Extracting baryon number susceptibilities at finite density from heavy-ion collisions

Volodymyr Vovchenko (University of Houston)

Hadron Ion Tea Seminar, LBNL, Berkeley, CA

July 21, 2026

Thanks to: F. Di Clemente, T. Gyure, V. Kuznietsov, G. Pihan, R. Poberezhniuk, H. Shah

QCD under extreme conditions

UNIVERSITY OF HOUSTON

What we know

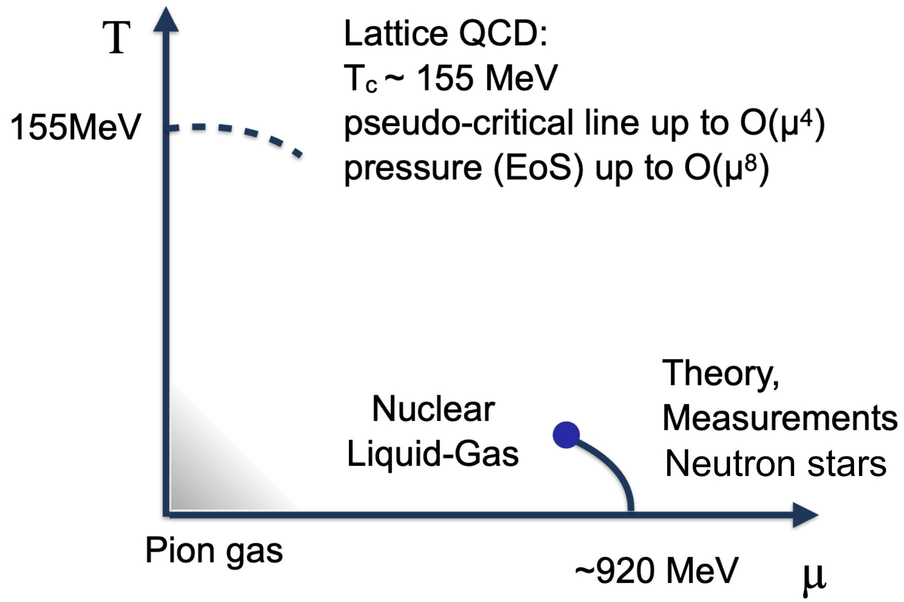


Figure courtesy of V. Koch

What we hope to know

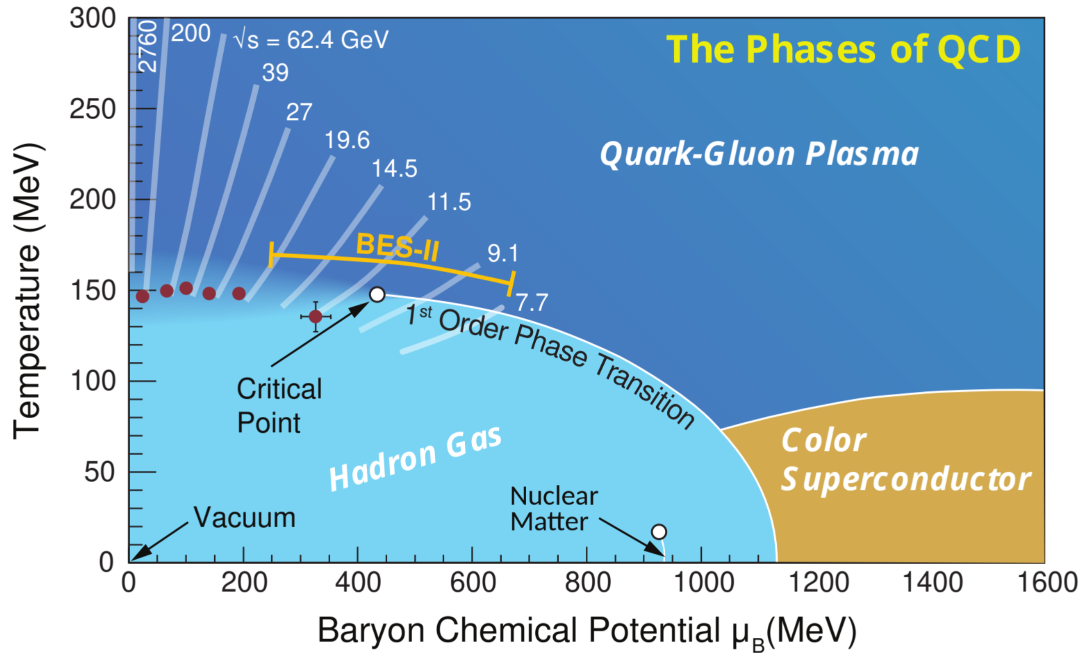


Figure from Bzdak et al., Phys. Rept. '20 & 2015 US Nuclear Long Range Plan

- 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

QCD phase diagram with constant entropy contours and search for critical point

H. Shah, M. Hippert, J. Noronha, C. Ratti, VV, PRC 113, L012201 (2026) & 2601.08823

H. Shah, **T. Gyure**, A. Leon, F. Di Clemente, M. Hippert, C. Ratti, VV, 2606.28282

Critical point predictions from some years ago

Lattice QCD

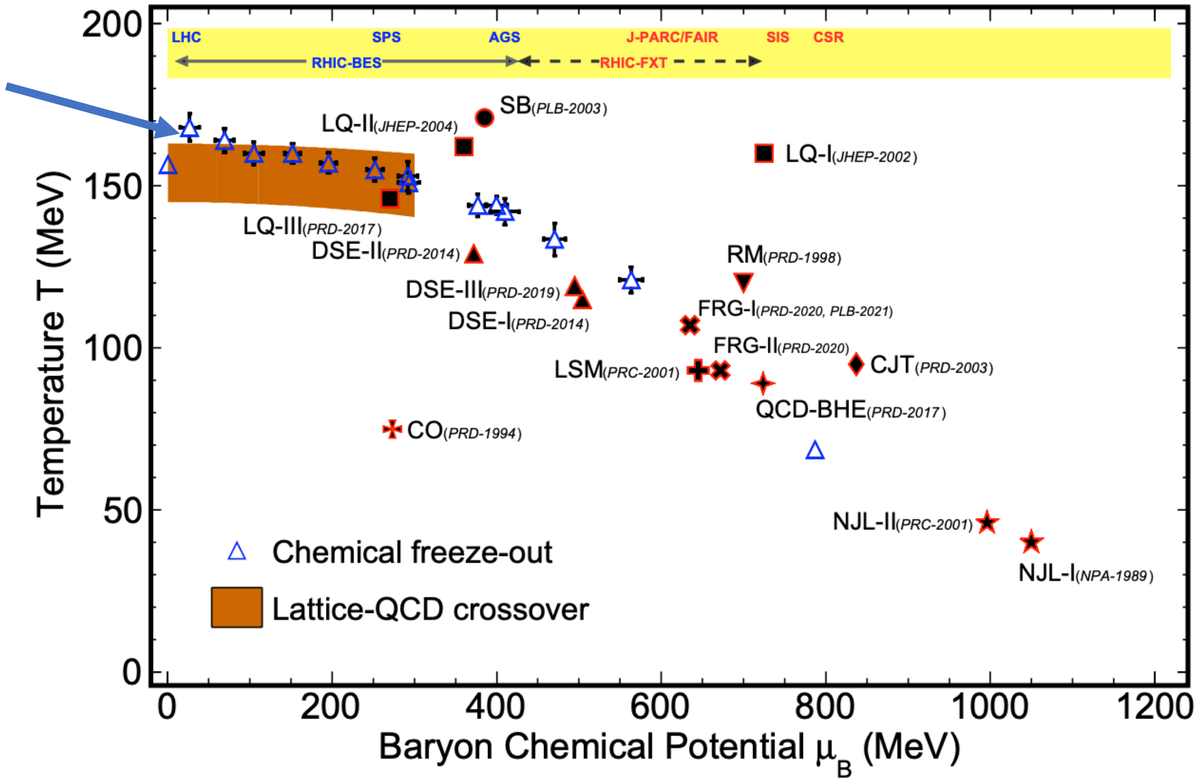


Figure adapted from A. Pandav, D. Mallick, B. Mohanty, Prog. Part. Nucl. Phys. 125 (2022)

- Including the possibility that the QCD critical point does not exist

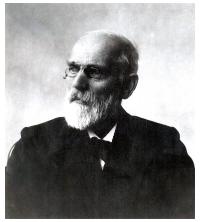
de Forcrand, Philipsen, JHEP 01, 077 (2007); VV, Steinheimer, Philipsen, Stoecker, PRD 97, 114030 (2018)

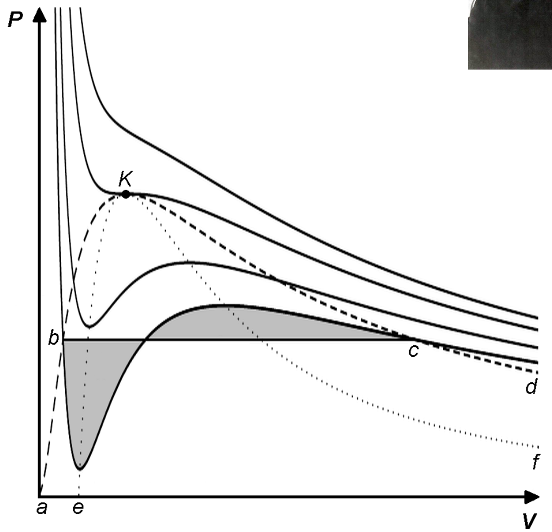
- Lattice QCD excludes the CP at $\mu_B < 450$ MeV on (one-sided) 2σ level

Borsanyi et al., PRD 112, L111505 (2025)

Extrapolating critical point from lattice QCD

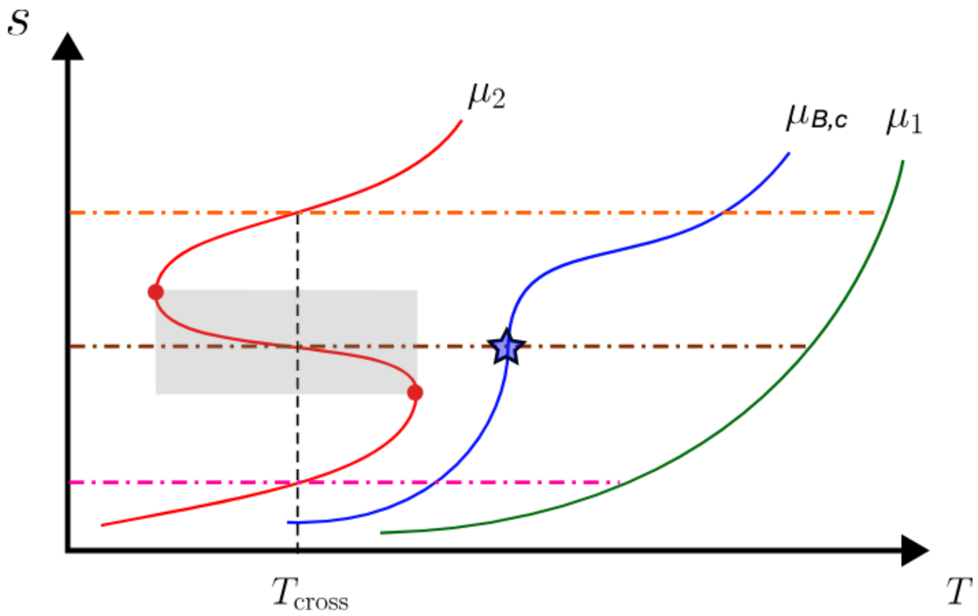
van der Waals (1873)





change of variables

Shah, Hippert, Noronha, Ratti, VV, PRC 113, L012201 (2026)



Critical Point:

