Spectator-induced electromagnetic effect on directed flow in heavy ion collisions

A. Rybicki[1,*] and A. Szczurek[1,2,†]

[1]*H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, 31-342 Kraków, Poland*
[2]*University of Rzeszów, Rejtana 16, 35-959 Rzeszów, Poland*
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We estimate the electromagnetic effect of the spectator charge on azimuthal anisotropies observed in heavy ion collisions. For peripheral Pb + Pb reactions at the top energy of the CERN Super Proton Synchrotron, $\sqrt{s_{NN}} = 17.3$ GeV, we predict this effect to bring very large distortions to the observed directed flow, v_1, of positive and negative pions emitted close to beam rapidity. The overall magnitude of this effect is comparable to values of v_1 reported by the WA98 experiment in the vicinity of target rapidity. We argue that also at lower rapidities the spectator-induced electromagnetic effect may result in the splitting of values of v_1 observed for positive and negative pions. Such a splitting is visible in the data reported by the STAR Collaboration from the BNL Relativistic Heavy Ion Collider Beam Energy Scan. Both effects are sensitive to the space-time scenario assumed for pion emission. Therefore, they bring new information on the collision dynamics.

I. INTRODUCTION

Azimuthal correlations between particles and the reaction plane, observed in noncentral collisions, constitute one of the main subjects of heavy ion collision studies. Since the primary nucleon-nucleon collisions being believed to be insensitive to the reaction plane, the latter phenomena are considered to be the source of information on *collective effects* present in the heavy ion reaction. A rich phenomenology [1–7] has therefore been developed. Among others, the success of the hydrodynamical approach [8] in describing these phenomena is to be quoted here.

The azimuthal correlations are usually quantified in terms of the Fourier coefficients of the azimuthal distribution of the outgoing particles with respect to the reaction plane. These are defined by [9]

$$v_n \equiv \langle \cos[n(\phi - \Psi_r)] \rangle, \qquad (1.1)$$

where ϕ denotes the azimuthal angle of the emitted particle, while Ψ_r is the orientation of the reaction plane defined by the impact parameter vector $\vec{b}$. Specifically, the first-order coefficient

$$v_1 \equiv \langle \cos(\phi - \Psi_r) \rangle \qquad (1.2)$$

reflects the *sideward collective motion* of the particles and is known as directed flow. A very sizable amount of experimental data on directed flow is at present available from the low-energy regime up to Large Hadron Collider energies [10–20]. It is known that v_1 depends on collision centrality, particle type, transverse momentum, and rapidity. For instance, the rapidity dependence of pion directed flow at Super Proton Synchrotron (SPS) energies is known to consist of a smooth passage through zero at midrapidity [16], while large values of v_1, of the order of 0.2–0.25, are reported

in the vicinity of target rapidity, in semicentral collisions [21].

In the present paper we point at the possible *electromagnetic component* of directed flow.

We estimate the size of the spectator-induced electromagnetic interaction on the collective motion of positive and negative pions. The spectator-induced electromagnetic effect on charged pion ratios $(\frac{\pi^+}{\pi^-})$ was discussed in our earlier paper [22]. This effect is in fact observed in experimental data [23] and results in very large distortions in ratios of charged pions observed at high rapidities and low transverse momenta. Measurements of directed flow offer a new way of spotting the influence of the spectator charge on the emission of final-state particles. They also provide a new source of information on the space-time evolution of the nonperturbative process of pion production.[1]

Our present analysis will be focused on peripheral Pb + Pb collisions occurring at the top energy available to SPS heavy ion experiments ($\sqrt{s_{NN}} = 17.3$ GeV). We choose peripheral collisions because they are characterized by the largest spectator charge and also large values of directed flow. We focus on the SPS energy range by virtue of the abundance of experimental data on the rapidity dependence of v_1, which also gives the possibility of comparison with our results as explained in Sec. III.

We note that the energy range of the SPS partially overlaps with that of the BNL Relativistic Heavy Ion Collider (RHIC) Beam Energy Scan, addressed in short in Sec. V.

