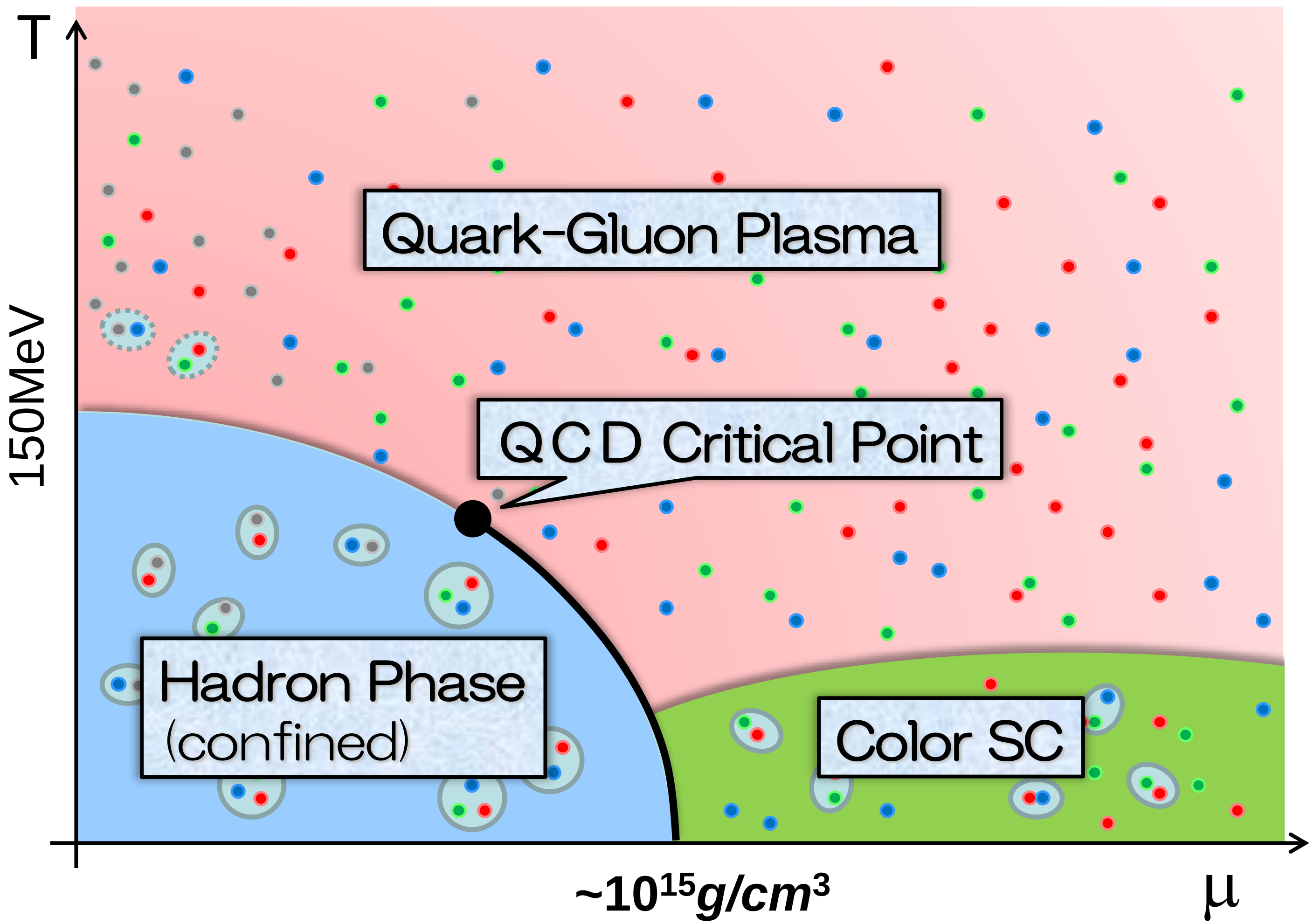
Workshop on Highly Baryonic Matter at RHIC-BES and Future Facilities (WHBM 2023), Tsukuba, 2023/04/30

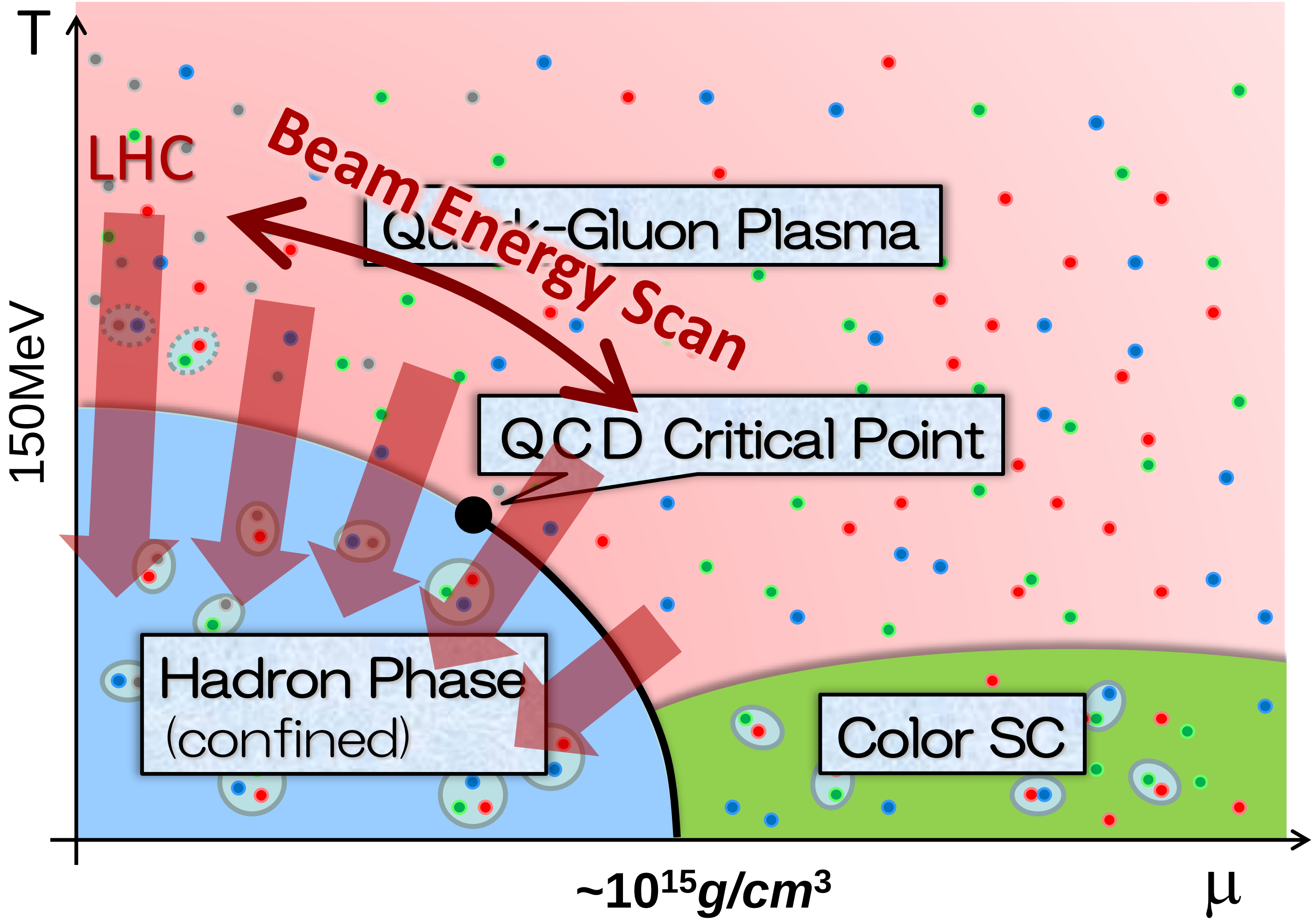
Critical Point and Fluctuations

Masakiyo Kitazawa (YITP, Kyoto)

