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Search for collective phenomena in high multiplicity events at Nuclotron and U-70

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Abstract

More than ten-year experimental search for collective phenomena in high multiplicity events has been carried out at the Laboratory of high energy physics at JINR. We present main results, which have been received at the U-70 accelerator (IHEP, Protvino) in the proton collisions and at Nuclotron (JINR, Dubna) in the nuclear interactions. For pp interactions, topological cross sections have been gone three orders down and achieved KNO-scaling variable $(n/\overline{n})$ 4.5. Probably, the tail of high multiplicity distribution stipulates gluon splitting. In the region of high multiplicity, the formation of pions is predominant. Some collective phenomena are predicted in this region. Using charged multiplicity data, we could restore total (sum of charged and neutral particles) multiplicity and have implemented unique research for fluctuations of the neutral particle number at the given total multiplicity. The revealed growth of scaled variance may indicate the pion (Bose-Einstein) condensate formation. The excess of soft photon yield at interactions of the Nuclotron beams (d, Li and C) with a carbon target has been confirmed. This can be connected with the pion condensate formation. Currently, we prepare two-shoulder electromagnetic calorimeter to carry out experimental studies at BM@N setup and plan to take part in new experiments on heavy ion collisions at Nuclotron.

1. Introduction

Our studies of hadron and nuclear interactions in the high multiplicity (HM) region have started more than 10 years ago [1]. In the 1970s, physicists thought about searching for HM events during carrying-out of the experiment at the Mirabelle bubble chamber

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[2] to understand how essential part of energy of colliding particles is transformed into secondaries. It is known that HM events are extreme rare ones. So, to find them out, it is necessary either to increase the set of statistical data or to include into setup the trigger device to suppress registration of small multiplicity events. The chamber method did not allow increasing considerably quantity of scanning events and to observe HM events [2].

The fulfilment of such investigations at the U-70 accelerator has become possible with development of electronics and mathematical methods of data processing. Profound effect on the physical investigation program executable at U-70 have impacted results obtained at heavy ion collisions at RHIC and SPS accelerators. We have carried out the experiment at the SVD (Spectrometer with Vertex Detector) setup made for studying of the near threshold production of charmed particles in interactions of the 70-GeV proton beams with nuclear targets [3]. This setup has been modified. It includes the following elements: a silicon vertex detector (10 planes), a scintillator hodoscope (HM trigger) [4], a magnetic spectrometer (18 proportional chambers and a magnet), a Cherenkov counter and an electromagnetic calorimeter with the large aperture. Drift tracker on the straw-tube base has been also manufactured at JINR, it allows sewing the charged particle tracks leaving vertex detector and incoming to the magnetic spectrometer.

Thermalization project is aimed at searching for new collective phenomena predicted in the HM region. At the U-70 energy in these events mainly light pions (charged and neutral) are produced. Pions are bosons. With the multiplicity growth their average energy is decreasing. When it is descending up to a certain critical value, the pion or the Bose-Einstein condensate formation is possible. For revealing this phenomenon, Begun and Gorenstein [5, 6] are proposed to measure the scaled variance of neutral pion number (the ratio of the variance to the average multiplicity) according to total multiplicity.

These investigations have been carried out by the SVD-2 Collaboration in two stages [7–9]. During the first longer stage, the charged pion multiplicity is restored. For that the results obtained from the precision silicon detector have been used. This allowed to go down topological cross sections on three orders in comparison with the data obtained by Mirabelle Collaboration in seventies. Scaled KNO-variable, that is equal to the ratio of multiplicity to its average has got the quantity 4.5 at the existent maximum world value 3.5.

For description of the topological cross sections at the HM region and their behavior at the tail of the HM prediction, the gluon dominance model has been developed out [10–12]. In concordance with this model gluons are the basic sources of secondary hadrons, and valence quarks from the initial protons are staying in the leading particles. The tail of HM succeeds in description by taking into account of gluon splitting (Figure 1). It should be noted, over the whole period of the LHC work none of the groups measuring multiplicity distributions succeeded in working out universal Monte Carlo generator consistent with the data in the HM region [13]. It is possible that Monte Carlo codes lowering topological cross sections in the HM region do not take into account the gluon branching which is implemented even at the U-70 energy.

