Spectator-induced electromagnetic effects in heavy-ion collisions and space-time-momentum conditions for pion emission

V. Ozvenchuk,[1,*] A. Rybicki,[1] A. Szczurek,[1,2] A. Marcinek,[1] and M. Kiełbowicz[1]
[1]*Institute of Nuclear Physics, Polish Academy of Sciences, 31-342 Kraków, Poland*
[2]*University of Rzeszów, 35-959 Rzeszów, Poland*

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We present our calculation of electromagnetic effects, induced by the spectator charge on Feynman-x_F distributions of charged pions in peripheral Pb + Pb collisions at CERN SPS energies, including realistic initial space-time-momentum conditions for pion emission. The calculation is performed in the framework of our simplified implementation of the fire-streak model, adapted to the production of both π^- and π^+ mesons. Isospin effects are included to take into account the asymmetry in production of π^+ and π^- at high rapidity. A comparison to a simpler model from the literature is made. We obtain a good description of the NA49 data on the x_F and p_T dependence of the ratio of cross sections π^+/π^-. The experimental data favors short times ($0.5 < \tau < 2$ fm/c) for fast pion creation in the local fire-streak rest frame. The possibility of the expansion of the spectators is considered in our calculation, and its influence on the electromagnetic effect observed for the π^+/π^- ratio is discussed. In addition we discuss the relation between anisotropic flow and the electromagnetic distortion of π^+/π^- ratios, and study the influence of transverse expansion of fire streaks as well as their vorticity on this distortion. In this latter study we find that inclusion of rotation of fire streaks in our model gives a satisfactory description of the rapidity dependence of pion directed flow. We conclude that our implementation of the fire-streak model, which properly describes the centrality dependence of π^- rapidity spectra at CERN SPS energies, also provides a quantitative description of the electromagnetic effect on the π^+/π^- ratio as a function of x_F.

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I. INTRODUCTION

More than ten years ago [1] two of us presented model calculations on a somewhat spectacular electromagnetic effect caused by fast-moving spectators on charged pion momentum distributions at CERN Super Proton Synchrotron (SPS) energies. The effect is most peculiar in Feynman-x_F distributions of π^+ and π^- when limiting to low pion transverse momenta. This phenomenon, observed in the NA49 experiment [2,3], was explained in a simple toy model where a pointlike source of pions was assumed. The only free parameter of the model was the distance between the source and the spectator system, which in the present paper we will refer to as d_E. After the initial emission of π^+ and π^-, the calculation of their trajectories in the electromagnetic field of the two spectator systems was performed. A good description of the data was obtained when the original pion source was not far from the spectator. The best agreement with the experimental data [2] was obtained for $d_E \approx 0.5$–1 fm. The interpretation of this fact was not given in Ref. [1]. The simplest explanation could be a fast hadronization of the plasma, which seems difficult to reconcile with the present knowledge on pion decoupling times at midrapidity [4]. Definitely a deeper conclusion was not possible within the toy model considered in Ref. [1]. The same simple model was able to describe [5,6] a rather small effect of splitting of directed flow (v_1) for π^+ and π^- as observed at RHIC [7].

The old version of the model was rather simplistic. The question arises whether models with more realistic initial conditions can describe the electromagnetic effects observed for π^+ and π^- spectra. Recently it was shown that one can describe the broadening of the π^- rapidity distribution with centrality, as observed by the NA49 experiment [9], within a special (simplified) implementation of the fire-streak model, which we proposed in Ref. [8]. In our opinion the fire-streak model (see also Refs. [10–16]) provides realistic initial conditions for quark-gluon plasma creation at SPS energies, in particular obeying energy-momentum conservation. In this model, for peripheral collisions, the initial quark-gluon plasma moves with different velocities as a function of the impact parameter vector (b_x, b_y) (see Fig. 1). Do electromagnetic effects, seen in the π^+/π^- ratios, support such a picture? We will try to answer this question in the present paper. We consider also simplified initial conditions to investigate to what extent the fire-streak model with local energy-momentum conservation provides more realistic initial conditions to understand experimental results for the π^+/π^- ratio.

With the extended pion source, it seems difficult *a priori* to describe the data if different emission zones do not cooperate in a proper (generally unknown) way. Having the extended

*Vitalii.Ozvenchuk@ifj.edu.pl

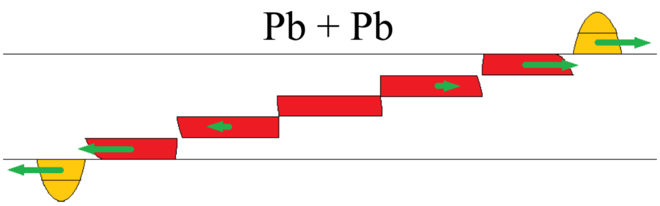

FIG. 1. The situation after the collision. The area marked in red shows the partonic matter. Each element moves with a different longitudinal velocity, which can be obtained from energy-momentum conservation [8].

source in the present calculation, we wish to understand in addition the success of the simplified calculation with the pointlike source [1]. We wish to address also the issue how important is the tilted condition [$v_z = v_z(b_x, b_y)$] for describing the electromagnetic effect.

This paper is organized as follows. In Sec. II we present a few general remarks on our approach. In Sec. III we provide a detailed description of the initial conditions for pion creation. We then discuss in Sec. IV the event generator implemented in our model. In Sec. V we present the results of the calculation of electromagnetic effects on the x_F distribution of charged pions within the fire-streak model. The summary and conclusions are given in Sec. VI.

II. GENERAL REMARKS ABOUT THEORETICAL APPROACH

The details of the electromagnetic effect were presented in Ref. [1] whereas the details about our version of the fire-streak model were given in Refs. [8,17]. We will not repeat these details here. However, we point out that in spite of the basic similarity of our approach formulated in Refs. [8,17] to the original fire-streak concept of Refs. [10–16], differences exist on the more detailed level. These become clearly apparent from the comparison of the cited works.

Our fire-streak model, in contrast to other models in the literature, has a rather small number of parameters, essentially only three free parameters for the so-called fire-streak fragmentation function [17]. It describes nicely the rapidity distributions of pions as well as the broadening in rapidity distributions when going from central to peripheral collisions, which is due to local energy-momentum conservation within a given fire streak [8].

As will be discussed below, the evolution of charged pions in the electromagnetic (EM) field of spectators requires long times. The long times of the EM evolution require to use a simple treatment of the plasma stage. Our fire-streak model has all necessary features. It is relatively simple, and describes the pion production at the SPS energies. In the future one could think to use a three-dimensional hydrodynamical program but this clearly goes beyond the present interest.

Instead, in the present analysis we will include anisotropic flow effects, thought to be of hydrodynamical origin, in a more phenomenological way, as an initial condition for the EM evolution. The initial conditions will be discussed in detail in Sec. III below.

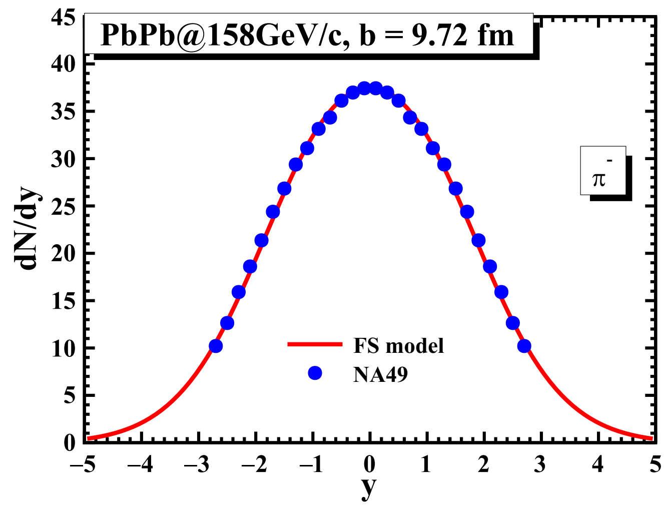

FIG. 2. The rapidity distribution of negative pions obtained from the fire-streak model (solid red line) in comparison to the NA49 experimental data [9] (blue symbols) for peripheral Pb + Pb collisions at top SPS energy.

