QCD臨界点付近における保存電荷高次キュムラントの時間発展

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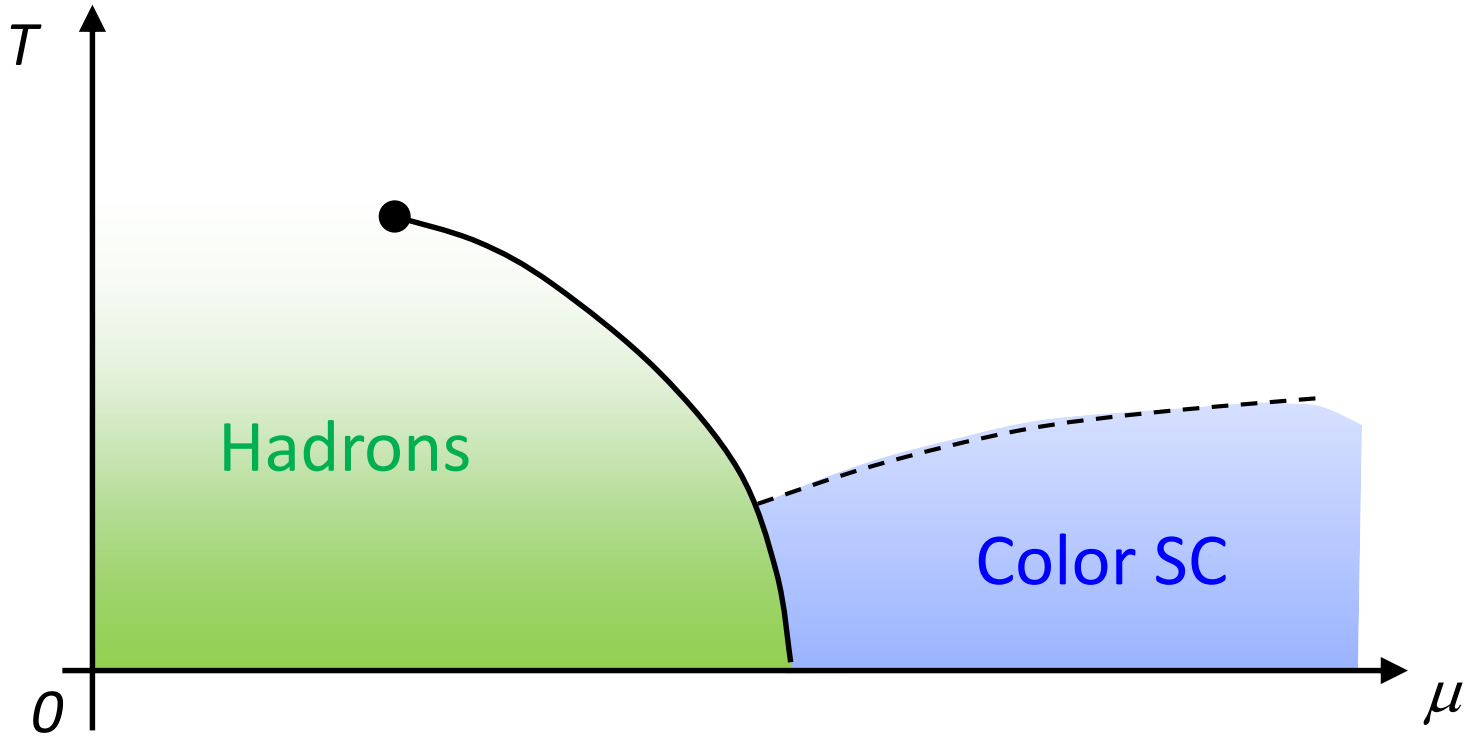
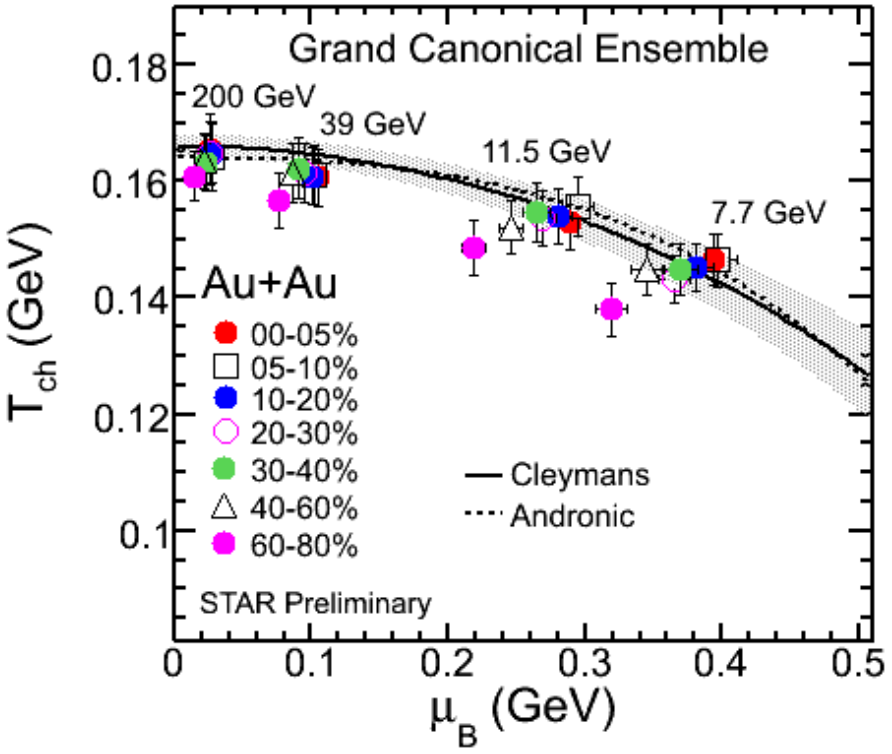
22pK102-9

Beam-Energy Scan



Beam-Energy Scan

STAR 2012



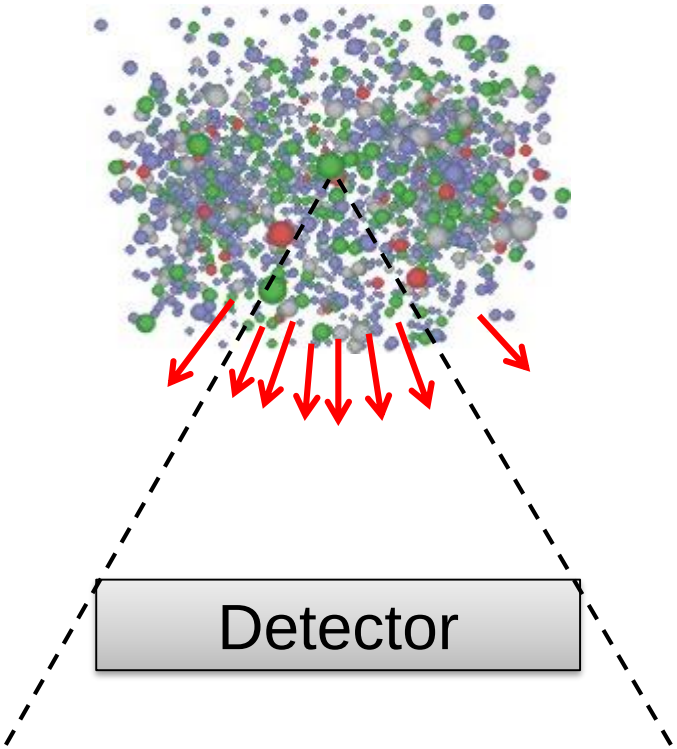
RHIC-BES-I, LHC, SPS-NA61

Future: RHIC-BES-II, J-PARC-HI, FAIR, NICA

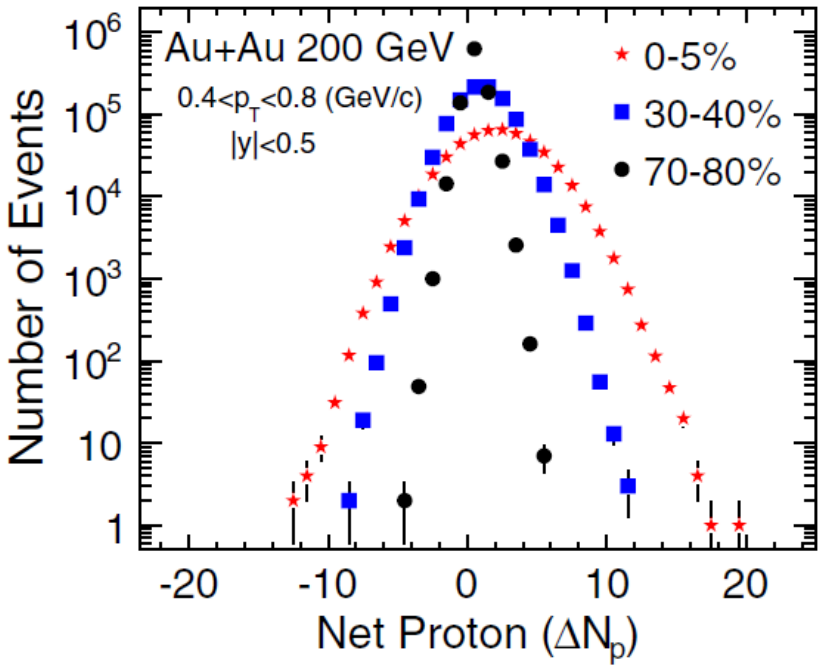
Event-by-Event Fluctuations

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

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



STAR, PRL**105** (2010)



Cumulants

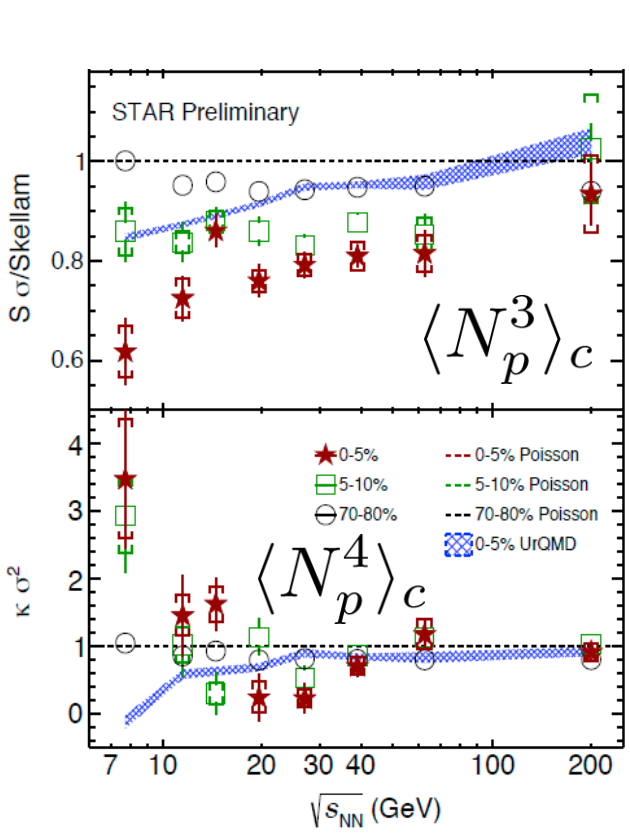
$$\langle \delta N_p^2 \rangle, \langle \delta N_p^3 \rangle, \langle \delta N_p^4 \rangle_c$$

