Fluctuation Probes of QCD Matter in Heavy-Ion Collisions

Volodymyr Vovchenko (University of Houston)

Hadron Ion Tea (HIT) Seminar, LBNL

March 11, 2025

Thanks to:

A. Bzdak, V. Koch, V.A. Kuznietsov, R. Poberezhniuk, J. Parra, C. Ratti

QCD under extreme conditions

What we know

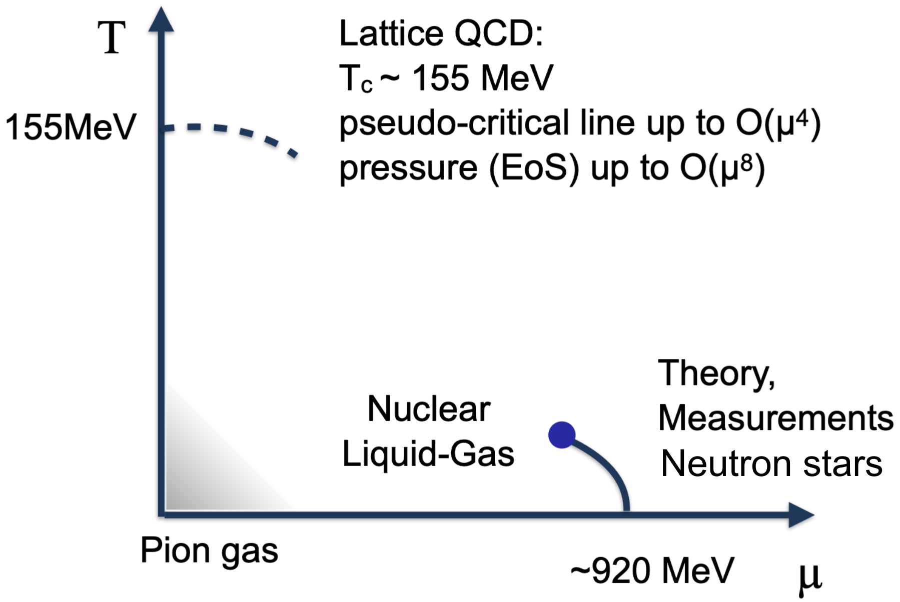


Figure courtesy of V. Koch

What we hope to know

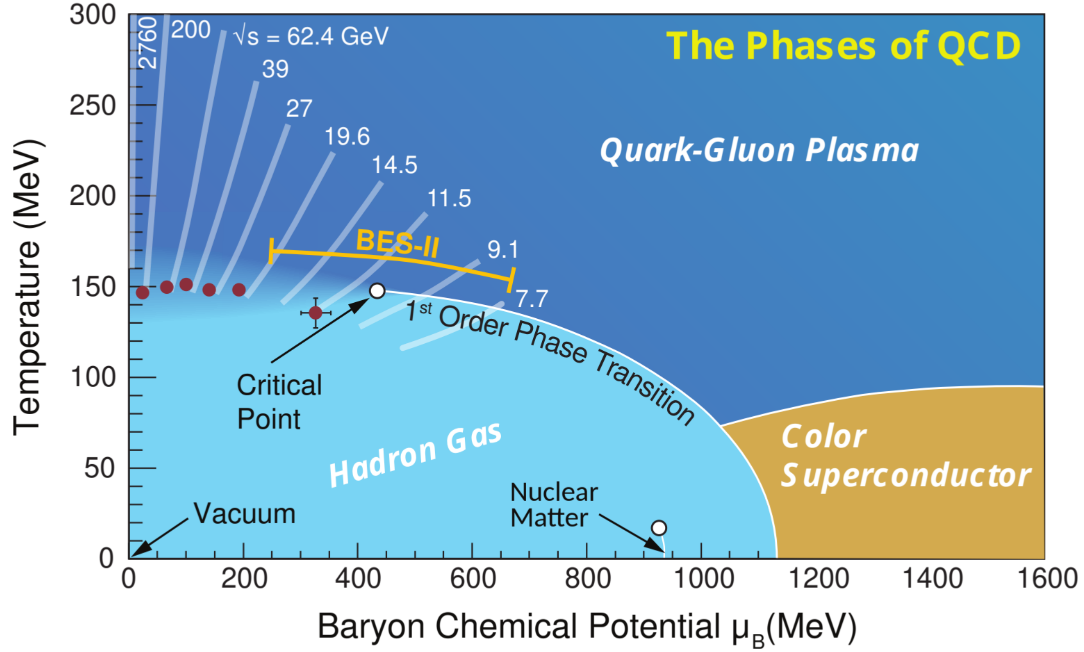
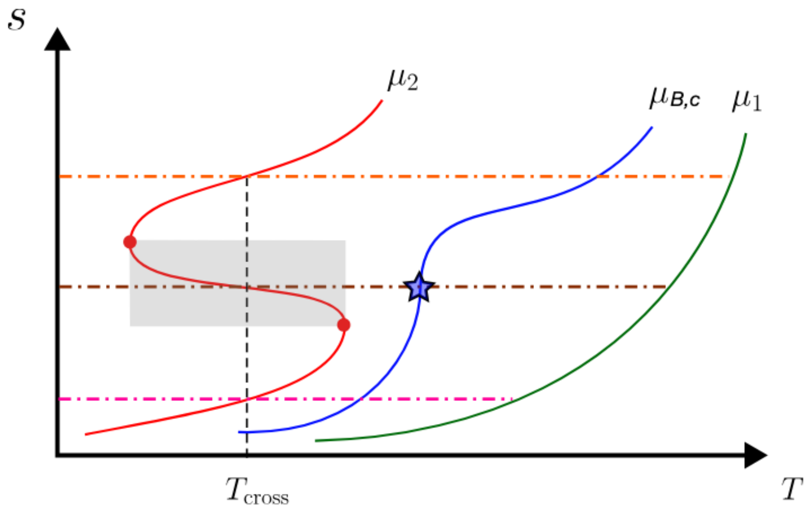


Figure from Bzdak et al., Phys. Rept. '20 & 2015 US Nuclear Long Range Plan

- 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:

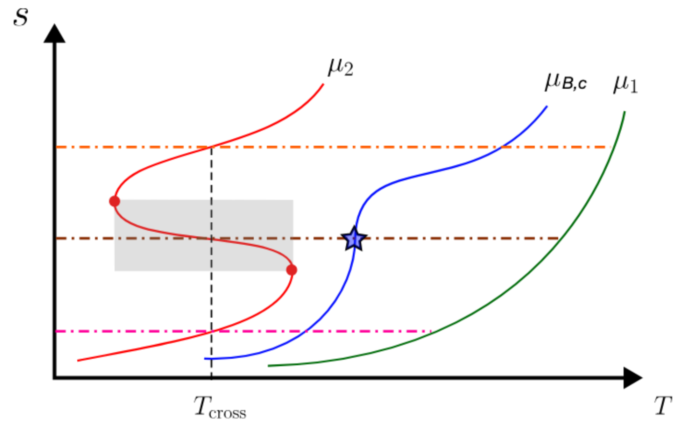
New developments

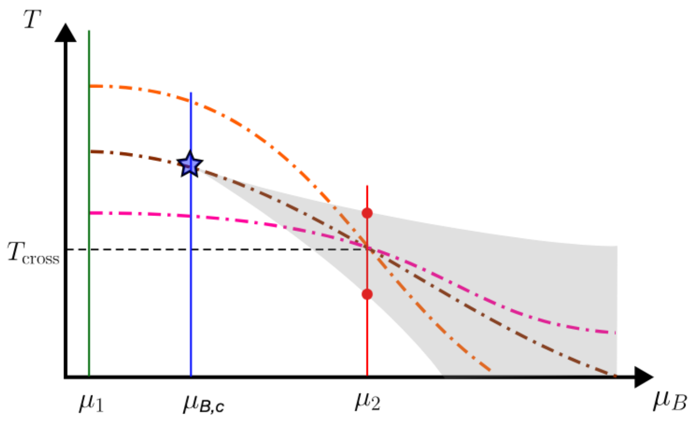
- H. Shah, M. Hippert, J. Noronha, C. Ratti, VV, "Locating the QCD critical point from first principles through contours of constant entropy density", arXiv:2410.16206

- S. Borsanyi, Z. Fodor, J. Guenther, P. Parotto, A. Pasztor, C. Ratti, VV, C.-H. Wong, "Lattice QCD constraints on the critical point from an improved precision equation of state", arXiv:2502.10267

Critical point and crossings of entropy density

- Entropy density s becomes multi-valued function of T and μ_B for a first-order phase transition
- It develops a distinctive S-shape as a function of T at $\mu_B = const$

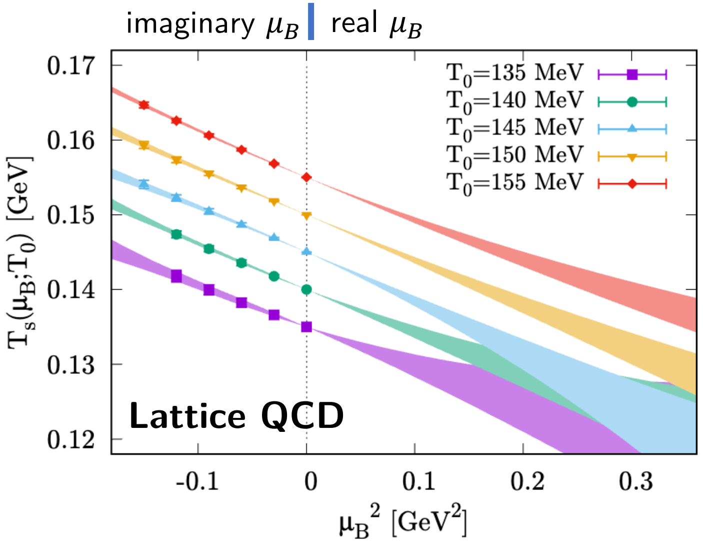




Critical Point:

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

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



S. Borsanyi et al., arXiv:2502.10267

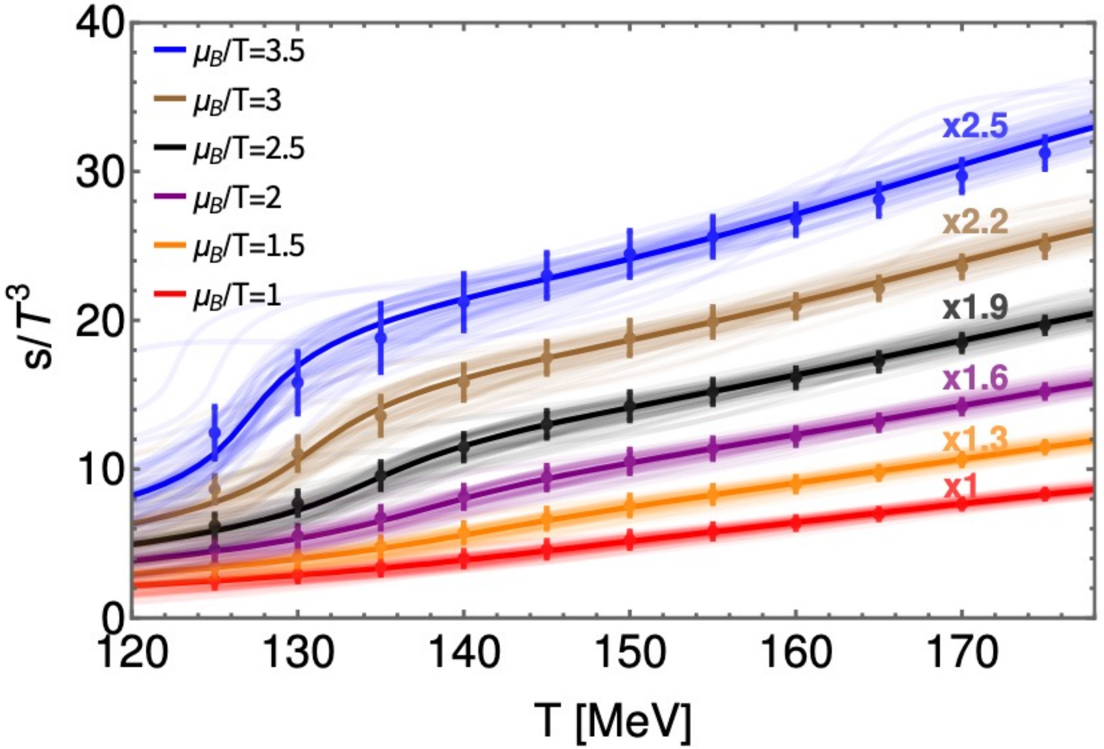
- Lattice QCD simulations at imaginary chemical potentials indicate that entropy contours are almost linear in μ_B^2

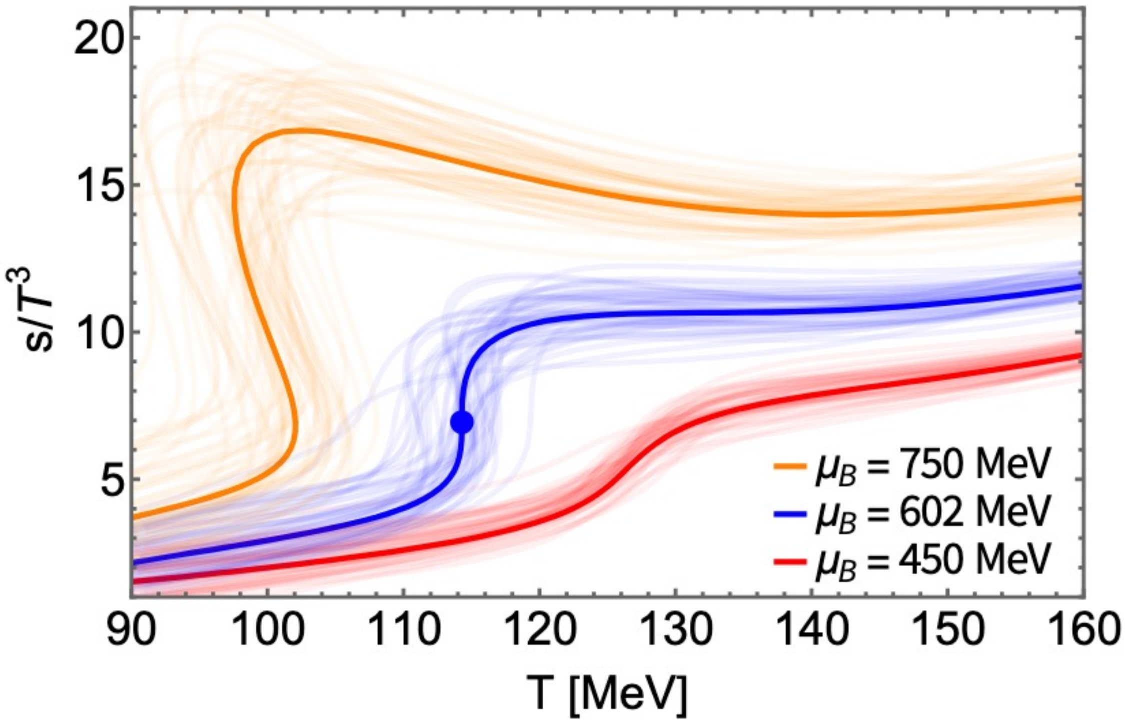
Idea: Follow contours of constant entropy density and look for crossings

