Proton number cumulants and correlation functions from hydrodynamics and the QCD phase diagram

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QM QUARK MATTER KRAKÓW 2022

April 6, 2022

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

VV, V. Koch, arXiv:2204.00137

BEST COLLABORATION

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QCD phase structure

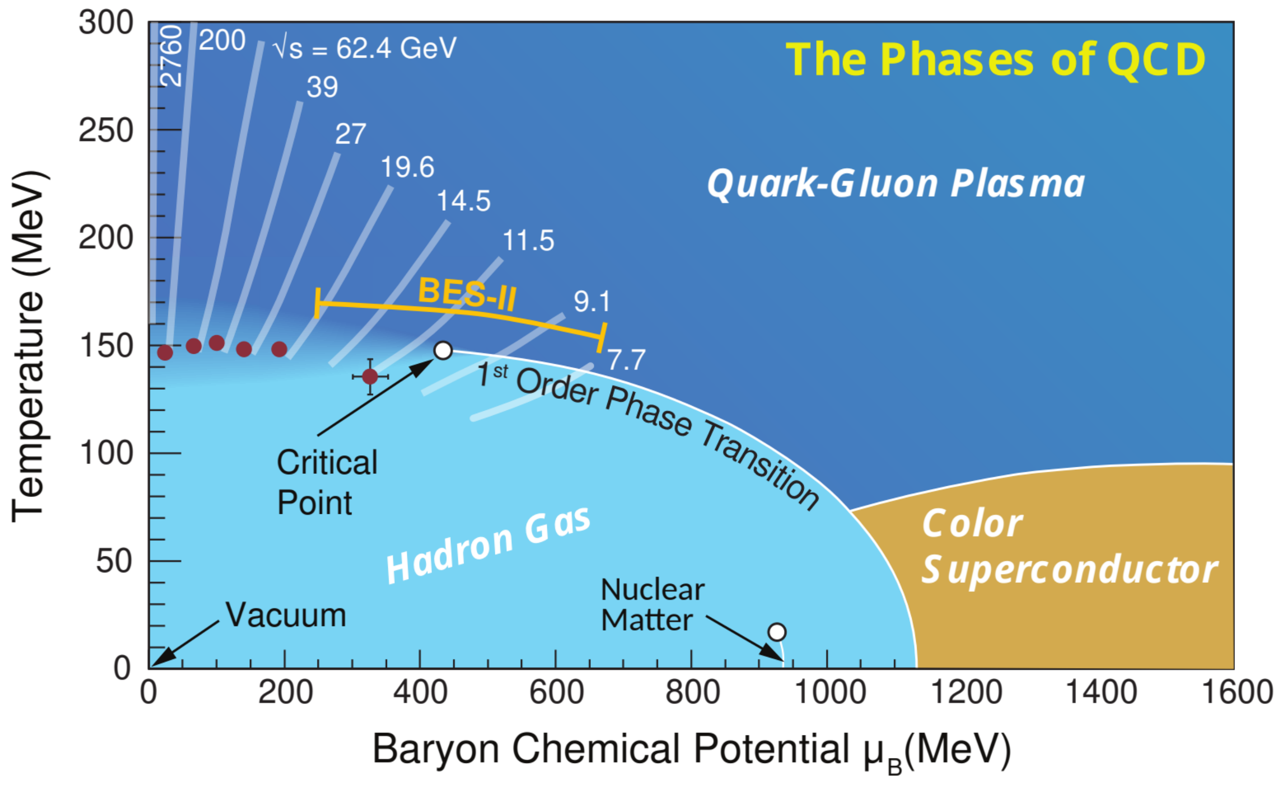


Figure from Bzdak et al., Phys. Rept. '20

- Dilute hadron gas at low T/n_B due to confinement, quark-gluon plasma high T/n_B
- Nuclear liquid-gas transition in cold and dense matter, lots of other phases conjectured

Is there a critical point and how to find it with heavy-ion collisions?

Event-by-event fluctuations and statistical mechanics

Cumulant generating function

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

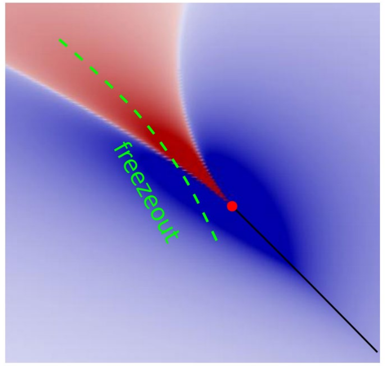
Grand partition function

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

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

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

- **(QCD) critical point** – large correlation length, critical fluctuations of baryon number



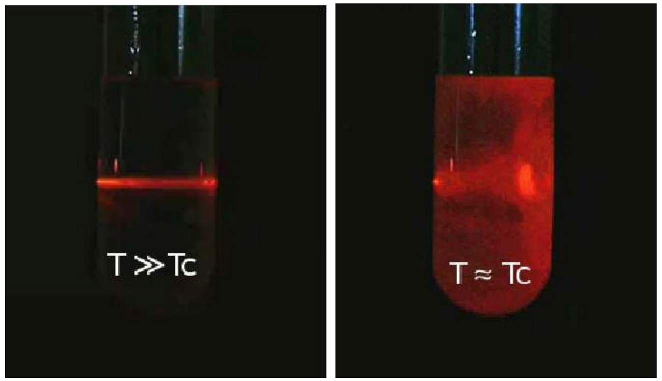
M. Stephanov, PRL '09, '11
Energy scans at RHIC (STAR)
and CERN-SPS (NA61/SHINE)

