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Jets and charged particles in p+Pb and Pb+Pb collisions with the ATLAS Experiment

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In these proceedings we summarize measurements by the ATLAS experiment related to jets and high-p_T charged particles in proton-lead and lead-lead collisions from run 1 of the LHC. In particular we summarize measurements of inclusive jets, dijets, the jet substructure, and inclusive charged particles. Related to that is the measurement of soft-hard correlations in pp collisions which is also summarized in these proceedings.

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1. Jets and charged particles in proton-lead collisions

In this section we summarize studies of jets and high-p_T charged particles in proton-lead (p+Pb) collisions by the ATLAS experiment [1] in the LHC run 1. We start from measurements of jet yields, going through measurements of correlations between soft and hard processes and end with the measurement of yields of charged particles.

Measurement of the inclusive jet production in p+Pb [2] 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) [3] 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, $R_{p\mathrm{Pb}}$, 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 [4]. In that study, the underlying event was characterized through measurements of the average sum of the transverse energy at large negative pseudorapidity, $\langle \Sigma E_{\mathrm{T}} \rangle$, which were reported as a function of hard scattering kinematic variables. The hard scattering was characterized by the average transverse momentum, p_T^{avg}, and pseudorapidity, η^{avg}, of the two highest transverse momentum jets in the event. It was found that the $\langle \Sigma E_{\mathrm{T}} \rangle$ is anticorrelated with the dijet p_T^{avg}, decreasing by 25% as p_T^{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 p+Pb results, since they indicate a nontrivial correlation between hard scattering kinematics and ΣE_{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 for 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_{targ}, and only weakly with that in the projectile proton, x_{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_{targ}), and is mostly insensitive to x in the other proton (x_{proj}). These results provide counter-evidence to claims that the observed centrality-dependence of the jet rate in p+Pb 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 conservation [5]). In the p+Pb 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_{proj}. The effect seen in the p+Pb data could be interpreted as a feature of nucleon-nucleon collision if the transverse energy production at small angles decreased strongly and continuously with increasing x_{proj} which is an opposite trend to the one presented here.

Another interesting phenomenon seen in p+Pb collisions is a significant increase of charged particle $R_{p\mathrm{Pb}}$ for $p_T \gtrsim 10-20$ GeV. This increase reached a maximum of 1.4 at $p_T \approx 60$ GeV [6]. 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 above. Thus, a measurement of jet fragmentation was performed [7] to shed light on the origin of this effect. In that measurement, the p+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, $R_{D(z)} = D(z)|_{p\mathrm{Pb}}/D(z)|_{pp}$, was evaluated. The measured $R_{D(z)}$ exhibited 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 were seen to be enhanced correspond to the same range in transverse momentum where the inclusive charged particle spectrum in p+Pb collisions was observed to be enhanced. While the results with the extrapolated reference are interesting, they also indicate that reference pp measurement at 5.02 TeV needs to be used to make sure that unexpected biases do not occur in these results.

2. Jets and charged particles in lead-lead collisions

First measurements of jet suppression by ATLAS [8, 9] were followed recently by a precise measurement of jet nuclear modification factor, R_{AA}, which was evaluated as a function of centrality, jet p_T, and jet rapidity [10]. 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_{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_{AA} shows a slight increase with p_T and no significant variation with rapidity. This later observation is particularly striking given the large differences in slopes of jet spectra and differences in the jet flavor at different rapidities. Also striking is the relatively sizable modification seen in 60-80% peripheral collisions with the $R_{\mathrm{AA}} \approx 0.8$ for jets with $p_T < 100$ GeV. This high-precision measurements of jet R_{AA} is only possible with a good understanding of the detector response, in particular the jet energy scale (JES) which was elaborated in Ref. [11].

A complementary measurement to the jet R_{AA} is the R_{AA} of charged particles [12]. In that analysis, the charged particle spectra were measured over a wide transverse momentum range, $0.5 < p_T < 150$ GeV, and in eight bins of pseudorapidity covering the range of $|\eta| < 2$. The charged particle R_{AA} shows a distinct p_T dependence with a pronounced minimum at about 7 GeV. Above 60 GeV, R_{AA} is consistent with a plateau at a centrality-dependent value which is approximately 0.55 for the 0-5% most central collisions. The R_{AA} distribution is consistent with flat pseudorapidity dependence over the whole transverse momentum range in all centrality classes.

