Rapidity scan approach for net-baryon cumulants with a statistical thermal model

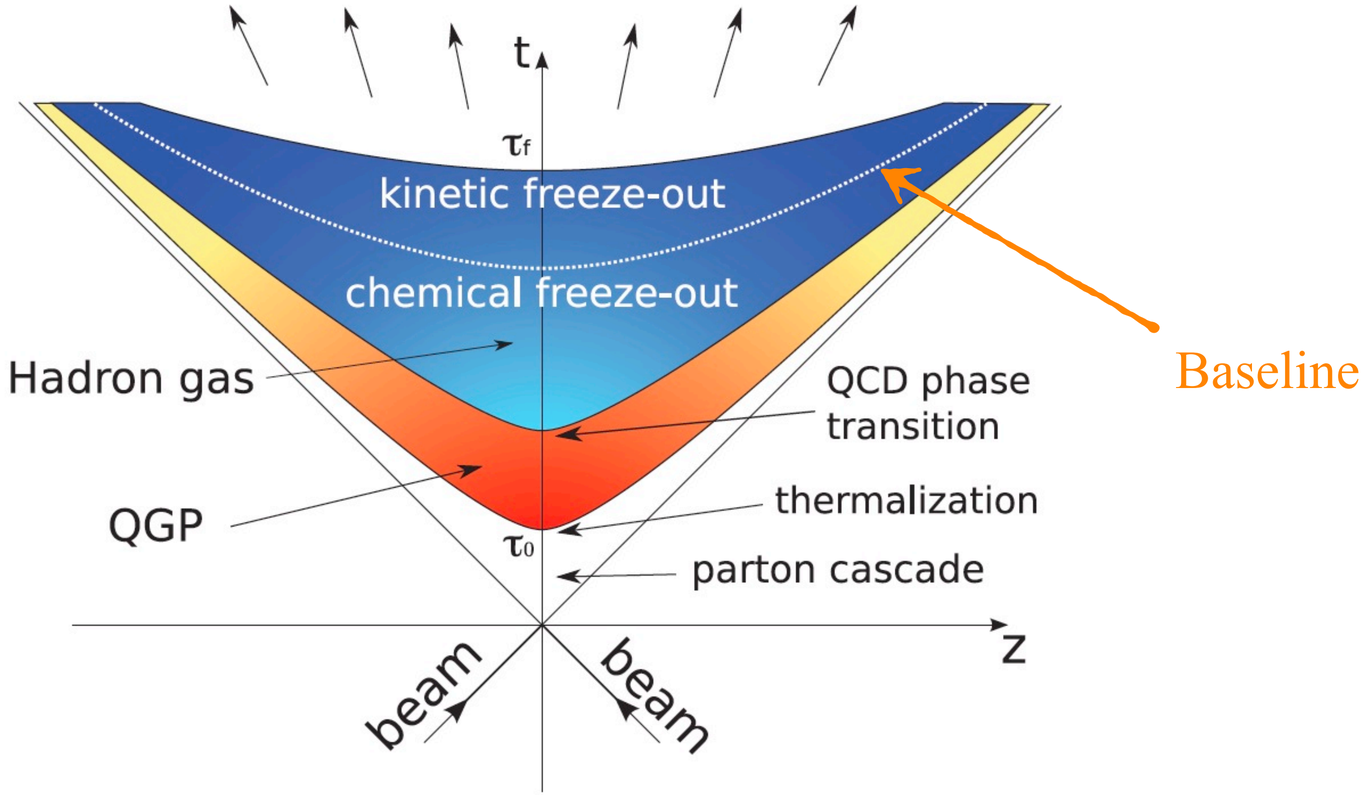
arXiv: 2311.11374 [nucl-th]

Jianing Li (IMP), Lipei Du (McGill) and Shuzhe Shi (Tsinghua)

Outline

- Introduction
- Net-baryon cumulants of inhomogeneous system in rapidity scan
- Extraction of thermodynamic variables on QCD phase diagram
- Summary and Outlook

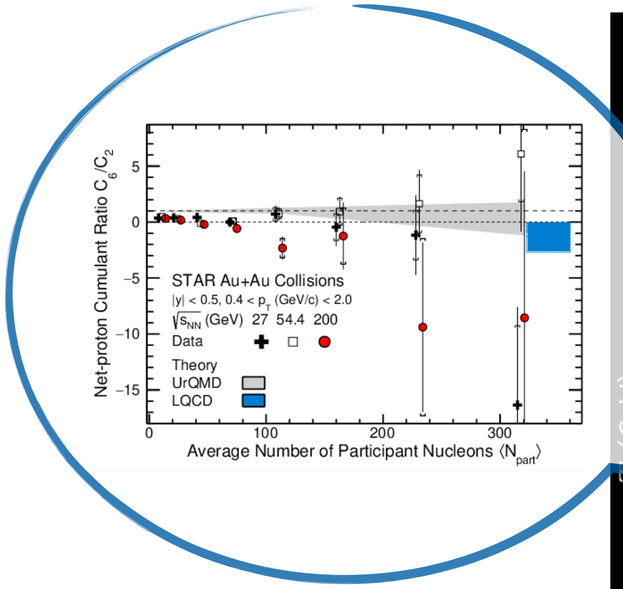
Spacetime evolution

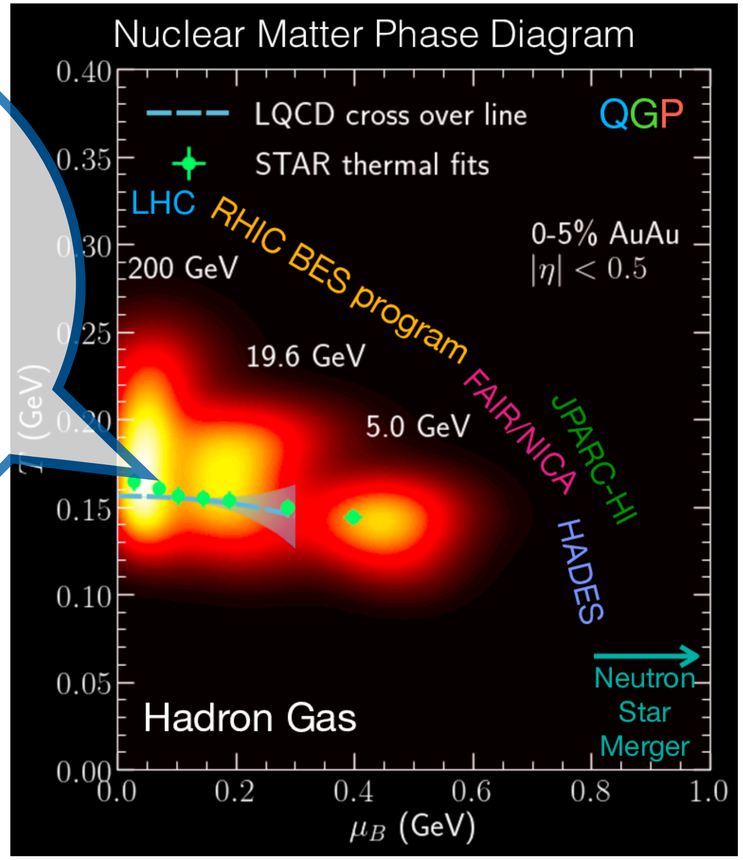


Space-time Evolution of a Heavy Ion Collision

Shusu Shi, *Event anisotropy v_2 at STAR*, PhD Thesis.

