Romanian Reports in Physics, Vol. 59, No. 4, P. 941–950, 2007

Dedicated to Prof. Dumitru Barbu Ion's 70th Anniversary

ČERENKOV HADRON PRODUCTION IN COLLISIONS OF RELATIVISTIC NUCLEI

E. K. G. SARKISYAN[1], L. K. GELOVANI[2], G. L. GOGIBERIDZE[3]

[1] *EP Division, Physics Department, CERN, CH-1211 Geneva 23, Switzerland,*
and University of Antwerpen, Physics Department, B-2610 Wilrijk, Belgium;
e-mail:sedward@mail.cern.ch
[2] *Joint Institute for Nuclear Research, RU-141980 Dubna, Moscow Region, Russia**
[3] *JINR***

(Received July 18, 2007)

Abstract. In this report we give the results of the search for Čerenkov-like radiation features in pion production in nucleus-nucleus collisions at the Dubna energies. The spike-center distributions are obtained to exhibit the structure expected from coherent gluon-jet emission dynamics. The energy distribution within spikes is found to have a significant peak over the exponentially decreasing inclusive spectrum. The value of the peak energy and its width are in a good agreement with those expected for pions produced in a nuclear medium in the framework of the Čerenkov quantum approach, or the NPICR model.

Key words: Čerenkov-like radiation, pion production, nucleus-nucleus collisions.

1. INTRODUCTION

The area of collective effects in particle production in high-energy collisions attracts a special interest as the hadron production process is yet far from being well understood. Possible coherent mechanisms of emission of particles are of specific interest as they provide a possibility to find the analogies and thus descriptions based on the already known and well understood mechanisms from other areas of physics, and the Čerenkov radiation is one of the most promising approaches in this sense. In series of papers, D. B. Ion with colleagues have successfully applied the features of Čerenkov radiation to particle production in high-energy physics [1–3] and astrophysics [4]. Following earlier ideas of mesonic [5] and scalar (pionic) [6] radiation in particle/nuclear collisions, the systematic investigations have been made for secondary mesons [1, 2] and photons [3] scattered in nuclear medium in terms of classical quantum mechanics. Recently the studies have

---

* On leave from Inst. of Physics, Tbilisi 380077, Georgia.
** Now at RadPharm Inc. Princeton NJ 08540, USA.

been further generalized and new phenomenon has been shown to be expected [7]. Characteristic signatures of the Čerenkov-like mechanism, such as the differential cross-sections and angle-energy correlations of produced particles, have been predicted.

Building theory of strong interactions, the Čerenkov-like radiation looks to be one of an important ingredient, and the ideas based on this approach have been developed in [8] within the QCD based coherent gluon-jet emission model. In this model the pseudorapidity distributions of centers of particle dense groups, called spikes, are proposed to be investigated. The distributions of spike centers are predicted to have two peaks due to destructive interference for quarks of the same colour (*pp* collisions) or to be singly peaked due to constructive interference for quarks of different colour (*e.g.* $p\bar{p}$ interactions). Observations in hadronic [9] interactions are found to be in agreement with these predictions.

Using the Dubna (JINR) data of relativistic nucleus-nucleus collisions, we have investigated dense groups of hadrons [10, 11] and found very good agreement with the predictions made by the two above discussed approaches for the coherent component of the hadroproduction process On the one hand, we analyzed distributions of the centers of spikes in the frame of the gluon-jet emission model and found two peaks as predicted. On the other hand, we investigated energy distribution within spikes for the features predicted by the nuclear pionic Čerenkov-like radiation (NPICR) approach [1, 2] and found the energy peak value and its width in agreement with this semi-classical approach. This coincidence, in our opinion, indicates a coherent emission mechanism to be an essential component in the hadron production process.

It is worth noting that spikes have been extensively investigated in all types of collisions using a stochastic picture of particle production, namely an intermittency phenomenon has been searched for and obtained [12]. In our studies [13], we also found the intermittency effect leading to multifractality and, then, to a suggestion of a possible non-thermal phase transition during the cascading. The latter observation have been confirmed in different reactions [12, 14].

