Jets and Jet-like Correlations at RHIC

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I present an overview of some of the recent results on jets and jet-like correlation measurements from the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory.

Jets are produced in the initial hard scatterings of an event and can therefore be exploited as probes of the hot and dense medium produced in heavy-ion collisions. Previous RHIC results indicate that this medium, the Quark Gluon Plasma (sQGP), is strongly coupled, with partonic degrees of freedom. High \( p_T \) colored partons passing through the sQGP are therefore believed to suffer energy loss via induced gluon radiation and elastic collisions, before exiting the medium and fragmenting in vacuum. Jet reconstruction and high \( p_T \) correlation studies allow us to investigate how the partons interact with the medium and how the medium responds to the partons moving through it. By comparing measurements from \( pp \) and \( d-Au \) to those in Au-Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV we aim to disentangle cold nuclear matter effects from those of the hot and dense sQGP.

I. INTRODUCTION

Over the past decade the RHIC experiments have produced significant evidence that a Quark Gluon Plasma (sQGP) is being produced in ultra-relativistic heavy-ion collisions. This sQGP is strongly coupled and has partonic degrees of freedom. Hard probes are now being used to study how partons interact with the medium, and how the sQGP responds to energy deposited by these highly energetic partons as they travel through it. The results from Au-Au collisions are compared to those from \( pp \) and \( d-Au \) collisions where no QGP is believed to be created.

Jet quenching, the loss of energy of hard scattered partons to the medium, was first observed at RHIC via the single particles nuclear modification factor, \( R_{AA} \) \[1\]. The nuclear modification factor is defined as the ratio of Au-Au \( p_T \) spectrum normalized to the number of binary collisions (\( N_{bin} \)) to that of the \( pp \) data measured at the same collision energy. The \( R_{AA} \) of high \( p_T \) particles in central Au-Au indicated a suppression of up to a factor of 5 \[1\], while photons, colorless objects, reveal an \( R_{AA} = 1 \) \[2\]. These results suggest that the suppression is due to partons interacting with, and hence loosing energy to, the hot and dense colored medium. \( R_{AA} \) measures however have a couple of limitations. First it is not possible to infer the initial partonic energy from the final state hadron. Second surface emission leads to an inherent insensitivity to the medium’s density; no matter how dense the medium those partons near the surface will always escape and be detected \[3\].

To attempt to alleviate both these issues the collaborations are now performing full jet reconstruction. An added advantage is that by studying the fragmentation patterns we can hope determine not only how much energy is lost from the initial parton but also how the energy is redistributed. Both STAR and PHENIX use jet finding algorithms from the FastJet package \[4\], in addition PHENIX uses a Gaussian filter code, details of which can be found here \[5\] and STAR has used a traditional mid-point cone algorithm \[6\].

Neither RHIC experiment has hadronic calorimetry included in their detector designs, hence the full jet energy is not directly accessible but is assessed by combining charged particle momenta via tracking devices with neutral energy measurements from electro-magnetic calorimetry. In addition the energy from long-lived neutral hadrons, such as the neutron and \( K^0_L \) is missed. This leads to a significant difference in the jet energy reconstructed and that of the initial, so-called particle level jet. This difference, as well as the jet energy resolution, has to be evaluated and corrected for before final results can be presented. For instance, the detector performances have been evaluated via simulations by STAR and show that the jet energy resolution in \( pp \) data varies from 10-25%, for 40-10 GeV/c jets \[7\].

II. JETS IN PP AND D-AU COLLISIONS

For \( pp \) collisions the reconstructed raw jet spectra reconstructed with the Anti-K_{T}, K_{T} and SISCone algorithms were the same within 10%, confirming that they have similar behaviours in this low multiplicity data, Fig. ref-Fig:JetCompare \[7\]. The inclusive jet, Fig. \[2\] and di-jet cross-sections, Fig. \[3\] have been measured by STAR using the increased statistics of the 2006 data \[8\]. A midpoint cone algorithm \[6\] with a cone radius of 0.7, a split-merge fraction 0.5 and a seed energy of 0.5 GeV was used. When hadronization and underlying event uncertainties are included both sets of data are well described by NLO theory \[9, 10\].

