Observation of an excess in the search for the Standard Model Higgs boson in the $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ decay mode with the ATLAS detector

Frank Filthaut
(Radboud University, Nijmegen / Nikhef)
on behalf of the ATLAS Collaboration

References:

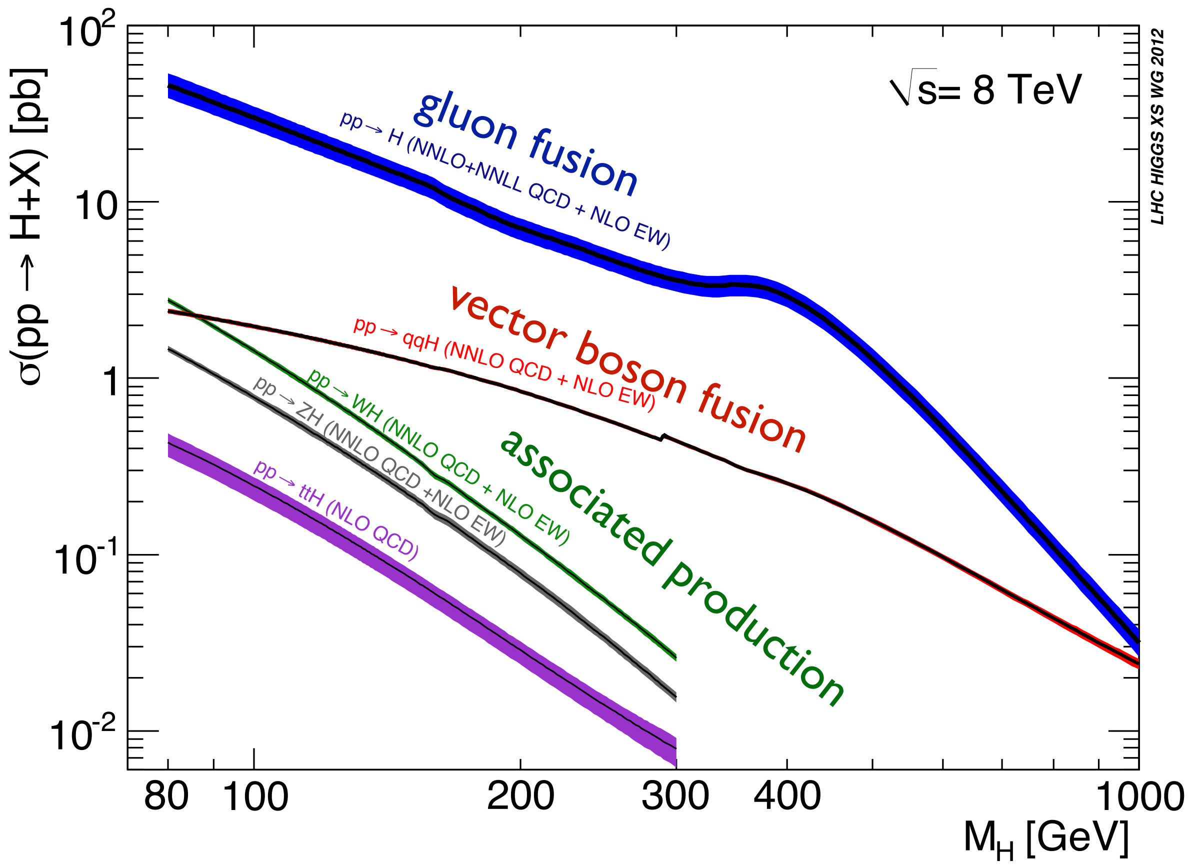
- 2011 cut-based analysis: arXiv:1206.0756 (subm. to PLB)
- 2012 cut-based analysis: ATLAS-CONF-2012-098
- Also part of the combination paper! arXiv:1207.7214 (subm. to PLB)

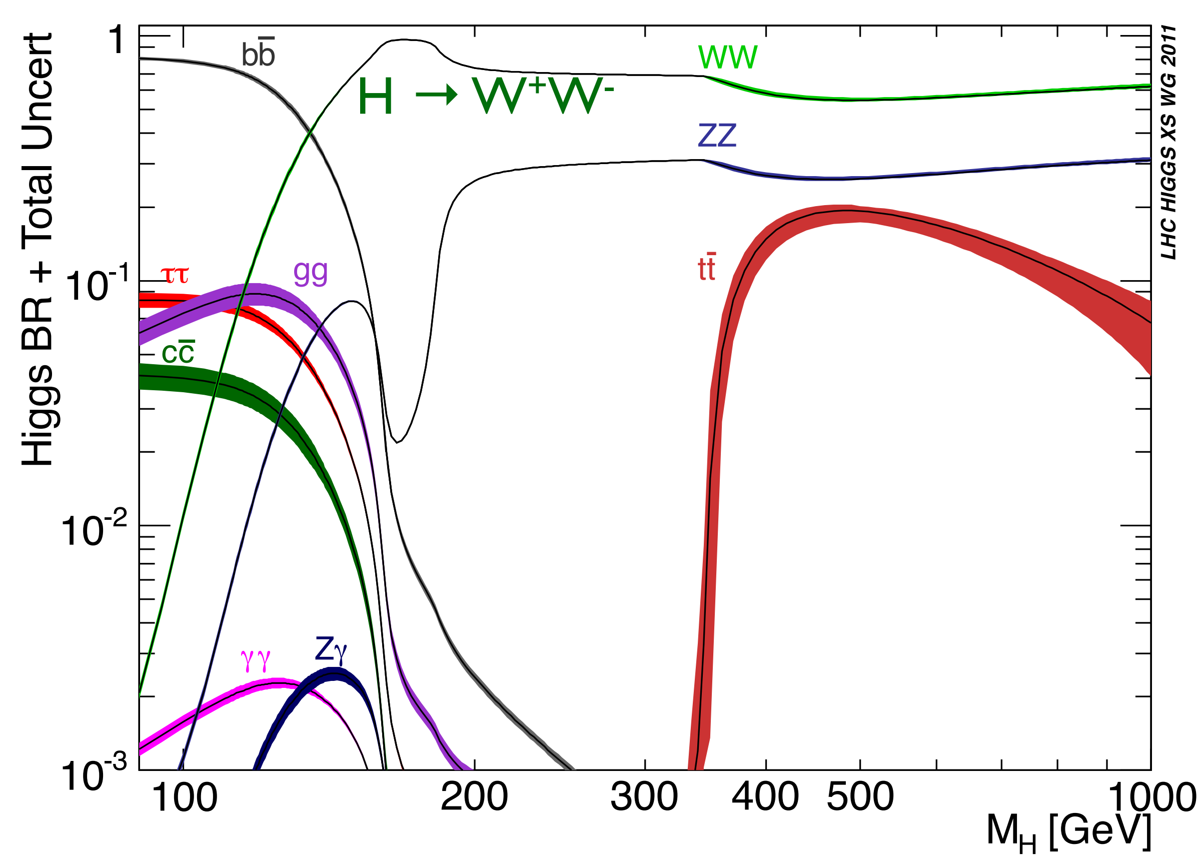
Motivation

Large Higgs boson production cross section combined with sizeable $WW^{(*)} \to l\nu l\nu$ branching fraction (ee/eμ/μμ + missing E_T signature)
➠ sensitive SM Higgs search channel over large M_H range (especially low M_H)

The challenges:

- many backgrounds (both irreducible and reducible)
- no clear mass peak due to 2 escaping ν





figures from https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

Strategy & Content

2011 result: observed 95% exclusion in range 133 GeV < M_H < 261 GeV

- no clear signal but worse limits than expected (127 GeV < M_H < 233 GeV)

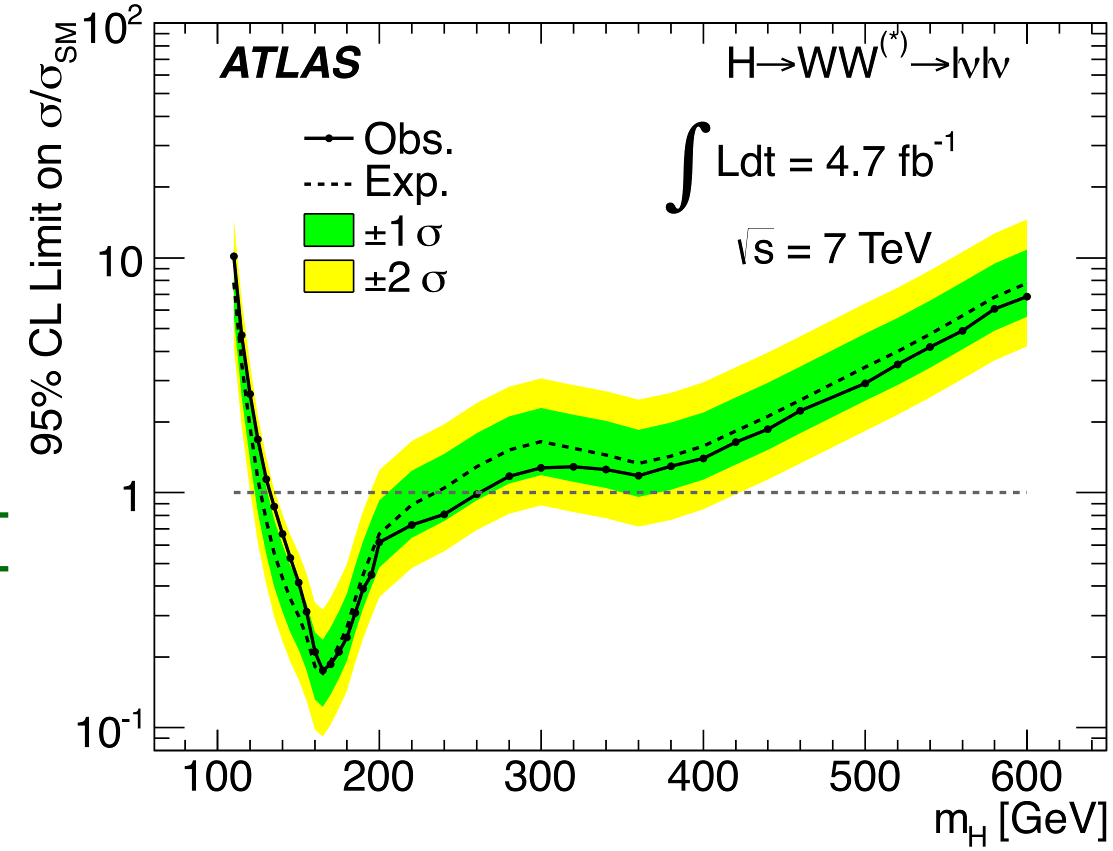
2011 and 2012 data analyses nearly identical (apart from absence of same-flavour channels for 2012)

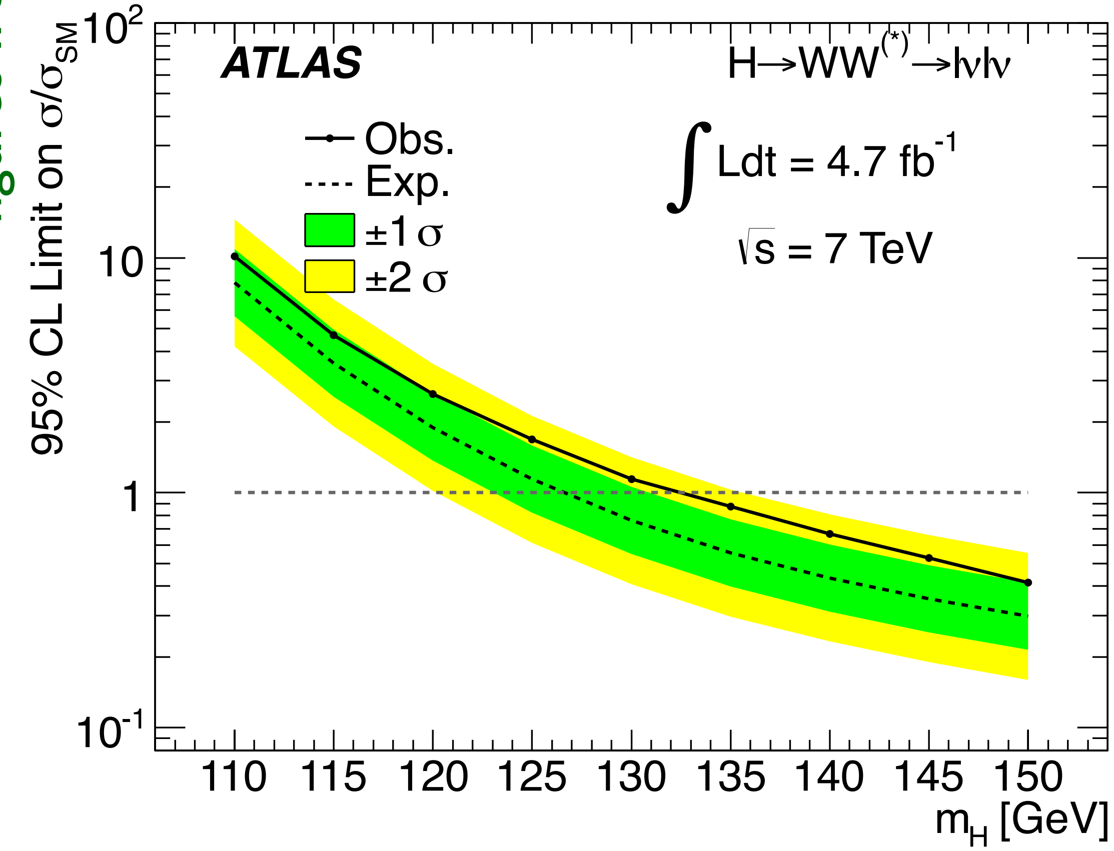
- but 2012 analysis was blinded (the blinding does not affect the control regions discussed later)

