Overview of new results from ATLAS heavy ion physics program

Martin Spousta
on behalf of the ATLAS Collaboration
Charles University in Prague, Institute of Particle and Nuclear Physics,
V Holesovickach 2, 180 00 Prague 8, Czech republic
E-mail: martin.spousta@cern.ch

Abstract. In this short paper we provide an overview of new results from the ATLAS physics program at the LHC as of spring 2015. We separately summarize the results from pPb collisions and Pb+Pb collisions along with some of their interpretations.

1. Introduction

In this short paper we provide an overview of new results from the ATLAS physics program at the LHC [1]. In fall 2010 and fall 2011, ATLAS has collected 7 µb−1 and 0.14 nb−1, respectively, of lead-lead (Pb+Pb) collisions at √s_{NN} = 2.76 TeV used for physics analyses. In fall 2012 a pilot proton-lead (pPb) run was realized delivering approximately 1 µb−1 of collisions at √s_{NN} = 5.02 TeV. The full pPb run at the same center of mass energy followed in the winter 2013 delivering approximately 28 nb−1. Some of the measurements done with Pb+Pb collisions use as a reference proton-proton (pp) collisions delivered at the same center-of-mass energy, that is √s = 2.76 TeV which were provided by the LHC in the year 2013. These pp collisions together with pp collisions at 7 or 8 TeV are used also to construct a reference at 5.02 TeV which is used in some of the pPb measurements. The results from pPb collisions are summarized in Sec. 2, the results from Pb+Pb collisions are summarized in Sec. 3.

2. Physics of pPb collisions

Prior to the first LHC runs of pPb collisions, the main motivation for running these collisions was to improve the understanding of the initial state effects of nuclear collisions, namely to quantify the modifications of parton distribution functions in the nuclear environment. The studies done with pPb data were primarily intended to be a reference for studies of processes in Pb+Pb collisions, where a deconfined matter is produced. However, the pPb collisions have brought several unexpected observations, such as the double-ridge structure in long range pseudorapidity correlations, significant centrality and rapidity dependence of the inclusive jet production, and an enhancement of charged particle yields. In this section we summarize the recent studies in pPb collisions provided by ATLAS starting from measurements of jet yields, going through measurements of correlations between soft and hard processes, Z boson, J/ψ and ψ(2) production, jet fragmentation, and closing by studies of the azimuthal correlations in pPb collisions.
Measurement of the inclusive jet production in pPb was expected to provide a valuable benchmark for the jet quenching measured in Pb+Pb collisions. Indeed, a good correspondence of the jet spectra measured inclusively in centrality with the pQCD prediction employing the EPS09 parameterization of nuclear parton distribution functions (nPDF) was seen, which confirms that the jet suppression seen in Pb+Pb collisions is due to final state effects. The nuclear modification factor of inclusive jets, $R_{pPb}$, exhibits only little (if any) deviation from unity. On the contrary, the ratios of inclusive jet spectra from different centrality selections show a strong modification of jet production at all $p_T$ at forward rapidities and for large $p_T$ at mid-rapidity, which manifests as a suppression of the jet yield in central events and an enhancement in peripheral events. These effects imply that the factorization between hard and soft processes is violated at an unexpected level in proton-nucleus collisions. Furthermore, the modifications at forward rapidities were found to be a function of the total jet energy only, implying that the violations might have a simple dependence on the hard parton-parton kinematics.

To improve the understanding of soft-hard correlations ATLAS measured the relationship between jet production and the underlying event in a pseudorapidity separated region in 2.76 TeV pp collisions. In that study, the underlying event was characterized through measurements of the average sum of the transverse energy at large negative pseudorapidity, $\langle \Sigma E_T \rangle$, which were reported as a function of hard scattering kinematic variables. The hard scattering was characterized by the average transverse momentum, $p_{T\text{avg}}$, and pseudorapidity, $\eta^{\text{avg}}$, of the two highest transverse momentum jets in the event. It was found that the $\langle \Sigma E_T \rangle$ is anticorrelated with the dijet $p_{T\text{avg}}$, decreasing by 25% as $p_{T\text{avg}}$ varies from 50 to 500 GeV. This general trend is reproduced by leading-order Monte Carlo (MC) generators. These anticorrelations measured in pp collisions provide a useful context for understanding the pPb results, since they indicate a nontrivial correlation between hard scattering kinematics and $\Sigma E_T$ production.