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The measured fragmentation functions of both STAR [11] and PHEINX [12] agree, within errors, with PYTHIA simulations [13], see Fig. 4. The PHENIX data use the Gaussian filter with a width of 0.3, and are fully corrected. While the data from STAR are not yet corrected to the particle level and are therefore compared to PYTHIA 6.410 [13], tuned to the CDF 1.96 TeV data (Tune A), predictions passed through STAR’s simulations and reconstruction algorithms. The agreement with PYTHIA simulations even for R=0.7 suggests that there are only minor NLO contributions beyond those mimicked in the PYTHIA parton-shower calculations at RHIC energies.

We also investigate jet production in d-Au collisions, where cold nuclear matter effects are expected to be present but no QGP formed. For example, the presence of the Au nucleus may induce additional initial and final state radiation, or result in scatterings of fragmentation particles as they escape the nucleus. The measured d-Au mid-rapidity jet nuclear modification factor, R_{CP}, where peripheral d-Au events are used instead of pp data, is shown from PHENIX in Fig. 5 left panel, for three different centrality bins. Here the Anti-\(k_T\) algorithm with R=0.3 was used. A slight modification of the jet spectrum is observed in d-Au collisions, with the central d-Au jet cross-section showing the greatest suppression. These results are consistent with the \(\pi^0\) results and are likely an indication of cold nuclear matter effects such as modifications of the nuclear PDFs and/or energy loss in the cold matter. Since these effects may result in more subtle modifications than that of the overall jet yields, another way to probe for these cold nuclear matter effects is via di-jet correlations. Re-scatterings in the nucleus may result in a broadening of the di-jet \(\Delta\phi\) distribution. The mean transverse momentum of the fragmentation

FIG. 1: The ratio of reconstructed jets for various FastJet algorithms, K_T/Anti-K_T and SISCone/Anti-K_T as a function of reconstructed jet p_T.

FIG. 2: Left: The 2006 measured inclusive jet cross section for pp collisions at \(\sqrt{s_{NN}}=200\) GeV. Right: (Data-Theory)/Theory.
FIG. 3: Left: The 2006 measured inclusive di-jet cross section for \( pp \) collisions at \( \sqrt{s}=200 \text{ GeV} \). Right: \( \text{(Data-Theory)}/\text{Theory} \).

FIG. 4: Left: PHENIX Run-5 \( pp \) charged particle (electrons rejected) fragmentation function as a function of \( z \) \( (=p_{\text{hadron}}/p_{\text{jet}}) \). A vertical scaling of \( c(p_{\text{jet}}^{k}) = 10^{k}, k=0, \ldots, 3 \) is applied. The shaded boxes indicate systematic uncertainties, and error bars indicate statistical uncertainties. From [12]. Right: Jet FF as a function of \( \xi \) for STAR using the \( \text{K}_{T} \), Anti-\( \text{K}_{T} \) and SISCone algorithms for \( R=0.7 \). The curves are the PYTHIA predictions.

products with respect to the jet axis, \( \langle \eta \rangle \), and the mean transverse momentum kick given to di-jet pair, \( \langle k_{T} \rangle \), are two variables used for these investigations. The \( \langle k_{T} \rangle \) was measured via di-hadron correlations and found to be constant at \( \approx 0.55 \text{ GeV}/c \) for all \( p_{T} \) triggers measured and for both \( pp \) and \( d-Au \) events at \( \sqrt{s}=200 \text{ GeV} \) [14]. However, as shown in Figure 5 right panel the \( \langle k_{T} \rangle \) is systematically higher for the \( d-Au \) data than for the \( pp \) data for all \( p_{T} \) jet and \( p_{T} \) trigger ranges measured. This suggests that while cold nuclear matter effects are small they still result in a minor deflection/broadening of partonic trajectories, the fragmentation appears to be unaffected.

