Measurement of properties of the Higgs boson in bosonic decay channels using the ATLAS detector

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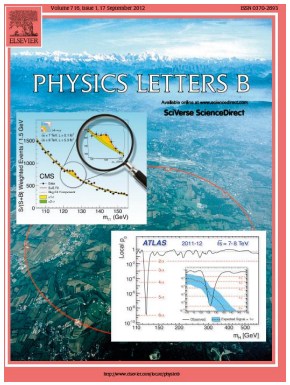
PASCOS 2013

Taipei, 20th –26th November, 2013

Outline

- **Introduction**
  - Production and decay modes
  - Channels overview
    - Selection
    - Event categories
    - Backgrounds
- **Properties** (see also the talk of Florian Bernlochner)
  - Mass
  - Coupling strengths
  - Production mechanisms
- **Summary**

Introduction



- Most striking result from ATLAS and CMS experiments, so far:
  4th July, 2012: *"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]

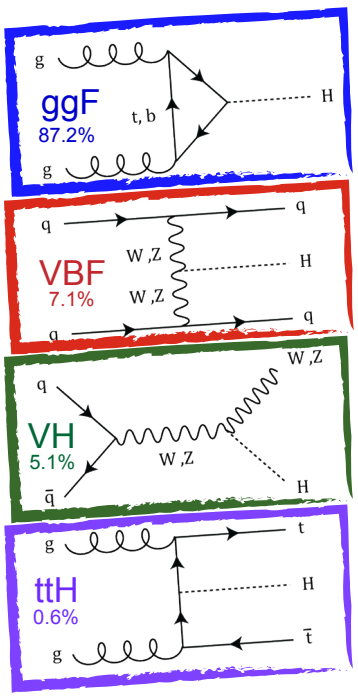
- **Since then:** compare the properties of the new particle with the SM predictions for the Higgs boson:
  - *"Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC"*
    [Phys. Lett. B 726 (2013), pp. 88-119]
  - *"Evidence for the spin-0 nature of the Higgs boson using ATLAS data"*
    [Phys. Lett. B 726 (2013), pp. 120-144]
  - **Other topics:**

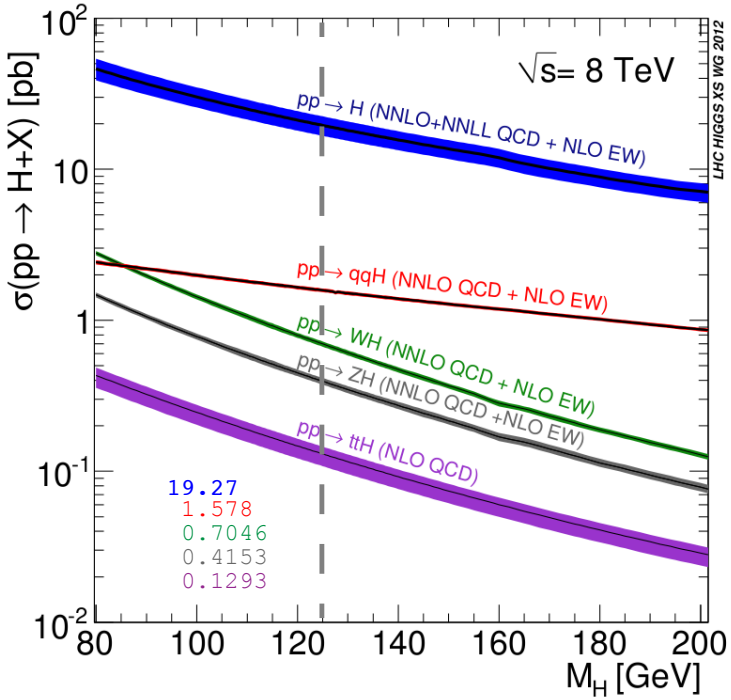
    couplings to fermions, differential cross section,...

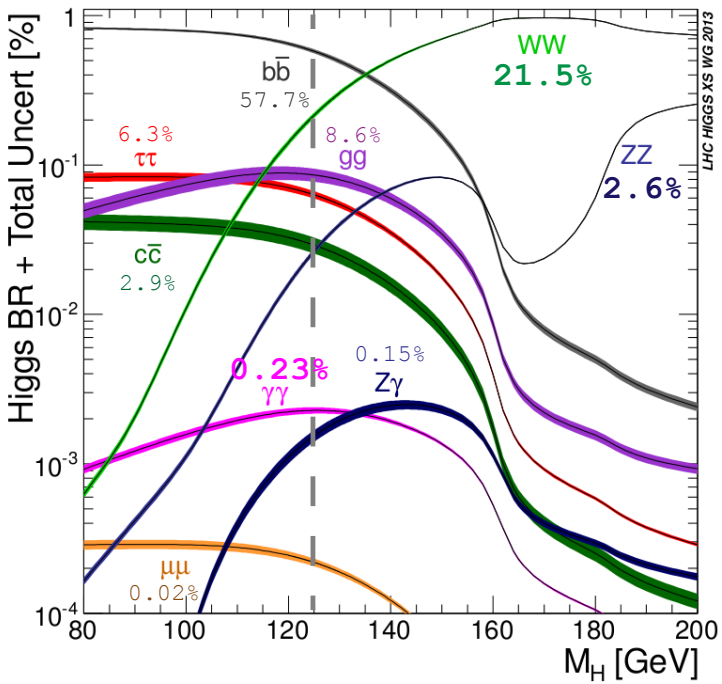
- **ATLAS results:** https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

Production and decay

- $\Gamma_H \simeq 4$ MeV @ $m_H = 125$ GeV
- $H \to WW$: allow a broad range of masses to be "scanned"
- $H \to ZZ/\gamma\gamma$: distinct signatures, but low statistics



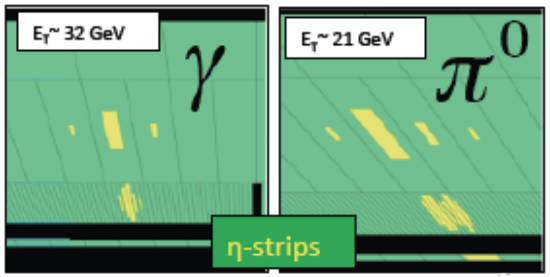




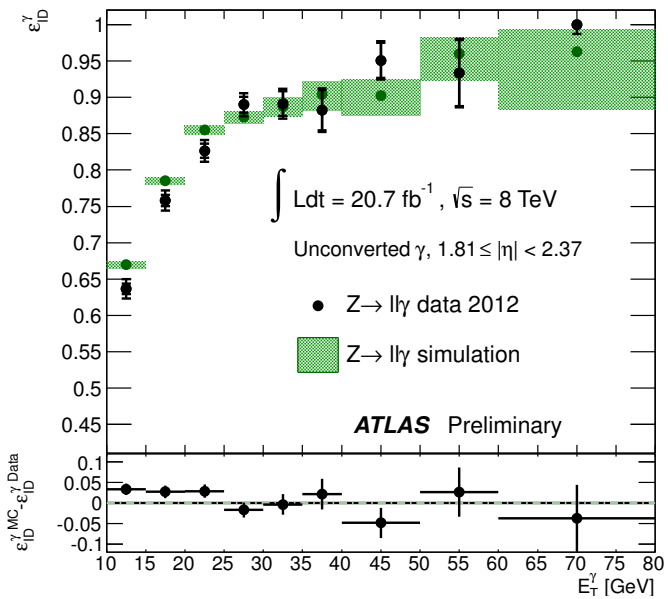
- Couplings determined by the mass: $g_{Hff} = \frac{m_f}{v}$; $g_{HVV} = \frac{2m_V^2}{v}$; ...

