Scientific assessment of future measurements at RHIC by High-pT Working Group

Kirill Filimonov
.LBNL...

Saskia Mioduszewski
.TAMU...

Denes Molnar
Department of Physics, Purdue University, 525 Northwestern Avenue, West Lafayette, IN 47907, USA and RIKEN BNL Research Center, 5000 Pennsylvania Avenue, Upton, NY 11973-5000, USA

Jiangyong Jia and Jiamin Jin
Department of Physics, Columbia University, 538 West 120th Street, New York, NY 10027, USA

...others...
.at other places...

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This is a summary of relevant future high pT measurements at RHIC - prepared by the RHIC-II High pT Working Group.

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I. PURPOSE AND SCOPE

In this document we motivate important future measurements at the Relativistic Heavy Ion Collider (RHIC) facility. In order to avoid overlap with the Heavy Flavor and Electromagnetic Probes working groups, we mainly focus on high-pT observables involving light quarks and gluons.

...anything else here?...

II. MOTIVATION FOR HIGH PT STUDIES

The main advantage of studying particles with high transverse momentum (p_T) in nuclear collisions is that their yields are rigorously calculable from the fundamental theory of quantum chromo-dynamics (QCD). Large p_T implies energetic ("hard") partons created in a process with large momentum transfer for which the theory is weakly-coupled and perturbation theory is, therefore, applicable.

The perturbative QCD program has been a great success at collision energies $\sqrt{s_{NN}} >\sim 50$ GeV **... refer to CERN, Tevatron, RHIC ...**

In heavy-ion collisions, the main objective of study is the dense nuclear matter created in the collision, in particular, its equation of state and transport properties (such as shear viscosity, or diffusion constants). The space-time evolution of the nuclear medium involves low ("soft") momenta and, hence, is out of the scope of perturbative QCD. However, high-p_T partons do interact with the medium leading to calculable modifications of high-p_T observables. Measurements of several different high-p_T observables can therefore provide a unique opportunity to infer the color charge density and geometry of the expanding medium, together with the strength and nature of the coupling between energetic partons and the soft medium. These pieces of information strongly constrain dynamical models of the collision and, combined with those models, help determine the degree of thermalization in the collision, the medium properties, and the nature of the quark-gluon phase transition (equation of state).

High-pT observables are also sensitive to the partonic wave functions of the incoming nuclei. Though the parton structure of nuclei is best studied at dedicated electron-nucleus (eA) collider facilities, such as the future eRHIC[19], a lot of information can be extracted from heavy-ion collision data in the meantime. Of most interest is the low $x \lesssim 10^{-3}$ region, where nonlinear QCD dynamics is expected to play a role leading to a coherent "color glass condensate" (CGC) state[7]. At RHIC energies CGC studies require measurements at forward (or backward) rapidities, a topic studied in depth by the Forward Physics Working Group.

III. PRESENT STATUS OF THEORY AND MEASUREMENTS

A. Perturbative QCD and parton energy loss

The main theory paradigm to address high-p_T physics at RHIC is factorized perturbative QCD (pQCD) supplemented with parton energy loss (jet-quenching) - for a detailed discussion see, e.g., [43]. In this approach energetic partons form in hard parton collisions, then travel through the nuclear medium, and eventually fragment to hadrons outside the medium via the same mechanism as in vacuum.

1. *Nucleon-nucleon collisions*

In the case of nucleon-nucleon collisions, final state interactions are absent and the formalism at leading-order (LO) gives the inclusive distribution of hadron species h in terms of the parton distributions (PDFs) $f_{i/p}$ for the various parton species i in the nucleon, the fragmentation functions (FFs) $D_{h/i}(z)$ describing the probability for a parton of species i to fragment into a hadron of species h with fractional momentum $z = p_h/p_i$, and the differential cross sections for the underlying partonic subprocesses $ab \to cd$ (Rutherford scattering, essentially) as

$$E_h \frac{d\sigma^{NN}}{d^3p} = K_{NLO} \sum_{abcd} \int_0^1 dz_c \int_{x_{a,min}}^1 dx_a \int_{x_{b,min}}^1 dx_b \, f_{a/p}(x_a, Q_a^2) \, f_{b/p}(x_b, Q_b^2) \, D_{h/c}(z_c, Q_c^2) \frac{\hat{s}}{\pi z_c^2} \frac{d\sigma^{ab\to cd}}{d\hat{t}} \delta(\hat{s} + \hat{u} + \hat{t}) \ . \quad (1)$$

In the above, massless partons are assumed, which at RHIC energies is applicable to gluons and light and strange quarks. The phenomenological factor $K_{NLO} \sim 1-3$ accounts for next-to-leading order (NLO) "corrections", while the limits $x_{a,min}$ and $x_{b,min}$ are determined kinematically by the rapidity and p_T of the hadrons of interest. The PDFs and FFs are nonperturbative but universal input quantities that can be extracted from e^+e^- and eN reactions[43]. On the other hand their Q^2 dependence, just like the partonic differential cross section, is calculable from perturbative QCD. The scale factors Q_i^2 in the PDFs are typically chosen to be proportional to $Q_a^2 = Q_b^2 \propto p_{c,T}^2$, while in the FFs $Q_c^2 \propto p_{h,T}^2$ with proportionality constants of order 1.

