Light Hadron Production in Proton–Proton Collisions at Different LHC Energies: Measured Data versus a Model *

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Experiments involving proton–proton collisions at energies √s_{NN}=0.9, 2.76 and 7 TeV in the large hadron collider produce a vast amount of high-precision data. In this work, we analyze two aspects of the measured data, viz., (i) the p_{T}-spectra of pions, kaons, proton-antiproton at the above-mentioned energies, and (ii) some of their very important ratio behaviors, in the light of a version of the sequential chain model. The agreements between the measured data and the model-based results are generally found to be modestly satisfactory.

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The production of hadronic particles in high energy heavy ion physics is of special interest to understand the underlying mechanisms leading to such reaction products and to test the predictions from non-perturbative QCD processes. The yield of identified hadrons, their multiplicity distributions, and the rapidity and transverse momentum spectra are the basic observables in heavy ion collisions. The measurement of such global observables has produced, over the years, new and interesting insights about the involved production mechanisms, allowing in turn to improve the theoretical description of the multiparticle production processes in heavy ion collisions.

In pp collisions at ultra-relativistic energies √s_{NN}=0.9, 2.76 and 7 TeV, the bulk of the particles produced at mid-rapidity have transverse momenta below 2 GeV/c. First principles calculations based on perturbative QCD are not able to provide detailed predictions of particle production.1 Our basic objective in the present work is to interpret a part of significant data, like the transverse momenta spectra and some ratio behaviors of pions, kaons and protons, obtained from pp collisions at large hadron collider (LHC) energies √s_{NN}=0.9, 2.76 and 7 TeV, with the help of the sequential chain model (SCM). The another goal of the present work is to put this alternative approach to a segment of LHC-data with a view to assessing the success(es)/failure(s) of it.

According to this SCM, high energy hadronic interactions boil down, essentially, to the pion-pion interactions; as the protons are conceived in this model as p = (π⁺ π₀ θ), where θ is a spectator particle needed for the dynamical generation of quantum numbers of the nucleons.2 The production of pions in the present scheme occurs as follows: the incident energetic π⁺-mesons in the structure of the projectile proton(nucleon) emits a rho(ω)-meson in the interacting field of the pion lying in the structure of the target proton, the ω-meson then emits a π-meson and is changed into an omega(ω)-meson. The ω-meson then again emits a π-meson and is transformed once again into a η-meson and thus the process of the production of pion-secondaries continues in the sequential chain of η-ω-π mesons. The production mechanism is shown schematically in Fig. 1. The two ends of the diagram contain the baryons exclusively.2–6

![Fig. 1. Feynman diagrams for the production of π in the sequential chain model.](image)

![Fig. 2. Feynman diagrams for the production of K⁺ in the sequential chain model.](image)

![Fig. 3. Feynman diagrams for the production of ℓ and p in the sequential chain model.](image)

In a similar fashion, the K⁻ (K⁺) and the baryon-antibaryon have been produced in the SCM, which are shown in Figs. 2 and 3, respectively.

The fundamental expressions for final (analytical) calculations are derived here on the basis of field-

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In Eqs. (1), (3) and (5), \( \Gamma \) with \( x \) different energy regions and for various collisions. The \( p \) with \( m \) and with \( T \) high energies, with \( d \) and \( N \), and the under impulse approximation method.agram techniques with the infinite momentum frame.

In Eqs. (2), (4) and (6), the following factors: (i) the specificities of the rearrangement term arising out of the partons inside the propagator for excited nucleons. The third term represents the common multiparticle production amplitudes along with extraneous production modes, and the last term indicates simply the phase space integration on the probability of the generation of a single \( \pi^+ \). These expressions are to be calculated by the typical field-theoretical techniques and are to be expressed, if and when necessary, in terms of the relevant variable and/or measured observables.

To arrive at the transverse momentum distribution of \( \pi^+ \), one has to consider Eq. (1), along with Eq. (8). For excess \( \pi^+ \) production, a factor represented by \( \left( 1 + \gamma \pi^+ p_T^+ \right) \) is to be operated on an inclusive cross section of \( \pi^- \) as a multiplier.

Adopting the above procedure, as we indicated for the production of positive pions, we obtain the transverse momentum distribution of \( K^- \), a multiplicative factor \( \left( 1 + \gamma K^- p_T^- \right) \), to be operated on the inclusive cross section of \( K^- \) production.
Similarly, for the production of protons, we obtain for the transverse momentum distribution of $p$ by operating a multiplicative factor $\sim (1 + \gamma^p p_T^2)$, on an inclusive cross section of $\bar{p}$.

Here we focus on the properties of the nature of the $p_T$-spectra and some particle-production ratios of some light hadrons, like $\pi^\pm, K^\pm, \bar{p}$ and $p$, in pp-collisions at energies $\sqrt{s_{NN}} = 0.9, 2.76$ and 7 TeV in LHC.

