Discovery of a New Boson in the Search for the Standard Model Higgs Boson at the LHC

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Lecture at the IMPRS Young Scientists Workshop

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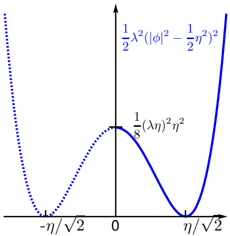
Outline

- Recap: Higgs mechanism in the Standard Model.
- The ATLAS and CMS experiments at the LHC.
- Intermezzo: statistical interpretation of experimental data.
- Standard Model Higgs boson searches at the LHC.

Recap: Higgs mechanism in the Standard Model

- Electroweak lagrangian $\mathcal{L}_{ew}$ invariant under SU(2)$_L$×U(1) gauge transformations.
- The Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism of spontaneous electroweak symmetry breaking introduces masses to the gauge bosons W, Z and the fermions preserving the gauge invariance of $\mathcal{L}_{ew}$:
  - Isotopic dublet of scalar fields: $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$.
  - $\mathcal{L}_\phi = |D_\mu \phi|^2 - \frac{1}{2}\lambda^2(|\phi|^2 - \frac{1}{2}\eta^2)^2 - g_f(\bar{\psi}_L \phi \psi_R + c.c.)$ with $D_\mu = \partial_\mu - ig\frac{1}{2}\vec{\tau}\cdot\vec{A}_\mu - ig'\frac{1}{2}YB_\mu$.
  - Local SU(2)$_L$ invariance allows the choice of ϕ as $\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \eta + \chi \end{pmatrix}$.



η: vacuum expectation value.

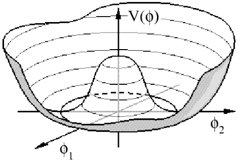
$\frac{1}{\sqrt{2}}\chi$: excitations of the field with respect to the vacuum $\phi = \eta/\sqrt{2}$.

λ: self-coupling constant.

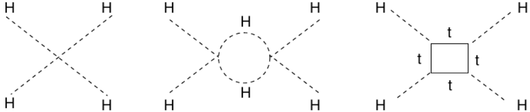
→ Mass of the scalar field (Higgs boson): $m_H = \lambda\eta$.
Masses of the gauge bosons: $m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\eta$, $m_W = \frac{1}{2}g\eta$.
Fermion masses: $m_f = g_f\eta$.

→ Value of m_H not prediced by the Standard Model.

Theoretical limits on the mass of the Higgs boson



- The self-coupling λ is a running constants due to quantum fluctuations imposing a lower limit to m_H:

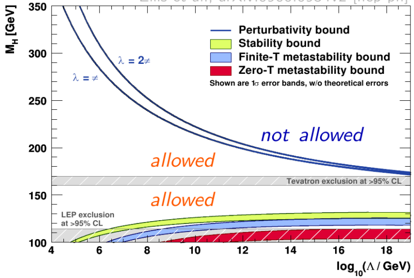


Boundaries on the Higgs boson mass from

(vacuum instability) $0 < \lambda(E) < \infty$ (non-perturbative regime).

Boundaries on m_H as a function of the scala Λ up to which the SM is valid

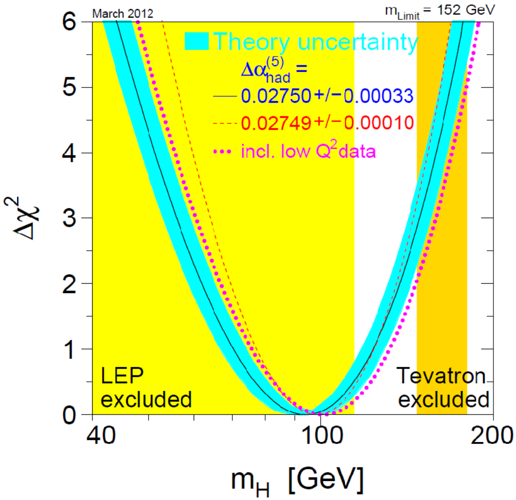
Ellis et al., arXiv:0906.0954v2 [hep-ph]



Validity of the SM up to the Planck scale $\Lambda = 10^{18}$ GeV requires

~ 125 GeV$< m_H <\sim 175$ GeV.

Experimental limits on the mass of the Higgs boson



Precision measurements of electroweak observables provide constraints on the Higgs boson mass (radiative corrections $\propto m_H^2$):

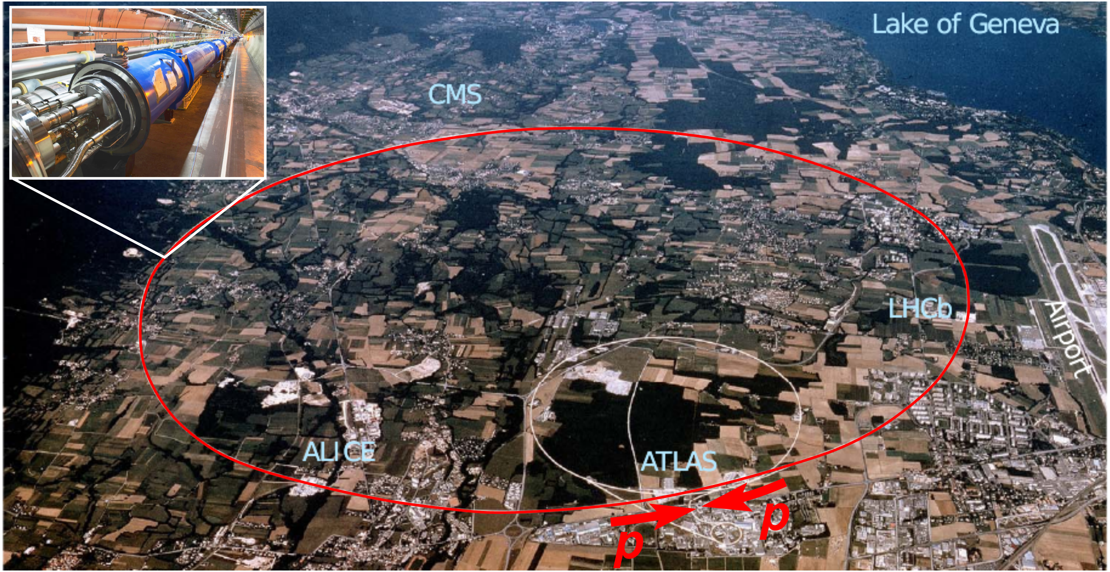
$$m_H < 171 \text{ GeV at 95\% CL.}$$

Results of direct searches

- LEP: $m_H > 114.4$ GeV at 95% CL.
- Tevatron: $m_H < 147$ GeV and $m_H > 180$ GeV at 95% CL.