At the second stage, multiplicity distributions of neutral pions and total multiplicity have been received. It is necessary to note, that the restoration of π^0 multiplicity using the event-by-event method at this experiment did not become possible because not all photons from the neutral pion decay get to the calorimeter. These difficulties are diminished owing to application of the unique method developing of SVD-2 Collaboration. This method has allowed restoring the number of events with given multiplicity of neutral pions. It is based on the Monte Carlo simulation and the comparison with data obtained earlier at the Mirabelle bubble chamber. Experimental values of the scaled variance at the HM total multiplicity get considerable deviations from the Monte Carlo generator predictions (figure 2) [8].

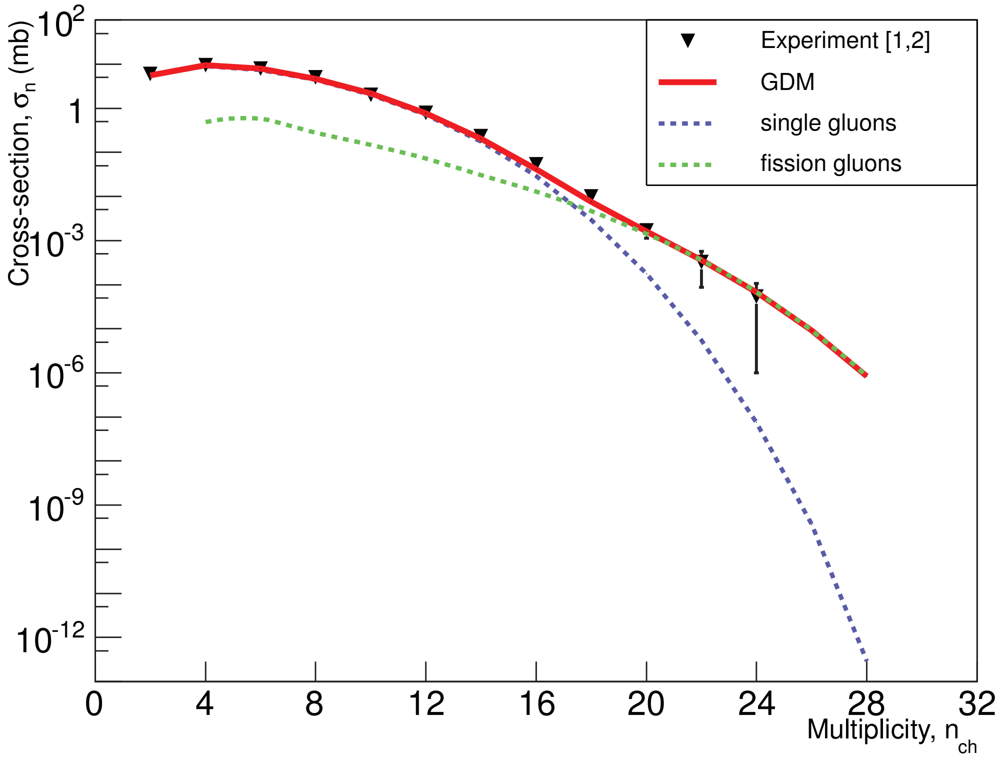

Figure 1: Topological cross sections σ_n versus charged multiplicity n_{ch} in GDM. The dashed blue line describes the contribution of single sources, the green line – the sources consisting of two gluons of fission, the solid red line is their sum.

