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

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Abstract

Measurements of vector boson production in lead-lead collisions provide essential control data for studies of jets and jet quenching in the quark gluon plasma. Because the electroweak bosons do not interact strongly in the plasma, measurements of their production rates can be predicted using standard high-energy event generators. In addition, the vector boson spectra are potentially sensitive to nuclear parton distribution functions. The ATLAS detector has proven to be an excellent apparatus in measurements involving photons, electrons and muons in the high occupancy environment produced in heavy-ion collisions. The experiment has recorded 158 µb⁻¹ of lead-lead and 29.85 nb⁻¹ of proton-lead data, both of which have similar integrated partonic luminosities. In this letter, measurements of γ, Z and W± production in lead-lead and proton-lead collisions are shown and compared to predicted rates from JETPHOX (for γ) and PYTHIA/POWHEG (for Z and W±).

Keywords: electroweak bosons, parton distribution functions, lepton charge asymmetry, lead-lead and proton-lead collisions

1. Introduction

Relativistic heavy ion collisions at the LHC are thought to create a strongly interacting matter composed of deconfined color charges well above the QCD critical temperature. At such temperatures, this strongly interacting matter is expected to take the form of a quark-gluon plasma (QGP) [1]. Hard scattering processes occurring in these ultrarelativistic heavy-ion collisions produce high transverse momentum partons that propagate through the medium and lose energy, resulting in the phenomenon of “jet quenching”. The experiments at the Relativistic Heavy Ion Collider (RHIC) have first observed partonic energy loss through measurements of hadrons resulting from the fragmentation of jets [2, 3, 4]. Measurements at the LHC have provided a more complete view of the effects of the quenching by using fully reconstructed jets [5, 6, 7, 8].

In this scenario, electroweak bosons (γ, Z, W±) provide additional ways to study partonic energy loss in the QGP. They do not interact strongly with the medium and therefore their production yields provide direct tests of scaling with a number of binary nucleon-nucleon collisions in the high multiplicity heavy-ion environment. In particular, their production is sensitive to modifications of the partonic structure of nucleons embedded in a nucleus, which are implemented as modifications [9, 10, 11] to the parton distribution functions (PDFs) measured in deep inelastic and proton-proton scattering experiments (“nPdfs”).

Electroweak boson production in proton-lead collisions also provide an excellent opportunity to test the nPDFs through the investigation of initial state effects in a system not expected to produce a hot dense QCD medium.

2. Experimental setup and data taking periods

The ATLAS detector is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle. The detector consists of four major sub-systems: the inner detector (ID), the electromagnetic calorimeter, the hadronic calorimeter and the muon spectrometer
(MS). A detailed description of the ATLAS detector can be found elsewhere [12]. The ID is immersed in a 2 T axial magnetic field and provides charged particle tracking in the range $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the vertex region and is surrounded by the silicon microstrip tracker and the transition radiation tracker. The calorimeters cover the range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and end-cap high-granularity lead liquid-argon calorimeters, with an additional thin liquid-argon presampler covering $|\eta| < 1.8$. The electromagnetic calorimeter is complemented by a hadronic calorimeter. Forward calorimeters (FCal) are located in the range $3.1 < |\eta| < 4.9$. On the inner face of the end-cap calorimeter cryostats, a minimum bias trigger scintillator (MBTS) $2.1 < |\eta| < 3.8$ is installed on each side of the detector. The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers that measure the deflection of muons in the magnetic field. The precision chambers cover the region $|\eta| < 2.7$ with three layers of monitored drift tubes (MDT), complemented by cathode strip chambers (CSC) in the innermost layer of the forward region. The muon trigger system covers the range $|\eta| < 2.4$ with resistive plate chambers in the barrel, and thin gap chambers in the end-cap regions. The zero degree calorimeters (ZDCs), covering $|\eta| > 8.3$ are primarily used in heavy ion collisions to measure the spectator neutrons from the colliding nuclei. The ATLAS detector also includes a multi-level trigger system [13]: level one (L1) and the software-based High Level Trigger (HLT), which is subdivided into the Level 2 (L2) trigger and Event Filter (EF). Muon and electron triggers are used to acquire the data used in the analyses described in this paper.

