33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

ICRC 2013

# Results of the CMS very forward calorimeter

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**Abstract:** It is one of the aims of the CMS experiment at the LHC to improve the understanding of hadronic multiparticle production and QCD in general. Of particular interest to the astroparticle physics community are the forward physics results, which probe the phase space where most of the primary energy in high energy collisions flows to. On the other hand the forward region is also where the small-x part of the hadronic wave-functions can be studied best. The parton distribution in hadrons at small-x is most uncertain and, for example, the search for the onset of saturation is ongoing. Data from CMS are already improving the hadronic event generators available to the analysis of cosmic ray data. Here we are reviewing some of the latests developments.

**Keywords:** CMS, forward physics, CASTOR

## 1 Introduction

One of the most severe problems of cosmic ray physics is the need to better understand hadronic interactions in extensive air showers [1, 2]. This will ultimately open up new opportunities for more precise analyzes of cosmic ray data. Many fundamental questions about the origin of high energy cosmic rays and their interaction with the environment while they travel from source to detection, could be answered [3].

The CMS experiment at the LHC is making important contributions towards this goal. Hadronic multiparticle production is observed at energies that were never before subject to detailed accelerator measurements. The precise data of the central detectors of CMS provide important information for the tuning of hadronic interaction models. Furthermore, a selection of forward subdetectors are studying the phase space where most of the primary energy in high energy interactions flows to. This is in particular relevant for air showers, where no energy is lost, but just transported down in the atmosphere. Forward physics is recognized as being of paramount importance for cosmic ray physics, but at the same time it is very difficult to study at accelerators.

The 2012 data taking at the LHC brought the center-of-mass energy one step closer to the very high energy collisions possible in extensive air showers. For the first time proton-proton (pp) collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ compared to the previous 7 TeV were recorded. Furthermore lead-lead (PbPb) and also proton-lead collisions were studied. The analysis of the proton-lead data is currently ongoing. A lot of information on nuclear effects and on the transition from proton-proton over proton-lead to lead-lead collisions will be obtained. This is also very relevant for cosmic-ray air showers, where protons or heavier nuclei hit the atmosphere to initiate extensive air shower cascades.

## 2 Experimental Setup

The CMS experiment [4] is one of the big multi-purpose experiments at the LHC. The goal is to record as much information as possible from hadronic collisions happening in the center of the experiment. This is achieved with a detector layout consisting of several subdetector layers. In the core, only centimeters away from the interactions, there is the silicon pixel tracker with 65 million channels followed by the silicon strip tracker with another 10 million strips. The silicon tracker also records the energy loss of particles. Next to the tracking there is the electromagnetic calorimeter, consisting of a homogeneous lead-tungsten crystal calorimeter with almost 80000 channels. Outside of the electromagnetic calorimeter there is the hadronic brass-scintillator sampling calorimeter. All those detectors are fitted within the 6 m inner radius of the solenoidal superconducting 3.8 T magnet. Outside of the magnet there is the muon tracking system integrated in the iron return yokes. The strong magnetic field prevents particles below $p_\mathrm{T} \approx 1$ GeV to reach to the calorimeters, however, the silicon tracker can reconstruct $p_\mathrm{T}$ even at $\approx 100\,\mathrm{MeV}$.

Next to these central detectors, CMS also extends its coverage far into the forward region. Beyond the pseudorapidity of about 3, the CMS experiment is equipped with several calorimeters. The hadronic forward calorimeter at $3 < |\eta| < 5.2$ is built from steel with quartz-fibre as active material. The CASTOR calorimeter at $-6.6 < \eta < -5.2$ is a sampling calorimeter with 14 longitudianl readout channels made of tungsten with quartz plates. The zero degree calorimeter at $|\eta| > 8.4$ is also consisting of tungsten and quartz plates.