2. EXPERIMENTAL DETAILS

The results presented here are based on the experimental data obtained after processing the pictures from the 2m Streamer Chamber SKM-200 [15] installed in a 0.8 T magnetic field. The chamber was irradiated at the Dubna JINR Synchrophasotron. A beam of magnesium nuclei with momentum 4.3 *A* GeV/*c* was used to collide with a magnesium target, while a 4.5 *A* GeV/*c* carbon beam interacted with a copper target. A more detailed description of the set-up design and data reduction procedure are given elsewhere [15–17].

A total of 14218 central Mg-Mg collisions and 663 C-Cu collisions were analyzed. In the utilized Mg-Mg sample only negative charged particles (mainly π^-

mesons with a portion of some 1% kaons) have been studied in the pseudorapidity ($\eta = -\ln\tan\frac{1}{2}\vartheta$) window of $\Delta\eta = 0.4$–2.4 (in the laboratory frame), while in the C-Cu sample all charged particles have been considered in $\Delta\eta = 0.2$–2.6. The angular measurement accuracy does not exceed 0.01 in η units.

To overcome an influence of the shape of the pseudorapidity distribution on the results, we use the "cumulative variable",

$$\tilde{\eta}(\eta) = \int_{\eta_{\min}}^{\eta} \rho(\eta')d\eta' \Big/ \int_{\eta_{\min}}^{\eta_{\max}} \rho(\eta')d\eta', \tag{1}$$

with the uniform spectrum $\rho(\tilde{\eta})$ within the interval [0, 1], as advocated in Ref. [18]. This transformation makes it possible to compare results from different experiments.

The spikes are extracted in each event from the ordered pseudorapidities scanned with a fixed pseudorapidity window (bin) of size $\delta\tilde{\eta}$. Spikes with a definite number of particles δn, hit in the bin, are determined and, for each δn, the distribution of centers of spikes, averaged over all events, is obtained. The center of spike is defined by $\tilde{\eta}_0 = (1/\delta n)\sum_{j=1}^{\delta n}\tilde{\eta}_j$.

To reveal dynamical correlations, the $\tilde{\eta}_0$-distribution is compared with analogous distributions obtained from the simulated pseudorapidity single-particle spectrum $\rho(\tilde{\eta})$ without any input information about particle correlations. The simulation procedure was as follows. The number of particles was randomly generated according to the multiplicity distribution of the data sample. Then, the pseudorapidities were distributed in accordance with the experimental $\tilde{\eta}$-spectrum corresponding to the generated multiplicity. In each case of the reactions considered here, the total number of the simulated events exceeded the experimental statistics by a factor of 100. It is clear that the statistical properties of this set are completely analogous to those of an ensemble resulting from arbitrary mixing of tracks from different events, subject to the condition of retention of the $\rho(\tilde{\eta})$-distribution. So, the obtained sample represents independent particle emission.

3. THE RESULTS

3.1. RESULTS ON SPIKE-CENTER DISTRIBUTIONS

The pseudorapidity spike-center $\tilde{\eta}_0$-distributions for four different-size $\delta\tilde{\eta}$-bins and for spikes of various multiplicities δn are shown in Figs. 1 and 2 for C-Cu and Mg-Mg collisions, respectively.

For each reaction type, a two-peak structure of the measured distributions (solid circles) is seen with the peaks in the neighbourhood of the same $\tilde{\eta}_0$, independent of the width and multiplicity of spike. The shape of the distributions is in agreement with the structure predicted by the coherent gluon-jet emission model [8] and is similar to that observed in hadronic interactions [9].

In order to estimate the position of the peaks and the distance between them, we fit these bumps with Gaussians and average over different spikes. The peaks are found to be placed at $\tilde{\eta}_0 \approx 0.17$ and 0.57 corresponding to $\eta_0 = 0.60 \pm$ $\pm\, 0.05(\text{stat}) \pm 0.12(\text{syst})$ and $1.30 \pm 0.03(\text{stat}) \pm 0.10(\text{syst})$ in C-Cu collisions, and in $\tilde{\eta}_0 \approx 0.19$ and 0.63 corresponding to $\eta_0 = 0.89 \pm 0.03(\text{stat}) \pm 0.08(\text{syst})$ and $1.63 \pm 0.05(\text{stat}) \pm 0.10(\text{syst})$ in Mg-Mg interactions.

