The Compact Muon Solenoid Experiment
Conference Report

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CMS: First Results

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Abstract

The status of CMS concerning the 2009 run and the first data recorded at 7 TeV in 2010 is reported. A summary of the LHC and CMS detector performance is given and the first CMS results are presented. In particular, emphasis will be given to low- p_T QCD Physics including charged hadron spectra, the measurement of Bose-Einstein (BEC) and angular Correlations, and of underlying event properties.

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Keywords: CMS, LHC

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INTRODUCTION

This report gives an overview of the first results obtained by the Compact Muon Solenoid (CMS) experiment with the data collected during the first months of the Large Hadron Collider (LHC) operations. In the following, after a brief description of the first performance of LHC and of the CMS detector, the results concerning charged hadron spectra, Bose-Einstein (BEC) and angular Correlations, Underlying Events (UE) and Diffraction studies are shown.

LHC AND CMS

After the 2009 startup with data taken at 0.9 TeV and 2.36 TeV center-of-mass energies providing the first LHC Physics results, the 2010-2011 LHC Physics program (1 fb^{-1} at 7 TeV) has started successfully. During the first two months of the run, the LHC achieved the designed intensity of 1.1×10^{11} protons per bunch. At the time of the present conference, the accelerator has delivered an integrated luminosity of 20 nb^{-1} .

A detailed description of CMS detector can be found elsewhere [1]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a uniform magnetic field of 3.8 T. The inner tracking system is the most relevant detector for the first analyses. It is composed of a pixel detector with three barrel layers at radii between 4.4 and 10.2 cm and a silicon strip tracker with 10 barrel detection layers extending outwards to a radius of 1.1 m. Each system is completed by two endcaps, extending the acceptance up to a pseudorapidity $|\eta| = 2.5$. Three detector sub-systems are used to trigger the detector readout for the data presented here. These are the forward hadron calorimeter (HF), the Beam Scintillator Counters (BSC) and the Beam Pick-up Timing for eXperiments (BPTX). The HF covers the region $2.9 < |\eta| < 5.2$, the two BSCs, located on either side of the IP at a distance of $\approx 11 \text{ m}$, are sensitive in the range $3.23 < |\eta| < 4.65$. The two BPTXs are located around the beam pipe at 175 m from the IP and provide precise information on the structure and timing of the LHC

FIGURE 1. Example of charged track reconstruction quality: Λ peak obtained with 2009 data.

beams.

All the CMS subdetectors were working properly at the LHC startup with more than 99% of detector channels operational. As a consequence, Physics results were obtained from the very early data. An example of detector performance is given in Fig. 1

PHYSICS RESULTS

The analyses described below are performed on minimum-bias data, whose composition is dominated by low momentum-transfer pp interactions. The minimum-bias data are commonly classified as elastic scattering, inelastic single-diffractive (SD) or double-diffractive (DD) dissociation and inelastic non-diffractive scattering. Collision events are triggered by coincidence of signals in BSC and BPTX detectors. Non single-diffractive (NSD) events are selected by requiring an Energy deposition ($E > 3$ GeV) in each side of HF. A veto against beam halo events is applied.

Transverse-momentum and pseudorapidity distributions of charged hadrons. The charged particle multiplicity from pp collisions as function of η and p_t are measured with three different methods [2, 3].

Pixel Clusters method. When a charged particle crosses the pixel detector, the energy released in the sensitive material is detected as a cluster of adjacent pixels with signal above a threshold. The method determines the charged particle multiplicity by counting the clusters in the pixel detector. Clusters due to loopers and secondary particles are removed by requiring the cluster length along z to be compatible with the hypothesis that the particle originates from the primary vertex.

Tracklet method. This method relies on the reconstruction of track fragments made up of two hits in pixel detector. The $\Delta\eta$ and $\Delta\phi$ between the two hits with respect to primary vertex are computed for each tracklet. Tracklet belonging to a primary particle have a sharp peak at 0 in the $\Delta\eta$ distribution, while tracklets from the combinatorial

FIGURE 2. Left: $dN_{ch}/d\eta$ distributions averaged over the three measurement methods and compared with UA5 [4] and ALICE [5] results. The shaded bands show the CMS systematic error. Right: charged-hadron yield in the range $|\eta| < 2.4$ in NSD events as a function of p_T . The solid lines represent the fit with the Tsallis function [6]

background and secondary particles have long tails in $\Delta\phi$. To reject fake tracklets a sideband subtraction method in $\Delta\phi$ is used.

