Spectator charge splitting of directed flow in heavy ion collisions

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work in collaboration with Andrzej Rybicki

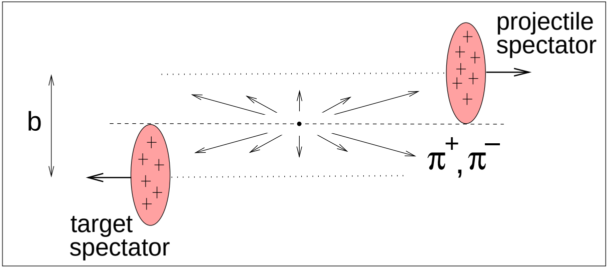
Introduction

- Noncentral collisions unambigously lead to azimuthal asymmetries and presence of spectators.
- Azimuthal correlations between particles and the reaction plane -- one of the main subjects of heavy ion collisions
- They provide information about collective effects.
- The presence of charged fast moving spectators generate strong electromagnetic fields.
- The electromagnetic effects modify single particle spectra.
- Does the electromagnetic effects influence the azimuthal correlations?
- If yes, can we gain a new information on the dynamical evolution of the participant system?

Introduction

1. The EM fields generated by the remnants (spectators) of peripheral collisions distort the charged pion spectra
   A. Rybicki and A. Szczurek,
   Phys. Rev. **C75** (2007) 054903.
2. This was supported by precise NA49 experimental data at $\sqrt{s_{NN}}$ = 17.3 GeV
   A. Rybicki,
   Acta Phys. Polon.**B42** (2011) 867.
3. Spectacular effects predicted and observed:
   - A dip for π^+ at $x_F = 0.15$
   - An accumulation of strength for π^- at $x_F = 0.15$
4. A. Rybicki and A. Szczurek,
   ``Spectator induced electromagnetic effect on directed flow in heavy ion collisions'', Phys. Rev. **C87** (2013) 054909.

Modelling a Peripheral Pb+Pb Collision

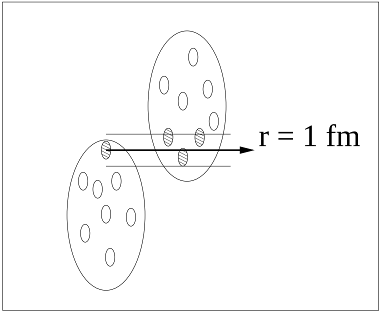


1. the collision takes place at a given impact parameter *b*.
2. The two charged spectator systems follow their initial path.
3. the participating system evolves until pions are produced.
4. charged pion trajectories are modified by EM interaction.
5. the spectator systems undergo a complicated nuclear deexcitation/fragmentation process (not fully understood).

Modelling a Peripheral Pb+Pb Collision at SPS

1. a peripheral Pb+Pb collision with a given number of participating N's (then b is fixed). The spectator systems = uniform spheres in their respective rest frames. $\rho = 0.17/\mathrm{fm}^3$. In CM frame the two spheres -- disks.
2. the pion emission -- single point in space. The emission time t_E is a free parameter. We assume that the initial (x_F, p_T) distribution of the emitted pion is that for underlying N+N collisions (rescaled).
3. charged pions, with their initial momenta traced in the EM field of the spectator charges until they reach a distance of 10,000 fm (from the original interaction point and from each of the two spectator systems).
4. the fragmentation of the spectator systems is neglected, the influence of participant charge, strong FSI are not considered.

Collision Geometry



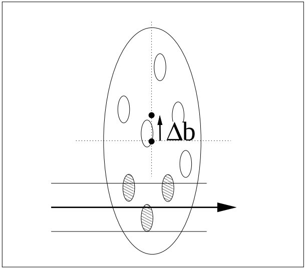
1. We adjust the geometry (centrality) of the Pb+Pb collision to 60 participating nucleons in order to make it comparable to the data sample from SPS.
2. The relation between the impact parameter b, the number of participating nucleons N_{part} and the spectator charge Q is defined by the nuclear density profile and the N+N cross section.

Collision geometry

How we fix initial impact parameter ?

