Proton-lead measurements using the ATLAS detector

Martin Spousta for the ATLAS Collaboration
Charles University in Prague

DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-04/275

Measurements of soft and hard particle production in proton-lead collisions at the LHC have provided surprising results. Measurements of jets and high-p_{T} hadrons have shown an unexpected enhancement in the production of high-p_{T} charged particles and a similarly unexpected variation of the jet yield with proton-lead collision centrality. Studies of correlations in the production of soft particles have provided results that suggest strong collective behavior similar to that observed in lead-lead collisions. We give a brief report on the latest proton-lead measurements done by ATLAS.

1 Introduction

Proton-nucleus collisions at high energies provide an opportunity to study the effect of an extended nuclear target on the dynamics of soft and hard scattering processes and subsequent particle production. This involves extraction of nuclear parton distribution functions as well as disentangling the potential interplay between the soft and hard processes. In this short report we summarize the recent measurements done by ATLAS [1, 2, 3, 4, 5, 6, 7] that may improve our understanding of the physics of proton-nucleus collisions.

The analyses summarized here use the data from proton-lead (p+Pb) collisions measured by the ATLAS experiment. The LHC provided p+Pb collisions in two runs. During the first run in September 2012 and the second run in early 2013 ATLAS has recorded integrated luminosity of approximately 1 $\mu\mathrm{b}^{-1}$ and 29 nb^{-1}, respectively. The LHC was configured with a 4 TeV proton beam and a 1.57 TeV per-nucleon Pb beam that together produced collisions with a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The higher energy of the proton beam results in a net rapidity shift of the nucleon-nucleon centre-of-mass frame relative to the ATLAS rest frame. This rapidity shift is 0.47 towards the proton beam direction.

Some of the measurements are evaluated for several intervals in collision centrality characterized by the total transverse energy measured from the section of ATLAS forward calorimeter (FCal) spanning the pseudorapidity interval $3.2 < \eta < 4.9$, $\sum E_{\mathrm{T}}^{\mathrm{Pb}}$. Centrality intervals were defined in terms of percentiles of $\sum E_{\mathrm{T}}^{\mathrm{Pb}}$ determined using standard techniques [8]. The Glauber model [9] and its Glauber-Gribov extension [10] were used to estimate $\langle N_{\mathrm{part}} \rangle$ or the average value of the nuclear thickness function, $\langle T_{\mathrm{Pb}} \rangle$, for each centrality interval. The Glauber-Gribov model takes into account event-to-event fluctuations in the nucleon-nucleon cross-section, σ_{NN}. Two sets of Glauber-Gribov $\langle N_{\mathrm{part}} \rangle$ results were obtained for two different values of the parameter, Ω, that determines the width of the assumed Gaussian fluctuations in σ_{NN}.

2 Charged particle multiplicities and p_{T} spectra

Historically, the basic experimental observables quantifying the particle production are the charged particle multiplicity and pseudorapidity distributions. Previous measurements at RHIC have shown that the rapidity integrated particle multiplicity in d+Au collisions scales with number of inelastically interacting, or "participating", nucleons, N_{part}. This scaling behaviour has been interpreted as a result of coherent multiple soft interactions of the projectile nucleon in the target nucleus, the so called wounded-nucleon model. The characteristic centrality dependence of charged hadron pseudorapidity distributions showing a strong increase in the yields of nucleus-going direction that was previously observed can be explained by the phenomenology of soft hadron production or in parton saturation models.

Similar features as those seen previously are observed in the charged particle multiplicities measured by ATLAS [2]. In the most peripheral collisions (centrality interval 60-90%), $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ has what appears to be a double-peak structure, similar to that seen in proton-proton (pp) collisions [11]. In more central collisions, the shape of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ becomes progressively more asymmetric, with more particles produced in the Pb-going direction than in the proton-going direction. The increase in the particle production in central relative to the most peripheral collisions is roughly linear in pseudorapidity. The N_{part} scaling of multiplicities exhibits a strong sensitivity to the Glauber modeling: while the standard Glauber modeling leads to a strong increase in the multiplicity per participant pair with increasing N_{part}, the Glauber-Gribov approach leads to a much milder centrality dependence.

