PHENIX Results from the RHIC Beam Energy Scan Program

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Search for the QCD Critical Point: Experimental Strategy

By systematically varying the RHIC beam energy, heavy ion collisions will be able to probe different regions of the QCD phase diagram.
The RHIC Beam Energy Scan Program: Overview

Species: Gold + Gold

Collision Energies $[\sqrt{s_{NN}}]$:
- 200 GeV (2010), 130 GeV, 62.4 GeV (2010),
- 11 GeV (2010, STAR only)

Species: Copper + Copper

Collision Energies $[\sqrt{s_{NN}}]$:
- 200 GeV, 62.4 GeV, 22 GeV

Species: Deuteron + Gold

Collision Energies $[\sqrt{s_{NN}}]$:
- 200 GeV

Species: Proton + Proton

Collision Energies $[\sqrt{s_{NN}}]$:
- 500 GeV, 200 GeV, 62.4 GeV
PHENIX RHIC Beam Scan Results

• Energy Loss: $\pi^0 R_{AA}$, $\phi R_{AA}$

• $J/\Psi$: Yield, $R_{CP}$

• Flow: $v_2$, $v_3$, $v_4$, participant quark scaling

• Critical point signatures
Searching for the Onset of Deconfinement: Energy Loss Measurements

\[ R_{AA}(p_T) = \frac{d^2 N^{AA} / dp_T d}{\langle N_{binary} \rangle d^2 N^{pp} / dp_T d} \]
PHENIX Energy Loss Measurements in the Beam Energy Scan: $\pi^0$

In Au+Au at 200 GeV:

- Strong suppression (x5) in central Au+Au collisions
- No suppression in peripheral Au+Au collisions
- No suppression (Cronin enhancement) in control d+Au collisions

Convincing evidence for **final state partonic** interactions $\rightarrow$ emergence of sQGP

From the Cu+Cu energy scan:

- Significant suppression at $\sqrt{s_{\text{NN}}} = 200$ and 62.4 GeV
- Moderate enhancement at $\sqrt{s_{\text{NN}}} = 22.4$ GeV

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π⁰ invariant yields:
Au+Au Collisions at 62.4 GeV

At lower $\sqrt{s}$ the contribution from some processes are larger:
- Running $a(Q^2)$
- PDF evolution
- $k_T$ smearing
- Higher-twist phenomena
\( \pi^0 \) invariant yields:

**Au+Au Collisions at 39 GeV**

The minimum bias spectra are fit with a power-law shape function for \( p_T > 4 \) GeV/c:

\[ f(x) = \frac{A}{(p_T)^n}, \]

\[ n_{200\text{GeV}} = 8.1 \pm 0.03 \]

\[ n_{62\text{GeV}} = 10.9 \pm 0.03 \]

\[ n_{39\text{GeV}} = 12.1 \pm 0.1 \]
Nuclear Modification Factor

- For the $R_{AA}$ measurement, obtaining a $p+p$ reference from the same experiment is vital. External references increase systematic errors.
  - 62.4 GeV $p+p$ data is available from PHENIX, however only up to $p_T < 7$ GeV/c (heavy-ion up to 10 GeV/c)
  - 39.0 GeV $p+p$ data is not yet available from PHENIX, but it is on our to-do list
    - Because of that we used data from a fixed target $p+p$ experiment at the Tevatron, E0706 ($\sqrt{s} = 39$ GeV, PRD68: 052001, 2003).
62.4 GeV p+p reference extrapolation

- Data from PHENIX for p+p collisions are available up to $p_T < 7$ GeV/c
- To extrapolate to higher $p_T$ points, a power-law function was used:
  - The limit of the fits is vital, contributing to the systematic errors.
- The systematic uncertainty is calculated from the errors of the power-law fit
- It agrees well with the CCOR data (ISR) in $p_T$ 7–10 GeV/c region
39 GeV $p+p$ reference

$p+p$ data are measured only in the fixed-target experiment E0706 at the Tevatron at a beam energy of 800 GeV. (Phys.Rev.D68:052001,2003)

The E0706 has a different rapidity acceptance: $-1.0 < y < 0.5$ (PHENIX $|y|<0.35$).

