Electroweak probes in heavy-ion collisions at the LHC with ATLAS

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Outline

Introduction
  Physics Motivation.
  The ATLAS Detector.
  Centrality in Pb+Pb and p+Pb collisions.

Measurements on vector bosons
  in p+Pb collisions
    Z bosons.  ATLAS-CONF-2014-020

  in Pb+Pb collisions
    Inclusive photons.  ATLAS-CONF-2012-051, ATLAS-CONF-2014-026
    $\gamma$ + jets.  ATLAS-CONF-2012-121
    Z + jets.  ATLAS-CONF-2012-119
    W bosons.  ATLAS-CONF-2014-023
Motivation

Electroweak probes (\(\gamma, W, Z\)) are produced in hard processes before the quark-gluon plasma (QGP) is formed and provide additional ways to study partonic energy loss in heavy ion collisions;

they do not interact strongly with the medium and therefore can act as standard candles for strongly-interacting processes such as jet-quenching;

the QGP is transparent to leptons which are produced as decay products of weak bosons;

Electroweak boson production mechanism makes them sensitive to parton distribution functions (PDFs) and nuclear effects: difference between cross sections in heavy ion collisions and those involving free nucleons (EPS09);

\(p+Pb\) collisions offer the perfect tool to discern between initial and final-state effects.
The ATLAS detector

Inner Detector – Tracking $|\eta|<2.5$

Calorimetry – $|\eta|<4.9$

Muon Spectrometer - $|\eta|<2.7$
Centrality

\[ \text{PbPb} \]
\[ \text{total FCal } E_T \]

\[ \text{pPb} \]
\[ \text{FCal } E_T \text{ on Pb-going side} \]

\[ \text{ATLAS} \]
\[ \text{Pb+Pb } \backslash s_{NN}=2.76 \text{ TeV} \]

\[ \text{dN/dE}_T [\text{TeV}] \]

\[ 10^6 \]
\[ 10^5 \]
\[ 10^4 \]
\[ 10^3 \]
\[ 10^2 \]
\[ 10^1 \]
\[ 10^0 \]
\[ 10^{-1} \]

\[ 0 \]
\[ 0.5 \]
\[ 1.0 \]
\[ 1.5 \]
\[ 2.0 \]
\[ 2.5 \]
\[ 3.0 \]
\[ 3.5 \]
\[ 4.0 \]

\[ \text{FCAL } E_T [\text{TeV}] \]

\[ (40-100\%) \]
\[ (20-40\%) \]
\[ (10-20\%) \]
\[ (0-10\%) \]

\[ \text{peripheral collisions} \]
\[ \text{central collisions} \]

\[ \text{ATLAS Preliminary} \]
\[ p+Pb, \sqrt{s_{NN}} = 5.02 \text{ TeV} \]
\[ \int L \, dt = 27.8 \text{ nb}^{-1} \]

\[ \frac{1}{N_{\text{evt}}} \, \text{dN/d} \Sigma E_T^{Pb} \]

\[ 10^{-2} \]
\[ 10^{-3} \]
\[ 10^{-4} \]
\[ 10^{-5} \]
\[ 10^{-6} \]

\[ 0 \]
\[ 100 \]
\[ 200 \]

\[ \Sigma E_T^{Pb} [\text{GeV}] \]

\[ p \]
\[ 4 \text{ TeV} \]

\[ Pb \]
\[ 1.57 \text{ TeV} \]

\[ y^{CM} \approx 0.465 \]
\[ -y \]
\[ +y \]
$Z$ bosons in p+Pb

$E_T$ leading $> 20$ GeV
$-3.5 < y^Z < 4.0$
background $\sim 3\%$

$p_T$ leading $> 20$ GeV
$-2.5 < y^Z < 2.5$
background $\sim 2\%$

Good agreement between channels

Centrality calibrated based on FCal $E_T^{Pb}$ with models for collision geometry:
standard Glauber ($\Omega = 0$);
Glauber-Gribov ($\Omega = 0.55$, $\Omega = 1.01$).
**Z boson cross sections p+Pb**

|                  | $|y^Z| < 2.5$   | $-3.5 < y^Z < 4.0$ |
|------------------|----------------|-------------------|
| $Z \rightarrow \mu^+\mu^-$ | $122.1 \pm 3.4 \pm 6.2 \pm 4.2$ | N/A               |
| $Z \rightarrow e^+e^-$     | $122 \pm 3 \pm 13 \pm 4$     | $144 \pm 5 \pm 17 \pm 5$ |
| $Z \rightarrow \ell^+\ell^-$| $122.7 \pm 2.4 \pm 5.3 \pm 4.2$ | $144.1 \pm 4.9 \pm 8.3 \pm 4.9$ |
| Model             | $114.4$         | $136.8$           |

Combination is performed using Heraverager $\chi^2$ minimization in nuisance parameter formalism; All uncertainties and their correlations considered.