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

$$\xi \to \infty$$

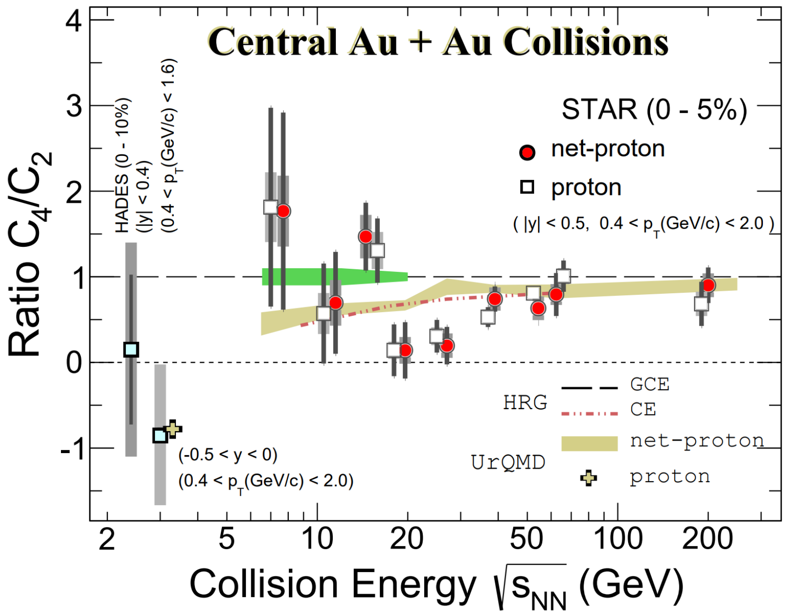
Looking for enhanced fluctuations
and non-monotonicities

Critical opalescence

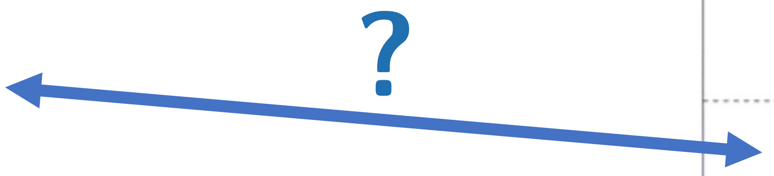


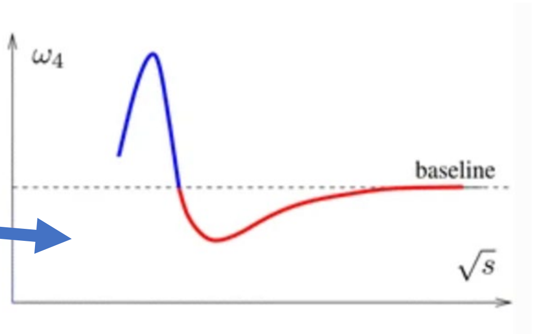
Experimental measurements

Beam energy scan in search for the critical point (STAR Coll.)



STAR Coll, Phys. Rev. Lett. 126, 092301 (2021); arXiv:2112.00240





M. Stephanov, Phys. Rev. Lett. (2011)

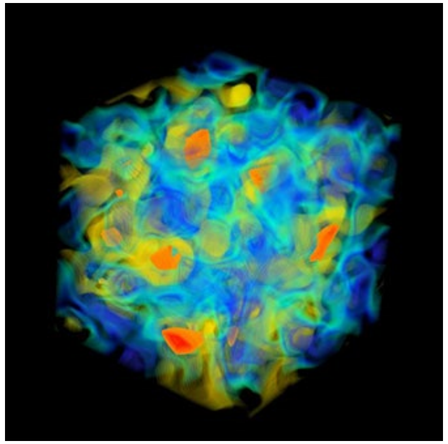
Reduced errors (better statistics), more energies, to come soon from RHIC-BES-II program, STAR-FXT etc.

Can we learn more from the more accurate data available for κ_2 and κ_3?

Other measurements: LHC-ALICE, GSI-HADES & CERN-NA61/SHINE Collaborations

Theory vs experiment: Challenges for fluctuations

Theory



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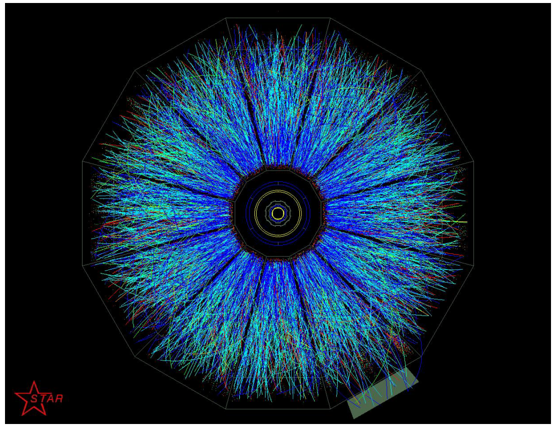
- Coordinate space
- In contact with the heat bath
- Conserved charges
- Uniform
- Fixed volume

Experiment



STAR event display

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

Need dynamical description

Dynamical approaches to the QCD critical point search

1. Dynamical model calculations of critical fluctuations
   - Fluctuating hydrodynamics
   - Equation of state with tunable critical point [P. Parotto et al, Phys. Rev. C 101, 034901 (2020)]

   Under development within the Beam Energy Scan Theory (BEST) Collaboration

   BEST COLLABORATION [X. An et al., Nucl. Phys. A 1017, 122343 (2022)]

2. Molecular dynamics with a critical point

   V. Kuznietsov et al., arXiv:2201.08486; **Poster: Wed 18:30 (T07_2)**

3. **Deviations from precision calculations of non-critical fluctuations**
   - 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)]

