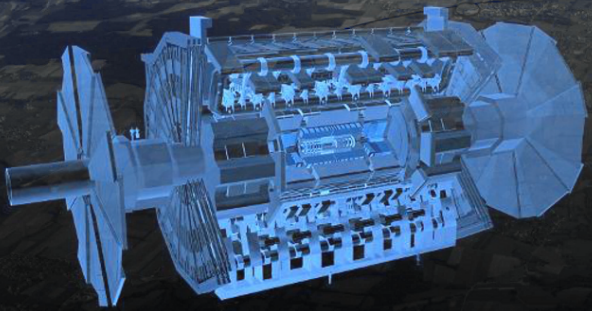
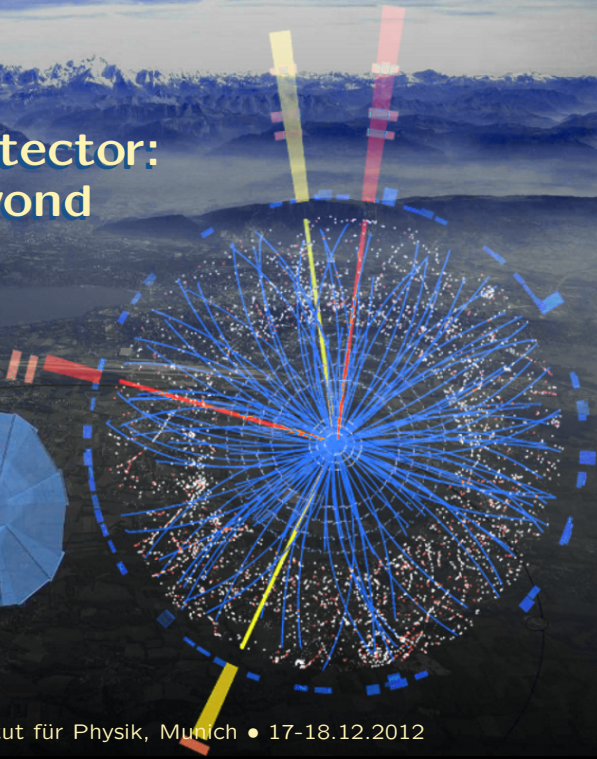
Higgs-like boson at the ATLAS detector: discovery and beyond

Sandra Kortner
on behalf of the ATLAS-MPP group





Project Review 2012 • Max-Planck-Institut für Physik, Munich • 17-18.12.2012

A busy year behind

Existence of a spin-0 neutral Higgs boson is predicted by the (simplest version) of the electroweak symmetry breaking mechanism in the Standard Model (SM). Introduced to explain the observed finite masses of elementary particles.

Higgs; Brout, Englert; Guralnik, Kibble, Hagen ⇒ Phys. Rev. Lett 13 (1964)

Search for the Standard Model Higgs boson

- Major breakthrough, July 2012:
  Discovery of a new Higgs-like particle.
  Phys. Lett. B 716 (2012) 1-29
- Updated search results in key channels.

The (SM) Higgs or not the Higgs?

- Properties of the new particle.
- Search for the Higgs bosons beyond the Standard Model.

ATLAS-MPP Higgs Working Group

Higgs enthusiasts at MPP:

S. Bethke, J. Bronner, K. Ecker, M. Goblirsch-Kolb, O. Kortner, S. Kortner, H. Kroha, A. Manfredini, R. Sandström, S. Stern, D. Zanzi

MPP contributions:

- Co-convenorship of the ATLAS Higgs Working Group, Oct 2010 - Oct 2012 (S. Kortner)
- Search and property measurements in several key analysis channels:

