Fluctuations as a probe of QCD critical point in light of RHIC BES-II

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On-line seminar series on RHIC Beam Energy Scan

October 22, 2024

Thanks to:

M.I. Gorenstein, M. Hippert, M. Kahangirwe, V. Koch, V.A. Kuznietsov, A. Lysenko, J. Noronha, R. Poberezhniuk, C. Ratti, O. Savchuk, H. Shah, J. Steinheimer, H. Stoecker

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QCD under extreme conditions

What we know

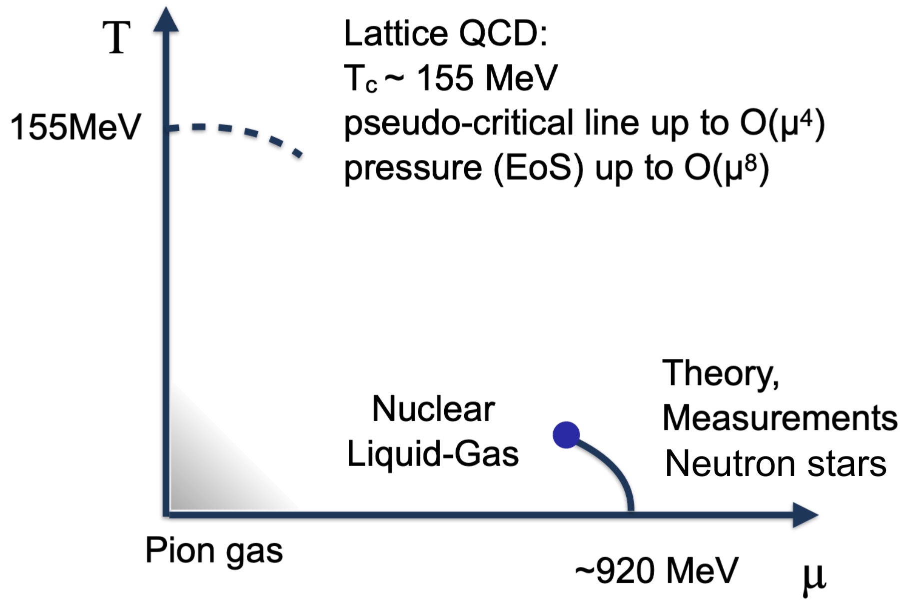

Figure courtesy of V. Koch

What we hope to know

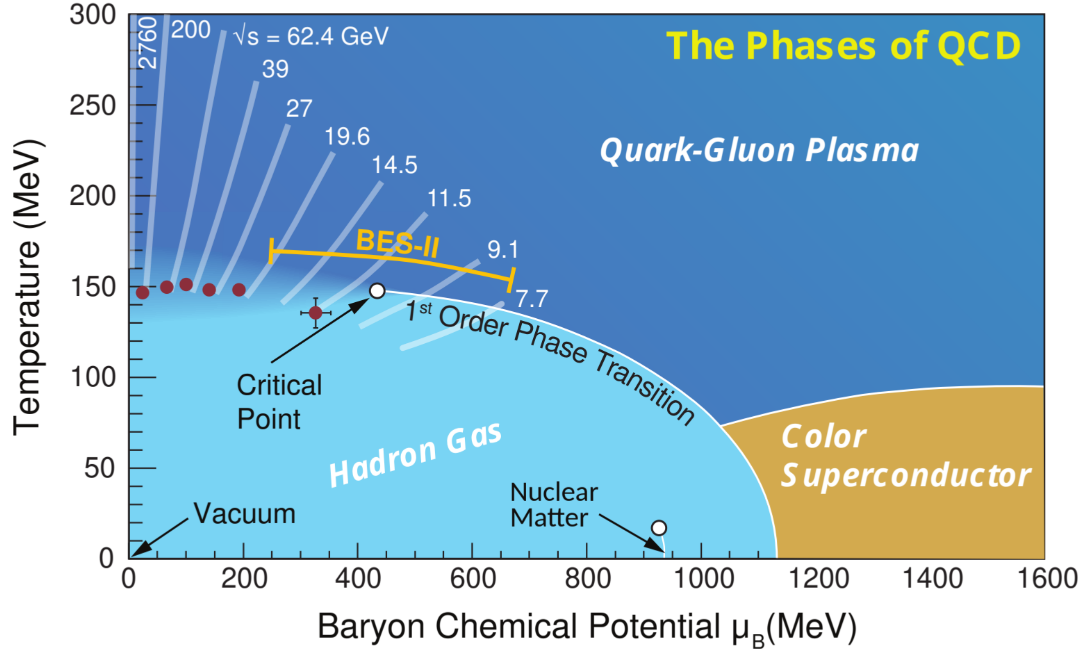

Figure from Bzdak et al., Phys. Rept. '20 & 2015 US Nuclear Long Range Plan

- Dilute hadron gas at low T & μ_{B} due to confinement, quark-gluon plasma high T & μ_{B}
- Nuclear liquid-gas transition in cold and dense matter, lots of other phases conjectured
- Chiral crossover at $\mu_B = 0$ which may turn into a *first-order phase transition* at finite μ_B

Key question: *Is there a QCD critical point and how to find it?*

QCD critical point theory estimates:

New developments

Critical point predictions as of a few years ago

All over the place...

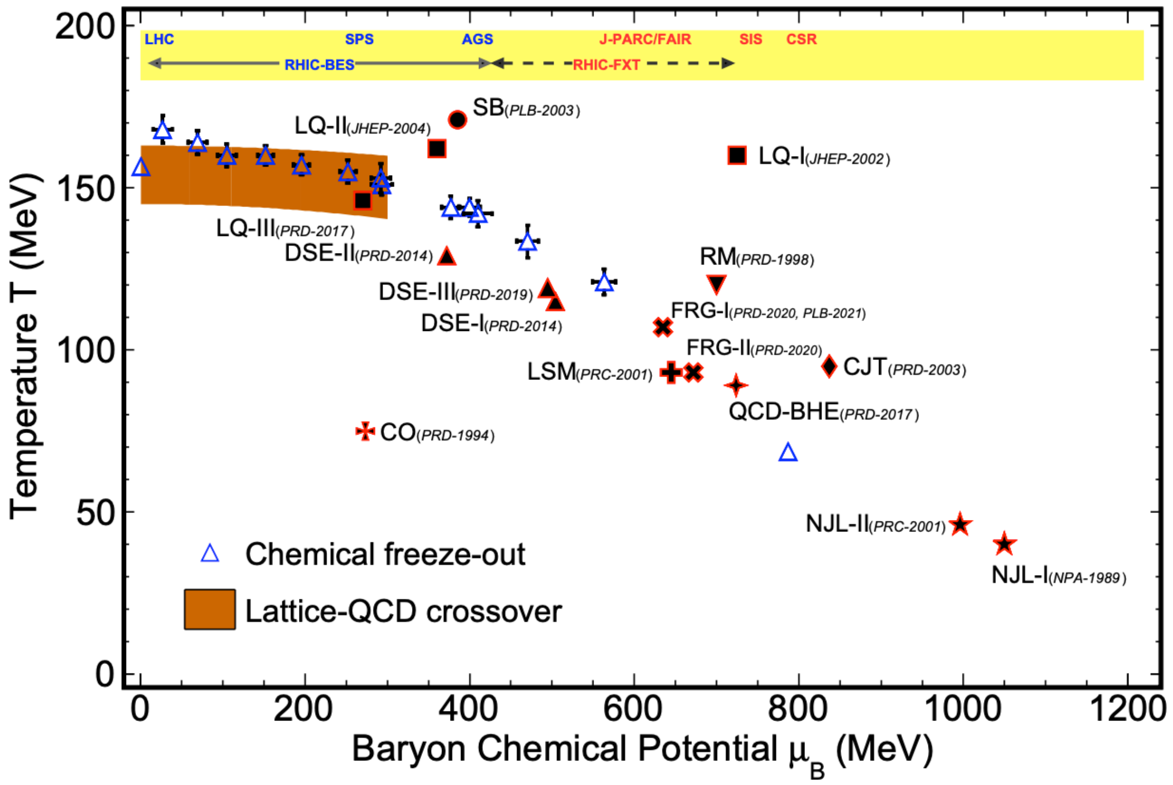

Figure adapted from A. Pandav, D. Mallick, B. Mohanty, Prog. Part. Nucl. Phys. 125 (2022)

Including the possibility that the QCD critical point does not exist at all

de Forcrand, Philipsen, JHEP 01, 077 (2007); VV, Steinheimer, Philipsen, Stoecker, PRD 97, 114030 (2018)

Effective QCD theories anchored with lattice QCD

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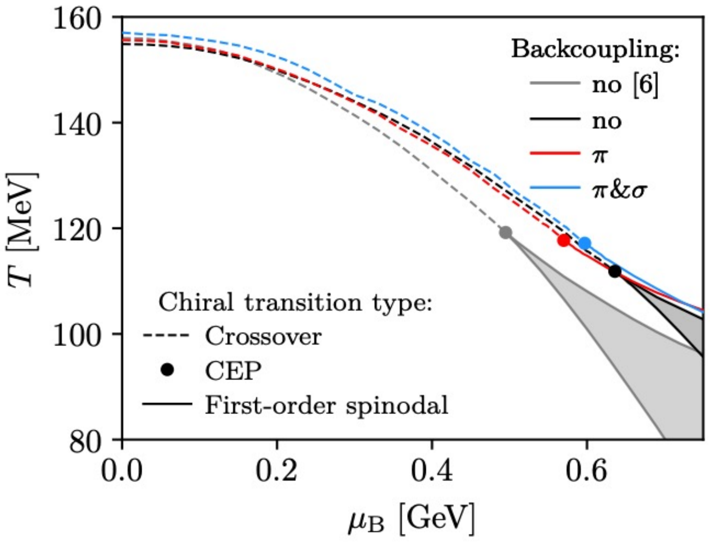
Dyson-Schwinger equations

truncation errors

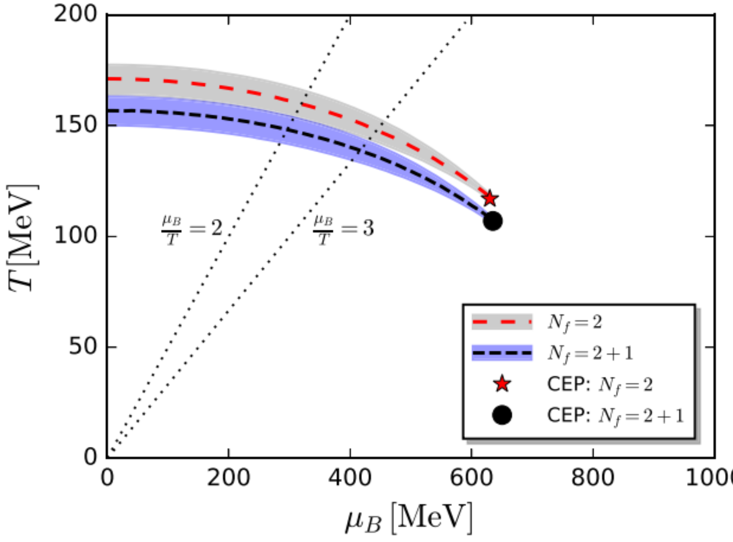


Gunkel, Fischer, PRD 104, 054202 (2021)

$T \sim 120$ MeV $\mu_B \sim 600$ MeV

Functional renormalization group

truncation errors

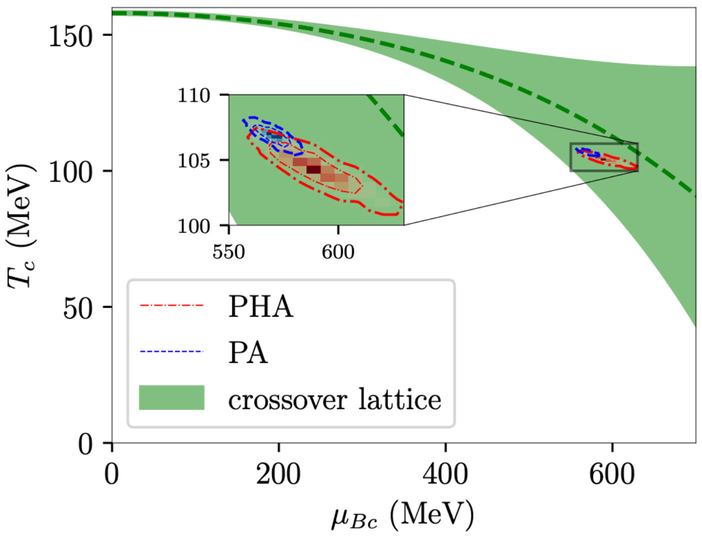


Fu, Pawlowski, Rennecke, PRD 101, 053032 (2020)

$T \sim 100$ MeV $\mu_B \sim 600 - 650$ MeV

Black-hole engineering

strongly-coupled only $(\eta/s = 1/4\pi)$



Hippert et al., arXiv:2309.00579

$T \sim 105$ MeV $\mu_B \sim 580$ MeV

- All in excellent agreement with lattice QCD at $\mu_B = 0$ and predict QCD critical point in a similar ballpark of $\mu_B/T \sim$ 5-6
- Other estimates:
  - Finite-size scaling of heavy-ion observables [R. Lacey, PRL 114, 142301 (2015); A. Sorensen, P. Sorensen, arXiv:2405.10278]
  - Extrapolation of Yang-Lee edge singularities [D.A. Clarke et al. (Bielefeld-Parma), arXiv:2405.10196; G. Basar, PRC 110, 015203 (2024)]

Searching for singularities in the complex plane

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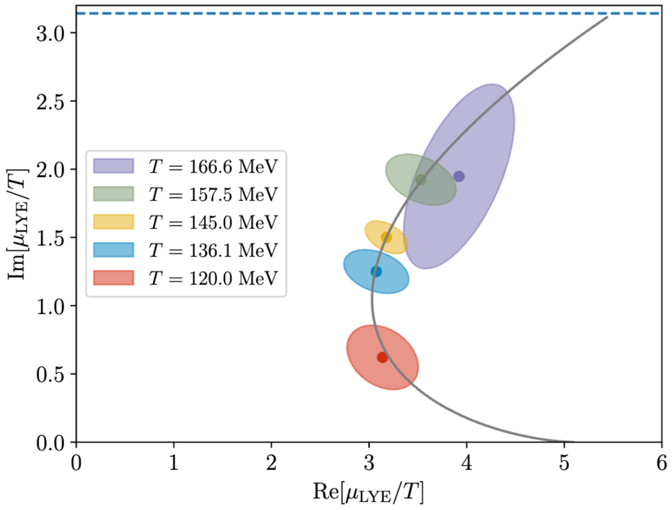
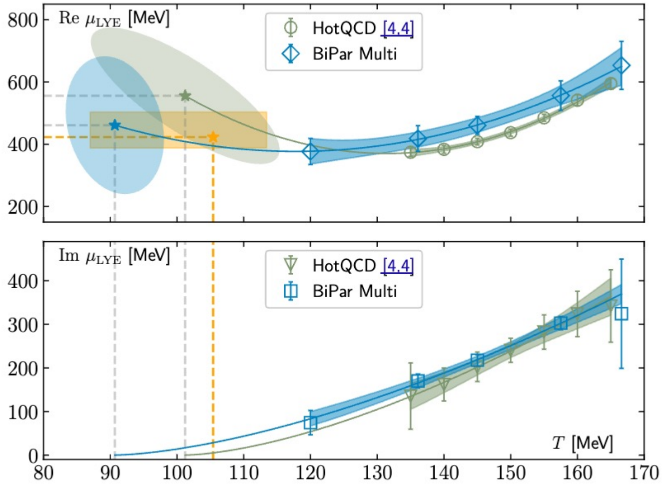
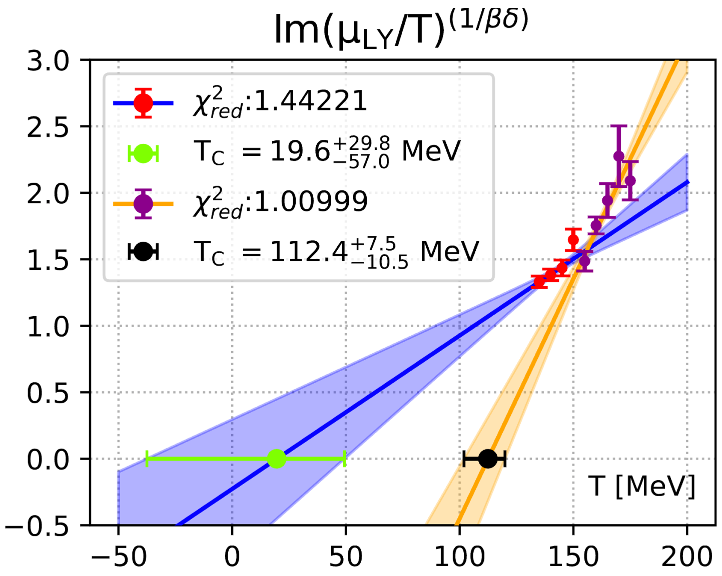
Critical point is a singularity on the real μ_B axis,
which turns into **Yang-Lee edge singularities** above T_c **in the complex plane** M. Stephanov, PRD 73, 094508 (2006)

Strategy: Extract YL edge singularity through (multi-point) Pade fits and see if it approaches the real axis as temperatures decreases





Variations in fit range etc.



