ATLAS: Vector-boson production plus N-jets

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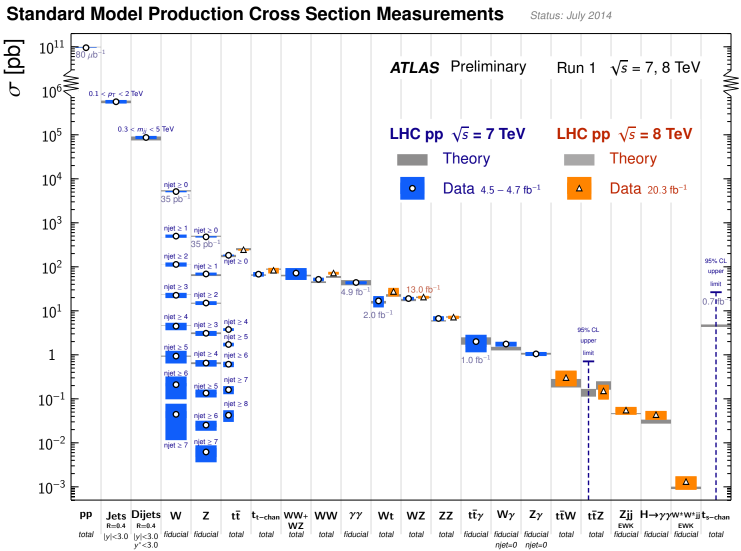
on behalf of the ATLAS Collaboration

Jet vetoes and multiplicity observables (JVMO 2014)

IPPP Durham, 16-18 July 2014

Summary of ATLAS measurements



Outline

Recent ATLAS results:

- $W+$jets cross section (ATLAS-CONF-2014-035) **NEW!**
- $Z+$jets cross section (JHEP 07 (2013) 032)
- $W+$jets/$Z+$jets cross section ratio (ATLAS-CONF-2014-034) **NEW!**
- $Z+b$-jets cross section (arXiv:1407.3643) **NEW!**
- $W+b$-jets cross section (JHEP 06 (2013) 084)
- $W+c$-jets cross section (JHEP 05 (2014) 068)

W+jets cross section

ATLAS-CONF-2014-035

For the production of a massive gauge boson accompanied by jets, jet transverse momenta up to 1 TeV are now, for the first time, accessible and allow access to a kinematic region where higher order EWK effects can become as important as those from higher-order pQCD corrections

W+jets cross section measurement at 7 TeV (4.6 fb^{-1})

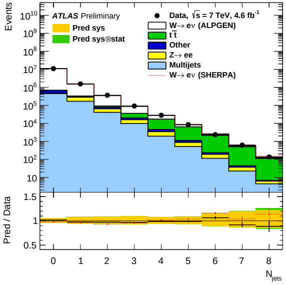
- Cross sections are shown as a function of the jet multiplicity up to 7 jets
- Differential cross sections are measured wrt the jet p_{T} and y for events with multiplicities up to 5 jets
- Differential cross sections are measured as a function of:
  - the scalar p_{T} sum of the jets (S_{T})
  - the scalar p_{T} sum of the jets, lepton and neutrino (H_{T})
  - the angular separation and invariant mass of the two leading jets in p_{T}
- The data are compared to predictions from BLACKHAT+SHERPA, HEJ, ALPGEN, SHERPA and MEPS@NLO

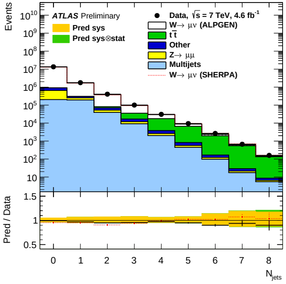
W+jets cross section

ATLAS-CONF-2014-035

Fiducial phase space at particle level:

- Lepton:
  - Electron channel: $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$)
  - Muon channel: $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.4$
  - Combined: $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$
- $W \to \ell\nu$ criteria:
  - Exactly one lepton
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV
  - $m_{\mathrm{T}} > 40$ GeV
- Jet criteria:
  - $p_{\mathrm{T}} > 30$ GeV
  - $|y| < 4.4$ GeV
  - Jet overlap removal: $\Delta R(\ell,\mathrm{jet}) > 0.5$





W+jets cross section

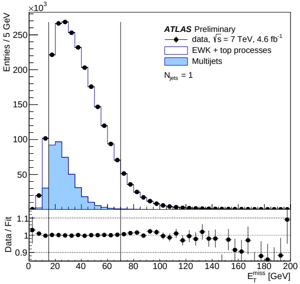
ATLAS-CONF-2014-035

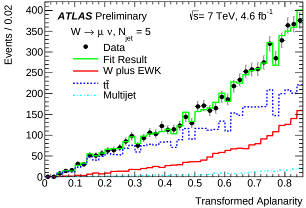
Background estimation:

- Multijet (data-driven):
  - Template from data events failing nominal lepton identification or isolation
  - Normalization from fit to E_T^{miss} distribution ($15 < E_T^{miss} < 80$ GeV)
- $t\bar{t}$ (data-driven):
  - Template from control region with ≥ 3 jets and ≥ 1 b-jet
  - Fit to the transposed aplanarity variable
- Simulated samples: single top, dibosons

Dominant systematic uncertainties:

- Jet energy scale (JES)
- At high jet multiplicities, $t\bar{t}$ background estimate



