Search for QCD Critical Point at J-PARC Heavy-Ion Program

Masakiyo Kitazawa
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REIMEI Workshop, J-PARC, Tokai, Dec. 13, 2017

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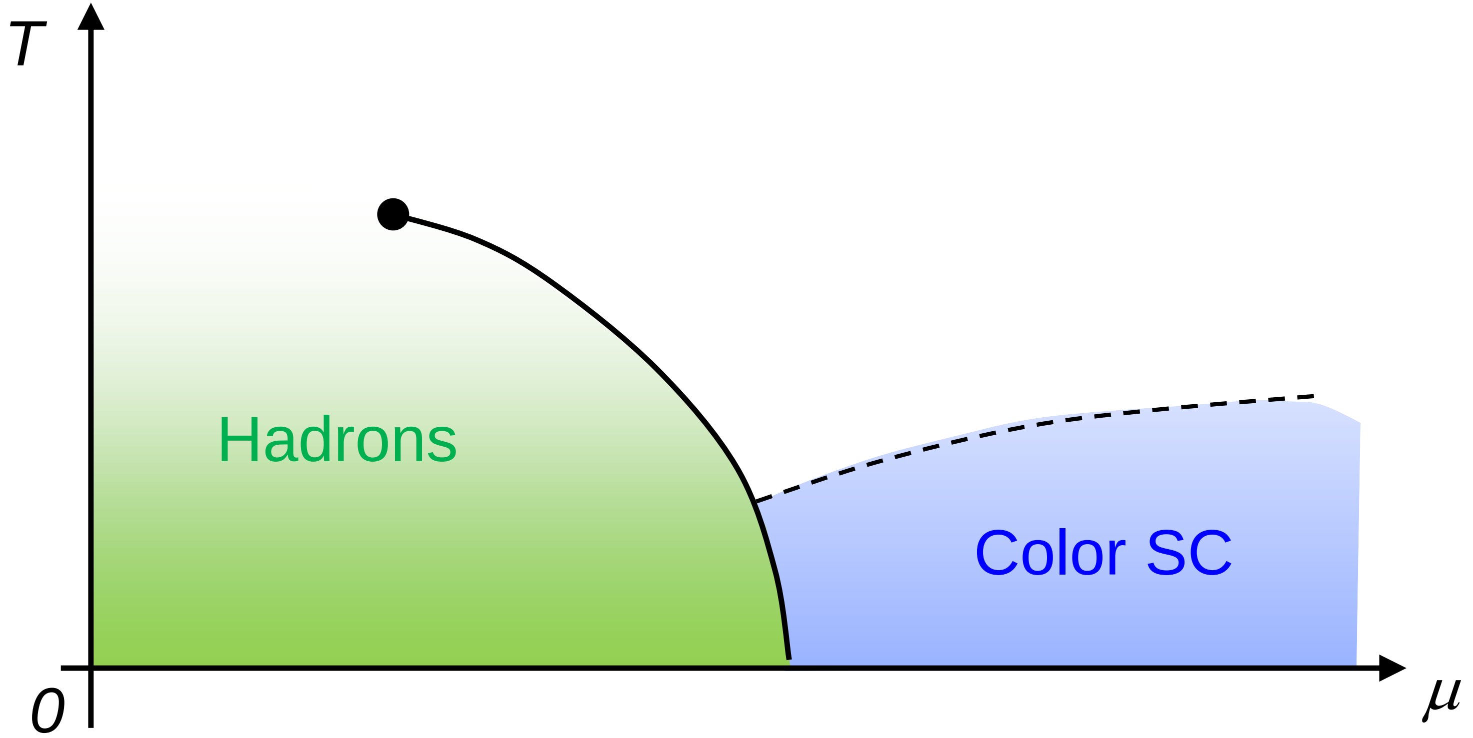
Two topics covered in this talk

① J-PARC Heavy-Ion Program

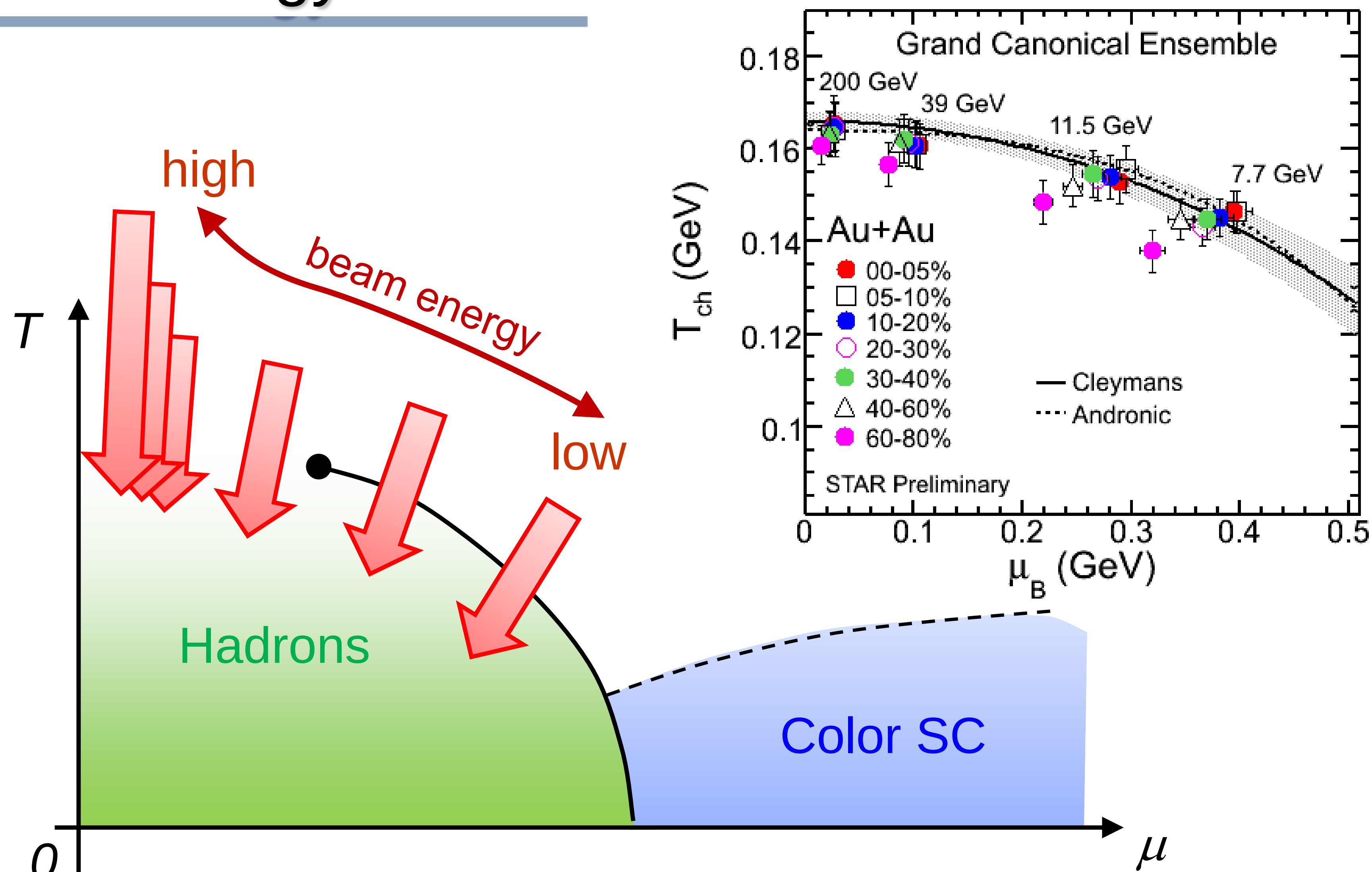
② Exp. Search for QCD-CP with fluctuations

REIMEI Workshop, J-PARC, Tokai, Dec. 13, 2017

Beam-Energy Scan

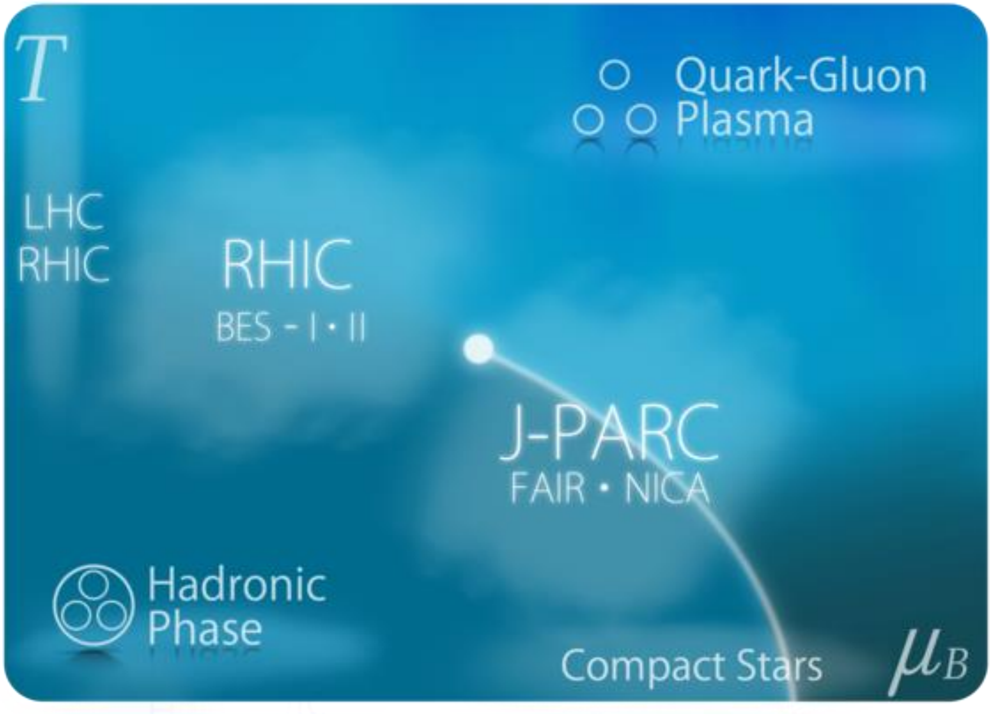


Beam-Energy Scan



Search for QCD phase structure / critical point

J-PARC Heavy-Ion Program (J-PARC-HI)



J-PARC-HI

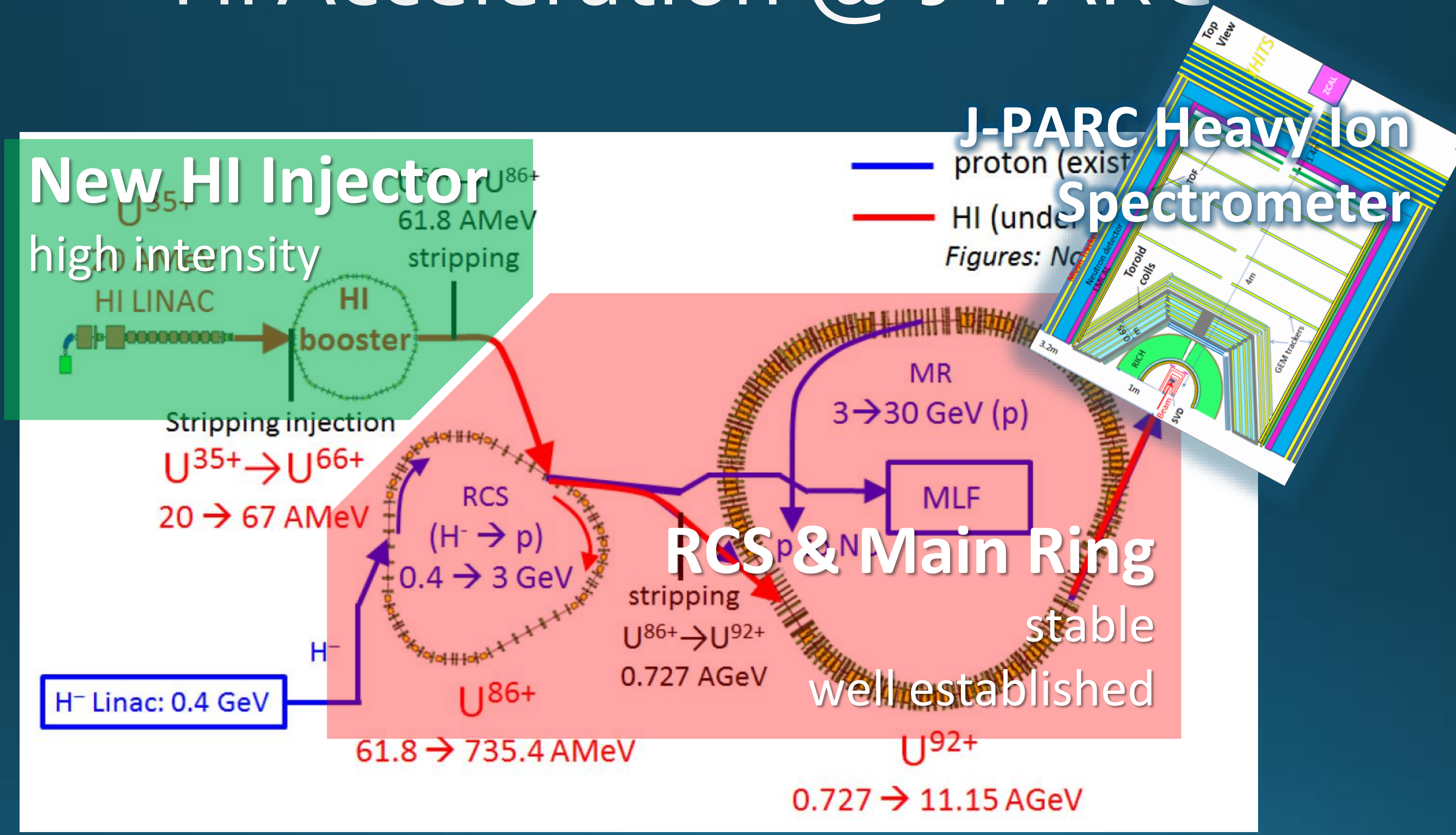
J-PARC = Japan **Proton** Accelerator Research Complex

J-PARC-HI = J-PARC **H**eavy-**I**on Program

- Beam energy: ~20GeV/A ($\sqrt{s}$~6.2GeV)
- Fixed target experiment
- High luminosity: collision rate ~10^8Hz
- Launch: (hopefully) 2025~

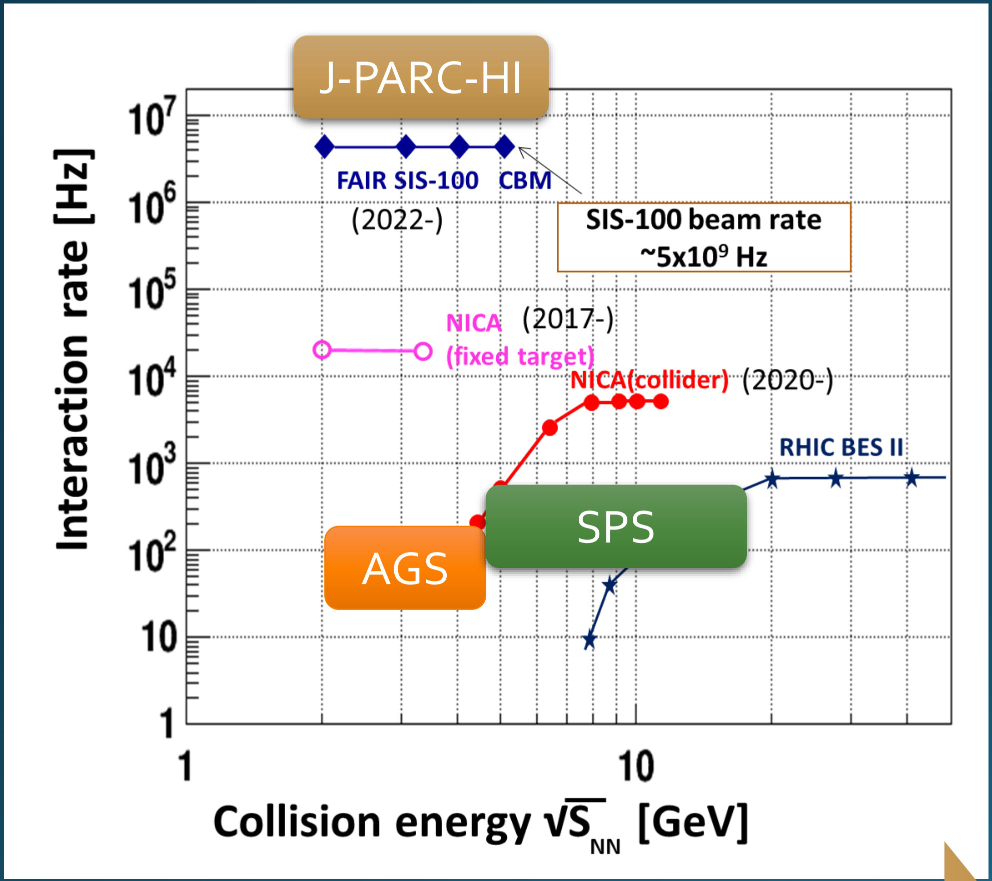
- White paper / Letter of Intent (2016)
  - http://asrc.jaea.go.jp/soshiki/gr/hadron/jparc-hi/

HI Acceleration @ J-PARC



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

Collision Rate



J-PARC-HI:

