Recent Heavy Ion Results on the Hard Scattering and Jet Quenching from the ATLAS and CMS experiments at the LHC

Andrzej Olszewski[1] on behalf of the ATLAS and CMS Collaborations

[1]Institute of Nuclear Physics, PAS, Radzikowskiego 152, 31-342 Kraków, Poland

DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-04/287

Recent results on studies of hard scattering processes and jet quenching in nuclear collisions from the ATLAS and CMS experiments at the Large Hadron Collider (LHC) are reviewed. They are based on high statistics samples of PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV collected at the LHC in 2011, and pp collisions at $\sqrt{s} = 2.76$ TeV and pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV collected in 2013. New results for the jet nuclear modification factor, R_{AA}, confirm a strong suppression of jet production. Modifications of jet fragmentation properties in PbPb collisions, are observed. In pPb collisions jets are not strongly modified, but some non-scaling behavior of jet rates in collisions with different centralities is observed by ATLAS. New measurements for the electroweak boson production in pPb collisions allow a more precise testing of parton distributions in lead nuclei with the conclusion that the EPS09 description of nuclear modifications of parton distribution functions is preferred.

1 Introduction

In collisions of heavy nuclei at very high energies, one expects creation of a hot and dense medium which may, under certain conditions, undergo transition to the so called Quark-Gluon Plasma (QGP) phase, where quarks and gluons are free to interact directly. In experiments at RHIC and LHC, it has been observed that properties of high transverse momentum particles and particle jets are modified in heavy nuclei collisions compared to collisions of protons and this was attributed to interactions of these particles with the medium created in the collision. It has been found that the best way to understand properties of the produced medium and whether it fits the properties of QGP is to study hard scattering processes. In such studies, we use nuclear modification factor R_{AB}, defined as:

$$R_{\mathrm{AB}} = \frac{\frac{1}{\mathrm{N}}\frac{\mathrm{d}^2 N^{\mathrm{jet}}_{\mathrm{cent}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}{\langle T_{\mathrm{AB}}\rangle_{\mathrm{cent}}\frac{\mathrm{d}^2\sigma^{\mathrm{jet}}_{pp}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}; \qquad N_{\mathrm{coll}} = T_{\mathrm{AB}} \times \sigma_{\mathrm{NN}},$$

to measure the deviation of yields produced in heavy ion collisions from the yield in pp scaled by the number of nucleon-nucleon collisions, N_{coll}, proportional to the mean nuclear thickness, T_{AB}, of the incoming nucleon fluxes. $R_{\mathrm{AB}} = 1$ means that production properties have not been modified with respect to pp collisions.

In the last few years experiments at LHC registered data from runs with collisions of lead nuclei at the center of mass energy of $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, from proton-proton runs taken as a reference data at the same energy and from pPb runs at the energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV resulting from a combination of asymmetric energies of lead nuclei at 1.58 TeV/N and protons at 4 TeV. Recent analyses from ATLAS [1] and CMS [2] are now using high statistics PbPb data from 2011, new pPb data from 2013, and high statistics pp data from 2013 with statistics 20 times higher than available before.

2 Jets in PbPb collisions

Jets provide a powerful tool to probe the hot and dense medium created in heavy ion collisions. Experiments at RHIC have shown first evidence of jet quenching by observation of suppression of high transverse momentum particles. At the LHC, a direct evidence of parton energy loss has been observed in significant modification of dijet and photon-jet p_{T}-balance and suppression of inclusive jet spectra with increasing collision centrality.

Recently ATLAS has shown new results on the jet suppression in PbPb collisions [3]. The jet nuclear modification factor, R_{AA}, has been measured as a function of jet transverse momentum, rapidity and centrality. A significant suppression of jets is observed at all centralities. The R_{AA} is as low as 0.5 in the most central (0-10%) collisions for jets with p_{T} up to 400 GeV. With increasing p_{T} a slow rise of R_{AA} is observed, with the slope varying with centrality and reaching zero in peripheral collisions. The jet R_{AA} measured as a function of rapidity shows no significant dependence within the measured rapidity range (Fig.1, top). R_{AA} measured as a function of centrality, expressed by number of participating nucleons, $\langle N_{\mathrm{part}} \rangle$, is decreasing monotonically from the value of 0.8 in most peripheral collisions to 0.4 in 1% of the most central ones (Fig.1, bottom), the behaviour observed before by CMS [4].

