Hard Scattering of Partons as a Probe of Collisions at RHIC using the STAR Detector System

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Introduction

Presented here is the current state of our investigations into the use of hard probes to study pp, pA, and AA collisions at the Relativistic Heavy Ion Collider (RHIC) being built at Brookhaven National Laboratory. The overall goal of the RHIC program is the discovery and study of the Quark-Gluon Plasma (QGP), which is predicted to be formed at the high energy densities reached at RHIC in high energy AA collisions. The term "Hard probes" as used in this document includes those particles whose origin is the result of a direct hard parton scatter (i.e qq, qg, or gg). The final states of these hard parton scatters which we propose to study include dijets, gamma-jet coincidences, and inclusive high P_t particle spectra.

A brief discussion of the physics objectives is given in section 1. This is followed by an introduction to the STAR detector system in section 2, with particular details given for the proposed STAR Electromagnetic Calorimeter (EMC). Our present simulation studies and results are given in section 3. We conclude with a summary and a discussion of our future plans in section 4.

1. Physics Objectives

Relativistic Heavy Ion collisions have been studied in *fixed target* experiments in the laboratory setting since the late 1970's. These studies started at the Lawrence Berkeley Laboratory BEVALAC accelerator at energies up to ~ 2 GeV/u. The studies have since been carried on at the Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS) at energies up to ~ 10 GeV/u, and at the CERN Super Proton Synchrotron (SPS) at energies up to 200 GeV/u. One of the difficulties in interpreting the results of these studies has been the lack of a well established and generally accepted theoretical framework for calculating the observables obtained in the experiments.

A major difference between these earlier studies and the experiments to be carried out at RHIC is that at the RHIC energy scale present theoretical estimates are that approximately half of the energy transfer from the projectile frame to the midrapidity region may be calculable using Perturbative Quantum Chromodynamics (PQCD). This makes available a well established model for comparison with the data to be obtained at RHIC.

With the lower energy beams used in the BEVALAC, AGS, and CERN heavy ion studies the most basic input to the calculational models has been the flux and energy of the projectile nuclei. In calculating the various observables measured in these experiments corrections are made to account for the Fermi momenta of the bound nucleons. At RHIC energies ($\sqrt{s}$ = 200 GeV) the basic inputs to the model (PQCD) are the flux and momentum *distributions* of the quarks and gluons in the colliding nuclei. An example of these quark and gluon momentum distributions, for partons in an unbound proton, are shown[1] in Fig.1

The horizontal axis in the histograms of Fig.1 are the variable Bjorken x. This variable is the portion of a nucleon's momentum which is carried by a particular parton. The vertical axes are the parton distribution function (i.e. the number of a particular type of parton) multiplied by Bjorken x. The Q^2 values for the two plots (10 and 100 GeV^2) are the four momentum transfer for the interactions at which these parton distributions are valid. The feature to notice in these plots is that the gluon distribution has been scaled down by a factor of ten so that it could be plotted on the same graph in the x regions lower than ~0.1. It is the scattering of these soft gluons, down to x values of ~0.01 - 0.02, which account for about half of the energy transferred from the projectile to the midrapidity frame at RHIC energies.

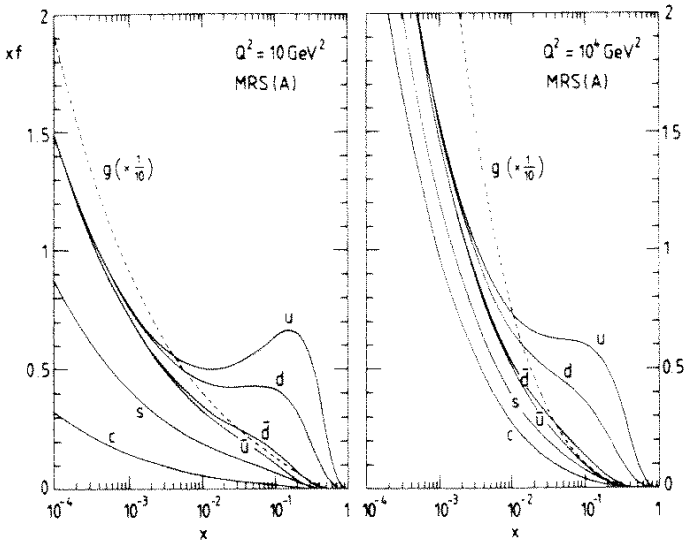


Fig. 1. MRS(A) partons shown as a function of x at Q^2 = 10 and 10^4 GeV^2.

