High $p_T$ physics at STAR

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Abstract. We discuss the capabilities of STAR in exploring the physics at high $p_T$ in ultrarelativistic heavy-ion collisions from RHIC at $\sqrt{s_{NN}} = 130$ GeV. Preliminary results show that the spectra of negatively charged particles get suppressed at larger $p_T$ in comparison to $p\bar{p}$ data. A strong azimuthal anisotropy observed at large transverse momentum region. A preliminary ratio $\bar{p}/p$ has been measured by STAR-RICH detector. Some ongoing studies and future plans are discussed.

Keywords. High $p_T$; energy loss; $v_2$; correlation.

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1. Introduction

A large amount of data has been collected from high energy heavy-ion collisions at SPS for various target–projectile combinations and for different incident energies [1]. Beginning with RHIC, an observable which is expected to play a dominant role for the first time in this field of study is high $p_T$ particles produced in the collisions [2]. Due to a considerable increase in the center-of-mass energy from top SPS energy ($\sqrt{s_{NN}} = 20$ GeV) to top RHIC energy ($\sqrt{s_{NN}} = 200$ GeV), it is expected that a large fraction of particles are to be produced due to the hard scattering of nucleon constituents.

The most direct observable of hard scattering is the observation of jets, generated due to fragmentation of the scattered partons. Even though jets are observed almost unambiguously in $e^+e^-, p\bar{p}$ and for lighter systems, in heavy-ion collisions it is almost impossible to identify jets unambiguously due to the presence of softer components in large numbers. The situation becomes more complicated due to the expectation that the jets produced at RHIC energies are relatively soft ($p_T \approx 2–3$ GeV). These soft jets are commonly known as minijets [3].

It is therefore necessary to look for observables which will carry the relevant information in the absence of full jet reconstruction. Different proposed measurements are based on various properties of the leading particles, e.g., the spectra of leading particles, asymmetries and correlations in rapidity and azimuth of leading particles, and the flavor dependence of high $p_T$ particles.

In recent years, observables related to the hard scattering of nuclear constituents are gaining importance for various reasons. One of the advantages of these observables is that they are expected to carry information from the very early stage of the collisions, as they are produced earlier than most of the other observables produced. Another advantage is that
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these production processes can be calculated using perturbative QCD (pQCD). Relatively precise prediction can therefore be made about the observables and interesting physics can be extracted from the observation after comparison with these predictions.

An interesting feature of these probes in the context of heavy-ion collisions is their expected sensitivity to the type of matter produced at the early stage of the collisions. These scattered partons are produced early, and pass through the dense medium produced in the collision. It is predicted that properties like fragmentation function of the jets produced by these scattered partons will get modified and the modification depends on the density of the medium [2].

A large number of predictions have been made for various observables, but there are several areas that are still debatable, including the exact formulation of medium modifications, and the interplay of soft and hard processes. The general feeling therefore is that ultimate conclusions can only be drawn from the data. But to explain the data satisfactorily it is important to understand the data available from $NN$ and $NA$ collisions at similar energies.

In this write-up we discuss the preliminary results available from STAR experiment for $AuAu$ collisions at $\sqrt{s_{NN}} = 130$ GeV. First, we will try to have a brief overview of the data available so far from $NN$, $NA$ and $AA$ collisions and the expectation from $AA$ system at RHIC energy. In §3 the detector systems used in STAR mainly for this type of physics will be discussed. In §4 we will discuss the preliminary results and discuss some of the possible interpretations of the results. Section 5 will deal with some ongoing studies which will show the capabilities of STAR in dealing with high $p_T$ observables. In §6 we will discuss some future programmes.

2. $pp$ to $AA$

In the early seventies, experiments at ISR, CERN found that the transverse momentum spectra of the produced particles show a clear deviation from exponential behaviour at $p_T > 2$ GeV/c. This deviation was then observed by many other experiments for a range of energies [4]. This region of spectra can be explained as generated by hard scattering of nucleon constituents (partons). Perturbative QCD can explain this spectra well with the inclusion of an initial transverse momenta of the constituent (initial $k_T$) along with large longitudinal momenta.

