საქართველოს მეცნიერებათა ეროვნული აკადემიის მოამბე, ტ. 13, №3, 2019
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 13, no. 3, 2019

Physics

Study of the Multiparticle Azimuthal Correlations of Pions in π^-(p, n, C) Collisions at Momentum of 40 GeV/c

Lida Chkhaidze*, Tamar Djobava, Lali Kharkhelauri*, Lali Akhobadze***

* *High Energy Physics Institute, Ivane Javakhishvili Tbilisi State University, Tbilisi, Georgia*
***European Organization for Nuclear Research (CERN), Geneva, Switzerland*

(Presented by Academy Member Anzor Khelashvili)

ABSTRACT. Multiparticle azimuthal correlations of pions (π^- and π^+) were studied at the moment of 40 GeV/c for π^-(p, n) and π^-C collisions within the standard transverse momentum analysis technique of P. Danielewicz and G. Odyniec using different approach. In order to study the multiparticle azimuthal correlations (i. e. the "directed" and "elliptic" flows), definite direction was separated in the phase space and with respect to this axis the correlations of π^- and π^+ mesons were observed in π^-(p, n, C) interactions. The data were obtained from Propane Bubble Chamber (PBC-500) systems utilized at JINR (Joint Institute for Nuclear Research). Experiment was performed at the Serpukhov synchrophasotron. The π^-(p, n) systems are the lightest studied one, in which collective flow effects (directed and elliptic) haven ever been detected for pions (π^- and π^+). As shown, the pions exhibit directed flow in all colliding systems π^-(p, n, C) consistent with that for protons in nucleus-nucleus systems. On the other hand, the absolute value of the directed flow parameter F insignificantly changes and it is almost the same within errors for π^- and π^+ mesons in all interactions. It should be mentioned that, there is no change of the sign of the elliptic flow in these interactions. The absolute value of elliptic flow parameter a_2 increases with increasing of the mass number of target A_T nuclei in π^-(p, n, C) collisions for (π^- and π^+) and almost does not change with the change of the sign of pions. The obtained results provide important information on the mechanism of meson-nucleon and meson-nucleus interactions at 40 GeV/c, as well as on characteristics of the produced nuclear matter. *© 2019 Bull. Georg. Natl. Acad. Sci.*

Key words: multiparticle azimuthal correlations, collision, mesons, proton, pion

The flow produces asymmetries associated with the reaction plane, in the particle emission patterns. Theoretically, those asymmetries can be linked to the fundamental properties of nuclear matter and, in particular, to the equation of state (EOS) [1, 2].

Two types of asymmetries were identified. One was the directed flow [3] in the reaction plane, associated with the matter "bouncing-off" within the hot participant region of overlap between colliding nuclei. The other was the squeeze-out [4] of the hot matter moving perpendicular to the reaction plane within the participant region. When energy increases into ultrarelativistic values the squeeze-out turns into an in-plane elliptic flow**.**

Spatial asymmetry in the initial state, associated with the reaction plane, gives rise to asymmetries in the particle emission patterns. Within the method of analysis of those asymmetries, proposed by Danielewicz and Odyniec [5], those asymmetries are used to estimate the direction of the reaction plane and the asymmetries themselves are assessed in relation to the estimated reaction-plane direction. In an experiment, the determination of the impact parameter **b** is not possible and therefore instead of **b,** vector sum of transverse momenta of projectile and target nuclear fragments or participant protons are used. The fragmentation region of projectile and target nuclei is not acceptable for experimental set-ups in some experiments and therefore the reaction plane is defined by the participant protons. This approach is preferable also for the light nuclear systems, because the multiplicity of the participant protons is larger than the number of detected fragments.

By now, the collective flow effects were investigated over a wide range of energies, from tens of MeV/nucleon to 7 TeV/nucleon in the center of mass. Having determined the reaction plane it is possible to find quantitative properties of the flows. At low and intermediate energies the average projection of particles momentum on the reaction plane is used quite frequently, as well as a slope of its dependence on the particle rapidity. Coefficients of the Fourier decomposition of particle azimuthal distributions are very popular at high energies. For example, the elliptic flow was explored by many collaborations at AGS [6, 7], GSI [8], NA49 [9], CERN/SPS [10, 11] by means of the second harmonic coefficient of Fourier analysis of the azimuthal distributions - v_2.

