XIV International Workshop Particle Correlations and Femtoscopy (WPCF2019)

Abstracts book

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June 3, 2019: Opening

Correlation femtoscopy: origins and achievements.

R. Lednicky

Joint Institute for Nuclear Research, Dubna, Russia.

A short introduction to correlation femtoscopy is given on the occasion of the 100th Anniversary of the birthday of Mikhail Isaakovich Podgoretsky.

June 3, 2019: New methods and facilities

Status of the MPD experiment.

A. Kisiel

Warsaw University of Technology, Warsaw, Poland.

MPD is a dedicated heavy-ion experiment at the NICA facility at JINR. The status of the preparation of the detector, together with its physics performance and running plans will be presented. Key element of the physics program of MPD are correlation measurements, including femtoscopy and collective flow. The motivation for the measurements, as well as design performance and Monte Carlo studies will be discussed.

Model dependent observation of Odderon from elastic pp and $p\bar{p}$ scattering at TeV energies.

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The unitarily extended Bialas-Bzdak model of elastic proton-proton scattering is applied, without modifications, to describe the differential cross-section of elastic proton-antiproton collisions and to extrapolate these differential cross-sections to LHC energies. Similarly, the differential cross-section of elastic pp scattering can be extrapolated with the same model from TOTEM data at LHC to D0 energies of 1.96 TeV. The differential cross-sections of elastic proton-(anti)proton collisions at 1.96, 2.76 and 7 TeV energies provide evidence for a crossing-odd part of the elastic scattering amplitude, the so -called Odderon effect. Within the framework of this model, the probability of Odderon observation is P = 0.99995 (1.96 TeV), P = 0.999997 (2.76 TeV) and P = 1.0 (7 TeV). These results will also be compared to the preliminary results (if available by the time of this conference) of a model-independent search of D0 and TOTEM for the discovery of Odderon at TeV energies.

Prospects of Event Shape Sorting.

B. Tomasik[1], J.Cimerman[2]

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The method of Event Shape Sorting allows to select events with similar distributions of hadrons in azimuthal angle. If it is used in connection with femtoscopy, it can select sources with both second and third order anisotropies at the same time, that can be visible in dependence of correlation radii on azimuthal angle and in the azimuthal distribution of hadrons. In this talk we demonstrate the particular ability of the method to recognise features of the source that would be hardly obtained with Event Shape Engineering. We also discuss the influence of statistical fluctuations on the sorting.

June 3, 2019: Femtoscopy in A+A, p+p , p+A and e^+e^- collisions at relativistic energies

Probing the meson–baryon strong interaction via femtoscopy in pp and p–Pb collisions with ALICE.

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The investigation of the strong interaction between different hadron pairs is one of the most fundamental problems in nuclear physics, but in several cases it is still very limited due to experimental challenges.

Thanks to the excellent tracking and particle identification capabilities of the ALICE detector, a variety of different measurements are possible, among them femtoscopy studies. Traditionally, femtoscopy is used to measure the size of the QGP fireball created in relativistic heavy-ion collisions, but it has been proved that femtoscopy can be used to effectively investigate the strong interaction for different particle pairs in different colliding systems.

Recent results of the kaon-proton correlation function measurement in pp and p–Pb collisions, showing the first experimental evidence of the K^0–n isospin breaking channel due to the mass difference between K^- and K^0, will be presented. The measured correlation functions will be compared with the available state-of-the-art theoretical models.

In addition, preliminary results of the measurements of the femtoscopic correlation of charged kaons and deuterons and their anti-particles at low relative momentum, studied with unprecedented precision in pp and p–Pb collisions at different collision energies, will also be presented.

Coulomb-correction for Levy-type sources.

S. Lökös[1,2], M. Nagy[2], M. Csanad[2]

[1]*Eszteházy Károly University,*

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In the investigation of two-particle momentum correlation , the Coulomb interaction between the constituents of the pair is the most important final state effect. In small systems like those created in e^+e^- or pp collisions, the so-called Gamow factor gives an acceptable description, however, in larger systems such as central or mid-central heavy ion collisions, more involved approaches are needed. In this my presentation I will shortly introduce the problem and investigate the Coulomb final state interaction for Levy-type source functions that were recently shown to be of much interest for a refined description of the space–time picture of particle production in heavy-ion collisions.

Lifetime and initial energy density estimations from a new exact solution of relativistic hydrodynamics - observation of a non-monotonic behaviour at RHIC.

G. Kasza

Wigner Research Centre for Physics, Budapest, Hungary.

We discuss a recently found family of exact and analytic, finite and accelerating, 1+1 dimensional solutions of perfect fluid relativistic hydrodynamics to describe the pseudorapidity densities and longitudinal HBT-radii and to estimate the lifetime parameter and the initial energy density of the expanding fireball in Au+Au collisions at various RHIC and LHC energies. From these exact solutions of relativistic hydrodynamics, we derive a simple and powerful formula to describe the pseudorapidity density distributions in high energy proton-proton and heavy ion collisions, and derive the scaling of the longitudinal HBT radius parameter as a function of the pseudorapidity density. We improve upon several oversimplifications in Bjorken's famous initial energy density estimate, and apply our results to estimate the initial energy densities of high energy reactions with data-driven pseudorapidity distributions. When compared to similar estimates at RHIC and LHC energies, our results indicate a surprising and non-monotonic dependence of the initial energy density on the energy of heavy ion collisions.

G. Kasza and T. Csorgo, arXiv:1811.09990.

June 3, 2019: Femtoscopy at RHIC and LHC: links to QGP physics

Femtoscopic picture of relativistic heavy ion collisions in integrated HydroKinetic Model.

