Treatment of event-by-event fluctuations for comparison with experiment

Volodymyr Vovchenko (LBNL)

On-line seminar series III on "RHIC Beam Energy Scan: Theory and Experiment"

November 30, 2021

Unterstützt von / Supported by

Alexander von Humboldt Stiftung/Foundation

QCD phase diagram with heavy-ion collisions

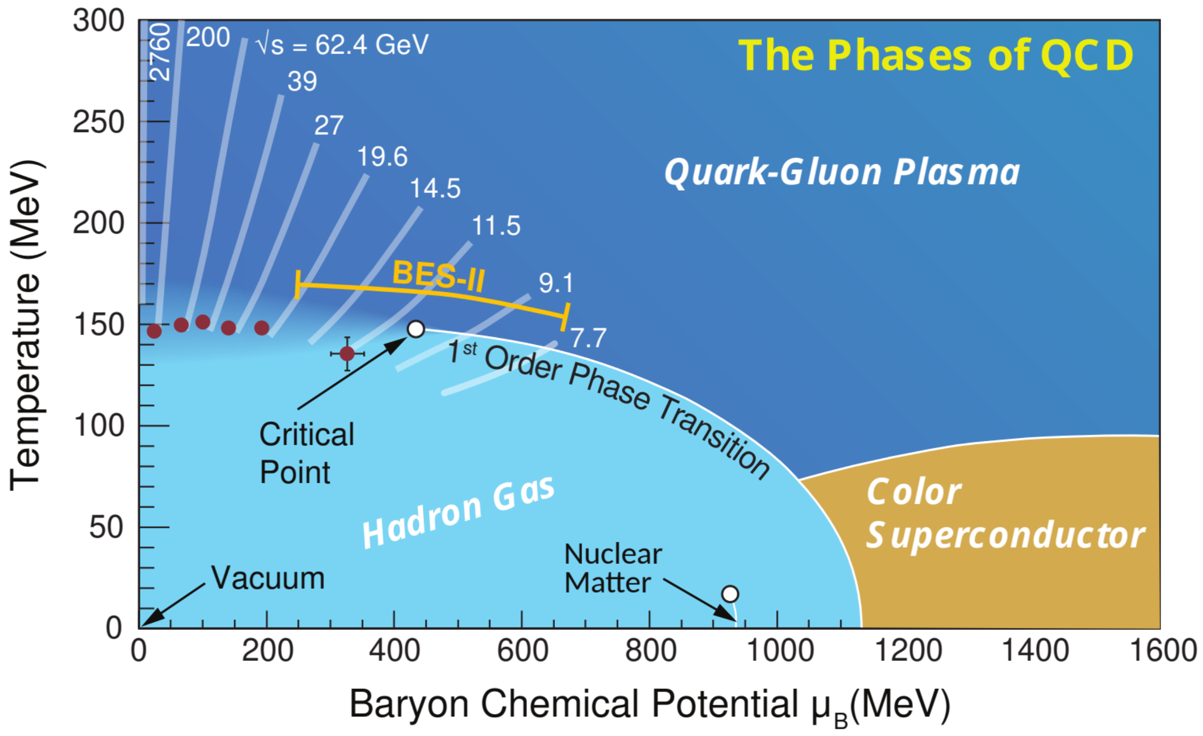
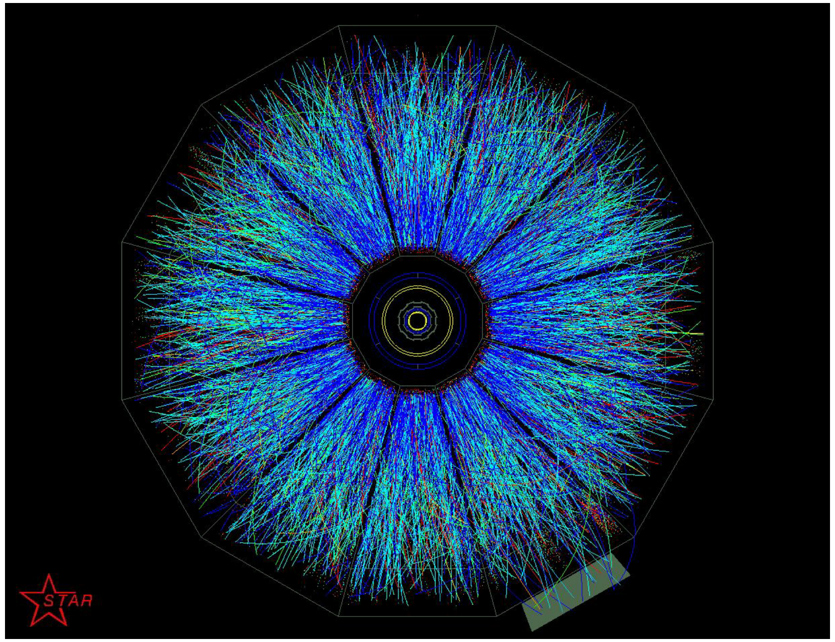


Figure from Bzdak et al., Phys. Rept. '20



STAR event display

Thousands of particles created in relativistic heavy-ion collisions

↓

Apply concepts of statistical mechanics

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

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

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

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

Event-by-event fluctuations and statistical mechanics

Cumulant generating function

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

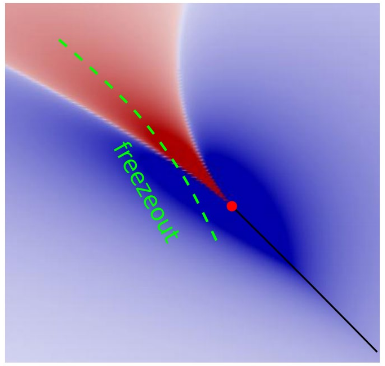
Grand partition function

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

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

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

- (QCD) critical point
- Test of (lattice) QCD at $\mu_B \approx 0$
- Freeze-out from fluctuations



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

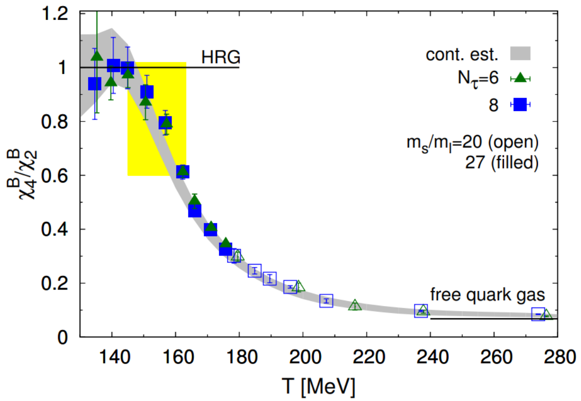
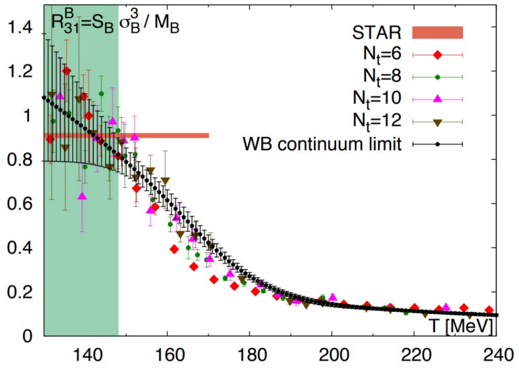
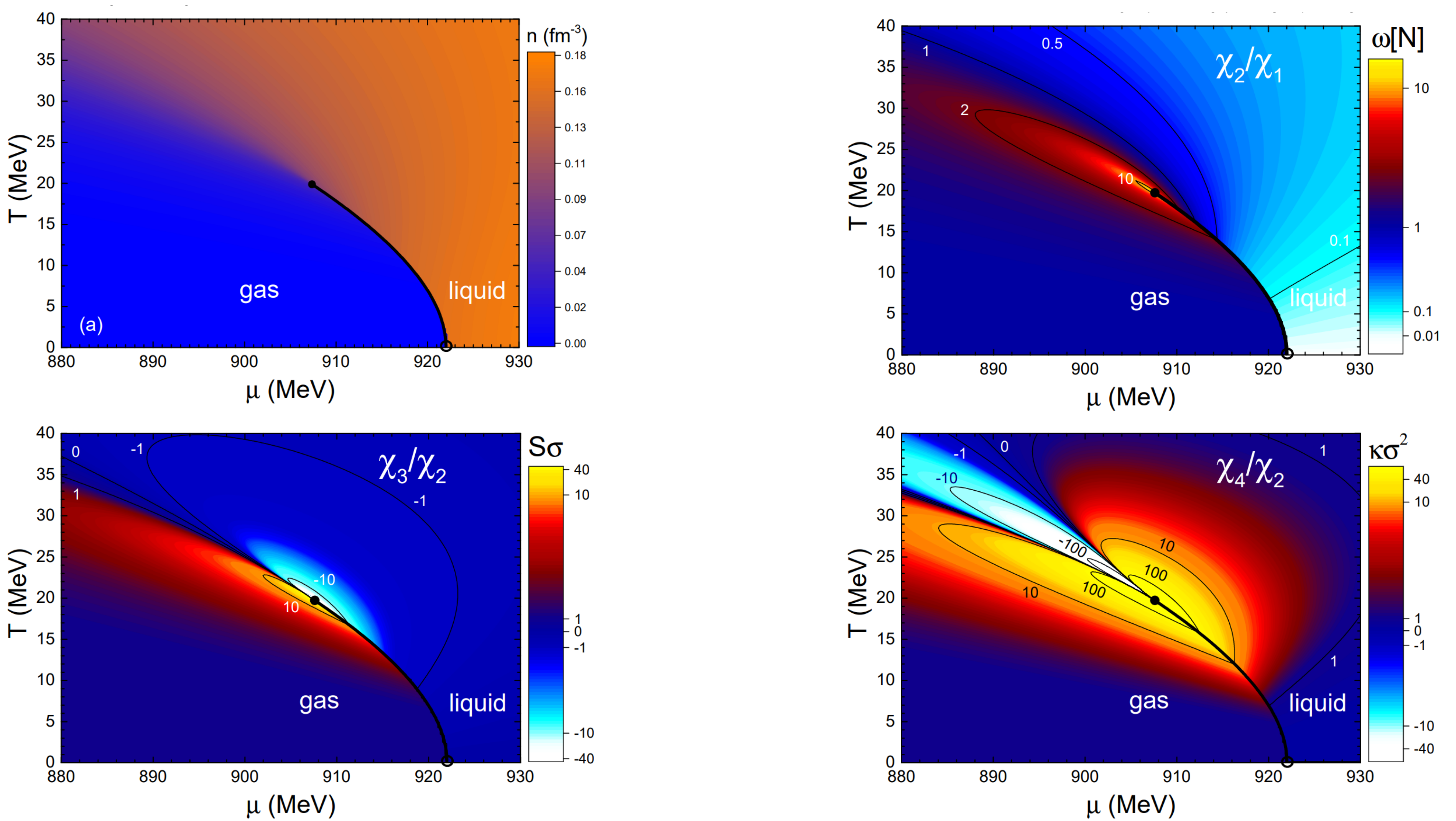


Figure from Bazavov et al. PRD 95, 054504 (2017)
Probed by LHC and top RHIC



Borsanyi et al. PRL 113, 052301 (2014)
Bazavov et al. PRL 109, 192302 (2012)
...

