STAR and the RHIC Energy Scan

*Helen Caines* for the STAR collaboration
Yale University
INT Mini-workshop on the QCD Critical Point
Seattle, Washington
August 2008
Outline

• Introduction
• STAR in the Energy scan era
  ▶ What our capabilities will be past 2010
• STAR current efforts for the energy scan
• STAR’s planned measurements
• STAR’s preferred run plan
• Summary and Conclusions
More than just a critical point search

Need to be careful not to just focus on Critical Point search:

• Is the Critical Point a valid concept in HI Collisions
  ‣ Do collisions form a thermodynamic state?
  ‣ If we don’t see evidence does it mean it is not there, we looking in the wrong place, or looking for wrong signals?
  ‣ Will semihard processes (noise) obscure the critical point (signal)?
  ‣ Can Critical Point concept be disproved?

• We are also asking other questions:
  ‣ What is the evolution of the unusual medium’s properties with $\sqrt{s}$
  ‣ Do any of the sQGP signatures turn off?
  ‣ Can we see evidence of ordered transition?
  ‣ What new surprises await in the unexplored region?
What we plan (currently) to look at

Many ideas, mostly qualitative or semi-quantitative

• Bulk properties
  ‣ ratios, spectra \( (T_{\text{ch}}, T_{\text{fo}}, \mu_B) \)

• Fluctuations & correlations of many varieties
  ‣ \( K/\pi, \langle p_T \rangle, v_2 \) (critical point fluctuations)
  ‣ pair correlations

• Energy dependence of flow characteristics \( (v_1 \text{ and } v_2) \)
  ‣ Collapse of proton flow (phase transition)
  ‣ \( N_q \) scaling? (deconfinement)
  ‣ \( \phi \) and \( \Omega \) (deconfinement)

• Signals of parity violation

• Other ideas spawned by prospect of data
If there, a critical point doesn’t hide…

- Hydro predicts that the evolution of the system is attracted to the critical point.
- Effect observed already for liquid-gas nuclear transition
- Focusing causes broadening of signal region - No need to run at exactly Critical Point energy

Image courtesy of C.Nonaka
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Correlation lengths expected to reach at most 2 fm (Berdnikov, Rajagopal and Asakawa, Nonaka): reduces signal amplitude, no sharp discontinuities

Finding evidence for a 1st order phase transition would immediately narrow location of the critical point.
Colliders are a great choice for E-scan

Acceptance

Acceptance for collider detectors is totally independent of beam energy
Colliders are a great choice for E-scan

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

Better control of systematics
STAR post 2010

Compatibility of FTPCs and FGT/HFT being investigated - only issue if run after 2010
Triggering using BBCs

Studies indicate BBCs can be used for triggering.

No. of particles larger than that for p+p.

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Sensitive down to single MIP hitting the detector

Triggering is not a problem
Particle identification

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

- TOF alone: \((\pi, K)\) up to 1.6 GeV/c, p up to 3 GeV/c
- TOF+TPC \((dE/dx, \text{topology})\) 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 \((\mu_B \text{ and } T)\)
Event-plane resolution

NA49 flow PRC used less than 500K events per energy

Better resolution than NA49 so smaller errors for same event count

Estimates used:
- $v_2$ from NA49
- $dN/dy$ using $1.5N_{\text{part}}/2$
- Tracks with $|y|<0.5$ (can probably do better)
- Events passed through simulators

Big improvement on $v_2$ measurements possible
Energy scan actually started year 1

2001: 19.6 GeV Au+Au

- Total recorded events = 175466
- Events with good vertex = 42412
- 10% centrality events = 5106

D. Cebra QM2008

Sufficient data to extract ratios, flow velocity, HBT radii, $v_2$

All data fit into systematics
2008 low energy beam test

Again injecting and colliding \( \text{Au+Au} \sqrt{s_{NN}} = 9.2 \text{ GeV} \)

- Setup and experimental DAQ problems with new harmonic number \( h=366 \) solved.
- Stable running with collisions at STAR ⇒ Data!!
  - Couldn’t cog simultaneously at PHENIX and STAR⇒limited data :-(
  - This problem will be fixed in the future by choosing a slightly different energy

Short test at Injecting Au+Au @ \( \sqrt{s_{NN}} = 5 \text{ GeV} \)

- Interrupted by power supply problems but did allow study of some beam characteristics.
- Additional important work needs to be done in Run 9.
Luminosity is the key issue

Determined collision rate for 2008 9 GeV Au+Au test to be ~1Hz.

