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Recent results on spectator-induced electromagnetic effects in ultrarelativistic light- and heavy-ion collisions

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This paper focuses on studies of spectator-induced electromagnetic (EM) effects on charged pion emission observed for three different colliding systems: Pb+gas, peripheral Pb+Pb and Ar+Sc collisions at CERN SPS energies. New data on Ar+Sc collisions from the NA61/SHINE experiment bring a first insight into EM effects in small systems. In this paper, we present the improvement of our phenomenological model description which takes into account spectator fragmentation as well as the possible influence of the net positive participant charge close to the spectator system.

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1. Introduction

A moving charge generates an electromagnetic field. Recent studies [1] suggest that one of the direct consequences of this electromagnetic law gives rise to a *spectator-induced electromagnetic (EM) effect* in heavy-ion collisions. This latter phenomenon can be understood as Coulomb interaction between charged particles emitted from the participant zone and two positively charged nuclear remnants that did not participate in the collision process, called spectator systems (see Fig. 1).

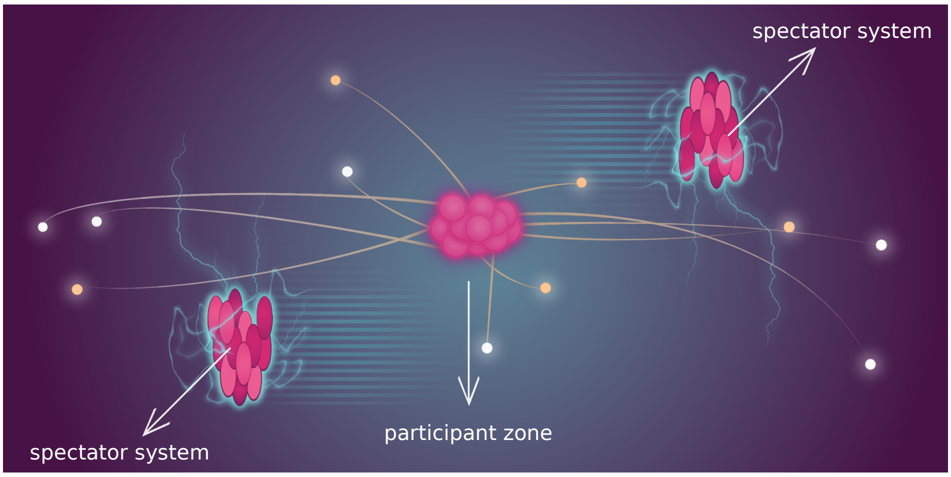

Figure 1: A graphic representation of a non-central nucleus-nucleus collision with a schematically outlined participant zone and two spectators systems.

The essence of the spectator-induced EM effect manifests itself in the observed change in the spectra of measured charged particles. It is induced by the electromagnetic field, generated by the highly charged spectator systems moving in the opposite direction with relativistic speed, acting on trajectories of charged particles produced in the non-central heavy-ion collision. Interest in the study on EM effects arise mostly from recent findings [1, 2, 3, 4] that have shown the spectator-induced electromagnetic effect is sensitive to the space-time evolution of the system and can become a new source of information in that matter.

So far, the research on that subject has been mostly restricted to the analysis of large colliding systems like peripheral Pb+Pb or Pb+gas reactions [5] at the SPS (Super Proton Synchrotron) energies at CERN. However, this paper provides a general overview of the results measured on spectator-induced EM phenomena for both light- and heavy-ion collisions. The main focus is placed on analysis on new data on Ar+Sc collisions from the NA61/SHINE Collaboration which provides the first investigation of the spectator-induced EM effect in small systems at the SPS energies. This work discusses also the implications of the evolution of the spectator system itself on the measured spectra of charged π mesons.

2. EM effects in ultra-relativistic light- and heavy-ion collisions

2.1 Comparison of the EM effect in peripheral Pb+Pb, Pb+gas and Ar+Sc collisions

Figure 2 (a)–(d) juxtapose experimental data of the spectator-induced EM effect observed in

π meson spectra obtained in heavy-ion collisions of Pb+gas and peripheral Pb+Pb reactions with new results measured in light-ion reactions such as intermediate and central Ar+Sc interactions. All four panels in Figure 2 show the π^+ over π^- ratio plotted as a function of Feynman variable x_F [1] for selected values of transverse momentum p_{T}, both variables x_F and p_{T} were considered in collision c.m.s. Presented results were obtained in the projectile fragmentation region ($x_F > 0$).

