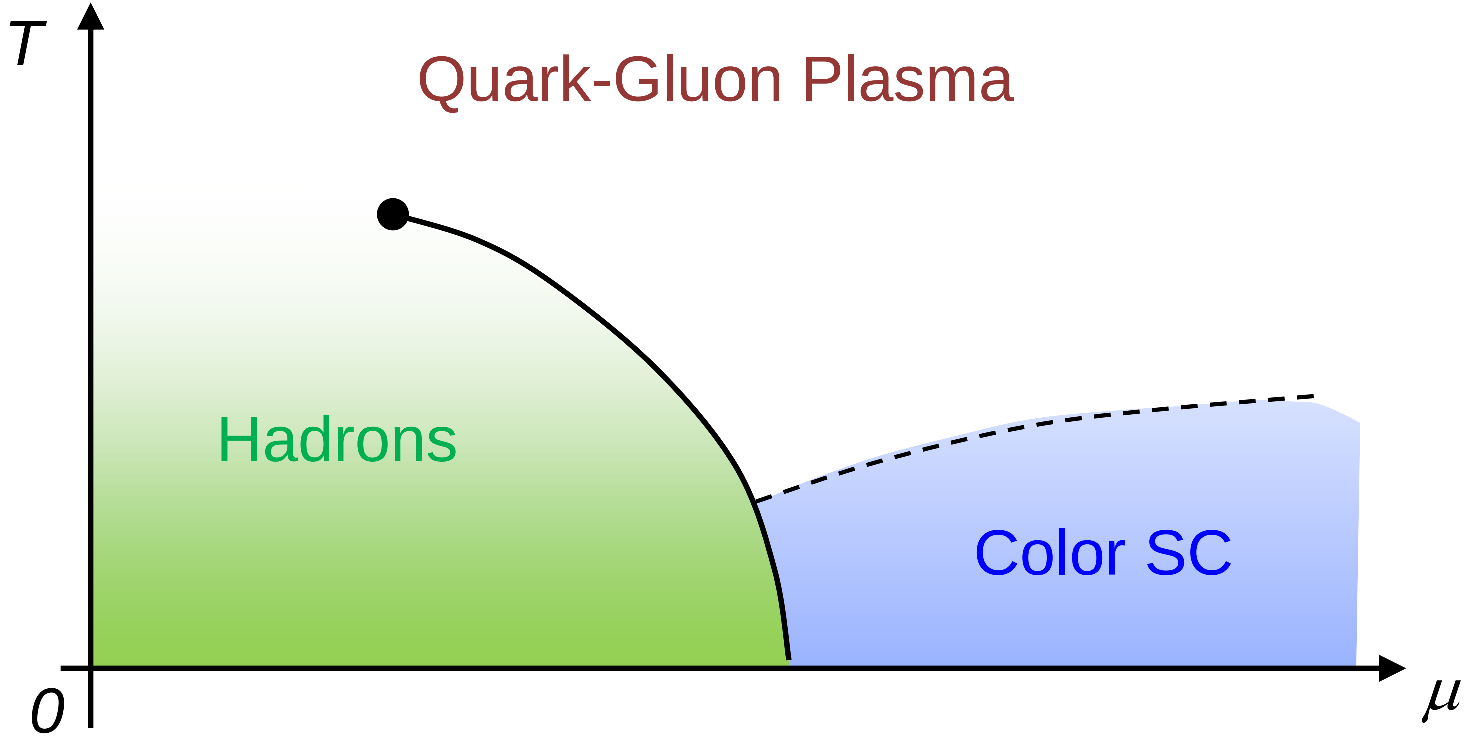
重イオン衝突実験における熱ゆらぎ
～非平衡性と非ガウス性を中心に～

Masakiyo Kitazawa

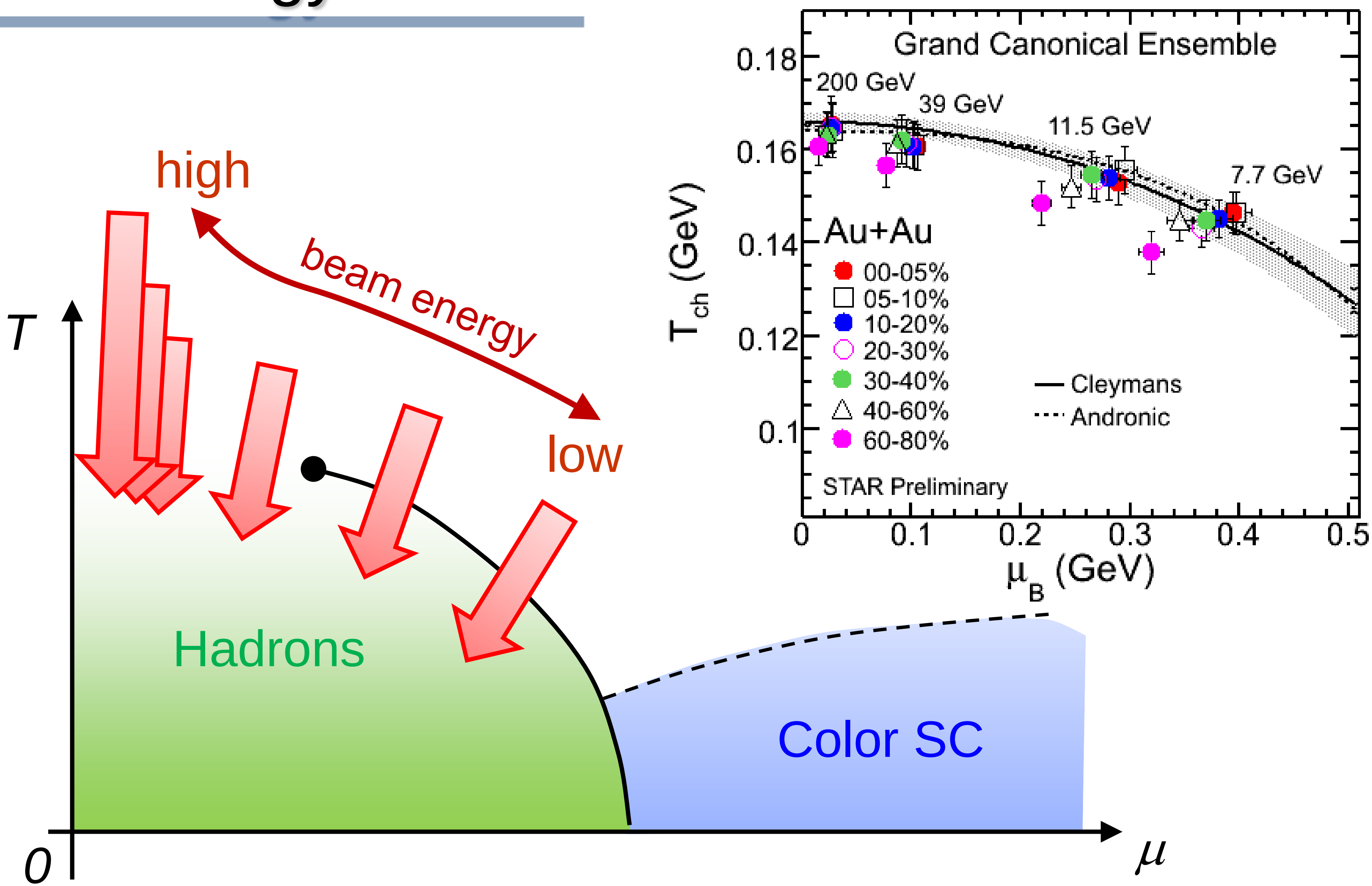
(Osaka U.)

Beam-Energy Scan



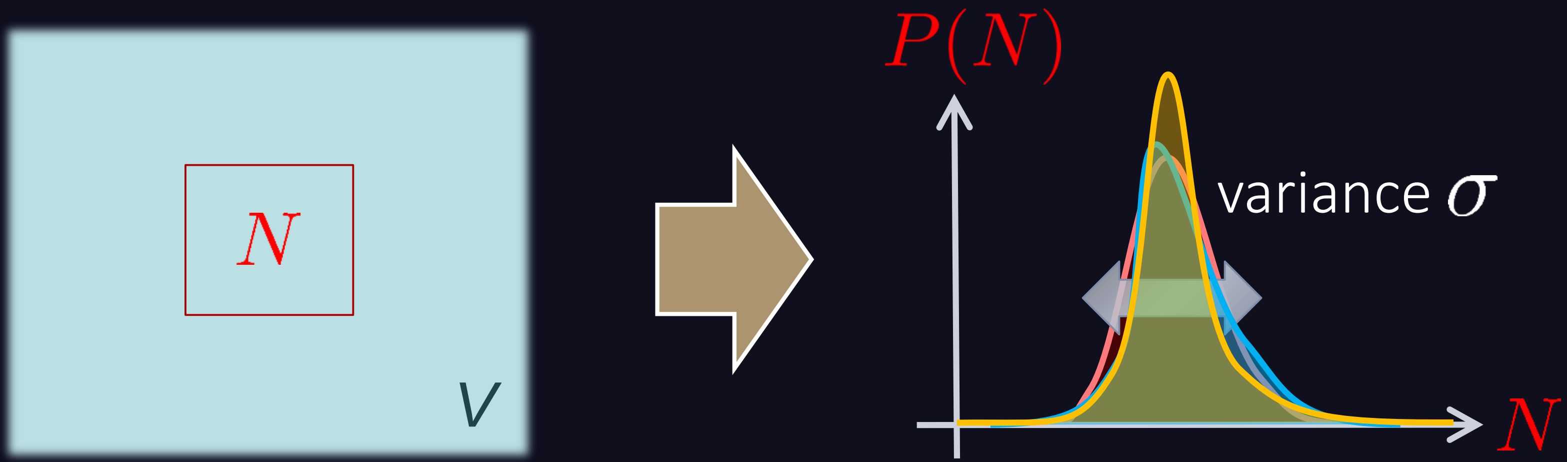
Beam-Energy Scan

STAR 2012



Bulk (Thermal) Fluctuations

Observables in equilibrium are fluctuating!



$$\langle \delta N^2 \rangle = V\chi_2 = \sigma^2$$

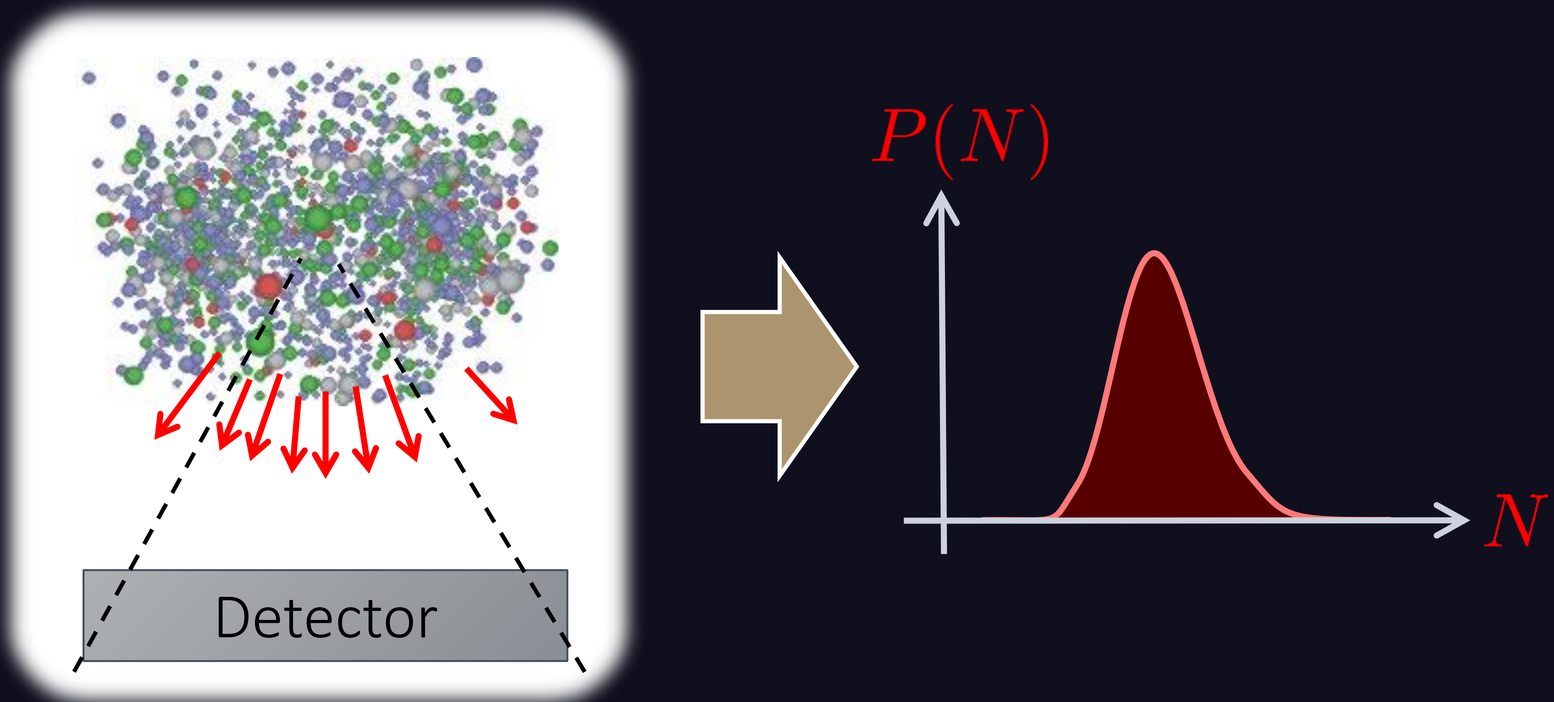
Gaussian

$$S = \frac{\langle \delta N^3 \rangle}{\sigma^3}$$

non-Gaussianity

$$\kappa = \frac{\langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2}{\chi_2 \sigma^2}$$

Event-by-Event Analysis



Pioneering studies on σ :

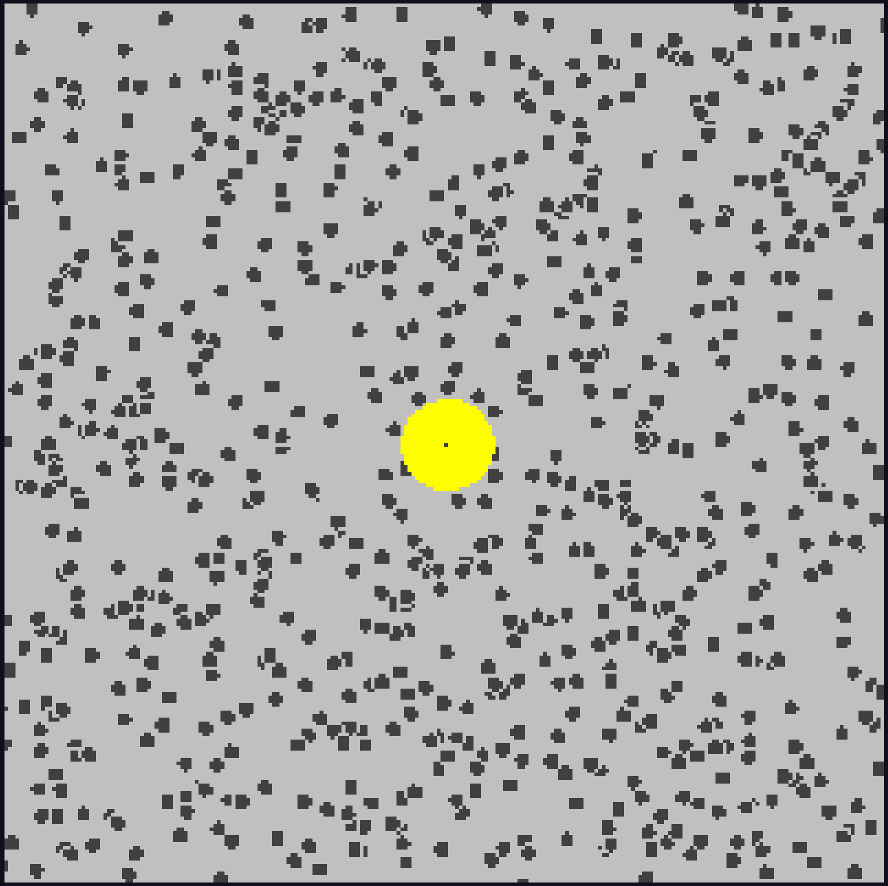
- Search of QCD critical point Stephanov,Rajagopal,Shuryak,PRL(1998)
- Quark deconfinement Asakawa,Heinz,Muller PRL; Jeon,Koch PRL(2000)

My Messages

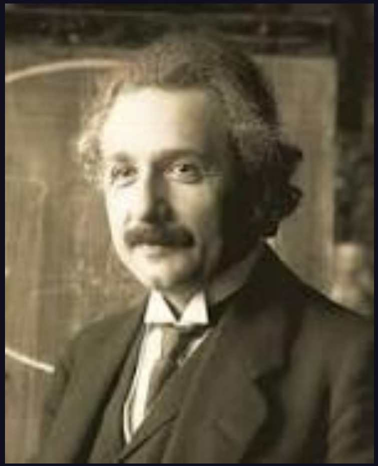
- Fluctuations are invaluable observables in HIC
- But, we must understand them in more detail
- It's possible, interesting, and important

Why Fluctuations?