The production of prompt photons, $Z$ and $W^\pm$ bosons analyses use data collected at $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions in 2011 with an integrated luminosity of 0.15 $nb^{-1}$, except for the muon decay channel in the $W^\pm$ analysis, with 0.14 $nb^{-1}$). The sample of events used in the prompt photons analysis was collected using the first level calorimeter trigger. This is a hardware trigger which sums the electromagnetic energy in towers of size $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$. A sliding window of size 0.2 $\times$ 0.2 was used to find electromagnetic clusters by searching for local energy maxima and keeping only those clusters with energy in two adjacent cells exceeding a threshold of 16 GeV. In the $Z \rightarrow e^+e^-$ and $W \rightarrow e\nu$ analyses, electron candidates were triggered using a similar trigger as for the photons, but with a lower threshold of $E_T > 14$ GeV. In the $Z \rightarrow \mu^+\mu^-$ analysis, muon candidates were selected using all three trigger levels. The L1 muon trigger searched for patterns of hits in the trigger chambers consistent with muons. If a muon had $p_T$ exceeding 4 GeV, the event was accepted for further processing by the high-level trigger (HLT). The L1 muon algorithm also identified regions of interest (RoI) within the detector to be investigated by the HLT. In the HLT, the track parameters of each muon were recalculated by including the precision data from the MDT or CSC in the RoI defined by the previous trigger level. Muon candidates were reconstructed either solely from the MS or using combined data from the MS and ID. In addition to the events selected using the RoI-based muon trigger, the reconstruction was performed over the whole MS by the HLT to identify muons with $p_T > 10$ GeV. Besides the requirement on the minimum transverse momentum of 10 GeV, another which requires a muon in coincidence with a total event transverse energy measured in the calorimeter at $|\eta| > 8.3$ in the ZDCs. This maximises the efficiency for events across all centrality classes to be discussed in the next paragraph.

The 2011 Pb+Pb analyses rely on the FCal to define the event centrality on a event-by-event basis, using the scalar sum of transverse energy deposited in this calorimeter, calibrated at the electromagnetic energy scale in the pseudorapidity range $3.1 < |\eta| < 4.9$ [14]. Glauber model calculations [15] relate centrality to the mean number of participating nucleons in the collision, $\langle N_{part}\rangle$, and the mean number of inelastic nucleon-nucleon collisions, $\langle N_{coll}\rangle$, following the procedure documented in Ref. [16].

$Z$ boson production analysis was also performed using the 2013 LHC p+Pb collision data at $\sqrt{s_{NN}} = 5.02$ TeV for two different beam configurations, considering that the directions of the proton and lead beams were reversed during the data taking period. The $Z$ bosons are reconstructed via the di-electron and di-muon decay channels following data quality requirements corresponding to an integrated luminosity of 29.1 $\pm$ 0.1 $nb^{-1}$ and 27.8 $\pm$ 0.9 $nb^{-1}$, respectively [17]. Electron candidates are first identified at the level one trigger (L1) with the cluster $E_T > 5$ GeV. The HLT incorporated tracking information from the ID and imposed electron identification requirements on the electrons. Two triggers were chosen: $E_T > 9$ GeV with tighter electron identification requirements at the HLT, and $E_T > 15$ GeV with looser identification requirements. Muons with $p_T > 8$ GeV were accepted by the HLT without prescaling. In order to characterize the p+Pb collision geometry each event is assigned a centrality classification based on the total transverse energy measured in the FCal on the Pb-going
side (-4.9 < |η| < -3.2), \( \sum E^{\text{Pb}}_{\text{coll}} \). The Glauber model approach [15] is used to calculate the mean number of participating nucleons in the collision, \( \langle N_{\text{part}} \rangle \) (in the p+Pb system the mean number of inelastic nucleon-nucleon collisions, \( \langle N_{\text{coll}} \rangle \), is taken as \( \langle N_{\text{part}} \rangle - 1 \)).

3. Isolated prompt photon production in Pb+Pb collisions

![Diagram](image)

Figure 1: Fully-corrected yields of prompt photons in four centrality intervals as a function of \( p_T \) in \(|\eta| < 1.37 \) and \( 1.52 < |\eta| < 2.37 \) using tight selection, isolation cone radius \( R_{\text{iso}} = 0.3 \) and isolation energy of 6 GeV. JETPHOX calculations, for p+p collisions and using the same isolation criterion, are shown by the yellow bands. Statistical uncertainties are shown by the error bars. Systematic uncertainties on the photon yields are combined and shown by the braces [18].