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

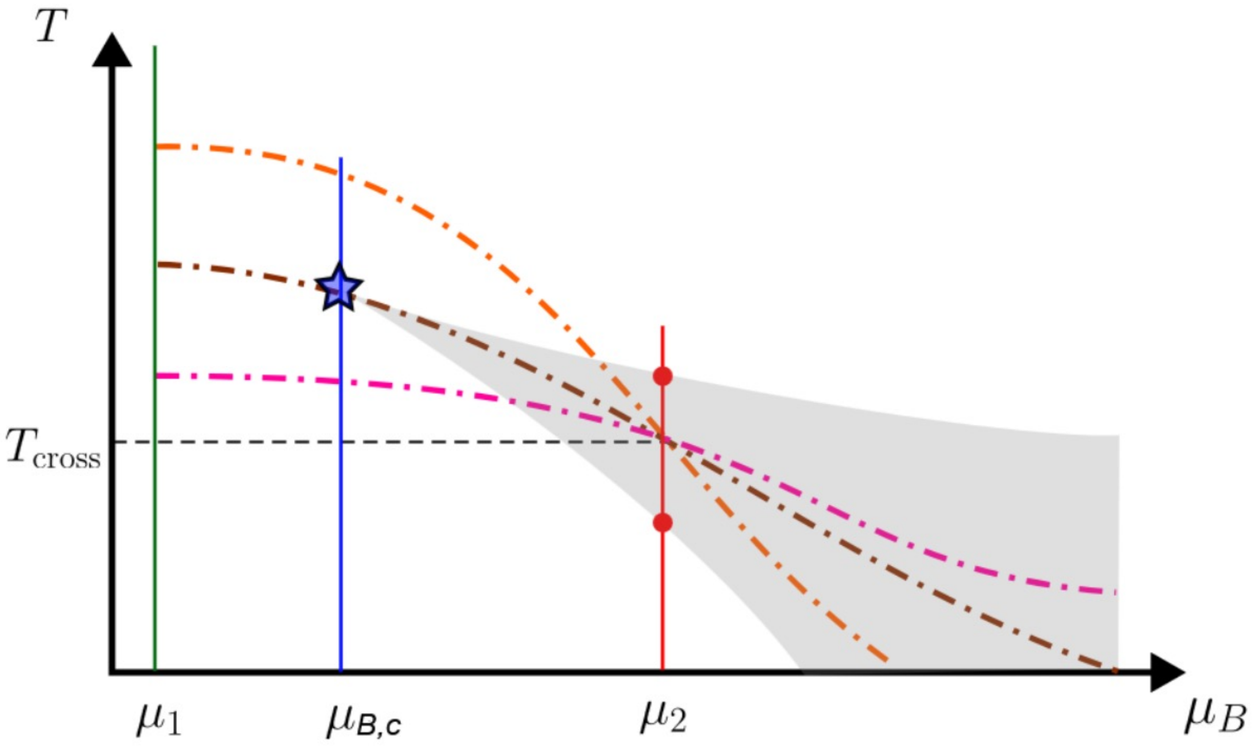
$$\left(\frac{\partial T}{\partial s}\right)_{\mu_B} = 0, \qquad \left(\frac{\partial^2 T}{\partial s^2}\right)_{\mu_B} = 0.$$

Strategy: Follow contours of constant entropy density away from $\mu_B = 0$ and look for crossings

Building the contours

UNIVERSITY OF HOUSTON

Shah, Hippert, Noronha, Ratti, VV, PRC 113, L012201 (2026)



$s_1 < s_c < s_2$

Define T-vs-μ_B **constant entropy line** through Taylor series

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

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

- Allows multiple T_0 values to correspond to same T_s at finite μ_B (parabolas cross)
- In contrast to the standard Taylor expansion, permits a description of a first-order phase transition (mean-field-like behavior)

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

expansion

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

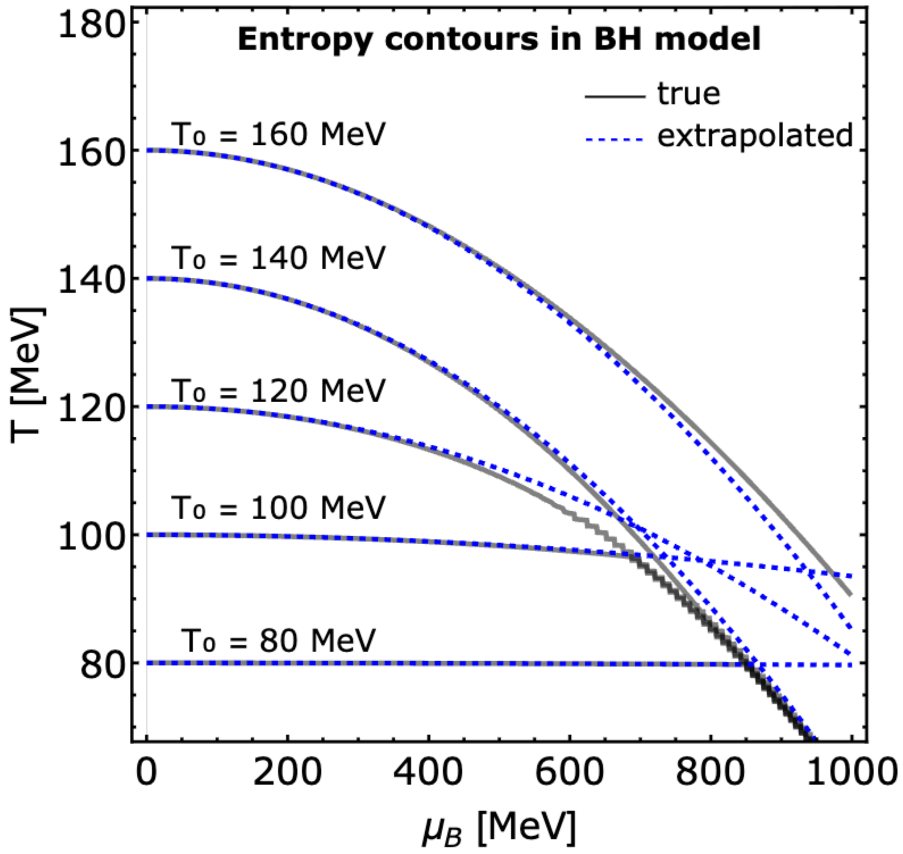
spinodals

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

critical point

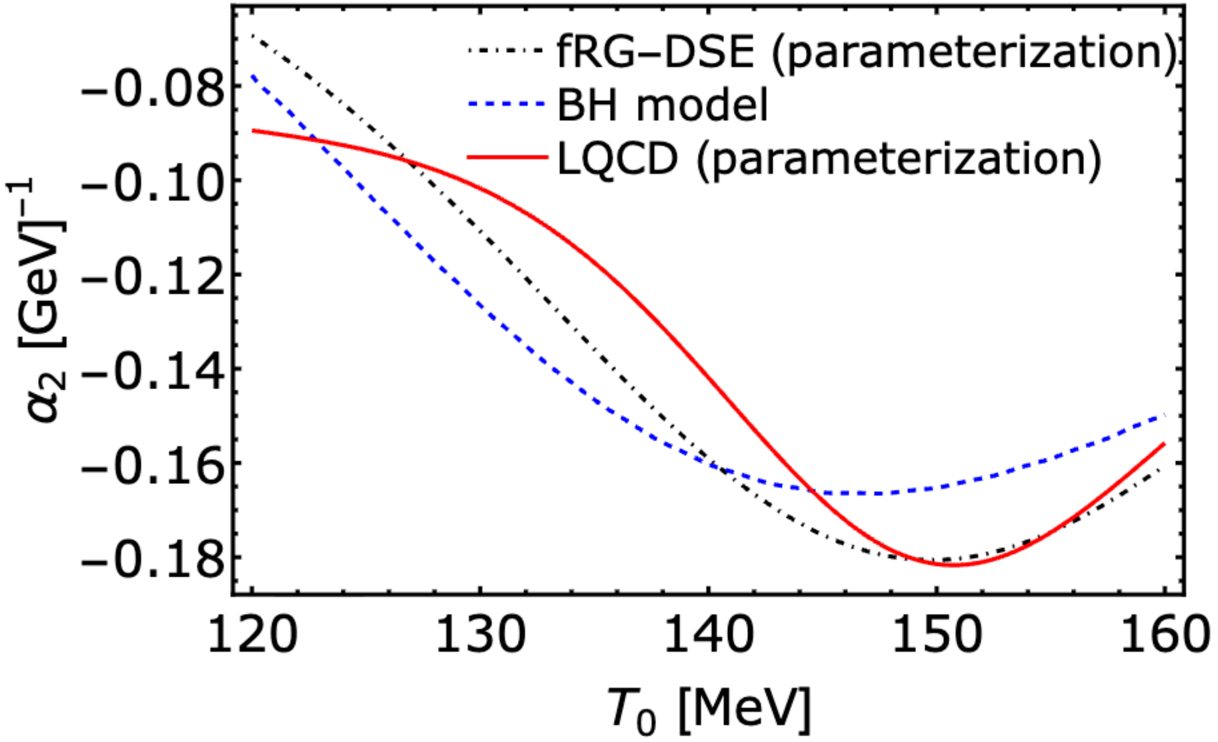
Testing with effective theories

Shah, Hippert, Noronha, Ratti, VV, arXiv:2601.08823



fRG-DSE: Lu, Gao, Liu, Pawlowski, PRD 113, 054019 (2026)

BH model: Hippert et al. PRD 110, 094006 (2024)



	true CP	extrapolated CP
✓ **fRG-DSE:**	(103,660)	(108,629)
✓ **BH model:**	(103,599)	(104,637)

✓ **free QGP:** no true CP and no extrapolated CP

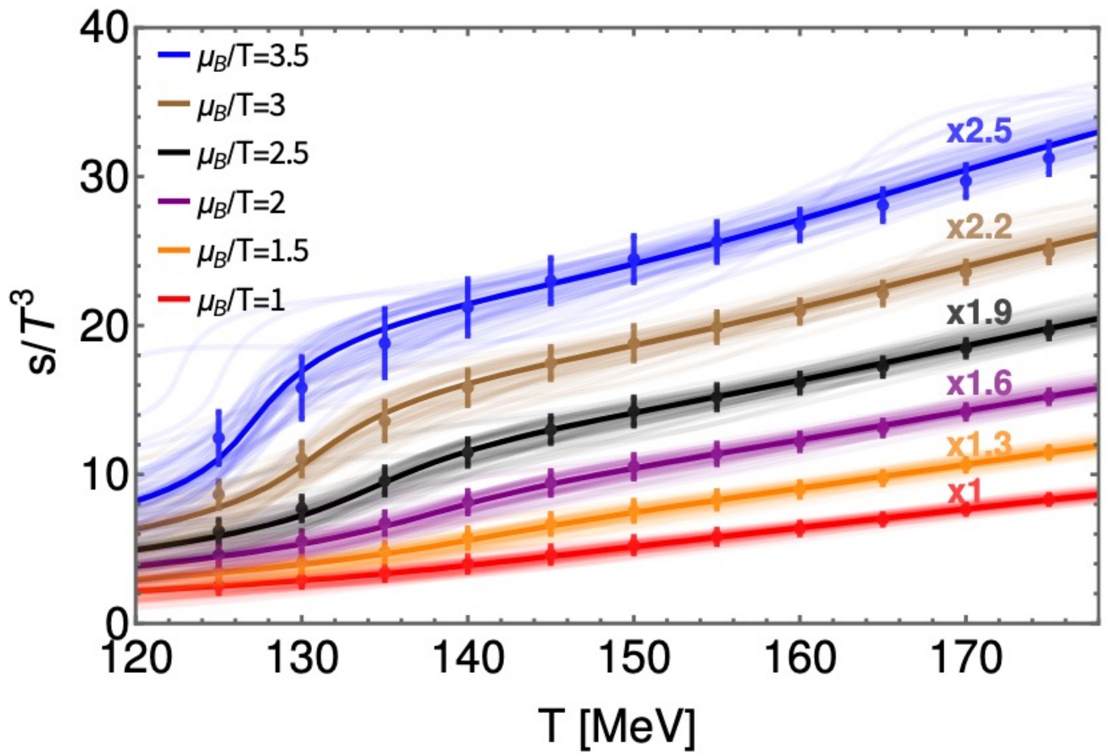
⚠ **HRG:** no true CP but fake extrapolated CP at ~(80,830) MeV