Beam-Energy Scan



Beam-Energy Scan

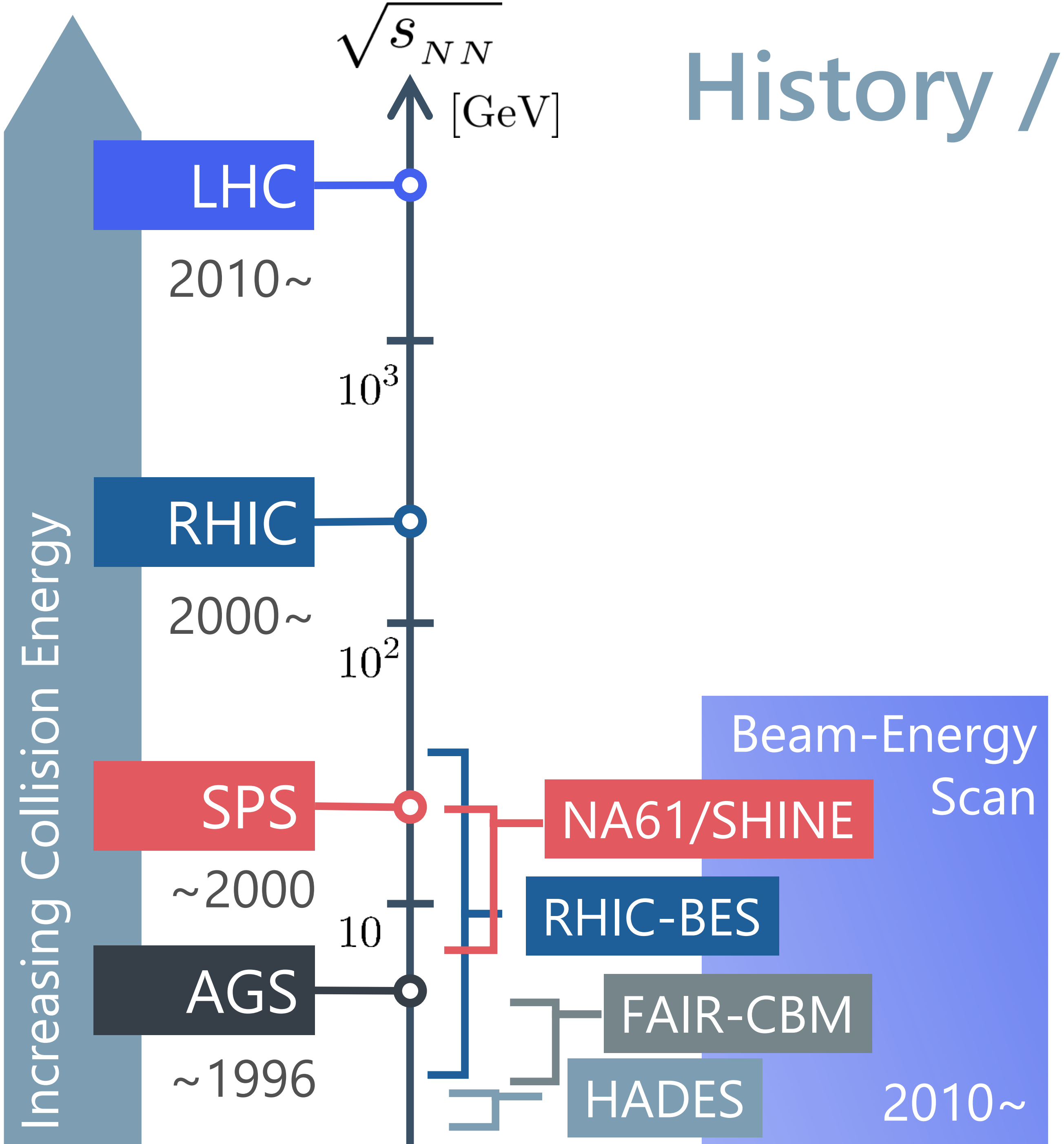


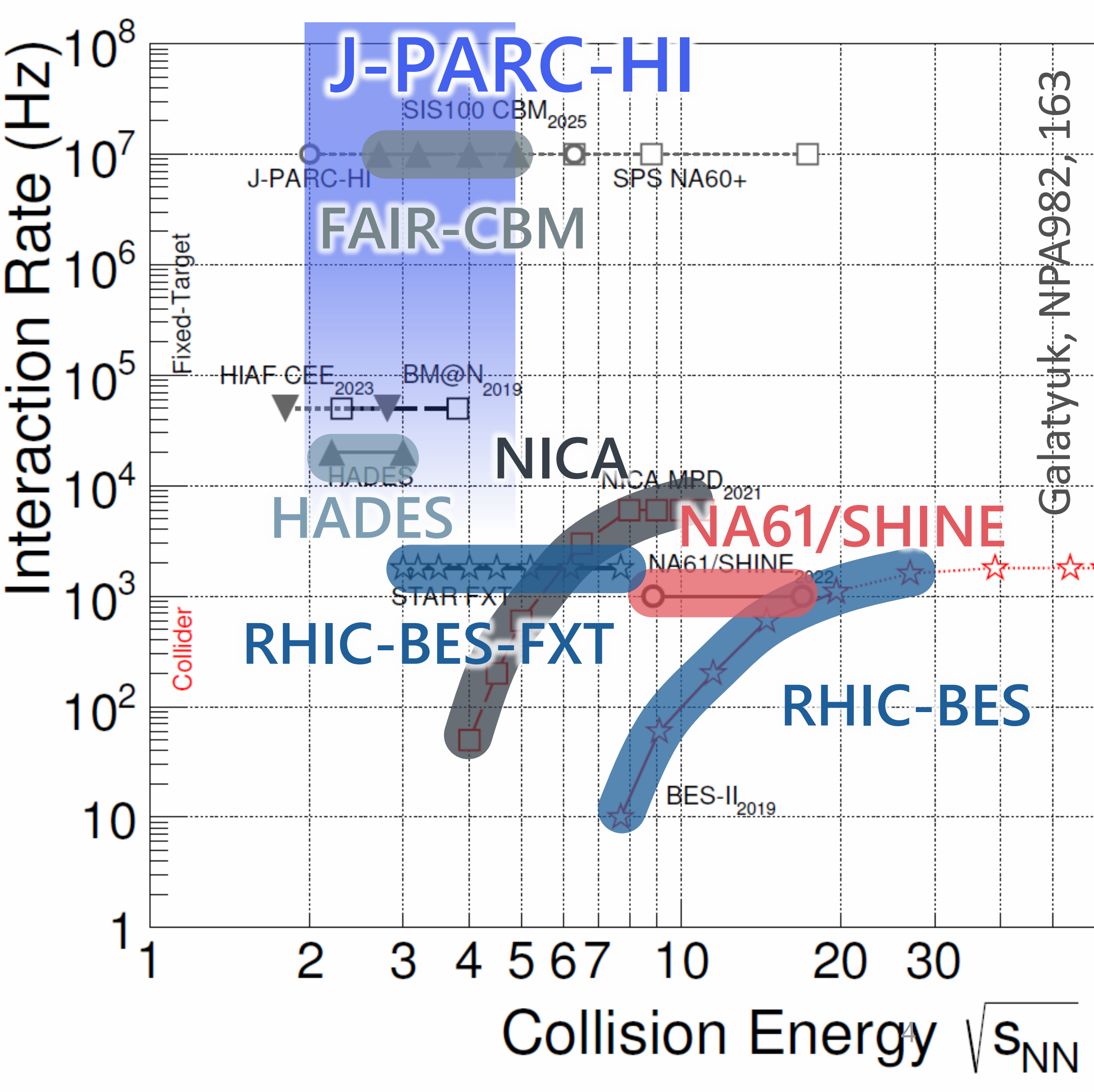
Experiments

- RHIC-BES
- HADES
- NA61/SHINE

- FAIR
- NICA
- J-PARC-HI
- …

History / Current Status of HIC





Three Topics

1 Event-by-event fluctuations of conserved charges

MK, Esumi, Nonaka, 2205.10030

2 Dilepton production rate at ultra-low-mass region as a signal of QCD phase transitions

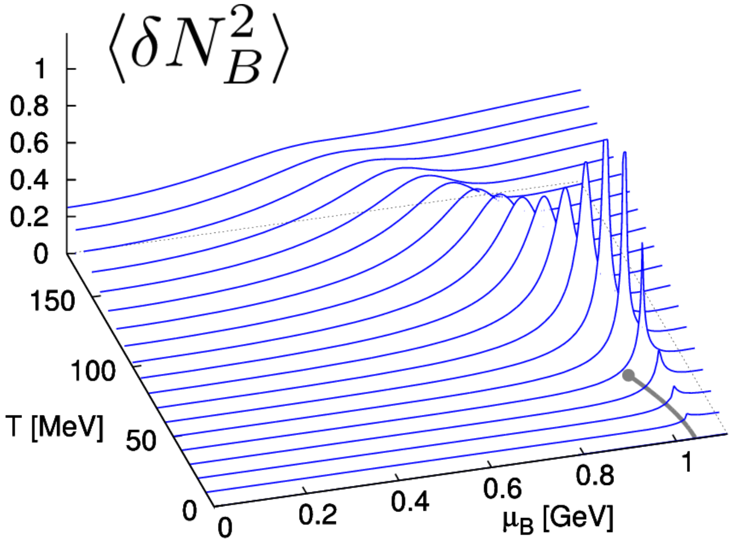
Talk by Nishimura, yesterday; Nishimura, MK, Kunihiro, 2302.03191; 2201.01963

3 Event selections

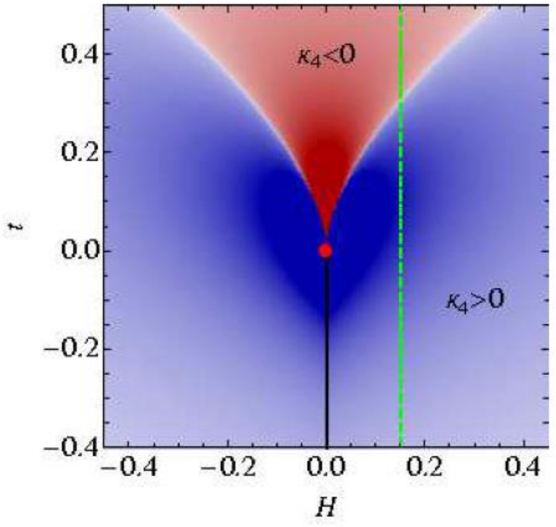
Fluctuations, Cumulants of Conserved Charges

$$\langle N^m \rangle_c = \chi_m V$$

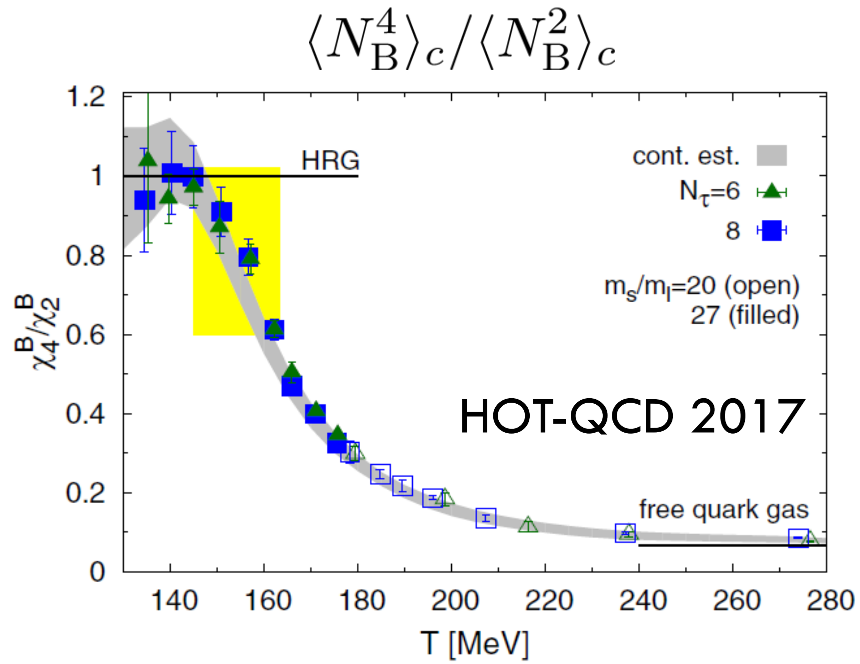
- Divergence and sign change at the QCD-CP. Stephanov,'09; Asakawa, Ejiri, MK,'09
- Volume dependence is canceled out in ratio. Ejiri, Karsch, Redlich,'05
- Direct comparison with lattice QCD simulations.
- Slower diffusion.



Asakawa, Ejiri, MK (2009)



Stephanov (2011)

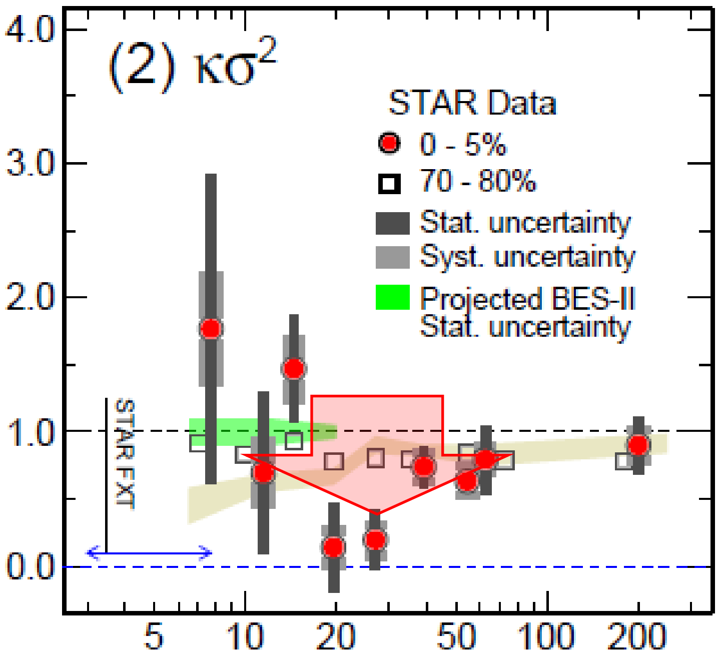


Experimental Results

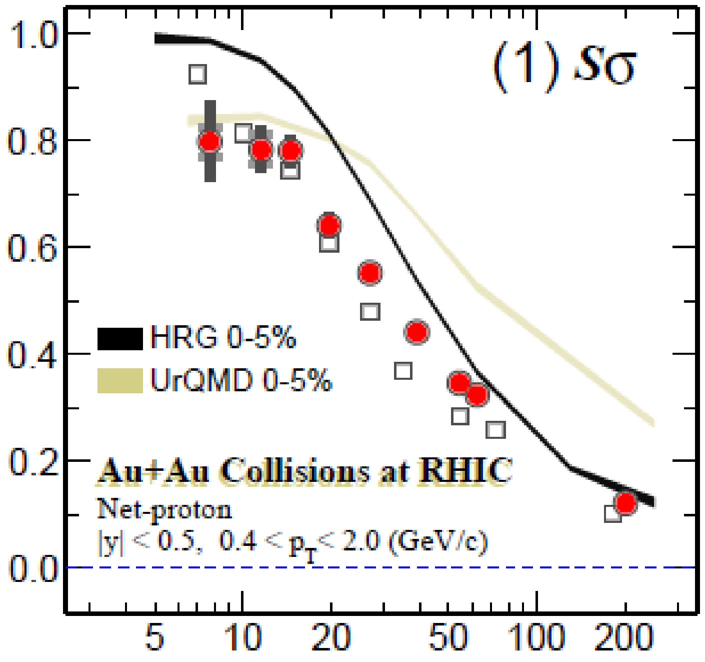
Net-proton number cumulants

STAR, 2020 (2001.02852)

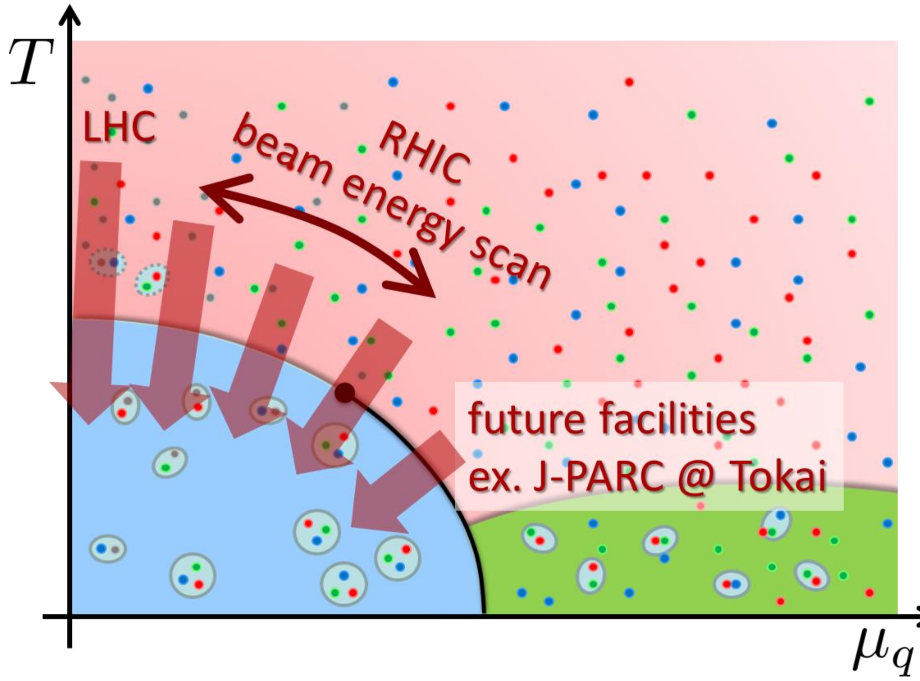
$\langle N_p^4 \rangle_c / \langle N_p^2 \rangle_c$