Improved limits and the discovery of the Higgs boson require the LHC.

The Large Hadron Collider



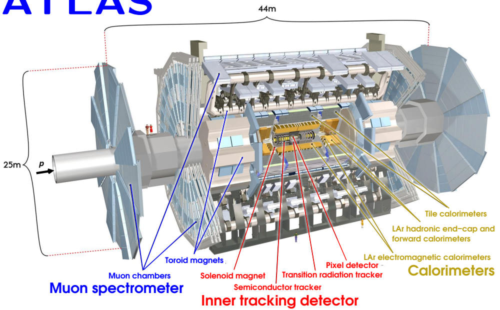
The Large Hadron Collider is a 27 km long collider ring housed in a tunnel 100 m underground near Geneva.

Present performance

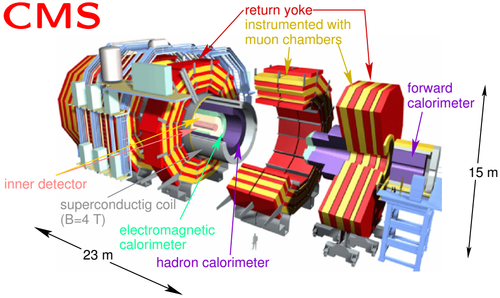
- pp collisions at $\sqrt{s} = 7$ TeV in 2011,
  $\sqrt{s} = 8$ TeV in 2012.
- Max. peak luminosity: $7 \cdot 10^{33}$ cm$^{-2}s^{-1}$.

The ATLAS and CMS experiments

ATLAS



CMS



Similar performances of the two detectors for the analyses presented today.

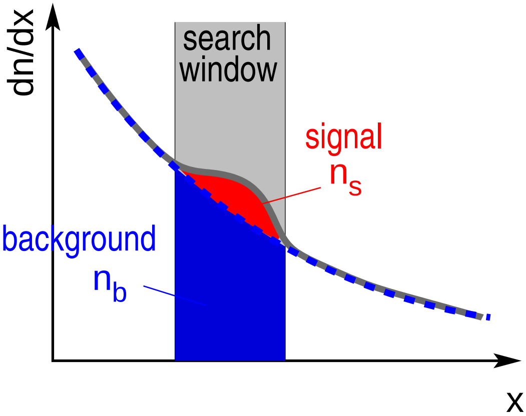
Muons.
- Coverage $|\eta| <$2.7, 2.4.
- Momentum resolution $\left.\frac{\sigma(p_T)}{p_T}\right|_{p_T=40\ GeV}$ ≈2%, 1%.

Electrons.
- Coverage with ID tracks $|\eta| <$2.5, 2.4.
- Energy resolution: $\left.\frac{\sigma(E_T)}{E_T}\right|_{E_T=40\ GeV} \approx$ 2%, 3%.

Photons. Energy resolution: $\left.\frac{\sigma(E_T)}{E_T}\right|_{E_T=40\ GeV} \approx$ 2%, 3%.

Missing E_T. $\sigma(E_T^{miss})$ ≈0.5 GeV$^{0.5} \cdot \sqrt{\sum E_T}$, 0.7 GeV$^{0.5} \cdot \sqrt{\sum E_T}$.

Intermezzo: statistical interpretation of experimental data



x: quantity characterizing the selected events, e.g. invariant mass.

Measured number of events in search window: n.

$$n = n_b + n_s$$
$$< n >= B + S.$$

Observed number of "signal" events:

$$n_s^{obs} = n - B.$$

Case 1: $n_s^{obs} > 0$ ("excess")

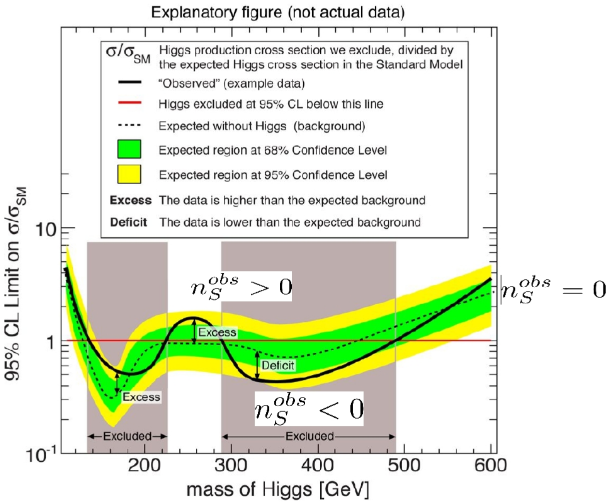
p_0: probability that a fluctuation of the background caused the excess.

$B \gtrsim 10$: distribution is Gaussian. p_0 related to the significance: $\frac{n_s^{obs}}{\sqrt{B}}$.

Case 2: $n_s^{obs} \leq 0$ or significance < 3 ("exclusion")

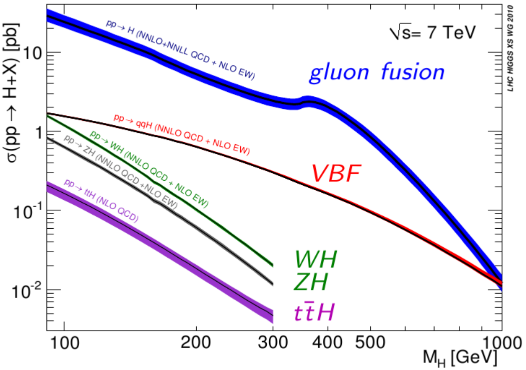
Determine the maximum value of S whic is compatible with the n_S^{obs} at 95% confidence level, i.e. chose S such that the probability of having missed a signal of strength S is $\leq 5\%$.

Intermezzo: exclusion limit plot

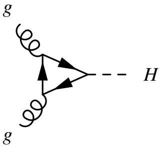


- Upper limit on S is usually expressed as a limit on the cross section.
- Cross section are expressed as multiples of the SM Higgs production cross section at a given m_H.
- Published exclusion limit plot take into account systematic uncertainties of the measurements.

