Measurement of the average very forward energy as a function of the track multiplicity at central rapidities in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

The average total energy as well as the hadronic and electromagnetic components of it are measured with the CMS detector at pseudorapidities $-6.6 < \eta < -5.2$ in proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$TeV. The results are presented as a function of the multiplicity of charged particle tracks in the region $|\eta| < 2$. This measurement is sensitive to correlations induced by the underlying event structure over very wide pseudorapidity regions. We test Monte Carlo event generator predictions commonly used in collider and ultra-high energy cosmic ray physics with respect to these new data. It is very interesting that some of the most recent event generator tunes have the largest tension with respect to the data.
1 Introduction

The description of inclusive hadron production in high energy hadron-hadron collisions remains subject to significant theoretical uncertainties. At TeV energies the dominant source of secondary particle production is the fragmentation of quarks and gluons in semi-hard scatterings [1], referred to as minijet production. However, various processes that cannot be directly calculated from first principles in quantum chromodynamics (QCD) also contribute to particle production, i.e., multiparton interactions (MPIs), and fragmentation of the remnants. Together with initial-and final-state radiation these additional particle production mechanisms are typically referred to as the underlying event and are modelled phenomenologically in Monte Carlo (MC) event generators with parameters tuned with the data [2–4]. In addition, especially in the forward phase space, diffractive processes play an important role [5]. Furthermore, final-state parton rescattering effects, a possible hydrodynamical phase transition, or other collective phenomena can impact and modify particle production in hadron-hadron collisions at high energies [6].

The energy carried by particles produced in the very forward region covered by the CASTOR calorimeter [7] of the CMS experiment has been shown to be a powerful probe of the activity of the underlying event [8, 9]. The measurements presented here provide the first correlation of hadron activity at very forward and central rapidities performed at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, providing a new approach to the study of hadron production at the CERN LHC. Such measurements, spanning huge rapidity intervals, provide additional information on the underlying event compared to measurements using only information from the central region (see for example [10, 11]). The data suggest a nontrivial correspondence between the activity in the very forward and the central regions.

The very forward region covered by the data contains the highest energy densities studied in proton-proton collisions at the LHC. The present results can therefore be also used to improve the predictions of event generators used in studies of cosmic rays that induce extensive air showers at ultra-high energies [12]. Specifically, current air shower simulations are known to significantly underestimate muon production [13, 14]. The fraction of the energy going into the production of electrons or photons compared to that going into long-lived hadrons has a crucial impact on the muon production rate in extensive air showers (as discussed, e.g. in Ref. [15]). Since CASTOR consists of separate electromagnetic and hadron calorimeters, the data presented here provide new information that may help understanding muon production in air showers.

2 Experimental setup and Monte Carlo simulation

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter that can provide a nominal magnetic field of 3.8 T. Within the solenoid volume in the central region are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. Muons are measured in gas-ionisation detectors embedded in the steel return yoke. The central detectors of CMS are complemented by calorimeters in the forward direction, which all rely on the detection of Cherenkov photons produced when charged particles pass through their active quartz components. The “hadron forward” (HF) calorimeters cover the pseudorapidity interval $3.0 < |\eta| < 5.2$ and use quartz fibres embedded in a steel absorber. The CASTOR calorimeter is a sampling calorimeter composed of layers of fused silica quartz plates and tungsten absorbers. It is located only on the negative side of CMS and covers the region $-6.6 < \eta < -5.2$. CASTOR is segmented into
16 azimuthal towers, each with 14 longitudinal channels. The two front channels have a combined depth of 20 radiation lengths and form the electromagnetic section of each tower. The remaining 12 channels constitute the hadronic section. The full depth of a tower amounts to 10 hadronic interaction lengths. A more detailed description of the CMS detector, together with a definition of the coordinate system used and all relevant kinematic variables, can be found in Ref. [16]. A detailed description of the CASTOR calorimeter is given in Refs. [7, 9, 17]. For triggering purposes, the Beam Pickup Timing for the eXperiment devices were used [18].

