What have we learned about the Quark-Gluon Plasma with the ATLAS detector at the LHC?

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Abstract

Recent results from lead-lead and proton-lead collisions, measured by the ATLAS experiment at the LHC, are presented. In lead-lead collisions, electroweak bosons are found to be produced proportionally to the number of binary nucleon-nucleon collisions, and to have rapidity distributions compatible with perturbative QCD calculations, suggesting no need for large nuclear PDF effects. Conversely the large suppression of inclusive jets, the elliptic flow of hadrons at high p_T and the direct measurements of jet v_2 support the need for a path-length dependent energy loss in the hot, dense medium. Proton-lead measurements provide new insights on particle production in small, longitudinally asymmetric systems, but require further insights into the fluctuating nature of proton-proton collisions. The modification factors for charged hadrons show a non-trivial dependence on centrality and rapidity, with a “Cronin” peak appearing only in the most central events, and in the lead-going direction. Finally the measurements of inclusive jets in proton-lead show a striking scaling in the R_{CP} suppression variable that is only a function of the jet momentum, while the suppression factor relative to PYTHIA jet cross sections show an enhanced yield in peripheral events, and a suppressed yield in central events.

Keywords: heavy ion collisions, proton-ion collisions, Large Hadron Collider, ATLAS experiment, jet quenching, particle multiplicities, nuclear suppression factors

1. Introduction

Since 2010, the ATLAS detector has taken heavy ion data at the highest available energies at the Large Hadron Collider (LHC) at CERN. The goal has been to elucidate the properties of the hot, dense medium formed in the collisions of heavy ions. ATLAS has three major subsystems [1], which make it a powerful detector for probing the properties of the quark-gluon plasma. The inner detector measures charged tracks out to $|\eta| < 2.5$ in full azimuth in three layers of pixel detectors and four layers of double-sided strip detectors. Muons are measured out to $|\eta| < 2.7$ using a combination of drift detectors and cathode strip chambers. Jets are measured in the large-acceptance, longitudinally-segmented electromagnetic and hadronic calorimeters, which extend to $|\eta| < 4.9$. The lead-lead data have been used to study the collective expansion of the medium as a function of collision geometry in great detail, as well as to investigate the energy loss of jets, by means of their suppression in central events. Electroweak bosons are used to verify the expected parton luminosity available in the initial state. The proton-lead data have been used to study collective behavior in small systems as well as the behavior of high p_T processes in the presence of a nucleus.

2. What have we learned from Pb+Pb

In the 2010 and 2011 runs, ATLAS collected $7 \mu\text{b}^{-1}$ and 0.14 nb^{-1} of lead-lead collision data, respectively. The 2010 dataset had relatively low luminosity, but also very low event-level pileup. The interaction rates were sufficiently

Figure 1. (left) Rapidity distribution of the number of Z bosons per minimum bias event, compared with the rapidity distribution from PYTHIA, scaled up by the mean nuclear thickness function multiplied by a cross section calculated at NNLO. Reproduced from Ref. [4]. (right) W charged asymmetry for the 0-80% centrality interval, as a function of the lepton η . Reproduced from Ref. [5].

low to collect the data with only minimum bias triggers. The 2011 dataset provided a much more detailed look at hard processes with triggers for jets, electrons, photons, and muons. This provided a complete first look at the soft physics sector (multiplicity, charged spectra and flow of charged hadrons) and the modification of hard processes in the hot, dense medium. The distributions have been found to compare well to a theoretical calculation which includes energy density fluctuations on the subhadronic level, based on classical Yang-Mills dynamics [2]. The fact that theory calculations can now reproduce data on the mean behavior of the flow coefficients $v_n(p_T)$ as a function of p_T and centrality shows that we are in a new era of understanding the soft sector. However, most of these calculations do not yet fully address the details of the longitudinal dynamics. In general, very little change in the flow coefficients is observed in $|\eta|$, a feature invariant with p_T and centrality.

Hard processes are probed in lead-lead collisions using both jets and electroweak bosons (photons and W/Z). While jets are expected to be modified in the hot, dense medium by a combination of elastic and radiative processes, electroweak bosons are not expected to interact with the medium. Thus, they should be produced similarly as in pp collisions, except effects related to isospin (the neutron fraction in the lead-lead system), and possibly modifications to the nuclear PDFs, e.g. as implemented in the EPS09 PDF set [3].

Fig. 1(left) shows the rapidity distribution of Z bosons measured in both the di-electron and di-muon channels for the 0-80% centrality interval (essentially a minimum bias distribution) [4]. It is compared to a theoretical prediction based on the rapidity distribution of Z bosons produced by PYTHIA, scaled up to a cross section calculated at NNLO precision. When the measurement is performed as a function of collision centrality, the yield of Z's is found to scale nearly linearly with the number of binary collisions.

