COMMENTS ON THE SPACE-TIME EVOLUTION OF THE SYSTEM CREATED IN THE NUCLEUS–NUCLEUS COLLISION AT HIGH ENERGY*

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The space-time evolution of the system created in the high-energy nucleus–nucleus collision is a complex, non-perturbative phenomenon which consequently largely escapes model-independent theoretical predictions. In this paper, we summarize the main findings gathered on this phenomenon from studies of spectator-induced electromagnetic effects as well as rapidity spectra in light- and heavy-ion systems at the CERN SPS. Main emphasis is put upon the evolution of the system in the longitudinal direction, where the CERN SPS energy regime is probably the highest where reasonably complete experimental coverage can be provided. Implications of these studies for other energy regimes, in particular the LHC, are shortly addressed.

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1. Introduction

Collisions of atomic nuclei at very high energies are one of the main sources of information on the fundamental strong force and, consequently, on the role it plays in interactions between quarks which are among the key ingredients of matter. Quite unfortunately, the bulk of processes occurring in such collisions belong to the low momentum transfer ("soft"),

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non-perturbative regime of the strong interaction. Consequently, unlike for the case of the electromagnetic interaction, our present knowledge of these processes cannot be considered as fully quantitative nor model-independent. This is in particular valid for the space-time evolution of the system of the highly energetic matter created in the collision, which, as it occurs on scales of space and time of the order of fm and fm/c, by definition escapes direct measurement. The situation can be considered as particularly difficult for the space-time evolution in the *longitudinal* direction where, on top of the above difficulties, experimental limitations in detector coverage become very significant *e.g.* at the Large Hadron Collider.

In the following, we will stress a few findings on the longitudinal evolution of the system obtained within a specific research programme which started from the relatively simple constatation [1] that electromagnetic (EM) distortions, induced by the spectator charge on ratios of charged π mesons (pions) produced in peripheral Pb+Pb collisions, remain sensitive to the details of the space-time evolution of the non-perturbative process of pion production. The programme is mainly realized at the energy regime of the CERN Super Proton Synchrotron where sufficient experimental coverage, not available at higher collision energies, is provided by the NA61/SHINE experiment [2]. The present findings of the programme and some of its implications for further studies will be shortly enumerated.

2. Spectator-induced electromagnetic effects in charged particle emission

The geometry of the (non-central) nucleus–nucleus reaction imposes its division into two different zones: the participant zone where new particles (mostly π mesons) are produced and the two nuclear remnants (spectator systems) which do not take direct part in the collision. The electric charge of the spectator system results in the presence of an electromagnetic field which modifies the trajectories of produced charged particles and, consequently, distorts their spectra in the final state. Two examples of such effects are shown in Fig. 1. The first is the characteristic distortion of π^+/π^- ratios in peripheral heavy-ion collisions at $\sqrt{s_{NN}} = 17.3$ GeV. The second example is the analogical effect for an intermediate centrality Ar+Sc collision at $\sqrt{s_{NN}} = 16.8$ GeV, which is the first ever measurement of a spectator induced electromagnetic effect in a "small" system at the CERN SPS. Very recently new NA61/SHINE data at $\sqrt{s_{NN}} = 8.8$ GeV were also released and we expect them to be presented soon at one of the forthcoming conferences[1].

[1] Experimental analysis of NA61/SHINE data performed by Sneha Bhosale.