CP Z(2) scaling inspired fit:

$$\mathrm{Im}\,\mu_{LY} = c(T - T_{CEP})^{\Delta}$$

$$\mathrm{Re}\,\mu_{LY} = \mu_{CEP} + a(T - T_{CEP}) + b(T - T_{CEP})^2$$

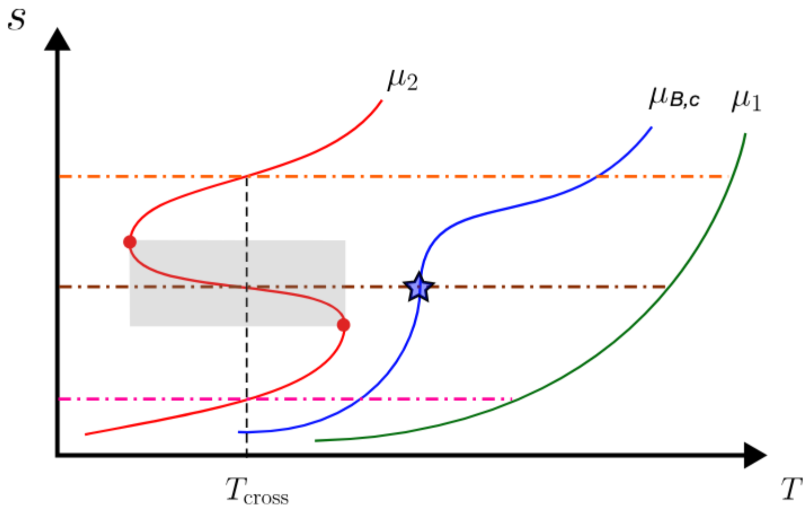
Extrapolated CP estimate:

T~90-110 MeV, μ_B~400-600 MeV

A. Adam et al. (Wuppertal-Budapest), LATTICE2024

D.A. Clarke et al. (Bielefeld-Parma), arXiv:2405.10196; G. Basar, PRC 110, 015203 (2024)

many things have to go right, systematic error still very large (up to 100%)



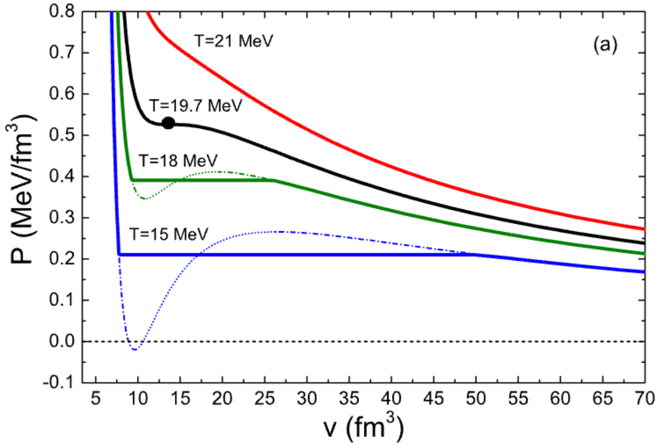
Locating the QCD critical point from first principles through contours of constant entropy density

Hitansh Shah, Mauricio Hippert, Jorge Noronha, Claudia Ratti, VV, arXiv:2410.16206

(Dated: October 22, 2024)

Critical point and crossings of entropy density

Usual case: Fix T, scan P over ρ_B FOPT exists if non-monotonic, apply Maxwell construction



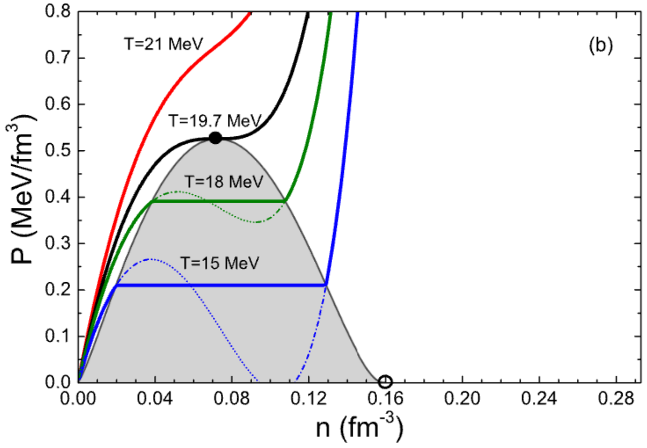
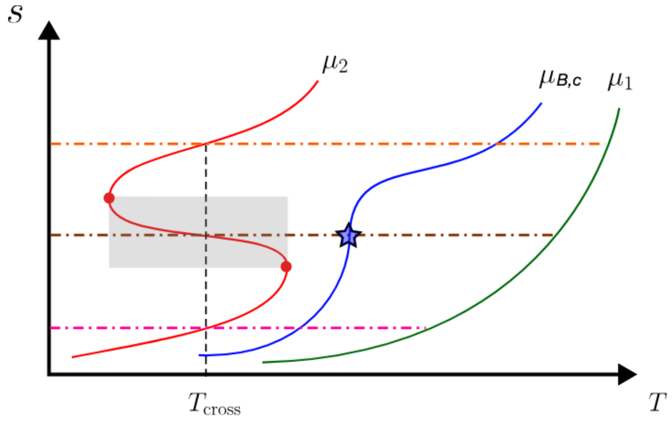


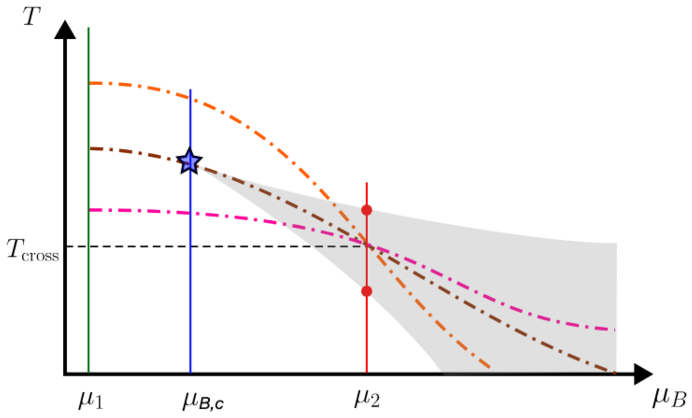
Figure from VV, Anchishkin, Gorenstein, PRC 91, 064314 (2015)

Critical Point:

$$\left(\frac{\partial P}{\partial \rho_B}\right)_T = 0, \qquad \left(\frac{\partial^2 P}{\partial \rho_B^2}\right)_T = 0.$$

Alternative: Fix μ_B, scan s over T FOPT exists if lines of constant entropy cross





Critical Point:

$$\left(\frac{\partial T}{\partial s}\right)_{\mu_B} = 0, \qquad \left(\frac{\partial^2 T}{\partial s^2}\right)_{\mu_B} = 0.$$

H. Shah, M. Hippert, J. Noronha, C. Ratti, VV, arXiv:2410.16026

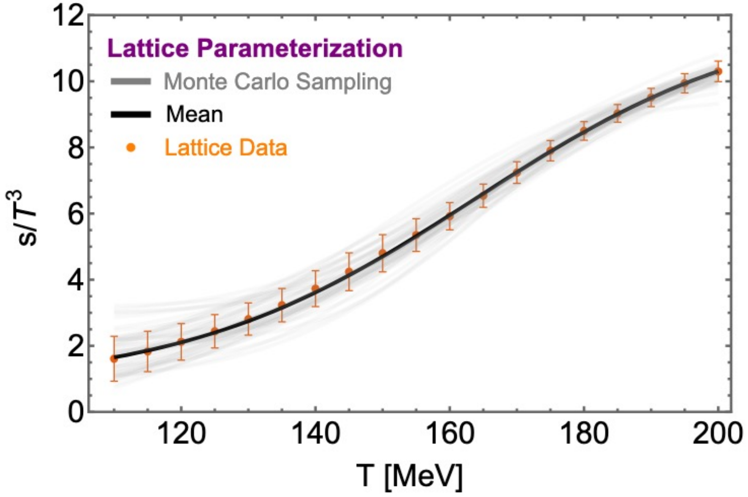
New expansion

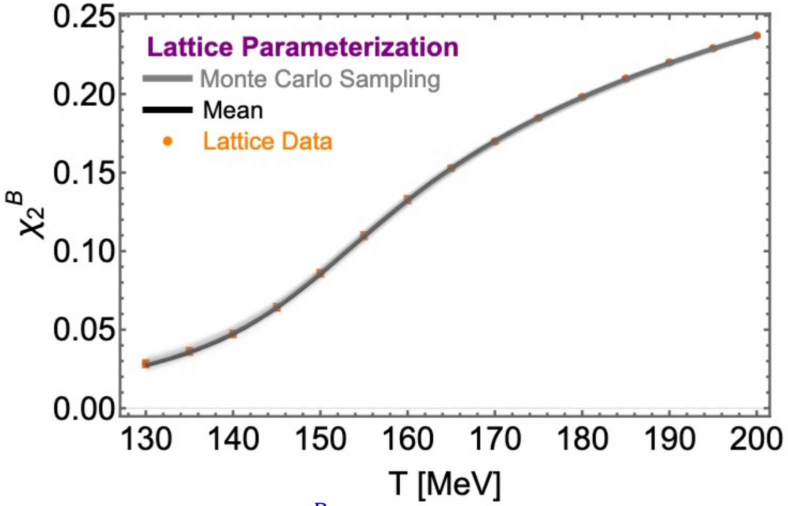
Define the s $=$ const. line in T-μ_B plane as an expansion around $\mu_B = 0$

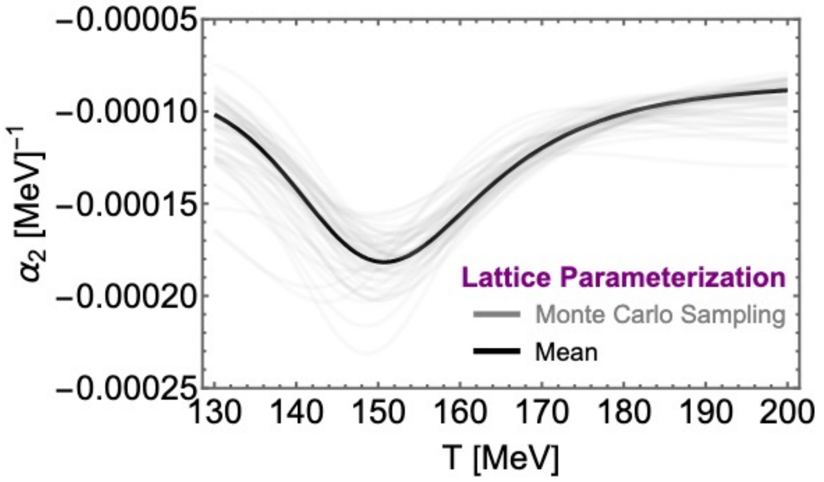
$$T_s(\mu_B;T_0) \approx T_0 + \sum_{n=1}^{N} \alpha_{2n}(T_0) \frac{\mu_B^{2n}}{(2\,n)!} + \mathcal{O}\left(\mu_B^{2(N+1)}\right) \qquad \alpha_{2n}(T_0) = \left(\frac{\partial^{2n} T}{\partial \mu_B^{2n}}\right)_s\Bigg|_{T=T_0,\mu_B=0}$$

$$\alpha_2(T_0) = -\frac{2T_0\chi_2^B(T_0) + T_0^2\chi_2^{B'}(T_0)}{s'(T_0)}$$

Parametrized continuum-extrapolated lattice QCD input $[s(T), \chi_2^B(T)]$ from Bayesian analysis







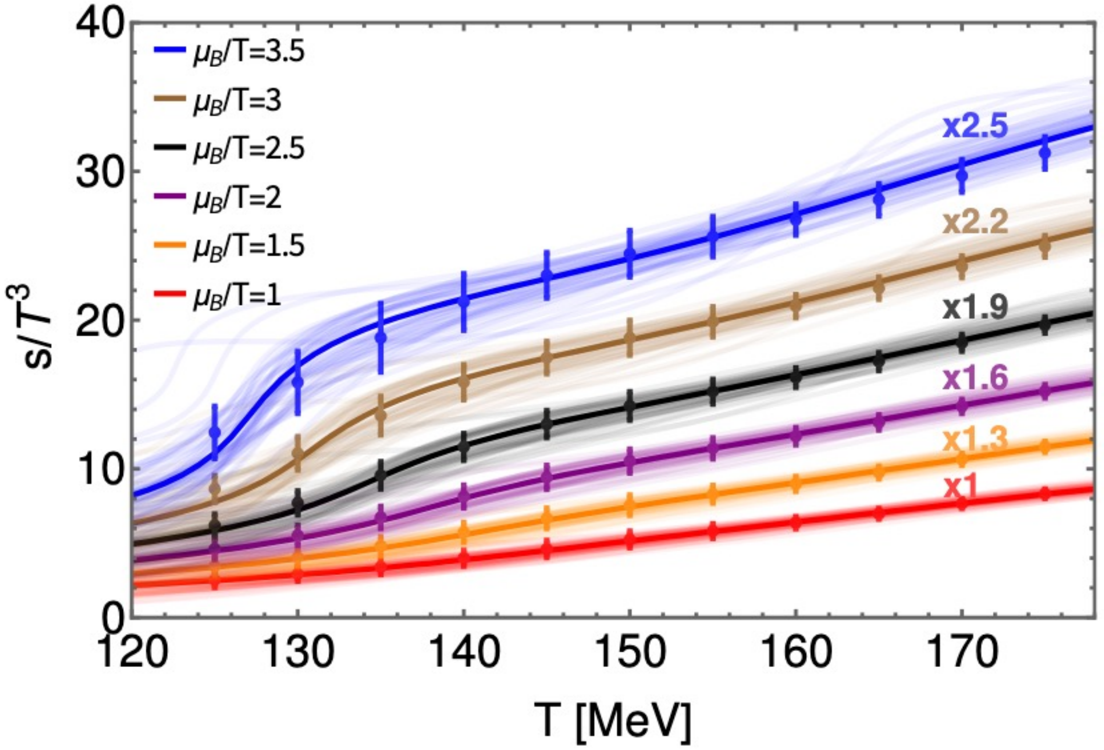
Lattice data for $s(T)$: Borsanyi et al., PLB 730, 99 (2014) Lattice data for $\chi_2^B(T)$: Borsanyi et al., PRL 126, 232001 (2021)

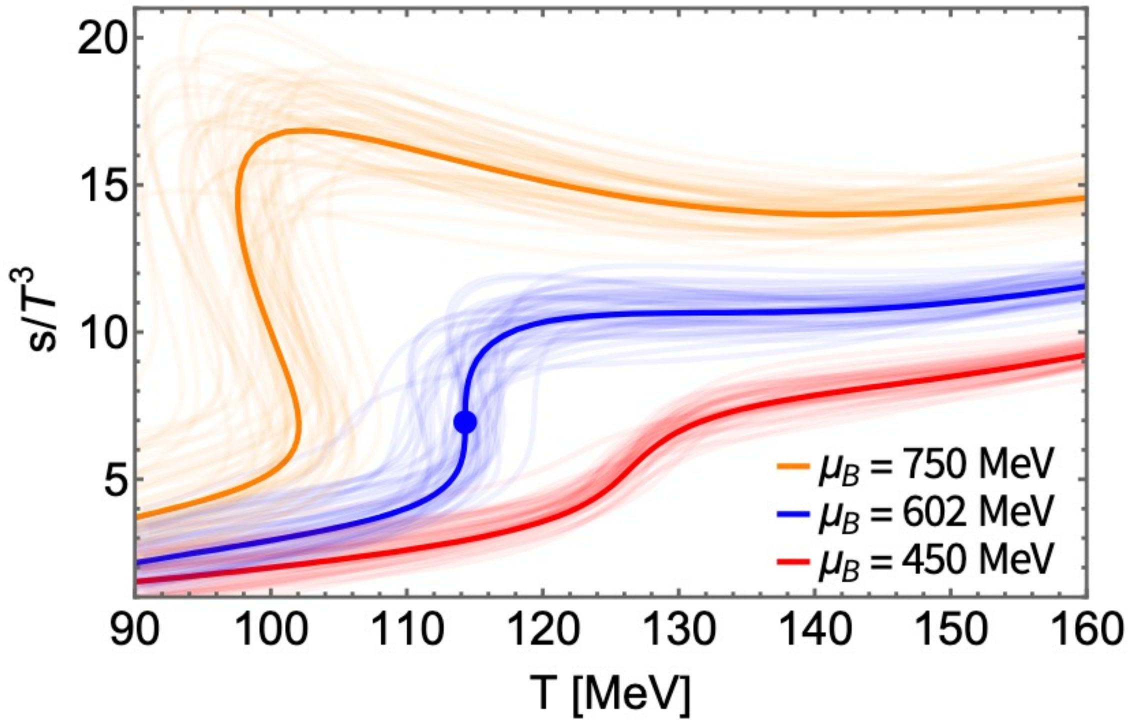
Propagation of the correlated lattice QCD uncertainties through Monte Carlo sampling of the parameter posterior distribution

H. Shah, M. Hippert, J. Noronha, C. Ratti, VV, arXiv:2410.16026

Entropy density at finite μ_B

$$T_s(\mu_B; T_0) = T_0 + \alpha_2(T_0)\frac{\mu_B^2}{2}$$





- Excellent agreement at low μ_B/T with available lattice QCD constraints

[Borsanyi et al., PRL 126, 232001 (2021)]

- First-order phase transition emerges at $\mu_B > 600$ MeV

H. Shah, M. Hippert, J. Noronha, C. Ratti, VV, arXiv:2410.16026

Locating the critical point

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$$T_s(\mu_B; T_0) = T_0 + \alpha_2(T_0)\frac{\mu_B^2}{2}$$