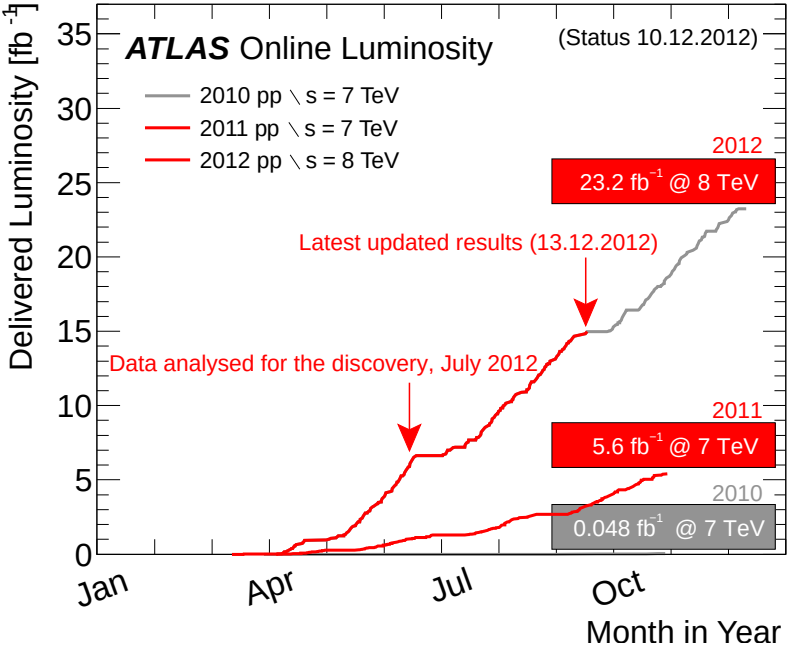
Standard Model (SM)

* $H \to ZZ^{(*)} \to 4\ell$ (K. Ecker, M. Goblirsch-Kolb, O. Kortner)
* $H \to WW^{(*)} \to \ell\nu\ell\nu$ (J. Bronner, R. Sandström)
* $H \to WW^{(*)} \to \ell\nu jj$ (R. Sandström)$^{*main\ co-editor}$
* $H \to \tau\tau$ (D. Zanzi)$^{*main\ co-editor}$
* Future prospects for $H \to \mu\mu$ (S. Stern)$^{*main\ editor}$

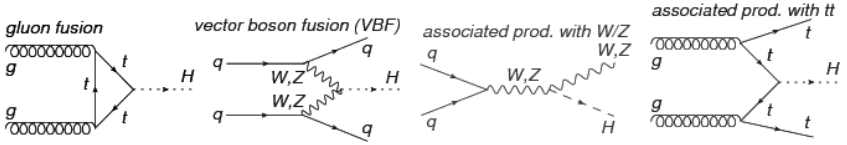
Minimal Supersymmetric extension of the Standard Model (MSSM)

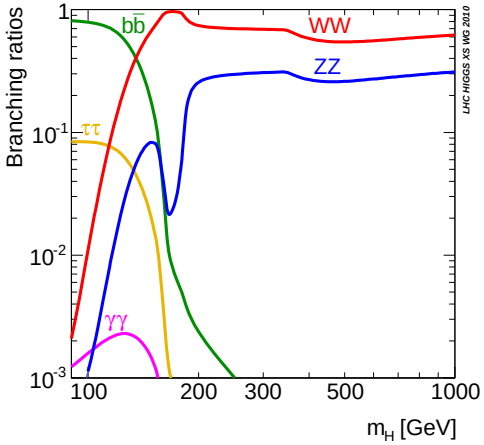
* $h/H/A \to \tau\tau$ (A. Manfredini)
* $h/H/A \to \mu\mu$ (S. Stern)$^{*main\ editor}$

LHC data delivery



SM Higgs boson at the LHC: Production and decays





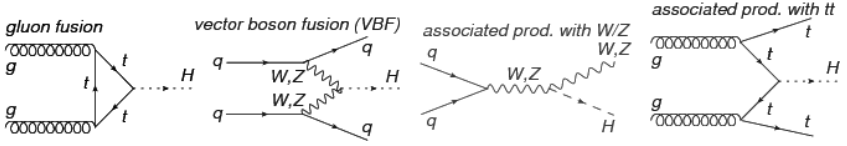
Low mass region, e.g. $m_H = 125$ GeV:

