Critical Point and Conserved Charge Fluctuations in Relativistic Heavy Ion Collisions

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With M. Kitazawa and M. Sakaida

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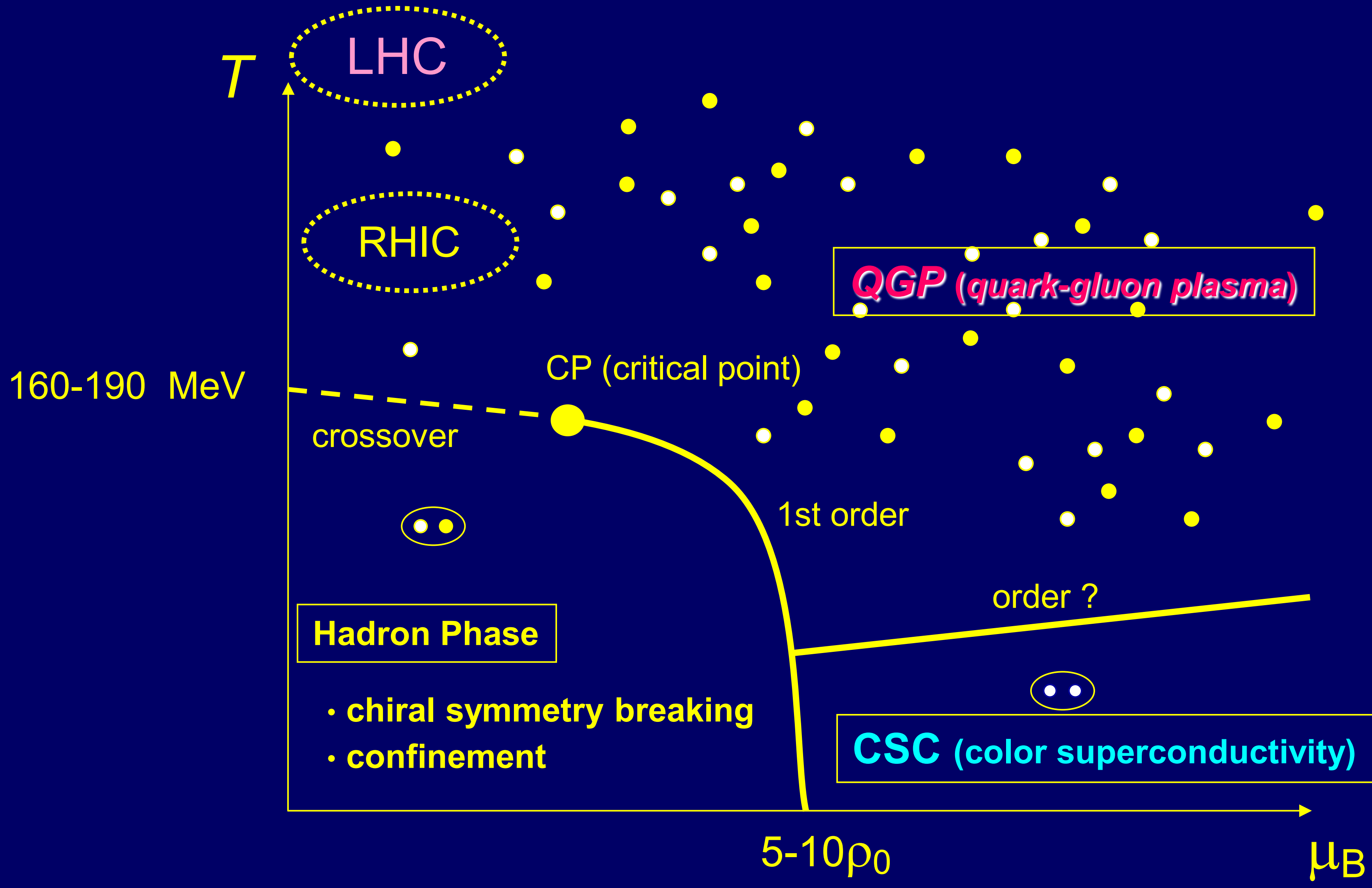
@INT Seattle

QCD Phase Diagram



M. Asakawa (Osaka University)

Why Conserved Charge Fluctuations ?

- Their values do not change during the phase transition
- Their values in QGP and Hadron Phase are different
- They change in Hadron Phase only by diffusion

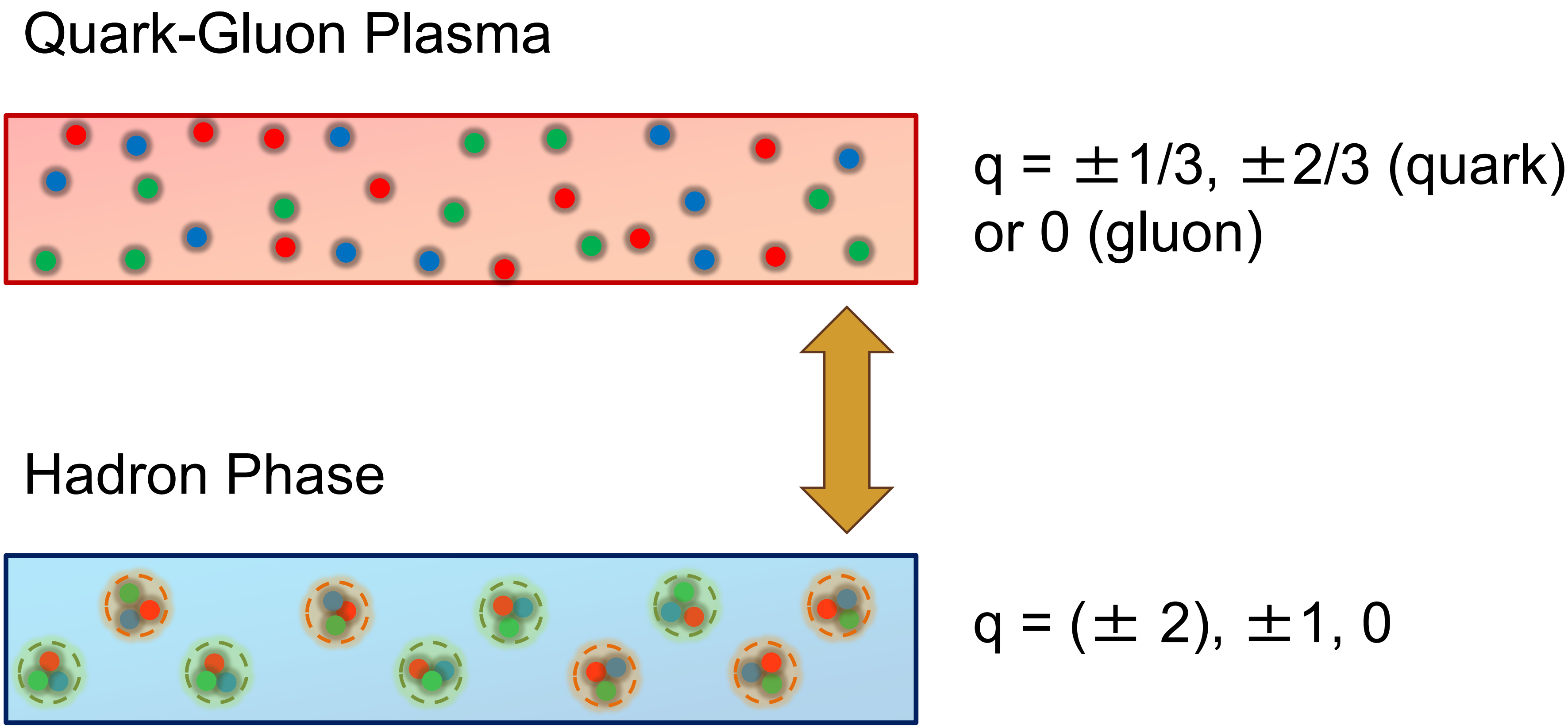
D measure for electromagnetic charge fluctuation

Heinz, Müller, M.A., Jeon, Koch, 2000

- Charge Fluctuation is a well-defined quantity,
  and can be measured on the lattice

- Lattice results and Effective Model results (equilibrium thermodynamics)
  are often compared with experimental results

Comparison of Hadron Phase and QGP



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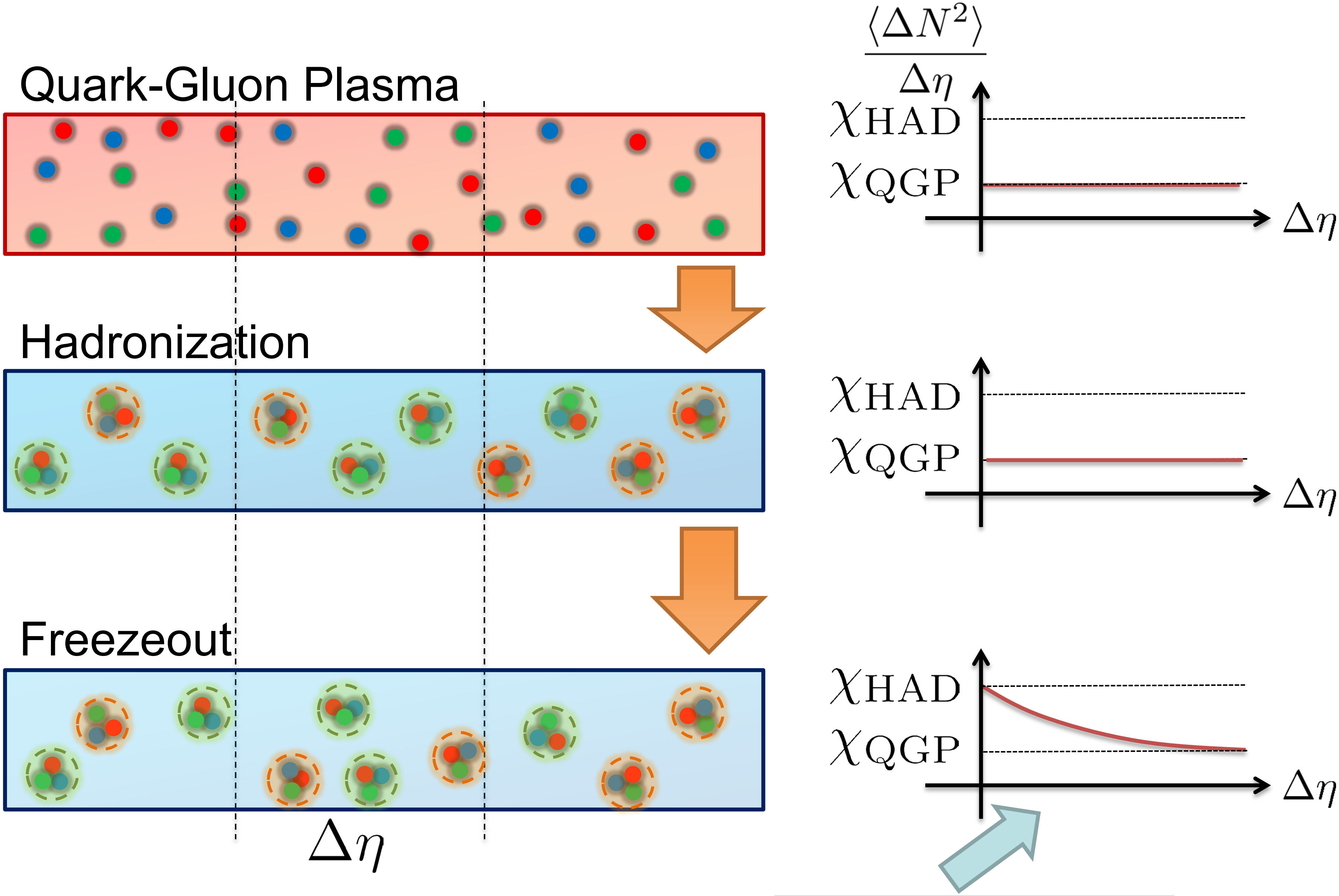
Time Evolution of C.C. fluctuation

