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STRONG AND ELECTROMAGNETIC COLLECTIVE EFFECTS FROM NA61/SHINE*

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This contribution presents new NA61/SHINE results on collective effects, including spectator-induced electromagnetic (EM) phenomena in charged pion emission in collisions at beam momentum of $150A$ GeV/c as well as directed flow for protons and charged pions as a function of transverse momentum and centrality in Pb+Pb collisions at $30A$ GeV/c. EM effects bring new, independent information on the space-time properties of the system. They may also suggest presence of the fast-moving participant charge close to the spectator system, as well as relatively fast spectator decay. The results on the directed flow at CERN SPS energies are complementary to STAR results and provide a bridge to FAIR and NICA energies. A specific picture of the longitudinal evolution of the system at CERN SPS energies emerges, where the centrality dependence of pion rapidity spectra is governed predominantly by the simple energy-momentum conservation and the collision geometry.

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1. Introduction

The main focus of the NA61/SHINE programme of studies of strongly interacting matter via a two-dimensional beam momentum and system size scan are central collisions [1, 2]. In recent years, however, new additions to the programme emerged which concentrate on non-central collisions, where specific collective effects appear.

This work first discusses charge asymmetries in pion production caused by modification of charged pion trajectories by electromagnetic fields generated by charged spectators [3]. The size of the effect depends on the strength

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of EM fields, so on the one hand, on the size of the spectator (its total electric charge and the charge distribution in configuration space) and, on the other hand, on the distance between the spectator system and the point (zone) of pion emission (decoupling from the medium governed by the strong interaction). In this way, spectator-induced EM effects bring information on the space-time properties of the collision and can also shed light on spectator fragmentation at CERN SPS energies [4].

The next subject is anisotropic flow in Pb+Pb collisions which is associated primarily with the strong interaction, although as will be shown, it may be also affected by the above-mentioned EM effects. The new NA61/SHINE results extend existing NA49 data [5]. They are complementary to STAR results [6] from the beam energy scan at RHIC providing data in the forward rapidity region. Lastly, they provide a bridge to FAIR and NICA energies.

The last part of the paper focuses on the longitudinal evolution of the system. A specific picture emerges, which can be connected to both observations addressed above.

2. Spectator-induced EM effects on charged pion ratio

2.1. Experimental results

Due to attraction of negative and repulsion of positive pions by the positively charged spectator system, a depletion of the π^+/π^- yields ratio appears for pions which are nearly co-moving with the spectator system (*i.e.* have rapidity close to the beam rapidity and small transverse momentum). This phenomenon was first observed at CERN SPS in Pb+Pb collisions by NA52 [7] and, much more precisely, the NA49 experiment [8]. The effect is shown in the left panel of Fig. 1 as a function of x_{F}[1] for several values of transverse momentum. One can notice that in this case, where the spectator charge $Q \approx 70$, the EM effect is very large, driving the π^+/π^- ratio to almost zero near beam rapidity.

New NA61/SHINE results [9] on the π^+/π^- ratio at the top CERN SPS beam momentum in intermediate centrality Ar+Sc and central Ar+Sc collisions are shown, respectively, in the middle and right panels of Fig. 1. Comparing intermediate centrality Ar+Sc to the Pb+Pb results, one can observe a much smaller EM effect than in peripheral Pb+Pb (expected since spectator charge $Q \approx 8$, thus almost 9 times smaller than for Pb+Pb collisions), but still large enough to break the isospin symmetry. The minimal value of the ratio allowed by the isospin symmetry, calculated as the ratio of numbers of protons to neutrons in the $^{40}_{18}$Ar nucleus, is $\pi^+/\pi^- \approx 0.8$, while the measured values go down to $\pi^+/\pi^- \approx 0.6$. It should be noted that this

[1] Feynman variable $x_{\mathrm{F}} = p_{\mathrm{L}}/p_{\mathrm{beam}}$, where p_{L} is pion longitudinal momentum and p_{beam} is the beam longitudinal momentum, both in collision centre-of-mass system.