Shape is well described by the model.

ATLAS Preliminary p+Pb 2013, $L_{int} = 29$ nb$^{-1}$ \ $s_{NN} = 5.02$ TeV

$y^Z$ asymmetry observed in data; Significant excess at backward rapidity (in Pb-going direction)
Fully-corrected yields of prompt photons:
4 centrality intervals as a function of $p_T$ (22.1-280 GeV) in $|\eta|<1.37$ (central) and $1.52<|\eta|<2.37$ (forward);
tight selection, isolation cone radius $R_{\text{iso}} = 0.3$ and isolation energy of 6 GeV.
Ratios on Photon Spectra

Ratios to JETPHOX NLO pQCD

Run with \( R = 0.3 \) 6 GeV;
Configurations:
- \( pp(\text{unity}) \);
- \( Pb+Pb \) (with no nuclear modification)/\( pp \) (black line);
- \( Pb+Pb \) (with EPS09 nuclear modifications)/\( pp \) (blue area).

Combined scale and PDF uncertainty on the JETPHOX calculation is shown by the yellow area.

Compared to:
- \( pp \) (yellow area);
- \( Pb+Pb \) (black line);
- nPDF EPS09 (blue area).
Photon-jet $x_{j\gamma}$ distributions

$E_\gamma > 60$ GeV: 60-90 GeV, $|\eta|<1.3$
Jet: anti-$k_T$, $R=0.2, 0.3$, $p_T>25$ GeV, $|\eta|<2.1$

$\gamma$-jet separation $\Delta \varphi > 7\pi/8$ (back-to-back)

Shape and integral compatible with PYTHIA for peripheral collisions.
With increasing centrality shift towards smaller energy fraction $x_{j\gamma}$ and reduction of the integral.
$Z$ boson distributions in Pb+Pb

$E_T > 20$ GeV, $|\eta| < 2.5$
background ~5%

$p_T > 10$ GeV, $|\eta| < 2.5$
background ~1%

$p_T$ averaged over $|y| < 2.5$

Spectral shape is centrality independent

Consistent with PYTHIA simulations in p+p scaled to NNLO cross section $\propto <T_{AA}>$

Z - jet correlations

0-20 % centrality

ATLAS Preliminary
Pb+Pb $|s_{NN}| = 2.76$ TeV, $\mathcal{L}_{int}=0.15$ nb$^{-1}$

Anti-$k_T$, Jet $R=0.3$, $p_T^{Z}>25$, $p_T^j > 60$ GeV, $p_T^{jet}/p_T^{Z}>25/60$

- PyTHIA: Mean=0.82±0.01
- Pb+Pb: Mean=0.62±0.04±0.04

0-20% Centrality

R = 0.3

ATLAS-CONF-2012-119

# of Z+jets events (fully unfolded and normalized per Z boson)

Jets and Z bosons are produced back to back in azimuth

Agreement with PyTHIA prediction worsens when moving to central events

20-80 % centrality

ATLAS Preliminary
Pb+Pb $|s_{NN}| = 2.76$ TeV, $\mathcal{L}_{int}=0.15$ nb$^{-1}$

Anti-$k_T$, Jet $R=0.3$, $p_T^{Z}>25$, $p_T^j > 60$ GeV, $p_T^{jet}/p_T^{Z}>25/60$

- PyTHIA: Mean=0.82±0.01
- Pb+Pb: Mean=0.76±0.06±0.06

20-80% Centrality

R = 0.3

ATLAS-CONF-2012-119

# of Z+jets events (fully unfolded and normalized per Z boson)

Jets and Z bosons are produced back to back in azimuth

Agreement with PyTHIA prediction worsens when moving to central events

Saturday, July 5, 14
**Boson - jet correlations**

**Z’s-jets**

Extracted $\langle p_T^{jet}/p_T^{Z} \rangle$ relative to MC simulations with no energy loss (PYTHIA: Z+jet events).

Stronger suppression for more central collisions.

The blue points refer to 0-80% centrality, and therefore are not independent relative to the black points.

**Photons-jets**

Downward shift of $\langle x_{j\gamma} \rangle$ (jets more quenched).
$W^\pm$ in Pb+Pb

Main background contributions:
- heavy flavour decays in multi-jet events ('QCD background');
- electroweak processes: $Z \rightarrow l^+ + l^-$ events;
- W/Z decays to $\tau$ which decays into $e$ or $\mu$.

