

EXPERIMENT PHENIX AT RHIC

PNPI participants of the PHENIX Collaboration:

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1. Introduction

PHENIX is one of two active experiments at Relativistic Heavy Ion Collider (RHIC) [1]. The experiment is conducted by a collaboration consisting of more than a thousand scientists from 70 institutions from 13 countries. The main goal of the PHENIX experiment, as well as relativistic heavy ion physics in general, is to study the nature and properties of the QCD matter under extreme conditions of high temperature and/or high baryonic density. One of the lodestars of the experimental program is an expected discovery of the Quark-Gluon Plasma (QGP), a new state of matter with dominance of the partonic degrees of freedom for essentially all momentum scales and over nuclear size distances.

Extensive study of heavy ion collisions at RHIC in 2000–2005 has indeed resulted in a discovery of a new state of matter – strongly coupled QGP (sQGP) [2]. Most of recent experimental efforts at RHIC were directed towards better understanding of the properties of the produced medium.

PNPI was involved in the PHENIX experiment from the very beginning. PNPI was responsible for the design and construction of the main detector of the central tracking system – multiwire focusing Drift Chambers (DCs) [3]. The DCs were successfully operated for last twelve years contributing to about 80 % of all scientific results of the collaboration. It is planned that the DCs will operate at least till 2015 with very vague plans for their replacement. Besides the hardware maintenance, PNPI experts take part in data taking, various physical analyses and interpretation of the results.

Last five years, the PHENIX Collaboration accumulated enormous amount of new experimental results. This paper presents mainly results obtained with participation of PNPI specialists and related to production of light hadrons in $p + p$, $d + Au$, $Cu + Cu$, and $Au + Au$ collisions at $\sqrt{s_{NN}} = 39\text{--}200$ GeV.

2. Elementary $p + p$ collisions

Left panel in Fig. 1 presents a compilation of experimental invariant differential cross sections for production of different hadrons in $p + p$ collisions at $\sqrt{s} = 200$ GeV [4]. These results provide precision tests for pQCD calculations at high transverse momenta and serve as a reference for heavier collision systems.

Measurements at low p_T were performed using the ToF subsystem [5] or in di-electron decay channel. Intermediate and high p_T results are based on measurements of photonic and hadronic decay channels for hadrons. Measurements in different decay modes agree with each other within uncertainties and extend over a wide range of transverse momenta up to 20 GeV/ c . The plot on the right shows a comparison of the measured invariant differential cross section for π^0 production with that calculated in the NLO pQCD [6]. Within the uncertainties, the calculations reproduce the experimental results, indicating good understanding of the basic particle production mechanisms at $p_T > 2$ GeV/ c in elementary hadronic interactions.

It is interesting to note that invariant differential production cross sections measured for all hadrons in $p + p$ collisions at $\sqrt{s} = 200$ GeV can be well described over the entire momentum range by the Tsallis distribution [7]. It has only two parameters, and it describes the particle p_T spectra both at low and high transverse momenta. The values of the two parameters extracted from the fits were found to be approximately the same for all mesons with a very weak mass dependence. The ability to describe all particle spectra with a common functional form allows one to estimate particle integrated yields on the basis of measurements performed even in a limited p_T range. The extracted values of the integrated yields were found to be in good agreement with previous PHENIX measurements [4].