Brownian Motion



from Wikipedia

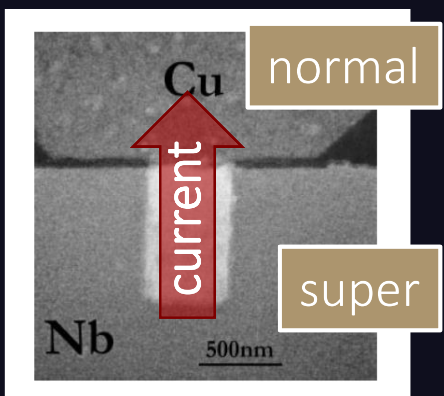


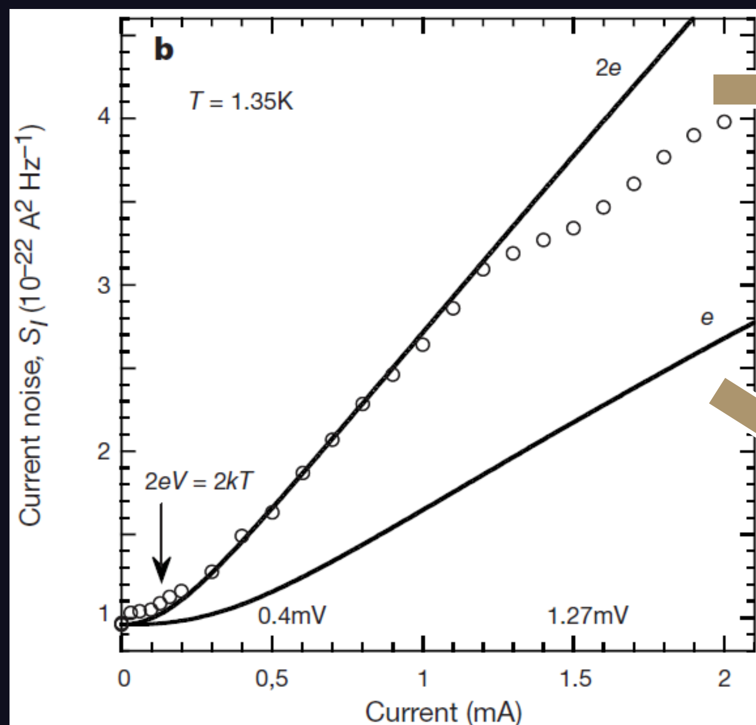
A. Einstein
1905

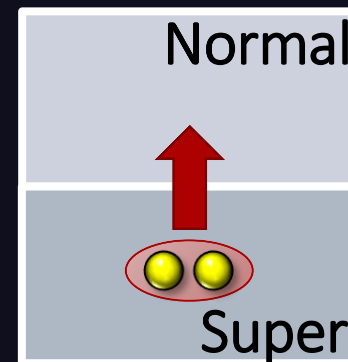
Fluctuations opened atomic physics

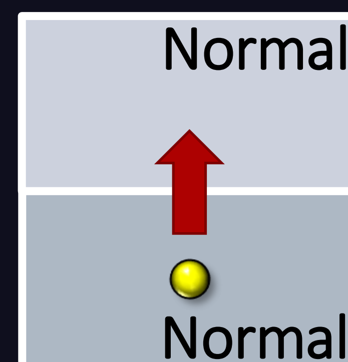
Shot Noise at Normal-Superconductor Junction

X. Jehl+, Nature**405**,50 (2000)







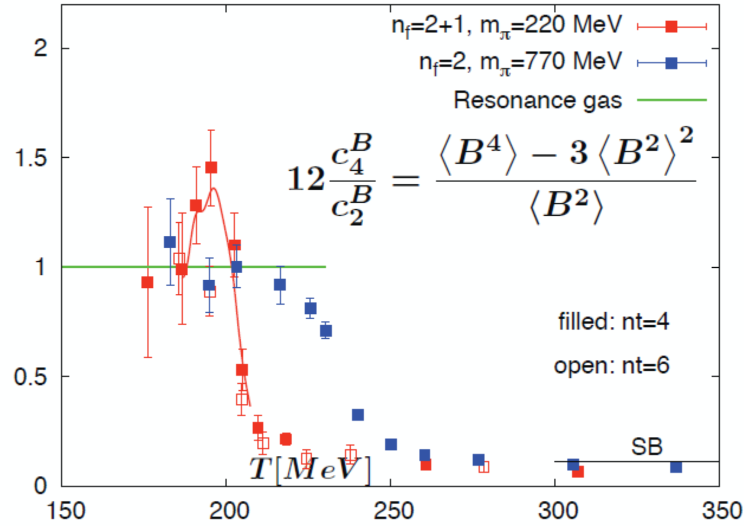


Similar experiments for fractional QHE ex. Saminadayar+, PRL**79**,2526(1997)

Conserved Charges : Theoretical Advantage

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

ex: on the lattice



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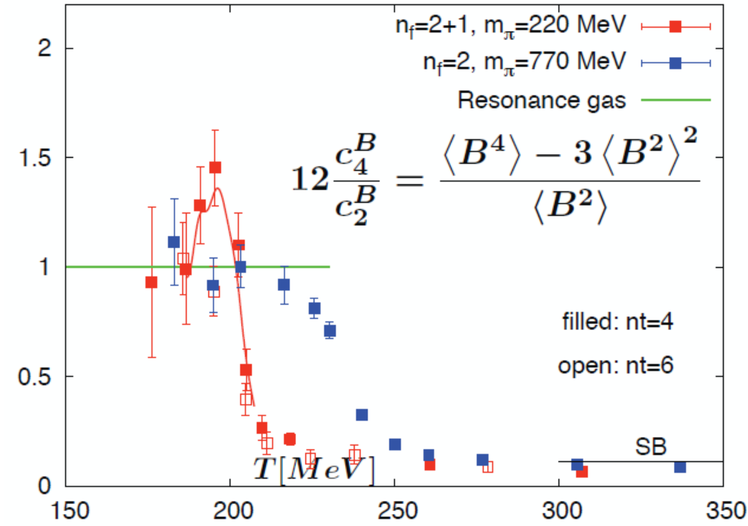
  ex: on the lattice



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

Asakawa, Ejiri, MK, 2009

Conserved-Charge Fluctuations

Fluctuations of CC : rigorously defined in a theory

- operators as the Noether current
- as derivatives of the partition function

They are lattice observables

Fluctuations of CC

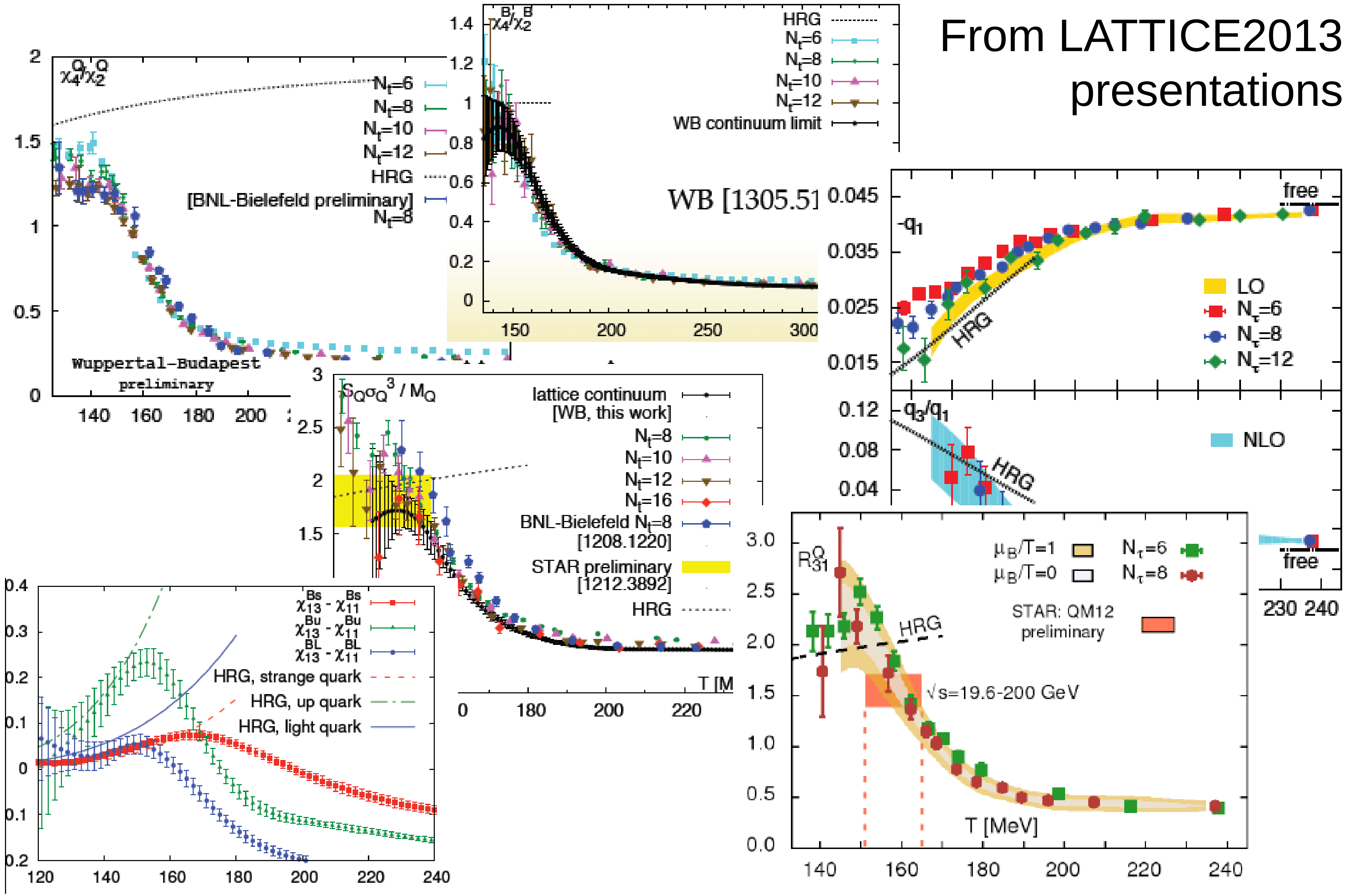
II

LAT-HIC crossover

QCD phase diagram 3, Wed. 11:00-13:30

Recent Progress in Lattice Community

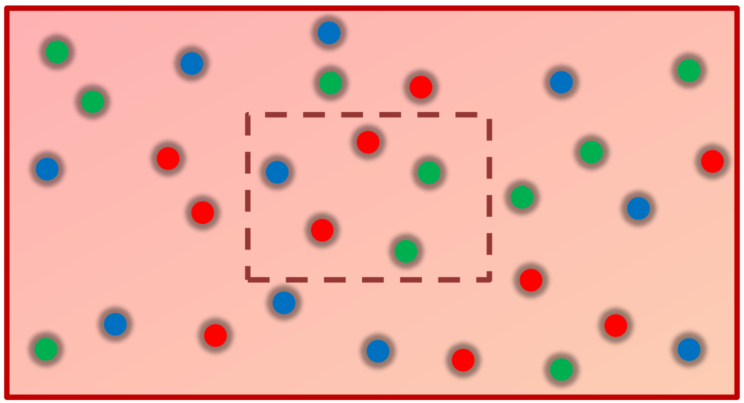
From LATTICE2013 presentations



Fluctuations

Free Boltzmann → Poisson

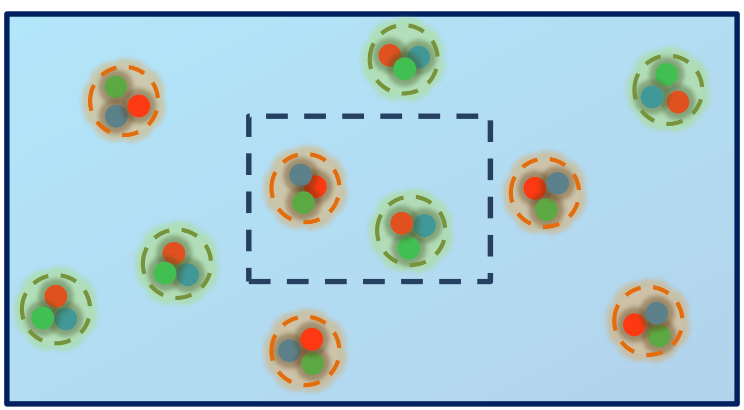
$$\langle \delta N^n \rangle_c = \langle N \rangle$$



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

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

$$3N_B = N_q$$



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Fluctuations

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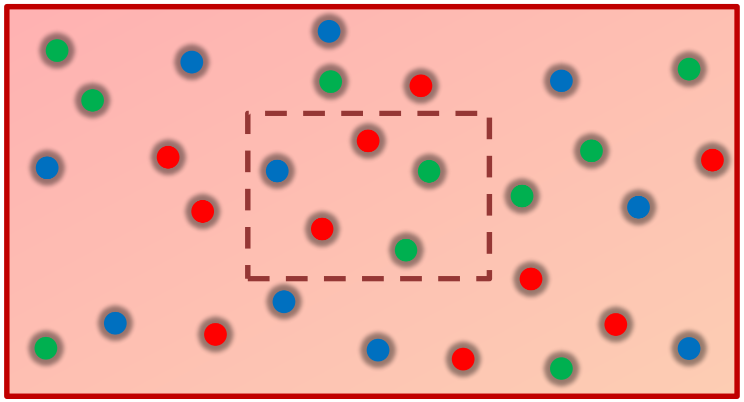
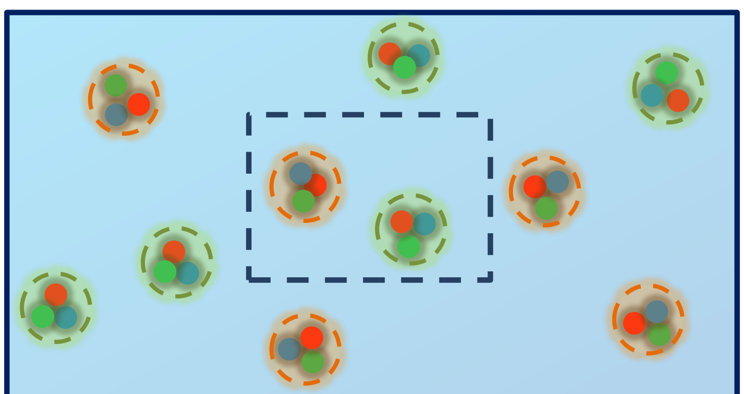
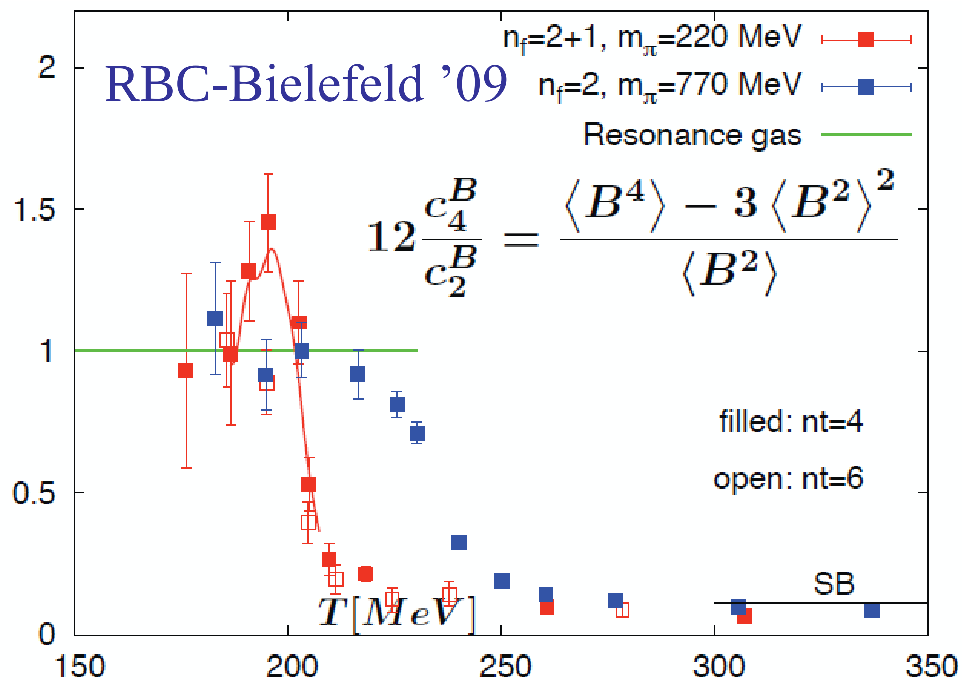


$$\langle \delta N_q^n \rangle_c = \langle N_q \rangle$$

$$3N_B = N_q$$

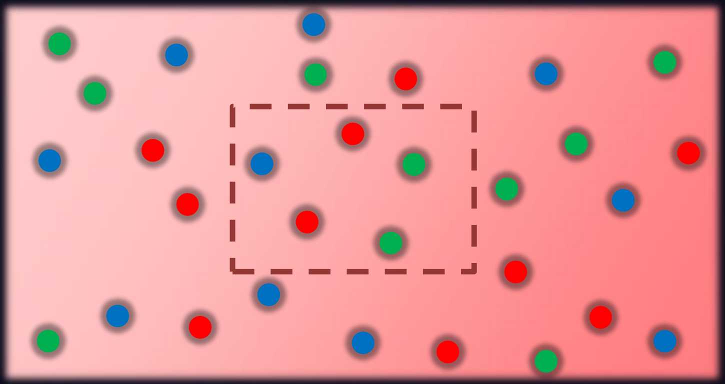


$$\Rightarrow \langle \delta N_B^n \rangle_c = \frac{1}{3^{n-1}} \langle N_B \rangle$$

