Introduction to Hard Scattering Processes and Recent Results from Hard Probes at RHIC and LHC

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Abstract. A summary is presented of recent heavy-ion collision results from hard scattering processes at RHIC and LHC. Hadrons with large transverse momentum are suppressed in heavy-ion collisions compared to proton-proton interactions, including those hadrons with heavy quarks (charm, beauty). Jets are quenched and modifications to their fragmentation are observed, the effects increasing with the centrality of the heavy-ion collision. The heavy-ion measurements are compared to those in proton-proton and proton-nucleus collisions. These results when compared to theory are consistent with the suppression and jet quenching being a product of parton energy loss in a hot QCD medium. Correlations are presented for di-jets, jets with trigger photons, and hadrons with trigger jets. The di-jet correlations exhibit a di-jet energy and momentum imbalance that increases with the centrality of the collision. The correlation results indicate that the parton energy loss is redistributed to lower momentum particles at larger angles from the axis of the hard-scattered parton.

1. Introduction

Hard or highly penetrating probes originate from hard scattering of partons (quarks and gluons) and are characterized typically by either large momentum transfer (i.e. large 4-momentum transfer squared $Q^2$), large transverse momentum ($p_T$) or a large mass ($m$) scale. Thus by definition, hard probes are highly penetrating observables used to explore properties of matter that cannot be viewed directly! Examples of these observables include radiation, high $p_T$ particles, jets, and particles with heavy quarks even at low $p_T$.

The study of the products of hard-scattering processes between constituent partons provides a means of investigating the hot QCD medium formed in relativistic heavy ion collisions (see [1, 2]). The production rates of hard processes are calculable in perturbative Quantum Chromodynamics (QCD). After the initial hard parton-parton collisions, scattered partons traverse the colored medium. The interactions of these scattered partons with the medium and momentum exchange lead to parton energy loss, which alters the distributions of fragmentation products in the final state. By comparing hard-scattering results in heavy ion collisions with those in elementary pp collisions, modifications of the parton fragmentation products can be studied. Thorough understanding of parton energy loss in the hot QCD medium requires detailed experimental and theoretical investigation. Shown in Figure 1 are cross sections (left ordinate) predicted in perturbative QCD and rates (right ordinate) of various hard probes as a function of center-of-mass energy. The cross sections for hard probes increases as the collision energy is increased.

In this paper, heavy-ion results from the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) will be presented for high $p_T$ particles ($R_{AA}$) and azimuthal
correlations, jet spectra (jet $R_{AA}$ and $R_{CP}$), jet-shape modifications, heavy-quark jets, photon-tagged jet correlations, jet-hadron and dijet correlations, and energy balance.

2. Why study proton-proton (pp), proton-nucleus (p-A) and nucleus-nucleus (A-A) collisions?

Comparisons of measurements in the pp, p-A and A-A colliding systems are expected to allow identification of final state effects due to the presence of a quark-gluon plasma (QGP) in A-A collisions. Comparing p-A to pp collisions allows determination of initial state effects, e.g. gluon saturation and effects of a possible color-glass condensate, and discrimination between different nuclear parton distribution functions. Furthermore, our overall understanding of these high energy nuclear collisions and the initial state of nuclei would be strengthened, if we could understand pp, p-A or d-A, and A-A collisions in a consistent framework. Can we unambiguously distinguish the initial state from the final state in these collisions? Is the initial state composed of gluon fields? To what extent are they saturated, and is there a color glass condensate? These questions about the initial state of nuclei still await resolution, and may require future electron-ion collisions at high energies for a final resolution.

It is important to determine the effects of cold nuclear matter on final state observables for A-A collisions. This requires the study of p-A collisions in order to determine the multiplicity and energy dependence of observables measured in p-A and A-A collisions. To extract precise information on parton energy loss mechanisms, it is instructive to compare hard scattering observables in pp, p-A, and A-A collisions at RHIC and LHC energies. For example, comparison of p-A events at the LHC with similar multiplicity A-A events at LHC and RHIC may shed light on these mechanisms as a function of the virtuality of the parton.