## 3 Identified Particles with the Central Detector

The silicon tracker of CMS was used to measure details of the spectra of identified particles up to center-of-mass energies of 7 TeV [5]. In Fig. 1 an example for such measurements is shown. The acceptance for this analysis depends also on the masses of the studied particles. For pions it reaches down to 100 MeV. The charge of the particles is also resolved. Such spectra are very important for general tuning of event generators also in extensive air showers. Several ratios of identified particles are shown in Fig. 2. This in particular is very interesting, since it was suggested that an increased baryon to meson ratio may explain at least part of the apparent muon deficit in air shower simulations [6].

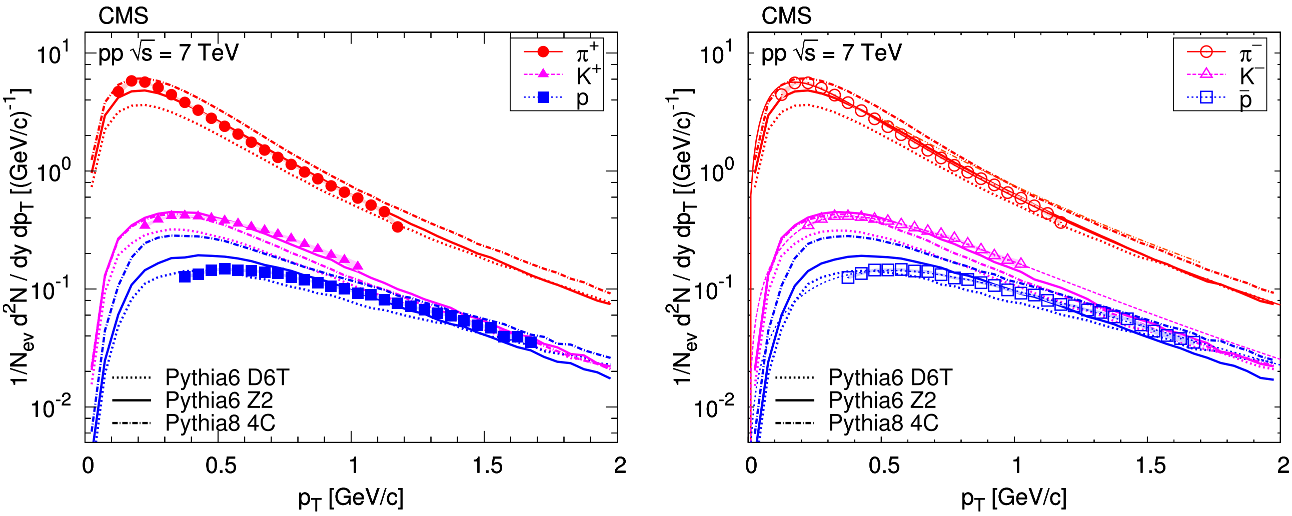


**Figure 1**: Identified spectra of hadrons in pp collisions at 7 TeV via the energy loss of particles in the silicon tracker. From Ref. [5].

