Higgs searches at the LHC: where do we stand?

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DESY

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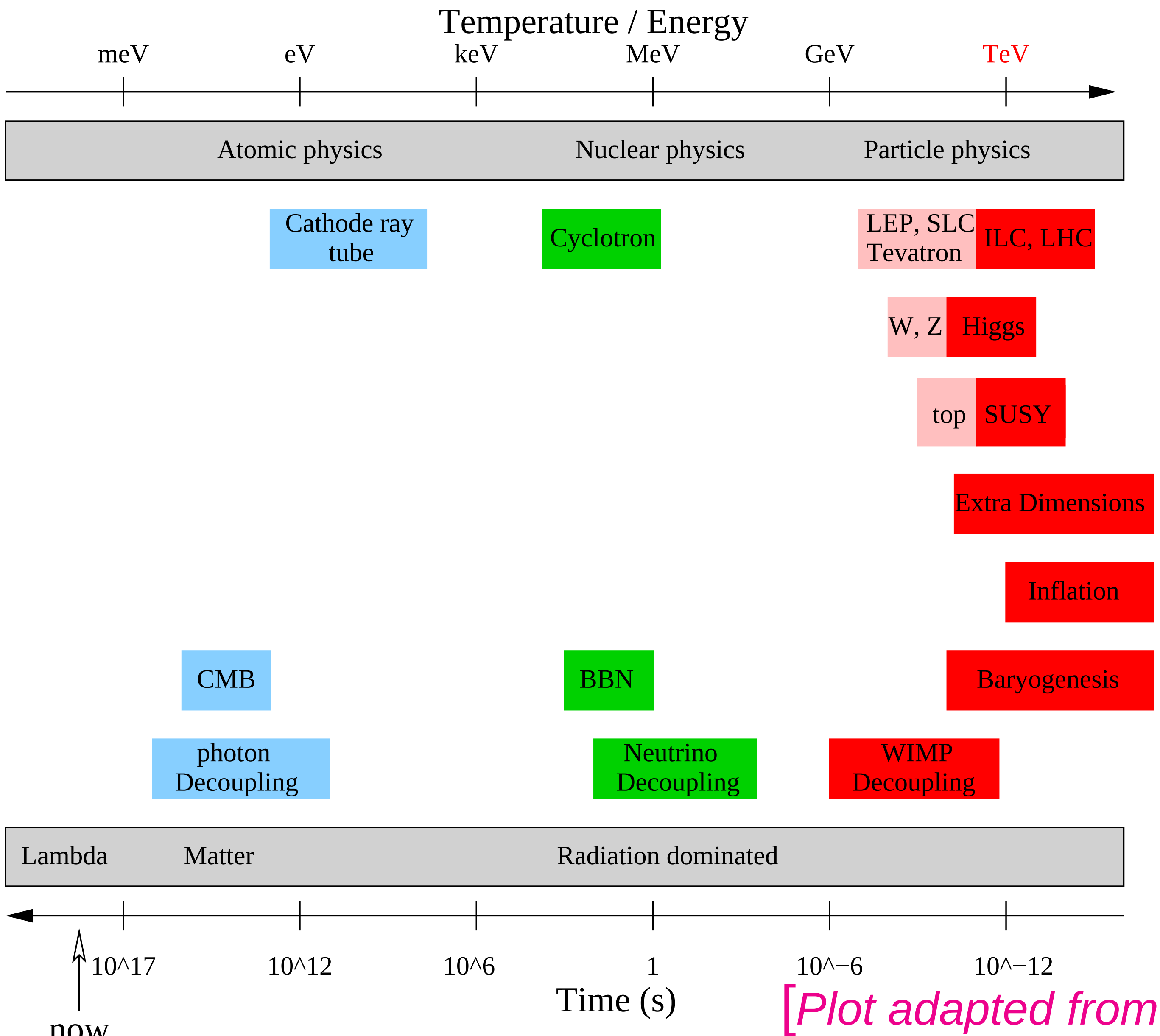
- Introduction
- Higgs searches at LEP and the Tevatron
- Latest results from the LHC: status and interpretation
- Conclusions

Introduction: exploring the Terascale

$$1\ \text{TeV} \approx 1000 \times m_{\text{proton}} \Leftrightarrow 2 \times 10^{-19}\ \text{m}$$



[*Plot adapted from J. Feng '05*]

How to find the Higgs (or more than one)?

- Heavy particle
  $\Rightarrow$ need high-energy collider, $E = mc^2$

- Unstable:
  $\Rightarrow$ need to look for decay products

- Comprehensive set of precision measurements and accurate theory predictions will be needed to establish the Higgs mechanism and to determine the Higgs properties

$\Rightarrow$ One of the main goals for physics at the LHC and a future Linear Collider

What's so special about the Higgs and electroweak symmetry breaking?

- The fundamental interactions of elementary particles are described very successfully by quantum field theories that follow an underlying symmetry principle:
  "gauge invariance"

- This fundamental symmetry principle requires that all the elementary particles and force carriers should be massless

- However: W, Z, top, bottom, ..., electron are massive, have widely differing masses

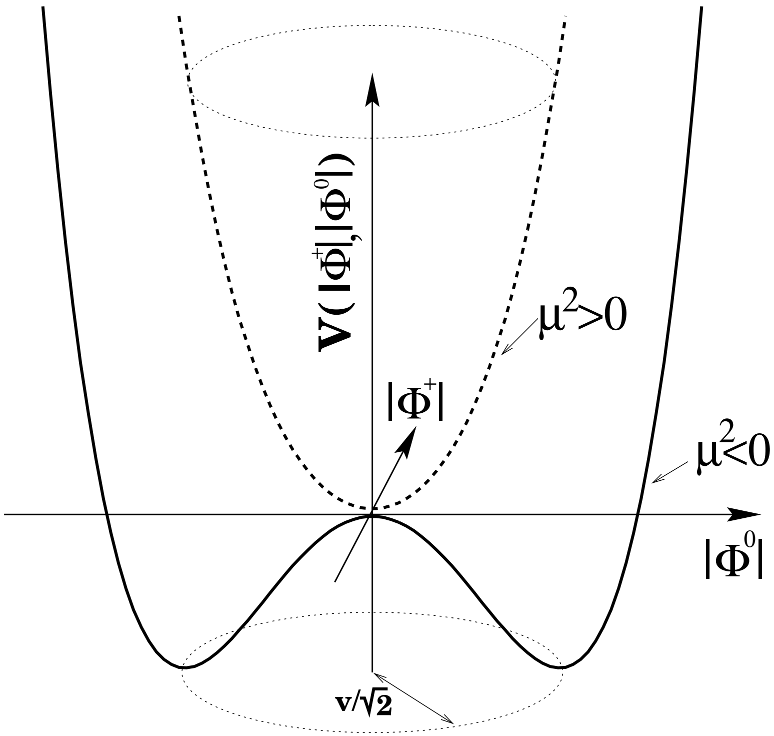
How can elementary particles acquire mass without spoiling the fundamental symmetries of nature?

The Higgs mechanism

Spontaneous symmetry breaking: the interaction obeys the symmetry principle, but not the state of lowest energy

New field postulated that fills all of the space: the Higgs field

The state of the lowest energy of the Higgs field (vacuum state) does not obey the underlying symmetry principle (gauge invariance)



$\Rightarrow$ Spontaneous breaking of the gauge symmetry

The Higgs field and the Higgs boson

Higgs mechanism: fundamental particles obtain their masses from interacting with the Higgs field

Higgs boson(s): field quantum of the Higgs field

(like the photon is the quantum of the electromagnetic field)

Higgs coupling to other particles is proportional to their masses

The postulated Higgs boson is a scalar particle (spin 0)

Up to now no fundamental scalar particle has been observed in nature

The Higgs mechanism sounds like a rather bold assumption to cure a theoretical / aesthetical problem

But: we know that there has to be new physics that is responsible for electroweak symmetry breaking

Our current description breaks down at the TeV scale

$\Rightarrow$ The physics of electroweak symmetry breaking must manifest itself at the TeV scale

Possible alternatives to the Higgs mechanism:

- A new fundamental strong interaction ("strong electroweak symmetry breaking")
- New dimensions of space (electroweak symmetry breaking via boundary conditions for SM gauge bosons and fermions on "branes" in a higher-dimensional space)

Higgs: last missing ingredient of the "Standard Model"

But: *the Standard Model cannot be the ultimate theory*

- The Standard Model does not include gravity

  $\Rightarrow$ breaks down at the latest at $M_{\text{Planck}} \approx 10^{19}$ GeV

- "Hierarchy problem": $M_{\text{Planck}}/M_{\text{weak}} \approx 10^{17}$

  How can two so different scales coexist in nature?