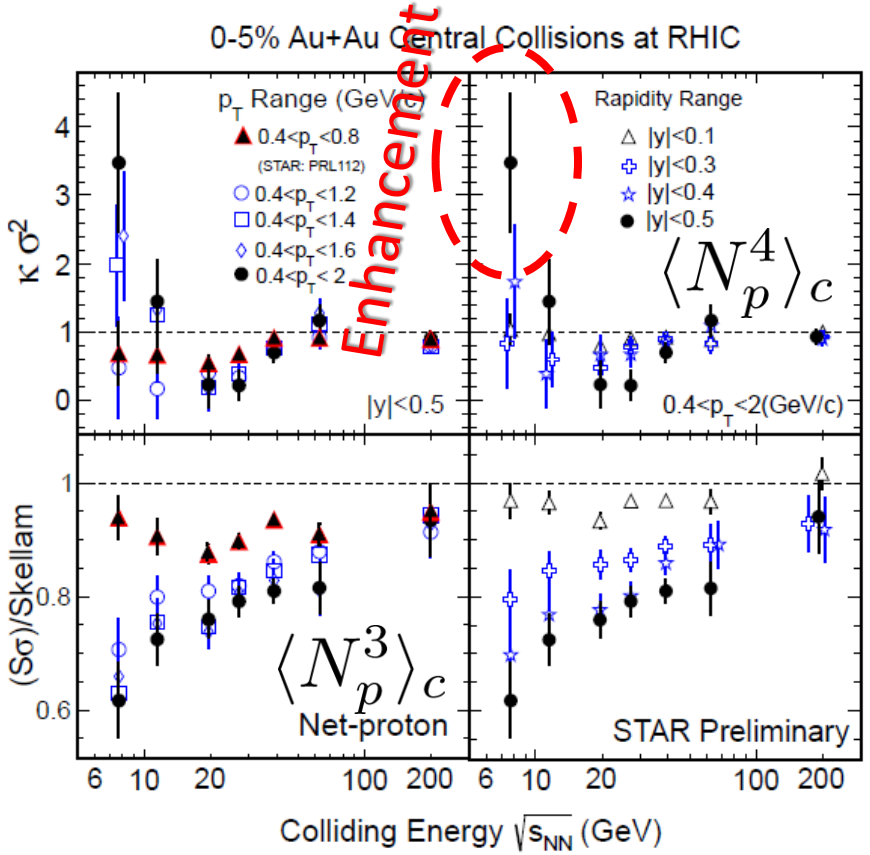
Higher-Order Cumulants

STAR Collab.
2010~

Higher-order cumulants: Sensitive to QCD phase structure!

Stephanov, 2009; Asakawa, Ejiri, MK, 2009

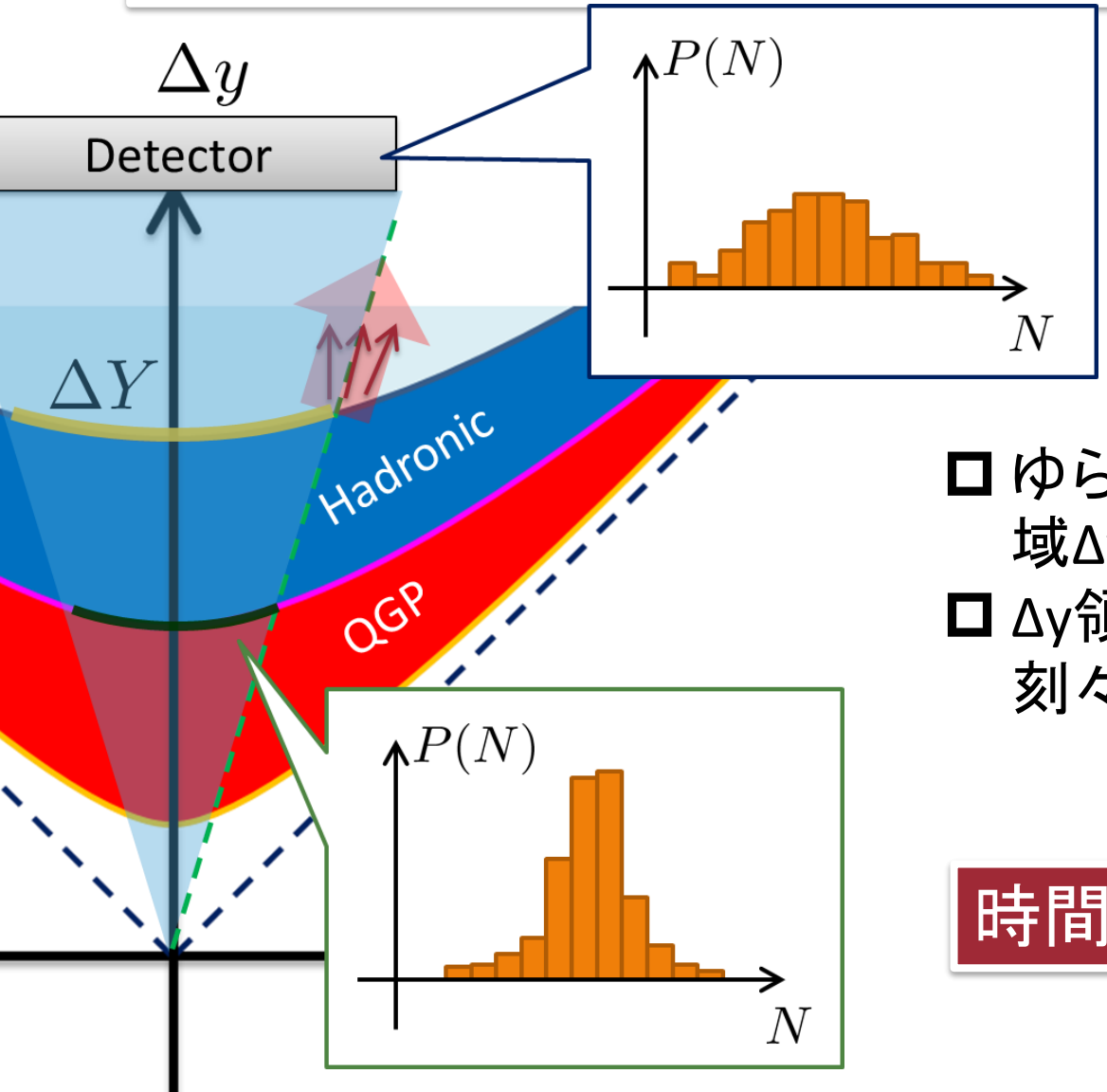




Non-zero **non**-Gaussian cumulants have been established!

Have we measured critical fluctuations?

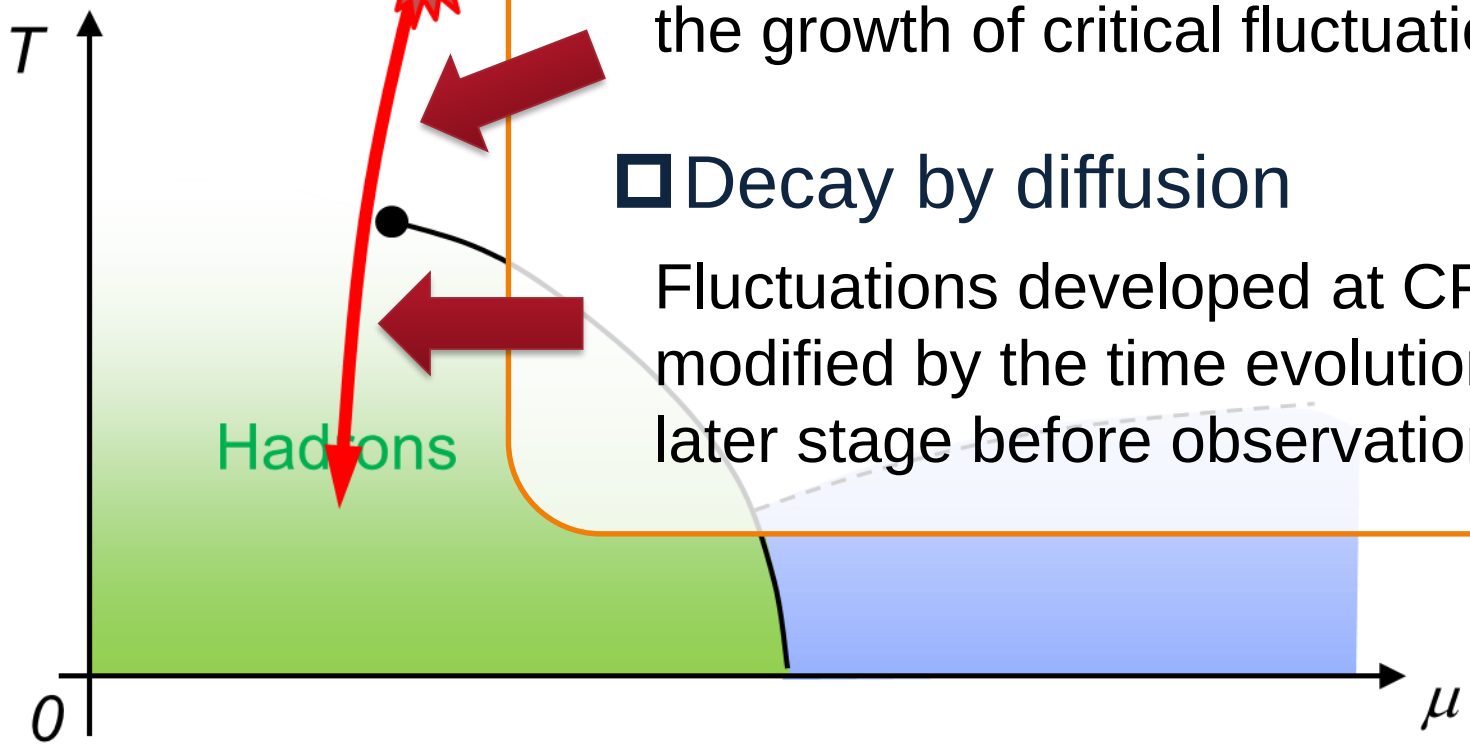
Caution
実験が観測するゆらぎ≠ある時刻の熱ゆらぎ



- ゆらぎは、あるラピディティ領域Δyで測定される
- Δy領域内の粒子数は、時々刻々と変化する

時間発展を論じる必要性

Effect of Dynamical Evolution



Growth

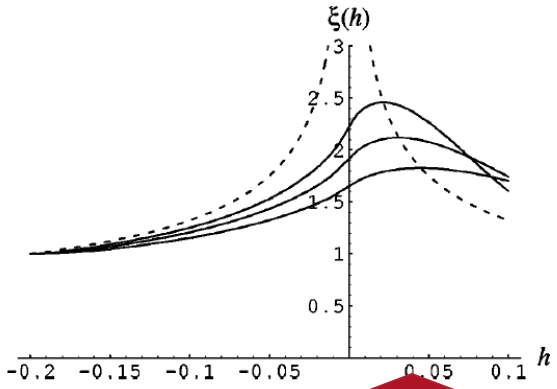
Critical slowing down suppresses the growth of critical fluctuation.