Rate can be increased by:

- factor 2 by adding more bunches - only 56 used for tests (max 120).
- factor 3-6 by operating with higher charge in bunches.
- factor few by running in continuous injection mode
- electron cooling in RHIC (?)

Expect to reach $\gamma^3$ rate even at lowest energies
Collisions Au+Au $\sqrt{s_{\text{NN}}} = 9$ GeV

From 2 days of running:
- 203395 triggers
- ~3500 good events
  (good ≡ primary vertex along beamline and within acceptance)

Still learning about trigger:
Some events were empty - trigger thresholds too low (shouldn’t happen again)
Collisions $\text{Au+Au} \sqrt{s_{NN}} = 9 \text{ GeV}$

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Unambiguous beam+beam events

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What about other bad triggers?

Investigated primary vertex location:

They are “real” collisions.

- Au+Au collisions
- Au+Beampipe collisions

Vertex X

Vertex Y

R. Reed
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Can see the change in beampipe material and thickness

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Can see the change in beampipe material and thickness

Since event rate so low plan to leave trigger as is and filter offline

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Helen Caines - INT QCD Critical Point - August 2008
Au+Au $\sqrt{s_{NN}}$=9 GeV

Clean PID for $\pi$, K, p + anti-particles

All strange particles up to $\Lambda$

Raw Yield 0.018/event

Invariant mass ($p\pi$) [GeV/c$^2$]
Au+Au $\sqrt{s_{NN}}=9$ GeV

Uncorrected charged particle mid-rapidity $p_T$ spectra out to $\sim4$ GeV/c.  
(Not corrected. Can’t extract physics yet)
$\mu_B/T$ trajectories and the Critical Point

$\mu_B/T (\bar{p}/p)$:
- Increases monotonically for cross-over/1\textsuperscript{st} order
- Decreases for C.P.
- If hadron emission occurs over a finite range in $T$ see measurable effect on ratio
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- Sampling in \( y_T \) preferentially selects on emission time.

- High \( y_T \rightarrow \) early emission
\( \frac{\bar{s}}{\bar{q}} \) production

Hadron Gas models cannot reproduce this peak/large ratio

Is this the same physics?

Anti-baryon annihilation?

Hadron Gas models cannot reproduce this peak/large ratio
Helen Caines - INT QCD Critical Point - August 2008

Hadron Gas models cannot reproduce this peak/large ratio

1 Million events gives few thousand $\bar{\Lambda}$ reconstructed at lowest $\sqrt{s}$

We can investigate in detail and fill in the gap at higher energies
Inverse slopes of $K^+ p_T$ spectra

There is also an apparent plateau in $T(K^+)$ around the same $\sqrt{s}$.

How far does this plateau extend?

Again STAR will fill in the gap.
K/$\pi$ fluctuations

Current STAR results consistent with NA49 at $\sqrt{s_{NN}} \sim 20$ GeV.

At higher energies results consistent with $\gamma_q = 1.6$ (from fit) but not with equilibrium scenario ($\gamma_q = 1$)

Georgio Torrieri; nucl-th/0702062(2007)

The fluctuations scale with $dN/d\eta$ rather than energy or system size.

