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_{ch}, T_{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 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

![Diagram with CP and focusing](image_url)
If there, a critical point doesn’t hide…

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 1\textsuperscript{st} 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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<th>BBC Inner</th>
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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: (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)
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 $1.5 \times N_{\text{part}}/2$
- 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 \( \text{Au}+\text{Au} \sqrt{s_{\text{NN}}} = 9.2 \text{ GeV} \)

- 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 \( \text{Au}+\text{Au} \at \sqrt{s_{\text{NN}}} = 5 \text{ GeV} \)

- 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

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

Determined collision rate for 2008 9 GeV Au+Au test to be $\sim$1Hz.
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)

Still learning about trigger:

Some events were empty - trigger thresholds too low (shouldn’t happen again)
Collisions Au+Au $\sqrt{s_{NN}} = 9$ 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
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- Au+Au collisions
- Au+Beampipe collisions
- Au+Be collisions

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
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

All strange particles up to $\Lambda$

Uncorrected charged particle mid-rapidity $p_T$ spectra out to $\sim 4$ 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/1st order
- Decreases for C.P.

- If hadron emission occurs over a finite range in $T$ see measurable effect on ratio
µ_B/T trajectories and the Critical Point

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• Increases monotonically for cross-over/1st order
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• If hadron emission occurs over a finite range in T see measurable effect on ratio

• Sampling in y_T preferentially selects on emission time.

• High y_T → early emission
Hadron Gas models cannot reproduce this peak/large ratio prediction for the midrapidity and 20 collisions at 20 GeV. The data at top SPS energy are also shown. AGS and higher energies at the RHIC, respectively. At SPS energies (NA49) together with the data for lower energies at the range are not yet available in the literature. Since both model, which takes into account antibaryon absorption, agrees and RHIC. The AGS experiments reported a Table IV and plotted in Fig. 8, together with those from AGS about 3–3.5 for central Au + Pb collisions at SPS energies. Errors are statistical. Preliminary results for Pb collisions at SPS energies. The measured values of the TABLE IV. The Pb yields at 20 GeV are used. Statistical Model: Cleymans & Redlich Phys. Rev. Lett, 81 (1998)

\[ \frac{\bar{\Lambda}}{\bar{p}} \approx \frac{\bar{s}}{\bar{q}} \approx \frac{K^+}{\pi^+} \]

Is this the same physics? Anti-baryon annihilation? Hadron Gas models cannot reproduce this peak/large ratio.
$\bar{s}/q$ production

Hadron Gas models cannot reproduce this peak/large ratio

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

Is this the same physics?

Anti-baryon annihilation?

We can investigate in detail and fill in the gap at higher energies
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/π 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
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)
  - $\Rightarrow$ low tracking efficiency

- PID cuts reduce efficiency further
  - $\Rightarrow$ reco. $< 50\%$ of all kaons
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**Issue 2:**

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 ↓5%
- signal is only 4%!
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ToF is essential
**K/\pi** measure with ToF

With ToF can improve:

- momentum range
- purity

\[
\frac{(K^+ + K^-)}{(\pi^+ + \pi^-)}
\]

\( \sqrt{s_{NN}} = 8.77 \text{ GeV} \)
**K/π measure with ToF**

With ToF can improve:
- momentum range
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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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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)
$v_2$ fluctuations

Near critical point fluctuations should be big - need calculations

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Nucleon Glauber - no room for other fluctuations/correlations
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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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?
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
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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

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

- P-even so may contain other effects

Under investigation
Parity violation

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B-field + deconfinement → strong threshold effect → BES

Helen Caines - INT QCD Critical Point - August 2008
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 $dN/d\eta$ 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

Collision overlap zone

Elliptic flow can enhance apparent fluctuations

Need 2$\pi$ coverage

STAR Preliminary

$0.5N_{\text{part}} \langle \Delta p_T \rangle^2 (\text{MeV/c})^2$

Number of participants $N_{\text{part}}$

Random
In-plane
Out-of-plane
More advanced tools

Differential analyses have been developed at RHIC

fluctuations

scale = full acceptance

variance

excess

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

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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

〈p_T〉 fluctuations - a closer look

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

These correlations, elongated in η_Δ but focused in θ_Δ, are identified as mini-jets

Amplitude of peak follows N_{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:

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

- Longitudinal fragmentation: 1D gaussian
- HBT and e+e-: 2D exponential
- Minijet Peak: 2D gaussian
- Away-side: -cos($\phi$)

M. Daugherty QM2008

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Au+Au 200 GeV pair correlations

Fit to p+p function + cos(2φΔ) (quadrupole term (aka flow))

Fits result in ~zero residuals

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%**: 

M. Daugherty QM2008
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- 46-55%
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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
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
\( \eta/s \) and the Critical Point

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Current estimates from 200 GeV data are near lower bound.

What is \( T \)?

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
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 1st 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:
Analysis of Au+Au $\sqrt{s_{NN}}=9$ GeV data

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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

A. Dumitru et al. arXiv:0804.3858

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
Event characteristics

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

![Graph showing the vertex $Z$ distribution for Au+Au 9.2 GeV events with $V_{radius} < 2$ cm. The distribution is spread over a large range in $V_z$ (cm). The table shows the number of events, with entries of 2076, mean of -4.162, and RMS of 40.82.]

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

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