Search for Higgs Boson Decays into Gauge Bosons with ATLAS

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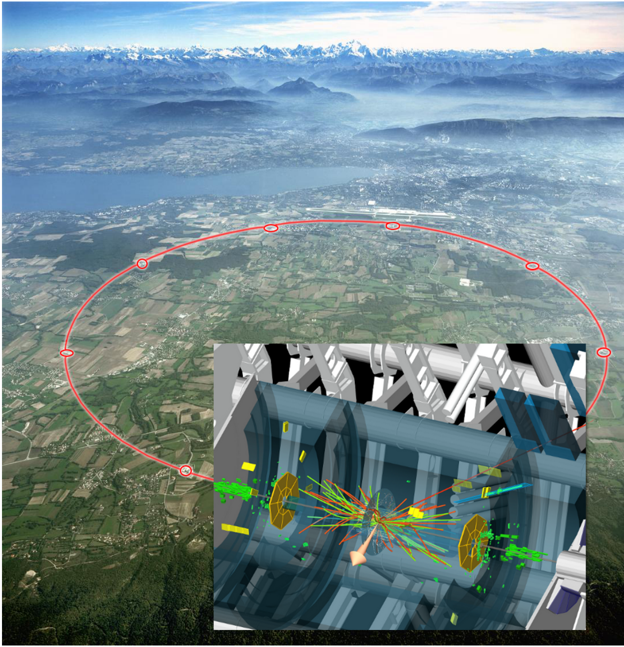
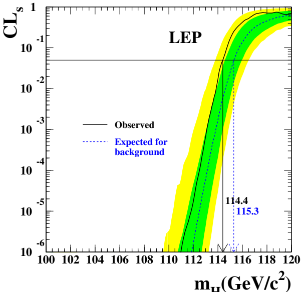
- Overview
- $H \to \gamma\gamma$
- $H \to ZZ$
- $H \to WW$
- Combination

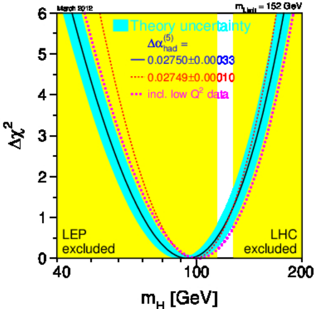


SM Higgs boson

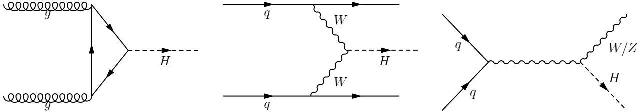
- Higgs mechanism gives an explanation for the Electroweak Symmetry breaking and generation of the W and Z masses
- Predicts a not yet observed neutral scalar particle with unknown mass and small cross-section
- Direct searches at LEP set lower bound $m_H > 114.4$ GeV at 95% CL
- Tevatron excludes $100 < m_H < 106$ GeV and $147 < m_H < 179$ GeV at 95% CL



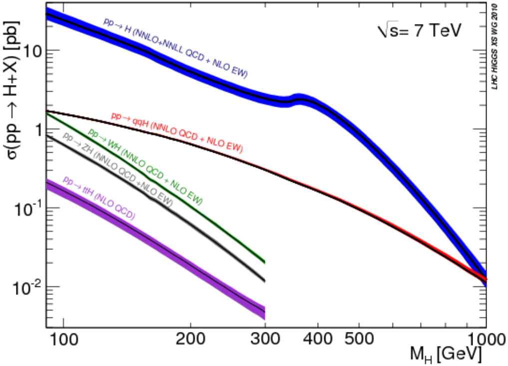
- Searching for the Higgs boson is one of the primary goals of LHC
- Higgs searches require sophisticated detectors designed to stringent performance requirements for particle identification, object energy/momentum measurements, E_T^{miss} measurement, b-tagging, etc



Higgs production



arXiv:1101.0593



- Gluon-gluon fusion (ggF)
  - POWHEG+PYTHIA
  - p_T with HqT v2.0
- Vector boson fusion (VBF)
  - POWHEG+PYTHIA
- Associated production:
  - WH/ZH
  - $t\bar{t}$H
  - PYTHIA
- Mass line shape uncertainty:
  - $(150\%) \times (\frac{m_H}{TeV})^3$

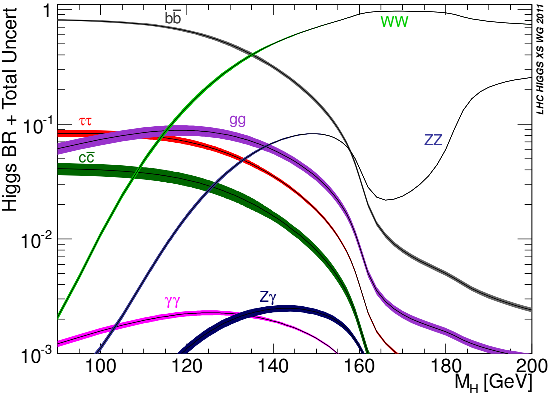
Theory uncertainties:

	ggF	VBF	WH/ZH	$t\bar{t}$H
QCD scale	+12% − 8%	±1%	±1%	+3% − 9%
PDF+α_S	±8%	±4%	±4%	±8%

Higgs decays

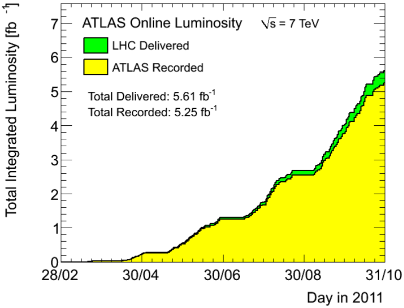
- Higgs couples to mass
- *WW* and *ZZ* dominate when kinematically allowed
- Many competing channels for $m_H < 160$ GeV
- SM backgrounds inhibit searches in channels with jets and/or neutrinos
- $B(W \to l\nu) = 10.8\%$
  $B(Z \to ll) = 3.4\%$
- Width for $m_H < 170$ GeV: $\Gamma_H < 100$ MeV

arXiv:1101.0593



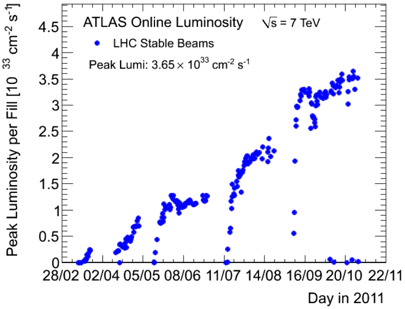
ATLAS experiment

- ATLAS is 93.5% efficient during stable LHC collisions
- Recorded $\int \mathcal{L} = 5.25\ fb^{-1}$
- Luminosity uncertainty is 3.9%
- High trigger efficiency for Higgs searches
  - Single lepton, di-lepton and di-photon triggers



LHC peak luminosity in 2011:

- $\mathcal{L}_{peak} \approx 3.6 \times 10^{33} cm^{-2} s^{-1}$
- pp inelastic $\approx 210\ MHz$
- $Z \rightarrow \mu\mu \approx 3\ Hz$
- $H[125\ GeV] \rightarrow WW \rightarrow l\nu l\nu$ $\approx 0.0003\ Hz$