Finally, we note that plasma in the Pb + Pb collision at SPS energies is not isospin ($u - d$ or $\bar{u} - \bar{d}$) symmetric. The asymmetry in quark/antiquark production is often called isospin effect. We will include the isospin effects due to initial quark asymmetry in a simplified, yet realistic way.

III. INITIAL CONDITIONS FOR PION CREATION

In this section we discuss the initial conditions for pion creation, which were implemented into our approach.

A. Rapidity distribution of pions

As was mentioned in Sec. I we previously studied the electromagnetic effects of the spectator charge on the momentum spectra of π^+ and π^- produced in peripheral Pb + Pb collisions at SPS energies [1,5] using a pointlike source for pion creation. In the present paper we use the initial (without electromagnetic effects included) rapidity distribution of negative pions[1] obtained from our version of the fire-streak model formulated in Refs. [8,17]. This model well describes the rapidity distribution of π^- in comparison to the NA49 experimental data [9], which is shown in Fig. 2 for the most peripheral collisions. The fire-streak fragmentation function into negative pions was parametrized in Ref. [8] in the form:

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

[1]The rapidity distribution of π^+ was not measured for the Pb + Pb collisions at SPS energies.

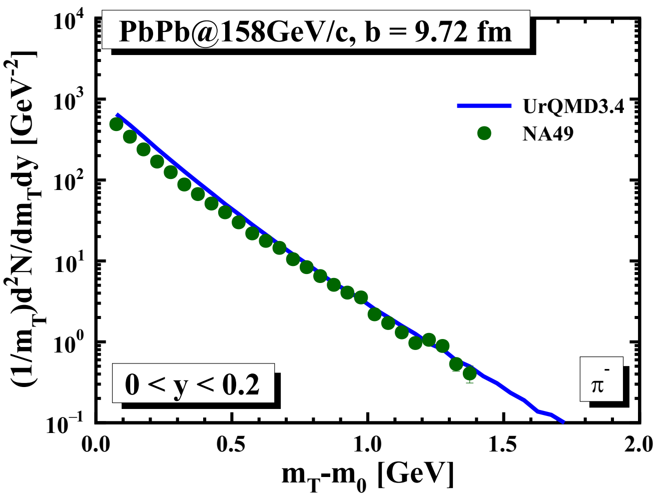

FIG. 3. The UrQMD v3.4 predictions (solid blue line) for the transverse mass spectrum at midrapidity ($0 < y < 0.2$) of π^- produced in peripheral Pb + Pb collisions at 158 GeV/c in comparison to the experimental data from the NA49 Collaboration (green symbols) [9].

where y is the rapidity of the pion, y_s is the fire-streak rapidity given by energy-momentum conservation, E_s^* is its total energy in its own rest frame, and m_s is the sum of cold rest masses of the two nuclear bricks forming the fire streak (see Ref. [8]). The free parameters of the function (1) are A, σ_y, and r, which appeared common to all fire streaks and independent of Pb + Pb collision centrality. The fit of the NA49 centrality selected Pb + Pb data [9] gave $A = 0.05598$, $\sigma_y = 1.475$, and $r = 2.55$. Finally, ϵ is a small number ensuring the continuity of derivatives ($\epsilon = 0.01$ was used in Ref. [8]). The expression (1) defines the distribution of negative pions created by the fragmentation of a single fire streak. The resulting pion spectrum in a given centrality was constructed as the sum of independent rapidity fragmentation functions:

$$\frac{dn}{dy}(y, b) = \sum_{(i,j)} \frac{dn}{dy}\big(y, y_{s_{(i,j)}}(b), E^*_{s_{(i,j)}}(b), m_{s_{(i,j)}}(b)\big), \qquad (2)$$

where (i, j) denominate the position of a given fire streak in the transverse (x, y) plane, and b is the impact parameter of the Pb + Pb collision.

B. Transverse-momentum distribution of pions

In Ref. [8] only rapidity distributions of pions were studied. For the discussion of electromagnetic effects we are interested also in transverse-momentum distributions of pions.

For the initial transverse-momentum distribution of pions we choose the one obtained from the UrQMD 3.4 simulations [18,19]. In Fig. 3 we compare the UrQMD 3.4 predictions with the NA49 data for the transverse-mass spectrum at midrapidity of negative pions produced in peripheral Pb + Pb collisions at top SPS energy. The model reasonably well describes the experimental data.

We parametrize the resulting UrQMD 3.4 predictions for transverse-momentum distributions of pions by the exponential function [20,21]:

$$\frac{dN}{dp_T} = \frac{Sp_T}{T^2 + mT} \exp\left[-(m_T - m)/T\right], \qquad (3)$$

where m is the mass of the pion, $m_T = \sqrt{m^2 + p_T^2}$ is its transverse mass, S and T are the yield integral and the inverse slope parameter, respectively. The transverse-momentum distributions of pions are normalized as follows:

$$\int_0^\infty \frac{dN}{dp_T} dp_T = S. \qquad (4)$$

The fit to the UrQMD v3.4 simulations at midrapidity is presented in Fig. 4 and it gives $T_{\pi^-} = 165$ MeV and $T_{\pi^+} = 163$ MeV. In general, the inverse slope parameter may depend

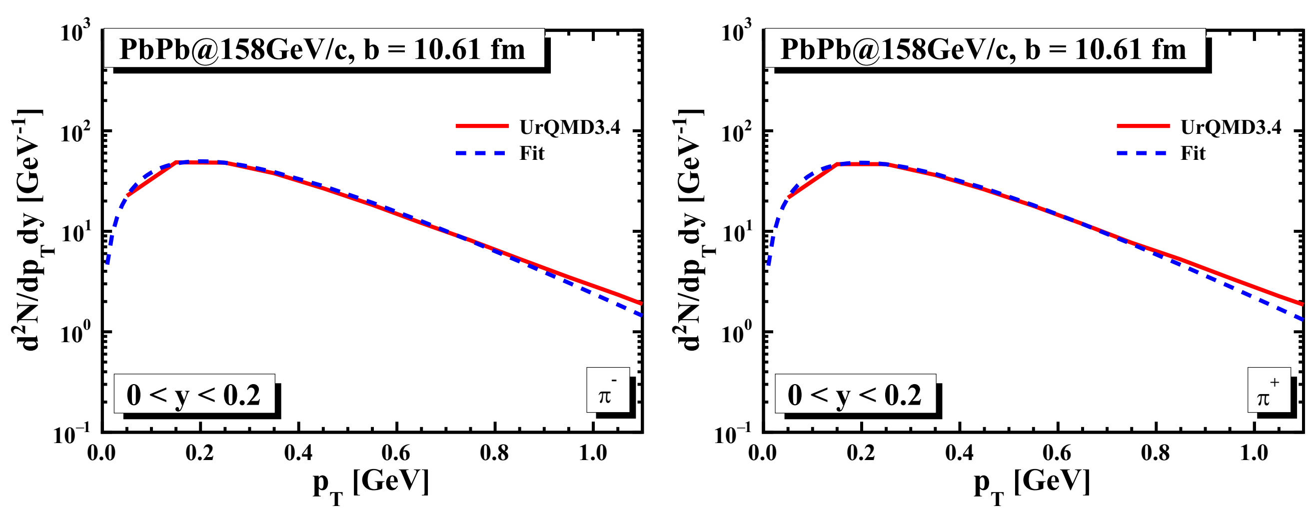

FIG. 4. The UrQMD v3.4 simulations (solid red lines) of transverse-momentum spectra at midrapidity of π^- mesons (left) and of π^+ mesons (right) produced in peripheral Pb + Pb collisions at 158 GeV/c beam momentum. The dashed blue lines represent the corresponding fits, made according to Eq. (3).

