Searches for the SM scalar boson in the $H \rightarrow W^+W^-$ channels with the ATLAS detector

Higgs Hunting 2012, Orsay

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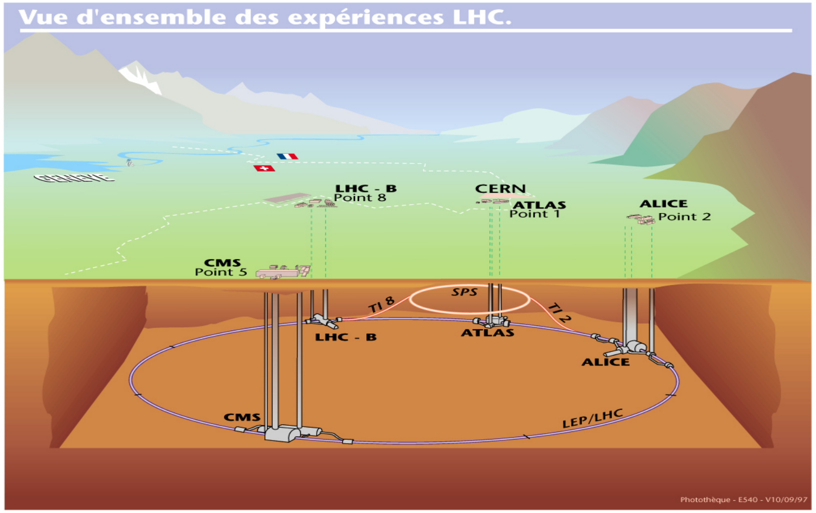
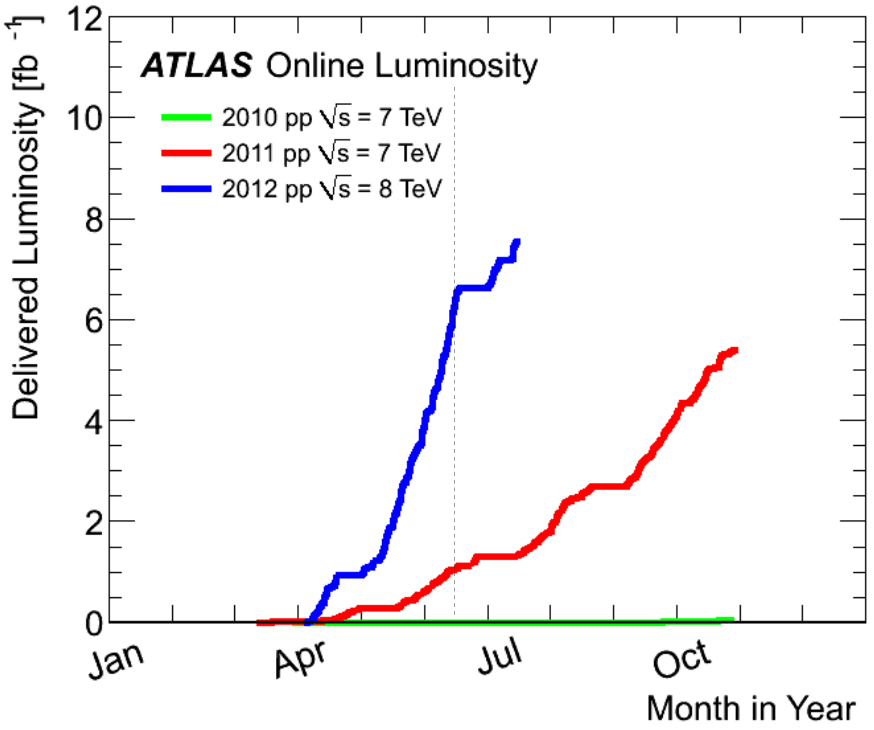
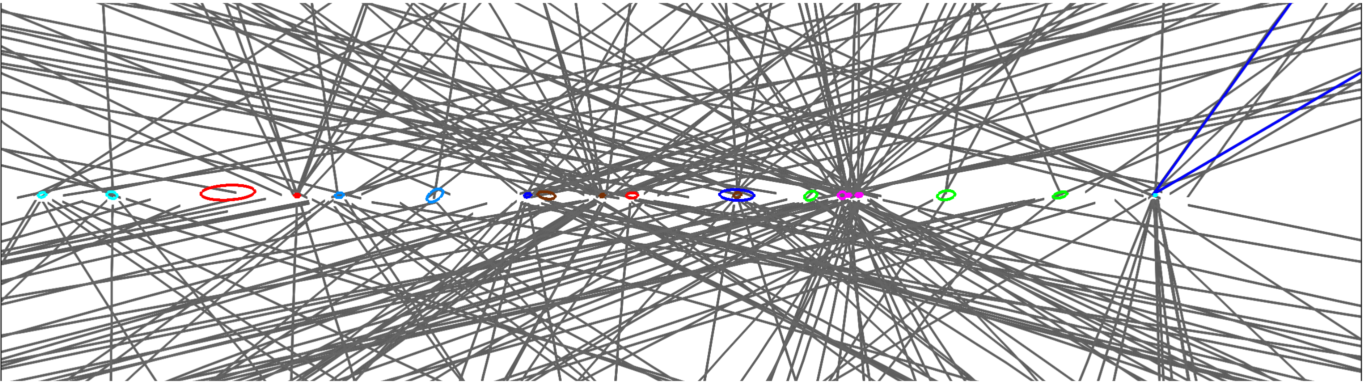
2012 is a great year !





	2011	2012
E_{CM}	7 TeV	8 TeV
Inst. lumi.	$\sim 3.10^{33}$ cm^{-2}s^{-1}	[3-7].10^{33} cm^{-2}s^{-1}
Int. lumi	(~500 pb^{-1}/week)	25 fb^{-1}/year ?
Bunch spacing	50 ns	50 ns

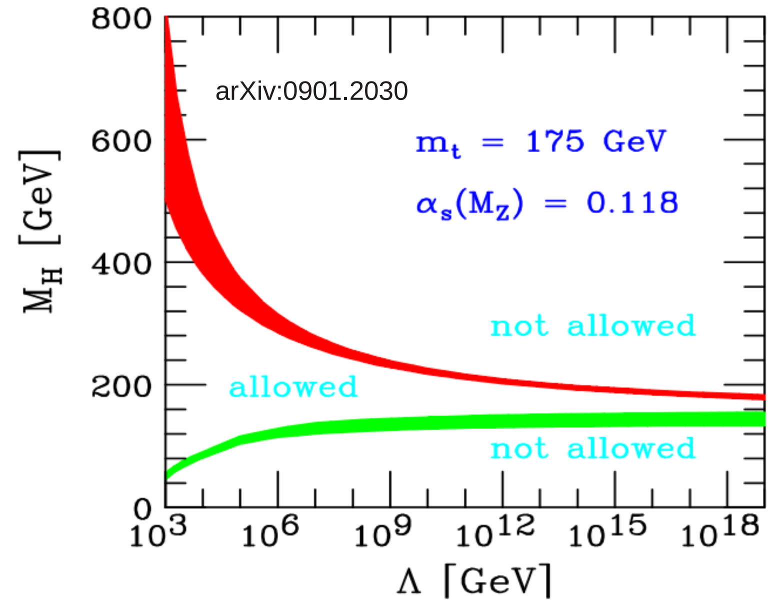
- Price to pay is high pile-up
- It complicates :

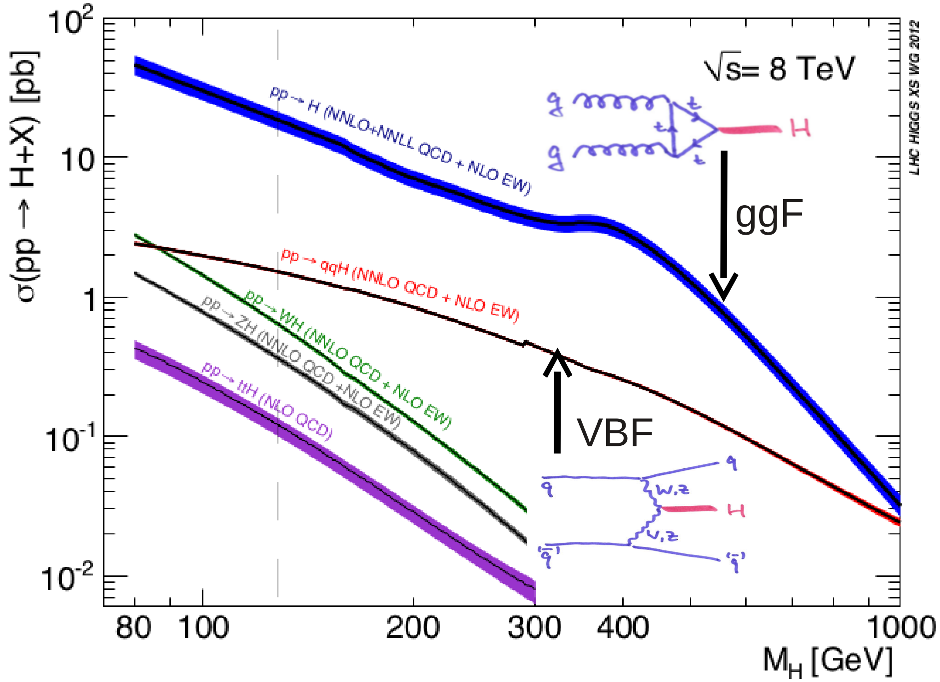


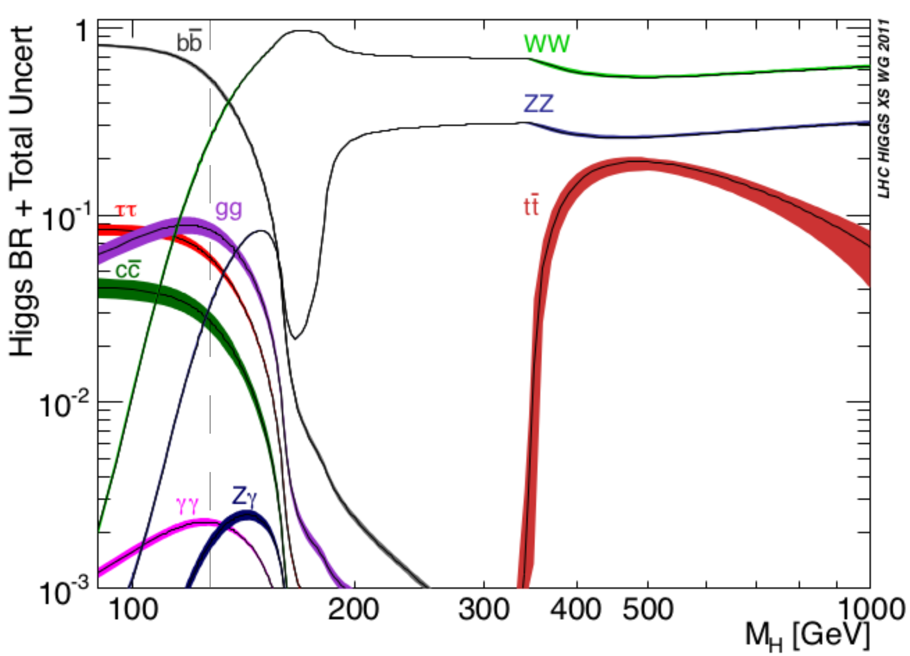
- Triggering
- Reconstruction and identification of physics objects
- Resolutions (Etmiss)
- Computing resources
- Simulation

Searches for the SM scalar boson

- Missing element of the Standard Model in order to explain the masses of the elementary particles
- Large production cross-section at LHC thanks to the large presence of gluons
- WW decays make searches in this channel the most efficient in the range in mass ~120-190 GeV