This paper is organized as follows. Section II contains the description of our Monte Carlo model. In Sec. III we present the results of our simulation, together with the comparison to experimental data. The discussion of our results is made in Sec. IV. In Sec. V, we comment on the experimental data from

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*andrzej.rybicki@ifj.edu.pl
†antoni.szczurek@ifj.edu.pl

[1]The cited paper [22] also contains a description of various works made in the past on electromagnetic effects in low- and high-energy nuclear collisions. For more details on this subject, see [24–42].
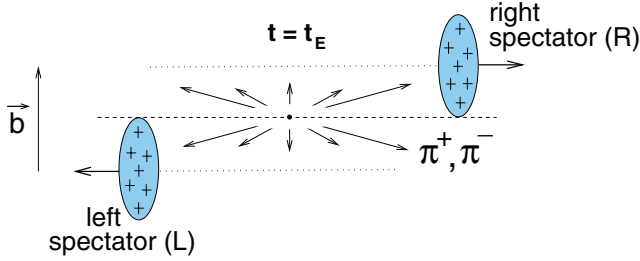
FIG. 1. (Color online) Our model of the peripheral Pb + Pb collision. The two spectator systems are denoted left (L) and right (R), respectively.

the RHIC Beam Energy Scan. Our conclusions are presented in Sec. VI.

II. THE MODEL

A detailed description of our model can be found in [22]. Only the aspects that are relevant for the present analysis will be listed below. Our aim is to obtain a realistic estimate of the influence of the spectator-induced electromagnetic interaction on the directed flow of pions. On the other hand, we wish to avoid the detailed discussion of the complex and poorly known mechanism of soft-particle production. Therefore we decide on a maximally simplified approach:

(i) We assume, as an example, a peripheral Pb + Pb collision involving $n_{\text{part}} = 60$ participating nucleons at $\sqrt{s_{NN}} = 17.3$ GeV. This is shown in Fig. 1. The two spectator systems are modeled as two homogeneous, Lorentz-contracted spheres. The reaction plane is defined by the collision axis (dashed line in the figure) and the impact parameter vector $\vec{b}$.

(ii) Charged pions are assumed to be emitted from a single point in position space, that is, the original interaction point. The time of pion emission, t_E, is a free parameter of our model; this parameter sets the initial conditions for the electromagnetic interaction. For peripheral Pb + Pb collisions studied here, the initial spectra of charged pions are assumed to be similar to those in nucleon-nucleon collisions [22].

(iii) Charged pions are then numerically traced in the electromagnetic field of the spectator charges until they reach a distance of 10 000 fm away from the interaction point and from each of the two spectator systems. The fragmentation of the spectator systems is neglected. We do not consider the effects of participant charge, strong final-state interactions, etc.

Several clarifications should be added to the above.

(i) The simplified geometry of the peripheral collision presented in Fig. 1 was determined on the basis of a dedicated study, discussed in detail in [22]. A geometrical Monte Carlo simulation served this purpose. In this model proper nuclear density profiles were used [43] and the elementary nucleon-nucleon cross section was assumed to be equal to 31.4 mb, in good agreement with

experimental $p + p$ data at this collision energy [44]. The geometrical impact parameter corresponding to 60 participating nucleons was found to be $b_{\text{geom}} = 10.61$ fm. Additionally, the center of gravity of each of the two spectator systems was found to be displaced by $\Delta b = 0.76$ fm relative to that of the original nucleus. The average spectator charge was $Q = 70$ elementary units.

Considering the exact shape of the spectator system as unimportant for our subsequent studies, and for the sake of clarity, we modeled the two spectator systems as homogeneously charged spheres. In the rest frame of each sphere, its density was the standard nuclear density $\rho = 0.17/\text{fm}^3$. The center of each sphere was additionally displaced by 0.76 fm in order to match the center of gravity of the spectator system. Thus our effective impact parameter (distance of closest approach between the two spheres' centers) was $b = b_{\text{geom}} + 2\Delta b = 12.13$ fm.

(ii) The simplification of initial conditions for pion emission (reduction of the emission zone to a single point in space and time, as discussed above) gives a convenient way to estimate the sensitivity of the electromagnetic effect to the basic characteristics of pion production (the pion formation time, the distance between the pion formation zone and the two spectator systems, etc.). The initial momentum spectra of pions (before the action of the electromagnetic field) are assumed to obey wounded nucleon scaling [45] and to be similar to underlying nucleon-nucleon events. As such, they are described by an analytical parametrization of average pion ($\frac{\pi^+ + \pi^-}{2}$) distributions in $p + p$ collisions, recorded by the NA49 experiment at the SPS [44]. More details on this parametrization are given in [22]. For simplicity, distributions of positive and negative pions are assumed to be identical. The experimental data cited above are expressed in terms of the Feynman variable[2] $x_F = 2p_L/\sqrt{s}$ and of transverse momentum p_T, and they cover the region from $x_F = 0$ to 0.85 and from $p_T = 0$ to 2.1 GeV/c. Only a small extrapolation toward higher x_F needs to be applied in the present analysis. The uncertainty of this extrapolation has little or no effect on the results presented in Sec. III. It should be underlined that full azimuthal symmetry is assumed for the initial emission of pions.