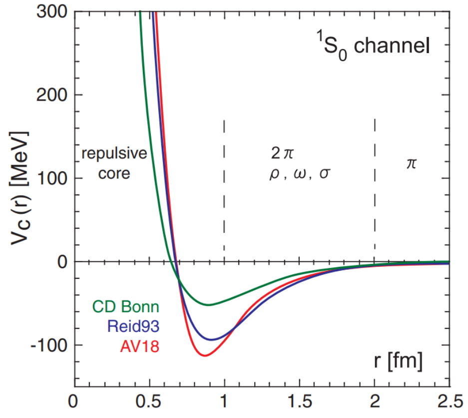


Figure from Ishii et al., PRL '07

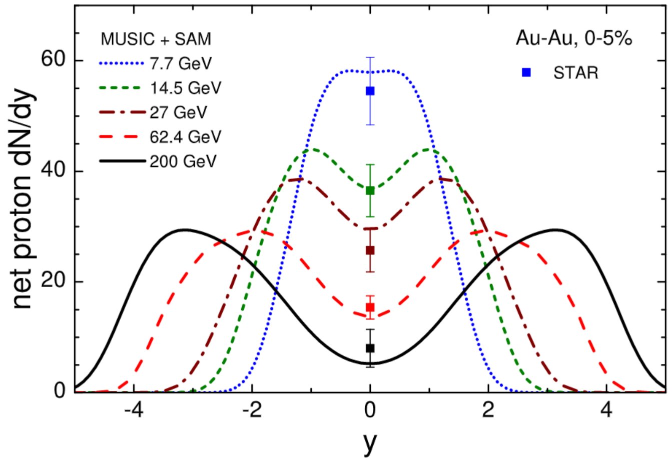
Hydrodynamic description within non-critical physics

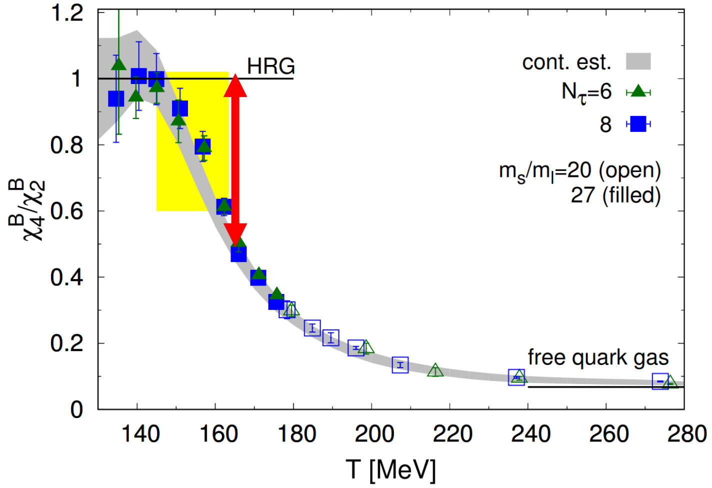
VV, V. Koch, C. Shen, Phys. Rev. C 105, 014904 (2022)

- Collision geometry based 3D initial state
  - Constrained to net proton distributions [Shen, Alzhrani, Phys. Rev. C '20]
- Viscous hydrodynamics evolution – MUSIC-3.0
  - Energy-momentum and baryon number conservation
  - Crossover equation of state based on lattice QCD [Monnai, Schenke, Shen, Phys. Rev. C '19]
- Cooper-Frye particlization at $\epsilon_{sw} = 0.26$ GeV/fm^3

$$\omega_p \frac{dN_j}{d^3p} = \int_{\sigma(x)} d\sigma_\mu(x)\, p^\mu \, \frac{d_j \, \lambda_j^{\rm ev}(x)}{(2\pi)^3} \exp\left[\frac{\mu_j(x) - u^\mu(x) p_\mu}{T(x)}\right].$$

- Particlization respects QCD-based baryon number distribution
  - Incorporated via baryon excluded volume $b = 1$ fm^3 [VV, V. Koch, Phys. Rev. C 103, 044903 (2021)]
- Incorporates exact global baryon conservation via a method SAM-2.0 [VV, Phys. Rev. C 105, 014903 (2022)]





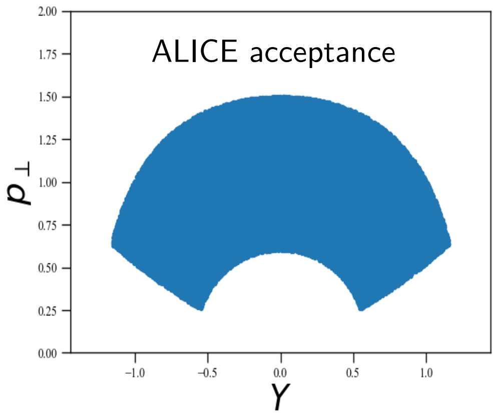
J. Karthein poster: Wed 17:30 (T07_1)