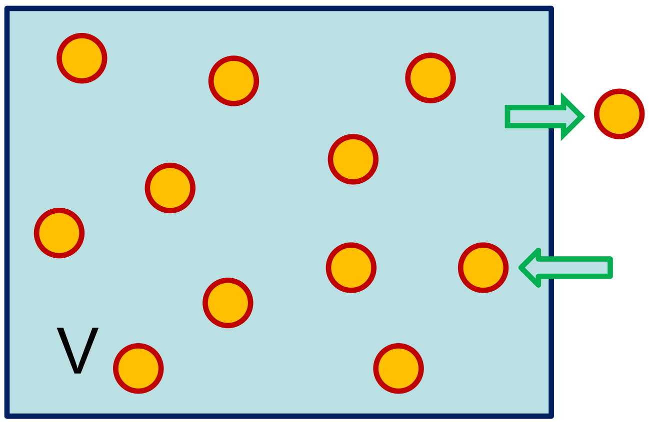


Through diffusion

Conserved and Non-Conserved Charge Fluc.

Necessary to consider dynamical evolution of fluctuation!

Conserved Charge

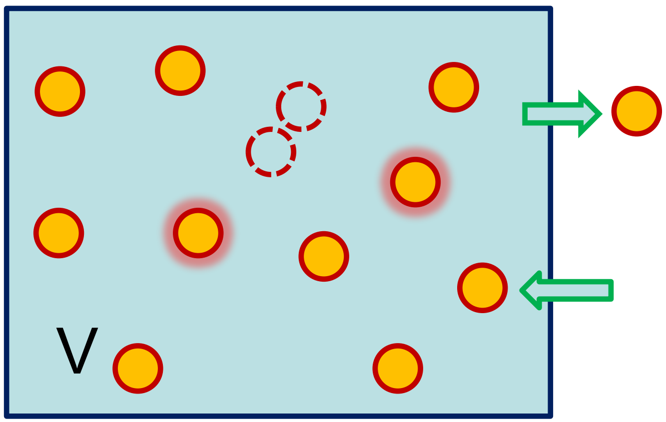


Only diffusion changes
the number of charge

relaxation time $\tau \to \infty$

for $V \to \infty$

Non-Conserved Charge

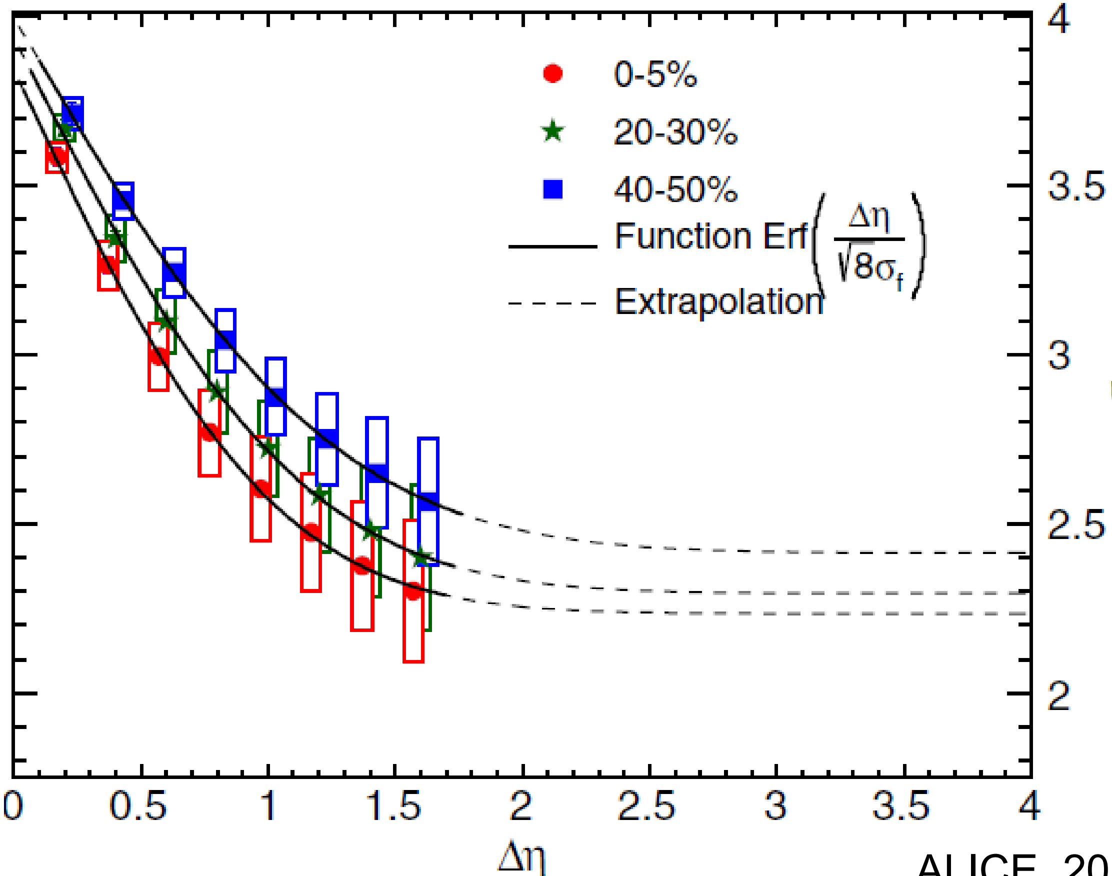


Charge can change
anywhere in the volume

$\tau \to$ finite

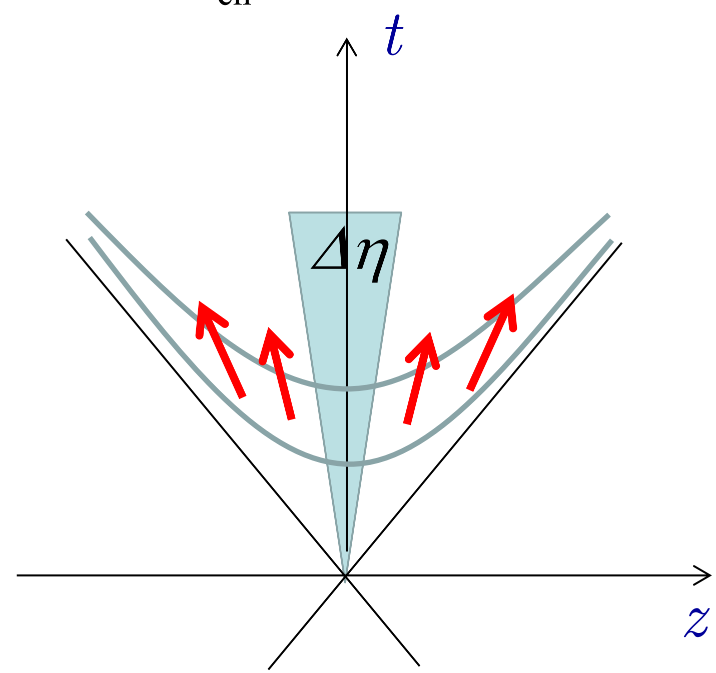
for $V \to \infty$

$\Delta\eta$ Dependence @ ALICE



ALICE, 2013

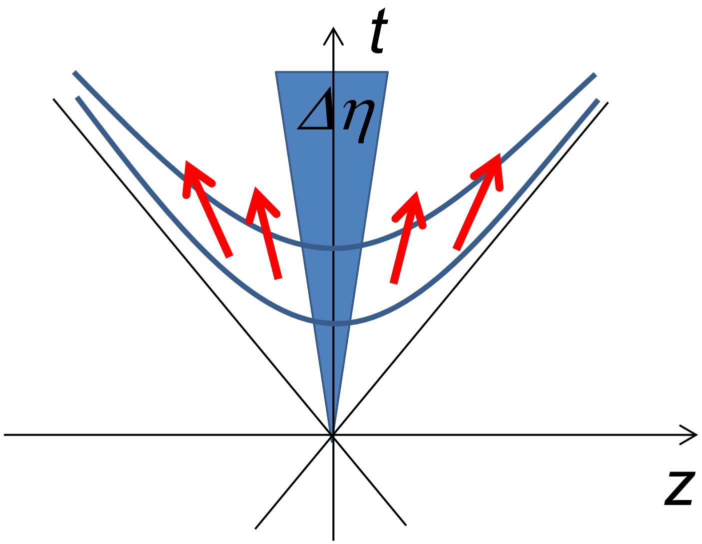
$$D = 4\frac{\langle \delta N_Q^2 \rangle}{N_{\mathrm{ch}}}$$

