Recent high p_T measurements in STAR

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Abstract. After five years of data taking, the STAR experiment at the Relativistic Heavy
Ion Collider (RHIC) at Brookhaven National Laboratory provides precise measurements of
particle production at high transverse momentum in p-p, d-Au, and Au-Au collisions at $\sqrt{s_{NN}} =$
200 GeV. We review recent results on the flavor dependence of high p_T particle suppression and
hadron particle spectra at $\sqrt{s_{NN}} = 62.4$ GeV. New results on two-particle angular correlations
for identified trigger particles and for low momentum associated charged hadrons in p-p and
Au-Au as well as near-side $\Delta\eta$ correlations will be presented and discussed.

1. Introduction
The RHIC facility at Brookhaven National Laboratory provides Au-Au collisions at the highest
energy presently available of $\sqrt{s_{NN}} = 200$ GeV. The high center-of-mass energy opens up the
hard scattering regime which is accessed by the measurements of particle production at large
transverse momentum and where pQCD is applicable. These high momentum particles originate
from parton fragmentation in the early stage of the collisions. The scattered partons can be
used to probe the produced medium of strongly interacting matter [1, 2].

A significant suppression of high p_T hadron production relative to a simple binary
collision scaling from proton-proton collisions has been observed in central Au-Au collisions
at RHIC [3, 4]. Additionally, it was found that jetlike correlations opposite to trigger jets
disappear and that the elliptic anisotropy in hadron emission is large and saturates at very
high transverse momenta [5, 6, 7]. All these findings are consistent with the picture of parton
energy loss (induced gluon radiation) of the scattered partons in the extremely dense medium
(jet quenching). In contrast, no suppression effects were seen in d-Au collisions [8], which
provide an important control measurement for the effects in cold nuclear matter. From the d-
Au measurements it was concluded that the observations made in Au-Au are due to final state
interactions in the high density medium produced in such collisions.

In this paper, recent high p_T results from the STAR experiment [9] are presented. From the
observations so far, particle production can be described dividing the transverse momentum axis
into three ranges. The first range, $0 \lesssim p_T \lesssim 2$ GeV/c, particles are produced via soft processes.
These particles are usually called bulk matter. In the intermediate range, $2 \lesssim p_T \lesssim 6$ GeV/c,
the interplay between the probe and the medium can be studied. Initial state nuclear effects
(e.g. Cronin) also contribute significantly in this range. The p_T range above ~ 6 GeV/c
seems to be the "clean" jet fragmentation regime where pQCD processes become dominant.
Inclusive hadron spectra from p-p interactions are well described by pQCD. In the next sections,
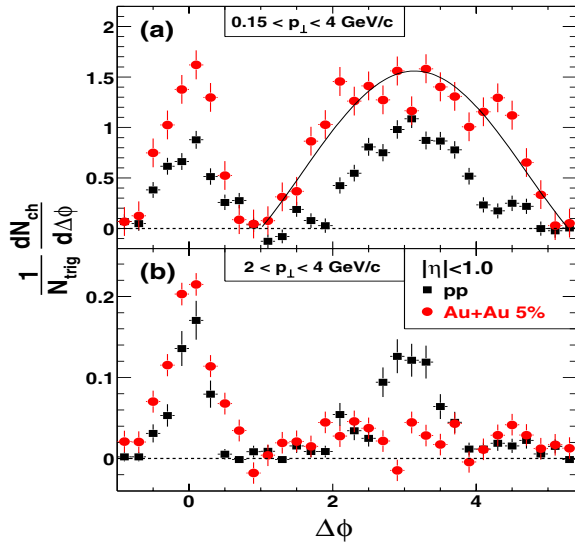
Figure 1. Background subtracted dihadron azimuthal angular distribution in p-p (solid circles) and 5% most central Au-Au collisions (solid squares) for $4 < p_T^{\rm trig} < 6$ GeV/c and two associated p_T ranges $0.15 < p_T^{\rm assoc} < 4$ GeV/c $(2 < p_T^{\rm assoc} < 4$ GeV/$c)$ upper (lower) plot ($|\eta| < 1$). The curve in the upper plot shows the shape of an $[A - B\cos(\Delta\phi)]$ function.
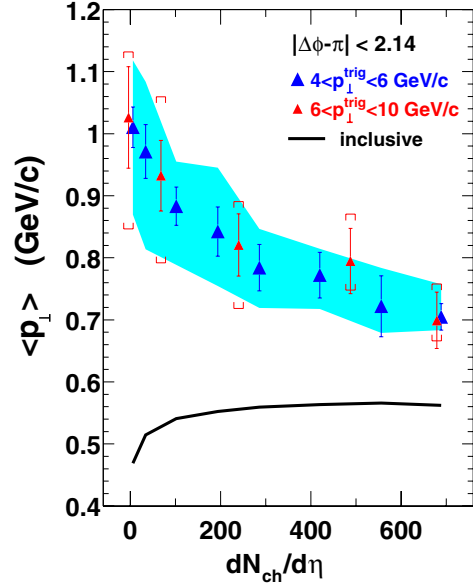
Figure 2. The $\langle p_T \rangle$ for the away-side associated charged hadrons selected in $4 < p_T^{\rm trig} < 6$ GeV/c (systematic errors are indicated by the shaded band) and $6 < p_T^{\rm trig} < 10$ GeV/c (systematic errors in caps) in Au-Au collisions. The leftmost data points are from p-p reaction. The solid line indicates the $\langle p_T \rangle$ for inclusive hadron production.

