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COMMENTS ON RAPIDITY DISTRIBUTIONS OF PIONS IN $p+p$ AND Pb+Pb COLLISIONS AT CERN SPS ENERGIES*

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This paper presents a set of comments on a specific model of the initial longitudinal evolution of the system created in the collision of two ultrarelativistic nuclei, as well as on its relation to interactions of single nucleons at the same collision energy. The model, largely based on pure local energy and momentum conservation in the initial stage of the collision, recently served to understand the centrality and energy dependence of rapidity distributions of π mesons (pions) in Pb+Pb reactions in the energy regime of the CERN SPS accelerator. Additionally, with no tuning nor adjustment to the experimental data, the rapidity distribution of pions produced by the "fire-streak fragmentation function" implemented in the model reproduced the experimental pion rapidity distribution in nucleon–nucleon interactions. The apparent difference in the absolute normalization was explained by the difference in the overall energy balance in the two reactions, resulting from the known effects.

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1. Introduction

Collisions of ultrarelativistic nuclei or nucleons are a very extensive and widely recognized source of information on the fundamental strong force. Most unfortunately, the bulk of processes occurring in these belong to the non-perturbative regime of the strong interaction theory, Quantum Chromodynamics (QCD). In the absence of usage of perturbative calculations, theoretical predictions for specific processes become extremely difficult if not impossible. This well-known fact resulted, in the past decades, in the

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emergence of several factors defining the potential success or failure of a relatively broad range of studies. One can name these as (1) the necessity to use phenomenological models, partially based on using *ad hoc* assumptions in the description of ultrarelativistic collision processes, (2) the pressing need for rigorous experimental verification of assumed model scenarios, and (3), possibly least realized, the need of maximizing the possible model-independence of specific studies. This last need was at the root of a specific research program of studies of electromagnetic (EM) effects in high-energy nucleus–nucleus collisions, aimed at the extraction of new information on the space-time evolution of particle production processes occurring therein. Specific findings resulting from this program inspired the creation of a new, very simple model of the longitudinal evolution of the system in position space, which will be concisely described in the present paper. The implications from the success of this model to describe specific observables in the CERN SPS collision energy regime will be discussed in the broader context of the present tentative conclusions from the experimental program of the "NA61/SHINE 2d scan". More details on these issues can be found in several papers [1–10], as well as in other proceedings to the present Congress [11–13].

2. Electromagnetic effects

The idea of studying electromagnetic effects emerged from the hope that the EM component of the reaction would possibly preserve information which otherwise could not be directly measured nor computed theoretically in a model-independent way, due to the non-perturbative character of the strong interaction (Sec. 1). In 2007, we managed to demonstrate that indeed, the electromagnetic distortion of π^+/π^- ratios was sensitive to the longitudinal distance d_{E} between the position of the pion formation zone and that of the spectator system *at the moment of pion emission* [5]. Consequently, we found a similar property for electromagnetically induced directed flow (see Ref. [1] and Fig. 1 (a)), resulting in charge splitting of total directed flow [2]. The overall conclusion was that EM effects on charged pion spectra bring new, independent information on the space-time evolution of the system, that is, on the evolution of particle production in (x, y, z, t). This is in contrast to the experimental information being by definition limited to the (p_x, p_y, p_z) space with possible particle identification, with the only exception known to us being HBT effects [14].

The consequence was the extraction of the information on d_{E} as a function of pion rapidity (relativistic velocity), which we collected from three different datasets, from WA98 [15], NA49 [3], and STAR [16]. This is shown in Fig. 1 (b). As it is evident from the figure, the distance between the pion emission point and the spectator decreases with increasing pion velocity, that is, *faster* pions are produced *closer* to the spectator system. Subsequently, we attempted to exploit this independent information on the space-time evolution of the system, to build up a well-defined picture of the longitudinal expansion of primordial matter created in the nucleus–nucleus collision.