Further insight was gained by estimating, from the dijet kinematics on an event-by-event basis, the scaled longitudinal momenta of the hard scattered partons in protons. This was done separately in the projectile and target beam-protons defined as moving to positive and negative rapidity, respectively. Transverse energy production at large negative pseudorapidity was observed to be linearly dependent on the longitudinal momentum fraction in the target proton, $x_{\text{targ}}$, and only weakly with that in the projectile proton, $x_{\text{proj}}$. This shows that the average level of transverse energy production is sensitive predominantly to the Bjorken-$x$ of the parton originating in the beam-proton which is headed towards the energy-measuring region ($x_{\text{targ}}$), and is mostly insensitive to $x$ in the other proton ($x_{\text{proj}}$). These results provide counter-evidence to claims that the observed centrality-dependence of the jet rate in pPb collisions simply arises from the suppression of transverse energy production at negative rapidity in the hard-scattered nucleon-nucleon sub-collision (being e.g. a consequence of an energy loss conservation). In the pPb data, the deviations from the expected centrality dependence are observed to depend only on, and increase with, $x$ in the proton, that is with $x_{\text{proj}}$. Therefore, for this effect to be consistent with arising from a feature of nucleon-nucleon collisions, transverse energy production at small angles should decrease strongly and continuously with increasing $x_{\text{proj}}$.

Better understanding of the interplay between soft and hard physics and centrality in pPb can be gained also from the measurement of $Z$ boson production. An important component of the measurement is the centrality bias correction which should reduce the correlation between hard process rates and the magnitude of the soft event activity. After applying the centrality bias correction the $N_{\text{coll}}$ scaled yield of $Z$ bosons is approximately centrality independent, consistent with a production mechanism that scales with the number of binary collisions – though this scaling is less good for Glauber-Gribov Colour Fluctuation model than for the simple Glauber model. The $Z$ boson production cross section measured as a function of rapidity and $x_{\text{Pb}}$ is systematically larger compared to predictions based on perturbative QCD calculations even after including effects from modifications of nPDF as predicted by EPS09.
While the next-to-leading order (NLO) pQCD with EPS09 does not fully describe the rapidity dependence of the Z boson production, it was found to describe well the rapidity dependence of the prompt $J/\psi$ production, measured over $p_T$ interval of 8-30 GeV [10]. In that measurement, the non-prompt and prompt $J/\psi$ production cross-section was evaluated as a function of $p_T$ and rapidity. Also measured was the $\psi(2)$ [11]. The non-prompt $J/\psi$ and $\psi(2)$ cross-sections were found to be described, though with large theoretical uncertainties, by FONLL calculations [12] which do not include nuclear effects. Further, the nuclear modification factor, $R_{p\text{Pb}}$, was evaluated based on an interpolation of the cross sections at 2.76, 7 and 8 TeV. The $R_{p\text{Pb}}$ of both prompt and non-prompt $J/\psi$ were measured to be above unity by about 10-30% showing no significant dependence on $p_T$ and rapidity. After applying the centrality bias correction, the $R_{p\text{Pb}}$ do not exhibit dependence on number of participating nucleons. The centrality bias correction also weakens the linear correlation between the self-normalized ratios of $J/\psi$, $\psi(2)$, and Z boson production and self-normalized transverse energy measured in the forward calorimeter, $E_T^{\text{Cal}}/E_T^{\text{Cal}}$.