While the quark distributions/structure functions shown are being determined in deep-inelastic scattering experiments, the same is not true for the gluon structure functions which will play such a vital role at RHIC. To quote from the conclusion in ref.1 "We believe that our analysis has considerably improved the detailed knowledge of the quark densities. However, the same is not true for the gluon distribution. At present there are, with the possible exception of the WA70 prompt photon measurements, no reliable direct constraints on the gluon".

An effect that further complicates the analysis for the RHIC data is the fact that there is a modification of the parton distributions for partons in nucleons which are bound together into a nucleus. This effect is known as shadowing. An example of shadowing for the quark distributions is shown[2] in Fig.2. What is shown is the ratio of the quark structure functions in bound nucleons divided by A times the quark structure function in unbound nucleons. What is observed is that there is a depletion in

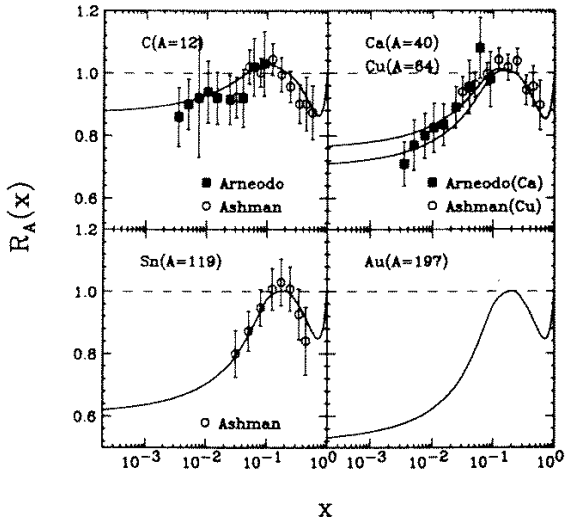


Fig. 2. The ratio of quark structure functions $R_A(x) \equiv F_2^A(x)/AF_2^N(x)$ as a function of x in small and medium x

the number of low x quarks and antiquarks. The magnitude of this depletion increases with increasing A. While no direct information is available that illustrates this shadowing effect for the gluon distributions, it is plausible to expect that the gluon distributions are modified in a similar fashion.

A Monte Carlo event generator model has been written by X.N.Wang and M.Gyulassy[2], which incorporates perturbative QCD models for multiple jet production and low P_t multistring phenomenology, to study jet and multiparticle production in high energy pp, pA, and AA collisions. Using this model (HIJING) the authors have investigated[3] the importance of minijets, nuclear shadowing, and jet quenching in high energy collisions. Fig. 3 shows some of their results.

The left hand panel of this figure shows the pseudorapidity density of charged particles expected at RHIC ($\sqrt{s}$ = 200 GeV) for central Au on Au collisions. The large increase in particle densities exhibited in the jump from the lowest (dotted) curve to the highest (dot-dashed) illustrates the importance of hard processes (jets) at the RHIC energy scale. The drop (~30%) from the top (dot-dashed) curve to the dashed curve demonstrates how large the effect of gluon shadowing may be on the observed particle multiplicities. The ~15% increase in the particle density at midrapidity from the dashed to the solid line shows how large the effect of jet quenching may be on the final particle multiplicities. The term jet quenching refers to the energy loss, dE/dl, of a high-p_T parton as it traverses the dense matter. There are PQCD estimates[4] that this energy loss may be dominated by induced gluon bremsstrahlung which depends on the infrared (Debye) screening scale for the medium. This infrared screening scale may vary significantly in the vicinity of the quark-gluon plasma transition.