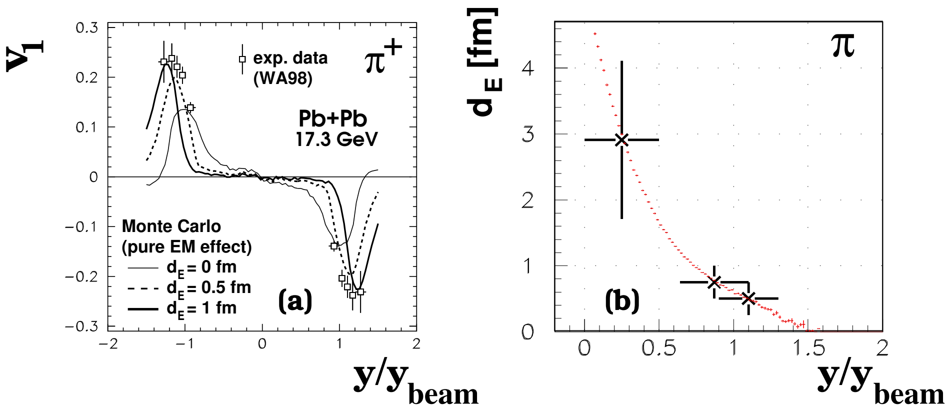

Fig. 1. (a) Electromagnetic effect on directed flow of π^+ mesons, drawn as a function of reduced pion rapidity in non-central Pb+Pb collisions at the top CERN SPS energy. The experimental data comes from Ref. [15]. Redrawn from Refs. [1, 2]. (b) Dependence of the distance $d_{\rm E}$ on reduced pion rapidity as deduced from experimental data from Refs. [3, 15, 16]. Redrawn from Ref. [4].

3. Longitudinal evolution of the system

The model of the initial evolution of the system as formulated below was independently, with no knowledge of earlier developments, proposed by Szczurek [6] and developed by the two other authors of the cited paper. One should point out, however, that partially similar ideas have, in fact, been present in the heavy-ion field since 1971 and are known under the general label of the "fire-streak model" [17–22]. Although very significant differences exist between the two models, in particular in the postulated ways of creation of hadrons from the initial primordial matter, below we keep the designation "fire-streak" to underline this (partial) similarity.

The proposed simple scenario naturally includes the findings presented in Fig. 1 (b) above, together with the general rule of energy-momentum conservation. The model starts from the three-dimensional nuclear density distributions which are divided into two-dimensional set of "bricks" of 1×1 fm^2 transverse size, and subsequently assumes that the "bricks" collide and form a two-dimensional set of longitudinal elements of excited matter which we label "fire-streaks". The model does not debate on the actual nature of fire-streaks, which can be regarded as, for instance, conglomerates of color strings or longitudinal elements of the quark–gluon plasma. Consequently, we assume that each fire-streak fragments independently into the different particles. This is to be understood as an implicit assumption that subsequent collective phenomena known in heavy-ion collisions (like azimuthal anisotropies) have negligible effects on charged π meson (pion) rapidity spectra, the description of which remains the principal aim of our work. The emission function (or "fire-streak fragmentation function", named such in order to differentiate from "standard" parton-to-hadron fragmentation function (FF) [23], was assumed to take the form [8] of

$$\frac{\mathrm{d}n}{\mathrm{d}y}\left(y, y_s, E_s^*, m_s\right) = A\left(E_s^* - m_s\right) \exp\left(-\frac{\left[(y-y_s)^2+\epsilon^2\right]^{\frac{r}{2}}}{r\sigma_y^r}\right), \qquad (1)$$

where y was the rapidity of the pion, y_s was the fire-streak rapidity (both taken in the collision center-of-mass system), and m_s was the sum of "cold" rest masses of the two "bricks" forming the fire-streak. It should be underlined that as these rest masses were defined by the geometry of the collision (see Fig. 2 (a)), both E_s^* and y_s were also defined be the latter geometry (and local energy-momentum conservation).

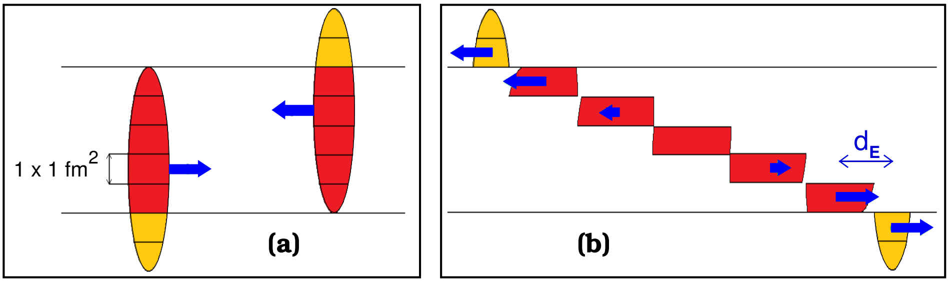

Fig. 2. Our model of the Pb+Pb reaction (a) before and (b) after the collision. Redrawn from Refs. [6, 7].