3. High $p_T$ particle suppression

Leading particles and correlations provide information on hard scattering in addition to, or as a substitute for, jets. The spectra of particles produced in A-A collisions can be compared to those in pp collisions, scaled by the number of binary nucleon-nucleon collisions in the A-A geometry. This is carried out through measurements using the nuclear modification factor, which is written as
\[ R_{AA}^i(p_T) = \frac{d^2N_{AA}^i/dp_Td\eta}{\langle T_{AA} \rangle d^2\sigma_{NN}^i/dp_Td\eta} \]  

with \( N_{AA}^i \) the yield for particle (or jet) type \( i \) in A-A collisions and \( \sigma_{NN}^i \) the cross section for particle type \( i \) in pp collisions. \( \langle T_{AA} \rangle \) is the ratio of the number of binary nucleon-nucleon collisions (typically calculated in the Glauber Model) to the inelastic nucleon-nucleon cross section. \( R_{AA} \) is unity when A-A collisions are a superposition of pp collisions, e.g. in the absence of nuclear effects such as parton energy loss. A version of this ratio, called \( R_{CP} \), is often used where the ratio of central to peripheral A-A collisions is taken.

The nuclear modification factor \( R_{AA} \) is investigated in heavy-ion collisions as a function of particle \( p_T \), collision energy \( \sqrt{s_{NN}} \), collision centrality and for different particle types. Shown in Figure 2 is \( R_{AA} \) for charged hadrons and pions in central collisions of heavy ions at SPS, RHIC and LHC energies, as labeled in the figure. At SPS energies there is an enhancement, commonly attributed to initial-state scattering and often called the Cronin effect [3]. A large suppression is observed at the higher energies of RHIC and the LHC at intermediate \( p_T \) (2–20 GeV) with a gradual rise for \( p_T \) beyond 20 GeV. Various model calculations are also shown, with widely diverging predictions at larger \( p_T \). Parameters used in the models are from fits to the RHIC data and extrapolated to the LHC energy. The predictions depend on the parton density and parton energy-loss mechanisms such as scattering and radiation used in the models (for details see [4, 5, 6, 7]). In all cases the suppression results from parton-energy loss in the dense medium.

![Figure 2. \( R_{AA} \) for charged hadrons and pions in central collisions of heavy ions at SPS, RHIC and LHC energies. Various model predictions (see text) are also shown. [8]](image)

Nuclear modification factors \( (R_{AA} \) and \( R_{CP} \)) exhibit medium-induced suppression at \( \sqrt{s_{NN}} = 0.2 \) TeV at RHIC and at \( \sqrt{s_{NN}} = 2.76 \) TeV at LHC. STAR has analyzed \( R_{CP} \) for charged particles in central (0-5%) relative to peripheral (60-80%) Au-Au collisions for a range of energies [9]. \( R_{AA} \) results for central Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV from ALICE [10] at the LHC.

![Figure 3. Preliminary \( R_{CP} \) for charged particles in central (0-5%) relative to peripheral (60-80%) Au-Au collisions for a range of energies [9]. \( R_{AA} \) results for central Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV from ALICE [10] at the LHC.](image)
LHC [10]. These data exhibit significant suppression as already seen at the top RHIC and LHC energies to a dominant Cronin-type enhancement at the lower energies. Disentangling the competition between parton energy loss (suppression) and Cronin-type effects (enhancement) requires further theoretical investigation and additional experimental measurements such as dihadron correlations, perhaps with identified particles, as a function of energy. The theoretical models will need further refinement to include the relative roles of various initial and final state effects including nuclear shadowing, initial state broadening via various mechanisms, multiparton correlations, parton energy loss and collective flow as a function of energy, which is clearly no small task.