They are separated by the following d_0 interval,

$$\begin{aligned} d_0 &= 0.68 \pm 0.06(\text{stat}) \pm 0.16(\text{syst}) \quad (\text{C} - \text{Cu}) \\ d_0 &= 0.75 \pm 0.06(\text{stat}) \pm 0.13(\text{syst}) \quad (\text{Mg} - \text{Mg}) \end{aligned} \tag{2}$$

in η units. These values are close to those from the above mentioned hadronic interactions.

The dynamical origin of the structure obtained is seen from a comparison of the experimental $\tilde{\eta}_0$-distributions with those based on the above described simulated events (open circles in Figs. 1 and 2). No peaks are seen in the simulated distributions, levelling off at the background, far below the measured peaks. This points to a dynamical effect in the formation of spikes in agreement with the coherent gluon radiation picture.

The d_0 values obtained and the conclusions made were obtained to be stable within experimental errors. To add is that no influence of hadronic jets to the effect observed has been observed pointing at the azimuthal isotropy of events with spikes [11].

3.2. IN SPIKE-ENERGY SPECTRA

The strong signal of the coherent emission dynamics obtained allows further search for its manifestation in the energy distribution, as predicted in the NPICR approach [1, 2]. In this model, the energy spectrum of pions, emitted through the coherent Čerenkov-like mechanism when a few-GeV proton passes the nuclear medium, is predicted to have a peak. This peak is expected to appear at 260 MeV when an absorption effect is neglected and at 244 MeV otherwise.

In Fig. 3 we compare the c.m.s. inclusive kinetic energy distribution, $F(K^*) =$ $= (1/E^* p^*)\mathrm{d}N/\mathrm{d}K^*$, with analogous spectra calculated for pions from spikes in Mg-Mg interactions. Here, E^* and p^* denote, respectively, the particle energy and momentum in the c.m.s. frame.

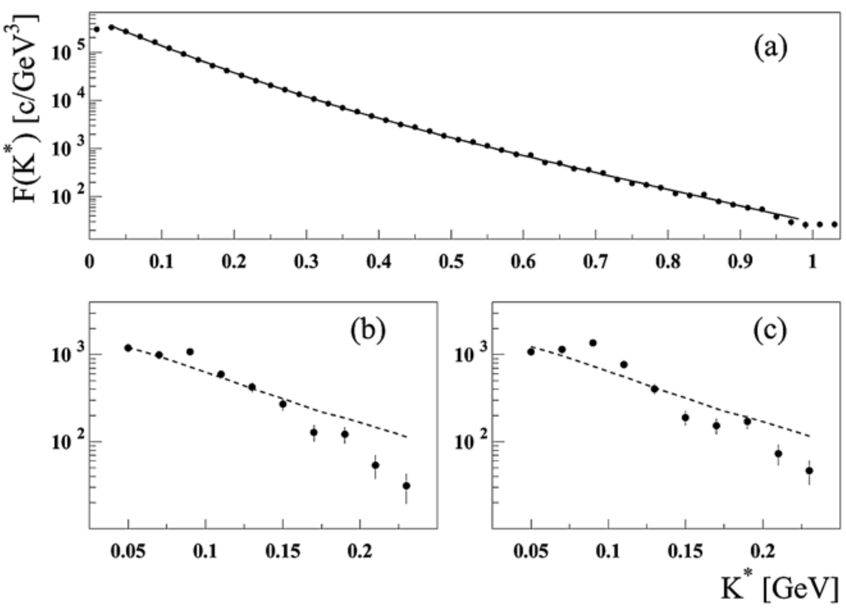

Fig. 3 – Inclusive kinetic energy distribution (a) and analogous distributions for spikes of negative pions in Mg-Mg interactions, (b) $\delta\tilde{\eta} = 0.1$, $\delta n = 6$ and (c) $\delta\tilde{\eta} = 0.15$, $\delta n = 7$. The solid line represents the exponential fit with Eq. (3), the dashed lines show the inclusive background.