QCD phase diagram & critical endpoint (CEP)





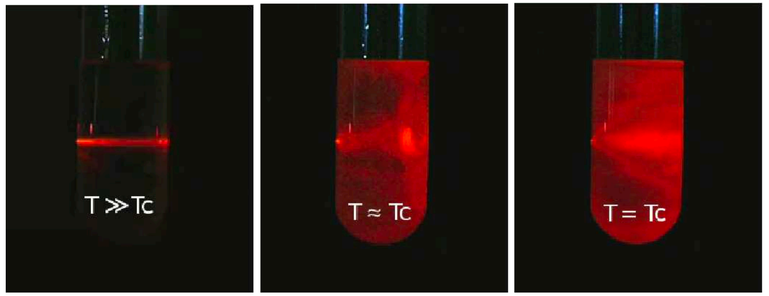
"… seem to favor a smooth crossover…"

STAR Collaboration,
Phys. Rev. Lett. 127, 262301

Beam energy scan & QCD phase diagram

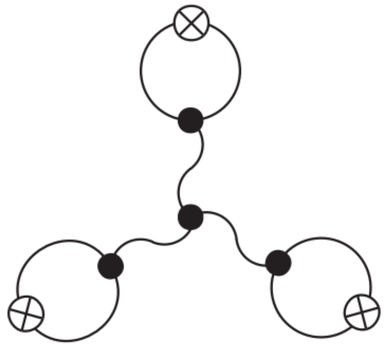
C. Shen, *in 28th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions*

Critical point: large ξ & fluctuations

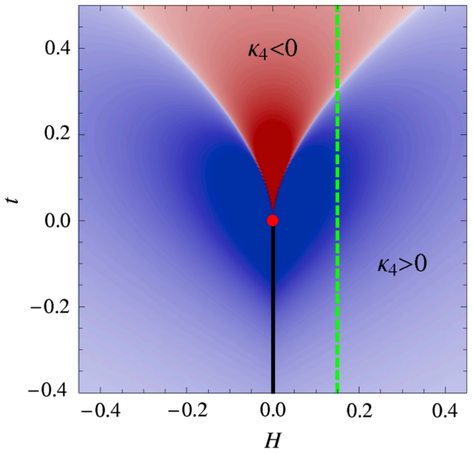


Enhancement

$$\kappa^n \propto \xi^{\frac{5}{2}n-3}$$

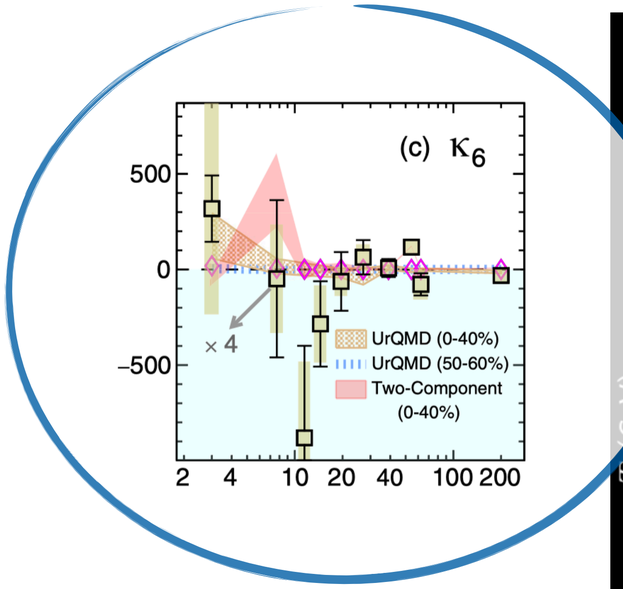


Non-monotonicity



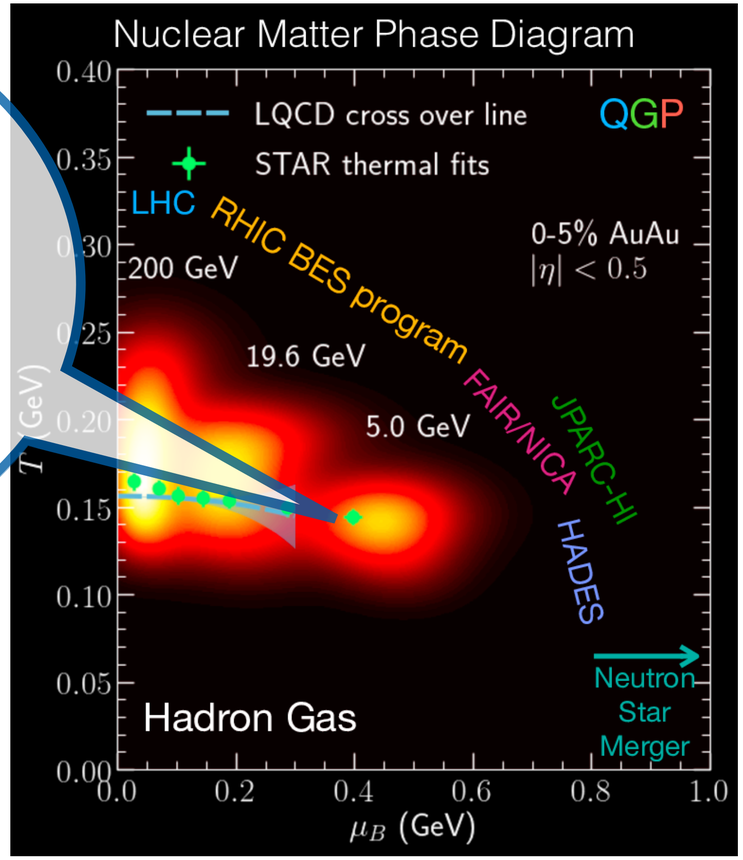
M. A. Stephanov, *Phys. Rev. Lett. 102, 032301*
M. A. Stephanov, *Phys. Rev. Lett. 107, 052301*

QCD phase diagram & critical endpoint (CEP)



"… expected from a first-order phase transition…"

STAR Collaboration,
Phys. Rev. Lett. 130, 082301



Beam energy scan & QCD phase diagram

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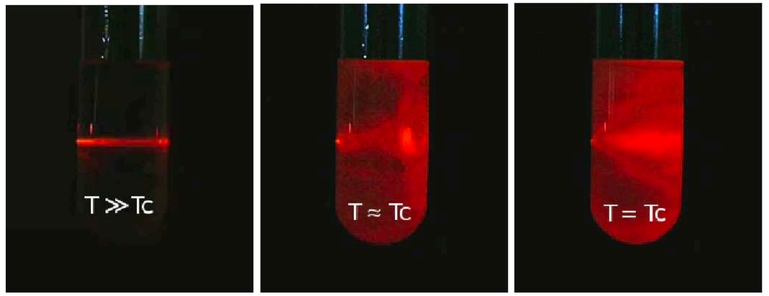

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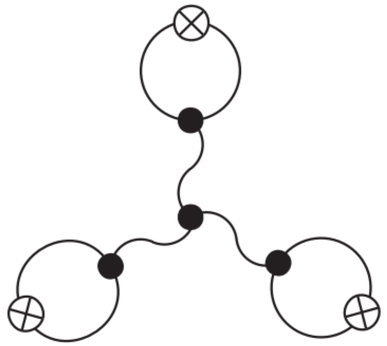
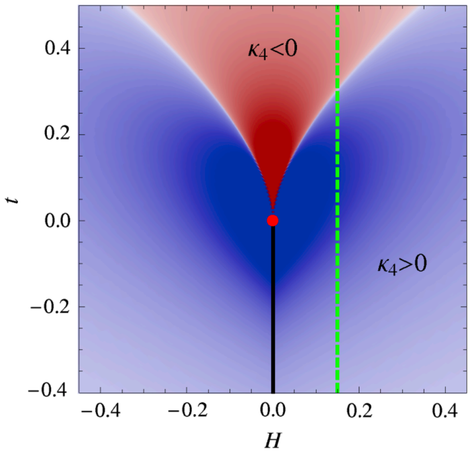