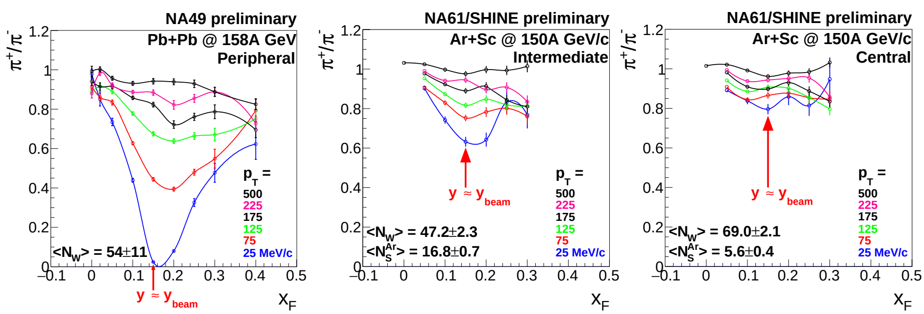

Fig. 1. New NA61/SHINE results [9] on the π^+/π^- ratio at the top CERN SPS beam momentum as a function of x_F for several values of transverse momentum, in intermediate centrality Ar+Sc and central Ar+Sc collisions (middle and right) compared to peripheral Pb+Pb collisions [8] (left). Only statistical uncertainties are shown.

is the first observation of the spectator-induced EM effect in such a small colliding system. Lastly, although in central Ar+Sc the spectator charge is only $Q \approx 3$, one cannot exclude that a 'shadow' of the EM effect is visible, since the characteristic p_T dependence of the π^+/π^- ratio seems to be preserved and the minimum (although not breaking the isospin symmetry) seems to be located at the beam rapidity.

2.2. Phenomenological description

In order to describe the EM effects in Pb+Pb collisions, a phenomenological model [3] was developed in which pions are produced at a distance d_E from the spectator system (Fig. 2, top, left), uniformly in the azimuthal angle and with longitudinal and transverse momentum distributions derived from $p+p$ collisions data. In this model, spectators are modelled as homo-

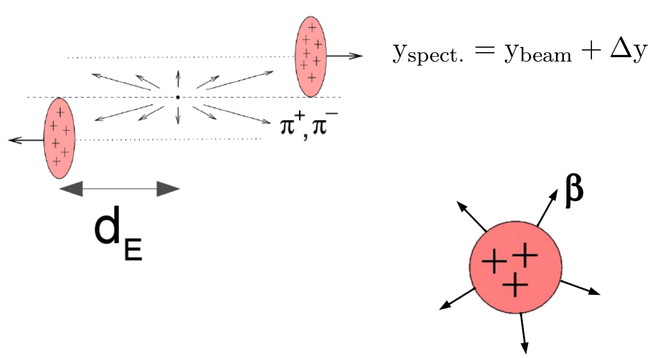

Fig. 2. Sketch of improvements (see the text) to the original model [3] of spectator-induced electromagnetic effects in ultrarelativistic nuclear collisions.

geneously charged spheres (in their rest frames) moving with beam rapidity. While this model was sufficient to explain the bulk of the large EM effect observed in Pb+Pb collisions, it fails for Ar+Sc collisions. This is shown by solid (red) curves in Fig. 3, where model calculations for two values of pion emission distance, $d_{\mathrm{E}} = 0.75$ fm describing optimally peripheral Pb+Pb collisions (top panel) and a smaller value $d_{\mathrm{E}} = 0.25$ fm (middle and bottom panels), are compared to the lowest p_{T} (the largest EM effect) results on the π^+/π^- ratio in the intermediate centrality Ar+Sc collisions.

