Sandra Kortner
on behalf of the ATLAS Collaboration

SM Scalar Boson search with the ATLAS detector

Recontres de Moriond EW • March 3rd - 10th, 2012

Max-Planck-Institut für Physik
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Latest Scalar (H) Boson searches with ATLAS

Searches performend in 12 distinct channels using the full 2011 dataset.

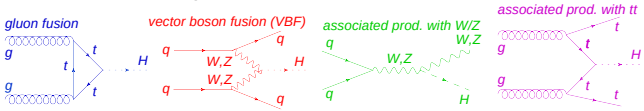
Channel	m_H range (GeV)	Backgrounds	$\mathcal{L}$ (fb^{-1})	Reference
low-m_H, good mass resolution				
$H \to \gamma\gamma$	110-150	$\gamma\gamma$, γj, jj	4.9	arXiv:1202.1414
$H \to ZZ^{(*)} \to 4\ell$	110-600	$ZZ^{(*)}$, $Z + jets$, $t\bar{t}$	4.8	arXiv:1202.1415
low-m_H, limited mass resolution				
$H \to WW^{(*)} \to \ell\nu\ell\nu$	110-600	WW, $t\bar{t}$, $W/Z + jet$	4.7	CONF-2012-012
$H \to \tau\tau(ll, lh, hh)$	100-150	$Z \to \tau\tau$, $t\bar{t}$	4.7	CONF-2012-014
$VH, H \to bb$	110-130	$W/Z + jets$, $t\bar{t}$	4.7	CONF-2012-015
high-m_H				
$H \to ZZ \to \ell\ell\nu\nu$	200-600	$diboson$, $t\bar{t}$, $Z + jets$	4.7	CONF-2012-016
$H \to ZZ \to \ell\ell jj$	200-600	$Z + jets$, $t\bar{t}$, $diboson$	4.7	CONF-2012-017
$H \to WW \to \ell\nu jj$	300-600	$W + jets$, $t\bar{t}$, multijets	4.7	CONF-2012-018

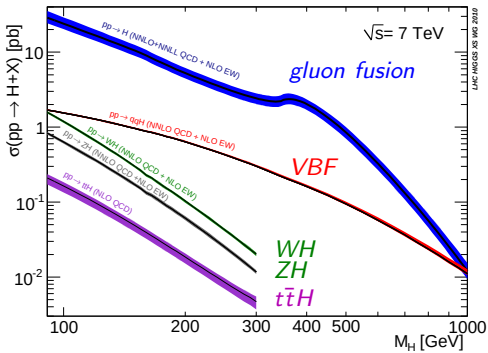
Limit setting:

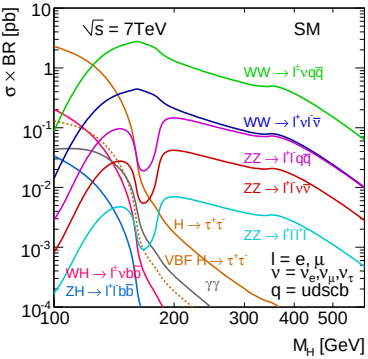
- Profile likelihood ratio is used to test the hypothesized signal strength $\mu = \sigma/\sigma_{SM}$ (Eur.Phys.J.C71:1554,2011).
- Exclusion limits on μ are set at a 95% confidence level using the CL_s method (J. Phys. G 28 (2002) 2693-2704).

Scalar boson production and decays

Cross-sections, br. ratios, theory uncertainties: arXiV:1101.0593 & arXiv:1201.3084







Typical size of uncertainties (exact values depend on M_H):

	ggF	VBF	WH/ZH	$t\bar{t}H$
QCD scale:	$^{+12\%}_{-8\%}$	$\pm1\%$	$\pm1\%$	$^{+3\%}_{-9\%}$
PDF + α_s:	$\pm8\%$	$\pm4\%$	$\pm4\%$	$\pm8\%$

Mass line shape: $(150\%) \times \left(\frac{M_H}{TeV}\right)^3$

POWHEG+PYTHIA for ggF(*) & VBF;

(*) Scalar boson p_T reweighted to HqT (v2.0) predictions.

PYTHIA for WH/ZH & $t\bar{t}H$.

Detector-related systematic uncertainties

Physics object	Source	Uncertainty on signal yield	Most affected channels
	luminosity	3.9%	
Photon	efficiency	11%	$\gamma\gamma$
Electron	efficiency	<3%	4ℓ
	energy scale	<1%	
	energy resolution	<0.5%	
Muon	efficiency	<1%	4ℓ
	momentum resolution	<1%	
Jet	energy scale	up to 12%	$\tau\tau$, $b\bar{b}$, $\ell\ell jj$, $\ell\nu jj$
	resolution	up to 20%	$\ell\nu jj$
b-tagging	efficiency	up to 15%	$b\bar{b}$
τ-jet	efficiency	up to 8%	$\tau\tau$

- Similar uncertainties also for the simulated backgrounds.
- Many background contributions are determined directly from data, by means of signal-free, background-enriched control data samples.
- Otherwise, event generators used:
  - $W/Z + jets$: `ALPGEN` (heavy flavor also with `POWHEG` or `SHERPA`)
  - $t\bar{t}$, single top: `MC@NLO`, `AcerMC`
  - Dibosons: `MC@NLO`, `SHERPA`, `PYTHIA`

Searches in the high-m_H region (200-600 GeV)

$H \to ZZ \to \ell\ell\nu\nu$

- m_H = 200 - 600 GeV.
- 4 sub-channels: (ee,$\mu\mu$)$\otimes$ (low-, high-pileup).
- $|m_Z - m_{\ell\ell}|$ <15 GeV.
- Different selections for m_H <280 GeV & m_H ≥280 GeV.
- Cuts on E_T^{miss}, $\Delta\phi_{\ell\ell}$, $\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{jet})$; $\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{\ell\ell})$
- m_T distribution for the limit setting.

$H \to ZZ \to \ell\ell jj$

- m_H = 200 - 600 GeV.
- 2 sub-channels: (untag, b-tag)
- 83 < $m_{\ell\ell}$ <99 GeV, 70 < m_{jj} <105 GeV.
- Cuts on E_T^{miss}, ΔR_{jj}.
- For m_H ≥300 GeV: $\Delta\phi_{\ell\ell}, \Delta\phi_{jj} < \pi/2$.
- ,,Untagged" channel: <2 b-tagged jets.
- ,,Tagged" channel: =2 b-tagged jets.
- $m_{\ell\ell jj}$ distribution for the limit setting.

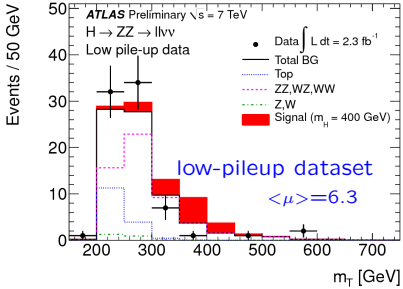
$H \to WW \to \ell\nu jj$

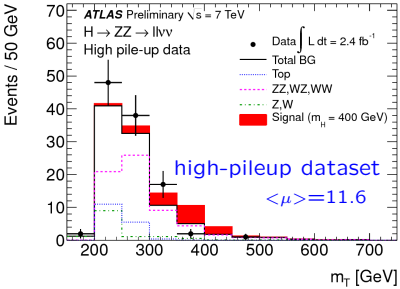
- m_H = 300 - 600 GeV.
- 6 sub-channels: (e, μ)$\otimes$(0-, 1-jet, VBF).
- 71 < m_{jj} <91 GeV.
- Cut on E_T^{miss}.
- Mass constraint: $m_{\ell\nu} = m_W$.
- For $H + 2jets$ (VBF): $\Delta\eta_{jj}$, m_{jj}, no central jets.
- $m_{\ell\nu jj}$ distribution for the limit setting.

$H \to ZZ \to \ell\ell\nu\nu$

Most sensitive channel in the high mass range.

Results based on shape of the transverse mass m_T. $\Rightarrow$ Pile-up dependent due to E_T^{miss} .





ZZ: simulation (11% norm. uncert.)

WZ: 3-lepton events.

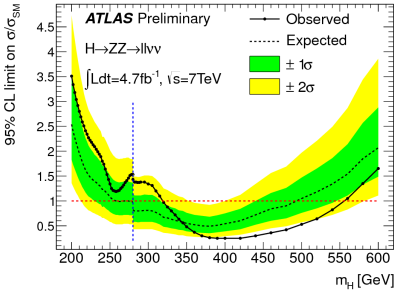
top: simulation.

Verified in $e\mu$ data & $m_{\ell\ell}$ sidebands.

$W + jet$: like-sign ee, $e\mu$.

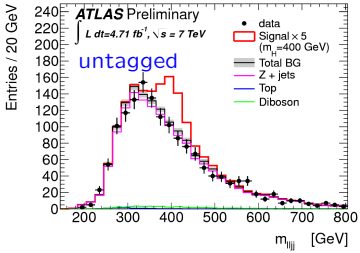
$Z + jet$: low $\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{jet})$.

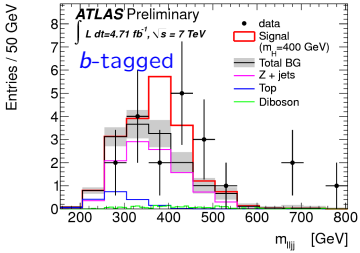
- Expected exclusion: 260-490 GeV.
- Observed exclusion: 320-560 GeV.

