Standard model Higgs boson results in boson decay modes using the ATLAS detector

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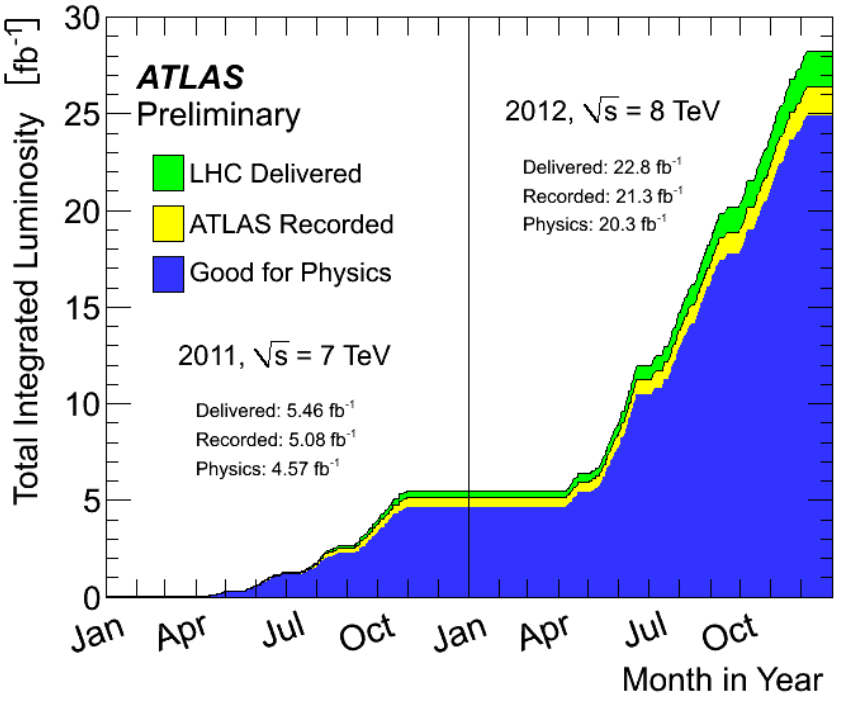
SUSY2014 Manchester July 21-26 2014

Introduction

LHC & ATLAS performance:

- Excellent performance of the LHC machine and ATLAS detector during the whole Run I
  - 90 / 95 % of data recorded good for physics in 2011 / 2012
- Results presented in this talk are based on 2011 and 2012 data at $s^{1/2}$ = 7 and 8 TeV
  L ~ 25 fb^{-1}

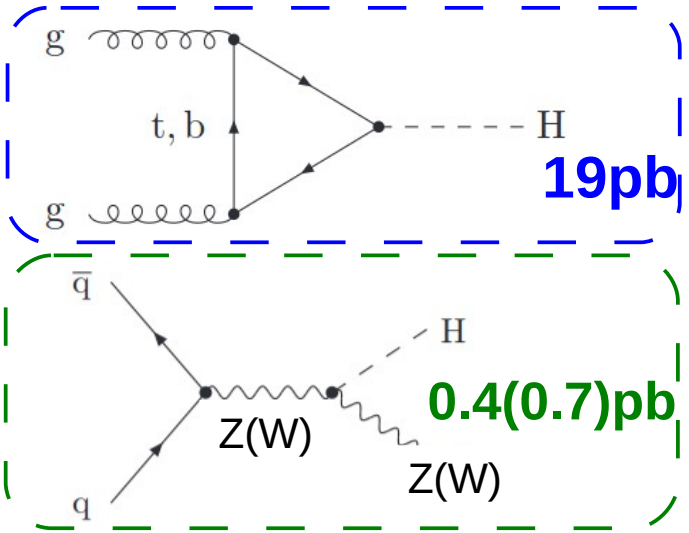


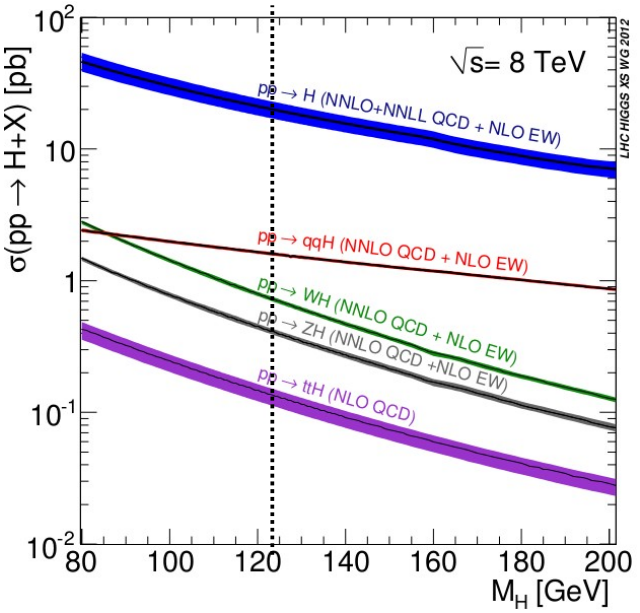
Outlook:

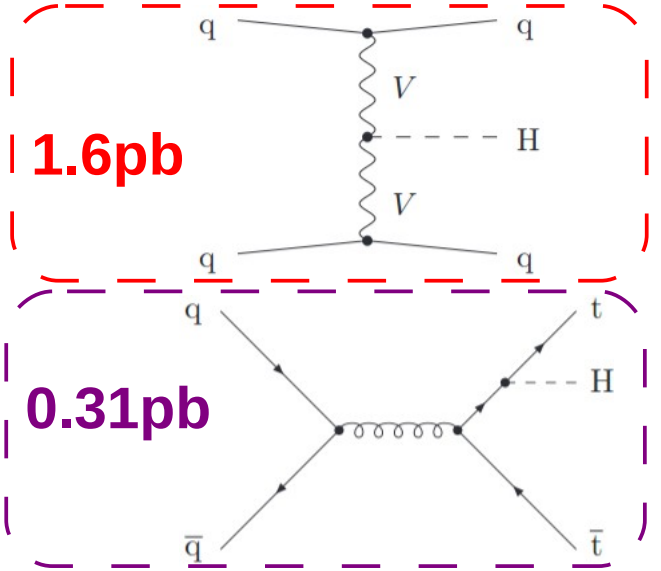
- Latest results on : **H → γγ** and **H → ZZ* → 4l** which include improvements on:
  - Modeling of the geometry of the detector,
  - Energy calibration of photons, electrons and muons
  - Methods used for the measurement of the properties...
- **H → WW* → lνlν** results and search for **H → Zγ**

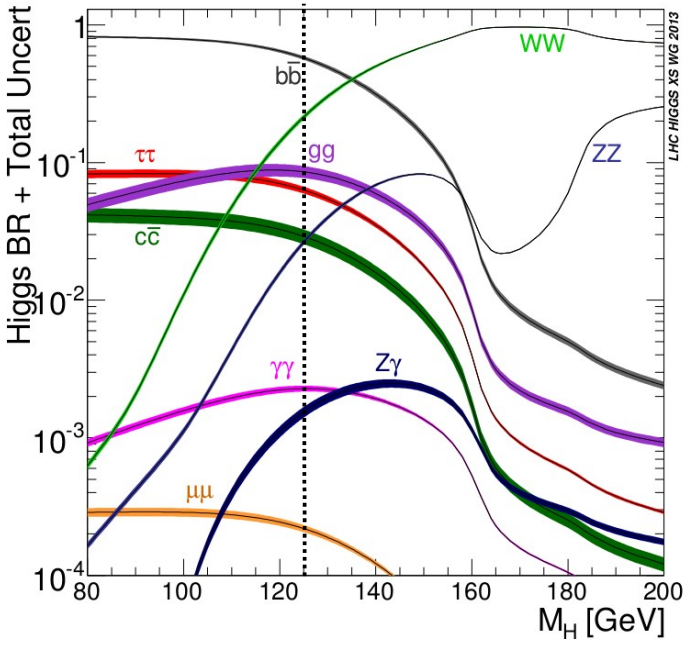
Higgs Boson production & decay channels

σ(pp → H) ~ 22 pb @ mH = 125 GeV









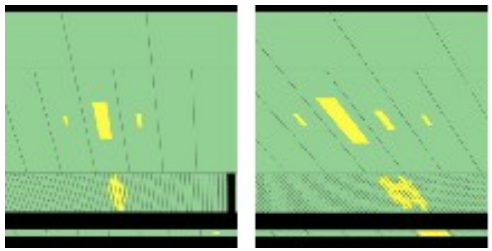
(@ mH = 125 GeV)

Channel (l=e,μ)	BR [%]	Specificities
H → WW* → lνlν	1	*clean signature but final state not fully reconstructible*
H → γγ	0.23	*clean signature, high background, good mass resolution*
H → ZZ* → 4l	0.013	*good mass resolution, low background but low statistic*
H → Z(→ ll)γ	0.011	*Low BR with Large background*

H → γγ: Event selection & Backgrounds

Event selection

- 2 high energy isolated photons, cut-based ID(2012) and MVA ID(2011)
- High rejection against jets thanks to fine EM granularity

