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First results of the CMS experiment on QCD physics

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Abstract

Results presented here constitute the first achievements of the rich QCD physics program of the CMS experiment at LHC. Using data from proton-proton collisions at center-of-mass energies of 0.9, 2.36 and 7 TeV, measurements of charged particle yields, Bose-Einstein correlations and underlying event features have been produced. These are among the first results concerning the properties and interactions of charged hadrons at the new energy frontier accessible at LHC.

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FIRST RESULTS OF THE CMS EXPERIMENT ON QCD PHYSICS

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Keywords: CMS; physics; QCD; low-pt; Bose-Einstein

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1. Introduction

The results reported here were obtained by the Compact Muon Solenoid (CMS) experiment during the first months of operation of the Large Hadron Collider (LHC) at CERN. At the end of 2009 LHC delivered pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV, while in March 2010 it has started colliding protons at $\sqrt{s} = 7$ TeV. The first period of data taking of CMS has been focused on the assessment of the detector performance, and on a series of measurements mainly regarding QCD physics at low momentum transfer.

In the following, after a brief description of the CMS detector, the results concerning charged hadron spectra, Bose-Einstein correlations and underlying event studies are shown.

2. Detector description

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry.

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CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of LHC, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the anticlockwise-beam direction. The polar angle, θ , is measured from the positive z axis and the azimuthal angle, ϕ , is measured in the x - y plane.

The inner tracker measures charged particles within the $|\eta| < 2.5$ pseudorapidity range. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules and is located in the 3.8 T field of the superconducting solenoid. It provides an impact parameter resolution of $\sim 15 \mu\text{m}$ and a transverse momentum (p_T) resolution of about 1.5 % for 100 GeV/ c particles.

A much more detailed description of CMS can be found in Ref. 1.

3. Trigger and event selection

All the analyses described below are performed on *minimum-bias* data, whose composition is dominated by “soft” (i. e. low momentum transfer) pp interactions. These are commonly classified as elastic scattering, inelastic single-diffractive (SD) dissociation, double-diffractive (DD) dissociation, and inelastic nondiffractive (ND) scattering ².

Triggering of collision events is based on a coincidence of signals in both sides of the beam scintillator counter (BSC) and beam pick-up (BPTX) detectors ¹. Event selection is refined by requiring at least one vertex reconstructed in the inner tracker, and applying a veto against events induced by beam halo. Non single-diffractive (NSD) events are selected by requiring a deposit of energy on each side of the forward calorimeter.

4. Charged hadron spectra

The densities of charged particles arising from the proton-proton collisions as a function of η and p_T are measured with three different methods ³.

When a charged particle passes through the pixel detector, the energy it releases in the sensitive material is detected as a cluster of adjacent pixels with signal above a given threshold. The **pixel cluster** method finds the charged particle density 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 interaction vertex.

The **tracklet** method relies on the reconstruction of track fragments made up of two hits in the pixel detector. For each tracklet, the $\Delta\eta$ and $\Delta\phi$ between the two hits with respect to the primary vertex are computed. If the tracklet belongs to a primary particle, the $\Delta\eta$ distribution has a sharp peak at 0, while tracklets from the combinatorial background and from secondaries have long tails in $\Delta\phi$. Thus, a sideband subtraction method in $\Delta\phi$ is used to reject fake tracklets.

The **track** method counts the fully reconstructed tracks in pixel and strip detectors. Details of the CMS tracking algorithm can be found in Ref. 4. The background

is reduced by requiring a track to have at least three hits in pixel and strips, and to be coming from the primary vertex.

The results of the three methods are compatible within the errors, thus they can be averaged to give a single measurement of the charged hadron spectra. The distributions of N_{ch} as a function of η and p_T are shown in Fig. 1. The main systematic uncertainties come from trigger, event selection and reconstruction efficiencies, and amount to about 5 %. The $dN_{\text{ch}}/d\eta$ results are comparable with the ones found by the UA5 and ALICE experiments ^{5,6}. The $d^2N_{\text{ch}}/d\eta dp_T$ distribution does not depend significantly on η , and is fitted, with the Tsallis function ⁷:

$$E \frac{d^3 N_{\text{ch}}}{dp^3} = \frac{1}{2\pi p_T} \frac{E}{p} \frac{d^2 N_{\text{ch}}}{d\eta dp_T} = C \frac{dN_{\text{ch}}}{dy} \left(1 + \frac{E_T}{nT}\right)^{-n}, \quad (1)$$

which parametrizes the exponential behavior at low p_T and the power-law behavior at high p_T of the particle density. In Eq. 1, y is the rapidity and E_T is the transverse energy of the charged particle, assumed to be a π meson. The average p_T value is found to scale as $\ln^2 s$; at 7 TeV is $\langle p_T \rangle = 0.545 \pm 0.005$ (stat.) ± 0.015 (syst.) GeV/ c .

Fig. 1. **Left:** Distributions of $dN_{\text{ch}}/d\eta$, averaged over the three measurement methods and compared with data from UA5 ⁵ (pp, with statistical errors only) and ALICE ⁶ (with systematic uncertainties). The shaded band shows systematic uncertainties of the CMS data. **Right:** Charged-hadron yield in the range $|\eta| < 2.4$ in NSD events as a function of p_T at $\sqrt{s} = 0.9, 2.36$ and 7 TeV. The solid lines represent fits of Eq. (1) to the data ³.