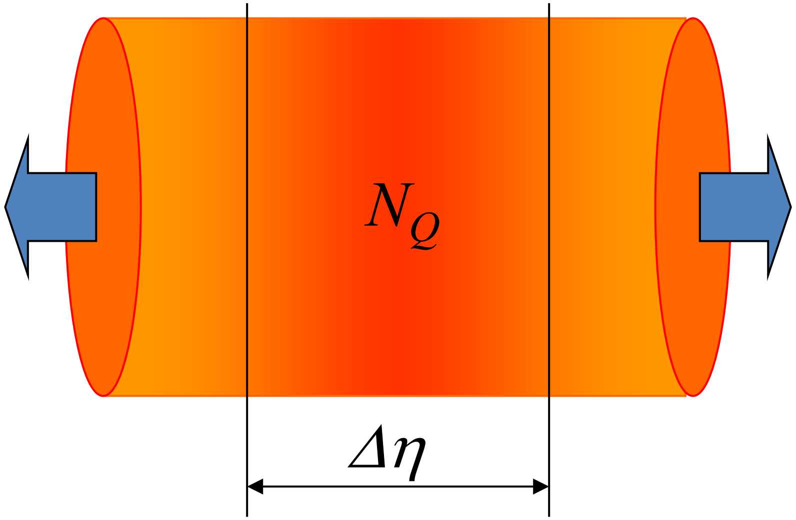


- *Freeze-out parameters: lattice meets experiment*

In this argument, no rapidity window dependence is taken into account

Time Evolution of Conserved Charge

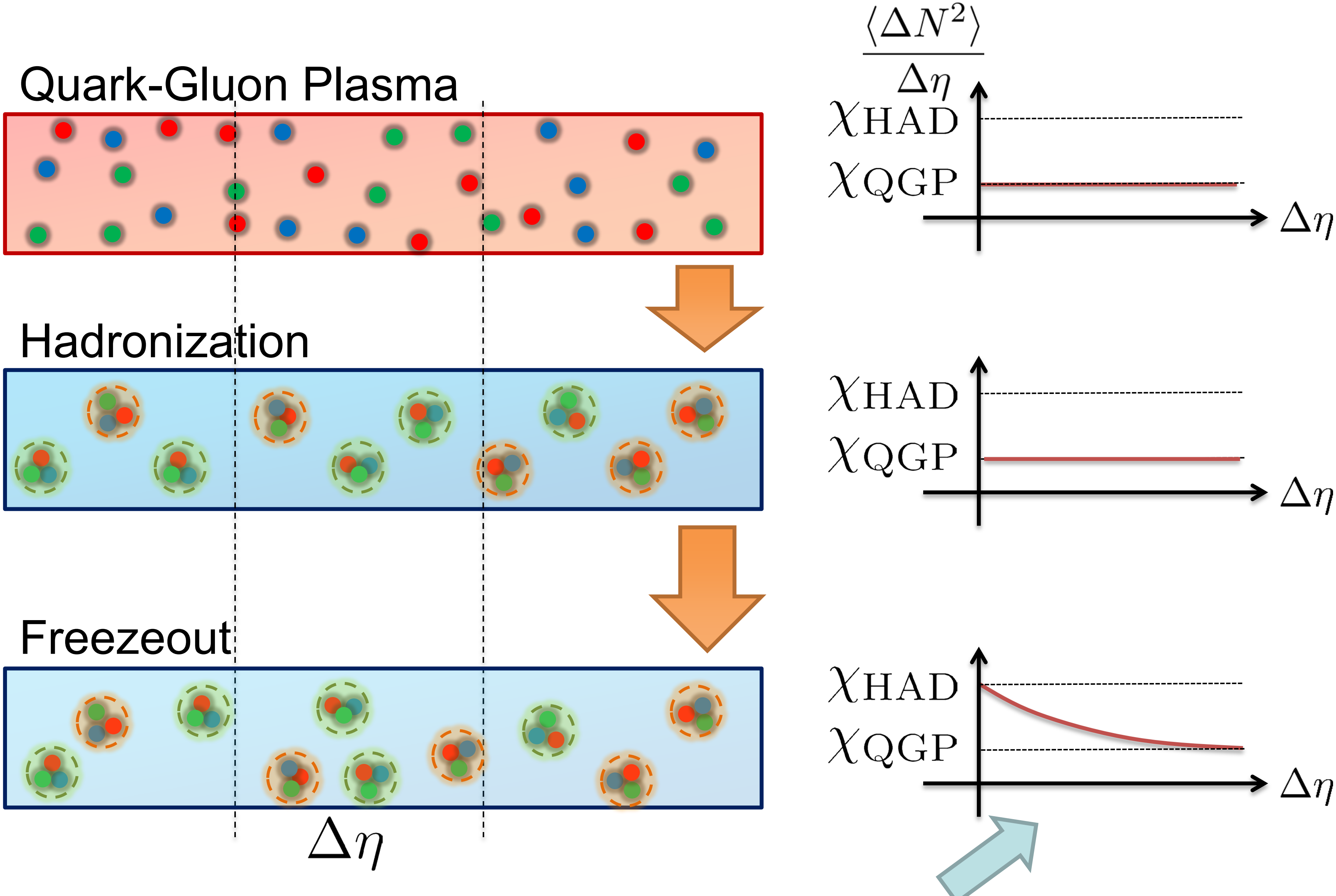




Variation of a conserved charge in $\Delta\eta$ is achieved only through diffusion

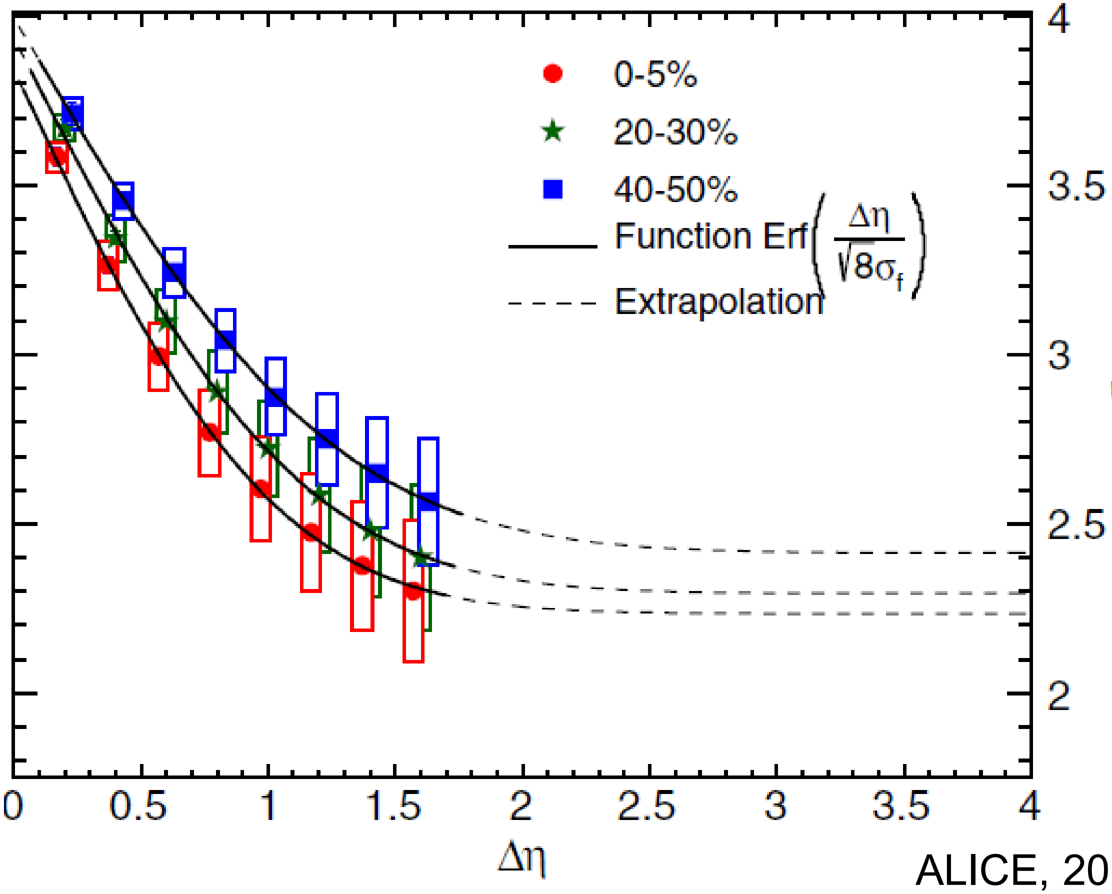
The larger $\Delta\eta$, the slower diffusion

Time Evolution of C.C. fluctuation



In the $\Delta\eta$ dependence of C.C. Fluctuation, history of system is encoded

$\Delta\eta$ Dependence @ ALICE



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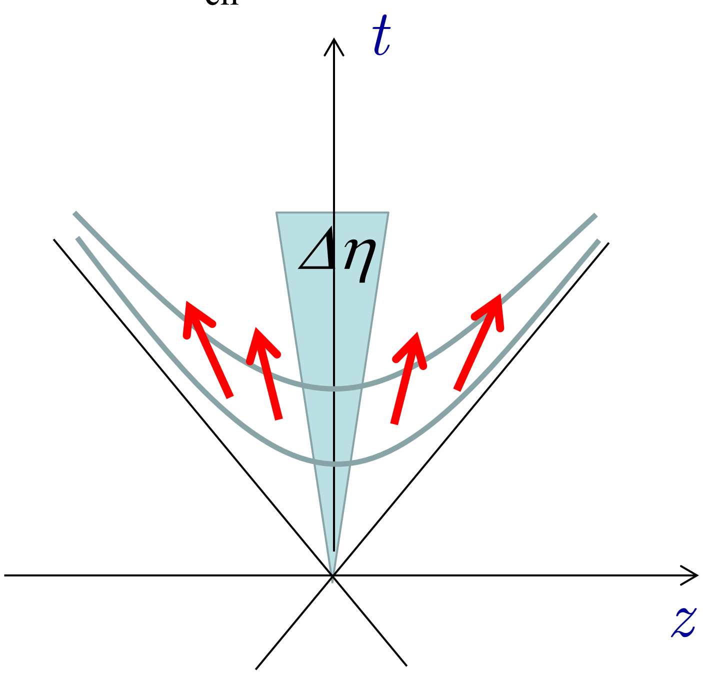

