of “interim framework”

Analysis in the long run

As long as the SM continues to be (roughly) compatible with the data:

⇒ Use full SM predictions including all available higher-order corrections + anomalous couplings

⇒ Appropriate tools needed

Anomalous couplings would in general change kinematic distributions

⇒ No simple rescaling of MC predictions possible

⇒ Not feasible for analysis of 2012 data set

⇒ Proposal of “interim framework”

If SM is ruled out ⇒ Move to other reference model

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data

Use state-of-the-art predictions in the SM and rescale the predictions with “leading order inspired” scale factors κ_i ($\kappa_i = 1$ corresponds to the SM case)

Note: scaling of couplings is in general not possible if higher-order electroweak corrections are included

In the SM: Higgs sector is determined by single parameter M_{H} ($+$ higher-order contributions)

$\Rightarrow$ Once M_{H} is fixed the Higgs couplings are determined and cannot be varied within the SM

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data

Scaling of couplings $\Leftrightarrow$ test of deviations from the SM

Note: acceptances and efficiencies are assumed to be as in the SM

$\Rightarrow$ This will have an impact on the interpretation in case a sizable deviation from the SM prediction gets established

$\Rightarrow$ Results obtained from the analyis with scaled couplings cannot be interpreted as “coupling measurements”

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data

Which kind of scaling factors should be considered?

In general, scale factors are needed for couplings of the new state to

t, b, τ, W, Z, $\ldots$

$+$ extra loop contribution to $\sigma(gg \to H)$, $\Gamma(H \to gg)$

$+$ extra loop contribution to $\Gamma(H \to \gamma\gamma)$

$+$ additional contributions to total width, Γ_H, from undetectable final states

Total width Γ_H cannot be measured without further assumptions (otherwise only coupling ratios can be determined, not absolute values of couplings)

Proposed "benchmarks" for scale factors κ_i

Different "benchmark" proposals, based on simplifying assumptions to reduce the number of free parameters

1 parameter: overall coupling strength μ

2 parameters: e.g. common scale factor κ_V for W, Z, and common scale factor for all fermions, κ_F

$\ldots$

For each benchmark (except overall coupling strength) two versions are proposed:

with and without taking into account the possibility of additional contributions to the total width

Proposed "benchmarks" for scale factors κ_i

If additional contributions to Γ_H are allowed

$\Rightarrow$ Determination of ratios of scaling factors, e.g. $\kappa_i \kappa_j / \kappa_H$

If no additional contributions to $\Gamma(H \to \gamma\gamma)$, Γ_H, $\ldots$ are allowed

$\Rightarrow$ κ_γ can be determined in terms of κ_b, κ_t, κ_τ, κ_W evaluated to NLO QCD accuracy

Examples of results for different benchmark scenarios with two free parameters: [*see Marumi's talk*]

It seems difficult to go beyond three free parameters in the near future

$\Rightarrow$ Benchmark scenarios of this kind are in general too restrictive to allow an interpretation within a "realistic" model like the MSSM

MSSM interpretation of scale factors κ_i?

MSSM:

- Higgs couplings to up-type and down-type fremions are different $\Rightarrow$ cannot be described in terms of common κ_F
- Large SUSY contributions can affect relation between coupling to $b\bar{b}$ and $\tau^+\tau^-$
- Extra contributions to $\sigma(gg \to H)$, $\Gamma(H \to gg)$, $\Gamma(H \to \gamma\gamma)$: $\tilde{\mathrm{t}}$, $\tilde{\tau}$, $\tilde{\chi}^{\pm}$, ...
- Extra contribution to total width: $H \to$ invisible, ...

$\Rightarrow$ General parametrisation needed to accomodate possible SUSY effects

Conclusions

- After the discovery we have now entered the phase of probing the properties of the new particle

Conclusions

- After the discovery we have now entered the phase of probing the properties of the new particle
- The observed signal could easily be accommodated within the MSSM and the NMSSM

Conclusions

- After the discovery we have now entered the phase of probing the properties of the new particle
- The observed signal could easily be accommodated within the MSSM and the NMSSM
- Interpretation is possible both in terms of the lightest and the second-lightest SUSY Higgs $\Rightarrow$ second possibility would imply an additional non-SM like light Higgs

Conclusions

- After the discovery we have now entered the phase of probing the properties of the new particle
- The observed signal could easily be accommodated within the MSSM and the NMSSM
- Interpretation is possible both in terms of the lightest and the second-lightest SUSY Higgs $\Rightarrow$ second possibility would imply an additional non-SM like light Higgs
- Determination of the properties of the new state at $\sim 126\ \mathrm{GeV}$: When interpreting the results we need to be careful about the assumptions made in the analyses

