XIV Polish Workshop on Relativistic Heavy-Ion Collisions: Interplay between soft and hard probes of heavy-ion collisions

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Book of Abstracts

Book of abstracts

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Session II / **2**

Evolution equations for medium-induced QCD cascades and their solutions

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"I am going present solutions of evolution equations for inclusive distribution of gluons as produced by jet traversing quark-gluon plasma. The the original equation is reformulated in such a form that the virtual and unresolved-real emissions as well as unresolved collisions with medium are resummed in a Sudakov-type form factor. The resulting integral equations are then solved most efficiently with use of newly developed Markov Chain Monte Carlo algorithms implemented in a dedicated program called MINCAS. Their results for a gluon energy density are compared with an analytical solution and a differential numerical method. Some results for gluon transverse-momentum distributions are also presented. They exhibit interesting patterns not discussed so far in the literature, in particular a departure from the Gaussian behavior - which does not happen in approximate analytical solutions.

Session IV / **3**

Insight into Multiplicity Dependence of Strangeness and Resonance Production from Small to Large System with ALICE at the LHC

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One of the important results of the LHC Run 1 was the observation of an enhanced production of strange particles in high multiplicity pp and p-Pb collisions at 7 and 5.02 TeV, respectively. A smooth evolution of yields of strange particles relative to the non-strange ones with event multiplicity has been observed in such systems. Results from Run 2 at the top LHC energy are extended exploiting a dedicated high multiplicity trigger. This offers the unique opportunity to study, in elementary collisions, the multiplicity range covered by semi-peripheral Pb-Pb collisions. We present the latest results on multiplicity-dependent strangeness production at LHC energies with ALICE. The strangeness enhancement is investigated by measuring the evolution with multiplicity of single-strange and multi- strange baryon production relative to non-strange particles. We also present recent measurements of mesonic and baryonic resonances in small collision systems. We investigate the system size dependence in different collision systems as well as lower collision energies to study how the hadronic scattering processes affect measured resonance yields, as well as the interplay between canonical suppression and strangeness enhancement. The measurement of the $\varphi(1020)$ meson as a function of multiplicity provides crucial constraints in this context. Energy and system-type invariance are discussed and an extensive comparison with statistical hadronization and QCD-inspired models are presented.

Session IV / **4**

Spin Polarization Dynamics for the Bjorken Hydrodynamic Background.

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Using relativistic hydrodynamic equations for polarized spin 1/2 particles we determine the space-time evolution of the spin polarization in the system. In our approach, we use the forms of the energy-momentum and spin tensors based on de Groot, van Leeuwen, and van Weert. The calculations are done in a boost-invariant and transversely homogeneous setup. We present how the formalism of hydrodynamics with spin can be used for the determination of physical observables related to the spin polarization required for the modeling of the experimental data.

Session V / **6**

Chiral symmetry restoration by parity doubling and the structure of neutron stars

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Recent lattice QCD studies at vanishing density exhibit the parity-doubling structure for the low-lying baryons around the chiral crossover temperature. This finding is likely an imprint of the chiral symmetry restoration in the baryonic sector of QCD, and is expected to occur also in cold dense matter, which makes it of major relevance for compact stars. By contrast, typical effective models for compact star matter embody chiral physics solely in the deconfined sector, with quarks as degrees of freedom. In this talk, we present a description of QCD matter based on the effective hybrid quark-meson-nucleon model. Its characteristic feature is that, under neutron-star conditions, the chiral symmetry is restored in a first-order phase transition deep in the hadronic phase, before the deconfinement of quarks takes place. We discuss the implications of the parity doubling of baryons on the mass-radius relation for compact stars obtained in accordance with the modern constraints on the mass from PSR J0348+0432, the compactness from GW170817, as well as the direct URCA process threshold. We show that the existence of high-mass stars might not necessarily signal the deconfinement of quarks.

