Recent STAR Heavy Ion Results

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for the STAR Collaboration
Outline:

- Introduction
- STAR detector system
- Recent results from HIC at STAR
- Summary and Outlook
Phase Diagram of Matter

The phase diagram of the water is established

- Phases (ice I-XV, liquid, vapor)
- Phase boundaries
- Phase transitions
- Triple Point (16)
- Critical Point (2)

The phase diagram of the nuclear matter is under study

- Phases
- Phase boundaries
- Phase transitions
- Triple Point
- Critical Point
The Relativistic Heavy Ion Collider

Commissioning 1999
- 3.83 km circumference
- Two separated rings
- 120 bunches/ring
- 106 ns bunch crossing time
- A+A, p+A, p+p
- Maximum Beam Energy:
  - 500 GeV for p+p
  - 200A GeV for Au+Au
- Luminosity
  - Au+Au: $2 \times 10^{26}$ cm$^{-2}$ s$^{-1}$
  - p+p: $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
- Beam polarizations
  - P=70%

Nucleus-nucleus collisions (AuAu, CuCu, dAu, CuAu, UU, ... $\sqrt{s_{NN}} = 7.7-200$ GeV)

Polarized proton-proton collisions $\sqrt{s} = 62.4, 200, 510$ GeV

RHIC is uniquely suited to map the QCD phase diagram at finite baryon density
Explore the QCD phase diagram

Vary collision energy to change temperature and baryon chemical potential

- Search for turn-off of signatures of sQGP.
- Search for 1st order phase transition from partonic to hadronic phase.
- Search for possible critical point.

Resonance gas model with free particle dispersion relations for all constituents: mesonic, baryonic and resonance degrees of freedom.

STAR white paper
“Studying the Phase Diagram of QCD Matter at RHIC”
STAR Note SN0493, Phys. Rev. C 81, 024911 (2010)

J. Cleymans et al.
Phys. Rev. C73, 034905

M. Tokarev
ISHEPP’16, Dubna, Russia
September 19-24, 2016
STAR detector at RHIC
The Solenoidal Tracker At RHIC (STAR)

- EEMC
- Magnet
- MTD
- BEMC
- TPC
- TOF
- BBC

TPC: full azimuthal coverage
- $-1.3 < \eta < 1.3$

Uniform acceptance for all beam energies

ToF: full azimuthal coverage
- $-0.9 < \eta < 0.9$

Low material budget in the tracking volume

Excellent PID: $\pi, K, p$ – TPC&ToF

$\Lambda, \Xi, \Omega$ – topological cuts
Particle Identification at STAR

Wide acceptance and excellent particle identification

Multi-fold correlations for identified particles
Identified Particle Acceptance at STAR

Au+Au 7.7 GeV

Au+Au 39 GeV

Au+Au 200 GeV

Homogeneous acceptance for all energies
Phase structure of QCD matter is experimentally studied at SPS, RHIC and LHC.

Dense, strongly-coupled matter and an almost perfect liquid with partonic collectivity has been created in HIC at RHIC.

STAR, PHENIX, PHOBOS, BRAHMS - White papers - Nucl. Phys. A757 (2005)

Experimental results from the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) support the hypothesis that a strongly-coupled nuclear medium with partonic degrees of freedom, namely the Quark-Gluon Plasma (QGP), is created in heavy-ion collisions at high energy.

“Exploring the Properties of the Phases of QCD Matter” – arXive:1501.06477

“The Hot QCD White Paper: Exploring the Phases of QCD at RHIC and the LHC” – arXiv:1502.02730
Nuclear matter at RHIC

Extreme conditions reached in heavy ion collisions:
- high multiplicity density \( \frac{dN_{\text{ch}}}{d\eta} \approx 700 \)
- high energy density \( \varepsilon_{\text{Bj}} \approx 4-5 \text{ GeV/fm}^3 \)
- various types of particles \( \pi, K, \ldots, \Omega, \ldots \)
- light (anti)nuclei, (anti)hypernuclei \( d, t, He, \ldots \)
**Observables:**

1. **1st order phase transition**
   - Azimuthally sensitive HBT
   - Directed flow $v_1$