The expected particle production rate in p+Pb collisions is determined by the product of the inelastic nucleon-nucleon cross-section, σ_{NN}, and the nuclear thickness function, $\langle T_{\mathrm{Pb}}\rangle$, which is averaged over a distribution of proton impact parameters incident on the nuclear target. The "nuclear modification factor" R_{pPb} can be therefore written as

$$R_{\mathrm{pPb}}(p_{\mathrm{T}}, y^{\star}) = \frac{1}{\langle T_{\mathrm{Pb}}\rangle}\frac{1/N_{\mathrm{evt}}\ \mathrm{d}^2N_{\mathrm{pPb}}/\mathrm{d}y^{\star}\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2\sigma_{\mathrm{pp}}/\mathrm{d}y\,\mathrm{d}p_{\mathrm{T}}}, \quad (1)$$

where nucleon-nucleon cross-section is approximated by pp cross-section, σ_{pp}, neglecting isospin effects. In the absence of nuclear effects at high-p_{T}, the R_{pPb} will be unity. The nuclear modification factor was extracted in two measurements, see Refs.[3, 4]. The reference pp cross-section was determined using the interpolation of cross-sections measured at the centre-of-mass energy of 2.76 and 7 TeV. The nuclear modification factors increase with momentum in the region $0.1 < p_{\mathrm{T}} < 2$ GeV, then they reach a maximum and decrease up to $p_{\mathrm{T}} \approx 8$ GeV and stay constant within the experimental uncertainties until p_{T} of ≈ 20 GeV. The magnitude of the peak strongly depends both on rapidity and centrality. It increases from the proton-going to Pb-going direction and from peripheral to central collisions. The constant region is less sensitive to the different centrality and rapidity intervals. The absolute magnitude of the R_{pPb} and its centrality behaviour strongly depend on the choice of the geometric model.

The nuclear modification factor of charged particles show signs of increasing in the region of $p_{\mathrm{T}} \gtrsim 30$ GeV. This trend does not have a strong rapidity dependence but is more pronounced in peripheral events. This result seems to show the same unexpected trend as was observed by the CMS Collaboration [12].

3 Jets and Z bosons

The nuclear modification factor R_{pPb} was measured also for jets [5] using as a reference the inclusive jet cross-section in $\sqrt{s} = 2.76$ TeV pp collisions x_T-interpolated to 5.02 TeV using previous ATLAS measurements of jet production at 2.76 and 7 TeV. Results were also reported for the central-to-peripheral ratio R_{CP}, made with respect to the 60-90% centrality bin. The centrality-inclusive R_{pPb} results for 0-90% collisions indicated only a modest enhancement over the geometric expectation. This is generally consistent with predictions from the modification of the parton distribution functions in the nucleus.

The results of the R_{CP} measurement indicate a strong, centrality-dependent reduction in the yield of jets in central collisions relative to that in peripheral collisions. The reduction becomes more pronounced with jet p_{T} and at more forward (p-going) rapidities. These two results are reconciled by the centrality-dependent R_{pPb} results, which show a suppression in central collisions and enhancement in peripheral collisions which is systematic in p_{T} and y^*. The R_{CP} and R_{pPb} data at forward rapidities were replotted as a function of $p_{\mathrm{T}} \cosh(y^*)$, the approximate total jet energy. When plotted this way, the results from different rapidity bins fall into roughly a single trend. This suggests that the mechanism responsible for the observed effects may depend only on the total jet energy or, more generally, on the underlying parton-parton kinematics such as the fractional longitudinal momentum of the parton originating in the proton x_p. If the relationship between the centrality intervals and proton-lead collision impact parameter determined within the geometric models is correct, these results imply large, impact parameter-dependent changes in the number of partons available for hard scattering. However, they may also be the result of a correlation between the kinematics of the scattering and the soft interactions resulting in particle production at backward (Pb-going) rapidities.

The influence of nuclear environment on the production of high-p_{T} particles was further tested by measuring the production of Z bosons [6]. The Z bosons were reconstructed via the di-electron and di-muon decay channels. Results from the two channels are consistent and combined to obtain a total cross-section of 144.1 $\pm$ 10.8 nb within the fiducial acceptance region. The total measured cross-section is compared to a baseline pQCD model in which nuclear binding and motion effects are neglected. The p_{T} dependence of the cross-section is in a good agreement with baseline pQCD, however the rapidity dependence shows significant asymmetry compared to the baseline pQCD. A relative excess in the Z boson differential cross-section is seen in the backward (Pb-going) part of the rapidity distribution. This asymmetry is more pronounced in central events and is apparently absent in peripheral events which are roughly symmetric about the centre of mass. Whether the relative asymmetry in central events compared to peripheral events is interpreted as an excess at backward rapidity or a deficit at forward rapidity depends on the choice of Glauber model centrality implementation. This centrality ordering is similar to that observed by ATLAS in high-p_{T} forward jets in p+Pb. The Z boson yield is expected to scale with number of binary collisions, $N_{\mathrm{coll}} = N_{\mathrm{part}} - 1$, however deviations from this scaling are observed, similarly as in the case of the charged particle yields. The charged particle yields are expected to scale with N_{part} and so the ratio $(\mathrm{d}N_Z/\mathrm{d}\eta)/(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y)$ was fitted by a function of the form $a \cdot (N_{\mathrm{part}} - 1)/N_{\mathrm{part}}$ which describes the data well. The agreement in the geometric scaling trends between these two very different observables suggests that both are reflecting the consequences of the initial state conditions of the nucleus.

