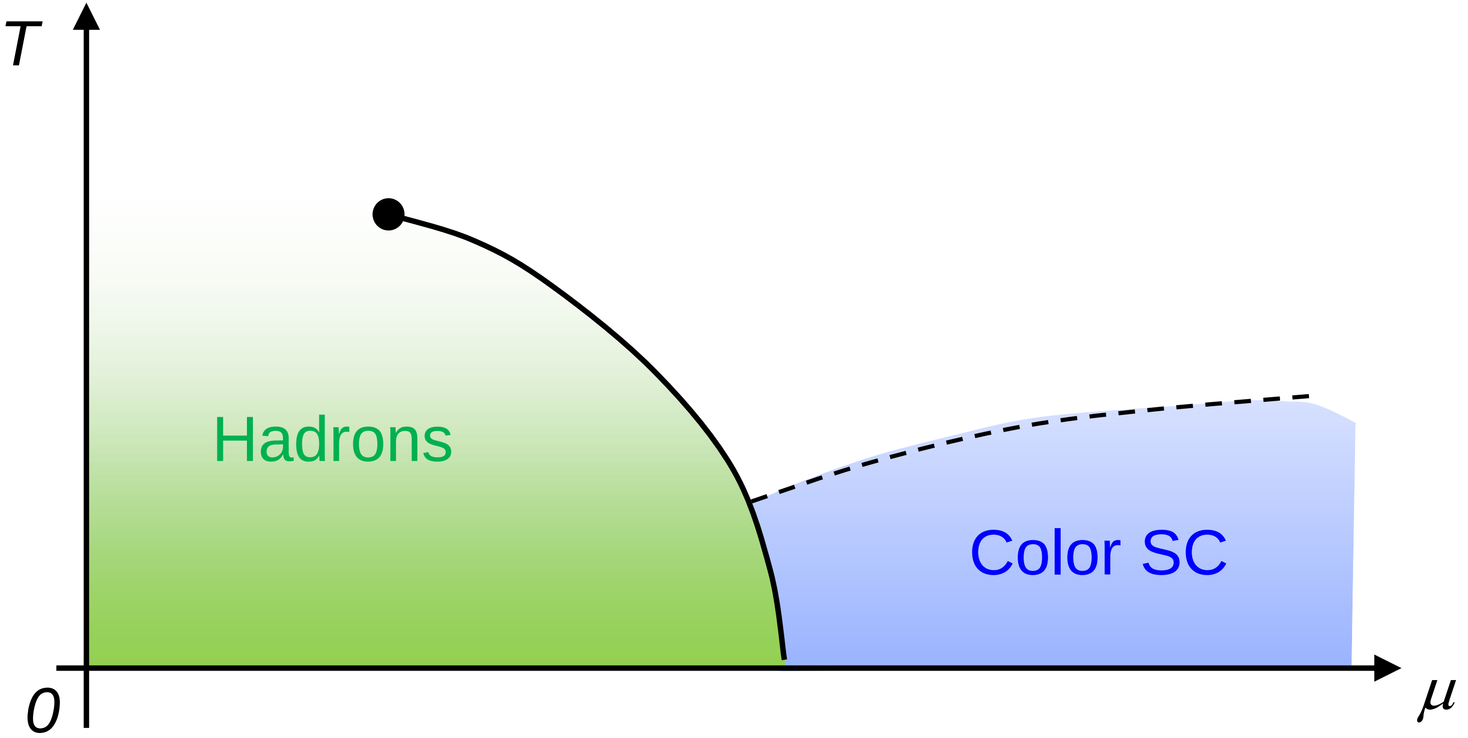
重イオン衝突における保存電荷ゆらぎのダイナミクス

北沢 正清

（阪大）

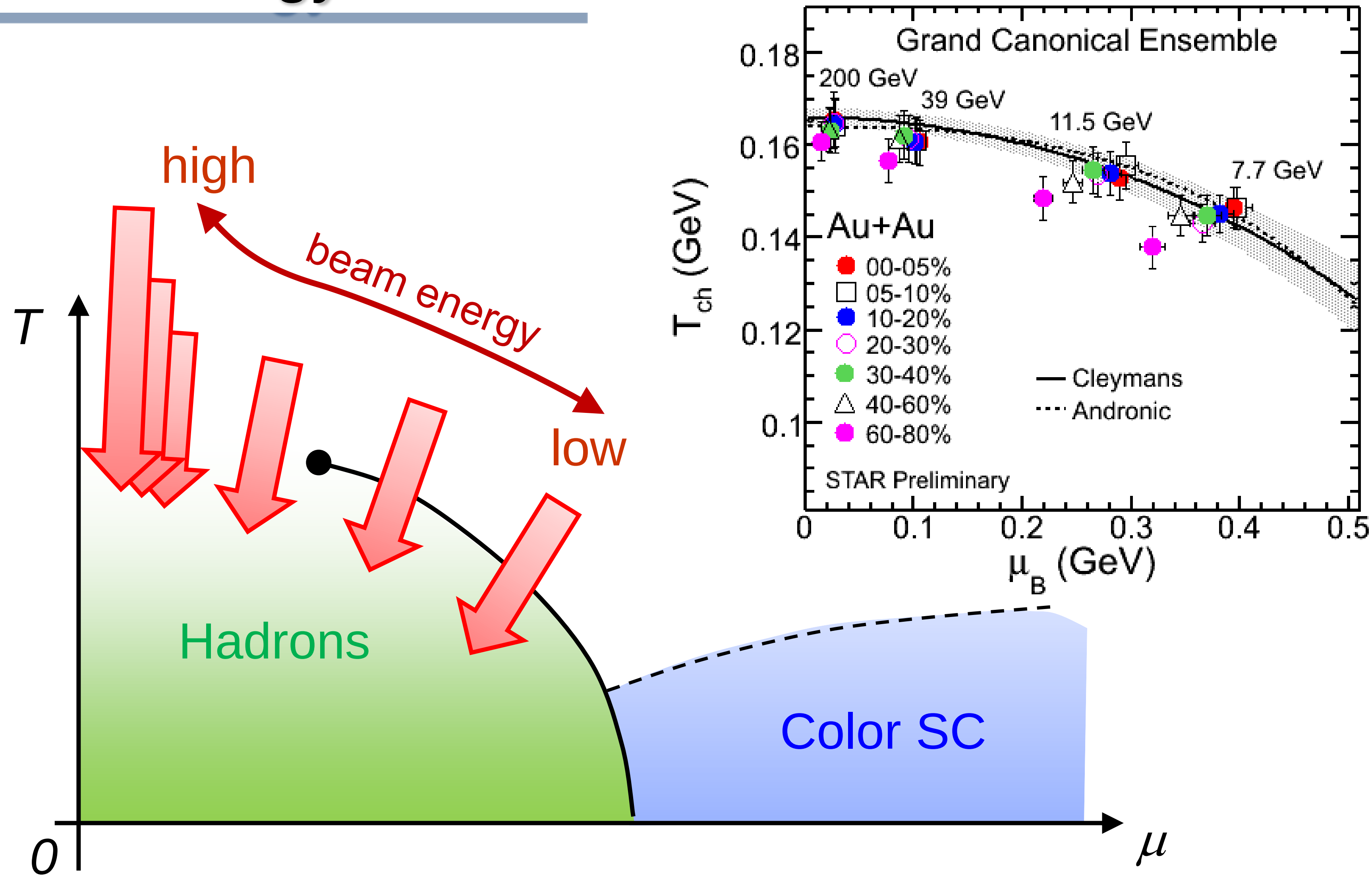
第17回Heavy Ion Pub, 広島大学、2013/Sep./13

Beam-Energy Scan



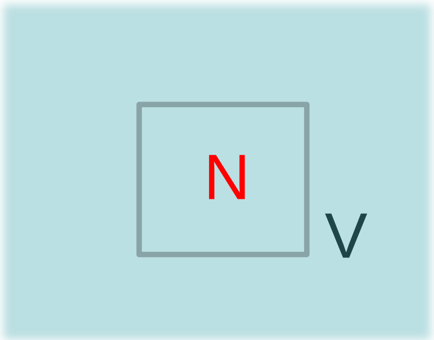
Beam-Energy Scan

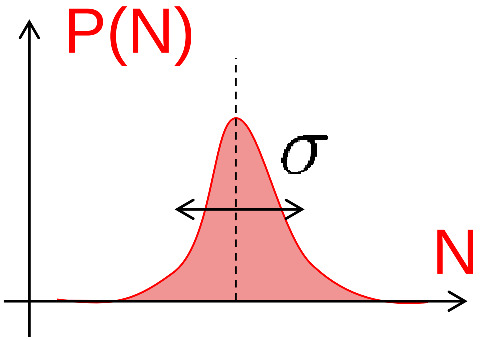
STAR 2012



Fluctuations

Observables in equilibrium are fluctuating.





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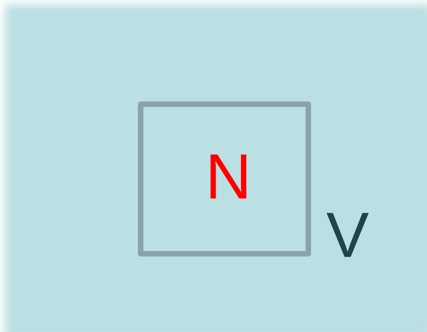
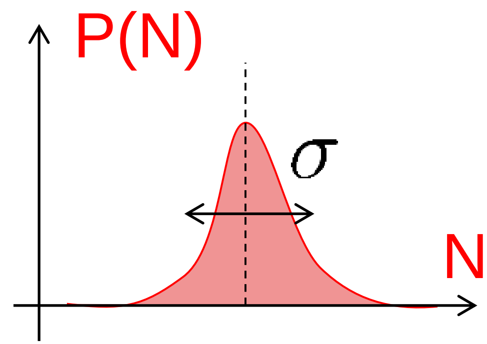




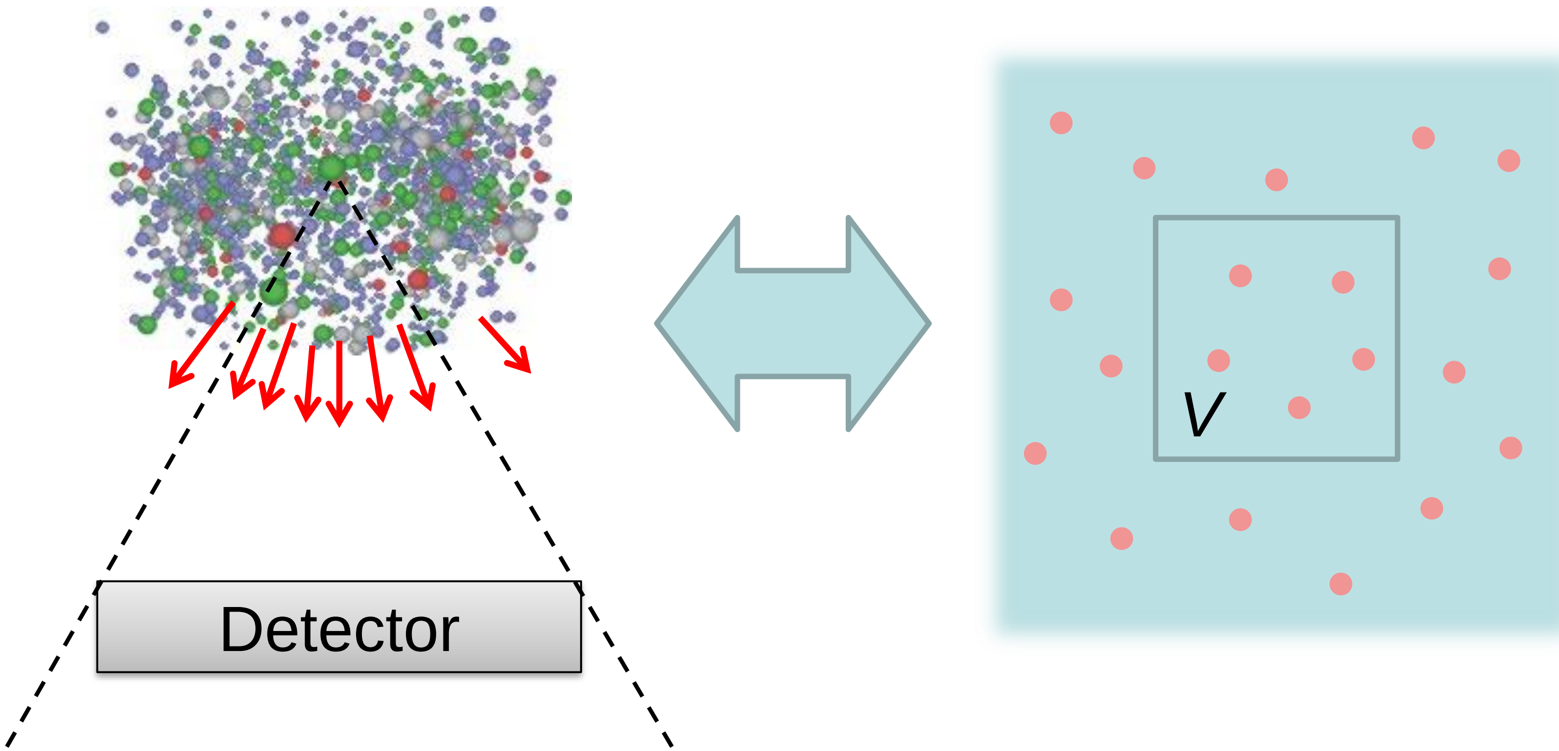
- Variance: $\langle \delta N^2 \rangle = V\chi_2 = \sigma^2$
- Skewness: $S = \dfrac{\langle \delta N^3 \rangle}{\sigma^3}$
- Kurtosis: $\kappa = \dfrac{\langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2}{\chi_2 \sigma^2}$

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

Non-Gaussianity

Event-by-Event Analysis @ HIC

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



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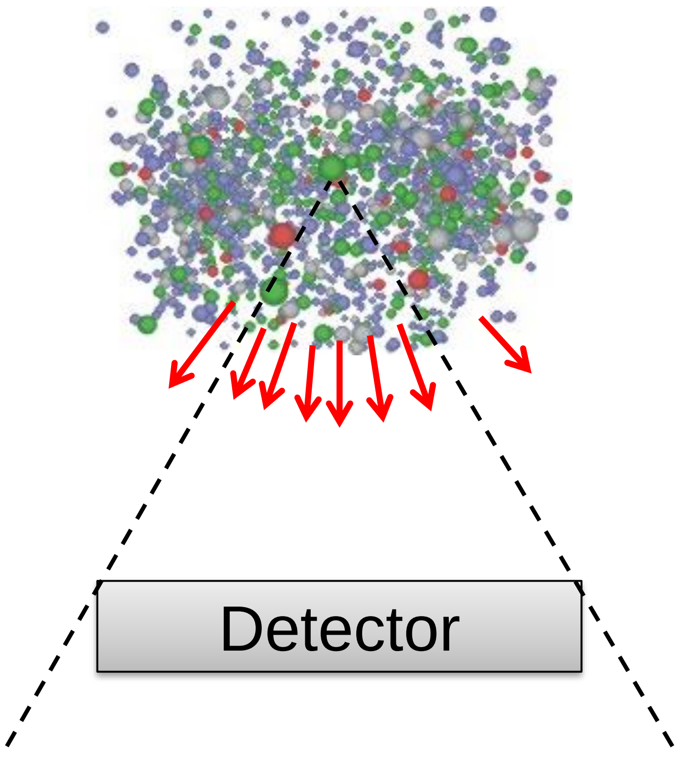
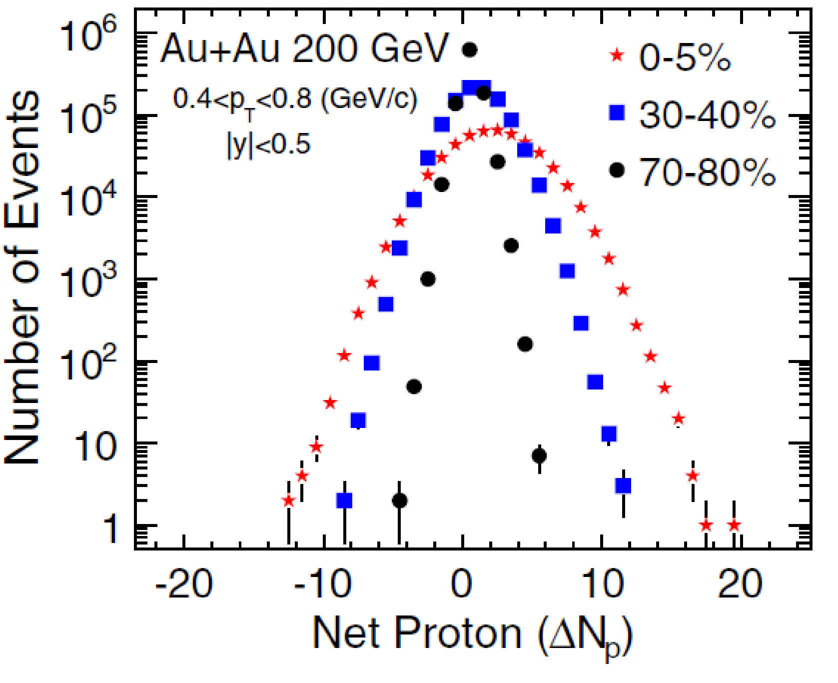


STAR, PRL**105** (2010)

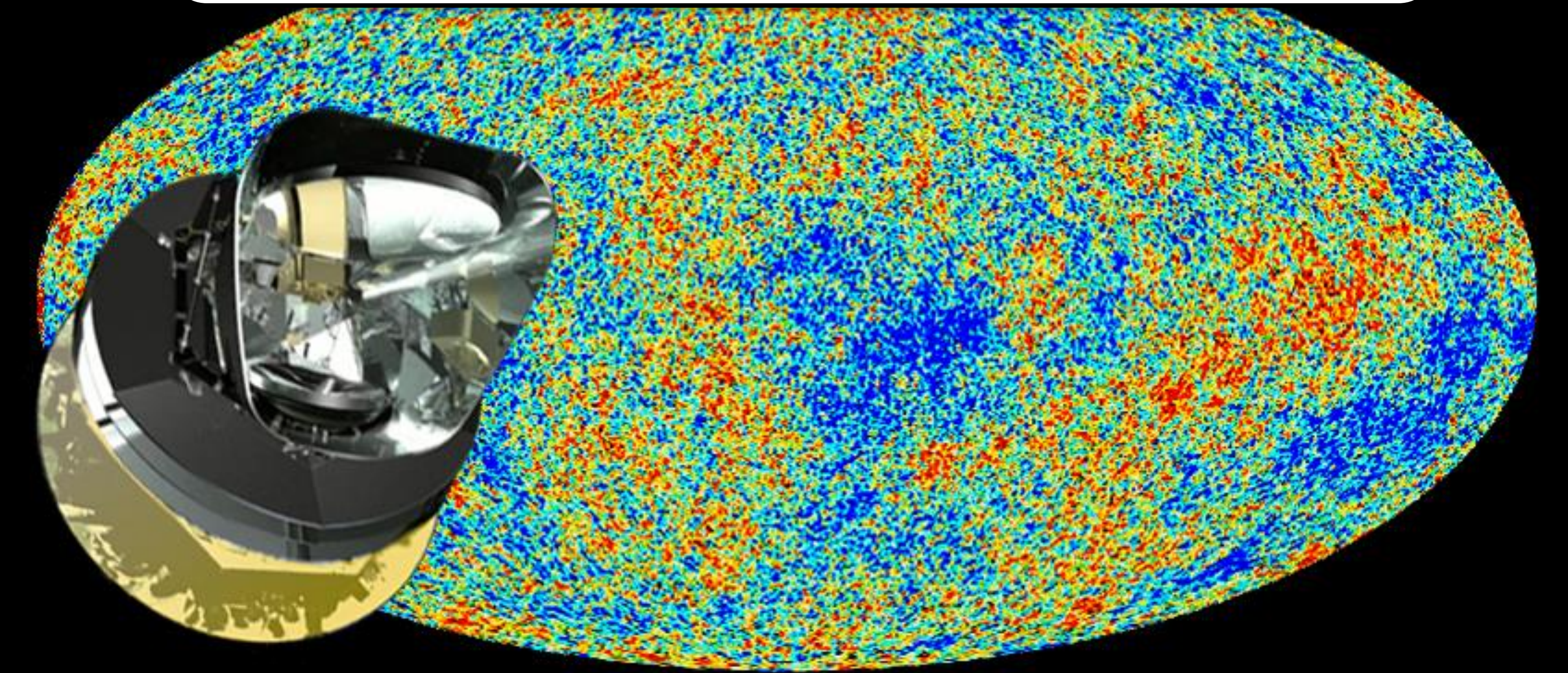


Non-Gaussianity in CMB

fluctuations (correlations)

$$\langle \delta n_1 \delta n_2 \rangle, \langle \delta n_1 \delta n_2 \delta n_3 \rangle, \langle \delta n_1 \delta n_2 \delta n_3 \delta n_4 \rangle_c, \cdots$$

→ Non-Gaussianity



PLANCK : statistics insufficient to see non-Gaussianity…(2013)

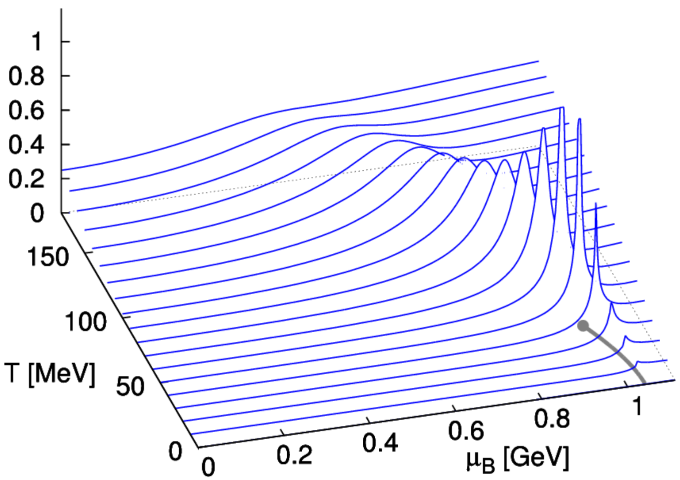
Fluctuations

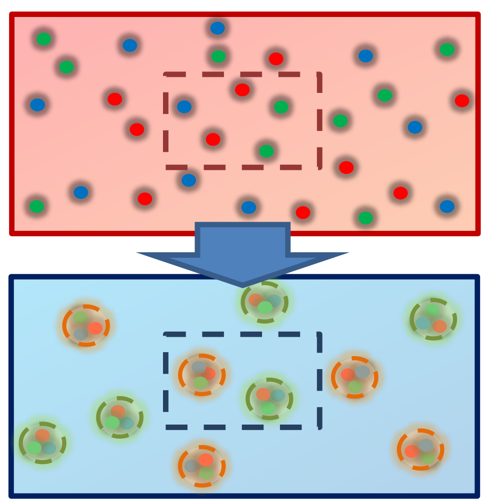
- Fluctuations reflect properties of matter.
  - Enhancement near the critical point

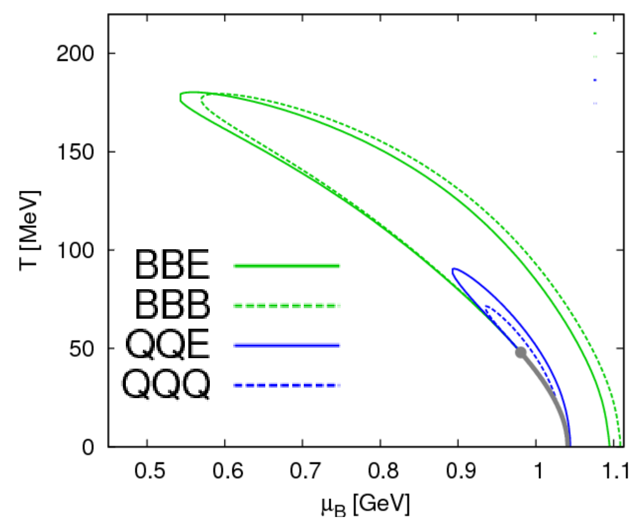
    Stephanov,Rajagopal,Shuryak('98); Hatta,Stephanov('02); Stephanov('09);…
  - Ratios between cumulants of conserved charges

    Asakawa,Heintz,Muller('00); Jeon, Koch('00); Ejiri,Karsch,Redlich('06)
  - Signs of higher order cumulants

    Asakawa,Ejiri,MK('09); Friman,et al.('11); Stephanov('11)



