Measurement of high-$p_T$ hadrons at RHIC-PHENIX

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Measurements from the RHIC experiments show a strong suppression in the yield of high-$p_T$ single hadrons and a clear reduction in strength of the di-jet signal in two-hadron azimuthal-angle correlation functions in central Au+Au collisions at RHIC. These measurements should provide direct information on the properties of the medium within which hard-scattered partons propagate. The PHENIX preliminary results on single high-$p_T$ hadron production and on particle azimuthal correlations are shown. The properties of the medium created in relativistic heavy ion collisions are discussed based on the results.

1 Introduction

The PHENIX experiment has been carried out at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory to find evidence of a phase transition from normal nuclear matter to a Quark-Gluon Plasma (QGP), a new phase of matter consisting of de-confined quarks and gluons, and is expected to be formed at very high energy densities above $\epsilon_c \approx 1$ GeV/fm$^3$.

One of the most exciting results to date at RHIC is that the yield of $\pi^0$ at high transverse momentum ($p_T$) in central $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions is suppressed compared to the yield in p+p collisions scaled by $N_{coll}$, the number of underlying nucleon-nucleon collisions. The suppression is a final state effect since it is absent in d+Au collisions. The direct photon yield is not suppressed in Au+Au collisions, meaning that the initial hard scattering yield in Au+Au is well reproduced as the $N_{coll}$ scaled yield in p+p. The observed hadron suppression is interpreted as a consequence of the energy loss of hard scattered partons traversing the hot and dense matter produced in central Au+Au collisions. This effect, known as jet quenching, is a possible signature for the creation of QGP.
2 Measurement of high-\( p_T \) hadrons

Identified hadrons that can be measured in PHENIX up to the highest \( p_T \) are \( \pi^0 \) and \( \eta \) via their \( 2\gamma \) decay mode.

2.1 Nuclear modification factor

The amount of nuclear modification in dense matter can be quantified by the nuclear modification factor (\( R_{AA} \)), which is the ratio of the measured yield to the expected yield from the scaled p+p yields, and is defined as follows:

\[
R_{AA}(p_T) = \frac{d^2N_{AA}/dp_Td\eta}{T_{AA}(b)d^2\sigma_{NN}/dp_Td\eta},
\]

where the numerator is the invariant \( \pi^0 \) yield in unit rapidity and the denominator is the expected yield in p+p collision scaled by the number of underlying nucleon-nucleon collisions, which in turn is defined with the nuclear thickness function \( T_{AA}(b) \) multiplied by the total cross section \( \sigma_{NN} \) with the impact parameter \( b \) representing collision centrality. If a hard-scattered parton goes through the bulk matter without any nuclear effects, the \( R_{AA} \) is unity.

![Graph](image)

Figure 1: Nuclear modification factor, \( R_{AA} \) of \( \pi^0 \) (triangles), \( \eta \) (circles), and direct photon (squares). In addition to the statistical and \( p_T \)-uncorrelated errors, point-to-point varying systematic errors are shown on the data points as boxes. An overall systematic error of \( T_{AA} \) normalization is shown at 1.

Figure 1 shows the preliminary Run-4 data of \( \pi^0 \) \( R_{AA} \) as a function of \( p_T \) along with final Run-2 results on \( \eta \) and direct photon \( R_{AA} \) in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV, as well as a theoretical prediction which employs the GLV model. As a result, a strong \( \pi^0 \) suppression by a factor of \( \sim 5 \) is observed, this suppression stays almost constant up to 20 GeV/c. The suppression pattern of \( \eta \) is similar to that of \( \pi^0 \), and this fact supports that the suppression occurs at partonic level. The GLV model describes the strong suppression well and it indicates the existence of bulk matter where the initial gluon density \( (dN^g/dy) \) is more than 1100, which corresponds to an energy density of approximately 15 GeV/fm\(^3\) in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV.
2.2 System-size dependence of jet quenching effect

The PHENIX Run-5 Cu+Cu data may give us some insight into the relationship between jet quenching effects and the properties of the medium through the systematic study of high-pT suppression in systems of different size. Figure 2 shows the comparison of \( R_{AA} \) in Au+Au collisions to that in Cu+Cu collisions. As shown on the right panel of Fig. 2, \( R_{AA} \) in Au+Au collisions is very similar to that in Cu+Cu collisions for similar number of participants. Also, the integrated \( R_{AA} \) as a function of the number of participants (\( N_{\text{part}} \)) in Au+Au collisions is very similar to that in Cu+Cu collisions as shown in the left panel of Fig. 2. \( R_{AA} \) in the Au+Au and Cu+Cu systems are very similar and follow the scaling with \( \ln R_{AA} \propto N_{\text{part}}^{2/3} \), which is proposed based on a model where energy loss depends on the path-length of hard scattered partons going through the 1+1D expanding medium.

![Figure 2: Left: Integrated \( R_{AA} \) as a function of the number of participant. Right: Comparison of \( R_{AA} \) between Au+Au and Cu+Cu at the similar number of participant (\( N_{\text{part}} \sim 74 \)).](image)

3 Jet modification

Two particle correlation is a powerful tool for understanding jets in heavy ion collisions. Measurements of two-hadron azimuthal angular correlation functions at the RHIC-STAR experiment show a clear reduction in strength of the di-jet signal in central Au+Au collisions. Furthermore, the recent PHENIX result shows a “dip” type away side jet shape. Figure 4 shows a correlation function for charged hadrons with a trigger particle in the intermediate \( p_T \) range (2.5 < \( p_T < 4.0 \) GeV/c) and the associated particle with 2.0 < \( p_T < 3.0 \) GeV/c. The elliptic flow contributions are estimated based on the measured elliptic flow and subtracted. While a clear structure of a near and away side jet peaks can be seen in peripheral collisions, the away side peak becomes broader and develops a “dip” around \( \delta \phi = \pi \). Since the hard scattered partons may propagate through the medium radiating gluons and interacting with the created medium until they fragment into jet clusters, the double peak structure in central collisions suggests a jet modification induced by interaction between the scattered partons and the medium. There are several theoretical models to explain this “dip” type away side peak. In some of the models, partons with velocities larger than the speed of sound in a QGP produce shock waves propagating in a Mach cone, or produce gluon radiation in a Cherenkov cone, with respect to parton’s momentum. The theoretical models for jet suppression via gluon radiation...
predict an accompanying jet broadening.

![Figure 3: Correlation Function for central, mid-central and peripheral events after subtraction of the flow contribution.](image)

4 Summary

The PHENIX preliminary results on identified single high-p_T hadron production in Au+Au and Cu+Cu collisions and on particle azimuthal correlations are shown.

According to the GLV calculation, the suppression factor of neutral pion supports the existence of bulk matter where initial gluon density (dN_g/dy) is more than 1100 in Au+Au collisions at √s_{NN} = 200 GeV. If collisions with similar number of participants are compared, there is little if any dependence of R_AA on system-size.

A clear “dip” type away side jet shape is observed with a trigger particle in the intermediate pT range. It suggests the modification of jets in dense matter.

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