JETS AT RHIC
HOW TO FIND THE BDMPS EFFECT AT RHIC USING INCLUSIVE HIGH P_T HADRONS AND HADRON PAIRS

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There is a rare and clear consensus among experimentalists [1] that 'jets' and hard-scattering phenomena in Relativistic Heavy Ion (RHI) collisions can best (if not only) be studied using leading particles, in the same way that these phenomena were originally discovered and mapped out in $p-p$ collisions.

1 Hard Scattering of the Constituents of the Proton in $p-p$

Hard scattering in $p-p$ collisions was discovered at the CERN ISR by the observation of an unexpectedly large yield of particles with large transverse momentum (p_T), with a power-law tail which varied systematically with the c.m. energy ($\sqrt{s}$) of the collision. [2] This observation, in 1972, proved that the partons of deeply inelastic scattering were strongly interacting. (See Fig. 1) Further measurements utilizing inclusive single or pairs of hadrons established that high p_T particles are produced from states with two roughly back-to-back jets which result from the 2-body scattering of constituents of the nucleon as described by QCD. Later experiments at the CERN and FNAL $\bar{p}-p$ colliders employed hadron calorimeters to directly measure the jets of hard-scattering.

2 Hard-scattering in A+A as a probe for hot/dense matter

Hard processes are considered good tools to study RHI collisions because they probe the early stage of the evolution of the hot dense system, during which a quark-gluon plasma (QGP) could be produced. Up to the present, hard scattering measurements in p+A and B+A collisions show little, if any, initial state longitudinal effect (energy loss), but do show significant initial state transverse effect (k_T broadening). For example, Drell-Yan production of lepton pairs in A+B collisions [3] is pointlike, proportional to $A \times B$, whereas any small initial state (longitudinal) energy loss would shift the steeply falling mass spectrum and sharply reduce the cross-section below the pointlike value. Transverse broadening causes inclusive single hadron production at a given p_T in A+A collisions to increase faster than A^2 ($A^{2\alpha}$, $\alpha > 1$, the "Cronin Effect" [4])

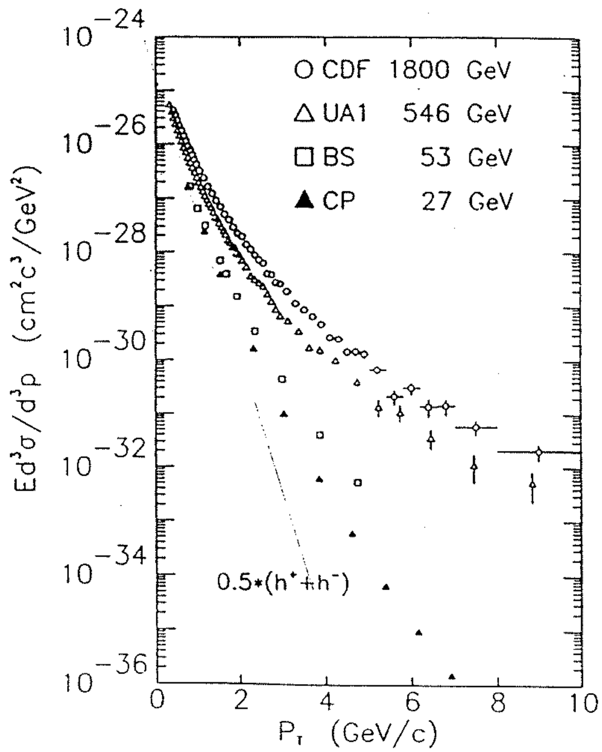

Figure 1: Invariant cross section for non-identified charged-averaged hadron production at 90° in the c.m. system as a function of the transverse momentum p_T compiled by CDF for a range of c.m. energies $\sqrt{s}$.

in some kinematic regions,[5] but has little, if any effect on the invariant mass spectrum of di-hadrons.[6]

