The Compact Muon Solenoid Experiment

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Fragmentation patterns of jets in pPb collisions in CMS

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Abstract

The nuclear parton distribution function and flavor composition of hard scattering processes can be accurately studied using the jet fragmentation functions. Recent measurements of the pPb nuclear modification factor (R_{pPb}), with diverging values for inclusive jets and charged hadrons, have raised question on jet fragmentation properties in pPb collisions. These spectra measurements are performed with pp reference at 5.02 TeV constructed by interpolation or extrapolation from different $\sqrt{s}$, and on steeply falling power-law spectra. As the jet fragmentation function is only evolving logarithmically with $\sqrt{s}$, this further underscores the importance of a direct measurement. Together with the CMS results in pPb inclusive jets and charge hadron R_{pPb} , we introduce the new CMS measurement of fragmentation function in pPb collisions, where within our uncertainties, jets in pPb is found to have identical fragmentation property vs. pp jets. We will further discuss the consistency and tension among the results, and their possible origins. This measurement also gives important reference for the interpretation of the fragmentation function in PbPb collisions.

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Fragmentation patterns of jets in pPb collisions in CMS

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Abstract

The nuclear parton distribution function and flavor composition of hard scattering processes can be accurately studied using the jet fragmentation functions. Recent measurements of the pPb nuclear modification factor (R_{pPb}), with diverging values for inclusive jets and charged hadrons, have raised question on jet fragmentation properties in pPb collisions. These spectra measurements are performed with pp reference at 5.02 TeV constructed by interpolation or extrapolation from different $\sqrt{s}$, and on steeply falling power-law spectra. As the jet fragmentation function is only evolving logarithmically with $\sqrt{s}$, this further underscores the importance of a direct measurement. Together with the CMS results in pPb inclusive jets and charged hadron R_{pPb} , we introduce the new CMS measurement of fragmentation function in pPb collisions, where within our uncertainties, jets in pPb is found to have identical fragmentation property vs. pp jets. We will further discuss the consistency and tension among the results, and their possible origins. This measurement also gives important reference for the interpretation of the fragmentation function in PbPb collisions

Keywords: fragmentation function, jet, pPb, nPDF, charged hadron, RpPb, nuclear modification factor

1. Introduction

Several measurements of jets and charged particles having large transverse momenta, or p_T , in 5.02 TeV pPb collisions have been made recently [1, 2]. In particular, these measurements calculate a ratio of the jet or charged particle spectrum with data taken from pp collisions at the same energy, scaled by the average number of binary nucleon-nucleon collisions [3]. This ratio is useful for revealing both initial and final state modifications to the spectra of pPb collisions. One of these recent measurements made by CMS of the charged particle nuclear modification factor, or R_{pPb} , at mid-rapidities shows a significant enhancement of high p_T particle production, with the R_{pPb} reaching values of approximately 1.4 above a p_T of 40 GeV [1]. Similar measurements of the jet nuclear modification factor by CMS and ATLAS have shown an enhancement of only about 10% at mid-rapidity [4, 5]. The measurements of the jet R_{pPb} are consistent with nuclear parton distribution function (nPDF) NLO calculations, but the charged particle measurement is larger than the NLO pQCD predictions [6]. Because these high p_T charged hadrons are produced almost entirely within jets, these two observations imply a modification of the pPb jet fragmentation function in the same p_T region as where the charged particle R_{pPb} shows an enhancement.

Additionally, the jet fragmentation function has been found have have significant modifications in PbPb collisions by both CMS and ATLAS [7, 8]. Measurement of the pPb jet fragmentation function therefore provides an important baseline check for any cold nuclear matter effects that could also modify the PbPb fragmentation function.

Here we describe a measurement by the CMS collaboration of the jet fragmentation function in pPb collisions at $\sqrt{s_{NN}}$ of 5.02 TeV. The jets used in the analysis are reconstructed using an anti- k_t algorithm having a distance parameter $R = 0.3$ [9], after the CMS particle-flow event reconstruction [10, 11]. Additionally a pp reference is constructed for $\sqrt{s}$ of 5.02 TeV using measurements of the jet fragmentation function at $\sqrt{s}$ at 2.76 and 7 TeV, because no pp data had been taken at 5.02 TeV at that time.

