Particle Identification in High Energy Collisions at RHIC

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This article provides a technical introduction to the study of collider physics by focusing on the concept of particle identification (PID). Through a general overview of the Relativistic Heavy Ion Collider (RHIC) and the Pioneering High Energy Nuclear Interaction Experiment (PHENIX), the author discusses the role of Vanderbilt University researchers in collaborative work at the Brookhaven National Laboratory. After explaining the concept of event reconstruction and centrality with graphical images of experimental results, the author outlines the time-of-flight method of particle identification in high energy physics. A final presentation of the design concept for the Multi-Gap Resistive Plate Chamber (MRPC) integrates the more traditional foundations of theoretical physics with the next generation of physics experimentation in the field.

I. Introduction

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is designed to perform a broad study of high energy collisions between heavy nuclei in order to investigate the behavior of nuclear matter at extreme conditions.[1] Other accelerators exist in the United States and around the world. But what makes RHIC unique is its ability to collide heavy ions, such as Gold (Au) and Copper (Cu) ions (of 197 and 64 atomic mass units, respectively) at relativistic energies (up to 200 billion electron volts). In a Gold-Gold collision, as many as 400 nucleons may collide, with many encountering each other head-on. It is believed that in particularly energetic head-on ("central") Gold-Gold collisions, the quarks that make up protons and neutrons disassociate into a de-confined state of matter. In such a state, these quarks move freely amongst each other unencumbered by the strong force. Theorists have suggested that matter may have existed in this state, called a 'Quark-Gluon Plasma,' microseconds after the Big Bang. Investigating this connection is a primary goal of RHIC. Should RHIC succeed, we will have artificially created a very rare natural phenomenon, allowing an otherwise mysterious piece of nature to be understood. RHIC is also being used to study the spin structure of the nucleons during collisions with polarized proton beams. Thus, RHIC has the ability to pursue a broad agenda of physics studies.

More specifically, RHIC is not actually one experiment. Rather, it is comprise of four collaborative projects led by many of the nation's top research institutions. When RHIC is operational, two counter-rotating beams continuously accelerate positively charged ions around a 2.4 mile ring where they cross at specific intersection regions. In four such intersection regions elaborate detectors have been constructed. Of these—STAR, PHENIX, BRAHMS and PHOBOS—Vanderbilt is an active member in the PHENIX collaboration. Each experiment observes the same physical phenomena, but each pursues its own method for doing so. Consequently the four

[1] The most common pronunciation sounds like the name "Rick" in the English language.

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experiments do have varying designs, but with complementary strengths and weaknesses for understanding the theoretical foundations of collider physics.

Initially, RHIC as was designed to run for ten years. Scientists are presently exploring the use of electron cooling in order to boost the luminosity of the two RHIC beams, however, and essentially create a new collider, which is tentatively dubbed "RHIC II".

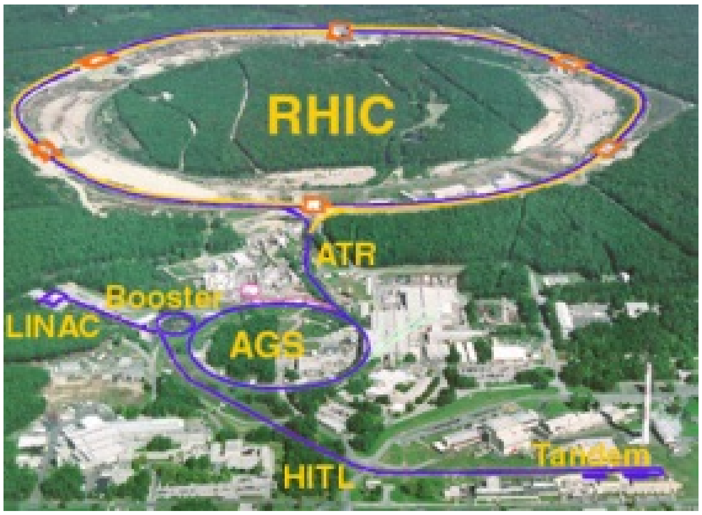

Figure 1. Aerial view of the RHIC complex at Brookhaven National Laboratory in Long Island, New York. The author has outlined the path heavy-ions make in their journey from 0 to 99.995% the speed of light: heavy-ions are initially stripped of their electrons in the Tandem Van de Graff; in the booster synchrotron they "surf" their way to 37% the speed light on the downhill slope of radio frequency waves; and in the Alternating Gradient Synchrotron (AGS) they accelerate to 99.7% the speed of light, at which point the heavy-ions are ready to enter RHIC.