There is, at present, considerable theoretical activity on how the medium at RHIC should affect partons. Substantial energy loss and rescattering are predicted in a hot, dense, deconfined QGP,[7] leading to enhanced acoplanarity and energy imbalance of the two 'back-to-back' final state jets. However, since the huge multiplicity of the underlying event in central Au+Au collisions deposits an energy comparable to the kinematic limit in a typical calorimetric jet finding cone, there is general agreement[1] that inclusive single and di-hadron production offer the best—if not the only—method of detecting hard-scattering effects in Relativistic Heavy Ion collisions. For example, in central Au+Au collisions at RHIC, in a jet finding cone of half angle $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, for the expected charged multiplicity density $dn/dy|_{y=0} \sim 1000$, with $\langle p_T \rangle \simeq 400$MeV/c, there is an average 'pedestal' energy of $\pi R^2 \times \frac{1}{2\pi}\frac{dE_T}{d\eta} \sim 300$GeV in a typical cone with R=1. This is to be compared with the kinematic limit $\sqrt{s_{\rm NN}}/2 = 100$ GeV. Of course, any increased energy loss in dense/hot matter would have dramatic effects on both single and di-hadron spectra, which can be measured.

3 Detecting medium effects in B+A collisions

Fig. 1 provides a good illustration for the discussion on jet effects in inclusive hadron p_T spectra. There is an exponential tail (e^{-6p_T}) at low p_T, which depends very little on $\sqrt{s}$. This is the soft physics region, where the hadrons are fragments of 'beam jets'. At higher p_T there is a power-law tail which depends very strongly on $\sqrt{s}$. This is the hard-scattering region, where the hadrons are fragments of the high p_T QCD jets from constituent-scattering. **My hope is that the QGP causes the high p_T partons to lose all their energy and stop, so that the high p_T tail will 'vanish' for central Au+Au collisions.** Clearly, even small energy losses, e.g. 6.0 → 5.0 GeV, would reduce the p_T scale of the inclusive hadron spectrum, thus producing a huge reduction of the cross section at a given p_T. This effect has been illustrated in recent calculations.[8] If the power-law tail returns when peripheral Au+Au collisions are selected,[9] this would be proof of a hot/dense medium (QGP) in central Au+Au collisions. More than likely, life will not be so simple; and considerable study of p+p, p+Au, possibly Si+Si and other B+A combinations, will be required to prove and quantify any medium effect.

A particularly attractive feature of the predicted medium effect is that it suppresses the main background (π production) to searches for the QGP using the 'penetrating' direct photon and lepton probes . For instance, the predicted π^0 suppression[8] by 'jet quenching' at RHIC is a factor of 10—*but the direct photons are not reduced.* Thus γ/π^0 is predicted to be greater than 10% for $p_T > 3$ GeV/c at RHIC, which has two important advantages, if true:

- $\gamma/\pi^0 \gtrsim 10\%$ is a value where measurements are feasible
- the predicted γ/π^0 versus p_T is much larger than observed for p-p collisions at any comparable $\sqrt{s}$

Similar considerations apply to detecting charm production via inclusive single leptons.[10] Depending on the exact model for $c - \bar{c}$ production, $e^{\pm}$ from charm dominates the $e^{\pm}$ from Dalitz decays of π^0 for $p_T \geq 1.5$ GeV/c. Any energy loss effect should ehance the $e^{\pm}$ from charm relative to the Dalitz background.