Session IV / **7**

Azimuthal anisotropy in 5.02 TeV Pb+Pb and 5.44 TeV Xe+Xe collisions with the ATLAS experiment

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The high-statistics experimental data collected by the ATLAS experiment during the 2015 Pb+Pb and 2017 Xe+Xe LHC runs are used to measure charged particle azimuthal anisotropy.
ATLAS measurements of differential and global Fourier harmonics of charged particles (v_n) in 5.02 TeV Pb+Pb and 5.44 TeV collisions in a wide range of transverse momenta (up to 60 GeV), pseudorapidity ($|\eta|$<2.5) and collision centrality (0-80%) are presented. The higher order harmonics, sensitive to fluctuations in the initial state, are measured up to n=7 using the two-particle correlation, cumulant and scalar-product methods. The elliptic and triangular flow harmonics show an interesting universal pT-scaling. The flow results allow to improve the understanding of initial conditions of nuclear collisions, hydrodynamical behavior of quark-gluon plasma and parton energy loss.

Session I / **8**

Do photon-induced processes survive in semi-central heavy-ion collisions?

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We calculate total and differential cross sections
for J/ψ photoproduction in ultrarelativistic lead-lead collisions
at the LHC energy $\sqrt{s_{NN}} = 2.76$ TeV.
In the present approach we use a simple model based on vector dominance
picture and multiple scattering of the hadronic ($c\bar{c}$) state
in a cold nucleus as an example.
In our analysis we use both the classical mechanics and quantum (Glauber)
formulae for calculating $\sigma_{tot,J/\psi Pb}$ which is a building
block of our model.
We compare our UPC results with ALICE and CMS data.
For semi-central collisions ($b < R_A + R_B$)
a modification of the photon flux is necessary.
We discuss different motivated by physics approximations.
We try to estimate the cross sections for different centrality bins
and for J/ψ mesons emitted in forward rapidity range ($2.5 < y < 4$)
corresponding to recent ALICE experimental results.
Reasonable results are obtained and open questions are discussed.

We study the invariant-mass distributions of dileptons produced in
ultrarelativistic heavy-ion collisions at very low pair transverse
momenta, $P_T \leq 0.15$ GeV.
Specifically, we investigate the interplay of thermal radiation with
initial photon annihilation processes, $\gamma\gamma \to l^+l^-$,
triggered by the coherent electromagnetic fields of the incoming
nuclei. For the thermal radiation, we employ the emission from the QGP
and hadronic phases with in-medium vector spectral functions
which describes the inclusive excess radiation observed over a wide
range of collision energies.
For the coherent photon fusion processes, whose spectrum is much softer
than for thermal radiation, we employ initial fluxes from the Fourier
transform of charge distributions of the colliding nuclei in
the equivalent-photon approximation.
We first verify that the combination of photon fusion, thermal

radiation and final-state hadron decays gives a fair description of the low-P_T invariant-mass as well as P_T spectra as recently measured by the STAR collaboration in $\sqrt{s_{NN}}$=200 GeV Au+Au collisions for different centrality classes, including experimental acceptance cuts. The coherent contribution dominates in peripheral collisions, while thermal radiation shows a markedly stronger increase with centrality. We extend the calculations to lower collision energies ($\sqrt{s_{NN}}$=17.3 GeV) and compare to the acceptance-corrected dimuon excess spectra measured by the NA60 experiment at the CERN SPS; the contribution from photoproduction turns out to be subleading. We also provide predictions for the ALICE experiment at the LHC. The resulting excitation function from SPS to LHC energies reveals a nontrivial interplay of photoproduction and thermal radiation.

Session V / **9**

Net-proton number fluctuations at the QCD critical point

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Fluctuations of the net-proton number can be measured experimentally and thus provide important information about the matter created during heavy ion collisions. Especially, these quantities may give clues about the conjectured QCD critical point. We discuss the beam-energy dependence of ratios of first four cumulants of the net-proton number, obtained using the phenomenologically motivated model in which critical mode fluctuations couple to protons and anti-protons. We find that our model is able to qualitatively capture both the monotonic behavior of the lowest-order ratio seen in the experimental data from the STAR Collaboration as well as the non-monotonic behavior of higher-order ratios. The dependence of our results on the coupling strength and location of the critical point in the (μ, T) plane is also discussed.