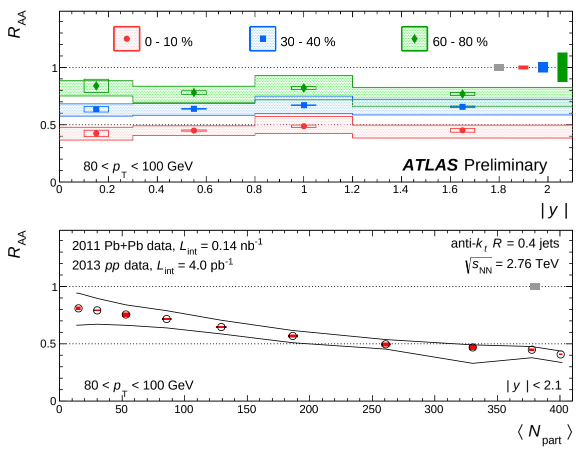

Figure 1: Top: R_{AA} for jets with $80 < p_{\mathrm{T}} < 100$ GeV shown as a function of $|y|$ for three centrality bins. Bottom: R_{AA} for jets with $80 < p_{\mathrm{T}} < 100$ GeV and $|y| < 2.1$ as a function of $\langle N_{\mathrm{part}} \rangle$ [3].

ATLAS presented also updated results on modifications of the jet fragmentation in PbPb collisions [5]. Modifications of distributions of longitudinal, $D(z)$, $z = p_{\mathrm{T}}^{\mathrm{had}}/p_{\mathrm{T}}^{\mathrm{jet}} \cos(\Delta R)$, and transverse, $D(p_{\mathrm{T}})$, momentum of jet particles relative to the jet axis have been studied by calculating ratios of distributions measured in central and peripheral collisions, $R_{D(z)} = D(z)_{\mathrm{cent}}/D(z)_{\mathrm{periph}}$. A significant modification of fragmentation is seen in more central collisions with enhancement of fragment yields at small values of momenta ($z < 0.04$, $p_{\mathrm{T}} < 4$ GeV) and at high ones ($z > 0.2$, $p_{\mathrm{T}} > 30$ GeV), and reduction at intermediate values (Fig.2). The enhancement at large z or p_{T} is seen more clearly for jets with small jet radii, $R = 0.2, 0.3$. Similar modifications in

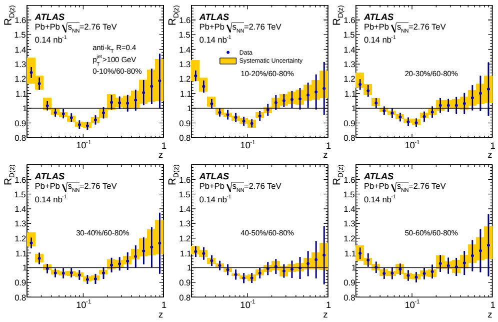

Figure 2: Ratios of $D(z)$ for six bins in collision centrality to those in peripheral (60-80%) collisions, for $R = 0.4$ jets [5].

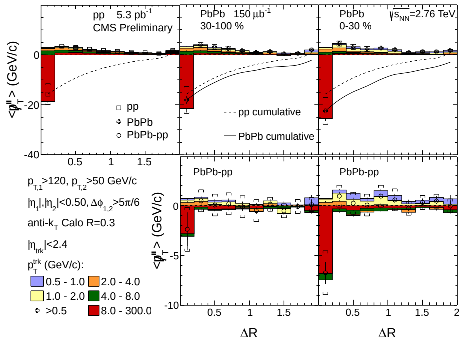

Figure 3: Top: Differential missing p_T distributions for pp and PbPb collisions, as a function of ΔR. Bottom: Difference between the PbPb and pp distributions [7].

jet fragmentation are seen also by the CMS experiment from the comparison of pp and PbPb collision data [6].