In order to study the characteristics of nucleus-nucleus interactions, the collective flows of protons, pions and Λ hyperons have been previously investigated by the authors of the paper [12-16]. The information about them in interactions of light projectile nuclei with various target nuclei is very limited. We believe that the results obtained in the paper will being brote a new light on the nature of the flows.

In this paper, we present multiparticle azimuthal correlations (i.e. the “directed” and “elliptic” flows) results of pions (π^- and π^+) at the momentum of 40 GeV/c in π^-(p, n, C) collisions. The data were obtained from the Propane Bubble Chamber of JINR at Serpukhov's synchrophazotron.

Experimental Data

The data were obtained from Propane Bubble Chamber systems (PBC-500). The 2 meter long Propane Bubble Chamber (PBC-500) was placed in the magnetic field of 1.5 T. The procedures for separating out the π^-(p, n, C) collisions in propane (C_3H_8) and the processing of the data including particle identification and corrections were described in detail in [17, 18]. The identification probability of π^-C collision events are one, π^-p - 0.338, of π^-n - 0.973. The corrections of missing particles are 1.023 for π^+-mesons, 1.046 - π^--mesons and 1.088 – for protons. Experimental data contain 25422 events, from which 12765 corresponds to π^-p, 3986 - π^-n, 8671 - π^-C collisions, respectivelly. The average multiplicity of all charged particles ($<n_{\pi\pm}>$) in π^-(p, n, C) collisions is 6.96±0.03 and $<n_{\pi-}>$ =3.52±0.02, $<n_{\pi+}>$ =3.33±0.02, $<n_\rho>$ =1.10±0.03. While, the average momentum of π^--mesons $<p_{\pi-}>$=5.31±0.32 GeV/c, $<p_{\pi+}>$ =3.07 ±0.18 GeV/c, $<p_{prot}>$ =0.345 ± 0.02 in π^-(p, n, C) collisions.

Only protons with momentum p<0.7 GeV/c were identified. The admixture of protons amongst positive charged pions was (12±5)%.

For the study of multiparticle azimuthal correlations the events have been selected by requiring the minimal number of pions (π^-or π^+), $N_{\pi^+} \geq 4$, $N_{\pi^-} \geq 4$, in π^-(p, C) collisions and $N_{\pi^+} \geq 3$, $N_{\pi^-} \geq 3$, in π^-n collisions, respectively. The pions with momentum of p>0.05 GeV/c and p < 40 GeV/c and the average errors in measuring the momentum < Δp/p > < 35% were selected for the analysis.

The Directed Flow of Pions

We have employed the transverse analysis method proposed by Danielewicz and Odyniec [5] in determining the azimuthal correlations between pions (π^- or π^+) in, π^-(p, n) and π^-C collisions. The advantage of the transverse analysis method is that it can be employed even at small statistics, which is typical for film detectors. The method relies on summation over transverse momenta of selected particles in the events.

The analysis was carried out in the laboratory system. To eliminate the correlation of the particle with itself (autocorrelations), we estimated the reaction plane for each particle, with contribution of that particle removed from the definition of the reaction plane. The reaction plane is spanned by the impact parameter vector **b** and the beam axis. Within the transverse momentum method, the direction of **b** is estimated event-by-event in terms of the vector constructed from particle transverse momenta:

$$\mathbf{Q_j} = \sum_{\substack{i=1 \\ i \neq j}}^{n} \omega_i \mathbf{P_i}^{\perp}, \tag{1}$$

where the sum extends over all fragments of projectile and targets or participant protons for light nuclei in an event, i is a particle index and ω_i is the weight factor, $\omega_i = y_i - y_c$, y_i is the rapidity of i-th particle, y_c is the average rapidity for fragments of projectile and targets or participant protons in each collision pairs [19]. Projection of the transverse momentum of each particle onto the estimated reaction plane is:

$$P_X{}'_j = \frac{\mathbf{P}_j^{\perp} \cdot \mathbf{Q}_j}{|\mathbf{Q}_j|}. \tag{2}$$