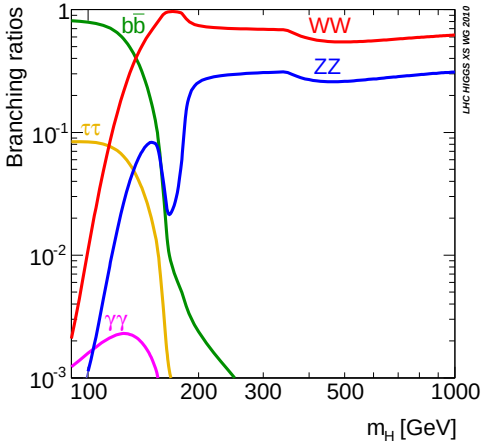
- $H \to \gamma\gamma$
- $H \to ZZ \to (\ell^+\ell^-)(\ell^+\ell^-)$
- $H \to WW \to (\ell^+\nu)(\ell^-\nu)$
- $H \to \tau^+\tau^-$ (large background)
- $H \to b\bar{b}$ (large background)

High mass region, e.g. $m_H = 300$ GeV:

- $H \to ZZ \to (\ell^+\ell^-)(\nu\nu)$
- $H \to ZZ \to (\ell^+\ell^-)(\ell^+\ell^-)$
- $H \to WW \to (\ell^+\nu)(\ell^-\nu)$
- $H \to WW \to (\ell^+\nu)(qq)$

SM Higgs boson at the LHC: Production and decays





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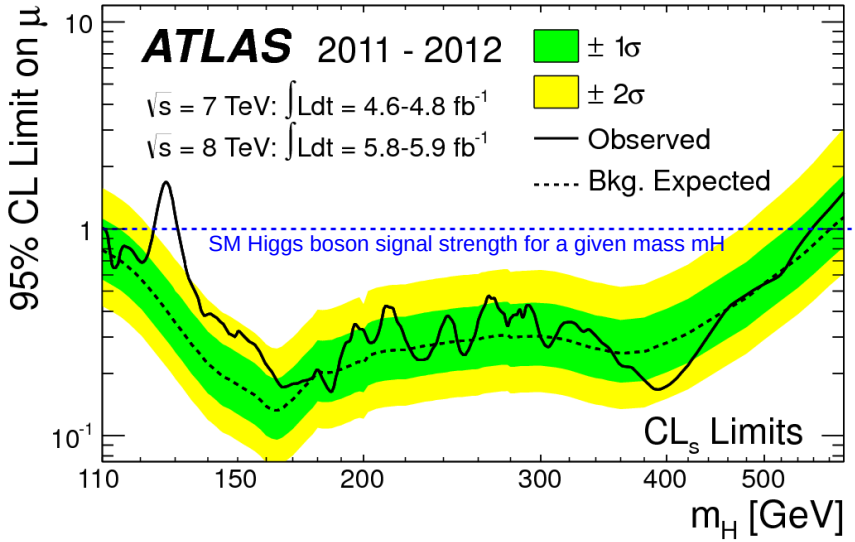
- $H \to WW \to (\ell^+\nu)(qq)$

Higgs hunters' independence day

Combined exclusion limits (July 2012)



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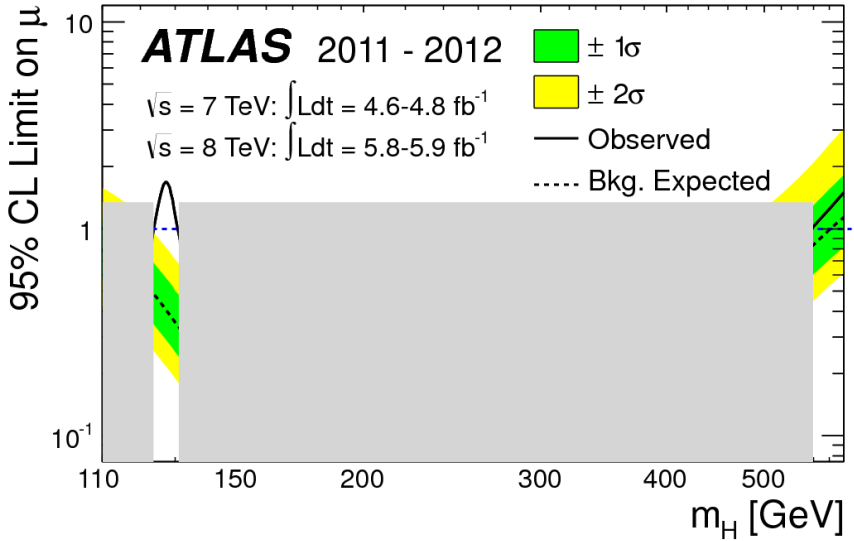
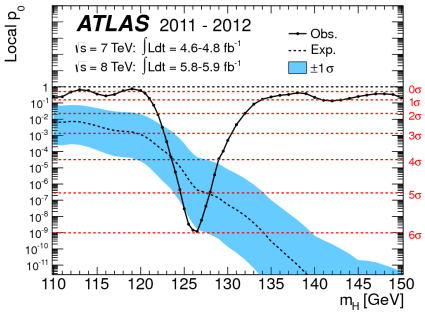


