SQM 2026

Contribution of critical fluctuations and baryon annihilation to proton number cumulants at $\sqrt{s_{\rm NN}} = 7.7-200$ GeV from hydrodynamics

Gregoire Pihan

Collaborators:
V. Vovchenko, J. Parra
R. Poberezhniuk, V.A. Kuznietsov,
M. Kahangirwe, H. Shah, C. Ratti

UNIVERSITY OF HOUSTON

U.S. DEPARTMENT OF ENERGY | Office of Science

The QCD phase diagram

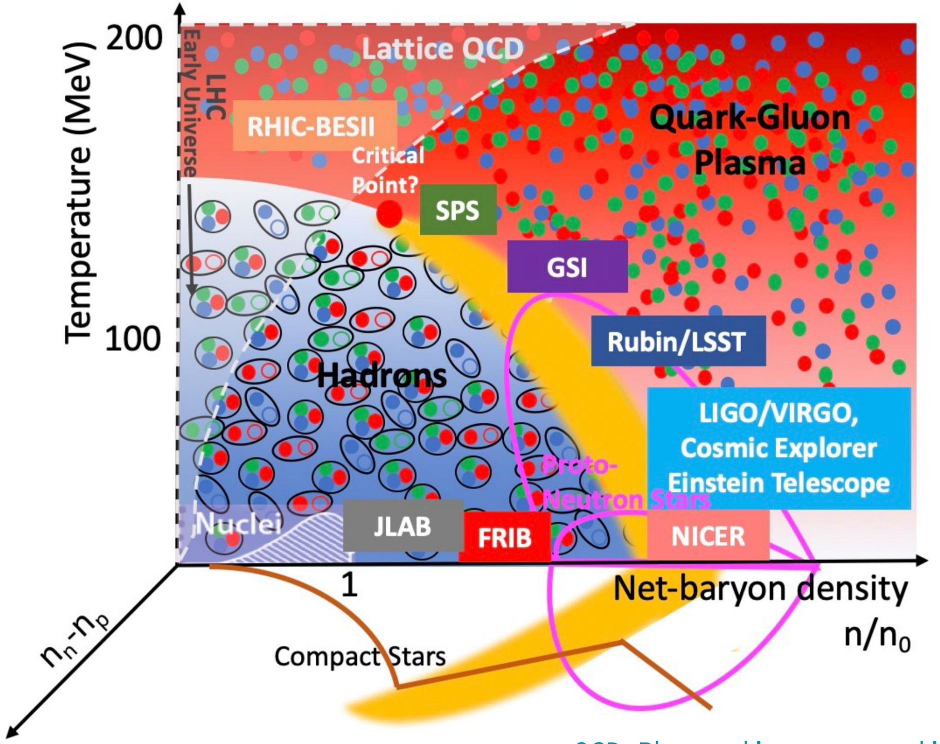
Different phase of nuclear matter

- ➢ Dilute hadron gas low T , μ_B
- ➢ Quark-gluon plasma high T, μ_B

Different type of transition?

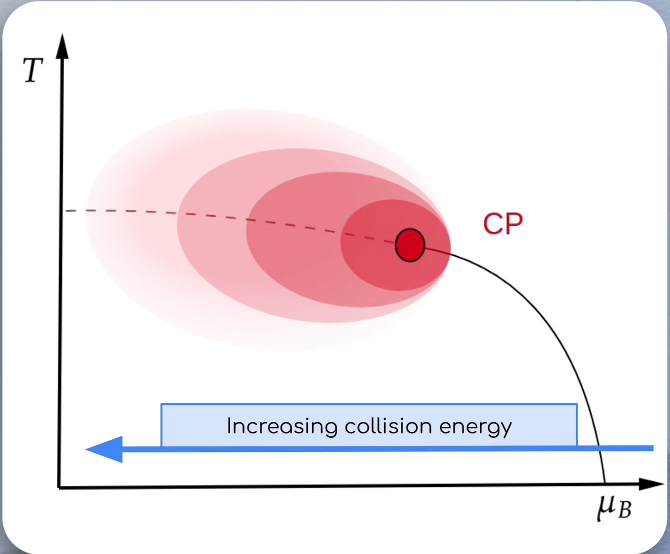
- ➢ Lattice: Crossover at muB = 0 GeV
  [Y. Aoki et al., Nature 443, 675]
- ➢ Effective QCD: 1st order?

Is there a critical point in the QCD phase diagram?



QCD Phase diagram credit

In the critical point region the fluctuations are largely enhanced

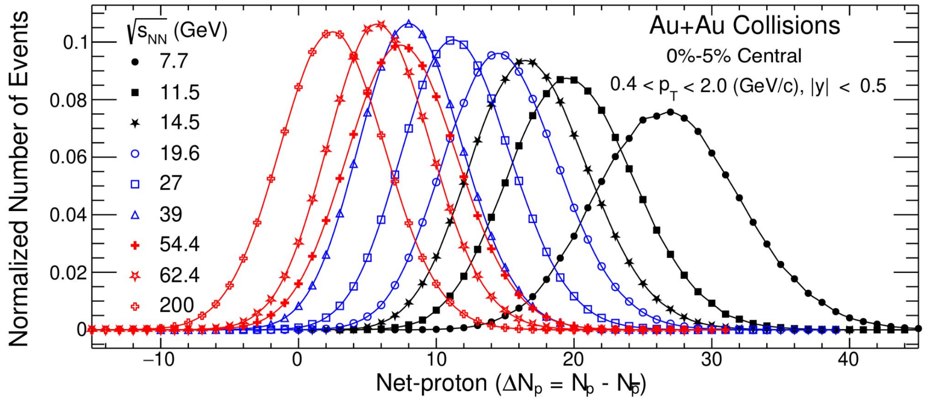


Higher order moments of the net-proton number distribution

$$\langle(\delta N_p)^2\rangle \propto \xi^2 \qquad \langle(\delta N_p)^3\rangle \propto \xi^{4.5} \qquad \langle(\delta N_p)^4\rangle \propto \xi^7$$

[M.A. Stephanov, Phys. Rev. Lett. 102, 032301]

Net-proton distribution as a function of the collision energy in Au-Au collisions at STAR



[STAR Collaboration Phys. Rev. Lett. 126, 092301]

Multi stage challenges for fluctuations observables

Highly dynamical environment

Short lived

Finite size effects

V. Vovchenko, R. Poberezhnyuk et al Phys. Lett. B 811, 135868

Proxies observables

VV, Jiang, Gorenstein, Stoecker, PRC 98, 024910

Finite acceptance

O. Savchuk, R. V. Poberezhnyuk, V. Vovchenko and M. I. Gorenstein Phys. Rev. C 101, 024917

Coordinate / momentum space

Ling, Stephanov, PRC 93, 034915

Late stage interactions

Steinheimer, Vochenko, Aichelin, Bleicher, Stoecker, PLB 776, 32

Equilibrium?

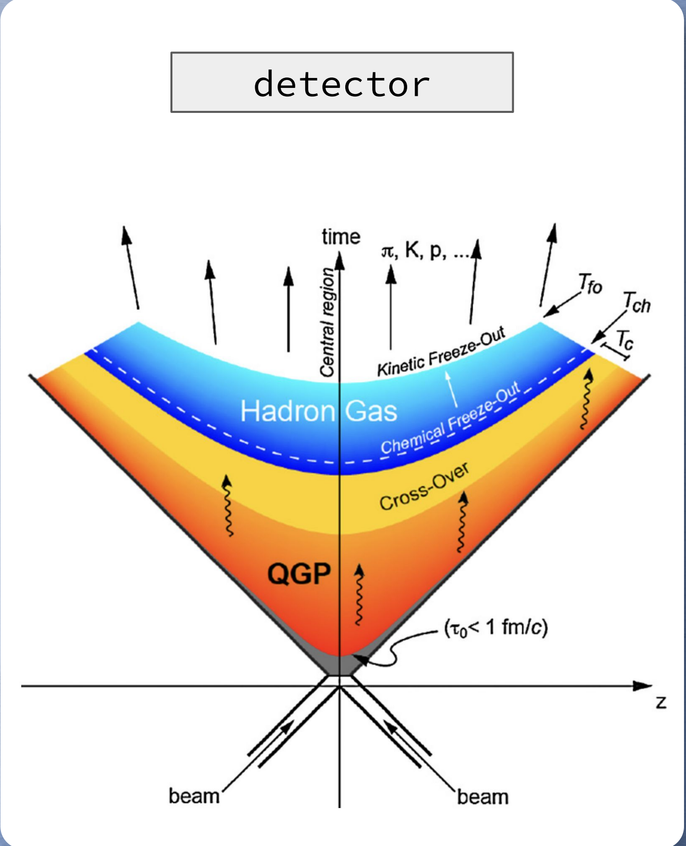
Retardation effects?

Grand Canonical Ensemble?

