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# Pseudorapidity distribution of charged hadrons in proton–proton collisions at $\sqrt{s} = 13$ TeV

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ABSTRACT

The pseudorapidity distribution of charged hadrons in pp collisions at $\sqrt{s} = 13$ TeV is measured using a data sample obtained with the CMS detector, operated at zero magnetic field, at the CERN LHC. The yield of primary charged long-lived hadrons produced in inelastic pp collisions is determined in the central region of the CMS pixel detector ($|\eta| < 2$) using both hit pairs and reconstructed tracks. For central pseudorapidities ($|\eta| < 0.5$), the charged-hadron multiplicity density is $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{|\eta|<0.5} = 5.49 \pm 0.01\,(\mathrm{stat}) \pm 0.17\,(\mathrm{syst})$, a value obtained by combining the two methods. The result is compared to predictions from Monte Carlo event generators and to similar measurements made at lower collision energies.



## 1. Introduction

The yields of charged hadrons are among the most basic physical observables in high-energy particle collisions and provide an essential first step in exploring the physics of a new energy regime. Studies of such yields have a long history in high-energy particle and nuclear physics, as well as in cosmic ray physics. At collider energies, the inclusive production of charged hadrons is driven by a combination of perturbative and nonperturbative quantum chromodynamics (QCD) phenomena, such as saturation of parton densities, multiparton interactions, parton hadronization, and soft diffractive scattering.

The yields of primary charged hadrons are commonly studied using their multiplicity as a function of pseudorapidity, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$. Of particular interest for understanding the physics of hadron production is the dependence of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ on the collision energy, which reflects the relative roles of soft- and hard-scattering contributions. Soft interactions, which are modeled phenomenologically, give rise to a significant fraction of the produced particles. Contributions from hard-scattering processes increase with increasing collision energies. Measurements are necessary to tune the modeling of these contributions in Monte Carlo (MC) event generators, and as reference data to study nuclear effects in proton–nucleus and nucleus–nucleus collisions. A good understanding of inclusive hadron production is also important to control the pileup backgrounds, from overlapping proton–proton collisions in a given bunch crossing, that affect all physics analyses at the LHC.

In this Letter, measurements of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ in the range $|\eta| < 2$ are reported for inelastic proton–proton (pp) collisions delivered by the CERN LHC at a center-of-mass energy of 13 TeV in June 2015. The analysis is based on 11.5 million events recorded at zero magnetic field during a special low-intensity beam configuration with 0.2–5% proton–proton interaction probability per bunch crossing. This special run was prepared by steering the beams such that their transverse separation was $\pm 3\sigma$ at the nominal CMS interaction point, where $\sigma$ denotes the standard deviation of the Gaussian beam profile. Following earlier analyses at $\sqrt{s} = 0.9$ TeV, 2.36 TeV [1], 7 TeV [2], and 8 TeV [3], $N_{\mathrm{ch}}$ is defined to include decay products of particles with decay length $c\tau < 1$ cm, where $\tau$ is the lifetime of the particle and $c$ is the velocity of light. Products of secondary interactions are excluded, and contributions from prompt leptons are removed.

The data are compared to PYTHIA8 v208 [4,5] (with the CMS underlying event tunes [6]: CUETP8S1 and CUETP8M1, using different parton densities), and to EPOS LHC [7] (LHC tune [8]). Both MC event generators reproduce well the main characteristics of the experimental data measured in hadronic collisions at lower energies, and provide predictions for the $\sqrt{s}$-dependence of hadron production observables using different implementations of the dominant

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underlying phenomena (multiparton interactions, parton saturation, diffractive scattering) [9,10].

