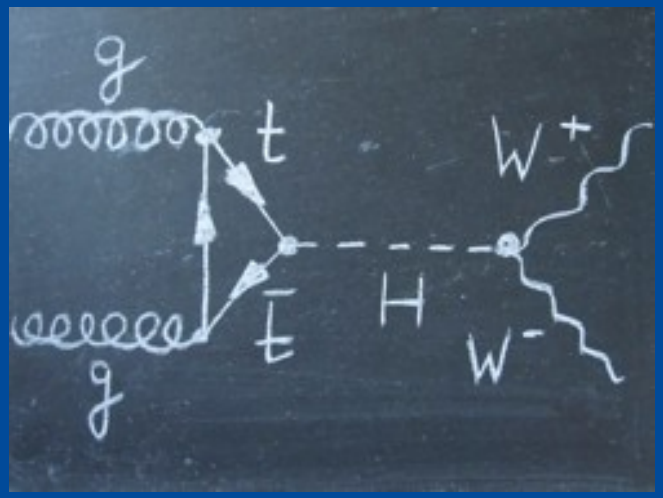
Search for the Standard Model Higgs Boson in $H \rightarrow WW \rightarrow l\nu\, l\nu$ with the ATLAS experiment



Evelyn Schmidt

Albert-Ludwigs-Universität Freiburg

ATLAS EXPERIMENT

FSP 101 ATLAS

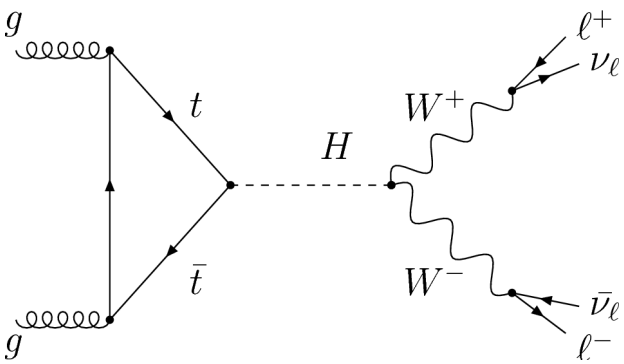
Deutsche Forschungsgemeinschaft DFG

SPONSORED BY THE Federal Ministry of Education and Research

UNI FREIBURG

MCTP Symposium 2012, University of Michigan, Ann Arbor, US

Outline



- SM Higgs Boson production and decay
- Analysis based on **4.7 fb^{-1}** :

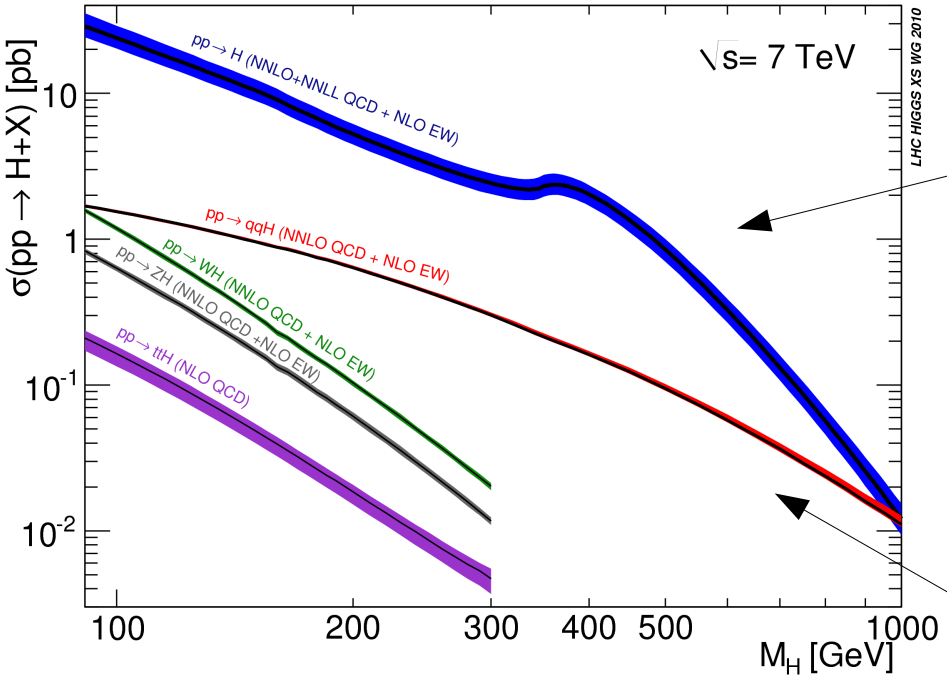
  → Introduction and selection

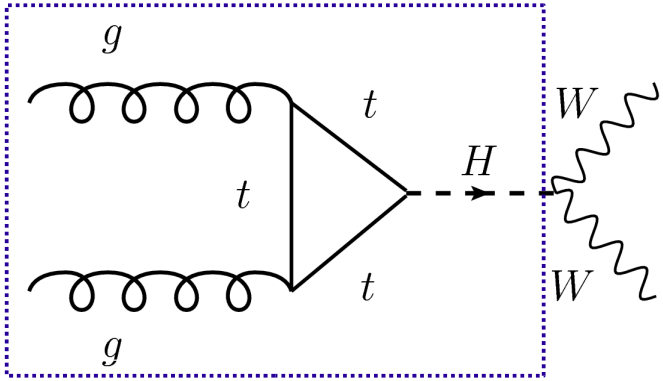
  → Background estimates
  - WW control region
  - ttbar and single top
  - Z+jets (ABCD method)
  - data-driven W+jets estimate

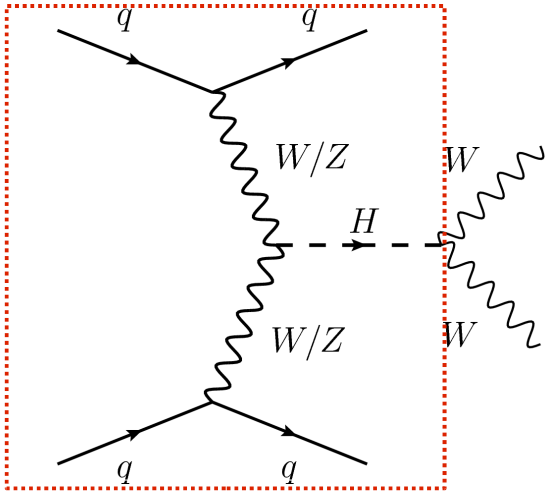
  → Systematic uncertainties

- Results and limits

Introduction





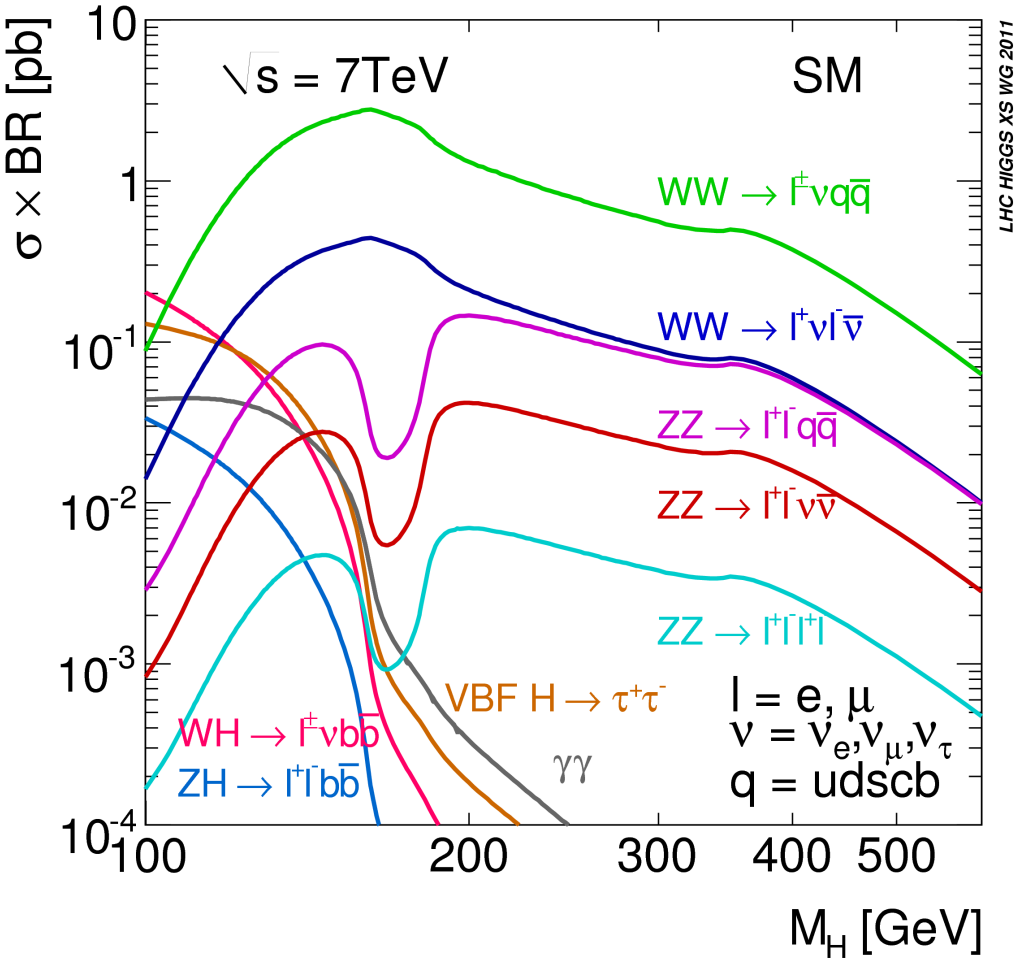


- Gluon fusion is the dominant mechanism for Higgs Boson production at present hadron colliders
- Second most important process: vector boson fusion (VBF)