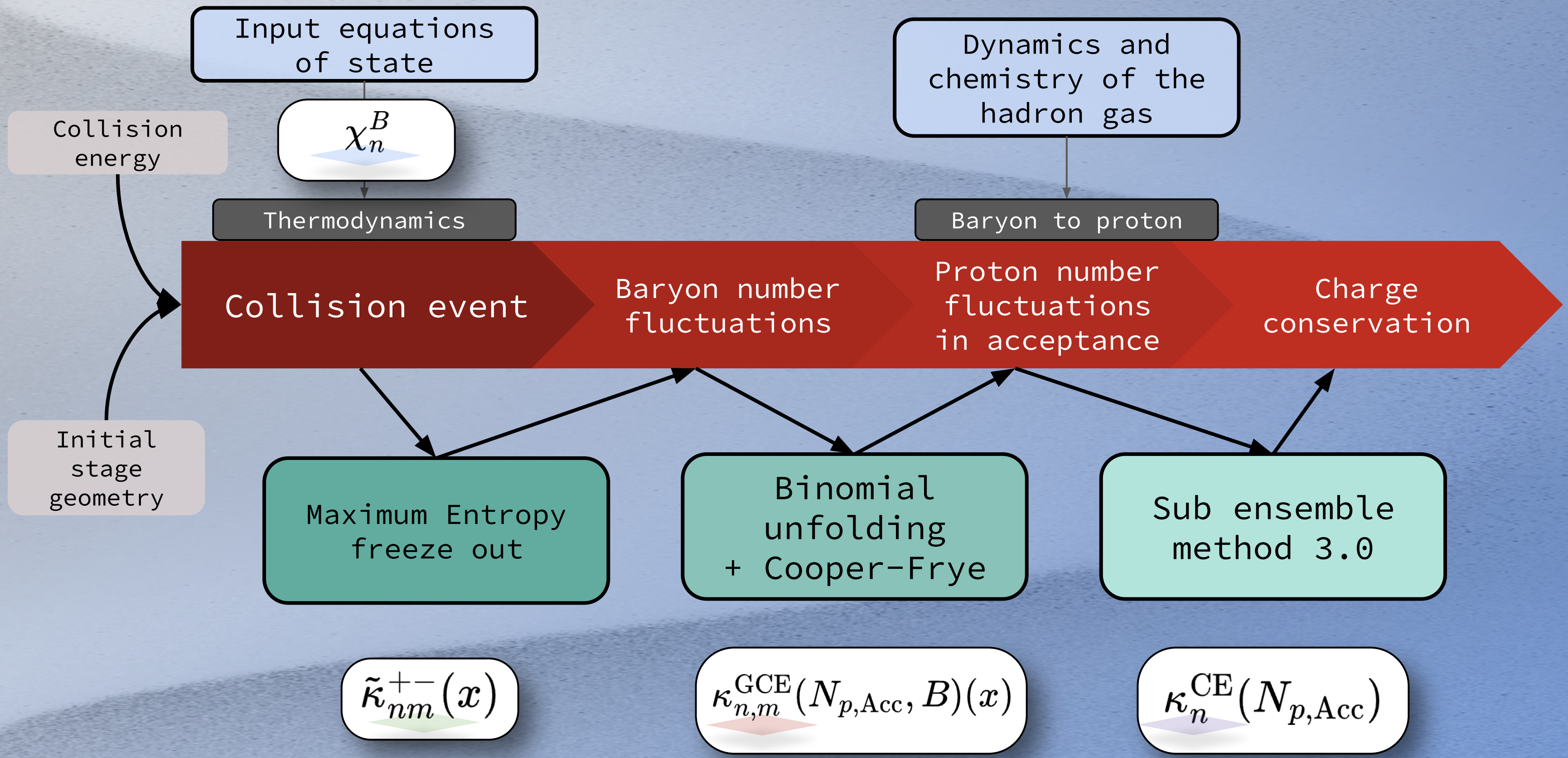
Baryon number ~ Proton number?

Thermal smearing?

Impact of hadron gas dynamics?



Roadmap from theory to experiment



Simulation of the collision event

Collision event | Baryon number fluctuations | Proton number fluctuations in acceptance | Charge conservation

Smooth collision event: iEBE-MUSIC

Transverse: Glauber model

$$\epsilon(x, y, \eta_s) \propto e(\eta_s) T_{\text{Proj}}(x, y) T_{\text{Targ}}(x, y)$$

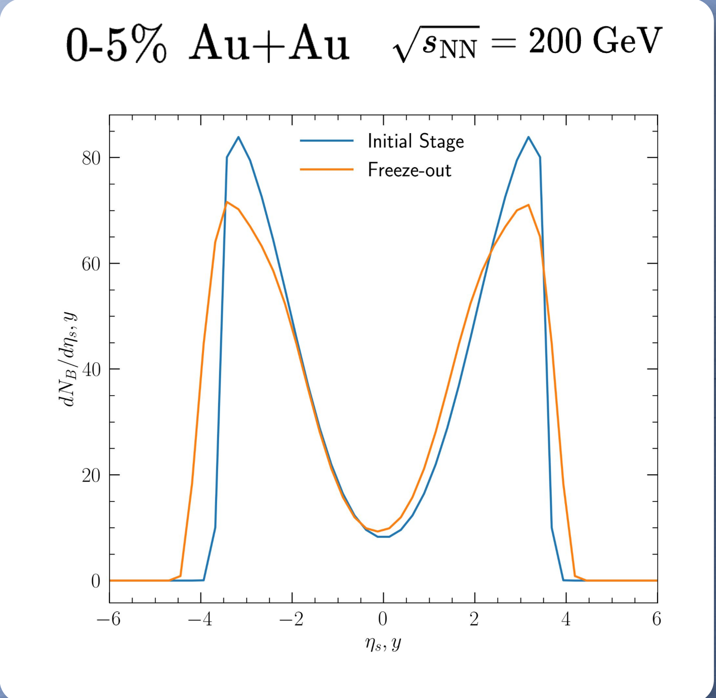
$$n_B(x, y, \eta_s) \propto f^{n_B}_{\text{Proj}}(\eta_s) T_{\text{Proj}}(x, y) + f^{n_B}_{\text{Targ}}(\eta_s) T_{\text{Targ}}(x, y)$$

Longitudinal: Density enveloppes

$$e(\eta_s, y_{CM}) \propto \exp\left[-\frac{(|\eta_s - y_{\text{CM}}| - \eta_0)^2}{2\sigma_\eta^2}\theta(|\eta_s - y_{\text{CM}}| - \eta_0)\right]$$

$$f^{n_B}_{\text{Proj}} \propto \theta(\eta_s - \eta_{B,0}) \exp[-\frac{(\eta_s - \eta_{B,0})^2}{2\sigma^2_{B,\text{out}}}] + \theta(\eta_s + \eta_{B,0}) \exp[-\frac{(\eta_s + \eta_{B,0})^2}{2\sigma^2_{B,\text{in}}}]$$

$$f^{n_B}_{\text{Targ}} \propto \theta(\eta_s + \eta_{B,0}) \exp[-\frac{(\eta_s + \eta_{B,0})^2}{2\sigma^2_{B,\text{in}}}] + \theta(-\eta_s - \eta_{B,0}) \exp[-\frac{(\eta_s + \eta_{B,0})^2}{2\sigma^2_{B,\text{out}}}]$$



Smooth collision event: iEBE-MUSIC

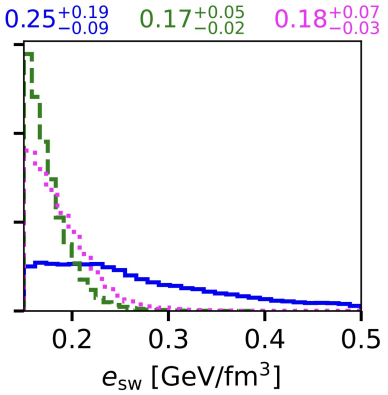
Freeze-out: constant energy density

Posteriors energy density for the BES energies

200 GeV

19.6 GeV

19.6 GeV



Jahan et al, Phys. Rev. C 113, 024919

Working Values

$$e_{\mathrm{sw}} = 0.18\ \mathrm{GeV/fm^3}$$

$$e_{\mathrm{sw}} = 0.25\ \mathrm{GeV/fm^3}$$

Net Baryon number fluctuations

Collision event | **Baryon number fluctuations** | Proton number fluctuations in acceptance | Charge conservation

NetB fluctuations on the hypersurface

Each hydro cell is in local equilibrium (GCE)

$$\kappa_n^{B,\mathrm{GCE}}(x) = \delta V(x) T(x)^3 \chi_n^B(x)$$

$\delta V = d\Sigma_\mu u^\mu \; (> 0)$ $x_i \equiv (\tau_i, x_i, y_i, \eta_i)$ $\chi_1^B(x) = n_B(x)$

Cells are statistically independent

$$\kappa_n^B = \sum_{i \in \mathrm{cells}} \delta\kappa_n^B$$

Ideal HRG

- Ideal Poisson/Skellam baseline
- Deviations?

4D TExS

- Lattice QCD expansion
- Strangeness neutrality (HIC)

Abuali, Jahan et al, Phys. Rev. D 112, 054502

2D TExS Ising

- Lattice QCD expansion
- Custom position of the CEP

Kahangirwe et al, Phys. Rev. D 109, 094046

Constant Entropy Contour (CEC)

- Lattice QCD expansion
- Prediction of CP from CEC

Shah et al, arXiv:2601.08823

Net Baryon number fluctuations

NetB fluctuations on the hypersurface

Each hydro cell is in local equilibrium (GCE)

$$\kappa_n^{B,\mathrm{GCE}}(x) = \delta V(x) T(x)^3 \chi_n^B(x)$$

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Cells are statistically independent

$$\kappa_n^B = \sum_{i \in \mathrm{cells}} \delta\kappa_n^B$$

Ideal HRG

- Ideal Poisson/Skellam baseline
- Deviations?