Using the temperature description, utilized to characterize a system of excited hadrons [17, 19–21], we parametrize the inclusive spectrum (Fig. 3a) by a sum of two exponents,

$$F(K^*) = A_1 \exp(-K^*/T_1) + A_2 \exp(-K^*/T_2), \tag{3}$$

where the temperatures $T_1 < T_2$ characterize [19] the two possible mechanisms of pion production, via Δ-resonance decay and directly, and are related to the pion average kinetic energies. The range of the parametrization shown is limited from below and from above due to detector effects and corresponding requirements on the momenta of pions. The fit gives $T_1 = 65 \pm 1$ MeV and $T_2 = 127 \pm 1$ MeV. These values are, in general, consistent with those obtained from the earlier analysis of the reaction under study [17] and from other experiments [19, 20]. Some difference in the values could be explained if one takes into account the difference in the sizes of the (pseudo)rapidity regions used [21].

The shape of the $F(K^*)$ distribution changes when the analysis is extended to spikes, Figs. 3b and 3c. The energy spectrum of particles belonging to a spike differs significantly from the exponential law (3) and has a peaked shape. To extract the NPICR-signal we compare the in-spike energy spectra with the renormalized inclusive distribution, or inclusive background, depicted by the dashed lines. The first peak is seen to be above background with a statistical significance of 2.7 and 4.1 standard deviations in Figs. 3b and 3c, respectively. This peak is located at the kinetic energy $K^* \approx 100$ MeV, or the total energy $E^* \approx 240$ MeV, in accordance with the NPICR prediction.

To estimate the position of the peak and its width and to make the results more comparable with the NPICR expectations, the E^*-distributions of particles in spikes of various size $\delta\tilde{\eta}$-bins and different δn-multiplicities are studied. Fig. 4 represents examples for these distributions. The following specific peculiarities are found.

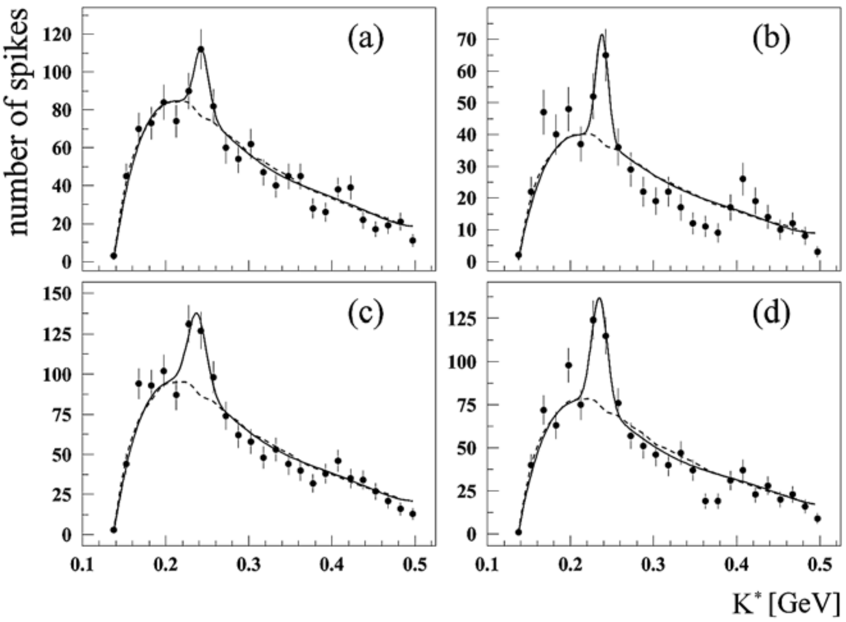

Fig. 4 – Total energy spectra for negative particles spikes of different $\delta\tilde{\eta}$-bins and multiplicities δn in Mg-Mg collisions: (a) $\delta\tilde{\eta} = 0.05$, $\delta n = 4$, (b) $\delta\tilde{\eta} = 0.08$, $\delta n = 5$, (c) $\delta\tilde{\eta} = 0.1$, $\delta n = 5$, (d) $\delta\tilde{\eta} = 0.15$, $\delta n = 6$. The solid lines represent the fit (see text), the dashed lines show the inclusive background.

