QCD studies at RHIC in polarized pp, dAu and AuAu collisions

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Abstract.
The Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) is a unique facility which allows to study the collision of different nuclei and polarized protons at variable energy.

The spin physics program at RHIC at BNL focuses on the collision of polarized protons at a center-of-mass energy of $200-500\,\text{GeV}$ to gain a deeper understanding of the spin structure of the proton in a new, previously unexplored territory. Several polarized fixed-target experiments have been conducted in the past to gain a deeper understanding of the spin structure of the proton. Those experimental efforts have been restricted to large values of Bjorken x. The role of the gluons to make up for the missing proton spin is currently only very poorly constrained from scaling violations in fixed target experiments. The need for a new generation of experiments to explore the spin structure of the proton is clearly apparent. The first polarized proton run in 2002 is the beginning of a multi-year experimental program which aims to address a variety of topics related to the nature of the protons spin such as the gluon contribution to the proton spin, the flavor decomposition of the quark and anti-quark polarization and the transverse spin dynamics of the proton.

Recent results at RHIC show that the collision of relativistic nuclei at a center-of-mass energy of $200\,\text{GeV}$ per nucleon pair, can be interpreted as hard scatterings among quarks and gluons that make up the incoming nuclei. The collision of p+p and d+Au show a clear back-to-back topology of two jets as expected from the underlying hard scattering. In head-on Au-Au collisions on the contrary, the formation of the ‘away-side’ jet is strongly suppressed. One possible explanation of the missing jet is that a quark traveling through a medium of free quarks and gluons, commonly known as the Quark-Gluon Plasma, would interact strongly and thus loose energy. This phenomena is called jet quenching and was predicted as a potential signature for the formation of the Quark-Gluon Plasma.

Recent results on the spin and relativistic heavy-ion program at RHIC will be discussed.

INTRODUCTION TO RHIC SPIN PROGRAM

The first polarized proton run from December 2001 until January 2002 (RUN 2) at RHIC at BNL is the beginning of a multi-year experimental program which aims to address a variety of topics related to the nature of the proton spin such as: 1. spin structure of the proton (gluon contribution of the proton spin, flavor decomposition of the quark and anti-quark polarization and transversity distributions of the proton), 2. spin dependence of fundamental interactions, 3. spin dependence of fragmentation and 4. spin dependence of elastic polarized proton collisions. A recent review and status of the RHIC spin program can be found in [1].

The principle approach to study spin effects is to measure an asymmetry (A) which quantifies the normalized difference of measured yields for different initial-state spin configurations. Ultimately, any combination of beam polarization, i.e. either longitudinal (L) or transverse (T), will be possible at RHIC to access different aspects of the proton spin structure. A crucial fact to remember is that the statistical significance of double spin asymmetries varies as $P^4 \int Ldt$ whereas for single spin asymmetries it varies as $P^2 \int Ldt$. Thus, the demand on high polarization is particularly important for the measurement of double spin asymmetries. A focus of the first polarized proton run was the measurement of a transverse single-spin asymmetry, A_N. Non-zero values for A_N have been observed at the FNAL E704 [2] experiment for $\vec{p}+p \rightarrow \pi + X$ at $\sqrt{s} = 20\,\text{GeV}$ and $0.5 < p_T < 2.0\,\text{GeV}$. Theoretical models that explain the E704 data also predict non-zero values for A_N for pion production at RHIC. Qiu and Sterman [3] attribute the measured asymmetry to a higher-twist pQCD effect. The group of Anselmino and Leader perform a global analysis of semi-inclusive DIS data from HERMES [4] and E704 data. This approach involves transverse $k_\perp$ effects in the quark distribution functions ('Sivers effect') [5] as well as in the fragmentation functions ('Collins effect') [6] to account as possible explanations for the measured asymmetries. Besides the theoretical interest in measuring A_N, it will serve as a potential candidate to monitor the RHIC beam polarization at a particular experiment ('local polarimeter').