1. We study this by means of a Monte Carlo simulation. Spatial distributions $\rho_p(r)$ and $\rho_n(r)$ for ^{208}Pb from Hartree-Fock-Bogoliubov (HFB) approach Mizutori et al. Our Monte-Carlo takes into account the neutron halo effect.
2. Nucleon is defined as participant if it is crossed by one or more nucleons from the other nucleus within a transverse radius of less than 1 fm.
3. We modify b until we get 60 participating nucleons.

Collision Geometry

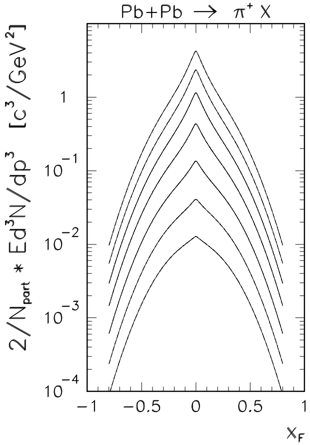


1. Another important parameter -- displacement Δb of the spectator protons′ centers w.r.t. the center of gravity of the original nucleus. Our MC gives $\Delta b = 0.76$ fm. Thus the effective distance of the closest approach between the spectator centers $b' = b + 2\Delta b = 12.13$ fm.
2. The spectator systems -- homogenous spheres with ρ=0.17/fm^3 and with properly shifted centers.

Initial Pion Emission

1. We reduce the unknown initial emission region to a unique point in space -- the original interaction point. We assume one emission time t_E (a free parameter).
2. We assume that the initial kinematical spectra of the emitted pions are similar to these in N+N collisions and that they follow wounded nucleon scaling.
3. Full azimuthal symmetry of the emission is assumed.
4. We neglect isospin effects i.e. assume equal initial emission spectra for π^+ and π^-
5. We construct a smooth two-dimensional parametrization that reproduces the most basic features of the pion production in pp coll. (it does not include the more subtle, local shape structures).

Initial Pion Emission



$p_T = 50, 100, 200, 400, 600, 800$, and 1000 MeV/c

The two top curves multiplied by 2.5 and 1.5. Good description of the NN data

Initial Pion Emission

Assumed form:

$$\frac{2}{N_{part}} \left. E\frac{d^3N}{dp^3} \right|_{Pb+Pb\to\pi X} = \sum_{n=1,2} a_n \exp\left(-(x/b_n)^{c_n}\right) \exp\left(-u_T/d_n\right) \quad , \quad (1)$$

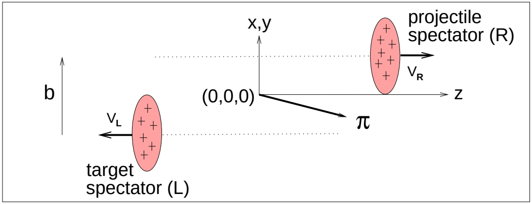
where $\pi = \pi^+$ or π^-, $N_{part} = 60$, $x = \sqrt{x_F^2 + g^2}$, $u_T = \sqrt{q^2 + p_T^2}$,

Parameters:

n	a_n (c^3/GeV^2)	b_n	c_n	d_n (GeV/c)		
1	2.32229	0.369967	2.	0.191506	$g =$	0.01
2	24.4563	0.0873833	1.001	0.12	$q =$	0.334968 (GeV

Propagation of Pions in the EM Field

1. The initially produced charged pions are subjected to the EM field of the two spectator systems. The spectator velocity remains constant and identical to the velocity of the parent Pb ion ($v_L = v_R \equiv v_S = 0.994c$).
2. We choose the overall CM system to calculate the evolution of pion trajectories. For symmetric Pb+Pb collisions this is also the N+N CM system.



Propagation of Pions in the EM Field

Time scale: such that at $t = 0$ the center of gravity of each of the spectator systems is found at $z_L = z_R = 0$.

$$\begin{aligned} \vec{R}_L(t) &= -\vec{b}/2 + \vec{v}_L \cdot t \ , \\ \vec{R}_R(t) &= \vec{b}/2 + \vec{v}_R \cdot t \ . \end{aligned} \quad (2)$$

