Results of Higgs Searches, and its Interpretation in the SM and its SUSY Extensions

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1) Higgs Search Channels

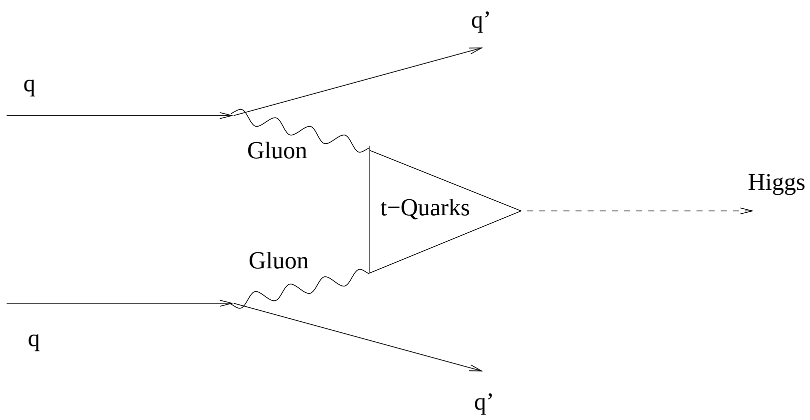
2) Present Results

3) Expectations in the SM and its SUSY Extensions

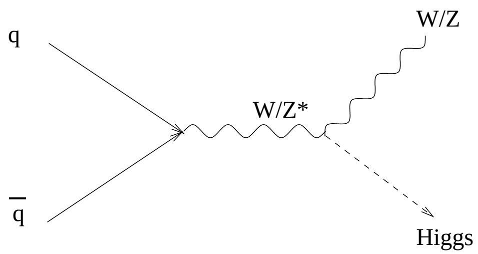
Higgs Production and Decays

Production mechanisms:

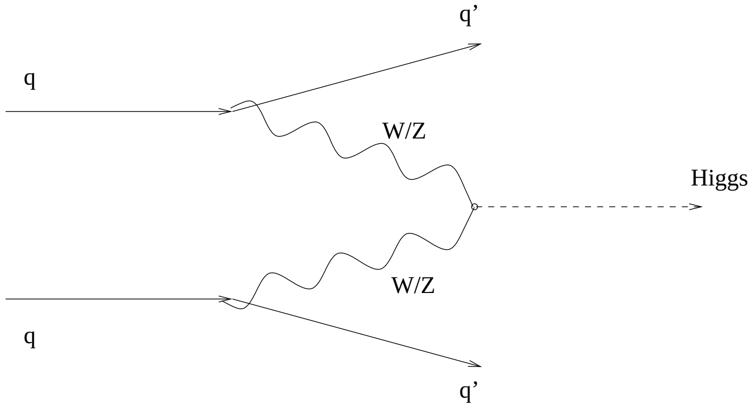
Dominant: Gluon-gluon fusion $g\,g \rightarrow H$ via a top-quark loop



Ass. production with W/Z-bosons: $q\,q \rightarrow H + W/Z$



LHC @14TeV: Vector Boson Fusion: $q\, q \to q'\, q' + W^+ + W^- \to q'\, q' + H$



Higgs decays:

Dominant for $M_H \gtrsim 135$ GeV: $H \to W\, W^{(*)} \to \ldots,\ H \to Z\, Z^{(*)} \to \ldots$

Dominant for $M_H \lesssim 135$ GeV: $H \to b\, \bar{b}$,
but (nearly) useless at a Hadron Collider

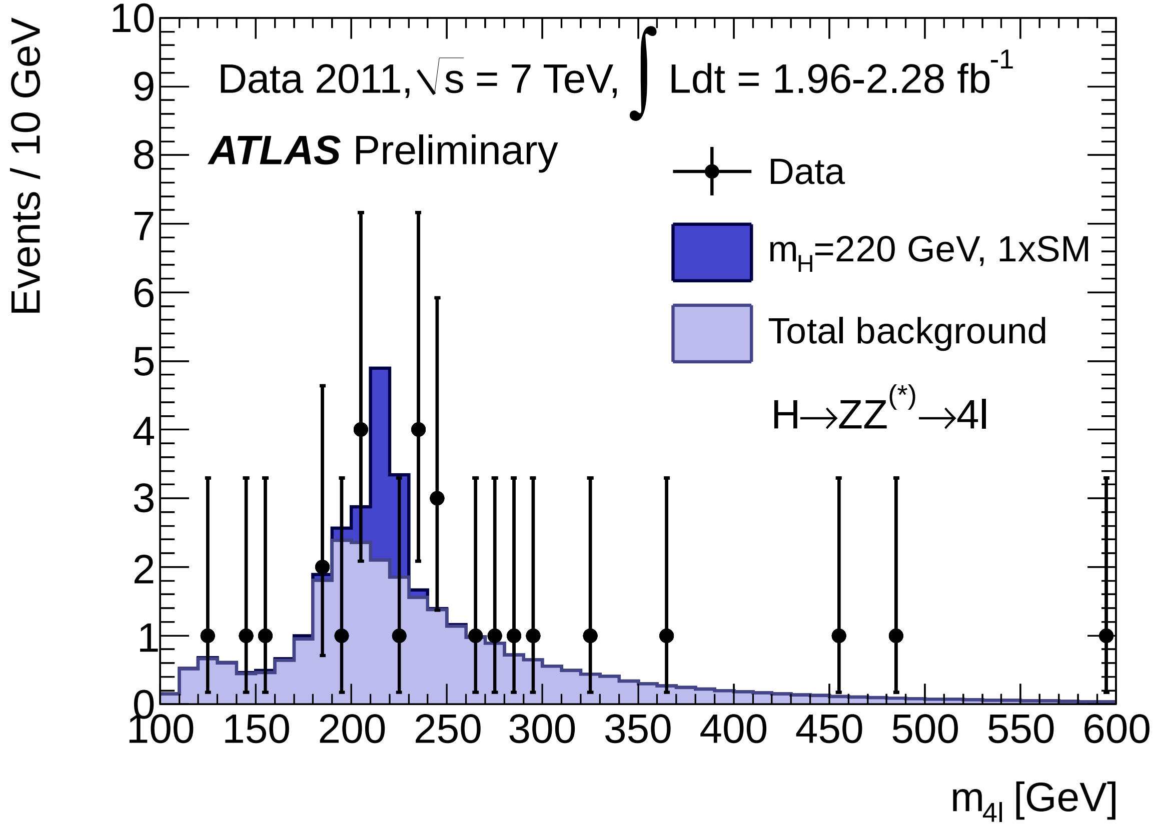
Useful for 120 GeV $\lesssim M_H \lesssim 135$ GeV: still $H \to W\, W^*$, $H \to Z\, Z^*$
and $H \to \gamma\gamma$, $H \to \tau^+\tau^-$

