PHENIX Results from the RHIC Energy Scan

Edward O’Brien
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The Physics Motivation

Use the flexibility of RHIC to carry out detailed energy and species scans with the point of determining:

- The evolution from partonic to hadronic matter through the QCD crossover region - QGP transition
- Location, if any, of a critical point on the QCD phase diagram
Physics Results of Energy and Species Scan

- Global variables
- $R_{AA}$
- Flow
RHIC Run History

12 Years, 12 Runs, 10 Energies, 6 Combination of Species

<table>
<thead>
<tr>
<th>RHIC Run</th>
<th>Year</th>
<th>Species</th>
<th>Energy</th>
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RHIC’s exceptional flexibility has enabled a Physics program of broad scope
Approximately half of RHIC’s running time has contributed in to the energy and species scan studies.
Global Variable $dN/d\eta$

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Global Variables $dE_T/d\eta$

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Global Variables $\varepsilon_{Bj} \tau$

$$\varepsilon_{Bj} = \frac{1}{A_{\perp}} \tau (dE_T/dy)$$

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Uncorrected multiplicity and E_T data for recent U+U and Cu+Au RHIC run superimposed on raw multiplicity and E_T distributions from pp, dAu, CuCu and AuAu data sets
HI collisions that pass close to a QCD critical point might demonstrate observable large fluctuations in correlation lengths of particular global variables.

Correlation length is $\xi$

Then

Variance: $\sigma^2 = \langle (\Delta N)^2 \rangle \sim \xi^2$

Skewness: $S = \langle (\Delta N)^3 \rangle / \sigma^3 \sim \xi^{4.5}$

Kurtosis: $K = \langle (\Delta N)^4 \rangle / \sigma^4 \sim \xi^7$

The strategy is to vary $\sqrt{s}$ and look for a sudden change in correlation length.

Lattice calculations say we don’t have to hit a bulls eye on the critical point. We just have to come close to see the fluctuations in $\xi$
- Correlation length related to moments of conserved quantities including net charge
- Correlation length should diverge at the critical point in the phase diagram
Net Charge Moments

They scale as correlation length

![Graphs showing correlation length for different energies and parton numbers.](image)
√s_{NN} Dependence of Net Charge Fluctuations

- Neither K nor S vary with centrality at 7.7, 39, 62.4 and 200 GeV
- Kurtosis vs energy is flat within errors
- Skewness tracks UrQMD prediction
- Analysis of data sets from √s = 19.6, 27 GeV still to be completed
ω Multiplicity fluctuations

ω_{ch,dyn} = \langle N \rangle/\text{var}(N) \text{ corrected for impact parameter fluctuations}

Mean multiplicity fluctuation flat for these 4 collision energies

Analysis of data sets from $\sqrt{s} = 19.6, 27$ GeV still to be completed
Global Variable Summary

- Global analysis of $dN/d\eta$, $dE_T/d\eta$ and $\varepsilon_{Bj}$ vs. centrality performed for data sets at $\sqrt{s} = 200, 130, 62.4, 39, 27, 19.6$ and $7.7$ GeV
  - Gradual evolution of the quantities with centrality and $\sqrt{s}$ has been observed
  - No obvious non-monotonic behavior at these collision energies
  - U+U data @ $\sqrt{s} = 193$ GeV shows $\sim20\%$ higher $dE_T/d\eta$ and $\varepsilon_{Bj}$ than Au+Au 200 GeV data at the most central collisions.
  - Maximum U+U $dN/d\eta$ shows no increase over Au+Au $dN/d\eta$

- Fluctuation analyses have been performed for net charge and multiplicity fluctuations at $\sqrt{s} = 200, 62.4, 39$ and $7.7$ GeV
  - No obvious non-monotonic behavior at these collision energies
  - Analysis of data sets from 27 and 19.6 GeV are on the way
From our 2008 paper PRC 101, 162301

Cu+Cu, 0-10% most central

- $\sqrt{s_{NN}} = 22.4$ GeV
- $\sqrt{s_{NN}} = 62.4$ GeV
- $\sqrt{s_{NN}} = 200$ GeV
$R_{AA}$ vs $\pi^0$