Given the excellent capabilities of the ATLAS detector calorimetry system, prompt photon production was measured based on detailed information about the shower shape of each measured photon with multiparameter selection on a set of nine shower properties [18]. The photons have been reconstructed after an event-by-event subtraction of the average underlying event in each calorimeter layer in small \( \Delta \eta \) intervals. Backgrounds originated from neutral hadrons in jets are suppressed by a tight shower-shape selection and by requiring no more than 6 GeV total transverse energy in a cone of \( R=0.3 \) around each photon. The residual hadronic background is removed using a double sideband method [19, 20], and the remaining signal is corrected for efficiency and resolution to arrive at the per-event yield of photons scaled by the mean nuclear thickness function \( \langle T_{\text{AA}} \rangle \) as a function of \( p_T \) (22 < \( p_T \) < 280 GeV), in each \( \eta \) (central: \( |\eta| < 1.37 \) and forward: 1.52 < |\( \eta \) < 2.37) and centrality interval as shown in Figure 1.

![Diagram](image)

Figure 2: Fully-corrected yields of prompt photons as a function of \( p_T \) in 1.52 < |\( \eta \) < 2.37 divided by that measured in \(|\eta| < 1.37 \) [18]. The yield ratio is compared to JETPHOX predictions, for three different configurations: for p+p collisions (yellow area), Pb+Pb collisions with no nuclear modification (red line), and Pb+Pb collisions with EPS09 nuclear modifications (blue area). Statistical uncertainties are shown by the bars. Systematic uncertainties on the photon yields are combined and shown by the braces [18].

The ratios of the photon yields between the forward and central rapidity regions partially cancel out some of the systematic effects on the efficiencies and unfolding correction factors, mitigate the effect of the theoretical uncertainties and fully remove the uncertainties in \( \langle T_{\text{AA}} \rangle \). Figure 2 shows these results compared to JETPHOX calculations for p+p, Pb+Pb and EPS09 PDF. Some sensitivity to the nuclear PDFs is seen, primarily through the expected depletion of photon yields in the forward direction expected when including the neutron PDFs to match the isospin composition of the lead nuclei.

4. Z boson production in Pb+Pb collisions

![Diagram](image)

Figure 3: The invariant mass distributions of \( Z \to e^+e^- \) (left) and \( Z \to \mu^+\mu^- \) (right) candidates, integrated over momentum, rapidity, and centrality. Bars represent the statistical uncertainty [21].

For the \( Z \to e^+e^- \) analysis, all electrons found in triggered events are paired with each other, requiring that at least one electron in the pair match a trigger object. The opposite-sign charged pairs with an invariant mass satisfying 66 < \( m_{ee} \) < 102 GeV are accepted as signal Z bo-
son candidates. The same-sign pairs in this window are taken as an estimate of the combinatorial background. In total, 772 opposite-sign pairs and 42 same-sign pairs are reconstructed.

![Figure 4: Z bosons rapidity (left panel) and transverse momentum (right panel) distributions in the 0-80% centrality interval. Both spectra are compared with PYTHIA distributions normalized to NNLO cross-section and scaled by \( T_{AA} \).
](image)

In the \( Z \to \mu^+ \mu^- \) analysis, single muons are reconstructed with several levels of quality. High quality muons are reconstructed in both MS and ID with consistent angular measurements, as well as with a good match to the event vertex. At least one muon in each pair, matched to the trigger, is required to be of such quality. If the second muon in the pair has hit patterns in the MS and ID satisfying criteria of high reconstruction quality, the minimum \( p_T \) threshold is set to 10 GeV for both muons. If the second muon fails this condition, both muons are required to satisfy \( p_T > 20 \) GeV. With these requirements, 1223 opposite-sign pairs and 14 same-sign pairs in the di-muon channel were found. The mass distributions from both lepton pairs from triggered Pb+Pb events are shown in Figure 3 [21].

The efficiency corrected rapidity and transverse momentum distributions of Z bosons in the 0-80% centrality interval are shown in the left and right panel of Figure 4, respectively. The results are compared to PYTHIA with the overall integral normalized to the NNLO cross-section and scaled by \( T_{AA} \)."
beam direction. The right panel of Figure 5 depicts the $p_T$ differential cross-section, within $|y| < 2.5$, showing a good shape agreement between the data and the baseline [17].