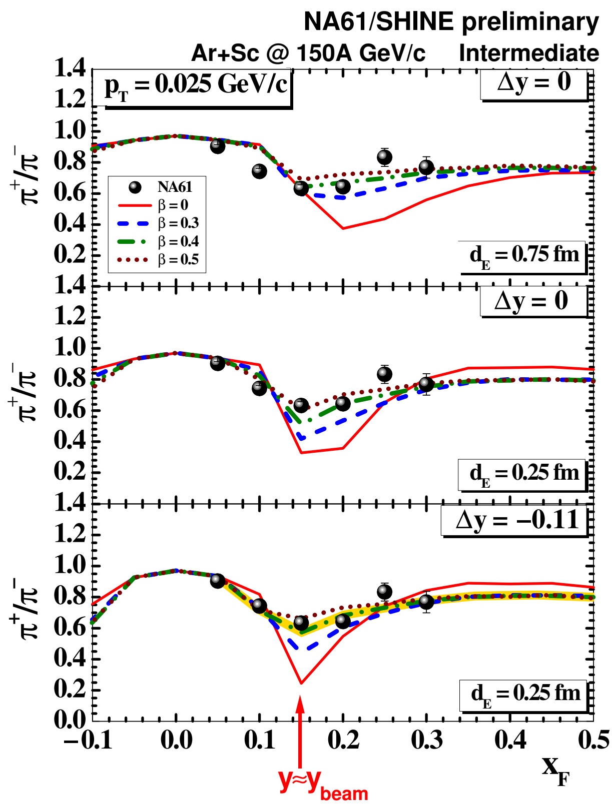

Fig. 3. (Colour on-line) 'Fitting' of the improved model [9] of spectator-induced electromagnetic effects in ultrarelativistic nuclear collisions to the lowest p_{T} (the largest EM effect) results on the π^+/π^- ratio in the intermediate centrality Ar+Sc collisions (lowest lying points in the middle plot in Fig. 1). Different lines represent different values of the β parameter, top panel differs in d_{E} from two others, while the bottom panel differs in Δy from the top and the middle. The model calculation associated with combination of parameters judged to be optimal is highlighted with thick light grey/yellow line in the bottom panel.

A better description of the experimental data is obtained if one allows for a 'decay' of the spectator — it is still modelled as a homogeneously charged sphere in each moment, but now it expands radially with a surface velocity β in its rest frame (Fig. 2, bottom right). In this way, time-averaged EM field which pions 'feel' is smaller and, consequently, the depletion of π^+/π^- ratio is reduced compared to the non-expanding spectator scenario. From Fig. 3, it is visible that significant expansion velocities — $\beta \geq 0.4$ — are needed to come close to the data points.

Yet better description is possible if the expanding charge sphere moves with a rapidity slightly smaller than the beam rapidity, expressed by a parameter $\Delta y = -0.11$. The calculation corresponding to the optimal set of the 3 model parameters is highlighted with the thick light grey/yellow line in the bottom panel of Fig. 3. Our tentative physical interpretation is that the observed effect is a superposition of the actual spectator system behaviour and that of participant charge present in the spectator vicinity. The effective charge cloud made of the two contributions will have its average rapidity lower than that of the spectator system and it will effectively expand both in the longitudinal and transverse directions.

As a result of the above analysis, one can put the optimal value of $d_{\mathrm{E}} = 0.25 \pm 0.25$ fm for intermediate centrality Ar+Sc collisions in the context of earlier results [10] obtained for Au+Au [6] and Pb+Pb [10, 11] collisions. This is visualised in Fig. 4. The earlier results were deduced from the π^+/π^- ratio as well as from EM splitting of the directed flow, which will be further discussed in Sect. 3. A trend is visible in which fast pions are decoupling from

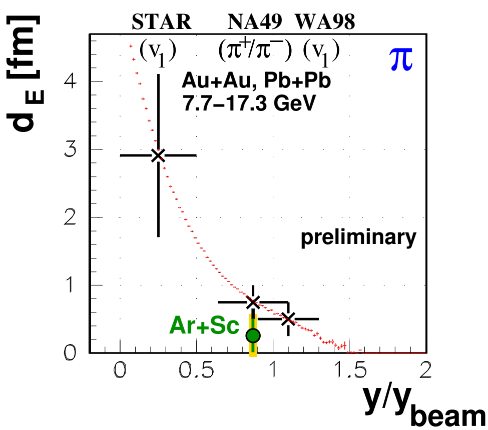

Fig. 4. Dependence of the distance d_{E} between pion emission point and the spectator system on pion rapidity. Au+Au and Pb+Pb points come from analysis of experimental data from Refs. [6, 10, 11]. The new NA61/SHINE Ar+Sc point [9] corresponds to optimal description of π^+/π^- ratio in the intermediate centrality Ar+Sc collisions.

the strongly interacting medium (freezing-out) close behind the spectator system. A picture of the heavy-ion collision in which this situation is natural will be discussed in Sect. 4.