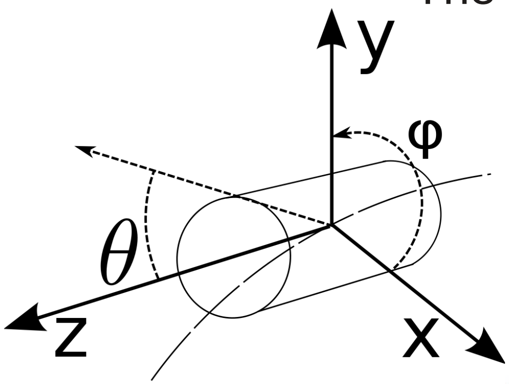


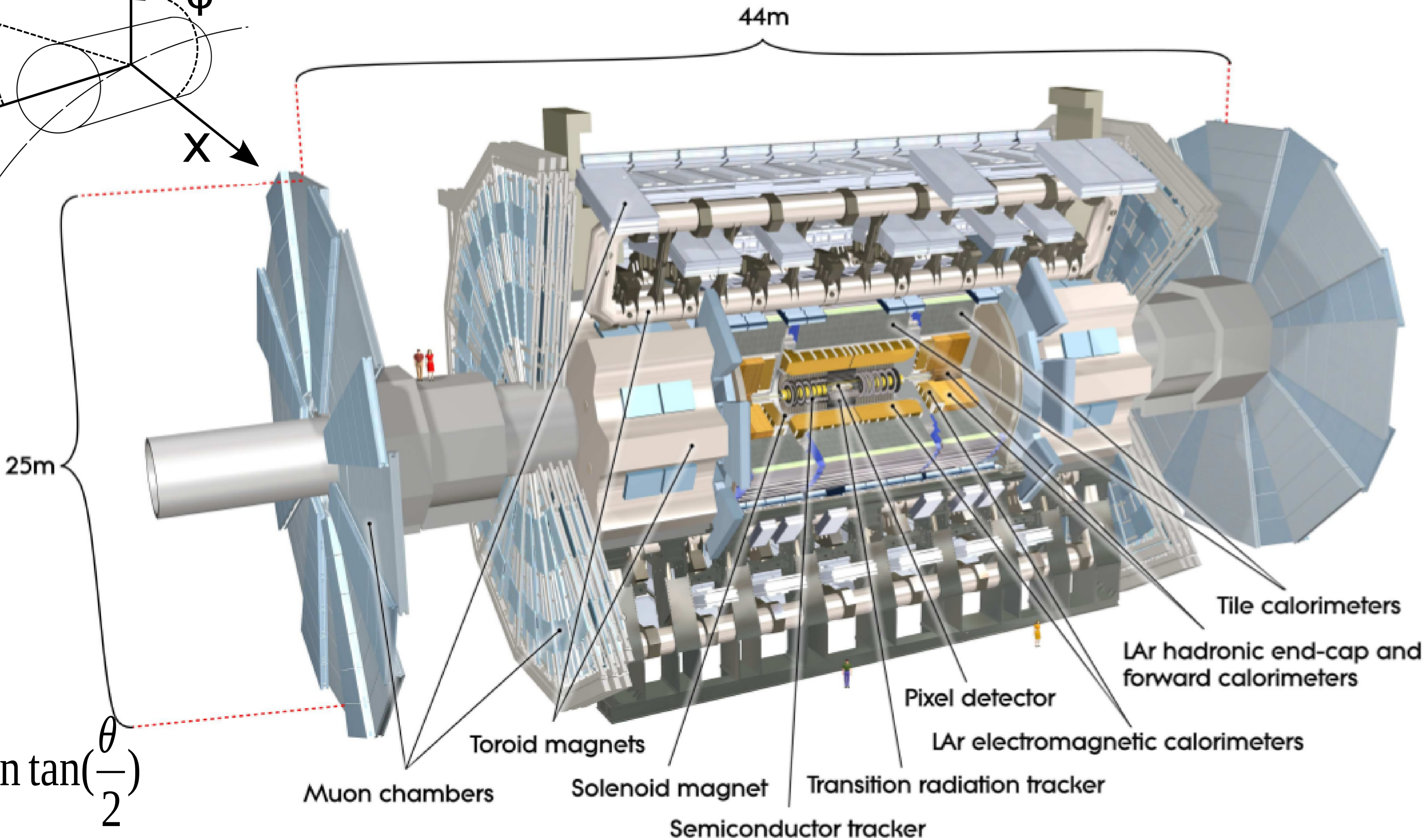


arXiv:1201.3084

A Toroidal LHC ApparatuS

The H → WW analyses rely on the information provided by **all** sub-detectors !



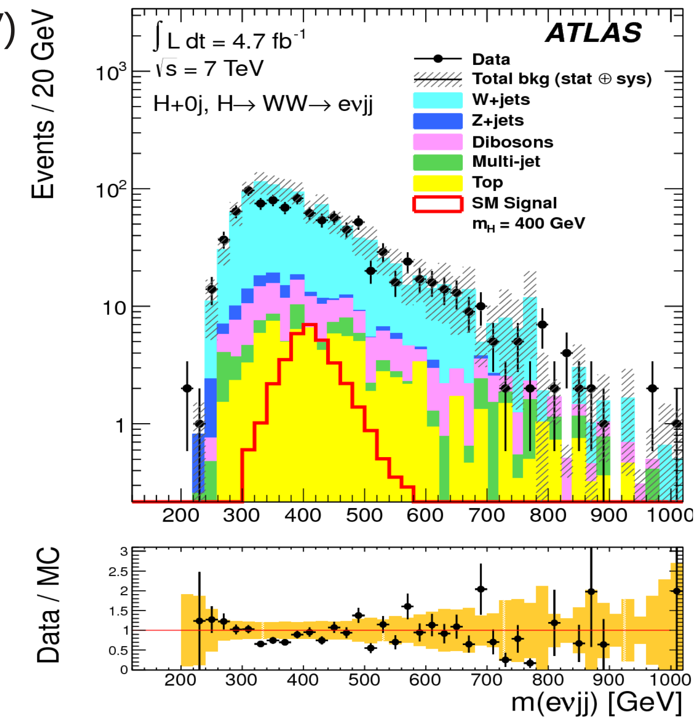


$$\eta = -\ln \tan(\frac{\theta}{2})$$

Recent 2011 results : lυjj (1)

Based on arXiv:1206.6074

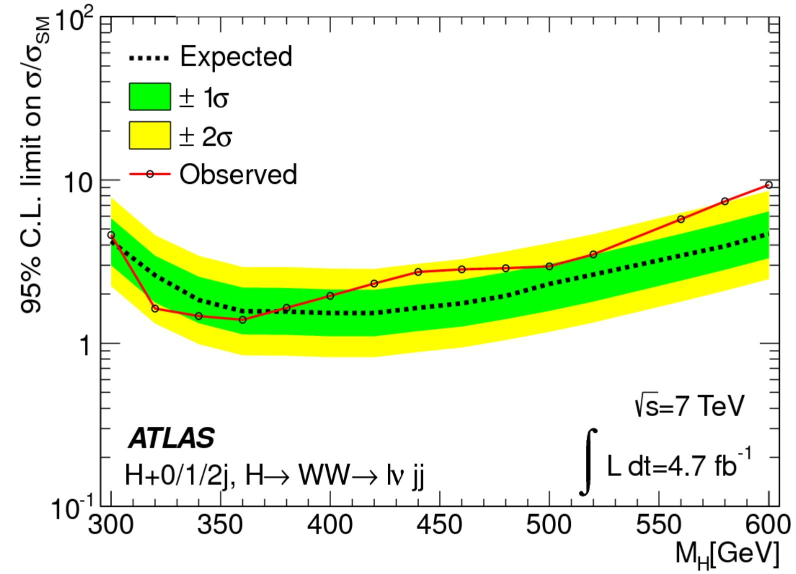
- Analysis selection targeted to high masses :
  - Electron or muon above p_T = 40 GeV (Veto extra one with p_T > 20 GeV)
  - 2 jets within $|\eta|$ < 2.8 above p_T = 40 GeV (one with p_T > 60 GeV)
    - ΔR_{jj} < 1.3 to suppress W+jets
    - b-tagged jet veto to suppress top background
    - Binning with 0 or 1 extra jet within $|\eta|$ < 4.5
  - Missing transverse energy above 40 GeV
  - W mass constrain on m_{jj} : [71, 91] GeV
  - Alternative selection for VBF with increased acceptance, opposite hemisphere and separation requirements for the tagging jets ($\Delta\eta_{jj}$ > 3) and m_{jj} > 600 GeV



- Background dominated by W+jets (~70%), top (~20%), Z+jets, diboson and multijets
- Non-resonant background modelled by a smooth function validated on MC and fitted in the W mass sidebands:

$$f(x) = \frac{1}{1+|a(x-m)^b|} e^{-c(x-200)}$$

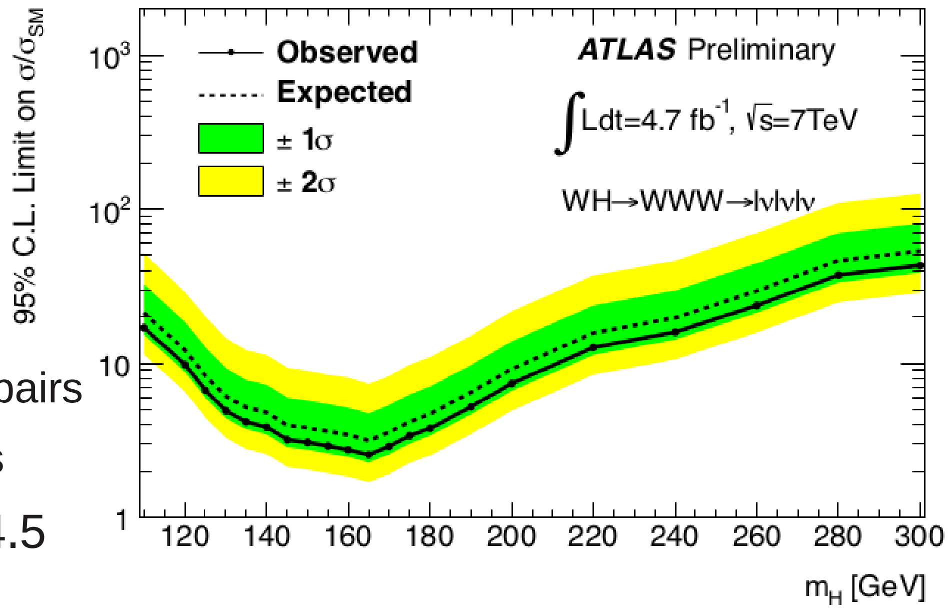
- Results well consistent with background-only hypothesis within 300 and 600 GeV



Recent 2011 results : WH → WWW → lνlνlν

Based on ATLAS-CONF-2012-078

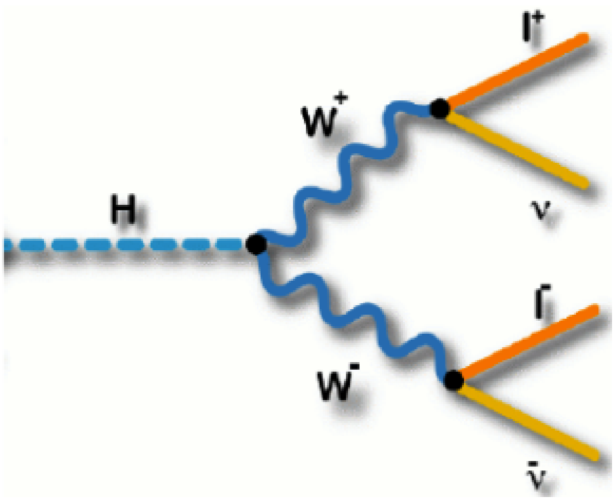
- Analysis selection:
  - Three isolated leptons above 10 GeV within |η| < 2.5
    - At least one triggering (i.e. >24 GeV for electrons or >21 GeV for muons)
  - Missing transverse energy above
    - 40 GeV for same flavour opposite-signs lepton pairs
    - 25 GeV for different flavour opposite-signs pairs
  - Counting of jets above p_T = 25 GeV with |η| < 4.5
  - Z mass veto



