STAR Results from Beam Energy Scan Program at RHIC

Bedanga Mohanty
(For the STAR Collaboration)
VECC, Kolkata

Outline:

- BES program at RHIC (2010 - 2011)
- Freeze-out conditions
- Partonic vs. hadronic degrees of freedom
- Search for the signatures of the phase boundary
- Search for the signatures of the critical point
- Summary

QM2009: Summary Talk - “Exploring the QCD phase diagram needs to be vigorously pursued to know properties of basic constituents of matter under extreme conditions. To make the QCD phase diagram a reality equal attention needs to be given to high baryon density region.”
Beam Energy Scan at RHIC

QCD Phase Diagram (Hadrons -- Partons)
Theory and Experimental approaches

History: Proposal in 2008

(A) Demonstrate RHIC/Experiment can operate below injection energy


(B) Establish observables

<table>
<thead>
<tr>
<th>NCQ scaling of $v_2$</th>
<th>Partonic vs. hadronic degrees of freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamical charge correlations</td>
<td>Partonic vs. hadronic degrees of freedom</td>
</tr>
<tr>
<td>Azimuthally sensitive HBT</td>
<td>$1^{st}$ order phase transition</td>
</tr>
<tr>
<td>$v_1$ vs. rapidity</td>
<td>$1^{st}$ order phase transition</td>
</tr>
<tr>
<td>Fluctuations</td>
<td>Critical point</td>
</tr>
</tbody>
</table>

Motivation:
Search for signals of phase boundary
Search for signals for critical point

arXiv:1007.2613
RHIC BES 2010-2011

Particle identification over $2\pi$ in azimuthal angle and more than two units in rapidity

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>Good events in Million MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>~ 5</td>
</tr>
<tr>
<td>7.7</td>
<td>~ 11</td>
</tr>
<tr>
<td>11.5</td>
<td>~ 17</td>
</tr>
<tr>
<td>19.6</td>
<td>~ 170</td>
</tr>
<tr>
<td>27</td>
<td>Expected ~ 150</td>
</tr>
<tr>
<td>39</td>
<td>~ 170</td>
</tr>
</tbody>
</table>

HLT: A. Tang, Poster Board No. 127
Freeze-out Conditions

Chemical freeze-out: Particle ratios

Kinetic freeze-out: Momentum distributions

L. Kumar, Energy scan, 27th May

Andronic et al., NPA 834 (2010) 237
Partonic vs. Hadronic Degrees of Freedom

Identified Hadron Elliptic Flow
Dynamical Charge Correlations

Related STAR presentations at QM2011:
(1) A. Schmah - Global & Collective dynamics, 23rd May
(2) D. Gangadharan - Global & Collective dynamics, 27th May
(3) S. Shi - Poster Board No. 16
(4) M. Mitrovski - Poster Board No. 19
(5) Q. Wang, Poster Board No. 34
(6) H. Wang, Poster Board No. 95

Published STAR papers at top RHIC energies:
PRL 99 (2004) 112301
PRL 87 (2001) 182301
PRL 106 (2009) 251601

And ShinIchi Esumi for the PHENIX Collaboration

QM2011 Bedanga Mohanty
Particle and Anti-Particle $v_2$

**Observations:** Different $v_2$ for particle and anti-particle.

\[ v_2 = \left< \cos 2(\phi - \psi) \right> \]

\[ \phi = \tan^{-1}(p_y/p_x) \]

\[ v_2(\text{baryon}) > v_2(\text{anti-baryon}) \quad \text{-- High net-baryon density ?} \]

\[ v_2(\pi^+) < v_2(\pi^-) \quad \text{-- Coulomb repulsion of } \pi^+ \text{, resonances or Chiral Magnetic Effect ?} \]

Possible interpretation:

QM2011

Bedanga Mohanty

Y. Burnier et al., arXiv:1103.1307
NCQ scaling of $v_2$

Observations:

- $\phi$ meson $v_2$ falls off the trend from other hadrons at 11.5 GeV.

QM2011

Bedanga Mohanty
Possible interpretations:

(A) Collectivity from partonic phase at 200 GeV

(B) $\phi$ decouples from the system early

(C) $\phi$ freeze-out at RHIC

$~ T_c$ from Lattice QCD

Small $\phi$ meson $v_2$ indicates collectivity contribution from partonic interactions decreases with decrease in beam energy
Dynamical Charge Correlations

Observations:

Measurement of charge correlations with respect to event plane

- Difference between same sign and opposite sign charge correlations decreases as beam energy decreases.
- Same sign charge correlations become positive at 7.7 GeV.