The dependence of the projection on the rapidity y was constructed for each interacting pair. For further analysis, the average transverse momentum in the reaction plane, $<P_x{}'_j (y)>$, is obtained by averaging over all events in the corresponding intervals of rapidity. The flow parameter F, which is the slope of $<P_x(y)>$ at its midrapidity cross-over. The component P_x of a particle in the true reaction plane is systematically larger than the component $P_x{}'$ in the estimated plane. Each event was randomly divided into two almost equal sub-events and the vectors Q_1 and Q_2 were constructed. The angle Φ between the true and estimated reaction planes was defined. Thus, the correction factor k=1/<cos Φ>, where <cos Φ> is determined from the ratio [5, 13]:

$$\langle \cos \Phi \rangle = \frac{\langle \omega P_X{}' \rangle}{\langle \omega P_X \rangle} = \langle \frac{\omega \mathbf{P}_j^{\perp} \cdot \mathbf{Q}_j}{|\mathbf{Q}_j|} \rangle \sqrt{\frac{\langle Q^2 - \sum_{i=1}^{n} (\omega P_i^j)^2 \rangle}{\langle n^2 - n \rangle}}, \tag{3}$$

where *n* is particles multiplicity in an event.

In the present paper in order to investigate the multiparticle azimuthal correlations of π − mesons we used the basic ideas of P. Danielewicz technique and constructed the vector Q using solely π − mesons. In our previous paper [15], similarly, we constructed the Q vector in dC, HeC, CC, CNe, MgMg, (d, He)Ta, CCu, CTa, and OPb collisions at momentum of 4.2, 4.5 GeV/c per nucleon from the transverse momentum vectors of only π − mesons. Clear evidence of azimuthal correlations for π^- mesons has been obtained. In the phase space the Q vector separates the axis (direction) and with respect to this axis pion correlations were observed [15].

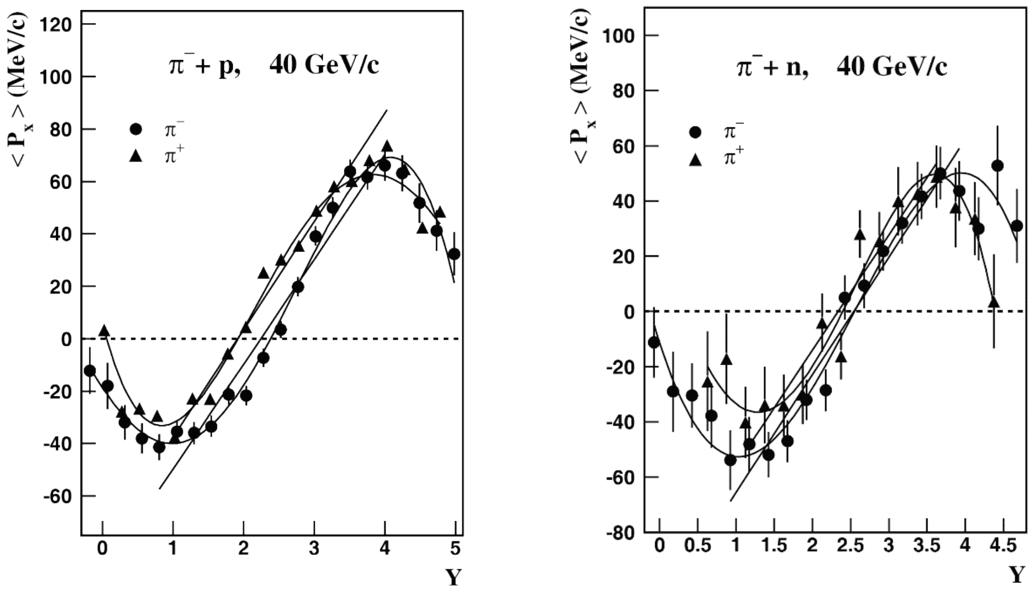

Fig. 1. The dependence of $<p_x(y)>$ on the rapidity y in π^-(p, n) collisions at the momentum of 40 AGeV/c for π^- (●) and π^+ (▲) mesons in experimental data, correspondingly. Straight lines stretches represent the slope of data at midrapidity, obtained by fitting the data with 1-st order polynomial within the intervals of the rapidity (see text). The curved lines guide the eye over data.