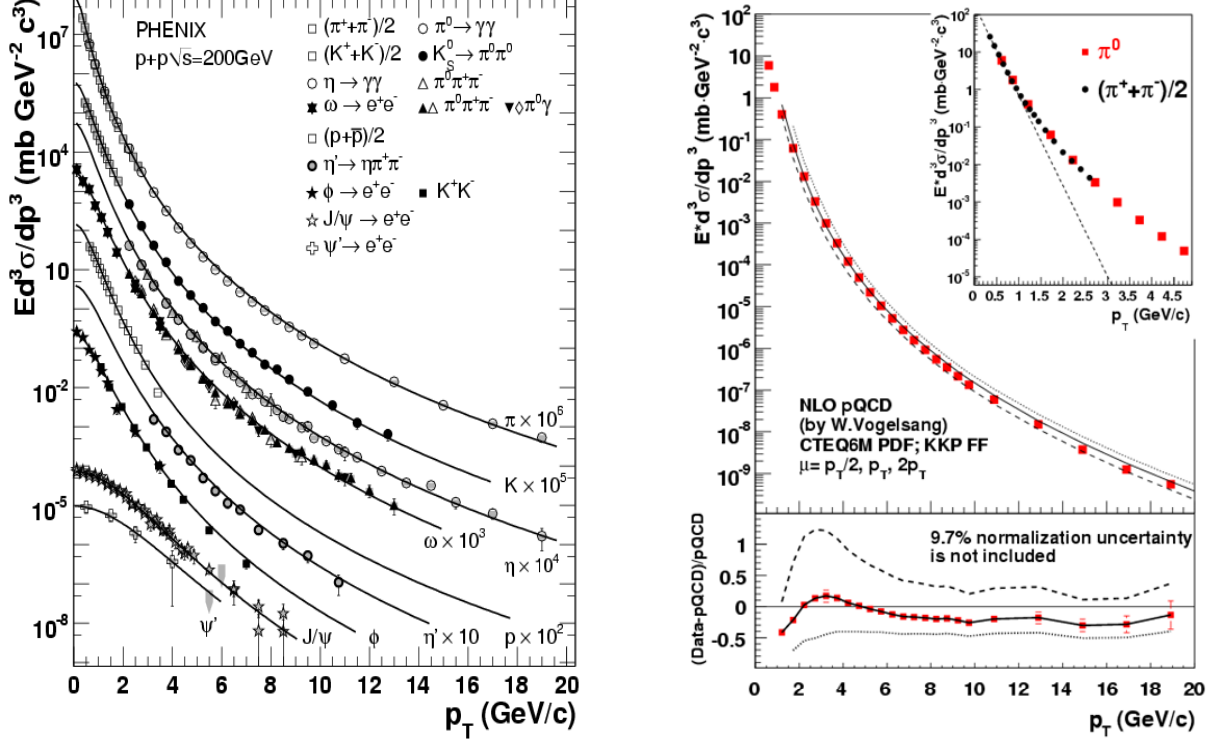


Fig. 1. Invariant differential cross sections for production of hadrons in $p + p$ collisions at $\sqrt{s} = 200$ GeV (left). Comparison of the measured cross section for π^0 mesons production with that calculated in the NLO pQCD (right)

3. Collisions of light and heavy nuclei

Invariant differential transverse momentum spectra for production of different hadrons were also measured in $d + \text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Figure 2 presents nuclear modification factors R_{dA} , which are the ratios of yields measured for particles in $d + \text{Au}$ and $p + p$ collisions and scaled by the corresponding numbers of binary nucleon-nucleon collisions estimated within the Glauber model [8]. The plots on the top and bottom correspond to the most central and peripheral $d + \text{Au}$ collisions, respectively. The results are shown for production of protons, π^0 , η , ω , ϕ , and η' -mesons [9–11].

For the rare hard scattering processes which are expected to scale with the number of binary collisions, the corresponding ratios should be equal to one in the absence of any collective nuclear effects. And indeed, in the most peripheral collisions the measured ratios at $p_T > 2$ GeV/c are consistent with unity within uncertainties, except probably for protons. At the same time, in central $d + \text{Au}$ collisions production of all hadrons is enhanced at intermediate p_T -values. Such an enhancement is not a new effect, it was previously observed in experiments at lower energies and was usually attributed to the Cronin effect [12]. It is interesting to note that the enhancement is about the same for all mesons, and it is on the level of 15 %, while for baryons it is much larger, on the level of 50 %. This observation is hard to reconcile with the explanation of the Cronin effect as appearing from soft multiple recapturing of partons in the initial state. At higher p_T -values ($p_T > 8$ GeV/c), the production of all hadrons is similarly suppressed by ~ 20 %, which could be attributed to modification of the parton distribution functions in heavy nuclei (shadowing effect). However, a quantitative description of this effect for light and heavy ion collisions is still missing.

