Higgs constraints and SUSY interpretation

Georg Weiglein

DESY

Hamburg, 09 / 2011

- Introduction: physics of electroweak symmetry breaking
- *HiggsBounds*: confronting arbitrary Higgs sectors with exclusion bounds from LEP, the Tevatron and the LHC
- Latest Higgs search results confronting the SM and SUSY
- Outlook

Introduction: physics of electroweak symmetry breaking

What is the mechanism of electroweak symmetry breaking?

- Standard Model (SM), SUSY, . . . :
  Higgs mechanism, elementary scalar particle(s)

- Strong electroweak symmetry breaking:
  a new kind of strong interaction

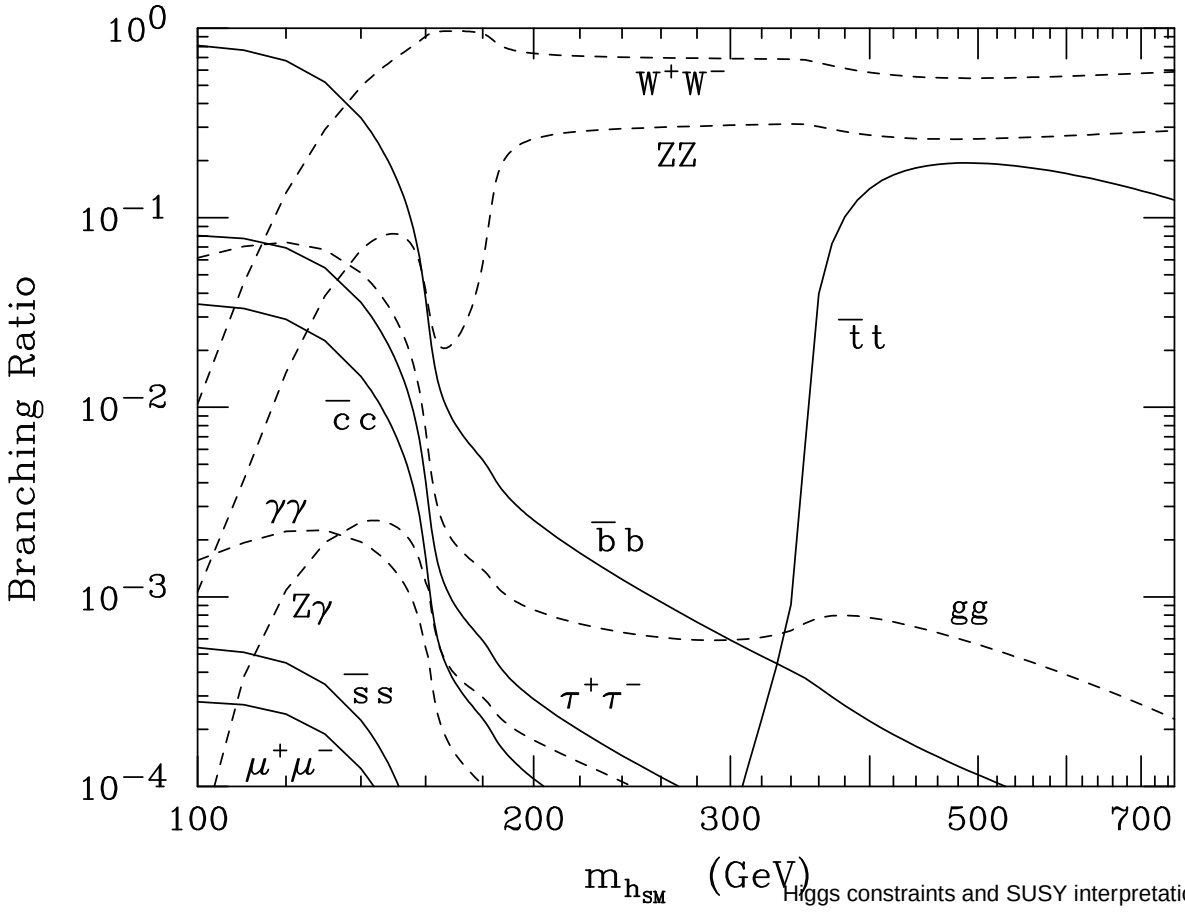
- Higgsless models in extra dimensions: boundary conditions for SM gauge bosons and fermions on Planck and TeV branes in higher-dimensional space

$\Rightarrow$ New phenomena required at the TeV scale

Higgs phenomenology: SM and beyond

Standard Model: a single parameter determines the whole Higgs phenomenology: M_{H}

Branching ratios of the SM Higgs:



$\Rightarrow$ dominant BRs:

$M_{\mathrm{H}} \lesssim 140$ GeV:

$H \to b\bar{b}$

$M_{\mathrm{H}} \gtrsim 140$ GeV:

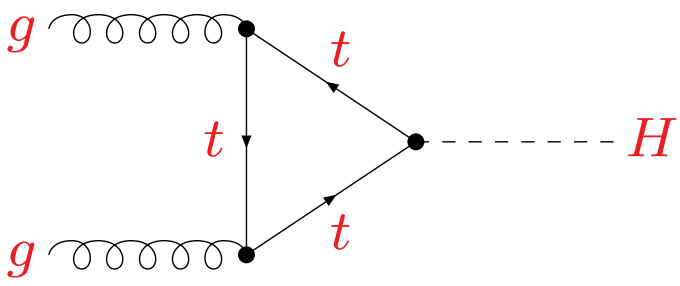
$H \to W^+W^-, ZZ$

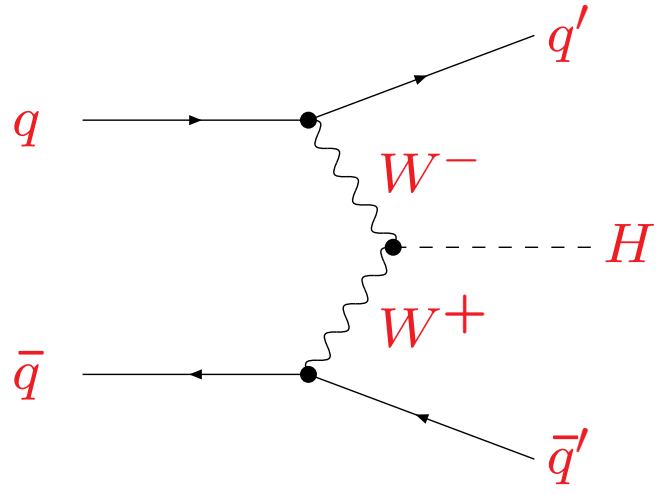
Production of a SM-like Higgs at the LHC

SM Higgs production at the LHC:

Dominant production processes:

gluon fusion: $gg \to H$, weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}' H$





Higgs physics beyond the SM

In the SM the same Higgs doublet is used “twice” to give masses both to up-type and down-type fermions

$\Rightarrow$ extensions of the Higgs sector having (at least) two doublets are quite “natural”

$\Rightarrow$ Would result in several Higgs states

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Example: SUSY in the “decoupling limit”

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Many extended Higgs theories have over large part of their parameter space a lightest Higgs scalar with properties very similar to those of the SM Higgs boson

Example: SUSY in the “decoupling limit”

But there is also the possibility that none of the Higgs bosons is SM-like

Higgs physics in Supersymmetry

"Simplest" extension of the minimal Higgs sector:

Minimal Supersymmetric Standard Model (MSSM)

- Two doublets to give masses to up-type and down-type fermions (extra symmetry forbids to use same doublet)
- SUSY imposes relations between the parameters

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- SUSY imposes relations between the parameters

$\Rightarrow$ Two parameters instead of one: $\tan\beta \equiv \frac{v_u}{v_d}$, $M_{\rm A}$ (or $M_{\rm H^\pm}$)

$\Rightarrow$ Upper bound on lightest Higgs mass, $M_{\rm h}$ (*FeynHiggs*):
[*S. Heinemeyer, W. Hollik, G. W. '99*], [*G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02*]

$$M_{\rm h} \lesssim 130\,\text{GeV}$$

Very rich phenomenology

SUSY $\oplus$ Higgs phenomenology

- Large enhancement / suppression of standard search channels possible

  Example: large enhancement of $H\bar{b}b$ coupling
  $\Rightarrow$ large suppression of BR($h \to \gamma\gamma$), BR($h \to WW^*$), ...

- New channels:
  - Higgs decays into supersymmetric particles (e.g., invisible Higgs decays)
  - Higgs production in SUSY decays
  - $h_i \to h_j h_j$ decays
  - ...

- Higgses with nearly degenerate masses: large interference effects, resonance-type behaviour possible

MSSM with complex parameters: a very light SUSY Higgs?

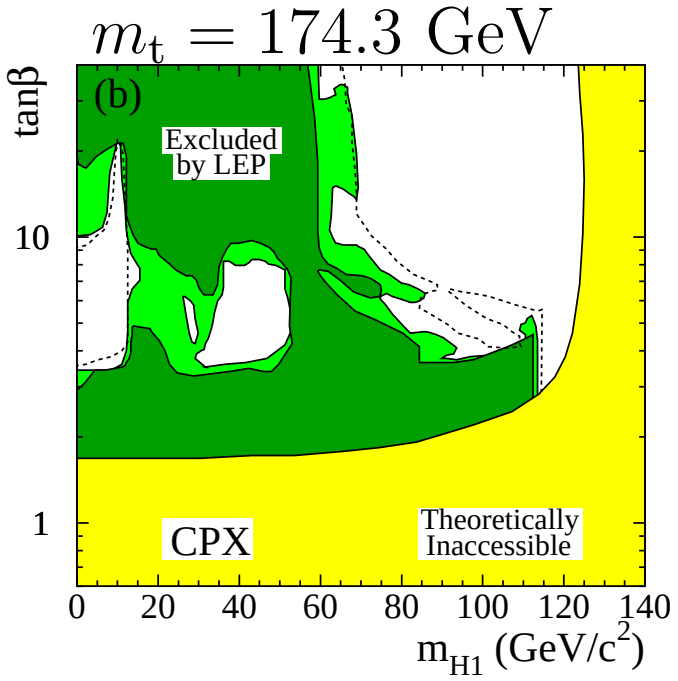
MSSM with $\mathcal{CP}$-violating phases (CPX scenario):

Light Higgs, h_1: strongly suppressed h_1VV couplings

Second-lightest Higgs, h_2, possibly within LEP reach (with reduced VVh_2 coupling), h_3 beyond LEP reach

Large $\mathrm{BR}(h_2 \to h_1 h_1) \Rightarrow$ difficult final state

[*LEP Higgs WG '06*]

