Investigation of the Properties of Nuclear Matter and Particle Structure at the Collider of Relativistic Nuclei and Polarized Protons

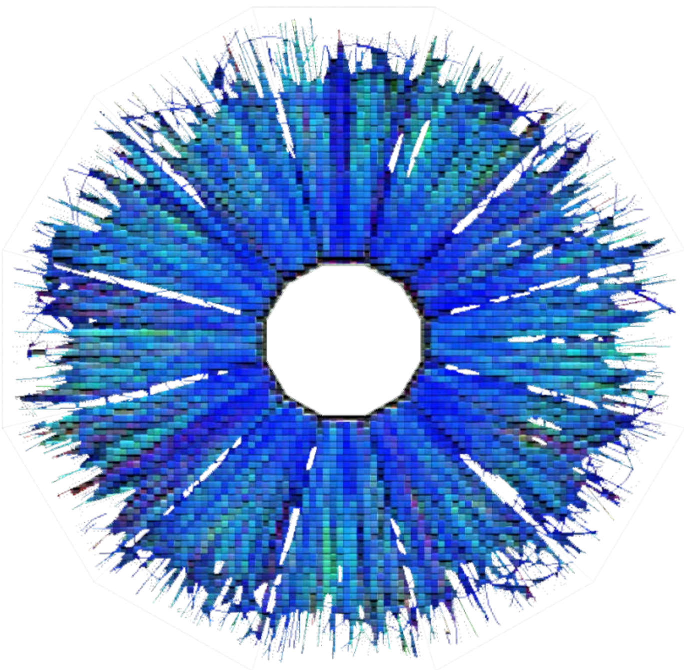
Project STAR (JINR Participation)

Extended annotation

A.A. Aparin, G.S. Averichev, H.N. Agakishiev, N.A. Balashov, V.V. Belaga, T.G. Dedovich, I.Zh. Bunzarov, N.Y. Chankova-Bunzarova, V.B. Dunin, J. Fedorishin, P. Filip, A.O. Kechechian, K.V. Klygina, V.V. Korenkov, E.A. Kuznetsov, R. Lednický, V.V. Lyuboshitz, V.V. Mitsyn, M.P. Osmachko, G.A. Ososkov, Yu.A. Panebrattsev, E.V. Potrebenikova, O.V. Rogachevski, N.E. Sidorov, E. Shakhaliev, M.V. Tokarev, N.I. Vorontsova, S.F. Vokal, I. Zborovsky

JINR TOPIC: *02-0-1066-2009/2021*

Project leaders: Richard Lednický, Yury Panebrattsev



Dubna, 2018

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Abstract

This document contains a summary of the results obtained by the JINR group during the second half of 2015 and the first part of 2018, as well as proposal to continue participation of the JINR in the STAR experiment in the years 2019–2021.

Among scientific results obtained by the JINR group are mentioned studying the scaling properties of the spectra of charged hadrons produced in Au+Au collisions, the first high statistic measurements of Λ-Λ-correlations (Phys. Rev. Lett. 114 (2015) 022301) and measurement of interaction between antiprotons (Nature 527 (2015) 345).

In **2016**, the run to study Heavy Flavor Physics has been hold at RHIC. At the present large statistics has been taken. The data processing is going on and the effects of suppression and collective flows in the events with open flavor (D_s, Λ_c, B, …) and quarkonia (J/ψ, Y) production are studied.

In the **year 2017** the data taken run with polarized protons beams has been performed by STAR at RHIC. STAR's highest scientific priority is the first significant measurement of the sign change of the Sivers' function, when compared to the value measured in SIDIS, and evolution effects in transverse momentum distributions through measurements of single spin asymmetries in $W^{+/-}$, Z, direct photon and Drell-Yan pairs production in transversely polarized p+p collisions at $\sqrt{s}$ = 500 GeV.

This project of the JINR–STAR group is focused on two compelling programs that are key to the completion of the RHIC mission. First, the study of isobaric collisions will provide enhanced clarity of the role of the magnetic field in the charge separation measurements. Second, STAR collaboration proposes the Beam Energy Scan II (BES-II) program which will dramatically enhance our understanding of the QCD phase diagram.

STAR's scientific priorities for 2018–2019

STAR scientific priority is the successful realization of the isobaric collision program. In 2018 two 3.5 week runs have started with collisions of Ruthenium-96 (Ru+Ru) and Zirconium-96 (Zr+Zr) at $\sqrt{s_{NN}}$ = 200 GeV. The following data analysis and comparison of results from these events will help clarify the interpretation of measurements related to the chiral magnetic effect. Since Ru nuclei have an atomic charge of 44 compared to 40 for Zr, Ru+Ru collisions will generate a magnetic field approximately 10% larger than Zr+Zr collisions while all else remains essentially constant. Comparison of charge separation results will aid in determining the fraction of those measurements which are related to the chiral magnetic effect by isolating the magnetic field dependence. Our understanding of the chiral magnetic effect will thereby be greatly advanced and have a fundamental impact beyond the field of high-temperature QCD.

STAR has recently reported the first observation of global polarization of Λ hyperons in heavy ion collisions. The discovery has been published in Nature 548, 62(2017). The polarization direction of Lambdas is correlated at the level of several percent with the direction of the system angular momentum in non-central Au+Au collisions. Main conclusion is the heavy ion collisions at RHIC produce the vortical fluid. STAR's priority is measurement and following data analysis of Au+Au collisions at $\sqrt{s_{NN}}$ = 27 GeV which will allow to make statistically significant Λ and $\overline{\Lambda}$ global polarization measurements. These measurements will take advantage of the newly installed Event Plane Detector's improved first-order reaction plane

resolution.

STAR's highest scientific priority for 2019–2021 is the commencement of the RHIC Beam Energy Scan II. BES-II is the research program to search for phase transition and critical point of QCD matter.

Three upgrades are planned for completion prior to the BES-II. Both the inner Time Projection Chamber (iTPC) and the end-Cap Time of Flight (eTOF) are on schedule for full installation in Run 19; increasing the rapidity and low transverse momentum acceptance of STAR, and extending our particle identification capabilities. The Event Plane Detector (EPD) will be fully installed for in 2018. The EPD provides enhanced event plane resolution and forward centrality measurements. JINR physicists are planned to participate in the work on the installation and preparation of the EPD (event plane detector) for these runs.

Below the table is showing the request of funding for the project in 2019 and 2021.

Table 1. Cost Estimate of Project

№	***Name***	***Full Cost (kUSD)***	***Expenses per Year (kUSD)***		
			2019	***2020***	***2021***
1.	*Materials and Equipment*	***45,0***	*15,0*	*15,0*	*15,0*
2.	*Payments for agreement based research*	***45,0***	*15,0*	*15,0*	*15,0*
3.	*Travel Expenses*	***165,0***	*55,0*	*55,0*	*55,0*
	Total direct expenses	***255,0***	***85,0***	***85,0***	***85,0***

1. Introduction

In 1993 JINR made a decision on participation of the Laboratory of High Energy and the Laboratory of Particle Physics in the STAR experiment (Solenoidal Tracker at RHIC) at the Relativistic Heavy Ion Collider (RHIC) in the Brookhaven National Laboratory. This decision was connected with extension of the physical research program performed at the Dubna Synchrophasotron to study relativistic hadron-nucleus, nucleus-nucleus interactions and processes with polarized deuterons. The RHIC collider has opened new possibilities to switch to unexplored energy region and study the nuclear matter in extreme conditions.

The goal of experimental investigations is to search for and study regularities of transition of quarks and gluons into protons and neutrons. Such the information is necessary for understanding of the theory of the strong interaction – Quantum Chromodynamics (QCD) – in nonperturbative region. The experiments with polarized protons were aimed to the direct measurement of the spin-dependent gluon distribution function, determination of the gluon contribution into the proton spin and the decision of the “spin crisis” problem.

Spin is a quantum number characterizing the fundamental property of every particle. It is connected with physics symmetries. Therefore, the study of polarization of quarks, gluons and sea quarks in the proton is one of the main problems of the modern particle physics. JINR maintains and develops the tradition of the experimental and theoretical researches in relativistic nuclear physics and spin physics. Note, first of all, the research program with polarized deuteron beams has been successfully performed at the Synchrophasotron. Therefore, the main contribution of the JINR to the STAR project was the participation in the creation of the detectors – the Central Barrel and End Cap Electromagnetic Calorimeters, for the study of the polarization phenomena.

The first run of data taking for Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at STAR has been performed in 2000. After five years of work at maximum RHIC energy main results were formulated: jet quenching, suppression of hadron yields at high transverse momentum, observation of collective flow of nuclear matter, constituent quark number scaling for elliptic flow. Based on the obtained results the important conclusion on creation of the strongly interacting matter in the central nucleus-nucleus collisions has been formulated: the produced matter is similar to perfect liquid and not ideal gas of quarks and gluons. In future the many results observed at RHIC were confirmed at higher energy at LHC.

- ***Recent STAR Heavy-Ion Results***

The STAR collaboration has completed successfully the first phase of the RHIC Beam Energy Scan program (Phase-I). A lot of new experimental results have been obtained. The measurements of particle spectra have been performed over a wide range of collision energy $\sqrt{s_{NN}}$ = 7.7–200 GeV, centrality and transverse momentum of produced particles. The fixed target mode in heavy-ion collisions at the STAR experiment also extends considerably the range of search for the new physics. Heavy quarks provide an exceptional probe in understanding properties of the hot and dense medium created in such collisions. The Heavy Flavor Tracker (HFT) and Muon Telescope Detector (MTD) upgrades at the STAR experiment at RHIC significantly improved the experimental capabilities of TPC, ToF and EMC detectors in measuring both open and hidden heavy flavor hadrons in heavy-ion collisions.

A new state of matter created in the heavy ion collisions is studied in the experiments with heavy quarks. It is considered that hadrons consisting from *c*-, *b*-quarks are good probes of the dynamical evolution of highly dense and hot medium. To study the properties of nuclear matter by D^0, J/ψ and Y mesons, which contain *c* and *b* quarks the new STAR detector subsystems – the precision vertex detector (Heavy Flavor Tracker) and the detector system registration of muons (muon Telescope Detector) have been installed. These subsystems have been used in 2014–2016 runs for data taking. The performed data analysis has shown that the suppression effect is observed for both heavy and light quarks. It was found that the suppression for D^0-meson production in central Au+Au collisions is significant ($R_{AA}^{D} \sim 0.2$) at high transverse momentum. For J/ψ-mesons the strong suppression ($R_{AA}^{J/\psi} \sim 0.2$) is seen for both small and high transverse momentum. At the present large statistics has been taken. The data processing is going on and the effects of suppression and collective flows in the events with open flavor (D_s, Λ_c, B, …) and quarkonia ($J/\psi, Y$) production are studied. The method of three-dimension correlation analysis applied for the study of low-transverse-momentum like-sign kaon pairs will be also used for search for significant non-Gaussian features in the heavy flavor source function.

- ***Recent STAR spin results and future spin measurements at RHIC***

A main goal of the spin physics program at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is to investigate processes of particle production in collisions of polarized protons, to understand the spin origin of the proton in terms of quarks and gluons as fundamental degrees of freedom of Quantum Chromodynamics. The ability to collide polarized beams at RHIC provides unique information on polarization phenomena over a wide range of collision energy, momentum and rapidity of the various probes produced (pions, photons, *W* bosons and jets). The STAR experiment at RHIC provides measurements of single and double-spin asymmetry in longitudinally and transversely polarized *p*+*p* collisions at $\sqrt{s}$ = 200 and 510 GeV to deepen our understanding of the proton spin structure and dynamics of parton interactions. Polarized processes with W^{-} boson production allow us to study the spin-flavor structure of the proton. The new results - the double longitudinal asymmetry, A_{LL}, of pion and jet production at $\sqrt{s}$ = 200 and 510 GeV, the single longitudinal, A_L, and transverse, A_N, asymmetry of *W* production at $\sqrt{s}$ = 510 GeV, are recently obtained by STAR. Measurements on the transverse spin transfer of Λ and anti-Λ in *p*+*p* collisions providing insights into transversely polarized fragmentation function and nucleon transversity distribution, and the nuclear modification of transverse spin asymmetry, A_N, from polarized p+Au collisions are widely discussed. The proposed Forward Calorimeter System (FCS) and Forward Tracking System (FTS) upgrades at STAR would significantly improve the capabilities of existing detectors for measurements of observables such as asymmetries of pion, jet, Drell-Yan pairs produced at forward rapidity.