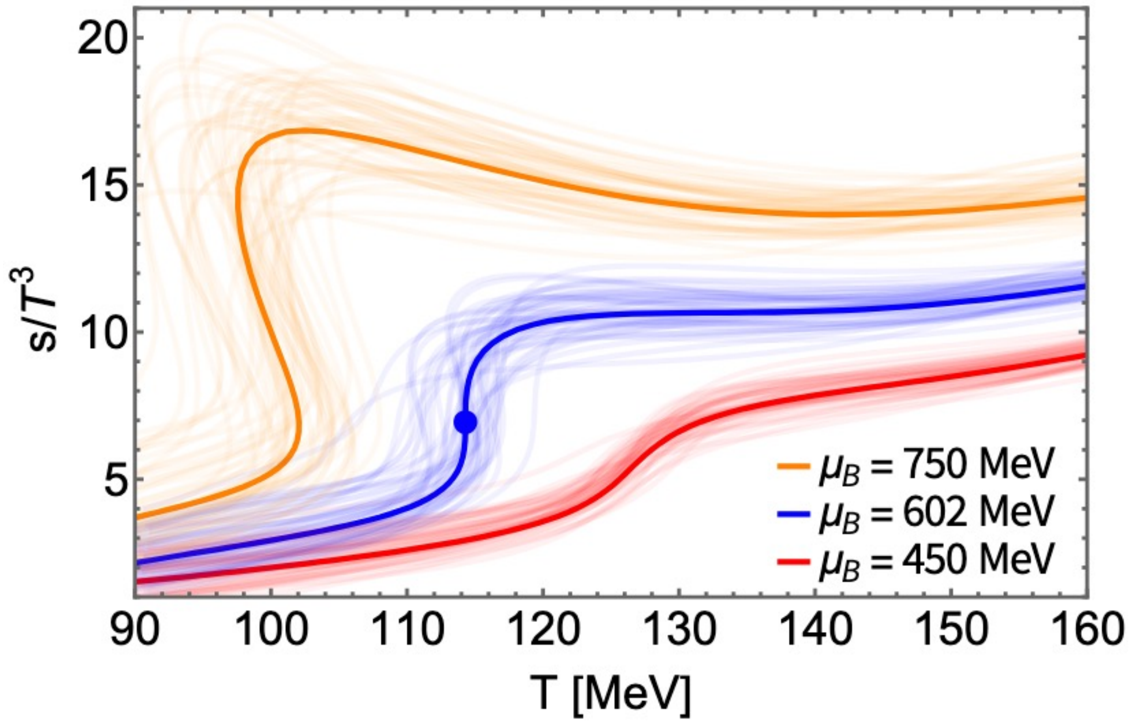
Marczenko et al., PRD 112, 034019 (2025)

Entropy density at finite μ_B at O(μ_B^2) from lattice QCD

UNIVERSITY OF HOUSTON

- Parametrized lattice QCD input from $\mu_B = 0$ [$s(T)$ and $\chi_2^B(T)$]





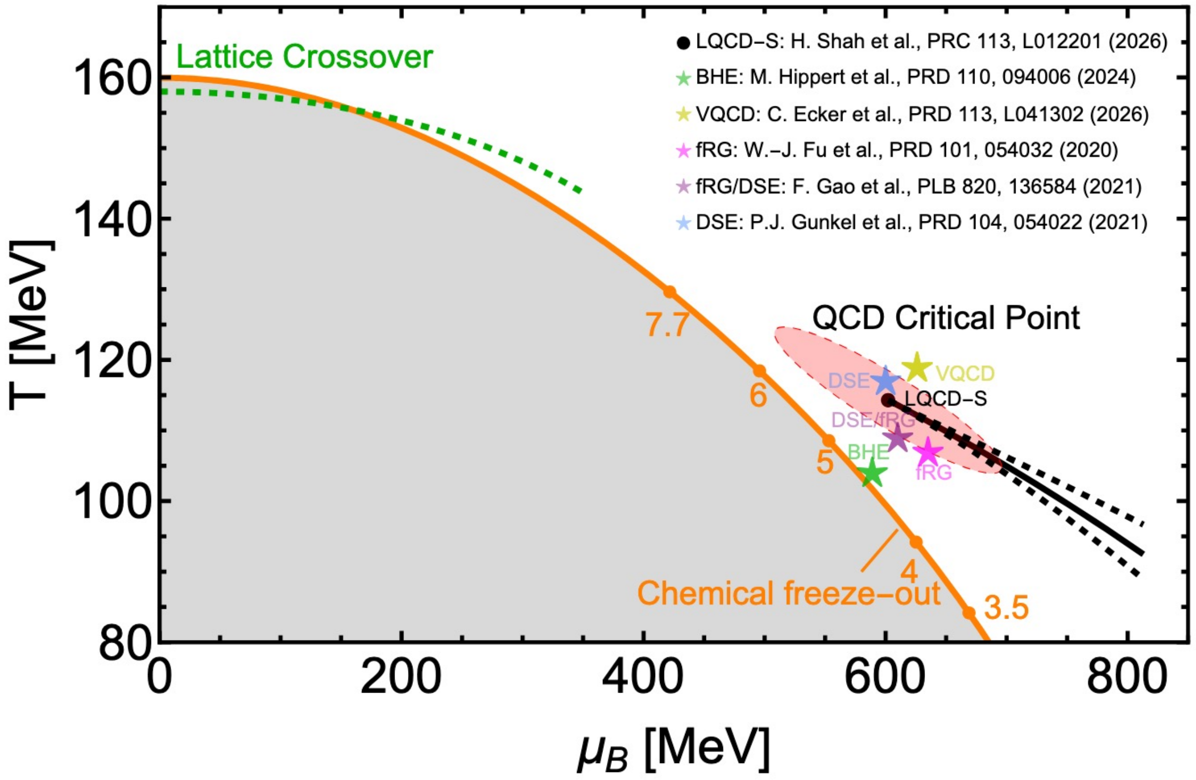
- Excellent agreement at low μ_B/T with available lattice QCD constraints from T'-expansion

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

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

Shah, Hippert, Noronha, Ratti, VV, PRC 113, L012201 (2026)

Candidate critical region



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

$$T_c = 114 \pm 7 \text{ MeV}, \quad \mu_B = 602 \pm 62 \text{ MeV}$$

Estimates from recent literature:

*YLE-1: D.A. Clarke et al. (Bielefeld-Parma), PRD 112, L091504 (2025)

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

BHE: M. Hippert et al., PRD 110, 094006 (2024)

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, 054022 (2021)

VQCD: C. Ecker et al., PRD 113, L041302 (2026)

Optimist's view: Different estimates converge onto the same region because QCD CP is likely there

Pessimist's view: Different estimates converge onto the same region because it's the closest not yet ruled out by LQCD

⚠ This is a candidate region subject to validity of the expansion (other estimates listed here have their own caveats). More rigorous constraints determine exclusion regions.

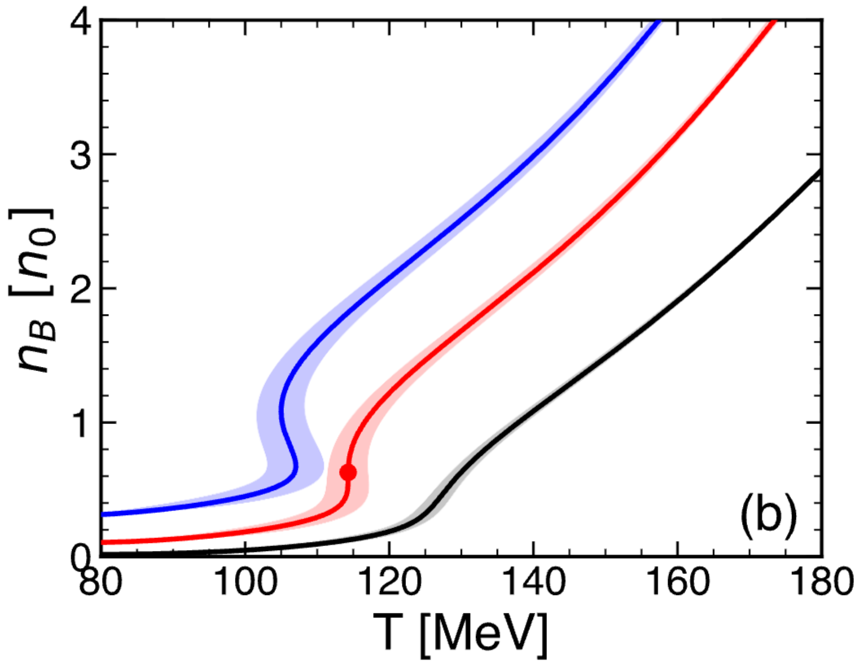
Equation of state

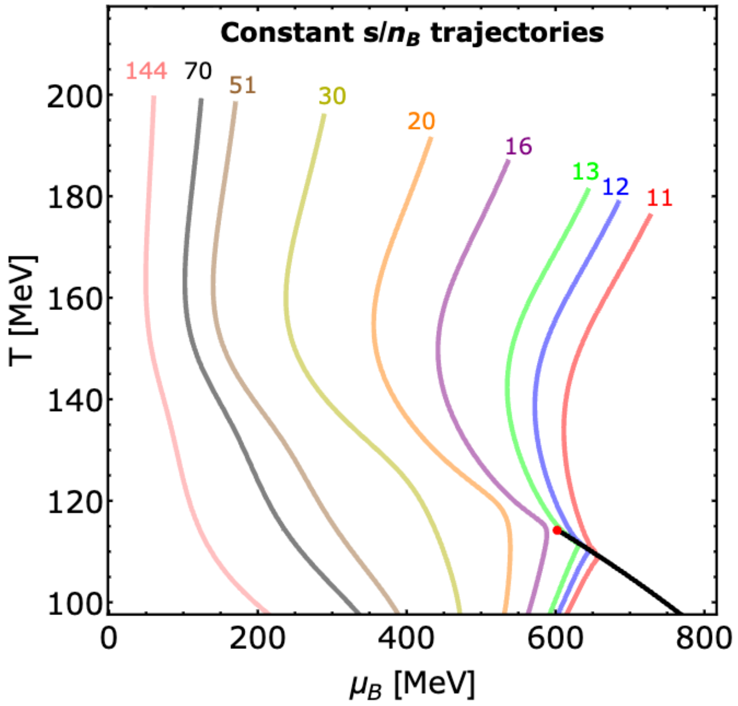
The method yields entropy density $s(T, \mu_B)$ across the (T, μ_B) phase diagram

→ Integrate over T to obtain the pressure $P(T, \mu_B)$ and the rest of the thermodynamics

$$\int_{T_{\rm low}}^{T} s(T', \mu_B) dT' = P(T, \mu_B) - P(T_{\rm low}, \mu_B)$$