$H \to \gamma\gamma$ overview

- $\mathscr{L} = 20.7(4.7)\ \text{fb}^{-1}$ (2012 (2011), $\sqrt{s} = 8(7)$ TeV)
- **Simple signature:** pair of high-p_T isolated photons
- Mass: $m^2_{\gamma\gamma} = 2p_{\gamma_1}p_{\gamma_2}(1-\cos\theta) \simeq p_{\gamma_1}p_{\gamma_2}\theta^2$

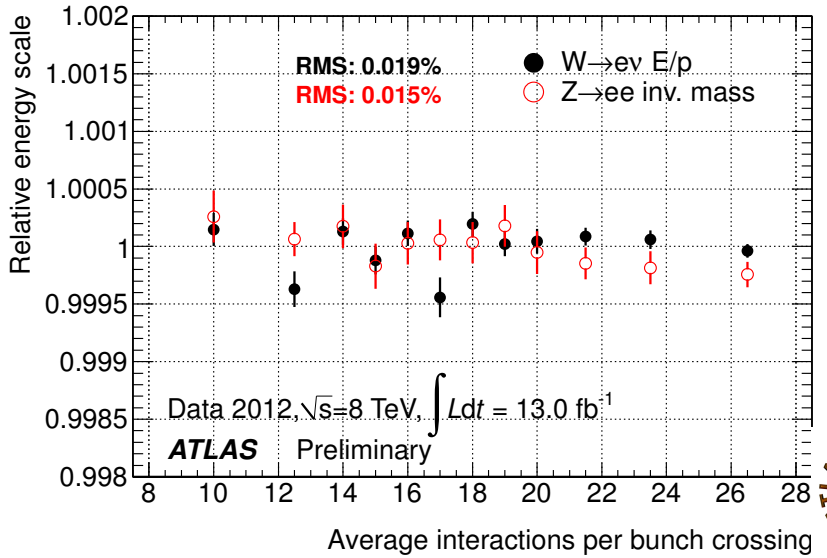


EM calo allows for discriminations of bkg such as $\pi^0 \to \gamma\gamma$

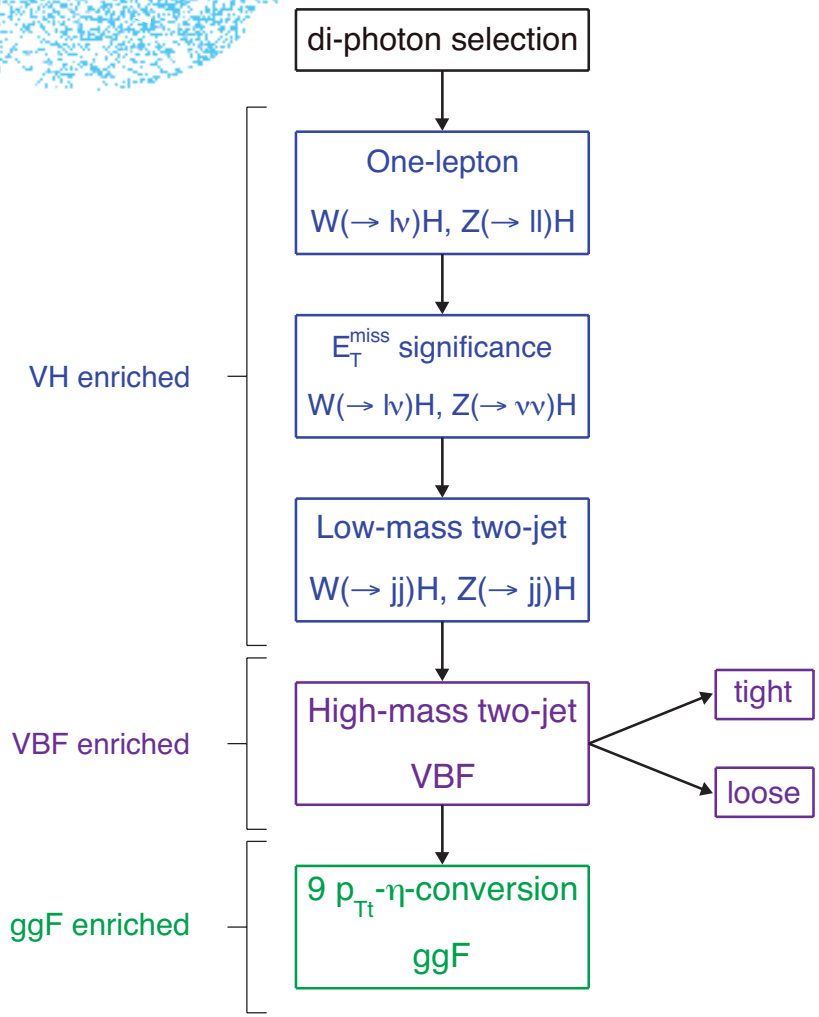


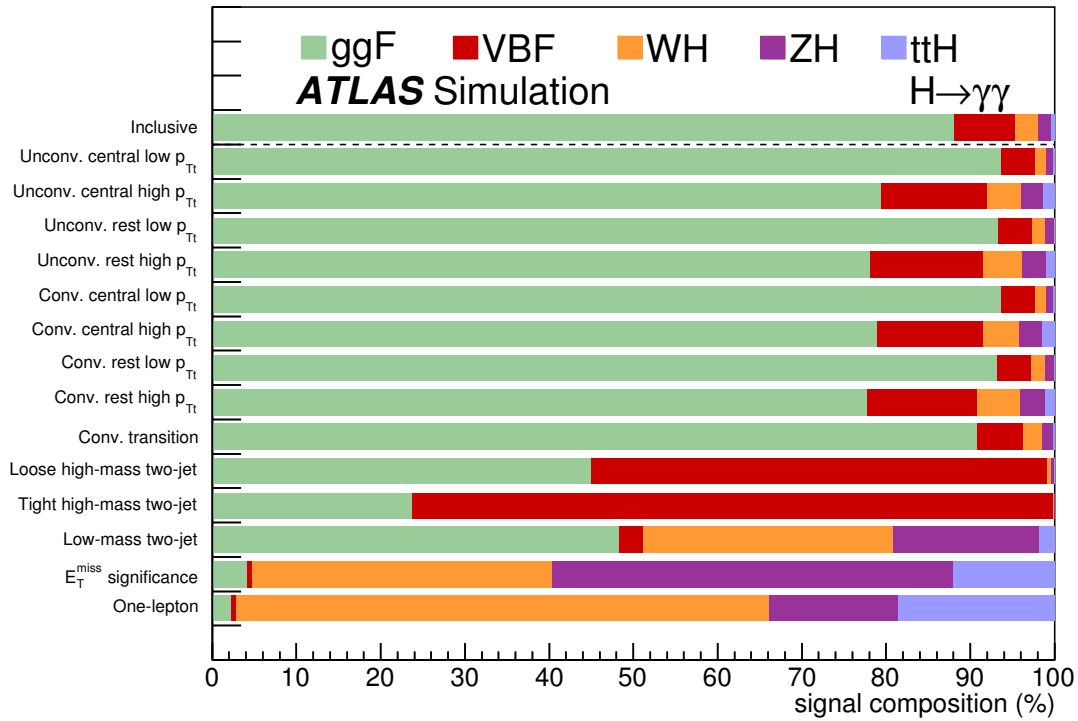
★ photon ID: main syst. unc. on signal yield (2.4%)
($\varepsilon_{\text{ID}}(E_T,\eta) \sim 85\% - 95\%$, for $E_T^\gamma > 30$ GeV)

