Study QCD Phase Diagram in High-Energy Nuclear Collisions

Nu Xu

Many Thanks to the Organizers!

(1) Nuclear Science Division, Lawrence Berkeley National Laboratory, USA
(2) College of Physical Science & Technology, Central China Normal University, China
Outline

1) Introduction: QCD Phase Structure
2) Part I: STAR BES-I Results (selected)
3) Part II: Quarkonia in HIC
1) After the discovery of the Higgs boson, the QCD degrees of freedom are well defined, at short distance.

2) Study dynamical structures of matter that are made from $q, g$. E.g. the confinement, nucleon spin, the QCD phase structure... Large $\alpha_s$ and strong coupling – QCD at long distance.
Study QCD Phase Structure at RHIC

**QCD Emergent Properties**

- Early Universe
- LHC Experiments
- RHIC Experiments
- Quark-Gluon Plasma
- Critical Point
- Color Superconductor
- Hadron Gas
- Nuclear Matter
- Neutron Stars
- Future FAIR Experiments
- RHIC Energy Scan
- 1st order phase transition
- Hadron Gas
- 900 MeV Baryon Chemical Potential
- 0 MeV
- 170 MeV
- Crossover
- Temperature

**Observables:**

1st order phase transition
- (1) Azimuthally HBT
- (2) Directed flow $v_1$

**Partonic vs. hadronic dof**
- (3) $R_{AA}$: N.M.F.
- (4) Dynamical correlations
- (5) $v_2$ - NCQ scaling*

**Critical point, correl. length**
- (6) Fluctuations*
- (7) Di-lepton production*

**Study QCD Phase Structure**
- Phase boundary?
- Critical point?

**BES-I:** $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39 GeV
Relativistic Heavy Ion Collider
Brookhaven National Laboratory (BNL), Upton, NY

- RHIC: The high-energy heavy-ion collider
  (i) Dedicated QCD collider
  (ii) $\sqrt{s_{NN}} = 200 - 5$ GeV
  (iii) $U, Au, Cu, d, p$

- RHIC: The highest energy polarized proton collider!
  $\sqrt{s} = 200, 500$ GeV

Animation M. Lisa
Part I

Recent Results from RHIC BES-I Program
STAR Experiment

Magnet  MTD  BEMC  TPC  TOF  BBC  EEMC

HFT
Particle Identification at STAR

Multiple-fold correlations for the identified particles!
STAR PID for ($\pi$, $K$, $p$)

Au+Au at 7.7 GeV

Au+Au at 39 GeV

Au+Au at 200 GeV
# STAR Detector Configurations

<table>
<thead>
<tr>
<th>Period</th>
<th>Detectors</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001-2010</td>
<td>TPC</td>
<td><em>u, d, s</em></td>
</tr>
<tr>
<td>2010</td>
<td>TPC + TOF</td>
<td><em>u, d, s + dilepton</em></td>
</tr>
<tr>
<td>2013</td>
<td>TPC + TOF + MTD</td>
<td><em>u, d, s, c, b + dilepton</em></td>
</tr>
<tr>
<td>2014</td>
<td>TPC + TOF + MTD + HFT</td>
<td></td>
</tr>
</tbody>
</table>

→ **STAR**: Large coverage, excellent PID, fast DAQ
- detects nearly all particles produced at RHIC
- multiple fold correlation measurements
- Probes: bulk, penetrating, and bulk-penetrating

→ **STAR**: Perfect mid-y collider experiment

→ **STAR**: Expanding into forward rapidity regions
(1) Hadron Spectra

\[ \sqrt{s_{NN}} = 39 \text{ GeV} \text{ Au+Au Collisions} \]
**Bulk Properties at Freeze-out**

**Chemical Freeze-out: (GCE)**
- Centrality dependence in $T_{ch}$ and $\mu_B$
- The effect seems stronger at lower energy.