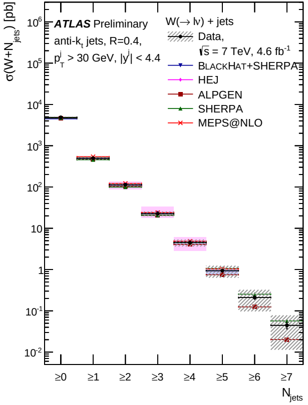


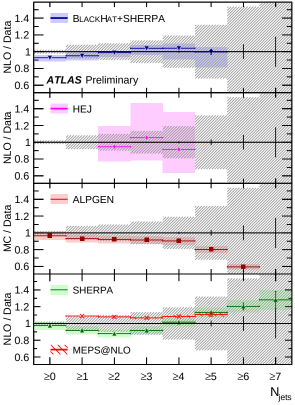
W+jets cross section

ATLAS-CONF-2014-035

Inclusive jet multiplicities:

- BLACKHAT+SHERPA is in good agreement for all jet multiplicities up to 5 jets
- ALPGEN and SHERPA predictions show different trends for jet multiplicities >4 jets, however both are in agreement within systematics
- MEPS@NLO describes the jet multiplicity with a similar level of agreement

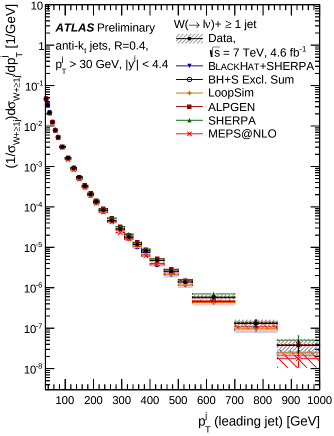


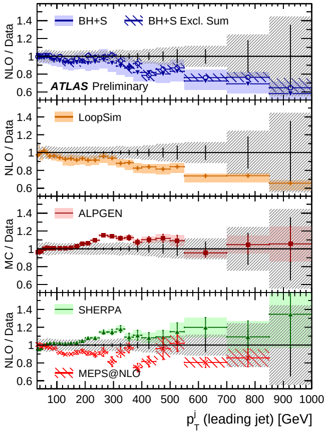


W+jets cross section

ATLAS-CONF-2014-035

- BLACKHAT+SHERPA, exclusive sums and LoopSim underestimate the data at high transverse momenta by $\sim 2\sigma$
- ALPGEN, SHERPA and MEPS@NLO are in fair agreement with the data

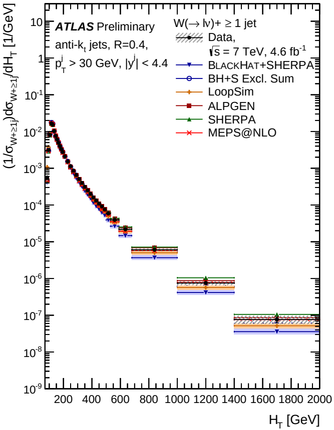


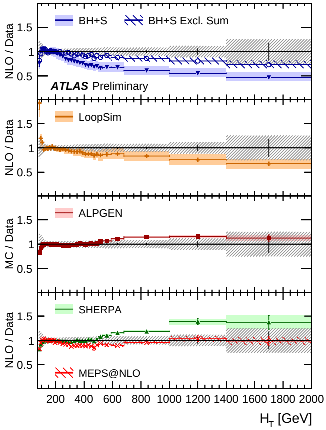


W+jets cross section

ATLAS-CONF-2014-035

- BLACKHAT+SHERPA is significantly lower than the data
- Better agreement by BLACKHAT+SHERPA exclusive sums and LoopSim
- MEPS@NLO agrees well with the data above 200 GeV





Z+jets cross section

JHEP 07 (2013) 032

Differential jet cross sections are accessible for large jet multiplicities and for energy regimes up to 1 TeV, which allows the modelling of the Z+jets process to be probed for typical phase-space regimes expected from new phenomena and from Higgs boson production, for example via vector-boson fusion (VBF)

Z+jets cross section measurement at 7 TeV (4.6 fb^{-1})

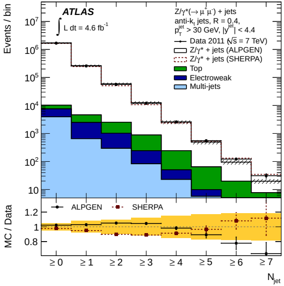
- Updates from the 2010 publication:
  - Extension to higher jet multiplicities and p_T, forward region
  - New variables: jet p_T ratio, H_T, S_T, Z p_T
  - Exclusive jet multiplicity ratios
  - Observables after VBF preselection, veto efficiencies
- Background estimation:
  - Data-driven multijet and semi-data-driven dileptonic $t\bar{t}$
  - Simulated samples: single top, dibosons

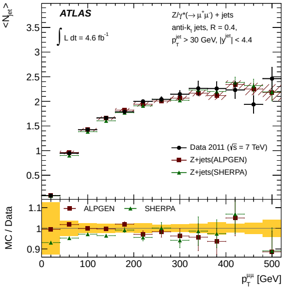
Z+jets cross section

JHEP 07 (2013) 032

Event selection:

- Lepton:
  - Electron channel: $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$)
  - Muon channel: $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.4$
- $Z \to \ell\ell$ criteria:
  - Exactly 2 OS leptons
  - $\Delta R(\ell,\ell) > 0.2$
  - $66 \leq m_{\ell\ell} \leq 116$ GeV
- Jet criteria:
  - $p_{\mathrm{T}} > 30$ GeV
  - $|y| < 4.4$ GeV
  - Jet overlap removal: $\Delta R(\ell,\mathrm{jet}) > 0.5$