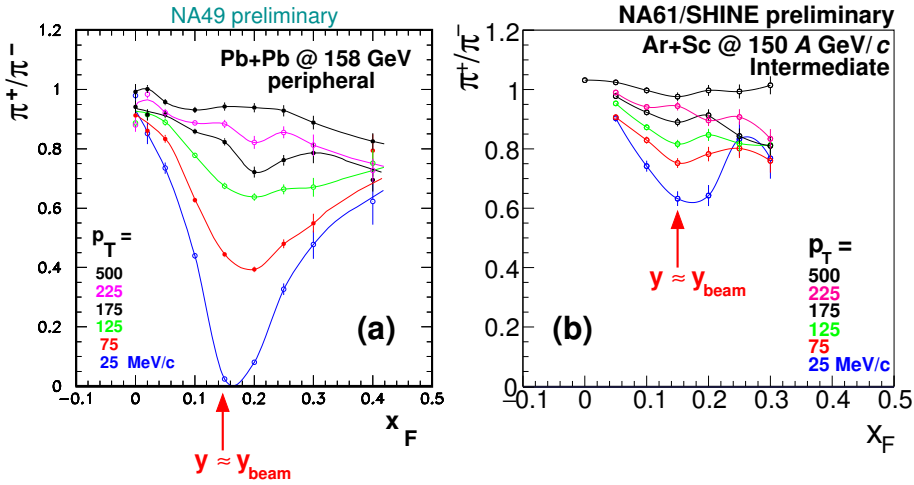


Fig. 1. Double differential measurement of π^+/π^- ratios emitted in (a) one hemisphere of the peripheral Pb+Pb collision [3], (b) the Ar hemisphere of the intermediate centrality Ar+Sc collision [4]. The measurements are made as a function of $x_{\mathrm{F}} = 2p_{\mathrm{L}}/\sqrt{s_{NN}}$ and transverse momentum p_{T} of the pion in the collision c.m.s.

Seen in terms of double differential observables as shown in Fig. 1, the electromagnetic distortion of charged pion spectra appears as quite a spectacular effect of lowering the π^+/π^- ratio for pions moving at low transverse momentum and close to or above spectator velocity (the beam rapidity corresponds to $x_{\mathrm{F}} = m_\pi/m_N \approx 0.15$ for pions). The effect is strong enough to break isospin symmetry imposed by the proton/neutron content of the argon nucleus even at intermediate centrality (Fig. 1 (b)). It has also been demonstrated to result in charge splitting of azimuthal anisotropy of $\pi^\pm$ emission with respect to the reaction plane [5], a phenomenon which has been observed by the STAR Collaboration [6]. We note that measurements of a similar type appeared recently from the ALICE experiment, in particular also for charmed particles [7].

On the other hand, it should be remembered that in the high-energy (ultrarelativistic) collision regime, the effect remains "hidden" as far as bulk observables are concerned. This is illustrated by Fig. 2, where the EM distortion remains unnoticeable for p_{T}-integrated pion $\mathrm{d}n/\mathrm{d}x_{\mathrm{F}}$ distributions, even if it reappears in the x_{F}-dependence of the p_{T}-integrated π^+/π^- ratio, and in an enhancement (depletion) of positive (negative) pion transverse momentum which, consequently, results in the charge splitting of the pion "sea-gull effect" [8] in peripheral Pb+Pb collisions visible in Fig. 2 (c).