Collisions of p-Pb at the LHC and d-Au at RHIC have been studied in order to investigate potential cold nuclear effects and initial state effects. Shown in Figure 4 are $R_{p\text{Pb}}$ and $R_{Pb\text{Pb}}$ for charged particles, and $R_{\gamma Pp\text{Pb}}$ for photons, $W^{\pm}$, and $Z^{0}$. Note, as expected, $R_{Pb\text{Pb}}$ for the non-strongly interacting gauge bosons is consistent with a value of 1. This is also the case for charged particles in p-Pb reactions, indicating no observation of initial state nuclear effects in the production of charged particles at mid-rapidity. The $R_{Pb\text{Pb}}$ for charged particles for central collisions at the LHC exhibits a strong suppression, as seen in Figure 2. The $R_{d\text{Au}}$ of neutral pions in $\sqrt{s_{NN}} = 0.2$ TeV minimum bias d-Au collisions at RHIC are also consistent with a value of 1, as seen in Figure 5. Also, shown in the figure are $R_{A\text{Au}A\text{u}}$ for central (10%) Au-Au collisions at the same energy. Clearly, for both cases p-Pb at LHC and d-Au at RHIC there appear to be no strong initial state effects, while for central A-A collisions at RHIC and LHC energies there is a strong suppression of high $p_T$ particles. Together these data provide strong evidence that the suppression is a final state effect.

Figure 4. $R_{p\text{Pb}}$ versus $p_T$, $E_T$ or $m$ for charged particles and for gauge bosons ($\gamma$, $W^{\pm}$ and $Z^{0}$) in central collisions [8, 11]. Also shown are $R_{p\text{Pb}}$ data for charged particles [12].

The suppression in A-A collisions is observed to increase with collision centrality. This can be seen in Figure 6 where $R_{Pp\text{Pb}}$ is presented as a function of $p_T$ for central (0-10%) and peripheral (70-80%) collisions at mid-rapidity[12]. Also shown for reference is the p-Pb data that exhibit no suppression. There is also a dependence of $R_{p\text{Pb}}$ on the particle-type for hadrons, as seen in Figure 7. The $\pi$'s, K's and protons exhibit increased suppression for the lighter hadrons over $1 < p_T < 8$ GeV. The $\pi$'s and K's have similar suppression above $p_T \sim 3$ GeV, whereas protons are less suppressed over the entire $1 < p_T < 8$ GeV range. Over this $p_T$ range there may be a combination of strong suppression and a mass-dependent radial flow or recombination in Pb-Pb that results in the observed $R_{p\text{Pb}}$ particle-type dependence. The suppression observed
Figure 5. $R_{dAu}$ for neutral pions in minimum bias d-Au collisions from PHENIX. Shown are two sets of data each taken with a different calorimeter system (PbGI and PbSc). Systematic errors are shown as bands, with the band around unity the uncertainty in the overall normalization. Shown for reference is $R_{AuAu}$ for central (10%) Au-Au collisions. [13]

for more central collisions in Pb-Pb and the $R_{pPb}$ mass dependence coupled with the absence of suppression in p-Pb suggests parton energy loss in the medium in A-A collisions.

Figure 6. $R_{pPb}$ for non-single diffractive interactions and $R_{PbPb}$ for central and peripheral collisions as a function of $p_T$. [12]

Figure 7. $R_{PbPb}$ for $\pi$, K, proton in central (0-5%) Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Adapted from [14].

4. Jets

Measurements of jets allow determination of the initial binary parton-parton scattering kinematics. Comparison of jet results in pp, p-A and A-A aids in discrimination of effects due to parton propagation in the medium, c.f. parton energy loss, from other effects that are derived from either the initial state or interactions in cold nuclear matter. Di-jet and $\gamma$-jet asymmetries relative to the collision geometry and orientation relative to the reaction plane can
The technique of jet reconstruction in p-A and A-A collisions follows that established in pp collisions, taking into account also the additional complications associated with the large hadronic background from soft particles in A-A collisions that is unassociated with the jet. Background subtraction techniques have been developed to be able to correctly determine the jet energy and shape. Clustering algorithms are used to distinguish hadrons from parton fragmentation and those presumably associated with the background. For jet measurements ATLAS and CMS incorporate both electromagnetic and hadronic calorimetry, while ALICE utilizes electromagnetic calorimetry and charged particle tracking to identify the hadronic component of jets. Clustering algorithms that are both infra-red and collinear-safe have been developed and are used to identify jets and to compare directly with theory. For jet-finding the anti-$k_T$ algorithm [15] from the FASTJET package [16] is used primarily. The soft background fluctuates event-to-event and is identified from the underlying event typically through the use of the $k_T$ [17] or iterative-cone algorithms. Finally the background is subtracted, detector efficiency and resolution corrections implemented, and the jet energy scale adjusted via data-driven and/or Monte Carlo techniques in order to derive a final jet energy spectrum. [18] Details of the implementation of these techniques for jet-finding in A-A collisions can be found in [19].

