

Recent PHENIX results on hard probes and direct photon production

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Abstract. A hot and dense matter called strongly interacting quark-gluon plasma (sQGP) is created in heavy ion collisions at RHIC energies. Detailed study of the properties of this new state of matter is a driving force of recent research at RHIC. In these proceedings we present most recent PHENIX results for system size and energy dependence of hadron and jet production at high transverse momentum in heavy ion collisions at RHIC. We also report latest results for direct photon production including soft direct photon yields and anisotropic flow.

1. Introduction

The main purpose of recent researches at RHIC is a detailed study of the properties of strongly interacting quark-gluon plasma (sQGP). Such a new state of matter is believed to be produced in central heavy ion collisions [1]. Properties of sQGP are studied by measuring yields and angular distributions of various particles produced in the final state. The main difficulty in this research is that measured particles are produced at different stages of the interaction and their properties relevant to sQGP stage can be smeared by later hadronic interactions. Reliable information about properties of sQGP could be gained by measuring as many signatures of sQGP as possible in dependence on size of the interacting system and collision energy.

In this proceeding we present the most recent PHENIX results for two very informative observables which are hadrons and jets at high transverse momentum (p_T) as well as soft direct photons. Hard scattered partons lose energy via rescattering and radiation traversing the medium produced in heavy ion collisions resulting in jet quenching. Thus measurement of high p_T hadron and jet production is a way to probe opacity and density of the produced medium. The electromagnetic probes such as direct photons are not affected by strong nuclear forces. Thus they are extremely valuable in constraining the time evolution of the medium.

2. Hadron production at high and intermediate transverse momentum

Production of identified hadrons and jets has been measured in p+p and heavy ion collisions. Potential collective effects in nuclear collisions are numerically studied with nuclear modification factor R_{AA} , which is a ratio of the yields measured for the same observable in A+A and p+p collisions scaled by the corresponding number of binary inelastic nucleon-nucleon collisions (N_{coll}), which is estimated using Glauber model [2].

Figure 1 shows nuclear modification factors (R_{dAu}) measured for reconstructed jets in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [3]. Plot on the figure 1a corresponds to minimum bias collisions while



plot on the figure 1b shows centrality dependence of R_{dAu} . In minimum bias collisions R_{dAu} is consistent with unity within uncertainties in the entire measurement range thus providing strong constraints on the initial state effects over a wide kinematic range. Results in minimum bias collisions are consistent with calculations that account for modification of parton distribution functions in nuclei with EPS09 parameterization [4]. Models that introduce energy loss agree with data better when assume smaller momentum transfers [5]. Figure 1b shows strong centrality dependence of R_{dAu} for inclusive jets. Observed centrality dependence presents a challenge for theoretical models, one of possible explanations is proton colour fluctuations [6]. Presented measurements in d+Au and future measurements in other collision systems like p+Au, $^3\text{He}+\text{Au}$ will help to test various theoretical models for centrality dependence of jet modification in small collision systems.