THE POLARIZED PROTON COLLIDER RHIC

The first collisions of polarized protons occurred in December 2001, ushering in a a new era to complement the ongoing relativistic heavy-ion program. RHIC is the first accelerator to accelerate and collide polarized protons, ultimately at high luminosity, at a center-of-mass energy of up to 500 GeV.

The key to maintain the proton polarization through acceleration despite its large anomalous magnetic momentum, is to perform a rotation of the proton spin by 180° in the horizontal plane around a particular axis. This manipulation is performed by helical dipole magnets, known as 'Siberian snakes', which have been used for the first time at a proton collider. With two Siberian snakes installed in each ring, cumulative tilt effects of the proton spin are canceled, thereby eliminating the influence of depolarizing spin resonances. Besides the installation of Siberian snakes, the PHENIX and STAR experiments are equipped with spin rotator magnets to allow for the precession from transverse to longitudinal polarization and thus to collide longitudinal polarized proton beams. These magnets have been successfully commissioned during the RHIC run in 2003 (RUN 3) and allowed the first collisions of longitudinally polarized protons at $\sqrt{s} = 200\,\text{GeV}$.

The first polarized proton run at RHIC (RUN 2) was carried out at a center-of-mass energy of 200 GeV. Each ring was loaded with 55 bunches of alternating polarization resulting in a a bunch crossing-time of 214 ns. A transverse polarization of about 20% was achieved at the injection energy of 24.6 GeV and was approximately maintained when the proton beams were accelerated to 100 GeV.

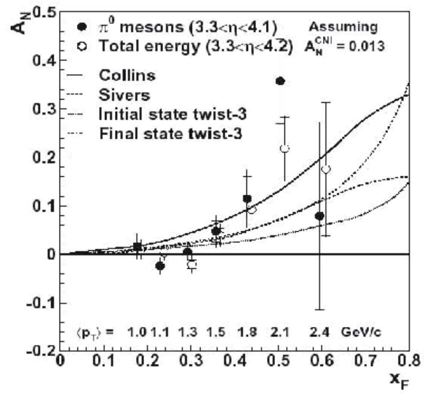

FIGURE 1. *Measurement of the transverse single-spin asymmetry of forward π^0 production, A_N, as a function of x_F by the STAR collaboration for $1.1 < p_T < 2.5$ GeV/c in comparison to pQCD model predictions evaluated at $p_T = 1.5$ GeV/c [7].*

FIRST POLARIZED PP RESULTS FROM STAR

The STAR collaboration has measured during the first polarized proton run (RUN 2) the transverse single-spin asymmetry, A_N, for forward π^0 production at $x_F \simeq 0.2-0.6$ and $p_T \simeq 1-3\,\text{GeV}$ [7]. A_N is extracted from :

$$A_N = \frac{1}{P}\frac{N^{\uparrow} - R\cdot N^{\downarrow}}{N^{\uparrow} + R\cdot N^{\downarrow}} \tag{1}$$

which requires three independent measurements: 1. the spin-dependent yields ($N^{\uparrow(\downarrow)}$) of forward π^0 production, 2. the relative luminosity $R = L^{\uparrow}/L^{\downarrow}$ and 3. the actual beam polarization P. The latter is the focus of a dedicated effort at RHIC to obtain a fast (relative) polarization measurement using pC elastic scattering at very small $|t|$ values. This Coulomb Nuclear Interference (CNI) polarimeter [8] will ultimately be calibrated to pp elastic scattering for a polarized hydrogen gas-jet target [9]. An upgrade program at the STAR experiment was performed with the installation of a beam-beam counter (BBC) [10] and a prototype forward-pion detector (FPD) [7]. In addition, a spin scaler system was commissioned to account for the beam polarization reversals every bunch crossing of 214 ns.