The existence of the Standard Model Higgs boson is excluded with 95% confidence level for almost all masses m_H from 110 GeV to 600 GeV,
except for $m_H \approx$ 120 - 130 GeV where an excess of events is observed in few channels.

Discovery of a Higgs-like particle (July 2012)

Probability that the background fluctuation would give the same or higher excess:



Local significance at 126.5 GeV: 5.9σ

Corresponding expected significance: 4.9σ

Signal significance in individual search channels:

Channel	July 2012
$H \to \gamma\gamma$	4.5σ
$H \to ZZ^{(*)} \to 4\ell$	3.6σ
$H \to WW^{(*)} \to \ell\nu\ell\nu$	2.8σ
$H \to \tau\tau$	no excess
$H \to bb$	no excess

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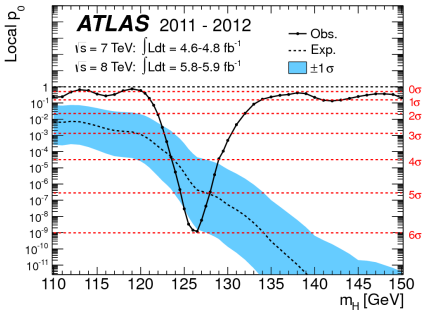

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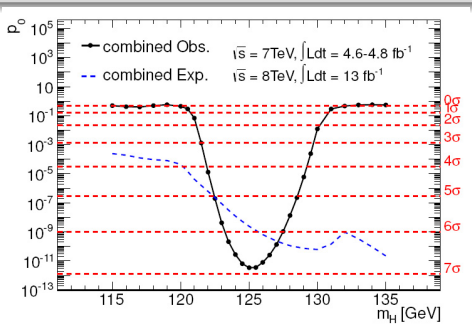
$H \to \tau\tau$	no excess
$H \to bb$	no excess

Discovery of a Higgs-like particle (December 2012)

Update with ∼1.8 time more data:



Local significance at 125.2 GeV: 7.0σ

Corresponding expected significance: 5.8σ

Signal significance in individual search channels:

Channel	July 2012	December 2012
$H \to \gamma\gamma$	4.5σ	6.1σ
$H \to ZZ^{(*)} \to 4\ell$	3.6σ	4.1σ
$H \to WW^{(*)} \to \ell\nu\ell\nu$	2.8σ	2.8σ
$H \to \tau\tau$	no excess	1.1σ
$H \to bb$	no excess	no excess

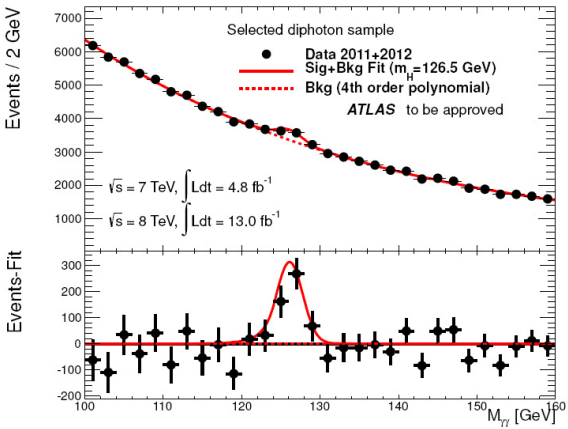
Latest updates of individual channels

CERN Council Week,
December 10-14, 2012

Huge background from $\gamma\gamma$ (1000×signal), γj ($4{\cdot}10^8$×signal) and jj (10^{10}×signal).
$\Rightarrow$ Need a powerful photon-jet separation.