While the $R_{p\text{Pb}}$ of $J/\psi$ shows an enhancement with no significant $p_T$ dependence, the previously measured charged particle $R_{\text{pPb}}$ exhibited a significant increase for $p_T \gtrsim 10-20$ GeV reaching a maximum of 1.4 at $p_T \approx 60$ GeV [13]. This unexpected excess in yields of charged particles seen across different rapidity bins contrasts with only little modification seen in the measurement of inclusive jet production discussed previously. Thus, a measurement of jet fragmentation was performed [14] to shed light on the origin of this effect. In that measurement, the $p\text{Pb}$ data were compared to a $pp$ reference, constructed by extrapolating the measured fragmentation functions in 2.76 TeV $pp$ collisions to 5.02 TeV. Using this reference, a ratio of fragmentation functions, $R_{D(z)} = D(z)|_{\text{pPb}}/D(z)|_{pp}$, was constructed. The measured $R_{D(z)}$ exhibits a z-dependent excess with a maximal magnitude of approximately 10% for $0.2 \lesssim z \lesssim 0.8$ in jets with $p_T > 80$ GeV. The $z$ and $p_T$ ranges over which the $R_{D(z)}$ distributions are enhanced correspond to the same range in transverse momentum where the inclusive charged particle spectrum in $p\text{Pb}$ collisions is enhanced.

Not only high-$p_T$ probes measured in $p\text{Pb}$ collisions brought new interesting physics, but also a region of low $p_T$ revealed unexpected strong signals. Shortly after the first $p\text{Pb}$ run a double-ridge structure in long-range pseudorapidity correlations was observed in high-multiplicity $p\text{Pb}$ collisions [15]. In subsequent studies [16] [17], the azimuthal structure of such long-range correlations was Fourier decomposed to obtain the harmonics $v_n$ as a function of $p_T$ and event activity. The extracted $v_n$ values for $n = 2$ to 5 decrease with $n$. The $v_2$ and $v_3$ values were found to be positive in the measured $p_T$ range. The $v_1$ was also measured as a function of $p_T$ and was observed to change sign around $p_T \approx 1.5 - 2$ GeV and then increase to about 0.1 for $p_T > 4$ GeV. The $v_2(p_T)$, $v_3(p_T)$ and $v_4(p_T)$ were compared to the $v_n$ coefficients in $p+\text{Pb}$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV with similar event multiplicities. Reasonable agreement was observed after accounting for the difference in the average $p_T$ of particles produced in the two collision systems. This agreement suggests that the long-range ridge correlations in high-multiplicity $p\text{Pb}$ collisions and peripheral Pb+Pb collisions are driven by similar dynamics.

3. Physics of Pb+Pb collisions

Not only $p\text{Pb}$ collisions but also measurements of high-$p_T$ photons and electroweak bosons in Pb+Pb collisions can be used to study the nuclear initial state effects and the role of the geometry of colliding nuclei. Recently, the prompt photon production [18] and the production of $W^\pm$ [19] was measured in Pb+Pb collisions. Earlier, the production of Z bosons in Pb+Pb collisions was studied [20].

Inclusive photon yields, scaled by the mean nuclear thickness function, were measured as a function of collision centrality and transverse momentum in two pseudorapidity intervals, $|\eta| < 1.37$ and $1.52 \leq |\eta| < 2.37$. The scaled yields in the two pseudorapidity intervals, as well as
the ratios of the forward yields to those at midrapidity, were compared to the expectations from next-to-leading order perturbative QCD calculations from Jetphox [21]. The scaled yields agree well with the predictions for $pp$ collisions within statistical and systematic uncertainties. Both the yields and ratios of prompt photons were 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 nucleon parton distribution functions. The data are unable to distinguish between the three scenarios. However, the overall consistency of the measured yields with Jetphox expectations for all centrality intervals demonstrates that photon yields in heavy ion collisions scale with $N_{\text{coll}}$, that is with the mean nuclear thickness, as expected.

The $W^-\pm$ boson production was measured in electron and muon decay channels. The differential production yields 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, $|\eta|$, within $|\eta| < 2.5$. The $W$ boson yields scaled by $1/N_{\text{coll}}$ were found to be independent of centrality and in a good agreement with NLO pQCD predictions. Due to the different isospin content of Pb+Pb compared to $pp$ collisions, the lepton charge asymmetry from $W^-\pm$ boson decays differs from that measured in $pp$ collisions. The lepton charge asymmetry agrees well with theoretical predictions using pQCD at NLO with CT10 [22] PDF sets with and without EPS09 nuclear corrections. Clearly, further improvements in the experimental precision and uncertainties in the theory are needed to establish the existence of nuclear effects. Despite that, these measurements provide further support for the interpretation of the clear modification of jet yields in Pb+Pb collisions as a function of centrality, relative to those measured in proton-proton collisions, as stemming from energy loss in the hot, dense medium.