For intermediate momenta $p_T \sim 2-5$ GeV, the approach overpredicts the curvature of the spectra. This can be corrected with a generalization of parton distributions to include transverse momenta k_T as

$$f_i(x, Q^2) \to \tilde{f}_i(x, k_T, Q^2) = f_i(x, Q^2) \, g(k_T), \qquad g(k_T) = \frac{e^{-k_T^2/\langle k_T^2 \rangle}}{\pi \langle k_T^2 \rangle} \ , \qquad \int dx_i f_i \to \pi \int dx_i \, dk_{T,i}^2 \tilde{f}_i \quad (2)$$

where the width of the Gaussian $\langle k_T^2 \rangle \sim 1-3$ GeV^2 is a phenomenological parameter.

... perhaps explain what happens at NLO - renormalization scale ...

The perturbative approach describes light particle yields in $p+p$ collisions at RHIC very successfully, as shown in Fig. 1. Next-to-leading order (NLO) pQCD calculations reproduce the measured photon and π_0 yields well at $\sqrt{s} = 200$ GeV [10, 11]. Moreover, the observed constant η/π_0 ratio (Fig. 2) provides further support for the pQCD paradigm (namely that both particles come from the same distribution of jets via a universal fragmentation process).

However, proton data [52] are significantly underpredicted by NLO pQCD even at $p_T \sim 7$ GeV as can be seen in Fig. 3. This is likely an indication that the real perturbative regime is at higher p_T for protons, probably because protons are too heavy (pQCD assumes $p_T \gg m$) and power corrections may be relevant[**?**]. NLO proton yield calculations are also quite sensitive to the renormalization scale [56].

The fact that at RHIC perturbative QCD works best for pions underscores the importance of identified particle measurements. Charged hadron yields have significant proton contributions, probably even at $p_T \sim 10$ GeV, which at present are not under good theoretical control. In the future it would be important to expand the measurable proton p_T range well beyond 7 GeV to test whether the theory works better at higher p_T.

2. *Nucleus-nucleus collisions*

In heavy-ion collisions the energetic partons interact with the medium as they propagate through the collision zone and typically lose energy. It has been argued that the dominant mechanism of energy loss is gluon radiation[44–48, 50]. For soft gluon radiation, energetic partons do not change direction appreciably and energy loss can therefore

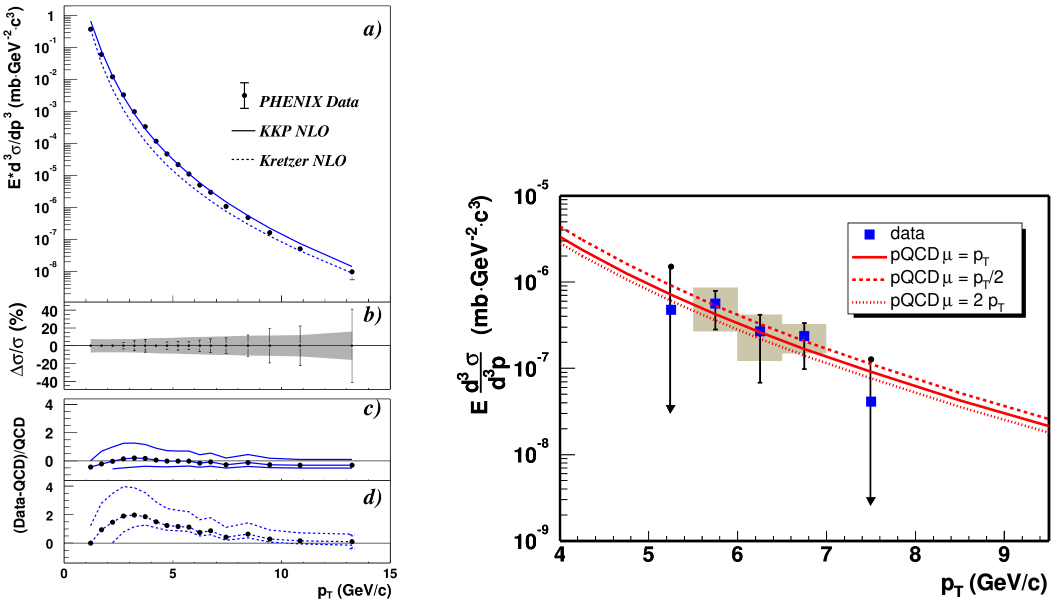

FIG. 1: Good agreement between neutral pion (left) and direct photon (right) spectra in $p+p$ collisions at RHIC [10, 11] and next-to-leading order (NLO) perturbative QCD calculations.

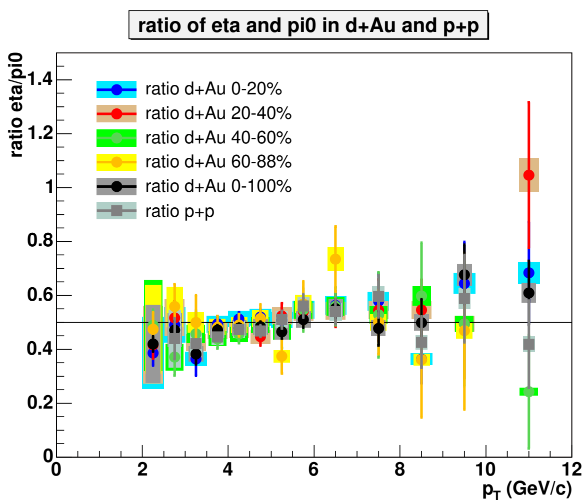

FIG. 2: Constant η/π_0 ratio observed by PHENIX in $p+p$ and $d+Au$ at $\sqrt{s_{NN}} = 200$ GeV at RHIC [51].