In the following, describe only the 2012 analysis

- selection
- background estimation
- results & systematics
- conclusion

figures from the 2011 paper





Selection

Leptons & Missing E_T

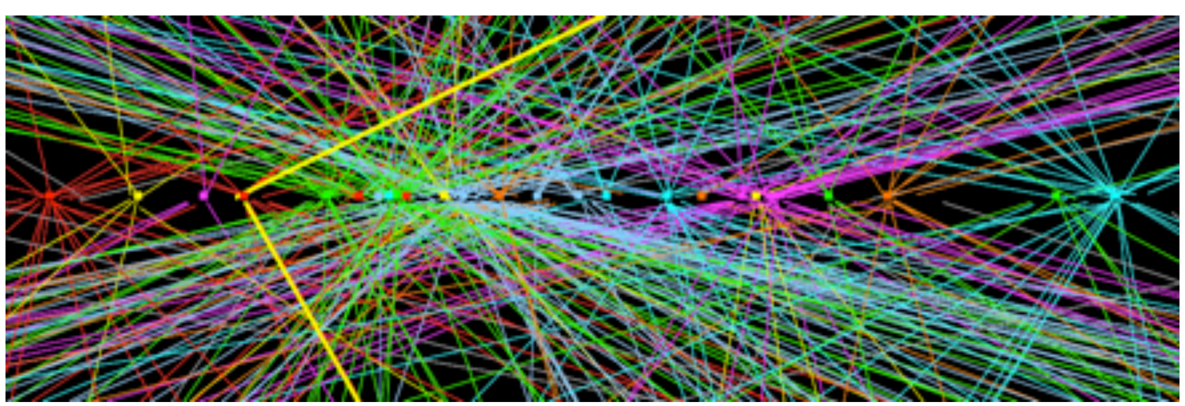
Two isolated, high-pT leptons (e,μ):

- $p_T(1) > 25$ GeV, $p_T(2) > 15$ GeV collected using single-lepton triggers ($p_T \gtrsim 25$ GeV)
- $m(e\mu) > 10$ GeV

Significantly increased pile-up compared to 2011, resulting in degraded E_T(miss) resolution

➠ use only e+μ final states

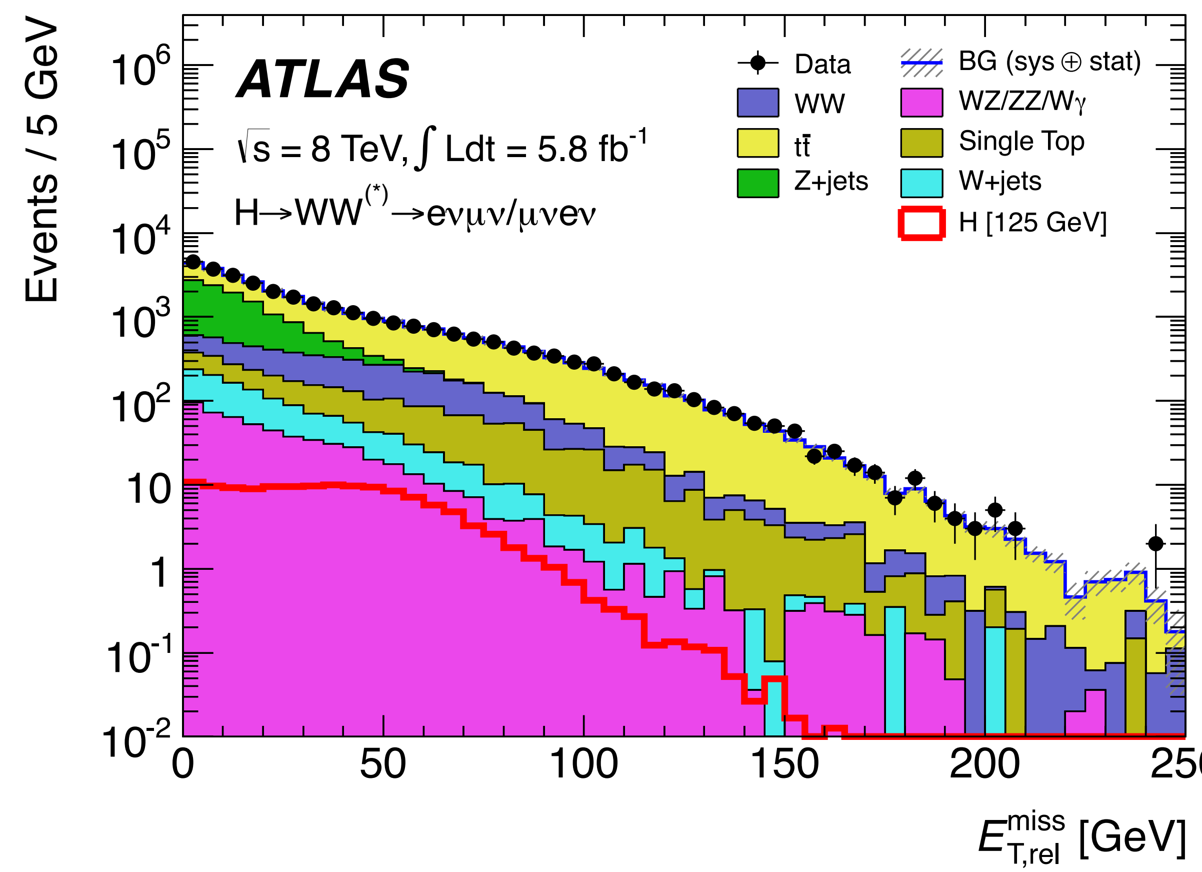
- 2011 selection includes also ee and μμ final states (with additional criteria to suppress Z/γ^* background)



Z→ μμ candidate, 25 reconstructed primary vertices

Suppress $Z/\gamma^* \to \tau\tau$ backgrounds requiring significant missing transverse momentum

- E_T(miss, rel) > 25 GeV



$$E_{T,rel}^{miss} = \begin{cases} E_T^{miss} \sin \Delta\phi & \Delta\phi < \pi/2 \\ E_T^{miss} & \Delta\phi > \pi/2 \end{cases}$$

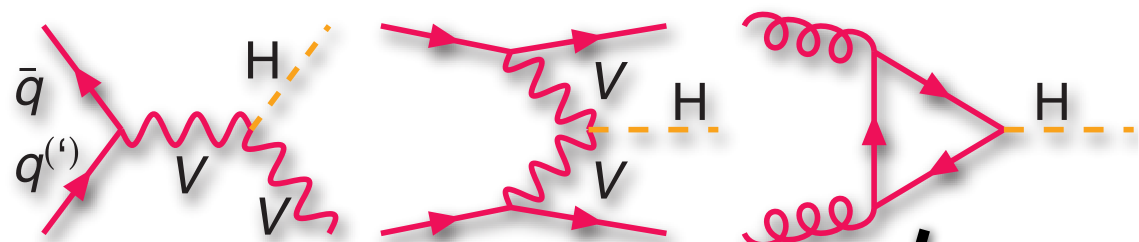
Δφ: angle between E_T(miss) vector and nearest object

- computation uses jets and leptons

Jet Multiplicity Dependence

Different signal production mechanisms (gluon fusion, VBF, associated production) lead to different kinematic signatures and jet multiplicities
➠ carry out analysis in different jet bins

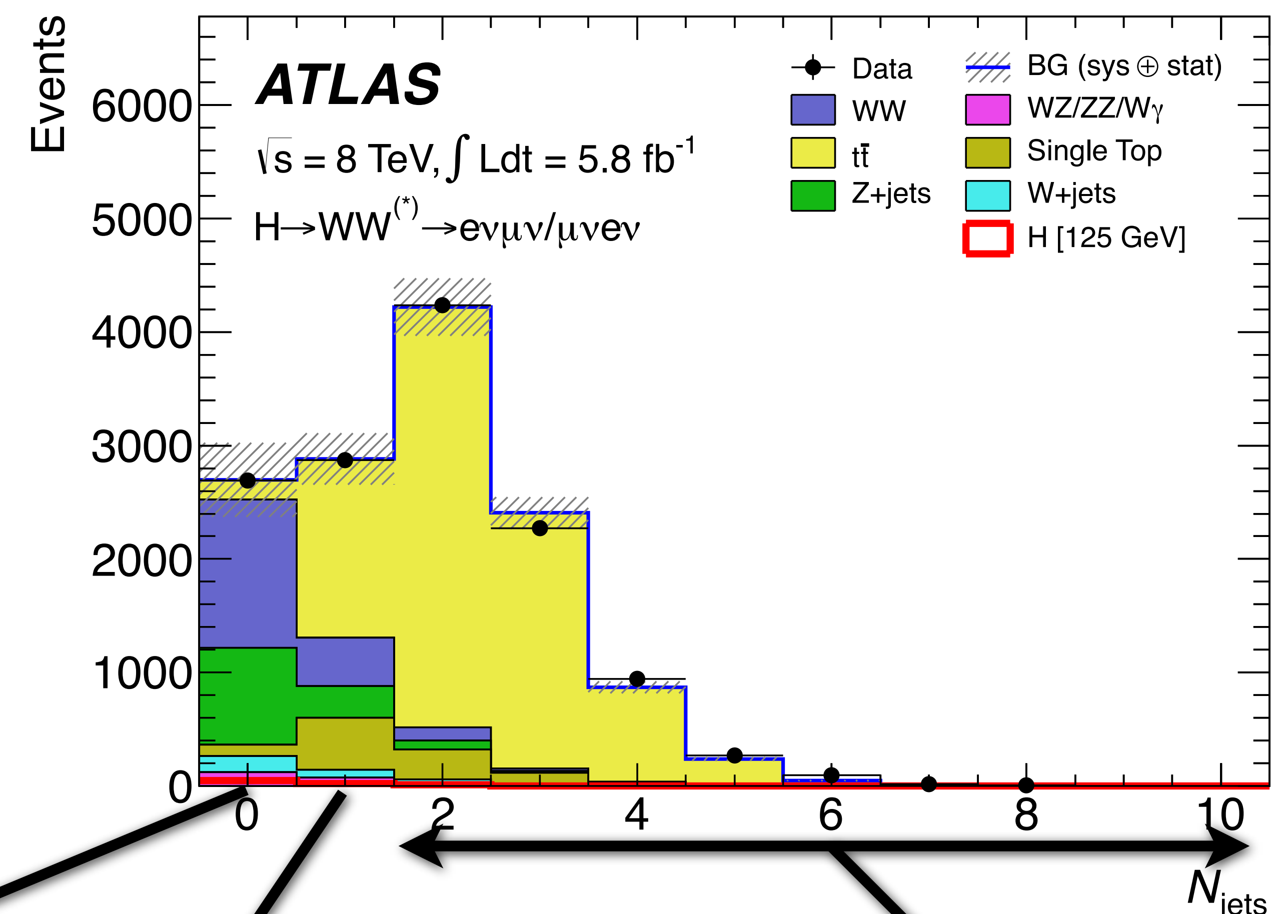
- jet counting: p_T > 25 GeV (p_T > 30 GeV for $|\eta|$ > 2.5)



no optimisation for this process

important for 2 jets

dominates for 0 jets



dominated by WW and (at this cut stage) Z/γ*+jets

dominated by WW and top

dominated by top

Multiplicity Dependent Selection

0-jet selection:

- $p_T(ll)$ > 30 GeV

1-jet selection:

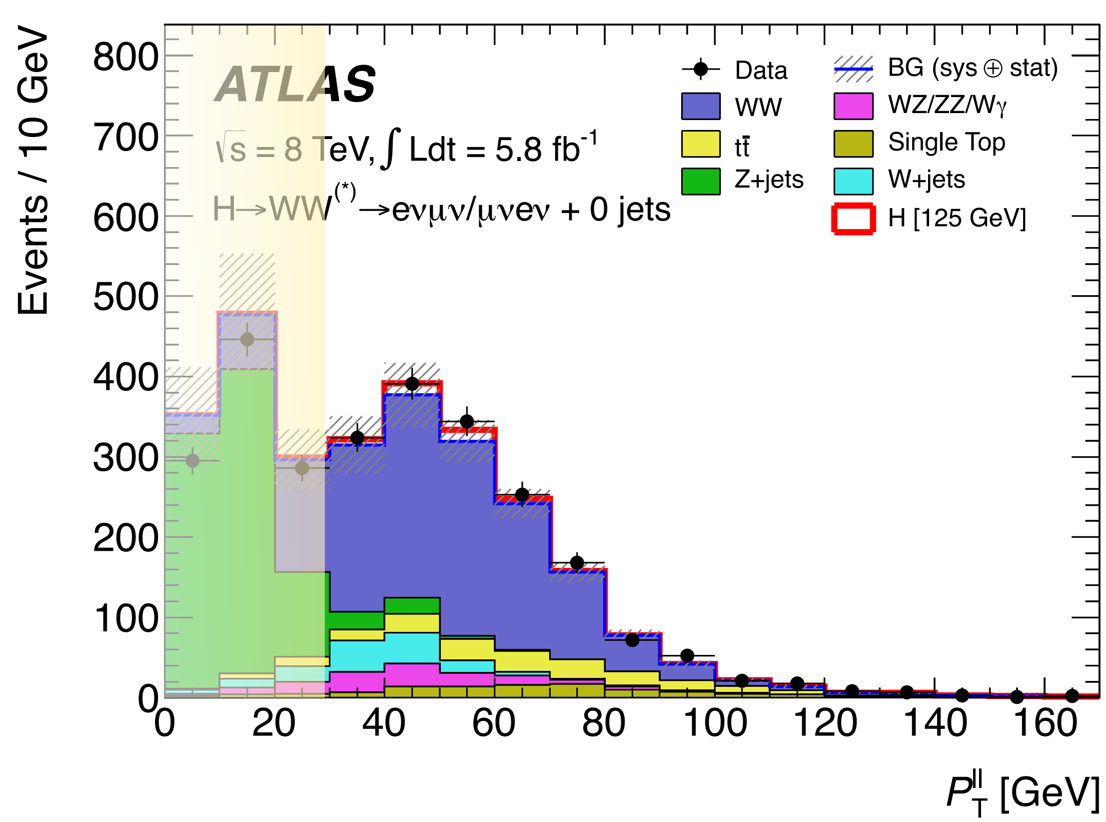
- b-jet veto (multivariate b-tagging algorithm, 85% ε_b point)
- $p_T(tot)$ < 30 GeV