★ Electron energy scale:
stability with pile-up and with time



$H \to \gamma\gamma$ sub-channels



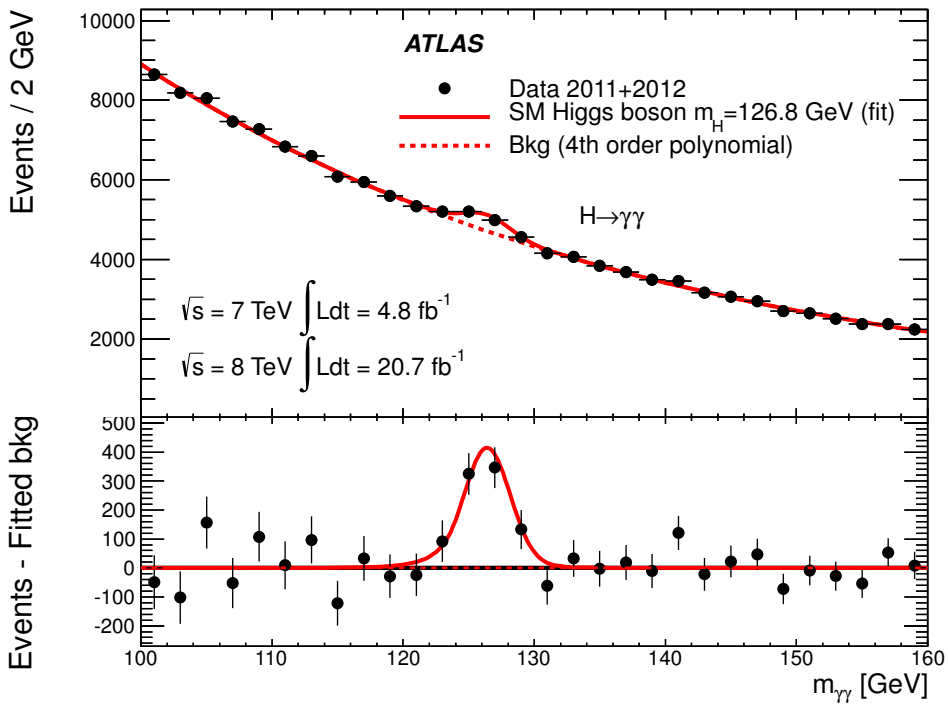


- Event categorization: increase sensitivity to signal and to separate Higgs production mechanisms

di-photon thrust axis in the transverse plane: $p_{Tt} = |(\vec{p}_T^{\gamma_1} + \vec{p}_T^{\gamma_2}) \times \hat{t}| \Leftarrow \hat{t} = (\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2})/|\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2}|$

$H \to \gamma\gamma$ background

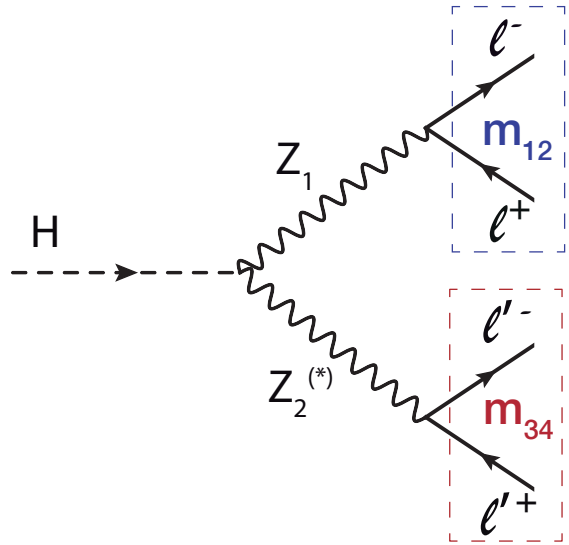
- Irreducible background: QCD $\gamma\gamma$ production ($\sim 75\%$)
- Reducible background: γj and jj (jets misidentified as photons), and DY (mis-reconstruction of electrons) ($\sim 25\%$)
- Shape parameters and the normalization of the background determined by a fit to the data