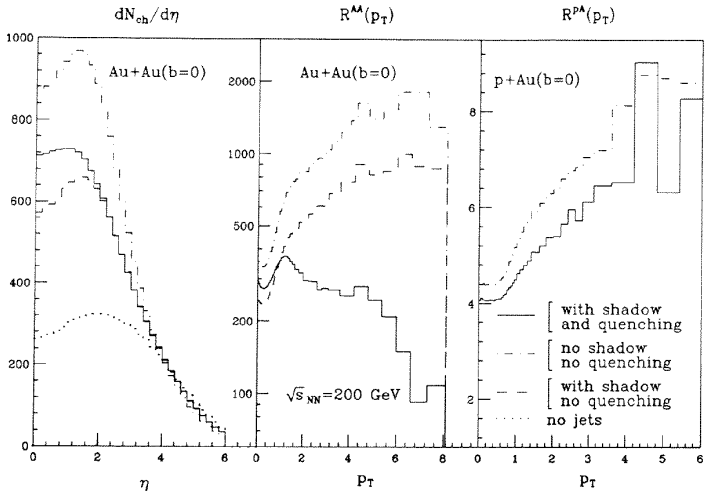


Fig. 3. Results of HIJING on the dependence of the inclusive charged-hadron spectra in central Au+Au and p+Au collisions on minijet production (dash-dotted), gluon shadowing (dashed), and jet quenching (solid line) assuming that gluon shadowing is identical to that of quarks and dE/dl = 2 GeV/fm. $R^{AB}(p_T)$ is the ratio of the inclusive p_T spectrum of charged hadrons in A+B collisions to that in p+p.

The middle panel of Fig.3 illustrates how these effects (gluon shadowing and jet quenching) change another of the final state observables, the inclusive transverse momentum spectra. From the figure it is seen that the gluon shadowing may decrease the yield of moderate P_t particles ($P_t \geq 5$ GeV/c) by a factor of two relative to the scaled pp yield. Also shown is the dramatic reduction (~ factor of 5) in the yield of these moderate P_t particles that may result from jet quenching.

The possible magnitude of the effects of gluon shadowing and jet quenching illustrated in Fig. 3 on such macroscopic final state observables as the pseudorapidity and P_t distributions points out the need to measure these effects directly to facilitate the

understanding of RHIC physics. While the magnitude of these effects may be large, it is not possible to deconvolute them by merely measuring something like the inclusive P_t spectrum. We plan to measure these effects directly using the STAR detector system with the Electromagnetic calorimeter.

There are a series of steps involved in such a study. The first step is to measure the gluon structure function in the proton using pp collisions at $\sqrt{s}$ = 200 GeV. One measures this structure function via two body kinematics[5] in hard qg scattering. The identifying tag for these events is a final state that consists of a γ and a jet. The γ and jet will be approximately back to back in the azimuthal angle φ, with roughly equal energies. The kinematic information is used to extract the x_{BJ} of the scattered gluon and quark. This preliminary measurement of the gluon structure function of the proton is significant in its own right as it has never been directly measured.

The next step is to measure the gluon structure function for nucleons bound in a gold nucleus. It is the modification of the structure function in the bound nucleon that is referred to as shadowing. One does this using p-Au running at RHIC. The final state kinematics allows one to select events in which the scattered gluon is from the Au nucleus.

Given the gluon structure function for nucleons bound in a gold nucleus, one now takes advantage of the available calculation tool, PQCD, to calculate what the inclusive moderate to high P_t spectrum should look like for AuAu collisions and compares this with the data. This allows for the possibility of studying modifications of the jet fragmentation function due to the media traversed by the hard scattered partons. It is this modification that is referred to as jet quenching.

This modification of the fragmentation function may yield a quantitative signal that the matter produced in the collisions has passed through a quark-gluon plasma.