In the rest frames of spectators:

$$\vec{E}'_L(\vec{r}'_c) = \begin{cases} k\ Q\ \vec{r}'_c\ /\ {r'_c}^3 & \text{for} \quad r'_c > R_s \\ k\ Q\ \vec{r}'_c\ /\ {R_s}^3 & \text{for} \quad r'_c < R_s \end{cases} \quad (3)$$

$$\vec{E}''_R(\vec{r}''_c) = \begin{cases} k\ Q\ \vec{r}''_c/{r''_c}^3 & \text{for} \quad r''_c > R_s \\ k\ Q\ \vec{r}''_c/{R_s}^3 & \text{for} \quad r''_c < R_s \end{cases} \quad (4)$$

$k \approx 1.44\ \mathrm{MeV \cdot fm}/e^2$, $R_s = [N_{spec}/(4/3\pi\rho)]^{1/3}$ is the sphere radius defined by N_{spec} ($R_s = 6.3$ fm).

Propagation of Pions in the EM Field

We transform the fields $\vec{E}'_L, \vec{E}''_R$ to the CM system (both electric and magnetic fields). From the general Lorentz transformation we get

$$\vec{E}_L(\vec{r},t) = \gamma_s \vec{E}'_L(\vec{r}'_c) - \frac{\gamma_s^2}{\gamma_s+1}\frac{\vec{v}_L}{c}\left(\frac{\vec{v}_L}{c}\cdot\vec{E}'_L(\vec{r}'_c)\right),$$
$$\vec{B}_L(\vec{r},t) = \gamma_s\left(\frac{\vec{v}_L}{c}\times\vec{E}'_L(\vec{r}'_c)\right) \tag{5}$$

for the left spectator and

$$\vec{E}_R(\vec{r},t) = \gamma_s \vec{E}''_R(\vec{r}''_c) - \frac{\gamma_s^2}{\gamma_s+1}\frac{\vec{v}_R}{c}\left(\frac{\vec{v}_R}{c}\cdot\vec{E}''_R(\vec{r}''_c)\right),$$
$$\vec{B}_R(\vec{r},t) = \gamma_s\left(\frac{\vec{v}_R}{c}\times\vec{E}''_R(\vec{r}''_c)\right) \tag{6}$$

for the right spectator.

Propagation of Pions in the EM Field

We now consider a charged pion emitted at time $t = t_E$ from the interaction point $\vec{r} = (0,0,0)$ with its initial momentum $\vec{p}_\pi(t = t_E)$.

$$\frac{d\vec{p}_\pi}{dt} = \vec{F}_\pi(\vec{r},t) = q_\pi \left(\vec{E}(\vec{r},t) + \frac{\vec{v}_\pi(\vec{r},t)}{c} \times \vec{B}(\vec{r},t) \right) . \qquad (7)$$

$\vec{E}(\vec{r},t) = \vec{E}_L(\vec{r},t) + \vec{E}_R(\vec{r},t)$ and $\vec{B}(\vec{r},t) = \vec{B}_L(\vec{r},t) + \vec{B}_R(\vec{r},t)$ are standard superpositions of fields.

The resulting pion trajectory $\vec{r}_\pi(t)$ is defined by its time-dependent velocity $\vec{v}_\pi(\vec{r},t)$:

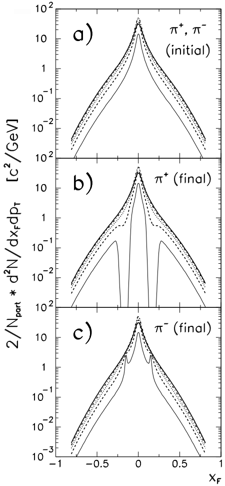
$$\frac{d\vec{r}_\pi}{dt} = \vec{v}_\pi(\vec{r},t) = \frac{\vec{p}_\pi \; c^2}{\sqrt{p_\pi^2 + m_\pi^2}} . \qquad (8)$$

Our calculation implicitly takes account of relativistic retardation effects (Jackson).

