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Measurement of charged particle multiplicities and densities in pp collisions at 7 TeV in the forward region

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Charged particle multiplicities are studied in proton-proton collisions in the forward region at a centre-of-mass energy of $\sqrt{s} = 7$ TeV with data collected by the LHCb detector. The forward spectrometer accesses a kinematic range of $2.0 < \eta < 4.8$ in pseudorapidity, momenta greater than 2 GeV/c and transverse momenta greater than 0.2 GeV/c. The measurements are performed using events with at least one charged particle in the kinematic acceptance. Results are presented as functions of pseudorapidity and transverse momentum.

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PoS(DIS2014)149

1. Introduction

The phenomenology of soft quantum chromodynamic (QCD) processes such as light particle production in proton-proton (pp) collisions cannot be predicted using perturbative calculations, but can be described by models implemented in Monte Carlo event generators.

A fundamental input used for the tuning process is the measurement of prompt charged particle multiplicities. In combination with the study of the corresponding momentum spectra and angular distributions, these measurements can be used to gain a better understanding of hadron collisions. An accurate description of the soft component of the interaction, known as the underlying event, is vital for understanding backgrounds in beyond the Standard Model searches or precision measurements of the Standard Model parameters. The forward region was previously studied with the LHCb detector, where an inclusive multiplicity measurement without momentum information was performed [2].

Interactions between two colliding protons at a centre-of-mass energy of $\sqrt{s} = 7$ TeV that produce at least one prompt charged particle in the pseudorapidity range of $2.0 < \eta < 4.8$, with a momentum of $p > 2\,\mathrm{GeV}/c$ and transverse momentum of $p_{\mathrm{T}} > 0.2\,\mathrm{GeV}/c$, are studied. A prompt particle is defined as a particle that either originates directly from the primary vertex or from a decay chain in which the sum of mean lifetimes does not exceed 10 ps. The information from the full tracking system of the LHCb detector is used, which permits the measurement of the momentum dependence of charged particle multiplicities. Multiplicity distributions, $P(n)$, for prompt charged particles are reported for the total accessible phase space region as well as charged particle densities for η and p_{T} ranges [1].

2. LHCb detector and track reconstruction

The LHCb detector [3] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector (VELO) surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream. The combined tracking system provides a momentum measurement with relative uncertainty that varies from 0.4 % at $2\,\mathrm{GeV}/c$ to 0.6 % at $100\,\mathrm{GeV}/c$, and impact parameter resolution of 20 μm for tracks with large transverse momentum. The direction of the magnetic field of the spectrometer dipole magnet is reversed regularly.

The reconstruction algorithms provide different track types depending on the sub-detectors considered. Only two types of tracks are used in this analysis. VELO tracks are only reconstructed in the VELO sub-detector and provide no momentum information. *Long* tracks are reconstructed by extrapolating VELO tracks through the magnetic dipole field and matching them with hits in the downstream tracking stations, providing momentum information. This is the highest-quality track type and is used for most physics analyses. Requiring charged particles to stay within the geometric acceptance of the LHCb detector after deflection by the magnetic field further restricts the accessible phase space to a minimum momentum of around $2\,\mathrm{GeV}/c$. The LHCb detector design minimises the material of the tracking detectors and allows a high track-reconstruction efficiency even for particles with low momenta. However, the limited number of tracking stations results in the presence of misreconstructed (*fake*) tracks. A reconstructed track is considered as fake if it does not correspond to the trajectory of a genuine charged particle. The fraction of fake long tracks is non-negligible as the extrapolation of a track through the magnetic field is performed over a distance of several metres, resulting in wrong association between VELO tracks and track segments reconstructed downstream. Another source of wrong track assignment arises from duplicate tracks. These track pairs either share a certain number of hits or consist of different track segments originating from a single particle.

3. Data set and simulation

The measurements are performed using a minimum-bias data sample of pp collisions at a centre-of-mass energy of $\sqrt{s}$ =7 TeV collected during 2010. The average number of interactions in the detector acceptance per recorded bunch crossing was less than 0.1. The contribution from bunch crossings with more than one collision (*pile-up* events) is determined to be less than 4 % and is considered as a correction in the analysis. Events with at least one reconstructed track segment in the VELO were selected. The data consists of 3 million events recorded in equal proportion for both magnetic field polarities.

Fully simulated minimum-bias pp collisions are generated using the PYTHIA 6.4 event generator [4] with a specific LHCb configuration [5] using CTEQ6L [6] parton density functions (PDFs). This implementation, called the LHCb tune, contains contributions from elastic and inelastic processes, where the latter also include single and double diffractive components. Decays of hadrons are performed by EVTGEN [7], in which final-state radiation is generated using PHOTOS [8]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [9], as described in Ref. [10]. Processing, reconstruction and selection are identical for simulated events and data. The simulation is used to determine correction factors for the detector acceptance and resolution as well as for quantifying background contributions and reconstruction performance.