## 2. CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. Within the magnet volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter, and the brass and scintillator hadron calorimeter. The tracker measures charged particles within $|\eta| < 2.4$. It has 1440 silicon pixel and 15 148 silicon strip detector modules, arranged in 14 tracking layers. The barrel region of the CMS pixel detector consists of three layers very close to the beam line. They are located at average radii of 4.3 cm (layer 1), 7.2 cm (layer 2), and 11.0 cm (layer 3), and provide excellent position resolution with their 150 μm × 100 μm pixels. The data sample used for this analysis was obtained while the magnet was off. Under these conditions, charged particles follow approximately straight trajectories, perturbed mostly by multiple Coulomb scattering. The pixel hits alone are sufficient to reconstruct vertices and tracks with high precision and purity. The beam pickup for timing (BPTX) devices were used to trigger the detector readout. They are located around the beam pipe at a distance of 175 m from the interaction point (IP) on either side, and are designed to provide precise information on the LHC bunch structure and the timing of the incoming beams. A detailed description of the CMS detector can be found in Ref. [11].

## 3. Event selection

Inelastic collision events are selected as follows: (i) online, a coincidence of signals from both BPTX devices is required, indicating the presence of both proton bunches crossing the IP; (ii) offline, at least one reconstructed interaction vertex is required, according to the tracklet or track vertex reconstruction methods described in Sections 4.1 and 4.2, respectively. While only the reconstructed collision vertex with the highest multiplicity (primary vertex) is used in the tracklet analysis, all reconstructed vertices in a given bunch crossing are processed for the track analysis.

A study of noncolliding bunches shows that the above requirements are sufficient to reject all backgrounds not originating from pp collisions. The probability to select events in the presence of a single (noncolliding) beam is about $5 \times 10^{-5}$ per bunch crossing, while the same probability is smaller than $3 \times 10^{-6}$ per bunch crossing in the absence of any beam. Consequently, the contribution of background events from beam, beam halo, and cosmic ray sources to the observed yields is negligible.

The results are corrected to correspond to a sample of inelastic collisions. The corrections from the detector-level offline event selection to the hadron-level event definitions are derived from MC simulations with PYTHIA8 v208 (tune CUETP8M1) and EPOS LHC (tune LHC), which cover a wide range of possible model ingredients. The detector response is simulated with GEANT4 [12] and processed through the same event reconstruction chain as collision data. The MC simulations are produced with the location and shape of the interaction region as extracted from data.

## 4. Data analysis

The analysis of the recorded data is performed with two reconstruction techniques based on hits of charged particles detected by the CMS pixel detector. While both start by searching for hit pairs in different layers at similar azimuthal angles $\phi$, the tracklet method (using hit pairs) performs background subtraction based on control samples in data, while the track method (using hit triplets) minimizes background contributions by requiring an additional hit in the detector. This results in a slightly narrower accessible $\eta$ range for the track method as compared to the tracklet method. Since various factors, such as detector alignment, material, detector response, and dependence on MC event generators, influence the two techniques somewhat differently, their final combination into a single measurement provides a more robust result.

### 4.1. Tracklets

Tracklets are pairs of hits in two layers of the silicon pixel detector. For a tracklet that is consistent with a charged hadron that originates at the primary vertex, the difference in pseudorapidity ($\Delta\eta$) and the azimuthal angle ($\Delta\phi$) between the two hits that make up the tracklet is small. The correlation between the hits in two silicon layers is analyzed to determine the charged hadron $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$. This method is capable of measuring and correcting for the combinatorial background and it is sensitive to hadrons with transverse momentum $p_{\mathrm{T}}$ as low as 0.04 GeV/$c$.

A tracklet-based vertex finder, as described in Ref. [13], is used for primary vertex reconstruction. In the first step, a hit from layer 1 is selected and a matching hit from layer 2 is sought. If the $|\Delta\phi|$ of the hits is smaller than 0.05, the $z$ position with respect to the counterclockwise-beam direction of the hits is extrapolated linearly and projected onto the beam axis. This procedure is repeated for every hit in layer 1, and the calculated $z$ positions are saved as vertex candidates. The primary vertex is determined in a second step. If the magnitude of the difference between the $z$ positions of any two vertex candidates is smaller than 0.12 cm, they are combined into a vertex cluster. The vertex cluster with the highest number of associated vertex candidates is selected as the primary vertex, and the final vertex $z$ position $z_v$ is given by the average $z$ position of the associated vertex candidates. The typical resolution of the primary vertex $z$ position is 0.02–0.1 cm, depending on the number of pixel hits. The vertex reconstruction efficiency is high even for low-multiplicity events with few pixel hits, with around 80% efficiency for events with 3 to 4 hits in layer 1, and 100% efficiency for events with more than 8 hits in layer 1.