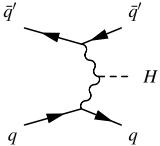
Higgs production cross section



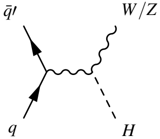
Currently exploited mechanisms



gluon fusion



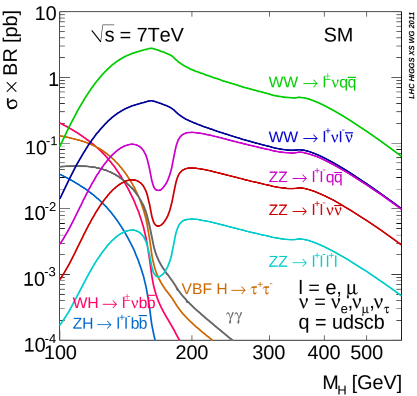
vector boson fusion

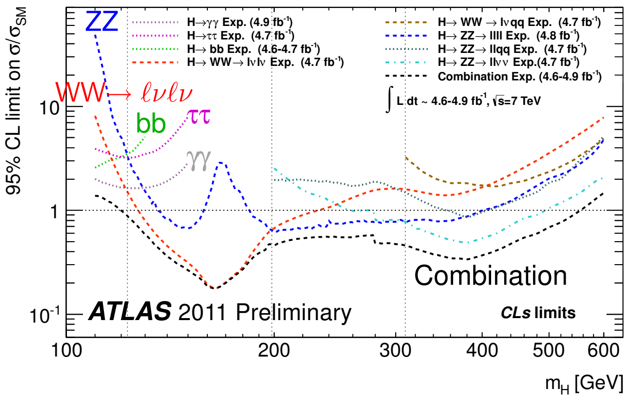


Higgs strahlung

Production of the Standard Model Higgs boson at the LHC

- The Higgs boson is unstable and to be detected via its decay products.
- Sensititivty of a given decay channel depends on $\sigma \times BR$ ($\rightarrow$ size of S) and the ability to separate the signal from background processes ($\rightarrow$ size of $\frac{S}{\sqrt{B}}$).





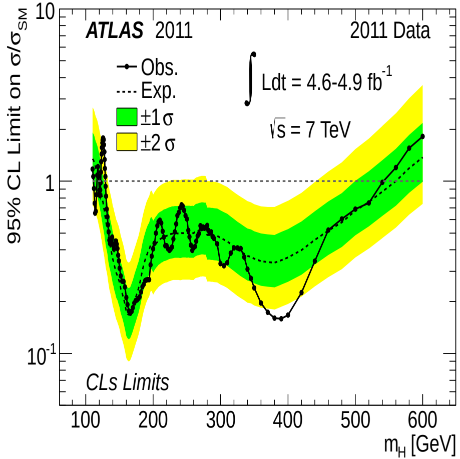
Higgs mass regions used in the analysis

The search for the Higgs boson is split into two mass regions:

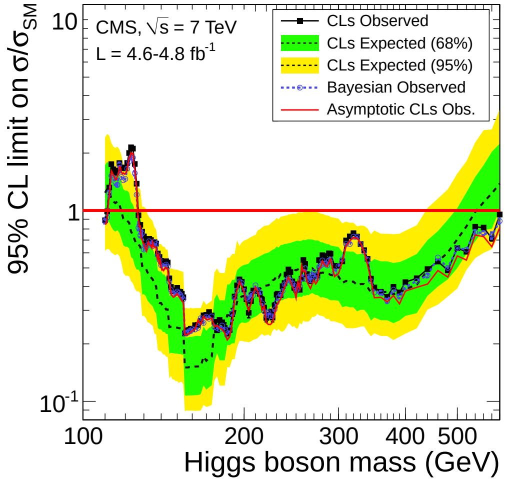
- $m_H > 200$ GeV, so-called "high-mass region":
  - The Higgs boson decays predominantly into W^+W^- and ZZ pairs.
  - Both W bosons and both Z bosons are real, "on-shell".
- $m_H < 200$ GeV, so-called "low-mass region":
  - Region favoured by electroweak precision data.
  - Decays into W and Z boson pairs with one real ("on-shell") and one virtual ("off-shell") boson.
  - $m_H \lesssim 150$ GeV: decays into τ lepton and b quark pairs contribute to exclusion limits.

Exlusion limits with the 2011 LHC data

ATLAS



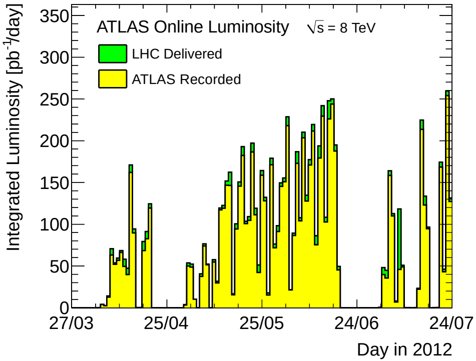
CMS



- Exclusion over a very wide mass range up to $m_H \sim 600$ GeV.
- Only a small mass windows between ~ 120 GeV and ~ 130 GeV was left open by the 2011 data analysis.
- Final answer expected from 2011+2012 data analysis.

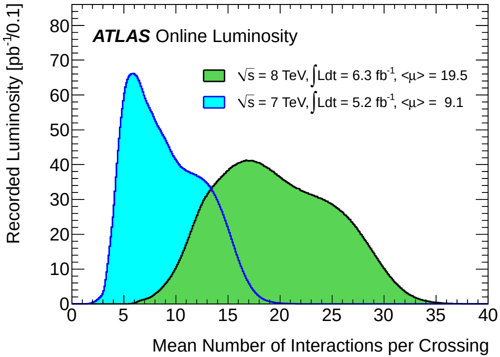
Experimental challenges in the analysis of 2012 data

Luminosity



- ~ 3 times higher luminosity per day in 2012 than in 2011.