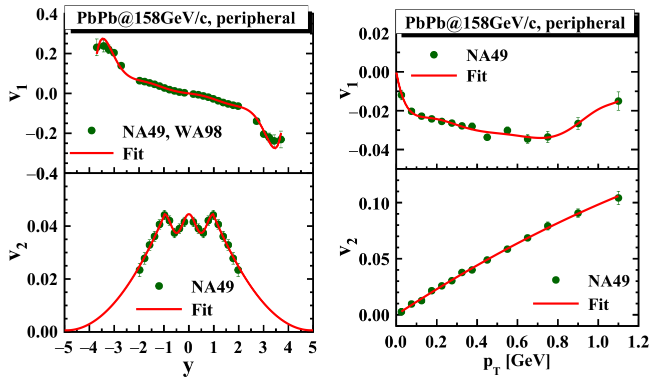

FIG. 5. Our fit to average v_2 (bottom row) and v_1 (top row) data obtained by the NA49 and WA98 collaborations. The left panels are for rapidity dependence while the right panels are for transverse momentum dependence.

on rapidity, $T = T(y)$. However, we performed the study on rapidity dependence of the inverse slope parameter by fitting the UrQMD results for different rapidity bins and extracting the inverse slope parameters for the corresponding rapidity. We figured out that the results of calculation of electromagnetic effects on the x_F distribution of charged pions do not depend much when changing the inverse slope parameter with the pion rapidity. Therefore, for further discussion we assume that the inverse slope parameter does not depend on rapidity and equals to its midrapidity value mentioned above.

C. Particle flow

In the present paper we wish to quantify (for the first time) the possible effect of pion flow on the observed π^+/π^- ratio. The particle flow is a well-established empirical and phenomenological fact observed at SPS, RHIC, and LHC energies. The flow is quantified in terms of the Fourier decomposition:

$$\frac{dN(y, p_T, \phi)}{dp_T d\phi} = \frac{dN(y, p_T)}{dp_T}[1 + 2v_1(y, p_T)\cos(\phi) + 2v_2(y, p_T)\cos(2\phi) + \dots] \tag{5}$$

for different particle species. The ϕ angle above is the azimuthal angle with respect to the reaction plane, in our case the plane spanned by the noncentral trajectories of the colliding nuclei (or outgoing spectators). The flow coefficients depend on collision energy, rapidity and transverse momentum. The symmetry dictated by the geometry imposes $v_2, v_1 \to 0$ when $p_T \to 0$. The electromagnetic effect is concentrated at rather small transverse momenta [1] so naively one could expect no significant influence from flow. In addition $v_2(-y) = v_2(y)$ and $v_1(-y) = -v_1(y)$.

The NA49 collaboration clearly observed [22] nonzero elliptic (v_2) and directed (v_1) pion flow coefficients. The nonzero flow coefficients are usually interpreted in terms of hydrodynamical evolution of the QGP fluid. A good description of the experimental data is obtained at midrapidities. Here we are interested rather in very forward rapidities (large x_F) where there is no general consensus on the underlying dynamics. Therefore in the following analysis we prefer rather to parametrize experimental data on v_2 and v_1 as a function of pion rapidity and transverse momentum. In Fig. 5 we show our fit to the NA49 data [22]. We present results for both elliptic v_2 (top row) and directed v_1 (bottom row). Our purely mathematical fit nicely represents the NA49 experimental data [22] in a broad range of rapidities and transverse momenta. For our electromagnetic effect we need data in a broad range of x_F, i.e., at rather large rapidities. Therefore we included also the data of the WA98 collaboration [23] into the fit.

In our calculation on electromagnetic evolution of pions we need to have $v_{1,2} = v_{1,2}(y, p_T)$, i.e., dependence on two variables y and p_T simultaneously. In the following we assume:

$$v_{1,2}(y, p_T) = v_{1,2}(y) \times v_{1,2}(p_T)/v_{1,2}^{\text{eff}}, \tag{6}$$

where $v_{1,2}^{\text{eff}}$ are effective parameters adjusted in order to nicely reproduce the separate dependences of v_1 and v_2 on y and p_T within such a factorized ansatz in our EM code.

D. Pion emission time

To start the calculation of electromagnetic effects we have to fix also the time of emission of pions from the fire streaks (which we consider as a longitudinally expanding plasma), and the corresponding initial position of the pion relative to the two spectator systems. This cannot be calculated from first principles and it is treated here as a free parameter. We assume the time of creation of pions, τ, in the fire-streak rest frame. Up to this time the fire streak evolves in the longitudinal direction. For our calculations of electromagnetic effect we have to calculate the actual position of pion creation in z for each (i, j) fire streak in the nucleus-nucleus center-of-mass system. This can be done by applying the Lorentz transformation

$$\tau \to t_{i,j}. \tag{7}$$

The transformation is given by the velocity of a given fire streak in the center-of-mass system, which in turn is given, in our model, by its position in the impact parameter plane (b_x, b_y) [8].

IV. EVENT GENERATOR FOR THE WHOLE REACTION

Having fixed the position of the pion and its momentum vector we can start the evolution of the charged pion trajectory in the electromagnetic field of both spectators using a Lorentz invariant formalism [1]. This evolution requires rather long evolution times. In our calculation we use $t_{\max}$ of the order of 10^4 fm/c. We note that this time is taken in the nucleus-nucleus center-of-mass system. In Fig. 6 we show the π^+/π^- ratio for different evolution times $t_{\max} = 10^2, 10^3$, and 10^4 fm/c. We see a convergence of the electromagnetically deformed π^+/π^- ratio only for $t_{\max} > 10^3$ fm/c. Such long times are required because the emitted pions of interest in the EM dip have velocities similar to spectators, i.e., stay close to spectators for fairly long time. For π^- mesons even an orbiting is possible [1].

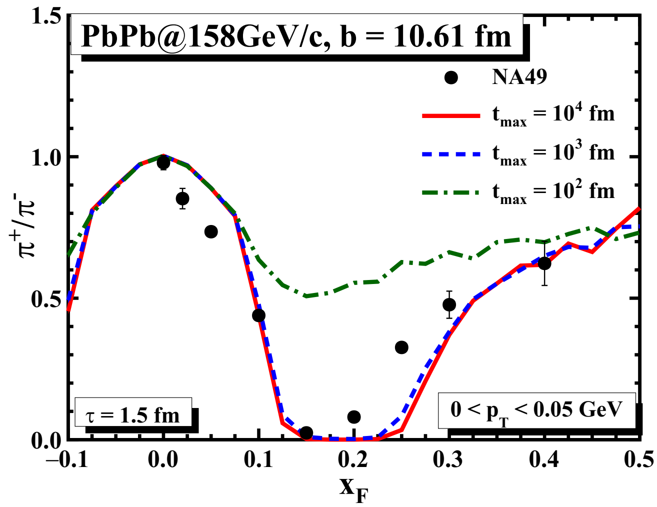

FIG. 6. The π^+/π^- ratio as a function of the time of the evolution $t_{\max}$. Here $\tau = 1.5$ fm/c was used for an example.

