The RHIC Beam Energy Scan - STAR’s Perspective
(why I advocate going down in energy when everyone is going up)

Helen Caines (Yale University) for the STAR collaboration

• The physics driving a BES
• Why RHIC?
• The main signatures
• A potential first scan
• Summary

44th Rencontres de Moriond
QCD and High Energy Interactions
March 14th-21st 2009
Cornerstones of RHIC Beam Energy Scan

“turn-off” of sQGP signatures
constituent quark scaling of elliptic flow

Evidence of an ordered phase transition
“wiggle” in directed flow

Evidence of passing through Critical Point fluctuations

Symmetry physics
parity violation

BES
The phase diagram of nuclear matter

At RHIC we transition to a new state of matter - the sQGP

Lattice QCD predicts:

- High $T$ & Low $\mu_B$ - Cross-over
- Low $\mu_B$ & High $T$ - 1st order transition
- Mid $\mu_B$ & Mid $T$ - Critical Point

Cannot calculate location of CP - an experimentally driven search
Colliders are a great choice for BES

Acceptance

Acceptance for collider detectors is totally independent of beam energy
Colliders are a great choice for BES

Acceptance

- Occupancy for collider detectors is much less dependent on beam energy
- Less problems with track merging, charge sharing hits etc..

Acceptance for collider detectors is totally independent of beam energy

Excellent control of systematics
Flow - early thermalization

Initial spatial anisotropy → Interactions → Final momentum anisotropy

Driving spatial anisotropy vanishes ⇒ self quenching
Flow - early thermalization

Initial spatial anisotropy

Interactions

Final momentum anisotropy

Driving spatial anisotropy vanishes $\Rightarrow$ self quenching

Fourier expansion used to describe the particles' angular distribution

\[
\frac{dN}{d\varphi} \propto 1 + 2v_n \cos[n(\varphi - \psi_R)] + \ldots
\]

Directed Flow $= v_1 = \langle \cos[(\varphi - \psi_R)] \rangle$

Elliptic Flow $= v_2 = \langle \cos[2(\varphi - \psi_R)] \rangle$

Helen Caines - Moriond - QCD - March 2009
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Sensitive to early interactions and pressure gradients
sQGP - elliptic flow scaling

- At low $p_T$ PID $v_2$ follows hydro. type scaling
sQGP - elliptic flow scaling

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- At intermediate $p_T$ $v_2$ displays constituent quark scaling $m_T = \sqrt{p_T^2 + m_0^2}$
- Evidence of quark degrees of freedom in early stages?
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  \[ m_T = \sqrt{p_T^2 + m_0^2} \]
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Do these effects turn off at lower energies?
- sufficient stats. with several million events (few days at 9 GeV)
1\textsuperscript{st} order transition - Directed flow

- Describes collective sideways motion produced particles and fragments
- Carries information about the earliest times of the collisions
- Can be pursued down to lowest collision energies - plot on left from only few K events
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It is predicted that a “wiggle” should appear at mid-rapidity if pass through a 1st order phase transition
Critical Point - $K/\pi$ and $p/\pi$ fluctuations

Measure $K/\pi$ event-by-event and study the width ($\sigma$) of the resulting distribution.

Strong fluctuations predicted near CP $K/\pi$:
- NA49 > STAR results
- CP at lower $\sqrt{s}$? different acceptances?
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Strong fluctuations predicted near CP

**$K/\pi$:**
- NA49 > STAR results
  - CP at lower $\sqrt{s}$?
  - different acceptances?

**$p/\pi$:**
- NA49 follow smoothly STAR results
  - Correlation negative due to large resonance contribution

Needs more detailed study
- charge separation
Advantages of analysis at STAR

- Good total event count statistics - 1-10M per beam energy
- Better statistics in each event - Large acceptance: full azimuthal, |y| < 1.0
  - Clean particle identification: (TPC, ToF, EMC)
- Continuity from high to low $\sqrt{s}$ - Systematic errors under better control

Can be pursued at all collision energies
Symmetries - Parity violation

In QCD, chiral symmetry breaking is due to nontrivial topological solutions; among the best evidence for this physics would be event-by-event strong parity violation.

- Topological charge density illustration of QCD vacuum structure of gluon-field configurations in 4-D (movie available) from lattice-based simulations

Box volume = 2.4 X 2.4 X 3.6 fm$^3$. Animation/Picture by Derek Leinweber
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large orbital angular momentum perp. to RP + large localized B fields + deconfined phase

⇒ strong P violating domains with diff. no. of left & right handed quarks

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large orbital angular momentum perp. to RP + large localized B fields
+ deconfined phase
\[ \Rightarrow \] strong P violating domains with diff. no. of left & right handed quarks


\[ \Rightarrow \] Preferential emission of like sign particles in the direction of the angular momentum i.e. opposite sides of the reaction plane

