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W/Z(+jets) Cross-Section Measurement with ATLAS

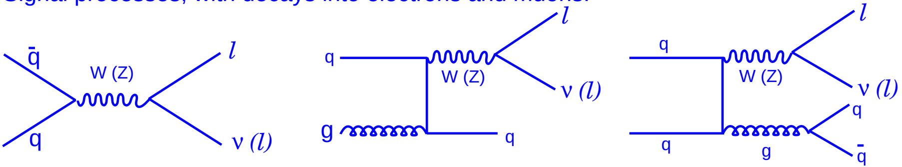
Presented results are based on the following two ATLAS CSC Notes:

- "Electroweak boson cross-section measurements with ATLAS" (M.Boonekamp, L.di Ciaccio)
- "W/Z+jets cross-sections at ATLAS" (J.Huston, B.Mellado)

"Physics at LHC" Seminar • 13.05.2008 • MPI, Munich

Motivation

Signal processes, with decays into electrons and muons:



Production of W and Z events at LHC allows for fundamental studies:

- Evaluation of the detector reconstruction performance (for Z decay products): can be assesed from the known Z-boson properties.
- Precision measurements (m_W, $\sin^2\theta_W$, lepton universality) as a test of QCD: theoretical uncertainties smaller than 1%, due to advanced higher order calculation.
- Constraints on the QCD and parton density functions (PDFs): differential momentum and rapidity distributions can be precisely measured, due to clean and fully reconstructed leptonic final states.

Study of W/Z with additional jets in the final state allows also for:

- Precision tests of the jet reconstruction algorithms.
- Tests of the Monte Carlo generators.
- Background estimation for many physics searches (Higgs boson, supersymmetry...).

Inclusive W/Z cross-section

Separate studies performed for four final states:

- $W \to e\nu$
- $W \to \mu\nu$
- $Z \to e^+e^-$
- $Z \to \mu^+\mu^-$

Signal and background processes

Monte Carlo data samples (full detector simulation):

Process	Generator	Cross-section [pb]	Available statistics [pb^{-1}]
Signal processes:			
$W \to e\nu$ ($\mu\nu$)	Pythia	20510 (20510)	11 (13)
$Z \to e^+e^-$ ($\mu^+\mu^-$)	Pythia	2015 (2015)	230 (249)
Background processes:			
QCD Jets	Pythia	$2333 \cdot 10^6$	0.02
$b\bar{b} \to \mu + X$	Pythia	$766 \cdot 10^6$	0.67
$b\bar{b} \to \mu\mu + X$	Pythia	$25 \cdot 10^6$	35
$W \to \tau\nu$	Pythia	20510	8
$Z \to \tau\tau$	Pythia	2015	129
$t\bar{t}$	MC@NLO	833	850
WW, ZZ, WZ	MC@NLO, Herwig	1275, 14.8, 27.0	15608, 2922, 6141

- All studies optimized for an integrated luminosity of 50 pb^{-1}.
- Cross-sections:
  W/Z normalized to NNLO prediction, $t\bar{t}$ at NLO, multijets at LO.

Cross-section measurement

Number of events N, passing all event selection criteria is given as:

$$N = \mathcal{L} \cdot \sigma \cdot A \cdot \epsilon + B, \text{ with}$$

$\mathcal{L}$ - integrated luminosity,
σ - signal cross-section,
A - signal acceptance (due to kinematic and angular cuts),
ϵ - signal reconstruction efficiency,
B - number of observed background events.