  Via quantum effects: physics at M_{weak} is affected by physics at M_{Planck}

  $\Rightarrow$ Instability of M_{weak}

  $\Rightarrow$ Would expect that all physics is driven up to the Planck scale

- Nature has found a way to prevent this

  The Standard Model provides no explanation

Hierarchy problem: how can the Planck scale be so much larger than the weak scale?

$\Rightarrow$ Expect new physics at the TeV scale to stabilise the hierarchy

Supersymmetry:

Large quantum corrections cancel out because of symmetry fermions $\Leftrightarrow$ bosons

Extra dimensions of space:

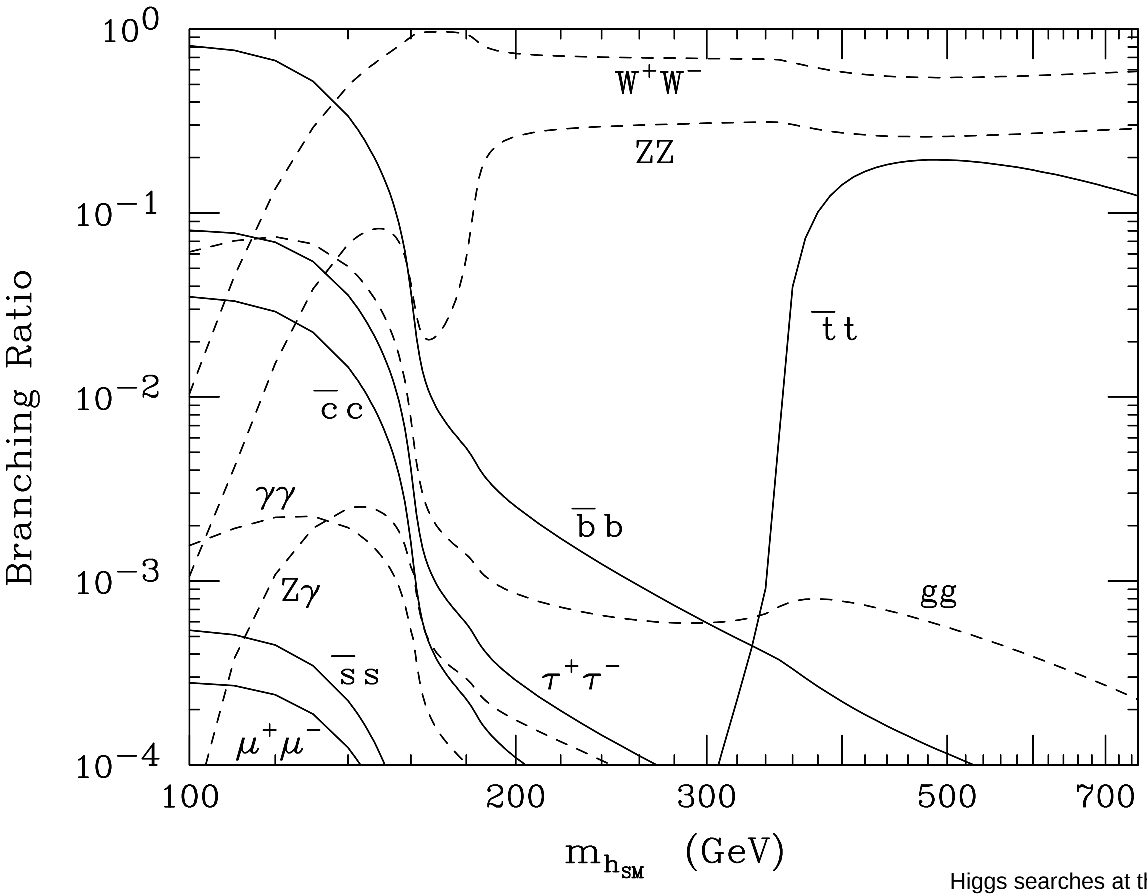
Fundamental Planck scale is $\sim \mathrm{TeV}$ (large extra dimensions),

hierarchy of scales is related to a “warp factor” (“Randall–Sundrum” scenarios)

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

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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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"

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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: $\tan\beta \equiv \frac{v_u}{v_d}$, $\quad M_\mathrm{A}$ (or $M_{\mathrm{H}^\pm}$)

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

$$M_\mathrm{h} \lesssim 135\,\mathrm{GeV}$$

Very rich phenomenology

BSM $\oplus$ 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, different phenomenology:
  - Experimental evidence for dark matter
    $\Rightarrow$ if dark matter particle is lighter than $M_{\mathrm{H}}/2$
    $\Rightarrow$ large branching fraction into invisible particles
    $\Rightarrow$ large suppression of all other BRs
  - Higgs production in decays of BSM particles
  - $h_i \to h_j h_j$ decays
  - Higgs–radion mixing, ...
  - Higgses with nearly degenerate masses: large interference effects, resonance-type behaviour possible

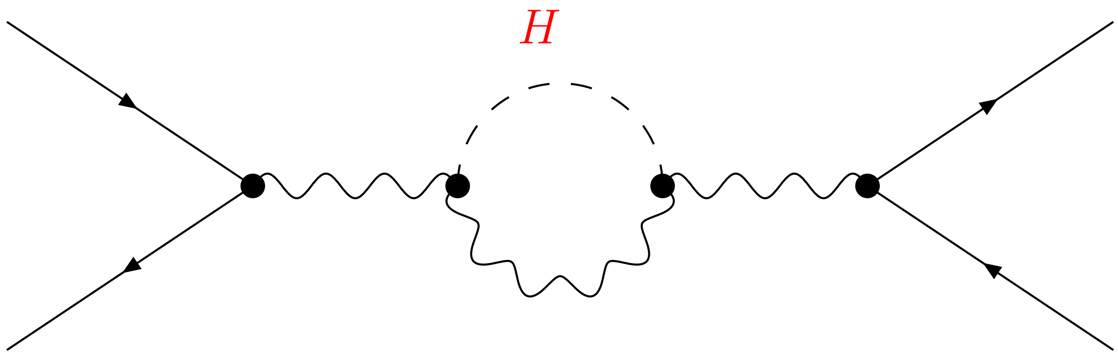
Indirect constraints

EW precision data:
$M_Z, M_W, \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}, \ldots$

Theory:
SM, MSSM, . . .

$\Downarrow$

Test of theory at quantum level: loop corrections



$\Downarrow$

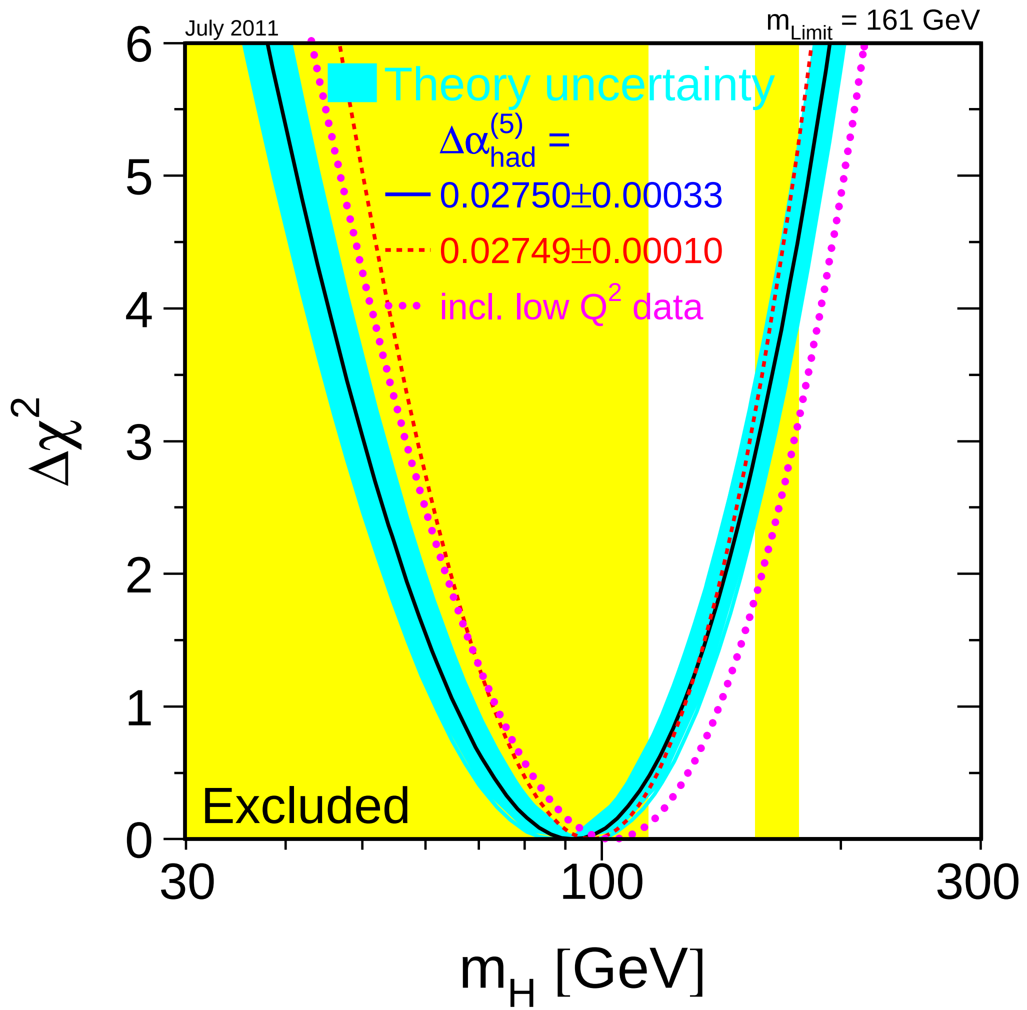
Sensitivity to effects from unknown parameters: M_{H}, $M_{\tilde{\mathrm{t}}}$, . . .