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

Entropy density at finite μ_B at $O(\mu_B^2)$

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



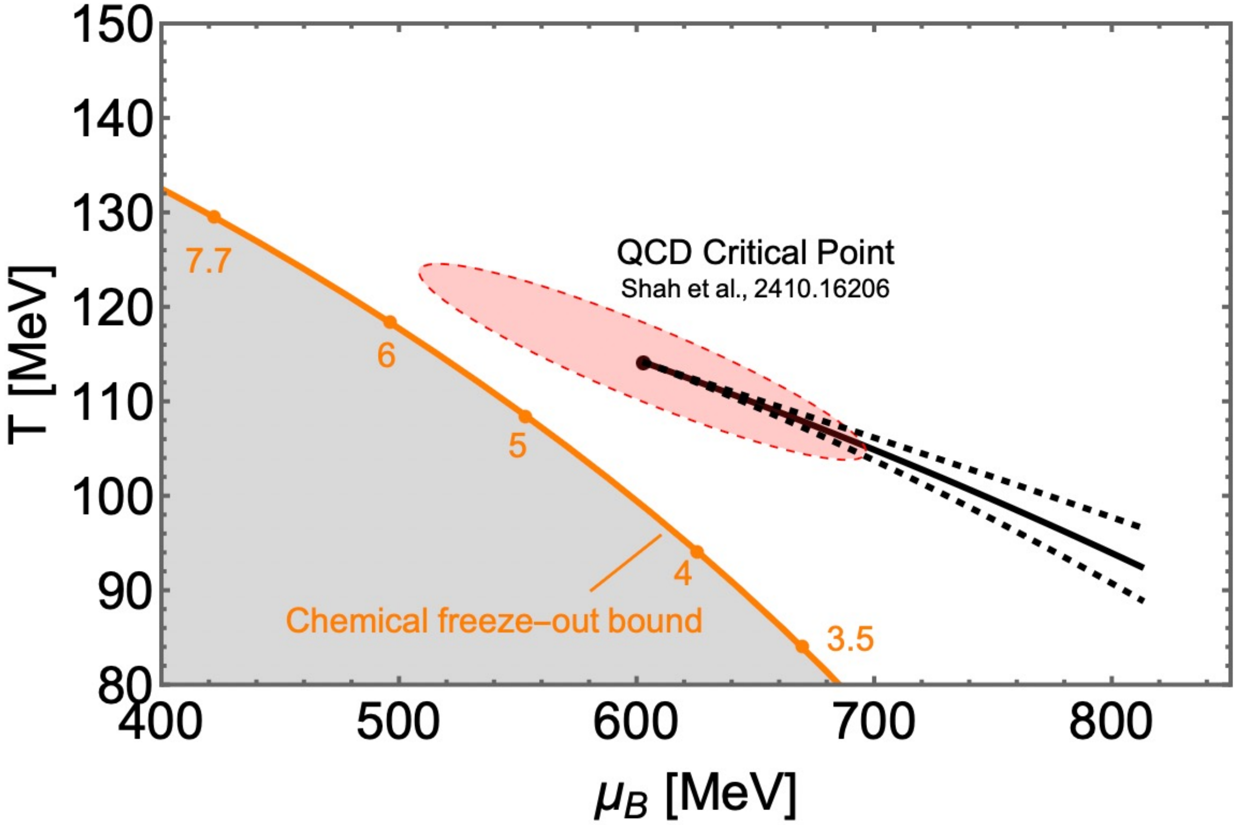


- Excellent agreement at low μ_B/T with available lattice QCD constraints
  [Borsanyi et al., PRL 126, 232001 (2021)]
- First-order phase transition emerges at $\mu_B > 600$ MeV

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

Locating the critical point

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

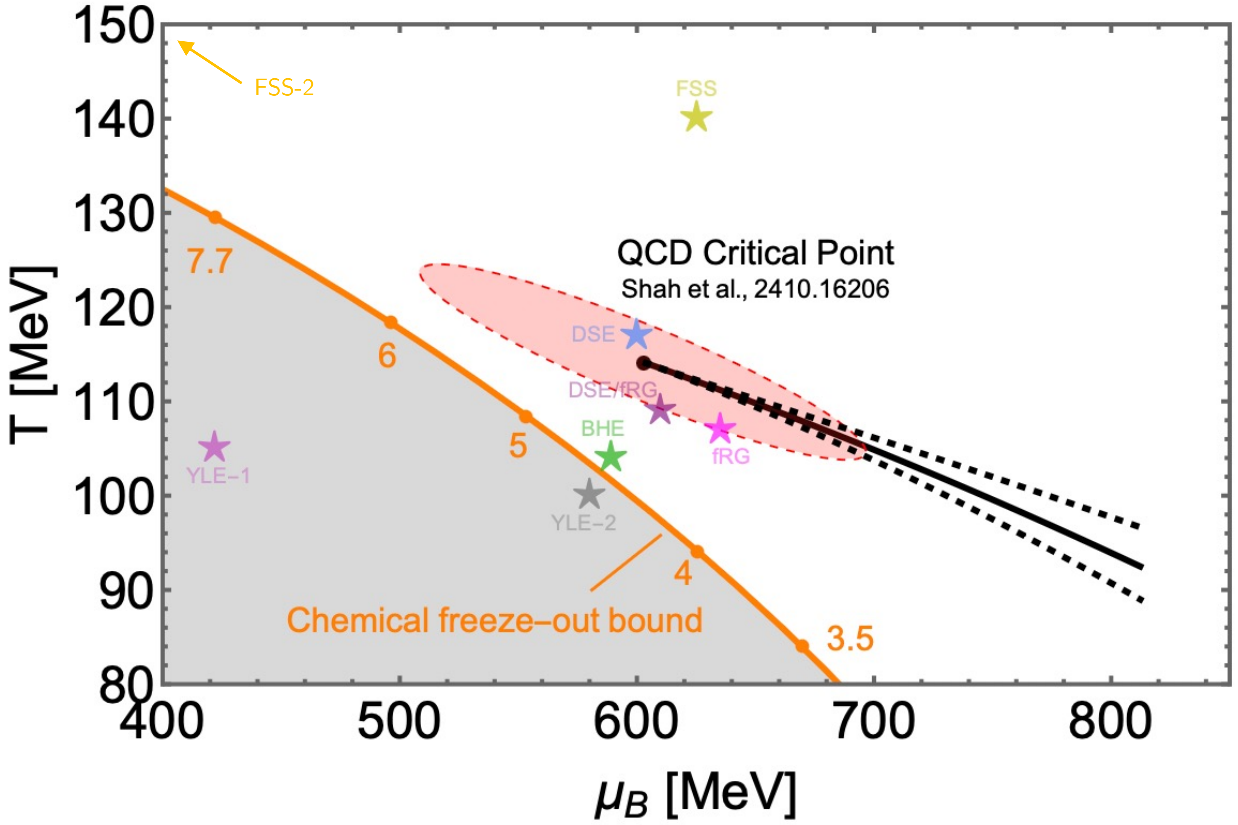


Critical point location at $O(\mu_B^2)$:

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

Locating the critical point

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



Critical point location at $O(\mu_B^2)$:

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

Similar to 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/fRG: Gao, Pawlowski., PLB 820, 136584 (2021)

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

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

FSS-2: R. Lacey, arXiv:2411.09139

Recent development: Extrapolations of $s = const$ contours from imaginary μ_B with strangeness neutrality

↪ CP excluded at $\mu_B < 450$ MeV at a (one-sided) 2σ level

S. Borsanyi, Z. Fodor, J. Guenther, P. Parotto, A. Pasztor, C. Ratti, VV, C.-H. Wong, arXiv:2502.10267

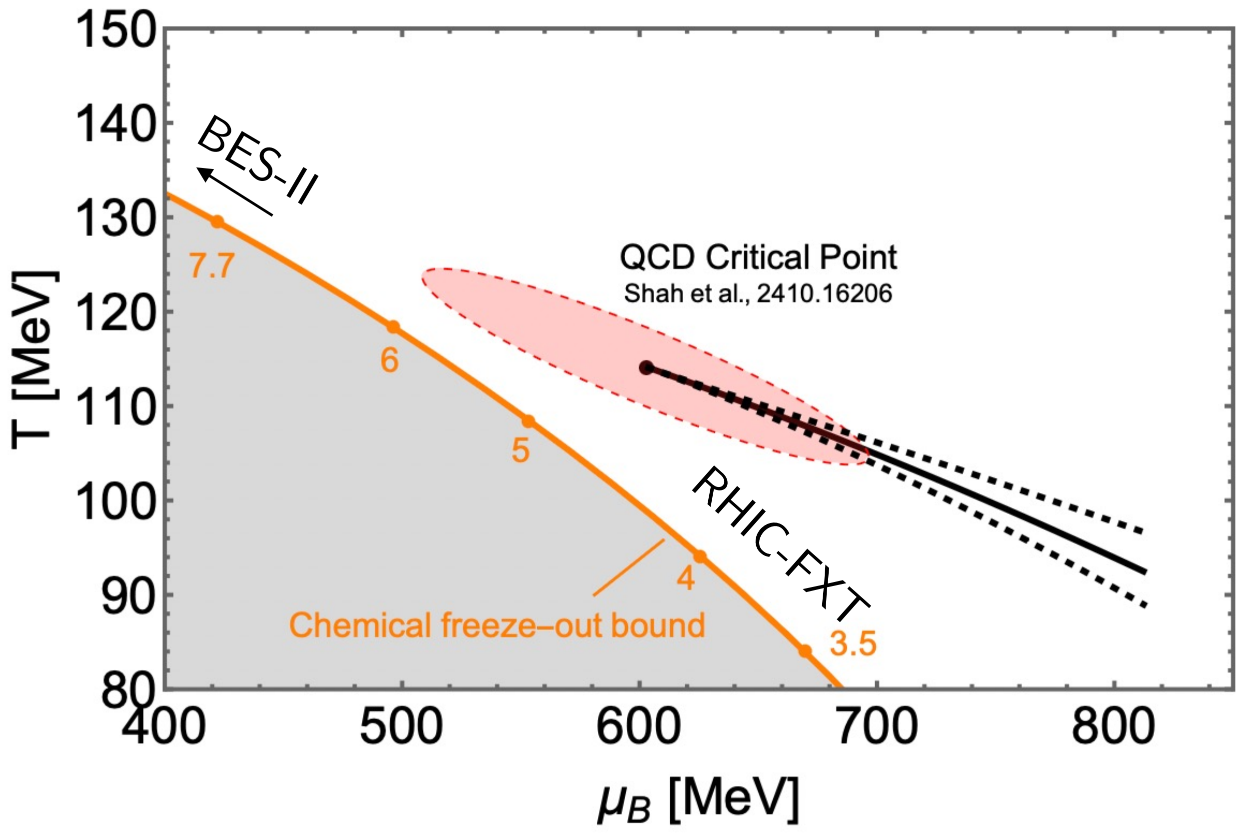
Critical point and heavy-ion collisions

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

- Sets the **lower bound** on the temperature of the CP [Lysenko, Poberezhnyuk, Gorenstein, VV, arXiv:2408.06473]
- **Caveats:** strangeness neutrality ($\mu_S \neq 0$), uncertainty in the freeze-out curve
- CP may be close to freeze-out at $\sqrt{s_{NN}} \sim 3.5 - 5$ GeV

Critical point, cumulants, and heavy-ion collisions

Event-by-event fluctuations and statistical mechanics

Cumulant generating function

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

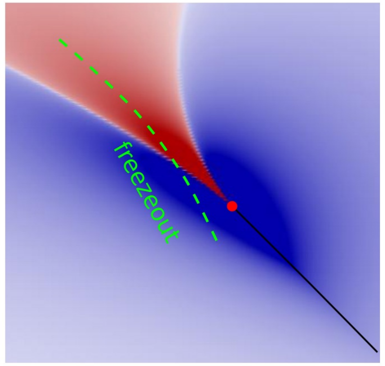
Grand partition function

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

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

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)

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

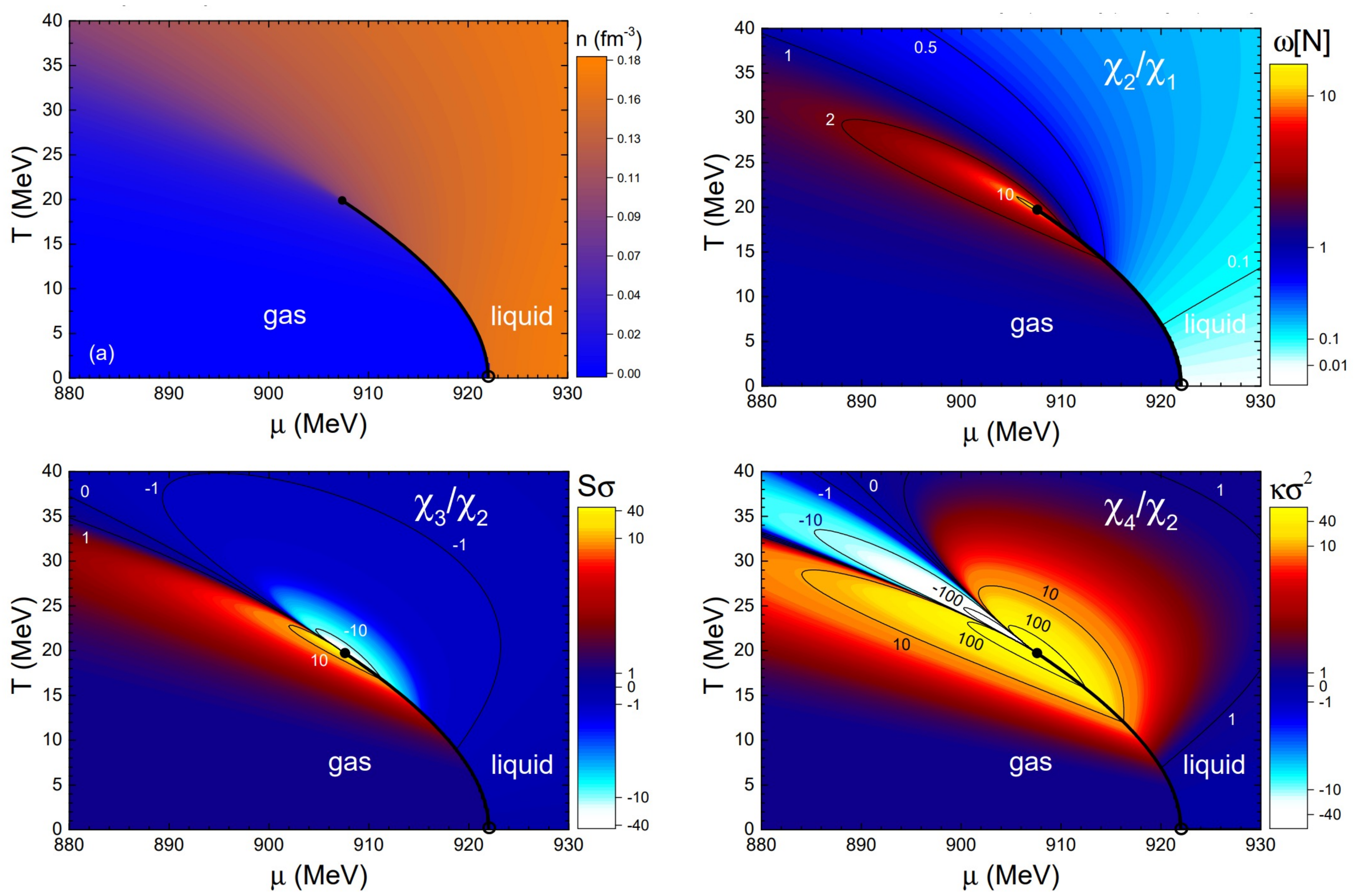
$$\xi \to \infty$$

Looking for enhanced fluctuations
and non-monotonicities

Other uses of cumulants:

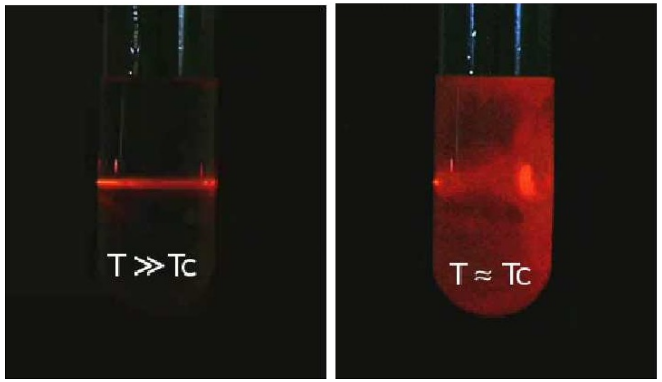
- **QCD degrees of freedom**
  Jeon, Koch, PRL 85, 2076 (2000)
  Asakawa, Heinz, Muller, PRL 85, 2072 (2000)
- Extracting the speed of sound
  A. Sorensen et al., PRL 127, 042303 (2021)
- Conservation volume V_C
  VV, Donigus, Stoecker, PRC 100, 054906 (2019)

