Jets, W and Z bosons in pA and AA collisions: ATLAS and CMS

ANTONIO SIDOTI

Istituto Nazione di Fisica Nucleare - Sezione di Bologna, Via Irnerio 46, 40126, Bologna, Italy
http://www.bo.infn.it
antonio.sidoti@bo.infn.it
URL: http://www.bo.infn.it

On behalf of the ATLAS and CMS Collaborations

Abstract. In these proceedings we will review the measurements related with jet physics, W and Z bosons performed by ATLAS and CMS during the heavy ion collisions program (Pb+Pb and p+Pb collisions) of LHC Run1 (2010-2013).

INTRODUCTION

Together with a very successful Run 1 physics program with p+p collisions at $\sqrt{s} = 7$ and 8 TeV, ATLAS (Ref.[1]) and CMS (Ref.[2]) performed very interesting measurements during the heavy ion collisions periods provided by the LHC. From 2010 to 2013 LHC provided Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, p+Pb and Pb+p collisions at $\sqrt{s_{NN}} = 5.02$ TeV and p+p collisions used as reference at $\sqrt{s} = 2.76$ TeV. The center of mass energy increase of the heavy ion collisions with respect to the one reached by the previous generation machine (RHIC at BNL) enables jet measurements in a larger phase space and opens the possibility to study W and Z bosons production in heavy ion collisions.

Hadronic jets are produced in heavy ion collisions by hard scattering processes. Accurate predictions of rates of production are possible with perturbative QCD (pQCD) calculations. Once produced, hadronic jets evolve in the QCD medium produced by the collision of the two nuclei and therefore can be used as probes of the quark-gluon plasma (QGP). However, to disentangle specific effects due to the dense QCD medium from non collective effects like the impact of nuclear modification in parton distribution functions (nPDF) and other effects, it is important to study the jet evolution in p+p collisions and in p+Pb collisions as well. Also using different probes insensitive to the dense QCD medium like electroweak bosons (W and Z) is fundamental to better understand the nature of the QGP.

These proceeding are organized as follows, jet measurements performed by ATLAS and CMS experiments are shown in the first section, while W and Z boson measurements are reported in the second section. A conclusion will briefly summarize results in view of the upcoming Run2.

JET MEASUREMENTS

A remarkable effect that occurs in high energy heavy ion collisions is the so-called jet quenching. This occurs when a di-jet event is produced in Pb+Pb collisions. In principle, without instrumental effects like jet energy miscalibration, inefficiency, etc., in p+p collisions the transverse energy of the jets is balanced such that, roughly, the $E_{T,1}$ of one jet is counterbalanced by $E_{T,2}$, the energy of the second jet ($E_{T,1} \approx -E_{T,2}$). At the contrary, in Pb+Pb collisions, jets loose...
their energy when they interact with the QCD medium produced in the collision. Hints of this effect were observed at RHIC heavy ion collider. Using the larger center of mass of the collisions produced by LHC, ATLAS and CMS were able to prove jet quenching and study its characteristics in a more quantitative way and with more statistics.

An important parameter to characterize Pb+Pb collisions is the centrality that is a quantitative measurement of how much the colliding nuclei overlap: small values of centrality indicate that nuclei collide head-on while large values indicate a large impact factor of the collisions. Experimentally centrality is measured with the energy deposited in forward region calorimeters\(^4\) which is correlated to the centrality and the number of binary collisions\(N_{\text{coll}}\) through the Glauber model.

ATLAS and CMS have measured the nuclear modification form factor \(R_{AA}\) ratio (Ref. [3, 6]) defined as:

\[
R_{AA} = \frac{\frac{d^2N_{\text{central}}}{d\eta dy}}{\langle T_{AA} \rangle \frac{d^2\sigma_{pp,jet}}{d\eta dy}},
\]

the ratio of the double differential jet production cross section measured in Pb+Pb collisions at a given centrality with respect to the one measured in p+p collisions with the same \(\sqrt{s_{NN}}\) corrected by the nuclear overlap geometrical factor \(\langle T_{AA} \rangle \) obtained through the Glauber model. \(R_{AA}\) factor measured by ATLAS as a function of the jet \(E_T\) and rapidity for different centrality values is shown in Figure 1-left. For central events, the jet production is reduced in Pb+Pb collisions with respect to p+p collisions by \(\approx 50\%\). A small logarithmic increase of \(R_{AA}\) with the jet \(E_T\) is observed indicating that the QCD medium formed tends to be more and more transparent with the increase of the probe momentum. The dependence on rapidity is interesting since the fraction of quark to gluon jets is modified by the jet rapidity (forward jets tend to be originated more by gluon than quarks).