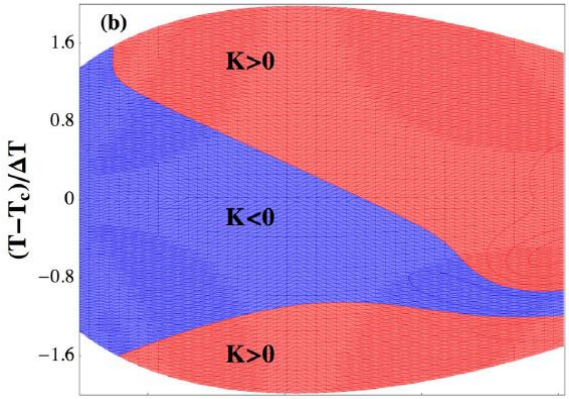
Decay by diffusion

Fluctuations developed at CP are modified by the time evolution in later stage before observation.

Dynamical Evolution of Critical Fluctuations

- Evolution of **spatially uniform "σ" mode**





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

THIS STUDY

Evolution of **conserved charge fluctuations**

Sakaida+, PRC2017; Murata, MK, in prep.

1. Conserved charges are directly observable.
2. Soft mode at QCD-CP is a conserved mode.

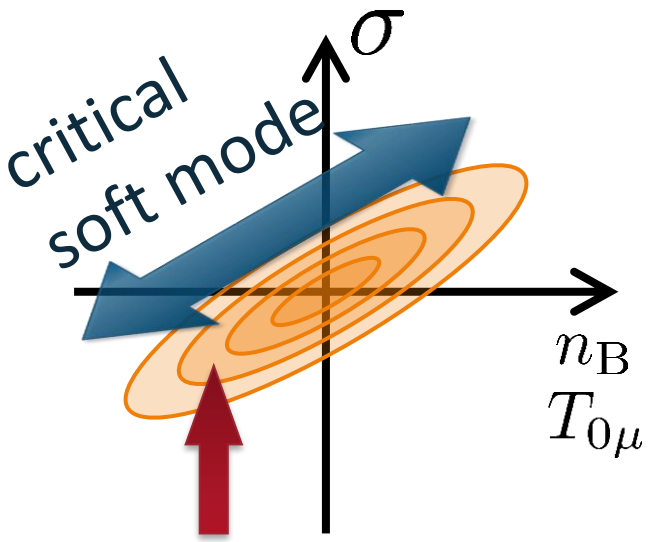
See also, Kapusta, Torres-Rincon (2012); Herold, Nahrgang, … (2015)

Soft Mode of QCD-CP = Conserved Mode

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

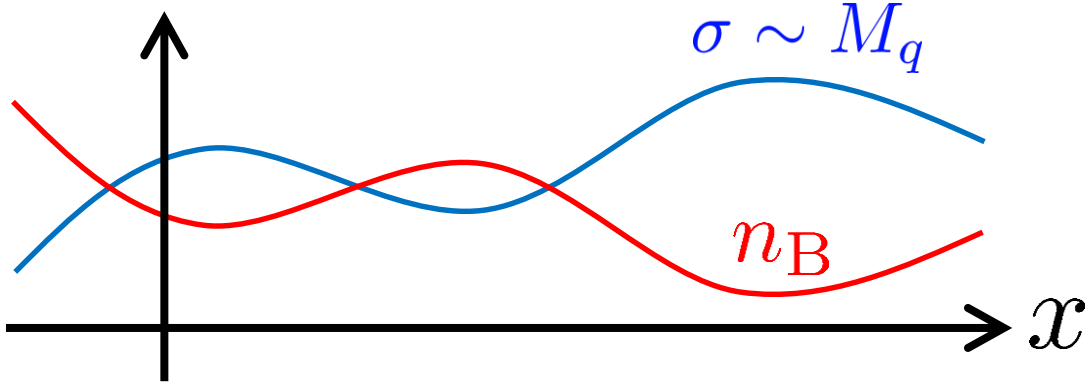
Fluctuations of σ and n_B are coupled around the CP!

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



σ: fast damping

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



Analysis of 2nd-order Cumulant

Sakaida, Asakawa, Fujii, MK (2017)

Evolution of baryon number density

Stochastic Diffusion Equation

$$\partial_t n = D(t)\partial_x^2 n + \partial_x \xi$$

$$\langle \xi(x_1,t_1)\xi(x_2,t_2)\rangle = \chi_2(t)\delta^{(2)}(1-2)$$

$D(t),\ \chi_2(t)$:parameters characterizing criticality

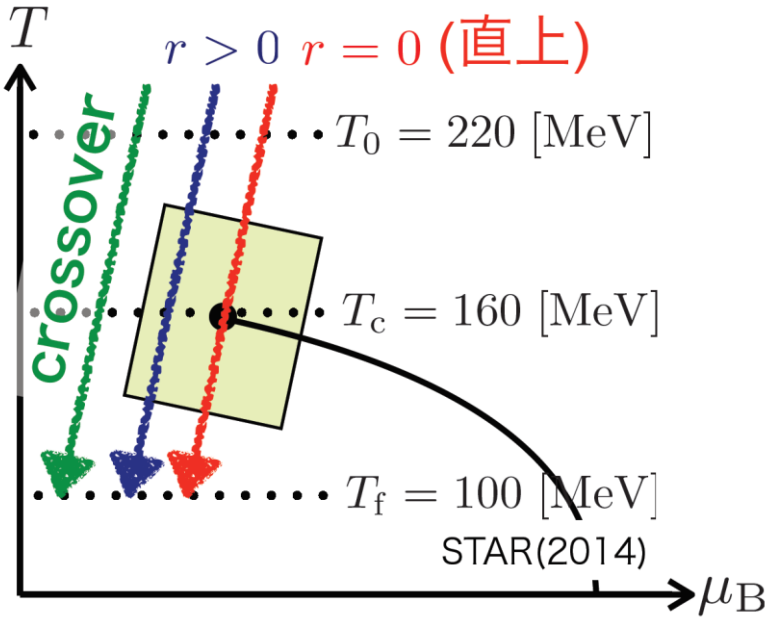
- n is a conserved charge.
- Analytically solvable.
- Neglect σ : Justified for slow dynamics.
- Applicable **only to 2nd order** fluctuations.

- This study: translationally-invariant solution

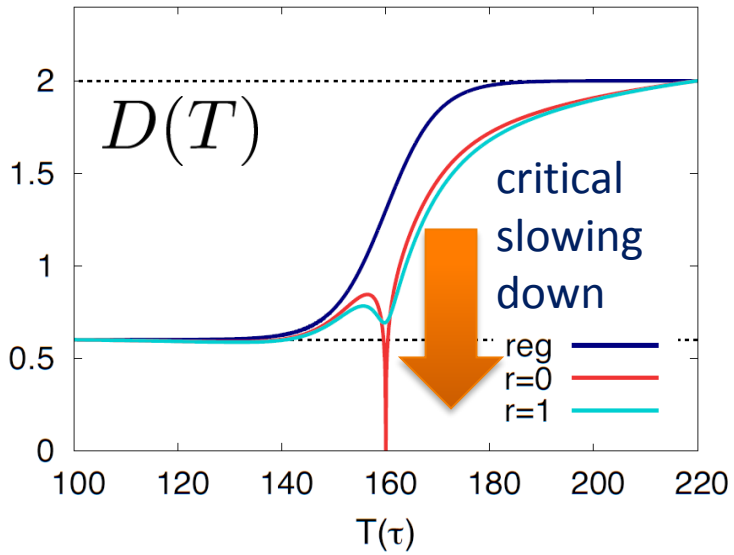
Parametrizing D(τ) and χ(τ)

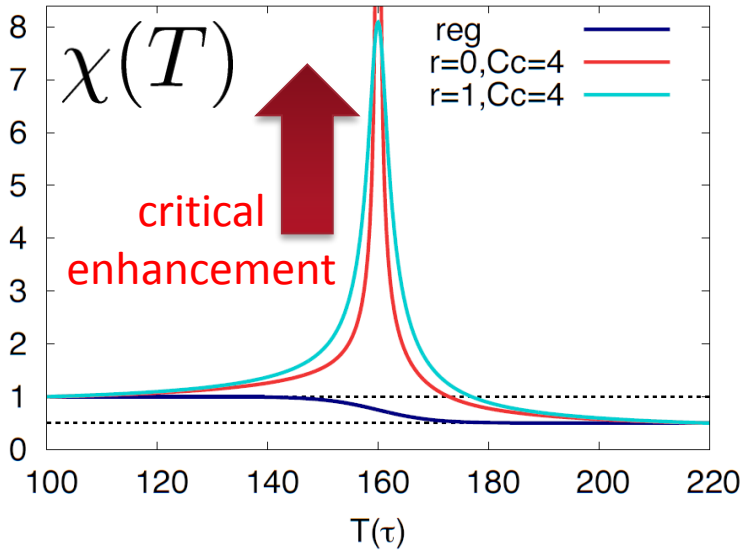
- Critical behavior
  - 3D Ising (r,H)
  - model H

Berdnikov, Rajagopal (2000)
Stephanov (2011); Mukherjee+(2015)



- Temperature dep.





