Beam Energy Scan at STAR
Yield and Flow Measurements

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Motivation

Goal:

Mapping the QCD phase-structure

1) Phase-boundary

2) Onset of de-confinement

3) QCD critical point

**RHIC BES:**

Collisions: Au+Au

**Collider Mode:**
\[ \sqrt{s_{NN}} = 7.7 - 62.4 \text{ GeV} \]

**Fixed Target Mode:**
\[ \sqrt{s_{NN}} = 3 - 13.7 \text{ GeV} \]

Data taking for phase -II of BES is completed in 2021.
The STAR Experiment
Selected Physics Results From BES

- Light and Strange Hadrons
  ① Freeze-out Parameters
  ② Particle Ratios
  ③ Nuclear Modification Factor
  ④ Collective Flow

- Nuclei and Hyper-nuclei
  ① Particle Yields
  ② Collective Flow

New results from Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV and 54.4 GeV
Freeze-out Parameters

**Chemical freeze-out:**
Particle ratios get fixed

**Kinetic freeze-out:**
Momentum distributions get fixed

- The difference between chemical and kinetic freeze-out temperatures increases with increasing energy
  → *Increasing hadronic interactions after chemical freeze-out at higher energies*

- Radial flow velocity increases with increasing energy

Particle Ratios (K/π)  
(Strange over non-strange)

Results from BES energies follow world data trend  
Smooth K^+/π^+ ratio vs. \( \sqrt{s_{NN}} \) including STAR data

New data : 3 GeV

References:
Particle Ratios ($K/\pi$)  
(Strange over non-strange)

- Results from BES energies follow world data trend
- Smooth $K^+/\pi^+$ ratio vs. $\sqrt{s_{NN}}$ including STAR data
- Thermal model describes data

New data: 3 GeV

Particle Ratios ($\phi/K$ and $\phi/\Xi$)

High baryon density matter: GCE vs CE

→ Data favor the Canonical Ensemble at high baryon density

→ Canonical suppression of strange hadrons at high baryon density

E917: Phys. Rev. C. 69.054901 (2004);

NPA772: A. Andronic et al. Nucl. Phys. A 772, 167 (2006);
+private communication

Md Nasim, RHIC-AGS 2021
Particle Ratios ($K^*0/K$ and $\phi/K$)

**Lifetime**: $\sim 4$ fm ($K^*0$) and $\sim 42$ fm ($\phi$)

$K^*0/K$: Ratio decreases with increasing multiplicity

$\phi/K$: Nearly independent of multiplicity

STAR: PRC 71, 064902 (2005)
STAR: PRC 93 (2016) (R) 21903
ALICE: PRC 91 (2015) 024609

Evidence of re-scattering on daughters of $K^*0$ in central A+A collisions
Baryon-to-Meson Ratio

- Baryon enhancement at intermediate $p_T$ in central collisions
  → Parton recombination model can explain the observed shape for $\sqrt{s_{NN}} \geq 19.6$ GeV

R. C. Hwa and C. B. Yang, PRC 75, 054904 (2007)
STAR: PRC 79, 64903 (2009)
STAR: PRC 93, 021903 (2016)
Baryon-to-Meson Ratio

- Baryon enhancement at intermediate $p_T$ in central collisions for $\sqrt{s_{NN}} \geq 19.6$ GeV

→ Parton recombination model can explain the observed shape

- Within the uncertainties no difference between central and peripheral collisions for $\sqrt{s_{NN}} \leq 11.5$ GeV

STAR: PRC 102, 34909 (2020)