The CMS experiment studied also particle momentum balance in jets [7]. It has been found that jets in PbPb collisions comprise more particles than pp jets and the difference increases with the collision centrality leading to 15 extra particles in jets with large momentum asymmetry and high (0-10%) collision centrality. Furthermore, contributions from jet particles have been studied in bins of transverse momentum and it has been found that in PbPb jets there is an excess of particles with low $p_T < 2$ GeV. The particle transverse momentum balance has been studied also as a function of ΔR, the distance from the jet axis. Results are shown in Fig.3. The momentum balance, shown by dashed and continuous lines for pp and PbPb collisions, respectively, is achieved only at large distances $\Delta R = 2$ and the excess of low p_T particles is seen up to large distances from the jet axis. A detailed measurement of the radial distribution of transverse momentum inside the core of the jet cone, called differential jet shape, has been shown by CMS in [8]. It has been found that jet shapes in peripheral (70-100%) PbPb collisions are similar to those in pp while in more central collisions (0-70%) a depletion is found in the range of $0.1 < R < 0.2$. In the most central PbPb collisions (10-30% and 0-10%), an excess of transverse momentum fraction emitted at large radii, $R > 0.2$, starts to show up, confirming moderate broadening of jets in the hot medium created in PbPb collisions.

3 Jets in pPb collisions

Studies of dijet properties in pPb collisions are of great importance to establish a QCD baseline for hadronic interactions with a cold nuclear matter. This is because these collisions are not expected to produce large volumes of hot partonic medium similar to PbPb collisions where both effects contribute.

Recently ATLAS performed measurements of jet production in pPb collisions [9]. In this analysis, inclusive jet modication factors, $R_{p\mathrm{Pb}}$, have been calculated as a function of p_T using as a reference 2013 pp data interpolated to pPb energy. Results are shown in Fig.4. The $R_{p\mathrm{Pb}}$ factors are all close to 1, so there is no jet suppression seen in inclusive pPb collisions.

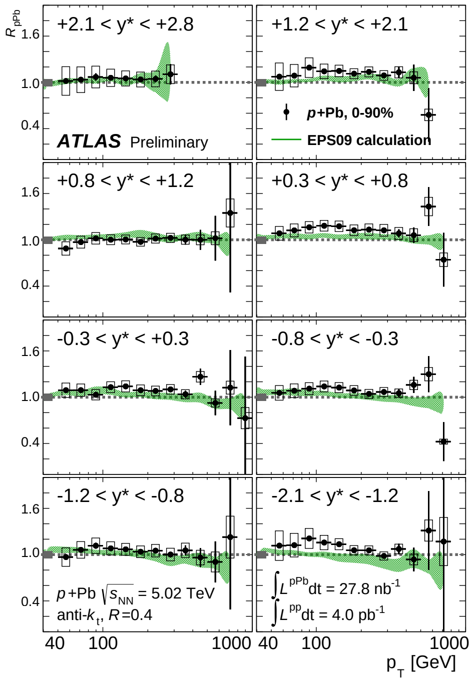

Figure 4: $R_{p\mathrm{Pb}}$ for $R = 0.4$ jets in 0-90% pPb collisions at different rapidity ranges. The green band represents a calculation using the EPS09 parton distribution function [9].