$\langle N_p^3 \rangle_c / \langle N_p^2 \rangle_c$



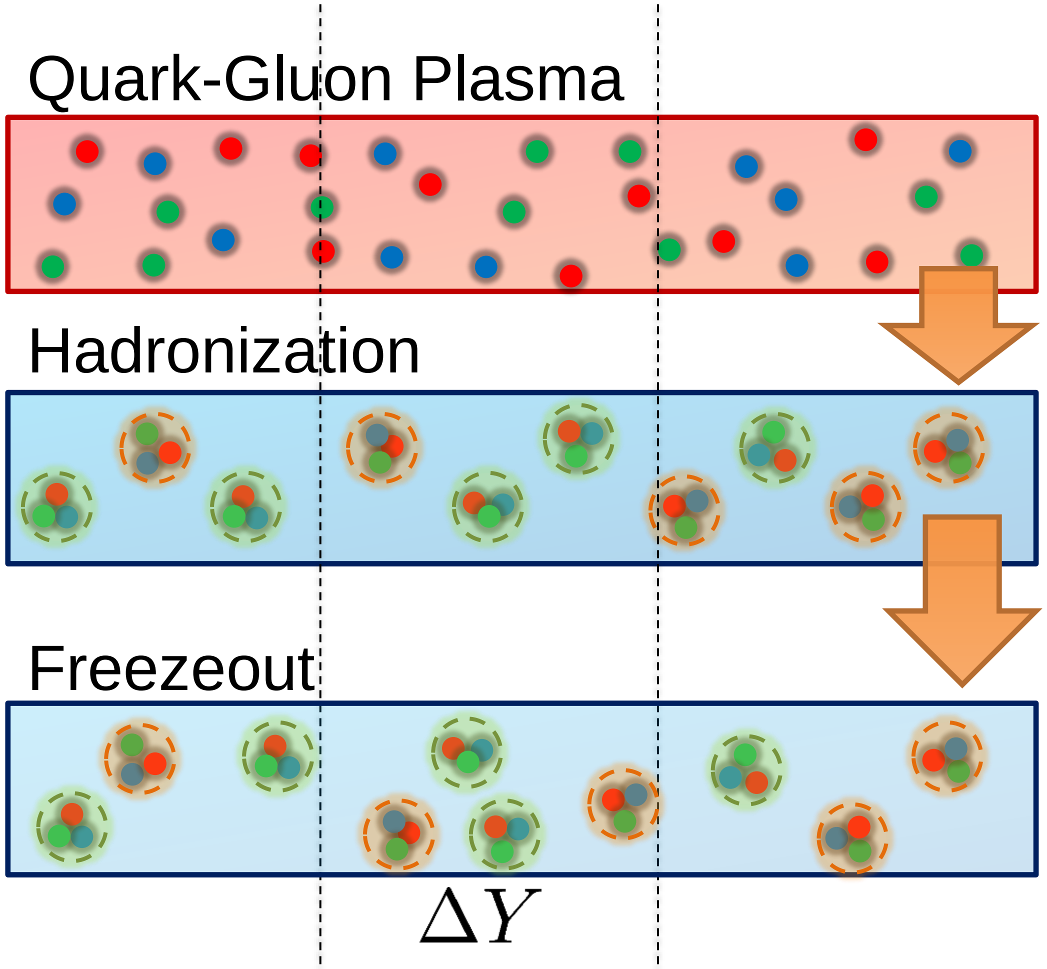
Non-Poisson and non-monotonic behaviors of the higher order cumulants.

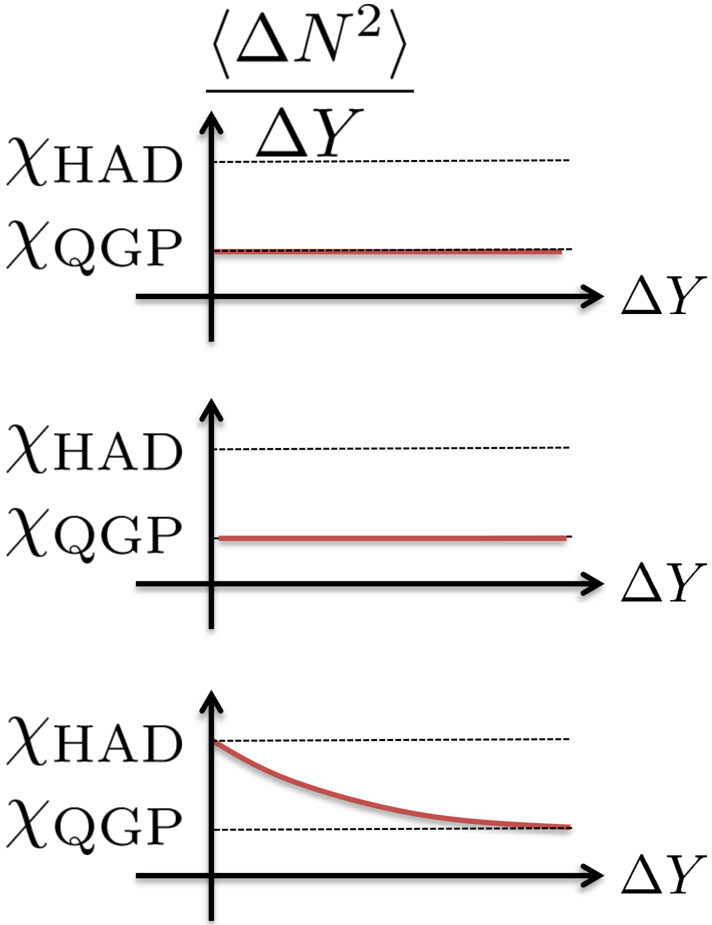


Questions

- ☐ When are these fluctuations generated?
- ☐ Is the use of proton # cumulants as a proxy of baryon's justified?

Evolution of Conserved-charge Fluctuations





Fluctuations of CC are modified by the diffusion.

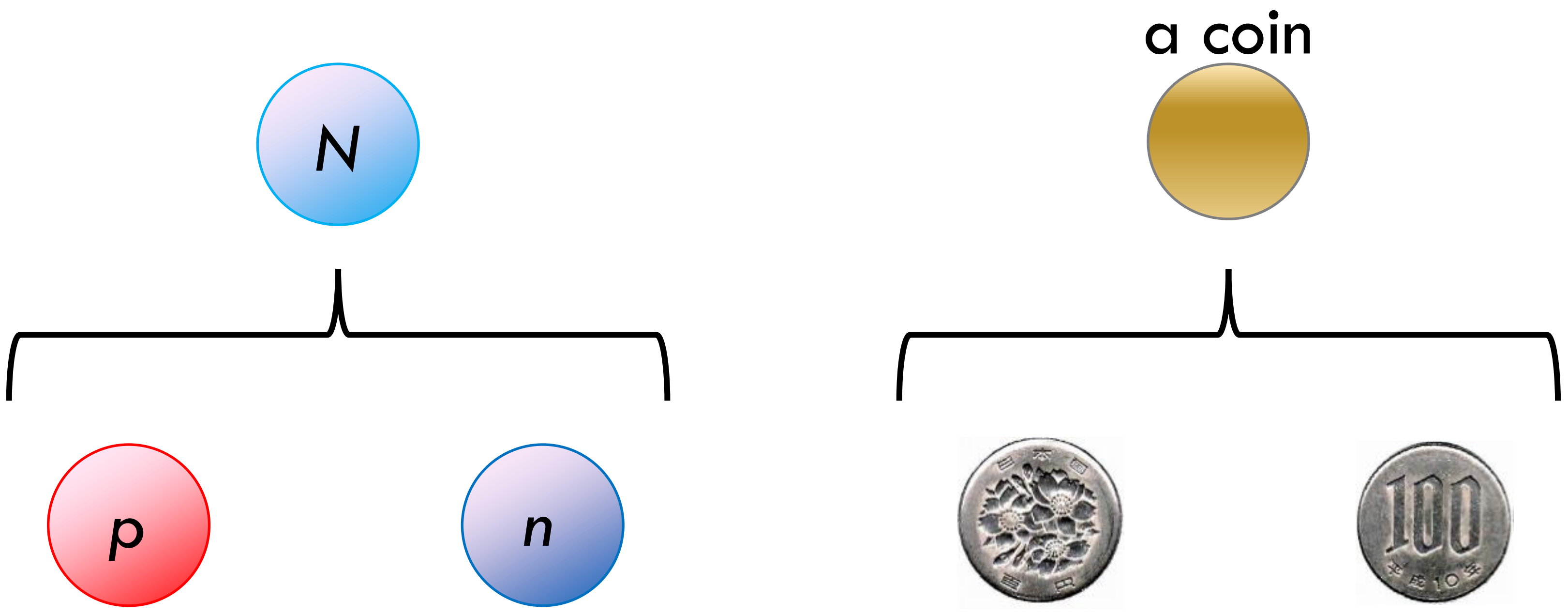
Relaxation time becomes longer as ΔY →large.

Experiments on $\langle N_Q^2 \rangle$

- ☐ No QGP signal @ RHIC ('02, '03)
- ☐ QGP signal? @ ALICE ('12)

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

Nucleon’s Isospin as Two Sides of a Coin



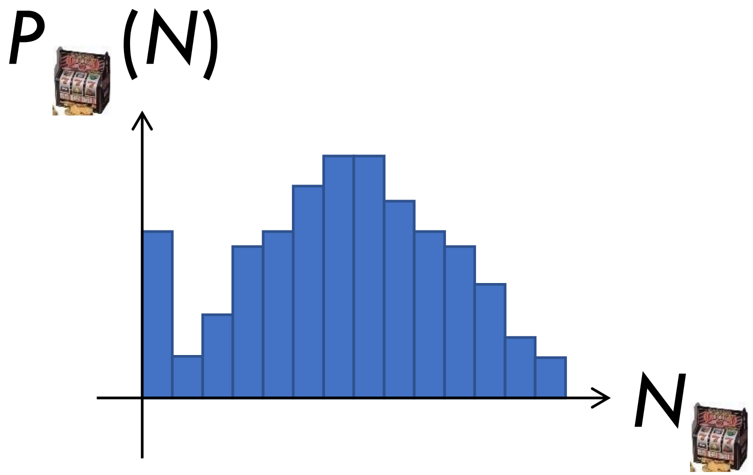
Nucleons have two isospin states.

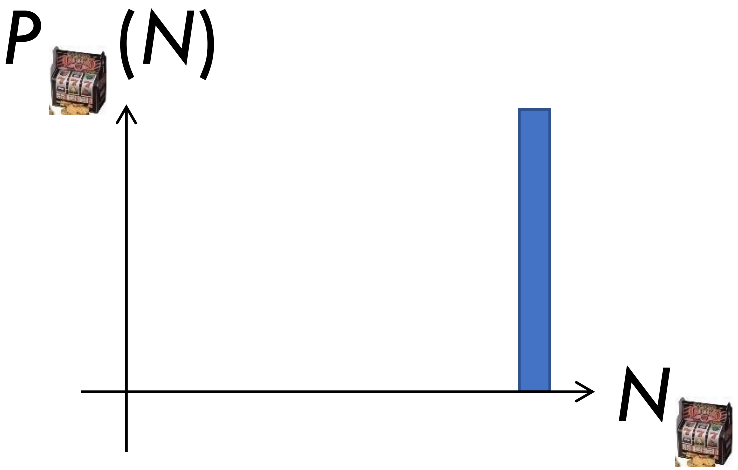
Coins have two sides.

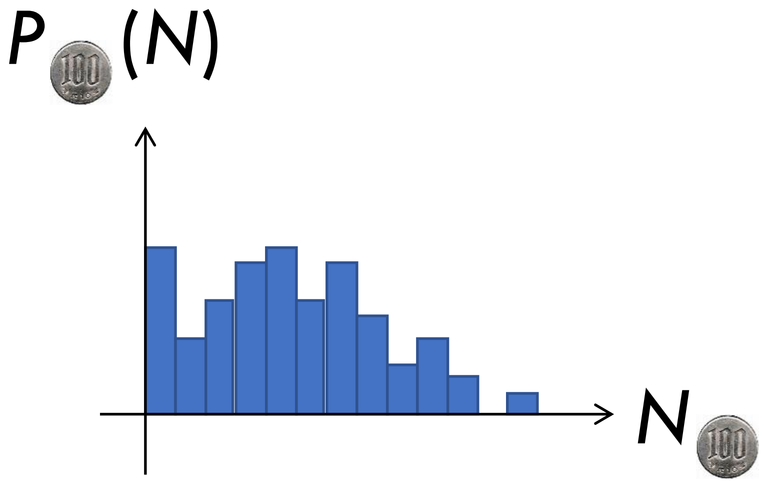
MK, Asakawa, 2012;2012

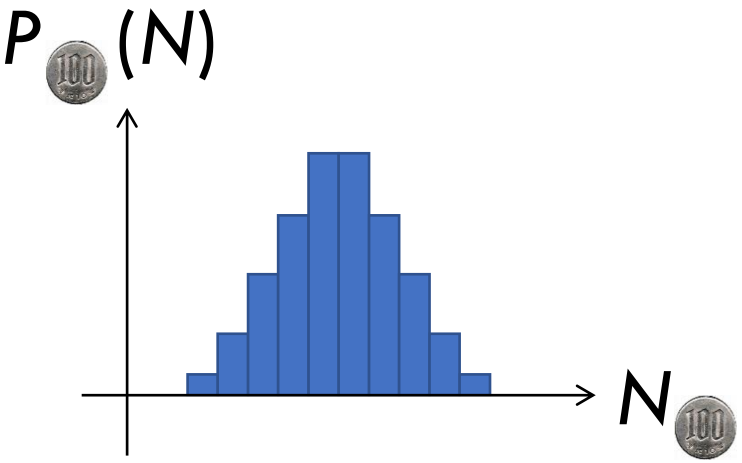
Slot Machine Analogy

Fixed # of coins

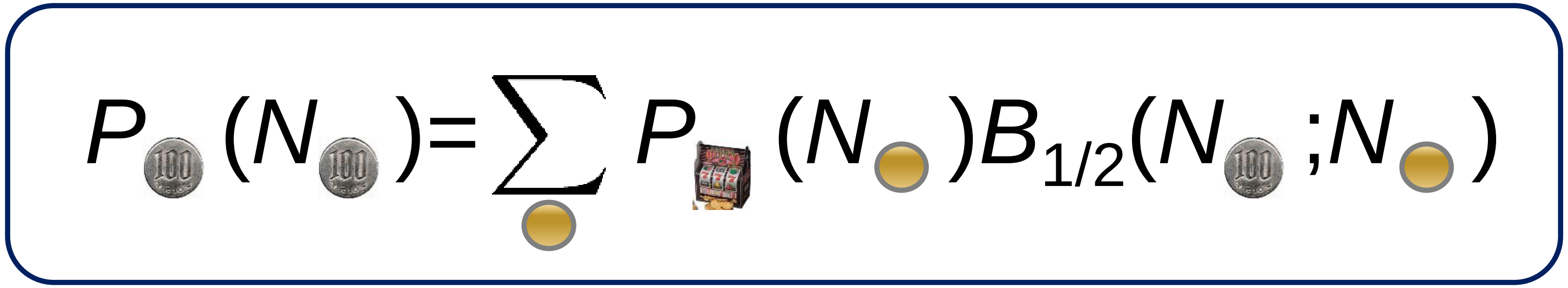








Reconstruction of Total Coin



☐Example

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

genuine info.   Poisson noise

Note: Higher order cumulants are more fragile.