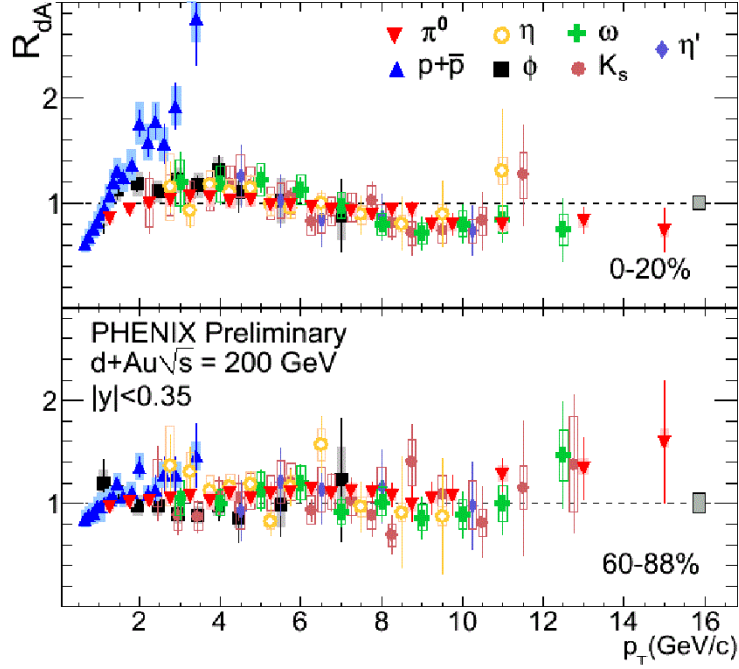


Fig. 2. Nuclear modification factors R_{dAu} for light hadrons in central (top) and peripheral (bottom) $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV

4. Heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV

Suppression of hadron production in Au + Au collisions at high p_T -values at RHIC and its absence for direct photons in heavy ion collisions and hadrons in $d + Au$ collisions provided the first evidence for formation of extremely dense medium in heavy ion collisions at RHIC [2]. Several models with very different physical assumptions describe the magnitude of the observed suppression, but predict slightly different evolution of R_{AA} with p_T [13–17]. Therefore, a precise measurement of R_{AA} at high p_T -values can be used to discriminate theoretical models and to put tighter constraints on the model free parameters.

The left panel of Fig. 3 presents nuclear modification factors measured for π^0 and η mesons in the minimum bias Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV [18]. The results obtained for π^0 and η mesons are consistent within uncertainties. Suppression of hadron production is now confirmed up to 20 GeV/c. A linear fit to R_{AA} for π^0 mesons at $p_T > 5$ GeV/c results in a slope consistent with zero, as shown in the right panel of Fig. 3. The slopes obtained from R_{AA} for η mesons are consistent with zero with the largest deviation less than two standard deviations for the most central collisions. While the results indicate that R_{AA} for η is consistent with a constant value, a slow rise of R_{AA} with the momentum increasing cannot be ruled out.

The centrality dependence of R_{AA} on p_T provides a means for studying the path-length dependence of the partonic energy loss. However, a better way to test the path-length dependence is to vary the particle emission angle at a fixed centrality. Figure 4 shows the dependence of R_{AA} measured for π^0 on the centrality expressed in terms of the number of participants (N_{part}) [19]. Each panel in this figure corresponds to a particular p_T bin. Three sets of points in each panel correspond to different emission angles with respect to the reaction plane. New measurements extend previous results up to 10 GeV/c, to the region where hard scattering is the main process for the particle production. For $N_{part} > 100$, the out-of-plane R_{AA} is nearly independent of the centrality, while the in-plane R_{AA} rapidly decreases with the centrality increasing. The parton path length in the medium in the direction normal to the reaction plane only weakly depends on the centrality resulting in nearly constant R_{AA} for π^0 -mesons. A shorter path length of the parent parton in the reaction plane results in smaller suppression of π^0 production. In the most central collisions where

the nuclear overlap region is nearly symmetric, the parton path length in the medium is about the same in all directions, and the in-plane values of R_{AA} start to match the out-of-plane R_{AA} -values.