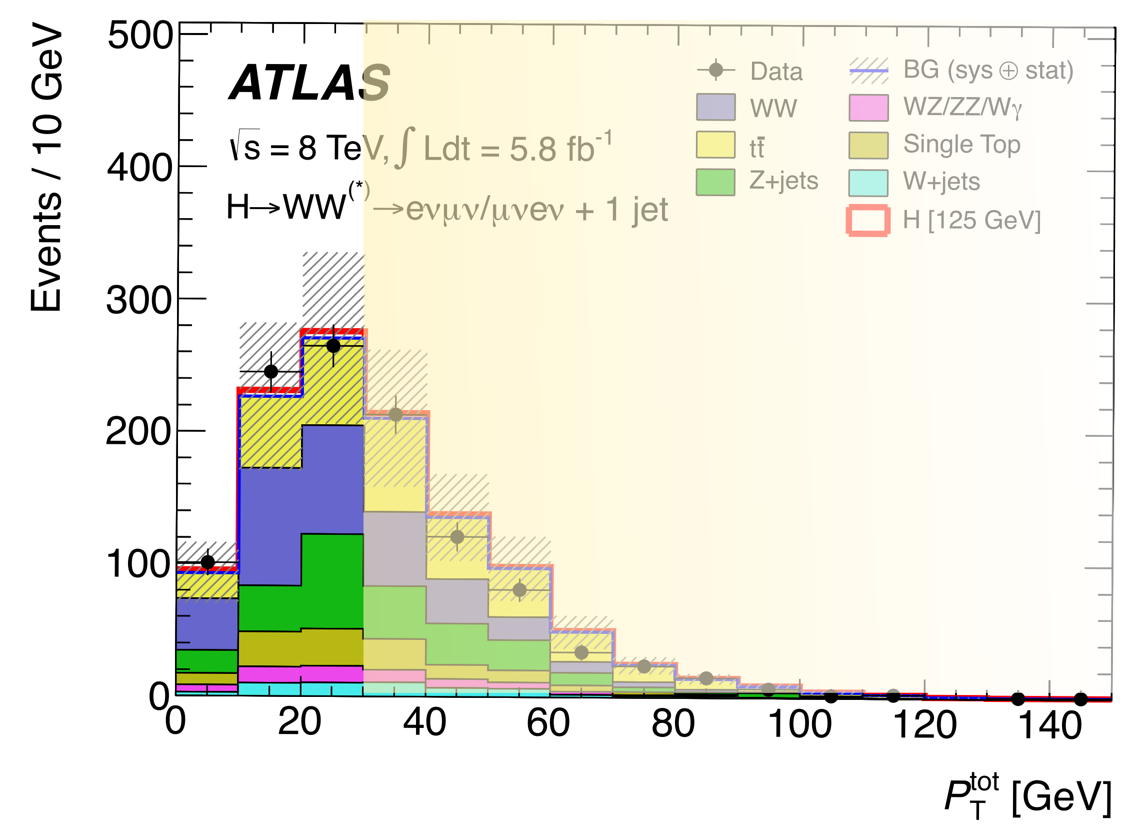
$$p_T^{tot} = |\mathbf{p}_T^{\ell 1} + \mathbf{p}_T^{\ell 2} + \mathbf{p}_T^{j} + \mathbf{p}_T^{miss}|$$

- $|m(\tau\tau)-m_Z|$ > 25 GeV (collinear approx.)

2-jet selection:

- 1-jet selection criteria
  - $p_T(tot)$ modified to include all jets
- leading jets ("tag jets" for VBF):
  - $\Delta y(jj)$ > 3.8
  - $m(jj)$ > 500 GeV
- no other jet with y between tag jets (Central Jet Veto)

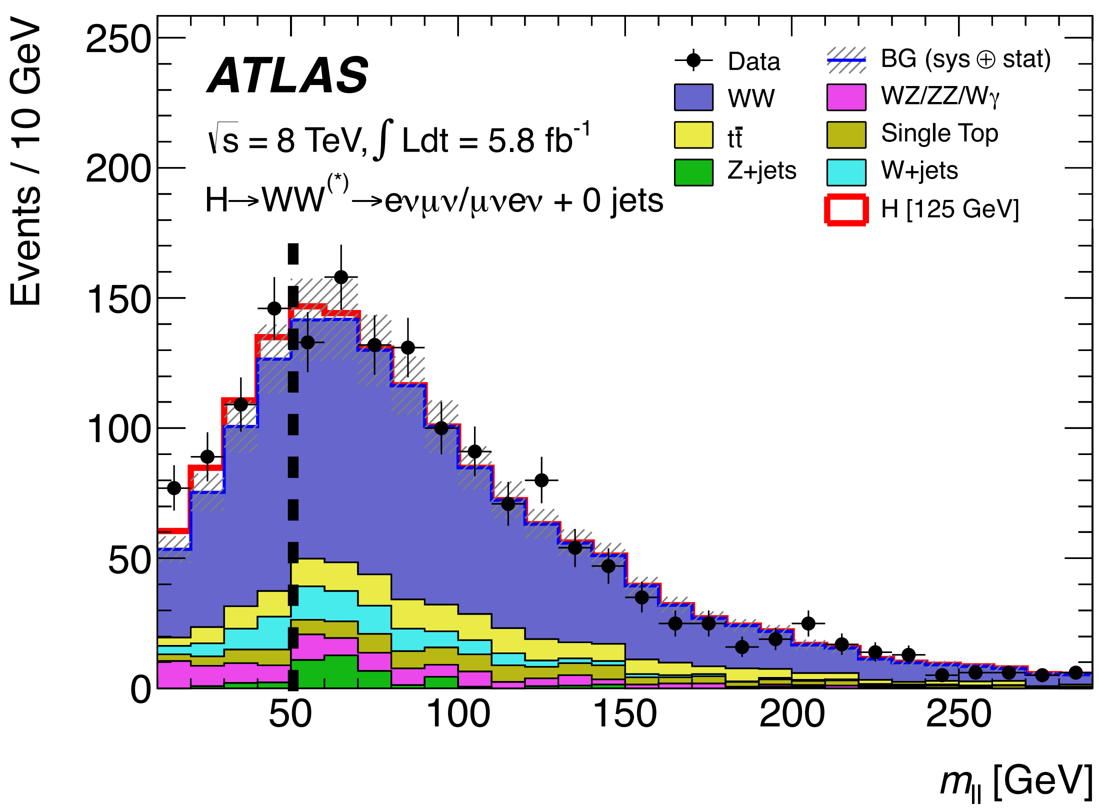


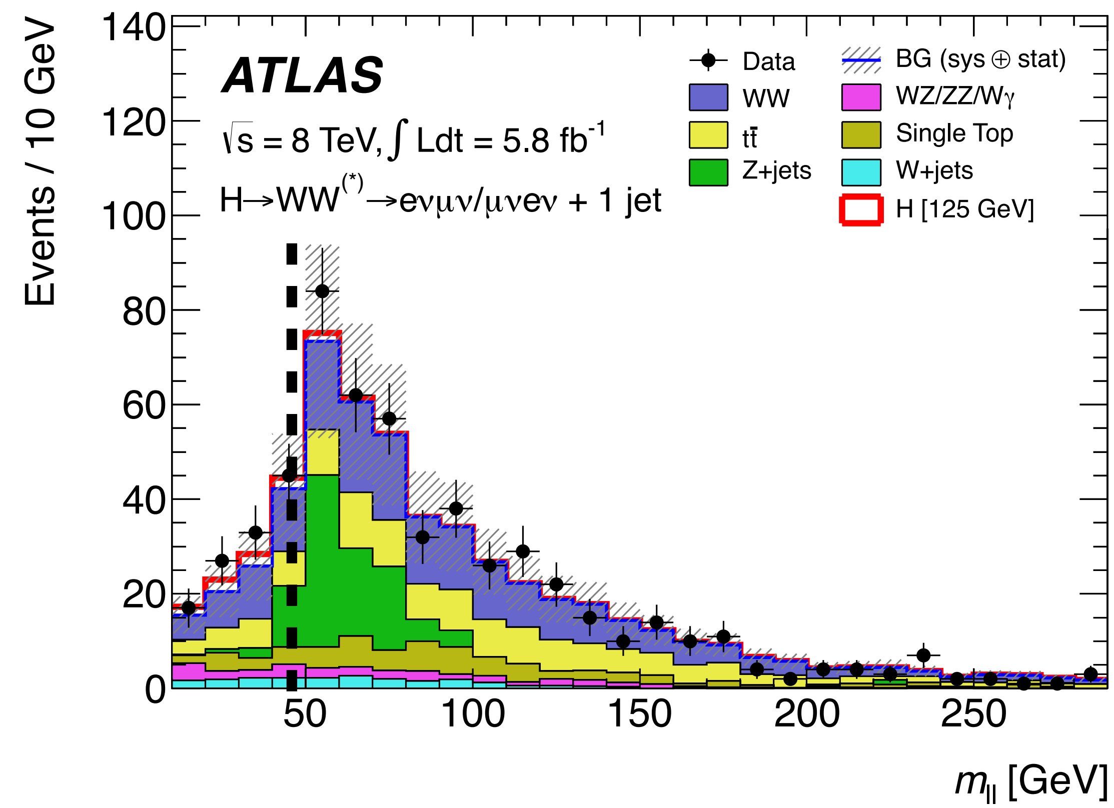


Kinematic Selection

Kinematic selection exploits spin correlations in W-boson decays due to Higgs boson's (assumed!) spin-0 nature:

- m(ll) < 50 GeV (m(ll) < 80 GeV for the 2-jet analysis)
- Δφ(ll) < 1.8

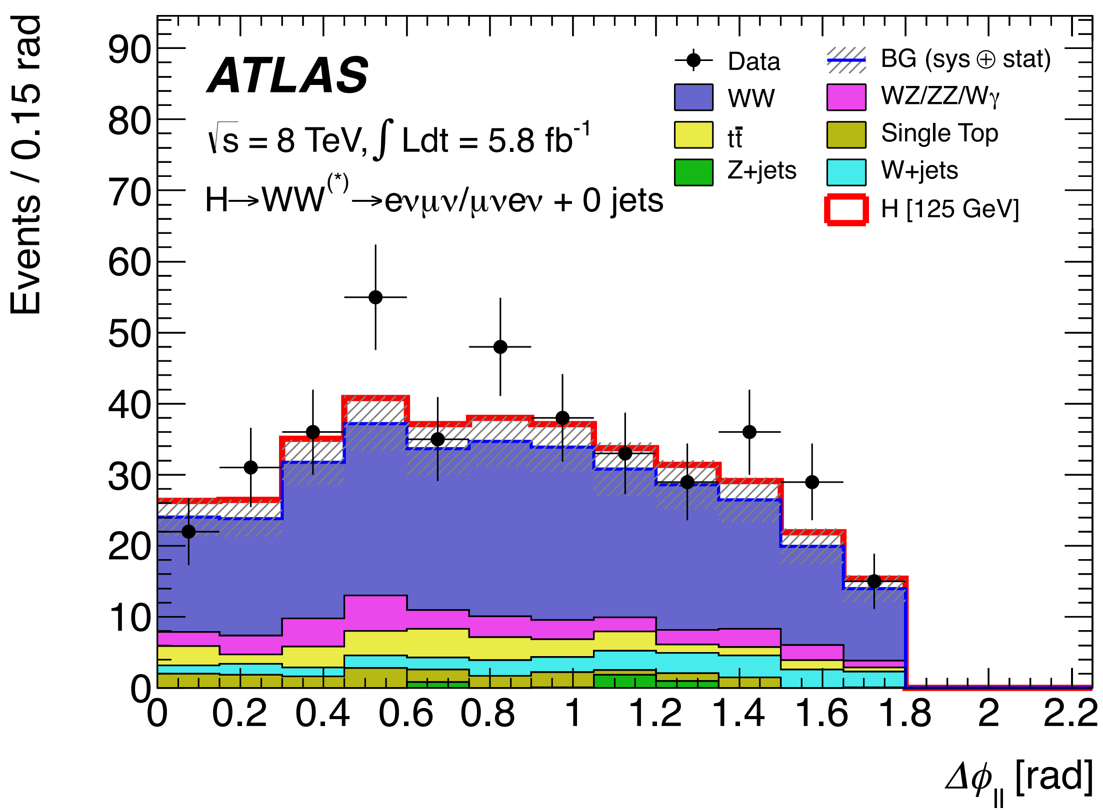


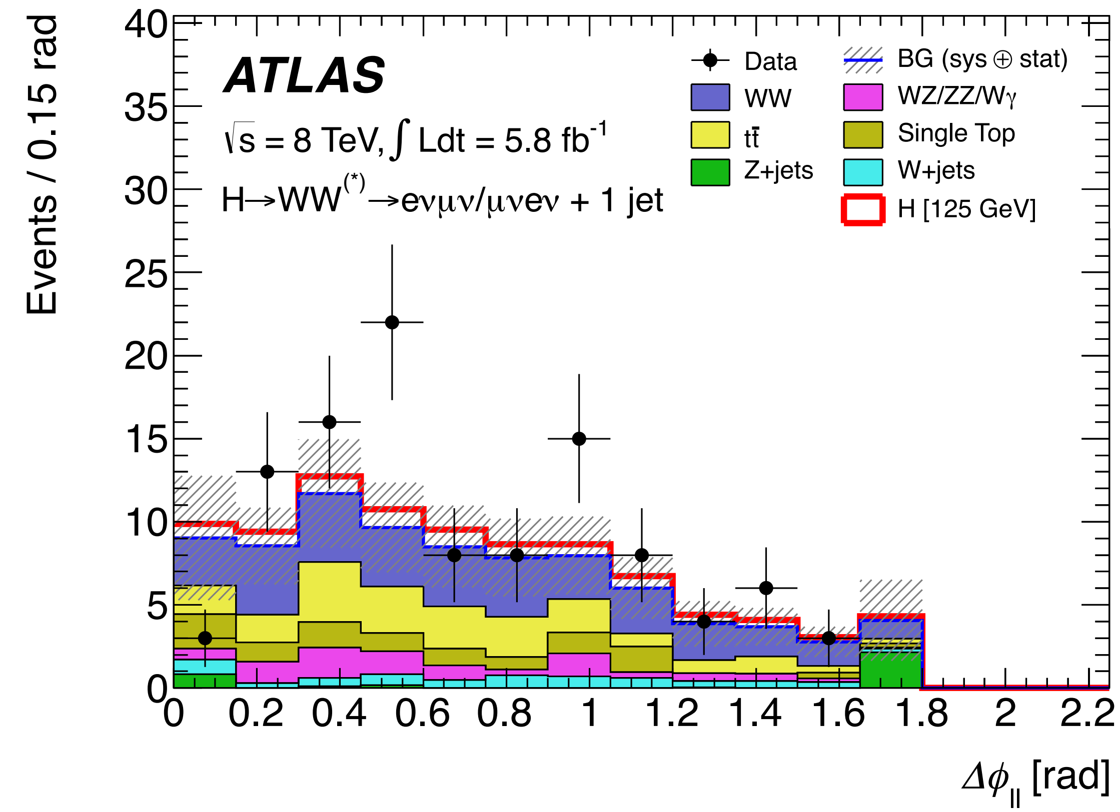


Kinematic Selection

Kinematic selection exploits spin correlations in W-boson decays due to Higgs boson's (assumed!) spin-0 nature:

- m(ll) < 50 GeV (m(ll) < 80 GeV for the 2-jet analysis)
- $\Delta\varphi(ll) < 1.8$





distributions made after all cuts

Background Estimation

Backgrounds

Major backgrounds:

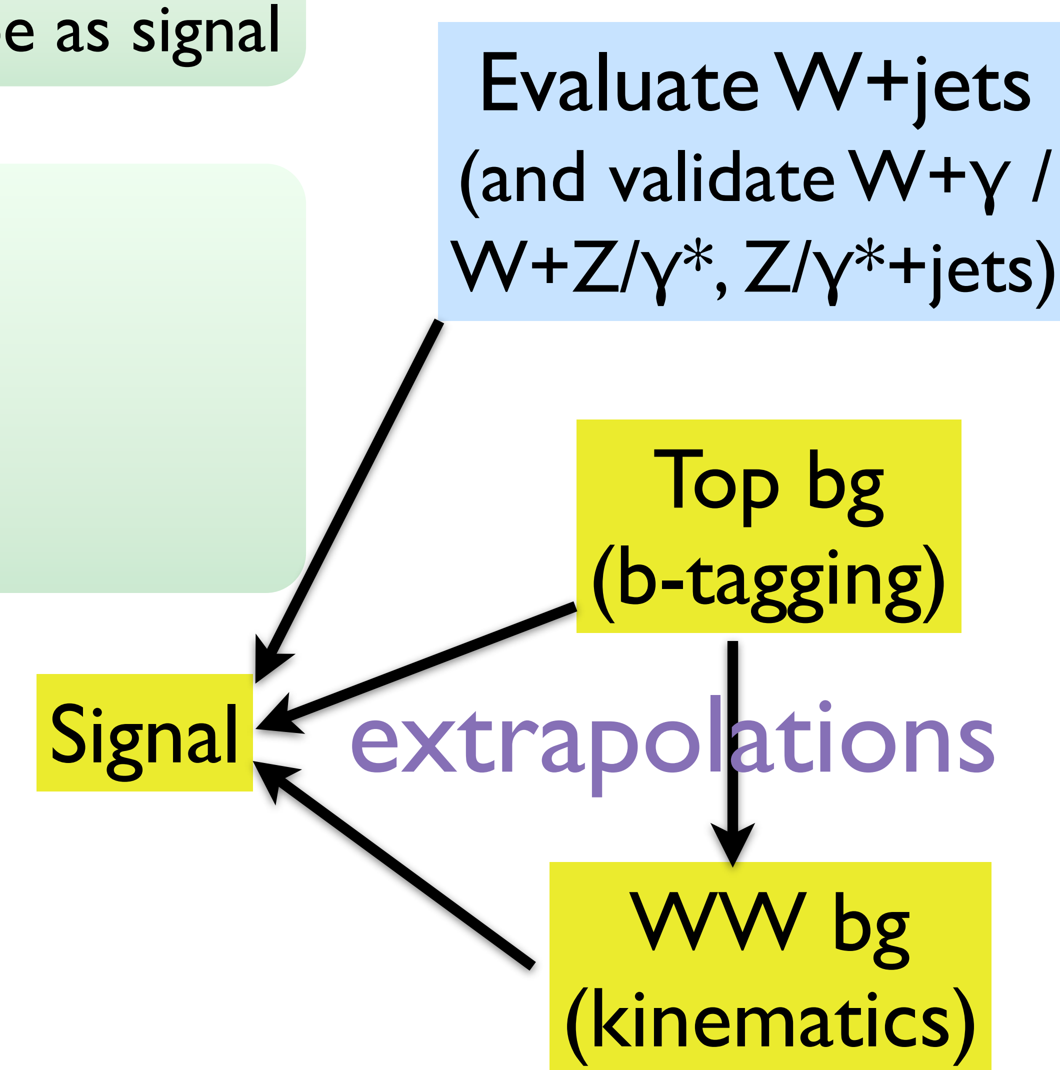
- 0-jet analysis: WW
- 1-jet analysis: WW, top (essentially $t\bar{t}$, Wt single-top)
- 2-jet analysis: top

Subleading backgrounds: W+jets, W+γ, W+Z/γ*, Z/γ*

- but (apart from Z/γ*) having similar m_T shape as signal

Need substantial input from data!

- completely: W+jets
- normalisation: WW, top
- cross-check: W+γ, W+Z/γ*, Z/γ*



W+Jets Background, Validation Region

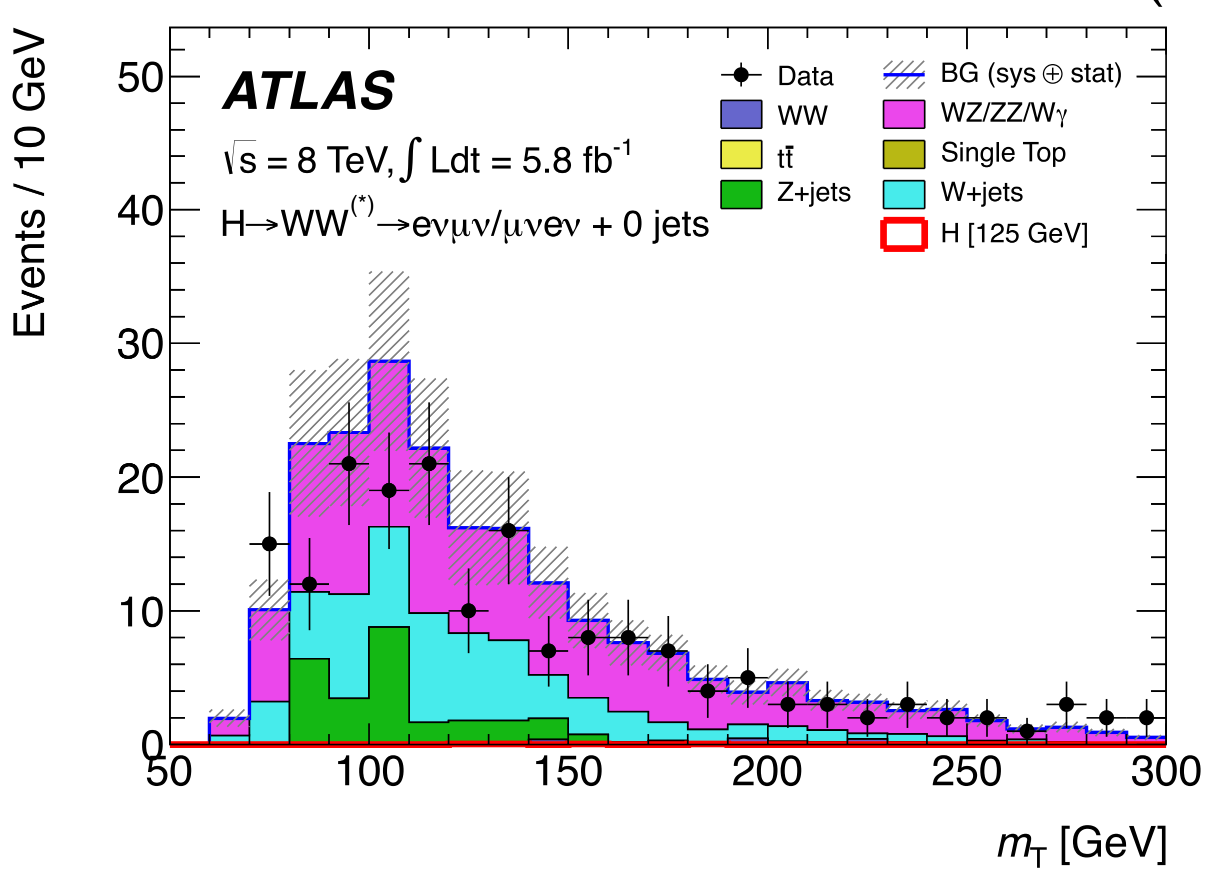
W+jets background: semileptonic decay or light-flavour jet faking electron

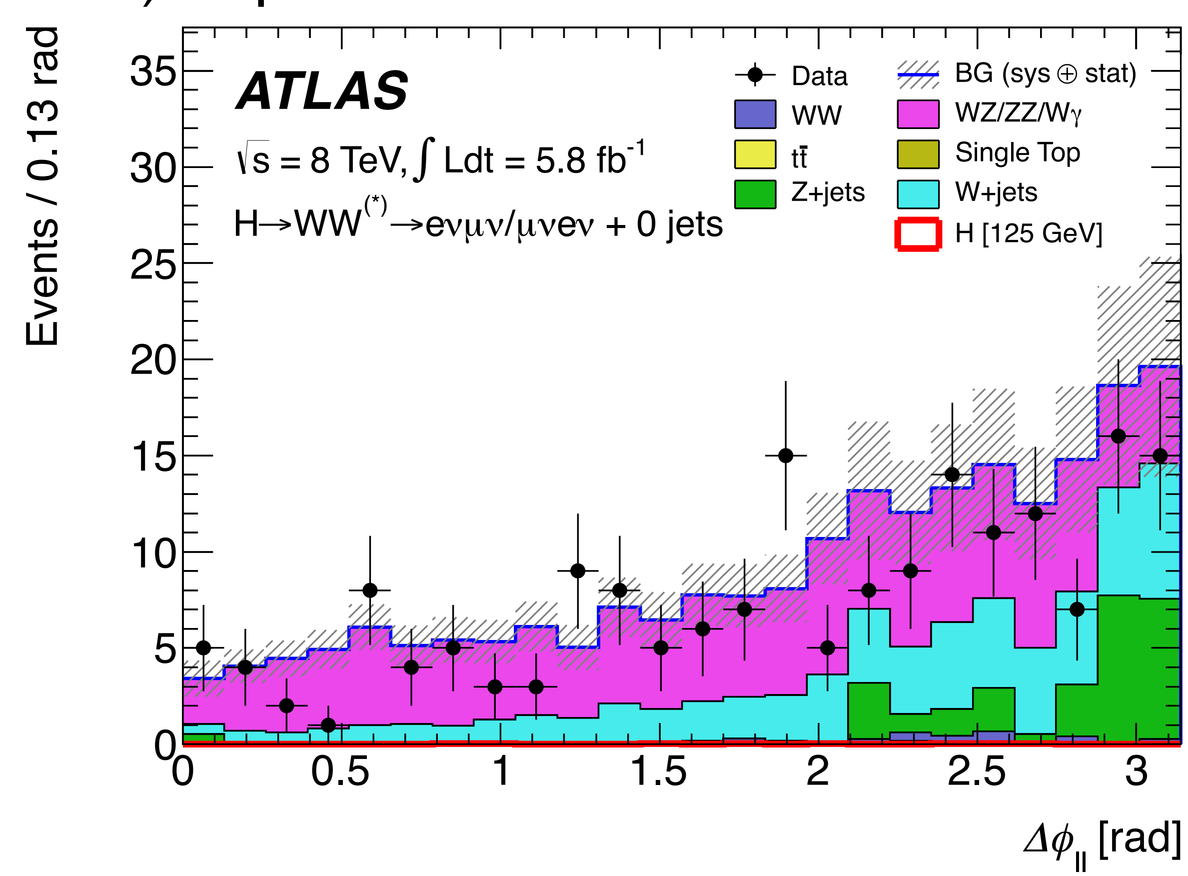
- estimate scaled from sample with one lepton satisfying all ID/isolation criteria and one satisfying only relaxed criteria
  - scale factor obtained from multijet sample, uncertainty ~ 40%

Validation carried out in region with same-sign leptons

- not dominated by a single background, but confirms our understanding of "fake" backgrounds: W+γ, W+Z/γ*, W+jets, Z/γ*+jets

after E_T(miss, rel) requirement





Top Background Normalisation

Normalise 1-jet, 2-jet top background from b-tagged control region

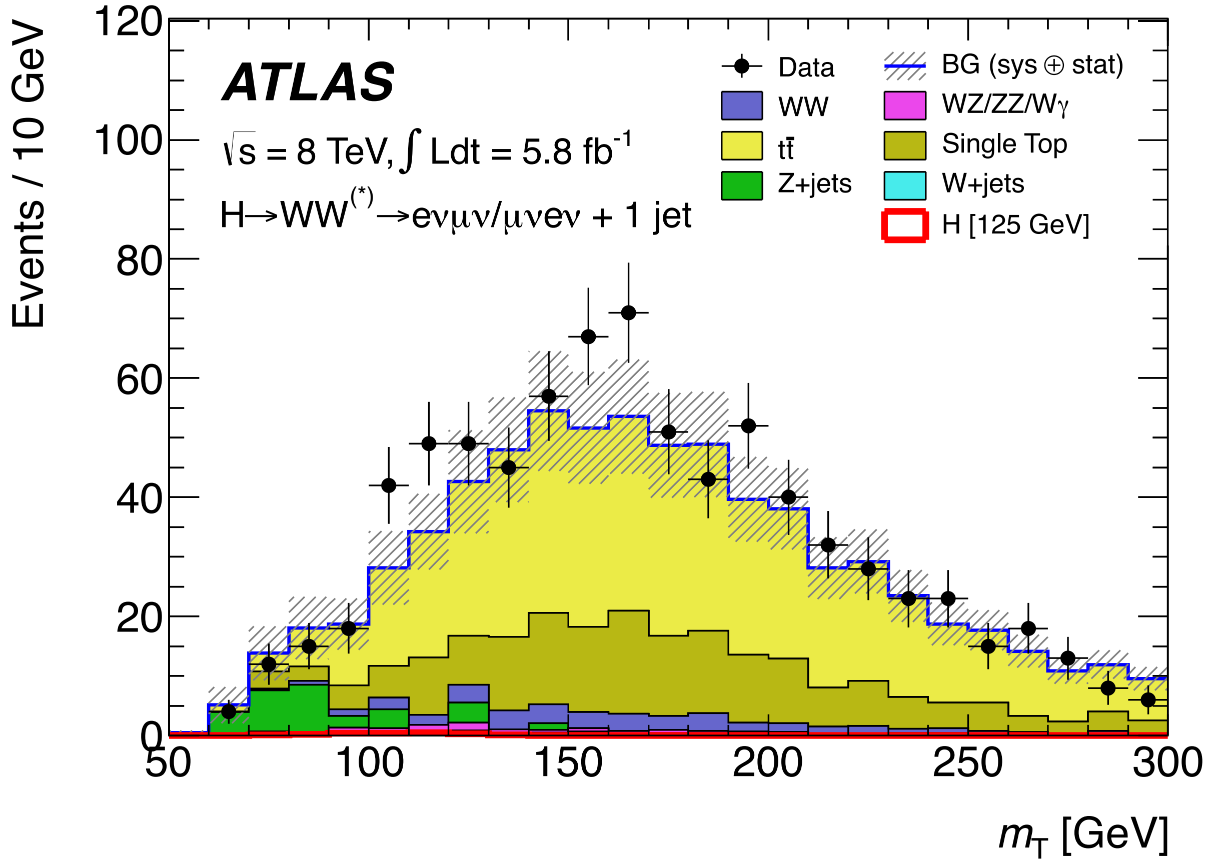
- without m_{ll} and $\Delta\varphi_{ll}$ cuts (1-jet)