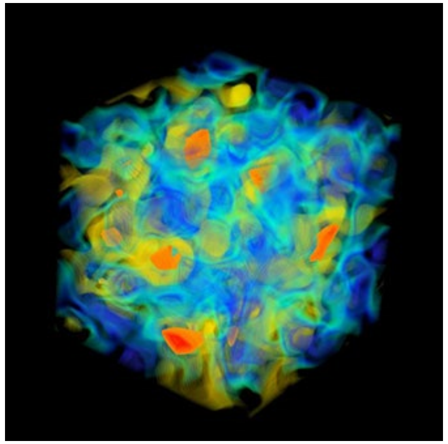
Example: Nuclear liquid-gas transition



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

Theory vs experiment

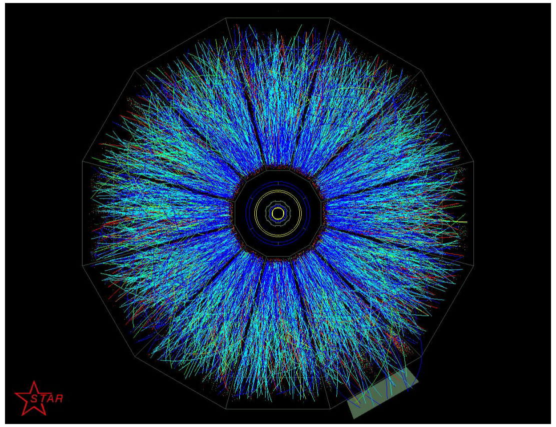
Theory



© Lattice QCD@BNL

- 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

Theory vs experiment

- **accuracy of the grand-canonical ensemble (global conservation laws)**
  - **subensemble acceptance method (SAM)**

VV, Savchuk, Poberezhnyuk, Gorenstein, Koch, PLB 811, 135868 (2020); JHEP 089(2020); arXiv:2106.13775

- **coordinate vs momentum space**

Ling, Stephanov, PRC 93, 034915 (2016); Ohnishi, Kitazawa, Asakawa, PRC 94, 044905 (2016)

- **proxy observables in experiment (net-proton, net-kaon) vs conserved charges in QCD (net-baryon, net-strangeness)**

Kitazawa, Asakawa, PRC 85, 021901 (2012); VV, Jiang, Gorenstein, Stoecker, PRC 98, 024910 (2018)

- volume fluctuations

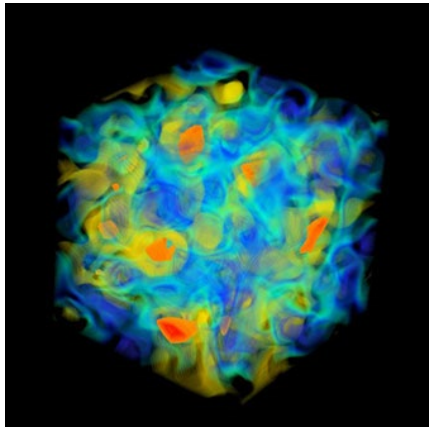
Gorenstein, Gazdzicki, PRC 84, 014904 (2011); Skokov, Friman, Redlich, PRC 88, 034911 (2013)
X. Luo, J. Xu, B. Mohanty, JPG 40, 105104 (2013); Braun-Munzinger, Rustamov, Stachel, NPA 960, 114 (2017)

- hadronic phase

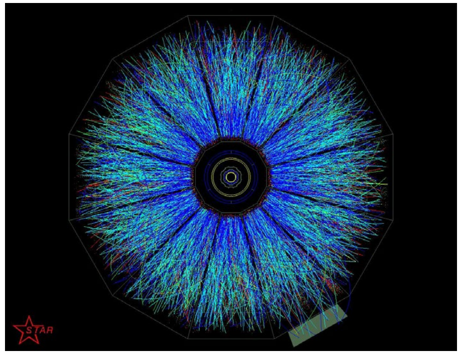
Steinheimer, VV, Aichelin, Bleicher, Stoecker, PLB 776, 32 (2018)

- non-equilibrium (memory) effects

Mukherjee, Venugopalan, Yin, PRC 92, 034912 (2015)
Asakawa, Kitazawa, Müller, PRC 101, 034913 (2020)



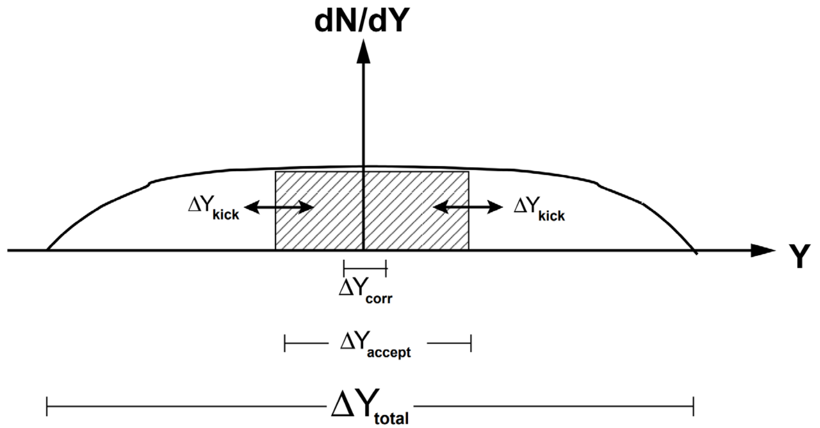
© Lattice QCD@BNL



STAR event display

When are the measured fluctuations grand-canonical?

- Consider event-by-event fluctuations of particle number in acceptance ΔY_{accept} around midrapidity

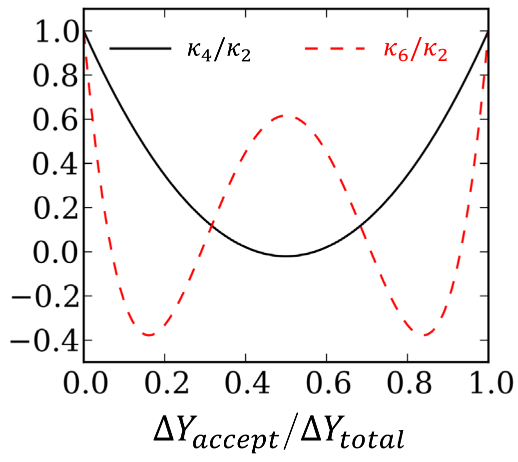


V. Koch, arXiv:0810.2520

- Scales
  - ΔY_{accept} – acceptance
  - ΔY_{total} – full space
  - ΔY_{corr} – rapidity correlation length (thermal smearing)
  - ΔY_{kick} – diffusion in the hadronic phase

- **GCE applies if $\Delta Y_{total} \gg \Delta Y_{accept} \gg \Delta Y_{kick}, \Delta Y_{corr}$**

- In practice $\Delta Y_{total} \gg \Delta Y_{accept}$ and $\Delta Y_{accept} \gg \Delta Y_{corr}$ are not simultaneously satisfied
  - Corrections from global conservation are large [Bzdak et al., PRC '13]
  - $\Delta Y_{corr} \sim 1 \sim \Delta Y_{accept}$ [Ling, Stephanov, PRC '16]



Subensemble acceptance method

VV, Savchuk, Poberezhnyuk, Gorenstein, Koch, PLB 811, 135868 (2020)

Subensemble acceptance method (SAM) – method to correct *any* EoS (e.g. *lattice QCD*) for **charge conservation** and extract the **susceptibilities**

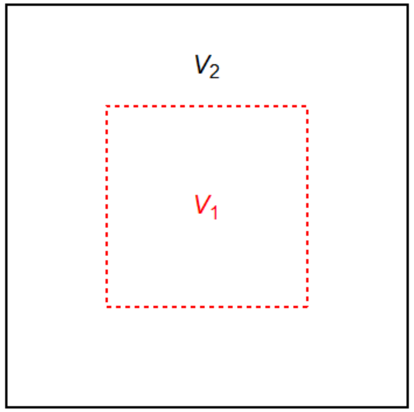
Partition a thermal system with a globally conserved charge B *(canonical ensemble)* into two subsystems which can exchange the charge

Assume thermodynamic limit:

$$V, V_1, V_2 \to \infty; \quad \frac{V_1}{V} = \alpha = const; \quad \frac{V_2}{V} = (1-\alpha) = const;$$

$$V_1, V_2 \gg \xi^3, \qquad \xi = \text{correlation length}$$

$$V_1 + V_2 = V$$

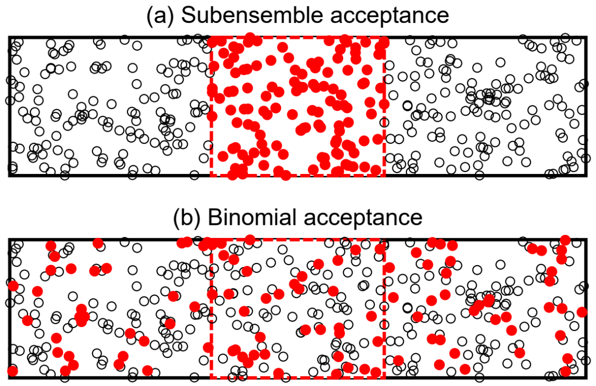


The canonical partition function then reads:

$$Z^{\rm ce}(T,V,B) = \mathrm{Tr}\, e^{-\beta \hat{H}} \approx \sum_{B_1} Z^{\rm ce}(T,V_1,B_1)\, Z^{\rm ce}(T,V-V_1,B-B_1)$$

The probability to have charge B_1 is:

$$P(B_1) \propto Z^{\rm ce}(T,\alpha V,B_1)\, Z^{\rm ce}(T,(1-\alpha)V,B-B_1), \qquad \alpha \equiv V_1/V$$



SAM: Computing the cumulants

VV, Savchuk, Poberezhnyuk, Gorenstein, Koch, PLB 811, 135868 (2020)

Cumulant generating function for B_1:

$$G_{B_1}(t) \equiv \ln\langle e^{t\,B_1}\rangle = \ln\left\{\sum_{B_1} e^{t\,B_1}\,\exp\left[-\frac{\alpha V}{T}\,f(T,\rho_{B_1})\right]\exp\left[-\frac{\beta V}{T}\,f(T,\rho_{B_2})\right]\right\} + \tilde{C} \qquad \beta = 1-\alpha$$

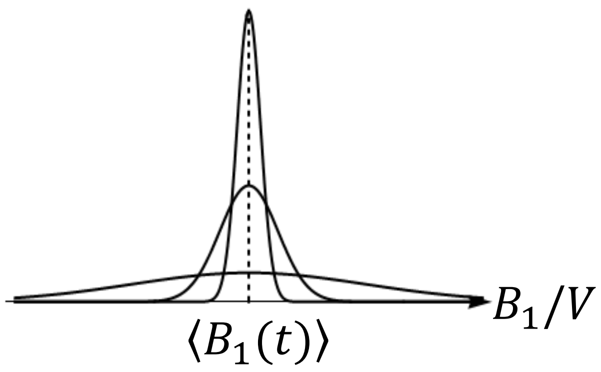
$$\tilde{\kappa}_1[B_1(t)] = \frac{\sum_{B_1} B_1\,\tilde{P}(B_1;t)}{\sum_{B_1}\tilde{P}(B_1;t)} \equiv \langle B_1(t)\rangle \qquad \text{with} \qquad \tilde{P}(B_1;t) = \exp\left\{tB_1 - V\,\frac{\alpha f(T,\rho_{B_1}) + \beta f(T,\rho_{B_2})}{T}\right\}.$$

Thermodynamic limit: $\tilde{P}(B_1;t)$ *highly peaked* at $\langle B_1(t)\rangle$

$\langle B_1(t)\rangle$ is a solution to equation $d\tilde{P}/\mathrm{d}B_1 = 0$:

$$t = \hat{\mu}_B[T,\rho_{B_1}(t)] - \hat{\mu}_B[T,\rho_{B_2}(t)]$$

$$\text{where} \quad \hat{\mu}_B \equiv \mu_B/T, \qquad \mu_B(T,\rho_B) = \partial f(T,\rho_B)/\partial\rho_B$$



$\boldsymbol{t=0}$**:** $\quad \rho_{B_1} = \rho_{B_2} = B/V$, $B_1 = \alpha B$, i.e. charge uniformly distributed between the subsystems

SAM: Cumulant ratios in terms of GCE susceptibilities

$$\kappa_n[B_1] = \left. \frac{\partial^{n-1} \tilde{\kappa}_1[B_1(t)]}{\partial t^{n-1}} \right|_{t=0} \quad \longleftrightarrow \quad \frac{\partial^n}{\partial t^n}: \; t = \hat{\mu}_B[T, \rho_{B_1}(t)] - \hat{\mu}_B[T, \rho_{B_2}(t)]$$

scaled variance $\quad \dfrac{\kappa_2[B_1]}{\kappa_1[B_1]} = (1-\alpha)\, \dfrac{\chi_2^B}{\chi_1^B},$ $\qquad \chi_n^B \equiv \partial^{n-1}(\rho_B/T^3)/\partial(\mu_B/T)^{n-1}$

skewness $\quad \dfrac{\kappa_3[B_1]}{\kappa_2[B_1]} = (1-2\alpha)\, \dfrac{\chi_3^B}{\chi_2^B},$

kurtosis $\quad \dfrac{\kappa_4[B_1]}{\kappa_2[B_1]} = (1-3\alpha\beta)\, \dfrac{\chi_4^B}{\chi_2^B} - 3\alpha\beta \left(\dfrac{\chi_3^B}{\chi_2^B}\right)^2.$

- Global conservation (α) and equation of state (χ_n^B) effects factorize in cumulants up to the 3rd order, starting from κ_4 not anymore
- $\alpha \to 0$ – GCE limit*, $\qquad \alpha \to 1$ – CE limit

*As long as $V_1 \gg \xi^3$ holds

For *multiple conserved charges* (joint B,Q,S cumulants up to 6th order) see VV, Poberezhnyuk, Koch, JHEP 10, 089 (2020)

Example: Lennard-Jones fluid

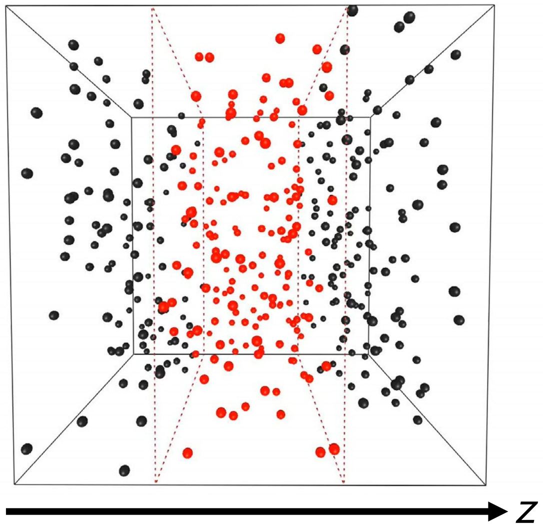
V. Kuznietsov, O. Savchuk, M.I. Gorenstein, V. Koch, VV, in preparation