High-luminosity x Fixed target

→World highest rate～10^8Hz

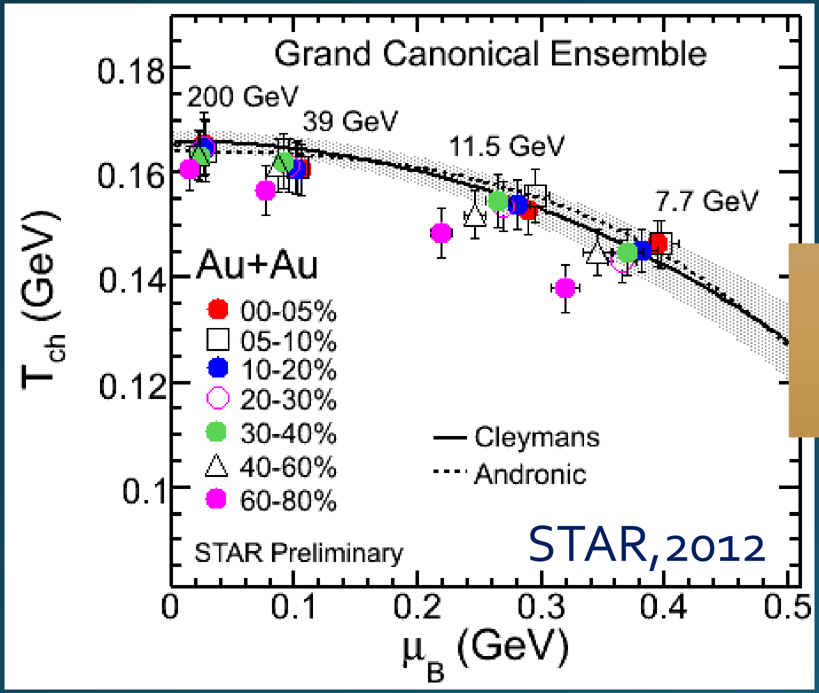
5-order higher than AGS,SPS

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

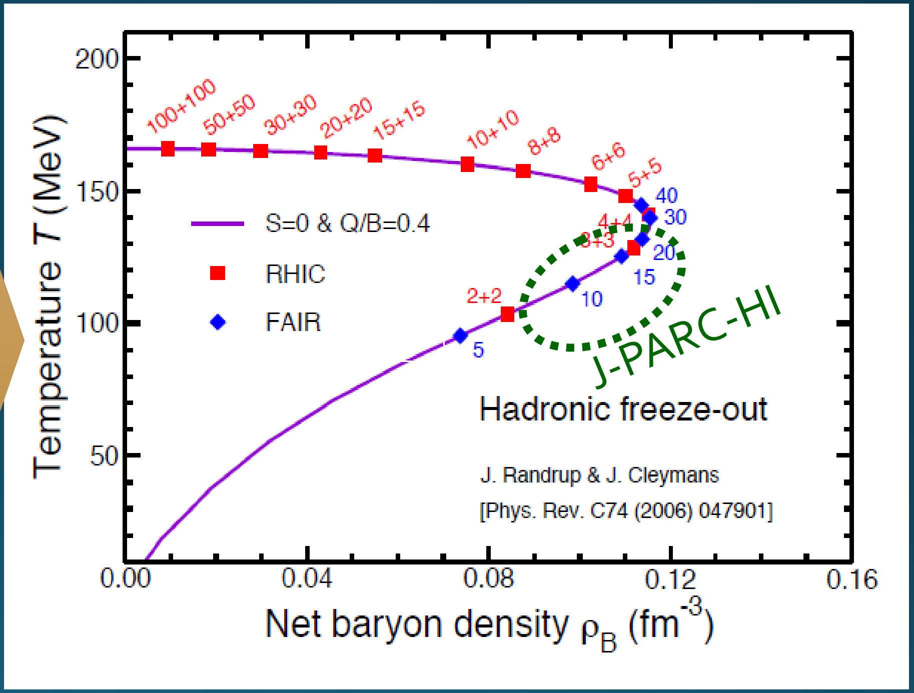
- High-statistical exp.
- higher order correlations
- various event selections
- search of rare events

Beam-Energy Scan

T, μ from particle yield



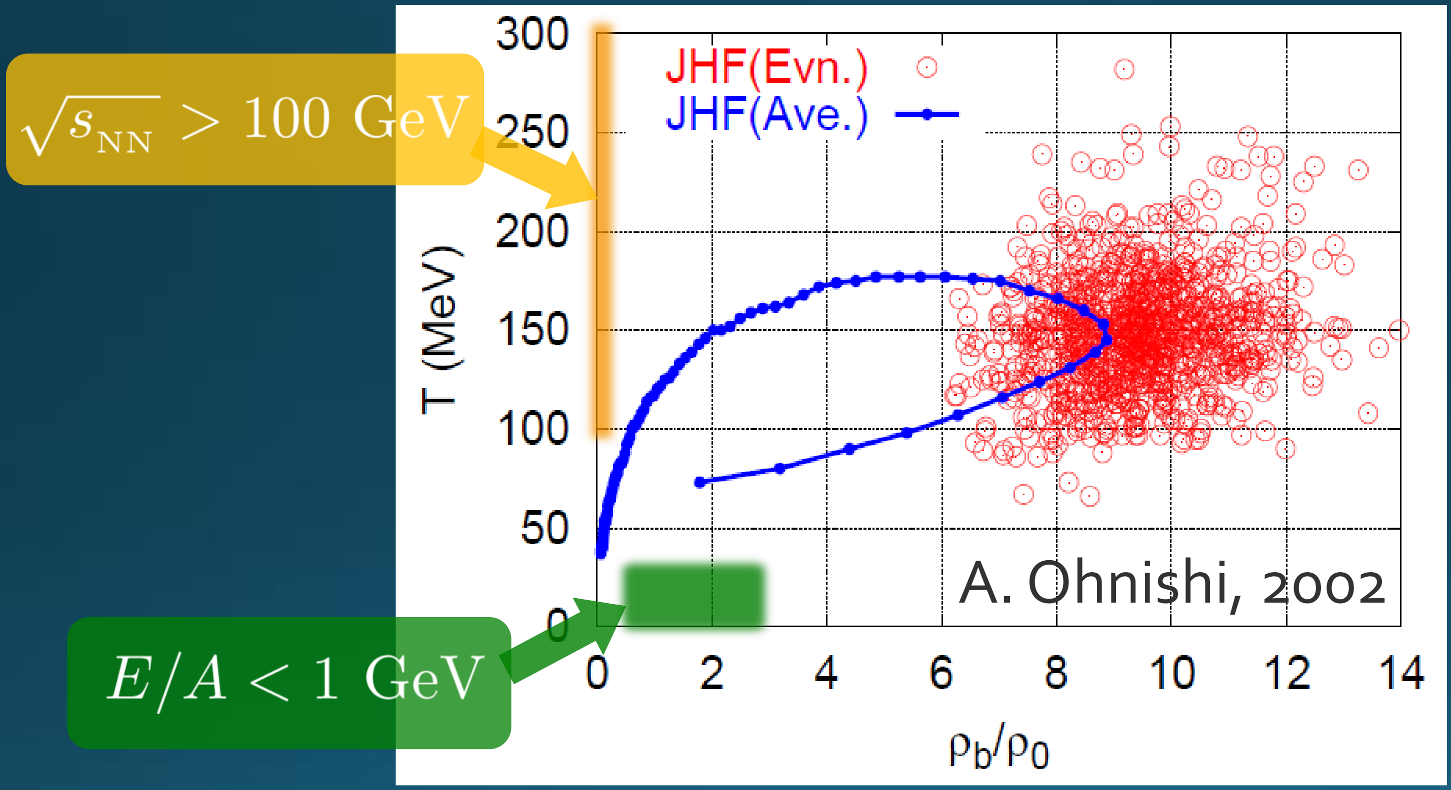
Translation to baryon density



J-PARC energy = highest baryon density

Maximum Density

Time evolution in T-ρ plane by JAM

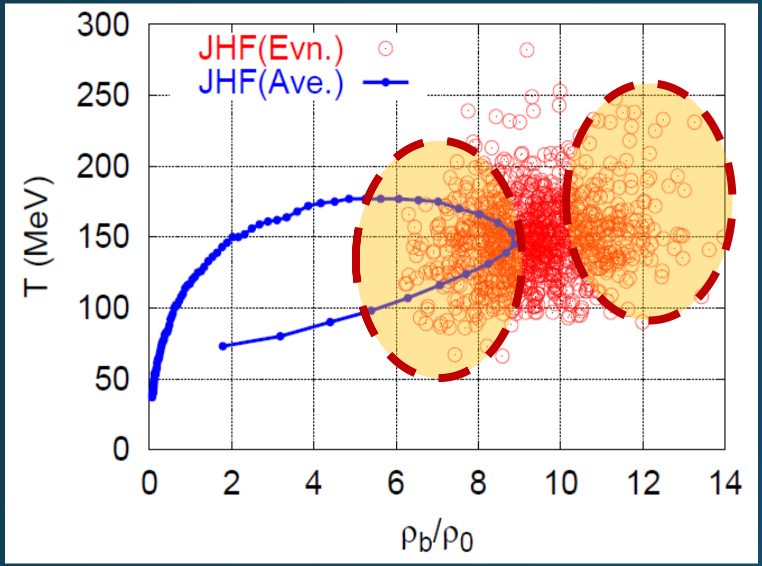


$$E/A = 20\text{GeV}$$

$$\sqrt{s_{NN}} \simeq 6\text{GeV}$$

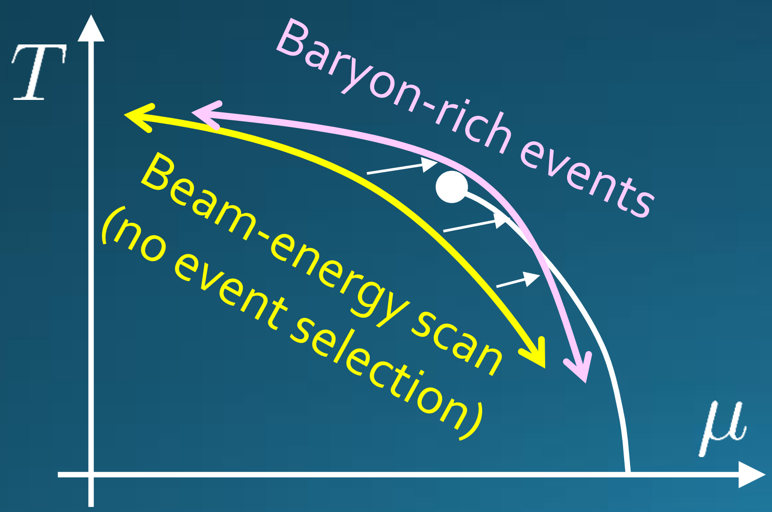
- ☐ Maximum density 5~10ρ_0 @ J-PARC energy
- ☐ Large event-by-event fluctuations?

Maximum Density Scan?

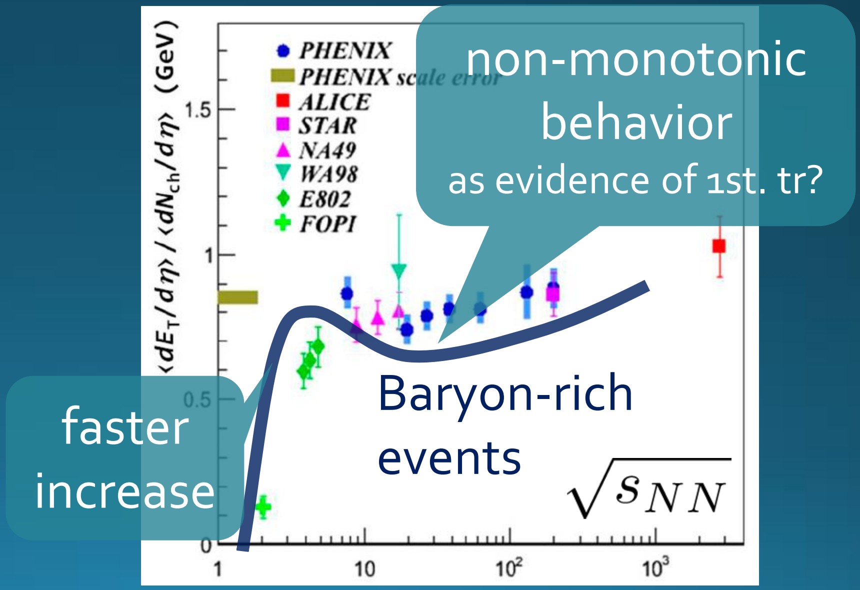


Large event-by-event fluctuations even after fixed centrality / collision energy

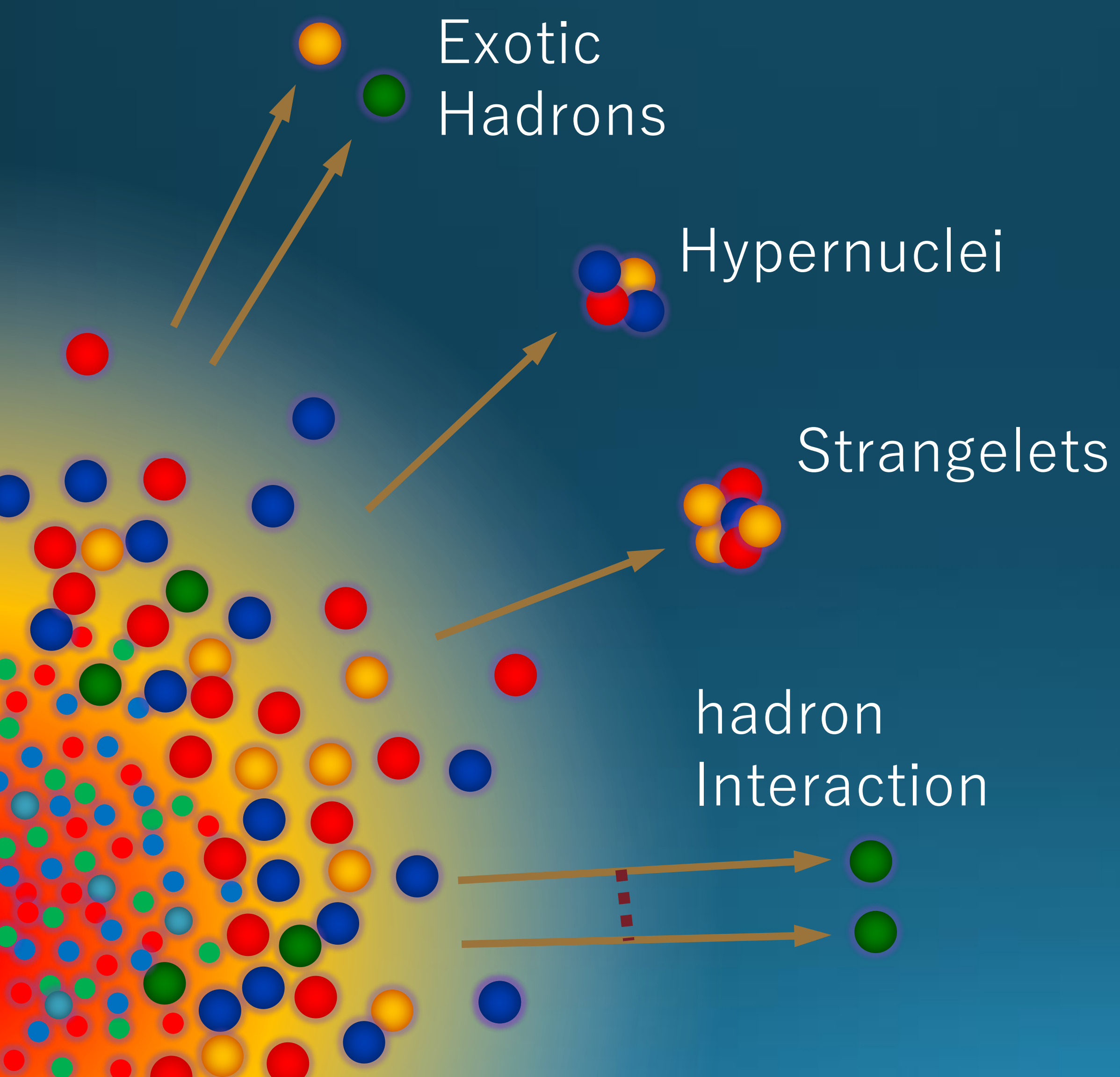
If we can select events, "maximum density" dependence can be studied experimentally.



average transverse energy



Search of Rare Events



- High density
- High luminosity
- High strange yield

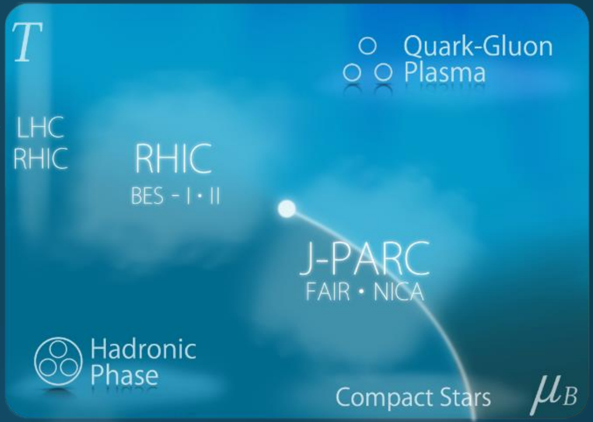
Rare-event Factory

- 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

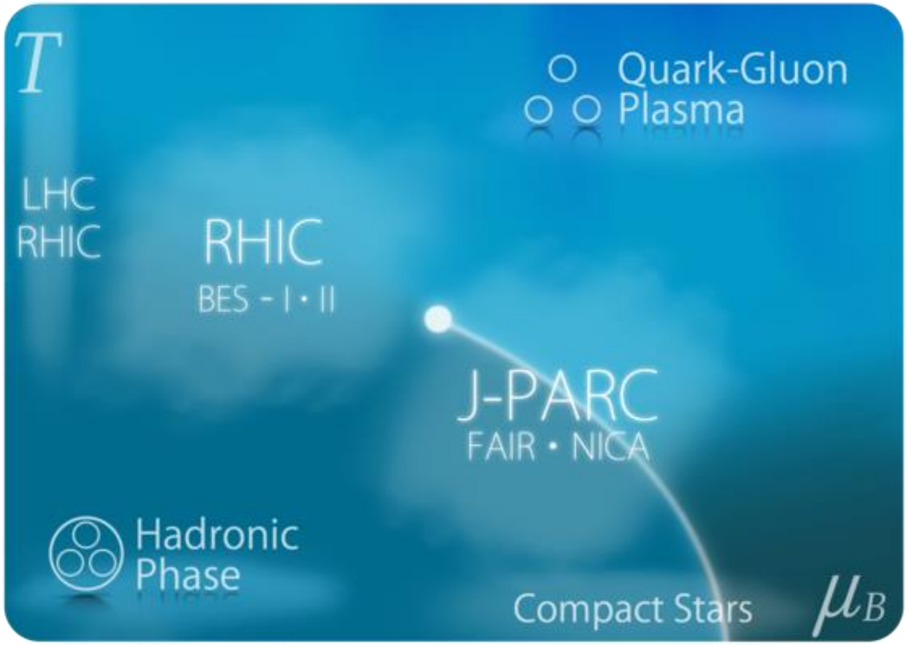


Visit J-PARC-HI Web Page
http://asrc.jaea.go.jp/soshiki/gr/hadron/jparc-hi/

☐ 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

Search for QCD Critical Point with Fluctuations

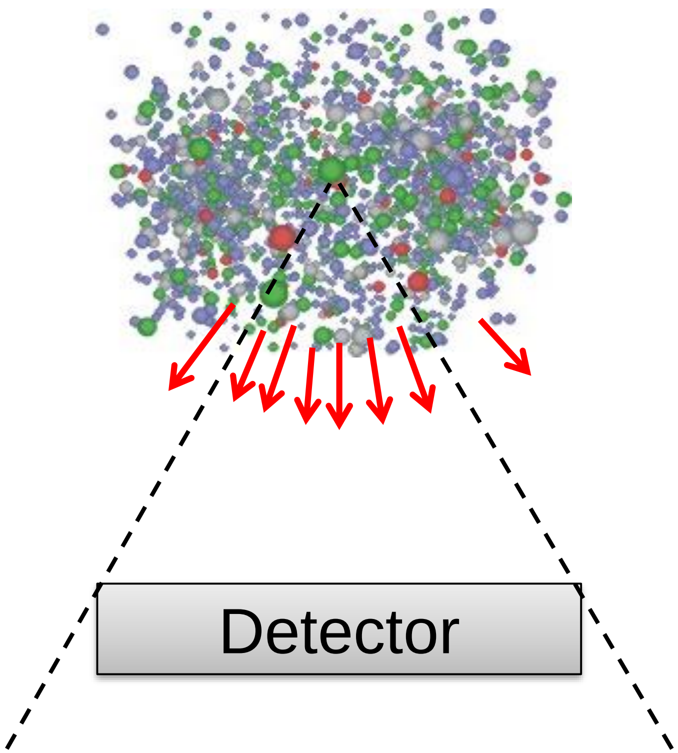


Sakaida, Asakawa, Fujii, MK, Phys. Rev. C95, 064509 (2017)
Asakawa, MK, Prog. Part. Nucl. Phys. 90, 299 (2016)
Ohnishi, MK, Asakawa, Phys. Rev. C94, 044905 (2016)
MK, Nucl. Phys. A942, 65 (2015)
MK, Asakawa, Ohno, Phys. Lett. B728, 386 (2014)