While going from $pp$ to $pA$ collisions, the yield should scale as $A$ of the nucleus if the reaction mechanism is due to the end product of independent binary collisions. It was however found that the yield is enhanced compared to the expectation from binary collisions. This enhancement known as Cronin effect is said to be originated due to initial scattering of the partons resulting in the broadening of initial $k_T$ [5]. Results from $pp$ collisions can be used as reference to test if the particle production in $AA$ collisions is due to independent binary collisions. To obtain the reference, the factor due to the geometry of the collision of the $AA$ system should be taken into account.

Partons are expected to loose energy while passing through the media. Even though the description of energy loss is not unique, it is argued that energy loss depends on the density of the matter and on the flavor of the scattered partons. This will therefore lead to several interesting probes involving the modification of the fragmentation function of jets (minijets). At RHIC energy a high density deconfined quark matter is expected to be formed. This matter can be probed by looking at the properties of the leading particles of the jets produced in the collisions.
3. STAR detector for high $p_T$ physics

The STAR experiment, shown in figure 1, has an extensive program for high $p_T$ physics [6]. The main detectors designed to deal with this type of physics are: (i) time projection chamber (TPC), (ii) ring imaging Cherenkov detector (RICH), and (iii) electromagnetic calorimeter (EMC). Along with these, the detectors used for triggering and event selection are the central trigger barrel (CTB) and zero degree calorimeter (ZDC).

3.1 STAR time projection chamber

The TPC is at the heart of STAR, covering a region of $|\eta| < 1.8$ having full azimuthal coverage. It has collected data in 2000 and 2001. The results being discussed here are from the 2000 data set. The TPC was operated inside a solenoidal magnet with 0.25 T magnetic field in 2000 run. Momentum resolution ($\Delta p_T/p_T$) of the tracks reconstructed from TPC at lower $p_T$ cut-off of 200 MeV/c is 2% and degrades up to 15% for higher $p_T$ up to 6 GeV/c. Momentum resolution is expected to improve considerably for 2001 run with a magnetic field of 0.5 T.

3.2 Description of RICH

A ring imaging Cherenkov (RICH) detector is included in the STAR experimental setup to provide charged particle identification at high transverse momentum. The STAR-RICH is positioned outside the outer radius of the STAR TPC and within the inner radius of the magnet at mid-rapidity. The STAR-RICH subtends an azimuthal angle of 20° and offers a coverage in pseudorapidity of $|\eta| < 0.3$ for collisions centered in the detector. Charged particles having velocities above the Cherenkov threshold velocity produce a pattern of
light which is collected on a detection plane. Particle identification is accomplished via pattern recognition and separation of pions and kaons is possible up to a momentum of \( \approx 3 \) GeV/c and proton identification is possible up to \( \approx 5 \) GeV/c.

### 3.3 Description of EMC

The STAR barrel electromagnetic calorimeter (BEMC) is among the first upgrades to the STAR baseline detector system [7]. The first \( \approx 20\% \) of the detector was installed for the 2001 run. STAR, which is nominally a slow detector, utilizes the BEMC to trigger on and study rare, high \( p_T \) processes (jets, leading hadrons, direct photons, heavy quarks) and provide large acceptance for photons, electrons, \( \pi^0 \) and \( \eta \) mesons in systems spanning polarized \( pp \) through Au–Au collisions. The calorimeter has a total depth of approximately 20 radiation lengths (20\( X_0 \)) at \( \eta = 0 \).