Using secondary vertex tagging, CMS performed a measurement of \(\langle R_{AA} \rangle\) for jets coming from a b-quark Ref. [5] thus increasing the heavy flavor content of the probing jet. The measured \(\langle R_{AA} \rangle\) is shown in Figure 1-right and doesn’t show any significant difference with respect to the \(\langle R_{AA} \rangle\) measured with inclusive jets. Additional investigations (Ref. [9]) to understand where the energy of the jets goes when it traverses the QGP have been reported in Ref. [10].

At the contrary the nuclear modification factor \(R_{p+Pb}\) is compatible with 1 for p+Pb collisions indicating no jet quenching (Ref.[8, 7]). A non negligible uncertainty in the measurement is given by the extrapolation procedure to get

\(^4\)In ATLAS the forward calorimetry coverage in pseudorapidity goes from \(3.2 < |\eta| < 4.9\) while in CMS it goes from \(3.0 < |\eta| < 5.2\).
The correct value for the reference p+p collisions at $\sqrt{s} = 5.02$ TeV that were realized only at the start of LHC Run2 (November 2015). The measured $R_{p+p}$ value evaluated in intervals of centrality Figure 2-right shows deviation from unity in particular for large $E_T$ jets. This could be caused by a slightly more problematic definition of the centrality in p+Pb collisions rather than in Pb+Pb collisions (cf Section ) or some needed modification in the nPDF functions since
it is observed that $R_{pPb}$ scales linearly with the jet total energy $E \simeq P_T \cosh(y^*)$ where $y^*$ is the rapidity measured with respect of the centre of mass rapidity $y_{CM}$ which is different from 0 in p+Pb collisions ($Y^* = y - y_{CM}$).

Fluctuations in the energy loss of jets in the QCD medium are studied measuring the jets suppression for neighboring jets (nbr) with $E^{nbr}_{T} > E^{nbr}_{T,min}$ in $\Delta R$\(^5\) with respect of a test jet. On an inclusive two jets sample, the $R_{AR}$ value defined as:

$$R_{AR} = \frac{1}{\text{d}N_{test}/\text{d}E_{T}} \sum_{i=1}^{N_{test}} \frac{\text{d}N^{nbr}_{jet,j}}{\text{d}E_{T}^{test}(E_{T}^{test}, E_{T}^{nbr}_{T,min}, \Delta R)}$$

is measured as a function of the $E_{T}^{test}$ and for different $\Delta R$ intervals and $E^{nbr}_{T,min}$ values. The ratio $R_{AR}$ is measured as the ratio of $R_{AR}$ for central events normalized to peripheral collisions with centrality values 40 – 80% and is shown in Figure 3. The suppression factor of $\sim 50\%$ is confirmed for all $E_{T}^{test}$ values while a weak increase is observed with $E^{nbr}_{T,min}$.

\[
\text{FIGURE 4.} \text{ Ratios of fragmentation functions in p+Pb compared to those in p+p collisions for the six } E_{T}^{jet} \text{ intervals after subtraction from underlying event (from Ref. [12]).}
\]

Dense QCD matter also modifies the momentum of particles inside a jet. Fragmentation function have been measured by both ATLAS and CMS for Pb+Pb collisions Ref [13, 14] and p+Pb collisions Ref [12, 15]. The fragmentation function $D(z) = \frac{1}{N_{jet}} \frac{\text{d}N}{\text{d}z}$ measured in p+Pb collisions normalized to p+p collisions is shown in Figures 4 and 5 as a function of $z = \frac{\hat{P}_{L,AB} \hat{P}_{T,AB}}{\hat{P}_{T,AB}}$\(^6\). While CMS doesn’t show a significant variation with respect to the p+p collisions, ATLAS shows an enhancement for values when charged-particles tracks bring more than 20% of the energy of the hadronic jets. However there are few differences that could explain the differences between the two measurements: the underlying event removal and the extrapolation method to get the reference for p+p collisions at $\sqrt{s} = 5.02$ TeV. For the latter, the data collected in November 2015 during p+p collisions at $\sqrt{s} = 5.02$ TeV will be of fundamental importance.

