STAR Results from the RHIC Beam Energy Scan

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for the STAR Collaboration
• Search for evidence of
  – Turn-off of QGP signatures
  – Critical point
  – First order phase transition

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>Min. Bias Events ($10^6$)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>4.3</td>
<td>2010</td>
</tr>
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<td>11.5</td>
<td>12</td>
<td>2010</td>
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<tr>
<td>19.6</td>
<td>36</td>
<td>2011</td>
</tr>
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<td>27</td>
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<td>39</td>
<td>130</td>
<td>2010</td>
</tr>
<tr>
<td>62.4</td>
<td>67</td>
<td>2010</td>
</tr>
</tbody>
</table>

arXiv:1007.2613
STAR Experiment

- Large $\eta$ coverage
  - $|\eta| < 1.0$
- Full azimuthal acceptance
- Uniform acceptance for all energies
STAR Experiment

- PID (TPC+TOF):
  - pion/kaon: $p \sim 1.6 \text{ GeV}/c$
  - proton: $p \sim 3.0 \text{ GeV}/c$
- Strange hadrons: decay topology & invariant mass

Similar acceptance over all RHIC energies

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Hui Wang for STAR
Search for Turn-off of QGP Signatures

• Balance Function
• Dynamical Charge Correlations
• Elliptic Flow
• $R_{cp}$ of Charged Hadrons
Observables

- **Balance Function**
  - Sensitive to the charge formation time and relative diffusion
  
  \[ B(\Lambda \eta) = \frac{1}{2} \left\{ \frac{N_+ (\Lambda \eta) - N_+ (\Lambda \eta)}{N_+} + \frac{N_- (\Lambda \eta) - N_- (\Lambda \eta)}{N_-} \right\} \]

- **Dynamical Charge Correlations**
  
  \[ \gamma_{\alpha \beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \]

- **Elliptic Flow**
  - Test of number-of-constituent-quark scaling at lower energies
  
  \[ \frac{dN}{d\varphi} \propto \left( 1 + 2 \sum_{n=1}^{+\infty} v_n \cos[n(\varphi - \psi_n)] \right) \]
Balance Function

\[
B(\Delta\eta) = \frac{1}{2} \left\{ \frac{N_{++}(\Delta\eta) - N_{++}(\Delta\eta)}{N_+} + \frac{N_{--}(\Delta\eta) - N_{--}(\Delta\eta)}{N_-} \right\}
\]

- Data are narrower than shuffled events at all energies
- Shuffled events are created by shuffling charges in a given event
Balance Function Width

- Balance function width is sensitive to hadronization time
- Balance functions narrow smoothly with increasing collision energy and as the collisions become more central

\[ \langle \Delta \eta \rangle = \frac{\sum B(\Delta \eta_i) \Delta \eta_i}{\sum B(\Delta \eta_i)} \]

- Most central (0-5%) events only
- Remove lowest bin when calculating \( \langle \Delta \eta \rangle \) to reduce HBT/Coulomb effects
Dynamical Charge Correlations

\[ \gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RH}) \rangle \]

Splitting between same and opposite-sign charges decreases with decreasing \( \sqrt{s_{NN}} \)
Elliptic Flow

- Baryon–meson splitting is observed when collisions energy ≥ 19.6 GeV for both particles and the corresponding anti-particles.
- For anti-particles, the splitting is almost gone within errors at 11.5 GeV.

- **Difference in positive/negative charged particle $v_2$**
  - Increasing with decrease of beam energy
  - Larger for baryons than mesons

- **Possible explanation**
  - Baryon transport to mid-rapidity?
  - Hadronic potential?
Search for Critical Point

• Particle Ratio Fluctuations
• $p_t$ Correlations
• High Moments of Net-protons and Net-charge Distribution
Observables

- **Particle Ratio Fluctuations**
  - Related to strangeness and baryon number fluctuations
  - Look for non-monotonic behavior of the fluctuations near critical point

\[ \nu_{\text{dyn},K\pi} = \frac{\langle N_K (N_K - 1) \rangle}{\langle N_K \rangle^2} + \frac{\langle N_\pi (N_\pi - 1) \rangle}{\langle N_\pi \rangle^2} - 2 \frac{\langle N_K N_\pi \rangle}{\langle N_K \rangle \langle N_\pi \rangle} \]

- **p_t Correlations**
  - Looking for non-monotonic change as a function of incident energy

\[ < \Delta p_{t,i} \Delta p_{t,j} > = \frac{1}{N_{\text{event}}} \sum_{k=1}^{N_{\text{event}}} \frac{C_k}{N_k (N_k - 1)} \]

\[ C_k = \sum_{i=1}^{N_k} \sum_{j=1,i\neq j}^{N_k} (p_{t,i} - < < p_t >>)(p_{t,j} - < < p_t >>) \]
Particle Ratio Fluctuations

- STAR data show no significant energy dependence for $K/\pi$ fluctuations.
- STAR data decrease smoothly with decreasing incident energy for $p/\pi$ and $K/p$ fluctuations.
- Disagreement between STAR and NA49 results for $K/\pi$ and $K/p$ fluctuations.
- No non-monotonic behavior is observed.
• Scaled correlations strongly decrease with decreasing energy below 39 GeV

• No non-monotonic behavior is observed

• Acceptance difference effect under investigation

• Freeze-out eccentricity sensitive to the 1st order phase transition\(^1\)

• STAR data shows smooth decrease with increasing energy. No conclusive deviations from UrQMD model observed

\(^1\) Kolb and Heinz, 2003, nucl-th/0305084


v\(_1\) is a manifestation of early pressure in the system

The v\(_1\) slope for net-proton changes sign between 7.7 and 11.5 GeV
Summary

• **sQGP Signatures:**
  • Several key sQGP signatures are either decreasing or not seen at low energies
  • Hadronic interactions become more important at low energies

• **Critical Point Signatures:**
  • No direct evidence from Particle Ratio and $p_t$ fluctuations

• **Softening of Equation Of State:**
  • Double sign change in directed flow of net-protons

• **Beam Energy Scan-II:**
  • Propose higher statistics data below 20 GeV
  • Fixed target proposal to extend $\mu_B$ coverage up to 800 MeV
Thank You