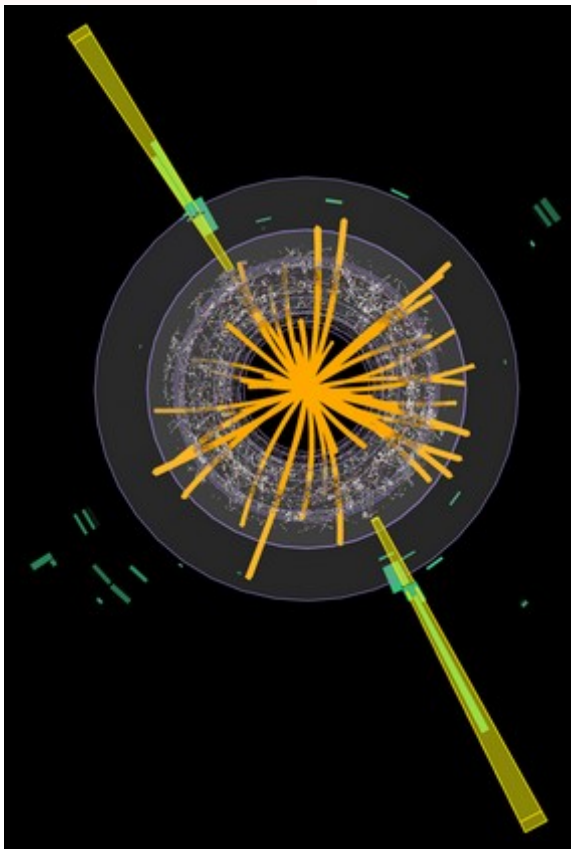


Background

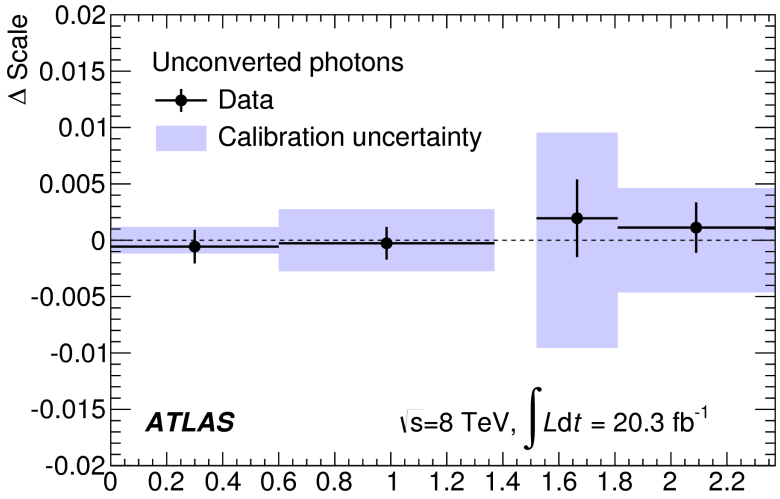
- SM irreducible diphoton → 75%
- Reducible γ jet & jet jet fake → 25%
  → Extracted from sideband

Categorization for mass measurement

- 10 categories depending on: η_γ ,P_{T_t}
  converted photon → 20% reduction on expected statistical uncertainty w.r.t analysis with no categories



Improved energy-scale calibrations for photons



- New MVA calibration
  → improve resolution on $m_{\gamma\gamma}$ by 10 %
- in situ using Z → e+ e- events, validation using Z → llγ (for photons)
- Typically 0.2-0.6%, depending on the category for the photon energy scale uncertainty

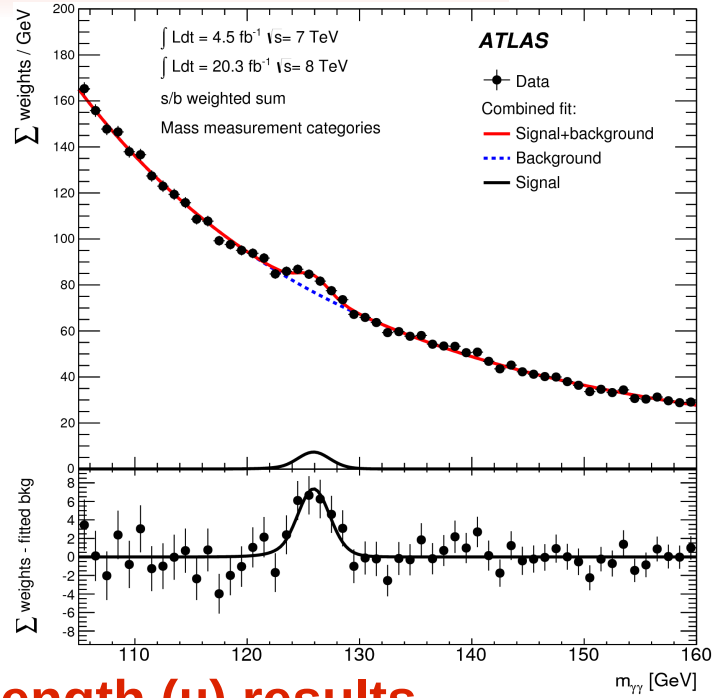
H → γγ: Mass & signal strength measurement

Modeling

- Signal model Crystall Ball + Gaussian
- Background:
  - Exponential (high pt categories → 4 categories)
  - Exponential of a 2nd order polynomial

Mass measurement method

- Simultaneous unbinned fit of the mass distribution $m_{\gamma\gamma}$ over the 10 categories with parameter of interest: Higgs boson mass M_H and signal strength μ

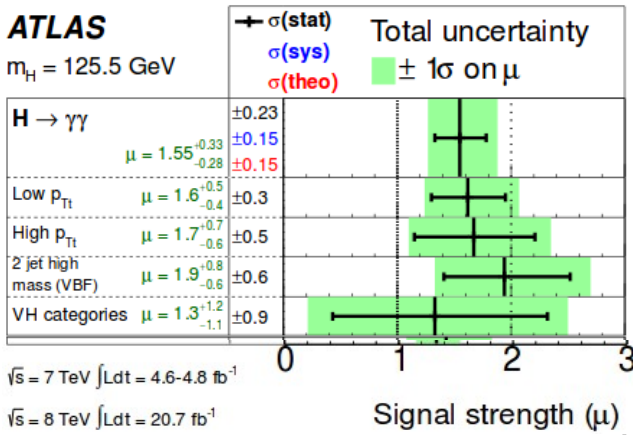


Mass results

- **M_H = 125.98 ± 0.42(stat) ± 0.28(syst) GeV**
- Previous (Phys.Lett B726 88 (2013)):
  - M_H = 126.8 ± 0.2(stat) ± 0.7(syst) GeV
- Stat. Unc increased (mainly due to statistical fluctuation)
- Syst. Unc. Reduced by a factor of 2.5, completely dominated by energy scale syst.

Signal strength (μ) results

- $\mu = \sigma_{obs} / \sigma_{SM}$
- Analysis optimized to measure μ in individual production mode



- tt(H → γγ): Observed (Expected) 95% CL limit of 6.5 (4.9) times SM for m_H = 125.4 GeV

H → γγ: Fiducial & differential cross section (XS)

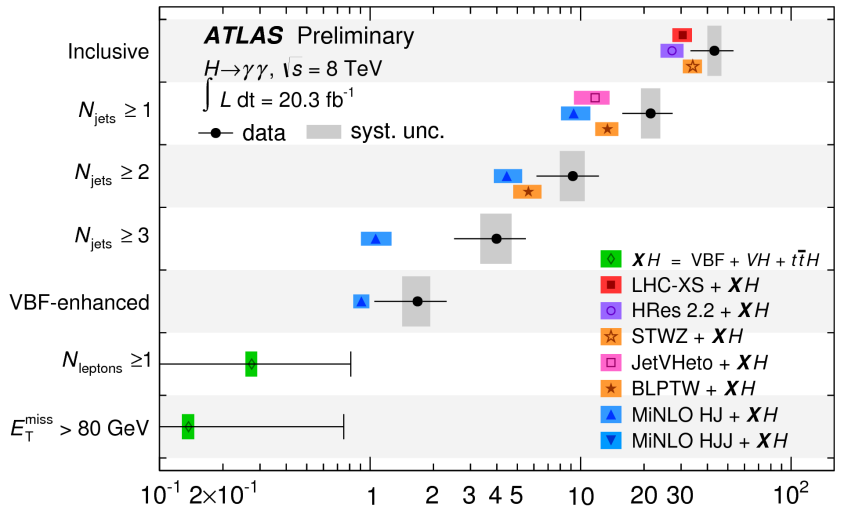
- Measurement of 7 fiducial XS and 12 differential XS as a function of Higgs boson kinematic variables & jets multiplicity,
- Signal extraction using Maximum likelihood fit of the $m_{\gamma\gamma}$ mass spectrum + yield corrected for detector effects.
- Test theoretical modeling of Higgs boson production mechanisms

2012 DATA ~ 20.3 fb^{-1}

Fiducial region definition

- 2 isolated photons
- γ_1 (γ_2) $P_T > 0.35$ (0.25) x $m_{\gamma\gamma}$
- $|\eta_\gamma| < 2.37$