Function (1) had altogether four free parameters. For the description of pion spectra in Pb+Pb collisions at the top CERN SPS energy of 158A GeV (corresponding to $\sqrt{s_{NN}} = 17.3$ GeV in the collision c.m.s.), only three of them were taken as free while the parameter ϵ was kept at 0.01 uniquely to ensure the continuity of derivatives. It should be stressed that formula (1) was taken quite *ad hoc*, and was not supposed to contain deep dynamical sense. The only physical meaning of (1) was given by the $(y - y_s)^2$ term ensuring that each fire-streak emitted pions in its own center-of-mass system and with forward–backward symmetry, and by the $(E_s^* - m_s)$ term defining the average number of produced pions to be proportional to the total available energy. The *total* rapidity distribution in a given Pb+Pb collision at a given impact parameter b was defined as the sum of these coming from all the individual fire-streaks [8]

$$\frac{\mathrm{d}n}{\mathrm{d}y}(y,b)=\sum_{(i,j)}\frac{\mathrm{d}n}{\mathrm{d}y}\left(y,\ y_{s_{(i,j)}}(b),\ E^{*}_{s_{(i,j)}}(b),\ m_{s_{(i,j)}}(b)\right)\,, \tag{2}$$

where (i,j) marked the position of the considered fire-streak in the transverse (impact parameter) plane.

4. Pion rapidity spectra

With the unique, centrality-independent function (1) with effectively three free parameters, the model formulated above describes the full centrality dependence of π^- meson rapidity spectra in Pb+Pb collisions as measured experimentally by the NA49 experiment (see Ref. [6] for a detailed description). An illustration is shown in Fig. 3 (a). Specifically, the change of shape of the rapidity distribution (narrowing when going from peripheral to central collisions, Fig. 3 (b) appears, through Eq. (2), as a natural consequence of the changing geometry of the reaction. This evidently strengthens the hypothesis that this simple model provides to first order a realistic description of the longitudinal evolution of the system as a function of time.

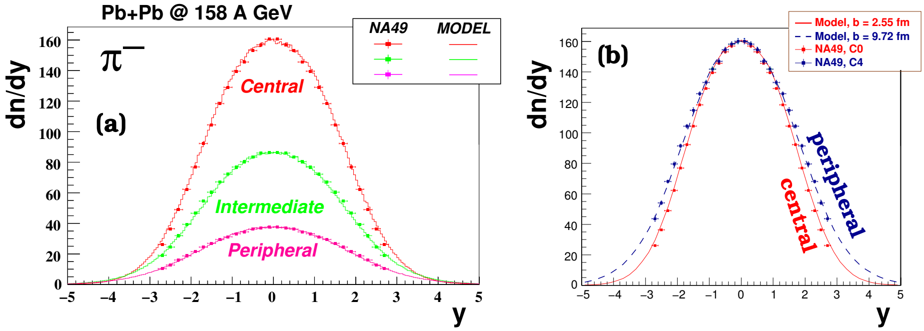

Fig. 3. Description of rapidity spectra of π^- mesons measured in Pb+Pb collisions at $\sqrt{s_{NN}}=17.3$ GeV (data points) by our model (histogram, curves). The distributions in panel (b) are adjusted at $y=0$. The experimental data were taken from Ref. [24] and the plots were redrawn from Refs. [6, 7, 25].

Quite a surprising constatation emerges from the comparison of the pion emission function (1) obtained from this successful description of Pb+Pb collisions (Fig. 3 (a)) to the experimental spectrum of π^- mesons in proton–proton collisions at the same energy ($\sqrt{s_{NN}}=17.3$ GeV). It is to be noted that up to this point of the analysis, the *ad hoc* function (1) is to be considered as an "abstract", "mathematical" object effectively describing the Pb+Pb data. The corresponding comparison is shown in Fig. 4 (b) and results in a surprising agreement of the shape of the two distributions, within a difference in normalization of 0.748. This latter factor can be fully understood as a direct consequence of the different energy repartition between different particles (protons, π mesons, K mesons, *etc.*) in Pb+Pb with respect to $p+p$ reactions. Consequently, it can be estimated (within 4% accuracy) directly from experimental data (see Ref. [8] for a more detailed description).