An important consideration when evaluating the ability of the STAR detector to make the measurement of the gluon structure function is the acceptance of the detector and the range of Bjorken x over which one can make the measurement. These quantities are shown in Fig. 4. The vertical axis is the pseudorapidity of the γ and the horizontal axis is that of the jet for a qg $\rightarrow$ γ-jet event. The rectangular box in the lower left hand corner shows the acceptance for the barrel EMC alone. One sees that if $|\eta_\gamma|$ is $\leq$ 1.0 and $|\eta_{jet}|$ $\leq$ ~0.35 then the event is within the acceptance of the barrel. The η range for the jet in the barrel is due to the finite (~0.7) radius typically used in jet finding codes and the requirement that all of the jet energy is intercepted by the barrel. The large increase in acceptance that one achieves with the addition of a single endcap EMC is shown by the area of Fig. 4 which is outside of the rectangular (EMC barrel) box. The range of Bjorken x is shown in Fig. 4 with the dashed

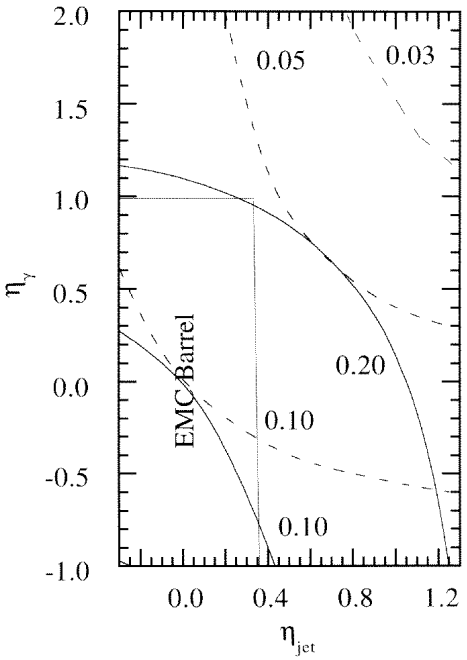


Fig. 4. Acceptance of STAR EMC (barrel + 1 endcap). Please see text for interpretation.

(gluon x value) and solid (quark x value) curved lines. The curve is not shown in this plot, but the lowest x value accessible for the gluon, ~0.02, has some acceptance in the upper right hand corner.

2. The STAR Detector

The STAR detector is a large acceptance device capable of tracking the large multiplicity of charged particles expected to be observed at RHIC. The baseline detector is a cylindrical Time Projection Chamber (TPC) located inside of a solenoidal magnet with a 0.5 T field to provide tracking, momentum analysis and particle identification of most of the charged particles at midrapidity. Momentum measurements will be made over a large pseudo-rapidity range ($|\eta| < 2$) with full azimuthal coverage ($\Delta\phi = 2\pi$). The Central Trigger Barrel (CTB), consisting of 240 scintillator slats, lies just outside of the TPC outer field cage and gives charged particle multiplicity information for $|\eta| \leq 1$ and 2π in azimuth. Vertex Position Detectors (VPD), consisting of lead converter directly in front of phototubes, are placed around the beam pipe on each side of the interaction region. The CTB ($|\eta|\leq1$), VPD ($4.8\leq|\eta|\leq5.0$), and direct readout of the wire planes incorporated in the TPC readout sectors ($1\leq|\eta|\leq2$) will be utilized to supply trigger information to STAR and luminosity information to both the STAR detector and the RHIC accelerator.

Improvements planned for STAR should significantly increase its physics capabilities. These additional detectors are the Silicon Vertex Tracker (SVT), an Electro-Magnetic Calorimeter (EMC), a highly segmented Time-of-Flight array (TOF), external time projection chambers (XTPC), and a photon multiplicity detector (PMD). The addition of the EMC is imperative for the physics study presented here. A cutaway view of the STAR detector is shown in Fig. 5 below.

