VBF H→WW in ATLAS

Ben Cerio

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UC Santa Cruz

Outline

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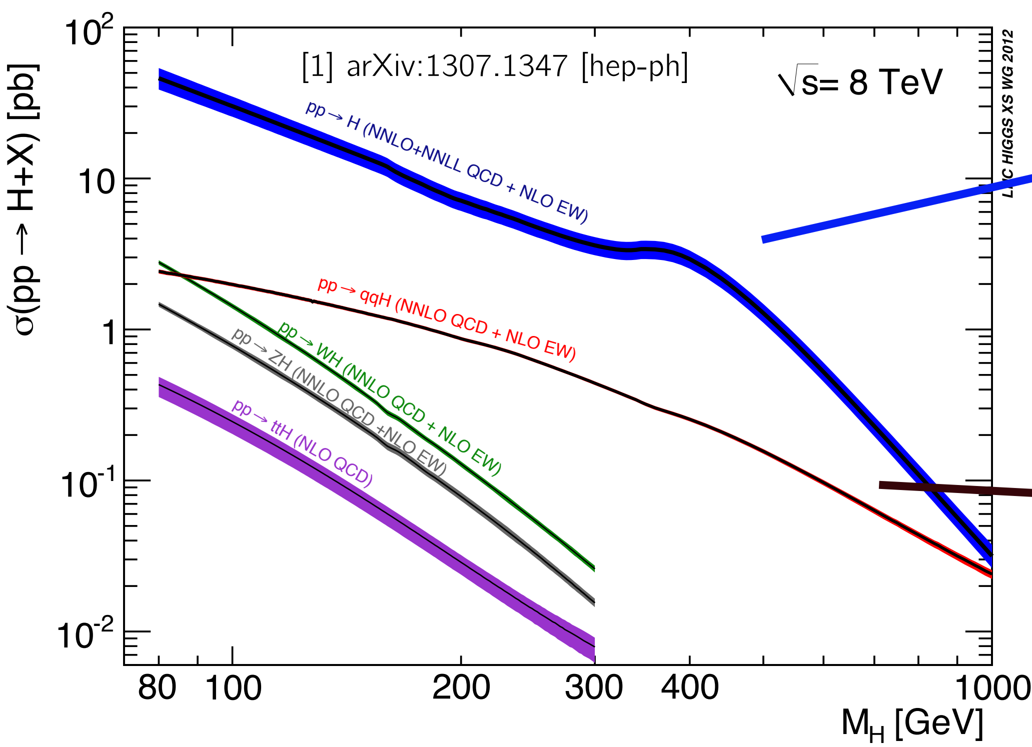
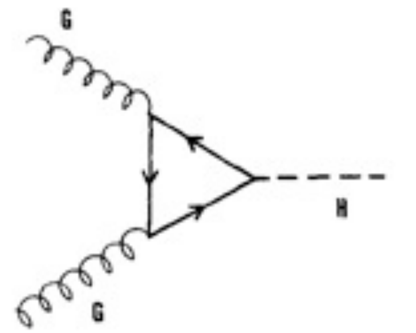
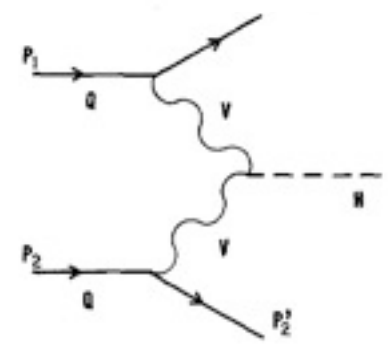
Physics context





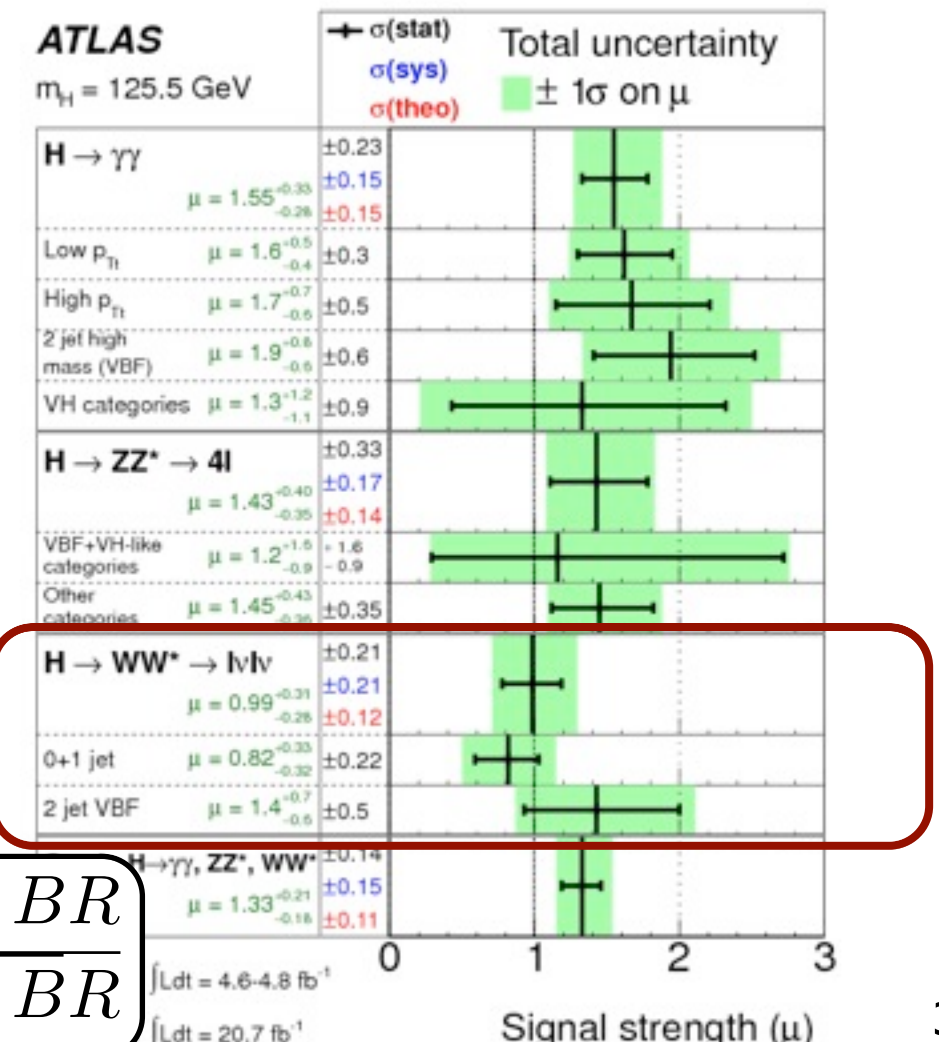
at m_H = 125 GeV:

σ = 19.3 pb



σ = 1.58 pb

[2] arXiv:1307.1427 [hep-ex]

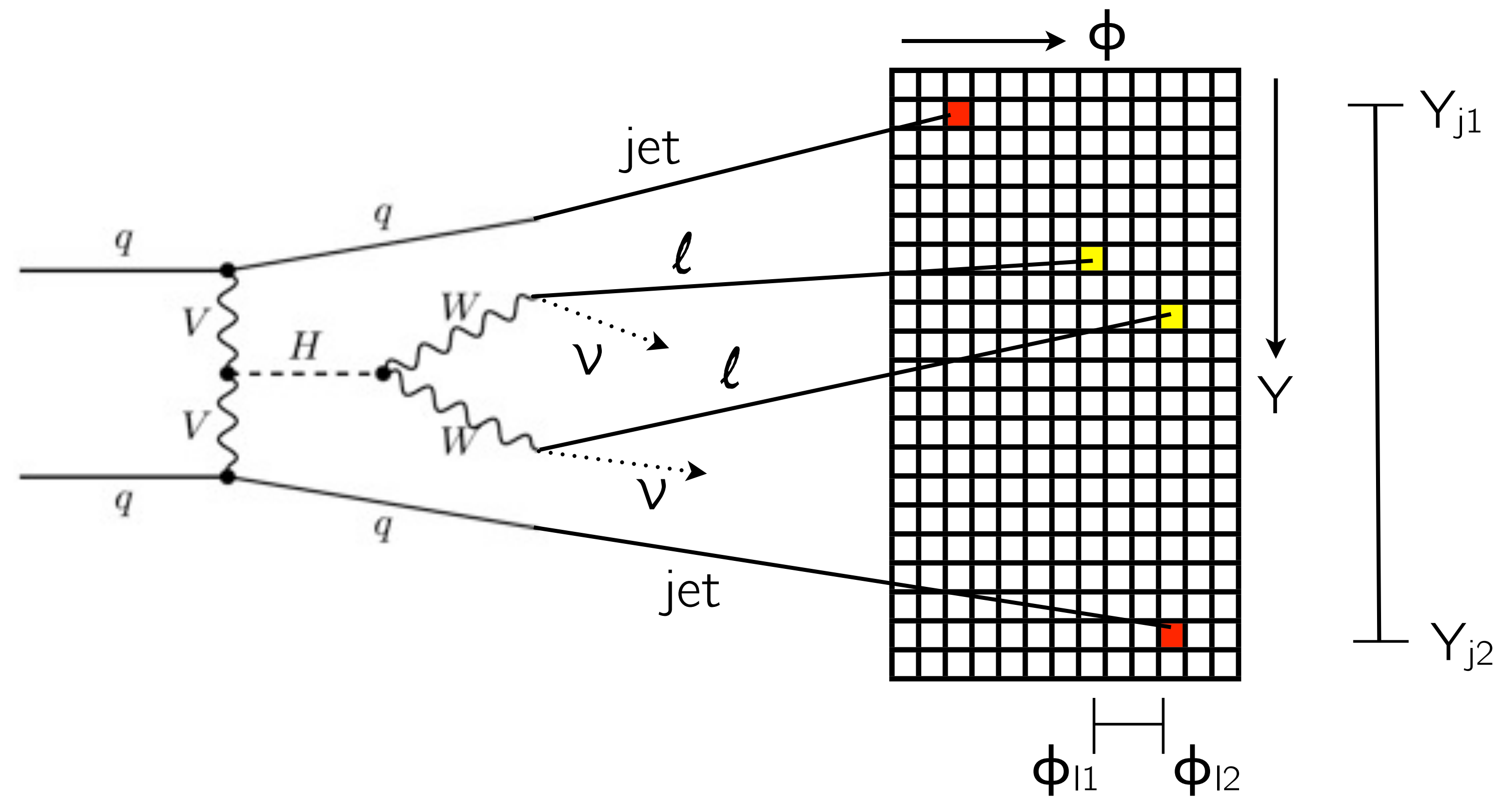


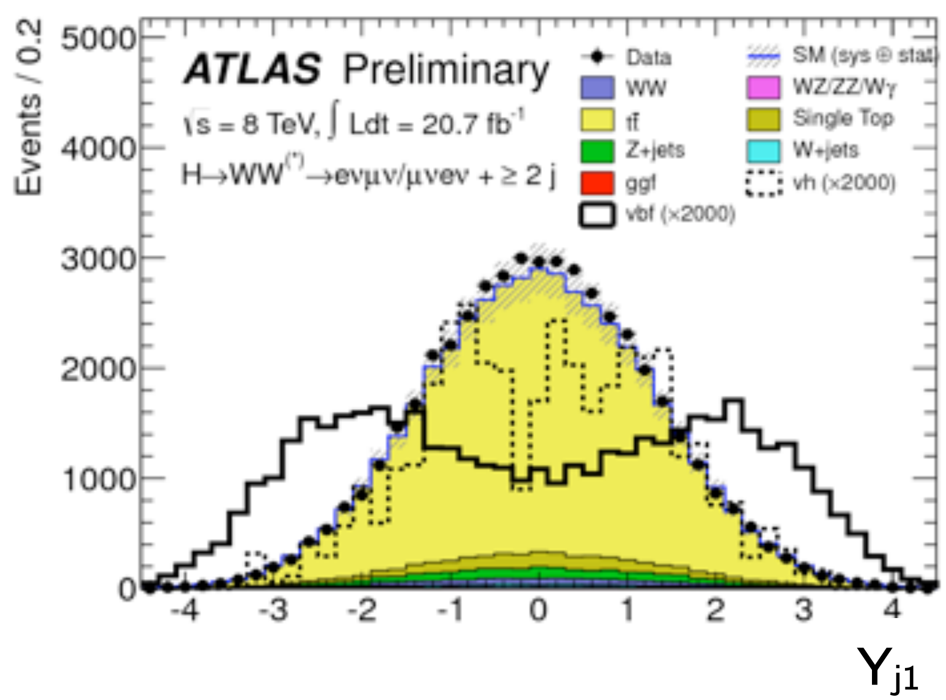
- Second largest Higgs production mode at the LHC
- VBF production in the WW decay is particularly interesting because it is a good probe of WWH coupling
- Deviation from SM rate could be window to extended Higgs sector
- While errors are large, VBF Higgs production is statistically consistent with the SM rate
  - $H \to \gamma\gamma \quad \mu_{VBF} = 1.9^{+0.8}_{-0.5}$
  - $H \to ZZ^* \to 4l \quad \mu_{VBF} = 1.2^{+1.5}_{-0.9}$

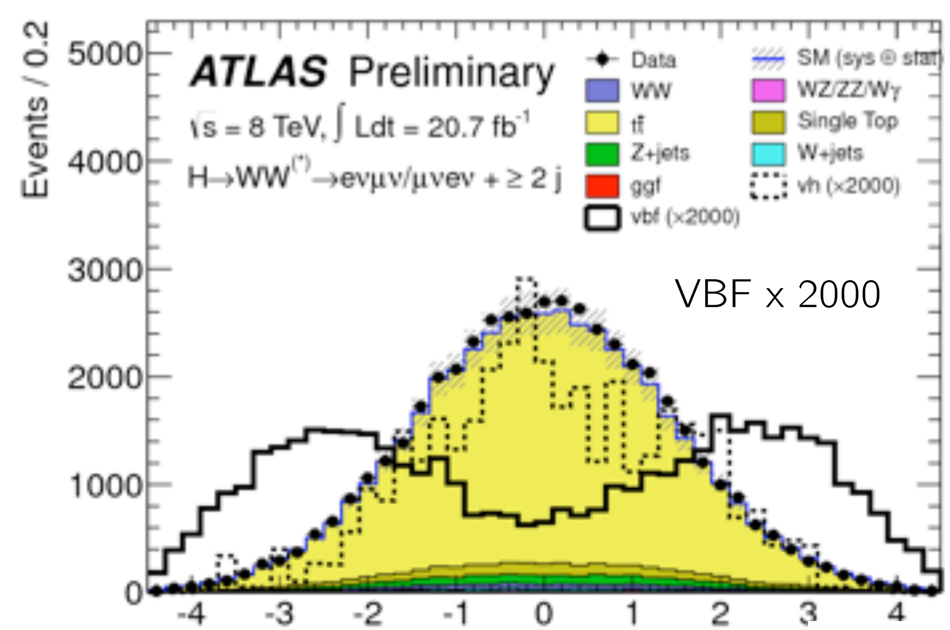
$$\mu = \frac{\text{observed } \sigma \cdot BR}{\text{expected } \sigma \cdot BR}$$

VBF H→WW→lνlν signature

- Two light-flavor jets with large rapidity gap
- Because there is no color flow between jets, little QCD activity in the central region
- Charged leptons are close in Φ due to spin 0 nature of Higgs and V-A nature of the weak force



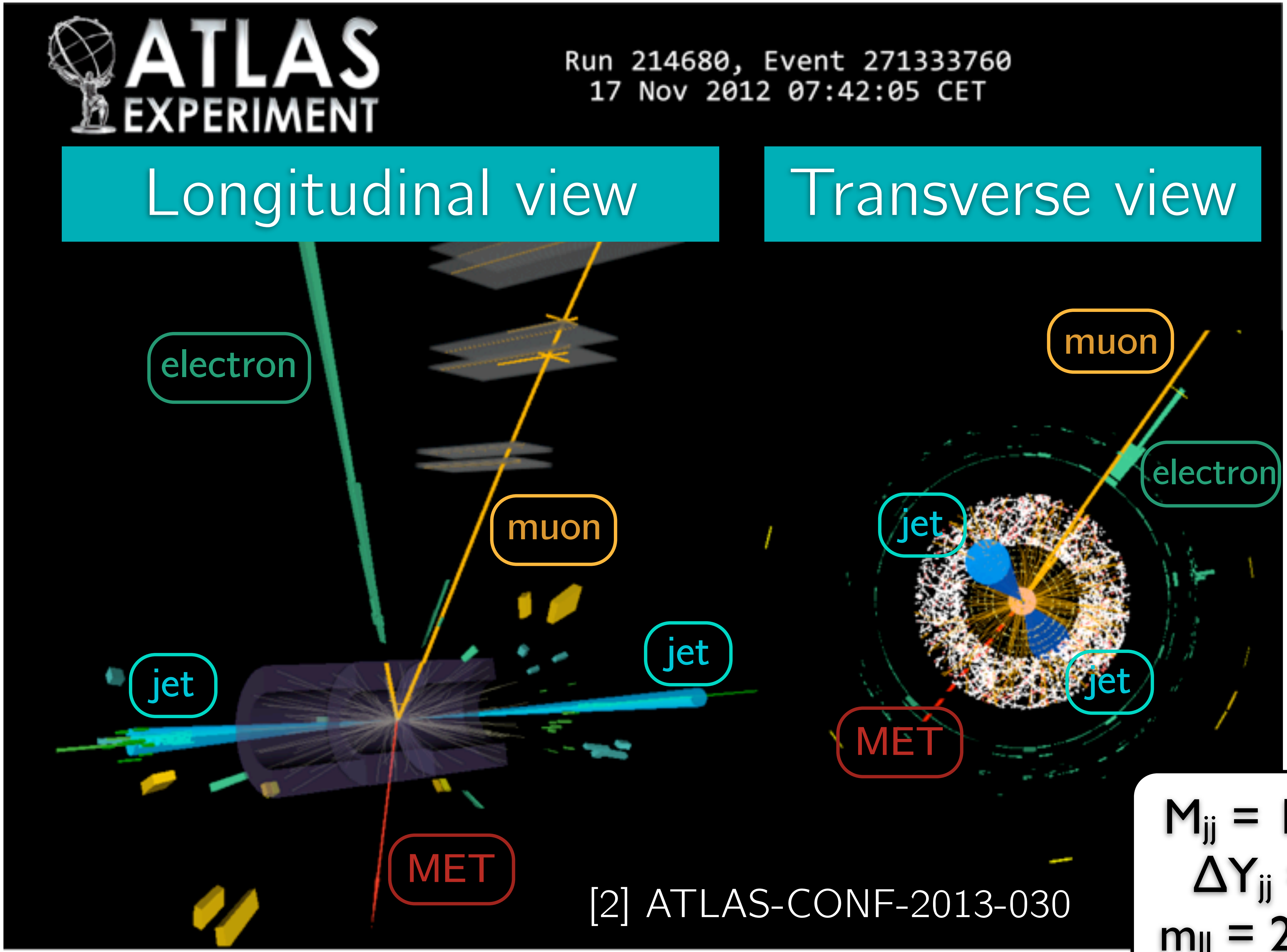




[3] ATLAS-CONF-2013-030

Y_{j2}

Event display

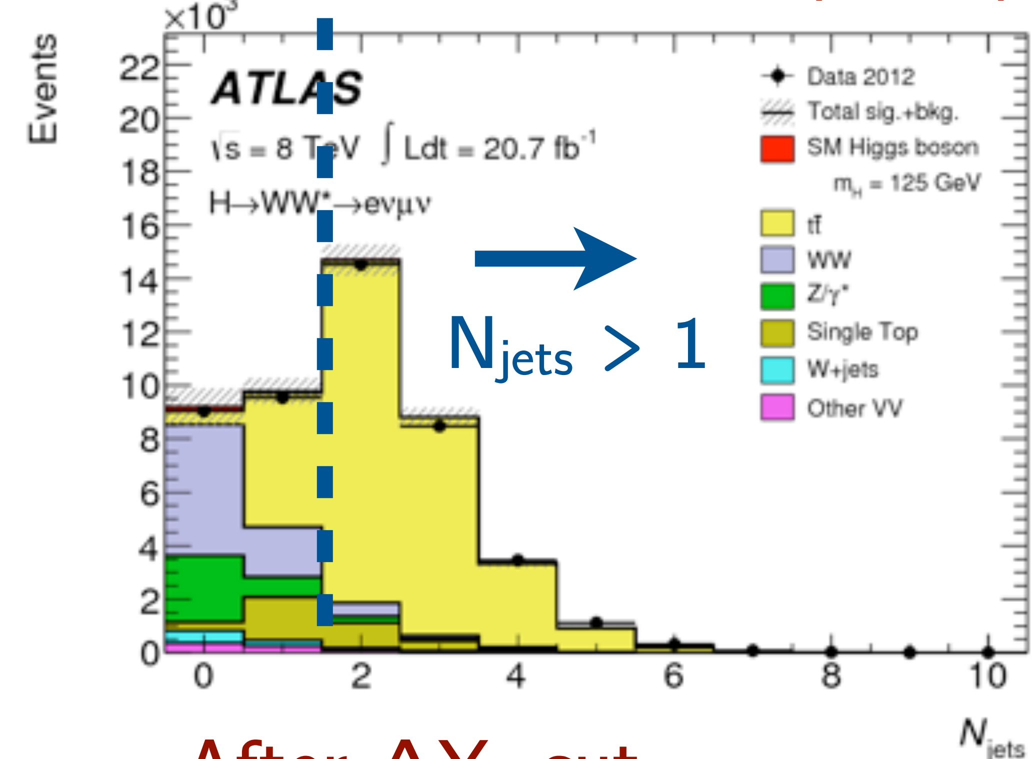


M_{jj} = 1.5 TeV
ΔY_{jj} = 6.6
m_{ll} = 21 GeV
m_T = 95 GeV

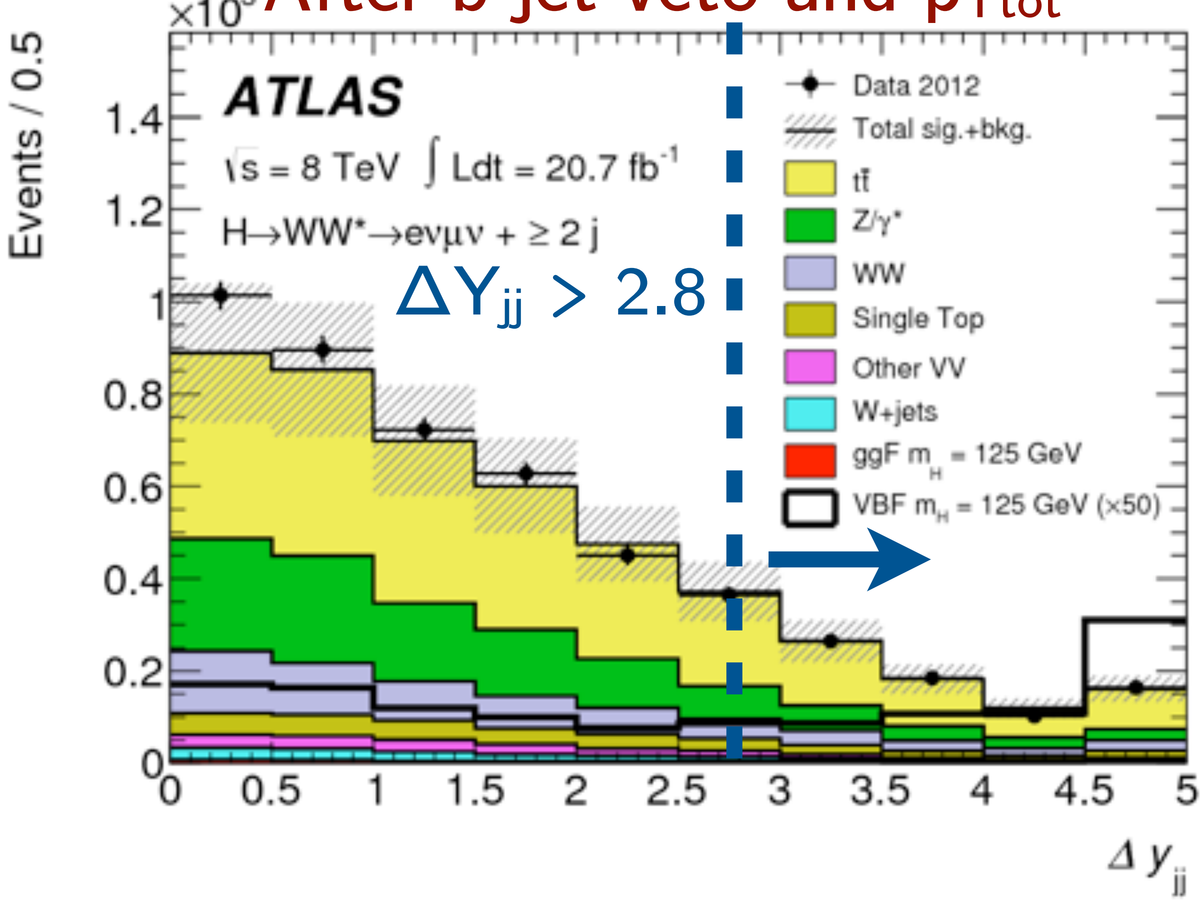
Event selection: VBF cuts

- Background is dominated by top after $N_{jets} > 1$
- Top suppressed with cuts that isolate VBF
  - $N_{btag} = 0$
  - $\Delta Y_{jj} > 2.8$ and $M_{jj} > 500$ GeV (highly correlated)
  - Veto events with jet (p_T>20 GeV) that falls in central rapidity region defined by tag jets
  - Require leptons to be in the central region