Conclusions

- After the discovery we have now entered the phase of probing the properties of the new particle
- The observed signal could easily be accommodated within the MSSM and the NMSSM
- Interpretation is possible both in terms of the lightest and the second-lightest SUSY Higgs $\Rightarrow$ second possibility would imply an additional non-SM like light Higgs
- Determination of the properties of the new state at $\sim 126 \text{ GeV}$: When interpreting the results we need to be careful about the assumptions made in the analyses
- Determination of $\mathcal{CP}$ properties will be challenging

Conclusions

- After the discovery we have now entered the phase of probing the properties of the new particle
- The observed signal could easily be accommodated within the MSSM and the NMSSM
- Interpretation is possible both in terms of the lightest and the second-lightest SUSY Higgs $\Rightarrow$ second possibility would imply an additional non-SM like light Higgs
- Determination of the properties of the new state at ~ 126 GeV: When interpreting the results we need to be careful about the assumptions made in the analyses
- Determination of $\mathcal{CP}$ properties will be challenging
  Framework for testing deviations of couplings from the SM
  Results on scale factors are not (yet) sufficiently general to allow interpretation in a realistic model like the MSSM

Outlook

The best way of experimentally proving that the observed state is not the SM Higgs is to find in addition (at least one) non-SM like Higgs!

A non-standard Higgs boson can be heavier but also lighter than the state observed at 126 GeV

Search for a light non-standard Higgs:

- Extend searches (e.g. $H \to \gamma\gamma$, $b\bar{b}H, H \to b\bar{b}$, ...) to the region below 100 GeV (such a scenario can be realised in the MSSM, NMSSM, ...)
- Such a light Higgs could be produced in a SUSY cascade, e.g. $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$

Backup

Higgs hunting: cross section limits vs. benchmark scenarios

Higgs searches at LEP, the Tevatron and the LHC:

Searches in different production and decay channels

Limits have been presented in two ways:

- For a specific model: SM, MSSM benchmark scen., . . .

  $\Rightarrow$ combination of different channels possible

  difficult to interpret for other models or w.r.t. changes in the input parameters or the theoretical predictions

- As cross section limits for a certain search topology

  $\Rightarrow$ exclusion bounds have to be tested channel by channel

  fairly model-independent and generally applicable

Search for heavy neutral SUSY Higgs bosons

- Experimental results in the MSSM are usually interpreted in the plane of the parameters M_{A}, $\tan\beta$, which govern the Higgs sector at tree level

  Search for heavy SUSY Higgs bosons via $H, A \to \tau^+\tau^-$ has highest sensitivity for small M_{A} and large $\tan\beta$

- Higher-order corrections, Higgs decays into SUSY particles

  $\Rightarrow$ full structure of the SUSY model enters

  $\Rightarrow$ other parameters are fixed in certain "benchmark scenarios"

How are the benchmark scenarios affected by the latest results from the LHC and how robust are the limits in the M_{A}–$\tan\beta$ plane w.r.t. other SUSY effects?

Benchmarks used so far for Higgs searches at the Tevatron and the LHC ($\mathcal{CP}$-conserving case)

[*M. Carena, S. Heinemeyer, C. Wagner, G. W. '02*]

Scenarios for general MSSM, no specific SUSY-breaking scenario assumed, no external constraints, M_A, $\tan\beta$ varied

- m_h^{max}-scenario: $X_t = 2\,M_{SUSY}$, $M_{SUSY} = 1$ TeV, $\mu = +200$ GeV

  $\Rightarrow$ maximal $m_h(\tan\beta)$ for fixed m_t, M_{SUSY}

- no-mixing scenario: $X_t = 0$, $M_{SUSY} = 2$ TeV

- small α_{eff} scenario:

  $M_{SUSY} = 800\,\mathrm{GeV}$, $\mu = 2.5\,M_{SUSY}$, $X_t = -1100$ GeV

  $\Rightarrow$ suppression of $h \to b\bar{b}$, $h \to \tau\tau$

- gluophobic Higgs scenario: $M_{SUSY} = 350$ GeV, $X_t = -750$ GeV

  $\Rightarrow$ suppression of $gg \to h$

Most widely used: $m_{\rm h}^{\rm max}$*-scenario*

Maximal $m_{\rm h}(\tan\beta)$ for fixed $m_{\rm t}$, $M_{\rm SUSY}$

$\Rightarrow$ Most conservative limits from LEP

Limits from $H, A \to \tau^+\tau^-$ searches at the LHC and the Tevatron are rather robust w.r.t. variations of the SUSY parameters

$\Rightarrow$ $m_{\rm h}^{\rm max}$-scenario has been the standard for presenting LHC results up to now

Note: limits from $H, A \to b\bar{b}$ searches have a much higher sensitivity to variations of the SUSY parameters