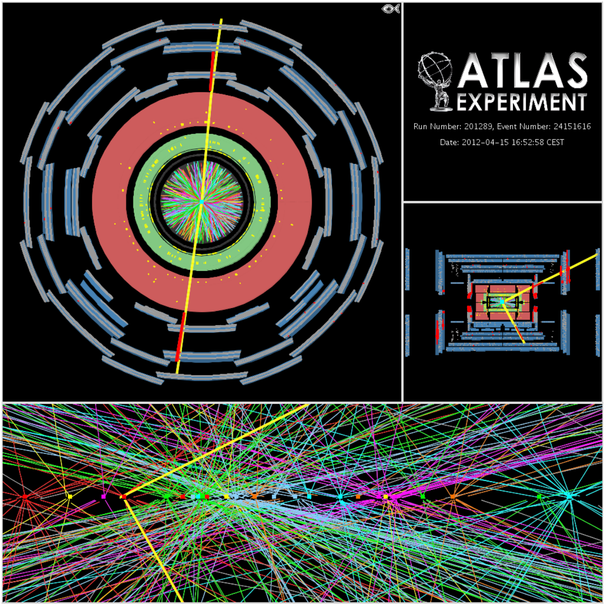
Drawback: high pile-up



- Up to 35 interactions per bunch crossing.
- On average 20 interactions per bunch crossing.

Example of an event with high pile-up

$Z \rightarrow \mu^+\mu^-$ candidate event with 25 reconstructed vertices

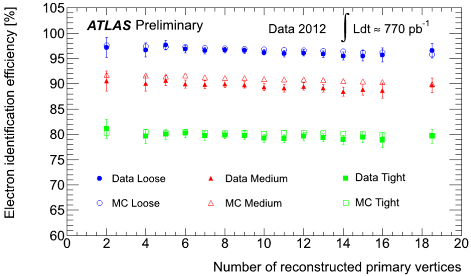


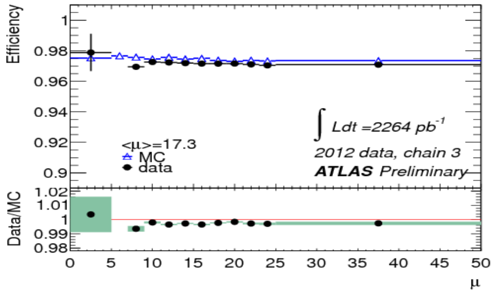
Challenges, tasks

- Reconstruction of all charged particle tracks and their vertices.
- Identification of the vertex with the interesting physics process ("primary vertex").
- Correct calorimeter response to the amount of pile-up in the event.

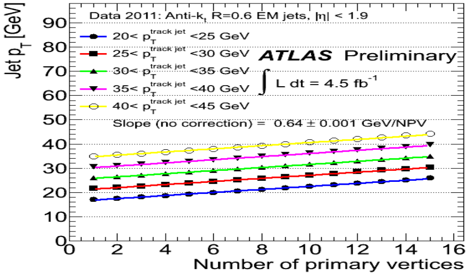
Performance under high pile-up

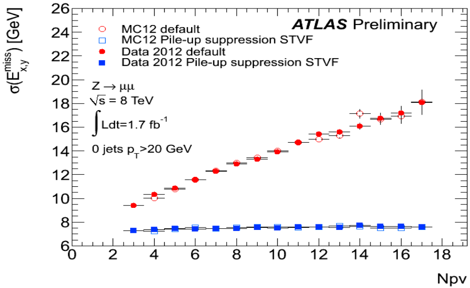
- Electron and muon identification efficiency unaffected by pile-up.



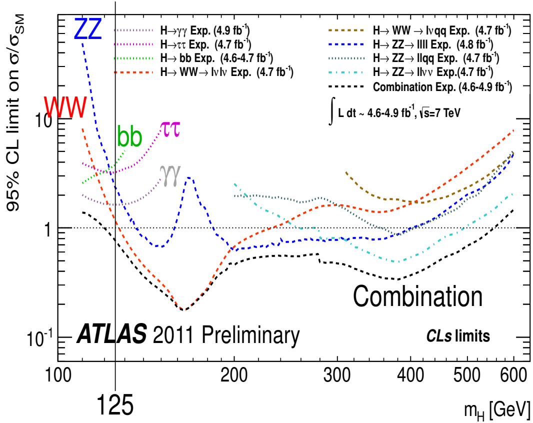


- Jet energy and missing transverse energy increase with increasing pile-up, but behaviour well understood and even correctable.





Decay channels with high sensitivity



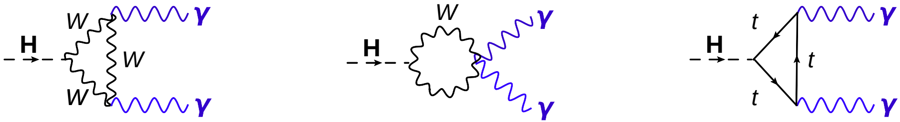
High sensitivity channels at $m_H \sim 125$ GeV

1. $H \to W^+W^- \to \ell\nu\ell\nu$.
2. $H \to \gamma\gamma$.
3. $H \to ZZ^* \to 4\ell$.
4. $H \to \tau^+\tau^-$.
5. $H \to b\bar{b}$.

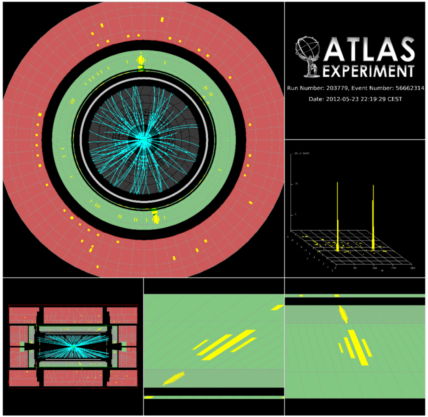
Channels 1 to 4 will be presented, $H \to b\bar{b}$ has not got the sensitivity to σ_{SM} with the existing amount of pp data.

$H \to \gamma\gamma$ channel

$H \to \gamma\gamma$ decay processes in lowest order



Final state topology



Two isolated high energy photons.

Background processes to $H \to \gamma\gamma$

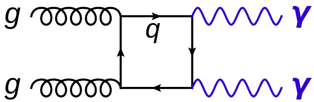
Reducible background

≥ 1 misidentified photon (usually $\pi^0 \to \gamma\gamma$ inside a jet).