recent measurements of the STAR collaboration concerning inclusive particle spectra and particle correlations in Au-Au collisions at 200 and 62.4 GeV will be discussed using this classification.

2. Low transverse momentum range

Although the subject of this paper is high p_T, low transverse momentum particle production is discussed for parton fragmentation products appearing in this kinematical range. Due to full azimuthal coverage, the STAR detector has good capabilities to study leading particle correlations. The correlation contribution from azimuthal anisotropy (elliptic flow) is measured with high precision [6, 7]. It was observed that jetlike azimuthal angular ($\Delta\phi$) correlations opposite to trigger jets in the p_T range $4 < p_T^{\rm trig} < 6$ GeV/c are suppressed for associate particle selected in $2 < p_T^{\rm assoc} < 4$ GeV/c in central Au-Au collisions, whereas no suppression was measured in p-p, d-Au and peripheral collisions [8]. The method of leading particle correlation most likely favors the selection of high p_T trigger particles near the medium surface. Therefore, the back-to-back parton has to go through the produced medium and can probe it. The suppression exhibits a continuous centrality dependence [5]. Dihadron $\Delta\phi$ correlation studies with respect to the reaction plane in the 20–60% most central collisions have shown [7] that the suppression depends on the path length traversed, which is in line with the jet-quenching scenario.

Because of momentum conservation the fragmentation products of the away-side jet must balance the momentum of the trigger jet. In Figure 1, upper panel, the background (flow plus pedestal) subtracted $\Delta\phi$ distribution for p-p and the 5% most central Au-Au collisions are shown for the same trigger p_T, $4 < p_T^{\rm trig} < 6$ GeV/c, but for an associate p_T range of $0.15 < p_T^{\rm assoc} < 4$ GeV/c [10]. One observes a clear back-to-back correlation peak which is
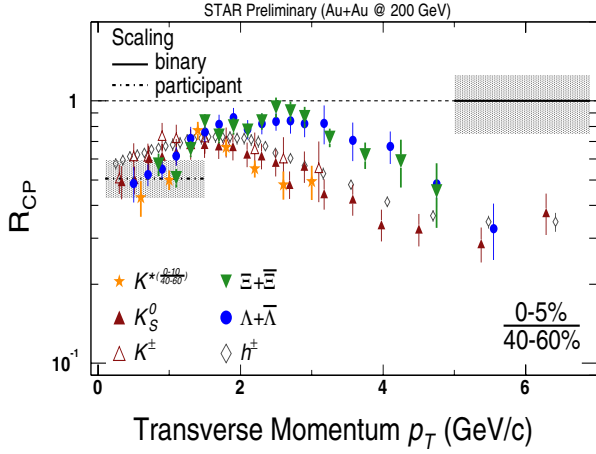
Figure 3. Nuclear modification factor $R_{CP}(p_T)$ for strange mesons and baryons using the centrality intervals 0–5% vs. 40–60% of the Au-Au collision cross section at $\sqrt{s_{NN}} = 200$ GeV.
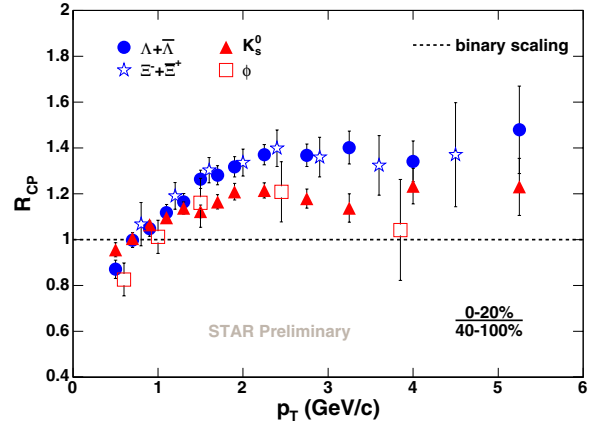
Figure 4. $R_{CP}(p_T)$ for hyperons (Λ, Ξ), K_s^0 and ϕ mesons in d-Au collisions. Here, the ratio is calculated using the centrality intervals 0–20% vs. 40–100%.