2. Jet Fragmentation Functions

The jet fragmentation functions are measured using 2.76 TeV pp data and 5.02 TeV pPb data taken in 2013, as well as 7 TeV pp data collected in 2011. For each data sample, events containing jets were selected using a dedicated jet trigger. The jets are then reconstructed using the anti- k_t jet clustering algorithm; an approach that is identical to previous CMS dijet analyses done on pPb data [12]. Here a distance parameter of $R = 0.3$ was used to reduce the effect of underlying event fluctuations and allow comparison with PbPb fragmentation functions. Selected jets are also required to have a pseudorapidity of less than 1.5 in the center of mass reference frame of the collision system being examined.

Once the jets are selected, all tracks within an angular distance of $R = 0.3$ are enumerated as a function of their p_T . This angular distance corresponds to the distance parameter used in jet clustering algorithm, but tracks falling in this cone are not necessarily always clustered into the jet (due to the clustering algorithm not always producing a perfectly cone-shaped jet). The tracks are also required to pass a track quality selection, and are corrected for the detector efficiency and acceptance. No unfolding of the jet p_T spectrum is done, but the effects of the jet resolution are accounted for in the systematic uncertainties.

In 5.02 TeV pPb and 7 TeV pp collisions, there is nontrivial contamination of the fragmentation function by underlying event particles which originate from processes other than the original hard scattering that produces the jet, such as multiple collisions in the lead ion, pile-up collisions, or initial state radiation. In order to remove these contributions, the particles in a cone of $R = 0.3$ that is rotated from each jet's axis by 90 degrees in the ϕ direction are subtracted from the fragmentation function.

The resulting track spectrum for each jet p_T bin is then divided by the track p_T bin width to make the spectrum differential, and is normalized by the number of jets selected. This normalization means there is no luminosity uncertainty in the measurement unlike measurements of the inclusive jet or charged particle spectrum.

The measured jet fragmentation functions in pp collisions at 2.76 and 7 TeV are shown in the top and bottom rows of Fig. 1, respectively. The 5.02 TeV pPb jet fragmentation function is shown in the top row of Fig. 2. In all three measurements, the systematic uncertainty dominating the measurement is the tracking uncertainty in the track p_T range from 500 MeV to approximately 30 GeV. At transverse momenta higher than this, the uncertainty in the jet energy scale is then the dominant factor, due to the jet p_T constraining the phase space into which high p_T charged hadrons can be produced. The shape of the fragmentation functions can also be seen to scale towards higher particle p_T as the jet p_T increases.

3. pp Reference Interpolation

In order properly interpret the results of the pPb jet fragmentation function, a pp reference at the same center of mass energy is needed. Unfortunately no 5.02 TeV pp data had been taken at the time of the analysis, so a pp reference was constructed from the 2.76 and 7 TeV fragmentation functions using a data-driven interpolation technique. The technique leverages the principle of QCD factorization to decompose the measured fragmentation functions into a linear combination of the fragmentation functions of quarks and gluons, which should be independent of the center of mass energy of the collision. The evolution of the measured fragmentation function with changing center of mass energy is then controlled by the different sampling of quarks and gluons in the (nuclear) parton distribution function. This sampling can be examined using a Monte Carlo generator, here PYTHIA, to integrate over the x and Q^2 phase space of the (n)PDF. The result of this is shown in Fig. 3, where the fraction of jets that result from gluons is plotted as a function of the jet p_T for all three center of mass energies used here.

Fig. 1. (Top row) The jet fragmentation functions in 2.76 TeV pp for anti- k_t jets having distance parameter $R = 0.3$ and center of mass pseudorapidity $|\eta_{CM}| < 1.5$. (Bottom row) The same quantities plotted in 7 TeV pp. For both rows a cone rotated in ϕ by 90 degrees is used to subtract the underlying event.

Fig. 2. (Top row) The 5.02 TeV pPb jet fragmentation functions in 5.02 TeV pPb for anti- k_t jets having distance parameter $R = 0.3$ and center of mass pseudorapidity $|\eta_{CM}| < 1.5$. (Bottom row) The interpolated pp reference interpolated from 2.76 and 7 TeV pp jet fragmentation functions for the same jet types and kinematic selections. A cone rotated in ϕ by 90 degrees is used to subtract the underlying event.