be introduced in the formalism via a *modified fragmentation function* $\tilde{D}$ [2, 49]

$$z_c \tilde{D}_{h/c}(z_c, Q_c^2, p_c) = \int d\varepsilon\, P_c(\varepsilon, p_c) \left[z_c' D_{h/c} D(z_c', {Q_c'}^2) + \bar{N}_g(\varepsilon) \bar{z}_g D_{h/g}(\bar{z}_g, Q_g^2) \right] \quad , \quad z_c' \equiv \frac{z_c}{1-\varepsilon} \quad , \quad \bar{z}_g \equiv \frac{z_c}{\varepsilon / \bar{N}_g(\varepsilon)} \qquad (3)$$

where $P_c(\varepsilon, p_c)$ is the probability for a parton of species c with momentum p_c to lose a fraction ε of its energy. The first term in the square brackets is the fragmentation contribution for the high-p_T parton, while the second term is that for the radiated gluons. The latter only contribute up to moderate $p_T <\sim 4$ GeV [5].

The above formula is already an approximation in that it considers only the average number $\bar{N}_g$ of gluons radiated for a given total energy loss fraction ε and, furthermore, only the average momentum fraction $\varepsilon/\bar{N}_g$ carried away by each gluon. A more complete treatment[**?**] would include a sum over probabilities $P_{n,c}(p_c)$ for emission of n gluons off a parton c, and for each n, integrals over the energy loss fractions $\{\varepsilon_{n,i}(p_c)\}$ corresponding to each radiated gluon i. In addition, energy loss depends on the spatial location where the parton is produced, therefore, there should be a spatial average included in (3). Finally, in noncentral collisions the average path the hard parton travels also depends on its direction of motion, generating an azimuthal angle dependence in the modified fragmentation function.

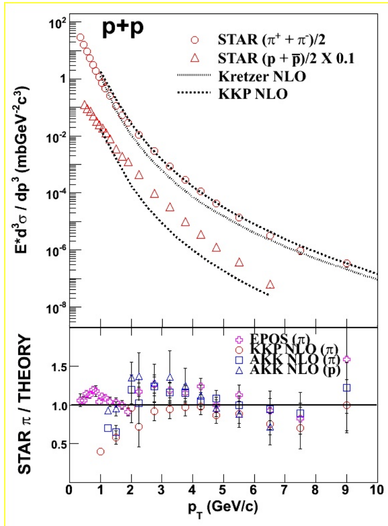

FIG. 3: Proton data (triangles) in $p+p$ at $\sqrt{s_{NN}} = 200$ GeV at RHIC reported by STAR compared to NLO pQCD calculation (dashed) [52]. Similar comparison for pion data is also shown (circles).

3. Energy loss models

The probability $P_c(\varepsilon, p_c)$ for energy loss can be determined from a phenomenological model. Popular approaches, such as those by Gyulassy, Levai, and Vitev (GLV) [1, 47, 48] or Wiedemann *et al* (WS) [44–46] are based on the Gyulassy-Wang model[6], which considers a medium with localized, static, random color potentials of Yukawa type

$$V_{ij}^a(q) = g\, T_{ij}^a\, \delta(q^0) \frac{e^{iqx}}{\vec{q}^{\,2} + \mu_D^2} \,. \tag{4}$$

Given a set of scattering centers at locations $\{x_i\}$, the spectrum of radiated gluons can be computed order by order in perturbation theory either diagrammatically (GLV) or using a path integral formulation (WS). The final results then need to be averaged over the distribution of scattering centers.

Several approximations are required to make the calculations tractable, such as, high-energy (Eikonal) limit, soft gluon radition, Poisson ansatz for multiple gluon radiation, and simplified parametrizations for the spacetime evolution of the medium. Many of these assumptions are expected to be carefully tested and improved upon during the next few years.

A useful, approximate energy loss formula from the GLV approach, for a medium that evolves via a longitudinal Bjorken expansion $\rho \propto 1/\tau$, is

$$\Delta E^{(1)} \approx \frac{9\pi C_R \alpha_s^3}{4} L \frac{1}{R_A^2} \frac{dN_g}{dy} \ln \frac{2E}{\mu_D^2 L} \tag{5}$$

where $C_R = 3$ for gluons, $4/3$ for quarks, dN_g/dy is the rapidity density of soft gluons (i.e., the partonic medium), R_A is the transverse radius of the medium, and L is the pathlength travelled by the jet until it escapes from the medium. The above expression is only the first term in the opacity expansion (i.e., corresponds to a single scattering with the medium) but it has been argued that subsequent scatterings affect parton energy loss by less than $\sim 20\%$ for $p_T^{jet} > 20$ GeV [2].

B. Nuclear suppression factor (R_{AB})

The most basic observable of nuclear effects in heavy-ion colllisions is the nuclear suppression factor

$$R_{AB}(p_T, y, b, h) = \frac{dN_h^{AB}}{p_T dp_T dy} / \frac{T_{AB}(b)\, d\sigma_h^{NN}}{p_T dp_T dy} \tag{6}$$

which is the ratio the observed spectra to the spectra in case of independent nucleon-nucleon scatterings. Here, T_{AB} is the nuclear overlap factor

$$T_{AB}(b) \equiv \int d^2s\, T_A(\vec{s}+\vec{b})\, T_B(\vec{s}) \ , \qquad T_A(\vec{s}) \equiv \int dz \rho_A\Big(\sqrt{z^2+\vec{s}^{\,2}}\Big) \ . \tag{7}$$

Alternatively, the suppression pattern can also be characterized by the central-to-peripheral ratio

$$R_{cp} = \frac{R_{AB}(b_{central})}{R_{AB}(b_{peripheral})} \ . \tag{8}$$

In the parton energy loss framework, R_{AB} depends on the density of the parton medium, the length L the jet parton travels in the nuclear medium, and the strength of coupling between the jet parton and the medium. Parton energy loss is mainly sensitive to a combination of these parameters, the so-called *transport coefficient* $\hat{q}$ [44]

$$R \equiv \frac{1}{2}\hat{q}L^3 \equiv \frac{L^2}{R_A^2}\frac{dN_g}{dy} \tag{9}$$

(dN_g/dy is the gluon rapidity density, R_A is the effective transverse nuclear radius).