Session VI / **10**

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.

Session VII / **11**

Mystery of baryon correlations

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Two-particle angular correlations are a robust tool which allows the exploration of the underlying physics phenomena of particle production in collisions of both protons and heavy ions by studying the 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). These correlations open up the possibility to study a number of mechanisms simultaneously. Many phenomena, including mini-jets, elliptic flow, Bose-Einstein correlations, resonance decays, conservation laws, are sources of correlations. Each one produces a characteristic distribution in $\Delta\eta\Delta\phi$ space and contributes to the final shape of the correlation function.

Latest measurements of correlations of identified particles show differences in particle production between baryons and mesons. The correlation functions for mesons exhibit the expected peak dominated by effects of mini-jet fragmentation and are reproduced well by general purpose Monte Carlo generators. For baryon pairs where both particles have the same baryon number, a surprising near-side anti-correlation structure is observed instead of a peak, implying that two such particles are rarely produced with similar momentum. These results present a challenge to the contemporary models and there is no definite theoretical explanation of the observation.

In this talk I will present an overview of latest baryon correlation measurements yielding startling results that are currently not understood.

Session VII / **12**

Probing space-time evolution at the femtometer scale in pp and Pb-Pb collisions with ALICE

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Quantum-mechanical effects and interactions cause correlations between particles with small momentum difference that carry information about the space-time evolution of the collision system on the femtometer scale. Measurements of these effects are usually done soon after new data arrive and provide an unique input to theoretical models. Nowadays, after almost a decade of the LHC operation and a significant amount of collected data, more differential and complex analyses are

carried out. In this talk I will highlight the most recent ones, showing the direction in which the femtoscopic studies are currently advancing.

Detailed studies of the azimuthal event shape have been performed with pion correlations. In Pb-Pb collisions, azimuthally-sensitive femtoscpy, measured with respect to the 2nd and 3rd order reaction plane, provides new insight into collective behaviour of the source. In elementary pp collisions, a sphericity-differential analysis allows to differentiate between jetty and spherical events, shedding new light on the dependence of the apparent radii on pair transverse momentum kT. In addition, femtoscopic correlations with unlike particles, such as pion-kaon pairs, probe the emission time difference between particle species.

Finally, the analysis of femtoscopic correlations is also being used to probe interactions at low relative momenta for a variety of particles and anti-particles that are not available as beams for scattering experiments.

Session VI / **13**

Geometry and Dynamics in Heavy-ion Collisions Seen by the Femtoscopy in the STAR Experiment

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Geometry and dynamics of the particle-emitting source in heavy-ion collisions at high energies can be inferred via femtoscopy method. Two-particle correlations at small relative momentum exploit Quantum Statistics and the Final State Interactions which allow one to study the space-time characteristics of the source of the order of 10–15 m and 10–23 s, respectively. The RHIC Beam Energy Scan (BES) program covers a significant part of the QCD Phase Diagram using collisions of Au nuclei for eight beam energies in the range from 7.7 to 200 GeV, which baryon-rich region should be studied via baryon femtoscopy. Thus, two-baryon measurements together with two-meson and meson-baryon correlations provide complementary information about the source characteristics.

In this talk, the STAR preliminary results on femtoscopic observables of various particle combinations of protons, pions, kaons nd lambdas from Au+Au collisions at BES energies will be presented. Determining how the properties of the particle-emitting source depend on collision energy is an important step towards understanding the physics of heavy-ion collisions. The BES program provides the possibility to study the energy dependence of the source sizes for various collision centralities. In addition to the source size, the measurements of non-identical particle combinations provide information about space-time asymmetries in emission process.