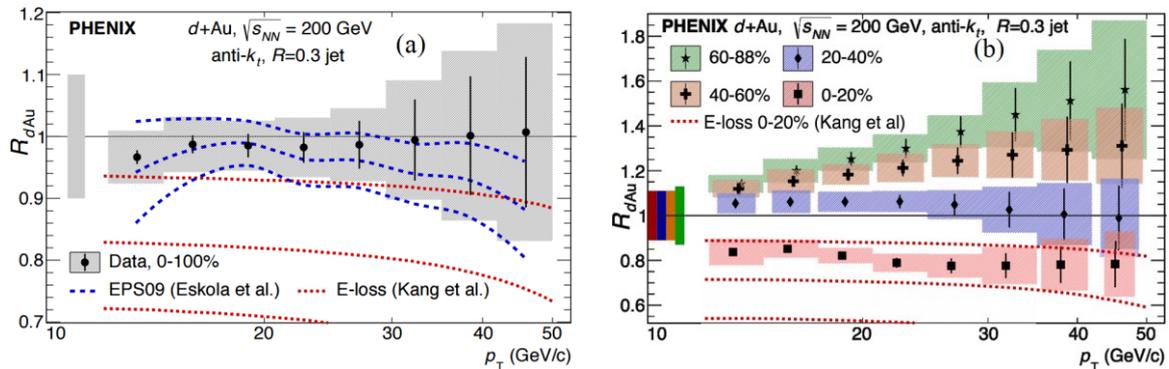


Figure 1. Nuclear modification factors measured for jets in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Figure 1a corresponds to minimum bias collisions; results are presented in comparison with theoretical model calculations. Figure 1b shows centrality dependence of the nuclear modification factor.

Figure 2 shows preliminary PHENIX results for nuclear modification factors (R_{AA}) measured for reconstructed jets in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. In most peripheral collisions R_{AA} is somewhat larger than unity but is consistent with it at high transverse momentum. The R_{AA} decreases with increasing centrality and in most central collisions production of jets is suppressed by about a factor of two. Suppression does not show any significant dependence on p_T at all centralities.

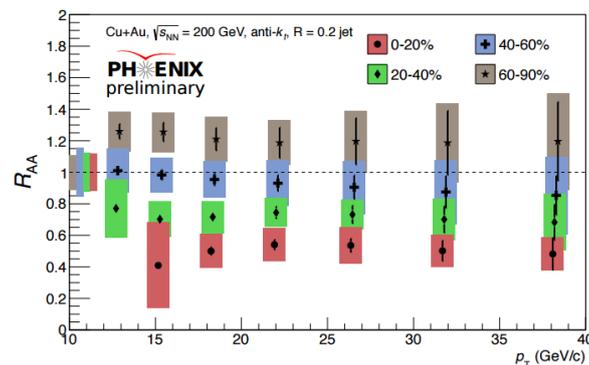


Figure 2. Centrality dependence of nuclear modification factor measured for reconstructed jets in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

Another important result is collision energy dependence of jet quenching. Nuclear modification factors were measured for π^0 's in Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 22-200$ GeV [7, 8]. Additional information comes from charged hadron measurements at the LHC in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [9]. These measurements show suppression of hadron production at collision energy

$\sqrt{s_{NN}} > 39$ GeV. Measurements at $\sqrt{s_{NN}} = 22$ GeV show no suppression consistent with previous measurements at the SPS where suppression was not observed also. Measurements also showed very similar suppression at high p_T of neutral pions in Au+Au collisions at $\sqrt{s_{NN}} = 39$ -200 GeV; similar suppression of neutral pions in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and charged hadrons in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Similarity of the nuclear modification factors measured in heavy ion collisions at different energies means that this parameter is biased by the shapes of particle production spectra. Instead one can look at fractional momentum loss [1,10]. Figure 3 shows dependence of fractional momentum loss on charged particle multiplicity as a measure of energy density. Regardless of similarity of nuclear modification factors the fractional momentum losses are quite different. Momentum losses increase by $\sim 50\%$ from central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV to most central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and by about a factor of six from 62 GeV to 2.76 TeV. Momentum losses monotonously increase with multiplicity and all measured points merge to one universal curve at high values of particle multiplicity independent of collision energy. One can also see that the same energy points corresponding to different nuclei follow the same scaling.

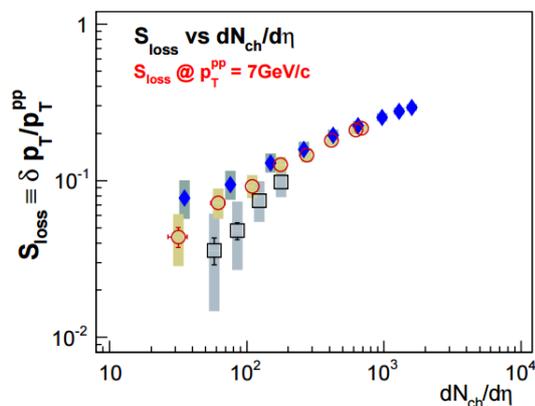


Figure 3. Fractional momentum loss in different collision systems as a function of charged particle multiplicity.