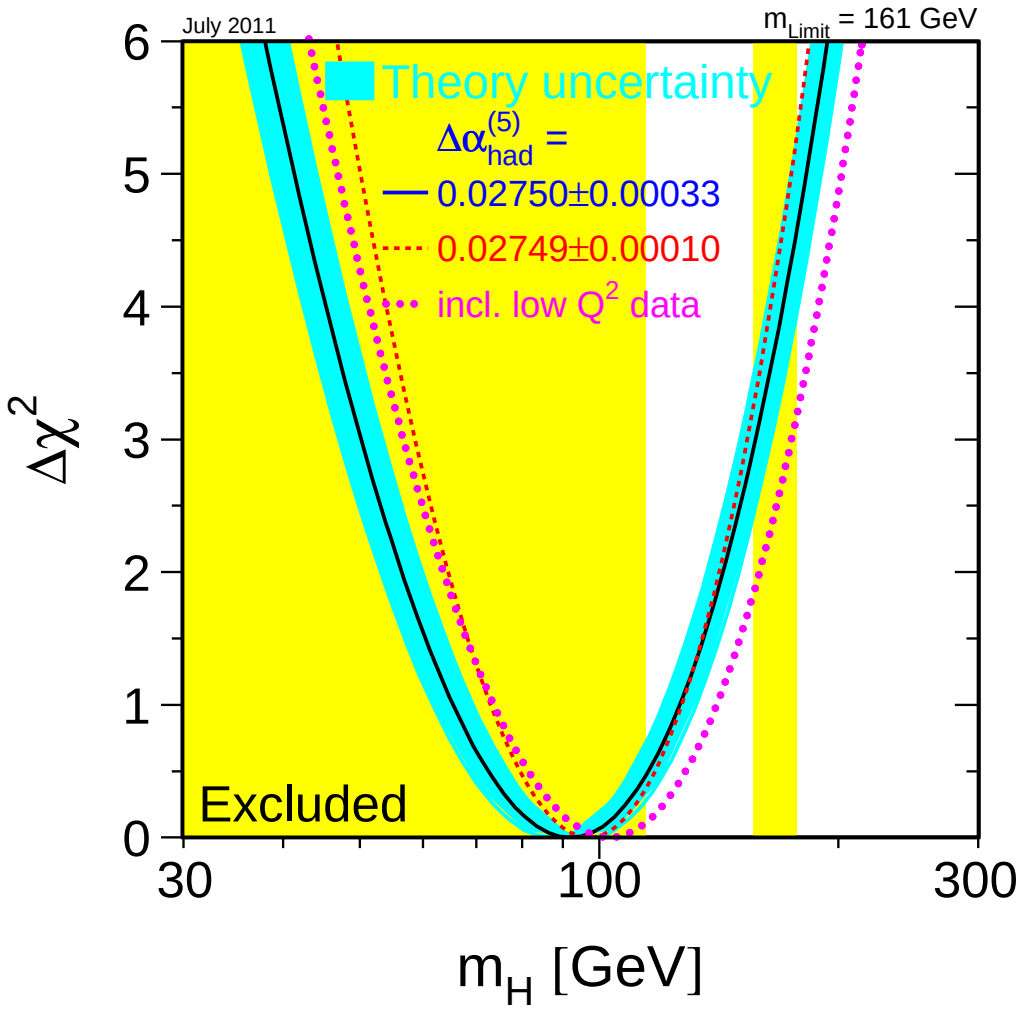


$\Rightarrow$ Light SUSY Higgs not ruled out!

What to expect? Constraints on the SM Higgs from electroweak precision data

Indirect constraint on $M_{\mathrm{H_{SM}}}$, no direct search limits included in the fit

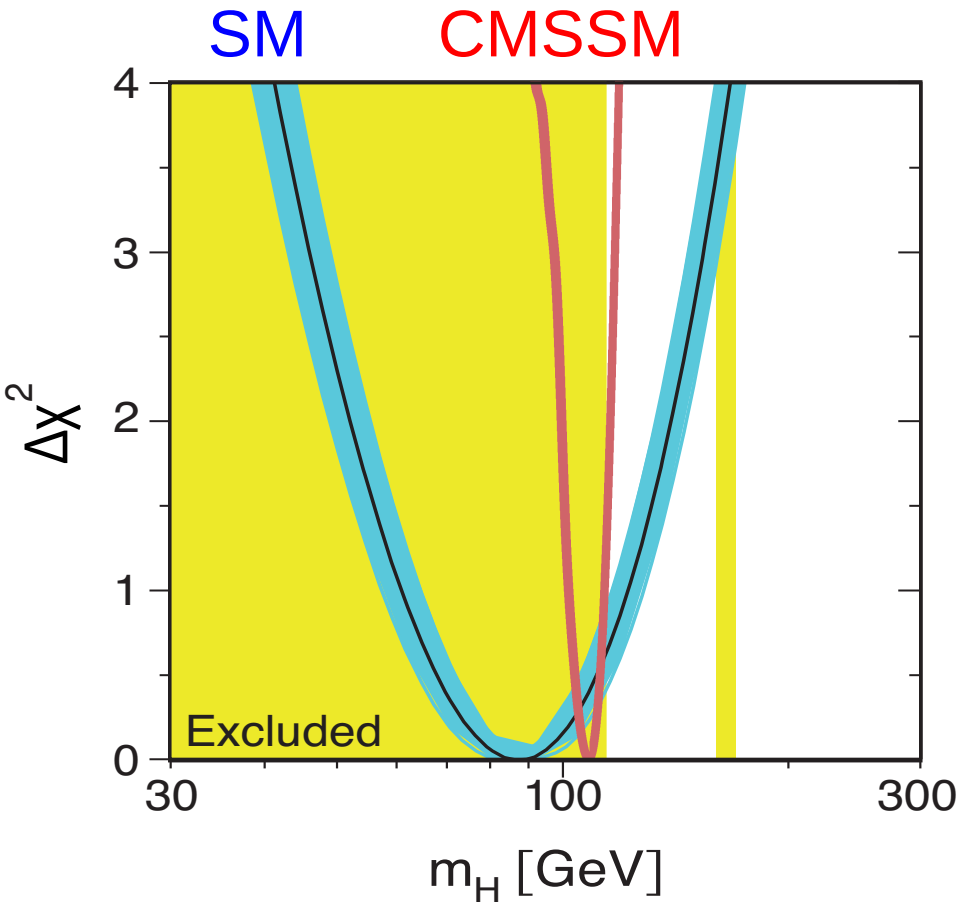
[*LEPEWWG '11*]

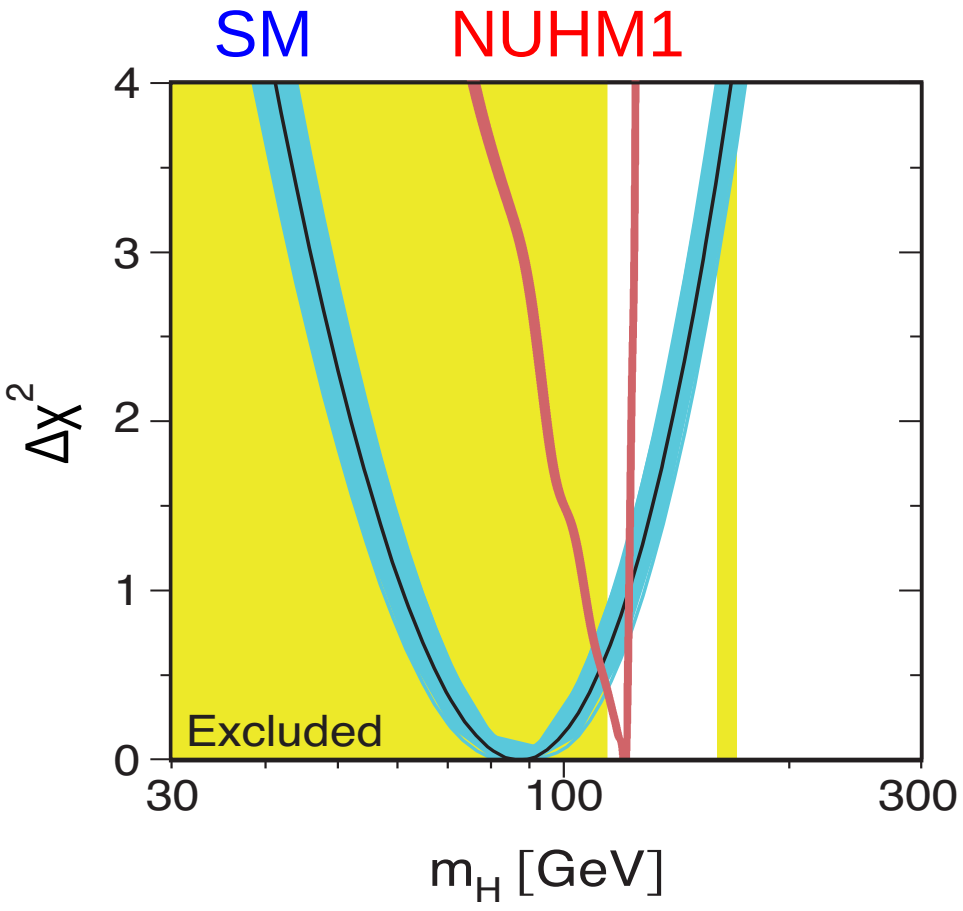


$\Rightarrow$ Preference for a light Higgs, $M_{\mathrm{H_{SM}}} < 161\ \mathrm{GeV}$, 95% C.L.

Indirect prediction for Higgs mass in SM and constrained SUSY models (CMSSM / NUHM1) from precision data

χ^2 fit for $M_{\rm h}$, without imposing direct search limits





$$M_{\rm h}^{\rm CMSSM} = 108 \pm 6 \text{ GeV} \qquad M_{\rm h}^{\rm NUHM1} = 121^{+2}_{-14} \text{ GeV}$$

$\Rightarrow$ Accurate indirect prediction; Higgs "just around the corner"?

How to infer the underlying physics from the experimental signatures?

- A Higgs or not a Higgs?
- Fundamental or composite?
- SM, MSSM or beyond?
- Is there other new physics; what is it?
- How does the observed new physics fit into the global picture (ew precision observables, flavour physics, . . .)?
- . . .

$\Rightarrow$ Intense effort will be needed to identify the nature of electroweak symmetry breaking

HiggsBounds: confronting arbitrary Higgs sectors with exclusion bounds from LEP, the Tevatron and the LHC

Higgs hunting at LEP, the Tevatron and the LHC: cross section limits vs. benchmark scenarios

Limits for different production and decay channels 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

Determination of 95% C.L. exclusion region from given cross section limits

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

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Determination of 95% C.L. exclusion region from given cross section limits

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.