Yu. Sinyukov, V. Shapoval, M. Adzhymambetov

Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine.

The pion and kaon femtoscopy radii depending on transverse momentum and multiplicity are studied for Au+Au collisions at the RHIC energy 200A GeV, LHC energies 2.76A TeV and 5.02A TeV for Pb+Pb collisions and 5.44A TeV for Xe+Xe collisions. The integrated HydroKinetic model (iHKM) is used for the corresponding analysis. The dependence of femto-radii on the initial sizes of colliding system and final multiplicities are investigated. The times of the maximal emission of pions and kaons are extracted from the analytical fit to the longitudinal femtoscopy radii.

Measurement of the strong interaction between matter and antimatter in heavy-ion collisions with ALICE.

L. Graczykowski

Warsaw University of Technology, Warsaw, Poland.

The strong interaction between baryons and antibaryons, especially those containing a strange quark, is not well understood due to limited possibilities to perform scattering experiments with beams of (anti)hyperons. Relativistic heavy-ion collisions provide a unique opportunity for such studies because the strong interaction among the large number of produced baryons and antibaryons results in a correlated pair production as a function of relative momenta, which can be directly measured using femtoscopy.

We present the most recent measurements of the femtoscopic correlation functions for proton-antiproton, proton-antilambda + antiproton-lambda and lambda-antilambda pairs performed by ALICE in Pb-Pb collisions at the energy of 2.76 TeV and 5.02 TeV per nucleon pair. The extracted values of scattering lengths and effective ranges of the strong interaction for proton-antilambda + antiproton-lambda and, for the first time, lambda-antilambda will be shown. In addition, indirect measurements of effective scattering parameters for heavier baryon–anti-baryon pairs will be presented. The meaning of the obtained values and possible consequences, such as the existence of baryon-antibaryon bound states or the inelastic scattering channels, will be discussed.

K^+K^- correlations in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV by the ALICE at the LHC.

K. Mikhaylov[1,2]

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[2] *Joint Institute for Nuclear Research, Dubna, Russia.*

Due to effects of quantum statistics and final-state interactions, momentum correlations of two or more particles at small relative momenta in their center-of-mass system, are sensitive to the space-time characteristics of the production processes at the level of fm (10^{-15} m). We report on the results of K^+K^- correlations in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV by the ALICE collaboration at the LHC. The obtained one-dimensional K^+K^- correlation functions are presented in three centrality classes and eight transverse momentum ranges. The K^+K^- mesons correlate due to the Coulomb final-state interactions and through the formation of $a_0(980)$ and $f_0(980)$ resonances. The K^+K^- femtoscopic source parameters, such as invariant radius Rinv and correlation strength λ, are extracted. The obtained radii increase with increasing centrality and decrease with increasing transverse momentum. The extracted parameters are compared with existing data for Bose-Einstein correlations of identical charged kaons studied by ALICE. The mass and coupling parameters for the $f_0(980)$ resonance are constrained.

Three particle Levy HBT from PHENIX.

B. Kurgyis

Eötvös Loránd University, Budapest, Hungary.

Bose-Einstein correlations of identical bosons reveal information about the space-time structure of particle emission from the sQGP formed in untrareativistic heavy ion collisions. Previous measurement of two particle correlations have shown that the source can be best described by a symmetric Levy distribution, and source parameters can be extracted this way. In this talk we measure three particle correlations 0-30% centrality Au+Au collision at $\sqrt{s_{\rm NN}} = 200$ GeV, and describe them with a Levy type source. This measurement together with two pion correlations may shed light on hadron creation mechanisms beyond chaotic emission. We measure three particle correlation strength (λ_3) as a function of pair transverse momentum. This parameter, combined with two particle correlation strength λ_2 (measured in two particle correlations) one may investigate the level of chaoticity and coherence in particle production.

Measurements of HBT correlations and Levy source parameters in $\sqrt{s_{\rm NN}} = 200$ GeV Au+Au collisions at the STAR experiment.

D. Kincses

Eötvös Loránd University, Budapest, Hungary.

To study the nature of the quark-hadron phase transition, it is important to investigate the space-time structure of the hadron emission source in heavy-ion collisions. Measurements of HBT correlations have proven to be a powerful tool to gain information about the source. In this study, Levy fits were performed to the measured one-dimensional two-pion correlation functions in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. The three extracted parameters are: the Levy scale parameter, R, which is in connection with the physical size of the source, the correlation strength parameter, λ, and the Levy exponent, α, which is related to one of the critical exponents (the correlation exponent η). In this talk, we report the current status of the analysis of the transverse mass dependence of the extracted Levy source parameters.

Azimuthally-differential pion femtoscopy in Cu+Au and Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV in the STAR experiment.

E. Khyzhniak

National Research Nuclear University, Moscow Engineering Physics Institute, Moscow, Russia.

Anisotropic flow is sensitive to the properties of system created in heavy-ion collisions. Azimuthally-sensitive femtoscopy with respect to the first-order event plane is coupled with the directed flow, and probes the space-time structure of the particle-emitting source. The knowledge of the source tilt can give a helpful experimental handle on the origin of the anisotropic flow. In addition, the tilt angle dependence on different collision systems at the same energy can provide constraints on theoretical models.

In the experiment, this information can be extracted by measuring pion femtoscopic radii as a function of the pair emission angle with respect to the first-order event plane.

In this talk, we present comparisons between the results of the measured tilt angle of the pion-emitting source at $\sqrt{s_{\rm NN}} = 200$ GeV in symmetric (Au+Au) and asymmetric (Cu+Au) collisions measured with the STAR experiment, and those estimated in the UrQMD model.