The double longitudinal asymmetry A_{LL} of the meson and jets production in collisions of polarized protons at the energy of $\sqrt{s}$ = 200 GeV has been measured. The asymmetry was used to extract the spin-dependent gluon distribution. A compelling evidence on positive sign of the integral gluon contribution ΔG in the proton spin was obtained. The growth of the single spin asymmetry A_N of pion production in experiments with transversally polarized protons was found. The first measurements of the single longitudinal asymmetry A_L of $W^{\pm}$ boson production in proton-proton collisions at energy $\sqrt{s}$ = 510 GeV allow us to extract spin-dependent distribution of sea u- and d-quarks ($\Delta\bar{u}, \Delta\bar{d}$).

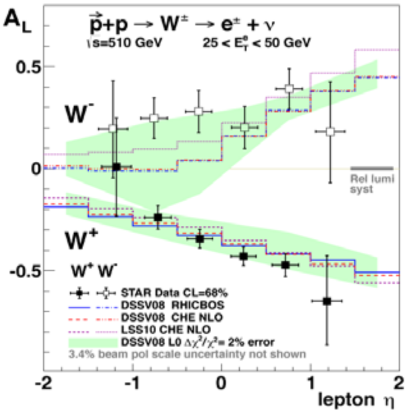

Figure 1. The single longitudinal asymmetry of $W^{\pm}$-boson production in pp-collisions at energy $\sqrt{s}$ = 510 GeV as a function of the W-boson’s decay lepton pseudorapidity.

- ***STAR’s priority for 2018–2019 is the isobaric collision program and global polarization measurements.***

In 2018 two 3.5 week runs have started with collisions of Ruthenium-96 (Ru+Ru) and Zirconium-96 (Zr+Zr) at $\sqrt{s_{NN}}$ = 200 GeV. The following data analysis and comparison of results from these events will help clarify the interpretation of measurements related to the chiral magnetic effect. Since Ru nuclei have an atomic charge of 44 compared to 40 for Zr, Ru+Ru collisions will generate a magnetic field approximately 10% larger than Zr+Zr collisions while all else remains essentially constant. Comparison of charge separation results will aid in determining the fraction of those measurements which are related to the chiral magnetic effect by isolating the magnetic field dependence. Our understanding of the chiral magnetic effect will thereby be greatly advanced and have a fundamental impact beyond the field of high-temperature QCD.

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STAR and extending our particle identification capabilities. The Event Plane Detector (EPD) will be fully installed for in 2018. The EPD provides enhanced event plane resolution and forward centrality measurements.

2. Project Results in 2015–2018. The specific JINR contribution

In this section the main results of the JINR–STAR group are presented. It includes information about STAR collaboration reports at international conferences prepared by the JINR team and scientific articles published in the referred journals with the major contribution of the JINR team.

At international conferences and STAR collaboration meetings 17 reports were presented among which the following overview reports deserve special attention:

- *Recent STAR Heavy-Ion Results*
  Mikhail Tokarev (for the STAR collaboration). Review talk at the XXIII International Seminar "Relativistic Nuclear Physics and QCD", Dubna, 2016. EPJ Web of Conferences 138, 01016 (2017).
- *Recent STAR spin results and future spin measurements at RHIC*
  Mikhail Tokarev (for the STAR Collaboration). Review talk at the XVII International Workshop on High Energy Spin Physics "DSIPN17", September, Dubna, 2017, Accepted for publication in Phys. Part. Nucl. Lett.
- *Correlation measurements of particle interaction at STAR*
  Richard Lednický (for the STAR Collaboration). Review talk at the International Conference Hadron Structure QCD, June 26 – July 1, Gatchina, 2016

Scientific results on data analysis from STAR facility and the results of the development of theoretical models and methods for data analysis on nucleus-nucleus collisions and proton spin structure were published in 12 articles. Below there is a brief overview of the main results.

2.1. Correlation Femtoscopy

A new and extremely interesting physical results were obtained with the active participation of JINR physicists in collaboration with colleagues from the Czech Republic, Slovakia and Russia, using the methods of correlation femtoscopy.

- ***The first high statistics measurement of $\Lambda\Lambda$ correlation***

Phys. Rev. Lett. 114, 022301 (2015)

First high statistics measurement of Λ–Λ correlation function in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. This research pioneered the venue of using RHIC as a hyperon factory to investigate hyperon-hyperon interactions. The STAR measurement can provide precious data for understanding of the hyperon-hyperon interaction which is an important input to various baryon-baryon interaction potential model as well as for the study of equation of state for neutron stars. The Λ–Λ interaction is also closely related to the existence of the H dibaryon, one of the most searched for exotic hadrons in nuclear collisions.

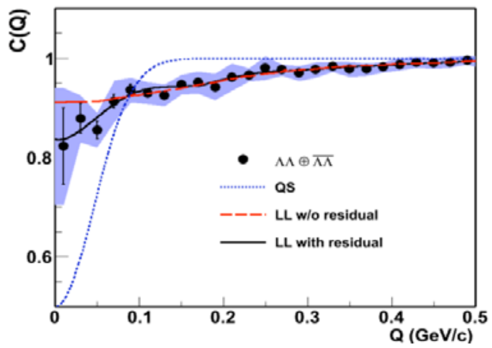


Figure 2. Correlation functions of $\Lambda-\Lambda$ and $\overline{\Lambda}-\overline{\Lambda}$ hyperon pairs.

The combined $\Lambda-\Lambda$ and $\overline{\Lambda}-\overline{\Lambda}$ correlation function for 0–80 % centrality Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Curves on Figure 2 correspond to fits using the Lednický and Lyuboshitz analytical model with and without a residual correlation term. The dotted line corresponds to Fermi statistics with a source size of 3.13 fm. The shaded band corresponds to the systematic error.

- ***Measurement of interaction between antiprotons***

Nature 527 (2015) 345.

One of the primary goals of nuclear physics is to understand the force between nucleons, which is necessary step for understanding the structure of nuclei and how nuclei interact with each other. Although anti-nuclei up to anti-helium-4 have been discovered and their masses measured, little is known directly about the nuclear forces between antinucleons. Here we study antiproton pair correlations among data collected by the STAR experiment with gold ions at 200 GeV per nucleon. Antiprotons are abundantly produced at such collisions. Thus making feasible to study details of the antiproton-antiproton interactions. Studies of two anti-proton correlation functions with data taken by the STAR experiment at RHIC show the attracting nuclear force between two anti-protons. The measurement of the two key parameters that charactering the corresponding strong interaction, namely, the scattering length (f_0) and effective range (d_0) are presented in Figure 3. As a direct knowledge from the interaction between two anti-protons, the simplest system of anti-nucleons (nuclei), our result provides a fundamental ingredient for understanding the structure of more sophisticated anti-nuclei and their properties.

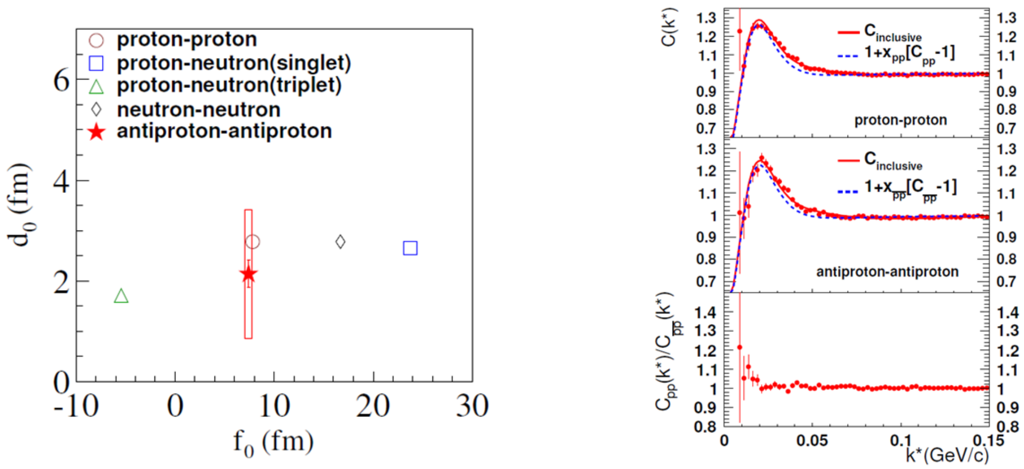


Figure 3. Correlation functions of $N-N$ and $\overline{N}-\overline{N}$ pairs.

- ***Possible effect of mixed phase and deconfinement upon spin correlations in the $\Lambda-\overline{\Lambda}$ pairs generated in relativistic heavy-ion collisions***

V.V. Lyuboshitz, Journal of Physics : Conference Series, v. 668 , 012130 (4 pages), 2016

Spin correlations for the $\Lambda-\Lambda$ and $\Lambda-\overline{\Lambda}$ pairs generated in relativistic heavy ion collisions, and related angular correlations at the joint registration of hadronic decays of two hyperons, in which space parity is not conserved are analyzed. The correlation tensor components can be derived from the double angular distribution of products of two decays by the method of "moments". The properties of the "trace" of the correlation tensor (a sum of three diagonal components), determining the relative fractions of the triplet states and singlet state of respective pairs, are discussed. Spin correlations for two identical particles ($\Lambda-\Lambda$) and two non-identical particles ($\Lambda-\overline{\Lambda}$) are considered from the viewpoint of the conventional model of one particle sources. In the framework of this model, correlations vanish at sufficiently large relative momenta. However, under these conditions, in the case of two non-identical particles ($\Lambda-\overline{\Lambda}$) a noticeable role is played by two-particle annihilation (two-quark, two-gluon) sources, which lead to the difference of the correlation tensor from zero. In particular, such a situation may arise when the system passes through the "mixed phase".

2.2. Spectra, nuclear modification factor

- ***Spectra of charged particles production in BES-I***

M.V. Tokarev (for the STAR Collaboration). Int. J. Mod. Phys. (2015) 1560103.

The JINR team of the STAR collaboration takes part in the analysis of the BES-I data. The transverse momentum spectra of charged hadrons produced in Au+Au collisions as a function of energy and centrality collision were obtained. The original method (z-scaling) of data analysis has been suggested and exploited for search for new phenomena in nuclear matter created in heavy ion collisions. The preliminary STAR data shown in Figure 4 covers a wide kinematical and dynamical range of particle production, collision energy $\sqrt{s_{NN}}$ = 7–200 GeV, centrality of collisions 5 %–80 % and momentum range p_T = 0.2–12 GeV/c.

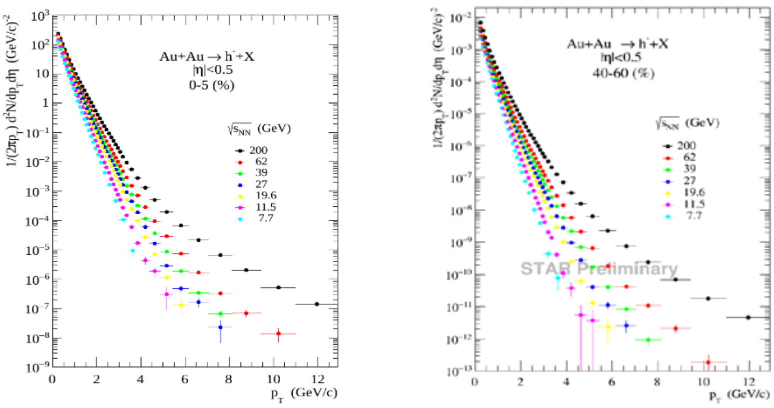


Figure 4. Transverse momentum distribution of negative charged particles production at BES-I energies as a function of collision energy for central and mid-central events.

As one seen from Figure 4 the data demonstrate strong energy and centrality dependence of spectra, exponential behavior of the spectra at low p_T and energy $\sqrt{s_{NN}}$, a power behavior of spectra at high p_T and energy $\sqrt{s_{NN}}$. One observes that difference of yields at various energies strongly increases with transverse momentum.