A sampling calorimeter using lead and plastic scintillator has been used for the detection of electromagnetic energy in STAR. A scintillation light detection scheme utilizing photomultiplier tubes (PMT) is adopted. A combination of plastic wavelength shifting and clear optical fiber has been selected for the transportation of light. The BEMC is located inside the aluminum coil of the STAR solenoid and covers \( |\eta| \leq 1.0 \) and \( 2\pi \) in azimuth, thus having complete overlap with TPC tracking. The front face of the calorimeter is at a radius of \( \approx 220 \) cm from the beam axis. Design for the barrel electromagnetic calorimeter includes a total of 120 calorimeter modules, each subtending 6\( \Delta \phi \) (0.1 radian) and 1.0 unit in \( \Delta \eta \). The modules are segmented into 40 towers, in two rows in \( \eta \) direction each subdivided into 20 towers. Each tower subtends 0.05 in \( \Delta \phi \) by 0.05 in \( \Delta \eta \). The full barrel calorimeter is thus physically segmented into a total of 4800 towers, each of which is projective, pointing to the center of the interaction diamond.

From the requirement of the precise electromagnetic shower reconstruction with high spatial resolution, a shower maximum detector (SMD) (essentially two layers of gas wire pad chambers) within the BEMC lead/scintillator stack has been implemented to provide high spatial resolution measurements of shower distributions in two transverse dimensions. After the use of shower maximum detector, the calorimeter tower sizes need only be chosen small enough to produce reasonable particle occupancies in typical events of interest.

To distinguish \( \pi^0 \)s and \( \gamma \)s at \( p_T \) as high as \( \approx 25 \) GeV/c at the radius of the STAR detector, an independent pre-shower detector readout of each tower is provided. These signals provide a measurement of the longitudinal shower development after only 1–1.5\( X_0 \) which significantly aids in both \( \pi^0/\gamma \) and electron/hadron discrimination. The first and second scintillating layers of the calorimeter comprise the pre-shower detector. Cross-section of one module of EMC, along with the detailed schematic description of tower and SMD are shown in figure 2.

In order to estimate the performance of the detector for high \( p_T \) physics, we have made detailed simulation with Au–Au events at RHIC full energy. Simulated hits are processed via ‘cluster finders’ for three subdetectors separately, and then the clusters from various subdetectors are matched to obtain the position and energy of the photon clusters. Invariant mass spectra of those photon candidates are shown in figure 3a. A background subtracted \( \pi^0 \) peak is shown in figure 3b. The detailed simulation results show that we can expect to obtain \( \pi^0 \) spectra starting from 3 GeV/c up to as large as 15 GeV/c.
4. Results

We discuss the preliminary results from three topics, e.g., spectra of charged particles, azimuthal anisotropy of charged particles at large transverse momenta and $p/p$ ratio up to $p_T = 2.5$ GeV/c. Apart from these three topics, the correlation analysis for charged particles at large $p_T$ form the topics for ongoing studies, for which we expect results soon.
4.1 High $p_T$ spectra of negatively charged particles

The spectra of negatively charged particles have been measured from RHIC in extensive detail. STAR has published spectra up to $p_T = 2$ GeV/c [8]. Other experiments have obtained the results for identified particles [9]. Here we discuss the preliminary spectra up to 6 GeV/c [10].

The spectra up to $p_T = 2$ GeV/c are used to describe the bulk properties of the system. Spectra in this range were described reasonably well using various models, e.g., thermal model, string model etc. Particles produced due to fragmentation of jets generated by hard scattered partons are expected to populate the large transverse momenta ($> 2$ GeV/c) region of the spectra. As the boundary between soft and hard is not known that well due to the presence of minijets, it is necessary to understand the spectra in whole $p_T$ region.

It is necessary to understand the shape, slope and other properties of the spectra in detail, because each of these parameters carries interesting information.

It is predicted that the effect of energy loss in dense nuclear medium would be the suppression of the spectra of leading particles. The energy loss is said to be dependent on the density of the matter. It is therefore essential to compare the spectra with respect to the spectra observed in $pp$ collisions at similar energies.

We show in figure 4 the preliminary $h^-$ spectra obtained from STAR. $h^-$ spectra from NA49 experiment for Pb + Pb collisions at SPS and $(1/2)(h^+ + h^-)$ spectra from UA1 for $p\bar{p}$ collisions are superimposed on STAR data.