Implemented in program *HiggsBounds*

[*P. Bechtle, O. Brein, S. Heinemeyer, G. W., K. Williams '08, '11*]

The program HiggsBounds

http://projects.hepforge.org/higgsbounds

HiggsBounds ⇒ test theo. predictions of models with arbitrary Higgs sectors against exclusion bounds from search for neutral and charged Higgses at LEP, Tevatron and the LHC

[*P. Bechtle, O. Brein, S. Heinemeyer, G. W., K. Williams '08, '11*]

Modes of operation: command line, subroutine and on-line version

HiggsBounds

Calling program...
program finished.

HIGGSBOUNDS

Results

```
**************************************************************

parameter point is UNEXCLUDED at 95 per cent C.L.
using the process with highest statistical sensitivity:
 (p p-bar)->V (h1)/VBF-> (b b-bar)+... where h1 is SM-like (CDF Note 10606, D0 Note 6226)
which has a theoretical rate vs. limit of
 0.78311159653235907

**************************************************************
**************   Additional Information   **************
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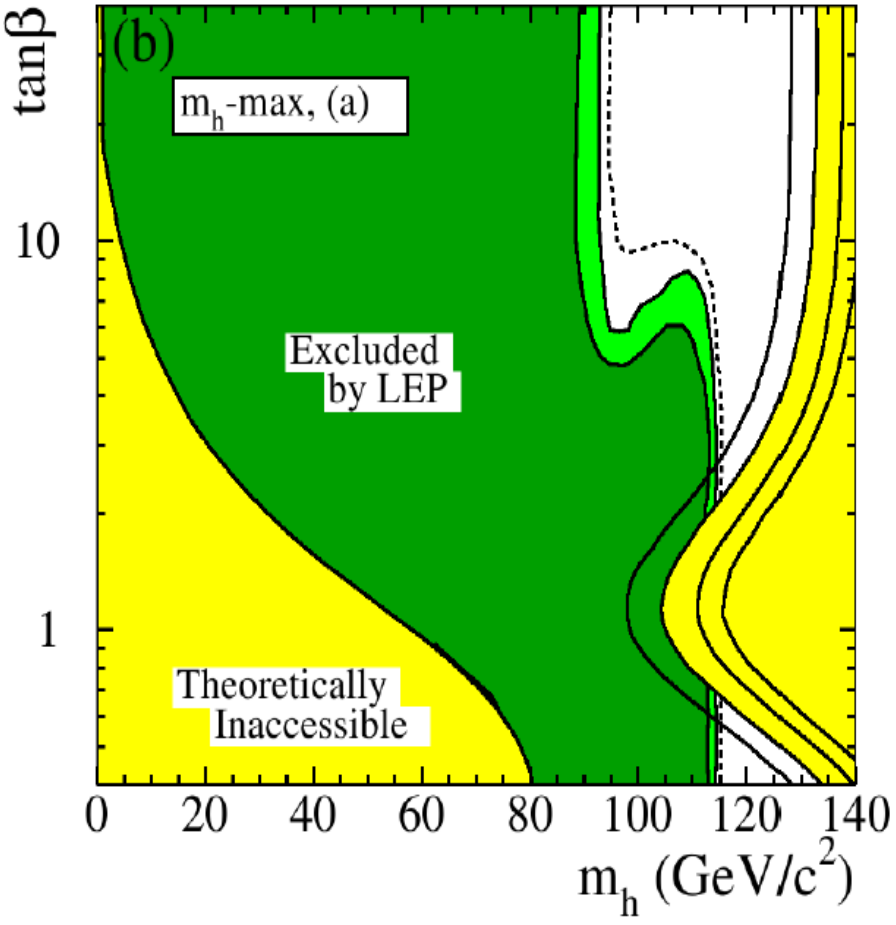
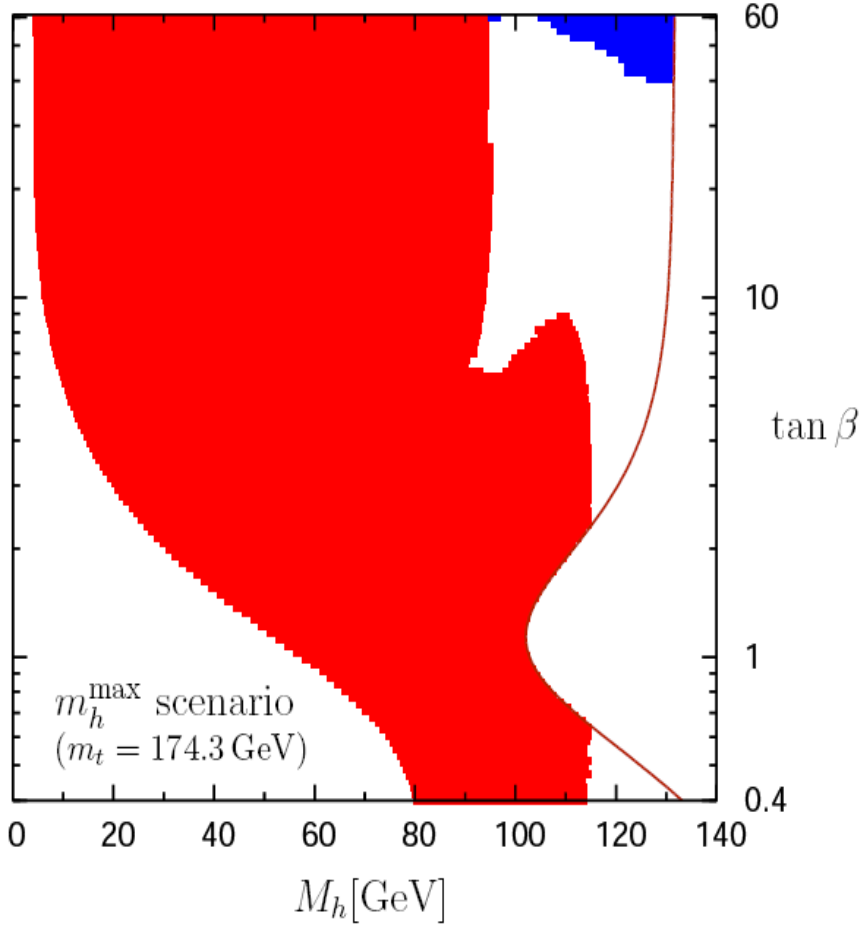
Latest version: 29.07.11, includes results from EPS '11