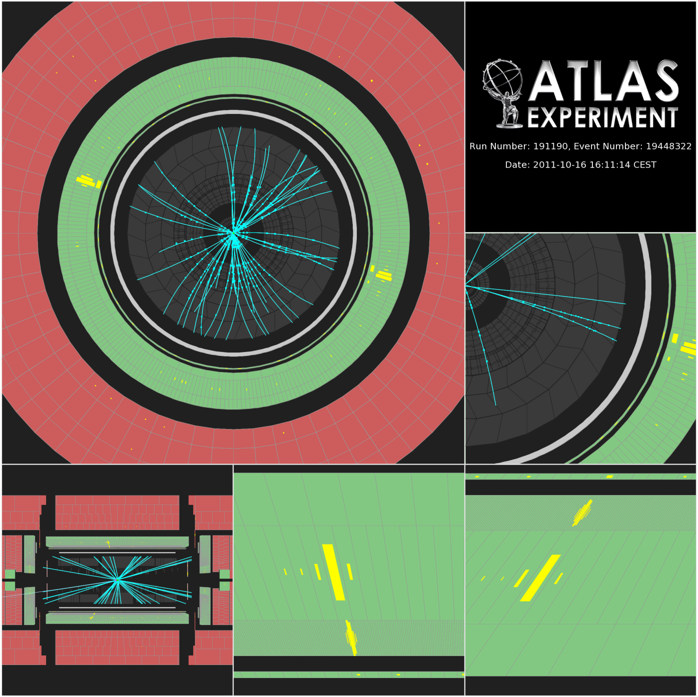
Higgs Boson Decays into Gauge Bosons

Channel	m_H range (GeV)	$\int \mathcal{L}$ (fb^{-1})	Reference
$H \to \gamma\gamma$	$110 - 150$	4.9	arXiv:1202.1414
$H \to ZZ \to 4l$	$110 - 600$	4.8	arXiv:1202.1415
$H \to ZZ \to ll\nu\nu$	$200 - 600$	4.7	CONF-2012-016
$H \to ZZ \to llqq$	$200 - 500$	4.7	CONF-2012-017
$H \to WW \to l\nu l\nu$	$110 - 600$	4.7	CONF-2012-012
$H \to WW \to l\nu qq$	$300 - 600$	4.7	CONF-2012-018

- A mass resonance search for $H \to \gamma\gamma$, $H \to ZZ \to 4l$
- A counting experiment for final states with neutrinos
- Limited mass resolution for final states with jets

Statistical procedure:

- Profile likelihood ratio to test signal strength $\mu = \sigma/\sigma_{SM}$ (Eur.Phys.J.C71:1554,2011)
- Exclusion limits on μ are set at a 95% confidence level with the CLs method (J. Phys. G 28 (2002) 2693-2704)
- Look Elsewhere Effect for resonance searches (Eur.Phys.J.C70:525,2010)



$H \to \gamma\gamma$

$\sigma \approx 40\ fb$

$\approx$ 70 signal events expected in 4.9 fb^{-1}

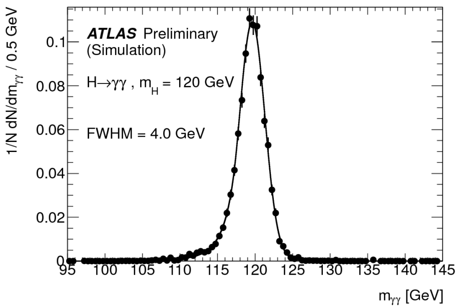
ggF: 87%
VBF: 7%
W/ZH: 5%

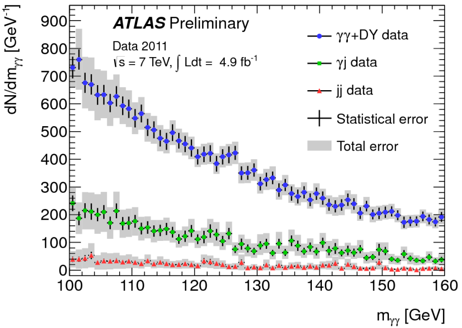
$m^2_{\gamma\gamma} = 2E_1E_2(1 - cos\alpha)$

$H \to \gamma\gamma$: analysis strategy

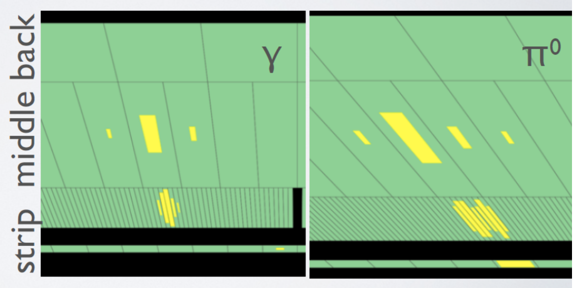
- Two isolated photons with $p_T > 40, 25$ GeV
- Search for a narrow mass peak in di-photon mass spectrum
- Requires excellent EM energy resolution
- Split events in 9 categories to optimize signal/background
- Irreducible SM backgrounds are fitted from sidebands
  - Background composition measured from data (for cross-checks)

$\gamma\gamma$	$j\gamma$	jj	Z/γ^*
$71 \pm 5\%$	$23 \pm 4\%$	$5 \pm 3\%$	$0.7 \pm 0.1\%$



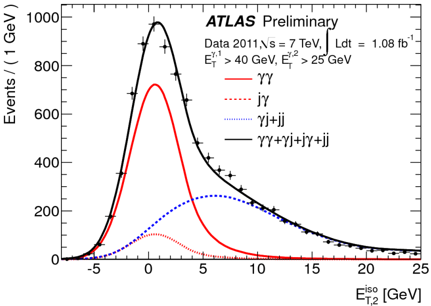


$H \to \gamma\gamma$: photon identification and isolation



- Fine η granularity in the strip layer to reject π^0
- EM shower shape to reject fake photons from jets
  $\approx O(8000)$ jet rejection
  85% photon efficiency
- Longitudinal segmentation to measure shower direction and to improve energy measurement

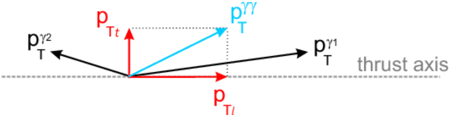
- Select isolated photons
- Excellent description of data by MC (cross-check)
- Uncertainty on event normalization from the isolation cut is 5%

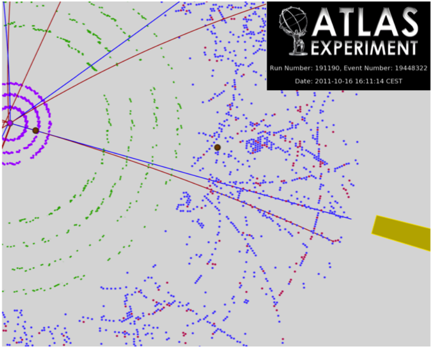


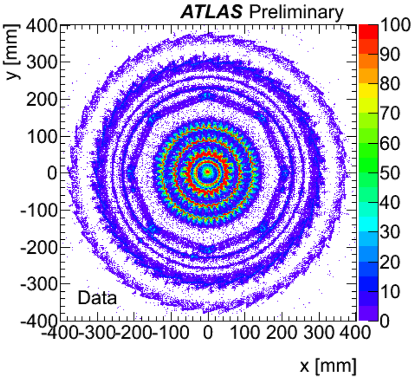
$H \to \gamma\gamma$: analysis categories

9 photon categories:

- Converted and unconverted
- Central, transition region and rest
- High and low $p_T(\gamma\gamma)$ orthogonal to the thrust axis divided at 40 GeV







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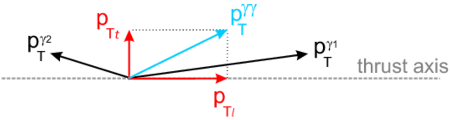
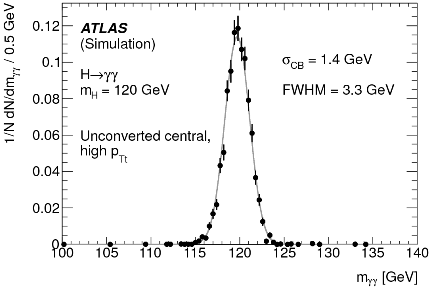
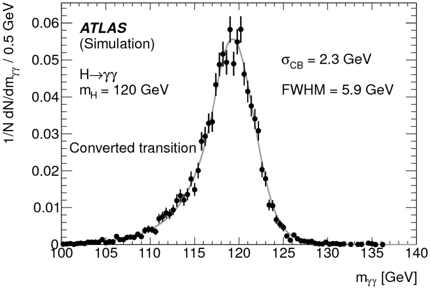