For $M_H \lesssim 120$ GeV: only $H \to \gamma\gamma$, $H \to \tau^+\tau^-$

Dominant Higgs Search Channels

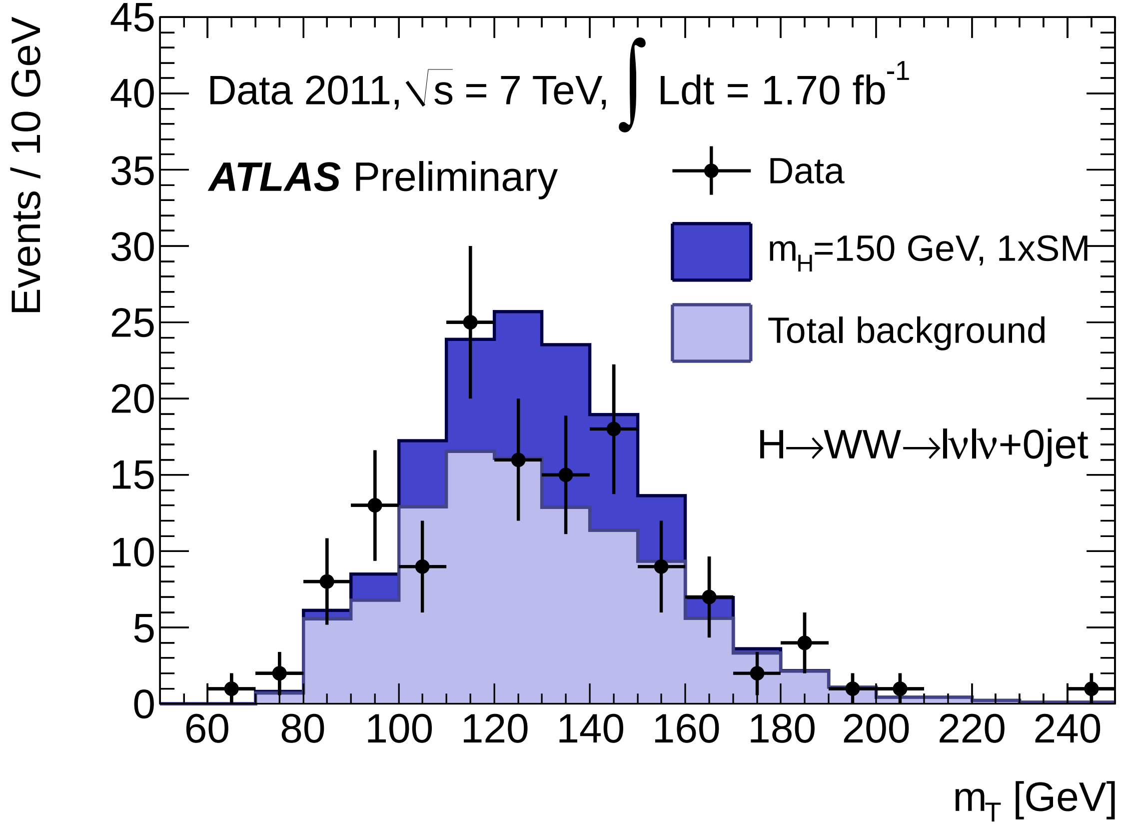
$H \rightarrow Z\,Z^{(*)} \rightarrow 4l$ (electrons/muons):

"Golden Channel", good mass resolution, but low branching ratio:



$H \to Z\,Z \to l^+\,l^- + \nu\,\bar{\nu}$: poor mass resolution, useful only for large M_H
$H \to Z\,Z \to l^+\,l^- + q\,\bar{q}$: somewhat larger BR, but large background

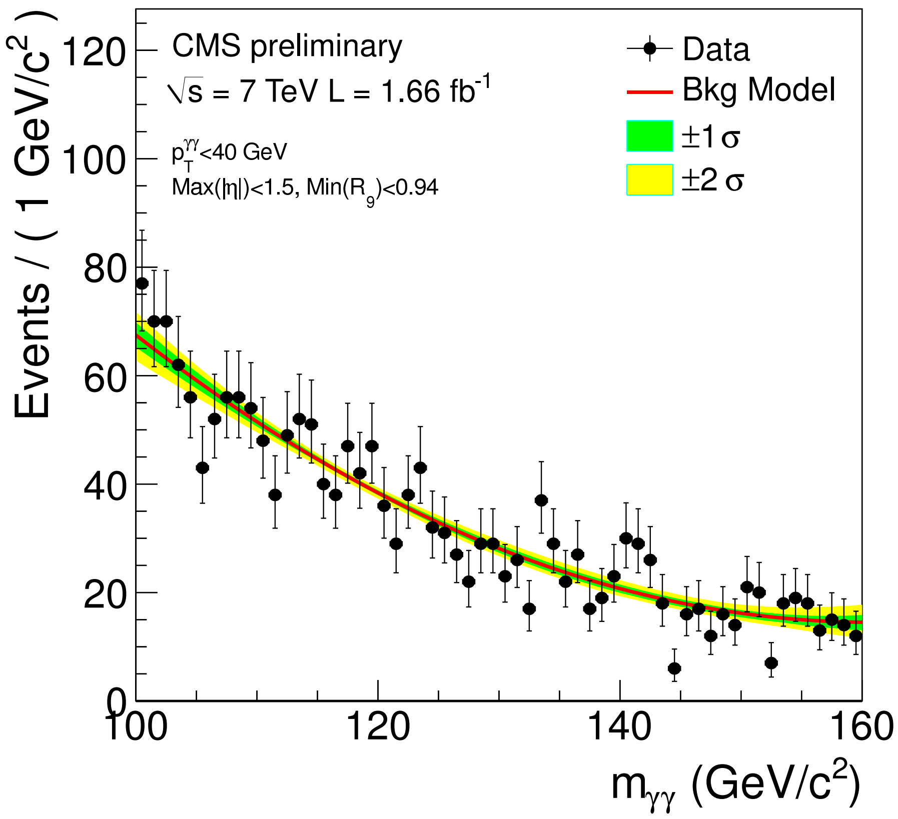
$H \to W\,W^{(*)} \to l^+\,l^- + \nu\,\bar{\nu}$ $(+1\ jet)$: larger BR, but poor mass resolution:



$W\,H \to l\,\nu + b\,\bar{b}$: larger BR, but poor mass resolution and small signal/background ratio

$Z\,H \to l^+\,l^- + b\,\bar{b}$: small signal/background ratio

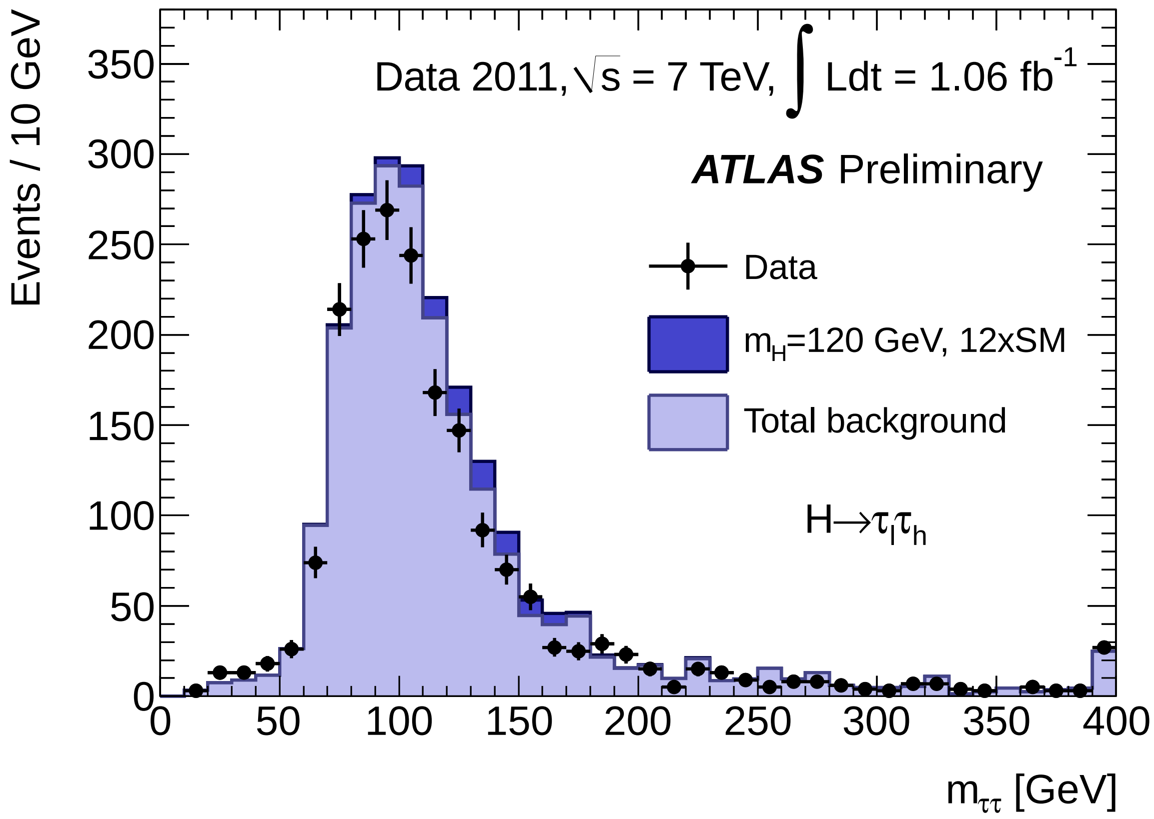
$H \to \gamma\,\gamma$: good mass resolution, but low branching ratio, only for low M_H:



$\to$ light excess at $m_{\gamma\,\gamma} \sim 140$ GeV

$H \to \tau^+\tau^- \to l^+l^- + 4\nu$: poor mass resolution, small signal/background ratio, only for low M_H

$H \to \tau^+\tau^- \to \tau_{hadr} + l + 3\nu$: small signal/background ratio, low M_H only:



All channels must be combined!

Presentation of the Combined Results:

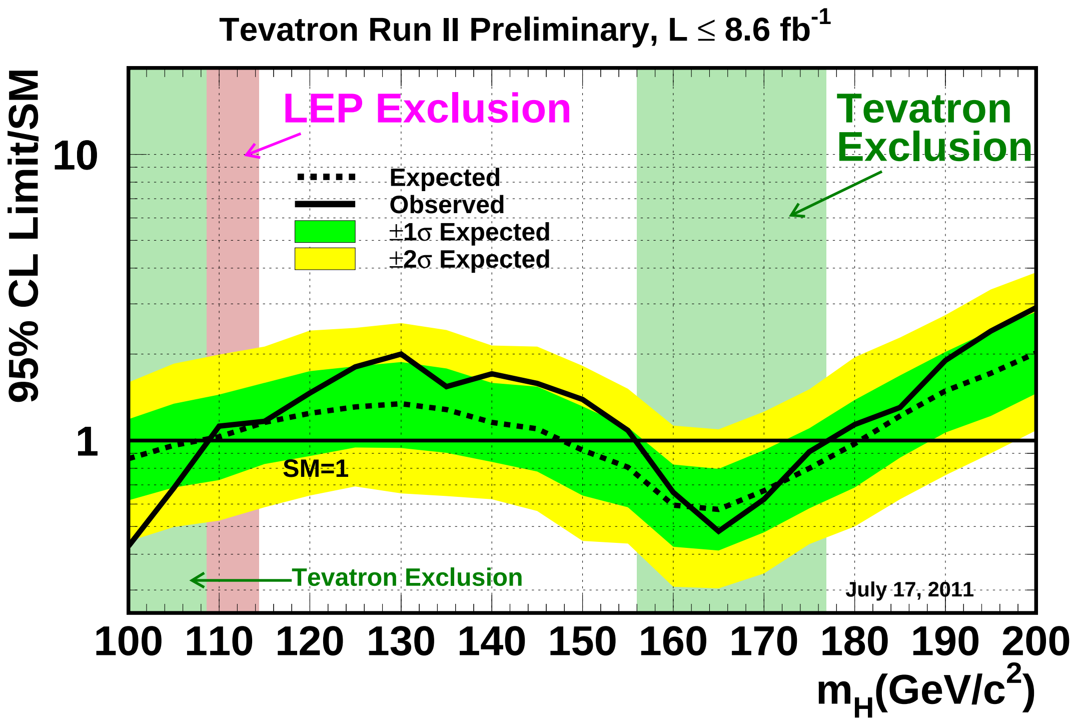
1) Assume a Higgs Boson of mass M_H, with an unknown production cross section $\sigma_{prod}(M_H)$ and branching ratios $BR(M_H)$ into the dominant channels:

$$\sigma_{prod}(M_H) \times BR(M_H) = R \times \sigma_{prod}(M_{H(SM)}) \times BR(M_{H(SM)})$$