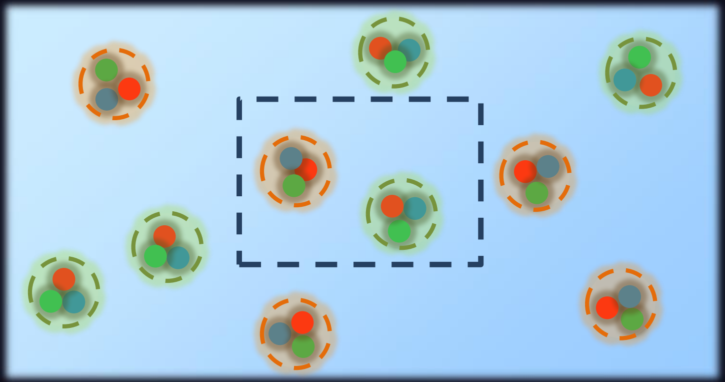


Electric Charge Fluctuation

Asakawa,Heinz,Muller; Jeon,Koch,2000



$$|q_q| = 1/3, 2/3$$



$$|q_B| = 1$$

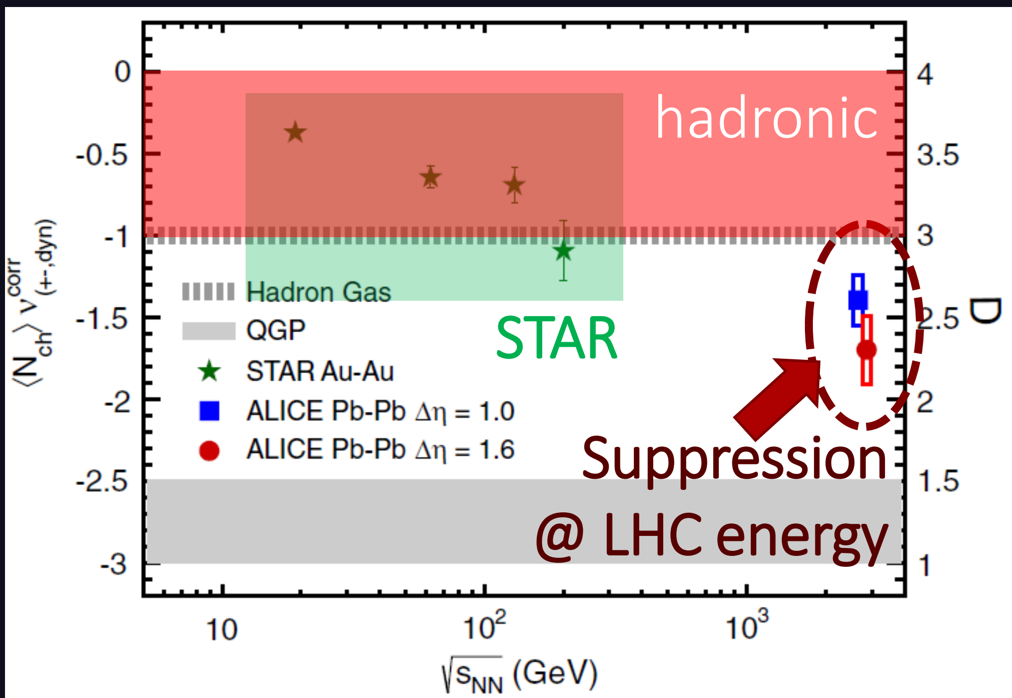
D-measure

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

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

Electric Charge Fluctuation

PHENIX (2002); STAR (2003)
ALICE, PRL **110**, 152301 (2013)



D measure

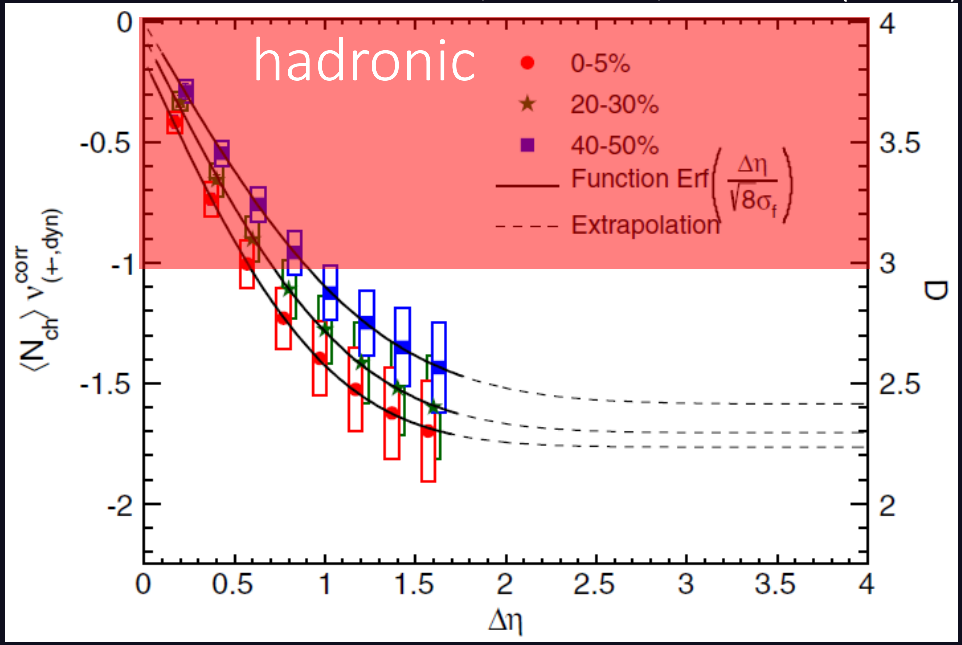
$$D = 4\frac{\langle \delta N_Q^2 \rangle}{\langle N_Q^+ + N_Q^- \rangle}$$

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

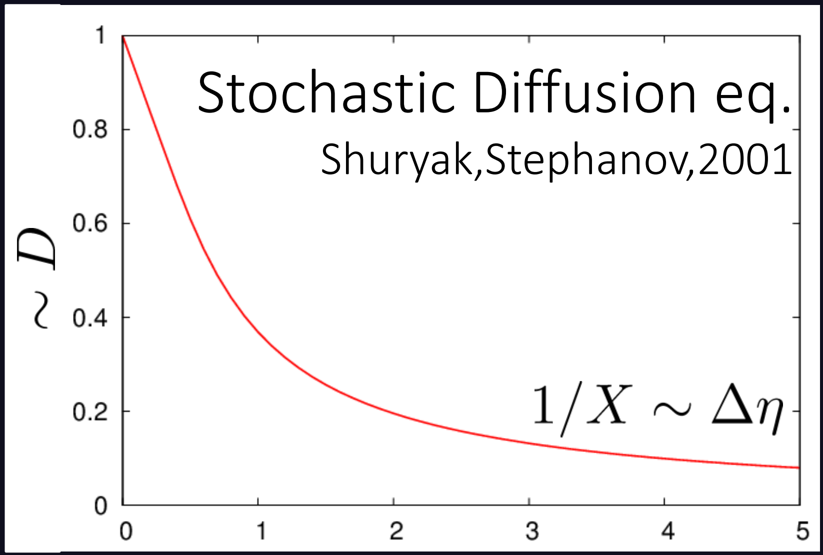
- No suppression at RHIC energy
- Fluctuations @ LHC **cannot** be described by hadronic d.o.f.

Rapidity Window Dependence

ALICE, PRL **110**, 152301 (2013)



- Smaller $\Delta\eta$
  more hadronic
- Larger $\Delta\eta$
  more QGP like

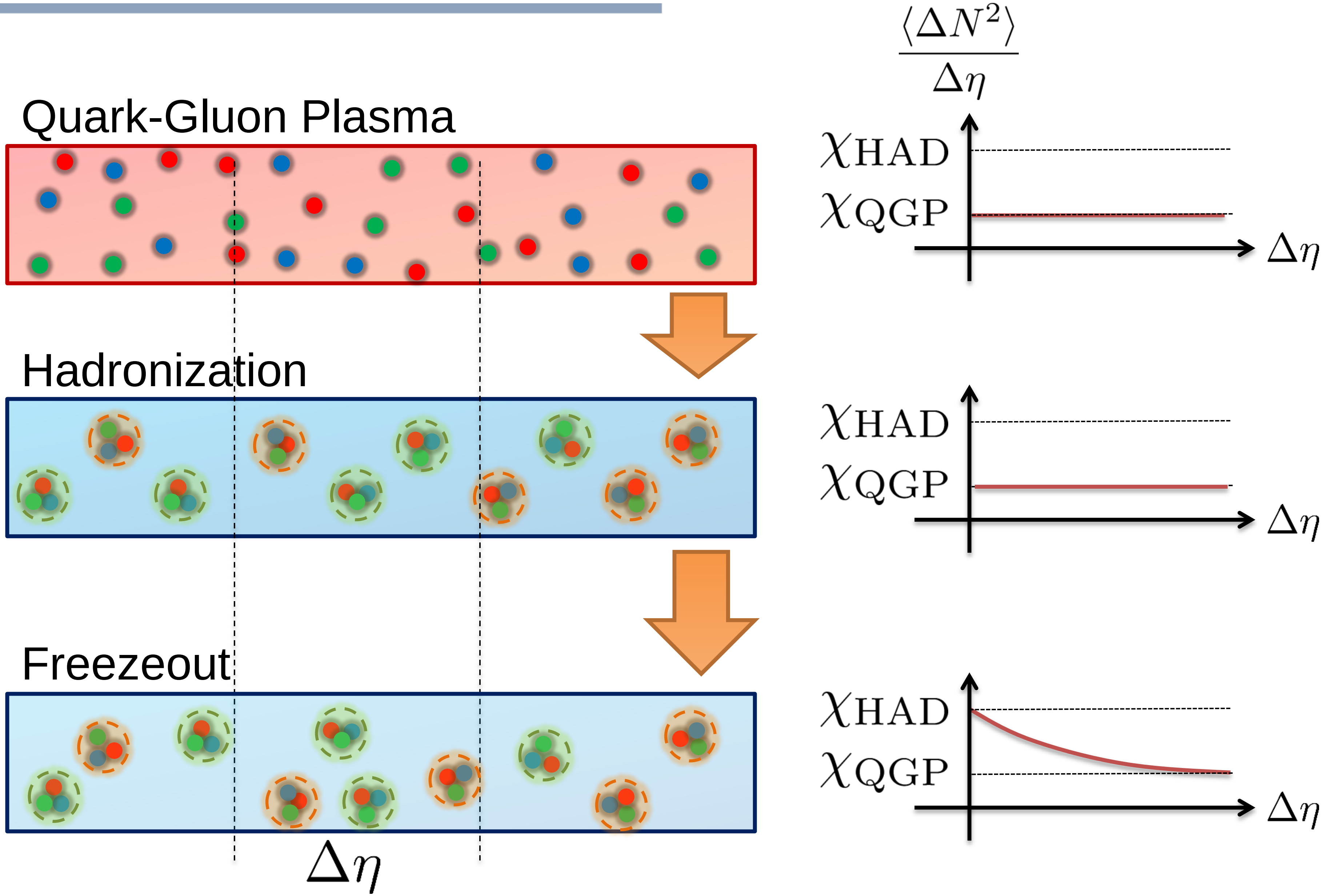


Same information in

- $\langle \delta N_Q^{(\mathrm{net})}(\eta_1)\delta N_Q^{(\mathrm{net})}(\eta_2)\rangle$
- $\simeq$ balance function

to be studied by fluctuating hydro.

Time Evolution in HIC



Various Contributions

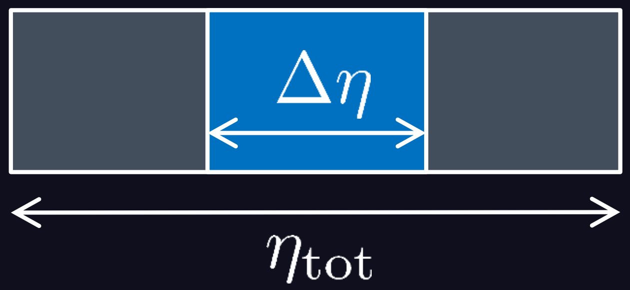
- Initial fluctuations ⬆ Enhance
- Effect of jets ⬆ Enhance
- Negative binomial (?) ⬆ Enhance
- Final state rescattering ↗ **Enhance** to Poisson
- Coordinate vs pseudo rapidities ↗ **Enhance** to Poisson
- Particle missID ↗ **Enhance** to Poisson
- Efficiency correction ↗ **Enhance** to Poisson
- Global charge conservation ⬇ **Suppress**

Global Charge Conservation

Jeon,Koch,2000
Bleicher,Jeon,Koch,2001

For equilibrated medium

$$\langle \delta N^2 \rangle_{\mathrm{exp.}} = \langle \delta N^2 \rangle_{\mathrm{GC}} \times \left(1 - \frac{\Delta y}{y_{\mathrm{tot}}}\right)$$



Global Charge Conservation

Jeon,Koch,2000
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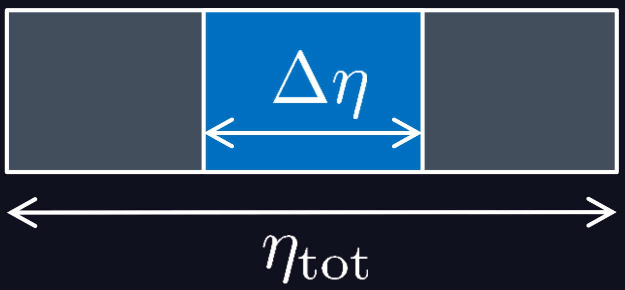
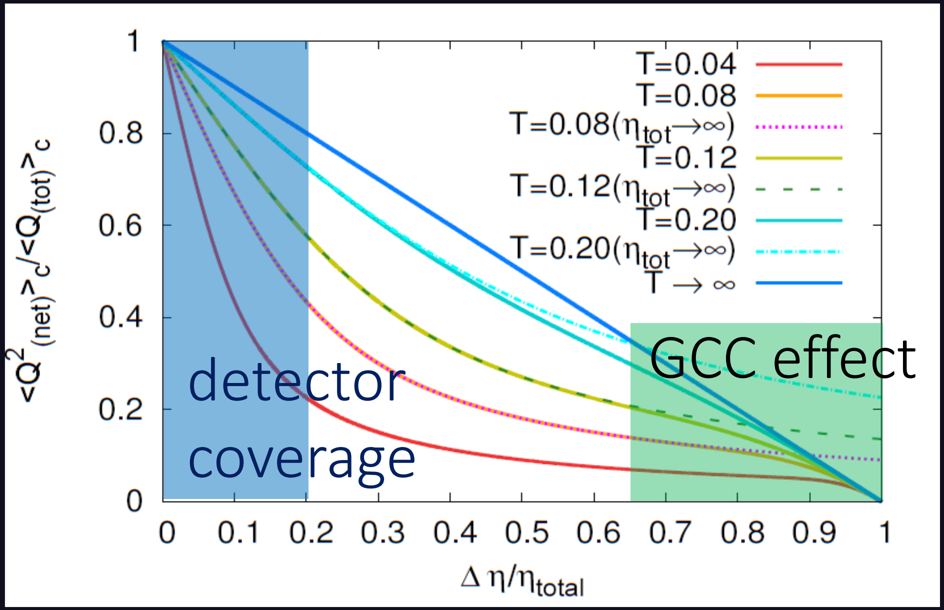


Solving the time evolution…



GCC effect on the hadronic diffusion **is negligible** in the ALICE result!

Sakaida, Poster I-35

Electric-Charge Fluctuations

- Electric charge fluctuations is suppressed at LHC!
- The suppression is most probably attributed to primordial physics
- Qualitative difference b/w RHIC and LHC

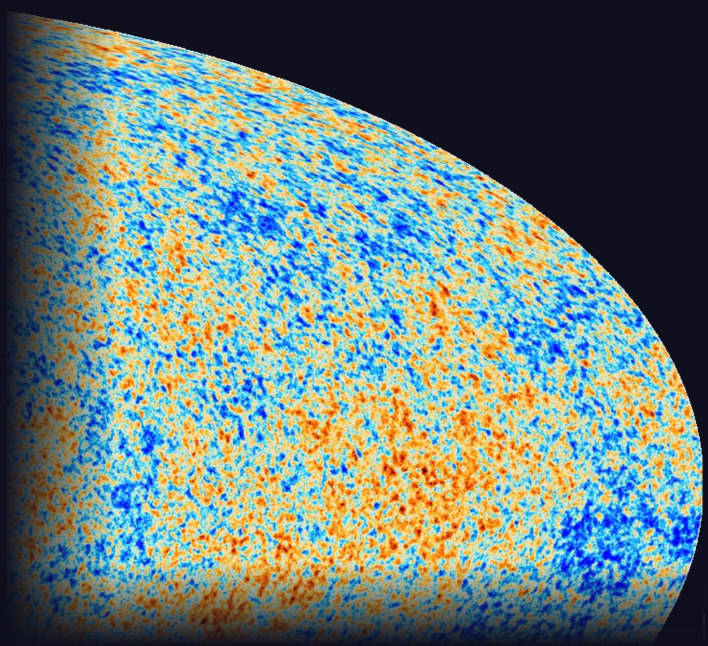
… but why?

Non Gaussianity

Non-Gaussianity

CMB

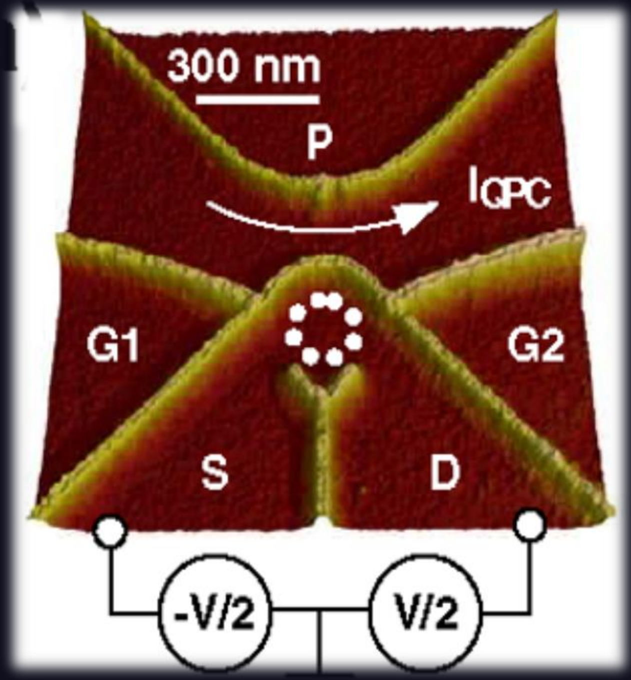
Cosmic Microwave Background



- No statistically-significant signals

Planck, 2013

Mesoscopic Systems



- Full counting statistics
- Cumulants up to 5th order

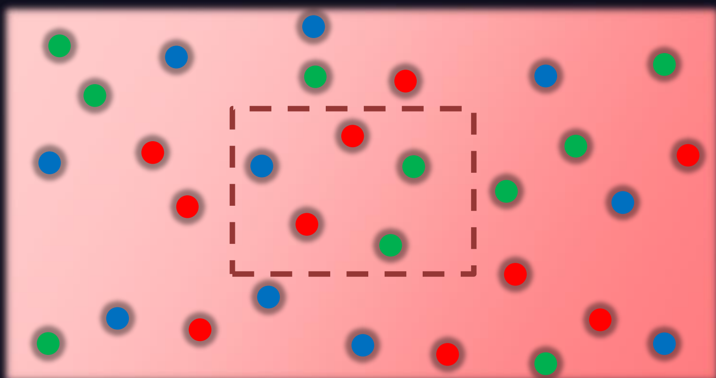
Gustavsson+, Surf.Sci.Rep.**64**,191(2009)

Non-Gaussianity in HIC

- Ratio of conserved charges
  Ejiri,Karsch,Redlich(2005)
- Critical enhancement
  Stephanov(2009)
- Sign change
  Asakawa,Ejiri,MK (2009); Friman+(2011); Stephanov(2011)
- Strange confinement
  BNL-Bielefeld(2013)
- Distribution funcs themselves
  Morita+(2013); Nakamura (Wed.)