In addition: high photon energy and direction resolution $\Rightarrow$ narrow signal peak.

Background determined directly from the fit to the data:



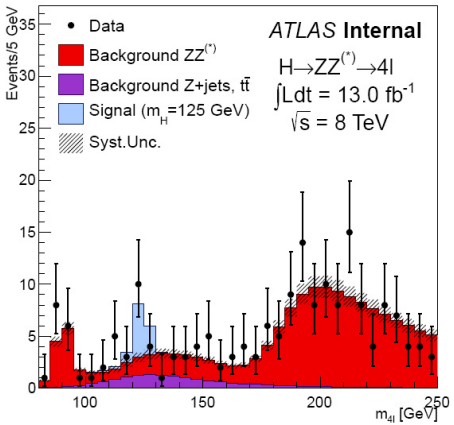
- Local signal significance: 6.1σ
  Discovery level reached already with this channel alone!
- Signal strength: $1.8^{+0.42}_{-0.36}$
  (2.4σ deviation from the prediction for SM Higgs boson)

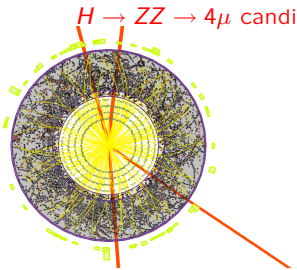
Around $m_{4\ell} \approx 126.6$ GeV:

Excess of ∼600 events above the expected ∼10 000 background events.

$H \to ZZ^{(*)} \to (\ell^+\ell^-)(\ell^+\ell^-)$

Very clean signature, but a rare process.
High lepton reconstruction efficiency is crucial.
High lepton energy/momentum resolution (1-2%) allows for a narrow signal peak.





Around the mass $m_{4\ell}$ of 125 GeV:

Excess of ∼10 events above the expected ∼8 background events.

Nr. candidates: 8 (4μ) + 6 ($2e2\mu$) + 4 ($4e$)

MPP contributions to the search analysis:

- Optimization of the muon selection acceptance, muon isolation studies.
- ZZ cross-section measurement as a cross-check of the theory prediction.
- $Z + jet$ background measurement from signal-depleted control data samples.

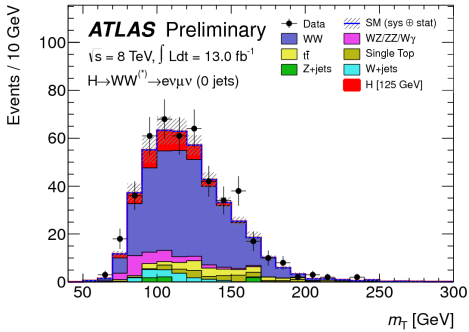
$H \rightarrow WW^{(*)} \rightarrow (\ell\nu)(\ell\nu)$

Most sensitive channel in a broad mass range, $m_H \sim$ 120-180 GeV.

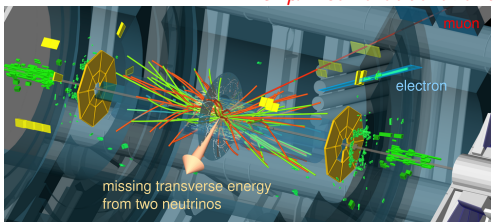
No exact mass reconstruction possible due to 2 neutrinos in the final state $\Rightarrow$

$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{miss}\right)^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,miss}\right|^2}$$

Precise knowledge of background (from signal-depleted control samples) is crucial.



$H \rightarrow WW \rightarrow e\nu\mu\nu$ candidate event



For the hypothesized mass m_H of 125 GeV:
Excess of ∼55 events above the expected ∼170 background events.