Any other equation of state adapted for heavy-ion collisions conditions (strangeness neutral) can be used too!

Constant Entropy Contour (CEC)

- Lattice QCD expansion
- Prediction of CP from CEC

Shah et al, arXiv:2601.08823

The maximum entropy freeze-out

The Max Ent method provides the least-biased reconstruction of particle multiplicity fluctuations consistent with the hydrodynamic correlations.

$$\hat{\Delta} G_{A_1 \ldots A_k} = \hat{\Delta} \mathcal{H}_{a_1 \ldots a_k} \prod_{i=1}^{k} P_{A_i}^{a_i}$$

$\hat{\Delta}$ Irreducible relative cumulants (IRC) operator

M.S. Pradeep, M.A. Stephanov Phys. Rev. Lett. 130, 162301

$\hat{\Delta} \mathcal{H}_{a_1 \ldots a_k}$ IRC of the K-points correlator of hydrodynamic fields $a_i = \epsilon, n_B$

$\hat{\Delta} G_{A_1 \ldots A_k}$ IRC of the K-points correlator of particles $A_i \in \mathrm{Particles}$

$P_{A_i}^{a_i}$

Hydro matching conditions projectors

The maximum entropy freeze-out

Assumptions

➢ B^+ B^- joint cumulants	$B^{\pm} = \left\{\hat{A}_i \ / \ q_{A_i} = \pm 1\right\}_{i \in \text{Particles}}$
➢ Boltzmann approximation	Particle IRCs = Particle factorial cumulants
➢ Cells are statistically independent	No correlation between cells
➢ Net-baryon density field only	$a_i = n_B \, \forall \, i$

Maximum Entropy B^+ B^- factorial cumulants

$$\tilde{\kappa}^{+-}_{nm}(x) = \tilde{\tilde{\kappa}}^{+-}_{nm}(x) + \hat{\Delta}\mathcal{H}_{n+m}(x)\left(P_+\right)^n\left(P_-\right)^m$$

The maximum entropy freeze-out

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- B^+ B^- joint cumulants — $B^\pm = \left\{\hat{A}_i \ / \ q_{A_i} = \pm 1\right\}_{i \in \text{Particles}}$
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Maximum Entropy B^+ B^- factorial cumulants

$$\tilde{\kappa}^{+-}_{nm}(x) = \boxed{\tilde{\tilde{\kappa}}^{+-}_{nm}(x)} + \hat{\Delta}\mathcal{H}_{n+m}(x)\left(P_+\right)^n\left(P_-\right)^m$$

The ideal-HRG factorial cumulants

$$\tilde{\tilde{\kappa}}^{+-}_{nm}(x) = \delta_{n,1}\delta_{m,0}\langle N_{B^+}\rangle(x) + \delta_{n,0}\delta_{m,1}\langle N_{B^-}\rangle(x)$$

Net Baryon to positive baryon fluctuations

The maximum entropy freeze-out

Collision event | Baryon number fluctuations | Proton number fluctuations in acceptance | Charge conservation

Assumptions

- $B^+ \ B^-$ joint cumulants — $B^{\pm} = \left\{\hat{A}_i \ / \ q_{A_i} = \pm 1\right\}_{i \in \text{Particles}}$
- Boltzmann approximation — Particle IRCs = Particle factorial cumulants
- Cells are statistically independent — No correlation between cells
- Net-baryon density field only — $a_i = n_B \, \forall \, i$

Maximum Entropy $B^+ \ B^-$ factorial cumulants

$$\tilde{\kappa}^{+-}_{nm}(x) = \tilde{\tilde{\kappa}}^{+-}_{nm}(x) + \hat{\Delta}\mathcal{H}_{n+m}(x)\left(P_+\right)^n\left(P_-\right)^m$$

The hydrodynamics correlators IRCs

$$\hat{\Delta}\mathcal{H}_{n+m}(x) = \delta V(x) T(x)^3 \bar{\chi}^B_{n+m} F_{nm}(\chi^B_2, \chi^B_3, \chi^B_4)$$

The maximum entropy freeze-out

Assumptions

➢ $B^+ \; B^-$ joint cumulants	$B^\pm = \left\{\hat{A}_i \;/\; q_{A_i} = \pm 1\right\}_{i\in\text{Particles}}$
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Maximum Entropy $B^+ \; B^-$ factorial cumulants

$$\tilde{\kappa}^{+-}_{nm}(x) = \tilde{\tilde{\kappa}}^{+-}_{nm}(x) + \hat{\Delta}\mathcal{H}_{n+m}(x)\left(P_+\right)^n\left(P_-\right)^m$$

<u>The hydrodynamic matching condition projectors</u>

$$P_\pm(x) = \pm\frac{\langle\delta N^\pm\rangle^{\text{HRG}}}{\langle\delta N^+\rangle^{\text{HRG}}+\langle\delta N^-\rangle^{\text{HRG}}}$$

The maximum entropy freeze-out

Assumptions

- B^+ B^- joint cumulants — $B^{\pm} = \left\{\hat{A}_i \ / \ q_{A_i} = \pm 1\right\}_{i \in \text{Particles}}$
- Boltzmann approximation — Particle IRCs = Particle factorial cumulants
- Cells are statistically independent — No correlation between cells
- Net-baryon density field only — $a_i = n_B \, \forall \, i$

Maximum Entropy B^+ B^- factorial cumulants and cumulants

$$\tilde{\kappa}^{+-}_{nm}(x) = \tilde{\tilde{\kappa}}^{+-}_{nm}(x) + \hat{\Delta}\mathcal{H}_{n+m}(x)\left(P_+\right)^n\left(P_-\right)^m$$

$$\tilde{\kappa}^{+-}_{nm}(x) \longrightarrow \kappa^{+-}_{nm}(x)$$

Positive Baryon to proton cumulants in the acceptance

Binomial protons in binomial acceptance

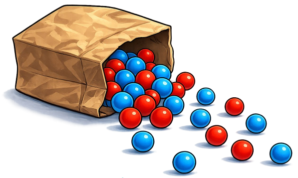
Baryon to proton

Isospin randomization

$$N + \pi \leftrightarrow \Delta$$

At equilibrium in the hadronic phase

$$P(N_p|N_B^{\pm}) = \text{Binomial}(N_N, q_{\pm})$$



$$q_{\pm}(x) = \frac{\bar{n}_p^{\text{FD}}}{\bar{n}_{B^{\pm}}}$$

M. Kitazawa, M. Asakawa Phys. Rev. C 86, 024904

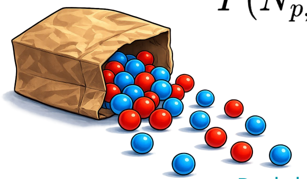
Protons to measured protons

Cooper-Frye ratio

Estimating the ratio of Acc/full

$$p(x_i) = \frac{\int_{\text{acc}} \frac{d^3p}{E_p} d\Sigma_\mu(x_i) p^\mu(x_i) f_p[u^\nu p_\nu, T(x_i), \mu_p(x_i)]}{\int \frac{d^3p}{E_p} d\Sigma_\mu(x_i) p^\mu(x_i) f_p[u^\nu p_\nu, T(x_i), \mu_p(x_i)]}$$

$$P(N_{p,\text{Acc}}|N_p) = \text{Binomial}(N_p, p)$$



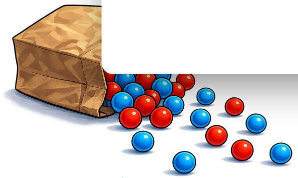
Bzdak, Koch, Phys. Rev. C 86, 044904

Binomial protons in binomial acceptance

Baryon to proton

Isospin randomization

At e



$n_{B^\pm}$

M. Kitazawa, M. Asakawa Phys. Rev. C 86, 024904

Protons to measured protons

Cooper-Frye ratio

$u_p(x_i)]$

$_p(x_i)]$

$N_p, p)$

Bzdak, Koch, Phys. Rev. C 86, 044904

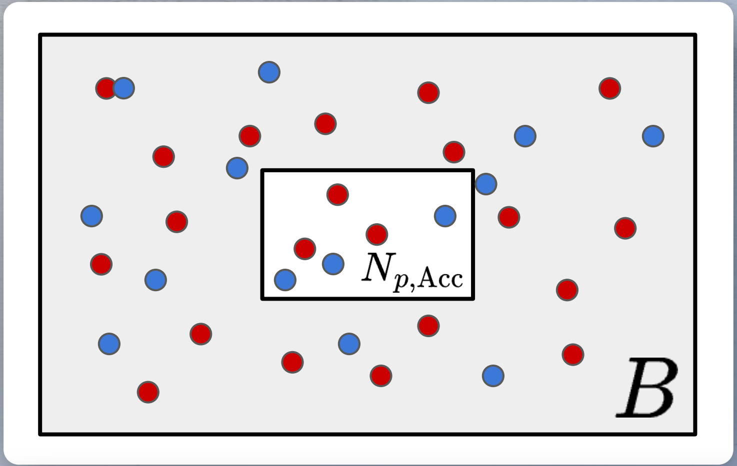
Total binomial distribution

$$\alpha_\pm(x) = q_\pm(x)p(x)$$

$$P(N_{p,\mathrm{Acc}} | N_B^\pm) = \mathrm{Binomial}(N_B^\pm, \alpha_\pm)$$

Positive Baryon to proton cumulants in the acceptance

Towards the global B conservation



$$G(t_+, t_-) = \ln \left\langle e^{\, t_+ B_+ + t_- B_-} \right\rangle$$

$$\widetilde{G}(t, t_B) = \ln \left\langle e^{\, t\, N_{p,\mathrm{Acc}} + t_B\, B} \right\rangle$$

$$B = B^+ - B^-$$

$$\widetilde{G}(t, t_B) = G\big(t_B + \theta(t, \alpha_+),\ -t_B\big)$$

GCE proton, total Baryon number joint cumulants

$$\kappa^{\mathrm{GCE}}_{n,m}(N_{p,\mathrm{Acc}}, B) = \sum_{k=1}^{n} B_{n,k}(c_1, c_2, \ldots, c_{n-k+1}) \sum_{q=0}^{m} \binom{m}{q} (-1)^{m-q}\, \kappa^{+-}_{k+q,\ m-q}$$

