Thoughts on Physics Topics for QM2005 and Beyond For RHIC Science Workshops

M. J. Tannenbaum
BNL/PHENIX Group
Brookhaven National Laboratory
Upton, NY 11973-5000 USA

(December 17, 2004)

I. INTRODUCTION

RHIC is a dedicated machine for studying the details of perturbative and non-perturbative QCD. The energy and luminosity allow both large x and small x studies. Although the Lagrangian of QCD is well known, much remains to be understood and tested about its solutions. Furthermore, early Au+Au measurements at RHIC have revealed the inadequacy of existing p-p data in many areas. Another important issue in comparing p-p to Au+Au collisions is whether signatures are unique to Au+Au collisions—for instance thermal distributions of low p_T particles and thermal chemical abundances occur in p-p and even e^+e^- collisions. This makes it much more difficult to use them as probes of RHI collisions.

Anisotropic flow and hydrodynamics seem to play a large and unique role in Au+Au collisions. These should be exploited in all A+A measurements, both v_2 and v_1. One must also look for flow, hydro and other suspected unique A+A effects in p-p and p+A collisions as a function of 'centrality' to see whether these effects are indeed unique to Au+Au collisions.

Also, as a general principle, I assume that any A+A measurement must have adequate p+A and p+p comparison data in order to allow precise and clear interpretation. The 62.4 GeV Au+Au run is a case in point about not having enough comparison data: only a limited set of measurements such as flow and to a certain extent ratios of identified particles can be understood without the p+p comparison data.

I try to organize and group issues of physics questions and experiments to answer them. Eventually I think that we have to make a matrix of Physics questions versus the probes and measurements we have that address them.

II. WHAT IS THE MEDIUM PRODUCED AT RHIC? WHAT ARE ITS PROPERTIES

.

1. If it is the QGP or sQGP, under what conditions is it produced? What are it's properties, e.g. temperature, density, transition temperature, equation of state, phases, viscosity, speed of sound, latent heat, specific heat, formation time, size, lifetime, etc?
2. How do we measure these properties of the medium?
3. How do the properties depend on $\sqrt{s_{NN}}$ and A? Is there a sharp or any transition as a function of $\sqrt{s_{NN}}$ and A?
4. If it is not the QGP, what is it?
5. Is the medium thermalized? How do we tell? What is the spatial and temporal scale of the thermalization?
6. Is the medium deconfined?
   (a) Is the Debye screening radius presumably revealed in quarkonium suppression the same as the Yukawa screening radius assumed in energy loss calculations? If so, does that prove deconfinement?
7. Is there chiral symmetry restoration? Is this question meaningful, since in any dynamic partonic interaction in p-p collisions, the partons exhibit zero mass, in sharp distinction to static properties such as magnetic moments of baryons?

III. MECHANISM OF JET SUPPRESSION

Jet suppression, as revealed by semi-inclusive π^0 and $\pi^{\pm}$ production in Au+Au and d+Au collisions, clearly indicates a unique interaction of color-charged probes (such as quarks and gluons from hard scattering) with the medium at RHIC, that is not observed in cold nuclear matter in either p+A or e+A collisions or in A+A collisions at $\sqrt{s_{NN}} \lesssim 31$ GeV. QCD predicts coherent radiative energy loss of the color-charged partons in the color-charged medium. Is this the explanation of the medium effect? If so, where does the energy go? In order to use this effect to measure the properties of the medium, the properties of the energy loss must agree in detail with the theory. At the moment they do not: for instance, the energy loss is predicted to depend on L^2 and to be independent of the energy of the partonic probe. So far, the data contradict both these important predictions of the QCD medium effect. Also the different systematics of baryons and mesons in the range $2 \leq p_T \leq 6$ GeV/c, $130 \leq \sqrt{s_{NN}} \leq 200$ GeV remain unexplained.