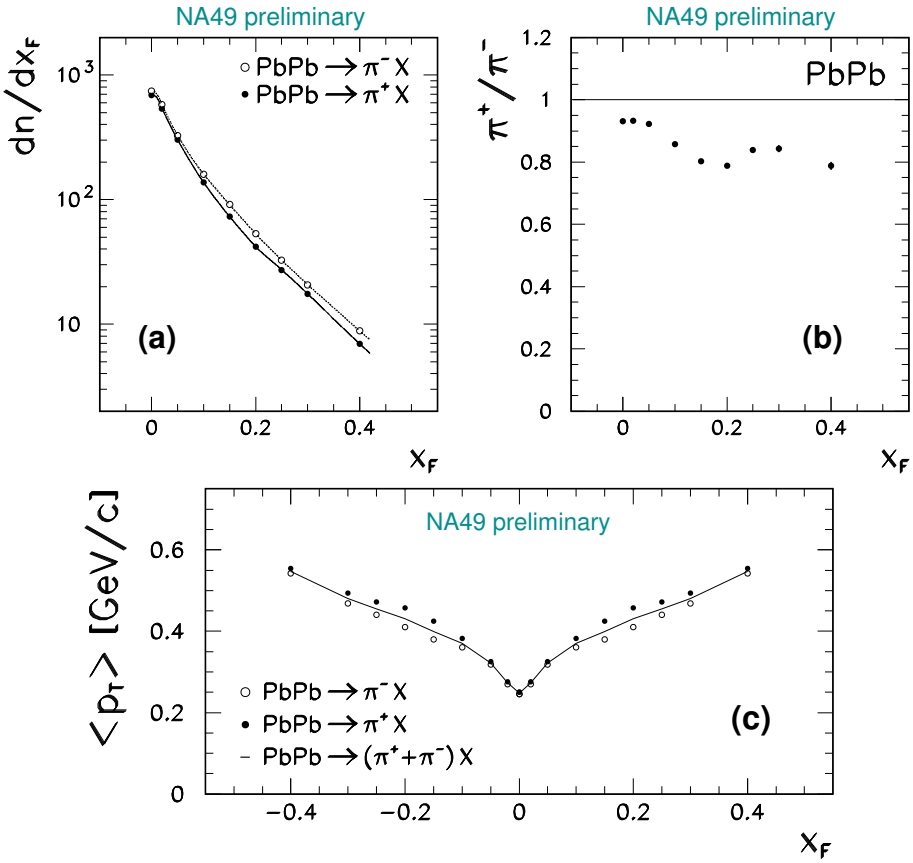


Fig. 2. x_{F}-dependence of (a) density of negative and positive pions emitted in one center-of-mass hemisphere of the peripheral Pb+Pb collision at $\sqrt{s_{NN}} = 17.3$ GeV, (b) ratio of π^+ over π^- densities, and (c) mean transverse momentum of positive, negative, and summed charged pions in both hemispheres. In panel (c), the values at $x_{\mathrm{F}} < 0$ are obtained by reflection. These results come from the analysis [3] presented in Fig. 1 (a).

3. Sensitivity of EM effects to the space-time evolution of the system

The original analysis demonstrating the sensitivity of the EM distortion of charged pion ratios to the space-time evolution of the (non-perturbative and, consequently, *a priori* unknown) process of pion production is presented in Fig. 3 (a). The modification of emitted pion trajectories by the spectator EM field was computed in the framework of a Monte Carlo code based on a simplified model of pion emission, assuming the longitudinal distance d_{E} between the pion formation zone and the spectator system (at the moment

of pion emission in the collision c.m.s.) as a free parameter [1]. As it is evident from the figure, a change of this distance by 1 fm brings a perfectly visible modification of the final-state π^+/π^- ratio for fast pions. This means that spectator-induced EM effects can be used to obtain new information on the space-time evolution of the system, which is completely independent from the (scarce) other sources of such information like the HBT analysis.

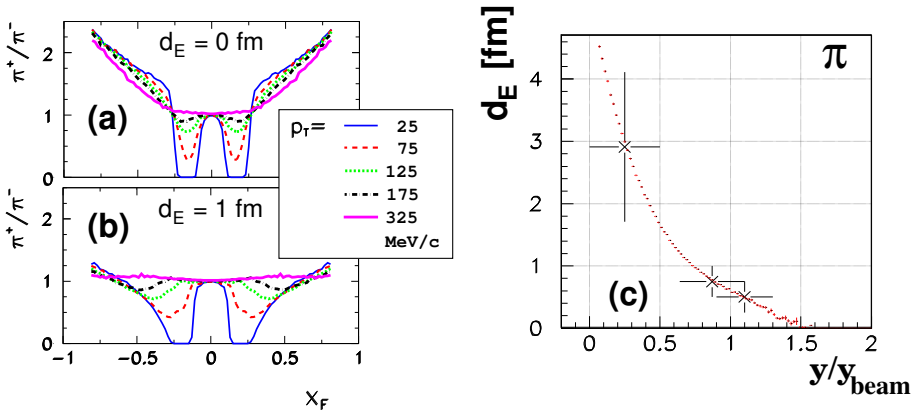


Fig. 3. (a), (b) Spectator-induced electromagnetic effect on ratio of π^+ over π^- mesons, computed in Ref. [1] for two values of the distance d_{E} between the pion formation zone and the spectator system, (c) dependence of the distance d_{E} on reduced pion rapidity, deduced in Ref. [9] on the basis of experimental data [3, 6, 10].

Several analyses followed the first study described above (see, *e.g.*, Refs. [11–15]). The main conclusions emerging from these can be summarized as follows:

1. The electromagnetic distortions of charged pion ratios and of azimuthal anisotropies bring the information that the distance d_{E} decreases as a function of pion rapidity as shown in Fig. 3 (c). This means that *faster* pions are produced *closer* to the spectator system.

2. The formation zone of fast pions moving at beam rapidity is in very close vicinity (below 1 fm) of the spectator remnant. On the other hand, at least for heavy-ion collisions, the corresponding longitudinal distance d_{E} is not zero.

3. The extrapolation of the above pion–spectator distance down to zero pion rapidity (Fig. 3 (c)) allows for the determination of the pion creation time at $y = 0$ on the basis of spectator-induced electromagnetic effects [9]. This gives 5.3 ± 2.2 fm$/c$ in the regime of $\sqrt{s_{NN}}$ of 8–17 GeV, which is in agreement with estimates obtained from the HBT-based analyses [16].