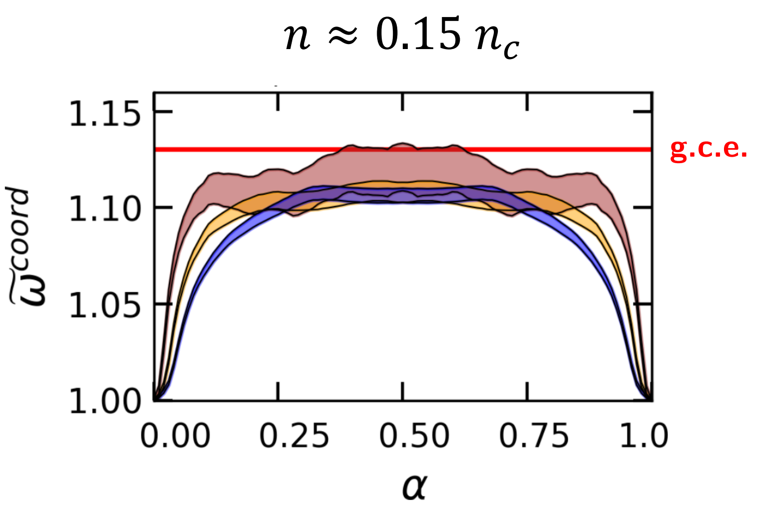
Classical molecular dynamics simulations* of a **Lennard-Jones fluid** along the (super)critical isotherm of the liquid-gas transition

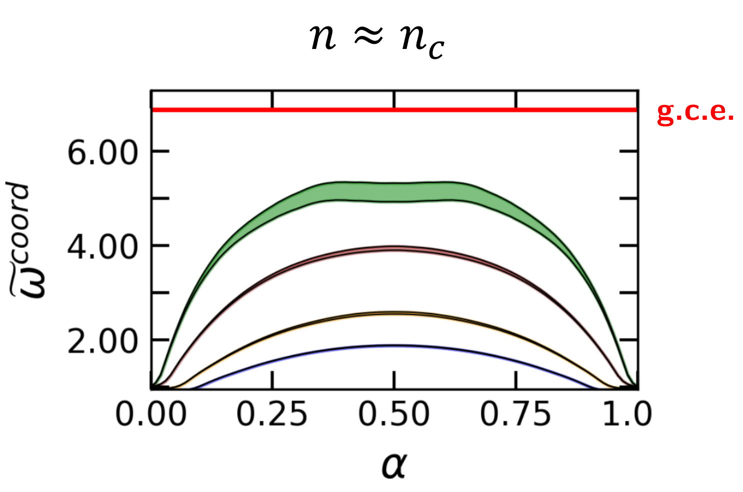
Microcanonical (const. *EVN*) ensemble with periodic boundary conditions

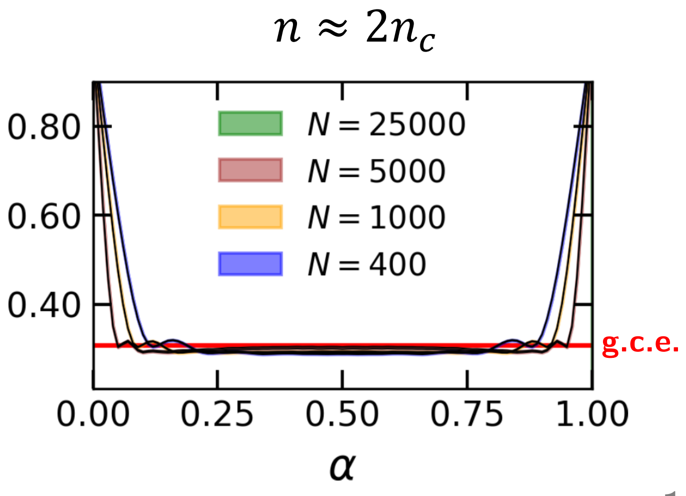
Variance of conserved particle number distribution inside coordinate space subvolume $|z| < z^{max}$ as time average

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









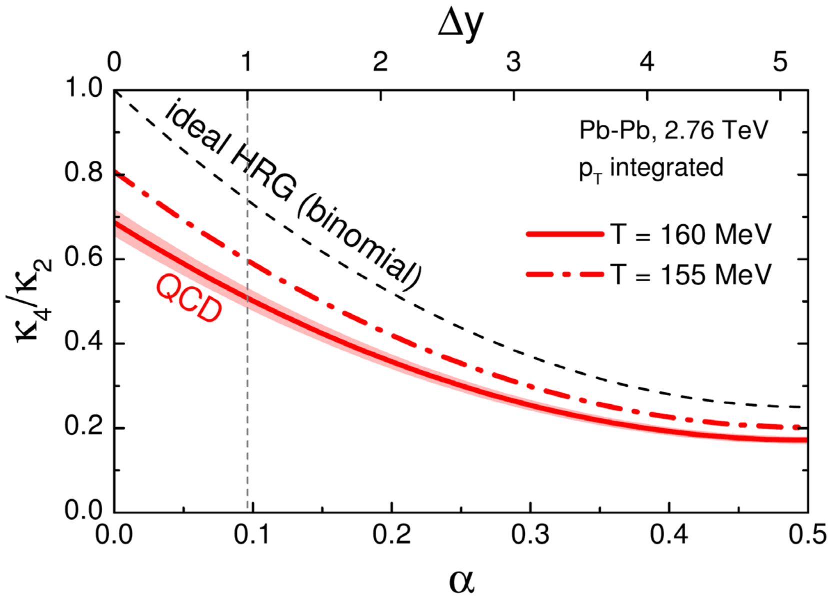
*Molecular dynamics code from https://github.com/vlvovch/lennard-jones-cuda

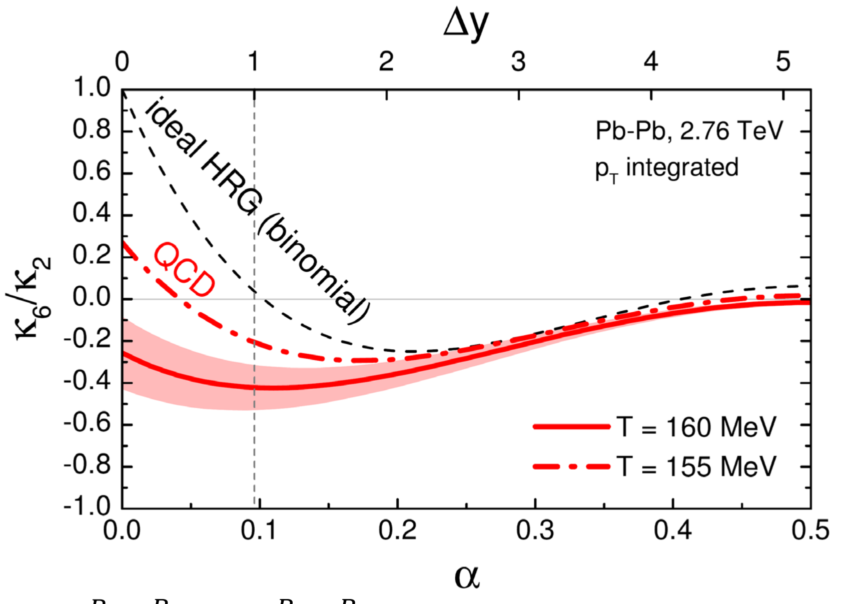
Net baryon fluctuations at LHC from lattice QCD ($\mu_B = 0$)

VV, Savchuk, Poberezhnyuk, Gorenstein, Koch, PLB 811, 135868 (2020)

Momentum rapidity $y \approx$ space-time rapidity η_s

$$\left(\frac{\kappa_4}{\kappa_2}\right)_{LHC} = (1-3\alpha\beta)\,\frac{\chi_4^B}{\chi_2^B} \qquad \left(\frac{\kappa_6}{\kappa_2}\right)_{LHC} = [1-5\alpha\beta(1-\alpha\beta)]\,\frac{\chi_6^B}{\chi_2^B} - 10\alpha(1-2\alpha)^2\beta\left(\frac{\chi_4^B}{\chi_2^B}\right)^2$$





Lattice data for χ_4^B/χ_2^B and χ_6^B/χ_2^B from Borsanyi et al., 1805.04445

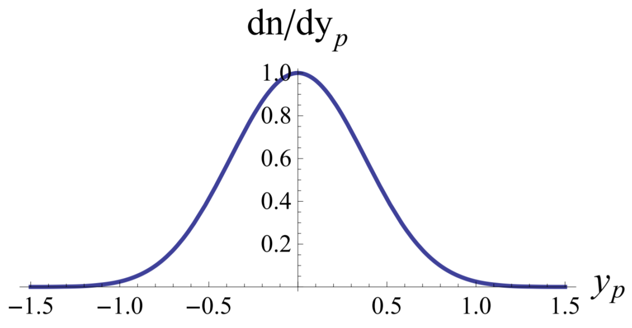
Theory: negative χ_6^B/χ_2^B is a possible signal of chiral criticality [Friman, Karsch, Redlich, Skokov, EPJC '11]

Experiment: $\alpha \approx \frac{N_{ch}(\Delta y)}{N_{ch}(\infty)} \approx \mathrm{erf}\left(\frac{\Delta y}{2\sqrt{2}\sigma_y}\right)$, for $\Delta y \approx 1$ the κ_6/κ_2 is mainly sensitive to the EoS

$N_{ch}(\Delta y)$ measurement: ALICE Collaboration, PLB 726 (2013) 610-622

SAM: Applicability and limitations

- Argument is based on partition in ***coordinate*** space but experiments measure in ***momentum*** space
  - OK at high energies where we have **Bjorken flow** $[Y \sim \eta_s = \mathrm{atanh}(z/t)]$
    - For small $\Delta Y_{acc} < 1$: corrections due to thermal smearing and resonance decays
    - Limited applicability at lower energies
- **Thermodynamic limit** i.e. $V_1, V_2 \gg \xi^3$:
  - OK at LHC where $\frac{dV}{dy} \sim 4000 - 5000$ fm^3 vs. $V_{lattice} \sim 125$ fm^3
  - Applicability is more limited near the critical point
- Assumes $\boldsymbol{T, \mu_B = const}$ everywhere



[Ling, Stephanov, PRC '16]

To address these issues one needs a ***dynamical description***

Approaches to dynamical modeling of fluctuations

1. Dynamical model calculations of critical fluctuations
   - Fluctuating hydrodynamics
   - Equation of state with tunable critical point
   - Predict CP signatures dependent on its location

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

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

2. **Study deviations from the non-critical baseline**
   - Include essential non-critical contributions to (net-)proton number cumulants
   - Exact baryon conservation + baryon excluded volume
   - Based on realistic hydrodynamic simulations

   [VV, C. Shen, V. Koch, arXiv:2107.00163]

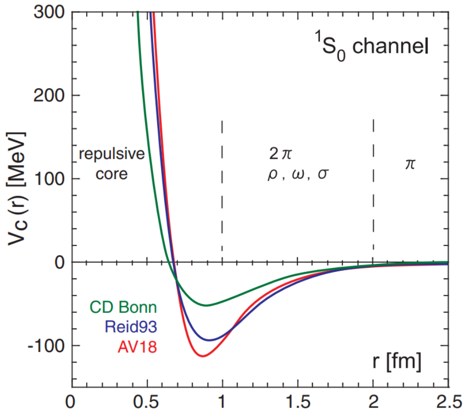
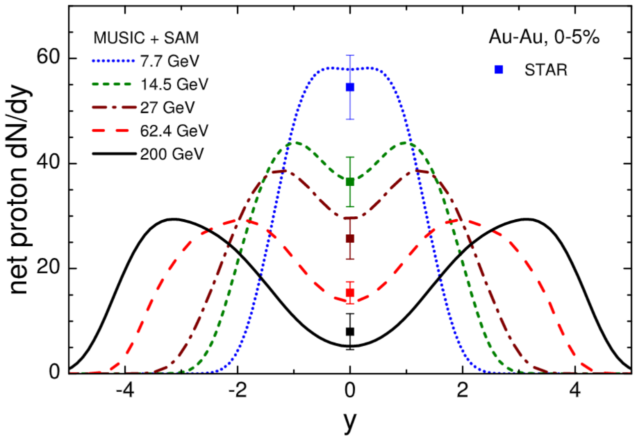


Figure from Ishii et al., PRL '07

Hydrodynamic description in a non-critical scenario

VV, C. Shen, V. Koch, arXiv:2107.00163



- Collision geometry based 3D initial state [Shen, Alzhrani, PRC '20]
  - Constrained to net proton distributions

