First Results From Au+Au Collisions at $\sqrt{s_{NN}} = 9.2$ GeV in STAR

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Outline

- Motivation
- STAR Experiment and Collisions at $\sqrt{s_{NN}} = 9.2$ GeV
- Results and Systematics: PID Spectra, Ratios, $v_1$, $v_2$ and $C_2(Q)$
- Summary and Outlook (RHIC Energy Scan)
Motivation

Map the QCD phase diagram through experiments
- Draw the QCD phase boundary
- Locate the QCD critical point

Plan:

Access to phase diagram

T and $\mu_B$ varies with $\sqrt{s_{NN}}$
T and $\mu_B$ measured from spectra and ratios of produced particles

Signatures
For locating different phases
For locating critical point

Aim of this talk is to discuss results from successful data taking in STAR with the Au+Au collisions at 9.2 GeV and demonstrate our preparedness for the future Beam Energy Scan program at RHIC

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STAR Experiment and Collisions at $\sqrt{s_{NN}} = 9.2$ GeV

Collisions recorded in STAR
Time Projection Chamber

Excellent Particle Identification

Analysis based on ~ 3000 good events collected at ~ 0.7 Hz in year 2008

Collider experiment: Uniform Acceptance for all beam energies

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Collision Centrality Selection

Monte-Carlo Glauber Model:

\[ \sqrt{s_{NN}} = 31.5 \text{ mb} \]

Negative Binomial Distribution fitted to the data

Fraction of hard component, \( x = 0.11 \)

NBD parameters: \( \mu = 1.12, k = 2.1 \)

\( \% \text{ cs} : N_{\text{part}} \)

- 0 - 10\% : 318
- 10 - 30\% : 203
- 30 - 60\% : 89

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Attributed to STAR

Identified hadron spectra at mid-rapidity

The slope of the spectra follows
\[ p < K < \pi \]
Spectra characterized by \( \frac{d^2N}{dp_T^2} \) and \( \langle m_T \rangle \)
We measure within our \( p_T \) acceptance at
mid-rapidity
\[ \sim 82 \% \text{ of total } \pi \text{ produced} \]
\[ \sim 47 \% \text{ of total } K \text{ produced} \]
\[ \sim 75 \% \text{ of total } p \text{ produced} \]
Yield and $<m_T>$ - Mesons at mid-rapidity

Yield and $<m_T>$ beam energy dependence consistent with the published data

Assuming a thermodynamic system:

$$T \sim <m_T> - m$$

entropy $\sim dN/dy$

$$\alpha \log(\sqrt{s_{NN}})$$

All errors are statistical and systematic added in quadrature
Yield and $<m_T>$ - Baryons at mid-rapidity

Both the yield and $<m_T>$ are close to the SPS results at similar energies

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Anti-particle to Particle ratios at mid-rapidity

The ratios follow the general $\sqrt{s_{NN}}$ trend

- $p_{\bar{p}}/p << 1$: Large baryon stopping
  - Large net protons
  - High $\mu_B$
- $K^-/K^+ \sim 0.4$: ~60% of $K^+$ from associated production with $\Lambda$
- $\pi^-/\pi^+ \sim 1$: similar source of production for $\pi^+$ and $\pi^-$

- At low energy pions are dominantly produced from $\Delta$ resonance

NA49: PRC 66 (2002) 054902,
PRC 77 (2008) 024903,
PRC 73 (2006) 044910


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Beam Energy Dependence of Particle Ratios

These ratios follow the observed beam energy dependence

$K/\pi$ ratios reflect strangeness production in heavy ion collisions

Total number of events for Au+Au 9.2 GeV ~ 3000

E895(AGS) : PRC 68 (2003) 054903

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Azimuthal Anisotropy Measurements

\[ \epsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle} \]

initial spatial anisotropy

\[ v_n = \frac{\text{Correlation to the reaction plane}}{e^{in(\phi - \psi_n)}} \]

="anisotropic flow"

\[ E \frac{d^3N}{d^3p} = \frac{1}{2\pi p_T dp_T dy} (1 + 2v_1 \cos(\phi - \Psi_R) + 2v_2 \cos(2(\phi - \Psi_R)) + \ldots) \]

anisotropy in momentum space

\[ \phi = \tan \frac{p_y}{p_x} \]

\[ v_2 = \langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \rangle \]

directed

\[ \Delta P = f(T, \varepsilon(\text{or V})) \rightarrow \text{EOS} \]

Within the assumptions of hydrodynamical calculations - Azimuthal Anisotropy measurements could be related to Equation Of State

\[ v_1, v_2 = f(p_T, \text{centrality}) \]

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Azimuthal Anisotropy - Directed Flow

$\nu_1$ for Au+Au 9.2 GeV shows different trend compared to Au+Au 200 and 62.4 GeV - possibly due to spectators
Azimuthal Anisotropy - Elliptic Flow

Au+Au 9.2 GeV (0-60%) (STAR Preliminary)

Pb+Pb 8.8 GeV (0-43.5%)

\[ V_2 \]

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

\[ \sqrt{s_{NN}} \ (\text{GeV}) \]

Au+Au 9.2 GeV : \(|\eta|<1,\]

only statistical errors are shown.

