Studies of jets in relativistic heavy ion collisions at RHIC through correlations

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LUX ET VERITAS

STAR

Confinement of quarks and gluons in nuclei led to the prediction of a new phase of matter called a Quark Gluon Plasma (QGP) which was probably present during the early stages of the universe. The Relativistic Heavy Ion Collider (RHIC) was built to recreate and study a QGP. Jets, narrow cones of particles produced during the formation of nuclear particles from quarks and gluons following the initial quark and gluon scattering in the nuclear collision, are one of the probes which can be used to to study the medium produced at RHIC. Jets can be studied by means of correlations with a particle with a large momentum transverse to the beam (p_T), since jets are commonly produced in binary collisions in back-to-back pairs. It has been confirmed that many of these large momentum particles originate from jets. These studies have led to observations of modifications of jets in heavy ion collisions. A new component not observed in p+p collisions is observed near the high p_T trigger particle and the jet 180˚ away is suppressed and its shape is modified. These measurements indicate the presence of a high density medium, suggestive of the QGP, at RHIC.

The search for the Quark Gluon Plasma

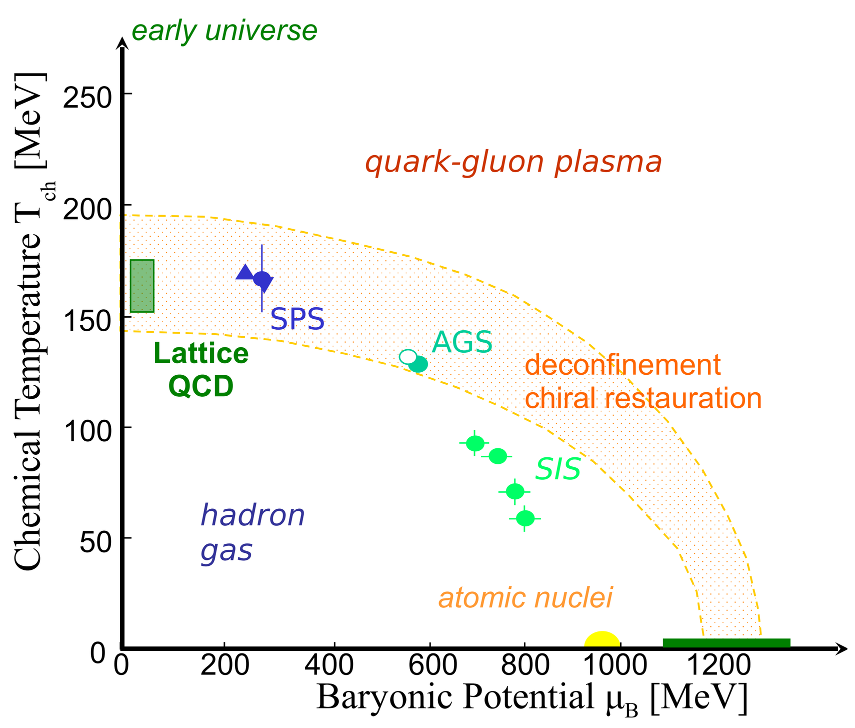

Figure 1: The phase diagram of nuclear matter

QCD predicts a phase transition in nuclear matter at high energy densities. This matter, called Quark Gluon Plasma (QGP), should have very different properties from normal nuclear matter due to the high temperature and densities. This dense, hot nuclear matter should have much more in common with the matter created after the Big Bang than nuclear matter at normal densities.

The Relativistic Heavy Ion Collider (RHIC) was built to study the QGP. The energy densities at RHIC are at or above the phase transition predicted by QCD.

The Relativistic Heavy Ion Collider

The Relativistic Heavy Ion Collider (RHIC) comprises two concentric rings, which allows for the study of many different types of ion collisions over two orders of magnitude in energy. Particles injected into the storage rings first go through a tandem van de Graaf accelerator, a linac, a booster synchronton and finally the Alternating Gradient Synchronton (AGS).