The STAR BBC consists of a hexagonal scintillator array structure at ± 3.5 m from the nominal interaction point with full azimuthal coverage. The BBC is the main device to make the relative luminosity measurement and to provide a trigger to distinguish pp collision events from beam related background events by means of timing requirements. The FPD prototype system which is installed at 7.5 m from the nominal interaction point facing the RHIC 'Yellow beam', consists of three lead-glass electromagnetic calorimeter modules together with a lead-scintillator calorimeter, which is a prototype module of the STAR endcap calorimeter. The latter device allows the reconstruction of π^0 mesons from their decay products ($\pi^0 \to \gamma\gamma$) by measuring the total energy and the transverse

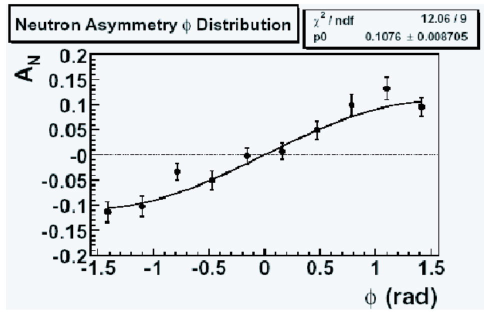

FIGURE 2. *Preliminary result of the measured neutron asymmetry as a function of the reconstructed azimuthal angle ϕ by the Local Polarimetry (PHENIX) collaboration using a Lead-Tungstate ($PbWO_4$) crystal electromagnetic calorimeter [13].*

shower profile. It consists of 12 independent towers, preshower detectors and a shower-maximum detector to perform a transverse shower profile measurement. This prototype module has been extensively studied using high energy electron test beams at SLAC. Its testbeam performance is well reproduced by a GEANT simulation.

Figure 1 shows the analyzing power, A_N, as a function of x_F measured by the STAR collaboration for $1.1 < p_T < 2.5$ GeV/c. The systematic uncertainty has been estimated to be $\delta A_N \sim 0.05$ which does not include the normalization uncertainty from the RHIC beam polarization measurement. The analyzing power of the CNI polarimeter at 100 GeV has not been measured yet and is assumed to be the same as the measured analyzing power at 24.6 GeV to determine the RHIC beam polarization [11, 12]. A_N is found to increase with x_F and is similar in magnitude to the measurement of A_N performed by the E704 experiment at $\sqrt{s} = 20$ GeV. These results are compared to pQCD model predications evaluated at $p_T = 1.5$ GeV/c involving different mechanism as discussed in the introduction, to account for the sizable observed transverse single-spin asymmetry A_N for forward neutral pion production.

FIRST POLARIZED PP RESULTS FROM PHENIX

The Local Polarimetry (PHENIX) collaboration installed as part of the PHENIX 'local polarimeter' development for neutral particle production a detector system located 1800 cm upstream and downstream of the RHIC IP12 collision point [13]. An electromagnetic calorimeter (EM-Cal) which consists of sixty (5×12 array) Lead-Tungstate ($PbWO_4$) crystals ($2.0 \times 2.0 \times 20.0\,\mathrm{cm}^3$) was installed on one side of the RHIC IP12 interaction region facing the RHIC 'blue beam'. The length of this 5×12 array corresponds to about 1 interaction length. Sets of scintillator counters before and after the Lead-Tungstate array were used to define trigger conditions for photon and neutron samples. Simulation studies yield a purity of 98% and 89% for photons and neutrons, respectively. The systematic uncertainty has been estimated to be about 16%. The hadron calorimeter (H-Cal) which is a sandwich tungsten/optical-fiber calorimeter is installed on the other side of the RHIC IP12 interaction region which faces the RHIC 'yellow beam'. Its total length of 23 cm corresponds to about 2 interaction lengths. A postshower counter which consists of five $PbWO_4$ crystals provides a horizontal position measurement. Both calorimeter modules have an angular coverage of approximately 3 mrad around zero degrees. A scintillator hodoscope has been setup around the RHIC IP12 interaction region to suppress beam related background events. Figure 2 shows the measured transverse single-spin asymmetry for forward neutron production, A_N, as a function of the reconstructed azimuthal angle which shows the expected $\sin\phi$-type azimuthal dependence. A fit to this dependence allows to extract the underlying transverse single-spin neutron asymmetry. A_N is found to be -0.112 ± 0.007 with $\chi^2/ndf = 1.7$. The average measured A_N value for positive x_F amounts to -0.109 ± 0.007 and -0.110 ± 0.015 for the EM-Cal and H-Cal polarimeters, respectively. Both results agree within statistical uncertainties.