Exact solutions of relativistic viscous hydrodynamics.

M. Csanad, M. Nagy

Eötvös Loránd University, Budapest, Hungary.

We present analytical solutions of relativistic viscous hydrodynamics, describing expanding fireballs with ellipsoidal symmetry, similar to fireballs created in heavy ion collisions. For (1+3) dimensional Hubble flow, the evolution of thermodynamic quantities is discussed, taking the first-order viscous corrections into account. For the presented analytical solutions, shear viscosity has a negligible effect, but the bulk viscosity contribution is significant. We investigate the temperature evolution for several values of bulk viscosity over entropy density (ζ/s), including values applied in AdS/CFT and lattice QCD calculations. We find that the bulk viscosity reduces the radial acceleration and thus inhibits the buildup of flow. Furthermore, our calculation shows that the bulk viscosity decelerates the thermodynamic evolution.

June 4, 2019: Femtoscopy in A+A, p+p , p+A and e^+e^- collisions at relativistic energies

Strange hadrons and neutron stars.

L. Fabbietti

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Neutron stars are among the most dense objects detected to this end and their composition, especially their innermost core, is not known up to know. Several hypotheses can be put forward: maybe only nucleons are contained within neutron stars, maybe also strange hadrons are formed or maybe neutrons stars are hybrid or quark stars! All these scenarios can only be tested indirectly by computing the equation of state of the different compositions and test the results against the measurement of the neutron star properties. In order to obtain some of these equations of state, the interaction among hadrons must be pinned down quantitatively. An effective an quite novel to study these interactions is represented by the femtoscopy technique in pp and pPb collisions at the LHC. In this talk an overview of the different scenarios for neutrons stars will be presented with particular emphasis on the role played by strange hadrons. Future measurements within hadron physics relevant to investigate these different scenarios will be discussed.

Beyond the scattering and hypernuclei experiments: a tale of the p$-\Lambda$ and $\Lambda - \Lambda$ correlation studies at ALICE.

D. Mihaylov

Technical University of Munich, Munich, Germany.

Femtoscopy is a technique to study correlations between particles with low rest-frame relative momentum k^*, which can be related to the emission source and interaction potential. In a pioneering study the ALICE collaboration used pp and p–Pb collisions to study the low-energy ($k^* < 100$ MeV/c) p$-\Lambda$ and $\Lambda - \Lambda$ interactions. This low energy regime is not accessible by any other experimental methods, hence this study provides a unique and complementary view into the interaction potentials of those systems.

The p$-\Lambda$ data allow us to distinguish between different interaction models, taking advantage not only of the very low k^* region, but exploiting the opening of the coupling to N$-\Sigma$, which is very well resolved within the available statistics. Further, the quality of the data is sufficient to probe the profile of the emission source.

The investigation of the $\Lambda - \Lambda$ correlation function can constrain the scattering parameters of the interaction potential and test the predictions of various theoretical models, including the latest lattice calculations by the HAL QCD collaboration, as well as impose strict limits on the allowed binding energy of a hypothetical bound state.

Unprecedented precision measurements of the proton$-\Xi$ interaction via the femtoscopy method.

B. Hohlweger

Technical University of Munich, Munich, Germany.

Femtoscopic studies of Baryon-Baryon pairs opens a new era of studying two particle interactions at colliders. In particular, small collision systems prove to be particularly well suited to probe the short-ranged strong potentials. Experimental data can be compared to local potentials thanks to the newly developed Correlation Analysis Tool using the Schrodinger Equation (CATS). By analyzing the p–Pb dataset it was possible to directly observe for the first time the strong interaction of the p-Ξ pair. The dataset of high multiplicity events of pp collisions allows a continuation of the study with unprecedented precision, that we present in this talk. The p-Ξ correlation function is used to validate potentials from different models, for example, based on lattice QCD and cEFT calculations, and to explore their implications for neutron stars.

Constraining the p−Σ^0 interaction for the first time employing femtoscopy in ALICE.

A. Mathis

Technical University of Munich, Munich, Germany.

Pioneering studies by the ALICE Collaboration demonstrated the potential of employing femtoscopy to investigate and constrain hyperon-nucleon and hyperon-hyperon interactions with unprecedented precision. In particular, the small size of the particle-emitting source in pp collision systems is particularly well suited to study short-ranged strong potentials. Such femtoscopic analyses are complementary to previous attempts to study the interaction with scattering experiments, which are difficult to perform due to the unstable nature of hyperon beams.

In this contribution, we present measurements from the ALICE Collaboration in high multiplicity pp collisions at $\sqrt{s}$ =13 TeV. The high statistics data sample collected by the ALICE experiment enable for the first time studies of the p-Σ^0 interaction. Newly developed analysis tools allow for a comparison of the measured correlation function between the particle pairs of interest to theory predictions. This enables us to verify calculations of the interaction using either potentials or wave functions as an input.

Precise experimental constraints of the strong interaction between a proton and a $|\mathrm{S}| = 3$ baryon using femtoscopy.

O. Vazquez Doce

Technical University of Munich, Munich, Germany.