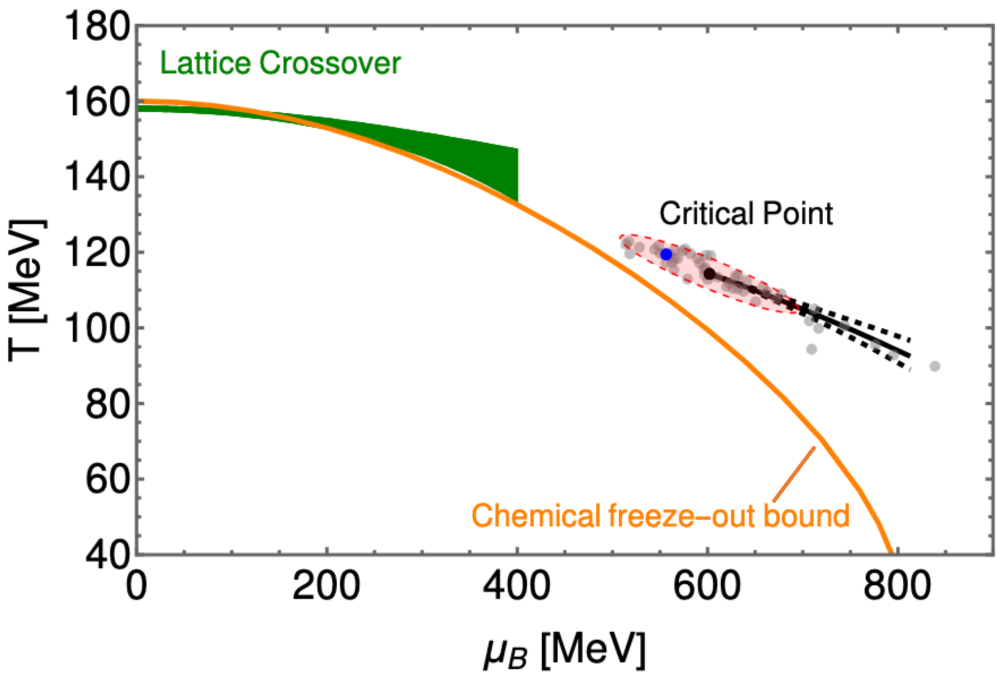
expansion

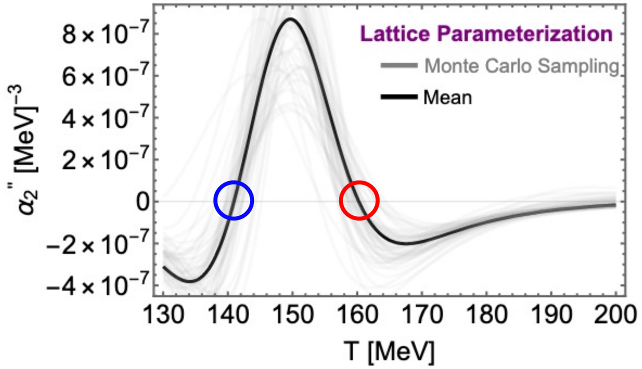
$$\left(\frac{\partial T}{\partial s}\right)_{\mu_B} = 0 \;\Rightarrow\; \mu_{B,c} = \sqrt{-\frac{2}{\alpha_2'(T_{0,c})}}$$

spinodals

$$\left(\frac{\partial^2 T}{\partial s^2}\right)_{\mu_B} = 0 \;\Rightarrow\; \alpha_2''(T_{0,c}) = 0$$

critical point





Critical point location:

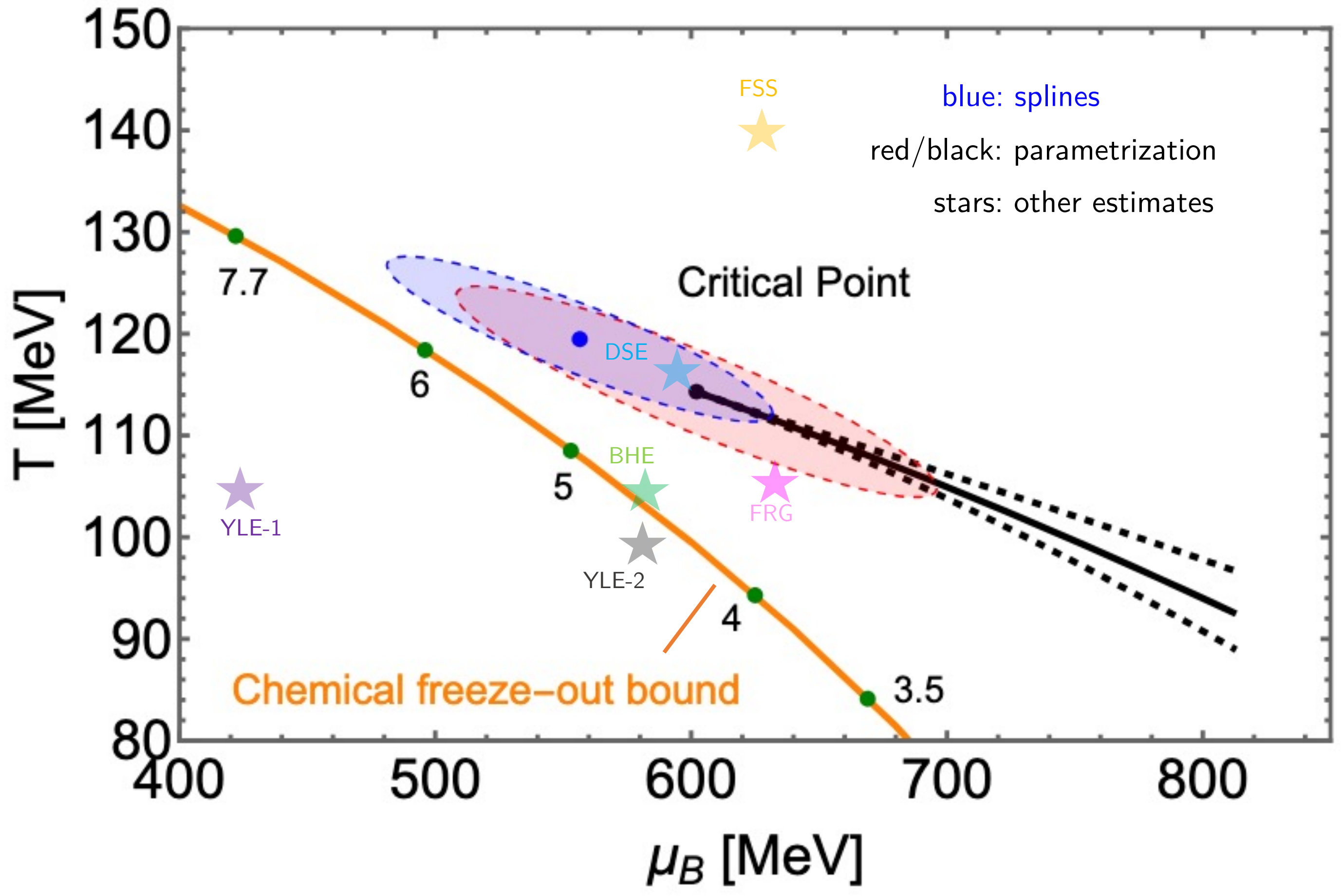
$T_c = 114.3 \pm 6.9$ MeV, $\mu_B = 602.1 \pm 62.1$ MeV

Second solution: CP at *imaginary* μ_B $\quad \tilde{T}_c = 197.1 \pm 7.1$ MeV, $\dfrac{\tilde{\mu}_{B,c}}{\tilde{T}_c} = i(3.50 \pm 0.30)$

cf. *Roberge-Weiss endpoint* at $\quad T_{RW} = 208 \pm 5$ MeV, $\mu_{B,RW}/T_{RW} = i\pi$

Bonati et al., PRD 93, 074504 (2016) H. Shah, M. Hippert, J. Noronha, C. Ratti, VV, arXiv:2410.16026

Comparison to other estimates in the literature



Cross-check using **splines** in place of **parametrization** yields consistent results

Other CP estimates from recent literature:

YLE-1: D.A. Clarke et al. (Bielefeld-Parma), arXiv:2405.10196

YLE-2: G. Basar, PRC 110, 015203 (2024)

BHE: M. Hippert et al., arXiv:2309.00579

FRG: W-J. Fu et al., PRD 101, 054032 (2020)

DSE: P.J. Gunkel et al., PRD 104, 052022 (2021)

FSS: A. Sorensen et al., arXiv:2405.10278

H. Shah, M. Hippert, J. Noronha, C. Ratti, VV, arXiv:2410.16026

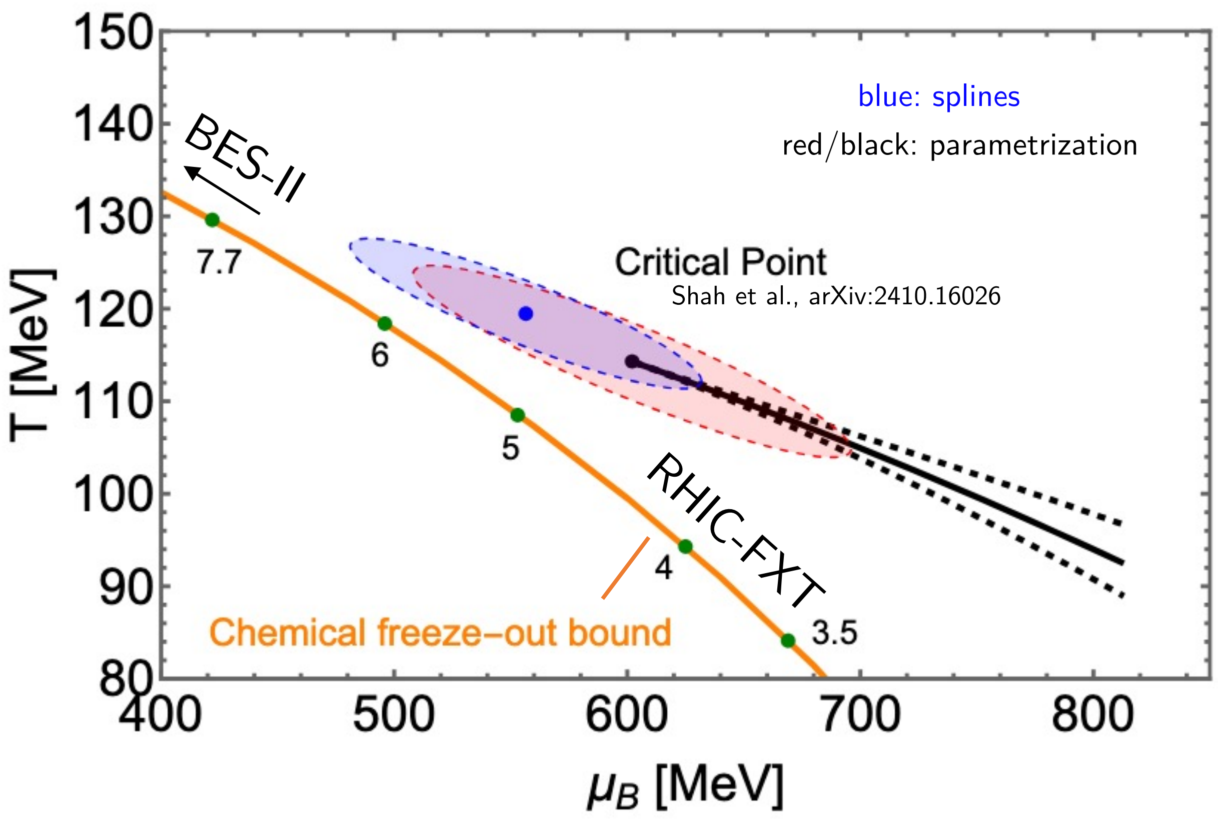
Search for critical point with heavy-ion collisions

Control parameters

- Collision energy $\sqrt{s_{NN}} = 2.4 - 5020$ GeV
  - Scan the QCD phase diagram
- Size of the collision region
  - Expect stronger signal in larger systems

Measurements

- Final hadron abundances and momentum distributions **event-by-event**



Chemical freeze-out curve and CP [**Artemiy Lysenko**, Poberezhnyuk, Gorenstein, VV, arXiv:2408.06473]

- Sets the **lower bound** on the temperature of the CP
- **Caveats:** strangeness neutrality ($\mu_S \neq 0$), uncertainty in the freeze-out curve
- Estimate through constant energy-per-hadron criterion [Cleymans, Redlich, arXiv:2408.06473]

Critical point, cumulants, and heavy-ion collisions

Event-by-event fluctuations and statistical mechanics

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Cumulant generating function

$$K_N(t) = \ln\langle e^{tN}\rangle = \sum_{n=1}^{\infty} \kappa_n \frac{t^n}{n!}$$

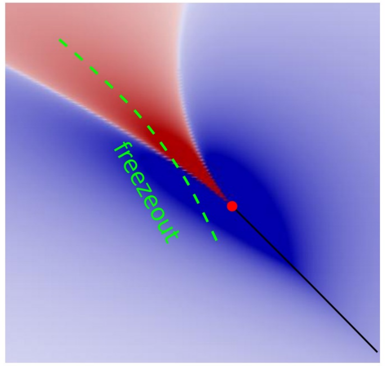
Grand partition function

$$\ln Z^{\rm gce}(T,V,\mu) = \ln\left[\sum_N e^{\mu N/T} Z^{\rm ce}(T,V,N)\right]$$

$$\kappa_n \propto \frac{\partial^n(\ln Z^{\rm gce})}{\partial \mu^n}$$

Cumulants measure chemical potential derivatives of the (QCD) equation of state

- **(QCD) critical point:** large correlation length and fluctuations



M. Stephanov, PRL '09, '11
Energy scans at RHIC (STAR) and CERN-SPS (NA61/SHINE)

$$\kappa_2 \sim \xi^2, \quad \kappa_3 \sim \xi^{4.5}, \quad \kappa_4 \sim \xi^7$$

$$\xi \to \infty$$

Looking for enhanced fluctuations and non-monotonicities

Other uses of cumulants:

- QCD degrees of freedom
  Jeon, Koch, PRL 85, 2076 (2000)
  Asakawa, Heinz, Muller, PRL 85, 2072 (2000)
- Extracting the speed of sound
  A. Sorensen et al., PRL 127, 042303 (2021)
- Conservation volume V_C
  VV, Donigus, Stoecker, PRC 100, 054906 (2019)

Example: (Nuclear) Liquid-gas transition

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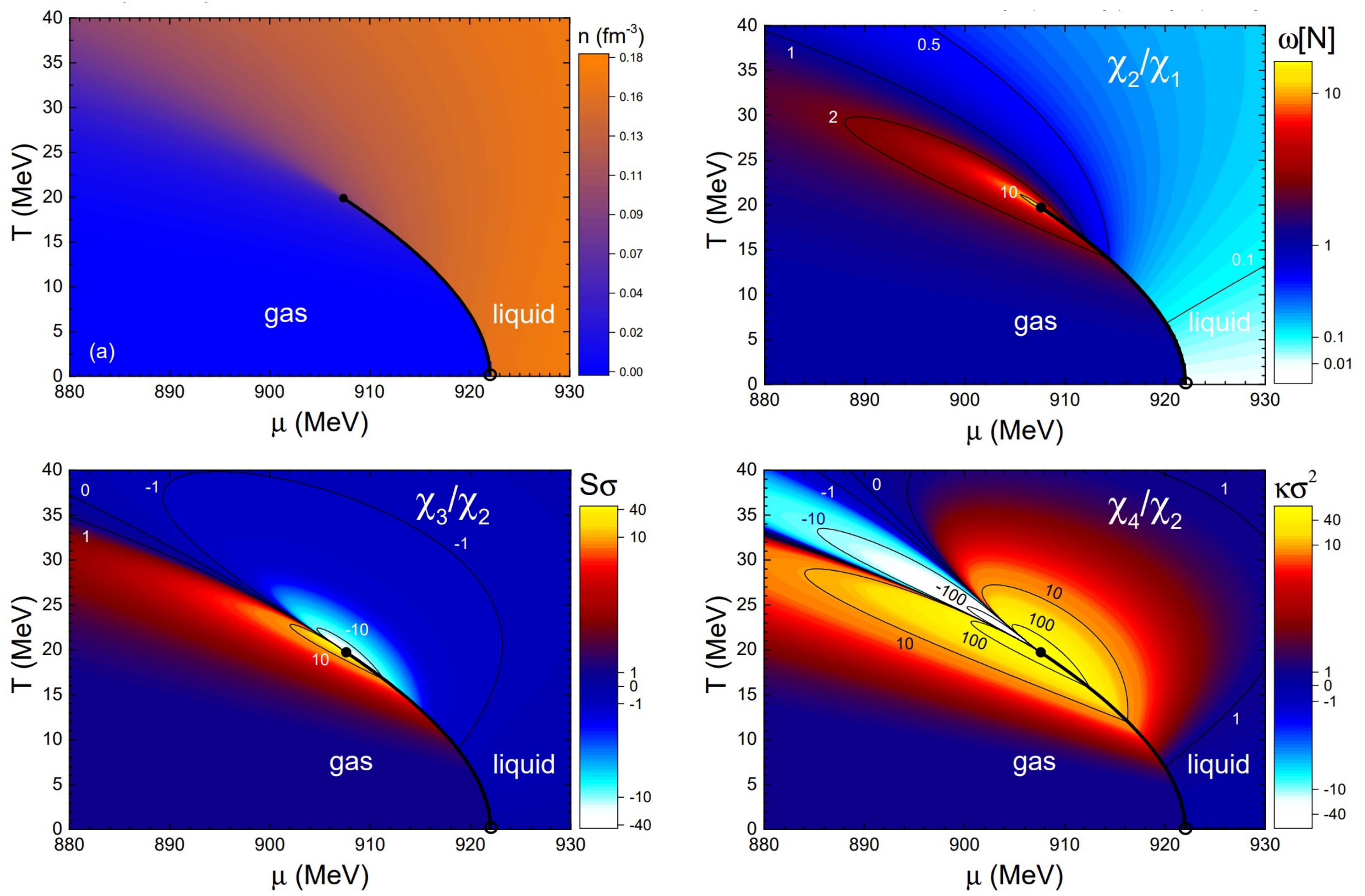
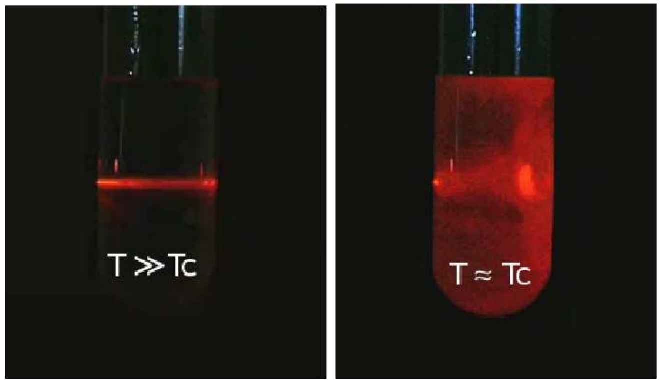


VV, Anchishkin, Gorenstein, Poberezhnyuk, PRC 92, 054901 (2015)