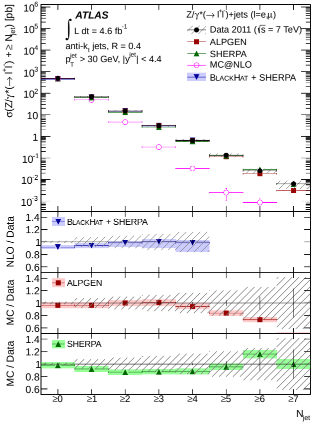


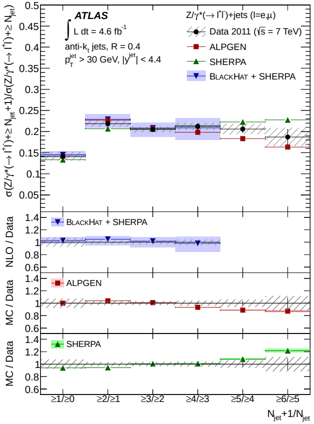
Z+jets cross section

JHEP 07 (2013) 032

Inclusive jet multiplicities and ratios $R_{\geq(n+1)/\geq n}$:

- Data are consistent with BLACKHAT+SHERPA, ALPGEN and SHERPA
- MC@NLO parton shower underestimates the observed rate for additional jet emission by a factor of 2, which leads to large offsets for higher jet multiplicities



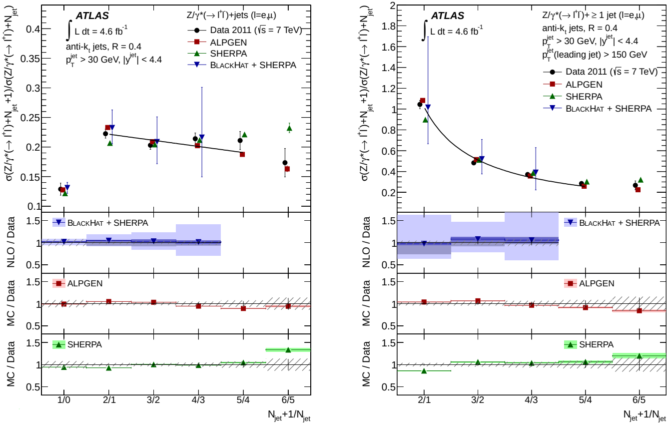


Z+jets cross section

JHEP 07 (2013) 032

Exclusive jet multiplicities at the LHC are expected to be described by means of two benchmark patterns (predicted in JHEP 10 (2012) 162 and PLB 224 (1989) 237):

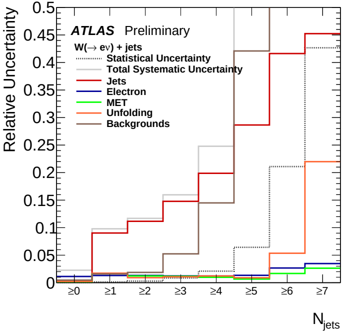
- 'Staircase scaling' with $R_{(n+1)/n}$ constant
- 'Poisson scaling' with $R_{(n+1)/n}$ inversely proportional to n (p_T^{jet}(leading jet) > 150 GeV)

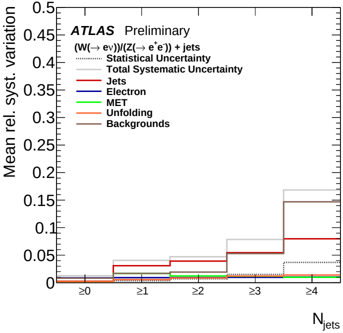


W+jets/Z+jets cross section ratio ATLAS-CONF-2014-034

W+jets/Z+jets cross section ratio (R_{jets}) at 7 TeV (4.6 fb^{-1})

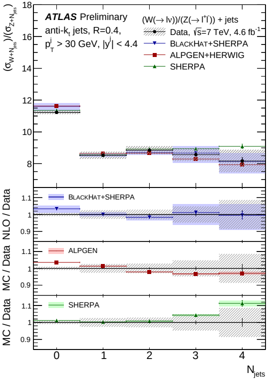
- Directly probes the difference between the kinematic distributions of the jet system recoiling against the W or Z bosons
- Is a more precise test of perturbative QCD (pQCD), since some experimental uncertainties and effects from non-perturbative processes, such as hadronization and multi-parton interactions, are greatly reduced in the ratio
- In the ratio, the systematic uncertainties that are positively correlated between the numerator and denominator cancel at the level of their correlations

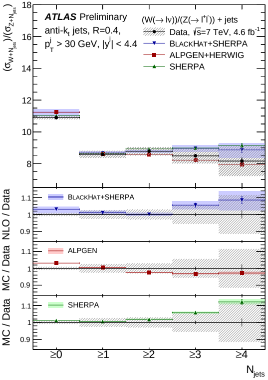




W+jets/Z+jets cross section ratio ATLAS-CONF-2014-034

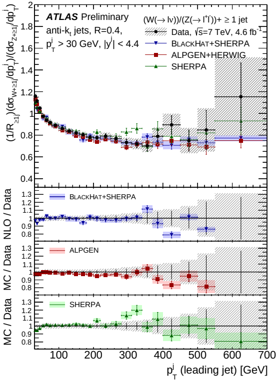
- BLACKHAT+SHERPA describes the data within theoretical uncertainties, although it does not include all contributions for events with at least 4 jets
- ALPGEN agrees with data, except in the 0 jet bin, where it deviates from the data by 2σ of the exp. uncertainties
- SHERPA is about 1σ of the exp. uncertainties greater than the measurement at high multiplicities, where the effects of hard QCD radiation are tested