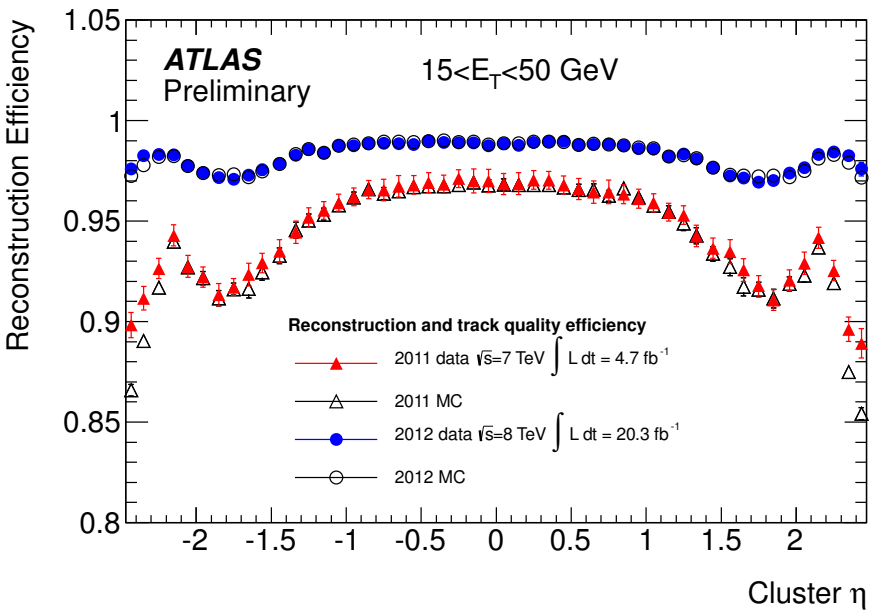


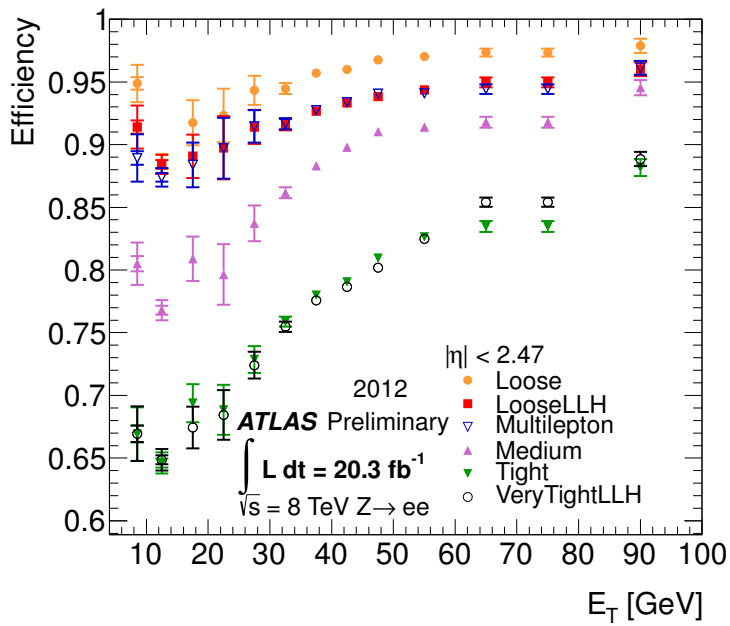
- ★ $m_{\gamma\gamma} = 126.8 \pm 0.2(\text{stat.}) \pm 0.7(\text{syst.})$ GeV
- ★ main syst. unc.: photon energy scale
- ★ significance of the observed peak is 7.4σ

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

- **Signature:** 2 pairs of same-flavour, opposite-charged, isolated leptons
- Leptons assigned to **quadruplets** of the same flavour and opposite charge, with $p_T > 20,\ 15,\ 10$ GeV for leading leptons
- Electron ID & reco: main syst. unc. on signal yield (2.4% - 9.4%)

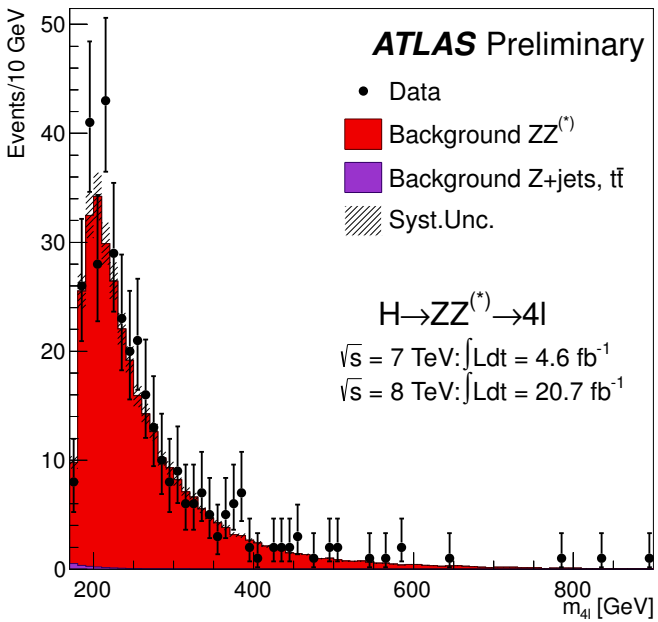


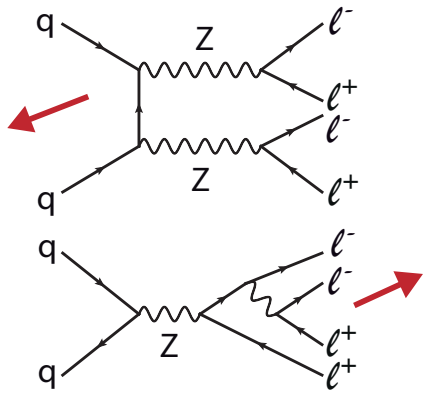


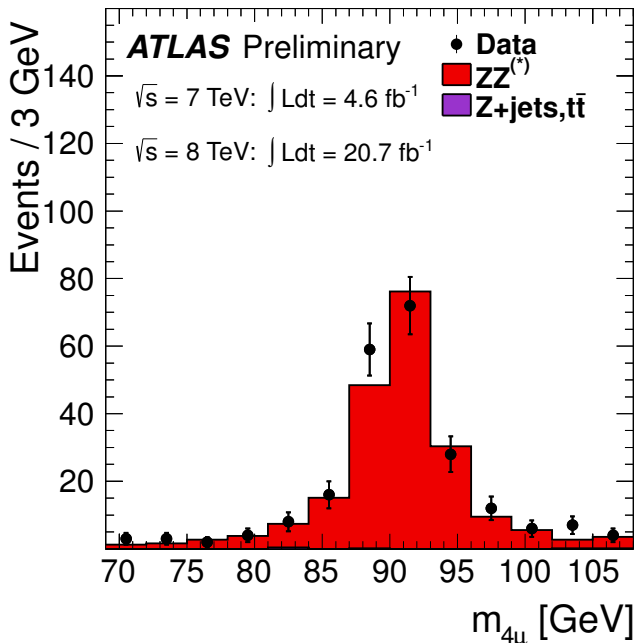


$H \to ZZ^* \to 4\ell$ backgrounds

- **Irreducible:** continuum ZZ production is the largest background
  - Normalization and $m_{4\ell}$ shape both taken from simulation
  - Single resonant Z peak and high mass resonance used to constrain ZZ contribution