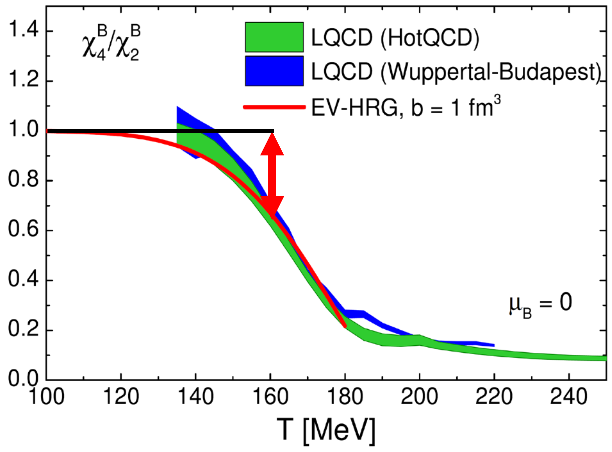
- Viscous hydrodynamics evolution – MUSIC-3.0
  - Energy-momentum and baryon number conservation
  - NEOS-BQS crossover equation of state [Monnai, Schenke, Shen, PRC '19]
  - Shear viscosity via IS-type equation

- 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 includes QCD-based baryon number distribution
  - Here incorporated via baryon excluded volume

[VV, Pasztor, Fodor, Katz, Stoecker, PLB 775, 71 (2017)]



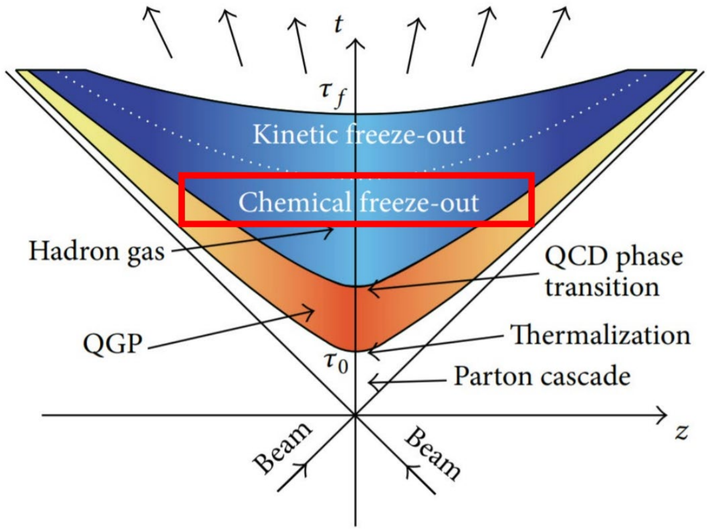
Calculating cumulants from hydrodynamics

- Strategy:
  1. Calculate proton cumulants in the experimental acceptance in the grand-canonical limit
  2. Apply correction for the exact global baryon number conservation

First step:

- Sum contributions from each hypersurface element x_i at freeze-out
  - Cumulants of joint (anti)proton/(anti)baryon distribution

$$\kappa_{n,m}^{B^{\pm},p^{\pm},\mathrm{gce}}(\Delta p_{\mathrm{acc}}) = \sum_{i\in\sigma} \delta\kappa_{n,m}^{B^{\pm},p^{\pm},\mathrm{gce}}(x_i; \Delta p_{\mathrm{acc}})$$



- To compute each contribution
  - GCE susceptibilities $\chi^{B^{\pm}}(x_i)$ define the distribution of the emitted (anti)baryons
  - Each baryon ends up in acceptance Δp_{acc} with binomial probability via the Cooper-Frye formula
  - Each baryon is a proton with probability $q(x_i) = \langle N_p(x_i)\rangle / \langle N_B(x_i)\rangle$

*For the Monte Carlo version of this procedure see [VV, Koch, Phys. Rev. C 103, 044903 (2021)]

Correcting for baryon number conservation with SAM-2.0

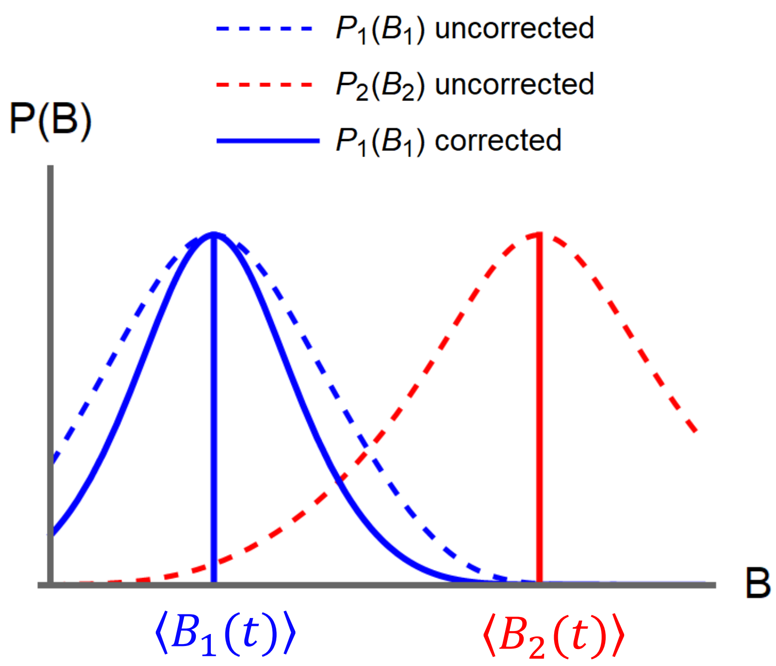
VV, arXiv:2107.00163 (to appear in PRC)

$$P_1^{\text{ce}}(B_1) \propto \sum_{B_1,B_2} P_1^{\text{gce}}(B_1) P_2^{\text{gce}}(B_2) \times \delta_{B,B_1+B_2}$$

SAM-1.0: uniform thermal system and **coordinate** space

SAM-2.0: apply the correction for *arbitrary* distributions inside and outside the acceptance that are peaked at the mean

- Spatially inhomogeneous systems (e.g. RHIC)
- Momentum space
- Non-conserved quantities (e.g. proton number)
- Map "grand-canonical" cumulants inside and outside the acceptance to the "canonical" cumulants inside the acceptance

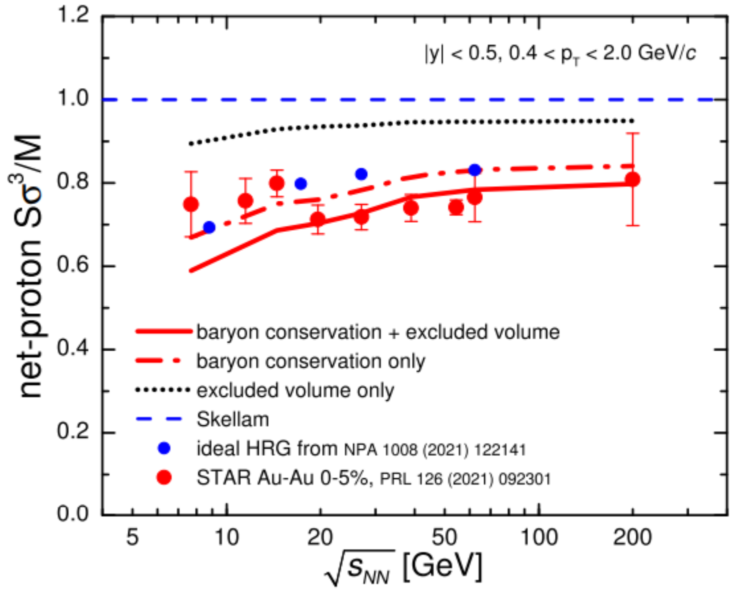


$$\boxed{\kappa_{p,B}^{\text{in,ce}} = \text{SAM}\left[\kappa_{p,B}^{\text{in,gce}}, \kappa_{p,B}^{\text{out,gce}}\right]}$$

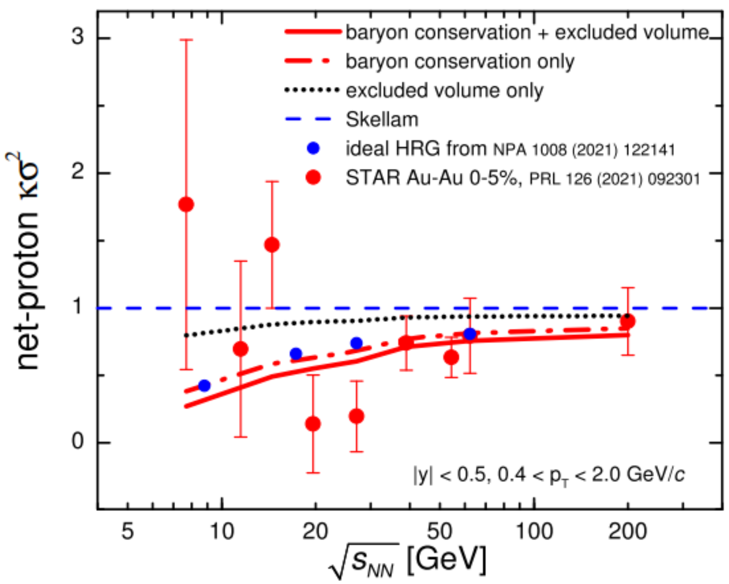
*Explicit expressions for any cumulant available via a Mathematica notebook at https://github.com/vlvovch/SAM

Net proton cumulant ratios

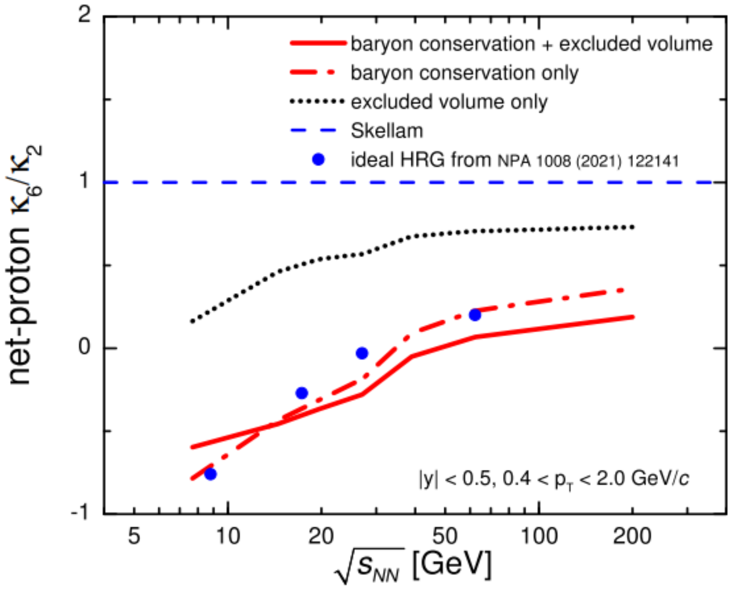
κ_3/κ_1



κ_4/κ_2



κ_6/κ_2



- Both the baryon conservation and repulsion needed to describe data at $\sqrt{s_{NN}} \geq 20$ GeV quantitatively
- Effect from baryon conservation is larger than from repulsion
- Canonical ideal HRG limit is consistent with the data-driven study of [Braun-Munzinger et al., NPA 1008 (2021) 122141]
- κ_6/κ_2 turns negative at $\sqrt{s_{NN}} \sim 50$ GeV