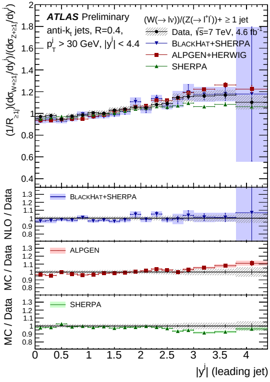




W+jets/Z+jets cross section ratio

- At low jet p_T ($<$ 200 GeV), the R_{jets} distribution falls as the leading jet p_T increases: different shapes in W+jets and Z+jets
- At low p_T, predictions present different trends from data, ALPGEN shows the best agreement
- Differences between predictions at high leading-jet rapidity due to the effects of the parton shower and PDF sets

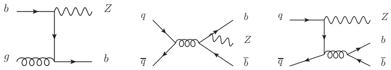




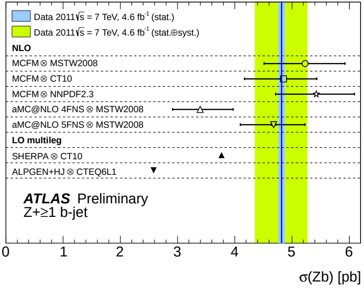
$Z + b$-jets cross section

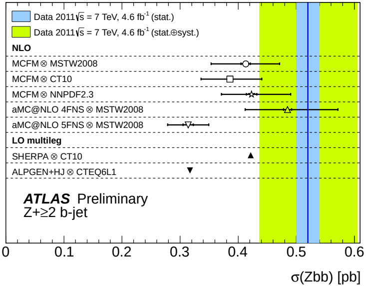
arXiv:1407.3643

$Z + b$-jets cross section at 7 TeV (4.6 fb^{-1})



- Heavy flavour production typically suffer from large theoretical uncertainties $\rightarrow$ $Z + b$-jets provide important experimental constraints to improve predictions
- Important bkg for ZH with $H \rightarrow b\bar{b}$
- Jet selection:
  - $p_{\mathrm{T}} > 20$ GeV, $|y| < 2.4$, b-tagging with 75% efficiency operating point
- Two schemes employed in pQCD:
  - **4-flavour number scheme (4FNS):** light quarks and gluons in initial state only, b-quark typically massive
  - **5-flavour number scheme (5FNS):** introduces initial state b-PDF, b-quark typically massless



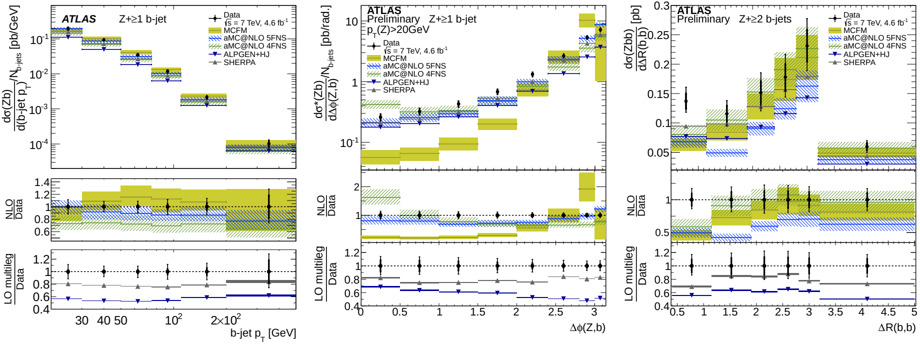


$Z + b$-jets cross section

arXiv:1407.3643

Measurement as a function of:

- b-jet p_T: good shape description by theoretical predictions, aMC@NLO 4FNS underestimates the data
- $\Delta\phi(Z,b)$: sensitive to additional radiation, bad description by MCFM at π, much better agreement by ALPGEN, SHERPA and aMC@NLO
- $\Delta R(b,b)$: sensitive to b-production mechanism, all predictions with reasonable description of the data except at low $\Delta R(b,b)$



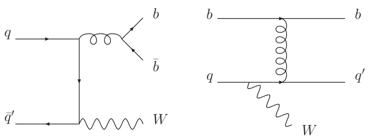
$W + b$-jets cross section

JHEP 06 (2013) 084

$W + b$-jets cross section at 7 TeV (4.6 fb^{-1})

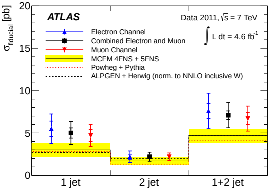
- LO Feynman diagrams:

$W + b\bar{b} + X$ $\qquad$ $W + b + X$

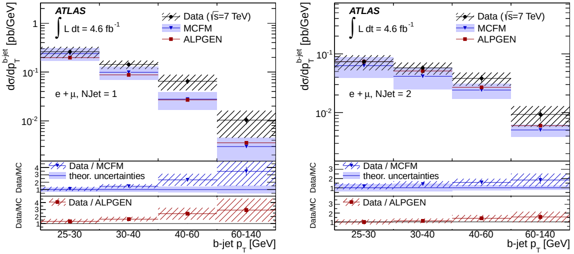


- Important bkg for ZH with $H \to b\bar{b}$

- $W + b$-jets cross section as a function of the jet multiplicity



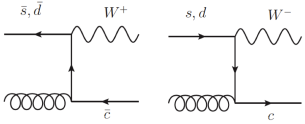
- $W + b$-jets cross section as a function of the $p_{\rm T}$ of the leading b-jet