II. Introduction to PHENIX

The Pioneering High Energy Nuclear Interaction Experiment (PHENIX) is one of four joint experiments at RHIC. In practice, it is a collaboration of about 500 scientists from Vanderbilt University and other portions of the United States, Japan, and around the world. After the initial construction, PHENIX and its sister experiment STAR were the first experiments at RHIC.

Vanderbilt has contributed to PHENIX in three areas. First, Vanderbilt provides detailed simulations of collision-events that allow scientists to quantify expected observations. For any experimental physicist, simulations are an important step in the process of discovery. The team of Vanderbilt researchers has been part of the planning and operation of PHENIX since its inception, and is home to two of the PHENIX detector subsystems. We designed and installed the three-tiered Pad Chamber system that is currently used in PHENIX, and we are currently pursuing the implementation of a new high-resolution, high momentum time-of-flight (TOF) detector using Multi-Gap Resistive Plate technology.

The primary method for exploring the physics of a collision-event is to observe what particles are created. What we use is a collection of detectors that operate in concert and are connected through a high-speed labyrinth of electronics and computing mechanisms. The whole PHENIX detector is a finely tuned piece of equipment that has the ability to filter through large amounts of raw data and store only the most desirable pieces. Heavy-ion collisions at RHIC occur at such a high rate that it would be too cumbersome to attempt to record all the physics data streaming through our detectors. The design and implementation these detectors, their electronics, their software, and the computing facility represents the technical side of experimental high energy nuclear physics.

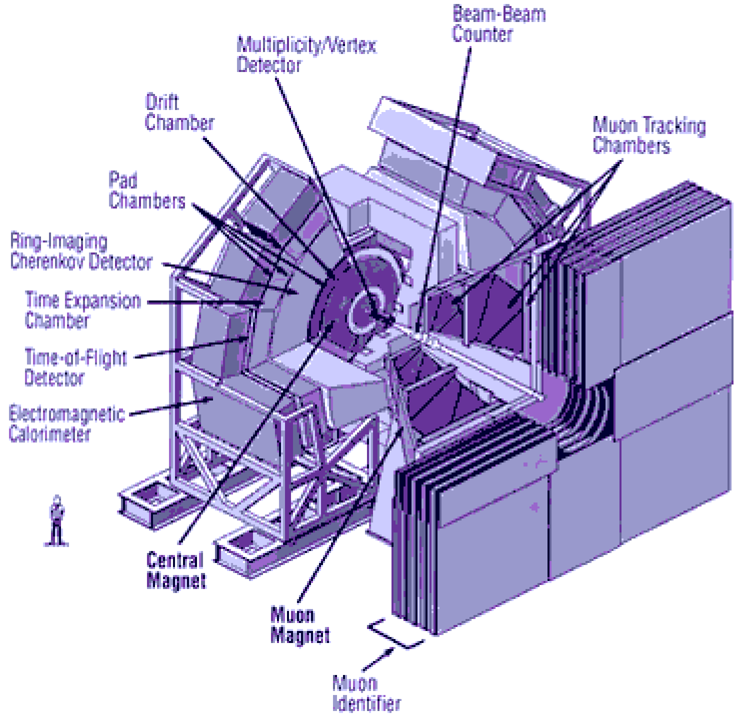

Figure 2. The PHENIX detector.

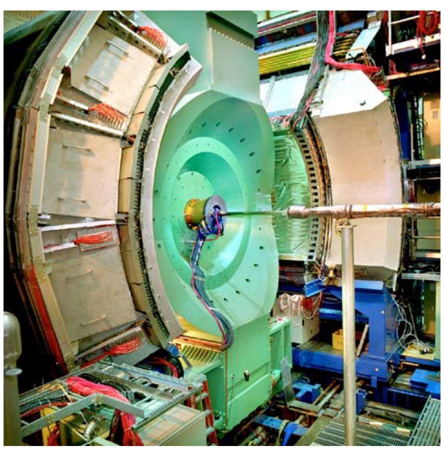

Figure 3. The PHENIX detector. The west arm, central magnet and beam pipe are found in the foreground, the east RICH is visible in the background, and the east arm is rolled into place.

Figure 4. This figure shows a very empty 'intersection region' looking west. A central magnet is surrounded on the sides by two larger muon magnets. When operational, researchers will fill the carriage in the foreground with detectors.