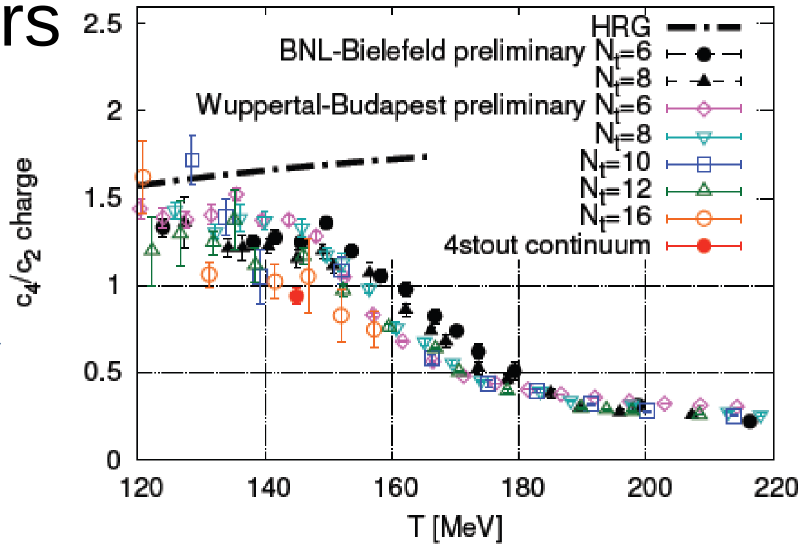




Conserved Charges : Theoretical Advantage

- Definite definition for operators
  - as a Noether current
  - calculable on any theory

ex: on the lattice



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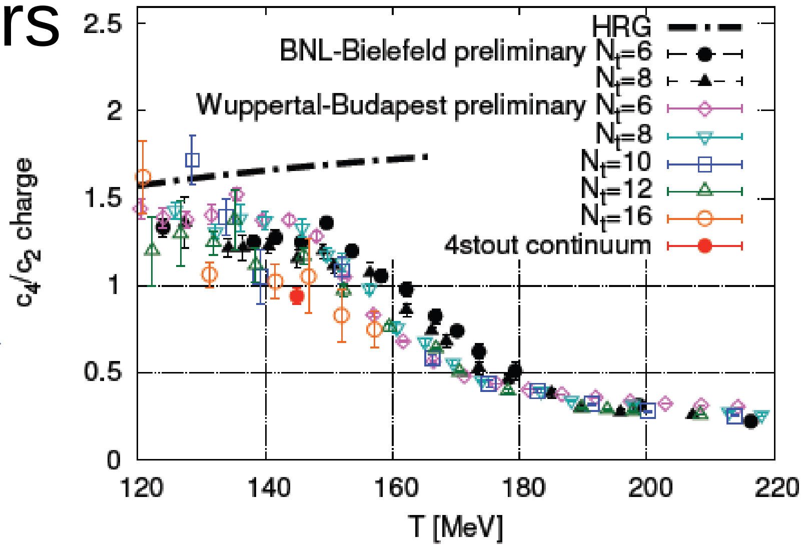


- Simple thermodynamic relations

$$\langle \delta N_c^n \rangle = \frac{1}{VT^{n-1}} \frac{\partial^n \Omega}{\partial \mu_c^n}$$

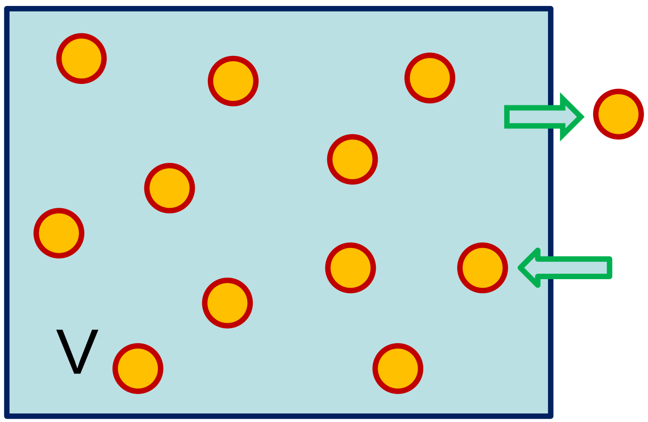
  - Intuitive interpretation for the behaviors of cumulants

ex: $$\langle \delta N_B^3 \rangle = \frac{1}{VT^2} \frac{\partial \langle \delta N_B^2 \rangle}{\partial \mu_B}$$

観測にかかるゆらぎは、いつ形成されたのか？

ゆらぎのダイナミクス（動的振る舞い）の議論が必要

保存電荷の場合

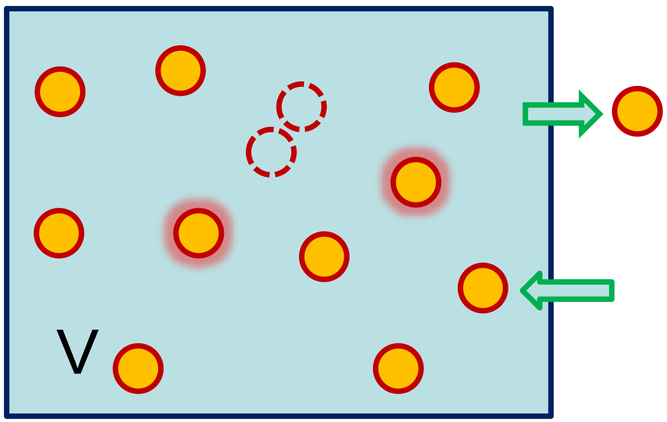


境界を通過する電荷のみが変化に寄与

$$\tau \to \infty$$

for $V \to \infty$

非保存電荷の場合

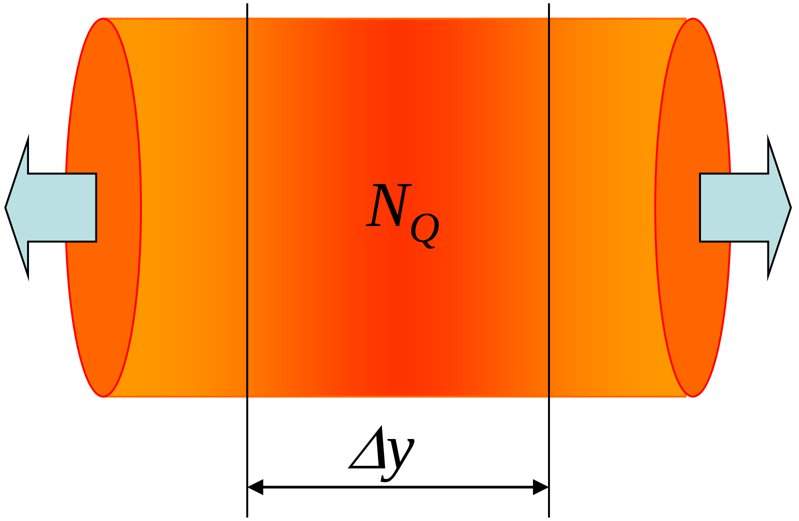


体積内の任意の場所で電荷が変化できる

$$\tau \to \mathrm{const.}$$

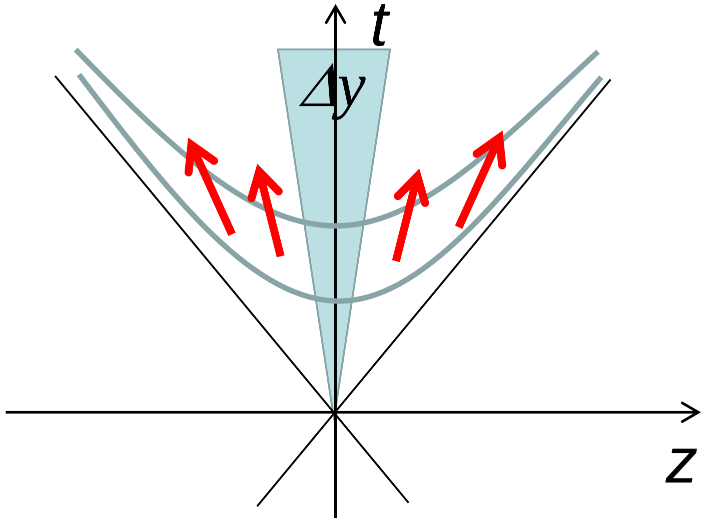
for $V \to \infty$

観測にかかるゆらぎは、いつ形成されたのか？



$\Delta\eta$内の保存電荷量は、初期段階のものが終状態まで生き残ることが期待できる。

Asakawa, Heinz, Muller, ’00
Jeon, Koch, ’00
Shuryak, Stephanov, ’02



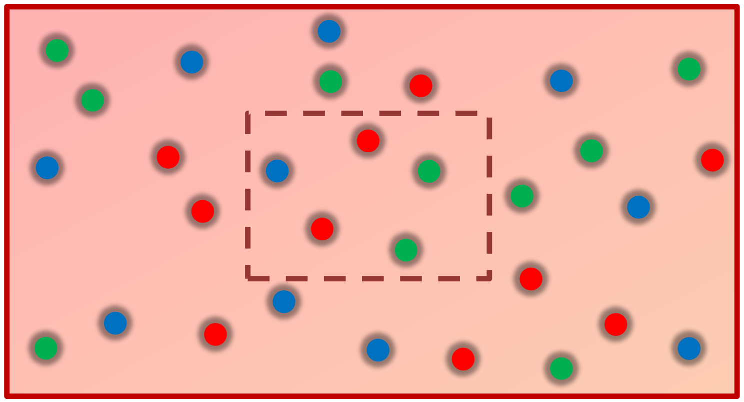
Note:

$$\text{STAR}\begin{cases} -0.5 < \eta < 0.5 \\ 0.4 < p < 0.8[GeV] \end{cases}$$

Fluctuations

Free Boltzmann → Poisson

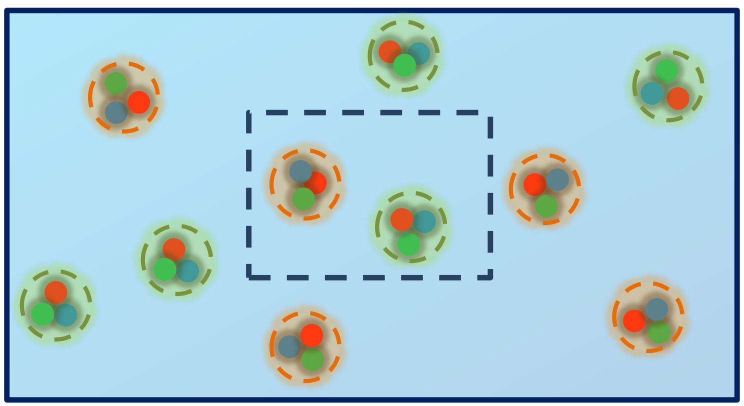
$$\langle \delta N^n \rangle_c = \langle N \rangle$$



$$\langle \delta N_q^n \rangle_c = \langle N_q \rangle$$

$$\Rightarrow \langle \delta N_B^n \rangle_c = \frac{1}{3^{n-1}} \langle N_B \rangle$$

$$3N_B = N_q$$



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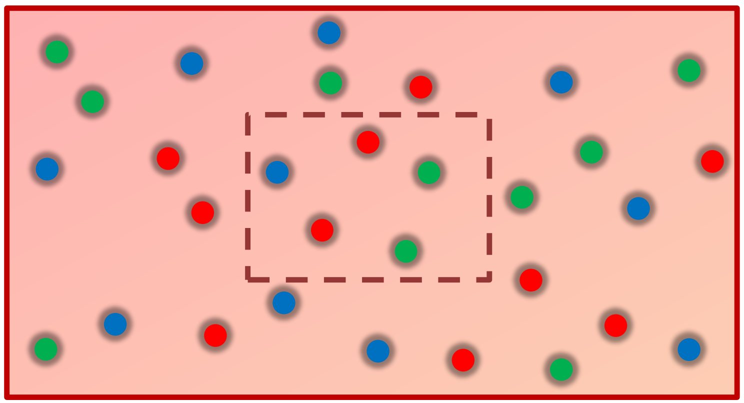

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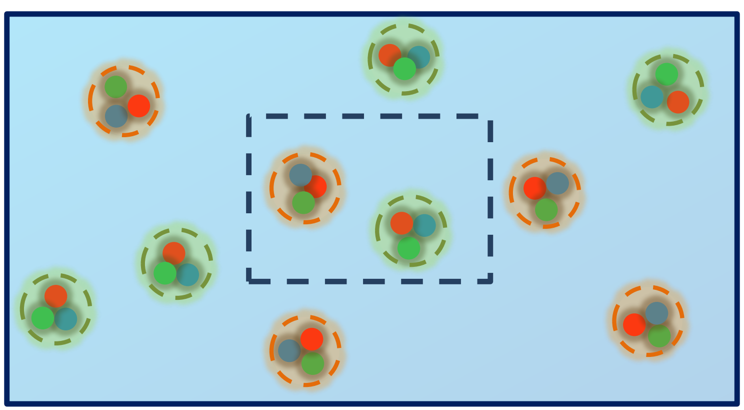

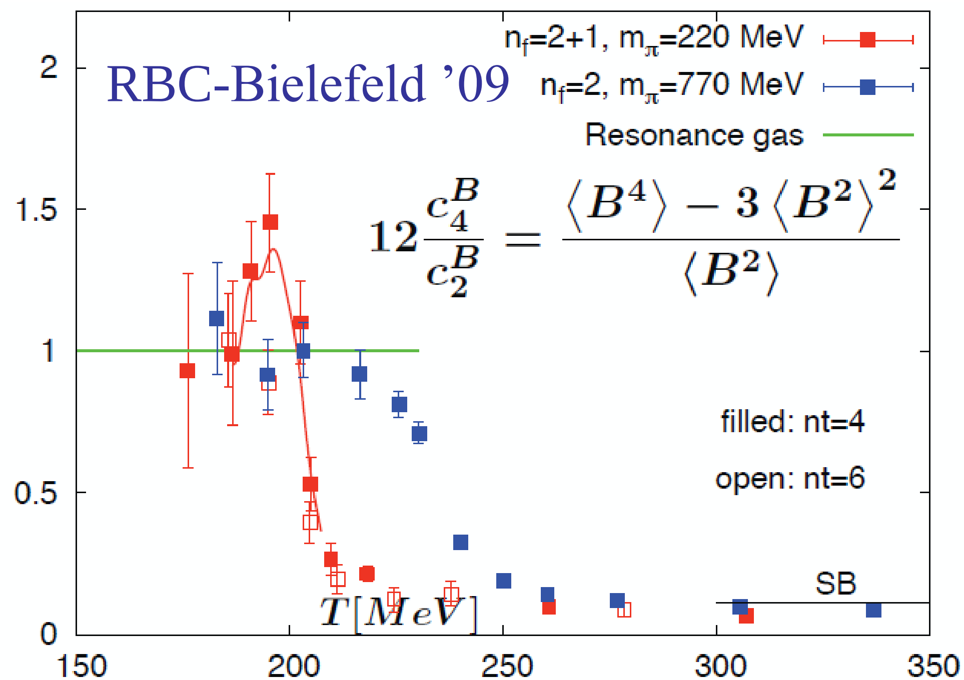

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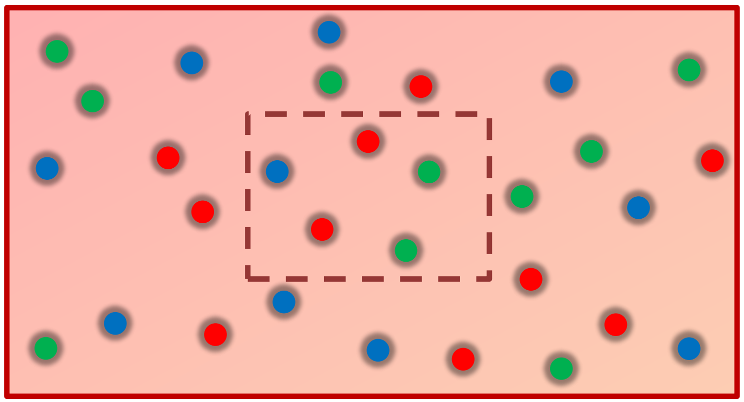

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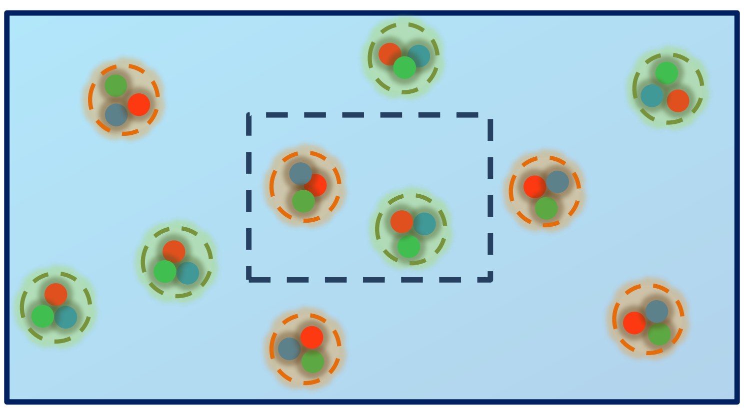

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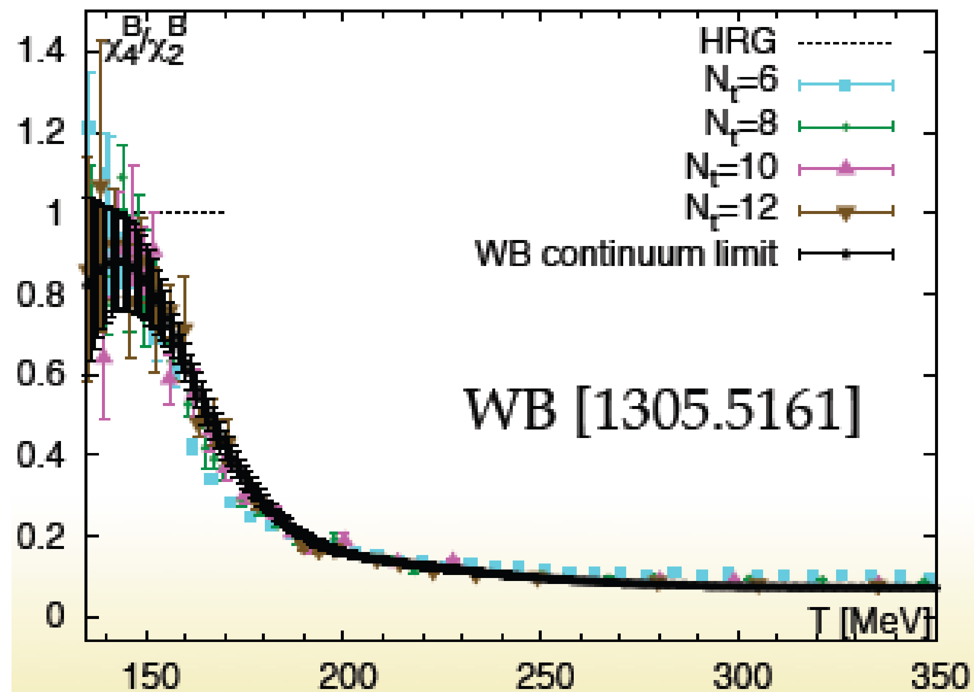
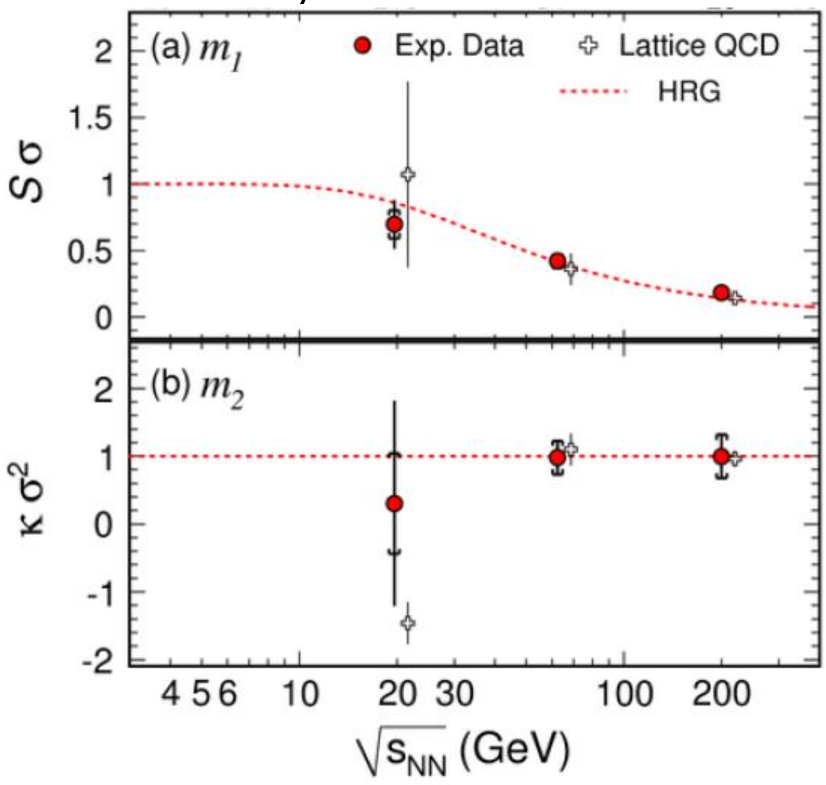


Proton # Fluctuations @ STAR-BES

STAR, PRL2010



$$S\sigma = \frac{\langle(\delta N_p^{(\mathrm{net})})^3\rangle}{\langle(\delta N_p^{(\mathrm{net})})^2\rangle}, \quad \kappa\sigma^2 = \frac{\langle(\delta N_p^{(\mathrm{net})})^4\rangle_c}{\langle(\delta N_p^{(\mathrm{net})})^2\rangle}$$

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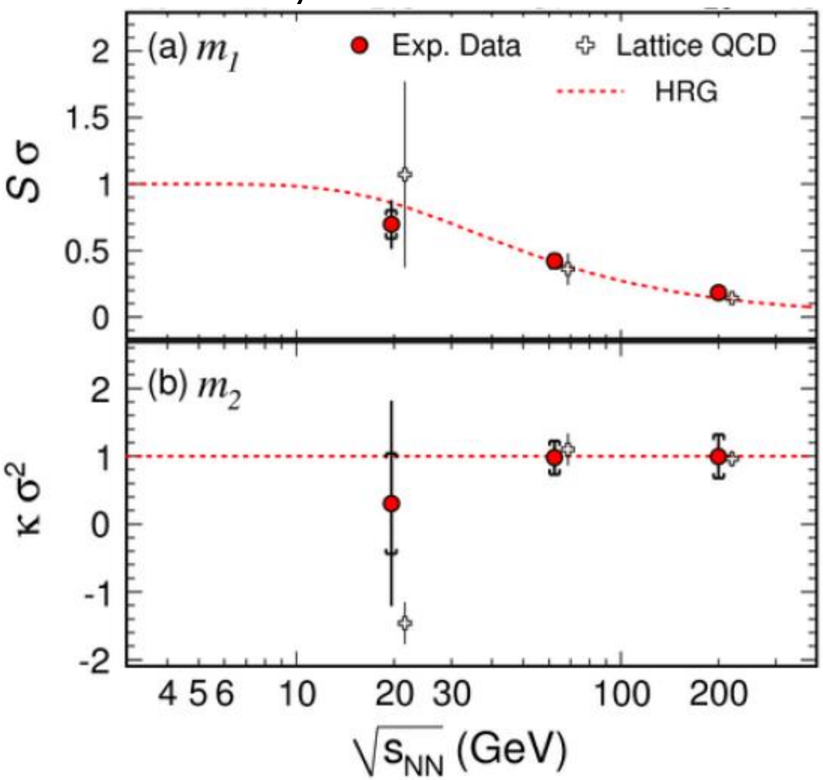
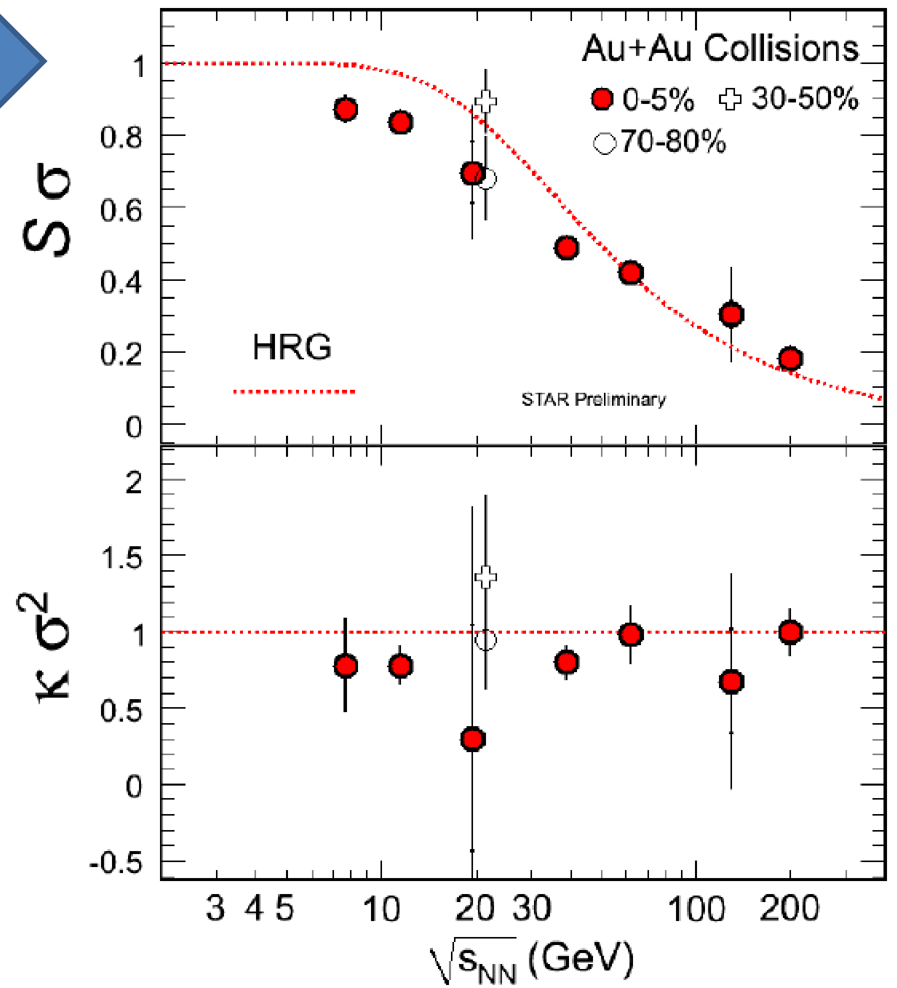