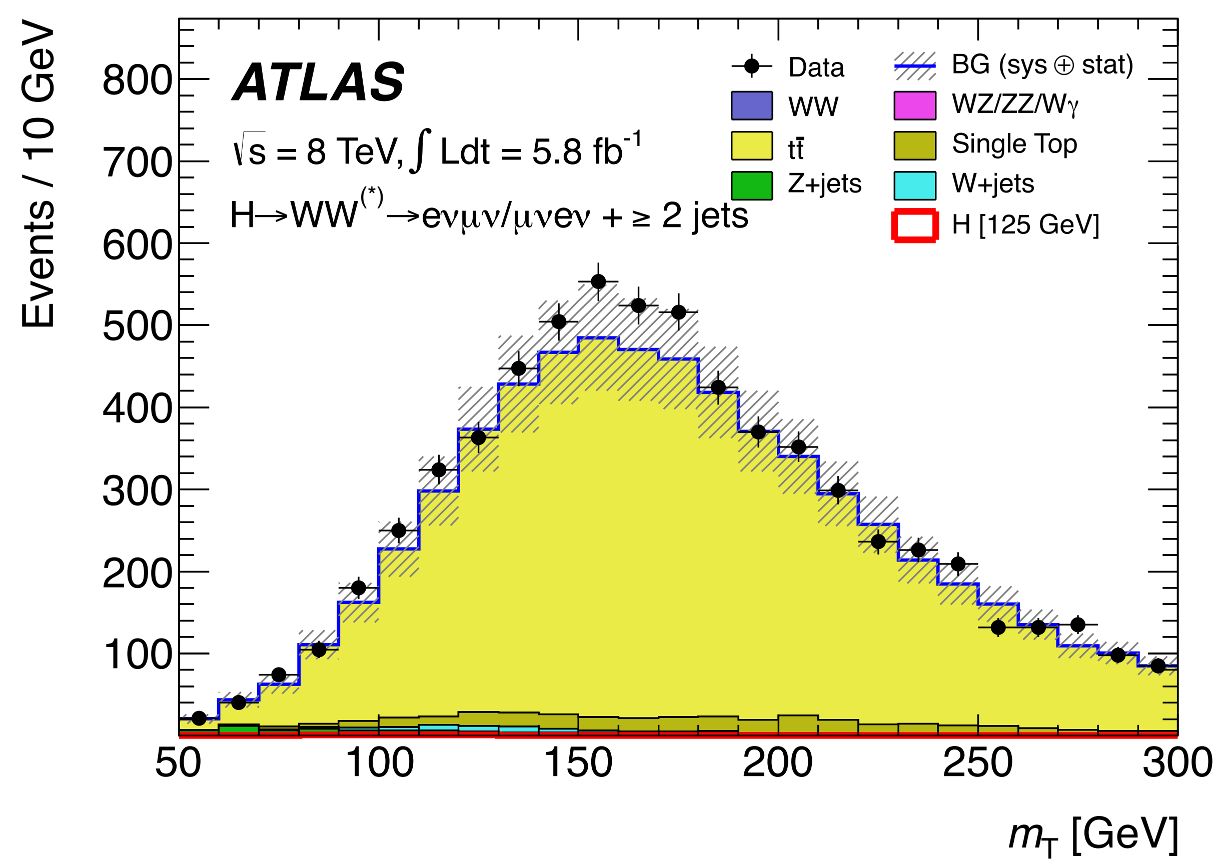
  1-jet data/MC normalisation factor: 1.11 ± 0.40 (stat. ⊕ syst.)

  2-jet data/MC normalisation factor: 1.01 ± 0.70 (stat. ⊕ syst.)

Top background in 0-jet analysis obtained from preselected sample scaled by probability not to observe any jet

- scale factor obtained from a b-tagged control sample; uncertainty ~17%





2-jet plot: after b-tag (no VBF cuts)

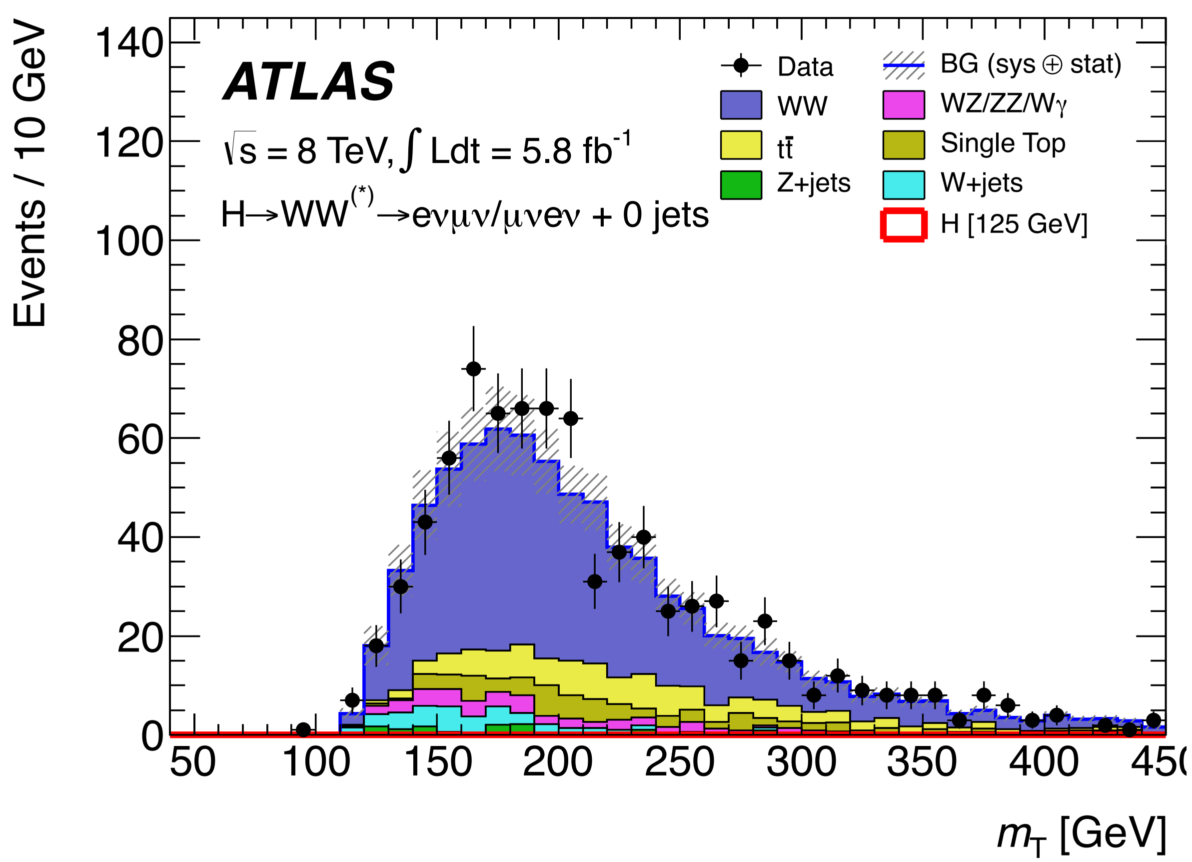
WW Background Normalisation

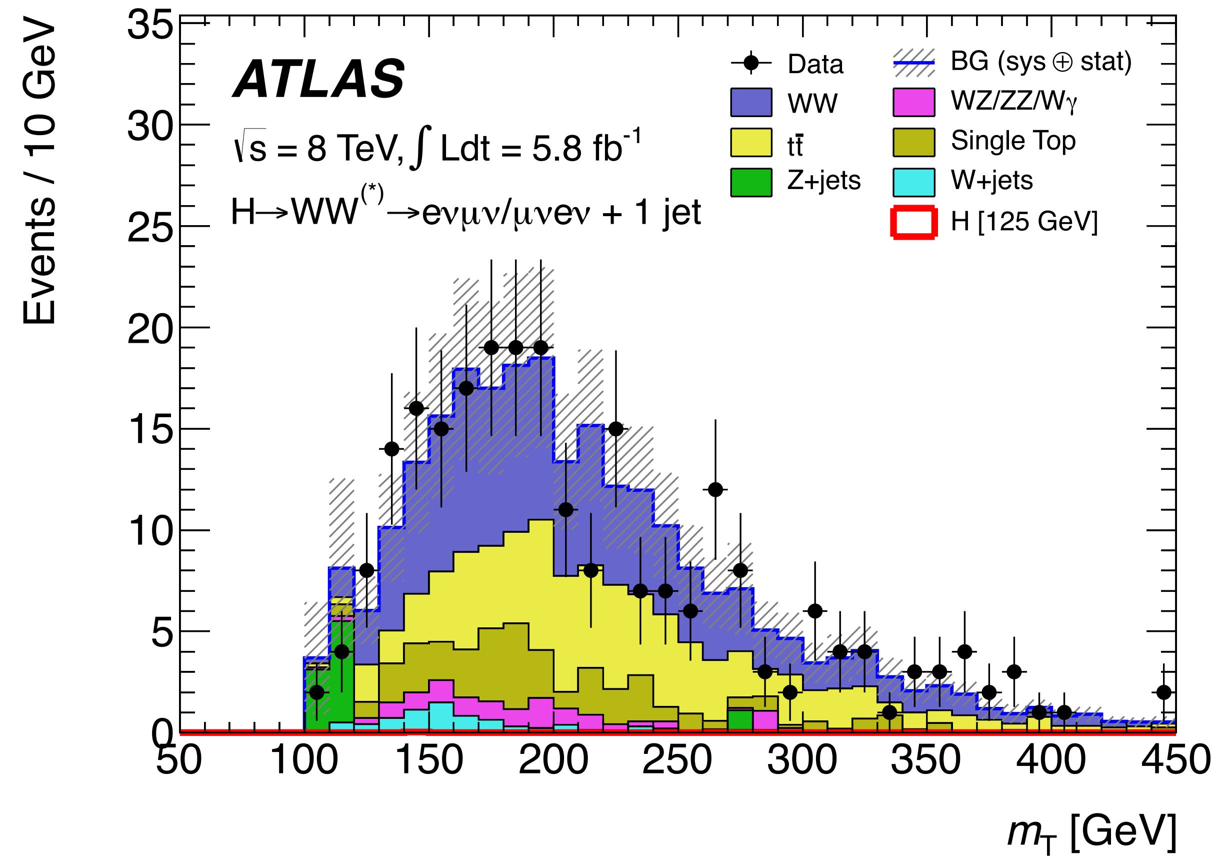
Normalise 0-jet / 1-jet WW background in control sample:

- remove $\Delta\varphi(ll)$ cut, require m(ll) > 80 GeV (instead of m(ll) < 50 GeV)

0-jet data/MC normalisation factor: 1.06 ± 0.14 (stat. ⊕ syst.)

1-jet data/MC normalisation factor: 0.99 ± 0.42 (stat. ⊕ syst.)





Top background is substantial, especially in the 1-jet analysis

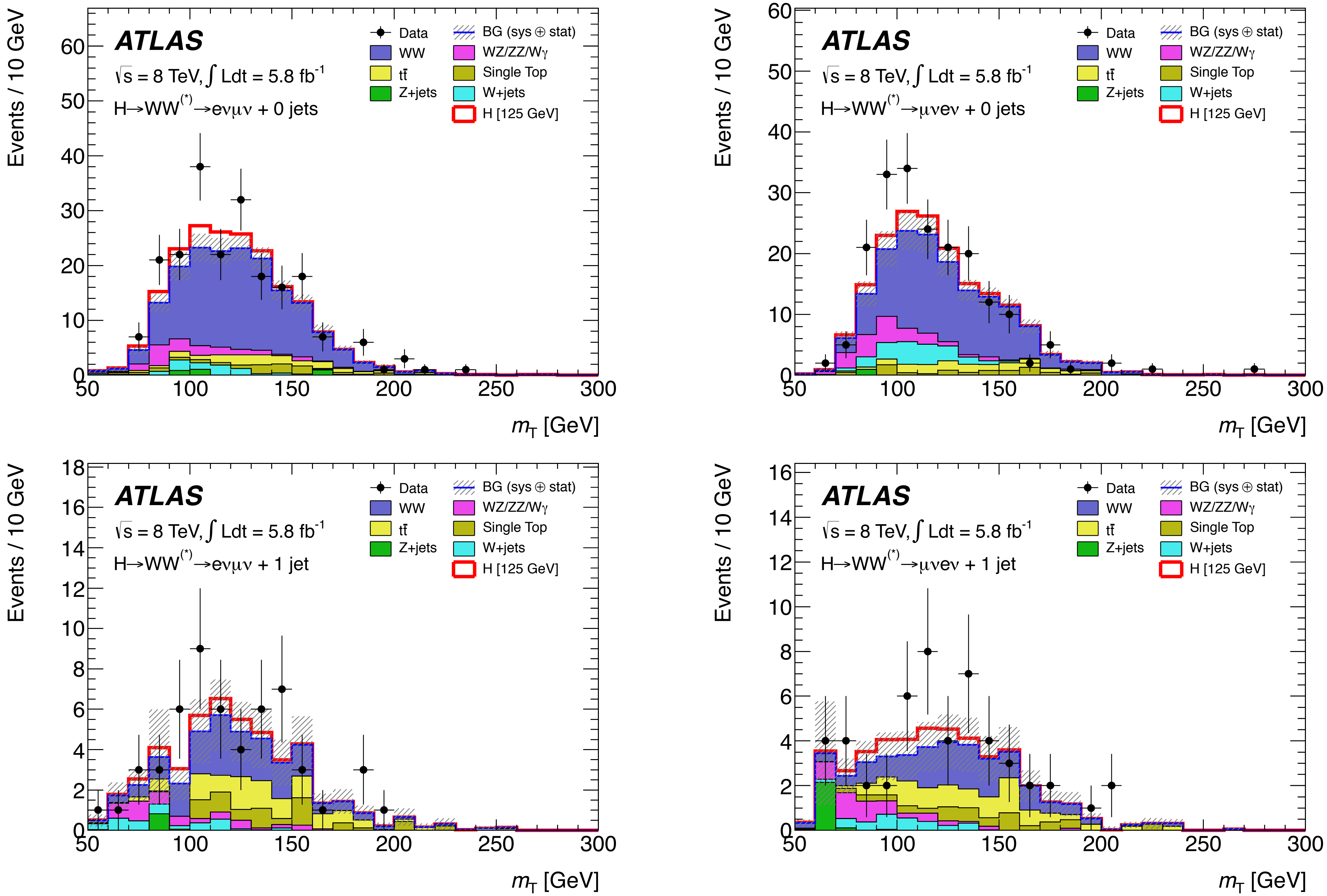
➠ use normalisation from previous slide

Results & Systematics

Results

Final results will be obtained from binned likelihood fits to m_T distributions

- 5 (3) bins for 0-jet (1-jet) analysis; no binning in 2-jet analysis
- excess of events!



