Update from the Beam Energy Scan

Daniel Cebra

For the STAR Collaboration
• Much progress has been made in understanding the phase diagram of QCD matter. We expect a cross-over at high energy. At lower energy there should be a first order transition.

• Mapping the features of the QCD matter phase diagram is key to our understanding dense matter.

• In 2009 the RHIC PAC approved a series of six energies to search for the turn-off of QGP signatures, the critical point, and evidence of a first order phase transition.
# Beam Energy Scan

<table>
<thead>
<tr>
<th>Collision Energies (GeV)</th>
<th>5</th>
<th>7.7</th>
<th>11.5</th>
<th>19.6</th>
<th>27</th>
<th>39</th>
<th>62.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Potential (MeV)</td>
<td>550</td>
<td>420</td>
<td>315</td>
<td>205</td>
<td>155</td>
<td>115</td>
<td>72</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observables</th>
<th>Millions of Events Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{cq}$ scaling $\pi/K/p/\Lambda$</td>
<td>8.5 6 5 5 4.5 4.5</td>
</tr>
<tr>
<td>$R_{CP}$ up to $p_T \sim 4.5, 5.5, 6.0$</td>
<td>15 33 24</td>
</tr>
<tr>
<td>Local Parity Violation</td>
<td>4 4 4 4 4 4</td>
</tr>
<tr>
<td>$v_2$ (up to $\sim 1.5$ GeV/c)</td>
<td>0.3 0.2 0.1 0.1 0.1 0.1</td>
</tr>
<tr>
<td>$v_1$</td>
<td>0.5 0.5 0.5 0.5 0.5 0.5</td>
</tr>
<tr>
<td>Azimuthally sensitive HBT</td>
<td>4 4 3.5 3.5 3 3</td>
</tr>
<tr>
<td>PID fluctuations ($K/\pi$)</td>
<td>1 1 1 1 1 1</td>
</tr>
<tr>
<td>net-proton kurtosis</td>
<td>5 5 5 5 5 5</td>
</tr>
</tbody>
</table>

### Total Number of Good Events Taken (Millions)

|                      | 0  | 4.3 | 11.7 | 36  | 70  | 130 | 67  |

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Daniel Cebra  
June 11, 2013  
RHIC/AGS Program Advisory Committee Meeting  
Brookhaven National Laboratory  
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Setting the Scene
Particle Identification

\[ \text{dE/dx} \]

\[ \langle \text{dE/dx} \rangle [\text{GeV/cm}] \]

\[ \text{q < 0} \]

\[ \text{Momentum [GeV/c]} \]

\[ \text{Counts} \]

\[ \text{Invariant Mass} \]

\[ \text{q < 0} \]

\[ \text{M}^2 [\text{GeV/c}^2]^2 \]

\[ \text{Counts} \]

\[ \text{K}^0_s \]

\[ \Lambda \]

\[ \Xi \]

\[ \Omega \]
**Hadron Spectra**

**STAR Preliminary**

\[(\frac{d^2N}{2\pi p_T dp_T}) (GeV/c)^{-2}\]

\[
\begin{align*}
\pi^+ & \quad \text{STAR Preliminary} \\
K^+ & \quad \text{STAR Preliminary} \\
\Lambda & \quad \text{STAR Preliminary} \\
K^0_s & \quad \text{STAR Preliminary} \\
\phi & \quad \text{STAR Preliminary}
\end{align*}
\]

\[p_T \text{ (GeV/c)} \]

**\(\phi, K^0_s\): Levy function fits**

**\(\Lambda, \Xi\): Boltzmann fits**

**\(\Lambda\): feed-down corrected**

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Adding the strange particle ratios to the $\pi$, $K$, and $p$ and using different ensembles in the thermal model, we can study the centrality and energy dependence of $T$ and $\mu_B$. 
The Horn and Other Yields

The STAR BES data are consistent with the NA49 results

The STAR Preliminary

STAR Ref.: B. I. Abelev et al., PRC79 (2009) 034909
B. I. Abelev et al., PRC81 (2010) 024911