Window to “new physics”

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*]

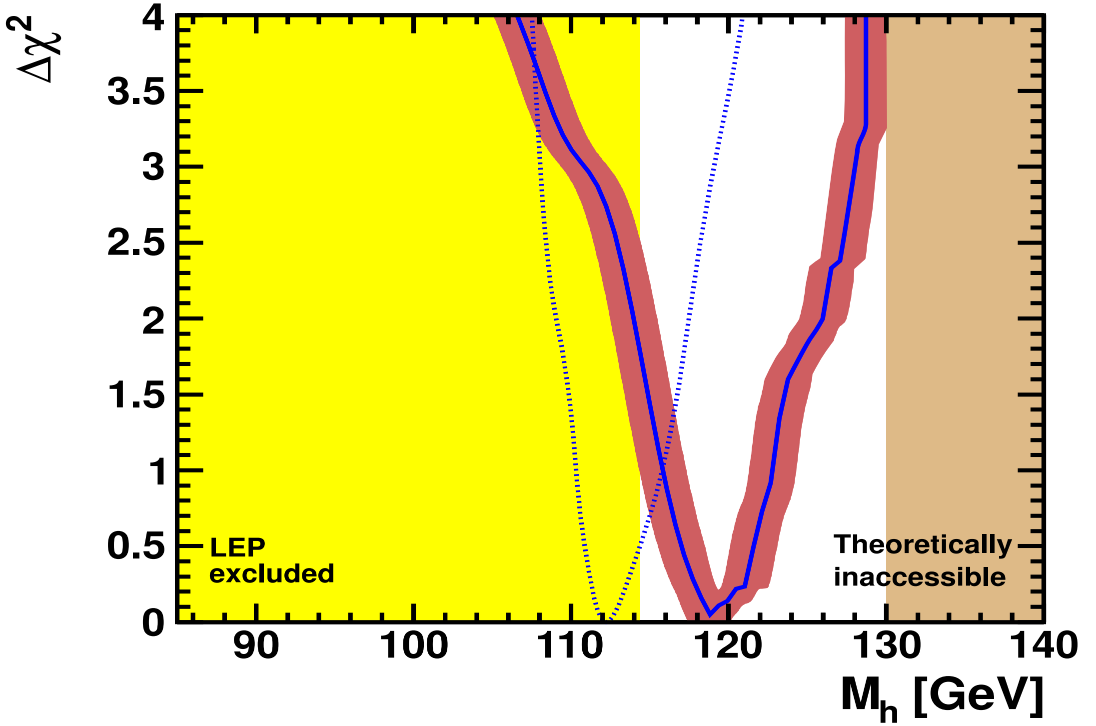


$\Rightarrow$ Preference for a light Higgs, $M_{\mathrm{H_{SM}}} < 161\ \mathrm{GeV}$, 95% C.L.

Indirect prediction for the Higgs mass in constrained SUSY model: pre-LHC vs. LHC2011

χ^2 fit for M_h, without imposing direct search limit

CMSSM:



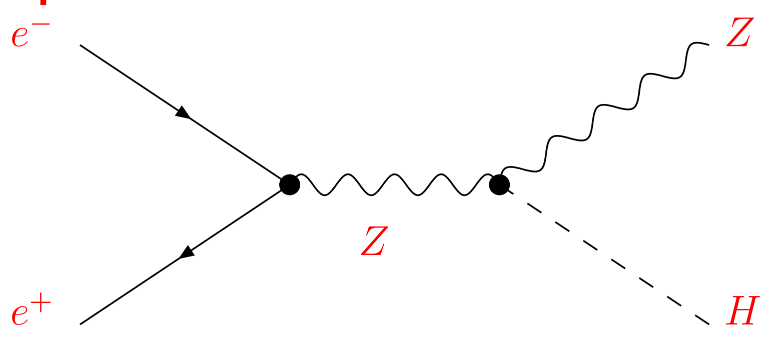
$\Rightarrow$ Accurate indirect prediction

Compatibility with LEP limit improves with the inclusion of LHC SUSY search limits

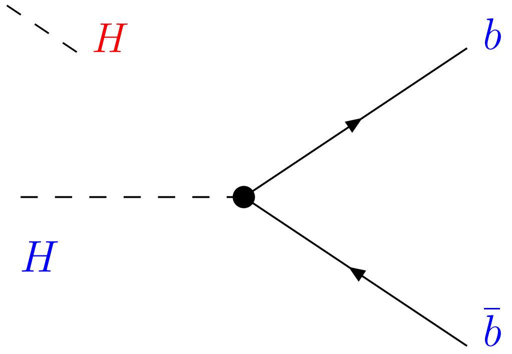
Higgs searches at LEP and the Tevatron

Search for the Standard Model Higgs at LEP

Dominant production process: $e^+e^- \to ZH$



Dominant decay process: $H \to b\bar{b}$



Highest energy: $E_{\mathrm{CM}} \approx 206$ GeV

Exclusion limit, 95% C.L.: [*LEP Higgs Working Group '03*]

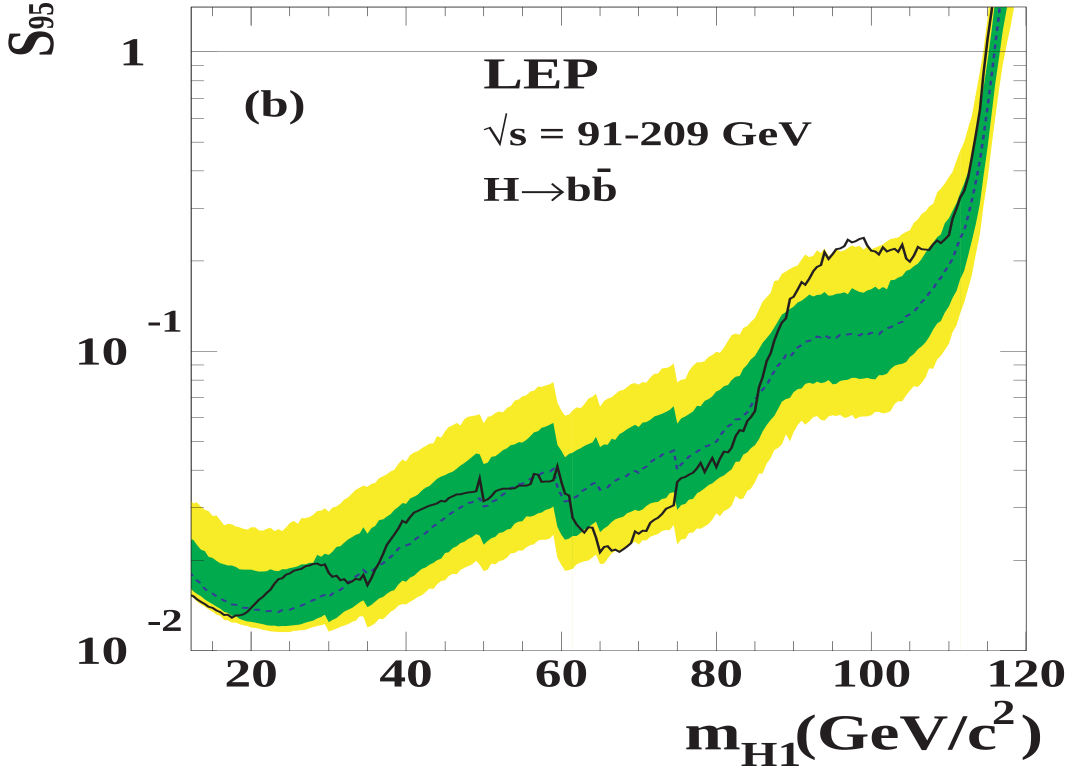
$$M_{\mathrm{H}} > 114.4\,\mathrm{GeV}\ (\text{expected: } 115.3\,\mathrm{GeV})$$

LEP limit on production cross section, normalised to SM case

95% C.L. upper bound:

– expected limit for background-only hypothesis, $\pm 1\sigma$, $\pm 2\sigma$

– observed limit



⇒ A Higgs with reduced couplings to gauge bosons is still possible below the limit on a SM-like Higgs

Example: MSSM with complex parameters: a very light SUSY Higgs?