$B_{n,k}$ Partial bell polynomials

$c_k \equiv \partial_t^k\, \theta(t, \alpha_+)\big|_{t=0}$

$\theta(t, \alpha_+) \equiv \ln\big(1 - \alpha_+ + \alpha_+ e^t\big)$

Sub ensemble Acceptance Method (SAM 3.0)

Collision event → Baryon number fluctuations → Proton number fluctuations in acceptance → **Charge conservation**

Connecting CE and GCE cumulants

$$\kappa_n^{\mathrm{CE}}(N_{p,\mathrm{Acc}}) = \mathrm{SAM}\left[\kappa_{l,m}^{\mathrm{GCE}}(N_{p,\mathrm{Acc}}, B)\right]$$

R. Poberezhniuk, V. A. Kuznietsov, GP, V. Vochenko in prep

Two first orders

$$\kappa_1^{\mathrm{CE}}(N_{p,\mathrm{Acc}}) = \kappa_{1,0}^{\mathrm{GCE}}(N_{p,\mathrm{Acc}}, B)$$

$$\kappa_2^{\mathrm{CE}}(N_{p,\mathrm{Acc}}) = \kappa_{2,0}^{\mathrm{GCE}}(N_{p,\mathrm{Acc}}, B) - \frac{\kappa_{1,1}^{\mathrm{GCE}}(N_{p,\mathrm{Acc}}, B)^2}{\kappa_{0,2}^{\mathrm{GCE}}(N_{p,\mathrm{Acc}}, B)}$$

QCD Phase diagram setups

Acceptance probabilities and EoS

Proton acceptance probability

- ➢ Freeze-out = constant energy density
- ➢ Hydro cells contribution = distribution

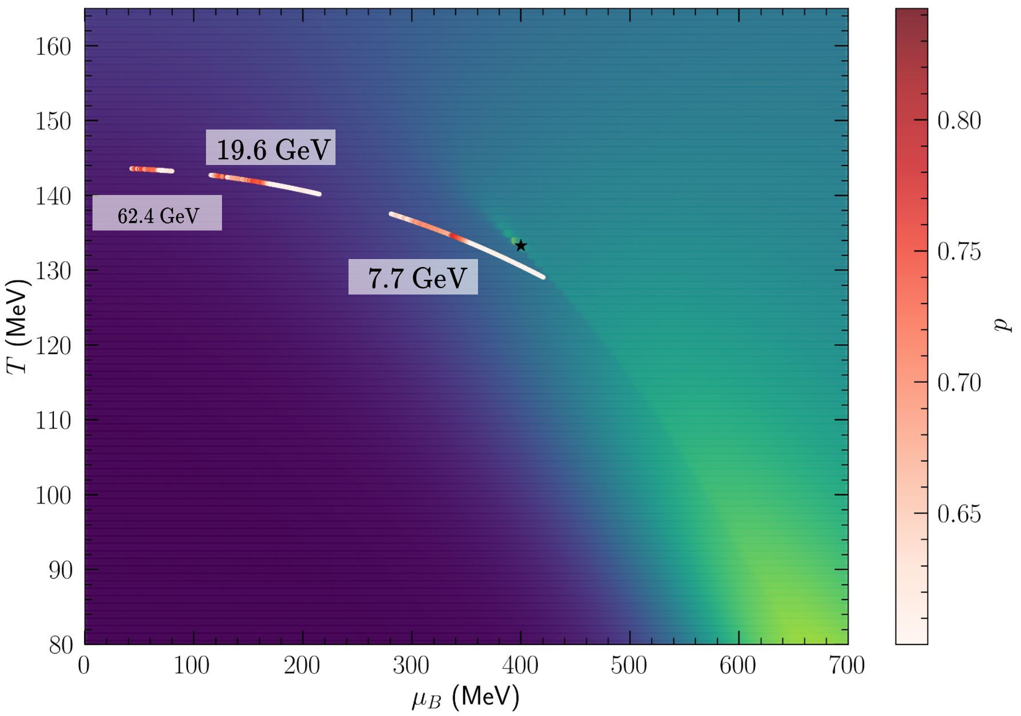
2D Ising T’ Expansion 400

3D Ising model mapped

Parameters:

$$T_c, \mu_c = 133.3, 400 \text{ MeV}$$

No strangeness neutrality



QCD Phase diagram setups

Acceptance probabilities and EoS

Proton acceptance probability

- ➢ Freeze-out = constant energy density
- ➢ Hydro cells contribution = distribution

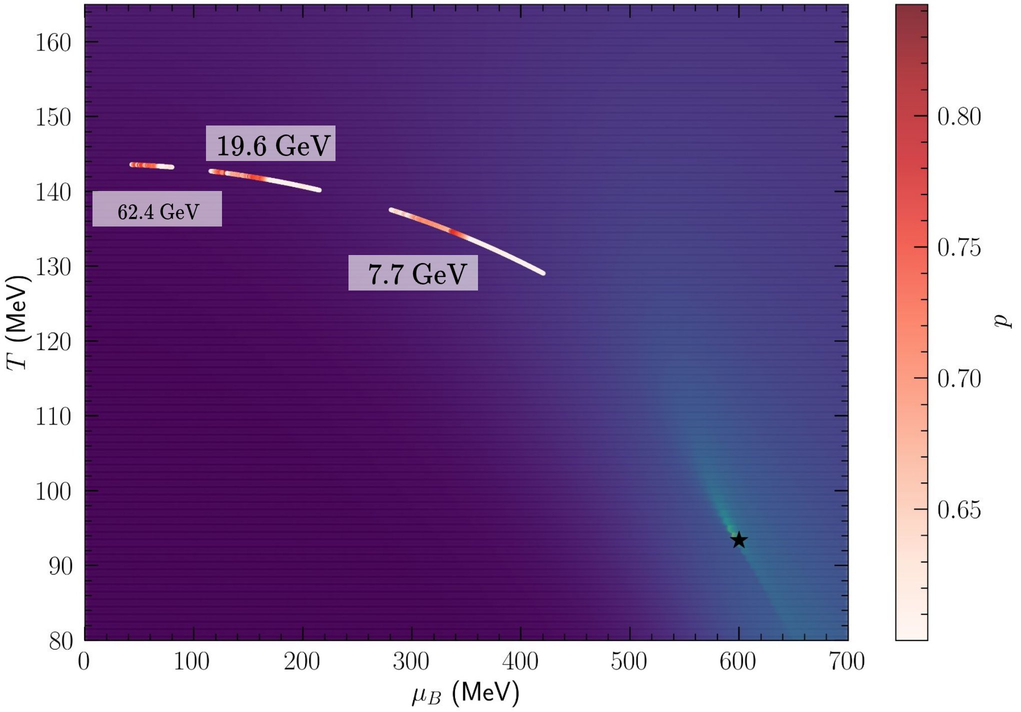
2D Ising T' Expansion 600

3D Ising model mapped

Parameters:

$$T_c, \mu_c = 93.4, 600 \text{ MeV}$$

No strangeness neutrality



QCD Phase diagram setups

Acceptance probabilities and EoS

Proton acceptance probability

- Freeze-out = constant energy density
- Hydro cells contribution = distribution

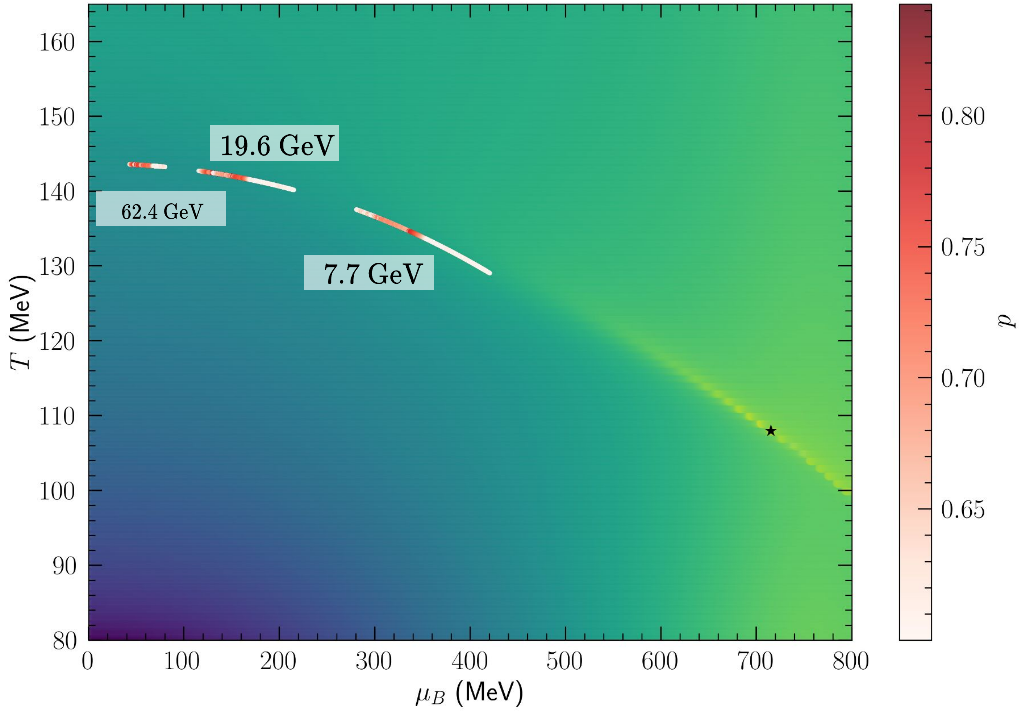
Constant Entropy contour

From lattice Taylor expansion

Parameters:

$$T_c, \mu_c = 108, 715 \text{ MeV}$$

Strangeness neutral



EoS comparison

EoS to data comparison

Close to experimental measurement

- ➢ Scale: Canonical correction
- ➢ Different EoS

Baseline?