5. Bose-Einstein correlation

Bose-Einstein correlation (BEC) is a constructive interference phenomenon which enhances the probability to emit pairs of identical bosons with a small distance in phase space ². If M is the invariant mass of the two particles, assumed to be π mesons, the proximity in phase space can be parametrized by the quantity $Q =$

$\sqrt{-(p_1 - p_2)^2} = \sqrt{M^2 - 4m_\pi^2}$. The enhancement is measured by the ratio $R(Q) = (dN_{\text{sig}}/dQ)/(dN_{\text{ref}}/dQ)$ between the dN/dQ distributions of the signal sample and of a reference sample that is expected not to have any BEC effect⁸. The ratio can then be fitted using the function

$$F(Q) = C[1 + \lambda\Omega(Qr)](1 + \delta Q), \quad (2)$$

where $\Omega(Qr)$ is the Fourier transform of the spatial distribution of the particle emitting region, having radius r , λ is the correlation strength and δ is a parameter accounting for long-range correlations in the reference sample.

The signal sample is built by taking all the pairs of same-charge tracks of each event. For the reference sample, seven possible choices have been considered. Four of them are built by recombining the tracks in the same event, making pairs of:

- opposite-charge tracks;
- opposite-charge tracks in which one has p inverted;
- same-charge tracks in which one has p inverted;
- same-charge tracks in which one has p_T inverted.

The other reference samples are built with pairs of same-charge tracks from different events, using three event-mixing methods:

- random mixing;
- similar $dN_{\text{ch}}/d\eta$;
- similar total invariant mass.

In order to reduce the baseline fluctuations introduced by each reference sample, a double ratio $\mathcal{R}(Q) = R_{\text{data}}(Q)/R_{\text{sim}}(Q)$ is built, where $R_{\text{sim}}(Q)$ is the ratio found in the GEANT-based⁹ simulation of the CMS detector response, with events produced by the PYTHIA 6.4 Monte Carlo generator¹⁰, which includes no BEC effects. Finally, a double ratio $\mathcal{R}_{\text{comb}}(Q)$ is built with respect to a combined reference sample, created by summing the dN/dQ distributions for the seven references listed above.

The distributions of $\mathcal{R}_{\text{comb}}(Q)$ for 0.9 TeV and 2.36 TeV data (Fig. 2 on the left) show a clear enhancement at low Q . Eq. 2, with two different parametrizations of $\Omega(Qr)$, is used to fit them: an exponential form (solid lines) and a Gaussian form (dashed lines)¹¹. The range $0.6 < Q < 0.9$ GeV is excluded from fits, because of distortions in the distributions due to the ρ resonance. Only the exponential form is found to describe well the data. The values of the BEC parameters found in the exponential fit are respectively $\lambda = 0.625 \pm 0.021$ (stat.) ± 0.046 (syst.) and $r = 1.59 \pm 0.05$ (stat.) ± 0.19 (syst.) fm at 0.9 TeV, and $\lambda = 0.663 \pm 0.073$ (stat.) ± 0.048 (syst.) and $r = 1.99 \pm 0.18$ (stat.) ± 0.24 (syst.) fm at 2.36 TeV.

The dependence of the BEC parameters from the charged multiplicity in the event is shown in Fig. 2 on the right. With increasing N_{ch} , an increase of the size r of the emission region, and a slight decrease of the strength λ are found. These results confirm what has been seen by previous experiments².

Fig. 2. **Left:** fits to the double ratios $\mathcal{R}_{\text{comb}}(Q)$ with exponential (solid lines) and Gaussian (dashed lines) functions, for 0.9 TeV (top) and 2.36 TeV (bottom) data. **Right:** values of the λ (top) and r (bottom) parameters as a function of the charged-particle multiplicity in the event for combined (dots) and same-charge inverted-momentum (open circles) reference samples at 0.9 TeV ⁸.

6. Underlying event measurements

In a typical event at a hadron collider, the hard scattering of incoming partons is usually accompanied by other processes: additional “soft” interactions among beam partons (multiple-parton interactions, MPI) and hadronization of non-interacting beam partons (beam-beam remnants, BBR). Products of MPI and BBR are collectively called the *underlying event* (UE). A good knowledge of UE is crucial for Monte Carlo tuning, precision Standard Model measurements, and searches for new physics.

Hard scattering in minimum-bias events usually has a back-to-back structure, where activity is concentrated in two regions roughly separated by an angle of 180° in ϕ . Assuming that the leading (i.e. highest- p_T) track is oriented as the partons coming from the hard scattering, the activity due from the UE can be studied looking at the region orthogonal to it in the transverse plane ¹².

Left pane of Fig. 3 shows the Σp_T distribution for the charged particles as a function of the angular distance $\Delta\phi$ from the leading track. The two peaks at 0° and at 180° are due to the hard scattering, while the non-null activity in the “transverse” region ($60^\circ < |\Delta\phi| < 120^\circ$) is attributed to the UE. In the figure, the predictions of several different tunes of the PYTHIA generator (see Ref. 12 for more details) are shown: none of them provides a satisfactory description of data in the UE region, the closest ones being the CW and DW tunes.

The activity due to the UE increases as a function of the leading track p_T , as shown in the right pane of Fig. 3. This behavior is well-reproduced by the CW and DW PYTHIA tunes, that “bracket” the data. The error bands in the figure correspond to the statistical and systematic errors, the latter being mainly due to tracker passive

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material, background contamination and uncertainties in the selection efficiency.

These measurements constitute a valuable input for the improvement of the Monte Carlo description of CMS data.

Fig. 3. **Left:** average scalar sum of transverse momenta of charged particles, per unit of η and per radian, plotted as a function of the azimuthal angle difference $\Delta\phi$ relative to the leading track. **Right:** average multiplicity of charged particles in the transverse region, $60^\circ < |\Delta\phi| < 120^\circ$, per unit of η and per radian, as a function of the leading track p_T ¹².

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