Fig. 4 shows that both the charged particle and π_0 suppression can be well reproduced[3] by the parton energy loss formalism, assuming a thermalized *gluon* plasma with gluon rapidity density $dN_g/d\eta = 1150$ expanding longitudinally via a Bjorken expansion $dN_g(\tau, y, \vec{x}_T)/dyd^2x_T \propto 1/\tau$. The corresponding entropy density is in good agreement with values needed by ideal (isentropic) hydrodynamic calculations to match the RHIC data (spectra and elliptic flow) at low momenta $p_T \lesssim 1.5$ GeV [53–55].

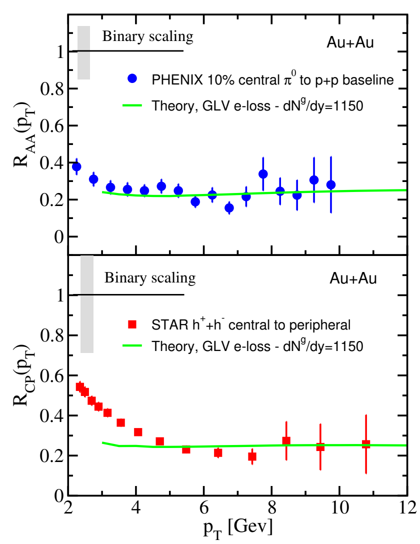

FIG. 4: Nuclear suppression factor R_{AA} for π_0 (top) and charged hadron R_{cp} (bottom) in $Au + Au$ at $\sqrt{s_{NN}}$ at RHIC from the GLV approach[3].

C. Azimuthal anisotropy v_2

A useful quantity that is sensitive to the *shape* of the collision region is the azimuthal anisotropy $v_2 \equiv \langle \cos 2\phi \rangle$ (also called "elliptic flow"). It is the second Fourier moment of the azimuthal momentum distribution

$$\frac{dN}{p_T dp_T d\phi}(p_T, y, \phi) = \frac{1}{2\pi}\frac{dN}{p_T dp_T}(p_t, y)\left[1 + 2\sum_{k=1} v_k(p_T, y)\cos(k\phi)\right] \ . \tag{10}$$

In the parton energy loss framework, azimuthal anisotropy arises in noncentral collisions due to the azimuthal angle dependence of the path length a parton travels, and thus the energy loss, in the medium[4, 58]. Fig. 5 shows a comparison between π_0 elliptic flow at RHIC and results from the GLV approach combined with a soft thermal component for the low $p_T < 2$ GeV particles [4]. The GLV prediction is qualitatively very similar to the data. This is an important consistency check because the parameters (gluon density) are already fixed by the nuclear suppression data. However, quantitative comparison **... put them on one fig?? ...** reveals that the perturbative approach *underpredicts* the data for $p_T \sim 3.5 - 5.5$ GeV by up to $\sim 20\%$. In this intermediate p_T regime, other mechanisms could also play a role (see Section III E). The main issue here is whether the high-p_T behavior is predicted accurately. Unfortunately, by $p_T \sim 8$ GeV the presently available data set has insufficient statistics for a quantitative conclusion.

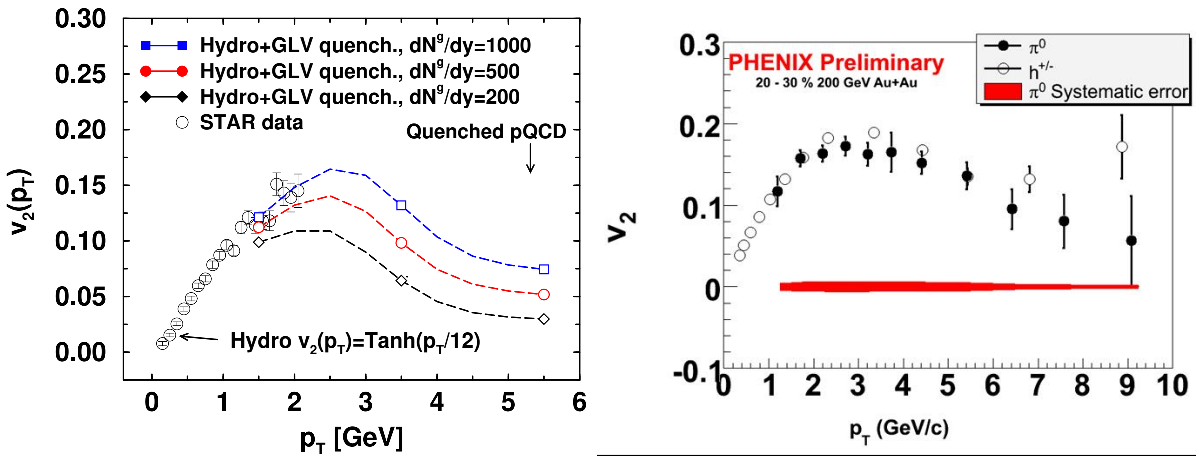

FIG. 5: Left: elliptic flow $v_2(p_T)$ in min-bias $Au + Au$ at RHIC from the GLV approach[4]. Right: pi_0 elliptic flow $v_2(p_T)$ in $Au + Au$ at $\sqrt{s_{NN}} = 200$ GeV, $20 - 30\%$ centrality [59].