The tracklet reconstruction is a separate procedure from the vertex reconstruction. There is no requirement on the $\Delta\phi$ of the hits. Instead, hits with the smallest $|\Delta\eta|$ are paired first to form tracklets (Fig. 1, top), and no hit may be used more than once. In contrast to the track analysis, all hits are accepted for the tracklet reconstruction, such that the analysis is relatively insensitive to the cluster charge simulation. Tracklets corresponding to charged hadrons that originate at the primary vertex display a sharp peak at $\Delta\phi = 0$, while the background tracklets from uncorrelated pixel hits have a wide $\Delta\phi$ spectrum. Fig. 1 (bottom) shows the combined data of primary charged hadrons (sharp peak) and tracklets from uncorrelated pixel hits (wide tails). To suppress the combinatorial background, only tracklets with $|\Delta\eta| < 0.1$ and $|\Delta\phi| < 1$ are selected. Since the combinatorial background is flat in $\Delta\phi$, a sideband region $1 < |\Delta\phi| < 2$ can be defined and used to estimate its magnitude, which is then subtracted from the signal region $|\Delta\phi| < 1$ to obtain the uncorrected $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$. Typical values of the estimated background fraction in the signal region increase with $|\eta|$ from 6% to 25%. The $\eta$ range for the tracklet method is limited to $|\eta| < 2$ to avoid a large acceptance correction.

Contributions from secondary particles, as well as the tracklet acceptance and reconstruction efficiency, have to be accounted for in order to determine the charged hadron $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ distribution. These correction factors are calculated as a function of the primary vertex $z$ position, pseudorapidity, and tracklet multiplicity, using the PYTHIA8 CUETP8M1 tune as a reference.

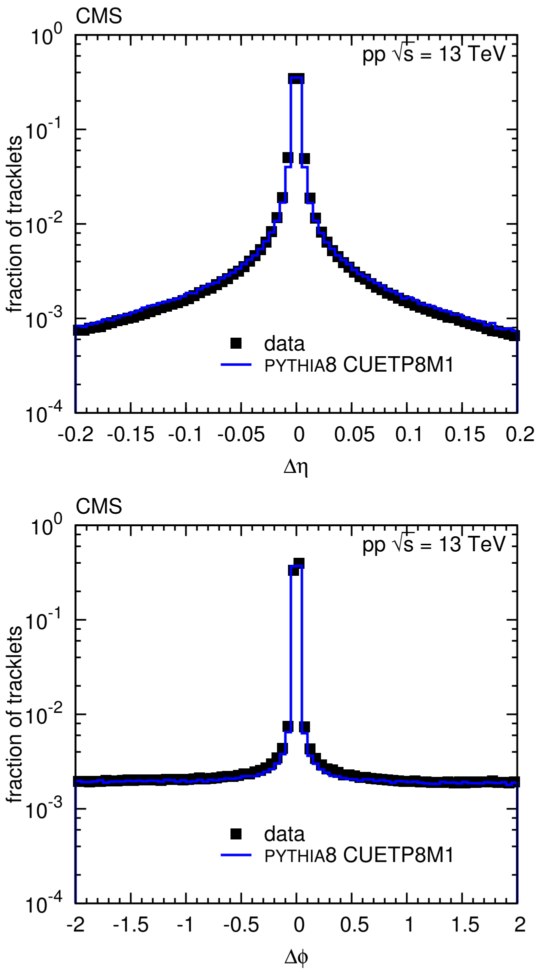


**Fig. 1.** The $\Delta\eta$ (top) and $\Delta\phi$ (bottom) distributions of hit pairs on tracklets in the data (squares) and from MC simulation (histogram).