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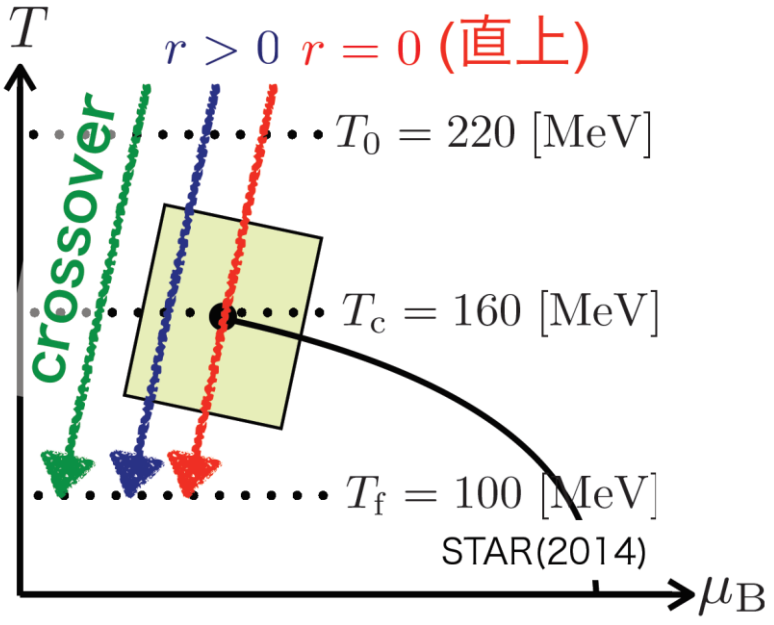

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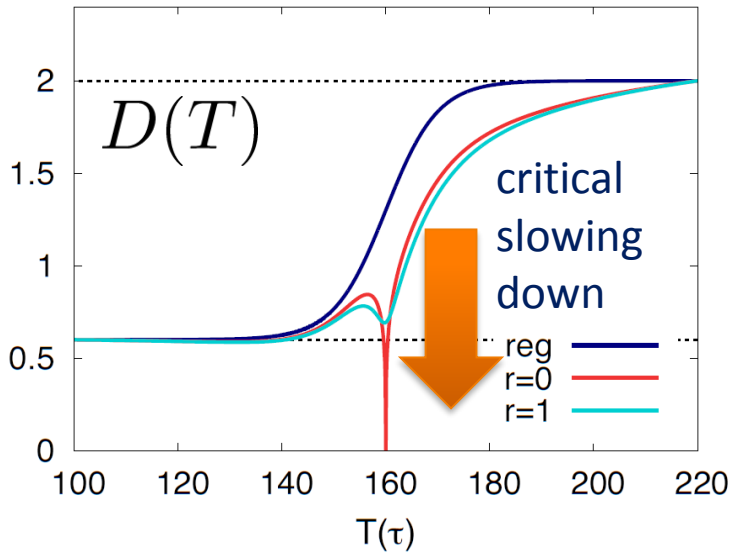
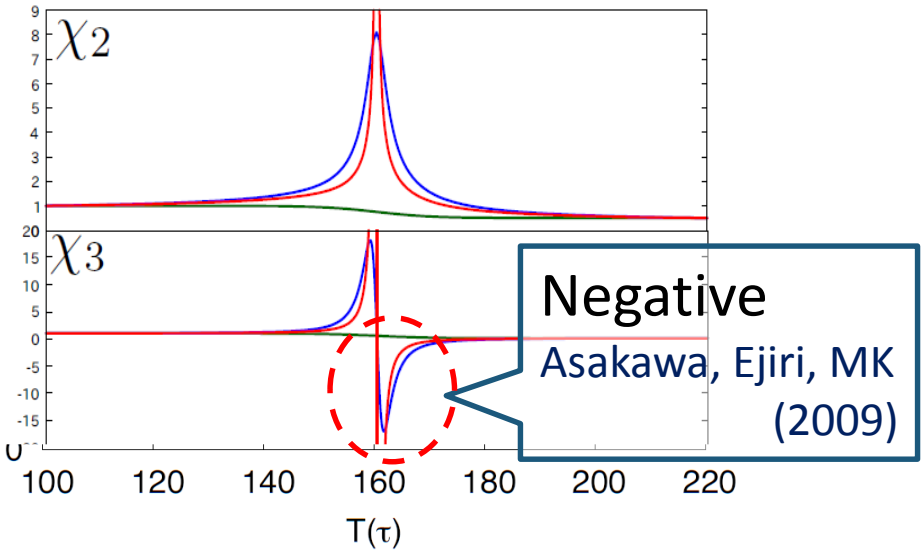
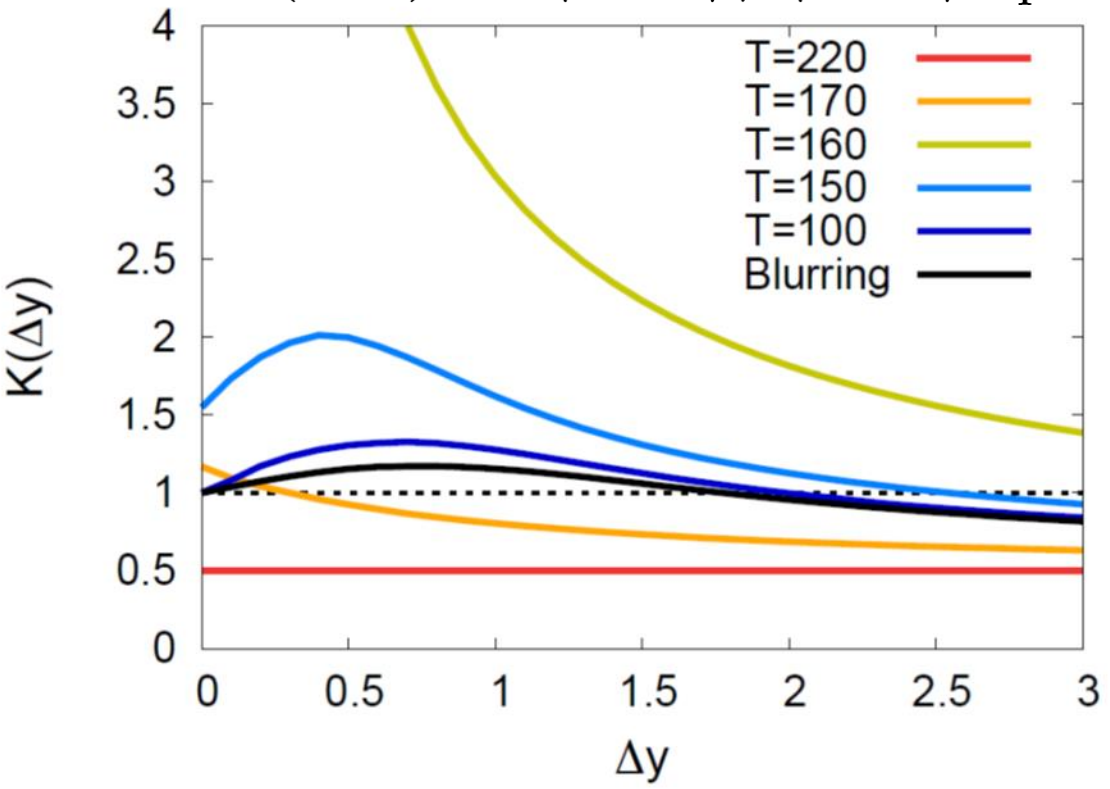


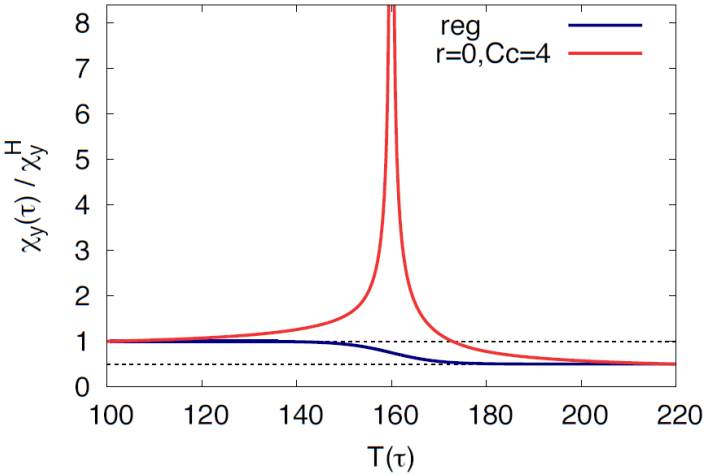


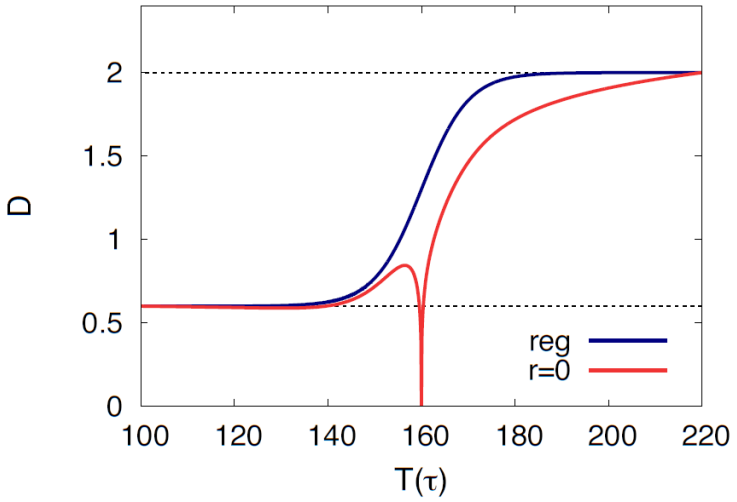
Critical Point / Cumulant

Sakaida+ (2017)

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







- non-monotonic Δy dep.

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

Exploring 3rd-order Cumulant

Murata, MK
in preparation

SDE + Non-linear effects

$$\partial_t n = \gamma(t)\partial_x^2 \frac{\delta\Omega[n]}{\delta n(x)} + \partial_x \xi$$

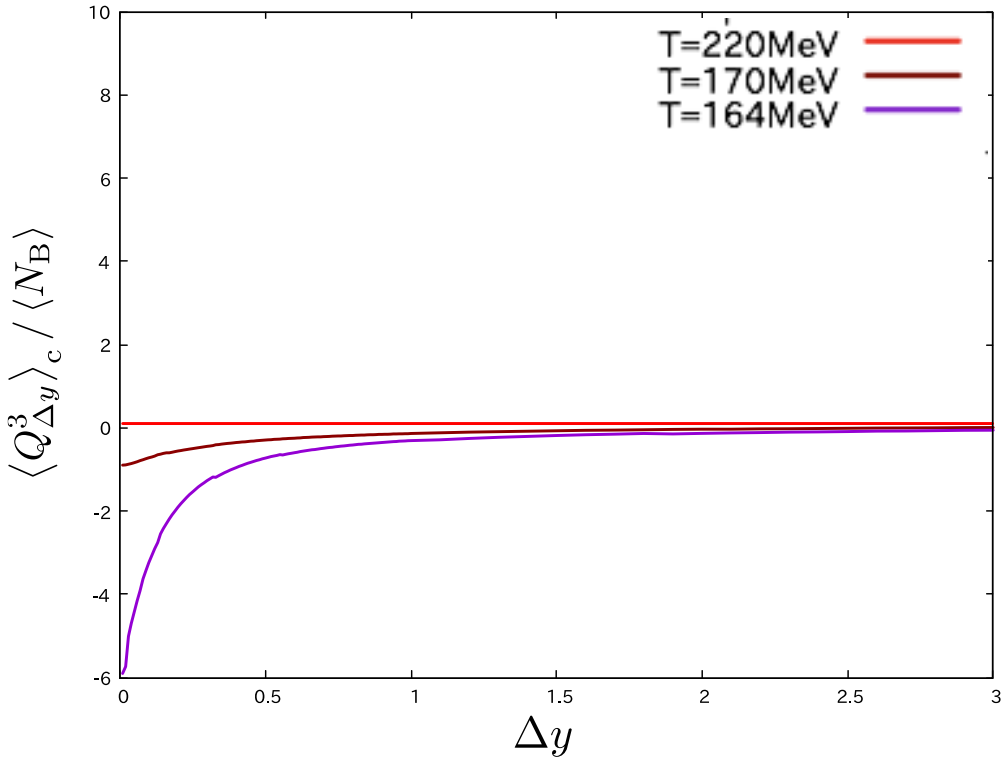
Effective potential

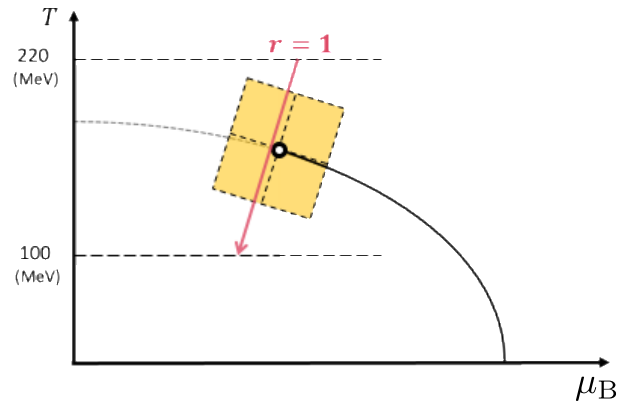
$$\Omega[n(x)] = \int dx \Big(c(\nabla n)^2 + \lambda_2 (n(x))^2 + \lambda_3 (n(x))^3 + \cdots \Big)$$