widely dispersed and shows a momentum balance shape. Similar results have been found by the NA45/CERES collaboration for pions with $p_T > 1.2$ GeV/c at CERN-SPS energies [11]. The away-side peak in Figure 1 exhibits two maxima symmetrically around the the peak center. Recently, it was suggested [12, 13] that these maxima can be expected from in-medium conical flow, caused by the energy deposition of partons traversing the produced matter faster than the speed of sound in the medium. Similar theoretical calculations for Mach shock waves in nuclear reactions have been performed by [14]. The resulting shock wave may give rise to increased particle production at well-defined angles with respect to the parton direction ($\Delta\phi_{\text{flow max.}} \approx \pi \pm 1$.). Further analysis with higher statistics will clarify the significance of the away-side structure.

In addition, it was found that the mean p_T of the back-to-back associated charged hadrons in the trigger p_T ranges $4 < p_T^{\text{trig}} < 6$ GeV/c and $6 < p_T^{\text{trig}} < 10$ GeV/c decreases with centrality in Au-Au collisions as illustrated in Figure 2. The solid line in the figure reflects the $\langle p_T \rangle$ for inclusive hadron production. For the most central events, the associate particles approach this line indicating thermal equilibration of the away-side fragmentation products with the bulk medium.

3. Intermediate transverse momentum range

Inclusive hadron suppression is quantified using the nuclear modification factor $R_{CP}(p_T)$, the ratio of the inclusive yields in central to peripheral collisions scaled by the number of binary collisions to take into account geometric effects. R_{CP} is expected to be one for pointlike incoherent processes (absence of nuclear effects). Deviations from unity indicate nuclear modifications such as the Cronin effect, shadowing and modifications of the fragmentation function in the produced medium.

In central Au-Au collisions, a suppression of high p_T particle production is observed. Moreover, R_{CP} exhibits a significant meson-baryon pattern in the intermediate p_T range ($2 \lesssim p_T \lesssim 6$ GeV/c) [15, 16]. This pattern is plotted in Figure 3 for charged hadrons, kaons, hyperons (Λ, Ξ) and the $K^\star$ resonance. The ϕ follows the meson trend as well (not shown). This pattern suggests a collective hadron production mechanism such as quark recombination or coalescence [17].
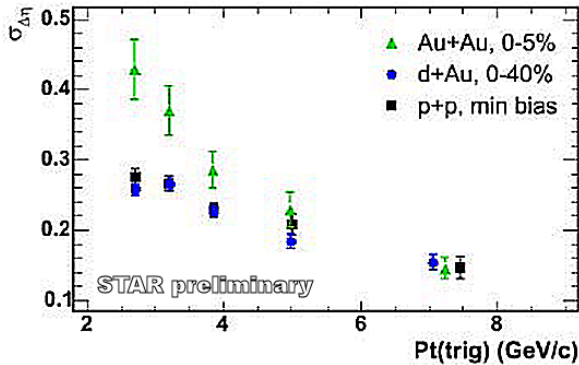
Figure 5. Near-side $\Delta\eta$ correlation width of charged hadrons as a function of p_T^{trig} for p-p (square), d-Au (circle) and central Au-Au collisions (triangle).
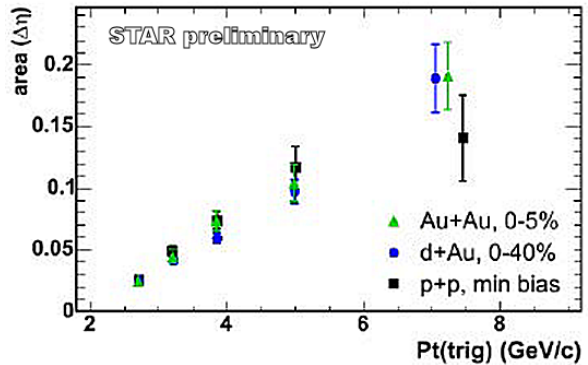
Figure 6. Trigger p_T dependence of the dihadron near-side $\Delta\eta$ correlation strength for p-p (square), d-Au (circle) and central Au-Au collisions.