Fiducial XS results

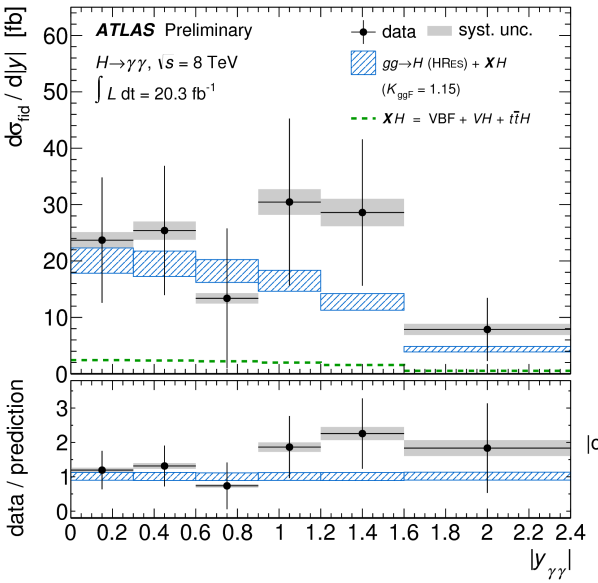


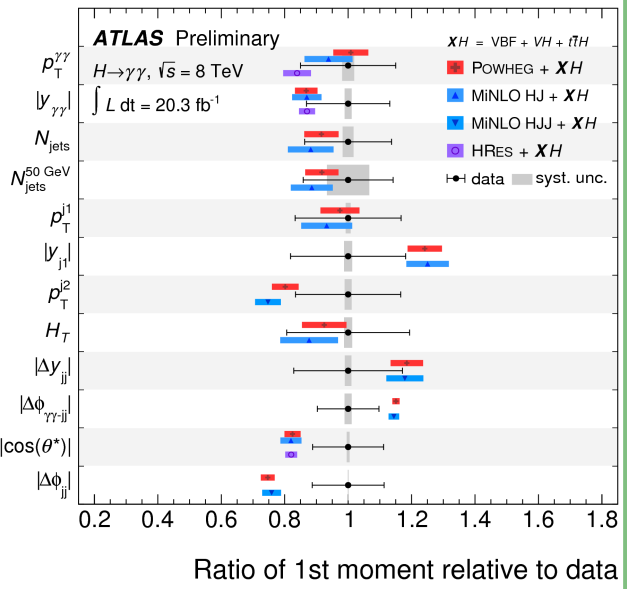
- Inclusive pp → H → γγ, σ_{fid}:

$$43.2 \pm 9.4\,(\text{stat.})\,^{+3.2}_{-2.9}\,(\text{syst.}) \pm 1.2\,(\text{lumi})\ \text{fb}$$

- Expected 30.5 ± 3.3 fb

Differential XS results





- Data in satisfactory agreement with theoretical predictions

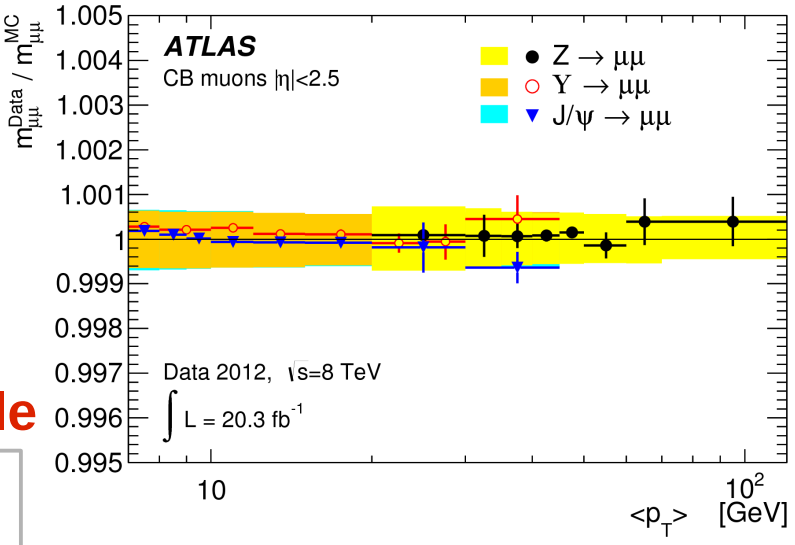
H → ZZ* → 4l: Event selection & Backgrounds

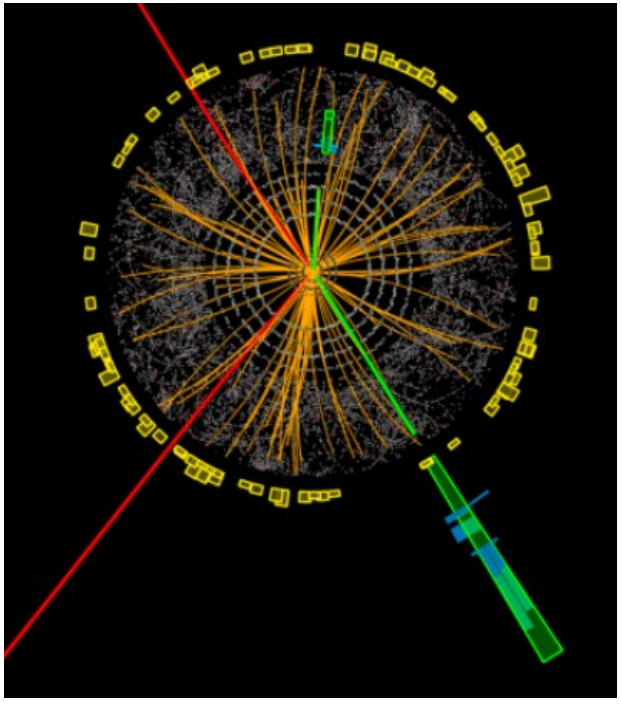
Event selection

- 2 same flavor and opposite sign pairs
  → 4e, 4μ, 2μ2e, 2e2μ
- Electron ID likelihood → reducible background reduced by a factor of 2 w.r.t cut-based selection
- Combined fit of track momentum and calorimeter cluster energy of electrons for E_T < 30 GeV
  → improves mass resolution ~ 4%
- FSR and leading Z mass constraint correction for the m_{4l} → improves mass resolution ~ 15%

Background

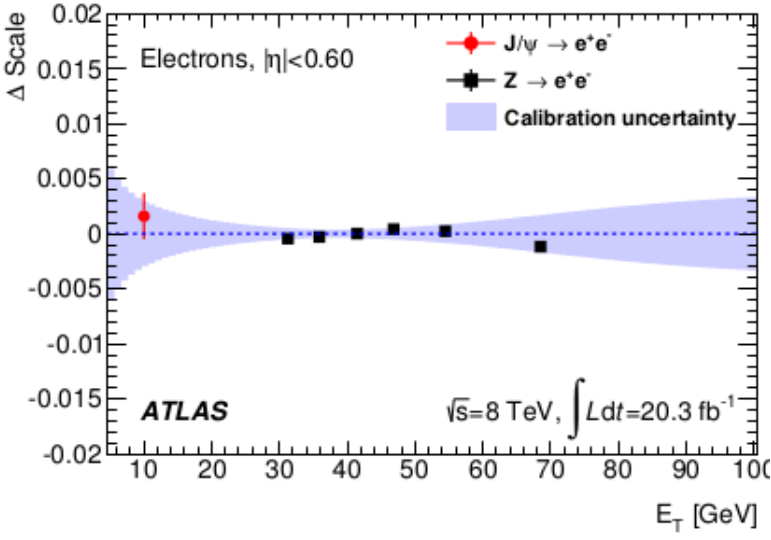
- SM ZZ → Monte Carlo simulation
- Z+jets, ttbar → estimated using data-driven methods





Electron /muon energy scale

- New MVA calibration + in situ using Z → e+ e- events
- Validation using J/Psi (for electrons)
  → the total syst. unc. is 0.05% on electron energy scale
- New muon MC p_T correction
  → Momentum scale Syst. Unc. Of 0.04% in barrel and 0.2% for |η| > 2



$H \to ZZ^* \to 4l$: Mass & signal strength measurement

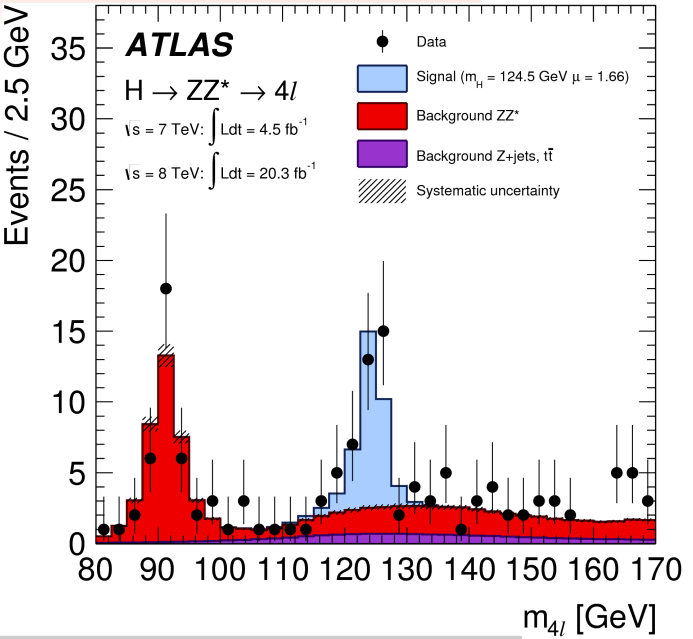
Shapes modeling

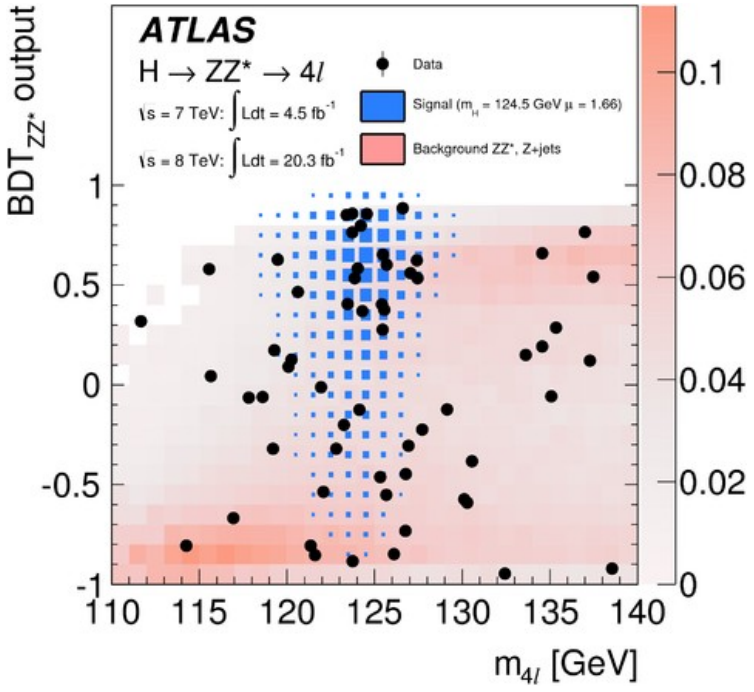
- Signal: simulation distributions smoothed using kernel density estimation method
- Background : ZZ* and Z + μμ reducible background from simulated events ; Z+ee from data-driven techniques