Data for asymmetric Pb+gas and symmetric peripheral Pb+Pb collisions were measured at $\sqrt{s_{\mathrm{NN}}} = 17.3$ GeV in the fixed target NA49 experiment (at the CERN SPS). In this paper, the term Pb+gas reactions should be interpreted as the collisions of the large lead projectile with smaller nuclei of gas (Pb+N, Pb+O) in the vicinity of NA49 target (see [5]). New results on Ar+Sc collisions were obtained in the NA61/SHINE fixed target experiment at CERN SPS at energy $\sqrt{s_{\mathrm{NN}}} = 16.8$ GeV.

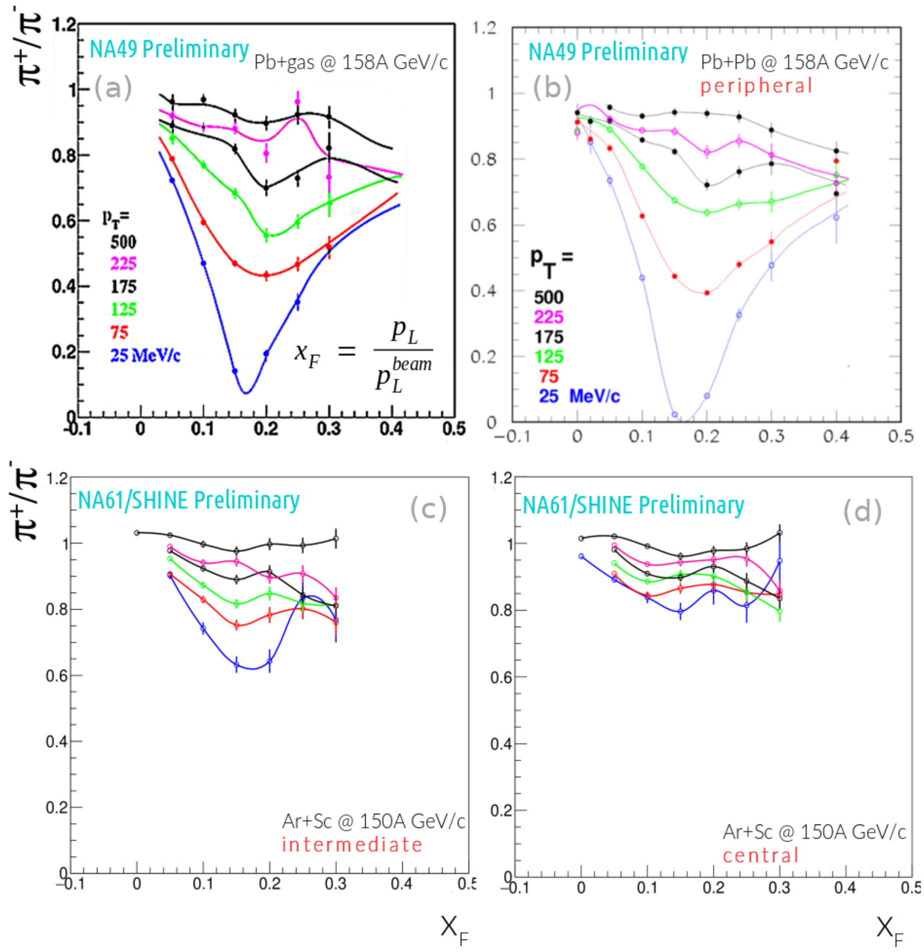

Figure 2: Panels (a)–(d) show ratios of π mesons (π^+/π^-) drawn as a function of x_F (in nucleon-nucleon c.m.s.) at several values of p_{T} for experimental data: (a) from Pb+gas collisions [5] and, (b) peripheral Pb+Pb reactions [1] measured in the SPS NA49 experiment at $\sqrt{s_{\mathrm{NN}}} = 17.3$ GeV, as well as (c) intermediate and (d) central Ar+Sc collisions obtained in the SPS NA61/SHINE experiment at $\sqrt{s_{\mathrm{NN}}} = 16.8$ GeV [6].