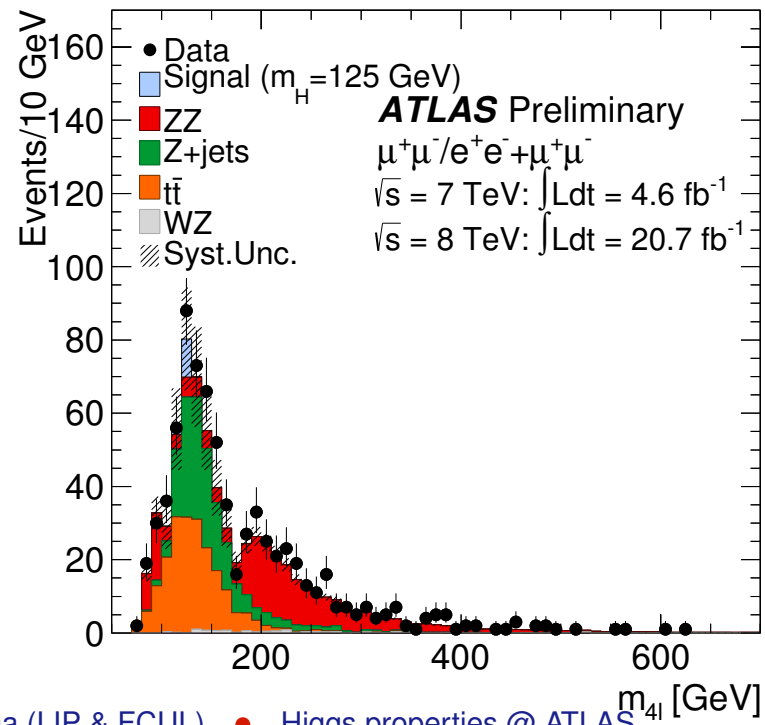


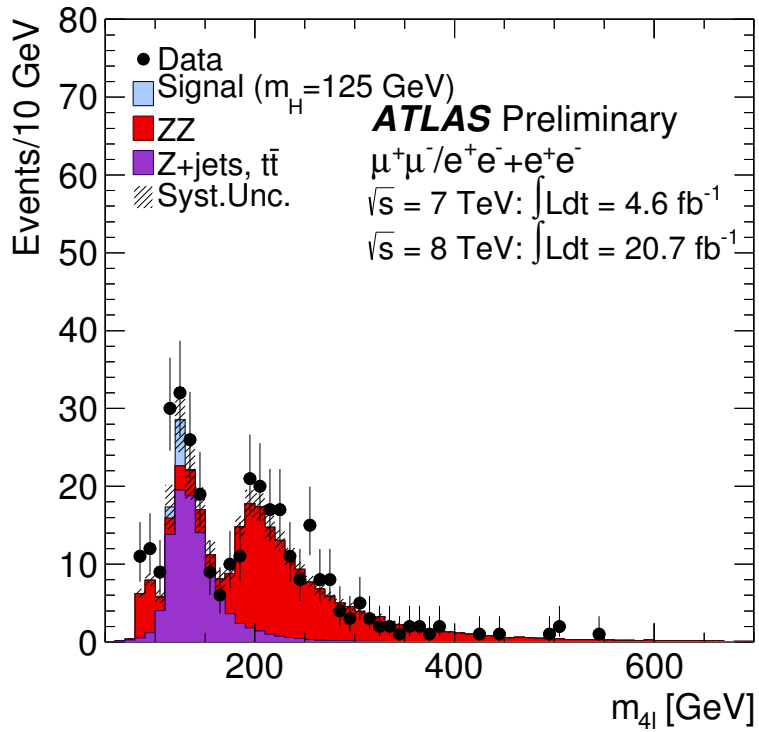




$H \to ZZ^* \to 4\ell$ backgrounds

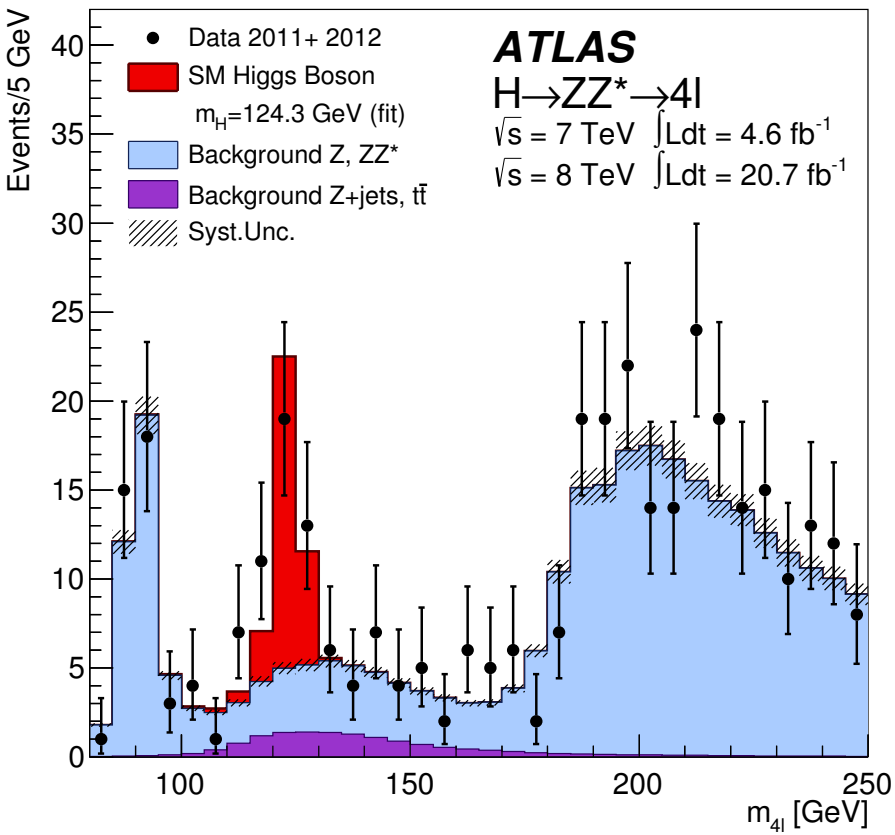
- **Reducible:** mainly $Z+$jets and $t\bar{t}$ processes (jets faking leptons)
  - composition depends on the flavour of the sub-leading lepton pair ($\ell\ell + \mu\mu$, $\ell\ell + ee$)
- **Approach:**
  - Normalization from data-driven methods: signal yields extrapolated from CRs using transfer factors obtained from simulation control samples
  - $m_{4\ell}$ shape derived from background simulation using relaxed lepton selection





$H \to ZZ^* \to 4\ell$ sub-channels

- Each $H \to ZZ^* \to 4\ell$ candidate is assigned to one of the three categories:
  - ⋆ VBF-like: 2 high-p_T jets; $|\Delta\eta_{jj}| > 3$; $m_{jj} > 350$ GeV
  - ⋆ VH-like: not VBF-like; additional isolated lepton with $p_T > 8$ GeV
  - ⋆ ggF-like: not VH- or VBF-like



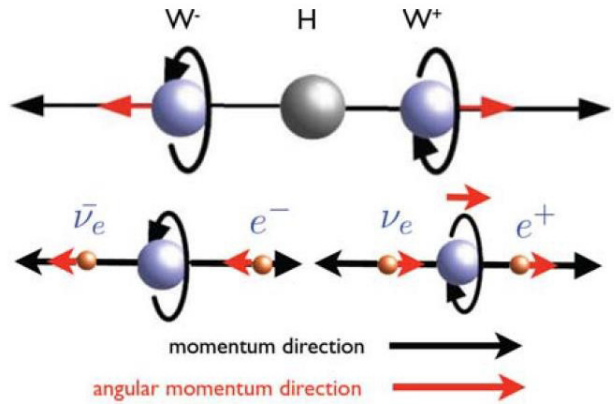
- ⋆ $m_{4\ell} = 124.3^{+0.6}_{-0.5}(\text{stat.})^{+0.5}_{-0.3}(\text{syst.})$ GeV
- ⋆ main syst. unc.: lepton energy and momentum scale ($\pm 0.2\% - \pm 0.4\%$)
- ⋆ significance of the observed peak is 6.6σ