**Figure 8.** Left: Di-jet energy asymmetry $A_J$ (defined in text) measured in $\sqrt{s_{NN}} = 2.76$ TeV central (0-10%) Pb-Pb events and in $\sqrt{s} = 7$ TeV pp data and Monte Carlo simulations using PYTHIA jets embedded in HIJING events. Right: Corresponding azimuthal angular correlation between leading and next-to-leading jet on opposite-side. Monte Carlo simulations using HIJING+PYTHIA Di-jets are also shown for comparison.

Measurements of complete jets were reported for the first time in A-A collisions by ATLAS [20] and CMS [21]. Displayed in the left panel of Figure 8 are the ATLAS measurements of the di-jet energy asymmetry $A_J$, where $A_J = E_{T1}E_{T2}/(E_{T1} + E_{T2})$ for $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb compared to $\sqrt{s} = 7$ TeV pp data and Monte Carlo simulations using PYTHIA jets embedded in HIJING events. T1 is defined as the highest energy jet with transverse energy $E_{T1} > 100$ GeV and T2 the highest transverse energy jet in the opposite hemisphere with $E_{T2} > 25$ GeV. The Pb-Pb events exhibit a large asymmetry in the jet energies with the opposite-side jet having...
lost considerable energy compared to the pp data and HIJING+PYTHIA simulations. This is a clear indication of jet quenching in Pb-Pb collisions at the LHC. In the right panel of Figure 8 the azimuthal angular correlation $\Delta \phi$ between the leading jet and the opposite-side jet indicates that the jet angles, however, are not appreciably altered and exhibit the expected peak at $\Delta \phi = \pi$ as seen in the pp data and HIJING+PYTHIA simulations. A preliminary result of a similar asymmetry in momentum for di-jets was recently reported by STAR for $\sqrt{s_{NN}} = 0.2$ TeV Au-Au for jets of considerably lower energy with $p_T^1 > 20$ GeV and $p_T^2 > 10$ GeV [22].

Jets have been measured in $\sqrt{s} = 0.9$, 2.76, 7 and 8 TeV pp, $\sqrt{s_{NN}} = 5.02$ TeV p-Pb and in $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb collisions at the LHC and in $\sqrt{s_{NN}} = 0.2$ TeV Au-Au collisions at RHIC. Displayed in the left panel of Figure 9 is the $R_{pPb}$ for fully-reconstructed jets in ATLAS [23] for $R=0.4$ and CMS [24] for $R=0.3$, and charged jets in ALICE [25] for $R=0.4$ at midrapidity in $\sqrt{s_{NN}} = 5.02$ TeV p-Pb collisions. The data are consistent with $R_{pPb} = 1$ over the range of jet momenta $25 < p_T < 800$ GeV/c. The $R_{AA}$ for fully-reconstructed jets measured in ALICE [26] for $R=0.2$ and CMS [27] for $R=0.3$ in $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb collisions for various centralities are shown in the right panel of Figure 9. Note that different techniques are used in the two experiments for the full jet measurements, as described above. The results are consistent and exhibit an increased suppression of jets compared to pp and p-Pb for more central collisions ($0-5\%$ and $0-10\%$) compared to less central collisions ($10-30\%$).