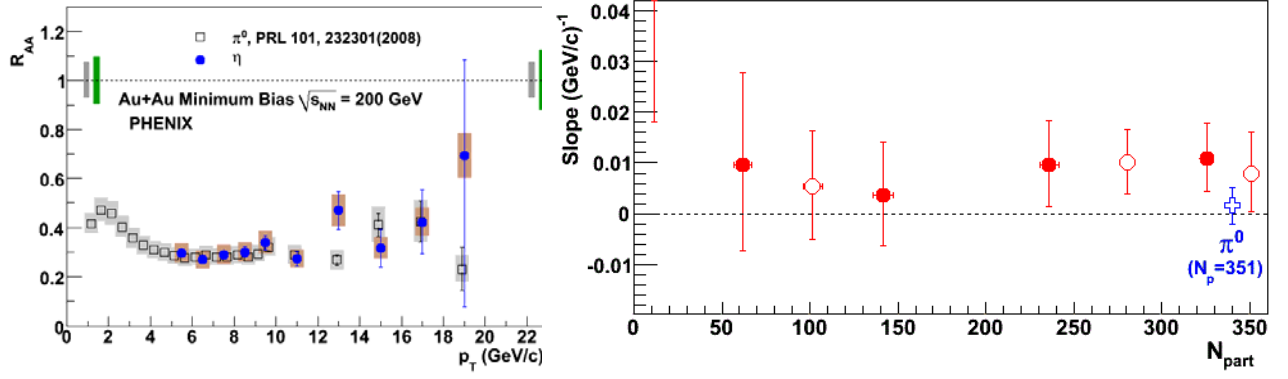


Fig. 3. Nuclear modification factors R_{AA} measured for π^0 and η in minimum bias Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV (left). Slopes from linear fits to R_{AA} measured for π^0 and η mesons at $p_T > 5$ GeV/c (right)

The azimuthal distribution of the produced particles can be described by a Fourier expansion, where the angular distribution up to the second order is $dN/d\Delta\phi \sim 1 + 2v_2 \cdot \cos 2\Delta\phi$, where v_2 is the elliptic flow coefficient. New v_2 measurements for π^0 and η mesons are shown in Fig. 5. The value of v_2 rapidly increases at low p_T -values, reaches a maximum at 2–3 GeV/c and then starts to decrease. At $p_T > 5$ GeV/c, the momentum dependence of v_2 is weak, although the uncertainties are rather large. Results for π^0 and η mesons are consistent, indicating no mass dependence of v_2 at high p_T . Non-zero value of v_2 at high p_T and similarity of v_2 values for π^0 and η are consistent with the parton energy loss dependence on the path length in the medium and fragmentation of partons in vacuum.

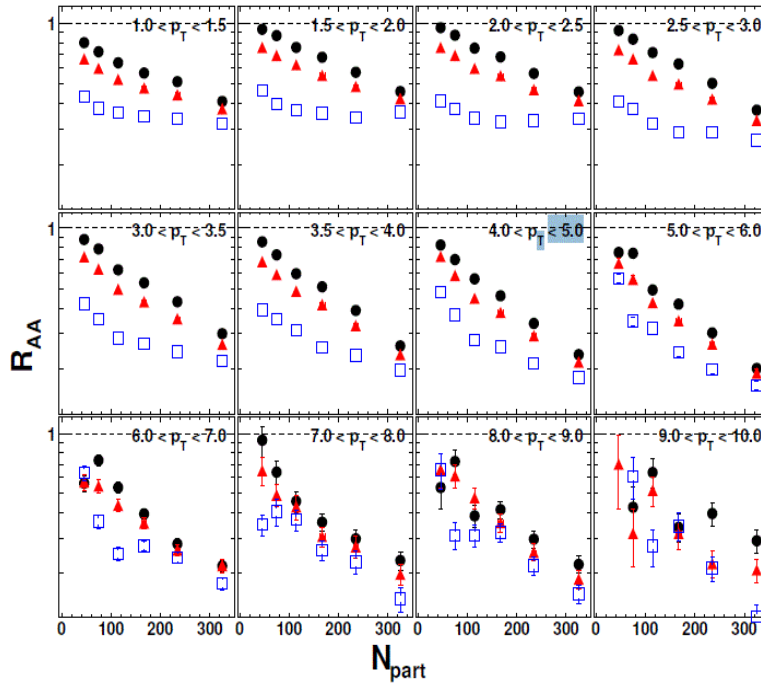


Fig. 4. Dependence of R_{AA} measured for π^0 on the centrality. Three sets of points in each panel correspond to different π^0 emission angles with respect to the reaction plane

