Simultaneous measurements of $t\bar{t}$, WW and $Z/\gamma^* \rightarrow \tau^+\tau^-$ production at $\sqrt{s} = 7$ TeV with the ATLAS detector

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37th International Conference on High Energy Physics
Valencia, Spain

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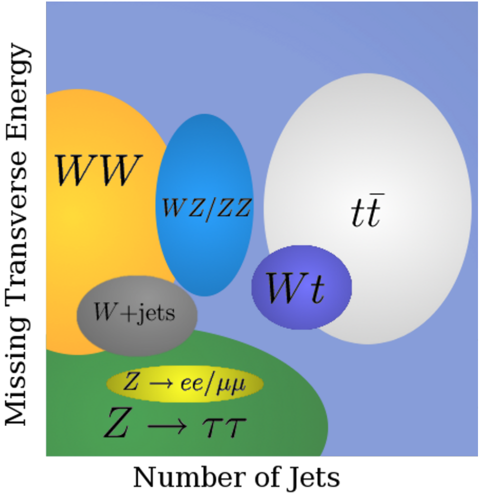
July 3, 2014

Motivation for simultaneous measurements

- *Provide a global test of the standard model.*
- *Making measurements of three processes using a common definition of the fiducial region allows for a unique exploration of the effect of parton distribution functions (PDFs) on cross-section predictions.*
- *Simultaneous cross-section measurements complement results obtained from dedicated analyses.*

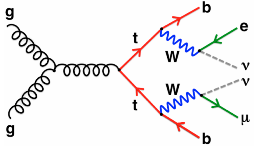
AIDA - An inclusive dilepton analysis

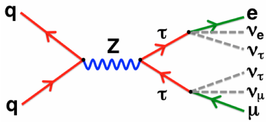
- Select opposite sign $e + \mu$ events
- Three main SM processes, $t\bar{t}$, WW, and $Z/\gamma^* \rightarrow \tau\tau$ can be distinguished in Missing E_T ($E_{\mathrm{T}}^{\mathrm{miss}}$) and jet multiplicity ($N_{\mathrm{jets}}$)
- Fit MC templates for these processes to data. Backgrounds remain fixed.
- Developed at CDF (Phys. Rev. D 78 (2008) 012003), here greatly extended at ATLAS (submitted to PRD - arXiv:1407.0573)

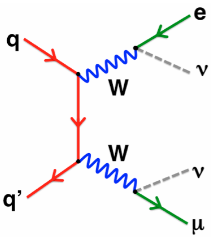


Modelling of signal processes

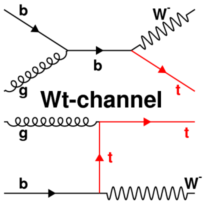
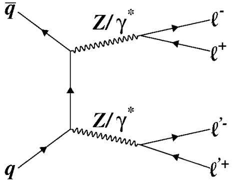
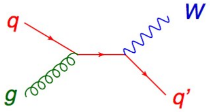
Process	Matrix Element + Shower + PDFs
$t\bar{t}$ $\sigma = 177 \pm 11$ pb (NNLO+NNLL)	MC@NLO+HERWIG+CT10
$Z/\gamma^* \to \tau\tau$ $\sigma = 1070 \pm 54$ pb $(M_{Z/\gamma^*} > 40)$ GeV$/c^2$	SHERPA+CT10 (LO ME+PS)
$qq' \to WW$ $\sigma_{\mathrm{NLO}} = 44.7^{+2.1}_{-1.9}$ pb	MC@NLO HERWIG CT10
$gg \to WW$ $\sigma_{\mathrm{NLO}} = 1.3^{+0.8}_{-0.5}$ pb	GG2WW HERWIG CT10
$gg \to H \to WW \to ll$ $\sigma_{\mathrm{NLO}} = 3.3 \pm 0.3$ pb	POWHEG PYTHIA6 CTEQ6L1