Fiducial kinematic region:
- $p_T \text{miss} > 25 \text{ GeV}$,
- $0 < |\eta_e| < 2.47$,
- having $p_T > 3 \text{ GeV}$

$P_{\text{miss}} = \sum_{i=1}^{ntrks} P_{\text{miss}}^i = -(p_1 + p_2 + ... p_{ntrks})$

$m_T = \sqrt{2p_T^\mu p_{\text{miss}}^\mu (1 - \cos \Delta \phi_{\mu, p_{\text{miss}}^\mu})}$

$m_T > 40 \text{ GeV}$
W± differential yields

The $\eta$-dependence of $W \rightarrow l \nu$ decays may be used to extract information pertaining to nuclear PDFs.

Centrality-integrated yields, with theoretical predictions from LO* and NLO PDF sets:

LO* uses the MRST PDF set;
NLO uses the CT10 PDF set, both with and without nuclear corrections (EPS09).

The charge asymmetry agrees with both LO* and NLO models;
No visible nuclear modifications.
Fiducial charge ratio less sensitive to LO*/NLO differences;

Yields independent of centrality for $W^\pm, W^+ W^-$, with $W^+ W^-$ ones almost identical;

Consistent with NLO predictions but not with LO*. 
Electroweak bosons acting as standard candles in QGP

Integrated boson yields show a clear scaling with number of binary collisions.
Summary

Z boson production measured in p+Pb collisions
  Centrality differential yield, rapidity differential and momentum differential cross sections presented. Significant asymmetry is observed in the rapidity differential cross section.

Boson (γ, Z, W±) measurements in HI collisions collected with ATLAS in 2011
  Centrality, pseudorapidity and pT dependence of γ production.
    First HI measurements at high pT in the forward region with forward/central ratios presented.
  Direct isolated γ inclusive in association with jets.
    Shape and integral compatible with PYTHIA for peripheral collisions.

Z bosons inclusive and in association with jets
  Z inclusive: spectral shape is centrality independent.
  Z+jets: agreement with PYTHIA prediction worsens when moving to central events.

W bosons inclusive
  Fiducial W+/W− as a function on <Npart> consistent with unity in each centrality class.
  Charge asymmetry as a function of |η| agrees with both LO* and NLO models with no visible nuclear modifications.

Rates of E-W bosons in Pb+Pb scale with the number of binary collisions
  Standard candle for color-charge interactions in a QCD medium.
Additional slides
Photon reconstruction in Pb+Pb

Photon production measurement is performed with a hermetic, longitudinally segmented calorimeter, which gives excellent spatial and energy resolution, and detailed information about the shower shape of each measured photon.

Underlying event removed in $\Delta \eta = 0.1$ regions from HI jet reconstruction

Photon clusters seeded using sliding window in 2nd calorimeter layer.

Photon identification is based on 9 shower shape variables

Second layer variables:
- Containment and width of showers

Hadronic leakage variables:
- Fraction of cluster $E_T$ in hadronic section

First layer variables:
- Rejects candidates with two showers ($\pi^0, \eta$)
Photon selection with shower shape variables in Pb+Pb

<table>
<thead>
<tr>
<th>Interval</th>
<th>$\Sigma E_T$ range</th>
<th>$\langle N_{\text{part}} \rangle$</th>
<th>$\delta(N_{\text{part}})/(N_{\text{part}})$</th>
<th>$\langle N_{\text{coll}} \rangle$</th>
<th>$\delta(N_{\text{coll}})/(N_{\text{coll}})$</th>
<th>$\langle T_{AA} \rangle$</th>
<th>$\delta(T_{AA})/(T_{AA})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>2.31-4 TeV</td>
<td>356</td>
<td>0.7%</td>
<td>1500</td>
<td>8%</td>
<td>23.4</td>
<td>3.0%</td>
</tr>
<tr>
<td>10-20%</td>
<td>1.57-2.31 TeV</td>
<td>261</td>
<td>1.4%</td>
<td>923</td>
<td>7%</td>
<td>15.1</td>
<td>3.1%</td>
</tr>
<tr>
<td>20-40%</td>
<td>0.66-1.57 TeV</td>
<td>158</td>
<td>2.5%</td>
<td>441</td>
<td>7%</td>
<td>6.88</td>
<td>5.2%</td>
</tr>
<tr>
<td>40-80%</td>
<td>0.044-0.66 TeV</td>
<td>45.9</td>
<td>6%</td>
<td>77.8</td>
<td>9%</td>
<td>1.22</td>
<td>9.4%</td>
</tr>
</tbody>
</table>

“Tight” selection - satisfies 9 shower shape selections per photon, tuned on photons in HI events

“Non-tight” selection - Background enhanced by selecting clusters that fail selections which usually reject having two distinct showers, or two merged showers
A multiparameter selection on a set of nine shower properties, coupled with an isolation criterion based on the energy deposited in the cone around a photon, gives measured purities ranging from 50% at low pT to greater than 90% at high pT.