The data are compared to a broad range of model predictions covering different parameter tunes as well as entirely different physics approaches. The models considered are PYTHIA 8 [19] (version 8.212) with tune CUETP8M1 [20], and tune 4C [3], combined with the MBR [21] model to describe diffractive processes. The data are also compared to the predictions of EPOS LHC [22] and SIBYLL 2.1 [23]. For these models, a detailed Monte Carlo simulation of the CMS detector response is performed with the GEANT4 [24] toolkit. The simulated events are processed and reconstructed in the same way as the collision data. Furthermore, predictions by QGSJETII.04 [25], SIBYLL 2.3c [26], PYTHIA 8 tune CP5 [Reference in preparation], and HERWIG 7.1 [27, 28] with the default tune for soft interactions [29] are also compared to the data. These simulations are produced only at generator level. A forward folding method is developed to compare generator-level simulations to the data. This technique can be used to compare any current or future model or theoretical prediction to the data and will be described in detail.

3 Data analysis and systematic uncertainties

The present analysis is based on data recorded during the low-luminosity startup operation of the LHC in June 2015, at a proton-proton centre-of-mass energy of 13 TeV. In this period the CMS solenoid was turned off. The data correspond to an integrated luminosity of 0.22 nb$^{-1}$, with an average proton-proton interaction probability of about 30% per bunch crossing.

The event selection criteria are optimised to select inelastic collision events with minimal bias. The residual contribution of electronic noise and beam background contained in these events is well below 1%. Events were selected online with an unbiased trigger requiring only the presence of two colliding bunches. The offline event selection requires activity in the HF calorimeters: at least one calorimeter tower with the reconstructed energy larger than 5 GeV is required on either the positive or negative pseudorapidity side of the CMS detector. In addition, at least one offline-reconstructed track in the CMS tracker with $|\eta| < 2$ is required. A modified tracking algorithm is used to take into account the absence of magnetic field. This is the same as that used for Ref. [30], where a more detailed description can be found. Information from the pixel tracker is used to reconstruct straight line tracks. Signals in all three layers of the pixel tracker are required to lie within a cone of radius $R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} < 0.02$ (where $\phi$ is azimuthal angle in radians) around the reconstructed track. The efficiency to find more than two hits in the pixel detector drops quickly for $|\eta| > 2$; the search for tracks is therefore limited to $|\eta| < 2$. Tracks are retained if they originate from the expected interaction region and are linked to at least one interaction vertex. The tracking has an efficiency of about 76% with a reconstruction probability of about 5% for charged particles with a transverse momentum $p_T$ larger than 200 MeV.

In order to reject events with more than one simultaneous pp interaction (pileup), an additional constraint on the reconstructed interaction vertices is applied. Events with two reconstructed vertices are rejected if the vertices are separated by more than 0.5 cm in the longitudinal direc-
Data analysis and systematic uncertainties

This minimises the rejection of events with high particle multiplicity, where the reconstruction may create multiple spurious vertices. The probabilities to select events with additional collisions that either do or do not create visible vertices in the tracker are evaluated from both data and simulation, and are found to be 1.5% and 2.3%, respectively. Correcting for the contribution of those falsely accepted events to the average forward energy is not straightforward, since it depends on the track multiplicity in the central region as well as on the interaction model used in simulation. The contribution from visible or invisible pileup events to the forward energy is therefore considered as part of the systematic uncertainty of the measurement.

The total energy deposited in CASTOR is obtained by summing the deposited energy in all calorimeter towers with energies above the noise threshold. The thresholds are determined independently for each tower and vary between 2 and 2.5 GeV. On average, the showers of single electrons and photons are contained to 76% within the electromagnetic section of CASTOR; those of single charged hadrons are contained to about 71% in the hadronic section. Moreover, the energies deposited by hadron-induced showers are smaller than those by electron-induced showers of the same particle energy, a feature known as noncompensation. These properties were precisely measured during a testbeam and are implemented in the detector simulation.

CASTOR energy scale. The energy scale uncertainty of CASTOR is 17% [9]. This is the dominant contribution.

CASTOR intercalibration. The determination of the electromagnetic and hadronic energies suffers from the uncertainty in the relative calibration (intercalibration) of the readout channels of the electromagnetic and hadronic sections. This uncertainty is found to be asymmetric and the influence on the average energy amounts to $-8\%$ for the electromagnetic and $+15\%$ for the hadronic energy.