$H \to WW^* \to \ell\nu\ell\nu$ overview

- **Signature:** 2 oppositely charged isolated leptons and $\not{E}_T$
  - $e\mu$ pair: dominates sensitivity to the Higgs boson signal
  - same flavour: larger backgrounds (DY)
  - cannot reconstruct a narrow mass peak due to neutrinos:

    $m_T = \sqrt{(E_T^{\ell\ell} + \not{E}_T)^2 - |\vec{p}_T^{\,\ell\ell} + \vec{\not{E}}_T|^2}$

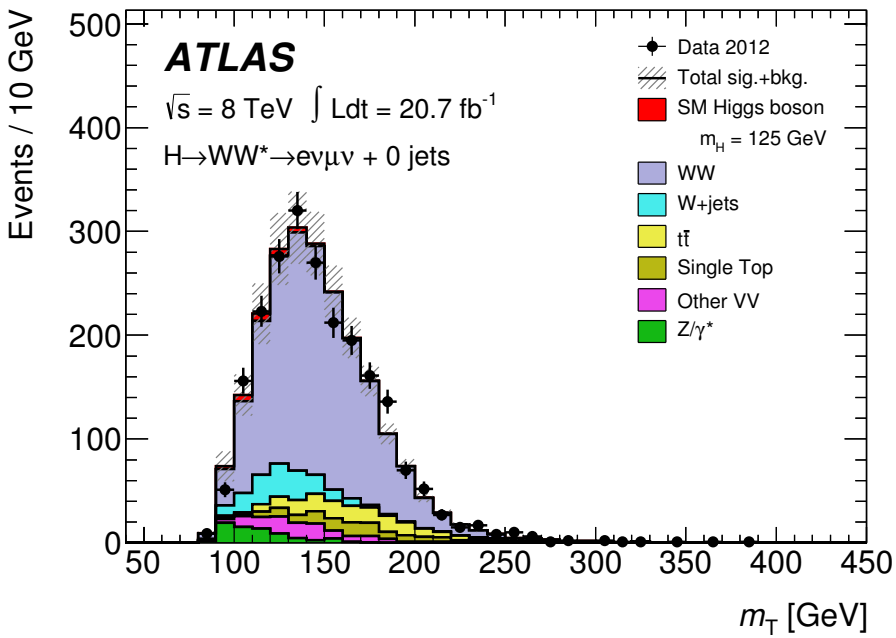
    (with $E_T^{\ell\ell} = \sqrt{|\vec{p}_T^{\,\ell\ell}|^2 + m_{\ell\ell}^2}$)



- **Higgs spin 0:** collinear leptons (low $m_{\ell\ell}$ and $\Delta\phi_{\ell\ell}$) $\Rightarrow$ suppress WW background
- **Production mechanism:** ggF (0 or 1 jet); VBF ($\geq$ 2 jets; low bkg and low theory uncertainty)
  - $\star$ VBF: $|\Delta y_{jj}| > 2.8$; $m_{jj} > 500$ GeV
- Jet energy scale and resolution and b-tagging efficiency are the main sources of experimental systematic uncertainty

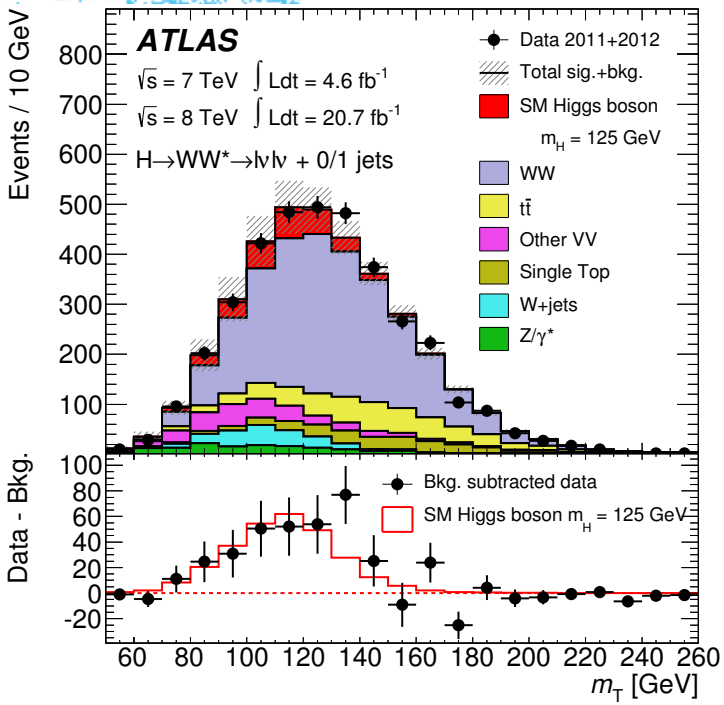
$H \to WW^* \to \ell\nu\ell\nu$ background

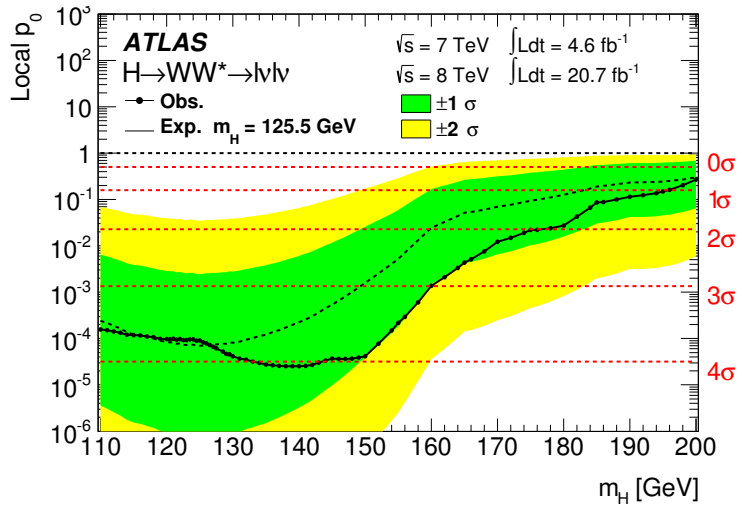
Background	Why fake signal?	criteria to reduce	normalized from
WW	large irreducible bkg	low $m_{\ell\ell}$	data
top ($t\bar{t}$ and single top)	lose a b-jet	b-jet veto	data
W+jets	jet fakes ℓ	tight iso & ℓ ID	data
Z+jets	fake/real $\not{E}_T$	$\not{E}_T$ + low $m_{\ell\ell}$	data
other diboson	lost/misidentified ℓ	veto extra ℓ	MC