To account for the difference between the actual pixel detector geometry and that used in the simulation, an additional correction is applied as a function of $\eta$ and the primary vertex position. This correction is obtained by taking the ratio between data and simulation of the geometrical distribution of tracklets in ($\eta$, $z_v$) bins. The size of this correction ranges from 0 to 5%. The largest correction factors are associated with the presence of inactive tracker modules in the data.

*4.2. Tracks*

The analysis only uses clusters whose width in the $z$ direction is compatible with that of a charged particle originating from the nominal collision point. The difference between the measured and the geometrically predicted widths is required to be smaller than 5 pixels.

Track finding involves identifying pixel hit triplets that fall on a straight line. All possible hit pairs are taken, the first hit from layer 1, and the second one from layer 2. If the difference between their azimuthal angles $\phi_1$ and $\phi_2$ is smaller than a certain value, $\Delta\phi_{1,2} < \alpha$, they are kept for the next step. For each hit pair, hits from layer 3 that have a small azimuthal difference with respect to the hit in layer 2 ($|\Delta\phi_{2,3}| < \alpha$) are collected. In addition, the vector joining the hits in the first and second layers and the vector joining the hits in the second and third layers are required to have polar angles that differ by, at most, $\alpha$ ($|\Delta\theta_{12,23}| < \alpha$). If multiple hits in the third layer satisfy the conditions above, the one with the smallest $\Delta\phi^2_{2,3} + \Delta\theta^2_{12,23}$ value is selected. The comparison of the $\Delta\phi$ distributions from signal and background shows that a value of $\alpha = 0.02$ gives the best signal significance.

The coordinates of the hits of the resulting triplets are used to perform a straight-line fit with parameters $(z_0, \eta, \phi)$ using Newton's method for minimization, where $z_0$ is the $z$ coordinate of the point of closest approach to the beam axis. The transverse impact parameter $d_0$ with respect to the beam axis is fixed to 0 for this fit. The average distance $\bar{d}$ from the fitted line to the hits is used in the determination of the vertex position to estimate the uncertainty in $z$, as $\sigma_z = \bar{d}/\sin\theta$. A track is accepted if the straight-line fit to the hits gives a vertex position $|z_0| < 20$ cm.

The acceptance of the track method is $|\eta| < 1.8$, slightly reduced compared to the tracklet method, since all three pixel barrel layers are used. According to the samples of pp events generated with PYTHIA8 CUETP8M1 and EPOS LHC, the tracking efficiency is flat at 80% in the region $|\eta| < 1.6$ owing to losses at low $p_T$, and increases to 85% for $p_T > 0.2$ GeV/$c$. For $|\eta| > 1.6$, the efficiency falls and is on average around 50%. The wide $p_T$ coverage down to 0.05 GeV/$c$ ensures a robust performance and fairly insensitive behavior to variations in the $p_T$ spectrum. The rate of duplicate tracks is below the percent level, while the fraction of misidentified tracks is in the range of 2–6%, rising with higher $|\eta|$ values. The fraction of reconstructed nonprimary particles is 2–3%.

An agglomerative vertex reconstruction [14] is performed using the fitted $(z_0, \sigma_z)$ values from the reconstructed tracks. The clustering of tracks into vertices ends when the smallest $\sigma_z$-normalized distance between vertex candidates is larger than 50. Duplicate tracks are removed based on the angle enclosed by their direction vectors. If this angle is smaller than 0.01, the one with a larger average distance $\bar{d}$ is removed. Vertices with at least three tracks are kept, unless there is only one vertex found in the event. In that case, there is no minimum for the number of tracks. Only tracks associated with a primary vertex are used in the physics analysis.

