# Mapping the Nuclear Matter Phase Diagram with STAR: Au+Al at 2.8 AGeV and Au+Au at 19.6 GeV

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## 1 INTRODUCTION

In ultra-relativistic heavy ion collisions a partonic state of matter was inferred from measurements made at energies of 200 GeV per nucleon pair. The Quark-Gluon Plasma (QGP) has been established based on two very important results [1]. First, the result describing the suppression of the away-side jet peak in central Au+Au collisions [2][3]. The observed suppression indicates the existence of a dense medium in which hadrons interact strongly with the medium early in the collision history. Second, the the result describing the hydrodynamic fit of the elliptic flow as a function of transverse momentum. Additionally, when scaling kinetic energy and elliptic flow by constituent-quark number, the separation of mesons from baryons disappears and all particles follow the same hydrodynamic curve. This property indicates degrees of freedom at the partonic level, i.e. the flow of quarks rather than hadrons. Once the QGP was supported by these strong pieces of evidence, characterization of the medium and determination of the baryon chemical potentials and temperatures where the QGP could exist became the next step.

The phase diagram of nuclear matter, see Figure 1, is mostly a schematic with only two known points: nuclear matter at room temperature [4] and the transition temperature ($\sim$175 MeV) at $\mu_B$ of zero [5]. The diagram displays the temperature versus baryon chemical potential and qualitatively illustrates the trends we see from theoretical calculations of the various transition curves [6] and the proposed location of the critical point [7] [8]. The chemical freeze-out curve represents the temperature and baryon chemical potential at which the thermal production of hadrons has ceased [9]. The kinetic freeze-out curve represents the temperatures and baryon chemical potentials at which elastic collisions and momentum transfer has ceased [9]. It is expected that the chemical freeze-out temperatures are always greater than the kinetic freeze-out temperatures [9]. The Beam Energy Scan (see next section) collision energies are thought to create equilibrated systems whose initial state is near the given $T$ and $\mu_B$, however we are unable to directly measure these initial state variables for the corresponding collision energies. The diagram will be better understood when the phase transition curve, the freeze-out curves and the critical point are determined.

## 2 THE BEAM ENERGY SCAN

The nuclear matter phase diagram (see Figure 1) is currently incomplete. Determining chemical freeze-out points, kinetic freeze-out points and the order of the phase transition all require multiple energies to be run with one given species of ion as well as running different species with similar energies [8] [10]. Already running heavy-ion collisions at high $\mu_B$ were the Super Proton

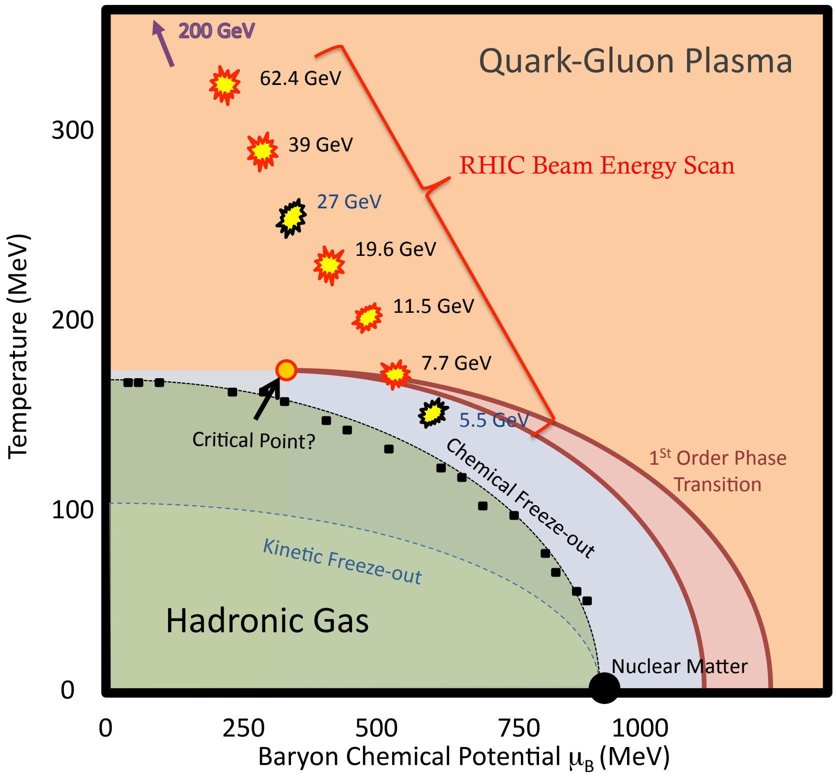


Figure 1: (Color Online) Nuclear matter phase diagram schematic with temperature versus baryon chemical potential $\mu_B$. For reference, room temperature is $\frac{1}{40}$ eV. The large black dot represents the proton at room temperature. The muave/pink area wedged by thick dark red lines represents the possible region where the first order phase transition [6] may occur. The blue region represents the thermal production of quark-antiquark pairs before chemical freeze-out. The green regions represent elastic collisions above the kinetic freeze-out curve, and below the kinetic freeze-out curve, the final state of hadrons with fixed momentum. Between the chemical and kinetic freeze-out curves, only particle decay contributes to changes particle number.