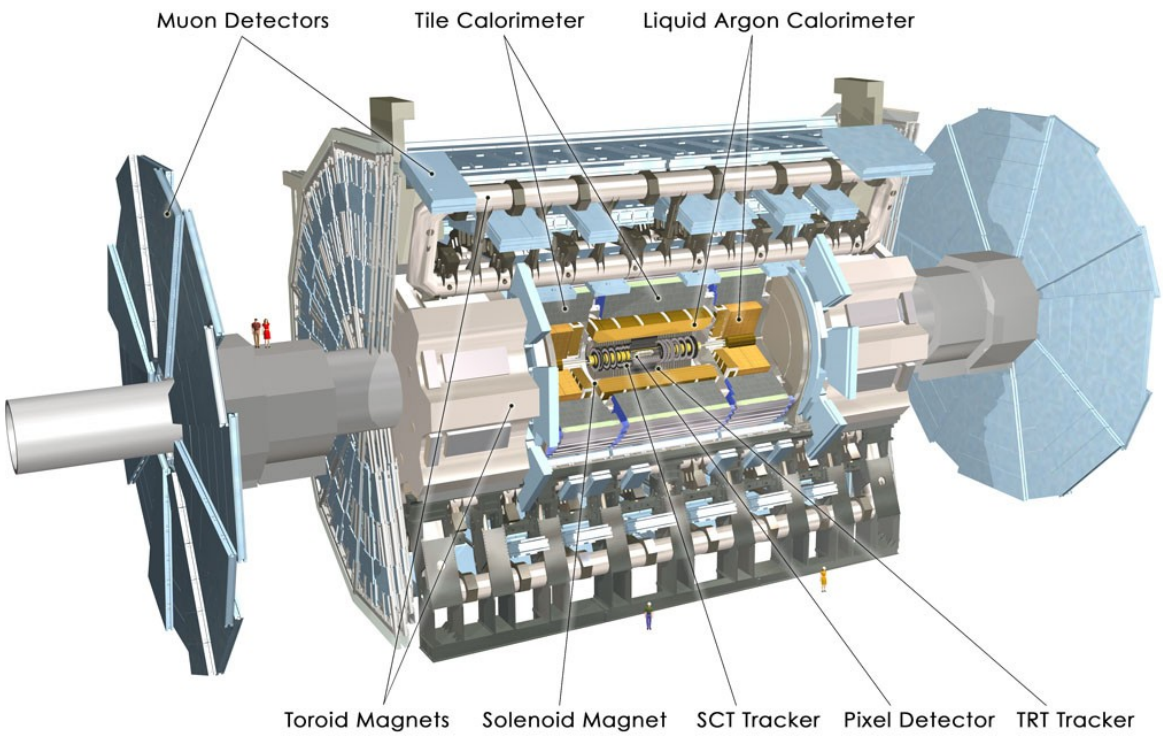
Introduction

H → WW → lν lν

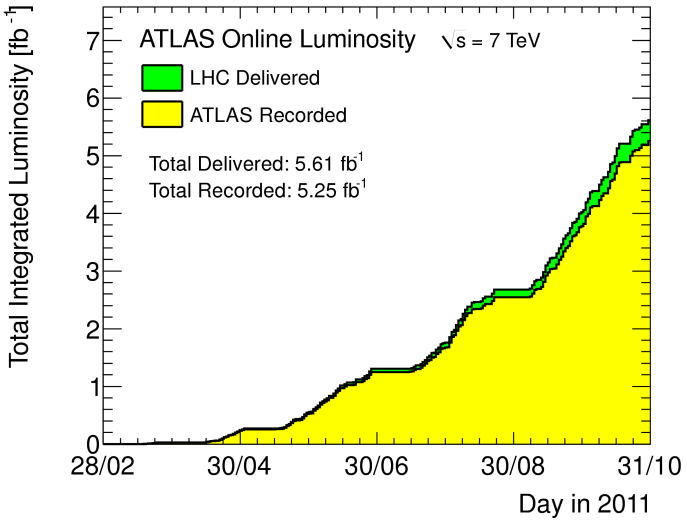
- very important at intermediate mass range
- clear signature of two high-p_T, opposite sign leptons and large transverse missing energy
- challenging because complete reconstruction of invariant mass of the final system not possible
- advantage of VBF signature: Two hard jets in opposite detector hemispheres
- Important backgrounds are:
  - irreducible WW SM production
  - but also W+jets, Drell-Yan and Top (tt + single top) process



Introduction



Analysis presented is based on data corresponding to an integrated luminosity of **5.25 fb^{-1}** recorded by ATLAS during stable beams and for pp collisions at 7 TeV centre-of-mass energy in 2011.

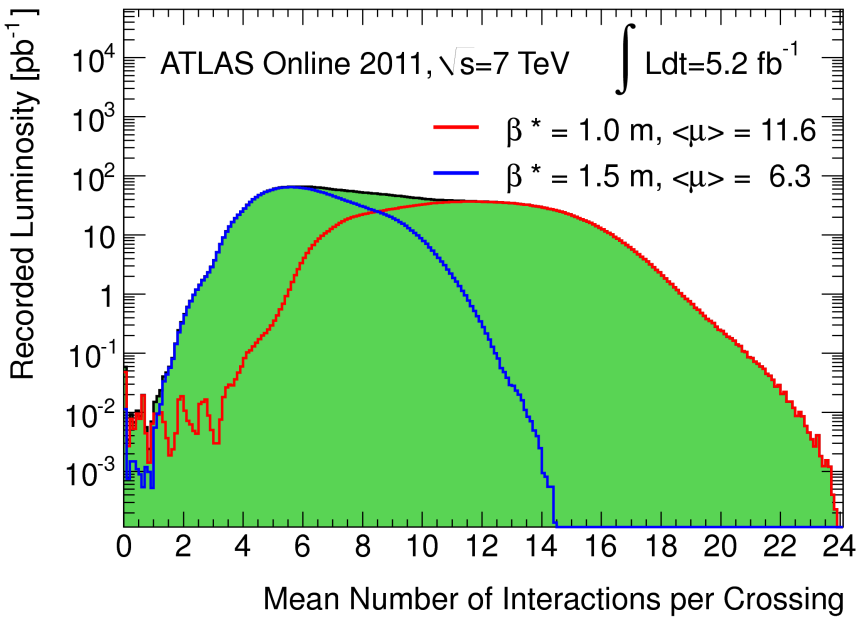


Introduction

Pile-up challenge:

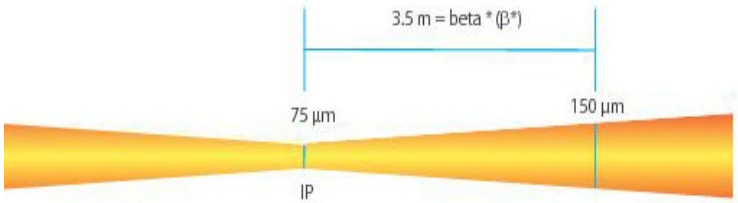
- 50 ns bunch spacing for ~all 2011 data

→ Substantial in- and out-of-time pileup
average number of pileup events: $\mu \approx 6$, $\mu \approx 11.6$



Mean Number of Interactions per Crossing:

- data taken before and after the September Technical Stop where the β^* was reduced from 1.5 m to 1.0 m.
- β^* is the distance to the interaction point (IP) where the beam width has doubled

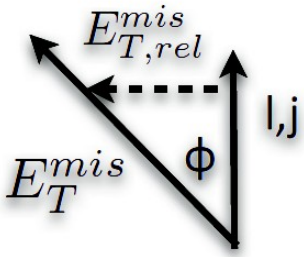


Event selection

Search for the Higgs boson in the H->WW*->lvlv decay mode
with 4.7 fb^{-1} of ATLAS data at $\sqrt{s}$ = 7 TeV (ATLAS-CONF-2012-012)
[link: http://cdsweb.cern.ch/record/1429660]

- Exactly two isolated leptons with opposite charge, leading lepton p_T > 25 GeV and subleading lepton p_T > 15 GeV
- Missing transverse energy
- 0, 1 or more then 2 accompanying jets

- **<u>Missing transverse energy</u>** E_T^{miss}**:**
  - Use cut on $E_T^{miss}(rel)$ instead of normal E_T^{miss}
  - Less sensitive to lepton momentum mis-measurement
  - Rejects events where the E_T^{miss} is pointing along the direction of a lepton or jet:



$$E_T^{miss}(rel) = \begin{cases} E_T^{miss} & \text{if } \min[\Delta\varphi(E_T^{miss}, l), \Delta\varphi(E_T^{miss}, j)] > \pi/2 \\ E_T^{miss} * \sin(\Delta\varphi) & \text{if } \min[\Delta\varphi(E_T^{miss}, l), \Delta\varphi(E_T^{miss}, j)] < \pi//2 \end{cases}$$

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- Exactly two isolated leptons with opposite charge, leading lepton p_T > 25 GeV and subleading lepton p_T > 15 GeV
- missing transverse energy
- 0, 1 or more then 2 accompanying jets

- **<u>Background processes</u> :**

  - SM WW process is irreducible background
  - Top (tt and single top) process
  - Z/γ*+jets events
  - W+jets events

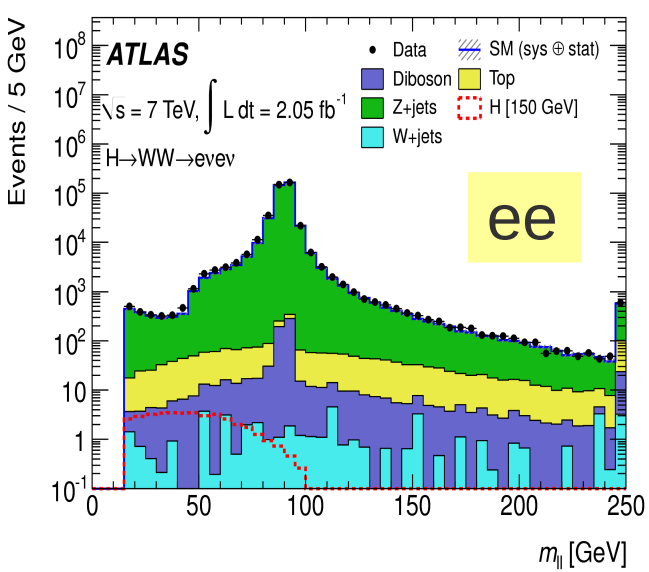
Event selection

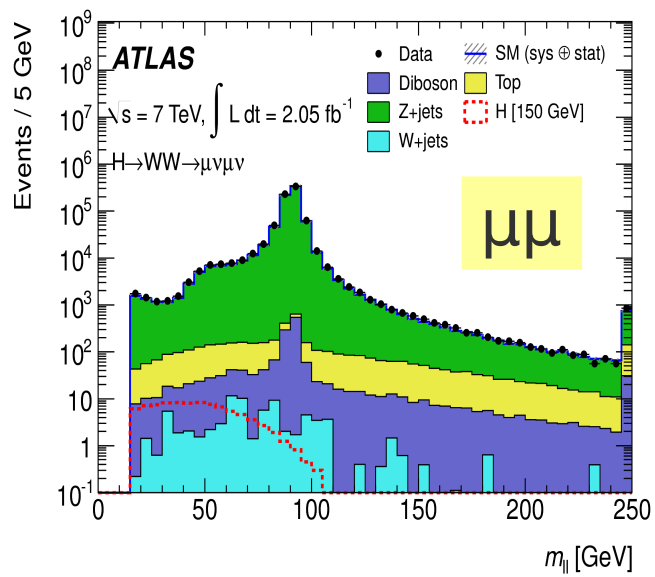
Event Selection

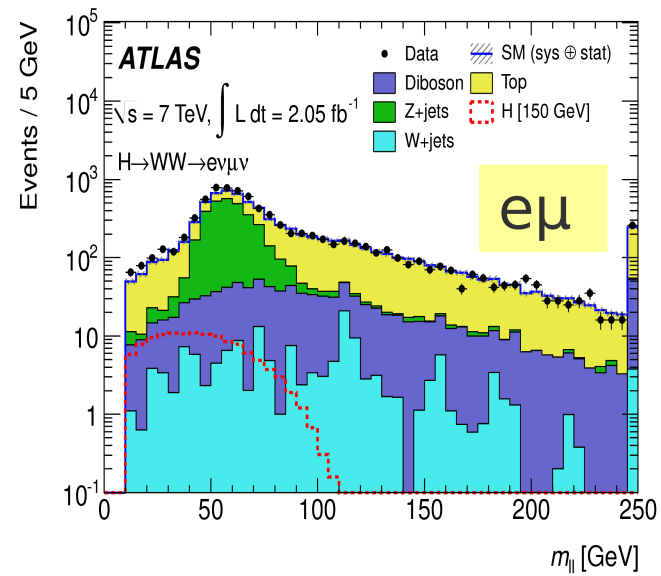
- Single electron or muon trigger ($p_T \geqslant 20$ GeV threshold)
- at least one primary vertex with at least 3 tracks