4. Event definition and data selection

In analogy with similar approaches adopted in previous measurements [11, 12], an event is defined as *visible* if it contains at least one charged particle in the pseudorapidity range of $2.0 < \eta < 4.8$ with $p_T > 0.2\,\mathrm{GeV}/c$ and $p > 2\,\mathrm{GeV}/c$.

Only high quality tracks traversing the full tracking system are considered. The kinematic criteria are explicitly applied to all tracks to restrict the measurement to a kinematic range in which reconstruction efficiency is high. To ensure that tracks originate from the primary interaction, it is required that the smallest distance of the extrapolated track to the beam line is less than 2 mm. Additionally, a track is required to originate from the luminous region; the distance z_0 of the track to the centre of this region has to fulfil $z_0 < 3\sigma_L$, where the width σ_L is of the order of 40 mm, determined from a Gaussian fit to the longitudinal position of primary vertices. This restriction also suppresses the contamination from beam-gas background interactions to a negligible amount.

PoS(DIS2014)149

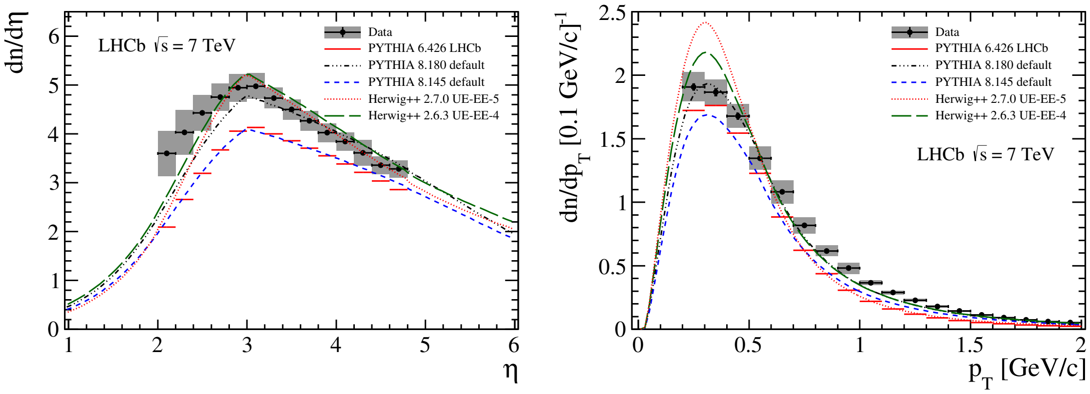

Figure 1: Charged particle density as a function of η (left) and p_{T} (right). The LHCb data are shown as points with statistical error bars (smaller than the marker size) and combined systematic and statistical uncertainties as the grey band. The measurement is compared to PYTHIA 8, HERWIG++ and the PYTHIA 6 LHCb tune predictions.

5. Analysis and systematic uncertainties

The measured particle multiplicity distributions and mean particle densities are corrected in four steps: (1) reconstructed events are corrected on an event-by-event basis by weighting each track according to a purity factor to account for the contamination from reconstruction artefacts and non-prompt particles; (2) the event sample is further corrected for unobserved events that fulfil the visibility criteria but in which no tracks are reconstructed; (3) in order to obtain measurements for single pp collisions, a correction to remove pile-up events is applied; (4) the effects of various sources of inefficiencies, such as track reconstruction, are addressed.

The precision of the measurements of charged particle multiplicities and mean particle densities are limited by systematic effects. The bin contents of the particle multiplicity distribution for the full event typically have a relative statistical uncertainty in the range of 10^{-4} to 10^{-2} for low and high multiplicities, respectively. The systematic uncertainties are typically around $1-10\,\%$, the largest contribution arising from the uncertainty of the amount of detector material.

6. Charged particle densities

The fully corrected measurement of mean particle densities in the kinematic region of $p > 2\,\mathrm{GeV}/c$, $p_{\mathrm{T}} > 0.2\,\mathrm{GeV}/c$ and $2.0 < \eta < 4.8$ is presented as a function of pseudorapidity and as a function of transverse momentum in Fig. 1; all corresponding numbers are tabulated in [1]. The data points show a characteristic drop towards larger pseudorapidities but also a falling edge for $\eta < 3$, which is caused by the minimum momentum requirement in this analysis. This feature is qualitatively described by all considered Monte Carlo event generators and their tunes.