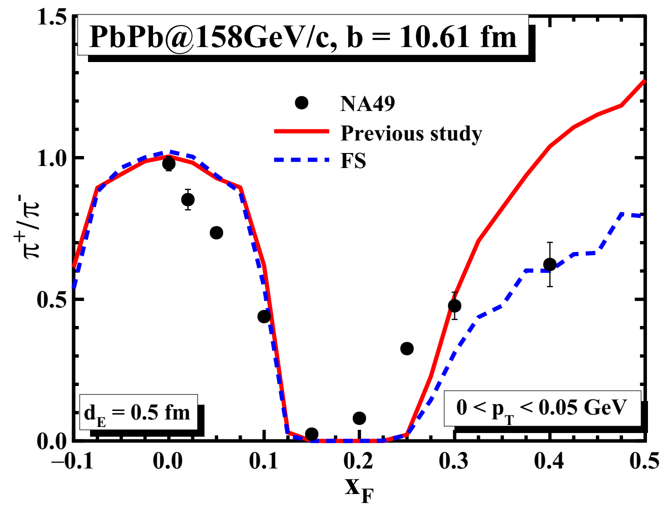

FIG. 7. The π^+/π^- ratio as a function of x_F for $0 < p_T < 0.05$ GeV/c obtained in our previous study [1] (solid red line) as well as from the intermediate model scenario described in the text (dashed blue line). Both simulations are taken with the distance d_E set to 0.5 fm. Simulation results are put in comparison to experimental data from NA49 (symbols).

In the center-of-mass system one needs to include both electric and magnetic fields generated by the moving spectators [1]. In the present calculation we assume that spectators move with the velocity of their initial parent beams. We perform the evolution of charged pions in the electromagnetic field generated by spectators separately for positively and negatively charged pions. After the evolution of pion trajectory is terminated a final event is generated. The events are used then to generate momentum spectra of π^+ and π^- in the final state of the collision.

To summarize, we generate 10^8 pions using a weighted Monte Carlo code with the corresponding weight:

$$W = \frac{dN}{dy} \cdot \frac{dN}{dp_T}^{\text{weighted}}, \tag{8}$$

where dN/dy is given by Eqs. (1) and (2). To be consistent with the fire-streak model one has to keep the normalization of the weighted transverse-momentum spectrum of pions equal to unity, i.e.,

$$\frac{dN}{dp_T}^{\text{weighted}} \equiv \frac{1}{S}\frac{dN}{dp_T}, \tag{9}$$

where dN/dp_T is given by Eq. (3) and its normalization is defined in Eq. (4). We generate the rapidity and transverse momentum of pions using an uniform random number generator in the following ranges of kinematical parameters: $y \in [-5; 5]$, $p_T \in [0; 1.1]$ GeV/c, $\phi \in [0, 2\pi]$.

V. RESULTS AND DISCUSSION

A. Simplified static source

We start with the comparison of our present work to the previous results published in Ref. [1]. In the previous study the pion emission source was reduced to a single point in space: $(x, y, z) = (0, 0, 0)$. The initial two-dimensional (x_F, p_T) distribution of pions was assumed similar to that in nucleon-nucleon collisions (the same distribution was assumed for π^+ and π^-). The time of pion emission, directly equivalent to the distance d_E between the pion source and the two spectator systems, was taken as a free parameter. The result for the π^+/π^- ratio as a function of x_F for the range of transverse momentum of pions, $0 < p_T < 0.05$ GeV/c, for this scenario and assuming $d_E = 0.5$ fm is presented in Fig. 7 (solid red line), in comparison to the NA49 experimental data [2].

In order to illustrate the role of the different elements of our fire-streak model in the description of the electromagnetic effect on π^+/π^- ratios, our comparison with the previous study will be made in a few successive steps. In the first step, we consider a specific, *intermediate* model scenario where the pion source is extended in the transverse direction, but *static*, and fixed at $z = 0$. The transverse extent of our source is defined by the initial transverse positions of the fire streaks in the (x, y) plane, given by the overlap of the two nuclei (see Ref. [8] for a detailed discussion). The pion emission time is arbitrarily set to 0.5 fm/c, which very closely corresponds to $d_E = 0.5$ fm. Finally, the initial two-dimensional (y, p_T) distribution of pions is initialized according to Eq. (8) with the rapidity distribution taken from the complete fire-streak model, Eq. (2), and with the transverse-momentum distribution taken from the UrQMD model. We underline the *intermediate* character of this step of our analysis as for the time being we keep the static source used in the previous study [1]; this results in a single value of d_E. This is to be opposed to the full fire-streak model scenario, which we will discuss later, in Sec. V C.

The results for the π^+/π^- ratio as a function of x_F are shown in Fig. 7 as the dashed blue line. It is clear from the figure that the inclusion of the transverse extent of the source and a more realistic description of the initial rapidity and transverse momentum distributions has a visible effect on the predictions of the model above $x_F = 0.25$. In this context we note that these results were obtained assuming the initial rapidity distribution for positive pions equal to that of negative pions.

B. Isospin correction

Consequently, as a next step we have to implement the *isospin correction*, namely the difference between rapidity distributions of positive and negative pions initially produced from the fire streaks. We proceed as follows. First we note that generally in $p+p$ collisions at SPS energies:

$$\frac{d\sigma_{pp\to\pi^+X}}{dy\,dp_T} \neq \frac{d\sigma_{pp\to\pi^-X}}{dy\,dp_T}. \tag{10}$$

This fact is well known experimentally [24], but can be also explained by QCD-based calculations [25]. Therefore, also for two colliding Pb nuclei ($Z=82, A-Z=126$) some discrepancy between π^+ and π^- distributions is to be considered, and seems indeed indicated by the compilation of numerical results from the NA49 experiment [26]. As no rapidity distribution of π^+ was measured for Pb + Pb collisions at top SPS energy, we assume that the latter can be approximated by postulating the y dependence of the π^+/π^- ratio in Pb + Pb reactions to be similar to that in the proper superposition of $p+p$, $n+p$, $p+n$, and $n+n$ collisions. We underline that the above assumption is made only for the π^+/π^- ratio rather than for π^+ and π^- yields. Following the approach proposed in Refs. [17,27], and invoking isospin symmetry in pion production for participating protons and neutrons ($n\to\pi^- = p\to\pi^+$), this ratio reads:

$$\frac{\frac{dN}{dy}(\mathrm{PbPb}\to\pi^+X)}{\frac{dN}{dy}(\mathrm{PbPb}\to\pi^-X)} = \frac{Z\frac{dN}{dy}(pp\to\pi^+X)+(A-Z)\frac{dN}{dy}(pp\to\pi^-X)}{Z\frac{dN}{dy}(pp\to\pi^-X)+(A-Z)\frac{dN}{dy}(pp\to\pi^+X)}, \tag{11}$$

where $Z=82$ and $A=208$ for the considered case of Pb + Pb collisions. We note that the above formula (11) is, within experimental uncertainties, valid for ratios of total π^+ over π^- multiplicities in peripheral Pb + Pb reactions provided by the NA49 Collaboration [26]. It is also equivalent to the prediction of the wounded nucleon model [28] for π^+/π^- ratios as a function of rapidity, once the isospin differences between protons and neutrons are included in this model.

Having the NA49 experimental data for rapidity distributions of positive and negative pions for the proton-proton collisions [24] and inserting them to Eq. (11), we construct the assumed π^+/π^- ratio in peripheral Pb + Pb reactions. This we show in Fig. 8 as a function of rapidity. The π^+/π^- ratio in Pb + Pb collisions obtained from the NA49 $p+p$ data is shown as the black symbols. A purely mathematical fit to the pseudodata (solid red line) will be used to parametrize this ratio. We notice a rather sizable π^+-π^- asymmetry at large rapidity.