At lower $dN/d\eta$:
HIJING - too high
AMPT (HIJING+rescattering) - good agreement

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Challenges for $K/\pi$ fluctuation measures

Need to measure ALL $K$ and $\pi$

Issue 1:

- decays: $K^+ \rightarrow \mu^+ \nu_\mu$ ($c\tau = 3.7$ m)
  \[ \Rightarrow \text{low tracking efficiency} \]

- PID cuts reduce efficiency further
  \[ \Rightarrow \text{reco. < 50\% of all kaons} \]
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**Issue 2:**

$z = \ln\{dE/dx\} - \ln\{\text{Bethe-Bloch}\}$

Misidentification using TPC $dE/dx$

$\pi \leftrightarrow K$, $\pi \rightarrow e$ identified as $K$.
$K/\pi \rightarrow (K+1)/(\pi-1)$ or
$(K-1)/(\pi+1)$

$K/\pi$ fluctuations distorted
- 0.5% swapping: width $\downarrow 5\%$
- signal is only 4%!
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ToF is essential
K/π measure with ToF

With ToF can improve:
- momentum range
- purity
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Au+Au 100k central $\sqrt{s_{NN}}=8.77$ GeV statistical errors:
- without ToF $\approx \pm 11\%$ (relative)
- with ToF $\approx \pm 5\%$ (relative)
Understanding the origin of $v_2$

- $v_2$ grows with $\sqrt{s}$
- $v_2/\varepsilon$ appears to reach hydro limit at top $\sqrt{s}$
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- Evidence of softening of EoS due to phase transition?
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Energy dependence gives important guidance to theoretical interpretation
Upper limit challenges models of initial eccentricity fluctuations
Nucleon Glauber - no room for other fluctuations/correlations
Data calls for different model of initial eccentricity (e.g. CGC)
$\sigma^2 / \langle v^2 \rangle$

Near critical point fluctuations should be big - need calculations

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Data calls for different model of initial eccentricity (e.g. CGC)

Measurement relies on central limit theorem, need acceptance - i.e. STAR
“Collapse” of proton $v_2$

Signature of phase transition (Stöcker, E. Shuryak)?

Problem: Different analysis different results. $v_2\{4\} \neq v_2\{2\} \neq v_{2\text{stand}}$

Results need to be reconfirmed.

Is difference due to non-flow and fluctuations or phase transitions?

Can help determine answer by measuring both $v_2$ and fluctuations in same detector
\( v_2 \) and de-confinement

- At low \( m_T - m_0 \) PID \( v_2 \) follows hydro. type scaling

- \( \phi \) and \( \Omega \) have large \( v_2 \) but small hadronic scattering cross-sections (not shown)
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- Evidence of quark degrees of freedom in early stages?
v\textsubscript{2} and de-confinement

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- At intermediate p\textsubscript{T} v\textsubscript{2} displays constituent quark scaling

- Evidence of quark degrees of freedom in early stages?

Do these effects turn off at lower energies?
- sufficient stats. with several million events (few days at 9 GeV)

Can we show this is not a hadronic effect?
Statistical error on $v_2$ with PID

Assuming 5 M Au+Au events at $\sqrt{s}=12.3$ GeV

0-43.5% measurements up to $(m_T-m)/n_q \sim 2$ GeV is promising.

Systematic errors will dominate
Parity violation

In non-central collisions:
large orbital angular momentum
(magnetic fields)+ deconfined phase
⇒ strong P violating domains

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(Voloshin PRC 70 (2004) 057901)

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

the asymmetry

\[\langle a_{\pm} \rangle = 0 \text{ so measure } \langle a_\alpha a_\beta \rangle\]
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Possible signal in non-central event

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

S. Voloshin QM2008

Under investigation
Parity violation

In non-central collisions:
large orbital angular momentum (magnetic fields)+ deconfined phase ⇒ strong P violating domains


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Possible signal in non-central event
\[ \langle a_\alpha a_\beta \rangle - \text{ P-even so may contain other effects} \]
Under investigation

B-field+deconfinement → strong threshold effect → BES
Non-statistical fluctuations are observed for all energies. They increase with $\sqrt{s}$ and are larger than predicted by HIJING. The fluctuation*\(dN/d\eta\) plateau for more central events.
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The fluctuation $\frac{dN/d\eta}{dN/d\eta}$ plateau for more central events.