III. Event Reconstruction

The first step in event reconstruction is to determine the centrality of a collision. When two nuclei collide, they do not always collide head on. Since theory predicts that the Quark-Gluon Plasma will be produced mostly in central collisions, the researchers will want to compare central and non-central collisions and look for differences between the two. Figure 4 shows three actual Au-Au events of different centrality from a run in 2004. When determining centrality, scientists sometimes refer to the number of participants, by which they mean the number of protons and neutrons that collide with one another. The nucleons that are not participants are known as spectators. In order to measure the number of spectators in a collision, PHENIX uses a pair of detectors that sit on the beam pipe, down stream from the primary vertex (central point) of the collision. The fragments of the participants, on the other hand, gain transverse momentum and pass through the two PHENIX arms, as shown in Figure 4. In a low centrality or peripheral collision, nuclei brush past each other and very few nucleons interact. In a more spectacular central collision, most of the nucleons collide.

For event reconstruction, we also observe the types of particles that are produced. We make direct observations of the properties of a collision-event, such as temperature, by observing leptons such as electrons and muons which do not interact by the strong force. Should the QGP be produced, it will be transparent to leptons. We observe hadronic phenomenon thorough our observations of the strongly interacting hadrons, such as φ mesons which indicate the production of strange quarks. This strangeness enhancement is a special signature of the QGP. In counting the multiplicity of baryons and mesons produced in central Au-Au collisions, we have observed that only mesons, and not baryons, are suppressed. By observing leptons and hadrons, we can reconstruct the pieces of a collision-event.

Once we know the centrality of a collision and have observed what particles were produced, we can reconstruct a single event. We are not limited to observing only one event, however, as the certainty of our observations is incumbent on our ability to examine numerous collisions for analytic purposes. Our collection of Au-Au data in the 2004 calendar year, for example, contains 500 million events. The presence of many events increases the statistical significance of our observations.

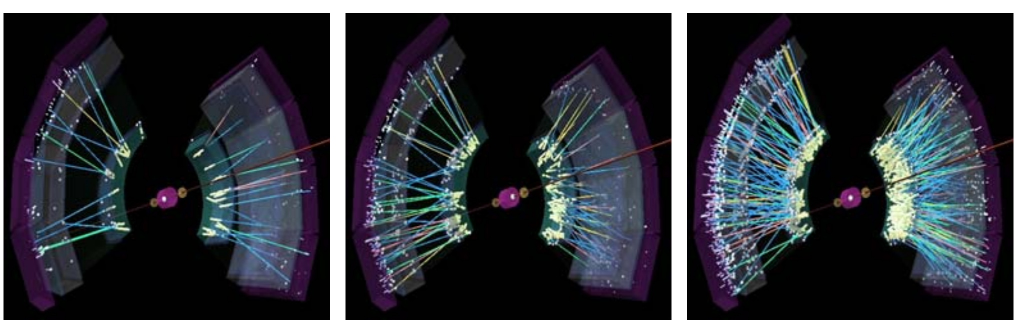

Figure 5. Event Reconstruction. The three different images in the figure show three actual events from gold-gold collisions—peripheral (left), semi-peripheral (center), and central (right).

IV. Particle Identification

One of the fundamental processes in event reconstruction is particle identification (PID); we need to know what kinds of particles pass through our detectors. The defining characteristics of any particle are its mass and its charge. Together, they are the invariant, observable properties that distinguish π from K and p from n, for example.

The charge of a particle is easily determined by its behavior in a magnetic field. The PHENIX magnets create a magnetic field around the collision-event that sweeps positive and negative particles in opposite directions, allowing us to determine the charge, which is almost always +1 or -1. Though a collision can produce particles with non-unitary charge, such as an alpha particle (q = +2), they are of low multiplicity and negligible. Neutral particles are unaffected by the PHENIX magnets.

The mass of a particle is not so directly determined, but can be derived from a particle's momentum and velocity. First, in order to determine the momentum p of a particle, we track the particle through a known magnetic field B and measure the radius of curvature r of its trajectory. We know the magnetic force acting on the charged particle, and we observe that the particle bends in a cyclotron orbit. By the Lorentz Force Law, and because ν and B are orthogonal,

$$F_{magnetic} = q(v \times B) = qvB$$

And,

$$F_{centripital} = m\frac{v^2}{r}$$

By Newton's Second Law,

$$F_{magnetic} = F_{centripital}$$

$$qvB = m\frac{v^2}{r}$$

$$qBr = mv = p$$

In order to determine the velocity of a particle, we measure the particle's time-of-flight t across a known distance L.

$$v = \frac{L}{t}$$

Knowing these two 'observables'—momentum and velocity—we can deduce the mass of a particle using the relation $p = mv$. Of course, these basic equations are slightly complicated by relativistic effects that must be taken into account for technical accuracy.