Best: $\sigma = 1.4$ GeV, S/B=0.11



Worst: $\sigma = 2.3$ GeV, S/B=0.01



$H \to \gamma\gamma$: systematic uncertainties

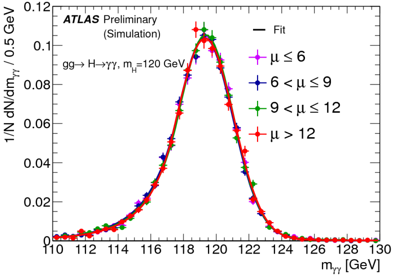
Event yield:

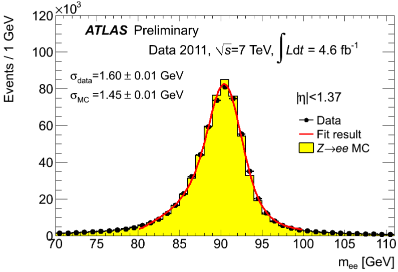
Efficiency	$\pm 11\%$
Pileup effects	$\pm 4\%$
Isolation	$\pm 5\%$
Trigger efficiency	$\pm 1\%$
Cross-section	$+15\% \quad -11\%$
Higgs p_T modeling	$\pm 1\%$
Total	$\approx 20\%$

Mass resolution:

Calorimeter energy resolution	$\pm 12\%$
Photon energy calibration	$\pm 6\%$
Pileup effect	$\pm 3\%$
Photon angle	$\pm 1\%$
Total	$\approx 14\%$

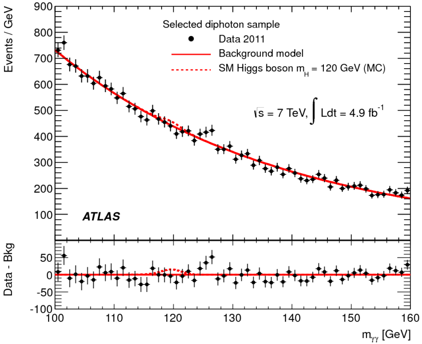
- Energy scale known to $\approx 0.5\%$ at m_Z
- Linear response at $< 1\%$
- Electron response in data is transferred to photons with MC

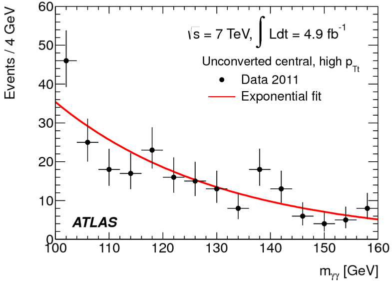


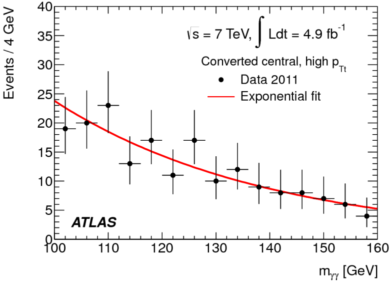


$H \to \gamma\gamma$

- Selected 22489 events
- $m_H = 125$ GeV:
  - Expect 69 signal events
  - Signal efficiency 35% for
- Fit signal with Crystal Ball + Gaussian
- Fit background with exponential
- Background modeling $\pm 0.1 - 7.9$ events depending on category



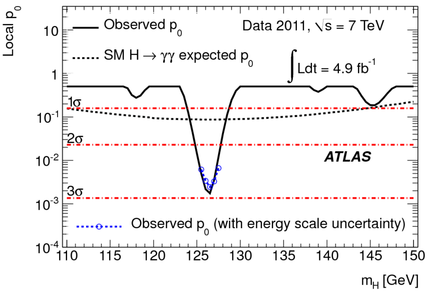




$H \to \gamma\gamma$: results

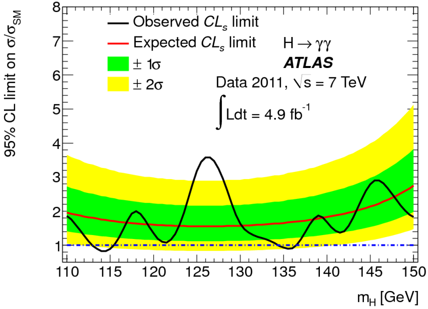
Consistency of observed data with background only hypothesis:

- The largest excess is at 126.5 GeV with local significance of 2.8 σ
- 1.5 σ with look-elsewhere effect in the range 110-150 GeV

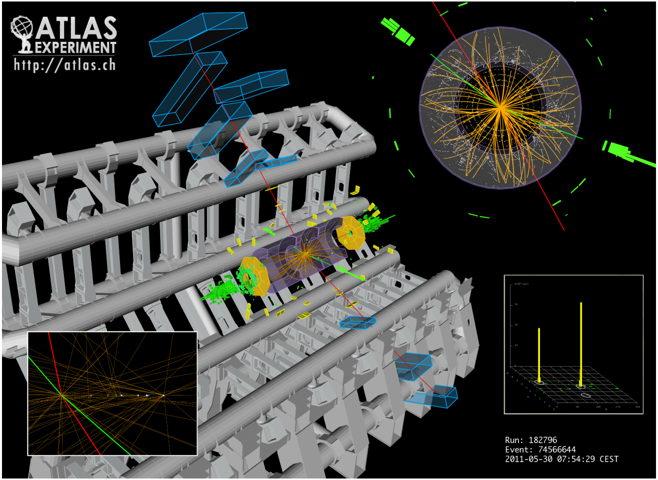


Exclusion limits:

- SM Higgs excluded at 95% confidence level in the ranges 113-115 GeV and 134.5-136 GeV
- Effect from the energy scale uncertainty on the Higgs mass is $\approx$ 0.7 GeV



$H \rightarrow ZZ \rightarrow 4l$



$m_H = 130\ GeV$:

$\sigma \approx 3\ fb$

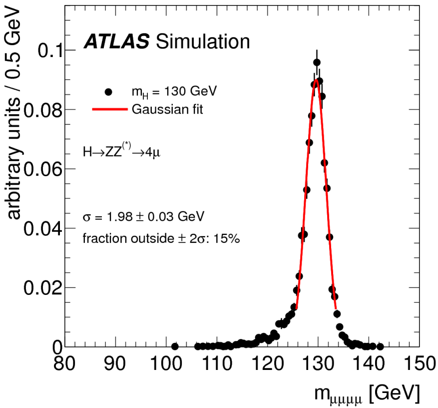
$\approx$ 2.6 signal events expected in 4.9 fb^{-1}

ggF: 88%
VBF: 7%
W/ZH: 5%

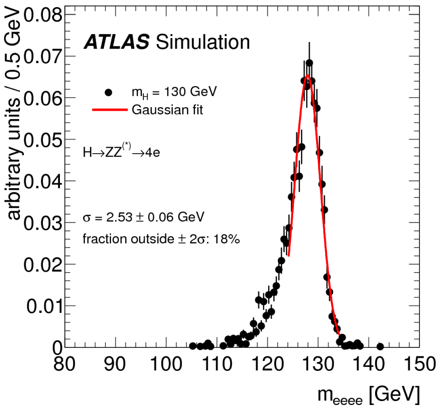
$H \to ZZ \to 4l$: analysis strategy

- Four isolated electrons or muons with $p_T > 20, 20, 7, 7$ GeV
- One pair of leptons must come from Z decay
- Search for a narrow mass resonance
- 4 event categories: $4e$, $2e2\mu$, 4μ
- Irreducible SM ZZ^* background
- Reducible Z+jets and $t\bar{t}$ backgrounds