$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{\text{miss}}|^2}, \quad E_T^{\ell\ell} = \sqrt{|\mathbf{p}_T^{\ell\ell}|^2 + m_{\ell\ell}^2}$$

Results in Numbers

leading electron → leading muon

Signal region yield for $e\mu$ and μe channels separately				
	0-jet $e\mu$	0-jet μe	1-jet $e\mu$	1-jet μe
Total bkg.	177 ± 4	162 ± 4	43 ± 2	40 ± 3
Signal	18.7 ± 0.3	14.9 ± 0.2	4.3 ± 0.1	4.2 ± 0.1
Observed	213	194	54	52

Consider eμ and μe final states separately because different backgrounds are expected

- especially W+jets, W+γ, W+γ^*

Only statistical uncertainties shown!

Systematic Uncertainties

Significant uncertainties on Higgs signal:

- μ_R, μ_F varied up/down by factor of 2 independently
  - 0 jet / 1 jet / 2 jets: 17% / 36% / 4% ⊕ 7% at M_H=125 GeV ← central jet veto
- PDF uncertainties: use PDF error sets + different PDFs
- modelling uncertainties: use alternative MC generators

Same approach for theoretical uncertainties on dominant backgrounds

- uncertainties can affect control regions differently than signal regions
  ➠ extrapolation uncertainties (small due to data-driven normalisation)
- scale variations, PDF uncertainties (independently for qq, qg, gg processes), modelling uncertainties (use alternative MC generators)

k-factor uncertainties for processes not normalised to data:

- W+γ: same scale uncertainty treatment as for signal, 11% (50%) for 0-jet (1-jet) channels
- W+Z/γ*: m(ll) dependent, 25% - 30%

Experimental systematics: jet energy scale, b-tagging, pile-up, E_T(miss, rel) modelling

- evaluate predictions with sources of uncertainty varied

Systematic Uncertainties

Leading relative uncertainties on signal / total background

- after additional $0.75\ M_H < m_T < M_H$ cut
  - represents better the signal sensitivity in a cut-based context
- m_T shape uncertainties relevant in fit essentially due to variations in background composition

Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal $\mu_{R,F}$	13	-
1-jet incl. ggF signal $\mu_{R,F}$	10	-
Parton distribution functions	8	2
Jet energy scale	7	4
WW normalisation	-	7
WW modelling and shape	-	5
W+jets fake factor	-	5
QCD scale acceptance	4	2
Source (1-jet)	**Signal (%)**	**Bkg. (%)**
1-jet incl. ggF signal $\mu_{R,F}$	28	-
WW normalisation	-	25
2-jet incl. ggF signal $\mu_{R,F}$	16	-
b-tagging efficiency	-	10
Parton distribution functions	7	1
W+jets fake factor	0	5

Event counts including systematic uncertainties

- again including the additional m_T cut, and accounting for correlations between signal and control regions

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

Statistical Analysis

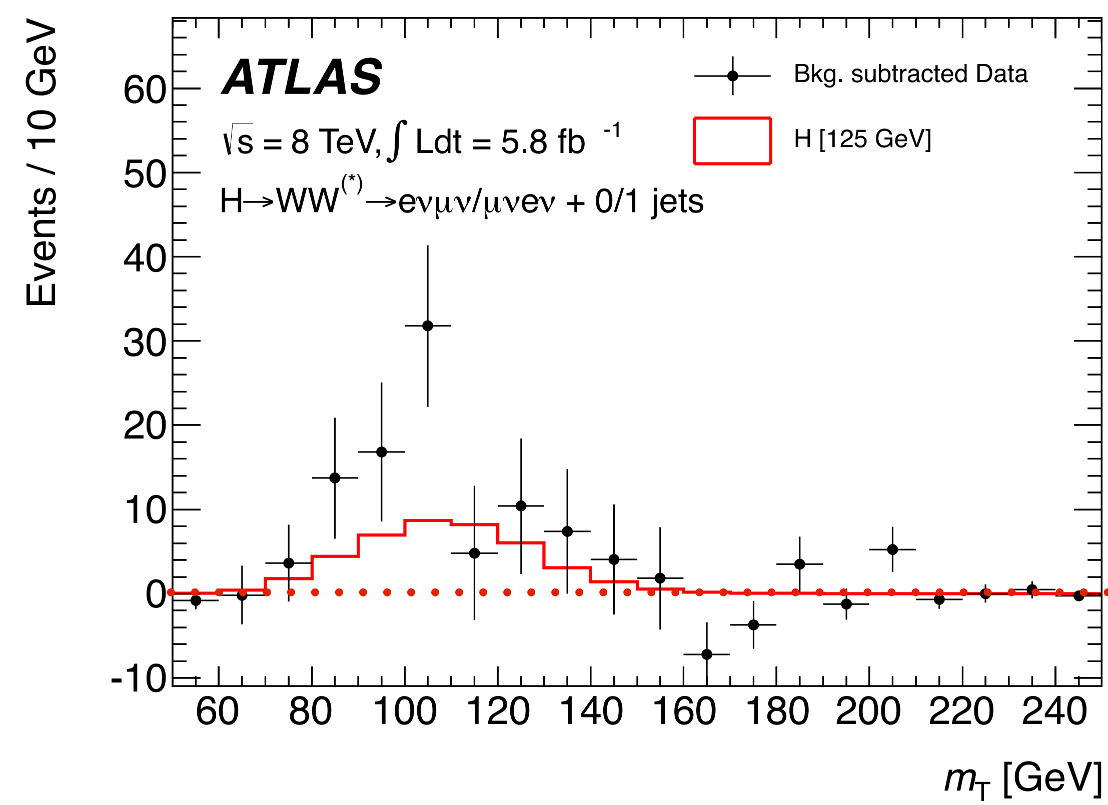
Use “standard” profile likelihood fit

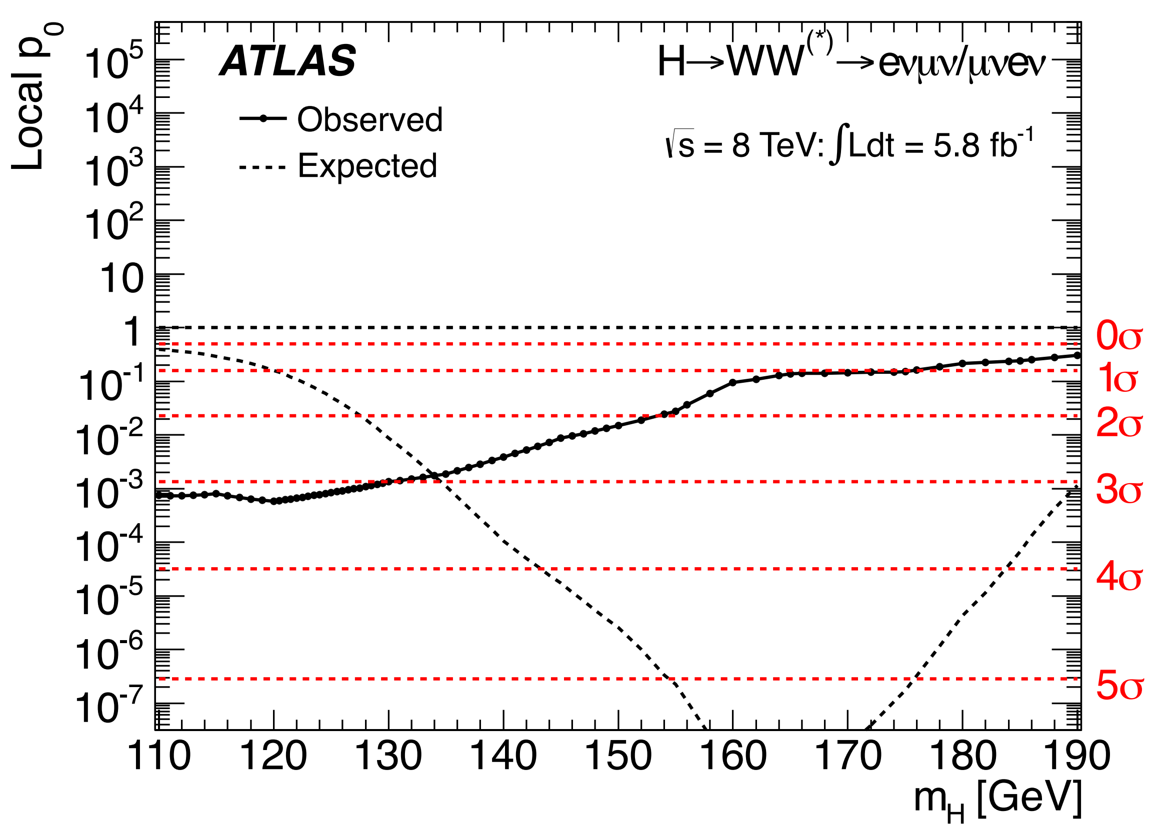
- fits systematics nuisance parameters in addition to signal strength μ

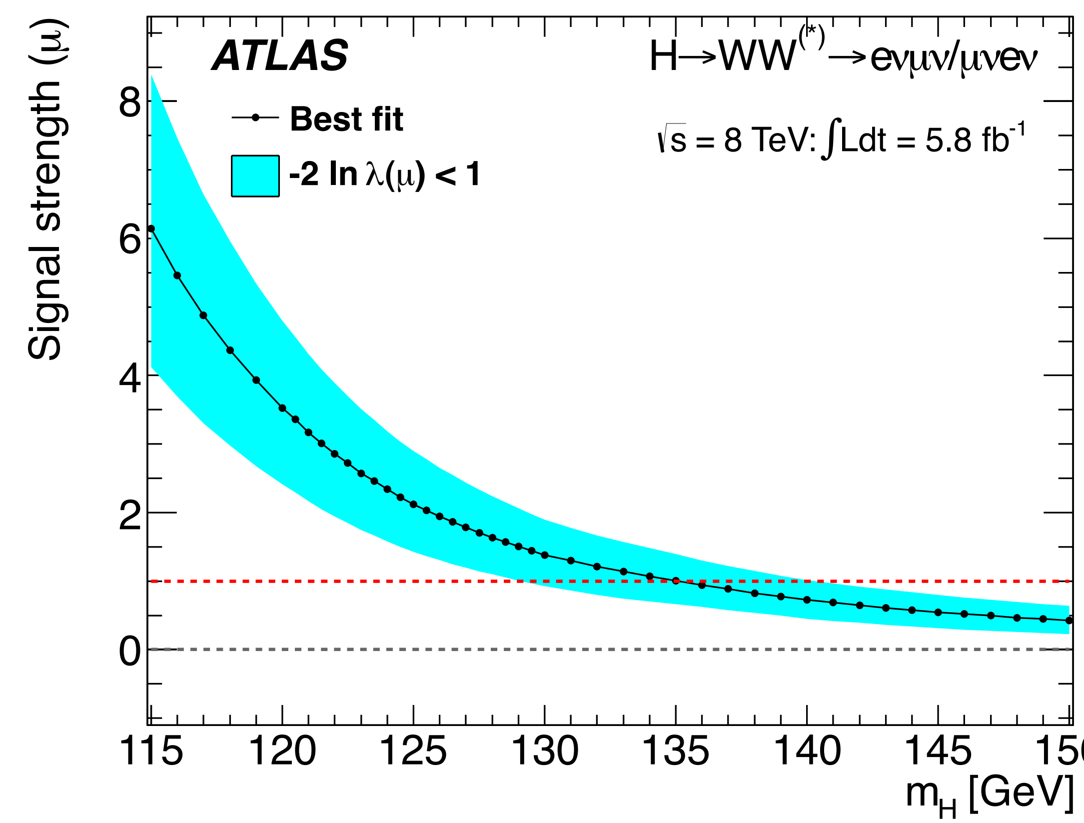
At M_H = 125 GeV, find a signal significance of 3.1σ ($p_0 = 8 \cdot 10^{-4}$)

- most significant at M_H = 120 GeV ($p_0 = 6 \cdot 10^{-4}$ ➠ 3.2 σ)

At M_H = 126 GeV, fit μ = 1.9 ± 0.7







Combination with 2011 Results

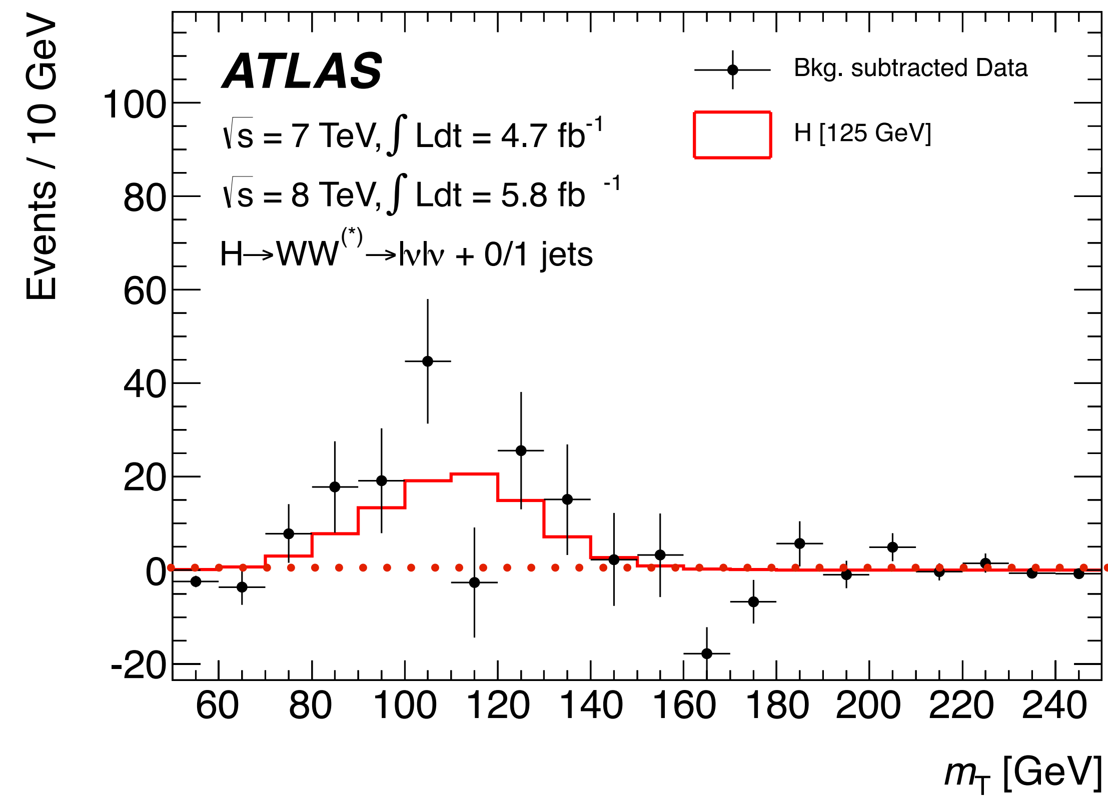
Combine datasets in a straightforward way (joint likelihood fit)