Integration constant at $T_{\rm low} = 80$ MeV matched to van der Waals HRG





Baryon density at the CP is $n_B \simeq 0.59 n_0 \simeq 0.09$ fm^{-3}

n_B in mixed phase region increases at lower T

Shah, Hippert, Noronha, Ratti, VV, arXiv:2601.08823

Critical point in 4D

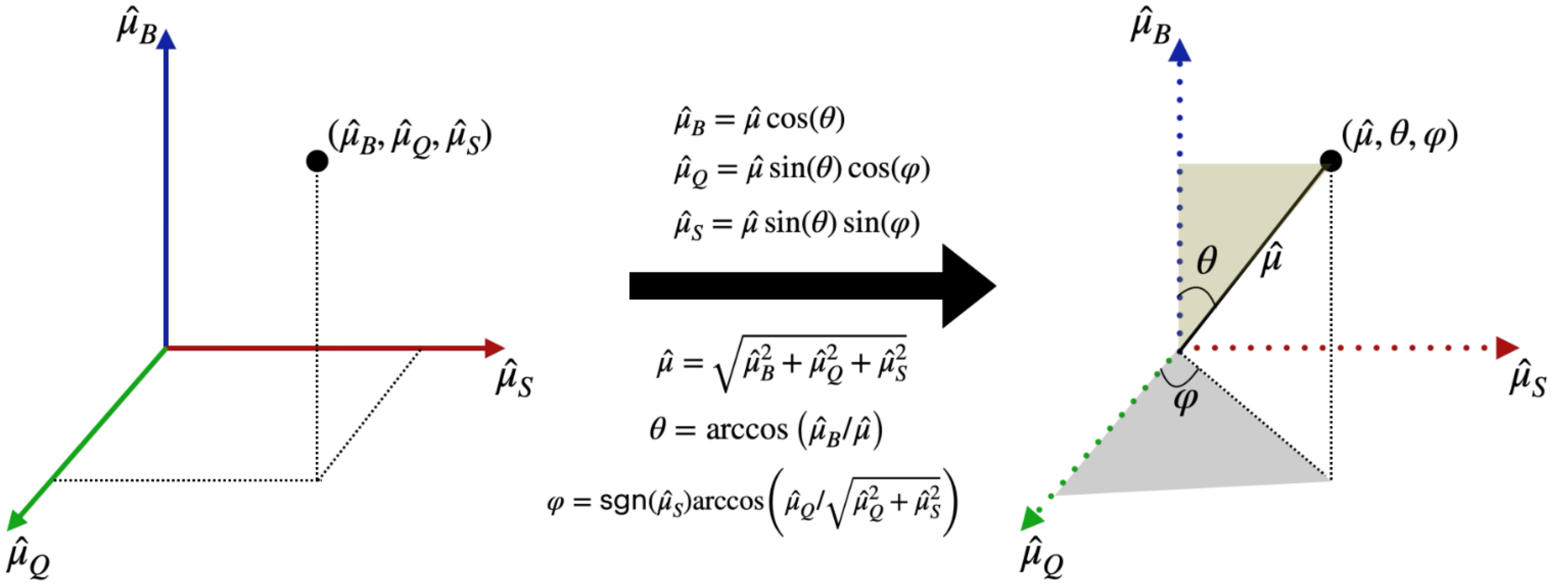
H. Shah, T. Gyure, F. Di Clemente, et al., 2606.28282

UNIVERSITY OF HOUSTON

So far, we restricted the analysis to $\mu_S = \mu_Q = 0$ conditions

General case: fix the direction in 3D space of (μ_B, μ_Q, μ_S) using spherical coordinates

A. Abuali, S. Borsanyi, et al., PRD 112, 054502 (2025)



Cartesian Coordinates **Spherical Coordinates**

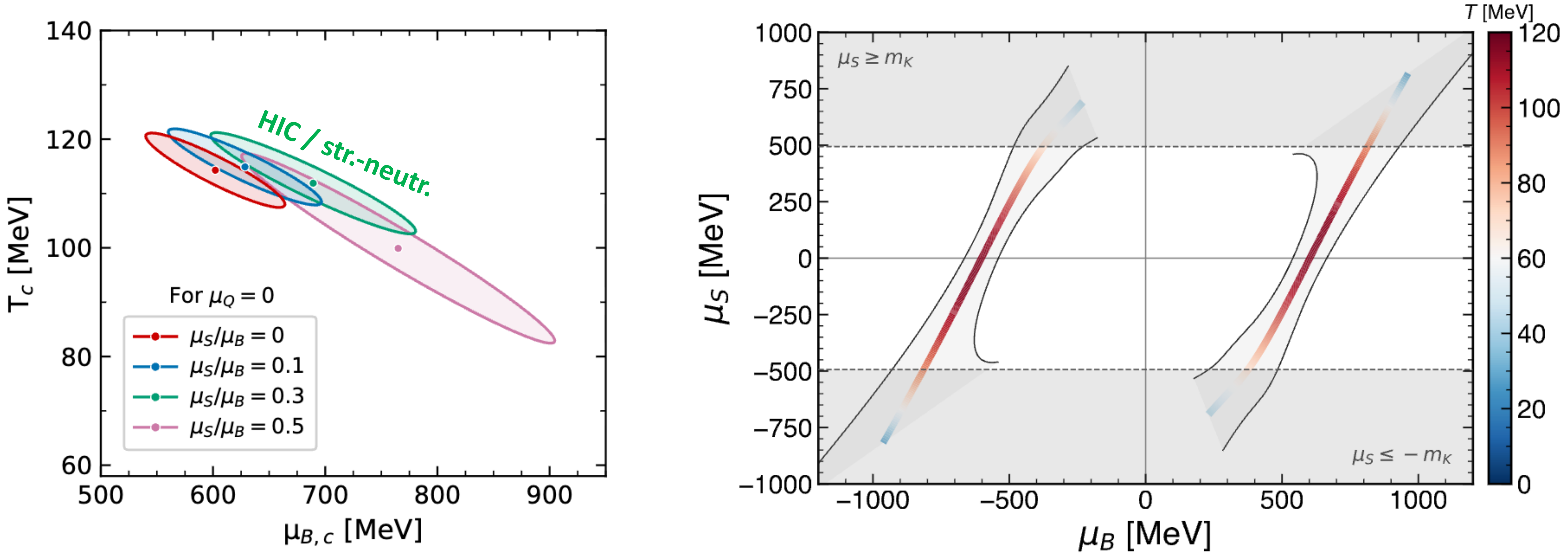
Every ray in (μ_B, μ_Q, μ_S): use **directional susceptibility** constructed from the six second-order susceptibilities.

$$\chi_2^B(T) \Longrightarrow \chi_2^{\theta,\varphi}(T) = c_\theta^2 \chi_2^B(T) + s_\theta^2 c_\varphi^2 \chi_2^Q(T) + s_\theta^2 s_\varphi^2 \chi_2^S(T) + 2c_\theta s_\theta c_\varphi \chi_{11}^{BQ}(T) + 2c_\theta s_\theta s_\varphi \chi_{11}^{BS}(T) + 2s_\theta^2 c_\varphi s_\varphi \chi_{11}^{QS}(T)$$

Critical point in 4D: $\mu_{\mathrm{B}} - \mu_S$ plane

H. Shah, T. Gyure, F. Di Clemente, et al., 2606.28282

Using the lattice QCD input for susceptibilities from [A. Abuali, et al., PRD 112, 054502 (2025)]



Heavy-ion collisions and strangeness neutrality ($n_S = 0 \leftrightarrow \mu_S \approx 0.15 - 0.30\mu_B$): $\mu_{B,c}$ shifts to the right.

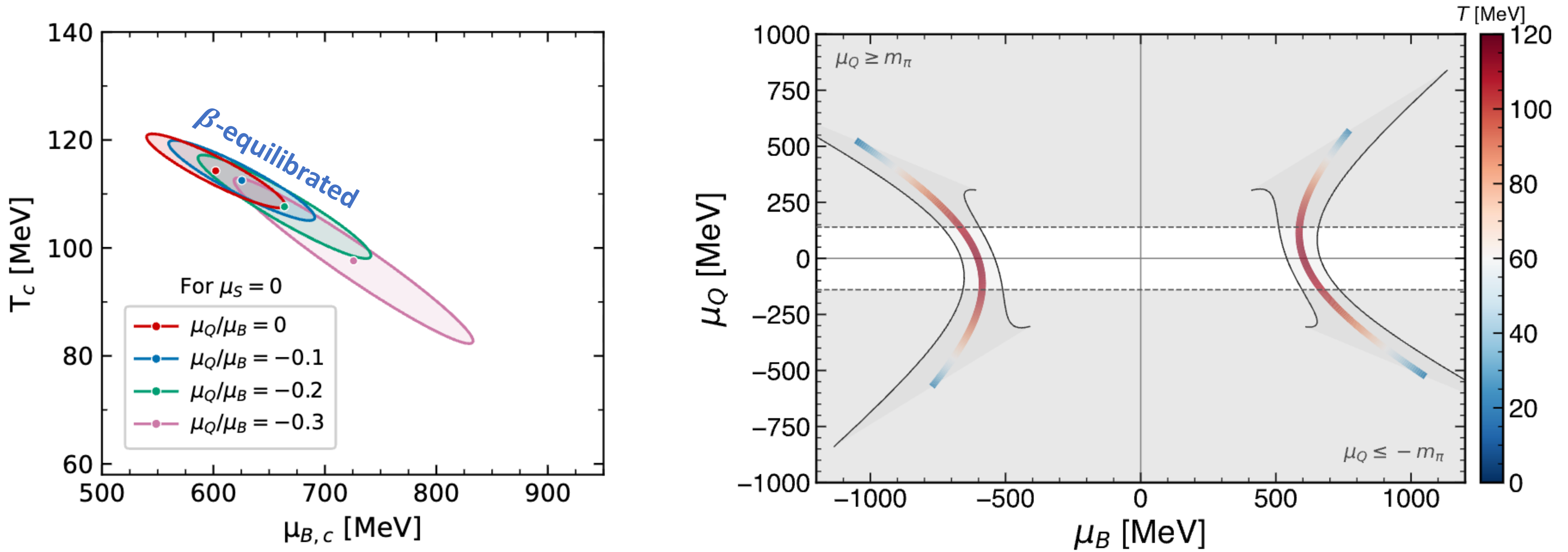
From $(T, \mu_B) = (114{,}602)$ MeV at $\mu_S = 0$ to $(T, \mu_B) = (112{,}689)$ MeV at $\mu_S = 0.3\mu_B$

Similar effect of an increased $\mu_{B,c}$ in recent functional QCD analysis [W.J. Fu et al., 2603.13455]