The PHENIX collaboration has measured the invariant differential cross section for inclusive neutral pion production, in $p+p$ collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ at mid-rapidity ($|\eta| < 0.35|$) as a function of p_T [14]. This analysis is mainly based on the PHENIX beam-beam counters and the PHENIX electromagnetic calorimeters. The PHENIX beam-beam counters cover a pseudo-rapidity range of $3.0 < |\eta| < 3.9$ with full azimuthal coverage. It was used to define a minimum-bias trigger which required the collision vertex to be within 75 cm of the nominal interaction point. A more restrictive vertex requirement of 30 cm was applied during the offline data analysis. The PHENIX electromagnetic calorimeters consist of two subsystems: two lead-glass sectors and six lead-scintillator sectors. This system is located at a radial distance of 5 m and spans a pseudorapidity range of $|\eta| < 0.35$ and an azimuthal interval of $\sim 22.5^\circ$ per sector. It provides a fine $\eta - \phi$ segmentation of $\Delta\eta \times \Delta\phi \sim 0.01 \times 0.01$ which allows to reconstruct both decay photons up to at least 20 GeV/c in p_T of the neutral pion. A high-p_T trigger was used to enhance the sample of reconstructed high p_T neutral pions. This trigger is based on a threshold requirement of analog sums among 2×2 groupings of adjacent EMCal towers. The efficiency of this 2×2 high-p_T trigger was determined from the minimum-bias trigger sample as a function of p_T and was found to be flat in p_T for $p_T > 3\,\mathrm{GeV/c}$ at the level of 0.78 ± 0.03. The integrated luminosity was determined from the number of minimum-bias triggered events using an absolute calibration of the respective trigger cross section based on a 'van der Meer scan'. The uncertainty of the luminosity normalization was estimated to be 9.6%. The minimum-bias trigger sample of 16 million triggered events corresponds to an integrated luminosity of $0.7\,\mathrm{nb}^{-1}$ whereas the 2×2 high-p_T sample of 18 million triggered events refers to an an integrated luminosity of $39\,\mathrm{nb}^{-1}$. The measured invariant differential cross section for inclusive neutral pion production for the minimum-bias triggered sample and the 2×2 high-p_T sample agree within statistical uncertainties in the range of overlap in p_T. The result of this analysis is shown in Figure 3. The measured differential cross section covers a p_T range of $\sim 1 - 14\,\mathrm{GeV}$. Those results are compared to NLO pQCD calculations using the CTEQ6M [15] set of parton distribution functions and two sets of fragmentation functions, 'Kniehl-Kramer-Pötter' (KKP) [16] and 'Kretzer' [17], which mainly differ in the gluon-pion fragmentation function, D_g^π. Overall, good agreement is found between these NLO pQCD calculations and the measured results. At low p_T which is dominated by gluon-gluon and quark-gluon interactions, the calculations based on the KKP fragmentation functions which includes a larger gluon-pion fragmentation function, D_g^π, than in the case of 'Kretzer', is in better agreement with the data.

