High-Energy Nuclear Collisions

I. STAR experiment at RHIC
II. Properties of medium and the QCD phase structure
III. The future of RHIC

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Part I: Introduction
Part II: STAR Experiment at RHIC
Part III: Properties of Medium and the QCD Phase Structure
Part IV: The Future of RHIC
High-energy Nuclear Collisions

Initial conditions

(1) Initial condition in high-energy nuclear collisions - Color Glass Condensation
(2) Cold-QCD-matter, small-x, high-parton density
   - parton structures in nucleon / nucleus

Initial high $Q^2$ interactions

(1) Hard scattering production - QCD prediction
(2) Interactions with medium - deconfinement/thermalization
(3) Initial parton density

Partonic matter - QGP
- The hot-QCD

Hadronization and Freeze-out

S. Bass

Hadronization and Freeze-out
III-(1) Initial Condition for High-Energy Nuclear Collisions
Small-x Measurements – *Initial Cond.*

200 GeV $p+p$ and $d+Au$ Collisions
Run8, STAR Preliminary

De-correlation, away side, central dAu collisions:
- CGC?
- Multiple scatterings?
III-(2) Parton Energy Loss in High-Energy Nuclear Collisions
Energy Loss in A+A Collisions

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}}{dp_T d\eta} / \frac{d^2\sigma^{NN}}{dp_T d\eta}$$

$p+p$                  $Au + Au$

leading particle suppressed

back-to-back jets disappear

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Hadron Suppression at RHIC

Hadron suppression in more central Au+Au collisions!
Suppression and Correlations

In central Au+Au collisions: hadrons are suppressed and back-to-back ‘jets’ are disappeared. Different from p+p and d+Au collisions.

**Energy density at RHIC:** \( \varepsilon > 5 \text{ GeV/fm}^3 \sim 30\varepsilon_0 \)

Parton energy loss: Bjorken 1982

(“Jet quenching”) Gyulassy & Wang 1992

...
1) Jets are seen in Au+Au collisions, extended the kinematical reach to jet energies > 40 GeV in central Au+Au collisions at RHIC

2) We see a substantial fraction of jets - in contrast to x5 suppression for light hadron $R_{AA}$
*III-(3) Heavy Flavor Production in High-Energy Nuclear Collisions
Quark Masses

1) Higgs mass: electro-weak symmetry breaking. (current quark mass)
2) QCD mass: Chiral symmetry breaking. (constituent quark mass)

Strong interactions do not affect heavy-quark masses.

Important tool for studying properties of the hot/dense medium at RHIC.

Test pQCD predictions at RHIC.
Flavor Dependence of Energy Loss

Data: \( R_{AA} \) of charged hadron \( R_{AA} \) in central Au+Au collisions
(NPE includes both Charm and Bottom contributions)

Model: Strong flavor dependence
NPE-Hadron Angular Correlations

1) STAR ($p_T > 5$ GeV/c): 
\textit{arXiv:1007.1200}

2) About 50% NPE from Bottom hadrons decay at RHIC for $p_T > 5$ GeV/c
A Constraint on D-B Energy Loss


$$R^{NPE}_{AA} = (1 - r^{eB}_{pp})R^{eD}_{AA} + r^{eB}_{pp}R^{eB}_{AA}$$

1) RHIC data constrain the Bottom and Charm production

2) Significant suppression of the Bottom at RHIC at $p_T > 5$ GeV/c  
=> Energy loss!

3) Direct measurements (vs. $b$, $p_T$) important

PHENIX: PRL 103, 082002(09); arXiv: 1005.1627
Status of NPE from p+p Collisions

STAR Heavy flavor decay electron ($p_T > 2.5$ GeV/c) differential cross section in 200 GeV p+p collisions:

1) An error in the efficiency correction in 2003 data analysis identified
2) New results from 2005 (SVT), 2006 (SVT) and 2008 (no SVT) are consistent. No change in total cross section!
3) Analysis for Au+Au collision under way
Charm Total Cross Section at RHIC

More results and HFT upgrade are needed
*III-(4) Bulk Properties in High-Energy Nuclear Collisions
\[ \tau d\sigma = dU + pdV \]

