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RECENT RESULTS ON SPECTATOR-INDUCED ELECTROMAGNETIC EFFECTS IN ULTRARELATIVISTIC LIGHT- AND HEAVY-ION COLLISIONS*

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We review our studies of spectator-induced electromagnetic (EM) effects on charged pion emission. For heavy-ion Pb+Pb and Au+Au reactions, we formulate a model which associates the size of EM effect with the space-time properties of the system of hot and dense matter formed in the collision. The first observation of the spectator-induced EM distortion of the π^+/π^- ratio in small systems at the CERN SPS allows the extension of our study to Ar+Sc collisions at $\sqrt{s_{NN}} = 17.3$ GeV. We improve our model description to take into account spectator fragmentation as well as the possible influence of the net positive participant charge close to the spectator system. This brings new information on the space-time evolution of pion production in small systems, and on the other hand, allows us to study the interplay between spectator fragmentation and electromagnetic phenomena also in ultrarelativistic heavy-ion collisions. A consistent picture of the space-time evolution of all the studied systems emerges, where the longitudinal evolution of the hot and dense matter created in the participant zone results in faster pions being produced closer to the spectator system.

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1. Introduction

In non-central ultrarelativistic ion collisions, charged spectator systems are torn off the colliding ('participating') parts of the nuclei. These systems generate electromagnetic fields which modify the trajectories of final-state charged particles emitted from the participant region. Since oppositely charged particles are oppositely affected, charge asymmetries arise in

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distributions of produced particles. These spectator-induced electromagnetic effects can be used as a new source of information on the space-time evolution of the system [1].

2. First results on spectator-induced EM effects: simple model

The spectator-induced EM effects were first observed more than 20 years ago in minimum bias Pb+Pb collisions at CERN SPS [2]. Twelve years later, in 2011, much more precise measurements were performed by the NA49 experiment in peripheral Pb+Pb collisions at CERN SPS [3] following quantitative model predictions given in 2007 by some of us [4]. The predicted and observed EM distortion (see experimental data points in Fig. 4) is visible as a strong depletion of the π^+/π^- ratio for pions at small transverse momenta and near-beam rapidity, *i.e.* nearly co-moving with the spectator system.

The model [4] used to give the first quantitative description of this effect is sketched in the top left part of Fig. 1. It assumes a point-like source of pions at a distance d_{E} from the spectator system, which emits particles with distributions motivated by the experimental $p+p$ collisions data. The spectator system in its centre of mass is modelled as a uniformly charged, static sphere, moving away from the emission point with beam rapidity in the collision centre-of-mass system.

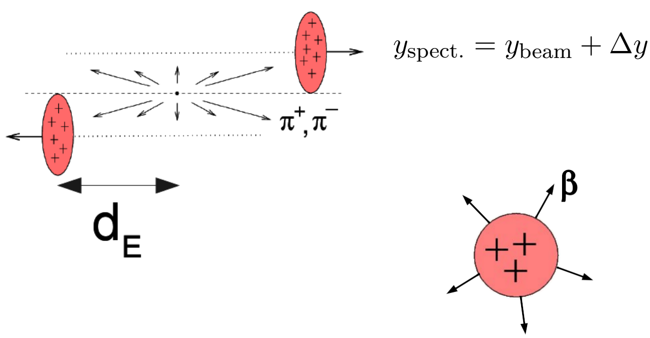

Fig. 1. Sketch of the model of spectator-induced electromagnetic effects used to describe Ar+Sc collisions, taking into account spectator expansion and possible net positive participant charge close to the spectator system [5, 6], based on the original model of [4] initially used for Pb+Pb collisions.

While this simple model is unable to reproduce quantitatively the details of the EM distortion, it catches its bulk properties and proves that the EM effect is sensitive to the space-time properties of the collision (only a limited range of d_{E} values can be considered to give a reasonable description of the π^+/π^- ratio) [3, 4]. Augmenting the observations by the results on the directed flow v_1 in Au+Au [1, 7] and Pb+Pb [8] collisions, one arrives at the conclusion that faster pions are produced closer to the spectator system [9].