STAR, 2011



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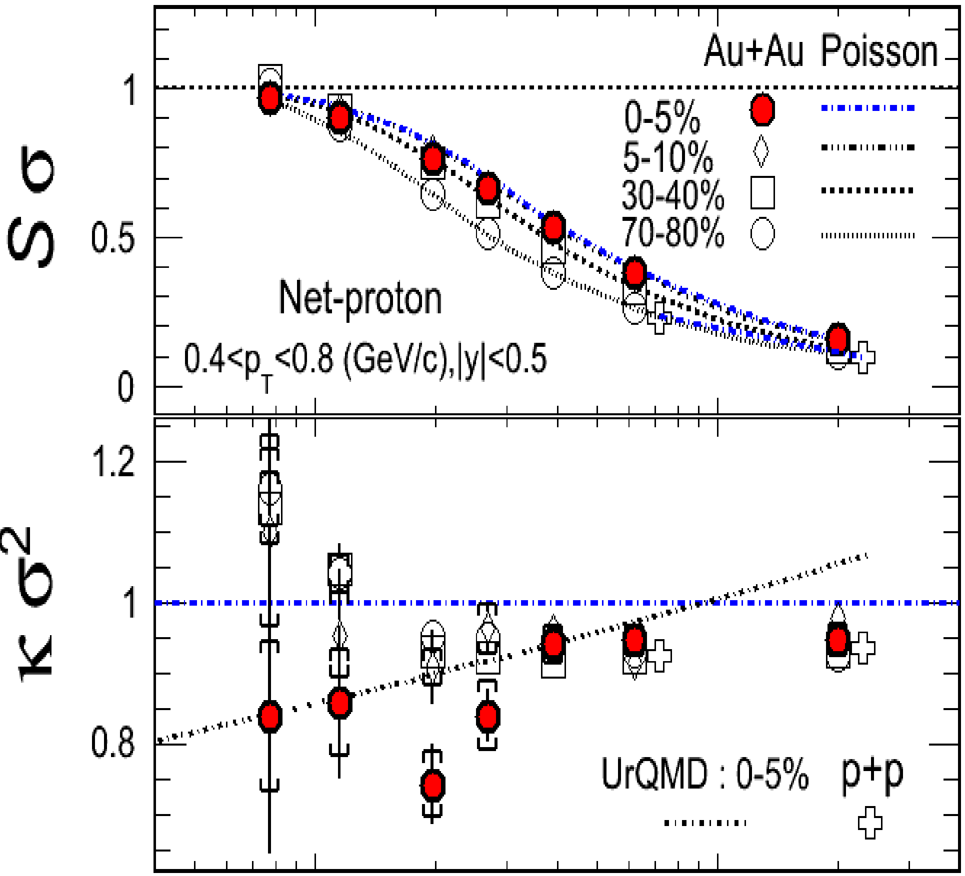
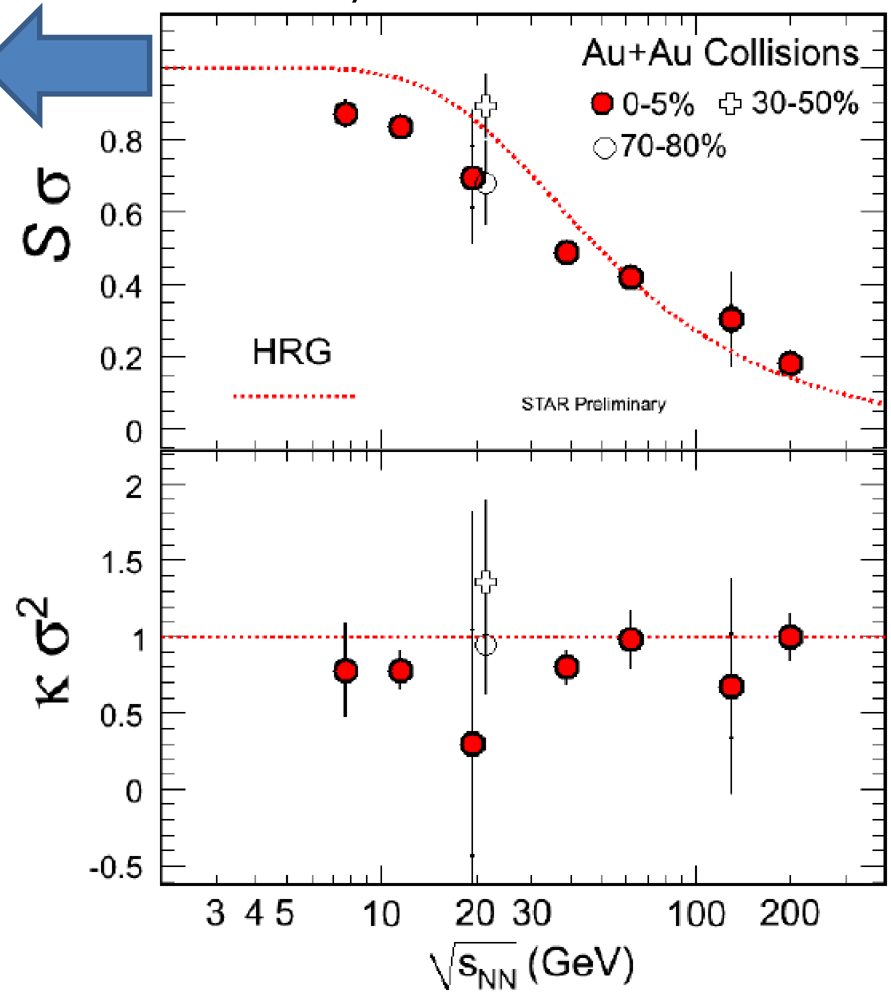
high μ ← → low μ

Proton # Fluctuations @ STAR-BES

STAR, 2012 (Quark Matter)



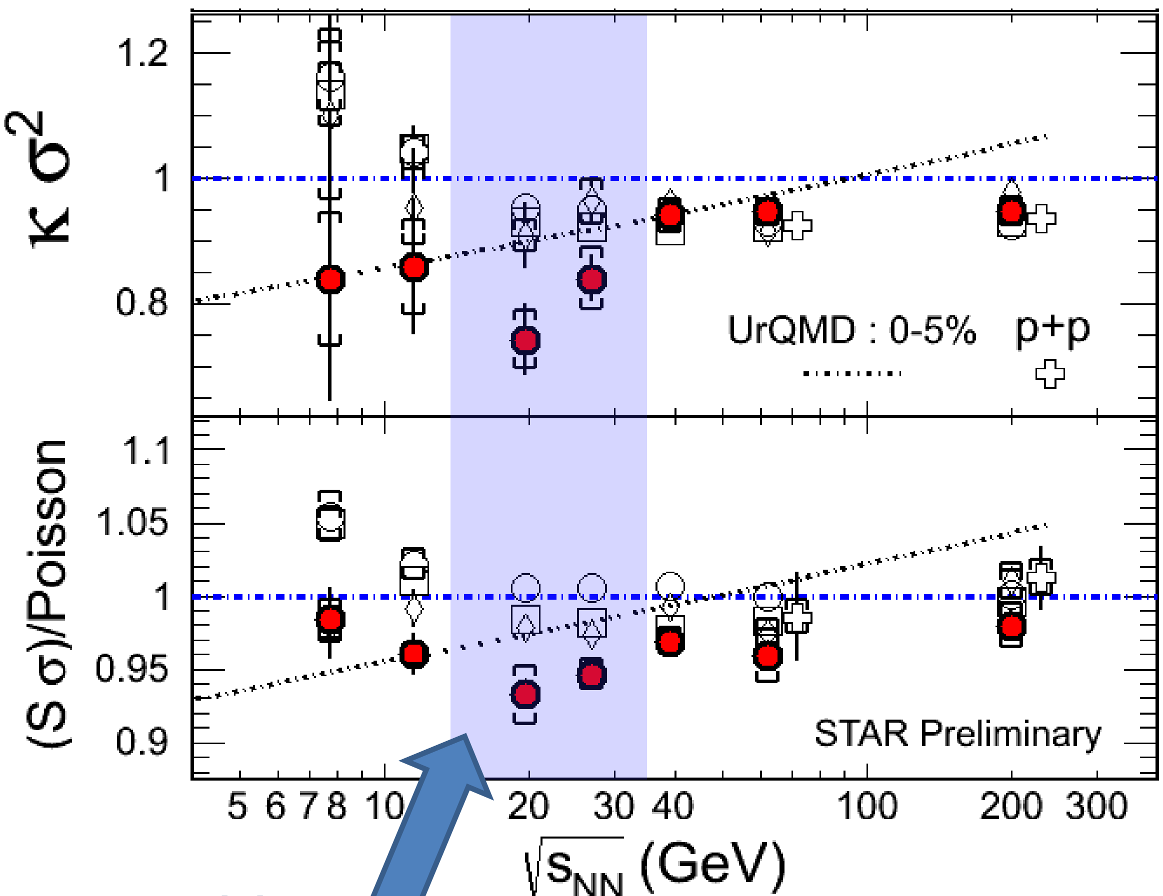
STAR, 2011



high μ

low μ

Proton # Cumulants @ STAR-BES



STAR,QM2012

$$\frac{C_4}{C_2}$$

$$\frac{C_3}{C_1} = \frac{C_3/C_2}{\text{Poissonian}}$$

Something interesting??

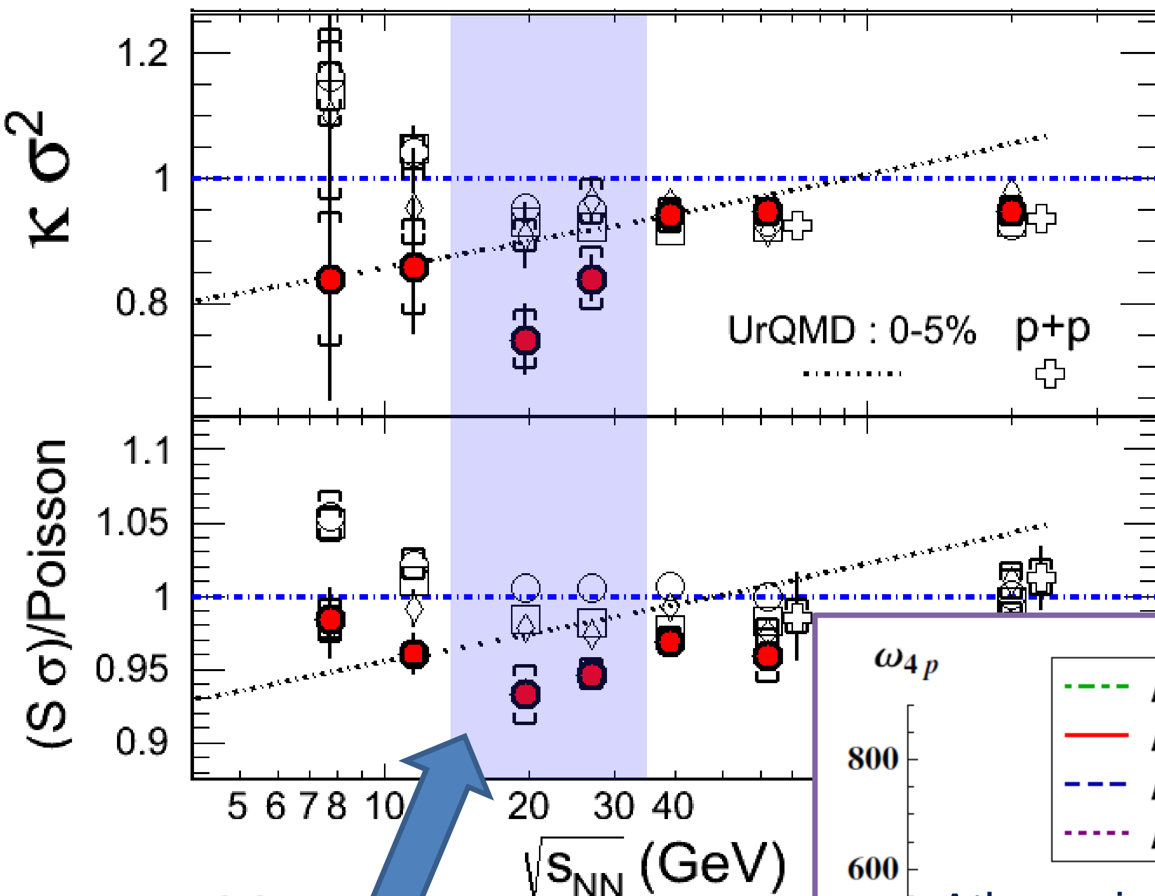
CAUTION!

proton number $\neq$ baryon number

MK, Asakawa, 2011;2012

Proton # Cumulants @ STAR-BES

STAR,QM2012

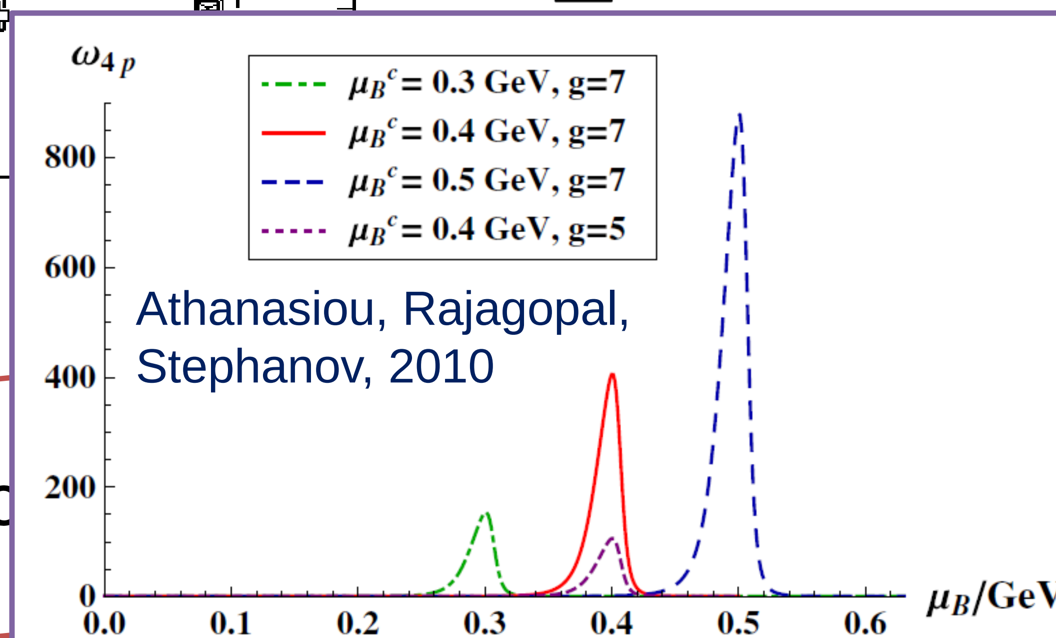


$$\frac{C_4}{C_2}$$

$$\frac{C_3}{\ } = \frac{C_3/C_2}{\ }$$

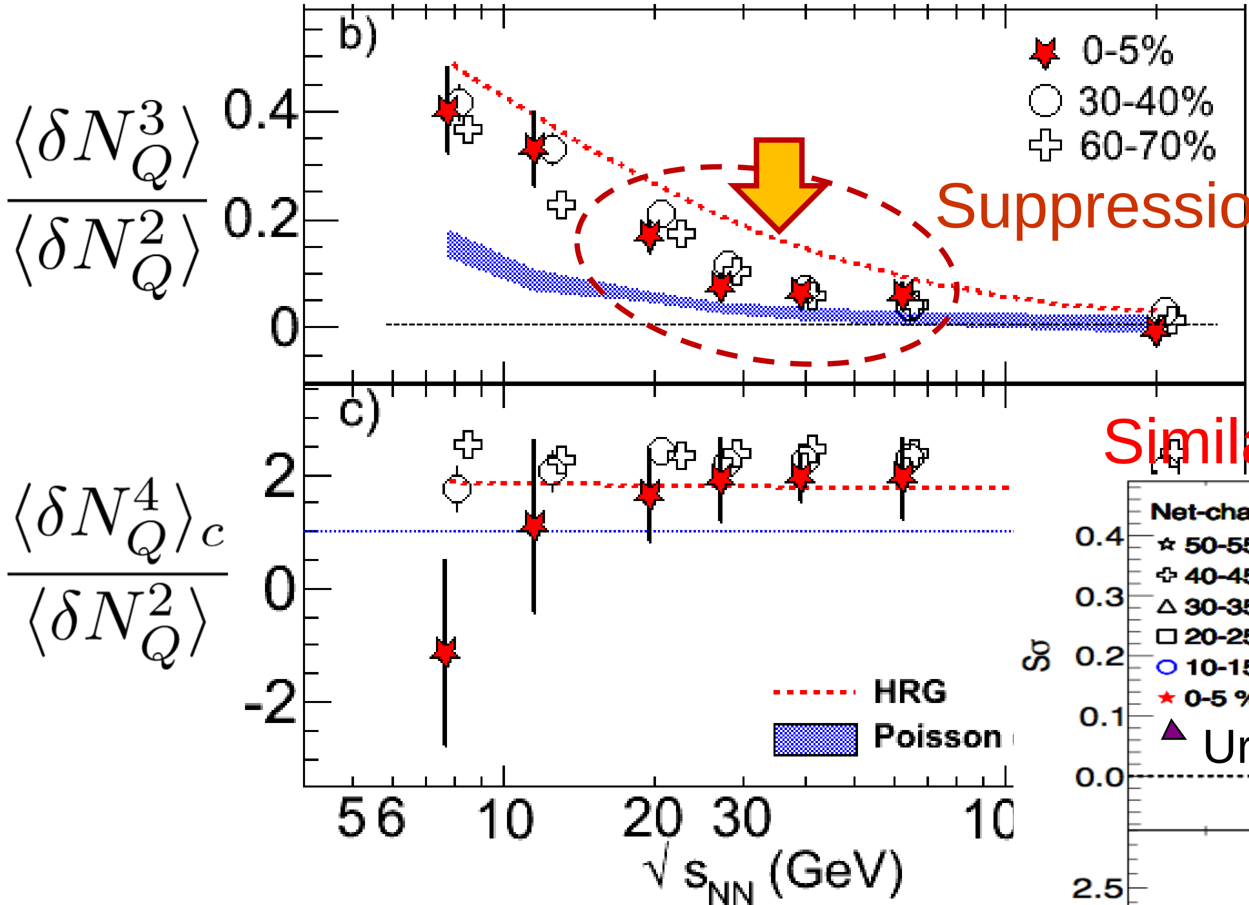
Something interesting??

pro

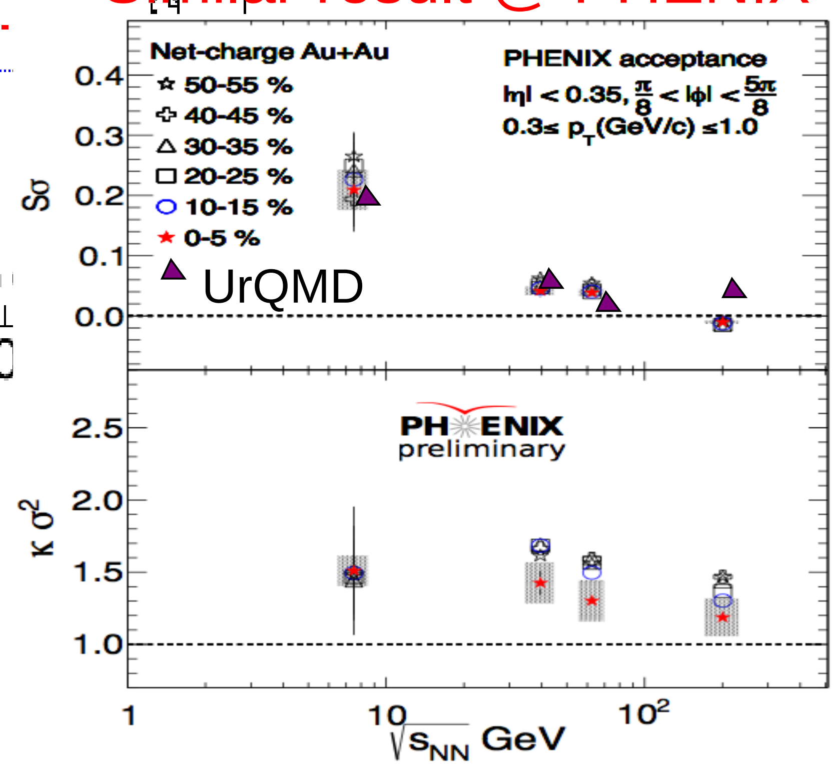


Charge Fluctuations @ STAR-BES

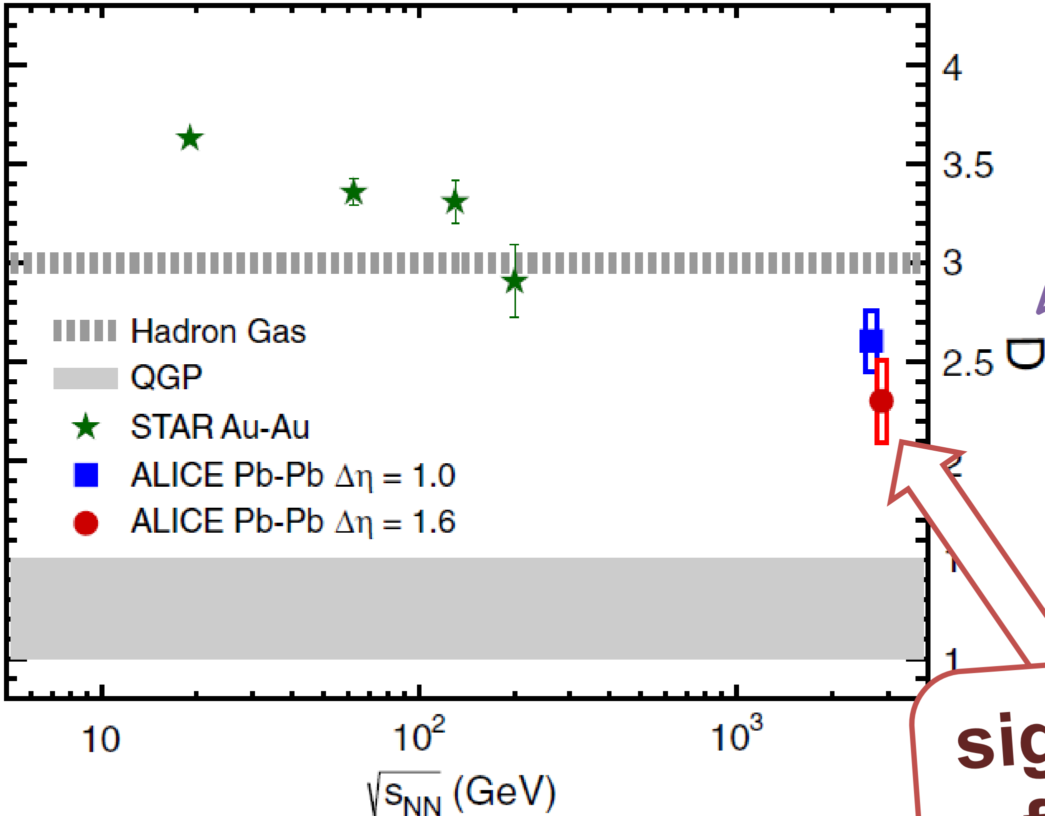
STAR, QM2012



Similar result @ PHENIX



Charge Fluctuation @ LHC



ALICE, PRL110,152301(2013)

D-measure

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

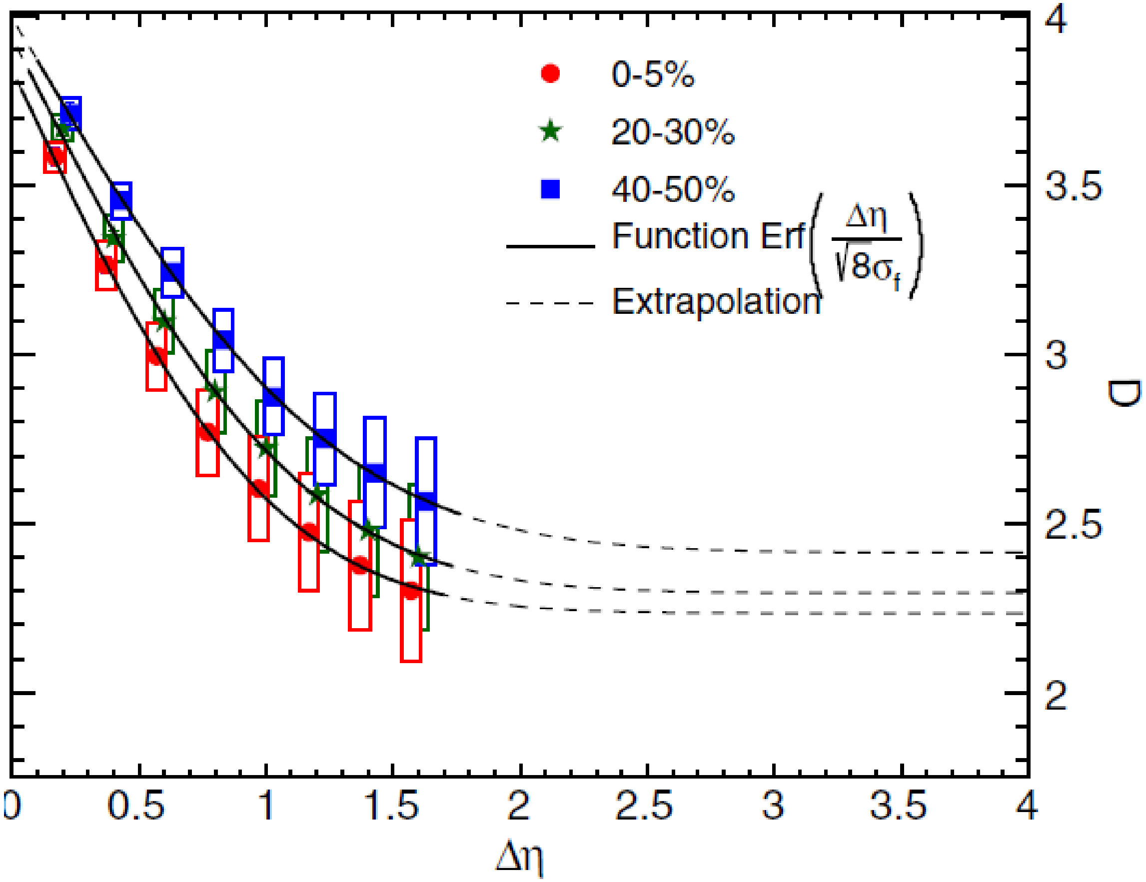
- D ~ 3-4 Hadronic
- D ~ 1 Quark

significant suppression from hadronic value at LHC energy!