Non-monotonicity



M. A. Stephanov, *Phys. Rev. Lett. 102, 032301*
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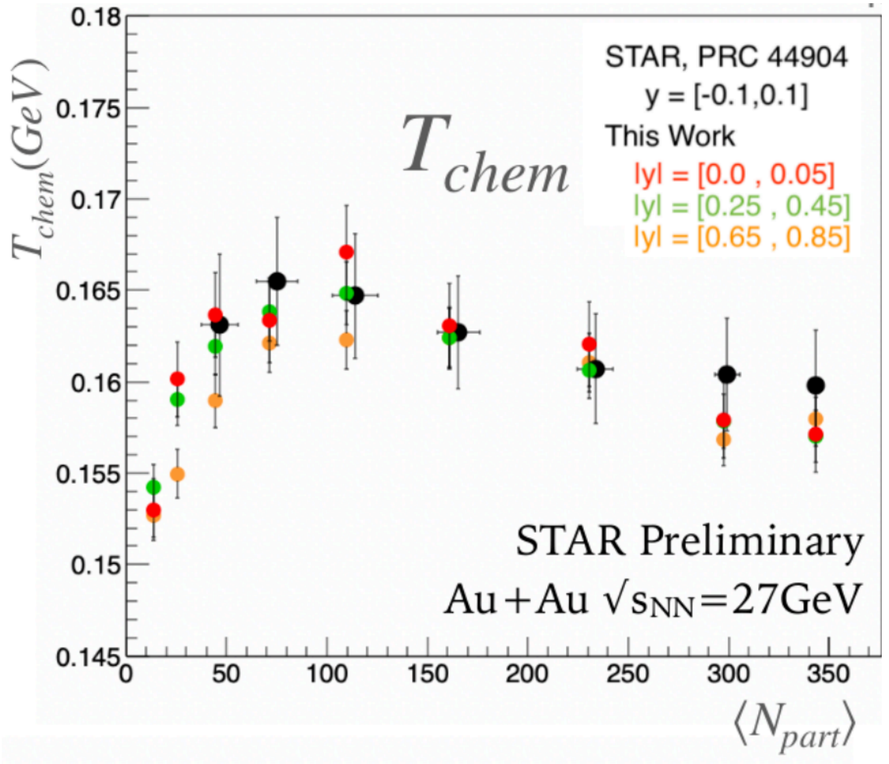
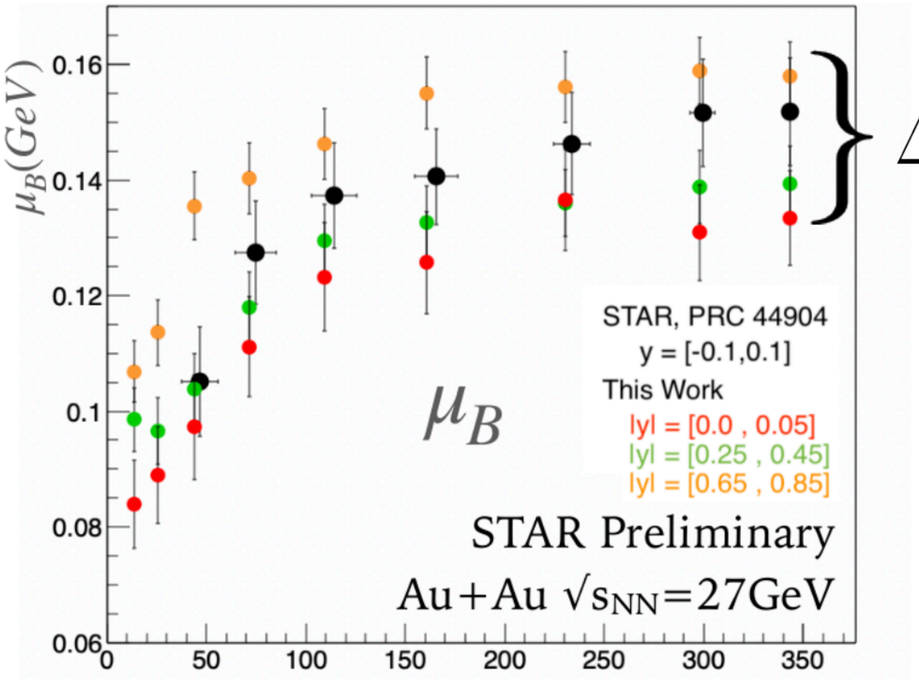
Rapidity scan



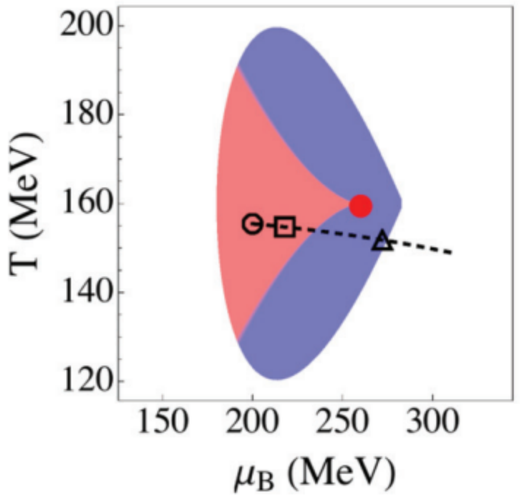


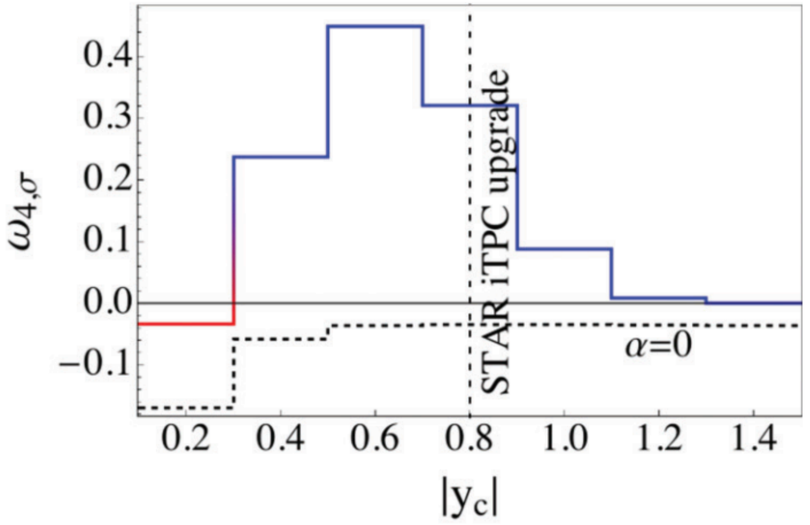
Chemical freeze-out fit by THERMUS at 27 GeV

H. Matthew, *Particle Production in Au+Au Collisions at Beam Energy Scan II Energies at RHIC, QM2023*

Rapidity scan can study QCD phase diagram in detail.