Acceptance correction based on a PYTHIA8 simulation.

The systematic uncertainty of the correction function is calculated based on the data to PYTHIA8 comparison.
\( \pi^0 R_{AA} \) in Au+Au at 39 and 62 GeV

- Still observe a strong suppression (factor of 2) in the most central \( \sqrt{s_{NN}} = 39 \) GeV collisions.
- \( R_{AA} \) from \( \sqrt{s_{NN}} = 62 \) GeV data is comparable with the \( R_{AA} \) from \( \sqrt{s_{NN}} = 200 \) GeV for \( p_T > 6 \) GeV/c.
- Peripheral \( \sqrt{s_{NN}} = 62 \) and 200 GeV data show suppression, but the \( \sqrt{s_{NN}} = 39 \) GeV does not.
$R_{AA}$ : Centrality Dependence

At higher $p_T$ ranges, the 62 GeV points are comparable to the 200 GeV points in all centralities.

$R_{AA}$ evolution in Au+Au at $\sqrt{s_{NN}} = 39, 62$ and 200 GeV:

- 62–200 GeV shows a large suppression
- 39 GeV shows suppression only in $N_{part}>100$
Energy and System-Dependence of $\pi^0 R_{AA}$

Total energy available of the collision:

$$E_{AA} \left( \frac{N_{\text{part}} \times \sqrt{s_{NN}}}{2} \right)$$

System size:
- Circles: Cu+Cu
- Squares: Au+Au

The $R_{AA}$ values seem to have the same trend.

SPS, max reach: $2 \times 208(\text{Pb}) \times 17.3 \text{ GeV} \left(\sqrt{s_{NN}}\right)/2 = 3598.4 \text{ GeV}$

$E_{AA} = 2 - 5 \text{ TeV}$

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$\phi \to K^+K^-$ Spectra in 62.4 GeV Au+Au Collisions
The $\phi$ is suppressed in central 200 GeV Au+Au collisions.

The $R_{AA}$ of the $\phi$ lies between that of the proton and the $\pi^0$. 

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\( \phi \rightarrow K^+K^- R_{AA} \) in 62.4 GeV Au+Au Collisions

Within the current precision, no suppression at 62.4 GeV. Similar to the 200 GeV results, the \( R_{AA} \) of the \( \phi \) lies between that of the proton and the \( \pi^0 \).
Searching for the Onset of Deconfinement: $J/\Psi$ Measurements
In 2010, PHENIX collected 700M (250M) MB events from 62.4 GeV (39 GeV) Au+Au collision.

Rapidity 1.2 < |y| < 2.2
PHENIX does not yet have a p+p reference at 62 and 39 GeV. Lacking a reference, $R_{CP}$ can still give us insight about the suppression level. The suppression is at a similar level at all energies.
PHENIX Dilepton Expectations at 39 GeV

How does the dilepton excess and $\rho$ modification at SPS evolve into the large low-mass excess at RHIC?

- 200M simulated events in ±20cm vertex
- If excess is the same at 39 GeV as 200, expect a 6 $\sigma$ result

Black: simulation with same enhancement as at 200 GeV
Blue: no enhancement
Searching for the onset of deconfinement: Flow Measurements

\[ v_1 = \frac{\langle p_x \rangle}{p_T} \quad \text{- directed flow} \]

\[ v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{p_x^2 + p_y^2} \quad \text{- elliptic flow} \]

\[ v_2 > 0: \text{in-plane emission of particles} \]

\[ v_2 < 0: \text{squeeze-out perpendicular to reaction plane.} \]
Elliptic Flow at 62 and 39 GeV: $\pi^0$

There is little change in the magnitude of $v_2$ from 39 GeV to 200 GeV.
$v_2\{\Phi_2\}, v_3\{\Phi_3\}, v_4\{\Phi_4\}$ at 62 GeV Au+Au

charged particle $v_n$ : $|\eta|<0.35$

reaction plane $\Phi_n$ : $|\eta|=1.0\sim2.8$
\( v_2, v_3, v_4 \) as a function of \( \sqrt{s_{NN}} \)

\( v_2, v_3, v_4 \) are independent of \( \sqrt{s_{NN}} \) for 39, 62.4, 200 GeV
This implies that the system demonstrates similar hydrodynamic properties from 39 GeV to 2.76 TeV
The magnitude of $v_2$ at 7.7 GeV is significantly lower than the magnitudes at 39, 62 and 200 GeV
Saturation of $v_2$ with beam energy

$v_2$ saturates for a given $p_T$ around or below 39 GeV

$\langle v_2 \rangle$ still increases mainly because of the $\langle p_T \rangle$ rise.