(iii) Charged pions, with their initial momentum vector defined above in point (ii), and weighted by their initial distribution, are subjected to the electromagnetic field of the two spectator systems. The pion trajectory $\vec{r}_\pi$ is given by the classical relativistic equation of motion:

$$\frac{d\vec{r}_\pi}{dt} = \vec{v}_\pi(\vec{r}, t) = \frac{\vec{p}_\pi \, c^2}{\sqrt{p_\pi^2 \, c^2 + m_\pi^2 \, c^4}}, \qquad (2.1)$$

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[2]All the kinematical variables addressed in this paper will be defined in the c.m. system of the collision.

where m_π is the pion mass, and the pion momentum is defined by the Lorentz force acting on the pion:

$$\frac{d\vec{p}_\pi}{dt} = \vec{F}_\pi(\vec{r}, t) = q_\pi(\vec{E}(\vec{r}, t) + \vec{v}_\pi(\vec{r}, t) \times \vec{B}(\vec{r}, t)). \tag{2.2}$$

Here, q_π is the pion charge, while $\vec{E}(\vec{r}, t)$ and $\vec{B}(\vec{r}, t)$ are standard superpositions of fields from the two spectator systems. Our equations take account of relativistic effects, including retardation. Technically, the propagation of the pion is performed numerically by means of an iterative procedure made in small steps in time, with variable step size. The iteration proceeds until the pion is 10 000 fm away from the interaction point and from each of the two spectator systems in their respective rest frames. Negative pions which do not escape from the potential well induced by the spectator system are rejected and do not enter into our final-state distributions.

III. RESULTS

In this section we present the results of our analysis. These will be displayed as a function of the scaled rapidity y/y_{beam}, where y and y_{beam} are the rapidity of the pion and of the incoming nucleus in the collision c.m. system. We decide on this particular variable in order to simplify the interpretation of our results and for an easier possible comparison with other collision energies (see also the discussion made in [16,46]).

A. Electromagnetic effect from one and two spectators

We start by discussing the basic features of the spectator-induced electromagnetic effect on the directed flow of pions. In particular, this will include the role of each of the two spectator systems in the overall effect. Figure 2 shows the directed flow v_1 of π^+ and π^-, induced by their electromagnetic interaction with the spectator charges. The value of v_1 is integrated over the transverse momentum of the pion, from $p_T = 0$ to 1 GeV/c. In all of the simulations presented in the figure we assume the simplest situation where the pion emission time t_E is equal to zero (immediate pion creation).

It should be underlined that as our simulation contains no initial azimuthal anisotropy (Sec. II), any nonzero value of v_1 apparent in Fig. 2 is indeed solely due to the electromagnetic interaction with the spectator systems. Therefore, we will refer to it as "electromagnetically-induced directed flow" in order to differentiate it from the "standard" flow phenomena which are caused by the strong interaction. In this context, several remarks are in order.

  (i) As is clearly apparent from the figure, the electromagnetic field induced by the spectator charges exerts a strong influence on the directed flow of charged pions. It can be held responsible for large values of v_1, exceeding 0.2 (20%) for negative pions close to beam rapidity.

 (ii) The directed flow induced electromagnetically by the two spectators (red solid curve, which goes through the black dots in the figure) exhibits a characteristic structure as a function of rapidity. Qualitatively, this structure recalls the overall behavior of pion directed flow as reported from experimental data (see, e.g., [16,21]). The directed flow displays a smooth transition through zero at $y/y_{\text{beam}} = 0$, with large values of flow (antiflow) at large negative (positive) rapidity.