Two-particle correlations at small relative momentum originate from final-state interactions of the particle pair and are sensitive to the size of the particle-emitting source. It has recently been demonstrated that the femtoscopic technique can be applied to pairs of baryons from small particle emitting sources, such as those produced in proton-proton or proton-nucleus collisions, to give direct insight into short-range strong baryon-baryon interactions. Results from the measurements by the ALICE Collaboration of $\mathrm{p}{-}\Omega^-$ pairs produced in high multiplicity pp collisions at $\sqrt{s} = 13$ TeV will be presented. Since the proton-proton interaction is well known, the proton-proton correlation function is used to constrain the size and shape of the baryon emitting source. Newly developed analysis tools allow us to compare the experimentally measured correlation functions to theory predictions using either potentials or wave functions as input. The precision of the measured $\mathrm{p}{-}\Omega^-$ correlation function makes possible to test predictions from recent phenomenological models and Lattice QCD calculations, including models predicting a bound nucleon$-\Omega^-$ di-baryon state, with high sensitivity. The precise evaluation of the nucleon-hyperon interaction is fundamental for understanding the interactions of strange and multi-strange baryons, and consequences for the equation of state for neutron-rich matter including hyperons will be discussed.

June 4, 2019: Femtoscopy at RHIC and LHC: links to QGP physics

Event-shape dependent same charge pion femtoscopy in pp collisions at $\sqrt{s} = 7$ TeV with the ALICE detector.

G. Simatovic

National Institute for Subatomic Physics Nikhef, Amsterdam, Netherlands.

Two-particle correlations in high-energy collision experiments have proven to be an invaluable tool for the investigation of the space-time evolution of the emission system. This is possible by extracting their homogeneity radii via the Bose-Einstein enhancement of identical boson production at low relative momentum. From previous observations it is clear that in pp collisions at $\sqrt{s} = 7$ TeV the average pair transverse momentum k_{T} range of such analyses is limited due to large background correlations that were attributed to mini-jet phenomena. To address this issue we analysed Bose-Einstein correlations of charged pion pairs in two classes of events categorized by their transverse sphericity ST: highly spherical events (ST$>$0.7), which are known for soft particle production and a lack of particle collimation, and jet-like events (ST$<$0.3) that are dominated by in-jet particle production and back-to-back momentum correlations. These event-shape classes are of particular interest because they give insight into the nature of correlated particle production in significantly different types of high-energy proton-proton collisions. In this talk we present two-particle momentum-space correlations (HBT) studies with the ALICE detector for both of these event categories, as well as 1D homogeneity radii for k_{T} values up to 1.2 GeV/c. In addition, we will discuss a new method for non-femtoscopic background removal and describe new avenues of investigation which are opened by these results.

Neutral kaon femtoscopy at STAR.

D. Pawłowska

Warsaw University of Technology, Warsaw, Poland.

Properties of nuclear matter can be studied by relativistic heavy-ion collisions in high energy experiments like STAR. One of the methods to learn about properties of nuclear matter is the femtoscopy, which relies on the information carried by particles produced in the collisions. Using femtoscopic observables, the source parameters related to space-time characteristics can be extracted. During heavy-ion collisions mostly pions are produced and therefore pion femtoscopy is a particularly useful tool. High statistics data sets from RHIC have also made it possible to study the strange particle correlations. The lightest strange hadrons are charged and neutral kaons. The strong interaction, which conserves the strangeness quantum number, is responsible for the production of the neutral kaon system. It is possible to study the neutral kaons, K^0_S, which can be measured through their decays products to charged pions.

In this talk, one-dimensional correlation functions of neutral kaon pairs in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured by the STAR experiment at RHIC will be presented.

Model independent Levy analysis and its applications.

T. Novák

Eszterházy Károly University, Eger, Hungary.

A model-independent expansion technique is presented here to describe nearly Levy-stable data. It can be utilized to describe such Bose–Einstein (HBT), dynamical (ridge) and other correlation functions which have a nearly Levy or "stretched exponential" shape. Applications of this technique on L3 and TOTEM data are also introduced.

June 4, 2019: Femtoscopy in A+A, p+p , p+A and e^+e^- collisions at relativistic energies

Results on Bose-Einstein correlations of charged hadrons in pp collisions at 13 TeV.

S. Padula

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Femtoscopic correlations between charged hadrons are measured over a broad multiplicity range, from a few particles up to about 250 reconstructed charged hadrons, in proton-proton collisions at a centre-of-mass energy of 13 TeV. The results are based on data collected using the CMS detector at the LHC in 2015, during runs with a special low pileup configuration. Three analysis techniques with different dependencies on simulations are used to remove the non-Bose-Einstein background from the correlation functions, and are found to give consistent results. One-dimensional studies of the lengths-of-homogeneity, $R_{\rm inv}$, and the intercept parameter, lambda, have been carried out for both inclusive events and high-multiplicity events selected using a dedicated online trigger. The measured lengths of homogeneity are studied as functions of particle multiplicity, pair average transverse momentum, and pair transverse mass. The results are compared with those from CMS collected at lower center-of-mass energies and to data from other LHC experiment, as well as with theoretical expectations from the color glass condensate and from hydrodynamical models.

Femtoscopic probes with strange particles in STAR.

G. Nigmatkulov

National Research Nuclear University, Moscow Engineering Physics Institute, Moscow, Russia.

Heavy-ion collisions provide information about the properties of the matter under extreme conditions. Measurement of strangeness production properties provides important information about the collision region evolution. The spatial and temporal characteristics of particle emission can be extracted using femtoscopy technique. In this talk, the centrality, energy and transverse mass dependence of the three-dimensional femtoscopic radii for charged kaons in Au+Au collisions will be presented. In addition, the first measurement of the proton$-\Omega$ correlation function in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} =\sim 200$ GeV will be shown and compared to (2+1)-flavor lattice QCD simulations.

Femtoscopy with identified particles for NICA/MPD.