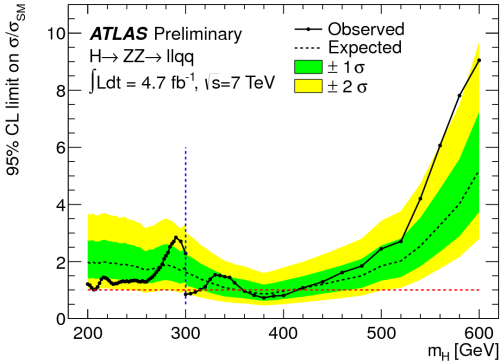


$H \to ZZ \to \ell\ell jj$

Z + jets: normalized by m_{jj}-sidebands. Shape from the simulation. (1-5% uncertainty)
top quark: normalized by $m_{\ell\ell}$-sidebands. Shape from the simulation. (3-4% uncertainty)
Diboson: from the simulation. (11% uncertainty)
Multijets: reverted electron-ID criteria. (50% uncertainty)



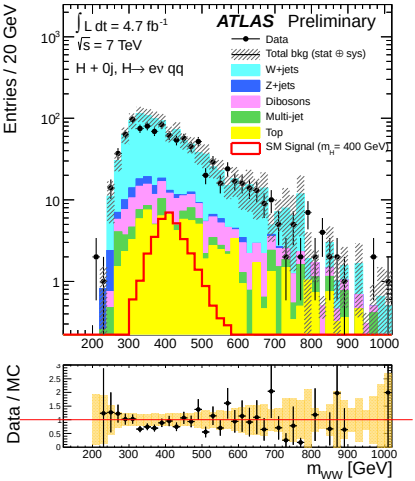


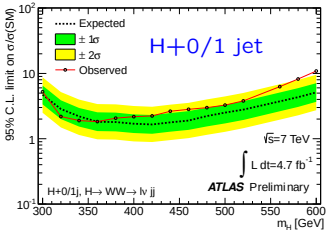


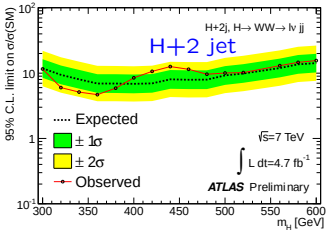
- Expected exclusion: 360-400 GeV.
- Observed excl.: 300-310, 360-400GeV.

$H \to WW \to \ell\nu jj$

- Invariant mass reconstruction by means of the $m(\ell\nu) = m(W)$ mass constraint.
- Analysis divided into jet categories: 0, 1, 2(VBF) jets.
- Background modeled directly from the fit to the $\ell\nu jj$ mass spectrum.
- Major systematic uncertainty from jet energy scale and resolution (10%-20%), as well as pile-up (10%-15%).







Searches in the low-m_H region

$H \to ZZ^{(*)} \to 4\ell$

- m_H = 110 - 600 GeV.
- 4 sub-channels: ($4e$, $2e2\mu$, $2\mu 2e$, 4μ)
- $m_{4\ell}$ distribution for the limit setting.

$H \to \gamma\gamma$

- m_H = 110 - 150 GeV.
- 9 sub-categories: ($p_T^{thrust} \otimes \eta_\gamma \otimes$ conversion)
- $m_{\gamma\gamma}$ distribution for the limit setting.

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

- m_H = 110- 600 GeV.
- 9 sub-channels: (ee, $\mu\mu$, $e\mu$) $\otimes$ (0-,1-jet, VBF)
- m_T shape (window) for the limit setting in 0- & 1-jet (VBF) channel.

$VH,\ H \to b\bar{b}$

- m_H = 110 - 130 GeV.
- 11 sub-channels:
  - * $\ell\nu b\bar{b}$: 4 p_T^W bins
  - * $\ell\ell b\bar{b}$: 4 p_T^Z bins
  - * $\nu\nu b\bar{b}$: 3 E_T^{miss} bins
- m_{bb} distribution for the limit setting.

$H \to \tau\tau$

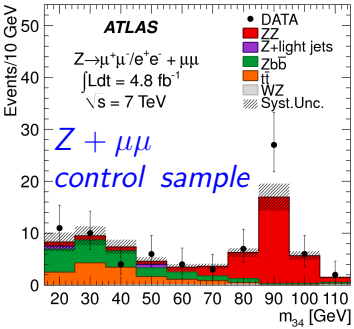
- m_H = 100 - 150 GeV.
- 12 sub-channels:
  - *$\ell\ell 4\nu$: (0-, 1-jet, VH, VBF)
  - *$\ell\tau_{had}3\nu$: VBF $\oplus$ $(e,\mu) \otimes$ (2×0-jet, 1-jet)
  - *$\tau_{had}\tau_{had}2\nu$: $\geq$1-jet
- m_{eff}, MMC or $m_{\tau\tau}$ for the limit setting.

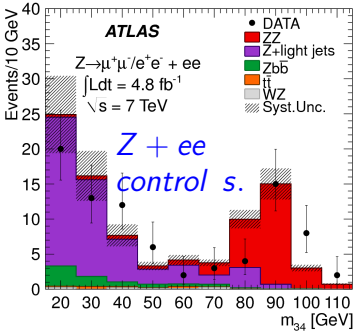
$H \to ZZ^{(*)} \to 4\ell$: The Golden

- High mass resolution (130 GeV: 1.5-2%). Above 350 GeV natural width dominates.
- High lepton reconstruction efficiency down to low p_T (7 GeV).
- Lepton performance well modeled by the simulation, independent of pileup.
- 0.2% - 2% uncertainty on the signal yield. 0.6% uncertainty on the m_{4e} scale.

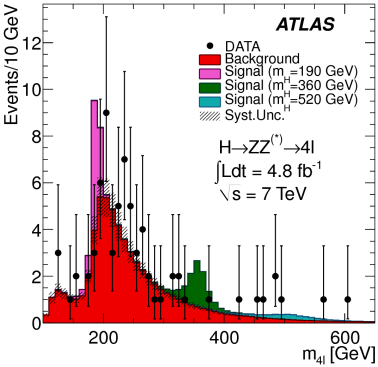
Background estimation:

- $ZZ^{(*)}$: from simulation. (QCD: 5%, PDF+α_s: 4-8%, 10% to account for $gg \to ZZ$)
- $Z + jets$: control region without charge, isolation and impact parameter criteria on the second lepton pair. (40-45% uncertainty)
- $t\bar{t}$: $e^{\pm}\mu^{\mp}$ pair consistent with m_Z and two additional same-flavor leptons.





$H \to ZZ^{(*)} \to 4\ell$: Results



Number of events in the full mass range:

	4μ	$2e2\mu$	$4e$
Expected	18.6±2.8	29.7±4.5	13.4±2.0
Observed	24	30	17

Small excesses observed around 3 mass values.

Local significance:

$m_{4\ell}$	125 GeV	244 GeV	500 GeV
Exp. w. signal	1.3σ	3.0σ	1.5σ
Observed	2.1σ	2.2σ	2.1σ

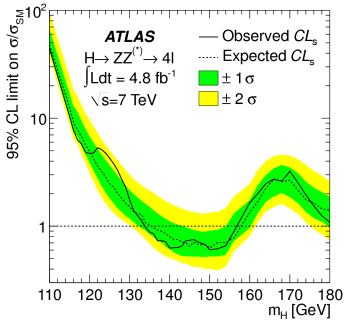
Expected limit:

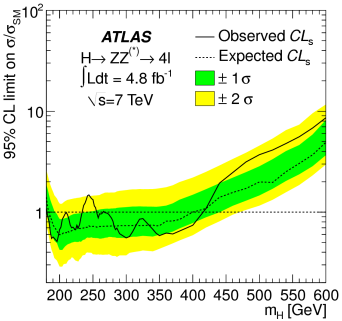
137-157, 184-400 GeV

Observed limit:

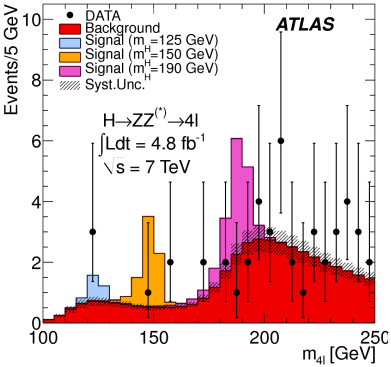
134-156, 182-233,

256-265, 268-415 GeV





$H \to ZZ^{(*)} \to 4\ell$: Results



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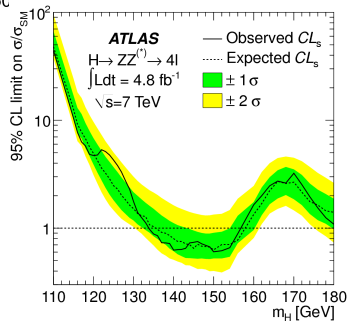
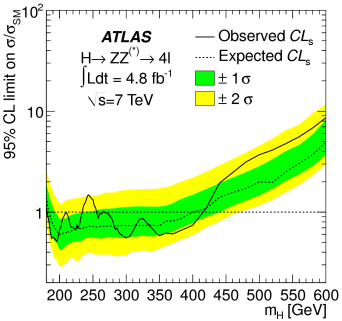