Example: (Nuclear) Liquid-gas transition



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

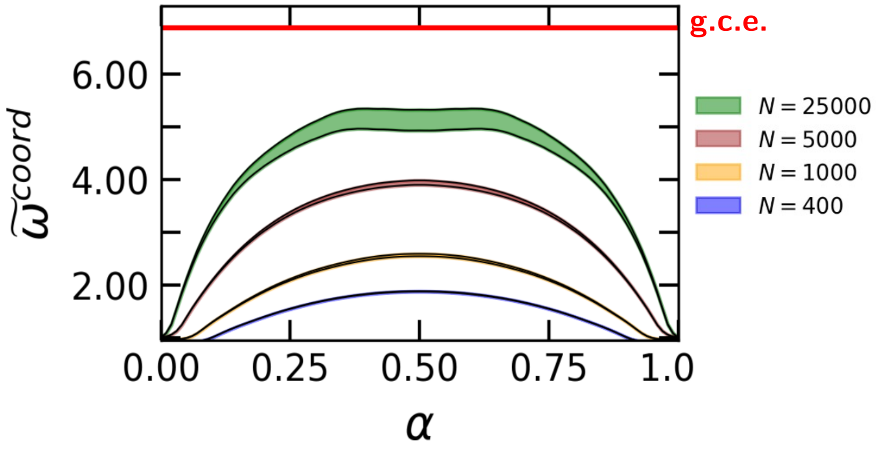
Example: Critical fluctuations in a microscopic simulation

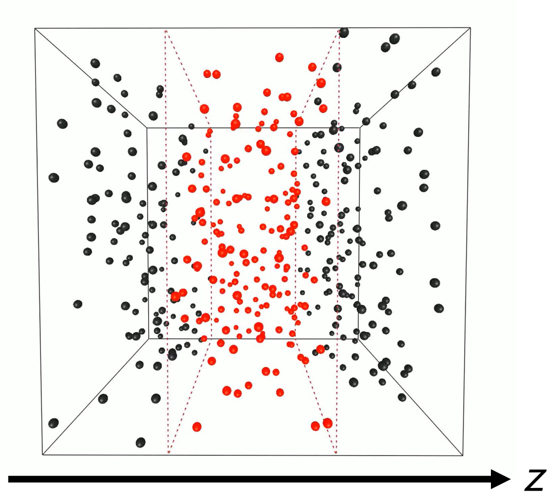
V. Kuznietsov et al., Phys. Rev. C 105, 044903 (2022)

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

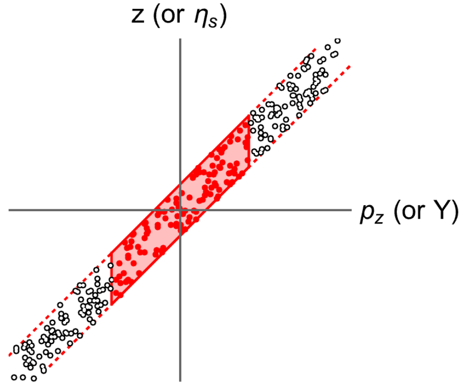
Scaled variance in coordinate space acceptance $|z| < z^{max}$

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





Heavy-ion collisions:
flow correlates p_z and z cuts



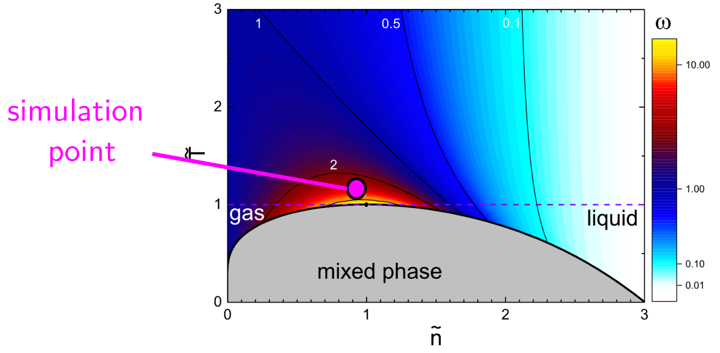
- Large fluctuations survive despite strong finite-size effects
- Need coordinate space cuts (collective flow helps)
- Here no finite-time effects

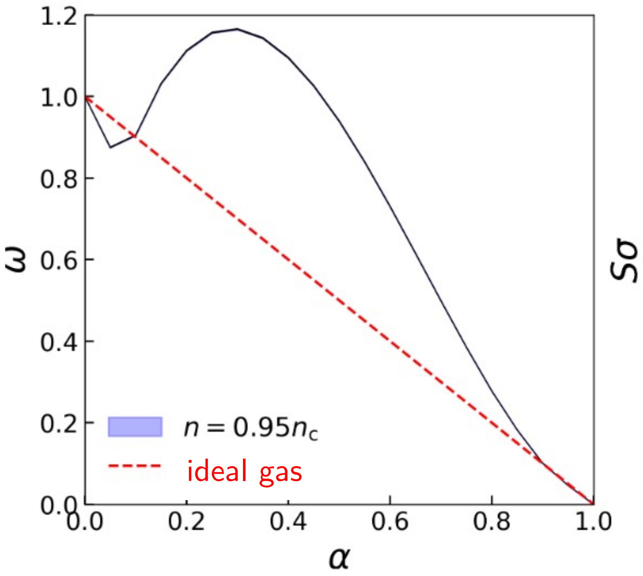
Collective flow and finite-time effects explored in V. Kuznietsov et al., Phys. Rev. C 110, 015206 (2024)

Non-Gaussian fluctuations from molecular dynamics

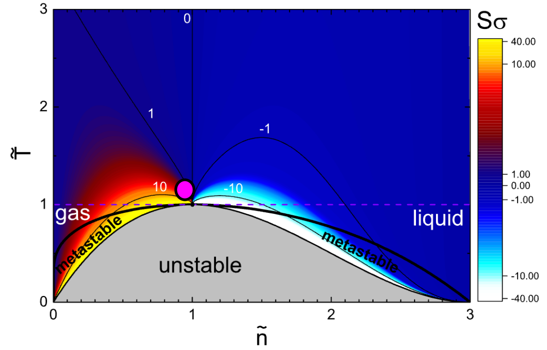
V. Kuznietsov, Gorenstein, Koch, VV, to appear

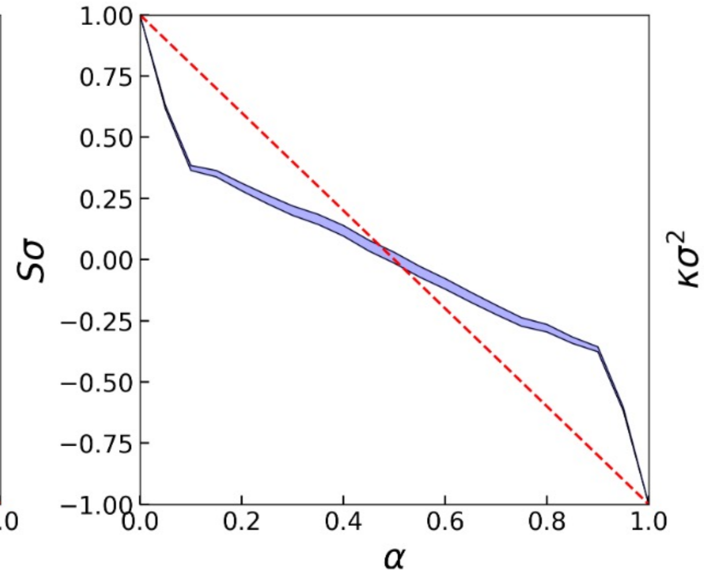
Scaled variance κ_2/κ_1



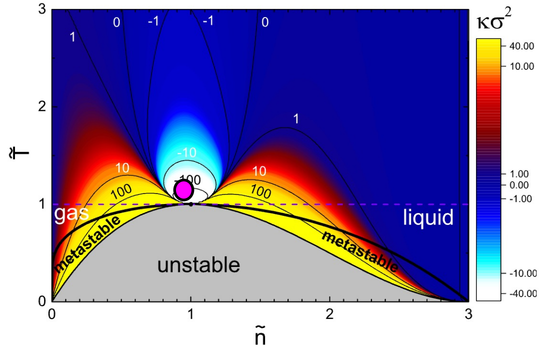


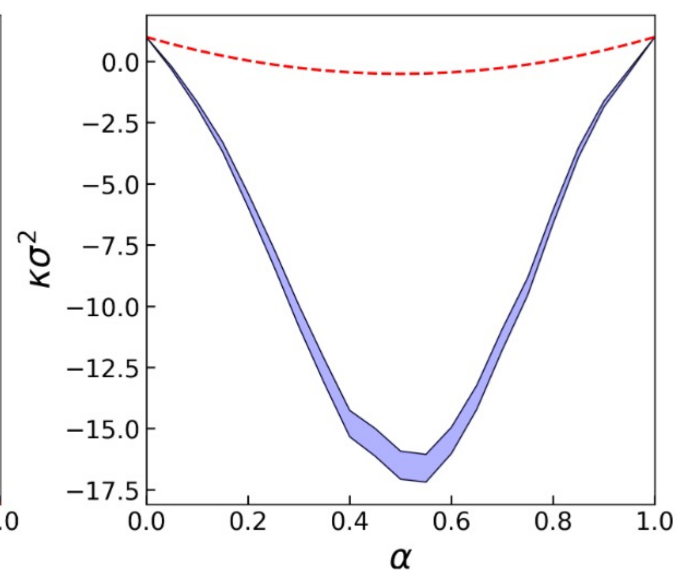
Skewness κ_3/κ_2



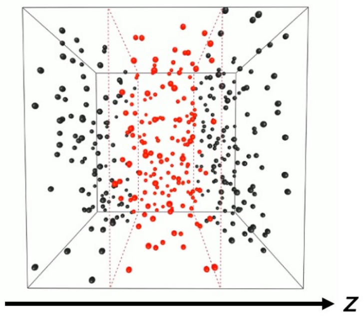


Kurtosis κ_4/κ_2



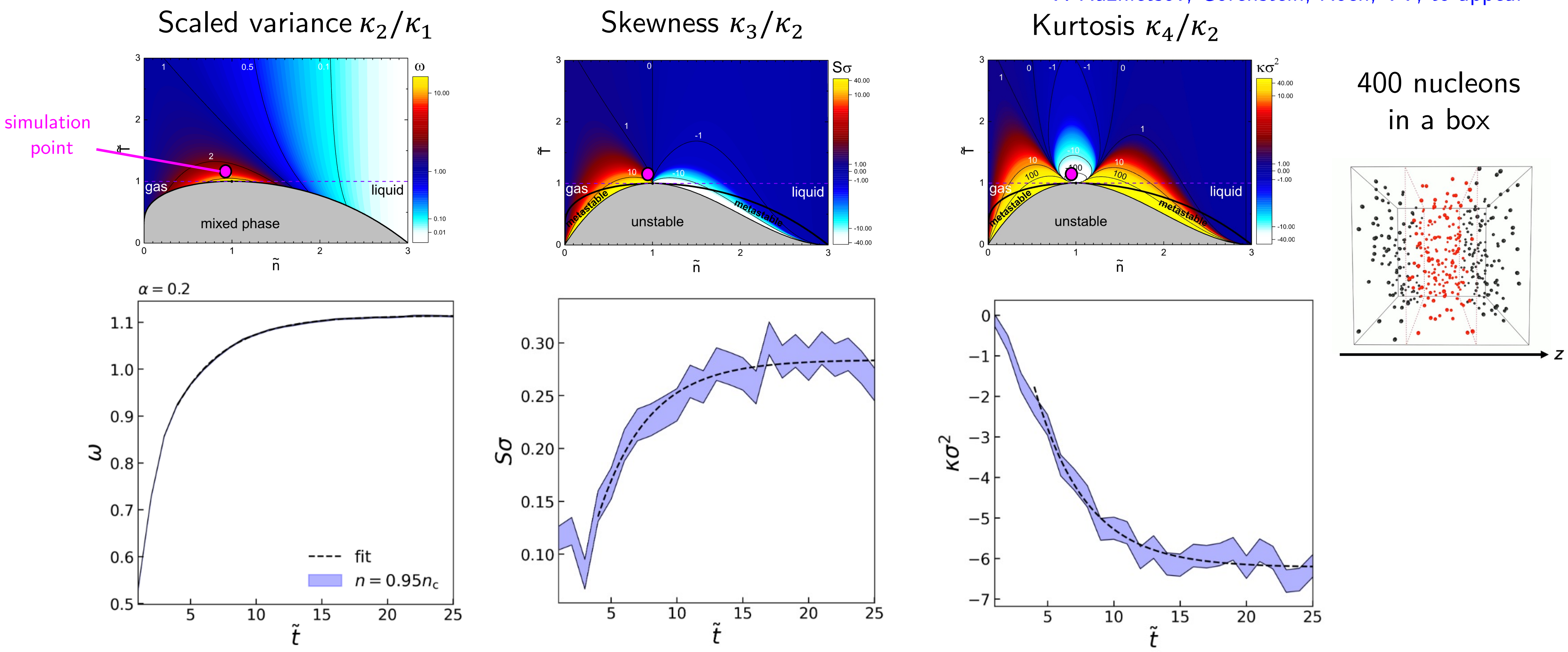


400 nucleons in a box



Non-Gaussian fluctuations from molecular dynamics

V. Kuznietsov, Gorenstein, Koch, VV, 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)

Theory vs experiment: Challenges for fluctuations

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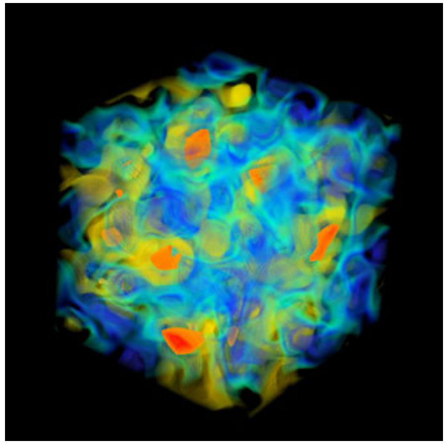
Theory



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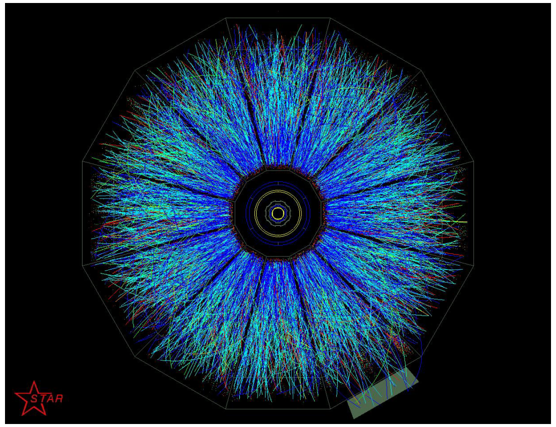
- Coordinate space
- In contact with the heat bath
- Conserved charges
- Uniform
- Fixed volume