All these E^*-distributions possess a non-exponential behaviour with a pronounced maximum in the vicinity of the value $E^*_{\mathrm{m}} = 240$ MeV regardless of bin size and multiplicity of spikes. The higher the multiplicity of spike is (at fixed $\delta\tilde{\eta}$ size), the more peaks appear. A multi-peak structure is observed for bins with the multiplicities $\delta n > 3$, while at $\delta n \leq 3$ only one peak occurs (not shown).

To reveal the dynamical signal we compare the in-spike energy distributions with the inclusive background (dashed-line). As for the above kinetic-energy distributions, the value of E^* of about 240 MeV is obtained to be the position of the most prominently and statistical-significantly peak over background. To estimate the background and to parametrize the signal, we use a fifth-order polynomial for the background and a Gaussian for the peak. The solid curve shows the result of this fit. After averaging over various spikes, the position of the peak and its width are found to have the values,

$$\begin{aligned} E^*_{\mathrm{m}} &= 238 \pm 3(\mathrm{stat}) \pm 8(\mathrm{syst})\ \mathrm{MeV}, \\ \Gamma_{\mathrm{m}} &= 10 \pm 3(\mathrm{stat}) \pm 5(\mathrm{syst})\ \mathrm{MeV}, \end{aligned} \tag{4}$$

respectively.

The location of the obtained centre of the Gaussian lies within the interval of energies expected for pions from the Čerenkov-like mechanism for incident protons of a few GeV, $224 \le E_{\mathrm{m}} \le 244$ MeV [1]. The value of E^*_{m} (4) is similar to the position of the peak observed in the π^+p invariant mass distribution in the analysis of coincidence measurements of (p, n) reactions on carbon at 1.5 GeV/c in the Δ-resonance excitation region [22], the effect connected with the NPICR mechanism [1, 2]. Also, the width Γ_{m} confirms an observation of the Čerenkov radiation signal expected to be $\Gamma \le 25$ MeV.

4. CONCLUSIONS

It is an honour and our pleasure to give here, in the Volume dedicated to the 70th birthday of Prof. Dumitru B. Ion, our report on the results of search for coherent, Čerenkov-like, emission mechanism of particle production, the topic being one of most scientific interests of D. B. Ion for many years. We are happy to present the studies which are in good agreement with his predictions.

In summary, a study of relativistic nuclear collisions is carried out with charged particles from central C-Cu and Mg-Mg collisions at a momentum of about $4.5\,A$ Gev/c of incident nucleon. The spike-center distributions and the energy spectra of particles within a spike are investigated for various narrow pseudorapidity bins and different spike multiplicities.

The spike-center distributions are found to possess a double-peak shape that is in agreement with the structure expected from the coherent gluon radiation model by I. M. Dremin. The obtained distance between the peaks as well as the shape of the distributions are similar to those observed recently in analogous studies of charged-particle spikes in hadronic interactions.

The coherent character of the particle-production mechanism is confirmed by studying energy distributions in Mg-Mg interactions. The inclusive energy spectra show monotonic exponential decrease with two specific temperatures, while the in-spike energy distributions are obtained to exhibit a peak at a position and of a width both consistent with the values expected from the theoretical calculations based on the hypothesis of nuclear pionic Čerenkov radiation, or NPICR model by D. B. Ion. The value of the peak energy is close to the recently observed maximum in the differential cross-sections studied in the coincidence experiments of a few GeV nucleon-nucleus interactions.

The complementary indications of the two independent models used, pointing out to the Čerenkov-like mechanism in the particle production process, signals on the importance of the features obtained and shows the coherent component to be an essential ingredient of the process. This gives clear evidence for the necessity of further efforts in search for this phenomena in experiment, and such plans, based on our results, are already made for pp collisions [23].