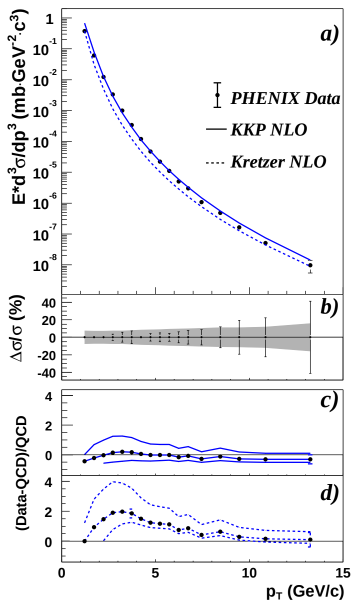

FIGURE 3. *Invariant differential cross section measurement by the PHENIX collaboration for inclusive neutral pion production in comparison to NLO pQCD calculations with equal renormalization and factorization scale of p_T using the 'Kniehl-Kramer-Pötter' (KKP) (solid line) and 'Kretzer' (dashed line) sets of fragmentation functions (a). The relative statistical errors (points) and point-to-point systematic errors (band) (b). The relative difference between the measured cross-section and the NLO pQCD calculations using the KKP (c) and the 'Kretzer' (d) set of fragmentation functions [14].*

SUMMARY AND OUTLOOK OF THE RHIC SPIN PROGRAM

The first polarized proton run at RHIC started a new era at BNL of exploring the spin structure of the proton. The main focus of the STAR experiment during the first polarized proton run (RUN 2) of transverse polarization was the measurement of a transverse single-spin asymmetry of forward π^0 production. In preparation of the first polarized proton run, an upgrade of the STAR experiment was performed with the installation of a beam-beam counter and a prototype forward pion detector (FPD) system, besides the commissioning of a spin scaler system. A new FPD system based on Pb-glass array calorimeters has been installed for the RHIC run in 2003 (RUN 3) [18]. First results on transverse single-spin asymmetries have been obtained and compared to model predictions. It will require more precise and differentiated measurements to discriminate among the competing models, e.g. a measurement of an azimuthal dependence of forward produced π^0 mesons around the reconstructed jet axis would point to a mechanism for the large measured transverse single-spin asymmetries as proposed by Collins as a final state effect. This would then open the potential to access transversity which is the least unmeasured parton distribution function. An upgrade of the existing electromagnetic FPD system by hadronic calorimetry would aid this effort to reconstruct the jet axis. The STAR detector will undergo major upgrade programs with the installation of the endcap calorimeter which is the principal device to explore the gluon polarization of the proton and the barrel calorimeter.

Large transverse single-spin asymmetries have been observed by the Local Polarimetry (PHENIX) collaboration for forward production of neutrons. The PHENIX collaboration has measured the invariant differential cross section for inclusive neutral pion production in $p+p$ collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ at mid-rapidity ($|\eta| < 0.35|$) as a function of p_T. Those measurements are found to be in good agreement with NLO pQCD calculations even at low p_T. This provides a solid basis for the planned polarized gluon density measurements with polarized protons at RHIC over a wide range in p_T [1].

HIGHLIGHTS FROM THE RHIC HEAVY-ION PROGRAM

One of the main goals of the Au-Au program at RHIC at BNL is to explore the formation of a new state of matter, often referred to as the Quark-Gluon Plasma, in the collision of Au-ion beams at a center-of-mass energy up to 200 GeV. Several signatures on the formation of the QGP have been suggested. A review of those signatures can be found in [19].

Signatures involving partonic collisions to probe a new state of matter play an important role at RHIC in distinction to previous fixed-target heavy-ion programs. It is predicted that energetic partons propagating through matter lose energy through gluon radiation with a magnitude of this energy loss that is strongly dependent on the color charge density. Partonic energy loss has been widely discussed as a potential sensitive probe for the formation of a new state of matter formed in the most violent collisions of two Au nuclei at RHIC [20, 21]. A clean signature for partonic collisions in high-energy proton-proton collisions is the formation of back-to-back jets. The direct measurement of jets in Au-Au collisions is rather difficult. Probing the formation of a new state of matter through partonic energy loss can be studied through azimuthal correlations and inclusive spectra of high p_T hadrons in comparison to proton-proton collisions. Those experimental results will be presented in the following for the four RHIC experiments which are studying the collisions of Au nuclei.