Thus,

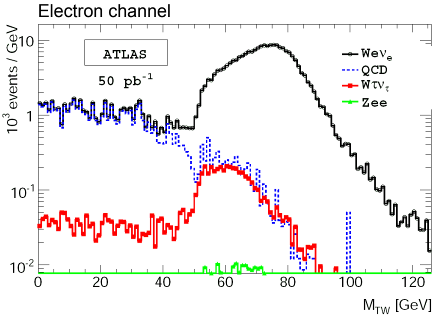
$$\sigma = \frac{N - B}{\mathcal{L} \cdot A \cdot \epsilon}, \quad \text{and} \quad \frac{\delta\sigma}{\sigma} = \frac{\delta N \oplus \delta B}{N - B} \oplus \frac{\delta\mathcal{L}}{\mathcal{L}} \oplus \frac{\delta A}{A} \oplus \frac{\delta\epsilon}{\epsilon}.$$

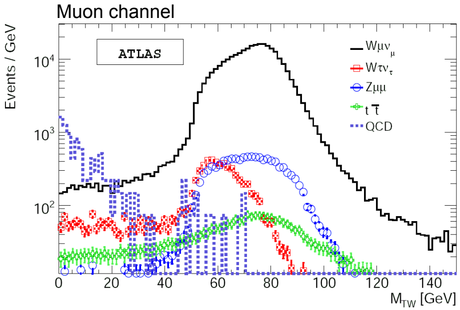
δN - purely statistical origin, $\delta N/N \sim 1/\sqrt{\mathcal{L}}$.
$\delta B, \delta A, \delta\epsilon$ - of both theoretical and experimental origin;
considered as systematic uncertainties,
can be constrained using auxiliary measurements from data.
$\delta\mathcal{L}$ - given externally, decreases with improved understanding of LHC.

$W \to (e\nu,\ \mu\nu)$ event selection - measuring N_W

- Single-lepton trigger (threshold at $p_T >$20 GeV): `e20` , `mu20`
- Exactly one reconstructed lepton with $|\eta| <$2.5 and $p_T >$25 GeV: `medium electron outside` $1.37 < |\eta| < 1.52$, `isolated muon`
- Cut on the transverse missing energy: $E_T^{miss} >$25 GeV.
- Cut on the transverse mass of the (ℓ, ν)-system: $M_T >$40 GeV.

Transverse mass distribution after all selection criteria:





$W \to (e\nu,\ \mu\nu)$ background estimation - measuring B_W

Dominant background for $W \to e\nu$: QCD multijets.

- Jet production and fragmentation at LHC are largely unknown (uncertainty of about a factor 3).
- QCD background control sample needs to be defined from data:
  - Selection using single photon trigger and photon identification. (Sample is free of the signal events.)
  - Resulting E_T^{miss}-distribution is same as in the signal.
  - Allows for estimation of the rejection after the cut on E_T^{miss}.
- Resulting bg. contribution to the total number of events: $(0 \pm 4)\%$.

Dominant background for $W \to \mu\nu$: $W \to \tau\nu$ and $Z \to \mu\mu$.

- Muons from QCD jets are rejected by the p_T and isolation cuts.
- Dominant backgrounds are theoretically well understood, can be esimated based on the simulation

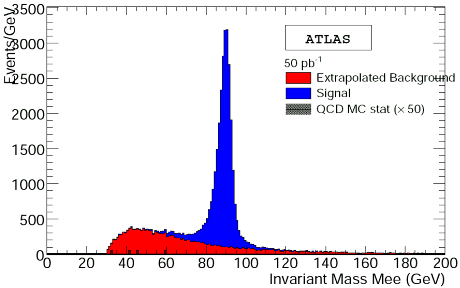
  (2-3% uncertainty from W and τ branching fractions and from PDF-uncertainties.)

$Z \to (e^+e^-, \ \mu^+\mu^-)$ event selection - measuring N_Z, B_Z

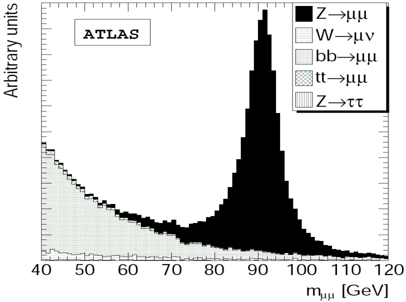
- Single-lepton trigger (threshold at p_T >10 GeV): `e10` , `mu10`
- At least two reconstructed leptons with $|\eta|$ <2.5 and p_T >20 GeV: `loose electrons outside` $1.37 < |\eta| < 1.52$, `isolated standalone muons`
- Isolated leptons of opposite charge.
- Di-lepton invariant mass: 80< M_{ee} <100 GeV, 70< $M_{\mu\mu}$ <110 GeV.