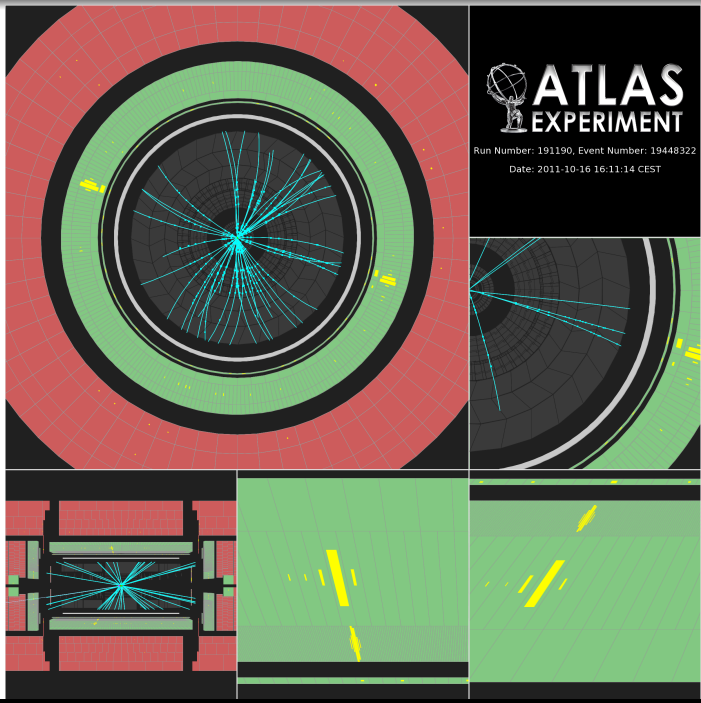


$H \to \gamma\gamma$: The Beautiful

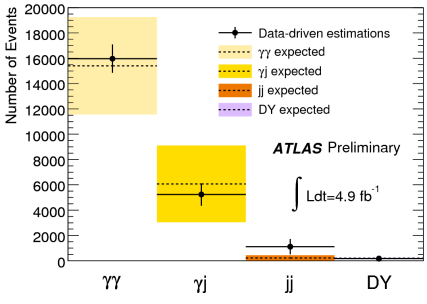
- $E_T(\gamma_1)$ >40 GeV,
  $E_T(\gamma_2)$ >25 GeV

  Main backgrounds:
  * irreducible $\gamma\gamma$ (30 pb);
  * reducible γj (200 nb);
  * reducible jj (500 μb).

- Powerful γ/jet separation is crucial.
- Need an excellent $m_{\gamma\gamma}$ mass resolution.



$H \to \gamma\gamma$: Signal and Background



Background composition
tested with control data.
(inverted photon isolation and ID criteria)

- Fraction of true $\gamma\gamma$ events: (71±5)%.

Total background from fit to $m_{\gamma\gamma}$ spectrum.

- Simultaneous fit to all 9 categories.
- Exponential function,
  free slope and normalization.
- Modeling uncertainty (per category):
  0.1 - 7.9 events.

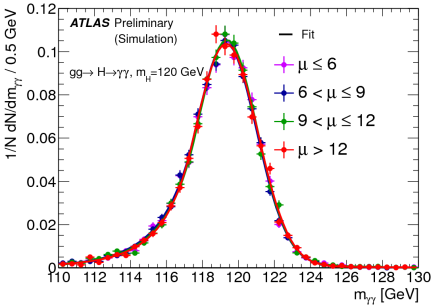
Analysis divided in 9 orthogonal categories
with different $m_{\gamma\gamma}$ resolutions
(photon $\eta \otimes$ conversion status $\otimes$ $p_T^{\gamma\gamma(thrust)}$).

Mass reconstruction robust against the pileup.

Signal $m_{\gamma\gamma}$ modeling:
Crystal Ball* (core) and Gaussian function (tails).

- σ_{CB} = 1.4 - 2.3 GeV (m_H=120 GeV)
- $FWHM$ = 3.3 - 5.9 GeV (m_H=120 GeV)

Mass scale uncertainty: 0.7 GeV (m_H=120 GeV).

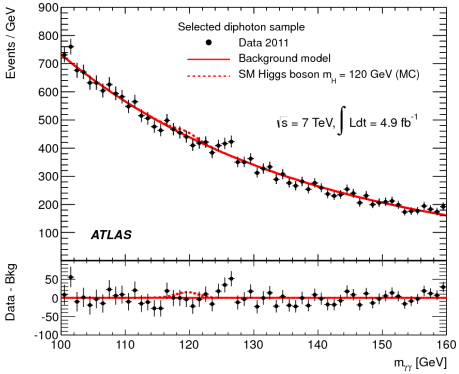


* Crystal Ball: Gaussian core portion and a power-law low-end tail. (J.E.Gaiser, SLAC-R-255 (1982))

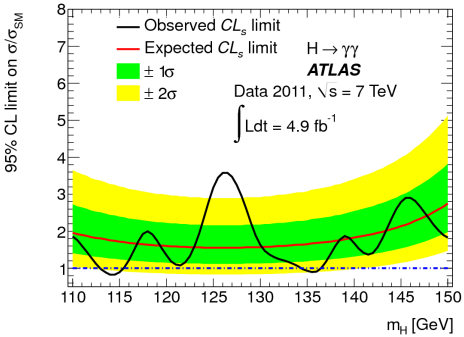
$H \to \gamma\gamma$: Results

Invariant $m_{\gamma\gamma}$ distribution,

summed over all categories:



Exclusion limit:



- Observed exclusion:

  113-115 GeV, 134.5-136 GeV.

Largest excess of events observed at 126.5 GeV.

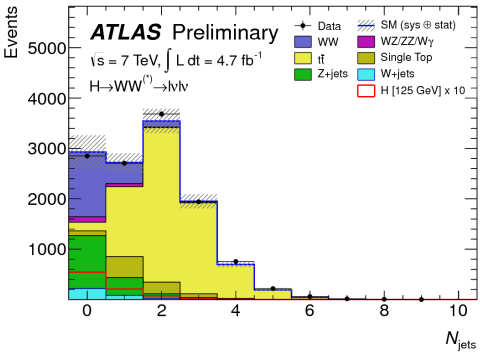
- Local significance: 2.8σ (Global: 1.5σ for m_H =110-150 GeV).

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

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

No mass reconstruction possible due to $2\nu \Rightarrow m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{miss}\right)^2 - \left|\vec{p}_T^{\ell\ell} + \vec{p}_T^{miss}\right|^2}$

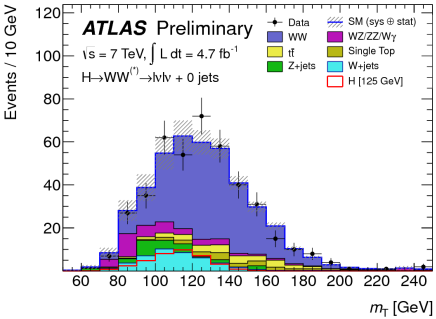
Selection criteria	Background suppression
Two isolated opposite-sign leptons ($p_T >$ 25,15 GeV)	$W + jets$, QCD
Large missing transverse energy (E_T^{miss}); Z veto	Drell-Yan, $Z + jets$
Jet multiplicity (0/1/2$_{VBF}$ jets), b-jet veto	$t\bar{t}$
Topological cuts ($m_{\ell\ell}, \Delta\phi_{\ell\ell}$)	WW
Additional jet-bin-dependent cuts ($p_T^{\ell\ell}$, $\vec{p}_T^{tot}$)	Z/DY, soft jets

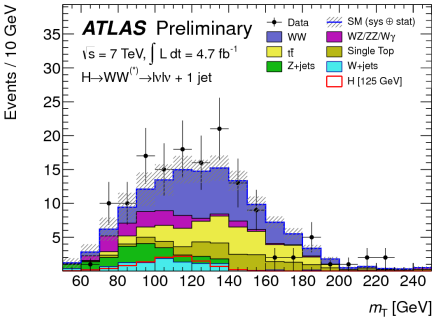


Background estimation:

- WW: control sample (no $\Delta\phi_{ll}$ cut, modified $m_{\ell\ell}$ cut) For $m_H >$300 GeV only fromsimulation.
- top: control samples (i) no tagging requirements, (ii) b-jet tag requirement.
- $Z + jets$: control s. $|m_{\ell\ell} - m_Z| <$15 GeV, correcting for mismodeling of E_T^{miss} tails.
- $W + jets$: control sample with inverted lepton ID passing loose criteria.

$H \to WW^{(*)} \to \ell\nu\ell\nu$: Results

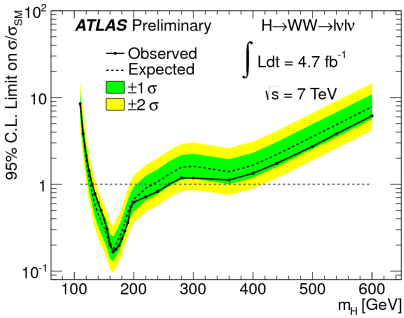




m_H=125 GeV	0-jet ee	0-jet $\mu\mu$	0-jet $e\mu$
Total bkg.	58±5	114±10	257±13
Signal	3.8±0.1	9.0±0.1	25±0.2
Observed	52	138	237

m_H=125 GeV	1-jet ee	1-jet $\mu\mu$	1-jet $e\mu$
Total bkg.	21±3	37±5	76±6
Signal	1.1±0.1	2.3±0.1	6.0±0.1
Observed	19	36	90

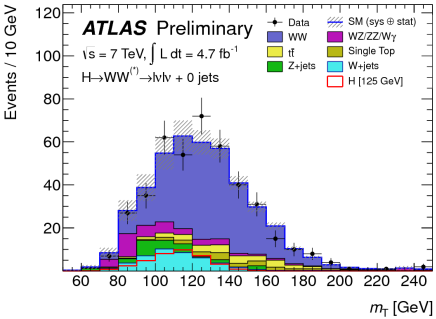
(Statistical uncertainties only.)