- Exactly two tight and isolated leptons, leading lepton $p_T > 25$ GeV
  subleading lepton $p_T > 15$ GeV
- Opposite charge
- $m_{ll} > 12$ GeV (10 GeV) for ee/μμ, (eμ)

Common selection
0-jet, 1-jet, 2-jets channel





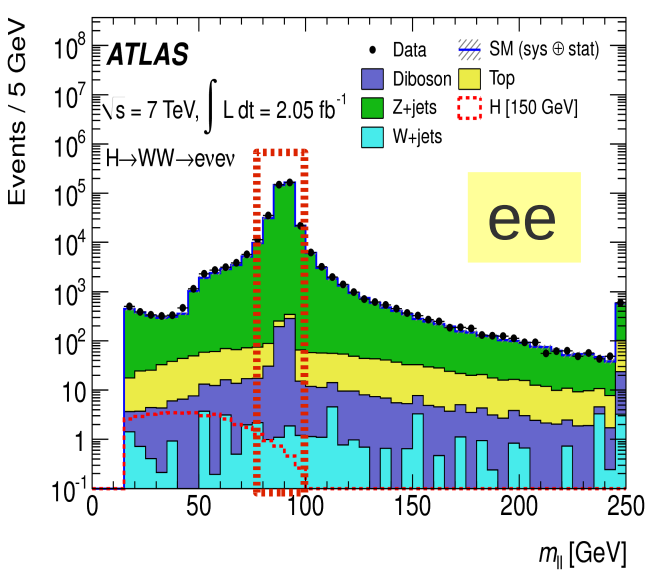


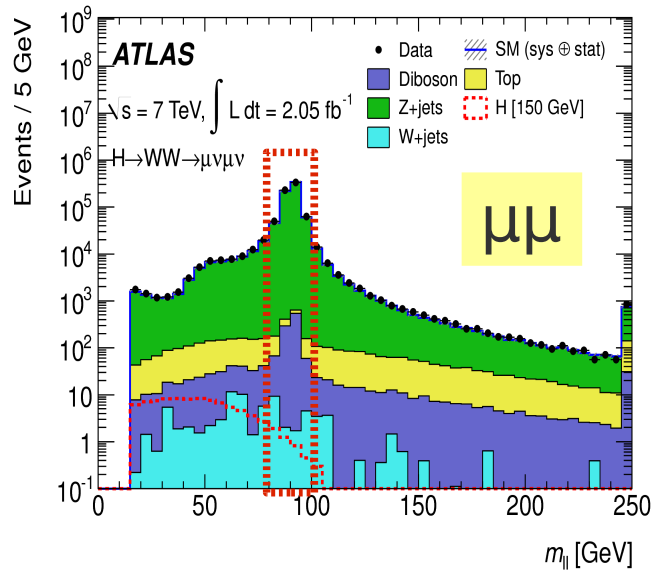
Event selection

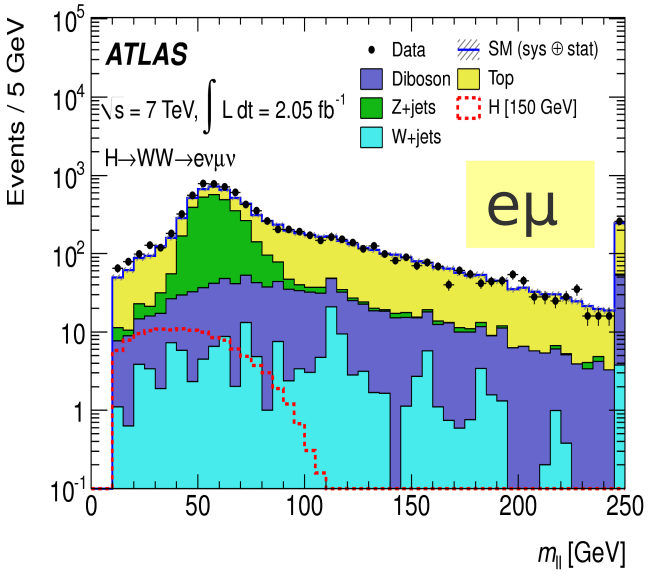
Event Selection

- Exactly two tight and isolated leptons, leading lepton p_T > 25 GeV
  subleading lepton p_T > 15 GeV
- Opposite charge, m_{ll} > 12 GeV (10 GeV) for ee/μμ, (eμ)
- Z veto : | m_{ll} - m_Z | > 15 GeV for ee/μμ

Common selection
0-jet, 1-jet, 2-jets channel







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- Exactly two tight and isolated leptons, leading lepton p_T > 25 GeV
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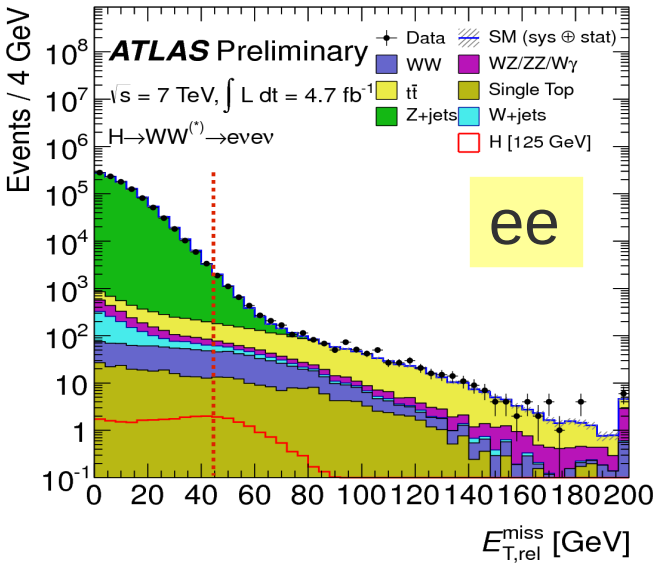
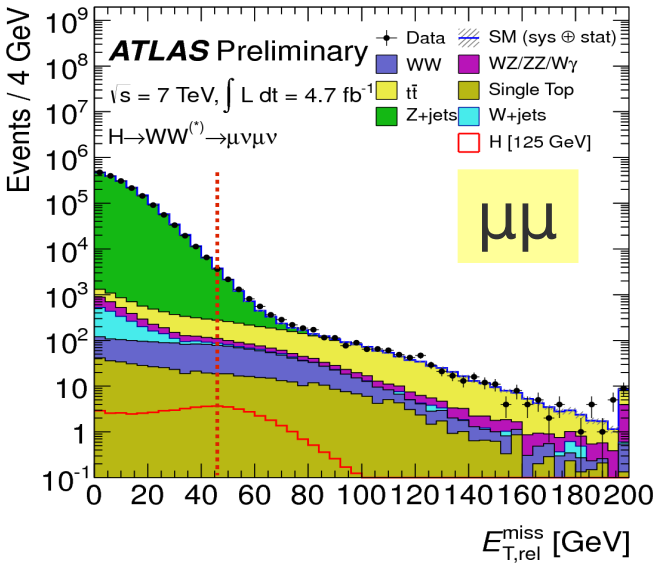
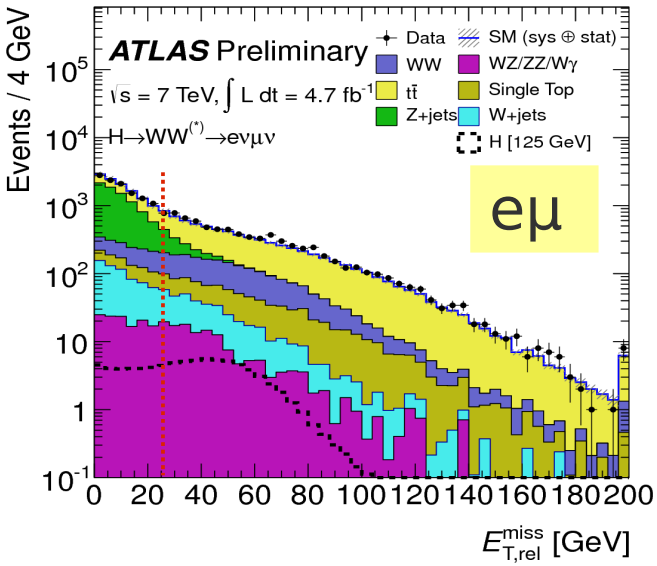
- Opposite charge, m_{ll} > 12 GeV (10 GeV) for ee/μμ, (eμ)
- Z veto : | m_{ll} - m_Z| > 15 GeV for ee/μμ
- $E_{T,rel}^{miss}$ > 45 (25) GeV for ee/μμ , (eμ)

Common selection
0-jet, 1-jet, 2-jets channel







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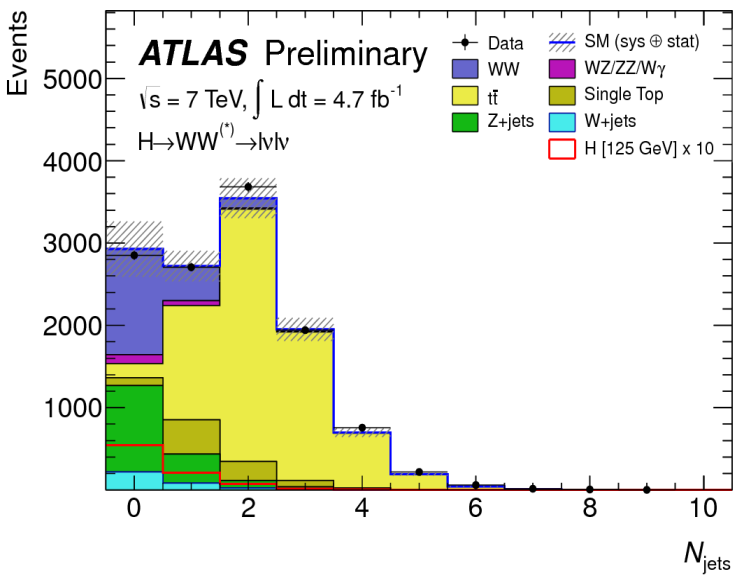