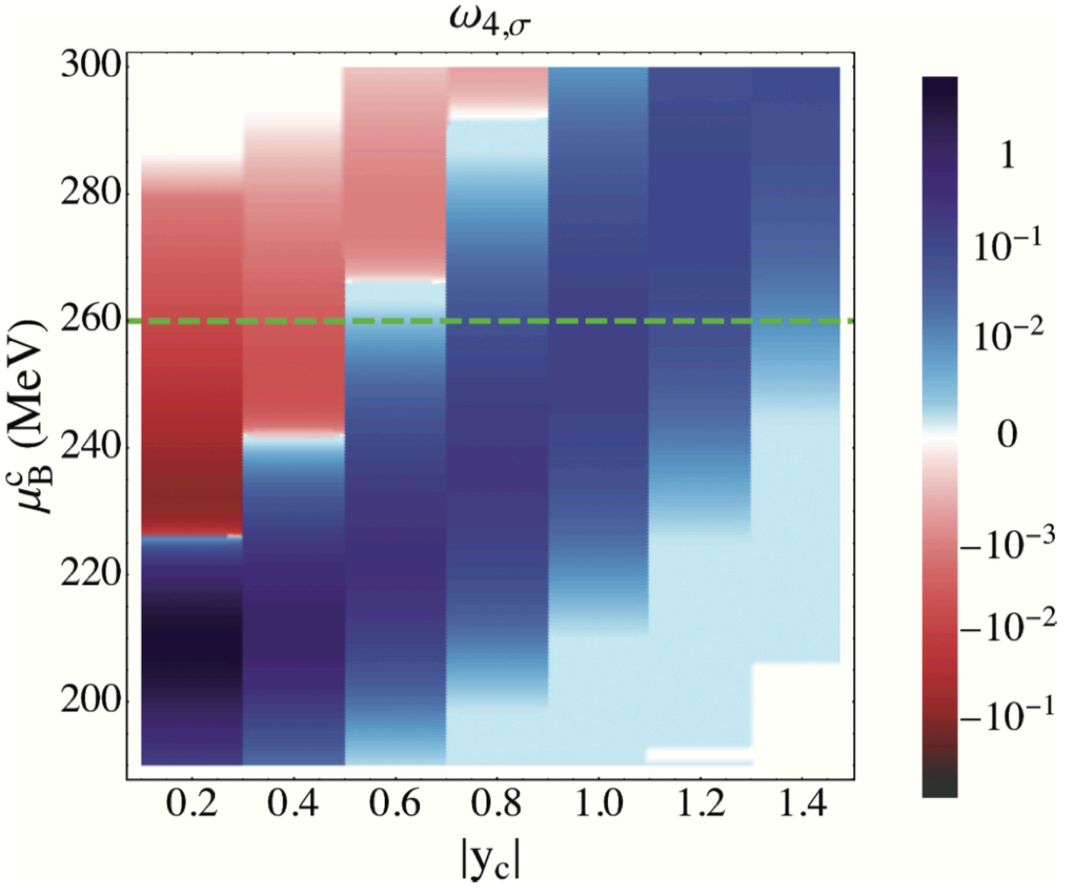
Rapidity scan





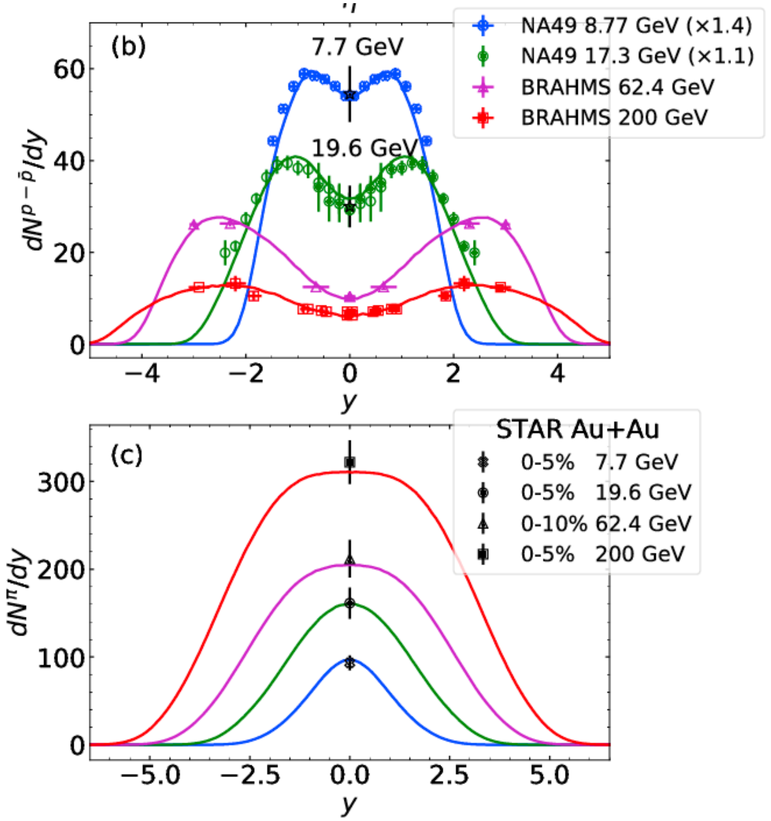
Rapidity scan based on 3D Ising model

J. Brewer, S. Mukherjee, K. Rajagopal, and Y. Yin, *Phys. Rev. C 98, 061901(R)*



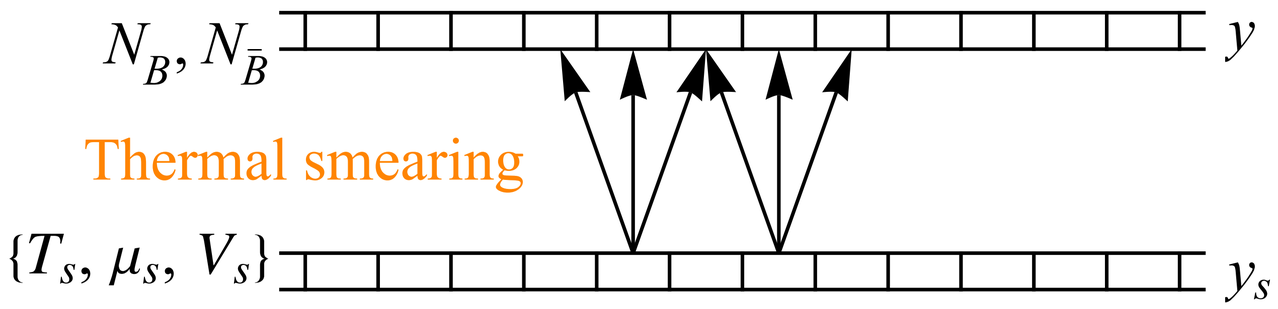
Rapidity scan can search CEP in detail.

Particles radiated from an inhomogeneous fireball

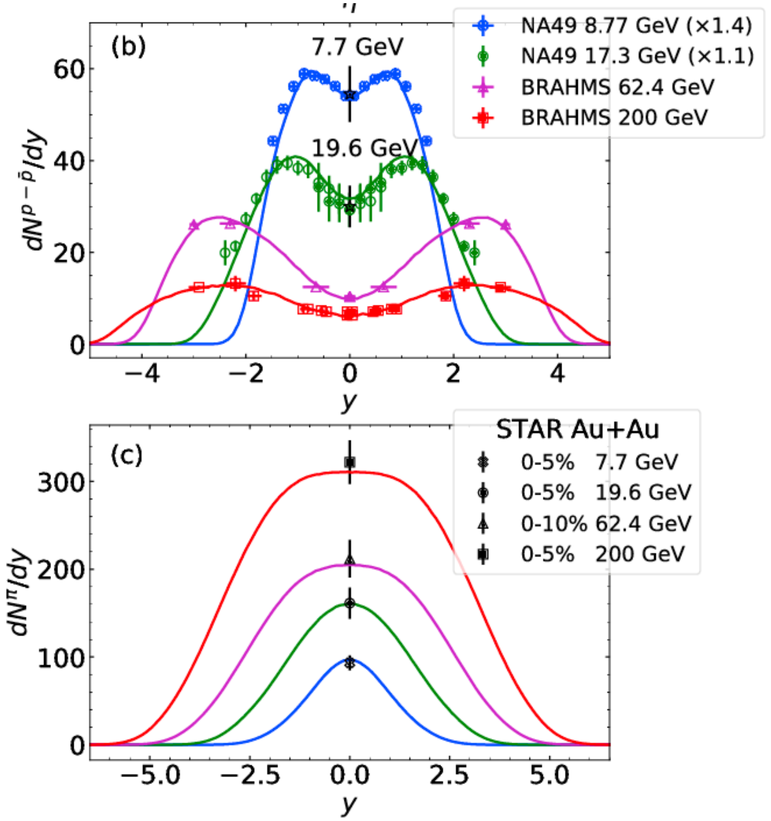


L. Du, H. Gao, S. Jeon and C. Gale,
arXiv: 2302.13852 [nucl-th]

Particles radiated from an inhomogeneous fireball



Particles radiated from an inhomogeneous fireball



L. Du, H. Gao, S. Jeon and C. Gale,
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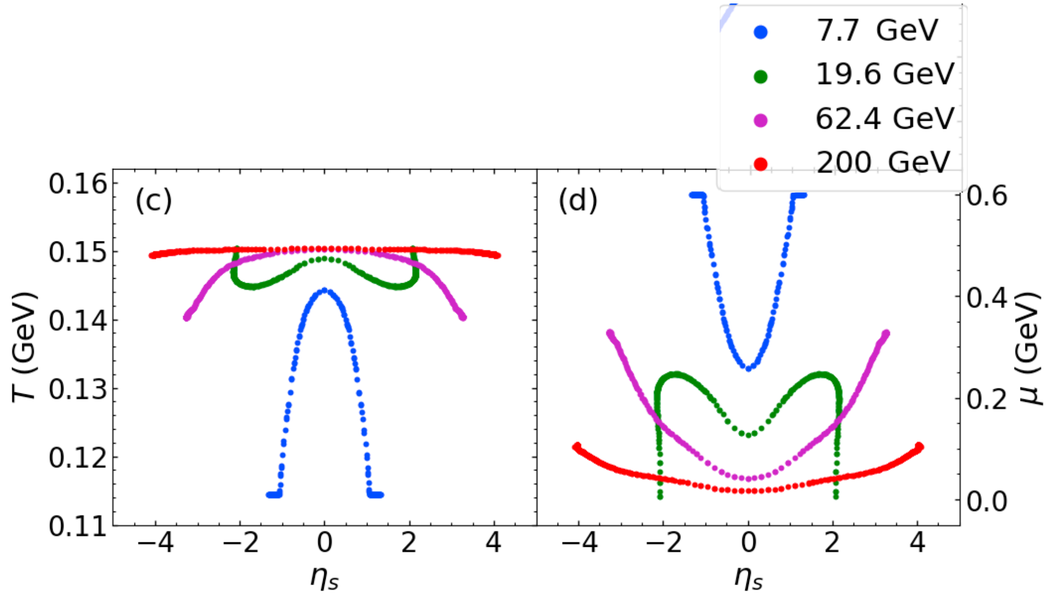
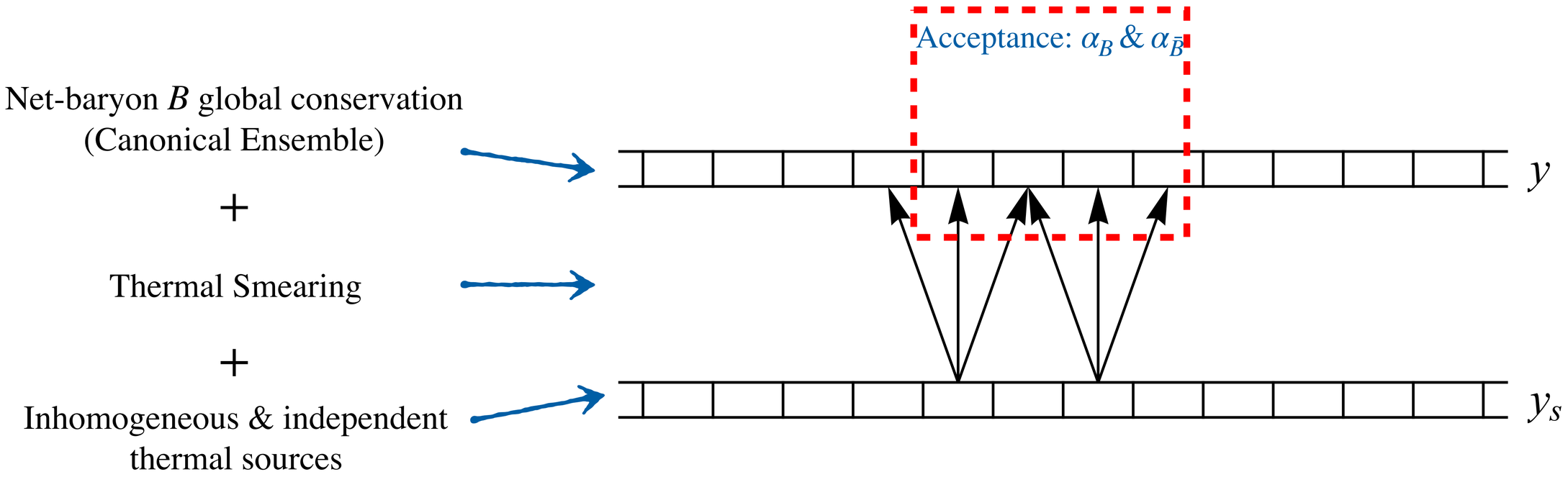


