Study QCD Phase Structure in High-Energy Nuclear Collisions

- Selected results from RHIC beam energy scan program

Nu Xu

LBL

STAR: PRL126, 092301(2021); arXiv: 2101.12413
Outline

1) Introduction

2) STAR Experiment at RHIC

3) Selected Results from BES-I
   - Collectivity
   - Chirality
   - Criticality

4) BES-II and Beyond
Phase Structure of Strong Interactions

For given degrees of freedom, phase diagram tells us how matter (re)organized itself under external conditions.

Phase Diagram of Water: QED at Work

E. Fermi

Gordon Baym

“Notes on Thermodynamics and Statistics” (1953)

1983 US NP LRP
- by Gordon Baym

QCD Phase Diagram
High-Energy Nuclear Collisions and QCD Phase Diagram

1) At $\mu_B = 0$, smooth crossover (LGT);
2) Large $\mu_B$, 1st order phase transition $\rightarrow$ QCD critical point
1) QCD transition temperature:
\( T_{PC} = 156.5 \pm 1.5 \text{ MeV} \)

2) Chiral crossover line
\[
T_{PC}(\mu_B) = T_{PC}^0 \left[ 1 - \kappa_2 \left( \frac{\mu_B}{T_{PC}^0} \right)^2 - \kappa_4 \left( \frac{\mu_B}{T_{PC}^0} \right)^4 \right]
\]
\( \kappa_2 = 0.012(4), \quad \kappa_4 = 0.00(4) \)

3) Chiral transition temperature:
\( T_C = 132^{+3}_{-6} \text{ MeV} \)

4) QCD critical end point:
\( T_{CEP} < T_C, \quad \mu_{B, CEP} \gtrsim 3T_C \)

H.T. Ding, F. Karsch et al., 2020

Motivation & Plans
The workshop is motivated by a growing body of theoretical and experimental evidence that the critical point on the QCD phase diagram, if it exists, should appear on the QGP transition boundary at baryo-chemical potential \(~100 - 500\) MeV, corresponding to heavy ion collisions with c.m. energy in the range \(5 - 50\) GeV/u. Identifying and pinning down this point with experimental measurements would be a major step forward in the world-wide effort to determine the properties of QCD at high temperature and density.

CAN WE DISCOVER THE QCD CRITICAL POINT AT RHIC?

Mapping the phase diagram. Finding the landmark that would go in any future book on QCD. Can RHIC do this?

Yes, IF:
- Accelerator & detector capabilities permit measurement of the event-by-event fluctuations of the hadronic observables I described, at a sequence of energies like that I described
- Nature is kind, and puts \( m_b < 50 \text{ MeV} \)

If YES:
- The landmark discovered. Our map of the QCD phase diagram then anchored by experiment.
- Assuming reasonable progress in lattice QCD, quantitative comparison between theory & experiment for \( m_b \)
- FAIR (and RHIC) can study the first order phase transition.

- Collider upgrade;
- Detector upgrades;
- Theory efforts
STAR Detector System

- Large acceptance
- Excellent PID with uniform efficiency
- Modest rates
Install, commission and use 10% of the CBM TOF modules, including the read-out chains at STAR, started to work in 2019

**CBM participating in RHIC Beam Energy BES-II in 2019-2021:**

- Complementary to part of CBM physics program: Phase-0 CBM
  \[ \sqrt{s_{NN}} = 3 - 7.2 \text{ GeV} \ (750 \geq \mu_B \geq 420 \text{ MeV}), \] especially for the study of strange hadrons, hyper-nuclei production and baryon-correlations
# Particle Identification with TOF