4 How Everything You Want To Know about JETS can be done in PHENIX with leading particles in each arm c.f. CCOR

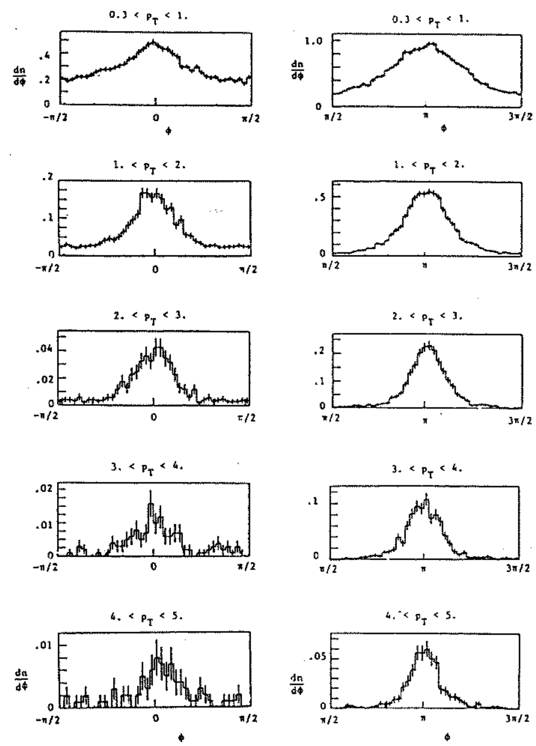

Figure 2: CCOR measurement of two particle correlations in azimuth: azimuthal distributions of charged particles as a function of their transverse momentum p_T are plotted relative to a triggering neutral with $p_{T\,t} \geq 7.0$ GeV/c which defines the zero of azimuth, $\phi = 0$.

In Fig. 2, [11] charged particles with $|\eta| < 0.7$ in the same 'arm' as the triggering π^0 are on the left, with those in the opposite 'arm' to the trigger on the right. As the p_T of the charged particle increases, the full width $\Delta\phi$ of the away side peak (plots on the right) narrows, but more slowly than $1/p_T$. This clearly shows that the jets **are not collinear in azimuth** (they have a net transverse momentum k_T)—if there were only fragmentation transverse momentum, then $p_T \times \Delta\phi$ would remain constant, equal to $< j_T >$, the mean transverse momentum of fragmentation. Both k_T and j_T can be derived from this plot.[11]

An excellent approximation to the fragmentation function (Fig. 3) can be obtained by plotting the same data in the variable x_E, which is the ratio of the

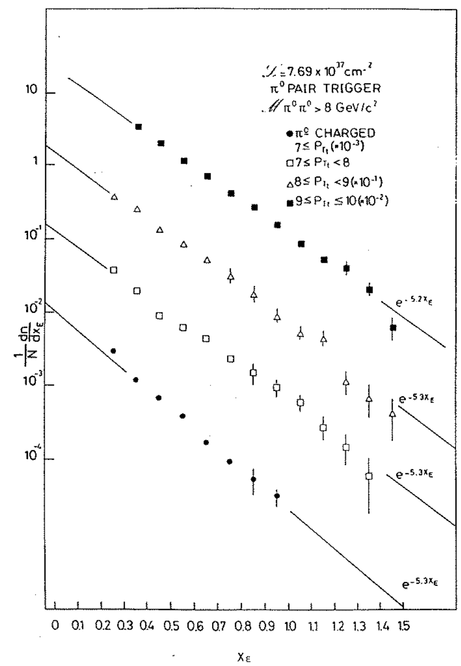

Figure 3: Distribution in x_E for a charged pion (or π^0) observed roughly back-to-back to a triggering π^0 of transverse momentum p_{Tt}, where both pions have $|\eta| < 0.5$ in the c.m. system. The exponential, $e^{-5.3x_E}$, which fits all the data can easily be converted to e^{-6z}, where z is the fragmentation variable.

component of p_T of the second pion, opposite in azimuth to the triggering pion, divided by p_{Tt}: $x_E = p_T \cos(\phi - \pi)/p_{Tt}$. With a medium effect, this plot will be severly smeared by the difference of path length in hot matter traversed by the two outgoing partons. The invariant mass spectrum of opposite azimuth di-hadrons should be a better analyzer of the medium effect since the invariant mass of the outgoing parton-pair is reduced by energy loss wherever the parton-pair is born. Details remain to be worked out for RHI collisions, but there is no question that inclusive single and di-hadron spectra can be used to measure the properties of hard scattering in A+A collisions, just as they have done in p-p.[12]

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