R_{CP} was also studied by the STAR collaboration for ϕ mesons and hyperons in d-Au collisions [18] as illustrated in Figure 4. Here, the yields are enhanced for $p_T > 1$ GeV/c likely due to multiple soft scatterings before the hard interaction (similar to the Cronin effect). The meson-baryon pattern is also present with a much smaller magnitude than in the Au-Au case ($\frac{\text{baryon}}{\text{meson}} \approx 1.15$). In d-Au collisions, the intermediate p_T range should be dominated by jet fragmentation and one would expect one curve for all particles. Hence, the different behavior for mesons and baryons is a possible hint of the quark content dependence of the Cronin effect (initial or final). Future high statistic analysis have to show whether the curves for mesons and baryons merge at even higher p_T for d-Au and Au-Au. For Au-Au collisions, one already notices a first hint around 6 GeV/c (cf. Figure 3).

Remarkably, the integrated yields of the $\Delta\phi$ correlation peaks for identified K_s^0 and Λ as leading particle do not show a significant flavor dependence at intermediate p_T [19]. This result does not favor the thermal quark coalescence as the dominant production source. Instead, it is more likely that one sees here the interplay between parton fragmentation and the produced bulk matter.

3.1. Pseudo-rapidity asymmetry in d-Au collisions

STAR has performed systematic studies of the pseudo-rapidity asymmetry and the centrality dependence of charged hadron production in d-Au collisions [20]. One observes a significant η dependence at the highest centrality bin (0–20% most central events) where the yields in the gold direction are higher than in the deuteron direction. The p_T dependence of the back(gold)-to-forward(deuteron) asymmetry ratio is in qualitative agreement with the saturation model [21, 22] but cannot be explained by initial state incoherent multiple scattering of the partons [23].

3.2. $\Delta\eta$ near-side dihadron correlations

Earlier STAR correlation analysis of soft hadrons ($p_T < 2$ GeV/c) in central Au-Au collisions have shown [24] that near-side correlations have a jetlike peak in $\Delta\phi$ ($x - y$ plane) and $\Delta\eta$ ($y - z$ plane) with a similar width as measured in p-p reactions. This peak sits on top of a very broad, nearly flat distribution which can be attributed to long-range correlations. A new analysis [25] has been performed using high p_T particles which are originating from jet fragmentation. Figure 5 shows the peak width of the jetlike $\Delta\eta$ near-side correlation as a function of the trigger p_T. This width is similar for p-p, d-Au and central Au-Au collisions at $p_T^{\text{trig}} > 6$ GeV/c but becomes broader for Au-Au when going to lower p_T^{trig}. However, the correlation strength is similar for all three collisions systems as shown in Figure 6. These
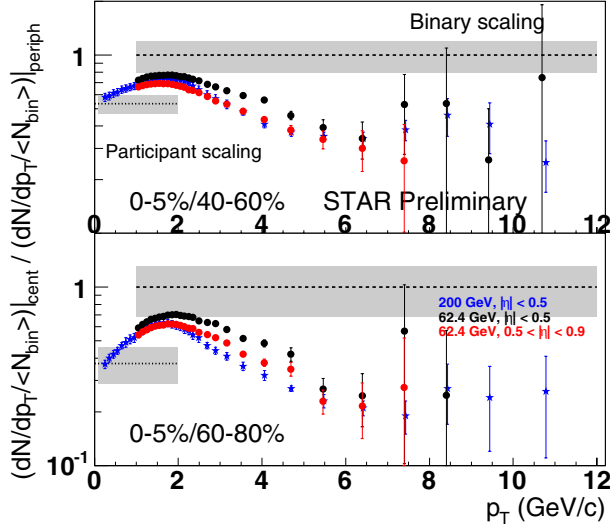
Figure 7. Charged hadron nuclear modification factor $R_{CP}(p_T)$ at cms energy of 62.4 (black and red points) and 200 GeV (blue points) for two different centrality interval ratios.
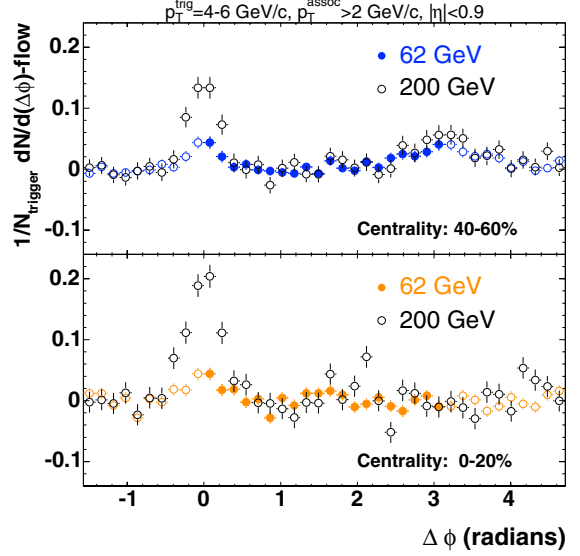
Figure 8. Dihadron azimuthal angular correlation distribution at $\sqrt{s_{NN}} = 62.4$ (full blue and orange points) and 200 GeV (open black points) for the kinematic cuts: $4 < p_T^{trig} < 6$ GeV, $p_T^{assoc} > 2$ GeV/c and $|\eta| < 0.9$.