2. **Partonic vs. hadronic dof**
   - $R_{AA}$: nucl. mod. factor
   - Charge separation
   - $v_2$ - NCQ scaling

3. **Critical point, correl. length**
   - Fluctuations

4. **Chiral symmetry restoration**
   - Di-lepton production

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**Systematic Study QCD Phase Structure**

- Onset of sQGP
- Phase boundary and critical point
- Chirial symmetry restoration

**BES-I:** $\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39$ GeV
- signatures for a phase transition
- signatures for a critical point
- boundary of phase diagram

Main focus of RHIC

Almost equidistant steps in $T_{ch}$–$\mu_B$ plane

AuAu @ 7.7, 11.5, 14.5, 19.6, 27, 39 GeV + 62 & 200 GeV

| $\sqrt{s_{NN}}$ (GeV) | $\mu_B$ (MeV) | $T$ (MeV) | nEvents (M) MB |
|-----------------------|---------------|-----------|----------------|
| 7.7                   | 420           | 140       | 4              |
| 11.5                  | 315           | 152       | 12             |
| 14.5                  | 260           | 156       | 20             |
| 19.6                  | 205           | 160       | 36             |
| 27                    | 155           | 163       | 70             |
| 39                    | 115           | 164       | 130            |
| 62.4                  | 70            | 165       | 67             |
| 200                   | 20            | 166       | 350            |
Flow of nuclear matter

Collectivity of partonic degrees of freedom
Number-of- Constituent Quark Scaling

Quark coalescence in the strongly interacting medium of quarks and gluons formed in heavy-ion collisions

STAR: Phys. Rev. Lett. 95 (2005) 122301
PHENIX: Phys. Rev. Lett. 98 (2007) 162301
Directed ($v_1$) & Elliptic ($v_2$) flow in AuAu

Fourier expansion of the momenta distribution

$$E \frac{d^3N}{dp^3} \propto \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos n(\varphi - \Psi_r) \right)$$

$$v_n = \langle \cos n(\varphi - \Psi_r) \rangle$$

$$\varphi = \tan^{-1}(\frac{p_y}{p_x})$$

- $v_1(y)$ sensitive to baryon transport, space momentum correlations and QGP formation.
- $v_2$ provides the possibility to gain information about the degree of thermalization of the hot, dense medium.
- The breaking of $v_2$ number of quark scaling will indicate a transition from partonic to hadronic degrees of freedom.
Flow vs. energy, centrality, particle mass

\[ v_2 \] of light nuclei scaled to the number of constituent quarks (NCQ) of their constituent nucleons, are consistent with NCQ scaled \( v_2 \) of baryons and mesons

NCQ scaling holds good for \( v_2 \) of light nuclei in Au+Au 39 GeV

L.Kumar (STAR), ICPAQGP 2010  
C.Jena (STAR), ICPAQGP 2010  
A. Schmah (STAR), QM 2011
Elliptic flow of identified particles in Au+Au

\[ \sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 \text{ GeV} \]

\[ \pi^-, \pi^+, K^-, K^+, K^0, p, \bar{p}, \phi, \Lambda, \bar{\Lambda}, \Xi^-, \bar{\Xi}^+, \Omega^-, \bar{\Omega}^+ \]

Dependence of \( v_2 \) on
- collision energy
- centrality
- transverse momentum
- type of particle
- (anti) particle
- barion-meson splitting
- NCQ scaling

Parton collectivity of the nuclear flow.
NCQ scaling & baryon – meson splitting

NCQ scaling

\[ \frac{v_2(B)}{v_2(M)} = \frac{3}{2} \text{ for perfect NCQ scaling} \]

\[ \Delta v_2 \text{ increases with decrease in energy.} \]

\[ \Delta v_2 \text{ relative to proton } v_2 \text{ (at } p_T = 1.5 \text{ GeV/c) shows a centrality dependence.} \]
Elliptic flow of light nuclei in Au+Au

\[ \sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, 62, 200 \text{ GeV @ } |y|<1. \]

STAR Collaboration
nucl-ex1601.07052

\( p, d, t, ^3\text{He} \) & \( \bar{d}, ^3\overline{\text{He}} \)

Mechanisms of light (anti-)nuclei production via coalescence, transport model,…

- Hadron & Quark DoF
- Quark Number Scaling

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Atomic mass number scaling $v_2/A$

$p, \overline{p}, d, \overline{d}, t, ^3\text{He}, ^3\overline{\text{He}}$  \hspace{1cm} $\sqrt{s_{NN}} = 7.7 - 200 \text{GeV}$

In the collision energy range
the light-nuclei production
favors the coalescence model.