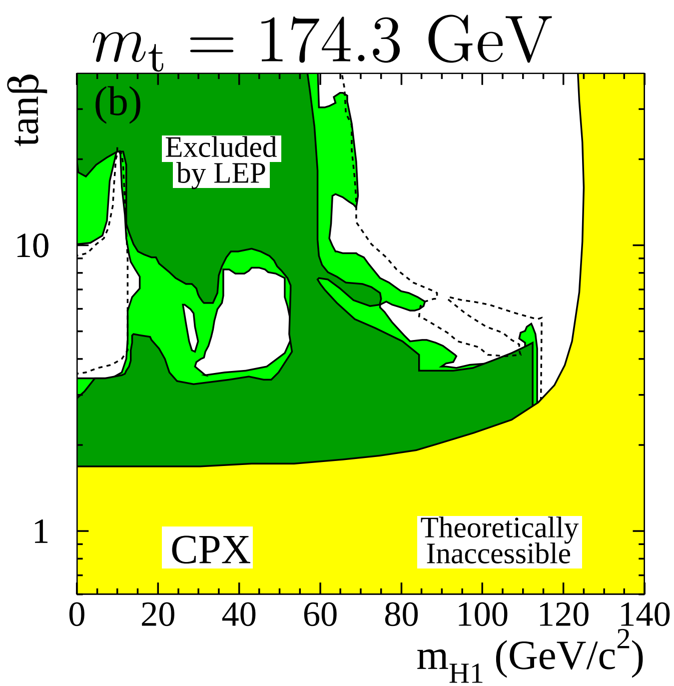
MSSM with $\mathcal{CP}$-violating phases (CPX scenario):

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 $\mathrm{BR}(h_2 \to h_1h_1)$ $\Rightarrow$ difficult final state

[*LEP Higgs WG '06*]

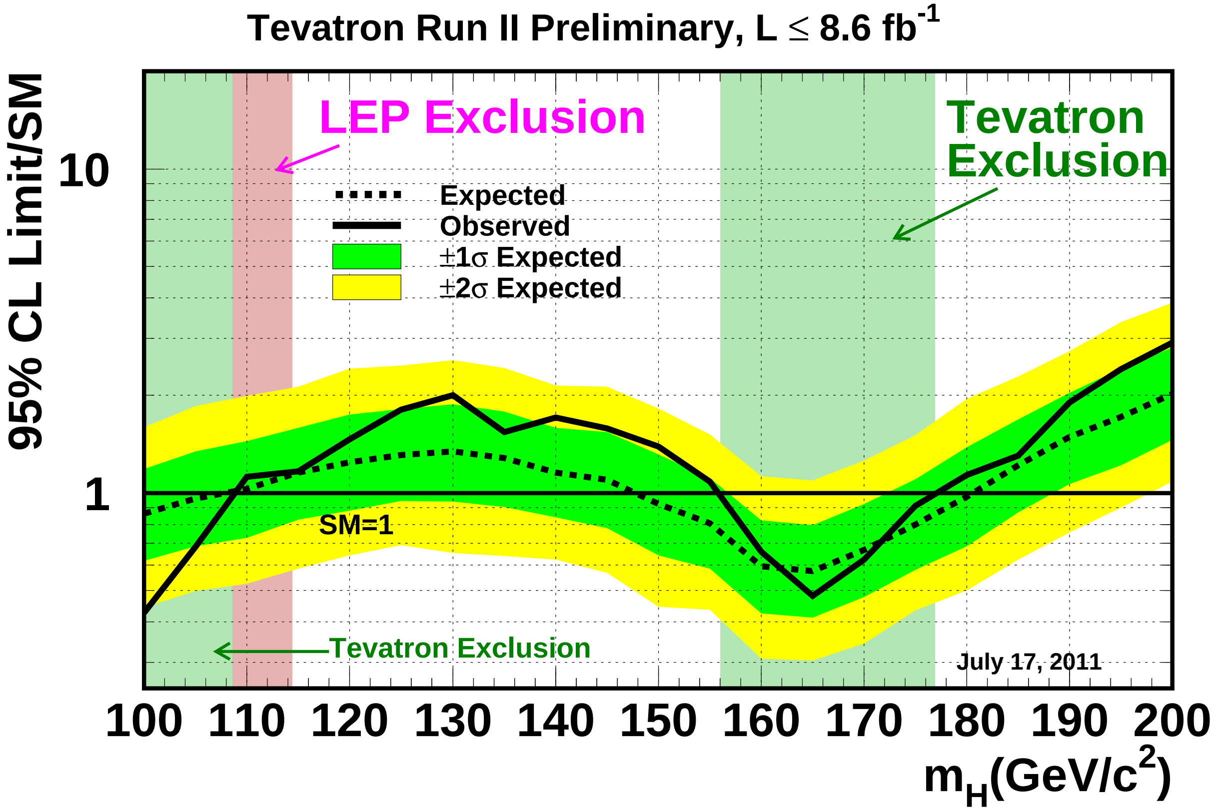


$\Rightarrow$ Light SUSY Higgs not ruled out!

SM Higgs search: Tevatron results

$(p\bar{p},\ E_{\rm CM} \approx 2\ {\rm TeV})$

Upper limit on the cross section (CDF $+$ D0 combined), normalised to the SM expectation [*CDF and D0 Collaborations '11*]



$\Rightarrow$ In the regions where the observed limit drops below 1 a SM-like Higgs is excluded at the 95% C.L.

Slight excess ($\sim 1\sigma$) in low mass region

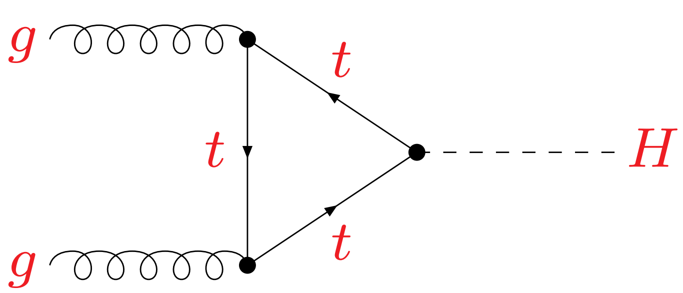
Latest results from the LHC: status and interpretation

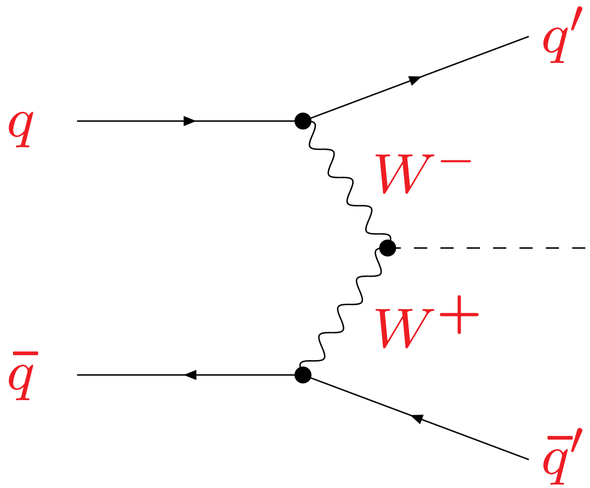
LHC, 2010 & 2011: pp, $E_{\mathrm{CM}} = 7\ \mathrm{TeV}$

Production of a SM-like Higgs at the LHC:

Dominant production processes:

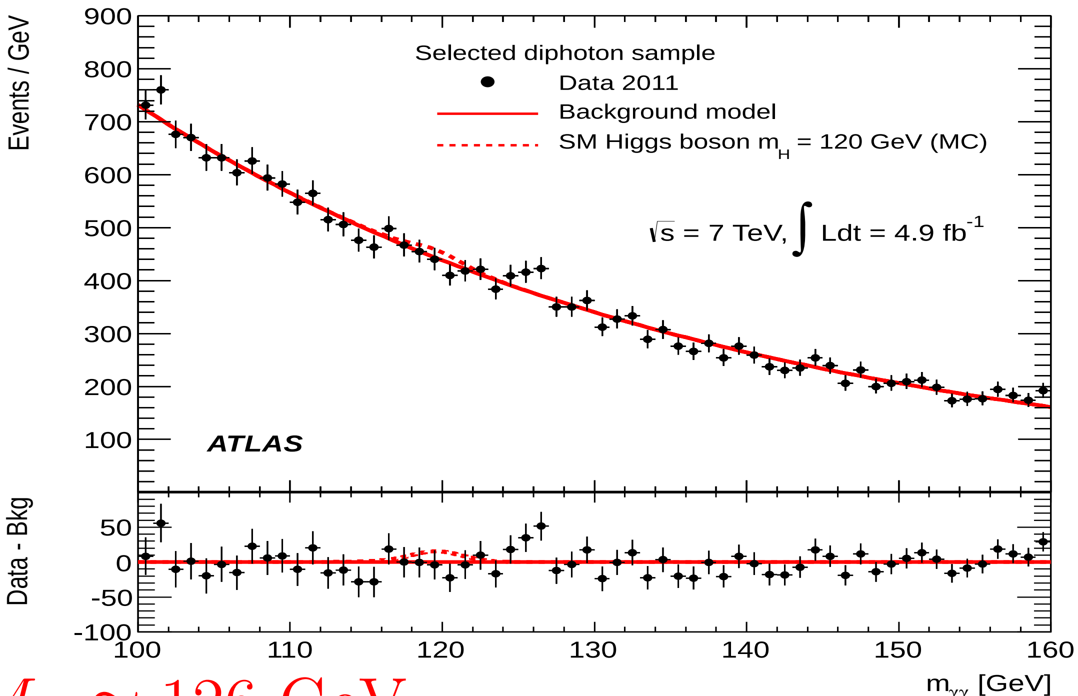
gluon fusion: $gg \to H$, weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'H$