Critical opalescence



$$\langle N^2 \rangle - \langle N \rangle^2 \sim \langle N \rangle \sim 10^{23}$$

in equilibrium

Example: Critical fluctuations in a microscopic simulation

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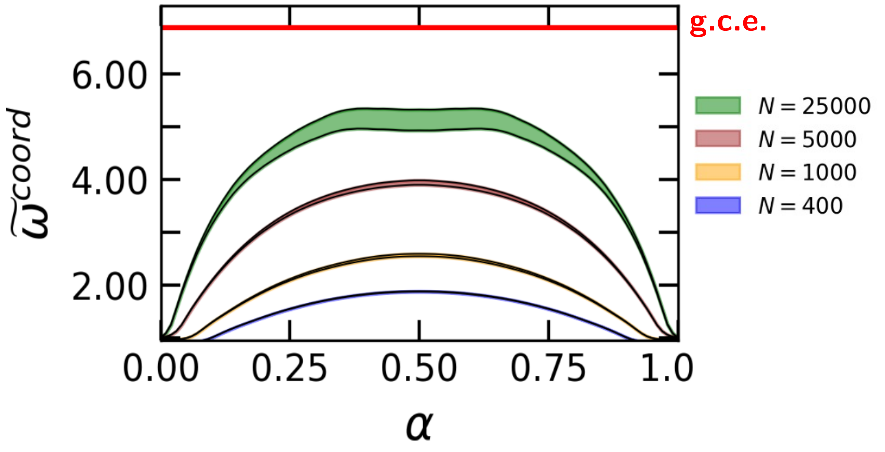
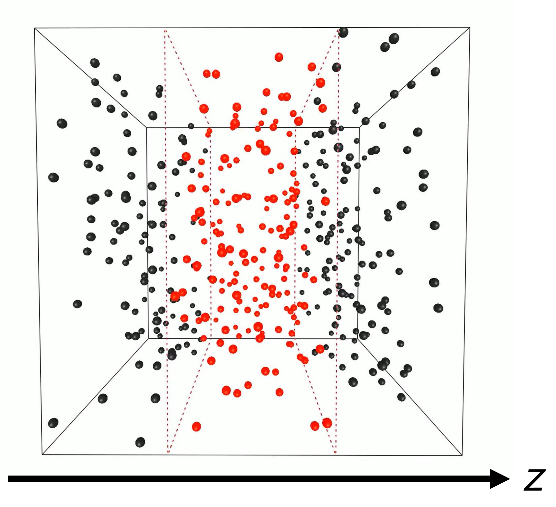
V. Kuznietsov et al., Phys. Rev. C 105, 044903 (2022)

Classical molecular dynamics simulations of the **Lennard-Jones fluid** near Z(2) critical point ($T \approx 1.06T_c$, $n \approx n_c$) of the liquid-gas transition

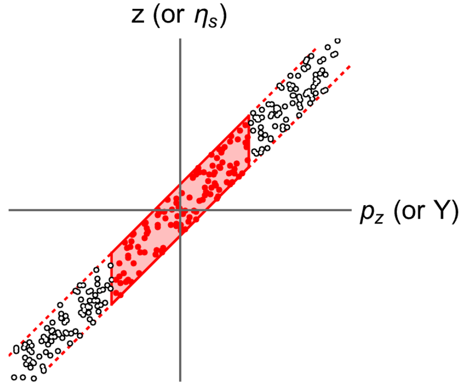
Scaled variance in coordinate space acceptance $|z| < z^{max}$

$$\tilde{\omega}^{\text{coord}} = \frac{1}{1-\alpha} \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle}$$





Heavy-ion collisions:
flow correlates p_z and z cuts

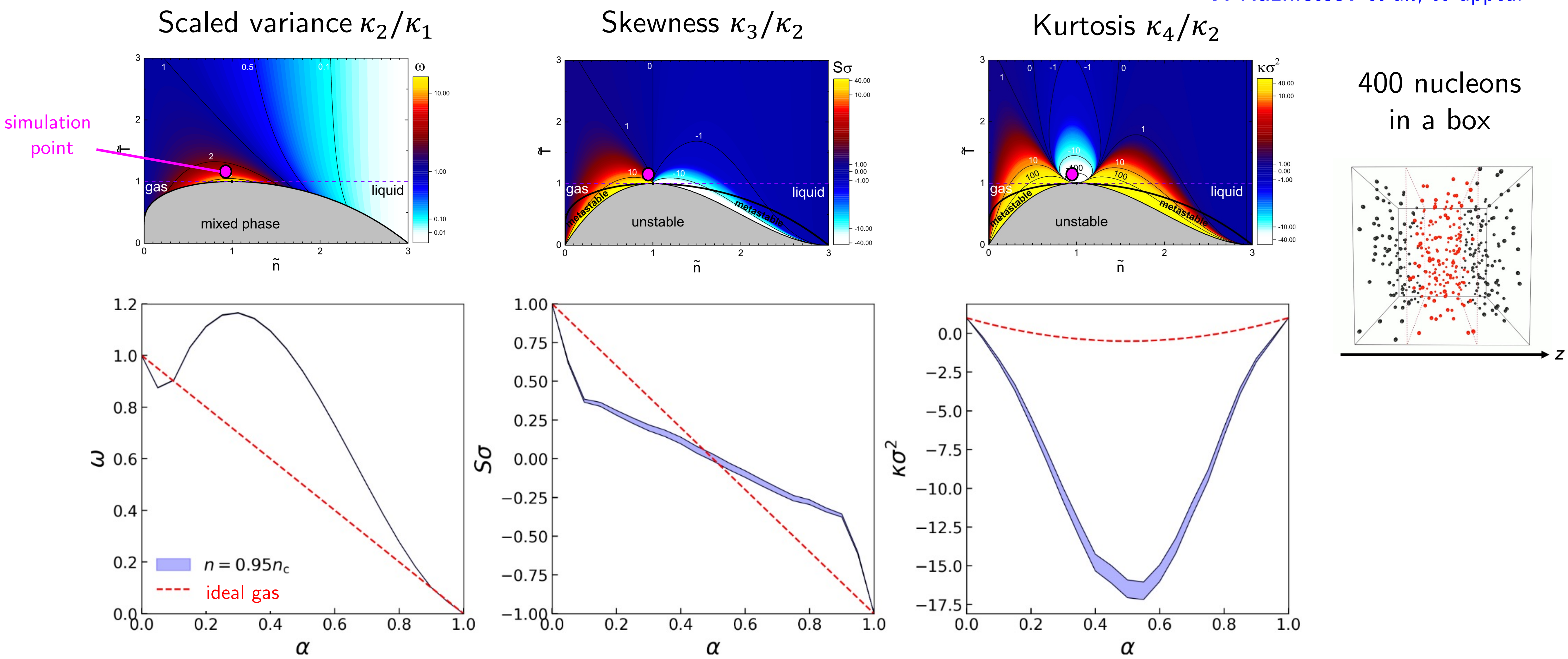


- Large fluctuations survive despite strong finite-size effects
- Need coordinate space cuts (collective flow helps)
- Here no finite-time effects

Collective flow and finite-time effects explored in V. Kuznietsov et al., Phys. Rev. C 110, 015206 (2024)

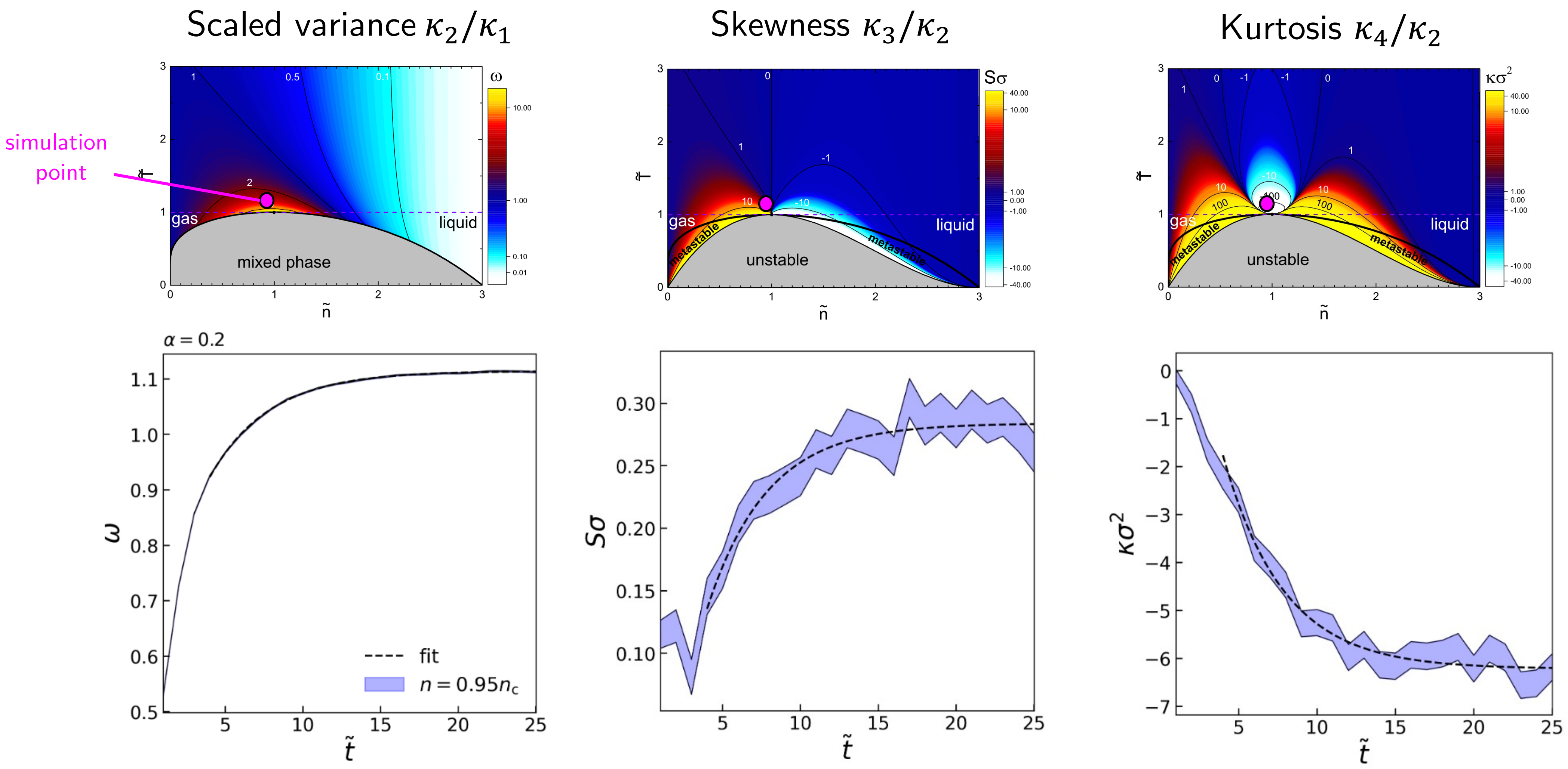
Non-Gaussian fluctuations from molecular dynamics

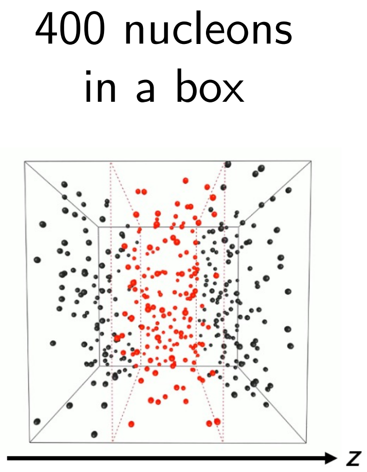
V. Kuznietsov et al., to appear



Non-Gaussian fluctuations from molecular dynamics

V. Kuznietsov et al., to appear





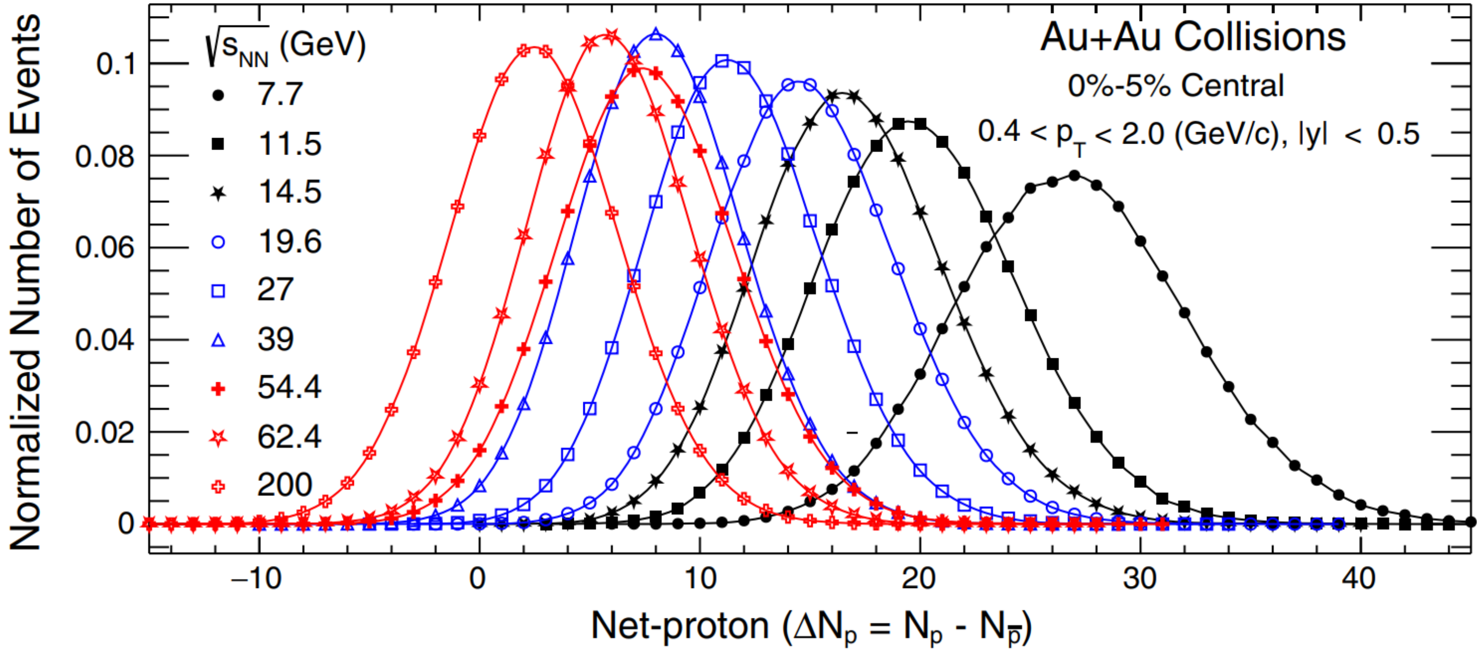
- (Non-)Gaussian cumulants equilibrate on comparable time scales

see also X. An et al., PRL 127, 072301 (2021); C. Chattopadhyay et al., PRL 133, 032301 (2024)

Measuring cumulants in heavy-ion collisions

Count the number of events with given number of e.g. (net) protons $P(\Delta N_p) \sim \frac{N_{\text{events}}(\Delta N_p)}{N_{events}^{total}}$

STAR Collaboration, Phys. Rev. Lett. 126, 092301 (2021)



Cumulants are extensive, $\kappa_n \sim V$, use ratios to cancel out the volume

$$\frac{\kappa_2}{\langle N \rangle}, \qquad \frac{\kappa_3}{\kappa_2}, \qquad \frac{\kappa_4}{\kappa_2}$$

Look for subtle critical point signals

Theory vs experiment: Challenges for fluctuations

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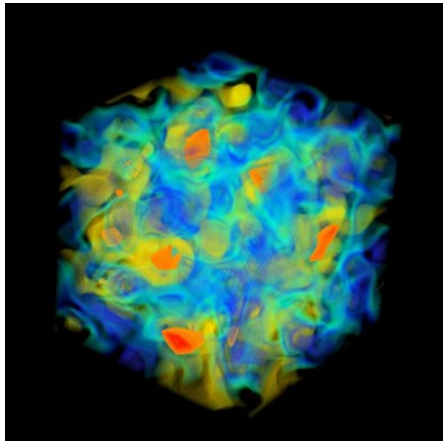
Theory



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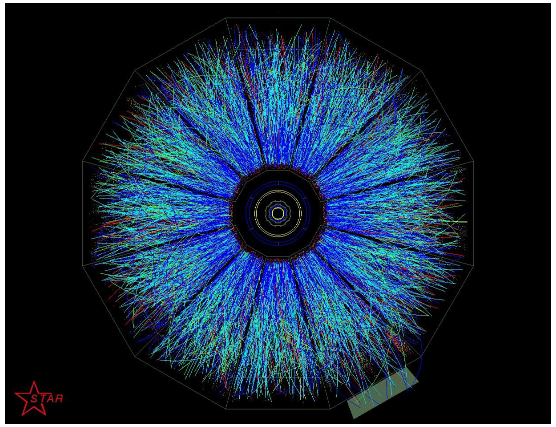
- Coordinate space
- In contact with the heat bath
- Conserved charges
- Uniform
- Fixed volume

Experiment



STAR event display

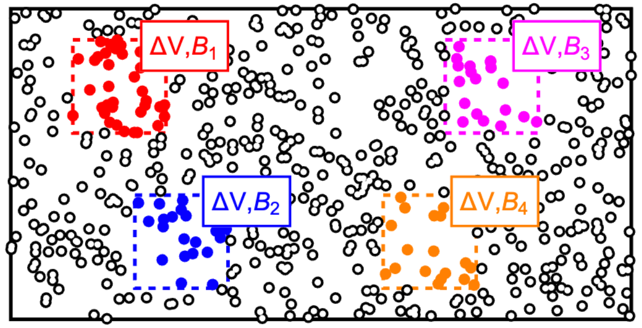
- Momentum space
- Expanding in vacuum
- Non-conserved particle numbers
- Inhomogenous
- Fluctuating volume

Need dynamical description

Exact charge conservation

VV, Savchuk, Poberezhnyuk, Gorenstein, Koch, PLB 811, 135868 (2020); VV, arXiv:2409.01397

