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Multiplicity distributions in the forward rapidity region in proton-proton collisions at the Large Hadron Collider

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Measured multiplicity distributions of primary charged particles produced in the forward rapidity region of the proton-proton (pp) collisions at the center-of-mass energy, $\sqrt{s} = 7$ TeV, at the LHC have been analyzed in terms of the negative binomial distribution function. Like the multiplicity distributions in the midrapidity region for the pp collisions at $\sqrt{s} = 7$ TeV, the distributions for the minimum bias events in the forward region are also better described with the superposition of two negative binomail distributions, as proposed by a two-component model of particle production from two processes, the *soft* and the *hard*. However, the multiplicity distribution for the "hard-QCD" events in a large pseudorapidity window does not oblige the two-component model.

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I. INTRODUCTION

The major experiments at the LHC [1], depending on specific physics requirements, have detector setups of different geometrical acceptance for detecting several kinds of particles in different kinematic ranges. Besides the specific physics goals, all these detector setups facilitate the study of the physics of the collisions, in general, by implicitly recording information on particle productions in terms of a few basic observables. Sometimes, comparisons of data recorded in different acceptance of detectors of these experiments could provide insight into the particle production mechanisms in different phase spaces of collisions, due to different kinematic origins. In this respect, out of the four major experiments at the LHC, the Large Hadron Collider beauty (LHCb) experiment has a unique standing. While ALICE, the CMS experiment, and the ATLAS experiment primarily address the midrapidity physics by measuring a majority of the produced charged particles in the midrapidity region, the LHCb setup allows the measurement of charged particles in the forward rapidity region, facilitating the study of forward physics.

The multiplicity distribution of primary charged particles produced in collisions is one of the most basic observables, characterizing the final states of multiparticle production process in a high-energy physics experiment. All the LHC experiments have measured [2–6] multiplicity distributions in proton-proton (pp) collisions at the available LHC energies in different kinematic ranges and for different classes of events. In the context of the present work, these LHC experiments, in spite of the differences in detector acceptance, have a common observation: the multiplicity distributions of produced particles at the new LHC energies have been found to be underestimated by several of the standard event generators/models (like PYTHIA, PHOJET, etc.) in use. This observation has made the study of multiplicity distribution at LHC energies all the more interesting.

II. OBJECTIVE

In this article, we analyze the primary charged particle multiplicity distributions in the forward rapidity region in proton-proton (pp) collisions at $\sqrt{s} = 7$ TeV, as measured by the LHCb experiment at the LHC, in terms of parameters of the negative binomial distribution (NBD) function. The two-parameter NBD function, as given below in Eq. (1), played a significant role in describing multiplicity distributions of produced charged particles in the midrapidity region in pp (and $p\bar{p}$) collisions for a wide range of the center-of-mass energy, including $\sqrt{s} = 7$ TeV.

$$P(n, \langle n\rangle, k) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)}\left[\frac{\langle n\rangle}{k+\langle n\rangle}\right]^n \times \left[\frac{k}{k+\langle n\rangle}\right]^k, \tag{1}$$

where $\langle n\rangle$ is the average multiplicity and the parameter k is related to dispersion D, ($D^2 = \langle n^2\rangle - \langle n\rangle^2$) by

$$\frac{D^2}{\langle n\rangle^2} = \frac{1}{\langle n\rangle} + \frac{1}{k}. \tag{2}$$

The NBD function could describe the charged particle multiplicity distributions in proton-antiproton ($p\bar{p}$) collisions at $\sqrt{s} = 540$ GeV at the superproton synchrotron (SPS) [7] at CERN in the full pseudorapidity (η) space as well as in limited pseudorapidity intervals (for high-momentum low-mass particles, the rapidity can be approximated to the pseudorapidity, $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle of the particle with respect to the counterclockwise beam direction). At $\sqrt{s} = 900$ GeV SPS energy, however, the single-NBD function could describe the data only for small pseudorapidity intervals at the midrapidity region. With the appearance of substructures