\( \sigma \) – entropy; \( p \) – pressure; \( U \) – internal energy; \( V \) – volume
\( \tau = k_B T \), thermal energy per dof

In high-energy nuclear collisions, interaction among constituents and density distribution will lead to:

**pressure gradient \( \leftrightarrow \) collective flow**

\( \leftrightarrow \) number of degrees of freedom (dof)
\( \leftrightarrow \) Equation of State (EOS)
\( \leftrightarrow \) No thermalization is needed – pressure gradient only depends on the density gradient and interactions.
\( \rightarrow \) Space-time-momentum correlations!
Timescales of Expansion Dynamics

microscopic view vs macroscopic view

scattering rate $\nu_{ab} \sim \int \frac{d^3 p_a}{(2\pi)^3} \frac{d^3 p_b}{(2\pi)^3} f_a(p_a)f_b(p_b)\sigma_{ab}(s)|\vec{v}_a - \vec{v}_b|$

expansion rate $\partial_\mu u^{\mu}$
dilution rate $\partial_\tau s$

A macroscopic treatment requires that the scattering rate is larger than macroscopic rates
Anisotropy Parameter $v_2$

$$\varepsilon = \frac{\left\langle y^2 - x^2 \right\rangle}{\left\langle y^2 + x^2 \right\rangle}$$

$$v_2 = \left\langle \cos 2\varphi \right\rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom
Collectivity, De-confinement at RHIC

- $v_2$ of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

- $n_q$-scaling novel hadronization process
- Partonic flow De-confinement

PHENIX: PRL\textbf{91}, 182301(03)
STAR: PRL\textbf{92}, 052302(04), \textbf{95}, 122301(05)
nucl-ex/0405022, QM05

S. Voloshin, NPA715, 379(03)
Models: Greco et al. PRC\textbf{68}, 034904(03)
Chen, Ko, nucl-th/0602025
Nonaka et al. PLB\textbf{583}, 73(04)

\ldots
Larger $v_2/\varepsilon_{\text{part}}$ indicates stronger flow in more central collisions.

**NO** $\varepsilon_{\text{part}}$ scaling.

The observed $n_q$-scaling does not necessarily mean thermalization, viscosities?!
**System Size Driven Collectivity**

\[ \sqrt{s_{NN}} = 200 \text{ GeV Collisions at RHIC} \]

**Collectivity:** Driven by number of participants and eccentricity.

**Caution:** Local equilibrium and perfect fluid

\[ \frac{V_2}{\langle n_q \times \varepsilon_{\text{part}} \rangle} \]

\[ \frac{(m_T - m)}{n_q} \quad \text{(GeV/c}^2\text{)} \]

**STAR:** *PRC81*, 44902(10)
Partonic Collectivity at RHIC

\( \sqrt{s_{NN}} = 200 \text{ GeV} \) \( ^{197}\text{Au} + ^{197}\text{Au} \) Collisions at RHIC

Low \( p_T (\leq 2 \text{ GeV}/c) \): hydrodynamic mass ordering
High \( p_T (> 2 \text{ GeV}/c) \): number of quarks ordering
s-quark hadron: smaller interaction strength in hadronic medium
light- and s-quark hadrons: similar \( v_2 \) pattern

\( \Rightarrow \textit{Partonic Collectivity at RHIC} ! \)
III-(5) Other Results in High-Energy Nuclear Collisions
First Observation of $\bar{\Lambda}H \rightarrow \bar{\Lambda}He + \pi^+$

- First observation of the anti-hypernucleus
- Heaviest anti-matter observed in laboratory

200 GeV Au+Au collisions at RHIC
- Equilibrium of s-quarks
- Thermal models (Stachel et al.)
Chiral Magnetic Effect (CME)

\[ j^{em} = \sum_a \left( E^a \cdot B^a \right) B^{em} = Q^a B^{em} \]

<table>
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<tr>
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<th>( E^a )</th>
<th>( B^a )</th>
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<td>( E^a \cdot B^a )</td>
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<td>( (E^a \cdot B^a)B^{em} )</td>
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Note:

(1) The \( j^{em} \) is the EM current and an observable. \( Q^a \) is the QCD topological charge which must exist.
(2) In vacuum, \( T=0 \), \( Q^a \) is the Instenton. Proven by the \( \eta' \) mass.
(3) In hot medium, \( T>0 \), \( Q^a \) is the Sphaleron.
Search for Local Parity Violation in High Energy Nuclear Collisions

The separation between the same-charge and opposite-charge correlations.