In the last few years, the Čerenkov mechanism of hadron production in high-energy (nuclear) collisions attracted quite interest [24] due to the observations made at RHIC [25] and their possible interpretation. Applied to these experimental data, the model of particle production via Čerenkov-like radiation, developed by D. B. Ion with his colleagues, is expected to shed new light on the problem and to make predictions for future experiments. In conclusion, let us wish the author further interesting and, as always, fruitful work in this important direction.

REFERENCES

1. D. B. Ion and W. Stocker, Phys. Lett. **B273**, 20 (1991);
   D. B. Ion and W. Stocker, Phys. Rev. **C48**, 1172 (1993);
   D. B. Ion and W. Stocker, Phys. Rev. **C52**, 3332 (1995).
2. D. B. Ion, Rom. J. Phys. **36**, 587 (1991);
   D. B. Ion, Rom. J. Phys. **36**, 595 (1991);
   D. B. Ion and W. Stocker, Rom. J. Phys. **38**, 539 (1993);
   D. B. Ion and A. Rosca, Rom. J. Phys. **38**, 655 (1993);
   D. B. Ion, A. Rosca, and C. Petrascu Rom. J. Phys. **39**, 395 (1994);
   W. Stocker and D. B. Ion, Acta Phys. Polon. **B24**, 1785 (1994);
   D. B. Ion and W. Stocker, Rom. J. Phys. **39**, 527 (1994);
   D. B. Ion and W. Stocker, Phys. Lett. **B346**, 172 (1995).
3. D. B. Ion and W. Stocker, Phys. Lett. **B258** (1991) 262;
   D. B. Ion and W. Stocker, Ann. Phys. **213**, 355, (1992);
   D. B. Ion and W. Stocker, Phys. Lett. **B311**, 339 (1993);
   D. B. Ion and W. Stocker, Phys. Lett. **B323**, 446 (1994).
4. D. B. Ion, W. Stocker, Astropart. Phys. **2**, 21 (1994).
5. W. Wada, Phys. Rev. **75**, 981 (1949);
   D. Ivanenko and V. Gurgenidze, Dokl. Akad. Nauk SSSR **67**, 997, (1949);
   D. I. Blokhintsev and V. L. Indenbohm, ZhETF **20**, 1123 (1950).
6. W. Czyż and S. L. Glashow, Nucl. Phys. **20**, 309 (1960);
   G. Yekutieli, Nuovo Cim. **13**, 446, 1306(E) (1959);
   P. Smrž, Nucl. Phys. **35**, 165 (1962).
7. D. B. Ion and E. K. Sarkisyan, Rom. J. Phys. **49**, 25 (2004);
   D. B. Ion and E. K. Sarkisyan, Rom. J. Phys. **49**, 671 (2004);