	$W(H \to WW)$	$Z(H \to WW)$	$V(H \to \tau\tau)$	$H \to ZZ$	Observed	Total Bkg.
Pre-selection	1.78±0.15	3.56±0.30	0.66±0.06	0.97±0.08	2077	2240±260
Z enriched	1.36±0.11	3.50±0.28	0.54±0.05	0.97±0.08	2056	2220±260
At most 1 jet, not b-tagged	1.24±0.12	2.22±0.21	0.48±0.05	0.80±0.07	1801	1960±240
$E_{\mathrm{T,rel}}^{\mathrm{miss}} > 40$ GeV	0.61±0.05	0.54±0.05	0.10±0.01	0.01±0.01	114	115±10
Z mass veto	0.47±0.05	0.04±0.01	0.04±0.01	−−	13	9.9±2.2
All cuts	0.34±0.06	0.03±0.01	0.02±0.01	−−	3	3.7±0.9
Z depleted	0.43±0.06	0.06±0.01	0.12±0.02	−−	21	12.49±1.07
At most 1 jet, not b-tagged	0.40±0.06	0.04±0.01	0.11±0.02	−−	7	4.9±0.9
$E_{\mathrm{T,rel}}^{\mathrm{miss}} > 25$ GeV	0.26±0.03	0.02±0.01	0.04±0.01	−−	1	1.22±0.24
All cuts	0.18±0.04	0.01±0.01	0.03±0.01	−−	0	0.25±0.15

Higgs decaying WW → $l\nu l\nu$

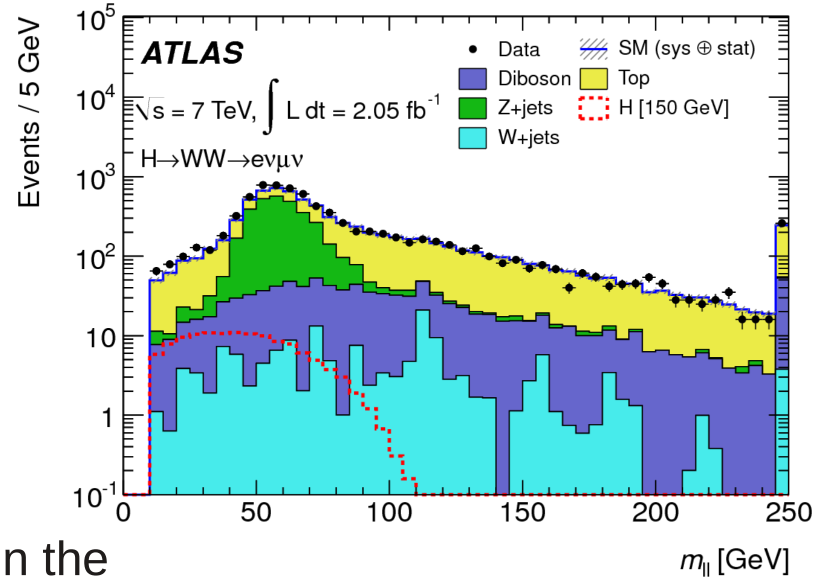
Presentation based on the latest 2012 results at ATLAS-CONF-2012-098
(or earlier publications for illustrative figures)



- Presence of two isolated high-pT leptons with opposite charges
  → suppresses part of the large multi-jets and W/Z+jets background
- Large missing transverse energy due to the escaping neutrinos
  → distinguishing from Drell-Yan Z/γ^* processes
- Standard Model scalar boson with spin 0 → small lepton opening angle
  → topology different from the di-boson WW continuum
- Privileged channel thanks to its high branching ratio but limited mass resolution
- « Counting experiment » carried out on the Higgs mass spectrum between 110 and 200 GeV
- Results presented here for an integrated luminosity of 5.8 fb^{-1} collected in 2012 at $\sqrt{s}$ =8 TeV in the opposite flavour (eμ and μe) channels

Selection (1) : leptons & missing E_T

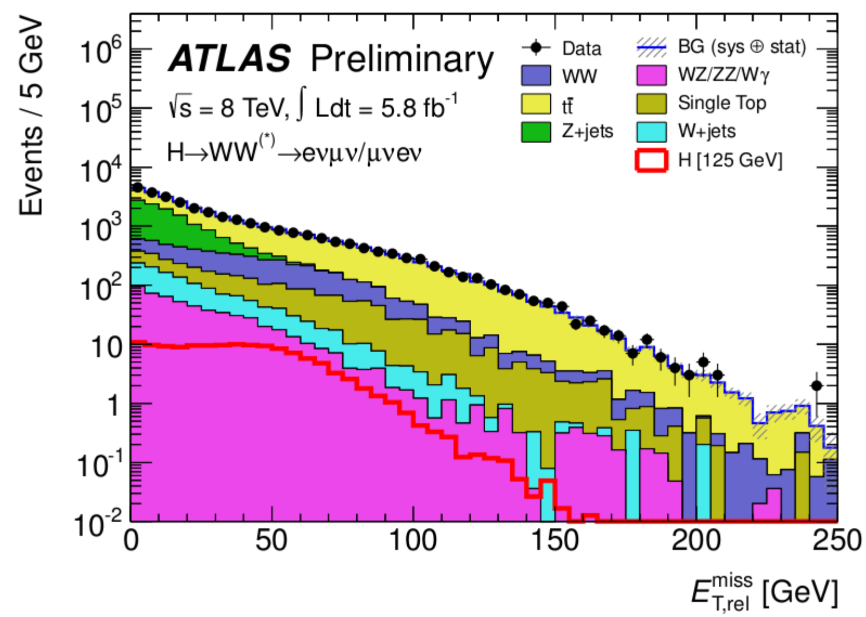
- Each event should contain two tightly-identified isolated leptons with opposite charges
  - p_T > 15 GeV
  - At least one with p_T > 25 GeV to fire the trigger
- Dilepton invariant mass m_{ll} > 10 GeV



- In order to reduce the background without any neutrino in the final state (Z+jets, di-jets), a large missing transverse energy is required
  - Actually, to reduce the impact on the missing transverse energy of particles energy mis-measurements, a projection ($E_T\text{miss}_{rel}$) of this $E_T$miss is used:
    - $E_T\text{miss}_{rel} = E_T\text{miss}$ if $\Delta\varphi > \pi/2$
    - $E_T\text{miss}_{rel} = E_t\text{miss}.\sin(\Delta\varphi)$ if $\Delta\varphi > \pi/2$

      With

      $\Delta\varphi = \min(\Delta\varphi(E_T\text{miss}, l), \Delta\varphi(E_T\text{miss}, \text{jet}))$
  - $E_T\text{miss}_{rel}$ > 25 GeV



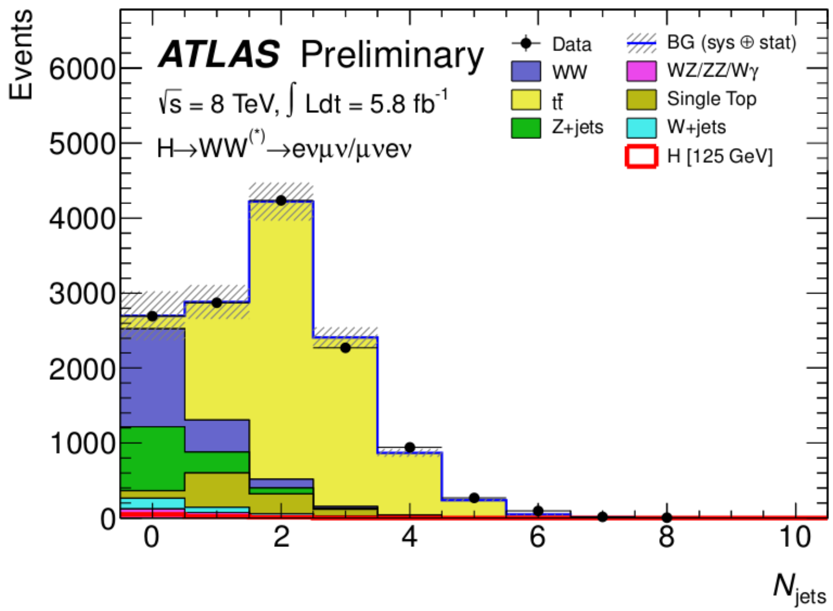
Selection (2) : Jet counting

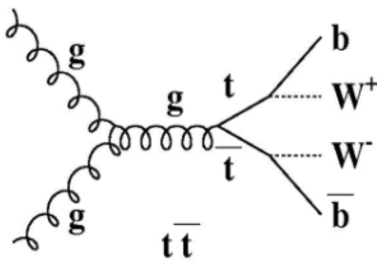
- The background composition and the scalar boson production mode (ggF, VBF, VH) being different, it is more efficient to proceed in optimizing the selection cuts as a function of the number of reconstructed jets

- Because of pile-up effects, the jet counting uses only jets with
  $E_T > 25$ GeV and $|\eta| < 2.5$ or $E_T > 30$ GeV and $2.5 < |\eta| < 4.5$

- Analysis split into the 0, 1 and 2-jets channels :

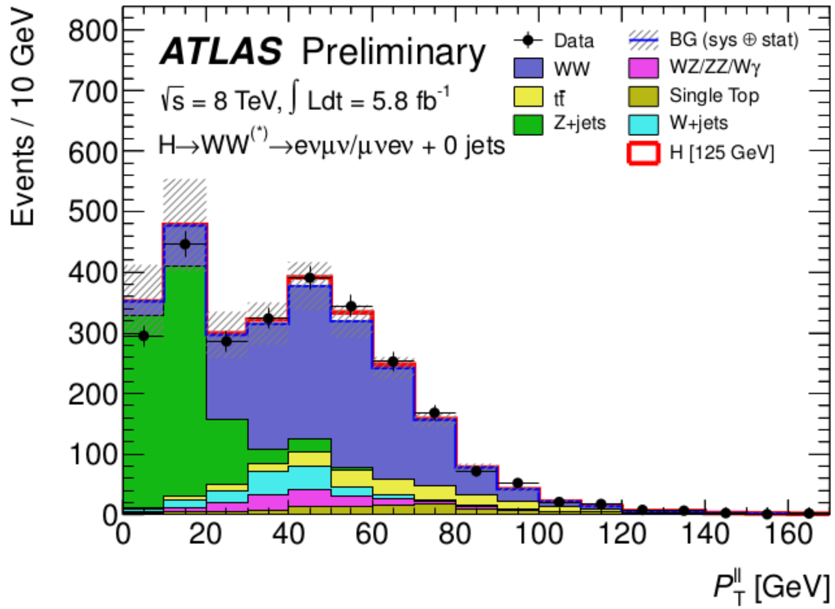
  - Highest sensitivity in the 0-jet channel (WW is the main background)
  - 1-jet channel also very sensitive but large top background
  - 2-jets channel suffers from lack of statistics but allows for probing the VBF production