- Strong external EM field
- De-confinement and Chiral symmetry restoration

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \]
Parity even observable

STAR; PRL 103, 251601(09); PRC 81, 54908(10).

Run 11 requests:
Beam Energy Dependence & U+U
Topological transitions have never been observed directly (e.g. at the level of quarks in DIS). An observation of the spontaneous strong parity violation would be a clear proof for the existence of such physics.

**Chiral Magnetic Effect:**
Kharzeev, Zhitnitsky, NP A797 67(07).
Kharzeev, McLerran, Warringa, NP A803 227(08).
Fukushima, Kharzeev, Warringa, PR D78, 074033(08).
*III-(6) Di-electron Distributions and Direct Radiations in High-Energy Nuclear Collisions

Xin Dong, NX, Yifei Zhang, Jie Zhao
Q. Wang, P.F. Zhuang
Di-lepton Program at STAR

Key measurements: yields, mass, $R_{AA}$, $v_2$ → thermalization, thermal rates
Slope Parameter Systematics

\[ m_T = \sqrt{p_T^2 + m^2} \]

\[ f \propto \exp(-m_T/T_{\text{slope}}) \]
Direct Radiation Measurements

Di-leptons allow us to measure the direct radiation from the matter with partonic degrees of freedom, no hadronization!

- Low mass region:
  \[ \rho, \omega, \phi \Rightarrow e^-e^+ \]
  \[ m_{\text{inv}} \Rightarrow e^-e^+ \]

  *medium effect*

  *Chiral symmetry*

- Intermediate region:
  \[ J/\psi \Rightarrow e^-e^+ \]
  \[ m_{\text{inv}} \Rightarrow e^-e^+ \]

  *Direct radiation*
*III-(7) Beam Energy Scan at RHIC

in

High-Energy Nuclear Collisions

Feng Liu, Bedanga Mohanty, Shusu Shi, Kejun Wu, Xiaoping Zhang, NX, Jie Zhao
Run 10: 200, 62.4, 39, 11.5 7.7 GeV

A great success, many thanks to CA-D!

1) Successful run, all goals were reached or exceed
2) Many thanks to CA-D
Collision Centralities

1) Collision geometries at different energies are under control
2) **Run 11 request**: 18 and 27 GeV Au+Au collisions
Particle Identification at STAR

\sqrt{s_{NN}} = 39\text{ GeV} \text{ Au + Au Collisions}

\begin{itemize}
  \item $K_s$
  \item $\phi$
  \item $\Lambda$
  \item $\Omega$
\end{itemize}

Invariant Mass (GeV)
1) At top energy, HLT, among other things, was used for J/Ψ online selection.
2) For BES, HLT used for collision vertex selection very effectively, very essential. HLT event selection efficiency better than 95%.
3) Selectivity is important for STAR’s future physics program at RHIC-II era.
*(III-(8)) QCD Phase Diagram in High-Energy Nuclear Collisions

Xiaofeng Luo, Bedanga Mohanty, Hans Georg Ritter, NX S. Gupta, F. Karsch, M. Stephanov
The QCD Critical Point

- LGT prediction on the transition temperature $T_C$ is robust.

- LGT calculation, universality, and models hinted the existence of the critical point on the QCD phase diagram* at finite baryon chemical potential.

- Experimental evidence for either the critical point or 1st order transition is important for our knowledge of the QCD phase diagram*.

* Thermalization has been assumed

M. Stephanov, K. Rajagopal, and E. Shuryak, PRL 81, 4816(98); K. Rajagopal, PR D61, 105017 (00)

Net-proton High Moments

1) STAR results* on net-proton high moments for Au+Au collisions at \( \sqrt{s_{NN}} = 200, 62.4 \text{ and } 19.6 \text{ GeV} \).