$\triangleright$ Monotonic rise with $p_T$
$\triangleright$ Mass ordering at low $p_T$
$\triangleright$ Reduction for more central collisions
Spectra

probing QCD phase diagram with identified particles: $\pi^{+/-}$, $K^{+/-}$ and $\bar{p}/p$
in STAR BES-I
$\pi^{+/−}$, $K^{+/−}$ and $p/\bar{p}$ spectra in Au+Au

Au+Au @ 14.5 GeV

Bose-Einstein fit

(m$_t$-m) Exponential fit

Double Exponential fit

Vipul Bairathi
QM’15, Kobe, Japan, Sept. 27 – Oct. 3, 2015

L. Kumar & STAR - ICPAQGP, 2010, India; CPOD2011; China; QM2014, Germany

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\( \pi^{+/--}, \ K^{+/--} \) and \( p/\bar{p} \) spectra in \( \text{Au+Au} \)

**Au+Au 19.6 GeV**

Spectra are characterized by \( dN/dy \) and \( <p_T> \) or \( <m_T> \)

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Spectra with strange probes

probing QCD phase diagram

with identified strange particles: $\varphi$, $K_S^0$, $\Lambda$, $\Xi$, $\Omega$

in STAR BES-I
Strange probes of QCD matter

STAR Collaboration
Phys. Rev. C 93 (2016) 21903

AuAu @ 7.7-39 GeV, |y|<0.5

φ meson spectra

Ω hyperon spectra

Transverse momentum spectra are well described by the Levy function with parameters $T$ & $n$

$$\frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy} = \frac{dN}{dy} \frac{(n-1)(n-2)}{2\pi n T(n T + m(n-2))} (1 + \frac{p_T^2 + m^2 - m}{n T})^{-n}$$

Coalescence formation

These hadrons are expected to provide information primarily from the partonic stage of the collision:

- relatively small hadronic cross section
- direct information from chemical freeze-out stage
- little or no distortion due to hadronic rescattering
- minimal distortion due to feed-down
Spectra of $K_S^0$, $\Lambda$, $\Xi$ particles & Au+Au, 14.5 GeV

$\sqrt{s}=14.5$ GeV

$\Lambda$ spectra are weak decay
- feed-down corrected:
- statistical uncertainties

Spectra vs. collision energy, centrality, transverse momentum
Systematic study of colliding energy, centrality, transverse momentum dependence of mid-rapidity deuteron and anti-deuteron production measured by the STAR experiment from Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39$, and $200$ GeV.

The coalescence parameter $B_2$

- measure of the phase space density for nucleons
- decreases as collision energy increases
Spectra with charged hadrons

probing QCD phase diagram with unidentified particles in STAR BES-I
Charged hadron spectra in Au+Au at 7.7-62.4 GeV

Peripheral spectra show stronger dependence on beam energy.

S.Horvat & STAR
PoS (CPOD 2013) 002

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Nuclear modification factor $R_{CP}$

$$R_{CP} = \frac{(N_{Bin})_P}{(N_{Bin})_C} \left[ \frac{d^2N}{2\pi p_T dp_T d\eta} \right]_C \left[ \frac{d^2N}{2\pi p_T dp_T d\eta} \right]_P$$

$N_{Bin} \equiv$ number of binary collisions (Glauber MC model)

Smooth transition in the intermediate to high $p_T$ range from suppression at $\sqrt{s_{NN}} = 39$ GeV to strong enhancement at $\sqrt{s_{NN}} = 7.7$ GeV.