<table>
<thead>
<tr>
<th></th>
<th>Net-charge</th>
<th>Net-Kaon</th>
<th>Net-proton</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kinetic cuts</strong></td>
<td>$0.2 &lt; p_T &lt; 2.0$ GeV/c, $</td>
<td>\eta</td>
<td>&lt; 0.5$</td>
</tr>
<tr>
<td><strong>Particle identifications</strong></td>
<td>Reject spallation p at $p_T &lt; 2.0$ GeV/c</td>
<td>TPC: $0.2 &lt; p_T &lt; 0.4$ GeV/c TPC/TOF: $0.4 &lt; p_T &lt; 1.6$ GeV/c</td>
<td>TPC: $0.4 &lt; p_T &lt; 0.8$ GeV/c TPC/TOF: $0.8 &lt; p_T &lt; 2.0$ GeV/c</td>
</tr>
<tr>
<td><strong>Efficiency corrections</strong></td>
<td>TPC: $\epsilon_{TPC} \sim 0.8$; TPC+TOF: $\epsilon_{TPC+TOF} \sim 0.5$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Centrality Definitions</strong></td>
<td>Un-corrected charge particles $0.5 &lt;</td>
<td>\eta</td>
<td>&lt; 1.0$</td>
</tr>
</tbody>
</table>
Data-sets for BES-I Program (2010 – 2017)

<table>
<thead>
<tr>
<th>√s_{NN} (GeV)</th>
<th>Events (10^6)</th>
<th>Year</th>
<th>*μ_B (MeV)</th>
<th>*T_{ch} (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>238</td>
<td>2010</td>
<td>25</td>
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<td>2010</td>
<td>112</td>
<td>164</td>
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<td>27</td>
<td>30</td>
<td>2011</td>
<td>156</td>
<td>162</td>
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<tr>
<td>19.6</td>
<td>15</td>
<td>2011</td>
<td>206</td>
<td>160</td>
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<tr>
<td>14.5</td>
<td>13</td>
<td>2014</td>
<td>264</td>
<td>156</td>
</tr>
<tr>
<td>11.5</td>
<td>7</td>
<td>2010</td>
<td>315</td>
<td>152</td>
</tr>
<tr>
<td>7.7</td>
<td>4</td>
<td>2010</td>
<td>420</td>
<td>140</td>
</tr>
</tbody>
</table>

*(μ_B, T_{ch}) : J. Cleymans et al., PRC73. 034905(2006)
STAR, arXiv:1007.2613

1) Largest data sets versus collision energy
2) STAR: Large and homogeneous acceptance, excellent particle identification capabilities. *Especially important for fluctuation analysis*
**Bulk Properties at Freeze-out**

**Chemical Freeze-out: (GCE)**
- Weak temperature dependence
- Centrality dependence $\mu_B$
- LGT: CP about $\mu_B \geq 500$ MeV?

- The $K^+/\pi$ ratio peaks at $\sqrt{s_{NN}} \sim 8$ GeV where model also predicted the peak of baryon density
- **HBDR**: ($\sqrt{s_{NN}} < 8$ GeV, $\mu_B \geq 420$ MeV)

- ALICE: B. Abelev et al., PRL 109, 252301(12); PR C88, 044910(13).
- STAR: J. Adams, et al., NPA757, 102(05); PR C96, 044904(17); X.L. Zhu, NPA931, c1098(14); L. Kumar, NPA931, c1114(14).
- J. Randrup and J. Cleymans, PR C74, 047901(06)
Studying the Phase Diagram of QCD Matter at RHIC

A STAR white paper summarizing the current understanding and describing future plans

01 June 2014

BES-II Whitepaper (2014)

(3GeV) \(7.7 \text{ GeV} < \sqrt{s_{NN}} < 19.6 \text{ GeV}\)

1) Accelerator upgrade \(\rightarrow\) increase luminosity;
2) Detector upgrades \(\rightarrow\) increase efficiency, improve precision and widen acceptance;
3) Main physics goal is to search for the illusive QCD critical point with Collectivity, Chirality and Criticality

7.7GeV: enhancement

PRL110, 142301(13), v2
PRL121, 032301(18), RCP

strong suppression due to QGP formation

[Graphs and data points related to QCD studies]
The emergent properties of QCD matter

Collectivity

\[
\begin{align*}
\partial_\mu [(\epsilon + p) u^\mu u^\nu - pg^{\mu\nu}] &= 0 \\
\partial_\mu [s u^\mu] &= 0 \\
\end{align*}
\]

\[
\frac{d^2 N}{p_T dp_T d\phi} = \frac{1}{2\pi} \frac{dN}{p_T dp_T} \left\{ 1 + \sum_{n=1}^{\infty} 2v_n(p_T) \cos[n(\phi - \Psi_R)] \right\}
\]