The underlying event (UE) is an important element of hadronic collisions and is defined as those particles not produced in the initial hard scatterings. Hence it includes beam-beam remnants, particles from initial and final state re-scatterings and those resulting from soft or semi-hard multi-parton interactions, pile-up is not included in the UE definition and must be removed. In \( pp \) events at RHIC the UE is small and is often neglected, however in \( d-Au \) collisions it becomes sizable. CDF initiated such an analysis [15]. First the jets are reconstructed, next each event is split into four sections defined by their azimuthal angle with respect to the leading jet axis (\( \Delta \phi \)). The range within \( |\Delta \phi|<60^\circ \) is the lead jet region and an away jet area is designated for \( |\Delta \phi|>120^\circ \). This leaves two transverse sectors of \( 60^\circ<|\Delta \phi|<120^\circ \) and \( 120^\circ<\Delta \phi<60^\circ \). One is called the TransMax region and is the
transverse sector containing the largest charged particle multiplicity. The second sector is termed the TransMin region. Two sets analyses can then performed, a “leading” jet study, where at least one jet is found in STAR’s acceptance, and a “back-to-back” study which is a sub-set of the “leading” jet collection. This sub-set of events has two (and only two) found jets with \( p_{T}^{\text{away jet}} / p_{T}^{\text{lead jet}} > 0.7 \) and \(|\Delta \phi_{\text{jet}}| > 150^\circ\), this selection suppresses hard initial and final state radiation of the scattered parton. The TransMax region has an enhanced probability of containing contributions from these hard initial and final state radiation components. Thus, by comparing the TransMax and TransMin regions in the “leading” and “back-to-back” sets we can extract information about the various components in the UE. The properties of the UE in both \( pp \) and \( d-Au \) events are being studied, this is the first time such an analysis has been undertaken for \( d-Au \) collisions. Since this study is performed at mid-rapidity it is likely that there is little to no contribution from the beam-beam remnants. Both the number of particles in and the momentum distribution of the underlying event appear to be largely independent of the leading jet’s \( p_T \) in both \( pp \) and \( d-Au \) collisions, Fig. 6. The mean transverse momentum is similar for \( pp \) and \( d-Au \) events in both the TransMax and TransMin regions as can be seen in Fig. 6 left panel. Meanwhile the average number of charged particles per unit \( \eta \) and \( \phi \) increases by \( \sim \)factor 5 from \( pp \) and \( d-Au \) collisions, right panel of Fig. 6. This increase in particle production is only slightly less than \( N_{\text{part}} \) scaling of the \( pp \)
data would predict, also shown in figure [9]. All the results are the same within errors for the “leading” and “Back-to-Back” data sets [17, 18], which suggests that the hard scattered partons emit very small amounts of large angle initial/final state radiation at RHIC energies.

III. JETS IN HEAVY-ION COLLISIONS

The presence of jets in heavy-ion events is clearly evident in Fig. 7, despite the significant underlying event. The left panel shows a di-jet event in the PHENIX detector from a ∼ 20% central Cu-Cu collision as found by the Gaussian filter algorithm [19]. The right panel shows a central Au-Au event in the STAR detector. Each grid cell indicates the summed \( p_T \) of the charged tracks reconstructed in the TPC and neutral energy recorded in the electro-magnetic calorimeter.

![Graph](image)

**FIG. 7:** Di-jets in heavy-ion events at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) Left: PHENIX Run-5 Cu-Cu ∼ 20% centrality. Charged tracks and photons are shown at the bottom by a lego plot. The distribution of the Gaussian filter output values of the event is shown at the top as a contour plot. The maxima in the filter density are reconstructed as jet axes, shown as red lines at the positions on the contour and Lego plots. Right: STAR central Au-Au event, the summed \( p_T \) of charged tracks and electro-magnetic calorimeter towers per grid cell are shown. Clear di-jet peaks emerge above the background.

In order to extract information regarding jets and the interactions of hard scattered partons with the sQGP it is essential to first understand the enormous background the jet is immersed in and its fluctuations. This background is predominantly formed from the soft underlying bulk particle production and is thus strongly dependent on the centrality of the collision. Schematically, assuming all the initial partonic energy is recovered by the jet finders the measured jet spectrum in Au-Au collisions is:

\[
\frac{d\sigma_{AA}}{dp_T} = \frac{d\sigma_{AA}}{dp_T} \otimes F(A, p_T)
\]

where \( F(A, p_T) \) accounts for the background and its fluctuations, which are a function of the jet area and the \( p_T \) of the reconstructed jet. Initially it was assumed that these fluctuations could be accounted for by a simple Gaussian ansatz, however more detailed studies have shown this modeling to be insufficient. If the background is due to independently emitted particles then in a fixed area the number fluctuations are well described by a Poisson distribution, while those of the mean \( p_T \) result in a Gamma distribution, assuming a fixed number of particles, \( M \) [21]. Therefore

\[
F(A, p_T) = \text{Poisson}(M(A)) \otimes \Gamma(M(A)\langle p_T \rangle)
\]