0jet bin: WW and Z+jets are dominant backgrounds

1jet bin: Top is the dominant background

⩾ 2jet bin: Top is the dominant background

Event selection

Event Selection

- Exactly two tight and isolated leptons, leading lepton $p_T > 25$ GeV
  subleading lepton $p_T > 15$ GeV
- Opposite charge, $m_{ll} > 12$ GeV (10 GeV) for ee/μμ, (eμ)
- Z veto : $| m_{ll} - m_Z| > 15$ GeV for ee/μμ
- $E_{T,rel}^{miss} > 45$ (25) GeV for ee/μμ , (eμ)

Common selection
0-jet, 1-jet, 2-jets channel

0 jet :

Jet veto
$p_T(\ell\ell) > 30$ (45) GeV
for eμ (ee/μμ)

1 jet :

b-jet veto
$p_T(tot)^* < 30$ GeV
$Z \rightarrow \tau\tau$ veto

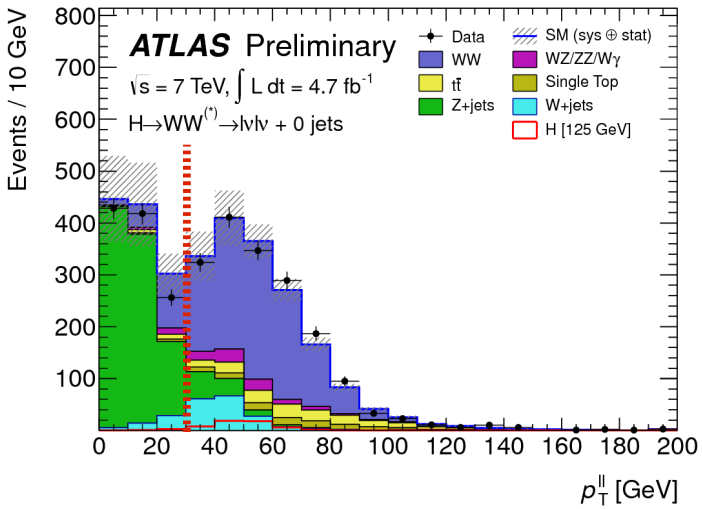
⩾ 2 jets :

Central jet veto ($p_T > 25$ GeV, $|\eta| < 3.2$)
b-jet veto
$\eta(j1)*\eta(j2) < 0$
$\Delta\eta(j1,j2) > 3.8$
$m_{jj} > 500$ GeV
$p_T(tot)^* < 30$ GeV
$Z \rightarrow \tau\tau$ veto

* $p_T(tot)$:
Vector sum of transverse momenta of the jets, the two leptons and MET

+ Common topological selection

Event selection



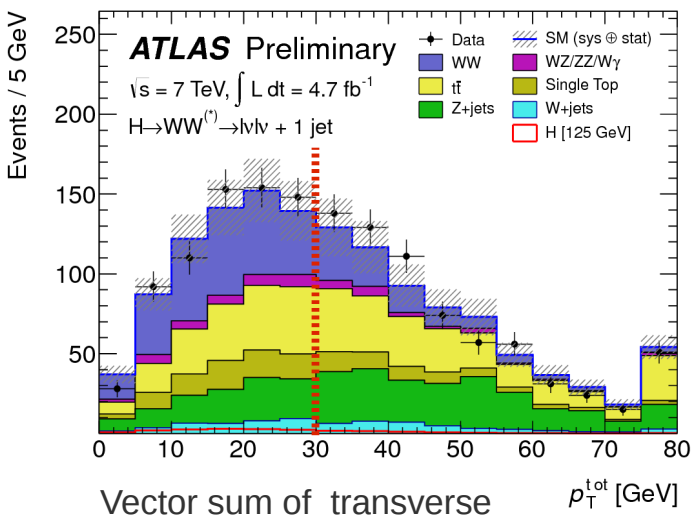
0 jet :

Jet veto

$p_T(\ell\ell) > 30\ (45)$ GeV

for eμ (ee/μμ)

reduction of Z+jets background



Vector sum of transverse momenta of the jets, the two leptons and MET

1 jet :

b-jet veto

reduction of top background

$p_T(\text{tot}) < 30$ GeV

to suppress background events with jets with p_T below threshold

$Z \rightarrow \tau\tau$ veto

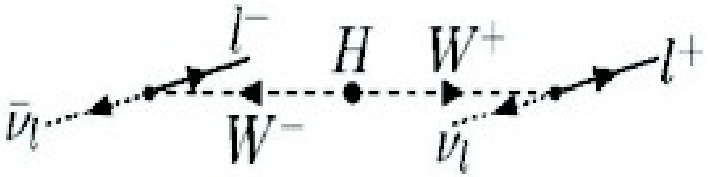
Event selection

Common topological selection:

Three signal regions are defined to optimize the selection for high signal acceptance

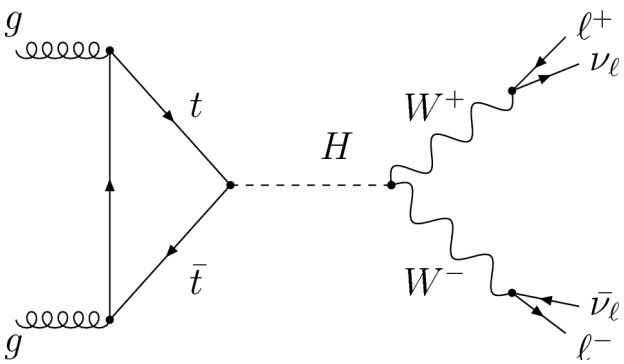
Low mass selection	Intermediate mass selection	High mass selection
m_H < 200 GeV	m_H = 200 GeV – 300 GeV	m_H > 300 GeV
m_{ll} < 50 GeV for 0,1 jet m_{ll} < 80 GeV for ⩾ 2 jets	m_{ll} < 150 GeV	---
$\Delta\phi(\ell\ell)$ < 1.8	$\Delta\phi(\ell\ell)$ < 1.8	---

- Azimuthal separation between signal leptons $\Delta\phi(\ell\ell)$ is a powerful discriminant against WW



- Leptons tend to emerge from interaction point in the same direction due to spin correlations in the WW system arising from the spin-0 nature of the Higgs boson

Outline



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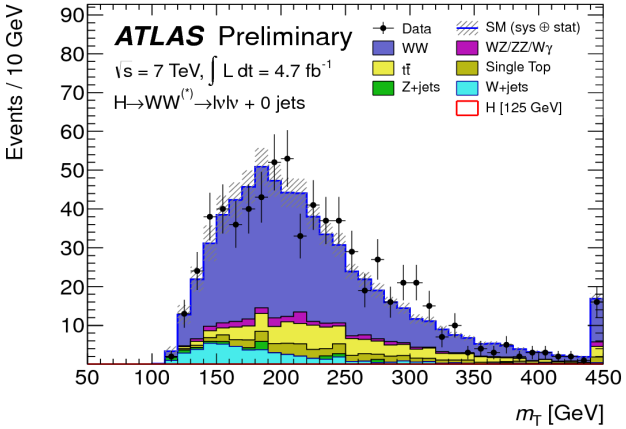
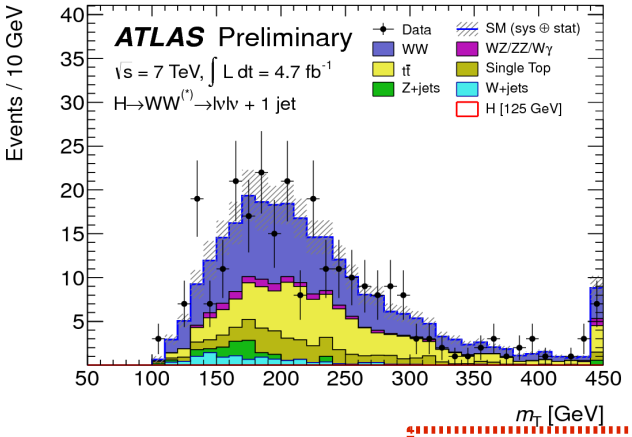
WW control region

WW control region is defined by the same cuts as for the signal region, but:

- m_{ll} > 80 GeV for m_H < 200 GeV
- For ee/μμ, $|m_{ll} - m_Z|$ > 15 GeV
  → effectively m_{ll} > 105 GeV
- Cuts on $\Delta\phi(\ell\ell)$ and M_T are removed

- WW background is normalized by a simultaneous fit to numbers of observed events in the signal and control region





WW CR	Signal	WW	WZ/ZZ/Wγ	tt	tW/tb/tqb	Z/γ*+jets	W+jets	Total Bkg	Obs.
0-jet	0.1 ±0.1	465 ±3	25 ±2	85 ±2	41 ±2	9 ±2	48 ±2	673 ±5	698
1-jet	0.1 ±0.1	126 ±2	10 ±1	83 ±2	33 ±2	9 ±2	11 ±1	272 ±4	269

- Only statistical uncertainties associated with the number of events are shown

Top background estimate

Top contribution in 0-jet channel: ~5%

estimated using data-driven method [arXiv:1101.1383], PRD84, 096005 (2011)

Number of top background events in the signal region estimated from:

- Top background yield in dilepton+ E_T^{miss} + inclusive jets data
- Jet veto efficiency measured by b-tag control region
  (with a MC based correction to account for single top events)

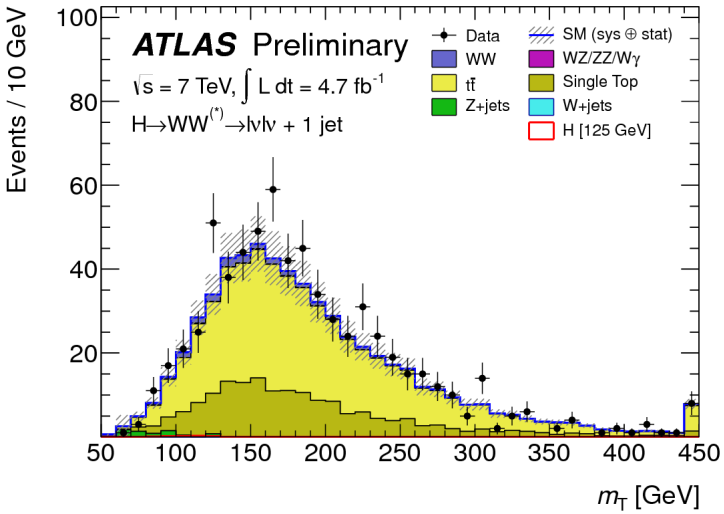
$$N_{\text{top}}^{\text{Est.}}(\ell\ell + E_T^{\text{miss}}, 0j) \simeq N_{\text{top}}^{\text{Data}}(\ell\ell + E_T^{\text{miss}}) \times \underbrace{P_2^{\text{MC}} \times \left(\frac{P_1^{\text{Btag,data}}}{P_1^{\text{Btag,MC}}}\right)^2}_{P_2^{\text{Exp}}}$$

