Beam Energy Scan Results from RHIC

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Abstract. In 2010 and 2011, RHIC ran the first phase of a planned beam energy scan program to probe, among other things, the nature of the phase transition between hadrons and Quark Gluon Plasma as the matter vs anti-matter excess increases. Many experimental findings are now available from that scan. In this talk, I discuss the meaning of those results and the future plans and motivation for the second phase of the RHIC beam energy scan.

1. Introduction
The Relativistic Heavy Ion Collider (RHIC) was built to create and study Quark Gluon Plasma (QGP) [1, 2]. The matter created in collisions at RHIC is so hot and dense that quarks and gluons become the relevant degrees of freedom, not hadrons [3]. Even before the discovery of quarks and the advent of Quantum Chromodynamics, Hagedorn realized that the exponential increase in the hadronic mass spectrum implies that there is a maximum temperature \( T \) in a hadronic gas [4]. As we put more energy into the hadron gas, the energy can go into creating ever more higher mass states instead of increasing \( T \) (leading to a maximum \( T_H \)). With Quantum Chromodynamics, however, we realize that once the energy density becomes high enough, quarks and gluons become the relevant degrees of freedom. The left panel of Fig. 1 shows finite temperature Lattice QCD calculations of the energy density of nuclear matter scaled by \( T^4 \) which is proportional to the number of degrees of freedom in the system. As the temperature of the system increases, the degrees of freedom increase but then start to saturate above \( T = 200 \) MeV. This saturation reflects the transition from a system where the energy pumped in to the system to heat it goes into creating heavier hadronic resonant states, to a system where hadronic states are irrelevant, quarks and gluons are the degrees of freedom, and pumping energy into the system goes into creating a hotter QGP. Lattice calculations have shown that when matter and anti-matter exist in equal amounts (zero baryon chemical potential \( \mu_B \)) that transition between QGP and hadrons is a smooth cross-over [5].

Although Lattice calculations show that the QGP to hadron phase transition is a smooth crossover at zero baryon density, it is thought to be a first-order phase transition at higher baryon densities [7]. Lattice calculations suffer from the sign problem at non-zero baryon chemical potential so it is not easy to infer from QCD where the transition from a smooth crossover to a first order phase transition occurs. The point where the smooth crossover and first order phase transition meet is called a critical point and represents an important landmark on the phase diagram of nuclear matter. Figure 1 (right) shows a schematic diagram of the phases of QCD. Full energy heavy-ion collisions at RHIC and those at the LHC, are nearly net baryon free and probe along the left axis of the diagram. The flexibility of RHIC makes it possible to probe...
Figure 1. (Left) Lattice QCD calculations showing the transition from hadronic degrees of freedom to a QGP. (Right) the QCD phase diagram with trajectories showing the regions that can be probed by RHIC [6].

Figure 2. (Left) The temperature dependence of $\eta/s$ for a variety of materials and a curve for the QCD equivalent which is not yet determined. (Right) Hydro calculations compared to data that can be used to better constrain the temperature dependence of $\eta/s$.

depth into the non-zero baryon chemical potential axis. By lowering the energy of the colliding beams, one initiates a system with larger net baryon density. By scanning down to lower and lower energies, the RHIC experiments can search for evidence of a critical point or of a first order phase transition. The first phase of this program has been completed at RHIC [8] with many results already available.
When reducing the beam energy, one also reduces the initial temperature of the QGP phase until at low enough energies, one presumably does not heat the colliding nuclei enough to reach the QGP phase. One of the most important conclusions from the first five years of RHIC operations was that the QGP created at RHIC was a nearly perfect fluid [9, 10]. This conclusion was based on the observation that the QGP phase of the collisions appears to be well described by nearly perfect hydrodynamic models. Only a relatively small amount of viscosity can be introduced before the agreement between the models and the data are spoiled. Most calculations have relied on a constant viscosity but as shown in Fig. 2 (left) in most other systems, the viscosity to entropy ratio depends strongly on the temperature and has a minimum where a phase transition occurs [11]. It is possible therefore that the average viscosity of the QGP will be smaller at lower energies than it is at higher energies. Varying the beam energy and the initial temperature of the system will allow us to better extract the temperature dependence of the viscosity to entropy ratio $\eta/s$.

Figure 2 (right) shows data on the flow harmonics for collisions at 2.76 TeV and at 200 GeV with hydrodynamic model calculations adjusted to fit the data [12]. For the higher energy collisions, a value of $\eta/s = 0.2$ is preferred while for 200 GeV, a value of 0.12 is preferred. This is an early indication of a temperature dependence for $\eta/s$. It’s also important to note that when looking only at the 2.76 TeV data, it is difficult to tell the difference between a constant $\eta/s$ and a temperature dependent $\eta/s$; note the solid and dashed curves in the figure are almost indistinguishable. The study of the temperature dependence of $\eta/s$ likely will require large data sets at a variety of beam energies such as have been generated with the first phase of the beam energy scan, or will be generated in the second phase.

2. Results from Beam Energy Scan Phase-One

Having reviewed the motivation for the beam energy scans, I will briefly discuss some of the results of the scan. In the first phase of the scan, small data-sets were collected at 7.7 and 11.5 GeV center of mass energy (several million events) with larger data sets (20 million events or larger) being collected at 19.6, 27, 39, and 62.4 GeV. The second phase of the beam energy scan will focus on increasing the precision of key results at the lower center of mass energies.