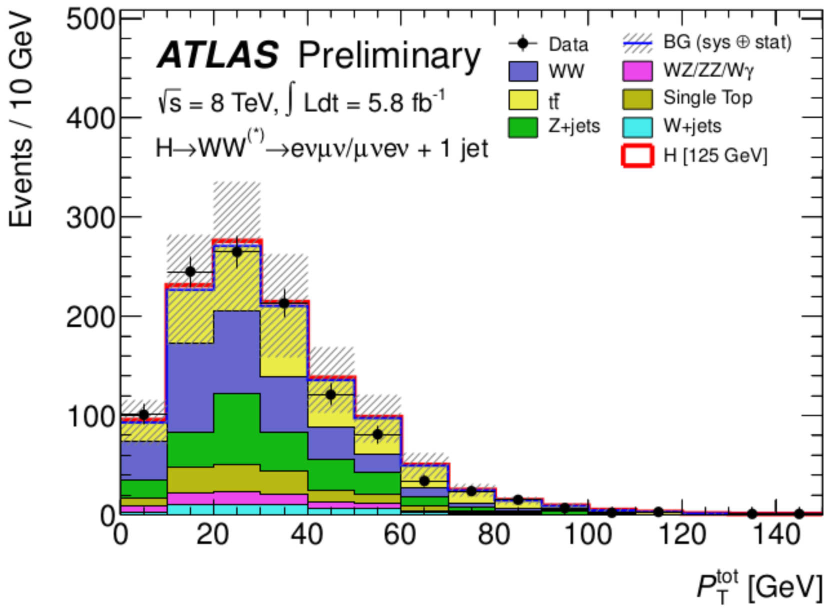




Selection (3) : analysis-dependent cuts

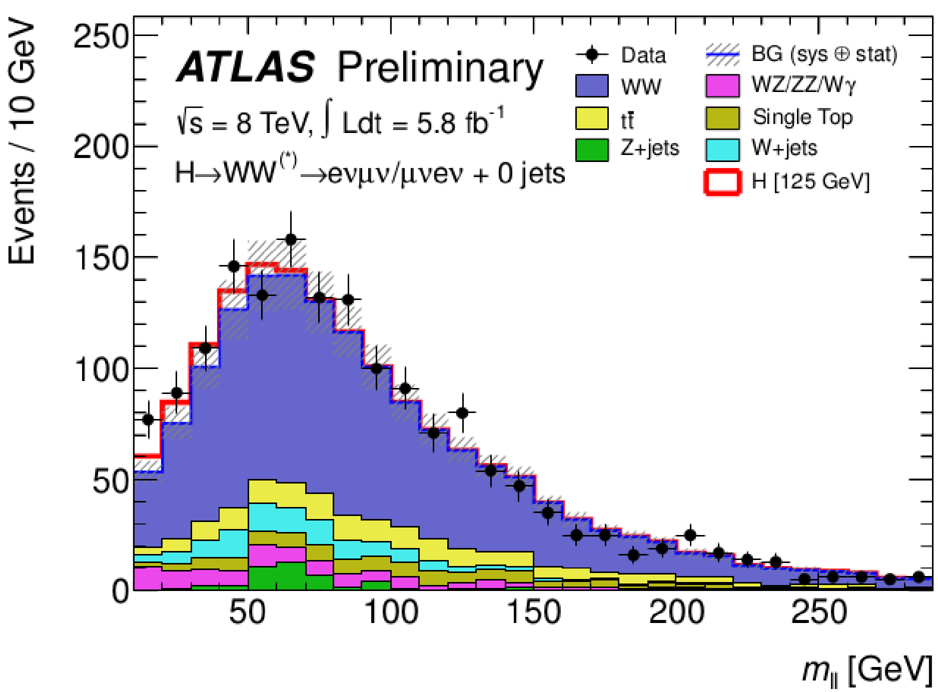
- In 0-jet, DY/Z is a large background which can be rejected by a cut on the transverse momentum of the di-lepton system $p_T(ll) > 30$ GeV
- In 1-jet, top is the dominant background after the preselection :
  - Rejection of events with *b-tagged* jet (track impact parameters and topological cuts on secondary vertices)
  - $|p_T tot| < 30$ GeV with $p_T tot$ the vectorial sum of the leptons momenta, the jet and the missing transverse energy direction
  - $Z \rightarrow \tau\tau$ veto : $|M_{\tau\tau} - M_Z| < 25$ GeV using the collinear approximation for $M_{\tau\tau}$
- In 2-jets, on top of the 1-jet cuts, the two “tag” (i.e. highest pT) jets must be separated by $|\Delta y|>3.8$, must have $m_{jj} > 500$ GeV and no other jet with $p_T > 20$ GeV in between

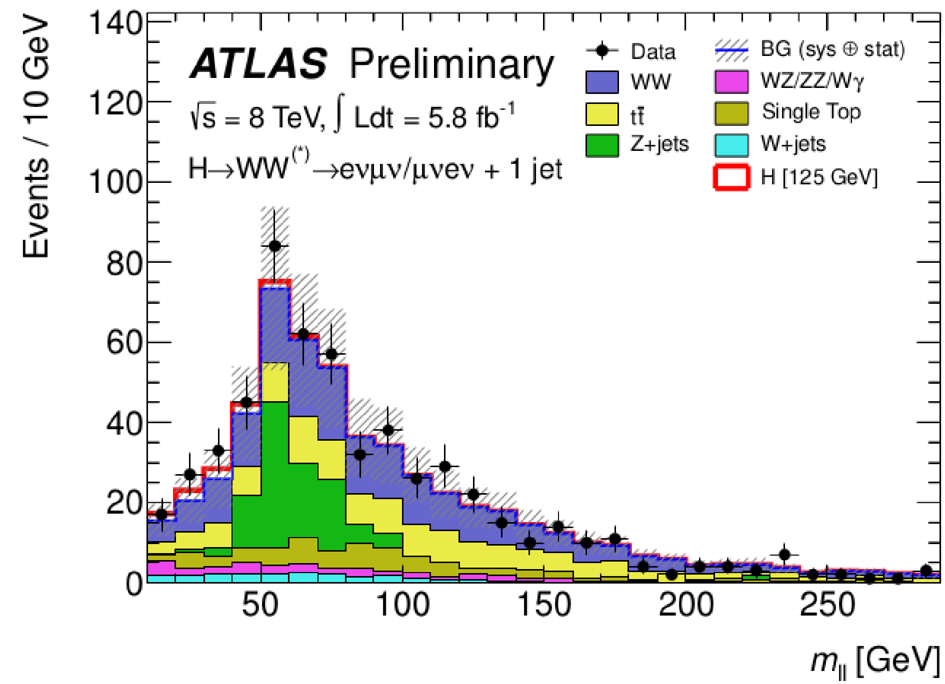




Selection (4) : Topological cuts

- The continuum QCD WW and top backgrounds can be controlled using cuts on:
  - the dilepton invariant mass: $m_{ll} <$ 50 GeV for 0/1-jet
    $m_{ll} <$ 80 GeV for 2-jets
  - the azimuthal angle between the leptons (exploiting the spin correlation in the scalar boson decays):
    $\Delta\varphi_{ll} < 1.8$
  - the transverse mass: $m_T^2 = m_v^2 + 2(e_v|\mathbf{p}_{T,i}| - \mathbf{p}_{T,v}.\mathbf{p}_{T,i})$ and $e_v^2 = \mathbf{p}_{T,v}.\mathbf{p}_{T,v} + m_v^2$
    (v=visible, i=invisible)





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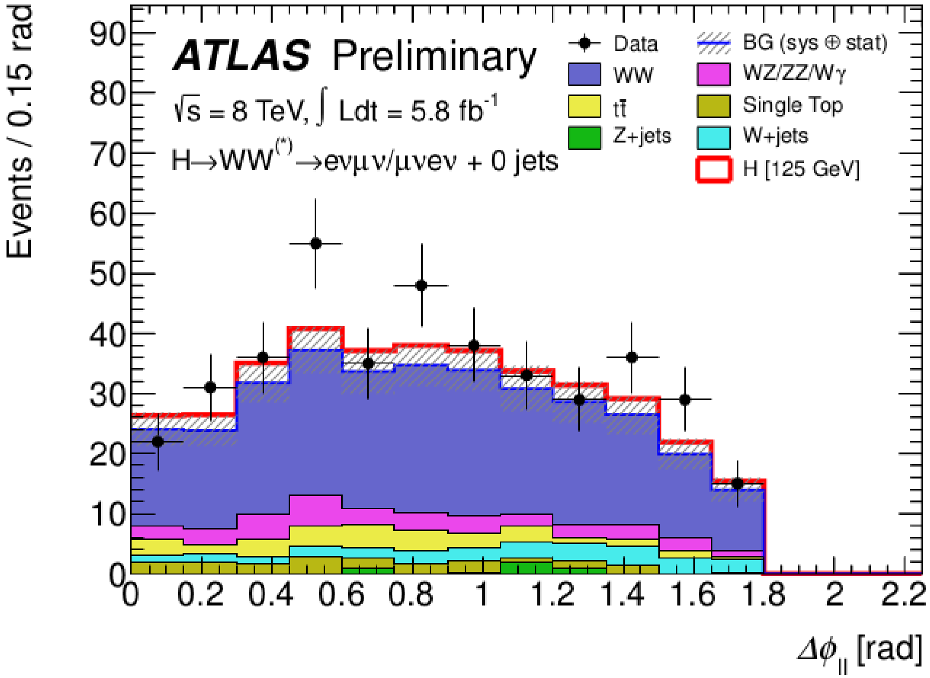
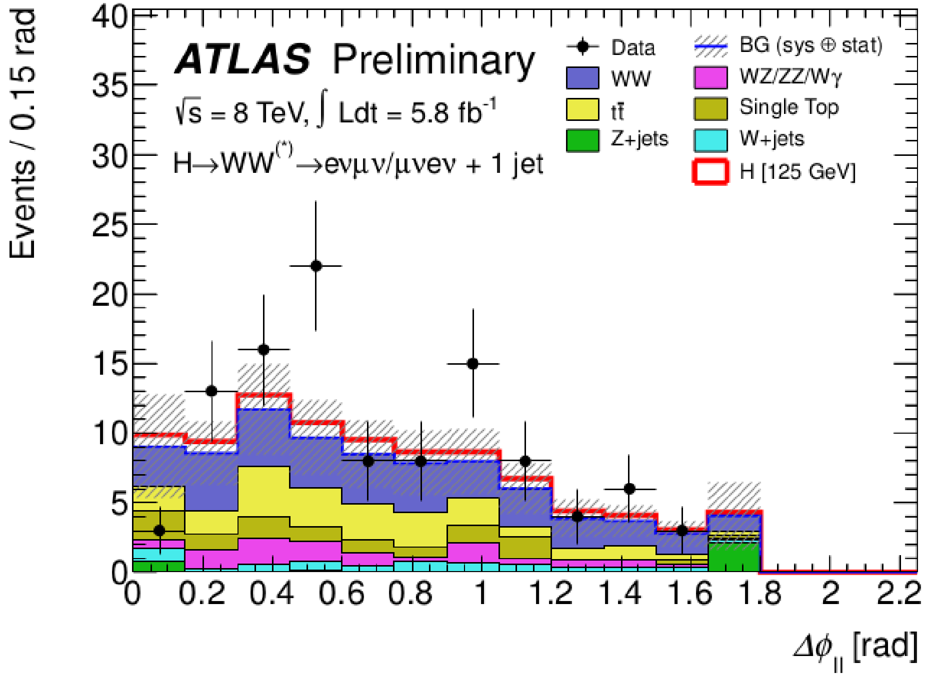
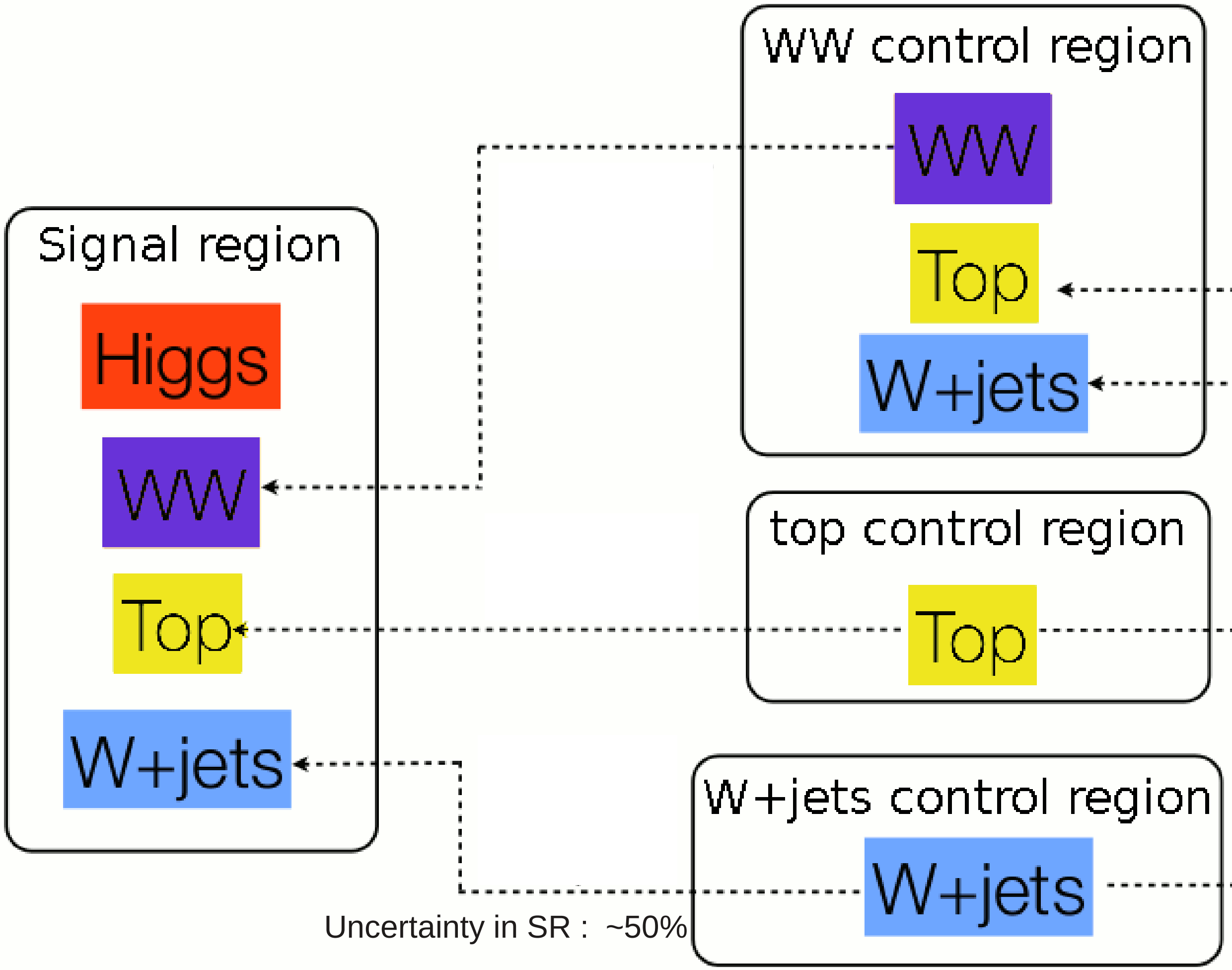
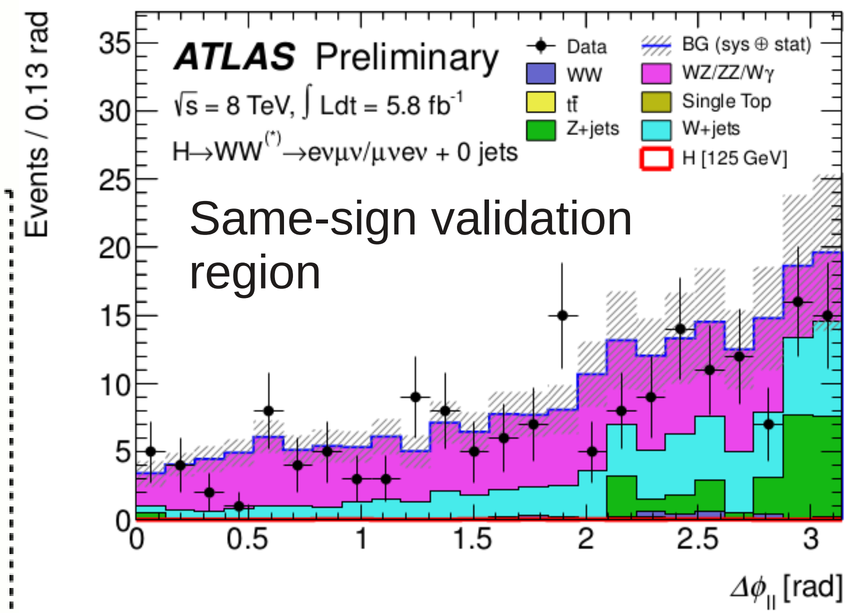