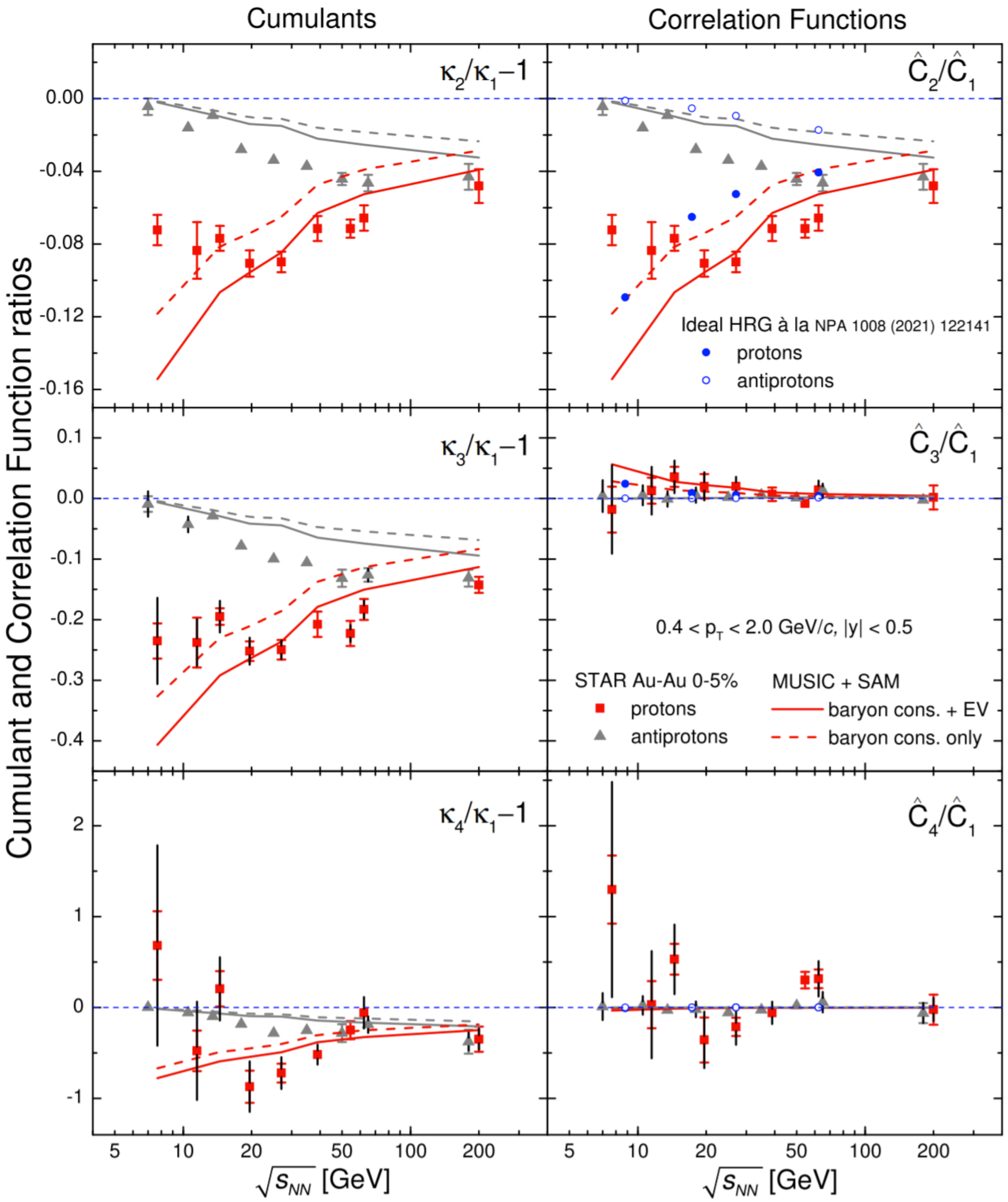
Cumulants vs Correlation Functions

- Analyze genuine multi-particle correlations via **factorial cumulants** [Bzdak, Koch, Strodthoff, PRC '17]

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

$\hat{C}_n^{\text{cons}} \propto \alpha^n$, [Bzdak, Koch, Skokov, EPJC '17] $\qquad \hat{C}_n^{\text{EV}} \propto b^n$ [VV et al, PLB '17]

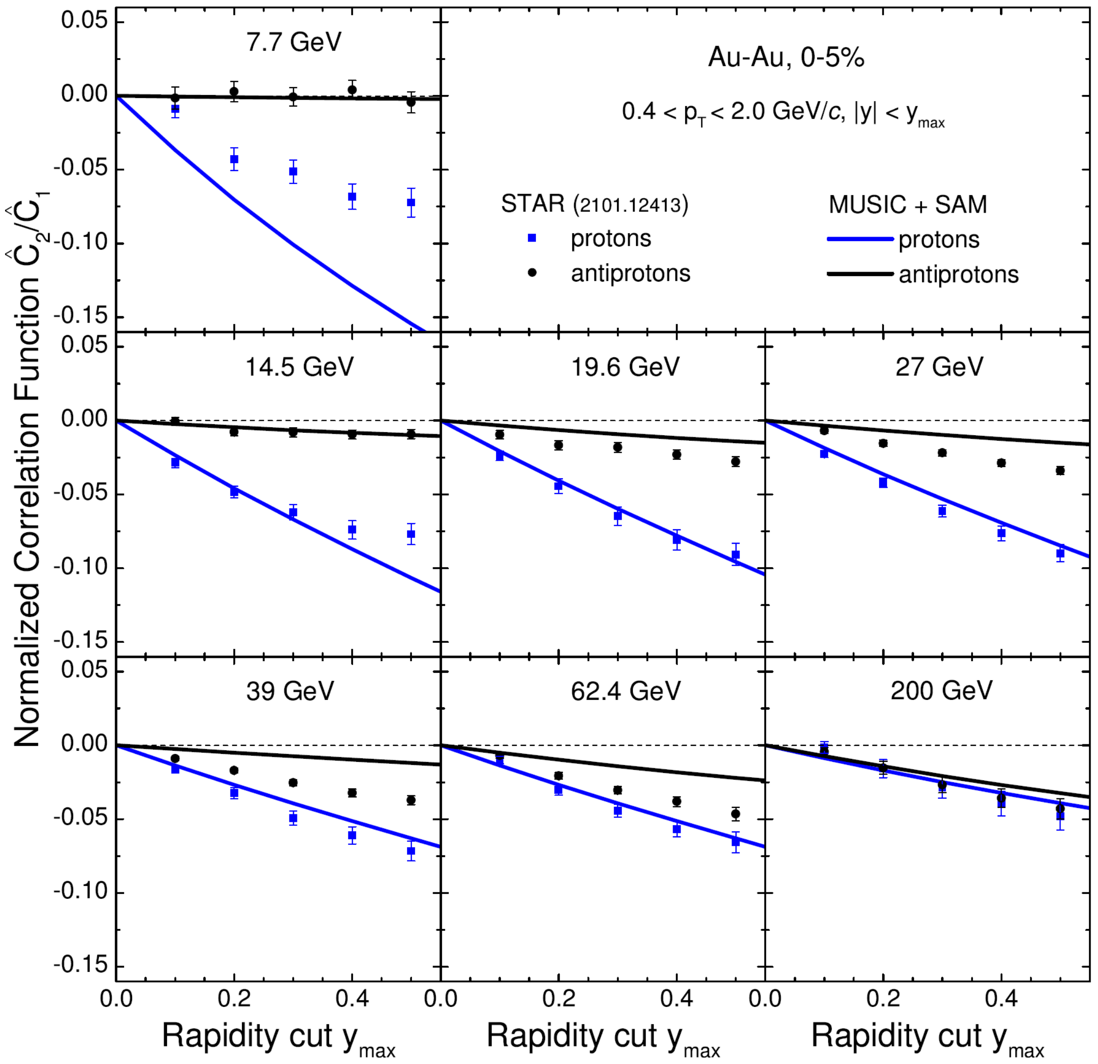
- Three- and four-particle correlations are small
  - Small positive $\hat{C}_3/\hat{C}_1$ in the data is explained by baryon conservation + excluded volume
  - Strong multi-particle correlations would be expected near the critical point [Ling, Stephanov, 1512.09125]
- Two-particle correlations are negative
  - Protons at $\sqrt{s_{NN}} \leq 14.5$ GeV overestimated
  - Antiprotons at $19.6 \leq \sqrt{s_{NN}} \leq 62.4$ GeV underestimated



*We use the notation for (factorial) cumulants from Bzdak et al., Phys. Rept. '20

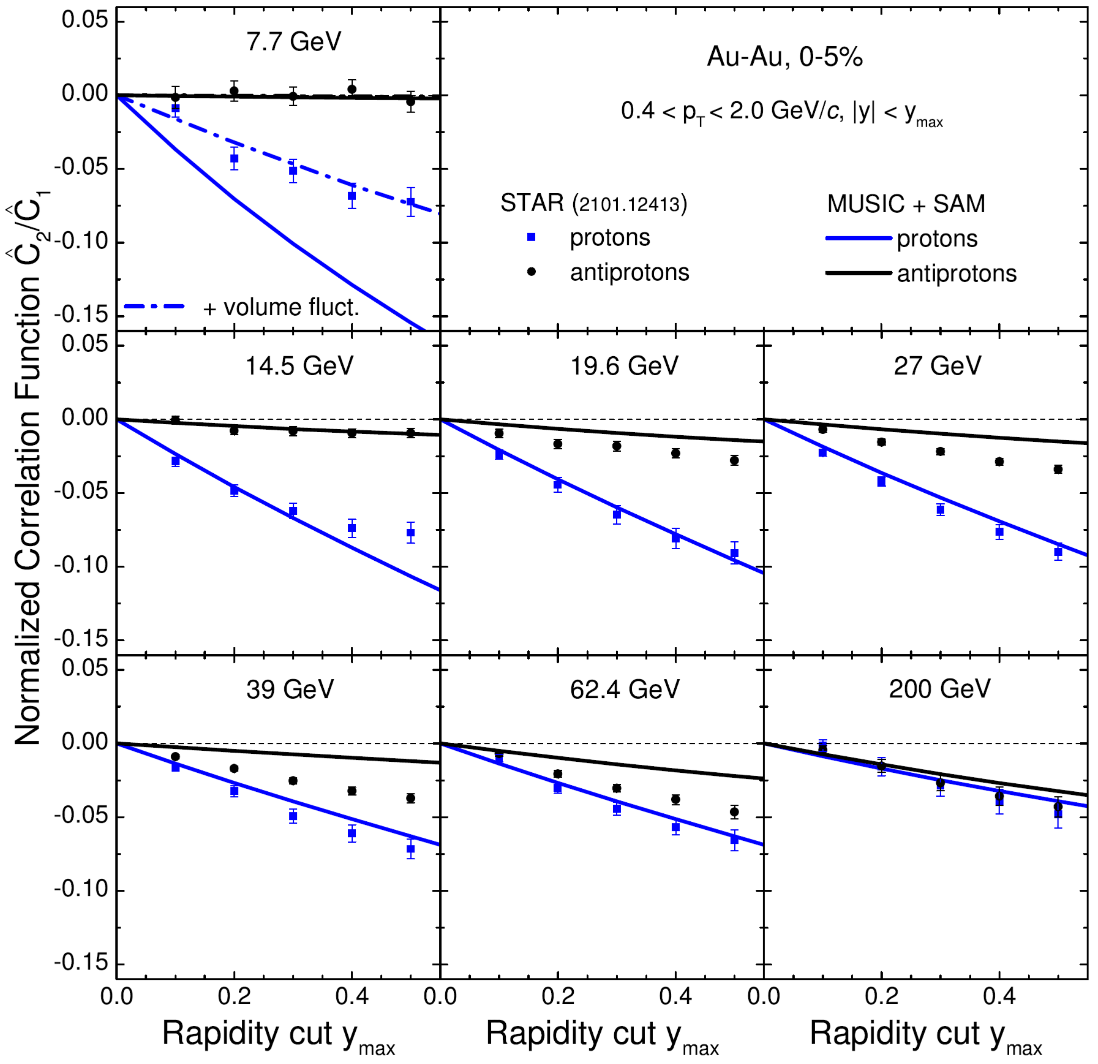
Acceptance dependence of two-particle correlations

- Changing y_{max} slope at $\sqrt{s_{NN}} \leq 14.5$ GeV?



Acceptance dependence of two-particle correlations

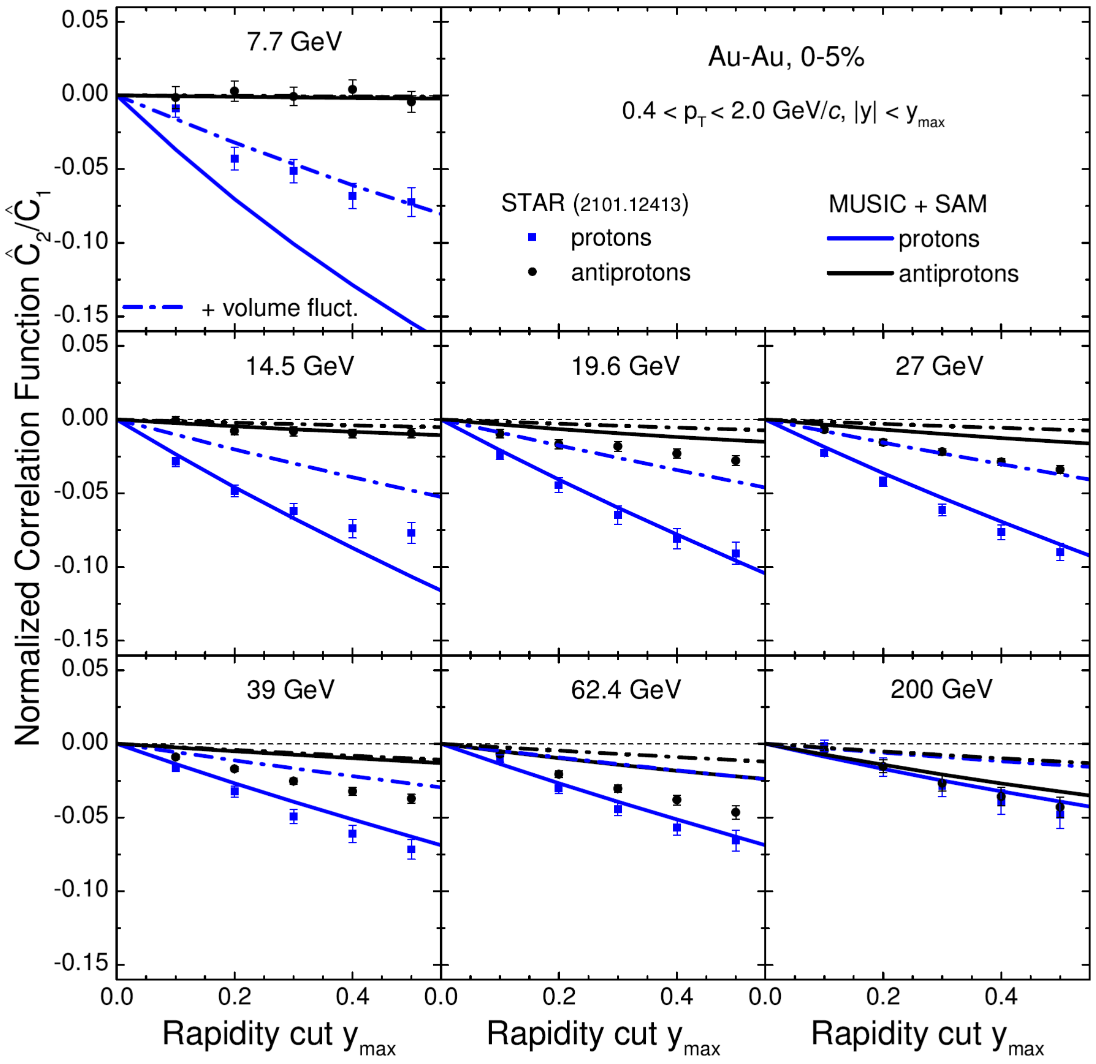
- Changing y_{max} slope at $\sqrt{s_{NN}} \leq 14.5$ GeV?
- **Volume fluctuations?** [Skokov, Friman, Redlich, PRC '13]
    - $C_2/C_1 \mathrel{+}= C_1 * v_2$