D. Dihadron correlations

Even more differential information is provided by dihadron correlations. Dihadron rates can be computed in the same perturbative framework as (1) **... do we need a formula here??? ...** There are two contributions - both hadrons can come from the same jet, or they come from different (back-to-back) jets.

A common approach is to study dihadron correlations as a function of the azimuthal angle difference between a high-momemtum (trigger) hadron and a lower-momentum (associated) hadron. In such azimuthal correlations, hadrons from the same jet make a near-side peak ($\Delta\phi \sim 0$), while those from back-to-back jets produce an away-side peak ($\Delta\phi \sim \pi$) Fig. 6 shows charged particle azimuthal correlations at RHIC in pp, dAu and $AuAu$ at $\sqrt{s_{NN}} = 200$ GeV near midrapidity (for both hadrons) [65**?**]. **... should add the PHENIX plots too ...** In the left plot, the suppression of the away-side peak in $AuAu$ relative to pp provides additional evidence for parton energy loss. For trigger hadrons moving out-of-plane ($p_T^{trig} > 4$ GeV, $p_T^{assoc} > 2$ GeV), the away-side yield is almost completely suppressed because the away-side parton travels a long pathlength across the dense matter and loses too much energy to produce associated hadrons with enough $p_T > 2$ GeV. On the other hand, at sufficiently high trigger and associated momenta ($p_T^{trig} > 8$ GeV, $p_T^{assoc} > 4$ GeV) the back-to-back correlation reappears in $AuAu$ as shown in the right plot.

...we clearly need more stuff here...

E. Intermediate pT regime

A lot of interesting phenomena concern the intermediate $2 < p_T < 6 - 7$ GeV regime. Strictly speaking this is not a region for high-pT physics because a rigorous first-principles theoretical approach is still lacking here. Nevertheless, the physics is very interesting and therefore we discuss it here.

Quark coalescence. An important experimental observation at intermediate p_T in $Au+Au$ reactions at $\sqrt{s_{NN}} =$ 130 and 200 GeV is a striking meson-baryon difference in the nuclear suppression pattern [23, 24, 26, 28–31] and the azimuthal anisotropy [23–27]. Mesons are less suppressed (R_{AA} is larger) than baryons, while elliptic flow is higher for baryons (it scales with constituent quark number). A promising mechanism to explain the meson-baryon difference is hadronization via quark coalescence/recombination [32–39]

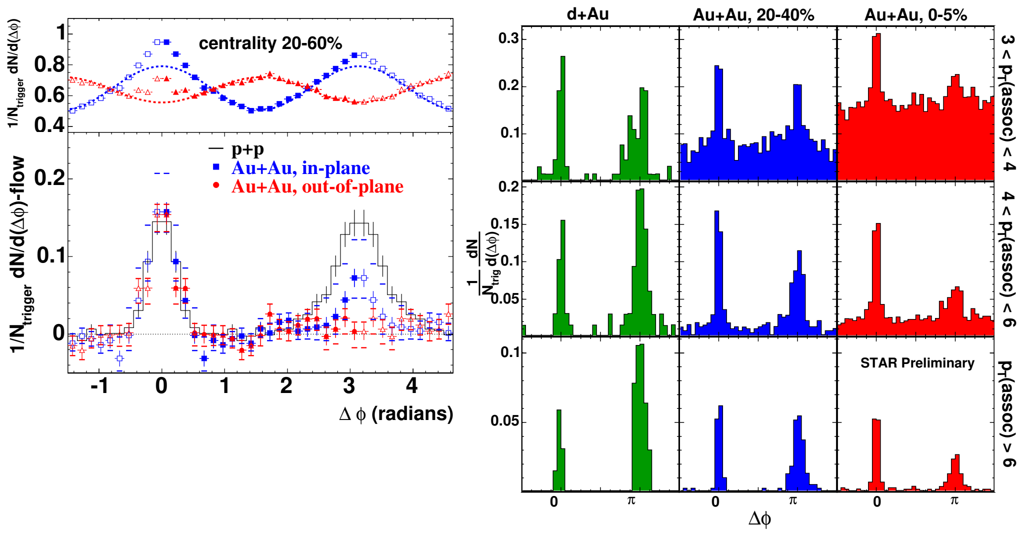

FIG. 6: Dihadron correlations as a function of the relative azimuthal angle in $p+p$, $d+Au$, and $Au+Au$ at RHIC [64, 65].

In the coalescence framework, in a dense parton medium mesons can form from a quark and antiquark, while (anti)baryons from three (anti)quarks. (higher Fock states can also contribute but their effect is small [42]). Compared to a pure fragmentation scenario, coalescence results in a density dependent enhancement of hadron yields, which helps explain the observed high p/π ratios at RHIC[35, 36] at intermediate $p_T < 6$ GeV. Quark number scaling of elliptic flow can also follow from coalescence[33, 37].

Despite successes, there are also several challenges to the model. Jet-like hadron correlations can only be obtained with very specific quark correlation patterns[66] that are not understood dynamically. A theoretical challenge with the *many* $\rightarrow$ *one* coalescence process is that it *temporarily* reduces entropy (subsequent resonance decays do generate enough entropy to compensate). More importantly, most results have been obtained with simple, unrealistic parameterizations for the quark distributions, whereas dynamical phasespace correlations can crucially affect coalescence yields[39]. In a dynamical approach, baryon abundances get reduced, and elliptic flow scaling is not automatic.