3. Directed flow

In non-central heavy-ion collisions, initial asymmetry in the coordinate space of the collision is transformed by multiple strong interactions into momentum asymmetry for final-state particles. The measure of this effect are anisotropic flow coefficients

$$v_n = \langle \cos(n(\varphi - \Psi_{\mathrm{RP}})) \rangle \,, \tag{1}$$

which are coefficients of the Fourier series expansion of the single particle spectrum in the azimuthal angle φ with respect to the symmetry (reaction) plane of the initial geometry.

One of difficulties of this analysis is estimation of the reaction plane orientation Ψ_{RP}. In the NA61/SHINE experiment, it is possible [12] with spectators detected in the Projectile Spectator Detector — a forward hadron calorimeter used also for centrality determination. An advantage of our experiment is that in a fixed target setup, tracking and particle identification is possible in a wide rapidity range as opposed to midrapidity in collider experiments. In this sense, new NA61/SHINE results on the anisotropic flow are complementary to the STAR data [6] from the RHIC beam energy scan.

The first flow coefficient v_1, directed flow, is shown in Fig. 5 (left) for charged pions and protons as a function of transverse momentum for 15% to 35% centrality class of Pb+Pb collisions at $30A$ GeV/c beam momentum. First, a significant mass dependence is apparent. Second, for pions charge splitting is visible, which is reminiscent of that observed earlier in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV [6] (right panel of Fig. 5). While the bulk of the directed flow comes from the strong interaction, this charge splitting in Au+Au collisions can be attributed to the spectator-induced electromagnetic effects [13].

Another result for the directed flow is its slope in dependence on rapidity, at midrapidity. It is depicted in Fig. 6 for charged pions and protons as a function of centrality estimated with energy deposited in PSD calorimeter again in Pb+Pb collisions at $30A$ GeV/c beam momentum. Again, significant mass dependence is clearly visible, with the slope for protons changing the sign at about 50% centrality.

In hydrodynamic models, rapidity dependence of the directed flow which yields non-zero values of the slope in midrapidity, comes from 'tilted source' initial conditions [14]. Such conditions happen to be natural within a picture of heavy-ion collisions discussed in the next section.

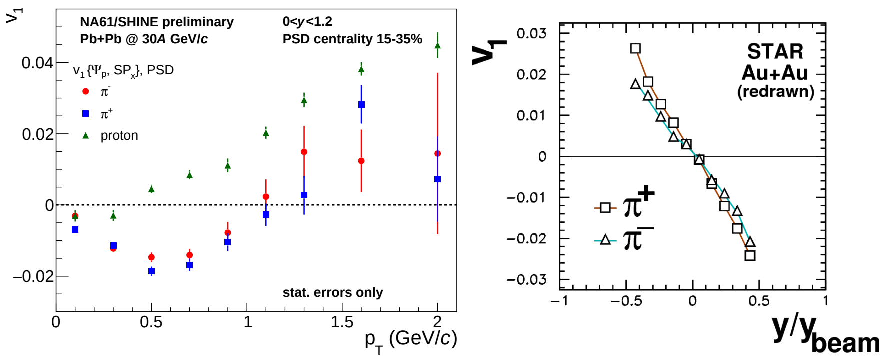

Fig. 5. Directed flow of charged pions and protons as a function of transverse momentum for 15% to 35% centrality class of Pb+Pb collisions at 30A GeV/c beam momentum [12] (left) possibly showing charge splitting of the flow for pions, sensitive to spectator-induced electromagnetic effects, first observed in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV [13] (right; original data from Ref. [6]). Only statistical uncertainties are shown.