S.Horvat & STAR
nucl-ex:1601.01644
STAR

**Transverse momentum $h^-$ spectra in Au+Au**

Int. J. Mod. Phys. (2015) 1560103

**BES-I energies**

**Top RHIC energies**

Wide kinematic and dynamical range of particle production:

- Beam energy $\sqrt{s_{NN}} = 7$-200 GeV
- Centrality 80% - 5% ($dN_{ch}/d\eta \mid_0 \approx 10$-600)
- Transverse momentum $p_T = 0.2$-12 GeV/c

Unprecedented conditions to search for new phenomena in nuclear matter produced in heavy ion collisions.
Search for scaling features at STAR

Probing the microscopic structure of hot QCD matter at multiple length scales
Self-similarity of hadron production

Int. J. Mod. Phys. (2015) 1560103
“Scaling” and “Universality” are concepts developed to understanding critical phenomena. Scaling means that systems near the critical points exhibiting self-similar properties are invariant under transformation of a scale. According to universality, quite different systems behave in a remarkably similar fashion near the respective critical points. Critical exponents are defined only by symmetry of interactions and dimension of the space.

H.Stanley, G.Barenblatt,…

Phase transition and critical phenomena in nuclear matter

The idea is to vary the collision energy and look for the signatures of QCD phase boundary and QCD critical point i.e. to span the phase diagram from the top RHIC energy (lower $\mu_B$ ) to the lowest possible energy (higher $\mu_B$). To look for the phase boundary, we would study the established signatures of QGP at 200 GeV as a function of beam energy. Turn-off of these signatures at particular energy would suggest the crossing of phase boundary. Similarly, near critical point, there would be enhanced fluctuations in multiplicity distributions of conserved quantities (net-charge, net-baryon).

STAR collaboration
Dimensional dynamical function versus dimensional measurables

\[ E d^3 N / dp^3 \] & \[ P_{1,2}, M_{1,2}, p, m, dN/d\eta \]

- Energy dependence of spectra
- Centrality dependence of spectra
- Exponential behavior of spectra at low \( p_T \) and energy \( \sqrt{s_{NN}} \)
- Power behavior of spectra at high \( p_T \) and energy \( \sqrt{s_{NN}} \)
- Difference of yields at various energies strongly increases with \( p_T \)

The study of critical phenomena in nuclear matter in terms of dimensionless variables

Int. J. Mod. Phys. (2015) 1560103
Self-similarity in Au+Au collisions

Self-similarity parameter

\[ z = z_0 \Omega^{-1} \]
\[ z_0 = \frac{S^{1/2}}{(dN_{ch}/d\eta|_0)^c m_N} \]
\[ \Omega = (1 - x_1)^{\delta_A} (1 - x_2)^{\delta_A} (1 - y_a)^{\varepsilon} (1 - y_b)^{\varepsilon} \]

- \( dN_{ch}/d\eta|_0 \) - multiplicity density
- \( c \) - "specific heat" of bulk matter
- \( \delta_A \) - nucleus fractal dimension
- \( \varepsilon \) - fragmentation fractal dimension

Dimension of fragmentation

\[ \varepsilon_{AA} = \varepsilon_0 (dN/d\eta) + \varepsilon_{pp} \]

Scaling function

\[ \Psi(z) = \frac{\pi}{(dN/d\eta) \cdot \sigma_{inel}} \cdot J^{-1} \cdot E \frac{d^3\sigma}{dp^3} \]

"Collapse" of data points onto a single curve

- Energy independence of \( \Psi(z) \)
- Centrality independence of \( \Psi(z) \)
- Dependence of \( \varepsilon_{AA} \) on multiplicity
- Power law at low- and high-z regions

Indication on energy dependence of \( \delta \) for \( \sqrt{s_{NN}} < 19.6 \) GeV
Model parameters: $\delta_A$, $\varepsilon_{AA}$, $c$

Parameters $\delta_A$, $\varepsilon_{AA}$, $c$ are determined from the requirement of scaling behavior of $\Psi$ as a function of self-similarity parameter $z$.