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Conservation Charge Transport in Hadron Phase

Naively,

Diffusion Equation,

$$\partial_\tau n = D\partial_\eta^2 n$$

Plus Fluctuation

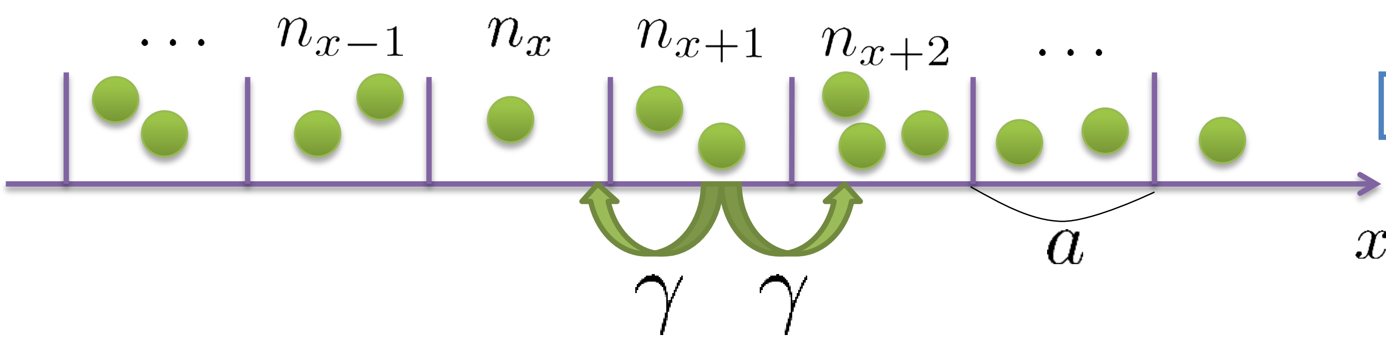
$$\partial_\tau n = D\partial_\eta^2 n + \partial_\eta \xi(\eta, \tau)$$

But it is known *stochastic forces for*
"Markov process for continuum variable(s)" are Gaussian

⇨ We will use a discrete formulation

Diffusion Master Equation (DME)

Divide spatial coordinate into discrete cells



probability

$P(\mathbf{n})$

Master Equation for *P*(*n*)

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

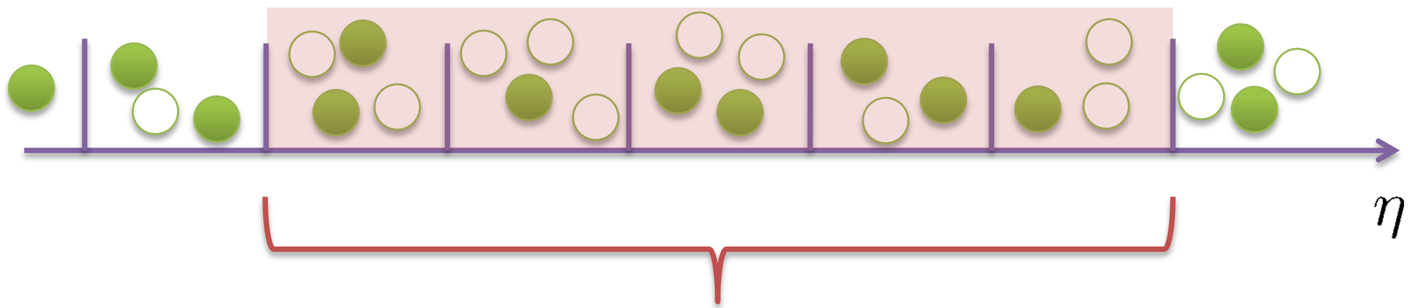
Solve the DME **exactly**, and take *a*→0 limit

No approximation is needed

Ono, Kitazawa, M.A., PLB 2014

Net Charge Number

Prepare 2 species of (non-interacting) particles



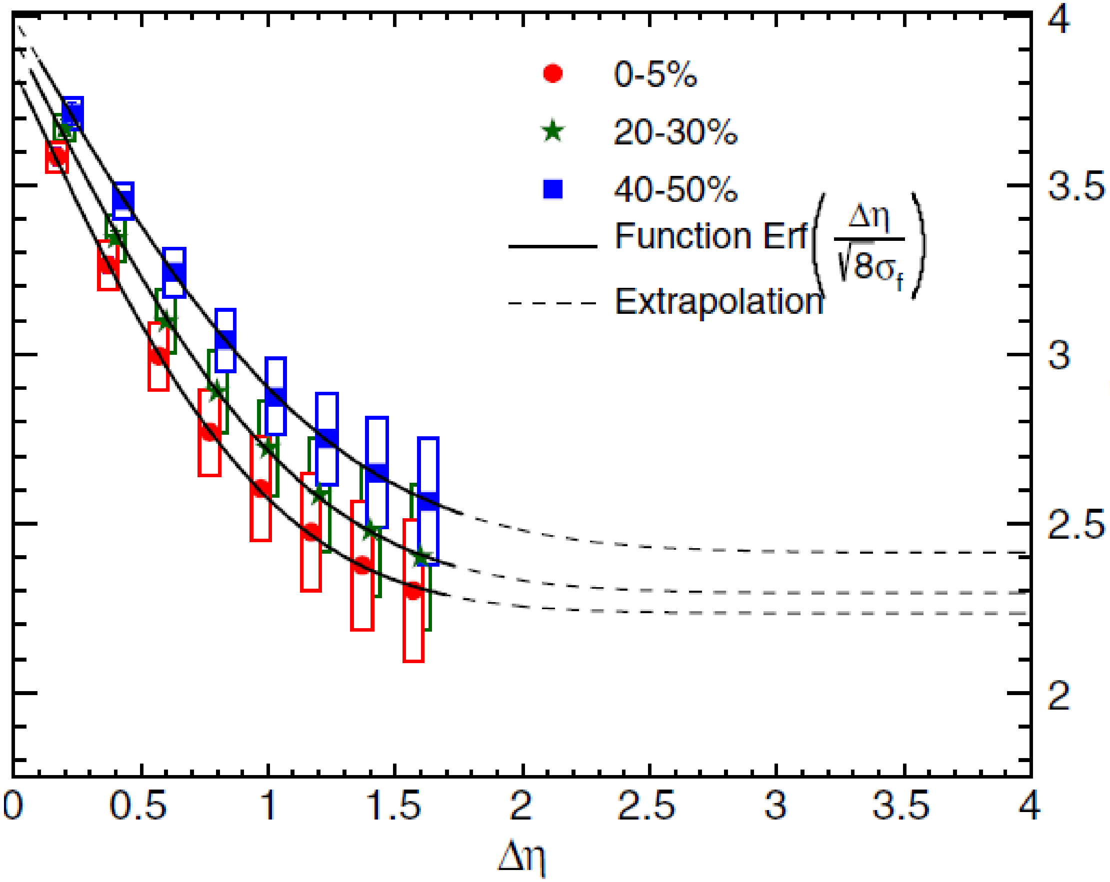
$$\bar{Q}(\tau,\Delta\eta) = \int_0^{\Delta\eta} \left(n_1(\tau,\eta) - n_2(\tau,\eta) \right) d\eta$$

Let us investigate

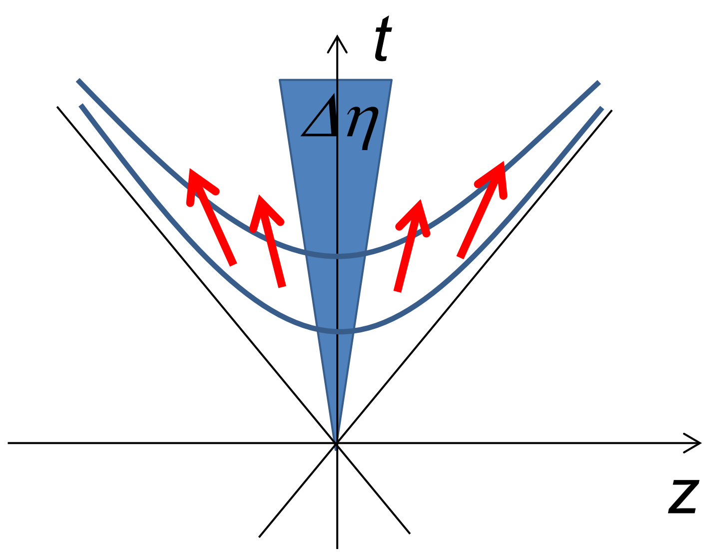
$\langle \bar{Q}^2 \rangle_c$ $\langle \bar{Q}^4 \rangle_c$ at freezeout time t

Closer Look: $\Delta\eta$ dependence

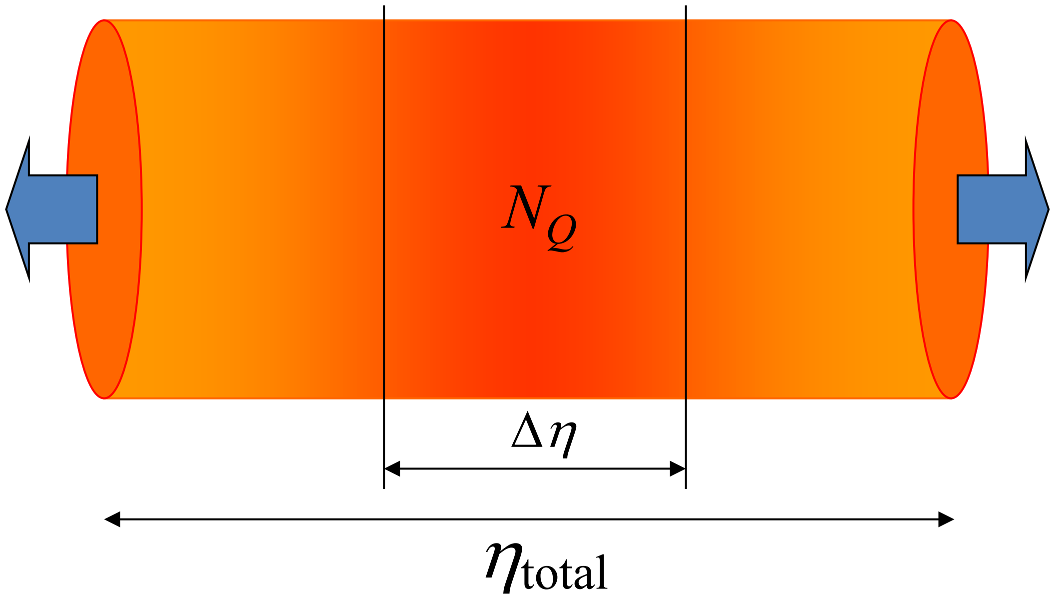
ALICE
PRL 2013



rapidity window



Finite Size Effect (Global Charge Conservation)?