The analysis of the obtained spectra has been performed in the framework of the z-scaling approach (Phys. Rev. D75, 2007, 094008; Int. J. Mod. Phys. A24, 2009, 1417; *Nucl. Phys. Suppl.* B245, 2013, 231). The results of data z-presentation are shown in Figure 5. The results demonstrate a "collapse" of data onto a single curve. This is confirmation of self-similarity of particle production in heavy ion collision over a wide scale range. The shape of the curve reveals the power behavior at low and high z. The energy dependence of the fractal and fragmentation dimensions and "specific heat" was found. The decrease of the fractal dimension δ_A of the nucleus at energy $\sqrt{s_{NN}}$ < 20 GeV was found.

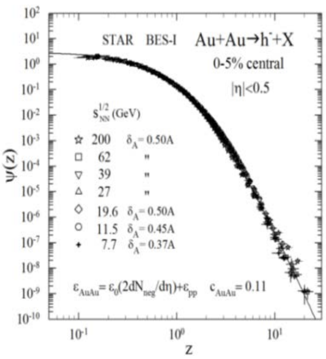


Figure 5. z-presentation of transverse momentum distribution of negative charged particle production at BES energies 7.7, 11.5, 19.6, 27, 39, 62.4, and 200 GeV at different centralities and central rapidity range.

Figure 6 shows the dependence of the constituent energy loss on the energy and centrality of collisions and transverse momentum of inclusive particle. It was found the energy loss decreases with p_T, increases with $\sqrt{s_{NN}}$ and centrality.

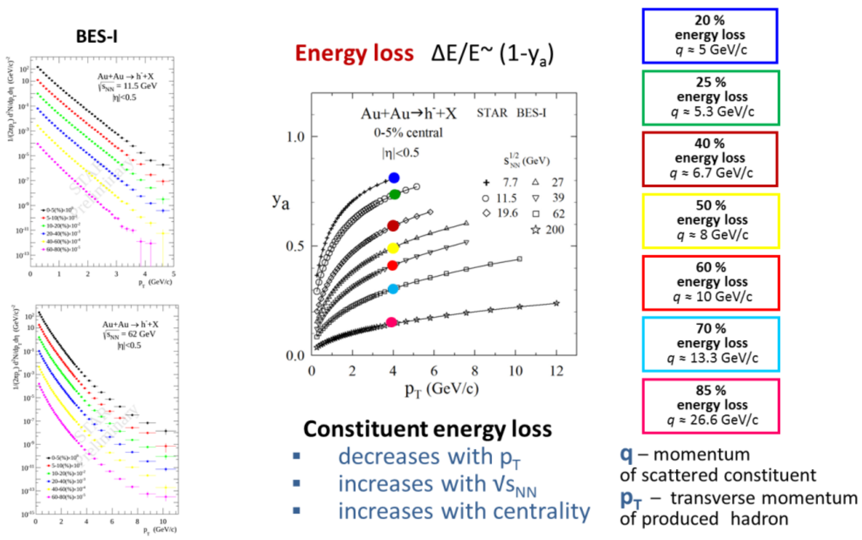
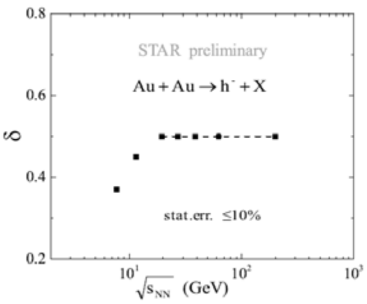


Figure 6. Momentum fraction y_a as a function of the energy and centrality of collision and the transverse momentum of inclusive particle.

The model parameters – nucleus fractal dimension $\delta_A = A \cdot \delta$, fragmentation fractal dimension $\varepsilon_{AA} = \varepsilon_0 (dN/d\eta) + \varepsilon_{pp}$ and "heat capacity" c, are determined from the requirement of scaling behavior of $\Psi(z)$ as a function of self-similarity parameter z. Figure **7** shows the dependence of these parameters on the collision energy. It was found that δ is independent of the energy for $\sqrt{s_{NN}} \geq 20$ GeV, ε_0 increases with the energy and c is independent of the energy over the range $\sqrt{s_{NN}}$ = 7.7–200 GeV. Note that, while δ decreases with decreased energy for $\sqrt{s_{NN}} \leq$ 20 GeV, the function $\Psi(z)$ preserves the shape in this range.



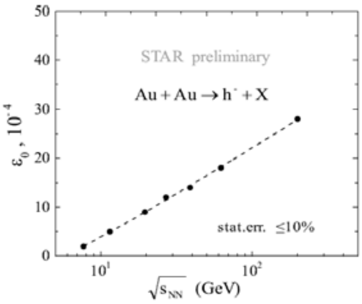


Figure 7. Model parameters δ and ε_0 as a function of collision energy $\sqrt{s_{NN}}$.

2.3. Spin physics

- ***Self-similarity of proton spin and asymmetry of jet production***

M.V.Tokarev, I.Zborovsky, Physics of Particles and Nuclei Letters, V.12, №2, 2015, pp.313–323

Spin is one of the most fundamental properties of elementary particles. The proton spin structure is studied for a long time in processes with polarized leptons and protons. The goal is to understand complete picture of the proton spin in terms of quark and gluon degrees of freedom.

The concept of z-scaling was extended for description of processes with polarized protons. The double longitudinal spin asymmetry, A_{LL}, of inclusive jets produced in proton-proton collisions at $\sqrt{s}$ =200 GeV (Phys. Rev. Lett. 115, (2015) 092002) measured by the STAR Collaboration at RHIC is shown in Figure 8. The asymmetry was analyzed in the framework of z-scaling approach. A hypothesis of self-similarity and fractality of the proton spin structure are suggested and developed. The possibilities to extract information on spin-dependent fractal dimensions of proton and jet fragmentation process from the asymmetry are justified. The spin-dependent fractal dimension of proton is estimated. Authors consider that the quantity is a new fundamental property of every particle as a mass, charge, spin.

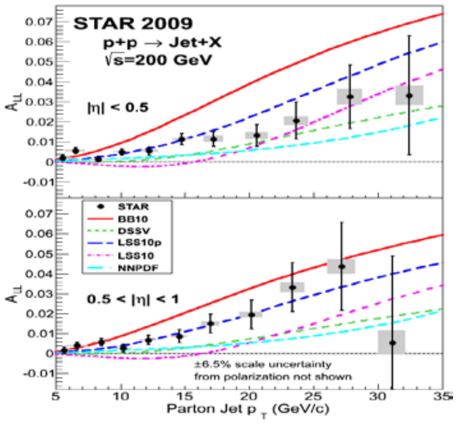


Figure 8. Double longitudinal spin asymmetry of jet production in polarized p-p collisions at $\sqrt{s}$ = 200 GeV, measured by the STAR collaboration.

Figure 9 shows the cross section of inclusive jet production in $\vec{p}+\vec{p} \rightarrow jet+X$ reaction in z-presentation and the ratio of the spin-independent and the spin dependent scaling functions and the corresponding fractal dimensions. The functions coincide each other with high accuracy in all considered region of z. The coincidence is the indication on self-similarity of polarization processes seen in the data z-presentation.

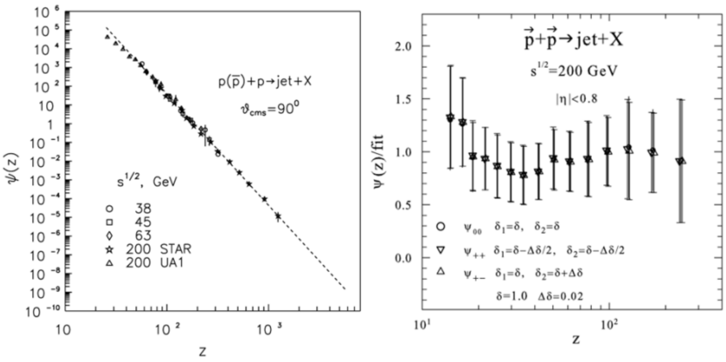


Figure 9. The ratios of the scaled spin-dependent and spin-independent functions for inclusive jet production in polarized p-p collisions at $\sqrt{s}$ = 200 GeV.

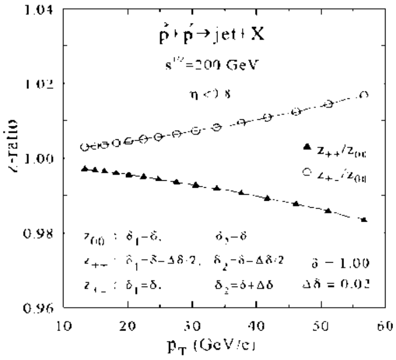


Figure 10. The ratios of the spin-dependent self-similarity parameters for inclusive jet production in polarized p-p collisions at $\sqrt{s}$ = 200 GeV.

The respective ratios of the spin-dependent self-similarity parameters $(z_{++}/z_{00}, z_{+-}/z_{00})$ as functions of the transverse momentum are shown in Figure 10. The effect of spin-spin interactions on the ratios does not exceed 4%. The ratio decreases as function of p_T for the interactions of protons with the same (positive or negative) helicities and increases with p_T for the opposite orientation of proton helicities. The larger values of z_{+-} mean that spin structure of proton can be probed with higher resolution (i.e. at smaller scales) in the collisions of protons with opposite helicities relative to the interactions where the protons have the same helicities. Similarly as for unpolarized processes, an abrupt change of the spin-dependent fractal dimensions should indicate on a spin phase transition. To test such hypothesis, the measurements of spin asymmetries and cross sections need very good accuracy. The measurements of non-zero asymmetry, A_{LL}, give us strong motivation to study fractal properties of proton spin in the reactions with inclusive jet production. We believe that considered scaling property for polarization processes reflects the self-similarity of the spin structure of the colliding objects and interaction mechanism of their constituents.

- ***Fractal structure of hadrons in processes with polarized protons***

M.V. Tokarev, I. Zborovsky, A.A. Aparin, Phys. Part. Nucl .Lett., Vol.12, № 1, 2015, 48–58

The concept of z-scaling previously developed for analysis of inclusive reactions in proton-proton collisions was applied for description of processes with polarized protons.

The z-scaling approach shows itself as an effective tool for sophisticated data analysis in searching for new phenomena, verification of theoretical models, etc. Extension of the method for analysis of polarization phenomena and verification of self-similarity of spin-dependent inclusive cross sections for particle production in p+p collisions is an interesting problem which could give new insight into the origin of proton spin at small scales. The spin-dependent fractal dimensions are new parameters of the z-scaling theory. They are new characteristics of polarization properties of proton structure, constituent interactions and hadronization process. The double longitudinal spin asymmetry A_{LL} of π^0-meson production and the coefficient of the polarization transfer D_{LL} of Λ-hyperon production in proton-proton collisions measured by STAR collaboration at RHIC were analyzed in the framework of z-scaling. The spin-dependent fractal dimensions of proton and fragmentation process with polarized Λ hyperon were estimated. A study of the spin-dependent constituent energy loss as a function of transverse momentum of the inclusive hadron and collision energy was suggested.

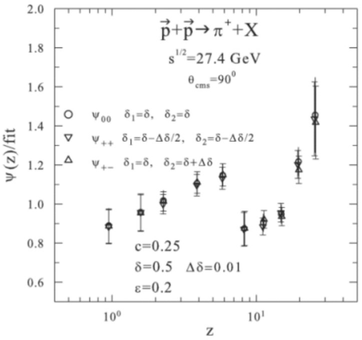


Figure 11. The ratios of the scaled spin-dependent and spin-independent functions for inclusive jet production in polarized p-p collisions at $\sqrt{s}$ = 200 GeV.

The scaled spin-dependent Ψ_{++}, Ψ_{+-} and spin-independent Ψ_{00} functions of pion production in proton-proton collisions at $\sqrt{s}$ = 27.4, 200 GeV and $\vartheta_{cms} = 90^0$ in z-presentation.