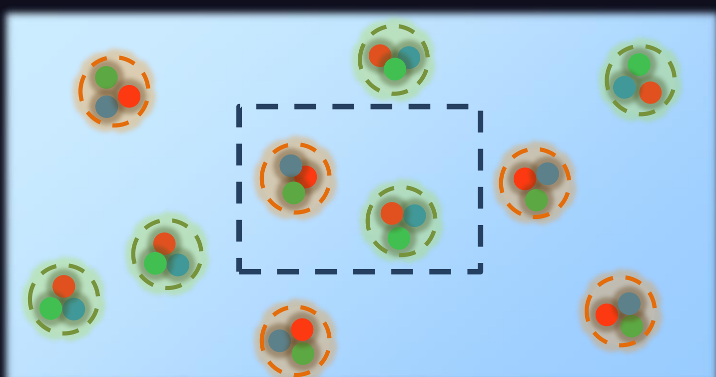
Ratio of Cumulants

Ejiri, Karsch, Redlich, 2005

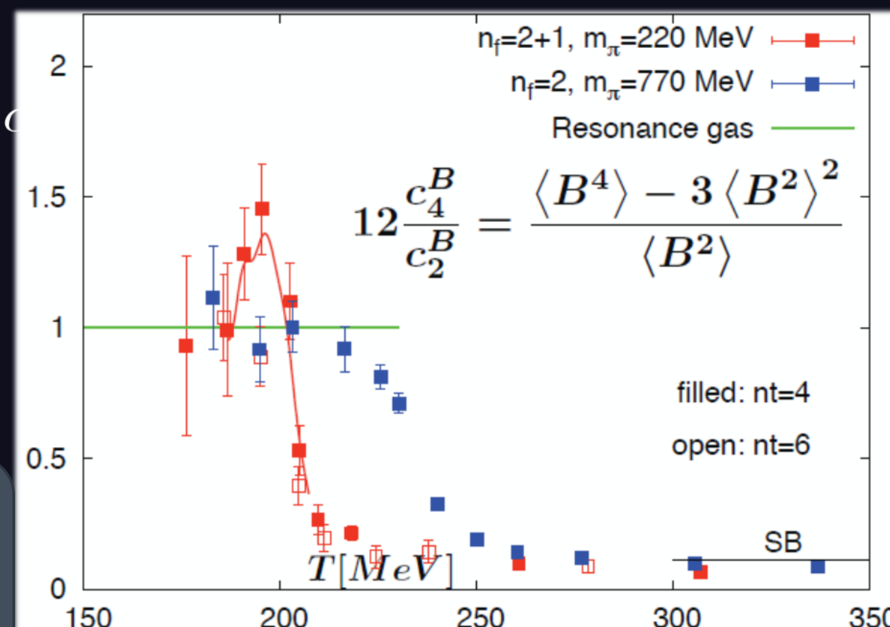


$$\langle \delta N_q^n \rangle_c = \langle N_q \rangle$$

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



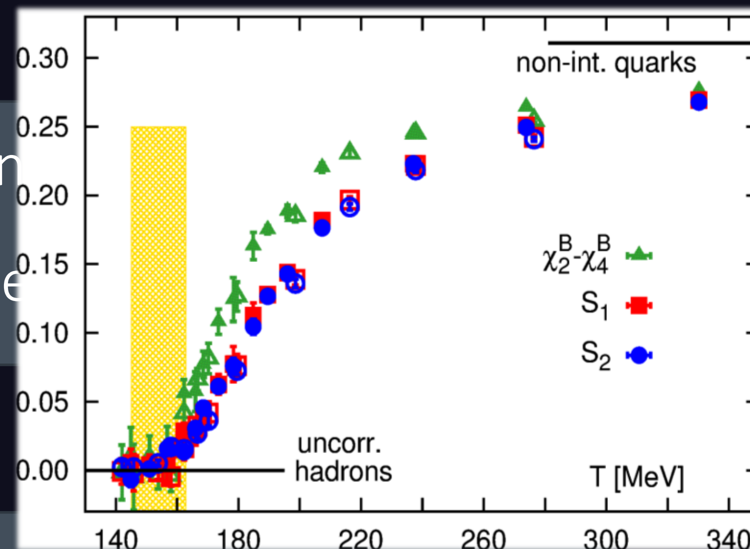
$\langle \delta N_B^n \rangle_c$



$$\frac{\langle \delta N_B^4 \rangle_c}{\langle \delta N_B^2 \rangle} = \begin{cases} 1 & \text{hadronic} \\ 1/9 & \text{quark-gluon} \end{cases}$$

Strange Confinement

BNL-Bielefeld,PRL(2013)
H.T. Ding, This Morning



Baryonic $\langle \delta N_B^2 \rangle = \langle \delta N_B^4 \rangle$

$$\langle \delta N_B^2 \rangle - \langle \delta N_B^4 \rangle_c \begin{cases} = 0 & \text{baryons con} \\ \neq 0 & \text{something e} \end{cases}$$

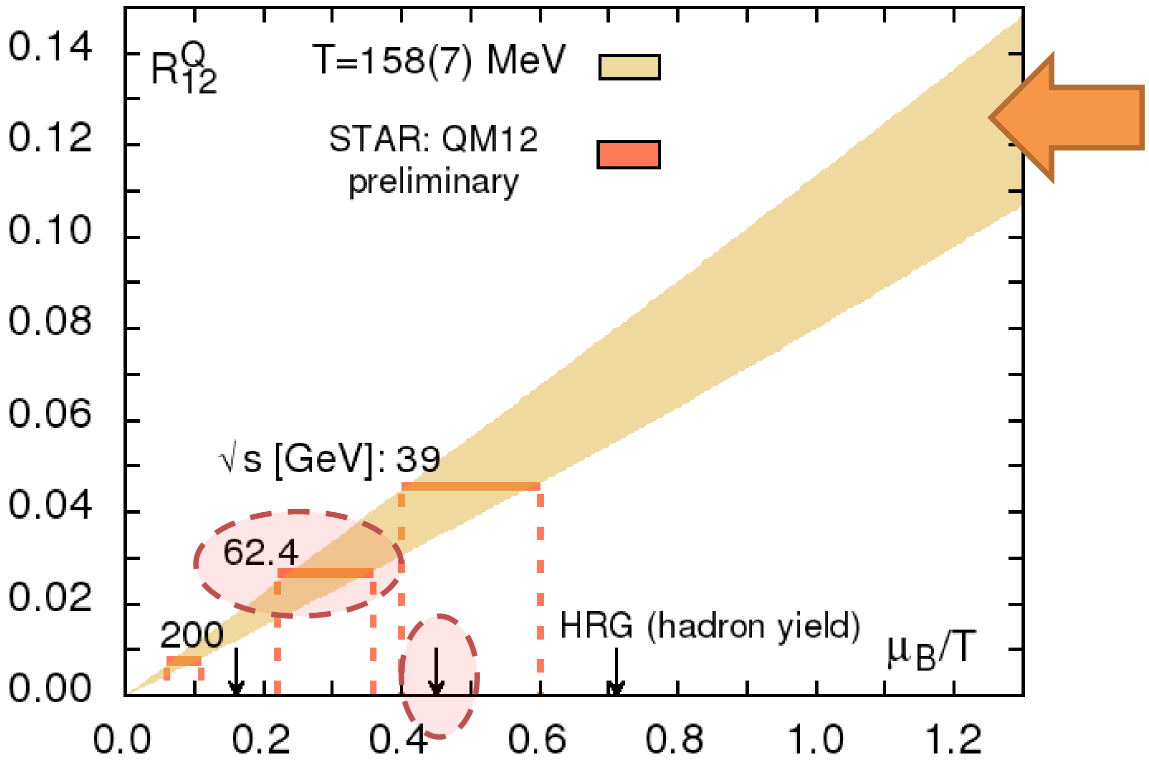
Strangeness

$$\langle \delta N_s \delta N_B^3 \rangle_c - \langle \delta N_s \delta N_B \rangle \begin{cases} = 0 & \text{strangeness confined} \\ \neq 0 & \text{something else} \end{cases}$$

Many lattice studies (LAT-HIC crossover):

Budapest-Wuppertal, 2013; BW,1403.4578; BNL-Bi.,1404.4043; Gupta+,1405.2206; Ratti, Wed.; Schmidt, Wed.; Nakamura, Wed.; Sharma, J-13

Cumulants : HIC@RHIC vs Lattice



parameter window constrained by lattice

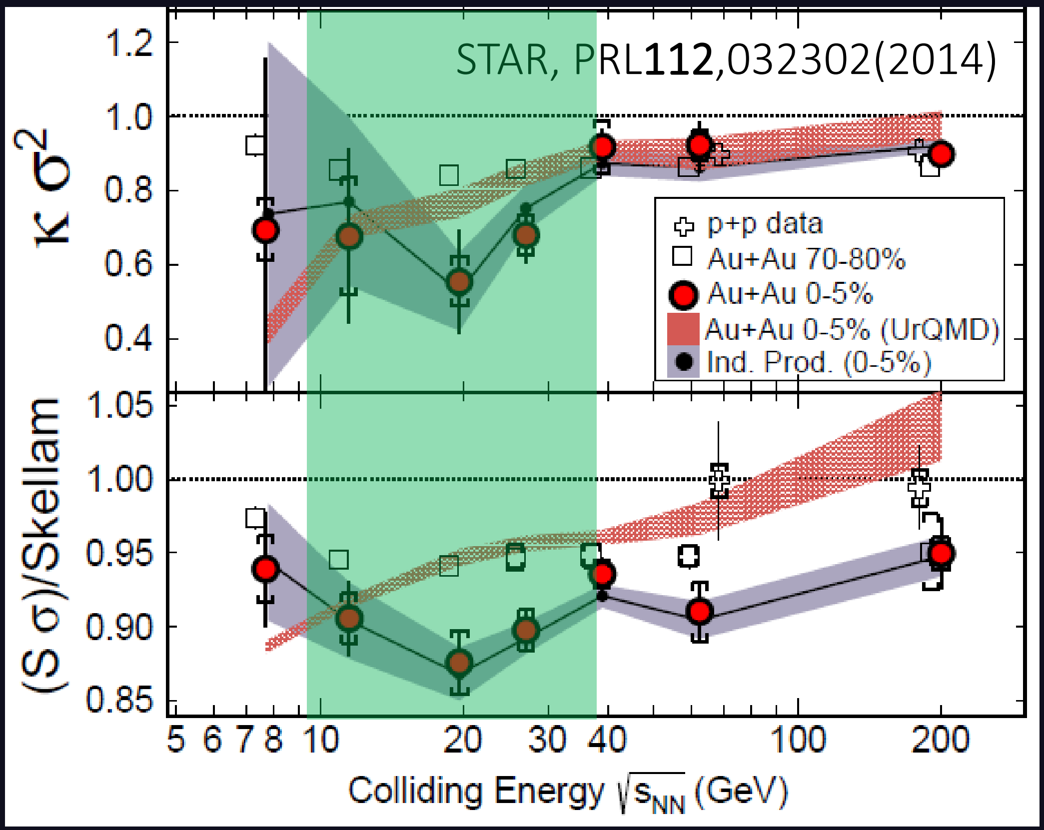
BNL-Bielefeld, LATTICE2013

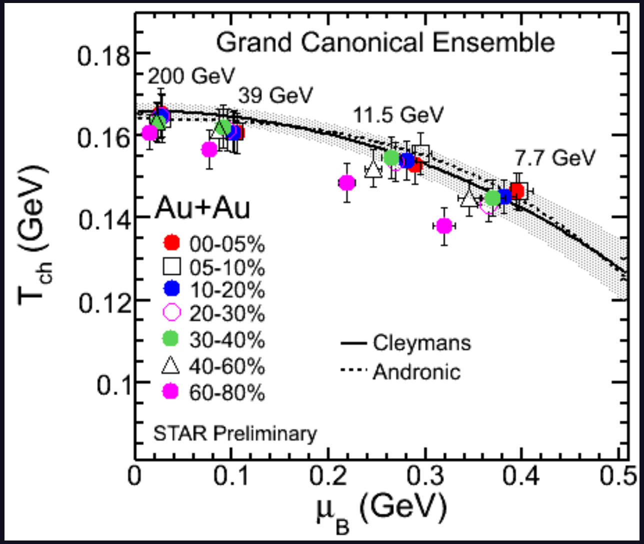
fluctuations "exp + lattice" ⟷ μ/T ⟷ particle abundance (chem. freezeout T)

discrepancy

Proton Number Cumulants at RHIC-BES

STAR 2012





- Exp. results are close to and less than Poissonian values.
- Something interesting around $\sqrt{s_{NN}} \simeq 20\mathrm{GeV}$

Effects of Various Contributions

- ☐ Initial fluctuations ⬆ Enhance
- ☐ Effect of jets ⬆ Enhance
- ☐ Negative binomial (?) ⬆ Enhance
- ☐ Final state rescattering ↗ **Enhance** to Poisson
- ☐ Coordinate vs pseudo rapidities ↗ **Enhance** to Poisson
- ☐ Particle missID ↗ **Enhance** to Poisson
- ☐ Efficiency correction ↗ **Enhance** to Poisson
- ☐ Global charge conservation ⬇ **Suppress**

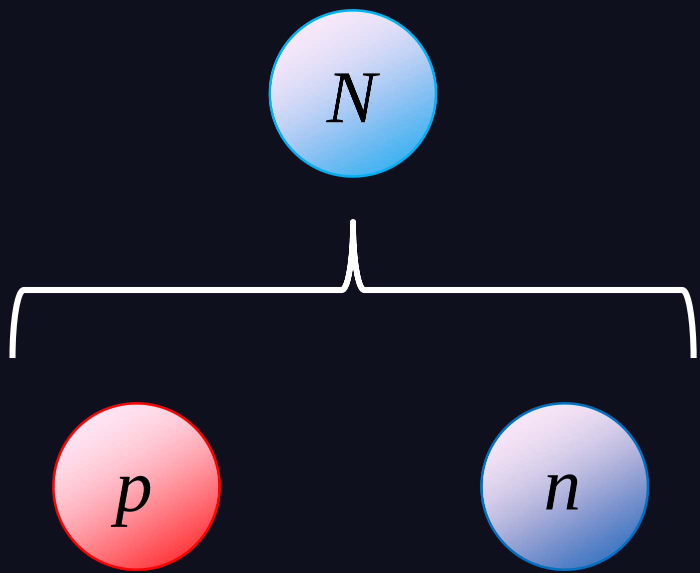
Caution!!

proton number cumulants $\neq$ baryon number cumulants

Let's clarify their relation!

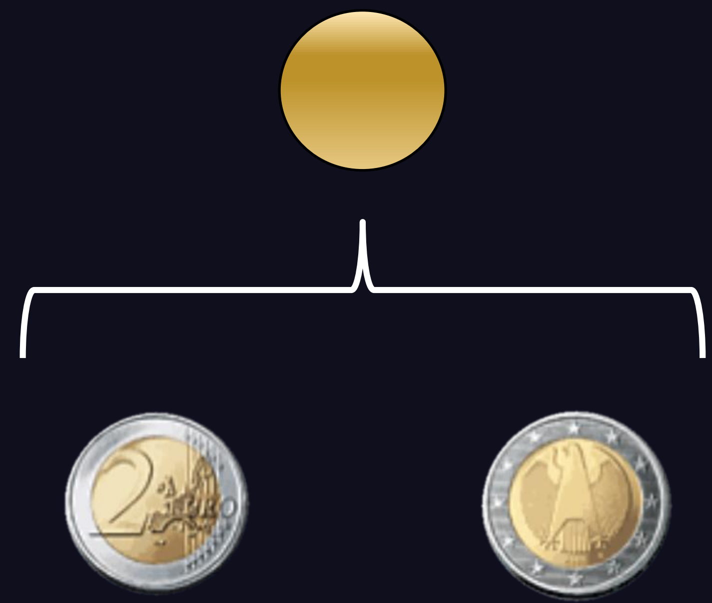
MK, Asakawa (2012;2012)

Nucleon isospin and a coin



Nucleon has
two isospin states.