Session I / **14**

Meson-deuteron correlation function

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Short-range correlations of particles produced in relativistic heavy-ion collisions are actively studied both theoretically and experimentally, as the correlation functions provide information about space-time structure of the interactions zone. The correlations result from quantum statistics, when one

deals with identical particles, and from final-state interactions of particles of interest. Light nuclei are also produced in relativistic heavy-ion collisions due to final-state interactions or coalescence and thus the questions arises how to compute a meson-deuteron correlation function. The function is experimentally accessible and an analysis of the data from the ALICE experiment at LHC is under way. We discuss the problem of meson-deuteron correlations from theoretical point of view and we show how to compute the correlation function taking into account the coalescence process of neutron and proton. Predictions of the pion-deuteron correlation function are presented.

Session VI / **15**

4He versus 4Li and production of light nuclei in relativistic heavy-ion collisions

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We propose to measure the yields of 4He and 4Li in relativistic heavy-ion collisions to clarify a mechanism of light nuclei production. Since the masses of 4He and 4Li are almost equal, the yield of 4Li predicted by the thermal model is five times bigger than that of 4He which reflects the different numbers of internal degrees of freedom of the two nuclides. Their internal structures are, however, very different: the alpha particle is well bound and compact while 4Li is weakly bound and loose. Within the coalescence model, the ratio of yields of 4Li to 4He is shown to be significantly smaller than that in the thermal model and the ratio decreases fast from central to peripheral collisions of relativistic heavy-ion collisions because the coalescence rate strongly depends on the nucleon source radius. Since the nuclide 4Li is unstable and it decays into 3He and p after roughly 30 fm/c, the yield of 4Li can be experimentally obtained through a measurement of the 3He − p correlation function.

Session VI / **16**

Quark Flavor Dependence of the Shear Viscosity in a Quasiparticle Model

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It is known that the quark-gluon plasma is well described in terms of the perfect fluid dynamics. However, for a more realistic investigation, the dissipative processes quantified by the transport parameters need to be included in the hydrodynamic evolution of the QGP. We study the quark-flavor dependence of the shear viscosity calculated in the relaxation time approximation of the Boltzmann equation. Effective masses of the light and strange quarks, as well as gluons, are introduced within a quasiparticle approach. They carry a non-trivial temperature dependence which comes in via the QCD coupling extracted from lattice simulations for pure Yang-Mills theory and for Nf=2+1 QCD.

Session II / 17

Theoretical way to the $\gamma\gamma \to \gamma\gamma$ from $AA \to AA\gamma\gamma$

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So far light-by-light scattering ($\gamma\gamma \to \gamma\gamma$) was not accessible for experiments because the corresponding cross section is rather low. Measurements of diphotons in ultra-peripheral collisions (UPCs) of lead-lead have been reported recently by the ATLAS [1] and CMS Collaborations [2]. Our theoretical results based on equivalent photon approximation in the impact parameter space [3] are in good agreement with the current data [1, 2].
We will discuss how to extend such studies to lower $\gamma\gamma$ energies where photoproduction of pseudoscalar and scalar resonances contribute to the two-photon final state. In addition, we consider the dominant background that arises from ɣɣ fusion into pairs of neutral pions [4]. Such π^0-pairs contribute to the background when only two of the four decay photons are within the experimental acceptance, the other two photons escape undetected. We will discuss in detail how to reduce the unwanted background.
We will present differential distributions and total cross section in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 5.05$ and 5.52 TeV [5,6] and cross section for Ar-Ar collisions at the energy equal to 6.3 TeV [7]. Results for ALICE and LHCb acceptance will be presented.

[1] ATLAS Collaboration, Nature Phys. 13 (2017) 852,
[2] CMS Collaboration, arXiv:1810.04602,
[3] M. Kłusek-Gawenda, P. Lebiedowicz, A. Szczurek, Phys.Rev.C93 (2016) 044907,
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[5] M. Kłusek-Gawenda, R. McNulty, R. Schicker, A. Szczurek, in preparation,
[6] M. Kłusek-Gawenda, EPJ Web Conf. 199 (2019) 05004,
[7] Z. Citron et al., arXiv:1812.06772.