E802 Ref.: L. Ahle et al., PRC58 (1998) 3523
L. Ahle et al., PRC60 (1999) 044904

E805 Ref.: J. L. Klay et al., PRC68 (2003) 054905
E877 Ref.: J. Barrette et al., PRC62 (2000) 024901

NA49 Ref.: S. Y. Afanasiev et al., PRC66 (2002) 054902
C. Alt et al., PRC77 (2008) 024903

NA49, PRC78,034918.
NA57, PLB595,68; JPG32, 427
STAR, PRL86,89,92,98; PRC83
Turn-off of QGP Signatures
Constituent Quark Scaling – BES Results

scaling by the number of quarks → partonic collectivity → deconfinement

Baryon/meson and high $m_t - m_0$ indicates NCQ scaling

**Particles:**
- Baryon/Meson splitting at 11.5 GeV
- No baryon/meson splitting at 7.7 GeV
- QGP Signature turned off

**Anti-Particles:**
- No baryon/meson splitting at 11.5 GeV
- QGP Signature turned off

• There is a remarkable difference between particles and their anti-particles, especially for the lowest energies in the range.

• Difference between particles and their anti-particle decreases with increasing beam energy.

• Most significant below 19.6 GeV

Possible explanation
• Baryon transport to mid-rapidity [J. Dunlop et al., PRC 84, 044914 (2011)]
• Hadronic potential [J. Xu et al., PRC 85, 041901 (2012)]

NCQ scaling seen at 200 GeV breaks down at lower energies
High $p_T$ suppression has been seen as a clear manifestation of energy loss by color objects (quarks) in a color medium (QGP).

Thermal emission from a radial expanding source or Cronin Effect

Perturbative QCD and parton energy loss

• $R_{cp}$ suppression NOT seen at lower energies!

⇒ The QGP signature is turned off.

⇒ Is QGP turned off?

⇒ Need p+A in this energy range.
Local Parity Violation – BES Results

The anisotropy attributed to the Chiral Magnetic Effect is gone at 7.7 GeV
Search for 1st Order Phase Transition
Elliptic Flow – BES Results

A reduction in flow or in the rate of increase in flow could indicate a softening of the equation of state.

- Elliptic Flow is rising rapidly with beam energy at AGS energies
- The rate of increase is reduced above 7.7 GeV for BES energies

Many caveats with this comparison:
- We need $v_2$ of identified particles
- We need consistent analysis methods between energy ranges
- Such detailed analyses are not available in the previous published results

⇒ This rough comparison highlights the need for STAR data below 7.7 GeV
Lattice QCD calculations predict a first order phase transition seen, as a discontinuity in the density.

First order phase transition is characterized by unstable coexistence region. This spinodal region will have the lowest compressibility.

$v_1$ is a manifestation of early pressure in the system.

We see a minimum of the $v_1$ signal between 11.5 and 19.6 GeV. New data are needed at 15 GeV.
Azimuthally Sensitive HBT - BES Results

• Initial eccentricity defined by overlap.
• A softening of the equation of state would change the spatial expansion of the system.
• This would be seen in $\varepsilon_F$.

• Checked suggestive CERES result
• The expansion (reduction of $\varepsilon_F$) slows above 7.7 GeV.
• No minimum in $\varepsilon_F$ is observed.

The E895 data are inconclusive
$\Rightarrow$ STAR data below 7.7 GeV are needed
Search for 1\textsuperscript{st} Order P.T. below 7.7 GeV
\rightarrow Fixed-Target
Fixed-Target Trigger:
- BBC-East
- Not-BBC-West
- TOFmult >70
- top 30% centrality Au+Au
- $10^6$ Au+Al rejection

Energies for Run14

<table>
<thead>
<tr>
<th>Collider mode Energies (GeV)</th>
<th>5</th>
<th>7.7</th>
<th>11.5</th>
<th>15</th>
<th>19.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Target $\sqrt{s}_{NN}$ (GeV)</td>
<td>2.5</td>
<td>3.0</td>
<td>3.5</td>
<td>4.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Fixed Target $\mu_B$ (MeV)</td>
<td>775</td>
<td>720</td>
<td>670</td>
<td>625</td>
<td>585</td>
</tr>
<tr>
<td>Fixed Target $y_{CM}$</td>
<td>0.82</td>
<td>1.05</td>
<td>1.25</td>
<td>1.39</td>
<td>1.52</td>
</tr>
</tbody>
</table>
Pion Fixed-Target PID, Acceptance, Spectra