Investigation and measurement of differences in the suppression of parton probes of different flavor or mass is important to determine parton energy loss mechanisms and flavor or mass dependences. Shown in the left panel of Figure 10 for central collisions of Pb-Pb is the $R_{AA}$ for D-mesons [28] and charged particles, which are dominated by pions. The suppression of D-mesons is consistent with that of charged particles, indicating that the energy loss of the heavier charm quark is not very different from that of light quarks. Also shown are the results from B-decays to $J/\psi$ for inclusive Pb-Pb collisions [29]. The B-decays are less suppressed, but the difference in centrality between the B results and the others in the figure must be noted and make up for the difference. Thus, it is not clear yet whether b-quarks are less suppressed for a
given collision centrality (which may reflect path-length, to some extent). Shown in the right panel of Figure 10 are the jet $R_{AA}$ from b-jets [30] and inclusive jets [27] measured in central Pb-Pb collisions. This result clearly indicates that the b-jet suppression is of similar magnitude to that of inclusive jets demonstrating the lack of flavor dependence in the quenching mechanism at these large momenta.

![Figure 10](image-url)

**Figure 10.** Left: $R_{AA}$ for D-mesons and charged particles in central collisions of Pb-Pb from ALICE [28], and B-decays to $J/\psi$ for inclusive Pb-Pb collisions from CMS [29]. Right: $R_{AA}$ for various particles (see legend), inclusive jets and b-jets measured in central Pb-Pb collisions from CMS [27, 30].

Parton energy loss in the QCD medium is expected to modify jet fragmentation in A-A collisions as compared to that in pp collisions. Patterns of fragmentation can be investigated and compared to pp collisions to determine any modifications. A measurement of the fragmentation function can be determined by measuring $R_{AA}$ or $R_{CP}$ as a function of the momentum fraction $z$, of the jet with momentum $p_{jet}$, that is carried by the detected particle of momentum $p$. This is defined as $z = p/p_{jet}$ or often designated as $\xi = \ln(1/z)$. The $R_{AA}$ measured by CMS [31] and $R_{CP}$ by ATLAS [32] are shown in the left panel of Figure 11. The two are consistent and exhibit enhancements at large $\xi$ representing more particles with low momentum fraction $z$ in Pb-Pb as compared to pp collisions. Likewise, there appears to be a slight enhancement observed at low $\xi$ or large momenta. Thus, jets are significantly modified in Pb-Pb compared to pp collisions.

This is also seen in the $\gamma$-hadron correlations measured by PHENIX at RHIC. The right-top panel of Figure 11 shows the yield per trigger for 0-40% central Au-Au collisions and pp collisions as a function of $\xi$ and $z_T$ (top scale). The $I_{AA}$ defined as the ratio of Au-Au to pp fragmentation functions is shown in the bottom-right panel. Also shown are pQCD-inspired model calculations, represented as curves in the figure. These incorporate parton energy loss and result in suppression at low $\xi$, reappearance of the lost energy in enhanced production of low $p_T$ particles, i.e. at larger $\xi$. See [33] and references therein for details in the models.

Jet modification can also be investigated by studying jet shapes in Pb-Pb collisions relative to those in pp collisions. The ratio of the charged particle density in central Pb-Pb relative to that in pp is shown as a function distance $r$ from the jet center for anti-$k_T$ jets in a cone of radius $R = 0.3$ in Figure 12. An increase in the ratio is observed for large distances near the
Figure 11. Left panel: Fragmentation function ratios $R_{AA}$ from CMS [31] and $R_{CP}$ from ATLAS [32] as a function of $\xi = \ln(1/z)$ of jets as defined in legend. Right panel: (top) $\gamma$-hadron correlation yield per trigger for 0-40% central Au-Au collisions (circles) and pp collisions (squares) as a function of $\xi$. (bottom) $I_{AA}$ ratio of Au-Au to pp fragmentation functions. Also shown are model calculations (curves), see text and [33] for details. The $\gamma$-hadron $p_T$ ranges are given in the legend and the dependence on $z_T$ is shown on the top scale.