MK, Asakawa, 2012;2012

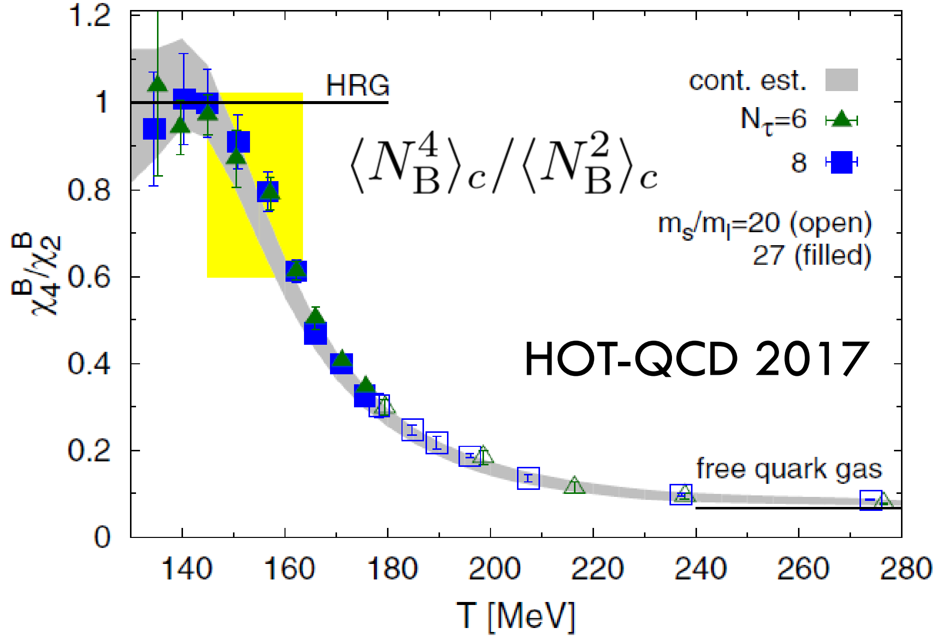
$\langle N_B^2\rangle_c/\langle N_Q^2\rangle_c$

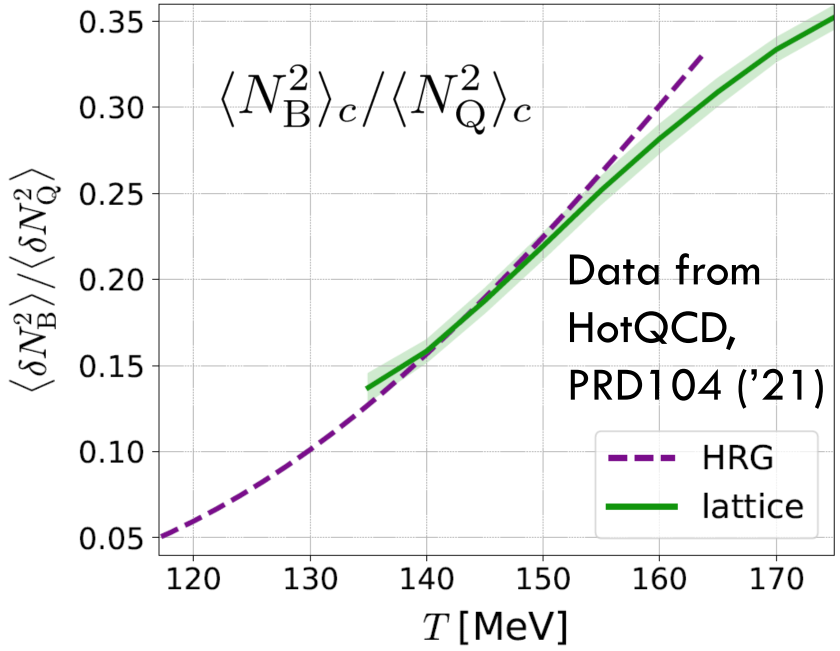
MK, Esumi, Nonaka, 2205.10030

$\langle N_{\mathrm{B}}^2\rangle_c/\langle N_{\mathrm{Q}}^2\rangle_c$

- Ratio of 2nd order: Suppress uncertainties from various experimental effects compared with higher orders.
- Almost linear T dependence around T_c^*.

- $\sqrt{s_{NN}} = 200\mathrm{GeV}$
- 0-5% centrality
- Δy dependence
- Construction of baryon number, p_T-acceptance correction





Experimental Data

$\langle N_p^2 \rangle_c$

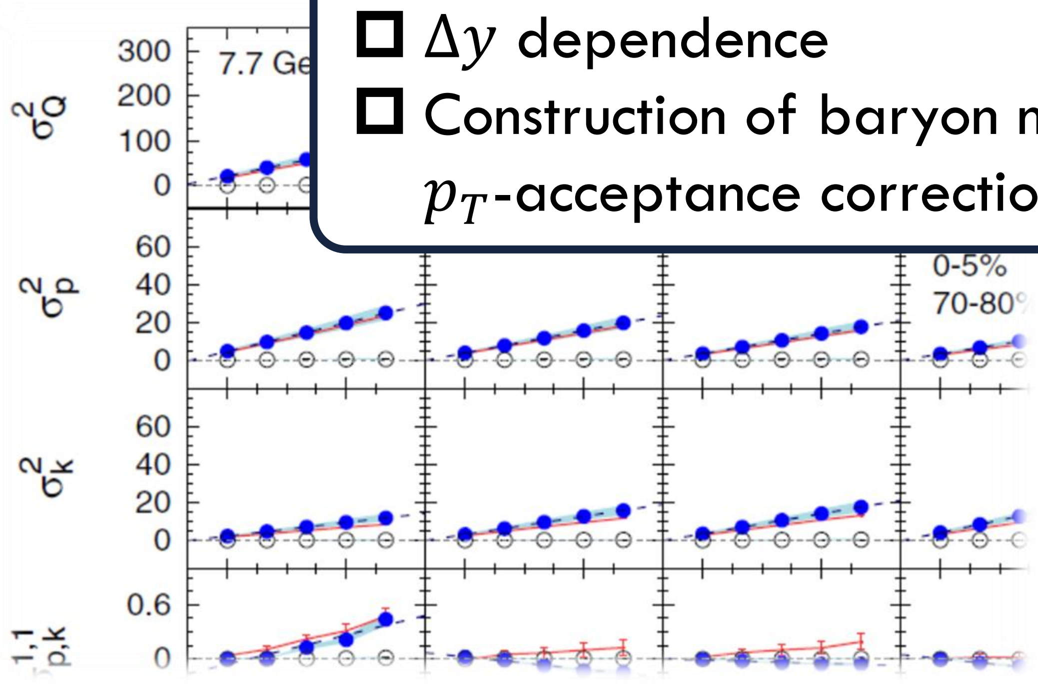
STAR, PRC104,024902 (2021)

- proton cumulants up to 4th order
- **rapidity window** Δy
- $0.4 < p_T < 2.0$GeV/c

$\langle N_Q^2 \rangle_c$

STAR, PRC100,014902 (2019)

- 2nd mixed cumulants of p, ,pi, K, Q
- **pseudo-rapidity window** $\Delta\eta$
- $0.4 < p_T < 1.6$GeV/c
- Total charge: private comm. A. Chattergee



- ☐ $\sqrt{s_{NN}} = 200$GeV
- ☐ 0-5% centrality
- ☐ Δy dependence
- ☐ Construction of baryon number, p_T-acceptance correction

- ☐ proton → baryon cumulants MK, Asakawa,'12;'12
- ☐ Rapidity is better than pseudo-rapidity Ohnishi, MK, Asakawa, '16
- ☐ Wider acceptance is more desirable.

p_T-Acceptance Correction

p_T Acceptance

$0.4<p_T<1.6$ [GeV/c]

PRC100,014902('19)

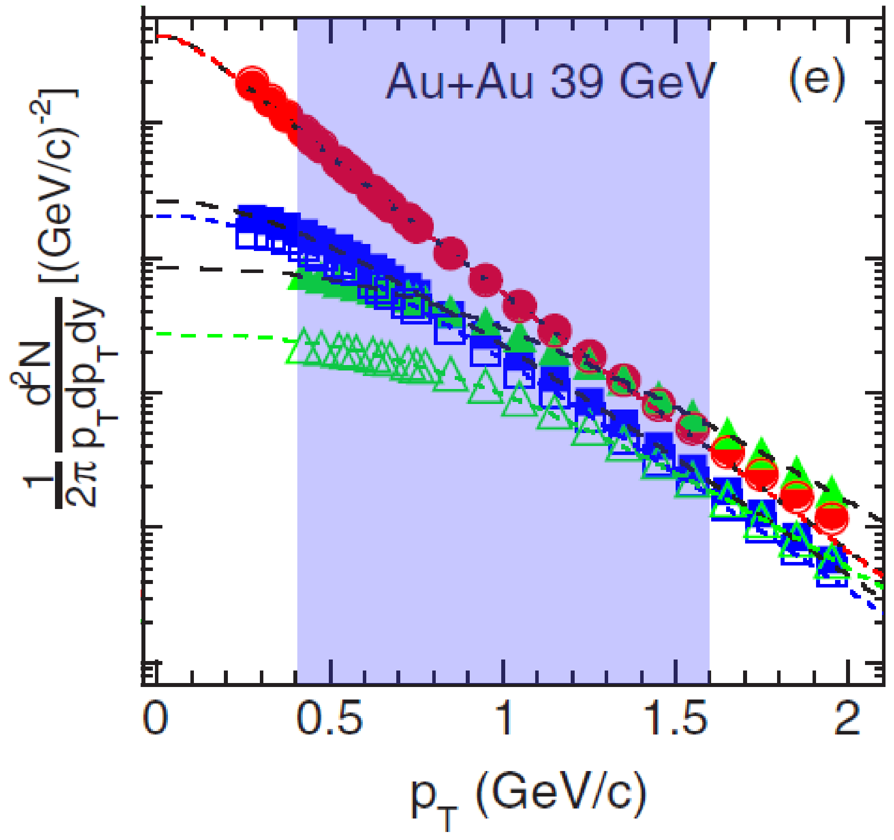
$0.4<p_T<2.0$ [GeV/c]

PRC104,024902('21)

Particles in p_T space

- Electric charge: **49%**
- Protons: **82%**

blast wave model @ $\sqrt{s_{NN}}$=200 GeV



Modification by p_T-cut should be corrected.
This study: Binomial distribution model.