(iii) The sign of electromagnetically induced directed flow for negative pions is opposite with respect to positive pions. For absolute values of v_1, differences in the shape of the two curves are seen close to beam rapidity.
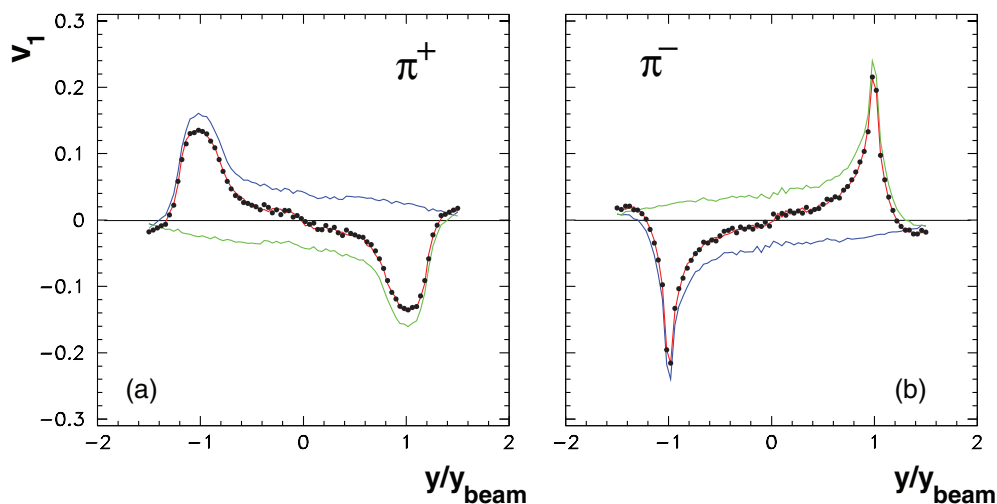

FIG. 2. (Color online) Spectator-induced electromagnetic effect on directed flow of (a) positive and (b) negative pions, in peripheral Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. The green solid curve shows the directed flow induced electromagnetically by the right (R) spectator. The blue solid curve shows the directed flow induced electromagnetically by the left (L) spectator. Black dots show the result of the addition of these two curves. The red solid curve displays the result of the simulation including both spectators. Note that in all the simulations $t_E = 0$ fm/c is assumed; the blue solid curve is obtained by reflection of the green solid curve about midrapidity.

(iv) What specifically follows from the above is that the spectator-induced electromagnetic interaction may result in the *splitting* of values of v_1 observed for positive and negative pions. This splitting exhibits a strong rapidity dependence and reaches very large values close to beam rapidity.

(v) The directed flow which is induced electromagnetically by each of the two spectators separately is also presented in the figure (with the two spectator systems being denoted "left" and "right" as in Fig. 1). The contribution of a single spectator does not remain confined to its collision hemisphere. On the contrary, it extends into the opposite hemisphere; thus the "right" spectator moving at positive rapidity exerts its influence on the pion v_1 down to and beyond $y/y_{\text{beam}} = -1$, and vice versa for the "left" spectator.

(vi) The value of v_1 obtained as the result of the electromagnetic interaction with both spectators (red solid curve, which goes through black dots in the figure) appears equal to the result of direct addition of the two single-spectator curves (displayed by the black dots).

Thus, as becomes evident from the above, the spectator-induced electromagnetic interaction appears strong enough to result in sizable effects and to play an important role in flow phenomena involving charged pions in heavy ion collisions. This imposes the necessity of more detailed studies, which will be presented below.

B. Dependence on initial conditions

The central issue of this paper is the sensitivity of the spectator-induced electromagnetic effect to the space-time evolution of the collision. This will be addressed in the present section.

Figure 3 shows the rapidity dependence of the electromagnetically induced directed flow of positive and negative pions, obtained by assuming two different values of the pion emission time: $t_E = 0$ and 1 fm/c. The values of v_1 are obtained by integration over p_T of the pion, with integration limits defined as in Sec. III A above. The curves in panels (a) and (b) of the figure are the same as the respective curves in Fig. 2. The following remarks are to be made.