Nucleus fractal dimension

$\delta_A = A \cdot \delta$

Fragmentation dimension

$\varepsilon_{AA} = \varepsilon_0 (dN/d\eta) + \varepsilon_{pp}$

“Specific heat”

$c$

- $\delta$ decreases with energy for $\sqrt{s_{NN}} \leq 20$ GeV
- $\delta$ is independent of energy for $\sqrt{s_{NN}} \geq 20$ GeV
- $\varepsilon_{AA}$ increases with energy
- $c$ is independent of energy

Search for discontinuity and correlations of the model parameters.
Phase diagram of nuclear matter

Particle yields and particle ratios allow to extract within the statistical equilibrium and blast wave models the chemical and kinetic freeze-out thermodynamic parameters.

\[ T_{\text{ch}} \text{ vs. } \mu_B \quad \text{and} \quad T_{\text{kin}} \text{ vs. } \beta \]

BW: E. Schnedermann et al., Phys.Rev. C 48 (1993) 2462.
Chemical Freeze out & BES I

- Statistical thermal model
- Quantum numbers (B, S, Q) are conserved on average

S. Wheaton & Cleymans, Comput. Phys. Commun., 180, 84-109 (2009)

- Particles used in fit: π, K, p, Λ, Ξ and their anti-particles.
- $T_{ch}$ increases as collision energy increases.
- $\mu_B$ decreases with increase in collision energy.
- Centrality dependence of $\mu_B$ is observed.

Vipul Bairathi & STAR
QM’15, Kobe, Japan, Sept. 27 – Oct. 3, 2015

Lokesh Kumar & STAR
QM’12, Nucl.Phys. A904-905 (2013) 256C
J.Cleymans et al. Phys. Rev. C 73 (2006) 034905
A. Andronic et al. Nucl. Phys. A 834 (2010) 237C
Kinetic Freeze out & BES I

- Hydro based model
- Local thermalization of particles at a kinetic freeze-out temperature and moving with a common radial flow velocity

- $\langle \beta \rangle$ decreases from central to peripheral collisions.
- $T_{\text{kin}}$ increases from central to peripheral collisions.
- An anti-correlation observed between $T_{\text{kin}}$ and $\langle \beta \rangle$.

E. Schnedermann, J. Sollfrank, U.W. Heinz
Phys. Rev. C 48, 2462 (1993)

Vipul Bairathi & STAR
QM’15, Kobe, Japan, Sept. 27 – Oct. 3, 2015

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September 19-24, 2016
Sophisticated STAR BES-I data analysis
The values of net-Kaon’s and net-Charge’s $\kappa\sigma^2$ and $S\sigma$/Skellam are consistent with Poisson distributions within errors. Non-monotonic behavior seen in net-Proton $\kappa\sigma^2$ in 0-5% and 5-10% central collisions.

Need more precise measurement below 20 GeV with finer steps in $\mu_B$ and increased rapidity acceptance.
Chiral Magnetic Effect

Three Effects:
1. Chiral Magnetic Effect
2. Chiral Magnetic Wave
3. Chiral Vortical Effect

Chiral anomaly creates differences in the number of left handed and right handed quarks. Leads to charge separation along the magnetic field lines.

STAR, Phys. Rev. Lett. 113 (2014) 52302

Daniel Cebra & STAR
34th Reimei Workshop J-PARC, Tokai, Japan, 2016

M. Tokarev ISHEPP’16, Dubna, Russia September 19-24, 2016
Hydro: from laminar to turbulent flow?

- Lambdas reveal their polarization through decay topology.
- Polarization expected through “vortical alignment with the event angular momentum vector.
- Polarization expected magnetic alignment with the event magnetic field.
- These effects can be disentangled looking at $\Lambda$ and anti-$\Lambda$.
- Goal is a definitive measurement of the magnetic alignment effect

\[
P_{\text{Vortical}} = (P_\Lambda + P_{\bar{\Lambda}}) / 2
\]
\[
P_{\text{Magnetic}} = (P_\Lambda - P_{\bar{\Lambda}}) / 2
\]

- Global polarization is positive for $\Lambda$ and anti-$\Lambda$.
- Corrections for feed-down from $\Sigma^0, \Xi^0, \Xi^-, \Omega^-$ decays.

Non-central Au+Au collisions

Fluid vorticity may generate global polarization of emitted particles
\[
\vec{\omega} = \nabla \times \vec{v}
\]

Viscosity dissipates vorticity to fluid at larger scale
Selected results from Au+Au collisions in the BES phase I program at RHIC

A reduction in the partonic energy loss.