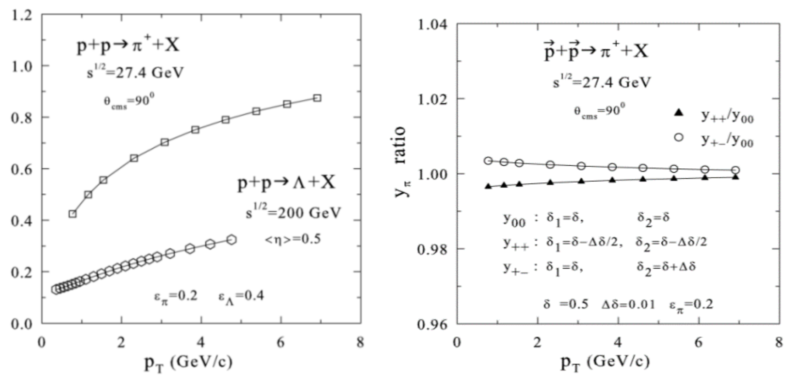


Figure 12. The momentum fraction y_a and the scaled ratio of the momentum fractions for pion production in unpolarized and polarized p-p collisions at $\sqrt{s}$ = 27.4 GeV.

2.4. Parton energy loss. Scaling of strangeness production

- ***Fractional Momentum Loss of Hadrons produced in Au+Au Collisions at BES Energies***

A. Kechechyan, STAR Regional Meeting, Warsaw, Poland, June 27–30, 2017

It has been established that in relativistic heavy-ion collisions a hot, dense medium is rapidly formed, capable of interacting with the high-p_T partons produced in primordial hard scattering and making them lose some energy while traversing the medium. Quantifying this energy loss is an important issue, because it is directly related to the properties of the medium.

The Alternative Method to Estimate Fractional Momentum Loss (FML) was suggested in the Phys. Rev.C 93, 024911 (2016) and used for analysis of RHIC (PHENIX) and LHC (ALICE) data.

STAR BES-I negative charged particle transverse momentum spectra in Au+Au were used for estimation of the fractional momentum loss as a function of collision energy and centrality.

Calculation of the difference of normalized transverse momentum spectra is performed at the same hadron yields. The events are divided into centrality classes: 0–5%, 5–10%, 10–20%, 20–40%, 40–60%, 60–80%. The fraction energy loss is defined as follows $\delta p_T / p_T = (p_T^0 - p_T^i)/p_T$, where index "0" corresponds to centrality 60–80%, and index "*i*" – to the other centralities.

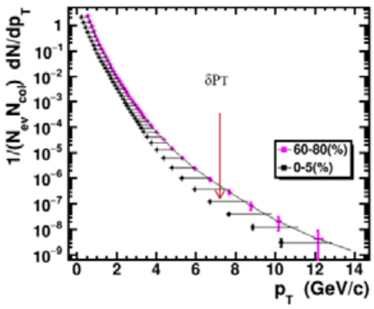


Figure 13. Normalized transverse momentum spectra at 0–5% and 60–80% centralities.

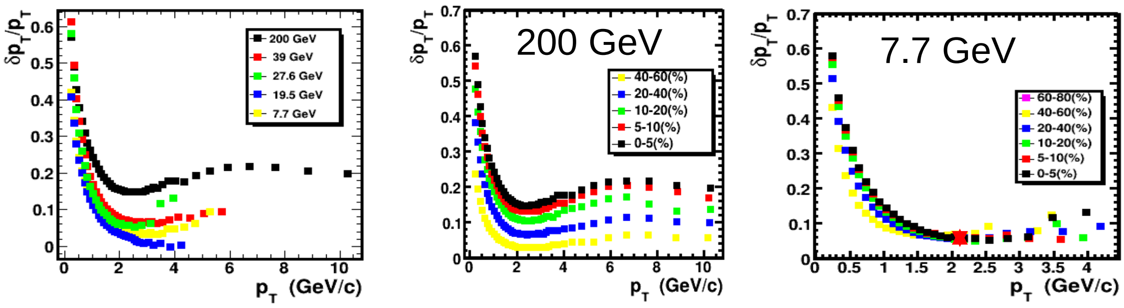


Figure 14. The fractal momentum loss as a function of transverse momentum and centrality at BES-I energies.

Preliminary results of analysis demonstrate that FML decreases with energy, strong centrality dependence of FML is found at 200 GeV and centrality difference of FML decreases with a collision energy.

- ***New indication on scaling properties of strangeness production in pp collisions at RHIC***

M.V.Tokarev, I.Zborovsky, International Journal of Modern Physics A Vol. 32, No. 5 (2017) 1750029 (42 pages)

The strange particles are traditionally used as special probes for studying the medium created in the collisions of protons or nuclei. Experimental data on transverse momentum spectra of strange particles produced in pp collisions at $\sqrt{s_{NN}}$ = 200 GeV obtained by the STAR and PHENIX collaborations at RHIC were analyzed in the framework of *z*-scaling approach. A microscopic scenario of constituent interactions was used to study the dependence of momentum fractions and recoil mass on the collision energy, transverse momentum and mass of produced inclusive particle, and to estimate the constituent energy loss. The obtained results can be useful in study of strangeness origin, in searching for new physics with strange probes, and can serve for better understanding of fractality of hadron interactions at small scales.

Figure 15 shows the spectra of strange meson and baryon production in *p*+*p* collisions in *z*-presentation. The solid line is the reference curve corresponding to negative pion production in $p+p$ collisions.

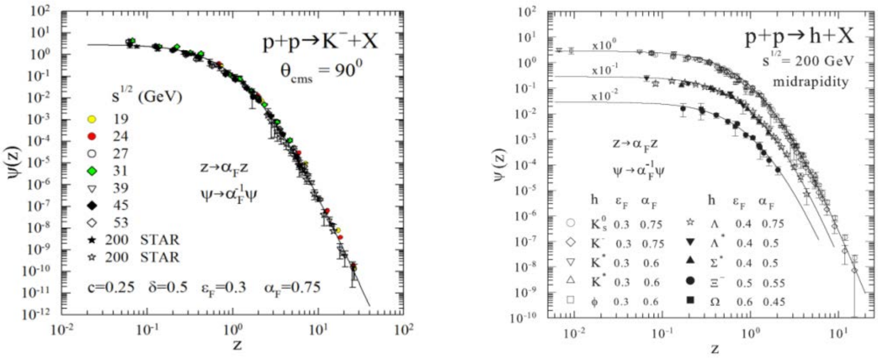


Figure 15. Spectra of strange particle production in *z*-presentations.

The function $\psi(z)$ exhibits two regimes of the behavior: one is seen in the low-z and the other one – in the high-z region. The amount of energy loss and its dependence on the collision energy and transverse momentum of the produced inclusive particle has relevance to the evolution of the hadron matter created in proton and nucleus collisions. In *z*-scaling approach, the relative energy loss of the scattered constituent with energy E is given by $\Delta E/E = (1 - y_a)$. Its dependence on $\sqrt{s}$, p_T and strangeness content of the produced hadron gives information on the medium created in the collisions of protons, and nuclei, and also on properties of the fragmentation and structure of the strange probes themselves.

Figure 16 shows the dependence of the momentum fraction y_a of strange meson and baryon production in $p+p$ collisions on transverse momentum.

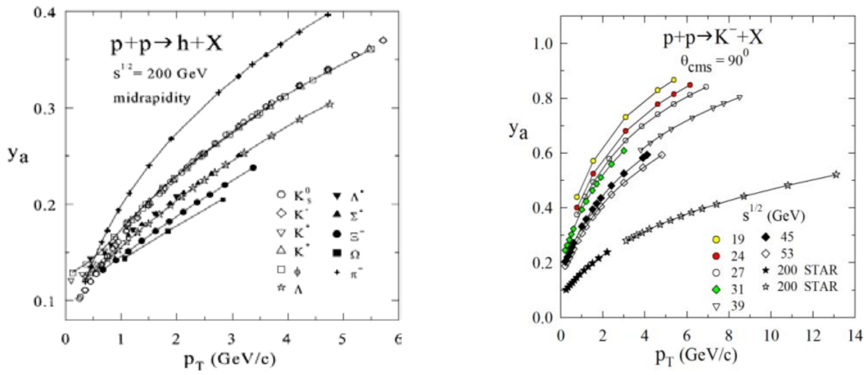


Figure 16. Momentum fraction of y_a as a function of collision energy and transverse momentum for different strange particles produced in p+p collisions.

One can see from Figure 16 the fraction y_a increases with p_T for all particles. The relative energy loss $\Delta E/E$ depends on a value of the fragmentation dimension ε_F. The energy loss decreases with increasing p_T for all particles. For a given $p_T > 1$ GeV/c, the energy loss is larger for strange baryons than for strange mesons. The growth indicates increasing tendency with larger number of strange valence quarks inside the strange baryon $(\Delta E/E)_\Omega > (\Delta E/E)_\Xi > (\Delta E/E)_\Lambda \approx (\Delta E/E)_{\Lambda*} \approx (\Delta E/E)_\Sigma$.

- ***Self-similarity of hard cumulative processes in fixed target experiment for BES-II at STAR***

Aparin A.A., Tokarev M.V., Zborovski I; Physics of Particles and Nuclei Letters, V.12, №2, 2015, pp.324–338

Search for signatures of phase transition in $Au + Au$ collisions is in the heart of the heavy ion program at RHIC. Systematic study of particle production over a wide range of collision energy revealed new phenomena such as the nuclear suppression effect expressed by nuclear modification factor, the constituent quark number scaling for elliptic flow, the "ridge effect" in $\Delta\phi - \Delta\eta$ fluctuations etc. To determine the phase boundaries and location of the critical point of nuclear matter the Beam Energy Scan (BES-I) program at RHIC has been suggested and performed by STAR and PHENIX Collaborations. The obtained results shown that the program (BES-II) should be continued. In this paper a proposal to use hard cumulative processes in BES Phase-II program is outlined. Selection of the cumulative events is assumed to enrich data sample by new type of collisions characterized by higher energy density and more compressed matter. This would allow finding clearer signatures of phase transition, location of a critical point and studying extreme conditions in heavy ion collisions.

2.5. Heavy flavor physics

▪ ***On the pair correlations of neutral K, D, B and B_s mesons with close momenta produced in inclusive multiparticle processes***

V.V. Lyuboshitz, Journal of Physics: Conference Series, v. 668, 012112 (2 pages), 2016

The phenomenological structure of inclusive cross-sections of the production of two neutral K mesons in hadron-hadron, hadron-nucleus and nucleus-nucleus collisions is investigated taking into account the strangeness conservation in strong and electromagnetic interactions. Relations describing the dependence of the correlations of two short-lived and two long-lived neutral kaons $K_S^0 K_S^0$, $K_L^0 K_L^0$ and the correlations of "mixed" pairs $K_S^0 K_L^0$ at small relative momenta upon the space-time parameters of the generation region of K^0 and $\overline{K}^0$ mesons have been obtained. These relations involve the contributions of Bose-statistics and S-wave strong final state interaction of two K^0 ($\overline{K}^0$)-mesons as well as of K^0 meson with $\overline{K}^0$-meson, and also the contribution of transitions $K^+ K^- \to K^0 \overline{K}^0$ and they depend upon the relative fractions of produced pairs $K^0 K^0$, $\overline{K}^0 \overline{K}^0$ and $K^0 \overline{K}^0$. It is shown that under the strangeness conservation the correlation functions of the pairs $K_S^0 K_S^0$ and $K_L^0 K_L^0$, produced in the same inclusive process, coincide, and the difference between the correlation functions of the pairs $K_S^0 K_S^0$ and $K_S^0 K_L^0$ is conditioned by the production of the pairs of nonidentical neutral kaons $K^0 \overline{K}^0$.

Analogous correlations for the pairs of neutral heavy mesons D^0, B^0 and B_S^0, generated in multiple processes with the charm (beauty) conservation are analyzed and differences from the case of neutral K mesons are discussed.

3. Plans for 2018–2019

3.1. Isobaric measurements

STAR has been searching for evidence of chiral magnetic/vortical effects for more than a decade, and so far the experimental observables support the pictures of the chiral magnetic effect and the chiral magnetic wave. To draw a firm conclusion, an effective way is needed to disentangle the signal and the background contributions, the latter of which are intertwined with collective flow. Collisions of isobaric nuclei, i.e. $^{96}_{44}$Ru+$^{96}_{44}$Ru and $^{96}_{40}$Zr+$^{96}_{40}$Zr, present a unique opportunity to vary the initial magnetic field by a significant amount while keeping everything else almost the same. Therefore, isobaric collisions will play a decisive role in verifying/falsifying the CME. Moreover, STAR has observed a significant excess of dilepton production at very low p_T at mid-rapidity in peripheral Au+Au collisions, which resembles the coherent photon-nucleus interactions in ultra-peripheral events. Collisions of isobaric nuclei will shed light on the origin of this excess.