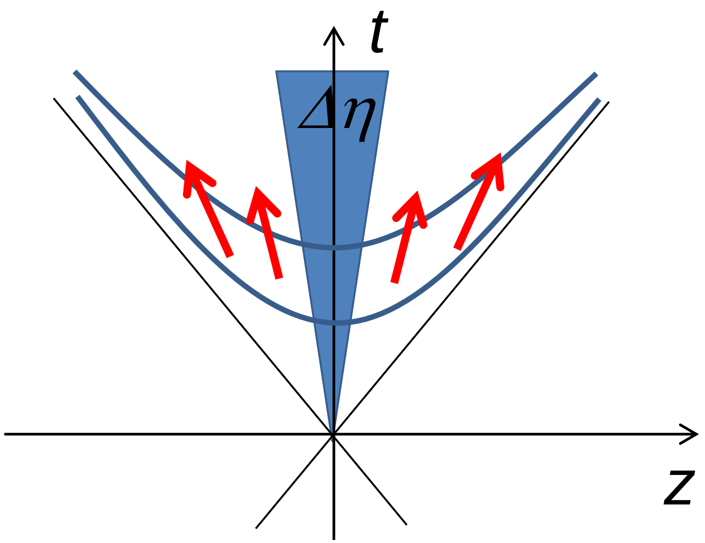
$\langle \delta N_Q^2 \rangle$ is not equilibrated at freeze-out at LHC energy!

Δη Dependence @ ALICE

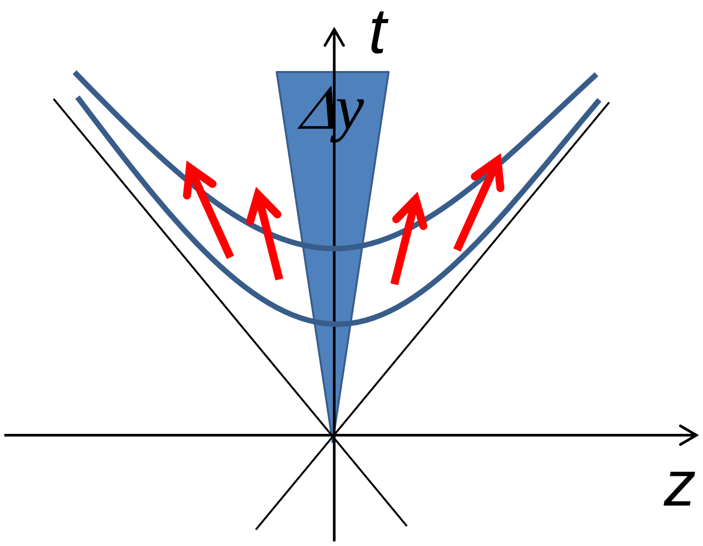
ALICE
PRL 2013

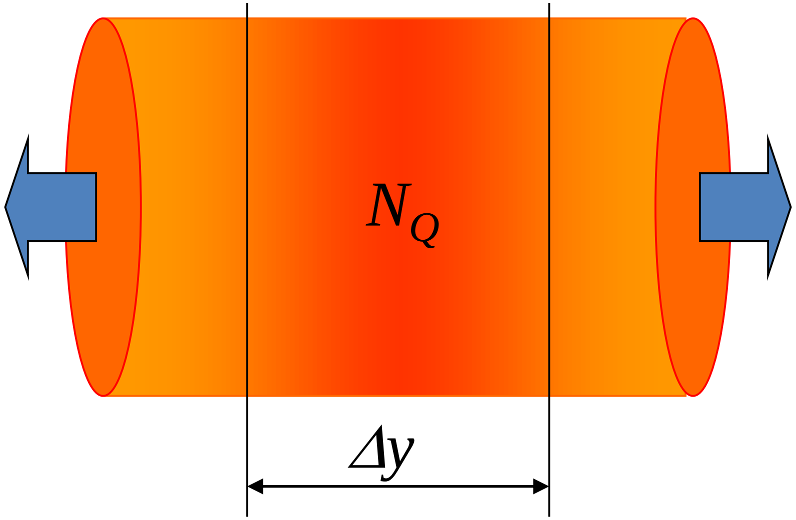


rapidity window



Time Evolution of CC

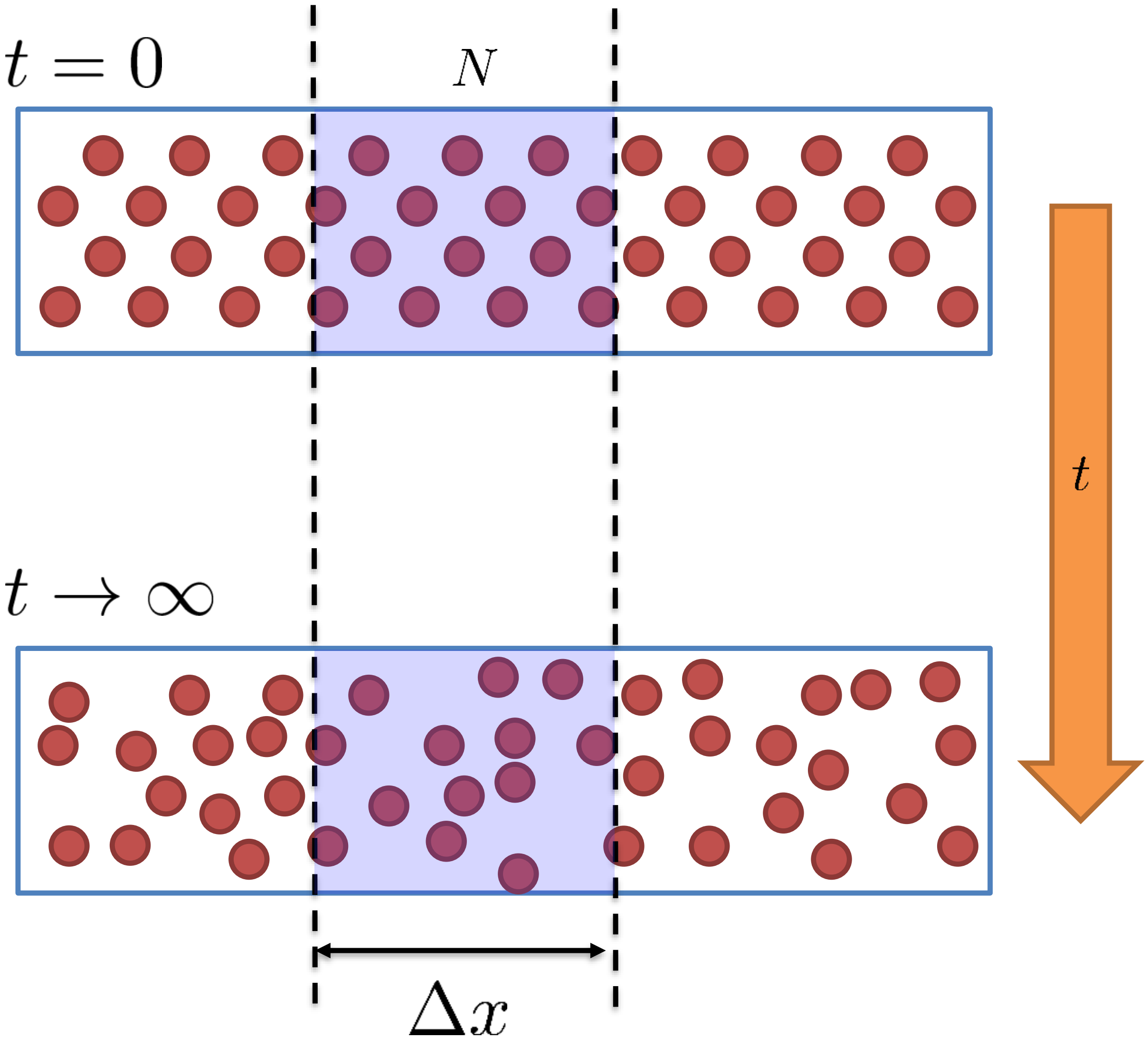


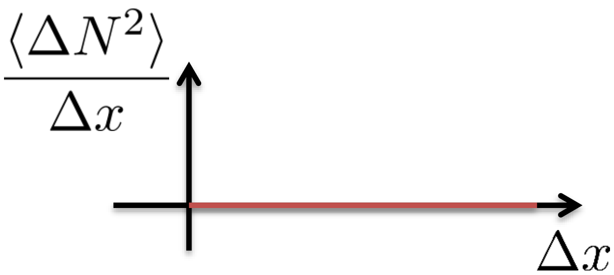


Variation of a conserved charge in Δy is achieved only through diffusion.

The larger Δy, the slower diffusion

Dissipation of a Conserved Charge





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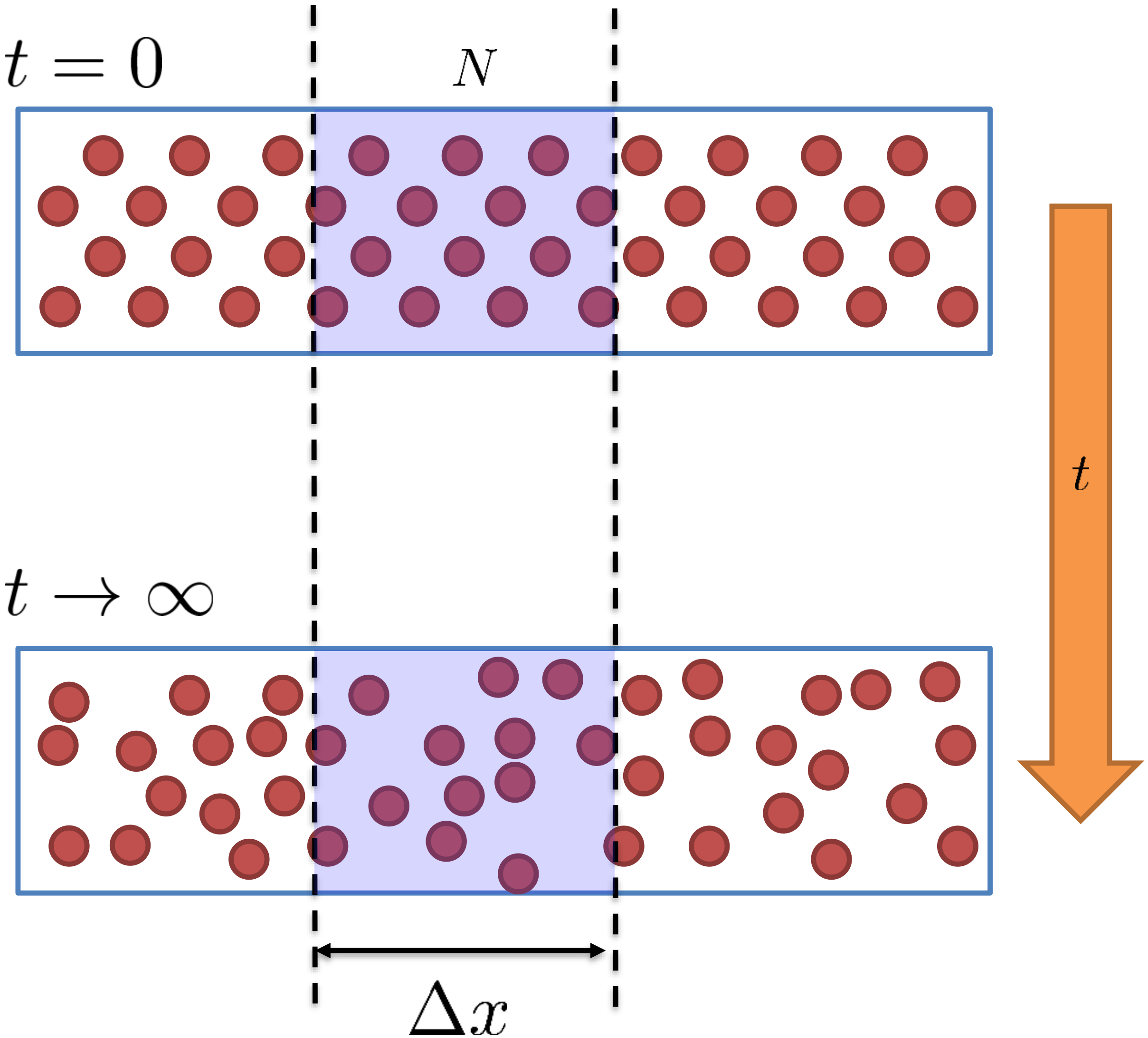
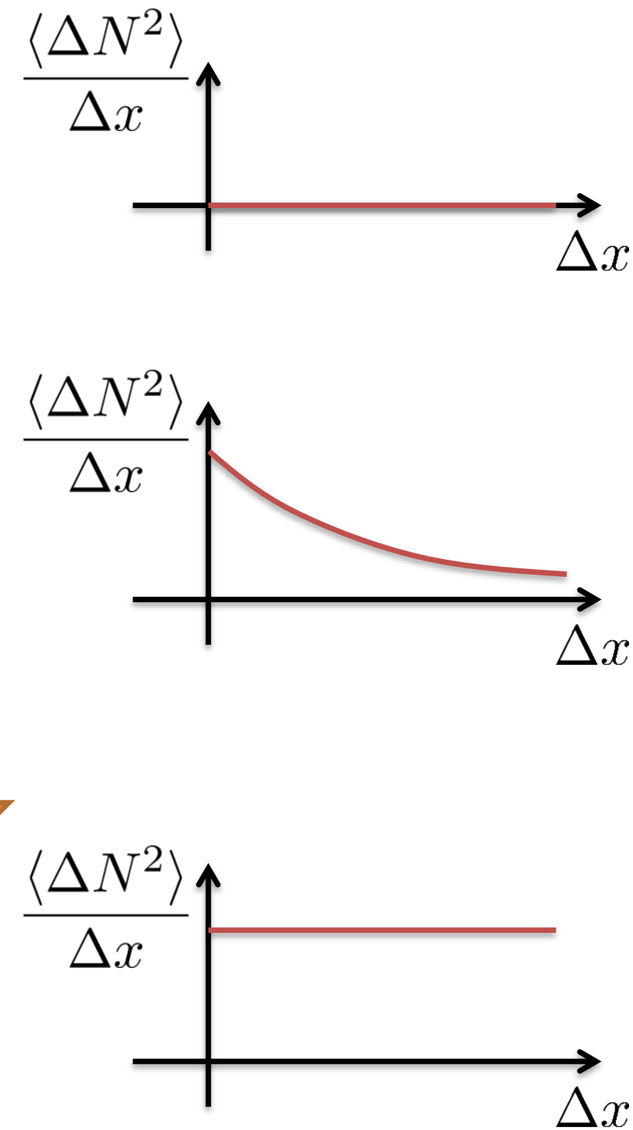
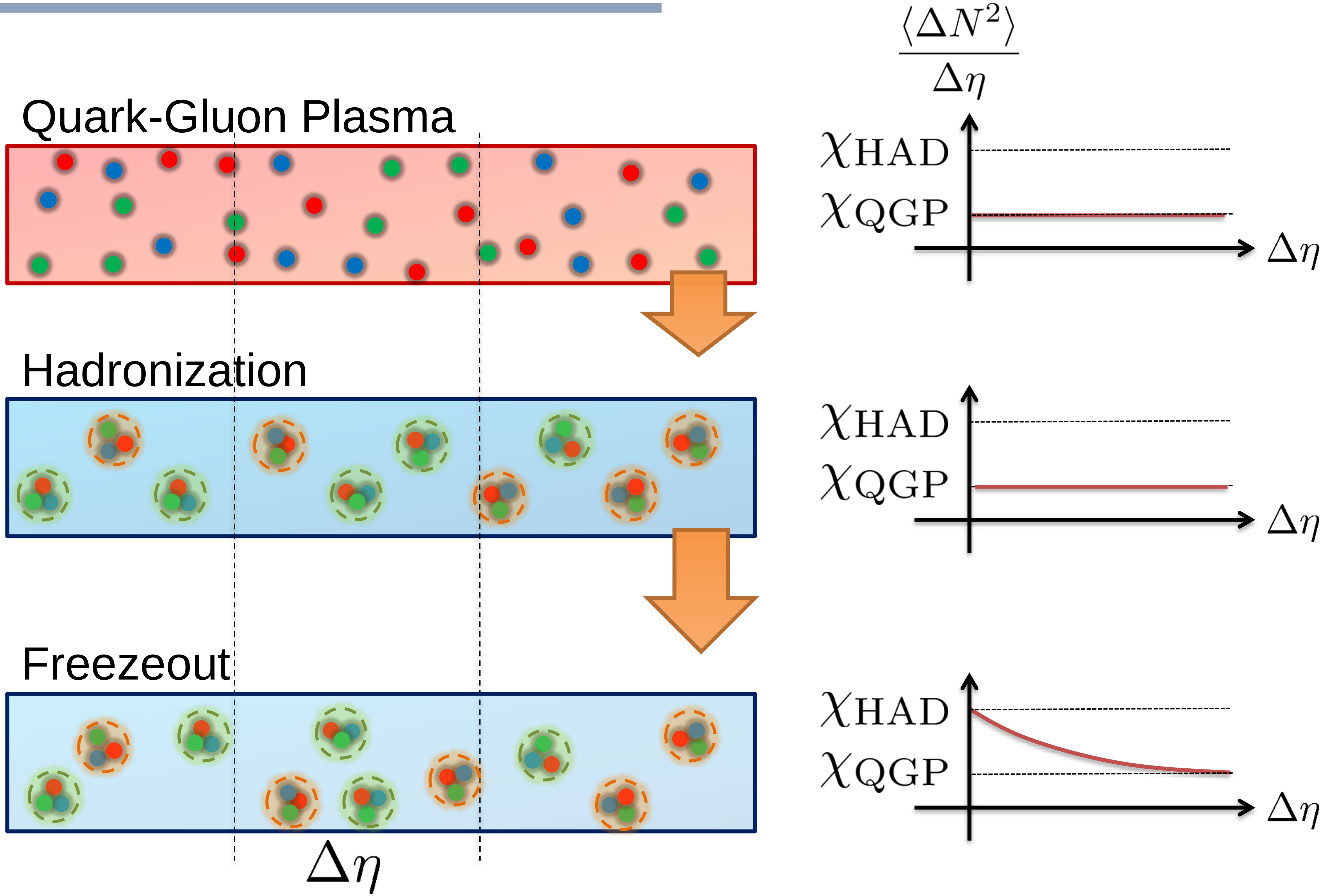




Time Evolution in HIC



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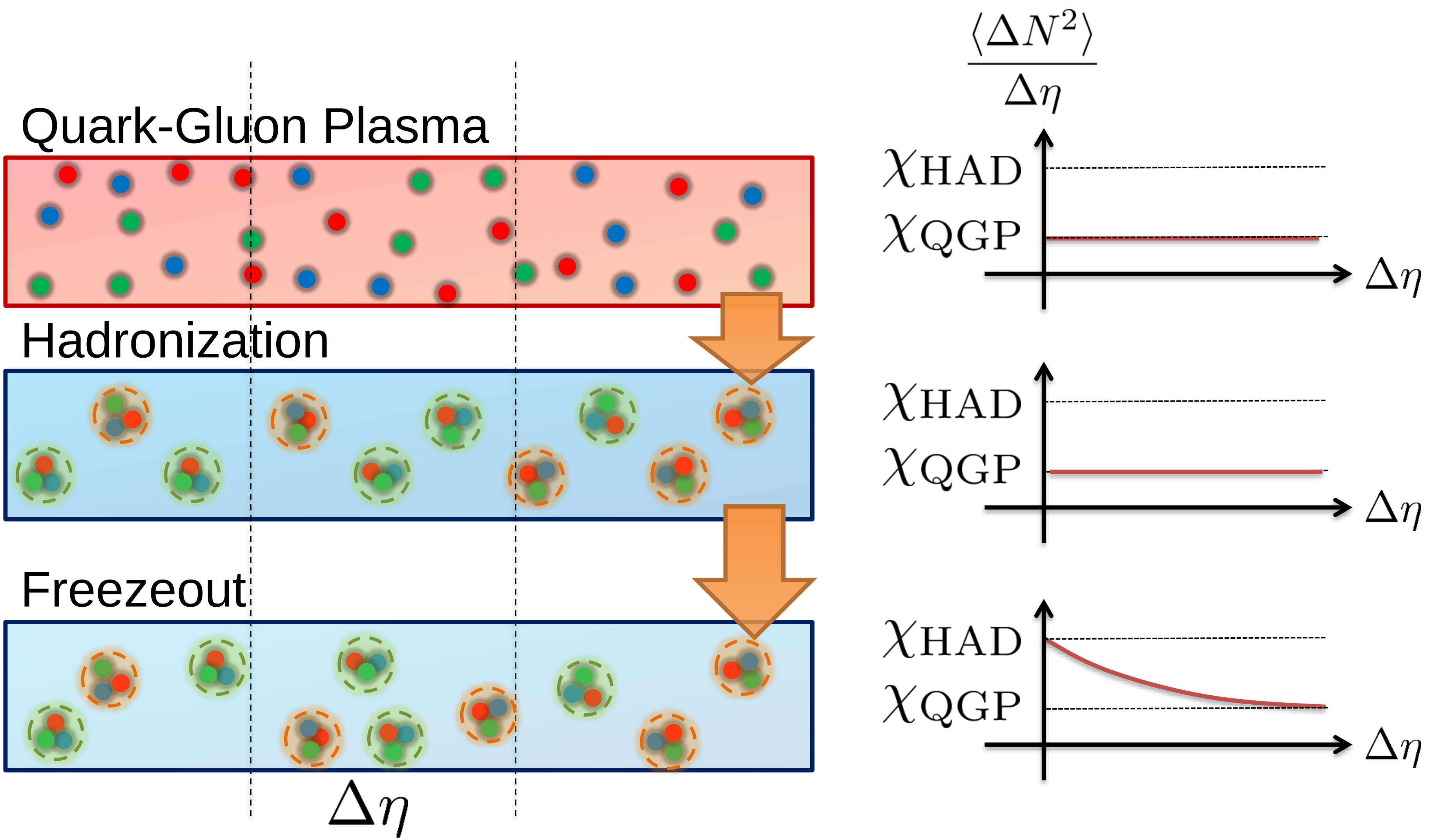

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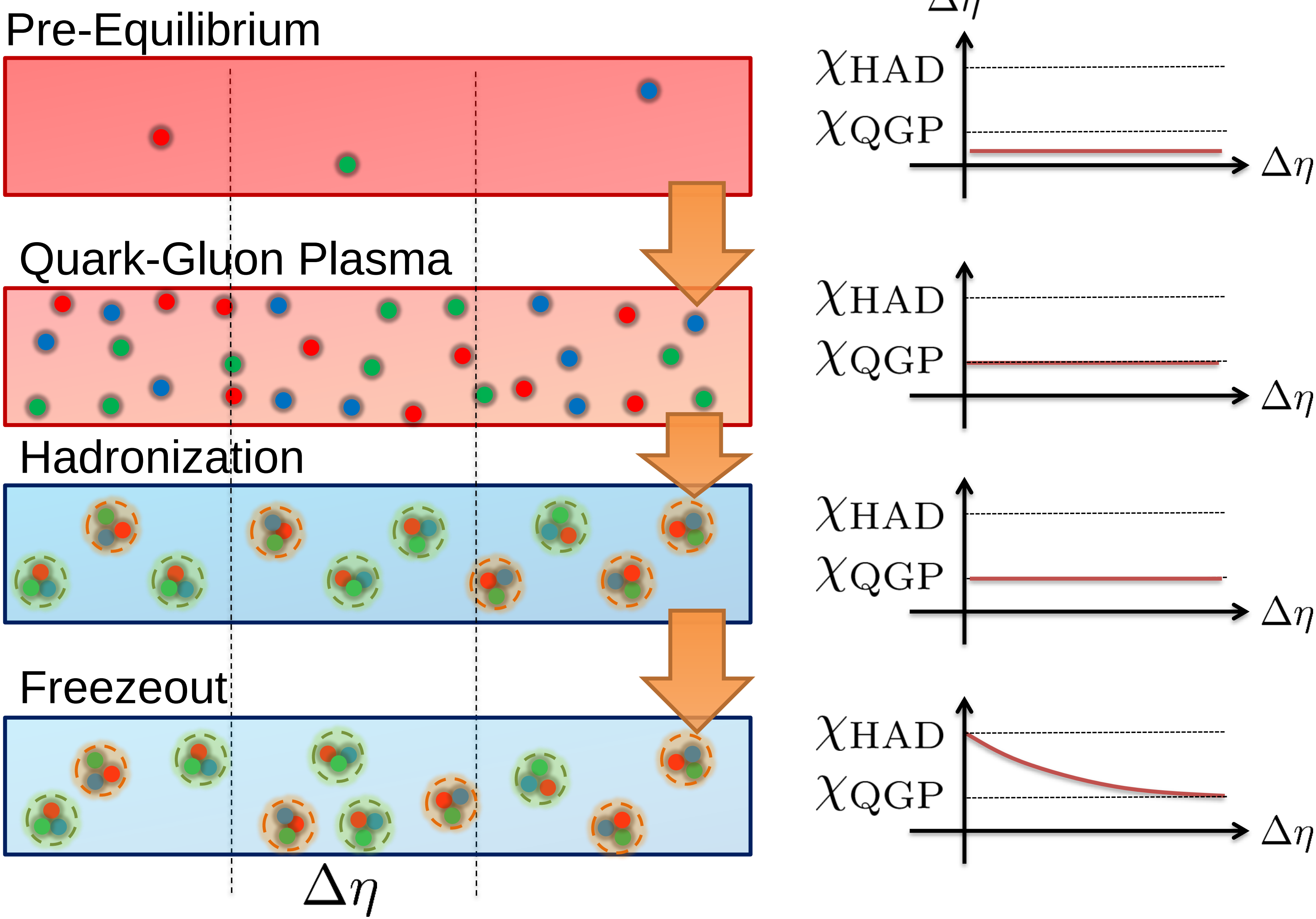