Non-monotonic variation with respect to $\mu_B$. Sensitivity to possible first-order phase transition effects.

To clarify whether the trend follows a monotonic or non-monotonic variation with a minimum.

A difference between the $v_2$ of baryons and mesons at intermediate $p_T$ is the key to the experimental observation of NCQ scaling and partonic collectivity at top RHIC energy.

The difference in $v_2$ between baryons and antibaryons are consistent with the finding that hadronic interactions dominate at lower beam energies.

The difference of dynamical charge correlations between same-sign and opposite-sign charges. One of the possible explanations is the Chiral Magnetic Effect.

STAR BES-I White paper
Rosi Reed & STAR,
RHIC/AGS Users Meeting, 2016
Fixed target program at STAR

probing QCD phase diagram
with identified particles over a range $\sqrt{s_{NN}} = 3.0$ to 7.7 GeV

The Fixed-Target Program will extend the reach of the RHIC BES to higher $\mu_B$ and lower $T$.

Goals:
- Search for evidence of the first entrance into the mixed phase.
- Control measurements for BES collider program searches for Onset of Deconfinement.
- Control measurements for Critical Point searches.
STAR @ Fixed target mode

Au+Au @ 3.9 GeV

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Fixed Target Mode & Au+Au @ 3.9 GeV

Test run 16

Excellent PID with TPC & TOF for fixed target events
The Fixed-Target Experiment at STAR

The Fixed-Target Experiment at STAR

BES Phase II

- BES program is designed to study the phase diagram of QCD matter.
- Need to access the lower energy range to study all region of the phase diagram.
- Fixed Target program along with key upgrades allows us to scan from $\sqrt{s_{NN}}$ 19.6 to 3.0 GeV (200-720 MeV in $\mu_B$)

| Collider energy (GeV) | Fixed-Target energy (GeV) | Center-of-mass rapidity | Single Beam Energy (GeV) | Chemical potential $\mu_B$ (MeV) (collider mode) | Chemical potential $\mu_B$ (MeV) (FT mode) |
|-----------------------|---------------------------|-------------------------|--------------------------|-----------------------------------------------|------------------------------------------|
| 19.6                  | 4.47                      | 1.52                    | 8.87                     | 205                                           | 589                                      |
| 17.2                  | 4.21                      | 1.46                    | 7.67                     | 230                                           | 608                                      |
| 14.5                  | 3.90                      | 1.37                    | 6.32                     | 250                                           | 633                                      |
| 13.0                  | 3.72                      | 1.32                    | 5.57                     | 288                                           | 649                                      |
| 11.5                  | 3.53                      | 1.25                    | 4.82                     | 315                                           | 666                                      |
| 9.1                   | 3.19                      | 1.13                    | 3.62                     | 370                                           | 699                                      |
| 7.7                   | 2.98                      | 1.05                    | 2.92                     | 420                                           | 721                                      |

D.Cebra, K.Meehan, Rosi Reed & STAR, RHIC & AGS Users Meeting 2016
D.Sebra & STAR, 34th Reimei Workshop J-PARC, Tokai, Japan, 2016

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September 19-24, 2016
Energy scan at low energy: Fixed target mode

Au+Al Beam Pipe Studies

Star results for spectra and Coulomb potential are consistent with AGS previous experiments.

Au+Au Beam FT Studies

STAR Preliminary

K. Meehan & STAR
RHIC & AGS Users Meeting, 2016

M. Tokarev
ISHEPP’16, Dubna, Russia

J. Klay et al. (E895 Collaboration),
Phys. Rev. C 68, 054905 (2003)
HBT correlations

\[ CF(q) = N((1 - \lambda) + \lambda K(q)G) \]

\[ G = e^{-\left(R_{\text{out}}^2 q_{\text{out}}^2 + R_{\text{side}}^2 q_{\text{side}}^2 + R_{\text{long}}^2 q_{\text{long}}^2 + 2R_{\text{os}}^2 q_{\text{os}} q_{\text{side}}\right)} \]