4μ : $\sigma = 2.0$ GeV

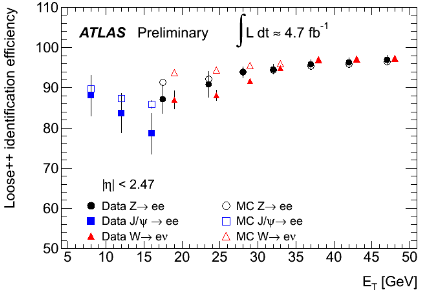


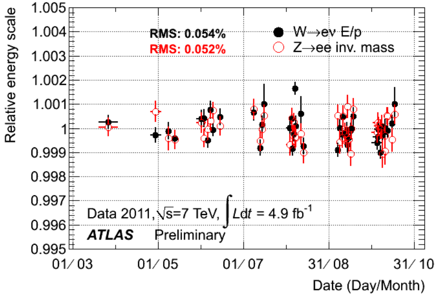
$4e$: $\sigma = 2.5$ GeV



Electrons

- Electron reconstruction and identification efficiency 85 – 90%
- Understand electron performance with benchmark data processes: $J/\psi \to ee$, $Z \to ee$ and $W \to e\nu$
- Track and calorimeter based isolation



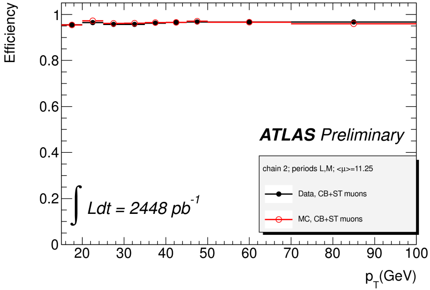


Systematic uncertainties:

- Efficiency: $< 3\%$
- Energy scale: $< 1\%$
- Energy resolution: $< 0.5\%$

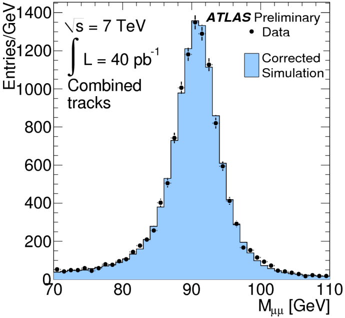
Muons

- Muon reconstruction and identification efficiency $> 95\%$
- Accurate alignment of inner detector and muon system (MS)
- Combined momentum measurement using ID and MS
- ID only momentum measurement for MS segments
- Track and calorimeter based isolation



Systematic uncertainty:

- Efficiency: $< 1\%$
- Momentum resolution: $< 1\%$

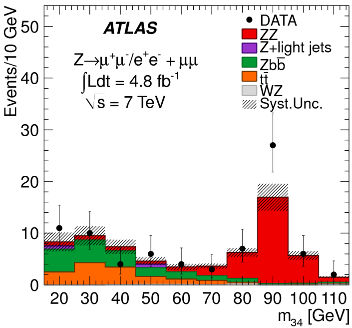


$H \to ZZ \to 4l$: backgrounds

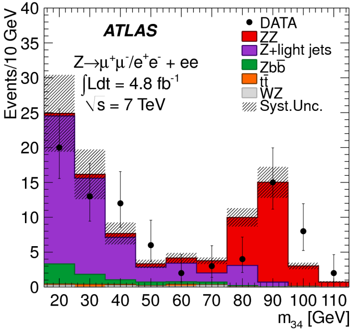
- Normalize $ZZ^{(*)}$ from MC
- Normalize reducible backgrounds from control regions
  - Z+jets background - relax lepton selection cuts
  - $t\bar{t}$ - $e\mu$ channel

		4μ	$2e2\mu$	$4e$
$ZZ^{(*)}$	$m_{4l} < 180$ GeV	2.1 ± 0.3	2.8 ± 0.6	1.2 ± 0.3
$Z + jet$ and $t\bar{t}$	$m_{4l} < 180$ GeV	0.16 ± 0.06	1.4 ± 0.5	1.6 ± 0.7
$ZZ^{(*)}$	$m_{4l} > 180$ GeV	16.3 ± 3.4	25.2 ± 3.8	10.4 ± 1.5
$Z + jet$ and $t\bar{t}$	$m_{4l} > 180$ GeV	0.02 ± 0.01	0.17 ± 0.08	0.18 ± 0.08

Relax impact parameter for $Z + \mu\mu$



Relax isolation cut for $Z + ee$

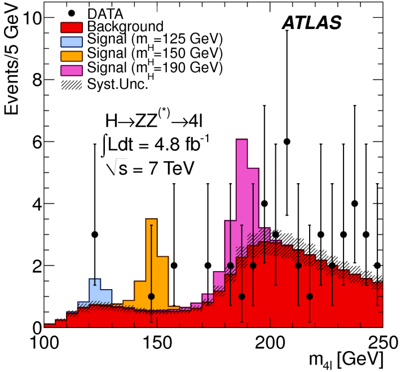


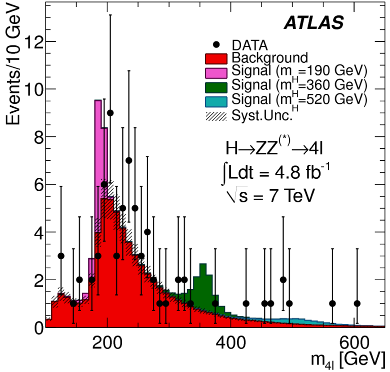
$H \to ZZ \to 4l$: four-lepton invariant mass

- Selected 71 candidate events
- Expect 62 ± 9 background events
- Fit four-lepton mass spectrum for Higgs signal

$m_{4l} < 180$ GeV:

	4μ	$2e2\mu$	$4e$
Total Bkg.	2.2 ± 0.3	4.3 ± 0.8	2.8 ± 0.8
$m_H = 130$ GeV	1.00 ± 0.17	1.22 ± 0.21	0.43 ± 0.08
Data	3	3	2





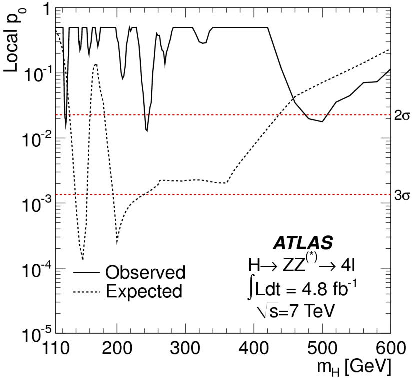
$H \to ZZ \to 4l$: results

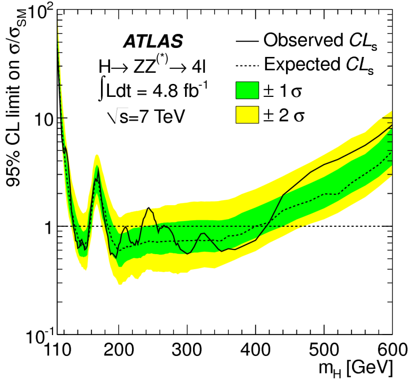
Consistency of observed data with background only hypothesis:

- Excesses at 125 GeV, 244 GeV and 500 GeV with local significances of 2.1, 2.2 and 2.1 σ
- None of these excesses is significant with the look-elsewhere effect included

Exclusion limits:

- SM Higgs is excluded in the mass ranges 134-156 GeV, 182-233 GeV, 256-265 GeV and 268-415 GeV at the 95% confidence level