Main search channels for a SM-like Higgs

- $H \to \gamma\gamma$: loop-induced process, rare decay, most sensitive channel for a light Higgs
  [$H \to b\bar{b}$: very challenging, huge QCD backgrounds]
  $H \to \gamma\gamma$: good mass resolution $\Rightarrow$ look for small peak in $\gamma\gamma$ invariant mass distribution over continuum background (estimated from data; sidebands) [*ATLAS Collaboration '12*]

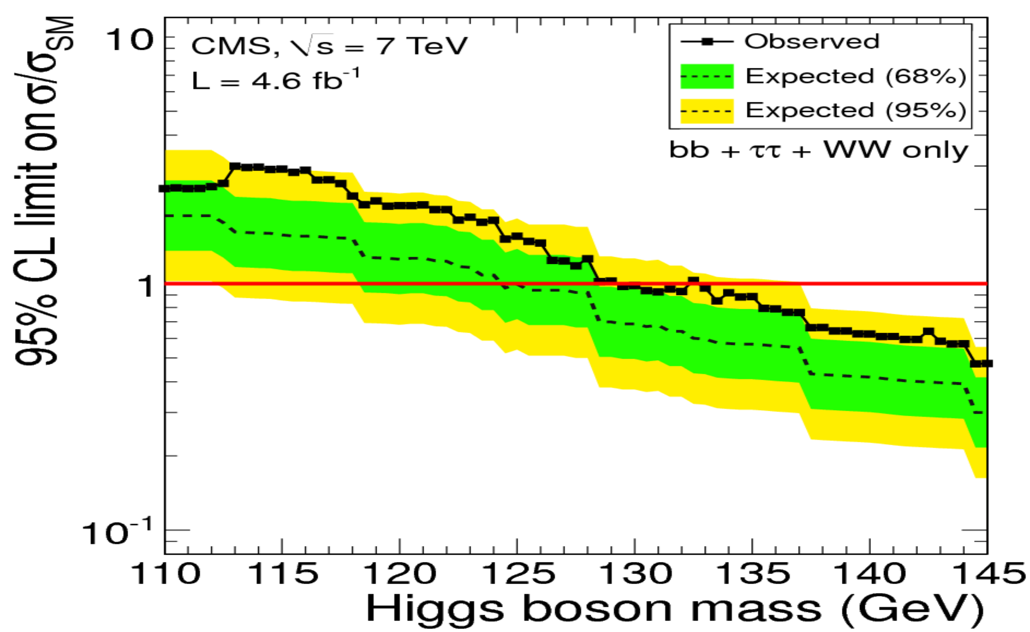


$\Rightarrow$ Excess at $M_\mathrm{H} \approx 126\ \mathrm{GeV}$

Main search channels for a SM-like Higgs

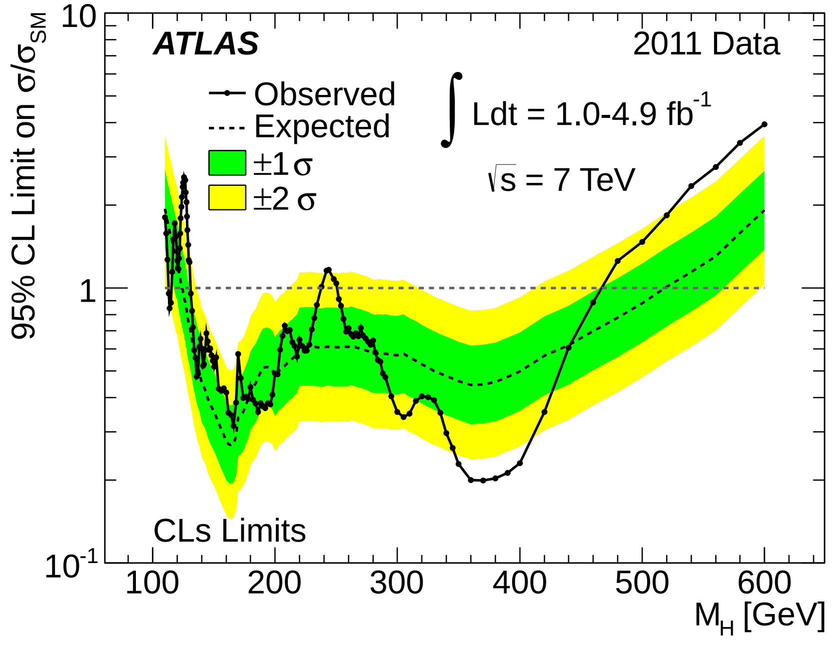
- $H \to ZZ^{(*)} \to 4l$: “golden channel” for Higgs searches at LHC; clean signal, but low statistics in low-mass region

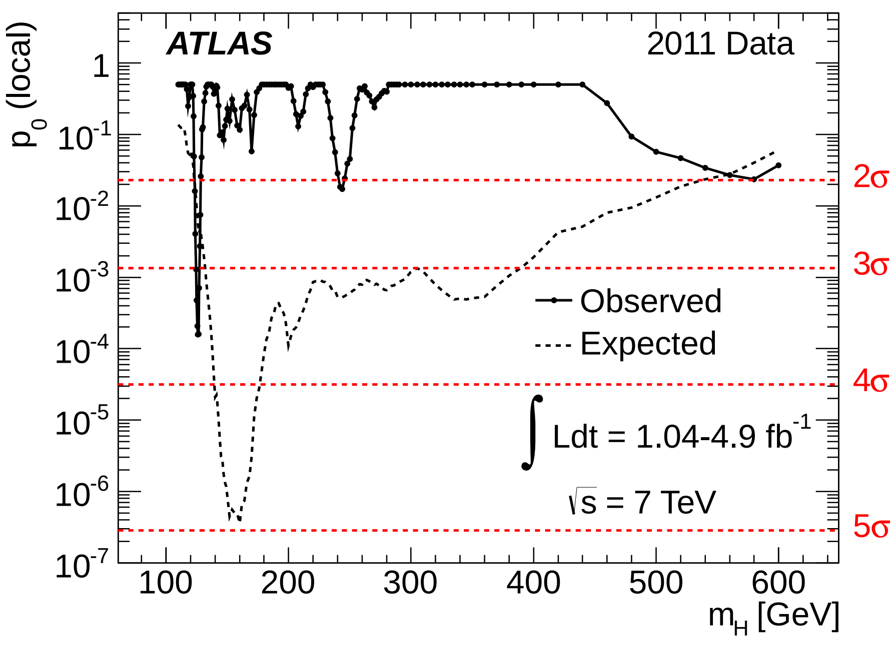
- $H \to WW^{(*)} \to l\nu\, l\nu$: higher rate, but poor mass resolution
  $\Rightarrow$ signal would give rise to a broad excess over a wide range of Higgs masses [*CMS Collaboration ’12*]