3. Ar+Sc: taking into account spectator expansion

Recently new preliminary NA61/SHINE results on π^+/π^- ratio in intermediate centrality and central Ar+Sc collisions at the top CERN SPS energy were presented [5, 6]. Focusing at the intermediate centrality, where the spectator charge is about 10 times smaller than in peripheral Pb+Pb collisions, but the EM effect is still large enough to break the isospin symmetry, one observes that the simple model of Sec. 2 is insufficient. An improved model, taking into account spectator expansion and possible net positive participant charge close to the spectator system is sketched in Fig. 1.

In this version, the spectator system in its centre-of-mass is modelled as a uniformly charged sphere, which expands with surface velocity β. The possible net participant charge is modelled by a reduced charged sphere rapidity in the collision centre-of-mass system, compared to the beam rapidity.

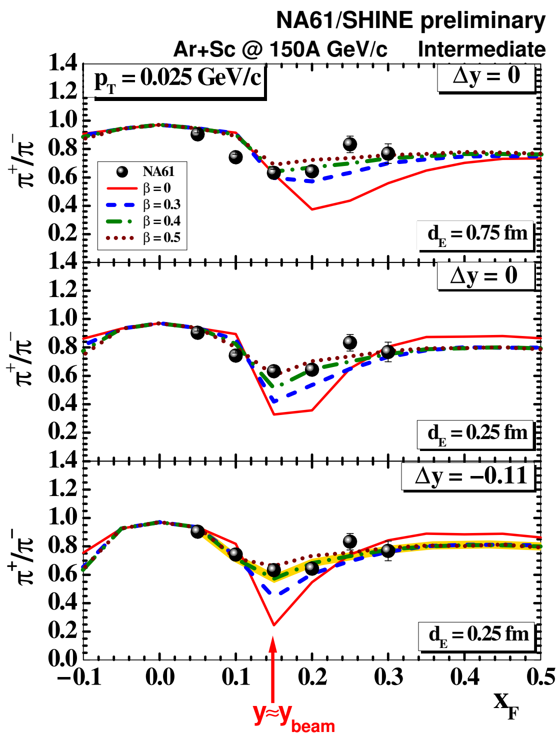

Fig. 2. (Colour on-line) 'Fitting' of the improved model [5] of spectator-induced electromagnetic effects in ultrarelativistic nuclear collisions to the lowest p_{T} (the largest EM effect) results on the π^+/π^- ratio in the intermediate centrality Ar+Sc collisions. Figure taken from [6]. The model calculation judged to be optimal is the one highlighted with thick light grey/yellow line in the bottom panel (see legends and the text for the parameters).

The 'fitting' of this model to the experimental data in the lowest p_{T} bin of the intermediate centrality Ar+Sc collisions at the top CERN SPS energy is shown in Fig. 2. The figure shows different combinations of the three model parameters (d_{E}, β, Δy). Clearly, lack of the spectator expansion yields a too strong EM effect. An optimal description is reached with a large expansion velocity $\beta = 0.4$ of the charge cloud. This demonstrates the sensitivity of the EM effects to the space-time evolution of the spectator system discussed further in Ref. [10]. While the optimal set of parameters suggests existence of some amount of participant charge near the spectator system, this effect is definitely much weaker than the previous one.

4. Back to Pb+Pb collisions: fire streaks

The simple model discussed in the previous sections has one major simplification, namely point-like source of pions. In this context, the space-time properties of the system expressed by the d_{E} parameter are averaged over the whole emission (freeze-out) hyper-surface. Recently, EM modelling was extended to remedy this problem [12].

The improved model, sketched in Fig. 3, is built upon a specific version of the fire streaks picture [11], which was inspired by the observation mentioned in Sec. 2, that faster pions are produced closer to the spectator system. In this model, colliding nuclei are considered as continuous 3D mass distributions sliced in the transverse plane into bricks. The bricks collide forming fire streaks with their kinematical properties given by the local (*i.e.* independently for each colliding bricks pair) energy-momentum conservation. It is assumed that each fire streak fragments independently into pions with the same rapidity distribution in the fire streak's centre-of-

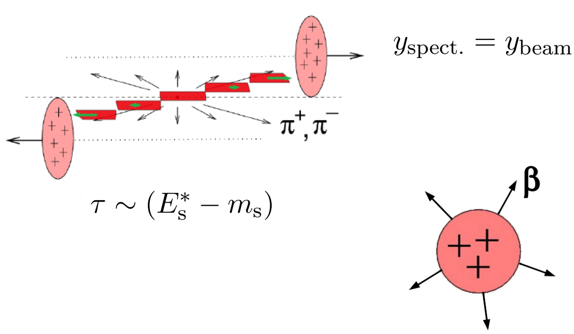

Fig. 3. Sketch of the model of spectator-induced electromagnetic effects built on top of the fire streaks model [11], used to improve description of Pb+Pb collisions, taking into account spectator expansion [12].