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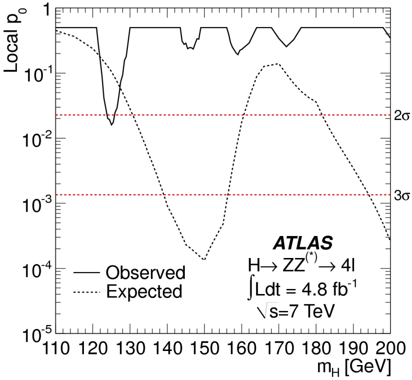
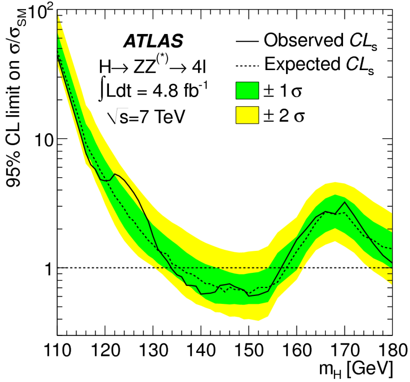
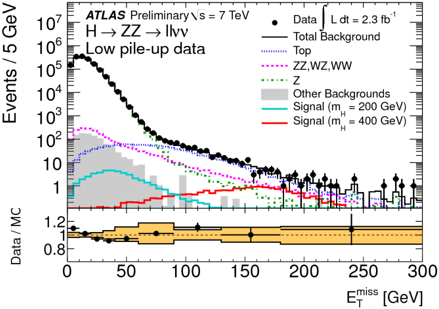




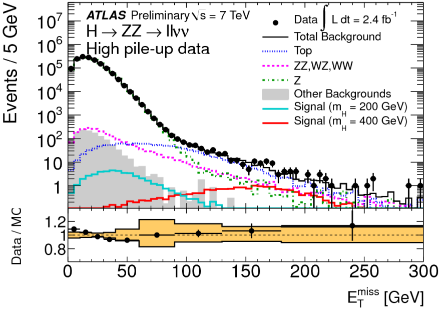
$H \to ZZ \to ll\nu\nu$: analysis strategy

- Pair of isolated electrons or muons consistent with Z decay
- Require lepton $p_T > 20$ GeV and significant missing transverse energy
- Several analysis categories to improve signal sensitivity
- Control regions for main backgrounds
  - Top, di-bosons, Z+jets/W+jets
- Search for an excess of events in transverse mass distribution

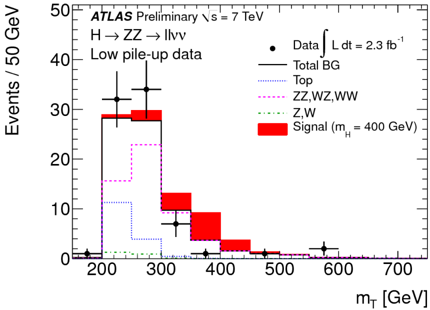
Lower pileup

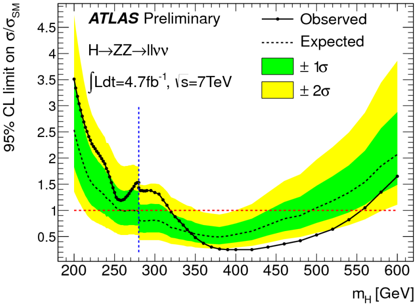


Higher pileup



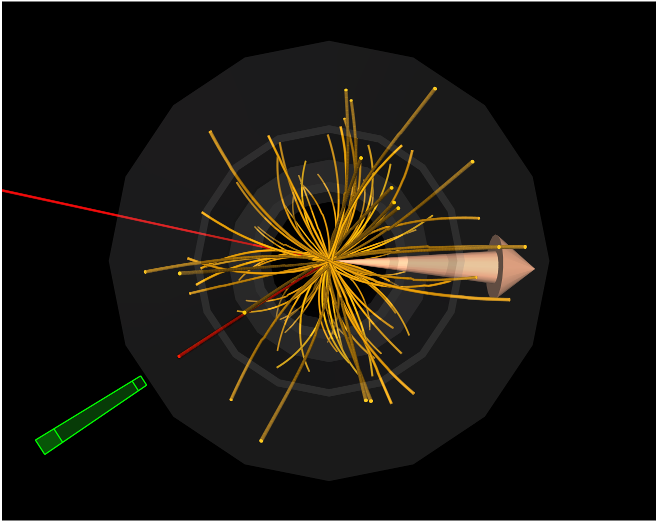
$H \to ZZ \to ll\nu\nu$: results





- Search for an excess of events in transverse mass distribution
- Split the analysis at $m_H = 280$ GeV
- SM Higgs is excluded in the mass range 320-560 GeV at the 95% confidence level
- Main uncertainties are from background normalizations which are estimated from data

$H \rightarrow WW \rightarrow l\nu l\nu$



$m_H = 125\ GeV$:

$\sigma \approx 100\ fb$

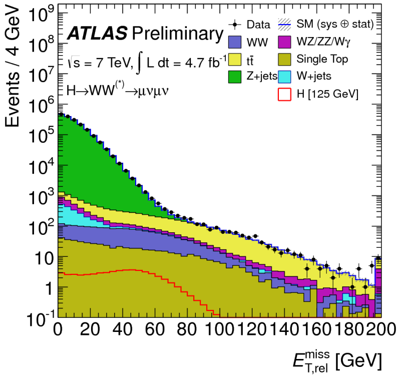
≈ 181 signal events expected in $4.9\ fb^{-1}$

A larger rate but difficult and diverse backgrounds

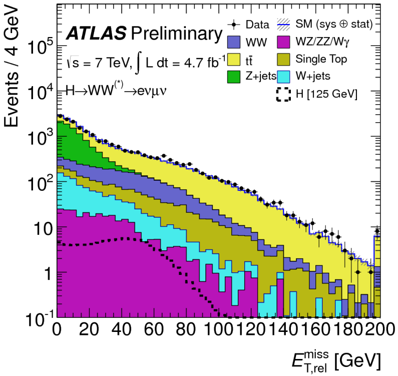
$H \to WW \to l\nu l\nu$: analysis strategy

- Pair of isolated opposite sign leptons ($p_T > 25, 15$ GeV)
- Veto Z with mass window $|m_{ll} - m_Z| < 15$ GeV for $ee, \mu\mu$
- Three lepton flavor channels plus jet multiplicity bins:
  - ee, $e\mu$ and $\mu\mu$
  - $E^{rel}_{T,miss} > 45\ GeV (25\ GeV)$ for ee and $\mu\mu$ ($e\mu$)
- Irreducible background from SM WW
- Reducible backgrounds from SM processes with mis-identified objects: W+jets, Z+jets, $t\bar{t}$, single top, $W + \gamma$, $W + \gamma^*$, WZ, ZZ

$\mu\mu$



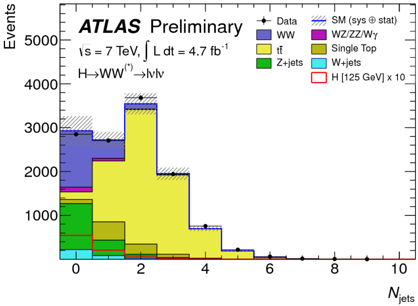
$e\mu$



$H \to WW \to l\nu l\nu$: jet multiplicity

Split by jet multiplicity:

- 0-jet: ggF vs. SM WW
  $\pm 25\%$ for $\sigma_{ggF}(m_H = 125\ GeV))$
- 1-jet: ggF vs. SM WW and top
  $\pm 37\%$ for $\sigma_{ggF}(m_H = 125\ GeV))$
- 2-jet: VBF vs. SM WW and top
  $\pm 5\%$ for $\sigma_{VBF}(m_H = 125\ GeV))$

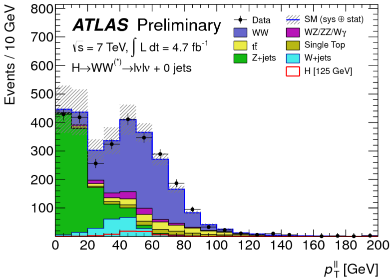


Main detector uncertainties:

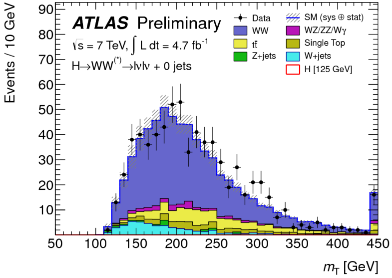
- Jet energy scale: $2 - 14\%$ as a function of jet p_T and η
- Jet energy from pileup: $< 5\%$ for jet $p_T > 25$ GeV
- B-tagging: $5 - 14\%$ as a function of jet p_T
- Missing energy: estimated by varying amount of pileup

$H \to WW \to l\nu l\nu$: selections

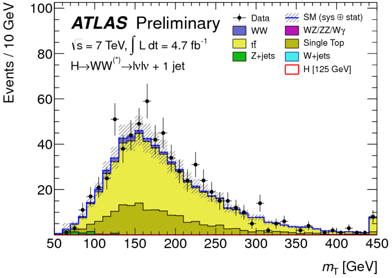
- 0-jet: $p_{T,\mu\mu,ee} > 45$ GeV to suppress Z+jet
- 1-jet: veto events with b-jets and high p_T^{total}
- Kinematic cuts to reduce SM WW
- SM WW normalized from data for $m_H < 200$ GeV
- Top normalized from data b-tagged samples
- W+jet is taken fully from data
- Z/γ^*+jet normalized from data
- $W\gamma$, $W\gamma^*$, WZ and ZZ from MC



0-jet WW control region

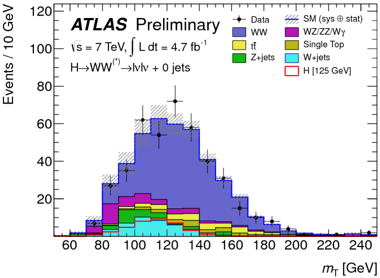


1-jet top control region



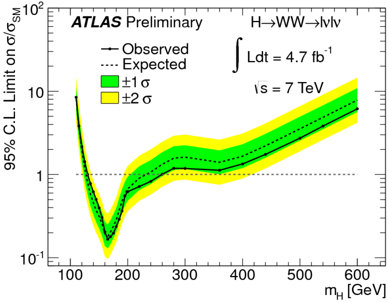
$H \to WW \to l\nu l\nu$: results

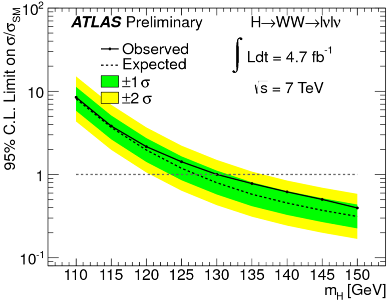
- Fit transverse mass distribution
- SM Higgs boson is excluded in the range 130-260 GeV at the 95% confidence level



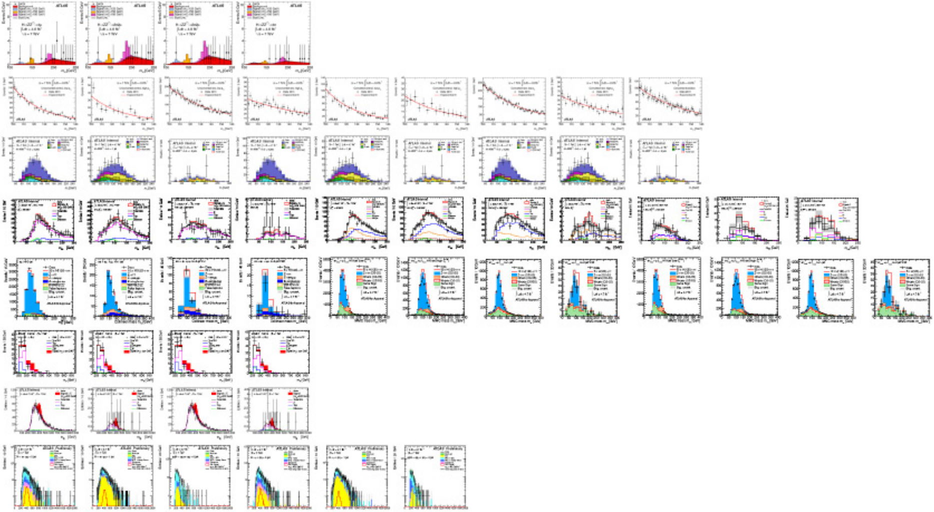
Stat only errors:

	0-jet	1-jet	2-jet
$m_H = 125\ GeV$	37.7 ± 0.3	9.4 ± 0.1	0.8 ± 0.1
Total Bkg.	429 ± 27	134 ± 13	1.8 ± 0.4
Obs.	174	56	0



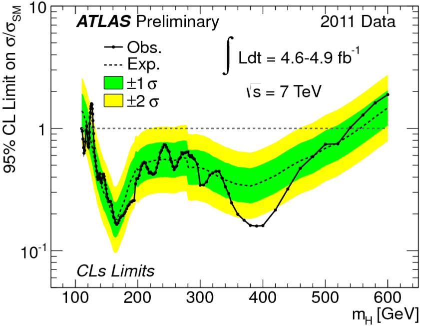


SM Higgs combination

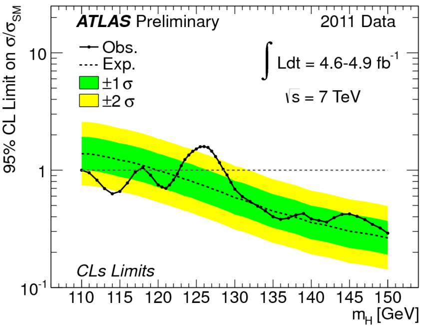


SM Higgs combination

Combined upper limits



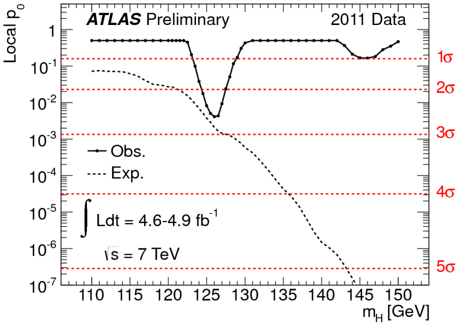
Zoom at the low mass



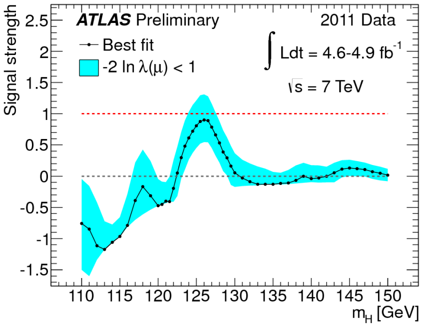
- SM Higgs boson is excluded in the ranges: 110-117.5, 118.5-122.5, 129-539 GeV at the 95% CL
- The combination includes additional channels: $H \to \tau\tau$, $H \to bb$, $H \to WW \to l\nu qq$, $H \to ZZ \to llqq$