Track method. It counts the tracks reconstructed in pixel and strip detectors. The background reduction is obtained by requiring a track to have at least three hits in pixels and strips and to come from the primary vertex. The three methods give compatible results that can be averaged into a single measurement of charged hadron spectra. The systematic errors amount to about 5% mainly from trigger, event selection and reconstruction efficiency. The distributions are shown in Fig. 2 where is clear that the $dN_{ch}/d\eta$ results agree with the ones published by UA5 and ALICE. The $d^2N_{ch}/d\eta dp_T$ distribution does not depend significantly on η . The energy dependence of the measured $dN_{ch}/d\eta$ at $\eta \approx 0$ is shown in Fig. 3 which includes data from various experiments. The CMS results show a steep increase between 0.9 and 7 TeV. The measured value at 7 TeV exceeds the predictions of the commonly used event generators.

Bose Einstein Correlations. In particle collisions, the space-time structure of the hadronization source can be studied using measurements of Bose–Einstein correlations (BEC) between pairs of identical bosons. Constructive interference affects the joint probability for the emission of a pair of identical bosons with four-momenta p_1 and p_2 . Experimentally, the proximity in phase space between final-state particles is quantified by the quantity $Q = \sqrt{-(p_1 - p_2)^2} = \sqrt{M^2 - 4m_\pi^2}$, where M is the invariant mass of the two particles, assumed to be pions with mass m_π . The BEC effect is observed as an enhancement at low Q of the ratio of the Q distributions for pairs of identical particles in the same event, and for pairs of particles in a reference sample that by construction is expected to include no BEC effect:

$$R(Q) = (dN/dQ)/(dN_{ref}/dQ), \quad (1)$$

FIGURE 3. Average value of $dN_{ch}/d\eta$ in the central η region as a function of $\sqrt{s}$ for several pp and $p\bar{p}$ experiments.

which is then fitted with the parameterization $R(Q) = C[1 + \lambda\Omega(Qr)] \cdot (1 + \delta Q)$. Ω is often phenomenologically parameterized as $\Omega(Qr) = e^{-Qr}$ or $\Omega(Qr) = e^{-(Qr)^2}$ (see [7]). The parameter λ measures the strength of BEC for incoherent boson emission from independent sources, δ accounts for long-distance correlations, and C is a normalization factor.

All pairs of same-charge particles with Q between 0.02 and 2 GeV collected at 0.9 and 2.36 TeV are used for the measurement [8].

Different methods are designed to pair uncorrelated charged particles and to define reference samples used to extract the distribution in the denominator of Eq. (1). *Opposite-charge pairs*: this data set is a natural choice but contains resonances (η , ρ , ...) which are not present in the same-charge combinations. *Opposite-hemisphere pairs*: tracks are paired after inverting the three-momentum of one of the two particles; this procedure is applied to pairs with same and opposite charges. *Rotated particles*: particle pairs are constructed after inverting the p_t of one of the two particles. *Pairs from mixed events*: particles from different events are combined with the following methods: i) events are mixed at random; ii) events with similar charged particle multiplicity in the same η regions are selected; iii) events with an invariant mass of all charged particles similar to that of the signal are used to form the pairs.

In order to reduce the bias due to the construction of the reference samples, a double ratio $\mathcal{R}$ is defined as $\mathcal{R}(Q) = R/R_{MC} = \left(\frac{dN/dQ}{dN/dQ_{ref}} \right) / \left(\frac{dN/dQ_{MC}}{dN/dQ_{MC,ref}} \right)$, where Q_{MC} and $Q_{MC,ref}$ refer to the Q distributions from the default simulation, which does not include a modeling of Bose–Einstein correlations. As none of the definitions of the reference samples is preferable *a priori*, an additional, “combined” double ratio $\mathcal{R}^{comb}$ is formed, where the data and MC distributions are obtained by summing the Q distributions of the seven corresponding reference samples.