2.1. Energy Density and Flow

Simply by estimating the number of particles created in the collisions one can get a rough estimate of the initial energy density of the system. This requires one to guess at how long after the initial collision, some form of matter has been created (the formation time of a QGP $\tau_0$). Figure 3 (left) shows estimates of the initial energy density scaled by $\tau_0$ [13]. Lattice calculations show that the QGP should form when the energy density gets much higher than 0.6 GeV/fm$^3$. For $\tau_0 = 1$ fm, even the lowest energy collisions can be expected to create a QGP according to this criteria and estimate. One should not therefore jump to the conclusion that no QGP will be formed in the lowest energy collisions. Even for $\tau_0 = 2$ fm, the central 7.7 GeV collisions would reach energy densities high enough for QGP formation.

One of the signatures of QGP formation is a large azimuthal anisotropy in particle production thought to be generated by elliptic flow as the QGP responds to azimuthal variations of pressure gradients in the system. Figure 3 (right) shows the second harmonic variation $v_2$ vs $p_T$ calculated from the four-particle cumulant method measured for several centralities and for energies ranging from 7.7 GeV up to 2.76 TeV [14]. It is striking how little this observable changes over such a wide range of energies. Note that the $\langle p_T \rangle$ of the particles does increase with energy so the average $v_2$ increases even if $v_2(p_T)$ does not. Also note that by looking at the ratio of different energies, one can see that the low-$p_T$ data where most of the particles are does increase by 30-40% from 7.7 to 2.76 TeV. The relatively small change in $v_2(p_T)$ for energies all the way down to 7.7 GeV provides some indication that a QGP may still exist even for the lowest energies.
2.2. NCQ Scaling of Positively and Negatively Charged Particles
While as noted before, the $v_2(p_T)$ for charged hadrons does not change very much from 7.7 GeV to 2.76 TeV, when looking at the particle type dependence of $v_2(p_T)$ we do see changes in behavior as the energy is decreased [15]. The six panels on the left in Fig. 4 show $v_2(m_T - m_0)$ for positively charged particles at six different energies. The panels on the right show the same for negatively charged particles. In the left panels, the baryons at all energies show a larger $v_2$ value at any given $m_T - m_0$. This enhancement of baryon $v_2$ is taken as evidence that some baryons and mesons at intermediate $p_T$ are created by the coalescence of constituent quarks at the hadronization phase boundary after the creation of a QGP [16]. As such, it is a good indicator for the presence of a QGP phase. For the positively charged particles in the left panels, this pattern of larger baryon $v_2$ exists at all energies. For negative particles shown in the left panel however, the pattern breaks down with anti-baryons no longer exhibiting an enhanced $v_2$ relative to mesons for energies below 19.6 GeV. The break down of the signal for coalescence can be traced to the reduced $v_2$ values for anti-baryons relative to baryons. This pattern and a more detailed look at differences between the other particle types suggests that this difference between positive and negative particles can either be related to the effect of mean-fields on partons [18] or on hadrons [17] in a system with ever increasing $\mu_B$, or that the quark number transported to mid-rapidity leads to quarks with a larger $v_2$ that then coalesce into hadrons [19]. This could be either due to a concentration of net-baryon number in the in-plane region of the overlap volume or a larger flow being built up to bring the quarks carrying the baryon number to midrapidity through greater interactions. In either case, the data do not necessarily or even likely indicate a break-down of coalescence.

Note that the results for the $\phi$-meson are very limited in their statistical precision. Larger data-sets need to be accumulated at the lower energies to better study the multi-strange hadron flow which is expected to reflect the partonic phase of the collisions more directly.

2.3. High $p_T$ Suppression
$R_{CP}$ (central spectra over peripheral each scaled by the number of binary collisions) also has a strong energy dependence. This ratio reflects changes in the shape of the spectra. At higher energies the higher momentum part of the spectra is suppressed because hard scattered partons lose energy in the QGP before they hadronize. At lower energies, instead of suppression an
enhancement is seen [20]. As the energy is reduced, the number of hard partons is also reduced leading to a much softer spectra at lower energies. Flow can cause an enhancement in the spectra at higher $p_T$ as abundant lower momentum particles are boosted into higher momentum where there are fewer particles to start with. This effect is stronger, for softer spectra. It’s not clear to me therefore whether the lack of suppression in the low energy spectra are the result of flow and an already reduced number of hard partons that can be quenched or due to a disappearance of quenching in a QGP. In my judgement the former is more likely than the latter so the data are not evidence for the disappearance of the QGP.

2.4. Conclusions

RHIC provides experimental access to the most interesting regions needed to study QCD thermodynamics. At RHIC, one can reduce the initial temperature from several times the critical temperature to temperatures just above or below $T_C$. Comparisons to models suggests there is a temperature dependence to $\eta/s$ with a smaller value needed to fit 200 GeV RHIC...
data than the 2.76 TeV LHC data. Data from the RHIC beam energy scan phase two can be used to map out the temperature dependence of $\eta/s$. The first phase of the beam energy scan led to several surprising discoveries including the $\mu_B$ dependence of $v_2$ and the non-monotonic variation of net proton $v_1$ trends (not shown in this proceedings). From the data at hand, it is plausible that a QGP may exist even at the lowest beam energy of 7.7 GeV but something interesting is happening below 20 GeV. A second phase of the scan is needed to accumulate sufficient events at lower energies to measure key observables.

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