Modelling of background contributions

Process	Matrix Element + Shower + PDFs	
Single Top $\sigma = 15.7 \pm 1.1$ pb (approximate NNLO)	MC@NLO+HERWIG+CT10	
WZ/ZZ $\sigma_{\mathrm{NLO}}(WZ) = 17.8 \pm 1.3$ pb $\sigma_{\mathrm{NLO}}(ZZ) = 5.9 \pm 0.3$ pb	ALPGEN+HERWIG+CTEQ6L1	
Fake or Non-prompt - W+jets and other processes	Data-driven	

Main object and event selection criteria

Electrons

- Cluster of energy in calorimeter consistent with electron hypothesis, and matched to a track
- $E_T > 25$ GeV & $|\eta| < 2.47$ (veto $1.37 < |\eta_{\mathrm{CL}}| < 1.52$)

Muons

- Track in both inner detector and muon spectrometer
- $p_T > 20$ GeV/c & $|\eta| < 2.5$

Isolation variables

- Measure activity within cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ centred around lepton candidate
  - $E_T^{\mathrm{cone}\Delta\mathrm{R}=0.2} = \sum |E_T|$
  - $p_T^{\mathrm{cone}\Delta\mathrm{R}=0.3} = \sum |p_T|$

Jets

- Anti-k_T $R = 0.4$ Topological cluster
- Count jet if $p_T > 30$ GeV/c and $|\eta| < 2.5$

Event

- Exactly two leptons of opposite charge
- Data Triggers : Muon $p_T > 18$ GeV/c or Electron $E_T > 22$ GeV
- Integrated luminosity 4.6 fb^{-1}

Fiducial region

- 1 electron $E_T > 25$ GeV, $|\eta| < 2.47$ (veto $1.37 < |\eta| < 1.52$)
- 1 muon $p_T > 20$ GeV, $|\eta| < 2.5$

Fake and non-prompt background

Main contributions

- Jets faking leptons
- Electrons from conversions
- Non-prompt muons from heavy flavor decays

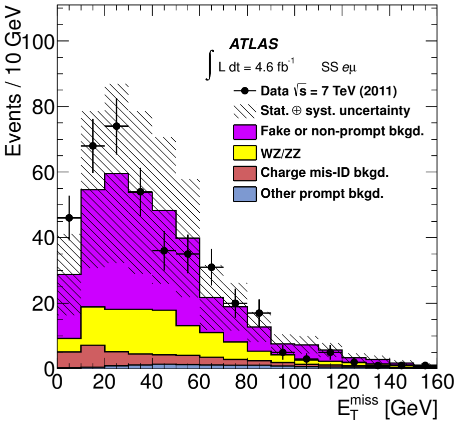
Data driven estimate

- Relax isolation and ID criteria ("Loose")
- Measure efficiencies for true and fake "Loose" leptons to pass "Tight" criteria
- Input into matrix method to extract background estimate

Cross-checks

- Check efficiencies in single lepton (W+jets) data
- Closure test of the matrix method in simulated samples
- Investigate same-sign charge control region

SAME SIGN CONTROL REGION



Likelihood fit and cross-sections

- Binned likelihood fit to the $E_{\mathrm{T}}^{\mathrm{miss}}$ vs N_{jets} phase space to determine signal yields N_{fit}.

Fiducial cross section

$$\sigma_{\mathrm{fiducial}}(pp \to X) = \frac{N_{\mathrm{fit}}}{\mathcal{C} \cdot \mathcal{L}}$$