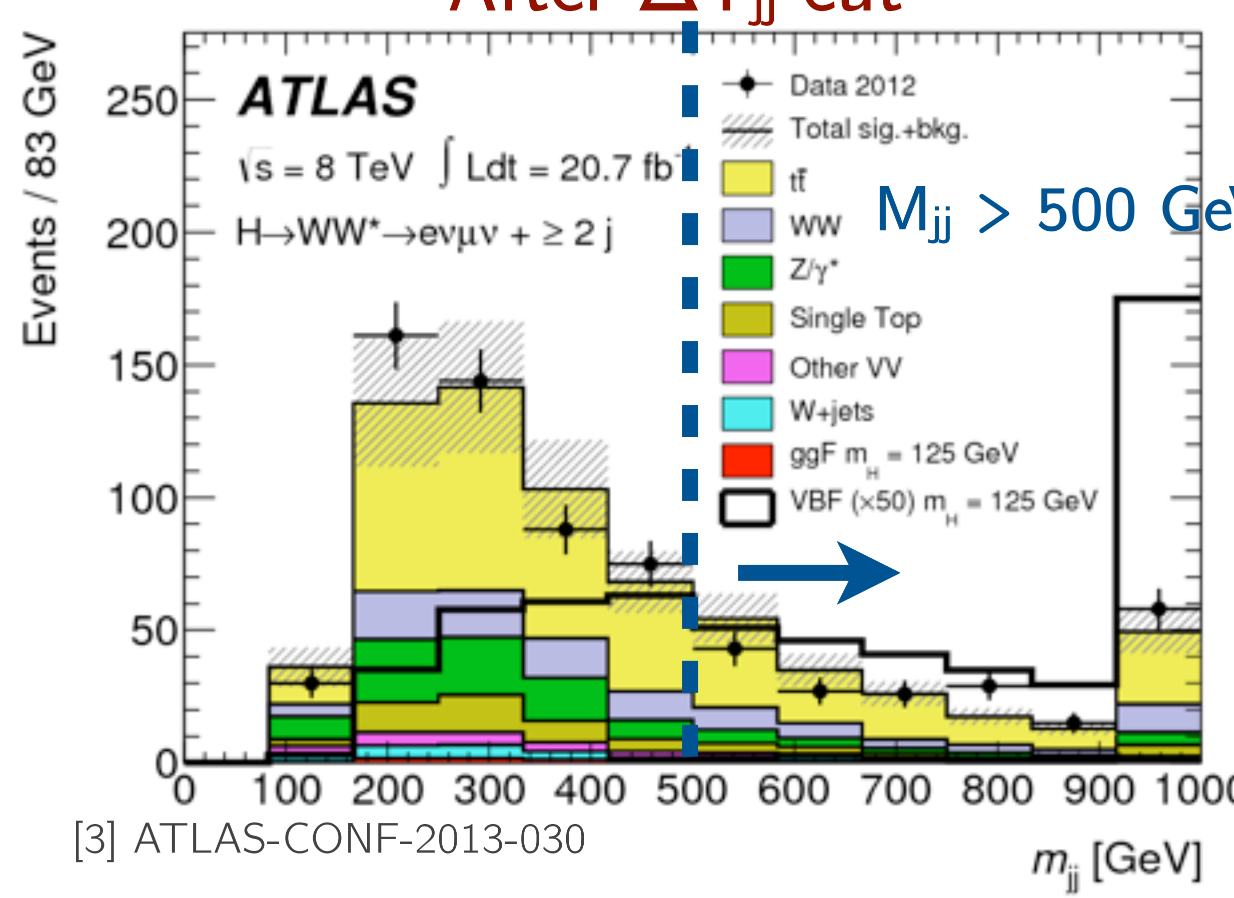
After pre-selection (MET)



After b-jet veto and p_{Ttot}



After ΔY_{jj} cut



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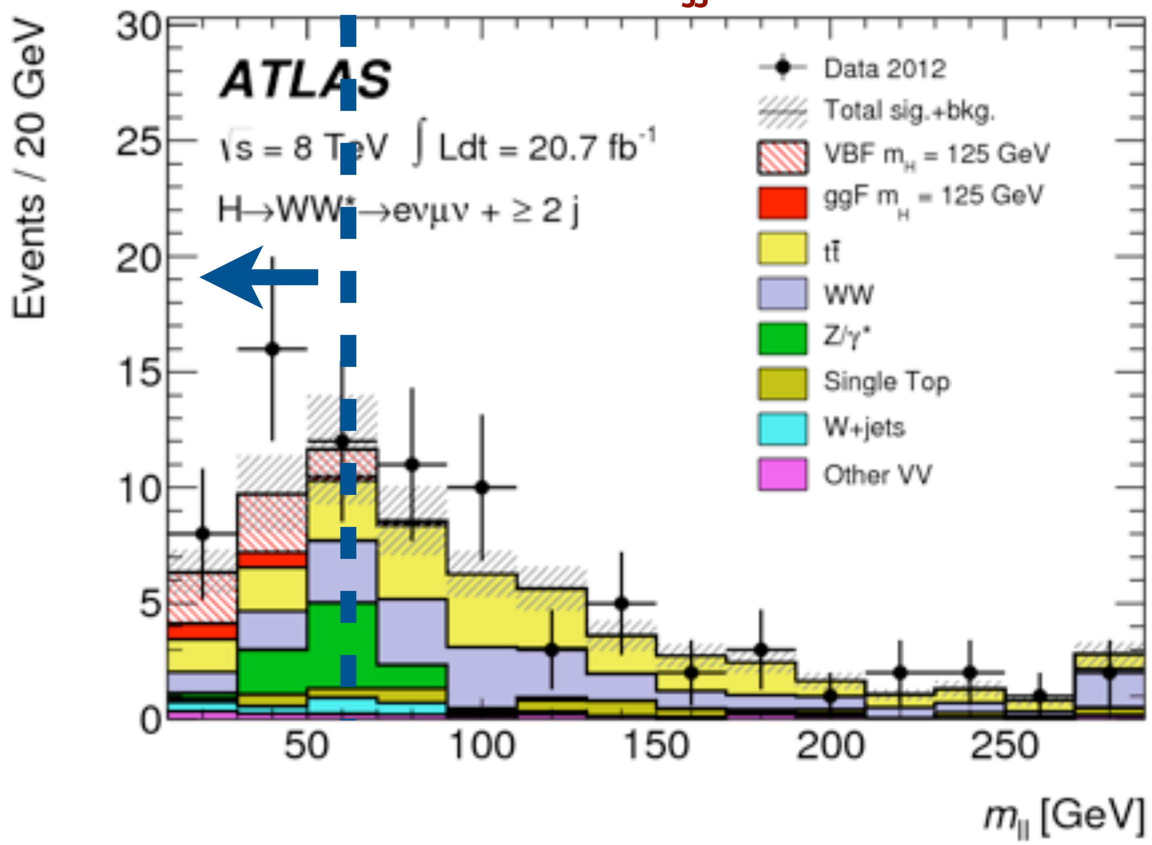
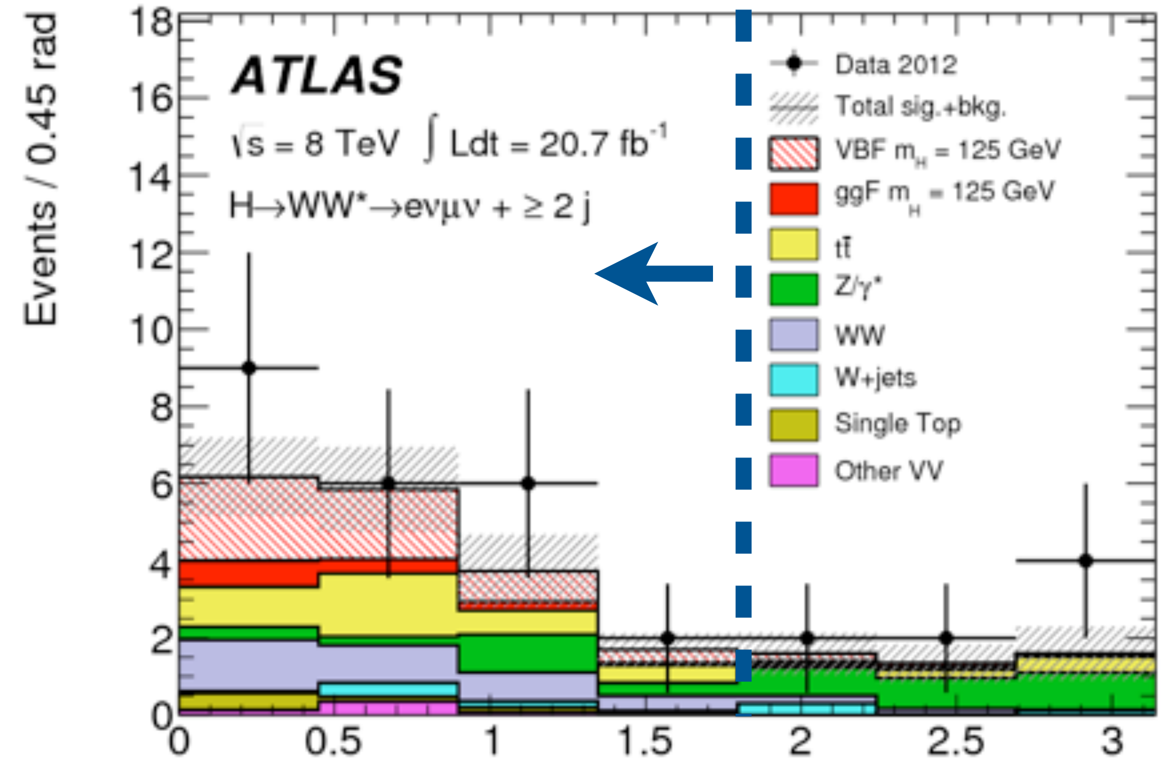
Event selection: WW→lνlν cuts

After M_{jj} cut

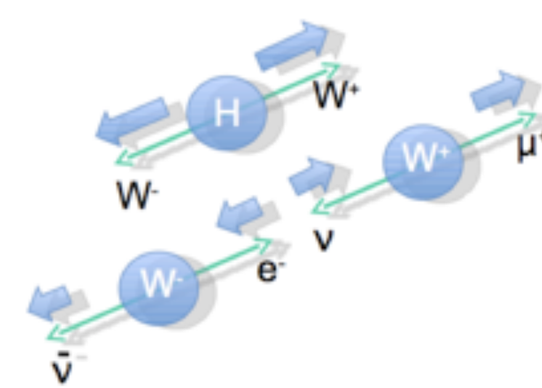


After M_{ll} cut



[3] ATLAS-CONF-2013-030

- After VBF cuts, background dominated by top, Z/DY (ττ), and WW
- Isolate the H->WW->lνlν topology
  - M_{ll} < 60 GeV (looser than other jet bins)
  - $\Delta\Phi_{ll}$ < 1.8



Top estimate

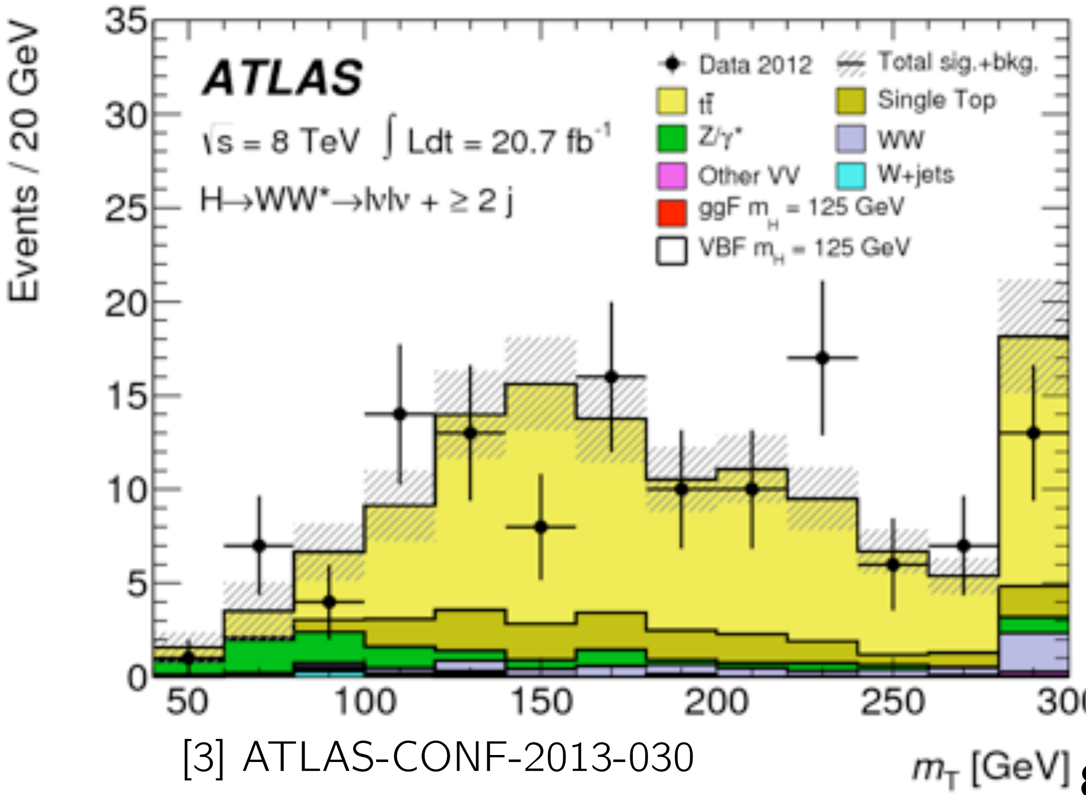
- Use top rich control region to estimate top contribution in signal region
  - Instead of vetoing on btagged jets, require exactly one
  - Apply VBF cuts: DY_{jj}, M_{jj}, no central jets, leptons in central region
  - Calculate normalization factor and extrapolate to signal region

$$\text{Top NF} = \frac{N_{data} - N_{MC}^{non-top}}{N_{MC}^{top}} \xrightarrow{\text{extrapolate to signal region}} N_{top}^{est} = \text{Top NF} \times N_{top}^{MC}$$

- Top NF = 0.59 ± 0.07 (stat) ± 0.09 (sys)
- Systematic on extrapolation from control to signal region is **15%**

compare $\alpha = \dfrac{N_{top}^{SR}}{N_{top}^{CR}}$ between MC@NLO and Alpgen

mT distribution in top CR

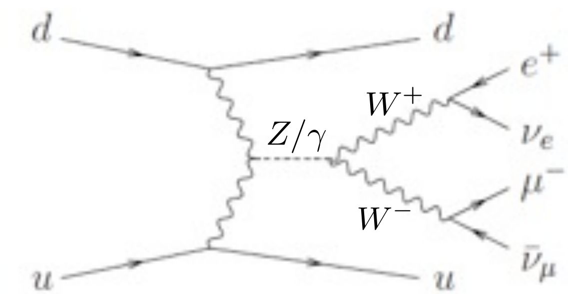


[3] ATLAS-CONF-2013-030

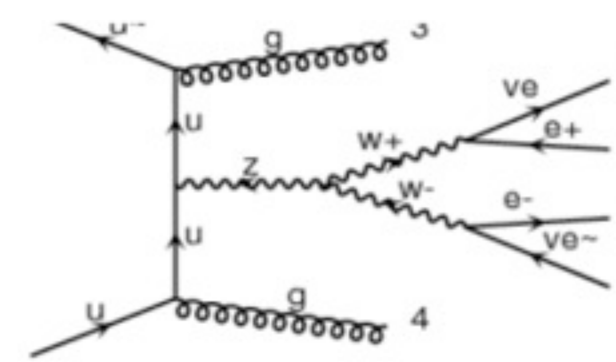
WW+2j estimate

- WW + 2j production is a large background to VBF (30% for eμ/μe, 8% for ee/μμ)
- Currently estimated with POWHEG+Pythia6 for QCD and Sherpa for EW
- Theory uncertainties on WW +2j are large

EW WW



QCD WW



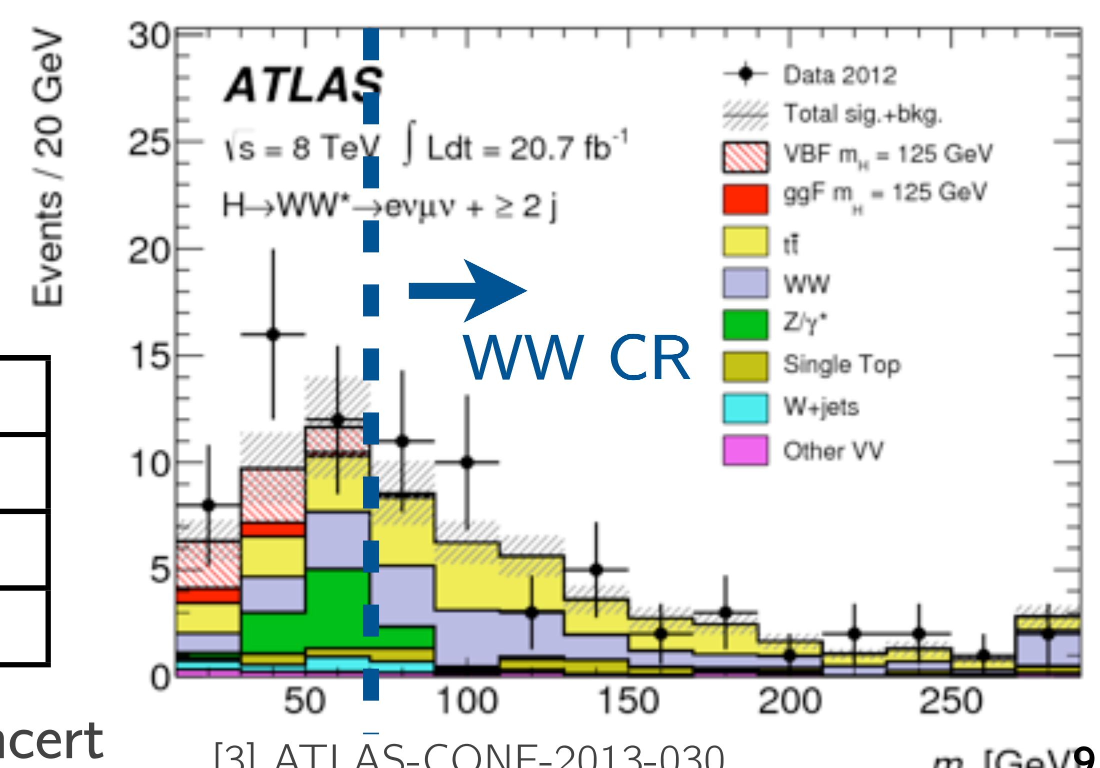
	QCD	EW	
QCD scale	47%	-	mc@nlo μ_r and μ_f variation
PDF	4%	3%	CT10 vs. MSTW2008
EW Modelling	-	11%	SHERPA vs. MADGRAPH

- **Work in progress:** Replace large theory systematic with statistical uncertainty from control region normalization factor
- **WW CR:** same as SR, but invert M_{ll} (M_{ll} > 60) and no $D\Phi_{ll}$ cut

In WW control region

Sample	Count
QCD WW	7.8
EW WW	7.0
Non WW	27

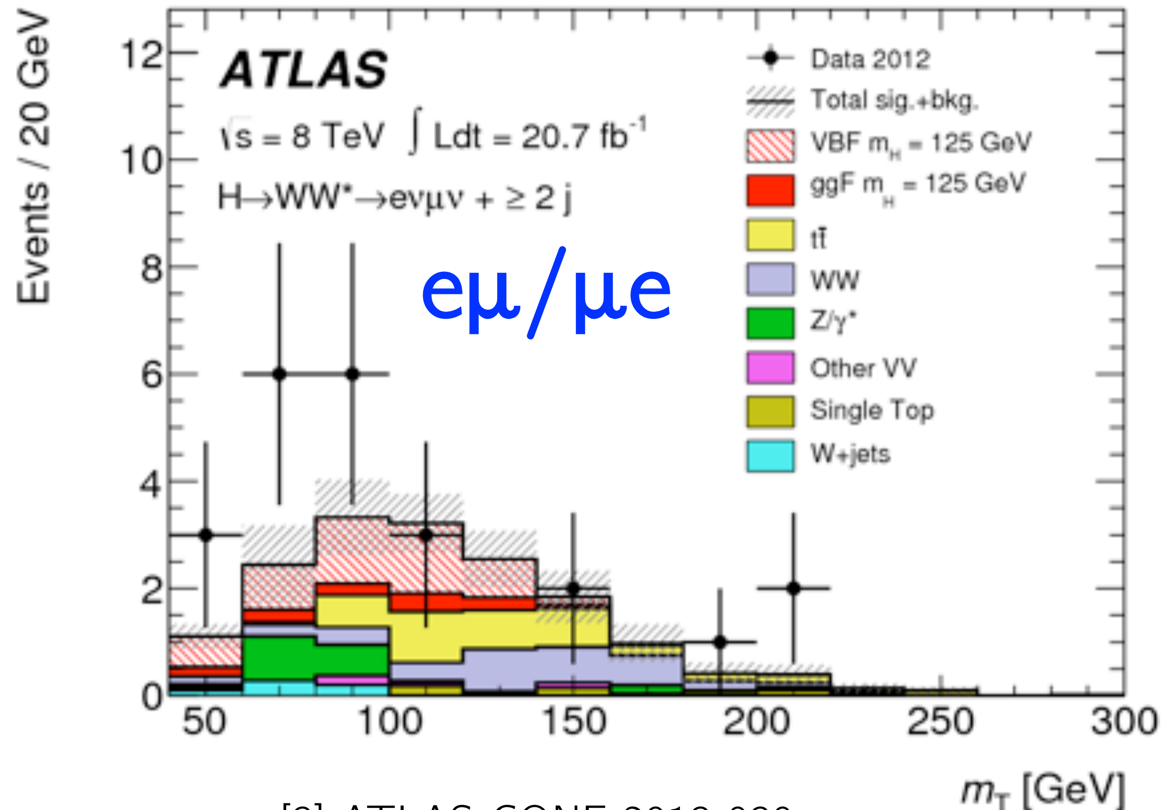
⇒ 40% stat. uncert



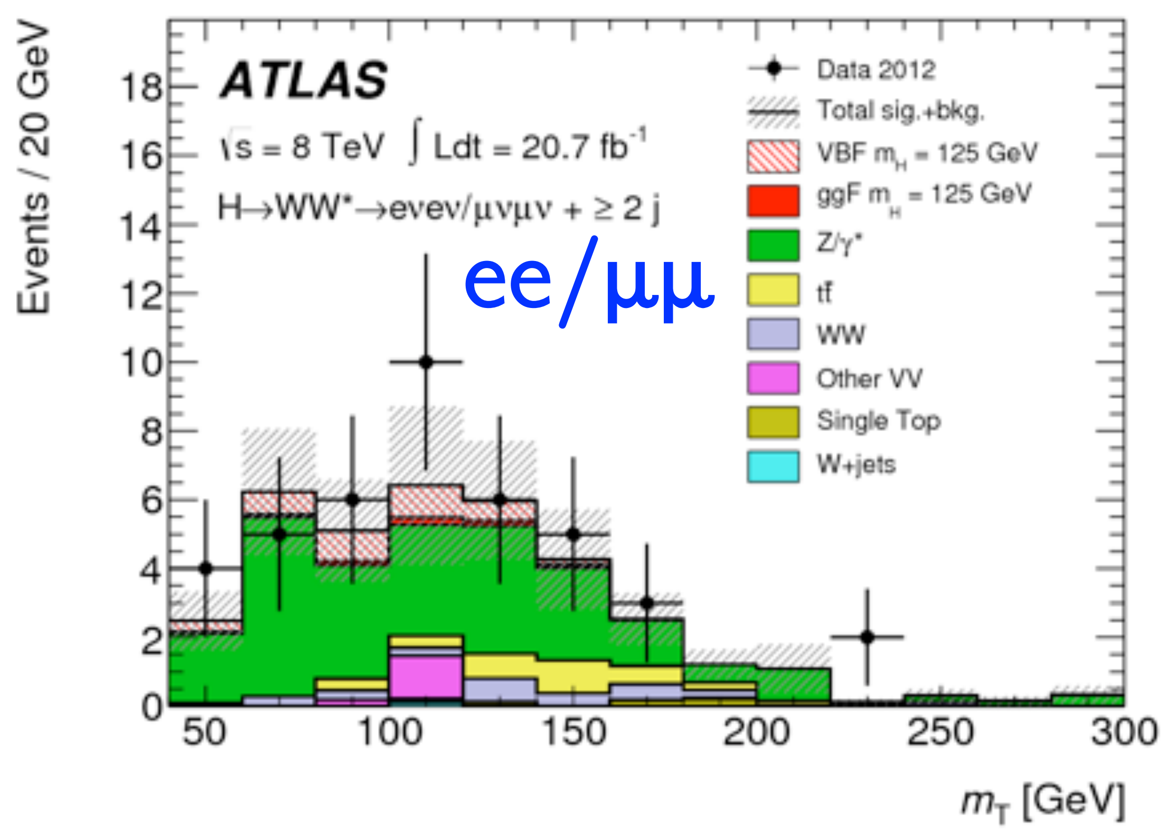
[3] ATLAS-CONF-2013-030

Signal region event yield summary

8 TeV only	eμ/μe	ee/μμ
VBF Higgs	5.1 ± 0.1	3.7 ± 0.1
ggF Higgs	1.3 ± 0.1	0.7 ± 0.1
WW / VV	4.1 ± 0.4	4.4 ± 1.1
ttbar / 1-top	4.4 ± 0.8	4.0 ± 0.6
Z/γ*	1.9 ± 0.5	25.0 ± 2.0
W+jets	0.6 ± 0.3	0.1 ± 0.2
Total non-VBF	**12.3 ± 1.0**	**34.2 ± 2.4**
Observed	**23**	**42**