**Kinetic Freeze-out:**
- Central collisions => lower value of $T_{kin}$ and larger collectivity $\beta$
- Stronger collectivity at higher energy
(2) BES Dependence Dielectrons

1) Low mass reg. ($M_{ee} \leq 1\text{GeV}$): no obvious energy dependence in the ratio of data/cooktail. At 19.6, the ratio is consistent with SPS results.

2) Intermediate mass reg. ($1 \leq M_{ee} \leq 3\text{GeV}$): clear energy dependence, correlated charm? Thermal radiation, $\sim \exp(-M_{ee}/T)$?
1) With in-medium broadened rho, model results are consistent with experimental data ($m_{ee} \leq 1 \text{ GeV/c}^2$) at $\sqrt{s_{NN}} = 200, 62.4, 39, 27$ and 19.6 GeV

2) In Au+Au collisions at 200 GeV, the centrality and $p_T$ dependence results on data/hadronic cocktails ($m_{ee} \leq 1 \text{ GeV/c}^2$) understood with current model calculations
(3) NCQ Scaling in $v_2$

In the hadronic case, no number of quark scaling and the value of $v_2$ of $\varphi$ will be small.

- $m_\varphi \sim m_p \sim 1$ GeV
- $ss \Rightarrow \varphi$ not $K^+K^- \Rightarrow \varphi$
- $\sigma_{\varphi\varphi} \ll \sigma_{\rho\pi, \pi\pi}$

* Thermalization is assumed!
Collectivity $v_2$ Measurements

1) Number of constituent quark (NCQ) scaling in $v_2$ => partonic collectivity => deconfinement in high-energy nuclear collisions

2) At $\sqrt{s_{NN}} < 11.5$ GeV, the $v_2$ NCQ scaling is broken, indicating hadronic interactions become dominant.
(a) Hydro + Transport: consistent with baryon results.
[J. Steinheimer, V. Koch, and M. Bleicher PRC86, 44902(13).]

(4) Higher Moments

1) High moments for conserved quantum numbers: $Q$, $S$, $B$, in high-energy nuclear collisions

2) Sensitive to critical point ($\xi$ correlation length):

$$\langle (\delta N)^2 \rangle \approx \xi^2, \quad \langle (\delta N)^3 \rangle \approx \xi^{4.5}, \quad \langle (\delta N)^4 \rangle \approx \xi^7$$

3) Direct comparison with calculations at any order:

$$S \ast \sigma \approx \frac{\chi_B^3}{\chi_B^2}, \quad \kappa \ast \sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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

References:

STAR net-proton results:

1) All data show deviations below Poisson beyond statistical and systematic errors in the 0-5% most central collisions for $\kappa\sigma^2$ and $S\sigma$ at all energies. Larger deviation at $\sqrt{s_{NN}} \sim 20$ GeV

2) Independent $p$ and $\bar{p}$ production reproduces the observed energy dependence of $\kappa\sigma^2$ and $S\sigma$

3) UrQMD model show monotonic behavior in the moment products

4) Higher statistics needed for collisions at $\sqrt{s_{NN}} < 20$ GeV. BES-II is needed.

**STAR: 1309.5681**
BES-II: e-cooling, iTPC Upgrades

A. Fedotov, W. Fischer, 2012

\[ \text{Luminosity } 1/(\text{sec.cm}^2) \]

<table>
<thead>
<tr>
<th>Relativistic Gamma</th>
<th>( 1 \times 10^{23} )</th>
<th>( 1 \times 10^{24} )</th>
<th>( 1 \times 10^{25} )</th>
<th>( 1 \times 10^{26} )</th>
<th>( 1 \times 10^{27} )</th>
<th>( 1 \times 10^{28} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sqrt{s_{NN}} ) (GeV)</td>
<td>~ 5</td>
<td>~ 20</td>
<td>~ 5</td>
<td>~ 20</td>
<td>~ 5</td>
<td>~ 20</td>
</tr>
<tr>
<td>Increasing factor</td>
<td>3-5</td>
<td>10</td>
<td>3-5</td>
<td>10</td>
<td>3-5</td>
<td>10</td>
</tr>
</tbody>
</table>

iTPC Upgrade: \(|\eta| \leq 1.1 \rightarrow |\eta| \leq 1.7|

1) BES-II at \( \sqrt{s_{NN}} < 20 \text{ GeV} \)
2) RHIC e-cooling will provide increased luminosity \( \sim x3 - 10 \)
3) STAR iTPC upgrade extend mid-rapidity coverage – beneficial to several crucial measurements