Taking into account the fit shown in Fig. 8, we can construct the π^+ rapidity distribution using the fire-streak model addressed in Sec. III A. We postulate that in analogy to the fragmentation function for negative pions, our isospin-corrected fire-streak fragmentation function into positive pions can be written as:

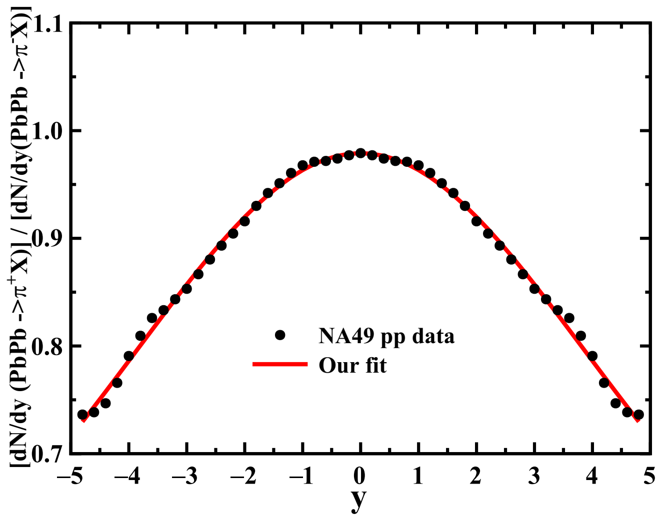

FIG. 8. The ratio (11) as a function of pion rapidity. The black symbols correspond to the results obtained by using NA49 *pp* data [24] (the corresponding procedure is described in the text), the solid red line represents our fit to the pseudodata.

$$\frac{dn}{dy}(y, y_s, E_s^*, m_s) = A(E_s^* - m_s)\exp\left(-I_c\frac{[(y-y_s)^2+\epsilon^2]^{\frac{r}{2}}}{r\sigma_y^r}\right), \tag{12}$$

where I_c will be treated as a new adjustable parameter. Just as a reminder, for negative pions $I_c = 1$ was assumed in Eq. (1) by definition. We find that once $I_c = 1.175$ is taken for positive pions, our fire-streak model provides a good (within 2–3 %) description of the fit shown in Fig. 8.

In Fig. 9 (left plot) we present the resulting comparison of the two initial rapidity distributions: the isospin-corrected distribution of positive pions (dashed blue line) and the distribution of negative pions (solid red line), both calculated within the fire-streak model as described above.

The effect of the isospin correction on the result of our simulation is demonstrated in Fig. 9 (right plot), where we show the resulting final state π^+/π^- ratio without (solid red line) and with (dashed blue line) isospin correction as a function of x_F. For both calculations the same simplified static source model is used as described in Sec. V A. We note that our isospin correction on the initial rapidity spectrum of π^+ gives quite a sizable effect on the calculated π^+/π^- ratio, after the inclusion of the electromagnetic effect caused by spectators.

C. Longitudinal evolution of the system

All the results presented so far were simulated with a partially simplified, intermediate model where the pion emission source was static in position space, and fixed at $z=0$. The pion emission time/distance was set to $d_E = 0.5$ fm in the collision center-of-mass system. Now we finally include the longitudinal evolution of the system along the z axis, given by the fire-streak velocities (Fig. 1). Consequently we have to introduce the pion creation time, τ, which we define for each

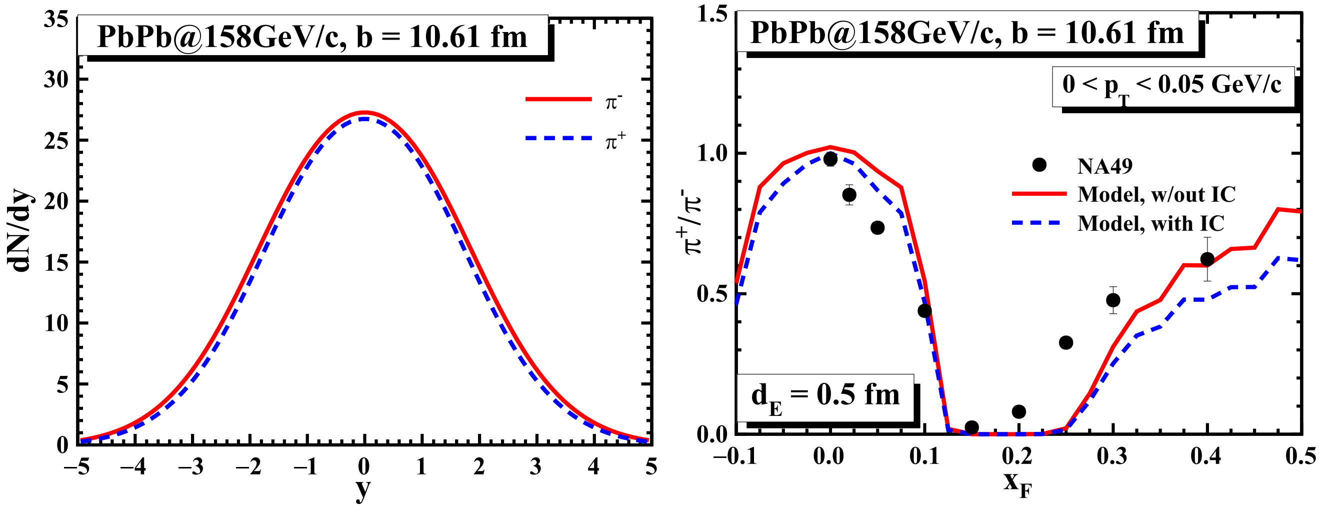

FIG. 9. Left: the isospin-corrected rapidity distribution of π^+ (dashed blue line) in comparison to the rapidity distribution of π^- (solid red line) as a function of pion rapidity, obtained from the fire-streak model as described in the text. Right: the final-state π^+/π^- ratio as a function of x_F for $0 < p_T < 0.05$ GeV/c, calculated without (solid red line) and with (dashed blue line) isospin corrections.

fire streak in its own rest frame. First we perform the simulations for various fixed values of τ: $\tau = 0.5; 1; 1.5; 2$ fm/c (please note that this way we assume the pion creation time is the same in the rest frame of each fire streak). The results of the simulation are presented in Fig. 10. As now they correspond to the complete fire-streak model (in its formulation, which we proposed in Ref. [8]), we label them "FS" to differentiate from the simplified intermediate scenario we used previously.

In comparison to Fig. 9 (right plot), we state that the inclusion of the longitudinal evolution of the system influences the observed electromagnetic distortion, and tends to increase the π^+/π^- ratios for pions at high x_F in the final state. On the other hand, after a detailed inspection of Fig. 10, one can

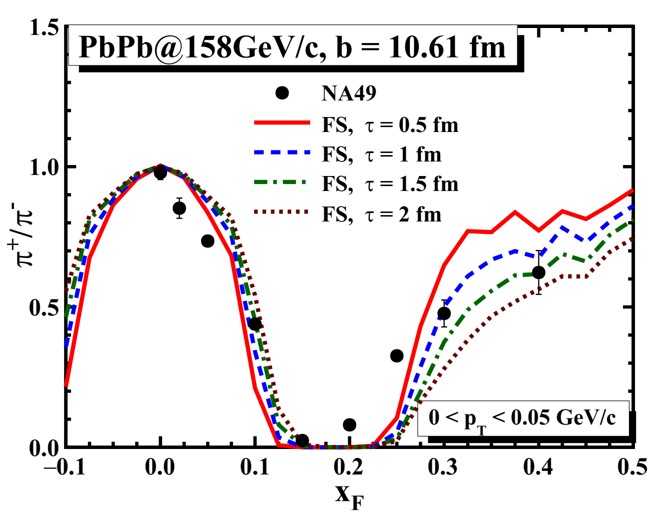

FIG. 10. The π^+/π^- ratio as a function of x_F for $0 < p_T < 0.05$ GeV/c calculated within our version of the fire-streak (FS) model with different pion creation times, in comparison to the NA49 data [2].

conclude that there is no configuration with fixed pion creation time that can well describe the experimental data.