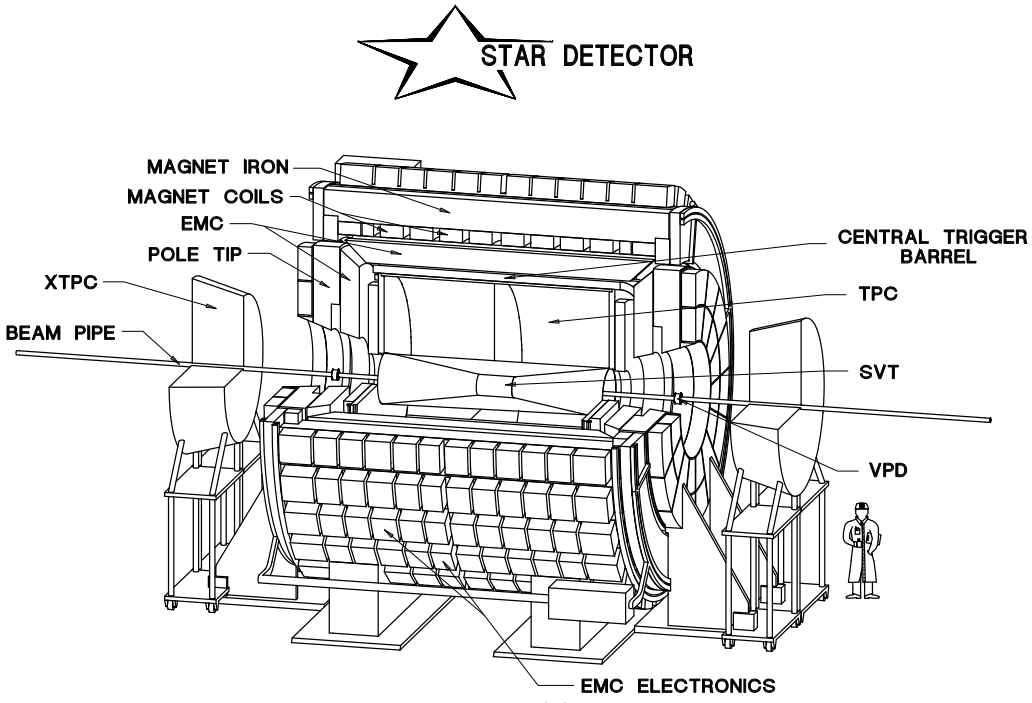


Fig. 5 Cutaway View of the STAR Detector

The proposed STAR Electromagnetic calorimeter consists of a barrel ($|\eta|\leq1$, $\Delta\varphi =$ 2) and one endcap (1 ´| |´2, ‘ = 2), both of which contain shower maximum

detectors. More information about the proposed calorimeter can be found in Ref. 5. Some of the basic parameters for the calorimeter are listed below:

Barrel

- ★ 20 layers of 5 mm thick Pb
- ★ 21 layers of 4 mm thick scintillator
- ★ ~18 radiation lengths thick
- ★ 1200 towers
- ★ 120 modules, 1 unit in η, 6° in φ
  - 10 towers/module
  - 2 tiles/layer/tower, 0.05 in η
  - Read-out with WLS fibers spliced to clear fibers
  - Fibers are coupled to edge of tiles with aluminized mylar
  - Allows depth, η segmentation

Endcap

- ★ 25 layers of 5 mm thick Pb
- ★ 26 layers of 4 mm thick scintillator
- ★ ~23 radiation lengths thick
- ★ 60 azimuthal sectors in two 180° halves, each composed of 9 towers
- ★ 540 towers

SMAX

- ★ wire/pad type

3. Simulation study and results

The investigation of STAR's ability to identify dijets via simulation studies has been an ongoing effort for a number of years. The results presented here are the outcome of recent efforts of Konstantin Shestermanov IHEP (Protvino Russia) and myself. As shall be elucidated in more detail in what follows, we utilize the STAR implementation of GEANT for detector simulation, the STAR analysis shell (TAS), and the full STAR Time Projection Chamber (TPC) tracking package.

STAR plans to carry out jet studies using the TPC and the EMC (i.e. no hadronic calorimetry). The general idea is that one uses the tracking information from the TPC for the charged final state particles and the EMC for the neutral energy.