Critical point in 4D: $\mu_\mathrm{B} - \mu_\mathrm{Q}$ plane

H. Shah, T. Gyure, F. Di Clemente, et al., 2606.28282

UNIVERSITY OF HOUSTON

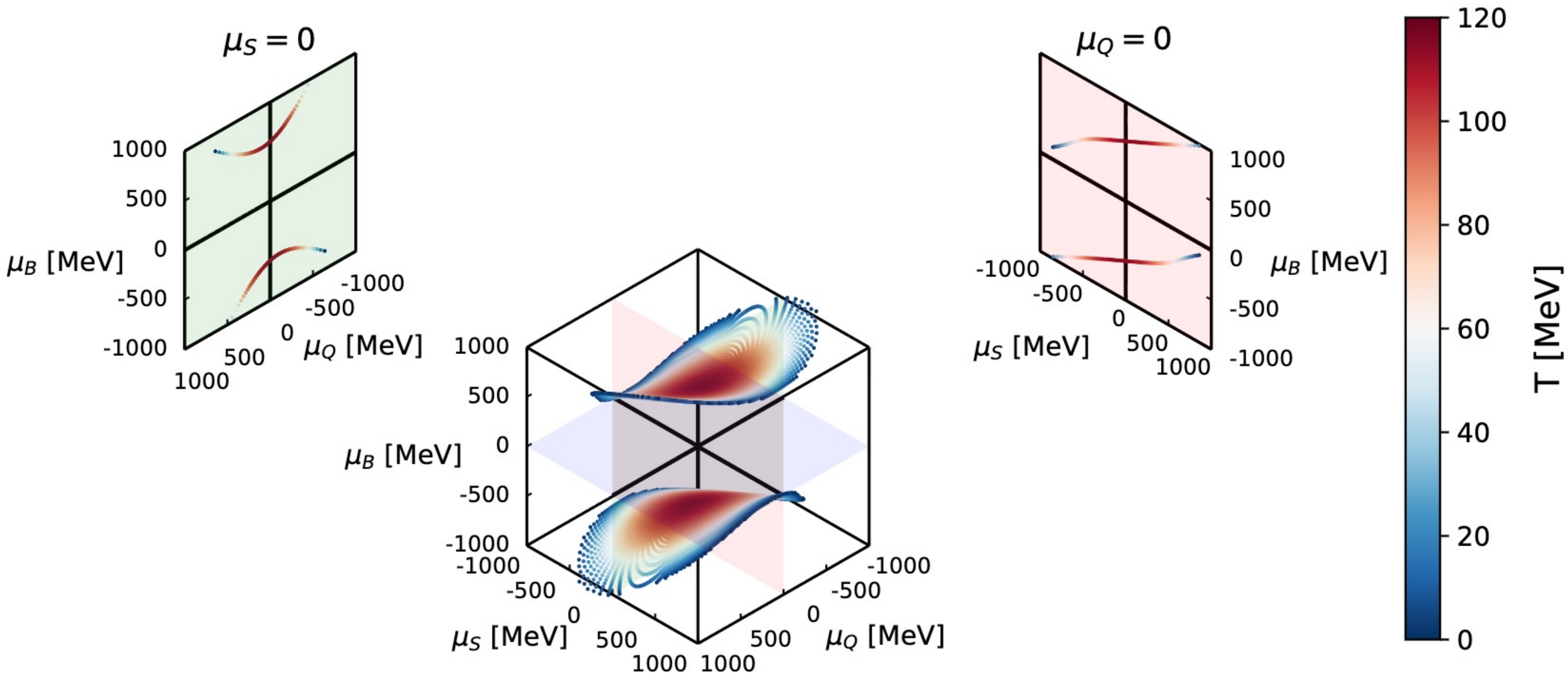


- ***β*-equilibrium matter** ($n_\mathrm{Q} \approx 0 \leftrightarrow \mu_\mathrm{Q} \approx -0.05 - 0.1\mu_B, \mu_S = 0$): **candidate CP is preserved and barely moves**
  - Suggests a possibility of a **first-order phase transition** in **neutron star mergers**
- **Large isospin asymmetry** ($|\mu_Q|/\mu_B \gtrsim 1$): **CP disappears**
  - Disfavors first-order phase transition **in the Early Universe for standard scenarios**

see also F. Gao, I. Oldengott, PRL 128, 131301 (2022); F. Di Clemente et al., 2511.11995

Critical point in 4D: critical surface

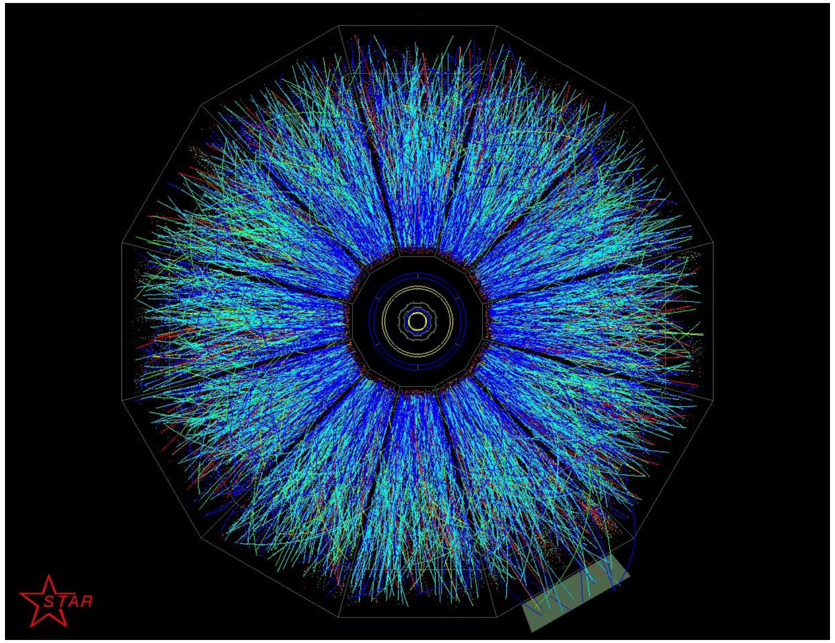
H. Shah, T. Gyure, F. Di Clemente, et al., 2606.28282



Caveats: Pion and kaon condensation, results are conditional on the accuracy of truncated expansion

Outlook: Full 4D EoS with a critical point in MUSES

Fluctuations in heavy-ion collisions



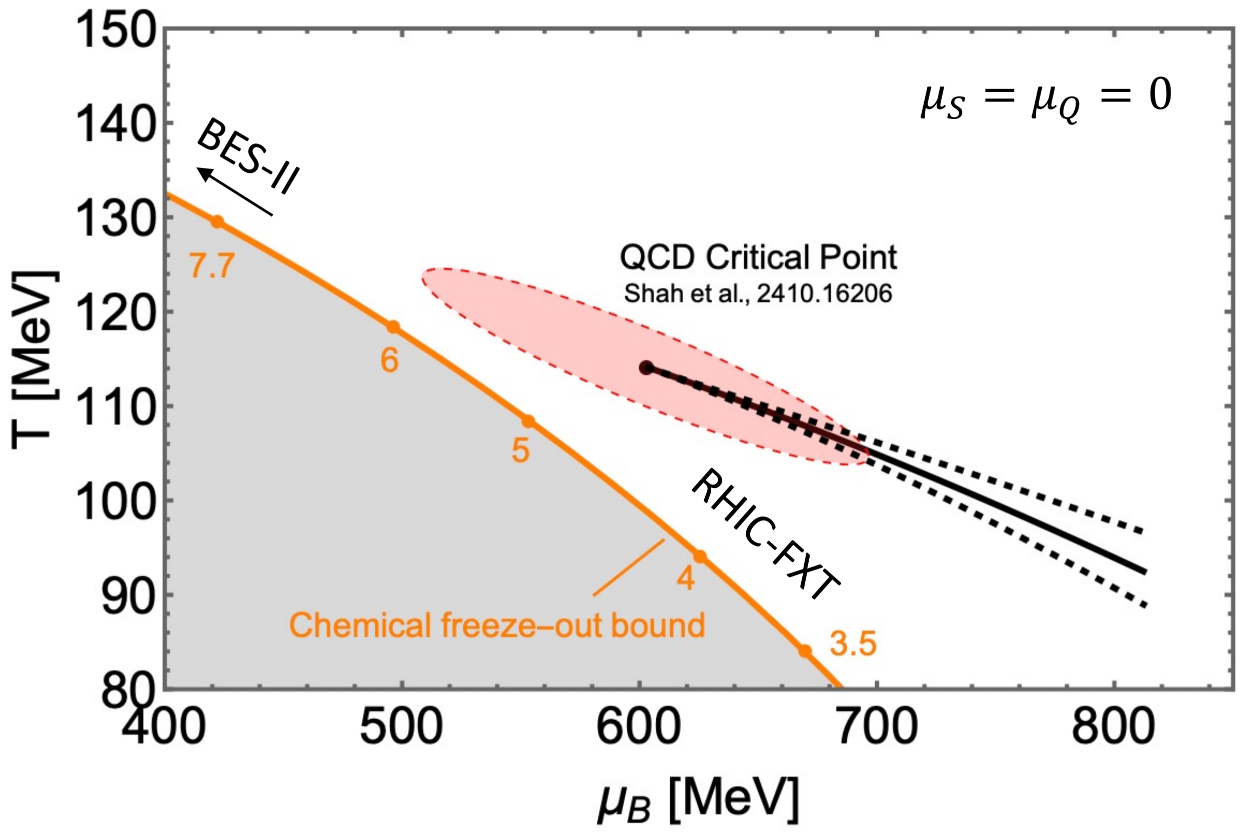
Critical point and heavy-ion collisions

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, Poberezhniuk, Gorenstein, VV, PRC 111, 054903 (2025)]

- **Caveats:** strangeness neutrality ($\mu_S \neq 0$), uncertainty in the freeze-out curve
- If the $\mu_B \simeq 600$ MeV predictions are true, the CP may be close to freeze-out line at $\sqrt{s_{NN}} \sim 3.5 - 5$ GeV

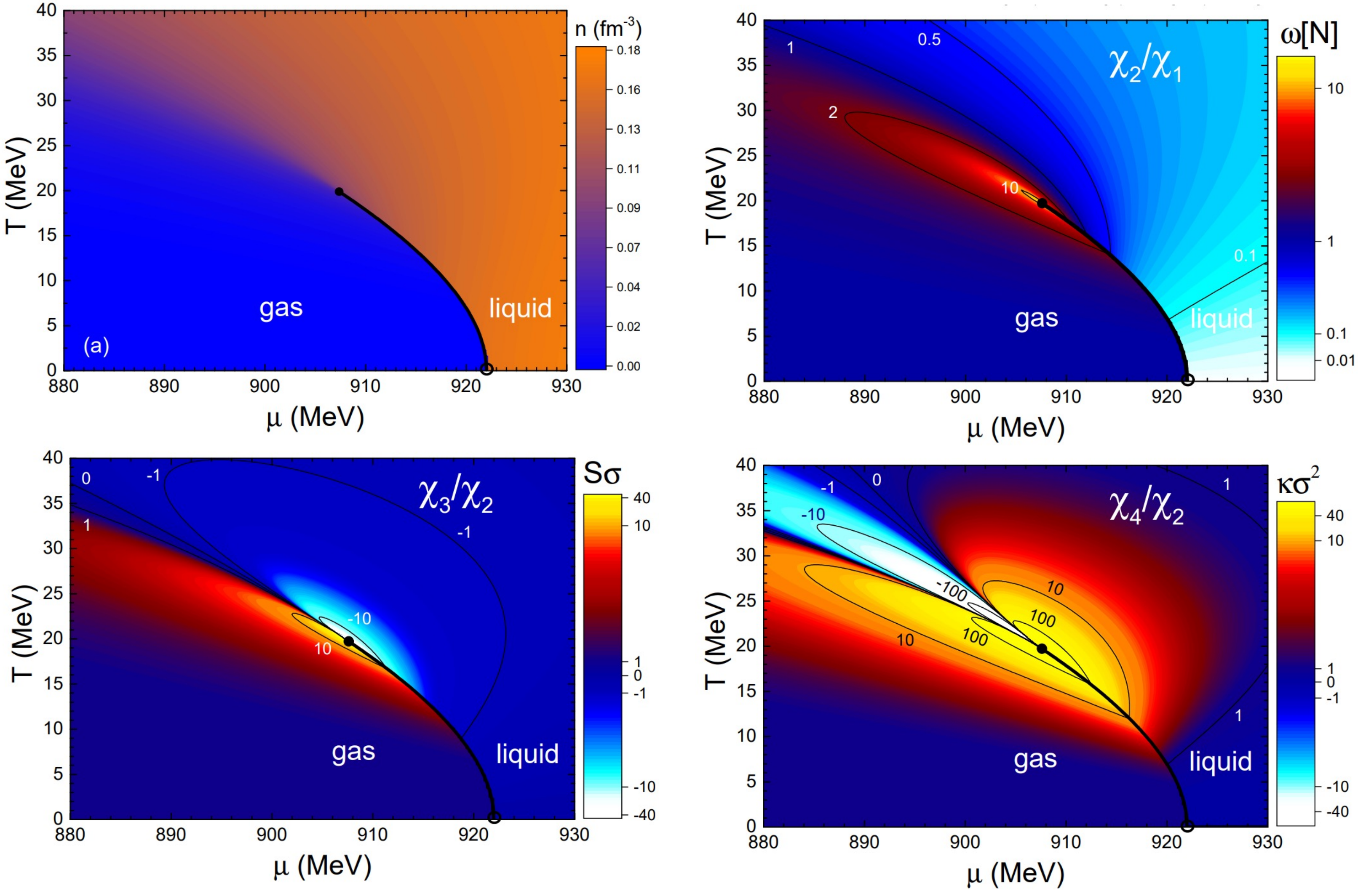
Example: (Nuclear) Liquid-gas transition