[3] ATLAS-CONF-2013-030



- Sensitivity is significantly higher in eμ/μe
- Clear excess in both channels
- Large contamination from DY with these MET cuts

$$m_T^2 = \left(\sqrt{m_{ll}^2 + |\vec{p}_{T ll}|} + E_T^{miss}\right)^2 - \left(\vec{p}_{T ll} + \vec{E}_T^{miss}\right)^2$$

Statistical treatment

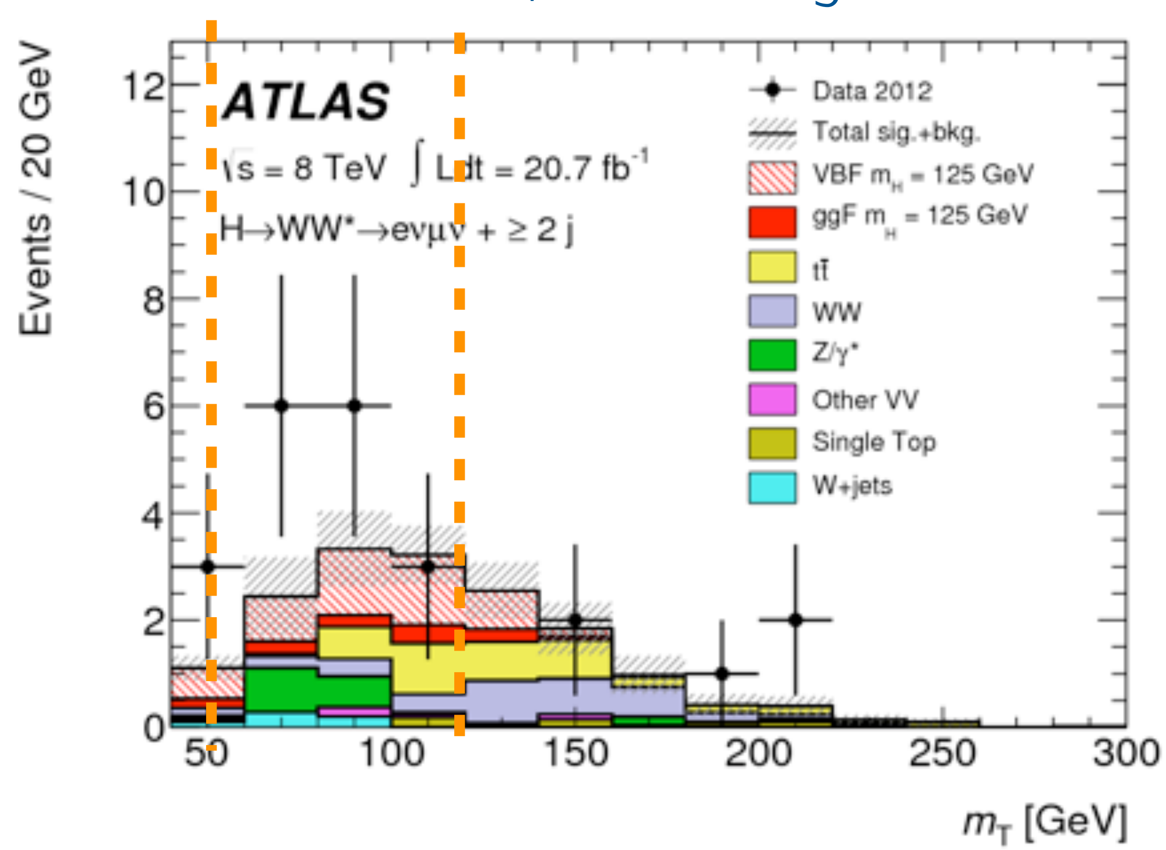
- Profile likelihood test statistic is used for statistical computations
- The top normalization is floating in the fit and is same for eμ/μe and ee/μμ
- The m_T distribution is used for fitting with bin boundaries of (30,50,120)
- Gluon fusion H→WW is considered a background with a floating normalization
- Object and theory systematics are profiled in the fit

Dominant systematics for VBF [%]

	Background	Signal
Source	$N_{jet} \geq 2$	$N_{jet} \geq 2$
Theoretical uncertainties		
QCD scale for ggF signal for $N_{jet} \geq 0$	-	-
QCD scale for ggF signal for $N_{jet} \geq 1$	-	-
QCD scale for ggF signal for $N_{jet} \geq 2$	-	4
QCD scale for ggF signal for $N_{jet} \geq 3$	-	4
Parton shower and UE model (signal only)	-	5
PDF model	1	3
$H \to WW$ branching ratio	-	4
QCD scale (acceptance)	-	3
WW normalisation	4	-
Experimental uncertainties		
Jet energy scale and resolution	7	6
b-tagging efficiency	2	-
f_{recoil} efficiency	-	-

[3] ATLAS-CONF-2013-030

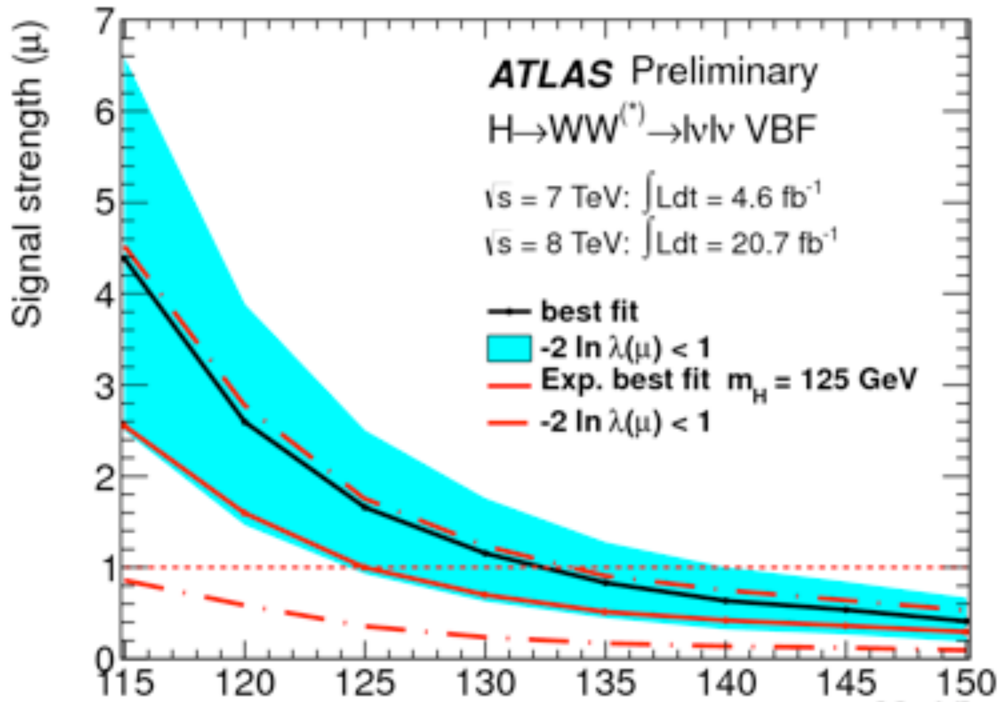
m_T fit binning



- note: these numbers are averaged over all processes

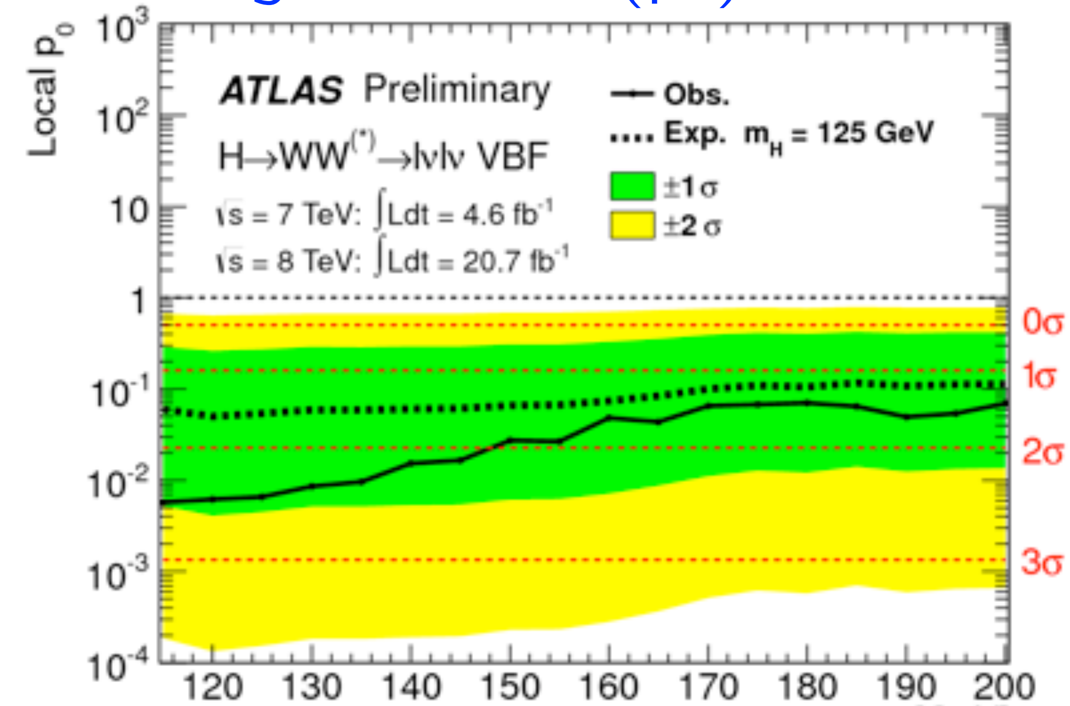
VBF Results

μ_{VBF} vs. m_H



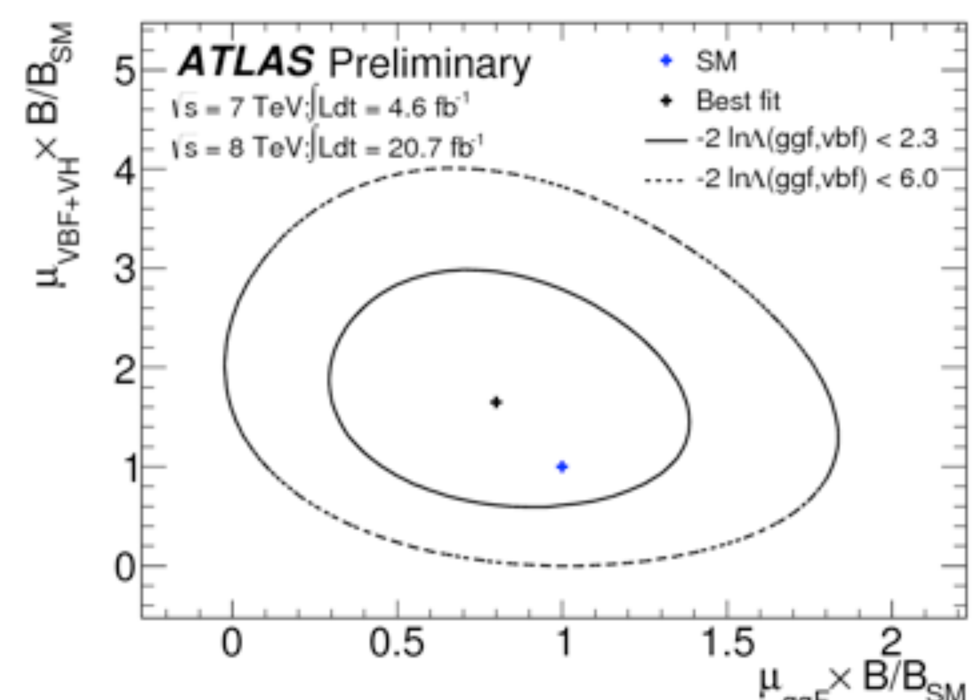
[3] ATLAS-CONF-2013-030

Significance (p_0) vs. m_H



[3] ATLAS-CONF-2013-030

Likelihood contours

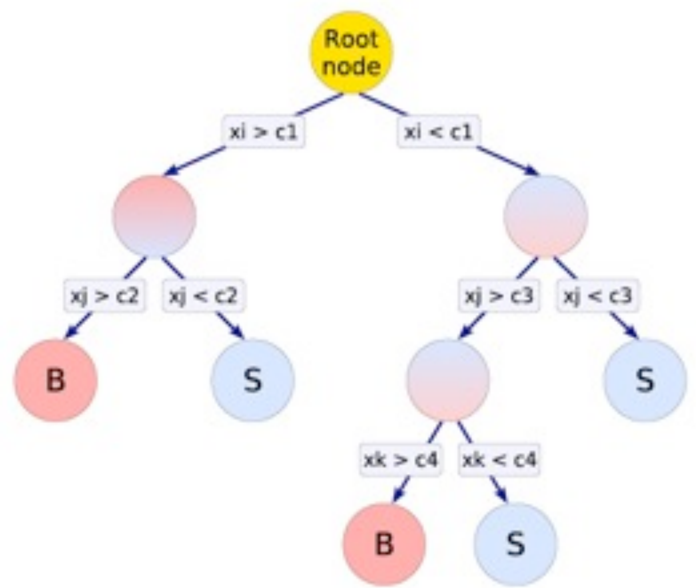


- At m_H = 125 GeV
  - Observed best-fit signal strength:
    1.66 ± 0.67 (stat) ± 0.28 (sys)
  - Significance
    - Expected: 1.6σ
    - Observed: 2.5σ

Ongoing studies

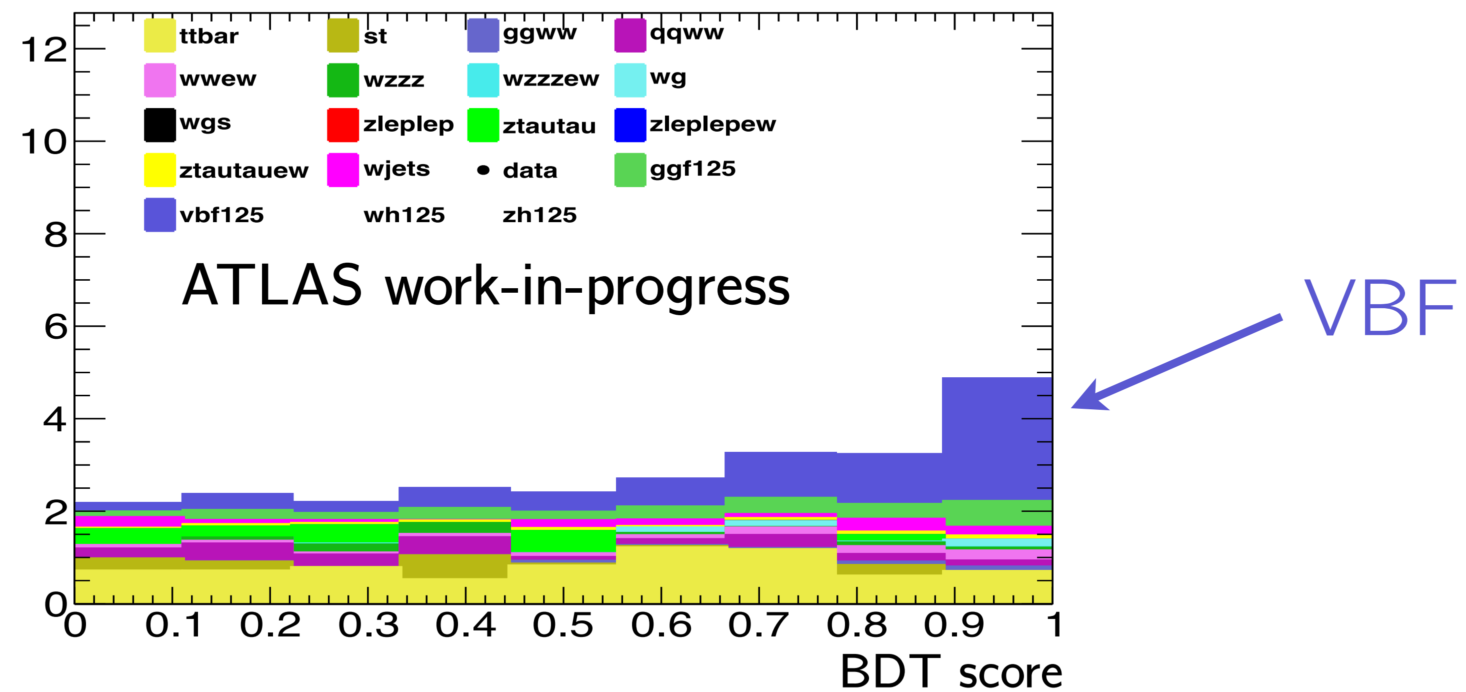
- VBF $H \to WW \to l\nu l\nu$ lends itself to multivariate techniques because it is a busy final state with many correlated physics objects
- Boosted decision tree (BDT) based multivariate analysis
  - Sequence of binary cuts on a collection of discriminating variables
- Nine BDT inputs for VBF analysis:
  - M_{jj}, ΔY_{jj}, p_{Ttot}, M_{ll}, $\Delta\Phi_{ll}$, outside lepton veto, m_T, sum of M_{lj}, E_T^{miss} centrality with respect to leptons
- Preliminary results without all systematics, sensitivity improvement of ~30%

BDT schematic



[3] arXiv:physics/0703039

BDT score in signal region



more background-like events ← → more VBF-like events

Conclusion

- VBF production in the H->WW channel is an important probe of the WWH coupling
- We have observed an excess of events with respect to the Standard Model background that is consistent with the Standard Model rate for VBF, corresponding to a signal strength of 1.66 ± 0.67 (stat) ± 0.28 (sys)
- We are currently studying the possibility of using a multivariate approach in this channel with promising results

Acknowledgements

Thanks to my ATLAS colleagues in the H->WW group and VBF subgroup

References

[1] arXiv:1307.1347 [hep-ph]

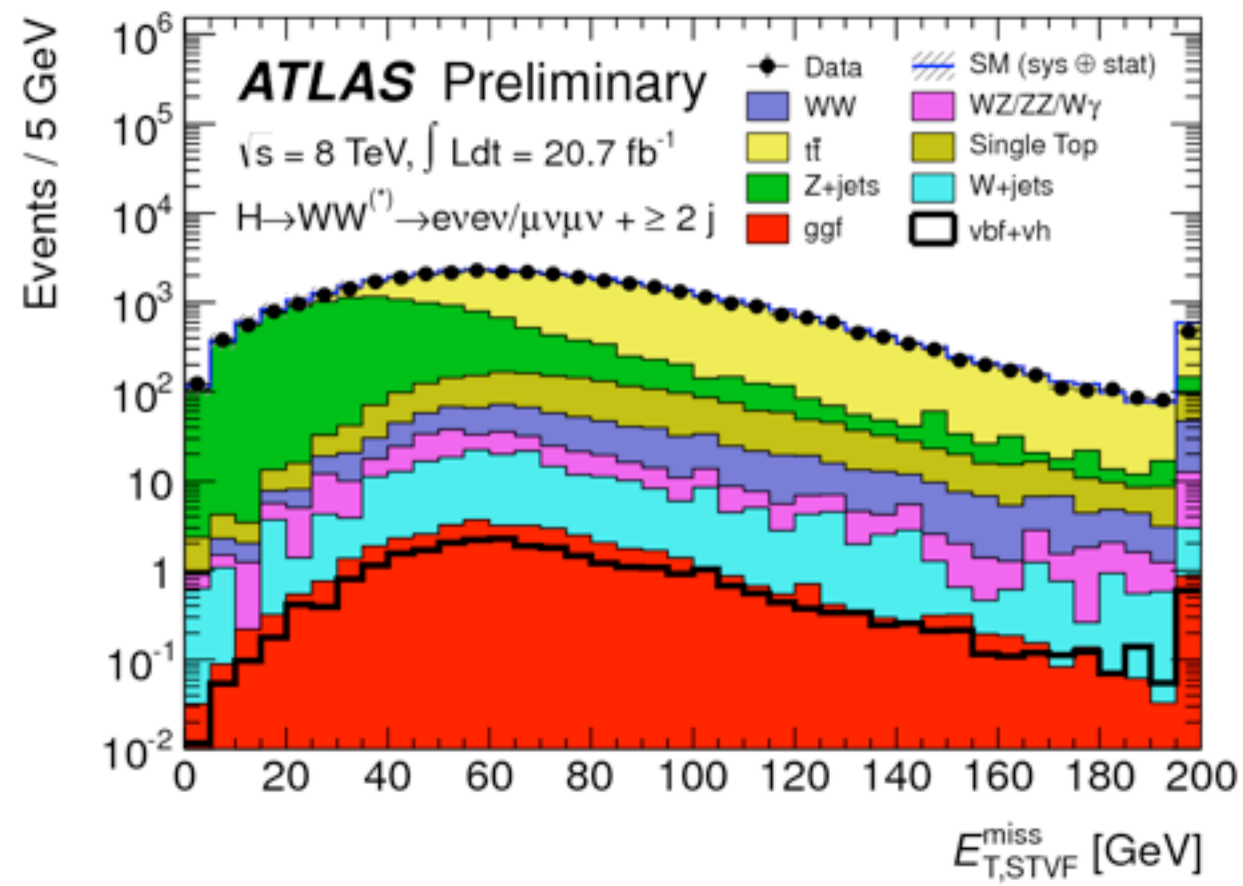
[2] arXiv:1307.1427 [hep-ex]