Pileup rejection. The uncertainty arising from the pileup contribution is estimated by considering alternative vertex multiplicity selections. Events with exactly one reconstructed vertex, as well as events with two vertices separated by less than 0.7 cm, are selected. These changes mainly affect the high-multiplicity region and lead to a systematic uncertainty of up to 10% in the highest multiplicity bin. Collisions that do not create visible vertices in the detector introduce an additional uncertainty that is below 0.8%.

HF energy scale. The uncertainty in the reconstructed energies in the HF calorimeters is 10% [31]. Varying the threshold for the event selection accordingly from 5.0 GeV per calorimeter tower to 4.5 and 5.5 GeV changes the average energies observed in CASTOR by less than 0.5%.

Tracking. The uncertainty of the track reconstruction has been previously determined from studies comparing data with simulation [30]. The uncertainties in the tracking and vertexing
Table 1: Summary of all detector-level uncertainties on the average energies measured with the CASTOR calorimeter. Ranges indicate the variation as a function of the track multiplicity.

<table>
<thead>
<tr>
<th>Source</th>
<th>Total energy</th>
<th>Electromagnetic energy</th>
<th>Hadronic energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASTOR energy scale</td>
<td>17%</td>
<td>17%</td>
<td>17%</td>
</tr>
<tr>
<td>CASTOR intercalibration</td>
<td>2–3%</td>
<td>−8%</td>
<td>+15%</td>
</tr>
<tr>
<td>HF energy scale</td>
<td>&lt;0.5%</td>
<td>&lt;0.5%</td>
<td>&lt;0.5%</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>1–5%</td>
<td>1–5%</td>
<td>1–5%</td>
</tr>
<tr>
<td>Pileup rejection</td>
<td>1–8%</td>
<td>1–8%</td>
<td>1–10%</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>0.05–1.6%</td>
<td>0.06–1.9%</td>
<td>0.06–1.8%</td>
</tr>
<tr>
<td>Total</td>
<td>18–19%</td>
<td>18–20%</td>
<td>20–26%</td>
</tr>
</tbody>
</table>

Efficiencies are found to affect the number of reconstructed tracks to 1.8 and 2–3%, respectively. These are combined linearly and a 5% systematic uncertainty in the number of reconstructed tracks is obtained. The calculation of the average energies is repeated with a systematically increased and decreased number of reconstructed tracks. The effect on the average energies is below 5%.

The deviations from the central value are calculated for every source of uncertainty individually. All uncertainties are uncorrelated and are therefore added in quadrature.

Most of the uncertainties discussed above are fully correlated between the total, electromagnetic, and hadronic energy. Thus, they cancel when taking ratios between the electromagnetic and hadronic components. This is not the case for the intercalibration uncertainty: a systematic decrease of the electromagnetic energy causes an increase of the hadronic energy, which leads to an asymmetric uncertainty on the ratio.

4 Forward folding of model predictions

The measured track multiplicity is distorted by the acceptance and efficiency of the CMS pixel tracker. Likewise, the energies observed in CASTOR are affected by the energy resolution, and the response of the calorimeter. In the present note, the data are not corrected for these instrumental effects, and should thus be compared to the results of full detector simulation. In order to allow for comparisons to other experimental data and to future model predictions, the distributions measured in high-energy physics experiments are typically unfolded relying on Monte Carlo simulations. In this note, a “forward folding” approach is used instead, in which all known detector effects are applied to a given simulation or theoretical prediction, as described in the following.

At the generator level, events are selected that match the detector-level event selection. At least one charged particle with $p_T > 200\text{ MeV}$ is required within $|\eta| < 2$. Furthermore, a fractional momentum loss of the scattered proton of $\xi > 10^{-6}$ is required. For the latter, all stable ($c\tau > 1\text{ cm}$) final-state particles are divided into two systems, $X$ and $Y$, based on their position with respect to the largest rapidity gap in the event. All particles on the negative side of the largest gap are assigned to the system $X$, while the particles on the positive side are assigned to the system $Y$. Based on this, $\xi$ is defined as $\xi = \max(M_X^2/s, M_Y^2/s)$, where $M_X$ and $M_Y$ are the invariant masses of the two systems. The selection based on $\xi$ is relevant at very low particle multiplicities and is chosen to best match the acceptance of the detector-level selection of minimally biased collision events, and also for consistency with previous CMS publications (e.g. Ref. [9]).