MPP contributions to the search analysis:

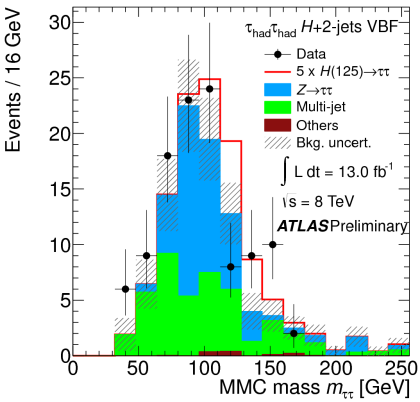
- Study of the top-quark and $b\bar{b}$ background in signal depleted control data.
- Emphasis on an exclusive Higgs search in the vector-boson-fusion production mode: moderate improvement of the signal sensitivity (just a few $H + 2jet$ candidates), especially important for the measurement of the Higgs couplings to W bosons.

$H \to \tau^+\tau^- \to (\ell\ell 4\nu,\ \ell\tau_{had}3\nu,\ \tau_{had}\tau_{had}2\nu)$

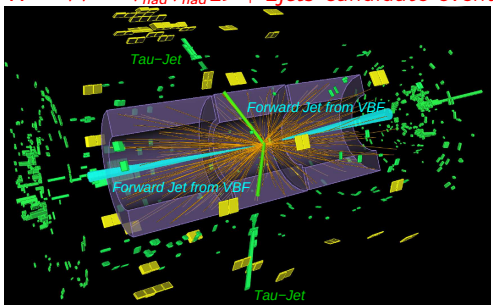
Low sensitivity, but this channel directly probes the Higgs boson couplings to fermions.

Event categories based on τ decay products and Higgs production modes:

- Similar sensitivity in the fully leptonic, semi-leptonic and fully hadronic final state.
- Vector-boson-fusion production mode provides the highest signal sensitivity.



$H \to \tau\tau \to \tau_{had}\tau_{had}2\nu + 2jets$ candidate event



For the hypothesized mass m_H of 125 GeV:
Overall excess of events corresponds to 1.1σ.
(Expected significance: 1.7σ)

MPP contributions to the search analysis:

- Main authors and editors for the fully hadronic channel.
- Corresponding performance measurements of the hadronic τ decays.

The Higgs or not the Higgs?

Is it a SM Higgs boson?

Properties of the newly discovered boson:

mass,

signal strength, couplings to vector bosons and fermions,

spin and CP properties,

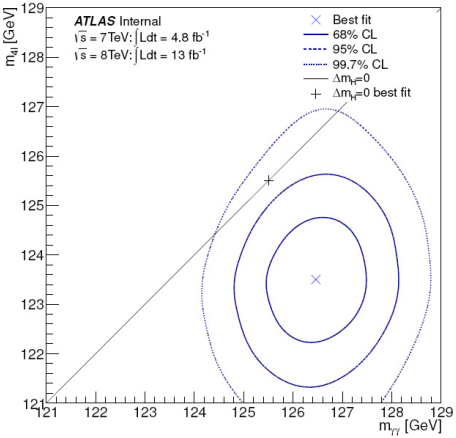
self-coupling.

Could it be just one of a few non-SM Higgses?

Search for the neutral MSSM Higgs bosons.

Mass of the new particle

- Measured in two channels with high mass resolution: $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to 4\ell$.
- Mass value is left as a free parameter in the fit to data.
  (Unlike in previous results, where different mass hypotheses have been tested.)
- Main systematic uncertainty: electron & photon energy scale and resolution.



Combined measurement:

$125.5 \pm 0.3(\text{stat}) \pm 0.7(\text{syst})$ GeV

- $\gamma\gamma$: $126.6 \pm 0.3(\text{stat}) \pm 0.7(\text{syst})$ GeV
- 4ℓ: $123.5 \pm 0.9(\text{stat}) \pm 0.4(\text{syst})$ GeV

$\Downarrow$

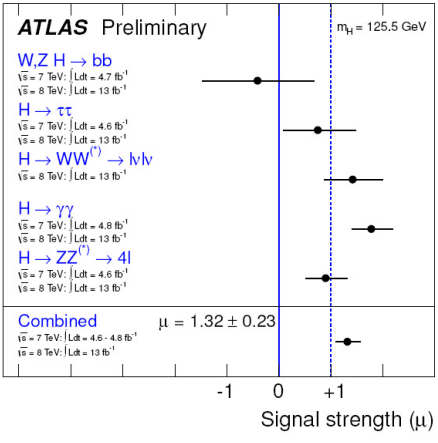
Deviation from the SM hypothesis of a single Higgs resonance: 2.9σ

MPP contributions:

- Mass measurement in the 4ℓ channel (muon momentum scale and resolution).