4 Ridge and flow

One striking observation in high-energy nucleus-nucleus collisions is the large anisotropy of particle production in the azimuthal angle ϕ. This anisotropy is often studied via a two-particle correlation of particle pairs in relative pseudorapidity ($\Delta\eta$) and azimuthal angle ($\Delta\phi$). The anisotropy manifests itself as a strong excess of pairs at $\Delta\phi \sim 0$ and π, and the magnitude of the excess is relatively constant out to large $|\Delta\eta|$. The azimuthal structure of this "ridge-like" correlation is commonly characterized by its Fourier harmonics, $\mathrm{d}N_{pairs}/\mathrm{d}\Delta\phi \sim 1+\sum_n 2v_n^2 \cos n\Delta\phi$. The v_n values are commonly interpreted as the collective hydrodynamic response of the created matter to the collision geometry and its density fluctuations in the initial state. For a small collision system, such as *pp* or p+A collisions, it was assumed that the transverse size of the produced system is too small for the hydrodynamic flow description to be applicable. Thus, it came as a surprise that ridge-like structures were also observed in two-particle correlations in high-multiplicity *pp* and p+Pb collisions.

Recent measurement done by ATLAS [7] explores the detailed properties of the ridge-like correlations and the flow via the two particle correlation (2PC) method. The two-particle correlations and v_n coefficients are obtained as a function of p_{T} for pairs with $2 < |\Delta\eta| < 5$ in different intervals of event activity, defined by either N_{ch}, the number of reconstructed tracks, or total transverse energy measured in FCal on the Pb-fragmentation side, $\sum E_{\mathrm{T}}^{\mathrm{Pb}}$. Significant long-range correlations (extending to $|\Delta\eta| = 5$) are observed for pairs at the near-side ($|\Delta\phi| < \pi/3$). A similar long-range correlation is also observed on the away-side ($|\Delta\phi| > 2\pi/3$), after subtracting the recoil contribution estimated using the 2PC in low activity events. The v_n, ($n = 2, 3, 4, 5$) values increase with p_{T} to $3-4$ GeV and then decrease for higher p_{T}, but remain positive in the measured p_{T} range. The $v_1(p_{\mathrm{T}})$ function is observed to change sign at $p_{\mathrm{T}} \approx 1.5-2.0$ GeV and to increase to about 0.1 at $p_{\mathrm{T}} > 4$ GeV. The magnitudes of v_n increase with both N_{ch} and $\sum E_{\mathrm{T}}^{\mathrm{Pb}}$. The extracted $v_2(p_{\mathrm{T}})$, $v_3(p_{\mathrm{T}})$, and $v_4(p_{\mathrm{T}})$ are compared to the v_n coefficients in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with similar N_{ch}. After applying a scale factor of $K = 1.25$ that accounts for the difference of mean p_{T} in the two collision systems, the shape of the $v_n(p_{\mathrm{T}}/K)$ distribution in Pb+Pb collisions is found to be similar to the shape of $v_n(p_{\mathrm{T}})$ distribution in p+Pb collisions. This suggests that the long-range ridge correlations in high-multiplicity p+Pb collisions and peripheral Pb+Pb collisions are driven by similar dynamics.

Acknowledgments

This work was supported by Charles University in Prague, projects INGOII LG13009, PRVOUK P45, and UNCE 204020/2012.

References

[1] ATLAS Collaboration. *JINST*, 3:S08003, 2008.

[2] ATLAS Collaboration. ATLAS-CONF-2013-096. https://cds.cern.ch/record/1599773.

[3] ATLAS Collaboration. ATLAS-CONF-2013-107. https://cds.cern.ch/record/1624333.

[4] ATLAS Collaboration. ATLAS-CONF-2014-029. http://cds.cern.ch/record/1704978.

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

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

[7] ATLAS Collaboration. arXiv:1409.1792.

[8] ATLAS Collaboration. *Phys.Lett.*, B710:363–382, 2012.

[9] M. Miller, K. Reygers, S. Sanders, and P. Steinberg. *Ann. Rev. Nucl. Part. Sci.*, 57:205–243, 2007.

[10] V. Guzey and M. Strikman. *Phys. Lett.*, B633:245–252, 2006.

[11] ATLAS Collaboration. *Phys. Lett.*, B688:21–42, 2010.

[12] CMS Collaboration. CMS-PAS-HIN-12-017. http://cds.cern.ch/record/1625865.