First measurement of jet suppression [23, 24] were followed recently by a precise measurement of jet nuclear modification factor, $R_{\text{AA}}$, which was evaluated as a function of centrality, jet $p_T$, and jet rapidity [25]. The jet yields were measured over the kinematic range of jet transverse momentum $32 < p_T < 500$ GeV, and absolute rapidity $|y| < 2.1$. The jet $R_{\text{AA}}$ was found to reach a value of approximately 0.5, implying that the jet yields are suppressed by a factor of two in central collisions compared to $pp$ collisions. The $R_{\text{AA}}$ shows a slight increase with $p_T$ and no significant variation with rapidity. This later observation is in particular striking given the large differences in slopes of jet spectra and differences in the jet flavor at different rapidities. Also striking is relatively sizable modification seen in 60-80% peripheral collisions with the $R_{\text{AA}} \approx 0.8$ for jets with $p_T < 100$ GeV.

A high-precision measurements of jet $R_{\text{AA}}$ is only possible with a good understanding of the detector response, in particular the jet energy scale (JES) which was elaborated in Ref. [26]. The JES was constructed by calibrating the heavy ion (HI) jets with respect to the standard $pp$ jets using the analysis of $pp$ collision data. The JES for the latter is well understood through a combination of in situ techniques in which the transverse momentum balance between a jet and a reference object such as a Z boson or $\gamma$ was measured. To establish a JES calibration for the HI jets, $pp$ data at $\sqrt{s} = 8$ TeV recorded in 2012 were analyzed and both $pp$ and HI jets were reconstructed. The $pp$ jets were then used as a reference to cross calibrate the HI jets. Applying the HI JES in data from different run periods requires to further consider the effects of different detector operating conditions as well as the fact that the flavor fractions are expected to change with beam energy. An uncertainty on the absolute JES was then derived for HI jets resulting from the “baseline” uncertainty on the reference jets, additional uncertainties in the cross calibration procedure itself and the flavor composition and response uncertainties of HI jets. Finally, differences in the response to quenched jets were evaluated and a systematic uncertainty which accounts for such differences was derived using the PYQUEN [27] sample. The PYQUEN generator was setup to run in two different configurations chosen to match the modifications of fragmentation functions measured in the data. The total JES uncertainty in central Pb+Pb collisions was found to be largest at low $p_T$, approximately 4% at 30 GeV, and
requiring the jet pair to traverse different lengths of the medium. The dependence of the azimuthal distribution, termed by as much as 20% between in-plane and out-of-plane directions and a significant elliptic event-plane. These measurements effectively study the path-length dependence of the jet transverse momentum is carried in the number of particles with \(0 < z < 0.2\) and an enhancement in fragment yield for \(z < 0.04\). A smaller, less significant enhancement was observed at large \(z\) in central collisions. Similar observations were done also for the distributions of transverse momenta of charged particles reconstructed inside jets. From the analysis of measured distributions it was concluded for the 0-10% most central collisions that the increase in the number of particles with \(0.02 < z < 0.04\) is less than one particle per jet. A decrease of about 1.5 particles per jet was observed for \(0.04 < z < 0.2\). Further it was concluded that in the 0-10% most central collisions a small fraction, <2%, of the jet transverse momentum is carried by the excess particles in \(0.02 < z < 0.04\) for central collisions, but that the depletion in fragment yield in \(0.04 < z < 0.2\) accounts on average for about 14% of jet \(p_T\). These observations should directly help to improve understanding of modifications of parton showers in the medium.

To improve understanding of the path length dependence of the jet quenching and the role of fluctuations in the jet quenching, three more differential measurements have been performed: the measurement of azimuthal dependence of inclusive jet yields and the measurement of correlation between dijet-asymmetry and event-shape variables and the measurement of azimuthal dependence of inclusive jet yields. From the analysis of the measured distributions it was concluded for the 0-10% most central collisions that the increase in the number of particles with \(0.02 < z < 0.04\) is less than one particle per jet. A decrease of about 1.5 particles per jet was observed for \(0.04 < z < 0.2\). Further it was concluded that in the 0-10% most central collisions a small fraction, <2%, of the jet transverse momentum is carried by the excess particles in \(0.02 < z < 0.04\) for central collisions, but that the depletion in fragment yield in \(0.04 < z < 0.2\) accounts on average for about 14% of jet \(p_T\). These observations should directly help to improve understanding of modifications of parton showers in the medium.