The hits of the final tracks are refitted by allowing the impact parameter $d_0$ to vary. The resulting set of parameters is used in a three-dimensional vertex fit, which is also used to determine the location and shape of the interaction region. As Fig. 2 (top) shows, the distribution of the number of reconstructed tracks in data is in fair agreement with the MC event generator predictions in particular at the higher multiplicities. The correction from track to charged particle multiplicity depends on the fraction of detected events as well as on the distribution of high multiplicity events (not shown in the figure).

Owing to the excellent vertex resolution (≈250 μm), the $\eta$ resolution is also very good. Thus, potential migrations between neighboring bins are very small, and the final generator-dependent corrections are applied bin-by-bin. The measured yields in each $\eta$ bin are multiplied by the ratio of the number of simulated primary charged hadrons to the number of the reconstructed tracks.

The performance of vertexing in simulation and in data was compared by determining the probability of reconstructing $k$ vertices in case of $n = 1, 2,$ and 3 simultaneous pp collisions. The extracted $p(k|n)$ conditional probabilities are used to estimate the average inelastic interaction probability $\mu$ per bunch crossing by assuming a Poissonian distribution for $n$. While PYTHIA8 CUETP8M1 gives $\mu = 0.0525 \pm 0.0003\,(\text{stat})$, EPOS LHC leads to $0.0545 \pm 0.0002\,(\text{stat})$. Taking their average as the central value and the difference as the systematic uncertainty, we estimate $\mu = 0.0535 \pm 0.0013\,(\text{syst})$. The product of the number of analyzed bunch crossings and $\mu$ gives the number of inelastic collision events, to be used for the calculation of the final $dN_{ch}/d\eta$ values.

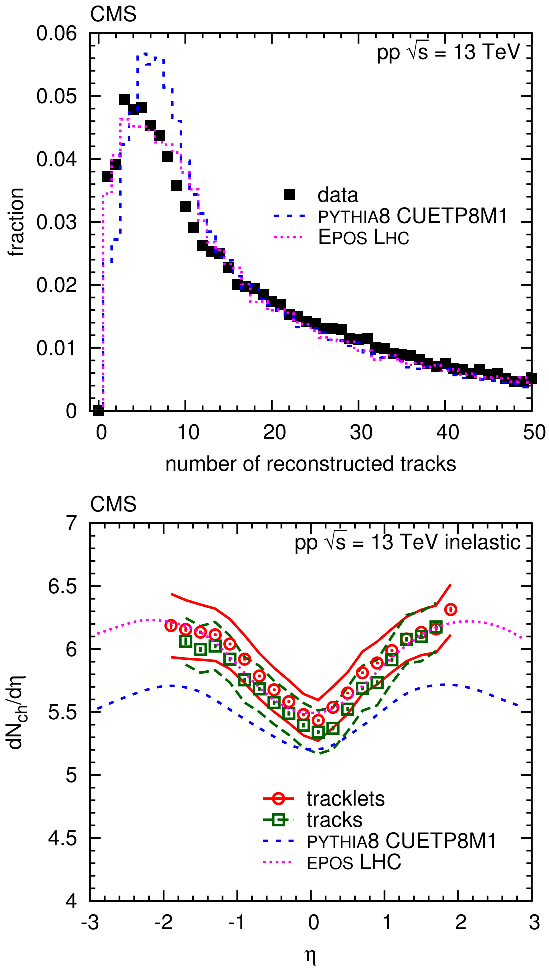


**Fig. 2.** (Top) Distributions of the number of reconstructed tracks per event from data and from simulations, for inelastic pp collisions. (Bottom) Distributions of the pseudorapidity density ($dN_{ch}/d\eta$) of charged hadrons in the region $|\eta| < 2$ for inelastic collision events, reconstructed using tracklets (open circles), and tracks (open squares), compared to PYTHIA8 CUETP8M1 and EPOS LHC predictions, shown as dashed and dotted curves, respectively. The solid and long-dashed lines encompassing the data points indicate the systematic uncertainties of the two reconstruction methods.