Nu Xu

(1) In high-energy nuclear collisions, $\sqrt{s_{NN}} \geq 200$ GeV, hot and dense *matter, with partonic degrees of freedom and collectivity*, has been formed.

(2) RHIC BES-I:
- [*partonic*] $< \mu_B \sim 110$ (MeV) ($\sqrt{s_{NN}} \geq 39$ GeV)
- [*hadronic*] $> \mu_B \sim 320$ (MeV) ($\sqrt{s_{NN}} \leq 11.5$ GeV)

(3) RHIC BES-II: focus at $\sqrt{s_{NN}} \leq 20$ GeV region with higher luminosity (x10) + detector upgrade

iTPC: Run18 (2017)
Exploring QCD Phase Structure

1. $T_{ini}$, $T_C$  
   LHC, RHIC

2. $T_E$  
   RHIC, SPS, FAIR

3. Phase boundary  
   RHIC, FAIR/NICA

LHC+RHIC  
$sQGP$ properties  
$\sqrt{s_{NN}} \sim 0.05 - 5$ TeV

RHIC+BES-II  
QCD phase structure and critical point  
$\sqrt{s_{NN}} \leq 20$ GeV

Future EIC  
Cold nuclear matter properties  
e + ion collisions

$\sqrt{s_{NN}} \leq 12$ GeV

exploration of QCD phase structure

hadronic phase

quark-gluon plasma

Chemical freeze-out

Partonic Matter

Hadronic Matter

quarkyonic matter?

$T_C = 175$ MeV
eSTAR: A Letter of Intent

The STAR Collaboration

October 1, 2013

Hot QCD Matter

Cold QCD Matter

gluon degrees of freedom dominant
Part II

Study Quarkonia Production at RHIC and LHC

Yunpeng Liu¹, Zebo Tang², Kai Zhou³, NX⁴, Pengfei Zhuang³

¹: Texas A&M, USA
²: USTC, Hefei, China
³: Tsinghua University, Beijing, China
⁴: CCNU and LBNL, China/USA
The QCD Phase Diagram and High-Energy Nuclear Collisions

1. \( T_{\text{ini}}, T_C \)  
   LHC, RHIC

2. \( T_E \)  
   RHIC
   SPS, FAIR

3. Phase Boundary  
   RHIC, FAIR/NICA

Baryon Chemical Potential \( \mu_B/T_C \)

Temperature \( T/T_C \)

Quark-gluon plasma  
\( (T_C = 175 \text{ MeV}) \)

heavy quark (hq):
clean, penetrating, bulk probes for studying the sQGP medium properties
Why Heavy Quark?

Mass Matters:
- Heavy quark masses are not altered in QCD medium
- Negligible thermal production in collisions

Tool for studying properties of the hot/dense medium at the early stage of collisions

Heavy quark collectivity
⇒ Thermalization
⇒ Deconfinement

B. Mueller, arXiv: 0404015
**Key Effects**

**Cold Matter Effects:**
1) Npdf: shadowing effect
2) Production cross-sections
3) Cronin effect

**Hot Matter Effects:**
1) Debye screening
2) Regeneration
In Nucleus-Nucleus Collisions

**Sequential Suppressions**

Debye Screening:

\[ J/\psi \rightarrow c + \bar{c} \quad r_{J/\psi} \gtrsim \lambda_D \approx \frac{1}{g(T) \cdot T} \]

1) Total # of \( J/\psi \) reduces
2) Sensitive to hot/dense medium


**Regenerations**

At the boundary of hadronization:

\[ c + \bar{c} \rightarrow J/\psi \]