Synchrotron (SPS) at CERN and the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL). At the Relativistic Heavy Ion Collider (RHIC) at BNL, several species of ions are collided to determine properties of the QGP and look for its signatures in data. In 2009, the STAR collaboration (Solenoidal Tracker At RHIC) proposed to run a beam energy scan (BES) to find the energies where QGP signatures could be observed [11]. The program intended to search for the critical point [7] – the proposed point where the first order phase transition is expected to change order – and further map the kinetic and chemical freeze-out curves by colliding Au beams in a range of energies from 5.0 GeV per nucleon pair (below the critical point [8]) to 39 GeV per nucleon pair (above the critical point)[11].

In 2010, the majority of the proposed energies for Au+Au collisions were run (62.4, 39, 11.5, 7.7) with two energies postponed for the following year, 2011. A test run at 5.5 GeV Au+Au was made and determined by accelerator experts to be too unstable to maintain in the RHIC rings or to bring into collision. Thus the lowest energy, below the proposed energy at which the critical point was thought to be [8], could not be run nor data collected. However, the STAR detector was able to record data from the beam halo (Au) colliding with the beam pipe (Al) with the vertices inside the main detector, the Time Projection Chamber (TPC), during both the 11.5 and 7.7 GeV per nucleon pair beams. These beam+pipe collisions have allowed the STAR collaboration to drop the center of mass energy below the 5.0 GeV scheduled energy and extend the low energy reach of the BES. The STAR collaboration can then compare the beam+pipe results with those of previous experimental programs, namely the fixed target heavy-ion program of the AGS.

# 3 FIXED TARGET COLLISIONS AT THE STAR DETECTOR

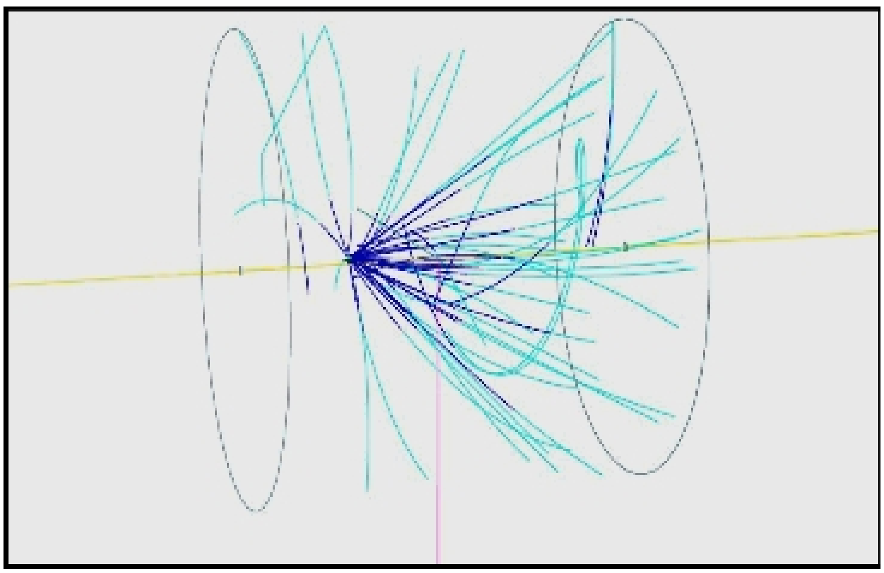

Figure 2: (Color Online) Fixed target collision as seen by the STAR detector and reconstructed. Note that the vertex is displaced from the beam line (the yellow line) and also displaced from the center of the detector (denoted by the pink line). All of the tracks are to one side of the vertex (to the right) rather than being symmetric about the collision point.

During data collection of previous low energy beam test runs at RHIC, the STAR collaboration found a large number of beam+pipe collisions that were recorded in addition to the good Au+Au collisions. An example of a reconstructed fixed target collision is shown in Figure 2. The yellow line denotes the beam line and the two black rings are the TPC end-caps. The pink line shows the center of the TPC. All of the tracks point to the right TPC end-cap where the light blue indicates the part of a track that was reconstructed with hits and the dark blue indicates the extrapolation of that track to the vertex. A few attempts were made to exclude beam+pipe collisions from data collection before the BES program began. However, those studies resulted in not only recording the data of these collisions but also reconstructing their vertices and tracks alongside the Au+Au collisions for the entire dataset.