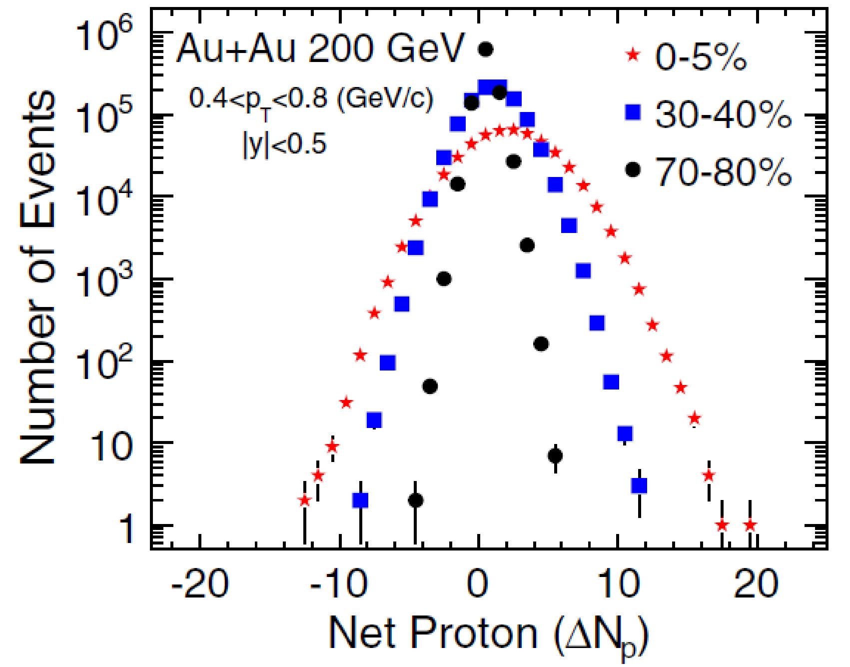
Event-by-Event Fluctuations

Review: Asakawa, MK, PPNP **90** (2016)

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



STAR, PRL**105** (2010)



Cumulants

$$\langle \delta N_p^2 \rangle, \langle \delta N_p^3 \rangle, \langle \delta N_p^4 \rangle_c$$

A Coin Game

① Bet 500YEN

② You get head coins of

A. 20 x 50YEN

B. 10 x 100YEN

Same expectation value.

A Coin Game

① Bet 500YEN
② You get head coins of

A. 20 x 50YEN

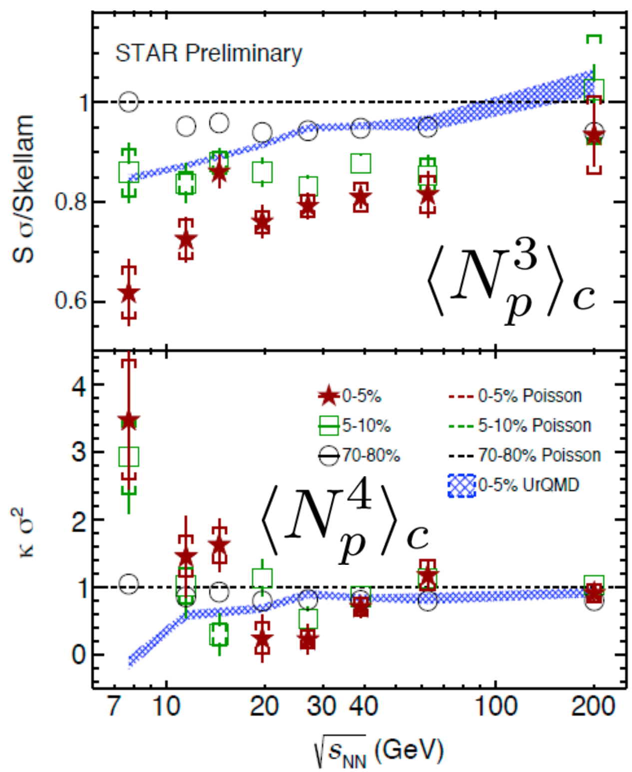
B. 10 x 100YEN

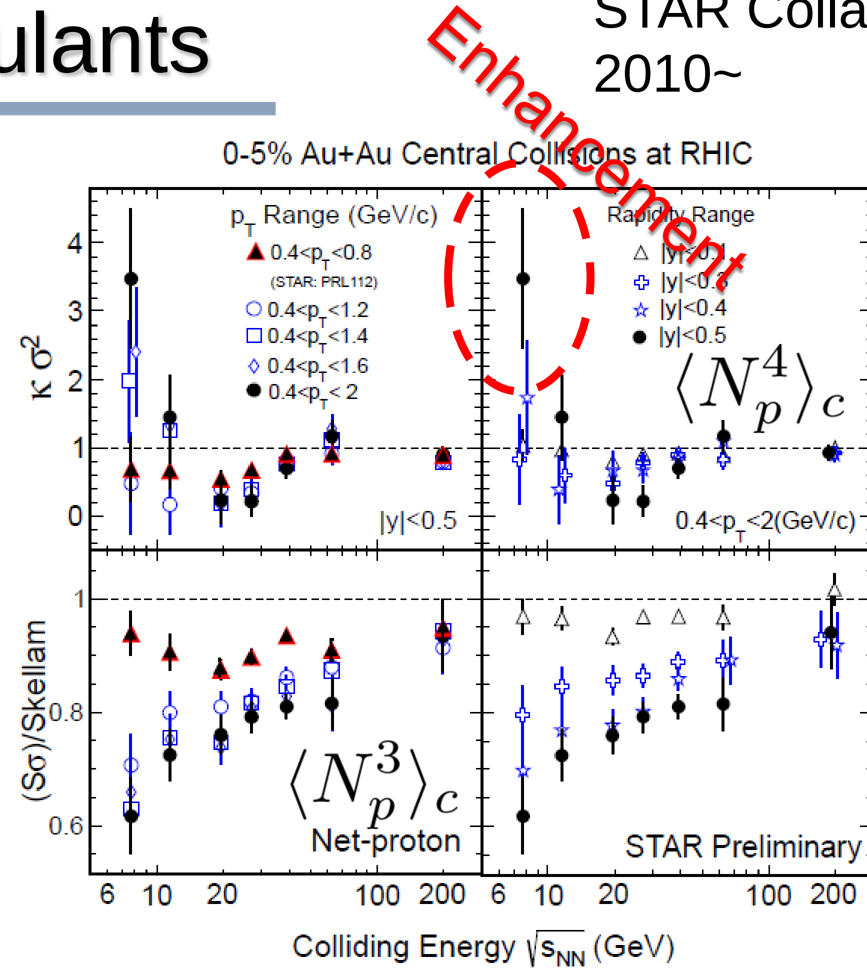
C. 1 x 1000YEN

Same expectation value.
But, different fluctuation.

Higher-Order Cumulants

STAR Collab. 2010~



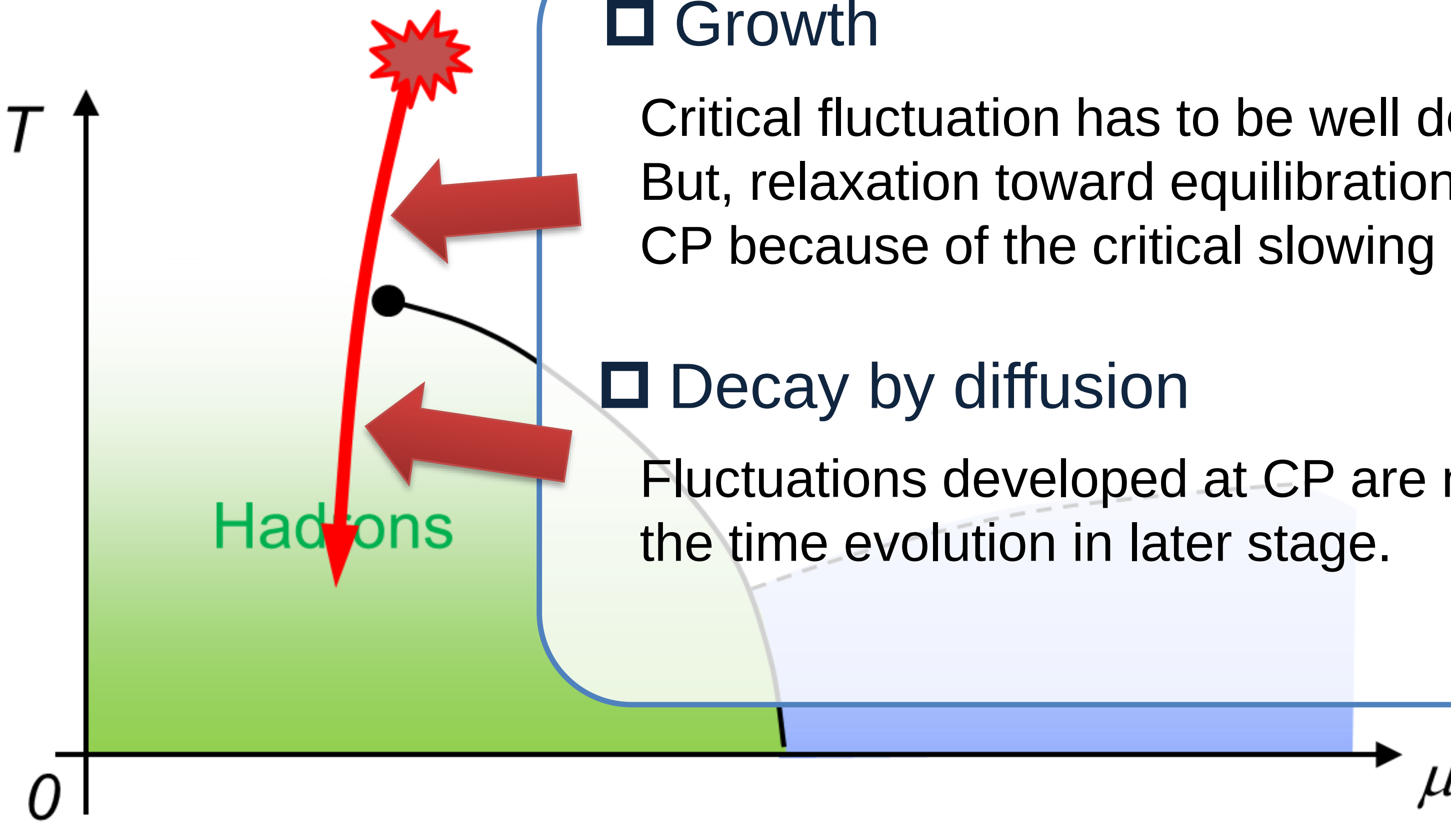


Non-zero **non**-Gaussian cumulants have been established!

Have we measured critical fluctuations?

Remarks on Fluctuations in HIC

Experiments cannot observe critical fluctuation in equilibrium directly.



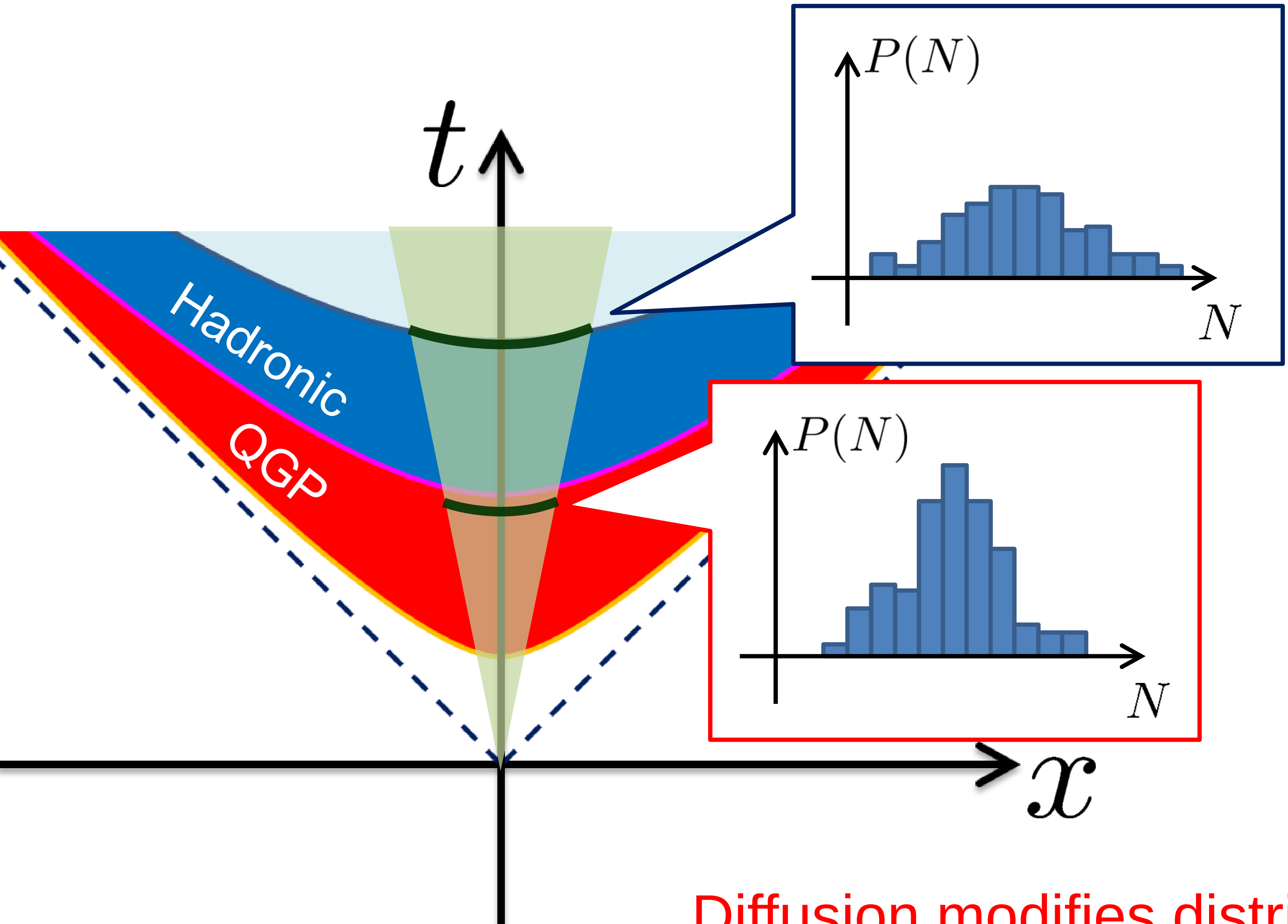
☐ Growth

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.