1) Total # of \( J/\psi \) increases
2) Sensitive to hot/dense medium

Modification Factors

1) Traditional $R_{AA}$ depends on the (TMD) $p_T$ integrated yields. Sensitive to $Npdf^*$ and model dependent parameter $n_{bin}$.

$$R_{AA} = \frac{\langle N \rangle^{AA}}{n_{bin} \langle N \rangle^{pp}}$$

2) The TMD dependent $r_{AA}(p_T^2)$ is more sensitive to dynamical medium effects including Cronin effect, Debye Screening, and Regeneration.

$$r_{AA}(p_T^2) = \frac{\langle p_T^2 \rangle^{AA}}{\langle p_T^2 \rangle^{pp}}$$

* H. Satz, arXiv: 1303.3493

TMD: transverse momentum distribution
Charm Production at RHIC

Open Charm:
(1) Initial production follows binary collisions
(2) Suppressed at $p_T > 3\text{GeV/c}$.

QM 2011, QM 2012

J/$\psi$: (closed Charm)
(1) Suppressed in more central collisions.
Similar observations at LHC
(2) Near zero $v_2$.

Where is the true QCD medium effect?

$He,\ et\ al.\ arXiv:1204.4442;\ Gossiaux,\ et\ al.\ arXiv:1207.5445$
Charm Interactions with Medium

1) As for light-quark hadrons, charm-quark hadrons show suppression at intermediate $p_T$ region: energy loss of $hq$!

2) At LHC, charm-quark hadrons show non-zero collectivity: strong interactions among $hq$ and the hot/dense medium.
Onia Production in HI Collisions

**Cold QCD effects**
- Shadowing, Cronin

**Pythia**
- heavy-quark

**Hot QCD effects**
- Debye screening
- Energy loss
- Regeneration

- \( p_T \) broadening (for all hadrons)
- \( p_T \) decreasing
- Thermalization (hq hadrons)

**Hydro + Transport**

**Hadronization**

\[ \sigma_{hf} \]

\[ R_{AA} \]

\[ r_{AA} \]
Driven by the initial heavy quark production cross-sections, much larger fraction of $J/\psi$s are formed via regeneration, at hadronization, at LHC than that from RHIC!
1) **LHC**: large fraction of final $J/\psi$s produced via regeneration leads to lower value of $<p_T>$

2) **SPS**: all final $J/\psi$s are survivors. Increase of $<p_T>$ due to the initial Cronin scatterings

3) **RHIC**: mixture of initial and regenerated $J/\psi$s
J/ψ v$_2$ Results

(1) J/ψ v$_2$ is consistent with zero for MB Au+Au collisions at RHIC.

(2) At LHC energy, finite value of the J/ψ v$_2$ is seen at the forward-$y$. Larger v$_2$ is predicted for mid-$y$ J/ψs.

Stronger regeneration effect at LHC!
(A) $J/\psi$ productions at SPS, RHIC and LHC

(B) $Upsilon$ production:
- RHIC: negligible regenerations, Cronin effect dominant.
- LHC: sizable contributions from regenerations.
Coalescence $J/\psi$ concentrate at the small transverse momenta: from low $p_T$ charm quarks and lower averaged $J/\psi \langle p_T \rangle$ and $\langle p_T^2 \rangle$. Initial shadowing effect is small on $r_{AA}$.

At LHC: Deconfinement and Thermalization of charm quarks!
Part II: Summary

(1) In high-energy collisions, transverse momentum distributions (TMD) are important!

(2) The effects of Debye Screening and Regeneration are opposite for quarkonia production. **They are all medium effects.**

(3) J/ψ production showing by $r_{AA}(p_T^2)$, demonstrated the influence of Debye screening and the regeneration, implying the formation of the hot/dense medium, the QGP, at RHIC and LHC.

At LHC: charm quarks are consistent with the scenario of thermalization.
Thank you!