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The correlation femtoscopy gives possibilities to measure the space-time characteristics of particle production processes due to the effects of quantum statistics (QS) and final state interactions (FSI). Femtoscopy at lower energies was intensively studied at AGS, SPS and in the Beam Energy Scan (BES) program. According to the physical program of MPD, it is also being planned to be studied. In the work we discuss possibilities to observe a change from the first order phase transition expected at low energies to the crossover one at high energies with different femtoscopy observables using hybrid models.

June 6, 2019: Collective flow and correlations

Overview of recent correlation measurements with ALICE.

M. Janik

Warsaw University of Technology, Warsaw, Poland.

The ALICE detector at the Large Hadron Collider at CERN has been optimized for excellent particle identification and tracking capabilities with the aim of studying the Quark-Gluon Plasma (QGP), a deconfined state of hadronic matter produced in ultra-relativistic heavy-ion collisions at the LHC.

One of the key observables used in the study of the QGP is two-particle correlations which allows the exploration of the underlying physics phenomena of particle production in collisions of both protons and heavy ions. Studying distributions of angles in $\Delta\eta\Delta\phi$ space (where $\Delta\eta$ is the pseudorapidity difference and $\Delta\phi$ is the azimuthal angle difference between two particles) opens up the possibility to study a number of physics mechanisms, including baryon production, strangeness production, mechanisms of energy loss, quantum statistics and others.

This talk will present a broad range of ALICE correlation measurements, using both unidentified and identified particles (including pions, kaons, protons, strange baryons and D-mesons) in the broad eta and momentum range, for different collision systems.

Elliptic and triangular collective flow of identified charged hadrons in Au+Au at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV.

P. Parfenov

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A central goal of current experiments at RHIC is to study the properties of the hot and dense QCD matter produced in energetic heavy-ion collisions. Such studies can give insight into the QCD phase diagram, as well as the transport coefficients of the strongly-coupled Quark Gluon Plasma (sQGP). Anisotropic flow measurements of identified particles play an essential role in such studies. We report on the measurements of elliptic (v_2) and triangular (v_3) flow of identified charged hadrons in Au+Au collisions at 200 GeV per nucleon pair center of mass energy measured with the STAR detector at RHIC. The results will be presented as a function of transverse momentum (p_{T}) and collision centrality for different particle species and compared with recent ALICE measurements in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV.

Anisotropic flow measurements from the NA61/SHINE and NA49 beam momentum scan programs at CERN SPS.

O. Golosov[1], I. Selyuzhenkov[1,2], E. Kashirin[1], V. Klochkov[2,3]

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The NA61/SHINE experiment at the CERN SPS has recently extended its program for the energy scan with Pb ions. In the past, the NA49 experiment, which preceded the NA61/SHINE, has also recorded data for Pb–Pb collisions at different energies. Together, the two experiments cover wide range of collision energies in the beam momentum range of 13–150A GeV/c provided by CERN SPS. Analysis of the new NA61/SHINE data and revision of the existing NA49 using modern measurement techniques allow for a new comprehensive systematic study of the collective flow relative to the spectator plane. The measurements at the lowest energy available at the SPS are also relevant for the preparation of the Compressed Baryonic Matter (CBM) heavy-ion experiment at the future FAIR facility in Darmstadt. We will present new NA61/SHINE results on directed and elliptic flow measurement in Pb–Pb collisions at 13 and 30A GeV/c relative to the spectator plane determined with the Projectile Spectator Detector. Also a new analysis of 40 and 158A GeV data collected by the NA49 experiment using forward spectator calorimeters (VETO and RCAL) will be shown. The flow coefficients are reported as a function of rapidity and transverse momentum in different classes of collision centrality. The new results are compared with existing results from previous NA49 analysis and the STAR data at RHIC.

Investigation of particle anti-particle elliptic flow difference.

M. Stefaniak

Warsaw University of Technology, Warsaw, Poland.

The azimuthal anisotropy of particle emission in the transverse plane, known as anisotropic flow, is used to study the properties of strongly interacting hot and dense medium created in the heavy-ion collision. Anisotropic flow coefficients are the key observables which reflect the viscous hydrodynamic response to the initial spatial anisotropy, produced in the early stages of the collision. In previous studies [1] performed by the STAR collaboration at the Relativistic Heavy Ion Collider (RHIC) the increase of the elliptic flow (v_2) difference between particles and antiparticles at the lower collision energies has been observed.

In this talk, we will present the STAR measurement of the two- and four-particle flow correlations for identified particles as a function of centrality, transverse momentum and beam energy. Our measurements will be compared with the EPOS model simulations as well, that will help in better understanding the sources of the proton-antiproton elliptic flow difference.

[1] STAR Collaboration: Phys. Rev. C 88 (2013) 14902.

Anisotropic flow measurements at NICA energies.

A. Taranenko

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Extensive measurements of azimuthal anisotropy in relativistic A+A collisions have provided invaluable insights on the expansion dynamics and the transport properties of the strongly interacting matter produced in such collisions. The recent results of flow measurements from the top SIS energy to the top SPS energy will be discussed with emphasis on techniques, interpretation, and uncertainties in the measurements. The prospects for future measurements at NICA energies will be presented and discussed.

June 6, 2019: Fluctuation in initial conditions

Application of Principal Component Analysis to establish a proper basis for flow studies in heavy-ion collisions.

I. Altsybeev

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Principal component analysis (PCA) is a transformation that converts a set of observations of possibly correlated variables into a set of values of linearly uncorrelated ones, called principal components. In analysis of heavy-ion collisions, PCA was recently applied to extract information about event-by-event fluctuations from two-particle correlations and to study nonlinear coupling between different harmonic flow modes.