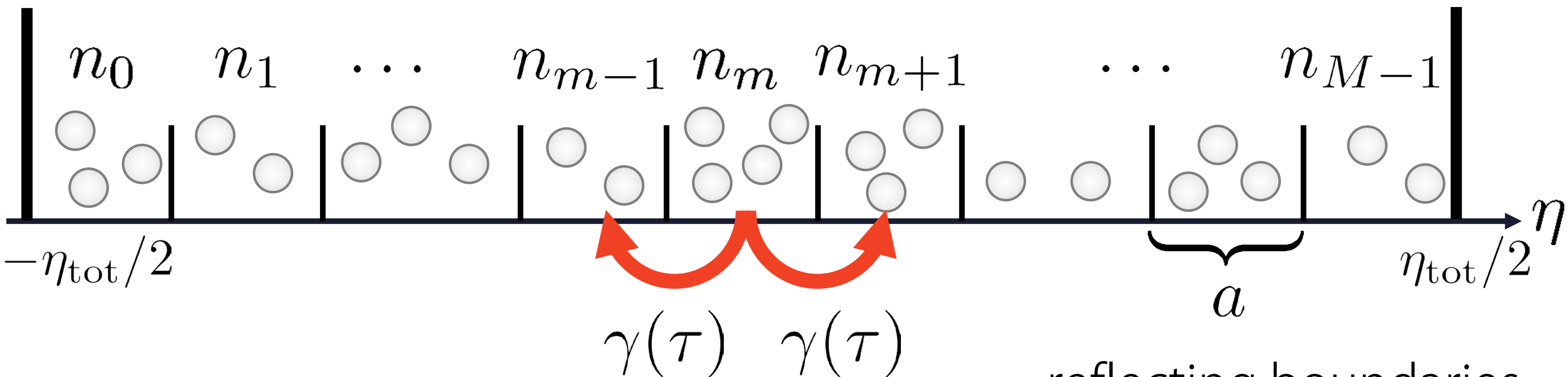
C. C. Fluctuation: 0 if the whole system is observed

$$\Rightarrow \quad \langle \delta Q^2 \rangle_{\text{obs}} = \langle \delta Q^2 \rangle_{\text{equil}} \times \left(1 - \frac{\Delta\eta}{\eta_{\text{total}}} \right) \quad ?$$

if the whole system is equilibrated (Bleicher, Jeon, Koch)

DME with Reflecting Boundaries

Sakaida, Kitazawa, M.A. , PRC 2014



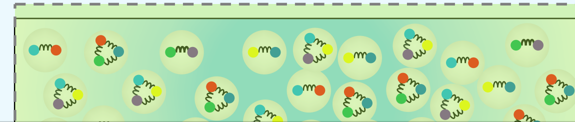
Diffusion Master Equation + **Boundary Condition(GCC Effect)** Particles do NOT flow in/out.

* Diffusion from Hadronization to Thermal Freeze-out
* Initial Condition : No Fluctuations
  or Fluctuations in Thermal QGP

Rapidity Window Dependence of Charge Fluctuations

Diffusion + Global Charge Conservation

If one looks at the Total System,
#Conserved Charge



Previous Study	Global Charge Conservation	Time Evolution	Higher Fluctuations
Bleicher, Jeon, Koch (2000)	○	×	×
Shuryak, Stephanov (2001)	×	○	×
Kitazawa, Asakawa, Ono (2013)	×	○	○
Our Study	○	○	○

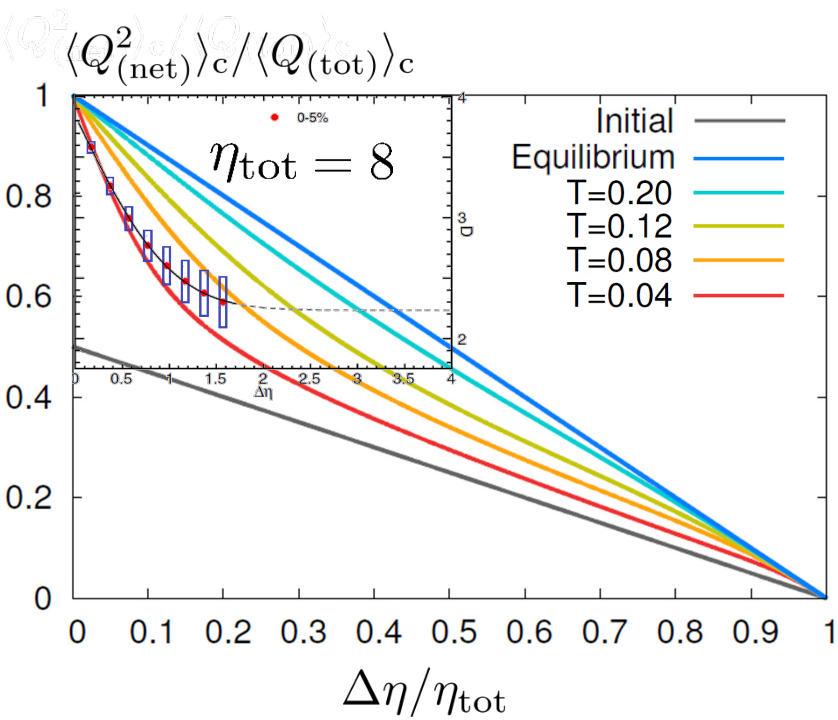
Naive Estimate of GCE Effect

$\eta_{\rm tot}$ $\Delta\eta$: Rap. Win.

Bleicher, Jeon, Koch (2000)

- ~~*Global Charge Conservation is important even at LHC*~~

Suppression of Charge Fluctuation observed @ALICE
→ ~~Global Charge Conservation~~
Fluctuations are NOT Equilibrated!!



Information on

＊Fluctuation in QGP
＊Time Evolution
＊Diffusion Coefficient

…etc.
is encoded

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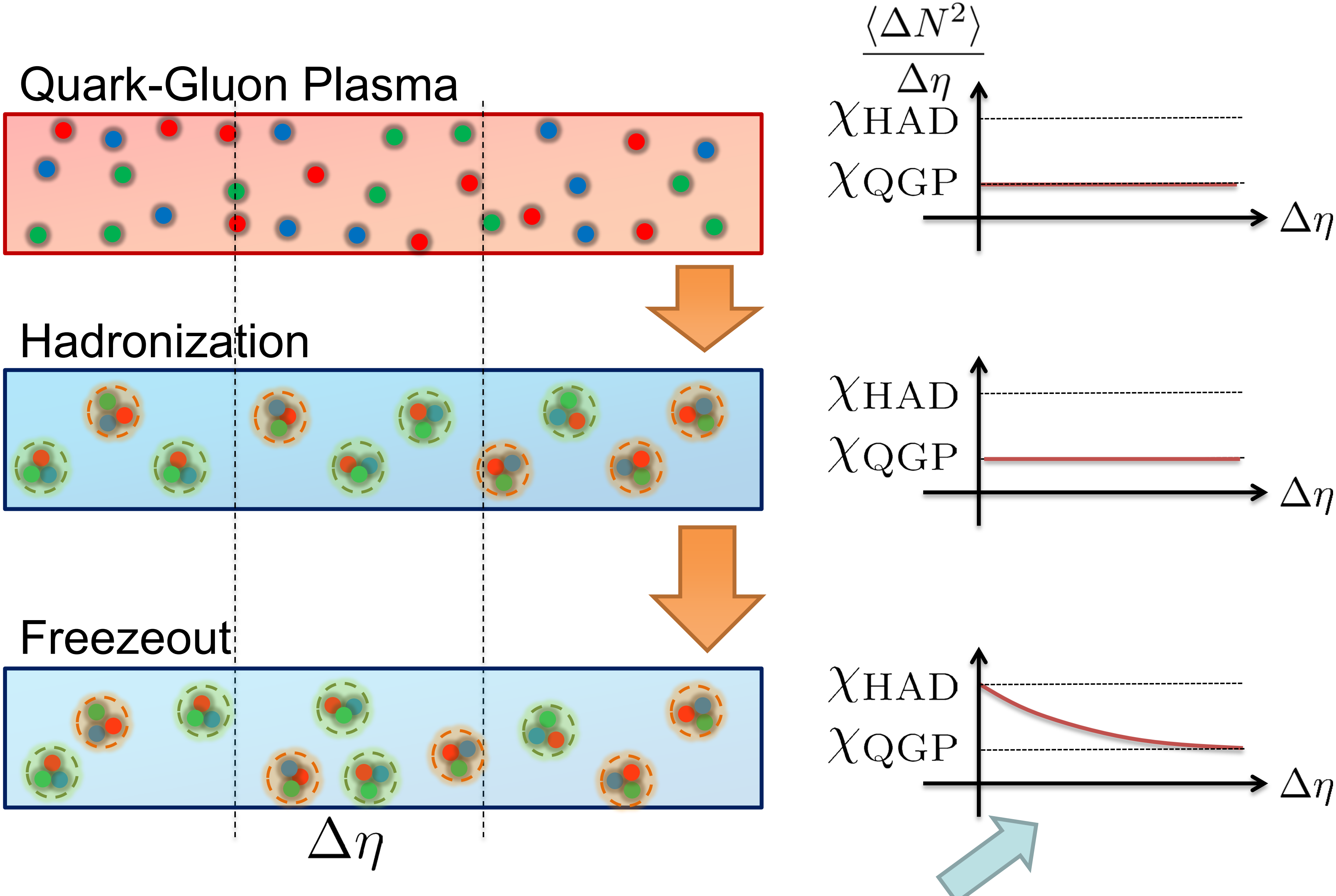
Time Evolution of C.C. fluctuation