Acceptance dependence of two-particle correlations

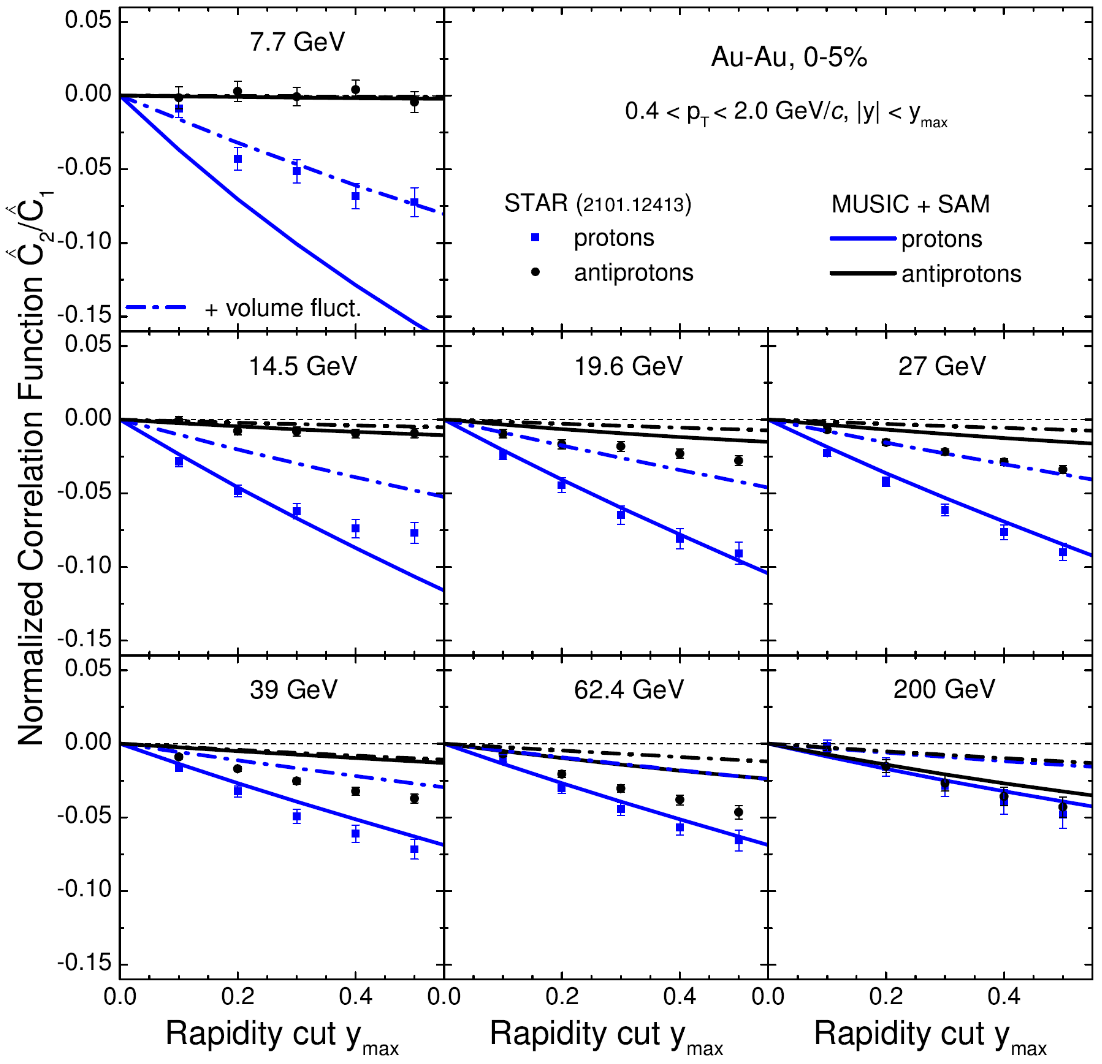
- Changing y_{max} slope at $\sqrt{s_{NN}} \leq 14.5$ GeV?

- **Volume fluctuations?** [Skokov, Friman, Redlich, PRC '13]
  - $C_2/C_1 \mathrel{+}= C_1 * v_2$
  - Can improve low energies but spoil high energies?



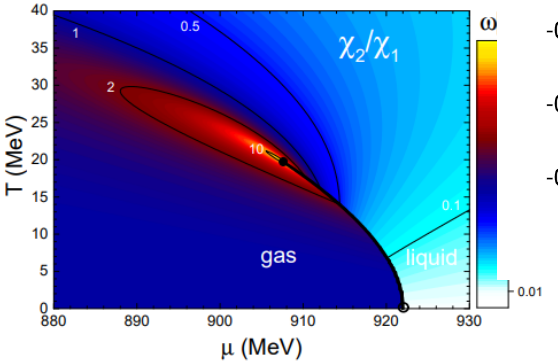
Acceptance dependence of two-particle correlations

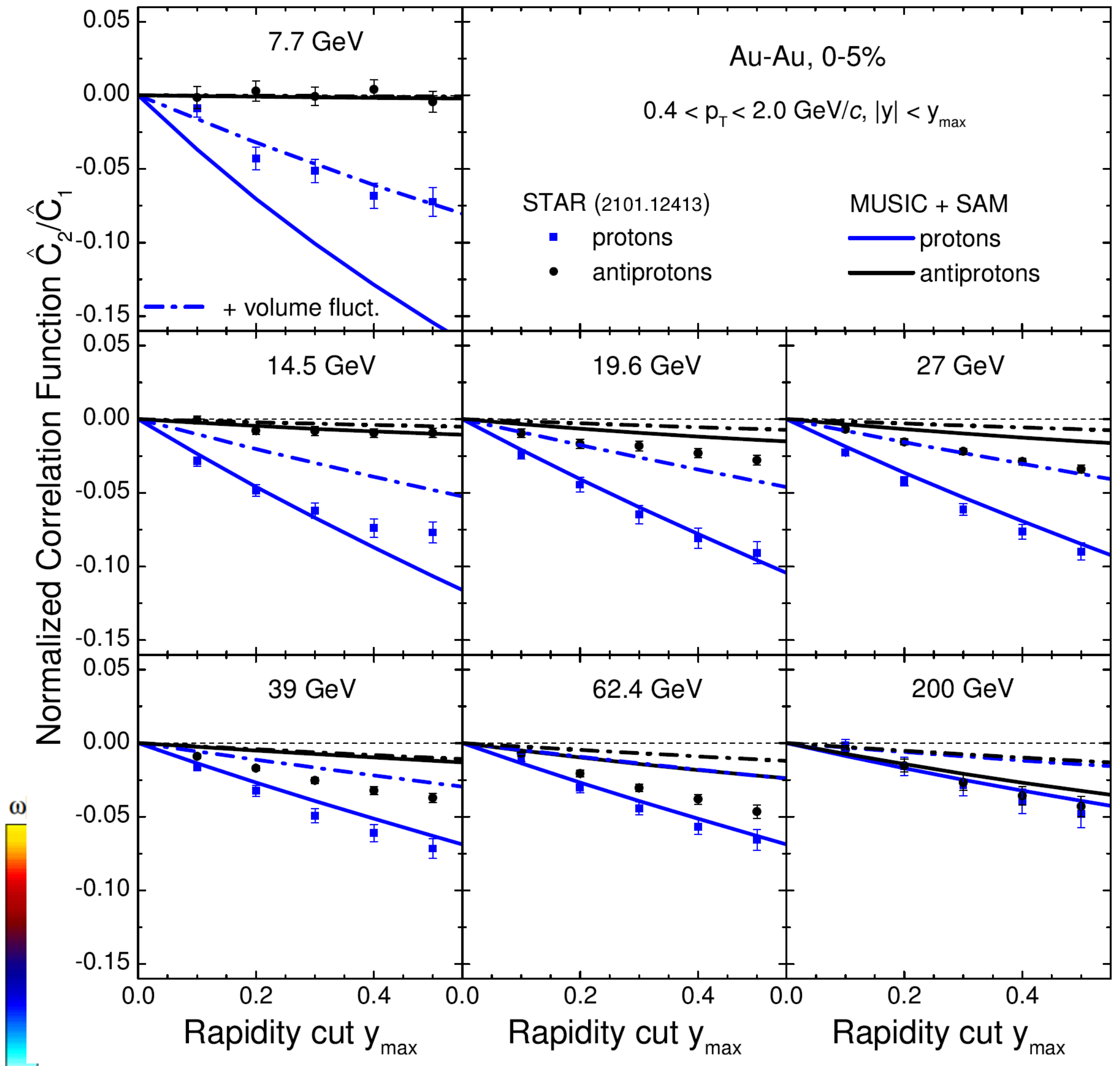
- Changing y_{max} slope at $\sqrt{s_{NN}} \leq 14.5$ GeV?
- Volume fluctuations? [Skokov, Friman, Redlich, PRC '13]
  - $C_2/C_1 \mathrel{+}= C_1 * v_2$
  - Can improve low energies but spoil high energies?
- **Exact electric charge conservation?**
  - Worsens the agreement at $\sqrt{s_{NN}} \leq 14.5$, higher energies virtually unaffected