Main RHIC Collisions

Species	√s (GeV)
Au+Au	9, 20, 62, 130, 200
Cu+Cu	62, 200
p+p	200, 400

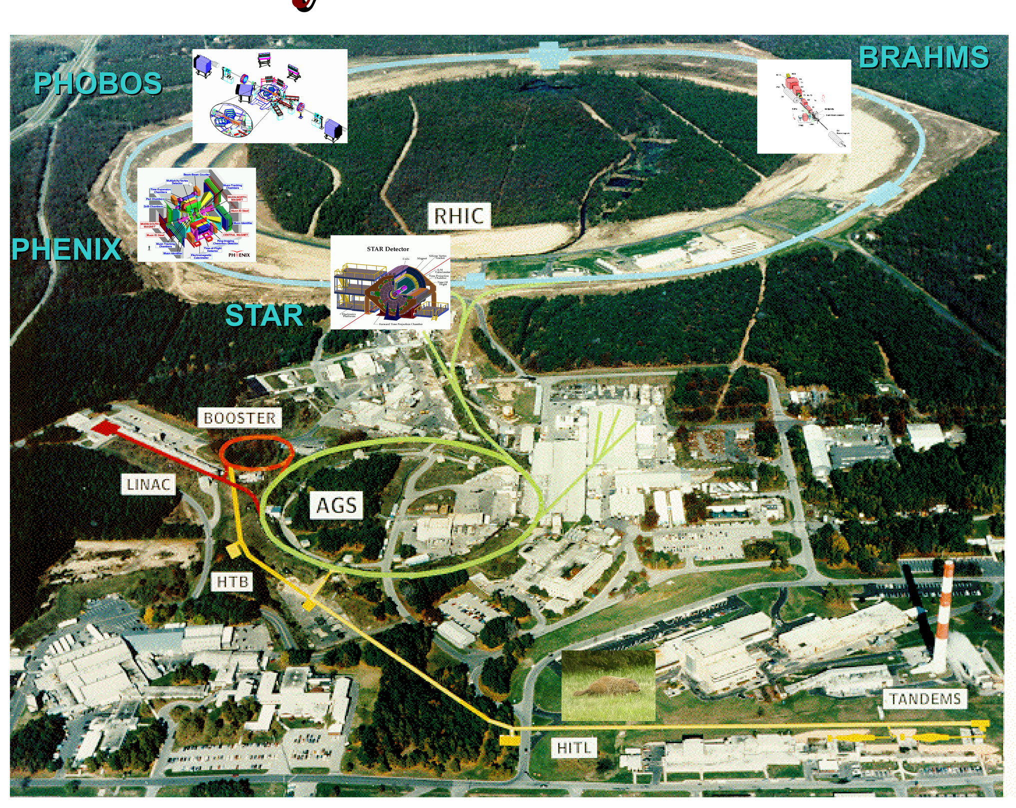

Figure 2: Picture of RHIC showing the different accelerators

Solenoidal Tracker At RHIC

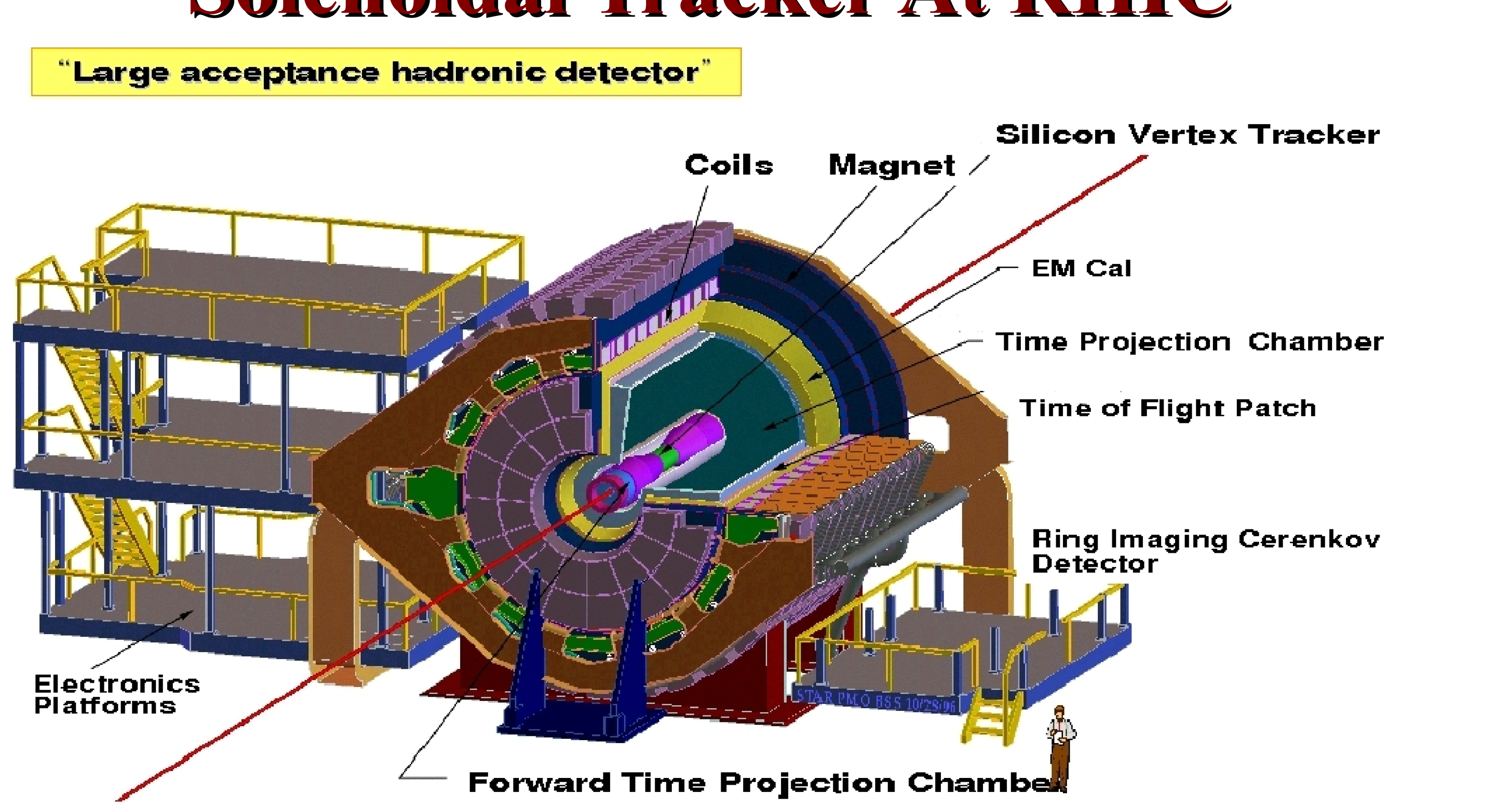

Figure 3: The STAR detector — Nucl. Instrum. Meth. A 499 (2003) 624

The Solenoidal Tracker At RHIC (STAR) was designed specifically to detect charged hadrons. STAR is a cylindrical detector, consisting of multiple subsystems, surrounded by a magnet which produces a field of 0.5 T. The primary detector is the Time Projection Chamber (TPC.) The TPC is approximately 4 m long with an inner radius of 50 cm and an outer radius of 2 m. High energy particles which travel through the volume of the TPC ionize the gas which fills the main cavity detector. There is a cathode in the center of the cavity and anodes at the ends. The electrons created by particles traversing the detector drift towards the anodes at a constant speed. This speed, the drift velocity, is dependent on the gas (P10, 90% Ar and 