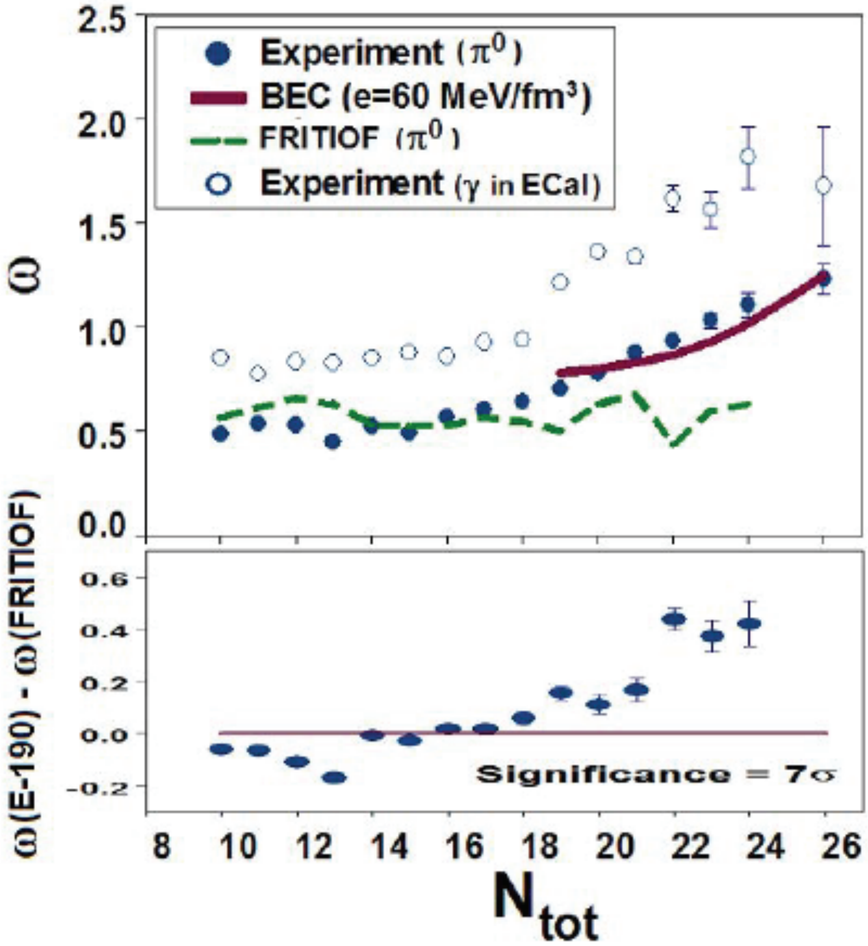

Figure 2: the measured scaled variance ω versus $N_{\rm tot}$ for π^0 mesons (•), photons (∘), MC code FRITIOF7.02 (the dashed curve) and theoretical prediction (solid curve) [5] for the energy density ε =60 MeV/fm^3. $N_{\rm tot} = N_{\rm ch} + N_0$ for π^0 mesons and $N_{\rm tot} = N_{\rm ch} + N_\gamma$ for photons.

As it was noted in the beginning, the HM study hides a lot of unexpected discoveries. Thus, in articles of two collaborations ATLAS [20] and LHCb [21] devoted study of two-particle Bose-Einstein (BE) correlations in pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV measured with the ATLAS and LHCb detectors correspondingly has been shown how parameters R and λ of the correlated function $C_2(R, \lambda)$ are changed with the multiplicity growth. The parameter R defines the size of an emission region. It goes to a constant value. The chaotic parameter λ takes into account partial incoherence of a source and it is equal to 1 at completely chaotic emission source. It equals 0 in the case of completely coherence source. Connection between two opposite phenomena, Bose-Einstein condensate and BE correlation for R and λ has been found out in [22] by Cheuk-Yin Wong.

After completion of the study of neutral pion number fluctuations, the SVD-2 Collaboration payed attention to the investigation of another collective phenomenon which can be related to the formation of a big amounts of particles. It becomes apparent through the increased (in comparison with theoretical estimations) yield of soft (smaller than 50 MeV) photons (SP) in hadrons and lepton interactions [14]. Exhaustive explanation of this phenomenon has not been found up to now. It is planned to study the possible connection of the SP production to the pion condensate. Such connection is predicted in the theoretical work [15]. Toward this end, the SVD-2 Collaboration has manufactured an electromagnetic calorimeter based on BGO crystals. Its checkout and calibration has been carried out at the SVD-2 setup at IHEP (Protvino). In 2015, it was transported to JINR for use in the experiment with 3.5 GeV beams (deuterium, lithium and carbon) of Nuclotron and carbon target. The calorimeter has been placed at the NIS-GIBS setup. For increasing the conversion pairs and separation neutrons from photons, the pre-shower detector with a lead converter has been included. Preliminary results have showed the excess of the SP yield in comparison with predictions calculated by means of Monte Carlo simulation [16, 17].