Theoretically: R can be larger or smaller than 1

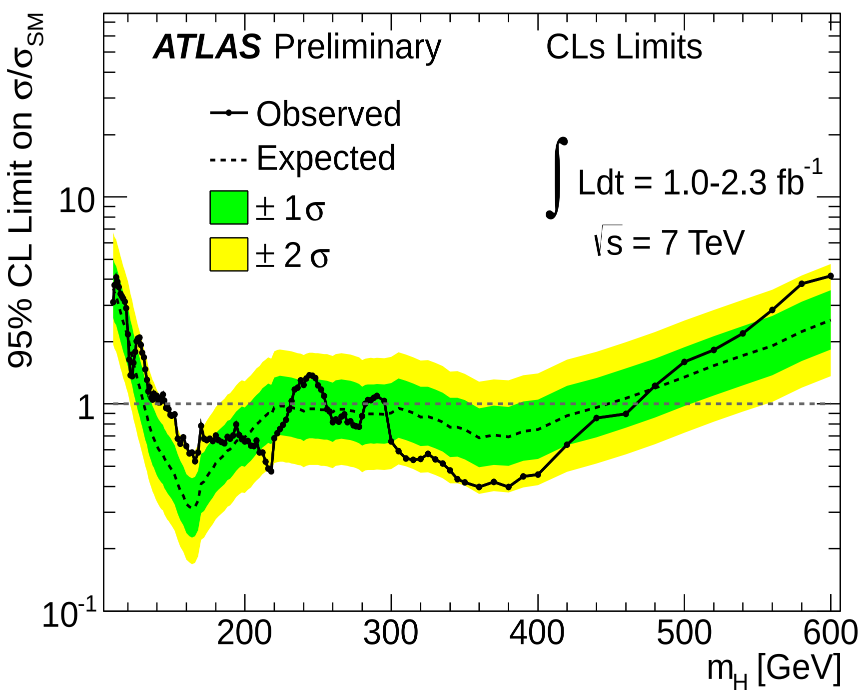
2) It is easier to verify the absence than the presence of a Higgs Boson of a given mass M_H!
$\longrightarrow$ For each value of M_H one can foresee ("expect"), how large R must be such that the absence of the Higgs Boson can be established at 95% confidence level
$\longrightarrow$ Plot this expected lower bound on R as function of M_H, together with the 1-σ (green) and 2-σ (yellow) bands
$\longrightarrow$ Show the observed lower bound on R

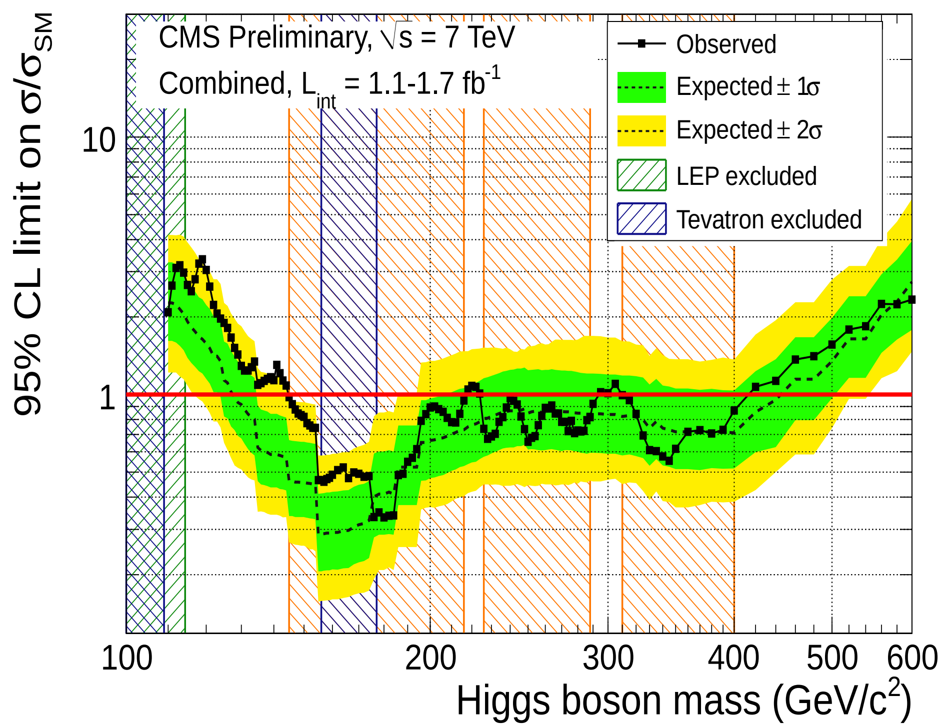
Tevatron, Combined Channels:



- The expected lower bound on R is below 1 ($\rightarrow$ sensitive to a SM-like Higgs boson) only for $M_H < 110$ GeV and 150 GeV$< M_H < 180$ GeV
- A black line above the dotted line indicates (slightly) more events than expected, but no significant excess seen!
  (Actually, a significant 5-σ excess is impossible to define from such plots)

ATLAS vs. CMS, Combined Channels:

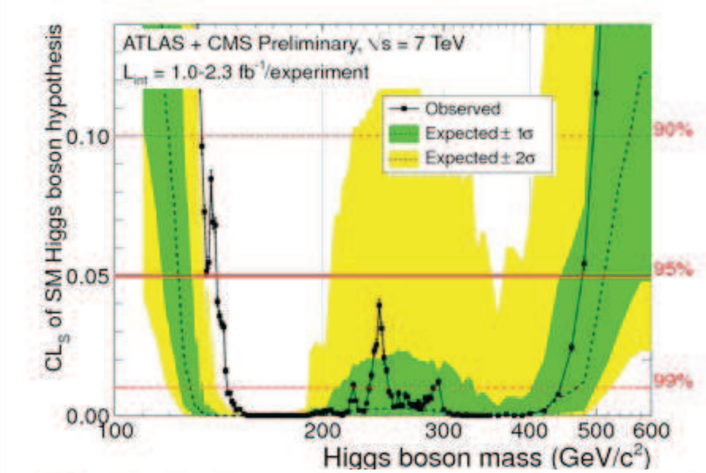


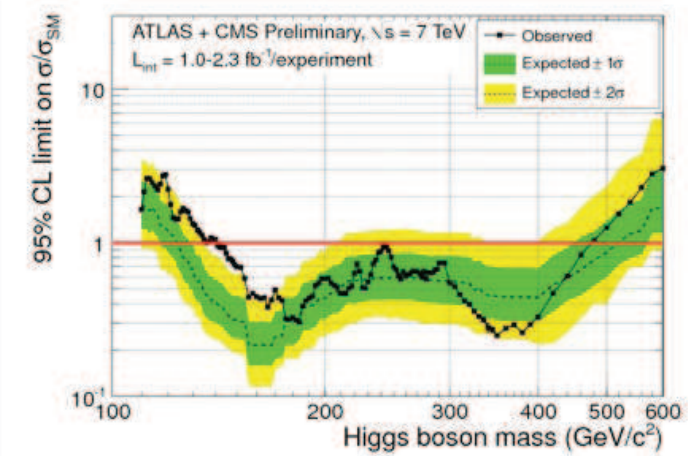


HCP Conference, 14-18 November: ATLAS and CMS results have been combined:

LHC Combination SM Higgs Boson

All Channels combined





Observed exclusion 95% CL
141-476 GeV

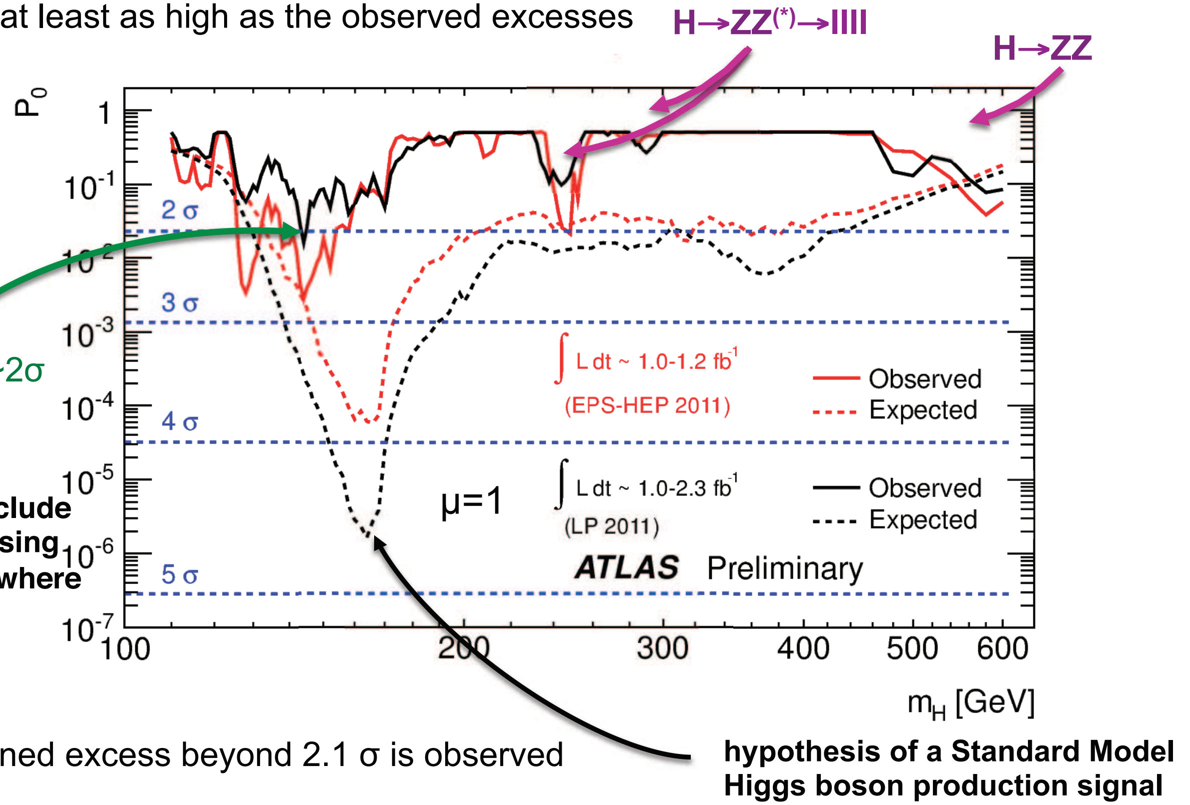
Expected exclusion 95% CL
124-520 GeV

What would we expect in the presence of a SM-like Higgs boson?

LOCAL P-VALUES

Local p-value of the SM Higgs combination at ATLAS :

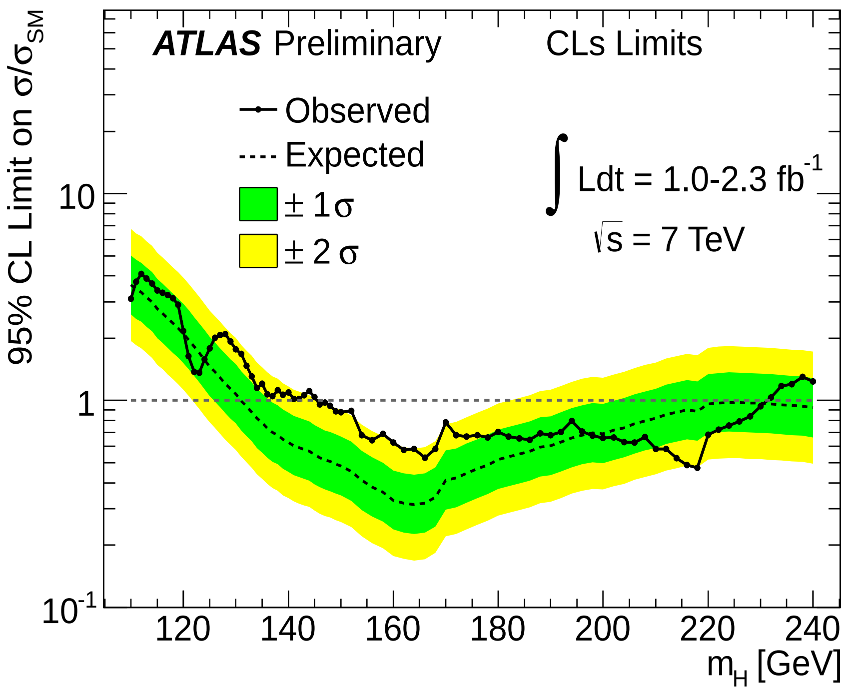
- The observed local p-value characterize probabilities for the predicted background to fluctuate at least as high as the observed excesses