Mass measurement method

2D fit to the m_{4l} range [110 - 140] GeV and BDT (multivariate discriminant trained against ZZ* SM)

→ improvement of 8% on statistical uncertainty w.r.t 1D fit





Mass results

- $M_H = 124.51 \pm 0.52(\text{stat}) \pm \mathbf{0.06(syst)}$ GeV
- Previous (Phys.Lett B726 88 (2013)):
- $M_H = 124.3^{+0.6}_{-0.5}(\text{stat})\ ^{+0.5}_{-0.3}\mathbf{(syst)}$ GeV

Signal strength results

Categorize into VBF, VH and ggF using BDT:

μ_{ggF}	$1.66\ ^{+0.45}_{-0.41}\ (\text{stat})\ ^{+0.25}_{-0.15}\ (\text{syst})$
μ_{VBF}	$0.26\ ^{+1.60}_{-0.91}\ (\text{stat})\ ^{+0.36}_{-0.23}\ (\text{syst})$
μ	$1.44\ ^{+0.34}_{-0.31}\ (\text{stat})\ ^{+0.21}_{-0.11}\ (\text{syst})$

H → ZZ* → 4l: Fiducial & differential XS

- Measurement of fiducial XS and differential cross section as a function of kinematic variables of the 4-leptons and jets multiplicity of pp → H → ZZ → 4l.
- Standard H → ZZ → 4l selection with signal extraction in m_{4l} = [118-129] GeV using Maximum likelihood fit of the m_{4l} mass spectrum + yield corrected for detector effects.

2012 DATA ~ 20.3 fb^{-1}

Fiducial region definition

- Replicate the analysis selection

Fiducial XS results

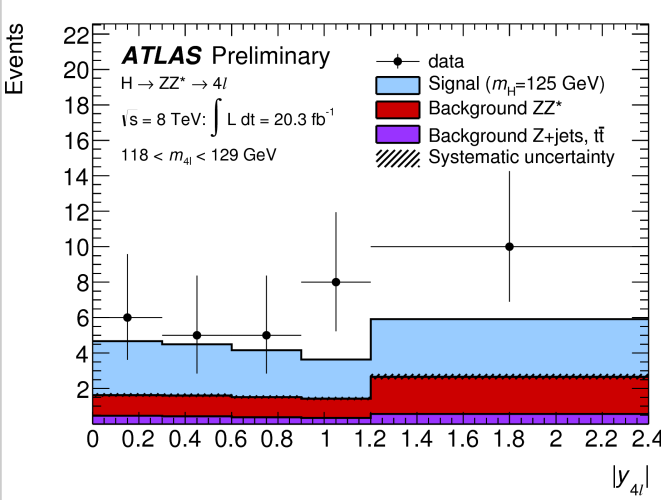
- Inclusive pp → H → ZZ → 4l:

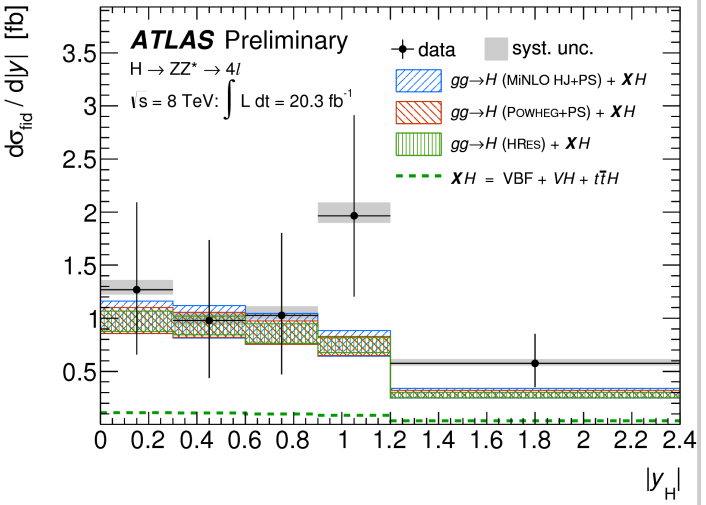
$$\sigma_{\text{tot}}^{\text{fid}} = 2.11^{+0.53}_{-0.47}(\text{stat})^{+0.08}_{-0.08}(\text{syst})\ \text{fb}.$$

- Compared with SM-based theoretical prediction

σ_{fid} = 1.30 ± 0.13 fb

Differential XS results





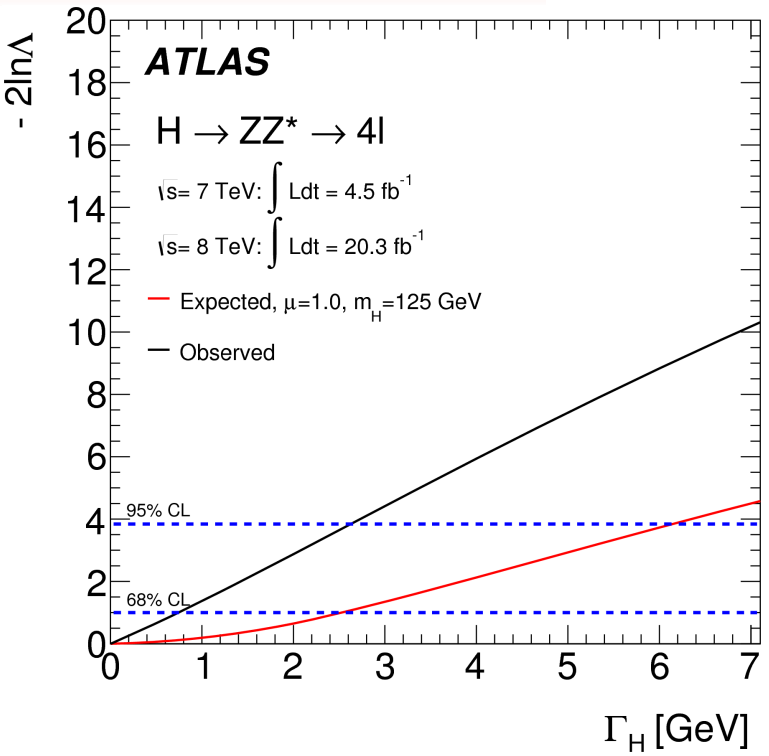
Conclusion

- Statistically limited
- But no significant deviation from any of the tested predictions is observed

Width measurements: H → γγ & H → ZZ*

Direct limit

- Set from the observed width of the invariant mass peak assuming no interference with background processes
- Limited by resolution of the detector
- **H → γγ:** 95% CL: $\Gamma_H < 5.0$ GeV (expected limit 6.2 GeV for μ = 1)
- **H → ZZ* → 4l:** using a per event error method,
  - Observed limit on total width $\Gamma_H < 2.6$ GeV at 95% CL,
  - Expected limit of 3.5 GeV for μ = 1.7, 6.2 GeV for μ = 1



Indirect limit

- Using off-shell Higgs boson signal strength in the H → ZZ → 4l and H → ZZ → 2l 2ν final states
- Observed (expected) 95% confidence level upper limit on Γ_H / Γ_H^{SM} in the range 4.8–7.7 (7.0–12.0)

$$\frac{\sigma^{gg\to H\to ZZ}_{off-shell}}{\sigma^{gg\to H\to ZZ}_{on-shell}} \propto \frac{\Gamma_H}{\Gamma_H^{SM}}$$

H→WW*→lνlν: Results

Event selection

- 2 high energy and opposite charge leptons
- Large missing ET

Categorization

- Flavor of the leptons: ee, μμ, eμ
- Jet multiplicity : 0 /1 jet (ggF), > 1 jets (VBF)