STAR Preliminary

QM2011
Bedanga Mohanty
Dynamical Charge Correlations

Possible interpretations:

(A) If linked to LPV effect - de-confinement and chiral symmetry restoration. Absence of difference in correlations means absence of phase transition.


Alternate Observables

(B) Charge asymmetry

LPV: $\langle A_+A_- \rangle_{UD} < \langle A_+A_- \rangle_{LR}$

(C) Conservation effects: momentum & Local charge and flow.

Reaction plane dependence balance function ~ difference between opposite and same charge correlations.

A. Bzdak, et al., PRC 83 (2011) 014905
S. Schlichting et al., PRC 83 (2011) 014913
Y. Burnier et al., arXiv:1103.1307

How to reconcile (A) with the fact $v_2(\pi^+) < v_2(\pi^-)$ at 7.7 GeV

QM2011
Bedanga Mohanty

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
Search for Signatures of Softening of Equation of State

Azimuthally Sensitive HBT Directed Flow

Related STAR Presentations at QM2011:
(1) Christopher Anson - Energy scan, 27th May
(2) Yadav Pandit - Poster Board No. 17

Published STAR papers at top RHIC energies:
PRL 93 (2004) 012301
PRL 101 (2008) 252301
PRL 92 (2004) 062301
Azimuthally Sensitive HBT

Observations:
Freeze-out eccentricity:
\[
\frac{R_y^2 - R_x^2}{R_y^2 + R_x^2} = 2 \frac{R_{s,2}}{R_{s,0}}
\]

Example:
Squared HBT radii relative to reaction plane angle

<table>
<thead>
<tr>
<th>Expt</th>
<th>√s_{NN} (GeV)</th>
<th>Centrality</th>
<th>η</th>
<th>Event Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGS/E895</td>
<td>2.35, 3.32,</td>
<td>7.4 - 29.7</td>
<td>+/- 0.6</td>
<td>1st order</td>
</tr>
<tr>
<td></td>
<td>3.84</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPS/CERES</td>
<td>17.3</td>
<td>10 - 25</td>
<td>-1.0 - 0.5</td>
<td>2nd order</td>
</tr>
<tr>
<td>RHIC/STAR</td>
<td>7.7, 11.5, 39,</td>
<td>10 - 30</td>
<td>+/- 0.5</td>
<td>2nd order</td>
</tr>
<tr>
<td></td>
<td>62.4, 200</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Non-monotonic variation in freeze-out eccentricity vs. beam energy

E895: PLB 496 (2000) 1
CERES: PRC 78 (2008) 064901
NA49: PRC 77 (2008) 064908
Azimuthally Sensitive HBT

Possible interpretations:
Eccentricity at freeze-out:
(i) life time of source
(ii) pressure gradient
(or energy density) and $c_s^2$

(A) Non-monotonic trends: Using HBT observables - Volume
Constant $\lambda_f (~1\text{fm})$ and transition from nucleon to pion dominated freeze-out

(B) Hadronic - Mixed Phase - QGP

Transport models show monotonic trends.
Could presence of mixed phase signal such a non-monotonic trend?

M. Lisa et al., 1104.5267

P. Kolb, U. W. Heinz nucl-th/0305084

QM2011
Bedanga Mohanty
Identified Hadron Directed Flow

Observations:

\[ v_1 = \langle \cos(\phi - \psi) \rangle \]
\[ \phi = \tan^{-1}(p_y / p_x) \]

<table>
<thead>
<tr>
<th>Expt</th>
<th>(\sqrt{s_{NN}} ) (GeV)</th>
<th>Centrality</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGS/E895</td>
<td>2.35, 3.0, 3.6, 4.1</td>
<td>(b = 5 - 7) fm</td>
</tr>
<tr>
<td>SPS/NA49</td>
<td>8.76, 17.3</td>
<td>(b = 5.3 - 9) fm</td>
</tr>
<tr>
<td>RHIC/STAR</td>
<td>7.7, 11.5, 39, 200</td>
<td>10-40%</td>
</tr>
</tbody>
</table>

Mid-rapidity proton \(v_1\) slope changes sign
Difference seen between proton and anti-proton

E895: PRL 84 (2000) 5488
Identified Hadron Directed flow

Possible interpretations:

$v_1$ probes earliest stage of collisions
The slope $dv_1/dy'$: transverse side motion relative to the beam direction.

(A) For nucleons, positive space momentum correlations + baryon stopping leads to wiggle or negative slope
-- R. Snellings et al., PRL 84 (2000) 2803

(B) 1st order phase transition could lead to event shape tilted w.r.t beam axis.
Different kind of flow orthogonal to normal flow (bounce-off).