Md Nasim, RHIC-AGS 2021
Nuclear Modification Factor

\[ R_{CP} = \left[ \frac{d^2N_{\text{central}}}{dp_T \, dy} \right] \cdot \left[ \frac{N_{\text{peripheral}}}{N_{\text{central}}} \right] \]

\[ \sqrt{s_{NN}} \geq 27 \text{ GeV} \]
- Suppression at high \( p_T \)
- Energy loss of partons in QGP
- Baryon vs meson at intermediate \( p_T \)
- Parton recombination

\[ \sqrt{s_{NN}} \leq 11.5 \text{ GeV} \]
- No suppression for the highest measured \( p_T \)
- Parton energy loss, if any, is subdominant
- Baryon –meson separation is not significant
Azimuthal Anisotropy

Pressure gradient transfers initial spatial anisotropy to final state momentum space anisotropy

\[
\frac{dN}{d\phi} = 1 + 2 \sum_{n=1}^{\infty} v_n \cos\{n(\phi - \psi_n)\}
\]

\[v_n = \langle \cos\{n(\phi - \psi_n)\} \rangle\]

The azimuthal anisotropy parameters \(v_n\) are sensitive probe to the matter created in heavy-ion collisions.

Elliptic Flow of Strange Hadrons

$\sqrt{s_{NN}} \geq 27 \text{ GeV}$
- Baryon-meson separation at intermediate $m_T-m_0$
  $\rightarrow$ Parton recombination

$\sqrt{s_{NN}} \leq 19.6 \text{ GeV}$
- No significant baryon-meson separation for the highest measured $m_T-m_0$
  $\rightarrow$ Probably dominated by hadronic interaction
$\phi$ mesons $v_2$: Probe to Partonic Collectivity

$\phi$ freezes out at higher temperature than $\pi, k, p$

$<p_T>$ of $\phi$ is almost independent of centrality unlike anti-protons

$\phi$ $v_2$ less affected by hadronic interaction compared to anti-proton

- Indicates possibly $\phi$ decouples early in the interaction
- Clean probe to partonic collectivity

Energy Dependence of $\phi$ meson $v_n$

(Partonic vs Hadronic)

$\phi$-meson $v_2$ at $p_T \sim 1.7$ GeV/c

Au+Au, 0-80%

$\frac{d\phi}{dy}$ vs $\sqrt{s_{NN}}$ (GeV)

New, 3, 7.2 GeV

STAR: PRL 110, 142301 (2013)
Energy Dependence of $\phi$ meson $v_n$

(Partonic vs Hadronic)

Less partonic contribution at low beam energy.

Could be related to the change of equation of states.

STAR: PRL 110, 142301 (2013)

Md Nasim, RHIC-AGS 2021
Collectivity at 3 GeV  
(Au+Au, FXT data)

• The measured $v_2$ for all particles are negative at 3 GeV
• The NCQ scaling breaks, especially for positively charged particles

→ Hadronic interaction dominated matter
Selected Physics Results From BES

• Light and Strange Hadrons
  ① Freeze-out Conditions
  ② Particle Ratios
  ③ Nuclear Modification Factor
  ④ Collective Flow

• Nuclei and Hyper-nuclei
  ① Particle Yields
  ② Collective Flow
Light Nuclei Production: d/p Ratios

Statistical thermal model describes the data.

Binding energies: \( \sim 2.2 \text{ MeV} \) for (anti-)deuteron

Freeze-out temperature: \( \sim 100 \text{ MeV} \)

Production mechanism of light nuclei is important to understand
Hyper-Nuclei Production

Important probe to Y-N interactions and hyperon contribution to nuclear EoS

A. Andronic et al, Phys. Lett. B 697, 203 (Private communications)

Md Nasim, RHIC-AGS 2021
Elliptic Flow of Nuclei

Nuclei $v_2$ show atomic number scaling

Nuclei production mainly through coalescence of nucleons
Directed Flow of Nuclei and Hyper-Nuclei

- First observation of hypernuclei collective flow ($v_1$) in heavy-ion collisions
- $v_1$ slope seems to follow atomic number scaling
  - Hypernuclei production mainly from coalescence of hyperons and nucleons
Summary