findings might likely be interpreted by the coupling of the medium-induced gluon radiation to the collective longitudinal flow [26, 27].

3.3. High p_T measurements at $\sqrt{s_{NN}} = 62.4$ GeV

High p_T particle production is suppressed by a factor of about 5 in central Au-Au collisions. It has also been shown [28] that the nuclear modification factor is $R_{AA} \sim 1$ at top CERN-SPS energy. In 2004, the experiments at RHIC took Au-Au data at $\sqrt{s_{NN}} = 62.4$ GeV to probe the onset of suppression. In the jet-quenching picture, one would naively expect that the suppression is smaller at this energy because a higher fraction of quark jets are produced and the energy loss in the medium dependence on the color charged of the partons. At top RHIC energies, the number of quark and gluon jets should be about the same [29]. On the other hand, the smaller initial energy density leads to less parton energy loss whereas the steeper partonic p_T spectrum generates larger leading hadron suppression for the same magnitude energy loss.

In Figure 7, the $R_{CP}(p_T)$ is shown for two different centrality interval ratios for $\sqrt{s_{NN}} =$ 62.4 and 200 GeV. Within the errors, the high p_T suppression is similar above $p_T > 6$ GeV/c for the two collision energies. Consequently, the suppression seems to be driven by the nuclear geometry. The difference of the curves at the intermediate p_T can be attributed to the Cronin effect.

Two-particle azimuthal angular correlation for two different centrality bins at 62.4 and 200 GeV is shown in Figure 8. In comparison to 200 GeV, the near-side correlation strength is a factor ~ 3 smaller at 62.4 GeV due to the steeper underlying partonic spectrum. The away-side suppression is similar for both energies.