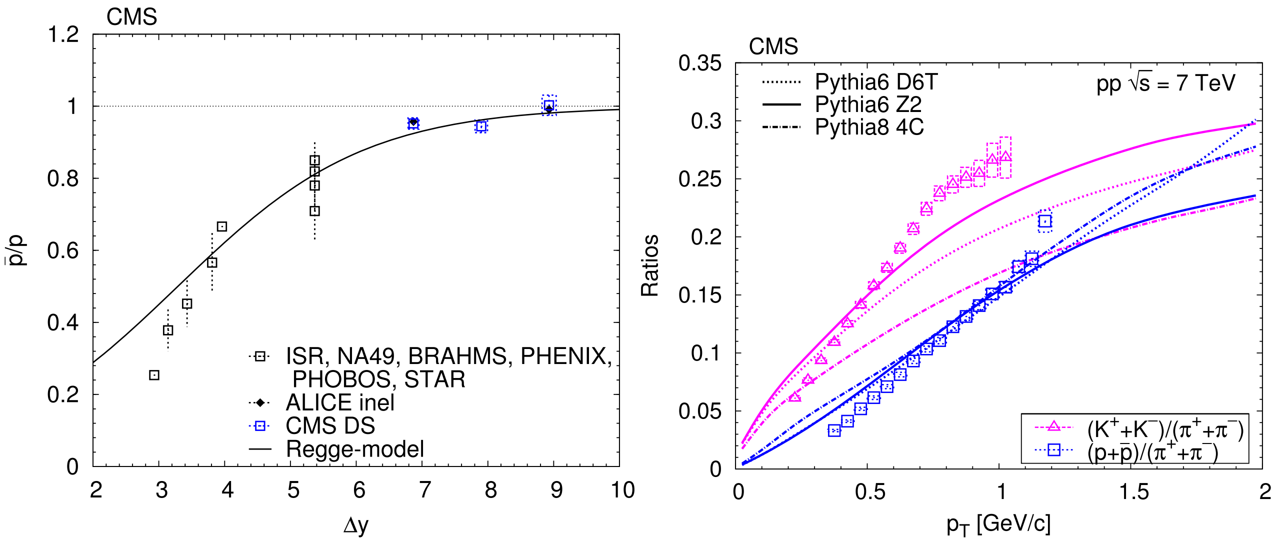


**Figure 2**: Left panel: Measured ratio of protons to anti-protons at different experiments. Right panel: Comparison of ratio of kaons to pions and protons to pions to model predictions. From Ref. [5].

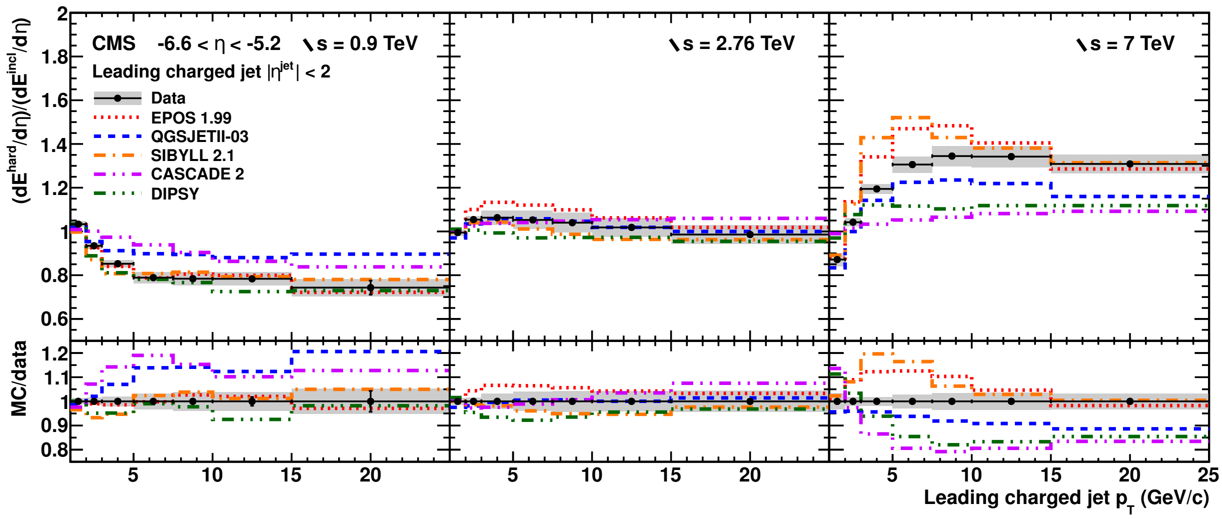


**Figure 3**: The average energy in events with a specific central activity relative to Minimum Bias data. See also Ref. [7].