Net-particle fluctuations at the LHC

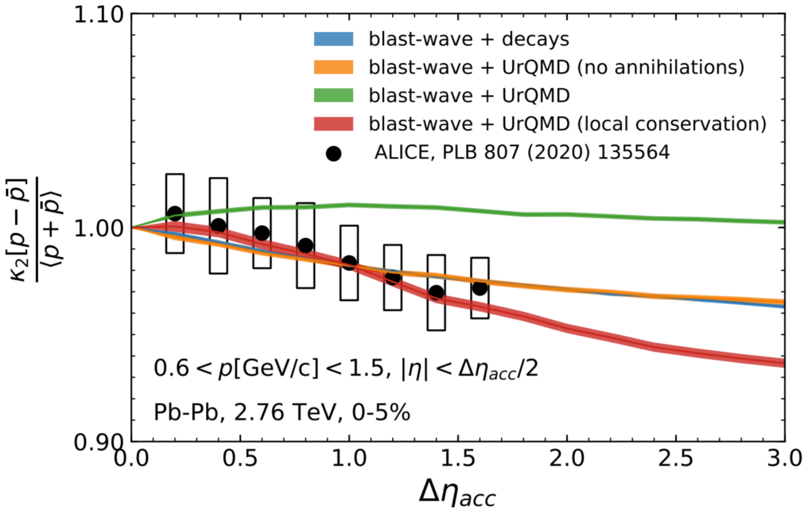
VV, Koch, Phys. Rev. C 103, 044903 (2021)

- Net protons described within errors and consistent with either global baryon conservation without $B\bar{B}$ annihilations or local baryon conservation with $B\bar{B}$ annihilations

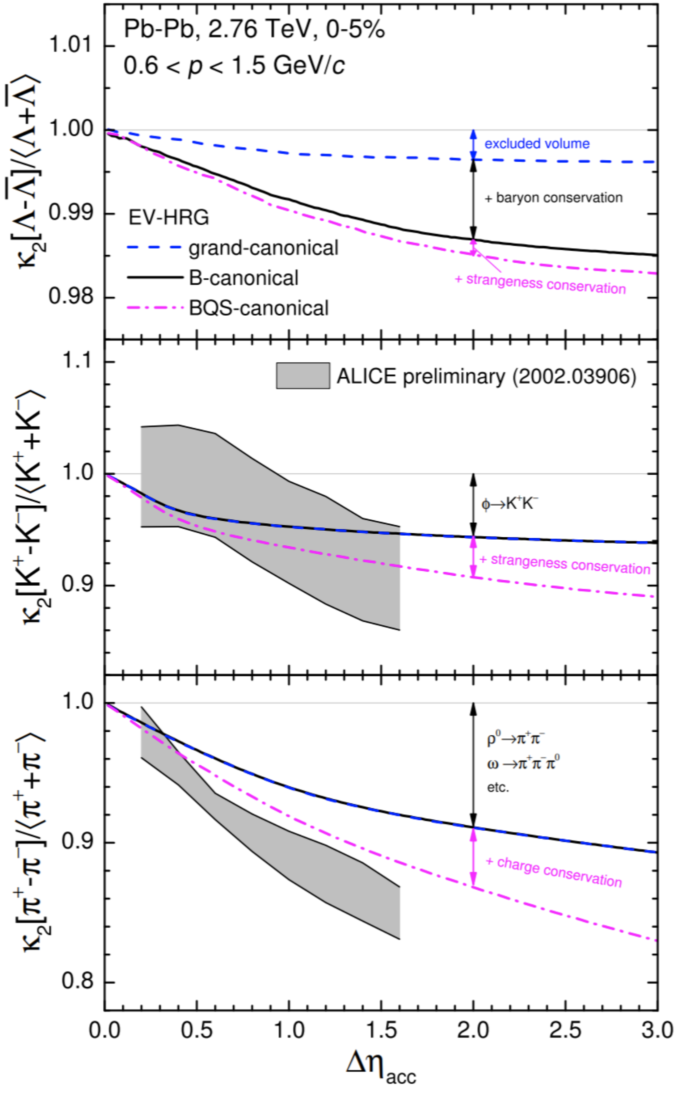
- Large effect from resonance decays for lighter particles + conservation of electric charge/strangeness