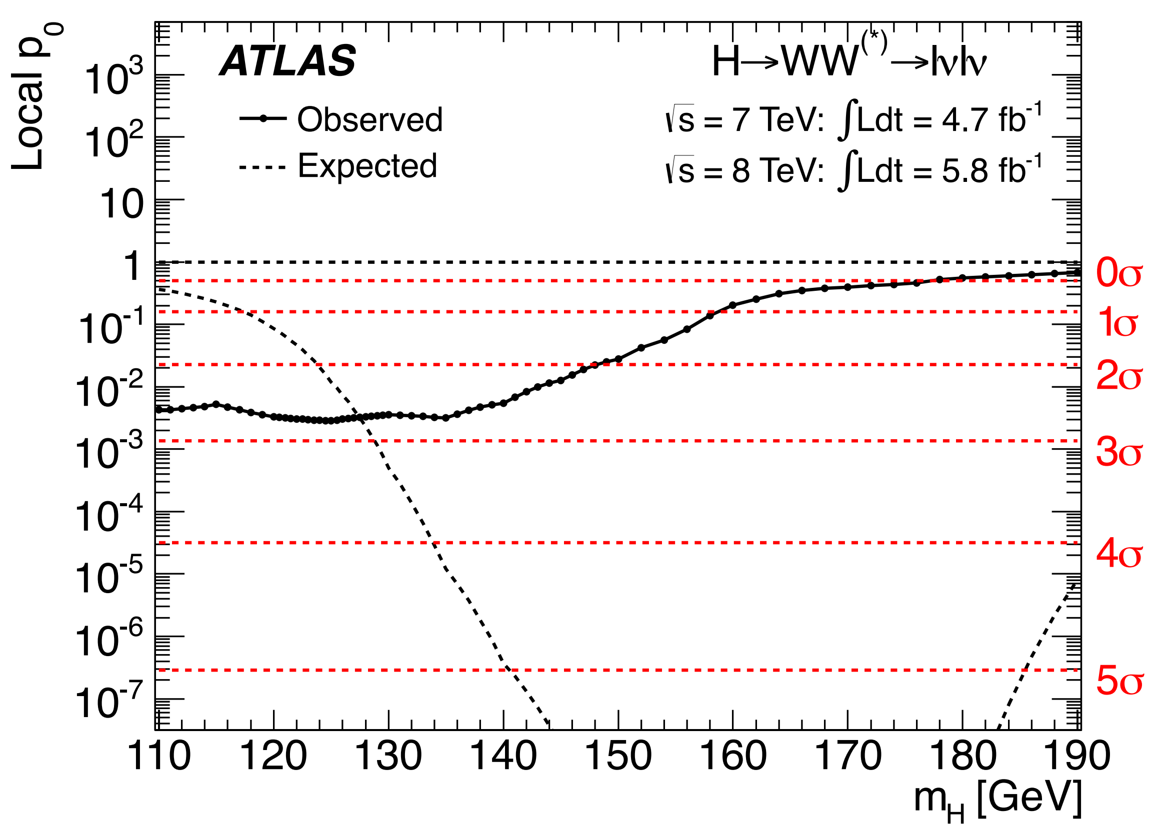
Significance at M_H = 125 GeV:

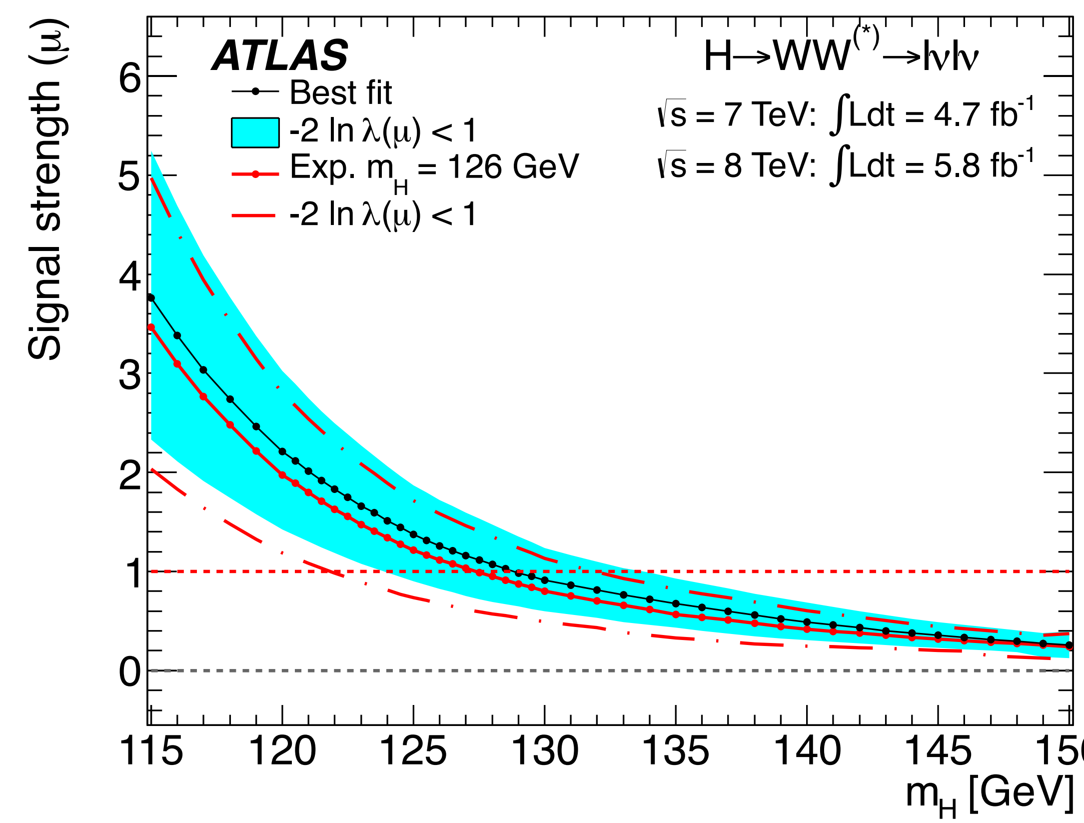
- $p_0 = 3 \cdot 10^{-3}$ (2.8σ)
  - expected: p_0 = 0.01 (2.3σ)

For M_H = 126 GeV, fit μ = 1.3 ± 0.5

- 2011 result alone: μ = 0.5 ± 0.6
  ➠ tension between 2011 and 2012 results acceptable

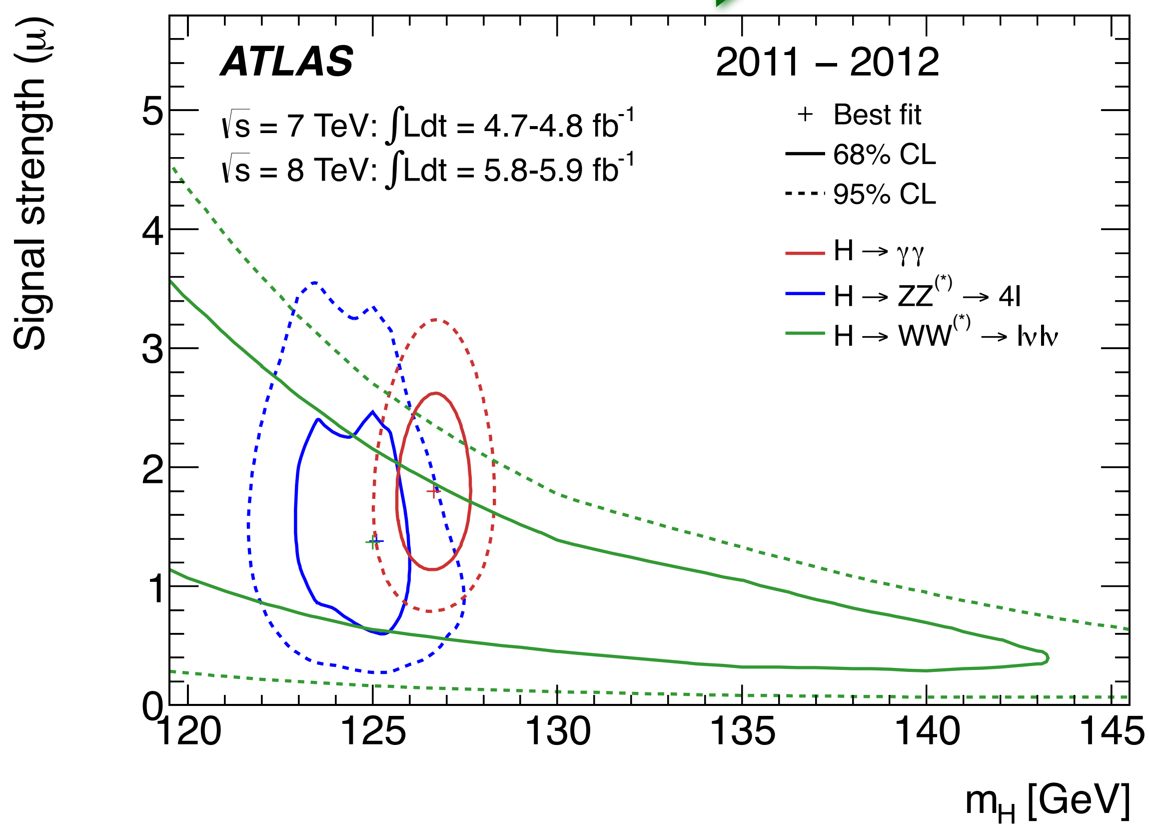




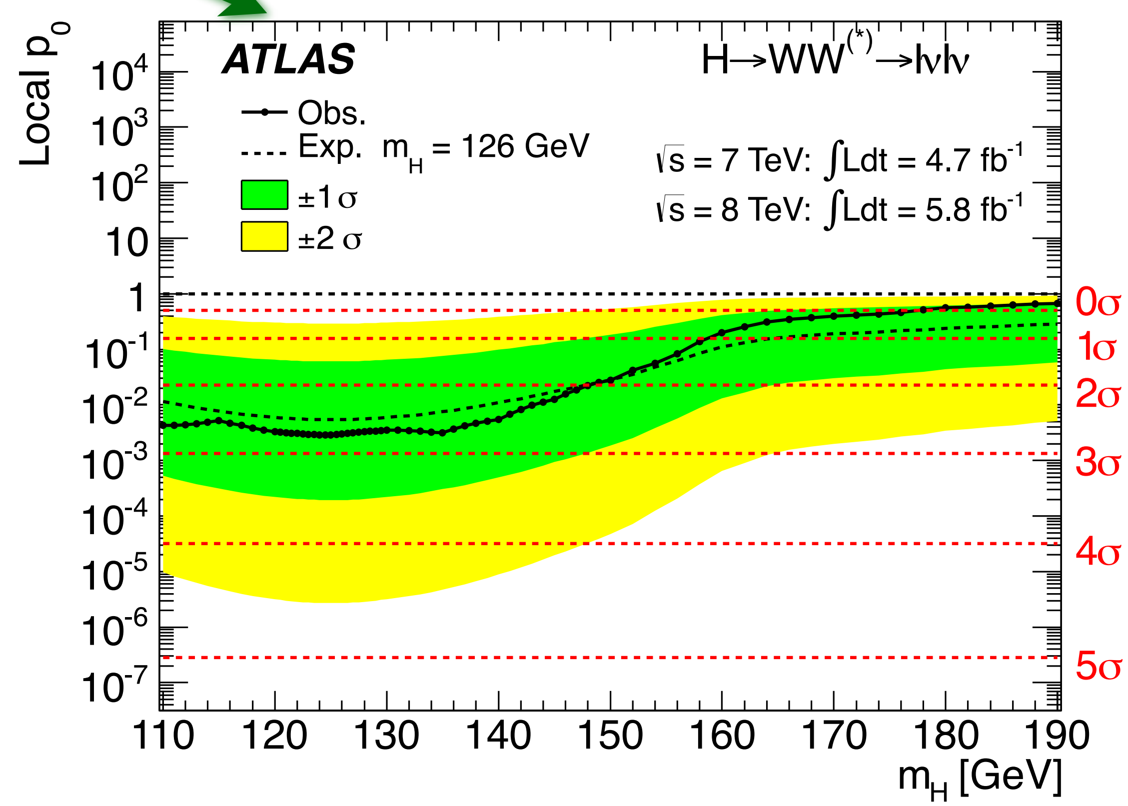


Consistency Checks

Agreement with high-resolution $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)} \rightarrow 4l$ analyses
and with expectation from an injected M_H = 125 GeV signal



2D likelihood scan



Conclusion

Conclusion & Outlook

With 5.8 fb^{-1} of $\sqrt{s}$ = 8 TeV (2012) data and 4.7 fb^{-1} of $\sqrt{s}$ = 7 TeV (2011) data, we find an excess of data consistent with a M_H = 126 GeV signal