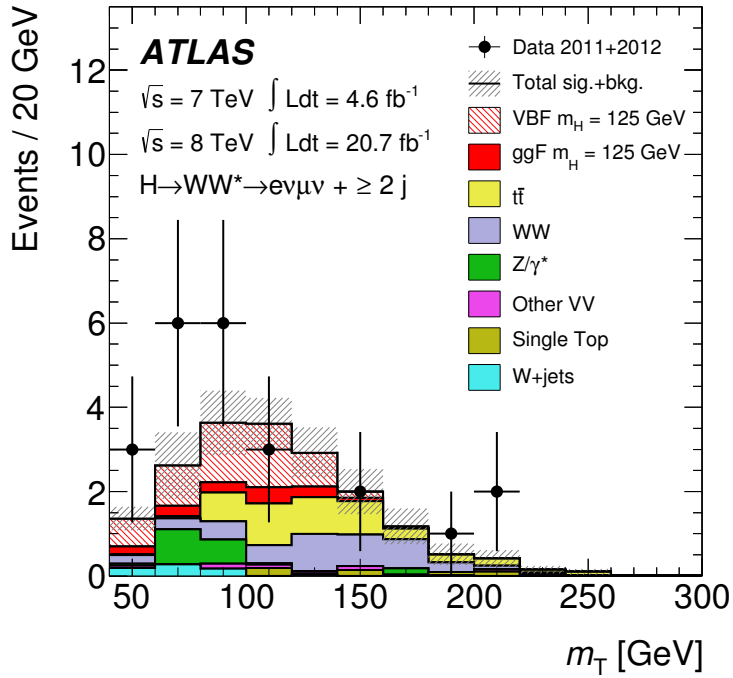


- WW CR, $N_{jet} \leq 1$ final states:
  - $|\Delta\phi_{\ell\ell}|$ criteria is removed
  - $m_{\ell\ell}$ bounds are modified

$H \to WW^* \to \ell\nu\ell\nu$ transverse mass



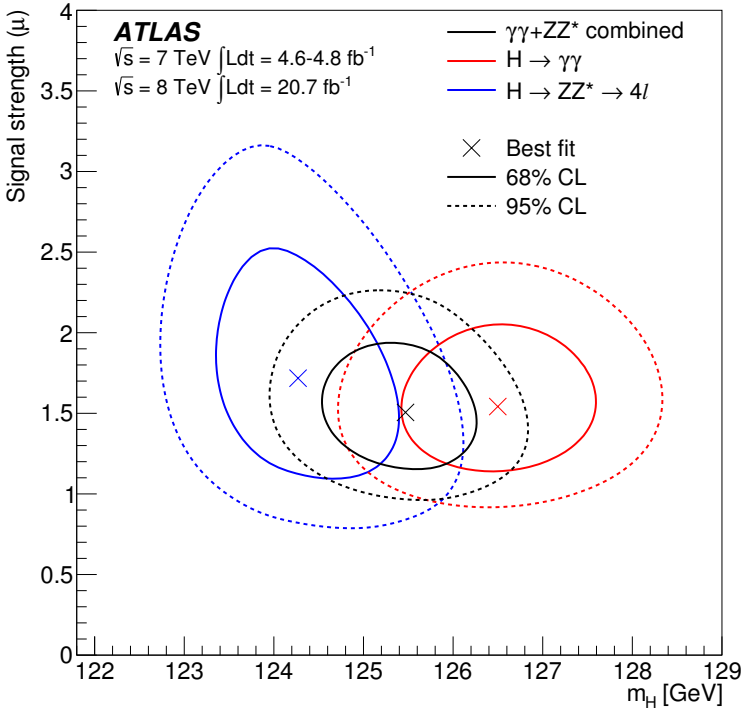




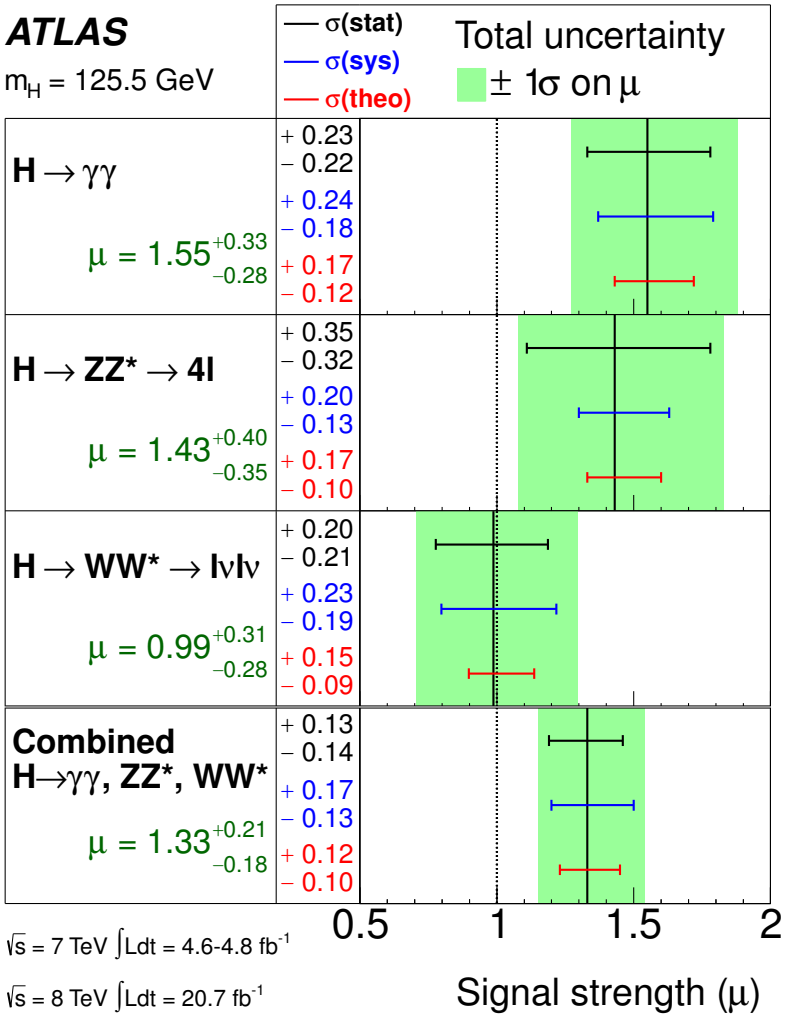
- excess of events observed in data
- VBF contributes 81% of the predicted signal in the $N_{jet} \geq 2$ final states
- maximum deviation (4.1σ) at $m_H = 140$ GeV