Before going into detailed comparison of different spectra, we can make the following statements about various results. Even though the NA49 result does not extend beyond 2 GeV/c and the UA1 result is for 200 GeV/c, it seems that the STAR spectra is flatter compared to other results. The mean transverse momentum for STAR is higher compared to NA49 and $p\bar{p}$ data. One of the possible explanations could be larger radial flow at RHIC.

For the interpretation of the results for new physics, it is essential to obtain suitable reference spectra. STAR has taken $pp$ data at 200 GeV this year, which will be used for reference spectra in further analysis, which is having the advantage that the systematics cancel out. But to compare data at 130 GeV, the closest collision energy used was for UA1 data at 200 GeV. From the available $p\bar{p}$ data in broad energy range (200 GeV to 900 GeV), parameterization was made to extrapolate UA1 spectra for 130 GeV. The parameter $R(130/200)$, the ratio of the parametrization at $\sqrt{s} = 130$ GeV and at 200 GeV range from 0.92 at $p_T = 2$ GeV/c to 0.45 at 6 GeV/c.

For extrapolating $pp$ data to Au–Au collisions as an extension of binary collisions, we need to calculate the average number of binary collisions for a specific centrality selection in Au–Au data. For a specific impact parameter selection corresponding to a fraction of the inelastic $AA$ cross-section $\sigma^{\text{inel}}_{AA}$, the average number of binary collisions $\langle N_{\text{binary}} \rangle$ can be calculated as $\sigma^{\text{inel}}_{\text{nn}}(T_{AA})$. Using the model dependence of the geometrical overlap for 5% central data we obtain the nuclear overlap function as $T_{AA} = 26$ mb$^{-1}$.

The right panel shows the ratio of STAR spectra with normalized $p\bar{p}$ spectra. The $p\bar{p}$ data have been corrected for collision energy difference and the geometry which corresponds to $\langle N_{\text{binary}} \rangle = 1050$. The vertical bars illustrate the error on the STAR measurement while the grey area estimates the total error, including the systematic error of the parametrization and normalization of the measurement. Two limits are shown on the plot. One corresponds to the ratio expected if the spectra is the result of independent binary collisions, where the ratio should be unity. The lower limit corresponds to the ratio expected
4.1 Preliminary result of the spectra of negatively charged particles from STAR.
(1/2)(h^- + h^-) spectra from UA1 result at 200 GeV for pp collision and for spectra
from NA49 at SPS energy are superposed on the STAR result. On the right panel, ratio
of STAR data with normalized pp data is shown.

It is seen that the ratio increases with p_T starting from the wounded nucleon limit, but it
never reaches binary collision limit. The near-linear increase in this p_T region can possibly
be the effect of phenomena like radial flow, onset of hard scattering. Interestingly the ratio
reaches a saturation value. A similar trend is observed by the Phenix collaboration [11].
This trend is contrary to Cronin effect where ratio goes beyond unity. This result is spe-
cially interesting because one of the possible explanations for this suppression compared
to binary collision limit is the energy loss of leading particles in dense medium.

4.2 Azimuthal anisotropy

Anisotropy observed in the azimuthal distribution of the produced particles carry important
information about the dynamical evolution of the system. While going from non-central
towards central collisions, the shape of the reaction zone transverse to the reaction plane
changes from the elliptical almond shape to more circular shape. The event plane is defined
by the beam direction and the direction of the impact parameter. Due to rescattering in the
evolving system, initial spatial anisotropy, which is higher for non-central collisions, can
can get converted into momentum space anisotropy. The anisotropy decreases with the system
expansion, so it is sensitive to the early stage of the collision.

The measure of this anisotropy known as elliptic flow is given by the coefficient of the
second harmonic (v_2) of Fourier expansion with respect to the event plane. Event planes
are usually determined event by event using the particles not used for the determination
of the azimuthal anisotropy. v_2 has been measured by STAR for various centralities and
at different transverse momenta [12]. Several attempts have been made successfully to
explain the data using hydrodynamical model for p_T below 2 GeV/c.