STAR Preliminary

AGS & RHIC comparison

Test run 2015
Hyperons & Hypernuclei

\[ \Xi, \text{ FT 4.5 GeV, Top 30\%, } p_t\, 1.0-1.4 \text{ GeV/c} \]

Counts

\[ \text{Invariant Mass (GeV/c^2)} \]

STAR Preliminary

STAR FXT could improve world hypertriton lifetime measurement

K.Meehan & STAR
RHIC & AGS Users Meeting, 2016

M.Tokarev

ISHEPP’16, Dubna, Russia

September 19-24, 2016
Spectra with heavy flavor probes

probing QCD phase diagram
with identified charm particles: $D^0$, $J/\psi$
in STAR with new detectors HFT and MTD

Talks by

Pavol Federič
“Heavy flavor measurements at the STAR experiment”
Pavla Federičová
“$J/\psi$ production at the STAR experiment”
The Solenoidal Tracker At RHIC

Mid-rapidity detector: $|\eta| < 1$, $0 < \varphi < 2\pi$

TPC, HFT, MTD

- **TPC**: precise momentum, energy loss
- **HFT**: topological reconstruction of D
  - $\sigma_{DCA} < 50 \, \mu m$ for kaon at 750 MeV/c
  - 1st layer of PXL $< 0.4% X_0$
  - Take data: 2014-2016
- **MTD**: trigger on and identify muons
  - Precise timing measurement ($\sigma \sim 100$ ps)
  - Fully installed in 2014

Topological reconstruction with HFT

- Greatly reduced combinatorial background (4 orders of magnitude)
- Highly improved $S/\sqrt{(B+S)}$ (~8-18)
Acceptance coverage: $-1 < \eta < 1$, $0 < \phi < 2\pi$

**Heavy Flavor Tracker at STAR**

TPC – Time Projection Chamber (main tracking detector in STAR)

HFT – Heavy Flavor Tracker
- SSD – Silicon Strip Detector
- IST – Intermediate SiliconTracker
- PXL – Pixel Detector

Excellent long-lived hadron and electron identification
Secondary vertex reconstruction with HFT → Full kinematic reconstruction of charmed hadron

Tracking inwards with gradually improved resolution:

$D^0 \rightarrow K^+ \pi^-$

$D_s^\pm \rightarrow K^+ K^- \pi^\pm$

**STAR Collaboration**
Michael Lomnitz, Heavy Flavor Workshop, BNL, Upton, 2016
Hao Qiu, ICHEP’16, Chicago, USA, 2016

M. Tokarev, ISHEPP’16, Dubna, Russia

September 19-24, 2016
D⁰ meson nuclear modification in Au+Au

D⁰ → K⁻ + π⁺

R_AA vs. pT & centrality

TPC & ToF

Strong charm-medium interactions and hadronization via coalescence at intermediate p_T.

Significant energy loss of charm quarks in the hot and dense medium for transverse momenta p_T > 3 GeV/c.
Spectra & $R_{AA}$ for $D^0 \rightarrow K^- + \pi^+$

Au+Au @ 200 GeV

TPC & ToF & HFT

New data are consistent with published results, with improved statistical precision.

$R_{AA}$ – significant suppression

$R_{AA} > 1$ for $p_T \sim 1.5$ GeV/c
Charm coalescence with the flowing medium

$R_{AA} \ll 1$ for $p_T > 2.5$ GeV/c
Strong charm-medium interaction leading to sizable energy loss

$\text{Similar suppression as pions at high } p_T$

STAR Collaboration
Michael Lomnitz, Heavy Flavor Workshop, BNL, Upton, 2016
Hao Qiu, ICHEP’16, Chicago, USA, 2016
STAR: PRL 113 (2014) 142301; PLB 655 (2007) 104

M. Tokarev ISHEPP’16, Dubna, Russia September 19-24, 2016
Invariant yield of $J/\psi$ in Au+Au at 200 GeV

First mid-rapidity measurement of $J/\psi$ yield in Au+Au collisions via di-muon channel for $0 < p_T < 15$ GeV/c.

Consistent with the di-electron results.