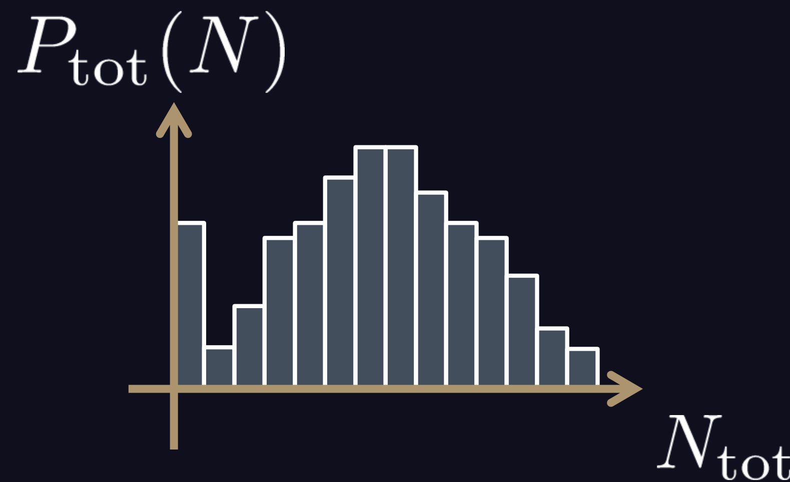
a coin

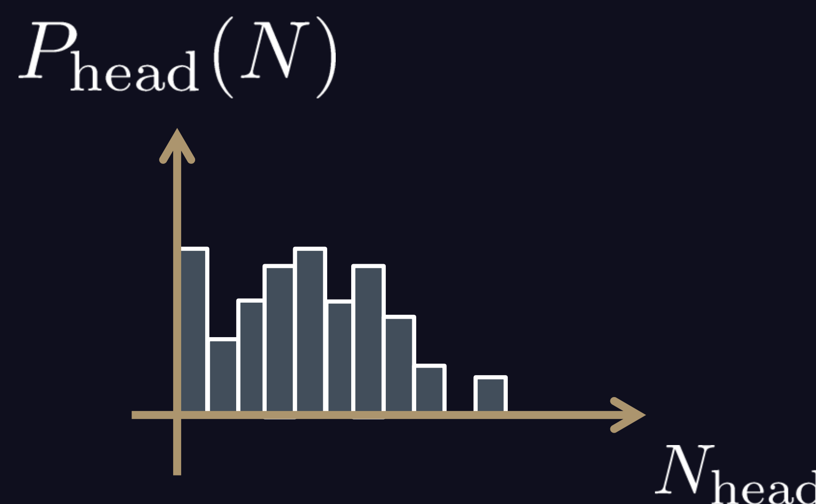


A coin has two sides.

MK, Asakawa,2012

Slot Machine Analogy



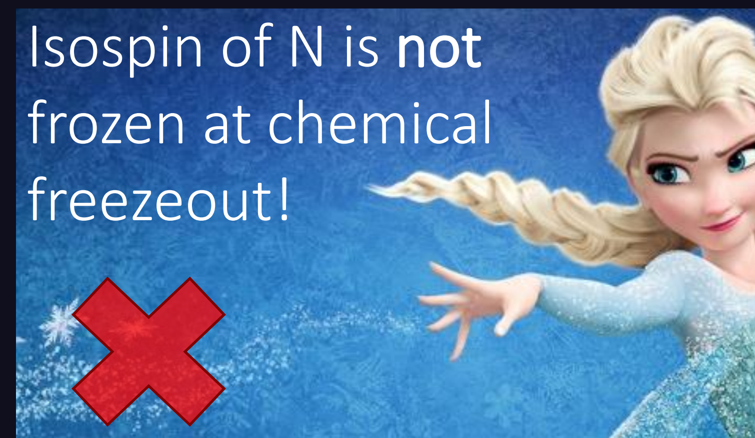


Reconstructing Total Coin Number

$$P_{\mathrm{head}}(N_{\mathrm{head}}) = \sum_{N_{\mathrm{tot}}} B_{1/2}(N_{\mathrm{head}}; N_{\mathrm{tot}}) P_{\mathrm{tot}}(N_{\mathrm{tot}})$$

Charge Exchange Reaction

$$p, n + \pi \rightarrow \Delta(1232) \rightarrow p, n + \pi$$



cross sections of p

$$p + \pi^+ \xrightarrow{3} \Delta^{++} \longrightarrow p + \pi^+$$

$$p + \pi^0 \xrightarrow{1},\; n + \pi^+ \longrightarrow \Delta^+ \xrightarrow{2:1} p + \pi^0,\; n + \pi^+$$

$$p + \pi^- \xrightarrow{2},\; n + \pi^0 \longrightarrow \Delta^0 \xrightarrow{1:2} p + \pi^-,\; n + \pi^0$$

$$n + \pi^- \longrightarrow \Delta^- \longrightarrow n + \pi^-$$

decay rates of Δ

$$p + \pi \rightarrow \Delta^{+,0}$$

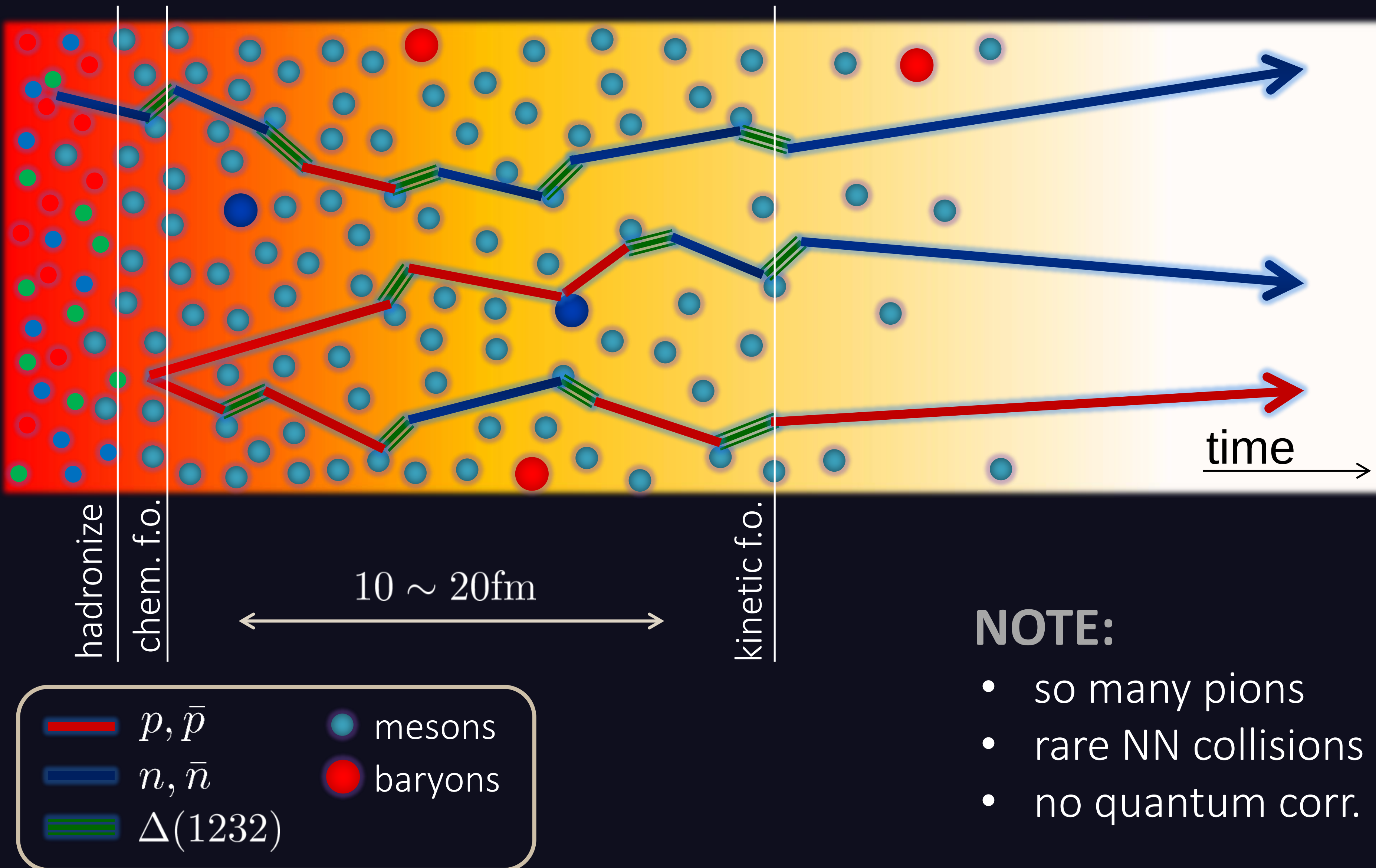
$$\rightarrow p : n$$

$$= 5 : 4$$

mean reaction time

< 5fm/c

Nucleons in Hadronic Medium



NOTE:

- so many pions
- rare NN collisions
- no quantum corr.

Difference b/w N_B and N_p

Assumptions: net-cumulants deviate from thermal value
But, $N_\mathrm{B}, N_{\bar{\mathrm{B}}}$ are Poissoian

$$\begin{cases} 2\langle(\delta N_p^{(\mathrm{net})})^2\rangle = \frac{1}{2}\langle(\delta N_\mathrm{B}^{(\mathrm{net})})^2\rangle + \frac{1}{2}\langle(\delta N_\mathrm{B}^{(\mathrm{net})})^2\rangle_\mathrm{free} \\ 2\langle(\delta N_p^{(\mathrm{net})})^3\rangle = \frac{1}{4}\langle(\delta N_\mathrm{B}^{(\mathrm{net})})^3\rangle + \frac{3}{4}\langle(\delta N_\mathrm{B}^{(\mathrm{net})})^3\rangle_\mathrm{free} \\ 2\langle(\delta N_p^{(\mathrm{net})})^4\rangle_c = \frac{1}{8}\langle(\delta N_\mathrm{B}^{(\mathrm{net})})^4\rangle_c + \cdots \end{cases}$$

genuine info. noise

Proton number cumulants are dominated by Poissonian noise

cf.) Nahrgang+, arXiv:1402.1238

Efficiency Correction

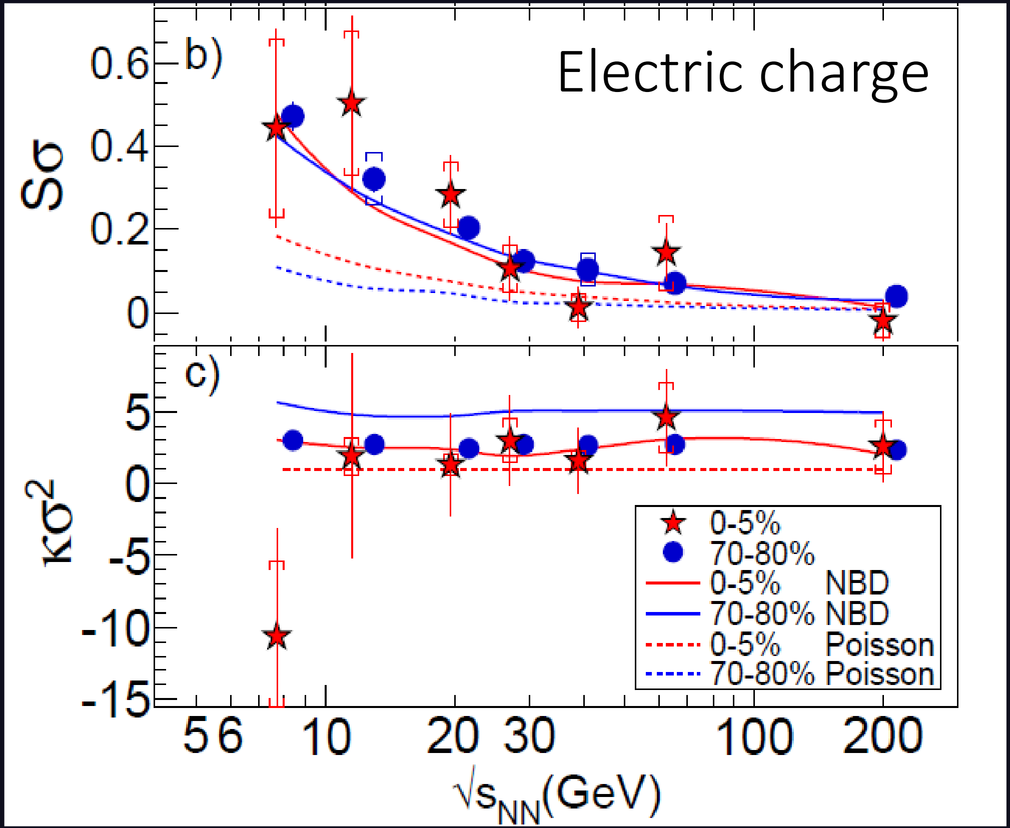
MK, Asakawa, 2012
Bdzak, Koch, 2012
STAR, 2013

If efficiency for each particle is uncorrelated

↓

binomial correction to distribution function

$$P_{\mathrm{exp.}}(N) = \sum_{N'} B_\epsilon(N;N')P(N')$$



STAR, arXiv:1402.1558

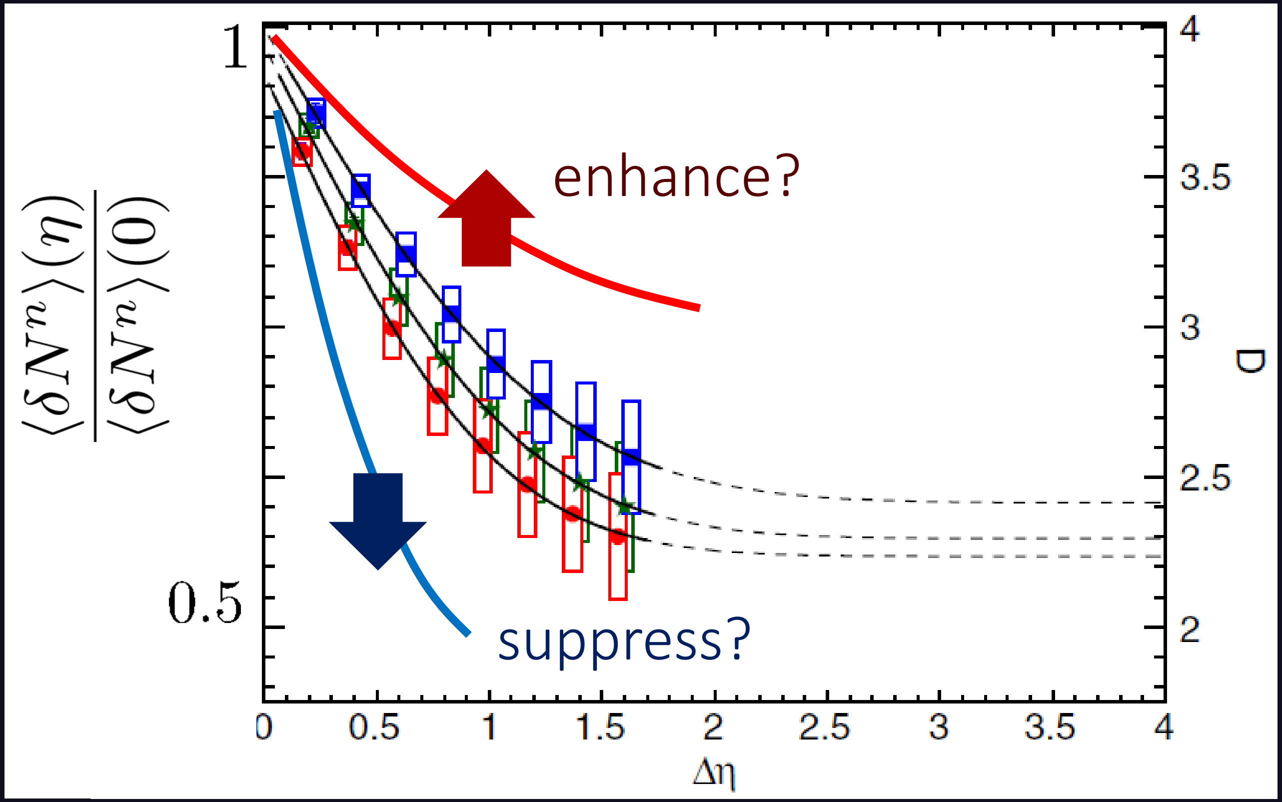
for Particle missID: Ono,Asakawa,MK, PRC,2013

More Information on/from Fluctuations

$\Delta\eta$ dependence

MK, Asakawa, Ono,PLB**728**, 386 (2014)

$\Delta\eta$ Dep. of Non-Gaussianity



How does the 4-th order cumulant behave as a function of Δη?

Fluctuating Hydrodynamics?

- Distributions in experiments are close to Poissonian
- Cumulants are expected to increase in the hadronic medium

These behaviors cannot be described by the theory of hydrodynamic fluctuations

Hydrodynamic Fluctuations

Landau, Lifshitz, Statistical Mechaniqs II
Kapusta, Muller, Stephanov, 2012
Stephanov, Shuryak, 2001

Stochastic diffusion equation

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

Markov (white noise)
+
continuity

Gaussian noise

Fluctuation of *n* is
Gaussian in equilibrium

cf) Gardiner, “Stochastic Methods”

How to Introduce Non-Gaussianity?

Stochastic diffusion equation

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

- Choices to introduce non-Gaussianity in equil.:
  - *n* dependence of diffusion constant *D*(*n*)
  - colored noise
  - discretization of *n*

How to Introduce Non-Gaussianity?