In this work, PCA is applied directly to event-by-event single-particle distributions in simulated A–A collisions, allowing to extract the most optimal basis for events from the data itself, which is opposed to the case when the basis is chosen by hand, like, for example, Fourier series expansion typically used for azimuthal angle decomposition. PCA is done separately in η and φ dimensions, obtained bases and decomposition coefficients are interpreted and compared to Fourier and polynomial expansions. Analysis is done also simultaneously in $\eta - \varphi$ dimensions, which allows one to study coupling of the longitudinal structure of events with the azimuthal particle distribution. Connections to some conventional observables are discussed.

Calculation of long-range rapidity correlations in the model with string fusion on a transverse lattice.

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In the framework of the model with the fusion of quark-gluon strings on a transverse lattice, we study the long-range rapidity correlations between various observables in high-energy hadronic interactions. As the observables we use the variables, including the intense ones (e.g. the mean transverse momentum), measured event-by-event in two acceptance windows separated in rapidity. For a realistic case with an inhomogeneous distribution of strings in the transverse plane we find explicit analytical formulas for the asymptotes of the correlation coefficients at a large string density. We analyze the properties of the obtained correlation coefficients and the prospects for their experimental observation. In this connection the influence on the results of the procedure of the collision centrality class fixation, commonly used in most of the modern high energy physics collider experiments, was also studied. For this purpose we modify the model with the string fusion on transverse lattice, imposing the additional restrictions on the variation of the total number of initial strings. The explicit analytical formulas for the asymptotes of the correlation coefficients in this case are also calculated. In the same model we also calculate the so-called strongly intensive observable between multiplicities of particles in two acceptance windows. We take into account the string fusion effects, leading to a formation of string clusters with new properties, and show that in this case this observable is equal to the weighted average value for different string clusters. Unfortunately the weighting factors depend on collision conditions; hence this observable loses its strongly intensive character. This work was supported by the RFBR grant 18-02-40075.

Study of forward-backward multiplicity fluctuations and correlations with pseudorapidity.

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Multiplicity correlations and fluctuations in two separated pseudorapidity intervals are used to be studied in terms of strongly intensive variables [1-3] and correlation coefficients [4] being evaluated for forward and backward pseudorapidity windows. In this work, the model with quark-gluon strings as objects extended in pseudorapidity space and acting as particle emitting sources was considered. To describe fluctuations at collision energies corresponding to SPS and future FAIR and NICA accelerators, a toy model with strings of fluctuating length has been developed, what allows one to abandon the assumption of the translation invariance in rapidity. The dependence of strongly intensive observables and correlation coefficients on the width of acceptance windows and the pseudorapidity separation between them is studied. The model gives results that are in a good agreement with the available data from the NA61/SHINE experiment.

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June 6, 2019: Searches for the critical point

Prospects for the study of event-by-event fluctuations and strangeness production with the MPD detector at NICA.

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The future heavy-ion collider NICA (JINR, Dubna) will provide a variety of beam types with the range of collision energies from 4 to 11 AGeV. New experimental data on event-by-event fluctuations and strangeness production allow addressing important QCD properties such as nature of deconfinement phase transition and existence of the Critical End Point (CEP). Heavy-ion collisions at NICA will be measured with the multi-purpose detector – MPD, which provides precise reconstruction of multiple physics channels. In my talk I will describe NICA physics goals and the MPD concept with an emphasis to detector performance in the study of the excitation function for the high order moments of the net-proton event-by-event multiplicity distributions. The results of a feasibility study for measuring at NICA spectra and yields of kaons and pions, and the strangeness-to-entropy ratio will be presented as well.

Bose-Einstein correlations at NA61/SHINE.

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The NA61/SHINE experiment at SPS investigates nucleon-nucleon collisions to understand the structures of the QCD phase diagram. The nature of the quark-hadron transition can be studied via Bose-Einstein momentum correlation functions, as these reveal the space-time structure of the hadron emitting source. The measured correlations functions can be described by correlation functions based on Levy-distributed sources. In this talk, we report on the latest NA61/SHINE measurements of Bose-Einstein correlations. We discuss the measurement of the Levy source parameters as a function of transverse mass. One particularly important parameter, Levy exponent alpha which describes the shape of the source is related to the critical exponent eta, and thus may shed light on the location of the critical end point of QCD phase diagram.

Spectra and fluctuations from the NA61/SHINE experiment.

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The goal of the NA61/SHINE experiment is to locate the position of the critical point of strongly interacting matter and to study the properties of the onset of deconfinement. A two-dimensional phase diagram scan program was completed last year. Measurements were performed and data were accumulated at 6 beam energies ($5.1 < \sqrt{s_{\mathrm{NN}}} < 16.8/17.3$ GeV) and for 6 colliding systems (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb) . In this report, the spectra and fluctuation results will be reviewed. In particular, inverse slope parameters and transverse mass of spectra, mean multiplicities, proton intermittency, as well as intensive and strongly intensive fluctuation measures are planned to be discussed.

June 6, 2019: Chiral magnetic effects and vorticity

Analytic model studies of polarized baryon production.