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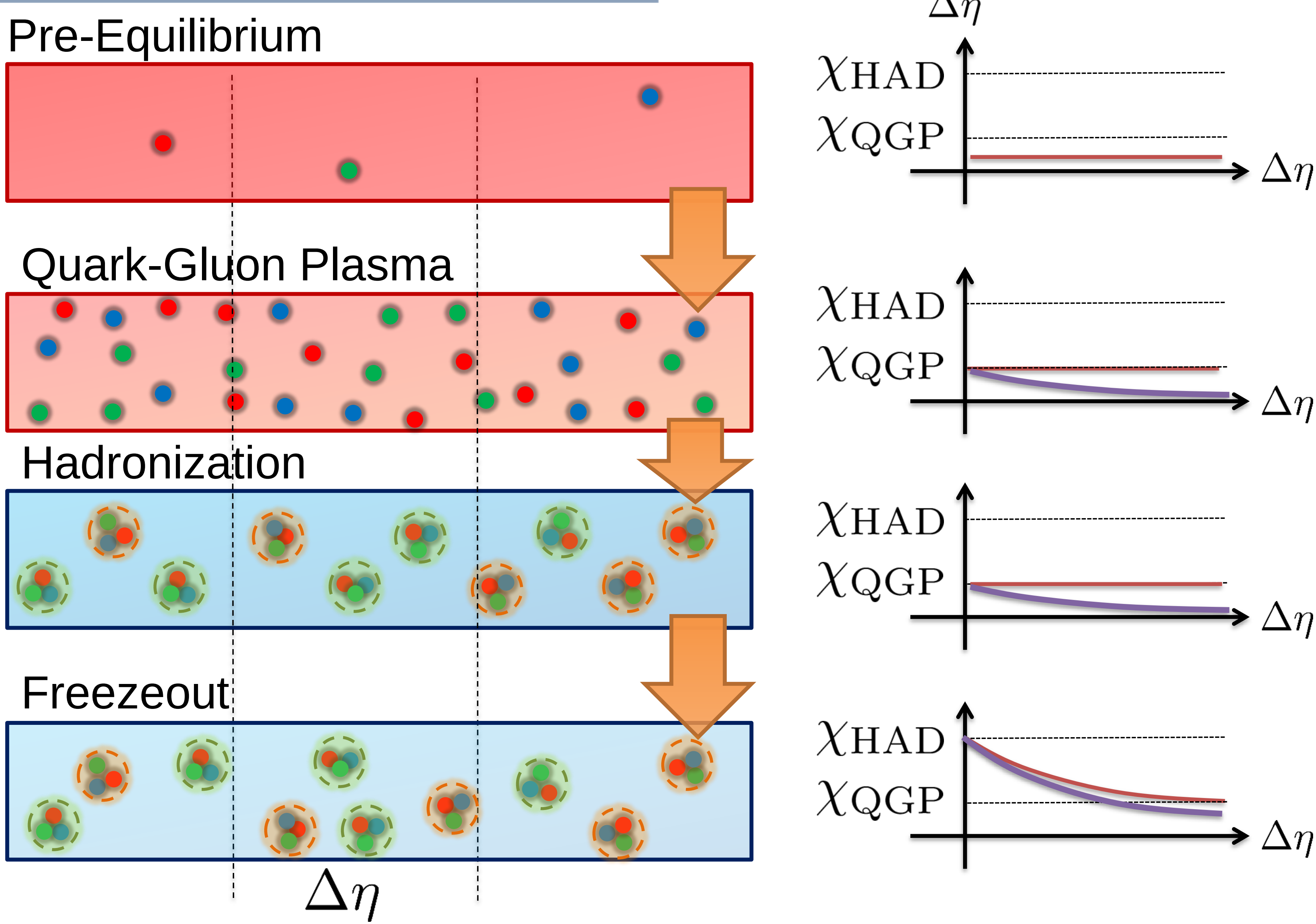
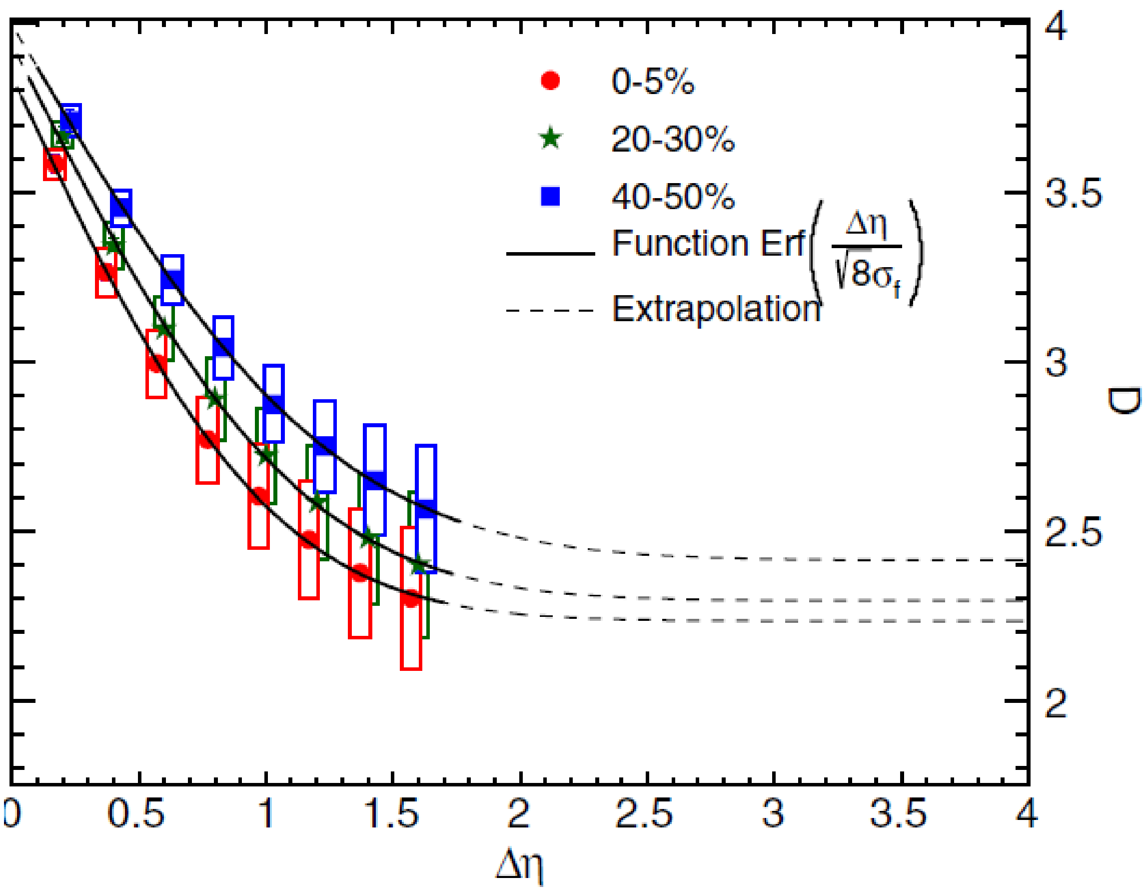
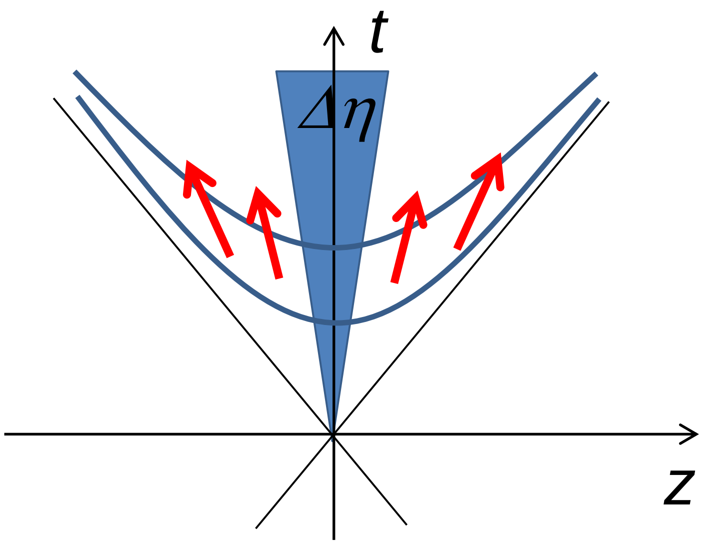


Δη Dependence @ ALICE

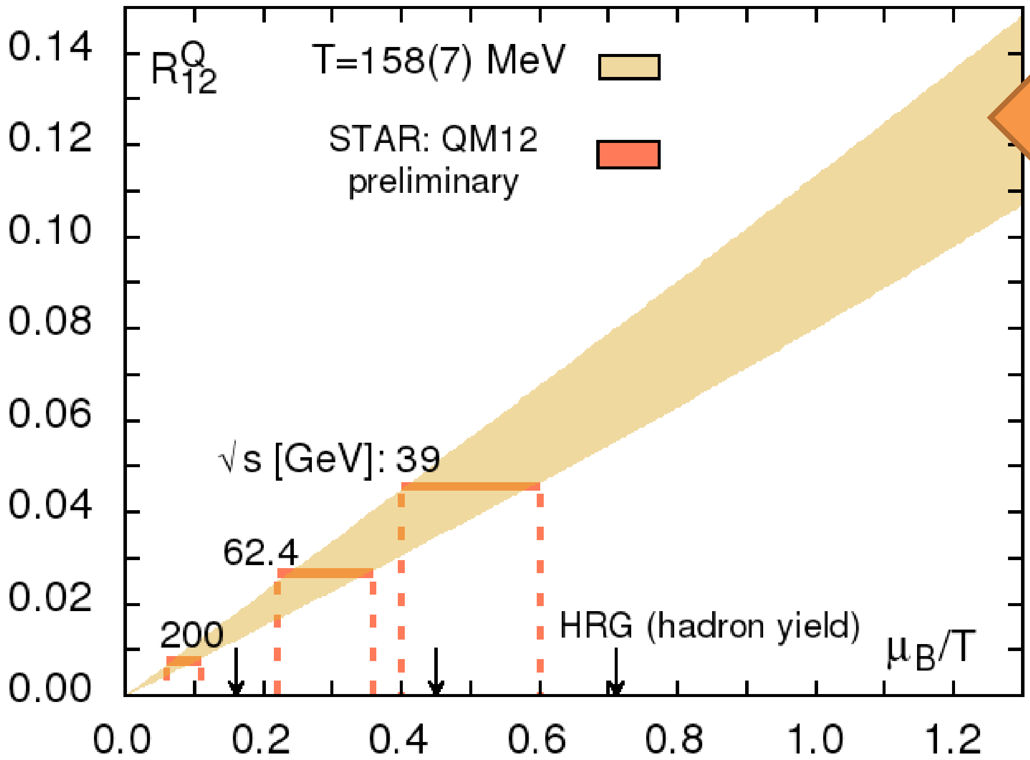
ALICE
PRL 2013





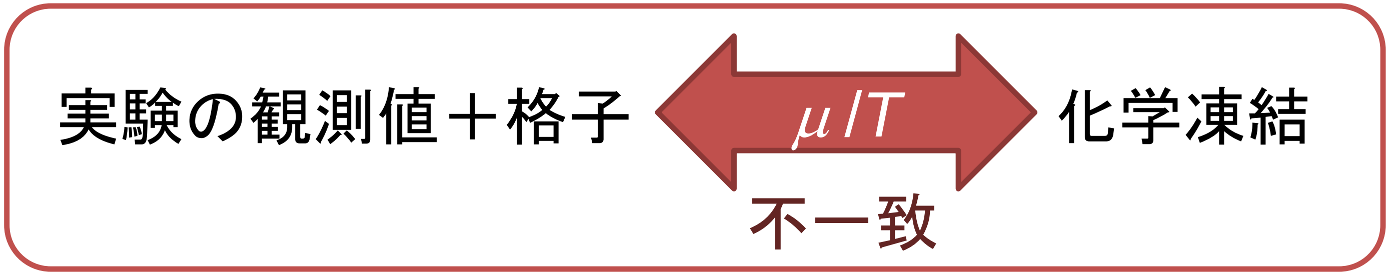
ゆらぎのΔη 依存性には、高温物質の
時間発展の歴史が刻まれている！

Cumulants : HIC vs Lattice



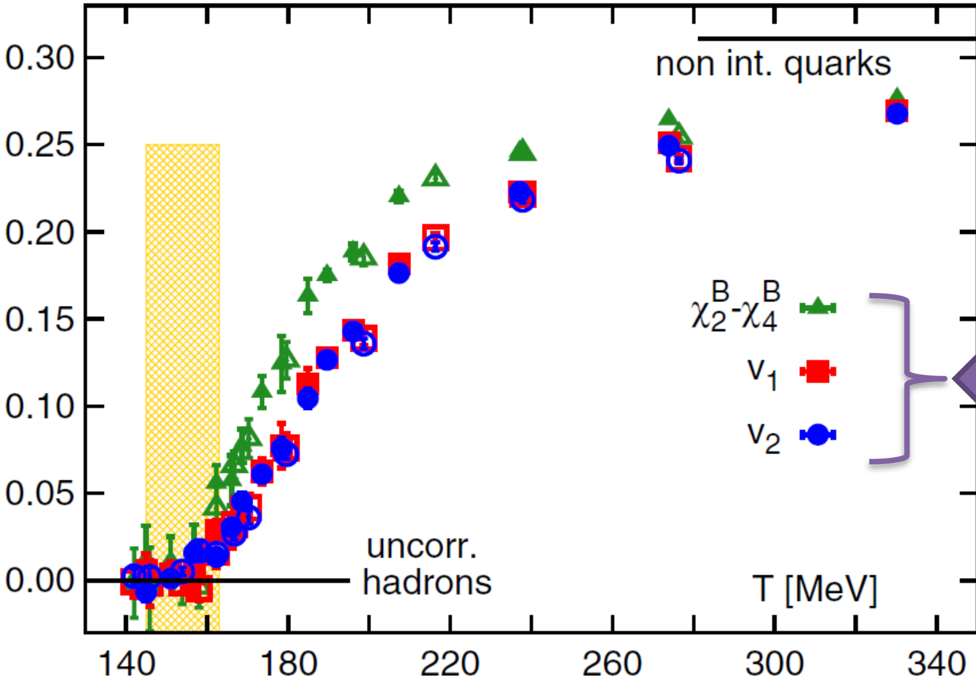
格子QCDで得られた
ゆらぎ- μ/T 関係線

HotQCD,
LATTICE2013



Cumulants as Probes of the Medium

高次キュムラントは、媒質の性質を理解するうえで有用



HotQCD, PRL 2013

ハドロン共鳴ガス(HRG)模型ではゼロになる量

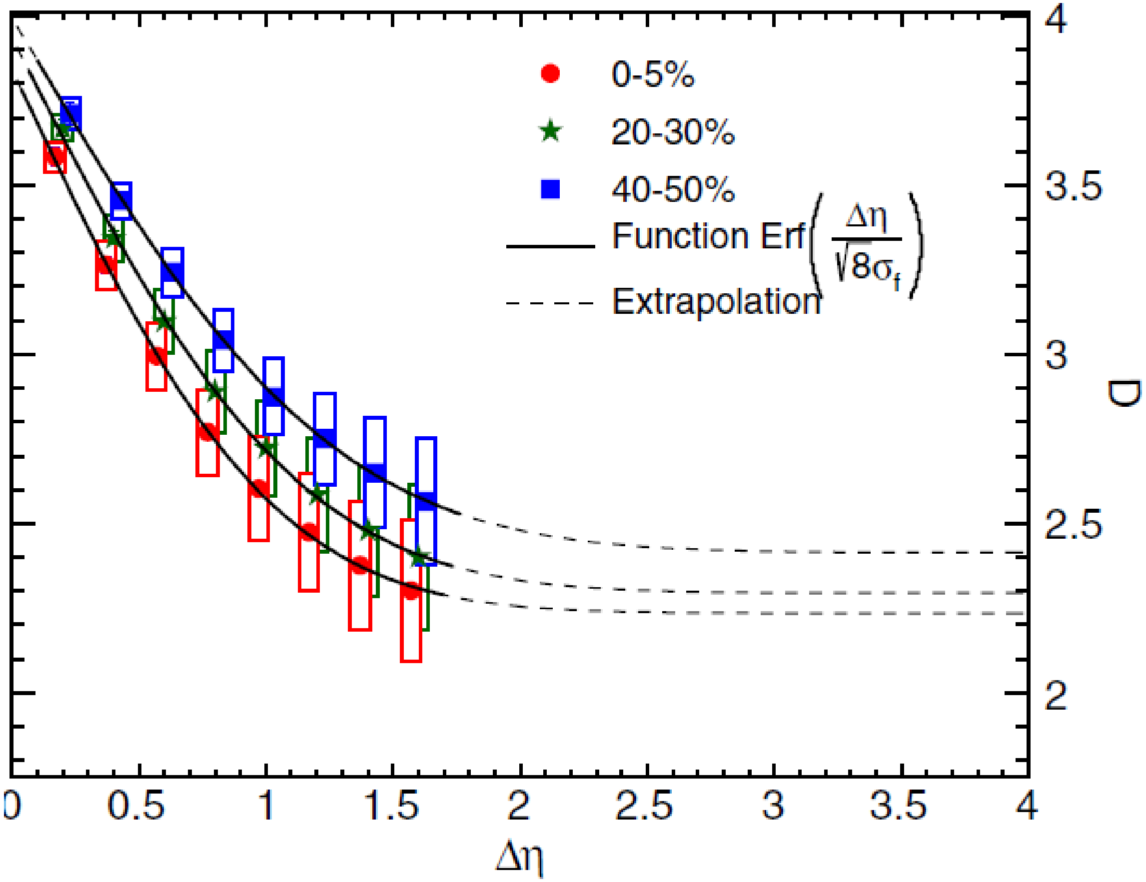
T<150MeVでの格子データは、HRG描像と矛盾しない

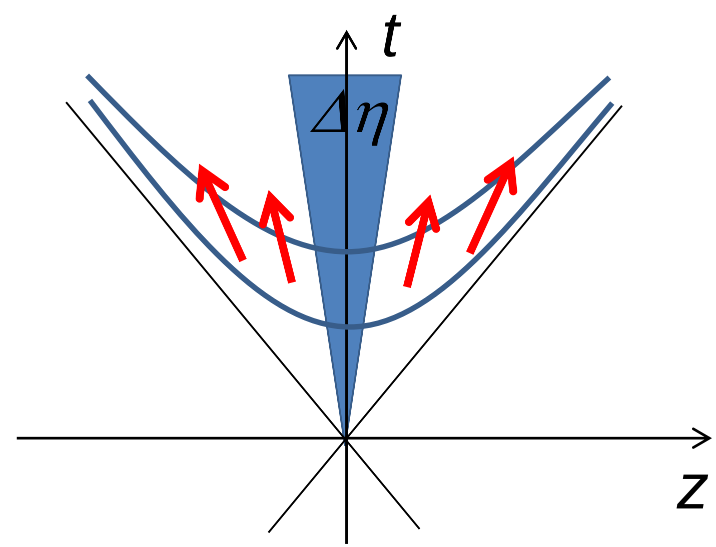
Time Evolution of Higher Order Cumulants

MK, Asakawa, Ono, arXiv:1307.2978
Sakaida, Asakawa, MK, in progress

Δη Dependence @ ALICE

ALICE
PRL 2013



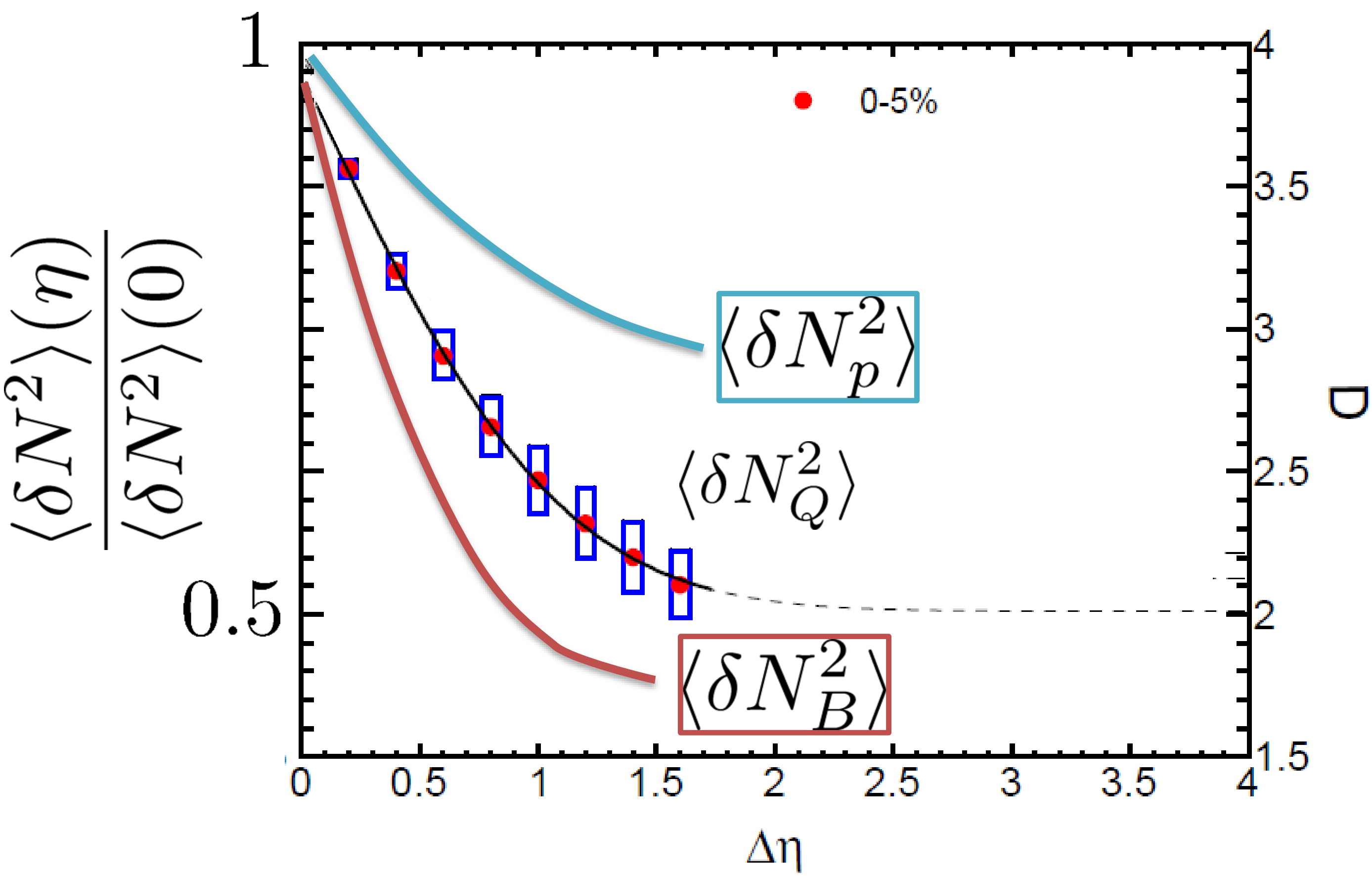


ゆらぎのΔη 依存性には、高温物質の
時間発展の歴史が刻まれている！

$\langle\delta N_B^2\rangle$ and $\langle\delta N_p^2\rangle$ @ LHC ?

$\langle\delta N_Q^2\rangle, \langle\delta N_B^2\rangle, \langle\delta N_p^2\rangle$

should have different Δη dependence.