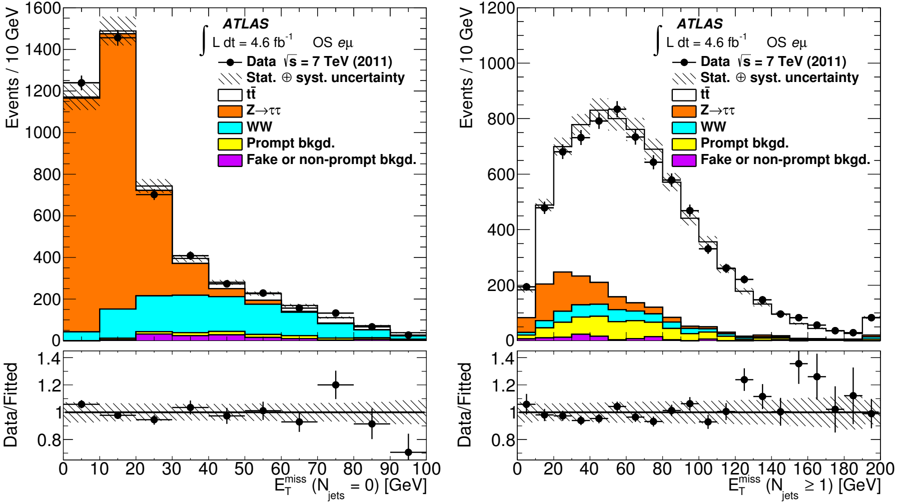
Total cross section

$$\sigma_{\mathrm{tot}}(pp \to X) = \frac{N_{\mathrm{fit}}}{\mathcal{A} \cdot \mathcal{B} \cdot \mathcal{C} \cdot \mathcal{L}}$$

- $\mathcal{C}$ is the ratio of the number of events passing the full event selection to the number of events in the fiducial region
- $\mathcal{A}$ is the kinematic and geometric acceptance of the fiducial region as a fraction of the complete phase space
- $\mathcal{B}$ is the branching fraction for $X \to e\mu$ + anything
- $\mathcal{L}$ is the integrated luminosity.

Fit results

- $N_{\mathrm{jets}} = 0, \geq 1$, where jets with $p_T > 30$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}}$ (20 bins, 0 to 200^+ GeV, with last bin also containing overflow, $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV)
- Fit region 2×20 bins



Summary of main systematic uncertainties

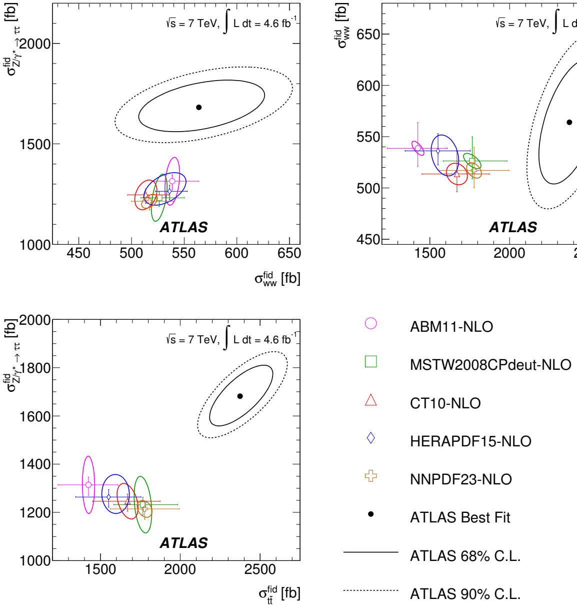
Source	Systematic Uncertainties (%)								
	$t\bar{t}$			WW			$Z/\gamma^* \to \tau\tau$		
	$\mathcal{C}$	$\mathcal{AC}$	Shape	$\mathcal{C}$	$\mathcal{AC}$	Shape	$\mathcal{C}$	$\mathcal{AC}$	Shape
ISR/FSR+Scale	± 1.1	± 0.4	$+1.0(-1.5)$	± 1.0	± 0.8	$+4.7(-3.5)$	± 1.1	± 0.4	$+0.7(-1.0)$
Generator	± 0.7	± 0.8	$+0.2(-0.0)$	± 0.6	± 0.5	$+4.5(-0.4)$			$+0.0(-0.7)$
Parton Shower	± 0.9	± 0.6	$+0.0(-0.5)$	± 0.5	± 1.0	$+3.5(-0.6)$	± 1.8	± 3.3	$+0.5(-0.6)$
PDF	± 0.6	± 1.7	± 0.5	± 0.1	± 0.7	± 1.6	± 0.2	± 1.3	± 0.8
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft terms	± 0.0		$+0.4(-0.2)$	± 0.0		$+8.1(-9.9)$	± 0.0		$+2.3(-0.2)$
$E_{\mathrm{T}}^{\mathrm{miss}}$ pile-up	± 0.0		$+0.1(-0.1)$	± 0.0		$+3.7(-4.5)$	± 0.0		$+1.0(-1.7)$
e reco., ID, isol.	± 3.2		$+0.0(-0.1)$	± 3.2		$+0.3(-0.3)$	± 3.3		$+0.0(-0.8)$
μ reconstruction	± 0.8		$+0.0(-0.0)$	± 0.8		$+0.0(-0.0)$	± 0.8		$+0.0(-0.0)$
Jet energy scale	± 0.8		$+1.4(-1.4)$	± 0.6		$+0.5(-4.8)$	± 0.5		$+1.4(-3.1)$
Jet E resolution	± 0.2		$+0.3(-0.0)$	± 0.2		$+0.0(-2.6)$	± 0.2		$+0.0(-0.1)$
JVF	± 0.8		$+0.1(-0.0)$	± 0.3		$+0.0(-1.7)$	± 0.2		$+0.0(-0.3)$
	$t\bar{t}$			WW			$Z/\gamma^* \to \tau\tau$		
Fake or Non-P	± 0.8			± 5.6			± 0.7		
Luminosity	± 1.8			± 1.8			± 1.8		
Beam energy	± 1.8			± 1.0			± 0.8		