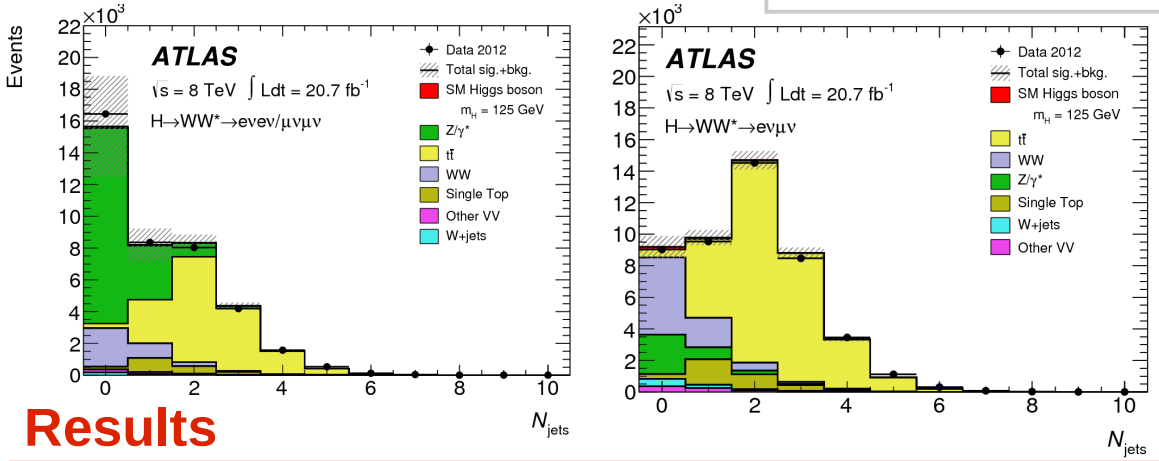
Main Backgrounds

- SM irreducible WW
- Top quark production

Data-driven estimation

Discriminant variables →

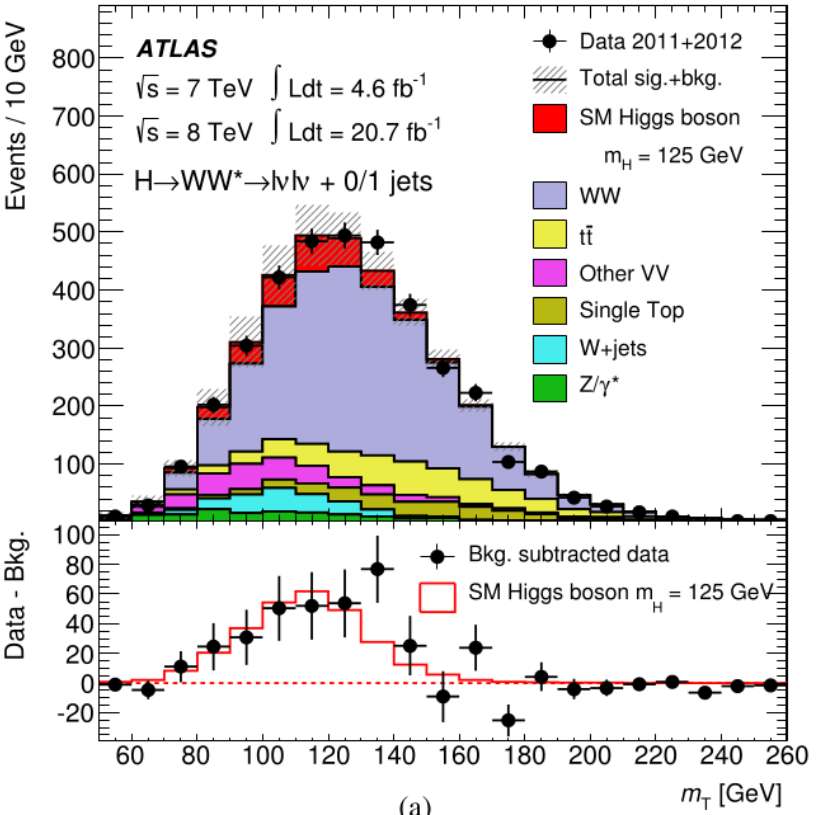
- Events not fully reconstructed due to 2 ν in the final state
- $\Delta\varphi_{ll}$, $p_{T,ll}$, m_{ll},
- $m_T = ((E_T^{\ell\ell} + E_T^{miss})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{miss}|^2)^{1/2}$



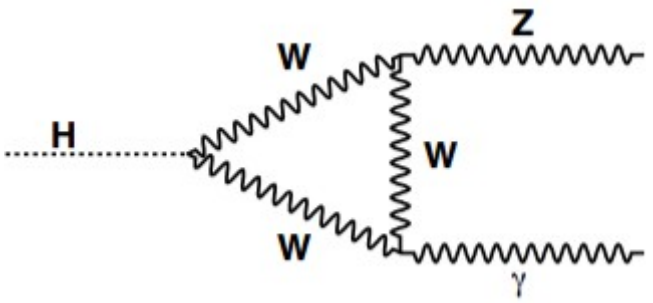
Results

- Signal extraction using 1D fit on m_T distribution
- Local p_0 value observed (expected)

  at m_H = 125.5 GeV: 3.8σ (3.7σ)
- μ = 1.01 ± 0.31



H → Zγ: Event selection & Backgrounds



Event selection

- One isolated photon
- 2 opposite sign same flavor leptons

} Objects selection as in $H \to \gamma\gamma, H \to ZZ^* \to 4l$

- $M_{ll} > M_Z - 10$ GeV, $115\ \text{GeV} < m_{ll\gamma} < 170$ GeV

Background

- SM irreducible $Z+\gamma, Z \to ll$, $Z \to ll\gamma$
- Reducible Z+jet

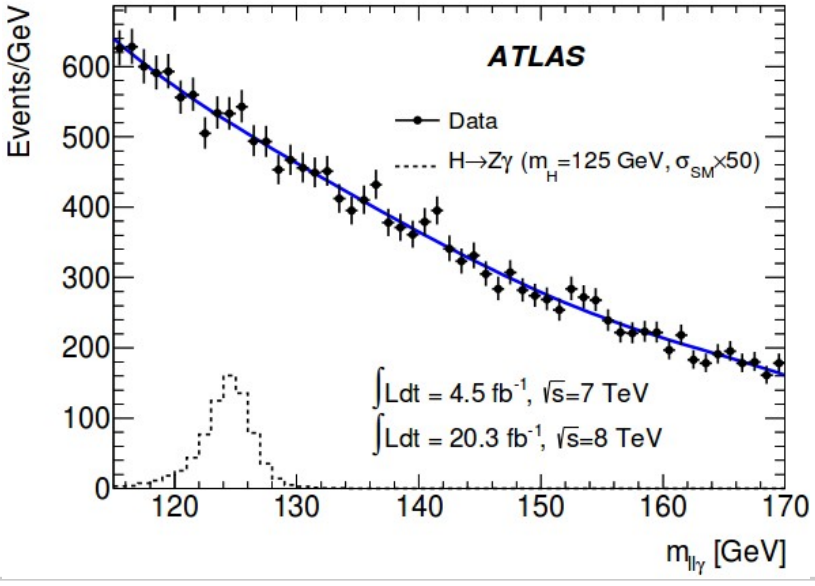
} Fitted to the data mass spectrum (sidebands)

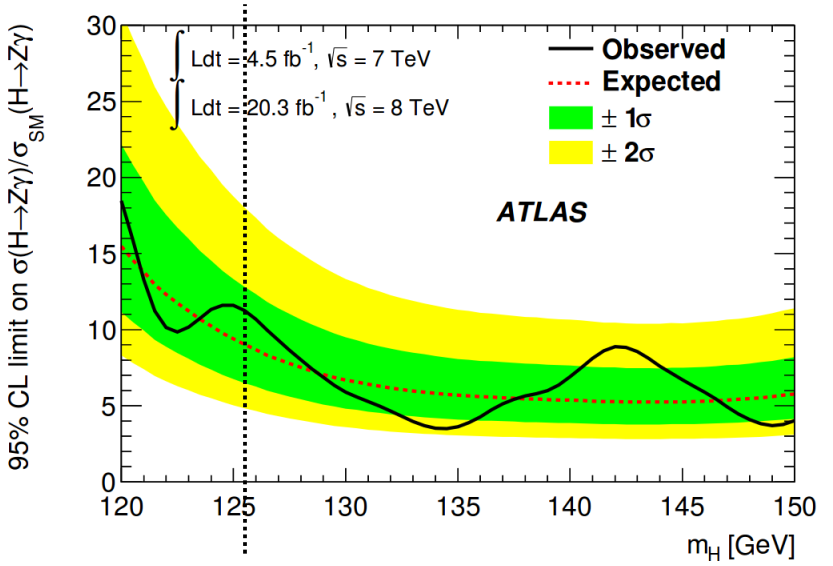
Categorization

- 10 categories depending on:
  - $S^{1/2}$, lepton flavor, $p_{T,t}$, $\Delta\eta_{Z\gamma}$

Results

- Results consistent with SM hypothesis in mass range [115, 170]
- Higgs boson of 125.5 GeV upper observed (expected)limit at 95% CL is 11 (9) times SM expectation





Conclusions

- Higgs boson discovered through the combination of the following channels:
  $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow WW^* \rightarrow l\nu l\nu$

- Latest updated results presented in this talk for $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$:
  - Including new calibration and analysis improvements.
  - Systematic uncertainty on the mass results:
    - Reduced by a factor of 2.5 for $H \rightarrow \gamma\gamma$ channel
    - Negligible using the $H \rightarrow ZZ^* \rightarrow 4l$ channel

- Coupling, spin CP, differential cross section → All compatible with SM expectations

- No observation in the search for $H \rightarrow Z\gamma$, compatible with SM hypothesis.

Material

- H → γγ & H → ZZ* → 4l mass and width: arXiv:1406.3827
- H → γγ signal strength: Phys. Lett. B 726 (2013) 88
- tt(H → γγ) signal strength limit: ATLAS-CONF-2014-043
- H → γγ XS: arXiv:1407.4222
- H → ZZ* → 4l: signal strength: To be submitted to PRD
- H → ZZ* → 4l XS: ATLAS-CONF-2014-044
- Indirect Width: ATLAS-CONF-2014-042
- H → WW* → lνlν: ATLAS-CONF-2013-030 & PLB 726 (2013) 89-119
- H → Zγ: PLB 732C (2014), pp. 8-27

Backup

H → γγ: Mass

arXiv:1406.3827

experiments generated with this measured signal yield. The average expected statistical uncertainty on the mass for $\mu = 1.3$ is 0.35 GeV and the fraction of pseudo-experiments with a statistical error larger than the one observed in data (0.42 GeV) is about 16%. From these pseudo-experiments, the distribution of fitted masses is compared to the input mass value to verify that the average statistical uncertainty provides 68% coverage. In the previous measurement, the expected statistical uncertainty was about 0.33 GeV for $\mu = 1.55$ and the observed statistical uncertainty (0.24 GeV) was better than expected. The change in expected statistical uncertainty mostly comes from the change in the fitted signal strength, which was slightly larger in the previous measurement, as the statistical uncertainty on the mass measurement is inversely proportional to the signal strength. Changes in the mass resolution and the event categorization also contribute to the change in the expected statistical uncertainty. The increase in the statistical uncertainty between the previous result and this result is consistent with a statistical fluctuation from changes in the measured masses of individual events. Assuming the SM signal yield ($\mu = 1$), the statistical uncertainty on the mass measurement is expected to be 0.45 GeV.