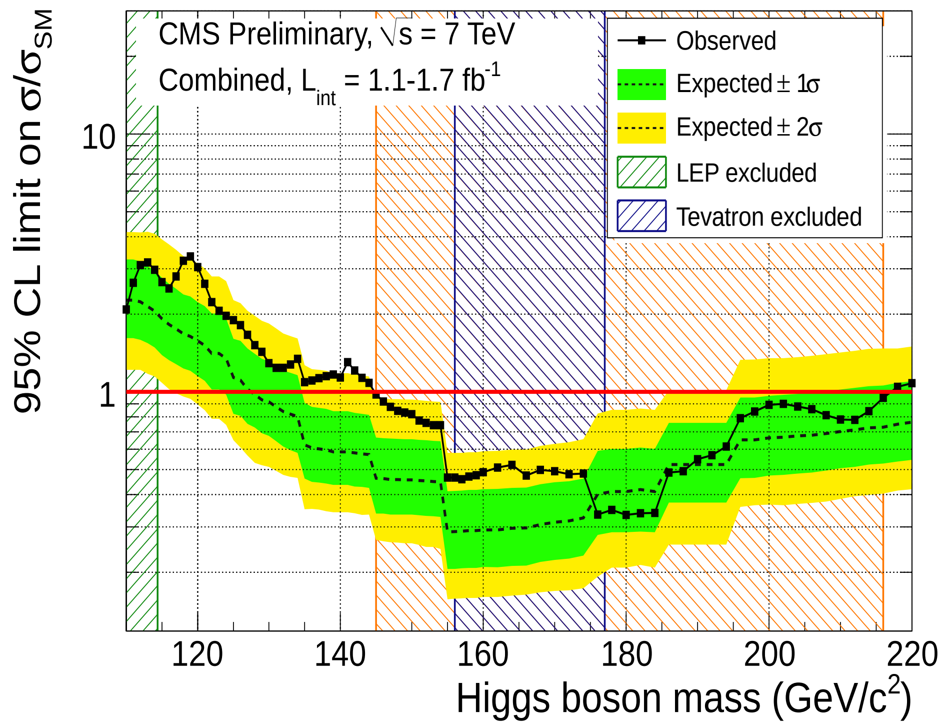


p-values do not include the trials factor arising from the look-elsewhere effect (LEE)

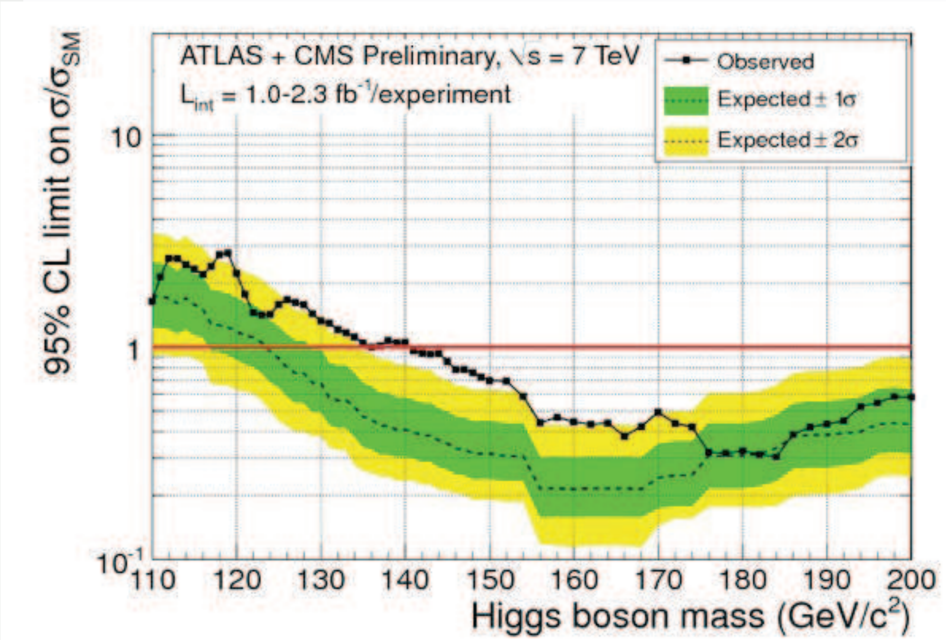
- No combined excess beyond 2.1 σ is observed
- No incompatibility with the Standard Model is seen in ATLAS

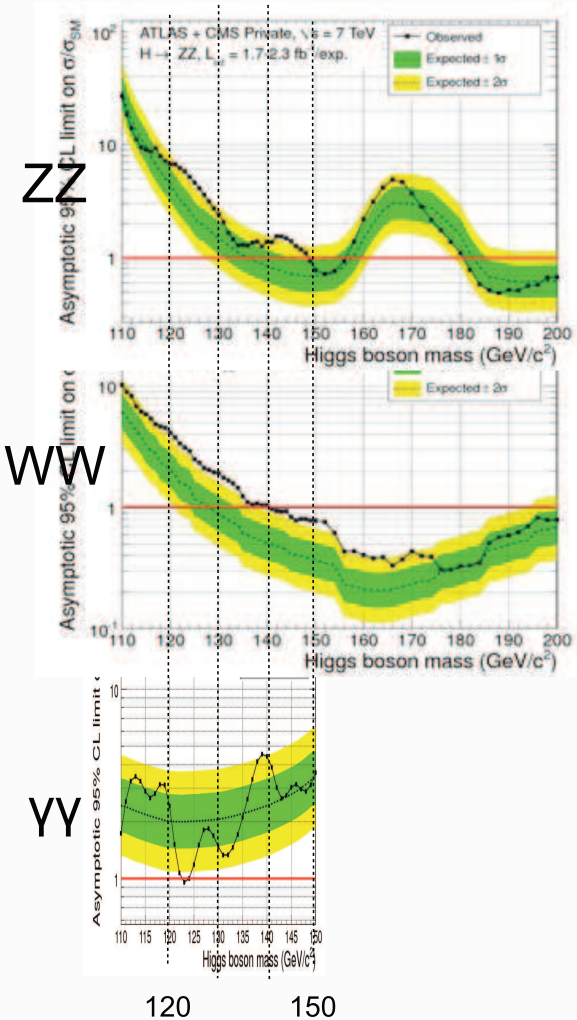
A closer look at the low mass region:





Zoom on low mass





Excess largely due to the WW channel with modulations induced by ZZ and γγ

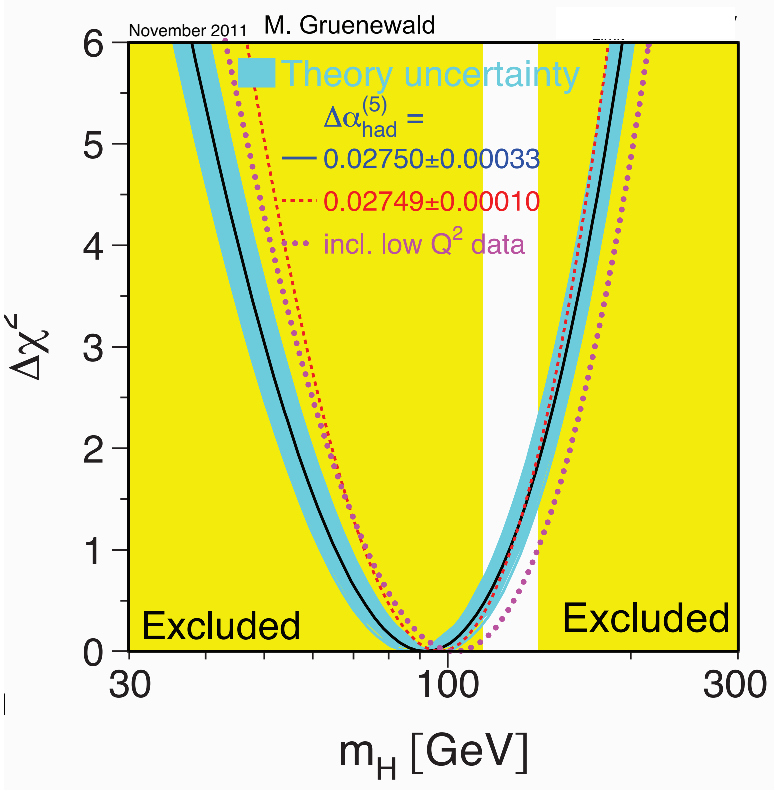
$\longrightarrow$ Slight excess for 135 GeV$< M_H <$ 150 GeV

$\longrightarrow$ Slight excess for $M_H \approx$ 120 GeV

But: After taking the "look-elsewhere effect" (LEE) into account,
the max. excess is 1.6 σ only!

Expectations for the Higgs Mass in the Standard Model:

From a combined fit to electroweak precision observables (M_W, M_Z, Γ_Z, $\sin\theta_W$, ...):
Best fit for M_H below the LEP bound of 114.6 GeV, hence:
Expect M_H close to 115 GeV! ✓



Consistency of the Standard Model up to the GUT/Planck scale (the running Higgs self coupling neither turns negative, nor explodes):

$$130 \text{ GeV} \lesssim M_H \lesssim 170 \text{ GeV}$$

Expectations in the Minimal Supersymmetric Standard Model (MSSM):

Two Higgs doublets H_u, H_d, which give:
– A light nearly SM-like CP-even Higgs boson h,
– A nearly degenerate SU(2)-doublet H (neutral, CP-even), A (neutral, CP-odd) and $H^{\pm}$

NOTE:

h must be light: $M_h^2 \sim M_Z^2 + \frac{3 m_{top}^4}{4\pi^2 \langle H_u \rangle^2} \ln \left(\frac{M_{\text{stop}}^2}{m_{top}^2} \right) + \ldots$

$\rightarrow$ 114 GeV $\lesssim M_h \lesssim$ 125...130 GeV (if $M_{\text{stop}} \rightarrow$ 1...3 TeV) ✓

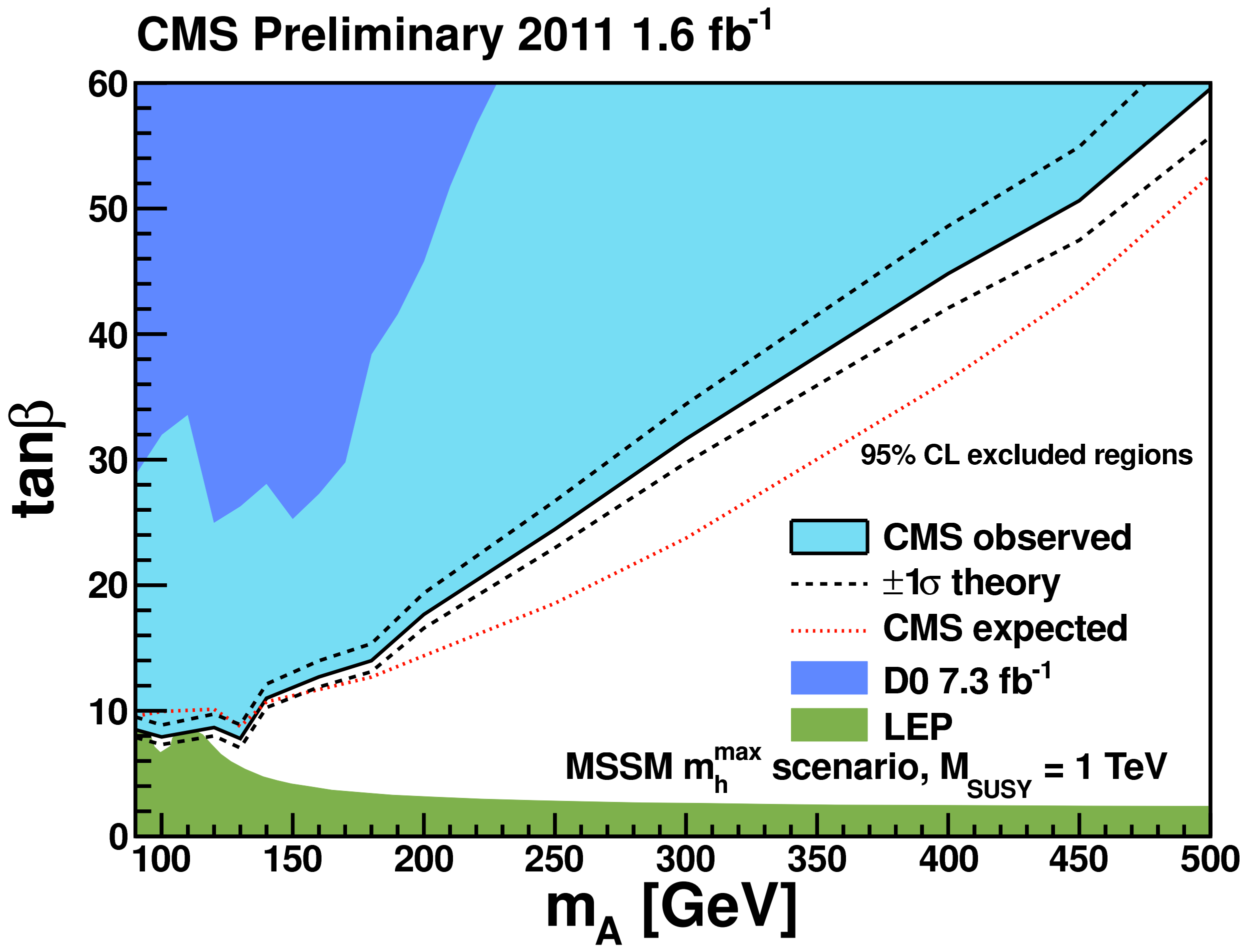
Best fit within the CMSSM (universal soft Susy breaking terms at the GUT scale), taking into account present lower bounds on squark (and hence stop) masses: $M_h \sim$ 119 GeV (J. Ellis et al.)