Four-dimensional migration tensors $k$ are calculated based on all available Monte Carlo sam-
5. Results

Various measurements of the average energy reconstructed with the CASTOR calorimeter in the region $-6.6 < \eta < -5.2$ are presented as a function of the track multiplicity for $|\eta| < 2$ in Figs. 1–3. The statistical uncertainties of the data are small and therefore not visible. The systematic uncertainties are shown with a gray band. The data are not corrected for detector

The migration tensor $k$ describes the probability to reconstruct an event with the central multiplicity $N_{\text{ch}}$ and forward energy $E_{\text{true}}$ for given values $N_{\text{ch}}$ and $E_{\text{true}}$. The four-dimensional tensors $k_{ij}^{lm}$ are constructed with 20 bins in $N_{\text{ch}}$ and $N_{\text{tracks}}$ ranging from 1 to 200 (dimensions $i$ and $l$), as well as 46 bins in $E_{\text{true}}$ and $E_{\text{reco}}$ ranging from 0 to 10 TeV (dimensions $j$ and $m$). The bins used at detector- and generator-level are identical. The range of $k$ is larger than that used for the final results in order to allow for the bin migration of events. Final results are presented for $N_{\text{tracks}}$ between 1 and 150.

All four dimensions of $k$ have one extra underflow bin to handle the event selection efficiency. If an event does not pass the event selection criteria at the generator level ($N_{\text{ch}} \geq 1$ and $\xi > 10^{-6}$), it is recorded in the underflow region with $N_{\text{ch}} = 0$ and $E_{\text{true}} = -1$ GeV. If an event is not selected at the detector level (one HF tower above 5 GeV and $N_{\text{tracks}} \geq 1$), it is recorded in the underflow region with $N_{\text{tracks}} = 0$ and $E_{\text{reco}} = -1$ GeV. In this way, the effects of inefficiencies and migrations from outside the visible phase space are included in the tensor $k$.

Two-dimensional distributions, $N_{ij}^{reco}$, describing the event yields in bins $(i, j)$ of $N_{\text{tracks}}$ and $E_{\text{reco}}$ can then be obtained for any given event generator or theoretical prediction by means of the following tensor contraction:

$$N_{ij}^{reco} = \sum_{l,m} k_{ij}^{lm} \times N_{lm}^{true},$$

where $N_{lm}^{true}$ is the distribution of generator-level events in bins $(l, m)$ of $N_{\text{ch}}$ and $E_{\text{true}}$. The average energy in each track multiplicity bin can be calculated from $N_{ij}^{reco}$ and can be compared to the data directly at the detector level. The results obtained by using the forward folding method coincide with those obtained with the full detector simulation to better than 1%.

The tensor $k$ depends slightly on the $\eta$- and $p_T$-distributions of the final state particles as well as their multiplicities in the physics model used as the input to the full detector simulation. To quantify this dependence, four tensors are provided based on PYTHIA 8 tune CUETP8M1, PYTHIA 8 tune 4C+MBR, EPOS LHC, and SIBYLL 2.1. A fifth tensor is obtained by combining the tensors of these models and serves as the central value for all forward-folded results. The spread of the results obtained with the individual tensors is taken as an estimate of the systematic uncertainty related to the model dependence; it is mostly well below 5%, but reaches 15% in a few bins. All five variations of $k$ will be made publicly available through a RIVET [32] plugin. This way, the forward folding can be applied to any other model prediction. Moreover, the full point-to-point correlation of the model-related uncertainty can be resolved.