6. **W boson production in Pb+Pb collisions**

The muons were reconstructed following the same criteria as of the $Z \rightarrow \mu^+\mu^-$ analysis. Decays-in-flight from pions and kaons contribute a small background fraction in this analysis. In order to reduce the QCD multi-jet contribution, a track-based isolation of the muon is imposed. This requires that the sum of the transverse momenta of ID tracks $\sum p_T^{ID}$ with with $p_T > 3$ GeV, within a cone radius $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ = 0.2 around the direction of the muon, be less than 10% of the muon $p_T$ (excluding the muon $p_T$ itself). Based on MC studies, the muon isolation ratio, $\sum p_T^{ID}/p_T$ is estimated to reject 50-70% of muons in QCD multi-jet events, depending on the centrality class, while retaining 95% of signal candidates.

In order to reconstruct electrons in the environment of heavy-ion collisions, the energy deposits from soft particle production due to the large underlying event (UE) must be subtracted as they distort calorimeter-based observables. The two-step subtraction procedure, described in detail in Ref. [7] has been applied, followed by the ATLAS heavy-ion standard electron reconstruction and identification algorithm [27]. The electron identification selections are based on criteria that use calorimeter and tracking information and have been optimised in bins of $\eta$ and $E_T$. Patterns of energy deposits in the first layer of the EM calorimeter, track quality variables, and a cluster-track matching criterion are used to select electrons. A calorimeter-based isolation variable, defined as the ratio between the total calorimeter transverse energy within a cone radius $\Delta R$ around the candidate electron-cluster and the cluster $E_T$, is used. The electron isolation ratio $\sum E_T^{ID}/E_T$ within $\Delta R < 0.25$ for this analysis is required to be less than 20%. This cut retains on average 92% of signal candidates while rejecting 42% of electrons from QCD multi-jet events. Important to note in this analysis, is that the electron decay mode of $W^\pm$ bosons is explored in the heavy-ion environment for the first time.

Due to the fact that the resolution in the missing transverse energy, $E_T^{miss}$, observed in the data using calorimeter cells, is at the level of 45 GeV in the most central heavy-ion events, the $W$ analysis employs a track based calculation that provides a four-fold improvement in resolution relative to the calorimeter-based method. The proxy for the true neutrino $p_T$, the event momentum imbalance, using this approach, is defined as the negative vector sum of all high-quality ID tracks with $p_T > 3$ GeV. The $W^\pm$ boson candidates are selected using muons or electrons in the final state with $p_T > 25$ GeV, extrapolated to $|y| < 2.5$ in events with large missing transverse momentum, $p_T^{miss} > 25$ GeV and large transverse mass of the charged lepton and neutrino system, $m_T > 40$ GeV. This set of requirements defines a fiducial region, for which $W^\pm$ boson production yields have been extracted after background subtraction and correction. After applying all the selection criteria and combining both channels, one obtains for the $W \rightarrow \nu \ell$ channel: $5870 \pm 100$ (stat) $\pm 90$ (syst) $W^+$, $5680 \pm 100$ (stat) $\pm 80$ (syst) $W^-$. For the $W \rightarrow e\nu$, $5760 \pm 150$ (stat) $\pm 90$ (syst) $W^+$, $5650 \pm 150$ (stat) $\pm 110$ (syst) $W^-$ [28]. Since the muon and electron channels agree, they have been combined. Figure 6 shows $W^+$ and $W^-$ boson production yields per minimum-bias collision and normalized to $(N_{coll})$, as a function of absolute pseudorapidity. The measurement is compared to NLO QCD theoretical predictions with (CT10+EPS09) and without (CT10) nuclear corrections. The EPS09 set [29] incorporates corrections to the PDF that account for contributions from shadowing, antishadowing, the EMC-effect, and Fermi motion.