Combined result from ATLAS

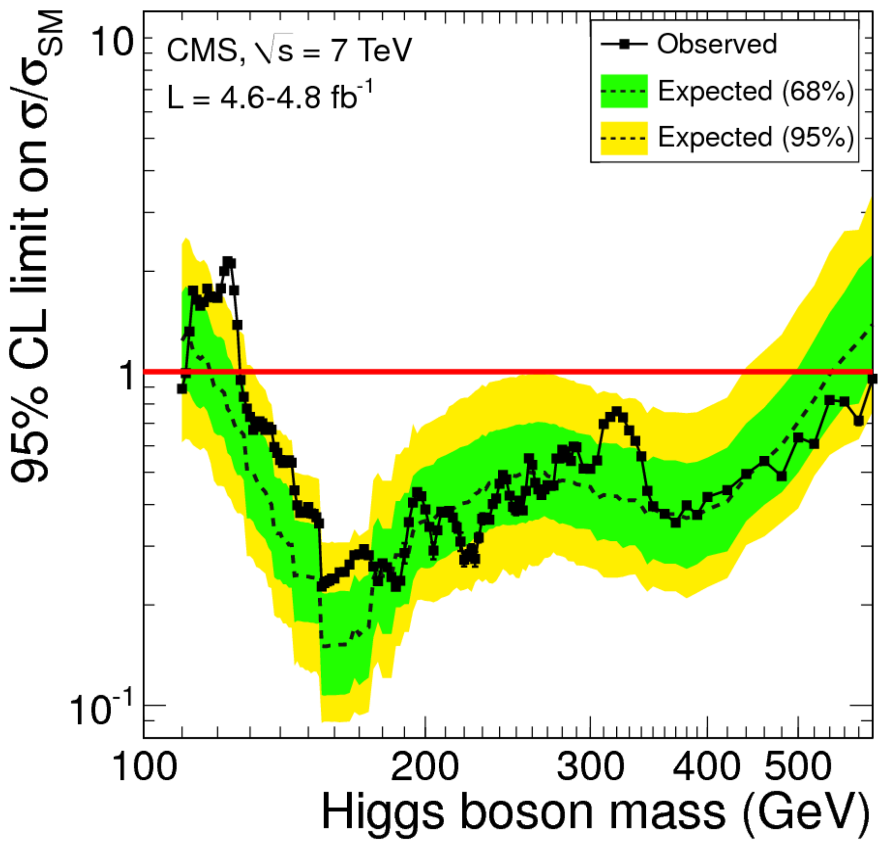
ATLAS SM Higgs search: combined upper limit normalised to the SM expectation (left) and observed result vs. expectation for a SM Higgs signal (right) [*ATLAS Collaboration '12*]





Combined result from CMS

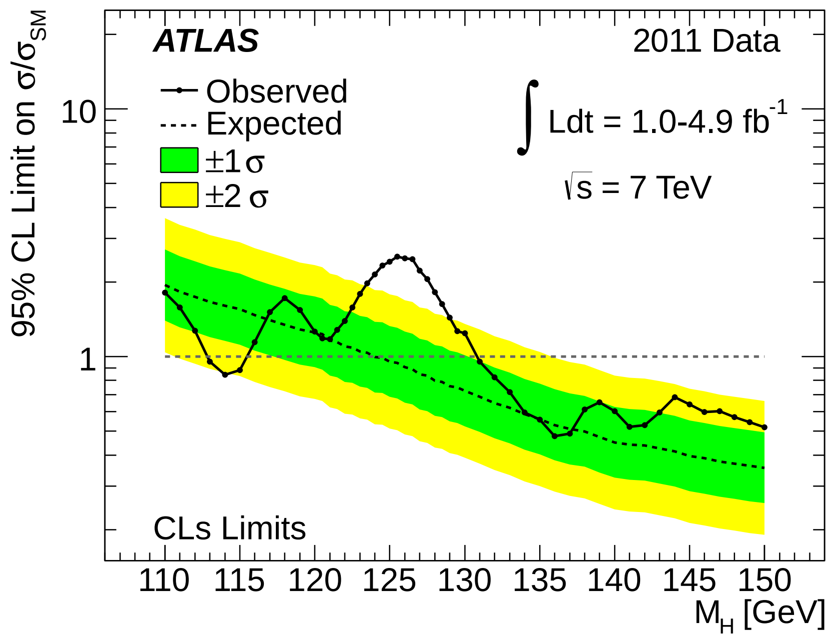
CMS SM Higgs search: combined upper limit normalised to the SM expectation [*CMS Collaboration '12*]

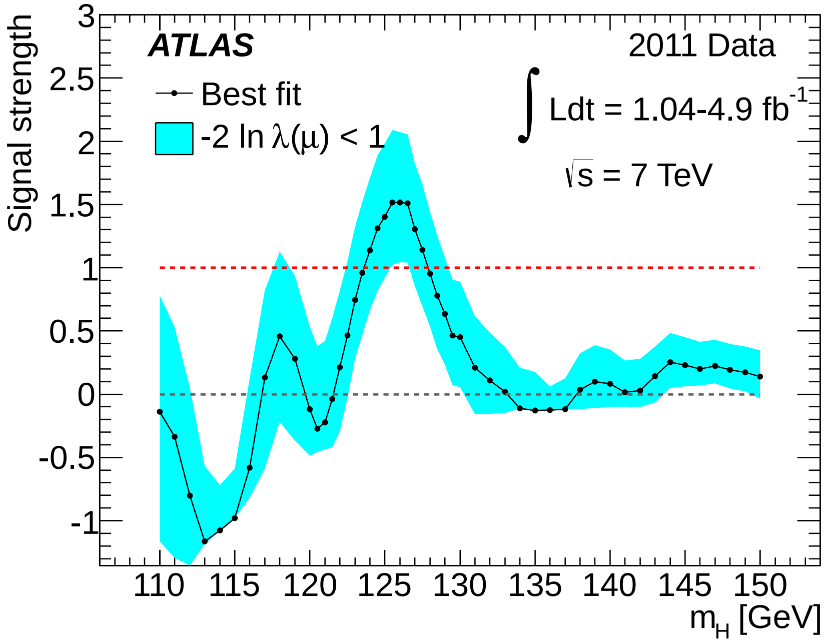


$\Rightarrow$ SM-like Higgs is excluded for $127 \text{ GeV} \lesssim M_{\mathrm{H_{SM}}} \lesssim 600 \text{ GeV}$

ATLAS result in low-mass region

ATLAS SM Higgs search: combined upper limit (left) and best-fit signal strength (right), normalised to the SM expectation [ATLAS Collaboration '12]



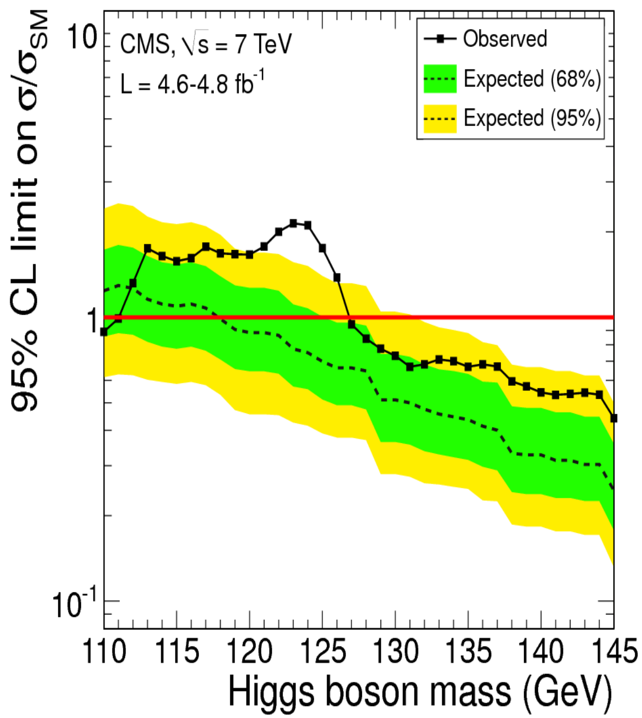


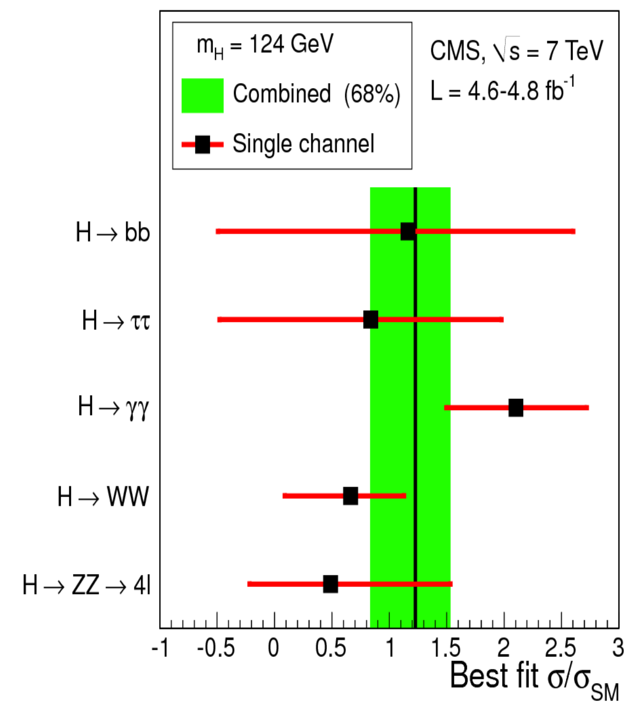
$\Rightarrow$ 3.6σ excess at $M_{\mathrm{H}} \approx 126\ \mathrm{GeV}$
signal strength compatible with SM expectation

Interpretation of excess is subject to “look elsewhere effect”