Proven capabilities with Beam Halo + Beam Pipe background events, Au_{Like} + Al at √s_{NN} = 4.5 GeV

Pion Acceptances

<table>
<thead>
<tr>
<th>y_{cm} = 0</th>
<th>y_{cm} = 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0 GeV</td>
<td>4.5 GeV</td>
</tr>
</tbody>
</table>

Mid-rapidity pion spectra

Au+Al Invariant Pion Yield

star preliminary
STAR Fixed-Target Run14 Goals

- All $Au_{Like} + Al$ data taken during BES were pile-up background events
  ➔ We need to develop a dedicated fixed-target trigger, however the test run request becomes irrelevant if RHIC runs 15GeV $Au+Au$ before running 200 GeV $Au+Au$.

- It is likely/possible that in the beam halo events studied in the BES data sets the projectile nucleus is a heavy projectile fragment from an upstream beam-gas nuclear interaction
  ➔ We request a test to intentionally steer the beams to graze the target to create known $Au+Au$ events.

  ➔ We will need the target to be designed, fabricated, and installed during this summer shutdown.

Physics goals for Run14 $Au+Au$ at 4.0 GeV:
- Elliptic flow of identified $\pi^+$, $\pi^-$, and $p$
- Directed flow of protons
- Azimuthally sensitive HBT of pions

These are our key 1st Order Phase Transition signatures
Search for the Critical Point
Naively, fluctuations are expected at the critical point.

STAR data show no significant energy dependence for $K/\pi$ fluctuations.

Smooth evolution with energy for $p/\pi$ and $K/p$ fluctuations.

No non-monotonic behavior is observed.

⇒ We need a more sensitive observable.
Higher Moments – Net Proton Skew/Kurtosis - BES

- Third (Skew) and Fourth (Kurtosis) moments are increasingly sensitive to fluctuations expected at a critical point.
- Ratios of cumulants allow volume terms to cancel.

- STAR data are similar to Poisson baseline at energies above 27 GeV.
- Deviations are seen at low energies.
- Signal size will be affected by finite size.
- The gap between 11.5 and 19.6 is large, might miss the critical point.
  ➔ Need data at 15 GeV

Additionally
  ➔ Need detailed theory with finite systems
  ➔ More data are needed ➔ BESII
Conclusions

1. **Turn-off of QGP signatures:**
   - NCQ scaling breaks down below 19.6 GeV
   - High $p_t$ suppression not seen below 19.6 GeV
   - LPV effect not seen below 11.5 GeV
   - The onset of deconfinement is below 11.5 GeV

2. **Evidence of the first order phase transition.**
   - Inflection in $v_2$ at 7.7 GeV
   - $v_1$ slope ($dv_1/dy$) double sign change, minimum near 15 GeV
   - Azimuthal HBT interpretation is challenging
   - Need more data near 15 GeV and below 7.7 GeV

3. **Search for the critical point.**
   - Measurements of $K/\pi$, $K/p$, or $p/\pi$ fluctuations
   - Measurements of Higher moments of the net-proton and charge
   - An Beam Energy Scan survey point is needed at 15 GeV
   - These are challenging analyses, more data/theory ➔ BESII
Backup
• $R_{CP}$ of strange particles at 39 and 27 GeV show a similar trend as that in higher energies.
• 19.6 shows intermediate behavior
• At 11.5 and 7.7 GeV, all particles $R_{CP}$ are larger than 1 at intermediate $p_T$. 
High $p_T$ Suppression: BES Results

- High $p_T$ suppression seen at 27 GeV and above
- 19.6 shows intermediate behavior
- At 11.5 and 7.7 GeV, all particles $R_{CP}$ are larger than 1 at intermediate $p_T$.

E. Sangaline QM2012
Higher Moments – Net Charge Skew/Kurtosis - BES

- Data are consistent Poisson baseline at highest energy.
- Deviations from Poisson at low energy.
  ➔ More theory is needed
  ➔ More data are needed

Draft paper in God Parent Committee