Propagation of Pions in the EM Field

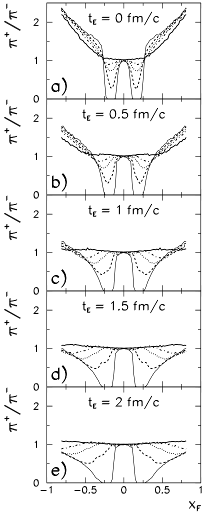
1. The propagation of the pion is made by means of an iterative Monte-Carlo procedure. This procedure starts at $\vec{r} = (0,0,0)$ and $t = t_E$ and calculates $\vec{F}_\pi(\vec{r},t)$, pion momentum and position in small steps in time.
2. The variable step size (!)
3. The procedure is iterated numerically until the distance of the pion from the origin $(0,0,0)$ is $r > R_{max}$ and from the spectators (in their respective rest frames) are $r'_c > R_{max}$ and $r''_c > R_{max}$. R_{max} = 10,000 fm is sufficiently large to reproduce asymptotic momenta.
4. The procedure is weighted -- each pion is generated with its proper weight $\frac{d^2N}{dx_F\,dp_T}$ (used to fill the final state pion spectra).
5. Negatively charged pions that do not escape from the spectator potential well are rejected by our procedure.

Charged Pion Spectra



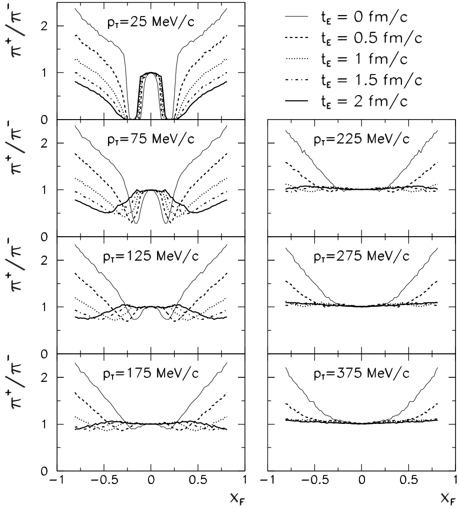
The effect is largest for pions moving close to spectator velocities ($x_F \approx \pm 0.15$) and at low transverse momenta ($p_T = 25$ MeV/c).

π^+/π^- Ratios



NA49 experimental data prefer short times

π^+/π^- Ratios



t_E = 0 fm/c
t_E = 0.5 fm/c
t_E = 1 fm/c
t_E = 1.5 fm/c
t_E = 2 fm/c
p_T=25 MeV/c
p_T=75 MeV/c
p_T=125 MeV/c
p_T=175 MeV/c
p_T=225 MeV/c
p_T=275 MeV/c
p_T=375 MeV/c
π^+/π^-
x_F

Directed flow

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.

$$v_n \equiv < cos[n(\phi - \Psi_r)] >, \tag{9}$$

where ϕ azimuthal angle of the emitted particle (pion), while Ψ_r is the orientation of the reaction plane defined (in our case) by the impact parameter vector $\vec{b}$.
The first order coefficient

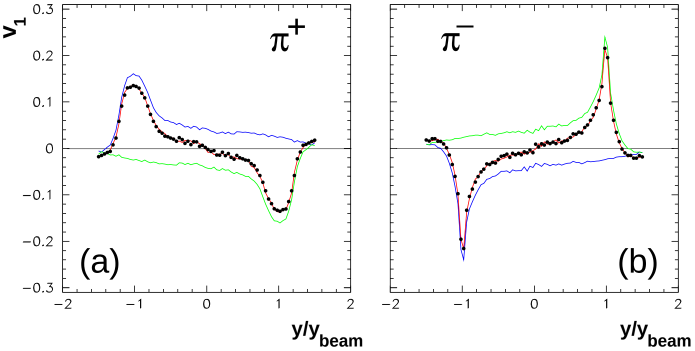
$$v_1 \equiv < cos(\phi - \Psi_r) >, \tag{10}$$

reflects the sideward collective motion and is known as directed flow.
Rich data on v_1 from FOPI, E877, WA98, NA49, STAR
but not for separate charges

What is known about directed flow

- From symmetry: $v_1(y) = -v_1(-y)$ (asymmetric function)
- v_1 has been measured at SPS, RHIC and LHC
- "Glauber" gives tilted initial conditions which leads to tilted pressure and hydrodynamics produces final v_1
  P. Bożek and I. Wyskiel, Phys. Rev. **C81** (2010) 054902.
  P. Bożek, Phys. Rev. **C85** (2012) 034901.
- the effect drops with collision energy
- $v_1^{\pi^+} \approx v_1^{flow} + v_1^{\pi^+,EM}$
  $v_1^{\pi^-} \approx v_1^{flow} + v_1^{\pi^-,EM}$
  (additivity of the effects-has been checked)
- Pure electromagnetic effect below