The use of hydrodynamics at higher p_T is questionable as we expect hard processes to
set in. For all the particles produced by independent binary collisions, we do not expect any
azimuthal anisotropy, as the jets are not correlated to the event plane. We can on the other hand expect some asymmetry for high $p_T$ particles in the case of the existence of a path length dependent energy loss [13]. For a non-central collision, the almond-shape reaction zone has larger path length in a direction perpendicular to the reaction plane compared to the in-plane direction. Jets produced out of plane will therefore lose more energy compared to the ones produced in plane, thereby giving non-zero $v_2$.

Figure 5 shows the variation of $v_2$ with transverse momentum of the charged particles for three different centralities. Expectedly, $v_2$ reduces with the increase in centrality. It is seen that $v_2$ increases with $p_T$ up to about 2 GeV/c. This dependence of $v_2$ with $p_T$ is in accordance with the hydrodynamical expansion of the system. For a scenario with pure hydrodynamical expansion at low $p_T$ and perturbative QCD with energy loss at larger $p_T$, $v_2$ is expected to saturate above $p_T = 2$ GeV/c. Interestingly, as shown in figure 5, $v_2$ increases monotonically up to $p_T \approx 2$ GeV/c, thereby attaining a saturated value. The $p_T$ region where the saturation occurs seems to be centrality dependent.

Even though the explanation of this variation of $v_2$ is not clear, it could be mentioned that something interesting is happening at $p_T$ larger than about 2 GeV/c.

4.3 Ratio of identified charged particles

The flavor dependence of the energy loss inside the dense media leads to different production yield for particles and antiparticles. Due to differences in gluon and quark fragmentation, leading particles from gluons are softer compared to the ones from quark. In nuclear collisions, we expect equal number of protons and antiprotons in the gluon fragmentation. Flavor dependence of quark fragmentation function on the other hand leads to the production of more protons than antiprotons, especially at higher $p_T$ due to the contribution of the valence quarks at large $x$ compared to gluons at small $x$. In other words, high $p_T$ proton will have smaller relative contribution from gluon jets than antiprotons. If gluon jets lose more energy than quark jets, one expects to have different suppression factors for protons and antiprotons. $\bar{p}/p$ ratio therefore are expected to decrease more strongly with increasing $p_T$. 

Figure 5. $v_2$ at different $p_T$ for three different centralities. Error bars are only statistical.
for the flavor dependent energy loss mentioned above [2]. Hijing predicts that the decrease should start even at $p_T$ of 2 GeV/c. STAR experiment, using the RICH, has measured $p$ and $\bar{p}$ up to $p_T$ of about 2.5 GeV/c. The transverse momentum limitation is mainly due to lack of statistics. We hope to cover the range up to 5 GeV/c in next year’s run. From the results of particle spectra and azimuthal anisotropy where the possible explanation is energy loss, we expected larger decrease in the ratio with $p_T$. But given the error bars we cannot conclude anything regarding the decreasing trend of the ratio. We hope that this year’s data with improved statistics will be able to address the question better.

5. Ongoing studies: Correlation of large $p_T$ particles

Identification of jets in heavy-ion collisions is almost impossible due to the presence of large background from soft particles. Jets of very large energy (>10 GeV) could possibly be identified using STAR EMC, but it is difficult to disentangle minijets having typical $p_T$ of 2–3 GeV/c.

Suggestions have been made for using some indirect method for obtaining the evidence of the produced jets in the collision and their properties by the use of correlation of various observables of the produced particles, e.g., $\eta$ and $\phi$ of the produced particles.

Fragments from jets are correlated in $\eta$ and in $\phi$ and they exhibit characteristic shape in the correlation function. Here we discuss the preliminary attempts to measure the azimuthal correlation function for particles having different $p_T$ intervals. It was suggested that with the increase in $p_T$ threshold, the background to the correlation function due to non-jet contributions get filtered out and a shape characterizing the jets will appear. This has been demonstrated for $p\bar{p}$ collisions using the Hijing event generator [14].