\(^5\)Where $\Delta R = \sqrt{\Delta\phi(test, nbr)^2 + \Delta\eta(test, nbr)^2}$.

\(^6\)Or an equivalent variable $\xi = \ln(1/z)$ for CMS.
FIGURE 5. Ratio of fragmentation function for $p+Pb$ using a $p+p$ reference. Starting from the leftmost column, fragmentation functions for jets with increasing $E_T$ are shown. Underlying event subtraction has been done using a 90 degree rotated cone in the $\phi$ direction. (from Ref. [15]).

W AND Z BOSONS

Electroweak bosons are produced with a significant rate in heavy ion collisions at LHC. They do not interact strongly with QCD matter and their properties have been measured in Pb+Pb, p+Pb and p+p collisions; therefore they complement the analysis of QGP. W and Z bosons are identified in heavy ion collisions with their leptonic decay channels. Background contamination for $W \rightarrow \ell \nu \ell$ are smaller than $\lesssim 10\%$ (Figure 6-left) while $Z \rightarrow \ell \ell$ are cleaner with less than $\lesssim 3\%$ of background contamination (Figure 6-right).

FIGURE 6. Left: Transverse mass distribution with the different background contribution for $W^+ \rightarrow \mu^+ \bar{\nu}_\mu$ (from [16]). Right: Dielectron invariant mass spectra: full black circles represent opposite-charge electrons, open black squares show same charge electron pairs (from Ref [17]). The Z boson yield is constant in Pb+Pb collisions Ref [18, 17] as a function of $<N_{\text{coll}}>$ (Figure 7-left) confirming that electroweak bosons and their leptonic decay products (electrons and muons) are unafected by the QCD matter. Also the ratio of production $R_{AA}$ scaled by $<T_{AA}>$ is compatible with unity showing that Z boson remain unaffected when traversing the QCD hot medium (Figure 7-right).

In a way that is reminiscent of $p+p$ collisions, W boson asymmetry measurement in Pb+Pb collisions give fundamental insight in the nPDF content since, at leading order, $W^+(W^-)$ are primarily produced by interactions between a $u(d)$ valence quark and a $\bar{d}(\bar{u})$ sea quark. The rapidity of the $W$ boson is primarily determined by the
momentum fractions $x$ of the incoming partons. Information on the nPDF can be extracted by measuring the charge asymmetry as a function of the pseudorapidity of the charged lepton from $W$ decays. Asymmetry measurements are more precise than just differential production ones since many uncertainties can cancel out in the ratio (in particular the luminosity uncertainty). The charge asymmetry is defined as:

$$A_{T}(\eta_{l}) = \frac{dN_{W^{+} \rightarrow e^{+}\nu_{e}} - dN_{W^{--} \rightarrow e^{-}\bar{\nu}_{e}}}{dN_{W^{+} \rightarrow e^{+}\nu_{e}} + dN_{W^{--} \rightarrow e^{-}\bar{\nu}_{e}}}$$

and is shown in Figure 8-left (Ref. [19]) where the impact of nuclear effects in the PDF is shown on the predictions. So far, more statistics and a better understanding of the uncertainties are needed to establish the existence of nuclear effects using $W$ asymmetry measurements. Nuclear effects are expected to modify the $Z$ production rapidity distribution asymmetrically (Ref. [16, 20]). Therefore nuclear effects in the PDF can be quantitatively evaluated with the forward-backward ratio defined as:

$$R_{FB} = \frac{d\sigma(+) / dy}{d\sigma(-) / dy}.$$  

$R_{FB}$ is shown in Figure 8-right and predictions using nuclear effects in PDF are clearly favoured.