(Voloshin PRC 70 (2004) 057901)
Symmetries - Parity violation

\[ \frac{dN_\pm}{d\phi} \sim 1 + 2a_\pm \sin(\phi - \Psi_{RP}) + \ldots \]

the asymmetry

Averages to zero due to random domains

instead measure

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \approx \left( v_{1,\alpha}, v_{1,\beta} - a_\alpha a_\beta \right) \]

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• Measurement follows expected trends

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S. Voloshin QM2008
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B-field+deconfinement → strong threshold effect → BES
Summary

Main themes of the STAR Beam Energy Scan:

- Search for turn-off of major sQGP signatures already established at top RHIC energies
- Search for first order phase transition signatures
- Search for evidence of critical point
- Symmetry Physics - Tracking potential strong parity violation signal with changing collision energy is a high priority
  + numerous other measurements

We propose to first scan available phase space with 6 equally spaced points $\sqrt{s}=5-39$ GeV (already have 62,130, 200 data)

Return to “interesting” regions for more detailed studies

The search for the QCD Critical Point is a “must do” experiment
- BNL PAC recommendation, May 2008
Collisions Au+Au $\sqrt{s_{\text{NN}}} = 9$ GeV

From 2 days of running:

- 203,395 triggers
- ~3,500 good events

(good $\equiv$ primary vertex along beamline and within acceptance)

Publishable quality data from this run
Collisions Au+Au $\sqrt{s_{NN}} = 9$ GeV

From 2 days of running:

- 203395 triggers
- ~3500 good events

(good $\equiv$ primary vertex along beamline and within acceptance)

Unambiguous beam+beam events

Publishable quality data from this run
### STAR’s beam energy scan proposal

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>Rate (Evts/sec)</th>
<th>10 hr days for 1 M Evts</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>0.8</td>
<td>34</td>
</tr>
<tr>
<td>7.7</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>11.5</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>17.3</td>
<td>33</td>
<td>0.8</td>
</tr>
<tr>
<td>27</td>
<td>92</td>
<td>0.3</td>
</tr>
<tr>
<td>39</td>
<td>190</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Energies spaced by constant multiplicative factor of $\sim 1.5$ between $\sqrt{s_{NN}} = 5.0$ and 62.4 GeV, except for 39 GeV, which is shifted slightly from 41 GeV to match existing pp data.
Particle identification

Use TPC+ToF(completed 2010) +EMCal+Topology

- TOF alone: (π,K) up to 1.6 GeV/c, p up to 3 GeV/c
- TOF+TPC(dE/dx, topology) up to 12 GeV (NIMA 558 (419) 2006)

Have track by track identification over large $p_T$, $y$ range
- necessary for fluctuation measures

Good quality PID spectra and ratios ($\mu_B$ and $T$)
What energies to pick?

Critical point estimates
- Chemical Freeze-out
- Heavy ion data

RHIC full range

Gavai, Gupta 2005
Ejiri, et.al. 2003
Fodor, Katz 2004

Peak in \( \langle K \rangle / \langle \pi \rangle \)

\( T_0 (\langle s_{NN} \rangle = 200 \text{ GeV}) \)

\( T_0 (\langle s_{NN} \rangle = 17.3 \text{ GeV}) \)

RHIC Low Energy Scan: \( 5.0 < \sqrt{s_{NN}} < 30 \text{ GeV} \)

Fair Energy Range: \( 5.5 < \sqrt{s_{NN}} < 8.2 \text{ GeV} \)
The Laundry List of Topics

Antiproton-to-proton ratio
Baryon to meson ratios
Charged-particle elliptic flow
Charged-particle directed flow
DCC searches
Elliptic flow for identified charged particles & for photons
Femtoscopy relative to $1$st-order reaction plane
Fluctuations of particle ratios, esp. $K/\pi$ & $p/\pi$
Fluctuations of $<p_T>$, $<v_2>$, multiplicity
Long-range forward-backward correlations
Net-proton & net-charge kurtosis
Nuclear modification factors
$p_T$ spectra of identified particles
Production of light nuclei and antinuclei
standard femtoscopy source parameters
strange to non-strange ratios (baryons and mesons)
Strong parity violation
Triggered correlations and “the ridge”
Untriggered pair correlations in $\Delta \eta$
Yields of strange particles
Yields and rations and statistical model fits
Upgrades: RHIC Electron Cooling

- Required if high statistics at $\sqrt{s_{NN}} < 5-6 \text{ GeV/u}$ are desired
- Planned RHIC-II electron cooling does not work at these energies
- Existing stochastic cooling does not work below transition, and is too slow

- Option 1: acquire Pelletron from FNAL when Tevatron operations end c. 2010
  - 20 m cooling area (fits existing straights)
  - Designed for cooling 0-9 GeV/c beams
  - ~10m tall; install in experiment hall?

- Option 2: construct cooler based on prototype RHIC-II ERL electron gun
  - In fabrication phase for ERL project

- Both options being investigated
  - ~x10 integrated luminosity improvement