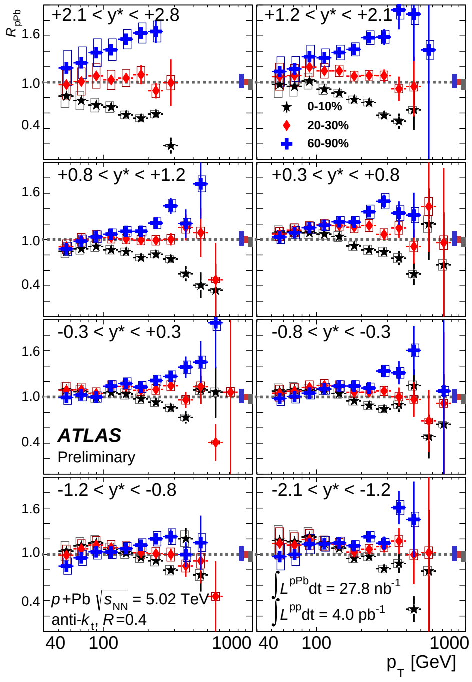

Figure 5: $\mathrm{R}_{p\mathrm{Pb}}$ for $R = 0.4$ jets in pPb collisions in central (black), mid-central (red) and peripheral (blue) events at different rapidity ranges [9].

Instead, a small 5-10% enhancement is visible over the scaled pp results. CMS has performed a similar measurement [10] and has come to similar conclusions except for observing some decrease in $R_{p\mathrm{Pb}}$ modification factors with jet p_{T} in the most backward range of the center-of-mass pseudorapidity, $-2.0 < \eta_{\mathrm{CM}} < -1.5$. ATLAS has measured also $R_{p\mathrm{Pb}}$ factors in 3 subsamples of events with different collision centrality (Fig.5). In such samples, jet rates have been found enhanced in peripheral collisions and suppressed in central collisions at forward rapidities, while not modified at low p_{T} and negative center-of-mass rapidity, y^* [9]. This pattern of the jet modification has been confirmed by R_{CP}, ratios of jet rates in central to peripheral pPb collisions. In addition, it has been found that R_{CP} ratios scale as a function of momentum p, in forward (proton going) direction $y^* > 0$, but not at $y^* < 0$ [9].

In order to study flavor dependence of the jet suppression CMS has measured also $R_{p\mathrm{Pb}}$ factors in production of b-quark jets [11] and B particles [12]. The b-jet measurements have been compared to PYTHIA Z2 tune pp calculations. The obtained $R_{p\mathrm{Pb}}$ ratios were found to be consistent with no suppression in the b-jet production. The same conclusion has been drawn also from the study of B meson production [12]. No flavor dependence of jet suppression has been found in PbPb collisions [13], despite the fact that jets are strongly quenched in these collisions.

A particularly useful tool for studying jet quenching are back to back jet pairs, called

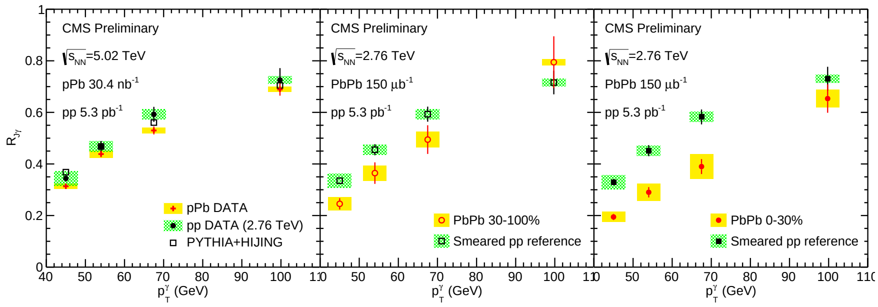

Figure 6: Fraction of photons associated to a jet (R_{J_γ}) as a function of the leading photon p_T in pPb (left), peripheral PbPb (middle), and central PbPb (right) [14].

dijets. CMS has measured a fraction of photons with a high p_T jet partner in pPb and in PbPb collisions and compared results to the measurements in pp collisions and to PYTHIA calculations [14]. It has been found (see Fig.6) that such dijets are not changed in pPb while they are suppressed in PbPb collisions. CMS has also measured directly distributions of the relative directions and momentum ratios of jets in pPb dijets and compared them with dijet properties in pp collisions. It has been found that in pPb collisions jets are not deflected and the jet momenta are essentially unmodified [15], while in PbPb collisions, the partner jets are pushed to lower p_T values [16].