From the direct comparison of the results on EM effects obtained in three different colliding

[1]The Feynman variable: $x_F = \frac{p_L}{\sqrt{s_{\mathrm{NN}}}}$

systems the following picture emerges:

– There are several similarities in the behavior of the data points observed between results obtained for Pb+gas and peripheral Pb+Pb collisions. The resemblance is both qualitative and quantitative. In the figures, experimental data display an evident excess of the negative over positive π mesons present for all the studied kinematic range. The moderate excess of negative over positive pions visible for the higher transverse momentum is a direct result of the isospin effect originated from the nucleonic composition of Pb projectile (surplus of neutrons over protons in the nucleus). For low values of p_{T} a characteristic structure as a function of x_F and p_{T} with a sharp decrease of π^+/π^- ratio that breaks isospin symmetry can be seen. The observed minimum of the charged π meson ratio, the position of which corresponds to pions moving longitudinally with the same velocity as spectator system ($x_F = m_\pi/m_p = 0.15$) in Pb+gas and peripheral Pb+Pb collisions, is a direct result of the electromagnetic interaction between charged pions and the spectator system.

– New data on Ar+Sc collisions, bring forward the first piece of information on EM effects in small systems. Surprisingly, the EM distortion of charged π meson ratios still remains well visible in the proximity of the $x_F = 0.15$ for intermediate Ar+Sc data presented in Fig. 2(c). In contrast to peripheral Pb+Pb collisions where the spectator charge of about 70 elementary units induces large lowering of $\frac{\pi^+}{\pi^-}$ ratio, the observed EM effects for intermediate Ar+Sc collisions (Fig. 2(c)) are significantly smaller at the same energy, however strong enough to break the isospin symmetry, account taken of the proportion between neutrons and protons in the ${}^{40}_{18}Ar$ nucleus. Breaking isospin symmetry takes place even if the spectator charge is around 9 times lower than in peripheral Pb+Pb collisions.

– Observed in Fig. 2(c) for the central Ar+Sc collisions, the slight decrease of $\frac{\pi^+}{\pi^-}$ ratio around beam rapidity may indicate a shadow of the EM effect still present even for a very low spectator charge.

2.2 Phenomenological description of EM effect including spectator dynamics

Figure 3 (a) –(f) show the results of a phenomenological study of electromagnetic effect in peripheral Pb+Pb and intermediate Ar+Sc collisions. Detailed information on the approach taken in the Monte Carlo simulation can be found in Ref. [1], below only a short summary of the fundamental assumptions implemented in the model is provided.

The simulation assumes that charged π mesons are emitted from a single point and interact electromagnetically with the spectator systems. In the most basic scenario the spectator systems are modeled as two charged uniform spheres in their rest frames, they are assumed to be stable. which means that they are characterized by a zero expansion velocity ($\beta = 0$, the red line in Fig. 3). The free parameter of the model is the distance d_E between the π meson freeze-out point and the spectator system at the moment of pion emission taken in collision c.m.s. Presented in Figure 3 results of MC studies were carried out for various values of distance d_E, for both peripheral Pb+Pb collisions and intermediate Ar+Sc reactions. From the Figure 3 it is immediately apparent that:

– Electromagnetic distortion of $\frac{\pi^+}{\pi^-}$ ratios is sensitive to distance d_E between pion emission zone and spectator systems. This is evident from comparison of the results of MC studies