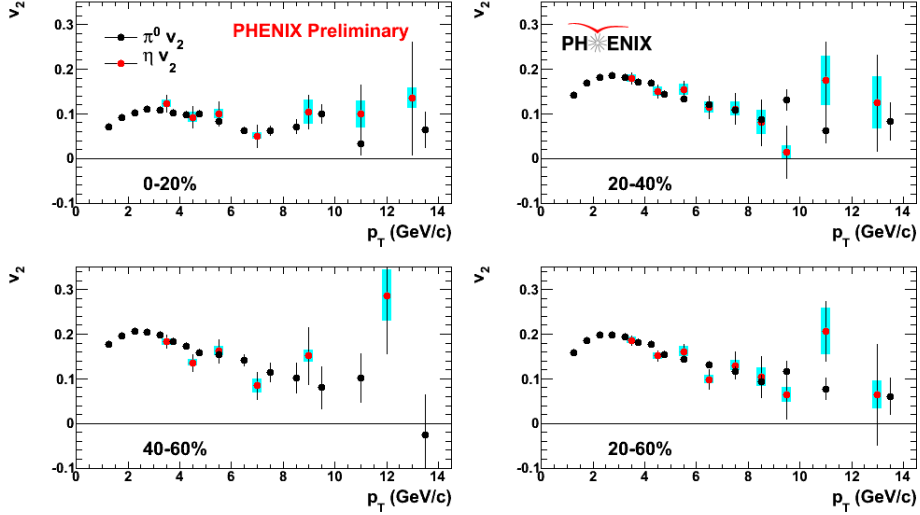


Fig. 5. Elliptic flow for π^0 and η mesons in Au + Au collisions at different centralities

The intermediate p_T region in heavy ion collisions is usually defined in a range of transverse momenta from 2 to 5 GeV/c. In $p + p$ collisions, the hadron production in this p_T range is well described by pQCD calculations [6]. However, in heavy ion collisions the situation is somewhat different. Figure 6 presents nuclear modification factors measured for different hadrons in the most central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. At $p_T > 5-6$ GeV/c, production of all hadrons and electrons from semileptonic decays of heavy flavor [20] is similarly suppressed by a factor of 4 to 5. Such behaviour is consistent with the parton energy loss in the dense medium and subsequent fragmentation in vacuum. However, at intermediate p_T -values the production of baryons is enhanced [10]. Although only a half of the sum of protons and antiprotons is shown in the figure, this behaviour takes place for other baryons also, including the strange sector [21, 22]. The production of K_s^0 and ϕ mesons is less suppressed than that of π^0 - and η -mesons. Such a difference cannot be explained by the Cronin effect and requires introduction of additional effects and particle production mechanisms to fragmentation of hard scattered partons. For the explanation of this difference, some recombination and radial flow models are usually involved [2]. However, none of the models could explain the whole set of results available in this kinematical region.

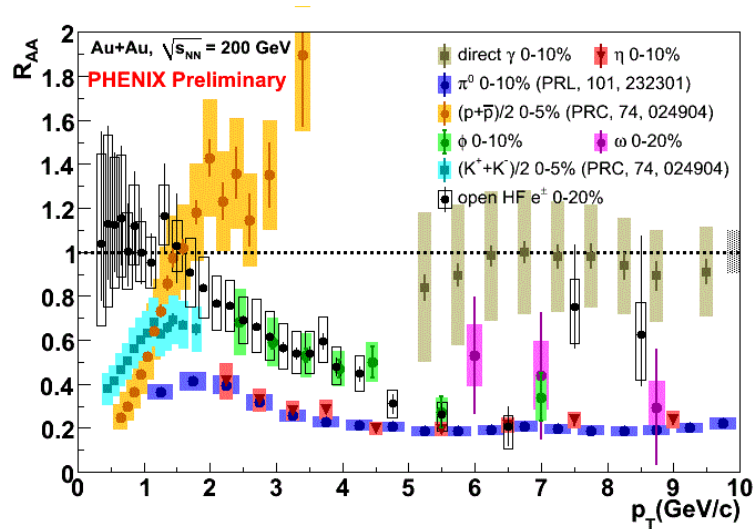


Fig. 6. Nuclear modification factors R_{AA} for different particles in the most central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV

5. Energy scan program

The main goal of the RHIC energy scan program is a detailed study of the QCD phase diagram and a search for the critical point. Low energy runs at RHIC are characterized by relatively low integrated luminosities, thus limiting the number of observables available for an experimental study.