### *4.3. Systematic uncertainties*

The systematic uncertainties in the final physics result come from several sources. According to the two MC event generators used, the two reconstruction techniques detect about 86–89% (for the tracklet method) and 86–90% (for the track method) of the inelastic pp events. The uncertainty in the number of unseen, mostly single-diffractive, collisions contributes about 3% to the total systematic uncertainty.

The systematic uncertainties in the tracklet method take into account the effects of the amount of noise in the pixel hits (1–3%), detector misalignment, pixel hit reconstruction efficiency, and cluster splitting (all below 1%). The tracklet-to-hadron correction shows a 2–3% dependence on the choice of the MC event generator. The total systematic uncertainty of the tracklet method is in the range 3–4%.

For the track method, requiring three hits on a straight line greatly reduces the effects of pixel noise and cluster splitting. In addition, hits with cluster shapes that are not compatible with their positions are excluded from the analysis, and tracks close in $(\eta, \phi)$ are cleaned as described in Section 4.2. The loss of any of the three hits because of pixel reconstruction inefficiency would lead to the loss of the triplet, resulting in a systematic uncertainty of 1.8% from the tracking efficiency, independent of the choice of the MC event generator. The effect of detector misalignment on the angular distributions is several orders of magnitude smaller than the values of the selection criteria, and is therefore neglected. The sensitivity to the vertexing efficiency is included in the 2–3% systematic uncertainty associated with the estimate of $\mu$, as discussed in Section 4.2. Uncertainties on track-level corrections are estimated from the differences obtained using the two MC generators, and are at the level of 2–3%. The total systematic uncertainty of the track method is in the range of 3–4%.

The track analysis was also performed using only matched hits of double-sided modules in the strip tracker. The result is compatible with that from the pixel-only analysis within the systematic uncertainties. Because of the larger corrections and the more restricted $|\eta|$ range, the result with the strip tracker is not included in the final combination.

Finally, we also used the method of counting reconstructed pixel hits, as described in Ref. [2], which is subject to different background and systematic effects, and the measurements are within the systematic uncertainties of the results reported in this Letter.

## 5. Results

For the tracklet analysis, all recorded bunch crossings are used (about 170 000 collision events), while for the track analysis only 1 million of them are used (about 55 000 collision events). After corrections, the agreement between the tracklet and track $dN_{ch}/d\eta$ results is better than 2% at central pseudorapidity and better than 3% at forward pseudorapidities, as shown in Fig. 2 (bottom). Hence, averaging their $dN_{ch}/d\eta$ values is justified. Since the systematic uncertainties dominate and are mostly correlated between the two analyses, the simple mean of the central values and of systematic uncertainties are taken. The fraction of primary charged leptons is ≈1% of the total long-lived charged particles produced, and the correction from detector-level tracklets and tracks is done for charged hadrons only.

Pseudorapidity density distributions of charged hadrons in the region $|\eta| < 2$ for inelastic pp events are shown in Fig. 3 (top). The data points and uncertainties are symmetrized in $\pm\eta$. In the range $|\eta| < 0.5$ the average pseudorapidity density is $dN_{ch}/d\eta|_{|\eta|<0.5} = 5.49 \pm 0.01\,(\text{stat}) \pm 0.17\,(\text{syst})$. While the predictions of both PYTHIA8 (with CUETP8S1 and CUETP8M1) and EPOS LHC agree with the measured central value, the measured $dN_{ch}/d\eta$ distribution in the full $\eta$ range is better described by the latter. The uncertainty band of PYTHIA8 corresponds to the envelope of the uncertainties of the tune parameters of CUETP8S1; the EPOS LHC predictions have no uncertainty associated with its parameter settings.

