

# Transverse momentum and pseudorapidity distributions of charged hadrons at CMS

Yen-Jie Lee for the CMS Collaboration

Laboratory for Nuclear Science, MIT, Cambridge, MA 02139-4307, USA

DOI: <http://dx.doi.org/10.3204/DESY-PROC-2010-01/208>

Charged-hadron transverse-momentum and pseudorapidity distributions in proton-proton collisions at  $\sqrt{s} = 7$  TeV are measured with the CMS detector at the LHC. The measured charged-hadron multiplicity per unit of pseudorapidity is  $dN_{\text{ch}}/d\eta|_{|\eta|<0.5} = 5.78 \pm 0.01$  (stat.)  $\pm 0.23$  (syst.) for non-single-diffractive events, higher than predicted by commonly used models. The mean transverse momentum is measured to be  $0.545 \pm 0.005$  (stat.)  $\pm 0.015$  (syst.) GeV/c. The results are compared with measurements at lower energies.

*Introduction.* Measurements of particle yields and kinematic distributions are an essential first step in exploring a new energy regime of particle collisions. Such studies contribute to our understanding of the physics of hadron production, including the relative roles of soft and hard scattering contributions, and help construct a solid foundation for other investigations. In the complicated environment of LHC  $pp$  collisions [1], firm knowledge of the rates and distributions of inclusive particle production is needed to distinguish rare signal events from the much larger backgrounds of soft hadronic interactions. They will also serve as points of reference for the measurement of nuclear-medium effects in Pb-Pb collisions at LHC. Soft interactions in  $pp$  collisions are commonly classified as elastic scattering, inelastic single-diffractive (SD) dissociation, double-diffractive (DD) dissociation, and inelastic non-diffractive (ND) scattering [2]. All results presented here refer to inelastic non-single-diffractive (NSD) interactions. The measurements reported here are of  $dN_{\text{ch}}/d\eta$  and  $dN_{\text{ch}}/dp_T$  in the  $|\eta| < 2.4$  range [3] and closely follow our previous analysis at centre-of-mass energies of  $\sqrt{s} = 0.9$  and 2.36 TeV [4]. The data for this study are drawn from an integrated luminosity of  $1.1 \mu\text{b}^{-1}$  recorded with the Compact Muon Solenoid (CMS) experiment [5] during the first hour of the LHC operation at  $\sqrt{s} = 7$  TeV. These results are the highest centre-of-mass energy measurements of the  $dN_{\text{ch}}/d\eta$  and  $dN_{\text{ch}}/dp_T$  distributions conducted at a particle collider.

*Experimental methods.* A detailed description of the CMS experiment can be found in Ref. [5]. The detectors used for the analysis are the pixel and silicon-strip tracker (SST), covering the region  $|\eta| < 2.5$  and immersed in a 3.8 T axial magnetic field. The pixel tracker consists of three barrel layers and two end-cap disks at each barrel end. The forward calorimeter (HF), which covers the region  $2.9 < |\eta| < 5.2$ , was also used for event selection. The detailed Monte Carlo simulation (MC) of the CMS detector response is based on GEANT4 [6]. Any hit in the beam scintillator counters (BSC,  $3.23 < |\eta| < 4.65$ ) coinciding with colliding proton bunches was used for triggering the data acquisition. A sample mostly populated with NSD events was selected by requiring a primary vertex (PV) to be reconstructed with the tracker [7], together with at least one HF tower in each end with more than 3 GeV total energy. Beam-halo and other beam-background events were rejected as described in Ref. [4]. The fraction of

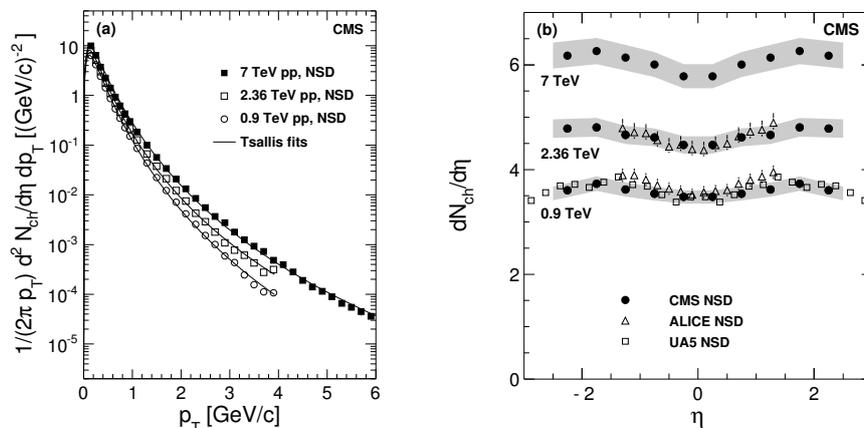


Figure 1: (a) Charged-hadron yield in the range  $|\eta| < 2.4$  in NSD events as a function of  $p_T$ . (b) Distributions of  $dN_{ch}/d\eta$ , averaged over the three measurement methods and compared with data from UA5 [15] ( $p\bar{p}$ , with statistical errors only) and ALICE [17] (with systematic uncertainties). The shaded band shows systematic uncertainties of the CMS data. The CMS and UA5 data are averaged over negative and positive values of  $\eta$ .

background events in the data after selection is less than  $2 \times 10^{-5}$ . 55k events satisfying the selection criteria are selected for analysis.