Such a modeling of \( F(A, p_T) \) gives a good description of the the summed \( p_T \) in the random cones of area A on a toy simulation where particles with \( dN/d\eta = 650 \) are thrown with a \( T = 290 \text{ MeV} \). The mean of the \( F(A, p_T) \) distribution is given by \( pA, \rho \) is the median\{\( p_T^{\text{jet,reco}}/A_i \)\} in the event and \( p_T^{\text{jet,reco}} \) is the reconstructed jet \( p_T \); When however the FastJet jet finders are used, the description is not exact, suggesting that the jet finders clustering does not occur in a truly random fashion, as should be expected. To investigate the resilience of the
jet finding in heavy-ion events to these fluctuations we are using probe embedding into real Au-Au events. A particle, or jet, of a known transverse momentum, $p_T^{\text{embed}}$, is embedded into an event, the Anti-$K_T$ algorithm run and the reconstructed jet containing the embedded probe identified. Then

$$\delta p_T = p_T^{\text{jet, reco}} - p_T^{\text{embed}}$$

is calculated. The $\delta p_T$ distributions are then calculated over many events for different embedded objects. Single pions, PYTHIA jets, and qPYTHIA jets (where the fragmentation pattern is altered from that of vacuum fragmentation) \[22\] have been used as well as various $p_T^{\text{embed}}$. Figure 8 left panel shows the resulting $\delta p_T$ distribution for a single 30 GeV/c pion embedded into a 0-20% central Au-Au event \[23\]. The right panel of Fig. 8 shows the distribution of the event-wise difference

$$\Delta \delta p_T = \delta p_T^{\pi} - \delta p_T^{\text{jet}},$$

between $\delta p_T$ for a PYTHIA-generated jet with $p_T > 30$ GeV/c probe and that of a pion with the same $p_T$, $\eta$, and $\phi$. Similar results are seen when qPYTHIA jets are used and for lower $p_T$ probes. This study reveals the Anti-$K_T$ response is insensitive to the fragmentation pattern of the probe, greater than 70% of the time $|\Delta \delta p_T| < 200$ MeV/c. This is a crucial property for the jet finder used in heavy-ion jet quenching studies since we do not yet have a complete description of the fragmentation functions of partons which traverse the sQGP. Also importantly the Anti-$K_T$ algorithm has been shown to respond in a predominantly geometric fashion and hence is fairly impervious to back-reaction effects \[24\].

![FIG. 8: Left: $\delta p_T$ distribution for a single pion with $p_T = 30$ GeV/c embedded into a 0-20% central Au-Au event. Right: The event-by-event difference in $\delta p_T$ for a PYTHIA embedded jet, $p_T > 30$ GeV/c, and a single pion with same $p_T$, $\eta$, and $\phi$ as the jet.](image)

For unbiased jet reconstruction one would expect the jet $R_{AA}$ to be close to unity, possible deviations might occur due to initial state effects in the Au-Au collisions. However, the left panel of Fig. 9 shows that even for $R=0.4$ the jet $R_{AA}$ is likely below unity, due to the large systematic errors the results are just compatible with unity \[25\]. The jet $R_{AA}$ is however significantly above that of single hadrons with $p_T > 20$ GeV/c ($R_{\text{hadron}}^{AA} \approx 0.2$). One can also observe that there are significant differences between the results for the $K_T$ and Anti-$K_T$ algorithms which is expected given their different responses to the heavy-ion background. The ratio of the number of reconstructed jets for $R=0.2$ compared to $R=0.4$ is less for Au-Au data than for $pp$ right panel of Fig. 9 \[25\]. Taking these two results together we conclude that the jet algorithms do not recover as much of the original partonic energy in Au-Au events as the same algorithms and settings run on $pp$ data. Further, Fig. 9 indicates that this is likely due to the fact that particles are emitted at larger cone angles in Au-Au events compared to $pp$ events with the same jet energy, with considerable energy, even at higher jet $p_T$ outside of $R=0.4$.

Di-jet coincidence rate measurements provide us with evidence that there is a path-length dependence to the partonic energy loss. In this analysis “trigger” jets are identified which have a reconstructed jet $p_T > 20$ GeV/c when only particles with $p_T > 2$ GeV/c are considered by the Anti-$K_T$ algorithm. These trigger jets also contain a barrel electro-magnetic calorimeter tower with $E_{\text{tow}} > 5.4$ GeV. This high z fragmentation requirement biases the trigger jet to being preferentially emitted from the surface of the medium and/or to have only minimally interacted with the medium. Such a surface bias in turn maximizes the average distance traversed by the recoil jet through the medium. If partonic energy loss is dependent on the path-length through the medium, the recoil jet will therefore reveal a greater suppression than that observed for the unbiased jet
population. The relative probability of reconstructing a di-jet pair in Au-Au is compared to that in pp is shown in Fig. 10. This relative probability is suppressed by an approximate factor of 5 \cite{26}, i.e. a much stronger rate of suppression than observed for the inclusive jets. This results supports the notion of a path length dependent energy loss term.