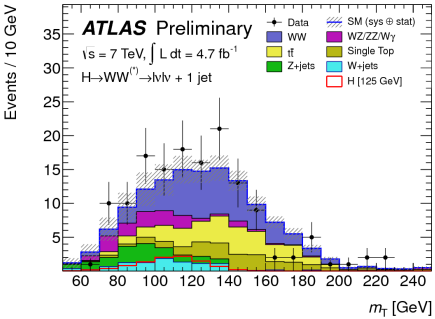


Expected exclusion: 127-234 GeV

Observed exclusion: 130-260 GeV

$H \to WW^{(*)} \to \ell\nu\ell\nu$: Results

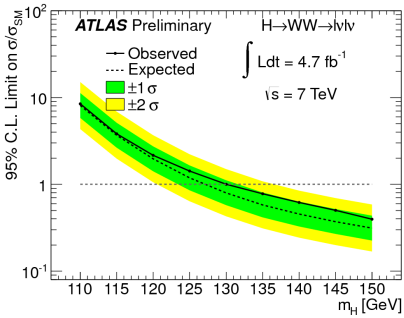




m_H=125 GeV	0-jet ee	0-jet $\mu\mu$	0-jet $e\mu$
Total bkg.	58±5	114±10	257±13
Signal	3.8±0.1	9.0±0.1	25±0.2
Observed	52	138	237

m_H=125 GeV	1-jet ee	1-jet $\mu\mu$	1-jet $e\mu$
Total bkg.	21±3	37±5	76±6
Signal	1.1±0.1	2.3±0.1	6.0±0.1
Observed	19	36	90

(Statistical uncertainties only.)



Expected exclusion: 127-234 GeV

Observed exclusion: 130-260 GeV

$(W/Z)H \rightarrow (\ell\ell, \ell\nu, \nu\nu)bb$

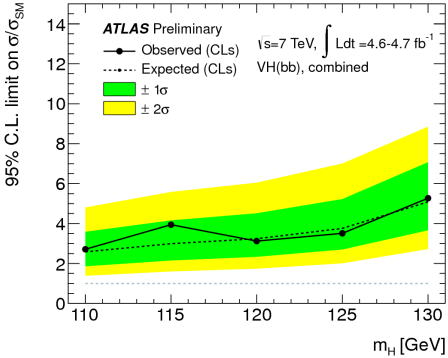
Selection requires exactly two b-tagged jets: E_T^{b1} >45 GeV, E_T^{b2} >25 GeV.

W/Z and H boson recoil away with significant p_T:

- 4 p_T^W-categories in $WH \rightarrow \ell\nu bb$: <50, [50,100), [100,200), ≥200 GeV
- 4 p_T^Z-categories in $ZH \rightarrow \ell\ell bb$: <50, [50,100), [100,200), ≥200 GeV
- 3 E_T^{miss}-categories in $ZH \rightarrow \nu\nu bb$: [120,160), [160,200), ≥200 GeV

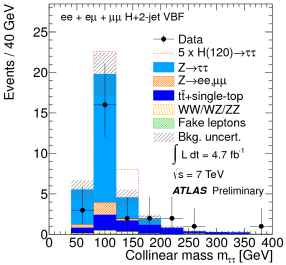
Major backgrounds:

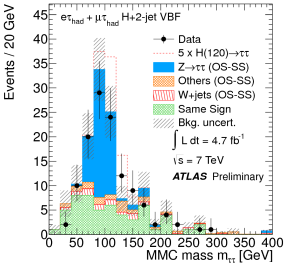
- *$W/Z + jets$*: shape from simulation; normalization from W/Z+2*jet* with 0/1 b-tags, and from m_{bb} sidebands.
- *top*: shape from simulation, normalization from m_{bb} sidebands and control data (3-jet bin, $m_{\ell\ell}$ sidebands)
- *diboson*: from simulation.
- *multijets*: templates from reversed lepton ID fitted to control data; For $\nu\nu b\bar{b}$ channel: $\Delta\phi(E_T^{miss}, \vec{p}_T^{miss})$ & $\Delta\phi(E_T^{miss}, b-jet)$

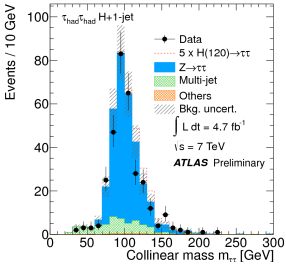


$H \to \tau\tau \to (\ell\ell 4\nu,\ \ell\tau_{had}3\nu,\ \tau_{had}\tau_{had}2\nu)$

Mass reconstruction possible due to the collinearity of τ decay products.
Sub-channels separated into different jet categories (0-, 1-jet, 2-jet VH, 2-jet VBF).

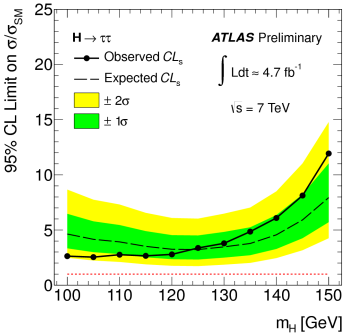






Major backgrounds:

- $Z \to \tau\tau$: normalization from theory, shape from $Z \to \mu\mu$ data by replacing μ with simulated τ decay (10% uncert.).
- *Fake leptons and $\tau - jets$*:
  * $\ell\ell 4\nu$: reversed lepton isolation (30-40%);
  * $\ell\tau_{had}3\nu$: same-sign charge (20%);
  * $\tau_{had}\tau_{had}2\nu$: tracks multiplicity from two τ candidates (20%).



Combination

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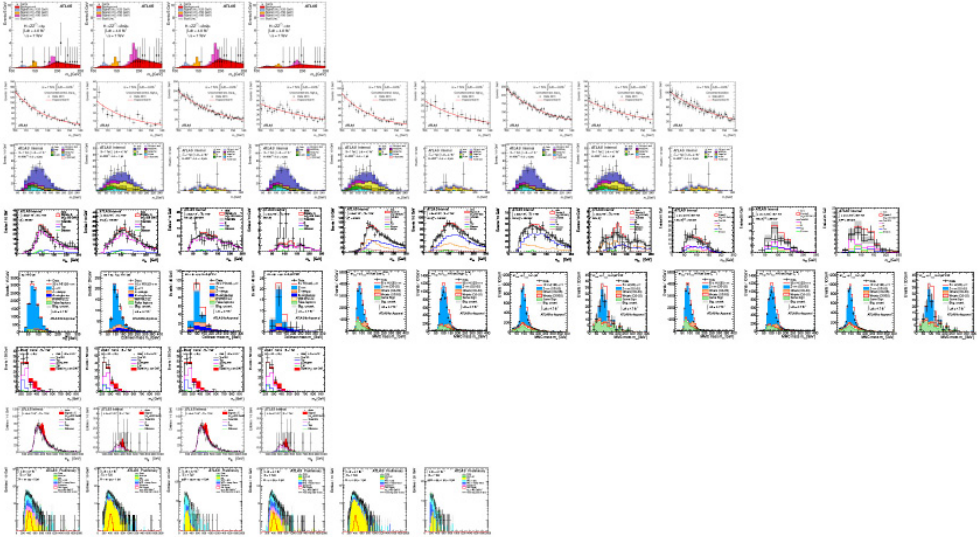
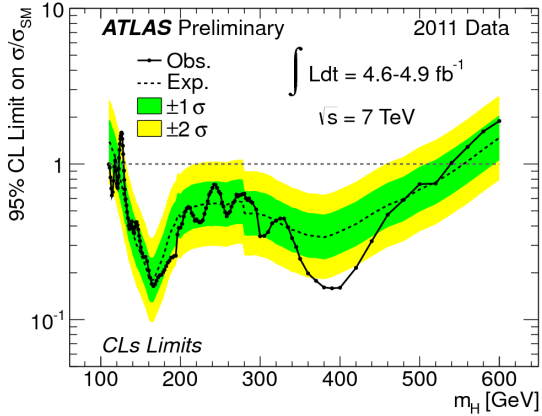
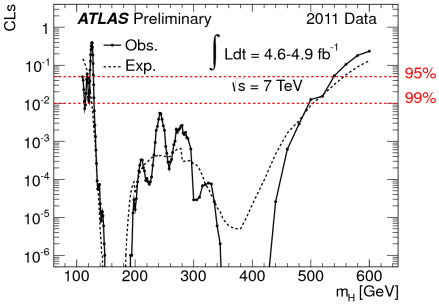


Combined exclusion limit





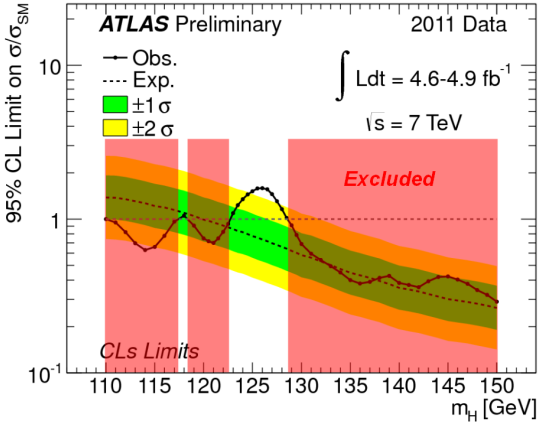
Expected exclusion at 95% CL: 120-555 GeV

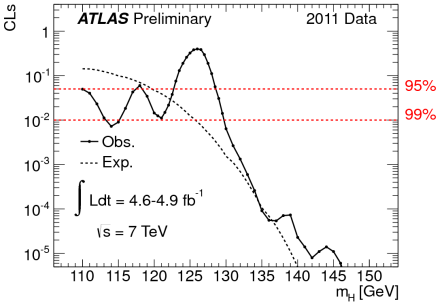
Observed exclusion at 95% CL: 110-117.5, 118.5-122.5, 129-539 GeV

Observed exclusion at 99% CL: 130-486 GeV

Combined exclusion limit

Zoom in:





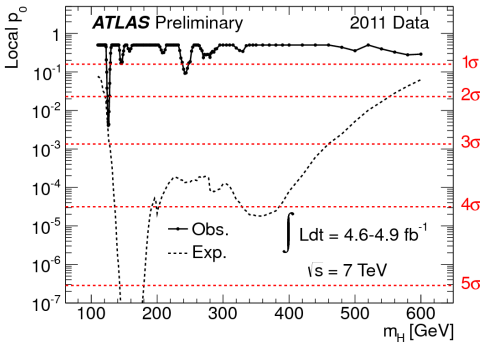
Expected exclusion at 95% CL: 120-555 GeV