(QCD) critical point: large correlation length and fluctuations

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

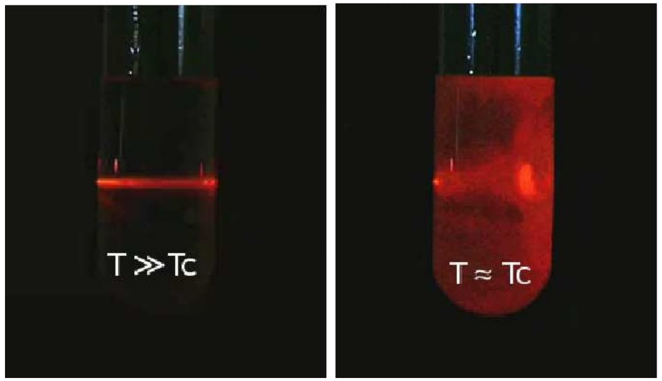
$$\xi \to \infty$$

M. Stephanov, PRL '09, '11



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

Critical opalescence

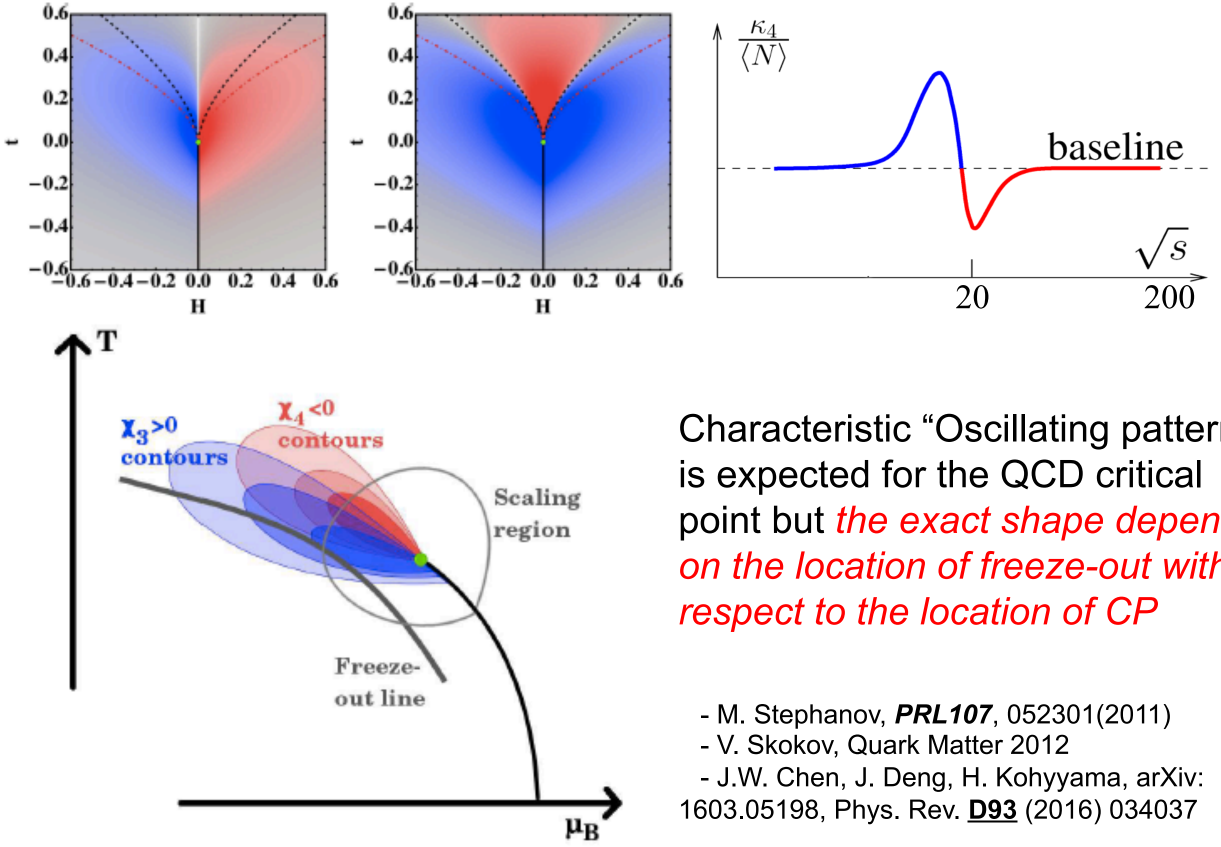


$$\langle N^2 \rangle - \langle N \rangle^2 \sim \langle N \rangle \sim 10^{23}$$

in equilibrium

Equilibrium Expectations and Beam Energy Scan

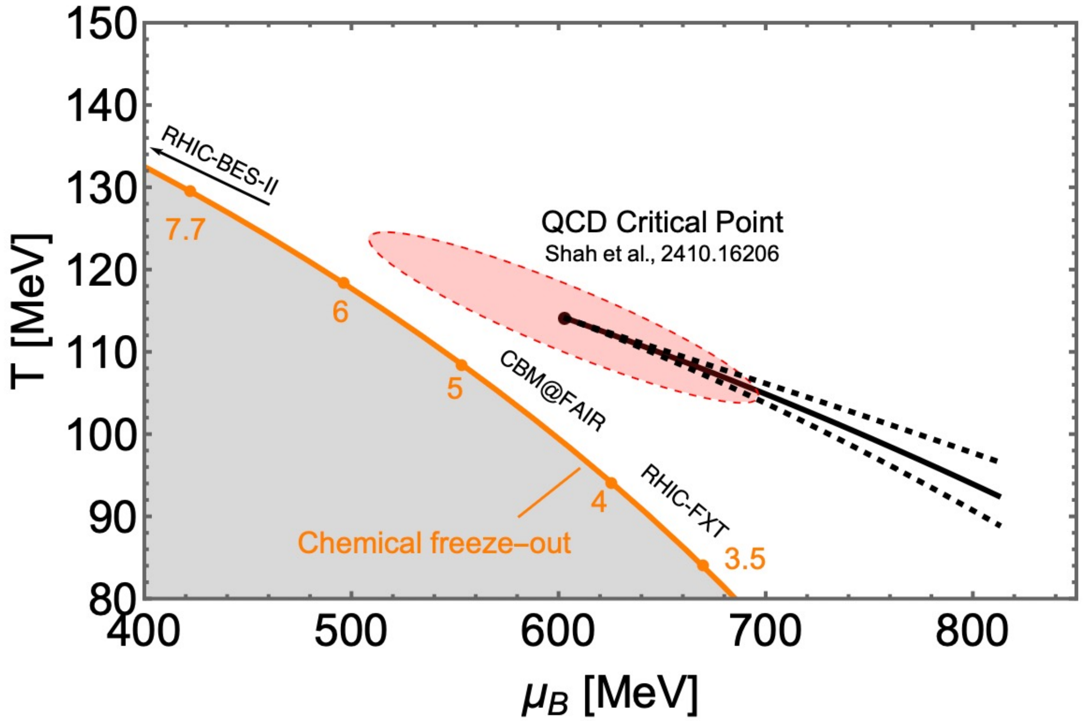
Expectation from Calculations

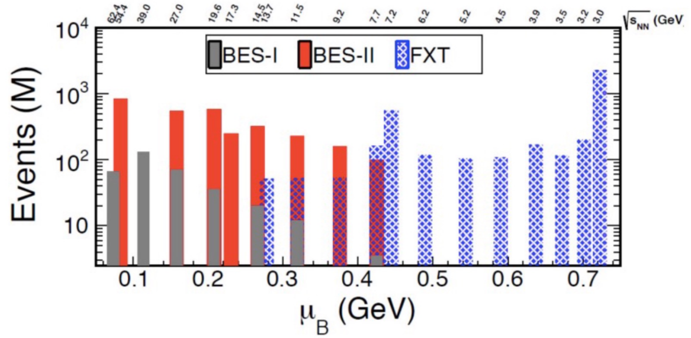


Characteristic "Oscillating pattern" is expected for the QCD critical point but *the exact shape depends on the location of freeze-out with respect to the location of CP*

- M. Stephanov, ***PRL107***, 052301(2011)
- V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, arXiv: 1603.05198, Phys. Rev. **D93** (2016) 034037

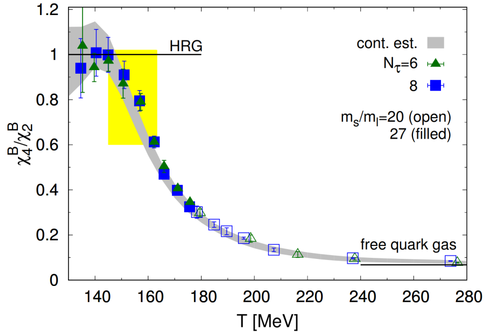
N. Xu, CPOD 2016





Theory vs experiment

guidance from theory (e.g. lattice)

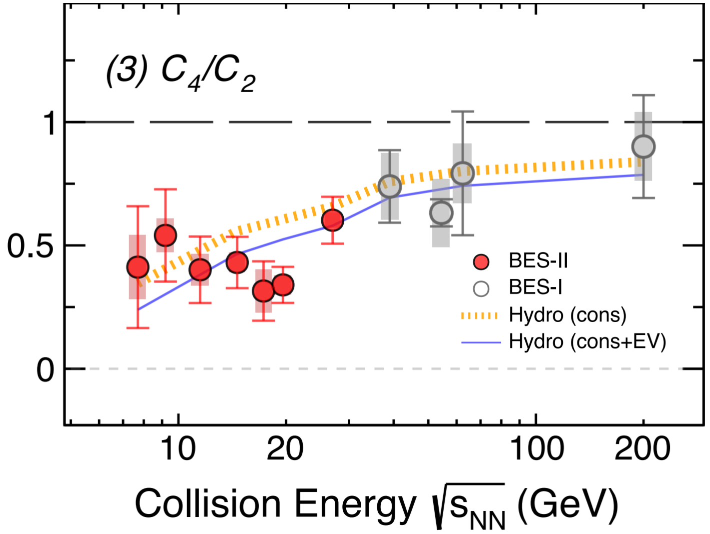


hydro simulation

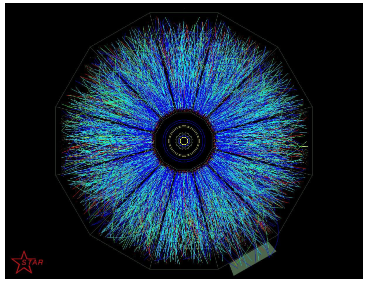
hadronic phase

canonical effects

kinematic cuts



experiment (the real thing)



event selection

track reconstruction

efficiency correction

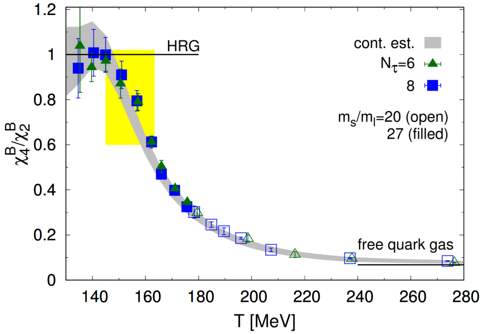
CBWC

purity

Theory vs experiment

guidance from theory (e.g. lattice)

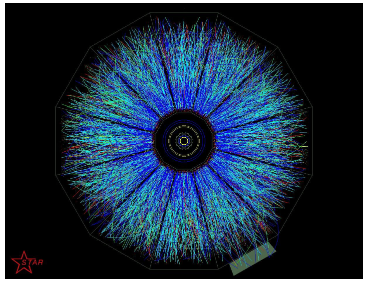
experiment (the real thing)