[3] ATLAS-CONF-2013-030

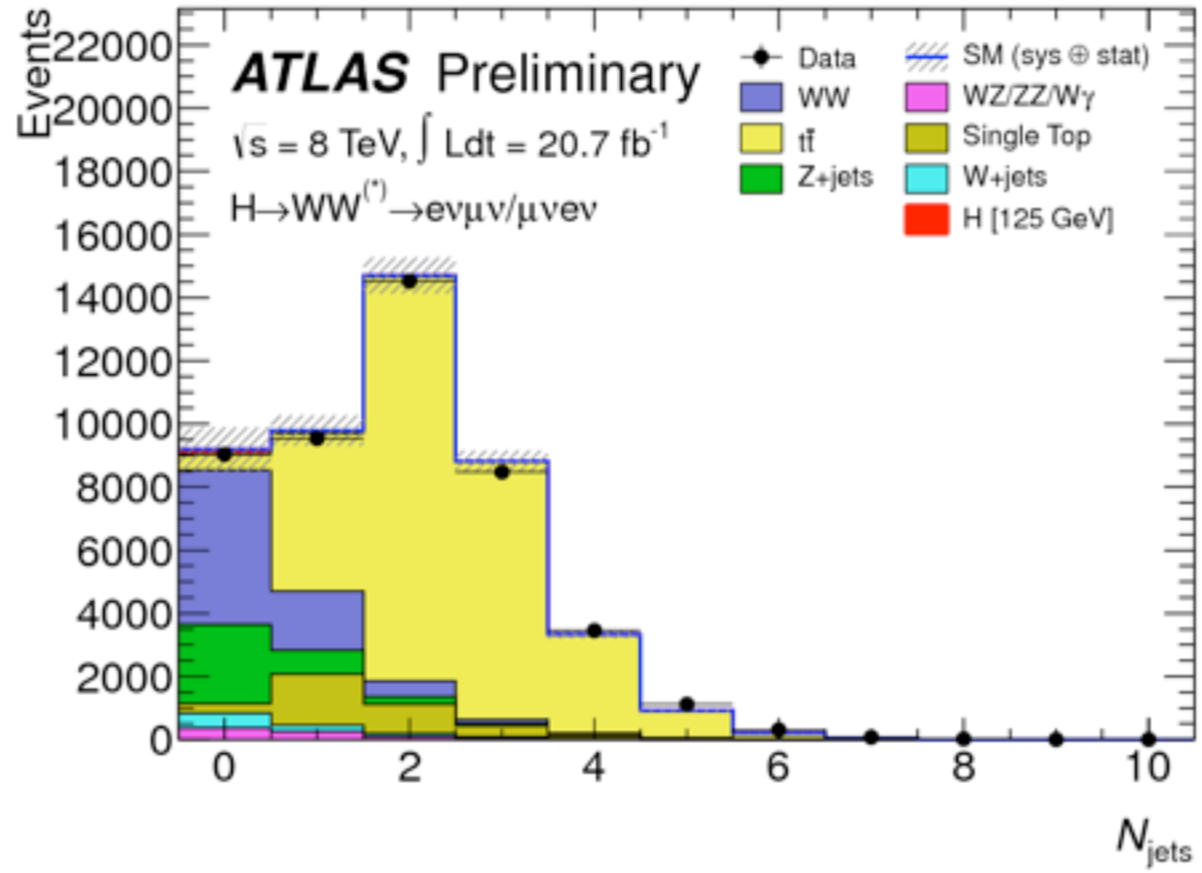
[4] arXiv:physics/0703039 [physics.data-an]

BONUS MATERIAL

Missing transverse momentum distributions for events after pre-selection for (a) E_{T,rel}^{miss} for N_{jet} ≤ 1, (b) p_{T,rel}^{miss} for N_{jet} ≤ 1, and (c) E_{T,STVF}^{miss} for N_{jet} ≥ 2 modes. The plot in (b) is made after the requirement on E_{T,rel}^{miss} and the one in (c) after the requirement on E_T^{miss}. The plot in (d) shows the f_{recoil} distribution in ee+μμ events passing the N_{jet} = 0 selection after m_{ll} < 50 GeV for simulated DY, non-DY and signal processes. The shaded area (too small to be visible in these figures) represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources. The signal is overlaid as a red curve in (a) and (b); in (c), the ggF signal is stacked at the bottom while the VBF signal is overlaid as a thick black line. Selections are listed in Table 2. Details are given in Section 3.3.1.



Jet multiplicity for events in 8 TeV data. The plots are shown for the (a) eμ+μe and (b) ee+μμ channels after pre-selection and E_{T,rel}^{miss} > 25 GeV and > 45 GeV, respectively. The signal is too small to be seen. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.



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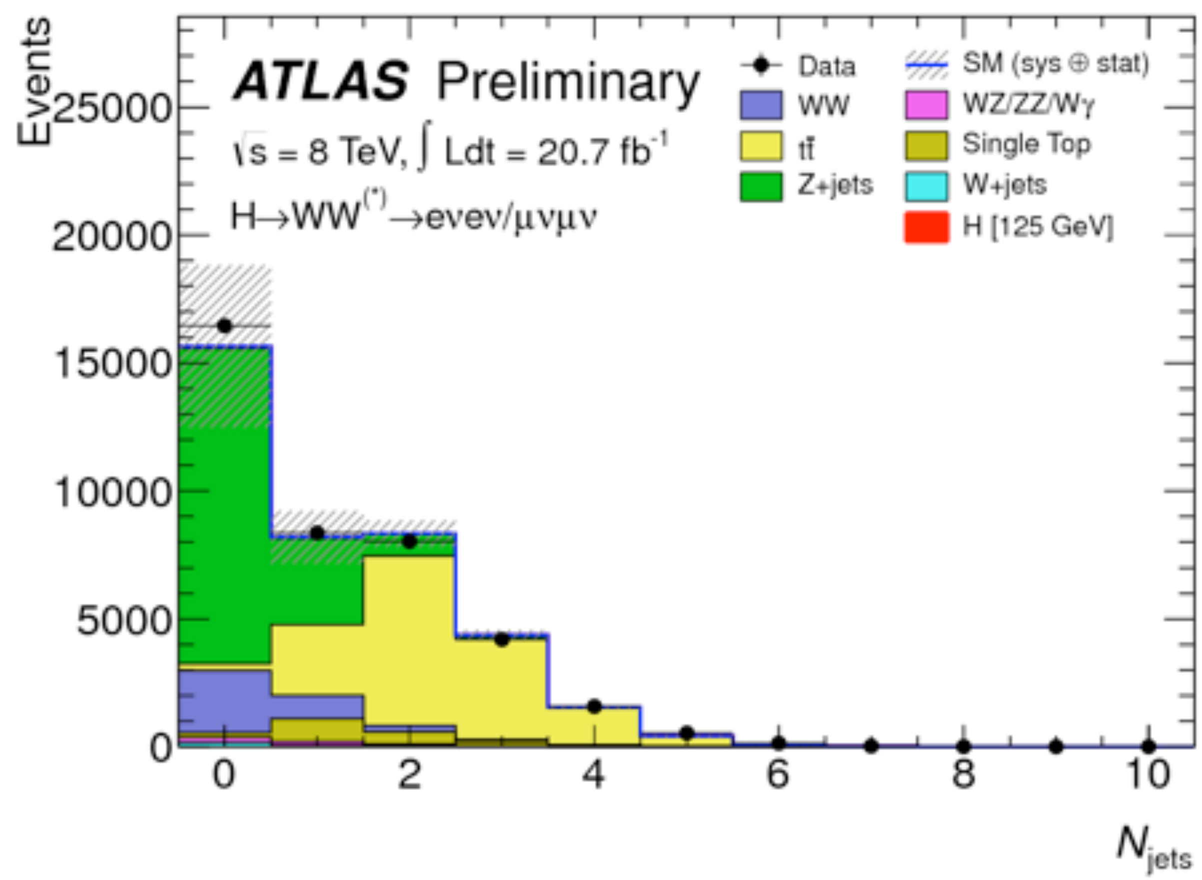
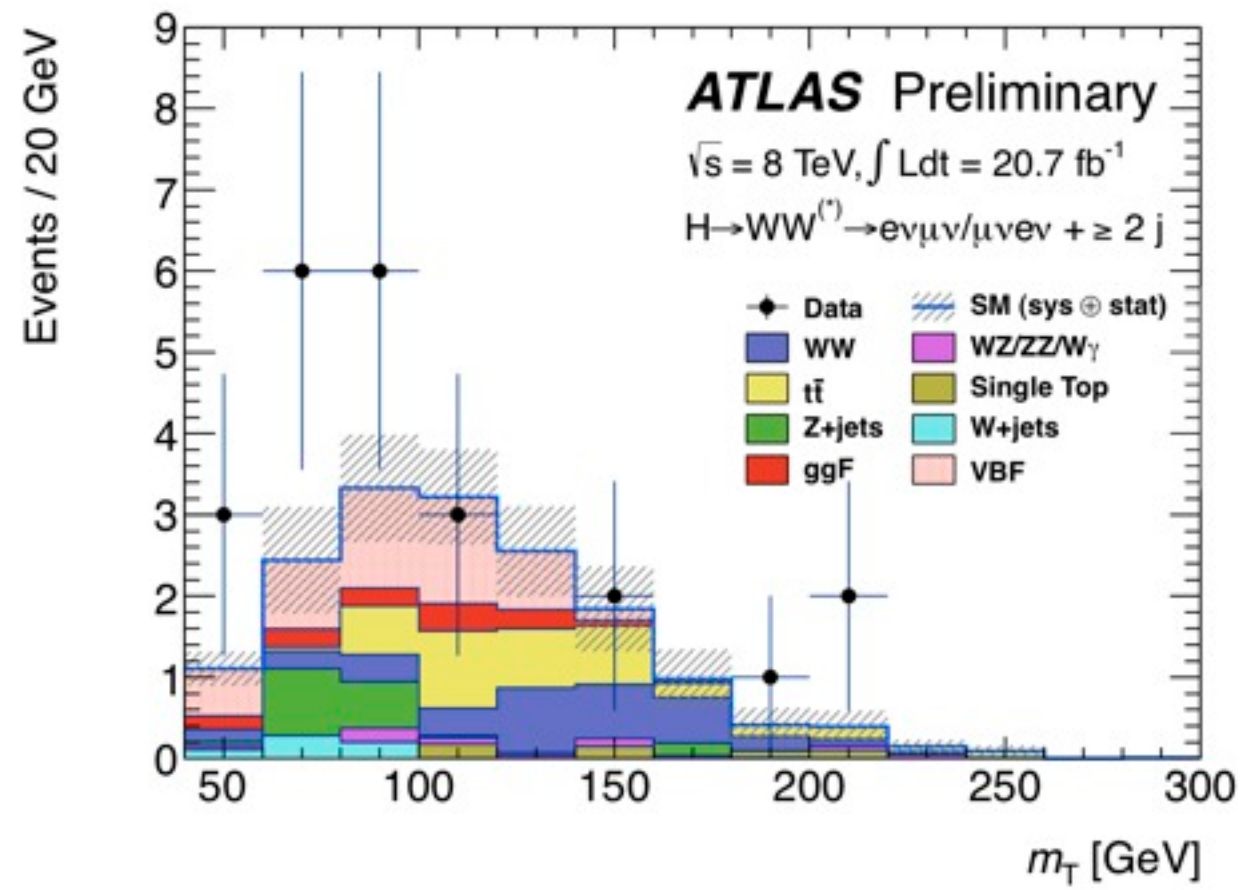


Distribution of the transverse mass, m_T, for 8 TeV data. The plots are shown for the eμ+μe (left) and ee+μμ (right) channels in N_{jet} = 0 (top), N_{jet} = 1 (middle), and N_{jet} ≥ 2 modes (bottom). The distributions are shown prior to splitting the samples into two m_{ll} regions for the eμ+μe channel in the N_{jet} ≥ 2 and = 1 modes, as described in Table 2. The visible signal is stacked at the top of the background. For the N_{jet} ≥ 2 mode, the signal is plotted separately for the ggF and VBF production processes. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.



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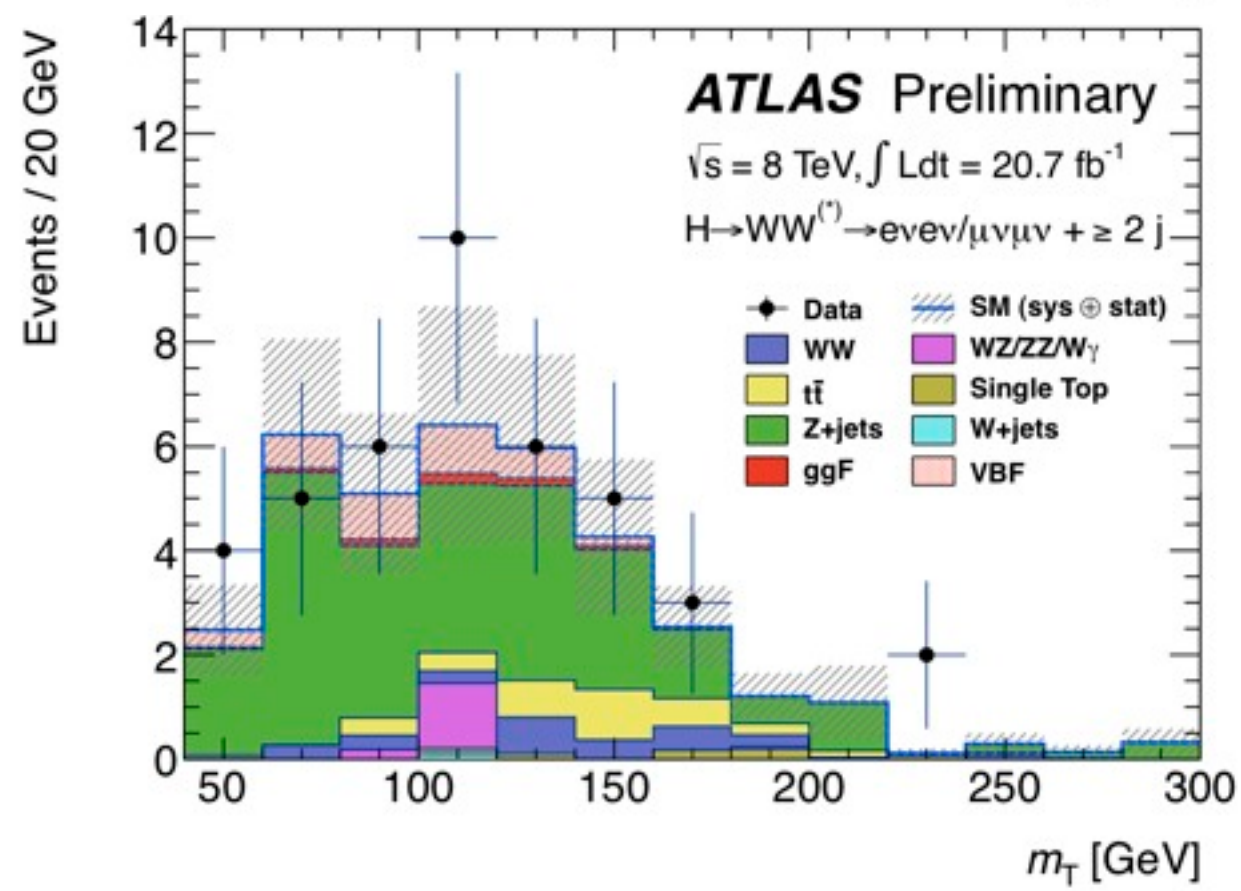
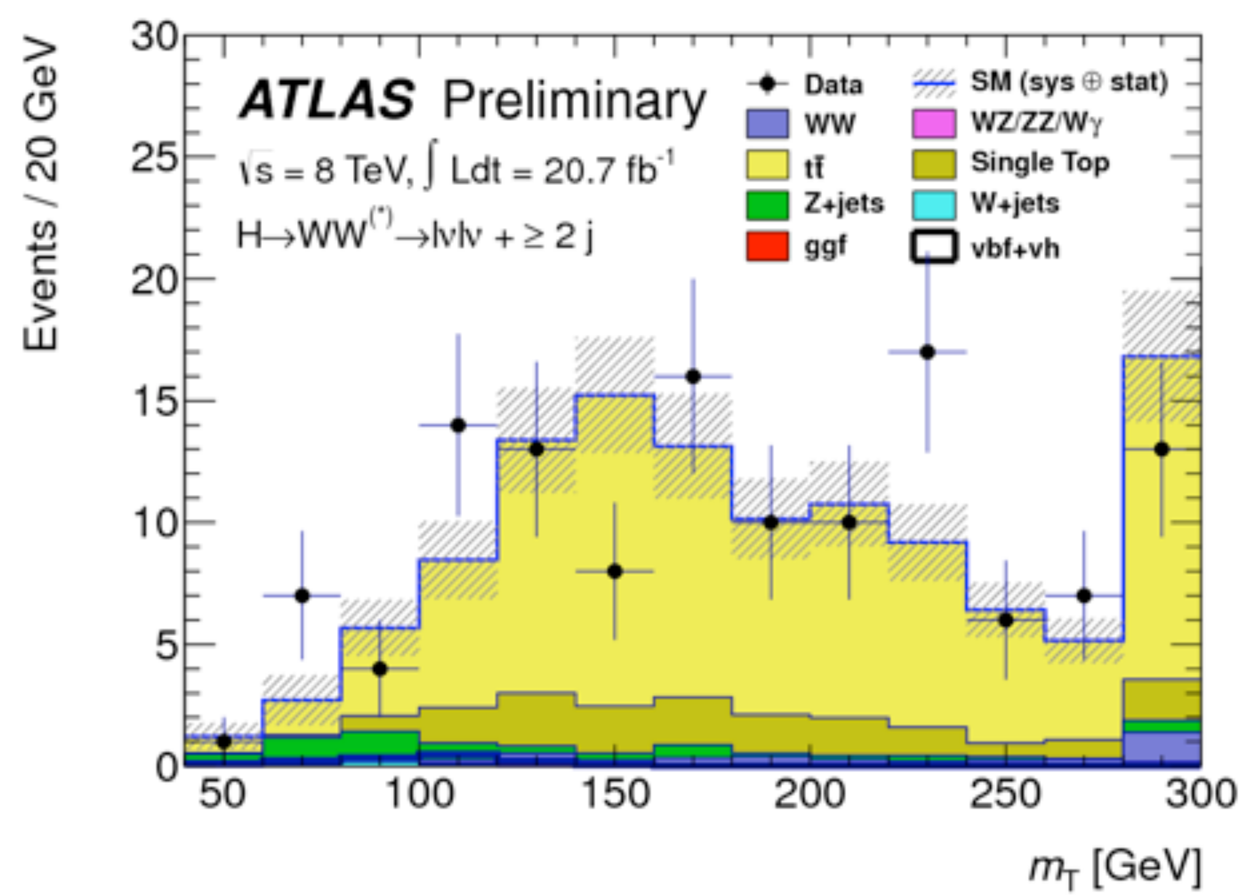
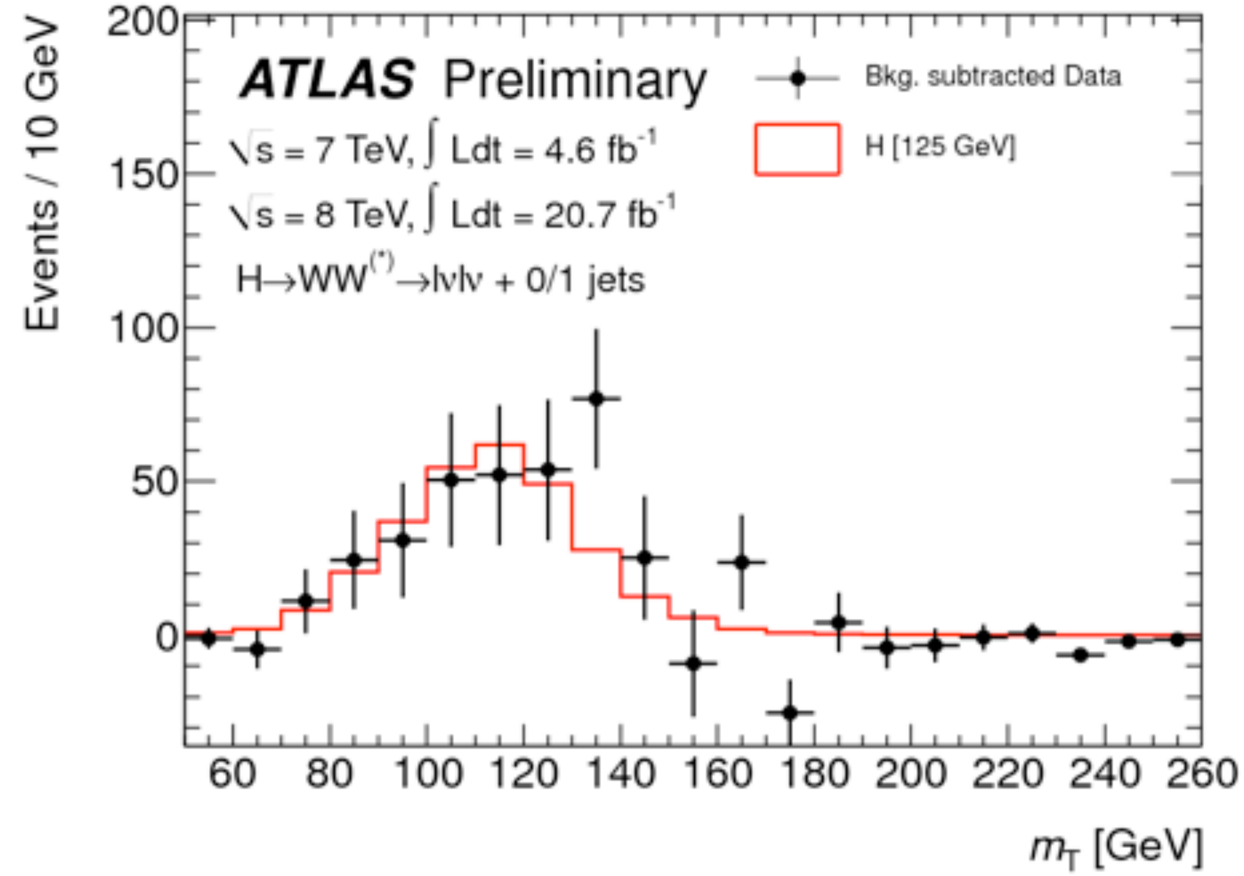


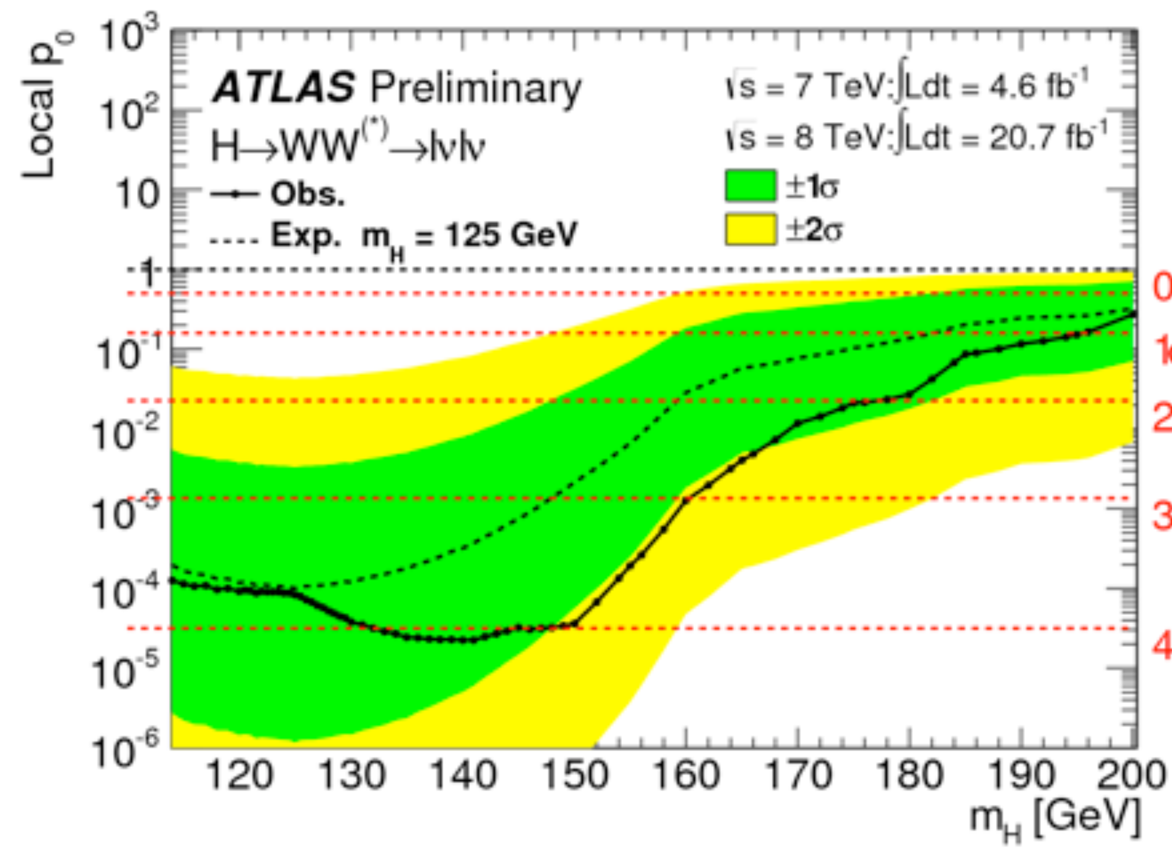
Distributions of m_T in (a) N_{jet} = 1 and (b) N<sub>jet</
sub> ≥ 2 top background control regions. The distributions are normalised to the data. The right-most bin in (b) represents the overflow.   The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.