It seems indeed difficult to expect that all the longitudinal elements of excited matter will be characterized by the same pion creation time τ. In fact we expect that the fire-streak lifetime increases with its excitation energy, that is,

$$\tau = F(E_s^* - m_s), \tag{13}$$

where F is a monotonically increasing function and E_s^* and m_s stand, respectively, for the total energy and the cold mass of the fire streak, as described in Eq. (1). For this reason, we try to simulate an initial configuration with the pion creation time, which is not fixed. For the present work, we choose the following simple linear dependence:

$$\tau = a(E_s^* - m_s) + \tau_0, \tag{14}$$

where $\tau_0 = \tau_{min} = 0.5$ fm/c and $\tau_{\max}$ is set to be 2 fm/c, which gives us $a \approx 0.08$ (for energies given in GeV).

In Fig. 11 we present (by the solid red lines) the results of calculation of the electromagnetic effect on the π^+/π^- ratio as a function of x_F in peripheral Pb + Pb collisions at top SPS energies, with the pion creation time parametrized as in Eq. (14). The results are shown for two different ranges of pion transverse momentum: $0 < p_T < 0.05$ GeV/c (left plot) and $0.05 < p_T < 0.1$ GeV/c (right plot). While generally, the solid red line reproduces the main features of the x_F and p_T dependence of the electromagnetic effect, the detailed shape of the minimum at $x_F \approx 0.15$–0.2 is still rather poorly described by the simulation. At this point we notice that in the calculations made so far we always assumed that spectators were *stable*, at least on the time scale when electromagnetic fields interact with charged pions (in our simulation the spectator systems were taken as two stable, homogeneously charged spheres as described in Ref. [1]). However, the spectators are rather highly excited systems [29]. Therefore, presently we impose a scenario with expansion of the spectators. In its own rest frame, each of the two spectator systems is

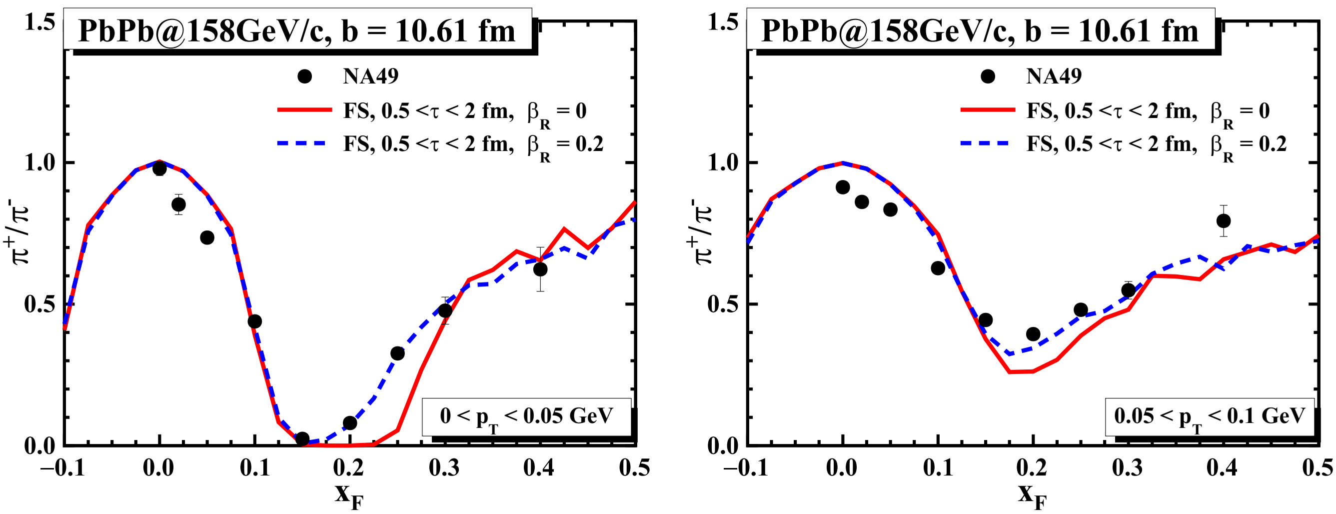

FIG. 11. The results of calculation of electromagnetic effects on the π^+/π^- ratio as a function of x_F in peripheral Pb + Pb collisions at top SPS energy, obtained within our version of the fire-streak (FS) model with the pion creation time given by Eq. (14) for two different ranges of pion transverse momentum: $0 < p_T < 0.05$ GeV/c (left plot) and $0.05 < p_T < 0.1$ GeV/c (right plot). The scenario with stable spectators is shown by the solid red lines, and the scenario with expanding spectators with the radial surface velocity, $\beta_R = 0.2$, is presented by the dashed blue lines.

taken as a homogeneously charged sphere, expanding radially with a given surface velocity β_R. We introduce this surface velocity β_R as an additional free parameter. The configuration with τ given by Eq. (14) and $\beta_R = 0.2$ (in the spectator rest frame) gives the best description of the NA49 experimental data [2] for both ranges of pion transverse momentum, $0 < p_T < 0.05$ GeV/c and $0.05 < p_T < 0.1$ GeV/c, as shown in Fig. 11 by the dashed blue lines. We note that the surface velocity $\beta_R = 0.2$ corresponds, for the radially expanding sphere, to a mean velocity of spectator expansion of $0.15c$. This is reminiscent of the characteristic spectator expansion velocity of $0.16c$ obtained by Cugnon and Koonin at a much lower collision energy [30].

Finally, in Fig. 12 we demonstrate the effect of the pion flow on the observed π^+/π^- ratio as a function of Feynman x_F, for v_1 and v_2 included together. We find no effect for v_2, and a non-negligible effect for v_1. The reason for this is the following. As shown in Fig. 5, v_1 is large at large rapidities and diverges quickly from $v_1 = 0$ at $p_T = 0$. Vice versa, v_2 is small at large rapidities y and grows rather slowly with p_T, being 0 at $p_T = 0$.

The present description of the experimental data by our simulation is satisfactory for faster pions (with $x_F \geqslant 0.1$). Our present conclusion is that in this kinematic region, the electromagnetic distortion of π^+/π^- ratios can be successfully described once five basic components are taken into