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We utilize known exact analytic solutions of perfect fluid hydrodynamics to analytically calculate the polarization of baryons produced in heavy ion collisions. Assuming local thermodynamical equilibrium also for spin degrees of freedom, baryons get a net polarization at their formation (freeze-out). This polarization depends on the time evolution of the Quark-Gluon Plasma (QGP), which can be described as an almost perfect fluid. By using exact analytic solutions, we thus can analyze the necessity of rotation (and vorticity) for non-zero net polarization. In this talk the first analytical calculations are given for the polarization four-vector. We use three hydrodynamical models; one solution is the spherically symmetric Hubble flow (a somewhat oversimplified model, to demonstrate the methodology). The second one is a somewhat more involved one, that corresponds to a rotating and accelerating expansion, and is thus well suited to investigate some main features of the time evolution of the QGP created in peripheral heavy-ion collisions (although there are still many numerous features of a real collision geometry that are beyond the reach of this simple model). The third and most complex model is the so called Buda–Lund model (generalized for rotation). This solution has more parameters than the above mentioned ones, thus we can see, how the changes in the parameters can affect the polarization; the effect of the vorticity, acceleration and temperature gradient can also be disentangled.

June 6, 2019: Femtoscopy at intermediate energies: links to the EoS

The shape of the correlation function.

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The correlation function measured in ultrarelativistic nuclear collisions is clearly non-Gaussian. We discuss the effects that may influence its shape. By making use of models we assess how much the individual effects modify the shape. In particular, we focus on the parametrisations expressed with the help of Levy-stable distributions. We show that the Levy index may deviate substantially from 2 due to non-critical effects such as non-spherical shape, resonance decays, event-by-event fluctuations and functional dependence on q_{inv} or similar.

Two-pion intensity-interferometry in central and non-central collisions of Au(1.23AGeV)+Au with HADES.

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We present results on azimuthally-integrated and recently performed azimuthally-dependent analyses of identical pion intensity interferometry (HBT) studied in collisions of Au+Au at $\sqrt{s_{\mathrm{NN}}} = 2.4$ GeV. The data are taken with the HADES spectrometer at SIS18/GSI Darmstadt. We study the dependence of the space-time extent of the pion emitting source on the pair transverse momentum and on the collision centrality. We observe a substantial charge sign difference of the source radii, most pronounced at low transverse momenta. The extracted source parameters do well complement the beam-energy dependencies at higher energies. Furthermore, we study the evolution (with transverse momentum, centrality, and collision energy) of both the eccentricity and the tilt angle of the $\pi\pi$ emission ellipsoid.

Convolutional neural network for centrality in fixed target experiments.

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Fixed target experiments have an unique possibility to measure centrality of colliding systems by hadronic calorimeters on the beam line. This is usually achieved by the detection of all forward nucleon spectators and is accomplished with fluctuation and correlation measures with lower biases than in collider experiments. However, hadronic calorimeters have much lower resolution than multiplicity detectors that introduces additional volume fluctuation to the measures. We examined the net implementation for a Geant model of the modular Projectile Spectator Calorimeter of the NA61/SHINE experiment. In this report, we present the first attempt to increase resolution capacity of the spectator detector by implementing a convolutional neural network. The data were generated in the framework of SHIELD MC for the collisions of the lightest available system (Be7+Be9) and for the highest beam momentum (150A GeV/c). Two ways of determination centrality – by number of forward spectators and by forward energy – are considered. In comparison with the classical histogram analysis method, the net shows a slight increase of centrality selection accuracy after the implementation.

June 7, 2019: Charge fluctuations, correlations and balance functions

Multiplicity fluctuations in the dynamical clusterization model.

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We discuss the recently measured event-by-event multiplicity fluctuations in relativistic heavy-ion collisions. It is shown that the observed non-monotonic behaviour of the scaled variance of multiplicity distribution as a function of collision centrality (such effect is not observed in a widely used string-hadronic models of nuclear collisions) can be fully explained by the correlations between produced particles promoting cluster formation. We define a cluster as a quasi-neutral gas of charged and neutral particles which exhibits collective behaviour. The characteristic space scale of this shielding is the Debye length. We split a Canonical Ensemble or a Micro Canonical Ensemble with a very large volume into cluster, which is by definition, a Grand Canonical Ensemble, with the rest of the system acting as a reservoir. P(N) in a cluster is given by Negative Binomial distribution while the rest (reservoir), treated as a superposition of elementary collisions, is described by Binomial distribution. The ability to generate spatial structures (cluster phase) sign the propensity to self-organize of hadronic matter.

Charge and isospin fluctuations in a non-ideal pion gas with dynamically fixed particle number.

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We study the behavior of the non-ideal pion gas with the dynamically fixed number of particles formed on an intermediate stage in ultrarelativistic heavy-ion collisions. A pion spectrum is calculated within the self-consistent Hartree approximation. General expressions are derived for cross-covariances of the number of various particle species in the pion gas of an arbitrary isospin composition. The behavior of cross-variances is analyzed for the temperature approaching the critical temperature for the Bose-Einstein condensation. In case of the system with equal averaged numbers of isospin species, the variance of the charge, $Q = N_{\pi^+} - N_{\pi^-}$, diverges at the temperature approaching the critical one, whereas variances of the total particle number, $N = N_{\pi^+} + N_{\pi^-} + N_{\pi^0}$, and that of a relative abundance of charged and neutral pions, $G = (N_{\pi^+} + N_{\pi^-})/2 - N_{\pi^0}$, remain finite in the critical point. Then we study fluctuations in the pion gas with small isospin imbalance $0 < |G| << N$ and $0 < |Q| << N$ and calculate shifts of the effective masses, chemical potentials, values of critical temperatures and cross-variances.

Correlations with charge and mean transverse momentum in AA collisions at high energy in string fusion approach.