- \(v_1\) Directed flow;
- \(v_2\) Elliptic flow;
- \(v_3\) Triangle flow
Anisotropy Parameter $v_2$

coordinate-space-anisotropy $\rightarrow$ momentum-space-anisotropy

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

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

Sensitive to initial/final conditions, EoS and degrees of freedom
Partonic Collectivity at RHIC

- Low $p_T (\leq 2 \text{ GeV/c})$: hydrodynamic mass ordering
- High $p_T (> 2 \text{ GeV/c})$: number of quarks scaling (NCQ)
  - u-, d-, and s-quarks flow!

- Partonic Collectivity!
- De-confinement Au+Au collisions at RHIC!

STAR: PRL116, 62301(2016)
1) First application of MAPS technology in high energy collisions, excellent position resolution;
2) Measured $D^0, D^\pm, D_s^\pm, \Lambda_c$ and obtained two conclusions:
   - “These results suggest that charm quarks have achieved local thermal equilibrium with the medium created in such (200GeV Au+Au) collisions”
   - Hadronization via quark coalescence process

STAR: PRL 113, 142301(14); PRC 99, 034908(19); PRL 118, 212301(17); PRL 123, 162301(19); PRL 124, 172301(20)
\[ \sqrt{s_{NN}} = 3 \text{ GeV (FXT) Au+Au Collisions} \]

- At 3 GeV, NCQ scaling is absent, hadronic interactions dominant!
- Critical point searches focus in 3 - 20 GeV region

Stated in a more natural way:

At 3 GeV, NCQ scaling is absent, hadronic interactions dominate.
Critical point searches focus in the 3 - 20 GeV region.
Criticality
Conserved Quantities (B, Q, S)

1) In strong interactions, baryons (B), charges (Q) and strangeness (S) are conserved;
2) Higher order moments/cumulants describe the shape of distributions and quantify fluctuations. They are sensitive to the correlation length $\xi$, phase structure;
3) Direct connection to theoretical calculations of susceptibilities.

| Measured multiplicity $N$, $\langle \delta N \rangle = N - \langle N \rangle$ |
|-----------------|-----------------|
| mean: $M = \langle N \rangle$ | $= C_1$ |
| variance: $\sigma^2 = \langle (\delta N)^2 \rangle$ | $= C_2$ |
| skewness: $S = \langle (\delta N)^3 \rangle / \sigma^3$ | $= C_3 / C_2^{3/2}$ |
| kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^3 - 3$ | $= C_4 / C_2^2$ |

Moments, cumulants and susceptibilities:

| 2nd order: $\sigma^2/M \equiv C_2 / C_1 | = \chi_2 / \chi_1$ |
| 3rd order: $S\sigma \equiv C_3 / C_2 | = \chi_3 / \chi_2$ |
| 4th order: $\kappa\sigma^2 \equiv C_4 / C_2 | = \chi_4 / \chi_2$ |

$\chi_1$, $\chi_2$, $\chi_3$, $\chi_4$ are theoretical calculations of susceptibilities.

- Skewness $(S)$ → asymmetry
- Kurtosis $(\kappa)$ → sharpness
Expectations for QCD Critical Point

- Characteristic “Oscillating pattern” is expected for the QCD critical point but the exact shape depends on the location of freeze-out with respect to the location of CP

- Critical Region (CR)

Analysis Methods and Corrections

1) Centrality bin correction;
2) Efficiency corrections;
3) Statistical uncertainty estimation;
4) Pileup correction (FXT)

- X.F. Luo, PRC 91, 034907(15); T. Nonaka et al., PRC 95, 044917(17); X.F. Luo et al., PRC 99, 044917(19)
- T. Nonaka et al., NIM A984, 164632(20)
Event-by-Event Net-Proton Distributions (raw)