The event selection efficiency was estimated with simulated events using the PYTHIA [8, 9] and PHOJET [10, 11] event generators. At  $\sqrt{s} = 7$  TeV, the fraction of SD (DD) events in the selected data sample, estimated with PYTHIA and PHOJET, are 6.8% (5.8%) and 5.0% (3.8%), respectively. The overall correction for the selection efficiency of NSD processes and for the fraction of SD events remaining in the data sample lowers the measured charged-particle multiplicity by 6% compared with the uncorrected distribution.

The  $dN_{ch}/d\eta$  distributions were obtained with three methods, based on counting the following quantities: (i) clusters in the barrel part of the pixel detector; (ii) pixel tracklets composed of pairs of clusters in different pixel barrel layers; and (iii) tracks reconstructed in the full tracker volume. The third method also allows a measurement of the  $dN_{ch}/dp_T$  distribution. The three methods are sensitive to particles down to  $p_T$  values of about 30, 50, and 100 MeV/ $c$ , respectively. The measurements were corrected for the geometrical acceptance, efficiency, fake and duplicate tracks, low- $p_T$  particles curling in the axial magnetic field, decay products of long-lived hadrons, photon conversions and inelastic hadronic interactions in the detector material. The PYTHIA parameter set from Ref. [9] was chosen to determine the corrections.

*Results.* For the measurement of the  $dN_{ch}/dp_T$  distribution, charged-particle tracks with  $p_T$  in excess of 0.1 GeV/ $c$  were used in 12 different  $|\eta|$  bins, from 0 to 2.4. The Tsallis parametrization [12, 13, 14],

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

was fitted to the data. The  $p_T$  spectrum of charged hadrons is shown in Fig. 1. The average  $p_T$  (extrapolated to  $p_T = 0$ ) is  $\langle p_T \rangle = 0.545 \pm 0.005$  (stat.)  $\pm 0.015$  (syst.) GeV/ $c$ .

Experimental uncertainties related to the trigger and event selection are common to all the analysis methods. The total event selection uncertainty, including the SD fraction and the selection efficiency of the BSC and HF, was found to be 3.5%. Additional 3% and 2% uncertainties were assigned to the tracklet and track reconstruction algorithm efficiencies, respectively. All other uncertainties are identical to those listed in Ref. [4]. The  $dN_{\text{ch}}/d\eta$  measurements based on tracklet method were repeated on a separate data sample without magnetic field, for which almost no  $p_T$  extrapolation is needed, and gave results consistent within 1.5%. The final systematic uncertainties for the pixel counting, tracklet, and track methods were found to be 5.7%, 4.6%, and 4.3%, respectively, and are strongly correlated.

The  $dN_{\text{ch}}/d\eta$  distributions from the three different methods were averaged and are shown in Fig. 1. For  $|\eta| < 0.5$ , the average charged multiplicity density is  $dN_{\text{ch}}/d\eta = 5.78 \pm 0.01$  (stat.)  $\pm 0.23$  (syst.) for NSD events. The  $\sqrt{s}$  dependence of the measured  $dN_{\text{ch}}/d\eta|_{\eta \approx 0}$  and average  $p_T$  is shown in Fig. 2. The  $dN_{\text{ch}}/d\eta$  results reported here show a rather steep increase between 0.9 and 7 TeV, which is measured to be  $66.1\% \pm 1.0\%$  (stat.)  $\pm 4.2\%$  (syst.). Using a somewhat different event selection, the ALICE collaboration has found a similar increase of  $57.6\% \pm 0.4\%$  (stat.)  $^{+3.6\%}_{-1.8\%}$  (syst.) [16].

In summary, charged-hadron transverse-momentum and pseudorapidity distributions have been measured in proton-proton collisions at  $\sqrt{s} = 7$  TeV. The measured  $dN_{\text{ch}}/d\eta$  value is higher than most predictions and provides new information to constrain ongoing improvements of soft particle production models and event generators. The mean transverse momentum are also measured in the region  $|\eta| < 2.4$ . These studies are the first steps in the exploration of particle production at the new centre-of-mass energy frontier, and contribute to the understanding of the dynamics in soft hadronic interactions.

**Acknowledgements.** We congratulate and express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTDS (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

## References

- [1] L. Evans and P. Bryant (editors), *JINST* **3** (2008) S08001.
- [2] W. Kittel and E. A. De Wolf, World Scientific, Singapore, 2005.
- [3] CMS Collaboration, *Phys. Rev. Lett.* **105** (2010) 022002 [arXiv:1005.3299 [hep-ex]].
- [4] CMS Collaboration, *JHEP* **02** (2010) 041.
- [5] CMS Collaboration, *JINST* **3** (2008) S08004.
- [6] Geant4 Collaboration, *Nucl. Instrum. and Methods* **A506** (2003) 250.
- [7] F. Sikler, arXiv:0911.2767 [physics.ins-det].