\( E_{T,\text{iso}} \) is the transverse energy in the full depth of the calorimeter in a ring of \( R=0.3 \) around the photon direction, with photon removed

"Isolated": \( E_{T,\text{iso}}(R=0.3) < 6 \text{ GeV} \)

Simulated isolation distribution, normalized to data for \( E_{T,\text{iso}}<0 \), showing increasing fluctuations in central events

Non-tight photons from data, normalized for \( E_{T,\text{iso}}>8 \text{ GeV} \), showing how jets fill the tails in the isolation distributions
Direct photon spectra in Pb+Pb

Yields scaled by $<T_{AA}>$ and compared to JETPHOX predictions

Ratio: Data/JETPHOX $\approx 1$
**W boson channels combination**

\[ W \rightarrow \mu \nu \mu \]
\[ W \rightarrow e \nu_e \]

combined using:

\[ \bar{x} = \frac{1}{w} \sum_{l=\mu,e} w_l x_l \]
\[ w_l = \frac{1}{(\delta x_l^{unc})^2} \]
\[ w = \sum_{l=\mu,e} w_l \]

individual measurements from muon and electron channels, and weights associated with them and individual uncorrelated and correlated uncertainties

\[ \delta \bar{x}^{unc} = \frac{1}{\sqrt{w}} \]
\[ \delta \bar{x}^{cor} = \frac{1}{2} \sum_{l=\mu,e} \delta x_l^{cor} \]

- \( W^+ \rightarrow \mu^+ \nu_\mu: 5900 \pm 100 \text{ (stat)} \pm 86 \text{ (syst)} \)
- \( W^- \rightarrow \mu^- \nu_\mu: 5700 \pm 100 \text{ (stat)} \pm 83 \text{ (syst)} \)
- \( W^+ / W^- = 1.03 \pm 0.03 \text{ (stat)} \pm 0.02 \text{ (syst)} \) in the muon channel
- \( W^+ \rightarrow e^+ \nu_e: 5800 \pm 150 \text{ (stat)} \pm 91 \text{ (syst)} \)
- \( W^- \rightarrow e^- \nu_e: 5700 \pm 150 \text{ (stat)} \pm 110 \text{ (syst)} \)
- \( W^+ / W^- = 1.02 \pm 0.04 \text{ (stat)} \pm 0.01 \text{ (syst)} \) in the electron channel

- \( p_T^l > 25 \text{ GeV} \)
- \( p_T^{miss} > 25 \text{ GeV} \)
- \(|\eta^l| < 2.5 \)
- \( m_T > 40 \text{ GeV} \)
Table 1: Signal and background simulated event samples used in this analysis. $W \rightarrow \ell \nu_{\ell}$ events include all nucleon combinations, whereas background processes use only $pp$ simulations. The variable $p_T$ is the average $p_T$ of the two-outgoing partons involved in the hard-scattering process evaluated before modifications from initial- and final-state radiation.

<table>
<thead>
<tr>
<th>Physics process</th>
<th>Generator</th>
<th>PDF set</th>
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<tbody>
<tr>
<td>$W \rightarrow \mu \nu_{\mu}$</td>
<td>POWHEG+PYTHIA8</td>
<td>CT10</td>
</tr>
<tr>
<td>$W \rightarrow \mu \nu_{\mu}$</td>
<td>PYTHIA6</td>
<td>MRST LO*</td>
</tr>
<tr>
<td>$W \rightarrow e \nu_e$</td>
<td>POWHEG+PYTHIA8</td>
<td>CT10</td>
</tr>
<tr>
<td>Di-jet</td>
<td>PYTHIA6</td>
<td>MRST LO*</td>
</tr>
<tr>
<td>$17 &lt; p_T &lt; 140$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z \rightarrow \mu^+ \mu^-$</td>
<td>PYTHIA6</td>
<td>MRST LO*</td>
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<td>$W \rightarrow \tau \nu_{\tau} \rightarrow \mu \nu_{\mu} \nu_{\tau}$</td>
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