Net-proton Cumulants vs. Energy and Centrality

STAR: 2101.12413

Au+Au Collisions at RHIC

\[ |y| < 0.5, \ 0.4 < p_t < 2.0 \text{ (GeV/c)} \]

C_1, C_2, C_3, C_4 vs. Averaged Number of Participant Nucleons \( \langle N_{\text{part}} \rangle \)
Energy Dependence of Net-p Cumulants

1) Cumulants of net-proton distributions, top 5% central and 70-80% peripheral collisions. Efficiency and acceptance correction applied

2) Value of mean increase as energy decreases, effect of baryon stopping


1) HRG and transport model predicted monotonical energy dependence: AMPT, JAM, UrQMD. Suppression at low energy due to conservation;

2) The 3rd and 4th orders: **deviate from the Poisson limit** in the most central collisions!

3) ‘**Attractive**’ of protons at the 7.7 GeV collisions? [STAR: PRL126, 092301(21)]
“Nonmonotonic Energy Dependence of Net-Proton Number Fluctuations”

<table>
<thead>
<tr>
<th></th>
<th>2\textsuperscript{ND} order</th>
<th>3\textsuperscript{RD} order</th>
<th>4\textsuperscript{TH} order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Monotonic, 3.4(\sigma)</td>
<td>Non-Monotonic, (1.0\sigma)</td>
<td>Non-Monotonic, (3.1\sigma)</td>
</tr>
<tr>
<td>Model*</td>
<td>(\langle (\delta N)^2 \rangle \sim \xi^2)</td>
<td>(\langle (\delta N)^3 \rangle \sim \xi^{4.5})</td>
<td>(\langle (\delta N)^4 \rangle \sim \xi^7)</td>
</tr>
</tbody>
</table>

* M. Stephanov, PRL\textbf{102}, 022301(09)
### Statistical Tests

#### Top 0 - 5% Au + Au Collisions at RHIC

<table>
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<tr>
<th></th>
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<th></th>
</tr>
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<tbody>
<tr>
<td>7.7 – 27 GeV</td>
<td>C₂/C₁</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>C₃/C₂</td>
<td>&lt; 0.001</td>
<td>7.54e⁻³</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>C₄/C₂</td>
<td>5.53e⁻³</td>
<td>4.50e⁻³</td>
<td>1.45e⁻²</td>
<td>2.21e⁻³</td>
</tr>
<tr>
<td>7.7 – 62.4 GeV</td>
<td>C₂/C₁</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
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</tr>
<tr>
<td></td>
<td>C₄/C₂</td>
<td>&lt; 0.001</td>
<td>1.28e⁻¹</td>
<td>1.07e⁻²</td>
<td>5.77e⁻³</td>
</tr>
</tbody>
</table>

- Models predict monotonical energy dependence: Statistically do not agree with data, especially at finite baryon density region
- Statistical analysis → **non-monotonic energy dependence**

Comparison Between 200 GeV p+p and Au+Au Collisions

1) In 200GeV p+p collisions, high order cumulants ratios of net-protons are found to be positive for , $C_4/C_2$, $C_5/C_2$ and $C_6/C_2$;

2) For QCD matter, LGT predicted negative net-baryon $C_5/C_2$ and $C_6/C_2$;

3) Direct evidence for the QGP formation in 200GeV Au+Au central collisions!

HotQCD Collaboration, PRD101, 074502 (2020)
Proton High Moments at High Baryon Density Region

1) HADES data and hadronic transport model UrQMD predicted negative $C_4/C_2$ at 3 GeV $\rightarrow$ Hadronic interactions dominant;

2) Fill the gap $2 < \sqrt{S_{NN}} < 7.7$ GeV and pin down QCD critical point $\rightarrow$ CBM Experiment at FAIR

HADES: PRC102, 024914(20)
The emergent properties of QCD matter

BES-II and Beyond
- Larger acceptance
- Even better PID with uniform efficiency
- Modest rates

- iTPC, EPD & eTOF upgrades completed
- All are in data-taking for BES-II program