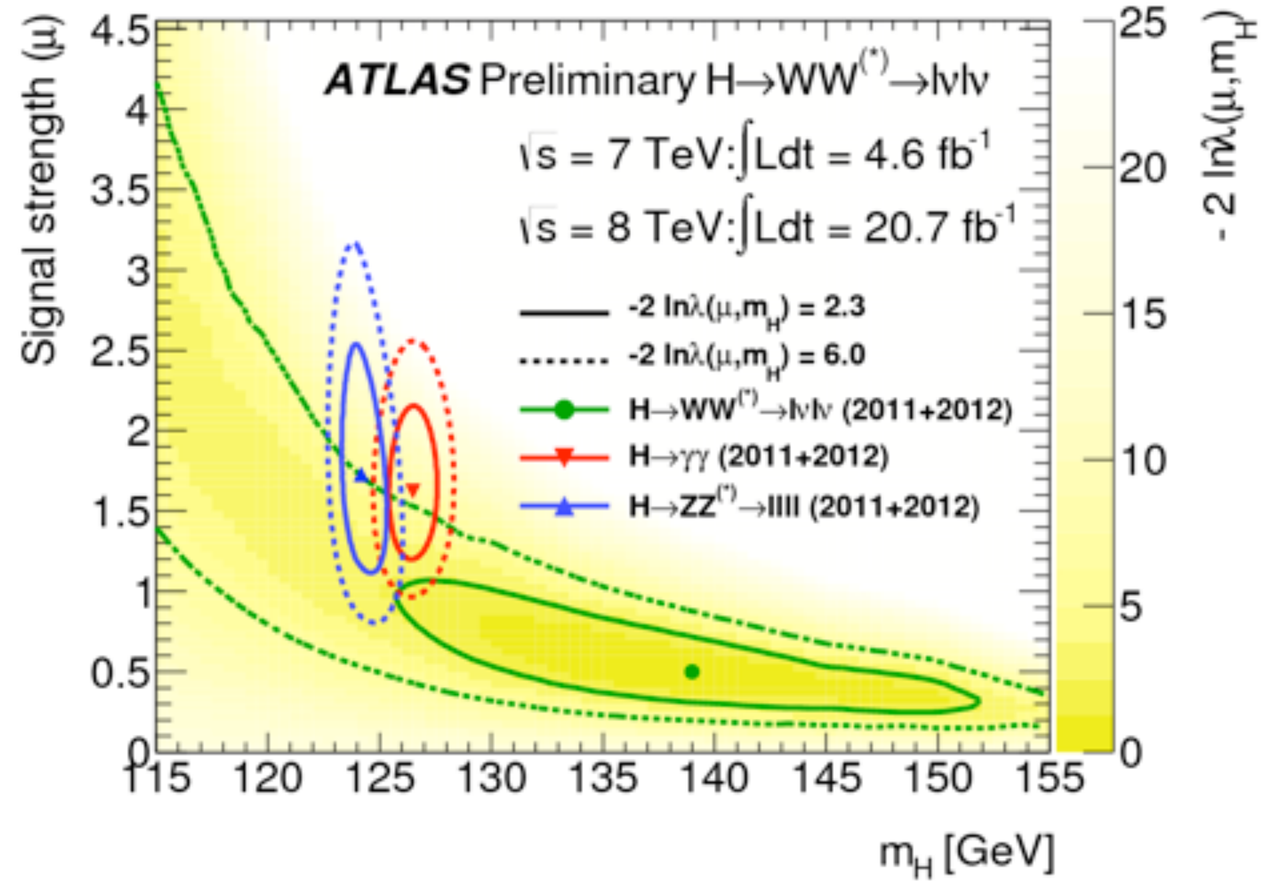
Background-subtracted m_T distribution for N_{jet} ≤1 in 7 and 8 TeV data. The signal is overlaid. The error bars represent the statistical uncertainties of the data and the subtracted background; it does not include the systematic uncertainties of the latter.



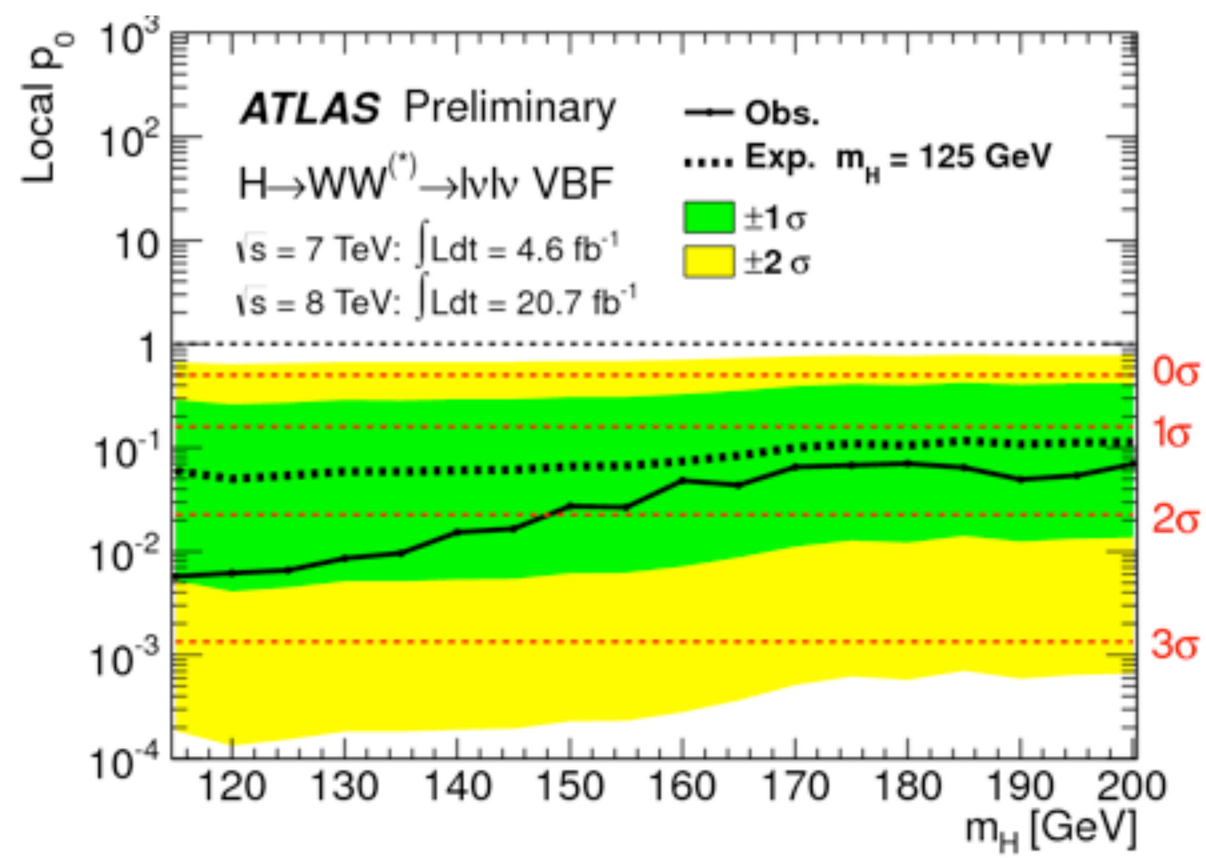
Results for (a) p₀ and (b) 95% CL upper limit using combined 7 TeV and 8 TeV data. The p₀ is the given probability for the background-only scenario as a function of mH. The expected 95% CL upper limit is computed in the absence of a signal. The upper limit is on the cross section normalised to the SM cross section. For both figures, the smaller green bands represent ± 1σ uncertainties on the expected values, and the larger yellow bands represent ± 2σ uncertainties.



Signal strength parameter μ vs. mH: (a) fitted μ value for the given mH and (b) two-dimensional likelihood contours of -2lnλ(μ,m_H) in the best-fit signal strength.



VBF results for (a) p₀ and (b) 95% CL upper limit using 8 TeV data considering VBF as signal and ggF as part of the background. Details are given in the caption of Fig. 10.



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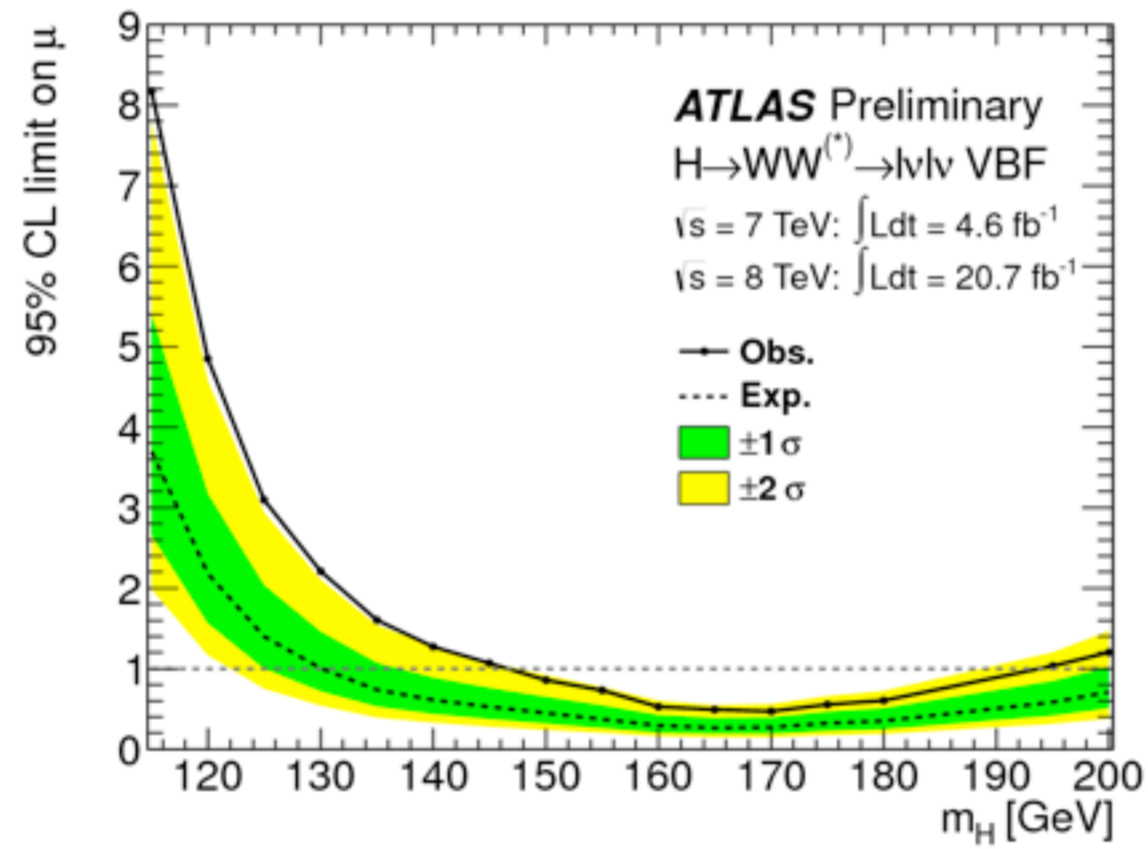
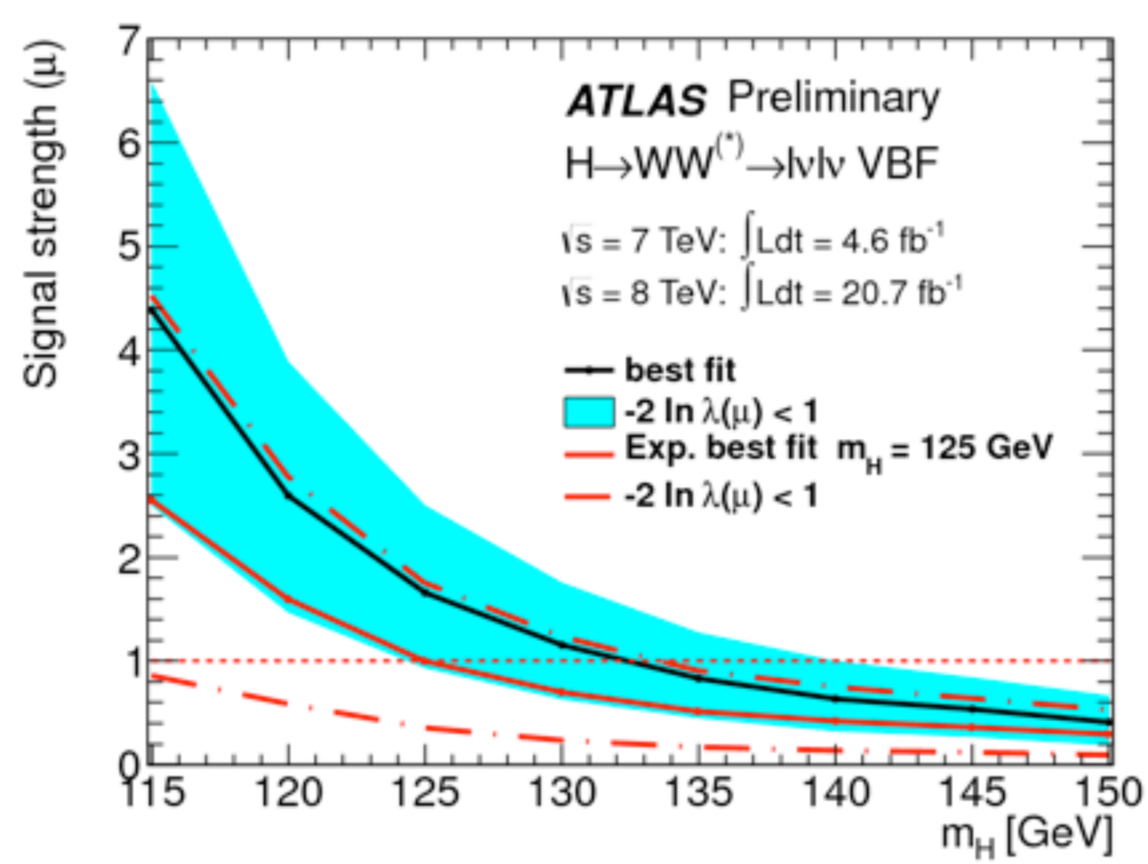
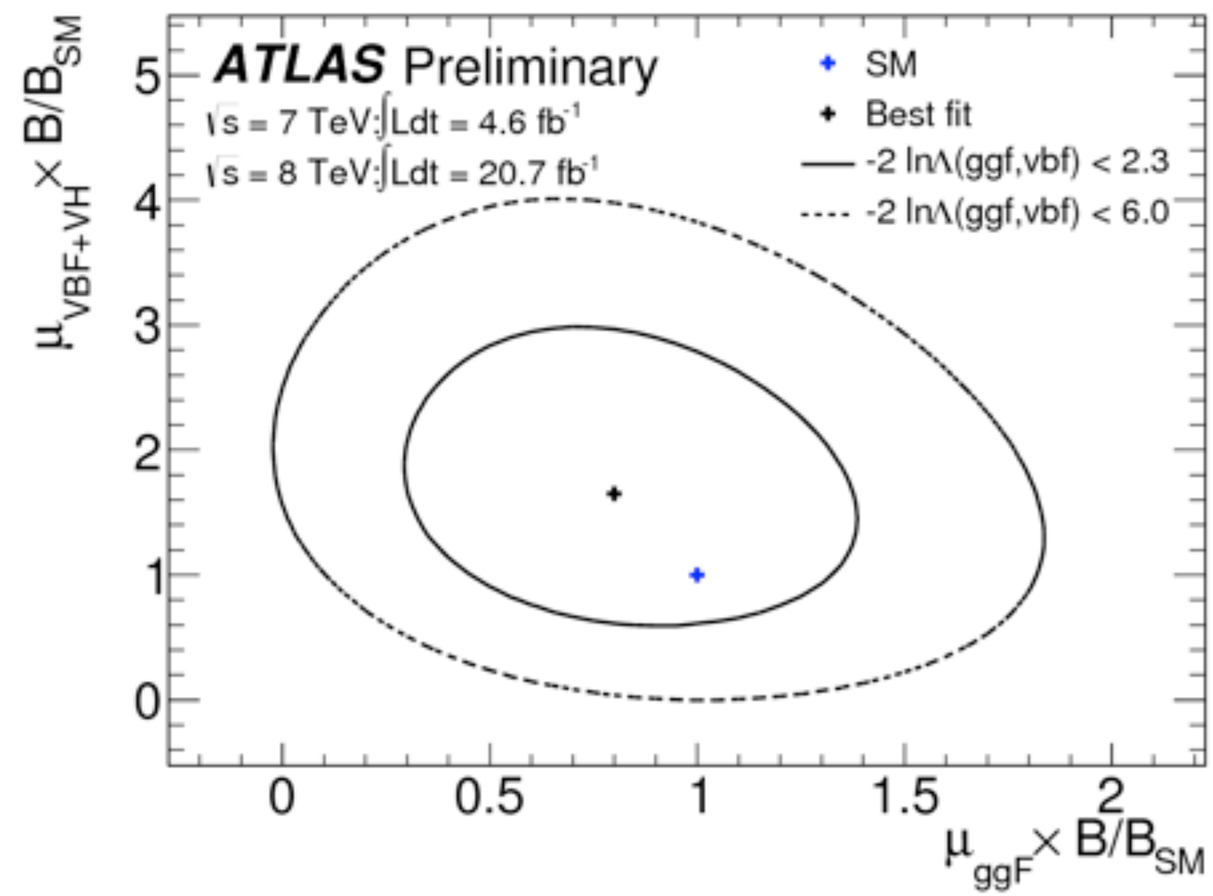
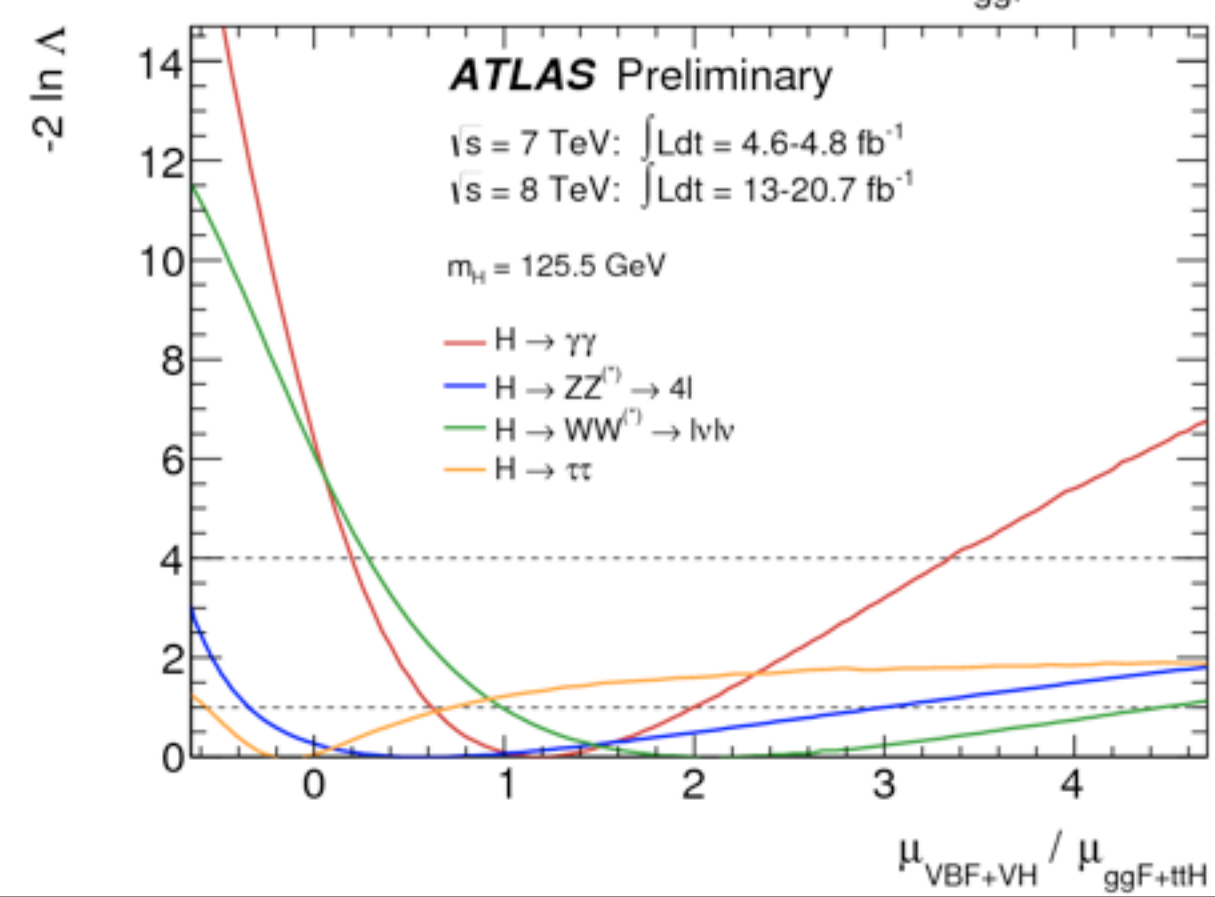


VBF signal strength parameter μ. The observed (solid black line with shaded cyan band) and the expected result (solid red line with dashed band) are shown.