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?**

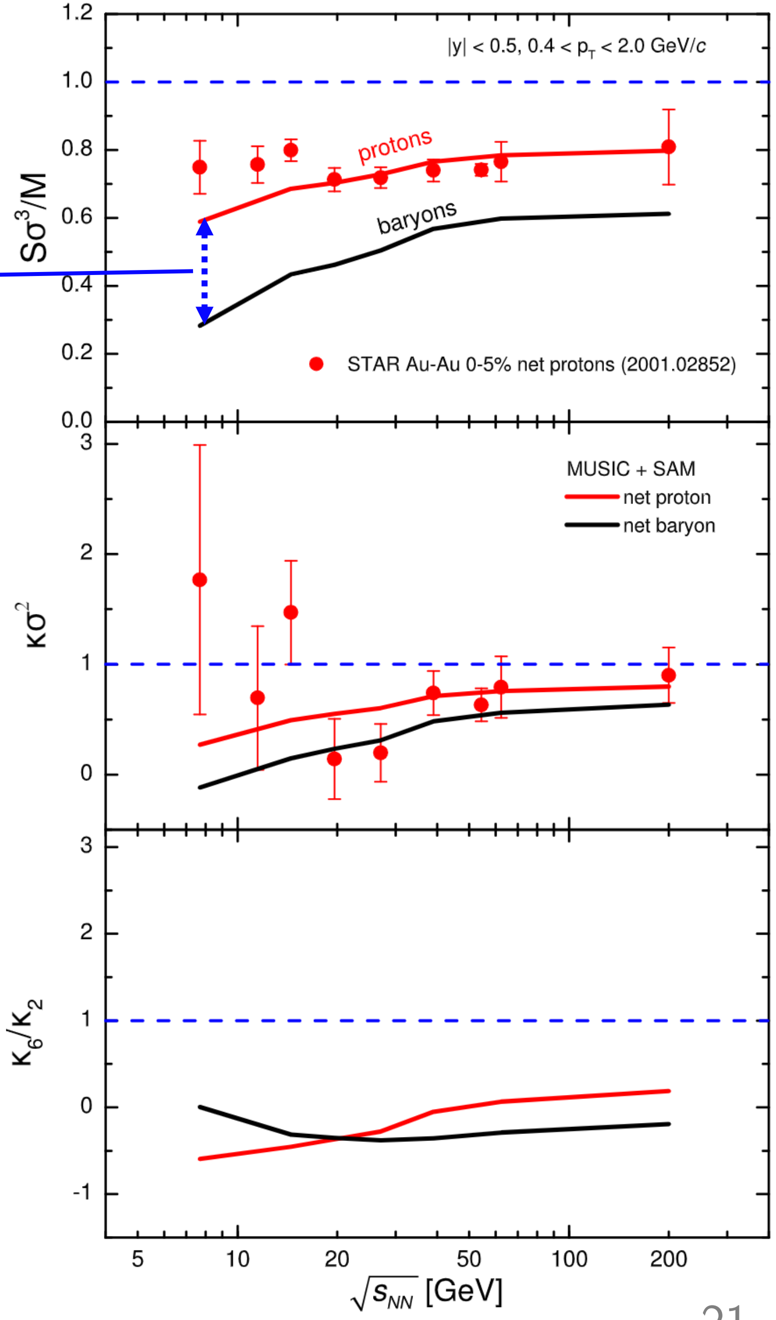


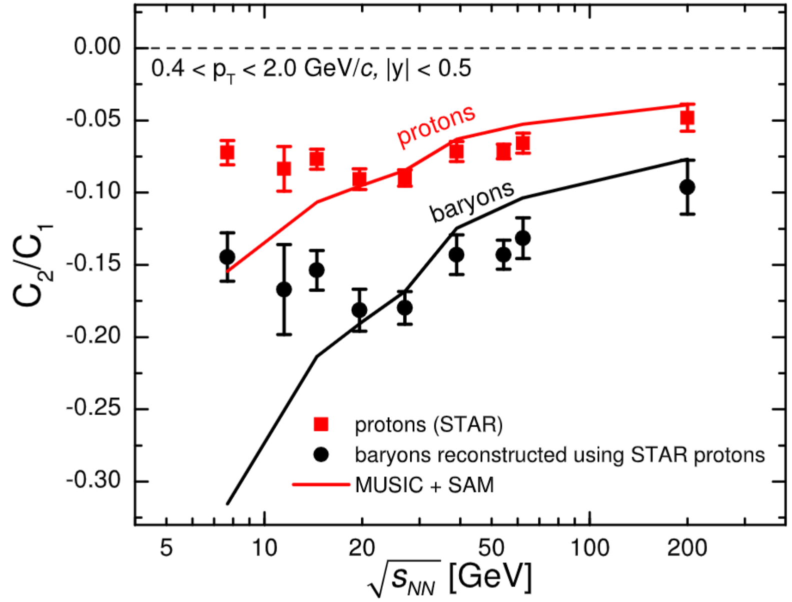


Outlook: baryon cumulants from protons

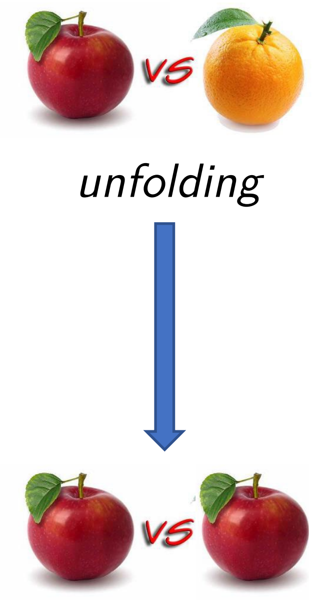
- **net baryon $\neq$ net proton**

- Baryon cumulants can be reconstructed from proton cumulants via binomial (un)folding based on isospin randomization [Kitazawa, Asakawa, Phys. Rev. C 85 (2012) 021901]
  - Amounts to an additional "efficiency correction" and requires the use of joint factorial moments, only experiment can do it model-independently





$$\boxed{\frac{\hat{C}_2^B}{\hat{C}_1^B} \approx 2\,\frac{\hat{C}_2^p}{\hat{C}_1^p}}$$



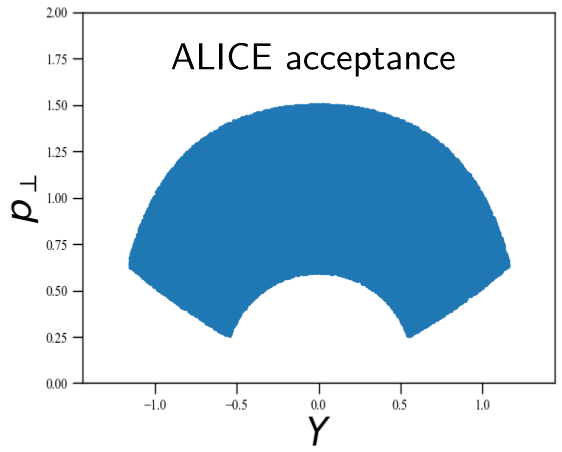
Net-particle fluctuations at the LHC

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

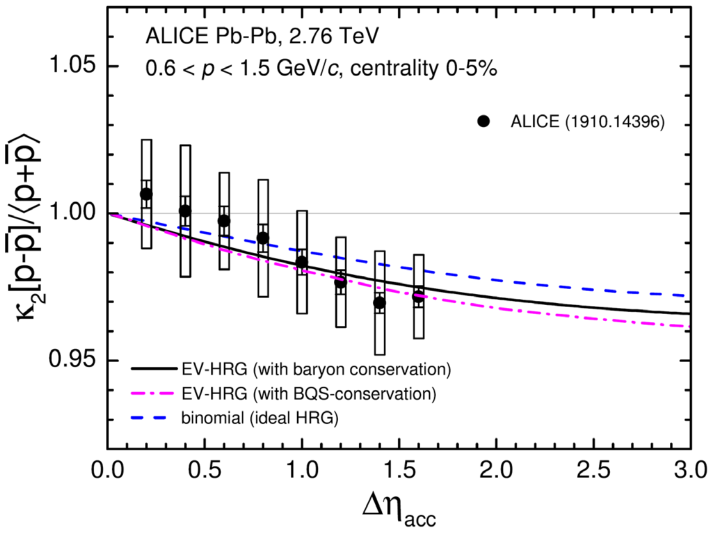
- Net protons described within errors but not sensitive to the equation of state for the present experimental acceptance

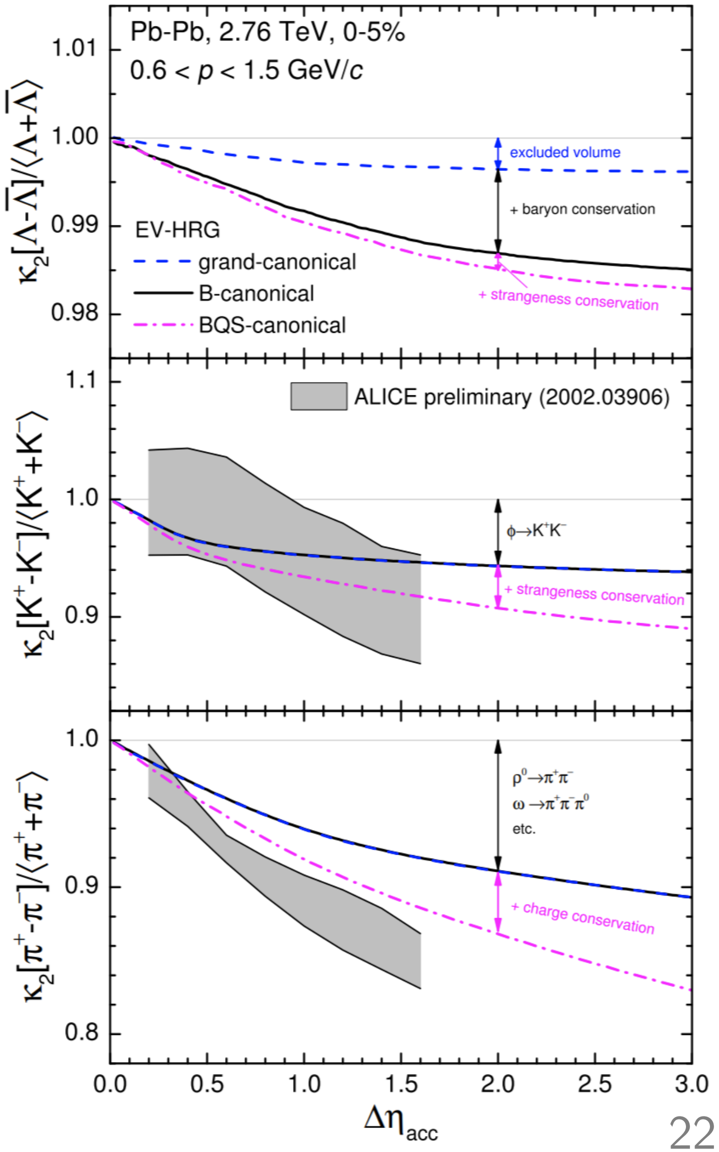
- Large effect from resonance decays for lighter particles + conservation of electric charge/strangeness

- Future measurements will require larger acceptance



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



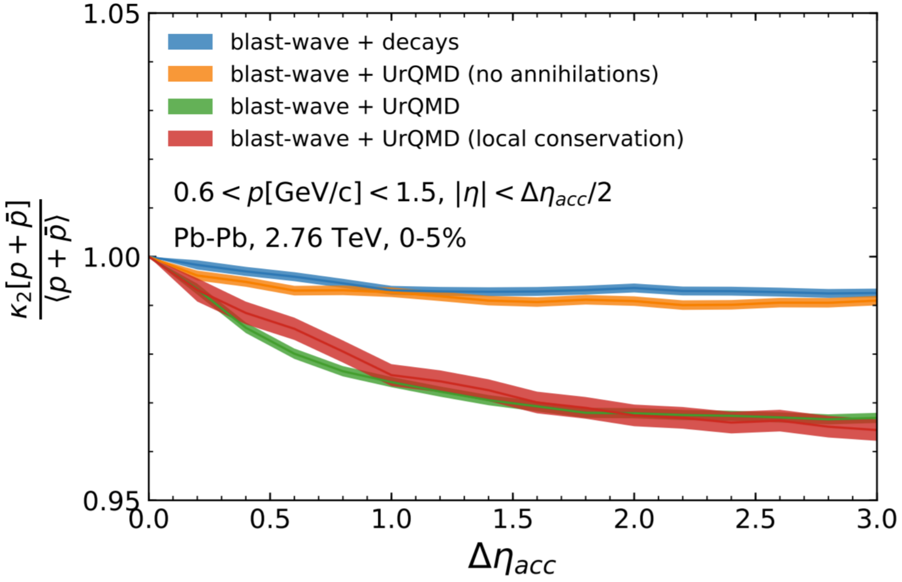


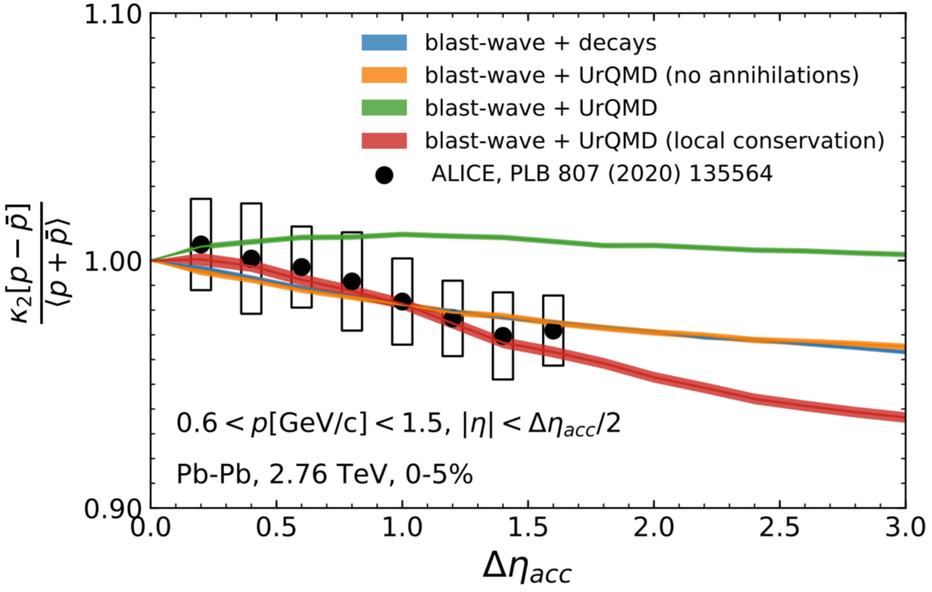
Effects of baryon annihilation and local conservation

O. Savchuk, V.V., V. Koch, J. Steinheimer, H. Stoecker, arXiv:2106.08239

Baryon annihilation $B\bar{B} \to n\pi$ in afterburners (UrQMD, SMASH) suppresses baryon yields

$\langle p + \bar{p} \rangle \searrow$ $\longrightarrow$ $\dfrac{\kappa_2[p - \bar{p}]}{\langle p + \bar{p} \rangle} \nearrow$