Tsallis Blast Wave fits to di-electron results assuming zero velocity for $J/\psi$.
J/ψ meson nuclear modification in AuAu @ 200 GeV

\[ R_{AA}(p_T) = \frac{\sigma_{pp}^{\text{in}}}{N_{\text{coll}}^{AA}} \cdot \frac{d^2N_{AA}/dp_Td\eta}{d^2\sigma_{pp}/dp_Td\eta} \]

- \( R_{AA} \) vs. \( p_T \) is consistent with di-electron channel results for the entire \( p_T \) range within uncertainties in all centralities.
- Strong suppression at low \( p_T \).
- Less suppression at higher \( p_T \).

Takahito Todoroki & STAR
SQM 2016, Berkeley, USA, June 27 - July 1, 2016

STAR Collaboration
Phys. Lett. B722 (2013) 55
Phys. Rev. C90 (2014) 024906

M. Tokarev
ISHEPP’16, Dubna, Russia
September 19-24, 2016
The **STAR** Upgrades and **BES** Phase II

Collider mode

\[ 7.7 < \sqrt{s_{NN}} < 20 \text{ GeV} \]

\[ 300 < \mu_B < 420 \text{ MeV} \]

Fixed target mode

\[ 3 < \sqrt{s_{NN}} < 7.7 \text{ GeV} \]

\[ 420 < \mu_B < 750 \text{ MeV} \]
New Detectors for BES Phase II

**iTPC Upgrade:**
- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves $dE/dx$
- Extends $\eta$ coverage from 1.0 to 1.5
- Lowers $p_T$ cut-in from 125 MeV/c to 60 MeV/c

**EndCap TOF Upgrade:**
- Rapidity coverage is critical
- PID at $\eta = 0.9$ to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR

**EPD Upgrade:**
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

**Major improvements for BES-II.**

A. Schmah & STAR
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September 19-24, 2016
Beam Energy Scan II (2019-2020)

STAR upgrade for BES II

- Select the most important energy range 5 to 20 GeV
- Improve significance
  Long runs, higher luminosity (eCooling)
- Refine the signals
  Detector improvements (iTPC, eToF, EPD)
- Extend Range
  Fixed Target Opportunity
- Concurrent Theory Initiative

Beam Energy Scan Theory Collaboration

| $v_{SNN}$ (GeV) | 7.7 | 9.1 | 11.5 | 14.5 | 19.6 |
|-----------------|-----|-----|------|------|------|
| $\mu_B$ (MeV)   | 420 | 370 | 315  | 250  | 205  |
| BES I (Mevts)   | 4.3 | --- | 11.7 | 24   | 36   |
| Rate (Mevts/day)| 0.25| 1.7 | 2.4  | 4.5  |
| BES I $\mathcal{L}$ (1x10$^3$/cm$^2$sec) | 0.13 | 1.5 | 2.1  | 4.0  |
| BES II (Mevts)  | 100 | 160 | 230  | 300  | 400  |
| eCooling (Factor) | 4   | 4   | 4    | 3    | 3    |
| Beam Time (weeks)| 12  | 9.5 | 5.0  | 5.5  | 4.5  |

BES-II whitepaper: http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598
iTPC proposal: http://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
Event-Plane Proposal-May. 2016
eTOF Proposal-January, 2016

M. Tokarev
ISHEPP’16, Dubna, Russia
September 19-24, 2016

D. Cebra & STAR Collaboration
RHIC & AGS Users Meeting 2016
Conclusions

- Some of STAR results from RHIC Beam Energy Scan-I were reviewed.
- The wide range of collision energy ($\sqrt{s_{NN}} = 7-200$ GeV), centrality, various probes ($\pi, p, K, J/\psi, e, \mu, \Lambda, \Xi, \Omega, d,..$) allows us to scan the phase diagram of nuclear matter over a wide range of $T$ and $\mu_B$.
- The obtained data are basis for verification of different theoretical models, transition scenarios and properties of nuclear matter (the hydro of ideal liquid, NCQ scaling, jet quenching, the spinning QGP etc.).
- The collider and fixed target modes with new detector systems ($HFT, MTD, iTPC, EPD, eTOF$) significantly improve the capabilities of STAR for BES II to detect key features of QCD phase diagram.
Thank you for your attention!
Back-up slides
Thank you for your attention!