Figure 12. Ratio of the number of charged tracks with $p_T > 1$ GeV/c in Pb-Pb central collisions relative to that in pp for $p_T > 100$ GeV/c jets using anti-$k_T$ with $R = 0.3$ as a function of radial distance from the center of the jet from [34].
cone "edge" ($r = R$) with a depletion at intermediate distances. This is indicative of broadening of the jet, and is suggestive of parton energy loss. Detailed studies of the particle densities as a function of cone size for central Pb-Pb exhibit enhanced particle densities that also increase with cone size relative to pp or peripheral Pb-Pb collisions [35].

The centrality dependence of jet $R_{AA}$ can be seen in Figure 13. As expected jet quenching, like high $p_T$ particle suppression, increases (i.e. jet $R_{AA}$ decreases) for more central collisions. This reflects the increase in the size of the medium as collisions become more central and may be the reason for the slight differences in jet $R_{AA}$ observed by the three collaborations (above) for slightly different centrality ranges.

![Figure 13. $R_{AA}$ for jets with $80 < p_T < 100$ GeV and $|y| < 2.1$ as a function of $\langle N_{part} \rangle$. [36]](image)

ATLAS, ALICE and CMS have measured finite values of $v_2$ for particles and jets at large transverse momenta in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. All three experiments agree well in the measurements of $v_2(4)$ for $< p_T < 20$ GeV over the entire range of centralities [38, 37]. At larger momenta CMS has measured a value of $v_2 \simeq 0.02$ over the range $20 < p_T < 50$ GeV for particle tracks in 0-5 % central collisions [37]. ATLAS finds $v_2^{jet} \simeq 0.02$ over the range $50 < p_T < 200$ GeV for jets in 5-10 % central collisions [38]. ALICE measures a somewhat larger $v_2^{jet}$ than ATLAS but with lower track $p_T$ threshold and with fairly large uncertainties for charged jets in the range $50 < p_T < 100$ GeV.[26] Since hydrodynamics is not expected to play any direct role at these larger transverse momenta, a significant value of $v_2$ at these momenta is highly indicative of a path length dependence of parton energy loss. The partons lose more energy in the out-of-plane direction than in-plane due to the elongation out-of-plane in the overlap region, thus resulting in a finite value of $v_2$ from the different path lengths in- and out-of-plane.

Direct photons are not expected to interact strongly with the medium in Pb-Pb collisions. Thus, they can be used to determine the kinematics of the initial hard scattering. This is substantiated in Pb-Pb collisions where $R_{AA}^{\gamma} = 1.0$ within uncertainties, which indicates that the yields of isolated photons in Pb-Pb is a superposition of those measured in pp data. Photons at leading order are produced back-to-back with an associated parton of nearly identical transverse momenta. Thus, measurements of back-to-back photons and jets can be used to test jet quenching and the energy lost by the parton by comparison with the photon. Shown in Figure 14 are $R_{J\gamma}$ of isolated prompt photons with jets that are back-to-back with the photon from ATLAS [39] and CMS [40]. The ATLAS data are for photon $60 < p_T^{\gamma} < 90$ GeV at mid rapidity, with $p_T^{jet} > 25$ GeV within a back-to-back azimuthal angular range $\Delta\phi_{J\gamma} > 7\pi/8$. The CMS data are for isolated photons with transverse momentum $p_T^{\gamma} > 60$ GeV and an associated jet with $p_T^{jet} > 30$ GeV in the same back-to-back range. Also shown are Monte Carlo simulations of hard scattering using PYTHIA superimposed on data in the ATLAS case, with PYTHIA alone and PYTHIA+HYDJET in the CMS case. The pp reference data are also shown for CMS. The
R$_{J\gamma}$ is observed to decrease with increasing centrality ($N_{\text{part}}$) and remains below the values from the PYTHIA+Monte Carlo simulations and pp reference data, except for the least central Pb-Pb case. In addition, no angular broadening is observed (not shown) beyond that seen in the pp data and MC reference at all centralities. Similar results have been observed for Z-jet back-to-back coincidence measurements [41]. Furthermore, the average ratio of jet transverse momentum to photon transverse momentum for the most central events was found by CMS to be $0.73 \pm 0.02$ (stat.) $\pm 0.04$ (syst.), which is lower than the value of 0.86 seen in the pp data and that predicted by PYTHIA + HYDJET at the same centrality [40].