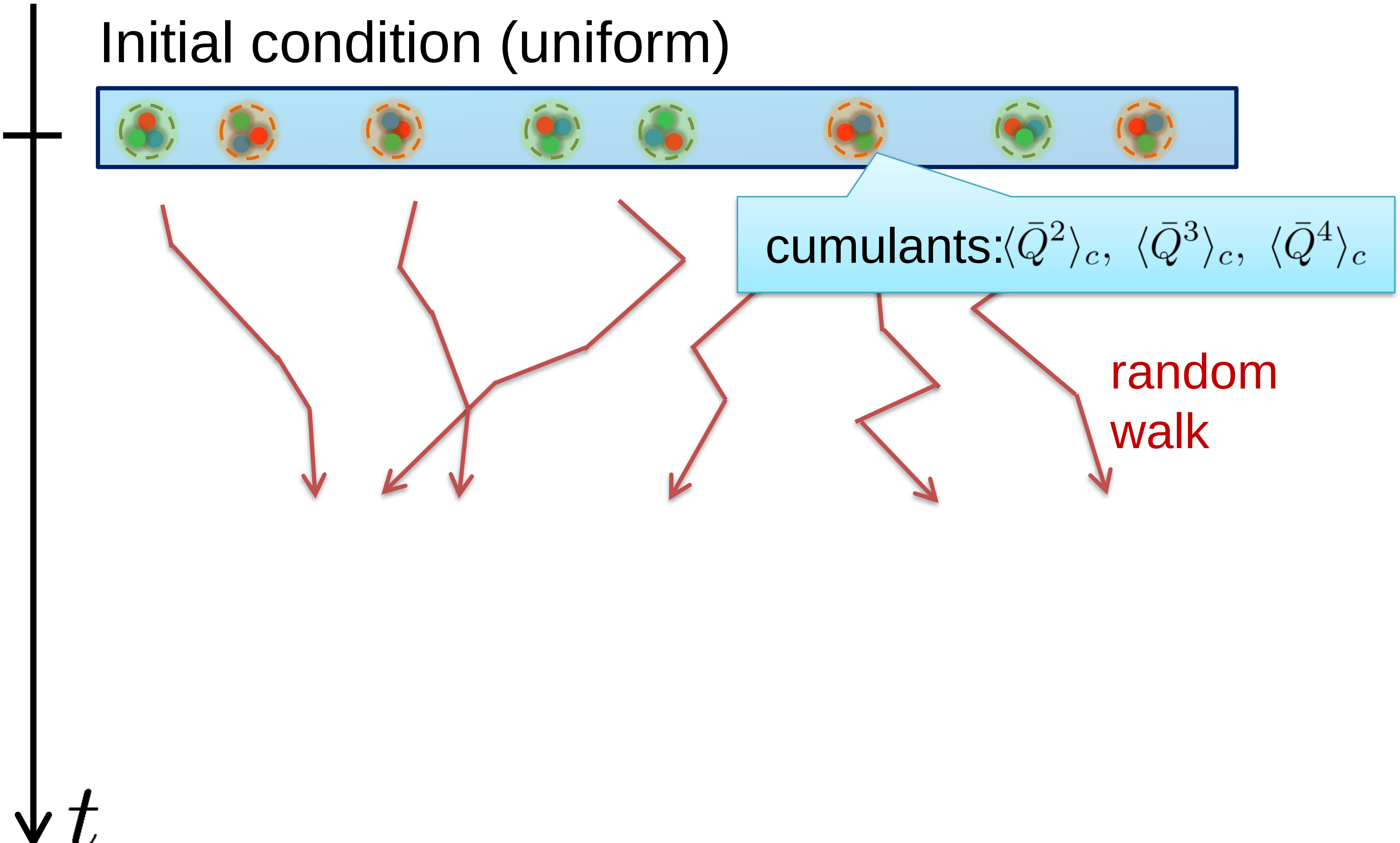
Time Evolution of Fluctuations



Diffusion modifies distribution

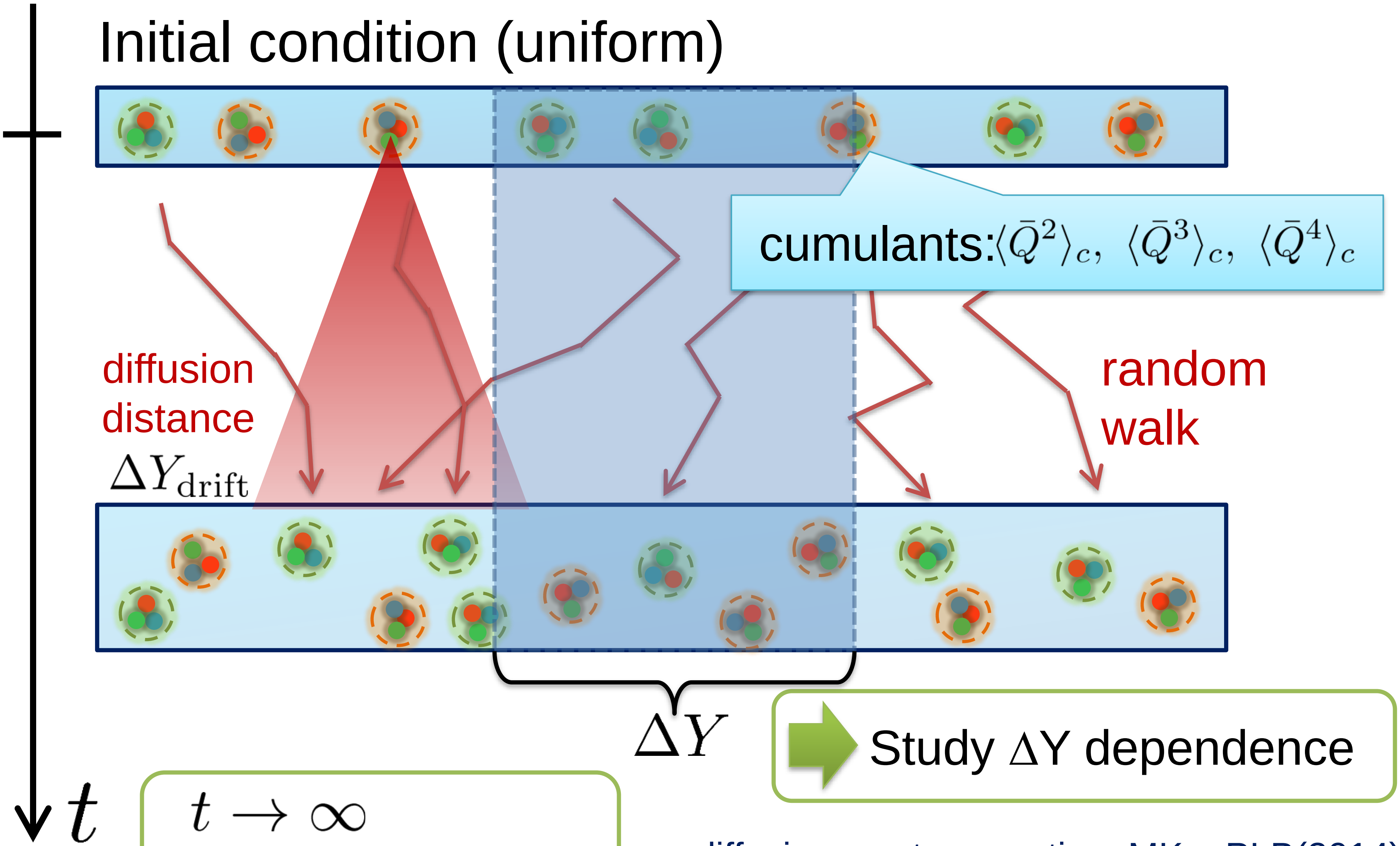
Diffusion in Hadronic Stage

(Non-Interacting) Brownian Particle Model



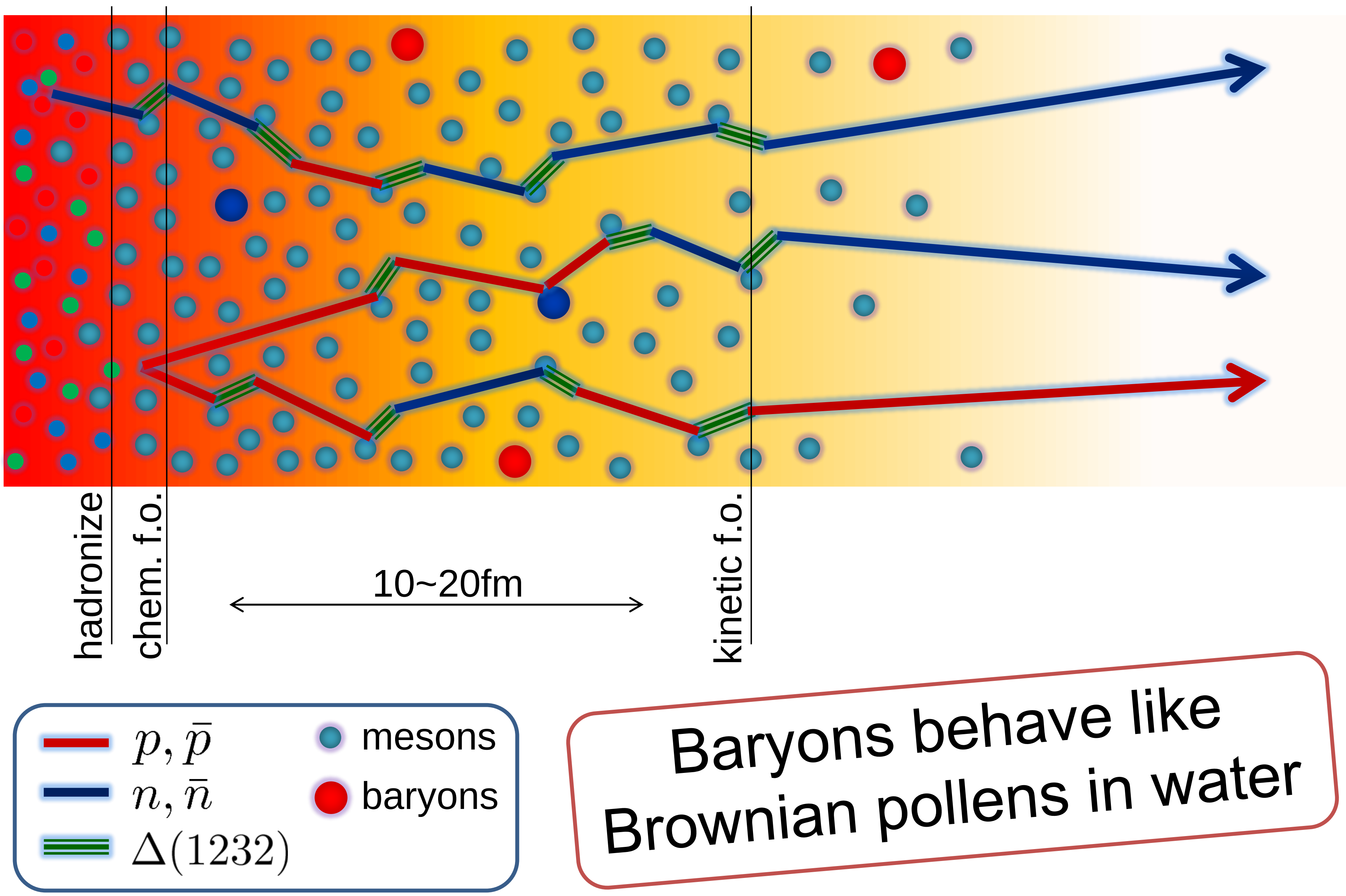
diffusion master equation: MK+, PLB(2014)
probabilistic argument: Ohnishi+, PRC(2016)

(Non-Interacting) Brownian Particle Model



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

Baryons in Hadronic Phase



Baryons behave like Brownian pollens in water

Rapidity Window Dep.

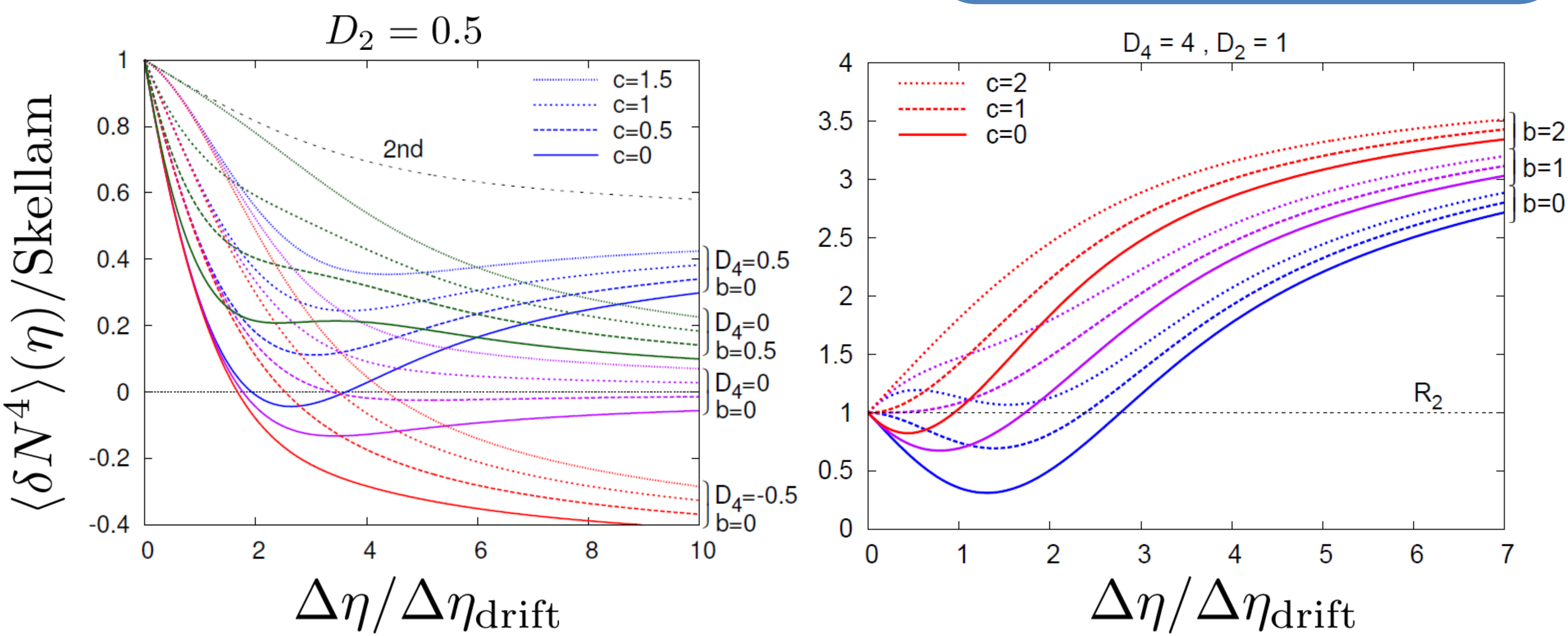
4th-order cumulant

MK+, 2014
MK, 2015

Initial Conditions

$$D_4 = \frac{\langle Q^4_{(\mathrm{net})}\rangle_c}{\langle Q_{(\mathrm{tot})}\rangle} \qquad b = \frac{\langle Q^2_{(\mathrm{net})} Q_{(\mathrm{tot})}\rangle_c}{\langle Q_{(\mathrm{net})}\rangle}$$

$$D_2 = \frac{\langle Q^2_{(\mathrm{net})}\rangle_c}{\langle Q_{(\mathrm{tot})}\rangle} \qquad c = \frac{\langle Q^2_{(\mathrm{tot})}\rangle_c}{\langle Q_{(\mathrm{tot})}\rangle}$$



- Different initial conditions give rise to different characteristic $\Delta\eta$ dependence.
- Non-monotonic behaviors can appear in $\Delta\eta$ dependence.

Finite volume effects: Sakaida+, PRC90 (2015)

Rapidity Window Dep.

4th-order cumulant

MK+, 2014
MK, 2015

Initial Conditions

$$D_4 = \frac{\langle Q^4_{(\mathrm{net})}\rangle_c}{\langle Q_{(\mathrm{tot})}\rangle} \qquad b = \frac{\langle Q^2_{(\mathrm{net})} Q_{(\mathrm{tot})}\rangle_c}{\langle Q_{(\mathrm{net})}\rangle}$$

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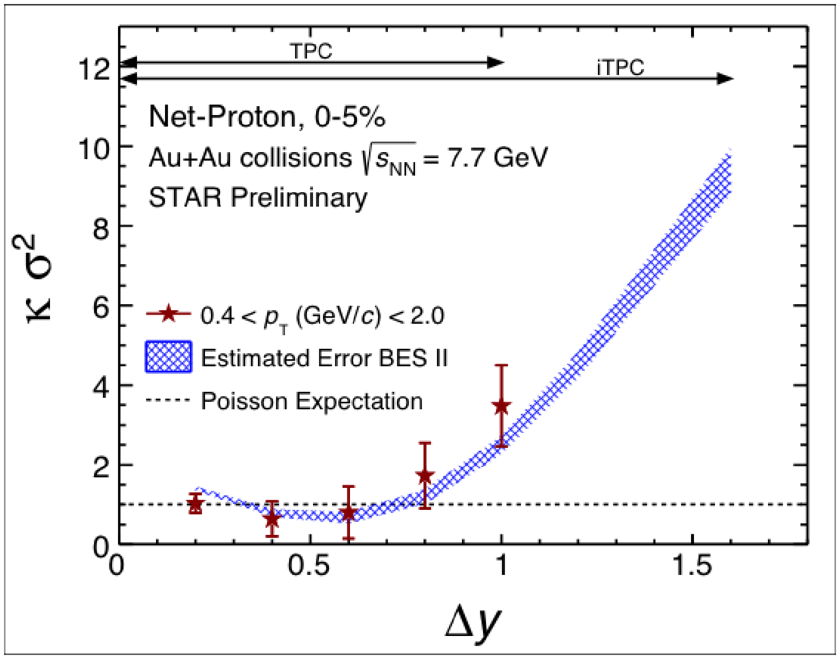
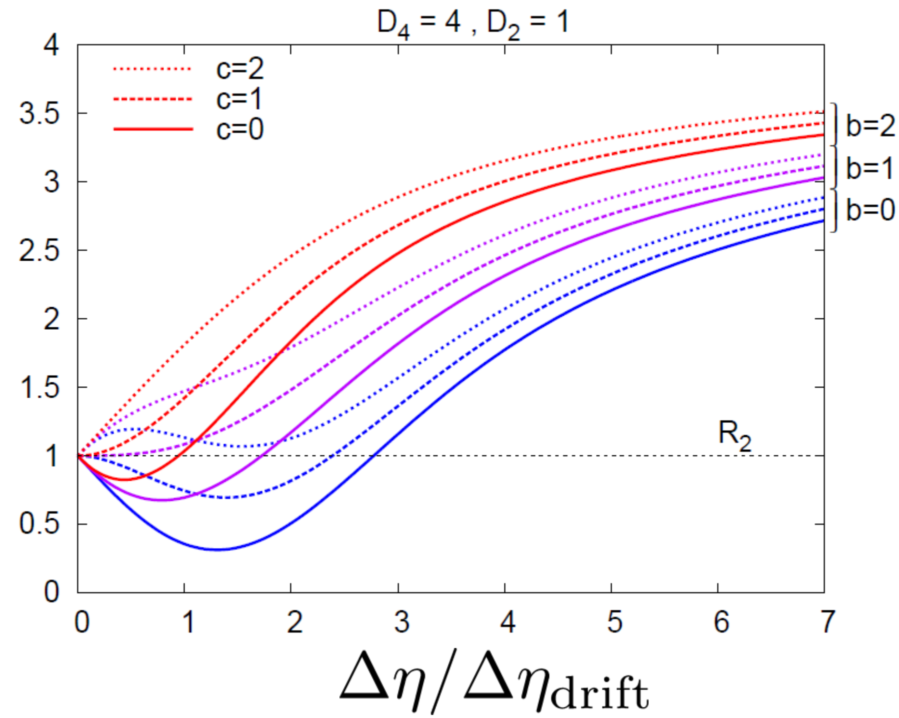
STAR Collab. (X. Luo, CPOD2014)





- Different initial conditions give rise to different characteristic $\Delta\eta$ dependence.
- Non-monotonic behaviors can appear in $\Delta\eta$ dependence.