Stochastic diffusion equation

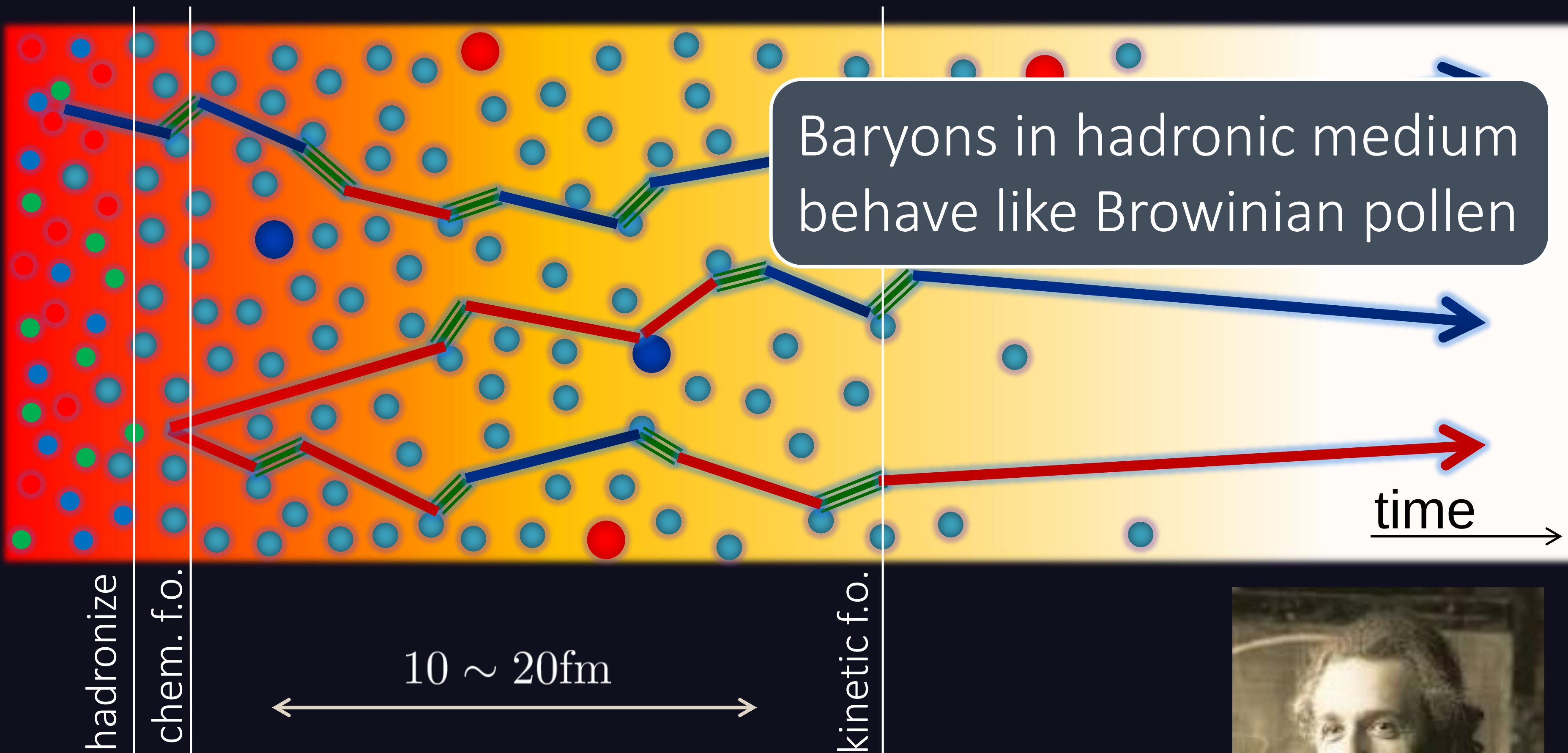
$$\partial_\tau n = D\partial_\eta^2 n + \partial_\eta \xi(\eta, \tau)$$

- Choices to introduce non-Gaussianity in equil.:
  - *n* dependence of diffusion constant *D*(*n*)
  - colored noise
  - discretization of *n* ← **our choice**

REMARK: Fluctuations measured in HIC are almost Poissonian.

Nucleons in Hadronic Medium

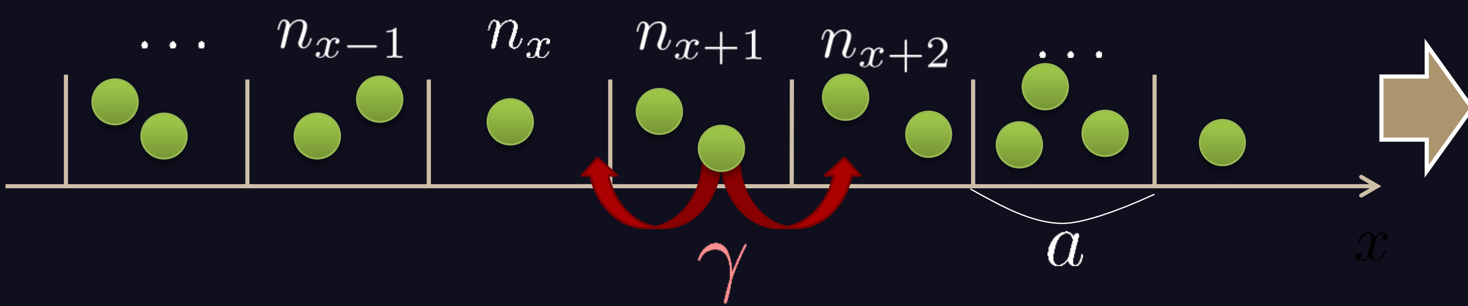
Baryons in hadronic medium behave like Browinian pollen



Diffusion Master Equation

MK,Asakawa,Ono,PLB**728**,386(2014)

Divide spatial coordinate into discrete cells



probability

$P(\mathbf{n})$

Master Equation

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

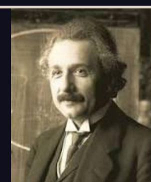
Solve the DME **exactly**, and take $a \to 0$ limit

hadronization
chemical freezeout

Initial condition

- boost invariance
- locality of fluctuations
- small cumulants

τ



Brownian diffusion

kinetic freezeout

Comments:

- agreement with stochastic diffusion eq. up to Gaussian fluctuaion
- Poisson (Skellam) distribution in equilibrium: consistent with HRG

Solution of DME in a→0 Limit

1st order (deterministic) $\langle n \rangle$

- consistent with diffusion equation with $D=\gamma a^2$

  ⇨ Continuum limit with fixed $D=\gamma a^2$

2nd order $\langle \delta n^2 \rangle$

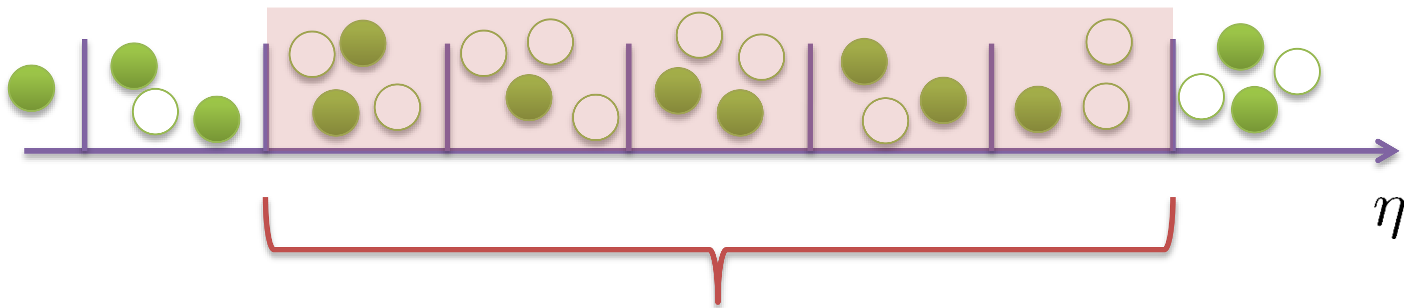
- consistent with stochastic diffusion eq.
  (for sufficiently smooth initial conditions)

Shuryak, Stephanov, 2001

Nontrivial results for non-Gaussian fluctuations

Net Charge Number

Prepare 2 species of (non-interacting) particles



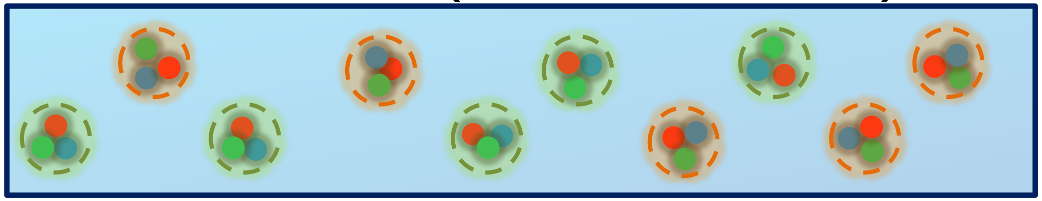
$$\bar{Q}(\tau) = \int_0^{\Delta\eta} d\eta \, (n_1(\eta,\tau) - n_2(\eta,\tau))$$

Let us investigate

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

Time Evolution in Hadronic Phase

Hadronization (initial condition)



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

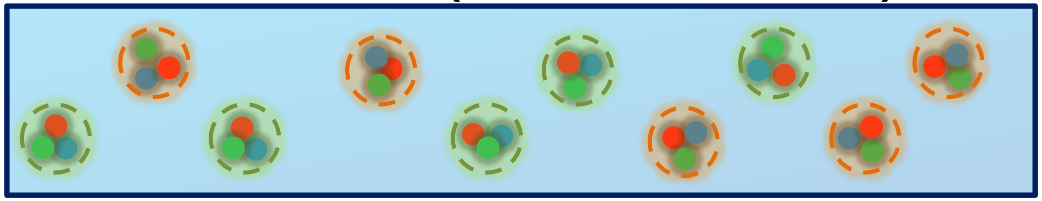
$\langle \bar{Q}^2 \rangle_c \quad \langle \bar{Q}^4 \rangle_c$ — suppression owing to local charge conservation

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

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

Time Evolution in Hadronic Phase

Hadronization (initial condition)



Time evolution via DME

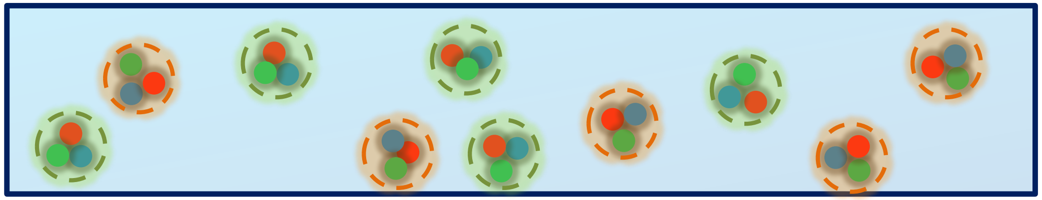
- Boost invariance / infinitely long system
- Local equilibration / local correlation

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

suppression owing to local charge conservation

strongly dependent on hadronization mechanism

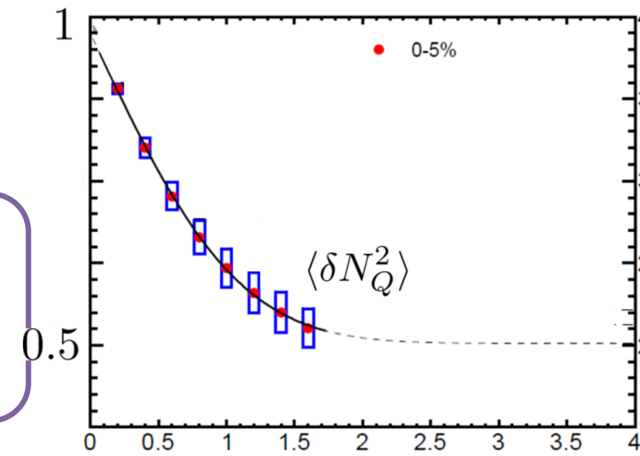
Freezeout

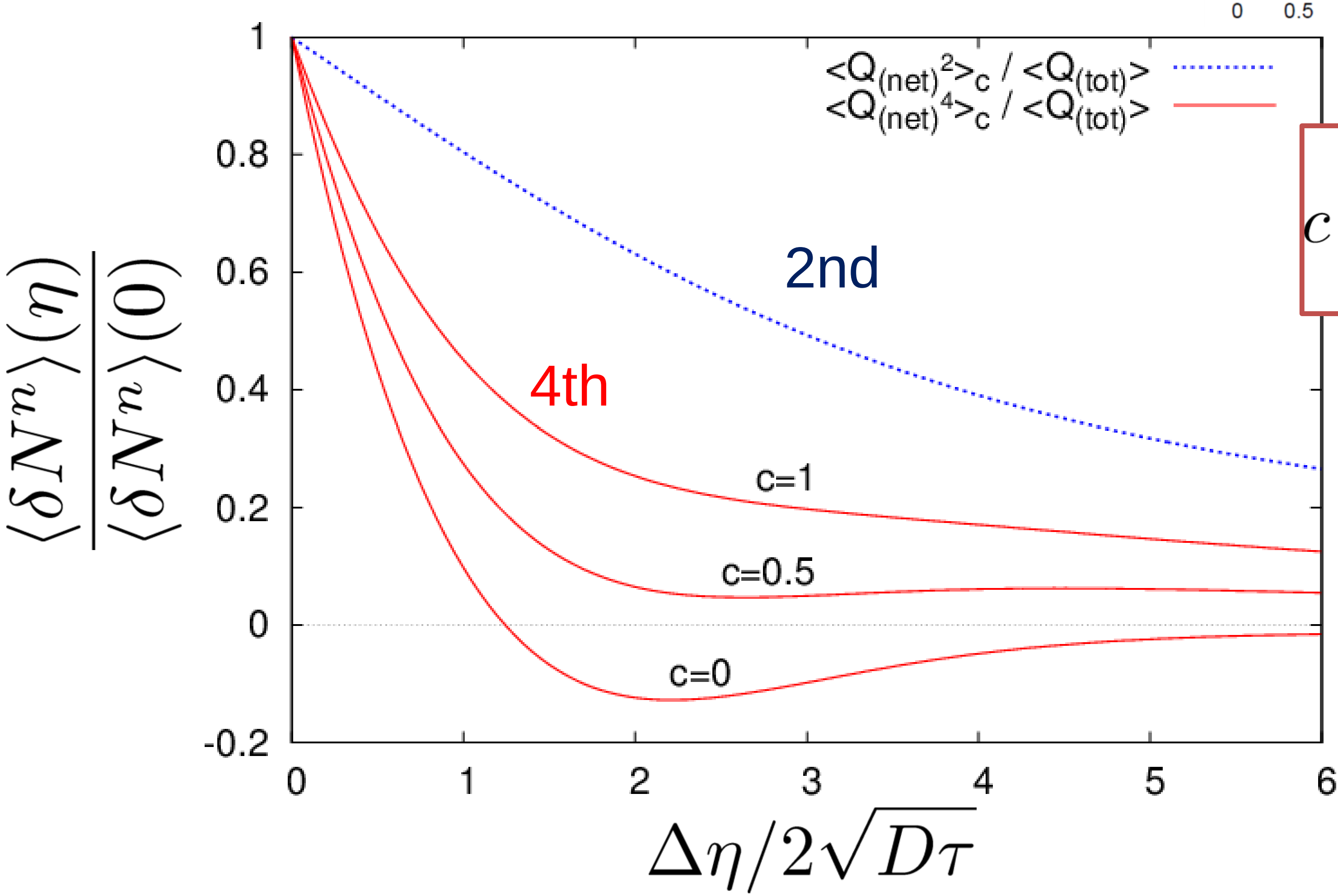


$\Delta\eta$ Dependence at Freezeout

Initial fluctuations:

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



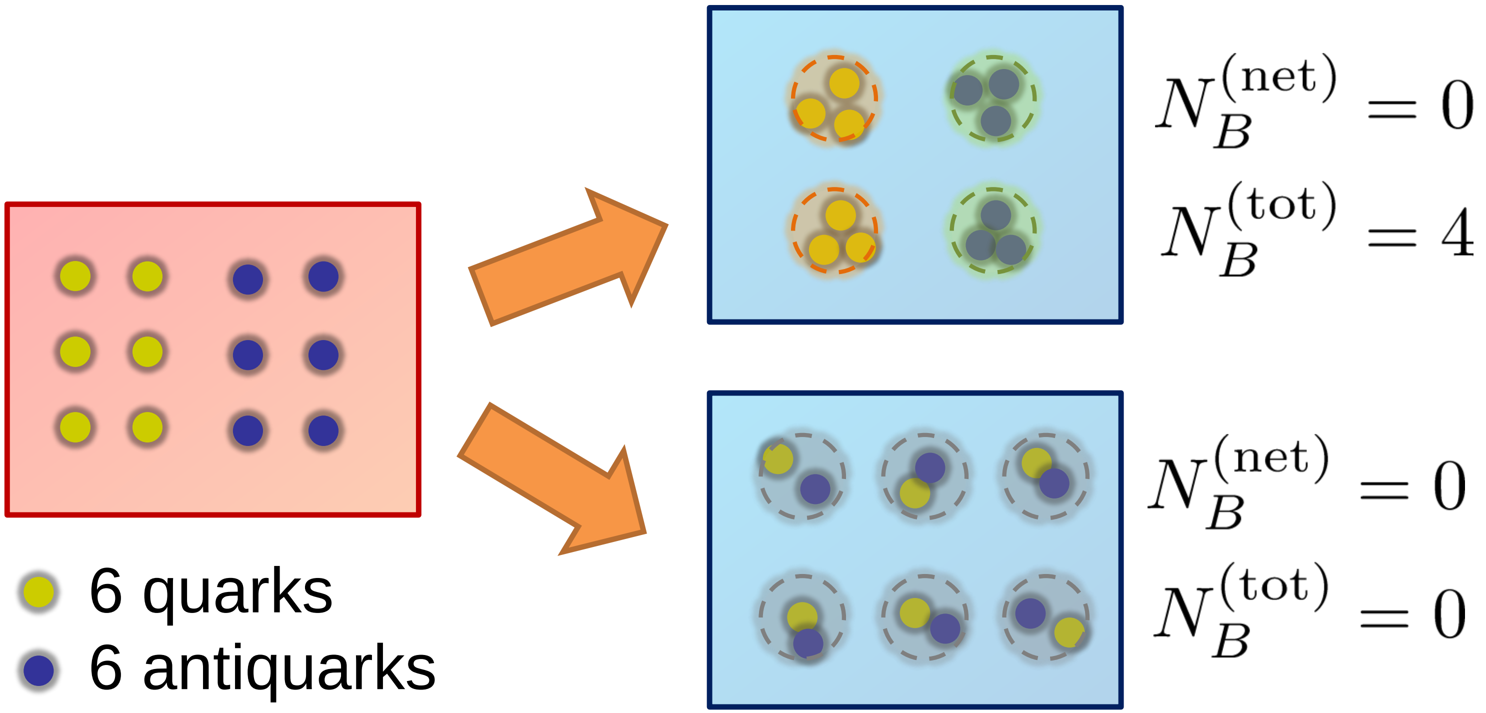


$$c = \frac{\langle Q_{(\mathrm{tot})}^2 \rangle_c}{\langle Q_{(\mathrm{tot})} \rangle}$$