$W$ boson production studies have been performed also in $p+Pb$ collisions (Ref. [21]). The forward-backward asymmetry defined as:

$$R_{W,p+Pb}(\eta_{lab}) = \frac{N(\eta_{lab})}{N(-\eta_{lab})}$$

is shown in Figure 9-left and is compared with predictions with PDF using nuclear modification factors that are favored by data. However, even pdf with EPS09 nuclear effect don’t seem to predict well the data of the $W$ boson charge asymmetry (Figure 9-right). A possible explanation of this discrepancy might be the fact that nuclear modification effects could be different for up and down quarks in heavy nuclei.

As anticipated in the previous section, some caution has to be given to centrality measurement in $p+Pb$ collisions. In fact the presence of any hard process (including jets, $Z$ and $W$ boson production) is correlated with a larger transverse energy in the underlying event. Consequently, more energy may be deposited in the Pb-going side of the forward calorimeters\footnote{In $p+Pb$ collisions the centrality value of an event is determined by the measurement of the forward calorimeter energy deposited in the Pb-going side.} in events containing a hard scattering process than in those that do not contain one causing a
FIGURE 8. Left: W asymmetry measurements as a function of the lepton pseudorapidity compared with theoretical predictions using CT10 and CT10+EPS09 NLO sets where this latter include nuclear effects (from Ref. [19]). Right: $R_{FB}$ distributions of $Z$ bosons in p+Pb collisions corrected to full acceptance combining dielectron and dimuon channels compared with predictions using different PDF (from Ref.[20]).

FIGURE 9. From Ref. [21]. Left: Forward-backward asymmetry of charge-summed W bosons, as a function of the lepton pseudorapidity. Right: Lepton charge asymmetry, $N^+ - N^-$, as a function of the lepton pseudorapidity. Theoretical predictions with (CT10+EPS09, dashed green line) and without (CT10, solid red line) PDF nuclear modifications are also shown, with their uncertainty bands.

centrality bias. This has been observed by PHENIX at RHIC in $d+Au$ (Ref.[22]) and by ALICE in p+Pb collisions (Ref.[23]). The centrality bias is corrected with a data driven method (Ref.[16]), and the invariance of the yield of $Z$ bosons as a function of $<N_{part}>$ after the centrality bias correction is shown if Figure 10-left. The $Z$ boson differential
yield is shown in Figure 10-right. The \( <N_{\text{coll}}>/sigma_N^{\text{central}}\)-scaled ratio of central to peripheral events \( R_{\text{CP}} \) defined as:

\[
R_{\text{CP}}(y_z^*) = \frac{<N_{\text{coll}}>/sigma_N^{\text{central}}}{<N_{\text{coll}}>/sigma_N^{\text{peripheral}}} \times \frac{dN_z^{\text{central}}/dy_z^*}{dN_z^{\text{peripheral}}/dy_z^*}
\]

shows changes in the rapidity distribution for different centrality bins. The slight slope difference of \( R_{\text{CP}}(y_z^*) \) between central and peripheral events indicates that the Z boson asymmetry is slightly larger for central events than for peripheral ones.

**FIGURE 10.** Left: Evidence for binary scaling of the Z boson yields after the centrality bias correction. Right: The Z differential yield as a function of the rapidity \( y_z \) is reported for different centrality values (top). \( R_{\text{CP}} \) as a function of \( y_z \) is reported (bottom). (From Ref. [16])

**SUMMARY**

A new era of heavy ion collisions at the largest energies and integrated luminosity has started with LHC Run1. Hadronic jets and electroweak bosons are powerful tools to understand the properties of quark-gluon plasma since the former are affected by the QCD matter while the latter are not. Measurements of processes involving jets and electroweak bosons performed in Pb+Pb, p+Pb and p+p collisions test characterize the impact of different aspects occurring in heavy ion collisions like nuclear effects in PDF, different fragmentation functions, etc. We expect for the incumbent Run2 of LHC a larger wealth of data collected with larger energy in the centre of mass of collisions.

**ACKNOWLEDGMENTS**

It is a pleasure to thank here our colleagues R. Nania and P. Antonioli from the ALICE collaboration group in Bologna for useful discussions and the LHCP2015 local organizing committee for the wonderful organization of the conference.
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