The general form of our SCM-based transverse-momentum distributions for $p + p \to C^- + X$-type reactions can be written as follows:

$$
\frac{1}{2\pi p_T} \left. \frac{d^2N_C}{dp_T dy} \right|_{p+p\to C^-+X} = \alpha_C - \frac{1}{N_C^R} \exp(-\beta_C \times p_T^2).
$$

(9)

The values of $\alpha_C$ and $\beta_C$, for example, can be calculated from the following relations

$$\alpha_C = (1 - \frac{2.38}{(n_{\pi^-})_{pp} x}) \exp(-2.68 \frac{(n_{\pi^-})_{pp} x}{(n_{\pi^-})_{pp} (1-x)})$$

(10)

$$\beta_C = (\frac{2.38}{(n_{\pi^-})_{pp} x}) \exp(-2.68 \frac{(n_{\pi^-})_{pp} x}{(n_{\pi^-})_{pp} (1-x)})$$

(11)

For the calculation of $(N_R^-)_{pp}$, we use Eq. (7). The values of $(\alpha_C^-)_{pp}, (N_R^-)_{pp}$ and $(\beta_C^-)_{pp}$ for $K^-$ and $\bar{p}$ can be calculated in a similar way by using Eqs. (3)–(6).

Table 1. Values of $\alpha$, $N_R$ and $\beta$ for pions, kaons, and the antiproton and proton productions in $p + p$ collisions at $\sqrt{s_{NN}} = 0.9, 2.76$ and 7 TeV.

| $\pi^-$ | $\pi^+$ |
|---------|---------|
| $\alpha_{\pi^-}$ | $\alpha_{\pi^+}$ |
| $\beta_{\pi^-}$ | $\beta_{\pi^+}$ |
| $N_R^{\pi^-}/\sqrt{s_{NN}}$ | $N_R^{\pi^+}/\sqrt{s_{NN}}$ |
| 0.310 | 2.054 |
| 0.128 | 0.350 |
| 0.128 | 2.054 |

| $K^-$ | $K^+$ |
|-------|-------|
| $\alpha_{K^-}$ | $\alpha_{K^+}$ |
| $\beta_{K^-}$ | $\beta_{K^+}$ |
| $N_R^{K^-}/\sqrt{s_{NN}}$ | $N_R^{K^+}/\sqrt{s_{NN}}$ |
| 0.130 | 1.354 |
| 0.248 | 0.133 |
| 0.248 | 1.354 |

| $\bar{p}$ | $p$ |
|---------|-----|
| $\alpha_{\bar{p}}$ | $\alpha_p$ |
| $\beta_{\bar{p}}$ | $\beta_p$ |
| $N_R^{\bar{p}}/\sqrt{s_{NN}}$ | $N_R^{p}/\sqrt{s_{NN}}$ |
| 0.073 | 1.154 |
| 0.248 | 0.085 |
| 0.248 | 1.154 |

| $\bar{p}$ | $p$ |
|---------|-----|
| $\alpha_{\bar{p}}$ | $\alpha_p$ |
| $\beta_{\bar{p}}$ | $\beta_p$ |
| $N_R^{\bar{p}}/\sqrt{s_{NN}}$ | $N_R^{p}/\sqrt{s_{NN}}$ |
| 0.095 | 1.243 |
| 0.148 | 0.108 |
| 0.148 | 1.243 |

The values of $(\alpha_C^-)_{pp}, (N_R^{C^-})_{pp}$ and $(\beta_C^-)_{pp}$ ($C^-$ stands for $\pi^-, K^-$ or $\bar{p}$, respectively) for different energies are listed in the left panels of Table 1. The experimental data for the inclusive cross sections versus $p_T$ (GeV/c) for $\pi^-$, $K^-$ and $\bar{p}$ production in $p + p$ interactions at $\sqrt{s_{NN}} = 0.9, 2.76$ and 7 TeV are taken from Ref.[8] and are plotted in Figs. 4(a), 4(c) and 4(e), respectively. The solid lines in those figures depict the SCM-based plots while the dotted lines show the Pythia-induced calculations.

To arrive at the transverse momentum distribution of $\pi^+$, $K^+$ and $p$, one must consider Eqs. (1)–(6) and (8)–(10). For excess $\pi^+$ production, the factor $(1 + \gamma^{\pi^+} p_T^{\pi^+})$ is to be operated on $\frac{1}{2\pi p_T} \left. \frac{d^2N}{dp_T dy} \right|_{p+p\to \pi^+X}$ as a multiplier. Here $\gamma^{\pi^+} \simeq (20\pi^2 g_\pi^\pi g_\pi^\pi)/\sqrt{s} \simeq 0.44$.[3] Taking $\langle p_T \rangle_{\pi^+} \simeq 0.31$ GeV/c,[9] the calculated values of $\alpha_{\pi^+}$ for different energies are listed in the right panel of Table 1. The values of $(N_R^{\pi^+})_{pp}$ and $(\beta_{\pi^+})_{pp}$ remain the same and are listed in the right panel of Table 1.

