J-PARC Heavy-Ion Program and Search of the QCD Critical Point

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Two topics covered in this talk

① J-PARC Heavy-Ion Program
② Exp. Search for QCD-CP with fluctuations
Beam-Energy Scan

Hadrons

Color SC
Beam-Energy Scan

Search for QCD phase structure / critical point
J-PARC Heavy-Ion Program (J-PARC-HI)
J-PARC
Japan Proton Accelerator Research Complex

High-power Proton Beam
- T2K (Tokai-to-Kaminoka)
- Hadron physics
- etc...
J-PARC
Japan Proton Accelerator Research Complex

J-PARC-HI = J-PARC Heavy-Ion Program

- Beam energy: ~20GeV/A ($\sqrt{s}$~6.2GeV)
- Fixed target experiment
- High luminosity: collision rate $\sim10^8$Hz
- Launch: (hopefully) 2025~

- White paper / Letter of Intent (2016)
  - http://asrc.jaea.go.jp/soshiki/gr/hadron/jparc-hi/
HI Acceleration @ J-PARC

- Use of reliable/high-performance RCS & main ring
- → Reduce cost and time
Collision Rate

J-PARC-HI:
High-luminosity X Fixed target → World highest rate \( \approx 10^{8} \text{Hz} \)

5-order higher than AGS, SPS

AGS, SPS \( = \) J-PARC-HI
1 year \( = \) 5 min.

- High-statistical exp.
- various event selections
- higher order correlations
- search of rare events
Beam-Energy Scan

$T, \mu$ from particle yield

Translation to baryon density

J-PARC energy = highest baryon density
Maximum Density

Time evolution in $T$-$\rho$ plane by JAM

- $\sqrt{s_{NN}} > 100$ GeV
- $\sqrt{s_{NN}} \approx 6$ GeV
- $E/A = 20$ GeV

- Maximum density $5\sim10\rho_0$ @ J-PARC energy
- Large event-by-event fluctuations?

A. Ohnishi, 2002
Search of Rare Events

- Exotic Hadrons
- Hypernuclei
- Strangelets

- High density
- High luminosity
- High strange yield

Rare-event Factory

- creation
- properties
- interaction
Future Plan

Recent activities:

- June 2016: White Paper uploaded
- July 2016: Submission of LOI
- Aug. 2016: International Workshop
- Sep. 2016: Symposium @ JPS meeting

Future plan:

- 2020: Funding request to MEXT
- 2021: Earliest approval of funding
- 2021-2022: Construction of HI Injector
- 2021-2023: Construction of HI injection system in RCS
- 2023-2024: Construction of HI spectrometer
- 2025: First collision

Visit J-PARC-HI Web Page
http://asrc.jaea.go.jp/soshiki/gr/hadron/jparc-hi/
To Summarize this part...

One more experimental facility!
Search for QCD Critical Point with Fluctuations

Observables are fluctuating even in an equilibrated medium.
Thermal Fluctuations

Observables are fluctuating even in an equilibrated medium.

- **Variance:** $\langle \delta N^2 \rangle = V \chi_2 = \sigma^2$
- **Skewness:** $S = \frac{\langle \delta N^3 \rangle}{\sigma^3}$
- **Kurtosis:** $\kappa = \frac{\langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2}{\chi_2 \sigma^2}$

$\delta N = N - \langle N \rangle$

Non-Gaussianity

Review:
Asakawa, MK, PPNP90 ('16)
A Coin Game

① Bet 25 Euro
② You get head coins of

A. 50 x 1 Euro
B. 25 x 2 Euro

Same expectation value.
A Coin Game

① Bet 25 Euro
② You get head coins of

A. 50 x 1 Euro
B. 25 x 2 Euro
C. 1 x 50 Euro

Same expectation value.
But, different fluctuation.
Event-by-Event Fluctuations

Fluctuations can be measured by e-by-e analysis in experiments.

Cumulants
\[ \langle \delta N_p^2 \rangle, \langle \delta N_p^3 \rangle, \langle \delta N_p^4 \rangle_c \]
Event-by-Event Analysis @ HIC

Fluctuations can be measured by e-by-e analysis in experiments.
Non-zero non-Gaussian cumulants have been established!