- Jet-veto survival probability $P_1^{Btag} = N_{0j}^{Btag} / N_{all\ jets}^{Btag}$
  is determined from b-tagged sample
- P2 : fraction of top events passing the jet veto cut

Top background estimate

Top contribution in 1-jet-channel: largest background

- Definition of control region:
  - b-jet veto is reversed
  - cuts on m_{ll} and $\Delta\phi(\ell\ell)$ are removed
- Top background MC prediction is normalized to the data using the control sample



- Fitted normalization propagates to both WW control region and signal region
- Total uncertainty on estimated top background in signal region is ~ 30 %

Top CR	Signal	WW	WZ/ZZ/Wγ	tt	tW/tb/tqb	Z/γ*+jets	W+jets	Total Bkg	Obs.
1-jet	1.1 ±0.1	21 ±1	1.5 ±0.2	422 ±4	165 ±3	6 ±2	negl.	615 ±6	675

- Only statistical uncertainties associated with the number of events are shown

W+jets estimate

The W+jets background contribution is estimated using a data control sample of events with two leptons:

- one lepton passing the identification and isolation criteria used in the analysis
- one lepton failing the above mentioned criteria but passing the loosened ones

Estimated W+jets background

W+jets control region to determine normalization

$$N_{\text{one id(from W)+one fake}} = \frac{N_{\text{id obj}}}{N_{\text{anti-identified}}} \times N_{\text{one id(fromW)+one fakeable}}$$

Fake factor (Observable)

Apply same kinematic selection as signal region

The prediction of the W+jets contamination in the signal region is determined by scaling down the number of events in the data control sample by a normalization “fake factor”.

Summary: Data Driven Background Estimation

Backgrounds either partially or fully determined from data

$N_{\text{Signal Region}} = \alpha \times N_{\text{Control Region}}$

Signal Region

- Higgs(VBF+ggF)
- WW
- tt + single t
- W jets

$$\alpha_{WW} = \frac{N_{WW}^{sig}}{N_{WW}^{ctrl(WW)}}$$

$$\alpha_{tt} = \frac{N_{top}^{sig}}{N_{top}^{ctrl(top)}}$$

$$\alpha_{Wj} = \frac{N_{Wj}^{sig}}{N_{Wj}^{ctrl(Wj)}}$$

WW control

- WW
- tt + single t
- W jets

top control

- tt + single t

W control

- W jets

remove $\Delta\varphi$ and m_T cuts, invert m_{ll} cuts

$$\beta_{tt} = \frac{N_{top}^{ctrl(WW)}}{N_{top}^{ctrl(top)}}$$

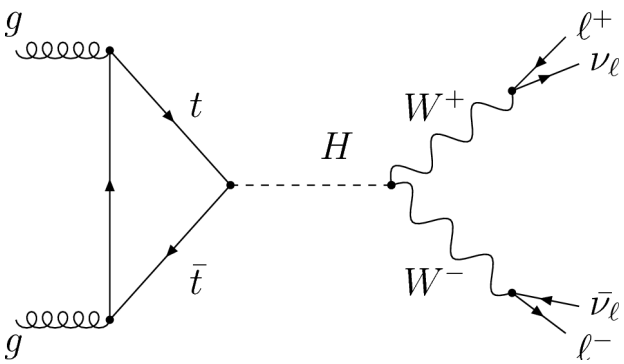
1j: remove topological cuts, invert b-jet veto

$$\beta_{Wj} = \frac{N_{Wj}^{ctrl(WW)}}{N_{Wj}^{ctrl(Wj)}}$$

require 2nd lepton to fail tight but pass loose selection

0j: estimate top background from b-jet survival probability

Outline



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Systematical uncertainties

Experimental uncertainties:

- Related to jet energy scale < 14 % for jets with $p_T > 25$ GeV and $|\eta| < 4.5$
- Additional contributions from pile-up < 5 % for jets with $p_T > 25$ GeV
- Electron efficiency uncertainties: 2-5 %
- Electron/Muon momentum scale and resolution uncertainties < 1%
- Uncertainty on b-tagging efficiency 5 % - 14 % depending on jet p_T

Systematical uncertainties

Uncertainties on background estimates based on control regions:

Total uncertainty on predicted background in signal region	0-jet channel	1-jet channel
WW background	10 %	24 %
Top background	23 %	30 % (1 jet and ⩾ 2 jets channel)
Z/γ^*+jets	56 %	25 %

W+jets	$p_T < 30$ GeV	$p_T > 30$ GeV
total uncertainty on fake factor	30-50 %	100 %

Systematical uncertainties

Theoretical uncertainties on signal production cross-section:

- QCD renormalisation and factorisation scales are varied up and down by a factor of 2 independent uncertainties on ggF signal production are assumed for the inclusive cross section and the cross-section with at least one or two jets

  → relative uncertainties depend on m_H : 25 % at 125 GeV for H + 0jet
  37 % at 125 GeV for H + 1jet

- Uncertainty on VBF signal cross section in the H + 2jet channel and on acceptance associated with the jet veto requirement is around 5 %

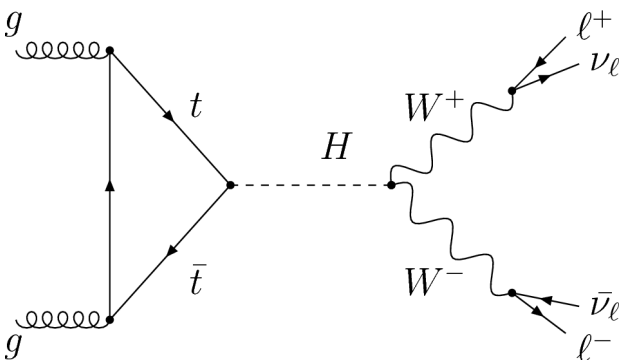
- Uncertainty on cross-section of events produced via ggF in the H + 2 jet channel is around 25 %

Additional uncertainty due to Higgs line shape description in the POWHEG Monte Carlo

- Added in quadrature for both the ggF and VBF channel: 150 % x $(m_H / 1\ \text{TeV})^3$

Relative PDF uncertainty on dominant ggF signal process is about 8 %

Outline



- SM Higgs production and decay
- Analysis based on **4.7 fb^{-1}** :

  → Introduction and selection

  → Background estimates
  - WW control region
  - ttbar and single top
  - Z+jets (ABCD method)
  - data-driven W+jets estimate