## 4 Results Using the Very Forward Calorimeter CASTOR

At low center-of-mass energies the forward remnant is depleted with rising $p_{\mathrm{T}}$ at central rapidity, while at high energies the forward activity is correlated to central activity. This complex behavior is shown in Fig. 3 and is well described by all models that have been tuned to LHC data previously [7]. It is interesting to note that it was also found that cosmic-ray related models based on Gribov-Regge theory, SIBYLL 2.1 [8], QGSJetII.3 [9] and EPOS 1.99 [10], describe the data to the same level of accuracy even without a dedicated re-tuning to LHC data. This study is very sensitive to the multi-parton-interaction component of hadronic interactions and the agreement with the cosmic ray models indicates that multiple interactions in the Glauber or Gribov frameworks are compatible with this data.

The measurement of the very forward energy flow in PbPb minimum bias data at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$ are shown in Fig. 4 [11]. This analysis extends the pseudorapidity coverage of CMS by 1.5 units of pseudorapidity towards the beam rapidity, which is a unique feature at LHC. This wide acceptance allows to explore phase-space regions not accessible to other experiments. While the centrality-dependence of the very forward energy flow relative to the most central events is almost independent of pseudorapidity up to $|\eta| < 5$, in the very forward direction it is distinctively different. This result indicates significantly less dependence on the impact parameter of the collision at low-x.

Also here, when these data are confronted to existing models it is found that no model can describe all aspects of the observed phase-space. The Gribov-Regge type models EPOS [10] and QGSJetII [9] perform better in the forward region, while HYDJET [12] and AMPT [13] are better at mid-rapidities.

## 5 First Combined CMS+TOTEM data

For the first time a combined data set has been analyzed by the CMS and TOTEM collaborations simultaneously [14]. The pseudorapidity density of charged particles in proton-proton collisions at 8 TeV has been measured at central pseudorapidities with CMS and at the same time at forward rapidities with TOTEM. In Fig. 5 the pseudorapidity density of charged tracks is shown from central pseudorapidty up to $\eta = 6.5$. At 8 TeV the agreement found with models is limited. Such measurements over very wide intervals in pseudorapidty are very powerful in testing models.

The combination of CMS and TOTEM data has great potential during the next years to maximize the impact of forward physics results.

## 6 Summary

This is a very brief introduction about the measurements of the CMS experiment relevant to the cosmic ray community.

The CMS experiment is actively involved in improving hadronic interaction models, which explicitly includes the models used for the simulation of extensive air showers. Those models are now also used within CMS (and other LHC experiments) for detector level studies. After the end of the long shutdown 1, the LHC will collect data at center-of-mass energies of up to 14 TeV. Precise accelerator data are paramount in improving hadronic interaction models.

Furthermore, the closer collaboration of the CMS and TOTEM experiments has significant potential to lead to another set of new measurements at very forward pseudorapidities with a high impact on the cosmic ray community.

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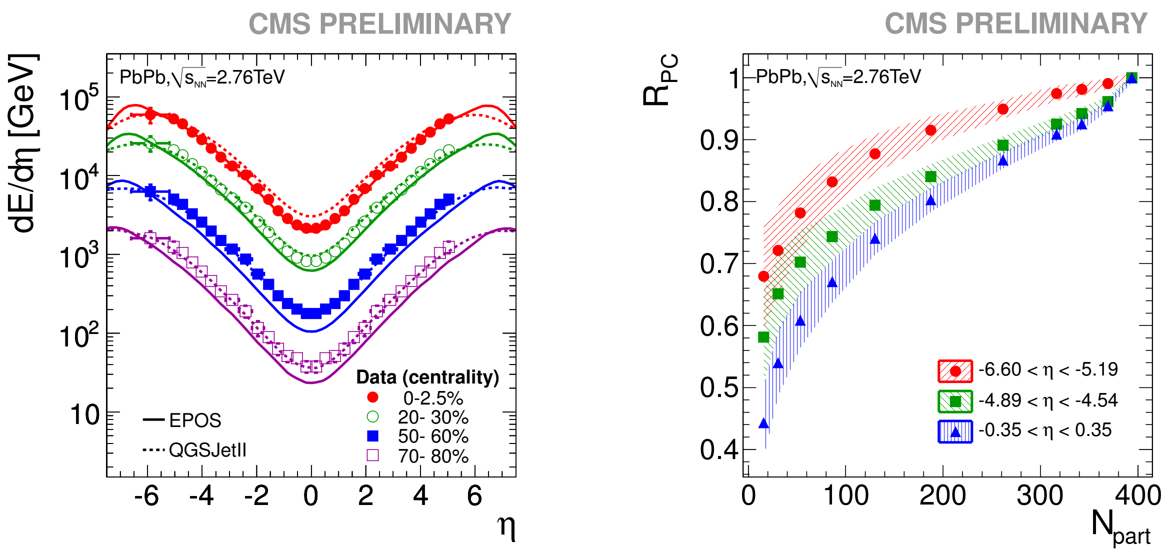