The center-of-mass energy dependence of $dN_{ch}/d\eta$ is shown in Fig. 3 (bottom). For comparison with the $\sqrt{s} = 13$ TeV results presented in this Letter, inelastic pp measurements at lower energies (ISR [15,16], UA5 [17,18], PHOBOS [19], and ALICE [20]) are also plotted. The measured values are empirically fitted using a second-order polynomial in $\ln(s)$ as $1.55 - 0.113\ln(s) + 0.0168\ln(s)^2$, where $s$ has the units GeV$^2$, which provides a good description of the available data over the full energy range. The PYTHIA8 and EPOS LHC event generators globally reproduce the collision-energy dependence of hadron production in inelastic pp collisions.

## 6. Summary

The pseudorapidity distribution of charged hadrons has been measured by the CMS experiment, operated at zero magnetic field, at the LHC in proton–proton collisions at $\sqrt{s} = 13$ TeV. Using two

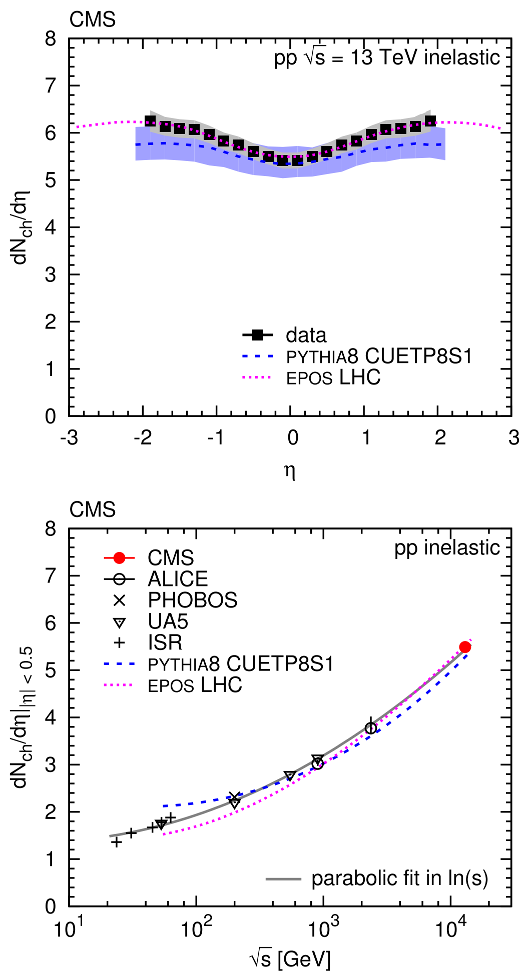


**Fig. 3.** (Top) Distributions of the pseudorapidity density of charged hadrons in the region $|\eta| < 2$ in inelastic pp collisions at 13 TeV measured in data (solid markers, combined track and tracklet results, symmetrized in $\eta$), and predicted by the PYTHIA8 CUETP8S1 and the EPOS LHC event generators (curves). The grey shaded area encompassing the data points indicates their correlated systematic uncertainties. The blue band corresponds to the envelope of the CUETP8S1 tune parametric uncertainties. (Bottom) Center-of-mass energy dependence of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{|\eta|<0.5}$ including ISR [15,16], UA5 [17,18], PHOBOS [19], and ALICE [20] data. The solid curve shows a second-order polynomial in $\ln(s)$ fit to the data points, including the new result at $\sqrt{s} = 13$ TeV. The dashed and dotted curves show the PYTHIA8 CUETP8S1 and EPOS LHC predictions, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

methods, based on hit pairs and straight-line tracks in the barrel region of the CMS pixel detector, a charged hadron multiplicity at midrapidity, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{|\eta|<0.5} = 5.49 \pm 0.01\,(\mathrm{stat}) \pm 0.17\,(\mathrm{syst})$, has been obtained for inelastic pp events. In the central region, the measured $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ distribution is consistent with predictions of the PYTHIA8 (with the CMS underlying event tunes CUETP8S1 and CUETP8M1) and EPOS LHC (LHC tune) event generators, while those in a wider $\eta$ range are better described by the latter. These results constitute the first CMS measurement of hadron production at the new center-of-mass energy frontier, and provide new constraints for the improvement of perturbative and nonperturbative QCD aspects implemented in hadronic event generators.

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