- Experimental uncertainties on electron reco.,ID, isol. are largest on $t\bar{t}$ and $Z/\gamma^* \to \tau\tau$.
- $E_{\mathrm{T}}^{\mathrm{miss}}$ soft terms and fakes and non-prompt are dominant uncertainties on WW
- Pile-up refers to modeling of additional pp interactions in the same and neighboring bunch crossing
- JVF (Jet Vertex fraction) is defined as the ratio of the sum of the p_T of charged particle tracks that are associated with both the jet and the primary vertex, to the sum of the p_T of all tracks belonging to the jet

Cross-section results

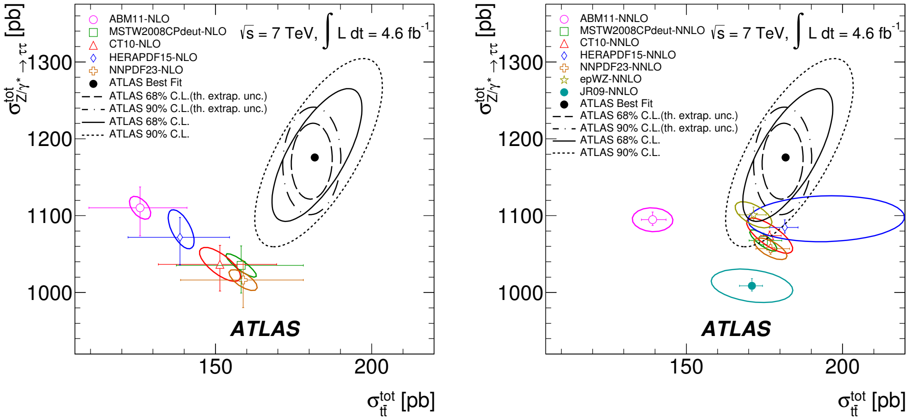
Process	$t\bar{t}$	WW	$Z/\gamma^* \to \tau\tau$
Fitted Yield $N_{\rm fit}$	6049	1479	3844
$\mathcal{C}$	0.482	0.505	0.496
$\mathcal{AC}$	0.224	0.197	0.0115
Branching Ratio B	0.0324	0.0324	0.0621
$\sigma_{\rm fiducial}$ [fb]	2730	638	1690
Statistical	1.5%	5.0%	2.0%
Systematic	5.1%	$+13.7(-14.9)$%	$+5.5(-7.0)$%
$\sigma_{\rm tot}$ [pb]	181.2	53.3	1174
Statistical	1.5%	5.0%	2.1%
Systematic	$+5.4(-5.3)$%	$+13.8(-14.9)$%	$+6.1(-7.5)$%
Luminosity	1.8%	1.8%	1.8%
LHC beam energy	1.8%	1.0%	0.8%