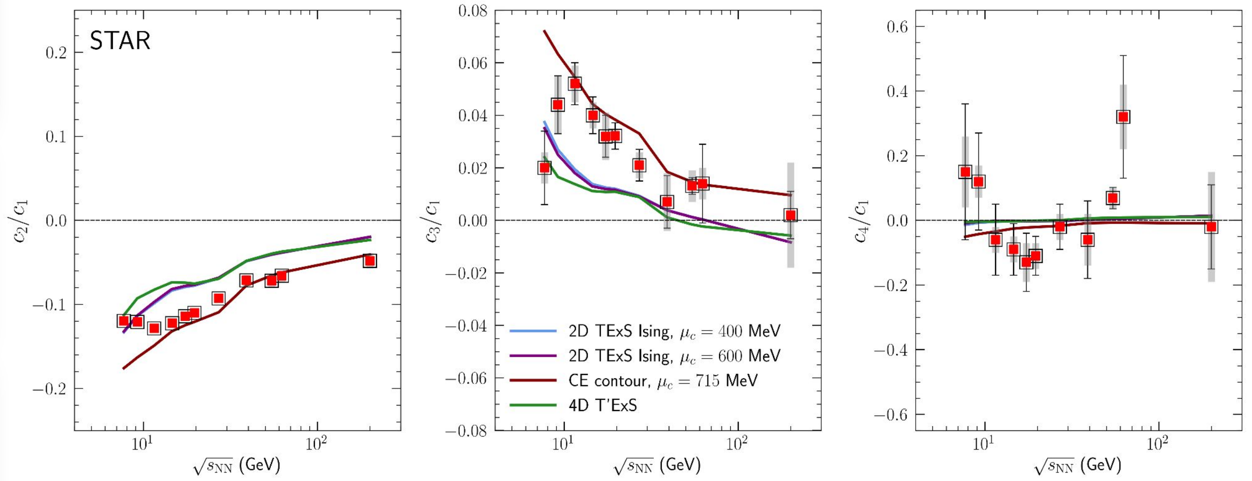
$$\hat{\Delta}\mathcal{H}_{n+m}(x) = \delta V(x) T(x)^3 \bar{\chi}^B_{n+m} F_{nm}(\chi^B_2, \chi^B_3, \chi^B_4)$$

EoS consistency

NEOS-BQS

$T_{\text{fo}}\ \mu_{B,\text{fo}}$ → EoS

$T_{\text{fo}}\ \mu_{B,\text{fo}}$ → iHRG



GP, M. Kahangirwe, H. Shah, R. Poberezhniuk C. Ratti, V. Vovchenko in prep

EoS comparison

EoS to data comparison

Close to experimental measurement

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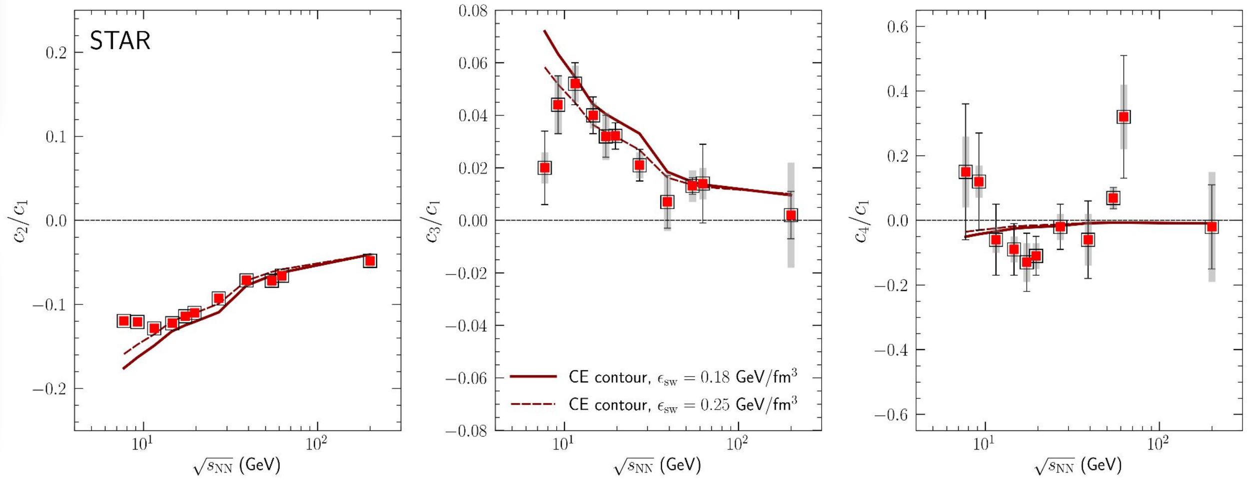
FO energy density?

$e_{\mathrm{sw}} = 0.18\ \mathrm{GeV/fm^3}$ $\quad e_{\mathrm{sw}} = 0.25\ \mathrm{GeV/fm^3}$

$$e_{\mathrm{sw}} \sim 0.34 - 0.38\ \mathrm{GeV/fm^3}$$



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EoS comparison

EoS to data comparison

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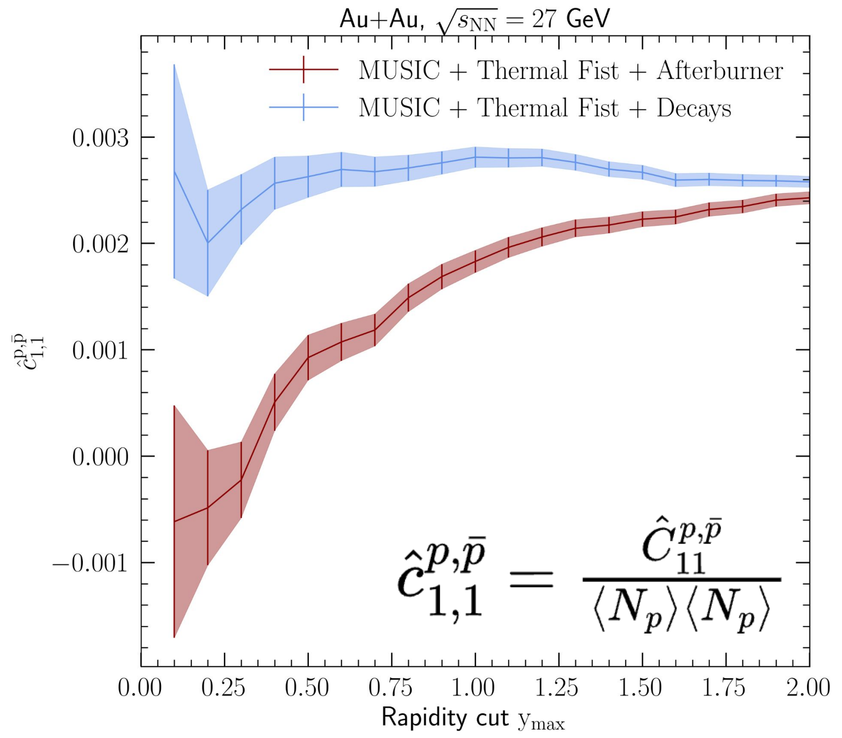
FO energy density?