Observed exclusion at 95% CL: 110-117.5, 118.5-122.5, 129-539 GeV

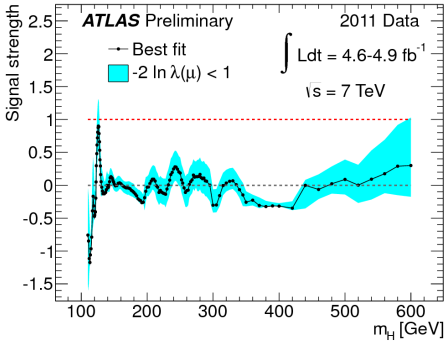
Observed exclusion at 99% CL: 130-486 GeV

Breakdown of an observed excess

Probability that the excess is caused by a background fluctuation:

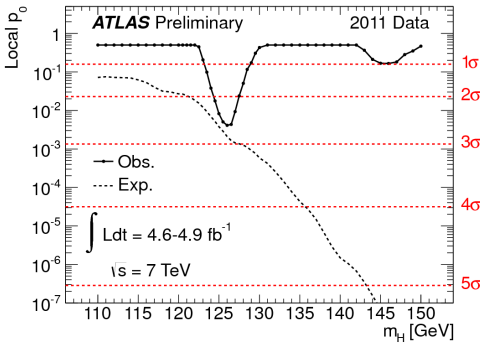


Best fit signal strength $\mu = \sigma/\sigma_{SM}$:

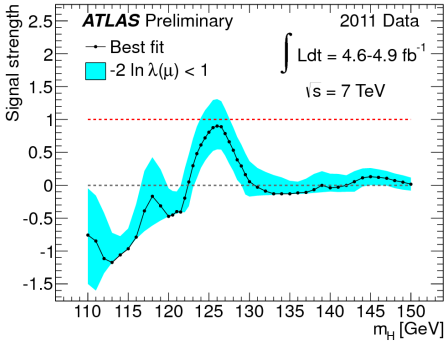


Breakdown of an observed excess

Probability that the excess is caused by a background fluctuation:



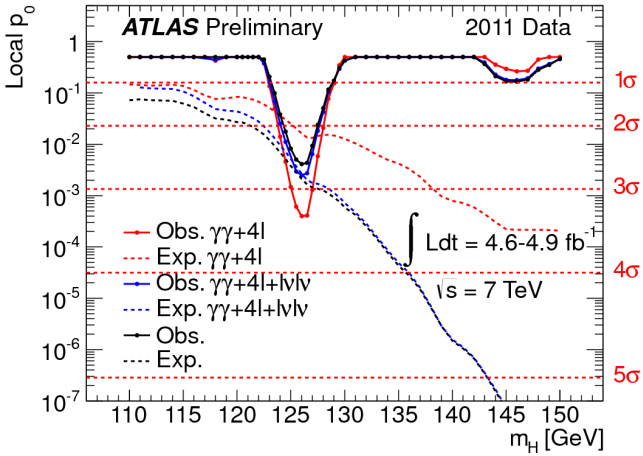
Best fit signal strength $\mu = \sigma/\sigma_{SM}$:



Excess of events observed at 126 GeV:

- Observed local significance 2.5σ (expected 2.9σ).
- Best-fit signal strength at 126 GeV: $\hat{\mu} = 0.9^{+0.4}_{-0.3}$.
- Global probability of such a background fluctation anywhere in the full explored mass range (110-600 GeV): 30%;
  in the mass range (110-146 GeV): 10%.

Excess in individual channels



- Excess is mainly observed in two high-resolution channels:
  $\Rightarrow H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to 4\ell$ combined: 3.4σ local significance.
- No such excess (yet?) in $H \to WW^{(*)} \to \ell\nu\ell\nu$, $H \to \tau\tau$, $H \to b\bar{b}$.
  $\Rightarrow$ All channels combined: 2.5σ local significance.

(Not) The end

2011 has been a fantastic year.

ATLAS is deeply grateful to the machine team for the outstanding performance of the LHC.

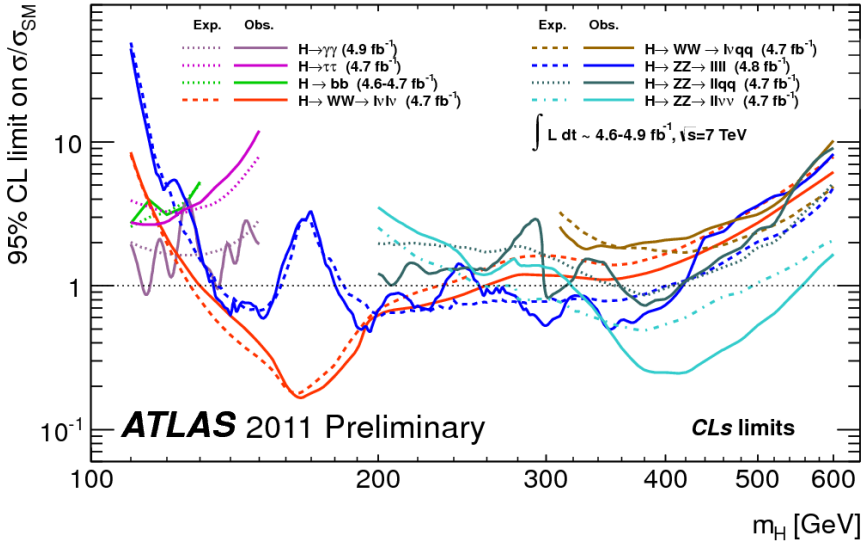
- Excellent ATLAS performance, from detector to physics (116 papers submitted or published).
- Scalar Boson searches in 12 distinct channels, using full 2011 dataset.
- Allowed Scalar Boson mass has been squeezed into a tiny region: 117.5-118.5 GeV or 122.5-129 GeV
- In the low-mass region no exclusion was possible due to an excess of observed events compared to the expectation.
- The excess is most compatible with the Standard Model Scalar Boson hypothesis with m_H around 126 GeV.
  Statistical significance not large enough (yet) to draw definite conclusions.

This year may reveal the truth.