(i) The electromagnetically induced directed flow displays a clear dependence on the pion emission time. In the region of beam rapidity, the position of the minimum (maximum) in the valley (peak) in pion v_1 shifts from
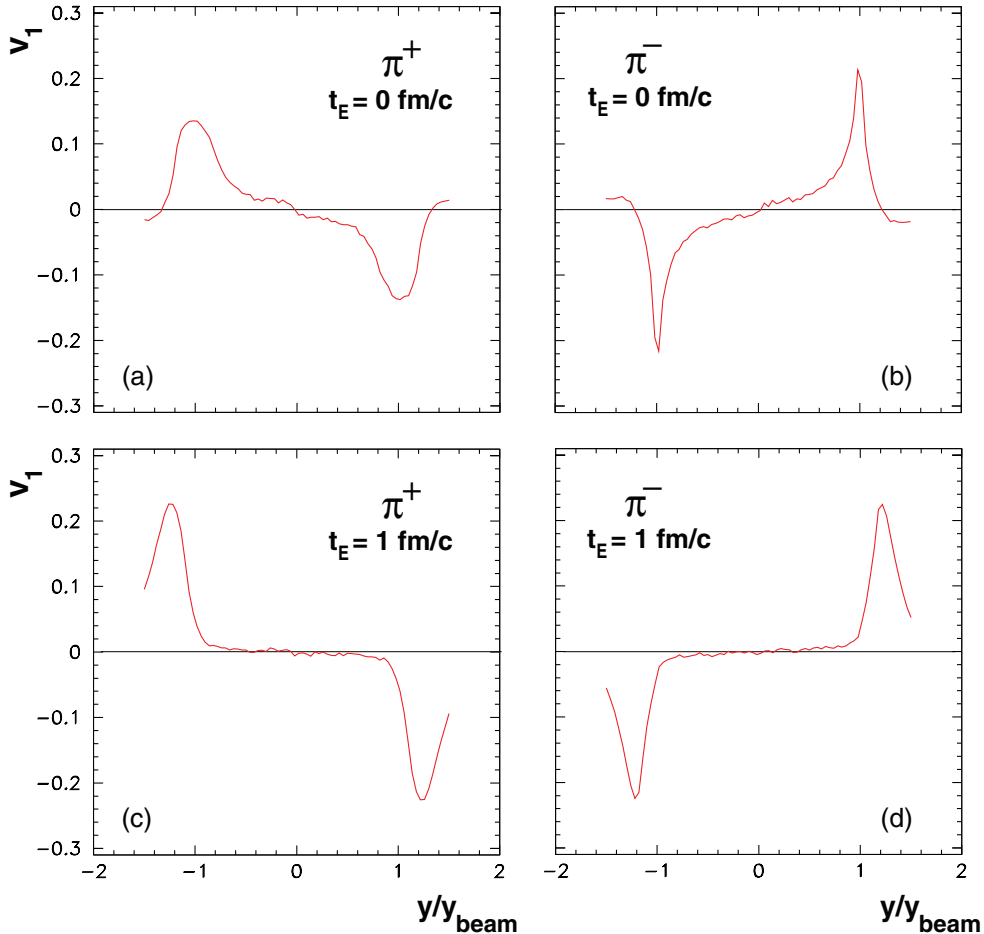

FIG. 3. (Color online) Spectator-induced electromagnetic effect on directed flow of positive and negative pions, in peripheral Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. The top and bottom panels correspond to different values of the pion emission time t_E.

$y/y_{\rm beam} = 1$ at $t_E = 0$ fm/c to above $y/y_{\rm beam} = 1.2$ at
$t_E = 1$ fm/c. At the collision energy discussed here,
this shift in $y/y_{\rm beam}$ corresponds to a shift of about 0.6
units in rapidity. The actual shape of the valley (peak)
also exhibits sensitivity to t_E.

(ii) Also in the region of lower rapidities, and down to
midrapidity, the change in t_E results in changes of v_1.
For instance, at $y/y_{\rm beam} = 0.5$ the absolute values of
v_1 go from about 2.4% at $t_E = 0$ fm/c down to about
0.5% at $t_E = 1$ fm/c.

(iii) What follows from the above is that the electro-
magnetically induced splitting of v_1 for π^+ and π^-,
mentioned in Sec. III A, will also exhibit sensitivity
to t_E.

These observations demonstrate that the spectator-induced
electromagnetic effect is indeed sensitive to the initial condi-
tions, which are set for the electromagnetic interaction by
the emission time t_E. Changes in the pion emission time,
or equivalently in the position of the pion formation zone
with respect to the two spectator systems, will result in
changes of v_1 which should be observable in experiment. In
other terms, the electromagnetic effect on directed flow is
indeed sensitive to the space-time evolution of pion produc-
tion and provides new information on the dynamics of the
collision.