For a systematic study of jet quenching, nuclear modification factors for π^0 mesons were measured in Cu + Cu and Au + Au collisions at different energies: $\sqrt{s_{NN}} = 22, 39, 62$ and 200 GeV [23]. Such flexibility in collision systems and energies allows to control the size of the interaction region and the amount of energy pumped in this region. Figure 7 presents a summary of all nuclear modification factor measurements for neutral pions. It shows the integrated nuclear modification factors as a function of the total energy stored in the system, which depends both on the number of participating nucleons and on the interaction energy. Different colours in Fig. 7 correspond to different collision energies, boxes and circles correspond to Au + Au and Cu + Cu collision systems, respectively. In Au + Au interactions, the production of π^0 mesons is suppressed in central collisions at all energies. The factors measured at $\sqrt{s_{NN}} = 62$ and 200 GeV are very similar in absolute values at $p_T > 6$ GeV/c. In central Cu + Cu collisions, the production of π^0 -mesons is suppressed at $\sqrt{s_{NN}} = 62$ and 200 GeV, while at the energy of $\sqrt{s_{NN}} = 22$ GeV the opposite effect is observed [24]. The production of π^0 -mesons at this energy is enhanced, which is usually associated with the Cronin effect. In Fig. 7 one can see that all measured factors tend to follow the same universal dependence. The green line in the plot corresponds to the maximum energy achieved in Pb + Pb collisions at the SPS. The plot qualitatively explains why suppression of high- p_T hadrons was not observed at the SPS before RHIC.

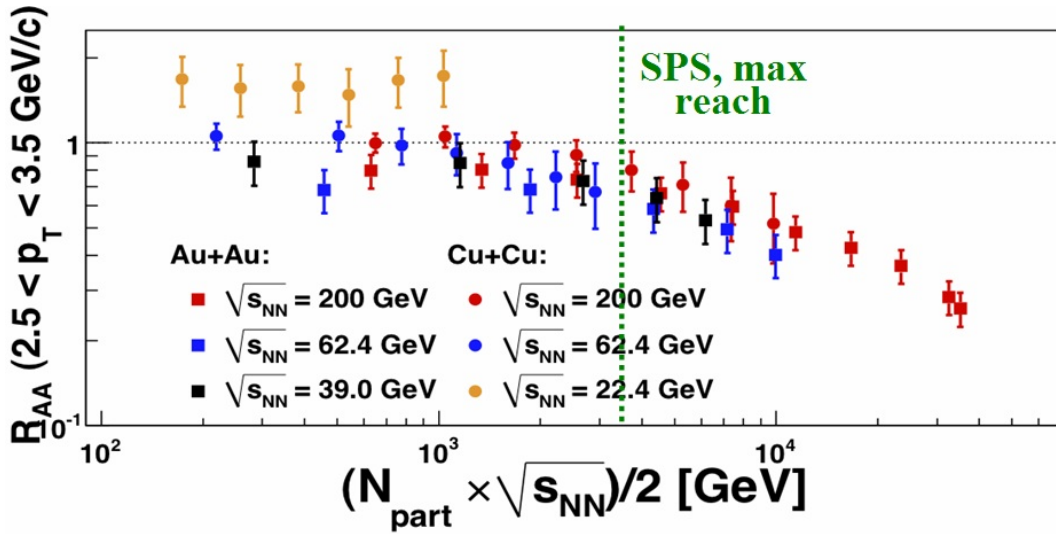


Fig. 7. Integrated nuclear modification factors for π^0 -mesons as a function of total energy stored in the system. Different colours correspond to different collision energies, boxes and circles correspond to Au + Au and Cu + Cu collision systems, respectively

Observation of a large azimuthal anisotropy for the particles produced at RHIC became one of the key evidences for creation of dense partonic medium in heavy ion collisions [2]. At sufficiently strong interactions between quanta of the medium, the interaction region can experience local thermalization and hydrodynamic flow. In this case, an initial spatial anisotropy of the nuclear overlap region transforms in the momentum anisotropy of the produced particles.

Different orders of the flow v_2 , v_3 , and v_4 were measured for unidentified charged hadrons as a function of the transverse momentum in Au + Au collisions at $\sqrt{s_{NN}} = 39, 62,$ and 200 GeV. Within the uncertainties, the flows of the same order perfectly match with each other at these interaction energies. What is even more striking is that the quark number scaling, first observed for identified hadrons in Au + Au collisions at

$\sqrt{s_{NN}} = 200$ GeV, is also preserved at lower collision energies of $\sqrt{s_{NN}} = 39$ and 62 GeV. The quark number scaling is usually explained by assuming that the flow is generated at the partonic level, indicating that the produced medium is characterized not only by high temperatures and high densities but also by partonic degrees of freedom. Preservation of the quark number scaling suggests that the quark-like degrees of freedom are still important at interaction energies as low as $\sqrt{s_{NN}} = 39$ GeV.