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in multiplicity distributions at higher energies and in larger pseudorapidity intervals, the weighted superposition or convolution of more than one function including one NBD function, as proposed by several models [8–11], representing more than one source or process of particle productions could explain the data better. Such a substructure in SPS data at $\sqrt{s} = 900$ GeV and in Tevatron data at $\sqrt{s} = 1.8$ TeV [12] could be well explained by weighted superposition of two NBD functions [9], as given by Eq. (3). The multiplicity distributions of primary charged hadrons in nonsingle diffractive events in pp collisions at $\sqrt{s} = 7$ TeV in the midrapidity region also could be well explained [13] by the two-NBD function.

$$\begin{aligned} P_n(\sqrt{s}, \eta_c) &= \alpha_{\mathrm{soft}}(\sqrt{s}) \\ &P_n[\langle n\rangle_{\mathrm{soft}}(\sqrt{s}, \eta_c), k_{\mathrm{soft}}(\sqrt{s}, \eta_c)] + [1 - \alpha_{\mathrm{soft}}(\sqrt{s})] \\ &P_n[\langle n\rangle_{\mathrm{semihard}}(\sqrt{s}, \eta_c), k_{\mathrm{semihard}}(\sqrt{s}, \eta_c)], \end{aligned} \tag{3}$$

where α_{soft} is the fraction of "soft" events and is a function of $\sqrt{s}$ only. The other parameters, functions of both the $\sqrt{s}$ and the η_c, have usual meanings as described for Eq. (1) with suffixes in parameters indicating respective components.

At this point, discussing other models or approaches of multiparticle production involving NBDs would be relevant. The framework of the weighted superposition mechanism of different classes of events has been extended from the two-component to a three-component model [14] for explaining possible new physics at the LHC at $\sqrt{s} =$ 14 TeV. The third component would attribute to the eventual new class of high multiplicity events, which would be manifested by the appearance of a new elbow structure in the tail of multiplicity distribution of the pp collisions at the highest planned center-of-mass energy at the LHC. So far, the multiplicity distributions for the pp collisions up to $\sqrt{s} = 7$ TeV are available, and these distributions have no such new structure, in the tail of the distributions, which calls for application of the model. A very recent theoretical approach [15], following the Glasma flux tube model, has shown that the multiplicity distribution of multiparticle production could be described by a convolution of a number of NBD functions as a natural consequence of several impact parameters of the collisions. The model reproduces the multiplicity distributions data of pp collisions in a small pseudorapidity window ($|\eta| < 0.5$) at the LHC energies. The scope of the present work is, however, restricted to the analysis of the LHCb data in terms of a single NBD and a superposition of two NBDs, as prescribed by the two-component model of Ref. [9].

According to the two-component model of Ref. [9], the multiplicity distribution of hadronic collisions can be explained by weighted superposition of two NBDs, representing two classes of events, "semihard events with minijets or jets" and "soft events without minijets or jets". It is noteworthy that the "semihard" events involving hard parton-parton scatterings (due to high momentum transfer) resulting in QCD jets of high transverse momentum above a certain threshold are also referred to as "hard-QCD" events.

The LHCb experiment has measured [6] multiplicity distributions of primary charged particles produced in the pp collisions at $\sqrt{s} = 7$ TeV in the pseudorapidity coverages, $-2.5 < \eta < 2.0$ and $2.0 < \eta < 4.5$, for two classes of events: the minimum bias and the hard QCD. The hard-QCD events were chosen out of the minimum bias events by selecting events with at least one particle with transverse momentum greater than 1 GeV/c. The multiplicity distributions for both the event classes were measured for small pseudorapidity windows of width $\eta_c = 0.5$ scanning over the η range of the detector coverage as well as for the wide η window, $\eta_c = 2.5$ ($2.0 < \eta < 4.5$). We analyze these distributions in the forward rapidity in terms of the NBD that has been successful in describing the midrapidity data. We discuss the results, comparing with observations in a similar analysis of data at the same $\sqrt{s}$ at the midrapidity region. For the midrapidity region, we consider the distributions, measured by the CMS experiment [4], as there exists [13] a similar phenomenological study of the CMS data in terms of the NBD formalism.