C. Dependence on transverse momentum

Up to now, for simplicity, only the rapidity dependence
of p_T-integrated directed flow has been discussed in this
paper. In the present section we study its dependence on the
transverse momentum of the pion. This is shown in Fig. 4. The
electromagnetically induced directed flow exhibits a strong
dependence on pion p_T. In particular, this is valid close to
beam rapidity where very large absolute values of v_1 (of the
order of 0.6 for positive pions) are attained at the lowest
considered value of transverse momentum, $p_T = 75$ MeV/c.
The absolute value of the electromagnetically induced v_1
rapidly decreases with increasing p_T. On the other hand,
little or no dependence on pion p_T is apparent in the region
of lower absolute values of $y/y_{\rm beam}$, down to midrapidity.
The overall pattern of dependence on initial conditions,
discussed in Sec. III B above, repeats itself also at fixed values
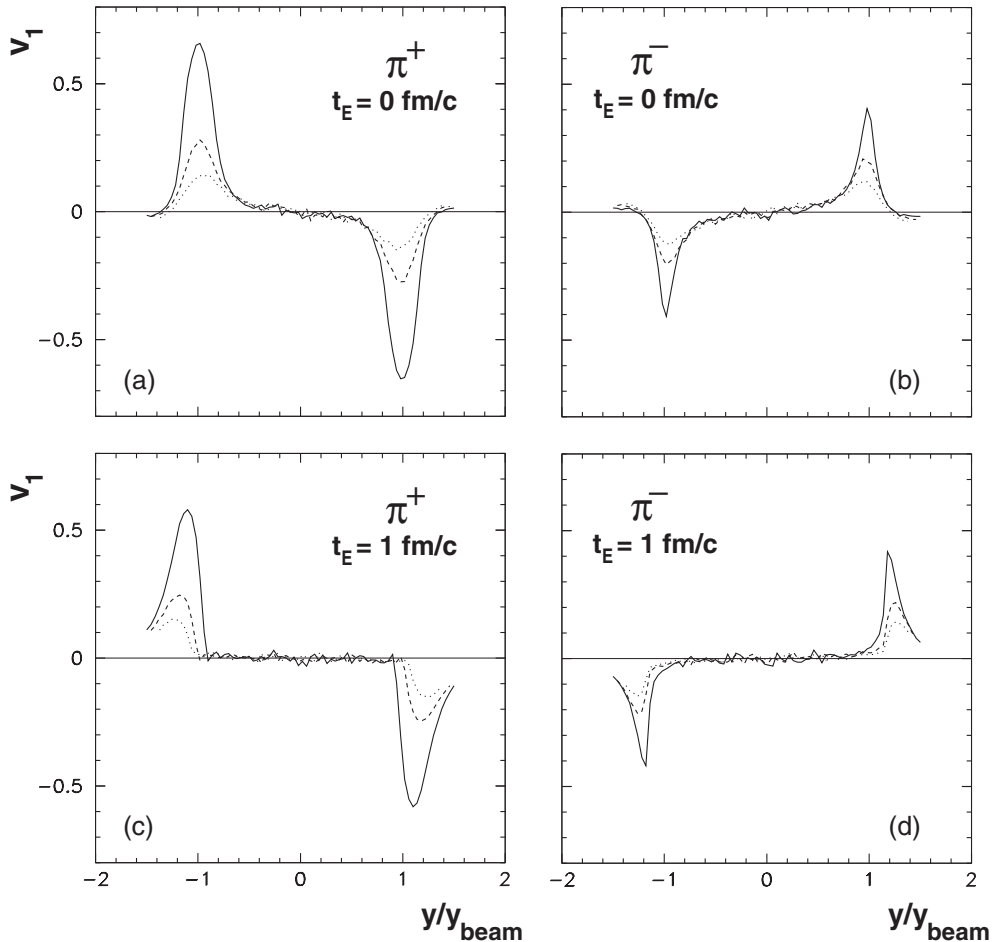of p_T.

FIG. 4. Spectator-induced electromagnetic effect on directed flow of positive and negative pions in peripheral Pb + Pb collisions at $\sqrt{s_{NN}} =$ 17.3 GeV, shown at fixed values of pion transverse momentum: $p_T = 75$ MeV/c (solid), $p_T = 125$ MeV/c (dashed), and $p_T = 175$ MeV/c (dotted). The top and bottom panels correspond to different values of the pion emission time t_E.

D. Comparison to experimental data

Given the charge-asymmetric nature of the electromagnetic effect discussed here, any comparison of our work to experimental data must involve measurements of directed flow of pions of a given charge, either π^+ or π^-. This constitutes an important practical difficulty as most results published on the rapidity dependence of v_1 involve (if particle identification is available at all) only "charged pions," i.e., summed π^+ and π^-. One data set which fulfills our requirement comes from the WA98 experiment, and it contains a measurement of positive pions near target rapidity made by means of the Plastic Ball detector, in Pb + Pb collisions at $\sqrt{s_{NN}} =$ 17.3 GeV. This measurement is presented in [21], but a more detailed description of the analysis can be found in [47]. The latter reference specifies the corresponding centrality definition as 40–80% of the Pb + Pb cross section. Following the discussion made therein, we expect that differences with respect to our definition of the peripheral collision (Sec. II) would only have a small effect on the actual values of v_1.