![Image of R$_{J\gamma}$ vs N$_{\text{part}}$ for Pb-Pb collisions](image)

**Figure 14.** Left: R$_{J\gamma}$ of isolated prompt photons with back-to-back jets from ATLAS [39] with R=0.2. Right: R$_{J\gamma}$ from CMS with R=0.4 [40]. Data shown as a function of centrality as represented by $N_{\text{part}}$ for $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb collisions, see text for details.

It is important to understand what happens to the energy lost by partons as they traverse the medium. There is some indication from the fragmentation function measurements above that the jet suppression leads to redistribution of the lost energy to lower momentum particles. The top-left panel of Figure 15 shows the dependence of $I_{AA}$ on the angular distribution of particles on the away-side of the trigger $\gamma$ for $\gamma$-hadron correlations in 0-40% central Au-Au collisions [33]. The $\gamma$ and hadron momentum ranges are shown in the legend, with the $\gamma$-hadron azimuthal angle difference defined as $\Delta$. Three regions of away-side angles are presented, as indicated in the figure. In going from the larger away-side hadron acceptance range $|\Delta\phi - \pi| < \pi/2$ to the smaller ranges of $|\Delta\phi - \pi| < \pi/3$ and $|\Delta\phi - \pi| < \pi/6$, the observed enhancement at larger $\xi$ (lower momentum particles) is reduced, becoming negligible for the most restrictive range. However, the suppression at low $\xi$ remains in the cases studied. The bottom-left panel depicts the ratio of $I_{AA}$ for full away-side acceptance to the most limited, $|\Delta\phi - \pi| < \pi/2$ divided by $|\Delta\phi - \pi| < \pi/6$. The $I_{AA}$ is observed to vary with significant enhancement at larger $\xi$ as the away-side hadron acceptance becomes less limited, indicating that the enhancement at large $\xi$ is due to hadrons emitted at the large angles associated with $|\phi - \pi| > \pi/6$.

STAR has studied jet-hadron correlations, measuring the widths of the peaks on the away-side of the jet in 0-20% central Au-Au collisions [42]. $D_{AA}$ measures the $p_T$ difference between Au-Au and pp collisions for each $p_{T_{\text{assoc}}}$ bin with mean $\langle p_{T_{\text{assoc}}} \rangle$ as defined below:
Thus, $D_{AA} \neq 0$ indicates modification of jet fragmentation in Au-Au compared to pp collisions. $D_{AA} = 0$ represents the case where Au-Au collisions have identical fragmentation patterns in $p_T$ as pp collisions for all $p_T^{assoc}$ bins. It is expected that the near-side trigger jet has a surface bias, making it more likely that the away-side hadron traverses a larger distance in the medium and that effects of parton energy loss will be prominent for the away-side hadrons. Furthermore, the widths of the trigger jets (defined to be the near-side) are observed to be the same in Au-Au and pp collisions in this study. Shown in the right panel of Figure 15 are the away-side momentum difference $D_{AA}$ for two ranges of jet reconstructed momentum. The measured $D_{AA}$ show that high $p_T^{assoc}$ hadrons on the away-side are suppressed and those at low $p_T^{assoc}$ are enhanced. This indicates that jets in Au-Au are significantly softer than those in pp collisions. Also shown in the figure are YAJEM Monte Carlo model calculations of in-medium shower evolution which incorporate radiative and elastic energy loss. This model qualitatively describes the general trends of the jet-hadron correlation data.