III. ANALYSIS AND DISCUSSIONS

We fit the multiplicity distributions of primary charged particles, as measured [9] by the LHCb, in the five pseudorapidity windows of width $\eta_c = 0.5$ in the η range, $2.0 < \eta < 4.5$, for the minimum bias events with the NBD function as given in Eq. (1). The Table I contains the values of the parameters obtained by the best fits, along with the corresponding values of χ^2/ndf. As can be seen from the χ^2/ndf values, the single-NBD function is far from a satisfactory description of the multiplicity distribution for the minimum bias events. The fitted values of the NBD parameters, however, show consistent dependence on the position of the η bin. The average multiplicity ($\langle n\rangle$) decreases, and the k parameter increases, indicating broader distributions in the pseudurapidity bins in the more forward regions.

TABLE I. Values of parameters of NBD functions as obtained by fitting the multiplicity distributions for the primary charged particles in minimum bias events in pp collisions at $\sqrt{s} = 7$ TeV for five small η windows.

η window	k	$\langle n\rangle$	χ^2/ndf
$2.0 < \eta < 2.5$	1.92 ± 0.02	3.49 ± 0.03	195.80/18
$2.5 < \eta < 3.0$	1.98 ± 0.02	3.40 ± 0.03	231.59/18
$3.0 < \eta < 3.5$	2.12 ± 0.02	3.26 ± 0.03	228.71/18
$3.5 < \eta < 4.0$	2.35 ± 0.03	3.08 ± 0.03	233.34/18
$4.0 < \eta < 4.5$	2.81 ± 0.05	2.88 ± 0.03	240.78/18

The multiplicity distributions for the minimum bias events could be better described by the weighted superposition of two NBDs, as can be seen from the plots in Fig. 1, where the multiplicity distributions along with the single-NBD and the two-NBD fits have been plotted. The deviation for the single-NBD fits is more for the distributions in the more forward region. Although from the plots in the Fig. 1 and the χ^2/ndf, as listed in the Table II, it is clear that two NBDs describe the minimum bias data better, the values of the fit parameters with large errors in these small rapidity intervals, as tabulated, are not suitable to reveal systematic behavior of the parameters. At this point, we recollect that the multiplicity distributions of the charged hadrons produced in events of pp collisions at $\sqrt{s} =$ 7 TeV [4] in overlapping pseudorapidity bins of different widths, $|\eta| = \eta_c = 0.5$ to 2.4, also fit better [13] to the two-NBD function than a single-NBD function. It is worth mentioning, however, that the clan-structure description of Ref. [9] failed to match the midrapidity LHC data [12,13].

In the context of the hard-QCD events, it may be noted that the LHCb experiment selected an event with at least one particle with transverse momentum greater than 1 GeV/c in the range $2.5 < \eta < 4.5$, as a "hard" event. A similar approach was adopted [16] by the CDF experiment at the Tevatron, Fermilab, where two isolated subsamples, soft and hard, were analyzed separately to reveal that the properties of the soft sample were invariant as a function of the center-of-mass energy. The CDF experiment isolated events considering the events with no particle of transverse energy, $E_T > 1.1$ GeV, as soft events. Although none of the other experiments of the LHC has

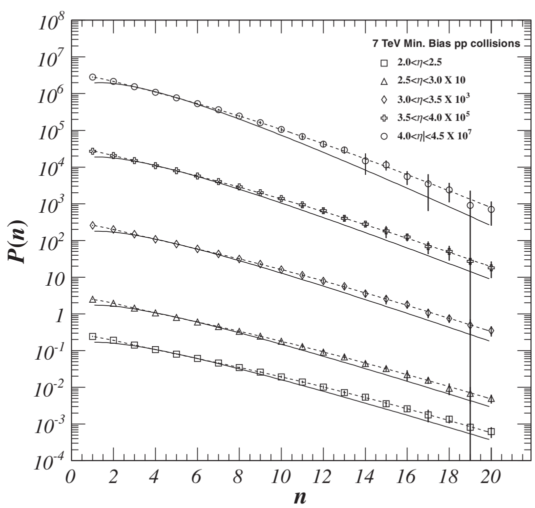

FIG. 1. Primary charged particle multiplicity distributions for minimum bias pp collisions at $\sqrt{s} = 7$ TeV for different η windows of width $\eta_c = 0.5$ scanning over the η range $2.0 < \eta < 4.5$. The solid lines drawn along the data points correspond to respective fits of a single NBD, while the dotted lines represent the two-NBD fits. The error bars include both the statistical and the systematic uncertainties.

