Jet fragmentation with the ATLAS detector

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Abstract

We report on the measurements of jet fragmentation in Pb+Pb collisions with the ATLAS detector at LHC. The data were collected during 2011 heavy ion run providing Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. These measurements are expected to provide an insight into the modifications of jets initiated by partons passing through hot and dense QCD matter created in heavy ion collisions.

1 Introduction

Measurement of jet fragmentation is essential for understanding the jet quenching. Jet quenching refers, collectively, to a set of possible modifications of parton showers by the quark-gluon plasma through interactions of the constituents of the shower with the colour charges in the plasma. Shower constituents may be elastically or inelastically scattered resulting in both deflection and energy loss of the constituents of the shower. This modification of jet internal structure may be then detected as a modification of the jet fragmentation functions. Jet quenching was first observed at RHIC via suppression of high-$p_T$ charged particles and later measured at LHC using fully reconstructed jets.

First measurements of the jet fragmentation done at LHC using data collected during 2010 heavy ion run suggested that the modification of jet internal structure in Pb+Pb collisions is rather weak if any. Larger luminosity of 2011 run enabled to perform more precise measurement which indeed lead to an observation of a modest but significant change in the jet fragmentation. In this short report, we present the latest measurements of jet fragmentation performed by ATLAS using data collected during 2011 heavy ion run.

2 Data selection

Total integrated luminosity used for the presented measurements is 0.14 nb$^{-1}$. The data were selected using high-level trigger (HLT) seeded by a Level-1 minimum-bias trigger. The Level-1 trigger required a total transverse energy measured in the calorimeter of greater than 10 GeV. The HLT jet trigger required a presence of underlying-event-subtracted jet with transverse energy greater than 20 GeV. A total of 14.2 million events were selected after passing standard event-quality criteria. The reference Monte Carlo (MC) event sample was obtained by overlaying simulated PYTHIA$^{13}$ pp hard-scattering events at $\sqrt{s} = 2.76$ TeV onto 1.2 million minimum-bias Pb+Pb events recorded in 2011.

The centrality of Pb+Pb collisions was characterized by $\Sigma E_T^{\text{FCal}}$, the total transverse energy measured in the forward calorimeters. Measurement was performed in seven centrality bins defined according to successive percentiles of the $\Sigma E_T^{\text{FCal}}$ distribution ordered from the most central to the most peripheral collisions: 0–10%, 10–20%, 20–30%, 30–40%, 40–50%, 50–60%, and 60–80%.
3 Characterizing jet fragmentation

Jets used in the presented measurements were reconstructed with the anti-
$k_t^{14}$ algorithm with distance parameter values $R = 0.2, 0.3,$ and $0.4$. The internal structure of the jet was characterized by measuring the transverse momentum ($p_T^{ch}$) and longitudinal momentum fraction ($z \equiv p_T^{ch}/p_T^{jet} \cos \Delta R$) distributions of charged particles with $p_T^{ch} > 2$ GeV produced within an angular range $\Delta R = 0.4$ of the reconstructed jet directions. Here, $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$ where $\Delta \phi$ ($\Delta \eta$) is the difference in azimuthal angles (pseudorapidities) between the charged particle and jet directions. Jets were required to have $p_T^{jet} > 85, 92,$ and 100 GeV for $R = 0.2, 0.3,$ and $0.4,$ respectively.

Two different sets of charged-particle fragmentation distributions were measured for each centrality bin and $R$ value, the transverse momentum distribution,

$$D(p_T) \equiv \frac{1}{\varepsilon} \left( \frac{1}{N_{jet}} \frac{\Delta N_{ch}}{\Delta p_T^{ch}} - \frac{dN_{ch}^{UE}}{dp_T^{ch}} \right),$$

and the fragmentation function,

$$D(z) \equiv \frac{1}{\varepsilon} \left( \frac{1}{N_{jet}} \frac{\Delta N_{ch}}{\Delta z} - \left. \frac{dN_{ch}^{UE}}{dp_T^{ch}} \right|_{p_T^{ch} = z p_T^{jet}} \right).$$

Here $N_{jet}$ represents the total number of jets in a given centrality bin, $\Delta N_{ch}$ represents the number of measured charged particles within $\Delta R = 0.4$ of the jets, $1/\varepsilon$ stands for the tracking efficiency correction, and $dN_{ch}^{UE}/dp_T^{ch}$ represents the background contribution coming from the underlying event (UE) which is subtracted. The background contribution,

$$\frac{dN_{ch}^{UE}}{dp_T^{ch}} = \frac{1}{N_{cone}} \frac{\Delta N_{ch}^{cone}(p_T^{jet}, \eta^{jet})}{\Delta p_T^{ch}},$$

is evaluated for each jet radius separately in events having at least one jet above the jet $p_T$ thresholds using $N_{cone}$ cones of radius $R = 0.4$ covering the full inner detector by a regular grid. Any such cone having a charged particle with $p_T^{ch} > 6$ GeV was assumed to be associated with a real jet in the event and was excluded from the UE background determination. The subtracted background was further corrected to account for proper pseudorapidity distribution of UE and for the elliptic flow.