Nuclear effects in Au-Au and d-Au collisions have been studied at RHIC in comparison to proton-proton data measured at RHIC using the following ratio usually referred to as the nuclear modification factor:

$$R_{AB}(p_T) = \frac{d^2N/dp_T d\eta}{T_{AB} d^2\sigma^{pp}/dp_T d\eta} \tag{2}$$

where $d^2N/dp_T d\eta$ is the differential yield per event in the nuclear collision $A+B$, $T_{AB} = < N_{AB} > /\sigma^{pp}_{inel}$ describes the nuclear geometry, and $d^2\sigma^{pp}/dp_T d\eta$ for $p+p$ inelastic collisions is determined from the measured $p+p$ differential cross section.

Figure 4 shows $R_{AB}(p_T)$ from the STAR Collaboration for minimum bias and central $d+Au$ collisions which reflects a clear enhancement in contrast to the central $Au+Au$ collisions, exhibiting large suppression in hadron production at high p_T [22].

Figure 5 shows experimental results in $Au+Au$ and $d+Au$ collisions as obtained by the PHENIX Collaboration [23]. The top panel of Figure 5 shows $R_{dAu}(p_T)$ for inclusive charged particles $(h^+ + h^-)/2$ compared to R_{AuAu} observed in $Au+Au$ collisions. The

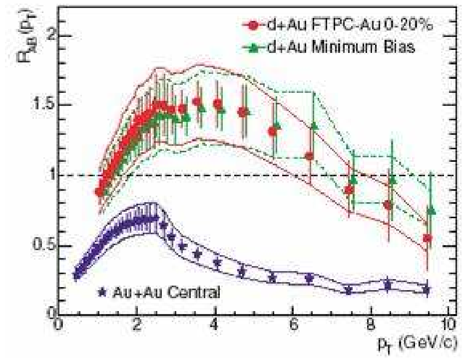

FIGURE 4. *$R_{AB}(p_T)$ for minimum bias and $d+Au$ collisions, and central $Au+Au$ collisions as obtained by the STAR collaboration. The bands show the normalization uncertainty. The error bars represent the quadratic sum of statistical and systematic errors [22].*

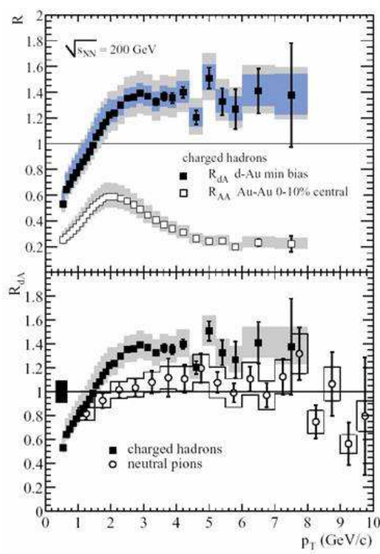

FIGURE 5. *Nuclear modification factor R_{dAu} for $(h^+ + h^-)/2$ in minimum bias $d+Au$ collisions compared to R_{AuAu} in the 10% most central $Au+Au$ collisions as obtained by the PHENIX collaboration. Inner bands show systematic errors. Outer errors bands include in addition normalization uncertainties (top). Comparison of R_{dAu} for $(h^+ + h^-)/2$ and the average of the π^0 measurements in $d+Au$ collisions. The bar at the left indicates the systematic uncertainty in common for the charged and π^0 measurements [23].*

lower panel compares the $(h^+ + h^-)/2$ result for $R_{dAu}(p_T)$ to the π^0 result in $d+Au$ collisions. The data clearly indicate that there is no suppression of high p_T particles in $d+Au$ collisions which is in contrast to the results obtained in $Au+Au$ collisions. An enhancement of inclusive charged particle production in $d+Au$ collisions is found at $p_T > 2\,\mathrm{GeV/c}$.