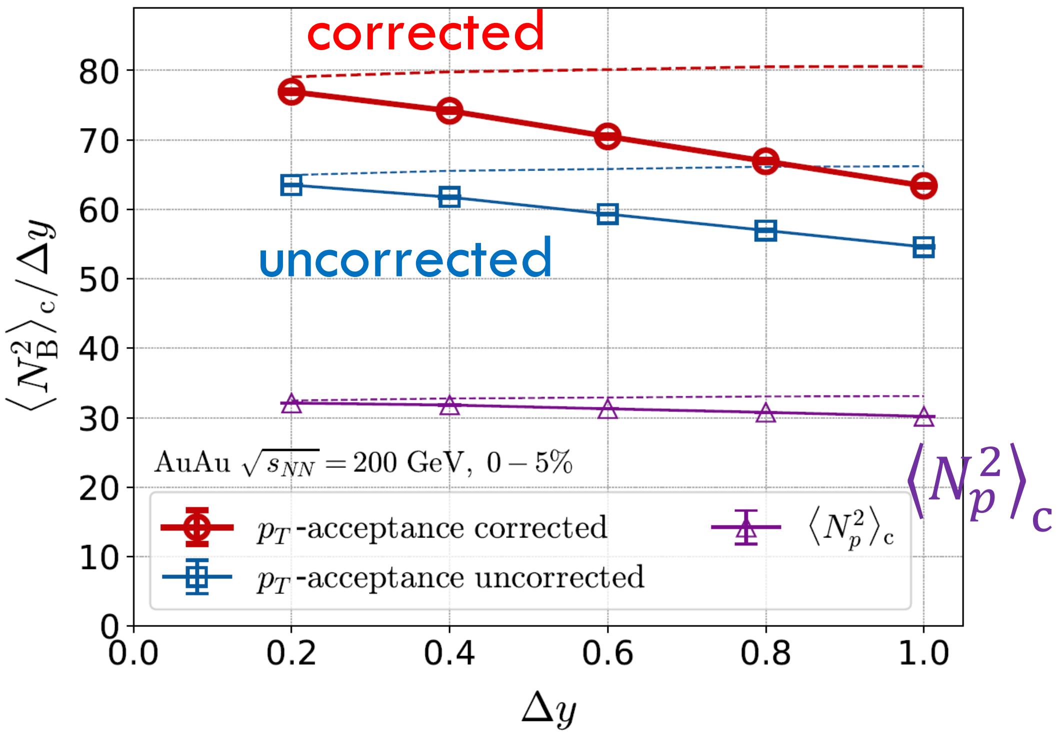
$$\langle N_{\rm net}^2\rangle_c^{\rm corrected} = \frac{1}{p^2}\Big(\langle n_{\rm net}^2\rangle_c - (1-p)\langle n_{\rm tot}\rangle_c\Big)$$

MK, Asakawa, '12, '12

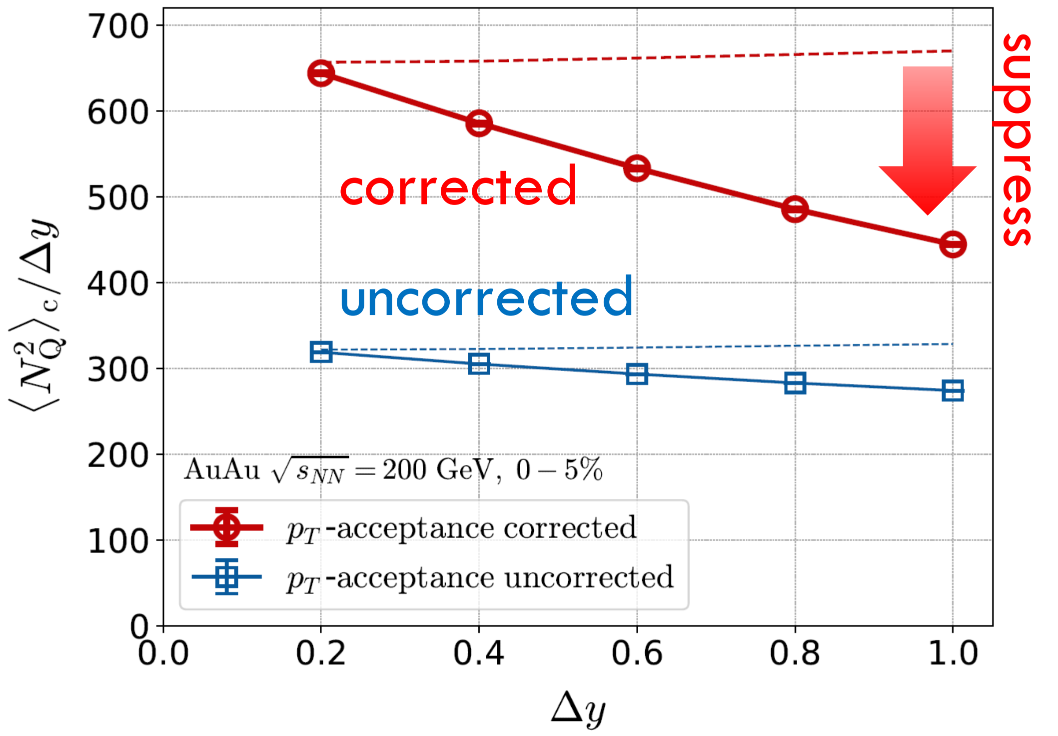
Cumulants: Proton→Baryon & Acceptance Correction

Data from STAR, '19, '21

$\langle N_B^2 \rangle_c / \Delta y$



$\langle N_Q^2 \rangle_c / \Delta y$



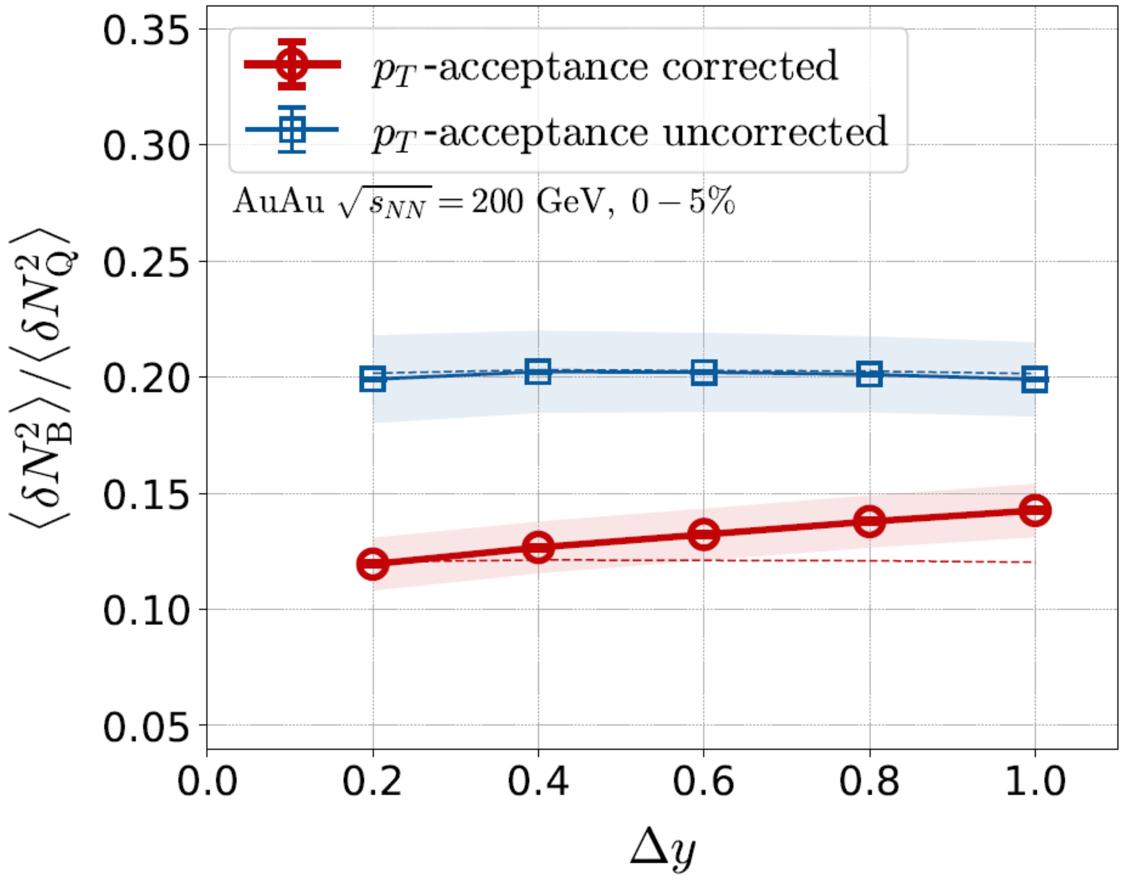
dashed:
$\langle N^{\mathrm{tot}} \rangle$
Poisson

- Deviation from Poissonian is clarified by the acceptance correction.

$$\langle N_{\mathrm{net}}^2 \rangle_c^{\mathrm{corrected}} = \frac{1}{p^2} \Big(\langle n_{\mathrm{net}}^2 \rangle_c - (1-p) \langle n_{\mathrm{tot}} \rangle_c \Big)$$

MK, Asakawa, '12, '12

$\langle N_B^2\rangle_c/\langle N_Q^2\rangle_c$



p_T-acceptance **un**corrected

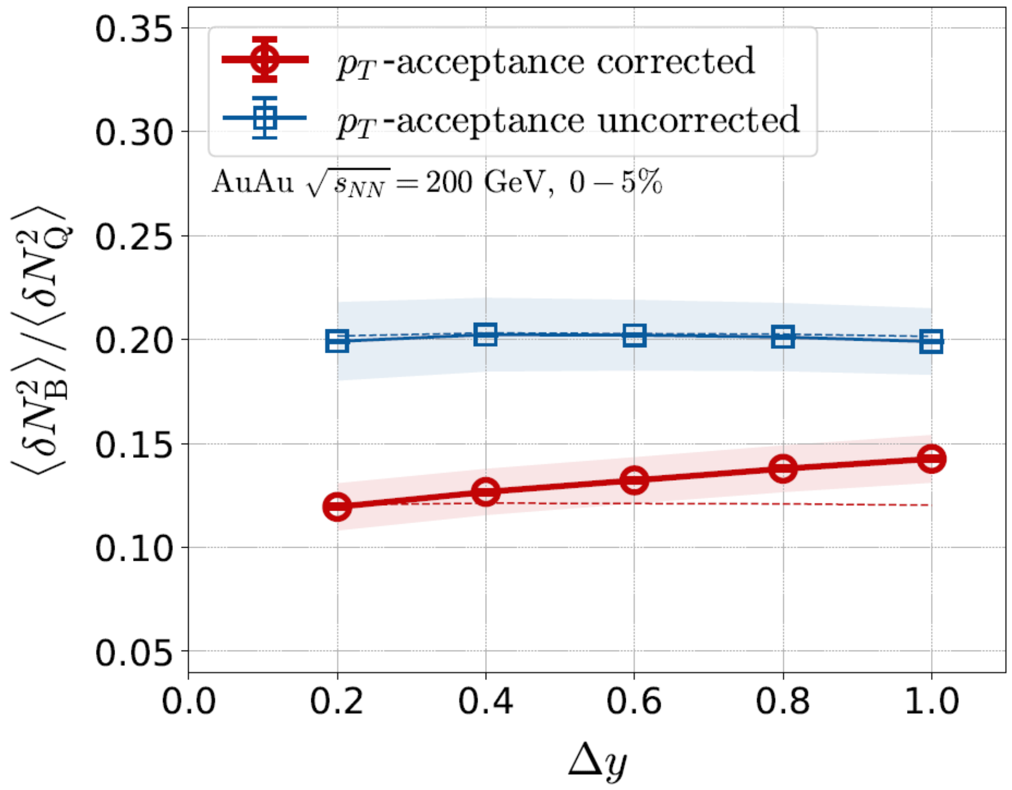
p_T-acceptance corrected

dashed: Poisson

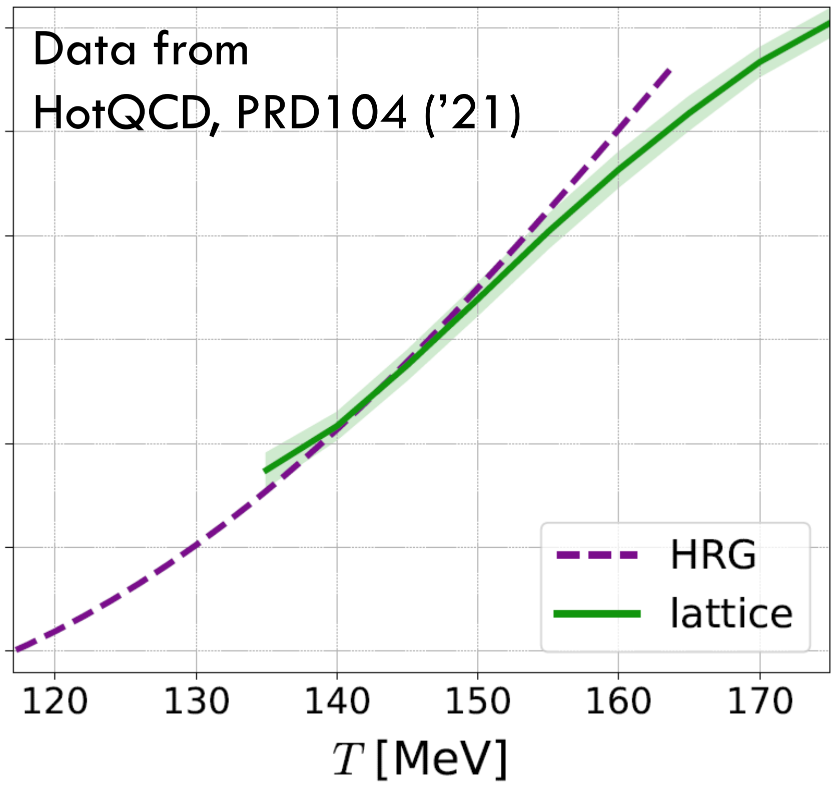
- $\langle N_B^2\rangle_c/\langle N_Q^2\rangle_c$ becomes smaller due to the p_T-acceptance correction.
- Clear Δy dependence → non-thermal effects behind fluctuations