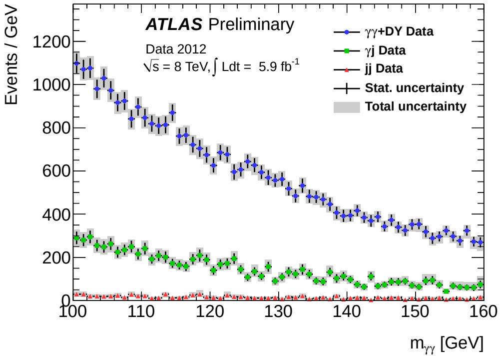
$\to$ Main handle against this background: isolation requirement.

Irreducible background

Continuum production of ≥ 2 isolated photons, e.g.



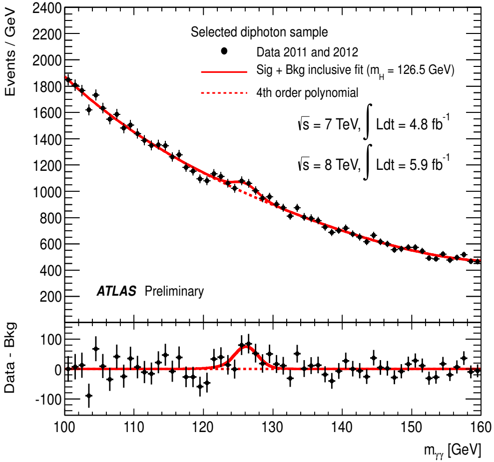
Difficult to predict quantitatively, however know to fall with increasing $m_{\gamma\gamma}$.



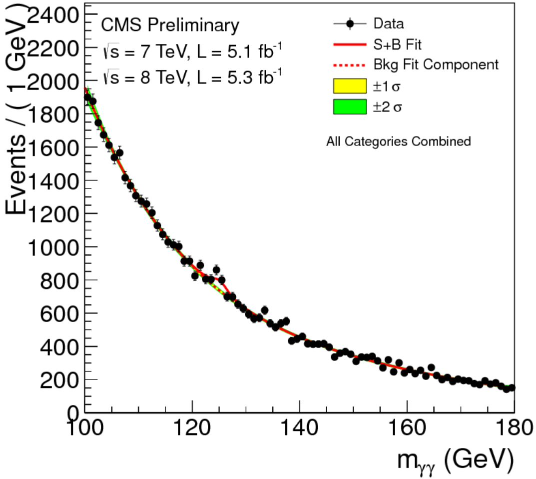
- Background determined from data by a fit.
- Function modelling the background shape optimized by means of the simulated background data.

Di-photon invariant mass spectra

ATLAS



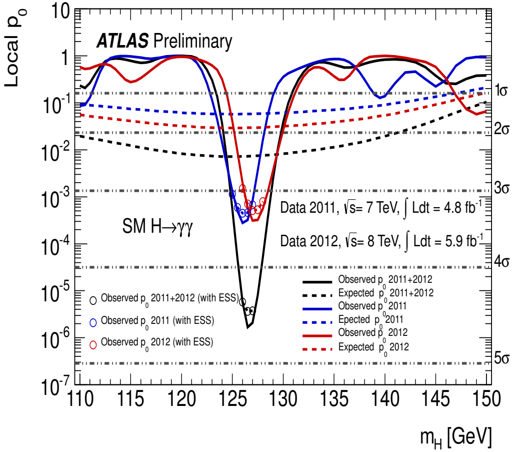
CMS



ATLAS and CMS observe a significant excess at $m_H \approx 126$ GeV!

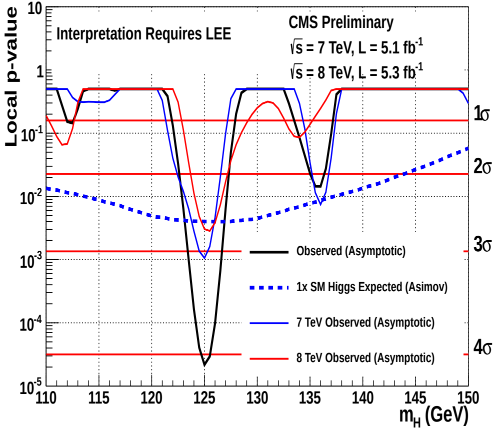
Significances of the observed excesses

ATLAS



Local significance of the excess at $m_{\gamma\gamma} = 126.5$ GeV: 4.5σ.

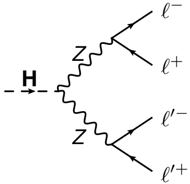
CMS



Local significance of the excess at $m_{\gamma\gamma} = 125$ GeV: 4.1σ.

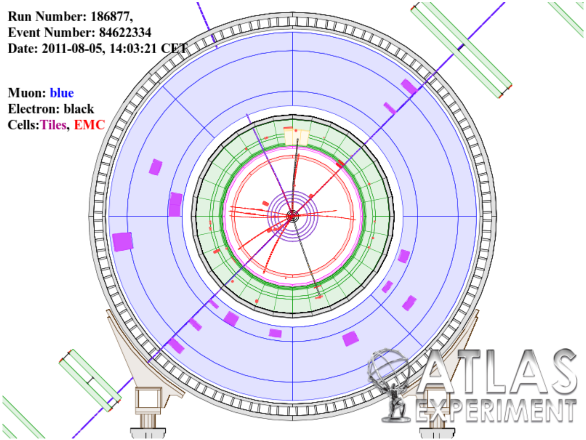
$H \to ZZ^* \to 4\ell$ channel

$H \to ZZ^* \to 4\ell$ in lowest order:



$\ell, \ell' = e, \mu$

Final state topology



- Four isolated charged leptons emerging from the same vertex.
- One lepton pair with an invariant mass close to m_Z.

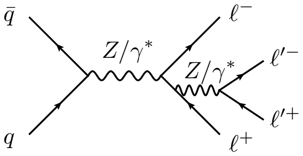
Background processes to $H \to ZZ^* \to 4\ell$

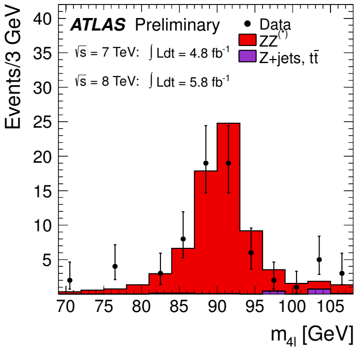
Reducible background

- Z+jets: 2 isolated leptons from the Z decay.
  2 non-isolated leptons inside the jets.
- $t\bar{t}$: $t \to Wb \Rightarrow$ 2 isolated leptons from the W decay.
  2 non-isolated leptons inside the b jets.
  $m_{\ell^+\ell^-}$ usually not close to m_Z.