1. How does the apparent jet energy loss depend on p_T, $\sqrt{s_{NN}}$, A, reaction plane, rapidity, x_{Bj}? Will B+A collisions, e.g Cu+Au, help in this regard?

2. Do the 62.4 GeV data clarify the source of the intermediate p_T baryon-meson anomaly or the systematics of π^0 suppression?

3. Does the fractional energy loss remain constant for the largest p_T values we are able to measure?

4. What fraction of the energy loss is 'elastic' and what fraction is LPM-bremsstrahlung-like?

5. Is there any effect on the medium-interaction due to either longitudinal or transverse flow?

6. Do the identified particle ratios remain constant for $p_T \geq 6$ GeV/c? Is the clear non-x_T scaling of this effect a clue to its origin?

7. How does the baryon-meson anomaly depend on rapidity or in asymmetric Cu+Au collisions?

8. How does the apparent energy loss depend on the mass of the quark (gluon) and/or identified particle used as a probe?

9. Can the azimuthal anisotropy of high p_T particles be explained by energy loss, or is there additionally a flow effect on the outgoing quark or gluon?

10. If the partons flow, does the flow depend on the mass of the parton? How? e.g. Do charm quarks lose energy and/or flow?

11. Do Drell-Yan or direct photon production exhibit any reaction-plane dependence or suppression? I would expect some suppression since it is conceivable that the quarks on the backside of the colliding nuclei may lose energy in the hot matter created by the earlier collisions of the front-side quarks. Of course this may all be washed out by the uncertainty principle.

12. In γ-Jet or identified particle correlations, how does the fragmentation function get modified by the medium? For instance, is it simply that the parton loses energy, so that the fragmentation function appears modified if you don't correct for the energy loss, or does the fragmentation function really change in the medium for a fixed energy parton? In either case how does the modification or apparent modification depend on the p_T of the probe, pathlength in the medium, or other properties of the medium?

13. How is the apparent lost energy of the parton probe distributed in the medium? Is it near or in the jet, or absorbed by the medium as a whole? Where does the lost energy go?

14. 2-dimensional $\eta - \phi$ properties of jet quenching and fragmentation—do the jet fragments exhibit a conical, or other non-standard shape, in Au+Au collisions compared to p-p? If so, how does it depend on p_T, etc?

15. What are the spatial and temporal properties of fragmentation? Do the jets fragment within or outside of the medium? Does the formation time depend on the identity of a fragment?

16. Can we reconstruct jets in p-p, p+A, A+A collisions? How does the medium modify the jets?

IV. SOFT PHYSICS, HYDRO AND FLOW

1. Do quarks, gluons and particles flow differently?

2. Do Quarkonia flow? If so, or if not, what do you learn?

3. Can we prove or disprove hydro? Measure all systematics of v_2, v_1 and p_T spectra of all identified particles: Is hydro correct in detail?

4. Is there a charge asymmetry with respect to the reaction plane defined by v_1?

5. Multidimensional HBT measurements of all identified particles, source imaging, whatever.

6. Fluctuations: average p_T, n_{ch}, E_T. Anything else?

7. What is the influence of the H-BT correlation on fluctuations?

   (a) Does an ensemble of same charged particles fluctuate more or less than the same number of randomly charged particles?

   (b) Is the correlation length derived from fluctuations, the same as that of HBT measurements?

8. Systematics of identified particle production, p_T, $\sqrt{s_{NN}}$ in p-p p+A, A+A as a function of "centrality": Are A+A 'signature' effects such as flow, hydro, 'temperature' and 'thermal abundances' properties of A+A collisions or of the underlying p+p collisions?

9. Write the definitive paper on centrality.

10. Multiplicity and E_T distributions in p-p, p+A, A+A distributions—do they follow the Wounded Nucleon Model, Additive Quark Model? Is the upper edge of the E_T distribution in Au+Au consistent with ~ 1000 convolutions of the $p-p$ spectrum? Do jets have anything to do with the apparent deviation from WNM at mid rapidity? Is the contribution of jets to E_T and multiplicity distributions in p-p and A+A collisions negligible at RHIC as it is at lower energies?