10% CH_4), the pressure (1 ATM), and the electric field (148 V/cm) and is roughly 5 cm/µs in STAR. The direction and momentum of charges hadrons can be reconstructed from the track it leaves in the TPC.

Motivation

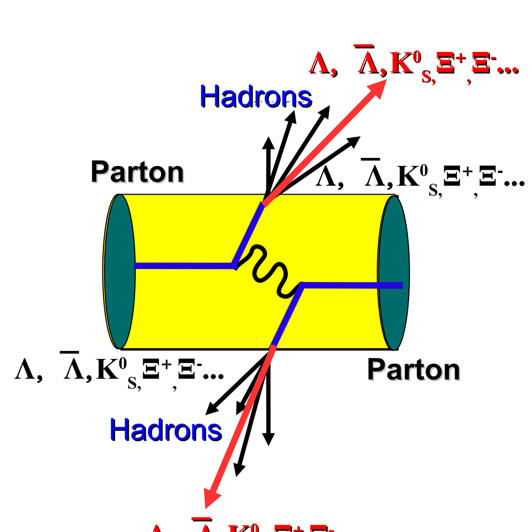

Figure 4: Schematic diagram of jets in a heavy ion collision

In p+p and e⁻+e⁻, showers of particles called jets are created when two partons (quarks or gluons) suffer a hard (high momentum transfer) collision. Usually two jets are produced back-to-back, or azimuthally 180° apart.

Jets are of interest because they could serve as a probe of the medium produced. If heavy ions were a superposition of nucleon-nucleon collisions, the same phenomenon would be observed in heavy ion collisions. However if a medium such as the QGP is produced, jets, which are predominantly produced early in the collisions, must travel through this medium before detection. Since jets have been studied extensively in elementary collisions, it should be possible to determine how the properties of the medium modify the jet.