**Figure 4**: Left panel: Measurements of the average energy deposit per unit of pseudorapidity in PbPb events over the full CMS acceptance range. Right panel: Energy flow relative to most central PbPb collisions as a function of centrality for different pseudorapidities. See also Ref. [11].

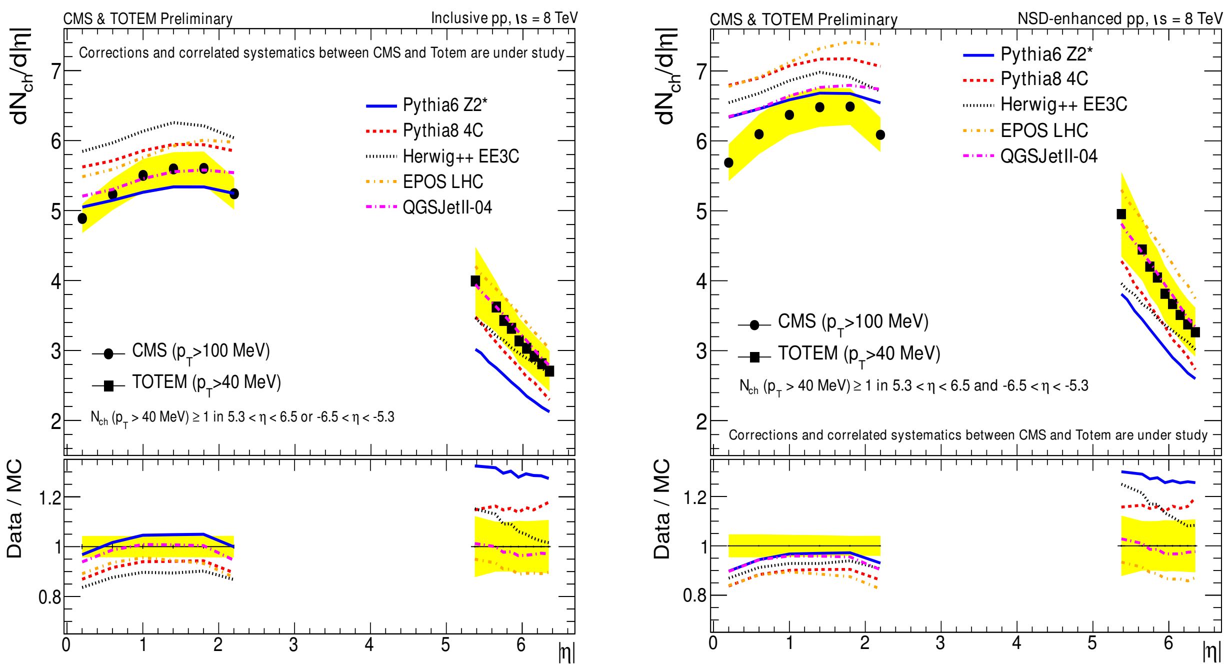


**Figure 5**: Charged particle density for inclusive (left) and non-single-diffractive (right) event selections. This is the first combined result from CMS and TOTEM data. From Ref. [14].