Studies of the nuclear stopping power in PbPb collisions at 2.76 TeV with CMS

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Abstract

The energy flow at very high pseudorapidity in PbPb collisions is sensitive to the very low-x components of the nuclear wave-function. The CASTOR calorimeter extends the pseudorapidity coverage of CMS to -6.6, which is only 1.4 units away from the beam rapidity. A comparison of the centrality dependence of forward energy flow to that at lower pseudorapidities can shed light on the gluon saturation at low-x. This problem can also be approached by a direct comparison of PbPb and pp energy flow in the forward region. This analysis is based on data taken in 2010. The energy flow in the pseudorapidity range of -5.2 to -6.6 has been measured for 2.76 TeV PbPb collisions over a wide range of centrality and also for minimum bias pp collisions. These data are compared to energy-flow measurements for pseudorapidities between -5.2 and +5.2. The very large angular coverage of the CMS detector allows for a test of limiting fragmentation of energy flow, and for an estimate of nuclear stopping. Finally, these data are compared to predictions of hydrodynamic models and microscopic event generators.

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1. Introduction

The Compact Muon Solenoid (CMS) experiment has, due to its unprecedented forward coverage, a good sensitivity to a possible new low-x regime in the parton dynamics. When the gluon density is not too high, this growth can be described by linear evolution. At very high gluon densities, and thus very small values of $x$, the non-linear gluon recombination becomes important, resulting in the saturation of the gluon density. The RHIC experiments have observed the suppression of high rapidity hadrons, protons, anti-protons and back-to-back di-hadron correlations produced in $\sqrt{s_{NN}} = 200$ GeV/d-Au collisions. It has been widely speculated that such effects are related to gluon saturation. At the LHC energy of $\sqrt{s_{NN}} = 2.76$ TeV, the accessible $x$ values in AA collisions are 30-45 times lower than at RHIC allowing studies of the parton distribution in a new kinematic region.

2. The Experimental Apparatus

In this paper the data from the calorimeters of the CMS [1] experiment are analyzed. The central barrel part of the electromagnetic and hadronic calorimeters cover the pseudorapidity of up to $|\eta| < 1.3$ and the endcaps of these up to $|\eta| < 3$. The calorimetric acceptance of CMS is extended into the forward phase-space by the hadronic forward (HF) calorimeter and the CASTOR very forward calorimeter. The HF acceptance in pseudorapidity is $3.1 < |\eta| < 5.2$, while CASTOR is installed on one side of CMS and covers $-6.6 < \eta < -5.2$. 

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The corresponding data analysis for the acceptance range $-5.2 < \eta < 5.2$ (barrel, endcap and HF calorimeters) has been presented elsewhere [2], with the small variation of using transverse energy instead of energy. In this paper, the measurement range is extended to $\eta = -6.6$ using CASTOR data, and subsequently the data over the full acceptance is analyzed in terms of the energy dispersion of the lead projectiles.

The CASTOR calorimeter is a Tungsten/Quartz sampling calorimeter using the Cherenkov light of charged particle showers in the Quartz material. The detector is segmented in 14 longitudinal modules and 16 azimuthal sectors. The two front modules comprise the electromagnetic section of the calorimeter with a depth of 20 radiation lengths. The overall depth of the calorimeter is around 10 hadronic interaction lengths.

Due to the location of CASTOR very close to the beam pipe in a region where radiation levels are very high and residual magnetic field effects from the solenoid are relevant, the operation and calibration of CASTOR are a challenge. The absolute energy scale of CASTOR used for this paper is determined from a cross-calibration to HF using minimum bias pp data at $\sqrt{s} = 7$ TeV. The overall systematic uncertainty of this procedure is currently 22%, where the biggest contributions are the absolute energy scale uncertainty of HF (10%), the model dependence of the extrapolation from HF to CASTOR (10%) and a geometric shift of CASTOR by magnetic fields (16%). The latter can be corrected for when ongoing studies are providing the necessary information with sufficient accuracy. Furthermore, in the future it is planned that the absolute energy scale determination of CASTOR is replaced by a more universal approach with improved precision and less model dependence.

The systematic uncertainties determined for CASTOR do not depend appreciably on the centrality. For more details on the calibration procedure and an extensive discussion of the systematic uncertainties read Ref. [3].

The noise level of the calorimeter is determined from zero bias data. For the average noise energy deposited in CASTOR per event a noise level of 10 GeV is found, which is < 1% with respect to the signals of at least TeV even for peripheral hadronic collisions.