Irreducible background

- Continuum $ZZ^* \to 4\ell$ production.
- Special case: $Z \to 4\ell$.

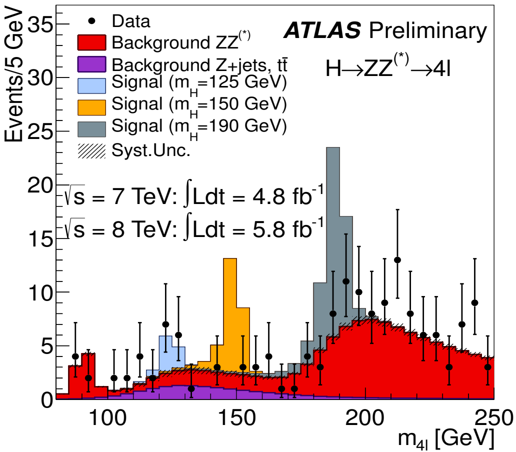




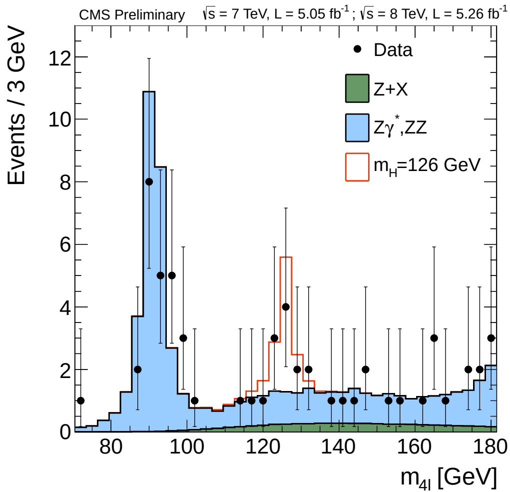
Irreducible $ZZ^* \to 4\ell$ background well modelled by the MC simulation.

Final 4 lepton invariant mass distributions

ATLAS



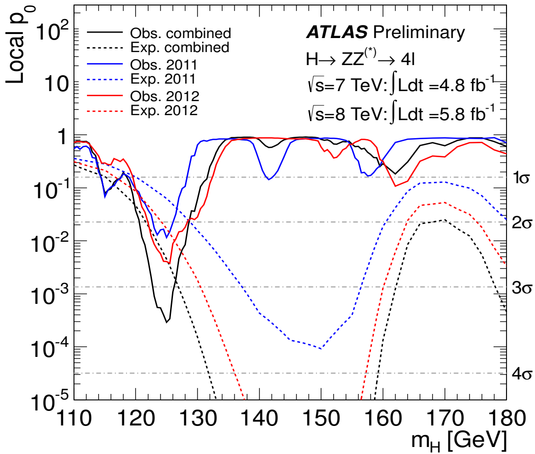
CMS



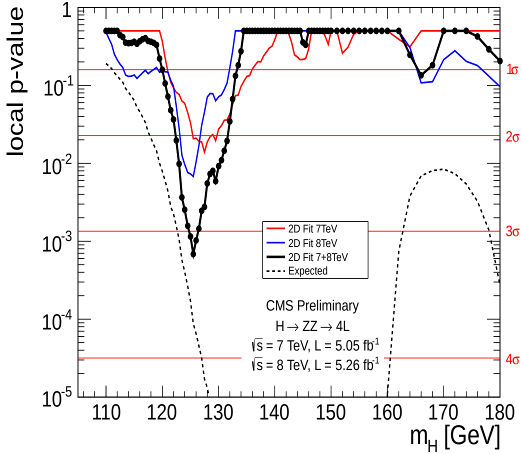
ATLAS and CMS observe an excess at $m_H \approx 126$ GeV!

Significances of the observed excesses

ATLAS



CMS

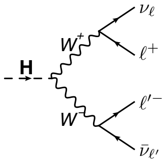


Local significance of the excess at $m_{\gamma\gamma} = 125$ GeV: 3.4σ.

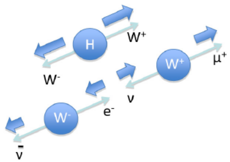
Local significance of the excess at $m_{\gamma\gamma} = 125.5$ GeV: 3.2σ.

$H \to W^+W^- \to \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$ channel

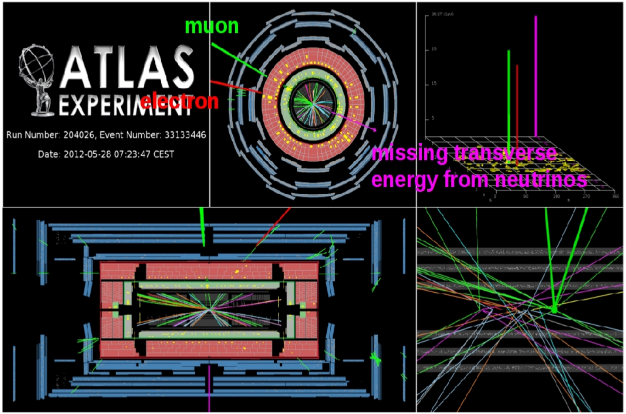
$H \to W^+W^- \to \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$ in lowest order



Angular correlations



Final state topology



In pp collisions

- $\vec{p}_{tot,||} \neq 0.$
- $\vec{p}_{tot,\perp} = 0.$

$\Rightarrow$ Only $\vec{p}_{\nu_\ell,\perp} + \vec{p}_{\bar{\nu}_{\ell'},\perp}$ can be measured.

$\Rightarrow$ Full mass reconstruction impossible.
Only "transverse mass" m_T can be calculated.
$m_T = m_{\ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}}$ with $p_z = 0$ for all particles.

Background processes to $H \to W^+W^- \to \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$

Reducible background

- W+jets: isolated charged lepton plus a neutrino from the W decay, a non-isolated lepton inside a jet.
- Multijet events: Non-isolated charge leptons inside jets, small E_T^{miss}.

$\longrightarrow$ W+jets and multijet background is suppressed by requiring isolated leptons and large E_T^{miss}.