Jet finding routines generally work by looking for directed energy flow coming from an event. The first part of our analysis entails how we get from the data that comes out of the STAR detectors to the energy flow out of the interaction vertex. The analysis starts with the momentum analyzed charged particle tracks found in the TPC. The pad row crossings (hits) in the TPC are passed to the present TPC tracking code. The tracks which are returned, and used in this analysis, contain the inefficiencies and finite momentum resolutions from the present tracking code. At no point is kinematic information from GEANT used to assist in this analysis. Each of the found TPC tracks is projected outward to see if it intersects with the barrel EMC. If the track intersects the barrel, a parameterized amount of energy is subtracted out of the struck tower. In the analysis presented here the parameterization is only a function of the momentum magnitude for the track. Whether or not a track intersects the barrel EMC, all the found TPC tracks are projected back to the primary interaction vertex. The total energy for the

track is calculated, assuming that the track is due to a pion, and this energy for the track is entered into the appropriate η-φ histogram bin. No particle ID is used at present so it is assumed that all tracks are charged pions.

Once the energy in the EMC has been corrected for all of the found TPC tracks which strike the barrel, the resulting energy in the EMC is multiplied by 1/sampling factor for neutral energy, to arrive at the deduced incident neutral energy. This quantity 1/sampling factor was extracted via the GEANT response to electromagnetic energy, and has a value of approximately 16.

At this point the charged energy histogram (evaluated at the primary vertex) is added bin by bin to the neutral energy histogram, to end up with the histogram (in η-φ) of the total energy flow out of the primary vertex. It is this last histogram that is used as the input to the jet finding code.