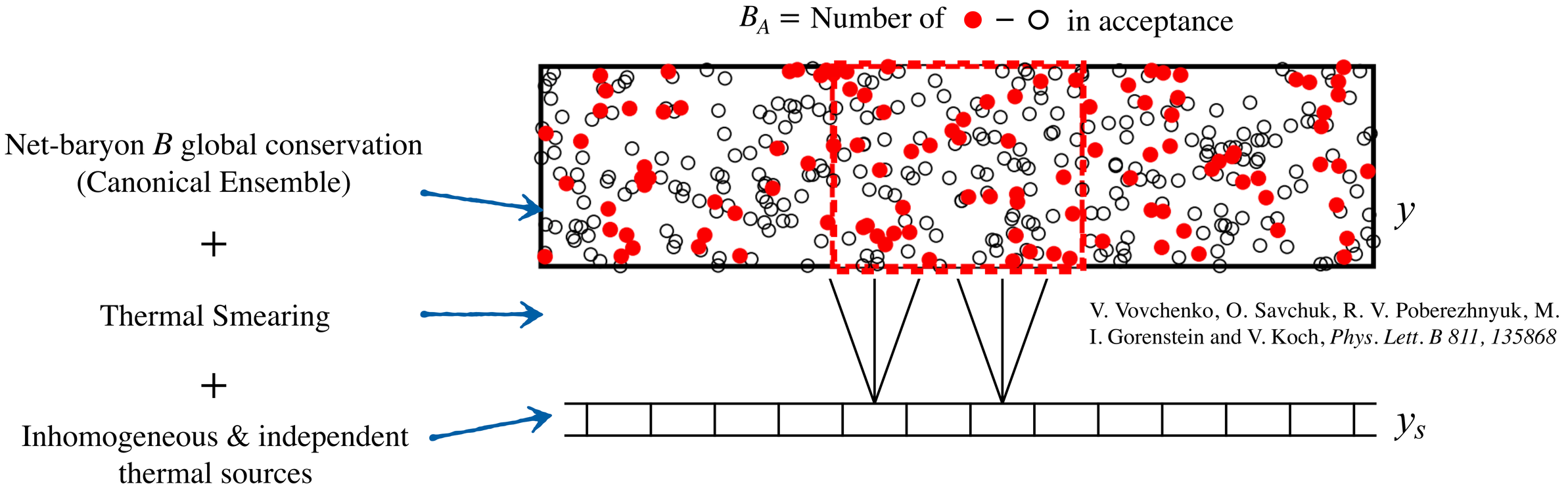
Inhomogeneous fireballs are extracted.

Particles radiated from an inhomogeneous fireball



Framework of rapidity scan based on continuous-source model

Particles radiated from an inhomogeneous fireball



Framework of rapidity scan based on continuous-source model

"...the net baryon number fluctuates due to the finite acceptance."

P. Braun-Munzinger, B. Friman, K. Redlich, A. Rustamov and J. Stachel, *Nucl. Phys. A 1008, 122141*

Cumulant generating function in finite acceptance range

Cumulant generating function

$$g_B(t) = \frac{B}{2}\ln\left[\frac{q_1(t)}{q_2(t)}\right] + \ln\left\{I_B\left[2\sqrt{\mathcal{Z}\bar{\mathcal{Z}}}\sqrt{q_1(t)\,q_2(t)}\right]\right\}$$

JL, L. Du and S. Shi, 2311.11374 [nucl-th]

$$q_1(t) = 1 + \alpha_B + \alpha_B e^{t}$$

$$q_2(t) = 1 + \alpha_{\bar{B}} + \alpha_{\bar{B}} e^{-t}$$

$$\mathcal{Z} = \langle N_B \rangle$$

$$\bar{\mathcal{Z}} = \langle N_{\bar{B}} \rangle$$

$$\kappa_n^B = \left.\frac{\partial^n g_B(t)}{\partial t^n}\right|_{t=0}$$

The 1st to 6th cumulants

$$\kappa_1^B = \langle B_A \rangle$$

$$\kappa_2^B = \left\langle (\delta B_A)^2 \right\rangle$$

$$\kappa_3^B = \left\langle (\delta B_A)^3 \right\rangle$$

$$\kappa_4^B = \left\langle (\delta B_A)^4 \right\rangle - 3\left\langle (\delta B_A)^2 \right\rangle^2$$

$$\kappa_5^B = \left\langle (\delta B_A)^5 \right\rangle - 10\left\langle (\delta B_A)^3 \right\rangle \left\langle (\delta B_A)^2 \right\rangle$$

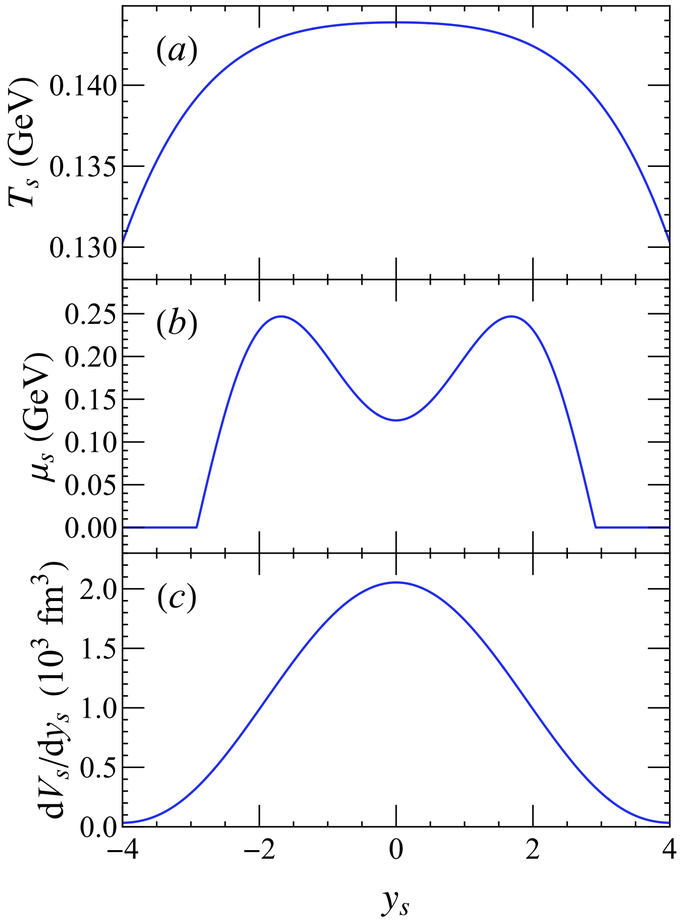
$$\kappa_6^B = \left\langle (\delta B_A)^6 \right\rangle - 15\left\langle (\delta B_A)^4 \right\rangle \left\langle (\delta B_A)^2 \right\rangle - 10\left\langle (\delta B_A)^3 \right\rangle^2 + 30\left\langle (\delta B_A)^2 \right\rangle^3$$