Experiment



STAR event display

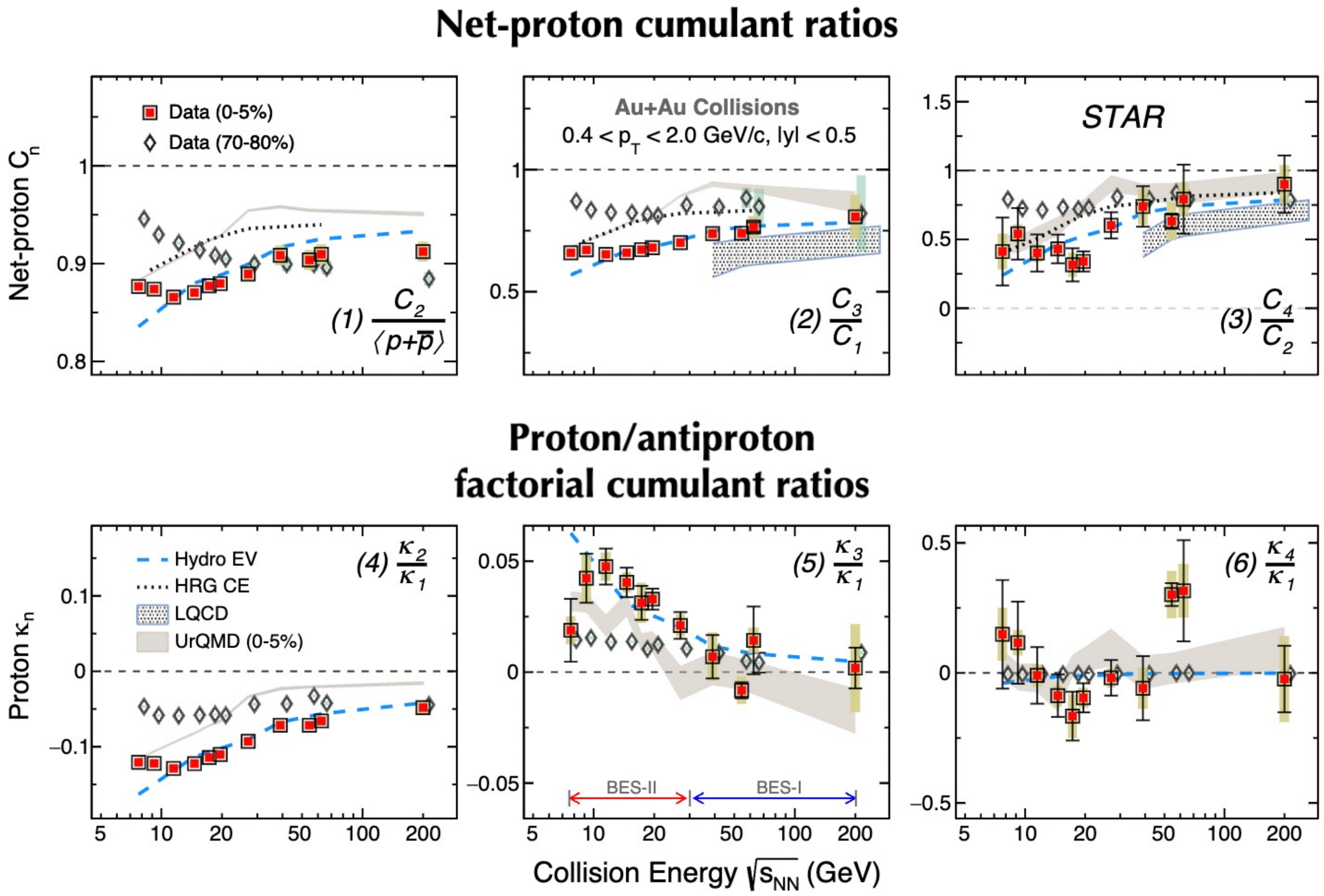
- Momentum space
- Expanding in vacuum
- Non-conserved particle numbers
- Inhomogeneous
- Fluctuating volume

Need dynamical description

Proton cumulants from RHIC-BES-II

RHIC-BES-II data

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



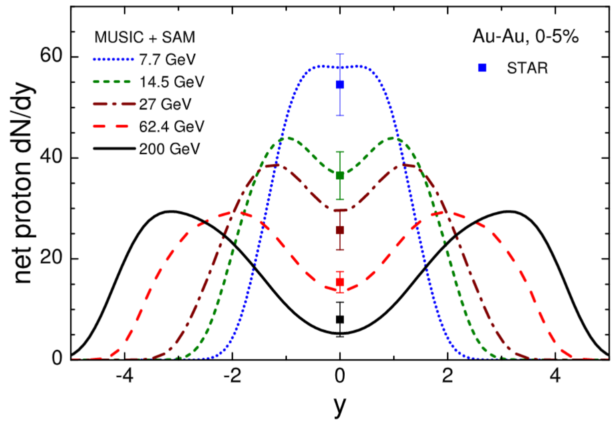
Hydro EV: VV, V. Koch, C. Shen, Phys. Rev. C 105, 014904 (2022)

What is hydro EV?

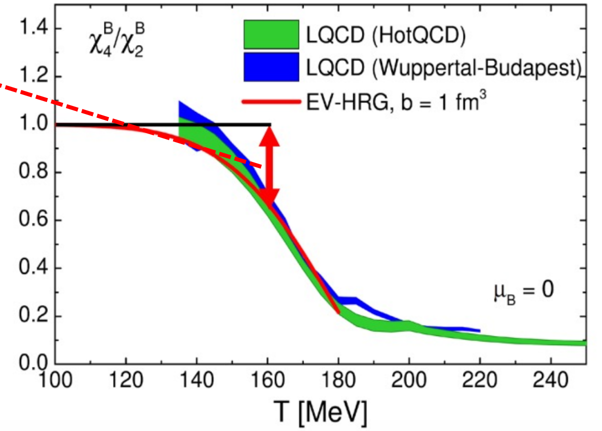
Hydro EV: Non-critical hydro baseline at RHIC-BES

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)]



- Non-critical contributions computed at particlization ($\epsilon_{sw} = 0.26$ GeV/fm^3)
  - 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



- Included: baryon conservation, repulsion, kinematical cuts
- 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-II (Factorial) cumulants

A. Pandav, CPOD2024

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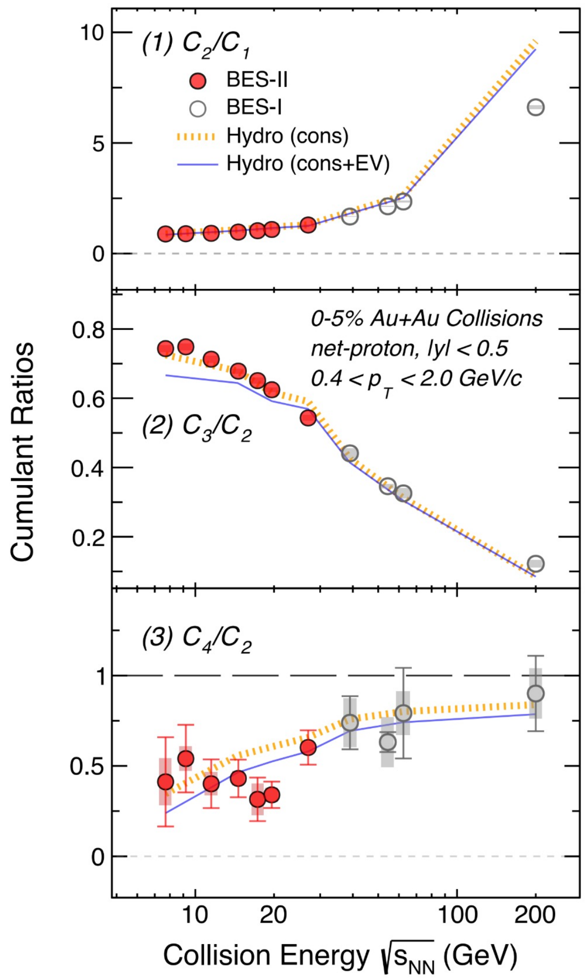
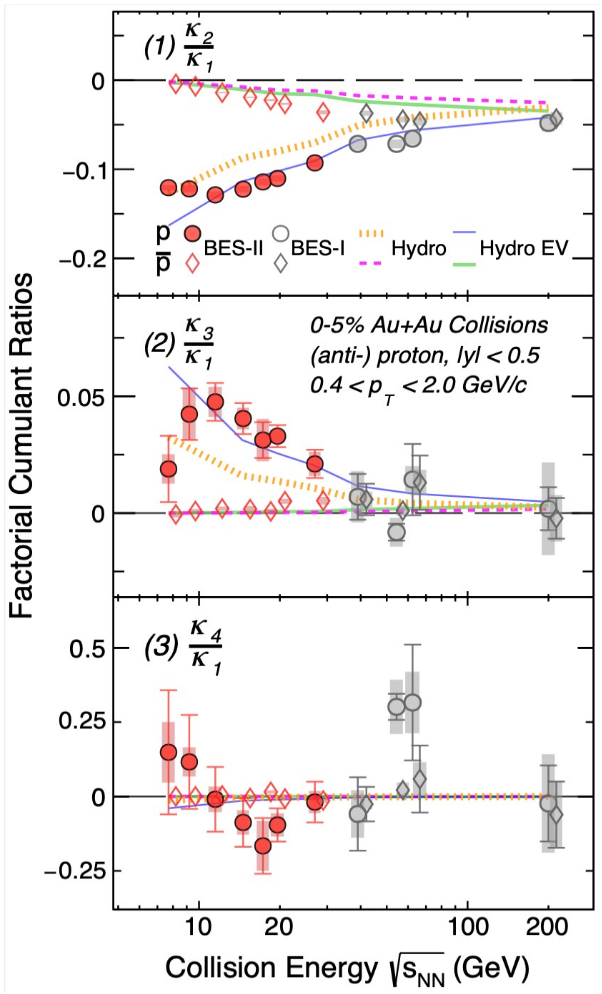
Net-proton cumulant ratios

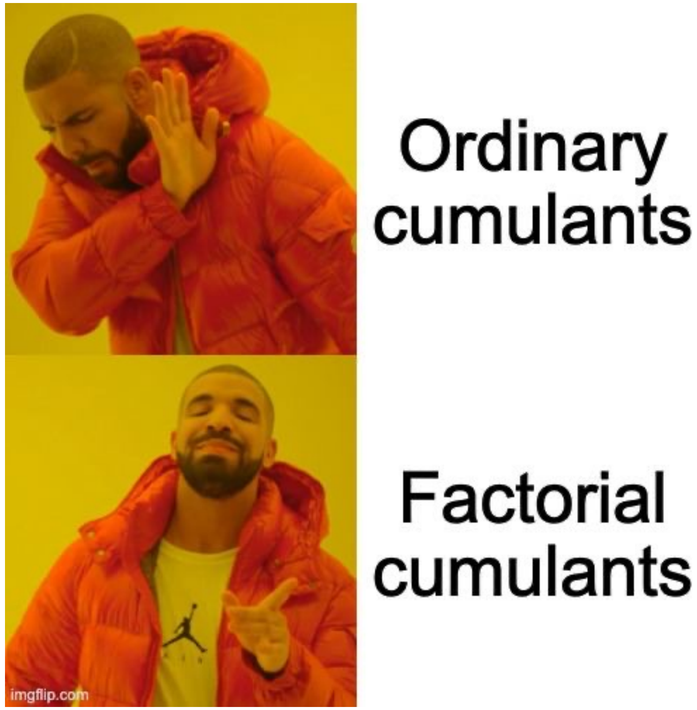


Proton/antiproton factorial cumulant ratios



- More structure seen in factorial cumulants

Conclusion 1:



What are the factorial cumulants?

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

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

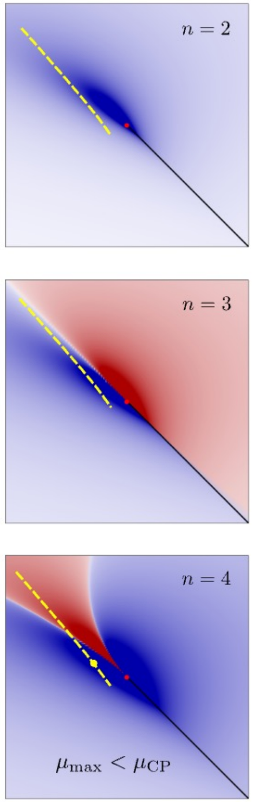
- proton vs baryon $\hat{C}_n^B \sim 2^n \times \hat{C}_n^p$ **same sign!**
  [Kitazawa, Asakawa, PRC '12]

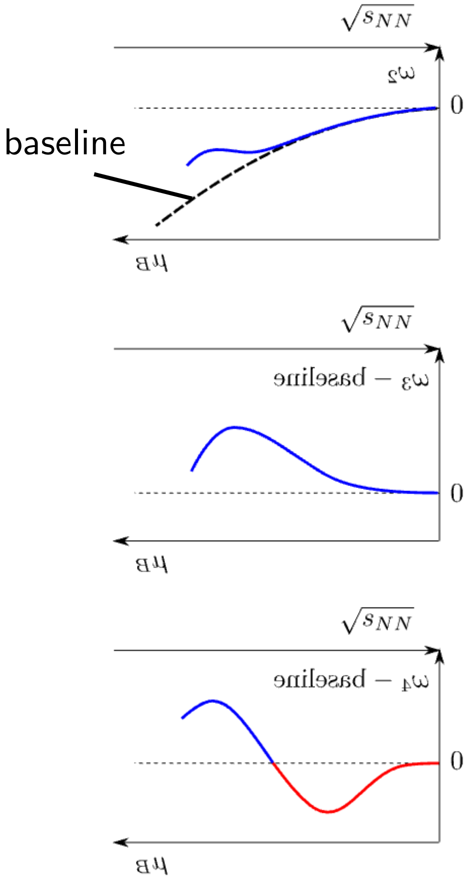
Factorial cumulants from RHIC-BES-II

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

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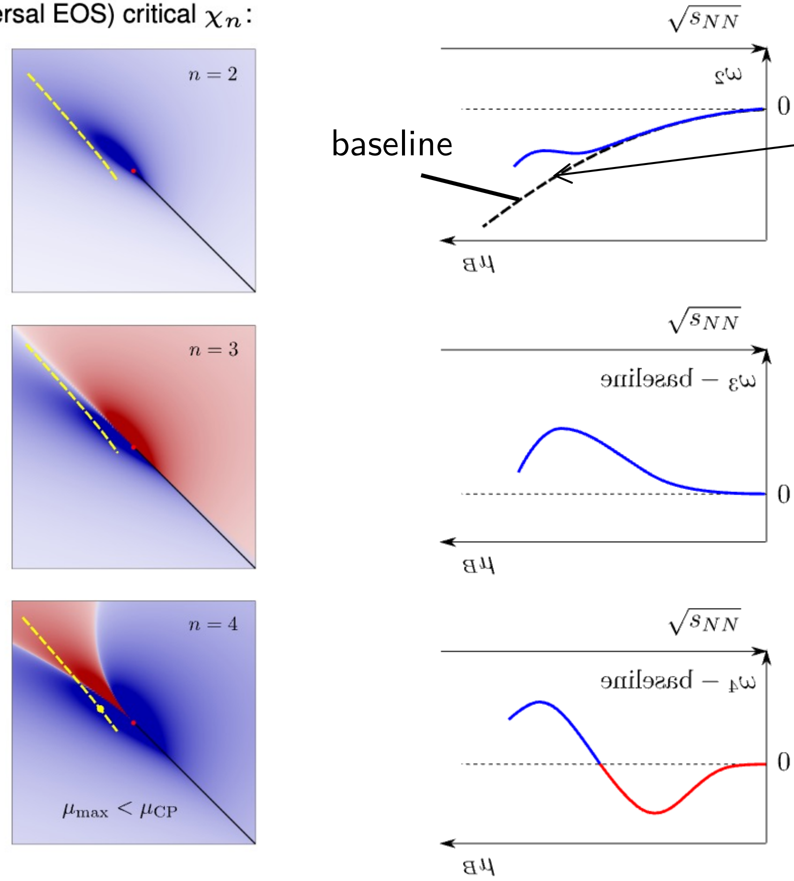

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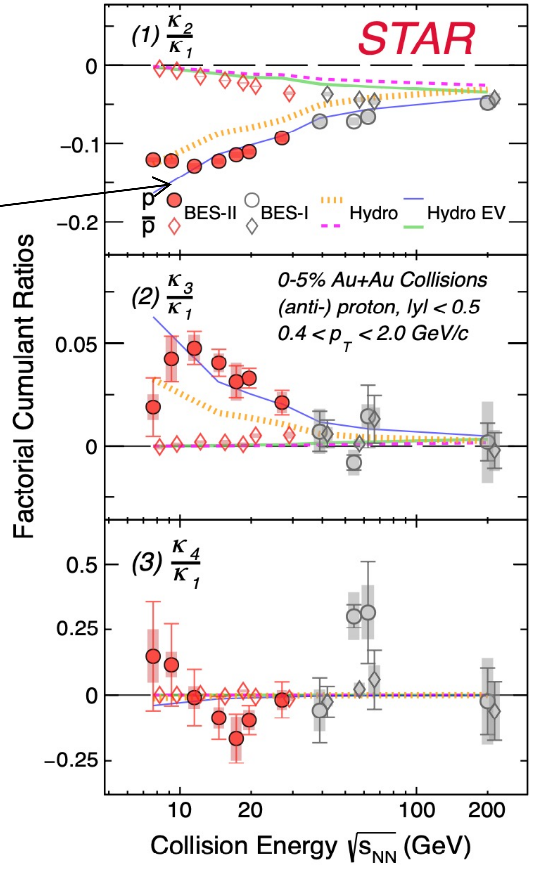
STAR data:



A. Pandav, CPOD2024

baseline (hydro EV):