D. B. Ion and M. L. Ion, Rom. J. Phys. **50**, 947 (2005);
D. B. Ion and M. L. Ion, Rom. J. Phys. **51**, 867, (2006).
8. I. M. Dremin, JETP Lett. **30**, 140 (1979);
I. M. Dremin, Sov. J. Part. Nucl. **18**, 31 (1987).
9. I. M. Dremin *et al.*, Yad. Fiz. **52**, 536 (1990);
N. M. Agababyan *et al.*, EHS/NA22 Collab., Phys. Lett. **B389**, 397 (1996);
S.-S. Wang, R. Liu, Z.-M. Wang, Phys. Lett. **B427**, 385 (1998).
10. G. L. Gogiberidze, L. K. Gelovani, E. K. Sarkisyan, Phys. Lett. **B430**, 368 (1998);
G. L. Gogiberidze, L. K. Gelovani, E. K. Sarkisyan, Phys. Lett. **B471**, 257 (1999).
11. G. L. Gogiberidze, L. K. Gelovani, E. K. Sarkisyan, Phys. At. Nucl. **64**, 143 (2001);
G. L. Gogiberidze, L. K. Gelovani, E. K. Sarkisyan, Nucl. Phys. Proc. Suppl. **92**, 75 (2001).
12. E. A. De Wolf, I. M. Dremin, W. Kittel, Phys. Reports **270**, 1 (1996);
W. Kittel, E. A. De Wolf, *Soft Multihadron Dynamics* (World Scientific Publishing Co. Pte. Ltd., Singapore, 2005).
13. E. K. Sarkisyan *et al.*, Phys. Lett. **B347**, 439 (1995).
14. D. Ghosh *et al.*, Z. Phys. **C71**, 243 (1996);
S.-S. Wang, R. Liu, Z.-M. Wang, Phys. Lett. **B438**, 353 (1998);
D. Ghosh *et al.*, Z. Phys. **C71**, 269 (1997);
D. Ghosh *et al.*, Phys. Rev. **C59**, 2286 (1999);
D. Ghosh *et al.*, Europhys. Lett. **63**, 805 (2003);
M. K. Ghosh, A. Mukhopadhyay, G. Singh, J. Phys. **G32**, 2293 (2006).
15. A. Abdurakhimov *et al.*, Instrum. Exp. Tech. **21**, 1210 (1979).
16. M. Anikina *et al.*, Phys. Rev. **C33**, 895 (1986).
17. L. Chkhaidze *et al.*, J. Phys. **G22**, 641 (1996).
18. A. Białas and M. Gazdzicki, Phys. Lett. **B252**, 483 (1990);
W. Ochs, Z. Phys. **C50**, 339 (1991).
19. R. Brockmann *et al.*, Phys. Rev. Lett. **53**, 2012 (1984).
20. S. Nagamia, M. Gyulassy, Adv. Nucl. Phys. **13**, 201 (1984).
21. S. Backović *et al.*, JINR Rapid Comm. *2*[**53**], 58 (1992).
22. J. Chiba *et al.*, Phys. Rev. Lett. **67**, 1982 (1991).
23. V. V. Avdeichikov *et al.*, JINR preprint P1-2004-190 (2004) [in Russian];
E. S. Kokoulina, A. Ya. Kutov (for SVD-2 Collab.), arXiv:0707.0067 [hep-ph].
24. I. M. Dremin, Nucl. Phys. **A767**, 233 (2006);
I. M. Dremin, Nucl. Phys. **A774**, 853 (2006);
I. M. Dremin, L. I. Sarycheva, K. Yu. Teplov, Eur. Phys. J. **C46**, 429 (2006);
I. M. Dremin, Nucl. Phys. **A785**, 365 (2007);
V. Koch, A. Majumder, X.-N. Wang, Phys. Rev. Lett. **96**, 172302 (2006);
A. Majumder, Xin-Nian Wang, Phys. Rev. **C73**, 051901 (2006);
B. Muller, J. L. Nagle, Ann. Rev. Nucl. Part. Sci. **56**, 93 (2006).
25. STAR Collab., J. Adams *et al.*, Phys. Rev. Lett. **95**, 152301 (2005);
PHENIX Collab., S. S. Adler *et al.*, Phys. Rev. Lett. **97**, 052301 (2006);
PHENIX Collab., A. Adare *et al.*, arXiv:0705.3238 [nucl-ex].