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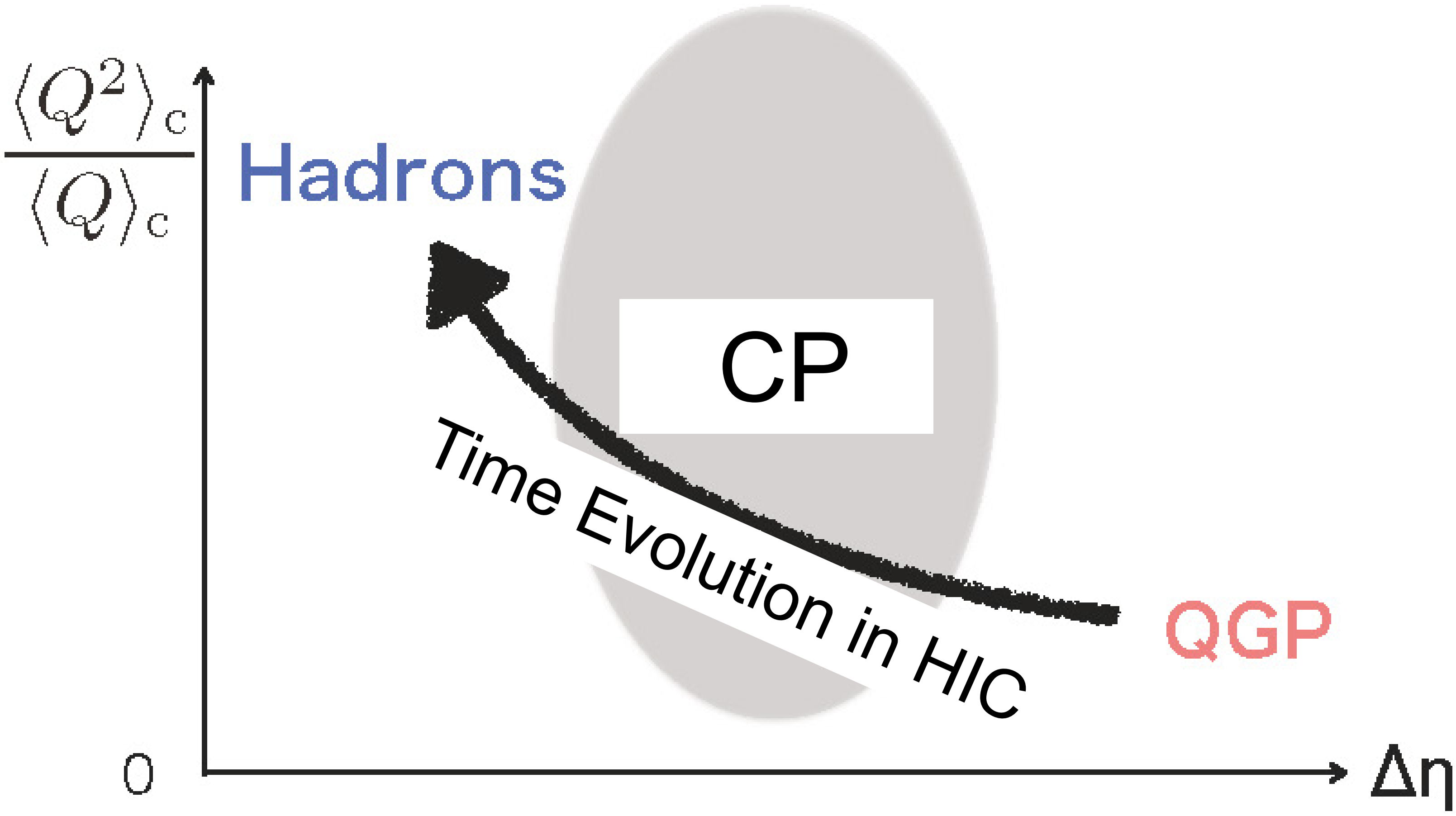
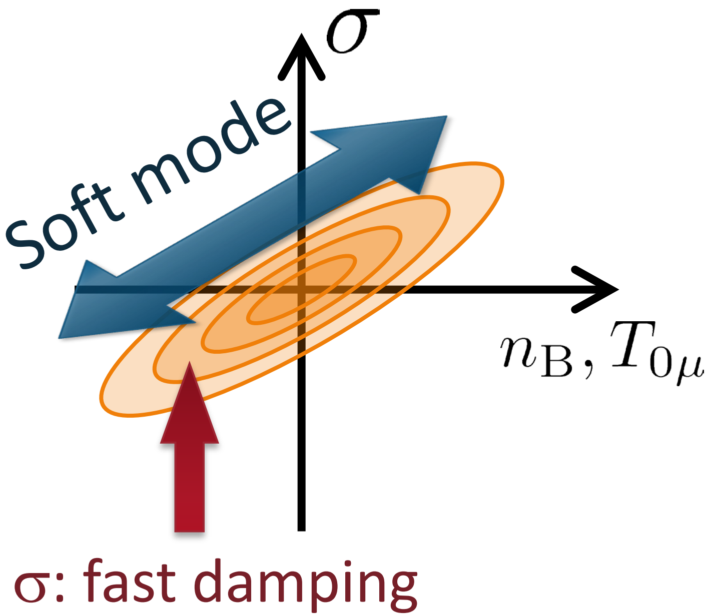
Critical Fluctuation and Δη Dependence



Critical Mode = Diffusive Mode

Fujii (2004)
Fujii, Ohtani (2005)
Son, Stephanov (2005)



Soft mode of QCD CP

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

$\sim k^2$

Evolution of baryon number density

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

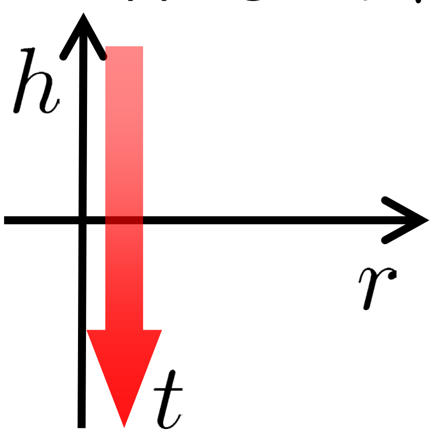
$$\langle \xi(x_1, t_1) \xi(x_2, t_2) \rangle = \chi_2(t) \delta^{(2)}(1-2)$$

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

Parametrization of *D* & χ_2

Berdnikov, Rajagopal (2000)
Stephanov (2011)
Mukherjee, Venugopalan, Yin (2015)

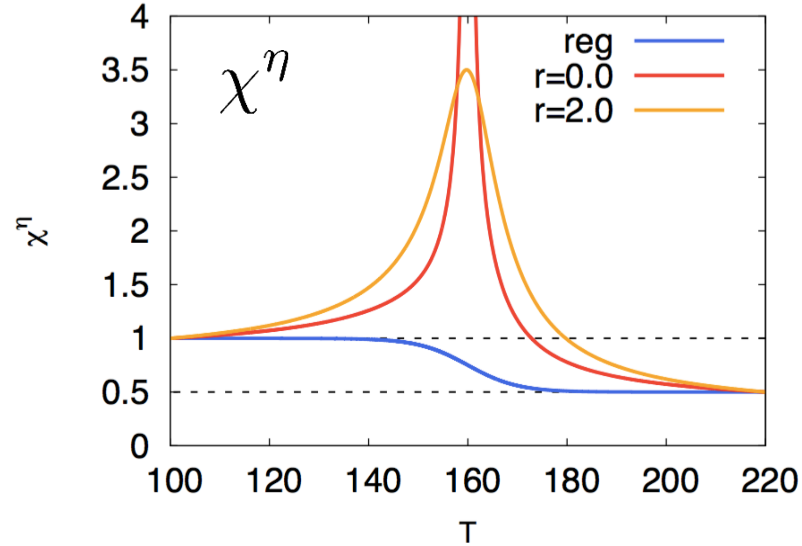
- model-H (3d-Ising)
- $\chi \sim \xi^{1.96},\ D \sim \xi^{-1.044}$
- mapping to (T,μ) / time evolution