A similar study has been performed using W bosons in lead-lead collisions, measured in the single muon channel, but with jet background suppressed by requiring a large missing- E_T based on charged tracks with $p_T > 3$ GeV. The residual jet background is taken from full simulations based on PYTHIA and is rescaled to the muon $p_T = 10 - 20$ GeV, giving only 3.7% average background in the region $p_T > 25$ GeV. The yield of W bosons per event, divided by the mean number of binary collisions, is found to be constant with collision centrality, within statistical and systematic errors, and are reasonably well described by the NLO cross sections. The right panel of Fig. 1 shows the charge asymmetry $(W^+ - W^-)/(W^+ + W^-)$ as a function of the lepton η in the 0-80% centrality interval [5]. The data is well described by the NLO cross sections, as well as by a similar LO* calculation.

With the current data, there is no need to incorporate any nuclear modifications of the PDFs to understand either the yield and centrality dependence of Z and W boson production, or their rapidity dependence.

While electroweak bosons demonstrate the expected scaling with the number of binary collisions, and show no strong effects from the nuclear wave function, jet rates and structure are clearly modified substantially by the hot,

Figure 2. (left) Charged hadron v_2 for the 40-50% centrality interval, as a function of p_T for $p_T < 20$ GeV, compared with data from ALICE from the LHC, and STAR and PHENIX from RHIC, reproduced from Ref. [6]. (right) $v_2(p_T)$ for fully reconstructed jets, reproduced from Ref. [7].

dense medium. Large asymmetries were seen in the comparison of the leading and subleading jets produced in more central heavy ion collisions. Also, the inclusive yields of jets are suppressed by a factor of about two in the 0-10% centrality interval, relative to the peripheral 60-80% interval. ATLAS has studied the path length dependence of jet suppression both by looking at the charged particle v_2 at high transverse momentum ($p_T > 10$ GeV) [6], and by the v_2 of fully-reconstructed jets with $p_{T,jet} > 45$ GeV [7], as seen in the left and right panels, respectively, of Fig. 2. It is interesting to note that the jet v_2 in the 40-50% centrality interval (lower left subpanel) is continuous at low jet p_T with the highest- p_T charged hadron v_2 for events with the same centrality selection. More detailed studies of these quantities, especially with the higher energy and luminosity available in the next LHC run, should enable a full investigation of the path-length dependence of jet quenching.

3. What have we learned from proton-lead collisions

The proton-lead program at the LHC was the first time nuclei were bombarded with high energy protons since Fermilab fixed target program, with a huge jump in collision energy (over a factor of 100). While originally intended to isolate the effects of the nuclear wave function on hard processes, even the very first measurements of soft and semi-hard observables (e.g. multiplicity, charged particle spectra) have revealed subtle conceptual issues pertaining to both nucleon-nucleon collisions, and to the conditions under which a quark-gluon plasma can be formed [8].

The estimation of the collision geometry, e.g. the average number of participating nucleons, or the average number of binary collisions, had been explored in p+A collisions at FNAL, using cross section ratios, and in d+Au collisions already at RHIC, using a similar methodology to that applied in heavy ion collisions. In the latter approach, the distribution of a geometric quantity, e.g. the number of participants, is estimated from a Glauber model, and then one models the inclusive proton-lead or lead-lead distribution of an experimental observable as a convolution of that observable of nucleon-nucleon collisions. Central to this process is the assumption that every nucleon-nucleon collision is the same as the others and that a nucleon always interacts with another nucleon according to the same cross section. However, this assumption is known to be incorrect. The fact that diffractive cross sections are relatively large in proton-proton collisions already suggests that the nucleon wave function is a superposition of Fock states (typically expressed in partonic language), which have different absorption probabilities on the different Fock states of the oncoming nucleon. This leads to event-by-event fluctuations in the effective nucleon-nucleon cross section. Alvioli and Strikman [9], have interpreted these cross-section fluctuations as color fluctuations, where the partonic content of the nucleon can have widely varying spatial extent event by event. Thus, even for proton-nucleus collisions at fixed impact parameter, configurations of the nucleon which cover a large transverse size could lead to single

Figure 3. (left) $dN_{ch}/d\eta$ for proton-lead collisions, after selecting on different centrality intervals using the ATLAS forward calorimeter in the lead-going direction. (right) The scaled rapidity density as a function of centrality, for several η regions and using three Glauber-Gribov calculations [9]. Both figures reproduced from Ref. [10].

events with an unusually large number of participants than that for other events. ATLAS has implemented Alvioli and Strikman's parametrization of the nucleon-nucleon cross section fluctuations, which are characterized by a parameter Ω , zero in the “hard disk” case, estimated to have a value of $O(0.5-1)$ based on diffractive and multi-nucleon collision data. In the most central 1% of events, the different choices of Ω give values of $\langle N_{part} \rangle$ that are 35-55% larger than the standard Glauber calculations.

Fig. 3 shows the inclusive charged-particle pseudorapidity distributions for different centrality selections [10]. It is observed that the most peripheral collisions have the most symmetric distributions, while the most central events are asymmetric, with a larger multiplicity in the lead-going direction. It is intriguing that for $\Omega = 0.55$, the particle density scaled by $\langle N_{part} \rangle/2$ is approximately constant near $\eta = 0$. This is a behavior seen at lower energies and something that is violated in the most central events by the standard Glauber calculations. It is also noted that the particle yields per participant pair increase systematically in the forward (lead-going) region ($2 < \eta < 2.7$) and decreases systematically in the backwards (proton-going) direction ($-2.7 < \eta < -2$). This is suggestive of the scenario suggested in Ref. [11] in which the rapidity distribution is symmetric in the participant center-of-mass frame, shifting with respect to the nucleon-nucleon frame in more central events as $\Delta y = (1/2) \ln N_{coll}$.