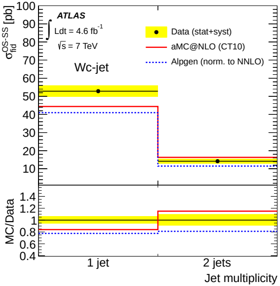


$W + c$-jets cross section

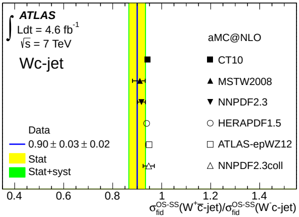
$W + c$-jets cross section at 7 TeV (4.6 fb^{-1})

- W boson in association with a single charm quark is produced at LO by the scattering of a gluon and a down-type quark (d, s, b)





- Directly sensitive to the s-quark distribution function in the proton at Q on the order of m_W
- Select signal as Opposite Sign − Same Sign (OS−SS) events where pair produced quarks ($Wb\bar{b}$, $Wc\bar{c}$) are subtracted automatically!



Other recent vector-boson production measurements

Hadronic W/Z cross section (arXiv:1407.0800)

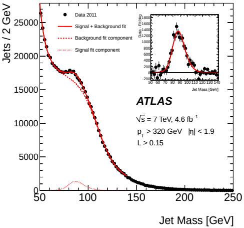
- Reconstruct hadronic decay product as a single merged jet in the final state
- Boost the jet constituents to the jet CoM frame:
  - QCD jets: isotropic topology
  - W/Z jets: back-to-back topology
- Build likelihood ratio discriminant with different jet shape variables: thrust, sphericity and aplanarity

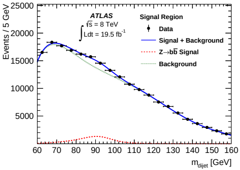
$Z \to b\bar{b}$ cross section (arXiv:1404.7042)

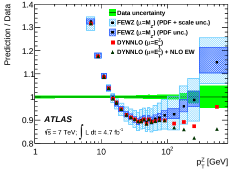
- Separate signal and control regions with a Neural Network single discriminant S_{NN} based on η_{dijet} and $\Delta\eta$(dijet, balancing jet)

Z/γ^* p_{T} distribution (arXiv:1406.3660)

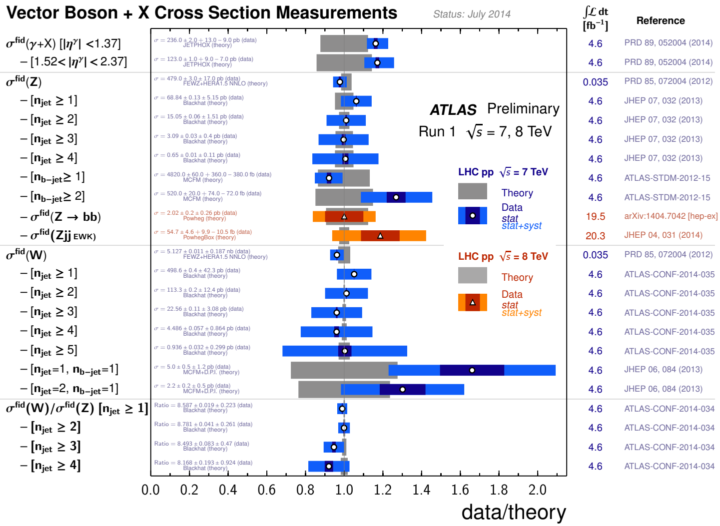
- Measurement used to tune the PYTHIA8 and POWHEG+PYTHIA8 generators







Data/theory ratio of Vector Boson+X measurements



Conclusions

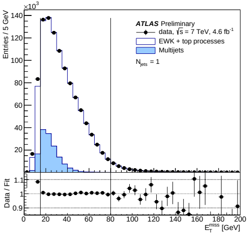
- Vector-boson production in association with light and heavy-flavor jets is one of the basic measurements of the LHC physics programme:
  - Essential for the understanding of basic physics
  - Test of the current theoretical predictions
  - Input to more refined generators and PDF sets
  - Background for new physics searches
- Extending the measured phase space with new results:
  - New variables, extending the reach in jet p_T, multiplicity
  - Exploring more complex final states: $W/Z+$heavy flavor jets
  - New measurements of cross-section ratios
- Theoretical predictions also advancing greatly:
  - Some "tuning" needed to perfectly match the data
  - Heavy flavor matching and modeling is a hot topic
- Stay tuned for new results at 8 TeV and 13/14 TeV soon!