Control regions (1)

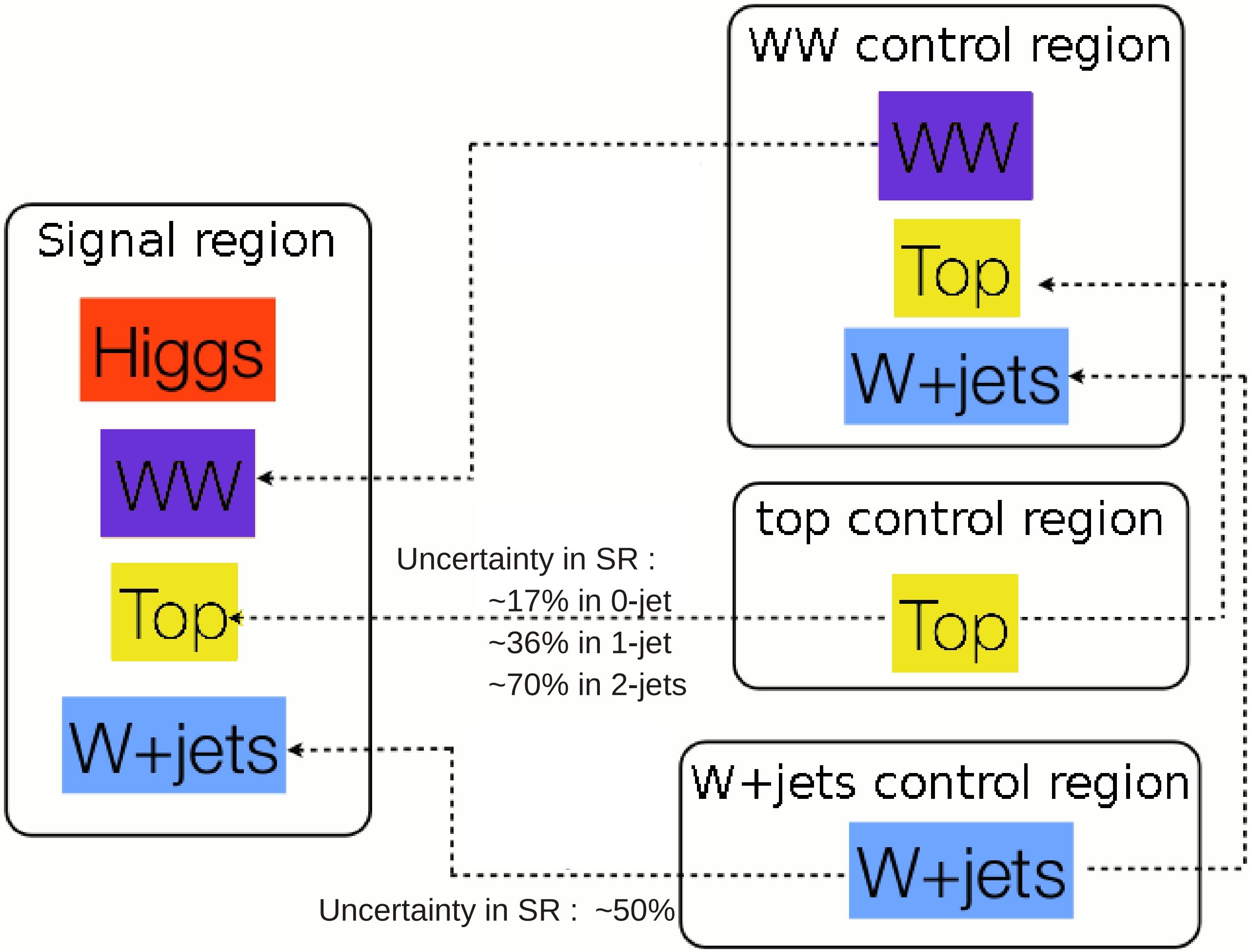
- The dominant backgrounds are estimated from data :





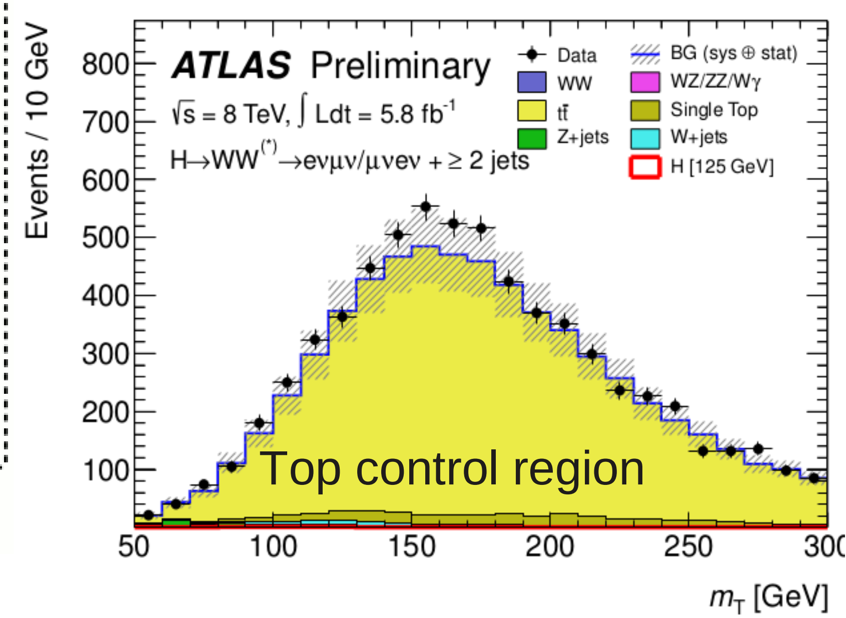
- Based on a sample failing the complete lepton selection + a “fake factor” estimated on di-jets events

Control regions (2)



- 0 jet : preselection multiplied by (probability that top passes b-jet veto)² (estimated on a sample containing a b-jet)

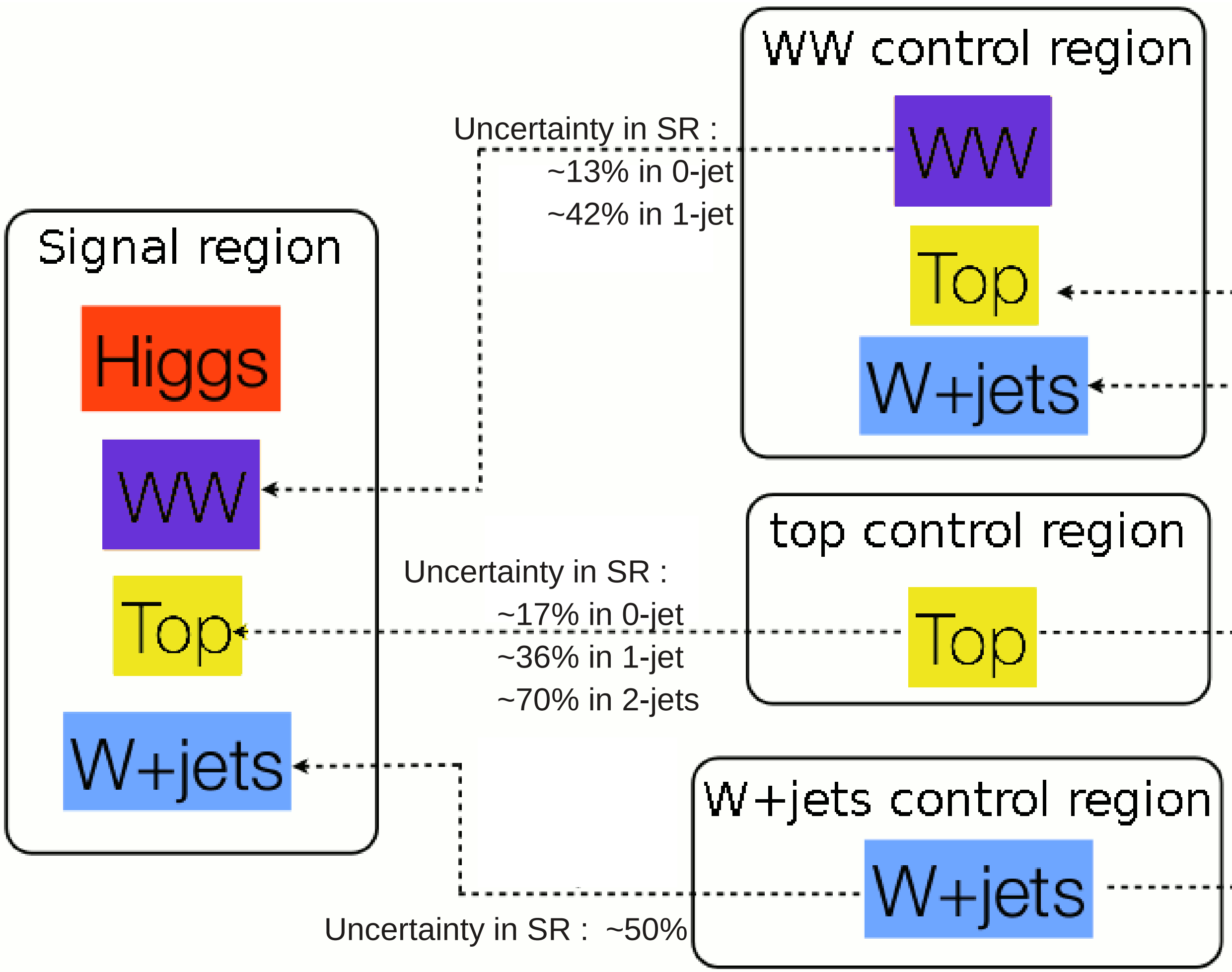
- 1/2 jet : based on an sample enriched in b-jets and built without cuts on $\Delta\varphi_{ll}$, m_{ll} et m_T