STAR's highest scientific priority for 2018–2019 is the successful realization of the isobaric collision program. In 2018 two 3.5 week runs have started with collisions of Ruthenium-96 (Ru+Ru) and Zirconium-96 (Zr+Zr) at $\sqrt{s_{NN}}$ = 200 GeV. The following data analysis and comparison of results from these events will help clarify the interpretation of measurements related to the chiral magnetic effect. Since Ru nuclei have an atomic charge of 44 compared to 40 for Zr, Ru+Ru collisions will generate a magnetic field approximately 10% larger than Zr+Zr collisions while all else remains essentially constant. Comparison of charge separation results will aid in determining the fraction of those measurements which are related to the chiral magnetic effect by isolating the magnetic field dependence. Our understanding of the chiral magnetic effect will thereby be greatly advanced and have a fundamental impact beyond the field of high-temperature QCD.

In the search for the CME with the γ correlator, the non-flow backgrounds can be suppressed technically, e.g. with event planes at forward rapidities, but the approaches to remove or estimate the flow backgrounds are usually model-dependent and involve large uncertainties. To quantify the CME signal and the flow-related background in the γ correlations, we propose to collide isobaric nuclei of $^{96}_{44}$Ru and $^{96}_{40}$Zr, where the magnetic field can be significantly varied while the backgrounds are almost fixed. Ru+Ru and Zr+Zr collisions at the same beam energy are almost identical in terms of particle production, which is illustrated with the Monte Carlo Glauber simulation. The ratio of the multiplicity distributions from the two collision systems is consistent with unity almost everywhere, except in 0–5% most central collisions, where the slightly larger radius of Ru (R_0 = 5.085 fm) plays a role against that of Zr (R_0 = 5.02 fm). For the CME analysis, we focus on the centrality range of 20–60%, so that the background difference due to the multiplicity is negligible.

One of the main goals of the project in 2019 is analysis of this data and obtaining new physical results.

3.2. Global polarization at 27 GeV

Global polarization can arise from spin coupling to both the fireball vorticity and the spectator magnetic field. Vortical coupling aligns emitted particle spin with the total system angular momentum, which can be partially transferred to the mid-rapidity fireball. Particle spins may also (anti-) align to the short lived magnetic field (in the same direction as the total angular momentum) via intrinsic magnetic moment coupling. The vortical coupling would be even with respect to baryon number, while the magnetic coupling would be odd. STAR has seen a positive (6σ) even signal and a small (1.5σ) odd signal for the $\Lambda-\overline{\Lambda}$ system in the BES-I data.

The vorticity and magnetic field present during the evolution of a heavy ion collision are crucial inputs to the Chiral Vortical Effect (CVE) and Chiral Magnetic Effect (CME), respectively. These two effects are among the RHIC program's most exciting and visible topics today. To test the hypothesis of a magnetically-induced splitting between the Λ and $\overline{\Lambda}$ global polarization, we propose to focus on a single energy and obtain high statistics there. Collisions at 19.6 GeV and lower energy will be obtained in the BES-II, so we focus on $\sqrt{s_{NN}}$ > 19.6 GeV. The high-statistics at one energy will also provide more differential study of possible p_T and rapidity dependence of the global polarization itself. This, in turn, would be important in clarifying potential difference in Λ and $\overline{\Lambda}$ global polarization due to stopping and final-state absorption. An approximate factor 15 increase in statistics is therefore needed to realize a 3σ splitting in the hyperon polarization (assuming the central value stays fixed) driving our request for 1B minbias events.

4. Project Plans for 2019–2021

4.1. Beam Energy Scan (BES-II): Collider mode

The BES-I scientific program has localized the most interesting regions and has identified the observables which are likely to be the most discriminating for understanding the QCD phase structure. However, several of the key measurements were found to require higher statistics in order to provide a quantitative physics conclusion. A second phase of the beam energy scan (BES-II) which is driven by the precision requirements of this suite of physics observables is proposed. The main driver for the numbers of events needed in BES-II program is three observables: net-proton kurtosis, elliptic flow of φ meson and dielectron production.

Improved $\kappa\sigma^2$ for net-protons: The search for Critical Point (CP) location requires quantitative measurements of the variation of net-proton $\kappa\sigma^2$ with beam energy. The current measurements have large statistical uncertainty at all collision energies from $\sqrt{s_{NN}}$ = 7.7 to 27 GeV. These errors preclude any conclusion of a non-monotonic or monotonic variation of the observable with beam energy. We will need to achieve a statistical error of less than 10% on $\kappa\sigma^2$ for each beam energy. The requested high statistics will allow us to pursue the net-proton distribution studies at higher orders (higher than the 4^{th}) where one expects increased sensitivity to the criticality. In addition, we will also study the higher moments of the net-kaons with better accuracy.

Improvements in υ_2 of φ mesons and testing of NCQ scaling: This measurement will allow us to quantitatively address the suspected decrease, followed by an absence, of partonic collectivity below $\sqrt{s_{NN}}$ = 19.6 GeV. It is necessary to make measurements up to $p_T = 3\ \mathrm{GeV}/c$ with a statistical error of less than 10% on υ_2. This will allow us to test in NCQ scaling detail for many particle species, including multi-strange particles. These measurements will answer decisively the question how much φ meson flow there is compared to that of light quark hadrons. Lack of the collectivity of the φ meson will provide clear evidence of the hadronic interaction dominated medium in the low energy heavy ion collisions.

Improvements in the low-mass dilepton measurements: The event size of the data sets that were collected during BES-I for energies below 19.6 GeV has been too small to allow for meaningful measurements in the low-mass range of the dielectron spectrum, let alone in the intermediate mass range. The proposal for measurements in the context of BES-II would therefore not be as much as an improvement, but rather a first measurement of the dielectron invariant mass spectrum in this particular collision energy range. The proposed dielectron event statistics allow the BES-II measurements to have statistical uncertainties that are comparable to those in the previously published at 200 GeV. The systematic uncertainties will be improved by the iTPC upgrade. The combined improvement of the systematic and statistical uncertainties will allow the BES-II data to better constraint different models that within BES-I uncertainties could otherwise not be distinguished.

4.2. Beam Energy Scan (BES-II): Fixed target mode

In the normal collider mode, the lowest collision energy available at RHIC is 7.7 GeV. The fixed-target (FXT) program at STAR, with the iTPC and eTOF upgrades, will enable the energy scan to be extended to also cover the range from 3.0 to 7.7 GeV. It is important to measure key observables at energies lower than 7.7 GeV in the fixed-target program:

- Number-of-constituent-quark scaling of elliptic flow is a key QGP signature. At fixed-target energies, the *NCQ* scaling for particles is expected to break. The elliptic flow is a mid-rapidity observable, and PID is necessary in order to observe the *NCQ* scaling.
- A rapidity correlator is sensitive to QGP formation. The BES-I data show the balance function narrowing signal decreases with decreasing beam energy. This signal is almost, but not quite, gone at 7.7 GeV. Lower energy measurements are needed to demonstrate that this signature disappears. A key to the sensitivity of this measurement is the width of the total rapidity window.
- Strangeness enhancement is seen as an important QGP signature. The energy range covered by the fixed-target program sees the opening of several strange particle production channels. The strange particle production is maximum at mid-rapidity, and cleanly identifying weakly decaying strange hadrons requires clean PID for the daughters.

In order to understand the nature of the phase transition the study of several observables which are expected to have sensitivity to the compressibility are suggested. Among them there are the directed flow of protons, the tilt angle of the pion source, the volume of the pion source, the width of the pion rapidity density distribution, the elliptic flow of protons, the Coulomb potential of the pion source, the life-time of the emitting source. The observation of enhanced fluctuations would be the clearest evidence that the reaction trajectory of the cooling system had passed near the possible critical end point on the QGP/hadronic gas phase boundary.

The eTOF detector of STAR facility will provide electron ID at mid-rapidity for all energies of the fixed-target program. This provides the first opportunity to study the evolution of the low-mass dilepton excess in this collision energy region in which the low-mass yield might be also sensitive to the emitting source temperature in addition to being sensitive to the total baryon density. These dependencies will help us to understand the mechanism of in-medium ρ broadening which is the fundamental probe of chiral symmetry restoration in hot, dense QCD matter.

The energy regime covered by the fixed-target program (3.0 to 7.7 GeV) should be optimal for the formation of matter (as opposed to anti-matter) hypernuclei. At energies below 3.0 GeV, few hyperons are produced. Meaningful samples of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ will be observed at all the fixed-target energies. Searches for multi-strange hyper-nuclei (${}^{5}_{\Lambda\Lambda}\mathrm{H}$ and ${}^{6}_{\Lambda\Lambda}\mathrm{He}$) make appealing physics goals of FTP.

4.3. STAR upgrades for BES II

The limited event statistics from BES-I have already allowed significant progress to be made toward the goals that were established at the outset of this program. There are clear indications that hadronic interactions dominate at the lower BES energies and several observables associated with the formation of a partonic phase at top RHIC energy show indications of turn-off. The successful performance of the BES-II program and further understanding of the phase diagram of QCD matter is only possible with the STAR upgrade, in combination with the higher RHIC luminosities due to electron cooling. New systems – the internal Time Projection Chamber (iTPC) and Event Plane Detector (EPD), will increase STAR's mid-rapidity acceptance, event plane resolution, and centrality determination. The BES phase II program requests Au+Au collisions at $\sqrt{s_{NN}}$ = 19.6, 14.6, 11.5 and 7.7 GeV after electron cooling upgrade. The fixed gold target will allow collisions at low energy $\sqrt{s_{NN}}$ = 4.5, 4.0, 3.5, and 3.0 GeV, respectively. These events can be triggered upon and recorded without reducing the number of collider events.

The inner TPC upgrade will provide the increase of transverse momentum acceptance from p_T > 125 MeV to p_T > 60 MeV/c, improve dE/dx resolution from 7.5 % to 6.2 %, and increase acceptance from $|\eta| < 1$ to $|\eta| < 1.5$. The endcap Time-Of-Flight will provide PID of $\pi/K/p$ for the whole iTPC acceptance in the collider and fixed target modes. The Event Plane Detector will provide large η coverage $2.1 < |\eta| < 5.1$ compared to TPC ($|\eta| < 1.0$), high η (radial, 16) and azimuthal (24) segmentation, good timing resolution (~ 1 ns), and additional mid-rapidity independent event plane and centrality determination independent from TPC. It will be also used as a trigger detector for BES-II.

So the STAR upgrades (iTPC+eTOF+EPD) is crucial to extend energy reach to overlap/ complementary AGS/FAIR/NICA/JPARC and provide the unprecedented coverage and PID for critical point search in BES-II.

The following aspects of BES Phase-II physics program will benefit from presently planned improvements and upgrades to the various sub-systems of the STAR detector.

- **Better acceptance for the STAR TPC in rapidity** and p_T:

– This will enable the study of rapidity dependence of freeze-out dynamics. For a given beam energy, expanding the rapidity range offers the possibility of extending the μ_B range, thereby scanning a larger part of the phase diagram.

– It will extend measurements of v_1 beyond the information contained in the slope of $v_1(y)$ close to midrapdity. A broadened rapidity acceptance will expand our understanding of the role of baryon transport on the v_1 measurements.

– It will permit us to study of the rapidity dependence of higher moments of net-proton/net-charge distributions, to understand the role of charge/baryon number conservation, to provide an experimental approach to determine the effect phase-space limitations on the critical fluctuations measurements, and reduce the effect of centrality resolution on the higher moments.

– It will improve the low p_T acceptance, which will better constrain the physics of freeze-out dynamics, by reducing the systematic uncertainties associated with extracting the yields of various particles.

– It will improve the strange and multi-strange hadron reconstruction efficiency, which will strengthen quantitative conclusions about partonic collectivity.