$$\delta B_A = B_A - \langle B_A \rangle$$

X. Luo and N. Xu, *Nucl. Sci. Tech. 28, 112*

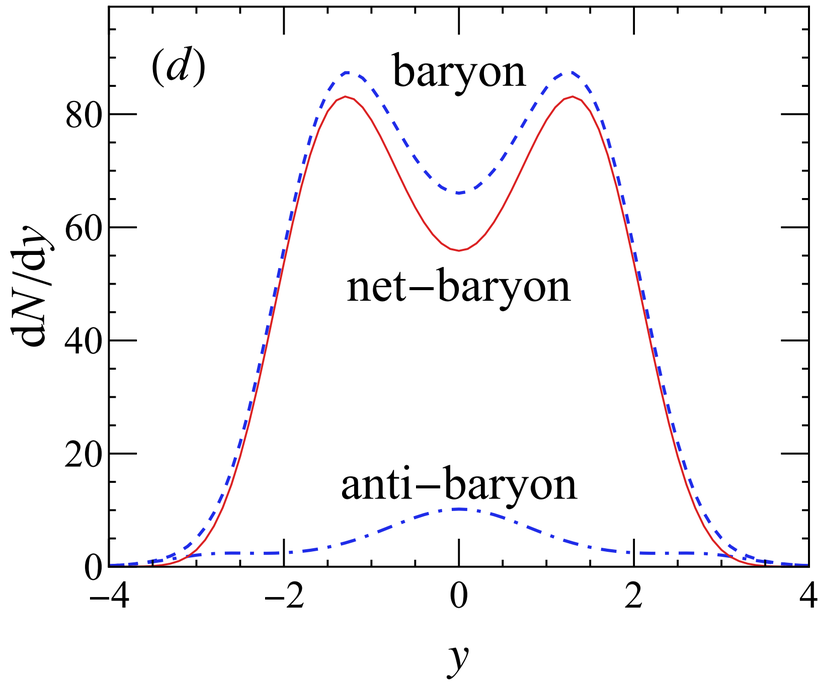
(Anti-)baryons yields in Au + Au @ 19.6 GeV

Inhomogeneous fireball

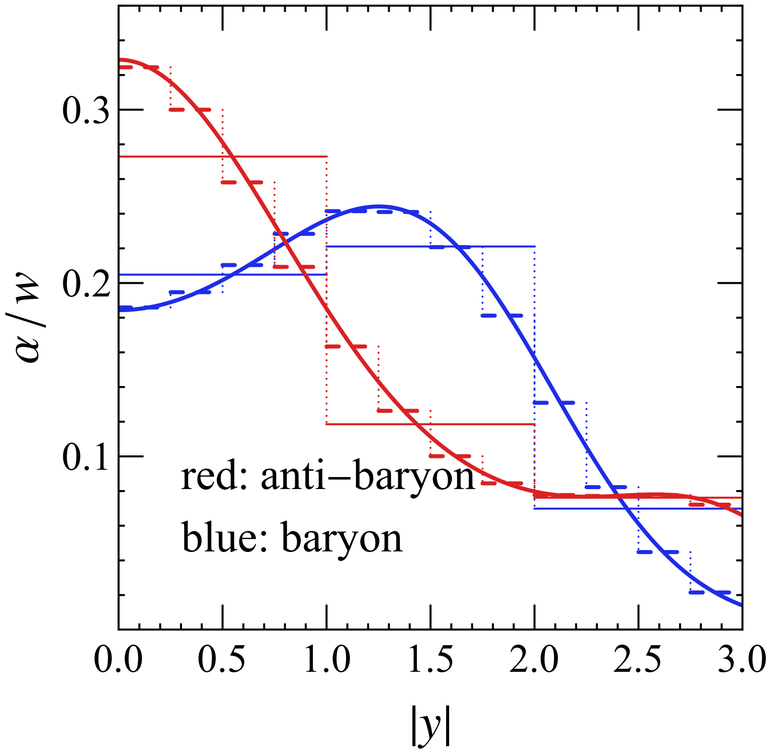


L. Du, H. Gao, S. Jeon and C. Gale,
arXiv: 2302.13852 [nucl-th]

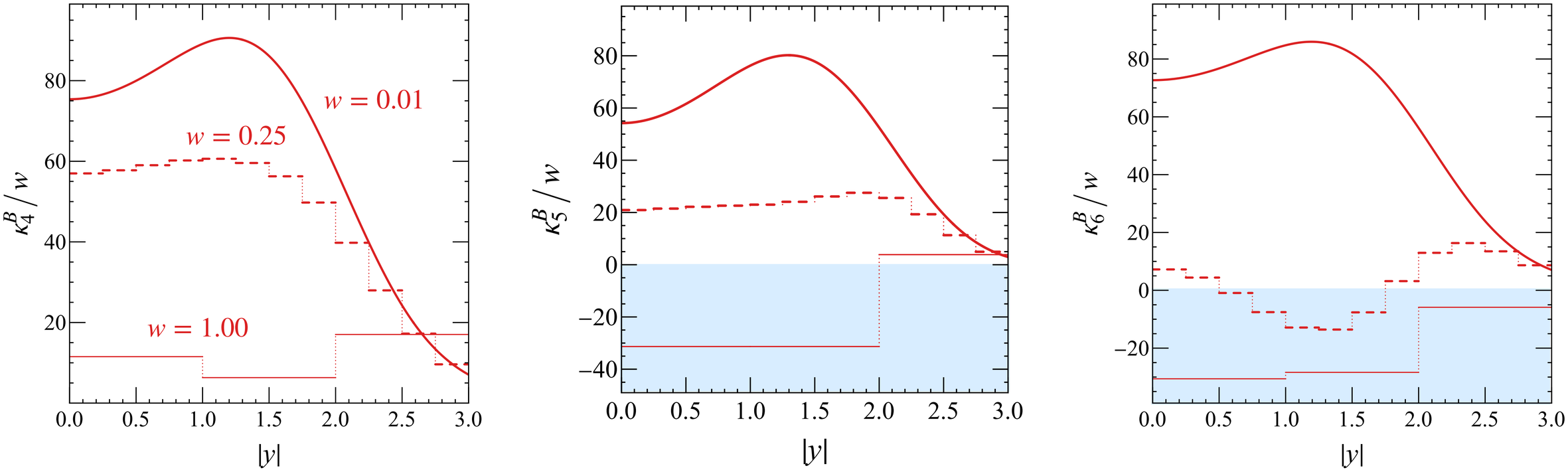
Particle yields



Acceptance



Cumulants of Au + Au @ 19.6 GeV in rapidity scan

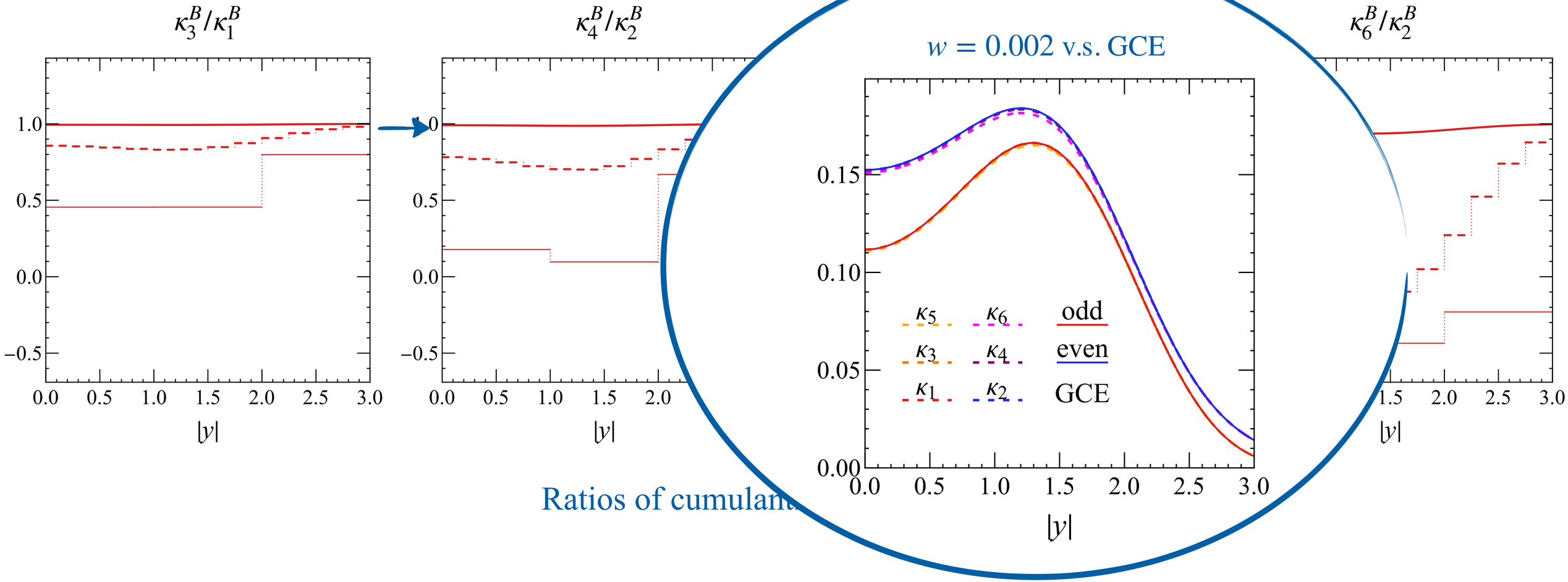


The 4th to 6th cumulants in rapidity scan

"... five and six...show a difference in sign."