4. The electromagnetic modification of π^+/π^- ratios appears sensitive to the space-time details of spectator break-up. This appears particularly important for the small colliding systems at intermediate centrality (Fig. 1 (b)), where the spectator charge is made up of only a few spectator protons. However, also for peripheral Pb+Pb collisions, the inclusion of the corresponding expansion of spectator charge is a prerequisite for obtaining a correct description of the shape of the EM distortion at $x_{\mathrm{F}} = 0.15$–0.2 and at low transverse momenta [14]. This opens the perspective for following the interplay between fast pion production and spectator (lower energy, nuclear) physics, and possibly for differentiation between the different spectator decay channels [15].

5. Finally, our most recent study [14] investigates in detail the role of the different physical phenomena in building up the characteristic distortion structure presented in Fig. 1 (a). It becomes evident that this structure emerges a conglomerate of: (a) collision geometry, (b) shape of initial pion (y, p_{T}) spectra, (c) isospin effects, (d) the longitudinal evolution of the system, and (e) the pion creation proper time. The effects of azimuthal anisotropies (flow) are small and the effects of transverse expansion and vorticity appear negligible.

6. Consequently, as the effects (a)–(d) enumerated above can be put under good phenomenological control as discussed in Ref. [14], the EM distortion of π^+/π^- ratios can be used to estimate the pion creation time. For fast pions, the latter appears of the order of $0.5 < \tau < 2$ fm/c, significantly shorter than for centrally produced pions discussed in point 3 above. This suggests a picture of "hotter" matter (with a longer lifetime) created in the centre and "streams" of "colder" matter (with a shorter lifetime) propagating at high forward and backward rapidities.

While the picture formulated above is far from being complete and remains subject to modification with the influx of new experimental data, some of its basic aspects can already be pointed out. This will be made in the following section.

4. Implications for the longitudinal evolution of the system

A simple phenomenological picture in which the decrease of the distance from the pion formation zone to the spectator system, Fig. 3 (c), appears as a purely natural effect, has been proposed in 2017 [17]. It is presented in Fig. 4. It postulates the formation of longitudinal "streams" of partonic matter emitting pions according to a uniform fragmentation function and

basically following local energy-momentum conservation. While the definition of the exact nature of these "streams" is by no means necessary for the model, we note that assuming them as conglomerates of colour strings seems natural to us. While the general similarity of this picture to the much older "fire-streak" scheme [18–23] has been rapidly pointed out, it should be underlined that the latter remains at best very partial as the same similarity is present, in our view, with respect to any phenomenological model containing explicit local energy-momentum conservation on the 1×1 fm^2 scale in the transverse plane of the collision.

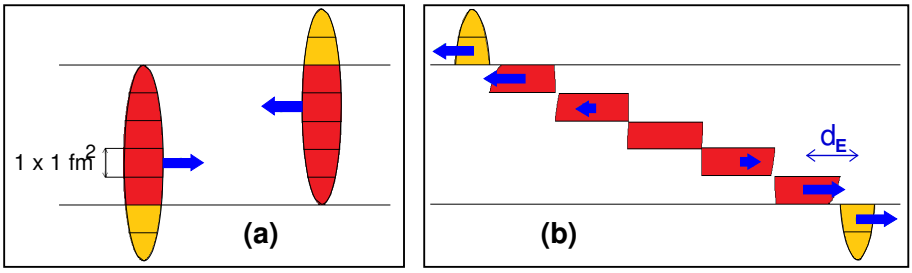


Fig. 4. Model of the Pb+Pb reaction (a) before and (b) after the collision [13, 17].

The comparison of the model constructed on the basis of the above picture to experimental data brought, up to now, the following conclusions:

1. The centrality dependence of rapidity spectra of π^- mesons produced in Pb+Pb collisions at $\sqrt{s_{NN}} = 8.8$ and 17.3 GeV [24] can be understood as a direct consequence of local energy-momentum conservation. This is shown in Fig. 5. Both the absolute pion yield and the change of shape of the pion rapidity distribution as a function of impact parameter can be described by our model using a single fragmentation function for the longitudinal element ("fire-streak") of excited partonic matter.

2. This function (see Ref. [25] for its algebraic parametrization), characteristic for the "stream" of matter created at a given collision energy, describes the shape of the pion rapidity distribution not only for Pb+Pb but also for p+p collisions. Indeed, as it was discovered subsequently to the study of Pb+Pb collisions [17], the "fire-streak fragmentation function" matches the shape of the spectrum of pions measured in inclusive inelastic p+p collisions at the same value of $\sqrt{s_{NN}}$ [26, 29], with no further modification nor adjustment to experimental data. An example is shown in Fig. 5 (d). As it has been demonstrated in Ref. [25], the difference in normalization between p+p and Pb+Pb collisions can be directly calculated, in a model-independent way, as a

consequence of the different energy balance in the two reaction types. This brings the conclusion that a single "stream" of excited matter, with specific properties similar to the multiple "streams" formed in Pb+Pb collisions, could form in p+p reactions.