When scaled by $\langle p_T \rangle$ the energy dependence is removed but still higher than HIJING.
Challenges for $\langle p_T \rangle$ fluctuation measures

Acceptance

Elliptic flow can enhance apparent fluctuations

Need $2\pi$ coverage
More advanced tools

Differential analyses have been developed at RHIC fluctuations

Allow a more detailed investigation of fluctuation measures

Rely heavily on acceptance and statistics
The $\langle p_T \rangle$ fluctuations appear to rise a log($\sqrt{s_{NN}}$).

Need to fill in the gap to check.
\[ \langle p_T \rangle \text{ fluctuations - a closer look} \]

The \( \langle p_T \rangle \) fluctuations appear to rise as a function of \( \log(\sqrt{s_{NN}}) \).

Need to fill in the gap to check.

Increase in fluctuations as a function of centrality are concentrated in a near-side peak.

These correlations, elongated in \( \eta_\Delta \) but focused in \( \theta_\Delta \), are identified as mini-jets.

$\langle p_T \rangle$ fluctuations - a closer look

Increase in fluctuations as a function of centrality are concentrated in a near-side peak.

These correlations, elongated in $\eta_\Delta$ but focused in $\theta_\Delta$, are identified as mini-jets.

Amplitude of peak follows $N_{\text{bin}}$ scaling except most central events.

Pair correlations in p+p

Pair densities $\rho(\eta_1-\eta_2, \phi_1-\phi_2)$ for all possible pairs in same and mixed events.

Correlation measure is:

$$\frac{\rho_{\text{same}} - \rho_{\text{mixed}}}{\sqrt{\rho_{\text{mixed}}}} \equiv \frac{\Delta \rho}{\sqrt{\rho_{\text{ref}}}} \propto \frac{\# \text{ correlated pairs}}{\text{particle}}$$

- Longitudinal fragmentation
  - 1D gaussian
- HBT and e+e-
  - 2D exponential
- Minijet Peak
  - 2D gaussian
- Away-side
  - -cos(\phi)
Au+Au 200 GeV pair correlations

Fit to p+p function + $\cos(2\phi_{\Delta})$ (quadrupole term (aka flow))

Fits result in ~zero residuals

STAR Preliminary

M. Daugherty QM2008
A low $p_T$ ridge

Same-side peak

83-94%

Little shape change from peripheral to 55% centrality

55-65%

Large change within ~10% centrality

46-55%

Smaller change from transition to most central

0-5%

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Sharp transition in peak and width at $\rho \sim 2.5$ for both 62 and 200 GeV

What causes this rapid transition? (not observed in $p_T$ correlations)

Transverse particle density

$$\tilde{\rho} = \frac{3}{2} \frac{dN_{ch}}{d\eta} / S$$

M. Daugherty QM2008
$\eta/s$ and the Critical Point

- Near critical temperature $\eta/s$ is a minimum.
- Need to sit near $T_C$ while system evolves for this $\eta/s$ to dominate.
- If critical point acts as an attractor low $\eta/s$ values may indicate we are close.

What is $T$?

Current estimates from 200 GeV data are near lower bound

R. Lacey et al. PRL 98 (2007) 092301
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Estimates possible with BES:

Elliptic flow

$$ \frac{\eta}{s} \sim T \lambda_f c_s $$

R. Lacey et al. PRL 98 (2007) 092301

$p_T$ fluctuations

$$ \frac{\eta}{s} \sim \nu T $$

S. Gavin, M. Abdel-Aziz PRL 97 (2006) 16302

Current estimates from 200 GeV data are near lower bound

R. Lacey et al. PRL 98 (2007) 092301
STAR’s beam energy scan proposal

First scan aiming to cover wider range $\sqrt{s_{NN}}$ from 6-40 GeV

- Lower energies will focus on phase transition properties
- Higher energies will focus on disappearance of the partonic medium.
- Also beam development at 5 GeV, expanding on work in Run 9.