- **Centrality determination.** Currently, STAR uses the charged particle multiplicity measured in the TPC to determine the collision centrality. Fluctuation and correlation measurements are particularly sensitive to possible correlations between the charged tracks used for physics analysis and those used for centrality determination. This is best avoided, and will be achieved if collision centrality is determined from a separate detector in a different pseudorapidity region from the TPC.

- **Event-plane determination.** Measurements of elliptic flow in BES-I used the TPC for the event plane determination. Non-flow effects have been reduced by keeping an η gap (currently ~ 0.1–0.2) between the particles used for the correlation measurement and the event plane measurement. A dedicated event-plane detector centered at a pseudorapidity of 3 units would result in an η gap of about 2 units of pseudorapidity and thus would decrease the non-flow effects. Directed flow measurements in BES-I used the BBC detectors, which have poor event-plane resolution. A dedicated event-plane detector would improve physics performance and facilitate physics interpretation in such analyses also.

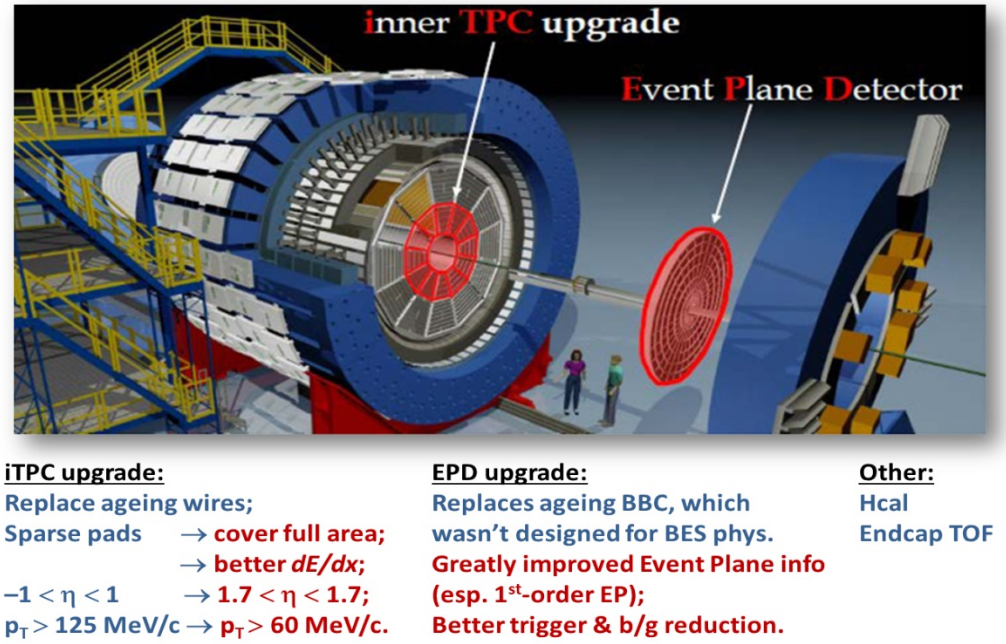


Figure 17.Upgrade of the STAR detector for BES Phase-II

- **Trigger performance.** The transverse beam size at the lowest RHIC energies was significantly greater than at $\sqrt{s_{NN}}$ = 200 GeV, causing collisions of ions in the beam halo with either the beam pipe or support-structure materials. At $\sqrt{s_{NN}}$ = 7.7 GeV, 80–98 % of the triggered reactions came from such beam on beam-pipe collisions. The situation will improve with the installation of an electron gun. A total increase in luminosity of about a factor 10 is expected, which will result in a trigger rate of several kHz at the highest BES energy. To exploit this, it is essential to trigger on all good Au+Au collisions with a constructible vertex.

4.4. JINR contribution to the Project

- **Participation in the STAR runs**

– JINR group responsibility in runs is the support of End Cap EMC in working condition
– Participation in assembly and testing of Event Plane Detector
– Development of new approach for data analysis – statistical method particle identification
– Participation in data taking and data analysis for BES-II

- **Global polarization study**

– Participation in data analysis of global polarization (isobaric nuclei, high statistic measurement at 27 GeV, BES-II measurements).
– Comparison of the polarization of Lambda hyperons in collisions of the ruthenium and zirconium nuclei. Studies of rapidity dependence of Λ hyperon polarization and possibility to measure Ξ hyperon polarization. It may allow us to distinguish the “vortex” model from model associated with the magnetic field effects.

- **Scaling and fractal structure study**

– The analysis of experimental data on energy scan for studying the scaling properties and the fractal structure of nucleus-nucleus collisions to search for signatures of phase transition and the critical point in nuclear matter.
– Fractal analysis of nucleus-nucleus collisions on event-by-event basis shown that the fractal dimension of event depends on a phase space used and related to constituent interactions. Therefore selection of events according to the fractal dimensions can give additional criteria to facilitate model verification and search for new phenomena.
– Self-similarity of charged hadron production (*z*-scaling) found at BES-I energies give strong motivation to study the phenomena with higher accuracy in BES-II measurements. The discontinuity of the model parameters (“heat capacity” and fractal dimensions) and their correlation are assumed to be indication on the existence of critical phenomena in a nuclear matter.
– New kinematical region (cumulative) of hadron production at high transverse momenta can be achievable at BES-II energies. The compressed nuclear matter created in the region can be studied by using the general concepts – “scaling” and “universality”, developed for description of the critical phenomena in multiparticle systems.

- **STAR–JINR GRID**

– STAR is interested in developing newer and more compact analysis data format and in 2016 the Data Summary file format known as a “MuDST” (micro-DST) was complemented by an emerging format known as “picoDST”. Using GRID technologies for processing data from the STAR facility at JINR computer cluster we plan to convert over a million of files from MuDST to PicoDST in 2019–2021.

5. STAR–JINR GRID Computing

The large luminosity of RHIC and high speed data acquisition system at the STAR are allowed to collect more than 24 Petabytes of information about Au + Au collisions. It is expected that by 2020 the amount of information will increase more than double. The taken data can no longer be processed only by the RHIC computer facility. Therefore, the use of the distributed data centers of different institutions of the STAR collaboration is one of the possible solutions to this problem. The Laboratory of Information Technologies of the JINR became the world's leading centers for the processing by the GRID system. Therefore, JINR resources can be used to process the STAR data. The results of this work of JINR group together with STAR software group at BNL were presented at the 7th International Conference «Distributed Computing and Grid-technologies in Science and Education» (GRID 2016, Dubna, July 2016) and XXVI International Symposium on Nuclear Electronics & Computing (NEC'2017, Becici, Budva, Montenegro, September 25–29, 2017).

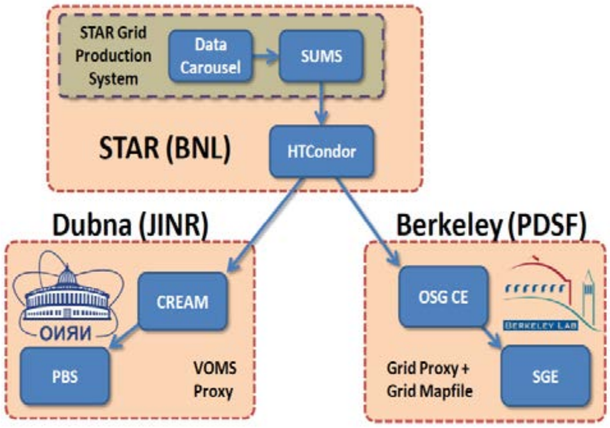


Figure 18. Grid Software Stack Architecture

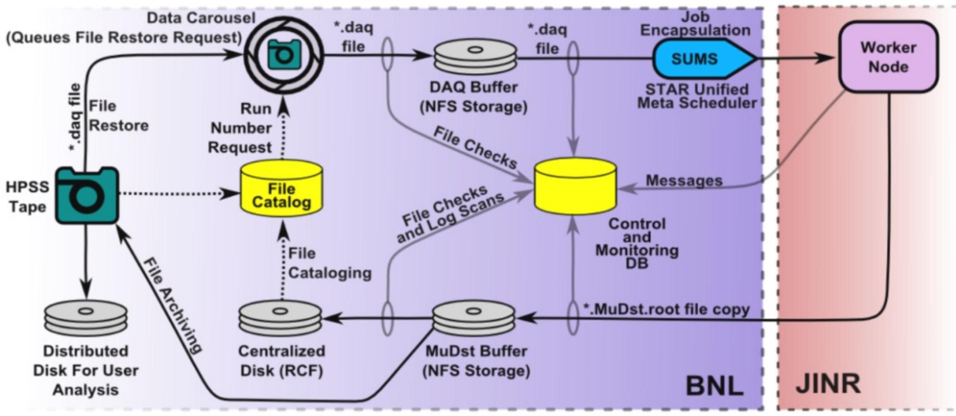


Figure 19. Current Grid Production Dataflow

6. Conclusions

The data from BES-I have allowed significant progress to be made toward the goals that had been established at the outset of this program. There is a clear indication that hadronic interactions dominate at the lower BES energies and several observables associated with the formation of a partonic phase at top RHIC energy have been turned-off. These findings corroborate the creation of QGP at the top RHIC energy. The BES-I program, with limited event statistics, has made important measurements towards critical point and first-order phase transition physics. This provides compelling reasons for high event statistics in a second phase of the program. These results from the BES-I have allowed us to focus the proposed BES Phase-II on the most crucial energy range from 7.7 to 20 GeV. Using the results from the BES-I program, we have been able to make estimates of the projected errors in a future program and using these to determine the statistics required for each observable in order to allow us to draw firm conclusions. The enhanced collider performance via increased luminosity due to electron cooling and longer bunches will allow for higher-precision measurements of the key observables. Furthermore, STAR detector upgrades (iTPC and EPD) will allow more comprehensive and refined measurements. A set of focused, high-precision, refined measurements will allow the BES Phase-II program to fundamentally enhance our understanding of the phase diagram of QCD matter.

Participation of the JINR group in the research program of the STAR Collaboration “Beam Energy Scan Phase II” and data analysis of results of measurements will be main goal of prolongation of the project STAR Experiment (JINR participation) for the period 2019–2021.

Attachment 1. Energy Scan Program (BES Phase II)

Physics Objectives and Specific Observables

The BES-I scientific program has localized the most interesting regions and identified the observables which are likely to be the most discriminating for understanding the QCD phase structure. However, several of the key measurements were found to require higher statistics in order to provide a quantitative physics conclusion. Therefore, we propose to run a second phase of the beam energy scan (BES Phase-II) which is driven by the precision requirements of this suite of physics observables. The bullets below provide an overview of the observables key to achieving the goals of the BES Phase-II program. Following those bullets are subsections detailing the requirements and expected resolution that will be reached for each key observable.

- **Onset of QGP.** Measurements to be carried out include: the nuclear modification factor as a function of p_T for produced hadrons, azimuthal anisotropy measurements as a function of p_T for identified hadrons with particular emphasis on the φ meson and the multi-strange hyperons, and the centrality dependence of charged particle correlations with respect to the reaction plane. Our current measurements show interesting trends in these measurements as a function of center-of-mass energies, and they point towards a possible turn-off of the signals of QGP below 19.6 GeV. The nuclear modification factor at high p_T having a value below unity is regarded as a signature of formation of hot and dense matter of quarks and gluons. Current measurements below 27 GeV do not have sufficient event statistics to extend in p_T to 5 GeV/*c*, thereby preventing a quantitative conclusion on the turn-off of this signal of QGP. In the azimuthal anisotropy measurements, the υ_2 of φ mesons plays a crucial role. Since generation of a large υ_2 of φ mesons requires partonic interactions prior to the formation of φ, an absence or a low value of υ_2 of φ mesons compared to other hadrons could indicate that the system created in heavy-ion collisions does not undergo the quark-hadron phase transition. Current measurements of υ_2 of φ mesons versus p_T at 11.5 and 7.7 GeV provides such an indication, but with large statistical errors on the data points. A high statistics measurement of υ_2 of φ mesons versus p_T is crucial in order to find out if a turn-off of partonic collectivity occurs below 19.6 GeV. The centrality dependence of a finite difference in charge correlations with respect to the reaction plane for same- and opposite-charge pairs is considered a signature of the Chiral Magnetic Effect. Within large statistical uncertainties, this difference is consistent with zero in BES-I measurements at 7.7 GeV. Since one of the prerequisites of this phenomenon is the formation of a partonic phase, a statistically significant null result at lower beam energies will be an observation of turn-off of QGP. With the higher event statistics of the BES Phase-II program further effects of the chiral magnetic wave, such as the chiral separation effect and the chiral vortex effect can also be studied.
- **First-order phase transition.** The relevant measurements include the slope of rapidity dependence of directed flow for protons and net-protons, and tilt angle of the source as measured through azimuthally sensitive femtoscopy. A minimum in $d\upsilon_1/dy$ versus center of mass energy has been argued to indicate the softest point in the EOS of the system formed in heavy-ion collisions. A statistically significant measurement has been obtained in BES-I, but the location of the minimum energy point has not been fixed precisely. Current measurements

suggest that it lies somewhere between the energy values of 19.6 and 11.5 GeV, corresponding to a μ_B difference of more than 100 MeV. Furthermore, differential measurements of this observable, like as a function of collision centrality at different beam energies and for different baryon and meson species would provide additional data to refine this signature of a first-order phase transition. These additional measurements require increased statistics compared to BES-I. The tilt of the emission source is also proposed to have sensitivity to the softest point in the EOS. This observable is a new measurement unique to BES Phase-II. A measurement of this observable was not possible with the BES-I data to the high statistics demands of the azimuthally sensitive femtoscopy analysis which is necessary to infer coordinate space anisotropies.