Example: MSSM $m_{\mathrm{h}}^{\mathrm{max}}$ benchmark scenario, comparison of HiggsBounds output with LEP Higgs Working Group results

Eur. Phys. J. **C 47** (2006) 547
[*LEP Higgs Working Group '06*]

HiggsBounds: m_{t} set to benchmark value, improved m_{h} prediction, Tevatron res. included

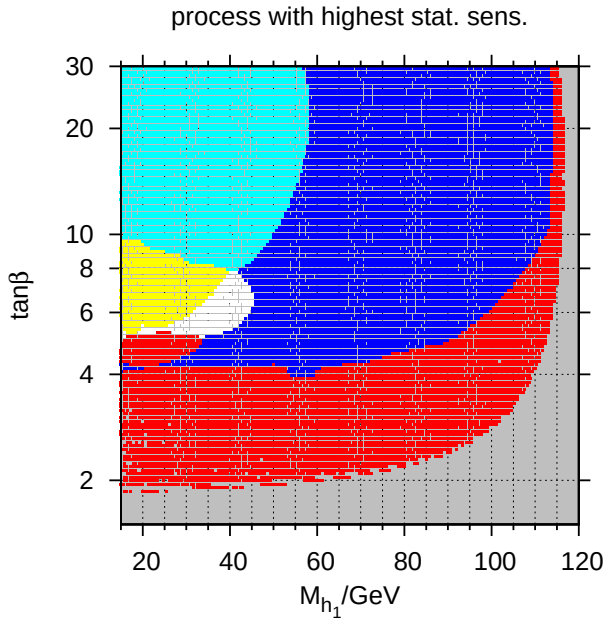




Example: analysis of LEP coverage in CPX scenario with improved theoretical prediction

For every parameter point: determine the search channel with the highest statistical sensitivity for setting an exclusion

[*P. Bechtle, O. Brein, S. Heinemeyer, G. W., K. Williams '08,'11*]



Channels:

$(\blacksquare) = (h_1 Z) \to (b\bar{b}Z)$

$(\blacksquare) = (h_2 Z) \to (b\bar{b}Z)$

$(\square) = (h_2 Z) \to (h_1 h_1 Z) \to (b\bar{b}b\bar{b}Z)$

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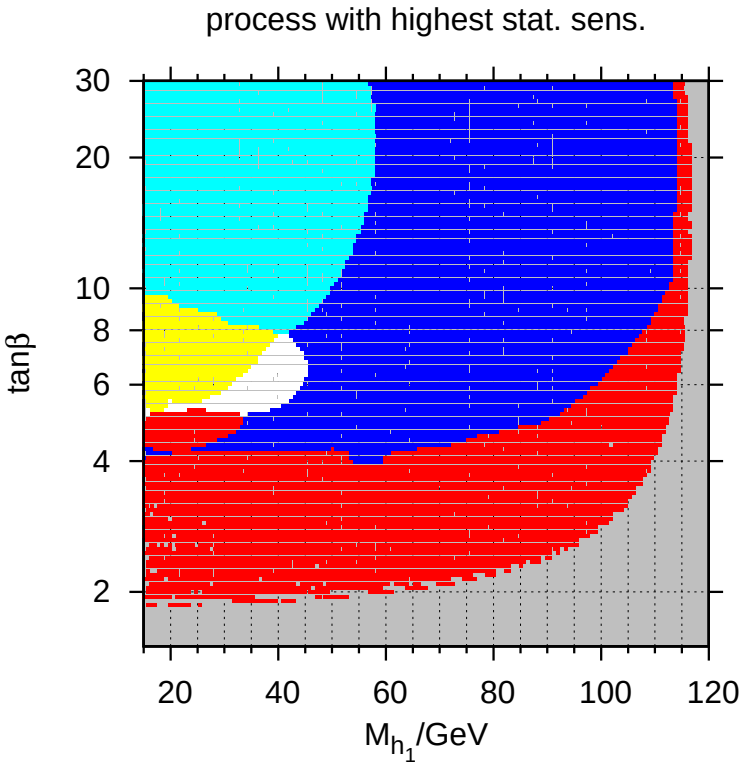
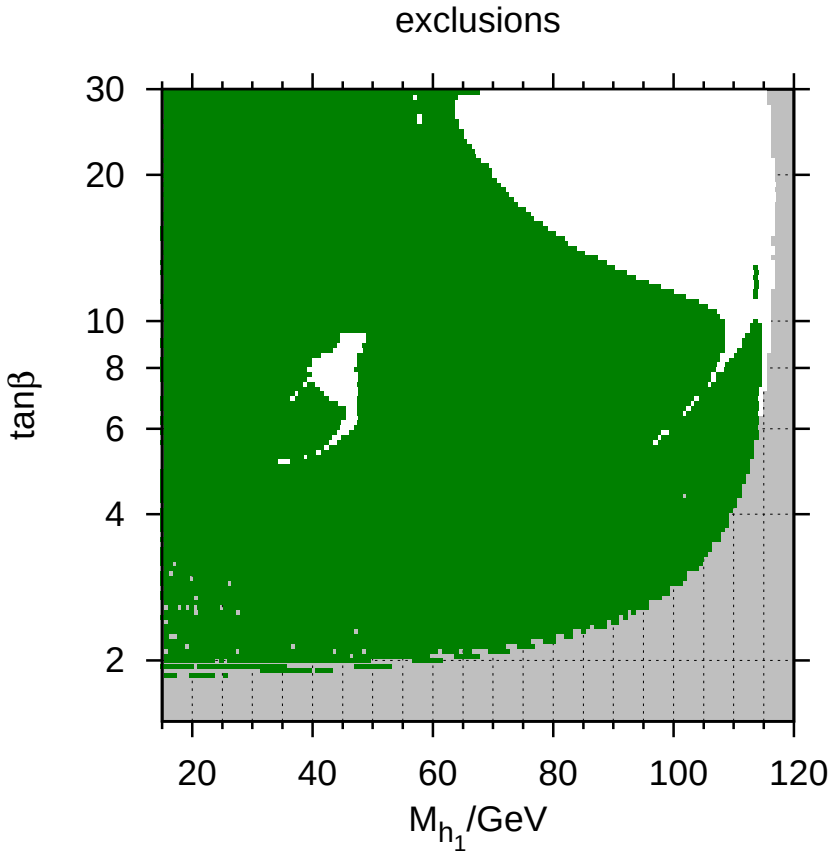
Search limits for MSSM with complex parameters (CPX scenario)

Channels (*HiggsBounds*)

$(\square) : (h_2 Z) \to (h_1 h_1 Z) \to (b\bar{b}b\bar{b}Z)$

Excluded region from LEP, 95% C.L. [*K. Williams, H. Rzehak, G. W. '11*]



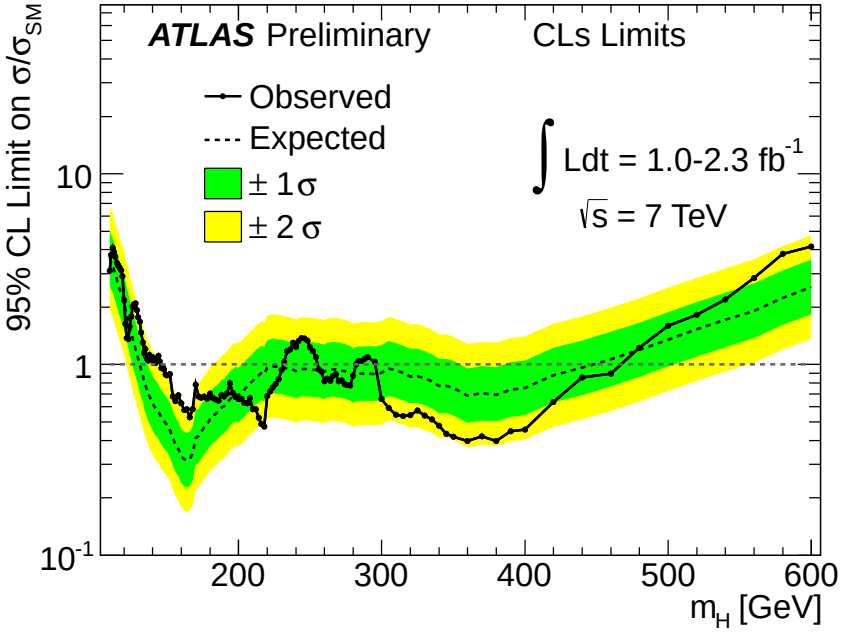