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The fluctuations involving a net electric charge of hadrons, produced in ultrarelativistic heavy ion collisions are studied to characterize the properties of the hot and dense quark-gluon medium [1,2]. They also carry important information on the collective dynamical effects in initial stages of AA collisions [3,4]. Experimentally, they are studied in terms of dynamical fluctuation parameter and the balance functions. These observables showed to be robust against volume fluctuations and centrality class width, being therefore strongly intensive variables. In this work, we studied several types of correlational and fluctuational measures in Pb–Pb collisions at the LHC energy using a dipole-based Monte Carlo model [5,6], in which the collectivity is implemented as an interaction between strings by string fusion model [7,8]. For the particle species discrimination, the modified Schwinger mechanism is used [9], where the effective string tension, according to the string fusion prescription, depends on the string density. We calculated a dynamical fluctuation measure the dynamical fluctuation parameter between electric charge, different particle yields, and propose a new measurement for the study of the simultaneous fluctuation of a net charge and mean transverse momentum of the produced particles. The results show that the inclusion of string fusion significantly improves the agreement of the model with experimental data. By analyzing the string fusion predictions and comparing with other approaches, we discuss the effect of different realizations of string collectivity on these observables.

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Studies of collective effects in pp collisions at the LHC with the balance function for the identified particles.

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Experiments at RHIC and the LHC have lately reported intriguing results that indicate the presence of collectivity in small collision systems. The first hints originated from two-particle azimuthal correlations studies. The charge dependent part of such correlations is studied using the balance function in the relative pseudorapidity ($\Delta\eta$) and azimuthal angle ($\Delta\phi$) of the particle pair. This measurement has been used as an effective tool to investigate the properties of the system created in high-energy heavy-ion collisions such as the hadronization time, the freeze-out conditions and to characterise its collective motion. In addition, the study of the balance function for different particle species in A-A collisions provides valuable insight to the chemical evolution of the QGP.

In this talk, we report the measurement of the balance function of identified particles in pp collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV recorded by ALICE. This analysis, performed as a function of multiplicity, is an important piece in understanding if the underlying physics phenomena of particle production are of a common origin across collision systems.

Multiplicity correlations with strongly intensive quantities.

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The strongly intensive observable between multiplicities in two acceptance windows separated in rapidity is calculated in the model with quark-gluon strings acting as particle emitting sources. The dependence of this observable on the two-particle correlation function of a string, the width of observation windows and the rapidity gap between them is presented. In the case with independent identical strings the peculiarities of its behaviour for particles with different electric charges are analyzed by taking into account a shape of the balance function obtained from pp collisions at the ALICE experiment. We also show that string fusion effects violate the property of strong intensity. We predict the changes in the behaviour of this observable with energy and collision centrality, arising due to the string fusion phenomena.

Two-particle transverse momentum correlations in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV.

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Two-particle correlations are powerful tools for studying the medium produced in heavy-ion collisions. In particular, two-particle transverse momentum correlations enable measurements of the collision dynamics sensitive to momentum currents. Their evolution with collision centrality, which is related to the system lifetime, provides information about the shear viscosity, η/s, and the system relaxation time, τ_π. We report on measurements of two-particle transverse momentum correlations as a function of centrality in Pb–Pb collisions using the ALICE detector at the LHC. The centrality dependence of the near side peak of the correlation function, particularly its longitudinal width, provides information about the shear viscosity of the produced medium. The data are compared to predictions from selected Monte Carlo models. The charge independent momentum correlator exhibits a longitudinal broadening from peripheral to central collisions that is qualitatively consistent with expectations from a model with viscous effects. We will discuss an interpretation of the observed broadening in the context of this model.

Production of light nuclei in relativistic heavy-ion collisions.

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Production of light nuclei in relativistic heavy-ion collisions at LHC is well described by both the thermal model, where light nuclei are in equilibrium with all other hadron species present in a fireball, and the coalescence model, where light nuclei are formed after the fireball decay due to final state interactions. We propose two methods to falsify one of the models.

It is advocated to compare a yield of ^{4}He to that of exotic nuclide ^{4}Li which has spin 2 and decays into ^{3}He and proton with the width of 6 MeV. The yield of ^{4}Li can be experimentally obtained through a measurement of the ^{3}He-proton correlation function. The alpha particle is well bound and compact while the nuclide ^{4}Li is weakly bound and loose. Since the masses are similar, the yield of ^{4}Li is according to the thermal model 5 times bigger than that of 4He because of 5 spin states of 4Li and only one of ^{4}He. The coalescence model predicts not only a significantly smaller yield of ^{4}Li (due to its loose structure) but the yield strongly decreases as the collisions become less central.

We also suggest to measure a hadron-deuteron correlation function which appears to carry information about a source of deuterons and allows one to determine whether a deuteron is directly emitted form a fireball or it is formed afterwards. The kaon-deuteron and proton-deuteron correlation functions are computed to illustrate the statement.

June 7, 2019: Resonances at RHIC and LHC

Precise measurements of light-flavour resonances production with ALICE: new results and opportunities.

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Differential measurements with unprecedented precision of light-flavour resonances have paved the way to use these probes in the study of several aspects of particle production and collision dynamics in relativistic heavy-ion collisions. A review of these opportunities will be discussed in this talk, which presents a comprehensive set of results obtained with ALICE. The most recent results from Run2 data on the production of meson resonances (f_0, f_2, ρ, charged and neutral K, ϕ) and baryon resonances ($\Lambda(1520)$, $\Xi(1530)$) will be shown for both small systems (pp and p–Pb) and Pb–Pb collisions. New observables, such us phi spin alignment, hadron-resonance correlation, and the spherocity-dependent investigation of resonance production will also be discussed.