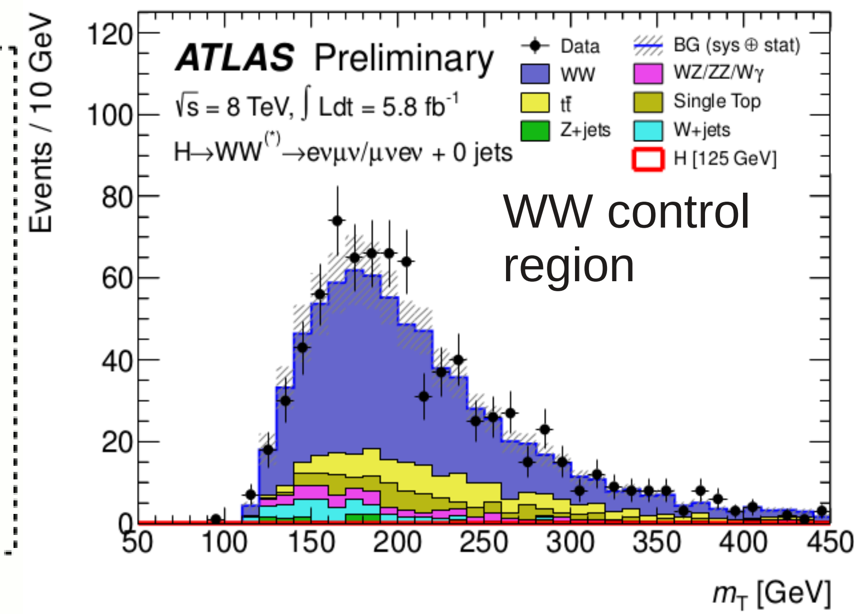
Composition of main control regions

	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W +$ jets	Total Bkg.	Obs.
WW 0-jet	0.3 ± 0.0	531 ± 5	43 ± 2	104 ± 3	62 ± 4	11 ± 4	38 ± 1	789 ± 9	820
WW 1-jet	0.1 ± 0.0	112 ± 3	13 ± 1	80 ± 3	34 ± 3	9 ± 4	7.7 ± 0.8	256 ± 6	255
Top 1-jet	2.2 ± 0.1	39 ± 2	10 ± 1	489 ± 6	195 ± 7	28 ± 7	7 ± 1	768 ± 12	840
Top 2-jet	4.9 ± 0.1	45 ± 2	11.7 ± 1.0	6371 ± 23	315 ± 10	45 ± 8	52 ± 3	6840 ± 26	7178

Control regions (3)



- WW control region built:
  - without cuts on $\Delta\varphi_{ll}$ and m_T
  - Requiring $m_{ll} > 80$ GeV



Composition of main control regions

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Systematic uncertainties

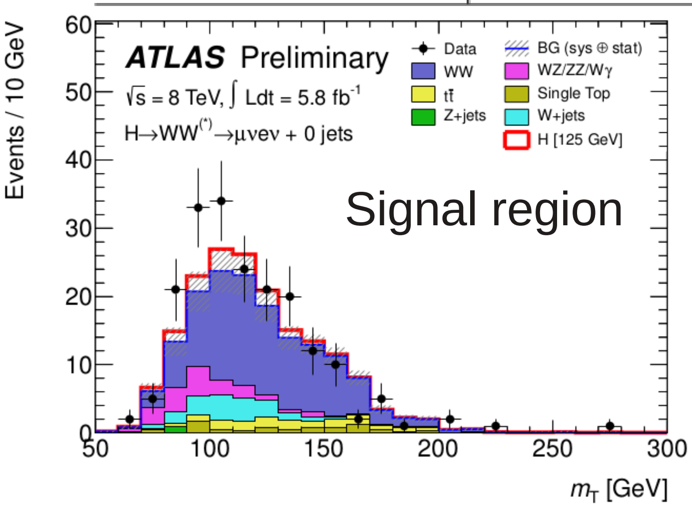
- For m_H~125 GeV, the cross-section uncertainty is at the ~17% level for 0-jet and ~36% for the 1-jet channel, ~10% for the VBF channel
- The underlying event and the parton showering modelling induce uncertainties at the 7-8% level on the signal
- Experimental sources of systematics are varied within their uncertainties, the dominant ones are the jet and missing transverse energy scales and resolutions

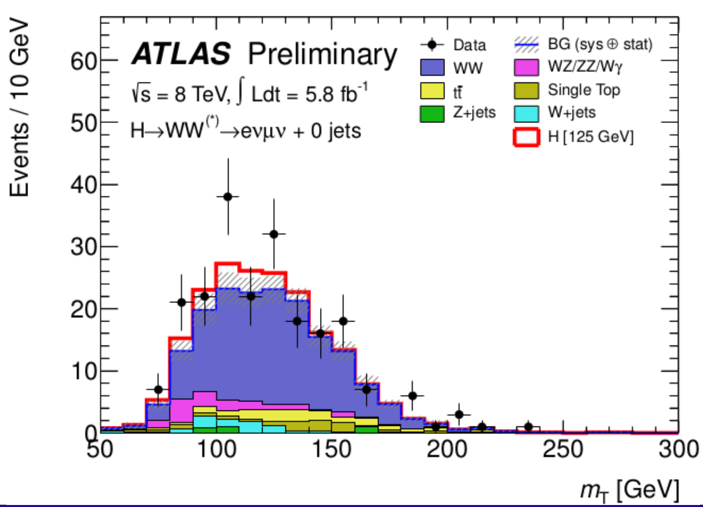
Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal ren./fact. scale	13	0
1-jet incl. ggF signal ren./fact. scale	10	0
Parton distribution functions	8	2
Jet energy scale	7	4
WW modelling and shape	0	5
QCD scale acceptance	4	2
WW normalisation	0	4
W+jets fake factor	0	4
Lepton isolation	3	3
Source (1-jet)	**Signal (%)**	**Bkg. (%)**
1-jet incl. ggF signal ren./fact. scale	28	0
2-jet incl. ggF signal ren./fact. scale	16	0
WW normalisation	0	14
b-tagging efficiency	0	8
Top normalisation	0	6
Pile-up	5	5

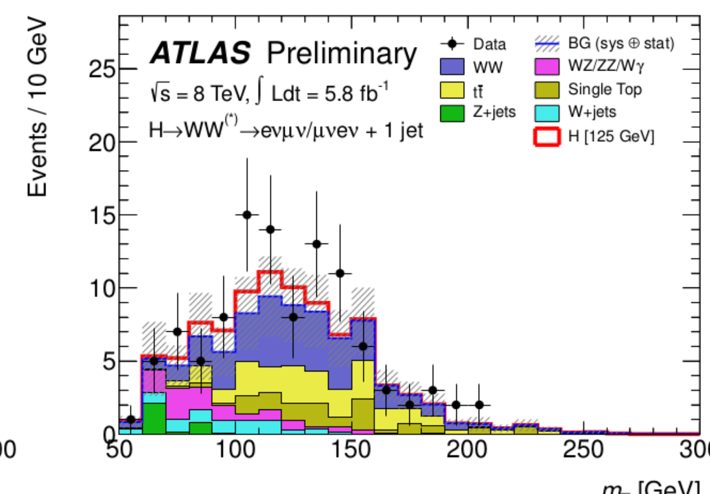
Results

Cutflow evolution in the different signal regions

$H+$ 0-jet	Signal 125 GeV	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W +$ jets	Total Bkg.	Obs.
Jet Veto	47.5 ± 0.4	1308 ± 9	125 ± 4	184 ± 4	109 ± 6	850 ± 32	138 ± 4	2714 ± 34	2691
$p_T^{\ell\ell} > 30$ GeV	43.4 ± 0.4	1077 ± 8	99 ± 4	165 ± 4	98 ± 5	47 ± 8	102 ± 2	1589 ± 14	1664
$m_{\ell\ell} < 50$ GeV	34.9 ± 0.4	244 ± 4	33 ± 2	28 ± 2	17 ± 2	5 ± 2	29 ± 1	356 ± 6	421
$\Delta\phi_{\ell\ell} < 1.8$	33.6 ± 0.4	234 ± 4	32 ± 2	27 ± 2	17 ± 2	4 ± 2	25 ± 1	$\boxed{339 \pm 6}$	$\boxed{407}$
$H+$ 1-jet	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W +$ jets	Total Bkg.	Obs.
1 jet	24.9 ± 0.3	396 ± 5	74 ± 3	1652 ± 12	479 ± 12	283 ± 20	68 ± 3	2953 ± 27	2874
b-jet veto	21.1 ± 0.3	334 ± 4	56 ± 2	349 ± 6	115 ± 6	236 ± 18	53 ± 2	1144 ± 21	1115
$\lvert\mathbf{p}_T^{tot}\rvert < 30$ GeV	12.2 ± 0.2	210 ± 3	30 ± 2	139 ± 4	63 ± 5	124 ± 14	23 ± 2	590 ± 15	611
$Z \to \tau\tau$ veto	12.2 ± 0.2	204 ± 3	29 ± 2	133 ± 3	61 ± 5	98 ± 12	23 ± 2	547 ± 14	580
$m_{\ell\ell} < 50$ GeV	9.2 ± 0.2	37 ± 1	10 ± 1	21 ± 1	12 ± 2	16 ± 5	8.0 ± 0.9	104 ± 6	122
$\Delta\phi_{\ell\ell} < 1.8$	8.6 ± 0.2	34 ± 1	9 ± 1	20 ± 1	11 ± 2	3 ± 2	6.4 ± 0.7	$\boxed{84 \pm 4}$	$\boxed{106}$
$H+$ 2-jet	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W +$ jets	Total Bkg.	Obs.
≥ 2 jets	14.5 ± 0.2	139 ± 3	30 ± 2	7039 ± 24	376 ± 11	104 ± 12	71 ± 4	7759 ± 29	7845
b-jet veto	9.6 ± 0.2	95 ± 2	19 ± 1	356 ± 6	44 ± 4	62 ± 9	21 ± 2	597 ± 12	667
$\lvert\Delta Y_{jj}\rvert > 3.8$	2.0 ± 0.1	8.3 ± 0.6	2.0 ± 0.4	31 ± 2	5 ± 1	4 ± 2	1.4 ± 0.5	52 ± 3	44
Central jet veto (20 GeV)	1.6 ± 0.1	6.5 ± 0.5	1.3 ± 0.3	16 ± 1	4 ± 1	1 ± 1	0.5 ± 0.3	29 ± 2	22
$m_{jj} > 500$ GeV	1.1 ± 0.0	3.2 ± 0.4	0.7 ± 0.2	6.2 ± 0.7	1.8 ± 0.6	0.0 ± 0.0	0.0 ± 0.2	12 ± 1	13
$\lvert\mathbf{p}_T^{tot}\rvert < 30$ GeV	0.8 ± 0.0	1.7 ± 0.3	0.3 ± 0.1	2.5 ± 0.5	0.8 ± 0.4	0.0 ± 0.0	0.0 ± 0.2	5.4 ± 0.7	6
$Z \to \tau\tau$ veto	0.7 ± 0.0	1.8 ± 0.3	0.3 ± 0.1	2.4 ± 0.4	0.8 ± 0.4	0.0 ± 0.0	0.0 ± 0.2	5.2 ± 0.7	6
$m_{\ell\ell} < 80$ GeV	0.7 ± 0.0	0.6 ± 0.2	0.1 ± 0.1	0.8 ± 0.3	0.3 ± 0.2	0.0 ± 0.0	0.0 ± 0.2	1.9 ± 0.5	3
$\Delta\phi_{\ell\ell} < 1.8$	0.6 ± 0.0	0.5 ± 0.2	0.1 ± 0.1	0.5 ± 0.3	0.3 ± 0.2	0.0 ± 0.0	0.0 ± 0.2	1.4 ± 0.4	2







Results (2)