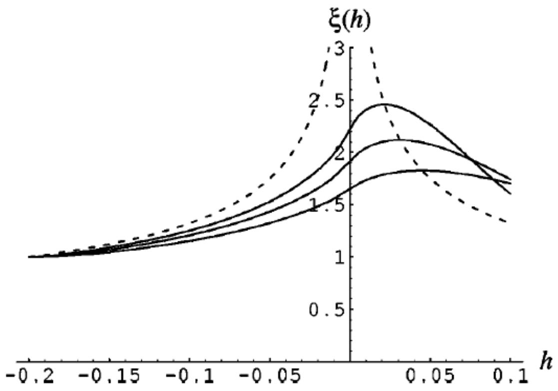
Finite volume effects: Sakaida+, PRC90 (2015)

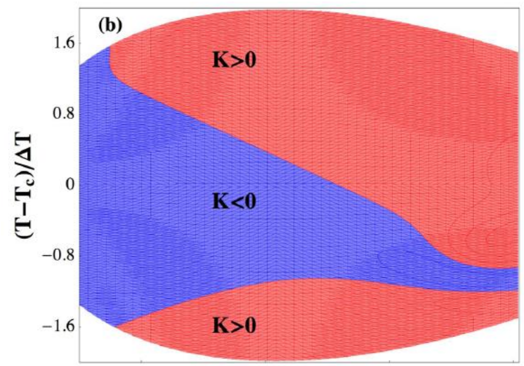
Dynamical Evolution near QCD Critical Point

Growth and Decay of Critical Fluc.

- Previous studies: uniform σ mode

Berdnikov, Rajagopal (2000)
Asakawa, Nonaka (2002)
Mukherjee+ (2015)

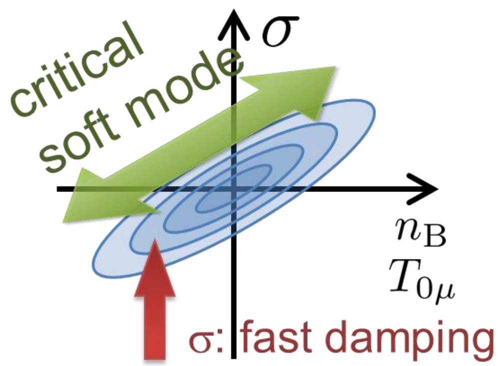


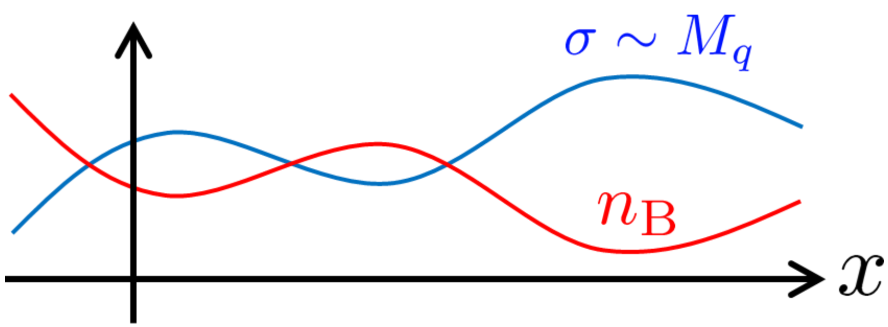


Recent Developments:
Kapusta, Torres-Rincon (2012)
Nahrgang, Herold+ (2014~)
Song+ (2016~)

- Problems:
  - The soft mode of QCD-CP is a conserved mode
  - Sigma mode is not directly observable

Fujii (2003)
Son, Stephanov (2004)





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 denepdence** of the cumulant
  - 2-particle **correlation function** in rapidity space

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
- χ: susceptibility (fluctuation in equil.)

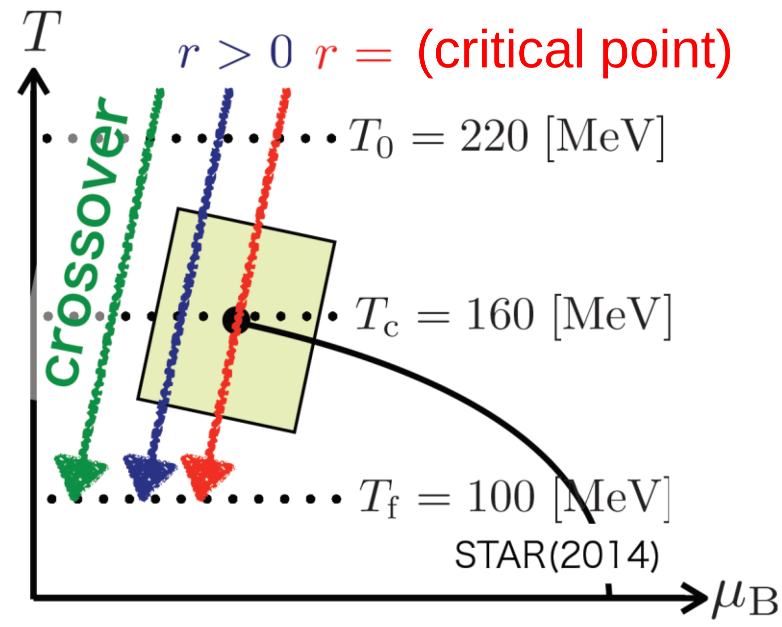
Review: Asakawa, MK, PPNP **90** (2016)

Parametrizing D(τ) and χ(τ)

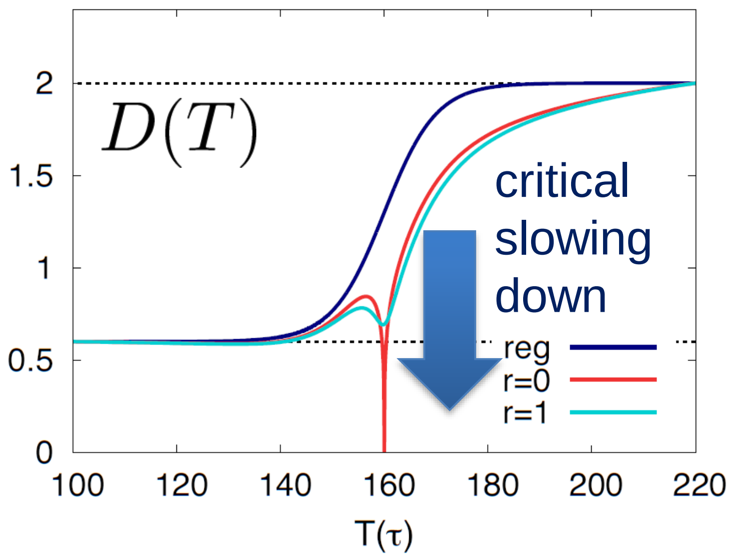
Sakaida+, 2017

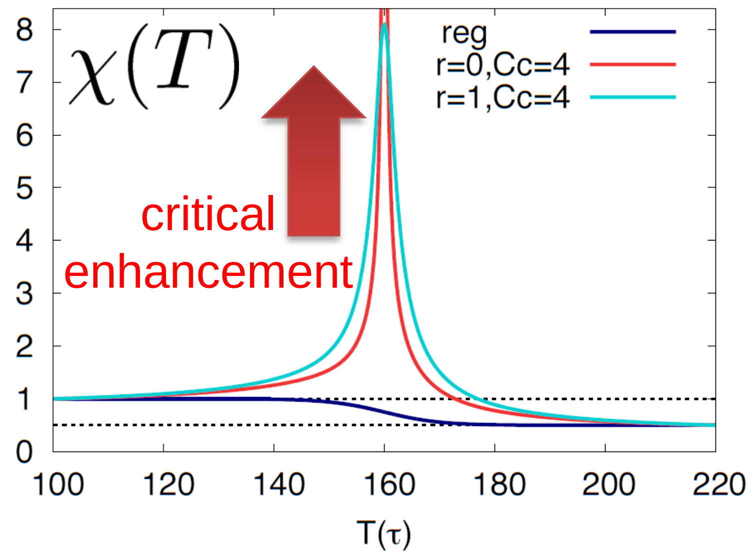
☐Critical behavior

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



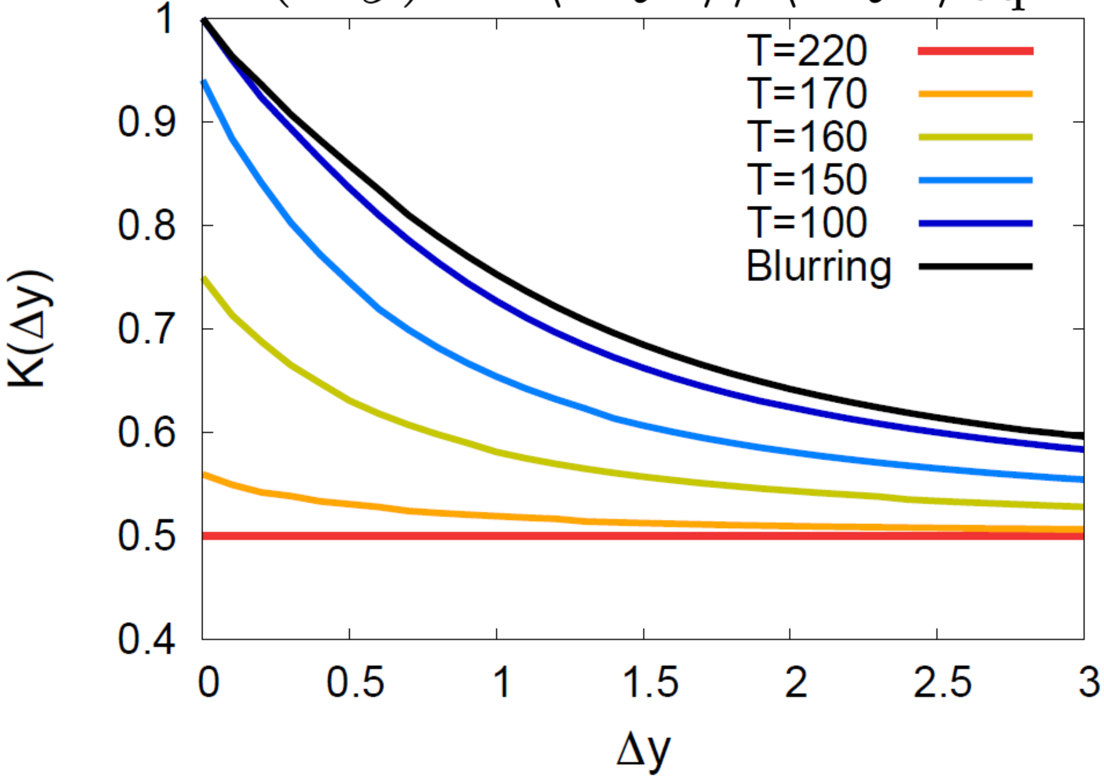
☐Temperature dep.

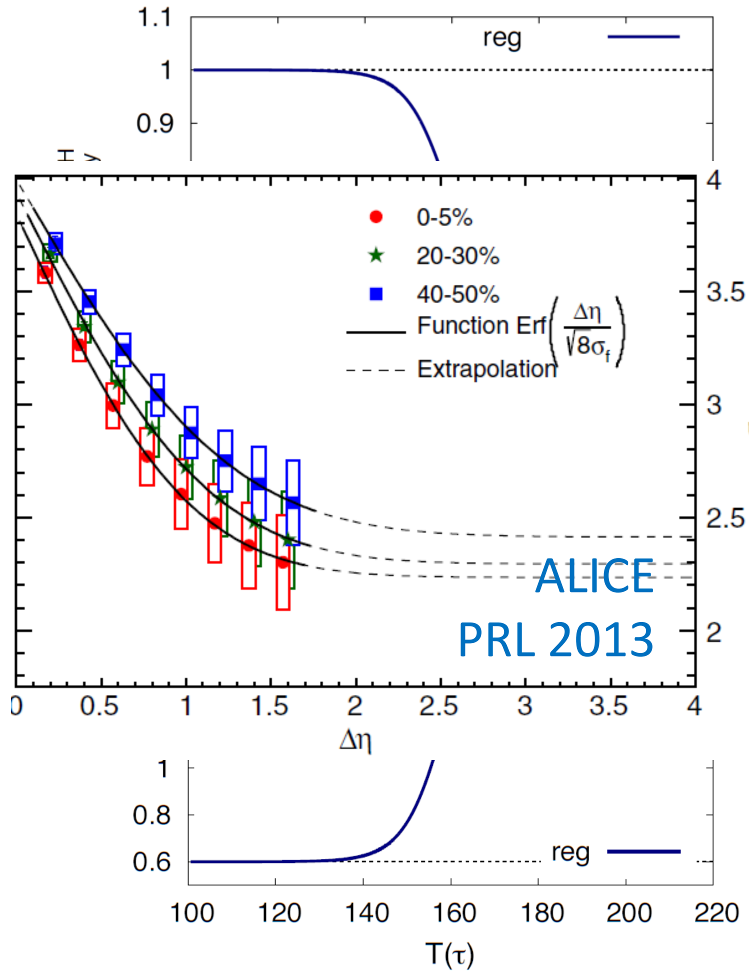




Crossover / Cumulant

$$K(\Delta y) = \langle \delta Q^2 \rangle / \langle \delta Q^2 \rangle_{\text{eq.}}$$





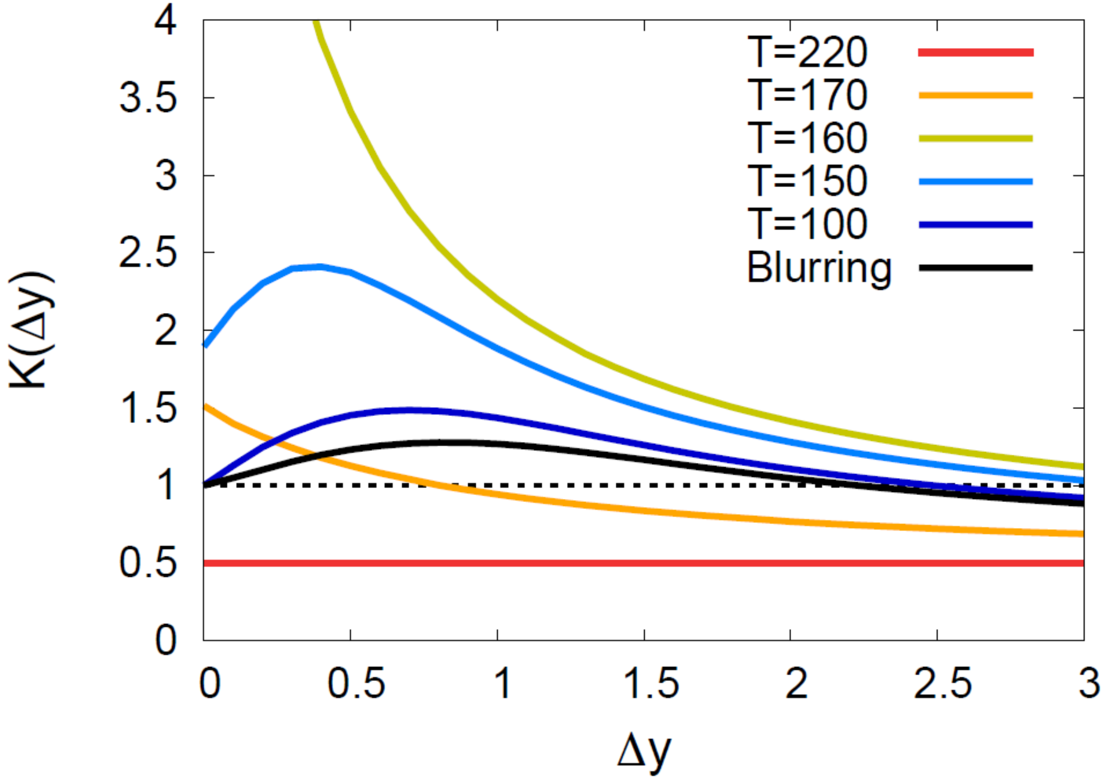
□ monotonically decresing

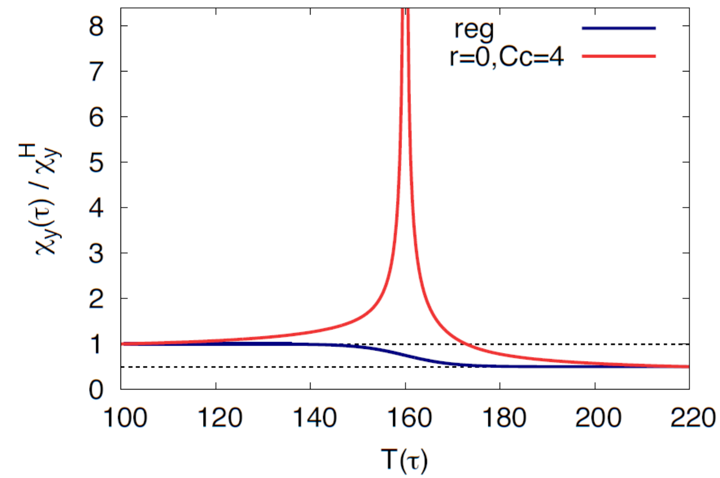
Analytic result | $\chi(\tau)$ monotonically increasing ⇨ $K(\Delta y)$ monotonically decreasing

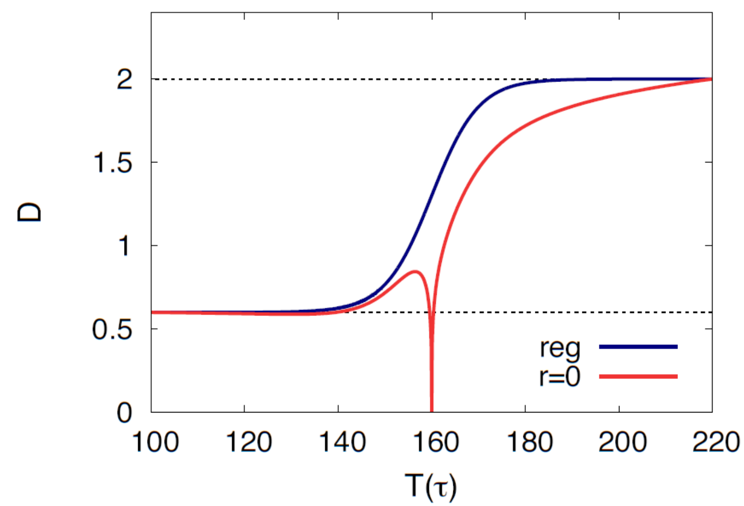
Critical Point / Cumulant

Sakaida+, 2017

$$K(\Delta y) = \langle \delta Q^2 \rangle / \langle \delta Q^2 \rangle_{\mathrm{eq.}}$$