The basic features of inclusive particle production are a useful context when considering the systematic behavior of charged hadron suppression, particularly at high p_T . This was studied to get a first hint as to whether high p_T processes were modified by the presence of a nuclear wave function. Using the data from the 2012 proton-lead pilot run, ATLAS has measured the modification of charged hadron production as a function of centrality, transverse momentum and y^* , the hadron rapidity in the center of mass frame (i.e. after compensating for the boost of the nucleon-nucleon collision system) [12]. While each hadron is originally treated as having the pion mass, the distributions are corrected using the hadron populations found in HIJING, which have been checked against all existing data from the proton-lead runs. The proton-proton reference data was constructed by interpolating inclusive charged hadron production data from $\sqrt{s} = 2.76$ and 7 TeV to form cross sections as a function of p_T and y^* . Fig. 4 shows the suppression factor $R_{pPb} = d^2N/dp_T dy^* / (T_{pPb} d^2\sigma_{pp}/dp_T dy^*)$. Several important features emerge from this systematic study. Up to the highest p_T studied (20 GeV), no strong nuclear modification is seen, in particular when using the $\Omega = 0.55$ fluctuation model. However, an enhancement at moderate p_T values, typically called the “Cronin effect”, can only be observed clearly in the most central events and at backwards (Pb-going) rapidities. From Fig. 3, this is the region of the highest particle density. It is intriguing that the transverse dependence of the enhancement, particularly the peak

Figure 4. Hadron suppression factor as a function of centrality, p_T and y^* , for three centrality intervals and using $\langle T_{pPb} \rangle$ calculated under three assumptions for NN cross section fluctuations. Reproduced from Ref. [12].

Figure 5. (left) Proton-lead data on the central-vs.-peripheral suppression factor R_{CP} as a function of collision centrality, relative to the 60-90% centrality interval. (right) Proton-lead data on jet suppression relative to a proton-proton spectrum calculated using PYTHIA (details described in the text). Both figures reproduced from Ref. [14].

at 3 GeV, resembles the same feature seen in the left panel of Fig. 2 for the high p_T behavior of v_2 . To suggest that the Cronin effect is a collective effect would have seemed preposterous before the observation of the “double ridge” at the LHC [8]. However, given the observation of higher-order flow harmonics and non-zero multiparticle cumulants [13], its interpretation as a possible collective effect seems more plausible at the present time.

While the charged hadron results seemed to suggest the absence of any nuclear modifications to high p_T processes, ATLAS has performed a similar measurement with fully reconstructed jets, using the anti- k_t algorithm with $R=0.4$ [14]. Doing so extends the kinematic reach of the underlying partonic $2 \rightarrow 2$ process to very high x , in particular by looking at jets in the far-forward region ($\eta < -3$) using the ATLAS forward calorimeter. The kinematic region was limited to the region in which the corrections applied to the raw jet yields were independent of proton-lead

centrality. The left panels of fig. 5 shows the nuclear suppression factor R_{CP} formed using the yields measured in the 60-90% centrality interval as the reference. It is observed that the yields measured in the 0-10% centrality interval are strongly suppressed relative to the peripheral events. This relative suppression increases with increasing rapidity in the proton-going direction. An interesting scaling behavior is observed by measuring the suppression as a function of the jet momentum, $p = p_T \cosh y^*$. All of the rapidity dependence collapses onto a single trend and the relative suppression is found to be a function only of the jet momentum, with a very strong suppression at high jet p . To compare the jet yields measured in proton-lead to proton-proton collisions, a reference jet spectrum was made using PYTHIA (version 6.425, AMBT2 tune, CTEQ6L1 PDFs). The suppression factors using this spectrum are shown in the right panel of Fig 5. For a minimum bias (0-90%) selection, no jet suppression is observed out to the highest p_T . Rather, the data is consistent with a small, but significant, enhancement near mid-rapidity, of about $R_{pPb}^{PYTHIA} = 1.2$. And yet, while a clear, albeit mild, suppression is observed in central events, the peripheral events show a rather strong enhancement, a phenomenon seen previously by PHENIX [15], but never fully explained theoretically. It remains a fascinating open question how to understand why the overall number of jets in proton-lead collisions is observed near or only slightly-above expected rates, while their behavior in both the most peripheral and the most central events are so strongly modified.

4. Conclusions

In this proceedings, recent results from the ATLAS experiment from lead-lead and proton-lead collisions have been shown. The lead-lead results indicate the presence of strong energy loss of jets in the hot, dense medium. However, the proton-lead results also require further investigation into the fluctuation nature of proton-proton cross sections, as well as a more detailed understanding of the scaling of hard processes with collision geometry, particularly at high x .

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