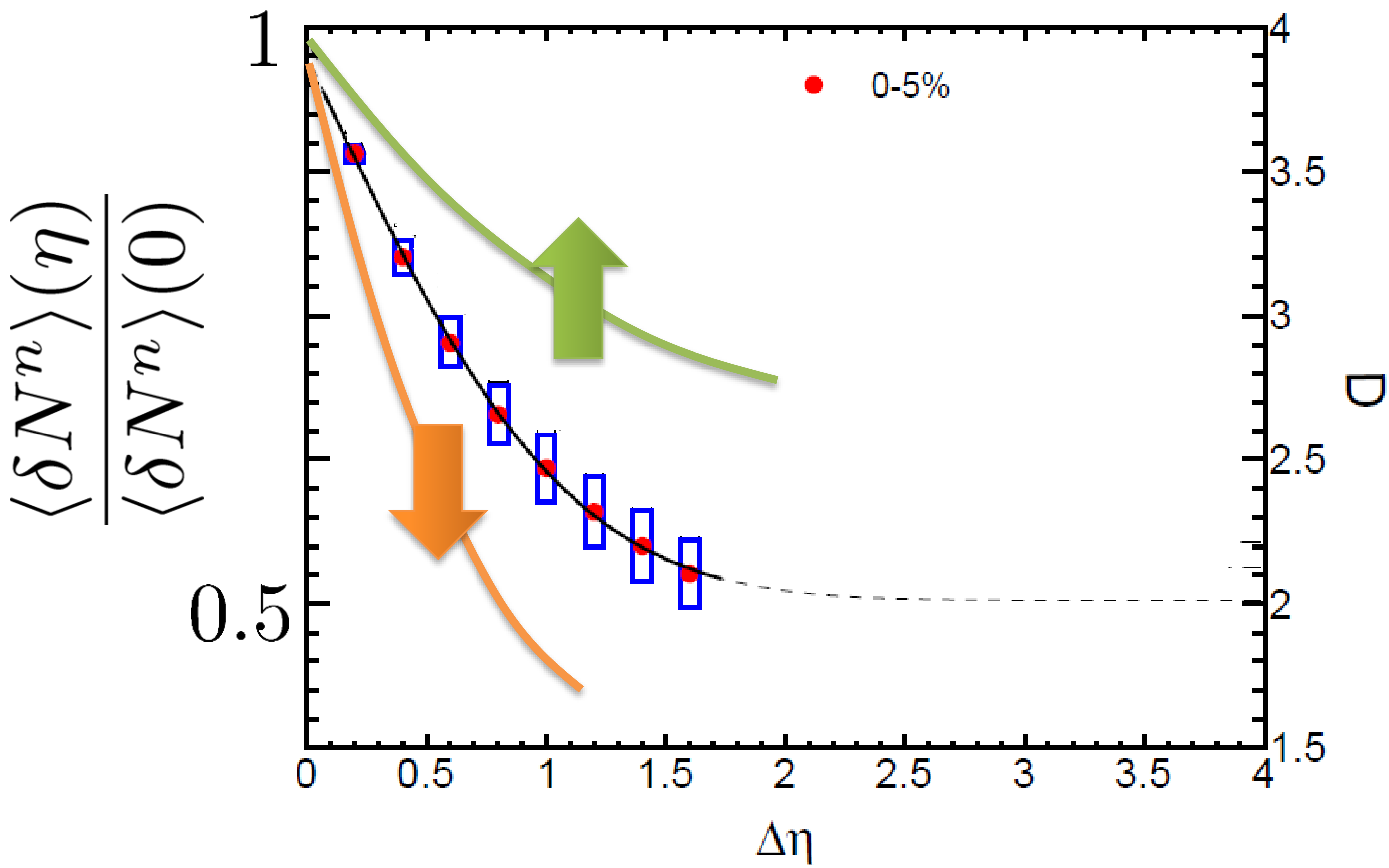


$$\langle(\delta N_p^{(\mathrm{net})})^2\rangle = \frac{1}{4}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^2\rangle + \frac{1}{4}\langle N_{\mathrm{B}}^{(\mathrm{tot})}\rangle$$

<δN_Q^4> @ LHC ?

How does $\langle \delta N_Q^4 \rangle_c$ behave as a function of $\Delta\eta$?

suppression or enhancement



Hydrodynamic Fluctuations

Landau, Lifshitz, Statistical Mechaniqs II
Kapusta, Muller, Stephanov, 2012

Diffusion equation

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

Stochastic diffusion equation

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

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Conservation Law

$$\partial_\tau n = -\partial_\eta j$$

Fick's Law

$$j = -D\partial_\eta n + \xi$$

Fluctuation-Dissipation Relation

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

Stochastic force

- Local correlation (hydrodynamics) $\langle \xi(\eta_1,\tau_1)\xi(\eta_2,\tau_2)\rangle \sim \delta(\eta_1-\eta_2)\delta(\tau_1-\tau_2)$
- Equilibrium fluc. $\langle \delta Q(t)^2 \rangle \xrightarrow[t\to\infty]{} \chi_2 \Delta\eta$

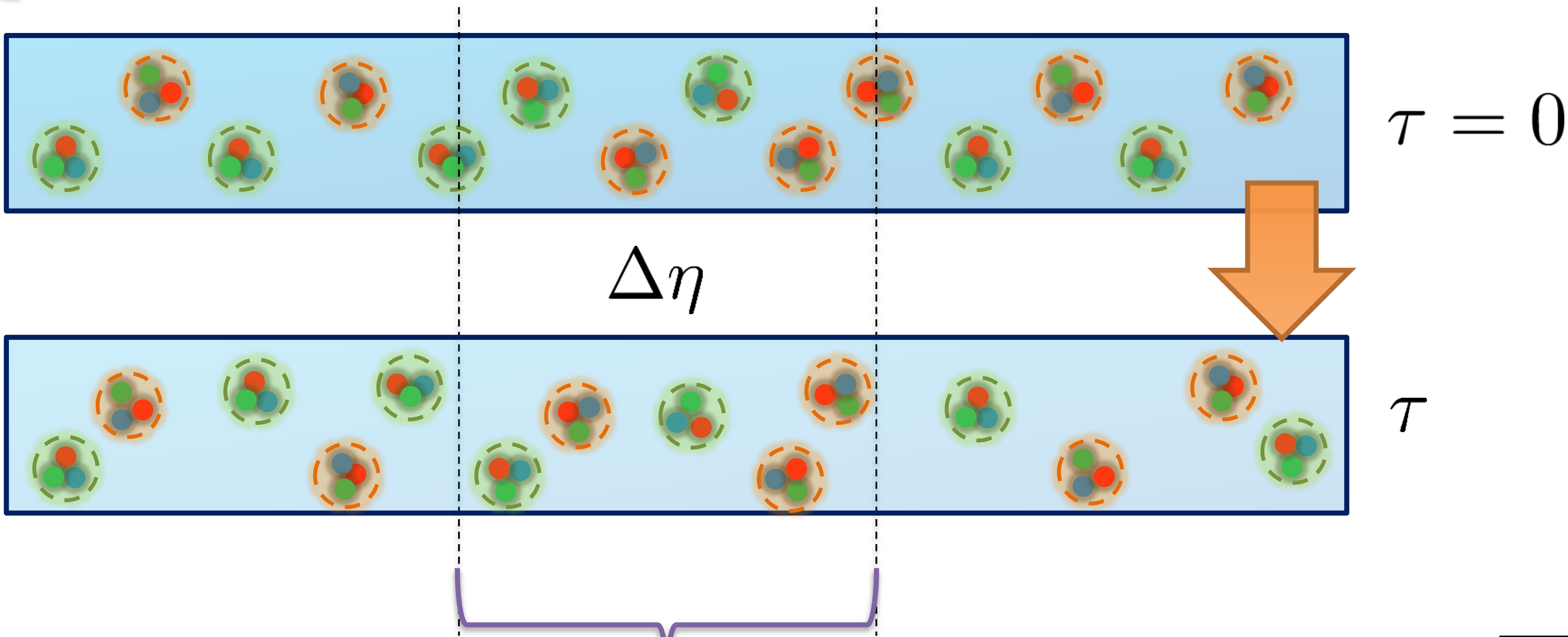
$$Q(\tau) = \int_0^{\Delta\eta} d\eta n(\eta,\tau)$$

χ_2 : susceptibility

$$\langle \xi(k_1,\tau_1)\xi(k_2,\tau_2)\rangle = \frac{2\chi_2}{D}\delta(k_1+k_2)\delta(\tau_1-\tau_2)$$

$\Delta\eta$ Dependence

- Initial condition: $\langle \delta n(\eta_1, 0)\delta n(\eta_2, 0)\rangle = \sigma_2 \delta(\eta_1 - \eta_2)$
- Translational invariance



$$Q(\Delta\eta, \tau) = \int_0^{\Delta\eta} d\eta n(\eta, \tau)$$

$$X = \frac{2\sqrt{D\tau}}{\Delta\eta}$$

$\Delta\eta$ Dependence

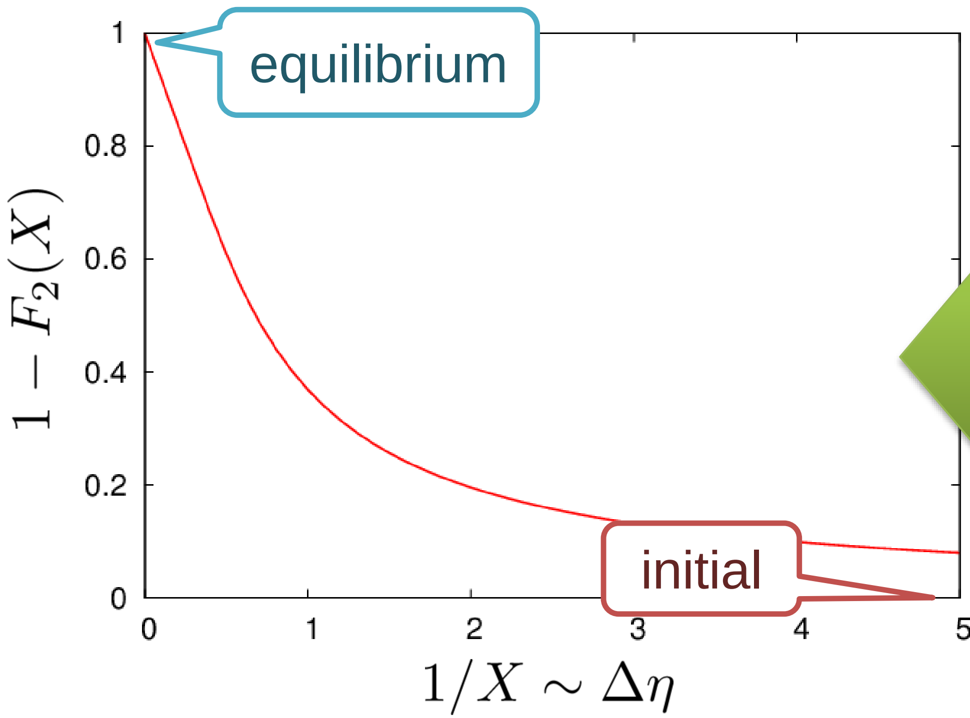
Shuryak, Stephanov, 2001

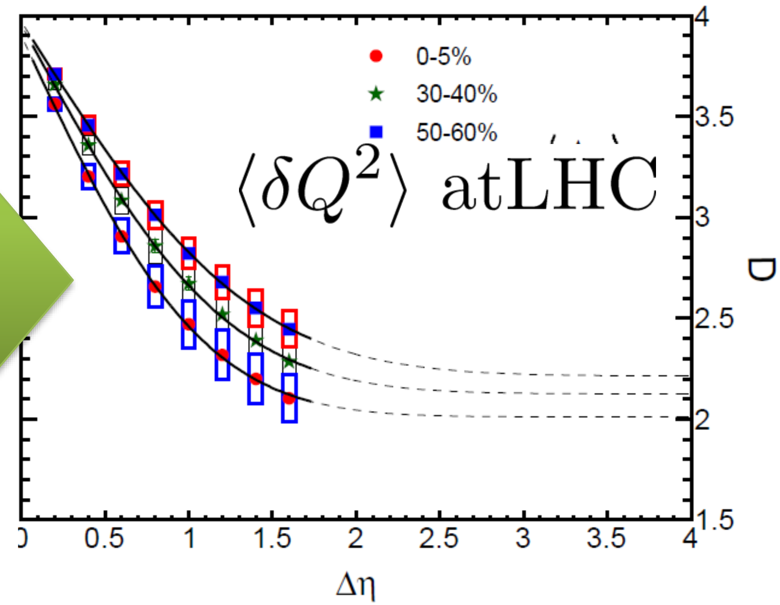
- Initial condition: $\langle \delta n(\eta_1, 0)\delta n(\eta_2, 0)\rangle = \sigma_2 \delta(\eta_1 - \eta_2)$
- Translational invariance

$$\langle \delta Q(\tau)^2 \rangle = \underbrace{\sigma_2 F_2(X)}_{\text{initial}} + \underbrace{\chi_2 (1 - F_2(X))}_{\text{equilibrium}}$$

$$Q(\tau) = \int_0^{\Delta\eta} d\eta\, n(\eta, \tau)$$

$$X = \frac{2\sqrt{D\tau}}{\ldots}$$





Non-Gaussian Stochastic Force ??

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

Stochastif Force : 3rd order

- Local correlation (hydrodynamics) $\langle \xi(\eta_1, \tau_1)\xi(\eta_2, \tau_2)\xi(\eta_3, \tau_3)\rangle$

$$\sim \delta(\eta_1 - \eta_2)\delta(\eta_2 - \eta_3)\delta(\tau_1 - \tau_2)\delta(\tau_2 - \tau_3)$$

- Equilibrium fluc. $\langle \delta Q(t)^3 \rangle \underset{t \to \infty}{\longrightarrow} \chi_3 \Delta\eta$

$$Q(\tau) = \int_0^{\Delta\eta} d\eta n(\eta, \tau)$$

χ_3 : third $-$ moment

Caution!

- $$\langle \xi(k_1,\tau_1)\xi(k_2,\tau_2)\xi(k_3,\tau_3)\rangle = \frac{\chi_3}{\gamma}\frac{k_1^2+k_2^2+k_3^2}{k_1k_2k_3}\delta(k_1+k_2+k_3)$$
$$\times\delta(\tau_1-\tau_2)\delta(\tau_2-\tau_3)$$

diverge in long wavelength

- No a priori extension of FD relation to higher orders

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diverge in long wavelength

- No a priori extension of FD relation to higher orders

- Theorem

Markov process＋continuous variable

➔Gaussian random force

cf) Gardiner, "Stochastic Methods"

- Hydrodynamics ➡ Local equilibrium with many particles

➡ Gaussian due to central limit theorem

Thee “NON”s

重イオン衝突での高次ゆらぎの観測・解析は、
物理学として**相当に**特殊な問題である。

- **Non-Gaussian**

通常、高次ゆらぎは観測困難。
適度に小さい系

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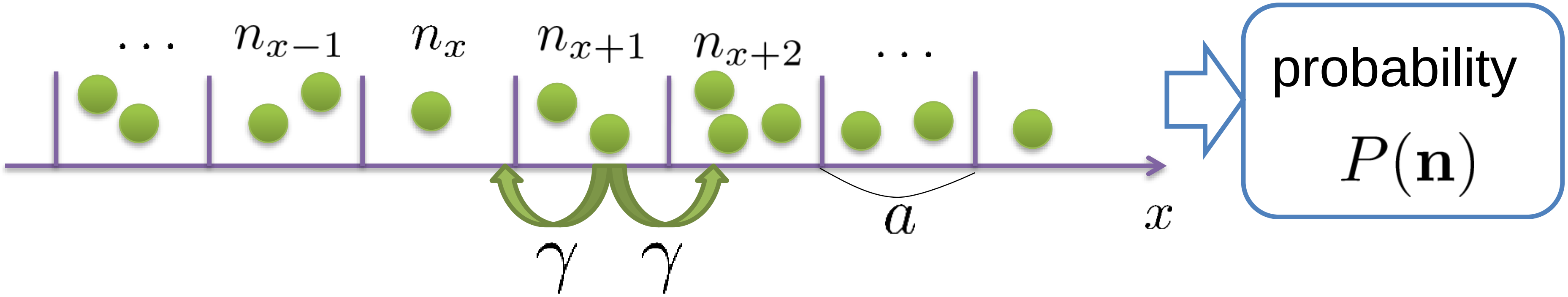
- **Non-critical**
  観測されたゆらぎの値は、
  自由ガスとたかだか2倍のずれ

- **Non-equilibrium**
  平衡に至る非定常過程を
  記述する必要性。

Diffusion Master Equation

Divide spatial coordinate into discrete cells



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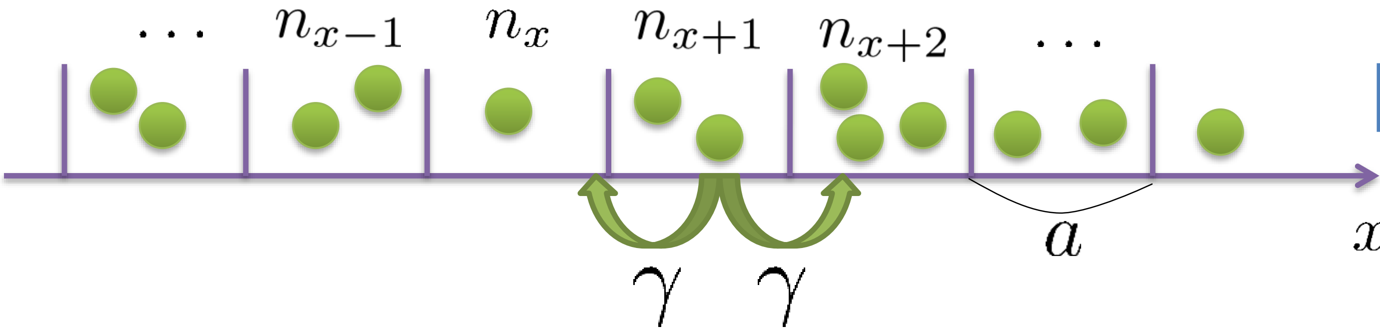

probability

$P(\mathbf{n})$

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 approx., ex. van Kampen's system size expansion

Solution of DME

1st $\langle \tilde{n}_k \rangle(t) = e^{-\omega_k t} \langle \tilde{n}_k \rangle_0$ $\omega_k \simeq \gamma a^2 k^2$

initial

- Deterministic part ←→ diffusion equation at long wave length (1/a<<k)

$$\partial_t \langle n_x(t) \rangle = \gamma a^2 \partial_x^2 \langle n_x(t) \rangle$$

- Appropriate continuum limit with $\gamma a^2 = D$

Solution of DME

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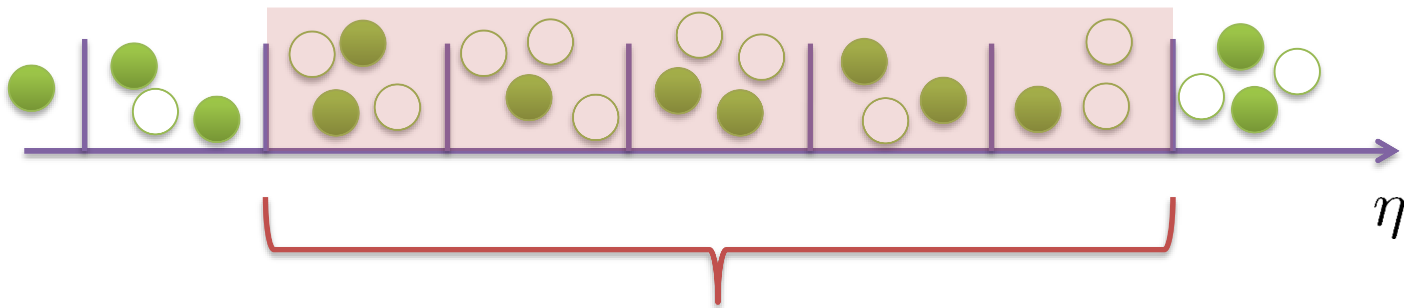
- Appropriate continuum limit with $\gamma a^2 = D$

2nd $$\langle \delta\tilde{n}_{k_1} \delta\tilde{n}_{k_2} \rangle(t) = \langle \tilde{n}_{k_1+k_2} \rangle_0 \left(e^{-\omega_{k_1+k_2} t} - e^{-(\omega_{k_1}+\omega_{k_2})t} \right) + \langle \delta\tilde{n}_{k_1} \delta\tilde{n}_{k_2} \rangle_0 e^{-(\omega_{k_1}+\omega_{k_2})t}$$

- Consistent with stochastic diffusion eq. (for smooth initial condition)

Net Charge Number

Prepare 2 species of (non-interacting) particles



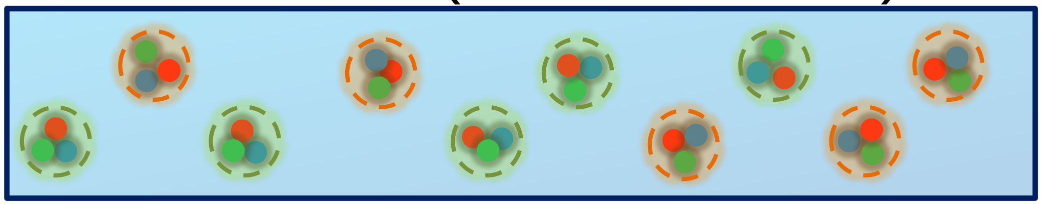
$$\bar{Q}(\tau) = \int_0^{\Delta\eta} d\eta \, (n_1(\eta,\tau) - n_2(\eta,\tau))$$

Let us investigate

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

Time Evolution in Hadronic Phase

Hadronization (initial condition)



- Boost invariance / infinitely long system
- Local equilibration / local correlation

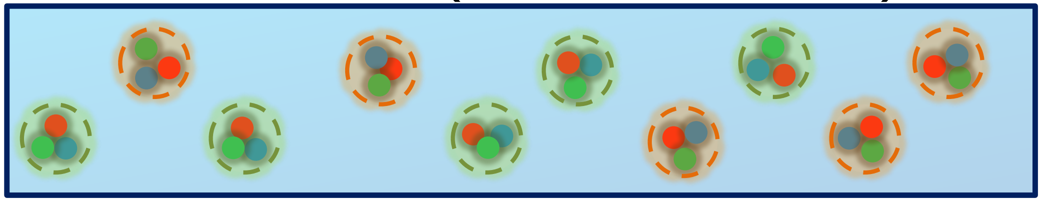
$\langle \bar{Q}^2 \rangle_c \quad \langle \bar{Q}^4 \rangle_c$ $\quad \langle \bar{Q}^2 Q_{(\mathrm{tot})} \rangle_c$ $\quad \langle Q^2_{(\mathrm{tot})} \rangle_c$

suppression owing to local charge conservation ($\langle \bar{Q}^2 \rangle_c$, $\langle \bar{Q}^4 \rangle_c$, $\langle \bar{Q}^2 Q_{(\mathrm{tot})} \rangle_c$)

strongly dependent on hadronization mechanism ($\langle Q^2_{(\mathrm{tot})} \rangle_c$)

Time Evolution in Hadronic Phase

Hadronization (initial condition)



Time evolution via DME

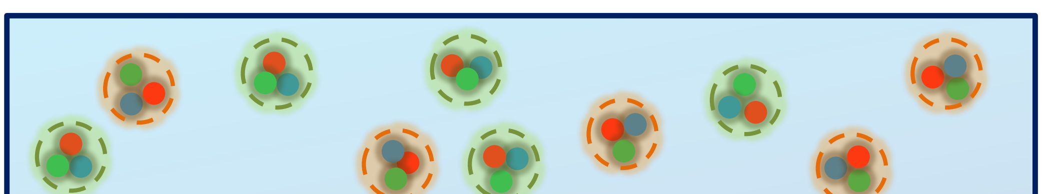
- Boost invariance / infinitely long system
- Local equilibration / local correlation

$\langle \bar{Q}^2 \rangle_c \quad \langle \bar{Q}^4 \rangle_c$ ← suppression owing to local charge conservation

$\langle \bar{Q}^2 Q_{(\mathrm{tot})} \rangle_c$

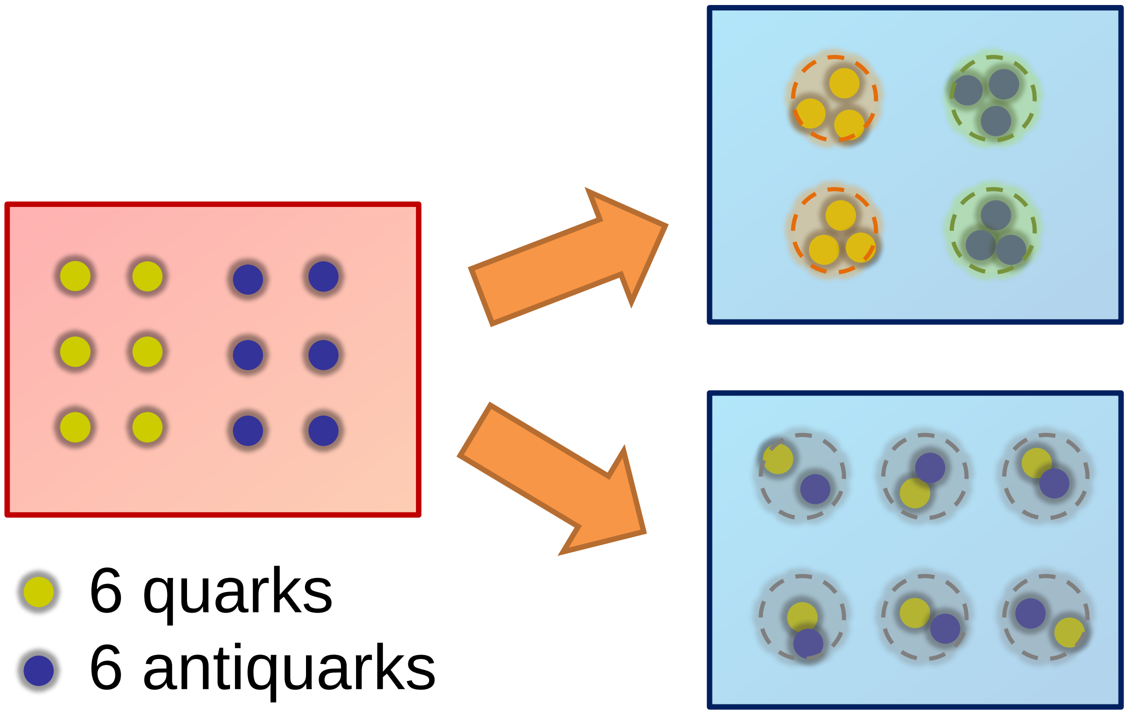
$\langle Q^2_{(\mathrm{tot})} \rangle_c$ ← strongly dependent on hadronization mechanism