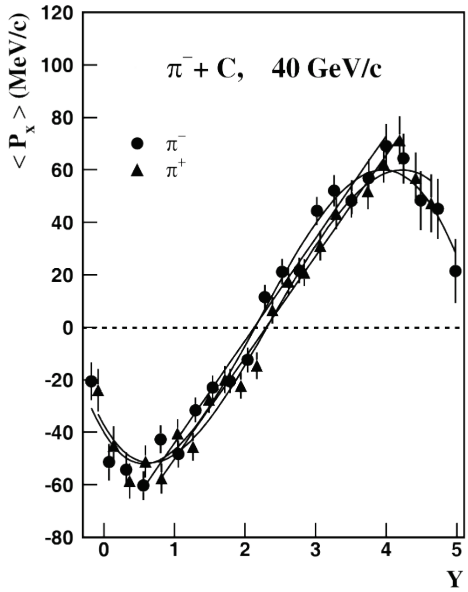

Fig. 2. The dependence of $<p_x(y)>$ on the rapidity y in π^-C collisions at the momentum of 40 AGeV/c for π^- (●) and π^+ (▲) mesons in experimental data, correspondingly. Straight lines stretches represent the slope of data at midrapidity, obtained by fitting the data with 1-st order polynomial within the narrow intervals of the rapidity (see text). The curved lines guide the eye over data.

Figs. 1, 2 show the rapidity dependence of the average in-plane transverse-momentum component for pions in π^-(p, n) and π^-C collisions. As one can see from the Figs. 1, 2 and the Table, the values of the flow parameter F of π^- and π^+ are the same for all collision pairs π^-(p, n, C) within the errors. In this case with respect to the direction separated by the Q vector of pions correlations are observed in the π^-(p, n, C) collisions, similarly as in [15].

Table. The values of directed and elliptic flows for $\pi^-$and π^+mesons in the experimental π^-(p, n, C) collisions

	N_{exp}	$N_{\pi-}$	$N_{\pi+}$	F $\pi-$ (MeV/c)	F $\pi+$ (MeV/c)	$a_{\pi-}$	$a_{\pi+}$
π^-p	12765 5706	34698 20446	32066 18273	40.0± 1.2	39.2 ± 2.3	-0.058±0.009	-0.060±0.010
π^-n	3986 930	11336 6731	7128 3210	42.6 ± 2.4	41.8 ± 4.6	-0.064±0.012	-0.061±0.024
π^-C	8671 5655	30350 21253	32751 23314	39.0 ±1.4	38.6 ±1.5	-0.080±0.008	-0.083±0.007

Pions Elliptic Flow

We have studied the pion "elliptic" flow in π^-(p, n, C) (40 GeV/c) collisions. The azimuthal φ distributions of the charged pions were obtained and are presented in Figs. 3, 4 where φ is the angle of the transverse momentum of each particle in the event with respect to the "reaction plane" ($\cos\varphi = P_x/P^{\perp}$). The reaction plane was constructed solely by π^- – mesons. The azimuthal angular distributions show maxima at φ=90° and 270° with respect to the event plane. The maximum are associated with preferential particle emission perpendicular to this plane (squeeze-out). To treat the data in a quantitative way, the azimuthal distributions were fitted with the Fourier cosine-expansion (given the system invariance under reflections with respect to the reaction plane)

$$\mathrm{dN/d}\varphi = a_0(1 + a_1\cos\varphi + a_2\cos 2\varphi)\,. \quad (4)$$

The elliptic anisotropy signature corresponds to the negative value of the coefficient a_2. This coefficient is the measure of the strength of the anisotropic emission. The values of the a_2 coefficient are extracted from the azimuthal distributions of the pions with respect to the reaction plane at mid-rapidity (Table).