H, A (and $H^{\pm}$) are relatively heavy with a common mass m_A

H and A decouple from the electroweak gauge bosons, but:

— can couple strongly to b-quarks
(coupling enhanced by $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$, if $\langle H_d \rangle$ is small)

— would be visible only in ass. production with b-quarks and decays into $\tau^+\tau^-$. No signal $\rightarrow$ blue/green region excluded:



The Next-to-Minimal Supersymmetric Standard Model (NMSSM):

An additional gauge singlet S, whose vev $\langle S \rangle$ explains the supersymmetric Higgs mass parameter μ of the MSSM

→ The simplest supersymmetric extension of the SM with a scale invariant superpotential

→ 3 CP-even, 2 CP-odd neutral Higgs bosons

Typically: heavy H, A as in the MSSM, but:

a) possibly strong mixings of the CP-even states h and S, and/or

b) possibly a light singlet-like CP-odd state A_1

Consequences of a): The mostly SM-like Higgs boson can have a mass well above 130 GeV (contrary to the MSSM), but with reduced couplings (reduced cross section) due to its mixing with S;
consistent with observations in the 140-150 GeV range ✓

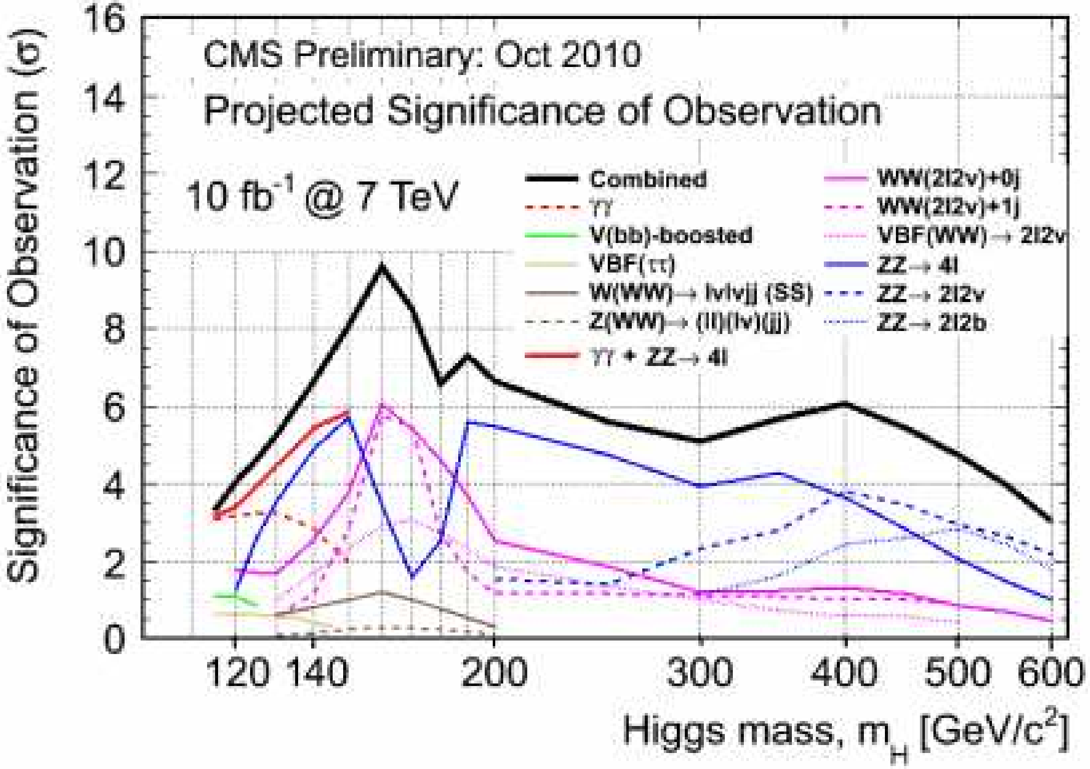
Consequences of b): The mostly SM-like Higgs boson h would decay dominantly into $h \to A_1 A_1 \to 4\,b$, $2\,b 2\,\tau$, $4\,\tau$, 4 gluons ... (dep. on M_{A_1})

→ $M_h < 114$ GeV would be consistent with constraints from LEP

→ For any M_h, h would be invisible in the standard search channels at the LHC! ✓

What to expect from combined $(5+5)fb^{-1}$ data?

→ From "exclusion" to "observation"?



Christmas (after CERN council meeting): combinations of all channels inside ATLAS and CMS?

Combination ATLAS + CMS: Christmas + 2 months?

Conclusions:

→ After combining $1-2\,fb^{-1}$ of data from ATLAS and CMS, a SM-like Higgs boson is excluded for $M_H = 141 - 476$ GeV

→ Slight excess for 135 GeV $\lesssim M_H \lesssim$ 150 GeV
→ Slight excess for $M_H \approx 120$ GeV

The low mass region is consistent with expectations from electroweak precision data and supersymmetry

Note: In a region of high sensitivity, it would be consistent to exclude a Higgs boson with SM-like couplings, but to see simultaneously signals of non-SM-like Higgs boson(s) with reduced cross section $\times$ BR

Note: If a SM-like Higgs boson gets excluded in the complete mass range, this is most likely a signal for a non-SM Higgs sector: Higgs bosons with reduced couplings, and/or unconventional decays!

End of 2012: $(15+15)fb^{-1}$ of data from ATLAS + CMS, 7 or 8 TeV?