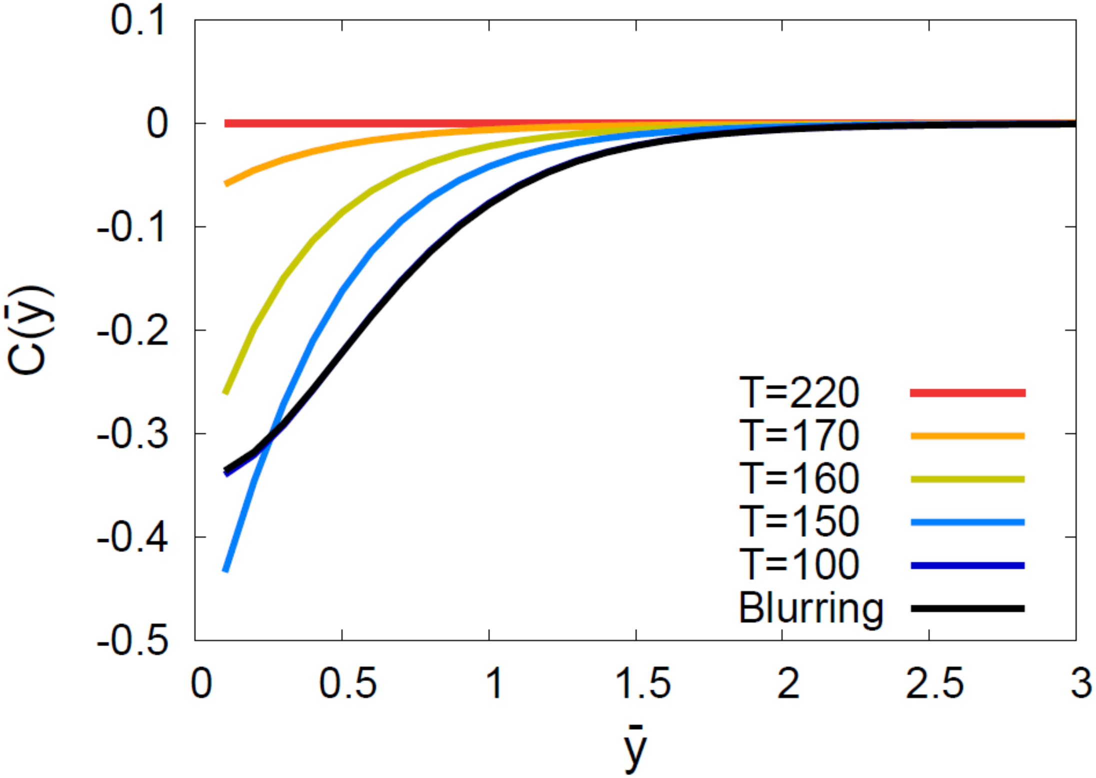


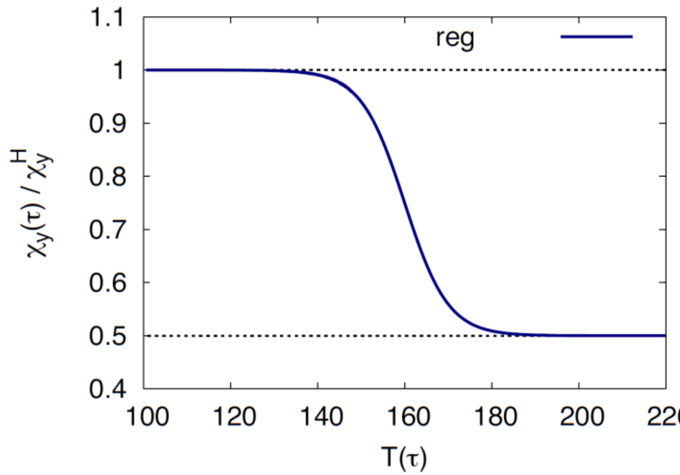
- non-monotonic Δy dep.

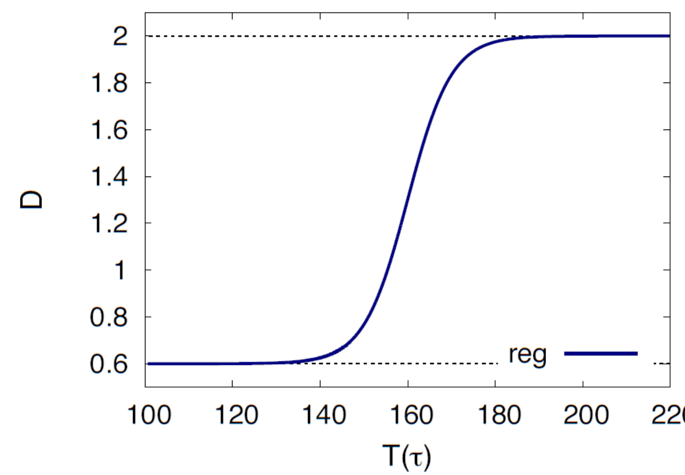
Analytic result: $K(\Delta y)$ non-monotonic → $\chi(\tau)$ non-monotonic

Crossover / Correlation Func.

$$C(\bar{y}) = \langle \delta n(\bar{y}) \delta n(0) \rangle / \chi_{\mathrm{hadron}}$$







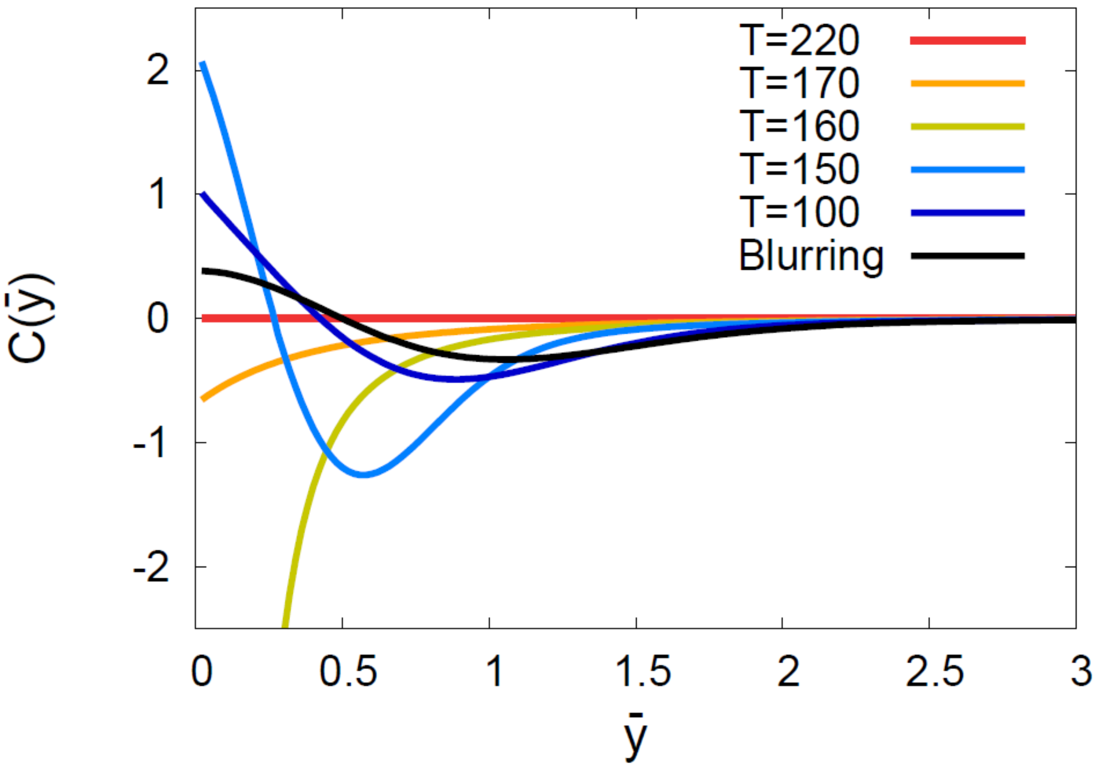
- monotonically decresing

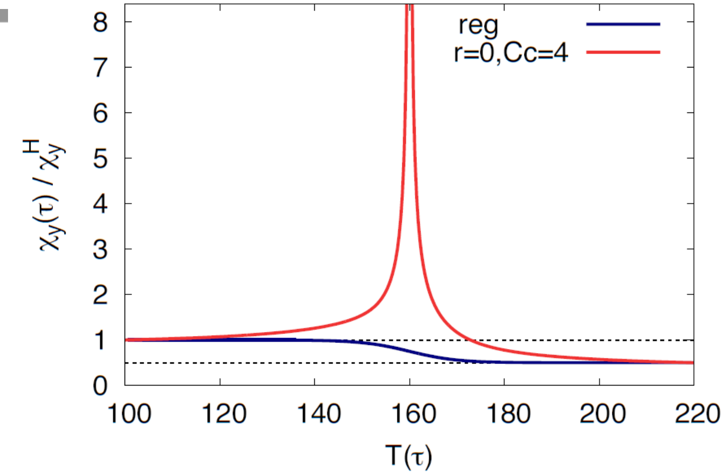
Analytic result: $\chi(\tau)$ monotonically increasing ⇒ $C(\bar{y})$ monotonically decreasing

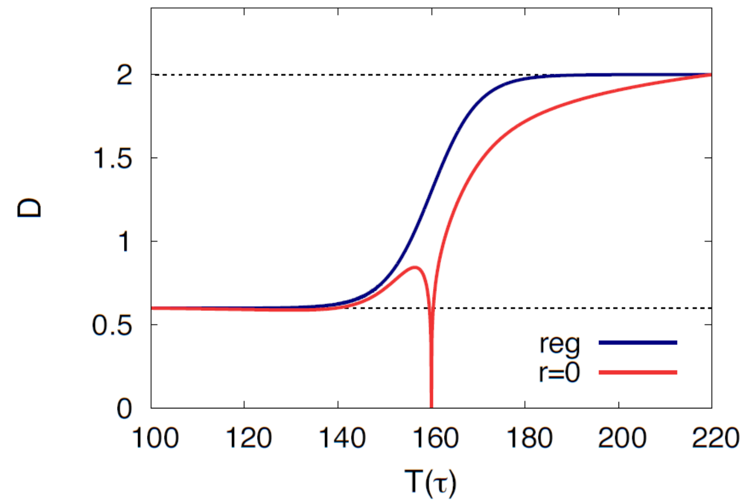
Criticap Point / Correlation Func.

Sakaida+, 2017

$$C(\bar{y}) = \langle \delta n(\bar{y}) \delta n(0) \rangle / \chi_{\rm hadron}$$







- ☐ non-monotonic Δy dep.

Analytic result: $C(\Delta y)$ non-monotonic → $\chi(\tau)$ non-monotonic

Summary

- Fluctuations observed in HIC are not in equilibrium.
- Non-equil. property can be understood from Δy dependence of cumulants.

- A simple diffusion model leads to non-monotonic Δy dependence of **higher order** cumulant.
- Non-monotnic Δy dependence of **2^{nd} order** cumulant is a signal of QCD critical point.

- **Detailed understanding on fluctuations can be obtained from Δy dependences of various cumulants!**
- **Future experiments will give us many useful information on QCD phase structure!**

Cumulants and Correlation Function

$$Q = \int_V dx n(x)$$

total charge

charge density

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

2nd order cumulant (fluctuation)

correlation function

1-to-1 correspondence

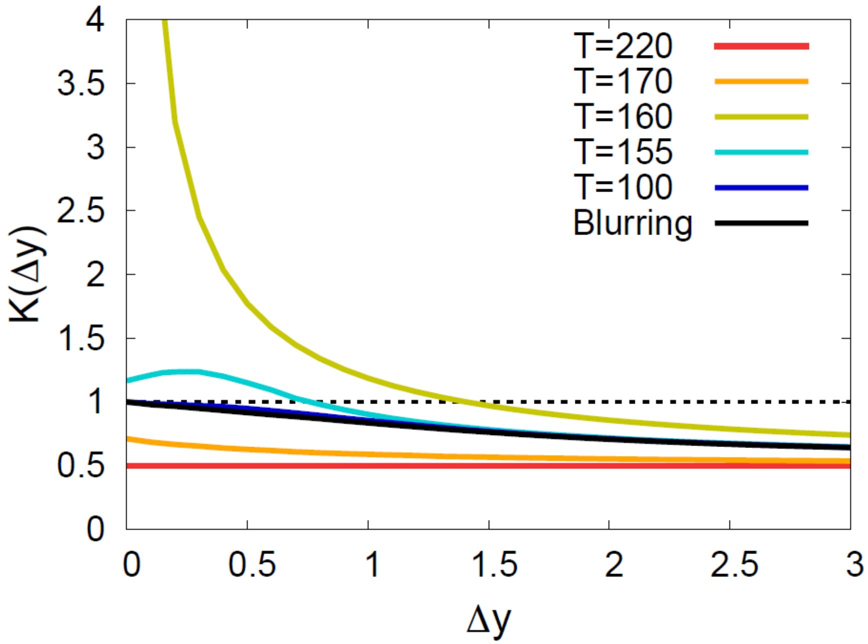
1-dim case

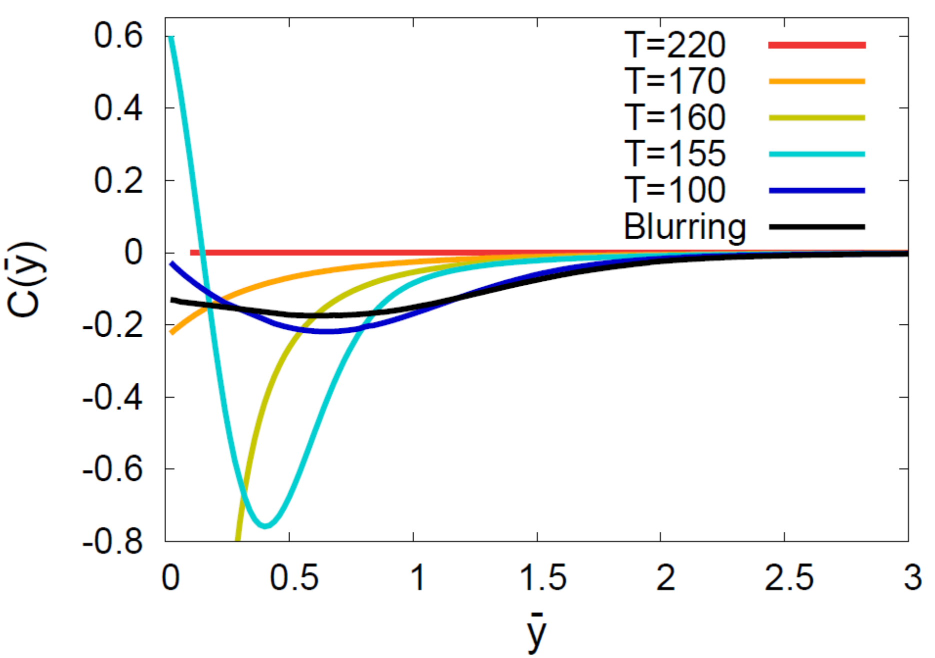
$$\langle \delta Q^2 \rangle_{\Delta y} = \int_{\Delta y} dy (\Delta y - |y|) \langle \delta n(y) \delta n(0) \rangle$$

Weaker Critical Enhancement

Sakaida+, 2017

$$K(\Delta y) = \langle \delta Q^2 \rangle / \langle \delta Q^2 \rangle_{\text{eq.}} \quad C(\bar{y}) = \langle \delta n(\bar{y}) \delta n(0) \rangle / \chi_{\text{hadron}}$$





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

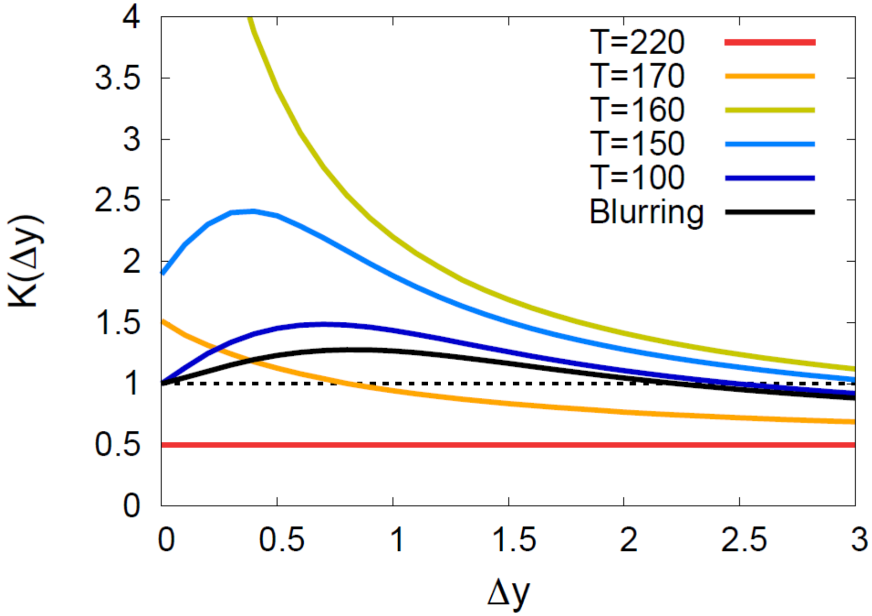
Analytic result: $K(\Delta y),\ C(\bar{y})$ monotonic ⇒ no information on $\chi(\tau)$

- C(y) is better to see non-monotonicity.