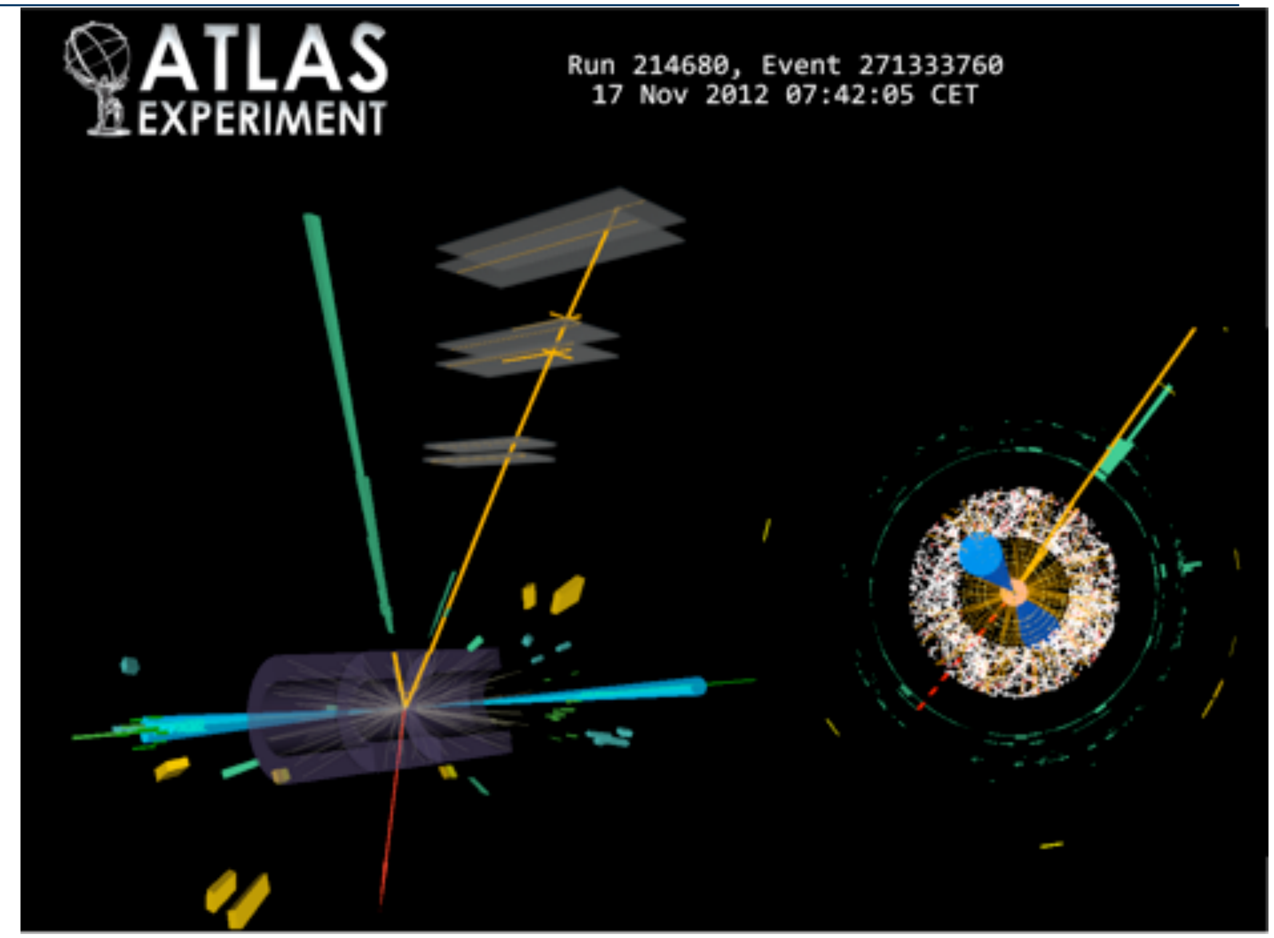
Likelihood contours for separate ggF and VBF signal strength parameters (a) and the likelihood curves for the ratio of the ggF/VBF strength parameters (b). hWW^(*) →lνlν analysis uses the combined 7 and 8 TeV data.



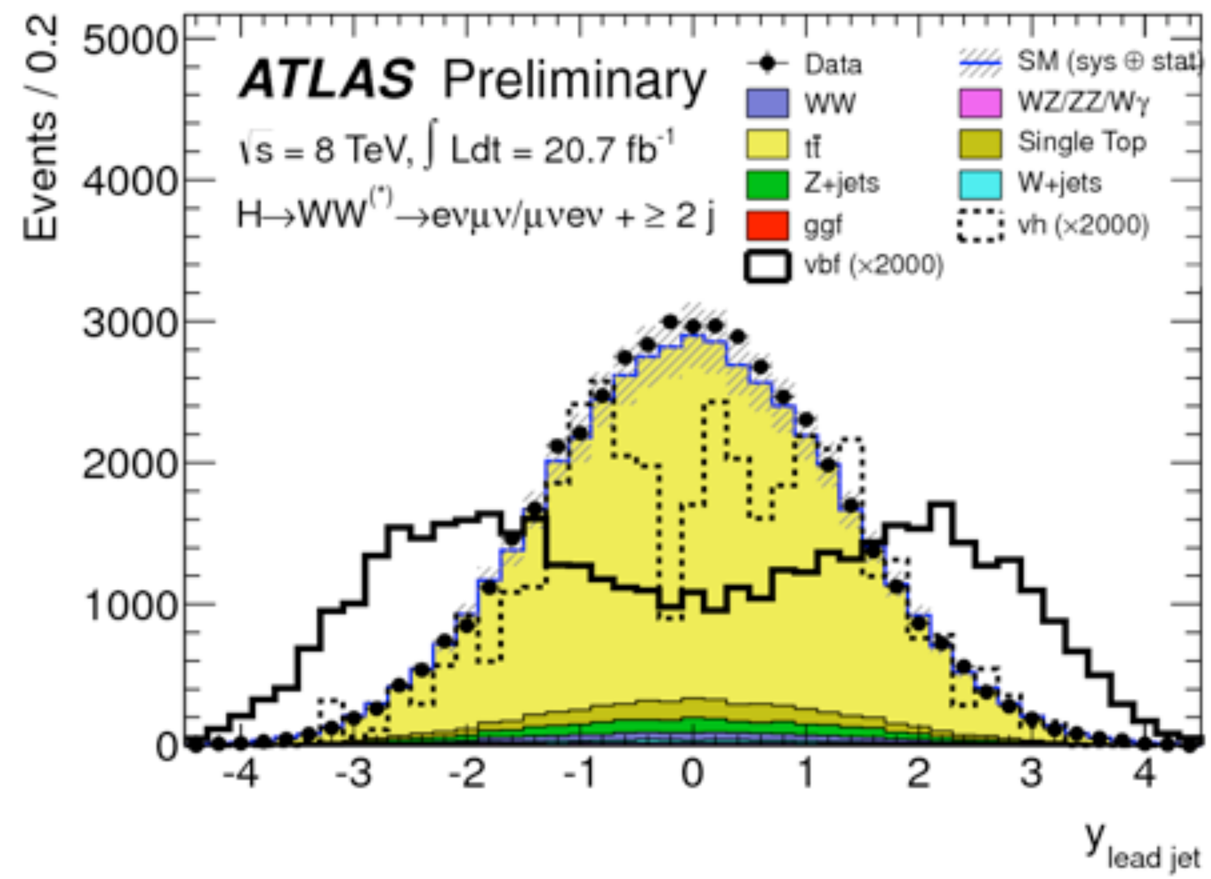


Likelihood contours for separate ggF and VBF signal strength parameters (a) and the likelihood curves for the ratio of the ggF/VBF strength parameters (b). hWW^(*) →lνlν analysis uses the combined 7 and 8 TeV data.

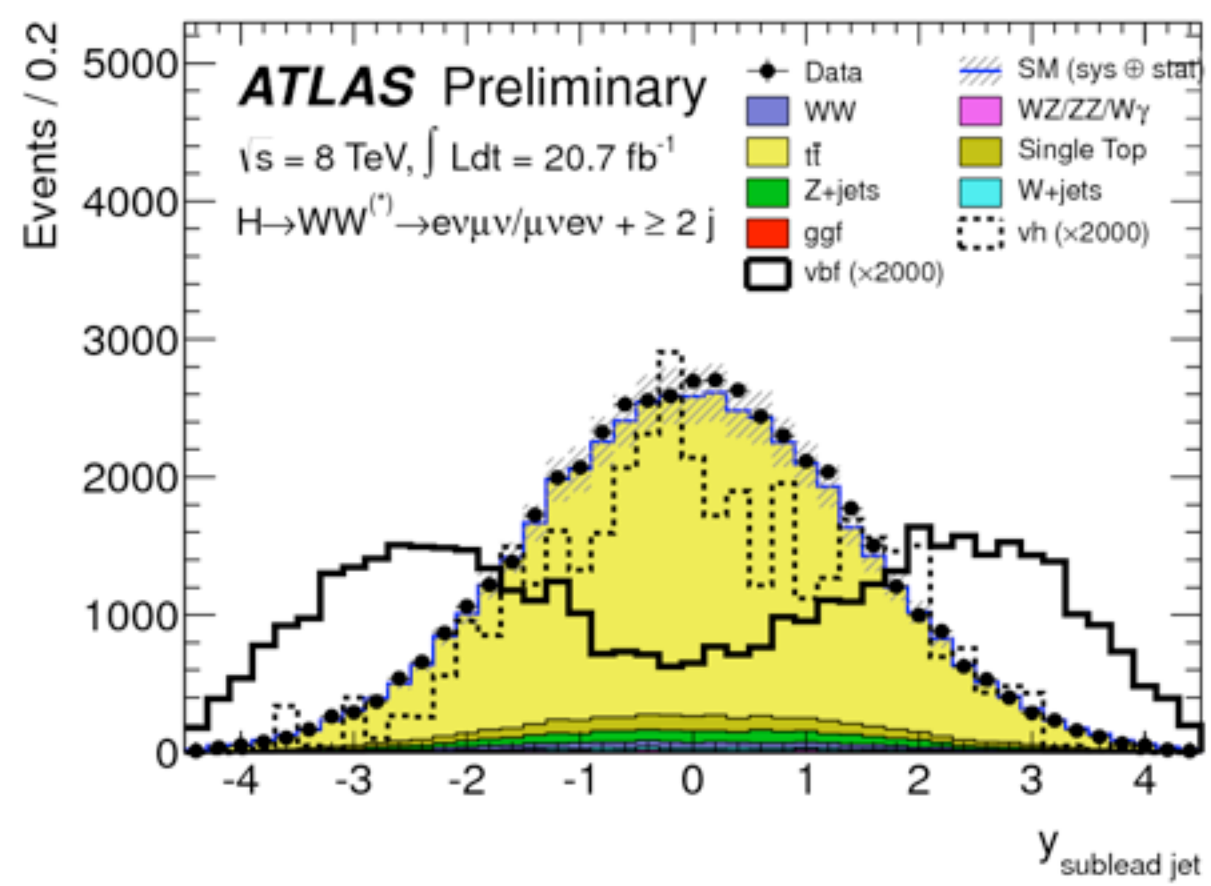
A candidate event for H → WW^(*) → eν μ ν + 2 jets produced via VBF, qq→Hqq. The event variables are: m_{jj} = 1.5 TeV, lΔy_{<emph>jj</emph>}l = 6.6, m_{ll} = 21 GeV, and m_T = 95 GeV. For the figure on the left (starting from the top left going clockwise): p_T of the electron is 51 GeV (thick green line), the muon is 15 GeV (orange line), the jet (right blue cone) is 68 GeV, the E_T^{miss} (thin dotted red line on the left) is 33 GeV, and the jet (left cyan cone) is 42 GeV. A view transverse to the beam direction is given on the right; previous descriptions of various objects apply except for E_T^{miss}, which is represented as a thick dotted line.



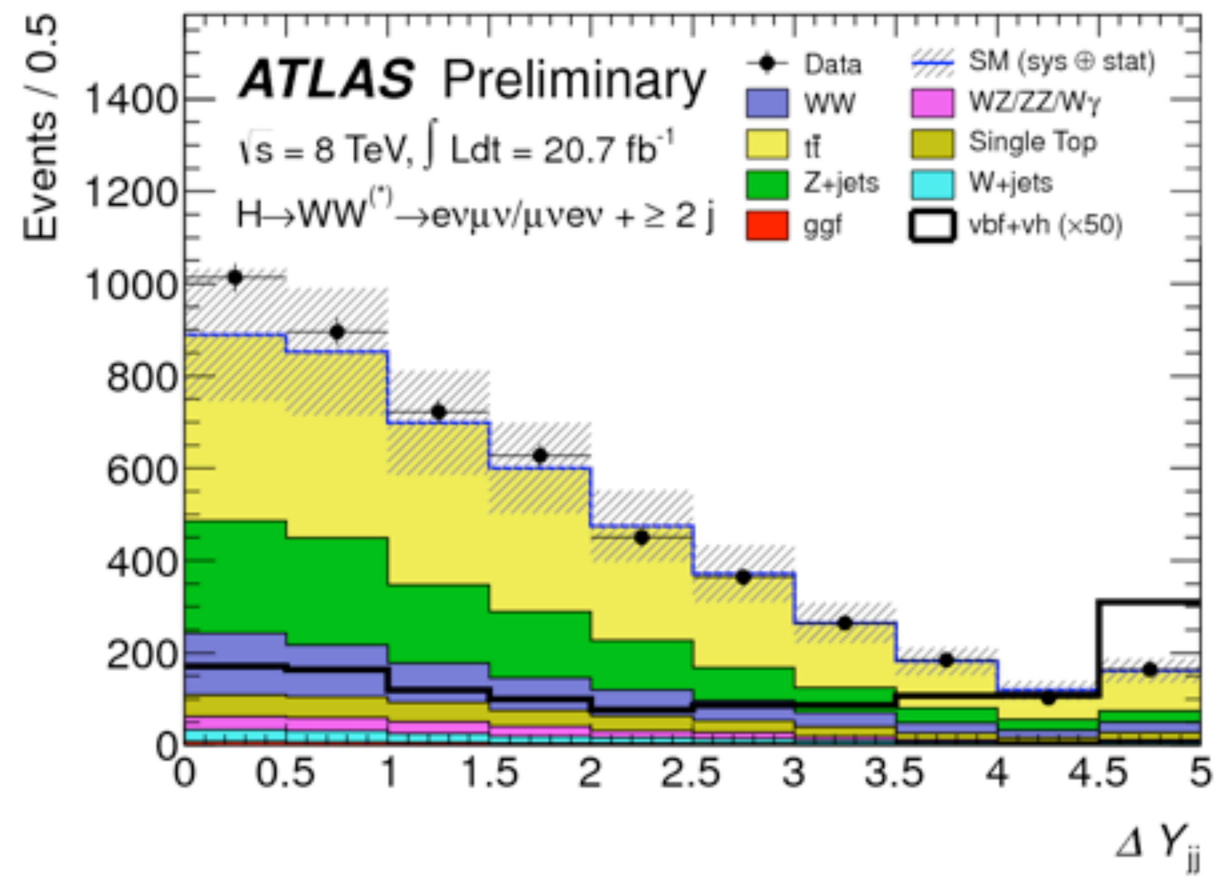
Rapidity distributions of the leading and sub-leading tagging jets. The distribution is shown at the 2 jets requirement, the signal is magnified by a factor 2000 to show the peculiar forward distribution of jets from the VBF process. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.



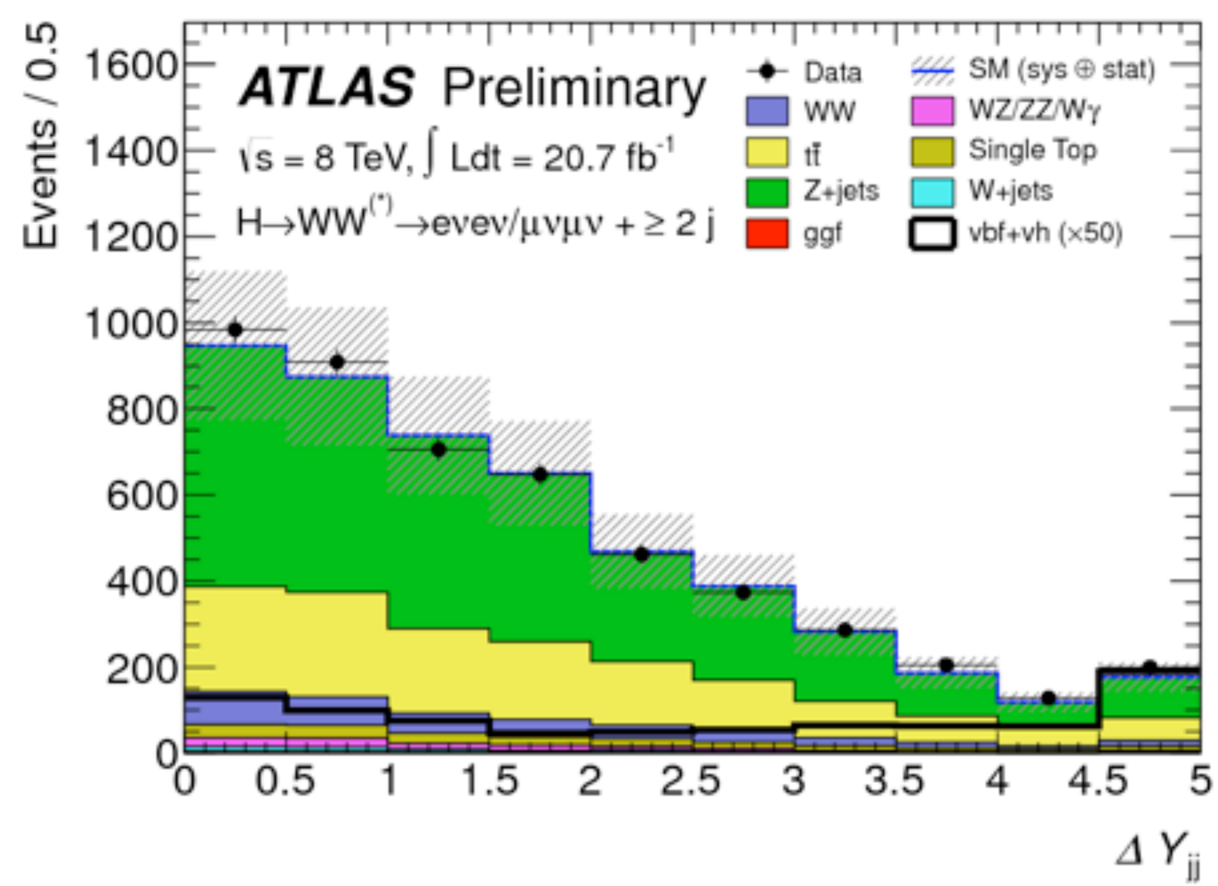
Rapidity distributions of the leading and sub-leading tagging jets. The distribution is shown at the 2 jets requirement, the signal is magnified by a factor 2000 to show the peculiar forward distribution of jets from the VBF process. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.



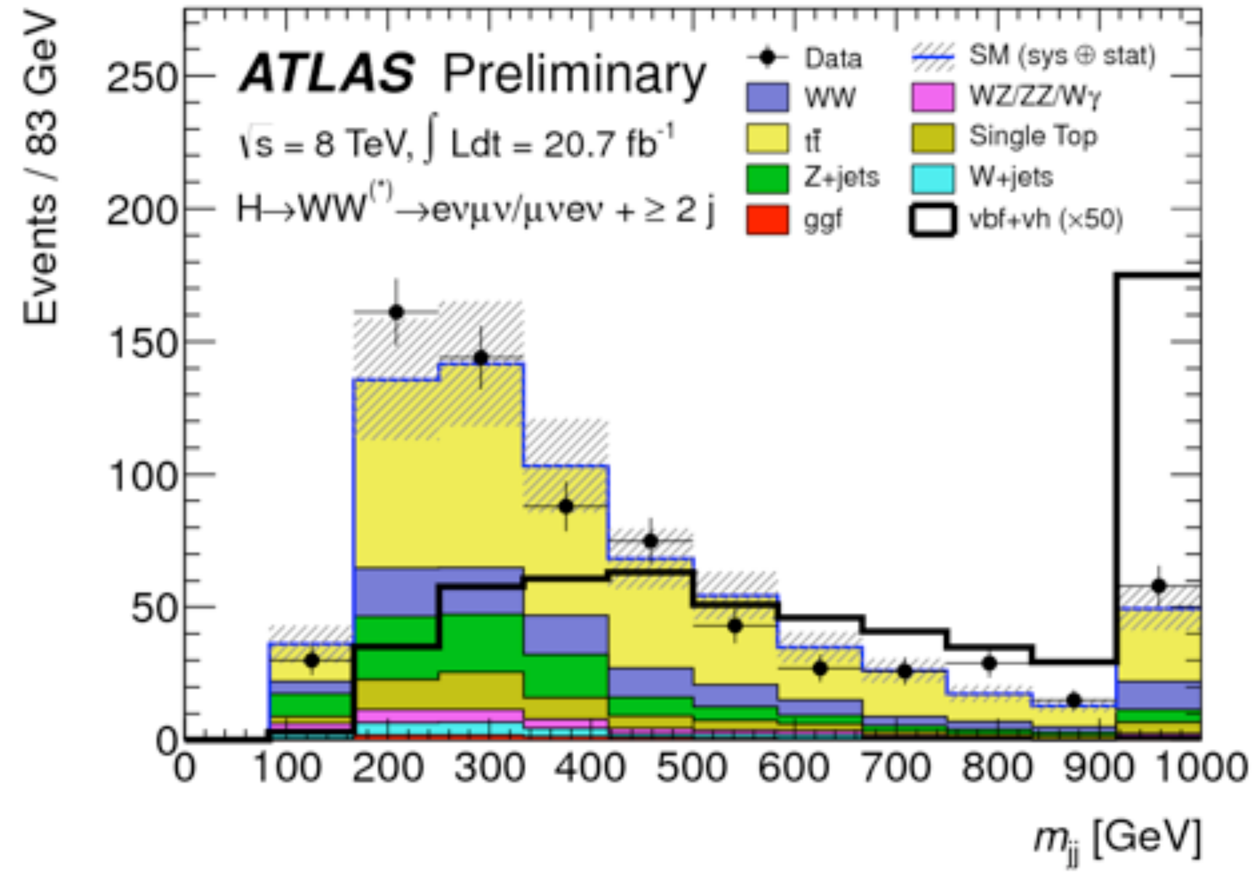
The IΔy_{<emph>jj</emph>}I and m_{jj} distributions after the p_T^{tot} < 45 GeV cut. p_T^{tot} is defined as the total transverse momentum of all leptons, jets and missing E_T passing the selection. The m_{jj} distribution is shown after the IΔy_{<emph>jj</emph>}I > 2.8 cut. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.



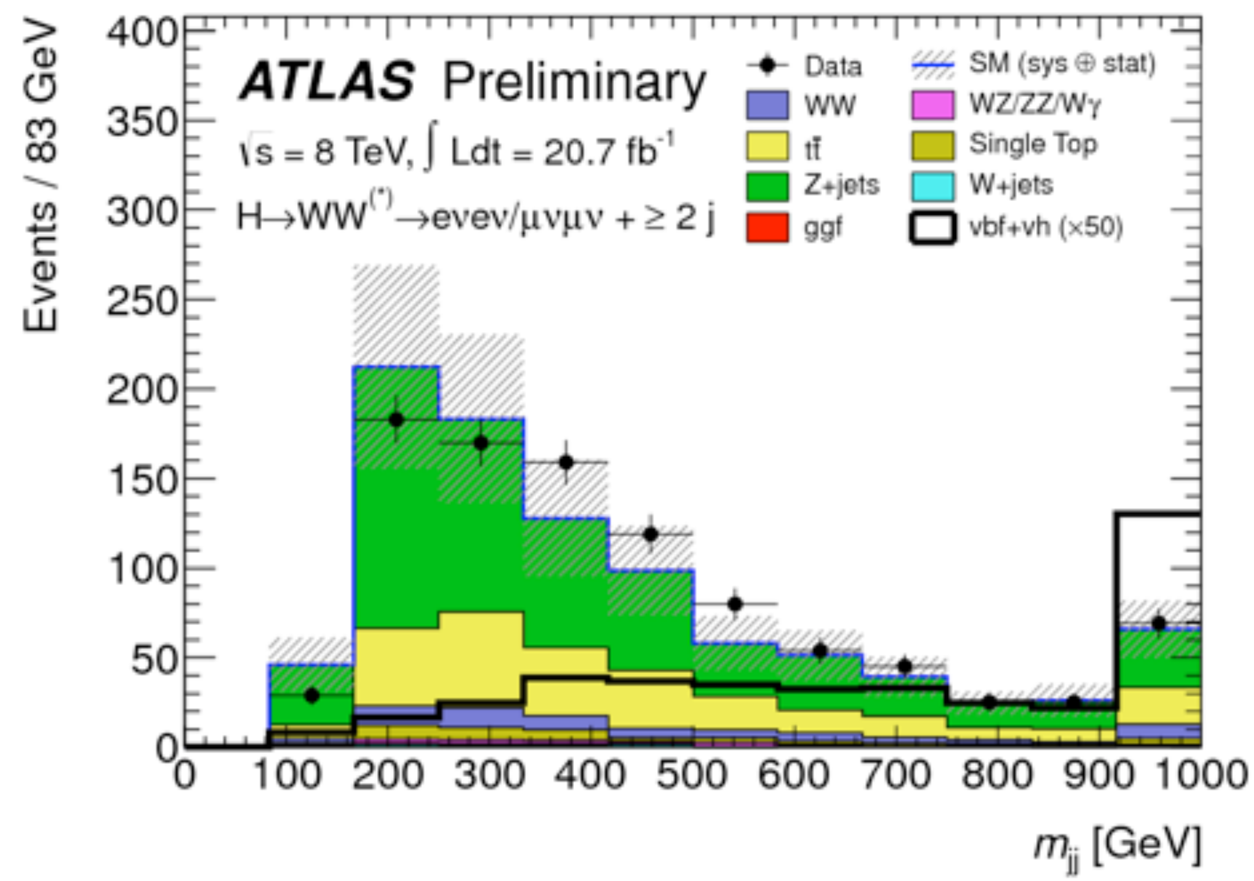
The IΔy_{<emph>jj</emph>}I and m_{jj} distributions after the p_T^{tot} < 45 GeV cut. p_T^{tot} is defined as the total transverse momentum of all leptons, jets and missing E_T passing the selection. The m_{jj} distribution is shown after the IΔy_{<emph>jj</emph>}I > 2.8 cut. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.