2) Sensitive to critical point**:
   \[ \langle (\delta N)^2 \rangle \approx \xi^2, \quad \langle (\delta N)^3 \rangle \approx \xi^{4.5}, \quad \langle (\delta N)^4 \rangle \approx \xi^7 \]

3) Direct comparison with Lattice results**:
   \[ S \* \sigma \approx \frac{\chi_B^3}{\chi_B^2}, \quad \kappa \* \sigma^2 \approx \frac{\chi_B^4}{\chi_B^2} \]

4) Extract susceptibilities and freeze-out temperature. An independent test on thermal equilibrium in heavy ion collisions.

\( \delta N \approx \xi^{2}, \quad \delta N \approx \xi^{4.5}, \quad \delta N \approx \xi^{7} \)

\( S \approx \chi_B^3, \quad \kappa \approx \chi_B^4 \)

** STAR: 1004.4959, PRL


F. Karsch and K. Redlich, arXiv:1007.2581

Estimated errors in Au+Au collision:

- ** Run 10: 7.7, 11.5, 39 GeV
- ** Run 11: 18, 27 GeV

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Net-proton High Moments & Lattice

1) The net-proton fluctuation is consistent with thermal model, unlike the transport.

2) Direct comparison with Lattice results. Q: chemical freeze-out vs. lattice conditions?

3) The baryon fugacity $\mu_B/T$ can be extracted independently.

$$S_B \cdot \sigma_B = \text{Tanh}(\mu_B / T)$$

References:
- F. Karsch and K. Redlich: 1007.2581
- R.V. Gavai and S. Gupta: 1001.2796
Susceptibilities and Moments

In the Boltzmann approximation, the HRG model provides a simple result for the thermodynamic pressure.

\[
\frac{p}{T^4} = \frac{1}{\pi^2} \sum_i \alpha_i (m_i / T)^2 K_2(m_i / T) \cosh[(B_i \mu_B + S_i \mu_S + Q_i \mu_Q) / T]
\]

The nth order susceptibilities:

\[
\chi_{q}^{(n)} = \frac{\partial^n (p / T^4)}{\partial (\mu_q / T)^n} = \frac{\partial^n (p / T^4)}{\partial (\mu_q)^n}, q = B, Q, S
\]

\[
\chi_{q}^{(1)} = \frac{1}{VT^3} < N_q >
\]

\[
\chi_{q}^{(2)} = \frac{1}{VT^3} < (\delta N_q)^2 >
\]

\[
\chi_{q}^{(3)} = \frac{1}{VT^3} < (\delta N_q)^3 >
\]

\[
\chi_{q}^{(4)} = \frac{1}{VT^3} (\langle (\delta N_q)^4 \rangle - 3 \langle (\delta N_q)^2 \rangle^2)
\]

\[
\kappa \sigma^2 = \frac{\chi_{q}^{(4)}}{\chi_{q}^{(2)}} = 1
\]

\[
S \sigma^3 = \frac{\chi_{q}^{(3)}}{\chi_{q}^{(1)}} = 1
\]

\[
S \sigma = \frac{\chi_{q}^{(3)}}{\chi_{q}^{(2)}}
\]

X.F. Luo
1. Skewness*Sigma of net-proton:

\[
(1) : S_B \sigma_B = \frac{X_B^{(3)}}{X_B^{(2)}} = S_{p-p} \sigma_{p-p} = \sum_{i \in \text{protons}} \frac{d_i (m_i / T)^2 K_2 (m_i / T) \sinh[(\mu_B + \mu_Q) / T]}{\sum_{i \in \text{protons}} d_i (m_i / T)^2 K_2 (m_i / T) \cosh[(\mu_B + \mu_Q) / T]} = \tanh(\mu_B / T) \quad (\mu_Q \ll \mu_B, S = 0)
\]