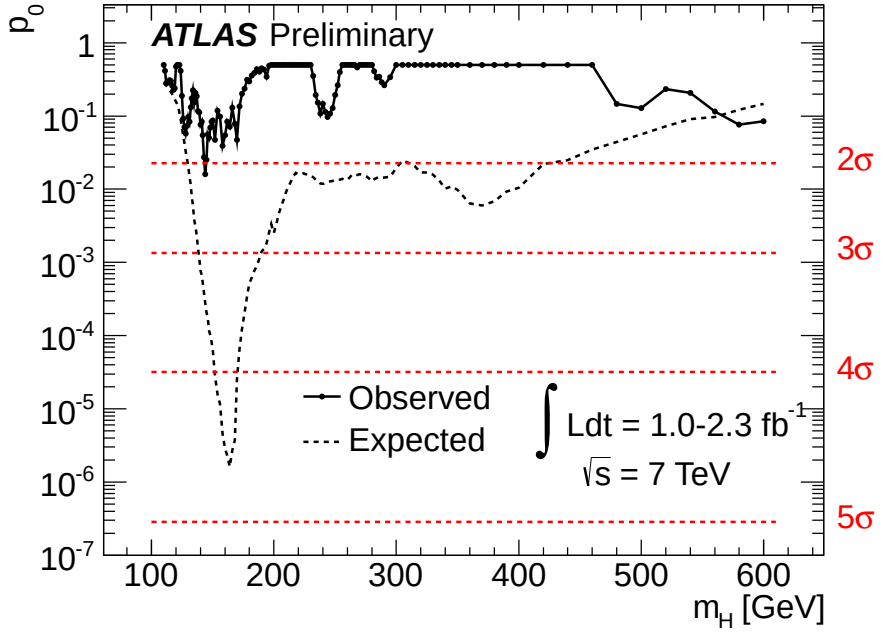
⇒ Confirmation of the "hole" in the LEP coverage

⇒ Very light Higgs boson is not excluded

Latest Higgs search results confronting the SM and SUSY

ATLAS SM Higgs search: combined upper limit normalised to the SM expectation (left) and observed result vs. expectation for a SM Higgs signal (right) [*ATLAS Collaboration '11*]

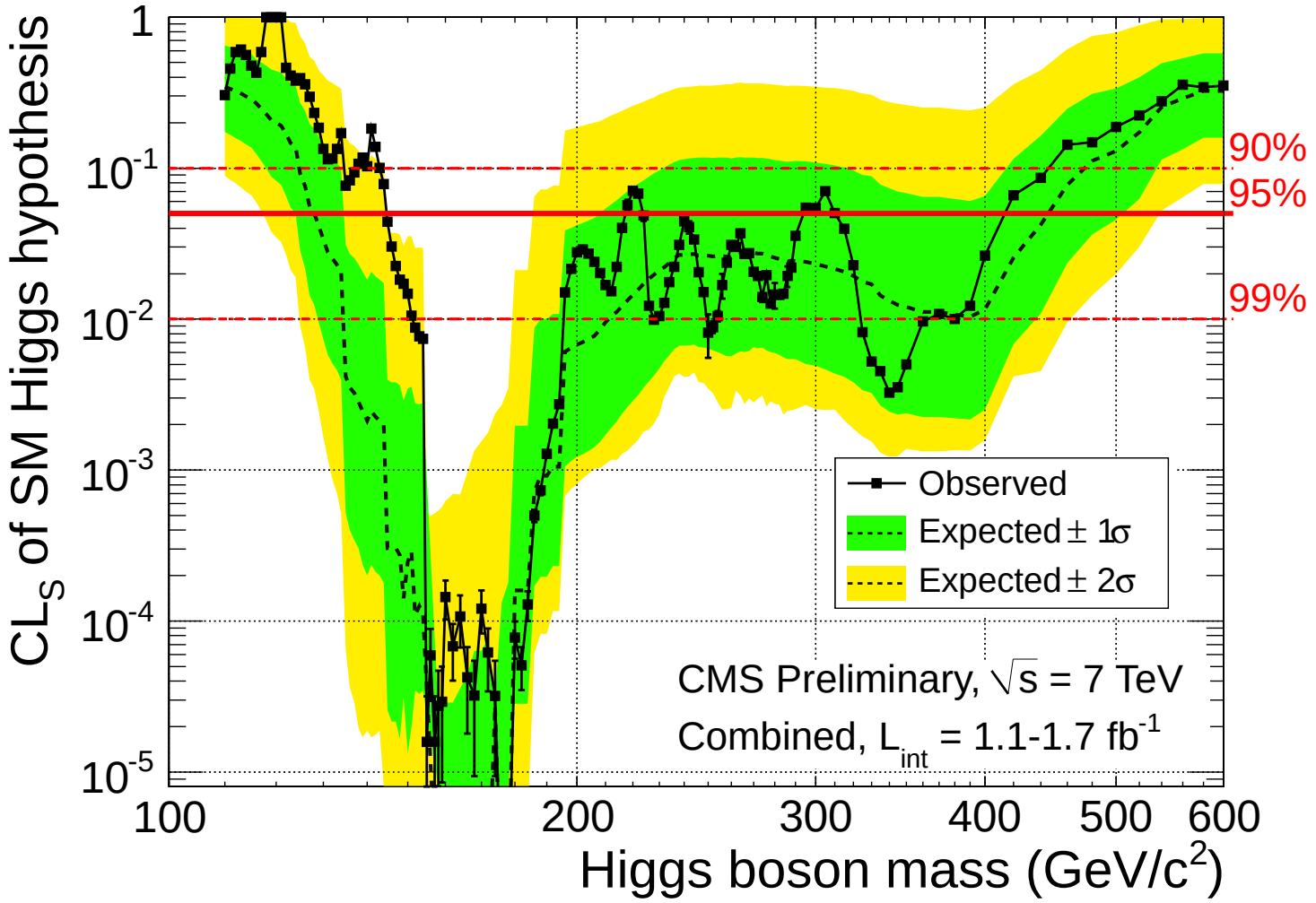




SM Higgs search: combined CMS results

Combined confidence limit vs. expectation for a SM Higgs signal

[*CMS Collaboration '11*]



SM Higgs searches, high-mass region

- LHC excludes (at least at 90% C.L.) the range of
  $145\ \mathrm{GeV} \lesssim M_{\mathrm{H_{SM}}} \lesssim 460\ \mathrm{GeV}$

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  ATLAS sees an excess beyond $M_{\mathrm{H_{SM}}} = 460\ \mathrm{GeV}$ ...

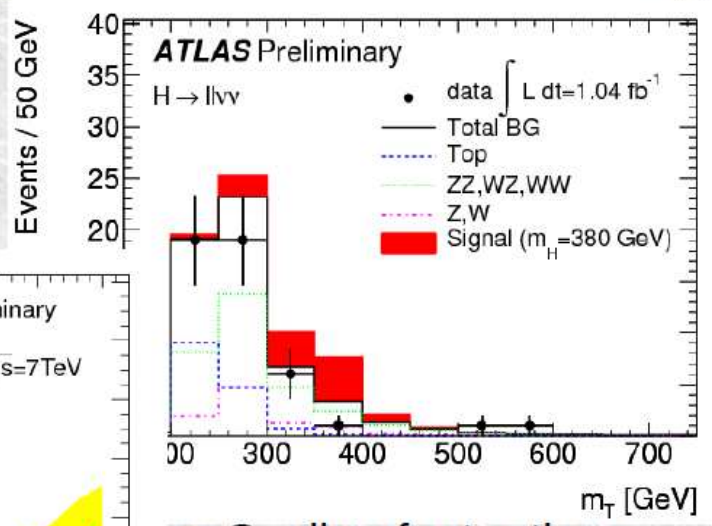
  However: a heavy SM-like Higgs appears to be theoretically questionable

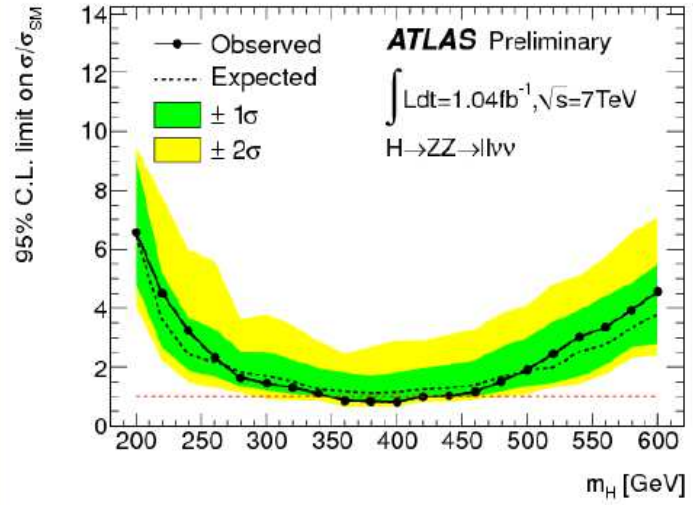
Prospects for SM Higgs searches in the high mass region

[*W. Murray, LHC2TSP Workshop '11*]

$H \rightarrow ZZ \rightarrow 2l\,2\upsilon$ (l = e,μ)

- ATLAS & CMS best channel for m_H>300