Figure 8 shows the flows of different order in dependence on the interaction energy. The left plot shows the elliptic flow for unidentified charged hadrons measured in a range of energies from units of GeV to 2700 GeV at the Large Hadron Collider. The measurements were performed for two values of the transverse momentum – 0.7 and 1.7 GeV/c. The elliptic flow is almost independent of the interaction energy at $\sqrt{s_{NN}} > 39$ GeV. At lower energies, the elliptic flow rapidly decreases suggesting a change in the basic properties of the produced medium. The plot on the right shows the integrated flows v_2 , v_3 and v_4 in dependence on the interaction energy. One can see that like in the previous case, the flows of higher order also do not depend on the interaction energy at $\sqrt{s_{NN}} > 39$ GeV. These results suggest similarity in the geometry of fluctuations in the nuclear overlap region, and in the properties and evolution of the produced medium at different collision energies of heavy nuclei.

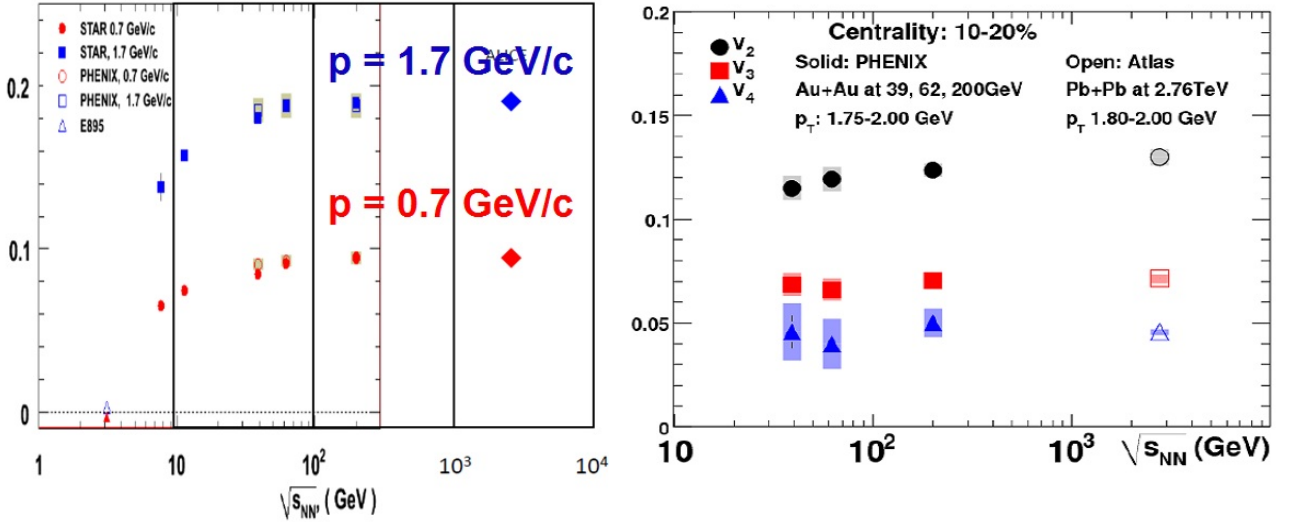


Fig. 8. The elliptic flow for unidentified charged hadrons measured in a range of energies from units of GeV to 2700 GeV at the Large Hadron Collider (left). The integrated flows v_2 , v_3 and v_4 in dependence on the interaction energy (right)

6. Conclusion

Last five years, the PHENIX Collaboration produced a wealth of new physical results. Only a few of them related to production of light hadrons were covered in this paper. New measurements of $R_{AA}(p_T, \varphi)$ and $v_2(p_T)$ at high p_T -values are qualitatively consistent with the parton energy loss scenario. Measurements of $R_{AA}(p_T)$ and the p/π production ratio at intermediate momenta are not consistent with hard scattering as the dominating particle production mechanism and require introduction of additional effects, such as the radial flow, recombination, *etc.* New detailed measurements of v_2 , v_3 and v_4 allow to test the scaling properties and help to get more accurate estimations for the viscosity to entropy ratio η/s .

Low energy scan results indicate that the jet quenching, development of the flow at partonic level, and strong interaction between the medium quanta are observed not only at full RHIC energy but also at lower collision energies of nuclei at $\sqrt{s_{NN}} > 39$ GeV. Future low energy program at RHIC will be devoted mostly to a study of lower nuclear interaction energies.

Full understanding and quantitative description of the complicated picture of heavy ion interactions are yet to be achieved.

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