Another dijet property studied by CMS in pPb collisions was an average dijet position in rapidity. This property is directly sensitive to momenta of interacting partons that could be modified in nuclear projectiles. CMS compared the pPb data with PYTHIA pp predictions and found that the best match is obtained if the EPS09 nuclear parton distribution function (PDF) is used in the model calculations [15].

4 Electroweak bosons in PbPb collisions

Electroweak (EW) bosons are colorless particles which are supposed not to interact with the hot and dense medium created in heavy ion collisions. Measured together with jets they may be used as a calibration tool in studies of jet quenching. In addition, the EW boson production mechanism (via $\mathrm{q\bar{q}}$ annihilation) makes them sensitive to parton distribution functions, thus suitable for studying nuclear modifications to PDFs (nPDFs).

In PbPb collisions, ATLAS measured R_{AA} ratios for isolated, direct photon yields to the reference pp rates calculated by JETPHOX model [17]. They were shown as a function of photon transverse momentum and compared with JETPHOX calculations in pp and PbPb collisions. Also a ratio of yields in forward to central rapidity regions has been studied. The photon cross-sections have been found to agree with simple scaling of pp rates, but the measurements could not discriminate between different PDF versions due to large systematic uncertainties.

ATLAS has updated also their results on the production of W bosons in PbPb collisions [18]. Yields of $W^\pm$ bosons have been studied as a function of the number of participating nucleons (collision centrality) and compared to PYTHIA CT10 model calculations (Fig.7). Results have been found compatible with simple pp scaling and in agreement with model calculations.

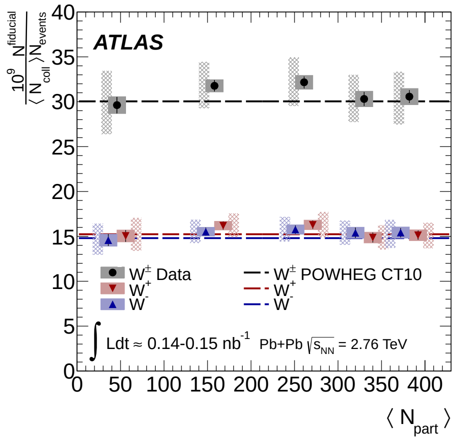

Figure 7: W boson production yield per binary collision as a function of the mean number of participants compared to the NLO QCD prediction [18].

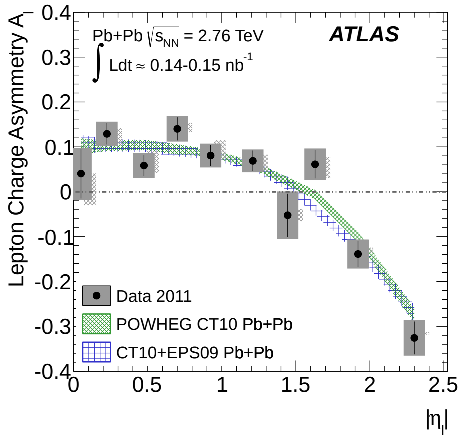

Figure 8: The lepton charge asymmetry $A_l = (N(l^+) - N(l^-))/(N(l^+) + N(l^-))$ from $W^{\pm}$ bosons as a function of the absolute pseudorapidity compared to predictions with CT10 and CT10+EPS09 NLO PDF sets [18].

The more sensitive to parton distributions, charge asymmetry in pseudorapidity, has also been studied (Fig.8) and found to be well described by model calculations, but results are not precise enough to see possible nuclear modifications to parton distributions.

5 Electroweak bosons in pPb collisions

Search for the effects of nuclear modifications to PDFs is even easier in pPb collisions, where final state effects are expected to be small or none. In such collisions, ATLAS measured recently the Z^0 boson production [19]. The cross-section measured as a function of boson rapidity exhibits a significant asymmetry in rapidity with excess over predictions from PYTHIA CT10 model in the backward (Pb-going) rapidity region. In the same measurement performed by CMS [20], Z^0 cross section has also asymmetric behavior, but a comparison is made with PYTHIA MSTW08 model and a good agreement with predictions is found (Fig.9). The forward to backward ratio of Z^0 production cross-sections measured by CMS favors parton distributions with nuclear modifications (Fig.10).