Freezeout



Total Charge Number

In recombination model,



$$N_B^{(\mathrm{net})} = 0$$
$$N_B^{(\mathrm{tot})} = 4$$

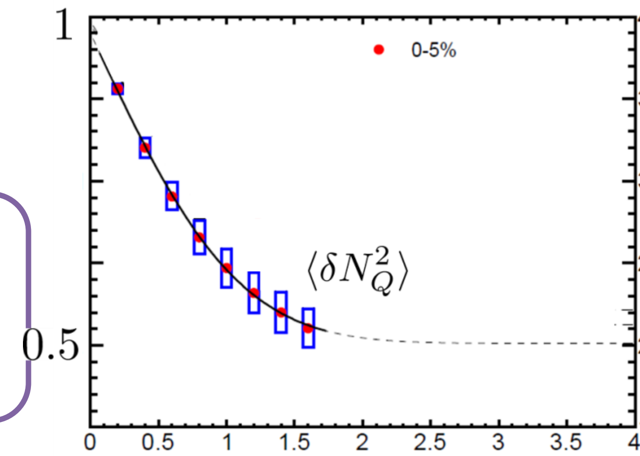
$$N_B^{(\mathrm{net})} = 0$$
$$N_B^{(\mathrm{tot})} = 0$$

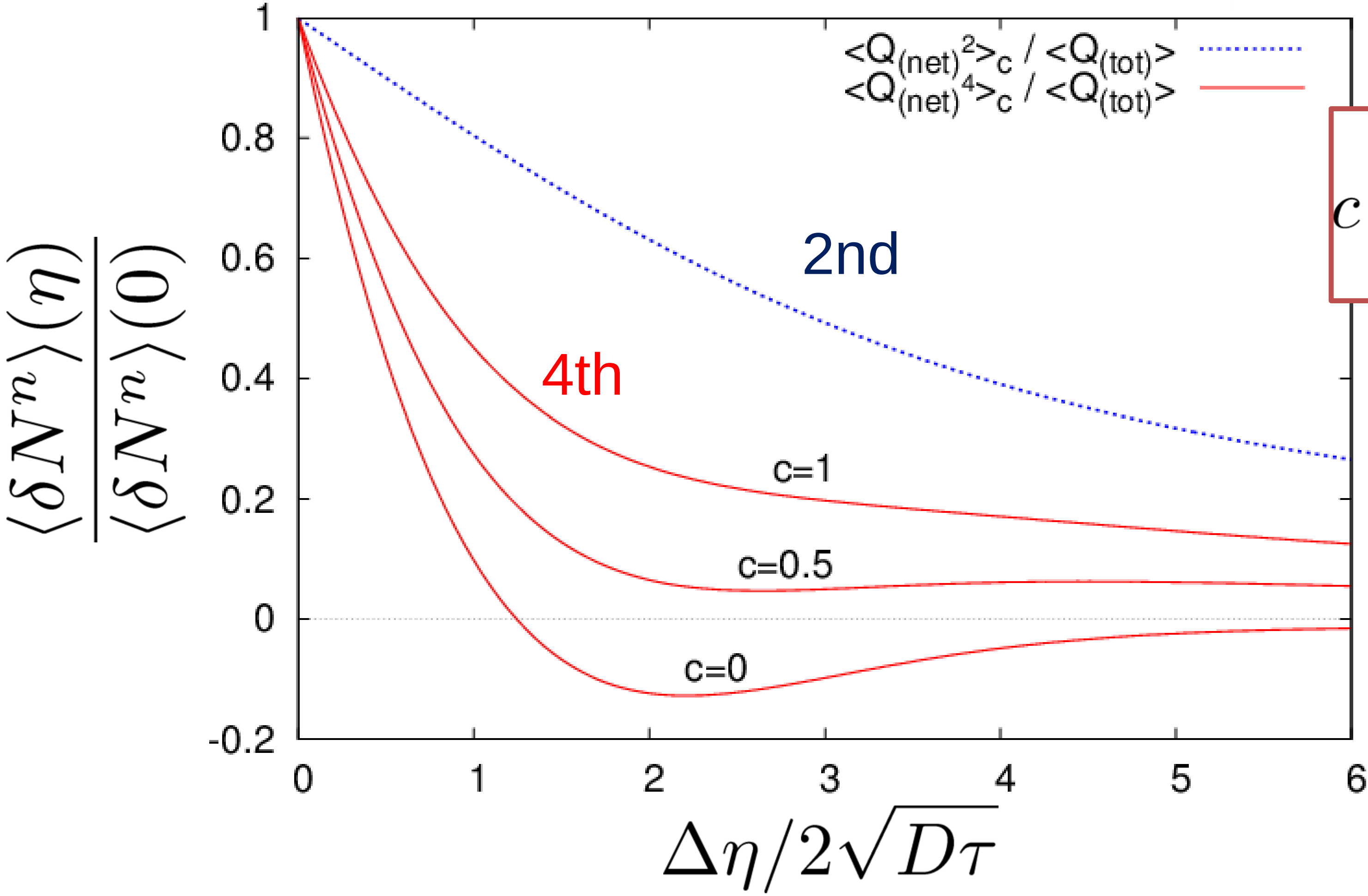
- $N_B^{(\mathrm{tot})}$ can fluctuate, while $N_B^{(\mathrm{net})}$ does not.

$\Delta\eta$ Dependence at Freezeout

Initial fluctuations:

$$\langle \bar{Q}^2 \rangle_c = \langle \bar{Q}^4 \rangle_c = \langle \bar{Q}^2 Q_{(\mathrm{tot})} \rangle_c = 0$$





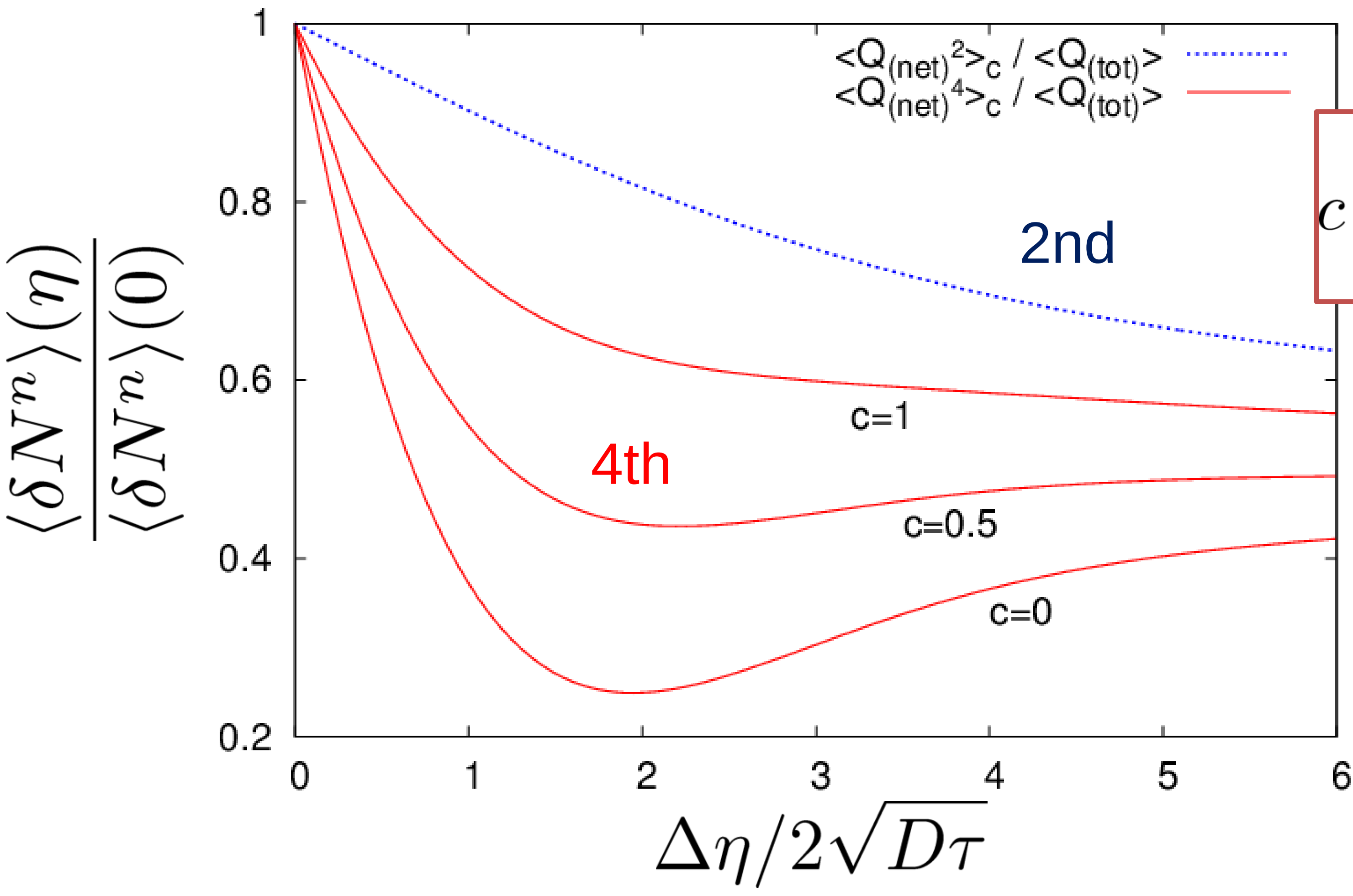
$$c = \frac{\langle Q_{(\mathrm{tot})}^2 \rangle_c}{\langle Q_{(\mathrm{tot})} \rangle}$$

parameter sensitive to hadronization

$\Delta\eta$ Dependence at Freezeout

Initial fluctuations:

$$\langle \bar{Q}^2 \rangle_c = \langle \bar{Q}^4 \rangle_c = \langle \bar{Q}^2 Q_{(\mathrm{tot})} \rangle_c = 0.5 \langle Q_{(\mathrm{tot})} \rangle$$

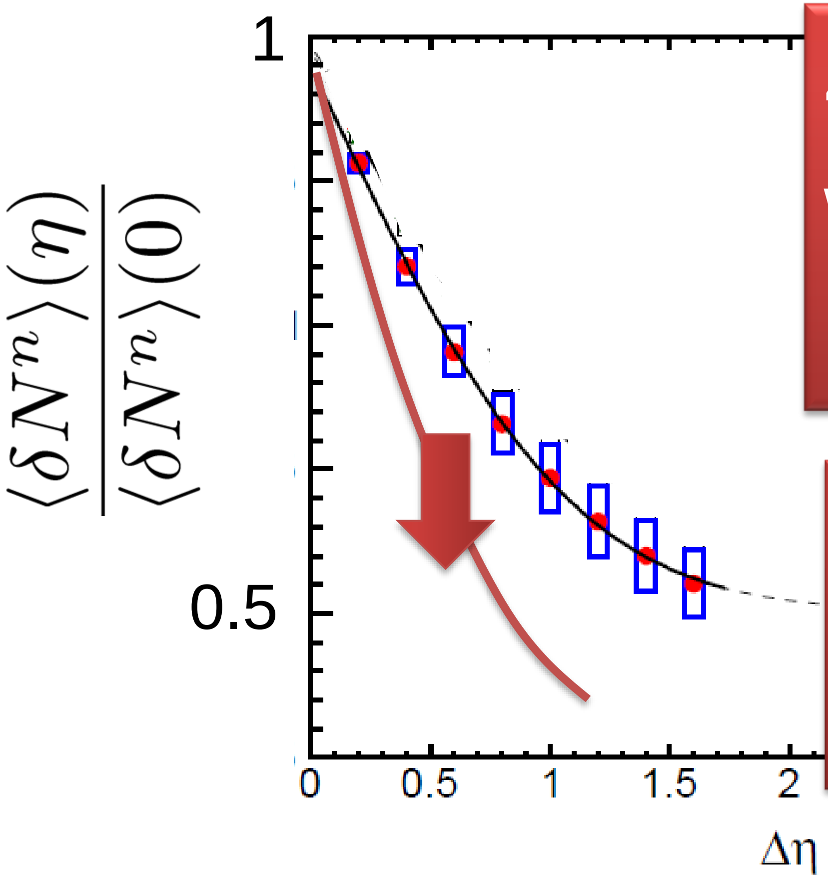


$$c = \frac{\langle Q^2_{(\mathrm{tot})} \rangle_c}{\langle Q_{(\mathrm{tot})} \rangle}$$

parameter sensitive to hadronization

$<\delta N_Q^4>$ @ LHC

Assumptions
- boost invariant system
- small fluctuations of CC at hadronization
- short correlation in hadronic stage



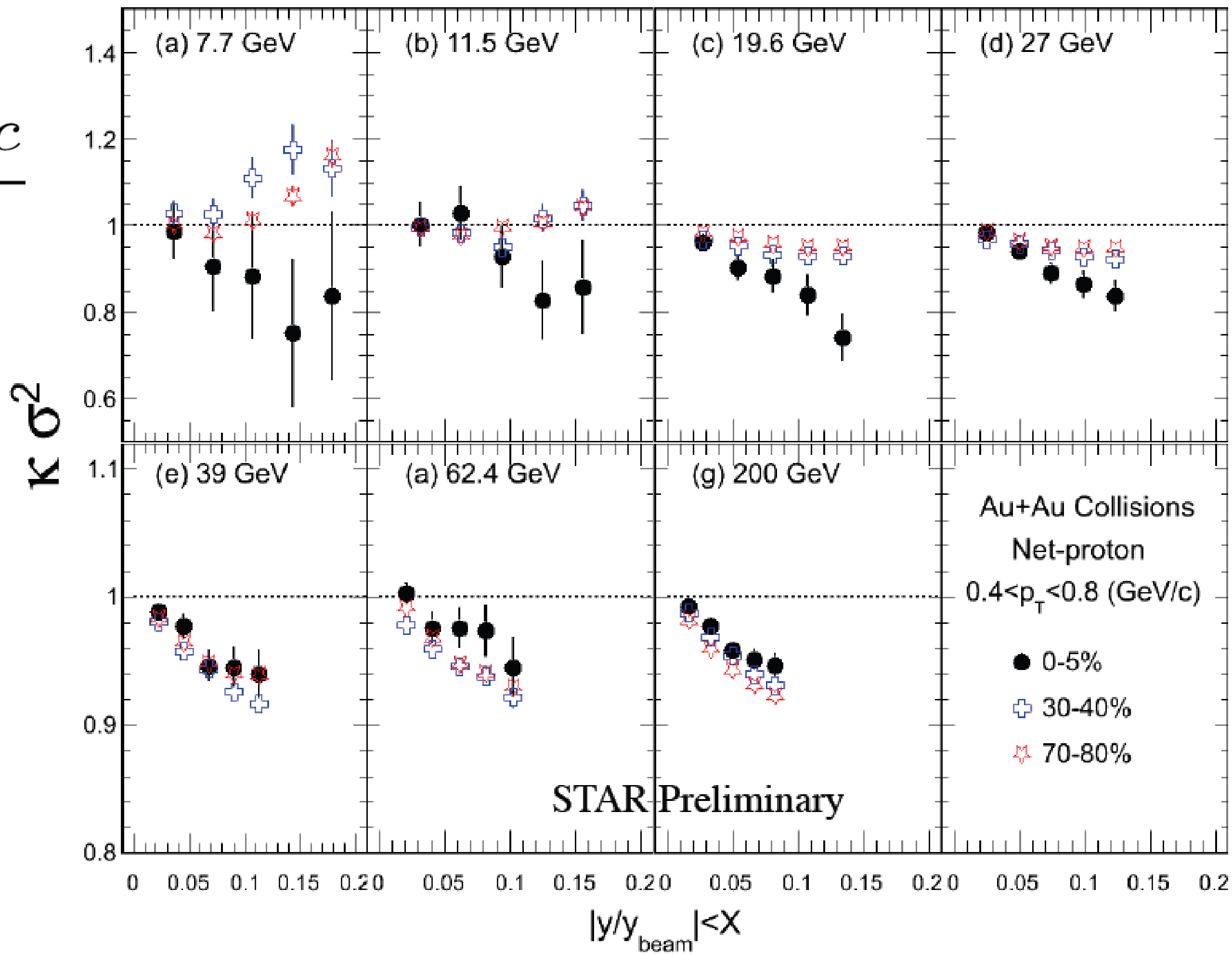
4th-order cumulant will be suppressed at LHC energy!

Δη dependences encode various information on the dynamics of HIC!

Δη Dependence at STAR

STAR, QM2012

$$\frac{\langle \delta N_p^4 \rangle_c}{\langle \delta N_p^2 \rangle}$$



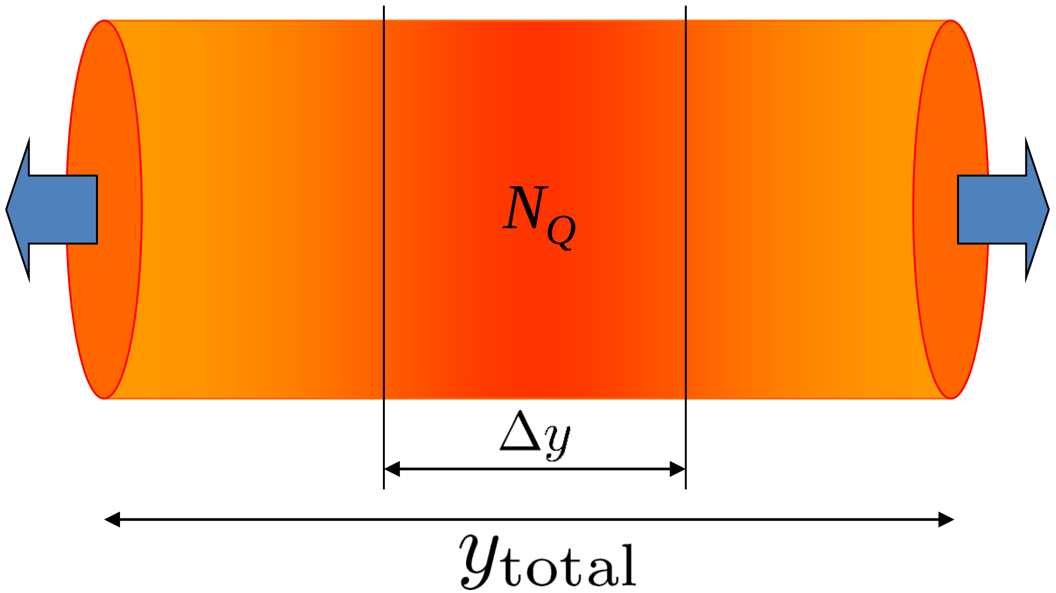
$\frac{\langle \delta N_p^4 \rangle_c}{\langle \delta N_p^2 \rangle}$ decreases as Δη becomes larger at RHIC.

Global Charge Conservation

坂井田、et al., in prep.

HICで作られたQGPは有限系

➡ 全系を観測すれば、保存電荷はゆらがない

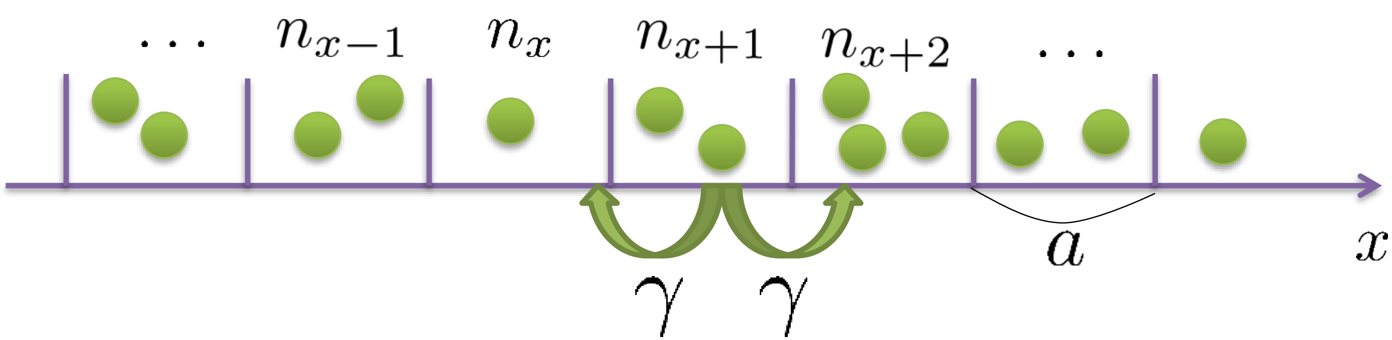


有限体積効果の考慮？？

$$\langle \delta Q^2 \rangle_{\rm obs} = \langle \delta Q^2 \rangle_{\rm equil} \times \left(1 - \frac{\Delta y}{y_{\rm total}} \right)$$