Di-lepton invariant mass distribution after event selection:

Electron channel



Muon channel



- Backgrounds (QCD for electrons; $b\bar{b}, t\bar{t}$ for muons): Estimated from the fit of (signal+background)-functions to data.

From event rates to cross-sections

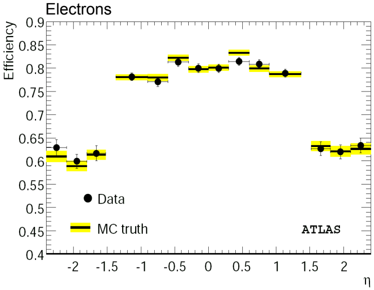
From the measured event rates N and B,
the cross-section can be determined if A and ϵ are known.

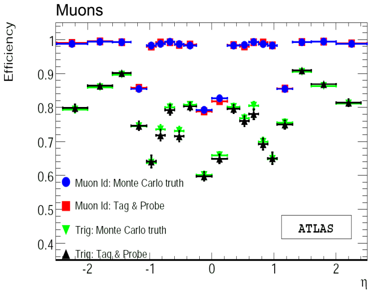
Acceptance-related theoretical systematic uncertainty:

- Comparing Pythia, Herwig and MC@NLO signal distributions.
- Differences originate from: initial/final state radiation, underlying event, parton density functions and matrix element corrections applied to parton showers.
- $\delta A/A = 2.3\%$ for W events, 1.1% for Z-events.

Uncertainty related to trigger and reconstruction efficiencies:

- Lepton trigger-, reconstruction- and isolation efficiencies can be determined from $Z \rightarrow \ell\ell$ data, using the "tag-and-probe" method.
- $\delta\epsilon/\epsilon = 2\%$ for electrons and muons.





Total W/Z Cross-Sections

Integrated luminosity of 50 pb^{-1}, $\delta\mathcal{L}/\mathcal{L}$=10%:

Process	$N(\times 10^4)$	$B(\times 10^4)$	$A \times \epsilon$	$\sigma^{measured}$ [pb]	$\sigma^{MC,truth}$ [pb]
$W \to e\nu$	22.67±0.04	0.61±0.92	0.215	20520±40±1060	20510
$W \to \mu\nu$	30.04±0.05	2.01±0.12	0.273	20530±40± 630	20510
$Z \to e^+e^-$	2.71±0.02	0.23±0.04	0.246	2016±16±72	2015
$Z \to \mu^+\mu^-$	2.57±0.02	0.010±0.002	0.254	2016±16±64	2015

Integrated luminosity of 1 fb^{-1}, $\delta\mathcal{L}/\mathcal{L}$=10%:

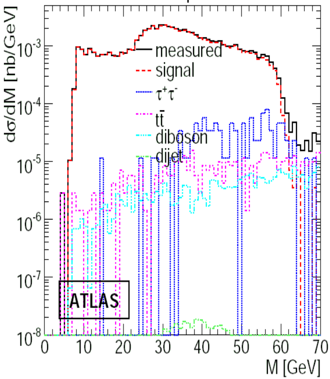
Process	$N(\times 10^5)$	$B(\times 10^5)$	$A \times \epsilon$	$\sigma^{measured}$ [pb]	$\sigma^{MC,truth}$ [pb]
$W \to e\nu$	45.34±0.02	1.22±0.41	0.215	20520± 9± 516	20510
$W \to \mu\nu$	60.08±0.02	4.02±0.05	0.273	20535± 7± 480	20510
$Z \to e^+e^-$	5.42±0.01	0.46±0.02	0.246	2016± 4±27	2015
$Z \to \mu^+\mu^-$	5.14±0.01	0.020±0.001	0.254	2016± 4±27	2015

- Measurement is dominated by the systematic error, event at low integrated luminosity. Ultimate precision is ~2%.
- W-channels dominated by the (QCD) background uncertainty.
- Z-channels have twice larger efficiency uncertainty (due to 2 leptons in the final state).