- High mass almost background free





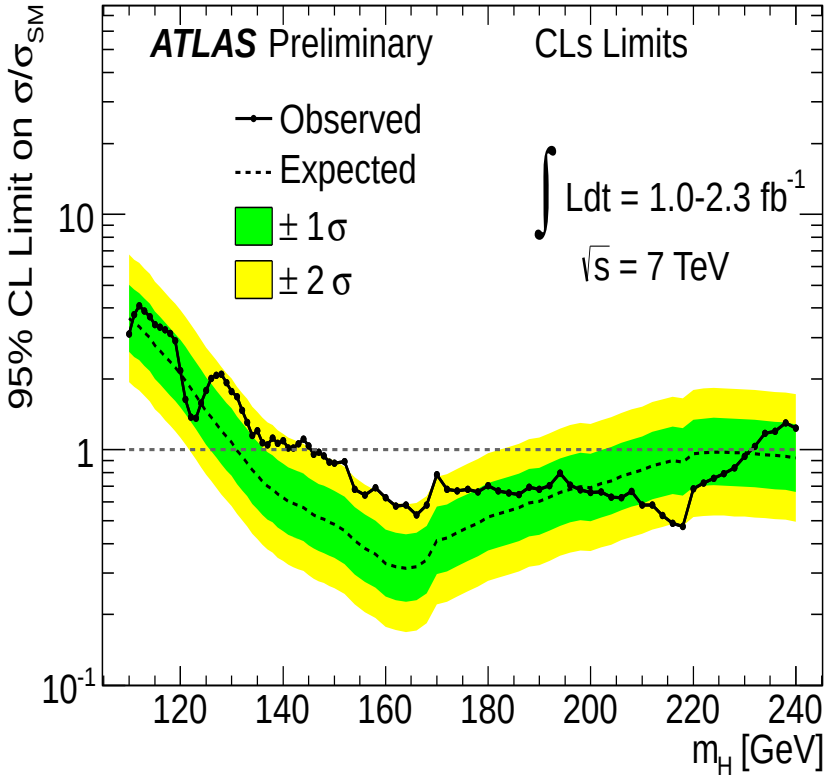
- Scaling faster than $1/\sqrt{l}$
- Should extend to 550+ by end of 2011

⇒ Large increase in coverage expected

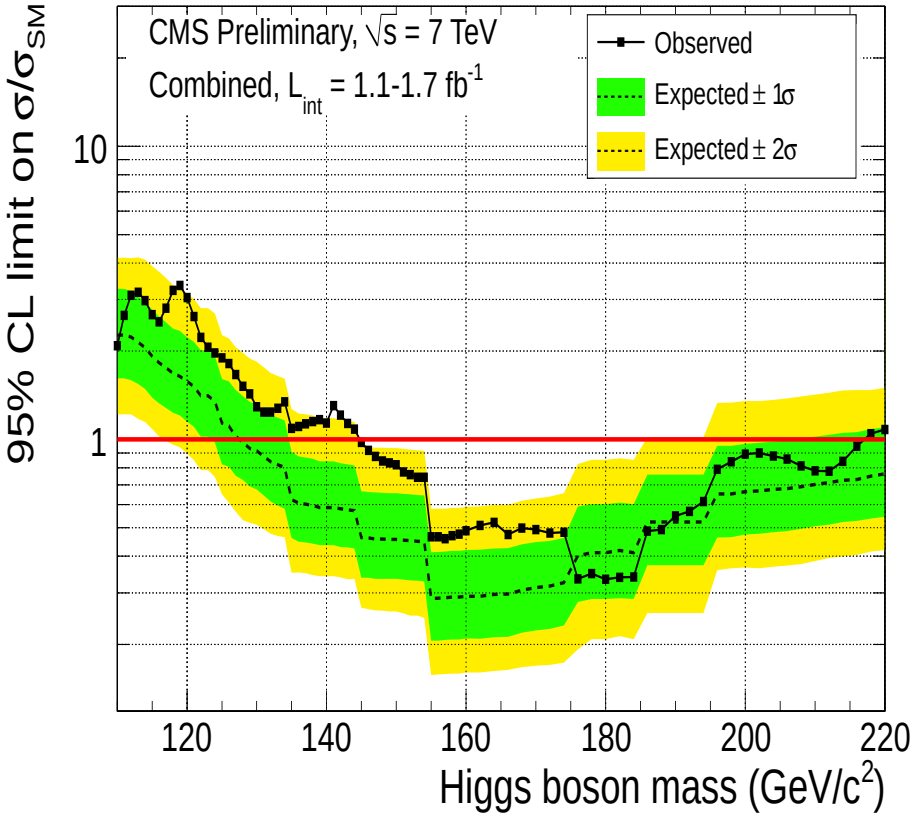
SM Higgs search: ATLAS and CMS results in the low mass region

Combined upper limit normalised to the SM expectation, low mass region

[*ATLAS Collaboration '11*]



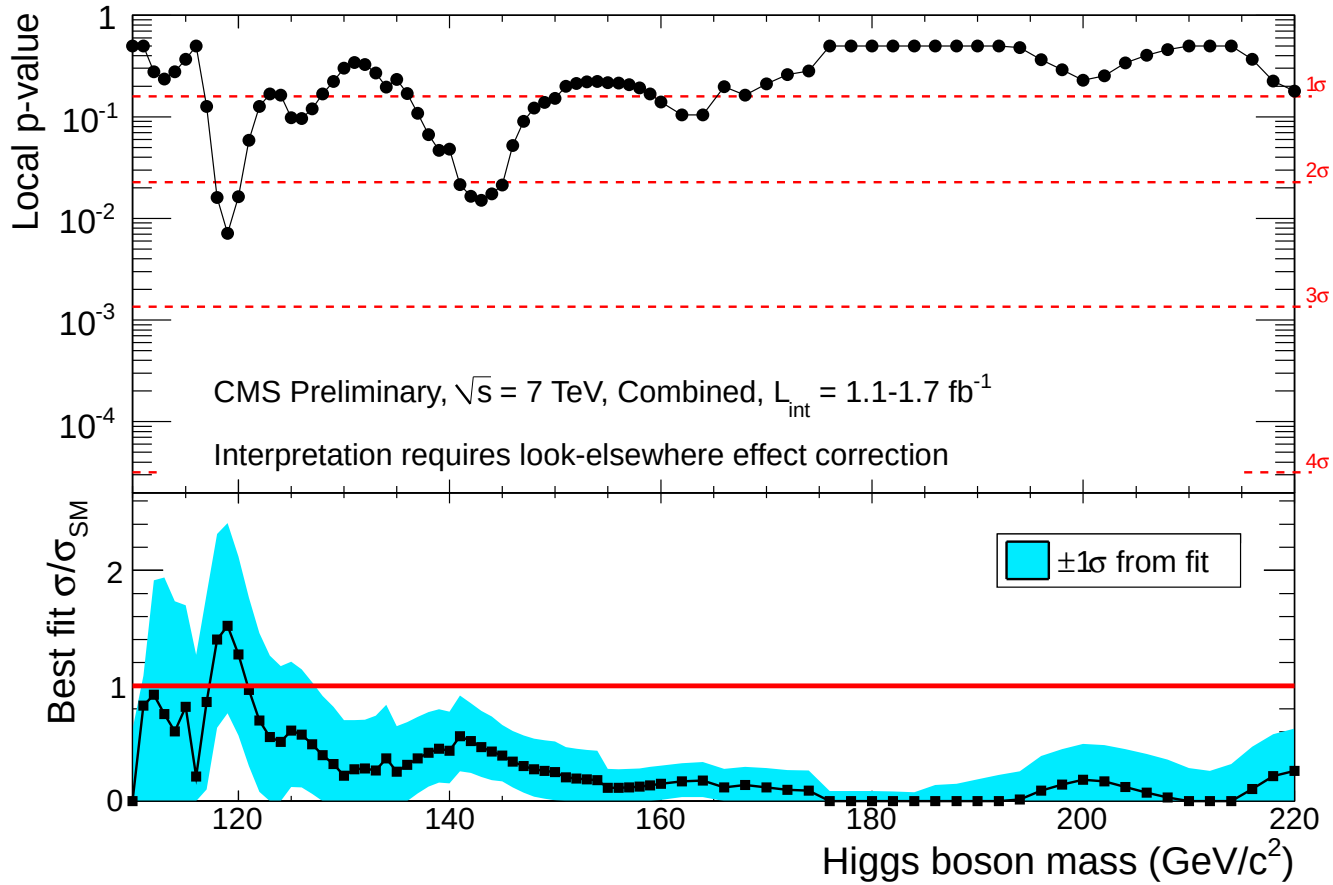
[*CMS Collaboration '11*]



⇒ Broad excess in low mass region

CMS results for SM Higgs searches: local p value and observed best-fit signal strength

[*CMS Collaboration '11*]

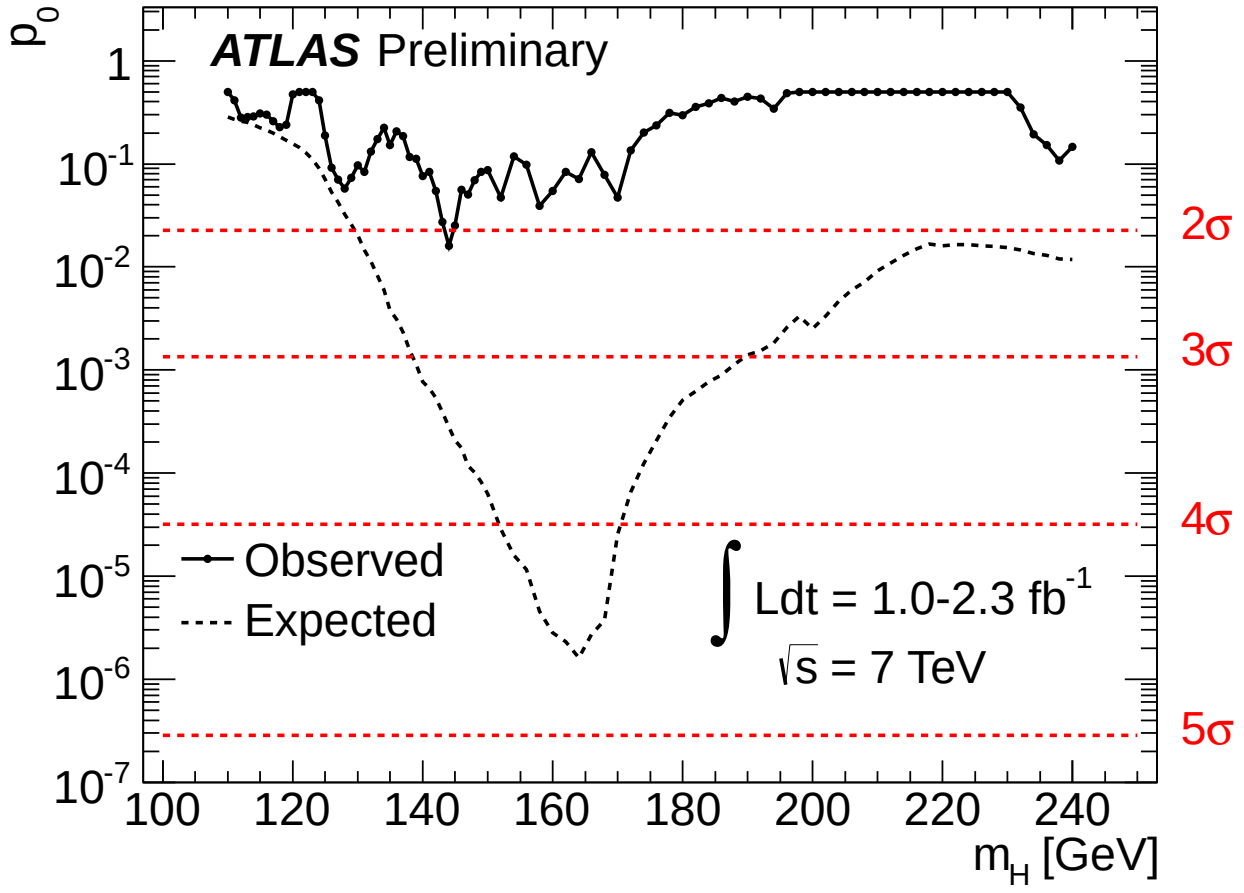


⇒ With LEE: probability to see an excess at least as large as the one observed in the data is ≈ 0.4

Best compatibility with a SM Higgs for $M_{\mathrm{H_{SM}}} \lesssim 125\ \mathrm{GeV}$

ATLAS results for SM Higgs searches: local p value vs. expectation for a SM Higgs signal

[*ATLAS Collaboration '11*]



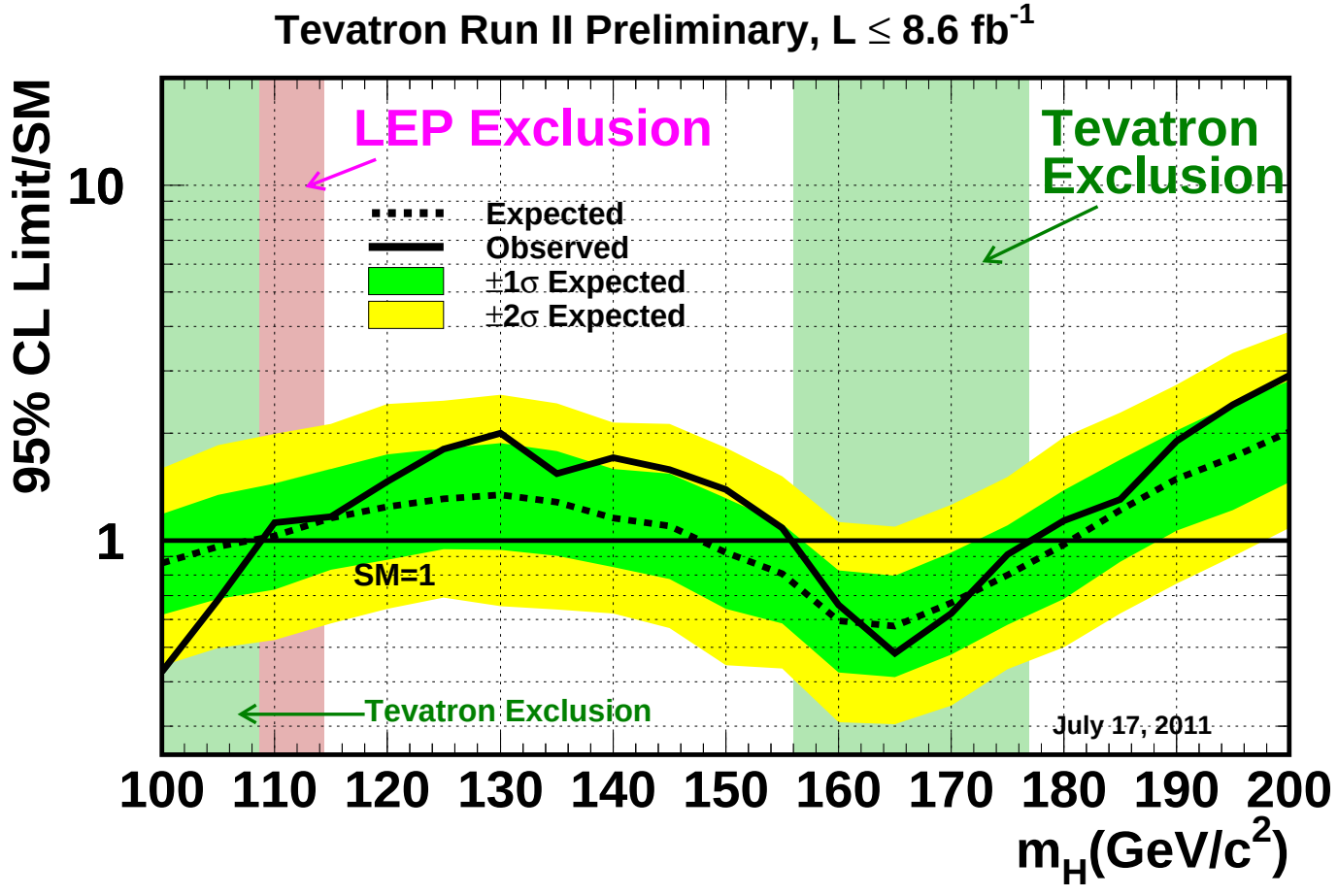
$\Rightarrow$ Best compatibility with a SM Higgs for $M_{\mathrm{H_{SM}}} \lesssim 130$ GeV

Slight deficit w.r.t. SM expectation

SM Higgs search: Tevatron results, CDF + D0