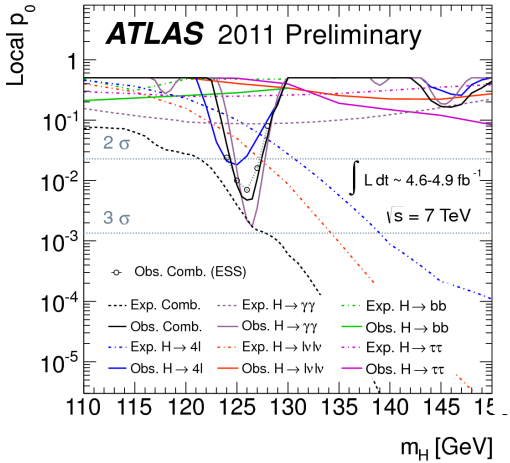
b

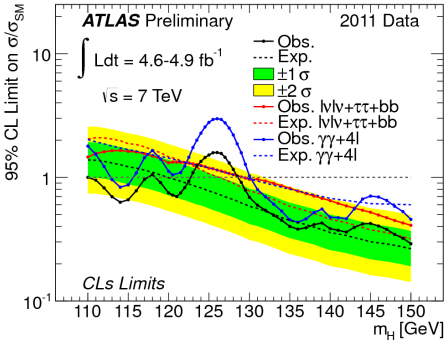
Backup

Combination: Individual channels

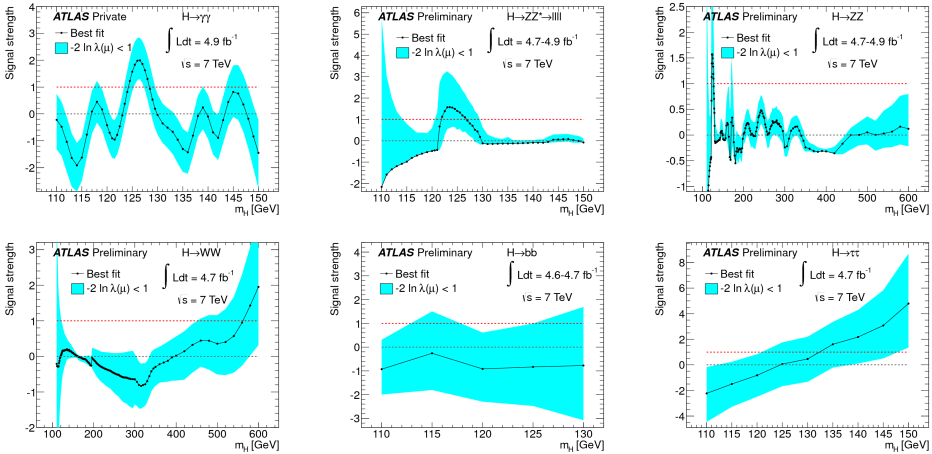


Combination: p0 and limits



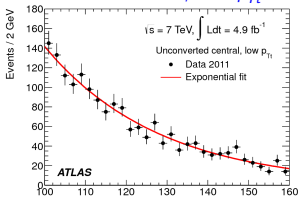


Combination: $\hat{\mu}$

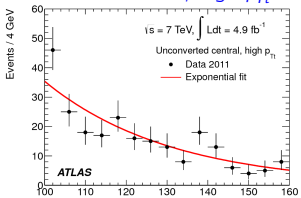


$H \to \gamma\gamma$: $m_{\gamma\gamma}$ in 9 categories

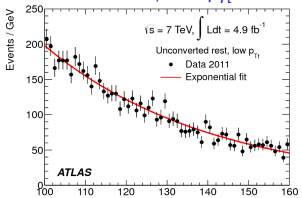
unconverted central, low p_{Tt}



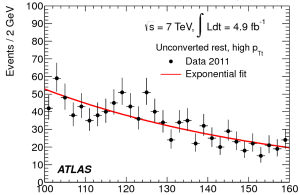
unconverted central, high p_{Tt}



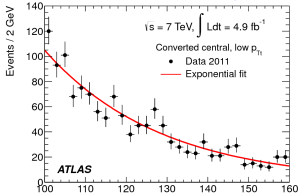
unconverted rest, low p_{Tt}



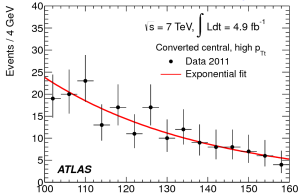
unconverted rest, high p_{Tt}



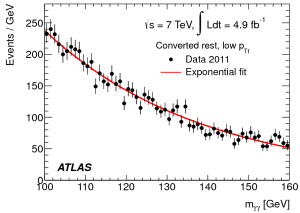
converted central, low p_{Tt}



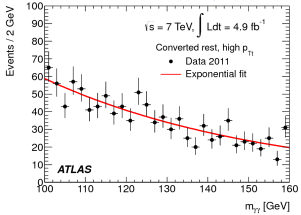
converted central, high p_{Tt}



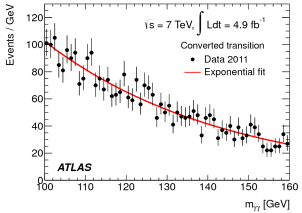
converted rest, low p_{Tt}



converted rest, high p_{Tt}

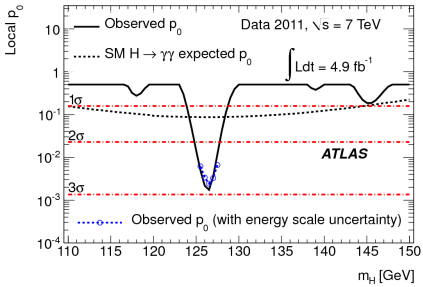


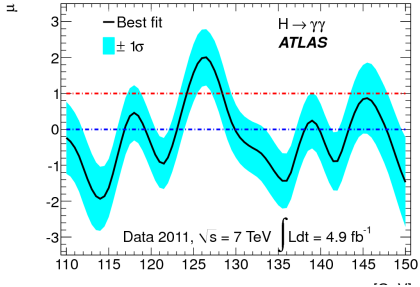
unconverted transition

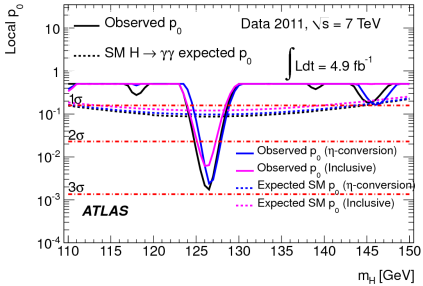


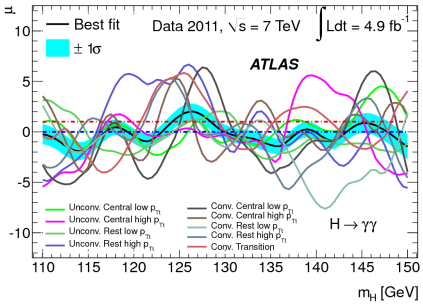
$H \to \gamma\gamma$: Excess at 126.5 GeV

- Local significance: 2.9σ without ESS; 2.8σ with ESS
- Global significance: 1.5σ

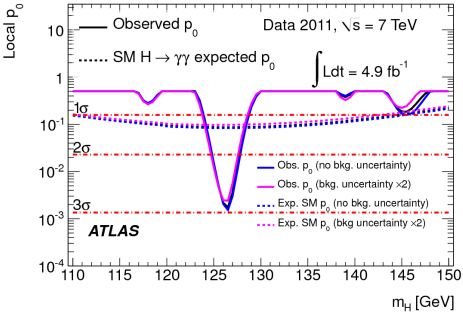


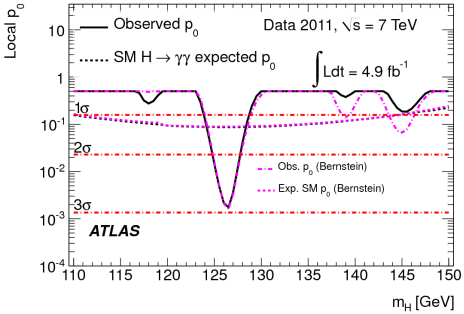




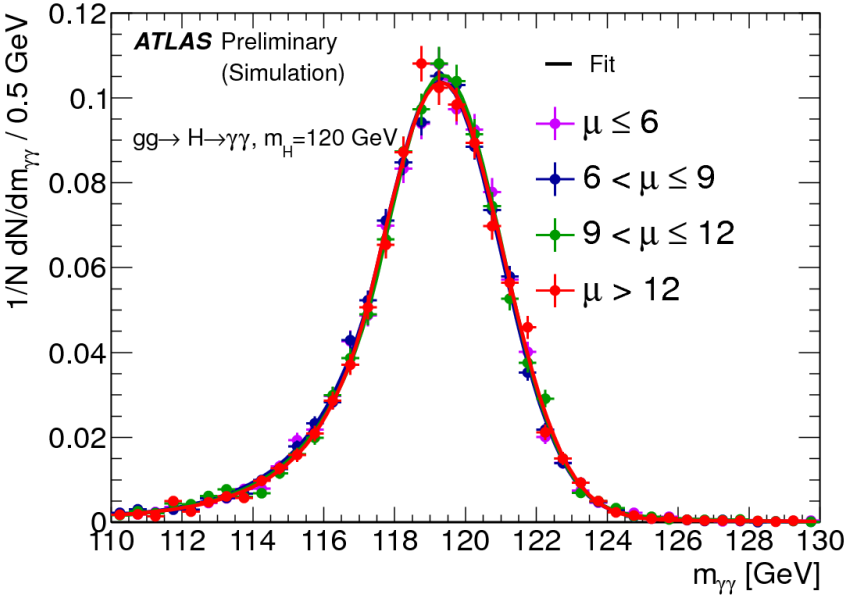


$H \to \gamma\gamma$: Background modeling

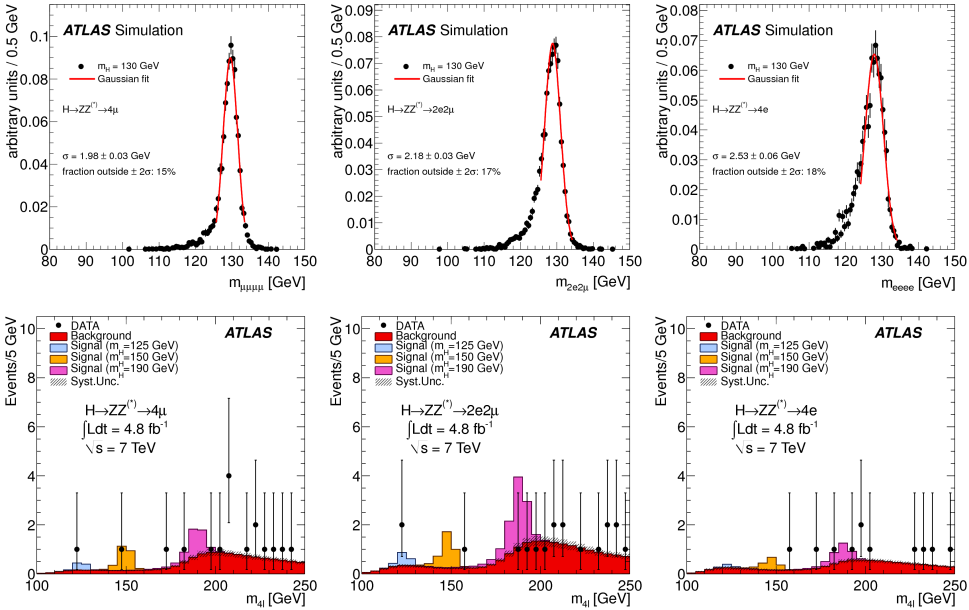




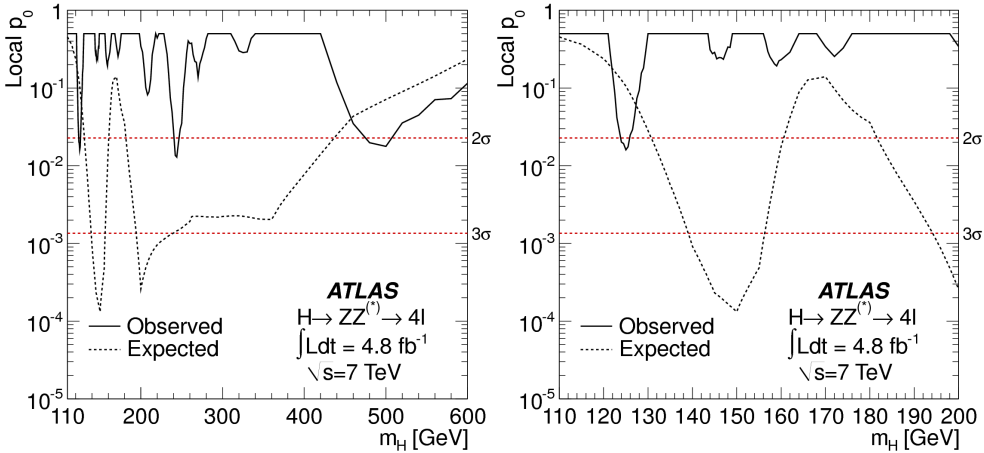
$H \to \gamma\gamma$: Signal reconstruction under pileup