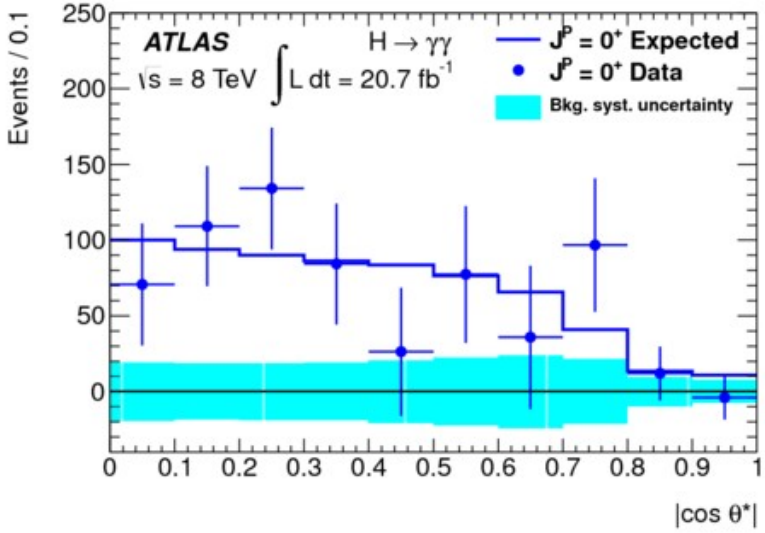
Theoretical Models

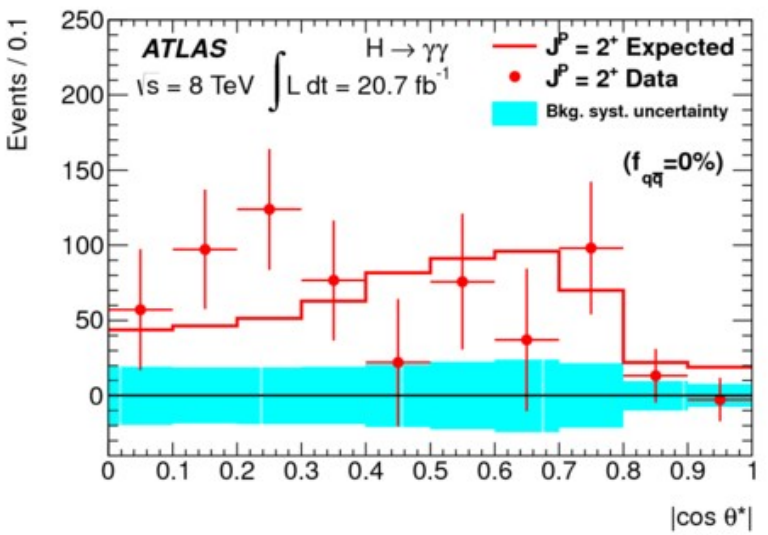
Name	Parton Shower	fiducial region	diff. XS	QCD Precision	Quark mass in loop	EW Prec.
Powheg+Py8	Pythia 8	inclusive	all	NLO(0j) + PS	$m_t=\infty$, $m_b=0$	-
MINLO HJ	Pythia 8	inclusive 1 jet	all	NLO(0,1j) + PS	$m_t=\infty$, $m_b=0$	-
MINLO HJJ	Pythia 8	inclusive 2 jets	all	NLO(2j) + PS	$m_t=\infty$, $m_b=0$	-
LHC XS	-	inclusive		NNLO+NNLL	finite m_t,m_b,m_c	NLO
STWZ (SCET)	-	inclusive		NNLO+NNLL'	$m_t=\infty$, $m_b=0$	-
HRes	-	inclusive	kinematics of Higgs + decay	NNLO+NNLL	finite m_t,m_b	-
BLPTW (SCET)	-	1 jet 2 jets		NLO + NNLL' approx. NLO +	$m_t=\infty$, $m_b=0$	-
JetVHeto	-	1 jet		(N)NLO + NNLL	finite m_t,m_b	-

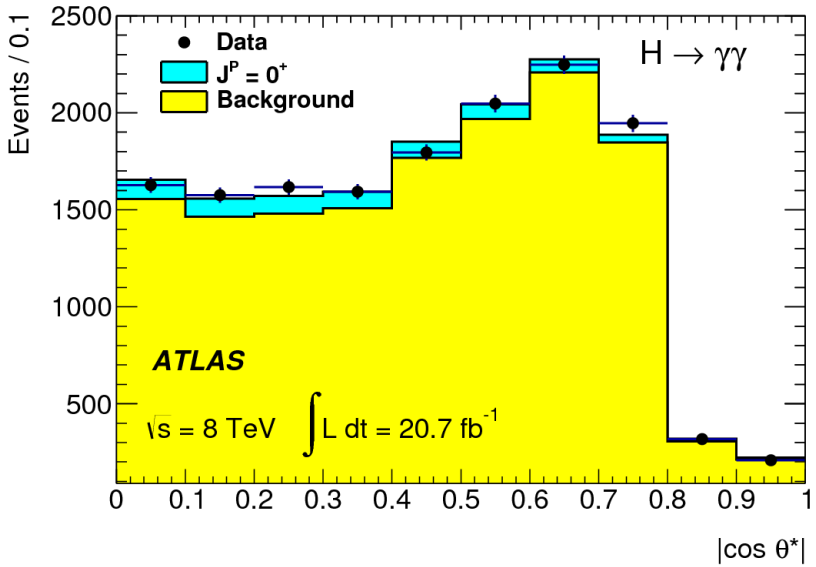
From S. Laplace at ICHEP conference 2014

H → γγ: Spin CP

- The standard model Higgs boson spin parity $J^P = 0^+$ hypothesis is compared with alternative hypothesis : 0^-, $1^\pm$, 2^+
- Polar angular distributions of the 2 photons sensitive to the Higgs boson spin







$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

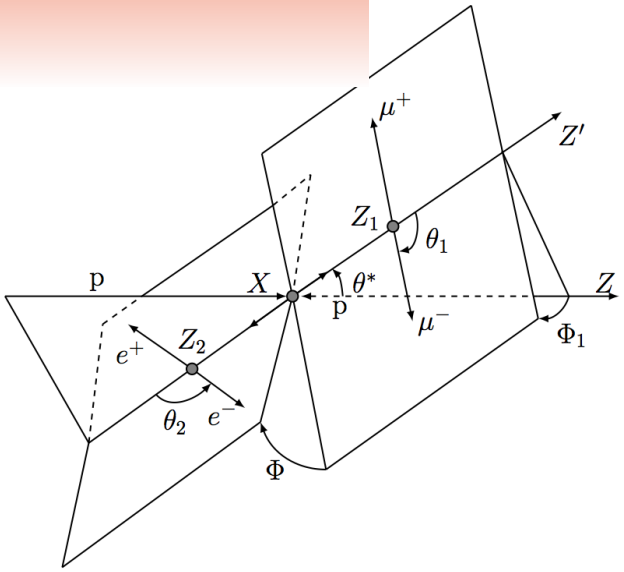
Results

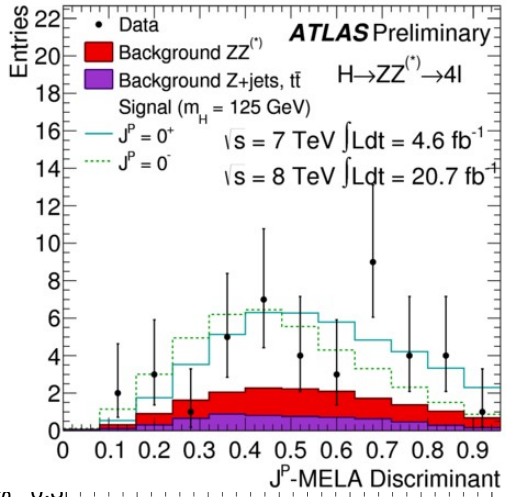
- In the signal region 122 GeV < $m_{\gamma\gamma}$ < 130 GeV
  → 2-D fit of the $m_{\gamma\gamma}$ and |cos θ*|
- In the side bands 1-D fit on $m_{\gamma\gamma}$
- 2^+ hypothesis excluded at 99.3% CL