Have we measured critical fluctuations?
Remarks on Critical Fluctuation

Experiments cannot observe critical fluctuation in equilibrium directly.

- **Growth**
  Critical fluctuation has to be well developed. But, relaxation toward equilibration is slow around CP because of the critical slowing down.

- **Decay by diffusion**
  Fluctuations developed at CP are modified by the time evolution in later stage.

Study this effect on higher-order cumulants.
Time Evolution of Fluctuations

Diffusion modifies distribution
Non-Interacting Brownian Particle System

Initial condition (uniform)

Cumulants: $\langle Q^2 \rangle_c, \langle Q^3 \rangle_c, \langle Q^4 \rangle_c$

Random walk

diffusion master equation: MK+, PLB(2014)

Probabilistic argument: Ohnishi+, PRC(2016)
Non-Interacting Brownian Particle System

Initial condition (uniform)

diffusion distance $\Delta Y_{\text{drift}}$

cumulants: $\langle \tilde{Q}^2 \rangle_c, \langle \tilde{Q}^3 \rangle_c, \langle \tilde{Q}^4 \rangle_c$

random walk

$\Delta Y$

Study $\Delta Y$ dependence

t $\rightarrow \infty$
Poisson distribution

diffusion master equation: MK+, PLB(2014)
probabilistic argument: Ohnishi+, PRC(2016)
Baryons in Hadronic Phase

hadronize
chem. f.o.

10~20fm

kinetic f.o.

\( p, \bar{p} \)
\( n, \bar{n} \)
\( \Delta(1232) \)

mesons
baryons

Baryons behave like Brownian pollens in water
Higher order cumulants can behave non-monotonically.
Non monotonic behavior of cumulants.
Approach initial value as $\Delta y \rightarrow$ large

finite volume effect: Sakaida+, PRC064911(2014)
More sophisticated analysis with factorial cumulants, MK, Luo (2017)
Experiments cannot observe critical fluctuation in equilibrium directly.

- **Growth**
  
  Critical fluctuation has to be well developed. But, relaxation toward equilibration is slow around CP because of the critical slowing down.

- **Decay by diffusion**
  
  Fluctuations developed at CP are modified by the time evolution in later stage.
Critical fluctuation is a conserved mode!

Fujii 2003; Fujii, Ohtani, 2004; Son, Stephanov, 2004

Fluctuations of $\sigma$ and $n_B$ are coupled around the CP!

$$\delta\sigma \simeq \delta n_B$$

$\sigma \sim M_q$

$n_B$

$s$ : fast damping

$F(\sigma, n) = A\sigma^2 + B\sigma n + Cn^2 + \cdots$
Dynamical Evolution of Critical Fluctuations

- Evolution of correlation length
  Berdnikov, Rajagopal (2000)
  Asakawa, Nonaka (2002)

- Higher orders (spatially uniform “σ” mode)
  Mukherjee, Venugopalan, Yin (2015)

- Dynamical evolution in chiral fluid model
  Nahrgang, Herold, ... (2014~)

- Correlation functions
  Kapusta, Torres-Rincon (2012)
Aim of This Study

- Describe **conserved nature** of critical fluctuation.
- We want to study **experimental observables**.
  - focus on a **conserved charge** (baryon number)
  - study evolution of **conserved-charge** fluctuation
- Concentrate on **2nd order** fluctuation. (not higher)
- We study
  - rapidity window dependence of the cumulant
  - 2-particle **correlation function**

Our Main Conclusion

Non-monotonicity in 2nd-order cumulants or correlation func. = Signal of QCD-CP
Stochastic Diffusion Equation (SDE)

- **Diffusion equation**

  \[ \partial_\tau n = D \partial_\eta^2 n \]

  - Describe a relaxation of a conserved density \( n \) toward uniform state without fluctuation

- **Stochastic diffusion equation**

  \[ \partial_\tau n = D \partial_\eta^2 n + \partial_\eta \xi(\eta, \tau) \]

  \[ \langle \xi(\eta_1)\xi(\eta_2) \rangle \sim \chi \delta(\eta_1 - \eta_2) \]

  - Describe a relaxation toward fluctuating uniform state
  - \( \chi \): susceptibility (fluctuation in equil.)