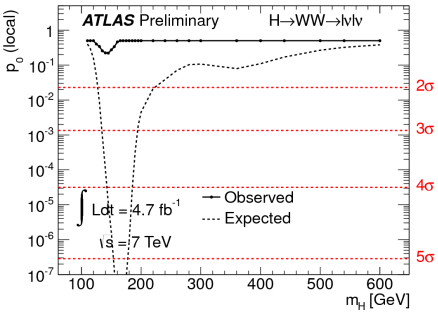
$H \to ZZ^{(*)} \to 4\ell$: Mass distributions

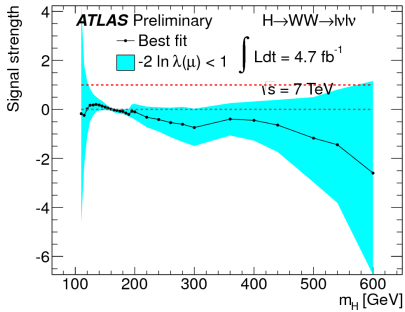


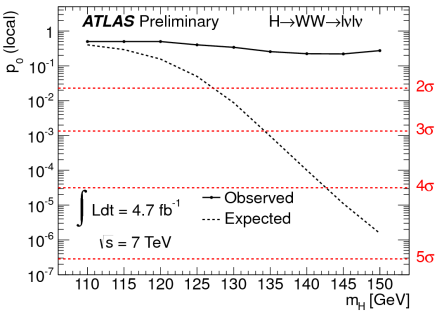
$H \to ZZ^{(*)} \to 4\ell$: Background compatibility

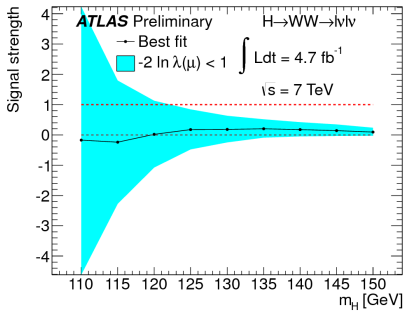


$H \to WW^{(*)} \to \ell\nu\ell\nu$: Background compatibility

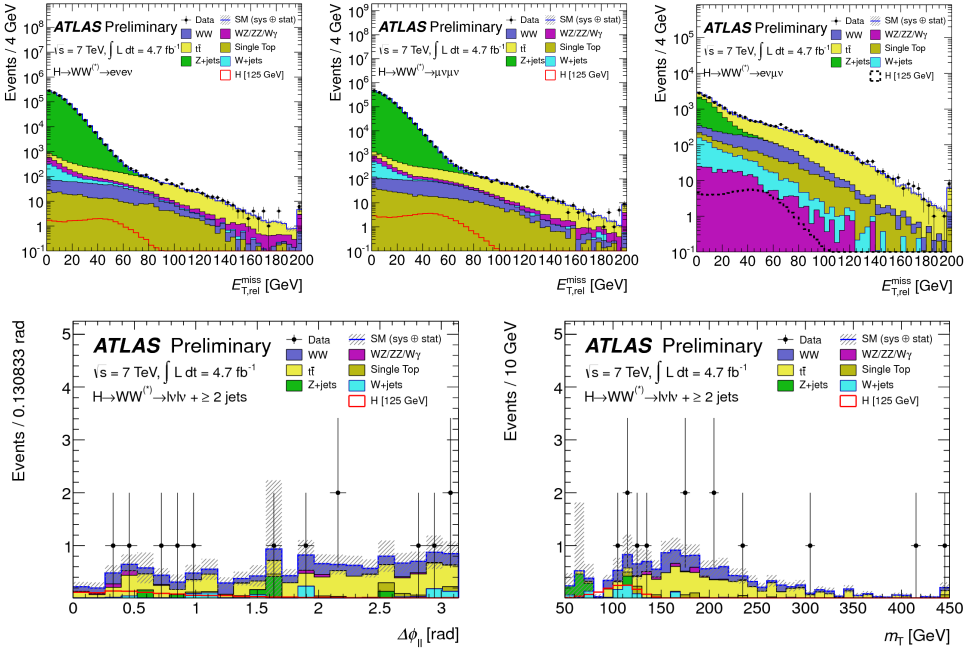




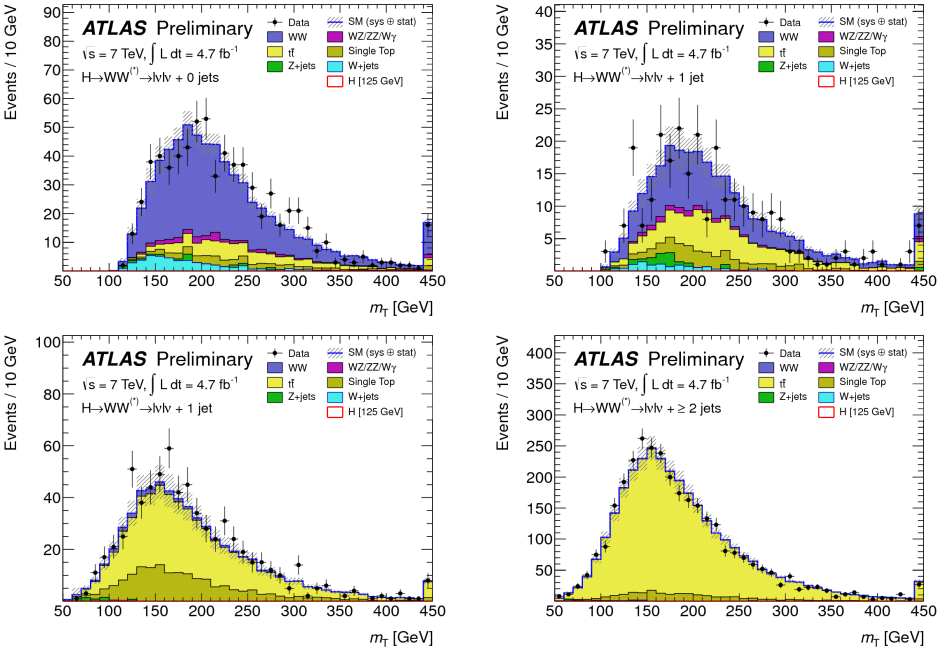




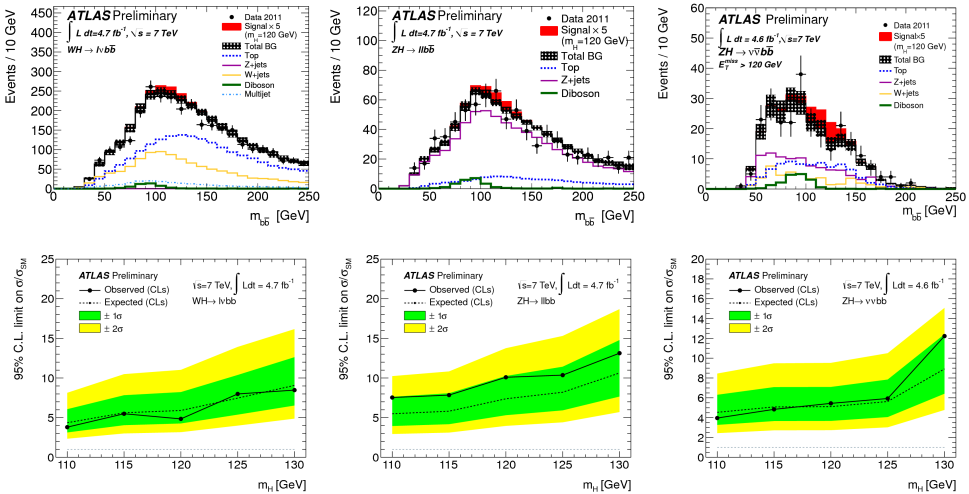
$H \to WW^{(*)} \to \ell\nu\ell\nu$: E_T^{miss}; VBF channel



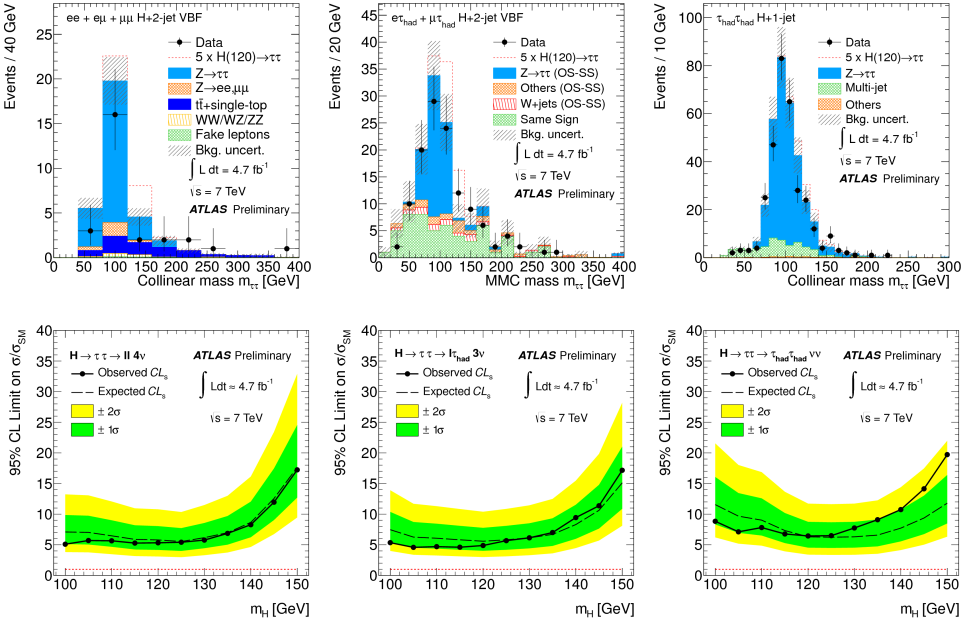
$H \to WW^{(*)} \to \ell\nu\ell\nu$: Control samples