Diffusion Equation w/ Boundaries

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



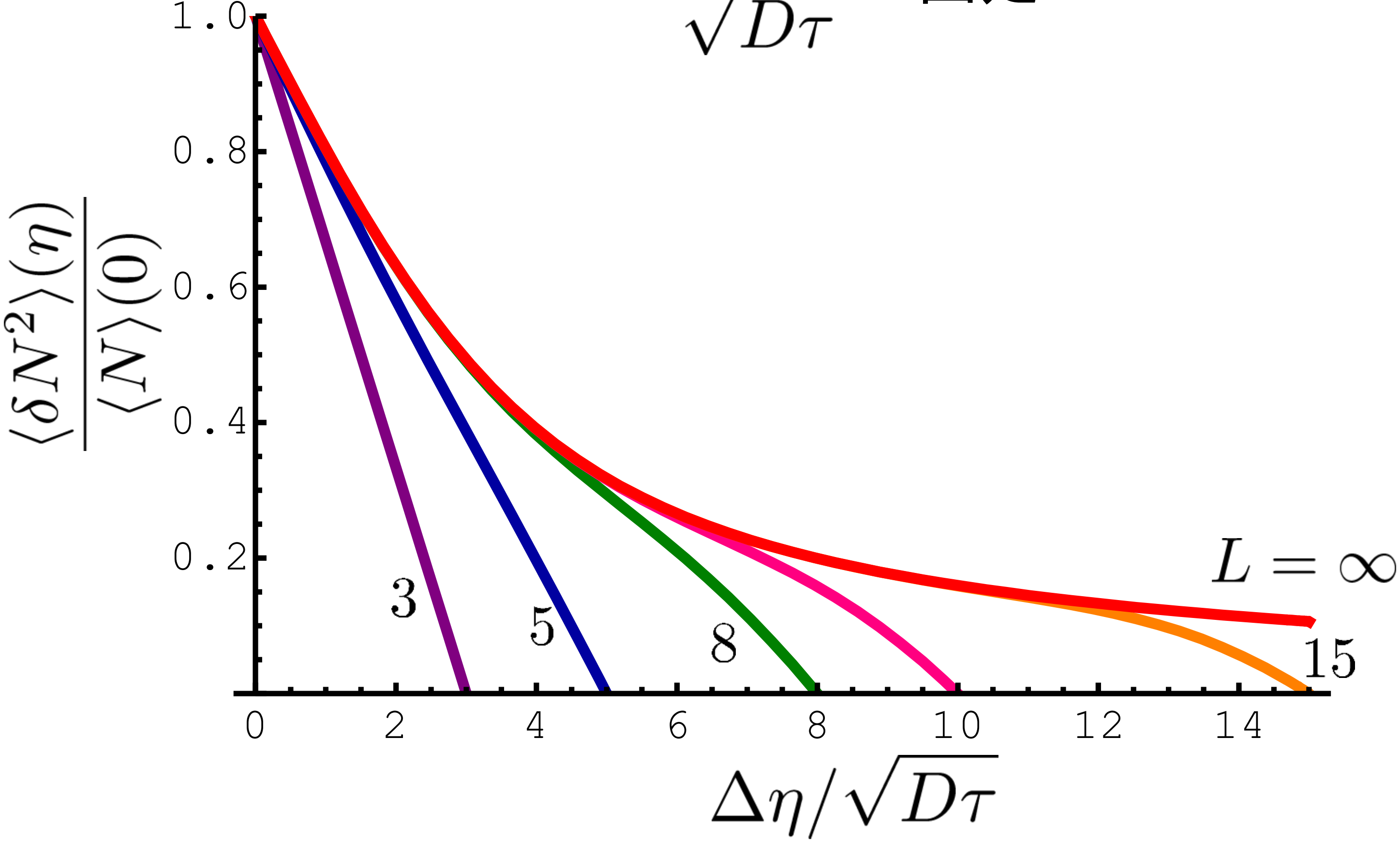
拡散方程式を、境界条件付きで解く

3 Free Parameters

$\Delta\eta$ $\sqrt{D\tau}$ y_{total}

Global Charge Conservation

$$L = \frac{y_{\rm total}}{\sqrt{D\tau}}$$:固定



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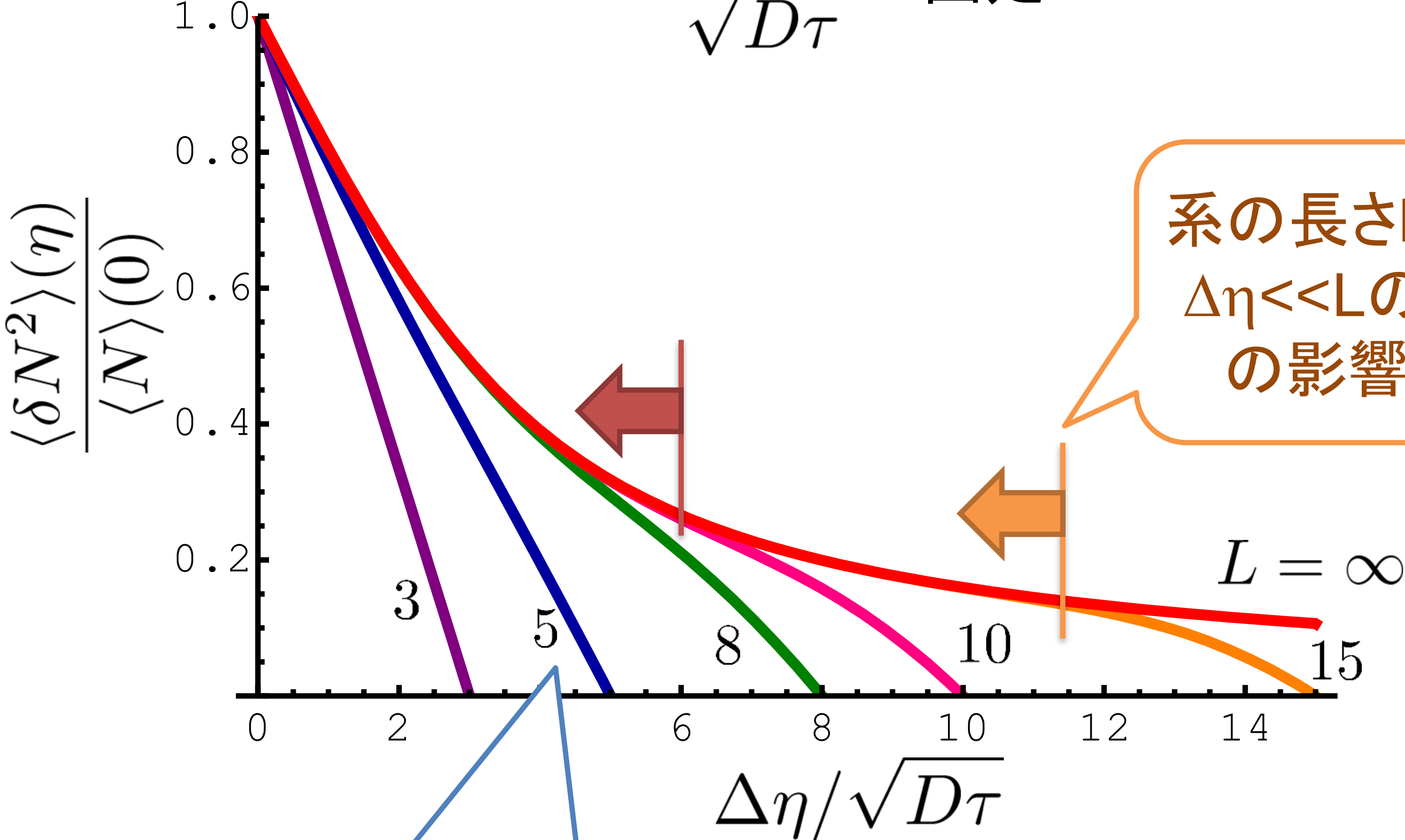
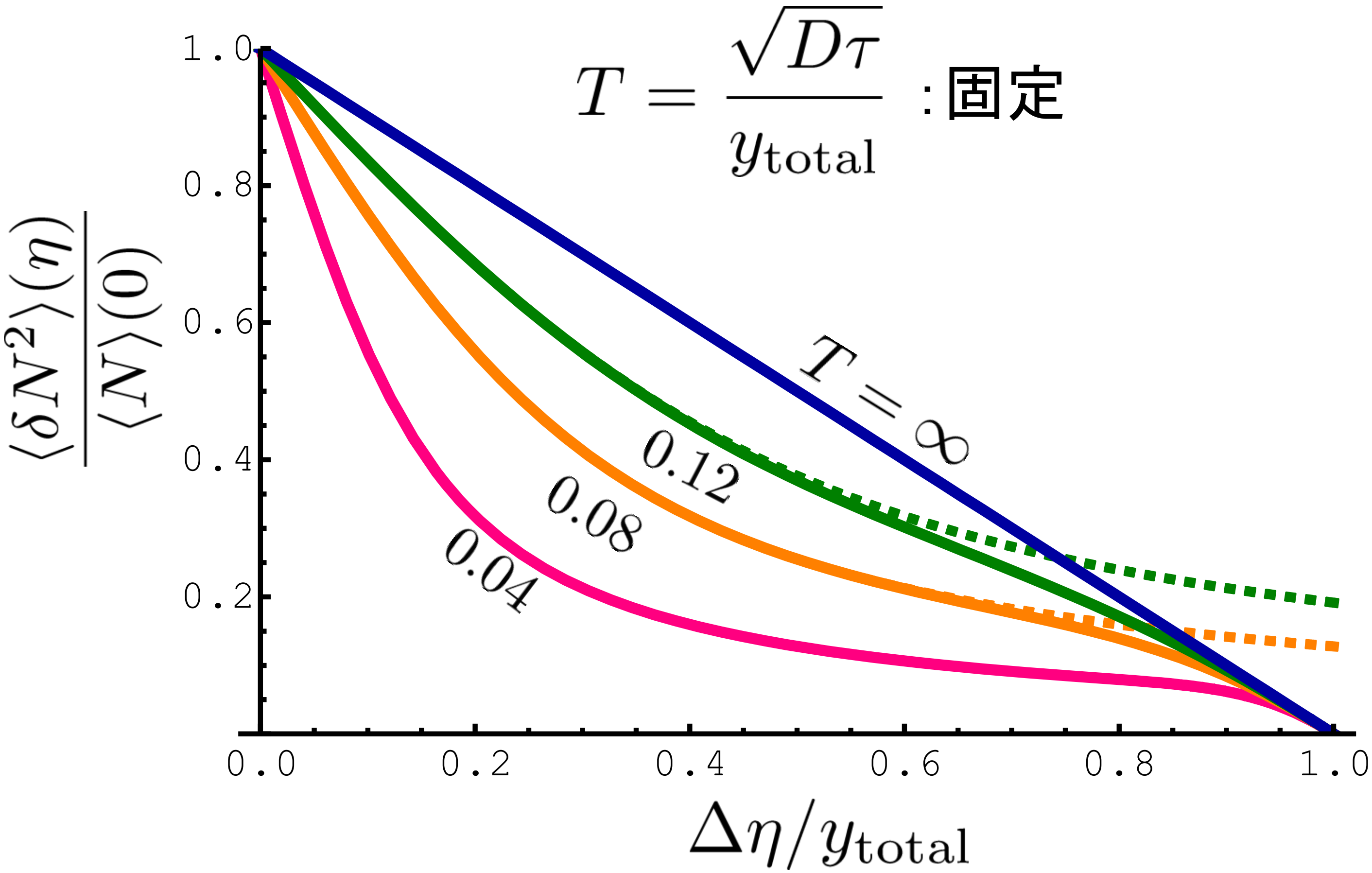


系の長さL が大きいと、Δη<<Lの領域は境界の影響を受けない

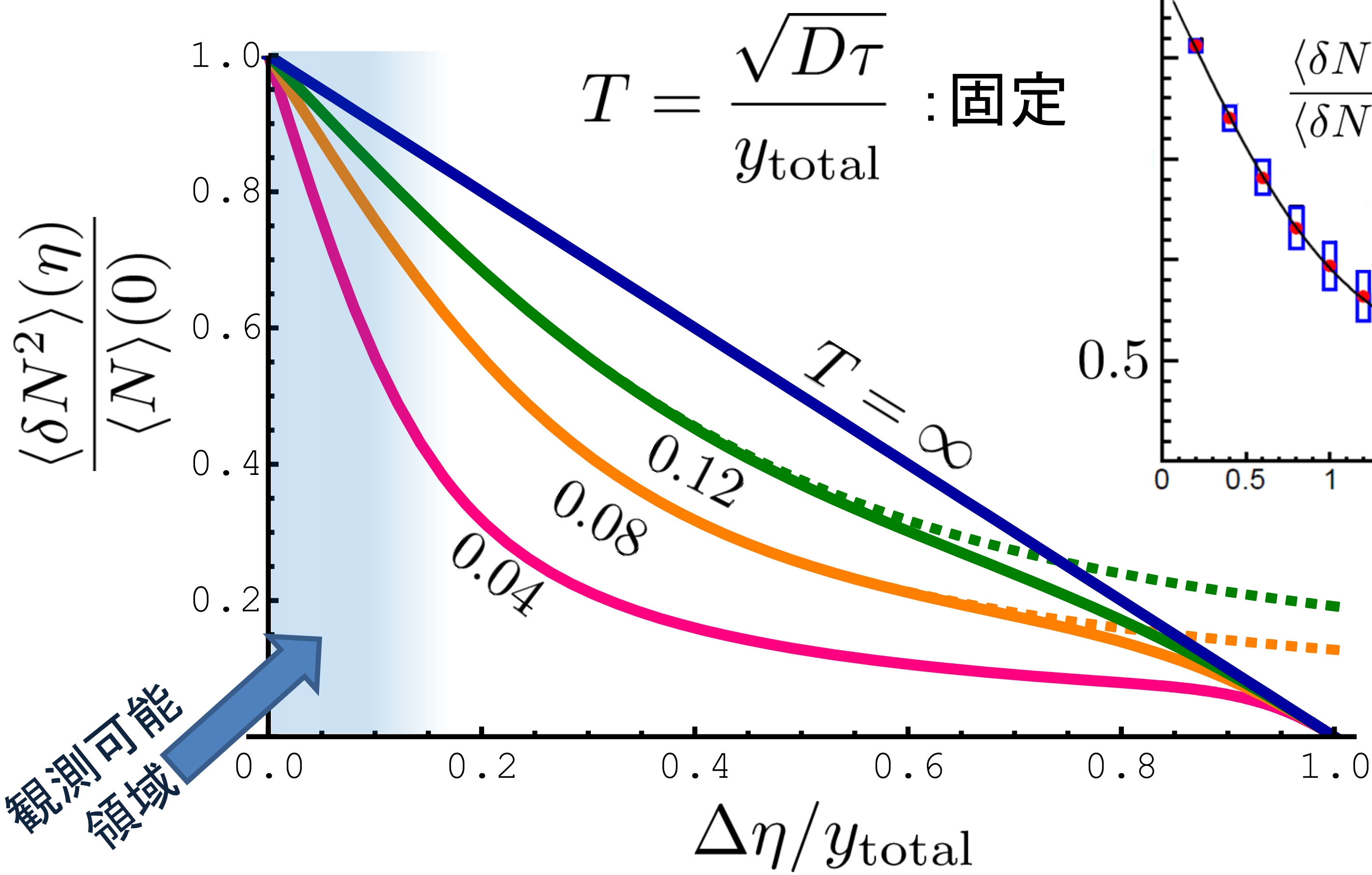
時間が十分経過すると、二項分布に漸近（熱平衡化）

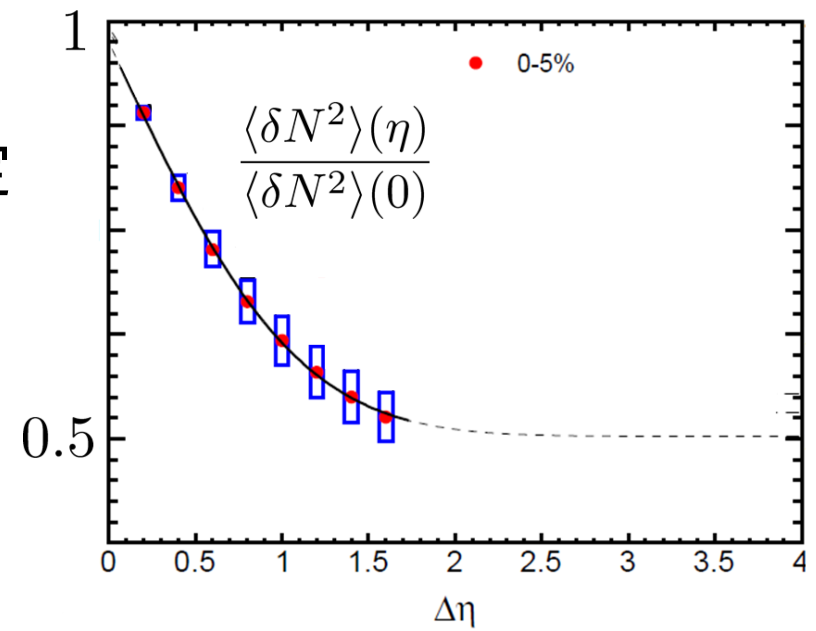
Global Charge Conservation



- 有限体積効果は、Δη依存性から読み取ることができる
- ALICEの結果には、有限体積効果はほとんど寄与しない

Global Charge Conservation





- 有限体積効果は、Δη依存性から読み取ることができる
- ALICEの結果には、有限体積効果はほとんど寄与しない
- STARでは？！？

Summary

Plenty of physics in $\Delta\eta$ dependences of various cumulants

$$\langle N_Q^2 \rangle_c, \ \langle N_B^2 \rangle_c, \ \langle N_Q^4 \rangle_c, \ \langle N_B^4 \rangle_c, \ \langle N_{ch}^2 \rangle_c, \cdots$$

Physical meanings of fluctuation obs. in experiments.

Diagnosing dynamics of HIC

- history of hot medium
- mechanism of hadronization
- diffusion constant

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Plenty of physics in $\Delta\eta$ dependences of various cumulants

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Search of QCD Phase Structure

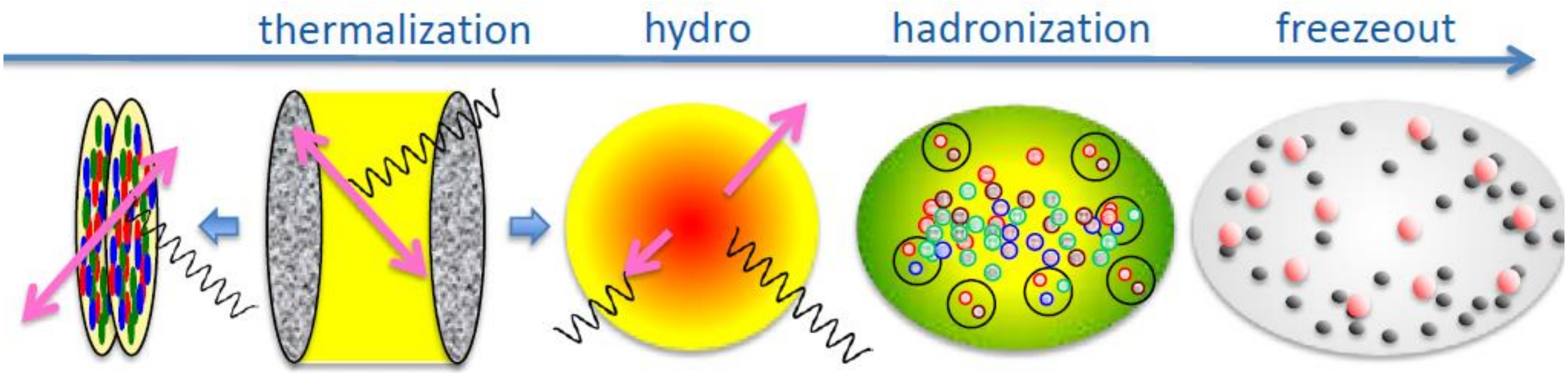
Summary

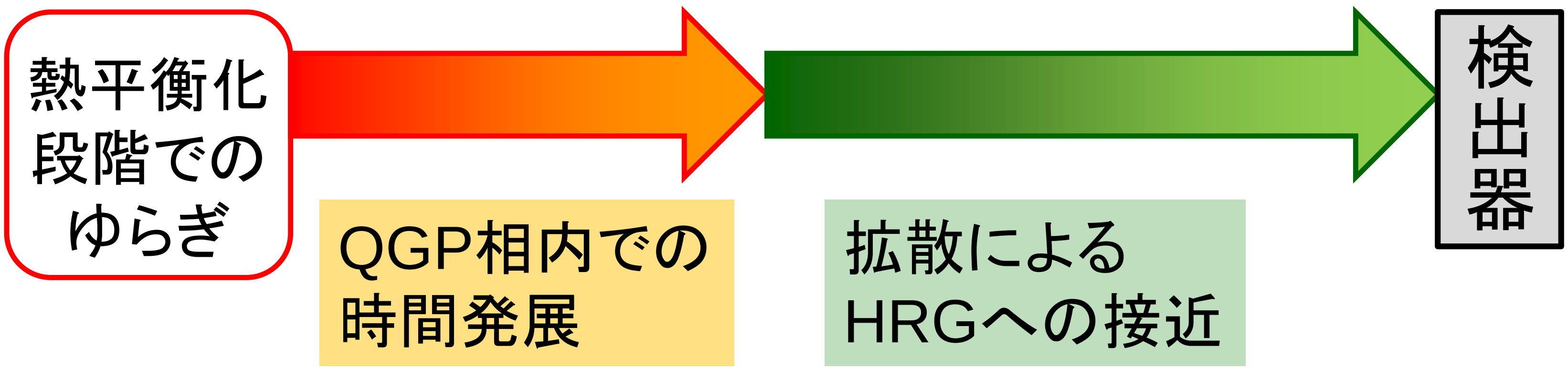
- Conserved charge fluctuations are observable both in lattice simulations and heavy ion collisions. The comparison of the results in these two “experiments” will provide us many information to understand the QCD at nonzero T/m.

- A lot of efforts are required both sides:
  - Lattice: Higher statistics
  - HIC: reconstructing baryon #, acceptance, etc.

- Rapidity window dependences of cumulants in HIC are valuable tools to understand the non-thermal nature of fluctuations.

高温物質の時間発展





初期エネルギー密度 ⟶ 体積ゆらぎ

まとめ

保存量初期ゆらぎの痕跡は終状態に残されており LHC、RHICで観測にかかり始めている

ただし、RHIC-BES領域では即座にQCD相構造が直ちに見えるほど明瞭ではないので、

実験的課題

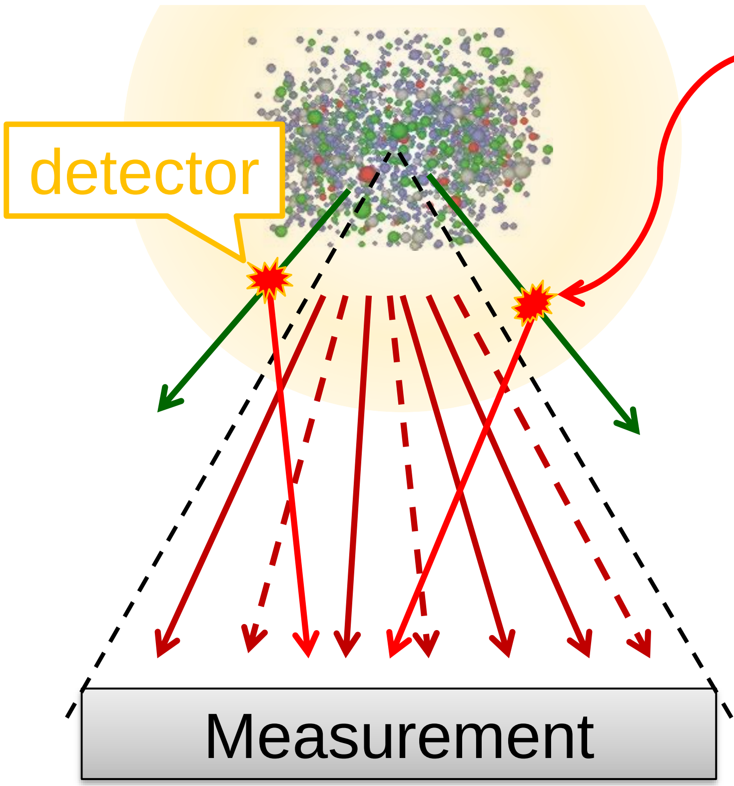
- バリオン数ゆらぎの構成
- Q_4/Q_2@ALICE
- Dy依存性@STAR
- efficiency, acceptance, …
- エネルギーゆらぎ
- BES from RHIC to LHC

理論的課題

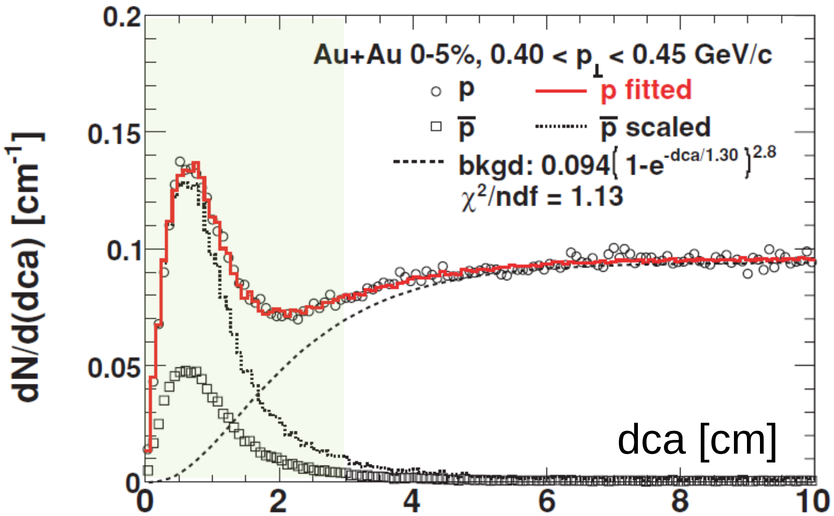
- RHIC D-puzzleの解決
- RHIC-BESの結果の解釈
- 2点相関関数等との比較
- 新しい観測量の提案

Secondary Protons

MK+, in preparation



20% of observed protons @ STAR



STAR, PRC79,034909(2009)

Secondary Protons

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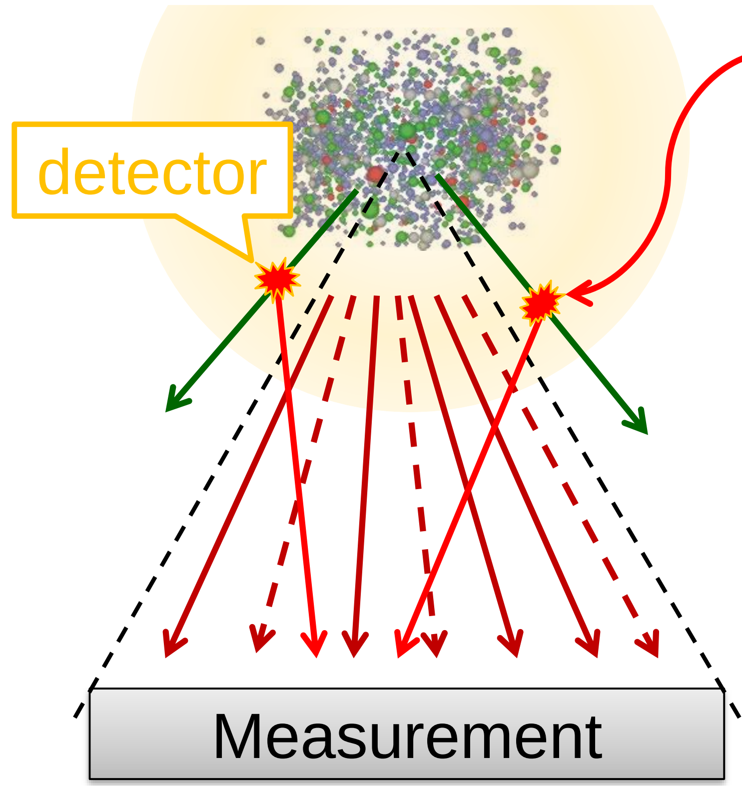
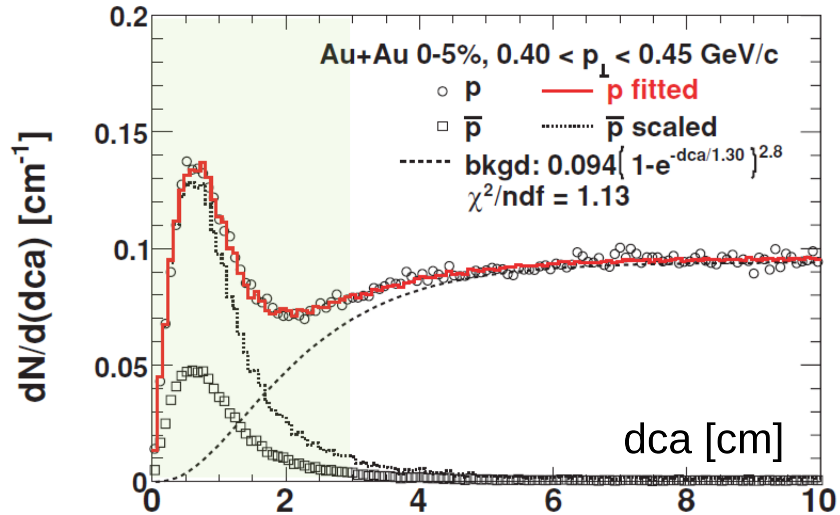


Secondary (knockout) protons

20% of observed protons @ STAR



STAR, PRC79,034909(2009)

Their contribution can be eliminated!

$$\langle(\delta N_p^{(\mathrm{QGP})})^n\rangle_c = \langle(\delta N_p^{(\mathrm{exp})})^n\rangle_c - \langle N_p^{(\mathrm{2nd})}\rangle$$