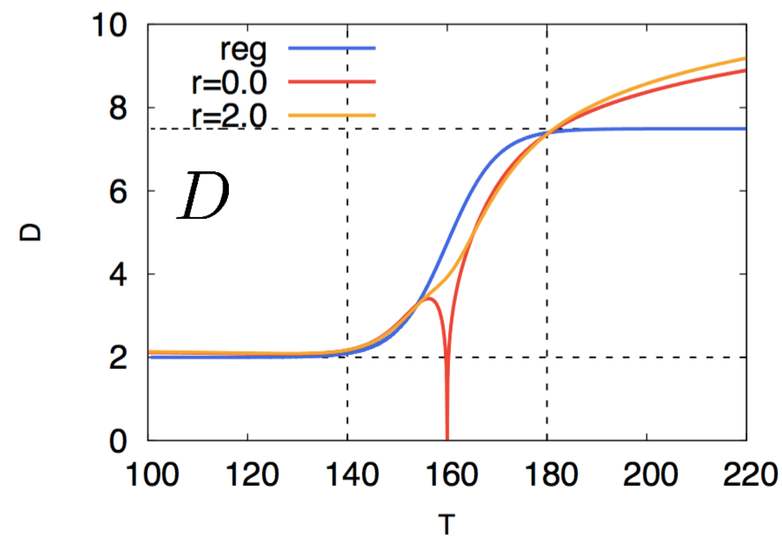


1D Bjorken expansion

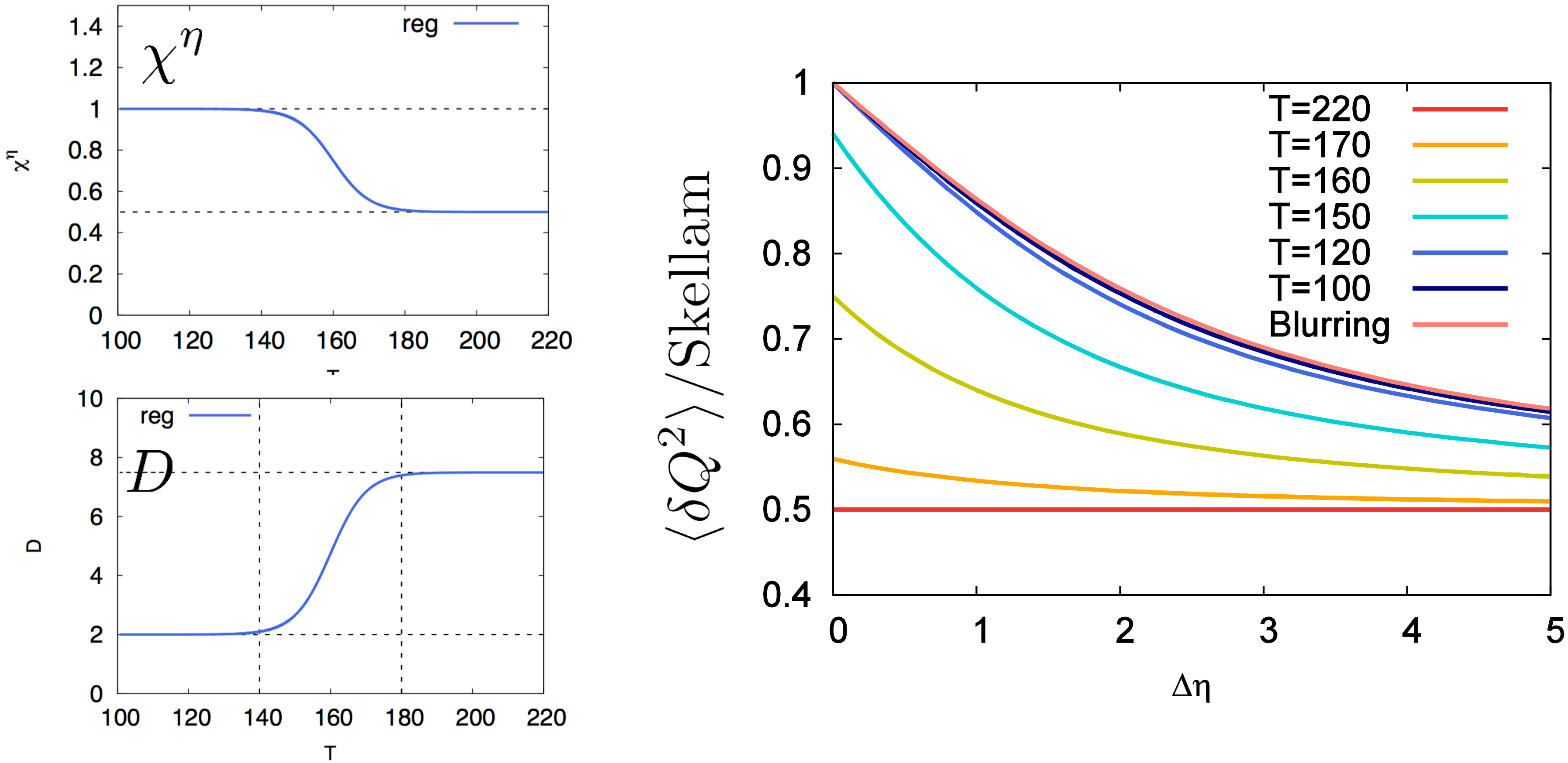
$c_s^2 = 0.2$

- $\chi^\eta_{\mathrm{QGP}}/\chi^\eta_{\mathrm{hadron}} = 0.5$
- QCD CP at T=160MeV
- kinetic f.o. at T=100MeV