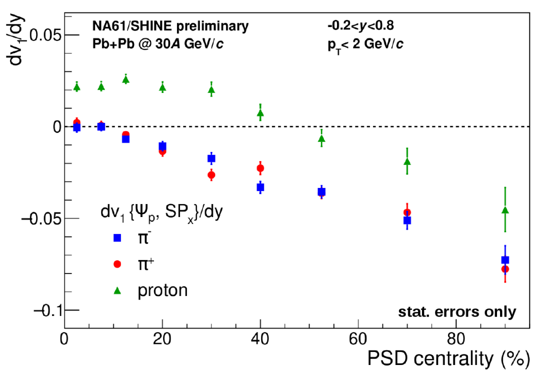

Fig. 6. Slope of directed flow at midrapidity for charged pions and protons as a function of centrality estimated with energy deposited in PSD calorimeter in Pb+Pb collisions at 30A GeV/c beam momentum. Only statistical uncertainties are shown.

4. Longitudinal evolution of the system

Figure 7 shows a sketch of the picture of ultrarelativistic heavy-ion collisions proposed in Ref. [15]. We note that in specific aspects, the latter approach has some similarity to the fire streaks model of Refs. [16, 17]. Before the collision (top panel), nuclei are considered continuous 3D distributions of matter, divided into bricks of 1 fm^2 transverse size. These bricks collide and form fire streaks (bottom), with kinematical properties given by local energy-momentum conservation, *i.e.* imposed for each colliding brick pair as opposed to imposing it for the whole nuclei.

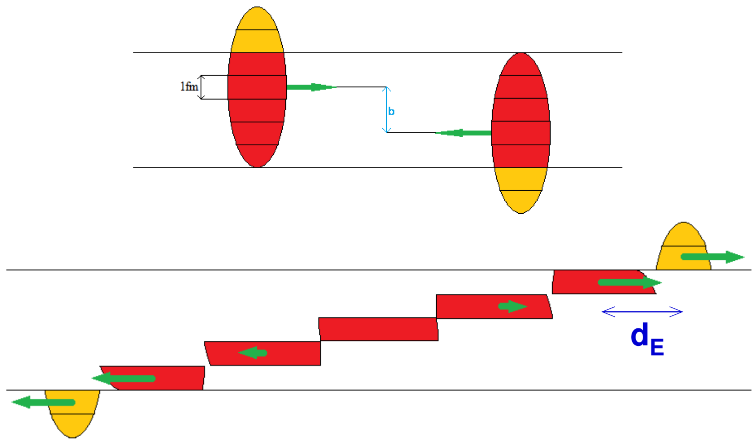

Fig. 7. Sketch of the model of ultrarelativistic heavy-ion collisions proposed in Ref. [15] before the collision (top) and after the collision (bottom). d_{E} illustrates the correspondence between this model and spectator-induced electromagnetic effects in charged pion emission, which were its original motivation (see Fig. 4).

The final ingredient of the picture is that each fire streak fragments into pions independently of the other fire streaks, contributing

$$\frac{\mathrm{d}n}{\mathrm{d}y} = A\left(E_{\mathrm{s}}^{*} - m_{\mathrm{s}}\right) \exp\left(-\frac{\left[(y-y_{\mathrm{s}})^2 + \epsilon^2\right]^{\frac{r}{2}}}{r\sigma_y^r}\right) \tag{2}$$

to the overall pion rapidity distribution, where y_{s} is the fire streak rapidity, E_{s}^{*} its invariant mass, m_{s} sum of masses of the two colliding bricks (to account for the baryon number conservation) and A, ϵ, r, σ_y are free parameters fitted to the data.

It should be noted that while originally this model was motivated by the observation that fast pions are produced close to the spectator system (Sect. 2.2, Fig. 4), it also naturally provides

— the 'tilted source' initial conditions which may lead to observed rapidity dependence of the directed flow in Pb+Pb collisions (Sect. 3), and

— fast-moving participant charge in spectator vicinity (see Fig. 7), possibly affecting EM effects in Ar+Sc (Sect. 2) and Pb+Pb [4] collisions.