$0.6 < p < 1.5$ GeV$/c$, $\Delta\eta_{acc} = 1.6$

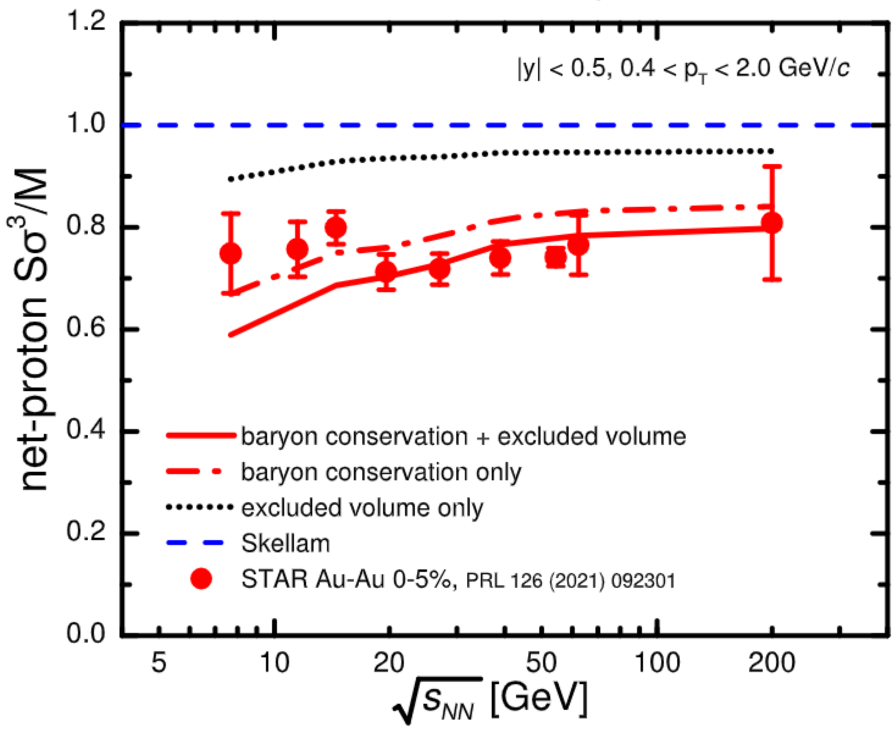


O. Savchuk et al., Phys. Lett. B 827, 136983 (2022)

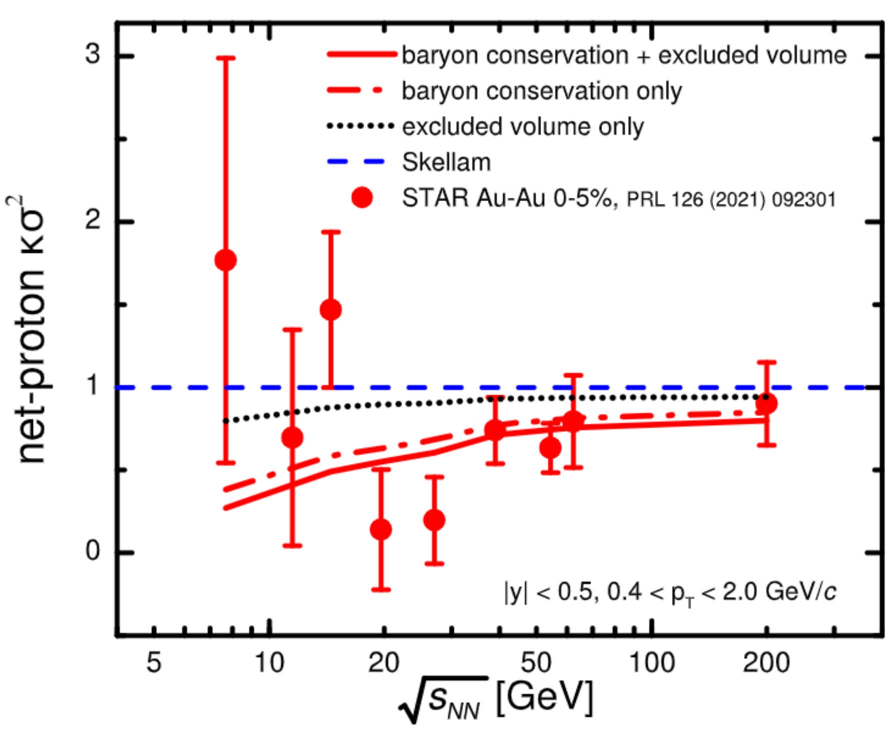


Net proton cumulant ratios

κ_3/κ_1



κ_4/κ_2



- Data at $\sqrt{s_{NN}} \geq 20$ GeV consistent with non-critical physics (baryon conservation and repulsion)
- Effect from baryon conservation is larger than from repulsion
- Excess of skewness in data at $\sqrt{s_{NN}} < 20$ GeV – *hint of attractive interactions?*

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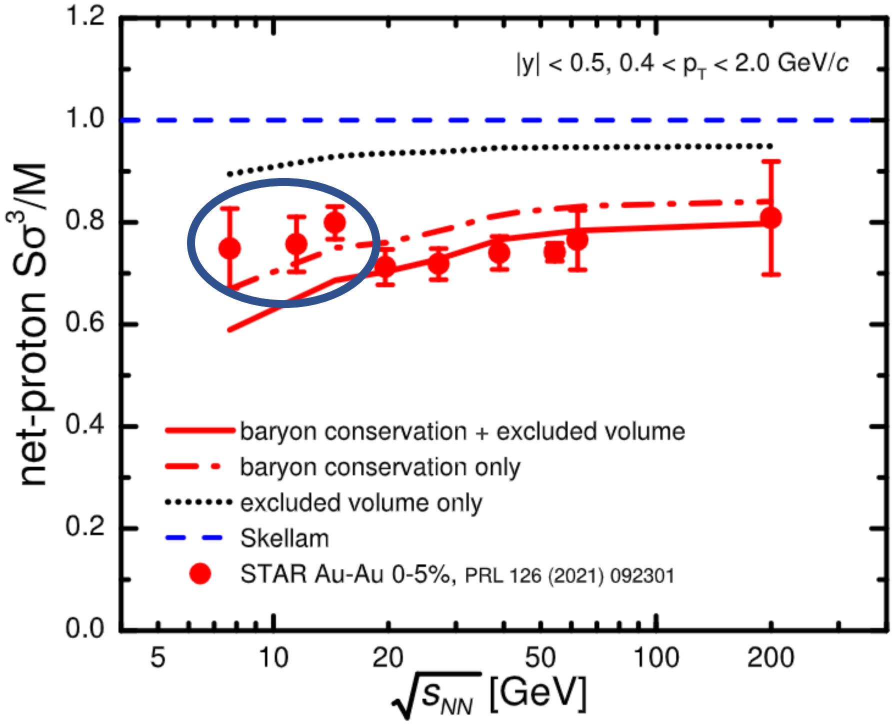
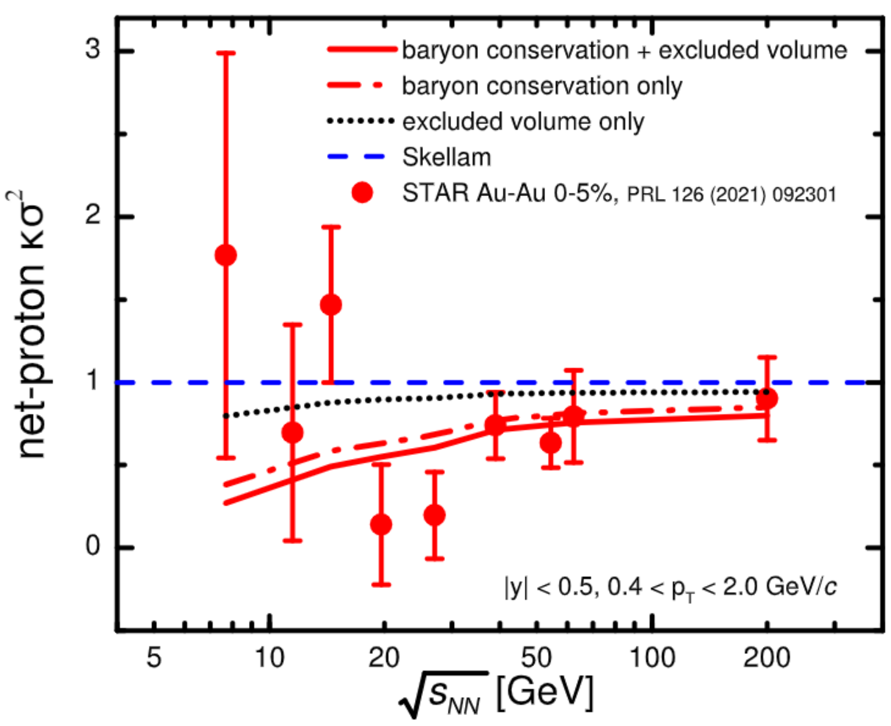