$e_{\mathrm{sw}} = 0.18\ \mathrm{GeV/fm^3}$ $\quad$ $e_{\mathrm{sw}} = 0.25\ \mathrm{GeV/fm^3}$

$$e_{\mathrm{sw}} \sim 0.34 - 0.38\ \mathrm{GeV/fm^3}$$

Late stage interactions

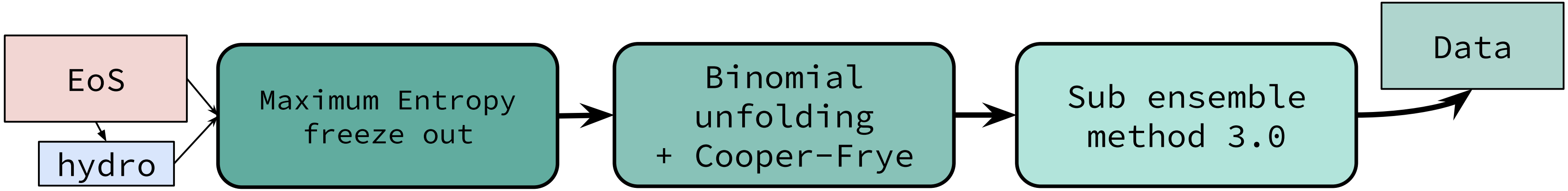
- Long range correlation
- Annihilations



J. Parra, GP, V. Koch, V. Vovchenko in prep

Conclusion

- ➢ Measuring fluctuations in heavy-ion experiments is not straightforward
- ➢ Corrections on the cumulants can be evaluated using the pipeline:



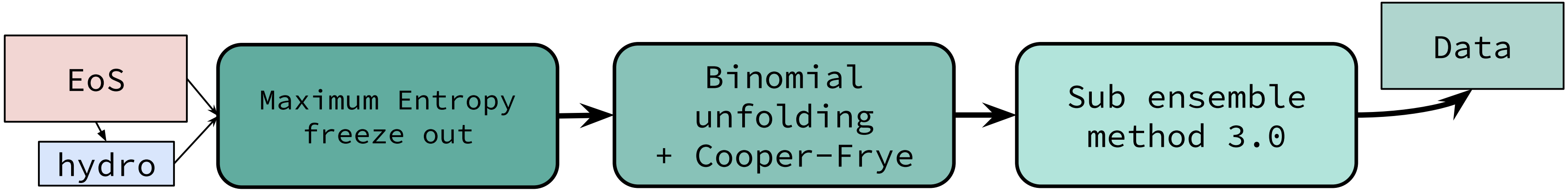
- ➢ Calculation of the factorial cumulants based on the literature susceptibilities, relatively good agreement.

HRG baseline?

Freeze-out energy density

EoS Mixing

- ➢ Measuring fluctuations in heavy-ion experiments is not straightforward
- ➢ Corrections on the cumulants can be evaluated using the pipeline:

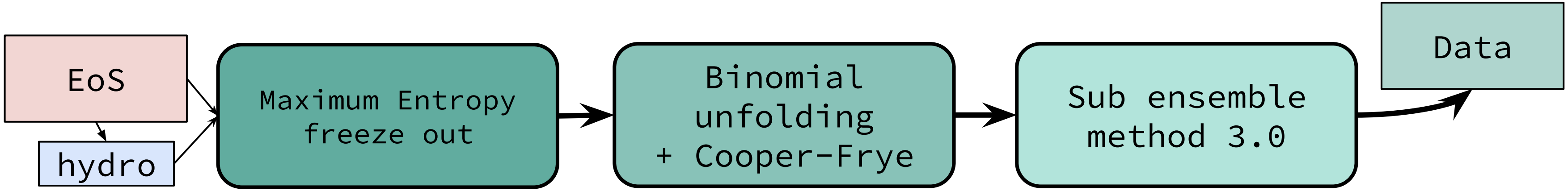


- ➢ Calculation of the factorial cumulants based on the literature susceptibilities, relatively good agreement.

HRG baseline? Freeze-out energy density EoS mixing

Can we do more?

- Measuring fluctuations in heavy-ion experiments is not straightforward
- Corrections on the cumulants can be evaluated using the pipeline:



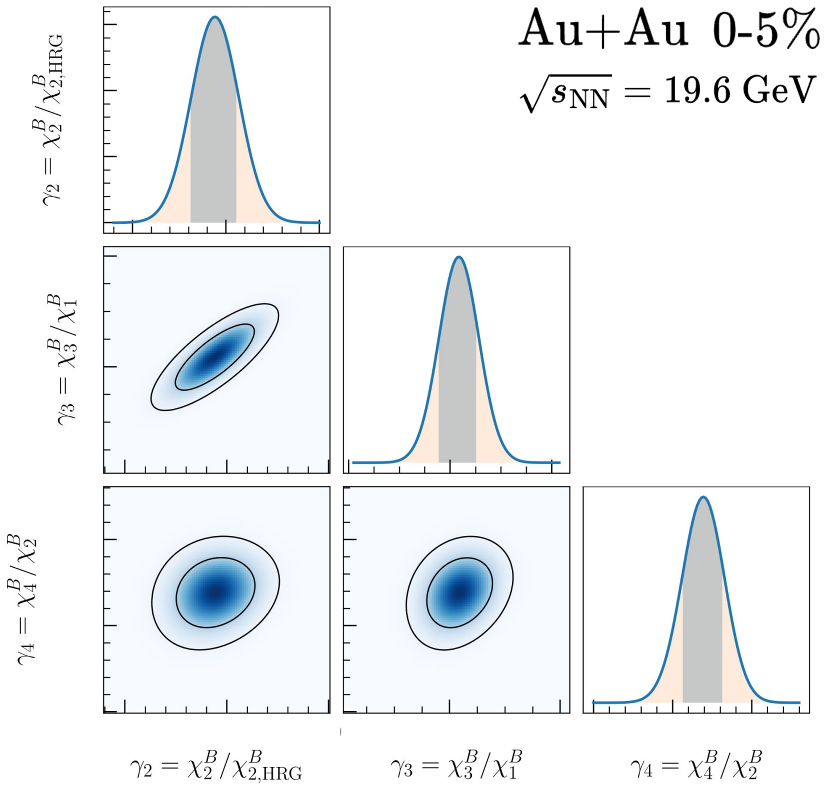
- Calculation of the factorial cumulants based on the literature susceptibilities, relatively good agreement.

HRG baseline?

Can we do more? YES!

Extracting QCD susceptibilities

Bayesian analysis on STAR data



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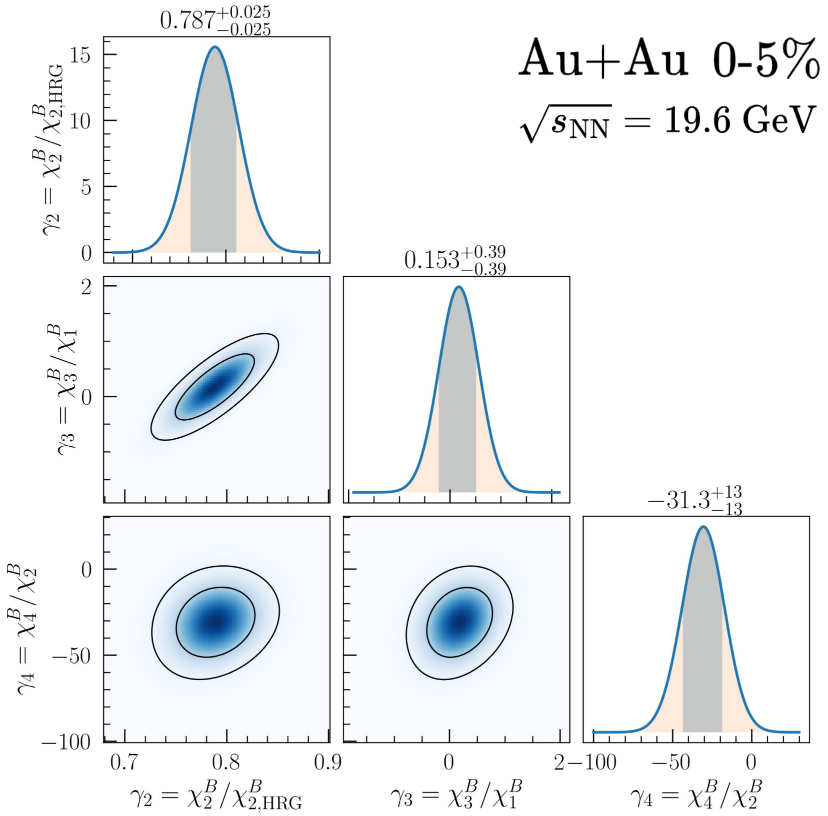
Extracting QCD susceptibilities

Bayesian analysis on STAR data

Extraction of QCD static response

Data driven approach to constrain QCD susceptibilities!



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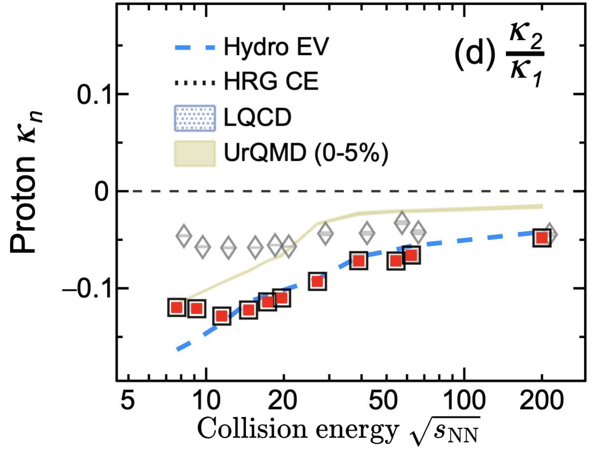
Extracting QCD susceptibilities