- $\mathcal{C}$ consistent across signal processes
- low $\mathcal{AC}$ on $Z/\gamma^* \to \tau\tau$ reflects high E_T requirements on leptons
- Systematic uncertainties dominate
- Overall uncertainties are smaller for fiducial cross-sections



- Cross-sections calculated using a specific PDF with error bars depicting the uncertainty due to the choice of renormalization and factorization scales, and contour represents intra-PDF uncertainty
- NLO predictions underestimate $Z/\gamma^* \rightarrow \tau\tau$ versus $t\bar{t}$, irrespective of the PDF model.
- *WW* fiducial measurement is consistent with predictions from each PDF model considered.

$Z/\gamma^* \to \tau\tau$ and $t\bar{t}$ total cross-sections (NLO & NNLO)



- Good overlap with most of the NNLO theoretical predictions and corresponding PDF sets.
- Difference in the uncertainties in theoretical predictions: in the NLO case scale uncertainties are dominant, while in the NNLO case the PDF model provides the dominant uncertainty.
- ABM11 employes lower value of α_s employed. At NNLO $\alpha_s = 0.113$, c.f. $\alpha_s = 0.117 - 0.118$ other PDF models.
- For JR09, the 5% difference in the $Z/\gamma^* \to \tau\tau$ cross-section is consistent with what is reported elsewhere (PhysRevD.80.114011).

Summary and conclusions

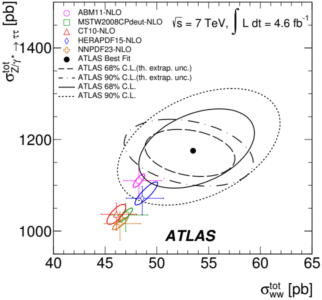
- First simultaneous extraction of the cross-sections for $t\bar{t}$, WW and $Z/\gamma^* \rightarrow \tau\tau$ processes at the LHC
- NLO predictions for $t\bar{t}$ and $Z/\gamma^* \rightarrow \tau\tau$ fiducial cross-sections underestimate measurements
- Comparisons of total cross-sections with NNLO calculations indicate that MSTW2008, CT10, HERAPDF, NNPDF, and epWZ describe the data well.
- Measurements are consistent with the previously published dedicated ATLAS cross-section measurements

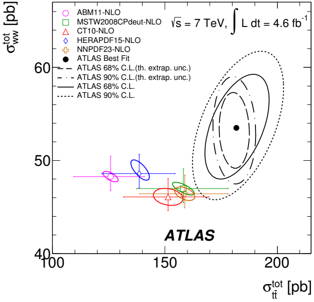
Backup slides

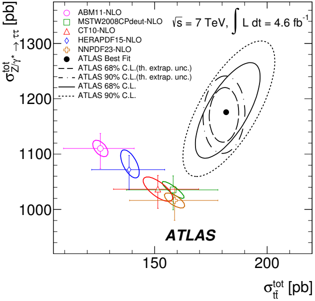
Comparison with other ATLAS measurements