HIC vs HRG&LAT

From data @ STAR



HRG+Lattice

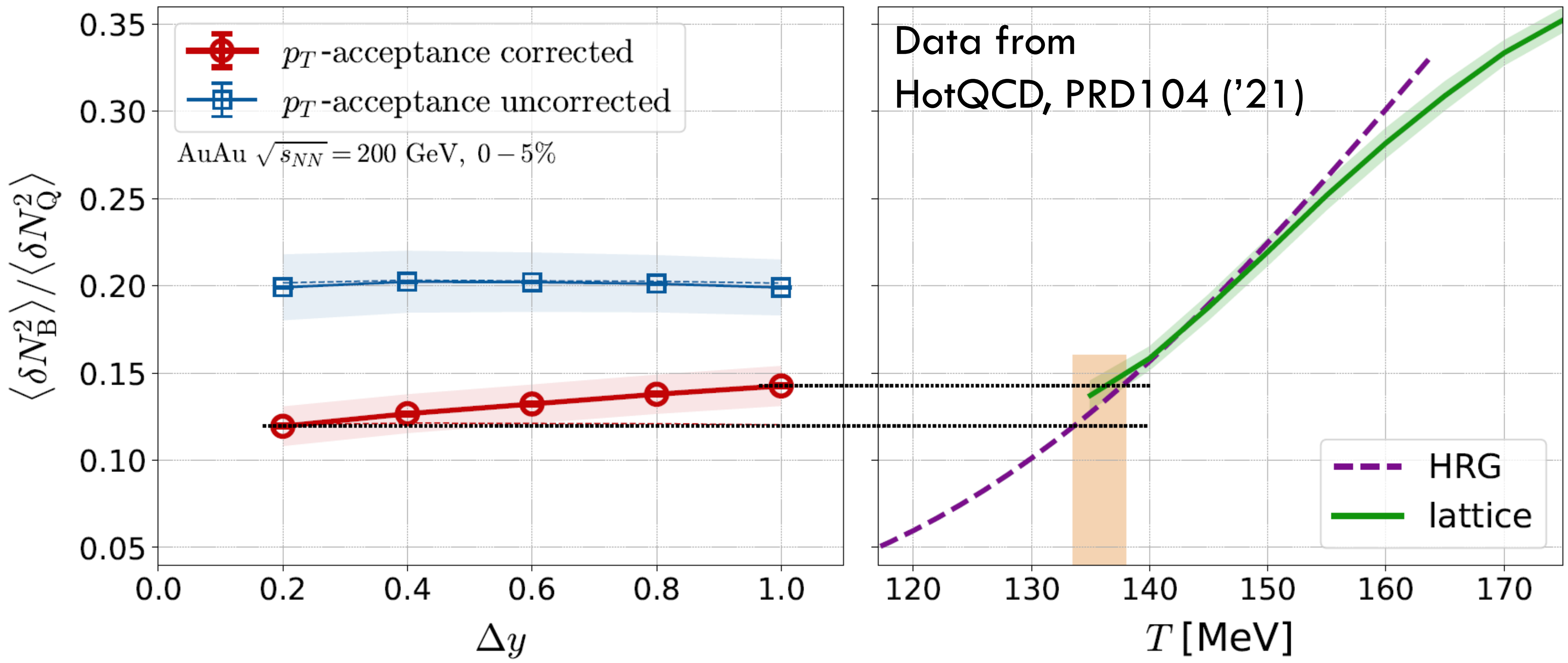


- $T = 134 \sim 138$ **MeV**
- Significantly lower than $T_{\rm chem}$

HRG: QMHRG2020
Bollweg+, PRD104, 7 ('21)
Volume dep. corrected
plot by MK

HIC vs HRG&LAT

From data @ STAR | **HRG+Lattice**



- $T = 134 \sim 138$ **MeV**
- Significantly lower than T_{chem}

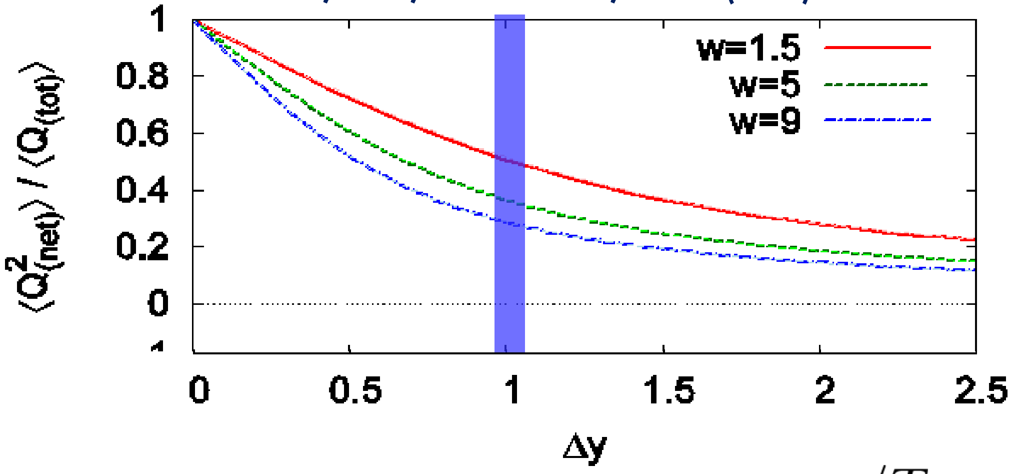
HRG: QMHRG2020
Bollweg+, PRD104, 7 ('21)
Volume dep. corrected
plot by MK

Effect of Diffusion and Rapidity Conversion

- Blurring due to diffusion & rapidity conversion ($Y \to y$)
  - Stronger modification in Q than B
- Resonance Decays
  - About 30% charged particles come from RD
  - Enhancement of charged particles

⇒
- Increase $\langle N_Q^2 \rangle$
- Reduce $\langle N_B^2 \rangle_c / \langle N_Q^2 \rangle_c$

Ohnishi, MK, Asakawa, PRC ('16)



$w = m/T$

These effects will be more important for higher order cumulants!

Three Topics

1 Event-by-event fluctuations of conserved charges

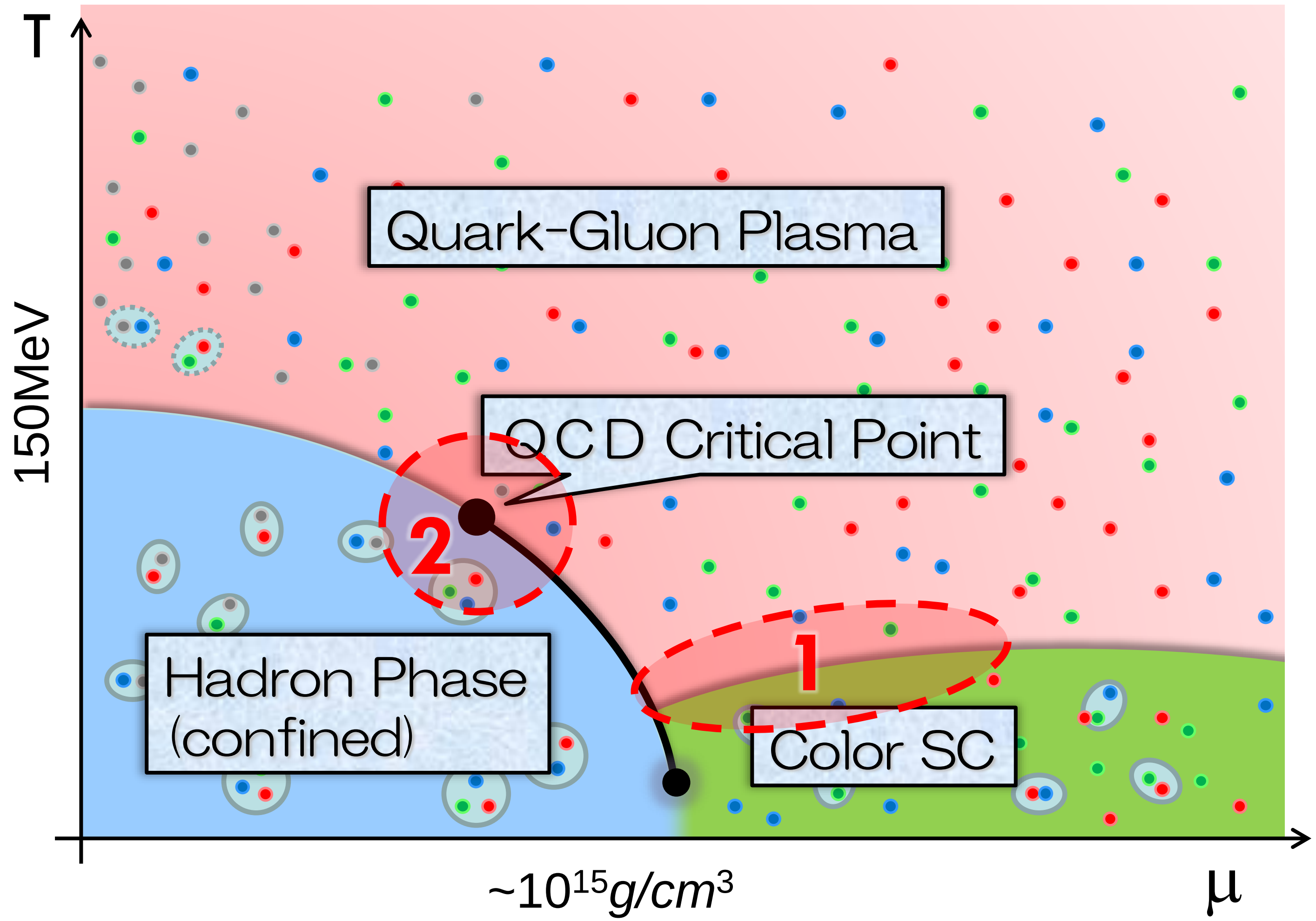
MK, Esumi, Nonaka, 2205.10030

2 Dilepton production rate at ultra-low-mass region as a signal of QCD phase transitions

Talk by Nishimura, yesterday; Nishimura, MK, Kunihiro, 2302.03191; 2201.01963

3 Event selections

Purpose



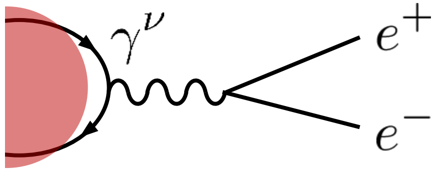
Explore

1. color superconductivity
   Nishimura+, PTEP2022, 093D02 ('22)
2. QCD critical point
   Nishimura+, PTEP2023, in press

in heavy-ion collisions

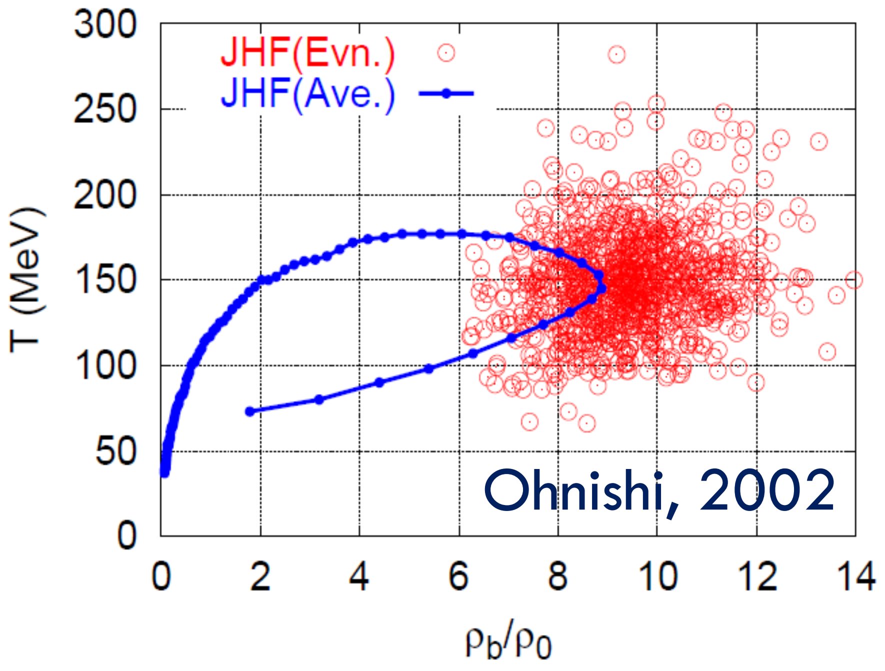
using

dilepton production rate



Observing CSC in HIC

- **Difficulties**
  - CSC would not be created if Tc is not high enough.
  - Even if created, its lifetime would be short.
  - Since CSC is created in the early stage, its signal would be blurred during the evolution in later stage.