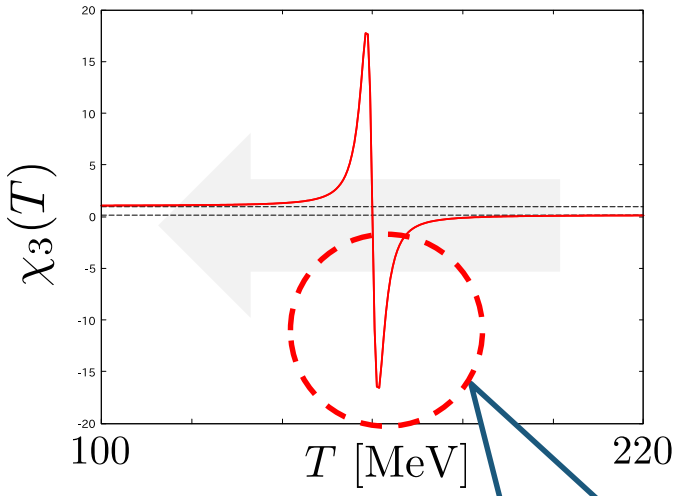
- $c=\lambda_3=0$ ➔ SDE
- λ_3 characterizes skewness: $\lambda_3 = \chi_3/\chi_2^3$
- Solve this equation **at the leading order** in λ_3 with $c=0$.
  - $\lambda_3 \to 0$ @ QCD-CP
  - $c=0$ → short ξ.
- Numerical analysis: Nahrgang, QM2018

Time Evolution: Near CP

Murata, MK
in preparation



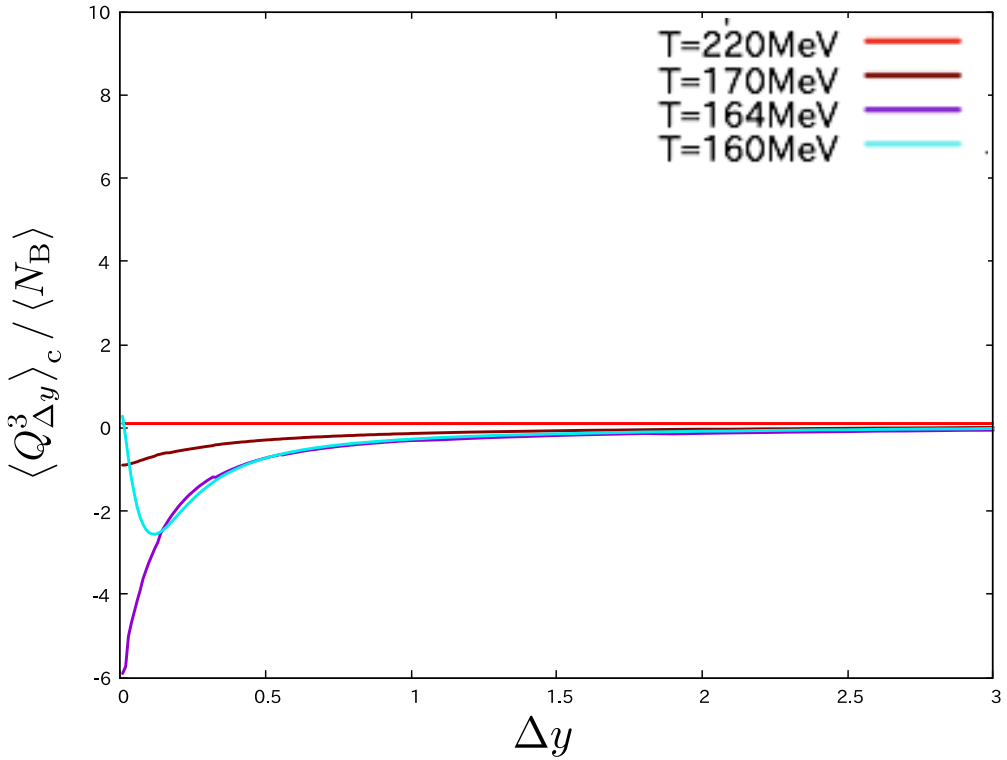


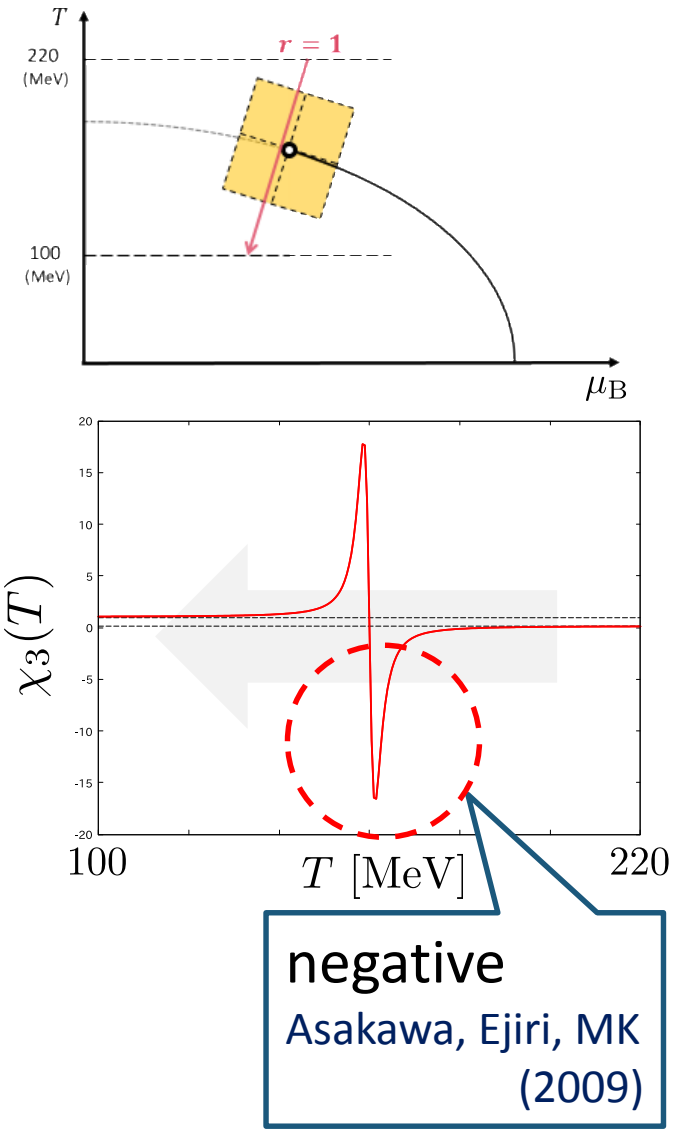


negative
Asakawa, Ejiri, MK
(2009)

Time Evolution: Near CP

Murata, MK
in preparation





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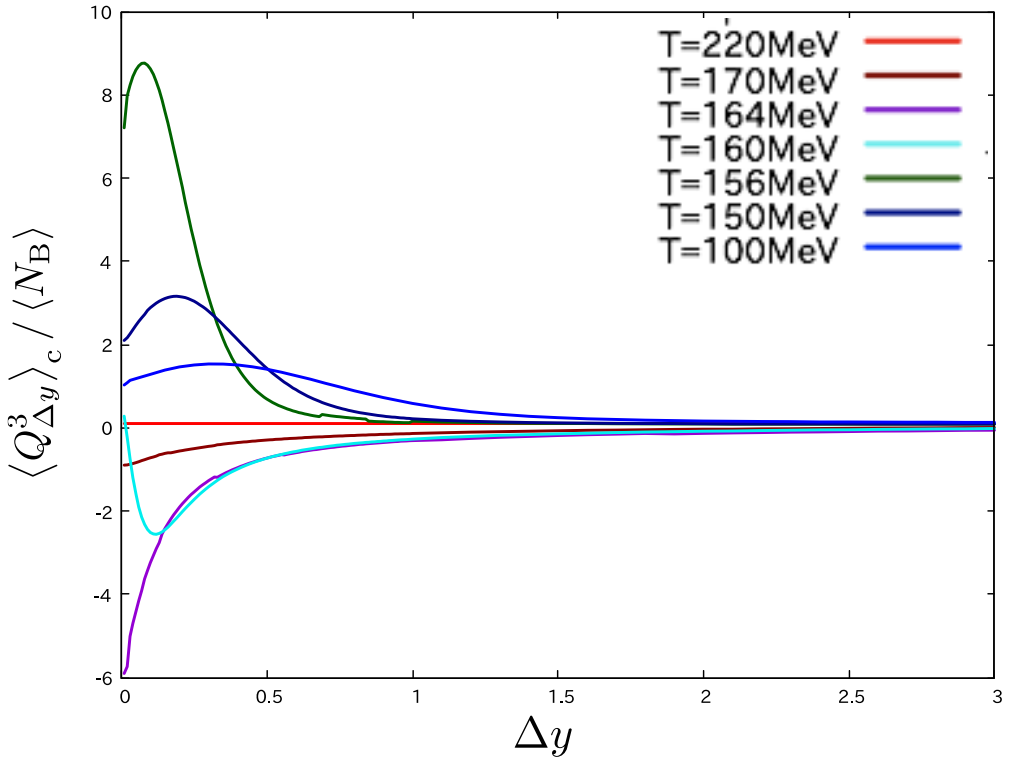
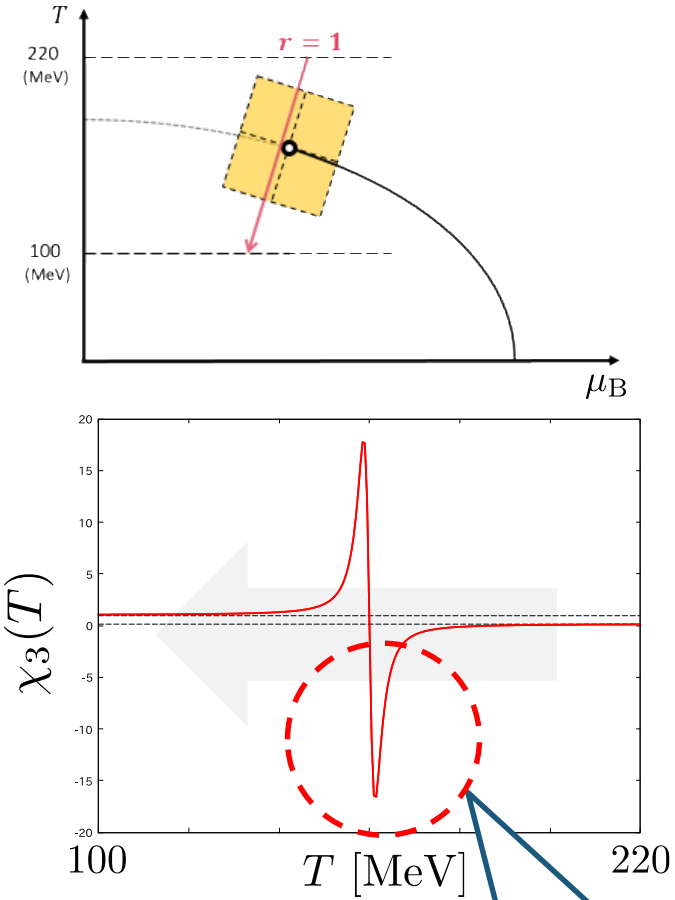
Asakawa, Ejiri, MK (2009)