Figure 5 shows the experimental data from WA98, superimposed with the rapidity dependence of the electromagnetically induced directed flow as obtained from our work. For the latter, three values of the pion emission time are assumed: $t_E = 0$, 0.5, and 1 fm/c. Our results are integrated over p_T from 0 to 1 GeV/c. The curves corresponding to $t_E = 0$ and 1 fm/c are the same as in Fig. 3.

As can be seen in the figure, the values of v_1 obtained from our simulation, and resulting exclusively from the spectator-induced electromagnetic interaction, appear comparable to those measured by experiment.

The above statement should clearly be taken with some caution. Account should be taken of the simplicity of our model and of various detailed issues related to the measurement

[21]. These problems are beyond the scope of the present paper.

Nevertheless, it seems clear that a very sizable part of the measured directed flow of π^+ *may have an electromagnetic origin*. We note that this observation is consistent with our analysis of the influence of spectator charge on π^+/π^- ratios in peripheral Pb + Pb collisions at the same energy. Here, pion emission times assumed in the range $t_E = 0.5$–1 fm/c also result in good agreement between our model and experimental data [48]. These values of the t_E parameter seem to be shorter than the decoupling time necessary to understand, e.g., Hanbury-Brown-Twiss (HBT) data (see, e.g., [52]). The latter are, however, times required to understand midrapidity HBT data. In addition, these times clearly depend on center-of-mass energy (see a summary of the world data in [52]). Finally, t_E should rather be interpreted as the *distance* of the pion formation zone from the spectator, for pions emitted with approximately beam or target rapidities, than simply the pion decoupling time.

From the theoretical side the electromagnetic effect could also be present in the quarkish phase, the effect being neglected in the present analysis. This seems, however, more complicated as it includes a hadronization process which may actually strongly depend on pion (pseudo)rapidity. We think that more refined analyses, including also the possible electromagnetic splitting of higher harmonics of azimuthal distributions, are necessary in order to provide a better understanding of these issues. Only then one can start more complicated modeling of the space and time dependence of meson production.

IV. SUMMARY AND DISCUSSION

Summing up the principal results of our work, we can state the following:

(i) We devised a simple model of the Pb + Pb collision (Sec. II). This model does not contain any initial azimuthal anisotropy in pion emission but includes the electromagnetic interaction between the pion charge and the two spectator systems.

(ii) This model predicts sizable values of v_1 (electromagnetically induced directed flow) for positive and negative pions in the final state of the collision. For positive pions, the predicted values are comparable to those seen in experimental data. As such, a very large part of positive pion directed flow at and beyond the projectile and target rapidity may come from the electromagnetic interaction.

(iii) The sign of this effect is opposite for positively and negatively charged pions. This will result in a splitting of values of v_1 observed for π^+ and π^-.

(iv) The size of electromagnetically induced directed flow, and therefore also the size of the electromagnetic splitting addressed above, depends on the pion emission time t_E. The latter parameter defines, in our model, the details of the space-time evolution of pion production, such as, e.g., the time of pion formation, or the position of the pion formation zone with respect to the spectator system(s).
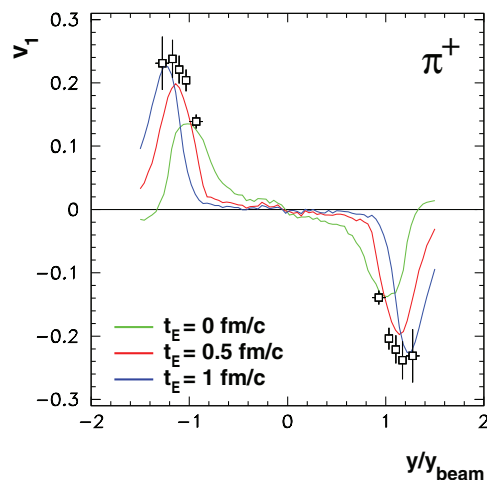

FIG. 5. (Color online) Comparison between experimental data on directed flow of positive pions obtained by the WA98 experiment (with data points redrawn from [21]) and our simulation of electromagnetically induced directed flow of π^+. The three curves correspond to three different values of the assumed pion emission time t_E. Note that the data points at positive $y/y_{\rm beam}$ are obtained by reflection about midrapidity.