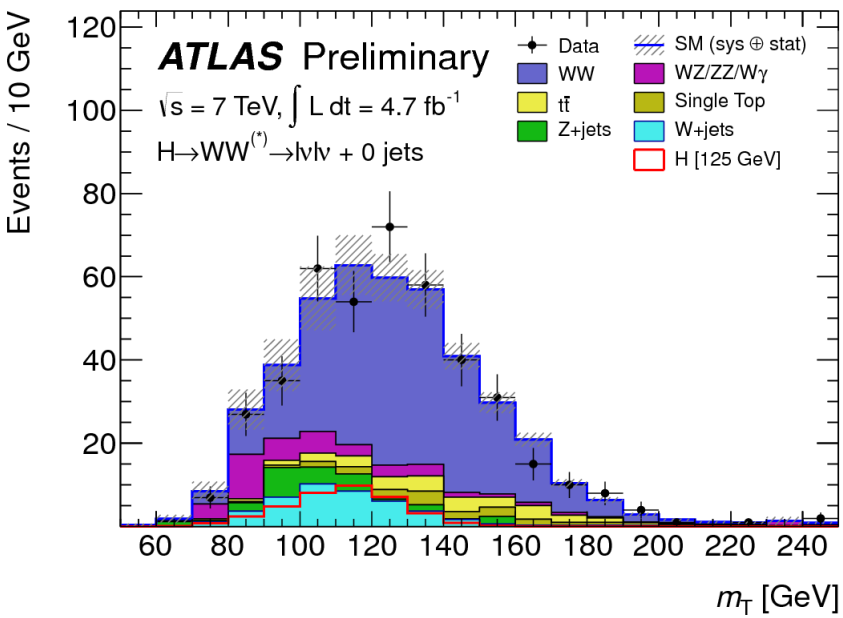
  → Systematic uncertainties

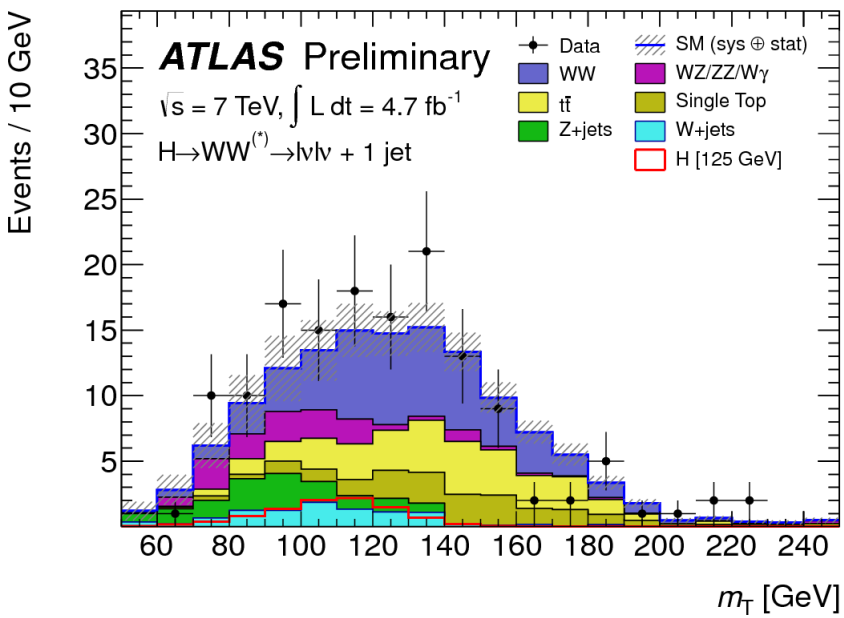
- Results and limits

H+0 jet and H+1 jet analysis, ee + μμ + eμ

m_T after all cuts

signal m_H = 125 GeV



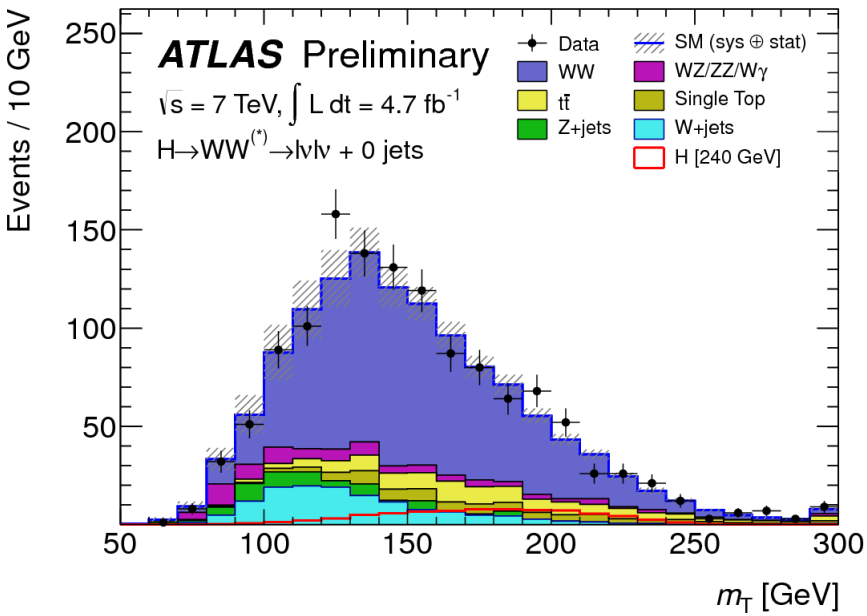


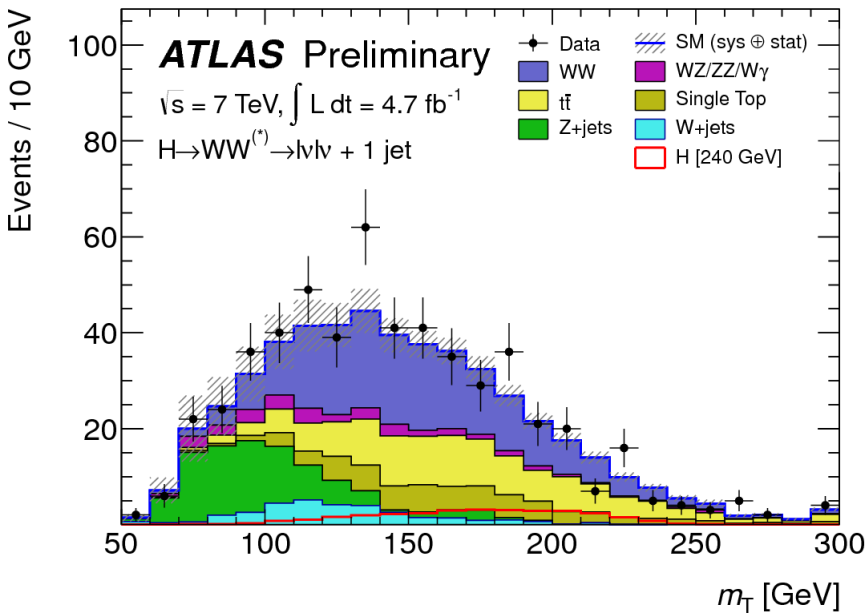
$$M_T = \sqrt{(E_T^{ll})^2 + (E_T^{\nu\nu})^2 - (\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,miss})^2}$$

H+0 jet and H+1 jet analysis, ee + μμ + eμ

m_T after all cuts

signal m_H = 240 GeV





$$M_T = \sqrt{(E_T^{ll})^2 + (E_T^{\nu\nu})^2 - (\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,miss})^2}$$

Final event numbers

		Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* + \text{jets}$	$W + \text{jets}$	Total Bkg.	Obs.
0-jet	$m_H = 125$ GeV	25 ± 7	110 ± 12	12 ± 3	7 ± 2	5 ± 2	13 ± 8	27 ± 16	173 ± 22	174
	$m_H = 240$ GeV	60 ± 17	432 ± 49	24 ± 3	68 ± 15	39 ± 9	8 ± 2	36 ± 24	607 ± 63	629
1-jet	$m_H = 125$ GeV	6 ± 2	18 ± 3	6 ± 3	7 ± 2	4 ± 2	6 ± 1	5 ± 3	45 ± 7	56
	$m_H = 240$ GeV	23 ± 9	99 ± 22	8 ± 1	73 ± 27	35 ± 19	6 ± 2	7 ± 7	229 ± 55	232
2-jet	$m_H = 125$ GeV	0.4 ± 0.2	0.3 ± 0.2	negl.	0.2 ± 0.1	negl.	0.0 ± 0.1	negl.	0.5 ± 0.2	0
	$m_H = 240$ GeV	2.5 ± 0.6	1.1 ± 0.7	0.1 ± 0.1	2.6 ± 1.3	0.3 ± 0.3	negl.	0.1 ± 0.1	4.2 ± 1.7	2

The expected numbers of signal (m_H=125GeV and 240 GeV) and background events after the full low m_H and intermediate m_H selections, including a cut on the transverse mass of $0.75\ m_H < m_T < m_H$ for m_H = 125 GeV and $0.6\ m_H < m_T < m_H$ for m_H = 240 GeV.

The uncertainties shown are the combination of the statistical and all systematic uncertainties, taking into account the constraints from control samples.

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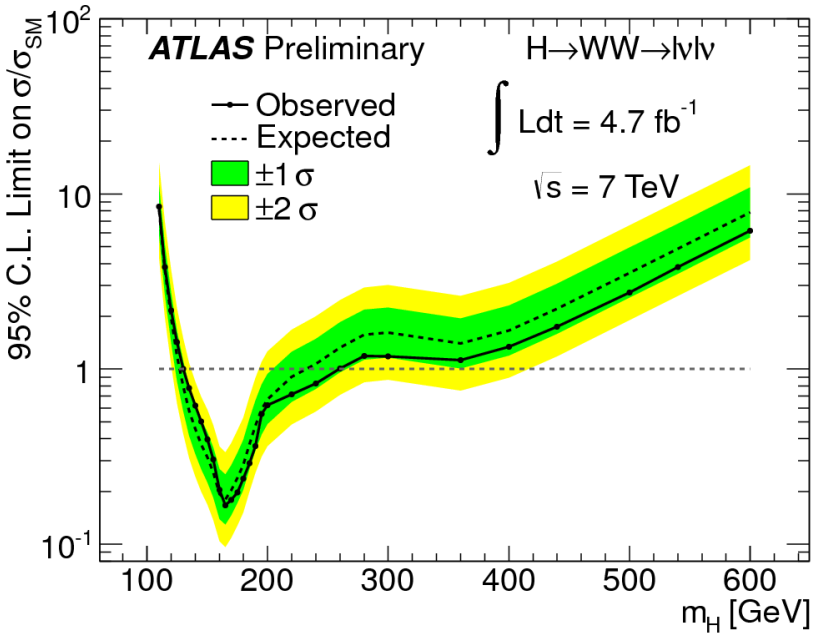
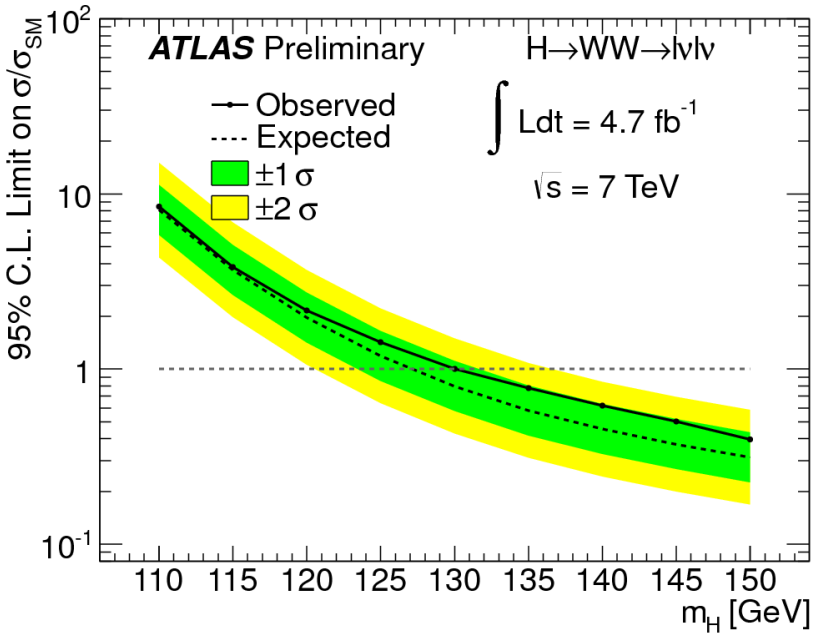
Limit

The expected (dashed) and observed (solid) 95% CL upper limits on the cross section, normalized to the Standard Model cross section, as a function of the Higgs boson mass. Expected limits are given for the scenario where there is no signal.



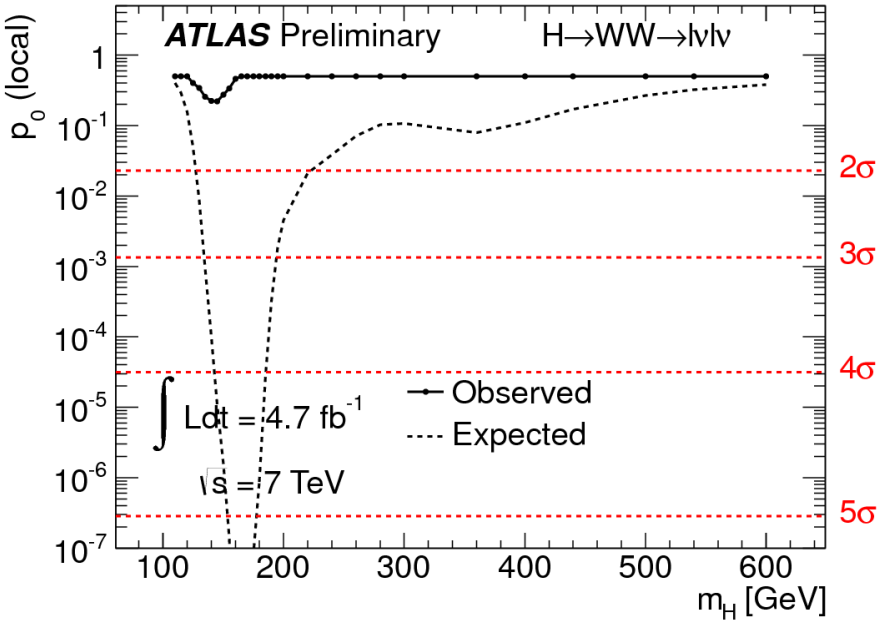


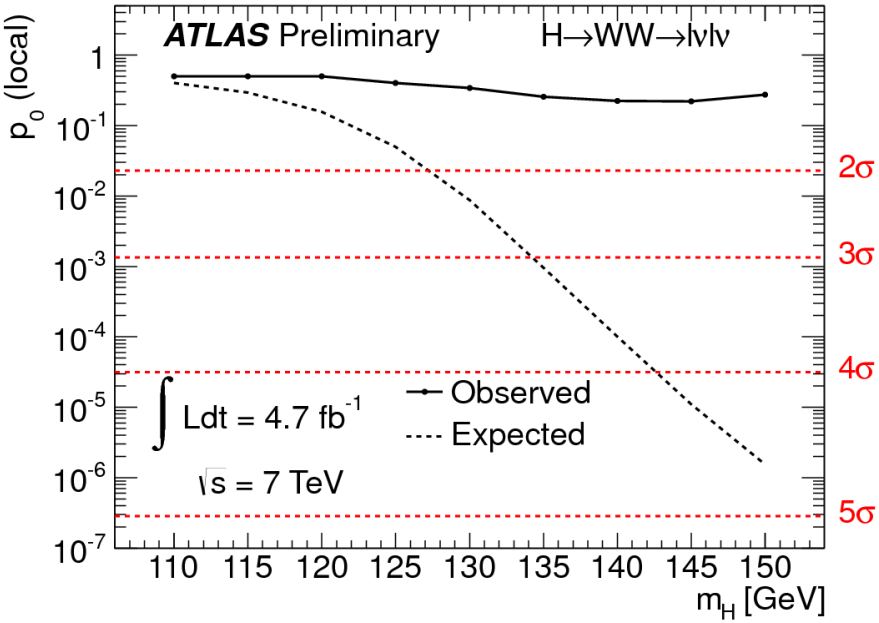
In absence of a signal, one would expect to exclude a SM Higgs boson at 95 % CL in the range of: $127 < m_H < 234$ GeV