parameter sensitive to hadronization

Total Charge Number

In recombination model,

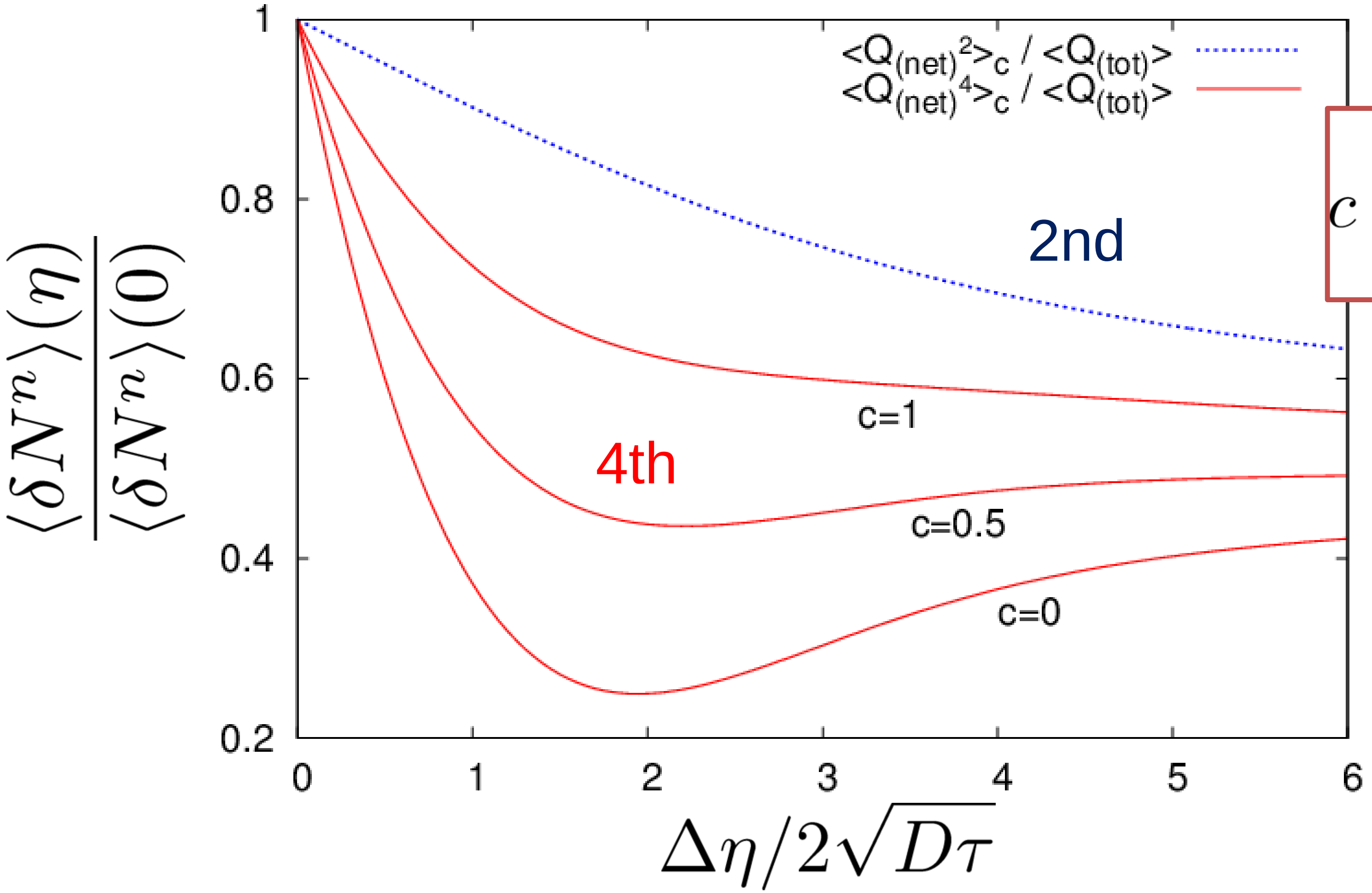


- $N_B^{(\mathrm{tot})}$ can fluctuate, while $N_B^{(\mathrm{net})}$ does not.

$\Delta\eta$ Dependence at Freezeout

Initial fluctuations:

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



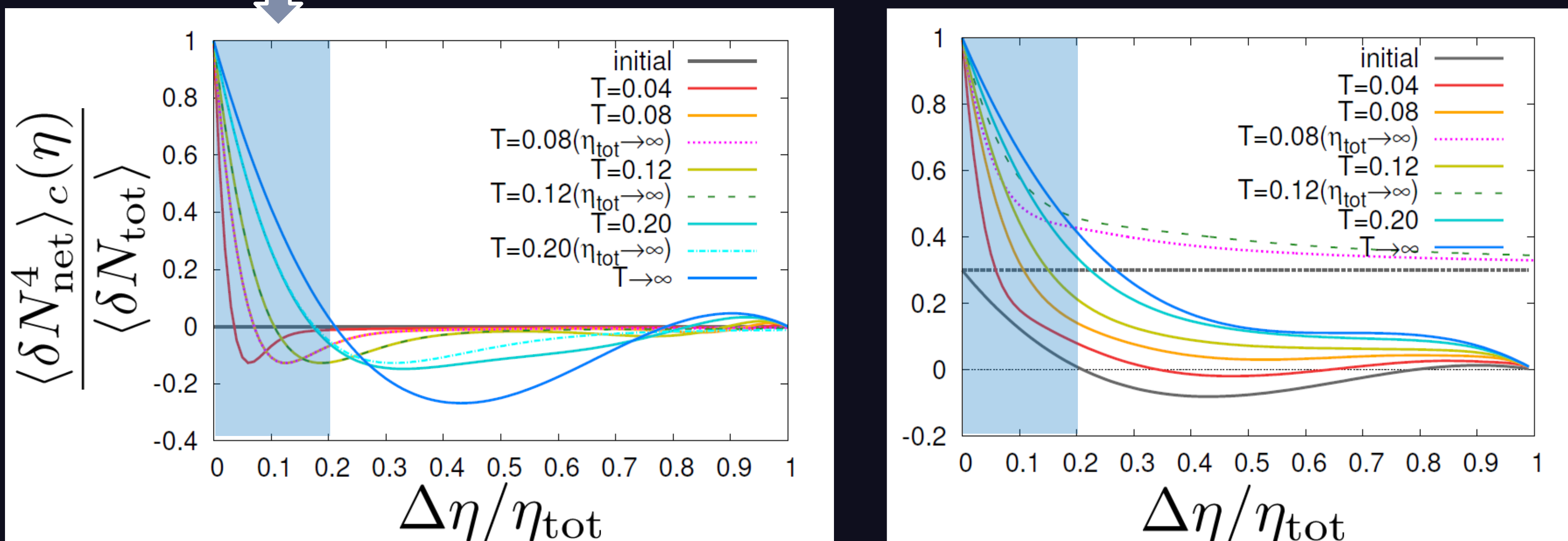
$$c = \frac{\langle Q^2_{(\mathrm{tot})} \rangle_c}{\langle Q_{(\mathrm{tot})} \rangle}$$

parameter sensitive to hadronization

4^{th} order Cumulant at ALICE

MK, Asakawa,Ono (2014)
Sakaida+, poster I-35

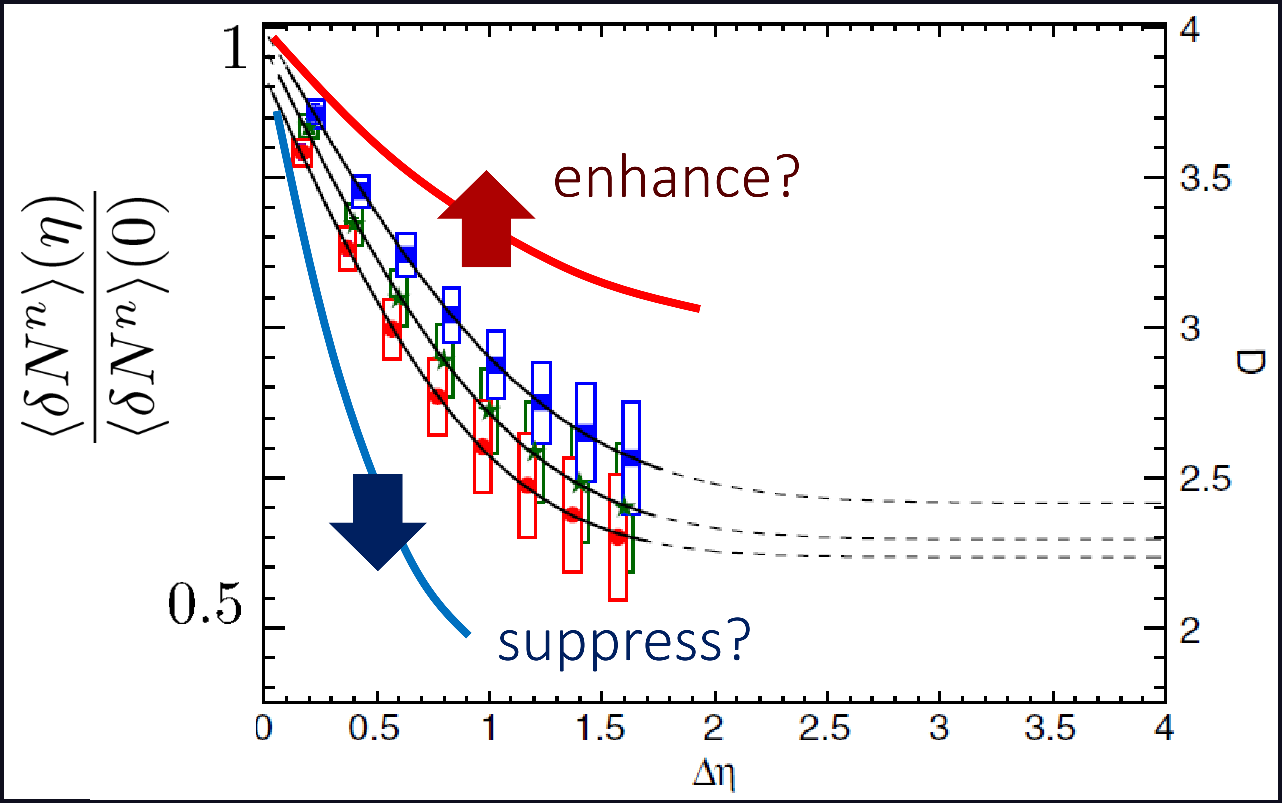
rapidity coverage at ALICE $(\eta_{tot} = 8)$



4th order cumulant is sensitive to
initial fluctuation / transport property / confinement

It can be non-monotonic and negative!

$\Delta\eta$ Dep. of Non-Gaussianity



How does the 4-th order cumulant behave as a function of $\Delta\eta$?

Suggestions to Experimentalists

- many conserved charges

  electric charge, baryon number, (and strangeness?)
  with different diffusion constans

- various cumulants

  second, third, fourth, mixed, (and much higher?)

- $\Delta\eta$ window dependences

  primordial thermodynamics, transport property, confinement
  no normalization

- Beam Energy Scan

  LHC, RHIC-BES, FAIR, NICA, J-PARC, …

My Messages

- ☐ Fluctuations are invaluable observables in HIC
- ☐ But, we must understand them in more detail
- ☐ It's possible, interesting, and important

We are just arriving at the starting point to explore QCD phase structure with fluctuations!

Summary

Fluctuations in HIC are nonthermal!

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

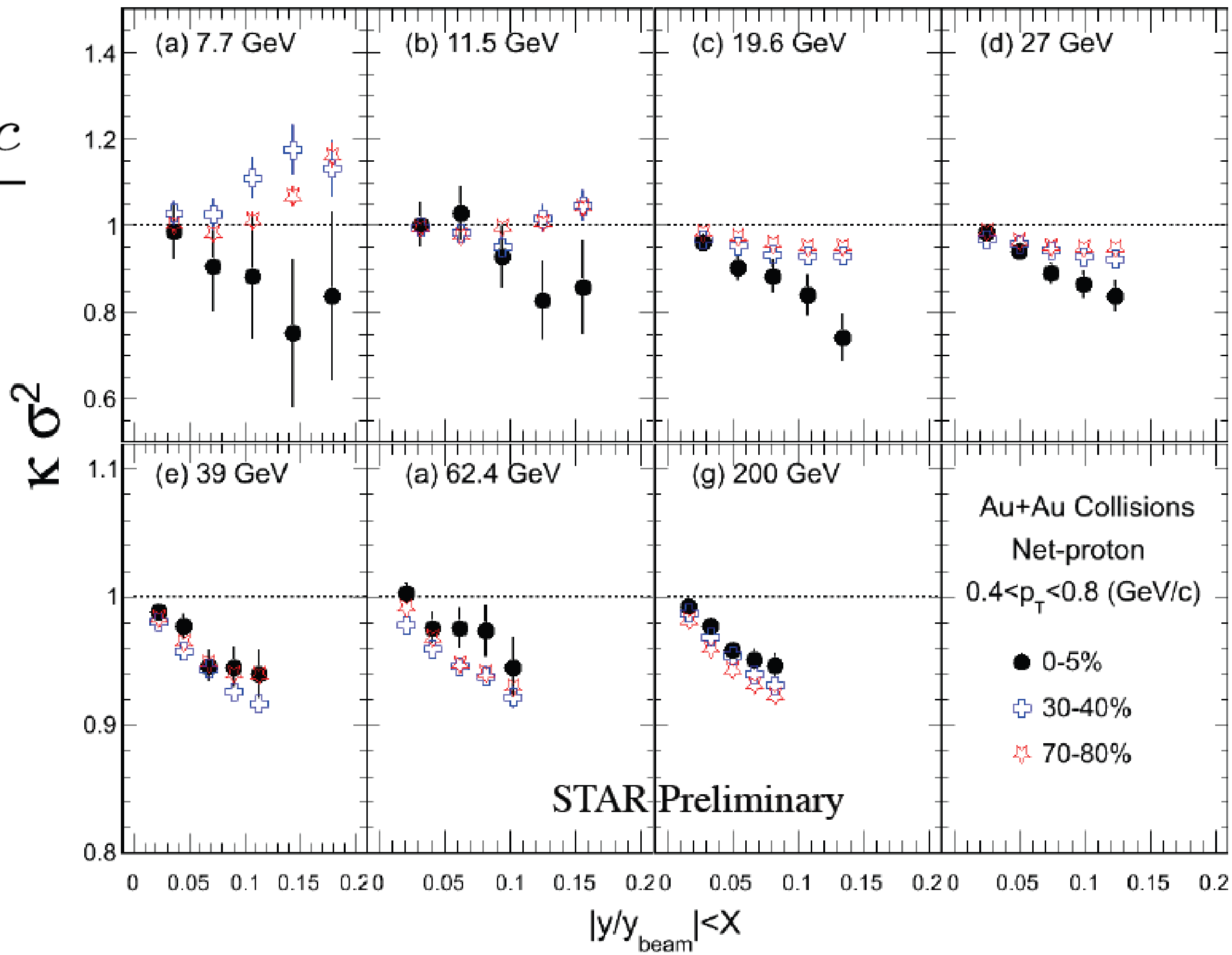
- history of hot medium
- mechanism of hadronization
- diffusion constant

backup

Δη Dependence at STAR

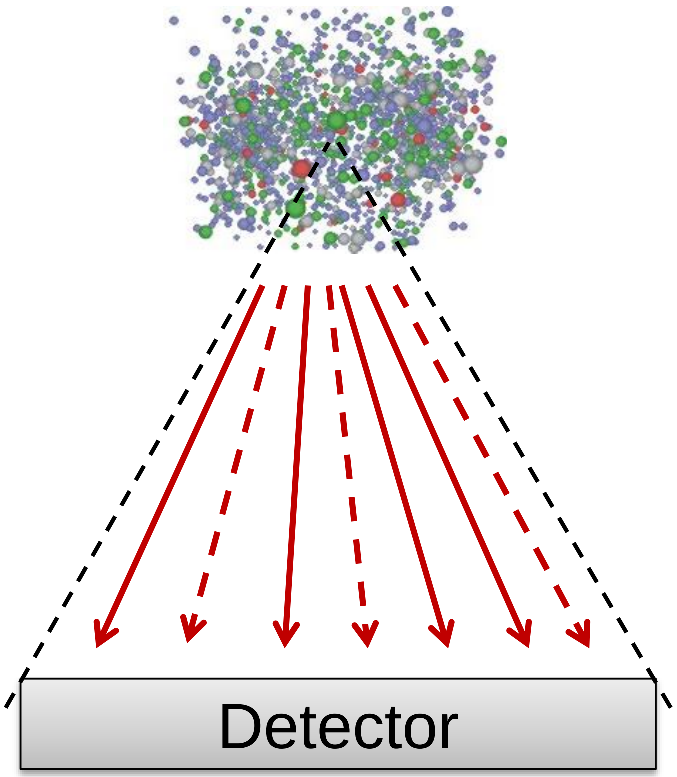
STAR, QM2012

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



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

Probability Distribution $\mathcal{P}(N_p, N_n, N_{\bar{p}}, N_{\bar{n}})$



- $\left\{ \begin{array}{l} \rightarrow N_N \text{ nucleons} \\ \dashrightarrow N_{\bar{N}} \text{ anti-nucleons} \end{array} \right.$

  ➡ $F(N_N, N_{\bar{N}})$

- $N_N \left\{ \begin{array}{l} N_p \text{ protons} \\ N_n \text{ neutrons} \end{array} \right.$

  ➡ $B(N_p; N_N)$

  binomial distribution func.

$$\mathcal{P}(N_p, N_n, N_{\bar{p}}, N_{\bar{n}}) = F(N_N, N_{\bar{N}}) B(N_p; N_N) B(N_{\bar{p}}; N_{\bar{N}})$$

- for any phase space in the final state.