Session IV / 18

Rapidity distributions of pions in p+p and Pb+Pb collisions at CERN SPS energies

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Our presentation will be based on our recent paper [1].

The centrality and energy dependence of rapidity distributions of pions in Pb+Pb reactions can be understood by imposing local energy-momentum conservation in the longitudinal "fire-streaks"of excited matter. With no tuning nor adjustment to the experimental data, the rapidity distribution of pions produced by the fire-streak which we obtained from Pb+Pb collisions reproduces the shape of the experimental pion rapidity distribution in p+p interactions, measured by the NA49 Collaboration at the same energy per nucleon. The observed difference in the absolute normalization of this distribution can be explained by the difference in the overall energy balance, induced by baryon stopping and strangeness enhancement phenomena occurring in heavy ion collisions. We estimate the latter effects using a collection of SPS experimental data on $\pi^{\pm}$, $K^{\pm}$, net p, and n production in p+p and Pb+Pb reactions. We discuss the implications of the above findings for the understanding of

particle production phenomena in both hadron-hadron and nucleus-nucleus collisions. In addition, we comment on the excellent accuracy in the determination of the energy balance at the SPS, which can be used as an independent tool to test different models for hadronic or nuclear reactions.

[1] A. Rybicki, A. Szczurek, M. Kiełbowicz, A. Marcinek, V. Ozvenchuk, Ł. Rozpłochowski, Phys. Rev. C **99** (2019), 024908

Session III / **19**

Multi-particle azimuthal correlations and flow in pp and p+Pb collisions with the ATLAS detector at the LHC

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The long-range azimuthal correlations in the nucleus-nucleus collisions are one of the signals of creation of the Quark-Gluon Plasma. At the LHC energies similar correlations are observed also in *p*+Pb and even *pp* collisions. After several years of successful operation of the Large Hadron Collider a wealth of data on pp, *p*+Pb and Pb+Pb collisions is available. This makes possible detailed studies of different aspects of the azimuthal correlations. The ATLAS experiment studied extensively the subevent cumulant methods which allow to remove non-flow correlations, especially in the events with low multiplicity like those in *pp* and *p*+Pb collisions. Most recently the elliptic flow in Z-boson tagged *pp* collisions was also measured.

Session III / **20**

Forward-backward correlations and multiplicity fluctuations in Pb-Pb collisions at √sNN = 2.76 TeV from ALICE at the LHC

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Forward-backward (FB) multiplicity correlations carry important information on the early dynamics of ultra-relativistic heavy ion collisions. In this talk, new data on forward-backward charged particle correlations and multiplicity fluctuations in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV are presented. The data are recorded with the ALICE detector at the LHC. We focus on the evolution of the correlation coefficient b_{corr} and the strongly-intensive quantity Σ as a function of the distance between forward and backward pseudorapidity intervals (η gap), the centrality of the collision and the width of the centrality bin. Both observables are studied by means of two different centrality estimators: charged particle multiplicity and spectator energy.

At the moment, the strong dependence of the measured magnitude of forward-backward correlations (b_{corr}) on the applied centrality estimator, and as a function of the width of the centrality bin, are well-established facts. In this presentation, we substantiate that the correlation strength, measured with the ALICE detector, appears to be dominated by geometrical fluctuations for wider centrality windows. This effect decreases significantly when narrowing the width of the centrality bin.

On the other hand, the most recent studies of the Σ variable indicate that this observable exhibits the properties of a strongly intensive quantity in terms of the Independent Source Model for Pb-Pb collisions at LHC energies. As such, it is independent on the centrality bin width and centrality estimator. The usage of Σ makes the measurement independent of effects such as fluctuations in the

initial state geometry. Therefore it provides information on the early collision dynamics which is more direct than that obtained from other observables.