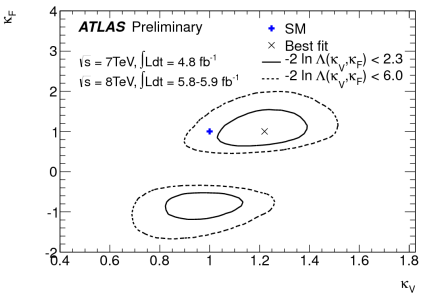
Signal strength and couplings to other particles

Signal strength left as a free fit parameter.



Coupling assumptions:

- Couplings to all fermions scale by the same factor $\kappa_F (= \kappa_t = \kappa_b = \kappa_\tau)$.
- Coupling strengths to all vector bosons scale by same factor $\kappa_V (= \kappa_W = \kappa_Z)$.



$\kappa_V \in [0.7, 1.4]$; $\kappa_F \in [0.5, 1.7]$

All measurements compatible with the SM Higgs boson hypothesis.

MPP contributions:

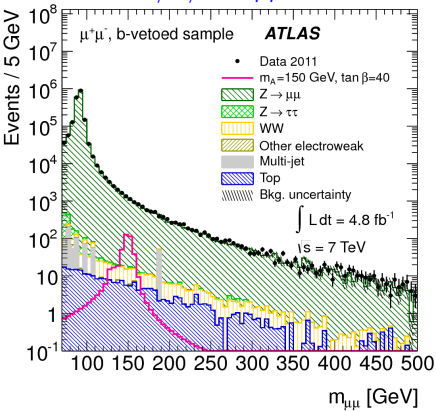
- Signal measurement in the *VBF* $H \to WW$, $H \to \tau\tau$ and $H \to ZZ \to 4\ell$ channels.
- Prospects for the measurements in the $H \to \mu\mu$ channel (300-3000 fb^{-1}).

Search for the neutral MSSM Higgs bosons

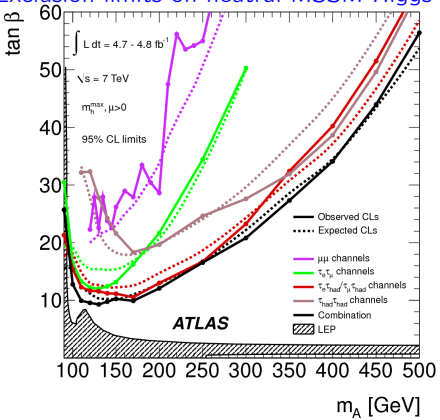
Higgs sector in the Minimal Supersymmetric extension of the Standard Model (MSSM):

- 5 physical Higgs bosons: h, H, A, H^+, H^-. Properties defined by m_A and $\tan\beta$.
- Newly discovered boson compatible with MSSM h/H Higgs boson in some parts of the parameter space.

Search in the $h/H/A \to \mu\mu$ channel



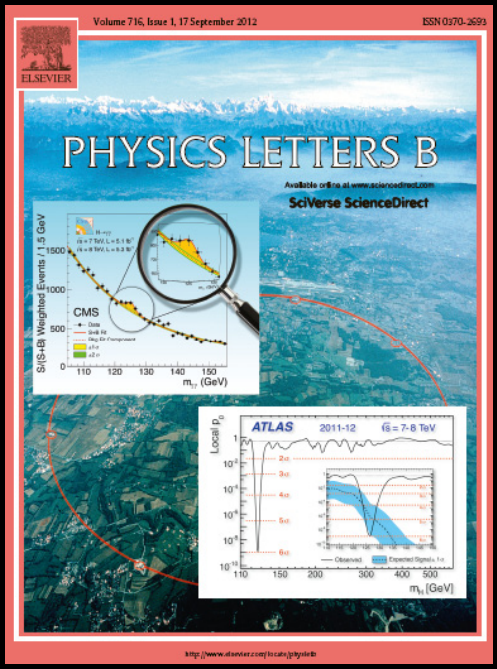
Exclusion limits on neutral MSSM Higgs



MPP contributions:

- Key (the only) author and editor of the $h/H/A \to \mu\mu$ search.
- Optimization of the search in the fully leptonic $h/H/A \to \tau\tau$ chanel.