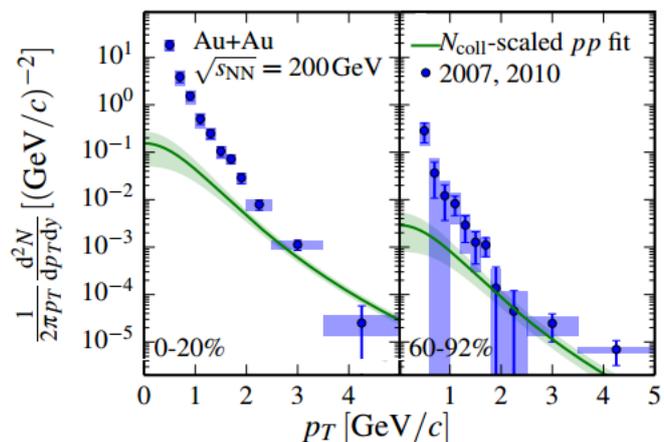


Figure 4. Direct photon p_T spectra in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Green curves correspond to N_{coll} scaled $p+p$.

3. Direct photons

Recently PHENIX measured centrality dependence of direct photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [11]. In figure 4 results are compared to yields measured in $p+p$ collisions at the same energy of $\sqrt{s} = 200$ GeV and scaled by N_{coll} . Direct photon yields in Au+Au collisions significantly exceed scaled $p+p$ yields at all centralities. Fits of excess yields to exponential function return slope parameters equal to ~ 240 MeV with no centrality dependence within uncertainties. At the same time photon yields depend on centrality and scale with number of participating nucleons (N_{part}) as N_{part}^α , where $\alpha = 1.48 \pm 0.08$ (stat.) ± 0.04 (syst.).

Important result is a measurement of direct photon anisotropy at low transverse momentum [12]. Figure 5 show dependence of elliptic (v_2) and triangular (v_3) flow on transverse momentum measured in different centrality bins. Flow was measured using two different methods; results shown with black and green markers agree well in the overlap region. Values of v_2 and v_3 are very similar to that previously measured for light hadrons. Similar to hadrons v_3 shows very weak dependence on collision centrality.

4. Conclusion

New measurements of jets and soft direct photons confirm previous findings and present a challenge for theoretical models. Theoretical models need to assume very early emission of direct photons from

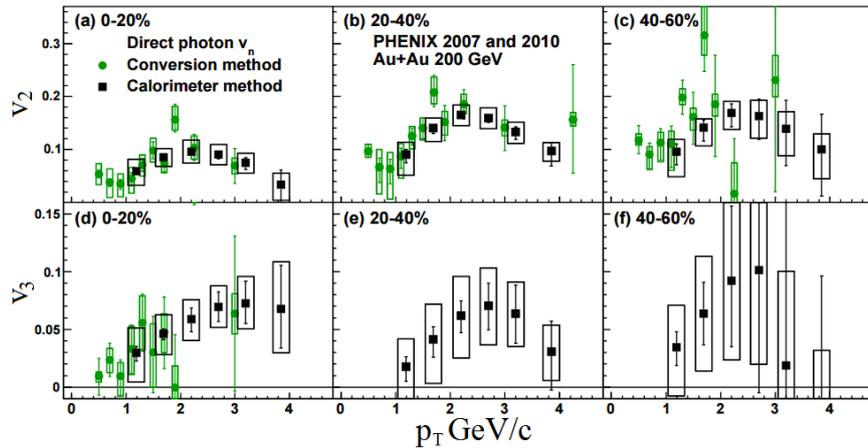


Figure 5. Elliptic and triangular flow for soft direct photons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Black and green markers to correspond to different measurement techniques.

the interacting system describe large excessive yields of direct photons. Large values of flow coefficients point to late emission of direct photons when temperature is lower but collective flow has time to develop. These two observations are difficult to reconcile within the same models and there is still no satisfactory description yet available.

Acknowledgments

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