To improve understanding of the path length dependence of the jet quenching and the role of fluctuations in the jet quenching, three more differential measurements have been performed: the measurement of azimuthal dependence of inclusive jet yields and the measurement of correlation between dijet-asymmetry and event-shape variables and the measurement of azimuthal dependence of inclusive jet yields. The results of these three measurements are described in the next paragraphs.

In the measurement of the azimuthal dependence of inclusive jet yields, the variation of inclusive jet suppression as a function of relative azimuthal angle, \(\Delta \phi\), with respect to the elliptic event plane was measured for jets with \(p_T > 45\) GeV in six different collision centrality bins. The variation of the jet yield with \(\Delta \phi\) was characterized by the parameter, \(v_2^{\text{jet}}\), and the ratio of out-of-plane (\(\Delta \phi \sim \pi/2\)) to in-plane (\(\Delta \phi \sim 0\)) yields. Non-zero \(v_2^{\text{jet}}\) values were measured in all centrality bins for jets with \(p_T < 160\) GeV. The jet yields were observed to vary by as much as 20% between in-plane and out-of-plane directions and a significant \(v_2^{\text{jet}}\) of 2-5% was observed even at very large jet \(p_T\). This \(v_2^{\text{jet}}\) is a direct measure of the differential energy loss suffered by hard partons as they traverse different path-lengths of the medium in events characterized by the same collision centrality.

Motivated by \(v_2^{\text{jet}}\) measurements, a similar analysis was performed for the dijet asymmetry. The dijet asymmetry, \(A_J\), was studied as a function of angle between the leading-jet and the elliptic event-plane. These measurements effectively study the path-length dependence of \(A_J\) by requiring the jet pair to traverse different lengths of the medium. The dependence of the \(A_J\) on the event-plane angle was quantified by calculating the second Fourier coefficient of the \(A_J\) azimuthal distribution, termed \(c_2\). The measured \(c_2\) signal is quite small ( \(\leq 2\%\)), however, it is consistently negative, indicating a slightly larger asymmetry when the dijet pair is oriented out-of-plane than in-plane. This measurement was further extended by repeating the analysis when
constraining the shape of the collision geometry by selecting events based on the magnitude of the second-order flow harmonic quantified by the magnitude of the $q_2$ vector. Within a given centrality interval, events with large $q_2$, i.e. events with a more elliptic geometry, show an increase in the $c_2$ for the 20-30% and 30-40% centrality bins. In other centrality intervals, the statistical precision of the results, obtained with additional binning in $q_2$, is insufficient to conclude the observation of any systematic dependence of $\langle A_1 \rangle$ on the event-plane angle.

To further constrain the energy loss models, the measurement of the correlations between jets that are separated by small relative angles was performed. The measured neighbouring jet pairs result primarily from hard radiation by the parton that occurs early in the process of the shower formation. Generally, two neighbouring jets originating from the same hard scattering should have more similar path lengths in the medium compared to the two jets in the previous dijet measurement. Therefore measuring neighbouring jets could probe differences in their quenching that do not result primarily from difference in path length as well as put some constraints to models in which a part of the parton shower radiates coherently in the response to the medium. The production of pairs of correlated jets was quantified using the rate of neighbouring jets that accompany a test jet, $R_{\Delta R}$. This observable was used in past by D0 collaboration to measure the strong coupling constant, $\alpha_s$, and to test its running over a large range of momentum transfers \[33\]. The $R_{\Delta R}$ was evaluated both as a function of test-jet $E_T$ and neighbouring-jet $E_T$. A significant dependence of $R_{\Delta R}$ on collision centrality was observed in both cases, suggesting a suppression of neighbouring jets which increases with increasing centrality of the collision. The centrality dependence of the suppression was further quantified using the centrality-to-peripheral ratio of $R_{\Delta R}$ distributions, $\rho_{R_{\Delta R}}$. The trends seen in $\rho_{R_{\Delta R}}$ evaluated as a function of neighbouring-jet $E_T$ indicate a decrease in suppression with increasing neighbouring-jet $E_T$. The $\rho_{R_{\Delta R}}$ evaluated as a function of test-jet $E_T$ exhibits a suppression reaching values of 0.5-0.7 in 0-10% central collisions and does not show any strong dependence on $E_T$.