V. STRUCTURE FUNCTION PHYSICS

1. Are the parton distribution functions of a nucleus simply A times the structure functions of a nucleon for all x, Q^2 and parton?

2. Measure the polarized, unpolarized and A dependence of the gluon structure function using direct photon production.

3. Test the CGC by directly measuring the gluon structure function at low x as a function of A in p+A collisions using the Nose Cone Calorimeter.

4. Use $W^{\pm}$ production to measure flavor identified polarized and unpolarized structure functions.

5. Use parity violation to search for new physics.

VI. QUARKONIA AND LEPTON PAIRS

1. Is there J/Ψ suppression, flow, recombination at RHIC?

2. How does the suppression, if any, or enhancement, if any, depend on p_T, y, $\sqrt{s_{NN}}$, A in A+A collisions? Would B+A collisions be useful?

3. How does the 'normal suppression' evolve from SpS to RHIC energies?

4. How high in A can we go at RHIC to check this?

5. Do χ_c, ψ', Υ follow the same suppression, non-suppression or flow pattern as J/Ψ ?

6. What more can we learn about charm production or combinatoric background to lepton pair production from charm using $e - \mu$ coincidences, compared to single e or single μ measurements?

7. Can we measure charm via hadronic decay modes ($K^{\pm}\pi^{\mp}$) up to $p_T \sim 18$ GeV/c in Au+Au (and p+Au, p-p) using the vertex and aerogel upgrades?

8. Can the medium or chiral symmetry restoration be probed using the vector mesons ρ, ω, ϕ?

9. Can we observe thermal photons using low mass lepton pairs or converted real photons?

10. Is the CERES enhancement real? If yes, what is it? If no, what caused it?

VII. CONCLUSIONS

The unanswered questions I raised here are huge in number. Just to show how many there really are, I include my list of topics for electron pairs from a 1996 collaboration meeting. How many of those questions have been answered or will be answered in the next 5 years? I also give the list of hard-scattering physics topics I made in 1999, of which 4 out of 6 have been studied and published, raising more new questions (see Section III) than answers. I can't imagine that anybody thinks that there aren't at least 20 more years of Physics left at RHIC, which will be helped immesurably for most of these questions by a factor of ~ 500 more luminosity and $\sim 20\%$ larger c.m. energy than the original design goals—don't laugh, it happened at the ISR. Of course, raising the A to 256 (ok 238) will help, also.

MJT Physics topics using electrons 11/96

Topic	Method	Comment
π^0	external conversions (+Dalitz) $m_{e^+e^-} \leq m_{\pi^0}$	Inclusive γ
η	$140 \leq m_{e^+e^-} \leq 400$ MeV/c^2	Dalitz decay
Direct γ	$400 \leq m_{e^+e^-} \leq 600$ MeV/c^2	Internal Conversion
ρ^0	$600 \leq m_{e^+e^-} \leq 900$ MeV/c^2	Lose money on every sale...
ω^0	$m_{e^+e^-} \simeq 782 \pm 8$ MeV/c^2	Should work (?)
ϕ	$m_{e^+e^-} \simeq 1019 \pm 4$ MeV/c^2	compare K^+K^-
Charm	$e^\pm$ inclusive $p_T \geq 1.1$ GeV/c	No combinatoric bkg.
$c - \bar{c}$	$1.6 \leq m_{e^+e^-} \leq 5$ GeV/c^2	Jet Quenching
$c - \bar{c}$	$1.6 \leq m_{e^\pm\mu^\mp} \leq 5$ GeV/c^2	Jet Quenching Msmt. Charm bkg for D-Yan
Drell-Yan	$4.0 \leq m_{e^+e^-}$ GeV/c^2	QCD Sanity check
J/Ψ	$m_{e^+e^-} \simeq 3097 \pm 0.09$ MeV/c^2	QGP or Bust Inclusive, Central $(AB)^\alpha$ p_T dependence
Ψ'	$m_{e^+e^-} \simeq 3686 \pm 0.3$ MeV/c^2	Rate Limit ?
Υ	$9.6 \leq m_{e^+e^-} \leq 10.6$ GeV/c^2	*Rate Limit*