As shown in Ref. [15] for Pb+Pb collisions at 158A GeV/c beam momentum, once this model is fitted to pion rapidity spectra at a given centrality, it can predict the whole centrality dependence of pion rapidity spectra both in terms of the yield and change of the shape. Recently, the study was extended to Pb+Pb collisions at $40A$ GeV/c beam momentum [18]. Figure 8 illustrates how well the fire streaks model describes centrality dependence of the shape of pion rapidity spectrum in Pb+Pb collisions at $158A$ GeV/c beam momentum (left) and $40A$ GeV/c beam momentum (right). In both cases, experimental data come from Ref. [19] and are scaled to the same peak height so that visual shape comparison is possible. In both cases, the most peripheral sample is compared to the most central one.

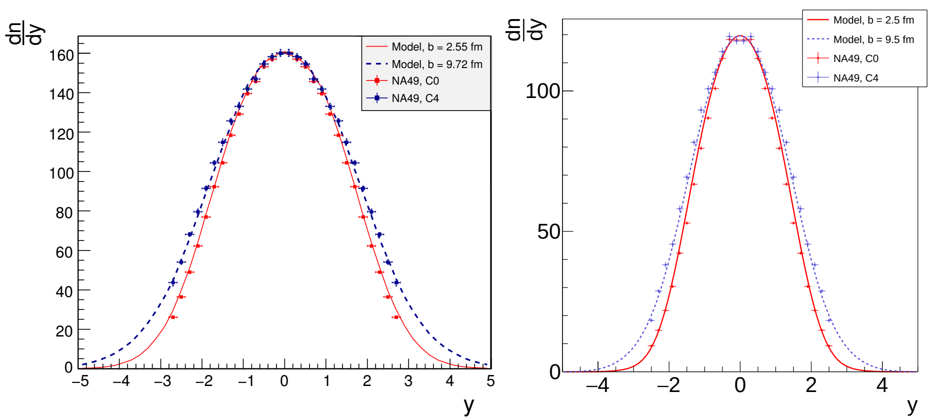

Fig. 8. Change of width of the π^- rapidity distribution from peripheral to central Pb+Pb collisions described by the fire streaks model for collisions at $158A$ GeV/c beam momentum (left; plot from Ref. [15]) and at $40A$ GeV/c beam momentum (right; plot from Ref. [18]). In both cases, experimental data come from Ref. [19] and are scaled to the same peak height so that visual shape comparison is feasible.

From this follows that *centrality dependence* of the longitudinal evolution of the system at CERN SPS energies, at least in the range of beam momenta $40A$ GeV/c to $158A$ GeV/c, is governed mainly by the somewhat trivial energy-momentum conservation and collision geometry — no non-trivial dynamical effects appear in fact necessary. Still such effects contribute to the fire streak fragmentation function, which is completely *ad hoc* in the model, although remarkably it turns out to correspond to the pion rapidity spectrum in $p + p$ collisions at the given energy [18].

It should be noted that with rapidity spectra measured by NA61/SHINE in many colliding systems within the two-dimensional beam momentum and system size scan [20], the study of the longitudinal evolution of the system can be extended to the variety of colliding systems and also to particles other than pions.

5. Summary and conclusions

New, preliminary results on collective effects are now available from the NA61/SHINE experiment. This includes the first observation of the spectator-induced electromagnetic effects in charged pion emission in small systems (Ar+Sc collisions) at the top CERN SPS energy. These lead to the improvement of phenomenological modelling of EM effects, providing new, independent information on the space-time properties of the system and suggesting the presence of a fast-moving participant charge in the spectator vicinity.

Furthermore, directed flow results for protons and charged pions as a function of p_{T} and centrality in Pb+Pb collisions at $30A$ GeV/c beam momentum were presented. They may be indicative of a charge splitting of the directed flow for pions due to spectator-induced electromagnetic effects. Thanks to broad rapidity acceptance, these results are complementary to studies performed in collider experiments at similar energies.

Motivated by the described results, a specific picture of the longitudinal evolution of the system at CERN SPS energies emerges, called in the present paper the fire streaks model. Within this picture, the centrality dependence of pion rapidity spectra is governed predominantly by the energy-momentum conservation and the collision geometry. Plethora of measurements available within the two-dimensional scan conducted by the NA61/SHINE experiment will allow to extensively test this model, yielding new information on the longitudinal evolution of the system as a function of its size and collision energy.

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