Results, separate spectators



Pb+Pb, $\sqrt{s_{NN}} = 17.3$ GeV

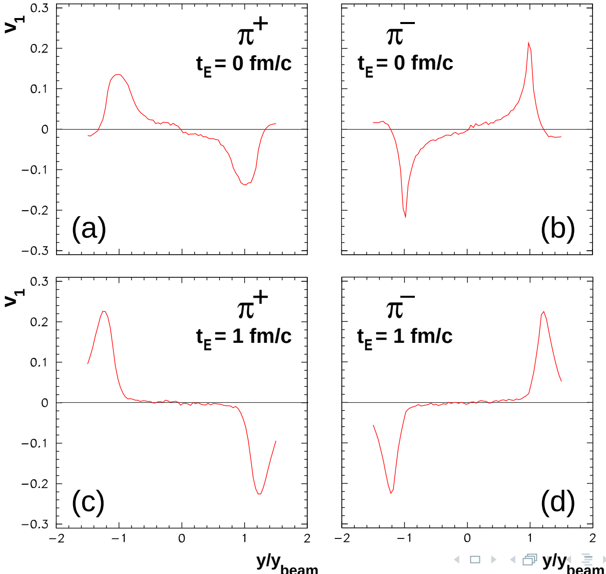
green solid -- only right spectator

blue solid -- only left spectator

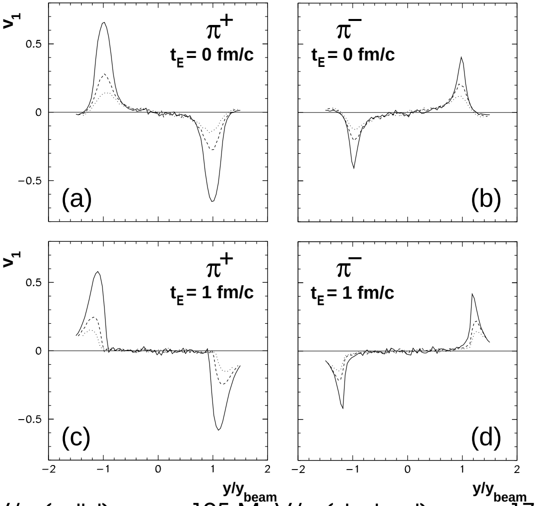
red solid -- both spectators

here t_E = 0 (!) (immediate emission)

Results, dependence on the emission time

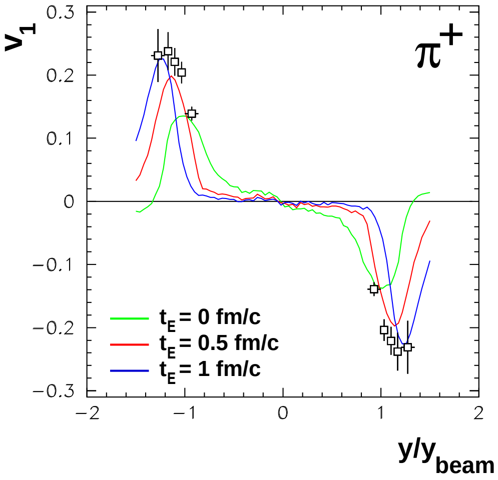


Results, dependence on transverse momentum



$p_T = 75$ MeV/c (solid), $p_T = 125$ MeV/c (dashed), $p_T = 175$ MeV/c (dotted)

Comparison to the WA98 data

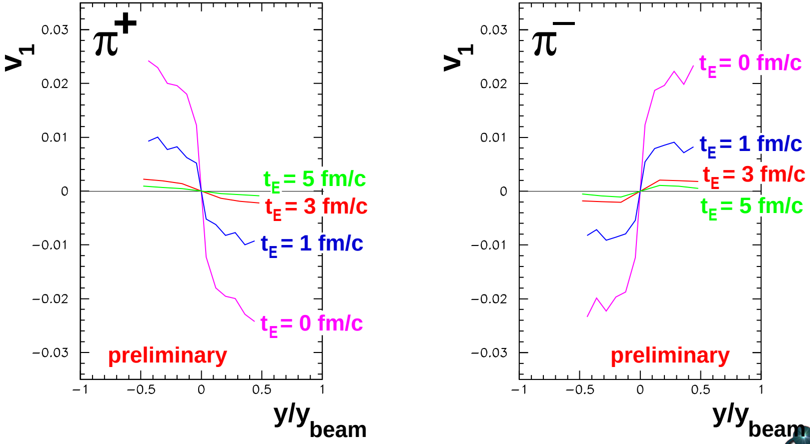


only positive pions (!)