STAR Collaboration, *Phys. Rev. Lett. 130, 082301*

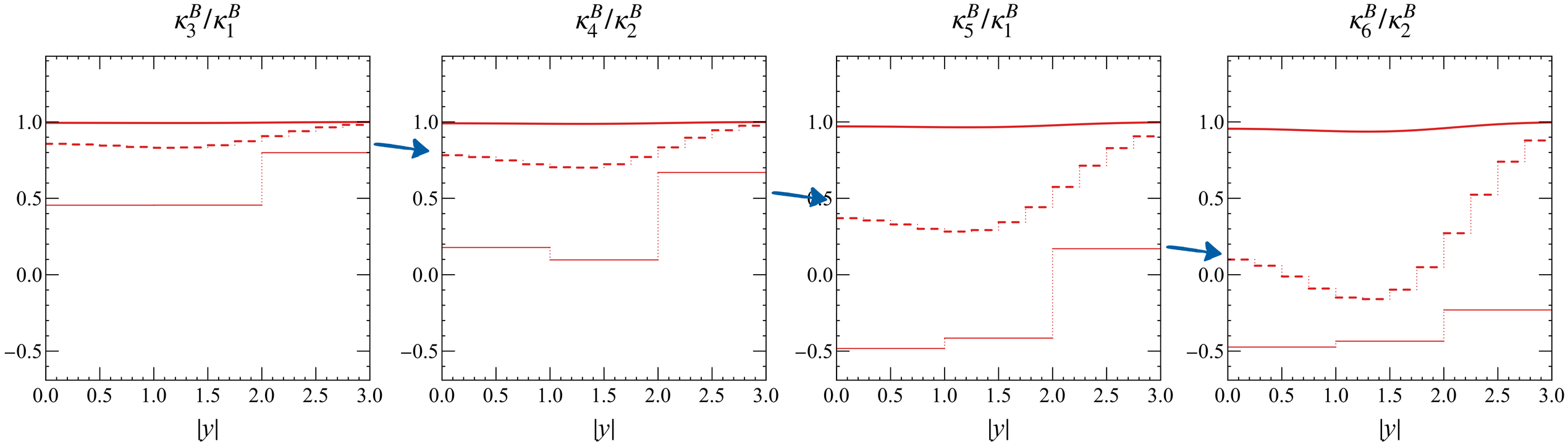
Cumulants of Au + Au @ 19.6 GeV in rapidity scan



Ratios of cumulant

Rapidity scan with tiny w approaches to GCE.

Cumulants of Au + Au @ 19.6 GeV in rapidity scan

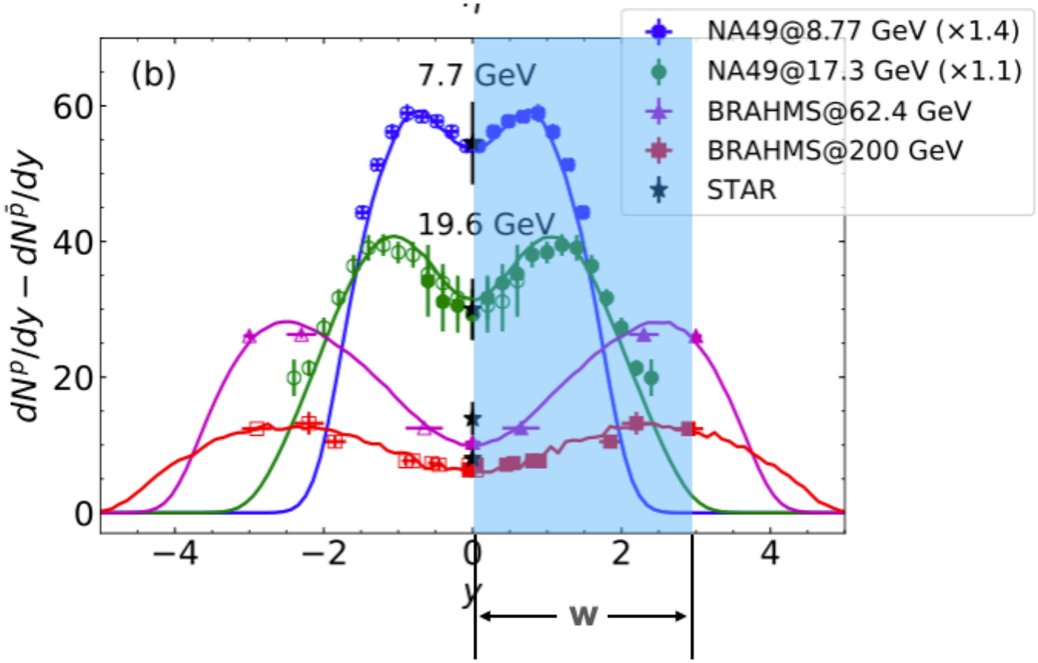


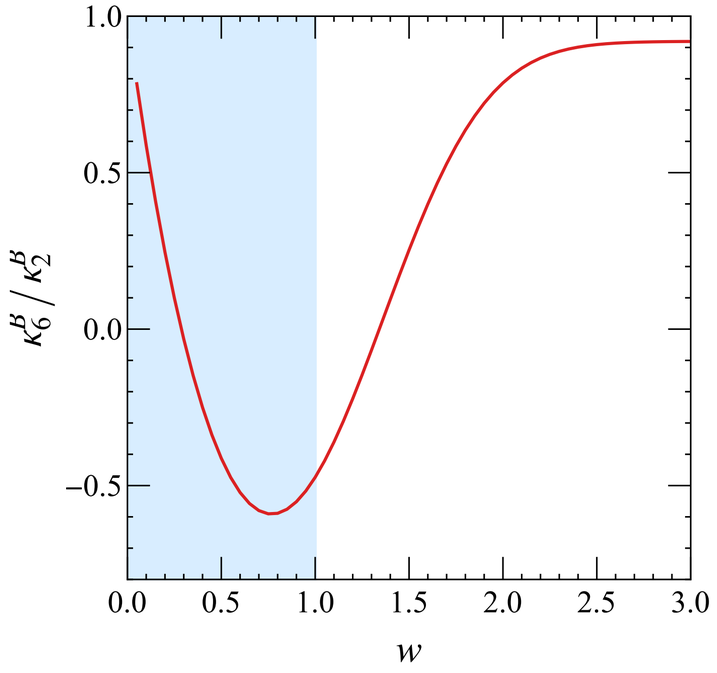
Ratios of cumulants in rapidity scan

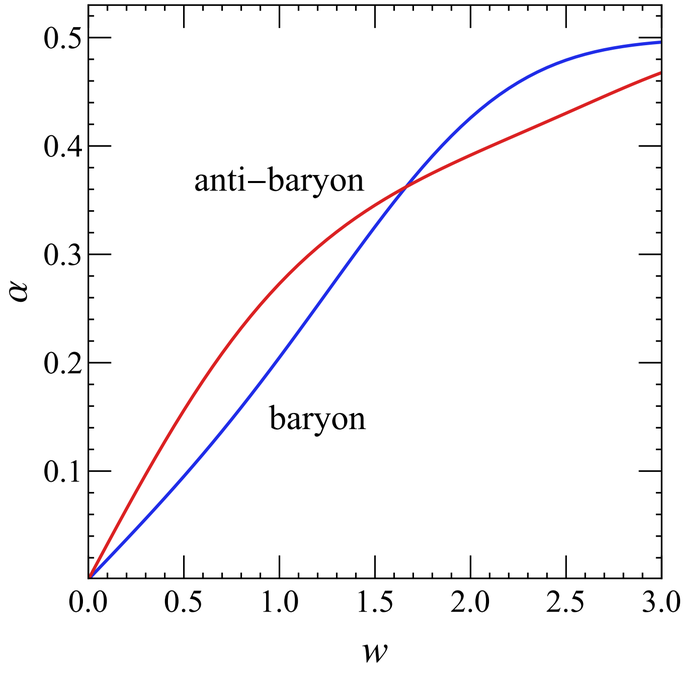
Ordering of ratios predicted in lattice QCD is also observed.