CMS result in low-mass region

Combined upper limit (left) and best-fit signal strength (right), normalised to the SM expectation [*CMS Collaboration '12*]





$\Rightarrow 3.1\sigma$ excess at $M_{\mathrm{H}} \approx 124$ GeV (smaller excess at ≈ 119 GeV)
signal strength compatible with SM expectation

Interpretation of excess is subject to "look elsewhere effect"

Summary on current situation of SM Higgs searches

Exclusion limits from LEP, Tevatron, ATLAS, CMS:

Allowed mass range for SM Higgs reduced to

$114~\mathrm{GeV} \lesssim M_{\mathrm{H_{SM}}} \lesssim 127~\mathrm{GeV}$

($+$ high mass region above $600~\mathrm{GeV}$)

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Excess observed by ATLAS and CMS in SM-like Higgs searches near $M_{\mathrm{H_{SM}}} \approx 125\ \mathrm{GeV}$, supported by several channels (in particular $\gamma\gamma$, ZZ^*)

Slight excess observed also at the Tevatron

Implications of the results from the SM Higgs searches for SUSY

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The SUSY relations imply an upper bound on the mass of the light $\mathcal{CP}$-even Higgs, M_h

$\Rightarrow$ In the MSSM: $M_\mathrm{h} \lesssim 135\ \mathrm{GeV}$

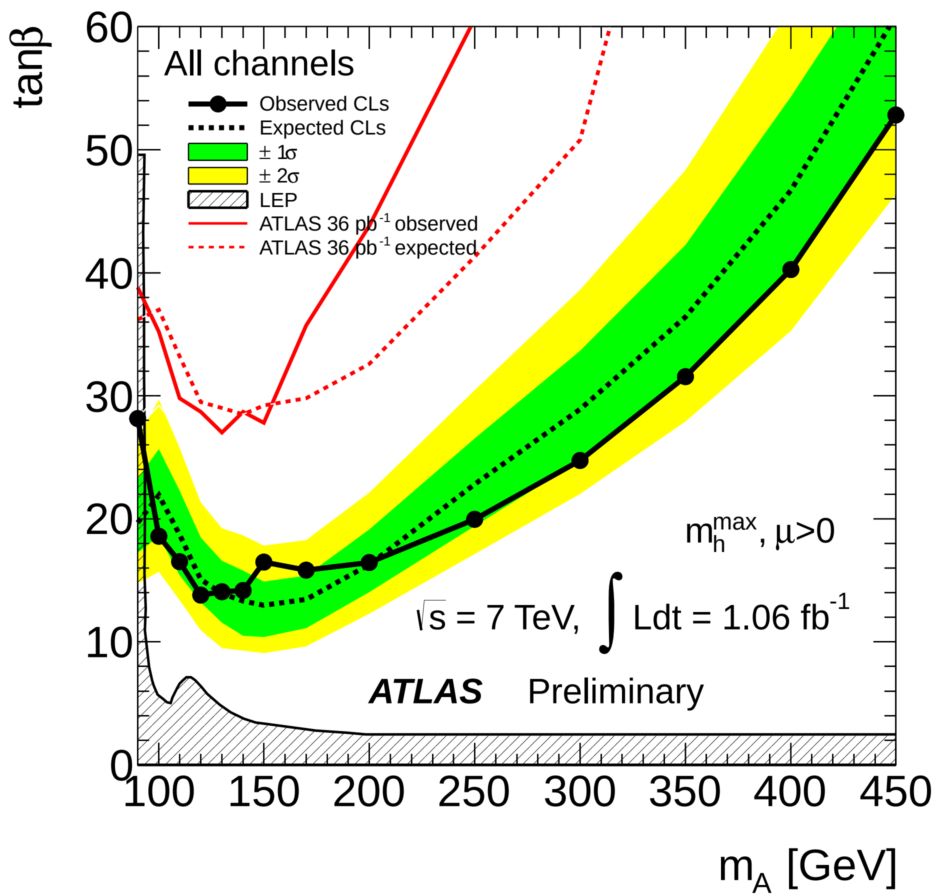
- The detection of a SM-like Higgs with $M_\mathrm{H} \gtrsim 135\ \mathrm{GeV}$ would have unambiguously ruled out the MSSM

  Region above the upper bound of the MSSM is meanwhile ruled out for a SM-like Higgs

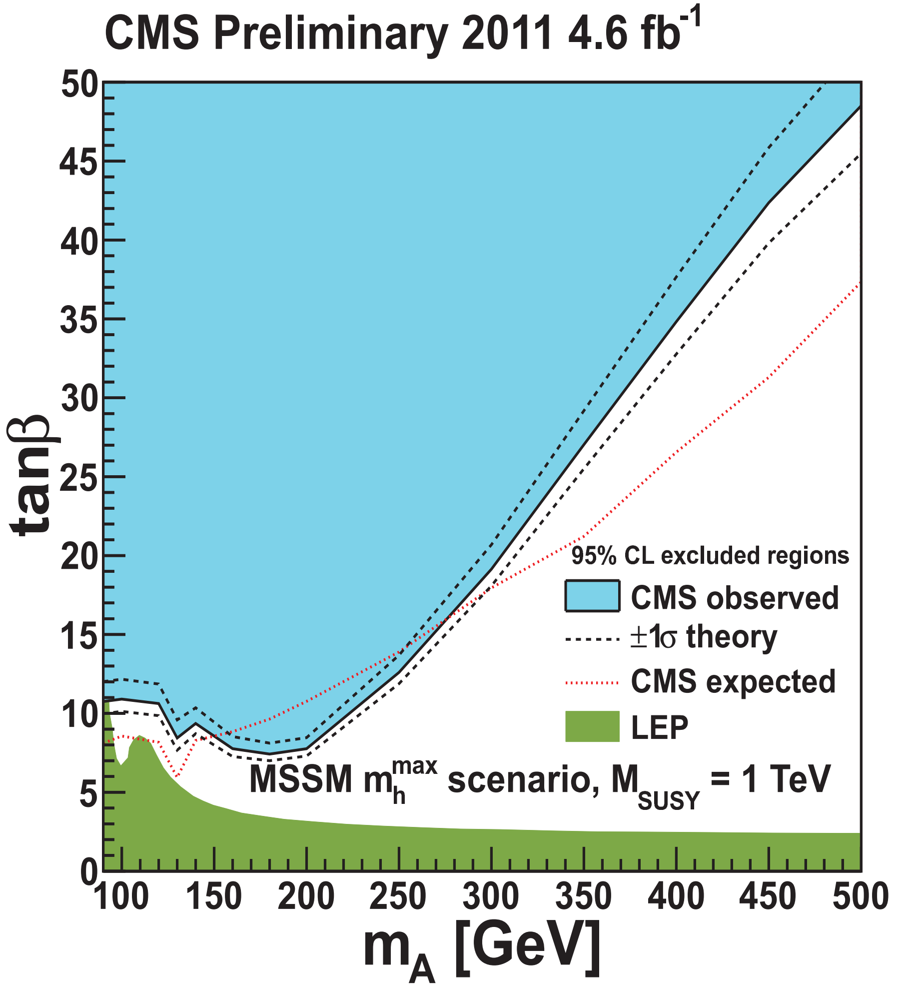
- Unexcluded low-mass region corresponds to the mass range predicted for the light $\mathcal{CP}$-even Higgs of the MSSM

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 narrow down the region of very low M_A

MSSM interpretation of latest Higgs search results from ATLAS and CMS

Statistical significance of reported excess near $125\ \mathrm{GeV}$ is not yet conclusive

In the following: investigate MSSM interpretation of assumed Higgs signal at $125 \pm 1\ \mathrm{GeV}$

Intrinsic theoretical uncertainties from unknown higher-order corrections, $\Delta M_\mathrm{h}^\mathrm{intr} \sim 2\ \mathrm{GeV}$, and parametric uncertaintes (variations of m_t by $\pm 1\sigma$) taken into account

Interpretation of an assumed Higgs signal at ~ 125 GeV

in terms of the light MSSM CP-even Higgs h

Assumed signal would imply a lower bound on M_h

$\Rightarrow$ Set parameters entering via higher-order corrections such that M_h is maximised ($m_\mathrm{h}^\mathrm{max}$ benchmark scenario)