TABLE II. Values of parameters of two NBDs as obtained by fitting the multiplicity distributions for the primary charged particles in minimum bias events in pp collisions at $\sqrt{s} =$ 7 TeV for five η windows, tabulated in the same order as in Table I.

k_{soft}	$\langle n \rangle_{\text{soft}}$	k_{semihard}	$\langle n \rangle_{\text{semihard}}$	χ^2/ndf
3.15 ± 2.56	5.14 ± 2.06	1.92 ± 0.96	1.53 ± 0.80	0.70/14
2.72 ± 2.23	4.54 ± 1.43	2.31 ± 2.25	1.32 ± 0.54	0.47/14
3.18 ± 1.65	4.63 ± 2.01	2.05 ± 1.19	1.43 ± 0.83	0.31/14
1.98 ± 0.54	1.53 ± 0.21	3.99 ± 2.99	4.73 ± 0.35	0.29/14
2.11 ± 0.95	1.30 ± 0.47	3.55 ± 0.89	3.93 ± 0.80	0.39/14

measured multiplicity distribution for the so-called hard-QCD events, the invariance of multiplicity distribution of soft events as a function of $\sqrt{s}$ has been revealed [13] in the analysis of the data of the CMS experiment [4] in terms of two NBDs. Considering that the two-component model of particle productions is valid in the forward region and that the criterion for isolating the hard-QCD events is proper, one may expect the multiplicity distributions for the hard-QCD events to be well described by a single-NBD function only.

We fit a single-NBD function to the multiplicity distributions of the produced primary charged particles for the hard-QCD events of LHCb experiments [5] in small non-overlapping pseudorapidity bins. The relevant plots are depicted in Fig. 2. The plots in Fig. 2 show that the single-NBD function fits reasonably well with the multiplicity distributions in small η windows. The values of χ^2/ndf for the respective plots are given in Table III. For two of the η windows, however, the values of χ^2/ndf are

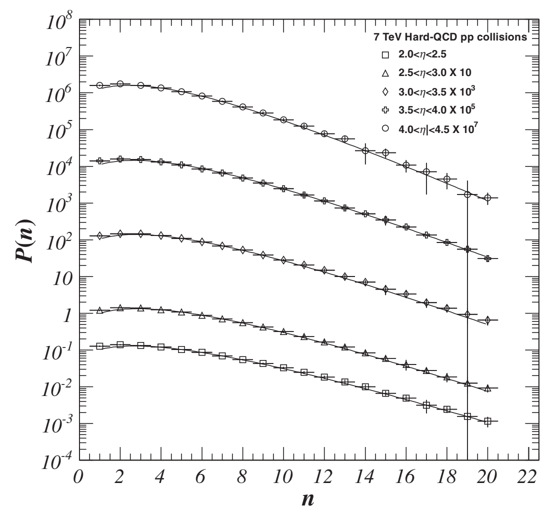

FIG. 2. Primary charged particle multiplicity distributions for the hard-QCD events in pp collisions at $\sqrt{s} = 7$ TeV for different η windows of width $\eta_c = 0.5$ scanning over the η range $2.0 < \eta < 4.5$. The solid lines drawn along the data points correspond to respective fits of a single NBD. The error bars include both the statistical and the systematic uncertainties.

not satisfactory. The values of the parameters $\langle n\rangle$ and k, as tabulated in Table III, show a systematic trend; the $\langle n\rangle$ decreases, and the k increases with a shift of the η window more toward forward rapidity. On the whole, the single NBD appears to describe the multiplicity distributions for the hard-QCD events in small η windows in the forward region.