STAR Detector System for BES-II

Compressed Baryonic Matter experiment at FAIR

PROGRESS REPORT 2019
Major Upgrades for BES-II

**iTPC:**
- Improves dE/dx
- Extends $\eta$ coverage from 1.0 to 1.5
- Lowers $p_T$ cut-in from 125 to 60 MeV/c
- Ready in 2019

**eTOF:**
- Forward rapidity coverage
- PID at $\eta = 0.9$ to 1.5
- Provided by CBM-FAIR
- Ready in 2019

**EPD:**
- Improves trigger
- Better centrality & event plane measurements
- Ready in 2018

1) Enlarge rapidity acceptance
2) Improve particle identification
3) Enhance centrality/event plane resolution

eTOF: STAR and CBM eTOF group, arXiv: 1609.05102
**RHIC BES-I & II** (2010-2017, **2019-2021**)

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>Events ($10^6$)</th>
<th>BES II / BES I</th>
<th>$\mu_B$ (MeV)</th>
<th>$T_{ch}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
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<td>1200</td>
<td>2017</td>
<td>83</td>
<td>165</td>
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<td>86</td>
<td>2010</td>
<td>112</td>
<td>164</td>
</tr>
<tr>
<td>27</td>
<td>30 (560)</td>
<td>2011 / 2018</td>
<td>156</td>
<td>162</td>
</tr>
<tr>
<td>19.6</td>
<td>538 / 15</td>
<td>2019 / 2011</td>
<td>206</td>
<td>160</td>
</tr>
<tr>
<td>17.3</td>
<td>250</td>
<td>2021</td>
<td>~227</td>
<td>~158</td>
</tr>
<tr>
<td>14.5</td>
<td>325 / 13</td>
<td>2019 / 2014</td>
<td>264</td>
<td>156</td>
</tr>
<tr>
<td>11.5</td>
<td>230 / 7</td>
<td>2020 / 2010</td>
<td>315</td>
<td>152</td>
</tr>
<tr>
<td>9.2</td>
<td>160 / 0.3</td>
<td>2020 / 2008</td>
<td>355</td>
<td>140</td>
</tr>
<tr>
<td>7.7</td>
<td>100 / 4</td>
<td>2021 / 2010</td>
<td>420</td>
<td>140</td>
</tr>
<tr>
<td>3.0 (FXT)</td>
<td>250 + 2B</td>
<td>2021</td>
<td>~720</td>
<td>~80</td>
</tr>
</tbody>
</table>

7.7GeV data goal, 100M, reached on May 1st

World largest data set!
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- Assuming reasonable progress in lattice QCD, quantitative comparison between theory & experiment for $\mu_B$.
- FAIR (and RHIC) can study the first order phase transition.

YES! Since 2010, RHIC and STAR have completed upgrades successfully and carried out the beam energy scan.

- World largest data sets from heavy ion collisions have been collected

- BEST: theory collaboration

- Is Nature kind?
Future Facilities for Heavy Ion Collisions

Collision Energy $\sqrt{s_{NN}}$ (GeV)

Heavy Ion Collision Interaction Rates (Hz)

Region of high baryon density

CBM
High rates, FXT experiment at FAIR

Fixed-Target

FAIR SIS100

HIAF

HADES

STAR FXT

STAR BES-II

ALICE

sPHENIX

Collider

μ_B (MeV) 750 400 200 20

μ_B (MeV) 10^7 10^6 10^5 10^4 10^3 10^2 10

μ_B (MeV) 1 5 10 50 100

1 5 10 2

10 3

10 4

10 5

10 6

10 7
The QCD Phase Diagram

2000 – 2021 BES-I & -II: search for the QCD CP at RHIC
- Lattice: CP may exist at \( \frac{\mu_B}{T} \geq 3 \)
- 3σ effect: non-monotonic collision energy dependence \( \sqrt{S_{NN}} \leq 20 \text{ GeV} \)

2021 – 2033 BES-III:
- fixed-target experiments at \( 2 \leq \sqrt{S_{NN}} \leq 5 \text{ GeV} \)
- Confirm first-order phase boundary and the QCD CP
Acknowledgements

STAR Collaboration and RHIC Operation


* students


**INT 2008

Thank you for your attention!