



# Jet fragmentation in $p$ +Pb and Pb+Pb with ATLAS

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## Abstract

The modification of jets in heavy ion collisions is a central tool to study the properties of QCD matter at high temperature and its interaction with hard probes. Jet production in heavy ion collisions is observed to be suppressed relative to expectations from  $pp$  collisions and the measurement of the longitudinal fragmentation functions in Pb+Pb can provide insight into mechanism of the modification of the parton showering by the QCD medium. In proton-nucleus collisions, a large amount of hot QCD matter is not expected to be made and no evidence of jet suppression is observed. However, an excess is observed in the production of high momentum charged particles in  $p$ +Pb collisions relative to  $pp$  collisions. The  $p$ +Pb fragmentation functions can provide insight into the high momentum charged particle excess and into a possible influence of Pb+Pb jet fragmentation by effects due to the nuclear initial state. The ATLAS measurements of charged particle fragmentation functions in  $pp$ ,  $p$ +Pb, and Pb+Pb collisions are presented.

**Keywords:** Heavy Ion, jet, fragmentation function,

## 1. Introduction

The measurement of inclusive jet production in heavy ion collisions at LHC [1] indicate a presence of jet quenching, strong energy loss of energetic jets in hot and dense QCD medium. The results of measurement of the structure of jets in Pb+Pb collisions [2] will be discussed to understand the mechanism of the jet quenching in more detail.  $p$ +Pb collisions are studied in order to investigate possible effects arising from the difference between a nucleon and a nucleus in the initial state of the collision. Study of jets in  $p$ +Pb collisions can provide information regarding the modifications of parton distribution functions within a large nucleus.

Additionally, the analysis of the jet internal structure in  $p$ +Pb collisions [3] presented here is motivated by the recent measurement of the inclusive jet production in  $p$ +Pb collisions [4] and the measurement of the production of high- $p_T$  charged hadrons [5, 6]. The inclusive jet production was found to be in a good agreement with expectations from EPS09 nuclear parton distribution function sets [7], while a significant increase of high  $p_T$  charged hadron yields compared to those from

$pp$  collisions is observed. The results of these measurements suggest some modification to the jet fragmentation functions in  $p$ +Pb collisions.

## 2. Data and the jet reconstruction

The analyses presented here utilize data recorded by ATLAS [8] from 2.76 TeV Pb+Pb, 2.76 TeV  $pp$ , and 5.02 TeV  $p$ +Pb collisions. A total integrated luminosity of 0.14  $\text{nb}^{-1}$  of Pb+Pb data, 28  $\text{nb}^{-1}$  of  $p$ +Pb data, and 4  $\text{pb}^{-1}$  of  $pp$  data triggered by the jet High Level Trigger was used. The configuration of LHC beams during the  $p$ +Pb operation produced collisions a rapidity shift of the centre-of-mass frame,  $\Delta y = 0.465$  units, relative to the ATLAS rest frame.

The performance of the measurement of fragmentation functions was evaluated using a sample of MC events obtained by overlaying simulated PYTHIA 6 [9] hard-scattering events onto randomly selected minimum-bias  $p$ +Pb and Pb+Pb events. Further, the  $pp$  and  $p$ +Pb data were compared to events generated with HERWIG++ MC [10] and the PYTHIA 8.165

MC [11]. More details about used MC samples can be found in [3].

Charged particles were reconstructed using a combination of silicon pixel and strip detector and transition radiation detector placed in the 2 T magnetic field and the pseudorapidity coverage of  $|\eta| < 2.5$ . An additional quality requirements were applied on track impact parameters with respect to the primary vertex and the number of hits in the silicon detectors.

The centrality of Pb+Pb collisions was characterized by the total transverse energy,  $\Sigma E_T^{\text{FCal}}$ , in the forward calorimeter (FCal) covering  $3.1 < |\eta| < 4.9$ . Jets were reconstructed using the anti- $k_t$  algorithm [12] with distance parameter  $R = 0.4$ . The subtraction of the underlying event (UE) contribution in Pb+Pb and  $p$ +Pb collisions is performed at the finer level of calorimeter cells. Energy to be subtracted is evaluated for each longitudinal calorimeter layer and  $\eta$  slice separately. The detailed description of the jet reconstruction can be found in Ref. [4].