4. High transverse momentum range

The large acceptance ($0 \leq \phi \leq 2\pi$ and $-1 \leq \eta \leq 1$) of the STAR Barrel Electromagnetic Calorimeter (BEMC) [30, 31] enables the study of identified particle spectra at even higher p_T to probe where pQCD becomes dominant above nuclear and coalescence effects. In addition,
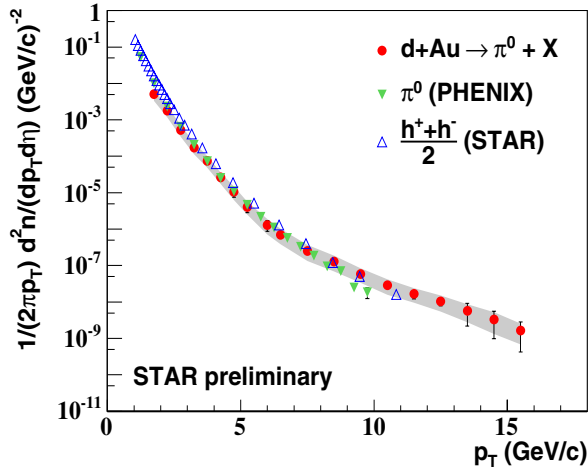
Figure 9. Inclusive neutral pion spectrum in d-Au collisions at $0 < \eta < 1$ (full circles). The error bars (shaded band) represent the statistical (systematic) uncertainties. Previous STAR measurements of the charged hadron cross section are shown by the open triangles, and the full triangles show π^0 results from PHENIX.
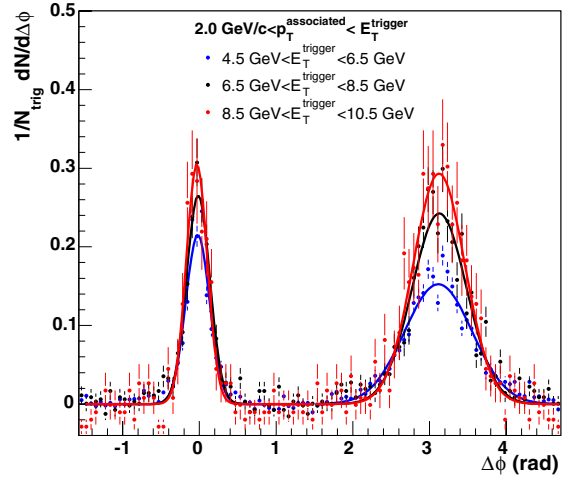
Figure 10. Pedestal background corrected photon-charged hadron $\Delta\phi$ correlation distribution for minbias d-Au collisions selected in the range $2.0\ \mathrm{GeV}/c < p_\mathrm{T}^\mathrm{assoc} < E_\mathrm{T}^\mathrm{trig}$ and three different $E_\mathrm{T}^\mathrm{trig}$ ranges as indicated in the figure.

the high statistic 200 GeV Au-Au data set of Run IV will certainly extend the inclusive hadron spectra to higher p_T.

Preliminary analysis of neutral pion production in d-Au collisions has shown the capability of the BEMC [32], with the p_T spectrum measured up to $\sim 15\ \mathrm{GeV}/c$ as plotted in Figure 9. The obtained spectrum shows reasonable agreement with previous STAR measurements on charged hadron cross sections [8] and the PHENIX results on π^0 production [33] as well as with NLO pQCD calculations [32]. Figure 10 shows the azimuthal angular photon - charged hadron correlation distribution in d-Au collisions at 200 GeV for different $E_\mathrm{T}^\mathrm{trig}$ ranges [34]. The leading photon can be selected up to $\sim 11\ \mathrm{GeV}/c$. The obtained width and strength of the near- and away-side correlation peak are similar the the ones obtained from charged dihadron correlations [35].

5. Summary and future challenges

In this paper, recent high p_T results on inclusive particle spectra and two-particle $\Delta\phi$ correlation at $\sqrt{s_\mathrm{NN}} = 62.4$ and 200 GeV are presented. Similar behavior of the R_{CP} and the dihadron correlation are observed which can be interpreted as the nuclear geometry as the driving force of the suppression. Correlation analysis with lower $p_\mathrm{T}^\mathrm{assoc}$ indicates thermal equilibration of the away-side fragmentation products with the bulk matter. The near-side $\Delta\eta$ correlation distribution can be interpreted as a coupling of the the parton energy loss to the collective flow. d-Au collisions provide essential information for the deeper understanding of the underlying mechanisms in Au-Au. The observed meson-baryon pattern can not be exclusively attributed to quark coalescence.

Further studies and measurements are needed to understand the evolution of the jet-quenching effect [36]. Minbias Cu-Cu collisions at $\sqrt{s_\mathrm{NN}} = 62.4$ and 200 GeV have been recorded this year. An additional low energy Au-Au run will be necessary to map the energy dependence of the suppression effect between top SPS ($\sqrt{s_\mathrm{NN}} = 17.4\ \mathrm{GeV}$) and 62.4 GeV. More details on

the modification of the fragmentation function in the medium are needed which can be probed by direct photon tagged correlation studies because the hard scattered photons are not suffering from the surrounded medium. Heavy quark tagged correlations will offer the possibility to discriminate between quark and gluon jets since heavier quark are dominantly produced by gluon fragmentation.

Acknowledgments

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