In the summer of 2010 the UCD group began in earnest to analyze the beam+pipe events and determine if physics extraction was possible. This required determining the energy at which the collisions occurred. The beam pipe ‘target’ (Al) is parallel to the Au ion beam and the

Au nucleus experiences energy loss while traveling through the metal of the pipe. Additionally, considerations of the detector geometry to determine acceptance and efficiency of tracking were made. Careful evaluation of variables for determining collision centrality with comparisons to an analytic Glauber model [12] [13] (a model to estimate the number of particles produced based on the number of nucleons participating in an inelastic collision) was one of the largest challenges of the initial study. After careful analysis of the data, a determination of the collision energy and centrality definition allowed for particle spectra to be produced. An example is shown in figure 3. Pion spectra in figure 3 have not yet been corrected for detector acceptance or efficiency, though those calculations are currently in progress.

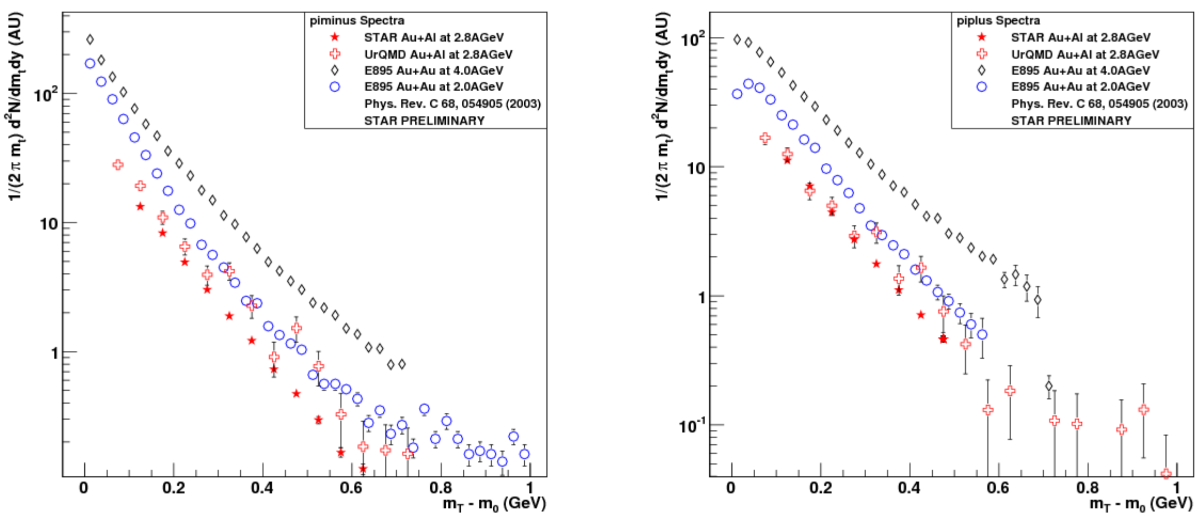


Figure 3: (Color Online) Pion spectra from E895 at 2.0 AGeV (open blue circles) and 4.0 AGeV (open black diamonds) Au+Au, STAR at 2.8 AGeV (solid red stars) Au+Al, and a UrQMD simulation of Au+Al at 2.8 AGeV (open red crosses). The plot on the left compares negative pion spectra and the plot on the right compares positive pion spectra.

Following the acceptance and efficiency corrections, a blast-wave [14] fit to the spectra will be made. Extracted from this fit will be the kinetic freeze-out temperature and the average velocity of particles. The baryon chemical potential, $\mu_B$, is found by taking the ratio of particle invariant yields, like $\frac{K^+}{\pi^+}$, and equating them to a Fermi-Dirac, Bose-Einstein, or Maxwell-Boltzmann distribution [15]. Since the energies and temperatures are large enough, most particles can be modeled by a Maxwell-Boltzmann distribution.

With these parameters extracted from the fits, we can plot points on the nuclear matter phase diagram indicating the chemical and kinetic freeze-out points for a given energy and species set: Au+Al at 2.8 AGeV.

## 4 Outlook

For my thesis, I will analyze the 19.6 GeV Au+Au data and expect to produce $\pi$, $k$, and $p$ spectra, fit each of the six spectra with a blast-wave model [14], calculate particle ratios and show where on the nuclear matter phase diagram this system achieves chemical and kinetic freeze-out. In addition, I will produce $\frac{dN}{dy}$ distributions (illustrating the number of hadrons produced as a function of rapidity) by utilizing the displaced vertex method I learned while analyzing the Au+Al collisions. In order to analyze Au+Al, vertices displaced from the center of the TPC were selected in order to have a wider acceptance of particle tracks. By looking at Au+Au vertices displaced beyond the symmetric acceptance limit, I can extend the rapidity coverage (acceptance) of STAR to get a full $4\pi$ acceptance within the TPC.

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