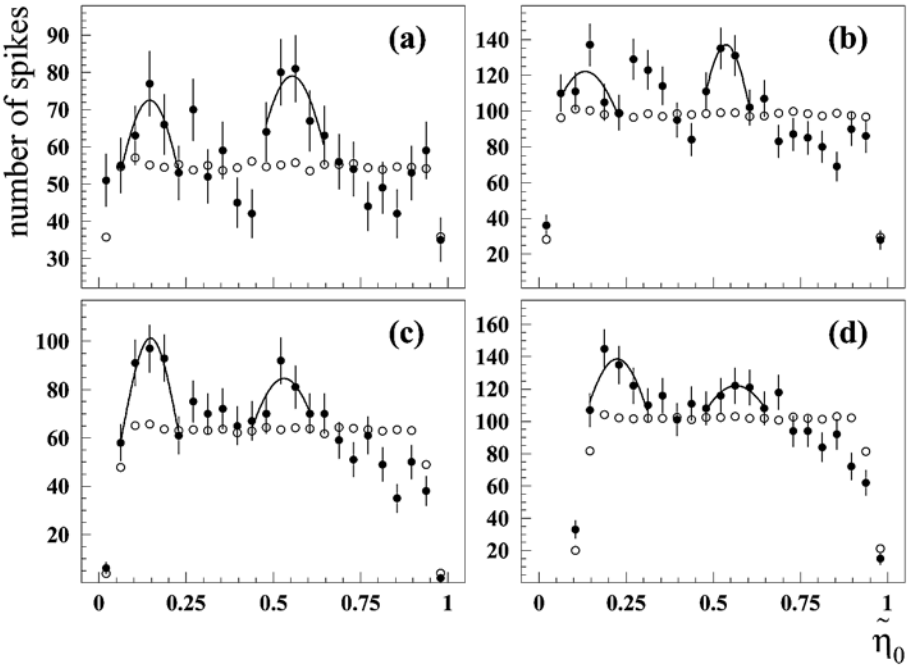

Fig. 1 – Experimental (●) and simulated (○) spike-center distributions in C-Cu collisions for different $\delta\tilde{\eta}$-bins and multiplicities δn: (a) $\delta\tilde{\eta} = 0.04$, $\delta n = 4$, (b) $\delta\tilde{\eta} = 0.08$, $\delta n = 5$, (c) $\delta\tilde{\eta} = 0.12$, $\delta n = 7$, (d) $\delta\tilde{\eta} = 0.02$, $\delta n = 9$. The curves represent Gaussian fits.

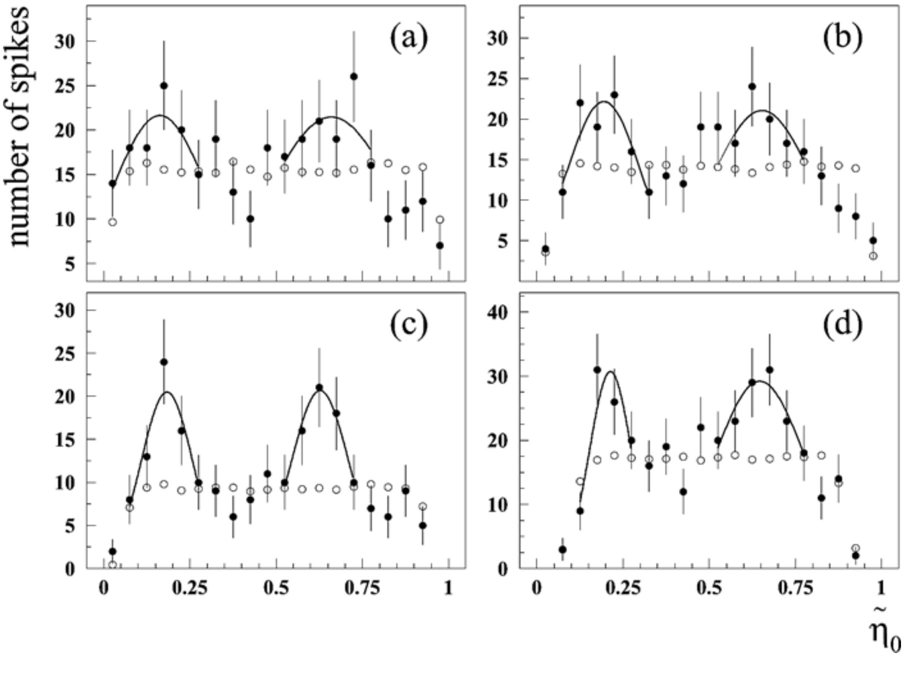

Fig. 2 – Experimental (●) and simulated (○) spike-center distributions in Mg-Mg collisions for different $\delta\tilde{\eta}$-bins and multiplicities δn: (a) $\delta\tilde{\eta} = 0.05$, $\delta n = 4$, (b) $\delta\tilde{\eta} = 0.1$, $\delta n = 5$, (c) $\delta\tilde{\eta} = 0.15$, $\delta n = 6$, (d) $\delta\tilde{\eta} = 0.25$, $\delta n = 7$. The curves represent Gaussian fits.