At present, JINR is implementing the mega-science project on the construction of the accelerator complex, the NICA collider [18]. There, high ions will be accelerated right up to uranium with the energy about 5 A GeV. Two setups are being created: MPD (multi-purpose detector) for study of nuclear matter properties with high baryon density in which it is expected to reveal the mixed phase consisted of hadronic and quark-gluon components, and also SPD (spin physics detector) setup for investigation of spin phenomena. Simultaneously with beginning of this project, at LHEP JINR the BM@N (Baryon matter at Nuclotron) setup ais produced for multi-strange particle study [19]. Two silicon planes of a vertex detector, six planes of gas detectors, two drift chambers, a calorimeter of zero angle for the plane reaction definition and two ToF systems are put at this setup. On this setup, the first results on registration of lambda hyperons formed in nuclear interactions have been obtained.

LHEP plans the electromagnetic calorimeter manufacture for the MPD setup based of "shashlyk"- type modules. The smaller size electromagnetic calorimeter for the photon registration is assembled at the BM@N setup from these modules. The module represents an assembly of the alternating lead planes and thin layers of scintillator. The low threshold of the recording photon energy by means of this calorimeter did not descend lower than 15 MeV. To register SP with the lower energy, the electronics with low threshold of registration is worked out. The production of the two-shoulder calorimeter based on modified modules with the possibility of the realization of an extensive program on the searching for new resonances in two-photon decays and other tasks are planned.

2. Physical program of future investigations at Nuclotron

Design of the mega-science NICA project in 2006 [18] has stimulated experiments at Nuclotron at JINR. After its renovation and upgrade, works on the BM@N setup creation has started. At this setup a wide program of AA interactions at a fixed target at 3.5-4.5 GeV is planned [19].

We have proposed the physical program for study. One of the basic detectors for its fulfilment is an electromagnetic calorimeter (ECal). It is collected from modules of the "shashlyk" type. The light on light guides that are put inside the module gets on a photomultiplier and is registered by the suitable electronics. We are planing implementing of the following investigations of pp, pA and AA interactions:

1. the Bose-Einstein condensate formation in nuclear interactions at high total multiplicity region [8];
2. the connection between the pion condensate and an excess yield of SP [16];
3. search for new resonances in the system of two γ-quanta (for example, f_0(500) or σ-meson etc.) [23, 24];
4. increased yield of η_0-mesons in AA-interactions [25];
5. γ- femtometry [26];
6. search for even component in the wave function of neutral pion [27];
7. coherence of SP by means of measurement of the flow, v_2, predicted by T. Kodama and T. Koide [28] and other questions.

Let us give short comments on 4) - 7) items. So, at study of interactions of 300 GeV-protons with nucleus of ^{20}Ne (data of FNAL), it has been found out the increased ratio of cross sections of the η_0 and π_0 meson formation in comparison with the same reactions on nucleons. Data on formation of particles with open strangeness (K^0, Λ and Σ) do not demonstrate such anomality which is observed for hidden strangeness particles.

Sole observation of pair photon interference has been carried out at SPS in WA-98 experiment (CERN) with the energy of lead ions 158 A GeV. The obtained estimations of parameters for correlated function C_2 are: $\lambda = (3.0 \pm 0.8) \times 10^{-3}$ and $R_{inv} = (5.4 \pm 1.0)$ fm. The contribution of direct photons (about 8%) exceeds theoretical calculations. R_{inv} is compared to the radius of the pion emission that indicates the emission of photons is realized at the last stage of nuclear matter development.

Generally accepted, pions have negative parity. However, author [27] formulates hypothesis about superposition even and odd components of parity for neutral pion. To prove this hypotheses, the distribution on the azimuth angle ϕ of decay π^0 to two pairs of e^+e^- should measure. The angle ϕ is the angle between two planes formed e^+e^- pairs. Sought distribution has been obtained in the KTeV-799 experiment (FNAL) with statistics 30000 events. Contribution of the positive parity state in expression for angle distribution $\frac{dF}{d\phi} = 1 + acos(2\phi) + bsin(2\phi)$ consisted of smaller than 3.3 %. Therefore, it is necessary to plan the experiment with higher statistics then in FNAL experiment. Setup with pair of calorimeters can solve this task at Nuclotron beams.

Koide and Kodama [28] propose to measure v_2 flow to define degree of coherence of direct SP. In the RHIC experiment (PHENIX Collaboration), the minimum value of p_{T} of the direct photons is about 500 MeV. They predict behavior of v_2 for smaller values and connect them with the coherence property of the photon emission.

3. Conclusion

Results of HM study testify to high potential of these experiments for new discoveries especially at using of electromagnetic calorimeters. Preparation and carrying out of such investigations is a foreground task at LHEP JINR.

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