Mass interval excluded by measurement: $130 < m_H < 260$ GeV

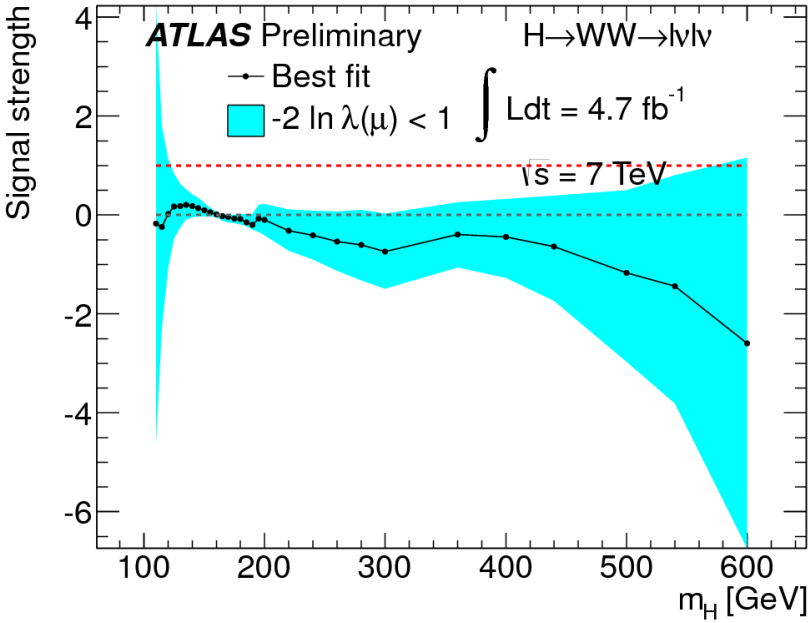
Local p-value

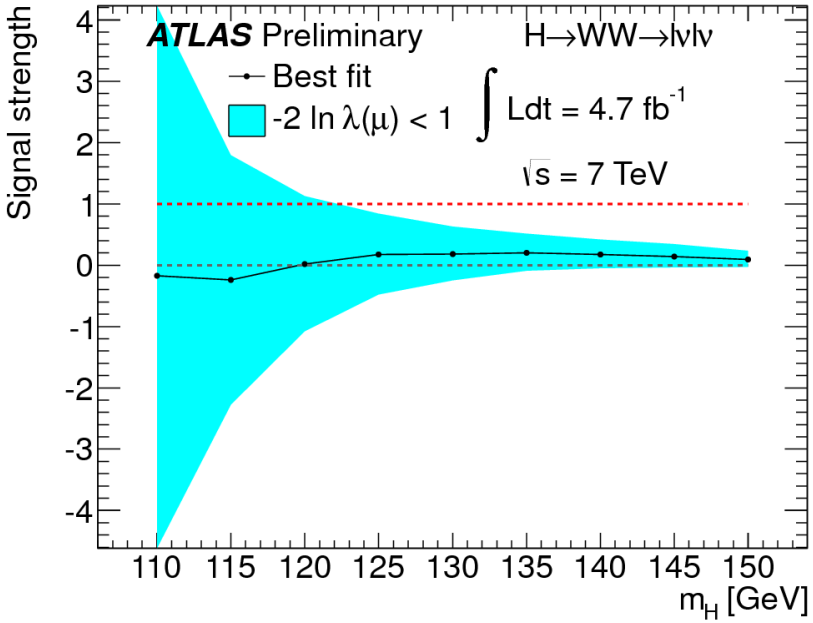
The expected (dashed) and observed (solid) probabilities for the background-only scenario as a function of m_H





Signal strength





Fitted signal strength parameter as a function of m_H for the whole mass range

$\mu = 0.17 \pm 0.66$ at 125 GeV

Summary

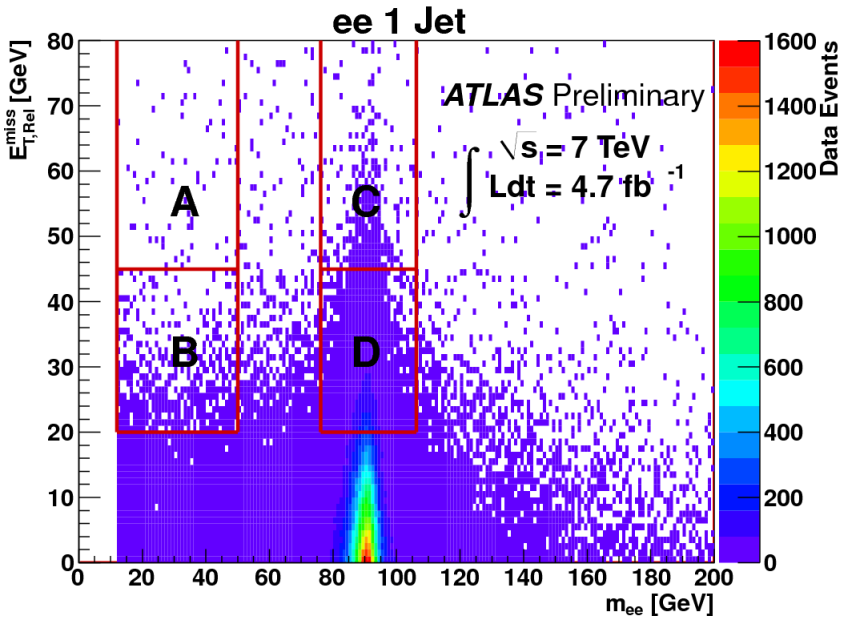
- H->WW*->lvlv analysis based on data corresponding to 4.7 fb^{-1} of integrated luminosity recorded by ATLAS in pp collisions at $\sqrt{s}$ = 7 TeV in 2011 has been presented
- Background estimates have been shown
- No significant excess of events over the expected background is observed
- The observations exclude the presence of a Standard Model Higgs boson with a mass $130 < m_H < 260$ GeV at 95 % confidence level
  (expected limit in case of no signal: $127 < m_H < 234$ GeV)
- Results for full 2011 dataset will be published in a paper soon

BACKUP

Z+jets estimate

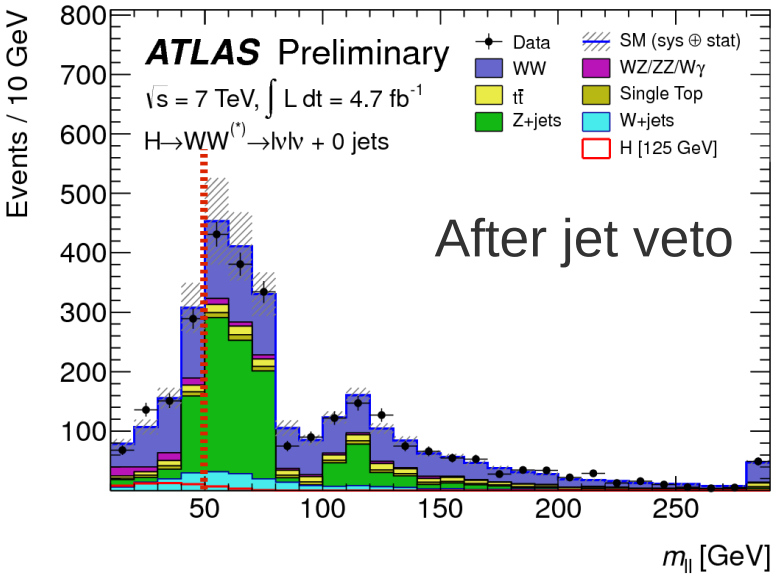
- Z + jets events mimic signal of 2 leptons and large (mismeasured) E_t^{miss}
- Use 'ABCD' method to estimate contribution, using 2D space of $E_{T,Rel}^{miss}$ and m_{ll}

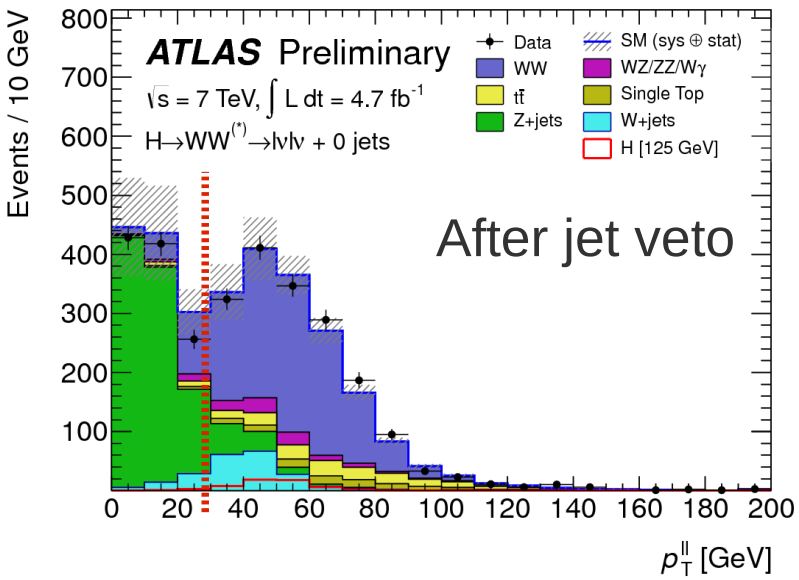
$$A^{est} = \frac{C^{data}}{D^{data}} \times B^{data}$$