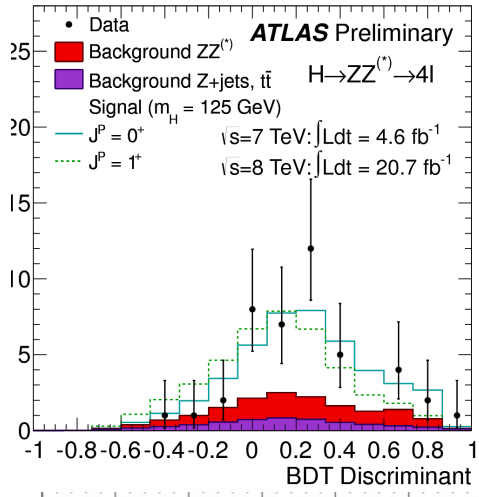
$H \to ZZ^* \to 4l$: Spin cp

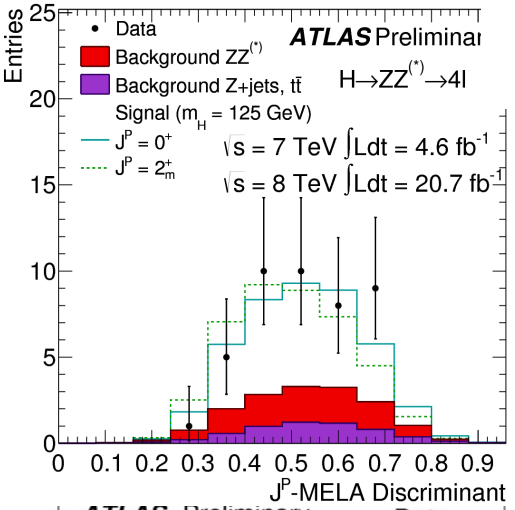
- In SM Higgs $J^P=0^+$
- Select events in range: 115 GeV< m_{4l} <150 GeV
- And perform test 0^-, $1^\pm$, $2^\pm$ using BDT and MELA
  - 5 production and decay angles: θ^*, θ_1 , θ_2 , Φ , Φ_1
  - Kinematic observables: m_{12}, m_{34}

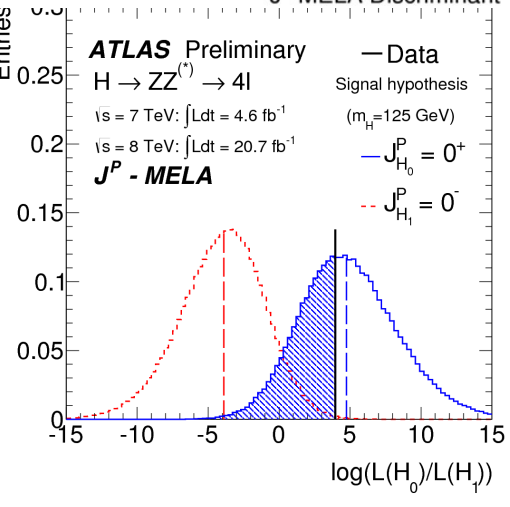
BDT input variables

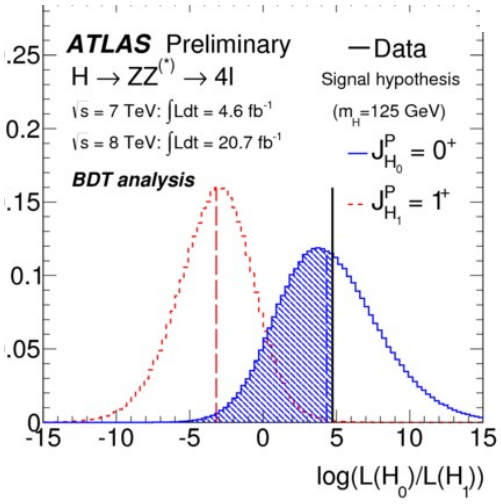


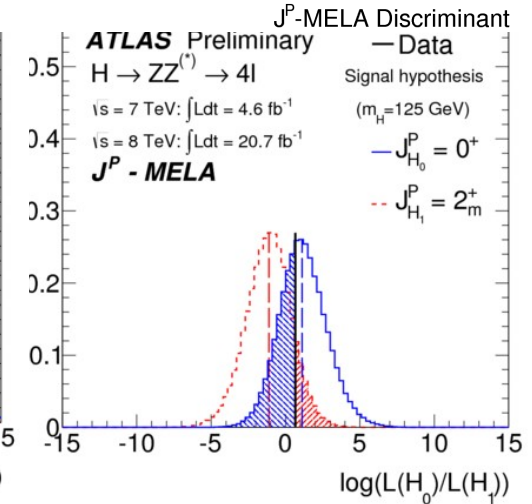








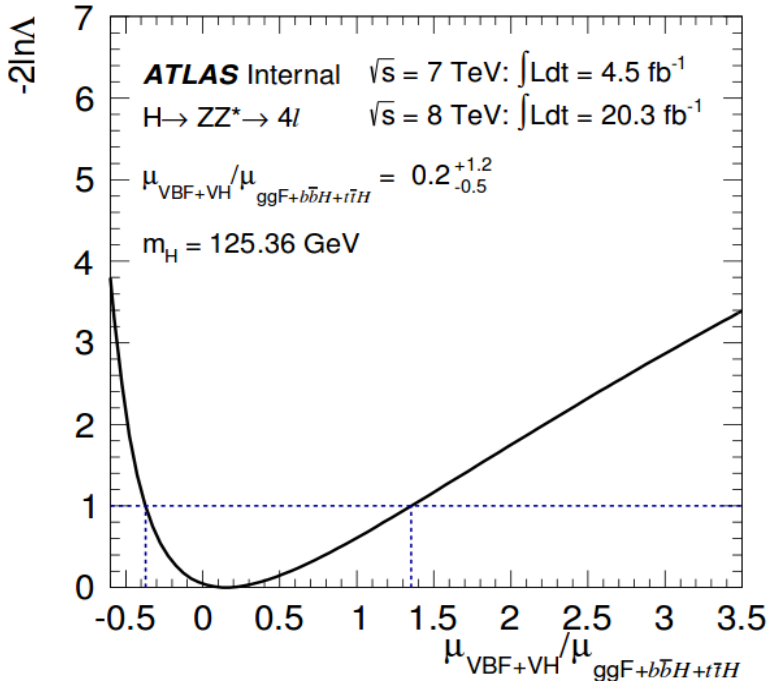


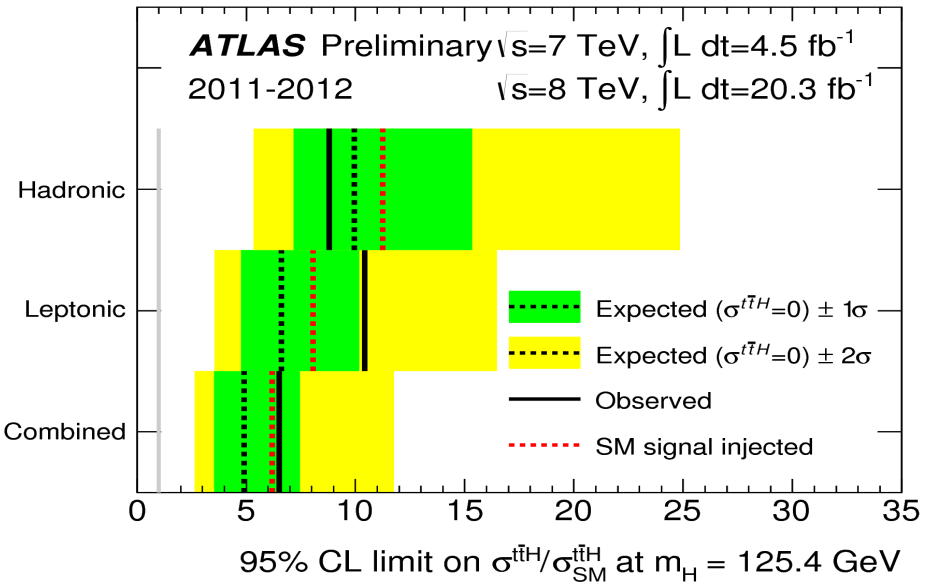


Results

- J^P compatible with 0+
- 0- ,1+ excluded at 97.8%CL
- 1- and 2+ excluded at 94%CL and 81.8%CL

Higgs coupling measurements





H→WW*→lνlν: Event selection & Backgrounds

Event selection

- 2 high energy and opposite charge leptons
- Large missing ET

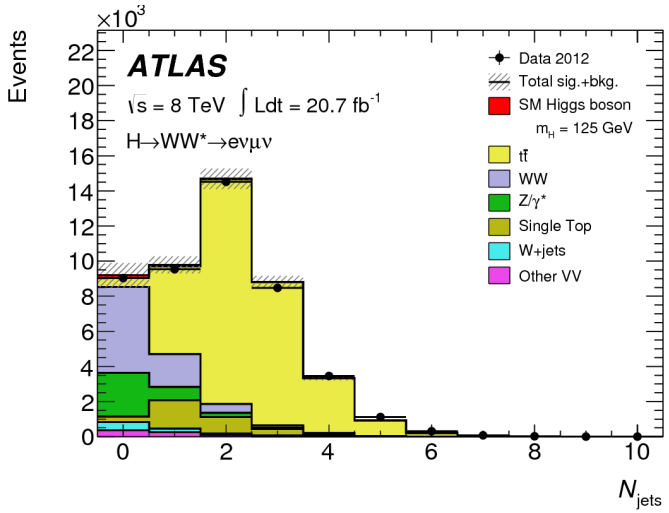
Background

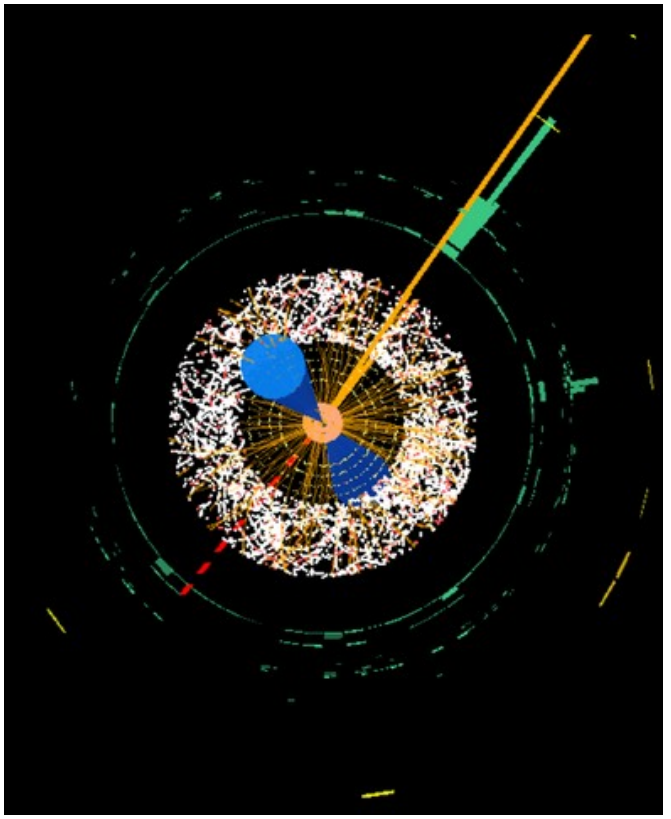
- SM irreducible WW
- Top quark production