The Pb+Pb analysis utilizes jets with  $p_T > 100$  GeV in the pseudorapidity range  $|\eta| < 2.1$ . Jets in  $p$ +Pb and  $pp$  measurements were selected within  $|y^*| < 1.6$  for which there is full tracking coverage and with  $45 < p_T < 260$  GeV. A jet isolation requirement was applied to prevent neighbouring jets from distorting the measurement.

### 3. Fragmentation functions measurement

The study of the jet internal structure is done by the measurement of jet fragmentation functions:

$$D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dz}, \quad (1)$$

where  $N_{\text{ch}}$  is the number of charged particles,  $N_{\text{jet}}$  is the number of jets under consideration and  $z$  is defined as:  $z \equiv p_T^{\text{trk}}/p_T^{\text{jet}} \cos \Delta R$  where  $p_T^{\text{trk}}$  and  $p_T^{\text{jet}}$  are the charged particle and jet transverse momenta, respectively. Only charged particles with  $p_T > 2$  GeV in the cone of 0.4 around the jet axis were used in the Pb+Pb analysis. The usage of charged particles with  $p_T > 3.5$  GeV ensures no UE contribution to the fragmentation functions in  $p$ +Pb. The UE contribution in the Pb+Pb measurement was estimated event-by-event using a grid of  $R = 0.4$  cones spanned over the calorimeter with the exclusion of cones containing a track with  $p_T > 6$  GeV. The estimation of UE contribution accounts for its  $p_T$ ,  $\phi$  and  $\eta$  variation.

The efficiency for reconstructing charged particles within jets was estimated separately in Pb+Pb,  $p$ +Pb,

and  $pp$  collisions and applied as a function of track  $p_T$  and  $\eta$ . The fragmentation functions were further corrected for the effects of jet and charge particle  $p_T$  resolution using the SVD unfolding procedure [13] in case of Pb+Pb analysis and using a two-dimensional Bayesian unfolding procedure [14] in  $p$ +Pb measurement.

In order to study the centrality dependence in Pb+Pb collisions ratios of fragment distributions in each centrality bin to those measured in the most peripheral bin were evaluated. In the absence of  $\sqrt{s} = 5.02$  TeV  $pp$  data,  $p$ +Pb fragmentation functions were compared to a reference constructed from the  $pp$  data obtained at  $\sqrt{s} = 2.76$  TeV and the extrapolation to  $\sqrt{s} = 5.02$  TeV using PYTHIA 6 and HERWIG++ MC generators. The extrapolation using PYTHIA 6 was used as the default method. More details can be found in Ref. [3]. The difference between those two references was included in the systematic uncertainties together with systematic uncertainty from the jet energy scale, jet energy resolution, unfolding, and tracking performance.

### 4. Results

Figure 1 shows ratios of fragmentation function in Pb+Pb collisions in different centrality bins to those in 60-80% peripheral bin. An enhancement in the fragment yield for  $z > 0.4$ , a suppression by up to 10% at intermediate  $z$ , and enhancement by 25% at very low  $z$  is observed in the most central collisions with respect to the peripheral bin. The size of the modification to the fragmentation functions gradually increase with increasing centrality. Recent theoretical calculations based on radiative energy loss [15, 16] can reproduce the general features of the result.

Fragmentation functions in  $pp$  collisions at 2.76 TeV compared to three MC generators in the six jet  $p_T$  intervals are shown in Fig. 2. The PYTHIA 6 MC fragmentation functions are approximately 10% higher than those in the data at low  $z$  and approximately 20% lower than the data at high  $z$ . Fragmentation functions evaluated with PYTHIA 8 MC are similar to PYTHIA 6 MC, but have slightly better agreement with the data. HERWIG++ exhibits an approximately opposite  $z$  dependence than PYTHIA 6 MC except the high- $z$  region where they decrease with respect to the data.

The ratios of  $p$ +Pb fragmentation functions to the extrapolated  $pp$  data using two MC generators in different jet  $p_T$  bins are presented in Fig 3. The ratios are largely consistent with unity for jets with  $p_T < 80$  GeV for both generators. Ratios evaluated for jets with  $80 < p_T < 260$  GeV show evidence for an excess of approximately 15% in the  $z$  range 0.2–0.8 for the extrapolation

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