Since inclusive charged particles measured at different transverse momenta come from jets of different original energies, there is no simple mapping between the modified charged particle yields and the modification of the jet internal structure. Thus, our understanding of the jet quenching should strongly profit from the direct measurement of jet fragmentation which was published in

Ref. [13]. In that measurement, it was found that the central-to-peripheral ratios of fragmentation functions of jets with $p_T > 100$ GeV show a reduction of fragment yield in central collisions relative to peripheral collisions at intermediate z values, $0.04 < z < 0.2$ 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 $0.02 < z < 0.04$ but the depletion in fragment yield in $0.04 < z < 0.2$ accounts on average for about 14% of jet p_T. This implies that the energy is redistributed to particles with $p_T < 2$ GeV. Recently, the dependence of the jet fragmentation on the jet p_T and η was explored [14]. In that measurement, the jet fragmentation was evaluated differentially in four bins of jet p_T ($p_T > 100$ GeV, $100 < p_T < 126$ GeV, $126 < p_T < 158$ GeV, $p_T < 158$ GeV) for jets with $|\eta| < 2.1$ and differentially in four bins of jet η ($|\eta| < 2.1$, $|\eta| < 0.3$, $0.3 < |\eta| < 0.8$, $1.2 < |\eta| < 2.1$) for jets with $p_T > 100$ GeV. It was shown that the difference in the modifications between different pseudorapidity selections is marginal for fragments with $p_T < 25$ GeV and $z < 0.25$. Only at high p_T of charged particle or high z a change in the trend may be observed, where the enhancement is systematically lower for more forward jets compared to jets measured in the central pseudorapidity region. No significant difference was observed between jets with $100 < p_T < 126$ GeV and jets with $126 < p_T < 158$ GeV. However, a clear difference is seen for jets with p_T in these two p_T intervals and jets with p_T in the interval of $158-398$ GeV where the enhancement at high-p_T of fragments is systematically lower. In that new measurement, more details on the transverse momentum flow was also provided by evaluating the integrals of yields of fragments as a function of centrality. These detailed measurements 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, a new dijet asymmetry measurement was performed [15]. This new measurement provides a first detector-effects corrected result on the dijet asymmetry in pp and Pb+Pb collisions. The asymmetry was measured in terms of x_{J}, which was defined as $x_{\mathrm{J}} = p_{T,1}/p_{T,2}$ where $p_{T,1}$ and $p_{T,2}$ are the leading and subleading jet transverse momentum, respectively. The measurement was performed differentially in $p_{T,1}$ and in collision centrality. The measured distributions were unfolded to account for the effects of experimental resolution on the two-dimensional $p_{T,1} - p_{T,2}$ distributions and then projected into bins of fixed x_{J}. The distributions show a larger contribution of asymmetric dijet pairs in Pb+Pb data compared to that in pp data. The contribution of asymmetric dijet pairs is shown to grow with centrality. In the 0-10% centrality bin at $100 < p_{T,1} < 126$ GeV, the x_{J} distribution develop a significant peak at $x_{\mathrm{J}} \approx 0.5$ indicating that the most probable configuration for dijets is for them to be highly imbalanced. This is in sharp contrast to the situation in the pp data where the most probable values are near $x_{\mathrm{J}} \approx 1$. The centrality-dependent modifications evolve smoothly from central to peripheral collisions, and the results in the 60-80% centrality bin and the pp data are generally consistent. At larger values of $p_{T,1}$ the x_{J} distributions are observed to narrow and the differences between the distribution in central

Pb+Pb and the pp data lessen. This is consistent with a picture in which the fractional energy loss decreases with jet p_T. This result constitutes an important benchmark for theoretical models of jet quenching and it provides constrains for modeling the dynamics of parton energy loss.

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