In case of heavy-ion collisions, additional contributions from background appear due to elliptic flow. As previously shown, elliptic flow is relatively high and increases with $p_T$. In addition to that, momentum conservation may generate azimuthal correlations.
Analysis is in progress by dividing the entire $p_T$ region up to 6 GeV/c into various ranges. As mentioned earlier, we expect to pick up signals from hard scattering mainly from higher $p_T$ particles. The correlation functions at lower $p_T$ intervals exhibit characteristic cosine shape, which shows the dominance of the contributions from elliptic flow. At intervals with larger $p_T$, the correlation function shows deviation from the pure cosine form. Figure 7 shows the correlation function for four centrality ranges for the $p_T$ range from 1.2 GeV/c to 2 GeV/c for $|\eta| < 0.75$. Normalization of the correlation function is done using the inclusive distribution.

We need to filter out hard scattering contribution from the measured correlation function. The effects contributing as background in this analysis are, elliptic flow, momentum conservation, effect from resonances etc.

We discuss here some of the approaches which can be taken in order to filter out the contributions of hard scattering from the correlation function.

(A) The simplest way is to eliminate the second harmonic in the correlation function completely. In this case the correlation function is fitted with the functional form
The difference between the fitted curve and the measured one gives the contribution other than the elliptic flow. This difference contains the contributions like (i) $\cos(\Delta \Phi)$ corresponding to momentum conservation and (ii) Gaussian profile corresponding to jets. It is essential to compare the results for other components obtained from the fit to the values obtained from other methods and analytical estimates [15]. The drawback of this method is that it also eliminates the possible second harmonic contribution to the correlation function from back-to-back jets.

(B) The contribution of elliptic flow at these transverse momenta can be estimated from the correlation of particles in large $p_T$ momentum region with low $p_T$ particles. The assumption of this method is that the jet contribution to low $p_T$ particles is negligible and their azimuthal distribution is governed by only elliptic flow. In this approach [16], two correlation functions can be obtained: (i) for particles with low $p_T$ (e.g. $p_T$ range from 0 to 0.8 GeV/c) and (ii) mixed correlation function between particles from two regions of $p_T$ (e.g. $p_T$ ranges from 0 to 0.8 GeV/c and 1.2 to 2 GeV/c or $p_T$ range from 0 to 0.8 GeV/c and 2 to 5 GeV/c). Two correlation functions are fitted with $v_2^2$, thereby obtaining $v_2$ for two cases. We can then obtain $v_2^{\text{high}}$ only for higher $p_T$ interval using the relation

$$v_2^{\text{mixed}} = \sqrt{v_2^{\text{low}} \times v_2^{\text{high}}}.$$ 

The functional form with elliptic flow using $v_2^{\text{high}}$ obtained from projection is used to subtract the background from the correlation function corresponding to large $p_T$ particles.

The methods of subtraction of background is still under discussion and hope to obtain background subtracted contributions soon.

6. Summary and future prospects

Exploring the physics at high $p_T$ is an important topic at RHIC. STAR experiment has explored a large range of observables related mainly to the leading particles. Preliminary results show very interesting observations. One of the possible explanations is the energy loss in a dense medium produced in the collision. The data shows that the spectra for negative particle is flatter compared to SPS and $p\bar{p}$ data. Ratio of the spectra to normalized $p\bar{p}$ data shows a saturation beyond $p_T = 2$ GeV/c. The result that the ratio is below binary collision limit raises the possibility of energy loss. The origin of large elliptic flow observed at $p_T > 2$ GeV/c can provide valuable information about the system. Capabilities of STAR in measuring $\bar{p}/p$ ratio provides insight about the flavor dependence of the phenomena. We hope to draw definite conclusion from this year’s data. Studies of two particle correlation are expected to provide information about the formation of jets.

STAR has taken data with full beam energy at RHIC, so we hope to add significantly with the statistics on the current understanding obtained from 130 GeV data. One significant improvement for this year’s run is that EMC took data with a large coverage, and we hope to have results from $\pi^0$ very soon. From high $p_T$ physics perspective another important event is that we have taken $pp$ data at RHIC, which will help us to serve as very good reference and several systematics can be understood better. We have also taken data with high tower trigger of EMC, which help us to select events with high $p_T$ particles considerably.
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