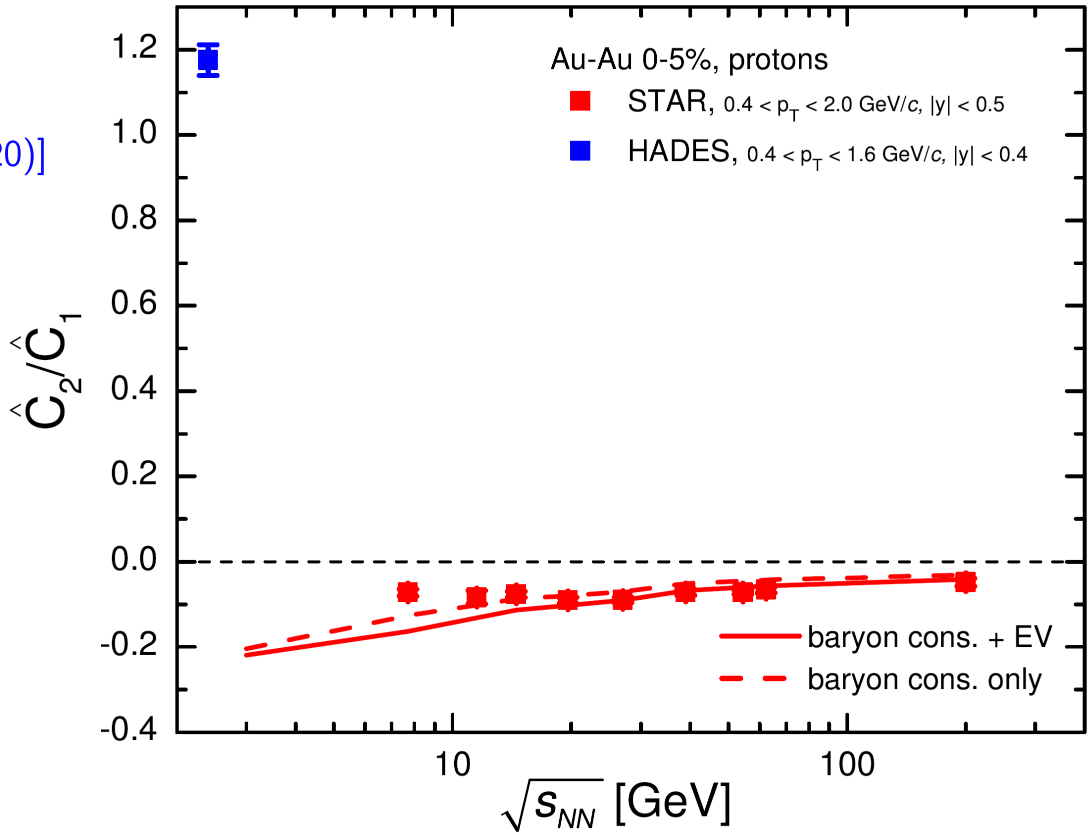




- ALICE data requires local baryon conservation across $\Delta y \sim \pm 1.5$ with UrQMD annihilations (no regenerations) or global conservation ($\Delta y \sim \Delta y_{tot}$) without annihilations
- Local conservation and $B\bar{B}$ annihilation can be constrained from data through the combined analysis of $\kappa_2[p - \bar{p}]$ and $\kappa_2[p + \bar{p}]$

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

- Intriguing hint from HADES @ $\sqrt{s_{NN}} = 2.4$ GeV: huge two-particle correlations!
  [HADES Collaboration, PRC 102, 024914 (2020)]
- Extend the calculations down to $\sqrt{s_{NN}} = 3$ GeV by means of the blast-wave model
- No change of trend in the non-critical baseline
- Other important effects to consider
  - Light nuclei formation
  - Nuclear liquid-gas transition



Data from STAR-FXT eagerly awaited!

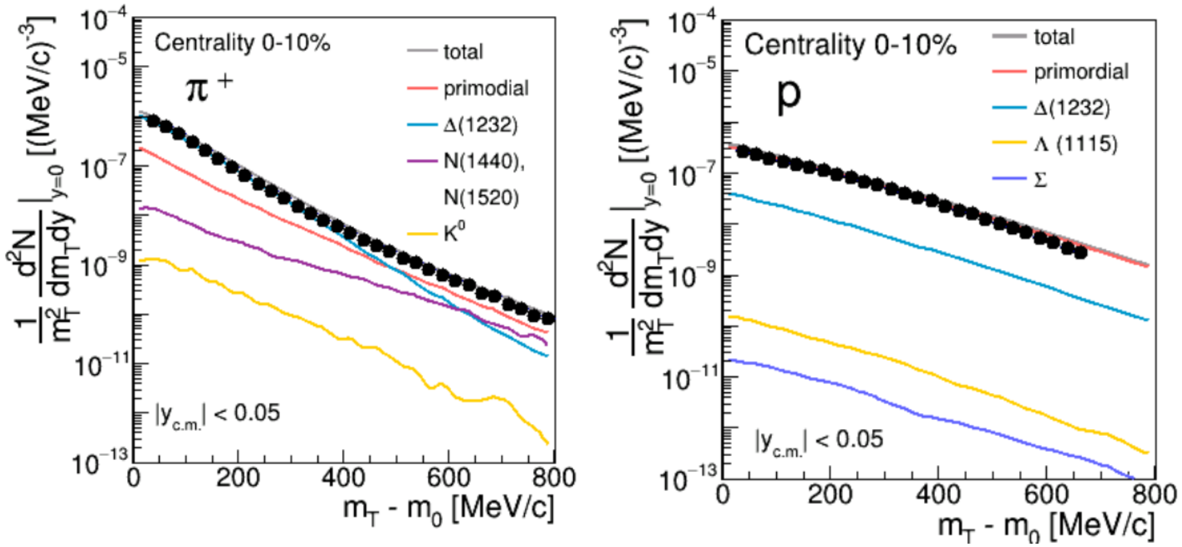
Thermodynamic analysis of HADES data

VV, Koch, in preparation

- 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

Extract χ_n^B directly from experimental data

Thermodynamic analysis of HADES data

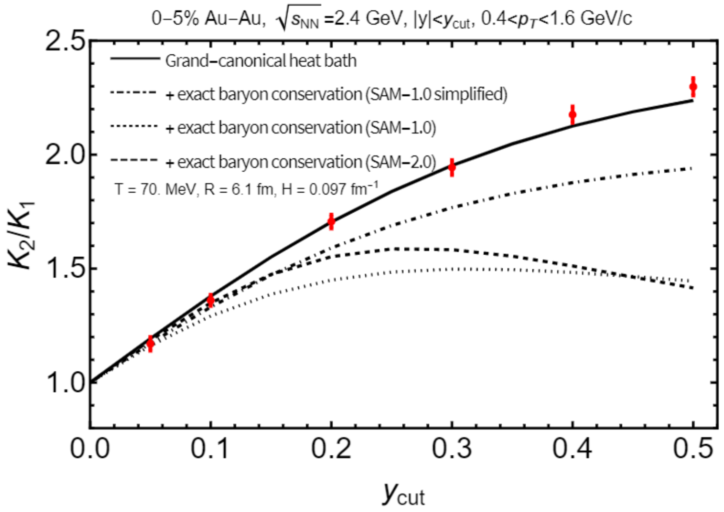
VV, Koch, in preparation

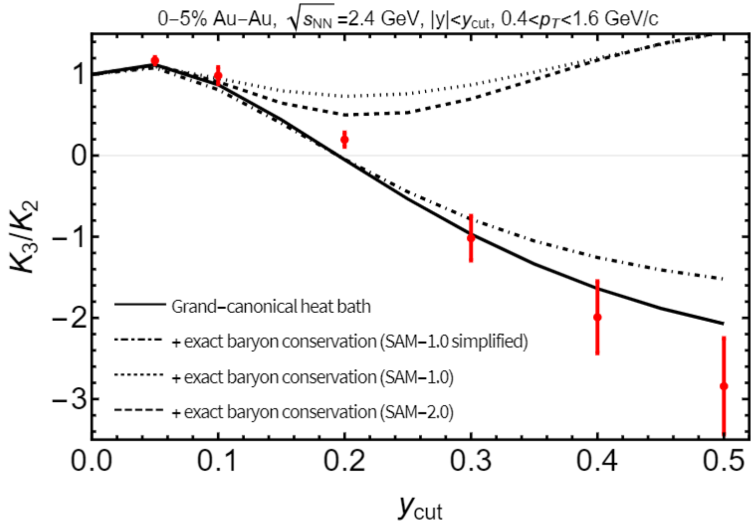
- In the grand-canonical limit (no baryon conservation) the data are described well with

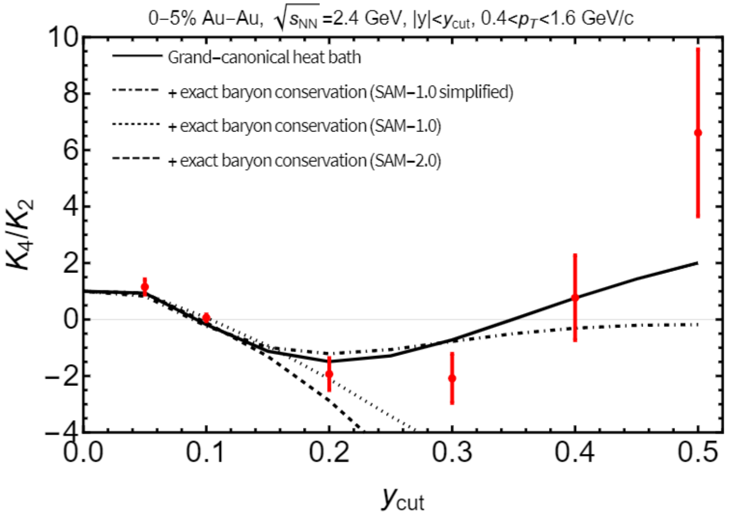
$$\frac{\chi_2^B}{\chi_1^B} = 9.35 \pm 0.40, \qquad \frac{\chi_3^B}{\chi_2^B} = -39.6 \pm 7.2, \qquad \frac{\chi_4^B}{\chi_2^B} = 1130 \pm 488$$

- Could be indicative of a critical point near the HADES freeze-out at $T \approx 70$ MeV, $\mu_B \approx 875$ MeV

- However, the results are challenging to describe with baryon conservation included

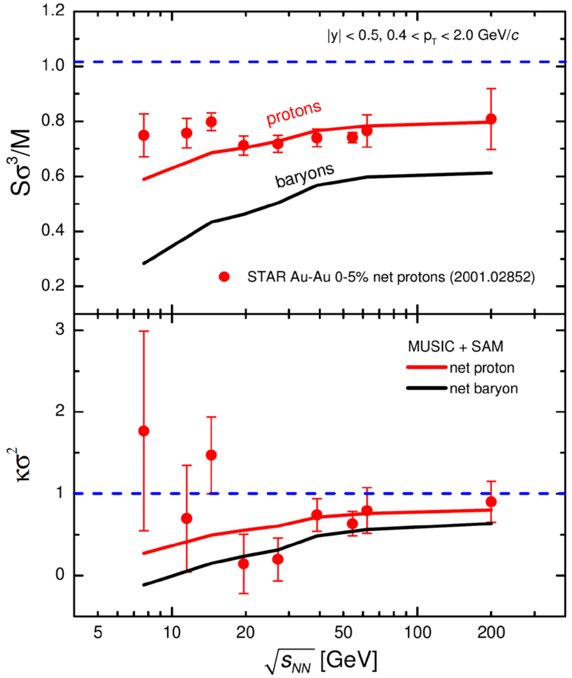


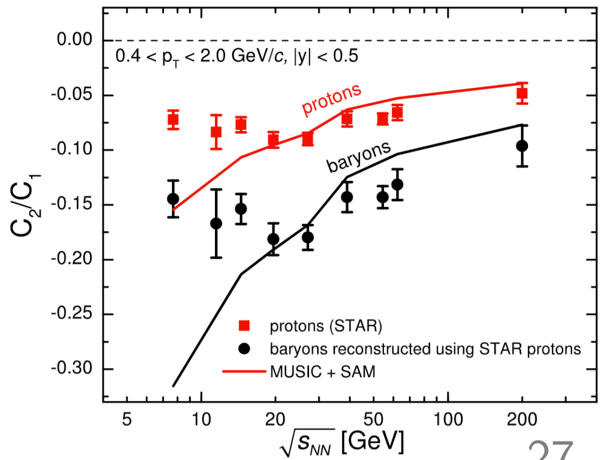




Summary

- Fluctuations are a powerful tool to explore the QCD phase diagram
  - test of lattice QCD and equilibration, probe the QCD critical point
- Quantitative analysis of central collisions at $\sqrt{s_{NN}}$=2.4-2760 GeV
  - Protons are described quantitatively at $\sqrt{s_{NN}} \geq 20$ GeV without critical point
  - Possible evidence for attractive proton interactions at $\sqrt{s_{NN}} \leq 14.5$ GeV
  - Significant quantitative difference between protons and baryons
- Factorial cumulants carry rich information
  - Small three- and four-particle correlations in absence of critical point effects
- HADES data point to potentially huge (multi-)proton correlations but at odds with baryon conservation





Thanks for your attention!