We continue to fit the NBD function to the multiplicity distributions for the wider pseudorapidity range, $\eta_c = 2.5$, in the η range $2.0 < \eta < 4.5$ for both the event classes. As can be seen from the χ^2/ndf values obtained from the best-fit methods and tabulated in Table IV, neither of the distributions fit a single-NBD function. This led us to the consideration of the weighted superposition of two NBDs in describing both the event classes. In the case of hard-QCD events, of course, the terminology of the two-component model with respect to Eq. (3) becomes irrelevant, and it is just the functional form of the equation that we are interested in. In Table V, we denote the two components of the multiplicity distribution of the hard-QCD events with suffixes 1 and 2. Figure 3 depicts the primary charged particle multiplicity distributions for the minimum-bias and the hard-QCD events along with corresponding best fits with a single-NBD function and with the superposition of two NBDs. The values of the fit parameters, obtained by the best fits in terms of χ^2/ndf, as well as the χ^2/ndf values are tabulated in Table V for two NBDs. Figure 3 and the χ^2/ndf values tabulated in Tables IV and V clearly indicate that the multiplicity distributions for both the minimum-bias and the so-called hard-QCD events, indeed, are better described by two NBDs than a single-NBD function for the large pseudorapidity bin, $\eta_c = 2.5$, in the η range $2.0 < \eta < 4.5$.

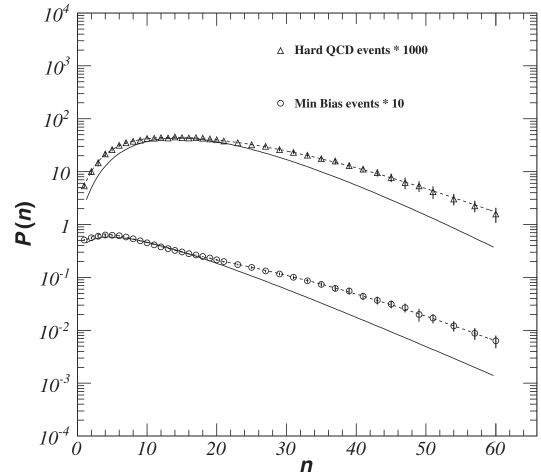

FIG. 3. Primary charged particle multiplicity distributions for the minimum-bias and the hard-QCD events in pp collisions at $\sqrt{s} = 7$ TeV for the η window of width $\eta_c = 2.5$ ($2.0 < \eta < 4.5$). The solid lines drawn along the data points correspond to respective fits of NBD, while the dotted lines represent the two-NBD fits. The error bars include both the statistical and the systematic uncertainties.

TABLE III. Values of parameters of NBD functions as obtained by fitting the multiplicity distributions for the primary charged particles in the hard-QCD events in pp collisions at $\sqrt{s} = 7$ TeV for five η windows of a width of $\eta_c = 0.5$ each.

η window	k	$\langle n\rangle$	χ^2/ndf
$2.0 < \eta < 2.5$	2.83 ± 0.05	4.95 ± 0.05	29.14/18
$2.5 < \eta < 3.0$	3.19 ± 0.04	4.86 ± 0.05	23.59/18
$3.0 < \eta < 3.5$	3.39 ± 0.05	4.64 ± 0.05	87.69/18
$3.5 < \eta < 4.0$	3.53 ± 0.33	4.45 ± 0.02	45.34/18
$4.0 < \eta < 4.5$	3.82 ± 0.06	3.97 ± 0.04	27.47/18

TABLE IV. Values of parameters of the single-NBD function as obtained by fitting the multiplicity distributions for the primary charged particles in pp collisions at $\sqrt{s} = 7$ TeV for η windows of width $\eta_c = 2.5$ ($2.0 < \eta < 4.5$).

Event class	k	$\langle n\rangle$	χ^2/ndf
Min. Bias.	1.81 ± 0.01	11.63 ± 0.06	853.78/37
Hard QCD	4.32 ± 0.08	19.35 ± 0.15	559.65/37

TABLE V. Values of parameters of two NBDs as obtained by fitting the multiplicity distributions for the primary charged particles in pp collisions at $\sqrt{s} = 7$ TeV for η windows of width $\eta_c = 2.5$ ($2.0 < \eta < 4.5$) for two classes of events, the minimum bias and the hard QCD, tabulated in the same order as in Table IV.