### 3. Analysis and Results

The energy density is measured in different centrality and pseudorapidity bins. For each bin the measured average energy deposit per event is determined. The experimental data are corrected for detector inefficiencies and acceptance effects. This correction is based on a detailed Monte Carlo simulation of CMS using several event generators. For this purpose the models HYDJET 1.8 [4], EPOS-LHC [5] and QGSJET II.3 [6] are used. EPOS-LHC and QGSJET II.3 are both models commonly used in cosmic ray physics and based on Gribov-Regge theory. Saturation effects are included in different ways. Furthermore the EPOS-LHC generator used in this analysis is tuned to LHC data. For the CASTOR calorimeter the identified model dependence of the correction factors is < 3% and the variation with centrality is $\approx 6\%$.

The essence of the study presented here is a measurement of the energy density, $dE/d\eta$, in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of pseudorapidity and collision centrality extending to very forward pseudorapidities. The data in $|\eta| < 5.2$ has been discussed in Ref. [2], however, here specifically the CASTOR data are included in the comparison to models.

The measured energy in units of pseudorapidity as function of pseudorapidity compared to different MC models is shown in Fig. 1. The very forward data from CASTOR indicate a slower rise of $dE/d\eta$ with $\eta$ as compared to the more central pseudorapidities. This points to the fact that
the peak of the energy density is reached very close to the acceptance of CASTOR. The AMPT [7] model has the qualitative overall best agreement with CMS data, while HYDJET 1.8 is excellent at central pseudorapidities but less accurate in the forward region. The EPOS-LHC and QGSJetII.3 models are better in describing the forward data, but both have difficulties at the center.

Also the $R_{CP}$ ratio, defined as the energy density for a specific centrality divided by the energy density for the most central events ($N_{\text{part}} = 394$), is calculated and compared to model predictions. In Fig. 2 (left panel) the $R_{CP}$ data are shown as a function of the centrality. The measurements with the CASTOR calorimeter in the very forward phase space exhibit a much flatter $R_{CP}$ for central collisions. The CASTOR data probes the softest part of the hadronic collision at lowest-$x$ values. The number of participants, $N_{\text{part}}$, is correlated to the impact parameter, $b$, of the collision. The largest values of $N_{\text{part}}$ correspond to the smallest $b$. Thus, the shape of $R_{CP}$ is related to the geometry of the PbPb collision. In the very forward direction the dependence of signals depend only weakly on the impact parameter for central PbPb collisions.

To compare the CMS data with the stopping power measurements of other experiments the most central events from 0 to 10% centrality are used. For these events the quantity $\langle \delta y \rangle_E$ is calculated, which is the average energy weighted pseudorapidity subtracted by the beam rapidity $\gamma_{\text{beam}} = 8$. To extend the CMS data beyond the acceptance of CASTOR, a log normal function is used, which fits very well to the measurements.

On the right panel of figure 2 the average net baryon production $\langle \delta y \rangle_B$ for several experiments and the average energy weighted rapidity loss $\langle \delta y \rangle_E$ from this measurement as function of the beam rapidity is shown. For the BRAHMS data at 62.4 GeV we have analysed public BRAHMS data with our technique to derive $\langle \delta y \rangle_B$ next to the published baryon stopping power $\langle \delta y \rangle_B$ [8]. While the latter is a measurement of the energy lost by the baryons traversing the interaction medium, the former is a measure of the energy released in this stopping process.

4. Summary

A measurement of the averaged energy density, $dE/d\eta$, in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV has been presented. The HYDJET 1.8 and EPOS-LHC models are close to the data at central rapidities,
Figure 2: Left panel: The $R_{PC}$ data in the very forward acceptance as function of $N_{\text{part}}$ compared to model predictions. Right panel: Comparison of measurements of the stopping power in the most central PbPb collisions of various experiments [9, 10, 11, 8] with the energy-weighted average pseudorapidity derived by CMS. The line is a fit from BRAHMS.

...however, at very forward rapidities the missing nuclear effects in HYDJET 1.8 become manifest, and the data indicate lower energy density beyond $\eta > 5$. All other models predict a suppression of the very forward energy densities, which is what is suggested by the data. None of the models is able to describe the data over the full phase-space of centrality and pseudorapidity presented here. The ratio $R_{PC}$ shows a significantly flatter dependence on the centrality in the very forward region compared to observations at more central pseudorapidities. This is a sign of a much more uniform structure of the nucleus at low values of $x$, which is consistent with saturation effects. From the CMS data, the average energy weighted rapidity loss $\langle \delta y \rangle_{E}$ was calculated. This result is compared to measurements of the baryon stopping power at lower energies. This confirms the trend observed before by RHIC.

References