Time Evolution: Near CP

Murata, MK
in preparation

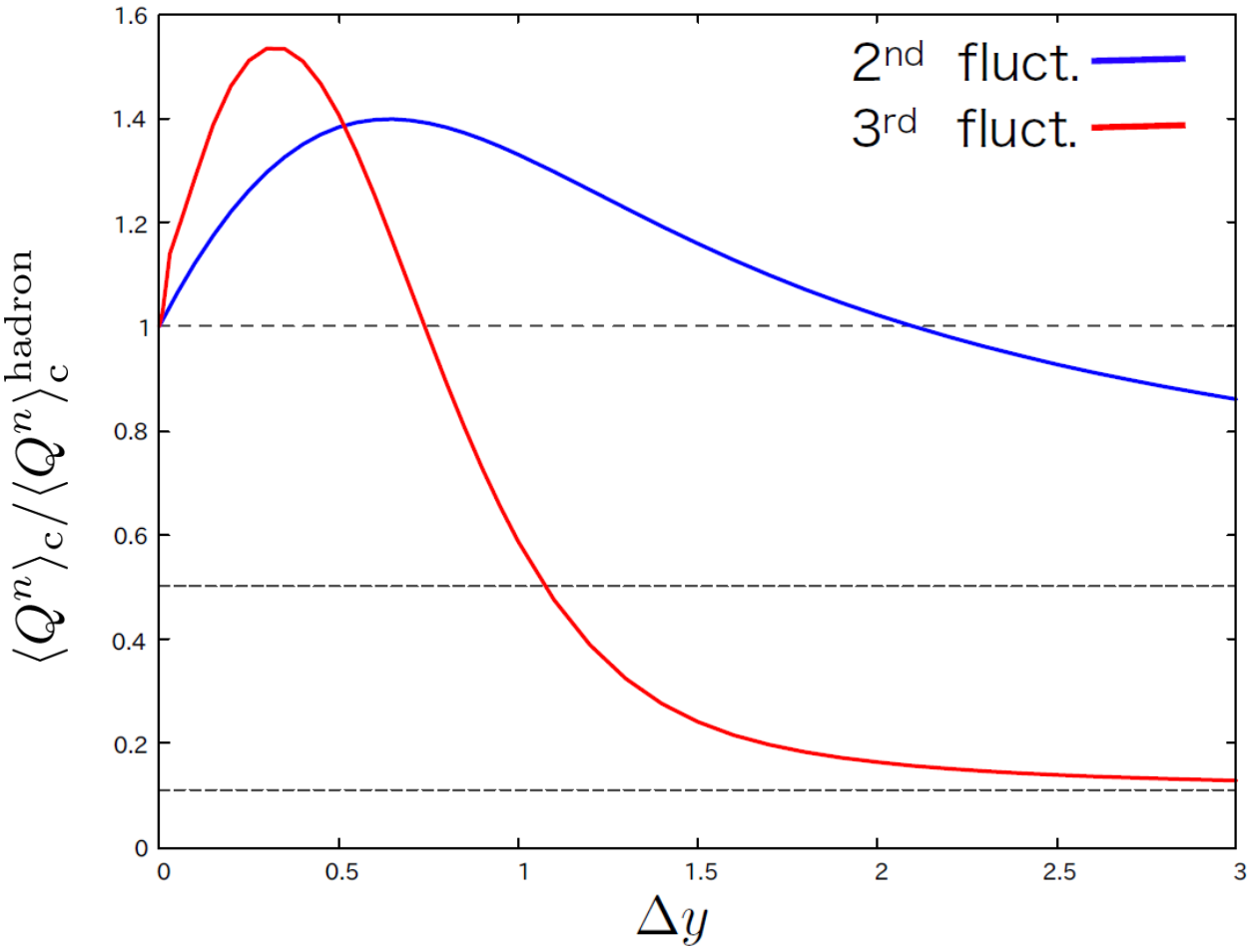




negative
Asakawa, Ejiri, MK (2009)

- Sharp peak survives as a remnant of criticarity
- Negative 3rd cumulant is buried by the diffusion.

Comparison of 2nd/3rd Cumulants



Sharper peak in 3rd order cumulant.

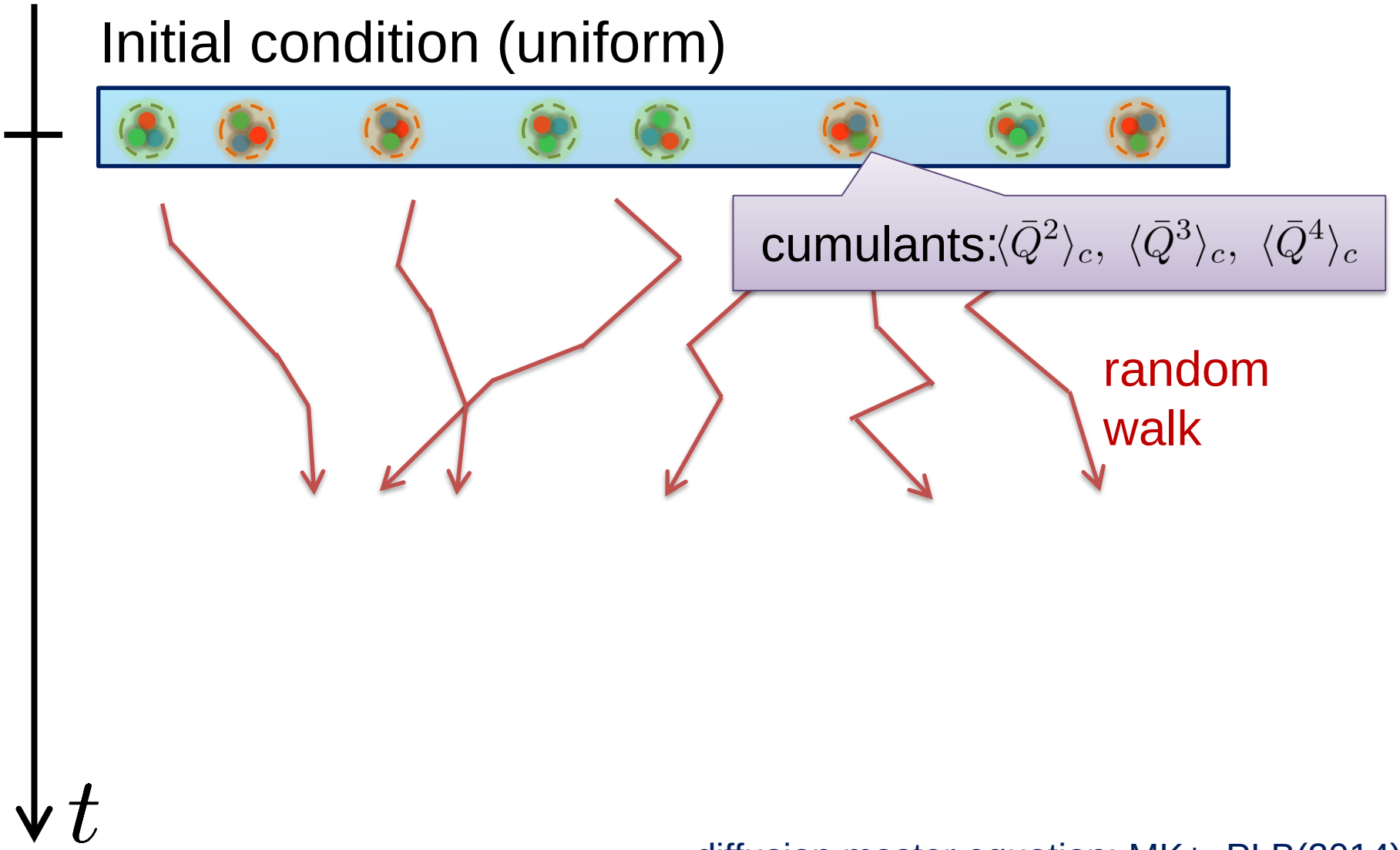
①Diffusion is much slower for higher order

②Remnant of negative χ_3.