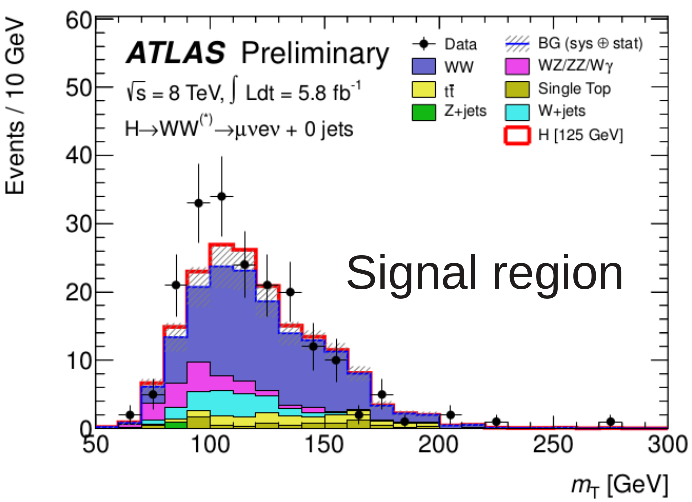
- Enriched signal region selected using a transverse mass window (not used in the final result) defined by

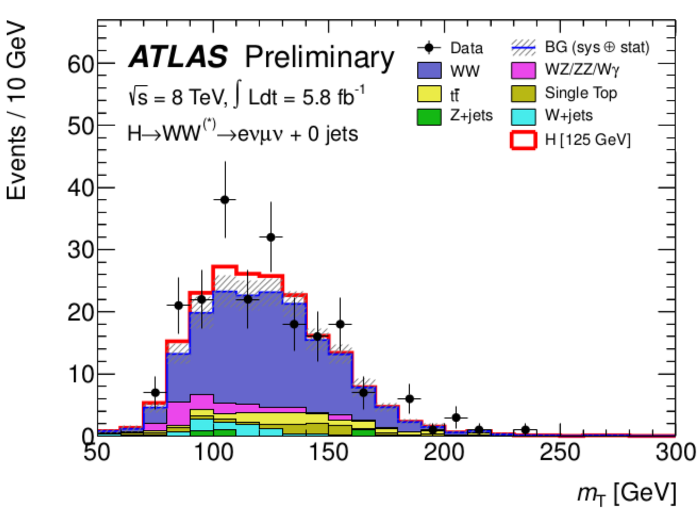
$$0.75 \times m_H < m_T < m_H,$$

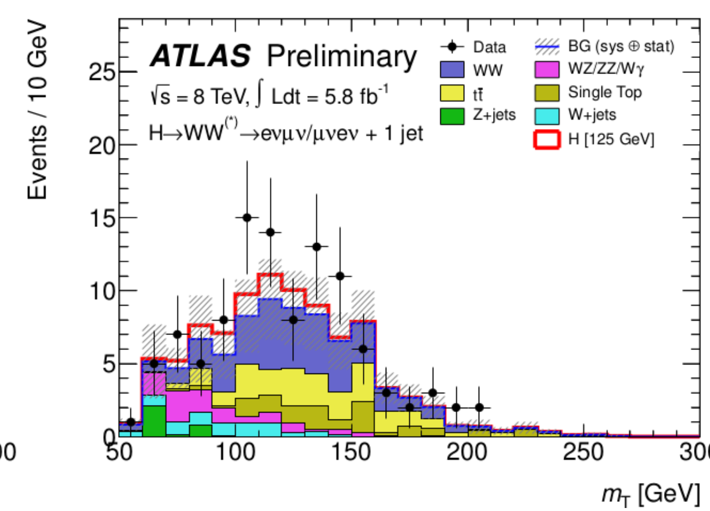
here below for m_H = 125 GeV :

	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* + \text{jets}$	$W + \text{jets}$	Total Bkg.	Obs.
$H+0$-jet	20 ± 4	101 ± 13	12 ± 3	8 ± 2	3.4 ± 1.5	1.9 ± 1.3	15 ± 7	142 ± 16	185
$H+1$-jet	5 ± 2	12 ± 5	1.9 ± 1.1	6 ± 2	3.7 ± 1.6	0.1 ± 0.1	2 ± 1	26 ± 6	38
$H+2$-jet	0.34 ± 0.07	0.10 ± 0.14	0.10 ± 0.10	0.15 ± 0.10	-	-	-	0.35 ± 0.18	0

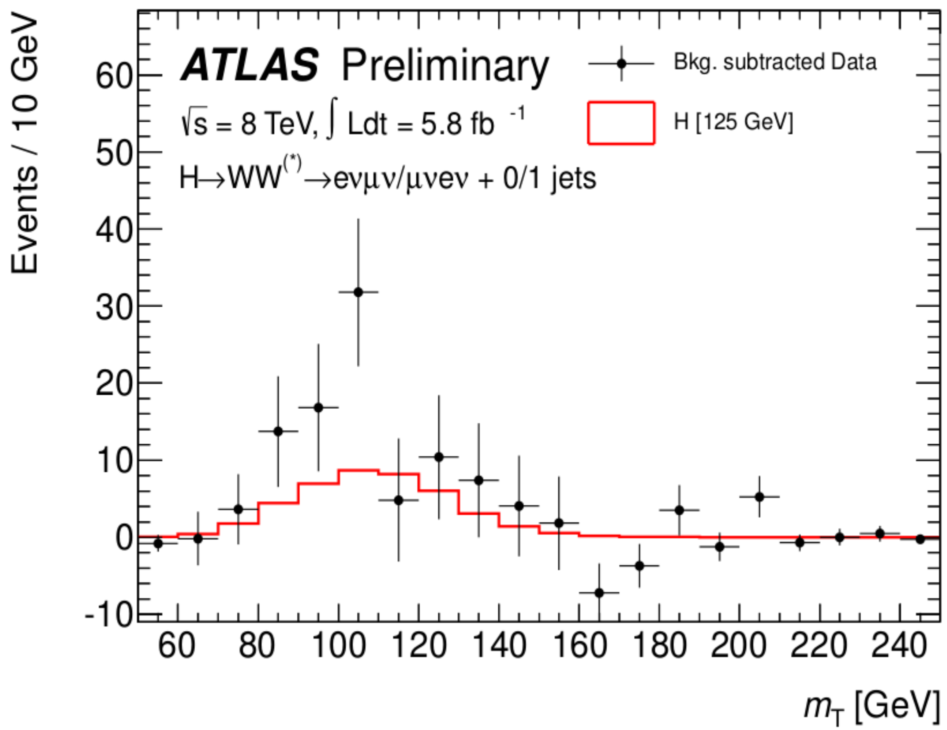
- Final statistical treatment uses a fit of the transverse mass distributions :

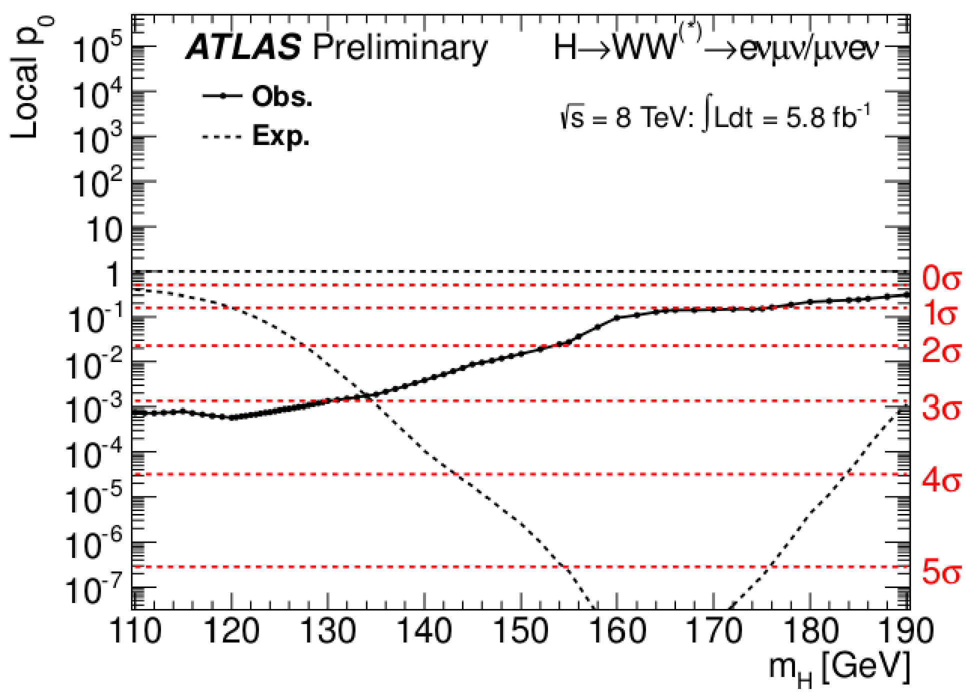






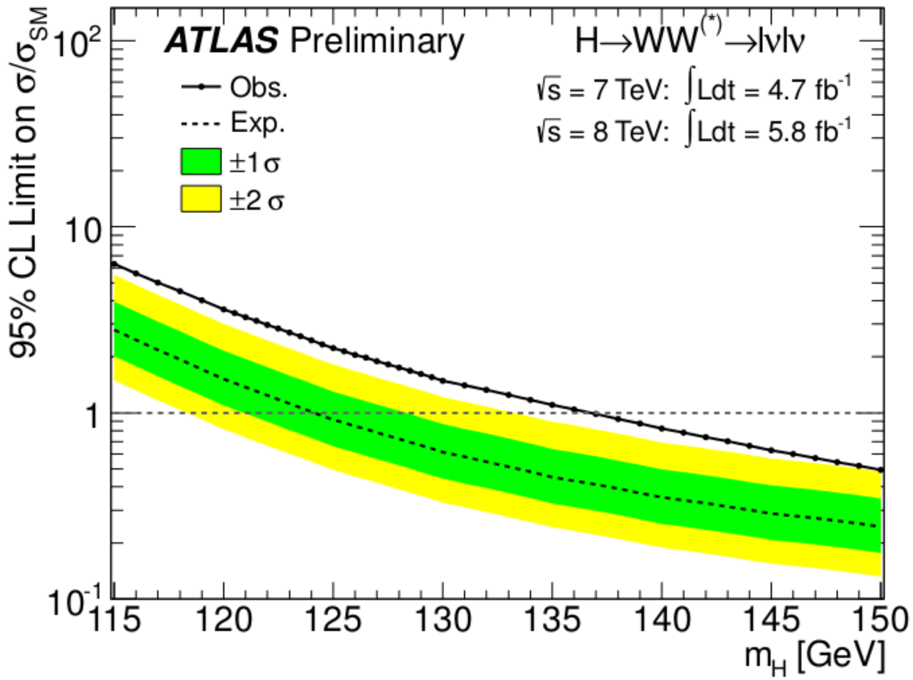
Results (3)

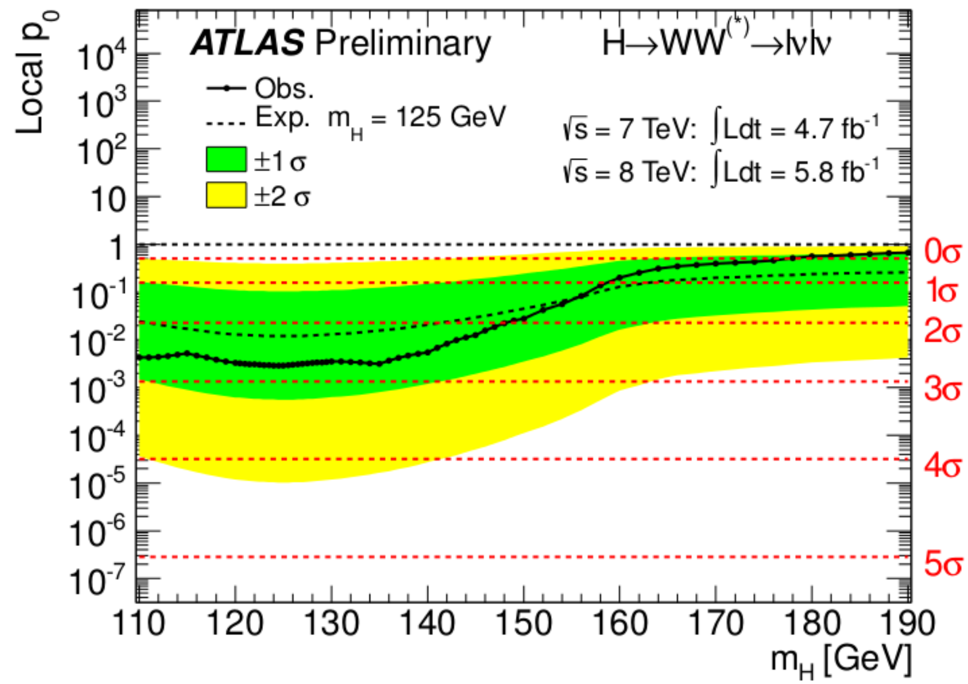




- Background-subtracted transverse mass distribution overlaid to the Standard Model scalar boson signal prediction on the left exhibiting a signal-like shape
- p0 plot on the right for the H $\rightarrow$ W^+W^- $\rightarrow$ lνlν analysis using L=5.8 fb^{-1} shows how unlikely is the background-only hypothesis
- p-value at 125 GeV is 0.0008 corresponding to a 3.1σ deviation
- Due to the limited mass resolution of this channel, the excess is visible on this Figure on a broad mass range