Mapping the QCD phase-diagram

$$\sqrt{s_{NN}} \geq 27\text{GeV}$$:
- There are clear evidence for QGP formation
- Hadronization at intermediate $p_T$ is dominated by quark coalescence

$$\sqrt{s_{NN}} \leq 11.5\text{ GeV}$$:
- Medium created is likely hadronic interaction dominated
- Lack of evidence for the quark coalescence at intermediate $p_T$

High precision measurements are needed for $$\sqrt{s_{NN}} < 20\text{ GeV}$$ (BES-II)

Understanding nuclei and hyper-nuclei production
- Thermal model describes yields (except $^{4}_\Lambda\text{H}$)
- Flow measurement indicates (hyper)nuclei production through coalescence
STAR BES-II

New measurements using high statistics data and with improved detector condition will be available soon.

Collider Mode:

<table>
<thead>
<tr>
<th>Collision Energy (GeV)</th>
<th>7.7</th>
<th>9.2</th>
<th>11.5</th>
<th>14.6</th>
<th>17.3</th>
<th>19.6</th>
<th>27</th>
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<tr>
<td>Good Events (M)</td>
<td>4.3</td>
<td>NA</td>
<td>11.7</td>
<td>12.6</td>
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<tr>
<td>Days running</td>
<td>19</td>
<td>NA</td>
<td>10</td>
<td>21</td>
<td>NA</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Data Hours per day</td>
<td>11</td>
<td>NA</td>
<td>12</td>
<td>10</td>
<td>NA</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Fill Length (min)</td>
<td>10</td>
<td>NA</td>
<td>20</td>
<td>60</td>
<td>NA</td>
<td>30</td>
<td>60</td>
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<tr>
<td>Good Event Rate (Hz)</td>
<td>7</td>
<td>NA</td>
<td>30</td>
<td>23</td>
<td>NA</td>
<td>100</td>
<td>190</td>
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<tr>
<td>Max DAQ Rate (Hz)</td>
<td>80</td>
<td>NA</td>
<td>140</td>
<td>1000</td>
<td>NA</td>
<td>500</td>
<td>1200</td>
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Performance in BES-II

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<th></th>
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</thead>
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<tr>
<td>Required Number of Events</td>
<td>100</td>
<td>160</td>
<td>230</td>
<td>300</td>
<td>250</td>
<td>400</td>
<td>NA</td>
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<tr>
<td>Achieved Number of Events</td>
<td>101</td>
<td>162</td>
<td>235</td>
<td>324</td>
<td>TBD</td>
<td>582</td>
<td>560</td>
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<td>fill length (min)</td>
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<td>45</td>
<td>25</td>
<td>45</td>
<td>50</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>Good Event Rate (Hz)</td>
<td>22</td>
<td>33</td>
<td>80</td>
<td>170</td>
<td>265</td>
<td>400</td>
<td>620</td>
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<tr>
<td>Max DAQ rate (Hz)</td>
<td>600</td>
<td>700</td>
<td>550</td>
<td>800</td>
<td>1300</td>
<td>1800</td>
<td>2200</td>
</tr>
<tr>
<td>Data Hours per day</td>
<td>13</td>
<td>13</td>
<td>13</td>
<td>9</td>
<td>15</td>
<td>10</td>
<td>9</td>
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<tr>
<td>Projected number of weeks</td>
<td>11-20</td>
<td>8.5-14</td>
<td>7.6-10</td>
<td>5.5</td>
<td>2.5</td>
<td>4.5</td>
<td>NA</td>
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<tr>
<td>weeks to reach goals</td>
<td>12.8</td>
<td>14.6</td>
<td>8.9</td>
<td>8.6</td>
<td>TBD</td>
<td>5.1</td>
<td>4.0</td>
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</table>

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New measurements using high statistics data and with improved detector condition will be available soon.