3rd & 4th Order Fluctuations

$N_\mathrm{B} \to N_p$

$$\langle(\delta N_p^{(\mathrm{net})})^3\rangle = \frac{1}{8}\langle(\delta N_\mathrm{B}^{(\mathrm{net})})^3\rangle + \frac{3}{8}\langle\delta N_\mathrm{B}^{(\mathrm{net})}\delta N_\mathrm{B}^{(\mathrm{tot})}\rangle,$$

$$\begin{aligned}\langle(\delta N_p^{(\mathrm{net})})^4\rangle_c =& \frac{1}{16}\langle(\delta N_\mathrm{B}^{(\mathrm{net})})^4\rangle_c + \frac{3}{8}\langle(\delta N_\mathrm{B}^{(\mathrm{net})})^2\delta N_\mathrm{B}^{(\mathrm{tot})}\rangle \\ &+ \frac{3}{16}\langle(\delta N_\mathrm{B}^{(\mathrm{tot})})^2\rangle - \frac{1}{8}\langle N_\mathrm{B}^{(\mathrm{tot})}\rangle,\end{aligned}$$

$N_p \to N_\mathrm{B}$

$$\begin{aligned}\langle(\delta N_\mathrm{B}^{(\mathrm{net})})^3\rangle =& 8\langle(\delta N_p^{(\mathrm{net})})^3\rangle - 12\langle\delta N_p^{(\mathrm{net})}\delta N_p^{(\mathrm{tot})}\rangle \\ &+ 6\langle N_p^{(\mathrm{net})}\rangle,\end{aligned}$$

$$\begin{aligned}\langle(\delta N_\mathrm{B}^{(\mathrm{net})})^4\rangle_c =& 16\langle(\delta N_p^{(\mathrm{net})})^4\rangle_c - 48\langle(\delta N_p^{(\mathrm{net})})^2\delta N_p^{(\mathrm{tot})}\rangle \\ &+ 48\langle(\delta N_p^{(\mathrm{net})})^2\rangle + 12\langle(\delta N_p^{(\mathrm{tot})})^2\rangle - 26\langle N_p^{(\mathrm{tot})}\rangle,\end{aligned}$$

Strange Baryons

Decay Rates:

Λ $m_\Lambda \simeq 1116[\mathrm{MeV}]$

$$p : n \simeq 1.6 : 1$$

Σ $m_\Sigma \simeq 1190[\mathrm{MeV}]$

$$p : n \simeq 1 : 1.8$$

Decay modes:

$\Lambda \rightarrow p + \pi^-$ 64%

$\Lambda \rightarrow n + \pi^0$ 36%

$\Sigma^+ \rightarrow p + \pi^0$ 52%

$\Sigma^+ \rightarrow n + \pi^+$ 48%

$\Sigma^0 \rightarrow \Lambda \rightarrow p + \pi^-$ 64%

$\Sigma^0 \rightarrow \Lambda \rightarrow n + \pi^0$ 36%

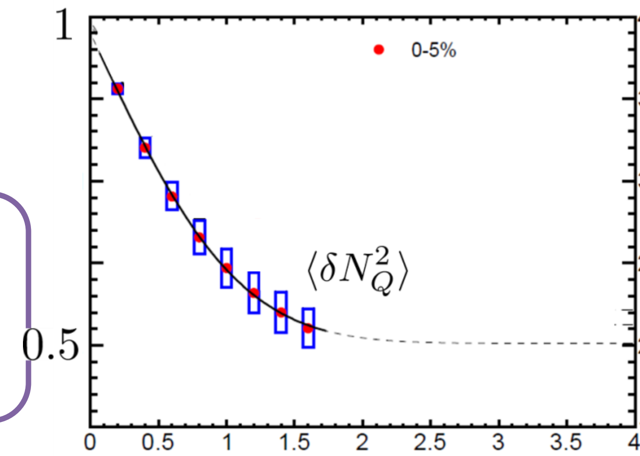
$\Sigma^- \longrightarrow n + \pi^-$

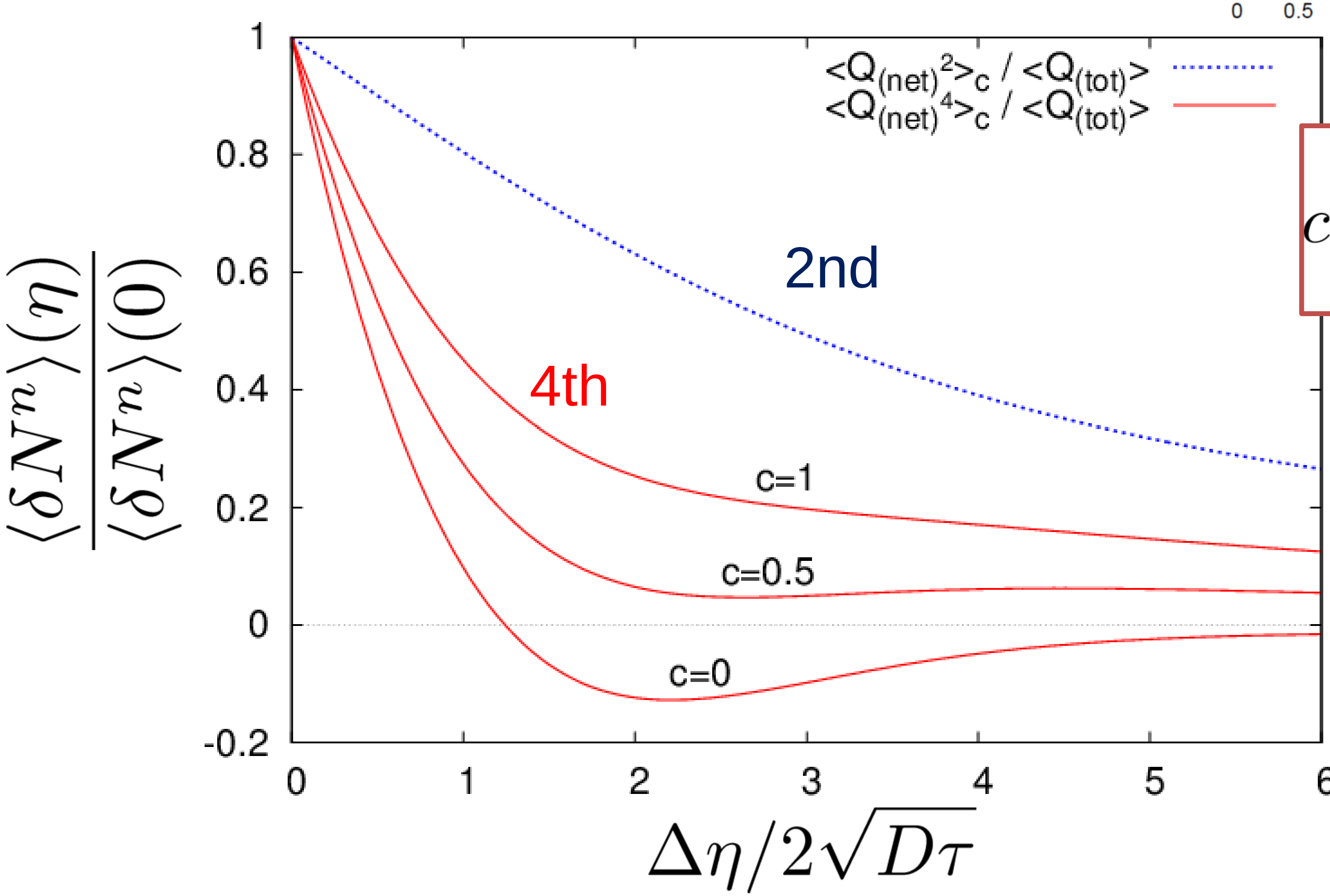
Regarding these ratios even, protons from these decays is incorporated into the binomial distribution. Then, $N_N \rightarrow N_B$

$\Delta\eta$ Dependence at Freezeout

Initial fluctuations:

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



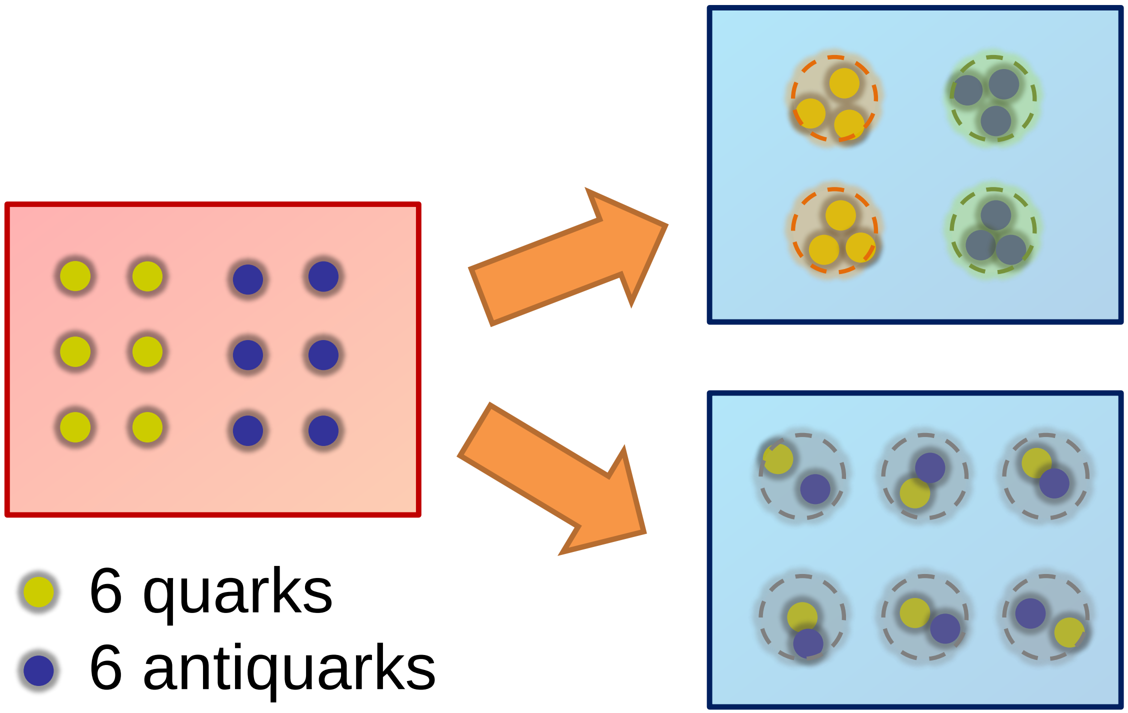


$$c = \frac{\langle Q_{(\mathrm{tot})}^2 \rangle_c}{\langle Q_{(\mathrm{tot})} \rangle}$$

parameter sensitive to hadronization

Total Charge Number

In recombination model,



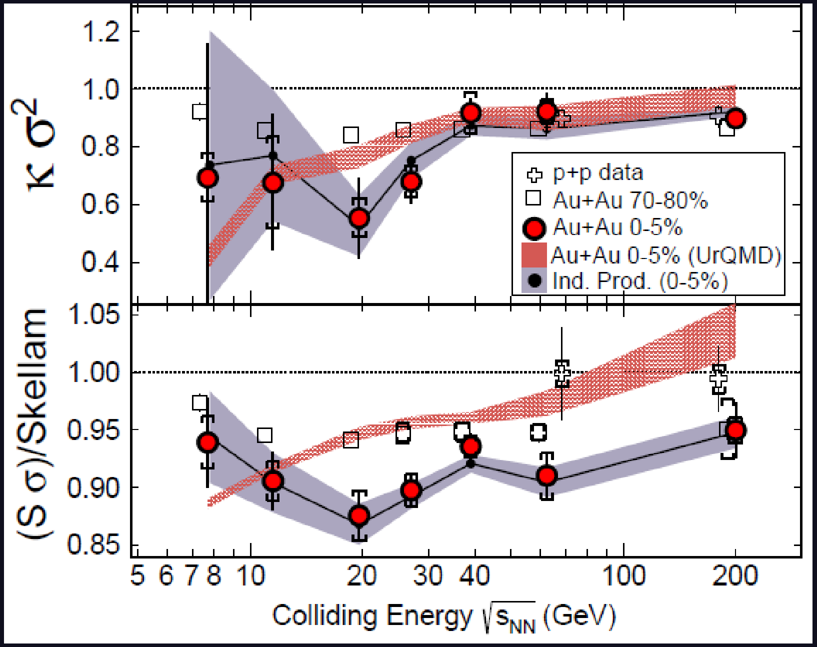
$$N_B^{(\mathrm{net})} = 0$$
$$N_B^{(\mathrm{tot})} = 4$$

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

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

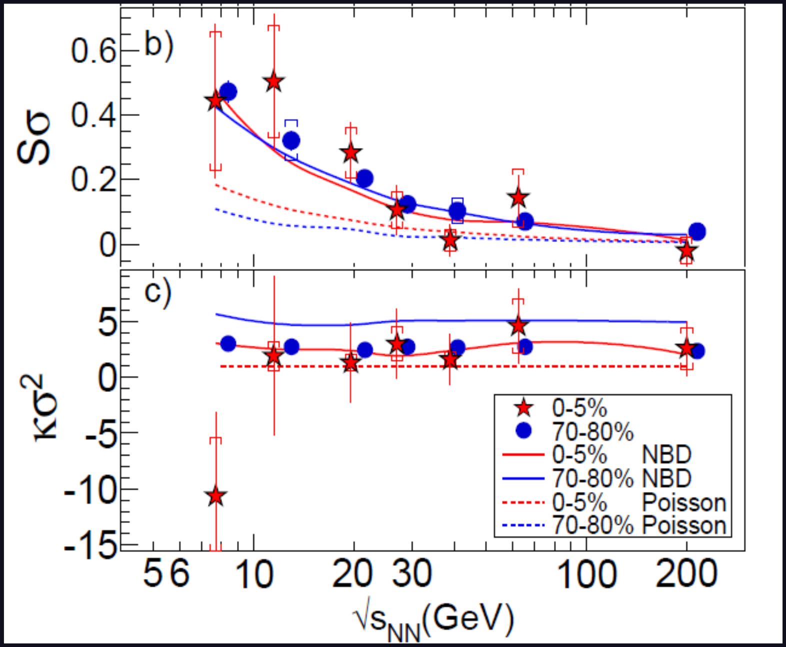
Higher Order Cumulants @ STAR

(Net-) Proton Number



STAR, PRL**112**,032302(2014)

(Net-) Electric Charge

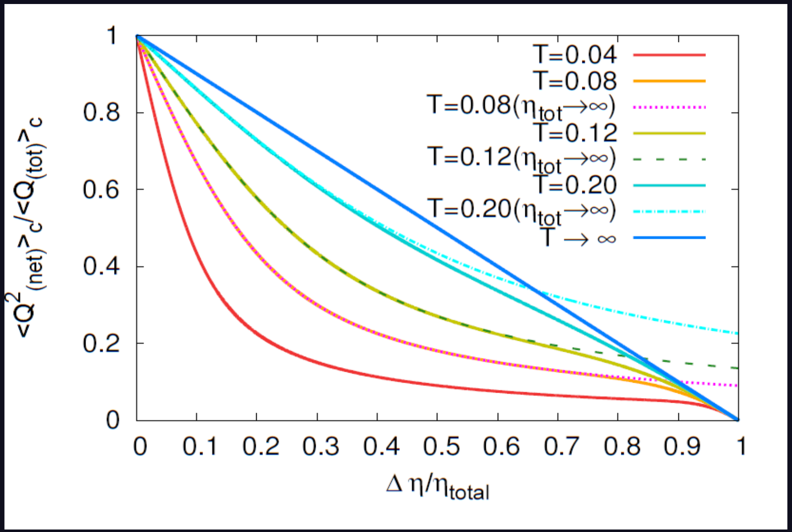


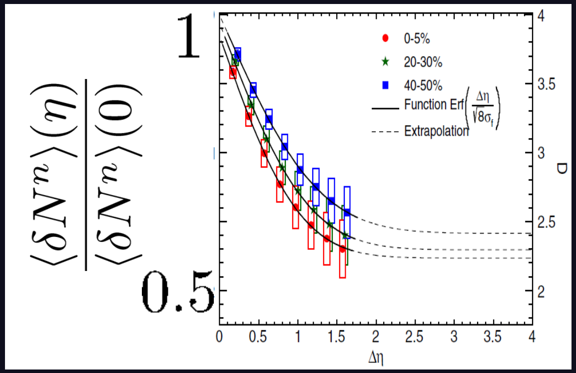
STAR, arXiv:1402.1558

- Exp. results are close to Poissonian values.
- Proton number cumulants are lower than the Poissonian values.

2^{nd} Order Cumulant

consistent with stochastic diffusion equation





Search of QCD Phase Structure

Stronger correlation length dep.

Stephanov, 2009

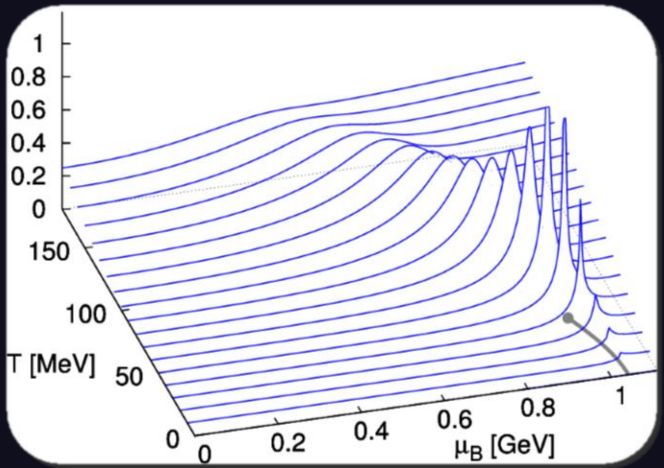
$$\langle \delta N^2 \rangle \sim \xi^2,\ \langle \delta N^3 \rangle \sim \xi^{4.5},\ \langle \delta N^4 \rangle_c \sim \xi^7$$

Sign of cumulants

Asakawa, Ejiri, MK, 2009
Friman+, 2011
Stephanov, 2011

$$\langle \delta N^n \rangle = T \frac{\partial^n}{\partial \hat{\mu}^n} \ln Z$$

$$\langle \delta N^3 \rangle = \frac{\partial}{\partial \hat{\mu}} \langle \delta N^2 \rangle$$



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

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