- **Critical Point.** A non-monotonic variation of the product of high moments for net-protons, specifically the $\kappa\sigma^2$ with beam energy has been considered in the literature as a signal for a CP. The current measurements indicate that the trend of net-proton $\kappa\sigma^2$ is flat from 200 to 39 GeV. Starting at 27 GeV, the values of $\kappa\sigma^2$ of net-proton show a clear drop. However the statistical errors on the measurements at 11.5 and 7.7 GeV are too large for the purpose of further gauging the energy dependent variations at the lower energies. A high statistics measurement of the possible rise in the $\kappa\sigma^2$ values at energies below 19.6 GeV would open up an exciting opportunity to study the QCD critical point physics at RHIC.
- **Chiral Phase Transition.** High statistics dilepton measurements to date provide the most powerful observable to understand in-medium effects and a possible chiral phase transition. While in the low mass region (around and below the ρ meson mass) there is the possibility of investigating symmetry restoration, the intermediate mass region allows a possible temperature measurement of the partonic phase. The BES program has clearly demonstrated STARs capability for such measurements for energies as low as 19.6 GeV. The results obtained so far are consistent with formation of a partonic phase, with partial restoration of chiral symmetry, and suggest the importance of baryon-dominated interactions in affecting the ρ meson spectra. BES Phase-II will offer a great new opportunity to make a high-statistics measurement of dileptons at energies below 27 GeV to see the effect of the possible turn-off of QGP and the increased baryonic interactions in the system.

Table 2 shows the statistics requires to make a precision measurement of each proposed observable at each proposed energy.

Table 2. Event statistics (in millions) needed for Beam Energy Scan Phase-II for various observables

Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to $p_T = 5$ GeV/c	–		160	125	92
Elliptic Flow (ϕ mesons)	100	150	200	200	400
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	50	75	100	100	200
Azimuthal Femtoscopy (protons)	35	40	50	65	80
Net-Proton Kurtosis	80	100	120	200	400
Dileptons	100	160	230	300	400
Required Number of Events	**100**	**160**	**230**	**300**	**400**

Beam request

The first goal of the BES program, namely the evidence for the disappearance of signatures of quark-gluon phase observed at the RHIC top energy, is already qualitatively reached with the results of BES-I. The enlarged statistics of BES Phase-II would allow us to improve on accuracy of earlier results, and to precisely determine at which collision energy QGP signatures disappear thus establishing the onset of deconfinement. The QGP signatures all seem to disappear at the low end of the BES-I energy range, which is consistent with the prior claim of the onset of deconfinement at 7.7 GeV. In order to test this claim and to establish precisely the energy of the onset of deconfinement it will be necessary to make measurements at energies around and below 7.7 GeV. The second and third goals, the discovery of first-order phase transition and CP, are equivalent to a large degree. That means that the discovery of one would signal the presence of the other. The net-proton v_1 measurements seem to imply that the softest point might be at energy between 11.5 and 19.6 GeV. The results from the recent 14.5 GeV dataset will help to clarify the critical energy range to establish a first-order phase transition. The evidence for a critical behavior from the net-proton kurtosis suggests that 19.6 GeV may be the most important energy. The recent 14.5 GeV run will help localize the energies of highest interest. We have developed a proposal which uses a step size of 50–60 MeV in μ_B. This decision can only be made after the high statistics data from the first year (2019) of BES Phase-II are available. The experimental program proposed will locate CP point if it lies within the search range in μ_B = 20–420 MeV. If, however, the CP location is at a μ_B value larger than the μ_B = 420 MeV which is a maximum μ_B value accessible with RHIC machine running in colliding mode in 2018/2019, we will continue the search with events obtained in fixed-target mode. This extended μ_B range will reach to about 720 MeV. Therefore, the present plan for the BES Phase-II covers the chemical potential range from the smallest values of about 20 MeV at RHIC top energies to those high enough to reach and exceed the theoretical expectations (see Table 3). It is important to push the study of chiral symmetry restoration through di-lepton measurements down to the region of the expected highest baryon density, which would be collision energy of about 8 GeV.

Table 3. Beam Use Request for BES-II for collider and fixed target modes.

Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Number Events	Priority	Sequence
9.8	19.6	4.5 weeks	Au+Au	400M MB	1	1
7.3	14.5	5.5 weeks	Au+Au	300M MB	1	3
5.75	11.5	5 weeks	Au+Au	230M MB	1	5
4.6	9.1	4 weeks	Au+Au	160M MB	1	7
9.8	4.5 (FXT)	2 days	Au+Au	100M MB	2	2
7.3	3.9 (FXT)	2 days	Au+Au	100M MB	2	4
5.75	3.5 (FXT)	2 days	Au+Au	100M MB	2	6
31.2	7.7 (FXT)	2 days	Au+Au	100M MB	2	8
19.5	6.2 (FXT)	2 days	Au+Au	100M MB	2	9
13.5	5.2 (FXT)	2 days	Au+Au	100M MB	2	10

Attachment 2. Self-similarity and fractal structure of nucleus-nucleus collisions

- **Charged Hadron Spectra and Parton Energy Losses**

The transverse momentum spectrum of hadrons produced in high-energy collisions of heavy ions reflects features of constituent interactions in the nuclear medium. The medium modification is one of the effects (recombination, coalescence, energy loss, multiple scattering,...) that affects the shape of the spectrum. The properties of the created medium are experimentally studied by variation of the event centrality and collision energy.

STAR has measured spectra of negative charged particle production in Au+Au collisions for the first phase of the RHIC Beam Energy Scan Program over a wide range of collision energy $\sqrt{s_{NN}}$ = 7.7–200 GeV, and transverse momentum of produced particle in different centralities at $|\eta| < 0.5$. The spectra demonstrate strong dependence on collision energy which enhances with p_T. The constituent energy loss as a function of energy and centrality of collisions and transverse momentum of inclusive particle was estimated in the *z*-scaling approach. The energy dependence of the model parameters – the fractal and fragmentation dimensions and "specific heat" was studied.

Figure 20 shows the negatively charged hadron yields in Au+Au collisions at $\sqrt{s_{NN}}$ =7.7, 39 and 200 GeV at mid-rapidity $|\eta| < 0.5$ as a function of transverse momentum p_T. The results are shown for the collision centrality classes of 0–5%, 5–10%, 10–20%, 20–40%, 40–60%, 60–80%. The distributions are measured over a wide momentum range 0.2 < p_T < 12 GeV/*c*. The multiplied factor of 10 is used for visibility. As seen from Figure 20 spectra fall more than eight orders of magnitude. Spectra demonstrate a strong dependence on collision energy and centrality at high p_T.The exponential behavior of spectra at low p_T and the power behavior of spectra at high p_T are observed.

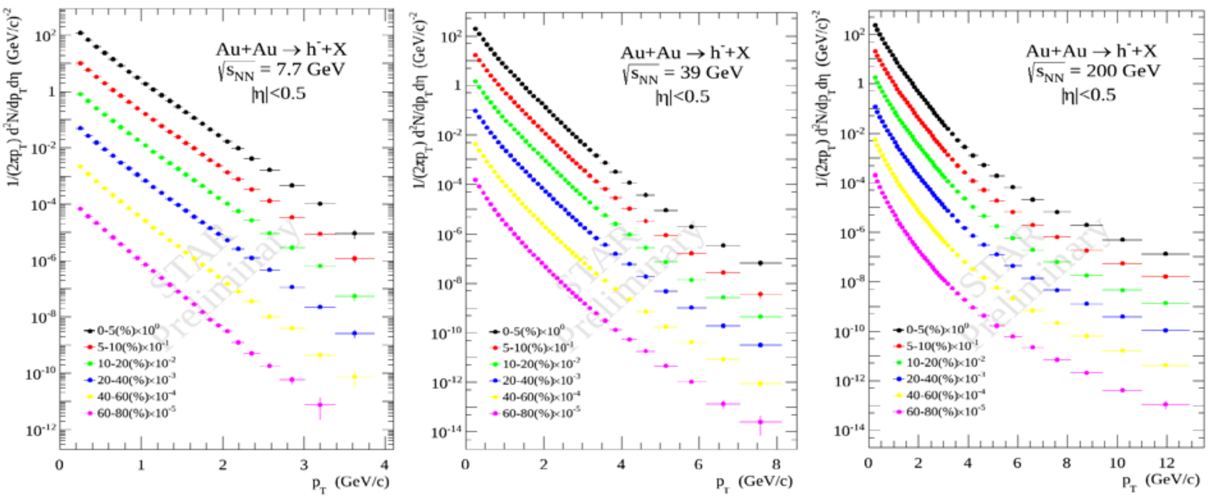


Figure 20: Transverse momentum distribution of negative charged particles production at BES energies 7.7, 39, and 200 GeV as a function of centrality.

The JINR team of the STAR collaboration takes part in the analysis of the BES-I data.

The original method of data analysis (z-scaling approach) has been suggested and exploited for search for new phenomena in nuclear matter created in heavy ion collisions. The analysis of the obtained spectra has been performed in the framework of the z-scaling approach (Phys. Rev. D75, 2007, 094008; Int. J. Mod. Phys. A24, 2009, 1417; Nucl. Phys. Suppl. B245, 2013, 231). The approach based on z-scaling is treated as manifestation of the self-similarity property of the structure of colliding objects (hadrons, nuclei), the interaction mechanism of their constituents, and the process of constituent fragmentation into real hadrons. In this approach the energy loss of the scattered constituent during its fragmentation in the inclusive particle is proportional to the value $(1-y_a)$.

Figure 21 shows scaling function $\Psi(z)$ as a function of self-similarity parameter z. The data z presentation corresponds to spectra of negatively charged particles produced in Au+Au collisions at energies $\sqrt{s_{NN}}$ = 7.7–200 GeV in the range $|\eta| < 0.5$ for most central (0–5%) and peripheral (40–60%) events as a function of the transverse momentum. We observe "collapse" of the data onto a single curve. The solid line is a fitting curve for these data. The derived representation shows the universality of the shape of the scaling curve for the BES-I energies. The energy dependence of the fractal and fragmentation dimensions and "specific heat" was found.