Review: Asakawa, MK, PPNP 90 (2016)
Soft Mode of QCD Critical Point

- Effective potential
  \[ F(\sigma, n) = A\sigma^2 + B\sigma n + Cn^2 + \cdots \]

- Time dependent Ginzburg-Landau
  \[
  \begin{pmatrix}
  \dot{\sigma} \\
  \dot{n}
  \end{pmatrix}
  =
  \begin{pmatrix}
  \Gamma_{\sigma\sigma} & \Gamma_{\sigma n} \\
  \Gamma_{n\sigma} & \Gamma_{nn}
  \end{pmatrix}
  \begin{pmatrix}
  \sigma \\
  n
  \end{pmatrix}
  \sim k^2
  \]

For slow and long wavelength,

SDE
\[
\partial_\tau n = D(\tau)\partial_\eta^2 n + \partial_\eta \xi
\]

singularities in \( D(\tau) \) and \( \chi(\tau) \)
Critical behavior

- 3D Ising \((r, H)\)
- model H

Temperature dep.

\[
D(T) \quad \text{critical slowing down}
\]

\[
\chi(T) \quad \text{critical enhancement}
\]
$K(\Delta y) = \frac{\langle \delta Q^2 \rangle}{\langle \delta Q^2 \rangle_{\text{eq.}}}$

- Monotonically decreasing

Analytic result $\chi(\tau)$ monotonically increasing $K(\Delta y)$ monotonically decreasing
Critical Point / Cumulant

\[ K(\Delta y) = \frac{\langle \delta Q^2 \rangle}{\langle \delta Q^2 \rangle_{eq.}} \]

- Non-monotonic \( \Delta y \) dep.
- Analytic result: \( K(\Delta y) \)
- \( \chi(\tau) \) non-monotonic

Sakaida+ , 2017
Criticap Point / Correlation Func.

\[ C(\bar{y}) = \langle \delta n(\bar{y})\delta n(0) \rangle / \chi_{\text{hadron}} \]

- Non-monotonic \( \Delta y \) dep.

The analytic result shows that \( C(\Delta y) \) is non-monotonic and \( \chi(\tau) \) is also non-monotonic, as indicated by the graphs.

Sakaida+, 2017
Cumulants and Correlation Function

\[ Q = \int_V dx n(x) \]

- **total charge**
- **charge density**

\[ \langle \delta Q^2 \rangle = \int_V dx dy \langle \delta n(x) \delta n(y) \rangle \]

- **2\textsuperscript{nd} order cumulant** (fluctuation)
- **correlation function**

1-to-1 correspondence

1-dim case

\[ \langle \delta Q^2 \rangle_{\Delta y} = \int_{\Delta y} dy (\Delta y - |y|) \langle \delta n(y) \delta n(0) \rangle \]
Crossover / Correlation Func.

\[ C(\bar{y}) = \frac{\langle \delta n(\bar{y})\delta n(0) \rangle}{\chi_{\text{hadron}}} \]

- monotonically decreasing

Analytic result

\[ \chi(\tau) \]
monotonically increasing

\[ C(\bar{y}) \]
monotonically decreasing

Sakaida+, 2017
Criticap Point / Correlation Func.

\[ C(\bar{y}) = \langle \delta n(\bar{y}) \delta n(0) \rangle / \chi_{\text{hadron}} \]

- non-monotonic \( \Delta y \) dep.

Analytic result

- \( C(\Delta y) \) non-monotonic
- \( \chi(\tau) \) non-monotonic

Sakaida+, 2017
Summary

- Fluctuations observed in HIC are not in equilibrium.
- Non-equil. property can be understood from $\Delta y$ dependence of cumulants.

- A simple diffusion model leads to non-monotonic $\Delta y$ dependence of higher order cumulant.
- Non-monotonic $\Delta y$ dependence of 2$^{nd}$ order cumulant is a signal of QCD critical point.