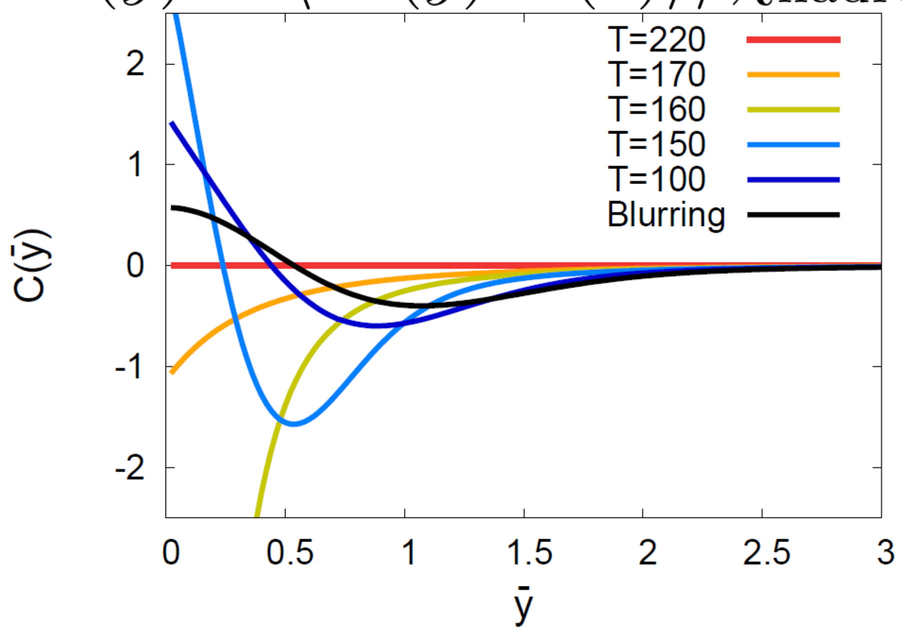
Away from the CP

Sakaida+, 2017

$$K(\Delta y) = \langle \delta Q^2 \rangle / \langle \delta Q^2 \rangle_{\text{eq.}}$$



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



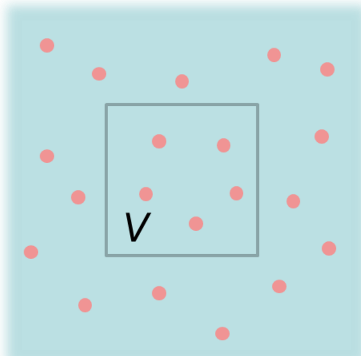
- Signal of the critical enhancement can be clearer on a path away from the CP.

Away from the CP → Weaker critical slowing down

Fluctuations: Theory vs Experiment

Theoretical analyses

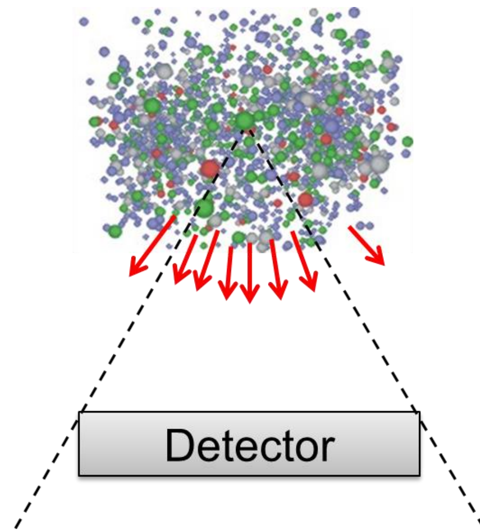
based on statistical mechanics



lattice, critical point,
effective models, …

Fluctuation in a spatial volume

Experiments



Fluctuations in a momentum space

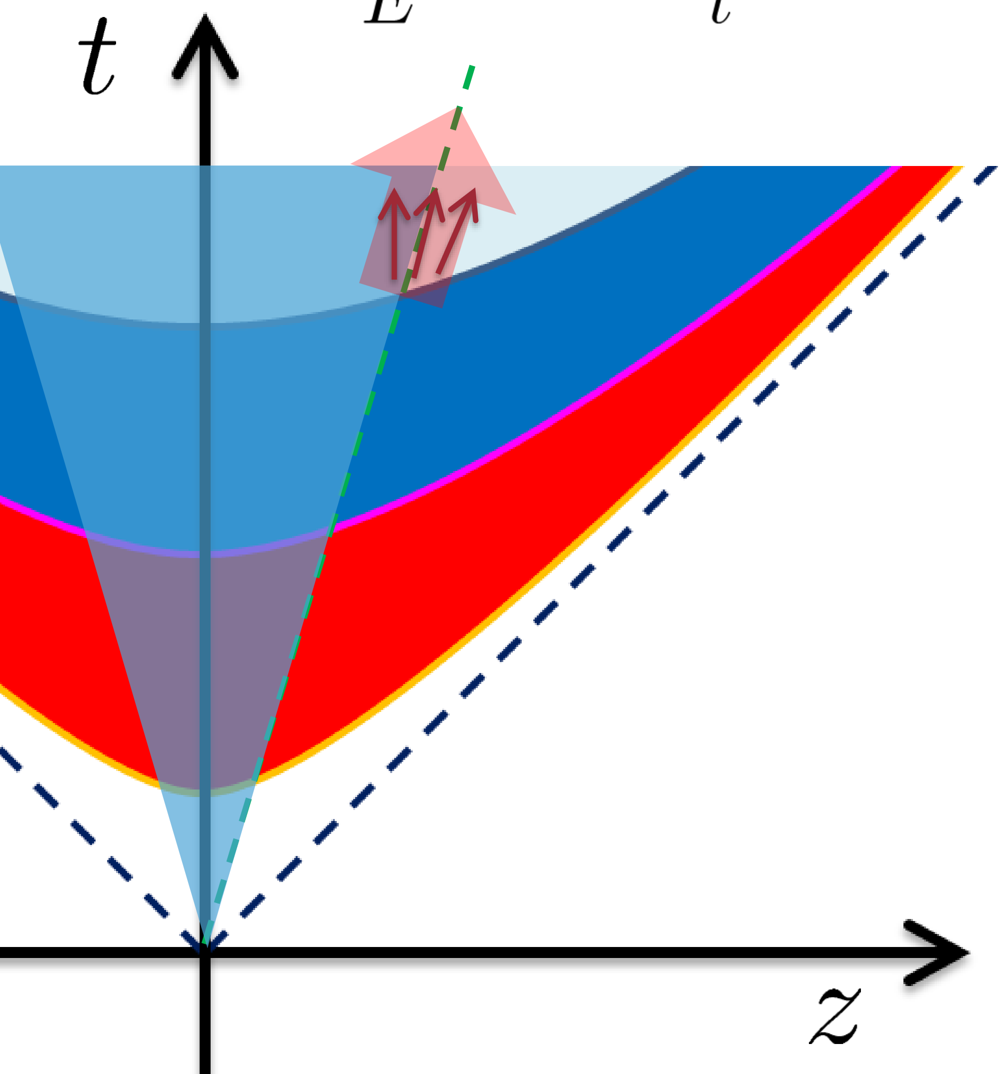
discrepancy in phase spaces

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

Thermal Blurring

Ohnishi, MK, Asakawa,
PRC94, 044905 (2016)

$$\frac{p_z}{E} = v_z = \frac{z}{t}$$



Under Bjorken picture,

coordinate-space rapidity *Y*

||

momentum-space rapidity *y* of medium

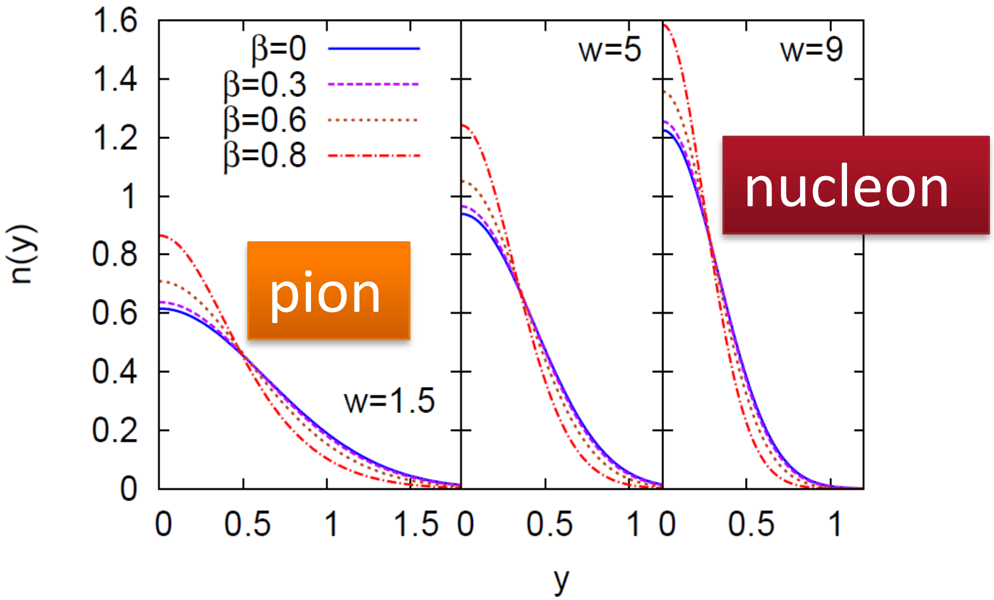
≀

momentum-space rapidity *y* of individual particles

$$\Delta y \simeq \Delta Y$$

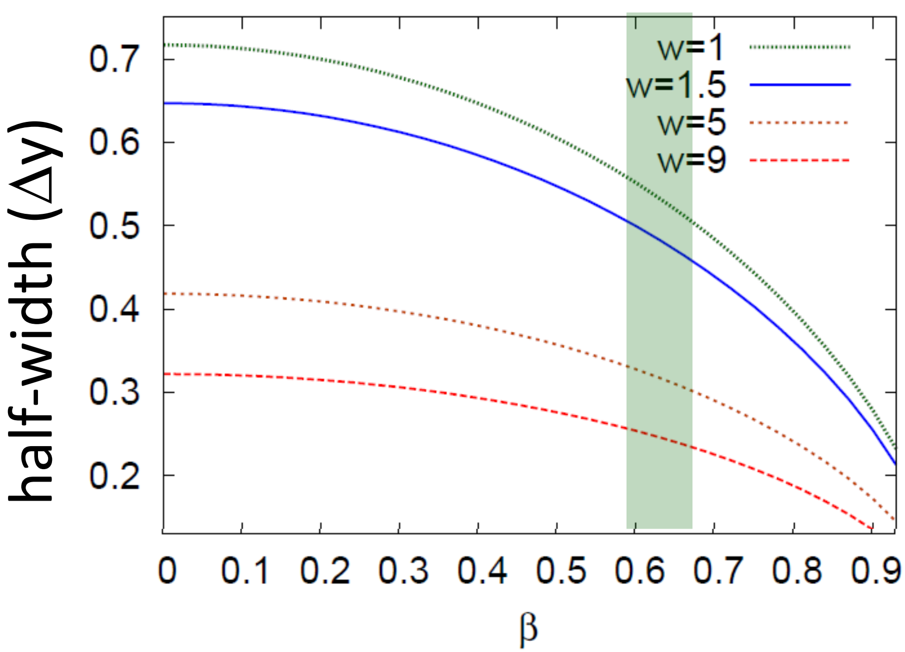
Thermal distribution in y space

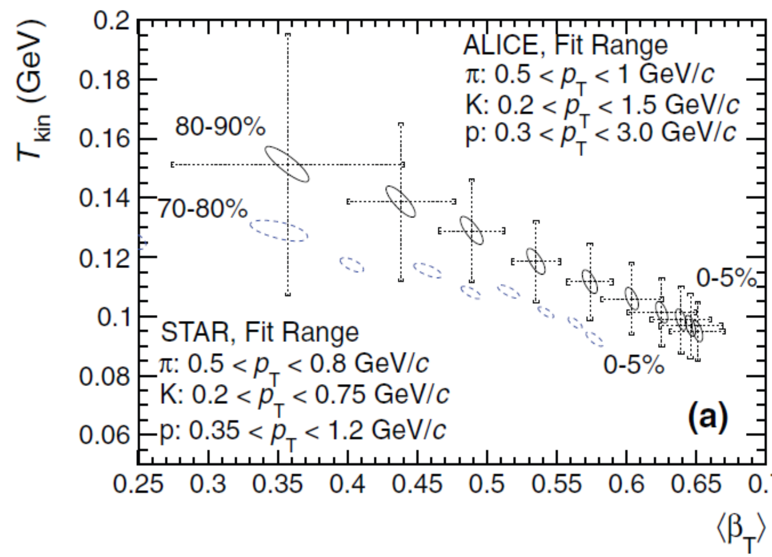
Ohnishi, MK, Asakawa, PRC94, 044905 (2016)



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

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



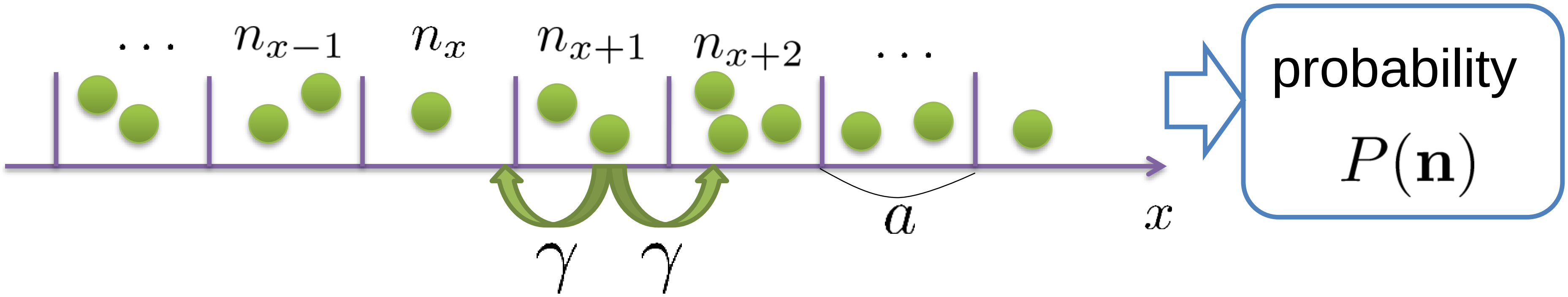


- blast wave
- flat freezeout surface

Diffusion Master Equation

MK, Asakawa, Ono, 2014
MK, 2015

Divide spatial coordinate into discrete cells



Diffusion Master Equation

MK, Asakawa, Ono, 2014
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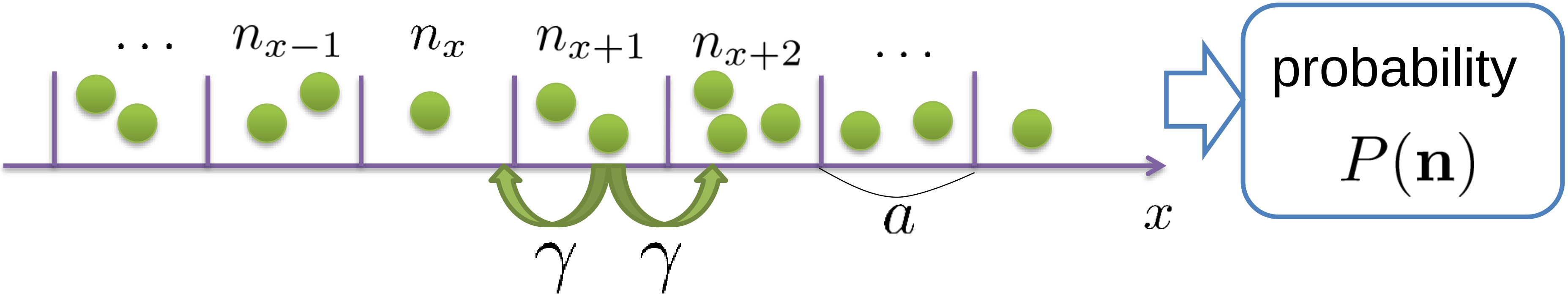
Divide spatial coordinate into discrete cells

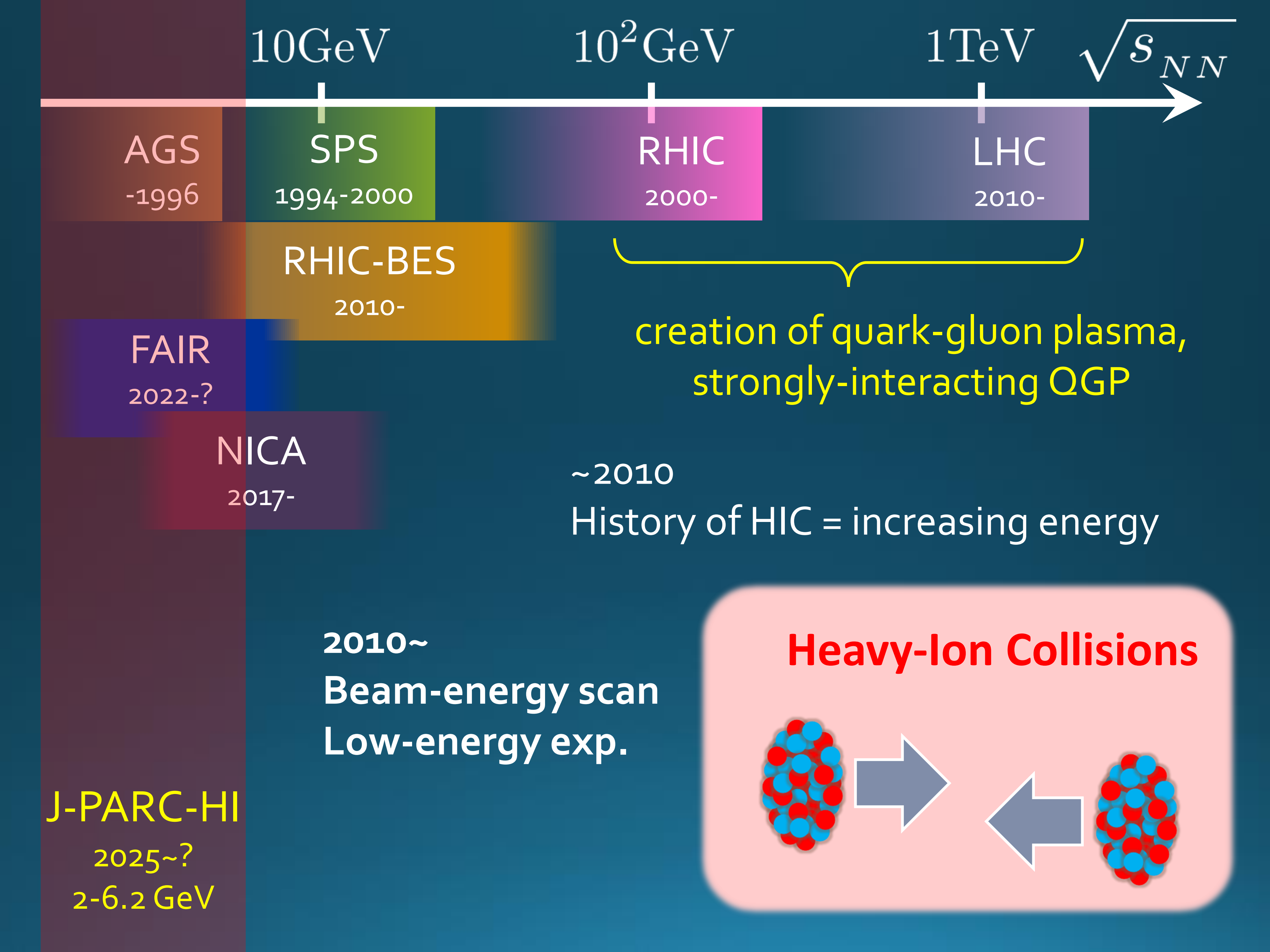


Master Equation for *P*(*n*)

$$\frac{\partial}{\partial t}P(\mathbf{n}) = \gamma \sum_x [(n_x+1)\{P(\mathbf{n}+\mathbf{e}_x-\mathbf{e}_{x+1}) + P(\mathbf{n}+\mathbf{e}_x-\mathbf{e}_{x-1})\} - 2n_x P(\mathbf{n})]$$