**Fixed Target Mode:**

<table>
<thead>
<tr>
<th>Beam Energy (GeV)</th>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>Expected Duration</th>
<th>Actual Duration</th>
<th>Proposed Events</th>
<th>Recorded Events</th>
<th>Year</th>
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<tbody>
<tr>
<td>3.85</td>
<td>3.0</td>
<td>4 days</td>
<td>3.5 days</td>
<td>100 M</td>
<td>258 M</td>
<td>2018</td>
</tr>
<tr>
<td>3.85</td>
<td>3.0</td>
<td>3 days</td>
<td>3.3 days</td>
<td>300 M</td>
<td>307 M</td>
<td><strong>2021</strong></td>
</tr>
<tr>
<td>3.85</td>
<td>3.0</td>
<td>3 weeks</td>
<td>TBD</td>
<td>2 B</td>
<td>TBD</td>
<td><strong>2021</strong></td>
</tr>
<tr>
<td>4.59</td>
<td>3.2</td>
<td>2 days</td>
<td>46 hours</td>
<td>200 M</td>
<td>200.6 M</td>
<td>2019</td>
</tr>
<tr>
<td>5.75</td>
<td>3.5</td>
<td>1 day</td>
<td>23 hours</td>
<td>100 M</td>
<td>115.6 M</td>
<td>2020</td>
</tr>
<tr>
<td>7.3</td>
<td>3.9</td>
<td>0.5 days</td>
<td>12 hours</td>
<td>50 M</td>
<td>52.7 M</td>
<td>2019</td>
</tr>
<tr>
<td>7.3</td>
<td>3.9</td>
<td>1 day</td>
<td>29 hours</td>
<td>100 M</td>
<td>117 M</td>
<td>2020</td>
</tr>
<tr>
<td>9.8</td>
<td>4.5</td>
<td>1 day</td>
<td>31 hours</td>
<td>100 M</td>
<td>108 M</td>
<td>2020</td>
</tr>
<tr>
<td>13.5</td>
<td>5.2</td>
<td>1 days</td>
<td>21 hours</td>
<td>100 M</td>
<td>103 M</td>
<td>2020</td>
</tr>
<tr>
<td>19.5</td>
<td>6.2</td>
<td>1 days</td>
<td>22 hours</td>
<td>100 M</td>
<td>118 M</td>
<td>2020</td>
</tr>
<tr>
<td>26.5</td>
<td>7.2</td>
<td>parasitic</td>
<td>2 days</td>
<td>none</td>
<td>155 M</td>
<td>2018</td>
</tr>
<tr>
<td>26.5</td>
<td>7.2</td>
<td>parasitic</td>
<td>3.5 days</td>
<td>none</td>
<td>317 M</td>
<td>2020</td>
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<td>26.5</td>
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<td>parasitic</td>
<td>TBD</td>
<td>none</td>
<td>TBD</td>
<td>2021</td>
</tr>
<tr>
<td>31.2</td>
<td>7.7</td>
<td>0.5 days</td>
<td>11.5 hours</td>
<td>50 M</td>
<td>50.6 M</td>
<td>2019</td>
</tr>
<tr>
<td>31.2</td>
<td>7.7</td>
<td>1 day</td>
<td>26 hours</td>
<td>100 M</td>
<td>112 M</td>
<td>2020</td>
</tr>
<tr>
<td>44.5</td>
<td>9.1</td>
<td>0.5 days</td>
<td>12 hours</td>
<td>50 M</td>
<td>53.9 M</td>
<td><strong>2021</strong></td>
</tr>
<tr>
<td>70</td>
<td>11.5</td>
<td>0.5 days</td>
<td>12 hours</td>
<td>50 M</td>
<td>51.7 M</td>
<td><strong>2021</strong></td>
</tr>
<tr>
<td>100</td>
<td>13.7</td>
<td>0.5 days</td>
<td>10 hours</td>
<td>50 M</td>
<td>50.7 M</td>
<td><strong>2021</strong></td>
</tr>
</tbody>
</table>
Thank You