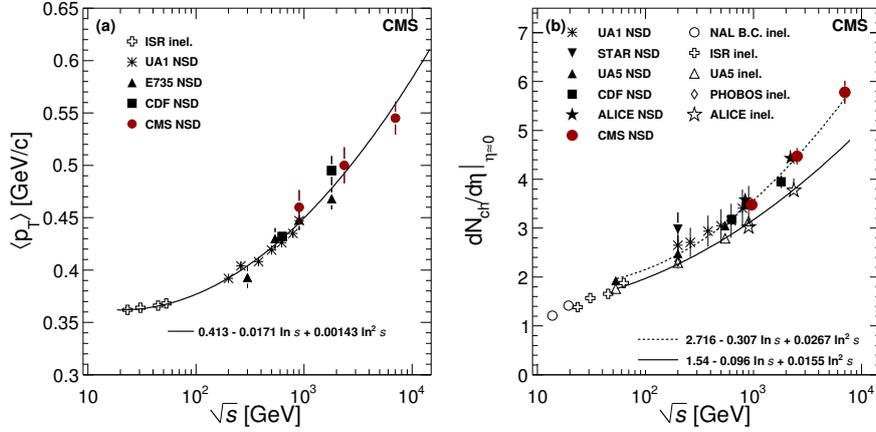


Figure 2: (a) Average  $p_T$  of charged hadrons as a function of the centre-of-mass energy. The CMS measurements are for  $|\eta| < 2.4$ . Also shown are measurements from the ISR [19] ( $pp$ ), E735 [20] ( $p\bar{p}$ ), and CDF [21] ( $p\bar{p}$ ) for  $|\eta| < 0.5$ , and from UA1 [18] ( $p\bar{p}$ ) for  $|\eta| < 2.5$ . The curve is a second-order polynomial fit to the data. The error bars on the CMS data include the systematic uncertainties. (b) Average value of  $dN_{ch}/d\eta$  in the central  $\eta$  region as a function of centre-of-mass energy in  $pp$  and  $p\bar{p}$  collisions. Also shown are NSD and inelastic measurements from the NAL Bubble Chamber [22] ( $p\bar{p}$ ), ISR [23] ( $pp$ ), UA1 [18] ( $p\bar{p}$ ), UA5 [15] ( $p\bar{p}$ ), CDF [24] ( $p\bar{p}$ ), STAR [25] ( $pp$ ), PHOBOS [26] ( $pp$ ), and ALICE [17] ( $pp$ ). The curves are second-order polynomial fits for the inelastic (solid) and NSD event selections (dashed). The error bars include systematic uncertainties, when available. Data points at 0.9 and 2.36 TeV are slightly displaced horizontally for visibility.

- [8] T. Sjöstrand, S. Mrenna, and P. Skands, *JHEP* **05** (2006) 026.
- [9] A. Moraes, C. Buttar, and I. Dawson, *Eur. Phys. J.* **C50** (2007) 435.
- [10] F. W. Bopp, R. Engel and J. Ranft, arXiv:hep-ph/9803437.
- [11] R. Engel, J. Ranft, and S. Roesler, *Phys. Rev.* **D52** (1995) 1459.
- [12] C. Tsallis, *J. Stat. Phys.* **52** (1988) 479.
- [13] G. Wilk and Z. Włodarczyk, *Eur. Phys. J.* **A40** (2009) 299.
- [14] T. S. Biró, G. Purcsel, and K. Ürmösy, *Eur. Phys. J.* **A40** (2009) 325,
- [15] UA5 Collaboration, *Z. Phys.* **C33** (1986) 1.
- [16] ALICE Collaboration, arXiv:1004.3514 [hep-ex].
- [17] ALICE Collaboration, *Eur. Phys. J. C* **68** (2010) 89
- [18] UA1 Collaboration, *Nucl. Phys.* **B335** (1990) 261.
- [19] A. M. Rossi et al., *Nucl. Phys.* **B84** (1975) 269.
- [20] E735 Collaboration, *Phys. Rev. Lett.* **60** (1988) 1622.
- [21] CDF Collaboration, *Phys. Rev. Lett.* **61** (1988) 1819.
- [22] J. Whitmore, *Phys. Rept.* **10** (1974) 273.
- [23] Aachen-CERN-Heidelberg-Munich Collaboration, *Nucl. Phys.* **B129** (1977) 365.
- [24] CDF Collaboration, *Phys. Rev.* **D41** (1990) 2330.
- [25] STAR Collaboration, *Phys. Rev.* **C79** (2009) 034909.
- [26] PHOBOS Collaboration, *J. Phys.* **G30** (2004) S1133.