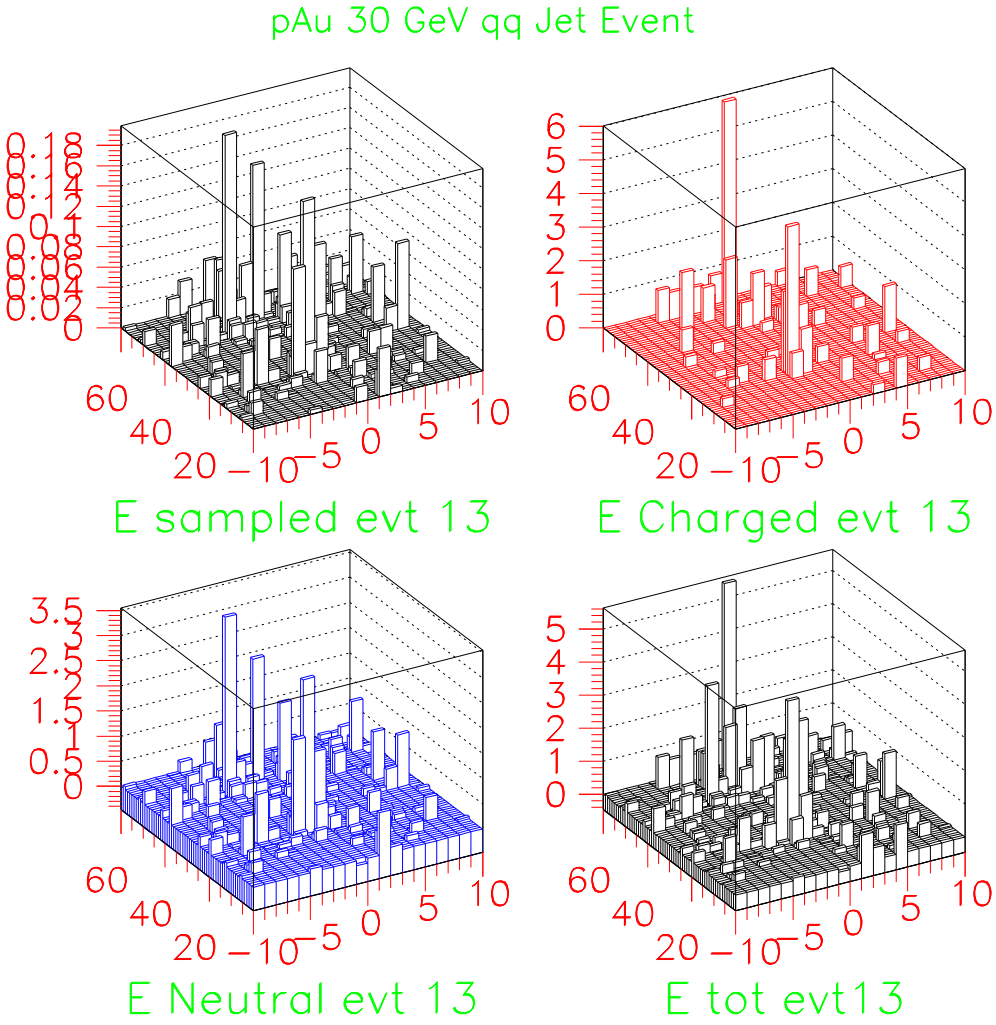


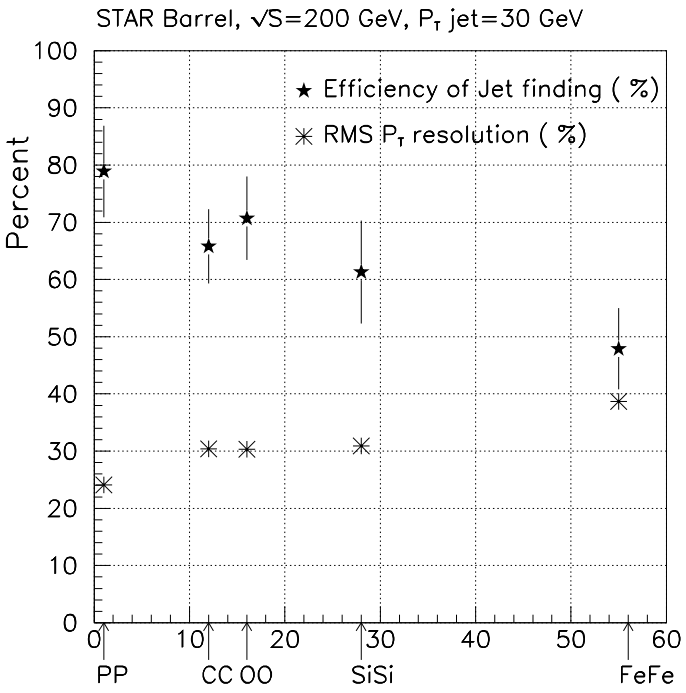
Figure 6. Pictorial representation of the Energy flow analysis. The axis that runs from -10 to 10 is the pseudorapidity bin number. This corresponds to a range of -1 to 1 in η*. The axis that runs from 0 to 60 is the* ϕ *bin number. This corresponds to 360° in azimuth. The vertical scale in all the plots is energy in units of GeV.*

This process is illustrated in Fig. 6. The event shown contained a 30 GeV/c P_t qq scatter in a pAu collision at $\sqrt{s}$ = 200 GeV. The upper left lego plot shows the sampled

energy in the EMC due to both the incident neutral and charged energy. The vertical scale in all of the lego plots of Fig. 6 is energy in units of GeV. The upper right lego plot shows the charged energy evaluated at the interaction vertex, as determined through the procedure described earlier using the TPC tracks and assuming that all tracks are pions. The lower left plot shows the deduced incident neutral energy for the event. Finally, the lower right plot shows the total energy flow out of the vertex for the event.

The jet finding code that we are using is a modified version of the UA1 jet finding code. The basic logic is that of a generic cluster finding algorithm. It looks through the η-φ bins in the energy flow histogram for bins that are greater than some threshold value, E_T^{Seed}. It orders these towers then, going from highest to lowest, sums all of the energy within some cone radius, R_0, around the seed tower. Finally these energy sums or clusters are compared to a final threshold, E_j. If they are greater than this final threshold then the energy cluster is identified as a jet. The modifications that have been made deal mainly with determining, on an event by event basis, what the soft background energy is in an event. This is done via an iterative process that sums all of the energy that is not included in a jet, divides this summed energy by the number of towers that are not included in jets, and then subtracts this background energy from all calorimeter towers. In the first pass of this iterative process this background energy is the sum of all the energy divided by the number of towers in the calorimeter. The user definable parameters in this jet finding code are the seed tower energy, E_T^{Seed}, the cone radius, R_0, and the minimum jet energy, Ej.