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

- Full hydro simulation
- Lattice QCD-like baryon susceptibilities (interacting HRG)
- Experimental kinematic cuts
- Global baryon conservation: SAM correction

Non-critical baseline (hydro EV) prediction

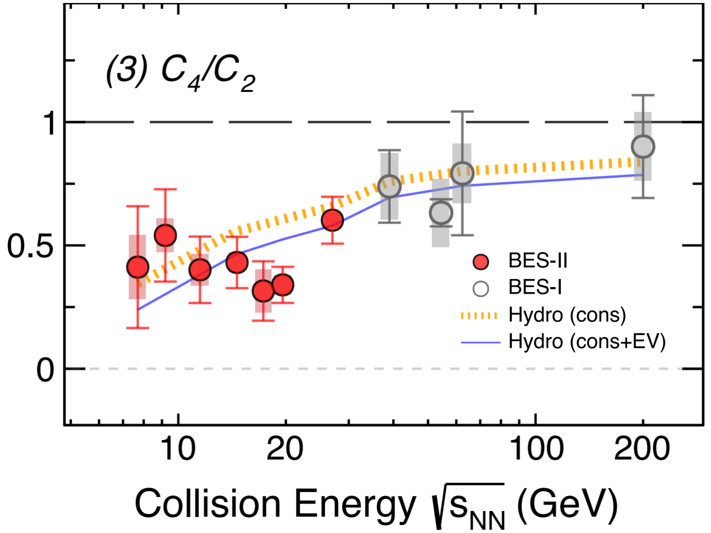


hydro simulation

hadronic phase

canonical effects

kinematic cuts



event selection

track reconstruction

efficiency correction

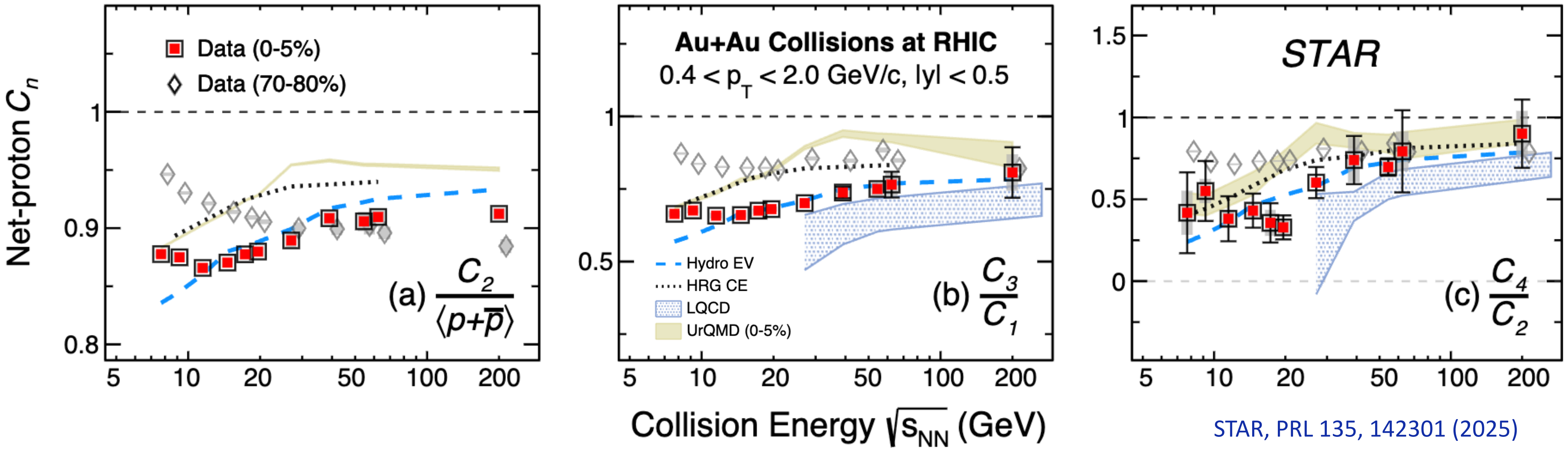
CBWC

purity

RHIC-BES-II data: Ordinary cumulants

UNIVERSITY OF HOUSTON

Net-proton cumulant ratios



STAR, PRL 135, 142301 (2025)

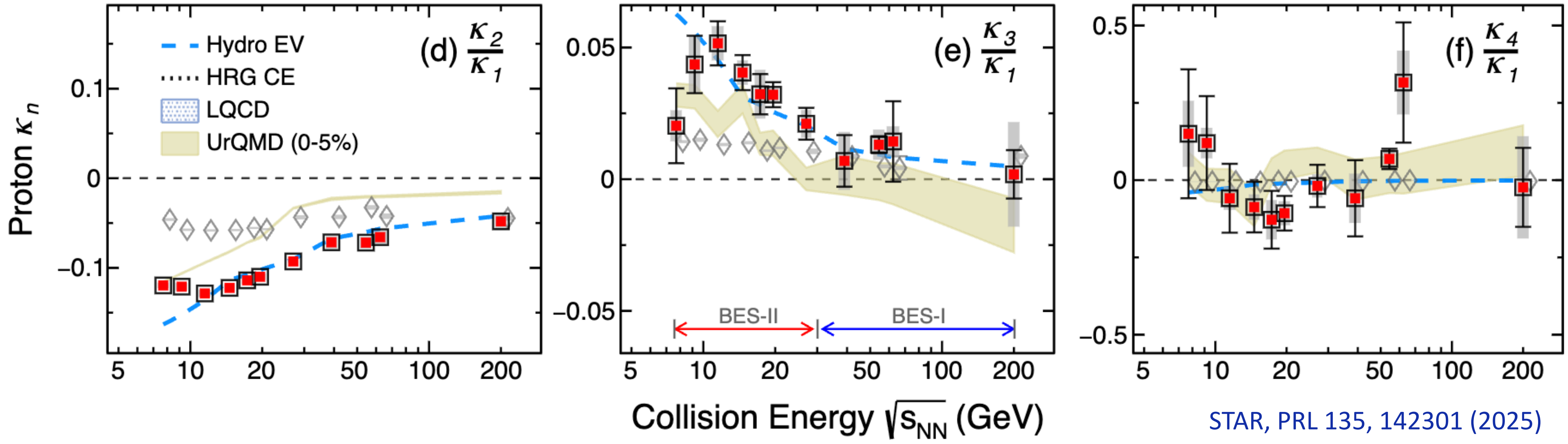
Hydro EV: VV, V. Koch, C. Shen, Phys. Rev. C 105, 014904 (2022)

Agreement with the baseline above $\sqrt{s_{NN}} \sim 10 - 20$ GeV

Deviations at lower energies. More pronounced in factorial cumulants.

RHIC-BES-II data: Factorial cumulants

Proton factorial cumulant ratios



STAR, PRL 135, 142301 (2025)

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

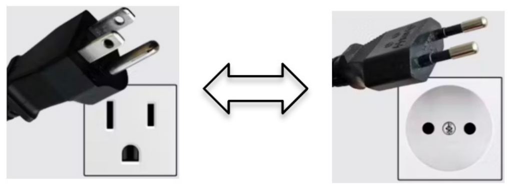
Factorial cumulants: linear combinations of ordinary cumulants.
Measure deviations from Poisson and isolate multi-particle correlations.

$$\hat{C}_1 = C_1 \qquad \hat{C}_2 = C_2 - C_1$$

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

STAR
Cumulants (C)
Factorial cumulants (κ)

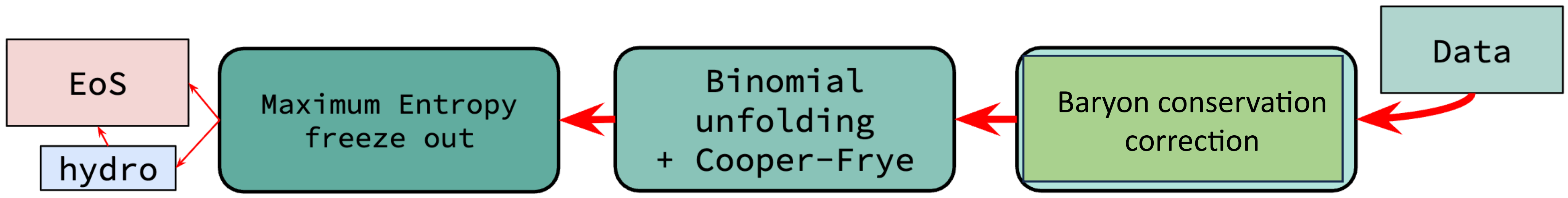
Others
Cumulants (κ)
Factorial cumulants (C)



From M. Arslandok, QM2025

Inference of baryon number susceptibilities from data

G. Pihan, R. Poberezhniuk, VV, to appear



Generalizing the hydro calculation

UNIVERSITY OF HOUSTON

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

- Particlization at a constant energy density ~0.26 GeV/fm^3
- Canonical (baryon conservation) statistical hadronization with excluded volume repulsion
- Drawback: Cannot incorporate arbitrary EoS, in particular one with a CP

Maximum entropy freeze-out [M. Pradeep et al., PRL 130, 162301 (2023); J.M. Karthein, PRD 113, 074010 (2026)]

- Incorporate single hydrodynamic mode – baryon density fluctuations
- Maximum entropy method defines local joint susceptibilities of particle numbers G. Pihan et al., to appear
  - Joint susceptibilities of baryons (+) and antibaryons (-)
- Use the χ_n^B input from *arbitrary EoS* (LQCD expansion, s-contours, functional QCD, …)

SAM-3.0: General correction for exact baryon conservation

- Based on saddle-point method [R. Poberezhniuk, V.A. Kuznietsov, G. Pihan, VV, 2607.01783]

Maximum entropy freeze-out

Problem: the equation of state encodes fluctuations of conserved baryon number via χ_n^B but experiment measures fluctuations of particle number (protons and antiprotons)

There are infinitely many ways to distribute conserved charge fluctuations among particles and antiparticles

Maximum entropy freeze-out: distribute fluctuations in a way that maximizes relative entropy

[M. Pradeep et al., PRL 130, 162301 (2023); J.M. Karthein, PRD 113, 074010 (2026)]

Incorporating single hydrodynamic mode – baryon density fluctuations – produces factorial cumulants

$$\hat{\chi}^{+-}_{nm}(x) = \delta_{m0}\delta_{n1}\bar{\chi}_1^{+} + \delta_{n0}\delta_{m1}\bar{\chi}_1^{-} + (-1)^m \underbrace{\hat{\Delta}\chi^B_{n+m}(x)}_{\text{difference to HRG}} \frac{\bar{\chi}_1^{+}(x)^n \bar{\chi}_1^{-}(x)^m}{(\bar{\chi}_1^{+}(x) + \bar{\chi}_1^{-}(x))^{n+m}}$$

$$\bar{\chi}_n^B(x) = \bar{\chi}_1^{+}(x) + (-1)^n \bar{\chi}_1^{-}(x)$$

HRG (Poisson) baseline

G. Pihan et al., to appear

$+$ is baryon, $-$ is antibaryon

$\hat{\Delta}\chi_n^B$ – **irreducible relative cumulants (IRCs)** that encode genuine multi-particle correlations

$$\hat{\Delta}\chi_2^B = \Delta\chi_2^B$$

$$\hat{\Delta}\chi_3^B = \Delta\chi_3^B - 3\Delta f\, \Delta\chi_2^B$$

$$\hat{\Delta}\chi_4^B = \Delta\chi_4^B - 6\Delta f\, \Delta\chi_3^B - [4 - 15(\Delta f)^2]\Delta\chi_2^B$$

$$\Delta\chi_n^B = \chi_n^B - \overline{\chi_n^B}$$

$$\Delta f = \frac{\bar{\chi}_1^{+} - \bar{\chi}_1^{-}}{\bar{\chi}_1^{+} + \bar{\chi}_1^{-}}$$