Bayesian analysis on STAR data

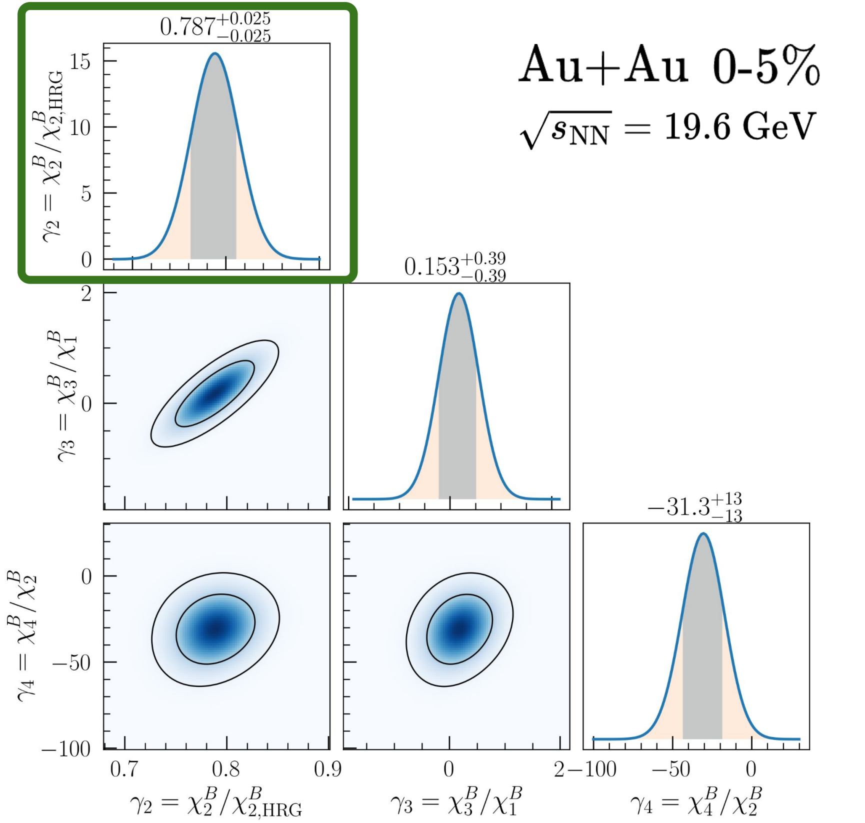
Extraction of QCD static response

Data driven approach to constrain QCD susceptibilities!

Possible at the 2nd order!



STAR Collaboration



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Extracting QCD susceptibilities

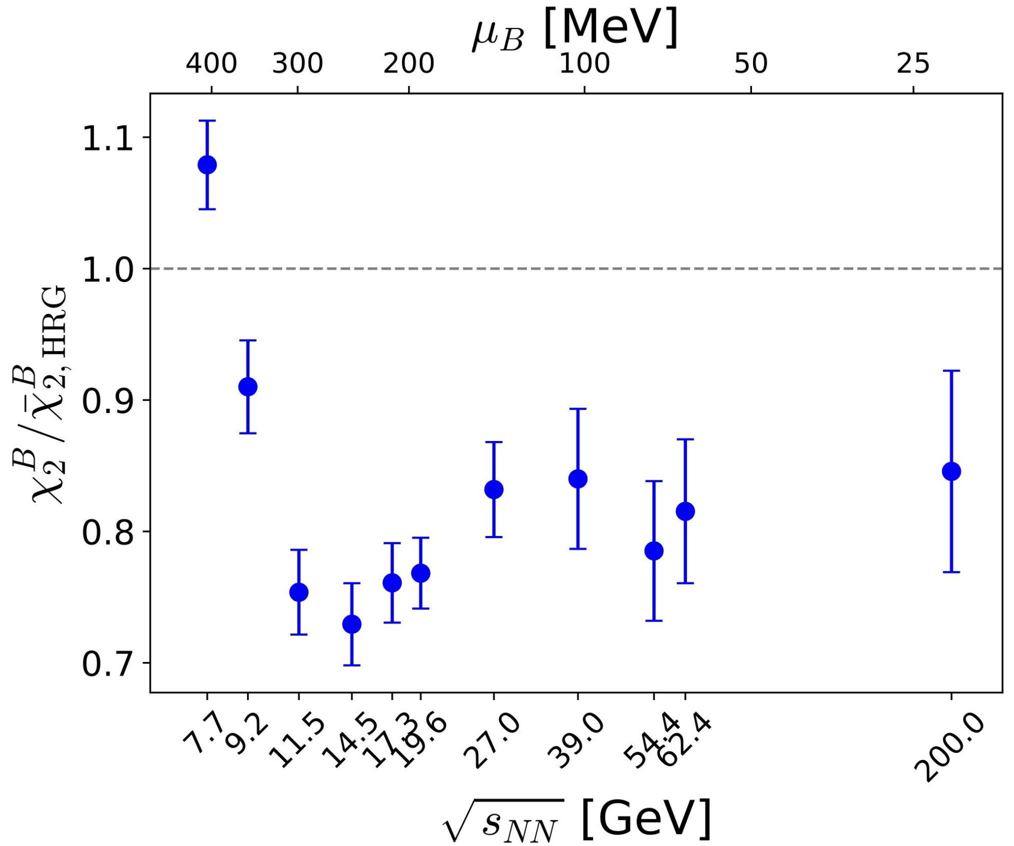
Deviations energy dependence

Deviations from Poisson baseline

Significant!

Non-monotonic structure

A change from repulsive to attractive interactions at small energies



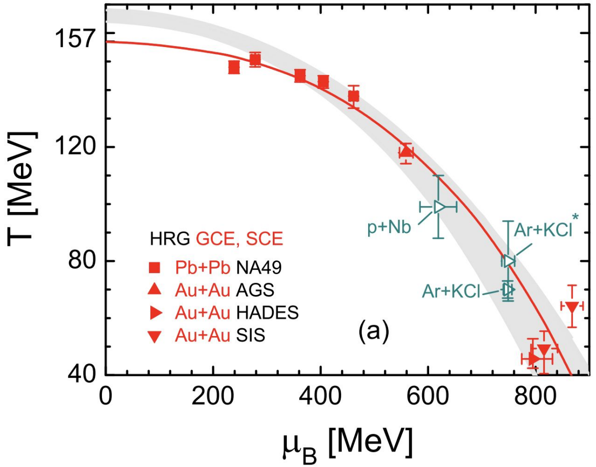
GP, R. Poberezhniuk, V. Vovchenko in prep

Extracting QCD susceptibilities

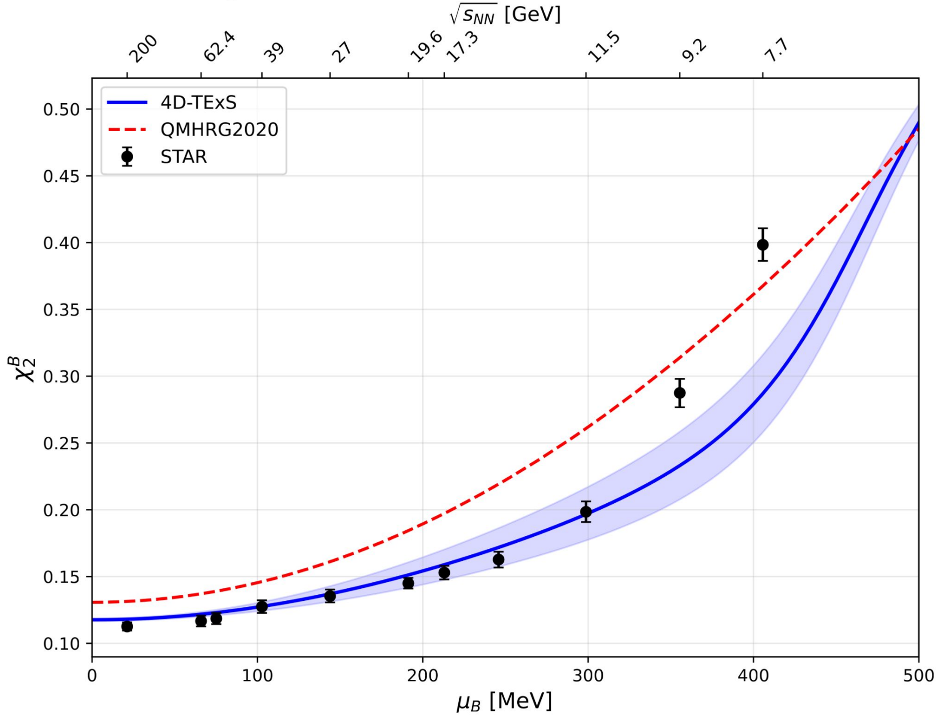
Comparison with 4D T'ExS EoS

Hadron Resonance Gas with Quark Model particle list

Strangeness neutral freeze-out line



V. Vovchenko et al Phys. Rev. C 93, 064906



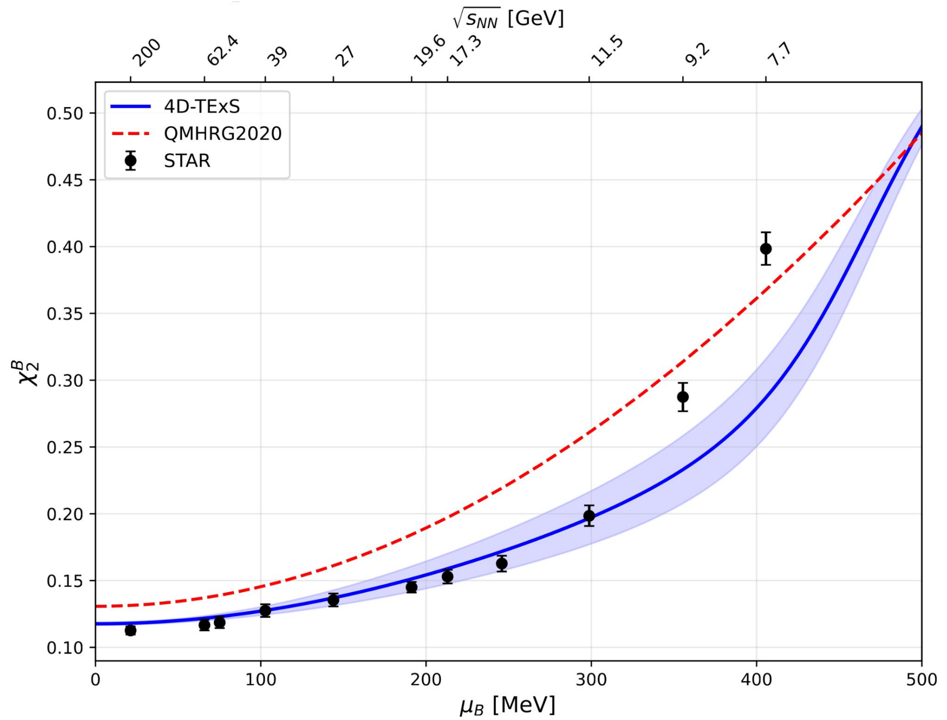
GP, R. Poberezhniuk, V. Vovchenko in prep