The production cross-sections for W boson in pPb collisions have been measured so far only by the CMS experiment [21]. They agree well with the scaled PYTHIA model predictions – only a small excess is seen in the production of W^- at negative η. This excess is investigated in the W^+/W^- charge asymmetry (Fig.11), which is a sensitive probe of the ratio of up to down quark PDFs. Explanation of the deviation between data and model predictions would require to assume a smaller nuclear modification to the down quark than to the up quark in the EPS09 nPDF. The forward/backward asymmetry in W boson production has been investigated by CMS to probe nuclear modifications in parton x distributions. There is a significant difference in this asymmetry as a function of $\eta_{\rm lab}$ between predictions from PYTHIA CT10 and EPS09

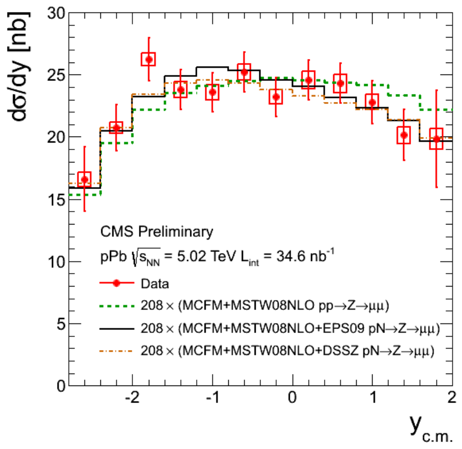

Figure 9: Differential cross-section of the Z^0 boson production in pPb collisions as a function of rapidity, compared to predictions from PYTHIA generator with different versions of PDFs [20].

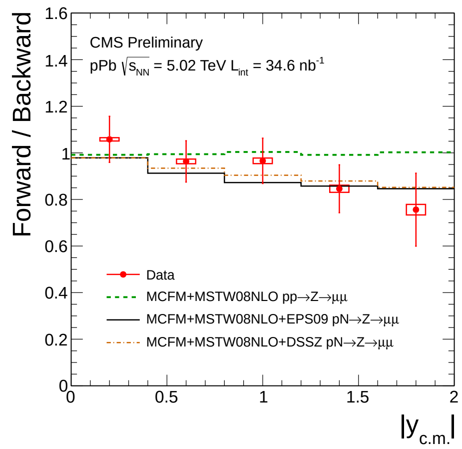

Figure 10: Forward-backward ratio of Z^0 boson cross-section in pPb collisions as a function of rapidity compared to predictions with nuclear modifications (EPS09 or DSSZ) and without them (green, dashed line) [20].

versions, but results of the measurement don't fully agree with either version (Fig.12), although a slightly better agreement is found with EPS09 nPDF calculations.

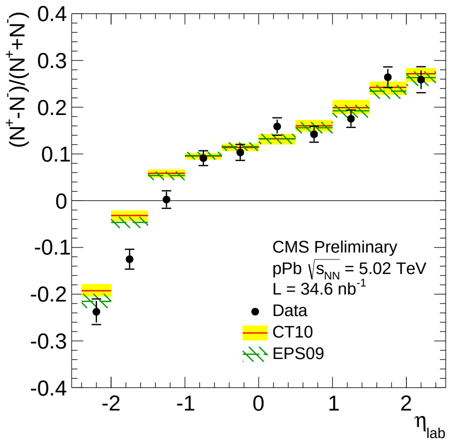

Figure 11: W boson charge asymmetry, $(\mathrm{N}^+ - \mathrm{N}^-)/(\mathrm{N}^+ + \mathrm{N}^-)$, as a function of the lepton pseudorapidity in the laboratory frame [21].