The BRAHMS measurement for R_{dAu} in comparison to $Au+Au$ results is shown in Figure 6 [24]. No suppression is observed in R_{dAu}, rather an enhancement at high p_T.

The nuclear modification factor R_{dAu} as obtained by the PHOBOS Collaboration is

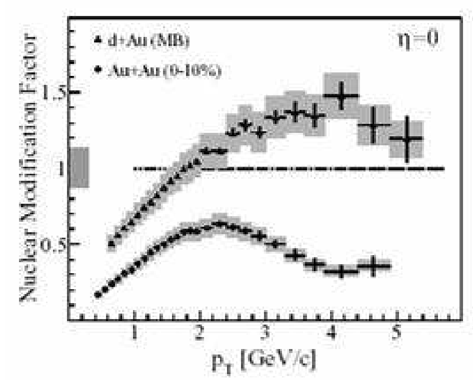

FIGURE 6. *Nuclear modification factor measured for minimum bias collisions of $d+Au$ data at $\sqrt{s_{NN}} = 200\,GeV$ compared to central $Au+Au$ collisions as obtained by the BRAHMS collaboration. Error bars represent statistical errors. Systematic errors are denoted by the shaded bands [24].*

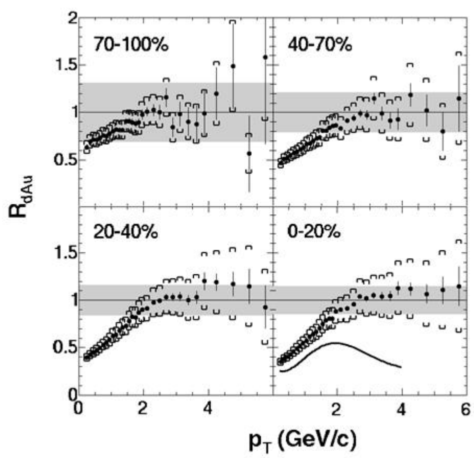

FIGURE 7. *Nuclear modification factor as a function of p_T for four bins of centrality as obtained by the PHOBOS collaboration. For the most central bin, the spectral shape for central $Au-Au$ data relative to the UA1 $p\bar{p}$ reference data set is shown for comparison. The shaded area and brackets shows the uncertainty in R_{dAu} due to various systematic uncertainties [25].*

shown in Figure 7 as a function of p_T using the UA1 $p\bar{p}$ reference data set [25]. For comparison, the result from central $Au+Au$ collisions is also shown. For central $Au+Au$ collisions, the ratio of the spectra to the UA1 $p\bar{p}$ reference data set rises rapidly up to $p_T \approx 2GeV\,\mathrm{GeV/c}$, but falls off at higher p_T. This is in striking contrast to the behavior seen for central $d+Au$ collisions.

In summary, all four RHIC experiments are consistent in their findings of a strong suppression of the inclusive hadron yields [22, 23, 24, 25] in addition to the back-to-back correlations [26] in central $Au+Au$ collisions in comparison to $p+p$ collisions. If the result of this suppression would be an initial state effect, e.g due to gluon saturation phenomena [27], it should be also observed in $d+Au$ collisions. However, no suppression in $d+Au$ collisions is observed. This has been consistently found among all four

RHIC experiments. The inclusive hadron yields are found to be enhanced at high p_T in comparison to $p+p$ collisions which suggests that the Cronin effect [28] plays an important role in $d+Au$ collisions. The strong suppression seen in $Au+Au$ collisions are attributed to final-state interactions with the hot dense medium created in $Au+Au$ collisions [20, 21].

It will be important to explore various other potential signatures suggested for the formation of a Quark-Gluon Plasma to make a firm statement about the nature of the new state of matter created in the collision of $Au+Au$ nuclei at RHIC. In addition, it will be crucial to examine the region of higher gluon density, kinematically accessible in the forward region at RHIC, to explore the role of gluon saturation phenomena in the RHIC energy region.

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