Almost perfect fluidity from 39 GeV to 2.76 TeV
Identified hadron $v_2$ in 62.4 GeV Au+Au Collisions

Partonic collective flow is observed down to 62 GeV and ...
Identified hadron $v_2$ in 39 GeV Au+Au Collisions

Partonic collective flow is observed down to 39 GeV
Flow Summary

- $v_2$, $v_3$ and $v_4$ are measured in 39, 62 and 200 GeV. The magnitudes are similar.
- $v_2$ of pion, kaon, and (anti)proton show quark number scaling down to 39 GeV.
- $v_2$ saturates in intermediate $p_T$.

These observations suggest similar initial geometry fluctuations and dynamic evolution of nuclear matter above 39 GeV.

Data taken at 19.6 and 27 GeV this year will help us fill in the “gap” in the excitation function.

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Searching for Signatures of the Critical Point: Fluctuations, Correlations
Near the critical point, the multiplicity fluctuations should exceed the superposition model expectation → No significant evidence for critical behavior is observed. Low energy results are being prepared.

\[ \omega_{\text{ch,dyn}} = \text{variance/mean, corrected for impact parameter fluctuations}. \]
Searching for the Critical Point with HBT $Q_{\text{inv}}$ Correlations

T. Csorgo, S. Hegyi, T. Novák, W.A. Zajc,

- This technique proposes to search for variations in the exponent $\eta$.
- The exponent $\eta$ can be extracted by fitting HBT $Q_{\text{inv}}$ correlations with a Levy function:
  \[ C(Q_{\text{inv}}) = \lambda \exp(-|Rq/hc|^{-\alpha}) \]

  $\alpha = \text{Levy index of stability} = \eta$
  $\alpha = 2$ for Gaussian sources
  $\alpha = 1$ for Lorentzian sources

- Measure $\alpha$ as a function of collision energy and look for a change from Gaussian–like sources to a source corresponding to the expectation from the universality class of QCD.

$\alpha(\text{Lévy}) = \eta(3d \text{ Ising}) = 0.50 \pm 0.05$
Like–Sign Pair Azimuthal Correlations

0.2 < \( p_{T,1} < 0.4 \) GeV/c, 0.2 < \( p_{T,2} < 0.4 \) GeV/c, \(|\Delta \text{ pseudorapidity}|<0.1\)

\[ C(\Delta \phi) = \frac{dN/d\phi_{\text{data}}}{dN/d\phi_{\text{mixed}}} \times \frac{N_{\text{events,mixed}}}{N_{\text{events,data}}} \]

Assuming that QCD belongs in the same universality class as the (d=3) 3–D Ising model, the expected value of \( \eta \) is 0.5 (Reiger, Phys. Rev. B52 (1995) 6659).

\[ C(\Delta \phi) \propto \Delta \phi^{-(1+\eta)} \]

- The power law function fits the data well for all species and centralities.

The exponent $\eta$ is independent of species, centrality, and collision energy. The value of $\eta$ is inconsistent with the $d=3$ expectation at the critical point.
Summary and Outlook

- $R_{AA}$:
  - $R_{AA}$ for $p_T > 6$ GeV is comparable between 200 and 62 GeV.
  - $R_{AA}$ at 39 GeV still shows a large suppression.
  - No significant suppression is observed for the $\phi$ at 62 GeV.
  - Initial measurements show suppression of J/$\Psi$ at 39 and 62 GeV.