The distributions $\mathcal{R}^{comb}$ for 0.9 and 2.36 TeV data show a clear enhancement at low Q as it can be seen in Fig. 4. The parameterization $\Omega(Qr) = e^{-Qr}$ and $\Omega(Qr) =$

FIGURE 4. Left: $\mathcal{R}^{comb}$ distributions fitted with exponential (full line) and Gaussian (dashed line) functions. Right: λ (top) and r (bottom) parameters as function of the charged-particle multiplicity at 0.9 TeV for the combined (dots) and Opposite-hemisphere same charge (open circles) reference samples.

$e^{-(Qr)^2}$ is used to fit $\mathcal{R}^{comb}$. Only the exponential form is found to fit reasonably the data and the BEC parameters measured with the combined reference sample are $\lambda = 0.625 \pm 0.021(\text{stat.}) \pm 0.046(\text{syst.})$ and $r = 1.59 \pm 0.05(\text{stat.}) \pm 0.19(\text{syst.})$ fm at 0.9 TeV; $\lambda = 0.663 \pm 0.073(\text{stat.}) \pm 0.048(\text{syst.})$ and $r = 1.99 \pm 0.18(\text{stat.}) \pm 0.24(\text{syst.})$ fm at 2.36 TeV. A significant increase of r with the charged-particle multiplicity and a slight decrease of λ are observed as shown in Fig.4 (right). These results agree with what has been measured by previous experiments [9].

Angular Correlations. The two-particle angular correlations are measured at the center-of-mass energies of 0.9, 2.35 and 7 TeV [10]. The p_t - inclusive charged two-particle correlation function is defined as

$$R(\Delta\eta, \Delta\phi) = \left\langle (N-1) \left(\frac{S_N(\Delta\eta, \Delta\phi)}{B_N(\Delta\eta, \Delta\phi)} - 1 \right) \right\rangle_N \quad (2)$$

where N represents the total track multiplicity of each event, $\Delta\eta = (\eta_1 - \eta_2)$ and $\Delta\phi = (\phi_1 - \phi_2)$ are the relative difference in pseudorapidity and azimuthal angle between two particles. At a fixed multiplicity bin, the signal distribution $S_N(\Delta\eta, \Delta\phi)$ is the charged two-particle pair density function (normalized to unit integral). It is determined by taking particle pairs within the same event, then averaging over all events. The background distribution $B_N(\Delta\eta, \Delta\phi)$ denotes the distribution of uncorrelated particle pairs (normalized to unit integral). It is constructed by randomly selecting two different events from the same multiplicity bin and pairing every particle from one event with the other event, representing a product of two single particle distributions.

To obtain quantitative results the 2-D correlation are projected into a 1-D pseudorapidity correlation function of $\Delta\eta$ and two different near-side and away-side $\Delta\phi$ ranges ($0 < \Delta\phi < \pi/2$ and $\pi/2 < \Delta\phi < \pi$ respectively). With Gaussian function fit $\Gamma(\Delta\eta) = K_{eff} \cdot \exp[-(\Delta\eta)^2/(4\delta^2)]$ the effective cluster size K_{eff} and decay width δ

can be estimated. Fig. 5 shows the results of K_{eff} and δ measured by the CMS experiment after the extrapolation to $|\eta| < 3$ and $p_t \approx 0$, as well as previous measurements at lower energies and in the same pseudorapidity coverage. The extrapolated CMS results are $K_{eff} = 2.50 \pm 0.01$ (stat) ± 0.06 (syst) ± 0.07 (extrap.), $\delta = 0.64 \pm 0.01$ (stat) ± 0.02 (syst) ± 0.03 (extrap.) for $\sqrt{s} = 0.9$ TeV, $K_{eff} = 2.65 \pm 0.03$ (stat) ± 0.07 (syst) ± 0.08 (extrap.), $\delta = 0.60 \pm 0.01$ (stat) ± 0.02 (syst) ± 0.03 (extrap.) for $\sqrt{s} = 2.36$ TeV, and $K_{eff} = 2.75 \pm 0.01$ (stat) ± 0.07 (syst) ± 0.09 (extrap.), $\delta = 0.59 \pm 0.01$ (stat) ± 0.02 (syst) ± 0.03 (extrap.) for $\sqrt{s} = 7$ TeV. The error bars in Fig. 5 include systematic uncertainties from both the experimental measurements and the extrapolations added in quadrature. The PYTHIA event generator again shows a similar energy dependence of K_{eff} and δ to the data, but essentially underestimate the magnitude of K_{eff} over the full energy range.