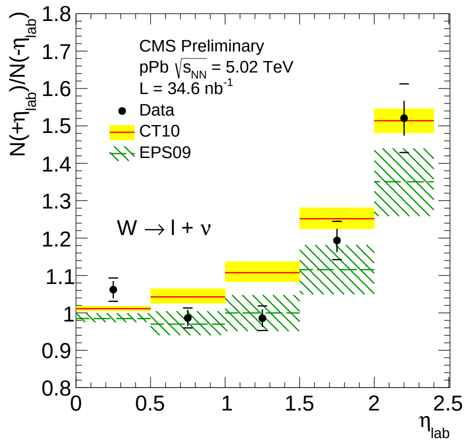

Figure 12: W boson forward/backward asymmetries $\mathrm{N}(+\eta_{\mathrm{lab}})/N(-\eta_{\mathrm{lab}})$ for positively charged leptons [21].

6 Summary

Recent results on hard scattering processes in nuclear collisions, obtained by ATLAS and CMS, are presented. They confirm that in PbPb collisions, jets are strongly quenched. The suppression of jet yields increases with centrality (down to $R_{AA} \simeq 0.5$), and continues to $p_T \simeq 400$ GeV. No strong flavor (b-quark) dependence of suppression is seen at high transverse momenta. Jet fragmentation is modified in PbPb collisions. ATLAS and CMS observe enhancements at low and high values of longitudinal and transverse momenta of jet fragments, and a suppression at intermediate values. CMS finds that the jet energy is distributed in PbPb collisions to more particles with lower p_T and going to large angles as compared to pp jets. In electroweak boson production, ATLAS observes a scaling of cross-sections with the number of elementary NN collisions. In pPb collisions, jets are not strongly suppressed. However, ATLAS observes no scaling-like variation of yields with centrality at forward rapidities. Latest results from pPb collisions allow more precise tests of parton distribution functions and indicate that EPS09 nPDF is preferred.

Acknowledgments

This work was supported in part by the National Science Center grants DEC-2011/03/B/ST/02631, by DEC-2013/08/M/ST2/00320 and by PL-Grid Infrastructure.

References

[1] ATLAS Collaboration, JINST 3 (2008) S08003.

[2] CMS Collaboration, JINST 3 (2008) S08004.

[3] ATLAS Collaboration, ATLAS-CONF-2014-025, http://cds.cern.ch/record/1702988.

[4] CMS Collaboration, CMS-PAS-HIN-12-004, http://cds.cern.ch/record/1472722.

[5] ATLAS Collaboration, arXiv:1406.2979 [hep-ex] (2014).

[6] CMS Collaboration, Phys. Rev. **C90** 024908 (2014).

[7] CMS Collaboration, CMS-PAS-HIN-14-010, http://cds.cern.ch/record/1703014.

[8] CMS Collaboration, Phys. Lett. **B730** 243 (2014).

[9] ATLAS Collaboration, ATLAS-CONF-2014-024, http://cds.cern.ch/record/1702986.

[10] CMS Collaboration, CMS-PAS-HIN-14-001, http://cds.cern.ch/record/1703004.

[11] CMS Collaboration, CMS-PAS-HIN-14-007, http://cds.cern.ch/record/1703013.

[12] CMS Collaboration, CMS-HIN-14-004, http://cds.cern.ch/record/1703520.

[13] CMS Collaboration, arXiv:1312.4198 [nucl-ex] (2013).

[14] CMS Collaboration, CMS-PAS-HIN-13-006, http://cds.cern.ch/record/1631991.

[15] CMS Collaboration, Eur. Phys. J. **C74** 2951 (2014).

[16] CMS Collaboration, Phys. Lett. **B718** 773 (2013).

[17] ATLAS Collaboration, ATLAS-CONF-2014-026, http://cds.cern.ch/record/1702992.

[18] ATLAS Collaboration, ATLAS-CONF-2014-023, http://cds.cern.ch/record/1702982.

[19] ATLAS Collaboration, ATLAS-CONF-2014-020, http://cds.cern.ch/record/1702971.

[20] CMS Collaboration, CMS-PAS-HIN-14-003, http://cds.cern.ch/record/1703012.

[21] CMS Collaboration, CMS-PAS-HIN-13-007, http://cds.cern.ch/record/1703270.