The measurements are compared to predictions from PYTHIA 6, PYTHIA 8 and HERWIG++. PYTHIA 8.145 with default parameters was released without tuning to LHC measurements and is not better than the LHCb tune of PYTHIA 6. In contrast, PYTHIA 8.180, which was optimised on central LHC data, describes the measurements significantly better than the previous version. The

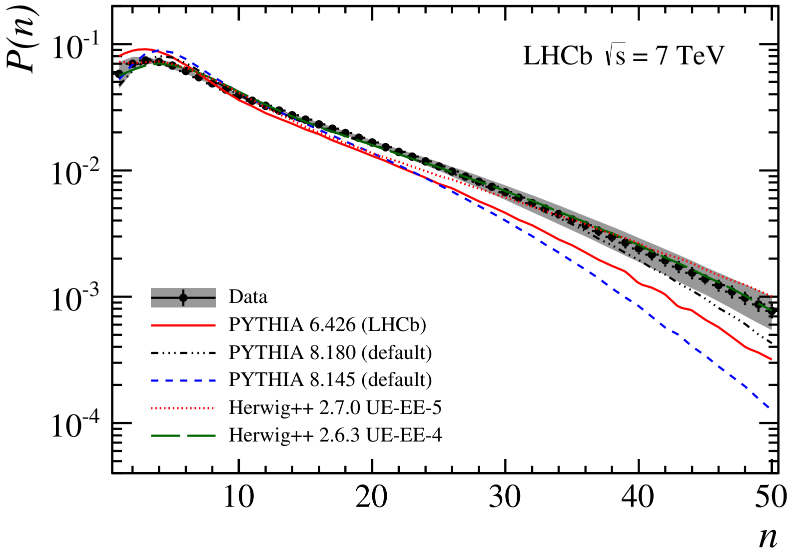

Figure 2: Charged particle multiplicity distribution in the full kinematic range of the analysis. The error bars represent the statistical uncertainty, the error band shows the combined statistical and systematic uncertainties. The data are compared to PYTHIA 8, HERWIG++ and the PYTHIA 6 LHCb tune predictions.

predictions of HERWIG++ are also in reasonably good agreement with data, although the charged-particle production rate is underestimated at small pseudorapidities. The HERWIG++ generator version 2.7.0, which uses tune UE-5, overestimates the number of prompt charged particles in the low p_{T} range but underestimates it at larger transverse momenta. The predictions of HERWIG++ in version 2.6.3, which relies on tune UE-4, show a more complete description of the data. Both event generators, PYTHIA 8 and HERWIG++, describe the data over a wide range whilst PYTHIA 6 is too low.

7. Multiplicity distributions

The charged particle multiplicity distribution in the full kinematic range of the analysis is shown in Fig. 2, compared to the predictions from the event generators. The corresponding mean value, μ, and the root-mean-square deviation, σ, of the distribution, truncated in the range from 1 to 50 particles, is measured to be $\mu = 11.304 \pm 0.008 \pm 0.091$ and $\sigma = 9.496 \pm 0.006 \pm 0.021$, where the uncertainties are statistical and systematic, respectively. Using the full range gives consistent results with the value obtained from the particle densities.

The prediction of the LHCb tune of PYTHIA 6 overestimates the data at low multiplicities, and underestimates the data at higher multiplicities. Calculations from recent generators are in better agreement with the measurement. While PYTHIA 8.145 gives an insufficient description of the data, the prediction of version 8.180 using Tune 4C shows reasonable agreement. The HERWIG++ event generator using the underlying event tune UE-4 shows good agreement with the measurement and reproduces the data better than the more recent UE-5 tune.

Charged particle multiplicity distributions for bins in pseudorapidity and p_{T} can be found in [1]. Comparisons of the binned distributions to the predictions of Monte Carlo generators show the same general features as discussed for the integrated distribution.

8. Summary

The charged particle multiplicities and the mean particle densities are measured in inclusive pp interactions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV with the LHCb detector. The measurement is performed in the kinematic range $p > 2\,\mathrm{GeV}/c$, $p_{\mathrm{T}} > 0.2\,\mathrm{GeV}/c$ and $2.0 < \eta < 4.8$, in which at least one charged particle per event is required. By using the full spectrometer information, it is possible to extend the previous LHCb results [2] to include momentum dependent measurements.

The comparison of data with predictions from several Monte Carlo event generators shows that predictions from recent generators, tuned to LHC measurements in the central rapidity region, show fair agreement with the data. While the phenomenology in some kinematic regions is well described by recent PYTHIA and HERWIG++ simulations, the data in the higher p_{T} and small η ranges of the probed kinematic region are still underestimated. None of the event generators considered are able to describe the entire range of measurements.

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PoS(DIS2014)149