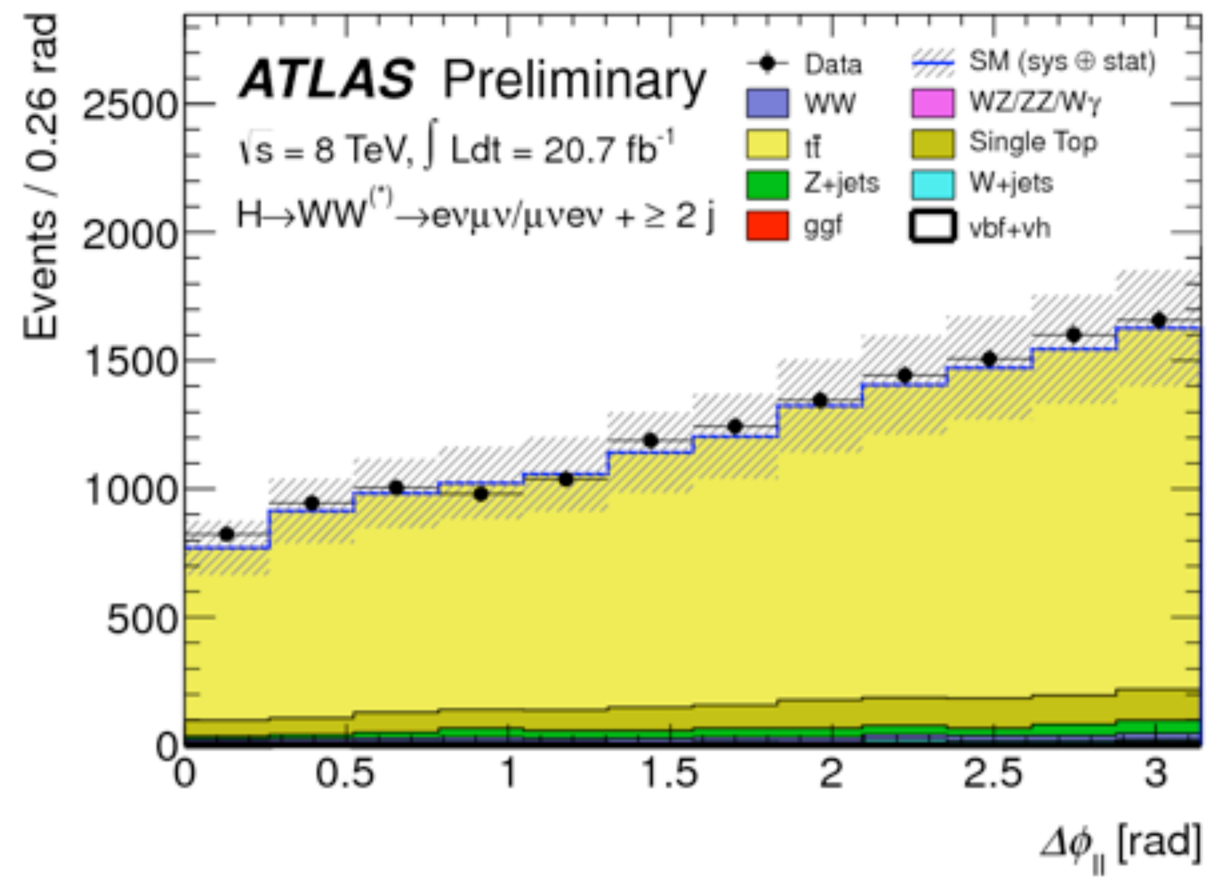
The lΔy_{<emph>jj</emph>}l and m_{jj} distributions after the p_T^{tot} < 45 GeV cut. p<sub>T</ sub>^{tot} is defined as the total transverse momentum of all leptons, jets and missing E_T passing the selection. The m_{jj} distribution is shown after the lΔy_{<emph>jj</emph>}l > 2.8 cut. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.



The lΔy_{<emph>jj</emph>}l and m_{jj} distributions after the p_T^{tot} < 45 GeV cut. p<sub>T</ sub>^{tot} is defined as the total transverse momentum of all leptons, jets and missing E_T passing the selection. The m_{jj} distribution is shown after the lΔy_{<emph>jj</emph>}l > 2.8 cut. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.



The lΔφ_{ll}l, m_T and m_{ll} distributions after the p_T^{tot} < 45 GeV cut in the top CR, defined by the requirement of one and only one b tagged jet . p_T^{tot} is defined as the total transverse momentum of all leptons, jets and missing E_T passing the selection. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.



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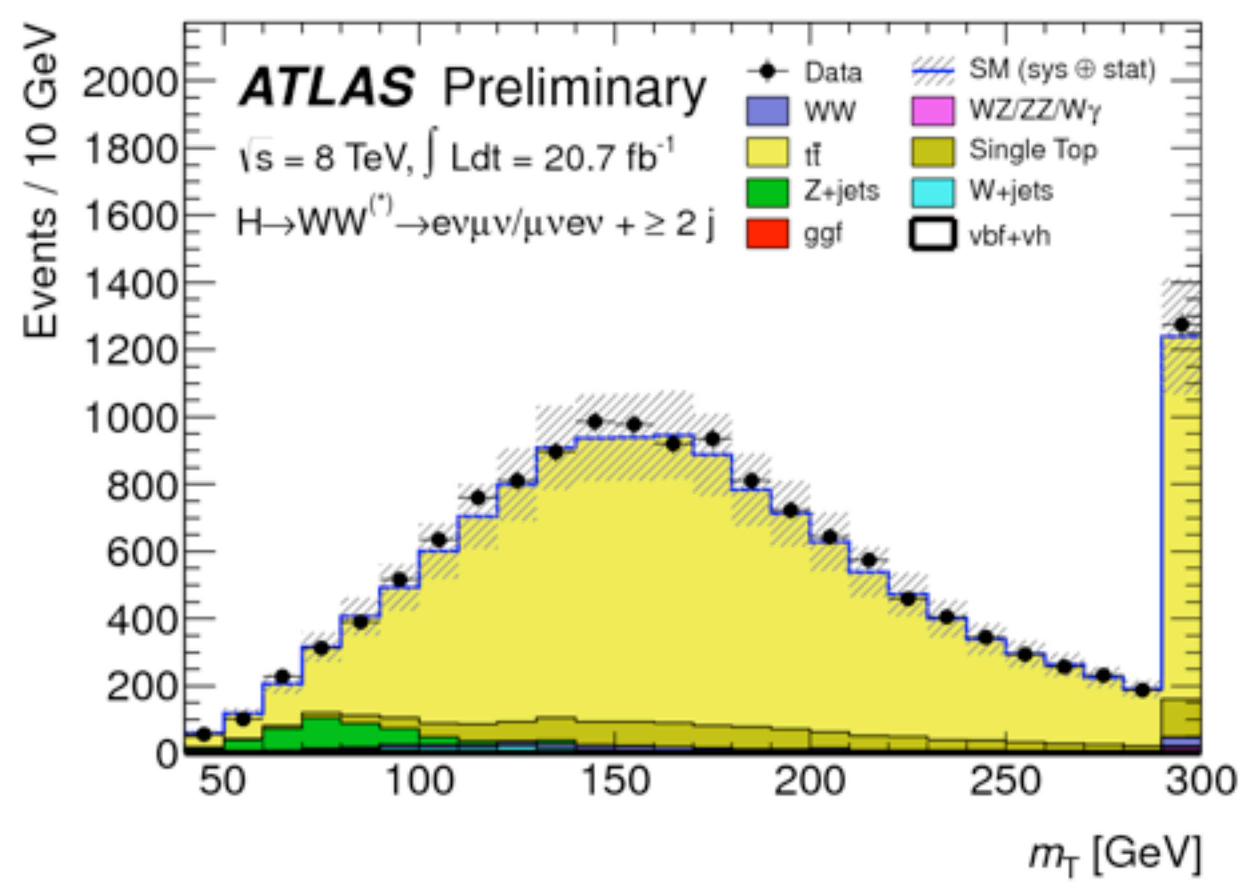
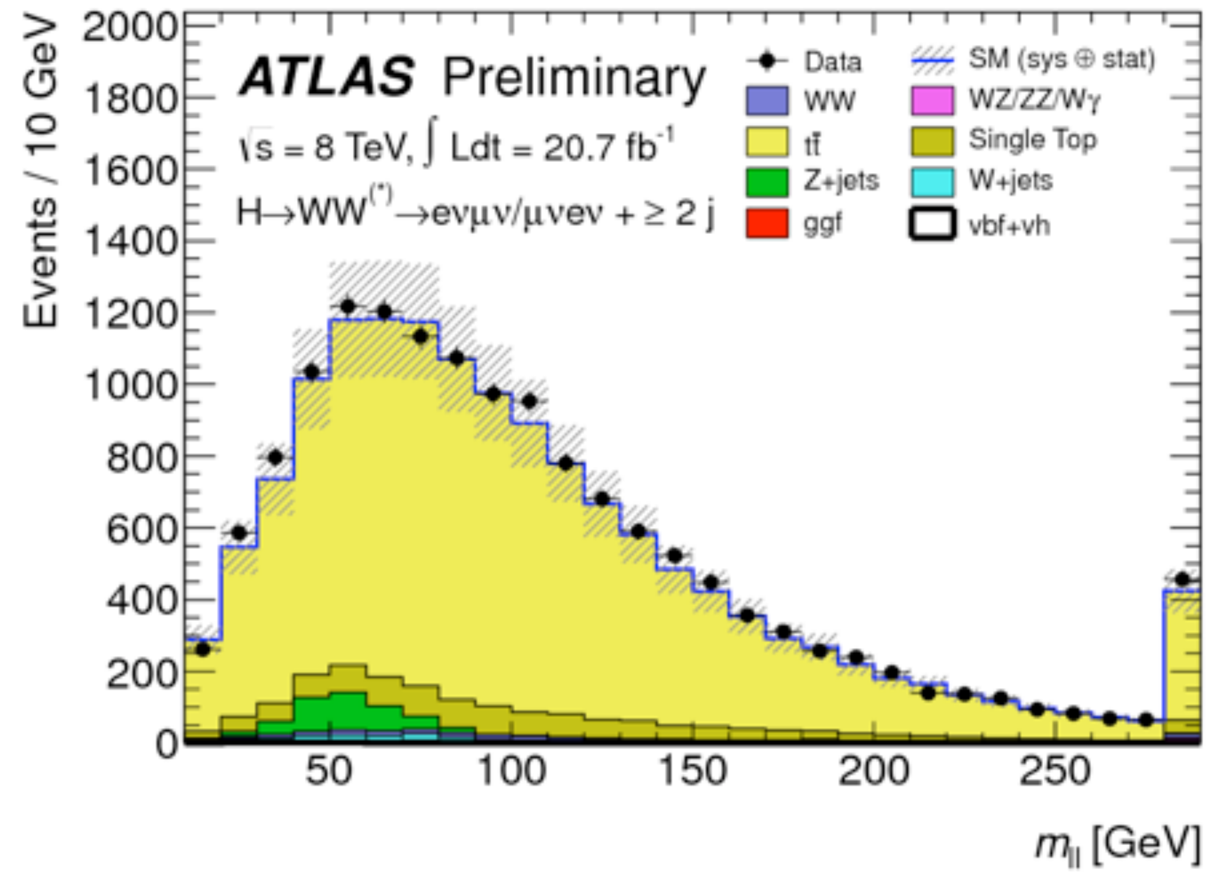
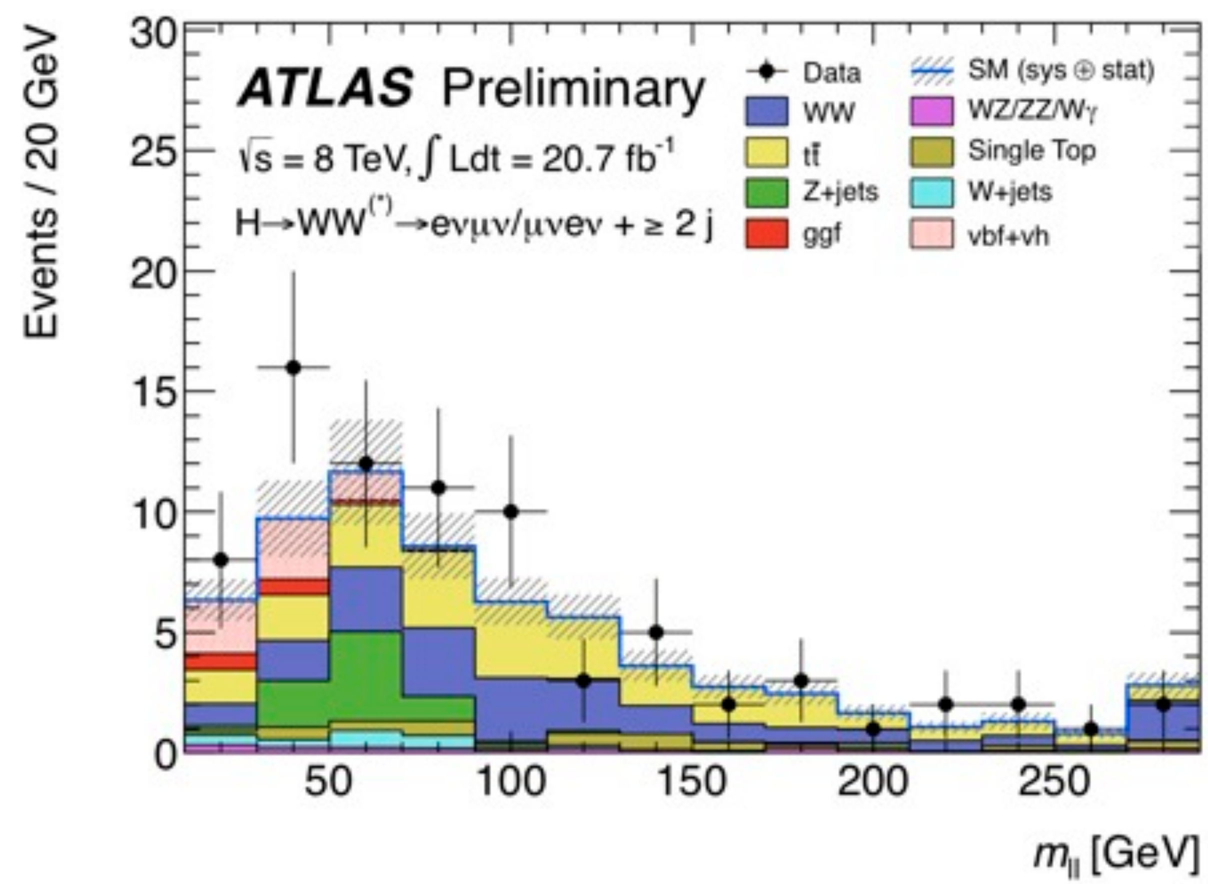


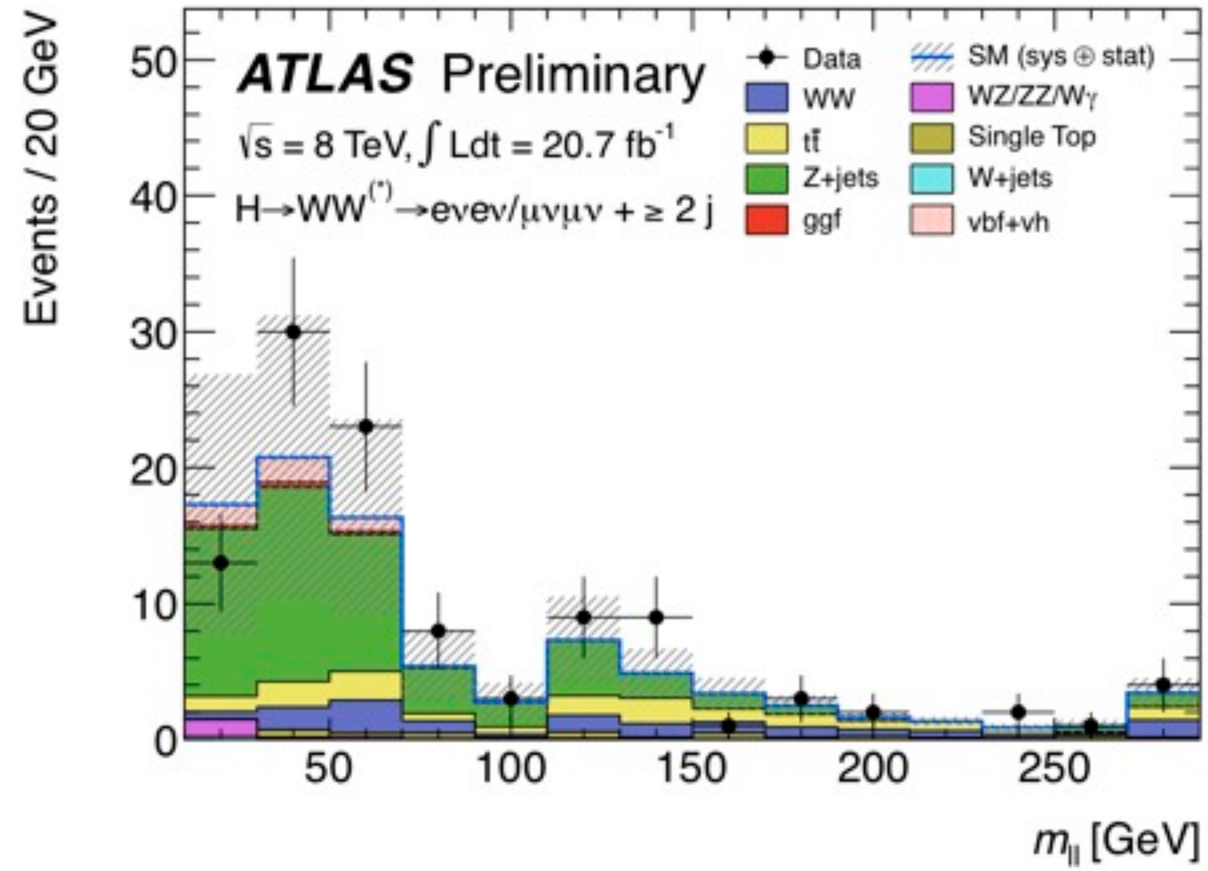
The lΔφ_{ll}l, m_T and m_{ll} distributions after the p_T^{tot} < 45 GeV cut in the top CR, defined by the requirement of one and only one b tagged jet . p_T^{tot} is defined as the total transverse momentum of all leptons, jets and missing E_T passing the selection. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.



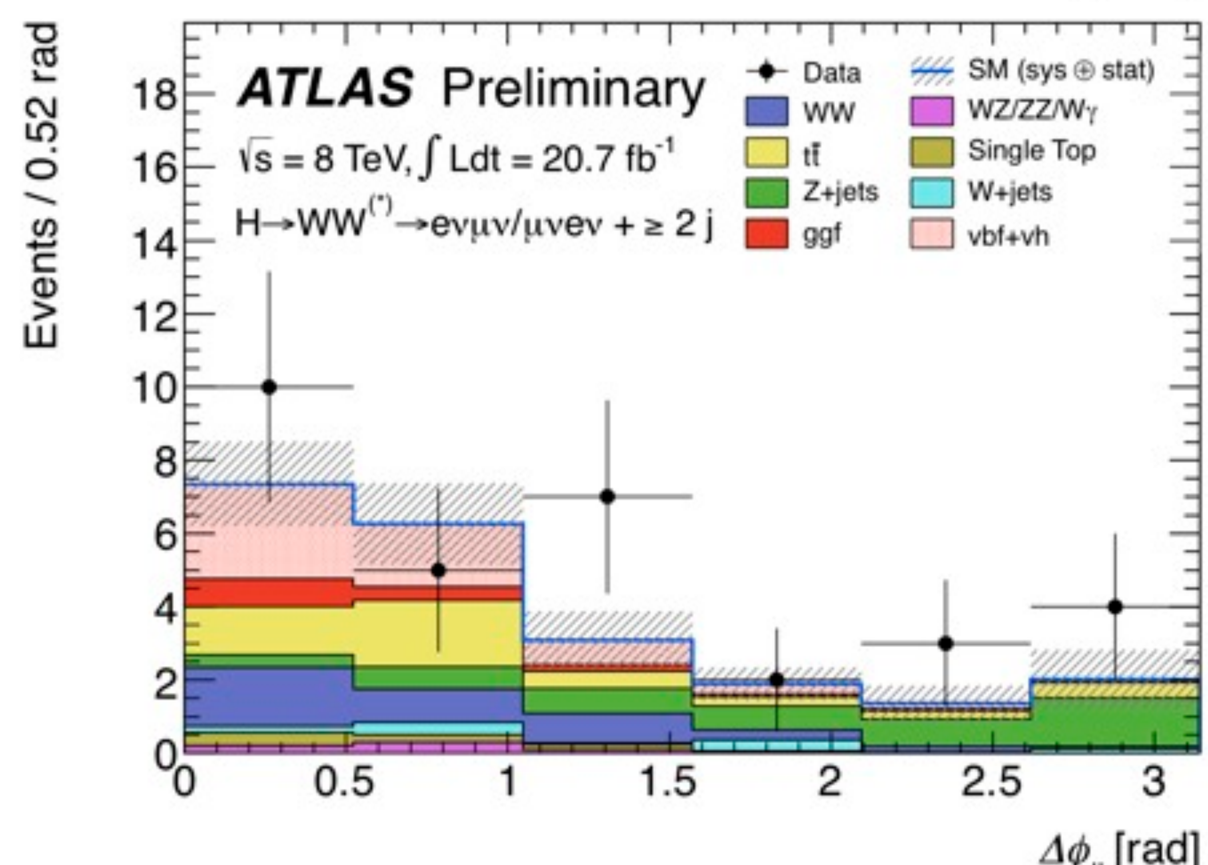
The m_{ll} and the lΔφ_{ll}l distributions after the outside lepton veto cut, accepting events with leptons between the two tagging jets. lΔφ_{ll}l is shown after the m_{ll} < 60 GeV cut. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.