Lower energies will be as close as possible to SPS while allowing, where possible, for collisions at both experiments

- Energy choices can be modified if theoretical guidance appears.
### STAR’s current energy scan proposal

14 weeks physics + 1 week commissioning

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Current “best guess” for optimization of run time and physics
Summary

The most exciting discovery potential of the beam energy scan is locating the critical point or 1\textsuperscript{st} order phase transition

- $K/\pi, \langle p_T \rangle, v_2$ (critical point fluctuations)
- Pair correlations
- Energy dependence of flow characteristics ($v_1$ and $v_2$)

Guaranteed results:

- Narrowing of region where exotic medium effects (dis)appear
  - Sizeable $v_2$ of $\phi$ and $\Omega$
  - $N_q$ scaling of $v_2$
  - Parity violation
- Detailed systematics help close the open theory issues referenced in the RHIC “white papers”
- Significant extension and improvement over existing SPS

Need more detailed predictions from theory - this workshop!

STAR and RHIC are ready for a focused low energy run ASAP
A second low energy run

After analysis of first data set we propose a second scan focused on specific energies

- Energies and physics topics will be chosen to explore in more depth the most interesting regions found in the first scan.
- Luminosity upgrades will be useful at the lowest energies unless first scan indicates those regions are not interesting.

Guaranteed results:
To be predicted once data from the first scan is analyzed.
Low energy beam tests

2006: One day of machine studies with protons

- Center of mass energy - 22 GeV
  - Magnet settings appropriate for Au+Au $\sqrt{s} \sim 9$ GeV equivalent to fixed target with $\sim 40$ AGeV beam.
- Results were very encouraging!

2007: Injecting and colliding Au+Au @ $\sqrt{s_{NN}} = 9.2$ GeV

- Running below design injection energy for the first time
- Same magnetic rigidity as 2006 low energy proton test
- Overall, the run was a major success!
  - For the first time at RHIC, the RF frequency limits could not accommodate 360 RF buckets.

Both tests successful for accelerator and STAR
Analysis of Au+Au $\sqrt{s_{NN}}=9$ GeV data

Preliminary (during run) conclusions very optimistic

**BUT:** in 2500 events on tape fewer than 1% vertices reconstructed

During 2008 d+Au run a contribution to the BBC coincidence rate from **beam-background coincidence** was identified:
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During 2008 d+Au run a contribution to the BBC coincidence rate from beam-background coincidence was identified:

- Background explained almost entire event rate during the low energy test
- Actual event rate was unknown and could be very low
- Time for physics program may therefore have been underestimated
- BBC alone is not a good measure of luminosity for the low energy run

Need another test run - try BBC&&CTB/TOF trigger
Low $p_T$ ridge prediction

Low $p_T$ caused by Glasma flux tube radiation + flow?
QGP boundary may be mapped by “turn on” of this ridge

Saturation physics motivated
onset related to energy density

- ridge gone below $\sqrt{s_{NN}} \approx 35$ GeV

Collisional Low Density Limit
onset related to particle density

- ridge gone below $\sqrt{s_{NN}} \approx 13$ GeV

A. Dumitru et al. arXiv:0804.3858
Event characteristics

The primary vertex location is spread over a large range in $z$. 

![Graph showing vertex distribution](image)

**Au+Au 9.2 GeV**

$V_{\text{radius}} < 2 \text{ cm}$

**Vertex Z distribution**

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<th>$h_{Vz}$</th>
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<td>Entries</td>
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<td>Mean</td>
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<td>RMS</td>
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</table>
Event characteristics

- We obtain a reasonable min-bias distribution
- Need to investigate low multiplicity trigger/vertex finding efficiency
  - Don’t get 100% of cross-section?

The primary vertex location is spread over a large range in z.
What energies to pick?

- Critical point estimates
  - Chemical Freeze-out
  - Heavy ion data
  - RHIC full range

- RHIC Low Energy Scan: $5.0 < \sqrt{s_{NN}} < 30$ GeV
- Fair Energy Range: $5.5 < \sqrt{s_{NN}} < 8.2$ GeV

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

peak in $\langle K_\perp^2 \rangle$

proton $v_2 \rightarrow 0$