3. The same phenomenological approach is successful in the description of the transition between proton–proton and asymmetric proton–carbon reactions, demonstrating that the asymmetry of the pion spectrum in the latter with respect to mid-rapidity is again a direct consequence of energy-momentum conservation. We leave the demonstration of this fact to a separate paper.

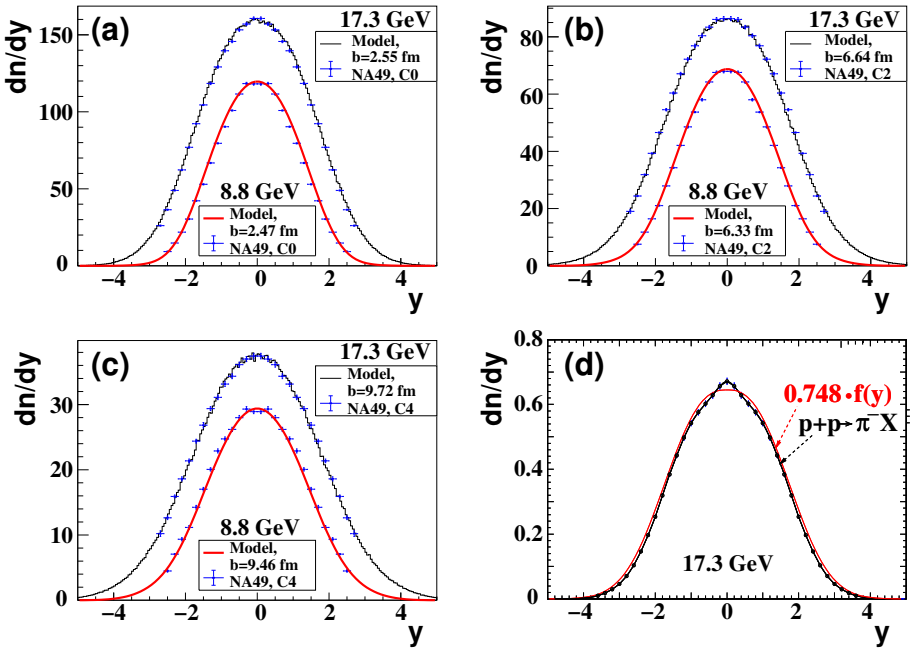


Fig. 5. Description of experimental data on π^- production by the model described in the text, for (a) central, (b) intermediate, and (c) peripheral Pb+Pb reactions at two energies, $\sqrt{s_{NN}} = 8.8$ and 17.3 GeV, put together with description of experimental p+p data at $\sqrt{s_{NN}} = 17.3$ GeV by the fragmentation function described in the text, scaled by a factor 0.748. The experimental data shown come from Refs. [24, 26]. The black model histogram comes from Ref. [17]. Panels (a)–(c) are redrawn from Ref. [27] and panel (d) from Ref. [28].

Thus, as it emerges from the above, at least in the energy regime of $8.8 \leq \sqrt{s_{NN}} \leq 17.3$ GeV quite simple a picture seems to be valid for the longitudinal space-time evolution of the system and of charged pion production, largely given by pure local energy-momentum conservation as drawn in Fig. 4. This picture provides a natural explanation for the change of pion creation time from centrally to forward produced pions discussed in point 6 in Sec. 3, because faster pions will be produced from faster and, consequently, less excited "streams" of matter, characterized by a lower invariant mass (see Ref. [17] for comparison). This situation is quantitatively illustrated in Fig. 6. We note apropos that the latter energy regime corresponds, following the claims made in Refs. [30–32], to the range of $\sqrt{s_{NN}}$ closely above the onset of deconfinement in heavy-ion collisions and where presently speculations are made about possibly similar phenomena occurring in proton–proton reactions [33, 34]. To what extent is a similar, simple picture of the longitudinal evolution of the system valid *below* the energy of the onset of deconfinement remains evidently to be clarified, following the availability of experimental data on particle spectra and electromagnetic effects.