Process	Source	σ_X^{tot} [pb]	Uncertainties Stat.	Syst.	Lumi.	Beam	Total	$\int \mathcal{L}\,\mathrm{d}t$ $[\mathrm{fb}^{-1}]$	Reference
$t\bar{t}$	Simultaneous	181	3	10	3	3	11	4.6	arXiv:1407.0573
	ATLAS Dedicated	177	7	15	8		18	0.7	JHEP05(2012)059
	ATLAS Dedicated	183	3	4	4	3	7	4.6	arXiv:1406.5375 [hep-ex]
	NNLO QCD	177					11		PhysRevLett.110.252004
WW	Simultaneous	53.3	2.7	7.7	1.0	0.5	8.5	4.6	arXiv:1407.0573
	ATLAS Dedicated	51.9	2.0	3.9	2.0		4.9	4.6	PhysRevD.87.112001
	NLO QCD	49.2					2.3		PhysRevD.80.054023
$Z/\gamma^* \to \tau\tau$	Simultaneous	1174	24	80	21	9	87	4.6	arXiv:1407.0573
	ATLAS Dedicated	1170	150	90	40		170	0.036	PhysRevD.84.112006
	NNLO QCD	1070					54		J.CPC.2011.06.008, EPJC 63 189-285

Total cross-sections (MCFM NLO predictions)







○ ABM11-NLO

□ MSTW2008CPdeut-NLO

△ CT10-NLO

◇ HERAPDF15-NLO

✣ NNPDF23-NLO

● ATLAS Best Fit

—— ATLAS 68% C.L.

······ ATLAS 90% C.L.

The matrix method for dileptons

- "Tight" leptons candidates (T)
- "Loose" and "Not Tight" lepton candidates (L)
- Decompose into events from two real prompt dileptons (R) and everything else (F)

$$\begin{pmatrix} w_{RR} \\ w_{RF} \\ w_{FR} \\ w_{FF} \end{pmatrix} = \mathcal{M}^{-1} \begin{pmatrix} \delta_{TT} \\ \delta_{TL} \\ \delta_{LT} \\ \delta_{LL} \end{pmatrix} \quad (1)$$

$$\mathcal{M}^{-1} = \frac{1}{(r_e - f_e)(r_\mu - f_\mu)} \begin{pmatrix} (1-f_e)(1-f_\mu) & -(1-f_e)\,f_\mu & -f_e\,(1-f_\mu) & f_e f_\mu \\ -(1-f_e)(1-r_\mu) & (1-f_e)\,r_\mu & f_e\,(1-r_\mu) & -f_e r_\mu \\ -(1-r_e)(1-f_\mu) & (1-r_e)\,f_\mu & r_e\,(1-f_\mu) & -r_e f_\mu \\ (1-r_e)(1-r_\mu) & -(1-r_e)\,r_\mu & -r_e\,(1-r_\mu) & r_e r_\mu \end{pmatrix} \quad (2)$$

$r(f)$ Probability of a true prompt ("fake") lepton to belong to the "Tight" category given it's in the "Loose" category

δ_{ij} equal to 1 or 0, depending on where an accepted event falls

$$w_{fakes}^{TT} = r_e f_\mu\, w_{RF} + f_e r_\mu\, w_{FR} + f_e f_\mu\, w_{FF} \quad (3)$$

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- Electrons from conversions
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Data driven estimate

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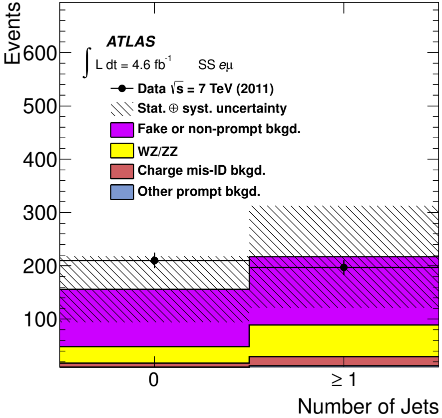
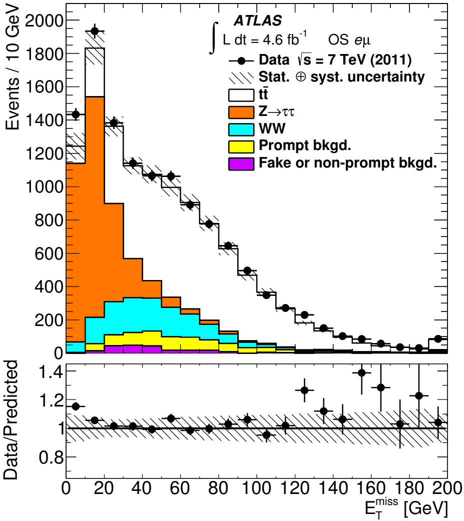