κ_4/κ_2



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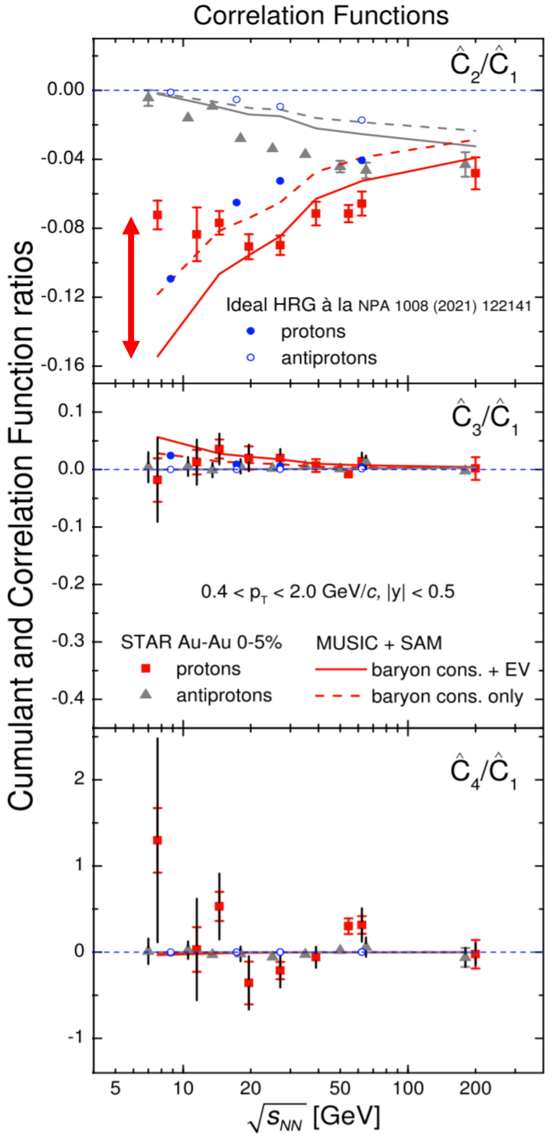
Correlation Functions

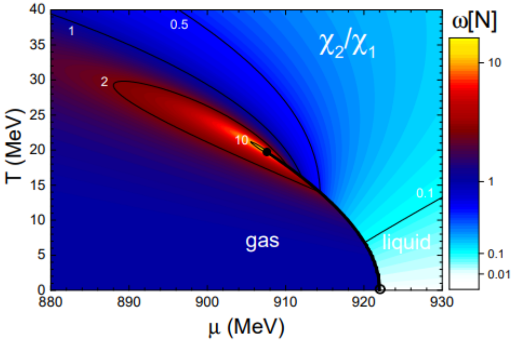
- Analyze genuine multi-particle correlations via **factorial cumulants** $\hat{C}_n$ [Bzdak, Koch, Strodthoff, Phys. Rev. C '17]

$$\hat{C}_1 = \kappa_1, \qquad \hat{C}_3 = 2\kappa_1 - 3\kappa_2 + \kappa_3,$$
$$\hat{C}_2 = -\kappa_1 + \kappa_2, \quad \hat{C}_4 = -6\kappa_1 + 11\kappa_2 - 6\kappa_3 + \kappa_4.$$

- Three- and four-particle correlations are small without a CP
  - Multi-particle correlations expected near the critical point [Ling, Stephanov, PRC '15]

- Signals from the data at $\sqrt{s_{NN}} \leq 20$ GeV
  - Excess of two-proton correlations
  - Possibility of significant 4-proton correlations
  - ***Critical point?***