mass frame, weighted by the production energy ($E^*_\mathrm{s} - m_\mathrm{s}$) of the fire streak ($E^*_\mathrm{s}$ is the invariant mass of the fire streak, while m_s is the sum of brick masses). All parameters of the single-fire-streak rapidity distribution were earlier fitted to the Pb+Pb collisions data [13]. The transverse momentum spectrum is motivated by the one found for pions in UrQMD 3.4 for the considered reaction. The final ingredient is the proper time τ at which the fire streak fragments into pions, which corresponds to the distance between the pion emission point and the spectator system. It is assumed to depend linearly on the fire-streak production energy ($E^*_\mathrm{s} - m_\mathrm{s}$) (more energetic fire streaks live longer in their centre-of-mass frame). This linear dependence gives 2 free parameters that need to be fitted to the data. The third one is the spectator expansion velocity β.

Figure 4 shows the 'fitting' of this model to the data in the two lowest p_T bins of the peripheral Pb+Pb collisions at the top CERN SPS energy. It is compared to the model of Sec. 2 (dash-dotted green line) and of Sec. 3 (dotted brown line). It is clear that only the new model with relatively short fire streak fragmentation proper times of up to 2 fm/c and a spectator expansion velocity $\beta = 0.2$ is able to provide a quantitative description of the experimental points for fast pions ($x_\mathrm{F} \geq 0.1$).

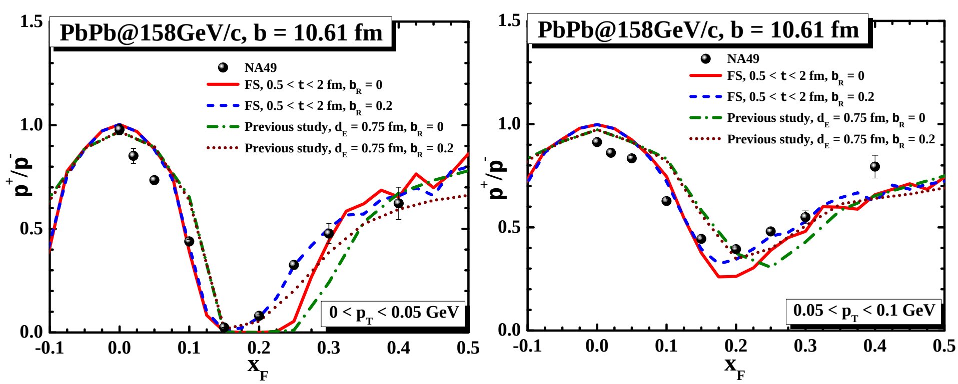

Fig. 4. (Colour on-line) 'Fitting' of the fire-streaks-based model [12] ('FS') of spectator-induced electromagnetic effects in ultrarelativistic nuclear collisions to the two lowest p_T (the largest EM distortions) results on the π^+/π^- ratio in the peripheral Pb+Pb collisions [3]. It is compared to calculations within the model ('Previous study') used in Sec. 3 to describe Ar+Sc collisions. The model calculation judged to be optimal is the one depicted with dashed blue line (see legends for the parameters).

5. Summary and conclusions

The presence of EM fields in the light- and heavy-ion collision results in charge-dependent effects on various observables. These effects are sensitive to the distance d_{E} between the pion emission site and the spectator system. The study of Pb+Pb, Au+Au and Ar+Sc collisions leads to a consistent picture of the space-time evolution of all these systems, where the longitudinal evolution of the hot and dense matter created in the participant zone results in faster pions being produced closer to the spectator system. The use of this fire streaks model [11] in EM simulation visibly improves the quantitative agreement with the experimental data.

Contrary to the large effect in peripheral Pb+Pb collisions, the moderate EM distortion in the intermediate centrality Ar+Sc collisions can only be described if spectator fragmentation is taken into account. This points to the conclusion that EM effects are also sensitive to the space-time evolution of the spectator system [10].

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