$\Rightarrow$ Lower bounds on M_A, $\tan\beta$

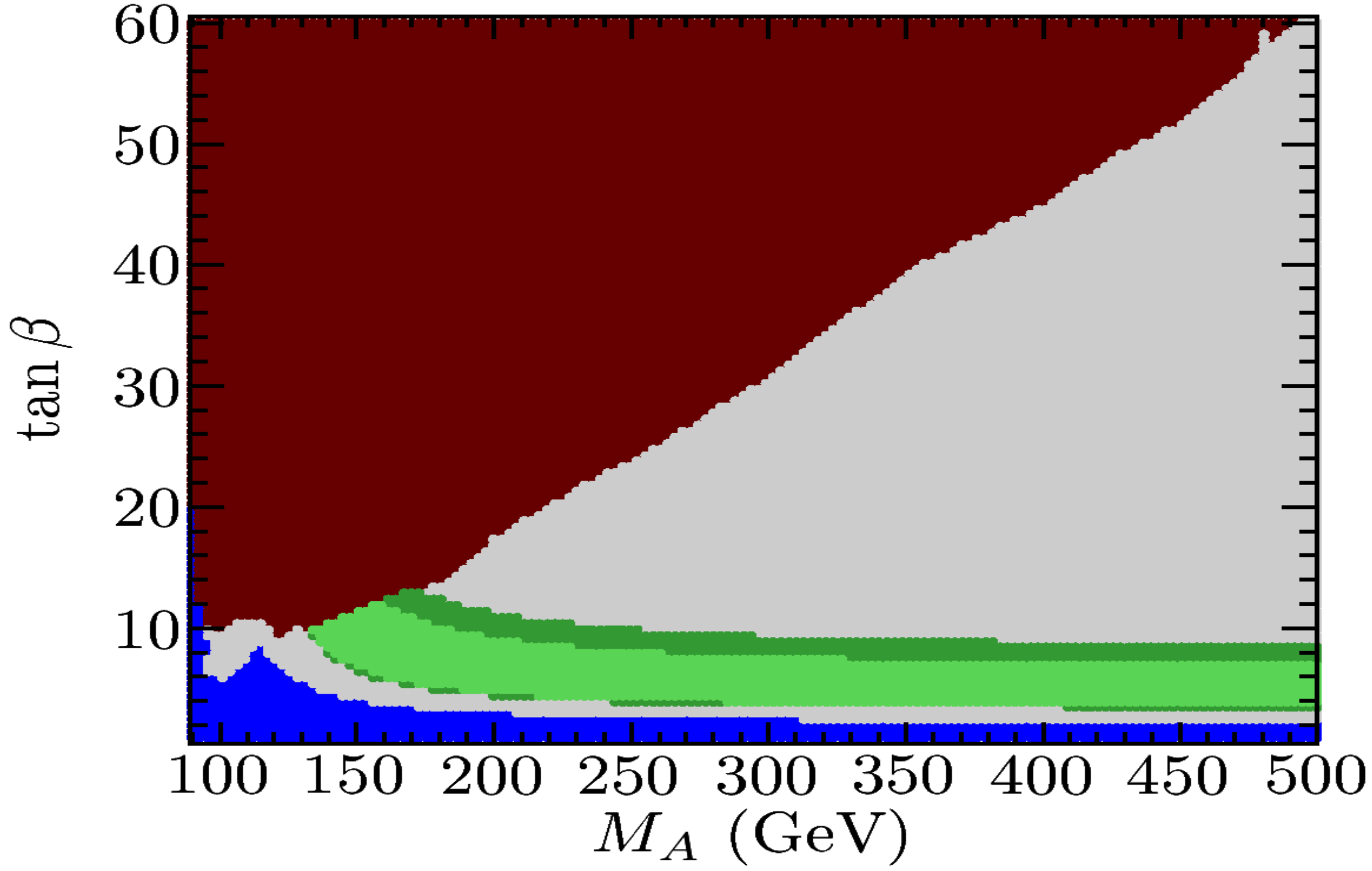
Search limits from LEP and from LHC $H, A \to \tau^+\tau^-$ search taken into account:

HiggsBounds

[*P. Bechtle, O. Brein, S. Heinemeyer, G. W., T. Stefaniak, K. Williams ’08, ’11*]

Lower bounds on M_A and $\tan\beta$ from assumed Higgs signal at ~ 125 GeV

Green region: compatible with assumed Higgs signal with / without m_t variation [*S. Heinemeyer, O. Stål, G. W. '11*]

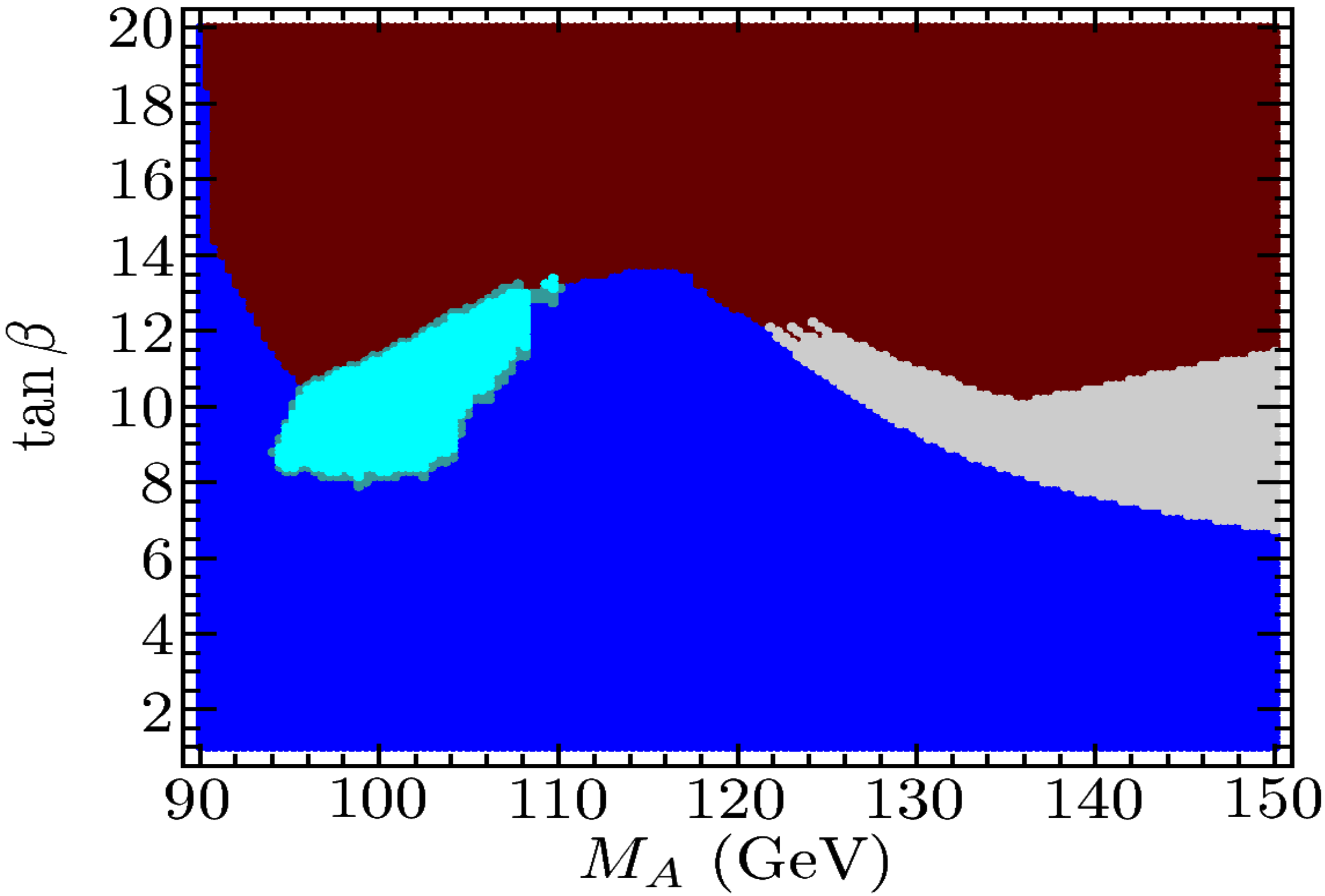


$\Rightarrow \tan\beta \gtrsim 3$, $M_\mathrm{A} \gtrsim 130$ GeV, $M_{\mathrm{H}^\pm} \gtrsim 152$ GeV

Interpretation of an assumed Higgs signal at $\sim 125\ \mathrm{GeV}$ *in terms of the heavy MSSM CP-even Higgs* H

Scan over M_{A}, $\tan\beta$, M_{SUSY}, X_{t}

[*S. Heinemeyer, O. Stål, G. W. '11*]



$\Rightarrow$ possible for low M_{A}, moderate $\tan\beta$

Interpretation of an assumed Higgs signal at ~ 125 GeV ***in terms of the heavy MSSM CP-even Higgs*** H

The light Higgs h in this scenario has a mass that is always below the LEP limit of $M_{H_{SM}} > 114.4$ GeV (with reduced couplings to gauge bosons, in agreement with LEP bounds)

Could have, for instance, $M_H \sim 125$ GeV, $M_h \sim 98$ GeV (slight excess observed at LEP at $M_h \sim 98$ GeV)

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

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- Figuring out the nature of an observed Higgs-like state (SM or something else, elementary or composite, . . . ?) will both be exciting and challenging