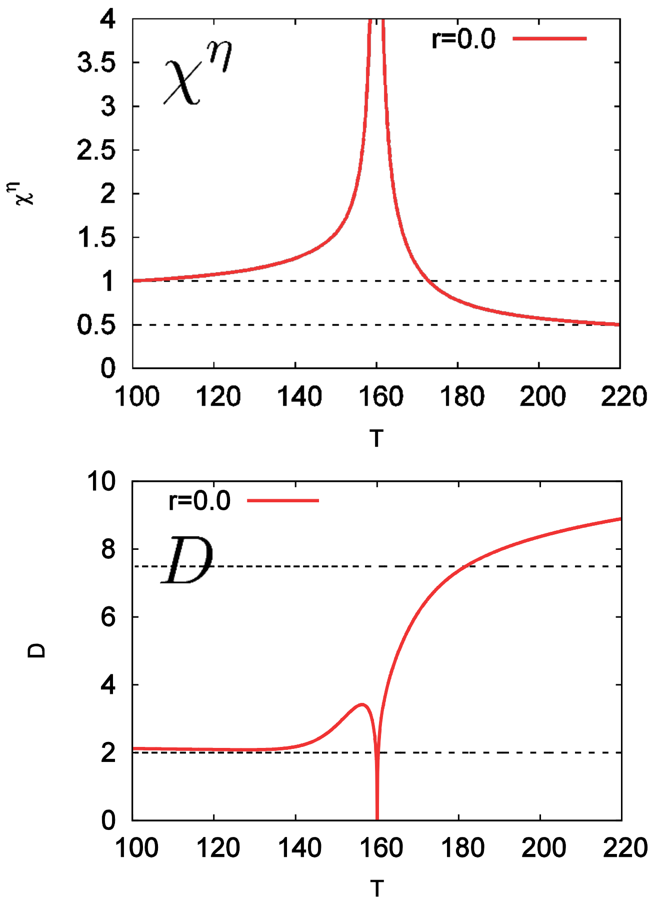


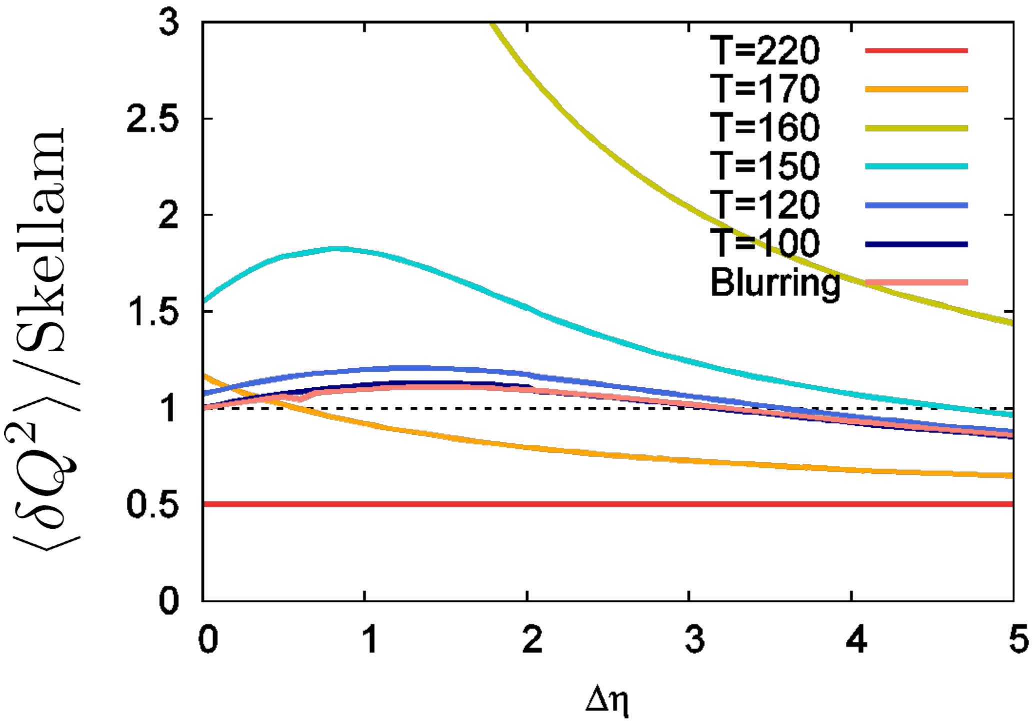


Time Evolution 1: No CP



2: Critical Point

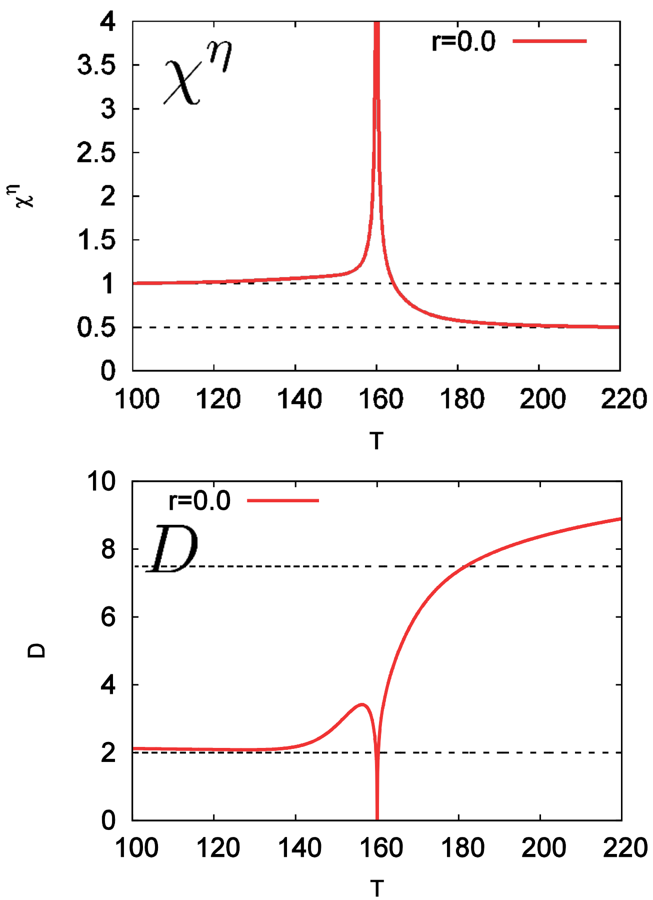


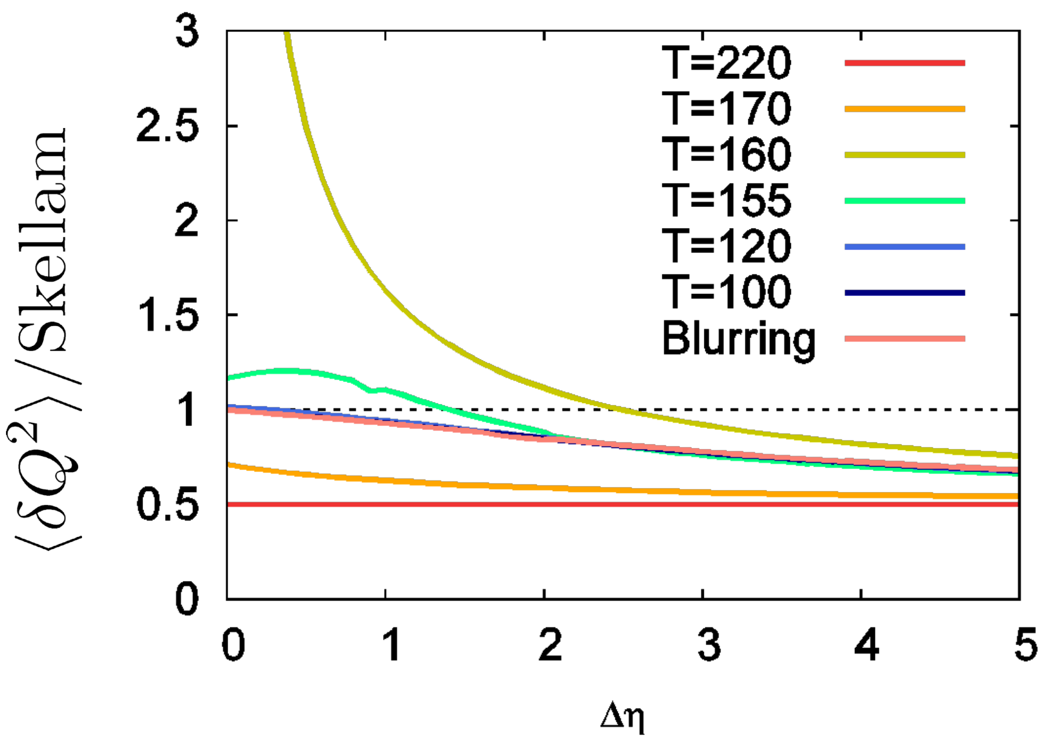


- Non-monotonic Δη dependence manifests itself.

➡ Robust experimental evidence of the existence of a peak in χ(T)

3: Critical Point (Narrower Critical Region)

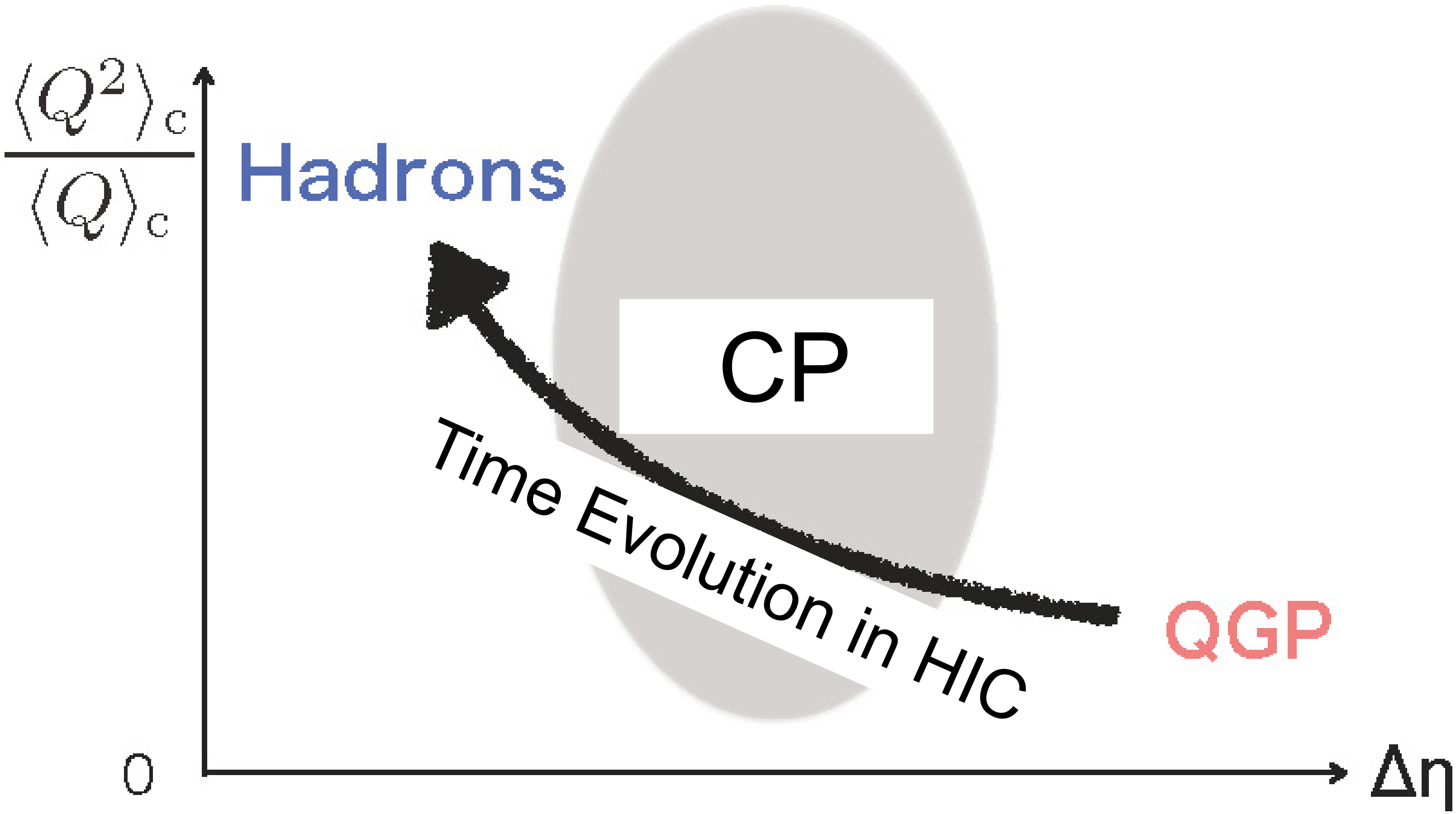




non-monotonic behavior

Peak in $\chi_2(T)$

Critical Fluctuation and Δη Dependence



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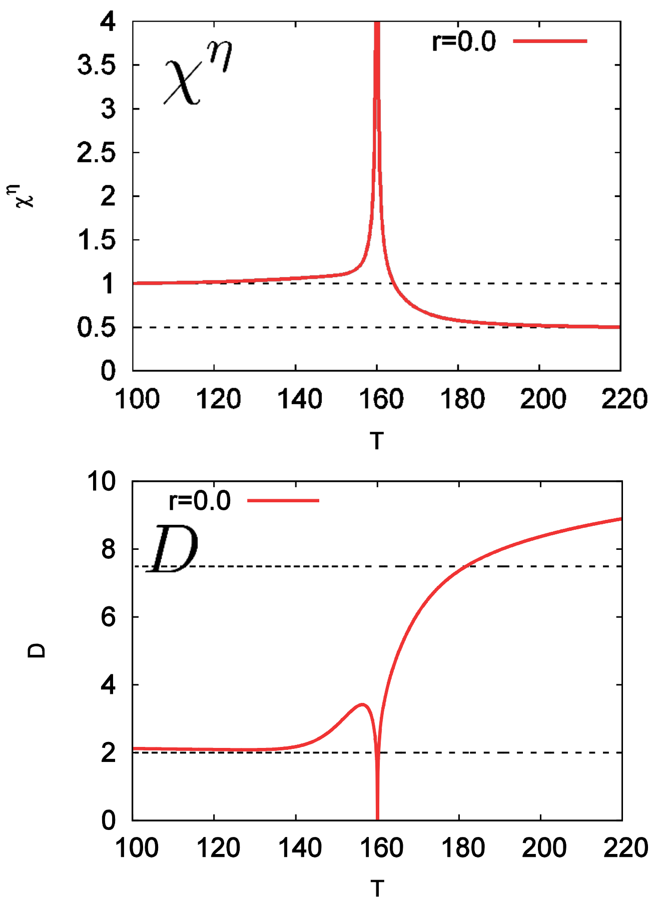

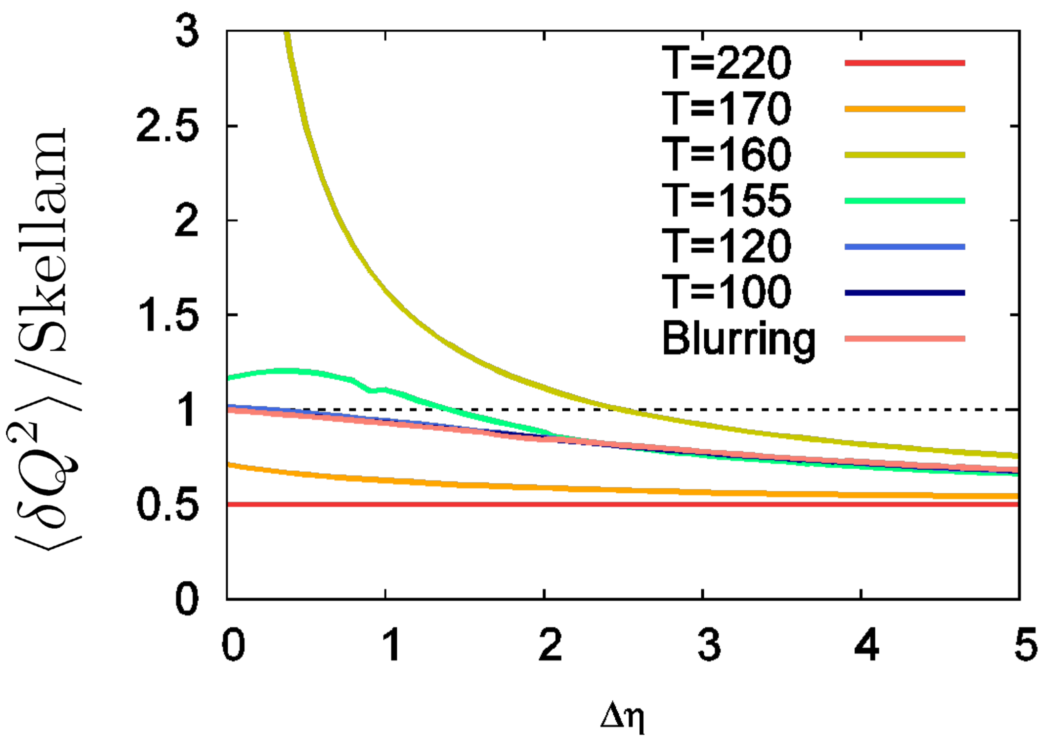

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