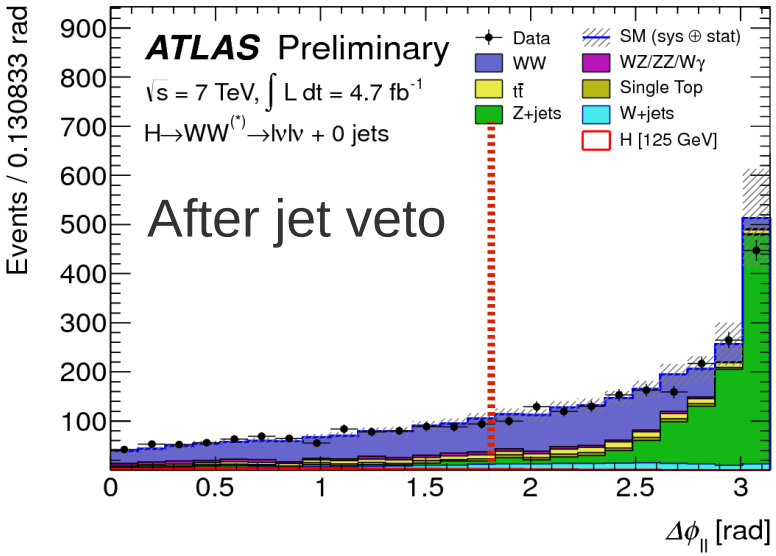


- Non-Z/γ*+jets contributions subtracted using MC

0jet channel, ee + μμ + eμ

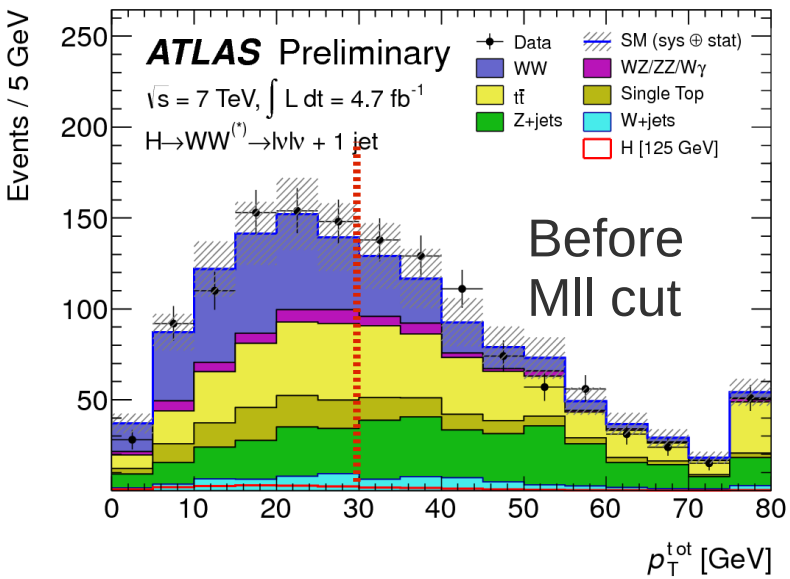


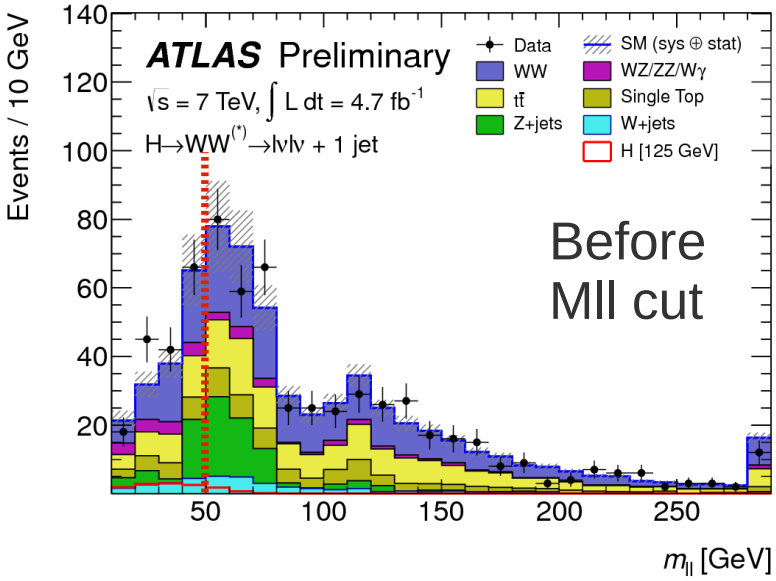


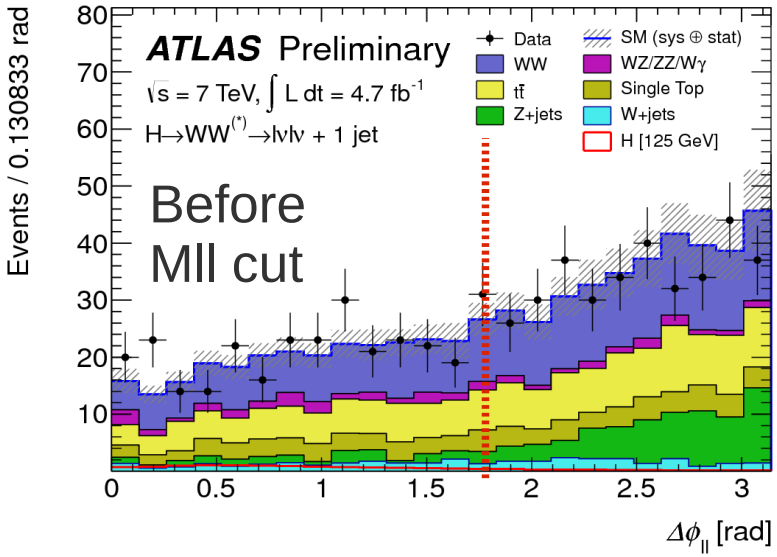


H + 0-jet Channel
Jet Veto
$p_T^{\ell\ell} > 30$ GeV
$m_{\ell\ell} < 50$ GeV
$\Delta\phi_{\ell\ell} < 1.8$
$0.75\, m_H < m_T < m_H$

1jet channel, ee + μμ + eμ







H + 1-jet Channel
1 jet
b-jet veto
$\lvert \mathbf{p}_{\mathrm{T}}^{\mathrm{tot}} \rvert < 30$ GeV
$Z \to \tau\tau$ veto
$m_{\ell\ell} < 50$ GeV
$\Delta\phi_{\ell\ell} < 1.8$
$0.75\, m_H < m_{\mathrm{T}} < m_H$

Cutflow

Expected numbers of signal and background events for low m_H selection

H + 0-jet	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	Z/γ^* + jets	W + jets	Total Bkg.	Obs.
Jet Veto	54.5 ± 0.2	1285 ± 79	106 ± 6	175 ± 12	95 ± 7	1038 ± 28	217 ± 4	2916 ± 115	2851
$m_{\ell\ell} < 50$ GeV	43.8 ± 0.2	316 ± 20	48 ± 5	30 ± 2	19 ± 2	157 ± 13	69 ± 2	640 ± 34	644
$p_T^{\ell\ell}$ cut	38.8 ± 0.2	285 ± 18	41 ± 4	28 ± 2	18 ± 2	24 ± 7	49 ± 2	444 ± 27	441
$\Delta\phi_{\ell\ell} < 1.8$	37.7 ± 0.2	279 ± 17	39 ± 4	27 ± 2	18 ± 2	23 ± 7	44 ± 1	429 ± 27	427
H + 1-jet	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	Z/γ^* + jets	W + jets	Total Bkg.	Obs.
1 jet	21.1 ± 0.1	390 ± 55	59 ± 4	1433 ± 80	430 ± 25	357 ± 17	82 ± 3	2752 ± 170	2707
b-jet veto	19.5 ± 0.1	360 ± 51	55 ± 4	401 ± 23	134 ± 8	333 ± 16	73 ± 3	1356 ± 92	1371
$\lvert\mathbf{p}_T^{tot}\rvert < 30$ GeV	13.0 ± 0.1	252 ± 35	33 ± 3	171 ± 10	78 ± 5	105 ± 8	35 ± 2	674 ± 55	685
$Z \to \tau\tau$ veto	13.0 ± 0.1	246 ± 34	32 ± 3	165 ± 10	75 ± 5	85 ± 7	35 ± 2	638 ± 53	645
$m_{\ell\ell} < 50$ GeV	10.2 ± 0.1	54 ± 7	14 ± 2	32 ± 2	18 ± 2	26 ± 4	12 ± 1	156 ± 14	171
$\Delta\phi_{\ell\ell} < 1.8$	9.4 ± 0.1	49 ± 7	14 ± 2	30 ± 2	17 ± 2	13 ± 3	10 ± 1	134 ± 13	145
H + 2-jet	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	Z/γ^* + jets	W + jets	Total Bkg.	Obs.
opp. hemispheres	3.8 ± 0.1	46 ± 1	6 ± 1	138 ± 3	21 ± 1	34 ± 4	8 ± 1	253 ± 5	269
$\lvert\Delta\eta_{jj}\rvert > 3.8$	1.8 ± 0.1	8.3 ± 0.4	0.9 ± 0.2	19.2 ± 0.9	2.2 ± 0.4	8.0 ± 2.0	1.5 ± 0.4	40.2 ± 2.3	40
$m_{jj} > 500$ GeV	1.3 ± 0.1	3.9 ± 0.3	0.4 ± 0.1	6.9 ± 0.4	0.7 ± 0.2	0.9 ± 0.4	0.7 ± 0.3	13.6 ± 0.8	13
$m_{\ell\ell} < 80$ GeV	0.9 ± 0.1	1.1 ± 0.2	0.1 ± 0.1	1.1 ± 0.2	0.2 ± 0.1	0.3 ± 0.3	0.2 ± 0.2	2.9 ± 0.5	2
$\Delta\phi_{\ell\ell} < 1.8$	0.8 ± 0.1	0.7 ± 0.1	0.1 ± 0.1	0.7 ± 0.2	negl.	0.3 ± 0.3	negl.	1.8 ± 0.4	1

Signal is for m_H=125 GeV

Basic event selection

Object selection:

- Electrons: tight++ electrons with author 1 or 3

  Pt > 15 GeV, $|\eta| < 2.47$ excluding crack region

  object quality check

  impact parameter cuts : abs(z0 w.r.t. PV) < 1mm, I.P. significance < 10

  Isolation: $\Sigma(P_T track/P_t e) < 0.13$, $\Sigma(E_T calo/P_t e) < 0.14$

  scale factors applied to MC

Selection details

- Muons : staco combined muons

  Pt > 15 GeV, |η | < 2.4

  hits requirement in pixel, SCT, TRT following MCP recommendations

  impact parameter cuts : abs(z0 w.r.t. PV) < 1mm, I.P. significance < 3

  Isolation: $\Sigma(P_T track/P_t \mu) < 0.15$, $\Sigma(E_T calo/P_t \mu) < 0.14$

  scale factors applied to MC

- Jets: Anti-kT jets with distance scale 0.4

  Pt > 25 GeV, |η | < 4.5

  JVF applied

  b-tagging/veto: CombNN, 80% working point

- overlap removal

  e-e: if Δ R < 0.1, remove lower-PT electron

  e-μ: if Δ R < 0.1, remove electron

  e-jet: if ΔR < 0.3 of selected jet, remove jet