The weak $c_2$ signal in the dijet asymmetry, the significant single jet $v_2$ and characteristic behavior seen in the neighbouring jet production can provide strong constraints in particular on the path length dependence of the energy loss.

The azimuthal anisotropy of particle emission is generally a useful tool to study the properties of the hot and dense matter created in heavy ion collisions. At high transverse momenta this anisotropy is understood to result from the path-length dependent energy loss of jets as they traverse the deconfined matter as discussed in previous paragraphs. At low transverse momenta ($p_T \lesssim 3 - 4$ GeV), this anisotropy results from a pressure driven anisotropic expansion of the created matter, with more particles emitted in the direction of the largest pressure gradient. In Pb+Pb collisions, ATLAS has performed event-averaged measurement of elliptic flow and higher order flow harmonics \[34\] [35] [36] [37], the event-by-event flow measurements \[38\] and the measurement of event plane correlations \[39\]. Recently, ATLAS has performed also the measurement of correlations between different flow harmonics in Pb+Pb collisions \[40\]. In that measurement, it was found that $v_2$ is anticorrelated with $v_3$ and this anticorrelation is consistent with similar anticorrelations between the corresponding eccentricities $c_2$ and $c_3$. On the other hand, it was observed that $v_4$ increases strongly with $v_2$, and $v_5$ increases strongly with both $v_2$ and $v_3$. The trend and strength of the $v_m - v_n$ correlations for $n = 4$ and 5 were found to disagree with $m - n$ correlations predicted by initial-geometry models. Instead, these correlations were found to be consistent with the combined effects of a linear contribution to $v_n$ and a nonlinear contribution that is a function of $v_2$ or of $v_2v_3$, as predicted by hydrodynamic models.

A complementary measurement to the measurement of correlations of azimuthal harmonics is the measurement of two particle pseudorapidity correlations \[41\]. Two particle pseudorapidity correlations can probe e.g. the rapidity profile of the initial-state fireball. This ATLAS measurement was done in the pseudorapidity range of $|\eta| < 2.4$ with charged particles having $p_T > 0.5$ GeV. The measured two particle correlation functions show a broad “ridge-like” shape
along $\eta_1 = \eta_2$ and a depletion at around $\eta_1 = -\eta_2$. The correlation functions were expressed in terms of $\eta_- \equiv \eta_1 - \eta_2$ and $\eta_+ \equiv \eta_1 + \eta_2$ which allows to separate the short-range correlation effects (centered around $\eta_- \approx 0$) from the genuine long-range correlations. Further, the measured two particle correlation functions were expanded in terms of products of Legendre polynomials, $T_n(\eta_1)T_m(\eta_2)$, and corresponding coefficients, $a_{n,m}$, were extracted. The first term, $\sqrt{\langle a_n^2 \rangle}$, is connected with the asymmetry between forward and backward particle production which was confirmed to be large as seen previously in other measurements. The second term reflects the even-by-event fluctuation of the width of charged particle multiplicities, $N(\eta)$. Significant mixed coefficients $\langle a_n, a_m \rangle$ are also observed. The most significant group of mixed coefficients $\langle a_n, a_{n+2} \rangle$ is found to be negative, implying that $a_n$ and $a_{n+2}$ are generally anticorrelated. The magnitudes of $\langle a_n, a_{n+2} \rangle$, were found to decrease quickly for larger $n$. These extracted coefficients are generally found to increase for peripheral collisions, which is consistent with the increase of the multiplicity fluctuation for smaller collision systems.

The above presented correlation measurements should help to better understand the (fluctuating) initial conditions of expanding medium and to further test the hydrodynamical paradigm.

The reader is welcome to follow the details in full publications which are listed in [42].

Acknowledgment

This work was supported by Charles University in Prague, projects PRVOUK P45 and UNCE 204020/2012, and by MSMT CR (project INGO LG13009).

References