CDF + D0 combined upper limit normalised to the SM expectation

[*CDF and D0 Collaborations '11*]



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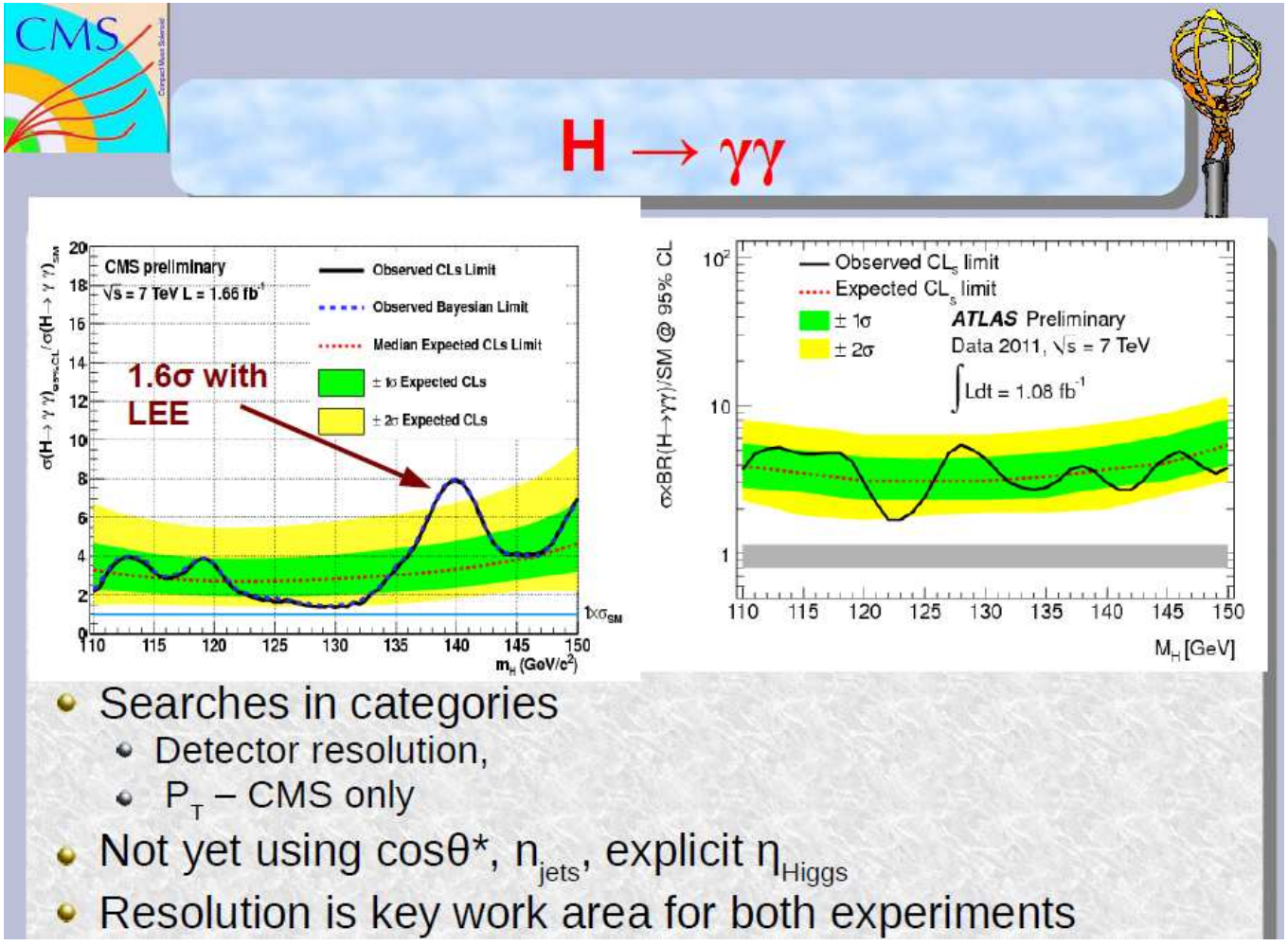
- What about a Higgs with $M_{\mathrm{H}} \approx 145\ \mathrm{GeV}$ with somewhat reduced $\sigma \times \mathrm{BR}(H \to WW^*)$?

  Difficult to get sufficiently large $\mathrm{BR}(H \to WW^*)$ in the MSSM, can better be accomodated in the NMSSM

CMS excess in $H \to \gamma\gamma$ search

[*W. Murray, LHC2TSP Workshop '11*]

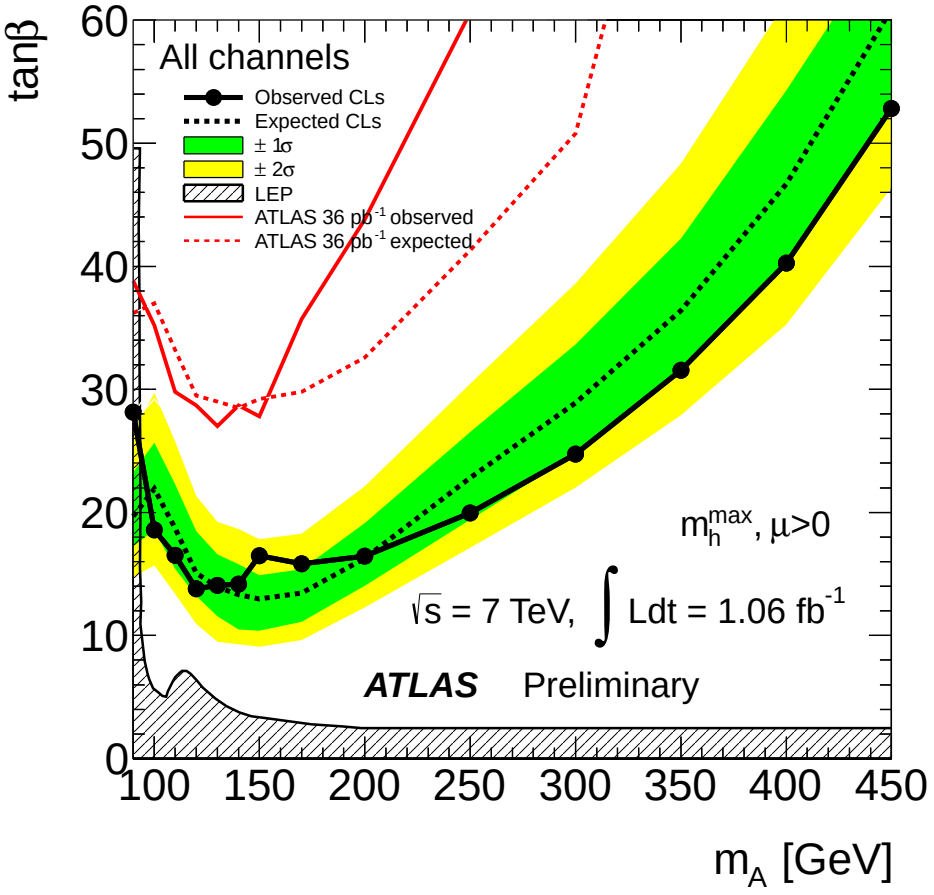


- Searches in categories
  - Detector resolution,
  - P_T – CMS only
- Not yet using cosθ*, n_{jets}, explicit η_{Higgs}
- Resolution is key work area for both experiments

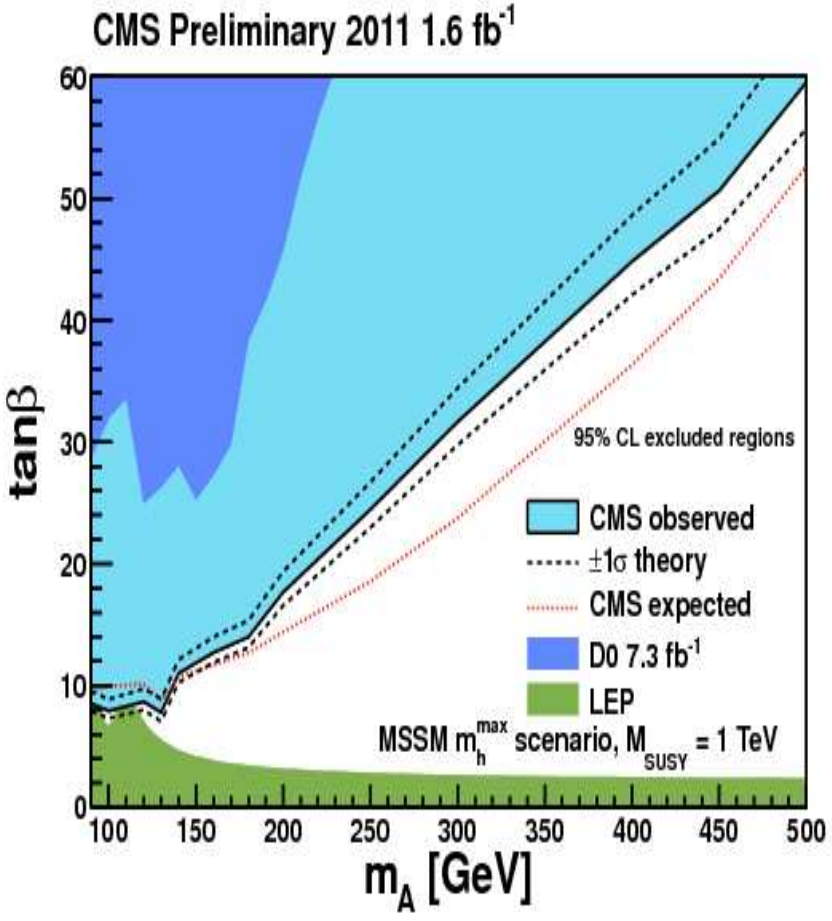
$\Rightarrow 1.6\sigma$ excess at $M_{\mathrm{H}} \approx 140\ \mathrm{GeV}$ after taking into account LEE

Search for the heavy SUSY Higgs bosons H, A: limits in the M_{A}–$\tan\beta$ plane

[*ATLAS Collaboration '11*]



[*CMS Collaboration '11*]

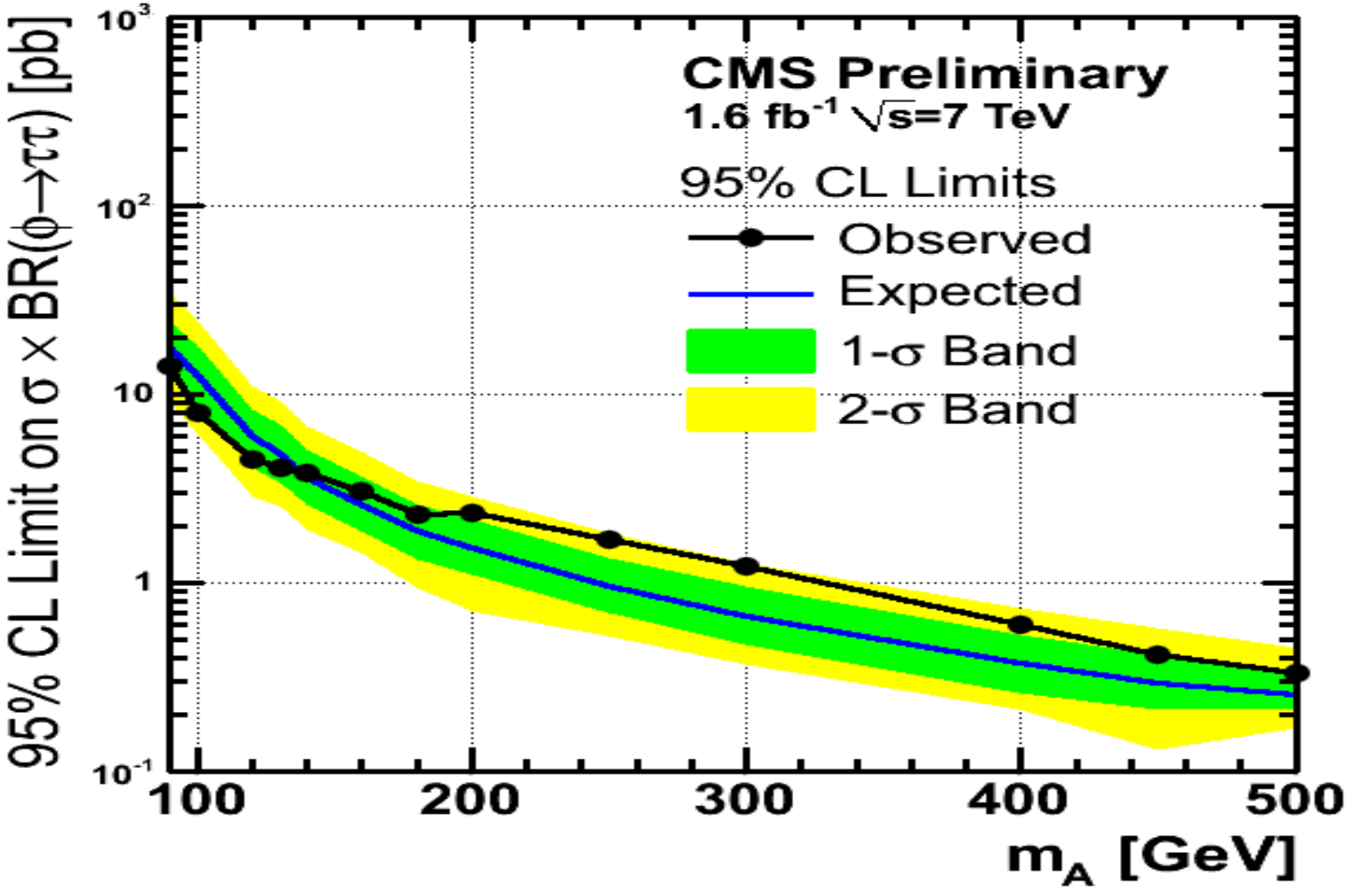


⇒ Large coverage in M_{A}–$\tan\beta$ plane

LHC + LEP start to close the region of very low M_{A}