Method

Because of the large number of particles produced in a typical heavy ion collision, it is difficult to accurately determine which particles were part of a jet. However, if jets are present, the particles created will be correlated in space. Studying these correlations is an alternative to identifying exactly which particles were part of a jet, a rather difficult task in a heavy ion environment.

Jets are likely to emit high p_T particles roughly in the direction of the initial fragmenting parton. Particles above a threshold p_T (trigger particles) are chosen to define the jet axis. The distribution of all particles in a p_T range (associated particles) in azimuth ($\Delta\phi$) is then determined. The distribution of particles in pseudorapidity (Δη) can also be investigated, where η = -ln[tan(θ/2)]. A combinatorial background must be subtracted to eliminate azimuthal correlations not caused by jets. p_T cuts are applied to the trigger and associated particles, are necessary to reduce the background but may exclude some of the jet.

Two peaks are seen, one around $\Delta\phi$ = 0 called the near-side peak and one around $\Delta\phi$ = 180° called the away-side peak.
. In p+p and d+Au collisions, the near-side peak is at small Δη and $\Delta\phi$. The away-side peak is already independent of Δη within STAR's acceptance due to differences between the rest frame of the hard parton scattering and the lab frame and between the jet axis and the direction of the leading hadron.

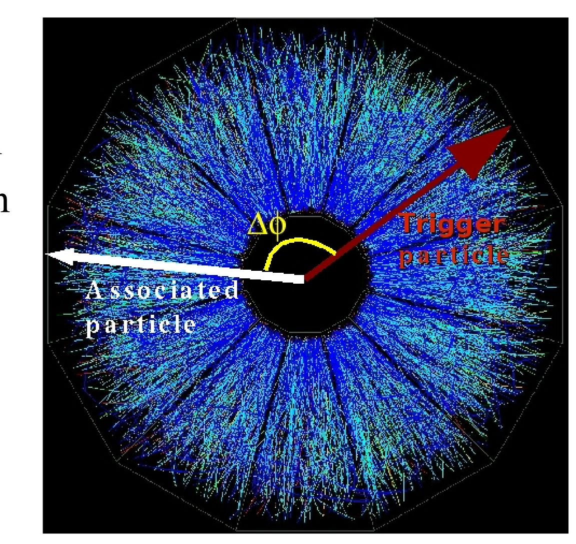

Figure 5: A sample collision in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV. The arrows represent tracks in the event.

Results: The Away-side

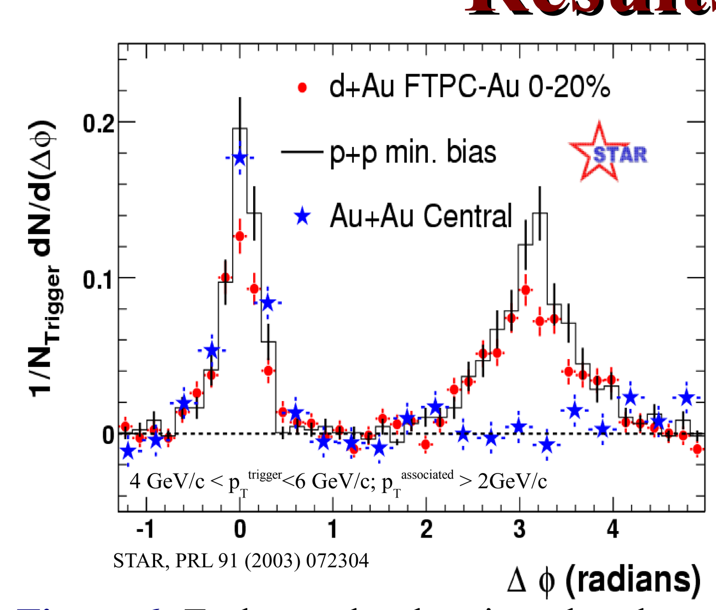

Figure 6: Early results showing that the away side peak is modified in central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

Early results for unidentified particles indicated that azimuthal correlations demonstrated modifications of jet-like signals in high energy Au+Au collisions relative to p+p. This is one of the proposed signs of the Quark Gluon Plasma. Data in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV indicated that, while both the near side peak (from the same jet as the trigger particle) and the away side peak could be seen in p+p, d+Au, and peripheral Au+Au collisions (not shown), the away side was not seen in central Au+Au collisions for associated particles with p_T >2 GeV/c.

This piqued interest in using azimuthal correlations to develop a better understanding of these correlations and the disappearance of the away side peak. The data in Figure 6 have been normalized to the number of trigger particles. Note that the background has been subtracted.