Beam Energy Scan at RHIC

1. A separate analysis for positive and negative pions
2. Au+Au collisions, $\sqrt{s_{NN}}$ = 7.7, 11.5, 39 GeV
3. Centrality: 10% -- 40%
4. Y. Pandit, (STAR Collaboration), Acta Phys.Pol. Suppl **5**, 439 (2012)
5. A carefull analysis of collision geometry as for the NA49 data.
    1. average number of participants $\approx$ 160
    2. average number of spectators $\approx$ 114+114
6. Preliminary analysis will be presented now.

Emission time dependence of directed flow



$\sqrt{s_{NN}}$ = 7.7 GeV, STAR, Beam Energy Scan

Strong dependence on the emission time

Further simplifications for this conference

At midrapidities theory predicts:

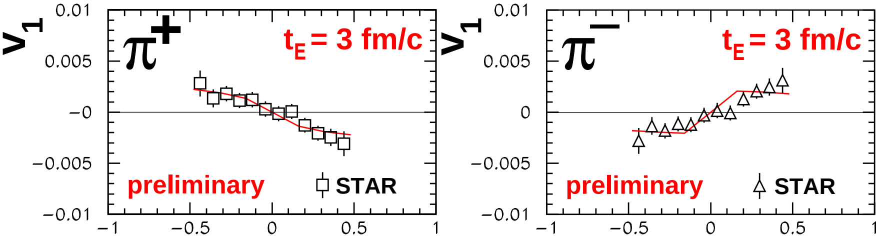
- $v_1^{\pi^+,EM} \approx -v_1^{\pi^-,EM}$

This means:

- $v_1^{\pi^+,EM} \approx (v_1^{\pi^+} - v_1^{\pi^-})/2$
- $v_1^{\pi^-,EM} \approx -(v_1^{\pi^+} - v_1^{\pi^-})/2$

The experimental data for "pure" electromagnetic directed flow is obtained in this way.

Fitting the emission time to "STAR" data



$\sqrt{s_{NN}}$ = 7.7 GeV, STAR, Beam Energy Scan

Summary/Conclusions, distortion of inclusive spectra

1. The EM interaction caused by the moving remnant charge produces visible distorsions in the final state distributions of π^+ and π^-.
2. The main feature of this ``Coulomb'' effect is a big dip in the π^+ density distribution at low transverse momenta in the vicinity of $x_F \approx \pm 0.15$, accompanied by a substantial increase of π^- density in the same region.
3. The effect is clearly sensitive to initial conditions (carry interesting information on the mechanism of the non-perturbative particle production process).
4. Our study demonstrates the importance of new, double-differential data on the x_F and p_T-dependence of pion production in peripheral nucleus+nucleus collisions.
   NA49 has such data!

Summary/Conclusions, splitting of v_1

1. Electromagnetic fields generated by charged, fast spectators lead to extra azimuthal distortions and so-called directed flow.
2. The effect on positive and negative pions is opposite and leads to a splitting of v_1. The splitting is superimposed on other effects (hydrodynamics)
3. The effect seems to be confirmed by the WA98 and STAR data.
4. The splitting strongly depends on the emission time of pions and can be therefore used to measure the emission time.
5. The splitting strongly depends on the transverse momentum of pions. This could be checked experimentally.

Outlook

1. Precise data for π^+ and π^- and different energies needed.
2. Test dependence on rapidity and transverse momentum.
3. Realistic modelling of the source is badly needed.
4. Procedure to extract emission time would be very useful (complementary information to HBT).
5. Time evolution of spectator systems should be better understood.
6. Other harmonics are also subjected to spectator EM splitting.
7. Exploration of the effect in particle species, rapidity, transverse momentum and centrality.