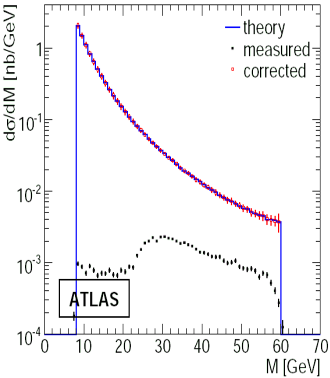
The acceptance uncertainty (theory uncertainty) can be constrained by the differential measurements:

- Drell-Yan invariant mass spectrum at low masses (below 60 GeV): allows for a better understanding/reduction of PDF uncertainties, since the shape is sensitive to the choice of PDF.

Event rates for each process



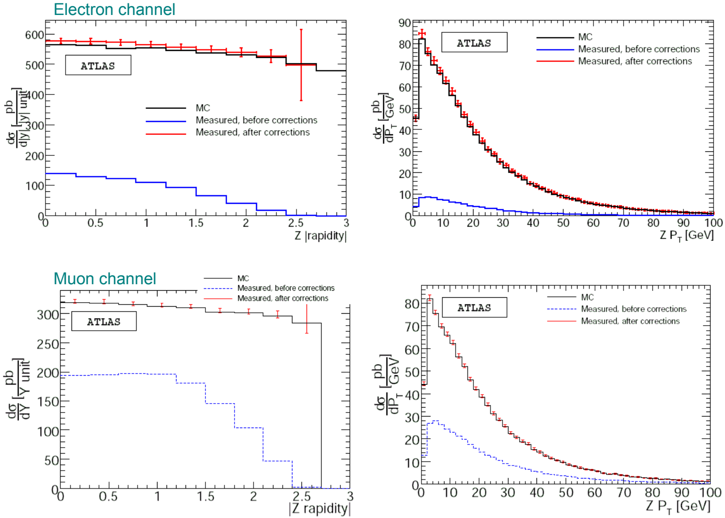
Overall event rate and cross-section



Differential Cross-Sections: p_T and rapidity

The acceptance uncertainty (theory uncertainty) can be constrained by the differential measurements:

- Similar is valid for the p_T and rapidity distributions of Z-events.



W/Z+Jets cross-section measurement

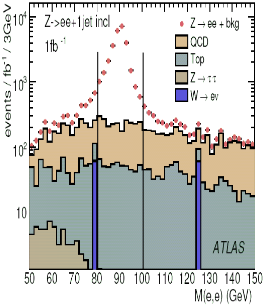
Separate studies performed for four final states
(Alpgen signal samples instead of Pythia):

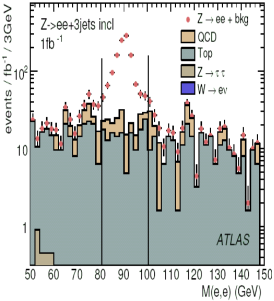
- $W \rightarrow e\nu + \geq$n Jets
- $W \rightarrow \mu\nu + \geq$n Jets
- $Z \rightarrow e^+e^- + \geq$n Jets
- $Z \rightarrow \mu^+\mu^- + \geq$n Jets (n=1,2,3,4)

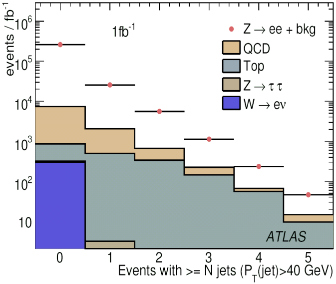
Event selection criteria are equivalent to those for inclusive searches.
Additionaly, one requires one or more jets with p_T >40 GeV.
Jet reconstruction performed using Cone-algorithm, cone size ΔR=0.4.