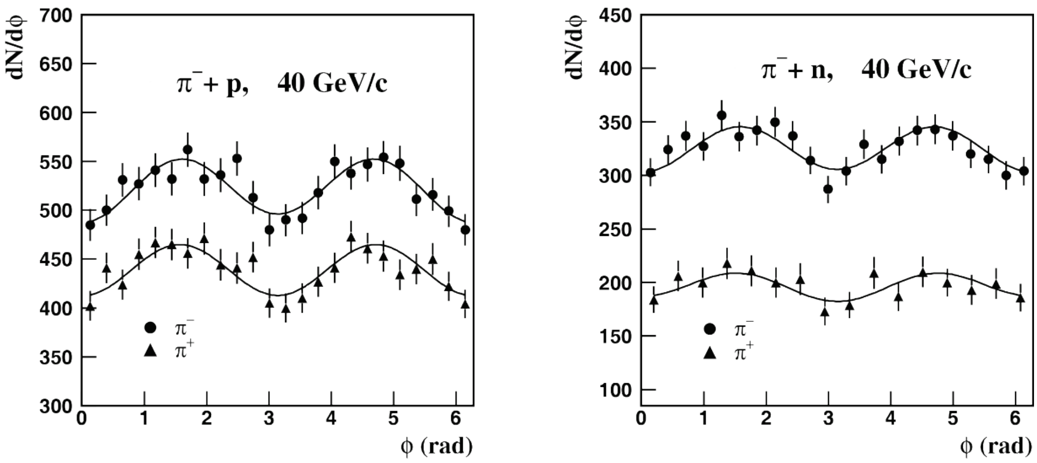

Fig. 3. The azimuthal distributions with respect to the reaction plane in π^-(p, n) collisions at the momentum of 40 AGeV/c for π^- (●) and π^+ (▲) mesons in experimental data, correspondingly. The curves are the result of the approximation by $dN/d\varphi = a_o(1 + a_1\cos\varphi + a_2\cos2\varphi)$.

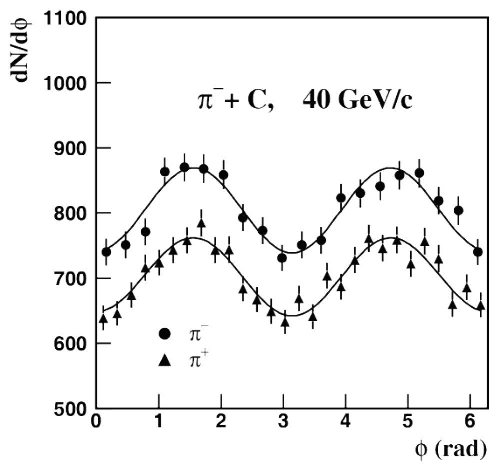

Fig. 4. The azimuthal distributions with respect to the reaction plane in π^-C collisions at the momentum of 40 AGeV/c for π^- (●) and π^+ (▲) mesons in experimental data, correspondingly. The curves are the result of the approximation by $dN/d\varphi = a_o(1+a_1\cos\varphi+a_2\cos2\varphi)$.

According to the investigations in Au-Au collisions at AGS [20], the sign of the elliptic flow changed at an apparent transition energy of $E_{tr} \sim 4$ GeV/nucleon. It should be mentioned that, no change of the sign of the elliptic flow was observed in pC and pTa collisions at 10 AGeV/c [16].

The elliptic flow was investigated by various groups for different systems. Comparison of the elliptic flow measurements of charged hadrons in CuCu and AuAu collisions at $\sqrt{S_{NN}}$= 62.4 and 200 GeV by PHOBOS Collaboration did not exhibit any dependence on $(A_P*A_T)^{1/2}$ [see Ref. [21] Fig 2 a, c]. The ALICE group has found about 30% increase in the magnitude of v_2 from $\sqrt{S_{NN}}$=200 Gev (AuAu) to 2.76 TeV (PbPb) (see Ref. [22] Fig 4).

Conclusions

Multiparticle azimuthal correlations of pions (π^- and π^+) emitted from π^-(p, n) and π^-C collisions at the momentum of 40 GeV/c have been studied.

1) The π^-(p, n) systems are the lightest, in which collective flow effects (directed and elliptic) have ever been detected for pions (π^- and π^+). As shown, the pions exhibit directed flow in all colliding systems π^-(p, n, C) consistent with that for protons in nucleus-nucleus systems. On the other hand, the absolute value of the directed flow parameter F insignificantly changes and it is almost the same within errors for π^- and π^+ mesons in all interactions.

   π^- mesons:

   (40.0± 1.2) MeV/c (π^-p) and (39.0 ±1.4) MeV/c (π^-C);

   π^+ mesons:

   (39.2 ± 2.3) MeV/c (π^-p) and (38.6 ±1.5) MeV/c (π^-C).