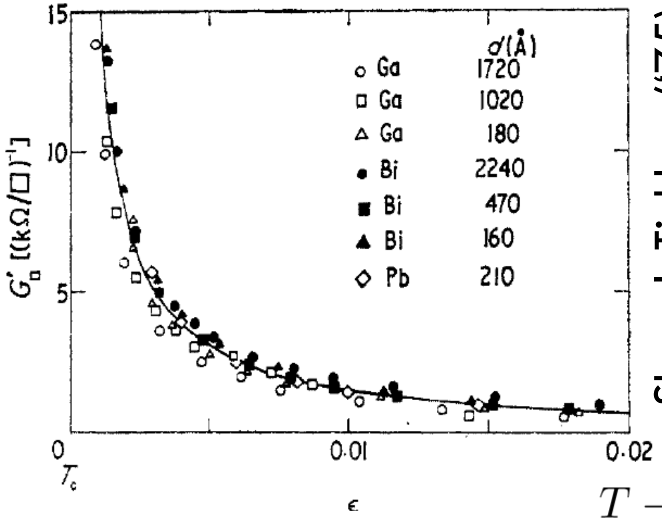
- **Strategy** in the present study:
  - Focus on precursory phenomena of CSC
  - Use dilepton production as an observable

Precursor of CSC

- **Anomalous behavior of observables near but above Tc of SC**
  - electric conductivity
  - magnetic susceptibility
  - pseudogap

- Enhanced pair fluctuations is one of the origins of precursory phenomena.
- More significant phenomena in strongly-coupled systems.

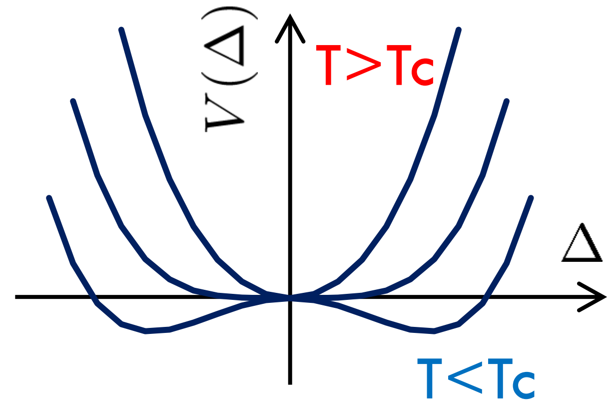
Electric conductivity



Skopal, Tinkham('75)

$$\varepsilon = \frac{T - T_c}{T_c}$$

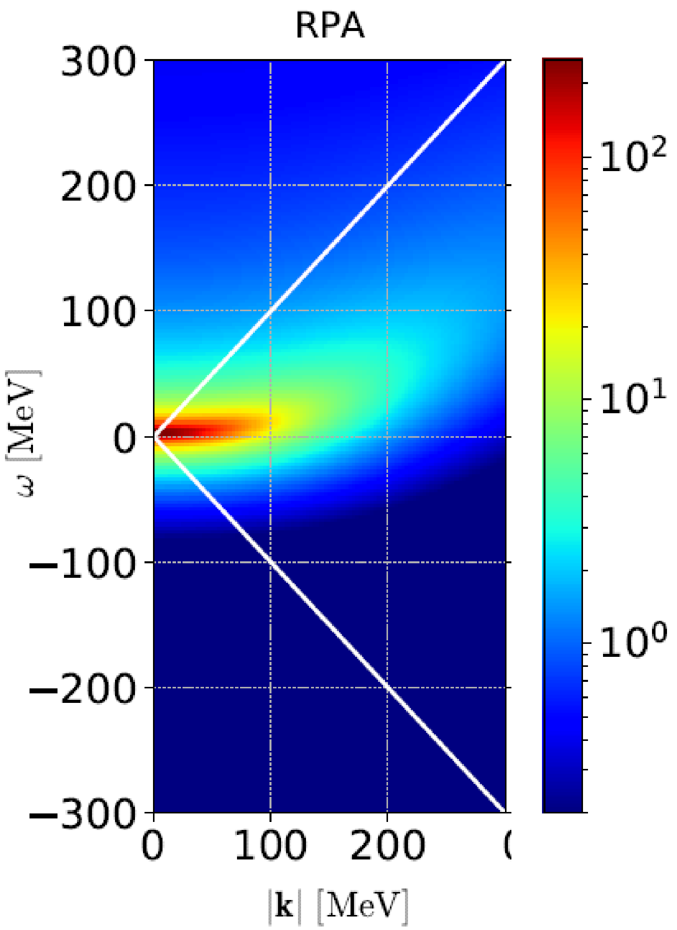
Landau's free energy



Dilepton Production from Soft Modes

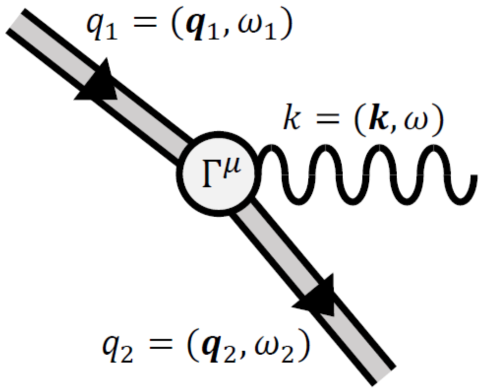
Soft Mode

- 2nd order phase transition ➔ massless mode $m \sim 1/\xi$
- CSC: diquark modes
- QCD-CP: $q\bar{q}$ modes



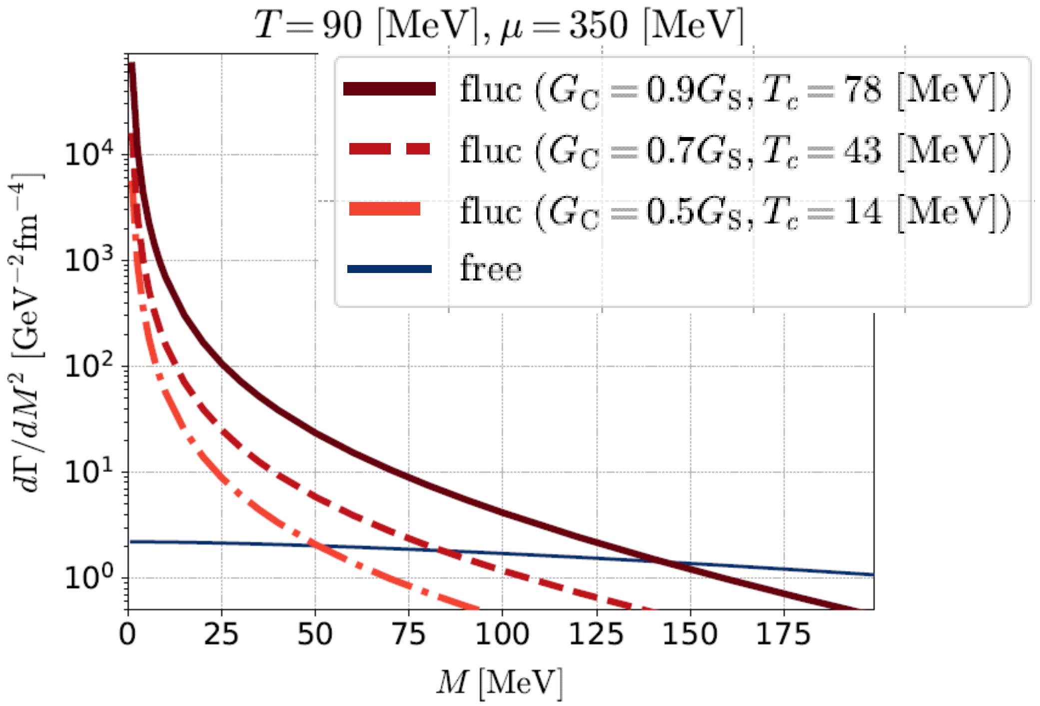
Dilepton Production

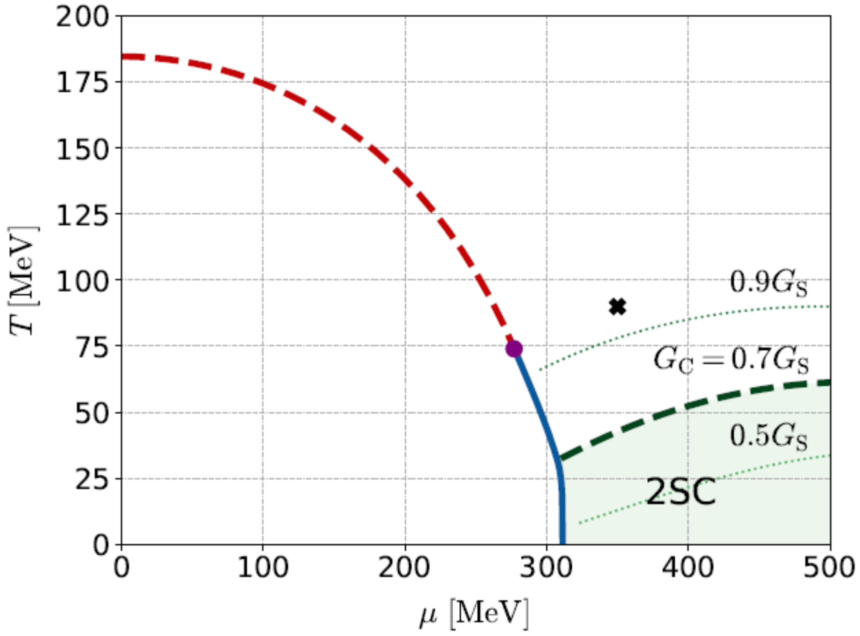
- Many soft modes in the system
- scattering of soft modes
- dilepton production at low ω, p



Dilepton Production from Diquark Soft Modes

Fixed Temperature





- Strong enhancement at low invariant mass, though the range of M is narrower than the previous results.
- **Observable in the HIC?**

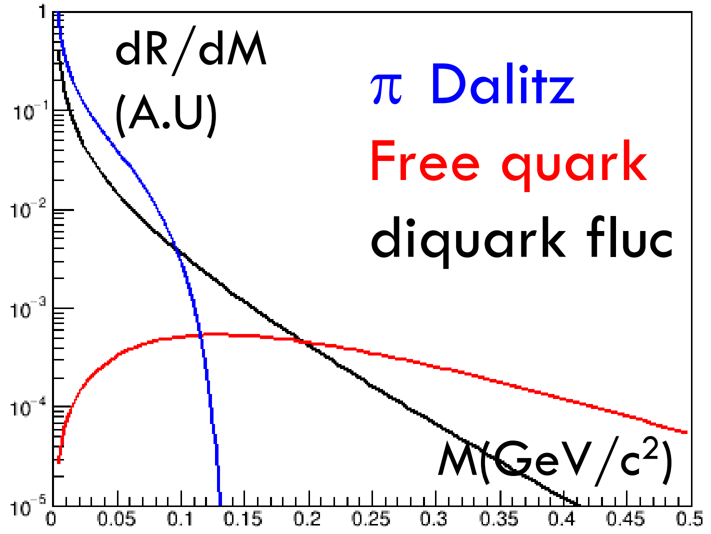
Challenges

Experimental

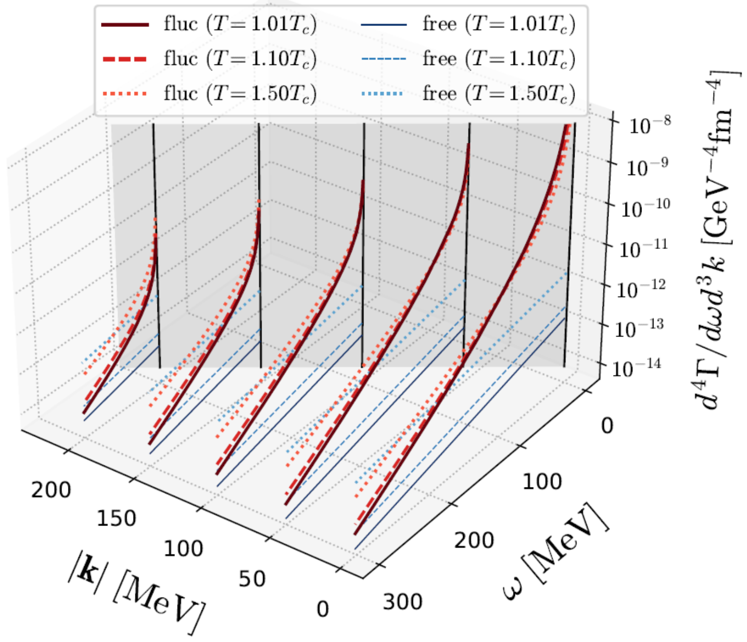
- Measurement in the ultra-low-mass region $m < 100\text{MeV}$.
  - Contaminated by Dalitz decay
  - Adjustment of magnetic field, etc.
- Accurate measurement of hadron yield, especially π^0.
- Measurement in (ω, p) plane

Theoretical

- Other production mechanisms in the ULMR
  - pQCD, hadronic, lattice, etc.
  - transport peak
- Momentum dependence