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

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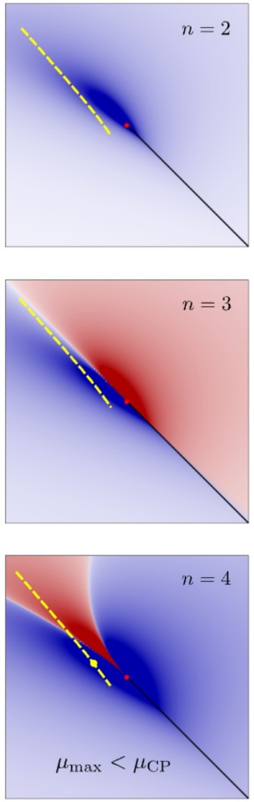
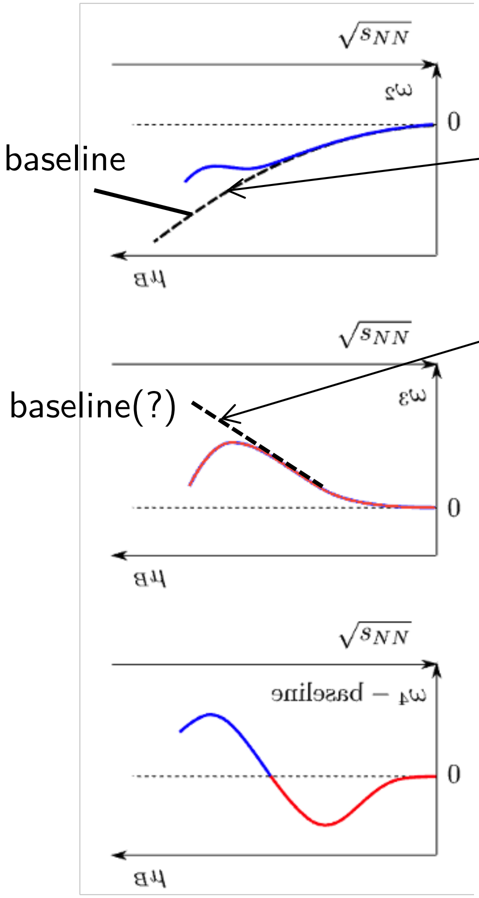
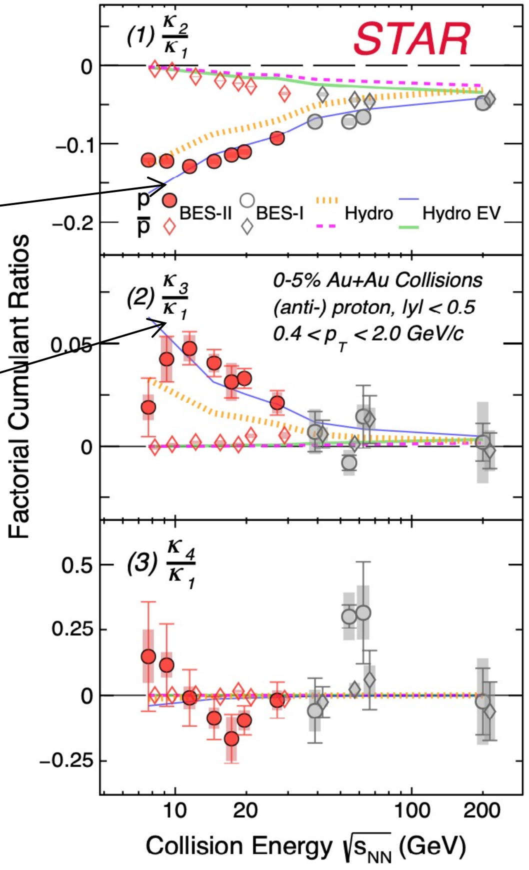


Bzdak et al review 1906.00936



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* $\hat{C}_2 - \hat{C}_2^{baseline} > 0$
  - *negative* $\hat{C}_3 - \hat{C}_3^{baseline} < 0$

Conclusion 2:

Controlling the non-critical baseline is essential

Factorial cumulants from RHIC-BES-II and CP

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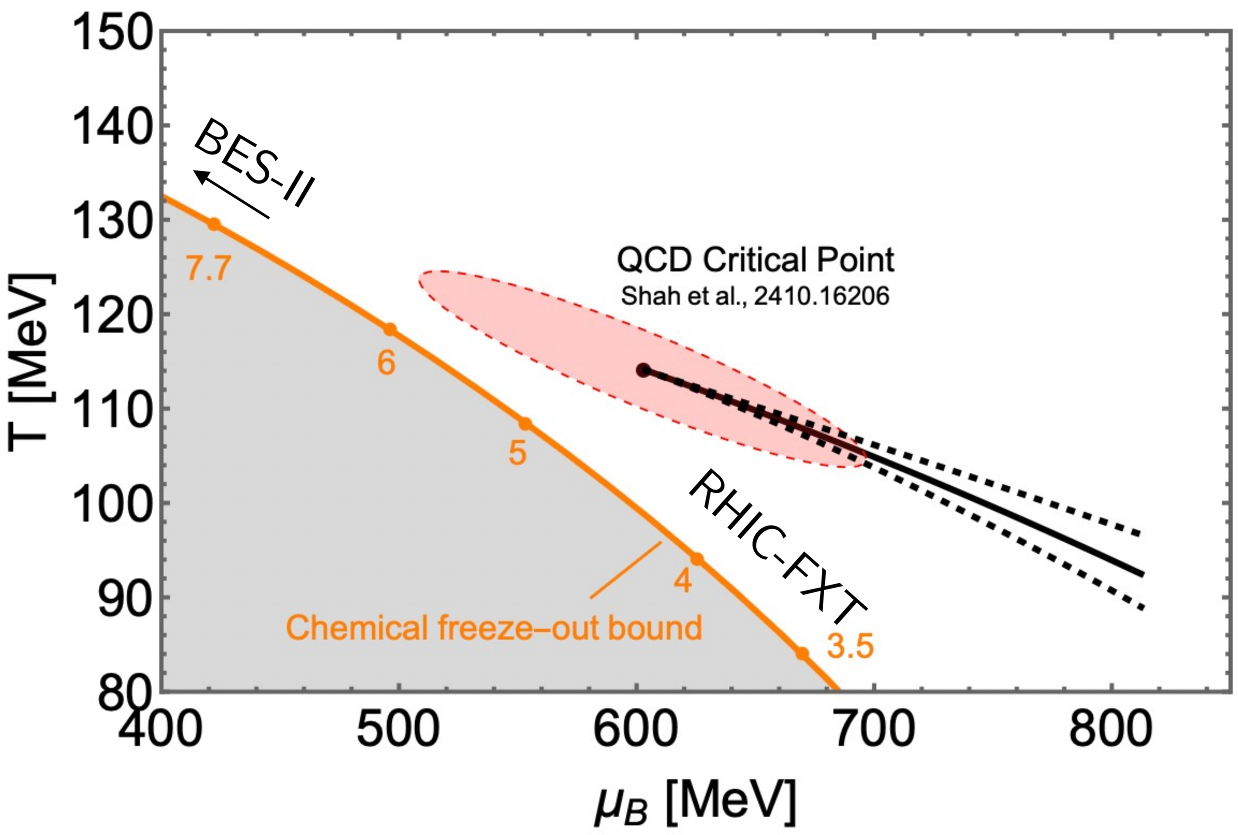
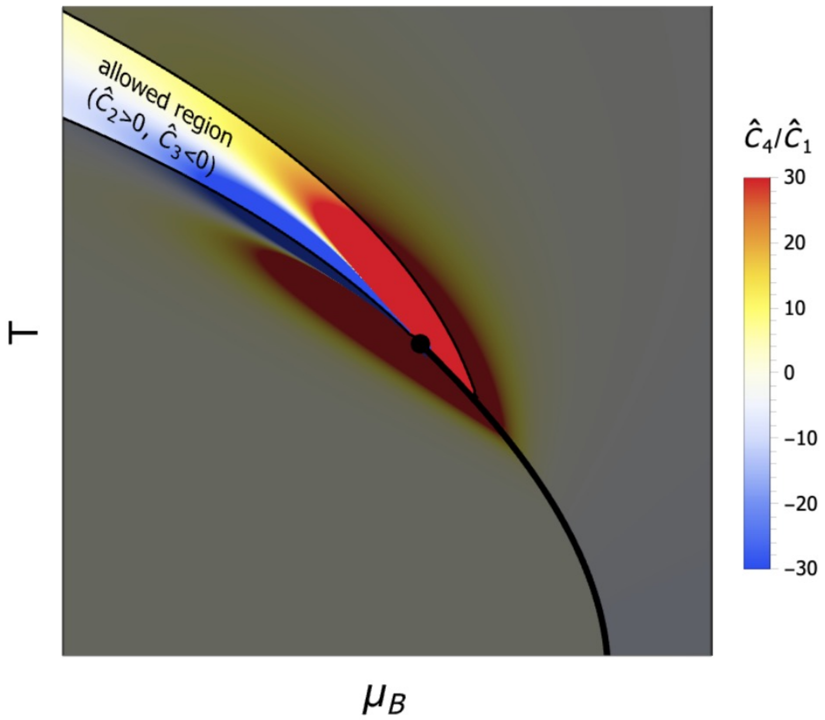
Equilibrium expectation



Exclusion plots

Exclude $\hat{C}_2<0$ & $\hat{C}_3>0$ regions on the phase diagram near CP

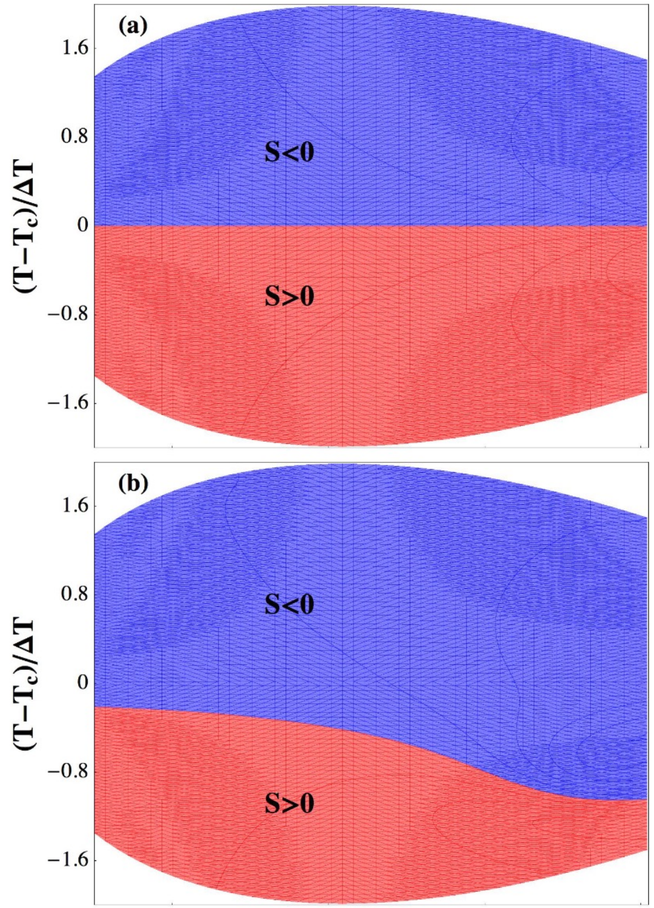


Adapted from Bzdak, Koch, Strodthoff, PRC 95, 054906 (2017) and based on the model from VV, Anchishkin, Gorenstein, Poberezhnyuk, PRC 92, 054901 (2015)

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

Factorial cumulants from RHIC-BES-II and CP

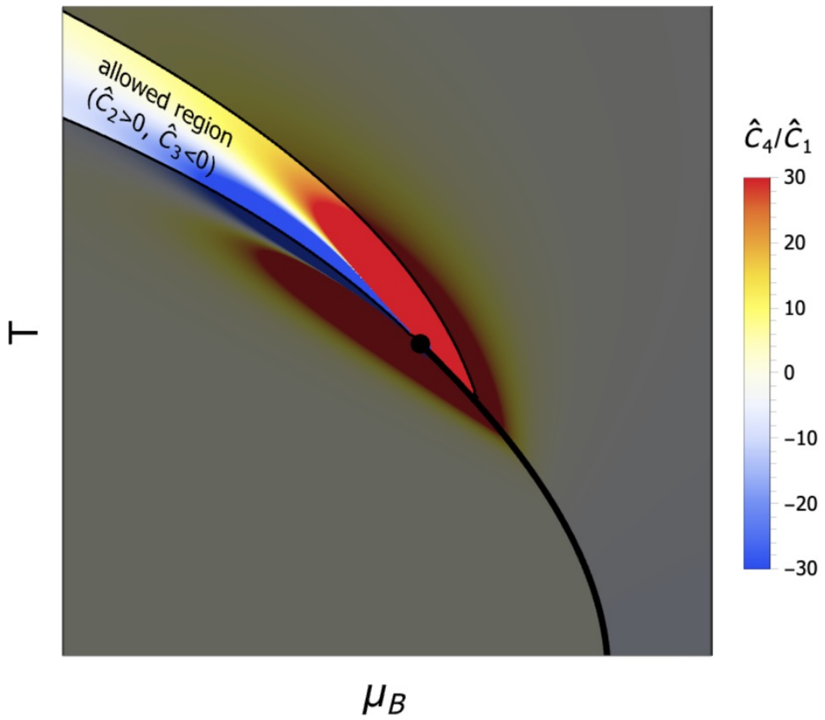
Memory effect



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

Exclusion plots

Exclude $\hat{C}_2<0$ & $\hat{C}_3>0$ regions on the phase diagram near CP

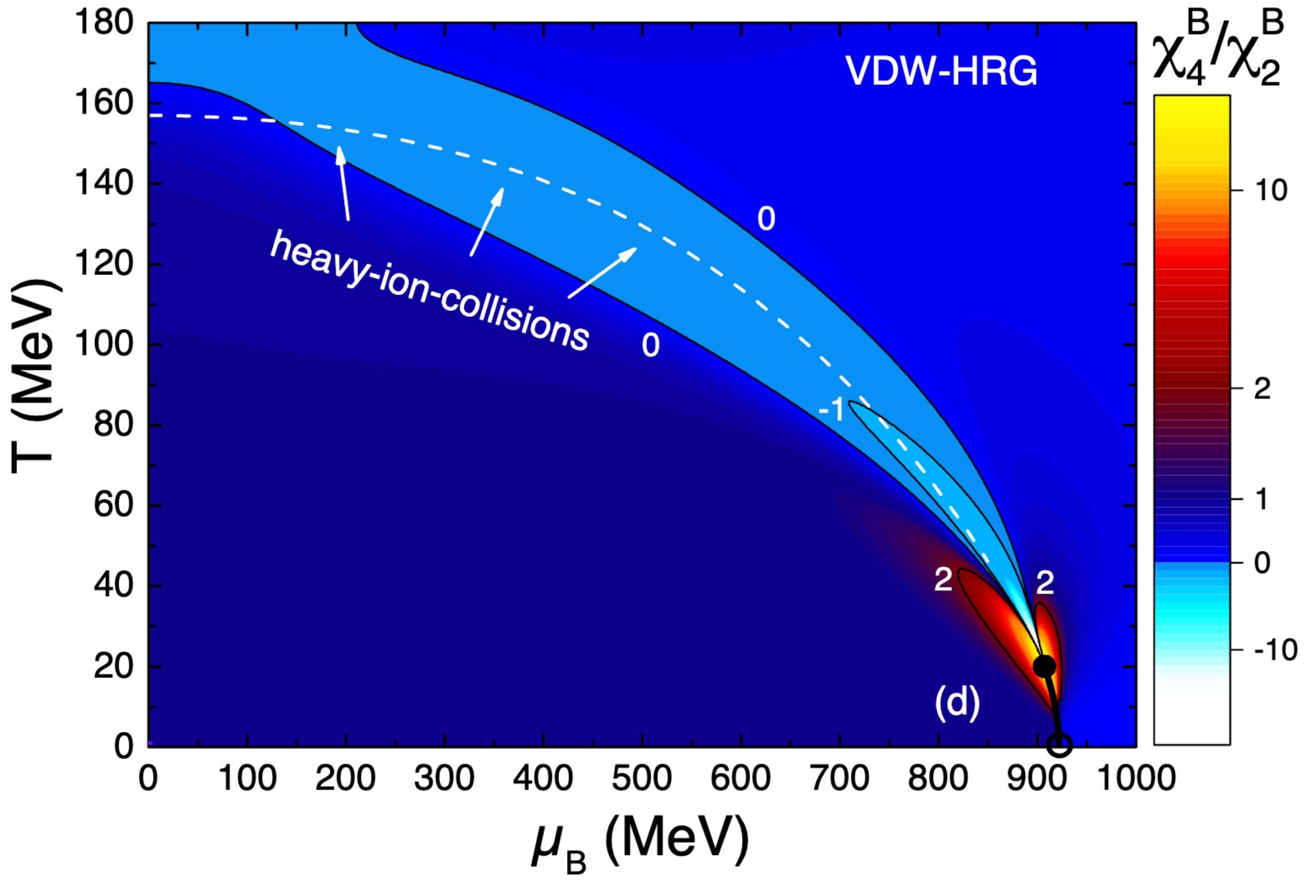


Adapted from Bzdak, Koch, Strodthoff, PRC 95, 054906 (2017)
and based on the model from
VV, Anchishkin, Gorenstein, Poberezhnyuk, PRC 92, 054901 (2015)