Two corrections were performed to account for the impact of finite jet energy resolution on the measured distributions. First, the energy of each jet entering the evaluation of $D(p_T)$ and $D(z)$ was shifted to account for the mean effect of the “upfeeding” in a steeply falling jet $p_T$ spectrum produced by the finite jet energy resolution. Then, obtained measured distributions were unfolded to the truth level using SVD – a one-dimensional Singular Value Decomposition (SVD) method$^{15}$ implemented in RooUnfold$^{16}$ which removes also the effects of finite charged particle $p_T$ resolution.

The fragmentation functions are steeply falling distributions. To evaluate the difference between the central collisions where the effect of jet quenching is expected to play a role and peripheral 60–80% collisions that can be used as a reference, the ratios $R_{D(p_T)}$ and $R_{D(z)}$ of $D(p_T)$ and $D(z)$ distributions, respectively, were calculated.

4 Fragmentation functions

To evaluate the centrality dependence of the fragmentation functions, ratios $R_{D(z)}$ were calculated of the $D(z)$ distributions for all centrality bins excluding the peripheral bin to the $D(z)$ measured in the peripheral, 60–80% centrality bin. The results of $R_{D(z)}$ ratios for $R = 0.4$ jets are shown in Fig. 1. The ratios for all centralities show an enhanced yield of low $z$ fragments ($z \lesssim 0.04$) and a suppressed yield of fragments at intermediate $z$ values ($0.04 \lesssim z \lesssim 0.2$) in more central collisions relative to the 60–80% centrality bin. For the 0–10% centrality bin, the yield of fragments at $z = 0.02$ is enhanced relative to that in the 60–80% centrality bin by 25% while the yield at $z = 0.1$ is suppressed by about 10%. The yield at $z > 0.4$ is enhanced in central with respect to 60–80% peripheral collisions. The size of the observed modifications at low, intermediate, and high $z$ decreases gradually.
from central to peripheral collisions. The same effects are seen in the ratios of transverse momentum distributions, $R_{D(p_T)}$, as well. The same effects are seen also for $R = 0.3$ and $R = 0.2$ jets. The fluctuations in the UE are approximately 100% (30%) smaller for $R = 0.2$ ($R = 0.3$) jets than they are for $R = 0.4$ jets and, thus, jets reconstructed with smaller jet radii have significantly better jet energy resolution.

To further quantify the effects of the modifications, observed in Fig. 1, on the actual distribution of fragments within the measured jets, the differences in fragmentation functions, $\Delta D(z) = D(z)|_{\text{cent}} - D(z)|_{60-80}$ were calculated as plotted on the left panels of Fig. 2. Then, integrals of these distributions, $\int \Delta D(z) dz$ were evaluated over three $z$ ranges chosen to match the observations: 0.02–0.04, 0.04–0.2, and 0.4–1. The results indicate an increase in the number of particles with 0.02 $< z < 0.04$ of less than one particle per jet in the 0–10% centrality bin relative to the 60–80% centrality bin. A decrease of about 1.5 particles per jet is observed for 0.04 $< z < 0.2$. The differences between the integrals of the fragmentation functions over 0.4 $< z < 1$ are not significant relative to the uncertainties.

The results for $\int \Delta D(z) dz$ further indicate that in the 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 $p_T^j$. The enhancement in the soft particles within jets extends clearly bellow $z = 0.02$ as can be seen from the evaluation of $D(z)$ distributions extended below the nominal cut of $z = 0.02$ shown in left panels of Fig. 2.

5 Conclusions

In this short report, the measurements by ATLAS of charged-particle fragmentation functions in jets produced in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions at the LHC are presented. Ratios of fragmentation functions in the different centrality bins to the 60–80% bin were presented and used to evaluate the medium modifications of jet fragmentation. Those ratios show an enhancement in fragment yield in central collisions for $z \lesssim 0.04$, a reduction in fragment yield for 0.04 $\lesssim z \lesssim 0.2$ and an enhancement in the fragment yield for $z > 0.4$. The modifications decrease monotonically with decreasing collision centrality from 0–10% to 50–60%. A similar set of modifications is observed in the $D(p_T)$ distributions over corresponding $p_T$ ranges, and for different jet radii. This measurement should shed a light into the modification of parton showers in hot and dense QCD medium.
Figure 2 – Left: The difference in unfolded distributions between 0–10% central and 60–80% peripheral collisions, $\Delta D(z)$ (top), $\Delta D(p_T)$ (bottom) respectively. Right: The unfolded fragmentation functions evaluated in the extended $z$-range of $z=0.01–1$ for 0–10% central and 60–80% peripheral collisions, $D_{ext}(z)$ (top), and the corresponding central-to-peripheral ratio, $R_{D_{ext}(z)}$ (bottom). All distributions are evaluated for $R = 0.3$ jets.

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References