Topics of First "N" Papers

1. ***``Measurement of hard π^0 in inclusive, central and peripheral Au+Au collisions---Discovery of QCD Energy loss in Hot Dense Matter.''***

   The assumption is that year one running with a full EM calorimeter in a single arm with recorded live integrated luminosity of 20 inverse microbarns should allow measurements of inclusive pizeroes to beyond 6 GeV/c in transverse momentum. Impact parameter dependence as a function of Zcal or E_T should also be posible although the rate for peripheral collisions may be inadequate. It is assumed that no trigger is available for the first year. The main problems are expected to be calibration, efficiency, and combinatoric background. In future years with higher luminosity, triggers using EMcal clusters are possible and desirable.

2. ***``Search for prompt photons in inclusive, central and peripheral Au+Au collisions---limits on γ/π for p_T < 10 GeV/c.''***

   Absent any new phenomenon such as a ``flash of photons'' or strong jet quenching in a Quark Gluon plasma, it is unlikely that a prompt photon signal will be able to be significantly extracted from the collossal background of photons from pizero and eta decays. The prompt photon/pizero ratio increases with increasing p_T which means the signal can only be seen at large p_T which usually means high luminosity. This physics is limited both by background and by rate. Non-linearity in the EM calorimeter is also crucial. It is vital, for instance, that two 3 GeV photons have the identical response as one 6 GeV photon. Extensive studies of photon/pizero separation from EM cluster algorithms and combinatoric problems such as false pairing of a candidate photon with a random photon to make a pizero, or loss of a real pizero by the same mechanism are required.

3. ***``Measurement of π^+, π^- at large p_T in inclusive, central and peripheral Au+Au Collisions''***

   Possibility of other hadrons, flavor tagging of jets a la CCHK ? Should have the same sensitivity as the pizero measurement in year one if the tracking coverage is the same as the EMcal. The issue for tracking is the ability to reconstruct tracks with high resolution at resonable efficiency. Triggers are possible and desirable in later years using pions above the RICH threshold (> 4 GeV/c).

4. ***``Measurement of correlations of charged particles/π^0 with all `hard' probes above in inclusive, central and peripheral Au+Au collisions''***

   Di-hadron measurements require full tracking and/or EMcal in both central arms and suffer a reduction in rate of roughly a factor of 6 (not counting p_T cuts) compared to inclusive single particle rates. Here's where we can measure the `acoplanarity' and energy imbalance of `jets', i.e. the ``k_T'' and ``x_E'' distributions.

5. ***``Measurement of Shadowing of the Gluon structure function in Au+Au Collisions''***

   from the rate of inclusive high p_T muons from heavy quark decay. This requires a single working muon arm and should produce a useful measurement with the year-1 luminosity. Problems are reconstruction efficiency, resolution and background. Evidently, understanding the background has a high priority to prove that the single muons are from heavy quark decay rather than light quark decay or punchthrough.

6. ***``Drell-Yan production of di-leptons as a function of centrality in Au+Au collisions''***

   This process is rate limited since it is essentially an electromagnetic process produced by hadron constituents. Thus high luminosity and a trigger are required which are not likely in year-1. An interesting issue that can be addressed in PHENIX is the associated multiplicity and E_T (the impact parameter dependence) for drell-yan production. The steeply falling mass spectrum and point-like scaling observed in p-p and p+A collisions also make Drell-Yan pairs a sensitive probe to search for energy loss of quarks and anti-quarks in the initial state of cold nuclear matter.