This motivated studies at lower p_T. Figure 6 shows that the away-side disappears for associated particles above 2 GeV/c; Figure 7 shows that the away-side reappears for associated particles above 1 GeV/c. However, the structure of the away-side is not the same in central Au+Au collisions and d+Au collisions. A dip appears in the away-side peak

Multiple models have been proposed to explain the structure of the away-side jet. One hypothesis is that the dips are the remnants of a Mach cone formed by a jet moving through the QGP, which would mean that their location is an indication of the speed of sound in the medium. It is also hypothesized that the kinematic cuts may favor jets which were deflected in azimuth, rather than 180° apart.

These structures disappear if the momentum of the associated particle is restricted to high momenta (p_T^{assoc} > 4 GeV,) a phenomenon known as punch-through. It is hypothesized that these jets are all either produced on the surface of the medium or are high enough energy jets that they could pass through the medium.

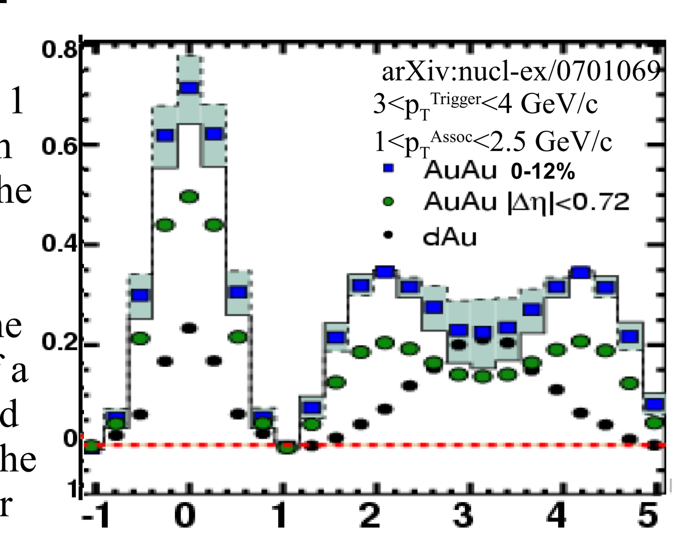

Figure 7: Results from lower momentum associated particles demonstrating that the away-side reemerges at low p_T, but its shape is significantly modified.

Results: The Near-side

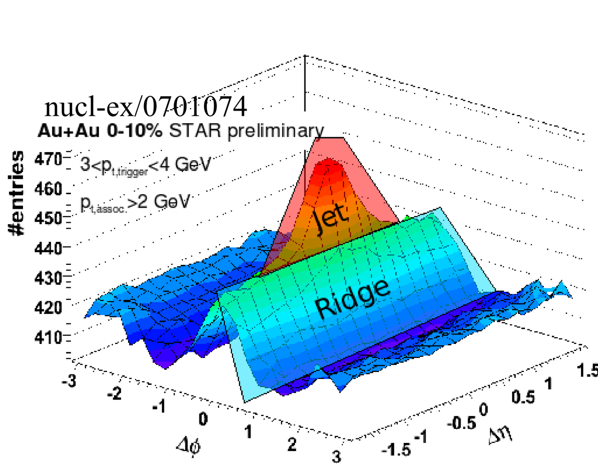

Figure 8: Early results showing that the away side peak is modified in central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

Modifications to the near-side are also observed. In p+p and d+Au collisions, there is a peak only at small Δφ and Δη. This feature, called the *Jet*, is visible in Au+Au collisions, but it sits on top of a new feature, called the *Ridge*, which is narrow in Δφ but broad in Δη. The *Jet* component not only has the same shape as the peak in p+p and d+Au collisions, but it also has the same particle composition and it can be described well by models which primarily include fragmentation.

The *Ridge* has a similar composition to the bulk of particles produced in a Au+Au collision and the spectrum of particles in the *Ridge* is also similar to those in the bulk. It is present even for high momentum (p_T>8 GeV/c) trigger particles. Explanations for the production of the Ridge include a bias in the correlation method, energy loss in the medium, and plasma instabilities.

Conclusions

Studies of jets using di-hadron correlations indicate that jets are significantly modified by the medium produced at RHIC. The particles in the away-side appear at lower momenta in Au+Au collisions than in p+p and d+Au collisions, and the shape is modified. Even the near-side is modified, with a novel feature, the *Ridge*, appearing in heavy ion collisions. These modifications imply that the medium at RHIC is hot and dense. Studies of fully reconstructed jets in STAR have begun, and studies of jets will continue to provide insight into heavy ion collisions.