2) It should be mentioned that, there are no change of the sign of the elliptic flow in these interactions. The absolute value of elliptic flow parameter a_2 increases with increasing of the mass number of target A_T nuclei in π^-(p, n, C) collisions for the pions (π^- and π^+) and almost does not change with the change of the sign of pions:

   π^- mesons:

   (-0.058±0.009) (π^-p) and -0.080±0.008 (π^-C);

π^+ mesons:
(-0.060±0.010) (π^-p) and (-0.083±0.007) (π^-C).

The authors are thankful to heterogeneous computing (HybriLIT) team of the Laboratory of Information Technologies of JINR for support of our calculations.

ფიზიკა

პიონების მრავალნაწილაკოვანი აზიმუტალური კორელაციების შესწავლა π^-(p, n, C) დაჯახებებში 40 GeV/c იმპულსის დროს

ლ. ჩხაიძე*, თ. ჯობავა*, ლ. ხარხელაური*, ლ. ახობაძე*

** ივანე ჯავახიშვილის სახ. თბილისის სახელმწიფო უნივერსიტეტი, მაღალი ენერგიების ფიზიკის ინსტიტუტი, თბილისი, საქართველო*
*** ბირთვული კვლევების ევროპული ორგანიზაცია (CERN), ჟენევა, შვეიცარია*

(წარმოდგენილია აკადემიის წევრის ა. ხელაშვილის მიერ)

შესწავლილ იქნა პიონების (π^- და π^+) მრავალნაწილაკოვანი აზიმუტალური კორელაციები π^-(p, n) and π^-C დაჯახებებში 40 გევ/c იმპულსის დროს პ. დანიელევიჩისა და გ.ოდუნიეცის სტანდარტული განივი იმპულსის ანალიზის მეთოდის განსხვავებული მიდგომით. მრავალნაწილაკოვანი აზიმუტალური კორელაციების (ე.წ. „მიმართული“ და „ელიფსური“ გამოდინებები) შესწავლის მიზნით ფაზურ სივრცეში განისაზღვრა გარკვეული მიმართულება და ამ ღერძის მიმართ პირველად იქნა დამზერილი π^- და π^+ პიონების კორელაციები π^-(p, n, C) დაჯახებებში. ექსპერიმენტული მასალა მიღებულ იქნა ბირთვული კვლევების გაერთიანებული ინსტიტუტის (JINR) მაღალი ენერგიების ლაბორატორიაში ფილმური დეტექტორის პროპანის ორმეტრიანი ბუშტოვანი კამერის (PBC-500) მეშვეობით. ექსპერიმენტი განხორციელდა სერპუხოვის სინქროპაზოტრონზე. π^-(p, n) ყველაზე მსუბუქი სისტემებია, რომლებშიც დღემდე დაკვირვებულა პიონებისათვის (π^- და π^+) კოლექტიური გამოდინებები (მიმართული და ელიფსური). როგორც ნაჩვენებია, პიონების მიმართული გამოდინებები ყველა აღნიშნულ დაჯახებებში π^-(p, n, C) მსგავსია პროტონების ანალოგიური გამოდინებებისა ბირთვ-ბირთვულ დაჯახებებში. მეორე მხრივ, მიმართული გამოდინების F პარამეტრის აბსოლუტური მნიშვნელობა უმნიშვნელოდ იცვლება და ცდომილების ფარგლებში თითქმის უცვლელია π^- და π^+ მეზონებისათვის აღნიშნულ ურთიერთქმედებებში. აღსანიშნავია, რომ ელიფსური გამოდინება არ იცვლის ნიშანს ამ დაჯახებებში. ელიფსური გამოდინების a_2 პარამეტრის აბსოლუტური მნიშვნელობა იზრდება სამიზნის მასური რიცხვის ზრდასთან ერთად π^-(p, n, C)

დაჯახებებში პიონებისათვის (π^- და π^+) და თითქმის არ იცვლება პიონების ნიშნის ცვლილებისას. მიღებული შედეგები იძლევა მნიშვნელოვან ინფორმაციას მეზონ-ნუკლონური და მეზონ-ბირთვული ურთიერთქმედებების მექანიზმზე **40** გევ/c იმპულსის დროს, რაც განსაზღვრავს წარმოქმნილი ბირთვული მატერიის მახასიათებლებს.