Given these uncertainties, further experimental tests of the model are essential. Quark correlations can, in principle, be deduced and tested via mapping out the quark content dependence of hadron correlations. There are many more hadron species than quarks, which allows one to overconstrain the model. Coalescence is also limited to a certain region in p_T, and thus all coalescence effects should disappear above $p_T > 6-7$ GeV. Experiments do, indeed, see the gradual disappearance of the baryon enhancement. In addition, hadron elliptic flow should also drop to its "pQCD value", as illustrated in Fig. 7.

It is important to note that in the coalescence approach there is significant pion production below $p_T < 4-5$ GeV in near-central $AuAu$ collisions at RHIC. Therefore, if coalescence is the right physics, the perturbative QCD regime can only start from $p_T >\sim 5$ GeV, even for pions.

Jet remnants. ... where did the energy go? ...

Hydrodynamic excitations. If the matter produced at RHIC behaves hydrodynamically, energy-momentum deposited by fast (supersonic) jets should generate hydrodynamic excitations, such as conical shocks[40, 41]. It was proposed that the shocks manifest themselves as a double-peak pattern in the away-side azimuthal correlations[40]. This idea generated significant theoretical and experimental interest.

For instance, it has been argued that parton energy loss, in particular multi-gluon radiation off an energetic parton, could lead to a similar pattern [61]. In addition, a realistic - but still only 2+1-dimensional - fluid dynamical calculation found negligible effects[69].

... mention color-Cherenkov ...

With such theory uncertainties, having accurate experimental data is paramount. However, recent measurements are quite inconclusive. Both PHENIX and STAR see a double-peak structure in the two-particle azimuthal correlations, once collective flow effects are subtracted, as shown in Figs. 8 (left plot) and 9 [63, 68]. The two peaks are roughly ± 1 radian away from the away-side $\Delta\phi = \pi$ direction. The magnitude of the signal, on the other hand, is quite different between the two experiments (PHENIX sees a much stronger effect), which might be due to some difference in the flow subtraction procedure. (In fact, there are no peaks in the raw signals.) To corroborate their two-particle result, STAR also studied three-particle correlations [63], namely azimuthal correlations relative to an high-pT trigger particle. Surprisingly, as shown in Fig. [?] (right plot), no characteristic conical flow signal was seen.

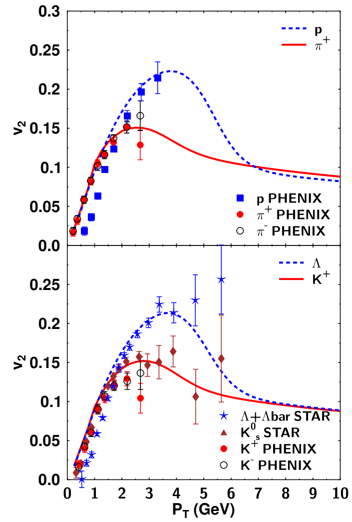

FIG. 7: Hadron elliptic flow $v_2(p_T)$ from quark coalescence [36].

Three-particle correlations are especially challenging because of statistics. The STAR results correspond to about half the Run-4 data data set. A more accurate three-particle measurement will require significantly higher luminosities, or much longer beam time.

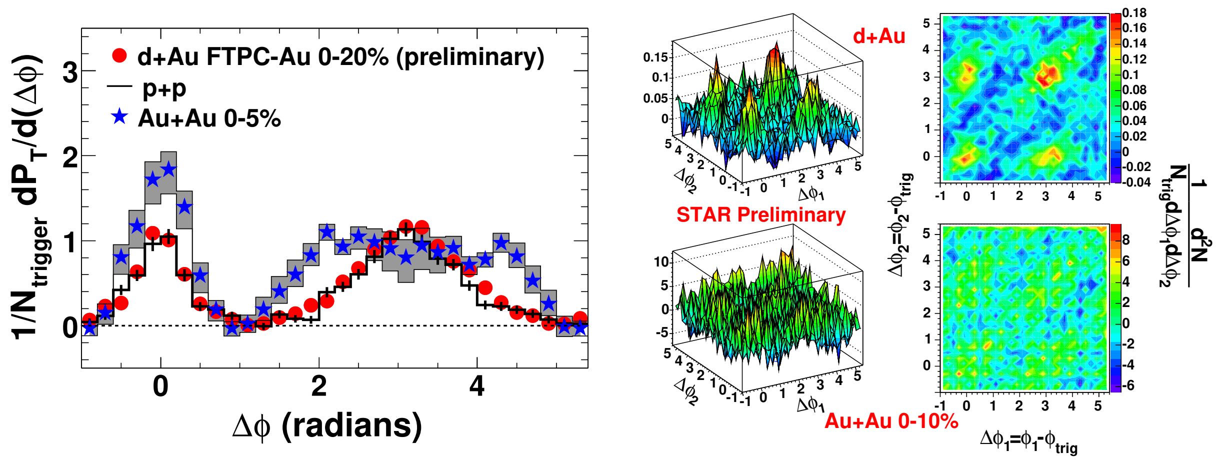

FIG. 8: Two-particle and three-particle azimuthal correlations at RHIC[63].

