Selected Results from STAR Beam Energy Scan Program

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(for the STAR Collaboration)
1) Turn-off of sQGP signatures

2) Search for the signals of phase boundary

3) Search for the QCD critical point

Triggering required effort, but was a solvable problem. Geometric acceptance remains the same, track density gets lower. Detector performance generally improves at lower energies.
STAR TPC - Uniform Acceptance over all RHIC Energies

Au+Au at 7.7 GeV

Au+Au at 39 GeV

Au+Au at 200 GeV

Crucial for all analyses
Selected Results
Suppression of Charged Hadrons ...

\[ R_{CP} = \frac{d^2Ndp_T d\eta / \langle N_{bin} \rangle(central)}{d^2Ndp_T d\eta / \langle N_{bin} \rangle(peripheral)} \]
... and its Disappearance

\( R_{CP} \geq 1 \) at lower energies - Cronin effect?
Enhancement vs. QGP suppression

Motivation: Agreement between the simulation and the data at low beam energies and its break down at higher energies could help to find the energy at which QGP becomes dominant.

- In HIJING (jet quenching off) $R_{CP}$ at lower energies is enhanced, but there is no quantitative agreement with charged hadron $R_{CP}$ from data.
- No suppression at higher energies observed, as expected (quenching was turned off).
Proton $R_{CP}$ > pion $R_{CP}$, similar to d+Au at $\sqrt{s_{NN}}$=200 GeV

$\Rightarrow$ Pions may serve as a better gauge for jet quenching within the $p_T$ range available through particle identification.
$R_{CP}$ : Identified Particles

- Antiproton $R_{CP} < \text{pion } R_{CP}$ for $p_T < 1\text{GeV/c}$
- Pion $R_{CP}$ suppressed for $\sqrt{s_{NN}} \geq 39\text{GeV}$
Azimuthal Anisotropy

\[ \frac{dN}{d\phi} \propto \left( 1 + 2 \sum_{n=1}^{+\infty} v_n \cos[n(\phi - \Psi_r)] \right) \]

\[ v_n = \left\langle \cos(n\phi - \Psi_r) \right\rangle \]

\[ \phi = \tan^{-1}\left( \frac{p_x}{p_y} \right) \]

- Directed flow \( v_1 \) is due to the sideward motion of the particles within the reaction plane. It is sensitive to baryon transport, space-momentum correlations and QGP formation.

- Elliptic flow \( v_2 \) results from the interaction among produced particles and is directly related to transport coefficients of produced matter.
Directed Flow of $p$ and $\pi$
Directed Flow of $p$ and $\pi$: mid-central

**Proton $v_1$ slope:** changes sign from positive at 7.7 GeV to negative at 11.5 GeV and remains small negative up to $\sqrt{s_{_{NN}}}=200$ GeV.

**Pion and antiproton $v_1$ slope:** always negative.

$\Rightarrow$ For $\sqrt{s_{_{NN}}} \geq 11.5$ GeV contradicts baryon stopping picture predicting opposite slope for protons and pions.

**Net-proton $v_1$ slope:** shows double sign change. Can not be explained by URQMD model but is qualitatively consistent with a prediction of hydrodynamic model with a first order phase transition

Δν₂: ν₂(Particles) - ν₂ (Antiparticles)

The difference between particles and anti-particles is observed.
A linear increase $Δν₂ = a \times μ_B$ for all particle species for $7.7 \text{ GeV} \leq \sqrt{s_{NN}} \leq 62.4 \text{ GeV}$. ⇒ The baryon chemical potential is directly connected to the difference in ν₂ between particles and antiparticles.
\( v_2(p_T) \): Transport model comparisons

- Purely hadronic system (UrQMD) does not explain relatively large elliptic flow at these energies.
- AMPT-SM provides the best description of the data (except of protons and anti-protons @ 7.7 GeV).
- In all other cases both AMPT and UrQMD under-predict \( v_2(p_T) \).

AMPT-SM: string melting version
Baryon–meson splitting is observed when collisions energy $\geq 19.6$ GeV for both particles and the corresponding anti-particles.

For anti-particles the splitting is almost gone within errors at 11.5 GeV.

NCQ Scaling Test: particles

- Universal trend for most of particles – $n_{cq}$ scaling not broken at low energies
- $\phi$ meson $v_2$ deviates from other particles in Au+Au@$(11.5 \& 7.7)$ GeV: ~ $2\sigma$ at the highest $p_T$ data point. Needs more data to make clear conclusion.

Reduction of $v_2$ for $\phi$ meson and absence of $n_{cq}$ scaling $\Rightarrow$ during the evolution the system remains in the hadronic phase  


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NCQ Scaling Test: antiparticles

![Graph showing the scaling test results for antiparticles across different energies. The graph plots \( v_2/n_q \) versus \( (m_T - m_0)/n_q \)](STAR: Phys.Rev. C88, 014902 (2013))
Beam Energy Scan Phase- II
STAR BES Program Summary

Explore QCD Diagram

Large range of \( \mu_B \) in the phase diagram !!!
STAR BES Program Summary

Large range of $\mu_B$ in the phase diagram !!!
Summary

★ STAR results from BES program covering large $\mu_B$ range provide important constraint on QCD phase diagram:

- $R_{CP}$ of unidentified charged hadrons turns-off near 39 GeV.
- Identified $R_{CP}$ is qualitatively similar and suggests that pions are less affected by (still unquantified) sources of enhancement.
- Proton $v_1$ slope changes sign between 7.7 GeV and 11.5 GeV.
- Net-proton $v_1$ slope shows double sign change between 7.7 GeV and 39 GeV.
- Particles-antiparticles $v_2$ difference increases with decreasing $\sqrt{s_{NN}}$ and is directly connected to baryon chemical potential.
- Baryon–meson splitting is observed when collisions energy $\geq 19.6$ GeV for both particles and the corresponding anti-particles.
- ...and many other results not covered in this talk.

★ Search for the critical point continues:

- Proposed BES-II program
- Fixed target proposal to extend $\mu_B$ coverage up to 800 MeV
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Backup slides
TPC:
Detects Particles in the $|\eta|<1$ range
$\pi, K, p$ through $dE/dx$ and TOF
$K^0_s, \Lambda, \Xi, \Omega, \phi$ through invariant mass

Coverage: $0 < \phi < 2\pi$ $|\eta| < 1.0$
Uniform acceptance: All energies and particles
Since the original design of RHIC (1985), running at lower energies has been envisioned.


In 2009 the RHIC PAC approved a proposal to run a series of six energies to search for the critical point and the onset of deconfinement.

These energies were run during the 2010 and 2011 running periods.

A landmark of the QCD phase diagram
Model summary

- HIJING captures beam energy dependence of spectra.
- Jet quenching as modeled in HIJING has a greater effect on higher beam energies.
- For AMPT, lower beam energies are better matched by SM off, while SM on better captures the beam energy dependence.

⇒ Physics of hadronization shifts from coalescence to fragmentation?
NCQ Scaling Quality: particles


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