Utilizing the canonical partition function in thermodynamic limit
compute **n-point density correlators**



$$\mathcal{C}_1(\mathbf{r}_1) \; = \; \rho(\mathbf{r}_1)$$

$$\mathcal{C}_2(\mathbf{r}_1,\mathbf{r}_2) = \chi_2\delta(\mathbf{r}_1-\mathbf{r}_2) - \frac{\chi_2}{V}$$

local correlation — balancing contribution (e.g. baryon conservation)

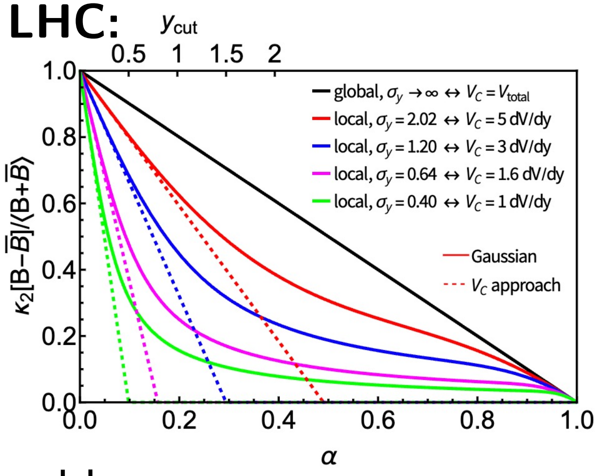
$$\mathcal{C}_3(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) = \chi_3\delta_{1,2,3} - \frac{\chi_3}{V}[\delta_{1,2}+\delta_{1,3}+\delta_{2,3}] + 2\frac{\chi_3}{V^2} \qquad \delta_{1,\dots,n} = \prod_{i=2}^{n}\delta(\mathbf{r}_1-\mathbf{r}_i)$$

local correlation — balancing contributions

$$\mathcal{C}_4(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3,\mathbf{r}_4) = \chi_4\delta_{1,2,3,4} - \frac{\chi_4}{V}[\delta_{1,2,3}+\delta_{1,2,4}+\delta_{1,3,4}+\delta_{2,3,4}] - \frac{(\chi_3)^2}{\chi_2 V}[\delta_{1,2}\delta_{3,4}+\delta_{1,3}\delta_{2,4}+\delta_{1,4}\delta_{2,3}]$$
$$+\frac{1}{V^2}\left[\chi_4+\frac{(\chi_3)^2}{\chi_2}\right][\delta_{1,2}+\delta_{1,3}+\delta_{1,4}+\delta_{2,3}+\delta_{2,4}+\delta_{3,4}] - \frac{3}{V^3}\left[\chi_4+\frac{(\chi_3)^2}{\chi_2}\right].$$

local correlation — balancing contributions

LHC:



Integrating the correlator yields cumulant inside a subsystem of the canonical ensemble

$$\kappa_n[B_{V_s}] = \int_{\mathbf{r}_1\in V_s} d\mathbf{r}_1 \dots \int_{\mathbf{r}_n\in V_s} d\mathbf{r}_n\, \mathcal{C}_n(\{\mathbf{r}_i\})$$

Momentum space: Fold with Maxwell-Boltzmann in LR frame and integrate out the coordinates

Fluctuations and beam energy scan

Dynamical approaches to the QCD critical point search

1. Dynamical model calculations of critical fluctuations BEST COLLABORATION [X. An et al., Nucl. Phys. A 1017, 122343 (2022)]
   - Fluctuating hydrodynamics (hydro+) and (non-equilibrium) evolution of fluctuations
   - Equation of state with a tunable critical point [P. Parotto et al, PRC 101, 034901 (2020); J. Karthein et al., EPJ Plus 136, 621 (2021)]
   - Generalized Cooper-Frye particlization [M. Pradeep, et al., PRD 106, 036017 (2022); PRL 130, 162301 (2023)]

   Alternatives at high μ_B: hadronic transport/molecular dynamics with a critical point

   [A. Sorensen, V. Koch, PRC 104, 034904 (2021); V. Kuznietsov et al., PRC 105, 044903 (2022)]

2. **Deviations from precision calculations of non-critical fluctuations**
   - Non-critical baseline is not flat [Braun-Munzinger et al., NPA 1008, 122141 (2021)]
   - Include essential non-critical contributions to (net-)proton number cumulants
   - Exact baryon conservation + hadronic interactions (hard core repulsion)
   - Based on realistic hydrodynamic simulations tuned to bulk data

   [VV, C. Shen, V. Koch, Phys. Rev. C 105, 014904 (2022)]

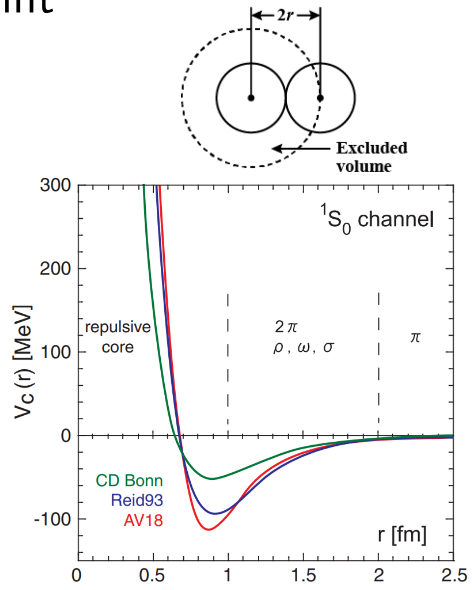


Figure from Ishii et al., PRL '07

Calculation of non-critical contributions at RHIC-BES

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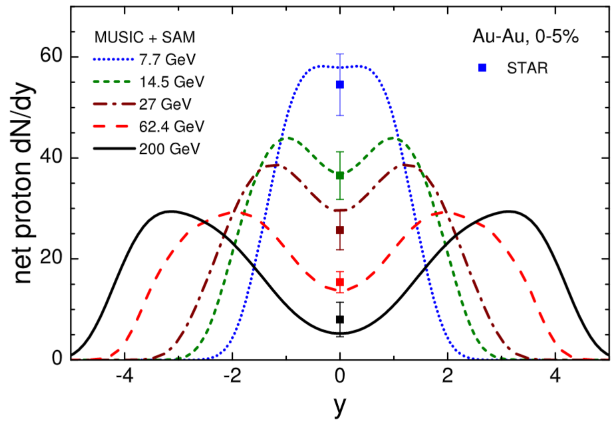
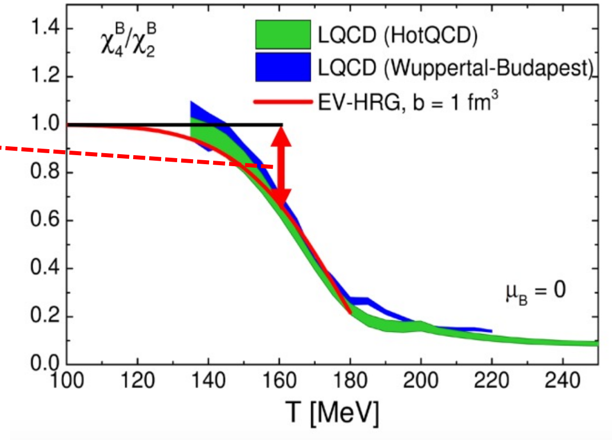
VV, V. Koch, C. Shen, Phys. Rev. C 105, 014904 (2022)

- (3+1)-D viscous hydrodynamics evolution (MUSIC-3.0)
  - Collision geometry-based 3D initial state [Shen, Alzhrani, PRC 102, 014909 (2020)]
  - Crossover equation of state based on lattice QCD [Monnai, Schenke, Shen, Phys. Rev. C 100, 024907 (2019)]
  - Cooper-Frye particlization at $\epsilon_{sw} = 0.26$ GeV/fm^3



- Non-critical contributions are computed at particlization
  - QCD-like baryon number distribution (χ_n^B) via **excluded volume** b = 1 fm^3 [VV, V. Koch, Phys. Rev. C 103, 044903 (2021)]
  - **Exact global baryon conservation*** (and other charges)
    - Subensemble acceptance method 2.0 (analytic) [VV, Phys. Rev. C 105, 014903 (2022)]
    - or FIST sampler (Monte Carlo) [VV, Phys. Rev. C 106, 064906 (2022)] https://github.com/vlvovch/fist-sampler



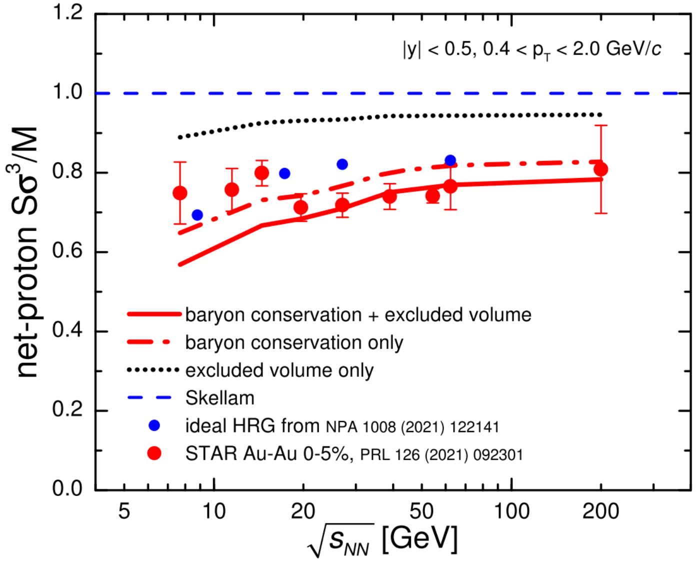
- Absent: critical point, local conservation, initial-state/volume fluctuations, hadronic phase

*If baryon conservation is the only effect (no other correlations), non-critical baseline can be computed without hydro
Braun-Munzinger, Friman, Redlich, Rustamov, Stachel, NPA 1008, 122141 (2021)

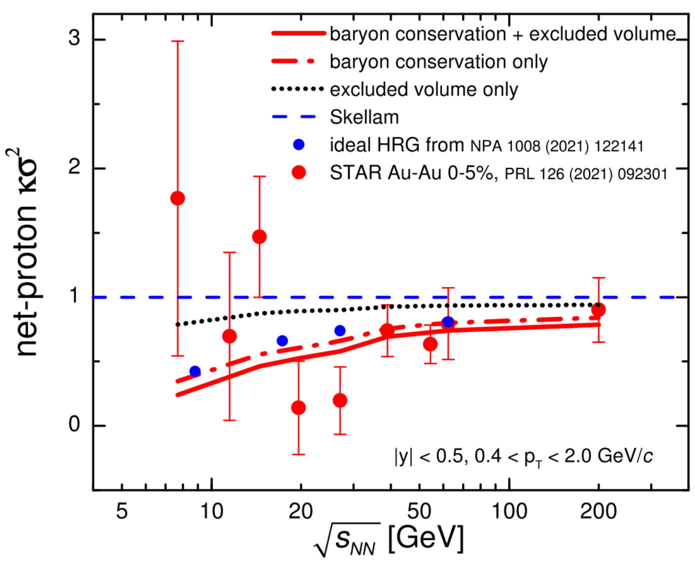
RHIC-BES-I: Net proton cumulant ratios (MUSIC)

VV, V. Koch, C. Shen, Phys. Rev. C 105, 014904 (2022)

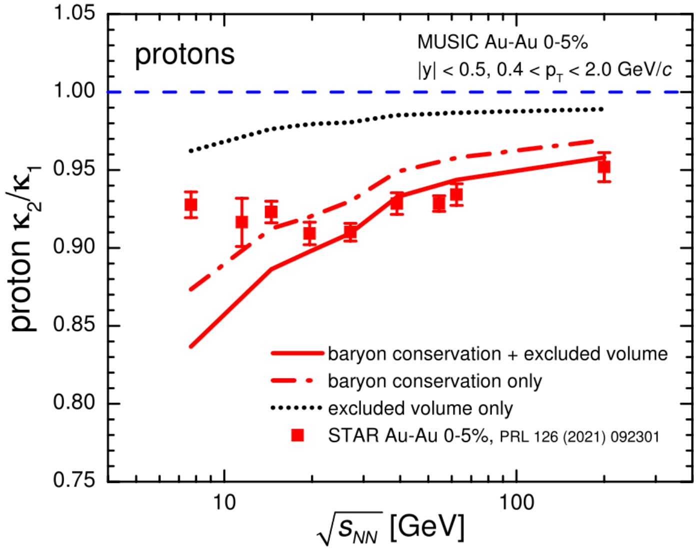
net proton C_3/C_1



net proton C_4/C_2



proton C_2/C_1

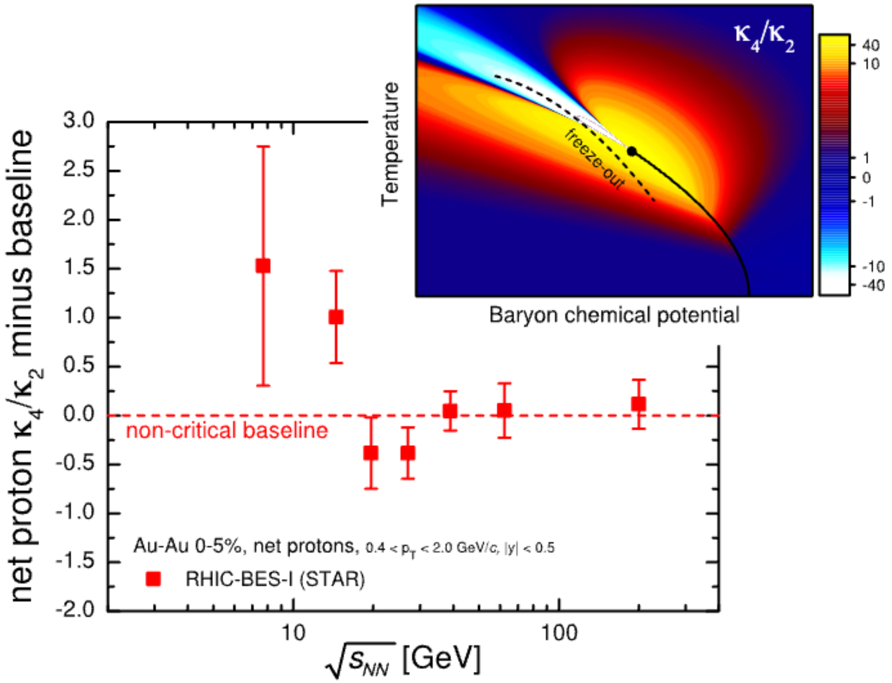


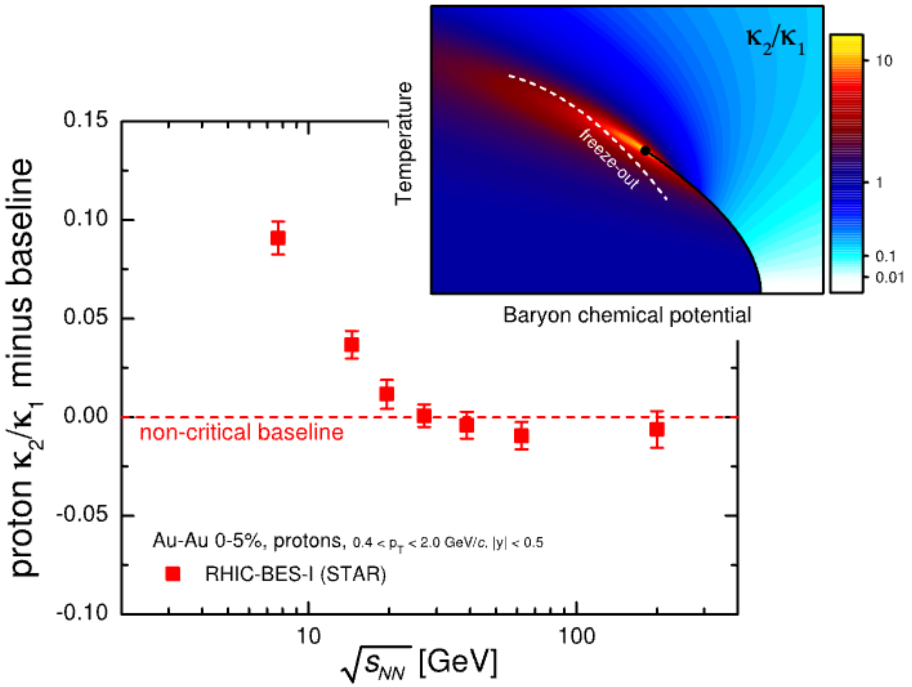
- Data at $\sqrt{s_{NN}} \geq 20$ GeV consistent with non-critical physics (BQS conservation and repulsion)
- Effect from baryon conservation is stronger than repulsion but both are required at $\sqrt{s_{NN}} \geq 20$ GeV
- Deviations from baseline at lower energies?