Session II / **21**

Chemical equilibration of QGP in hadronic collisions

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We performed state-of-the-art QCD effective kinetic theory simulations of chemically equilibrating QGP in longitudinally expanding systems. We find that chemical equilibration takes place after hydrodynamization, but well before local thermalization. By relating the transport properties of QGP and the system size we estimate that hadronic collisions with final state multiplicities dNch/dη⊠10ˆ2 live long enough to reach approximate chemical equilibrium for all collision systems. Therefore we expect the saturation of strangeness enhancement to occur at the same multiplicity in proton-proton, proton-nucleus and nucleus-nucleus collisions.

References: arXiv:1811.03040, arXiv:1811.03068

Session V / **22**

Multi-differential measurement of correlated pion-proton pairs in Heavy Ion Collisions

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The study of hadron formation, interaction and their properties in hot and dense QCD matter is one of the main topics in sub-nuclear physics. The short-lived states (∼1 fm/c), produced and decayed within the QCD matter contain fundamental information about the surrounding medium created in collisions of heavy-ions at relativistic energies as well as about the interaction. HADES measures rare and penetrating probes in the regime of 1-2 GeV kinetic energy per nucleon. Excitation of baryonic resonances is a key mechanism for meson, dilepton and strangeness production. The measured multi-differential spectra of mass, rapidity and transverse momentum of π^+p and π^-p correlated pairs from Au+Au collisions are going to be presented in this contribution as well as future research of correlations and femtoscopy in ALICE.

Session I / **23**

Chiral mixing in hot and dense matter

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I will briefly present the chiral mixing in hot and/or dense matter and a potential impact over the dilepton production rates.

Session VII / **24**

Forward backward correlations at the LHC with fluctuating strings

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We investigate the forward backward multiplicity correlations for PbPb and pPb at the LHC energies. We examine various variants of Glauber models with sources interpreted as strings with fluctuating end points, as well as the effect of the fluctuations from particle production. Favorable comparisons to the data from the ATLAS and ALICE collaborations are achieved.

Session IV / **26**

A unified quark-nuclear matter equation of state from the cluster virial expansion within the generalized Beth-Uhlenbeck approach

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We consider a cluster expansion for strongly correlated quark matter where the clusters are baryons with spectral properties that are described within the generalized Beth-Uhlenbeck approach by a medium dependent phase shift. We employ a simple ansatz for the phase shift which fulfils the Levinson theorem by describing an on-shell bound state with an effective mass and models the continuum by an anti-bound state located at the mass of the three quark threshold. The quark and baryon interactions are accounted for by the coupling to scalar and vector meson mean fields modelled by density functionals. At increasing density and temperature, due to the different medium dependence of quark and baryon masses, the Mott dissociation of baryons occurs and the nuclear clusters contributions to the thermodynamics vanish. It is demonstrated on this simple example that this unified approach to quark-nuclear matter is capable of describing crossover as well as first order phase transition behaviour in the phase diagram with a critical endpoint.

Session V / **27**

Recent results from NA61/SHINE experiment and physics plans beyond 2020

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NA61/SHINE is a multi-purpose experiment to study hadron-proton, hadron-nucleus and nucleus-nucleus collisions at the CERN Super Proton Synchrotron (SPS) with a large acceptance detector system. The measurements performed for a wide range of reactions provide valuable data for studying properties of hadronic matter under extreme conditions. They also provide precise results on hadron production for determining the neutrino flux in long-baseline neutrino experiments and for more reliable simulations of cosmic-ray showers.

The primary aim of the experiment is the investigation of the phase transition from hadron gas to quark-gluon plasma and the search for associated critical point. For this we have made a two-dimensional scan of the (T–μB) phase diagram by varying the momentum (13A-158A GeV/c) and the size of colliding systems (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb).

In this presentation the NA61/SHINE results on particle spectra as well as
fluctuations and correlations in p+p, Be+Be, Ar+Sc, and Pb+Pb collisions will be
presented. The evolution of non-monotonic structures in pion and strangeness production as a function of system size and energy will be addressed. The obtained results reflect very interesting features and might be related to the onset of deconfinement as well as to the onset of formation of large clusters of strongly interacting matter.