Unfolding of the measured event rates to obtain cross-section values requires a good knowledge of the jet reconstruction performance (in addition to the lepton performance).

All studies are performed for an integrated luminosity of 1 fb^{-1}.



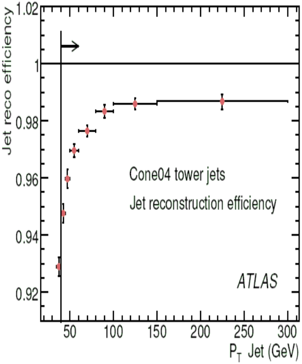


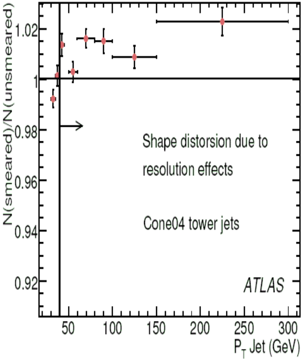


- Most important backgrounds are: *QCD jets*, $t\bar{t}$, $Z \rightarrow \tau\tau$.
  $t\bar{t}$ more important than QCD as the jet multiplicity increases.
- All backgrounds are estimated from the Monte Carlo samples.
  Data-driven background estimation still to be studied.
- Reconstructed event rates have to be unfolded into cross-sections, by taking into account lepton reconstruction efficiencies, as well as jet reconstruction efficiency and energy scale resolution.

Z+jets: Unfolding of detector effects

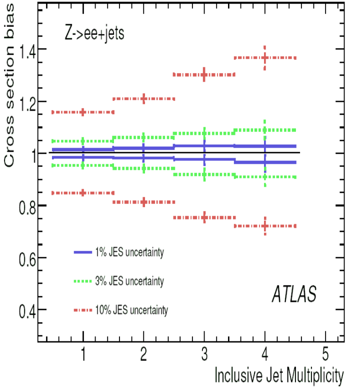
- Lepton trigger and reconstruction efficiencies determined by the "tag-and-probe" method.
- Jet reconstruction efficiency and resolution are derived based on the Monte Carlo truth (data-driven method to be studied):

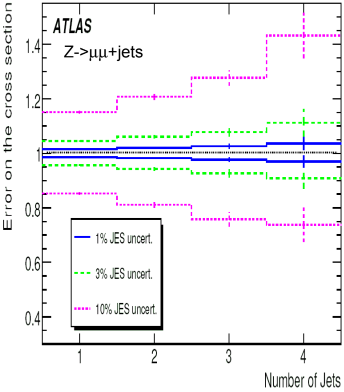




Z+jets: Cross-section mesurement

- Error on the cross-section measurement is dominated by the jet energy scale (JES):



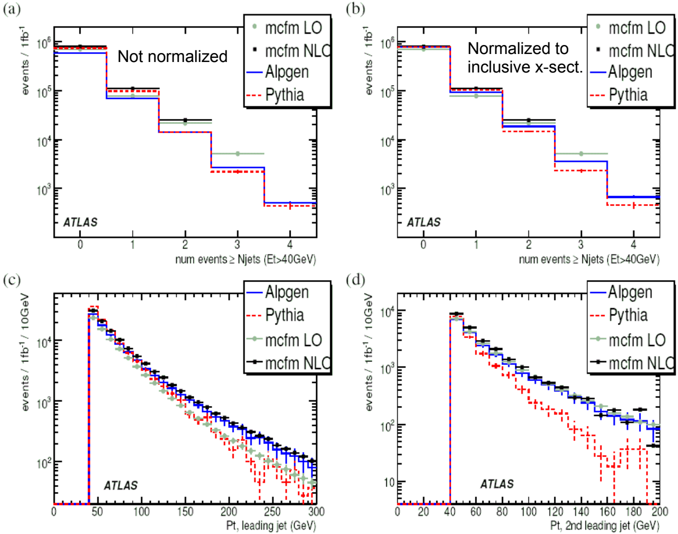


Difference between the LO and NLO cross-section predictions are on the order of 30%.