(v) As follows from the above, the electromagnetically induced directed flow, and the resulting splitting of v_1 for π^+ and π^-, bring new information on the space-time dynamics of the Pb + Pb reaction.

This has, in our view, important consequences for future studies of directed flow. It is of course clear that our model contains important simplifications. Among others, it intentionally neglects the initial pion flow induced by the strong rather than the electromagnetic force.[3] The inclusion of such phenomena is the domain of more detailed models and we leave it for future studies. However, it is clear from our work that the electromagnetic splitting of $v_1(\pi^+)$ and $v_1(\pi^-)$ addressed above will remain present also in more sophisticated phenomenological descriptions of the heavy ion collision. This inspires a set of proposals and remarks listed below.

(i) The study of the rapidity dependence of directed flow made separately for pions of a given charge, i.e., π^+ and π^-, will bring additional information on the dynamics of the heavy ion collision. This information will add up to the already rich phenomenological content of summed charged pion flow studies. The electromagnetic splitting of v_1 for positive and negative pions will provide information about the position of the pion formation zone with respect to the spectator systems. Specifically, also the lack of such splitting at a given rapidity would imply that the formation of pions occurs relatively far from the nearest spectator.

(ii) The situation should be similar for other produced particles, such as e.g., charged kaons. The situation for final-state protons should be at least partially different as protons at forward rapidity will come also from spectator fragmentation [24,49,50]. However, also in this case the role played by the electromagnetic repulsion of protons from the spectator systems should be investigated in detail.

(iii) Last but not least, our analysis brings attention to *asymmetric* nuclear collisions, e.g., $A + B$, $d + A$, or $p + A$ reactions. In such collisions, the electromagnetic influence of the two spectators would not cancel out at midrapidity, and therefore the role of single spectators could be isolated, yielding further information on the space-time evolution of the collision (see Fig. 2 for comparison).

All of the above observations are consistent with the results of our study of spectator-induced electromagnetic forces acting on charged pion ratios [22]. However, we feel that the precision of the present experimental measurements of the size of directed flow, the key role played by flow measurements in the present phenomenology of heavy ion collisions, and the overall interest of the community in such studies make the consideration of the role played by electromagnetic interactions important for future analyses.

V. DATA FROM THE RHIC BEAM ENERGY SCAN

In the context of the discussion above, and based on the comparison between the results of our simulation and existing SPS experimental data, it is important to note that the RHIC Beam Energy Scan (BES) program can also address the search for the spectator-induced electromagnetic effects discussed here.

Specifically, preliminary data on directed flow of positive and negative pions from the STAR experiment have already been reported in [51]. The measured values of $v_1(\pi^+)$ and $v_1(\pi^-)$ indeed display a signal of splitting which increases with increasing rapidity. At positive rapidity, $v_1(\pi^+)$ remains below $v_1(\pi^-)$, which follows our predictions for the electromagnetically induced directed flow, formulated in Secs. III A and III B above.

Presenting final conclusions on the nature of this effect probably requires more precise modeling of the space-time mechanism of charged pion production, including also its centrality dependence.

However, we note that the overall magnitude of the splitting of v_1 values seen by experiment looks (roughly) comparable to that predicted in the preceding sections, for the largest assumed values of the pion emission time t_E and in the relatively limited range of y/y_{beam} available to the measurement [51]. Thus, we believe that the observed splitting is indeed a signature of electromagnetically induced directed flow.

VI. CONCLUSIONS

The electromagnetic field induced by the presence of spectator systems may result in sizable distortions of the directed flow pattern observed for pions of a given charge (that is, π^+ and π^-) produced in heavy ion collisions. This implies the presence of the electromagnetic splitting of v_1 for particles of opposite charges. The size of this splitting depends on the space-time scenario of pion production and therefore brings new information on the collision dynamics. The comparison to experimental data suggests that a very large part of directed flow observed for positive pions may be of electromagnetic origin.

New experimental and phenomenological studies are needed in order to elucidate these questions, and possibly bring new insight into the evolution of the heavy ion reaction in space and time. On the experimental side, this implies measurements of particles of specific charges, for symmetric and asymmetric nuclear reactions. On the theoretical side, the possibility of verification of existing models of the heavy ion reaction by taking into account spectator-induced electromagnetic effects should be investigated. Furthermore, studies of the role of spectator-induced electromagnetic interactions for higher harmonics of the azimuthal distribution would also be highly indicated.

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[3]We keep in mind that the inclusion of the latter is necessary in order to describe the summed charged pion data (see, e.g., [16]).

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