Fig. 3. The fraction of gluon jets in PYTHIA or PYTHIA+HIJING simulation for the center of mass energies used here. The abscissa is either generator level or reconstructed level jet p_T for the histograms and points, respectively.

In order to construct a pp reference at 5.02 TeV, the jet fragmentation functions of 2.76 and 7 TeV pp data are first measured for the needed jet p_T bins. Then the jet p_T spectra are reweighted to be equal to that of the 5.02 TeV pPb data, allowing a direct comparison of the reference fragmentation function to the 5.02 TeV pPb data. If this reweighting was not done, the $\sqrt{s}$ dependence of the jet production cross section would bias the fragmentation function result towards harder fragmentation for the 7 TeV data, and softer fragmentation in the 2.76 TeV data. Define F_2 and F_7 to be the 2.76 and 7 TeV jet fragmentation functions after this reweighting procedure. Furthermore, define the gluon and quark fragmentation functions in pp collisions at 5.02 TeV to be G and Q , respectively. These quantities are all functions depending on the reconstructed track p_T . Additionally, represent the fraction of inclusive jets that are gluon jets at 2.76 and 7 TeV by the coefficients r_2 and r_7 . The fraction of jets that are quark jets is then simply $1 - r$. The values of r are taken from the Monte Carlo study of the gluon fraction mentioned previously. The two measured fragmentation functions can be expressed in terms of the gluon and quark fragmentation function basis as follows:

$$F_2 = r_2 G + (1 - r_2) Q \quad (1)$$

$$F_7 = r_7 G + (1 - r_7) Q. \quad (2)$$

Solving for Q and G yields

$$G = \frac{(1 - r_7)F_2 - (1 - r_2)F_7}{r_2 - r_7} \quad (3)$$

$$Q = \frac{-r_7 F_2 + r_2 F_7}{r_2 - r_7}. \quad (4)$$

Because r_5 is known from Monte Carlo simulation, the interpolated pp fragmentation function at 5.02 TeV, F_5 , can then be deduced

$$F_5 = r_5 G + (1 - r_5) Q = \frac{(r_5 - r_7)F_2 + (r_2 - r_5)F_7}{r_2 - r_7}. \quad (5)$$

It should be noted that the coefficients created from the gluon fractions are between 0 and 1, so the pp interpolation by definition lies somewhere inside the range bordered by the 2.76 and 7 TeV fragmentation functions, as expected. The result of the interpolation procedure is shown in the bottom row of panels in Fig. 2. In general the sources of systematic uncertainty are similar to those of the original measured fragmentation functions that are the inputs of the interpolation procedure.

4. Fragmentation Function Ratio

The ratio of the 5.02 TeV pPb fragmentation function and the pp interpolated reference is shown in Fig. 4 for the five jet p_T bins examined. Once again the dominant systematic uncertainties are the tracking at low and intermediate track p_T and the jet energy scale at large track p_T . The data is consistent with unity, indicating that there is no modification of the jet fragmentation function in pPb collisions with respect to the pp interpolation.

This result indicates that the significant modification of the jet fragmentation function seen in PbPb collisions is due to the production of a hot dense medium, and not some cold nuclear matter effect. The interpretation of this result within the context of existing charged particle and jet R_{pPb} measurements is more difficult, as these results seem to imply a modified fragmentation function which is not seen in this study [1, 4, 5]. However one must keep in mind that each of these three studies uses a different technique to construct the pp reference spectrum used; the CMS charged particle R_{pPb} measurement uses an approach based on x_T scaling and the R_{pPb} measurement uses an extrapolation from 7 TeV based on Monte Carlo. It is possible that the three measurements are consistent with each other, albeit on the edges of their uncertainties. 5.02 TeV pp reference data, which has been gathered recently during the LHC's Run 2, will remove the need for various interpolation procedures, largely reduce systematic uncertainties, and hopefully provide a more definitive description of the relationship between high p_T charged particles and the jets which produce them.

Fig. 4. Ratio of the measured pPb and pp reference jet fragmentation function for different jet p_T selections. A cone rotated in ϕ by 90 degrees is used to subtract the underlying event in both the numerator and denominator.

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