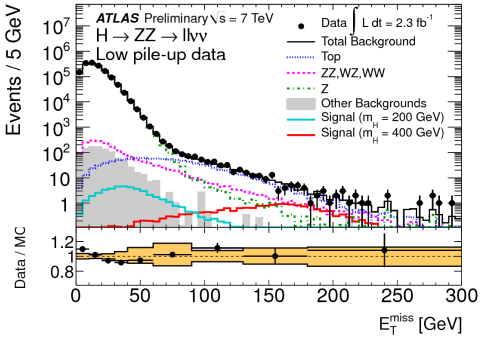
$(W/Z)H, H \to b\bar{b}$: $\ell\nu bb$, $\ell\ell bb$, $\nu\nu bb$

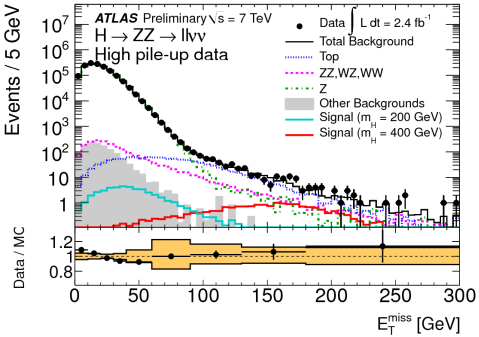


$H \to \tau\tau \to (ll, lh, hh)$

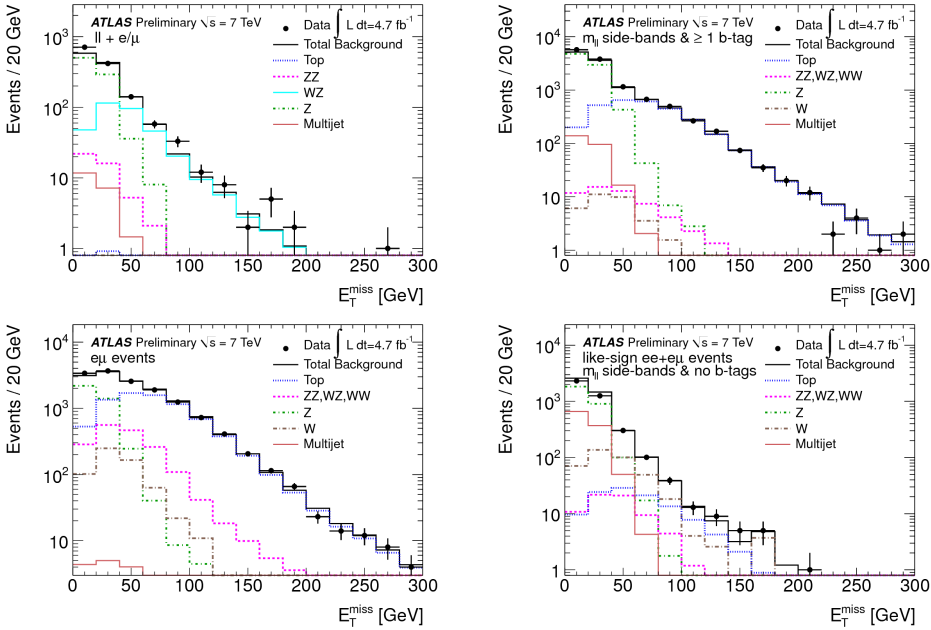


$H \to ZZ \to \ell\ell\nu\nu$: E_T^{miss}

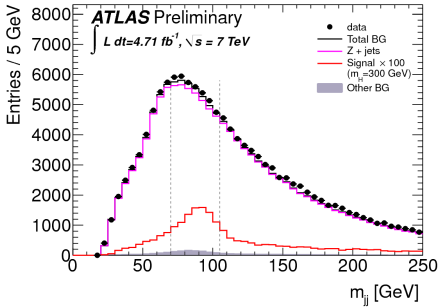


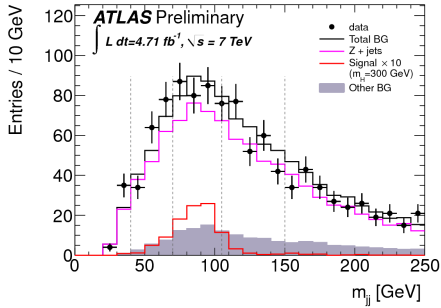


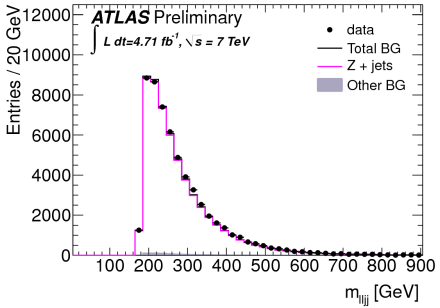
$H \to ZZ \to \ell\ell\nu\nu$: Control regions

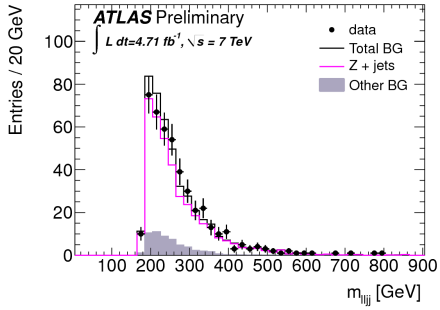


$H \to ZZ \to \ell\ell jj$: m_{jj}-sidebands

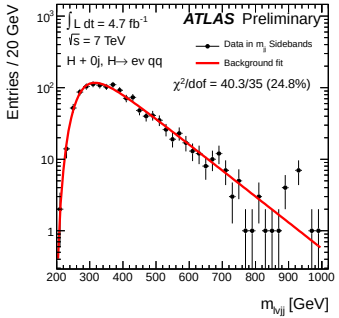


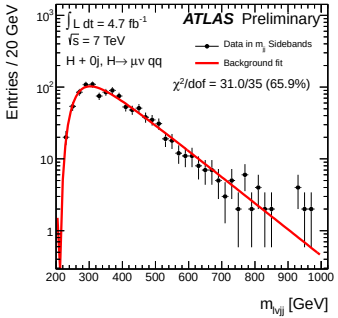


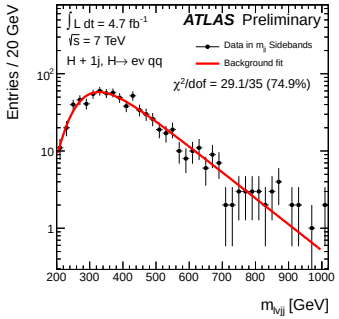


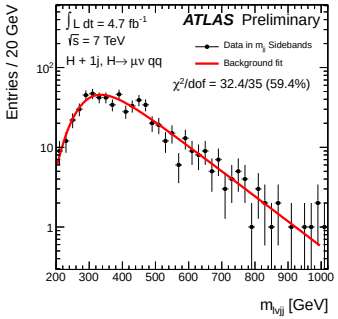


$H \to WW \to \ell\nu jj$: Control data

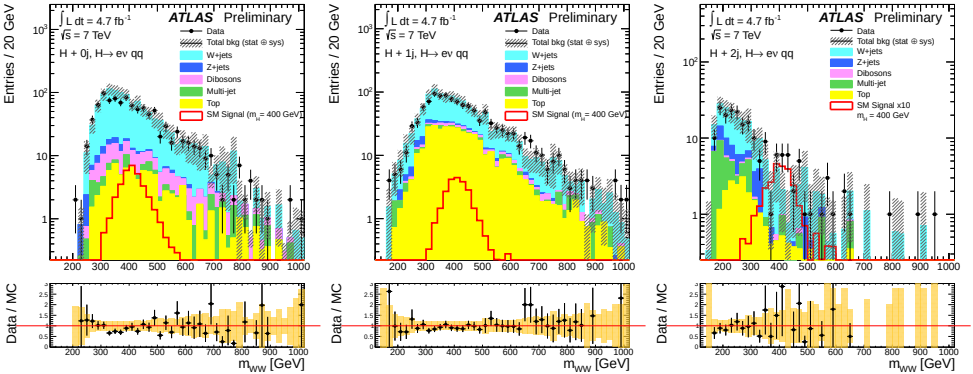




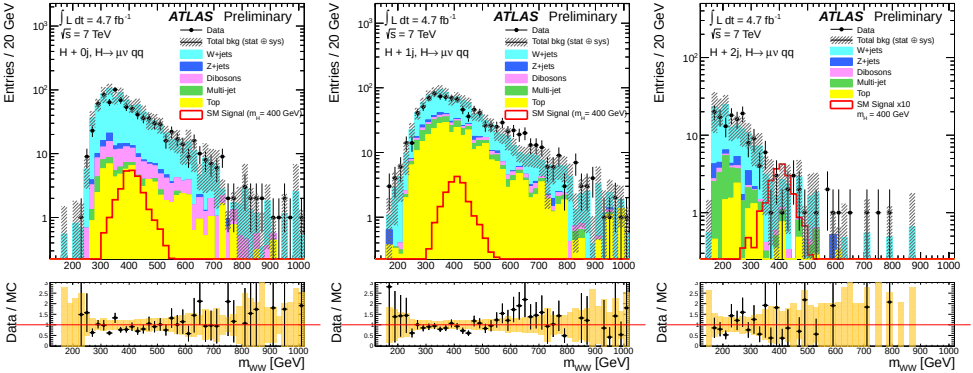




$H \to WW \to \ell\nu jj$: $m_{\ell\nu qq}$, electron channel



$H \to WW \to \ell\nu jj$: $m_{\ell\nu qq}$, muon channel



$H \to WW \to \ell\nu jj$: limits