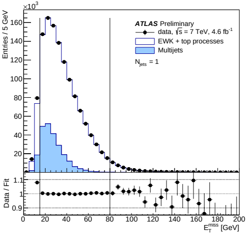
BACKUP

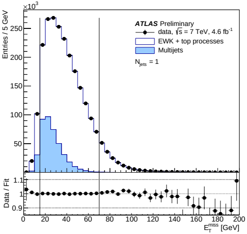
Backup: W+jets cross section

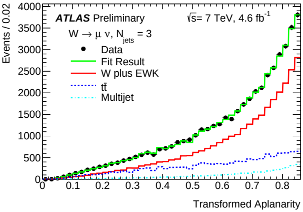
ATLAS-CONF-2014-035

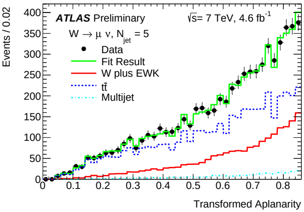
Template fits









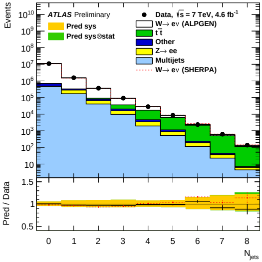


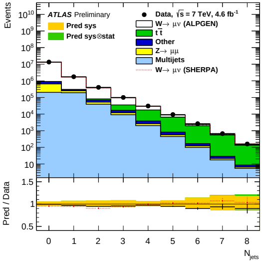
Backup: W+jets cross section

Breakdown for different jet multiplicities:

- At low multiplicities, very high signal purity
- At high multiplicities, large contribution from $t\bar{t}$

N_{jet}	0	1	2	3	4	5	6	7
	$W \to e\nu$							
$W \to e\nu$	94%	78%	74%	59%	37%	24%	14%	11%
Multijet	4%	11%	12%	11%	7%	6%	5%	4%
$t\bar{t}$	<1%	<1%	3%	18%	46%	63%	77%	81%
Single top	<1%	<1%	1%	2%	2%	2%	1%	1%
$W \to \tau\nu$, diboson	2%	3%	3%	3%	2%	1%	1%	1%
$Z \to ee$	<1%	8%	7%	7%	5%	4%	3%	3%
Total Predicted	11 100 000 ± 640 000	1 510 000 ± 99 000	352 000 ± 23 000	88 300 ± 5600	27 700 ± 1400	8420 ± 430	2510 ± 200	567 ± 61
Data Observed	10 878 398	1 548 000	361 957	91 212	28 076	8514	2358	618
	$W \to \mu\nu$							
$W \to \mu\nu$	93%	82%	79%	63%	40%	26%	17%	11%
Multijet	2%	11%	10%	10%	7%	5%	4%	3%
$t\bar{t}$	<1%	<1%	3%	20%	47%	65%	76%	84%
Single top	<1%	<1%	1%	2%	2%	2%	1%	1%
$W \to \tau\nu$, diboson	2%	3%	3%	3%	2%	1%	1%	<1%
$Z \to \mu\mu$	3%	4%	3%	3%	2%	1%	1%	1%
Total Predicted	13 300 000 ± 770 000	1 700 000 ± 100 000	383 000 ± 24 000	95 400 ± 5700	29 600 ± 1300	8860 ± 420	2370 ± 180	622 ± 66
Data Observed	13 414 400	1 758 239	403 146	99 749	30 400	9325	2637	663





Backup: W+jets cross section

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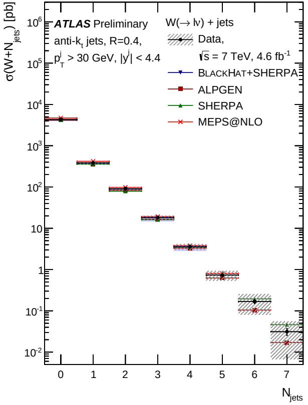
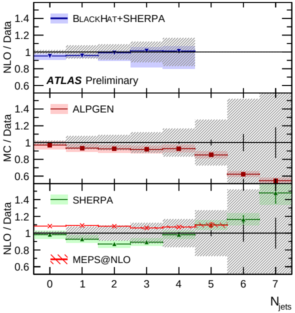
Exclusive jet multiplicities:

- BLACKHAT+SHERPA is in good agreement for all jet multiplicities up to 5 jets
- ALPGEN and SHERPA predictions show different trends for jet multiplicities > 4 jets, however both are in agreement within systematics
- MEPS@NLO describes the jet multiplicity with a similar level of agreement





Backup: W+jets cross section

ATLAS-CONF-2014-035

Summary of theoretical predictions

Program	Max. number of partons at approx. NNLO ($\alpha_s^{N_{\text{jets}}+2}$)	NLO ($\alpha_s^{N_{\text{jets}}+1}$)	LO ($\alpha_s^{N_{\text{jets}}}$)	Parton/Particle level	Distributions shown
LoopSim	1	2	3	parton level with corrections	Leading jet p_{T} and H_{T} for $W + \geq 1$ jet
BlackHat+SHERPA	–	5	6	parton level with corrections	All
BlackHat+SHERPA exclusive sums	1	2	3	parton level with corrections	Leading jet p_{T} and H_{T} for $W + \geq 1$ jet
HEJ	all orders, resummation			parton level	All for $W + \geq 2, 3, 4$ jets
MEPS@NLO	–	2	4	particle level	All
ALPGEN	–	–	5	particle level	All
SHERPA	–	–	4	particle level	All

Backup: Z+jets cross section

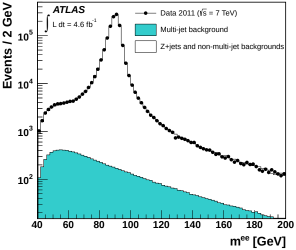
JHEP 07 (2013) 032

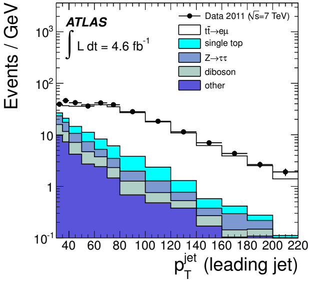
Background estimation:

- Multijet (data-driven):
  - Sample dominated by QCD obtained reverting electron identification, trigger, and sign requirement (electrons) or isolation cuts (muons)
  - Extract normalization by fitting di-lepton mass distribution using two template distributions: QCD from data, signal+other background distributions from MC
- Dileptonic $t\bar{t}$ (semi-data-driven):
  - Shape from $e^{\pm}\mu^{\mp}$ events in data
  - Normalization to $e^{\pm}e^{\pm}/\mu^{\pm}\mu^{\pm}$ final states derived from MC
- Simulated samples: single top, dibosons

Dominant systematic uncertainties:

- Jet energy scale (JES)





Backup: Z+jets cross section

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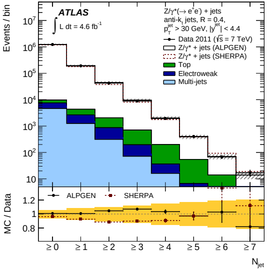
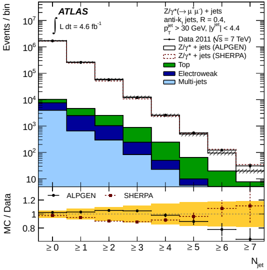
Breakdown for different jet multiplicities:

$Z\,(\rightarrow ee)$ channel								
	≥ 0 jets	≥ 1 jet	≥ 2 jets	≥ 3 jets	≥ 4 jets	≥ 5 jets	≥ 6 jets	≥ 7 jets
$Z\,(\rightarrow ee)$	1229000	188000	42300	8900	1810	339	56	9.2
$W \rightarrow e\nu$	450	135	36.4	9.5	0.52	< 0.5	< 0.5	< 0.5
$Z\,(\rightarrow \tau\tau)$	648	106	24.4	5.6	1.41	0.19	< 0.1	< 0.1
diboson	1830	1164	492	109	18.5	3.0	0.27	0.03
$t\bar{t}$, single top	2120	1670	1187	508	163	48	13.0	4.4
multi-jet	6400	1250	310	71	16.1	3.5	0.81	0.3
total expected	1239000	193000	44300	9600	2010	393	70	13.9
data ($4.6\,\mathrm{fb}^{-1}$)	1228767	191566	42358	8941	1941	404	68	17

$Z\,(\rightarrow \mu\mu)$ channel								
	≥ 0 jets	≥ 1 jet	≥ 2 jets	≥ 3 jets	≥ 4 jets	≥ 5 jets	≥ 6 jets	≥ 7 jets
$Z\,(\rightarrow \mu\mu)$	1710000	260000	56800	11700	2300	430	75	12.1
$W \rightarrow \mu\nu$	123	42.1	12.0	3.2	< 0.5	< 0.5	< 0.5	< 0.5
$Z\,(\rightarrow \tau\tau)$	1069	152	36.1	7.5	1.56	0.29	0.09	0.09
diboson	2440	1620	682	149	25.8	3.9	0.41	0.10
$t\bar{t}$, single top	2690	2130	1500	639	194	54	17.2	7.3
multi-jet	3900	650	295	83	23	5.7	2.1	0.18
total expected	1720000	265000	59400	12600	2540	490	95	19.8
data ($4.6\,\mathrm{fb}^{-1}$)	1678500	257169	56506	12019	2587	552	122	31





Backup: Z+jets cross section

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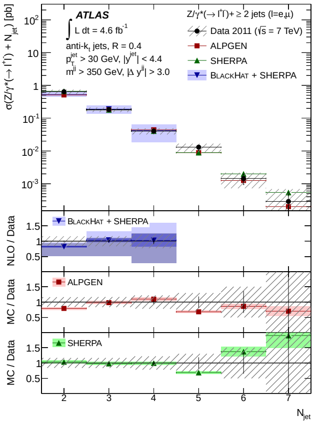
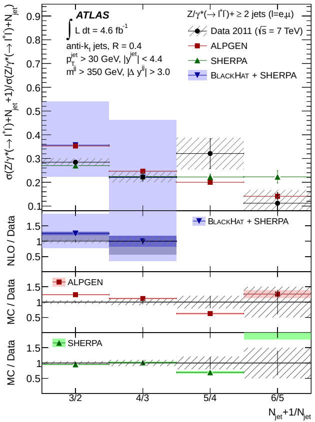
Scaling pattern also investigated for a VBF preselection (2 jets with $m_{jj} > 350$ GeV and $|\Delta y_{jj}| > 3.0$) $\rightarrow$ Exclusive jet multiplicities and ratios $R_{(n+1)/n}$:

- BLACKHAT+SHERPA prediction is consistent with data
- ALPGEN overestimates $R_{3/2}$
- SHERPA describes the multiplicity well