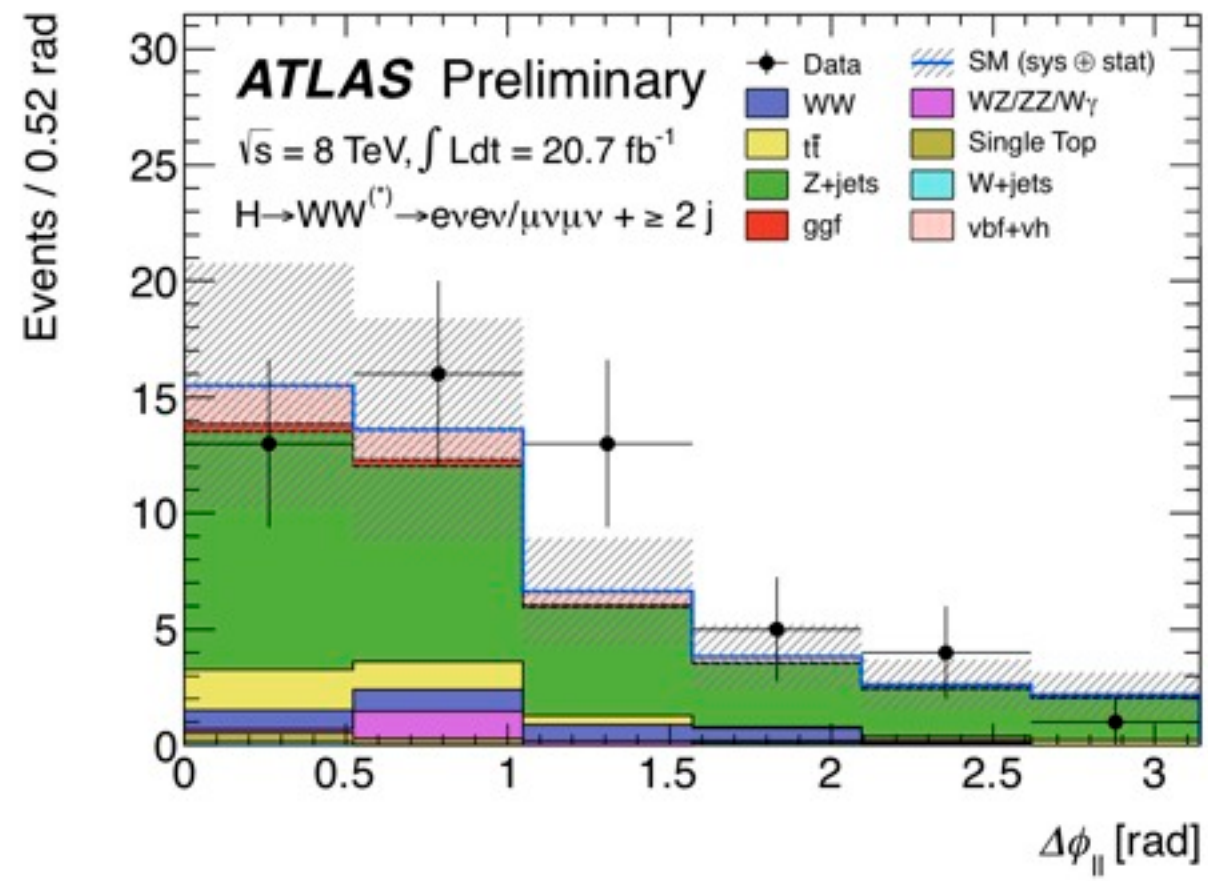
The m_{ll} and the lΔφ_{ll}l distributions after the outside lepton veto cut, accepting events with leptons between the two tagging jets. lΔφ_{ll}l is shown after the m_{ll} < 60 GeV cut. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.



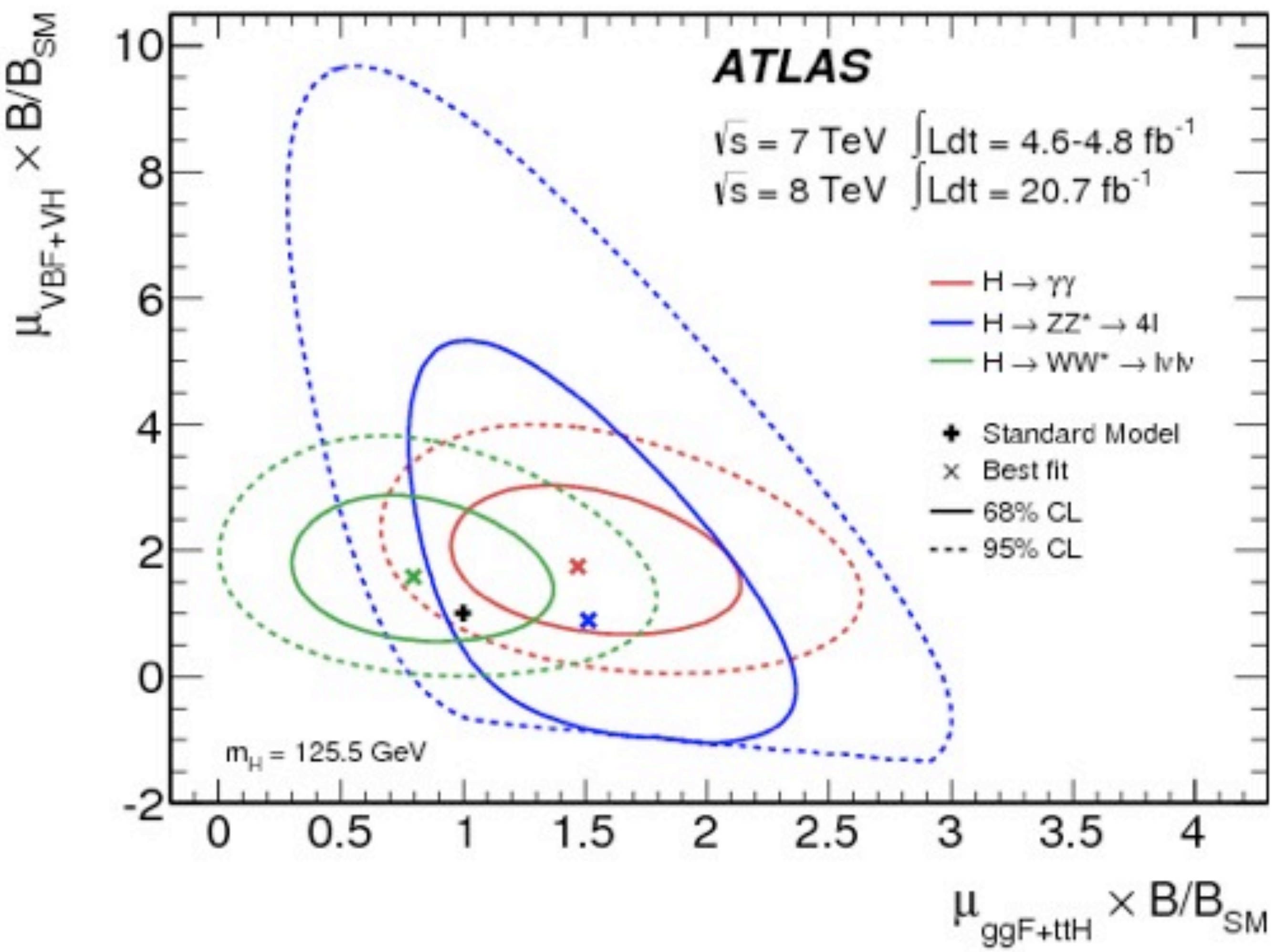
The m_{ll} and the lΔφ_{ll}l distributions after the outside lepton veto cut, accepting events with leptons between the two tagging jets. lΔφ_{ll}l is shown after the m_{ll} < 60 GeV cut. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.

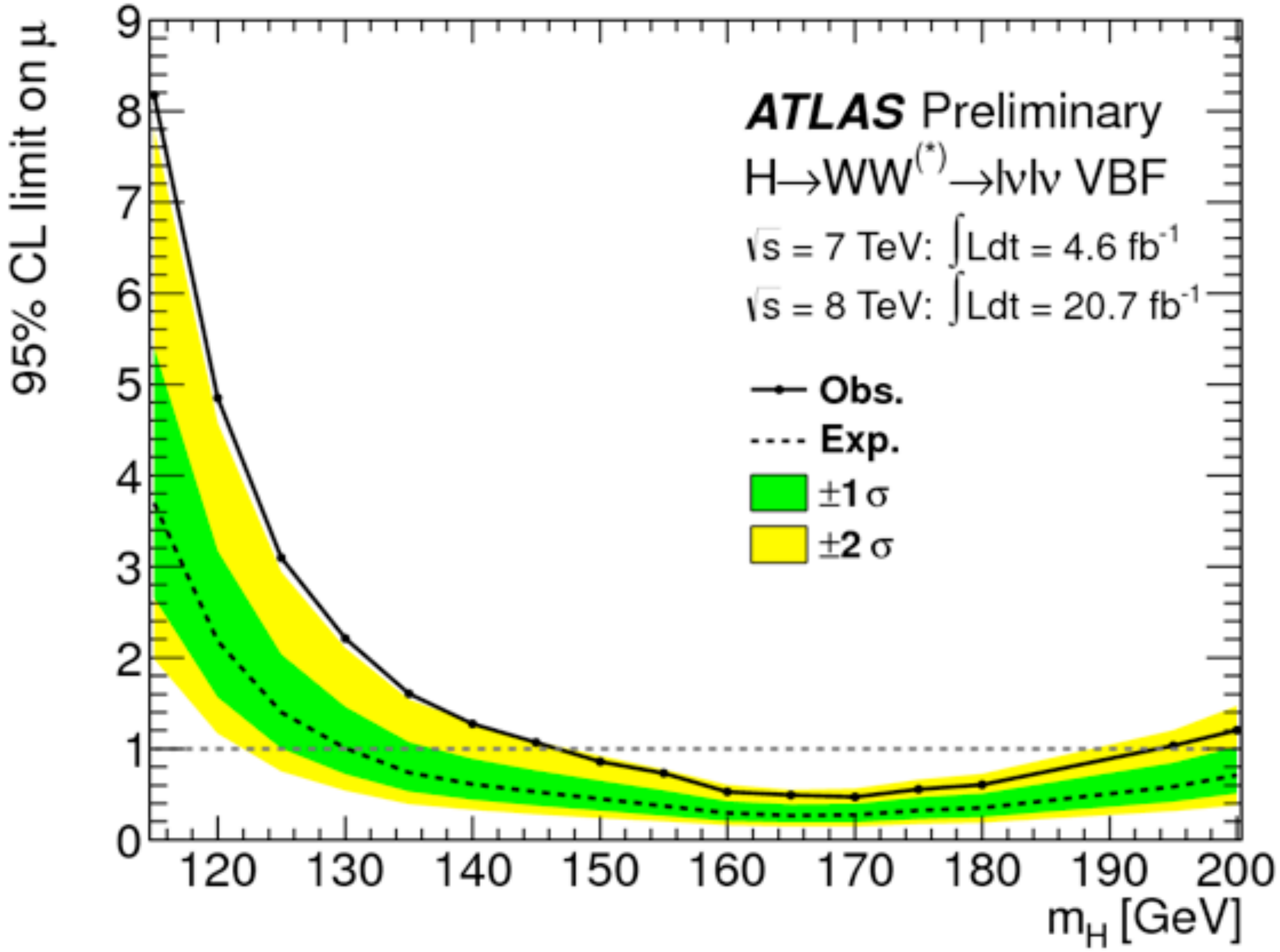


The m_{ll} and the lΔφ_{ll}l distributions after the outside lepton veto cut, accepting events with leptons between the two tagging jets. lΔφ_{ll}l is shown after the m_{ll} < 60 GeV cut. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.

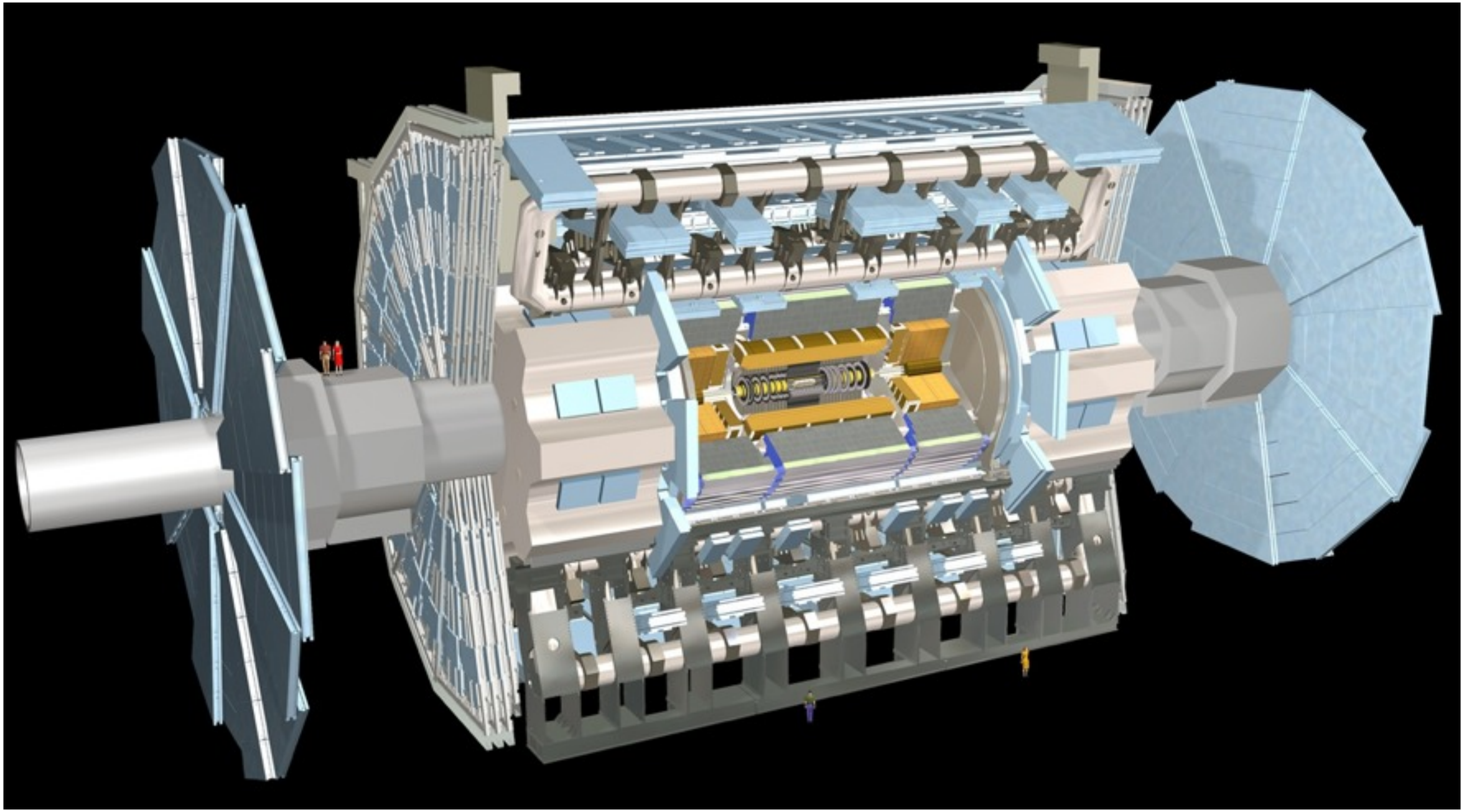


[1] arXiv:1307.1427 [hep-ex]





ATLAS Preliminary
H→WW(*)→lνlν VBF
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 20.7 fb-1
Obs.
Exp.
±1 σ
±2 σ
95% CL limit on μ
m_H [GeV]
0
1
2
3
4
5
6
7
8
9
120
130
140
150
160
170
180
190
200



Z/DY estimate

eμ/μe channel

- Z -> ττ is a non-negligible background in the signal region: 1.7 out of 9.7 background events
- Large MET tails in Z -> ττ -> eμ + neutrinos
- Z + jets is corrected in orthogonal Z rich region
  - $\Delta\Phi_{ll}$ < 1.8 in SR --> $\Delta\Phi_{ll}$ > 2.8 in Z control region

$$\frac{N_{data} - N_{MC}^{non-DY}}{N_{MC}^{DY}} \sim 0.93 \pm 0.11\text{(stat)}$$

- Additionally, VBF cut efficiencies are corrected in ee/μμ Z peak

ee/μμ channel

- With the MET > 45 GeV and MET_STVF > 35 GeV, DY remains a large contribution in signal region: 20.3 out of 26.6 background events
- MET mismodeling in DY is corrected with ABCD method:

A (SR) mll < 60 E_T^{miss} > 45	B |mll - mZ | < 15 E_T^{miss} > 45
C mll < 60 E_T^{miss} < 45	D |mll - mZ | < 15 E_T^{miss} < 45

$$N_{data}^{A} = N_{data}^{C} \cdot f_{MC} \cdot \frac{N_{data}^{B}}{N_{data}^{D}}$$

- Assumes small correlation between MET and M_{ll}. Correlation captured by f_{MC}, defined by

$$N_{MC}^{A} = N_{MC}^{C} \cdot f_{MC} \cdot \frac{N_{MC}^{B}}{N_{MC}^{D}}$$

$$f_{MC} = 1.03 \pm 0.10$$

Correction factor: $NF_{ABCD} = 0.81 \pm 0.06$

Top estimate

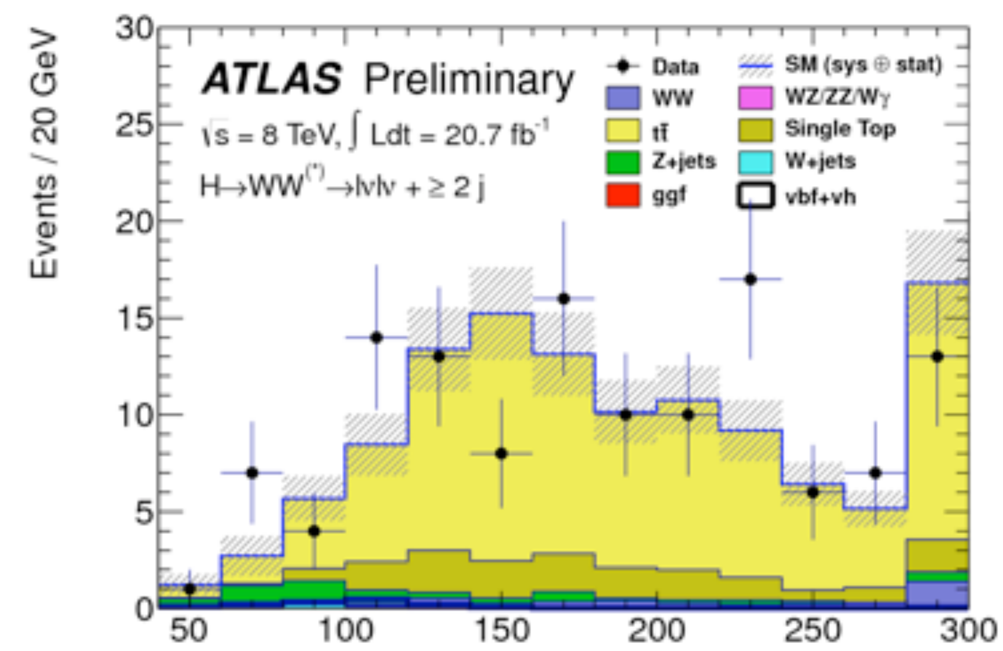
- Use top rich control region to estimate top contribution in signal region
- Top CR: instead of vetoing on btagged jets, require exactly 1

$$\text{Top NF} = \frac{N_{data} - N_{MC}^{non-top}}{N_{MC}^{top}} \xrightarrow{\text{extrapolate to signal region}} N_{top}^{est} = \text{Top NF} \times N_{top}^{MC}$$

Top CR selection	Top NF
$N_{Jet} \geq 2$	1.02
$N_{BJet} = 1$	1.02
$P_T^{total} < 45$	1.02
$\lvert M_{\tau\tau} - M_Z \rvert > 25$	1.02
$\Delta Y_{JJ} > 2.8$	0.89
$M_{JJ} > 500$	0.71
No jets > 20 GeV in central region	0.58
Leptons in central region	0.58

mismodeling in MC@NLO in this corner of phase space

mT distribution in top CR



[3] ATLAS-CONF-2013-030

- Systematic on extrapolation from CR to SR

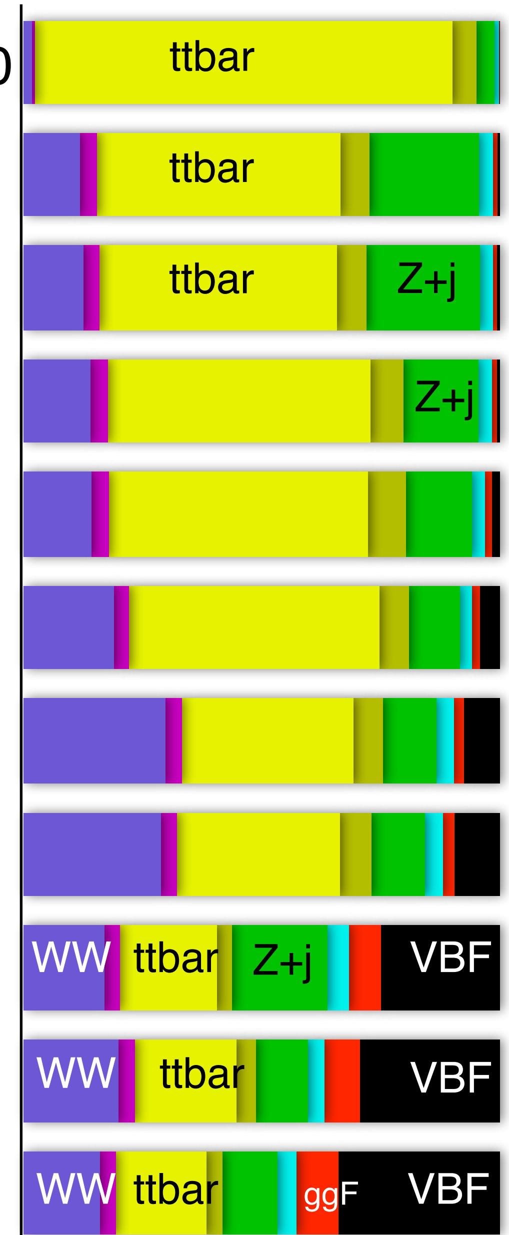
compare $\alpha = \dfrac{N_{top}^{SR}}{N_{top}^{CR}}$ between MC@NLO and Alpgen

Event selection summary

- Preselection: two oppositely charged leptons, leading lepton > 25 GeV, subleading > 15 GeV
  - eμ/μe: MET > 20 GeV
  - ee/μμ: cuts to suppress Drell Yan: $|M_{ll} - M_Z| > 15$, MET > 45, MET_STVF > 35

numbers from 21 fb^{-1} eμ/μe

	VBF +VH	Bkg +ggF	S-to-B
$N_{Jet} \geq 2$	43	48k	1-to-1000
$N_{BJet} = 0$	31	5.7k	1-to-200
$P_T^{total} < 45$	27	4.6k	1-to-200
$\lvert M_{\tau\tau} - M_Z \rvert > 25$	25	3.8k	1-to-200
$\Delta Y_{JJ} > 2.8$	12	680	1-to-50
$M_{JJ} > 500$	7.5	170	1-to-20
No jets > 20 GeV in central region	6.3	77	1-to-10
Leptons in central region	6.1	59	1-to-10
$M_{e\mu} < 60$	5.5	16.5	1-to-3
$\Delta\varphi_{e\mu} < 1.8$	5.1	12.4	1-to-3
$M_T < 150$	**5.0**	**9.7**	1-to-2



Z/DY estimate

eμ/μe channel

- Z -> ττ is a non-negligible background in the signal region: 1.7 out of 9.7 background events
- Large MET tails in Z -> ττ -> eμ + neutrinos
- Use data to correct MET cut efficiency in Z rich region
  - $\Delta\Phi_{ll} < 1.8$ in SR --> $\Delta\Phi_{ll} > 2.8$

$$\frac{N_{data} - N_{MC}^{non-DY}}{N_{MC}^{DY}} \sim 0.93 \pm 0.11(\text{stat})$$

- Additionally, VBF cut efficiencies are corrected in ee/μμ Z peak

ee/μμ channel

- With the E_T^{miss} cuts, DY remains a large contribution in signal region: 20.3 out of 26.6 background events
- Correct efficiency of MET cuts in the Z peak and extrapolate to low M_{ll} region

MET Correction factor: 0.81 ± 0.06

- VBF topological cuts efficiencies are corrected in low MET CR

A (SR) mll < 60 $E_T^{miss} > 45$	B |mll - mZ | < 15 $E_T^{miss} > 45$
C mll < 60 $E_T^{miss} < 45$	D |mll - mZ | < 15 $E_T^{miss} < 45$