Hints from RHIC-BES-I

VV, V. Koch, C. Shen, Phys. Rev. C 105, 014904 (2022)

Subtracting the hydrodynamic non-critical baseline



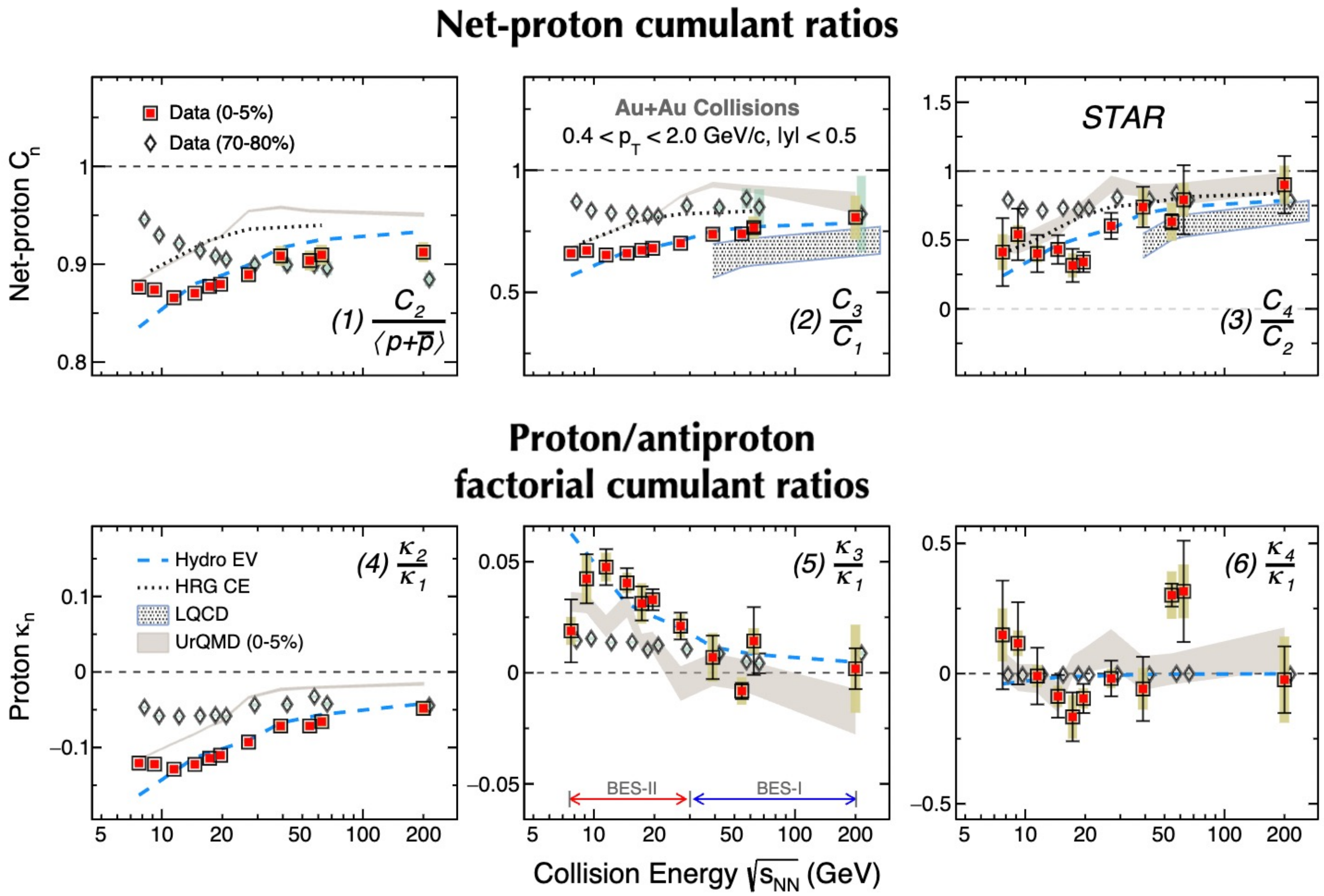


⚠ **Notation:** Here we use κ_n for cumulants and $\hat{C}_n$ for factorial cumulants, STAR Collaboration uses the opposite

Proton cumulants from RHIC-BES-II

RHIC-BES-II data

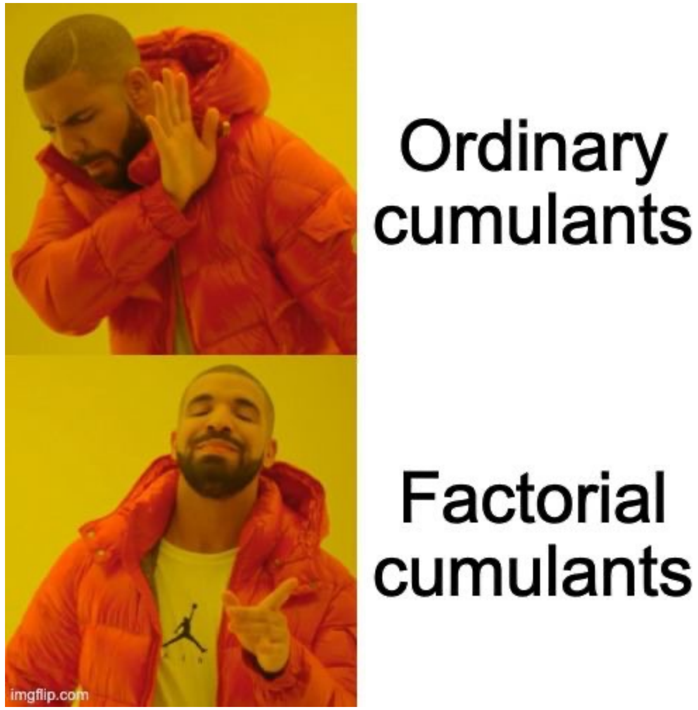
A. Pandav, CPOD2024, N. Xu, EMMI-Wroclaw-2024



Hydro EV: VV, V. Koch, C. Shen, Phys. Rev. C 105, 014904 (2022)

- No smoking gun signature for CP in ordinary cumulants
- More structure seen in factorial cumulants

Conclusion 1:



What are the factorial cumulants?

Factorial cumulants $\hat{C}_n$ vs ordinary cumulants C_n

Factorial cumulants: ~irreducible n-particle correlations

$$\hat{C}_n \sim \langle N(N-1)(N-2)\dots\rangle_c$$

$$\hat{C}_1 = C_1$$
$$\hat{C}_2 = C_2 - C_1$$
$$\hat{C}_3 = C_3 - 3C_2 + 2C_1$$
$$\hat{C}_4 = C_4 - 6C_3 + 11C_2 - 6C_1$$

Ordinary cumulants: mix corrs. of different orders

$$C_n \sim \langle \delta N^n \rangle_c$$

$$C_1 = \hat{C}_1$$
$$C_2 = \hat{C}_2 + \hat{C}_1$$
$$C_3 = \hat{C}_3 + 3\hat{C}_2 + \hat{C}_1$$
$$C_4 = \hat{C}_4 + 6\hat{C}_3 + 7\hat{C}_2 + \hat{C}_1$$

[Bzdak, Koch, Strodthoff, PRC 95, 054906 (2017); Kitazawa, Luo, PRC 96, 024910 (2017); C. Pruneau, PRC 100, 034905 (2019)]

Factorial cumulants and different effects

- Baryon conservation [Bzdak, Koch, Skokov, EPJC '17] — $\hat{C}_n^{\text{cons}} \propto (\hat{C}_1)^n / \langle N_{\text{tot}} \rangle^{n-1}$ *small*
- Excluded volume [VV et al, PLB '17] — $\hat{C}_n^{\text{EV}} \propto b^n$ *small*
- Volume fluctuations [Holzman et al., arXiv:2403.03598] — $\hat{C}_n^{CF} \sim (\hat{C}_1)^n \kappa_n[V]$ *depends on volume cumulants*
- **Critical point** [Ling, Stephanov, PRC '16] — $\hat{C}_2^{CP} \sim \xi^2$, $\hat{C}_3^{CP} \sim \xi^{4.5}$, $\hat{C}_4^{CP} \sim \xi^7$ ***large***

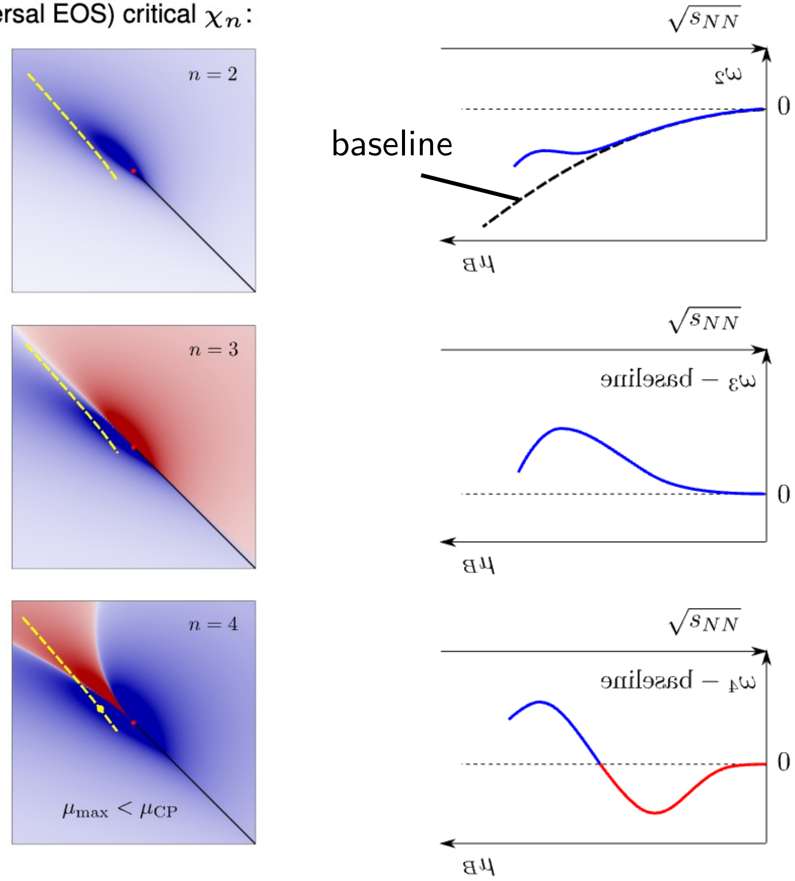
- proton vs baryon [Kitazawa, Asakawa, PRC '12] — $\hat{C}_n^B \sim 2^n \times \hat{C}_n^p$ **same sign!**

Factorial cumulants from RHIC-BES-II

From M. Stephanov, SQM2024 & arXiv:2410.02861

$$\omega_n = \hat{C}_n / \hat{C}_1$$

(universal EOS) critical χ_n:



Bzdak et al review 1906.00936

Expected signatures: bump in ω_2 and ω_3, dip then bump in ω_4 for CP at $\mu_B > 420$ MeV

Factorial cumulants from RHIC-BES-II

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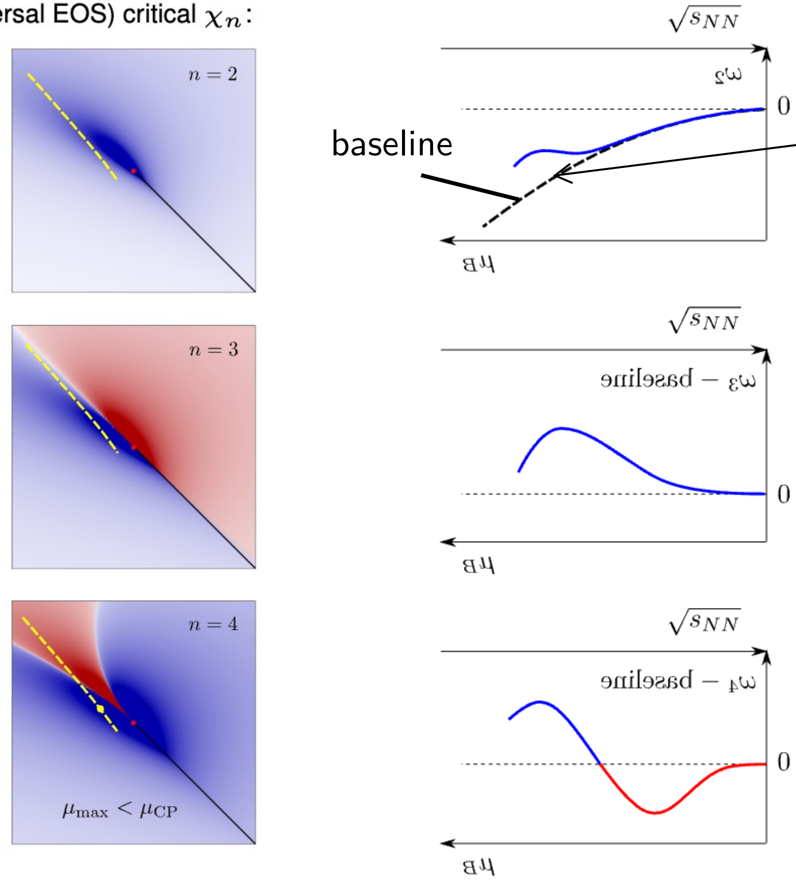
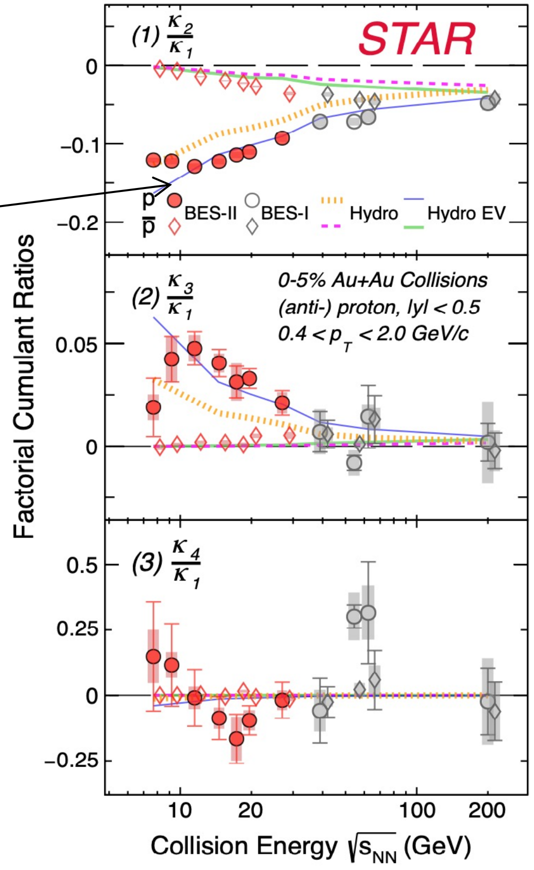


Bzdak et al review 1906.00936

STAR data:



A. Pandav, CPOD2024

baseline (hydro EV):

VV, V. Koch, C. Shen, PRC 105, 014904 (2022)

Expected signatures: bump in ω_2 and ω_3, dip then bump in ω_4 for CP at $\mu_B > 420$ MeV

Factorial cumulants from RHIC-BES-II

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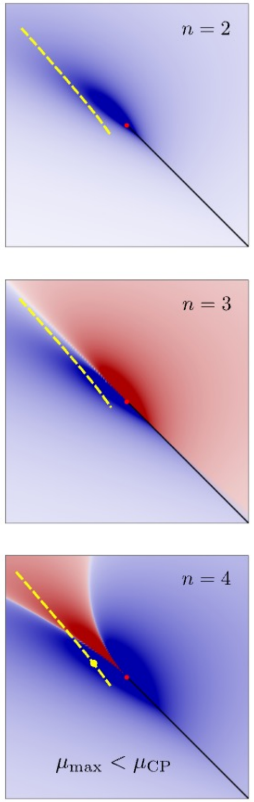
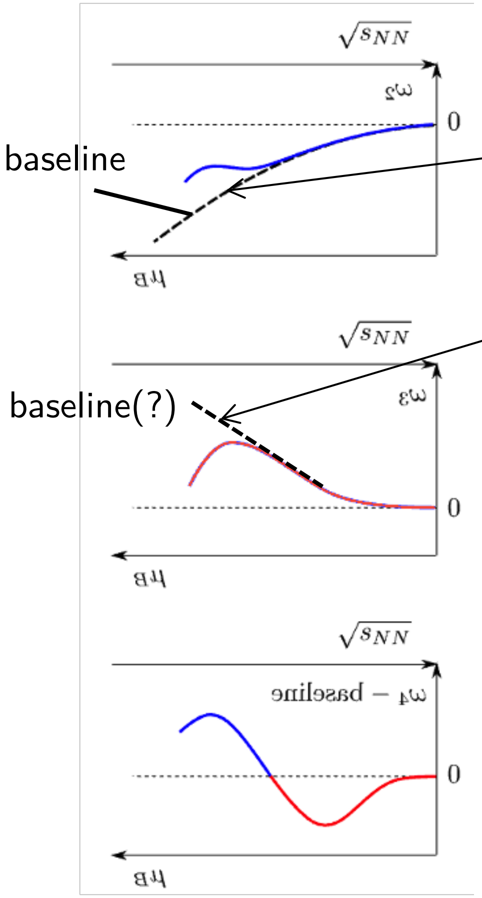
$\omega_n = \hat{C}_n / \hat{C}_1$

(universal EOS) critical χ_n:

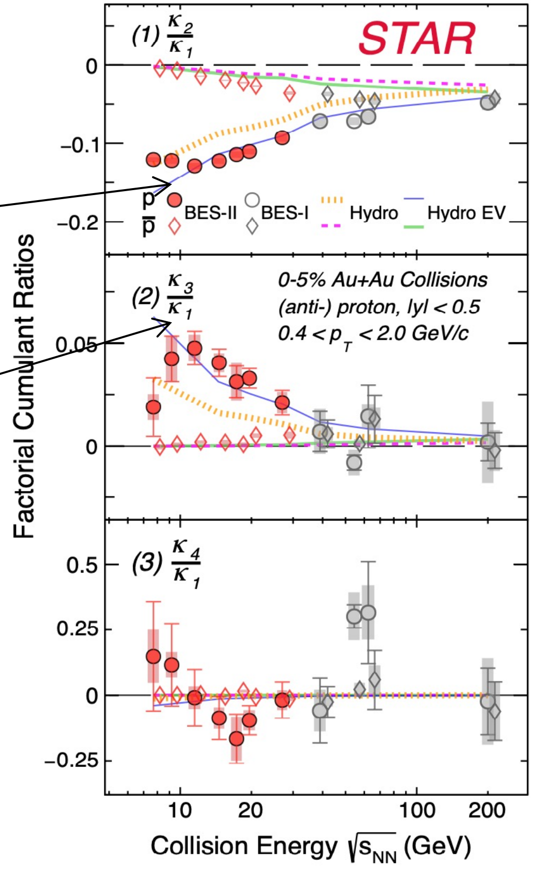


Bzdak et al review 1906.00936



Expected signatures: bump in ω_2 and ω_3, dip then bump in ω_4 for CP at $\mu_B > 420$ MeV

STAR data:



A. Pandav, CPOD2024

baseline (hydro EV):

VV, V. Koch, C. Shen, PRC 105, 014904 (2022)