The particles produced in a collision-event are mostly π (140MeV), K (493 MeV), and p (938MeV), and these are detectable by the PHENIX spectrometers. However, we are not only limited to what our detectors can observe directly. We can also observe other particles indirectly by correlating their decay products, as we do for neutral particles like the λ and φ mesons. We are even able to indirectly observe the very massive J/ψ particle (3097 MeV).

V. High Resolution Time-of-Flight and the MRPC Detector

The higher the momentum of a particle the more difficult it is to distinguish it from other particles. Of the different methods that can be used to perform PID at high transverse momentum (P_T), we find the time-of-flight (TOF) method to be the most desirable choice. Because the time-of-flight of a particle is fundamental to this method of PID, we seek to maximize the TOF acceptance of PHENIX both in terms of its physical coverage and in terms of the operational range of the detector. Extending the range of our acceptance in high-P_T is a technology issue. Covering a large area of the PHENIX spectrometer with a TOF subsystem is a cost issue. Ideally we would like a high-resolution TOF detector for high momentum particles that is also cost efficient. The challenge of resolving these two issues is a leading area of scholarly interest in high energy nuclear physics.

At present, Vanderbilt is planning to implement a detector that meets both challenges in early 2006. The type of detector we have chosen is a Multi-gap Resistive Plant Chamber (MRPC). The MRPC consists of a stack of resistive plates (made of glass) electrically floating in a 15kV/M uniform electric field such that there exist 6 gas gaps of 230 micron thickness (see Figure 5 for a schematic of the MRPC). Highly charged particles pass through these tiny gas chambers ionizing gas molecules and producing ion avalanches. The gas that we have chosen to use is a mixture of 95% $C_2H_2F_4$ and 5% isobutane. The ions produced in an avalanche induce a charge on a series of copper read-out strips on either side of the chamber, and an analog signal is produced that can be read-out by our electronics.