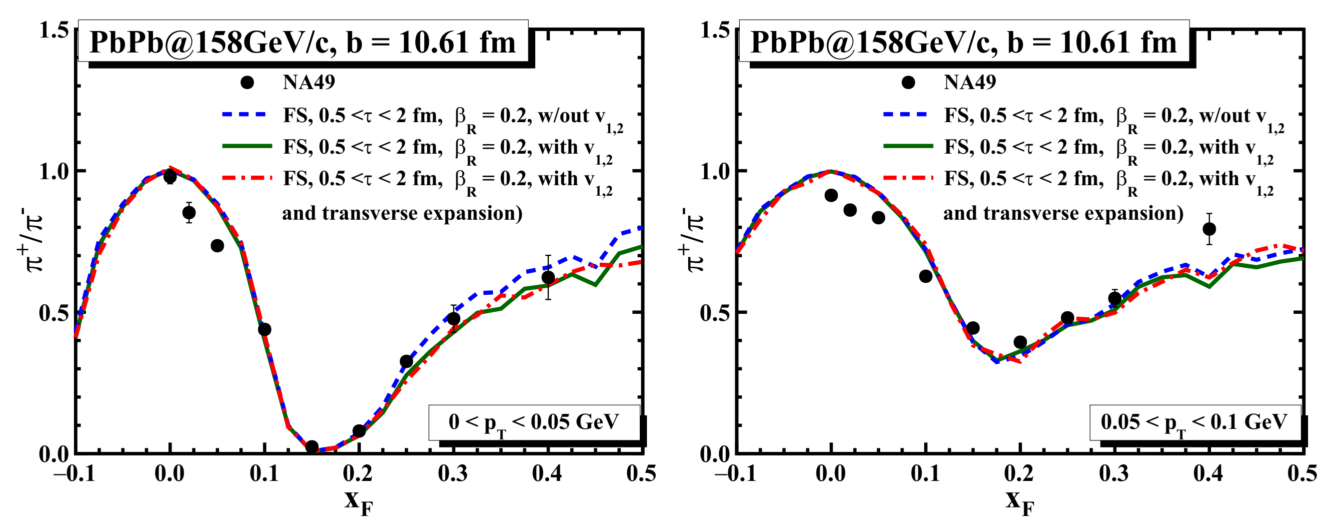

FIG. 12. The effect of inclusion of the initial v_1 and v_2 flow coefficients on the observed π^+/π^- ratio (solid green lines). The dashed blue lines are for the case when no flow is taken into account (the same as in Fig. 11). The dash-dotted red lines include the effect of change of the initial position of pions due to transverse expansion of the fire streaks.

account: (i) a realistic description of the longitudinal evolution of the system provided by the fire-streak model; (ii) isospin differences between initial π^+ and π^- emission; (iii) a proper pion creation time; (iv) the expansion of the spectator system; and (v) charged pion propagation through the electromagnetic field until relatively long times ($\sim 10^4$ fm/c). We note that relatively short pion creation times ($0.5 < \tau < 2$ fm/c) are needed the explain the experimental data. This is in contrast with significantly longer decoupling times obtained from other methods [4]. We interpret this difference as due to the fact that unlike for the cited papers, our study is in practice anchored to the regime of low pion transverse momenta and high rapidities ($x_F \geqslant 0.1$, $y \gtrsim y_{\text{beam}}$), most sensitive to the spectator charge. Finally, we remark that our simulation noticeably overpredicts the measured π^+/π^- ratios in the region $x_F \leqslant 0.05$, that is at central rapidities. This we attribute to the effect of participant charge, reported before at SPS energies [31]. We leave this effect for a future analysis.

D. Transverse expansion

In the present and following section we discuss the possible influence of two additional effects on the results of our calculation. First we address the issue of the transverse expansion of the fire-streak matter, up to now neglected in our analysis. This we estimate by modifying the transverse position of pion emission points at the pion emission time τ, with respect to the original fire-streak transverse position (b_x, b_y). Consequently, the transverse coordinates of the pion emission point are taken as:

$$x = b_x + \Delta x, \tag{15}$$

$$y = b_y + \Delta y. \tag{16}$$

Where the displacements Δx and Δy are randomly generated from a flat two-dimensional distribution within a maximum radius R given as

$$R = r_0 + \beta_{tr} \cdot \tau. \tag{17}$$

where we set $r_0 = 0.5$ fm as representative for the original transverse size of the fire streak while β_{tr} is tentatively set to $0.5c$. The result of this modification is shown as dash-dotted line in Fig. 12. The corresponding effect appears basically negligible, which we interpret as a consequence of the fact that the transverse expansion of the fire streak as modeled above will not modify the average transverse position of the pion emission point with respect to the spectator system, while the broadening of the corresponding distribution of (x, y) points will remain moderate for the values of τ discussed in Sec. V C. Thus we conclude that transverse expansion of fire streaks will not modify our conclusions significantly.

E. Vorticity of fire streaks

Another effect to be considered is the well-known phenomenon of vorticity of strongly interacting matter created in the collision [32]. This effect is potentially important as the rotation of fire streaks driven by shear viscosity, even for a short time in the early stage of the collision, will modify their trajectories and consequently also the position of the pion emission points with respect to the spectator system.

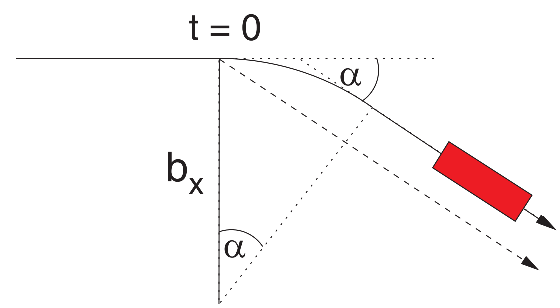

FIG. 13. Schematic drawing of the modification of fire-streak trajectory by rotation around the geometric center of the collision.

In the present section we estimate this effect in the following simplified way:

(i) We assume that starting from the moment of closest approach of the two nuclei ($t = 0$), the fire streaks rotate for a short time around the geometrical center of the collision, in a way that deflects their trajectory by a given small angle α (Fig. 13). We note that as it will be shown below, the value of the angle α can be constrained by experimental data on directed flow as a function of rapidity.

(ii) Consequently we assume that after the rotation by the angle α is complete, the fire streak will follow its modified trajectory until the time t in collision c.m. system reaches the value $t = \beta\gamma\tau$, where β is the total fire-streak velocity and $\gamma = (1-\beta^2)^{-\frac{1}{2}}$. At that moment t pions are emitted from the fire streak. As it follows from the above the pion emission point is shifted in the transverse (and also longitudinal) direction with respect to the case with no rotation, which we considered in Sec. V C. The size of the above shift increases with increasing α and τ.

(iii) Finally, the pion emission occurs following the prescription provided in Sec. III but taken along the modified fire-streak trajectory, that is, it is rotated by the angle α. We assume azimuthal isotropy of pion emission in the rotated frame (which corresponds, for the case with no rotation, to the simulation without flow shown in Fig. 12 as blue dashed line). The kinematical variables of the emitted pions in the rotated frame are recalculated back to the original collision c.m. system frame.

On the technical level, we simplify the simulation by assuming the fire-streak trajectory to be directly tilted by the angle α as it is shown in Fig. 13 (dashed line). This approximation appears excellent for the values of α considered here: the corresponding shift of the pion emission point is of the order of α^2 in the transverse and α^3 in the longitudinal direction.

In Fig. 14, we present the result of our simulation for the initial directed flow of pions (before the action of the EM field), assuming the rotation of the fire streaks by the angle

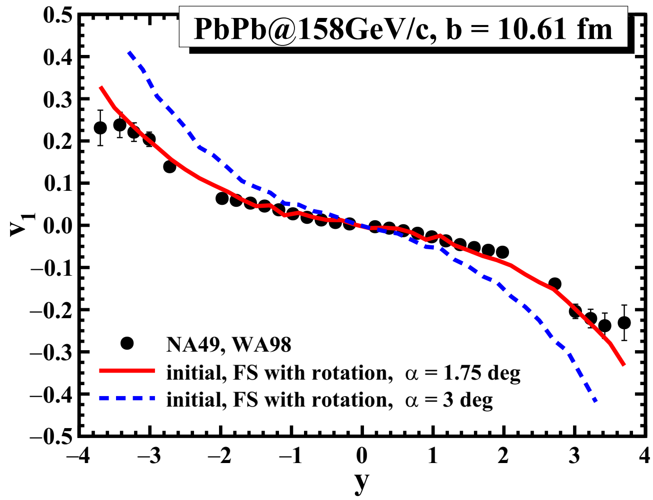

FIG. 14. Directed flow of initially emitted pions as a function of rapidity obtained by our simulation assuming fire-streak rotation by $\alpha = 1.75$ deg, superimposed with the experimental data from Refs. [22,23]. Our prediction for $\alpha = 3$ deg is also shown for comparison.