Another approach to study the energy redistribution due to parton energy loss in A-A collisions is to measure and correlate charged particles with the momentum imbalance of di-jets and centrality. [44] Di-jets were reconstructed by CMS and the di-jet imbalance, as presented above for ATLAS in Figure 8, was found to increase with centrality. CMS found that as the di-jet momentum imbalanced increases, the fragmentation pattern of the away-side jet becomes softer. This can be seen in Figure 16. Plotted is the missing $p_T$ of charged tracks projected onto the lead-jet axis as given by

$$D_{AA}(p_T^{assoc}) = Y_{Au/Au}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{Au/Au} - Y_{pp}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{pp}$$

(2)
\[ \hat{p}_T^\parallel = \sum_i -p_{T,i}^\parallel \cos(\phi_i - \phi_{\text{lead-jet}}) \] (3)

for tracks with momenta \( p_T > 0.5 \text{ GeV/c} \) at mid-rapidity (\( |\eta| < 2.4 \)) and jets with \( p_{T,jet} > 120 \text{ GeV/c} \) at \( |\eta| < 1.6 \). In the left panel the momentum is balanced between the lead-jet (negative values of \( \hat{p}_T^\parallel \)) and away-side jet (positive \( \hat{p}_T^\parallel \)) hemispheres. When only tracks inside the jet cones are included in the calculation of \( \hat{p}_T^\parallel \), shown in the middle panel, there is an excess of track momentum in the lead-jet direction and opposite that for tracks outside the jet cones as shown in the right panel.

Figure 16. Missing transverse momentum \( \hat{p}_T^\parallel \) of charged tracks projected onto the leading jet axis as a function of di-jet momentum asymmetry \( A_J \) for central collision event class 0-30%. Average values are plotted as data points, with colored regions for contributions from each track \( p_T \) range as designated in the legend. Left panel: all charged tracks. Middle panel: only charged tracks inside the jet cones of \( \Delta R < 0.8 \). Right panel: charged tracks outside the jet cones. Track selections are depicted relative to the jet cones in the top row of diagrams for each panel. Average values are plotted as data points, with colored regions for contributions from each track \( p_T \) range (in GeV): data (\( > 0.5 \)), blue (0.5-1.0), yellow (1.0-2.0), orange (2.0-4.0), green (4.0-8.0), red (\( > 8.0 \)).[44]

The results on di-jets from ATLAS and CMS show that there is an increase in the di-jet energy and momentum asymmetry as the centrality of the collision increases, which is consistent with energy loss of the parton as it traverses a larger distance in the medium. CMS results indicate that this imbalance is recovered only when lower \( p_T \) tracks, down to \( p_T = 0.5 \text{ GeV/c} \), are included in the calculation of \( \hat{p}_T^\parallel \).

5. Summary and Conclusions

In summary, the recent heavy-ion collision results from hard scattering processes at RHIC and LHC have provided a wealth of information to address parton energy loss in the medium. Hadrons with large transverse momentum and jets are suppressed in heavy-ion collisions compared to proton-proton collisions. Hadrons and jets with heavy quarks appear to also
be suppressed at about the same level as those with light quarks. The jet fragmentation is modified, with the modification increasing with the centrality of the heavy-ion collision. When a comparison of the heavy ion results is made to those in pp, p-A and theory, a consistent picture emerges. The suppression of particles and jets with large transverse momentum is a product of parton energy loss in the hot QCD medium. Di-jet correlations exhibit a di-jet energy and momentum imbalance that increases with the centrality of the collision. Correlations of di-jets, jets and trigger photons, and hadrons and trigger jets indicate that the parton energy loss is redistributed to lower momentum particles at larger angles from the axis of the hard-scattered parton.

In order to understand at a fundamental level the parton energy loss in QCD at high temperatures, its dependence on the properties of the parton and of the medium need further addressing. This leads to more specific questions. What is the dependence of parton energy loss on the properties (e.g. flavor, mass and energy) of the traversing parton? Can this be accessed experimentally in the final state, for example by incorporating identification of particles? What is the extent to which radiative and collisional energy loss mechanisms play a role? How does the energy loss depend on other properties of the medium, especially temperature? Can we say more about happens to the lost energy? How is it dependent on the virtuality of the parton and its pathlength in the medium? Answers to these questions are being pursued vigorously both theoretically and experimentally. More differential measurements with a well-determined initial state and controlled initial- and final-state geometries may provide the key to obtain these answers.

6. References

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