まとめ

- QCD臨界点付近における保存電荷3次キュムラント時間発展の、電荷保存則を尊重した解析。
- 有効ポテンシャルの非ガウス性を考慮した方程式を、摂動的に解いた。
- 3次キュムラントにピーク構造が出現
- **2,3次キュムラントの実験的解析・比較の重要性**
- Future
  - 有限体積効果（並進対称性を課さない解析）
  - ４次キュムラントの解析
  - 数値シミュレーションとの比較
  - 拡散モデルとの比較

(Non-Interacting) Brownian Particle Model



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

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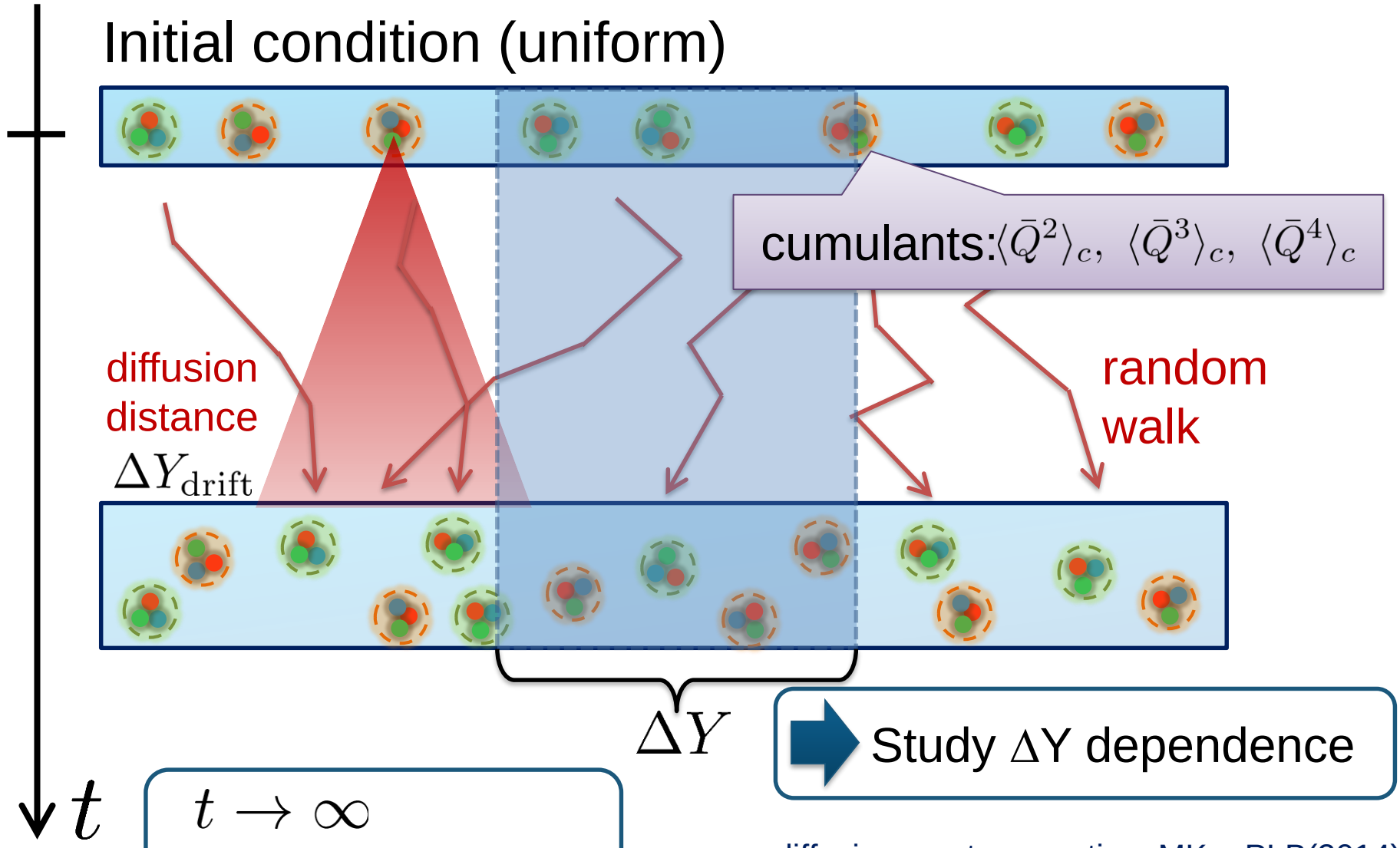

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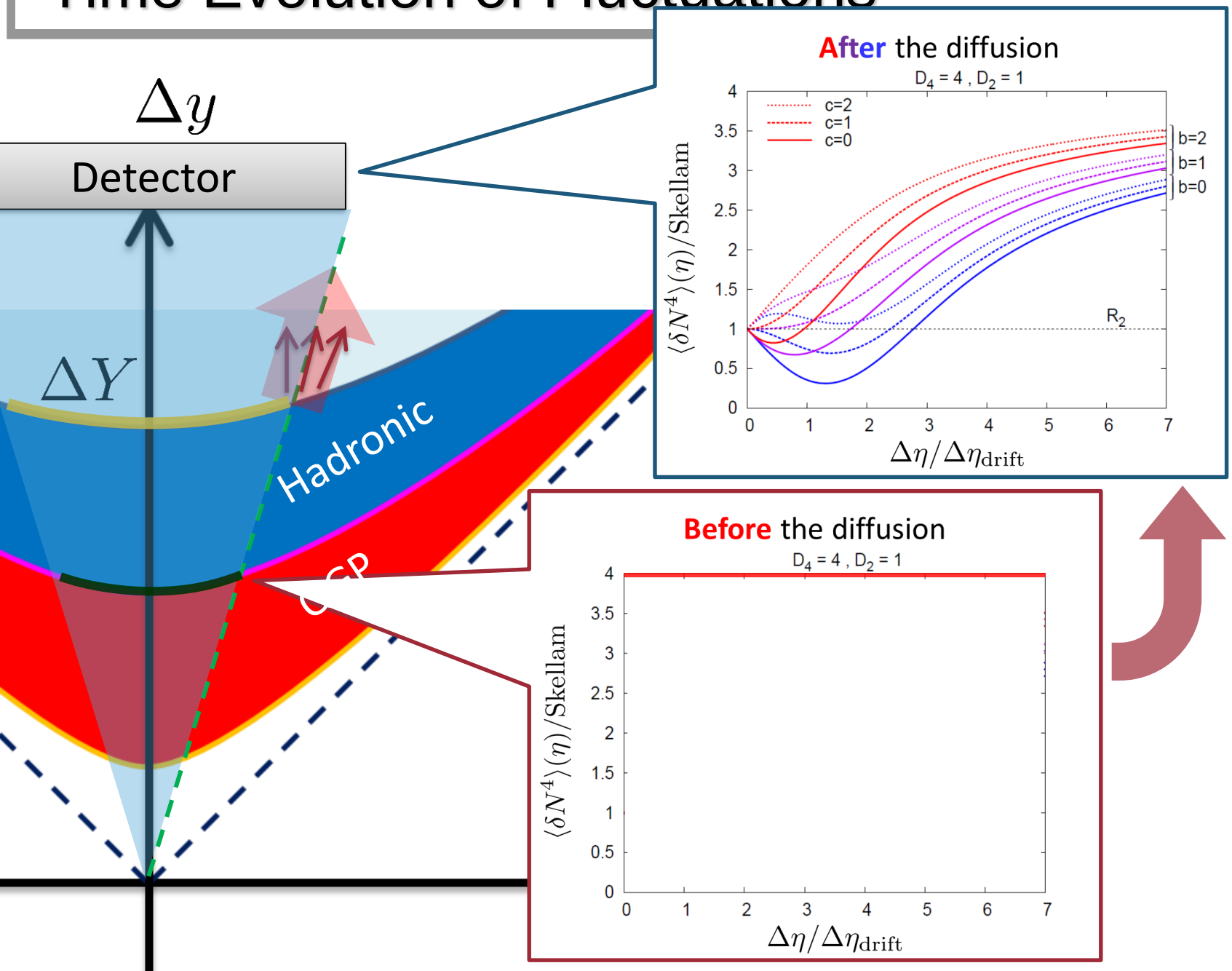
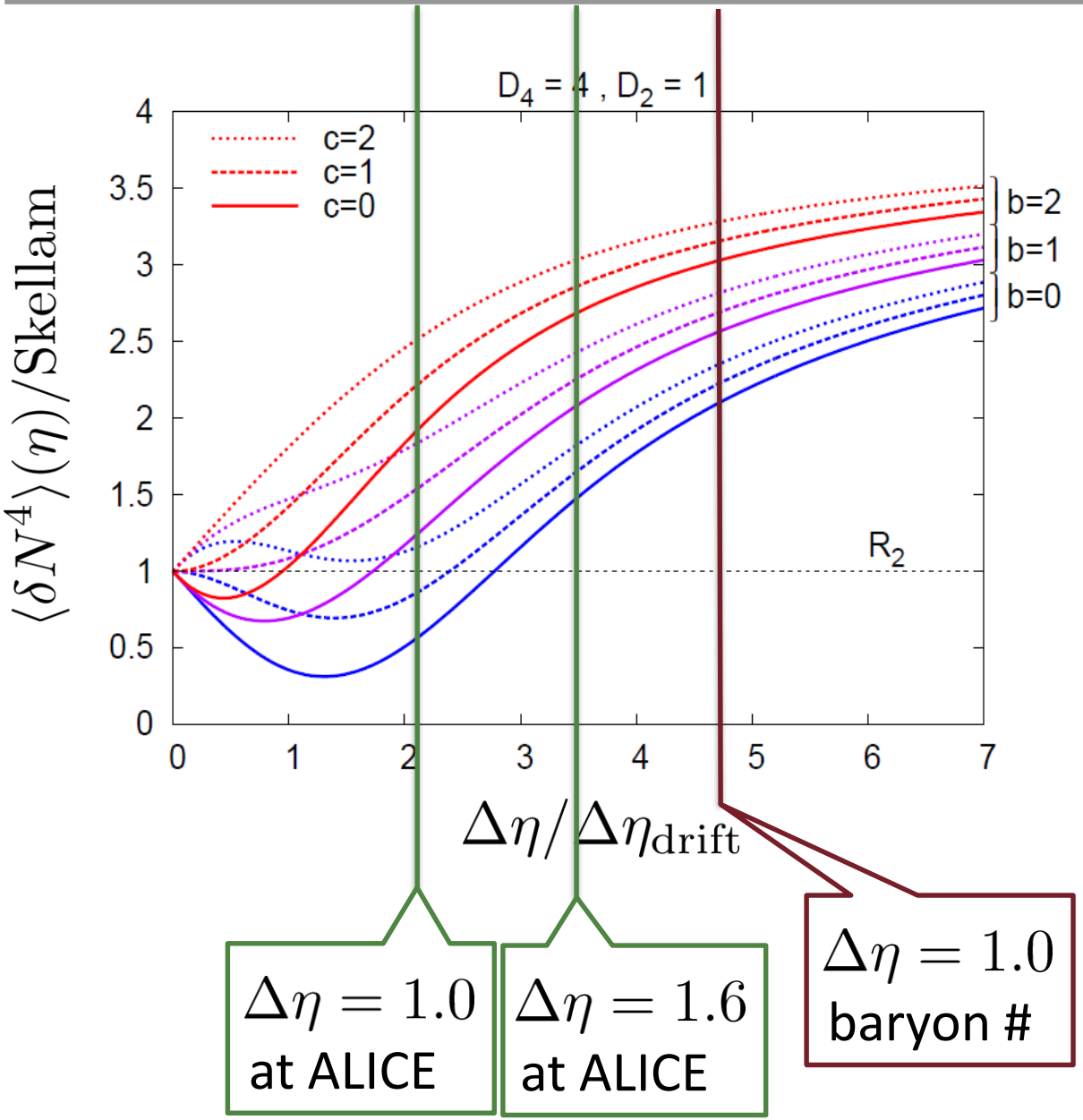
Time Evolution of Fluctuations



As a result of a simple random walk...