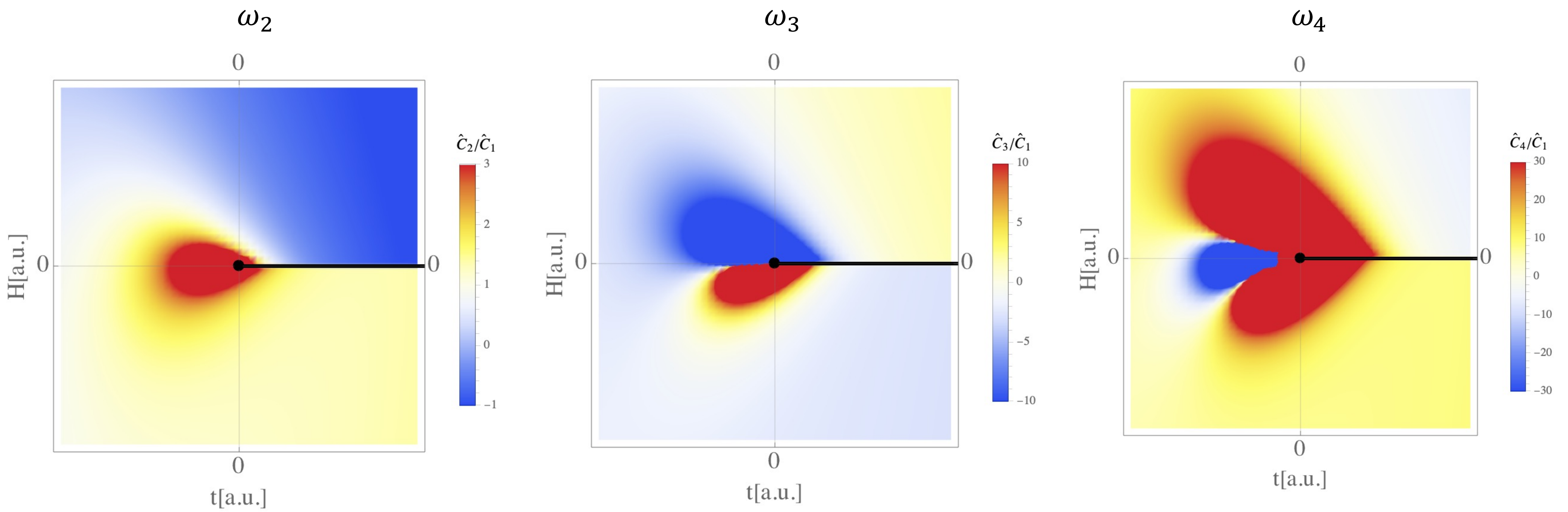
- describes right side of the peak in $\hat{C}_3$
- **signal relative to baseline:**
  - *positive* $\hat{C}_2 > 0$
  - *negative* $\hat{C}_3 < 0$

Conclusion 2:

Controlling the non-critical baseline is essential

Factorial cumulants from RHIC-BES-II and CP

Factorial cumulants in 3D-Ising model

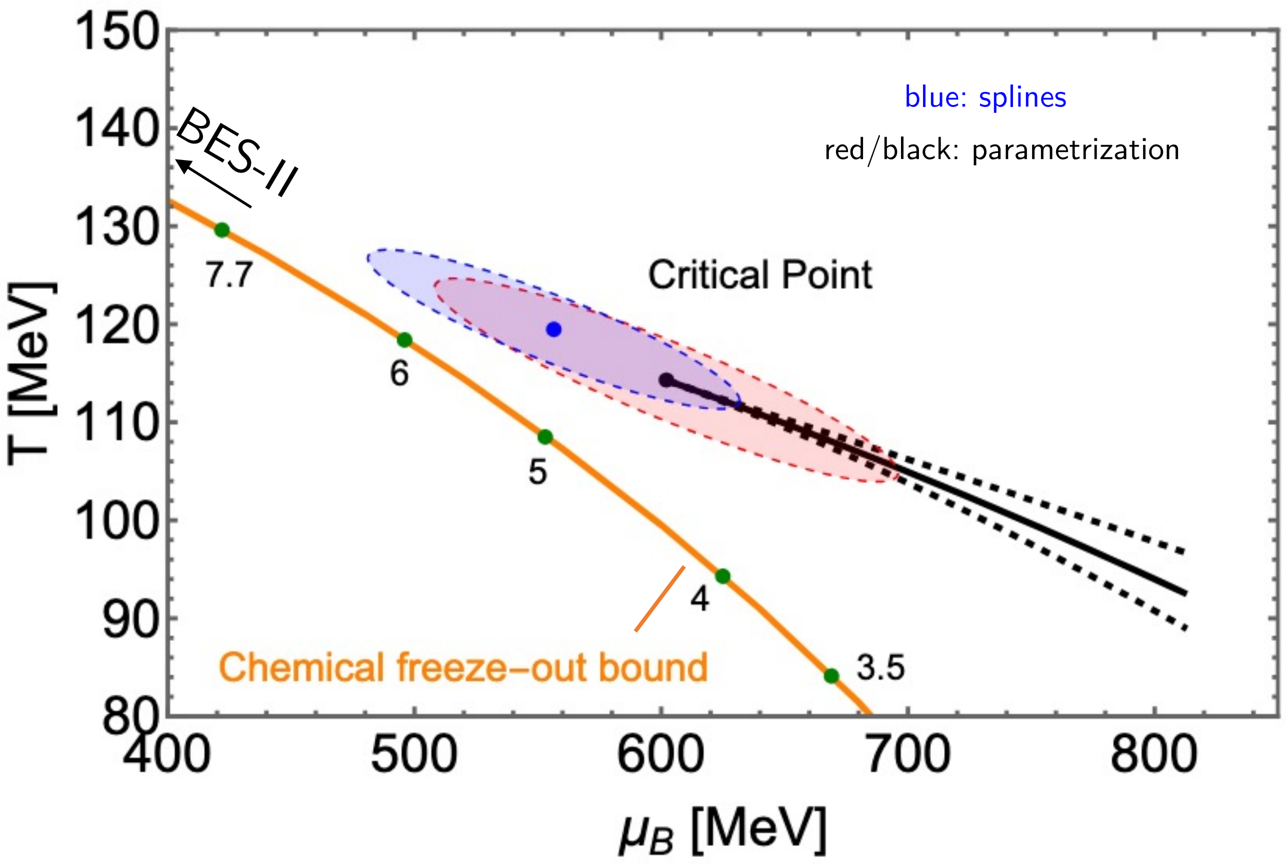


Adapted from Bzdak, Koch, Strodthoff, PRC 95, 054906 (2017)

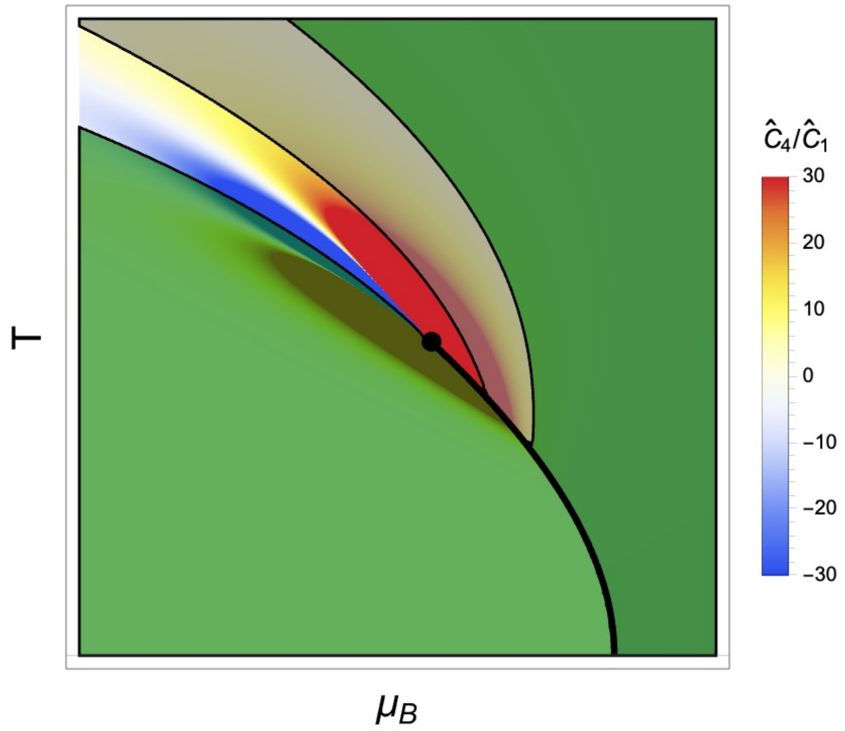
$\omega_n = \hat{C}_n/\hat{C}_1$

Factorial cumulants from RHIC-BES-II and CP

Exclusion plots



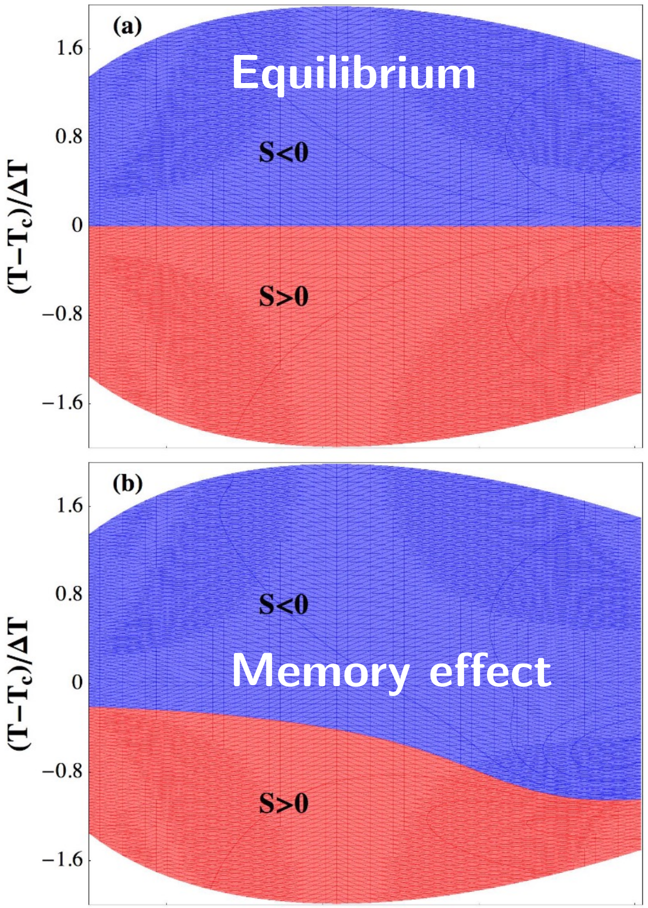
How it may look like in $T - \mu_B$ plane



Based on QvdW model of nuclear matter
VV, Anchishkin, Gorenstein, Poberezhnyuk, PRC 92, 054901 (2015)

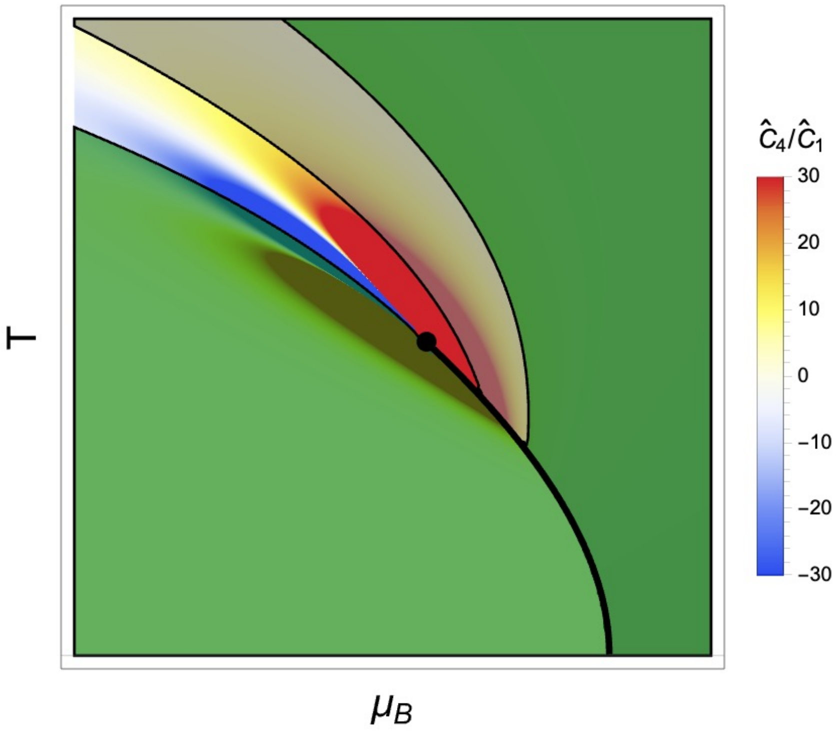
Freeze-out of fluctuations on the QGP side of the crossover?

Factorial cumulants from RHIC-BES-II and CP



Mukherjee, Venugopalan, Yin, PRC 92, 034912 (2015)

How it may look like in $T - \mu_B$ plane



Freeze-out of fluctuations on the QGP side of the crossover?

Interplay with nuclear liquid-gas transition

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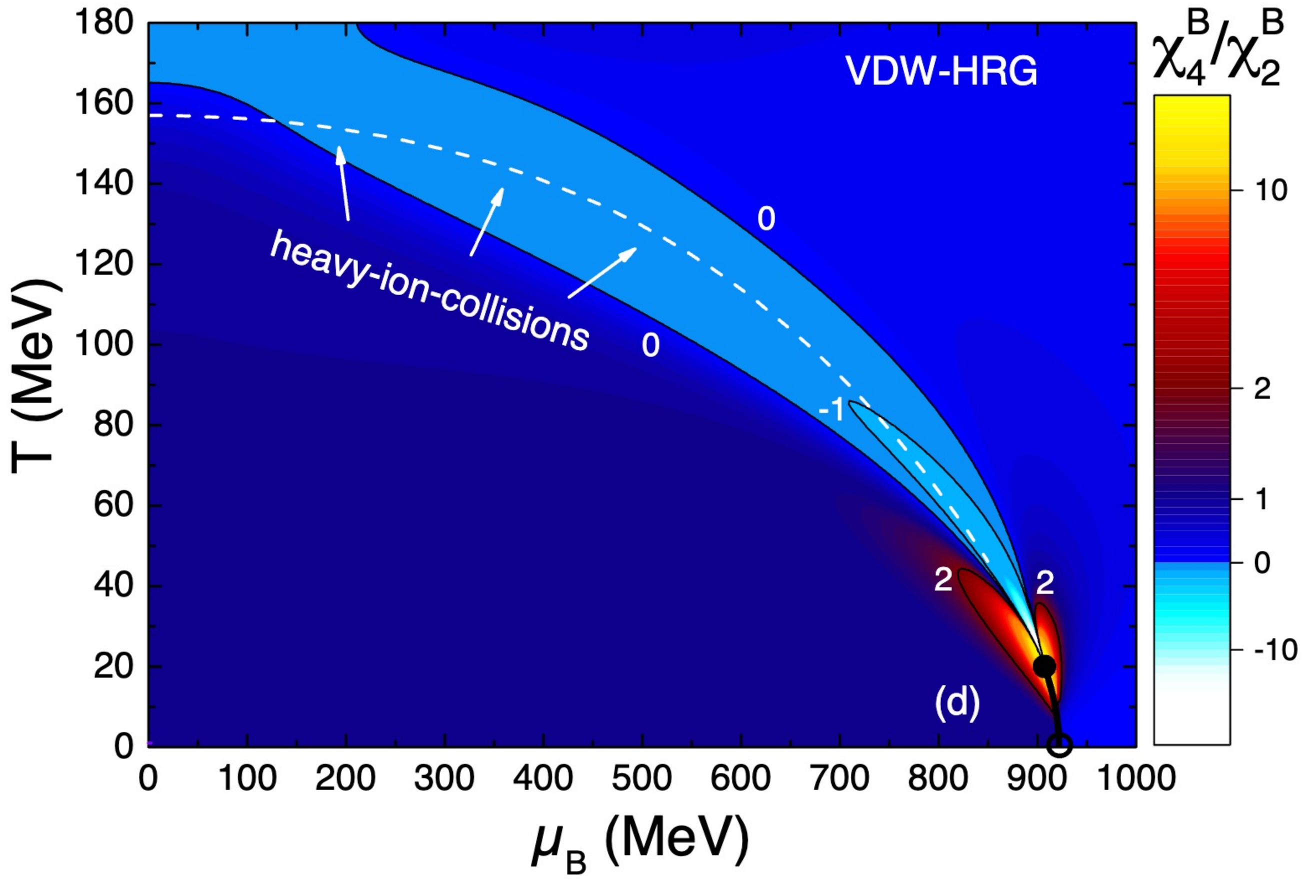
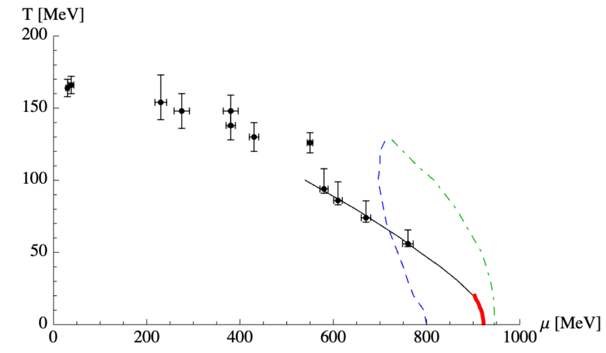
HRG with attractive and repulsive interactions among baryons

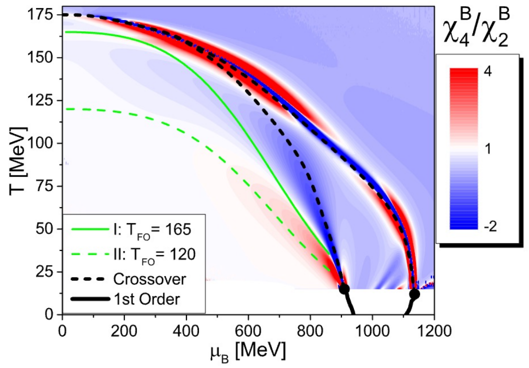


VV, Gorenstein, Stoecker, Phys. Rev. Lett. 118, 182301 (2017)