The motivation to study the open charm production at the SPS energies will be
presented. Results of first measurements will be shown.
Information on future (after the Long Shutdown 2) systematic measurements of open charm production in Pb+Pb will be provided. Planned major detector upgrade of the NA61/SHINE facility will be also presented.

Session VII / 29

Electromagnetic effects on charged pion spectra at SPS energies

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One of the main goals of the NA61/SHINE experiment at the CERN SPS is to study properties of strongly interacting matter by a two-dimensional scan of elementary and nuclear reactions as a function of system size and collision energy. This talk presents new results on a new observable relevant for this part of the NA61/SHINE program, which is the modification of positively (negatively) charged particle spectra by the electromagnetic repulsion (attraction) of final state particles by the charged nuclear remnant, the spectator system.

Preliminary measurements of π+/π- ratios in central and intermediate Ar+Sc collisions at beam momentum of 150A GeV/c are shown, and compared to NA49 data in peripheral Pb+Pb collisions at 158A GeV/c as a function of longitudinal and transverse pion momentum. In spite of a dramatic decrease in the magnitude of spectator charge, spectator-induced electromagnetic effects remain clearly visible in Ar+Sc reactions. This is the first measurement of these effect in small nucleus-nucleus systems at the CERN SPS. The experimental data brings new information on the space-time evolution of the Ar+Sc system, and on the production of charged π mesons. A comparison of a dedicated electromagnetic Monte Carlo simulation to the new experimental data is included in the talk. This demonstrates that a stable spectator cannot describe the data, which requires the inclusion of both expansion and decrease in average rapidity of the effective charge cloud, made of spectator and partly also participant charge. Conclusions on the space-time evolution of pion production are presented.

Session V / 30

Recent results from proton intermittency analysis in nucleus-nucleus collisions from NA61 at CERN SPS

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The search for experimental signatures of the critical point (CP) of strongly interacting matter is one of the main objectives of the NA61/SHINE experiment at CERN SPS. In the course of the experiment, an energy (beam momentum 13A –150A GeV/c) and system size (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La) scan is performed.

We investigate local proton density fluctuations connected to the critical behavior of the order parameter as a possible signature of the phase transition in the neighborhood of the CP. To this end, we perform an intermittency analysis of the proton second scaled factorial moments (SSFMs) in transverse momentum space, which we expect to scale according to a universal power-law in the vicinity of the CP.

Previous analyses of this sort revealed significant power-law fluctuations in the NA49 heavy ion collision experiment for the "Si"+Si system at 158A GeV/c; no intermittency was observed in NA49 "C"+C and Pb+Pb collisions at the same energy, nor in NA61/SHINE Be+Be collisions at 150A GeV/c. The fitted power-law exponent in "Si"+Si was consistent with the theoretically expected critical value, within errors, a result suggesting a baryochemical potential for the critical point in the vicinity of ˜250 MeV. We now extend the analysis to the similar-sized NA61/SHINE Ar+Sc system at 150A GeV/c.

In the calculation of scaled factorial moments, statistical techniques are employed in order to subtract non-critical background and enhance the signal in cases of low statistics. Our analysis is supplemented by both critical and non-critical Monte Carlo simulations, through which we estimate non-critical background effects on the quality and magnitude of uncertainties of the intermittency power-law fit, as well as explore the possibility of non-critical effects producing a spurious intermittency signal.

Session VII / 31

Particles' and antiparticles' flow difference studies

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Studying the properties of strongly interacting hot and dense medium created in heavy ion collisions has been accomplished in part by studying the azimuthal anisotropy of particle emission in the transverse plane, known as anisotropic flow. Flow measurements are key observable because it reflects 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 (v2) difference between particles and antiparticles with the decrease of the collision energy has been observed.
For some time, much theoretical interest has been invested in explaining the relationship between collision energy and elliptic flow. One of them is the *mean field* approach, where the increase of elliptic flow is the result of a repulsive potential of quarks, while the reduction of antiparticles' elliptic flow is the result of an attractive potential of antiquarks. Another possibility is the presence of transported protons in the examined medium. These are particles made of constituent quarks originating from the collided nuclei. Their correlations with the participant plane is stronger (increase the v_2) and they survive the entire evolution of the medium, while quarks and antiquarks produced in quark-gluon plasma participate only in part of this evolution scenario. This presentation will demonstrate experimental measurements aimed at better understanding the physical mechanisms driving the difference in observed elliptic flow between particles and antiparticles.