- Flow:
  - $v_2$ saturates at intermediate $p_T$ at 39 and 62 GeV.
  - Quark number scaling holds at 39 and 62 GeV.
  - $v_2$ at 7.7 GeV is significantly lower than $v_2$ at 39 and 62 GeV.

- Outlook:
  - Many measurements are being analyzed, including:
    - multiplicity, net charge, and transverse momentum fluctuations
    - local parity violation
    - identified particle spectra
    - 2–particle correlations
    - dilepton spectra

- Stay tuned for much more!
PHENIX Detector

Central Arm Tracking
   Drift Chamber
   Pad Chambers
   Time Expansion Chamb.

Muon Arm Tracking
   Muon Tracker

Calorimetry
   PbGI
   PbSc
   MPC

Particle Id
   Muon Identifier
   RICH, HBD
   TOF E & W
   Aerogel
   TEC

Global Detectors
   BBC
   ZDC/SMD Local Polarim.
   Forward Hadron Calo.
   RXNP

DAQ and Trigger System
   Online Calib. & Production

VTX
   Replaces HBD

Muon Trigger: $\mu$Tr FEE
RPC station 3
PHENIX 39 GeV Au+Au Event Displays
PHENIX 7.7 GeV Au+Au Event Displays
Triggering at Low Energy

The problem:

The placement of the trigger detectors (BBCs) are not optimized for low energy running. They have a reduced acceptance, especially below RHIC energies of ~20 GeV.

Fermi motion to the rescue!

At low energies, Fermi motion is enough to bring nucleons back into the BBC acceptance.
PHENIX Trigger Performance at 7.7 GeV

Tight timing cut on BBC North vs. South

URQMD normalized to match real data integral for PC1 hits > 40.

URQMD not matched to $z$ distribution in real data.

Estimate that the trigger fires on 77% of the cross section.

No indication of deviation of low multiplicity events from background.
Comparison with recent SPS $R_{AA}$

- In previous experiment at WA98 we see only (PRL 100 (2008), 242301) suppression at “ultra”–central (0–1%) collisions of Pb+Pb.
- The $x_T$ is overlapping between the SPS and RHIC intervals.
- The “onset” of the energy loss is dependent on system size and collision energy.
- The energy loss is present in lower energies also.

The magenta closed circles are the most comparable with the PHENIX results, as they have

The “onset” of the suppression depends on collision energy and centrality or system size (and $p_T$)
Energy dependence of CNMs

$R_G$ for $J/\psi$ production at RHIC

A systematic analysis at $y\sim0$ using EKS98 + $\sigma_{\text{breakup}}$ showed a clear collision energy dependence of $\sigma_{\text{breakup}}$.

JHEP 0902:014 (2009)

- Proper geometry dependence need to be included.
- Reduce uncertainties by measuring $d+Au$ at the same energy.
$E_{AA}$ dependence on $p_T$

In higher $p_T$ the scaling does not work.

shadowing? Bjorken energy density?
Lévy fits to $q_{\text{inv}}$ in Central 200 GeV Au+Au
How big is the target?

From a hydrodynamics calculation.

For a given chemical freeze–out point, 3 isentropic trajectories \((s/n_B=\text{constant})\) are shown.

The presence of the critical point can deform the trajectories describing the evolution of the expanding fireball in the \((T,\mu_B)\) phase diagram.

A large region can be affected, so we do not need to hit the critical point precisely.
Elliptic Flow: Excitation Function

There is a transition from squeeze-out flow to in-plane flow between AGS and SPS energies.
Statistical Model Fits

Extracted $T$ & $\mu_B$ values

For $\sqrt{s} \approx 10$ GeV, chemical freeze-out very close to phase boundary

Statistical Model Results

Results from different beam energies
Analysis of particle yields with statistical models
Freeze–out points reach QGP phase boundary at top SPS energies
J/ψ: analyzed 25% of 62 GeV statistics

Recombination (e.g. Rapp et al.)
J/ψ yield at 200 GeV is dominantly from recombination

Predict suppression greater at 62 GeV
J/ψ yield down by 1/3
Recombination down 1/10

600 M min. bias events → 500 J/ψ .:. measure J/ψ suppression

Key test of recombination!

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