5 Results

Various measurements of the average energy reconstructed with the CASTOR calorimeter in the region $-6.6 < \eta < -5.2$ are presented as a function of the track multiplicity for $|\eta| < 2$ in Figs. 1–3. The statistical uncertainties of the data are small and therefore not visible. The systematic uncertainties are shown with a gray band. The data are not corrected for detector
Figure 1: Top panel: Average total energy reconstructed in the CASTOR calorimeter as a function of the number of reconstructed tracks for $|\eta| < 2$. Bottom panel: Average total energy reconstructed in the CASTOR calorimeter normalised to that in the first bin ($N_{ch} < 10$) as a function of the number of reconstructed tracks for $|\eta| < 2$. In all figures, the data are shown as black circles and the corresponding systematic uncertainties with a gray band; horizontal bars are used to indicate the bin width. The predictions of various event generators are compared to the data, which are the same in both panels. The bands associated with the model predictions illustrate the model uncertainty.
5. Results

Figure 2: Top panel: Average electromagnetic energy reconstructed in the CASTOR calorimeter as a function of the number of reconstructed tracks for $|\eta| < 2$. Bottom panel: Average hadronic energy reconstructed in the CASTOR calorimeter as a function of the number of reconstructed tracks for $|\eta| < 2$. In all figures, the data are shown with black circles and the corresponding systematic uncertainties with a gray band; horizontal bars are used to indicate the bin width. The predictions of various event generators are compared to the data, which are the same in both panels. The bands associated with the model predictions illustrate the model uncertainty.
Figure 3: Ratio of average electromagnetic and hadronic energies reconstructed in the CASTOR calorimeter as a function of the number of reconstructed tracks for $|\eta| < 2$. The data are shown with black circles and the corresponding systematic uncertainties with a gray band; horizontal bars are used to indicate the bin width. Predictions of various event generators are compared to the data, which are the same in both panels. The bands associated with the model predictions illustrate the model uncertainty.

effects and are compared to a broad range of model predictions commonly used to describe hadron interactions at the LHC and in high energy cosmic ray air showers. These models are grouped in two sets: the first contains PYTHIA 8 tune CUETP8M1 and tune 4C+MBR, EPOS LHC and SIBYLL 2.1, for all of which full detector simulations are available. The error bands shown for these models only reflect the Monte Carlo statistical uncertainties. These become visible especially in the last bin. The second set of models consists of SIBYLL 2.3c, QGSJETII.04, PYTHIA 8 tune CP5, and HERWIG 7.1. Predictions from these models are obtained by means of the forward-folding method. The uncertainty bands shown for these models also include the systematic uncertainties from the forward-folding procedure discussed in the previous section.

The average total energy in CASTOR, shown in Fig. 1 (top), increases with the track multiplicity. This feature is consistent with the general behaviour of the underlying event measured at central rapidities (see for example [10, 11]) and is reproduced by all models considered. The shape of this feature can be associated to an initial correlation of central-to-forward event activity, which is dampened by energy conservation towards more violent collisions. All models describe these data with minor tensions only. Thus, the model parameter tunes for the underlying event, as determined at central rapidities, are consistent with the very forward data within experimental uncertainties. In detail, the energies predicted by PYTHIA 8 4C+MBR and SIBYLL 2.3c are slightly too low at small multiplicity. Conversely, at intermediate multiplicities, PYTHIA 8 CP5 predicts average energies larger than those observed.

The systematic uncertainty of the data is dominated by the energy scale uncertainty contribution, which is fully correlated between the multiplicity bins. Therefore, the distributions can be normalised to the first bin, so that, when comparing their shapes, the systematic uncertainty is significantly smaller (cf. Fig. 1, bottom). It is observed that the relative increase is steep at low multiplicities and becomes softer at higher multiplicities. All PYTHIA 8 tunes have very similar shapes, inconsistent with that observed in the data. The disagreement is strongest for PYTHIA 8 CP5, a tune optimised on underlying event data at central rapidity. This tune uses parton distribution functions at next-to-next-to leading order and features a softer MPI cutoff compared

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**Figure 3**

- **CMS Preliminary**

<table>
<thead>
<tr>
<th>$-6.6 \leq \eta \leq -5.2$</th>
<th>$0.22 \text{nb}^{-1} (13 \text{TeV})$</th>
</tr>
</thead>
</table>