A fruitful year behind...

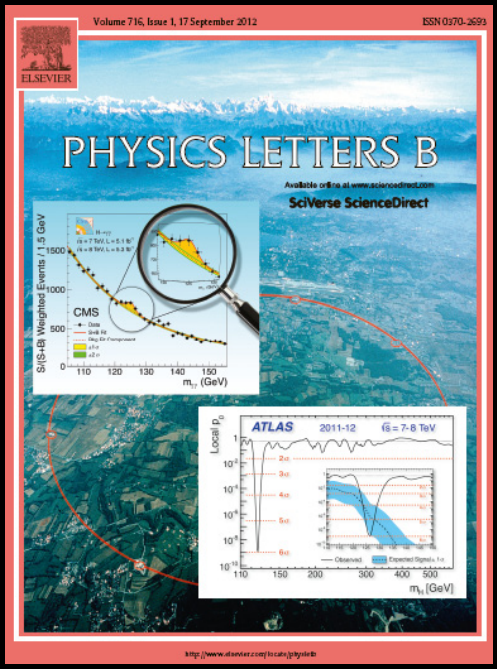


... after more than 20 years of dedication at the LHC:

We have discovered a new boson with a mass around 125 GeV.

Consistent with expectations for the Standard Model Higgs boson, but still within large uncertainties.

A fruitful year behind... and many busy ones ahead



... after more than 20 years of dedication at the LHC:

We have discovered a new boson with a mass around 125 GeV.

Consistent with expectations for the Standard Model Higgs boson, but still within large uncertainties.

More data are needed to really tell its nature..

Published results (MPP contributions, 2012)

Combined search

1. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1-29 (Preliminary: ATLAS-CONF-2012-093)
2. Combined search for the Standard Model Higgs boson in pp collisions at sqrt(s) = 7TeV with the ATLAS detector, Phys. Rev. D86 (2012) 032003
3. Combined search for the Standard Model Higgs boson using up to 4.9 fb?1 of pp collisions at sqrt(s) = 7 TeV with the ATLAS detector at the LHC, Phys.Lett. B710 (2012) 49-66 (Preliminary: ATLAS-CONF-2012-093)

$H \to ZZ \to 4\ell$

4. Search for the Standard Model Higgs boson in the decay channel $H \to ZZ \to 4\ell$ with 4.8 fb-1 of pp collisions at sqrt(s) =7 TeV with ATLAS, Phys.Lett. B710 (2012) 383-402 (Preliminary: ATLAS-CONF-2011-162)

$H \to WW \to (\ell\nu\ell\nu, \ell\nu jj)$

5. Search for the Standard Model Higgs boson in the $H \to WW \to \ell\nu\ell\nu$ decay mode with 4.7 fb-1 of ATLAS data at sqrt(s) = 7 TeV, Phys. Lett. B 716 (2012) 62-81 (Preliminary: ATLAS-CONF-2012-012)
6. Search for the Higgs boson in the $H \to WW \to \ell\nu jj$ decay channel at sqrt(s) = 7 TeV with the ATLAS detector, arXiv:1206.6074, Phys. Lett. B 718 (2012) 391-410 (Preliminary: ATLAS-CONF-2012-018)

$H \to \tau\tau$

7. Search for the Standard Model Higgs boson in the H to tau+ tau- decay mode in sqrt(s) = 7 TeV pp collisions with ATLAS, JHEP09(2012)070 (Preliminary: ATLAS-CONF-2012-014)

MSSM neutral Higgs

8. Search for the neutral Higgs bosons of the MSSM in pp collisions at sqrt(s) =7 TeV with the ATLAS detector, submitted to JHEP (Preliminary: ATLAS-CONF-2012-094)