$k_{\mathrm{soft}(1)}$	$\langle n\rangle_{\mathrm{soft}(1)}$	$k_{\mathrm{semihard}(2)}$	$\langle n\rangle_{\mathrm{semihard}(2)}$	χ^2/ndf
2.23 ± 0.15	7.30 ± 0.75	4.11 ± 1.00	23.38 ± 2.04	16.31/33
4.04 ± 0.62	10.64 ± 1.86	4.20 ± 0.85	24.47 ± 1.42	4.62/33

IV. SUMMARY AND REMARKS

We have analyzed the multiplicity distributions of primary charged particles in pp collisions at $\sqrt{s} = 7$ TeV, as measured by the LHCb experiment at the LHC. The LHCb has measured the multiplicity distributions in several small ($\Delta\eta < 0.5$) pseudorapidity windows mostly in the forward η region, $2.0 < \eta < 4.5$, as well as in a large η window ($\Delta\eta < 2.5$) for two classes of events, the minimum bias and the hard QCD. The distributions have been analyzed in terms of the NBD function.

For the minimum-bias events, we observe that the distributions in both the small and the large pseudorapidity windows could be better described by the weighted superposition of two NBDs than a single-NBD function—a feature similar to what has been exhibited by the multiplicity distributions of primary charged hadrons produced in the midrapidity region in the pp collisions at $\sqrt{s} = 7$ TeV.

The reasonable good fits of the single NBD to the multiplicity distributions for the hard events in small η windows also are more or less in agreement with the two-component model of the so-called hard and soft particle productions. But the need of a similar function formed by the weighted superposition of two NBDs in describing multiplicity distribution of the hard events in the large η window contradicts the concept of the discussed two-component model.

On the basis of the finding that the multiplicity distribution of hard events in the large η window deviates appreciably from a single NBD and requires weighted superposition of two NBDs, one may conclude that the discussed two-component model [9] does not conform fully with the multiplicity distribution in the forward-rapidity region of pp collisions at $\sqrt{s} = 7$ TeV. The finding could be attributed either to biased selection criterion of the hard events or to the possibility of a different particle production mechanism in different phase space.

It is worth discussing at this point that there exists no specific orthogonal variable, as yet, to separate the soft and the hard events in pp collisions. Isolating the hard (soft) events on the basis of having at least one (no) particle with the transverse momentum or transverse energy greater than a certain given value is a data driven approach and may inherit some biases, which need corrections. The selection criterion of the hard interaction events at the LHCb resulted the geometrical acceptance no longer independent of momentum, and the distributions were accordingly corrected by the collaboration [6]. In this study, we have analyzed the corrected distributions.

To conclude on the possibility of a different particle production mechanism at different phase space, direct comparison of a similar analysis in the midrapidity and in the forward rapidity is essential. Our study with the minimum-bias events at the forward rapidity and a comparison of the related results with a similar study with the midrapidity data [13] do not indicate the possibility of a different particle production mechanism in the framework of the two-component model. The results of our analysis with the hard-QCD events, on the other hand, could not be compared with the midrapidity data as there exists no measured multiplicity distribution for hard events in the midrapidity region at the LHC. In the present scenario, a similar analysis of isolated hard events of pp collisions in the midrapidity region would be useful to obtain a comprehensive picture on the role of the discussed two-component model vis-à-vis with the multiplicity distributions in different phase space in pp collisions at the LHC energies.

Also, other theoretical and phenomenological approaches [15,17,18], successful in describing the data at the midrapidity, may be compared with the LHCb data at the forward rapidity region. In Ref. [17], the CMS data [4] at the midrapidity have been successfully described in the framework of independent pair parton interactions [19] and in terms of the quark gluon string model [20,21] that fits better to the data than the independent pair parton interaction model. The midrapidity data have been analyzed [22] also in the light of another multiple scattering model of particle production, the dual parton model.

Note added.—During the review process of this article, we came across an article [23] that reports the analysis of minimum-bias multiplicity distributions measured by all the experiments at the LHC by weighted superposition of three NBD functions.

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