Analysis by Y. Morino



Three Topics

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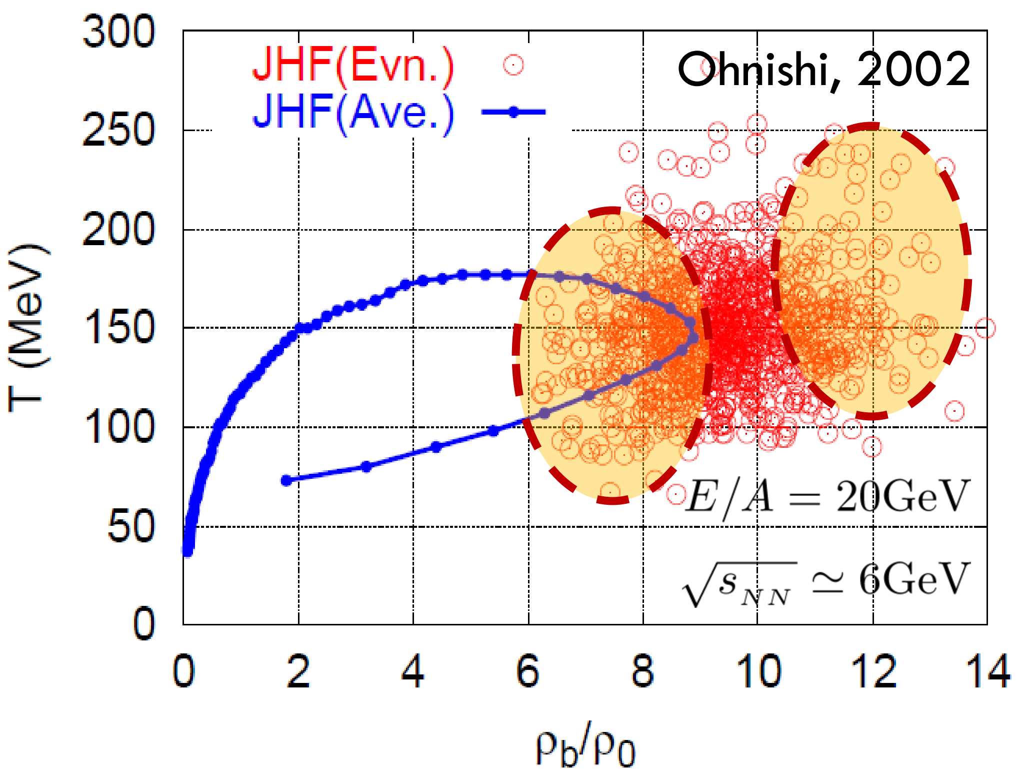
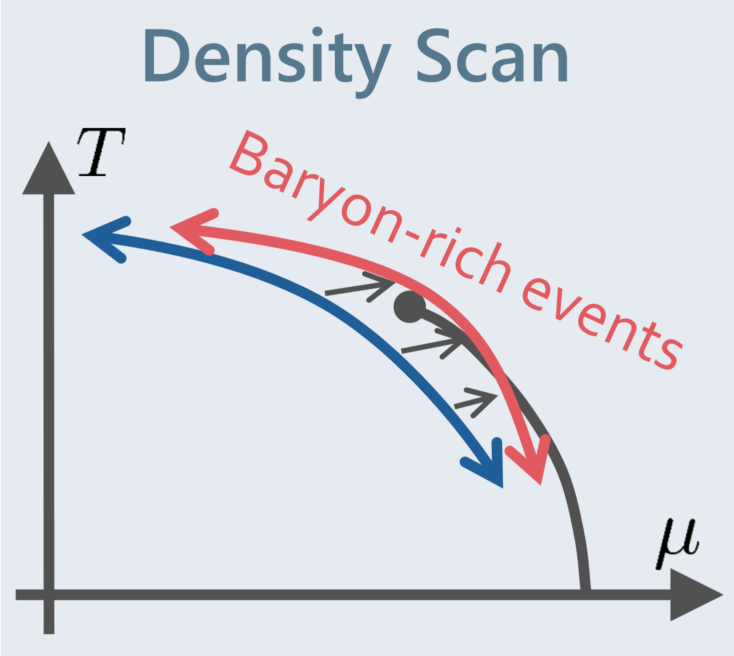
3 Event selections

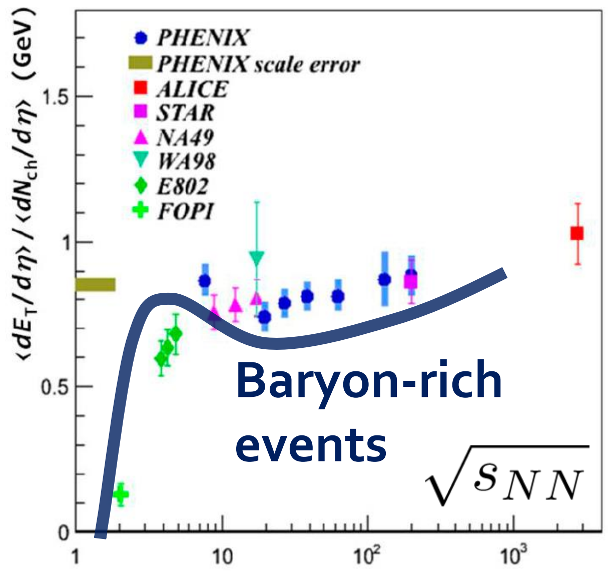
Sophisticated Event Selections

- Maximum baryon density has large event-by-event fluctuations

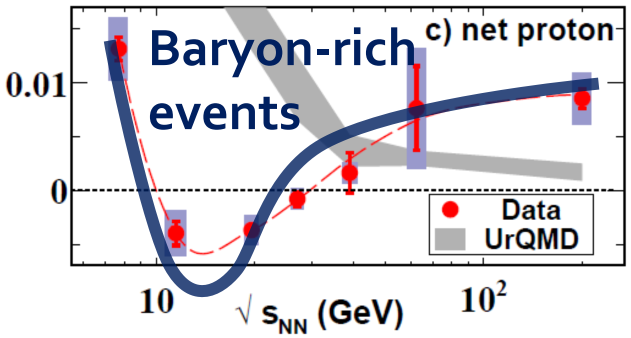




average transverse energy



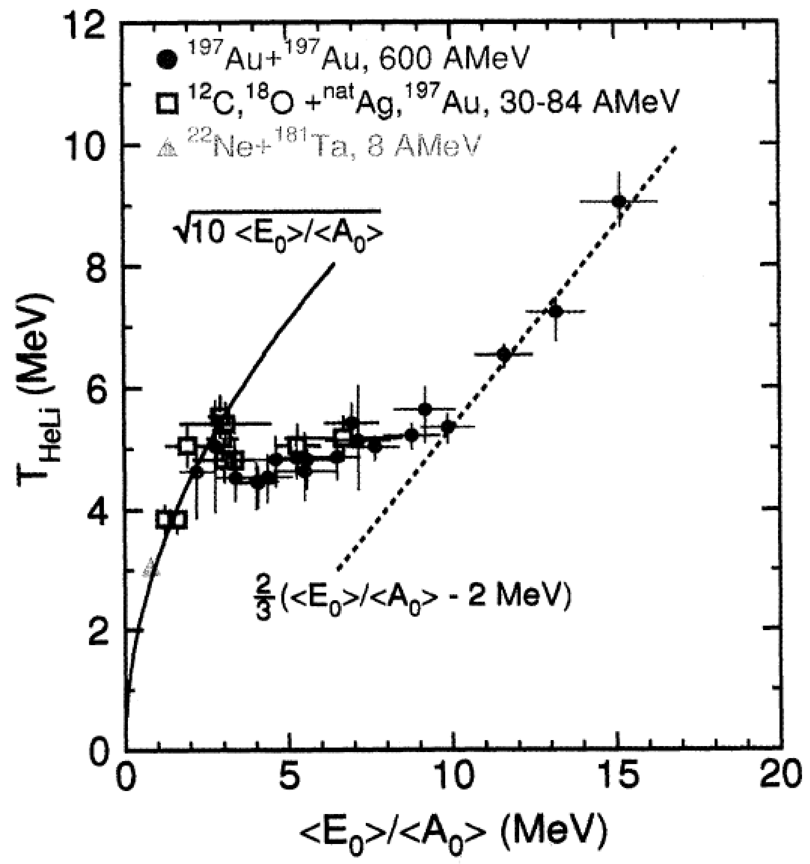
directed flow



- Event selection in terms of maximum baryon density (or, correlation analysis) should be a useful tool.

Nuclear Liquid-Gas Phase Transition

Pochodzalla+, PRL, 75, 1040 ('95)



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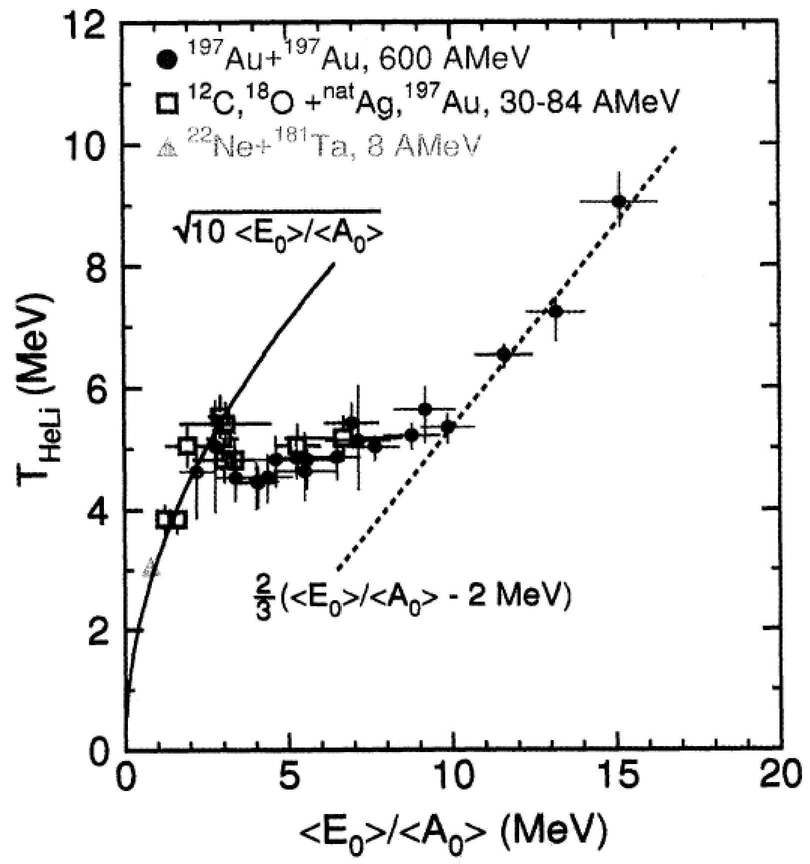
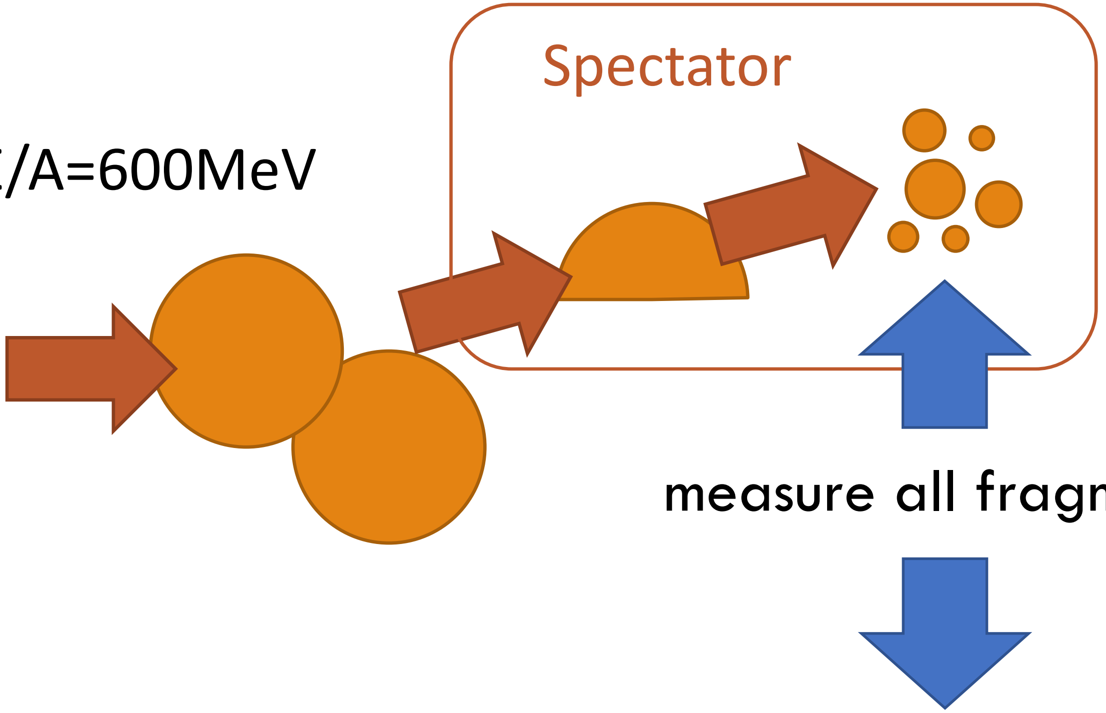


Experiment:



- ☐ Similar analysis in relativistic HIC requires **event-by-event total energy of the fireball.**

Summary

- Heavy-ion collisions will reveal phase transitions in dense QCD.
- We discussed 3 observables/method:
  - Event-by-event fluctuations of conserved charges
  - Dilepton production at ultra-low-mass-region
  - Event selection via baryon/energy density

- In each method, further refinements are necessary.