- Drell-Yan, Z+jets: two isolated charged leptons in opposite hemispheres, small E_T^{miss}.

$\longrightarrow$ Drell-Yan, Z+jets is suppressed by requiring large E_T^{miss} and collinearity of the charged leptons plus a Z veto.

- $t\bar{t}$: isolated charged leptons plus neutrinos from the W decay, b jets in the event.

$\longrightarrow$ $t\bar{t}$ background is suppressed byt cut on jets multiplicities and a b jet veto.

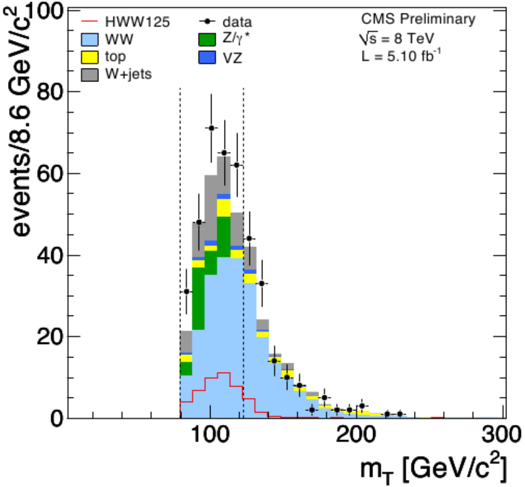
Irreducible background

- Continuum W^+W^- production: same final state like $H \to W^+W^-$, however leptons tend to be anticollinear.

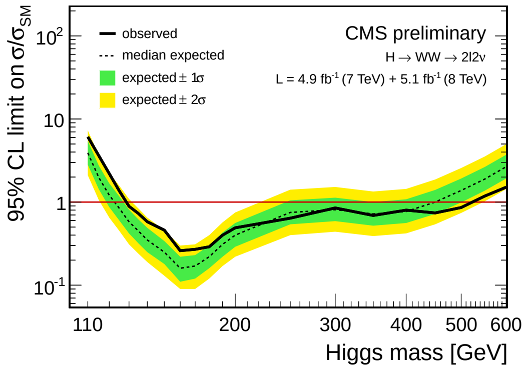
$\longrightarrow$ Irreducible background can be suppressed a bit by collinearity requirement.

$H \to W^+W^- \to \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$ channel – CMS results

m_T distribution in 2012 data



Exclusion limits with 2011+2012 data



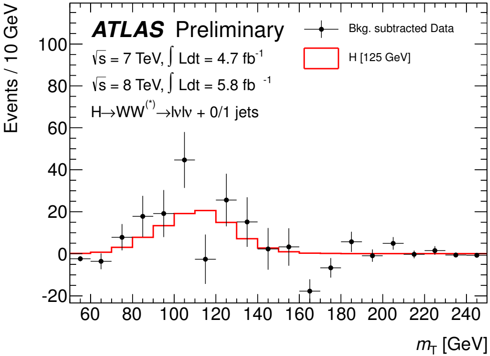
- Small excess of events observed in the transverse mass distribution, not sufficient to claim the evidence of a signal.

$\Rightarrow$ Exclusion limits at low masses worse than expected.

- $m_H < 129$ GeV not excluded by the measurements.

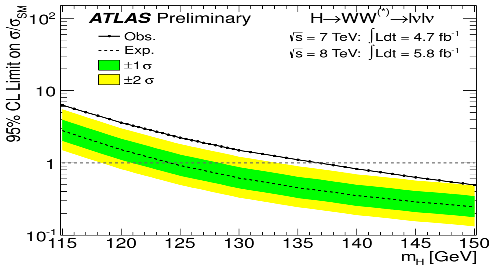
$H \to W^+W^- \to \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$ channel – ATLAS results

m_T distribution after background subtraction



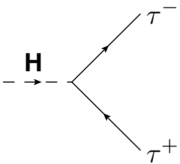
- Substantial excess of events compatible with a signal of a Higgs boson with $m_H \approx 125$ GeV.
- Significance of the excess:
  - 3.2σ for 2012 data;
  - 2.8σ for 2011+2012 data.

Exclusion limits



- Observed exclusion limits significantly worse than expected due to observed excess.
- $m_H \lesssim 135$ GeV not excluded.

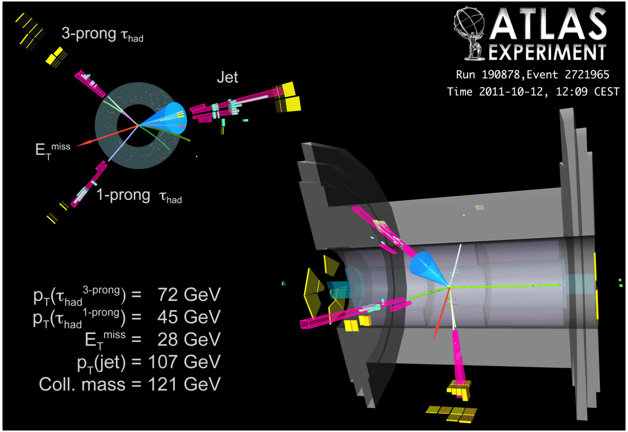
$H \to \tau^+\tau^-$ channel



- τ lepton unstable, needs to be detected via it decay products.
- τ lepton decays:
  - leptonic: $\tau^- \to \nu_\tau \ell^- \bar{\nu}_\ell$;
  - "hadronic": $\tau^- \to \nu_\tau + hadrons$.
- $m_\tau \ll E_\tau \Rightarrow \tau$ decays products are boosted into the direction $\vec{p}_\tau$.

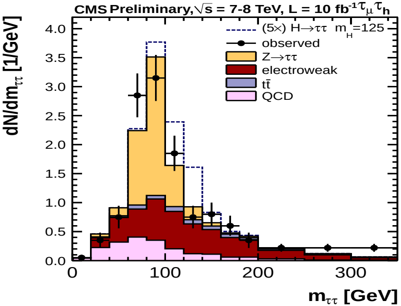
$\Rightarrow$ Collinear approximation assuming decay products with $\vec{p}_{product} \upuparrows \vec{p}_\tau$ allows reconstruction of m_H despite the presence of neutrinos.