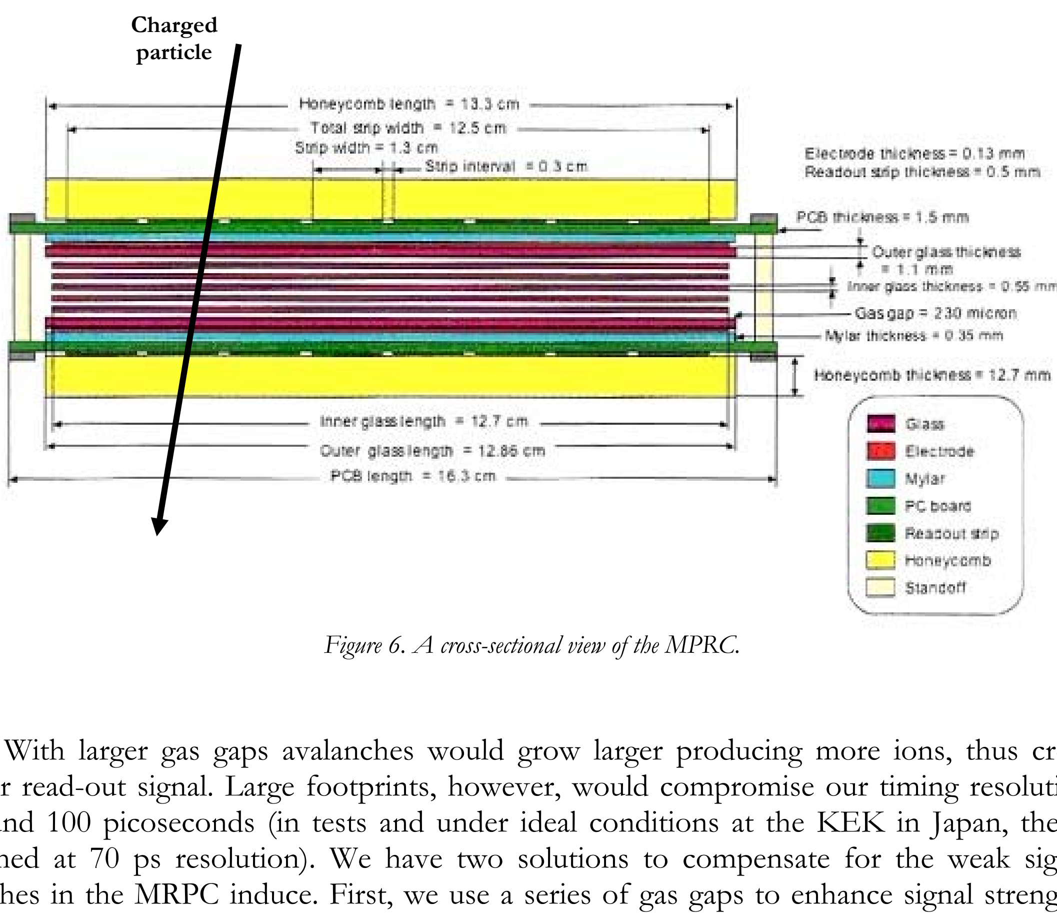

Figure 6. A cross-sectional view of the MPRC.

With larger gas gaps avalanches would grow larger producing more ions, thus creating a stronger read-out signal. Large footprints, however, would compromise our timing resolution goal of around 100 picoseconds (in tests and under ideal conditions at the KEK in Japan, the MRPC preformed at 70 ps resolution). We have two solutions to compensate for the weak signal that avalanches in the MRPC induce. First, we use a series of gas gaps to enhance signal strength—the induced charge from 6 small avalanches are additive. Additionally, we use on-board electronic amplifiers. For example, Figure 5 shows data taken from a more expensive scintillator-based TOF detector system. It will be our challenge to duplicate or improve on this plot with our new detector system in the future.

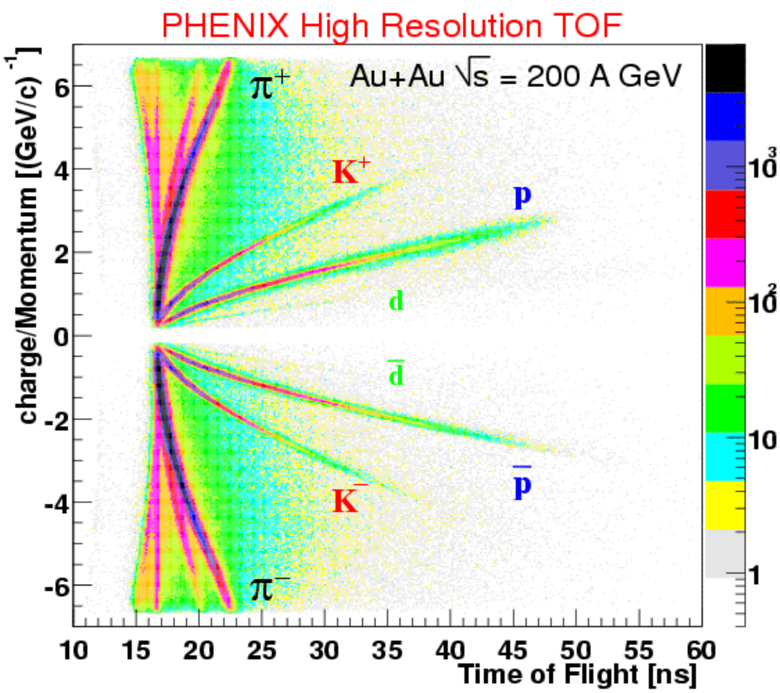

Figure 7. TOF-PID plot from PHENIX based on an Au-Au run in 2002.

VI. Future Experimentation

Several prototypes of the MRPC were installed in PHENIX in the first half of the 2005 calendar year. We are currently in the process of analyzing the physics data that has been successfully taken from the new prototypes. So far we believe the MRPC prototypes to be a success.

It is worth noting that MRPC detectors are being installed on two other heavy-ion, high energy nuclear experiments—STAR and ALICE. STAR is the sister experiment of PHENIX at RHIC. On the other hand, ALICE is one of the five experiments at the Large Hadron Collider (LHC) at the European Laboratory for Particle Physics (CERN) in Geneva, Switzerland. Much of the research and development of the MRPC was done by physicists at CERN. Finally, we acknowledge our invaluable collaboration with the STAR TOF group from Rice University.

Recommended Sources

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Brian T. Love *is a recent graduate who majored in Mathematics and Physics in the College of Arts & Science before receiving his Bachelor of Science degree in December 2004. A native of Dallas, Texas, he joined the Pioneering High Energy Nuclear Interaction Experiment (PHENIX) at the Brookhaven National Laboratory during the fall semester of his senior year. He hopes to pursue his research interest in nuclear physics at the graduate level over the next few years.*