- Detailed understanding on fluctuations can be established from the study of $\Delta y$ dependences of various cumulants!
Weaker Critical Enhancement

\[ K(\Delta y) = \frac{\langle \delta Q^2 \rangle}{\langle \delta Q^2 \rangle_{\text{eq}}} \quad C(y) = \frac{\langle \delta n(y) \delta n(0) \rangle}{\chi_{\text{hadron}}} \]

- Non-monotonicity in \( K(\Delta y) \) disappears.
- But \( C(y) \) is still non-monotonic.

Analytic result: \( K(\Delta y), \ C(y) \) monotonic \rightarrow no information on \( \chi(\tau) \)

- \( C(y) \) is better to see non-monotonicity.
Signal of the critical enhancement can be clearer on a path away from the CP.

Away from the CP → Weaker critical slowing down
Fluctuations and Elemental Charge

\[ \langle \delta N_q^n \rangle_c = \langle N_q \rangle \]

\[ \langle \delta N_B^n \rangle_c = \frac{1}{3^{n-1}} \langle N_B \rangle \]

Asakawa, Heinz, Muller, 2000
Jeon, Koch, 2000
Ejiri, Karsch, Redlich, 2005
Fluctuations: Theory vs Experiment

Theoretical analyses based on statistical mechanics
- lattice, critical point, effective models, ...

Experiments
- Fluctuations in a momentum space
- discrepancy in phase spaces

Asakawa, Heinz, Muller, 2000; Jeon, Koch, 2000; Shuryak, Stephanov, 2001
Thermal Blurring

\[ \frac{p_z}{E} = v_z = \frac{\dot{z}}{t} \]

Under Bjorken picture,

coordinate-space rapidity \( Y \)

\[ \parallel \]

momentum-space rapidity \( y \)

of medium

\[ \\]

momentum-space rapidity \( y \)

of individual particles

\[ \Delta y \approx \Delta Y \]
Thermal distribution in $y$ space

$w = \frac{m}{T}$

- pions $w \approx 1.5$
- nucleons $w \approx 9$

- blast wave
- flat freezeout surface
Diffusion Master Equation

Divide spatial coordinate into discrete cells

\[ P(n) \]
Diffusion Master Equation

Divide spatial coordinate into discrete cells

Master Equation for $P(n)$

\[
\frac{\partial}{\partial t} P(n) = \gamma \sum_x [(n_x + 1) \{P(n + e_x - e_{x+1}) + P(n + e_x - e_{x-1})\} - 2n_x P(n)]
\]

Solve the DME **exactly**, and take $a \to 0$ limit

No approx., ex. van Kampen’s system size expansion
History of HIC = increasing energy

Beam-energy scan
Low-energy exp.

Creation of quark-gluon plasma, strongly-interacting QGP

~2010
History of HIC = increasing energy
**Baryon Stopping**

Rapidity dep. of net-proton #

\[ \sqrt{s_{NN}} \approx 4 - 6\text{GeV} \]

Baryons stop at collision point

\[ \sqrt{s_{NN}} > 10\text{GeV} \]

Baryons pass through

Phase diagram from J-PARC White Paper

5GeV

20GeV

200GeV

Transparency

Rapidity

Quark-Gluon

Plasma

Compact Stars

J-PARC FAIR • NICA

Hadronic Phase
Variation of a conserved charge is achieved only through diffusion.

The larger $\Delta \eta$, the slower diffusion.
The graph illustrates the dependence of a certain quantity on the rapidity window, with different color segments representing different data points: 0-5%, 20-30%, and 40-50%.

The D-measure is defined as:

\[ D = 4 \frac{\langle \delta N_Q^2 \rangle}{\langle N_Q^+ + N_Q^- \rangle} \]

- \( D \sim 3-4 \) Hadronic
- \( D \sim 1-1.5 \) Quark
\[ D \sim \frac{\langle \delta N_Q \rangle^2}{\Delta \eta} \]

has to be a constant in equil. medium

Fluctuation of \( N_Q \) at ALICE is not the equilibrated one.
How does $\langle \delta N_Q^4 \rangle_c$ behave as a function of $\Delta \eta$? suppression or enhancement
How does \( \langle \delta N_Q^4 \rangle_c \) behave as a function of \( \Delta \eta \)?

- suppression
- enhancement
Hadrons