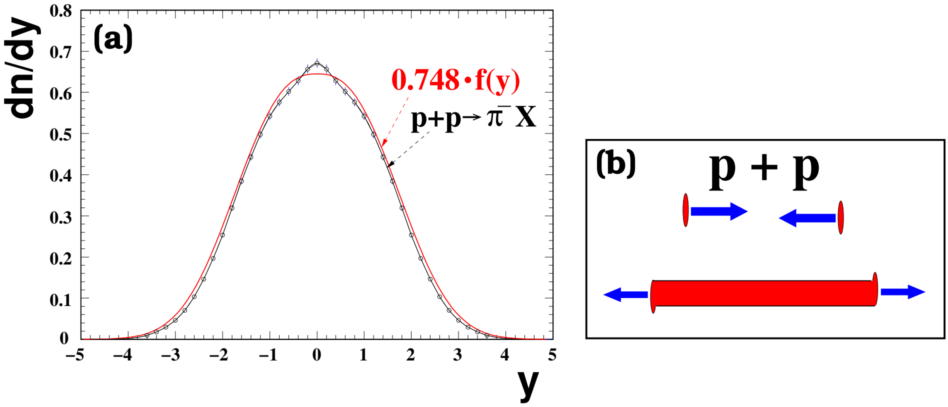

Fig. 4. (a) The fire-streak fragmentation function $f(y) \equiv \frac{\mathrm{d}n}{\mathrm{d}y}(y, 0, \sqrt{s_{NN}}, 2m_N)$, see Eq. (1), compared to the experimental distribution of π^- mesons produced in $p+p$ collisions at the energy of $\sqrt{s_{NN}} = 17.3$ GeV. The experimental data come from Ref. [26]. Redrawn from Ref. [6]. (b) Illustration of a single fire-streak object created in $p+p$ collisions.

The above constatation establishes a link between $p+p$ and Pb+Pb collisions at the top CERN SPS energy. A natural hypothesis for the apparent agreement between the pion rapidity distribution in $p+p$ and that from a single fire-streak in Pb+Pb reactions is that while numerous elongated streams of excited primordial matter are created in Pb+Pb events, a single such object, with at least partially similar properties, exists in the $p+p$ collision (see Fig. 1 (a) *versus* Fig. 4 (b)). The latter object should probably be understood as a complex conglomerate of microscopic dynamics, which when "transported" into the Pb+Pb reaction preserves the properties of pion emission in the longitudinal direction.

5. Energy dependence

It is evidently an important question whether the success of the approach presented in Secs. 3 and 4 achieved for $p + p$ and Pb+Pb reactions at the top CERN SPS energy ($\sqrt{s_{NN}} = 17$ GeV) extends to other collision energies. For the time being, a phenomenological analysis very similar to the above could have been performed at the twice lower energy of $\sqrt{s_{NN}} = 8.8$ GeV [12]. Identical conclusions were reached. This already suggests, in the context of the tentative conclusions from the two-dimensional NA61/SHINE scan [9, 10], that the simple picture formulated above describes the longitudinal evolution of the systems created above the onset of deconfinement at the CERN SPS energies. An evident need emerges to clarify whether the same picture applies also to $p + p$ and nucleus–nucleus collisions at lower collision energies ($\sqrt{s_{NN}} \leq 7$ GeV), or in the LHC energy regime. In the latter case, however, an evident difficulty emerges from the limited coverage of LHC experiments account taken of the full available phase space. This, to the best of my knowledge, results in the lack of complete rapidity distributions of identified pions, which remain a necessity in view of the falsification of the model.

6. Summary and conclusions

The simple model introduced in this paper was inspired by the findings from electromagnetic effects in nucleus–nucleus collisions, which show a decrease of the longitudinal distance between the pion formation zone and the spectator system at the moment of pion emission in the collision center-of-mass system. The apparent success of the model for the description of pion rapidity spectra in the proton–proton and lead–lead collision energy range of $8.8 < \sqrt{s_{NN}} < 17.3$ GeV suggests that at least in this regime, the longitudinal evolution of the system of hot and dense matter created in the nucleus–nucleus collision is largely dominated by collision geometry and local energy-momentum conservation. Following the state-of-the-art conclusions of the NA61/SHINE Collaboration from the scan of $p + p$ and nucleus–nucleus reactions as a function of system size and energy [9], this would imply quite a simple picture for the longitudinal expansion of the system above the onset of deconfinement. Whether the same picture can be applied to below the latter onset of deconfinement as well as at much higher energies (RHIC, LHC) is an interesting topic for further studies.

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