SM Higgs combination

Background-only probability



Best-fit signal strength $\mu = \sigma/\sigma_{SM}$

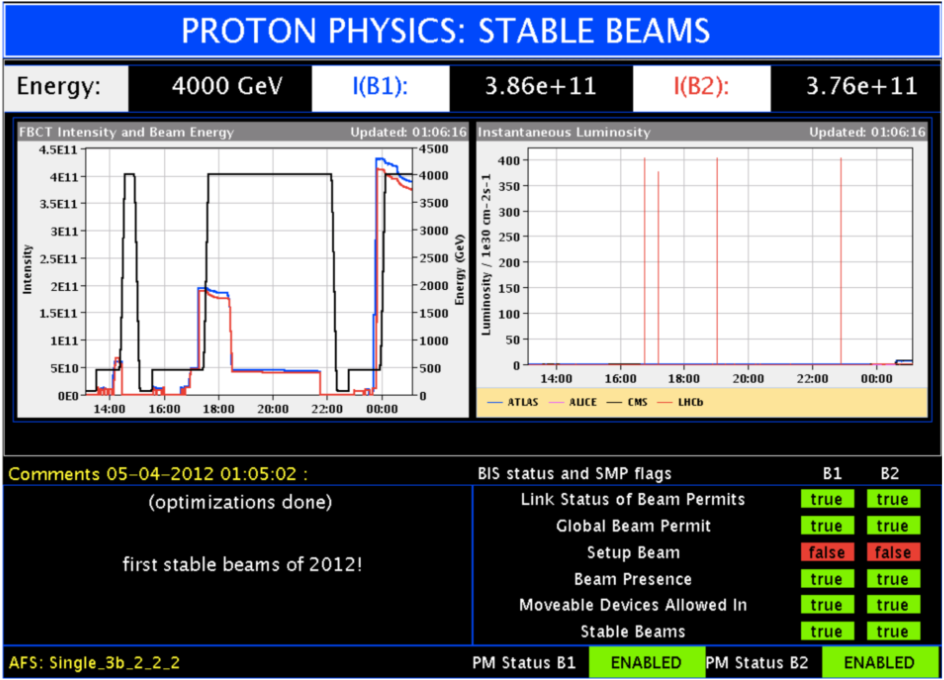


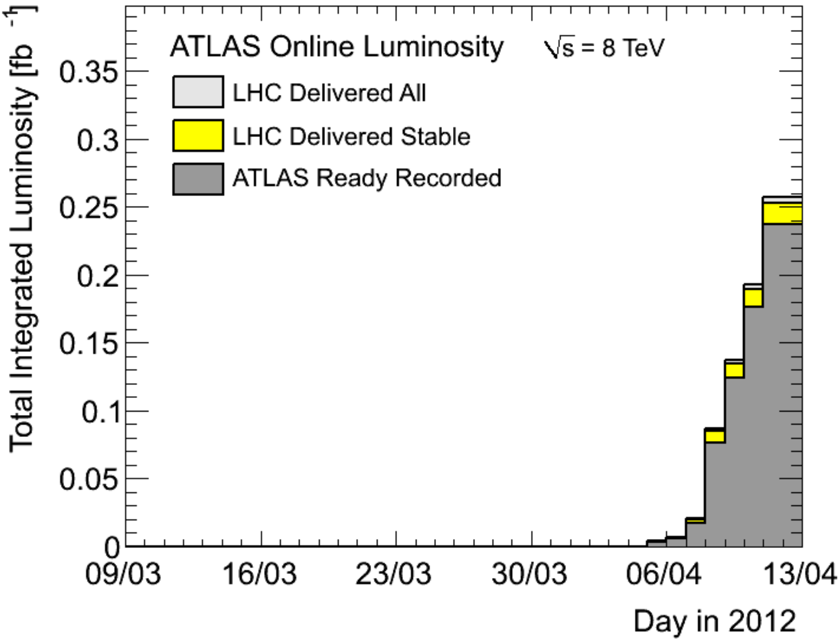
- An excess of events at $m_H \approx 126.5$ with a local significance 2.5 σ

  Expected significance for SM Higgs 2.9 σ

  Best-fit signal strength $\mu = 0.9 + 0.4 - 0.3$

- Global probability for such background fluctuation:
  $\approx$ 30% in the range 110 – 600 GeV
  $\approx$ 10% in the range 110 – 146 GeV


PROTON PHYSICS: STABLE BEAMS
Energy:
4000 GeV
I(B1):
3.86e+11
I(B2):
3.76e+11
FBCT Intensity and Beam Energy
Updated: 01:06:16
Intensity
Energy (GeV)
4.5E11
4E11
3.5E11
3E11
2.5E11
2E11
1.5E11
1E11
5E10
0E0
4500
4000
3500
3000
2500
2000
1500
1000
500
0
14:00
16:00
18:00
20:00
22:00
00:00
Instantaneous Luminosity
Updated: 01:06:16
Luminosity / 1e30 cm-2s-1
400
350
300
250
200
150
100
50
0
14:00
16:00
18:00
20:00
22:00
00:00
ATLAS
ALICE
CMS
LHCb
Comments 05-04-2012 01:05:02 :
(optimizations done)
first stable beams of 2012!
BIS status and SMP flags
B1
B2
Link Status of Beam Permits
true
true
Global Beam Permit
true
true
Setup Beam
false
false
Beam Presence
true
true
Moveable Devices Allowed In
true
true
Stable Beams
true
true
AFS: Single_3b_2_2_2
PM Status B1
ENABLED
PM Status B2
ENABLED



ATLAS Online Luminosity
$\sqrt{s}$ = 8 TeV
LHC Delivered All
LHC Delivered Stable
ATLAS Ready Recorded
Total Integrated Luminosity [fb^{-1}]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
09/03
16/03
23/03
30/03
06/04
13/04
Day in 2012

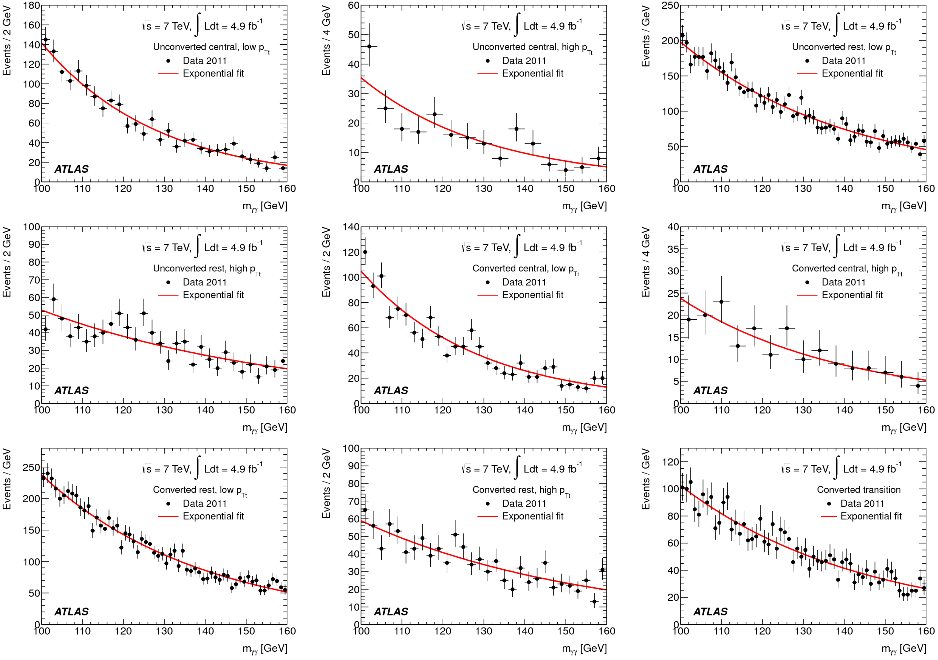
Conclusions and outlook

Congratulations to CERN for the fantastic LHC performance!

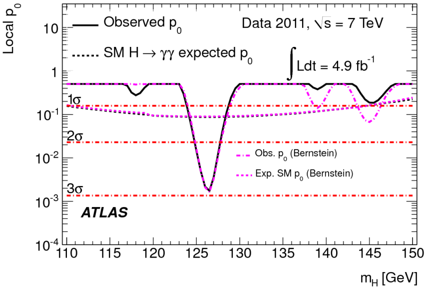
- ATLAS released SM Higgs boson searches in 12 distinct channels using full 2011 dataset
- Allowed Higgs mass is the ranges 117.5-118.5 GeV and 122.5-129 GeV at the 95% CL
- Observed an excess of events consistent with $m_H \approx 126.5$ GeV
- This year we will know if this is the SM Higgs boson!