Relation between collective radial flow and baryon stopping
Measurements could provide information EOS
Search for Critical Point

Conserved number fluctuations
Particle Ratio fluctuations

Related STAR Presentations at QM2011:
(1) T. Tarnowsky, Correlations and fluctuations, 23 May 2011
(2) A. Sarkar, Poster Board No. 93
(3) X. Luo, Poster Board No. 141
(4) L. Chen, Poster Board No. 146
(5) N. R. Shaoo, Poster Board No. 151

Published STAR papers at top RHIC energies:
PRL 105 (2010) 022302
PRL 103 (2009) 092301

Gavai and Gupta, PR D 78 (2008) 1143503
Cheng et al, PR D 79 (2009) 074505
Gupta, POS Lattice 2010 (2010) 007
**Higher Moments of Net-Protons**

**Observations:**

Correlation length and Susceptibilities diverge
Long wavelength or low momentum number fluctuations. Distributions are non-Gaussian

**Critical point:**

Higher moments:

- Measure of non-Gaussian nature
- Proportional to higher powers of $\xi$
- Kurtosis x Variance $\sim \chi^{(4)}/\chi^{(2)}$
- Skewness x Sigma $\sim \chi^{(3)}/\chi^{(2)}$
- Product of moment - Volume effect cancels

**Higher moments:**

M. A. Stephanov, PRL 102 (2009) 032301

**Net-protons:**

Y. Hatta et al., PRL 91 (2003) 102003

$\sim$ reflects net-baryons - conserved quantity
Neutrons immaterial due to isospin blindness of $\sigma$ field

Deviation from Poissionian expectations from 39 GeV and below
Higher Moments of Net-protons Possibilities with this measurement:

(A) Higher order correlations/ fluctuations deviate from HRG expectations at lower energies

(B) Significant deviations could potentially be linked to Chiral phase transition and Critical Point

(C) Study non-pertubative QCD
Accepted in Science: S. Gupta, X. Luo, B. Mohanty, H. Ritter and N. Xu; arXiv: 1105.3934


B. Friman, arXiv:1103.3511
M. A. Stephanov, arXiv:1104.1627

QM2011 Bedanga Mohanty
Fluctuations in particle ratios
-- Sensitive to particle numbers at chemical FO not kinetic FO
-- Volume effects may cancel

S. Jeon, V. Koch, PRL 83, 5435 (1999)

Differences could be due to difference in acceptance and/or PID selections --- under discussion

Observations:

Particle Ratio Fluctuations

Constant or monotonic trends observed
Apparent differences (results with Kaons) with SPS

QM2011 Bedanga Mohanty
Summary

Successful RHIC BES Program from Collider/Accelerator and experimental side

New observations:

- Identified hadron production & freeze-out parameters reveals high net-baryon density at these energies. Effect on several observables seen.

- Hadronic interactions at low energy. Small $\phi$ meson $v_2$ at 11.5 GeV. Disappearance of dynamical charge correlations.

- Interesting trends for observables related to softening of EOS. Non-monotonic variation of freeze-out eccentricity. Change in sign of proton $v_1$ with energy and centrality.

- Large acceptance & excellent PID allows for fluctuations measurements. Deviations from HRG and Poisson statistics. Is being used to study structure of the QCD phase diagram.

Need to complete the first phase of BES program

QM2011  Bedanga Mohanty
Outlook

Patrick Huck, Poster Board No. 97

STAR Preliminary

\[ \text{Au} + \text{Au} \oplus \sqrt{s_{NN}} = 39 \text{ GeV} \]

\[ dN / dN_{cm} \left[ c^2/\text{GeV} \right] \]

\[ e^+e^- \text{ invariant mass [GeV/c}^2] \]

\[ 82 \pm 13 \]

\[ 6\sigma \]

Z. Tang, Heavy Flavor, 24th May

The STAR Collaboration

Thanks

QM2011

Bedanga Mohanty
Back up
LPV energy dependence

STAR Preliminary

Balance function

STAR Preliminary

\[ N_{\text{part}} \times \Delta(\text{Asym. Corr.)} \]

\[ \langle A^+_{\text{up}} A^-_{\text{down}} \rangle_{\text{NN}} 40\% \]

\[ \langle A^+ A^- \rangle_{\text{NN}} \langle A^+ A^- \rangle_{\text{NN}} 40\% \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]

\[ \gamma_{\text{M2}(10^3)} \]