Interplay with nuclear liquid-gas transition

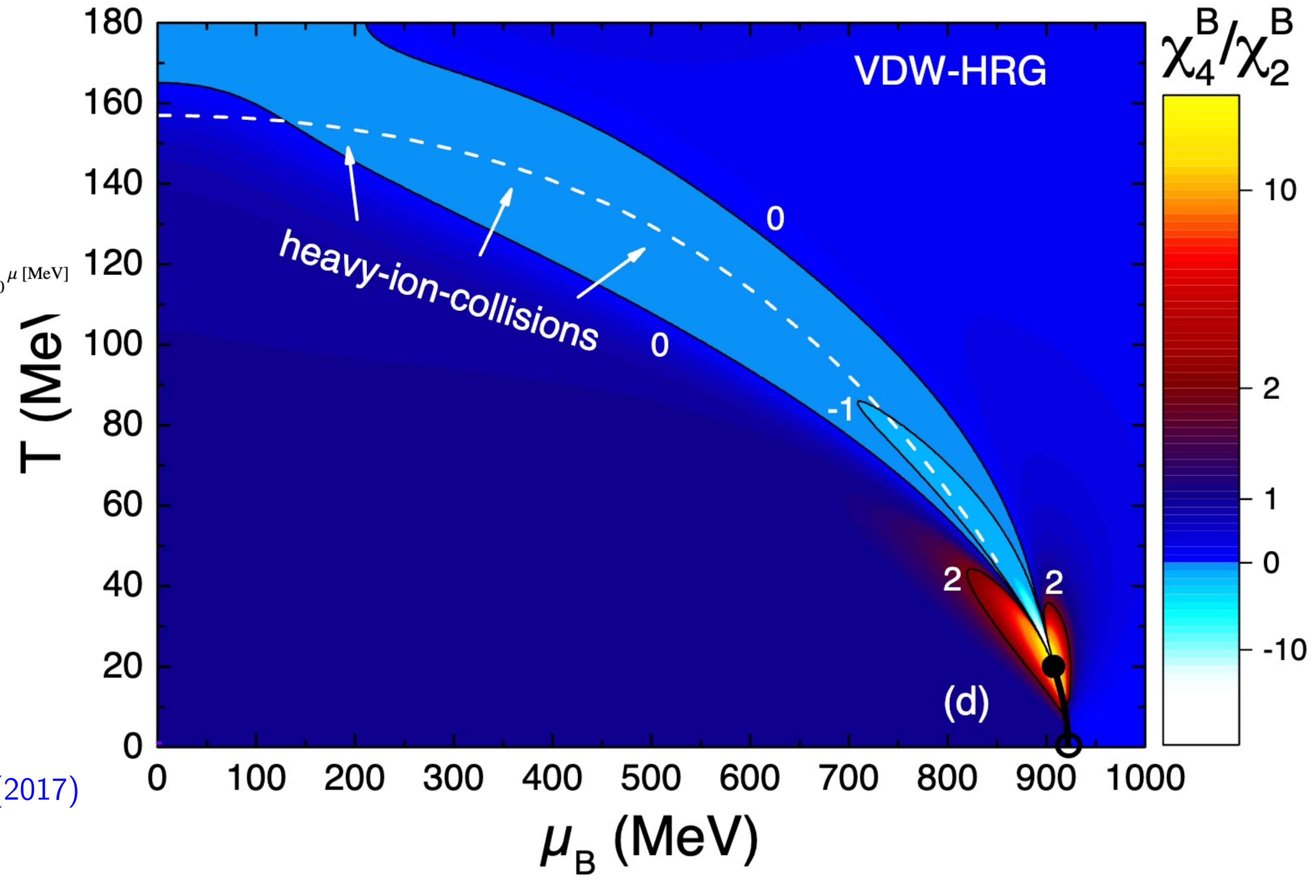


Floerchinger, Wetterich, NPA (2012)

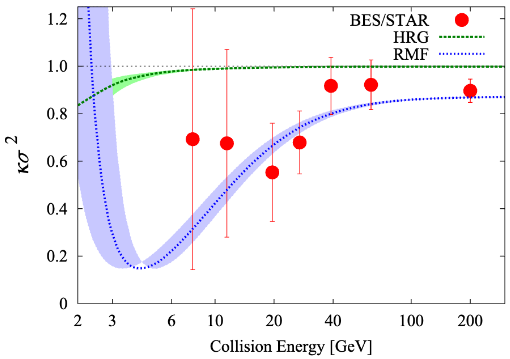


Mukherjee, Steinheimer, Schramm, PRC (2017)

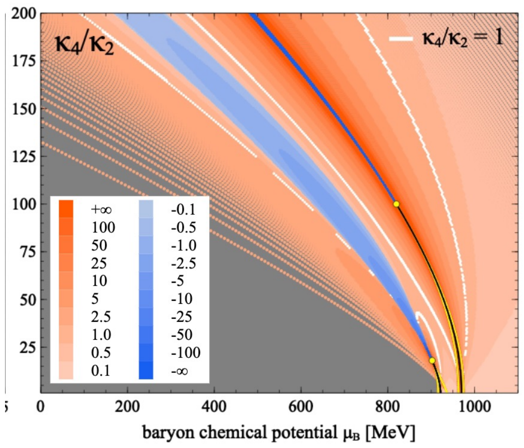
HRG with attractive and repulsive interactions among baryons



VV, Gorenstein, Stoecker, Phys. Rev. Lett. 118, 182301 (2017)



Fukushima, PRC (2014)



Sorensen, Koch, PRC (2020)

Scaled factorial cumulants, long-range correlations, and the antiproton puzzle

Acceptance dependence and long-range correlations

Long-range correlations: $\frac{\hat{C}_n}{(\hat{C}_1)^n} = \text{const.}$ at given $\sqrt{s_{NN}}$

- Global (not local) baryon conservation

  [Bzdak, Koch, Skokov, EPJC 77, 288 (2017)]

- + volume fluctuations

  [Holzmann, Koch, Rustamov, Stroth, arXiv:2403.03598]

- + (uniform) efficiency

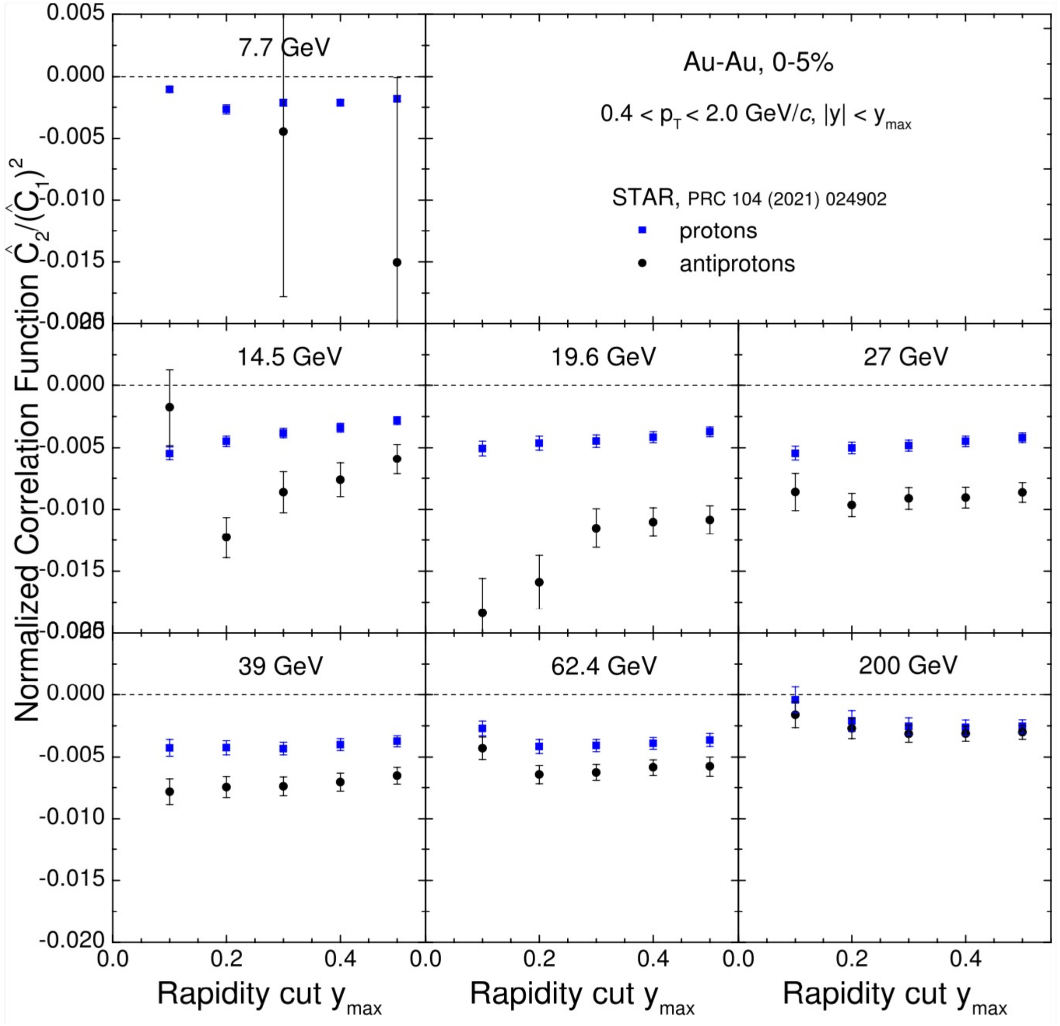
  [Pruneau, Gavin, Voloshin, PRC 66, 044904 (2002)]

In particular $\frac{\hat{C}_2^p}{(\hat{C}_1^p)^2} \approx \frac{\hat{C}_2^{\bar{p}}}{(\hat{C}_1^{\bar{p}})^2} = \text{const.}$

- Significant difference between p and $\bar{p}$ in BES-I
  - **The antiproton puzzle?**
- With BES-II one can test the scaling with greater precision and extended coverage in rapidity
  - No need for volume fluctuations corrections (CBWC)

A. Bzdak, V. Koch, VV, in preparation

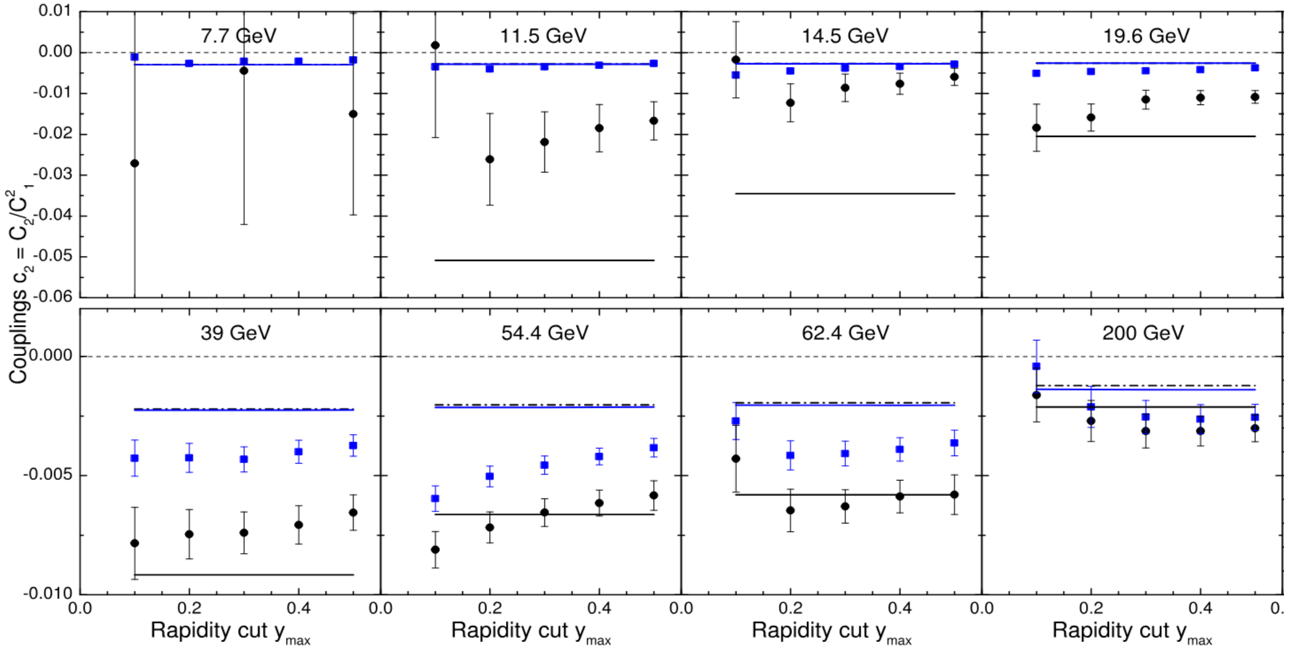
BES-I data



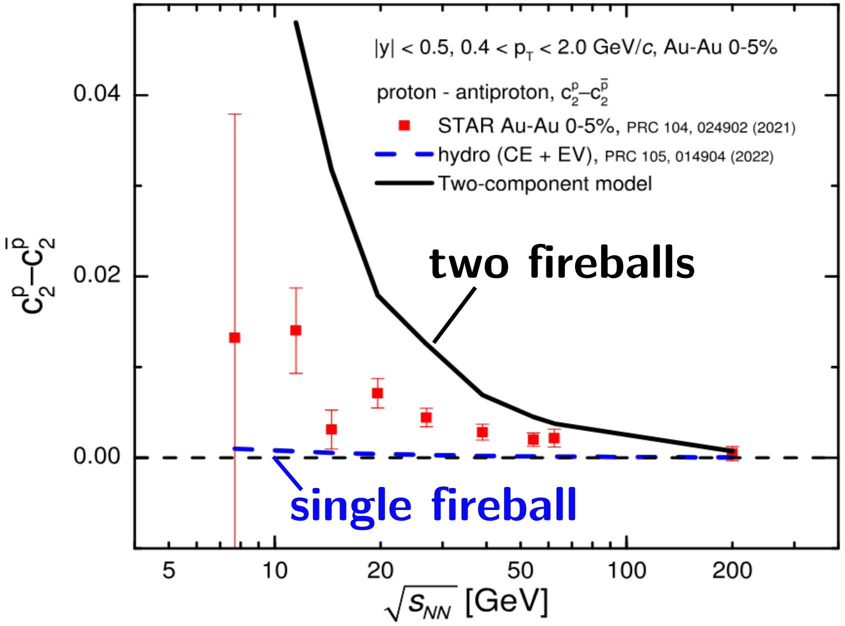
Factorial cumulants and two-component model

Two-component model: produced ($p\bar{p}$ pairs) and stopped protons come from two independent fireballs

Data lie in-between single and two-fireball models



Difference between p and $\bar{p}$



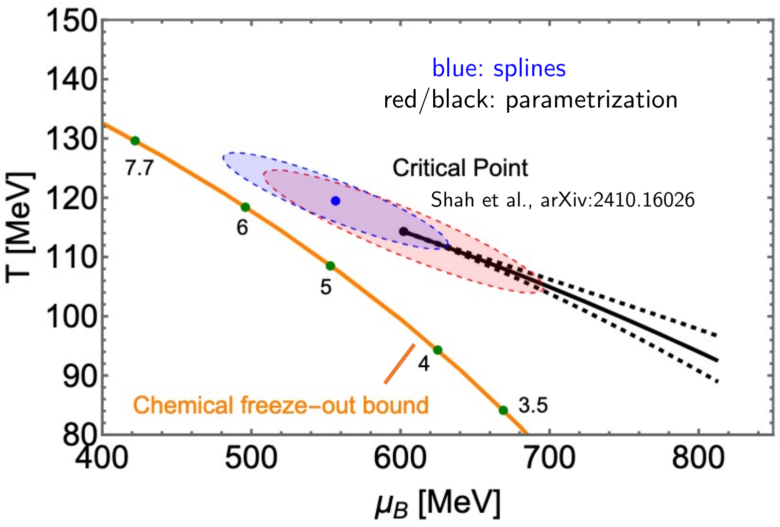
Opportunities for BES-II:

- Further tests of the splitting between protons and antiprotons in 2nd order cumulants with extended y coverage
- Critical point signal expected to break the scaling $\frac{\hat{C}_n}{(\hat{C}_1)^n} = \text{const.}$

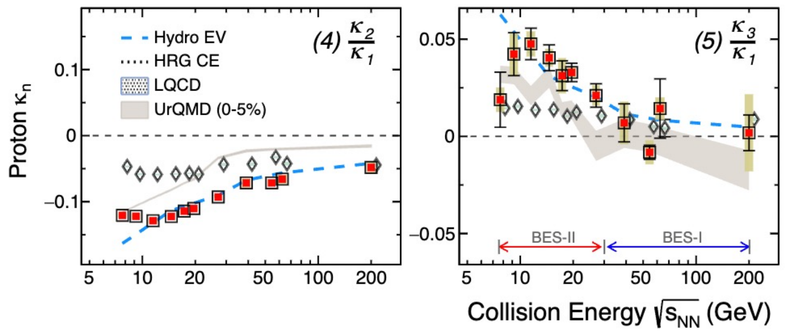
A. Bzdak, V. Koch, VV, in preparation

Summary

- Locating the QCD critical point from first-principles
  - New method based on contours of constant entropy places QCD CP at $T_c = 114.3 \pm 6.9$ MeV, $\mu_B = 602.1 \pm 62.1$ MeV
- Proton cumulants are uniquely sensitive to the CP but challenging to model dynamically, factorial cumulants are advantageous



- BES-II data is in
  - Consistent with predictions from non-critical physics @$\sqrt{s_{NN}} \geq 20$ GeV
  - Shows (non-monotonic) structure in factorial cumulants
  - Positive $\hat{C}_2$ and negative $\hat{C}_3$ after subtracting non-critical baseline at $\sqrt{s_{NN}} < 10$ GeV



Outlook:

- Improving first-principles constraints on CP location
- Improved description of non-critical baselines and quantitative predictions of critical fluctuations
- Acceptance dependence of factorial cumulants, understanding antiprotons

Thanks for your attention!