![Fig. 4. Plots for $\pi$, $K$, $\bar{p}$ and $p$ productions in $p + p$ collisions at energies $\sqrt{s_{NN}} = 0.9, 2.76$ and 7 TeV. Data are taken from Ref. [8]. Solid lines show the SCM-based theoretical plots while the dotted ones show the PYTHIA-based results.](image)

Similarly, we obtain the transverse momentum distribution of $K^+$, and the multiplicative factor $\sim (1 + \gamma^{K^+} p_T^{K^+})$ is to be operated on $\frac{1}{2\pi p_T} \left. \frac{d^2N}{dp_T dy} \right|_{p+p\to K^+X}$ as a multiplier. The $\gamma^{K^+}$ has been calculated, $\gamma^{K^+} \simeq (4\pi^2 g_{K^+N}^2 + 4\pi^2 g_{K^+K}^2)/2\sqrt{s} \simeq 0.082$.[3] We use the value of $\langle p_T \rangle_{K^+} \simeq 0.36$ GeV/c.[9] The right panel of Table 1 depicts all the calculated values of $\alpha_{K^+}$, $N_R^{K^+}$ and $\beta_{K^+}$.

We obtain the transverse momentum distribution of $p$ by operating a multiplicative factor $\sim (1 + \gamma^p p_T^2)$ on $\frac{1}{2\pi p_T} \left. \frac{d^2N}{dp_T dy} \right|_{p+p\to \pi^-X}$. We have the value of $\gamma^p \simeq 0.32$ (Ref. [3]) and take $\langle p_T \rangle_p \simeq 0.50$ GeV/c.[8] The right panel of Table 1 depicts all the calculated values of $\alpha_p$, $N_R^{p}$ and $\beta_p$ for energies $\sqrt{s_{NN}} = 0.9, 2.76$ and 7 TeV. In Figs. 4(b), 4(d) and 4(f), we have plot-
ted the experimental and theoretical results for $\pi^+$, $K^+$ and $p$ production in $p+p$ collisions at energies $\sqrt{s_{NN}} = 0.9$, 2.76 and 7 TeV, respectively. Data are taken from Ref. [8]. The solid lines in those figures are the SCM-based plots while the dotted lines show the PYTHIA-induced calculations.

The $(K^+ + K^-)/($$\pi^+ + $$\pi^-$$)$ and $(p + \bar{p})/($$\pi^+ + $$\pi^-$$)$ ratios at energies $\sqrt{s_{NN}} = 0.9$, 2.76 and 7 TeV have been calculated from Eq. (9) and Table 1, and the results are plotted in Figs. 5(a), 5(c) and 5(e). Data are taken from Refs. [8,10]. Similarly, $\pi^-/\pi^+$, $K^-/K^+$ and $p/\bar{p}$-ratios are plotted in the right panel of Fig. 5, i.e., Figs. 5(b), 5(d) and 5(f). Data are taken from Ref. [8]. The solid lines in those figures are the average SCM-based plots.

Let us make some general observations and specific comments on a case-to-case basis.

First, the very basic model used here is essentially of a non-standard type. The measures of invariant yields against transverse momenta ($p_T$) obtained on the basis of the SCM for pions, kaons and protons at LHC energies $\sqrt{s_{NN}} = 0.9$, 2.76 and 7 TeV are depicted in Fig. 4. The calculated values of $(\alpha C)_{pp}$, $(N_F)_{pp}$ and $(\beta C)_{pp}$ ($C$ stands for $\pi$, $K$ or $p$ respectively) of Eq. (9) have been listed in Table 1. Moreover, we compare the model-based calculations with the PYTHIA-based results. Comparisons show neither sharp disagreement nor any good agreement between these two. Results show a modest degree of success.

There are some disagreements of the model in describing the data in the low-$p_T$ region. These are due to the fact that the model has turned essentially into a mixed one with the inclusion of the power law due to the inclusion of the partonic rearrangement factor. This power law term disturbs, to a considerable extent, the agreement between the data and the model. However, the power-law part of the equation might not be the only factor for this type of discrepancy. The initial condition and dynamical evolution in heavy-ion collisions are more complicated than we expect. Till now, we did not know the exact nature of the reaction mechanism. One might take into account some other factors like the radial flow or thermal equilibrium. The thermal equilibrium was included in the blast-wave model in a recent work.[11] However, we are not able to include these factors. The model is, thus, different from the thermal model and the blast-wave model[11] in some way. These are the factors that the model is lacking.

Secondly, the calculated values of $K/\pi$ and $p/\pi$ are compared with the experimental ones, which are plotted in Figs. 5(a), 5(c) and 5(e). The $K/\pi$ ratios show a modest degree of success while for $p/\pi$, the theoretical values differ slightly from the experimental ones in the low-$p_T$ part. In a similar way, the $\pi^-/\pi^+$, $K^-/K^+$ and $p/\bar{p}$-ratios are plotted in the right panel of Fig. 5. Here the model reproduces the data modestly well.

One point needs to be addressed here. The $K^-/K^+$-ratios at $\sqrt{s_{NN}} = 0.9$, 2.76 and 7 TeV are calculated from Table 1 and they are ~0.98, 0.98 and 0.98, respectively. This is due to the extraneous mode of production of positive particles in the SCM. No hyperon has been produced in the present scheme of the SCM. The production mechanism of kaons are shown schematically in Fig. 2.

However, on the overall basis, the total approach might provide an alternative route to understand and interpret the behavior of high energy collisions.

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