All of the results presented in this document were done using only the barrel component of the STAR EMC. For the purposes of this study it was desirable to separate the effect of STAR's acceptance from the efficiency of the jet finding algorithm when applied to the STAR data. This was accomplished by looking at the directions of the hard scattered partons generated with the HIJING code. If the partons scatter within the psuedorapidity range from -.3 to +.3 then the event is stored for input to the STAR GEANT package. The results for pp, CC, SiSi, and FeFe events at $\sqrt{s}$=200 GeV, where each event contains a hard qq scatter with a P_t of 30 GeV/c, are shown in Fig. 7. The efficiency is defined as the number of dijet events found by the code divided by the number of input events. A dijet was defined to be found if the angle between the found jet and the parton in the X-Y plane was less than one radian, the two jets were back to back in φ to within 30°, and the jets energy was greater than or equal to 5 GeV (9 GeV for the FeFe data). The error bars shown for



the efficiency just reflect the statistical errors.

Also plotted in Fig. 7 are the Pt resolutions of the found jets for the various systems. These resolutions are the rms widths of the distributions of Pt of the partons - Pt of the jets.

As discussed previously, the gluon structure function measurement for Au will be measured via qg scattering in pAu running. As a start towards understanding STAR's capabilities for this important measurement, we've done a study of the efficiency of our present code to find dijets in pAu events as a function of the Pt of the parton scatter. The results of this study are shown in Fig. 8 for parton Pt values of 30, 20, 15, and 10 GeV/c. Also shown are the P_t resolutions for the jets. The efficiencies and resolutions are defined in the same manner as in the AA case.

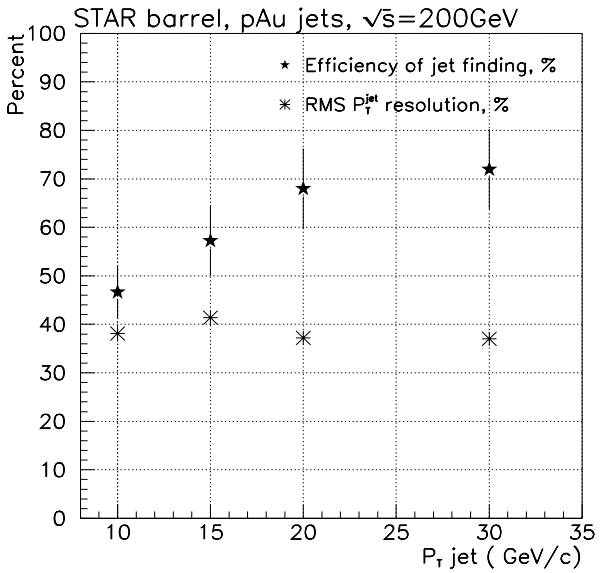


Fig. 8 Jet efficiencies and resolutions versus P_t.

3. Summary

Determining the initial conditions for the AA collisions that will take place at RHIC is important for understanding the data which will be taken at RHIC. A direct measurement of the gluon distributions for nucleons bound in a nucleus will enable the application of PQCD for understanding the RHIC data. This will allow us to deconvolute the effects of gluon shadowing and jet quenching on global final state observables such as the multiplicity density and the moderate to high portions of the P_t spectrum.

Our simulations to date give us confidence that STAR, with the addition of the proposed ElectroMagnetic Calorimeter, will be capable of pursuing this measurement. Among the current RHIC detectors STAR is unique in this capability.

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[1]A.D Martin, W.J. Sterling, and R.G. Roberts, Phys. Rev. D **50** (1994) 6734.
[2]X.N.Wang and M.Gyulassy, Phys.Rev. D **44** (1991) 3501, and Refs. there in.
[3]X.N.Wang and M.Gyulassy, Phys.Rev.Lett. **68** (1992) 1480.
[4]M.Gyulassy, M.Thoma, and X.N.Wang, LBL Report No.LBL-31003, 1991 (to be published).
[5] Conceptual Design Report for the STAR Electromagnetic Calorimeter. LBL Pub-5380.