To investigate further the jet broadening and softening indicated by the studies mentioned above we turn to jet-hadron correlations. In this analysis a “trigger” jet (defined as in the di-jet analysis above) is used to determine the jet axis and the $\Delta \phi$ correlation of all charged particles in the event relative to this axis is examined, for more details on this analysis see \cite{28}. An example of such a correlation is shown in Fig. 10 right panel, again a softening and broadening of the distributions of particles from jets is indicated for low $p_T$ associated. The per trigger $\Delta \phi$ distributions for $pp$ and Au-Au event, plotted as a function of the associated charged particle $p_T$, are summarized in Figures 11 and 12. The Gaussian widths of the away-side correlations in $pp$ and Au-Au are shown in Fig. 11. The Au-Au distributions are broader than those in $pp$ for low $p_T$ associated particles, accompanied by an significant increase in the low $p_T$ associated yields \cite{28}. For high $p_T$ associated particles the Au-Au recoil jet correlation width is equivalent to that of $pp$ but there is a significant reduction in the particle yield. Re-scattering of the initial parton could also potentially cause such a broadening rather than a modification of the fragmentation. Therefore the di-jet $\Delta \phi$ distributions in $pp$ and Au-Au data,
PYTHIA events, and PYTHIA jets embedded into Au-Au events were studied. The results are shown in right plot of figure 11. The distribution is broader for the Au-Au data, however much of this broadening can be attributed to de-resolution of the jet axis due to the large underlying event, as a similar broadening is also observed in the PYTHIA+Au-Au event data. A similar result has been reported by PHENIX, who show that the $\Delta \phi$ distributions of di-jet events in Cu-Cu collisions do not vary as a function of centrality. The red curve in the left plot of Fig. 11 indicates the expected width of the away-side $\Delta \phi$ distribution if the Au-Au fragmentation was pp-like, but with the jet axis direction smeared to reproduced the width of the $\Delta \phi$ Au-Au di-jet data. Clearly such a smearing cannot fully explain the observed broadening, and it also does not explain the enhanced low $p_T$ yields.

The integrated yield difference, $D_{AA} = \langle p_{T,assoc}^{AA} \rangle - \langle p_{T,assoc}^{pp} \rangle$ of the near- and away-side correlations as a function of $p_{T,assoc}$ are plotted in Fig. 12. As expected, the “surface” bias of the trigger causes the near-side $D_{AA}$ to be consistent with zero for all $p_{T,assoc}$. This means that there is an approximate energy balance, and a similarity of the associated $p_T$ particle distributions for Au-Au and pp data for the trigger jet. The away-side data, Fig. 12 right panel, reveals that the low $p_T$ hadron enhancement in the Au-Au data is approximately matched by the high $p_T$ associated particle suppression. This suggests that the broadening and softening observed in the away-side correlation data is indeed due to a modification of the partonic fragmentation and not from residual soft background particles.

To remove the surface bias of the trigger object introduced in the di-jet and jet-hadron analyses discussed above PHENIX have been investigating $\gamma$-hadron correlations. Direct photon-hadron correlations are an ideal channel for studying energy loss since direct photons do not interact via the strong force and hence traverse the sQGP unmodified. At leading order pQCD, direct photons are produced from a Compton scattering of $q + g \rightarrow q + \gamma$ or quark annihilation $q + \bar{q} \rightarrow g + \gamma$. To conserve energy and momentum a matching recoil
The energy of the photon can then be used as a proxy for the jet’s initial energy and the fragmentation function of the recoil jet can be calculated. \( \gamma \)-hadron \( \Delta \phi \) correlations have been measured in both \( pp \) and \( Au-Au \) collisions \[29\], an isolation cut is used around the trigger photon to reduce contamination from \( \pi^0 \) and fragmentation photons. A fragmentation function is then deduced for the recoil jet correlation at \(|\Delta \phi - \pi| \leq \pi/2\). The resulting distributions as a function of \( \xi = -\ln(x_E) \) where \( x_E = p_T^{hadron}\cos(\Delta \phi)/p_T^{photon} \) are shown in Fig. 13 for \( pp \) and central \( Au-Au \) collisions. The preliminary \( Au-Au \) and published \( pp \) data are plotted and compared to the TASSO measurement \[30\] and a Modified Leading Logarithmic Approximation (MLLA) in medium prediction \[31\]. The TASSO data and MLLA curve have been arbitrarily scaled down by a factor of ten to account for the limited PHENIX \( \eta \) acceptance as in \[32\]. The shape of the isolated \( pp \) data are in good agreement with the TASSO measurement of the quark fragmentation function from \( e^+e^- \) collisions.