$\Longrightarrow$ distinction between LO and NLO is possible for $<3\%$ JES uncert.

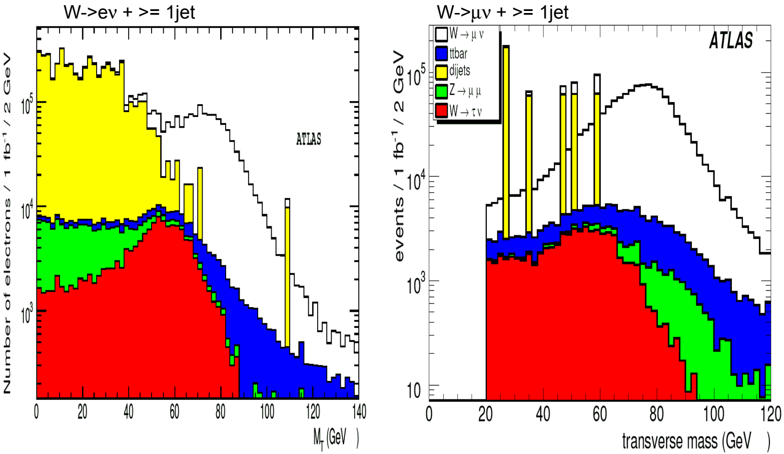
Z+jets: Comparison of event generators and MCFM

The measured $Z + jets$ cross-section can be compared to the theoretical calculations.
(LO and NLO calculations are provided by the MCFM package.)



$W \to (e\mu,\ \mu\nu) + jets$ event selection

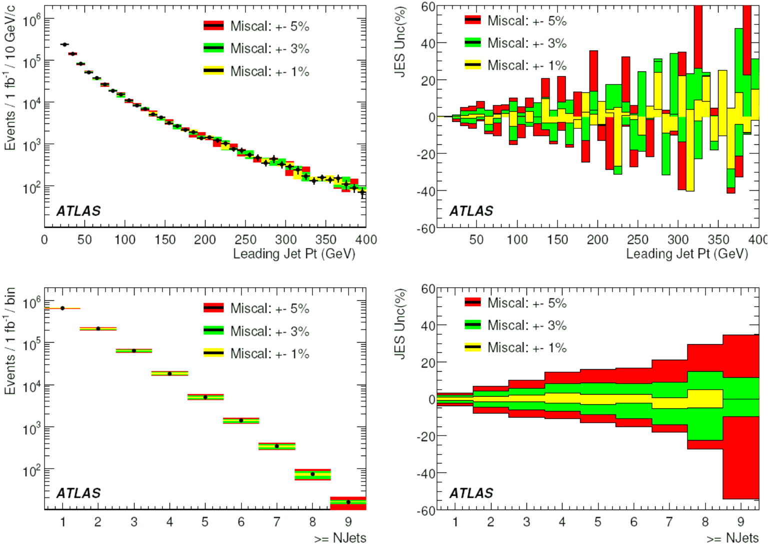
Similar selection criteria as for the inclusive analysis.



- QCD background needs to be estimated from the data, as described previously.

$W \to (e\mu,\ \mu\nu) + jets$: JES uncertainty

Dominant experimetal uncertainty comes from the jet reconstruction, will dominate over the theoretical (PDF) 3-5% uncertainties.



Summary

Study of W and Z production at LHC provides and important handle for the evaluation of the detector performance,
and allows for the precision tests of QCD predictions.

Most difficult background (and one of the most dominant ones) are the *QCD multijets*: contribution can be estimated only from real data.

Precision of the inclusive W/Z cross-section measurement is $\sim$2%, dominated by theoretical and experimental systematic uncertainties.

Precision of the W/Z+jets cross-sections measurement decreases with increasing the jet multiplicity (5-30%).
It is strongly dominated by the jet energy scale uncertainty:
JES uncertainty below 3% is needed for a reliable comparison of measurements and theoretical predictions.