Search for the heavy SUSY Higgs bosons H, A: cross section limit from CMS

[*CMS Collaboration '11*]

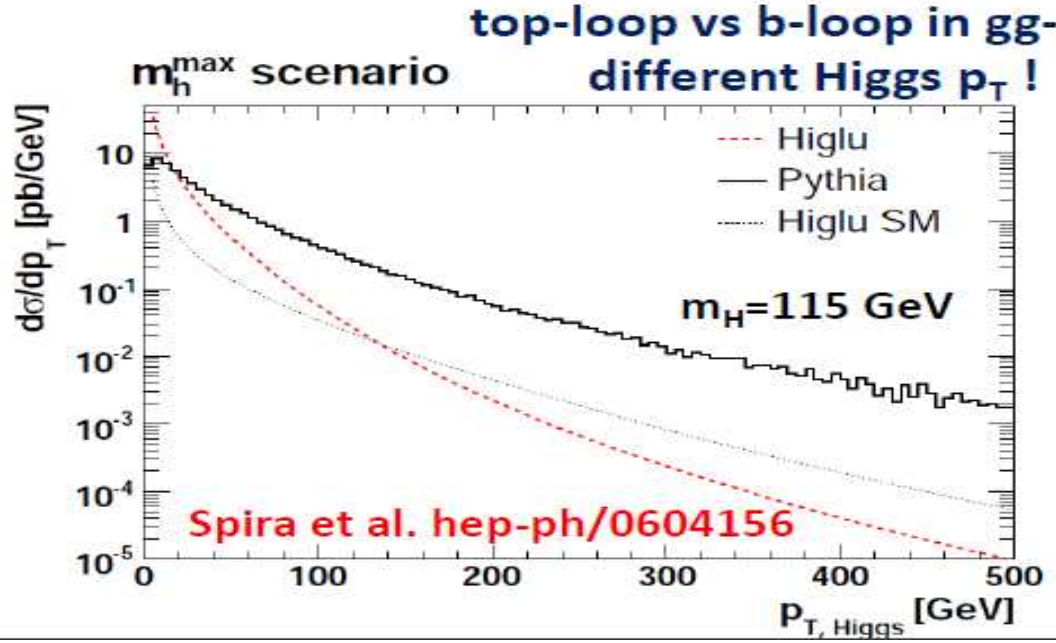


$\Rightarrow$ Excess for $M_{\mathrm{A}} \gtrsim 200\ \mathrm{GeV}$

However: acceptance for $gg \to H, A$ is overestimated

[*A. Nikitenko, LHC2TSP Workshop '11*]

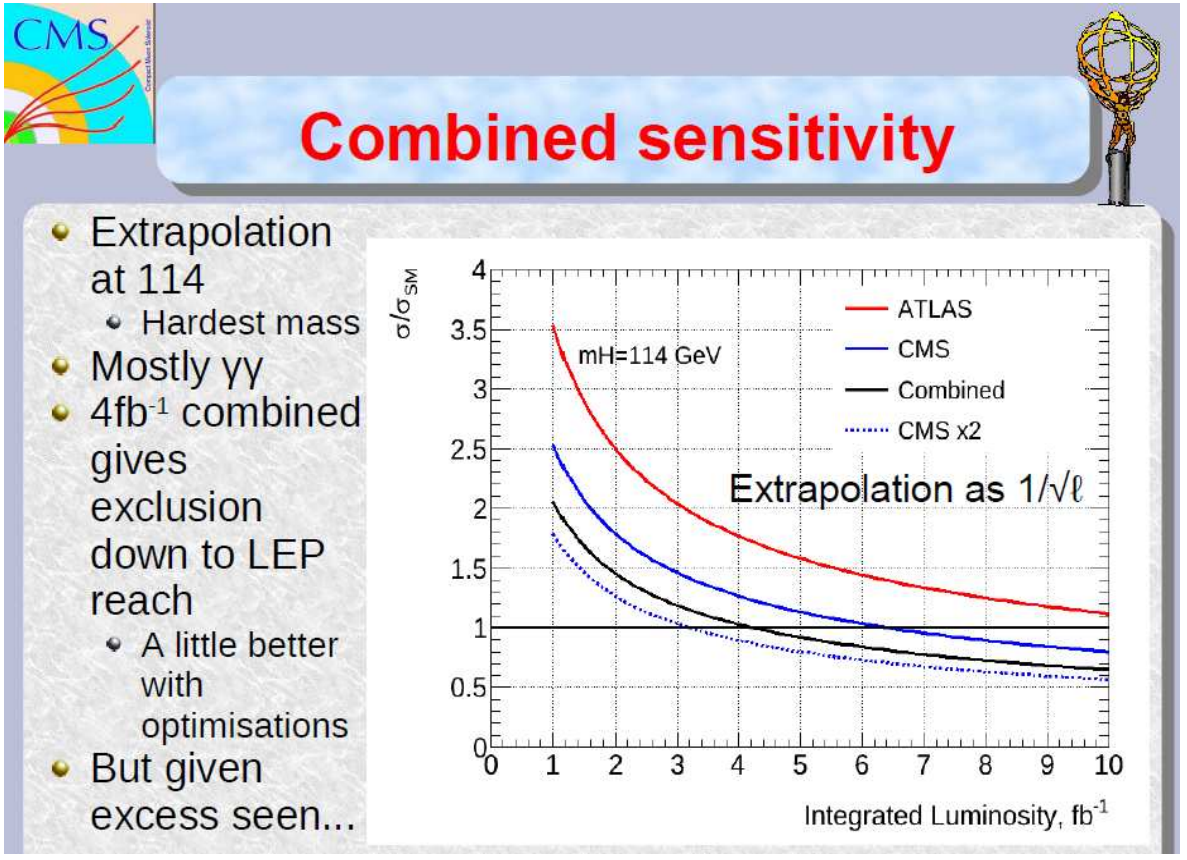
- **Remark on gg->ϕ generation**
  - **CMS used PYTHIA, ATLAS used POWHEG**
  - **both generators do not include b-quark in the loop:**
    - **acceptance for gg->ϕ is overestimated; how much ?**



Outlook

Prospects for searches for a $114\ \mathrm{GeV}$ SM-like Higgs:

[*W. Murray, LHC2TSP Workshop '11*]



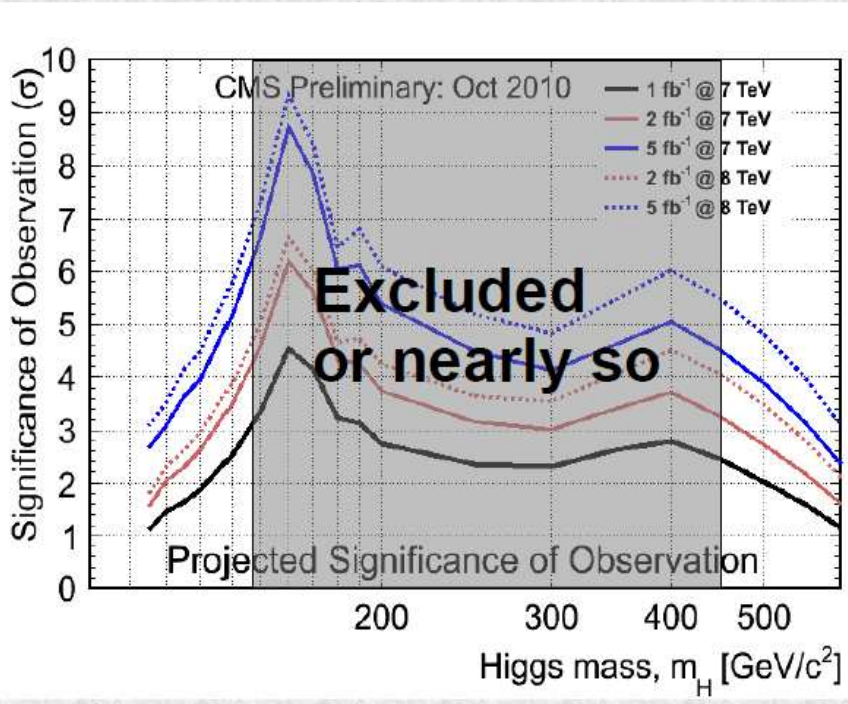
$\Rightarrow$ 2011 data, when combined between ATLAS + CMS, should provide 2σ sensitivity down to $M_{\mathrm{H}} = 114\ \mathrm{GeV}$

Prospects for the signal significance

[*W. Murray, LHC2TSP Workshop '11*]

Signal significance

- $5fb^{-1}$ gives either experiment large sensitivity
- Projections slightly optimistic at 115
  - Need $\gamma\gamma$ resolution!
  - Or SM cover needs combination



$\Rightarrow$ With 2012 data, ATLAS + CMS combined: expect sensitivity of at least 3.5σ