4th order : w/ Critical Fluctuation



$\Delta\eta = 1.0$ at ALICE

$\Delta\eta = 1.6$ at ALICE

$\Delta\eta = 1.0$ baryon #

Initial Condition

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

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

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

$$D_2 = \frac{\langle Q^2_{(\mathrm{net})} \rangle_c}{\langle Q_{(\mathrm{tot})} \rangle} = 1$$

$$D \sim M^{-1}$$

Solution

Evolution eqation of $\langle \delta n(x_1) n(x_2) n(x_3) \rangle$

$$\Rightarrow \langle N^3 \rangle_c$$

$$\langle \delta N^3 \rangle_{\Delta\eta} = \chi_3(\tau_0) \int dy \left[\frac{1}{2} \left(\mathrm{erf}\left(\frac{y + \Delta\eta/2}{\sqrt{2} d(\tau_0, \tau)} \right) - \mathrm{erf}\left(\frac{y - \Delta\eta/2}{\sqrt{2} d(\tau_0, \tau)} \right) \right) \right]^3$$

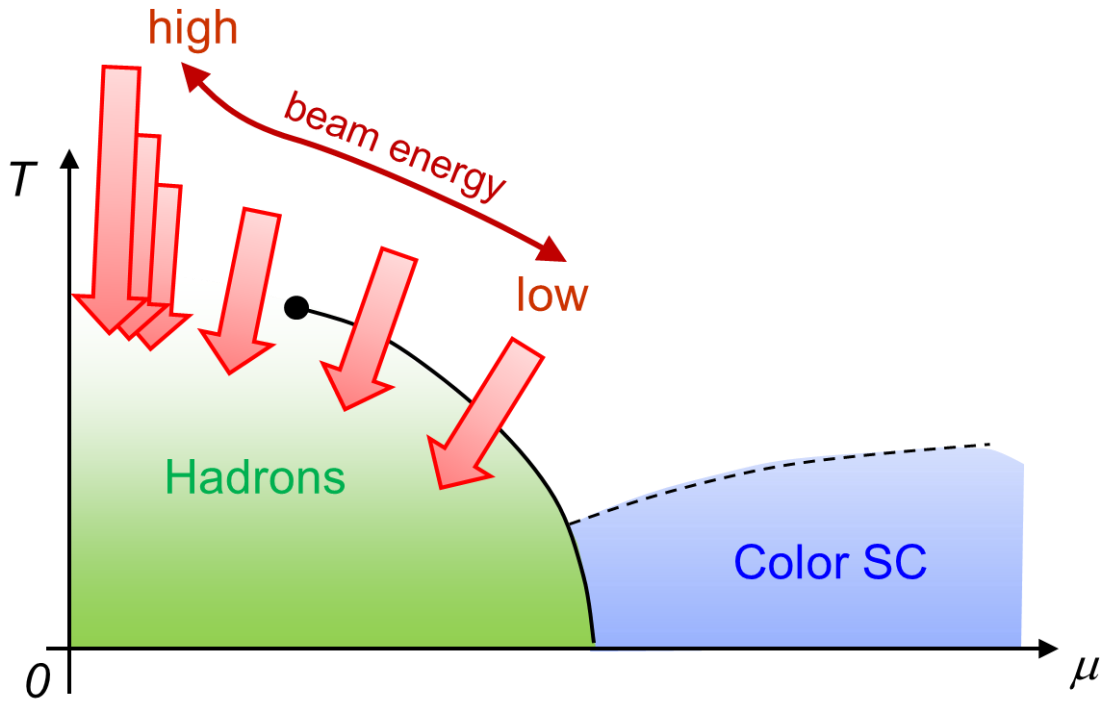
$$+3 \int dy \int_{\tau_0}^{\tau} d\tau' \frac{\chi_3(\tau')}{\chi_2(\tau')^2} \frac{D(\tau')}{\sqrt{2\pi} d(\tau', \tau)^3} \left[\left(y + \frac{\Delta\eta}{2} \right) e^{-\frac{\left(y + \frac{\Delta\eta}{2}\right)^2}{2 d(\tau', \tau)^2}} - \left(y - \frac{\Delta\eta}{2} \right) e^{-\frac{\left(y - \frac{\Delta\eta}{2}\right)^2}{2 d(\tau', \tau)^2}} \right]$$

$$\times \left[\frac{\chi_2(\tau')}{2} \left(\mathrm{erf}\left(\frac{y + \Delta\eta/2}{\sqrt{2} d(\tau', \tau)} \right) - \mathrm{erf}\left(\frac{y - \Delta\eta/2}{\sqrt{2} d(\tau', \tau)} \right) \right) \right.$$

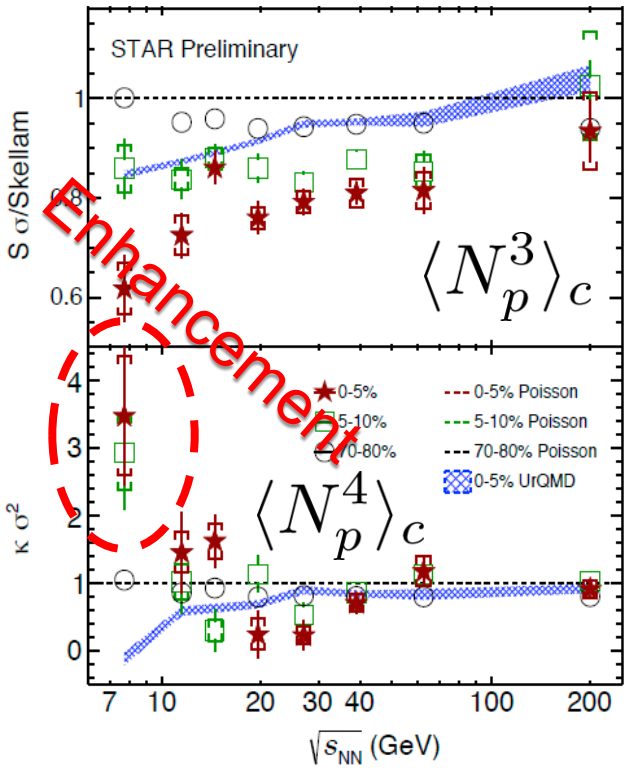
$$\left. -\frac{1}{2} \int_{\tau_0}^{\tau'} d\tau'' \left(\frac{d\chi_2(\tau'')}{d\tau''} \right) \left(\mathrm{erf}\left(\frac{y + \Delta\eta/2}{\sqrt{2(d(\tau'', \tau')^2 + d(\tau'', \tau)^2)}} \right) - \mathrm{erf}\left(\frac{y - \Delta\eta/2}{\sqrt{2(d(\tau'', \tau')^2 + d(\tau'', \tau)^2)}} \right) \right) \right]^2$$

QCD臨界点探索@ HIC

Beam-Energy Scan (BES)



陽子数高次キュムラント（STAR2016）

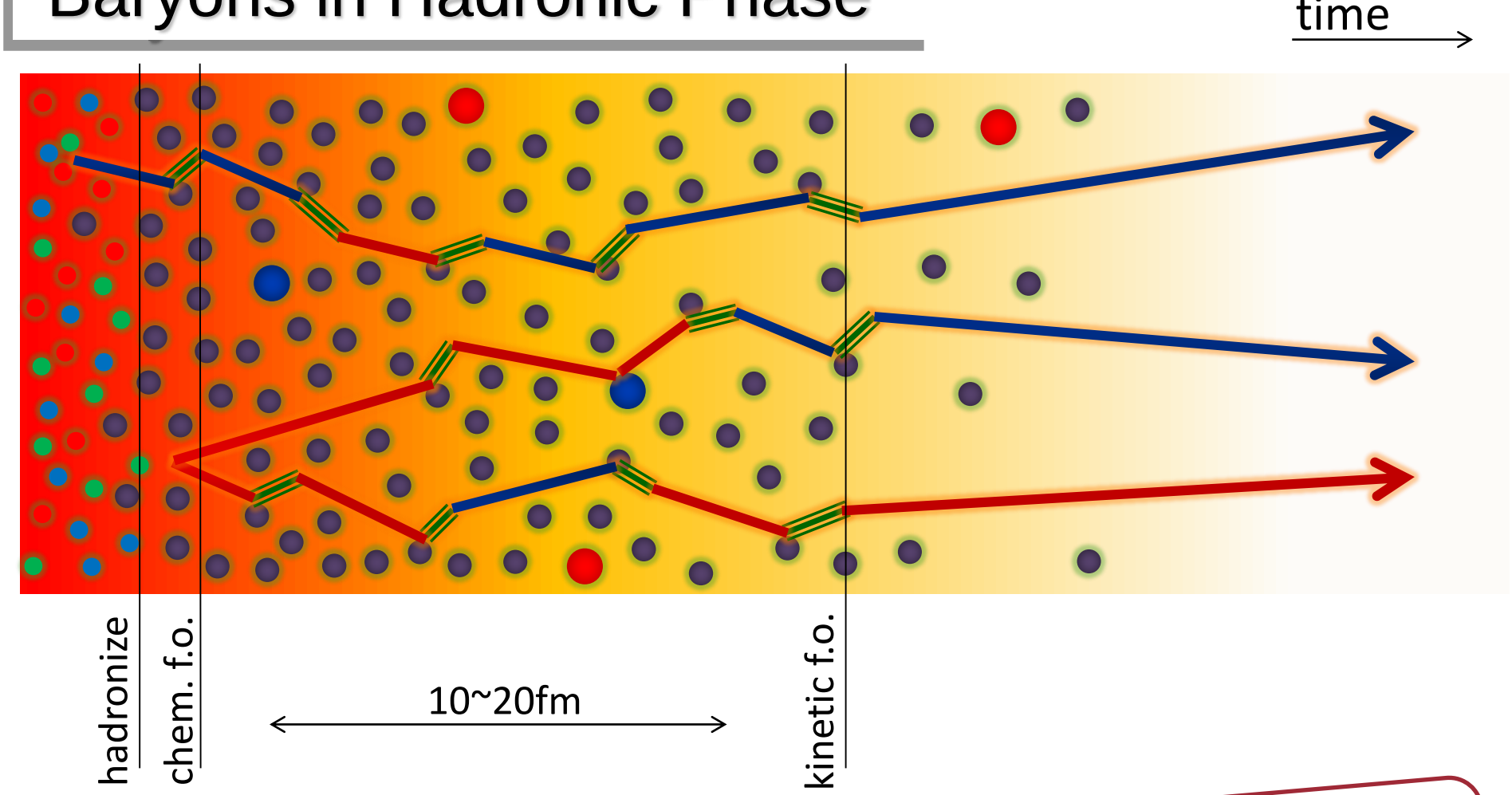


保存電荷のイベント毎ゆらぎを用いたQCD臨界点探索

STAR-BES-I (2010~2016) / ALICE (2013~) / NA61

future: STAR-BES-II, J-PARC-HI, NICA, FAIR

Baryons in Hadronic Phase



Baryons behave like
Brownian pollens in water