To leading-order, $W^+(W^-)$ bosons are primarily produced by interactions between the u(d) valence quark and d(u) sea quark. The rapidity of the $W$ boson is primarily determined by the momentum fractions, $x$, of the incoming partons. Therefore, information about the PDFs can be extracted by measuring the charge asymmetry as a function of the pseudorapidity of charged leptons produced from $W$ decays. In $p+p$ collisions, the overall production rate of $W^+$ bosons is larger than that for $W^-$ bosons as a result of the larger fraction of u valence quarks relative to d valence quarks in the
colliding system. On the other hand, in Pb+Pb collisions, the nuclei contain 126 neutrons and 82 protons. Thus, p+p interactions make up only \( \approx 15\% \) of the total number of nucleon-nucleon interactions, while neutron-neutron and proton-neutron combinations contribute \( \approx 37\% \) and \( \approx 48\% \), respectively. Figure 7 shows the lepton charge asymmetry as a function of absolute pseudo-rapidity. Both the CT10 and EPS09 predictions describe the data well.

![Figure 7: The lepton charge asymmetry \( A_\text{L} \) from \( W^\pm \) bosons as a function of absolute pseudo-rapidity compared to theoretical predictions from the CT10 and CT10+EPS09 NLO PDF sets. The kinematic requirements are \( p_T^l > 25\text{GeV}, p_T^{\text{miss}} > 25\text{GeV}, \) and \( m_T > 40\text{GeV} \). Statistical uncertainties are shown as black bars, whereas bin–uncorrelated systematic and statistical uncertainties added in quadrature are shown as the filled error box. Correlated uncertainties are shown as the hatched boxes and are offset for clarity. [28].](image)

The ability of electroweak bosons to act as standard candles in a QGP is depicted in Figure 8. As one can see, the results show that Z and W boson yields divided by \( \langle N_{\text{coll}} \rangle \) are independent of centrality. Thus, when produced in association with jets, the Z and W bosons introduce and additional possibility for exploring in-medium modifications - energy loss due to multiple scattering and gluon radiation - to energetic partons traversing the heavy-ion medium.

![Figure 8: Centrality dependence of Z boson yields for four transverse momentum intervals divided by \( \langle N_{\text{coll}} \rangle \) (on the left). Bars and boxes represent statistical and systematic uncertainties, respectively. [21]. W boson boson production yield per binary collision as a function of the mean number of participants \( \langle N_{\text{part}} \rangle \) for \( W^+, W^-, \) and \( W^0 \) bosons for combined muon and electron channels. Statistical errors are shown as black bars, whereas bin–uncorrelated systematic and statistical uncertainties added in quadrature are shown as the filled error box. Bin–correlated uncertainties are shown as the hatched boxes and are offset for clarity. These include uncertainties from \( \langle N_{\text{coll}} \rangle \). Also shown is an NLO QCD prediction. [28].](image)

7. Conclusion

The ATLAS heavy-ion program has made measurements of \( \gamma \), Z and \( W^\pm \) production in Pb+Pb and p+Pb collisions. In Pb+Pb collisions, photon yields, scaled by \( \langle T_{AA} \rangle \), were presented as a function of collision centrality, transverse momentum and pseudorapidity. The scaled yields were compared to expectations from JETPHOX as are the ratios of the forward yields to those near mid-rapidity. The observed photon yields agree well with the predictions for proton-proton within statistical and systematic uncertainties. Both the yields and ratios are also compared to two other pQCD calculations, one which uses the isospin content appropriate to colliding lead nuclei, and another which includes the EPS09 nuclear modifications to the proton parton distribution functions. Z boson production in the di-electron and di-muon channel in Pb+Pb collisions was presented. Within the statistical and systematic uncertainties, the per-event Z boson yield is proportional to the number of binary collisions estimated by the Glauber model. A measurement of W boson production in the electron and muon decay channels was also presented in Pb+Pb collisions. The differential production cross-sections and lepton charge asymmetry were each measured as a function of the average number of...
participating nucleons ($N_{\text{part}}$) and absolute pseudorapidity of the charged lepton. The results were compared to predictions based on next-to-leading-order QCD calculations. From these measurements a clear picture has emerged in which color neutral electroweak bosons are unmodified in the hot dense QCD medium and serve as a baseline for color sensitive probes as well as providing an opportunity to search for nuclear modification of PDFs. The $p+p$ Pb collision system has also opened another front with the results on $Z$ boson production in the di-electron and di-muon channels. The rapidity and momentum differential cross sections were presented and a significant excess in the direction of the Pb beam is observed in the rapidity distribution relative to a pQCD calculation which does not include nuclear modifications to the parton distribution functions.

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