$\alpha = 1.75$ deg, and compared to experimental data on charged pion directed flow from NA49 and WA98 shown before in Fig. 5. As it is evident from the figure, in our model the sidewards deflection of pion emission induced by the rotation of the fire streaks results in rapidity-dependent pion directed flow. This rapidly increases with the angle α resulting from the rotation, thus the experimental data on $v_1(y)$ can be used to constrain the value of the latter angle. We find that rotation by $\alpha = 1.75$ deg gives a good description of the experimental data. We find this fact interesting in itself, as it shows that within our simple approach a connection exists between the measured directed flow and vorticity.

As a consequence the above, in Fig. 15 (dash-dotted curve) we present the result of our full simulation made for the same values of τ as discussed in Sec. V C (Fig. 12, blue dashed curve) but including the rotation of fire streaks by a total angle $\alpha = 1.75$ deg. Evidently no significant change is visible with respect to the case with no rotation also shown in the figure (dashed curve). This is due to the small value of the angle α allowed for our model by the experimental data on v_1 (Fig. 14), which also results in a small displacement of the pion emission points. We conclude that for the relatively short pion emission times τ discussed here, fire-streak vorticity has no much effect on the electromagnetic distortion of π^+/π^- ratios. We also note the difference remaining between the result of our study on fire-streak rotation, and that made in Sec. V C where we applied directed flow from an explicit parametrization of experimental data as a function of pion rapidity and p_T. This we interpret as originating from the imperfect description of the p_T dependence of directed flow by our simplified model of fire-streak rotation, a subject we leave for a future study.

VI. SUMMARY AND CONCLUSIONS

In the present paper we investigated whether the electromagnetic effects observed in the projectile hemisphere of peripheral Pb + Pb collisions at SPS energies [2] can be described within the fire-streak model, in its simplified formulation from Ref. [8]. This model was shown to describe the broadening of the pion rapidity distribution as a function of centrality (or impact parameter). In our opinion the fire-streak picture provides realistic initial space-time conditions for quark-gluon plasma creation.

In the fire-streak model the plasma expands in the longitudinal direction, with its speed depending on the position in the impact parameter plane. The parts that are close to spectators move with velocities only slightly smaller than those of the spectators themselves. Pions are created after some

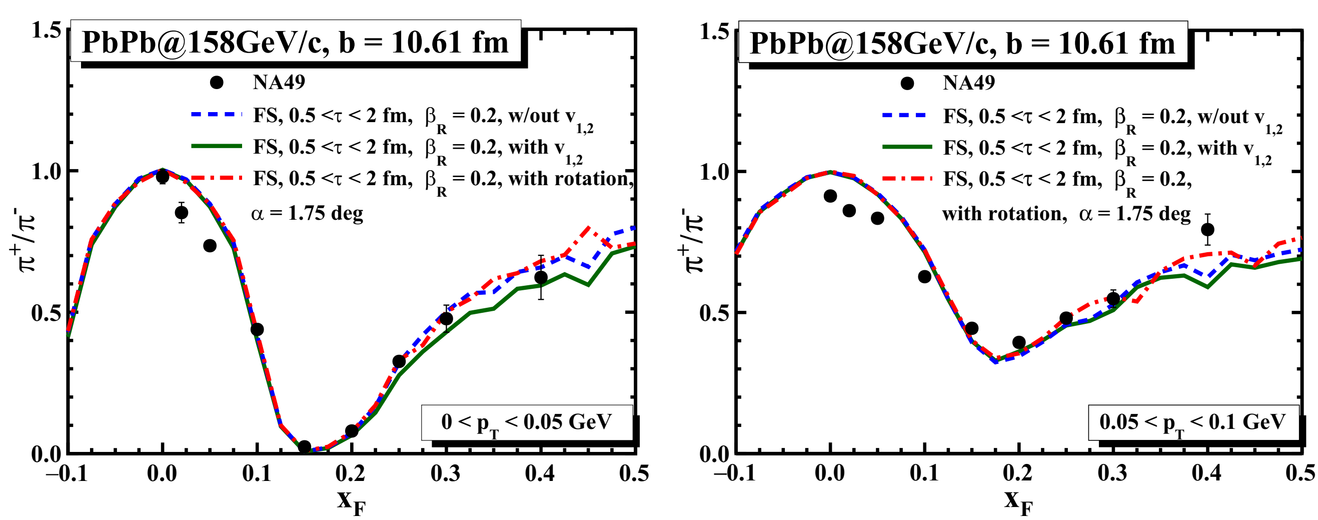

FIG. 15. The effect of inclusion of fire-streak rotation as described in the text on the observed π^+/π^- ratio (dash-dotted red lines). The dashed blue lines are for the case when no flow is taken into account and the green solid lines are for the case when flow is taken into account in the way described in Sec. V C (both dashed blue and green solid lines are the same as in Fig. 12).

time related to the hadronization process, which we treated with the help of a free parameter. After being created charged pions undergo strong electromagnetic fields generated by fast moving spectators (both electric and magnetic in the nucleus-nucleus center-of-mass system).

In sequence, we investigated the role of the different contributions to the observed effect: the transverse positions of the fire streaks, isospin differences between π^+ and π^- production, the longitudinal evolution of the system and corresponding pion creation time, and spectator expansion. We have obtained a satisfactory description of the experimental data for faster pions ($x_F \geqslant 0.1$). Rather small pion creation times have been necessary to describe the data ($0.5 < \tau < 2$ fm/c). These times are much shorter than claimed from other methods. We interpret this difference as resulting from the fact that our study was anchored to high pion rapidities, while the works summarized in Ref. [4] were dominated by the central rapidity region of pion production. A significantly better description of the experimental data was achieved once spectator expansion was taken into account. The postulated surface radial velocity of spectator expansion is $\beta_R = 0.2$. The corresponding mean expansion velocity, $0.15c$ is reminiscent of results obtained at lower energy [30].

In the present paper we have discussed also the role of the v_2 and v_1 flow for the electromagnetically modified π^+/π^- ratio. The v_2 and v_1 coefficients have been fitted to the NA49 and WA98 data as a function of the pion rapidity and transverse momentum. The proposed parametrization has been used then as an initial condition for the evolution of charged pions in the electromagnetic field of spectators. While the elliptic flow has turned out to be unimportant for the π^+/π^- ratio, the directed flow turned out to somewhat reduce the π^+/π^- ratio for $x_F > 0.25$.

Finally, we also evaluated the possible influence of transverse expansion of fire streaks, as well as of their vorticity on our results for π^+/π^- ratios. From our simple estimates we concluded no significant influence of neither effect on the electromagnetic distortion of π^+/π^- ratios. On the other hand, we have found that rotation of fire streaks results in the presence of rapidity-dependent directed flow. Consequently, after the inclusion of the latter rotation we have found that our model provides a satisfactory description of the experimental data on pion v_1 as a function of rapidity, which can be used to constrain the rotation angle. A rather small angle, smaller than 2 deg, is needed to describe the experimental data of NA49 and WA98 collaborations.

To sum up, it was demonstrated in previous works [8,17] that the fire-streak model, in its simplified formulation presented therein gives a good description of the centrality dependence of pion rapidity spectra at SPS energies. At present we conclude that the same model can properly describe the electromagnetic effects on charged pion ratios at large rapidity.

ACKNOWLEDGMENT

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