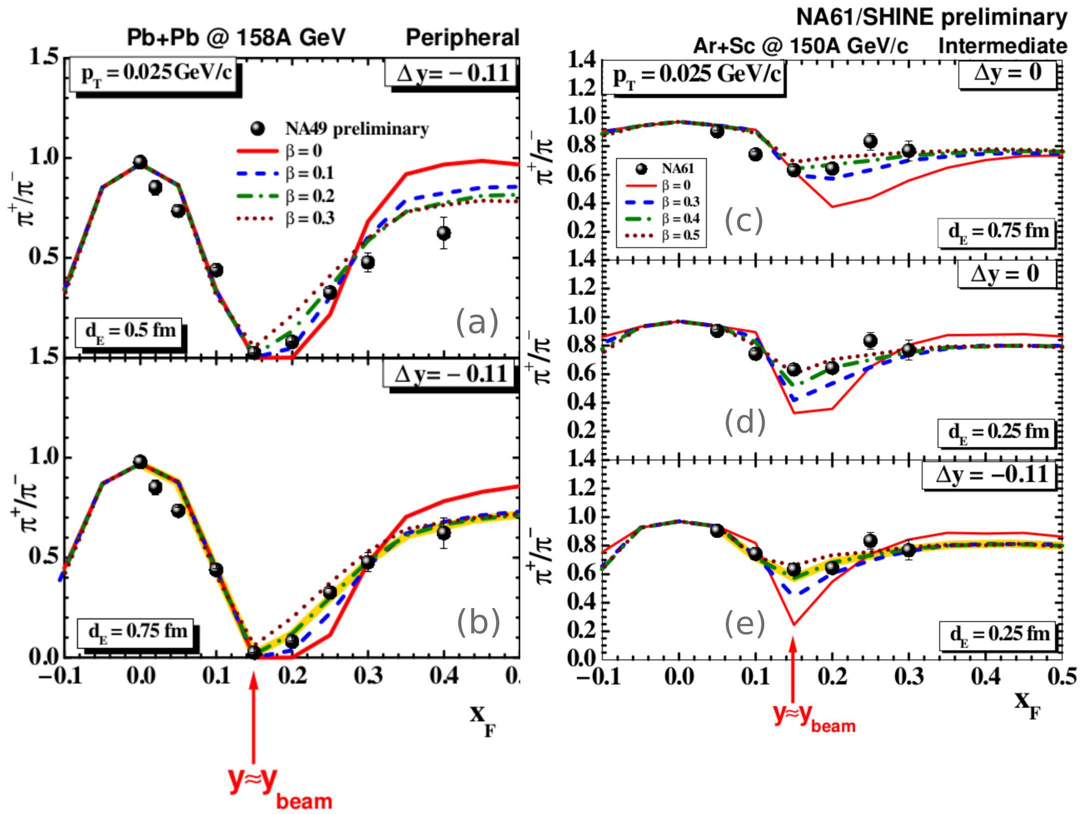

Figure 3: Panels (a)–(e) show the results of dedicated MC simulations (colour lines) of the EM distortion of $\frac{\pi^+}{\pi^-}$ ratios compared to experimental results on peripheral Pb+Pb collisions (panels (a) and (b)) and intermediate Ar+Sc collisions (panels from (c) to (e)). MC results are obtained for different combinations of three parameters: the distance d_E, the expansion velocity β and the rapidity shift of the effective charge cloud Δy (more description in the text). The optimal description of experimental data is indicated by the thick solid gray/yellow line in panel (b) for peripheral Pb+Pb collisions and in panel (e) for intermediate Ar+Sc reactions.

obtained for two different values of distance d_E, independently for peripheral Pb+Pb (panel (a) versus panel (b)) and intermediate Ar+Sc collisions (panel (c) versus panel (e)).

– Contrary to the case of peripheral Pb+Pb reactions, the non-expanding spectator system ($\beta = 0$) cannot describe the Ar+Sc experimental data. The MC description of the results for Ar+Sc collisions improves if the phenomenological analysis includes spectator dynamics like e.g. expansion of the corresponding charge cloud, with significant expansion velocity $\beta > 0$. The same becomes evident from a re-analysis of Pb+Pb collisions inspired by the new data on Ar+Sc reactions.

– In both reactions, the experimental data suggest a short longitudinal distance d_E between the emission zone of a high x_F ($x_F > 0.1$) pion and the spectator system ($d_E < 1$ fm).

– The optimal description is obtained by including the decrease in the rapidity of the expanding charged cloud in the model. This scenario is presented in Fig. 3 (b) for peripheral Pb+Pb and in Fig. 3 (e) for intermediate Ar+Sc collisions. It could be justified in the case when the electromagnetic effect is induced by an effective charge cloud consisting of the highly charged spectator and the faster part of participant matter.

3. Conclusions

This paper reports a short overview of the spectator-induced electromagnetic effects observed in three different colliding systems: Pb+gas, peripheral Pb+Pb and Ar+Sc collisions at CERN SPS energies. New data on Ar+Sc collisions from the NA61/SHINE experiment brought a first preliminary insight into EM effects in small systems.

In summary, the findings discussed above show that the presence of EM fields in the light- and heavy-ion collision results in charge-dependent effects on various observables. The phenomenological analysis of presented experimental data sheds new light on the space-time evolution of EM effects in nucleus-nucleus collisions. The EM distortion is sensitive to the distance d_E between the pion emission site and the spectator(s). The stable spectator scenario fails to describe the experimental results, this is most evident for a small system like intermediate Ar+Sc collisions. The outcome of the dedicated MC simulation indicates that there is a sensitivity to the space-time evolution of the spectator system which has to be taken into account. Further research should be undertaken to investigate the precise role of the evolution of the spectator system on the measured charged particle spectra.

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