Extracting QCD susceptibilities

Comparison with 4D T'ExS EoS

Agreement with lattice QCD based equation of state at low μ_B

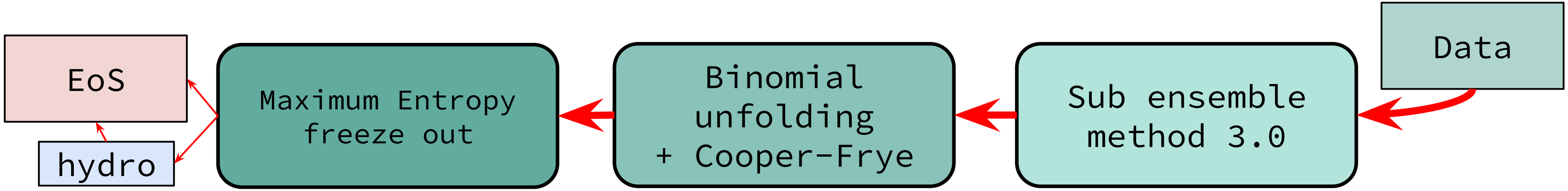
Deviation at large baryon chemical potential



GP, R. Poberezhniuk, V. Vovchenko in prep

- Measuring fluctuations in heavy-ion experiments is not straightforward

- Data driven constraints on the QCD susceptibilities:



Possible extensions?

- Inclusion of hydrodynamics energy density correlators and mixed correlators
- Consider B, Q and S as conserved charges for canonical corrections?
- Extend the bayesian analysis to other observables?

Thank you for your attention!

Simulation of the collision event

Collision event | Baryon number fluctuations | Proton number fluctuations in acceptance | Charge conservation

Smooth collision event: iEBE-MUSIC

Transverse: Glauber model

$$\epsilon(x,y,\eta_s) \propto e(\eta_s) T_{\text{Proj}}(x,y) T_{\text{Targ}}(x,y)$$

$$n_B(x,y,\eta_s) \propto f^{n_B}_{\text{Proj}}(\eta_s) T_{\text{Proj}}(x,y) + f^{n_B}_{\text{Targ}}(\eta_s) T_{\text{Targ}}(x,y)$$

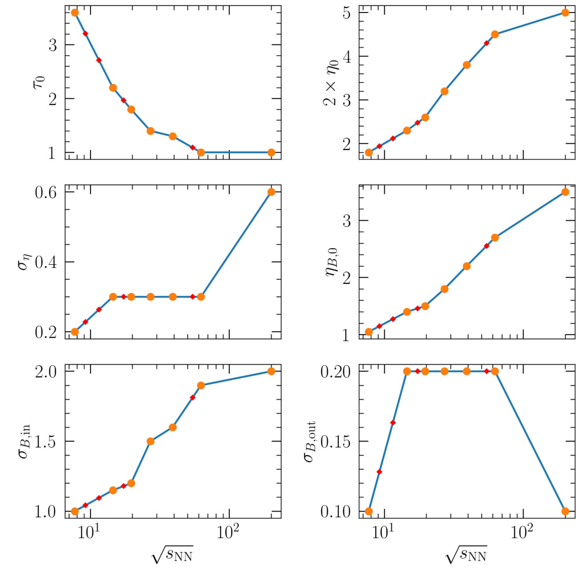
Longitudinal: Density enveloppes

$$e(\eta_s, y_{CM}) \propto \exp\left[-\frac{(|\eta_s - y_{\text{CM}}| - \eta_0)^2}{2\sigma_\eta^2}\,\theta(|\eta_s - y_{\text{CM}}| - \eta_0)\right]$$

$$f^{n_B}_{\text{Proj}} \propto \theta(\eta_s - \eta_{B,0}) \exp\left[-\frac{(\eta_s - \eta_{B,0})^2}{2\sigma^2_{B,\text{out}}}\right] + \theta(\eta_s + \eta_{B,0}) \exp\left[-\frac{(\eta_s + \eta_{B,0})^2}{2\sigma^2_{B,\text{in}}}\right]$$

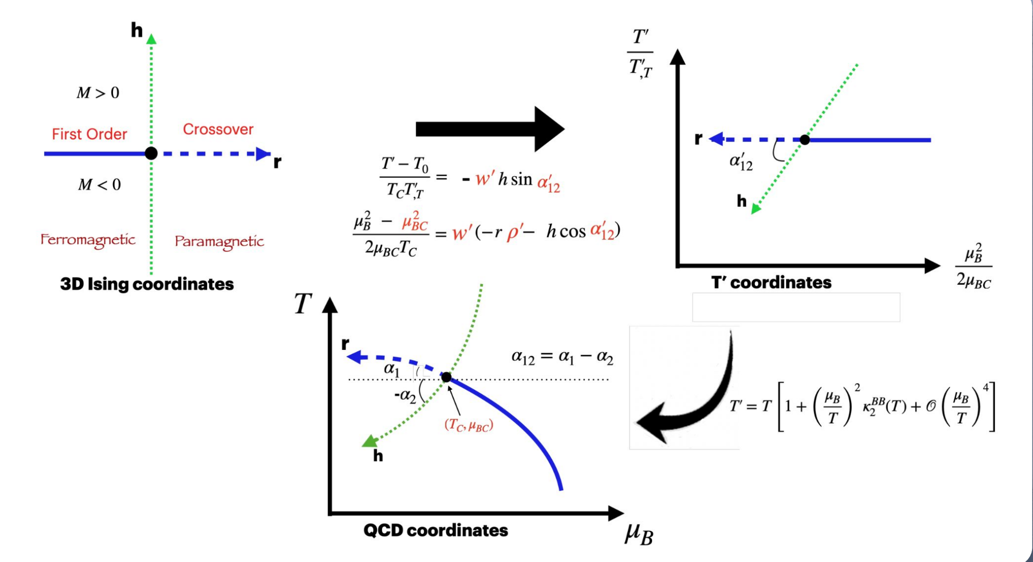
$$f^{n_B}_{\text{Targ}} \propto \theta(\eta_s + \eta_{B,0}) \exp\left[-\frac{(\eta_s + \eta_{B,0})^2}{2\sigma^2_{B,\text{in}}}\right] + \theta(-\eta_s - \eta_{B,0}) \exp\left[-\frac{(\eta_s + \eta_{B,0})^2}{2\sigma^2_{B,\text{out}}}\right]$$

Parameters tuned on the BES Au+Au charged hadron and net-proton rapidity distributions



Simulation of the collision event

3D Ising mapping



Parameters

$$T_c = 93.4 \text{ MeV}$$

$$\mu_{B,c} = 600 \text{ MeV}$$

$$\alpha_{12} = 90^o$$

$$\omega = 2.25$$

$$\rho = 1.0$$

Simulation of the collision event

Maximum Entropy FO details

Maximum Entropy cumulants

General definition of the particle cumulants

$$\kappa_{\hat{A}_1 \dots \hat{A}_k} = \left\langle \prod_{i=1}^{k} \delta N_{\hat{A}_i} \right\rangle$$

$$\hat{A}_i \equiv (x_A, p_A, q_A, s_A, g_A, m_A, \dots)_i$$

Cumulants from single particle distributions correlators

$$\kappa_{\hat{A}_1 \dots \hat{A}_k} = \int_{\hat{A}_1 \dots \hat{A}_k} G_{A_1 \dots A_k}$$

$$G_{A_1 \dots A_k} = \langle \delta f_{A_1} \dots f_{A_k} \rangle$$

IRCs from single particle distributions IRCs

$$\hat{\Delta}\kappa_{\hat{A}_1 \dots \hat{A}_k} = \int_{\hat{A}_1 \dots \hat{A}_k} \hat{\Delta} G_{A_1 \dots A_k}$$

[M.S. Pradeep, M.A. Stephanov Phys. Rev. Lett. 130, 162301]

Particle IRCs from hydrodynamics

$$\hat{\Delta}\kappa_{\hat{A}_1 \dots \hat{A}_k} = \hat{\Delta}\mathcal{H}_{a_1 \dots a_k} \prod_{i=1}^{k} P^{a_i}_{\hat{A}_i}$$