2. Skewness*Sigma of net-kaon:

\[
(2) : S_S \sigma_S = \frac{X_S^{(3)}}{X_S^{(2)}} = S_{K^+ - K^-} \sigma_{K^+ - K^-} = \sum_{i \in \text{kaons}} \frac{d_i (m_i / T)^2 K_2 (m_i / T) \sinh[(\mu_S + \mu_Q) / T]}{\sum_{i \in \text{kaons}} d_i (m_i / T)^2 K_2 (m_i / T) \cosh[(\mu_S + \mu_Q) / T]} = \tanh(\mu_S / T) \quad (\mu_Q \ll \mu_S, B = 0)
\]

3. Skewness*Sigma of net-pion: (Not apply for low energy)

\[
(3) : S_Q \sigma_Q = \frac{X_Q^{(3)}}{X_Q^{(2)}} \approx S_{\pi^+ - \pi^-} \sigma_{\pi^+ - \pi^-} = \sum_{i \in \text{pions}} \frac{d_i (m_i / T)^2 K_2 (m_i / T) \sinh(\mu_Q / T)}{\sum_{i \in \text{pions}} d_i (m_i / T)^2 K_2 (m_i / T) \cosh(\mu_Q / T)} = \tanh(\mu_Q / T) \quad (B = S = 0)
\]

\[
\begin{align*}
\frac{\mu_B}{T} & \approx \frac{1}{2} \ln \frac{1 + (S\sigma)_{p-p}}{1 - (S\sigma)_{p-p}} \quad \frac{\mu_S}{T} \approx \frac{1}{2} \ln \frac{1 + (S\sigma)_{K^+ - K^-}}{1 - (S\sigma)_{K^+ - K^-}} \\
\frac{\mu_Q}{T} & \approx \frac{1}{2} \ln \frac{1 + (S\sigma)_{\pi^+ - \pi^-}}{1 - (S\sigma)_{\pi^+ - \pi^-}}
\end{align*}
\]

Extract thermodynamic parameters at with fluctuations!

F. Karsch and K. Redlich, arXiv:1007.2581
(a) **Patonic matter**: coalescence of massive quarks for hadronization

→ Clear NQ scaling in $v_2$ !

(b) **Hadronic matter**: rescatterings amongst hadrons

→ No NQ scaling in $v_2$ !
AMPT model results:

1) In AMPT, the scaling in $v_2$ is independent of partonic cross sections.

2) The amplitude of $v_2$ depends on the value of the cross section.

$\Rightarrow$

The beam energy dependence of the partonic cross sections will not affect the $v_2$ scaling argument. Important for BES program.
Observable: Quark Scaling

 Observable: Quark Scaling

\[ m_\phi \sim m_p \sim 1 \text{ GeV} \]
\[- \text{ss} \Rightarrow \phi \quad \text{not} \ K^+K^- \Rightarrow \phi \]
\[- \sigma_{\phi h} \ll \sigma_{p\pi, \pi\pi} \]

*In the hadronic case, no number of quark scaling and the value of \( v_2 \) of \( \phi \) will be small.*
QCD Thermodynamics

1) At $\mu_B = 0$: cross over transition, $150 < T_c < 200$ MeV
2) The SB ideal gas limit: $T/T_c \sim 10^7$
3) $T_{ini}(\text{LHC}) \sim 2-3*T_{ini}(\text{RHIC})$
4) Thermalized, evolutions are similar, RHIC and LHC
The QCD Phase Diagram and High-Energy Nuclear Collisions

The nature of thermalization at the top RHIC and LHC energies:
- Heavy quarks
- Di-lepton
**Summary**

**STAR QCD physics program for next decade:**

**Spin Physics:** (cold nucleon)
- 200 GeV: $\Delta g$ inclusive and di-jets, $\gamma$-jet
- 500 GeV: *sea quark* helicity distributions
- 200/500 GeV: transverse spin phenomena

**Low-x Physics:** (cold nucleus)
- Study gluon-rich phenomena at RHIC
- Color glass condensate

**Heavy Ion Physics:** (hot nuclear matter)
- Thermalization at 200 GeV
- QCD phase boundary and critical point, started
- In medium properties
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