Plasma "push".
There are several arguments for a strongly-interacting quark-gluon plasma at RHIC[7–9]. If the interactions are indeed strong, one expects nearly hydrodynamic behavior, at least below some soft momentum scale. There is of course not a clear separation between the nearly thermal soft and nonequilibrium hard regimes, rather, a gradual transition. In fact, in a very strongly interacting system, "remnants" of the soft regime can extend out to quite large momenta[67]. In parton kinetic theory this occurs because a fraction of soft partons get accelerated to high momenta in multiple collisions.

IV. FUTURE MEASUREMENTS

A. Open issues/questions

The previous Section demonstrates the great success of the radiative parton energy loss paradigm. However, several crucial open questions remain. Here we list the issues that will drive future high-pT measurements at RHIC.

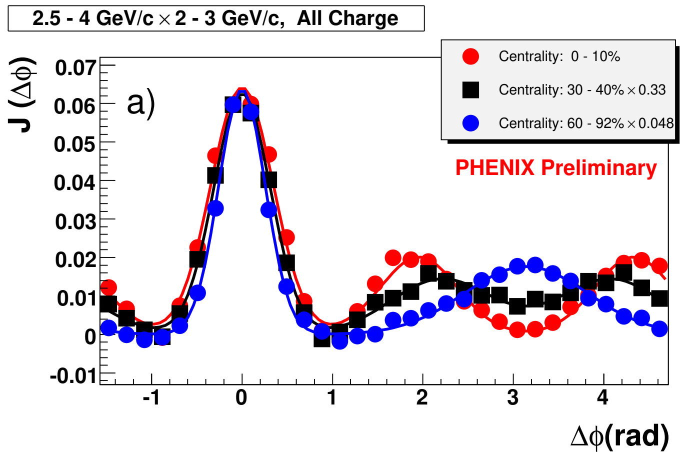

FIG. 9: Two-particle azimuthal correlation with collective flow subracted at RHIC[68].

... plasma-push v2 Fig. ...

FIG. 10: Elliptic flow contributions from parton kinetic theory in an opaque plasma[67]

identified particles at high pT. We have seen that the perturbative QCD approach, even in $p+p$, really works for mesons only. Moreover, in the intermediate p_T range several additional mechanisms are expected to play a role. Therefore, accurate measurements of identified pion and kaon elliptic flow at higher $p_T \gtrsim 10$ GeV, where the theory is more reliable, would be an important test of our understanding of parton energy loss in QCD.

heavy quark puzzle. An important cross-check of the formalism is the quark mass dependence of energy loss. This is discussed in depth by the Heavy-Flavor Working Group, and therefore we only mention it here briefly. The formalism predicts that heavy quarks lose less energy, which should be manifest when one contrasts light parton and heavy quark observables, such as the suppression pattern for π_0 and decay electrons from heavy mesons. However, recent measurements show a rather similar magnitude for π_0 and $e^{\pm}$ suppression [**?**], which is extremely difficult to reconcile within the inelastic parton energy loss framework [12].

This is a major puzzle. A recent suggestion toward a solution is that elastic energy loss could be more important than had previously been thought [13, 14]. An experimental way to "deconvolute" the two mechanisms is via their different energy dependence. With increasing jet energy, elastic energy loss $\Delta E_{elastic} \sim \sqrt{E}$ should become weaker compared to inelastic energy loss $\Delta E_{radiative} \sim E$ [4]. But to benefit from the different behavior, sufficient lever arm in p_T is required.

precise energy loss measurement. Hadronic observables do not allow for precise extraction of energy loss parameters because fragmentation always involves an additional convolution over the FF $D(z)$. For example, one does not know experimentally the jet energy. This uncertainty can be eliminated by measuring photon-hadron ("gamma-jet") correlations[17].

coupling between soft and hard physics...

B. Traditional observables with higher pT coverage

C. Gamma-jets

Gamma-jet events have long been considered the "golden" probe for directly measuring the energy loss of the hard-scattered parton propagating through the medium [17]. **... perhaps Xin-Nian can add more discussion here ...** The challenge in selecting these probes is separating the direct photons from those that come from hadronic decays or jet fragmentation. Experimentally, there are two possible methods to make such a measurement. One method is to measure both the correlation between π^0 and jets and the correlation between inclusive photons and jets. The inclusive photons include those photons from hadronic decays (mostly $\pi^0 \to \gamma + \gamma$). From the measurement of the π^0-jet correlation and a simulation of the π^0 decay, one can statistically subtract the γ(from π^0)-jet correlation from the inclusive γ-jet correlation. A second method is to isolate the pure direct γ with veto-cuts that eliminate (or at least minimize) the contribution of photons from π^0 and η decays. The second method is more statistically limited than the first, due to the large efficiency losses necessary to achieve high purity in the direct photon sample. In this section, the estimates for γ-jet statistics are made using the first method. According to the PHENIX publication on direct photons in Au+Au collisions [16], the fraction of direct photons increases rapidly for $p_T > 5$ GeV/c. At $p_T \sim 8$ GeV/c, approximately 60% of all photons are direct photons in the most central (0-10%) events. Based on Run-4 (Au+Au collisions) PHENIX analysis, and assuming 20 times these statistics in RHIC-II, there will be approximately 10k direct photons with a purity of 60% and 3k direct photons with a purity of 80%,. In the PHENIX experiment, cluster merging is a non-negligible effect for $p_T < 15$ GeV/c.