$\pi^0$, Au+Au 40-60%

- 39 GeV
- 62.4 GeV
- 200 GeV

Submitted to PRL arXiv:1204.1526v1

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$R_{AA}$ analysis of 27 GeV data is underway

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$R_{AA}$  \hspace{1cm} J/$\psi$

Submitted to PRC arXiv:1208:2251

$R_{AA}$ (200 GeV) PRC 84, 054912 (2011)
Global sys. = $\pm$ 9.2%

$R_{AA}$ (62.4 GeV) = PHENIX data/our estimate
Global sys. = $\pm$ 29.4%

$R_{AA}$ (39 GeV) = PHENIX data/FNAL data
Global sys. = $\pm$ 19%

$J/\psi \rightarrow \mu\mu$, $1.2 < |y| < 2.2$
R_{AA} Summary

• Jet quenching observed in central Au+Au collisions at $\sqrt{s} = 39, 62.4$ GeV is similar to but not as strong as $R_{AA}$ seen in Au+Au 200 GeV data
  – Less suppression as a function of $\sqrt{s}$ vs $p_T$ and centrality
  – $R_{AA} \sim 1$ for mid-peripheral (40-60%) Au+Au 39 GeV
  – Analysis of $\pi^0$ $R_{AA}$ for 27 GeV Au+Au is underway

• J/ψ suppression is very similar at all $N_{\text{part}}$ for particles produced in collisions of 200, 62.4 and 39 GeV ($1.2 < |y| < 2.2$)
Flow v2, v3 \( \pi, K, p \)
Flow $v_2$, $v_3$ \( \pi, K, p \)
NCQ scaling of $v_2$, $v_3$

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Flow Summary

- New v2 and v3 with PID have been measured in 62.4 and 39 GeV Au+Au data

- 200, 62.4 and 39 GeV PID data shows the same v2, v3 values. Observed flow is saturated in this energy range

- NCQ scaling of $v_n$ for identified charged hadrons, $KE_T/n_q < 1$ GeV observed for the beam energy range of 39–200 GeV confirms partonic flow down to 39 GeV
Conclusions - 1

- A large fraction of the extensive RHIC data set contributes to the energy and species scan
- Data has been analyzed at 7.7, 19.7, 27, 39, 62.4, 130, 193 and 200 GeV
  - A gradual evolution for $dN/d\eta$, $dE_t/d\eta$ and $\varepsilon_{Bj}$ vs $\sqrt{s}$ and $N_{part}$
  - $\varepsilon_{Bj}$ of U+U ~ 20% higher than Au+Au
  - No significant increase in the $dN/d\eta$ seen in U+U
- Net charge and multiplicity fluctuation analyses have been performed at 7.7, 39, 62.4 and 200 GeV
  - No non-monotonic behavior observed within sensitivity.
  - Additional data at 27 and 19.6 GeV to be analyzed
- Energy loss similar to that observed in 200 GeV Au+Au $R_{AA}$ is seen in 62.4 and 39 GeV data
  - The energy loss weakens as we decrease $\sqrt{s}$ and centrality
- $J/\psi$ suppression is very similar at all $N_{part}$ for particles produced in collisions of 200, 62.4 and 39 GeV ($1.2 < |y| < 2.2$)
Conclusions - 2

- 200, 62.4 and 39 GeV PID data shows the same v2, v3 values
- NCQ scaling of $v_n$ seen for $\pi$, K, p observed in range 39–200 GeV confirms partonic flow down to 39 GeV

Thank You
Back Up
Charged hadron results for $v_2$, $v_3$ and $v_4$ consistent with saturation of identified charged particles $v_n$ for beam energies of 39-200GeV

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Excitation plot of v2 and E_T/particle

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Global Variables $dE_T/d\eta$
Initial geometry HBT systematics

- System volume from 3D HBT as a analysis function of entropy density
- PHENIX data follow the global linear trend

![Graph showing HBT systematics with data points for various experiments and a trend line.](image-url)

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