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

Interplay with nuclear liquid-gas transition

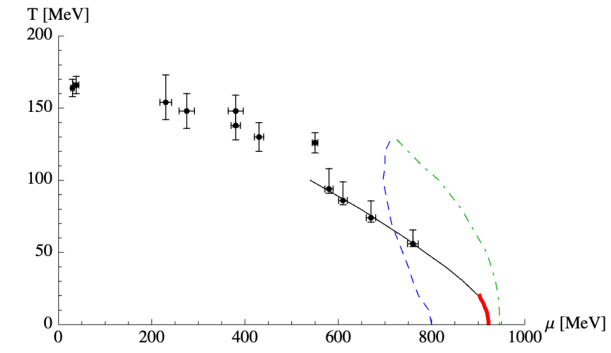
HRG with attractive and repulsive interactions among baryons



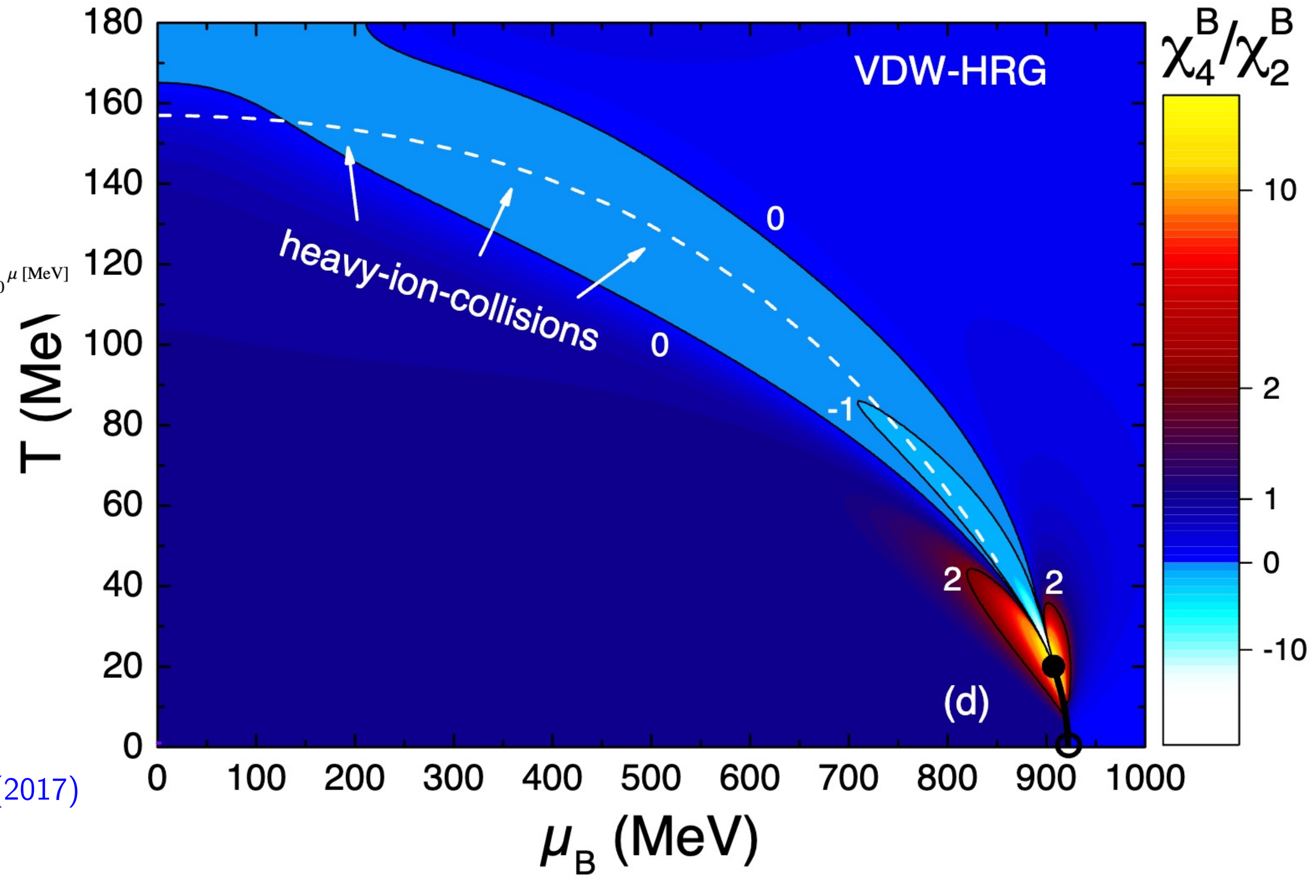
VV, Gorenstein, Stoecker, Phys. Rev. Lett. 118, 182301 (2017)

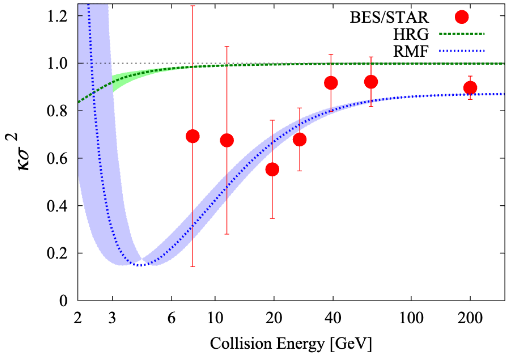
Interplay with nuclear liquid-gas transition

HRG with attractive and repulsive interactions among baryons

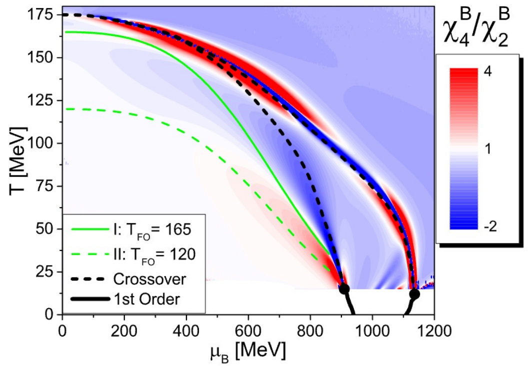


Floerchinger, Wetterich, NPA (2012)



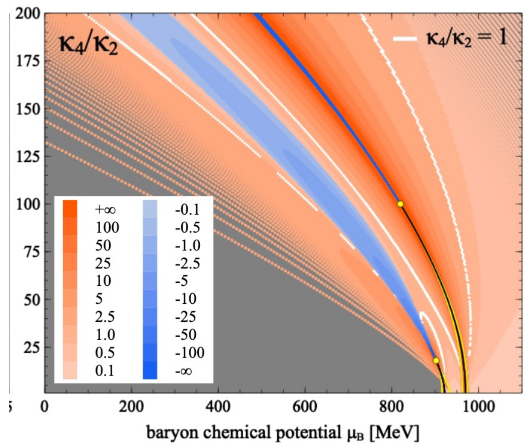


Fukushima, PRC (2014)



Mukherjee, Steinheimer, Schramm, PRC (2017)

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



Sorensen, Koch, PRC (2020)

Increasingly relevant at lower energies probed through RHIC-FXT

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

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

Scaled factorial cumulants

Bzdak et al. introduced reduced correlation functions – "couplings" [Bzdak, Koch, Strodthoff, PRC 95, 054906 (2017)]

Bzdak ratios $\boxed{\hat{c}_k = \frac{\hat{C}_k}{\langle N \rangle^k}}$

$$c_k = \frac{\int \rho_1(y_1) \cdots \rho_1(y_k) c_k(y_1, \ldots, y_k) dy_1 \cdots dy_k}{\int \rho_1(y_1) \cdots \rho_1(y_k) dy_1 \cdots dy_k}$$

integrated correlation function in rapidity

Long-range correlations lead to acceptance-independent couplings, for example

- Global (not local) baryon conservation
  [Bzdak, Koch, Skokov, EPJC 77, 288 (2017); Bzdak, Koch, PRC 96, 054905 (2017)]
- $+$ volume fluctuations
  [Holzmann, Koch, Rustamov, Stroth, arXiv:2403.03598]
- $+$ (uniform) efficiency
  [Pruneau, Gavin, Voloshin, PRC 66, 044904 (2002)]

$$c_2 = -\frac{1}{B}, \qquad c_3 = \frac{2}{B^2}, \qquad c_4 = -\frac{6}{B^3}.$$

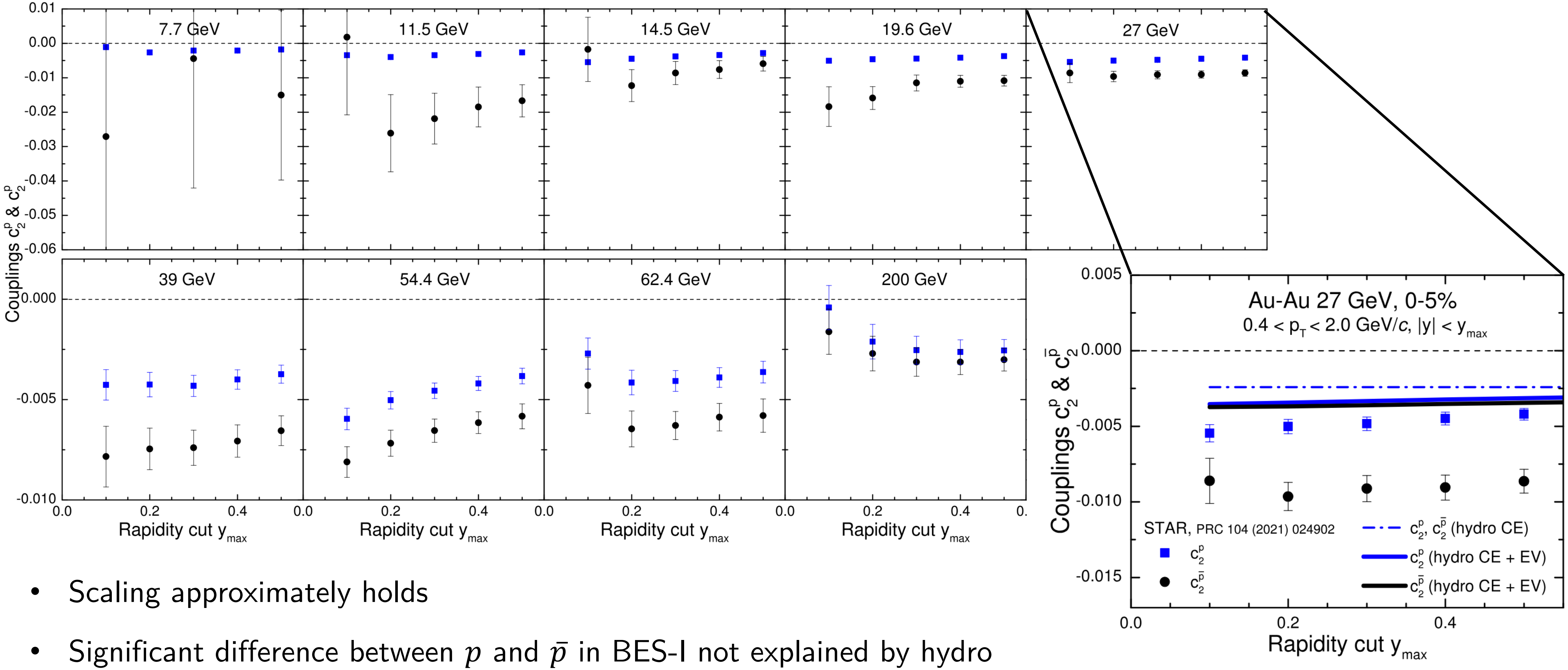
$$\hat{\tilde{c}}_{i,j} = \hat{c}_{i,j} + \frac{\kappa_2[V]}{\langle V \rangle^2}, \quad \text{for} \quad i+j=2.$$

all lead to

$\boxed{\frac{\hat{C}_k}{\langle N \rangle^k} = const.}$ at a given $\sqrt{s_{NN}}$ and $\boxed{\frac{\hat{C}_2^p}{\langle N_p \rangle^k} \approx \frac{\hat{C}_2^{\bar{p}}}{\langle N_{\bar{p}} \rangle^k} = const.}$ at a given $\sqrt{s_{NN}}$

Can be tested without CBWC/volume fluctuations correction A. Bzdak, V. Koch, VV, in preparation

Scaled factorial cumulants from RHIC-BES-I



- Scaling approximately holds
- Significant difference between p and $\bar{p}$ in BES-I not explained by hydro

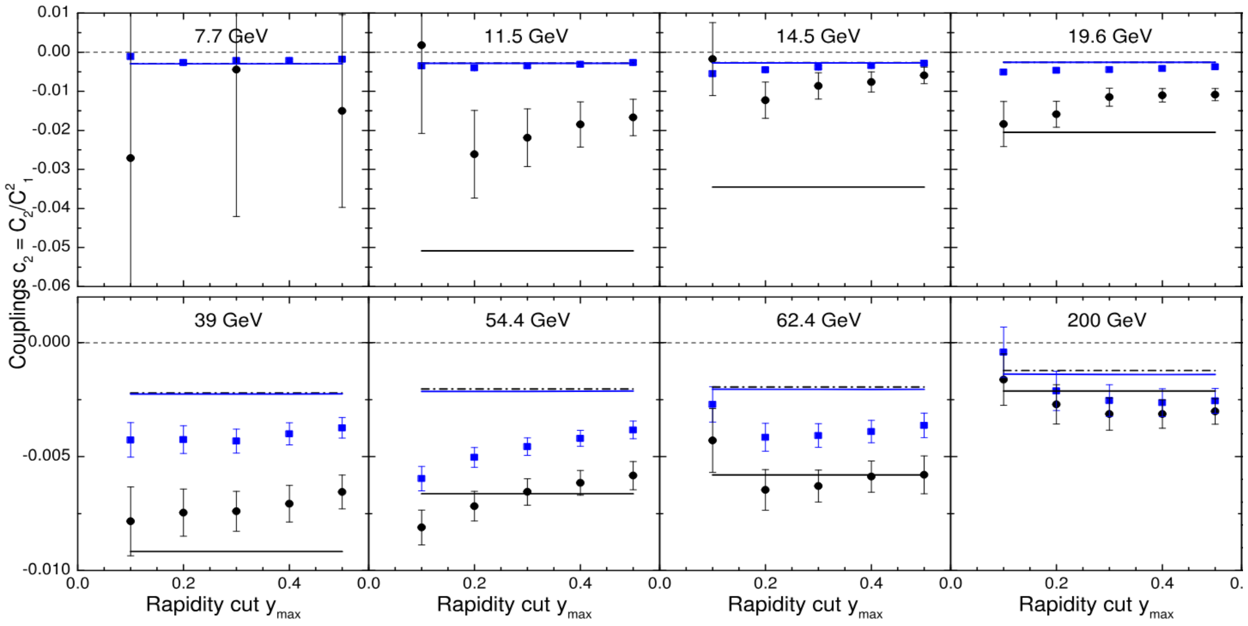
no single thermalized fireball?