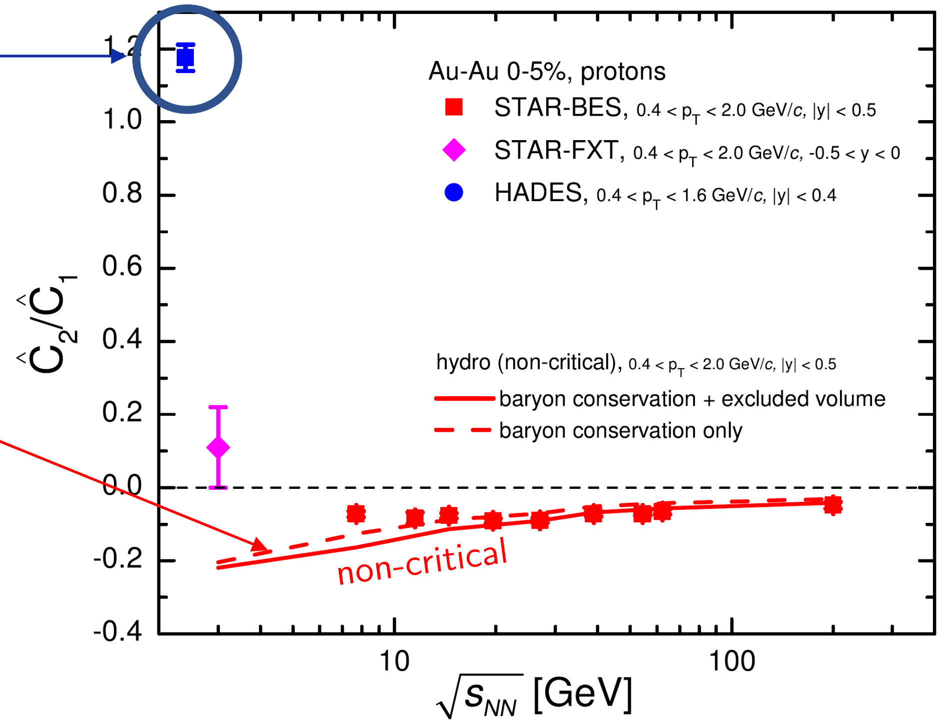
Lower energies $\sqrt{s_{NN}} \leq 7.7$ GeV

- Intriguing hint from HADES @ $\sqrt{s_{NN}} = 2.4$ GeV: huge excess of two-proton correlations!
  [HADES Collaboration, Phys. Rev. C 102, 024914 (2020)]

- No change of trend in the non-critical reference

- Additional mechanisms:
  - Nuclear liquid-gas transition
  - Light nuclei formation

- Fill the gap with ongoing/future data from STAR-FXT (e.g. arXiv:2112.00240), future experiments like CBM-FAIR



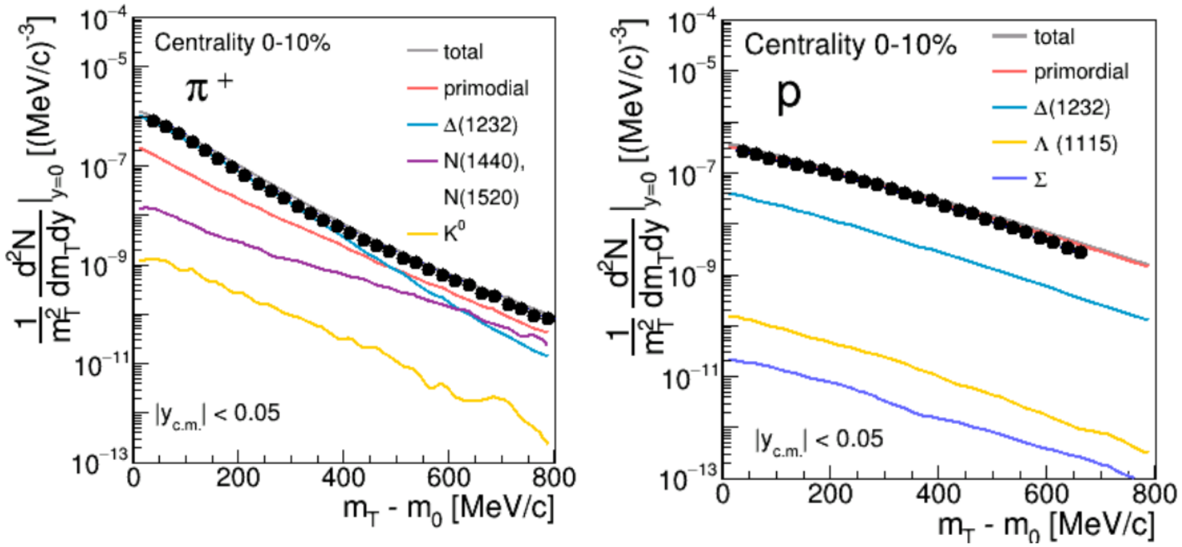
Thermodynamic analysis of HADES data

VV, Koch, arXiv:2204.00137

- Single freeze-out scenario: Emission from Siemens-Rasmussen hypersurface with Hubble-like flow
  - $\rightarrow$ Pion and proton spectra o.k.

  [S. Harabasz et al., PRC 102, 054903 (2020)]

- Uniform $T \approx 70$ MeV, $\mu_B \approx 875$ MeV across the fireball [A. Motornenko et al., PLB 822, 136703 (2021)]



- Fluctuations:
  - Same as before but incorporate additional binomial filtering to account for protons bound in light nuclei
  - Uniform fireball $\rightarrow$ Final proton cumulants are linear combinations of baryon susceptibilities χ_n^B at freeze-out