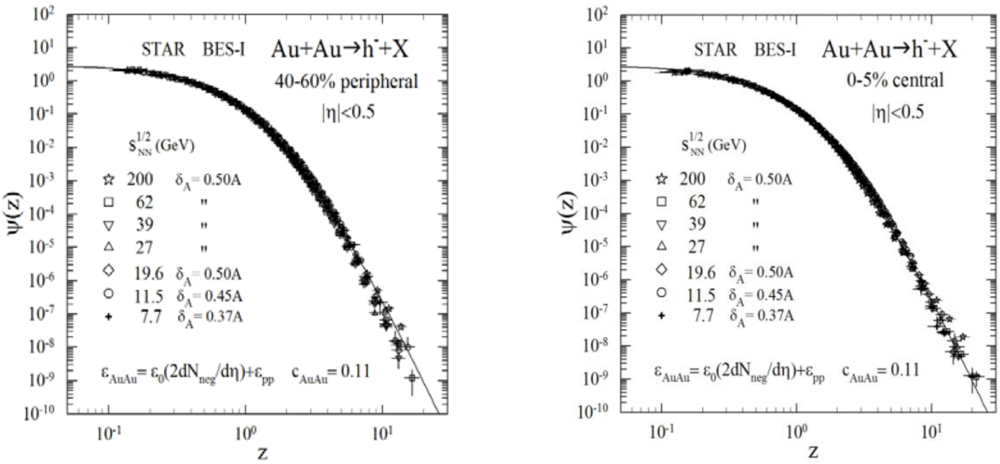


Figure 21: z-presentation of transverse momentum distribution of negative charged particle production at BES energies 7.7, 11.5, 19.6, 27, 39, 62.4, and 200 GeV at most central (0–5%) and peripheral (40–60%) collisions and central rapidity range ($|\eta|$<0.5).

The nuclear modification factor R_{AA} measured at RHIC at $\sqrt{s_{NN}}$ = 62.4, 130 and 200 GeV strongly shows a suppression of the charged hadron spectra at p_T > 4 GeV/c. This suppression was one of the first indications of a strong final-state modification of particle production in Au+Au collisions that is now generally ascribed to energy loss of the fragmenting parton in the hot and dense medium. At the BES-I energies the nuclear modification factor drastically changes with a collision energy. It increases with transverse momentum as the energy decreases. The study of the evolution of the energy loss with collision energy can be useful for searching for signature of phase transition and a critical point. The measured spectra (see Figure 21) allow us to estimate constituent energy loss in charged hadron production in Au+Au collisions at BES-I energies. The energy loss $\Delta E/E$ of the scattered constituent during its fragmentation in the inclusive particle is proportional to the value $(1–y_a)$.

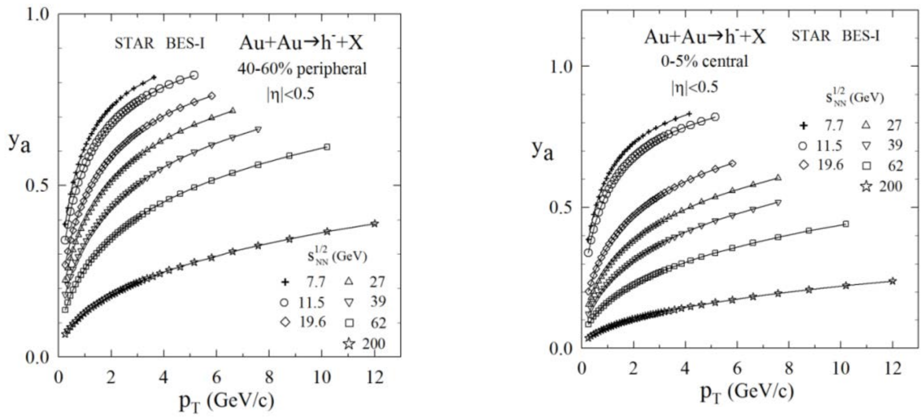


Figure 22: Momentum fraction y_a as a function of the energy and centrality of collision and the transverse momentum of inclusive particle.

Figure 22 shows the dependence of the fraction y_a for central (0–5%) and peripheral (40–60%) Au+Au collisions on the transverse momentum over a range $\sqrt{s_{NN}}$ = 7.7–200 GeV. The behavior of y_a demonstrates a monotonic growth with p_T. It means that the energy loss associated with the production of a high-p_T hadron is smaller than that with lower transverse momenta. The decrease of y_a with collision centrality represents larger energy loss in the central collisions as compared with peripheral interactions.

Attachment 3. List of publication of JINR group

1. Self-similarity of negative particle production from the Beam Energy Scan Program at STAR
M.V. Tokarev, International Journal of Modern Physics: Conference Series, 39, 1560103 (12 pages), 2015

2. Fractal structure of hadrons in processes with polarized protons at SPD NICA
M.V. Tokarev, I. Zborovsky, A.A. Aparin, Письма в ЭЧАЯ, ISSN:1814-5957, eISSN:1814–5973, Изд: ОИЯИ, 12, 1, 48-58, 2015

3. Self-similarity of hard cumulative processes in fixed target experiment for BES-II at STAR
M.V. Tokarev, I. Zborovsky, A.A. Aparin, Письма в ЭЧАЯ, ISSN:1814–5957, eISSN:1814–5973, Изд: ОИЯИ, 12, 2, 221–229, 2015

4. Self-similarity of proton spin and asymmetry of jet production
M.V. Tokarev, I. Zborovsky, Письма в ЭЧАЯ, ISSN:1814-5957, eISSN:1814–5973, Изд: ОИЯИ, 12, 2, 214–220, 2015

5. Cumulative hadron production in pA collisions in the framework of *z*-scaling
A.A. Aparin, M.V. Tokarev, International Journal of Modern Physics: Conference Series, 39, 1560110 (7 pages), 2015

6. Two-step procedure of fractal analysis
T.G. Dedovich, M.V. Tokarev, Physics of Particles and Nuclei Letters, ISSN:1547–4771, Изд: Pleiades Publishing, 13, 2, 178–189, 2016

7. Analysis of fractals with combined partition
T.G. Dedovich, M.V. Tokarev, Physics of Particles and Nuclei Letters, ISSN:1547–4771, Изд: Pleiades Publishing, 13, 2, 169–177, 2016

8. Self-similarity of strangeness production in pp collisions at RHIC
M.V. Tokarev, I. Zborovsky, Journal of Physics: conference series, ISSN: 1742–6588, eISSN: 1742–6596, Изд: IOP Publishing Limited, 668, 012087, 2016

9. J/psi production at low transverse momentum in p+p and d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
L. Adamczyk, ... A. Aparin et al. (STAR Collaboration), Physical Review C, Nuclear Physics, ISSN: 0556–2813, eISSN: 1089–490X, Изд:American Physical Society, 93, 6, 064904/1–064904/11, 2016

10. Upsilon production in U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV measured with the STAR experiment
L. Adamczyk, ... A. Aparin et al. (STAR Collaboration), Physical Review C, Nuclear Physics, ISSN: 0556–2813, eISSN: 1089-490X, Изд:American Physical Society, 94, 6, 064904/1–064904/9, 2016

11. Jet-like Correlations with Direct-Photon and Neutral-Pion Triggers at $\sqrt{s_{NN}}$ =200 GeV.
STAR Collaboration (L. Adamczyk (AGH-UST, Cracow) et al.)., Phys. Lett. B, 760, 689–696, 2016

12. Bulk Properties of the Medium Produced in Relativistic Heavy-Ion Collisions from the Beam Energy Scan Program.
L. Adamczyk ... A.A. Aparin et al. (STAR Collaboration), Physical Review C, Изд: American physical society, 96, 4, 044904/1-044904/34, 2017

13. Charge-dependent directed flow in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
L. Adamczyk, ... A. Aparin et al. (STAR Collaboration), Physical Revew Letters, ISSN:0031-9007, eISSN:1079–7114, Изд: American Physical Society, 118, 1, 012301/1–012301/8, 2017

14. New indication on scaling properties of strangeness production in pp collisions at RHIC
M.V. Tokarev, I. Zborovsky, Internatiional Journal of Modern Physics A, 32, 1750029(42 pages), 2017

15. Coherent diffractive photoproduction of ρ^0 mesons on gold nuclei at 200 GeV/nucleon-pair at the Relativistic Heavy Ion Collider
L. Adamczyk ... A.A. Aparin ... et al. (STAR collaboration), Physical Review C, Изд: American physical society, 96, 5, 054904/1–054904/12, 2017

17. Self-similarity of hadron production: *z*-scaling
Tokarev M.V.,Zborovsky I., Theoretical and Mathematical Physics, ISSN: 0040–5779, eISSN: 1573-9333, Изд:Springer New York, 184, 3, 1350–1360, 2016

18. Scaling of cumulative particle production and production of particles with large transverse momentum in proton-nucleus collisions at high energies.
A.A. Aparin, PhD thesis, JINR, November 19, 2017

Attachment 4. List of reports at international conferences, workshops, collaboration meetings

1. *R. Lednický (for the STAR Collaboration)*
“Correlation measurement of particle interaction at STAR”, Hadron Structure and QCD – 2016 (HSQCD'2016)
27 June 2016 – 1 July 2016, PNPI NRC KI, Gatchina, Russia.

2. *M.V. Tokarev (for the STAR Collaboration)*
“Search for new symmetries: self-similarity of strangeness production”, Hadron Structure and QCD – 2016 (HSQCD'2016)
27 June 2016 – 1 July 2016, PNPI NRC KI, Gatchina, Russia.

3. *M.V. Tokarev (for the STAR Collaboration)*
Recent STAR spin results and spin measurements at RHIC,
XVII Workshop on High Energy Spin Physics ", Dubna, Russia, September 11–15, 2017

4. *M.V. Tokarev, I. Zborovsky*
“Fractality of strange particle production in pp collisions at RHIC”,
18th Lomonosov Conference on Elementary Particle Physics MSU, Moscow, Russia, August 24 – 30, 2017.

5. *M.V. Tokarev, I. Zborovsky, A.O. Kechechyan*
“Fractality of strange particle production in pp collisions at RHIC”,
Regional STAR Meeting MEPhI, Moscow, Russia, August 23, 2017.

6. *A.O. Kechechyan*
Fractional Momentum Loss of Hadrons in Au+Au Collisions at BES Energies
Regional STAR Meeting MEPhI, Moscow, Russia, August 23, 2017.

7. *A.O. Kechechyan*
Fractional Momentum Loss of Hadrons in Au+Au Collisions at BES Energies
STAR Regional Meeting, Warsaw, Poland, June 27-30, 2017

8. *Valery V. Lyuboshitz, V.L. Lyuboshitz*
“Possible effect of mixed phase and deconfinement upon spin correlations in the $\Lambda\bar{\Lambda}$ pairs generated in relativistic heavy-ion collisions”.
– Talk at the XVII Advanced Research Workshop on High Energy Spin Physics – DSPIN-2017 (Dubna, September 11–15, 2017); allocated on the DSPIN-2017 website (PDF file). Submitted to Proceedings of DSPIN-2017 (*Journal of Physics: Conference series* , 2018) .
– 24-th International European Physical Society Conference on High Energy Physics – EPS-HEP 2017 (Venice, Italy, July 5 – 12, 2017). Proceedings of EPS-HEP 2017
(PoS (EPS-HEP2017) 653, *Proceedings of Science*, v. **314** , 2018)

9. *Valery V. Lyuboshitz, V.L. Lyuboshitz*
"On the pair correlations of neutral K, D, B and B_s mesons with close momenta produced in inclusive multiparticle processes". Talk at the XVII International Conference on Hadron Spectroscopy and Structure – HADRON 2017 (Salamanca, Spain, September 21–25, 2017); allocated on the Indico website of HADRON 2017 (PDF file). Submitted to Proceedings of HADRON 2017 (PoS (Hadron2017) 041, *Proceedings of Science* , v. **310** , 2018)

10. *L. Hajdu at al.*
"STAR's approach to highly efficient end-to-end grid production". XXVI International Symposium on Nuclear Electronics & Computing (NEC'2017), Becici, Budva, Montenegro, September 25–29, 2017

11. *G. Agakishiev at al.*
"Progress report on STAR's Expansion to JINR via GRID". The 7th International Conference "Distributed Computing and GRID-technologies in Science and Education" (GRID 2016), Dubna, JINR, July 4–9, 2016

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9. M.M. Aggarwal et al. (STAR Collaboration), “An Experimental Exploration of the QCD Phase Diagram: The Search for the Critical Point and the Onset of Deconfinement”, arXiv:1007.2613.
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12. R. Reed (for the STAR Collaboration), “STAR Detector Upgrades”, RHIC & AGS Users’ Meeting, 2016 RHIC & AGS Annual Users’ Meeting, Upton, BNL, January 7–10, 2016; https://www.bnl.gov/aum2016/.
13. White Paper “Low-Energy RHIC electron Cooler (LEReC)”, September 19, 2013.
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