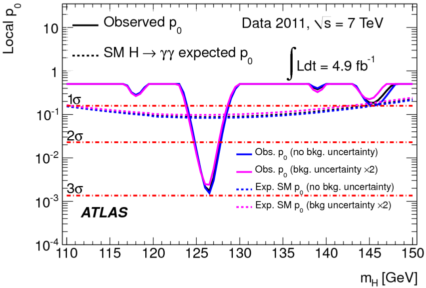
Backup

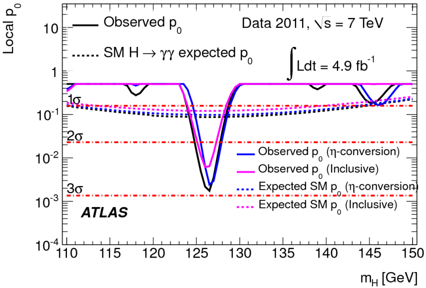
$H \to \gamma\gamma$

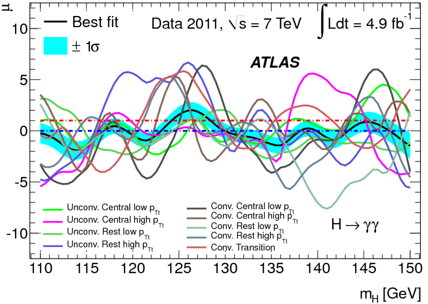


$H \to \gamma\gamma$



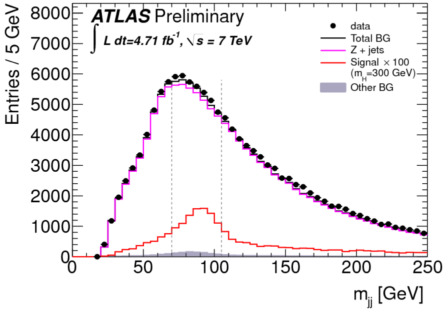


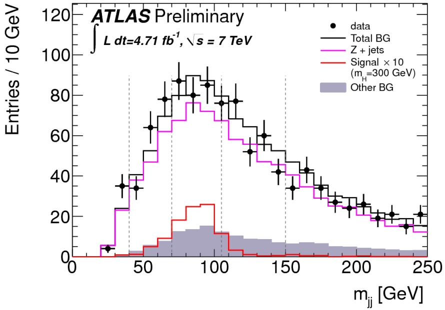




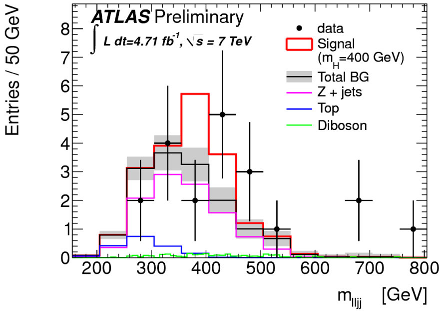
$H \to ZZ \to llqq$

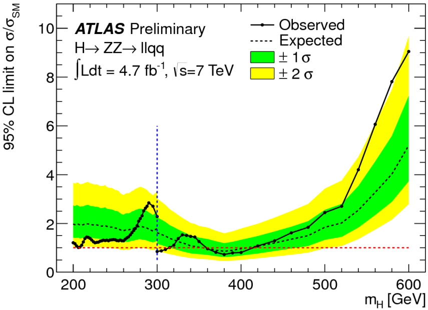
- Pair of isolated electrons or muons ($p_T > 20$ GeV) consistent with Z decay
- Two central jets from the same vertex as leptons
- Separate light jets and b-jets to improve signal sensitivity
- Z+jet and $t\bar{t}$ background shapes taken from MC and checked with data
- Z+jet and $t\bar{t}$ normalizations taken from sidebands





$H \to ZZ \to llqq$: results

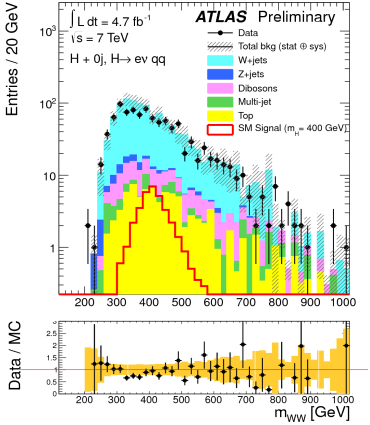


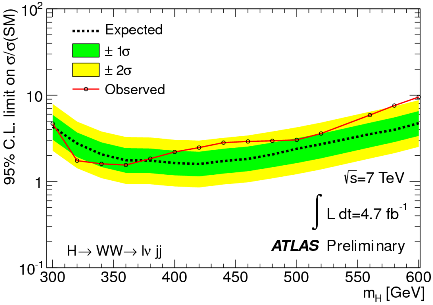


- Search for an excess of events using invariant mass distribution of two leptons and two jets
- Split the analysis at $m_H = 300$ GeV
- SM Higgs boson is excluded in the ranges 300-310 GeV and 360-400 GeV at the 95% confidence level

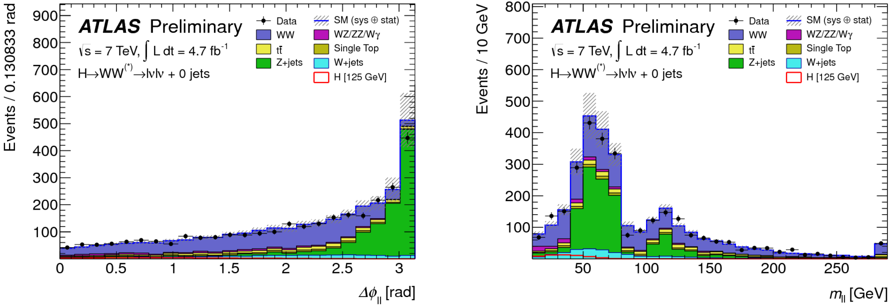
$H \to WW \to l\nu qq$

- Exactly one isolated electron or muon with $p_T > 40$ GeV
- Two central jets consistent with W decay
- Separate events by multiplicity of additional jets (ggF vs VBF)
- Search for an excess in event invariant mass distribution
- SM backgrounds are fitted from sidebands
- Approaching SM Higgs sensitivity



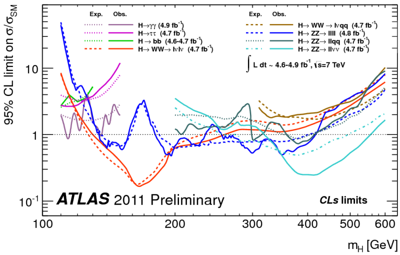


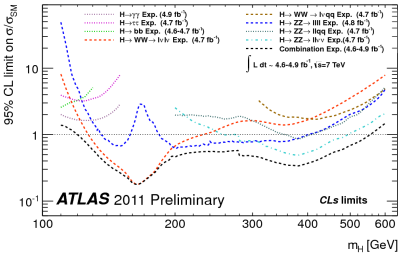
$H \to WW \to l\nu l\nu$: topological selections

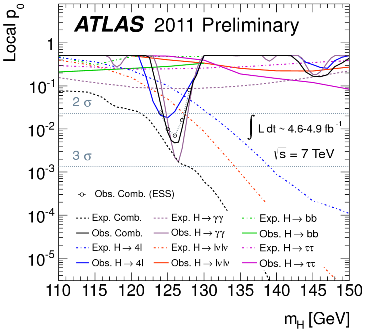


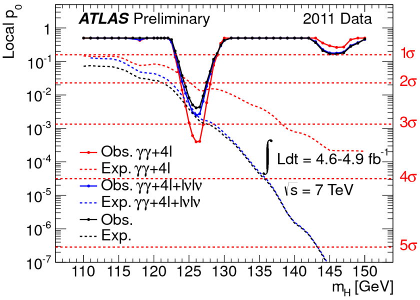
- Require small opening between two leptons for low mass Higgs
- Apply di-lepton invariant mass cut for low mass Higgs

Combination









Combination