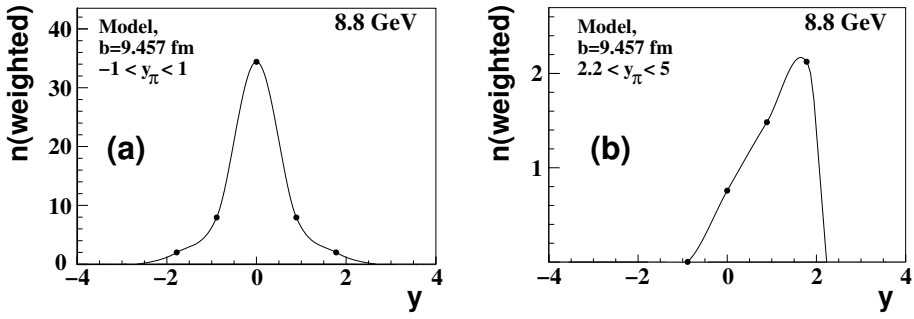


Fig. 6. Distributions of rapidity of the longitudinal "streams" of excited matter drawn in Fig. 4, modelled for the case of peripheral Pb+Pb collisions at $\sqrt{s_{NN}} = 8.8$ GeV for streams contributing to the production of (a) central and (b) forward-moving pions. Both distributions are weighted by the number of pions emitted from each stream. The solid line is drawn to guide the eye.

5. Discussion

Two remarks should be made following what has been said above.

The first remark concerns the obvious limitations of the simple picture of the space-time evolution of the system in the longitudinal direction formulated in Sec. 4. While this picture provides quite natural explanations for several characteristics of pion emission in the longitudinal direction (including a first fully quantitative description of the relatively complicated

structure induced by EM effects in Fig. 1 [14]), it evidently provides no explanation for the change in the energy balance between proton–proton and nucleus–nucleus reactions. This subject is discussed in detail in Ref. [25], where the latter change, connected to baryon stopping and strangeness enhancement phenomena, had to be estimated (with good accuracy) directly from experimental data.

A particularly important aspect of the latter problem is the strong modification of baryon spectra in nucleus–nucleus with respect to p+p collisions (the "nuclear stopping power" [35]). This seems for now inconceivable to be explained in the pure framework of the model from Fig. 4. Account taken that (net) baryon emission is an important probe of the longitudinal evolution of the system also in configuration space [36], it is clear that a more general, dynamical picture with rigorous treatment of momentum conservation, can strengthen and concretize the simple picture formulated above. Here, a significant effort has been undertaken on the basis of modern experimental baryon data [37].

The second remark concerns the applicability of ideas formulated above to processes other than "classical" heavy-ion collisions. Following an idea we worked out together with Antoni Szczurek and Mariola Kłusek-Gawenda, and as a direct consequence of the fact that the spectator EM field carries independent information on the space-time evolution of the process, it would be interesting to investigate the possible distortions of longitudinal spectra of leptons produced in ultra-peripheral collisions of the type Pb+Pb $(\gamma\gamma) \to l^+l^-$ [38–40], induced by the long-term action of the electromagnetic field. This option was considered by us as purely hypothetical up to the present moment, but is now entering into consideration as a consequence of the planned upgrade of the LHCb experiment [41]. This issue will be elaborated upon elsewhere [42].

6. Summary and conclusions

Electromagnetic effects induced by the spectator charge on trajectories of particles produced in non-central ultrarelativistic nucleus–nucleus collisions bring new, independent information on the space-time evolution of the created system. Our studies of these effects uncover the decrease of the longitudinal distance between the pion formation zone and the spectator system at the moment of pion formation, as a function of pion rapidity.

On that basis, a simple picture of the longitudinal evolution of the system was formulated, which provides a natural explanation for the centrality dependence of total yields and rapidity distributions of pions produced in the collision. The same picture establishes a link between p+p and nucleus–nucleus collisions, at least in the energy range of $8.8 \leq \sqrt{s_{NN}} \leq 17.3$ GeV,

which in heavy-ion reactions corresponds to deconfined matter following the claims made by the NA49 Collaboration. In this energy range, the highly energetic participant matter would evolve in longitudinal "streams", with different excitation energies and rapidities. This would result in shorter pion creation times for faster pions, and longer creation times for slower pions.

This space-time picture provides the first ever quantitative description of experimental data on spectator-induced electromagnetic effects on fast pions, emitted in peripheral heavy-ion collisions at $\sqrt{s_{NN}} = 17.3$ GeV as a function of x_{F} and p_{T}. The verification of this picture at lower and higher collision energies, and the application of electromagnetic distortions as a new source of information on other physical phenomena, are interesting topics for the future studies.

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