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

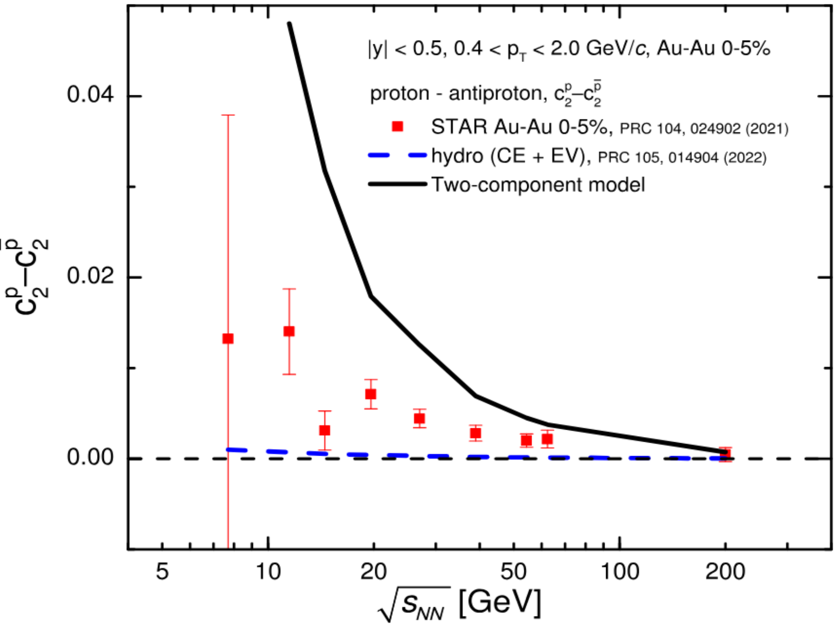
The antiproton puzzle and the two-component model

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



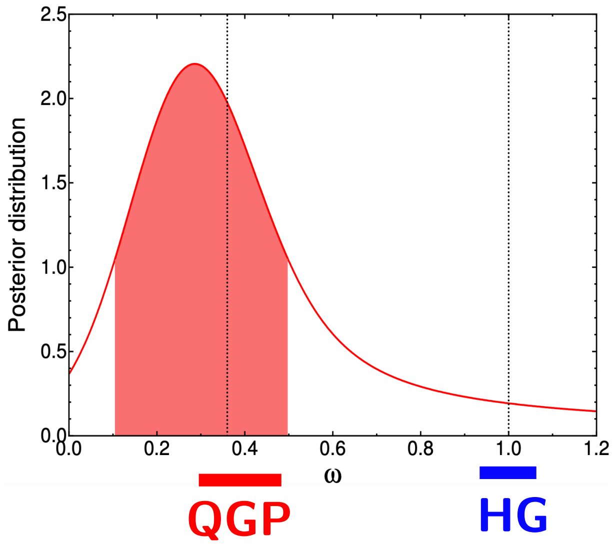
Difference between p and $\bar{p}$



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

Opportunities/wishlist for BES-II: Acceptance dependence of scaled factorial cumulants

- Further tests of the splitting between p and $\bar{p}$ in 2nd order cumulants with extended y coverage
- Covariance $c_{1,1}^{p,\bar{p}}$ to probe baryon annihilation
- Critical point signal expected to break the scaling $\frac{\hat{C}_n}{(\hat{C}_1)^n} = \text{const.}$ [Ling. Stephanov, PRC 93, 034915 (2016)]



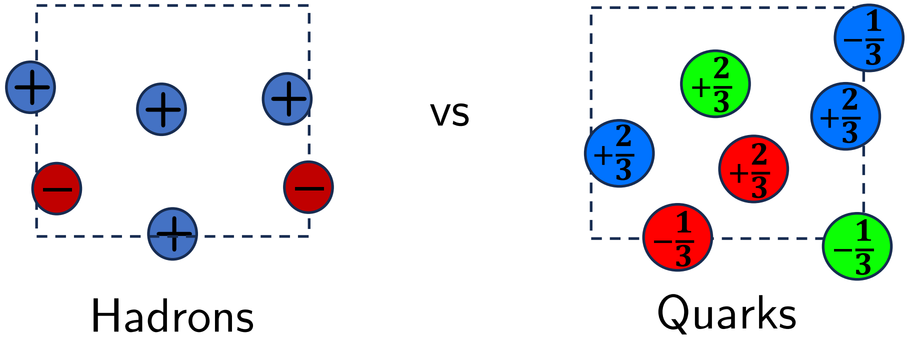
Charge fluctuations as a signature of QGP

- J. Parra, R. Poberezhniuk, V. Koch, C. Ratti, VV, in preparation

Charge fluctuations

An old idea: Hadrons carry integer electric charges, quarks carry *fractional* electric charges.

Koch, Jeon, PRL (2000);
Asakawa, Muller, Heinz, PRL (2000)



Fluctuations depend on the square of the charges and are smaller in the QGP

Quantified by:

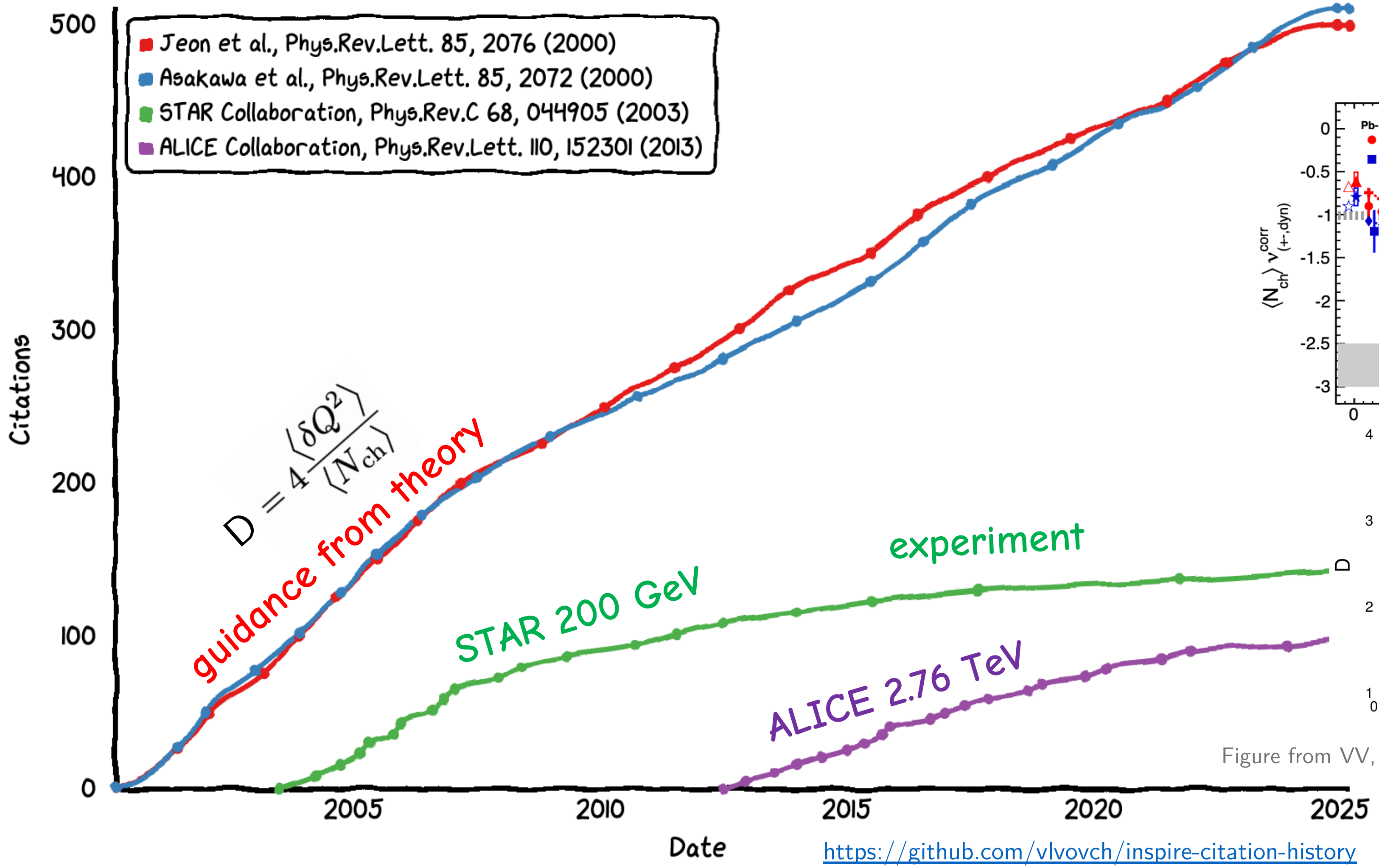
$$D = 4\frac{\kappa_2[N_+ - N_-]}{\langle N_{\rm ch}\rangle} = 4\frac{\kappa_2[Q]}{\langle Q^+ + Q^-\rangle}$$

Naïve grand canonical ensemble (GCE) expectations:

- $D_{HG} \approx 2.8 - 4$
- $D_{QGP} \approx 1 - 1.5$

No quantitative calculations have been done for QGP beyond GCE

Charge fluctuations: history



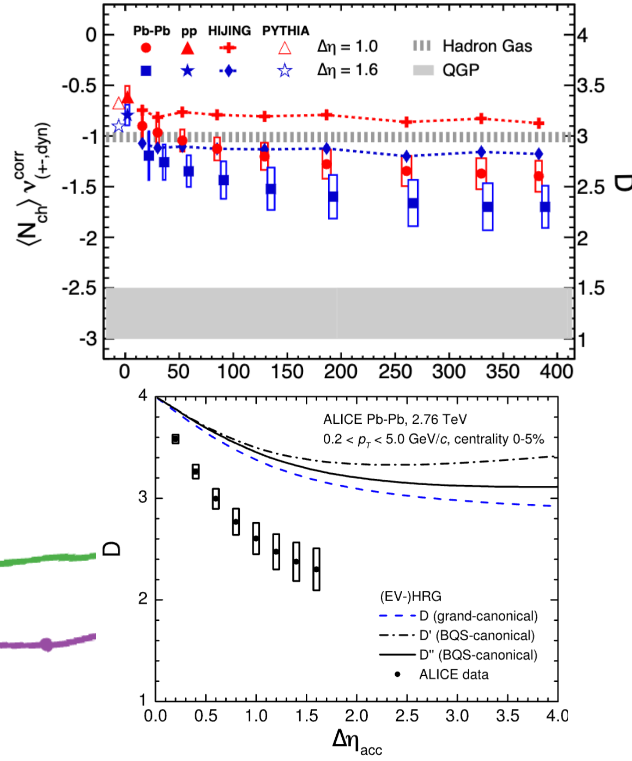
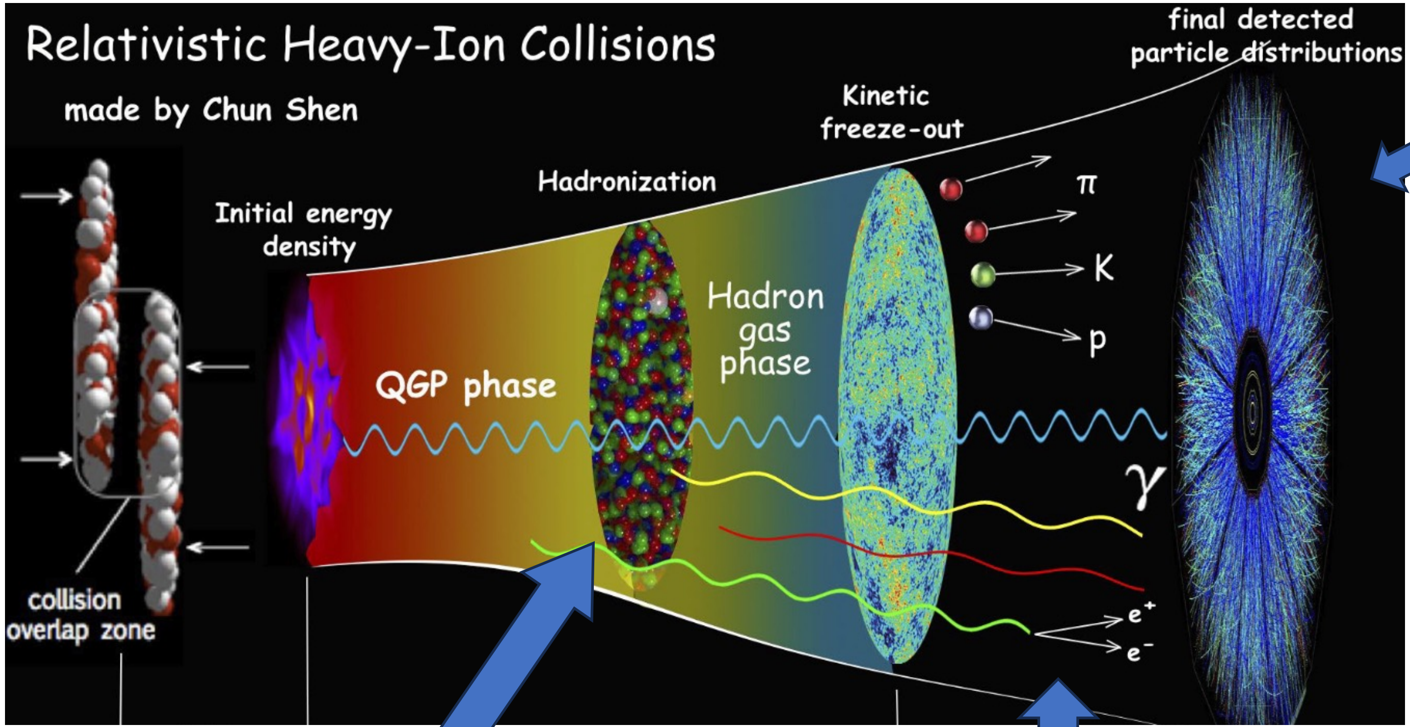


Figure from VV, Koch, Phys. Rev. C 103, 044903 (2021)

https://github.com/vlvovch/inspire-citation-history

Measurements came and went, conclusions are ambiguous. What more can be done?

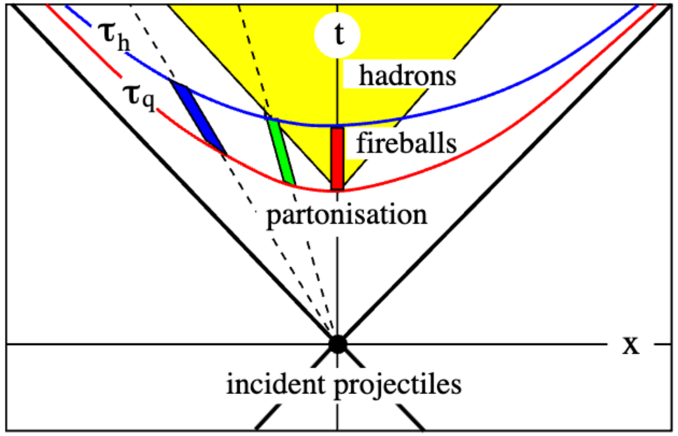
Charge fluctuations: stages



4. Kinematical cuts

never done for QGP

3. (Local) charge conservation



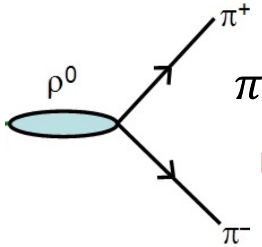
Castorina, Satz, IJMPE '14

never done both for HG and QGP

1. Fluctuations at hadronization (primordial charges)

$\boldsymbol{\omega}$ – Distinguishes hadron gas ($\boldsymbol{\omega \approx 1}$) from QGP ($\omega \approx 0.25 - 0.40$)

2. Resonance decays



$\pi^+\pi^-$ are correlated!

never done for QGP

Here we model these effects through novel charge density correlations formalism [VV, PRC '14]

Charge fluctuations: hadronization

Define ω as a measure of charge fluctuations at hadronization

variance

$$\omega = \frac{\kappa_2[Q]}{\langle N_{\mathrm{ch}}^{\mathrm{prim}} \rangle}$$

charged multiplicity

Hadron gas: $\omega_{HG} \approx 1$ (Poisson statistics)

Free QGP: $\omega_{QGP} \approx 0.36$ (Stefan-Boltzmann limit)

More generally:

$$\omega = \frac{\kappa_2[Q]}{\langle N_{\mathrm{ch}}^{\mathrm{prim}} \rangle} = \frac{VT^3 \chi_2^Q}{S} \frac{S}{\langle N_{\mathrm{ch}}^{\mathrm{prim}} \rangle}$$

$$= \frac{\chi_2^Q}{s/T^3} \frac{S}{\langle N_{\mathrm{ch}} \rangle} \frac{\langle N_{\mathrm{ch}} \rangle}{\langle N_{\mathrm{ch}}^{\mathrm{prim}} \rangle}$$