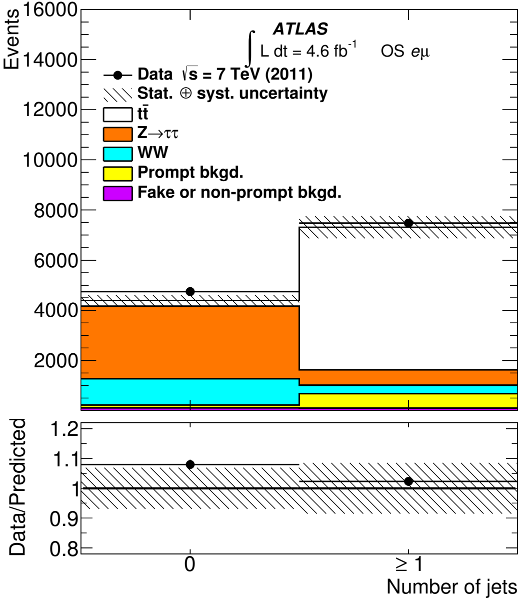
Expected yields and pre-fit MET distribution

Signal processes normalised to predictions from theory

Process	Total
$t\bar{t}$	5900 ± 500
WW	1400 ± 100
$Z \rightarrow \tau\tau$	3500 ± 250
Prompt bkgd.	680 ± 60
Fake or non-prompt bkgd.	210 ± 170
Predicted	11700 ± 600
Observed	12224



Pre-fit N_{jets} distribution



Template shape uncertainties

Monte Carlo "pseudo-experiments" are performed to estimate uncertainties on event yields due to systematic uncertainties affecting template shapes.

- For a given source of systematic uncertainty, S, sets of modified $E_{\mathrm{T}}^{\mathrm{miss}}$–$N_{\mathrm{jets}}$ signal and background templates are produced in which S is varied up and down by its expected uncertainty, while the template normalization remains fixed to its assumed standard model expectation.
- Pseudo-experiments are performed by fitting these modified templates to "pseudo-data" randomly drawn according to the nominal (i.e., no systematic effects applied) templates.
- Pseudo-data are constructed for each pseudo-experiment using the expected number of events, $\bar{N}_X$, and $E_{\mathrm{T}}^{\mathrm{miss}}$–$N_{\mathrm{jets}}$ shape for each process X. For each pseudo-experiment the following procedure is carried out.
- The expected number of events for process X is sampled from a Gaussian distribution of mean $\bar{N}_X$ and width determined by the uncertainty on $\bar{N}_X$. This number is then Poisson fluctuated to determine the number of events, N_X, for process X.
- The shape of process X in the $E_{\mathrm{T}}^{\mathrm{miss}}$–$N_{\mathrm{jets}}$ parameter space is then used to define a probability distribution function from which to sample the N_X events contributing to the pseudo-data for the pseudo-experiment.
- This is repeated for all processes to construct the pseudo-data in the $E_{\mathrm{T}}^{\mathrm{miss}}$–$N_{\mathrm{jets}}$ parameter space as the input to the pseudo-experiment.
- The pseudo-experiment is then performed by fitting the pseudo-data to the modified templates and extracting the number of events for each signal process, N_{sig}. This procedure is repeated one thousand times to obtain a well-defined distribution of N_{sig} values.
- The difference, ΔN_{sig}, between the mean value of this distribution and $\bar{N}_X$ is taken as the error due to template shape effects.
- To obtain the final template shape uncertainty, each positive $\Delta N_{\mathrm{sig}}/N_{\mathrm{sig}}$ value is added in quadrature to obtain the total positive error, and each negative value is added likewise to obtain the total negative error.