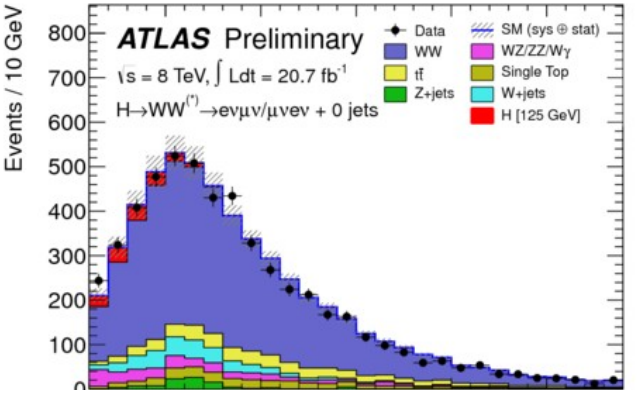
Data-driven estimation

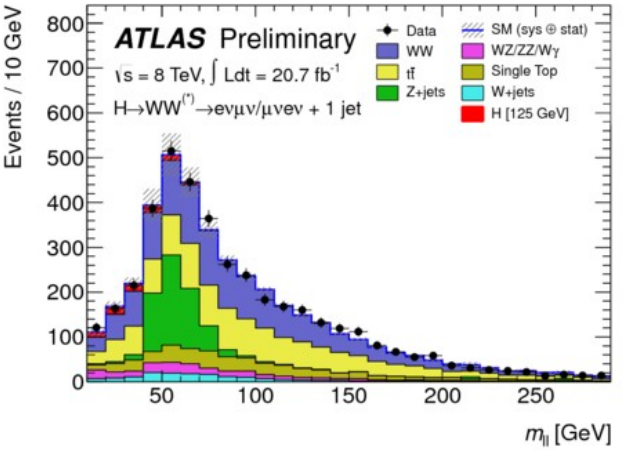
Categorization

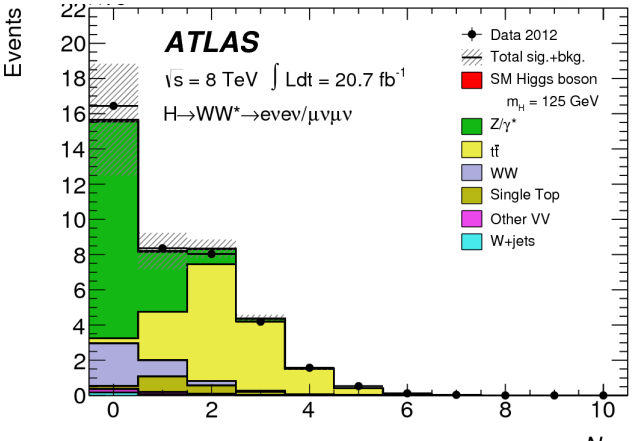
- Flavor of the leptons: ee, μμ, eμ
- Jet mulitplicity : 0 /1 jet (ggF), >1 jets VBF











Discriminants variables

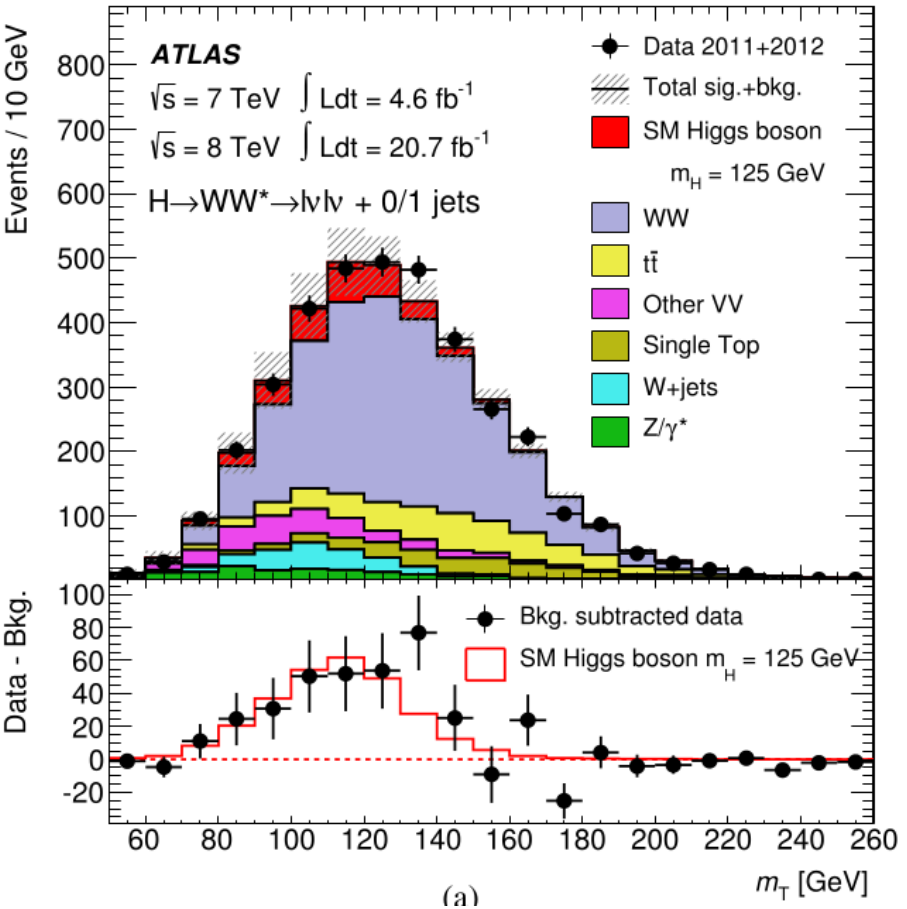
- Events not fully reconstructed due to 2 ν in the final state
- $\Delta\varphi_{ll}$, $p_{T,ll}$, m_{ll}, $m_T = ((E_T^{\ell\ell} + E_T^{miss})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{miss}|^2)^{1/2}$

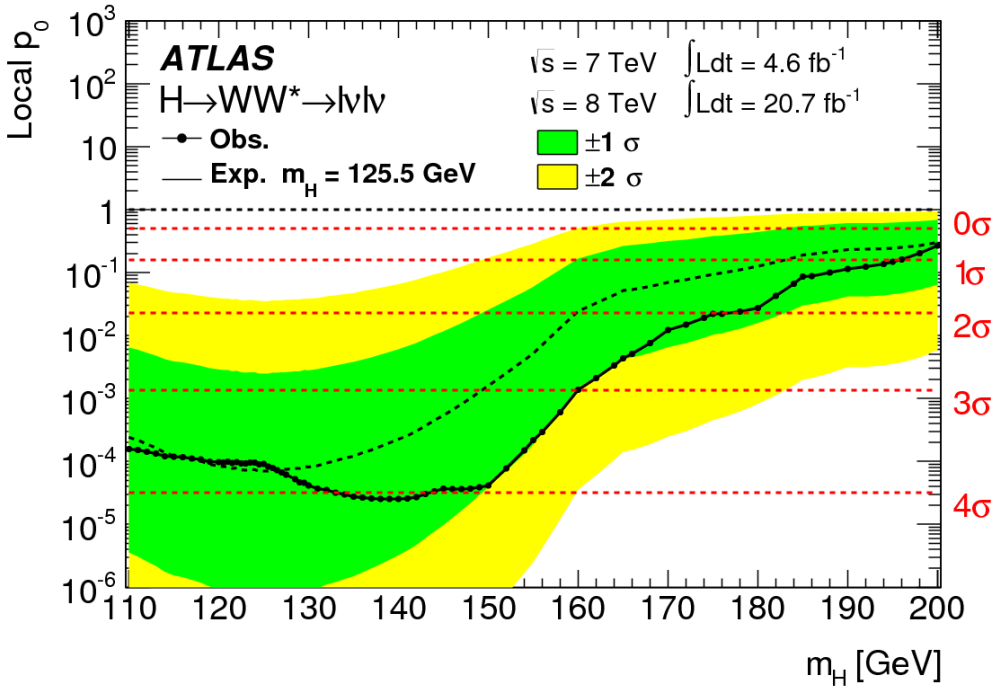
H→WW*→lνlν: Results

Results

- Signal extraction using 1D fit on m_T distribution
- Local p_0 value observed (expected)

  at m_H = 125.5 GeV: 3.8σ(3.7σ)
- μ = 1.01 ± 0.31





Spin CP measurement

- 1+ excluded at 92%CL
- 1- excluded at 98%CL
- 2+ excluded at 95%CL