The \( Au-Au \) results show depletion at low \( \xi \) and possible enhancement at high \( \xi \) compared to the \( pp \) data. These results again indicate that the energy lost by high \( p_T \) partons reappears as soft hadrons correlated with the initial parton’s path.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig13.png}
\caption{\( \xi \) distributions from PHENIX \( \gamma \)-hadron correlations in \( Au-Au \) data (black circles) and \( pp \) data (open blue circles) compared to TASSO data (green triangles) and MLLA in medium prediction (red curve).}
\end{figure}

\section*{IV. SUMMARY}

In conclusion, both PHENIX and STAR are making quantitative steps in our understanding of jet production and fragmentation in \( pp \), \( d-Au \), and \( Au-Au \) collisions at RHIC at \( \sqrt{s_{NN}} = 200 \) GeV over a wide kinematic range.

Both the jet and di-jet cross-section in \( pp \) collisions are well described by next-to-leading order calculations once hadronization and the effects of the underlying event are taken into account. PYTHIA simulations reproduce the measured distributions of the fragmentation products even at large jet resolution parameters indications that NLO corrections, beyond those implemented in PYHTIA, are small.

Jet production in \( d-Au \) collisions is slightly suppressed, particularly in central \( d-Au \) events when compared to binary scaled \( pp \) or peripheral \( d-Au \) data. Together with the \( k_T \) and \( j_T \) measurements as a function of jet \( p_T \) this indicates that there are small cold nuclear matter effects present but that these do not affect the shape and distribution of the fragmentation particles produced.

Underlying event measurements of the \( pp \) and \( d-Au \) data show no significant changes as a function of jet \( p_T \). The mean number of charged particles produced in the transverse region approximately scales with the number of participants in the event, while the mean \( p_T \) of these particles remains constant between \( pp \) and \( d-Au \) data.

Our understanding of the background, and most importantly its fluctuations, in heavy-ion events has significantly improved. The Gaussian ansatz of the fluctuations has been shown to be incorrect, they are more closely reproduced from a folding of a Gamma function with a Poisson that depend on the jet area, multiplicity of the background and its mean \( p_T \). It has also been shown that the Anti-\( K_T \) algorithm’s response to the background and its fluctuations is largely independent of the fragmentation pattern of the jet.

Using a jet resolution parameter of \( R=0.4 \) the measured jet cross-section in central \( Au-Au \) collisions does not binary scale compared to \( pp \) data, the jet \( R_{AA} < 1 \). This reveals that the lost partonic energy is spread to radii beyond \( R=0.4 \). Further the \( Au-Au \) \( R=0.2/R=0.4 \) ratio as a function of jet \( p_T \) is lower than that measured in \( pp \) showing this broadening is there for all radii. The di-jet reconstruction probability in \( Au-Au \) collisions is suppressed as would be expected if the partonic energy loss is pathlength dependent.
Both jet-hadron and direct photon-hadron correlations indicate an enhanced production of hadrons at low \( p_T \) compared to \( pp \) baseline measurements which appear to compensate the suppressed particle production at high \( p_T \). However, the high \( p_T \) associated particles while suppressed in number compared to \( pp \) data do not reveal any broadening in the jet-hadron correlations. This is in agreement with a scenario where the scattered parton loses energy in the sQGP but then fragments outside of the medium as it would in vacuum albeit with a reduced energy. The di-jet \( \Delta \phi \) distributions indicate no obvious deflection of the parton’s path although significant path length dependent energy is lost as it traverses the medium.

All of the measurements made in heavy-ion collisions show that energy lost by high \( Q^2 \) scattered partons re-appears as soft particle production, with properties similar to that of the bulk, that remains largely correlated to the jet axis.

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