HotQCD Collaboration, *Phys. Rev. D 101, 074502*

Cumulants of Au + Au @ 19.6 GeV in rapidity scan







Non-monotonicity induced by more particles accepted.

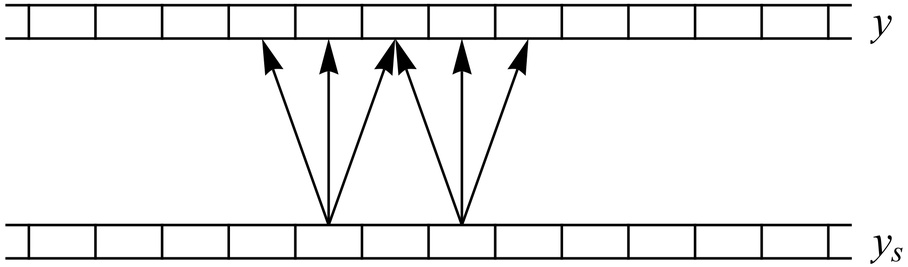
Thermodynamic variables on QCD phase diagram

$$\kappa_B^n = \left.\frac{\partial^n g_B(t)}{\partial t^n}\right|_{t=0}$$

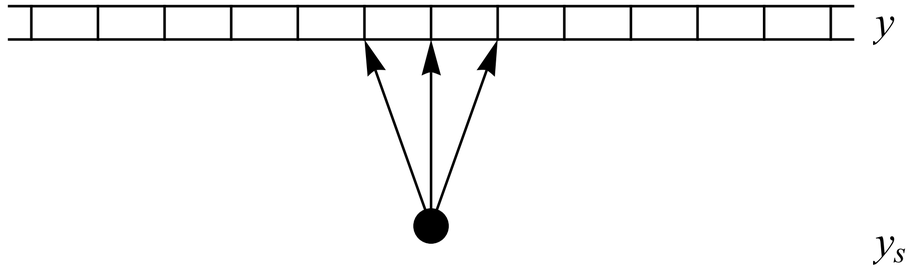
$$g_B(t) = \frac{B}{2}\ln\left[\frac{q_1(t)}{q_2(t)}\right] + \ln\left\{I_B\left[2\sqrt{\mathcal{Z}\bar{\mathcal{Z}}}\sqrt{q_1(t)\,q_2(t)}\right]\right\}$$

$$g_B(t) = \frac{B}{2}\ln\left[\frac{q_1(t)}{q_2(t)}\right] + \ln\left\{I_B\left[2Z\sqrt{q_1(t)\,q_2(t)}\right]\right\}$$

Nucl.Phys.A 1008, 122141



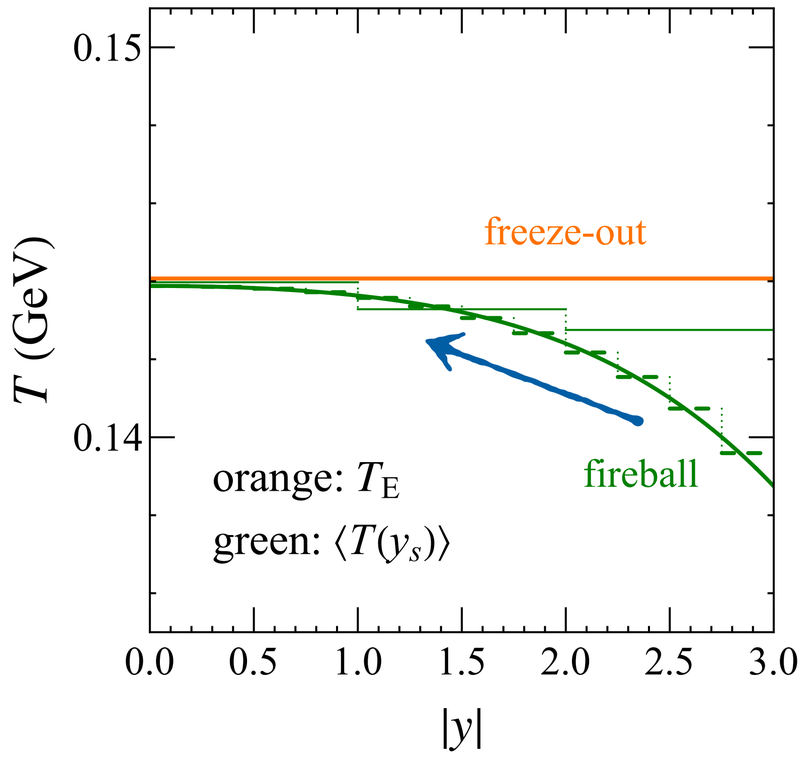
Inhomogeneous fireball

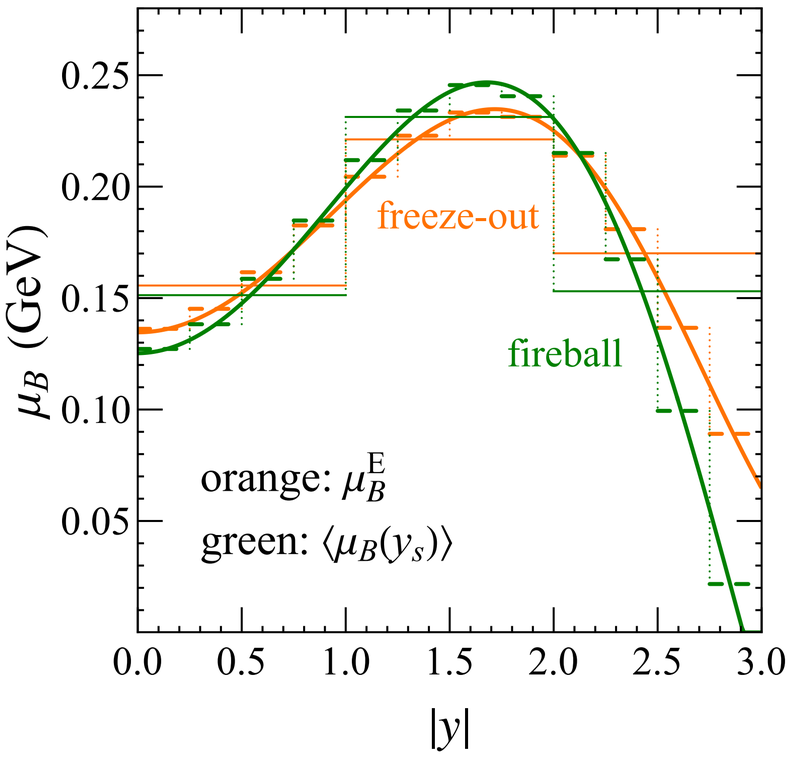


Point on QCD phase diagram

The same (anti-)baryon acceptance + $\mathcal{Z}\bar{\mathcal{Z}} = Z^2$

Thermodynamic variables on QCD phase diagram





T_{E} & μ_{E}: Extracted variables at chemical freeze-out

$\langle T\left(y_s\right)\rangle$ & $\langle \mu_B\left(y_s\right)\rangle$: Averaged variables of inhomogeneous fireball

Summary and Outlook

Summary

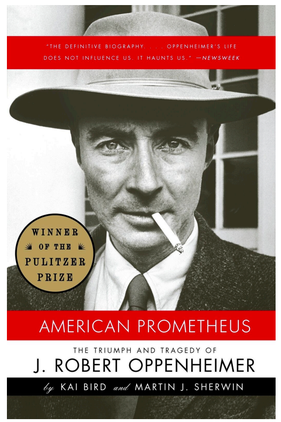
- We derive the expression for net-baryon cumulants generating function within finite rapidity ranges in CE
- Kinematic acceptances may significantly affect high-order cumulants
- We investigate the method to extract effective T & μ_B values on QCD phase diagram

Outlook

- Feed-down effect will refine the extraction method for T & μ_B
- Incorporate with critical behavior to study QCD phase transition
- Consider off-equilibrium dynamics of fluctuations in rapidity scan

"… interesting to see…offequilibrium scaling… in 'rapidity scan'"

Y. Yin, arXiv: 1811.06519



"We cannot know, as a matter of principle, the present in all its details."

Thanks~