FIGURE 5. (a) K_{eff} and (b) δ as a function of $\sqrt{s}$ using a model dependent extrapolation of CMS data to $p_T = 0$ and $|\eta| < 3$ (solid circles), as well as PHOBOS (solid squares), UA5 (solid triangles) and ISR (solid stars). Open circles and squares show the PYTHIA results respectively.

Underlying Event Activity. In a hadron collider, the hard parton scattering is accompanied by other processes: additional soft interactions among beam partons (Multi Parton Interactions, MPI) and hadronization of non interacting partons (Beam Beam Remnants, BBR). Products of MPI and BBR form the Underlying Event. Knowledge of UE is crucial for Monte Carlo tuning, precision Standard Model measurements and

searches for Physics beyond the SM. Assuming the leading track or jet gives the direction of the parton coming from the hard scattering, the activity due to UE dominates the region orthogonal to that direction in the transversal plane [11]. The Σp_t distribution for the charged particles as a function of the angular distance $\Delta\phi$ from the leading track is shown in Fig. 6 (left). The two peaks at 0° and $\pm 180^\circ$ are due to hard scattering while the non-null activity in the transverse region $60^\circ < |\Delta\phi| < 120^\circ$ is attributed to UE. None of the predictions shown in the figure provides a satisfactory description of the data in the UE region. The UE activity increases as a function of the leading track p_t as seen in Fig. 6 (right) and this behavior is well reproduced by some PYTHIA tunes. The error bars in the figure correspond to statistical and systematic errors.

These measurements allow for a better Monte Carlo tuning in view of a better description of CMS data.

FIGURE 6. Left: average scalar sum of charged particle p_t as a function of $\Delta\phi$ relative to the leading track. Right: average multiplicity of charged particles in the transverse region $60^\circ < |\Delta\phi| < 120^\circ$ as a function of the leading track p_t .

Diffraction. A substantial fraction of the total proton-proton cross section is due to diffractive reactions of the type $pp \rightarrow XY$, where X, Y are either protons or low-mass systems which emerge from the interaction with energy approximately equal to that of the incoming beam particles, to within a few per cent. The observation of a diffractive signal is dominated by the inclusive single-diffractive (SD) reaction $pp \rightarrow Xp$. Those events are selected mainly by requiring BPTX signals from both beams passing the IP in conjunction with a signal in either of the BSCs [12]. The selected events are plotted as a function of the following variables:

1) $E \pm p_z = \sum (E_i \pm p_{z,i})$, where the sum runs over all calorimeter towers, including HF and p_z is the longitudinal momentum (Fig. 7(left)).

2) E_{HF} , the energy deposition in the HF. Here diffractive events appear as a peak in the zero-energy bin of either the HF at forward rapidities (HF+) or the HF at negative rapidities (HF-), reflecting the presence of a large rapidity gap extending over HF+ or HF-.

3) N_{HF} , the multiplicity of the towers above threshold in the HF. Diffractive events cluster at zero multiplicities, also reflecting the presence of a large rapidity gap over HF

FIGURE 7. Distributions of the accepted events as a function of $E + p_z$ and N_{HF+} at 900 GeV. The predictions of PYTHIA and PHOJET are also shown, normalised to the data. The vertical bars indicate the statistical uncertainty of the data. The bands illustrate the effect of a $\pm 10\%$ energy scale uncertainty in the calorimeters.

(Fig. 7(right)).

To enhance the diffractive components in the data, a cut was applied to the HF energy sum. This cut mainly selects single-diffractive events with a Large Rapidity Gap over HF+. A comparison with PYTHIA and PHOJET in this region indicates that the latter agrees better with the data. In particular it gives a better description of the high-mass diffractive systems, at large values of $E \pm p_z$, E_{HF} and N_{HF} .

CONCLUSIONS

The LHC started in 2009 providing good quality data. The CMS detector had also a startup with impressive performance so that physics results from the very early data were obtained in a fast and efficient way. Soft hadron dynamics measurements in the new energy domain reveal problems of phenomenological models and allow to tune MC generators in view of hard scattering processing.

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