REFERENCES

1. Stocker H., Marhuhn J.A. and Greiner W. (1980) Collective sideward flow of nuclear matter in violent high-energy heavy ion. *Phys. Rev. Lett.*, **44:** 725.
2. Stocker H. et al. (1982) Jets of nuclear matter from high-energy heavy ion collisions. *Phys Rev.*, **25C:** 1873.
3. Hartnack C. et al. (1992) VUU and (R)QMD model of high-energy heavy ion collisions. *Nucl. Phys.*, **538A:** 53.
4. Hartnack C. et al. (1994) Azimuthal dependence of energy flow in central collisions of heavy Nuclei. *Mod. Phys. Lett.*, **9A:** 1151.
5. Danielewicz P. and Odyniec G. (1985) Transverse momentum analysis of collective motion in relativistic nuclear. *Phys. Lett.*, **157B:** 146.
6. Chung P. et al. (2001) Directed flow of Lambda hyperons in 2-AGeV to 6-AGeV Au+Au collisions. *Phys. Rev. Lett.*, **86:** 2533.
7. Pinkenburg C. et al. (2002) Production and collective behavior of strange particles in Au+Au collisions at 2-AGeV - 8-AGeV. *Nucl. Phys.*, **698A:** 495.
8. Ritman J. L. et al. (1995) On the transverse momentum distribution of strange hadrons produced in relativistic heavy ion collisions. *Z. Phys.*, **352A:** 355.
9. Appelshauser H. et al. (1998) Directed and elliptic flow in 158-GeV / nucleon Pb + Pb collisions. *Phys. Rev. Lett.*, **80:** 4136.
10. Aggarwal M.et al. (1998) Collective flow in 158-A-GeV Pb + Pb collisions. *Nucl. Phys.*, **638A:** 459.
11. Aggarwal M. et al. (1998) Recent results on Pb + Pb collisions at 158-A-GeV from the WA98 experiment at CERN. *Nucl. Phys.*, **638A:** 147.
12. Chkhaidze L. et al. (2002) Experimental study of collective flow phenomena in high-energy nucleus nucleus collisions. *Phys. Part. Nucl.*, **33:** 196.
13. Chkhaidze L. et al. (2007) Collective flow of protons and negative pions in nucleus-nucleus collisions at momentum of 4.2 / 4.5-10/c. *Nucl. Phys.*, **794A:** 115.
14. Chkhaidze L. et al. (2011) Collective flows of protons and pi-mesons in H-2 + C, Ta and He+C, Ta collisions at 3.4 GeV/nucleon. *Phys.Rev.*, **84C**: 064915.
15. Chkhaidze L. et al. (2012) Multiparticle azimuthal correlations of negative pions in nucleus-nucleus collisions. *Phys.Atom.Nucl.*, **75:** 811.
16. Chkhaidze L. et al. (2016) Study of collective flows of protons and π^- -mesons in p(C, Ta) and He(Li, C) collisions at momenta of 4.2, 4.5 and 10 AGeV/c. *Eur. Phys.J.*, **52:** 351.
17. Angelov N. et al. (1977) Investigation of Interactions of pi- Mesons with Carbon Nuclei at 40-GeV/c. *Yad.Fiz.* **25:** 1013-1020.
18. Balea O. et al. (1972) Multiplicity distributions in π^- p, π^- n and π^- C interactions at pc=40 GeV. *Phys. Lett.*, **39B:**571.
19. Beavis D. et al. (1992) Collective motion in Ar + Pb collisions at beam energies between 400-MeV/nucleon and 1800-MeV/nucleon. *Phys. Rev.*, **45C:** 299.
20. Pinkenburg C. et al. (1999) Elliptic flow: transition from out-of-plane to in-plane emission in Au+Au collisions. *Phys. Rev. Lett.*, **83:** 1295.
21. Alver B. et al. (2007) Elliptic flow, initial eccentricity and elliptic flow fluctuations in heavy ion collisions at RHIC. e-Print arXiv:**0707.4424**.
22. Aamodt A. et al. (2010) Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV. *Phys.Rev.Lett.*, **105:** 252302.

Received June, 2019