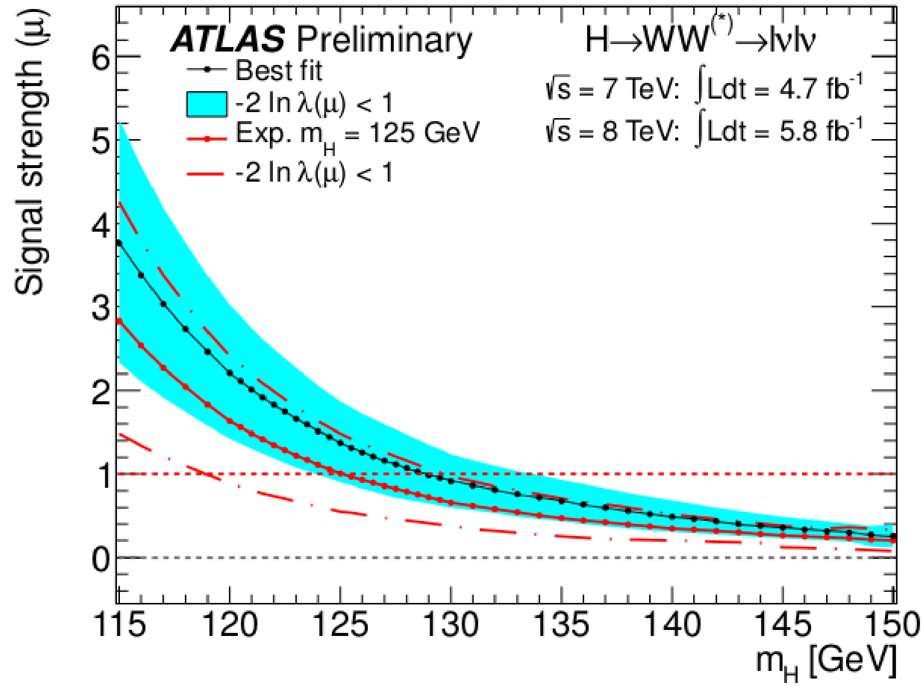
2011 + 2012 combined results

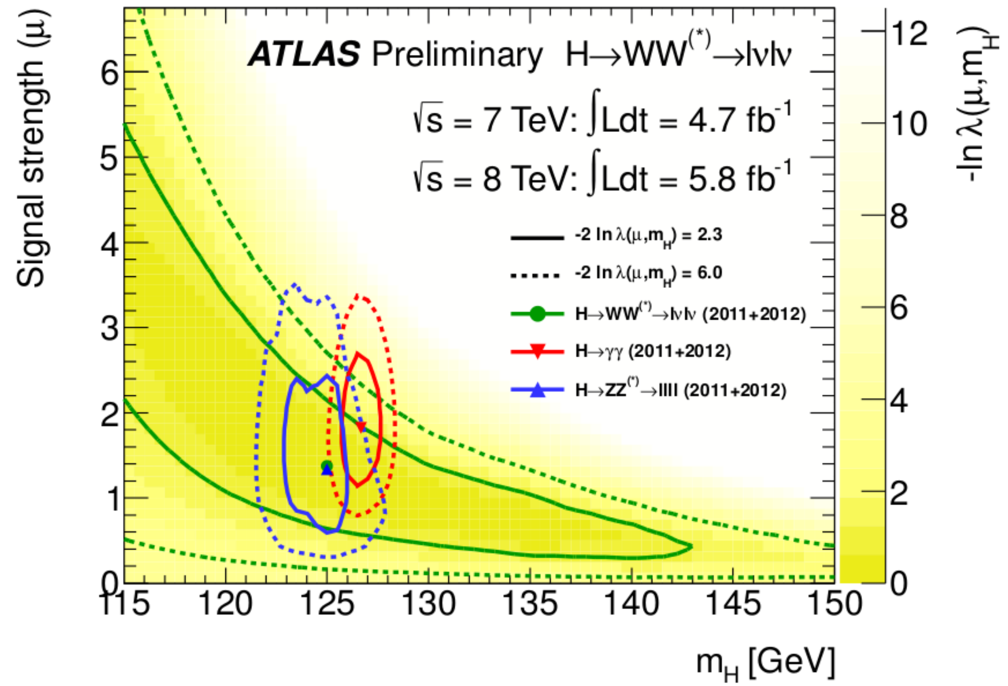




- Combining 2011 and 2012 data analyses results, the exclusion at 95% CLs was expected for masses above 124 GeV in the absence of a signal
- Due to the excess of observed events, the low mass signal region can not be excluded
- The p-value observed at 125 GeV is 0.003 corresponding to a 2.8σ deviation
- The injection plot on the right (corresponding to an injected SM Higgs at 125 GeV) shows that the shape and normalization of p_0 are in agreement with the presence of a signal at this mass

2011 + 2012 combined results (2)





- The fitted signal strength parameter as a function of m_H in black on the left figure shows the good agreement with the expected result for a signal hypothesis of m_H = 125 GeV in red

- The fitted signal strength at 125 GeV is $\mu = 1.4 \pm 0.5$

- Despite the limited mass resolution, the H → W^+W^- → lνlν channel is in good agreement with the H → ZZ and H → γγ results

Conclusion

- Year 2011 was a very nice year in terms of Standard Model scalar boson mass exclusion...
- Year 2012 is the year of discovery !

- A large excess of data over the Monte Carlo has been observed in the $H \rightarrow W^+W^- \rightarrow l\nu l\nu$ channel
- The excess is compatible with the (spin 0) Standard Model scalar boson prediction for a mass around 125 GeV

$$\mu = 1.4 \pm 0.5$$

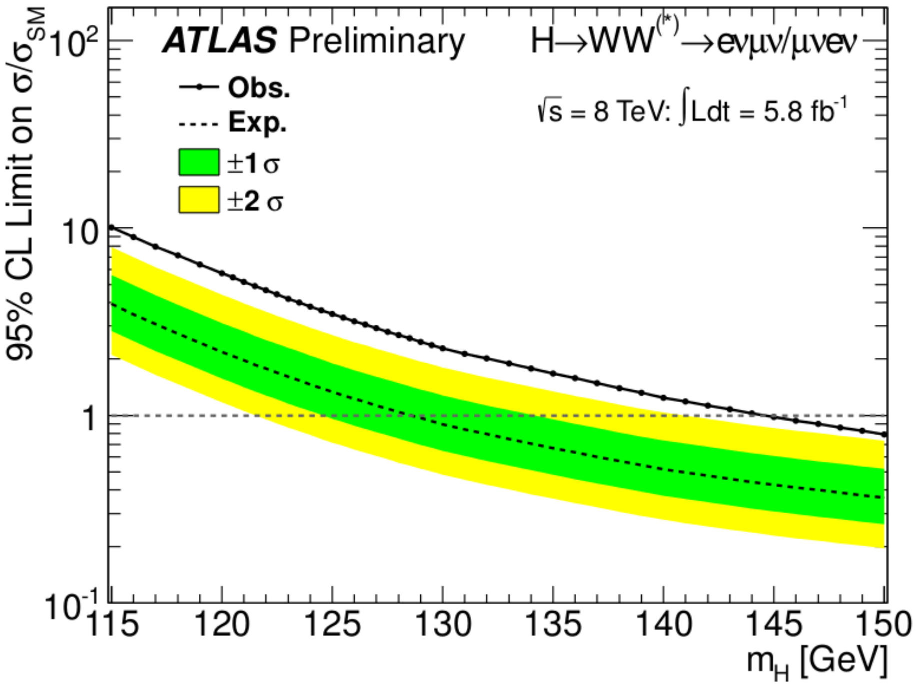
- These results will be documented in a paper in common with the ZZ and diphoton analyses, to be submitted at the end of the month

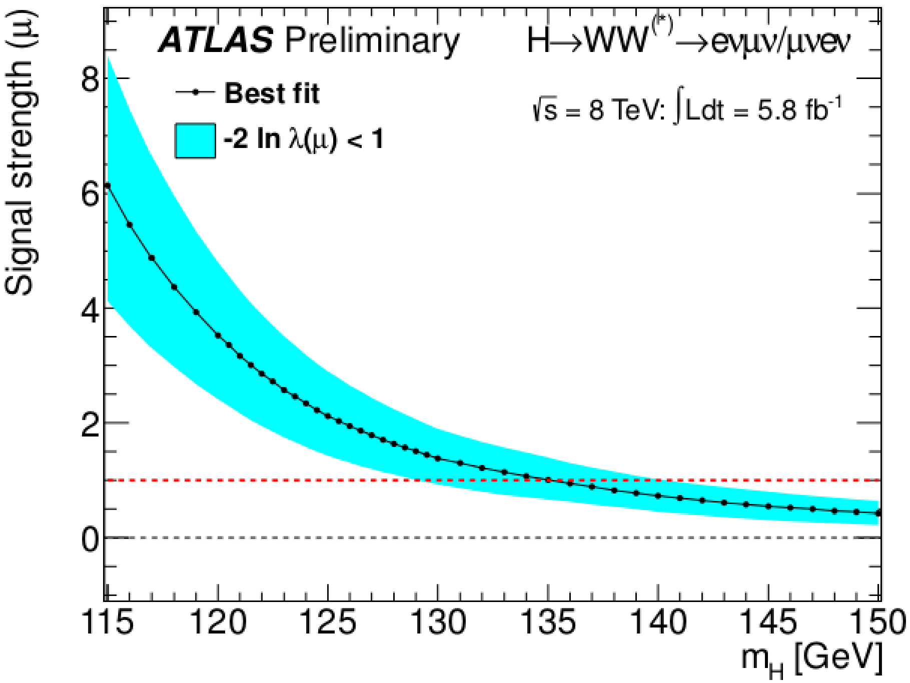
Backup slides

Monte Carlo samples

Process	Generator	m_H (GeV)	$\sigma \cdot \mathrm{Br}$ (pb)
ggF	POWHEG [18]+PYTHIA8 [19]	125	0.442
VBF	POWHEG [20]+PYTHIA8	125	$35 \cdot 10^{-3}$
WH/ZH	PYTHIA8	125	$25 \cdot 10^{-3}$
$q\bar{q}/g \to WW$	MC@NLO [21]+HERWIG [22]		5.68
$gg \to WW$	GG2WW [23]+HERWIG		0.16
$t\bar{t}$	MC@NLO+HERWIG		238.1
$tW/tb/tqb$	AcerMC [24]+PYTHIA8		84
inclusive W	ALPGEN [25]+HERWIG		$37 \cdot 10^{3}$
inclusive Z/γ^*	ALPGEN+HERWIG		$15 \cdot 10^{3}$
$Z^{(*)}Z^{(*)} \to 4l$	POWHEG+PYTHIA8		1.24
$WZ^{(*)}$	MADGRAPH [26,27]+PYTHIA [28]		1.54
$W\gamma^*$	MADGRAPH [29]+PYTHIA		9.26
$W\gamma$	ALPGEN+HERWIG		369

2012 results





Recent 2011 results : lʋjj

- Non-resonant background modelled by a smooth function

$$f(x)=\frac{1}{1+\left|a(x-m)^{b}\right|}e^{-c(x-200)}$$

validated on MC and fitted in the W mass sidebands

- Results well consistent with background-only hypothesis with 300 and 600 GeV