Backup: Z+jets cross section

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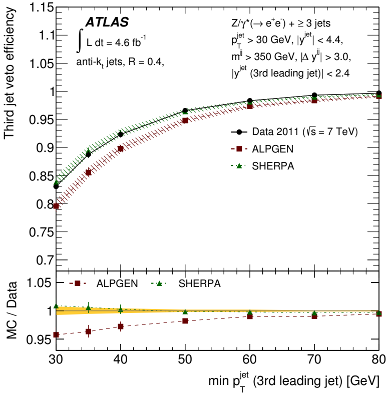
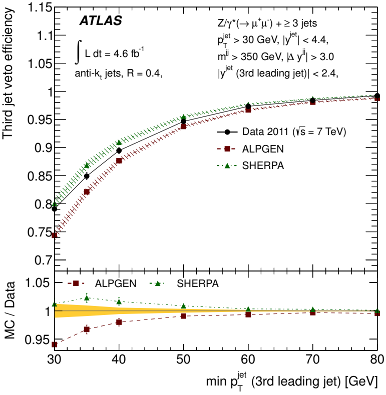
Fraction of events that pass a veto on a central ($|\eta| < 2.4$) third jet after the VBF preselection:

- ALPGEN predicts too small efficiency, the overestimate of $R_{3/2}$ in ALPGEN leads to an underestimate of the veto efficiency
- SHERPA has a good agreement with data





Backup: W+jets/Z+jets ratio

ATLAS-CONF-2014-034

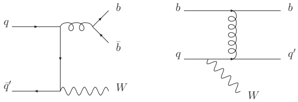
Particle-level phase space	
Lepton p_T and pseudorapidity η	$p_T > 25$ GeV, $\|\eta\| < 2.5$
W transverse mass and neutrino p_T	$m_T > 40$ GeV, $p_T > 25$ GeV
Z invariant mass and lepton-lepton angular separation	$66 < m_{\ell\ell} < 116$ GeV, $\Delta R_{\ell\ell} > 0.2$
Jet p_T, rapidity and jet-lepton angular separation	$p_T > 30$ GeV, $\|y\| < 4.4$, $\Delta R_{j\ell} > 0.5$

- In the ratio, the systematic uncertainties that are positively correlated between the numerator and denominator cancel at the level of their correlations
- The impact on the ratio of a given source of uncertainty was estimated by simultaneously applying the systematic variation due to this source to both W+jets and Z+jets events and performing the full measurement chain with the systematic variations applied
- The systematic uncertainties on the $t\bar{t}$ and multijet background estimates were considered to be uncorrelated
- The uncertainty on the integrated luminosity was treated as correlated

Backup: $W + b$-jets cross section

JHEP 06 (2013) 084

$W + b$-jets cross section at 7 TeV (4.6 fb^{-1})



- Particle-level phase space:

Lepton transverse momentum	$p_T^{\ell} > 25$ GeV
Lepton pseudorapidity	$\|\eta^{\ell}\| < 2.5$
Neutrino transverse momentum	$p_T^{\nu} > 25$ GeV
W transverse mass	$m_T > 60$ GeV
Jet transverse momentum	$p_T > 25$ GeV
Jet rapidity	$\|y\| < 2.1$
Jet multiplicity	$n \leq 2$
b-jet multiplicity	$n_b = 1$ or $n_b = 2$
Jet-lepton separation	$\Delta R(\ell, \text{jet}) > 0.5$

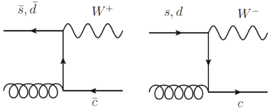
- The results are compared to the NLO predictions of MCFM and POWHEG, and to ALPGEN scaled by the NNLO normalization factor for the W cross section:
    - ALPGEN and POWHEG implement a **4-flavour number scheme (4FNS)**
    - MCFM includes a **5-flavour number scheme (5FNS)** to account for the presence of b-quarks in the IS originated from parton distribution functions

Backup: $W + c$-jets cross section

JHEP 05 (2014) 068

$W + c$-jets cross section at 7 TeV (4.6 fb^{-1})

- W boson in association with a single charm quark is produced at LO by the scattering of a gluon and a down-type quark (d, s, b)



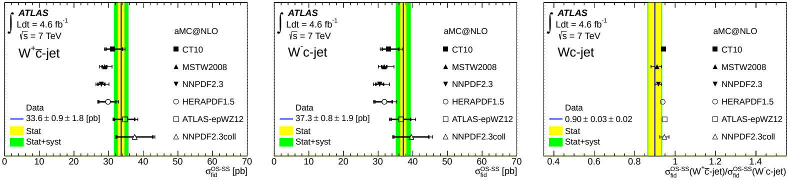
  $g\bar{s} \to W^+\bar{c}$ and $gs \to W^-c$ initial states dominant, while the reaction initiated by a d-quark contributes about 10% → Directly sensitive to the s-quark PDF!

- Event selection:
  - $W \to \ell\nu$:
    - Electron channel: $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$), $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV, $m_{\mathrm{T}} > 40$ GeV
    - Muon channel: $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.4$, $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV, $m_{\mathrm{T}} > 60$ GeV
  - c-jet:
    - Jet with $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$
    - Soft muon with $p_{\mathrm{T}} > 4$ GeV, $|\eta| < 2.5$
    - $\Delta R(\ell, \mathrm{jet}) < 0.5$

Backup: $W + c$-jets cross section

JHEP 05 (2014) 068

- Select signal as Opposite Sign − Same Sign (OS−SS) events where pair produced quarks ($Wb\bar{b}$, $Wc\bar{c}$) are subtracted automatically!



- Data and aMC@NLO comparison for different PDF sets:
  - Best agreement with ATLAS-epWZ12 and NNPDF2.3coll predictions
  - CT10, HERAPDF1.5 and MSTW2008 also are in agreement
  - NNPDF2.3 less favoured

- Ratio of strange to down sea quarks compared to HERA-PDF1.5 and ATLAS-epWZ12 → Data favour PDFs with symmetric light sea over the whole x range