$\Rightarrow$

Extract χ_n^B directly from experimental data

Thermodynamic analysis of HADES data

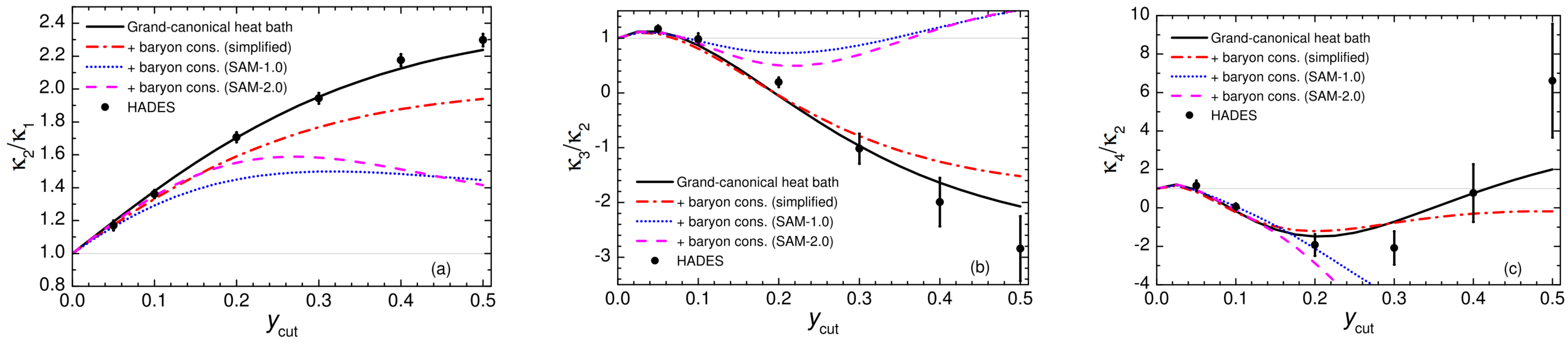
VV, Koch, arXiv:2204.00137

- In the grand-canonical limit (no baryon conservation) the data are described well with

$$\frac{\chi_2^B}{\chi_1^B} = 9.35 \pm 0.40, \qquad \frac{\chi_3^B}{\chi_2^B} = -39.6 \pm 7.2, \qquad \frac{\chi_4^B}{\chi_2^B} = 1130 \pm 488$$

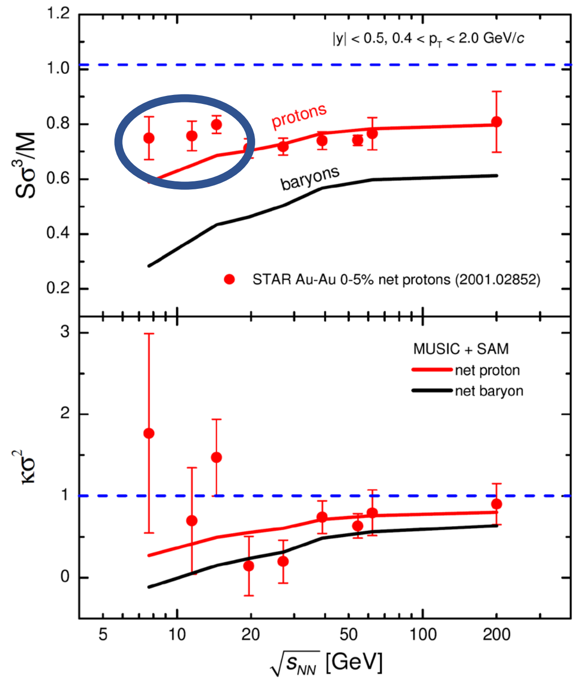
i.e. $\chi_4^B \gg -\chi_3^B \gg \chi_2^B \gg \chi_1^B$

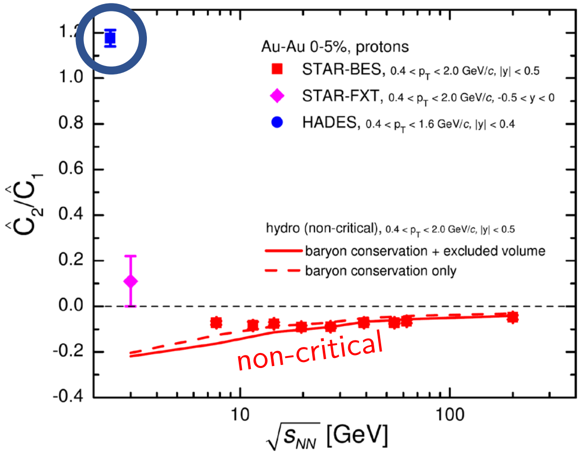
- Could be indicative of a *critical point* near the HADES freeze-out at $T \sim 70$ MeV, $\mu_B \sim 875$ MeV
- However, the results for $y_{cut} > 0.2$ are challenging to describe with baryon conservation included



Summary

- Hydrodynamic analysis of proton cumulants in central heavy-ion collisions $\sqrt{s_{NN}}$=2.4-2760 GeV
  - Protons are described quantitatively at $\sqrt{s_{NN}} \geq 20$ GeV by non-critical physics
  - Possible evidence for attractive proton interactions at $\sqrt{s_{NN}} \leq 14.5$ GeV
  - At LHC sensitive to baryon annihilations
- Factorial cumulants carry rich information
  - Small three- and four-particle correlations in absence of critical point effects
- HADES data point to huge (multi-)proton correlations
  - Critical point around $T \sim 70$ MeV, $\mu_B \sim 875$ MeV?
  - At odds with baryon conservation as acceptance increased





Thanks for your attention!

Backup slides

Acceptance dependence of two-particle correlations

- Changing y_{max} slope at $\sqrt{s_{NN}} \leq 14.5$ GeV?
- Volume fluctuations? [Skokov, Friman, Redlich, PRC '13]
  - $C_2/C_1 \mathrel{+}= C_1 * v_2$
  - Can improve low energies but spoil high energies?
- Exact electric charge conservation?
  - Worsens the agreement at $\sqrt{s_{NN}} \leq 14.5$, higher energies virtually unaffected
- **Attractive interactions?**
  - Could work if baryon repulsion turns into attraction in the high-μ_B regime
  - **Critical point?**