Results comparable to SPS results at similar beam energy.

AGS : PLB 474 (2000) 27
PHENIX : PRL 98 (2007) 162301
CERES : NPA 715 (2003) 615

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Interferometry Measurements

HBT measurements provides

Source dimensions (homogeneity region) - $R$

Source is chaotic or coherent - $\lambda$

$R_{\text{out}}$ - spatial + temporal extension of source

$R_{\text{side}}$ - only the spatial extension

$R_{\text{out}} / R_{\text{side}}$ - emission duration of source

$R_{\text{out}} / R_{\text{side}} \gg 1$ for a phase transition

Rischke & Gyulassy, NPA 608, 479 (1996)

Study HBT as a function of Beam Energy $\sim$ energy density
**Pion Interferometry Measurements**

Centrality: 0 - 30%

Error bars for Au+Au 9.2 GeV are statistical.

Systematic errors expected to be < 10% for each out, side and long.

Source parameters:

<table>
<thead>
<tr>
<th>Kt bin (GeV/c)</th>
<th>R_{out} (fm)</th>
<th>R_{side} (fm)</th>
<th>R_{long} (fm)</th>
<th>λ</th>
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<tbody>
<tr>
<td>0.15-0.25(GeV/c)</td>
<td>4.81 +/- 0.8</td>
<td>4.41 +/- 0.5</td>
<td>5.06 +/- 0.8</td>
<td>0.548 +/- 0.1</td>
</tr>
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</table>

Previously observed trend on beam energy followed

**STAR:** PRC 71 (2005) 044906, PRL 87 (2001) 082301
WA97: JPG 27 (2001) 2325

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**NA44:** PRC 58 (1998) 1656
E866: NPA 661 (1999) 439
NA49: PRC 77 (2008) 064908
Proposed Beam Energy Scan Program from STAR

<table>
<thead>
<tr>
<th>( \sqrt{s_{NN}} ) [GeV]</th>
<th>( \mu_B ) [MeV]</th>
<th>Goal [Events]</th>
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<tr>
<td>5.0</td>
<td>550</td>
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<tr>
<td>6.1</td>
<td>491</td>
<td>1 M</td>
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<td>7.7</td>
<td>410</td>
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<td>385</td>
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<td>39</td>
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</table>

Key measurements:

1. All PID hadron spectra/ratios and \( v_2 \)
2. Net-proton number Kurtosis
3. \( K/\pi, <p_T> \) … fluctuations

One potential measurable signature -

Large jump in 4\(^{th}\) moment of the event by event net-proton distribution expected

STAR has large acceptance, measures protons cleanly up to \( p_T \sim 1 \) GeV/c in TPC.

With Time Of Flight (2010) proton identification up to \( p_T \sim 3 \) GeV/c
Outlook

Locating the onset of several observations in high energy heavy-ion collisions at RHIC can be done in the beam energy scan program

Onset of Number of Constituent Quark Scaling in $v_2$ measurements and strange hadron $v_2$

Onset of Ridge
Enhanced correlated yield at large $\Delta \eta$ on near side

STAR : J. Putschke QM2006
M. Daugherity QM2008

Onset of High $p_T$ Suppression

STAR : PLB 655 (2007) 104
PLB 637 (2006) 161
PRL 97 (2006) 152301
Summary

- Identified particle spectra obtained from Au+Au collisions at 9.2 GeV, the hadron yields and ratios are similar to those obtained from SPS experiments at similar beam energies.
- Anti-proton to proton ratio ~ 0.01 indicating significant baryon stopping at mid-rapidity in these collisions
- $K^-/K^+ \sim 0.4$ indicating associated production for $K^+$
- Azimuthal Anisotropy ($v_1$ and $v_2$) measurements are similar to those obtained at SPS from collisions at similar energies
- Pion interferometry results follow the established beam energy trends

These results from the lowest beam energy collisions at RHIC demonstrate STAR experiment’s readiness to take up the proposed Beam Energy Scan Program.

Large and uniform acceptance for all beam energies in a collider set up, excellent particle identification (TPC+TOF) and higher statistics will help doing qualitative improvement on SPS results.

Beam Energy Scan Program will allow us to map the QCD phase diagram and locate the onset of several interesting observations at RHIC.
Thanks

Thanks to STAR Collaboration

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University of Illinois at Chicago
Creighton University
Nuclear Physics Inst., Academy of Sciences
Laboratory of High Energy Physics - Dubna
Particle Physics Laboratory - Dubna
Institute of Physics, Bhubaneswar
Indian Institute of Technology, Mumbai
Indiana University Cyclotron Facility
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University of Jammu
Kent State University
University of Kentucky
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Wayne State University
Warsaw University of Technology
University of Washington
Institute of Particle Physics
Yale University
University of Zagreb
## Beam Scan

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ [GeV]</th>
<th>$\mu_B$ [MeV]</th>
<th>Rate [Hz]</th>
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