Mass measurements and signal strengths

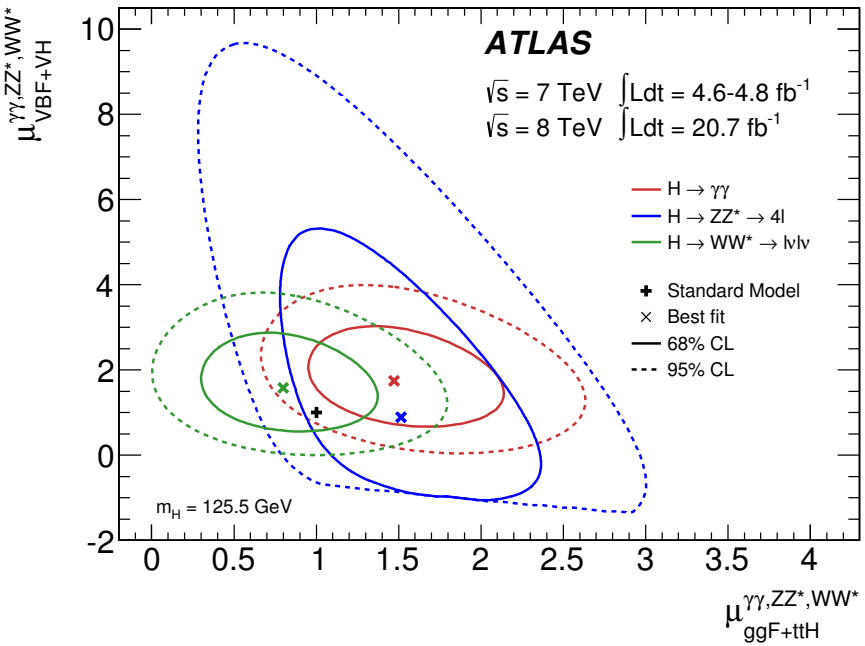
- signal strength: $\mu = \sigma_{\text{observed}}/\sigma_{\text{SM}}$



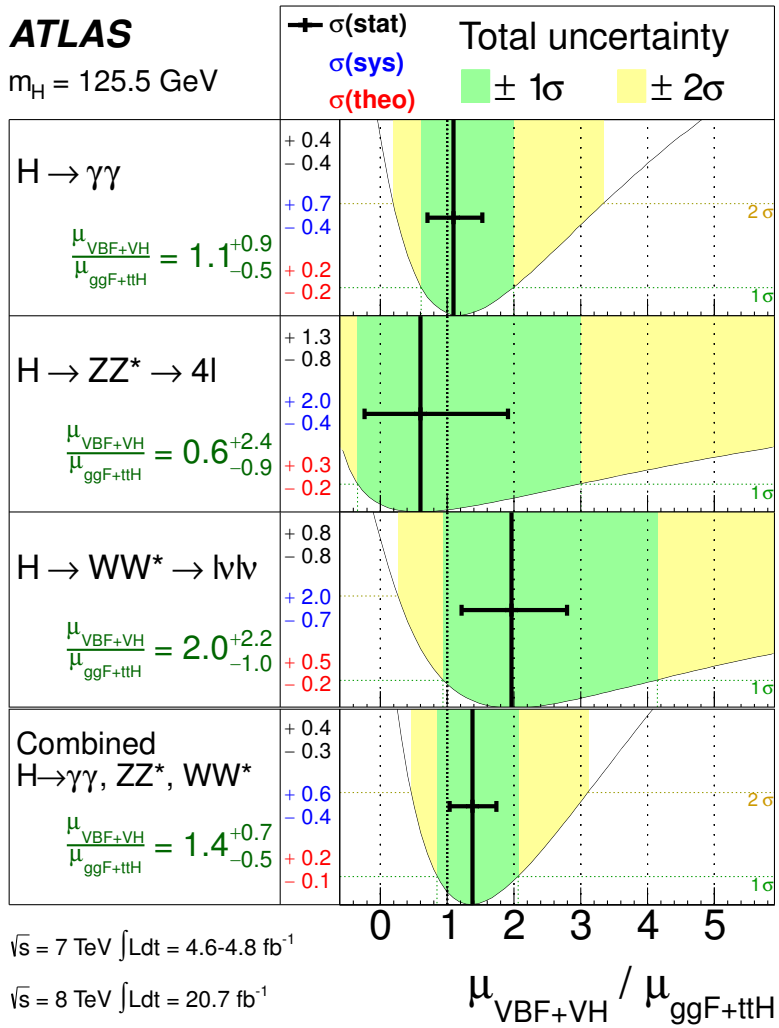
- μ largest deviation ($\sim 1.9\sigma$) observed in $H \to \gamma\gamma$



Production mechanisms



- Exploit sensitivity offered by categories to fit separately vector-boson mediated and gluon mediated processes



Summary

- Data recorded by the ATLAS experiment in 2011/2012 allowed to test the fundamental properties of the discovered Higgs boson
- Significance of the observed mass peak is 7.4σ in $H \to \gamma\gamma$ and 6.6σ in $H \to ZZ \to 4\ell$ channel (discovery level in each of these channels)
- Mass of the Higgs boson measured to be $m = 126.8 \pm 0.2(\text{stat.}) \pm 0.7(\text{syst.})$ in $H \to \gamma\gamma$ and $m = 124.3^{+0.6}_{-0.5}(\text{stat.})^{+0.5}_{-0.3}(\text{syst.})$ in $H \to ZZ \to 4\ell$ (better than 9 per mil)
- **All measurements are consistent with expectations for the SM Higgs boson**

Acknowledgements:

COMPETE PROGRAMA OPERACIONAL FACTORES DE COMPETITIVIDADE
QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL PORTUGAL 2007.2013
UNIÃO EUROPEIA Fundo Europeu de Desenvolvimento Regional
Governo da República Portuguesa
FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

References

- Papers:
  - Phys. Lett. B 716 (2012) 1-29
  - Phys. Lett. B 726 (2013) 88-119
- Conference notes:
  - ATLAS-CONF-2013-034 (Couplings Combination)
  - ATLAS-CONF-2013-030 (Higgs to $WW(\ell\nu\ell\nu)$)
  - ATLAS-CONF-2013-014 (Mass Combination)
  - ATLAS-CONF-2013-012 (Higgs to Diphoton)
  - ATLAS-CONF-2013-013 (Higgs to 4 leptons)

Backup Slides

Statistical method

- Construct a likelihood of Poisson probabilities, with expected numbers of events:

$$N^k = n^k_{\text{sig}} + n^k_{\text{bkg}}$$

- For the analysis k, signal scaling factors per each production i and decay f:

$$n^k_{sig} = \left(\sum_i \mu_i \times \sigma_{i,\text{SM}} \times A^k_{if} \times \varepsilon^k_{if} \right) \times \mu_f \times BR_{f,\text{SM}} \times \mathscr{L}^k$$

  - cross section modifier: $\mu_i = \sigma_i / \sigma_{i,\text{SM}}$
  - branching ratio modifier: $\mu_f = \text{BR}_f / \text{BR}_{i,\text{SM}}$

- Test hypothesized values of parameter of interest μ with profiled likelihood ratio:

$$q_\mu = -2\Delta \ln \mathscr{L} = -2 \ln \frac{\mathscr{L}(data|\mu, \hat{\theta}_\mu)}{\mathscr{L}(data|\hat{\mu}, \hat{\theta})}$$

  - maximized likelihood for a fixed μ
  - μ and θ that maximize likelihood