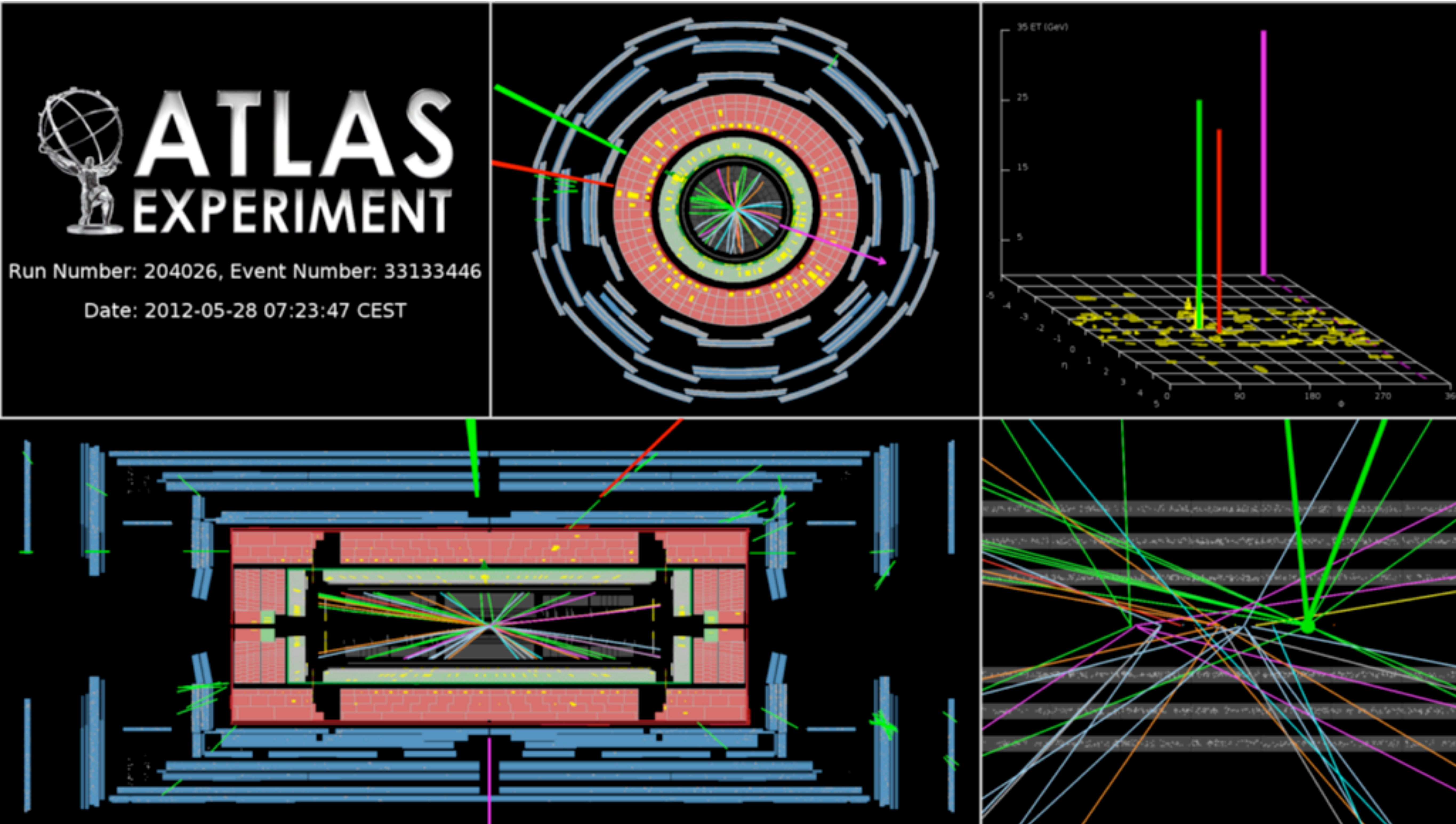
- $p_0 = 3 \cdot 10^{-3}$ (2.8σ)
  - expected: p_0 = 0.01 (2.3σ)
- $\mu = 1.3 \pm 0.5$
- consistent with results from high-resolution search channels

There remains a lot to be done! $H \rightarrow WW$ analysis aims:

- establish signal in separate production channels (WH/ZH, VBF in addition to gluon fusion)
- determination of spin / CP properties

2012 eμ candidate

- $p_T(e) = 33$ GeV, $p_T(\mu) = 29$ GeV, $m_T = 94$ GeV



Backup

MC

Signal (5 GeV steps, 110 GeV < M_H < 200 GeV):

- ggF, VBF: POWHEG+PYTHIA (CT10) ⇔ MC@NLO+HERWIG (CT10)
- WH, ZH: PYTHIA8 (CTEQ6L1)

Backgrounds:

- WW: MC@NLO+HERWIG (CT10) ⇔ POWHEG+PYTHIA8 (CTEQ6L1)
- gg → WW: gg2WW+HERWIG (CT10)
- (W,) Z/γ^*: ALPGEN+HERWIG (CTEQ6L1, reweighted to MRSTMCal)
- ZZ: POWHEG (CT10)
- Wγ: ALPGEN+HERWIG (CTEQ6L1)
- W+Z/γ^*: MadGraph+PYTHIA (CTEQ6L1)
- single top (s-channel, Wt): MC@NLO+HERWIG (CT10)
- single top (t-channel): AcerMC+PYTHIA8 (CTEQ6L1)
- ttbar: MC@NLO+HERWIG (CT10)

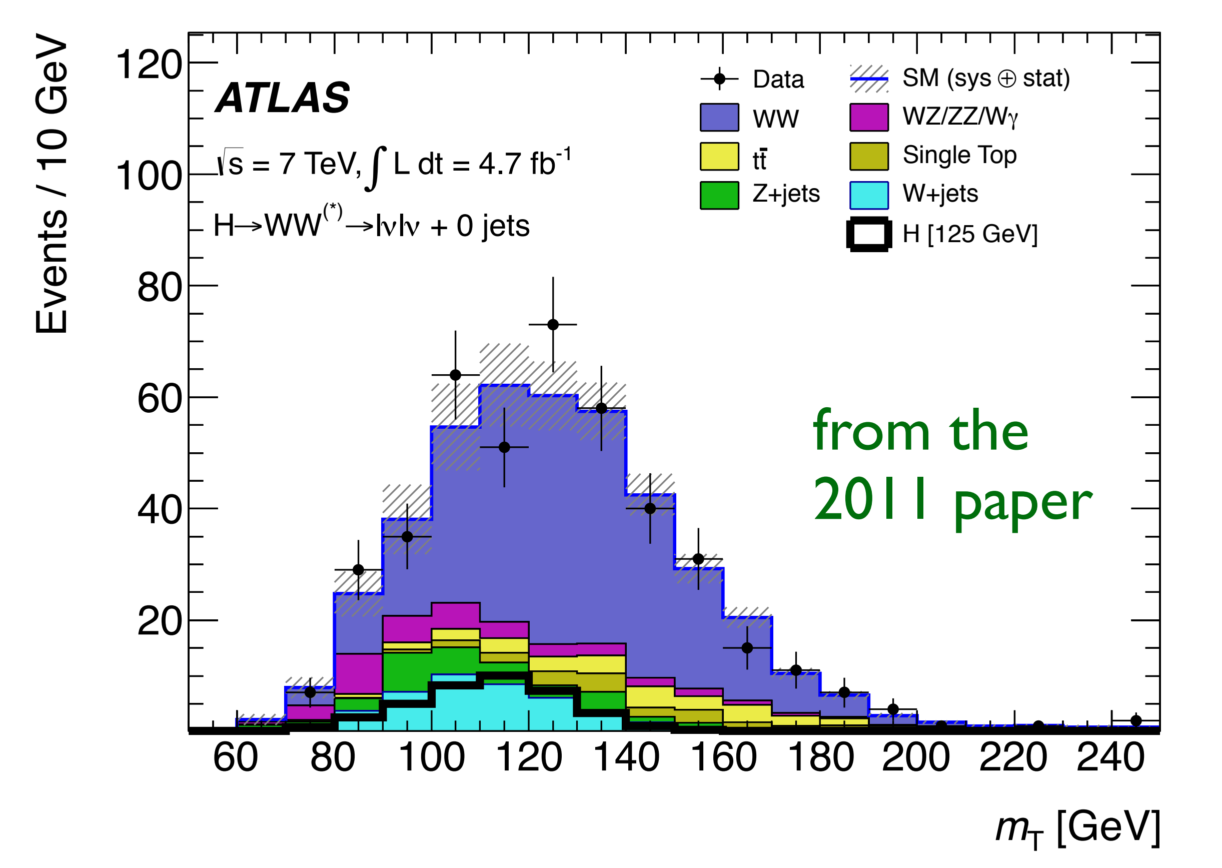
Blind Analysis

Did not want to get biased by desire to exclude or see an excess, so carried out a blind analysis initially. Excluded events satisfying b-jet veto and subset of 2011 kinematic cuts exploiting spin correlations:

- 82.5 GeV < m_T < 140 GeV
- m_{ll} < 50 GeV
- $\Delta\varphi_{ll}$ < 1.8

Blinding does not affect control regions

Unblinding done after scrutiny of intermediate results with 4.2 fb^{-1}



from the 2011 paper

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{miss}|^2}, \quad E_T^{\ell\ell} = \sqrt{|\mathbf{p}_T^{\ell\ell}|^2 + m_{\ell\ell}^2}$$

Lepton Selection & Trigger

Triggers used: loosest unprescaled single-lepton triggers

- single electron: 24 GeV isolated e OR 60 GeV e w/o isolation requirement
- single muon: 24 GeV isolated μ OR 36 GeV μ w/o isolation requirement

Lepton isolation:

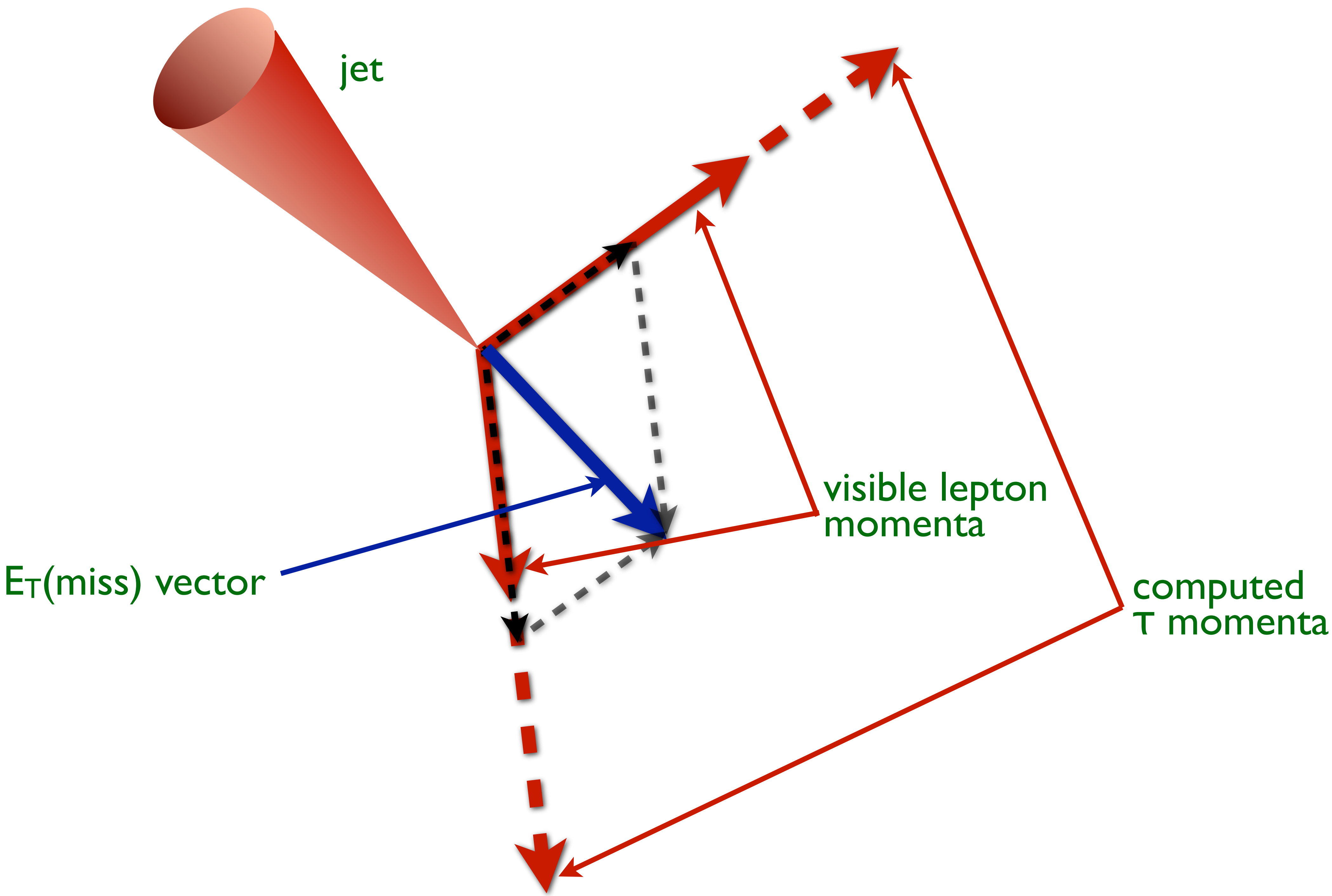
- electrons:
  - p_T(tracks, $\Delta R<0.3$)/p_T < 0.12 (0.16) for p_T < 25 GeV (p_T > 25 GeV)
  - pile-up/UE corrected E_T(CAL, $\Delta R<0.3$)/p_T < 0.16
- muons:
  - p_T(tracks, $\Delta R<0.3$)/p_T < min(0.01*p_T - 0.105, 0.15)
  - pile-up/UE corrected E_T(CAL, $\Delta R<0.3$)/p_T < min(0.014*p_T-0.15, 0.20)

Impact parameter cuts

- $|d_0/\sigma(d_0)| < 3$; $|\Delta z \sin\theta| < 0.4$ mm (e), 1 mm (μ)

Collinear Approximation

Decompose E_T(miss) vector into components along visible leptons



Statistical Analysis

Binned likelihood function

- signal binned in m_T: 5 bins (0 jet), 3 bins (1 jet), no binning (2 jets)
- WW, top control regions accounted for as additional Poisson terms (not binned in m_T)

Systematic uncertainties accounted for using profiling

- one nuisance parameter θ_i for each (independent) source of uncertainty i
- parametrised dependence of expected event counts on θ_i
- gaussian constraint terms

$$\mathcal{L}(\mu, \vec{\theta}) = \left\{ \prod_{k=e\mu,\mu e} \prod_{j=0}^{2} \prod_{i=1}^{N^j_{\text{bins}}} \mathcal{P}(N_{ijk} | \mu s_{ijk} + \sum_{l}^{N_{\text{bg}}} b_{ijkl}) \right\} \times \left\{ \prod_{i=1}^{N_\theta} \mathcal{G}(\tilde{\theta} | \theta) \right\}$$

No (significant & important) m_T shape dependent uncertainties on individual backgrounds ➠ shape variations caused by varying relative normalisations