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

Session II / **32**

Far-from-equilibrium hydrodynamics

Author: Michał Spalinski[None]

In a number of settings (including models of kinetic theory and strongly coupled supersymmetric Yang-Mills theory), the pressure anisotropy of boost-invariant flow is known to exhibit attractor behaviour well before local equilibration is attained. I will describe some aspects of this phenomenon and its possible implications for relativistic hydrodynamics.

Session VI / **33**

Joining hard thermal loops with soft deconfinement in the EoS

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The hard thermal (dense) loop (HTL) approach for the quark-gluon plasma

and the hadron resonance gas (nuclear statistical equilibrium) model for low-density hadronic matter are well-studied limits of the equation of state for strongly interacting matter. However, when investigating the transition between both phases of QCD in heavy-ion collisions or in Astrophysics, the question arises how to join these two limits, wishfully on the basis of quark and gluon degrees of freedom where hadrons emerge as bound states and condensates determine the phase structure.
I will elucidate the problem on two examples:
1) Compact star astrophysics, where the requirement to describe the high mass of 2M_sun for pulsars puts strong constraints on the construction of the junction between nuclear and quark matter [1], and
2) Heavy-ion collisions, where joining the hadron resonance gas and HTL quark-gluon matter directly results in too high transition densities [2].
I present a possible road to the solution within a generalized Beth-Uhlenbeck EoS that emerges from a cluster decomposition for the ϕ –derivable

approach which is capable of describing a QCD phase diagram with a critical endpoint or also a crossover all over case [3].

[1] I. Tews et al., Astrophys. J. 860 (2018) 149
[2] A. Khvorostukin et al., Eur. Phys. J. C 48 (2006) 531
[3] N.-U. Bastian and D. Blaschke, arxiv:1812.11766 [nucl-th]

Session III / **34**

ALICE results on the production of charged particles in pp, p-Pb, Xe-Xe and Pb-Pb collisions at the LHC

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We discuss the energy and system size dependence of the charged-particle production at the LHC. The charged-particle multiplicity density (dN/deta), total charged-particle multiplicity (Ntot) and transverse momentum (pt) spectra are presented in the narrow centrality bins spanning 0-100% interval. The results are compared to phenomenological models and theoretical calculations based on different mechanisms of particle production in nuclear collisions.

Session I / **35**

Exploring the QCD phase diagram

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Session III / **36**

Highlights and open questions in heavy ion physics

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Session IV / **37**

Light-by-light scattering in lead-lead collisions in the ATLAS experiment - from evidence to observation

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Light-by-light (LbyL) scattering, $\gamma\gamma \to \gamma\gamma$, is a quantum-mechanical process, forbidden by the classical theory of electrodynamics, but possible in Quantum Electrodynamics via a loop diagram. Despite the small cross-section, it is theoretically possible to observe this process in ultra-peripheral

high energy heavy-ion collisions. Based on 0.48 nb^{-1} of 2015 Pb+Pb data, a first direct evidence of LbyL scattering was established by the ATLAS Collaboration in 2017 with 4.4σ significance over the background-only hypothesis. The observation of LbyL scattering was reported by ATLAS Collaboration in 2019, based on 2018 Pb+Pb dataset corresponding to integrated luminosity of 1.73 nb^{-1}. In total, 59 events were found in the signal region with a background expectation of 12 ± 3 events. The observed signal significance over the background-only hypothesis amounts to 8.2σ. The measured fiducial cross-section is 78 ± 13 (stat.) ± 8 (syst.) nb.

Session I / **38**

Welcome