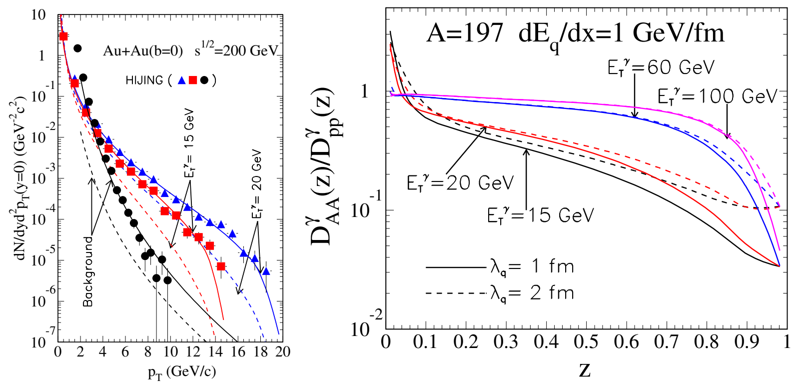

FIG. 11: Photon-triggered away-side hadron yields (left), and ratio of effective fragmentation function in AA to fragmentation function in pp (right) for various jet energies [17].

D. Flow and jets

In nucleus-nucleus collisions, the expansion (flow) of the opaque partonic medium can induce modification of jet shapes as was suggested in [18]. In particular, the jet cone created by the fragmenting parton would become azimutally *asymmetric*, as illustrated in Fig. 12. Measurements of this effect would provide important constraints, coming from the high-pT sector, on the soft dynamics in heavy-ion collisions. However, jet cones are very hard to reconstruct at RHIC because typical jet energies are too low. **... any chance for seeing this at higher pT?? ...**

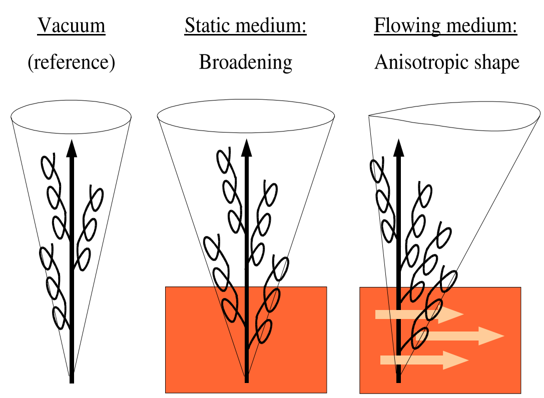

FIG. 12: Asymmetric jet cones due to coupling between jets and the flow of the soft partonic medium [18].

E. Di-hadron correlations

F. 3D jet tomography

Extending jet tomography measurements in the third, rapidity, dimension provides a unique way to study the full 3-dimensional shape (both transverse and beam direction) of the medium created in nuclear collisions. It has been recently suggested [20, 21] that at higher rapidities, while the production points of jets is along the beam direction, the soft medium "tilts" away from it as shown in Fig. 13. Such a tilted distribution generates a unique pattern of large flow anisotropies that can be tested with high-pT measurements at forward and backward rapidities $|\eta| > 2$ (see Fig. 13). Such measurements could also provide a unique way to differentiate between the color glass condensate scenario and perturbative minijet production [20].

Unfortunately, the current RHIC experiments have no capabilities to measure high-pT particle correlations at high rapidities - therefore, significant upgrades or a new detector design [22] would be required.

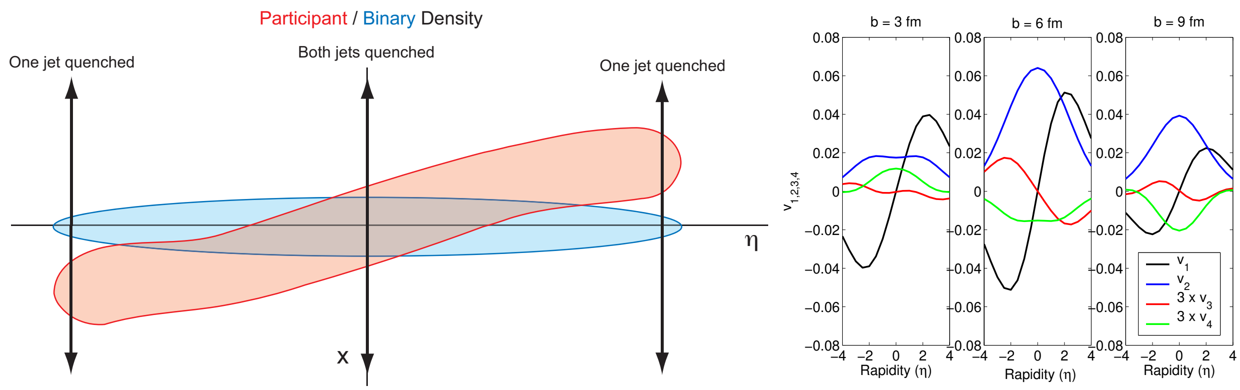

FIG. 13: Left: spatial distributions for high-pT jet (blue) and the low-pT medium (right) expected in a noncentral AA collision [21]. Right: flow anisotropy signatures generated by parton energy loss in the unique spatial geometry [21].

G. Opportunities in the intermediate pT regime

... this still needs to be done ...

V. SUMMARY

In summary, we identify the following main directions for future high-pT measurements at RHIC. i) Extension of coverage to higher pT, to study a regime where perturbative QCD is more reliable. ii) Particle correlations - gamma-hadron (clean jet energy), jet tomography versus rapidity (3D geometry), two- and three-particle correlations (understand jet-medium coupling, various mechanisms in intermediate pT region). iii) Identified heavy flavor observables (quark mass dependence).

Overall, we believe the major driving force of future high-pT experiments at RHIC will be heavy-flavor measurements. This is where most high-pT theoretical interests, and efforts, lie currently.

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