Solve the DME **exactly**, and take *a*→0 limit

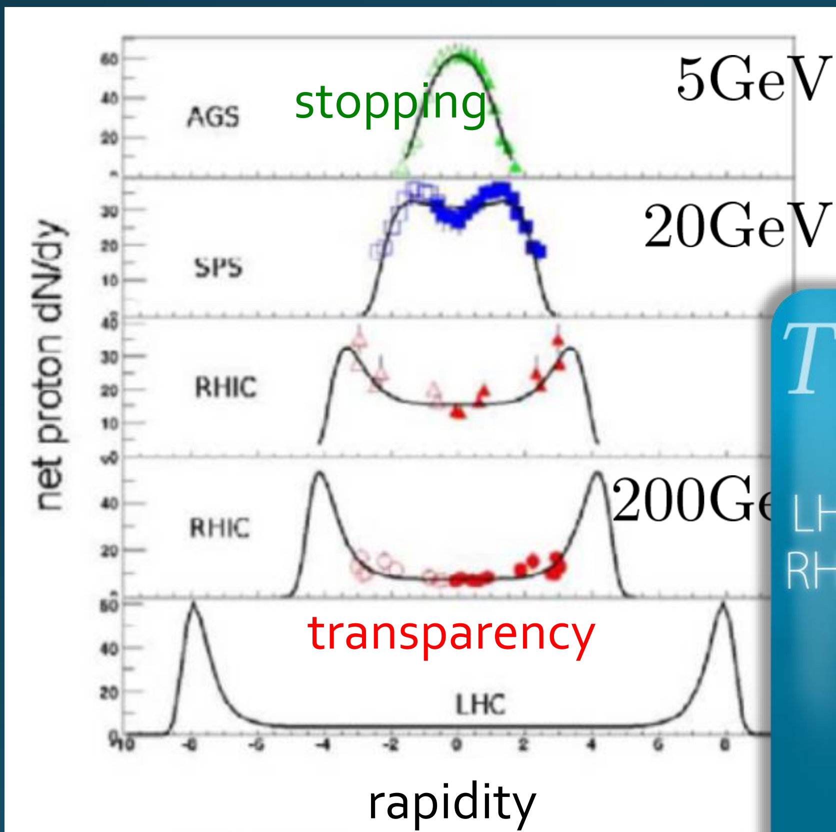
No approx., ex. van Kampen's system size expansion



10GeV
10^2GeV
1TeV
$\sqrt{s_{NN}}$
AGS
-1996
SPS
1994-2000
RHIC
2000-
LHC
2010-
RHIC-BES
2010-
FAIR
2022-?
NICA
2017-
J-PARC-HI
2025~?
2-6.2 GeV
creation of quark-gluon plasma,
strongly-interacting QGP
~2010
History of HIC = increasing energy
2010~
Beam-energy scan
Low-energy exp.
Heavy-Ion Collisions

Baryon Stopping

rapidity dep. of net-proton #



$$\sqrt{s_{NN}} \simeq 4 - 6\mathrm{GeV}$$

Baryons stop at collision point

$$\sqrt{s_{NN}} > 10\mathrm{GeV}$$

Baryons pass through

phase diagram from J-PARC White Paper

Soft Mode of QCD Critical Point

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

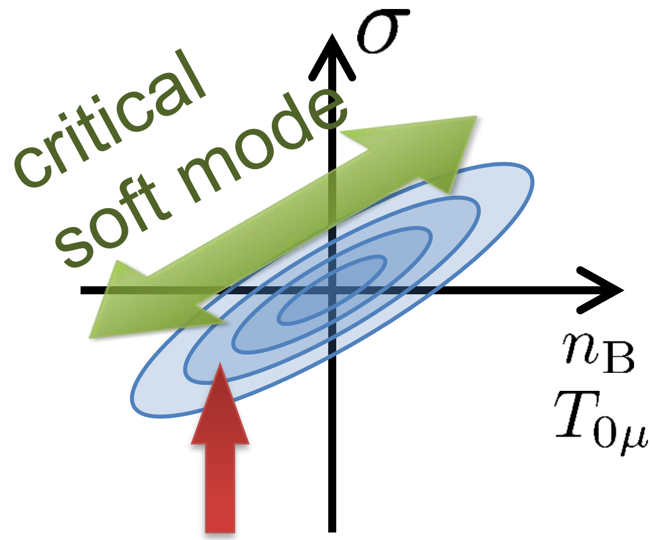
- Effective potential

$$F(\sigma, n) = A\sigma^2 + B\sigma n + Cn^2 + \cdots$$

- Time dependent Ginzburg-Landau

$$\begin{pmatrix} \dot{\sigma} \\ \dot{n} \end{pmatrix} = \begin{pmatrix} \Gamma_{\sigma\sigma} & \Gamma_{\sigma n} \\ \Gamma_{n\sigma} & \Gamma_{nn} \end{pmatrix} \begin{pmatrix} \sigma \\ n \end{pmatrix}$$

$\sim k^2$



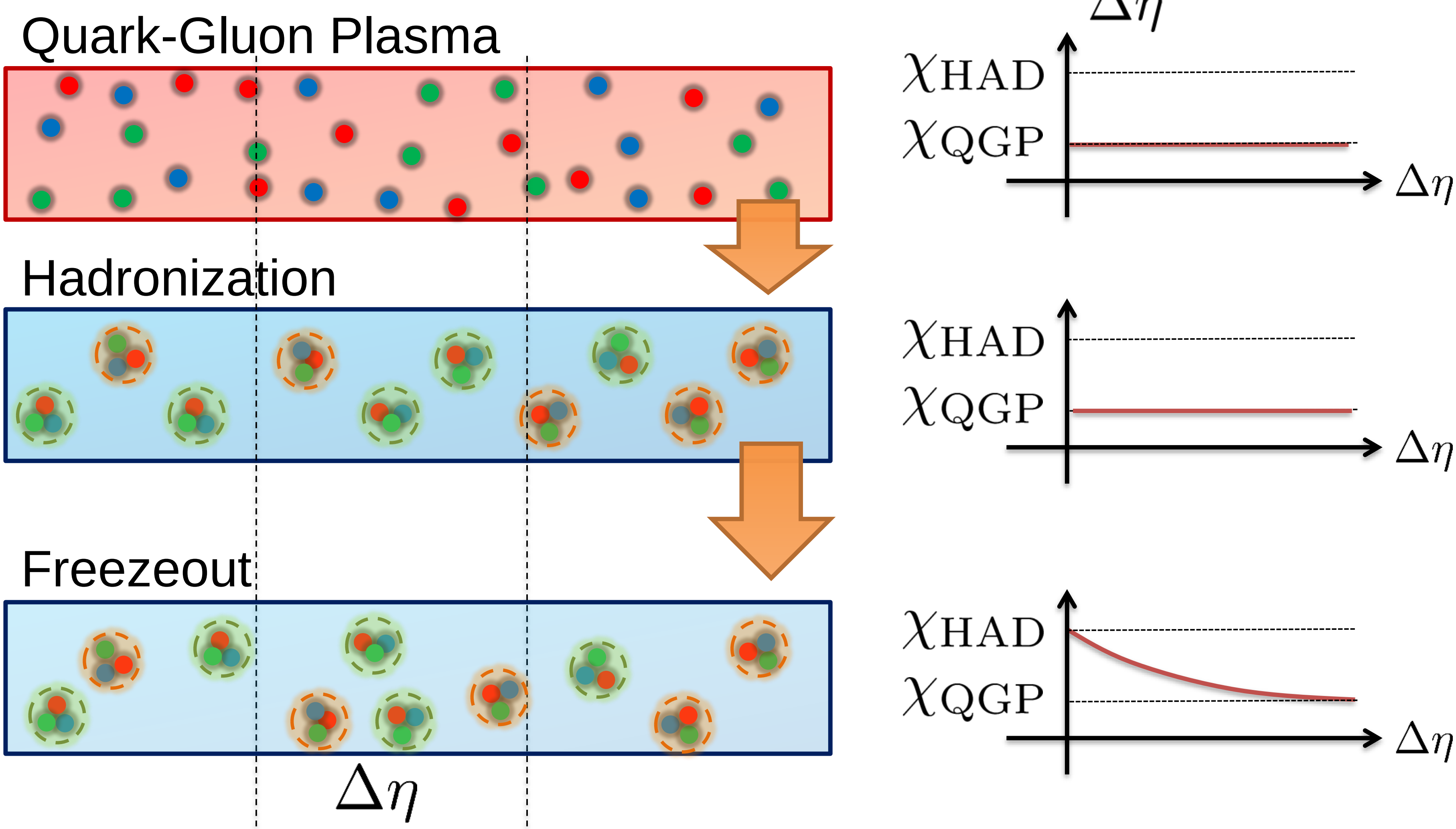
σ: fast damping

For slow and long wavelength,

SDE $\quad \partial_\tau n = D(\tau)\partial_\eta^2 n + \partial_\eta \xi$

singularities in $D(\tau)$ and $\chi(\tau)$

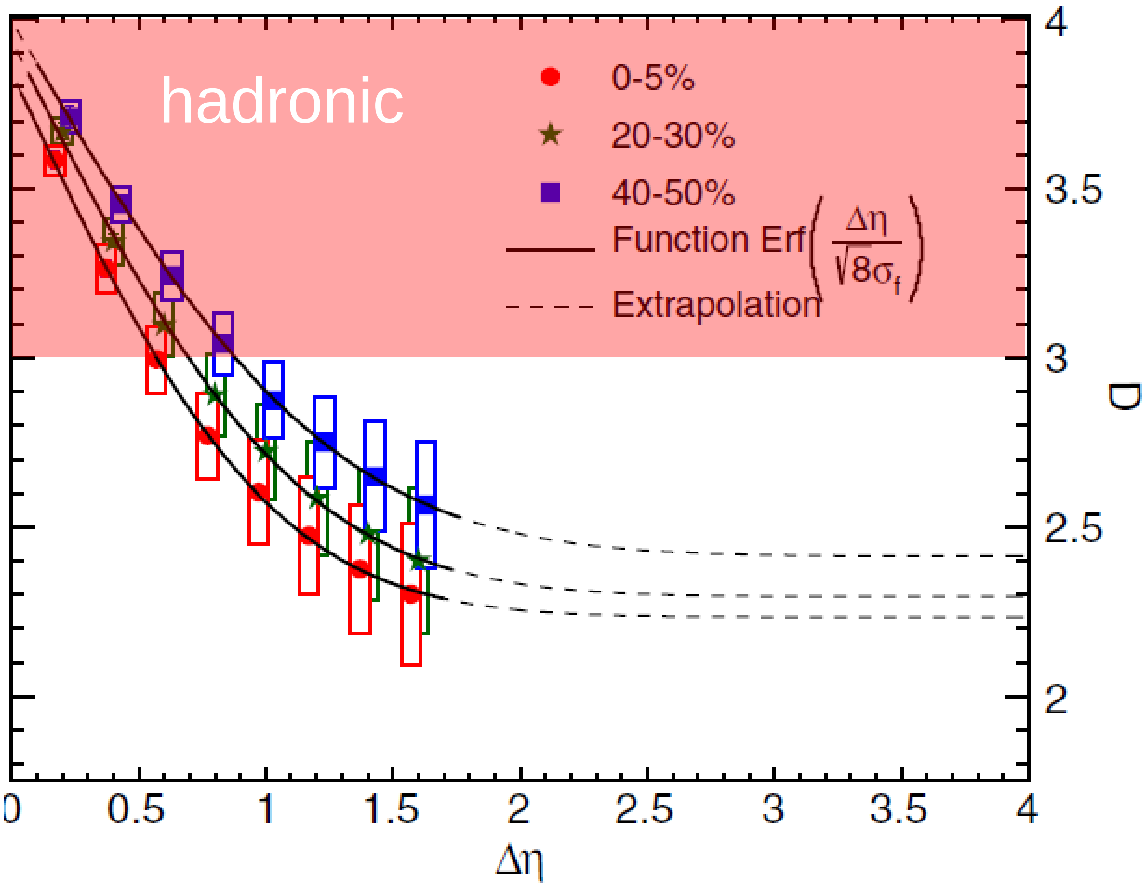
Time Evolution of Fluctuations



Variation of a conserved charge is achieved only through diffusion. ⇨ The larger $\Delta\eta$, the slower diffusion

Δη Dependence @ ALICE

ALICE
PRL 2013

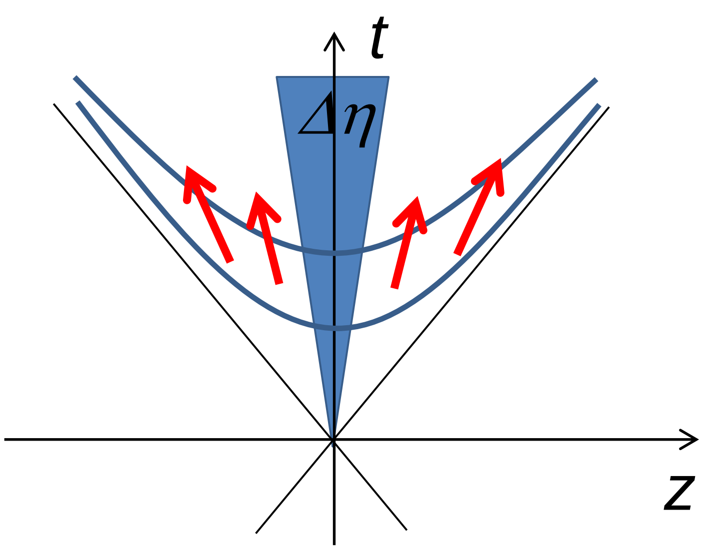


rapidity window

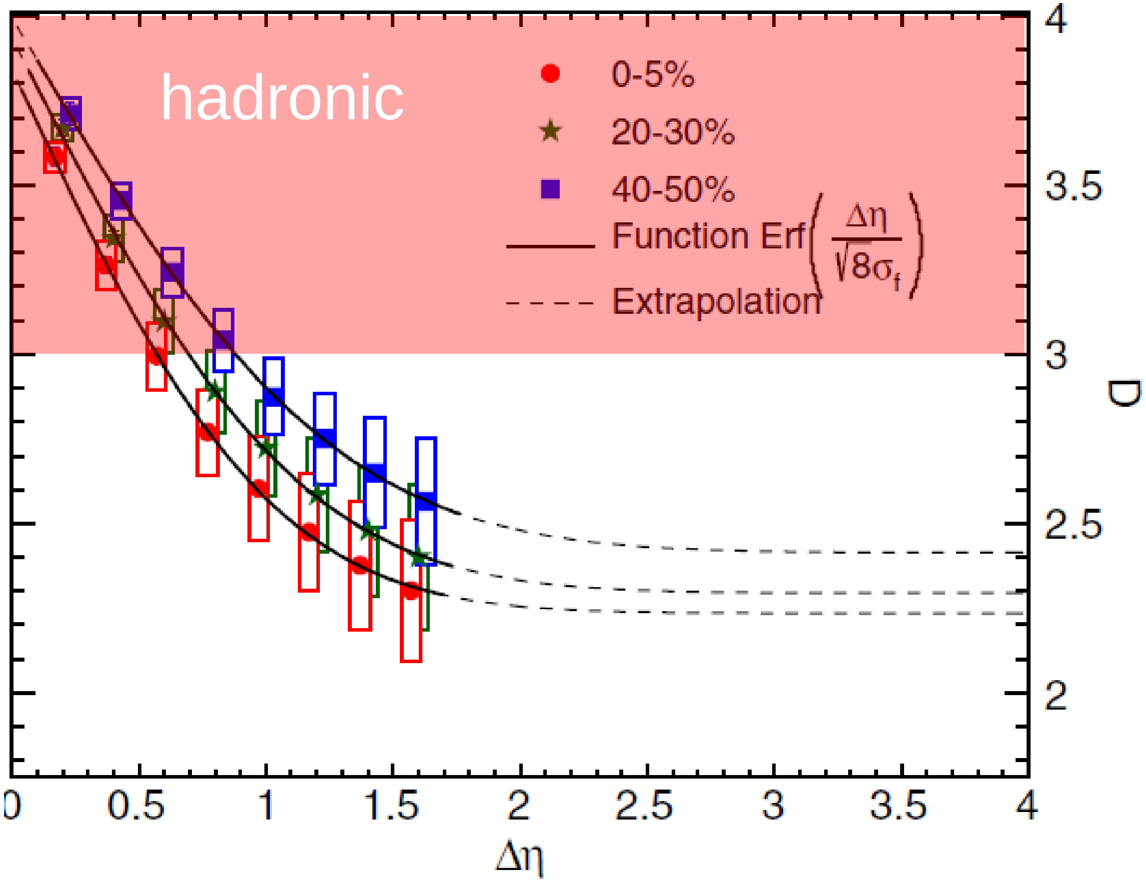
D-measure

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

- D ~ 3-4 Hadronic
- D ~ 1-1.5 Quark



Δη Dependence @ ALICE



rapidity window

$$D \sim \frac{\langle \delta N_Q \rangle^2}{\Delta\eta}$$

has to be a constant in equil. medium

Fluctuation of N_Q at ALICE is not the equilibrated one.