The EoS

e.g. lattice QCD

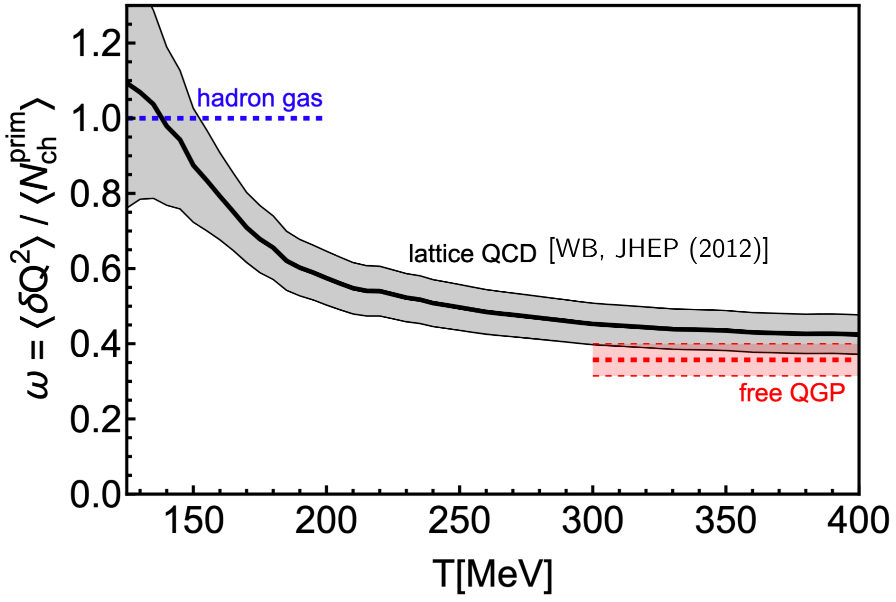
$S/N_{\mathrm{ch}} = 6.7 \pm 0.8$ (LHC)

$\gamma_Q \approx 1.67$ (decays)

from thermal model

P. Hanus, A. Mazeliauskas, K. Reygers, PRC (2019)

ω from lattice QCD



Charge fluctuations: other stages

2. Hadronic phase (resonance decays)

- Decays are local and conserve charge but increase charged multiplicity, $\langle N_{ch} \rangle = \left\langle N_{ch}^{prim} \right\rangle \gamma_Q$, where $\gamma_Q \approx 1.67$
- Total charge susceptibility does not change, $\chi_2^{Q,final} = \chi_2^{Q,prim}$, but balance between self-correlation and two-particle correlations does

3. Local charge conservation [VV, PRC 110, L061902 (2024)]

- 2-point charge density correlator with a balancing term
- Local charge conservation introduced through modulation of the balancing term

$$C_2^Q(\mathbf{r}_1, \mathbf{r}_2) \equiv \langle \delta\rho_Q(\mathbf{r}_1) \delta\rho_Q(\mathbf{r}_2) \rangle$$

$$C_2^Q(\mathbf{r}_1, \mathbf{r}_2) = \chi_2^Q \left[\underbrace{\delta(\mathbf{r}_1 - \mathbf{r}_2)}_{\text{local correlation}} - \underbrace{\frac{\varkappa(\mathbf{r}_1, \mathbf{r}_2)}{V_{\rm tot}}}_{\text{balancing contribution}} \right] \qquad \mathbf{r} = \eta$$

$$\underbrace{\varkappa(\eta_1, \eta_2) \propto \exp\left[-\frac{(\eta_1 - \eta_2)^2}{2\sigma_\eta^2} \right]}_{\text{local charge conservation}}$$

4. Kinematical cuts

$$\kappa_2[Q]|_{|\eta|<\eta_{\rm cut}} \propto \int_{-\eta_{\rm cut}/2}^{\eta_{\rm cut}/2} d\eta_1 \int_{-\eta_{\rm cut}/2}^{\eta_{\rm cut}/2} d\eta_2 C_2^Q(\eta_1, \eta_2)\, p(\eta_1) p(\eta_2)$$

Acceptance probability $p(\eta)$ from blast-wave model

Putting everything together

$$D = 4\left\{1 - \left(1 - \frac{\overset{\text{hadronization}}{\omega}}{\underset{\text{decays}}{\gamma_Q}}\right)\frac{\overset{\text{pair acceptance}}{\langle p^2(\eta)\rangle}}{\underset{\text{acceptance}}{\langle p(\eta)\rangle}} - \frac{\overset{\text{hadronization}}{\omega}}{\underset{\text{decays}}{\gamma_Q}}\frac{\overset{\text{local charge conservation}}{\langle p(\eta_1)p(\eta_2)\rangle_{\varkappa}}}{\underset{\text{acceptance}}{\langle p(\eta)\rangle}}\right\}$$

ω - Charge fluctuations at hadronization

$\omega_{HG} = 1$ $\qquad$ $\omega_{QGP} = 0.36$

γ_Q - Resonance decays

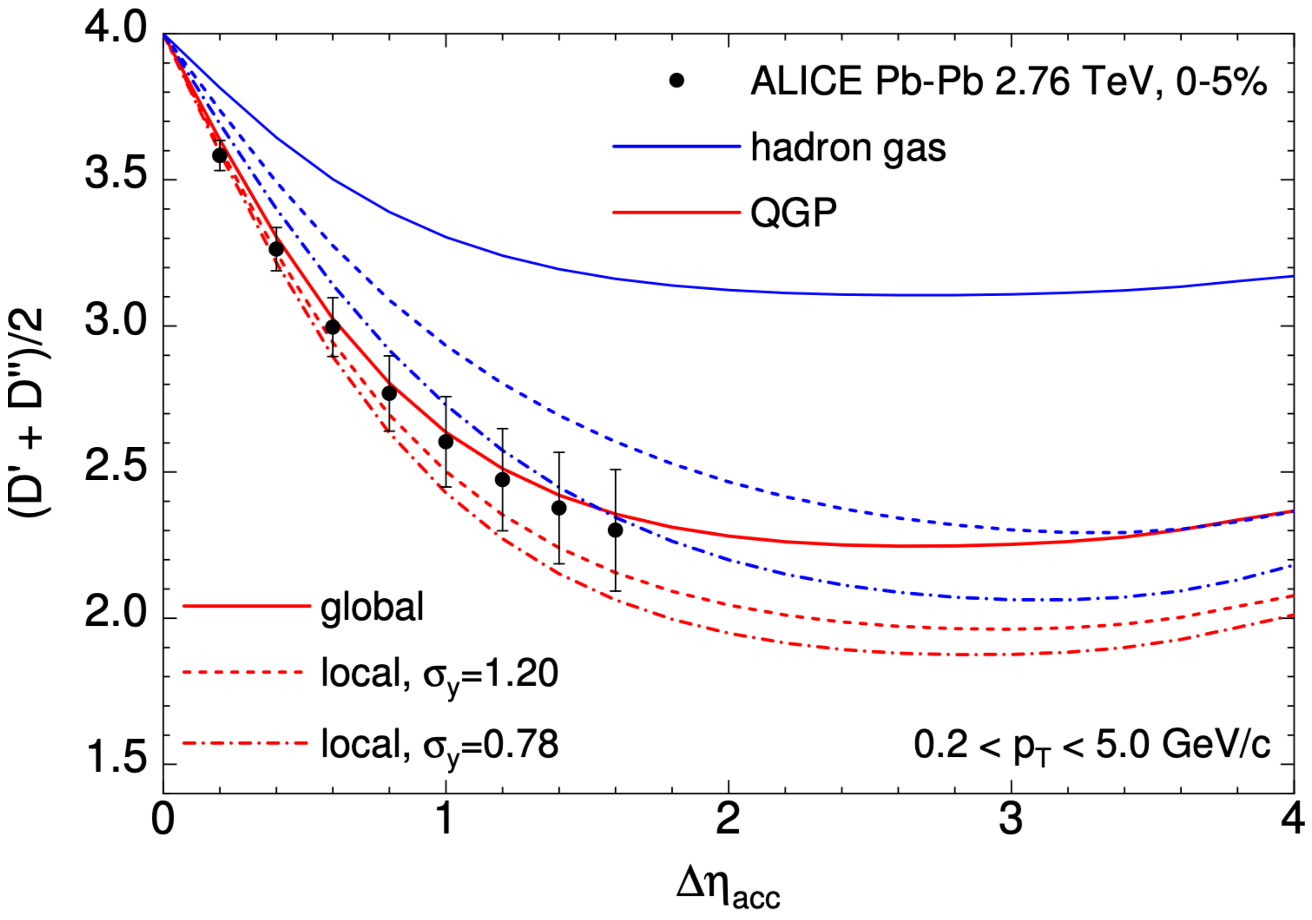
$\langle p(\eta_1)p(\eta_2)\rangle_{\varkappa}$ - Pair acceptance weighted with Local Charge Conservation

$\frac{\langle p^2(\eta)\rangle}{\langle p(\eta)\rangle}$ - Momentum Acceptance Cuts

using $p(\eta)$ from the blast-wave model

D-measure at LHC: comparison with experiment

$$D = 4\left\{1 - \left(1 - \frac{\omega}{\gamma_Q}\right)\frac{\langle p^2(\eta)\rangle}{\langle p(\eta)\rangle} - \frac{\omega}{\gamma_Q}\frac{\langle p(\eta_1)p(\eta_2)\rangle_{\varkappa}}{\langle p(\eta)\rangle}\right\}$$



Parameters used:

$\omega_{HG} = 1$ $\omega_{QGP} = 0.36$

$\gamma_Q = 1.67$

- Vary σ_y to accommodate global vs local charge conservation
  - Here values of σ_y are based on local baryon conservation estimates

VV, PRC 110, L061902 (2024)

Hadron gas scenario requires a very local charge conservation range

D-measure at LHC: Bayesian analysis

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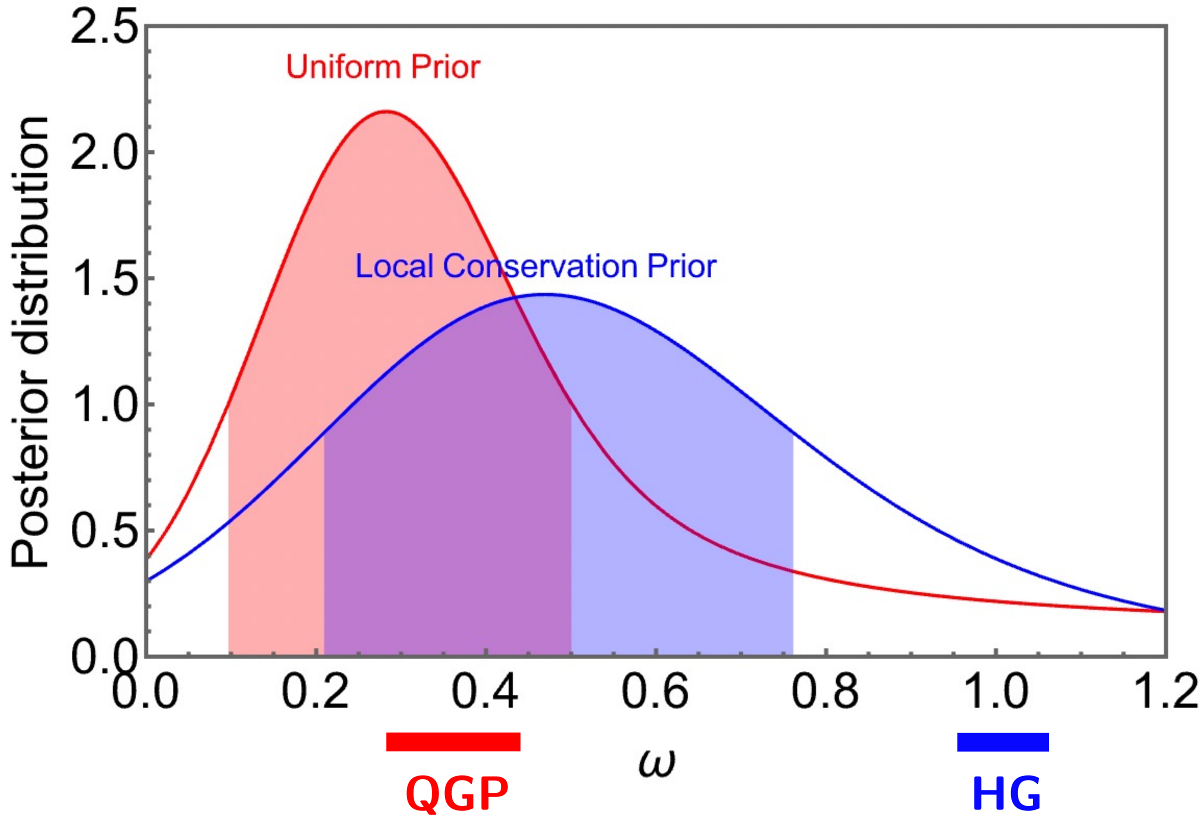
Vary primordial fluctuation ω (HG vs QGP) and correlation volume V_C (local conservation) freely



- Uniform prior

$\omega \in U(0, 1.2)$, $V_c \in U(0, V_{tot})$,

Bayes factor (QGP : HG) $= 8.74$

- Local conservation prior

$\omega \in U(0, 1.2)$, $V_c \in$ Gaussian at $(0.20 \pm 0.05) V_{tot}$

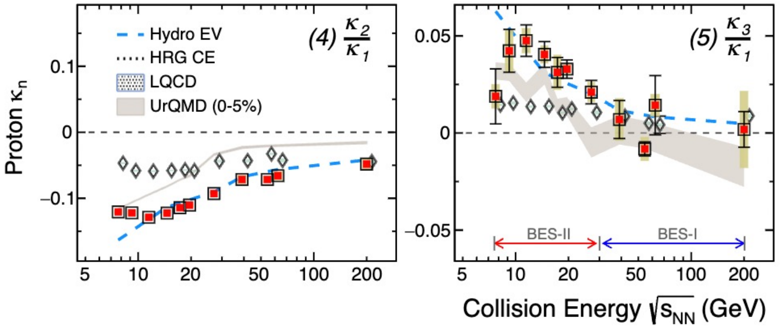
Bayes factor (QGP : HG) $= 4.93$

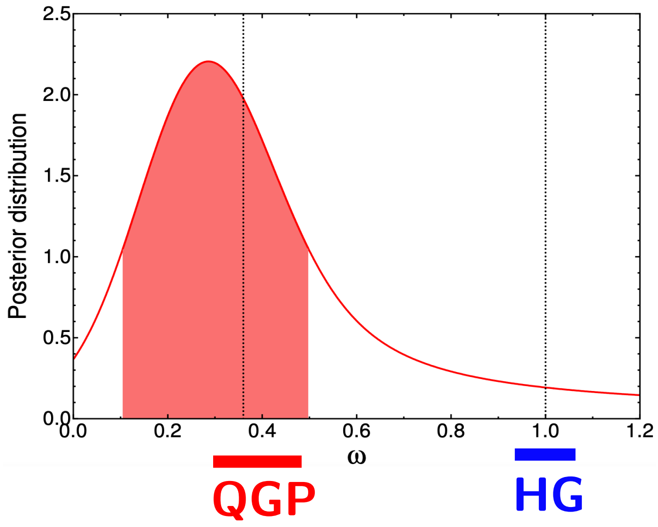
Moderate evidence for freeze-out of charge fluctuations in QGP

<u>Sensitivity to assumed prior currently under investigation</u>

Summary

- **Lattice-based constraints on the QCD critical point**
  - Rule out QCD CP at $\mu_B < 450$ MeV at a 2-sigma level
  - 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
- **RHIC-BES-II data is in**
  - Non-critical physics describe the proton data at $\sqrt{s_{NN}} \geq 20$ GeV
  - $\hat{C}_2 - \hat{C}_2^{baseline} > 0$ and $\hat{C}_3 - \hat{C}_3^{baseline} > 0$ at $\sqrt{s_{NN}} < 10$ GeV
    - May indicate freeze-out of fluctuations on the QGP side of crossover
  - The antiproton puzzle indicates incomplete thermalization of the system
- **Net-charge fluctuations at the LHC revisited**
  - Moderate evidence for charge fluctuations freeze-out in the QGP





Outlook:

- Improved description of non-critical baselines and quantitative predictions of critical fluctuations
- Acceptance dependence of factorial cumulants, understanding antiprotons

Thanks for your attention!