- **Data**
- **Syst. uncertainty**
- **PYTHIA8 CUETP8M1**
- **PYTHIA8 4C+MBR**
- **EPOS LHC**
- **Sibyll 2.1**

**MC/data**

- **N_{tracks} (|\eta|<2)**

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6. Summary and discussion

The observables introduced provide a new approach to characterise particle production, and to study the properties of the underlying event. The measured average total energy as function of the track multiplicity is described with only minor tension by all models. This is a very good indication that underlying event parameter tunes performed at mid-rapidity can be extrapolated to Pythia 8 CUETP8M1 (see Ref. [GEN-17-001, in FR, will be provided before FSQ-18-001, reference will be inserted here] for details). The data therefore provide relevant information for future generator improvements and tunes. EPOS LHC, QGSJETII.04, and HERWIG 7.1 predict saturation at multiplicities above 80, which is not seen in the data in the same way. Both versions of SIBYLL provide predictions in agreement with the data. These normalized results indicate some interesting potential to further improve the underlying event model predictions in the very forward direction.

The individual electromagnetic and hadronic energy distributions are shown in Figs. 2 (top) and 2 (bottom). All models, with the exception of SIBYLL 2.3c, describe the electromagnetic component well. Also Pythia 8 4C+MBR slightly underestimates the electromagnetic energy at low multiplicities. Conversely, most models tend to overestimate the hadronic component, again with the exception of SIBYLL 2.3c and Pythia 8 4C+MBR. These data can be in particular relevant in the context of the simulation of cosmic ray induced extensive air showers since they point to the accuracy of the modelling of the production of neutral pions versus charged pions or other non-resonant hadrons. As the energies in $-6.6 < \eta < -5.2$ are already close to the peak of the forward-directed energy flow, this will have an important impact on modelling of complete extensive air shower cascades.

The data are finally also used to determine the ratio of the average electromagnetic and hadronic energies (Fig. 3). Here, the relative calibration of the electromagnetic and hadronic section is the main remaining source of uncertainty and results in a highly asymmetric uncertainty band. The measured ratio is approximately constant over the whole multiplicity range. This measured ratio depends on the details of hadronization in the observed phase space. Deviations of model predictions from the data hint on underlying differences of final state hadron production mechanisms contributing to the observed average energies. The contribution of string fragmentation, remnant fragmentation, initial- or final-state radiation, or eventual effects of a very dense hydrodynamical phase have to be considered to understand these data. Also the decay of short-lived resonances has an important impact on this ratio.

The observed independence of the measured ratio from track multiplicity indicates that no dramatic change of the particle production mechanism is observed at this very forward pseudorapidity. We note that all model predictions are lower than the data, specifically those of the modern tunes, Pythia 8 CP5 and SIBYLL 2.3c, whereas the QGSJETII.04, SIBYLL 2.1, and HERWIG 7.1 models give the best description of the ratio within the systematic uncertainties.
to the very forward direction within experimental uncertainties. However, it is also found that in a shape analysis of the same data we see very significant model differences and partly large deviations from the data. Thus, there is remaining opportunity to further improve the particle production models in this very forward phase space. Among all models, SIBYLL 2.1 shows the best reproduction of the measured multiplicity dependence of the average total energy.

The data is also presented separately for the average electromagnetic and hadronic energy per event as a function of central track multiplicity. This is useful to study different underlying particle production mechanisms, since the former is mostly due to decaying neutral pions, and the latter related to the production of non-resonant hadrons; most commonly charged pions. We find a general good description of all models of the electromagnetic energy – with the exception of SIBYLL 2.3c. Notably, the predicted energy in hadrons reveals a significantly larger spread compared to the electromagnetic energy between the different models.

The data are also presented in terms of the ratio between the electromagnetic and hadronic energies. The data exhibit a larger fraction of electromagnetic energy compared to the models, and disagree with the two most recent model tunes, SIBYLL 2.3c and PYTHIA 8 CP5. This deficiency implies an increased difficulty to solve the muon deficit in ultra-high energy air shower simulations since more energy will be channelled into the electromagnetic part of the cascade and will subsequently be lost for the generation of further hadrons [15].

References