$H \to \tau^+\tau^-$ candidate event



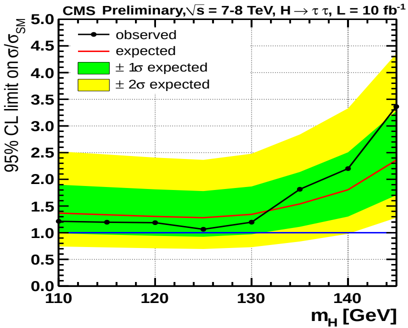
CMS results for the $H \to \tau^+\tau^-$ channel

$m_{\tau\tau}$ in the vector boson fusion category



- Measured mass distribution perfectly compatible with the background distribution.
- Same situation in other categories.

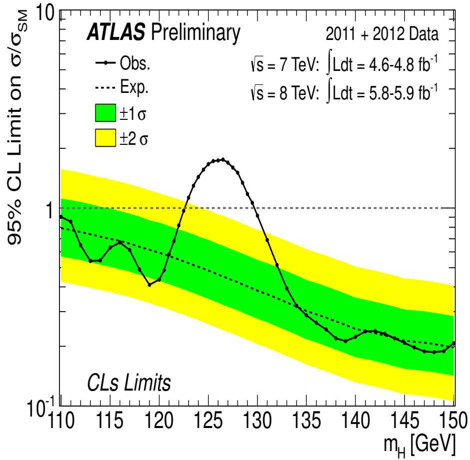
Exclusion limits



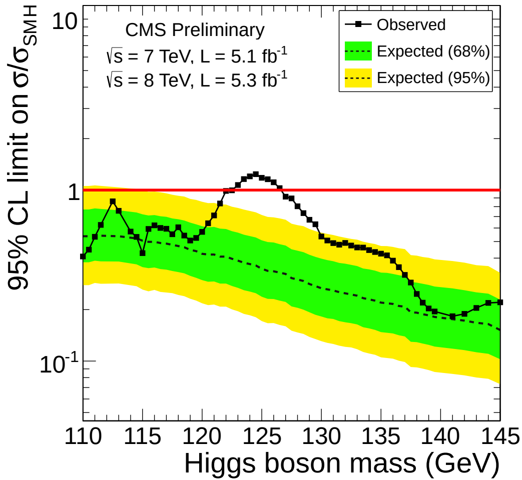
- $m_H \approx 125$ GeV almost excluded with 95% confidence level in this channel.
- Increased statistics and the ATLAS results to be published in September needed to clarify the situation.

Statistical combination of the results – exclusion limits

ATLAS

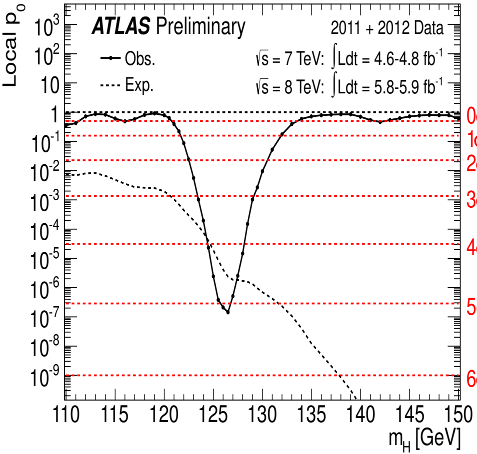


CMS

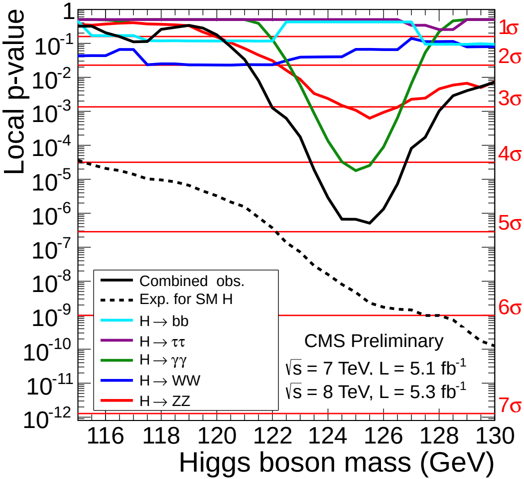


Statistical combination of the results – significances

ATLAS



CMS



Significance of the excess at $m_H = 126.5$ GeV: 5.0σ.
Significance will increase after inclusion of 2012 $H \to WW$ results.

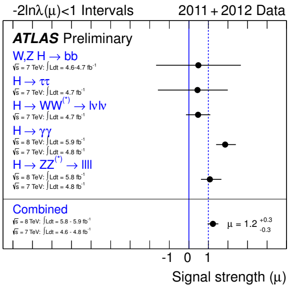
Significance of the excess at $m_H = 125$ GeV: 4.9σ.

$\Rightarrow$ Discovery of a new particle with $m_H \approx 126$ GeV!

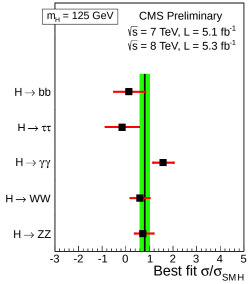
Properties of the new particle

- Quantum numbers
  - Spin integral, but $\neq 1$ due to Landau-Yang theorem about $\gamma\gamma$ decays.
    $\Rightarrow$ The new particle is a boson.
  - CP unkown.
- Production strengths (normalized to SM prediction)

ATLAS



CMS



- Branching ratios and couplings. Measurements have started, however very limited sensitivity/precision with present amount of data.

$\Rightarrow$ The new particle's properties are compatible with the Standard Model Higgs boson, but measurements of the spin, CP quantum numbers, the production strengths and the couplings are needed to confirm this interpretation.

Conclusions and outlook

- ATLAS and CMS have discovered a new neutral boson with a mass of about 126 GeV.
- The new boson is compatible with a Standard Model Higgs boson, but measurements of its properties are needed to confirm that it is the Higgs boson.
- Five times more pp collision data at $\sqrt{s} = 8$ TeV will be recorded by ATLAS and CMS until the end of 2012. This will make the following measurement possible:
  - Precise measurement of the mass of the new boson,
  - Branching ratio into τ lepton and b quark pairs,
  - First measurements of the couplings to gauge bosons and fermion, however with large errors.
- From 2014 LHC will deliver ~ 100 fb^{-1} per year which will enable us to measure the spin and CP of the boson.