Subensemble acceptance method 3.0

UNIVERSITY OF HOUSTON

Problem: equilibrium fluctuations assume grand-canonical heat bath. In HICs there is no heat bath, total net baryon number is conserved exactly. [R. Poberezhniuk, V.A. Kuznietsov, G. Pihan, VV, 2607.01783]

SAM-3.0: Apply correction for baryon number conservation

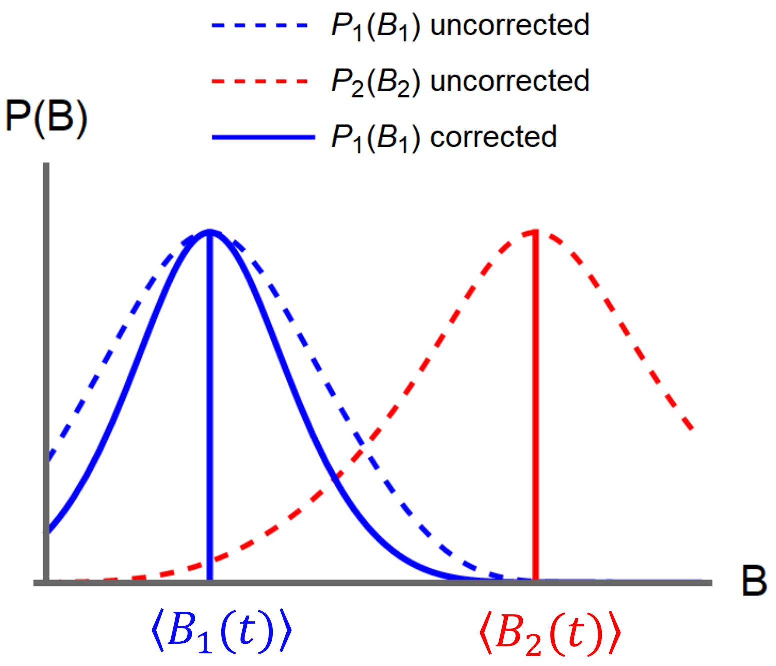
- Compute grand-canonically and perform correction at final step
- Requires joint accepted proton (X) and 4π baryon (B) cumulants, summed over all Cooper-Frye cells

$$\kappa_1^{X|B} = \kappa_1^X,$$

$$\kappa_2^{X|B} = \kappa_2^X - \frac{(\kappa_{11}^{XB})^2}{\kappa_2^B},$$

$$\kappa_3^{X|B} = \kappa_3^X - 3\,\frac{\kappa_{11}^{XB}\kappa_{21}^{XB}}{\kappa_2^B} + 3\,\frac{(\kappa_{11}^{XB})^2\kappa_{12}^{XB}}{(\kappa_2^B)^2} - \frac{(\kappa_{11}^{XB})^3\kappa_3^B}{(\kappa_2^B)^3},$$

$$\begin{aligned}\kappa_4^{X|B} = \kappa_4^X + \frac{1}{\left(\kappa_2^B\right)^4}\Bigg\{&\left(\kappa_{11}^{XB}\right)^2\left[-6\,\kappa_3^B\left(\kappa_2^B\kappa_{21}^{XB} - 2\,\kappa_{11}^{XB}\kappa_{12}^{XB}\right) + \kappa_4^B\left(\kappa_{11}^{XB}\right)^2\right]\\ &- \kappa_2^B\left[4\,\kappa_2^B\kappa_{11}^{XB}\left(\kappa_2^B\kappa_{31}^{XB} - 3\,\kappa_{12}^{XB}\kappa_{21}^{XB}\right) + 6\left(\kappa_{11}^{XB}\right)^2\left(2\left(\kappa_{12}^{XB}\right)^2 - \kappa_2^B\kappa_{22}^{XB}\right)\right.\\ &\left.+\,3\left(\kappa_2^B\right)^2\left(\kappa_{21}^{XB}\right)^2 + 4\left(\kappa_{11}^{XB}\right)^3\kappa_{13}^{XB}\right]\Bigg\} - 3\,\frac{\left(\kappa_3^B\right)^2\left(\kappa_{11}^{XB}\right)^4}{\left(\kappa_2^B\right)^5}.\end{aligned}$$

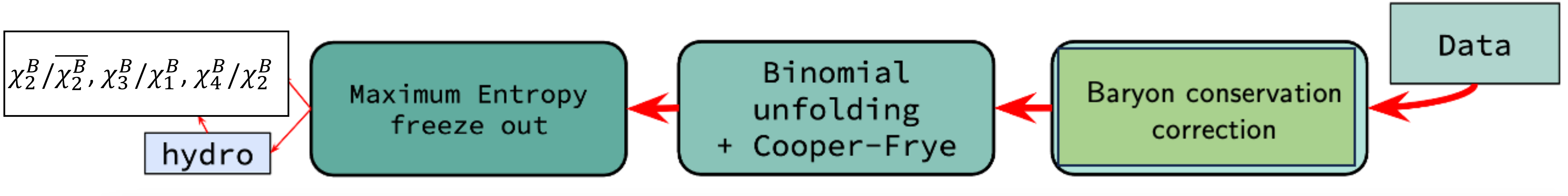


Open source (Mathematica and header-only C++): https://github.com/UH-Physics-NuclearTheory/SAM3

Bayesian EoS inference

Instead of using χ_n^B as an input, extract χ_n^B's that fit data directly at each energy

Specifically, the ratios $\chi_2^B/\overline{\chi_2^B}, \chi_3^B/\chi_1^B, \chi_4^B/\chi_2^B$ where $\overline{\chi_2^B}$ is the HRG baseline



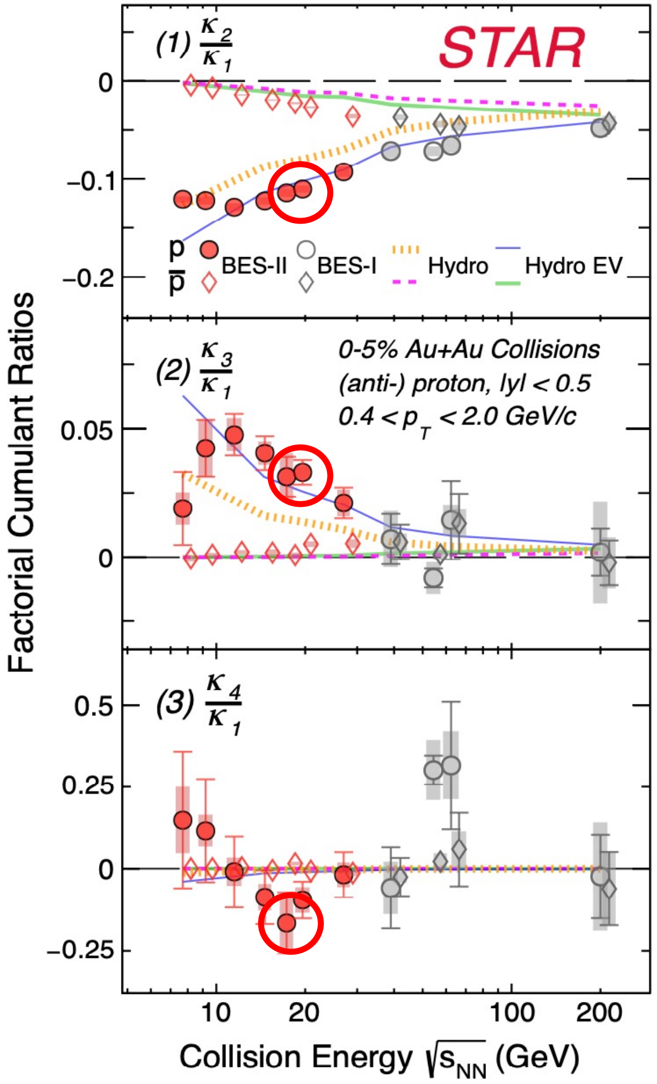
Adapted from G. Pihan, SQM2026

Our first analysis uses collider-mode BES data only.

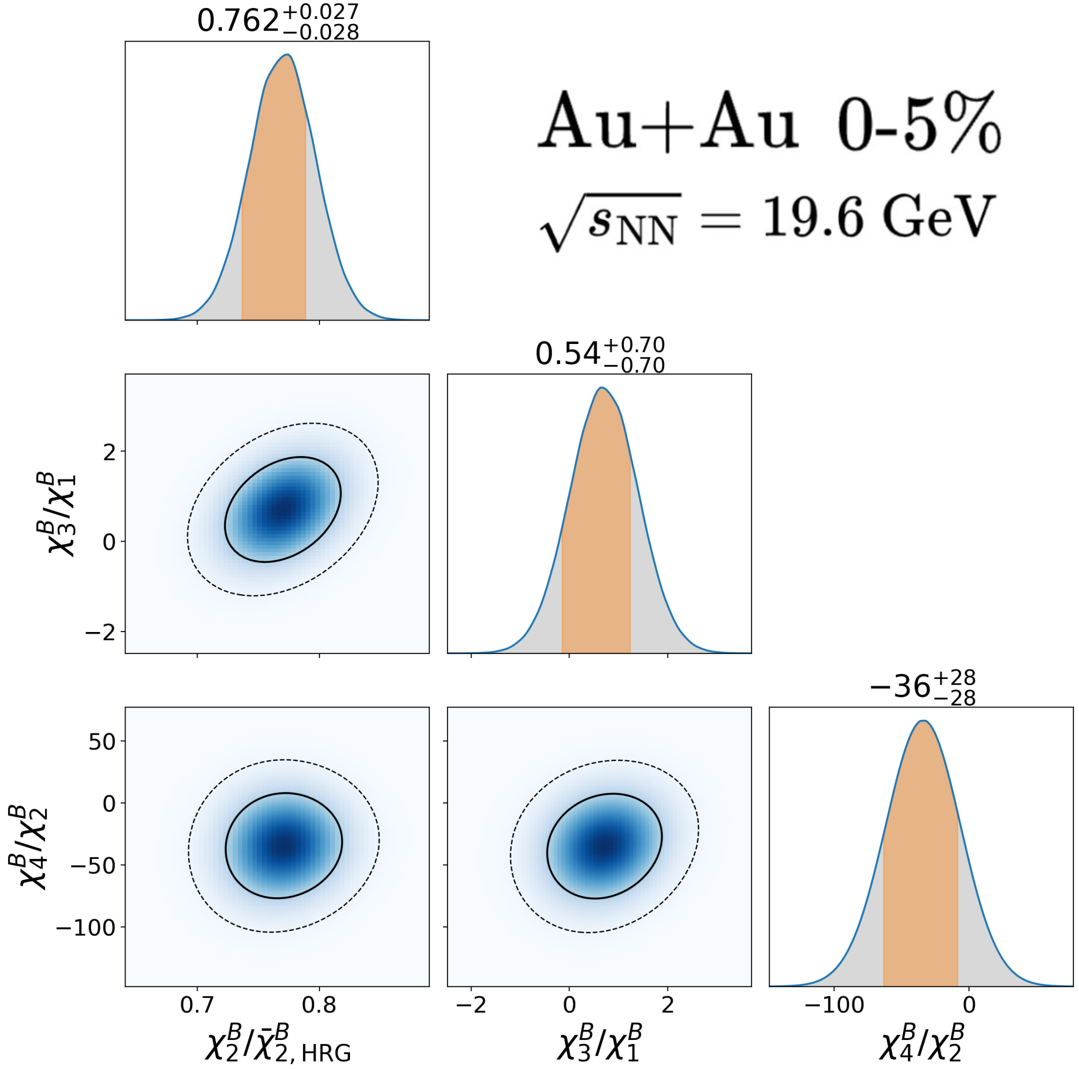
FXT inference is deferred pending improved theoretical modeling (currently no hydro below 7.7 GeV) and volume-fluctuation corrections (being refined in STAR).

Bayesian inference: 19.6 GeV

UNIVERSITY OF HOUSTON

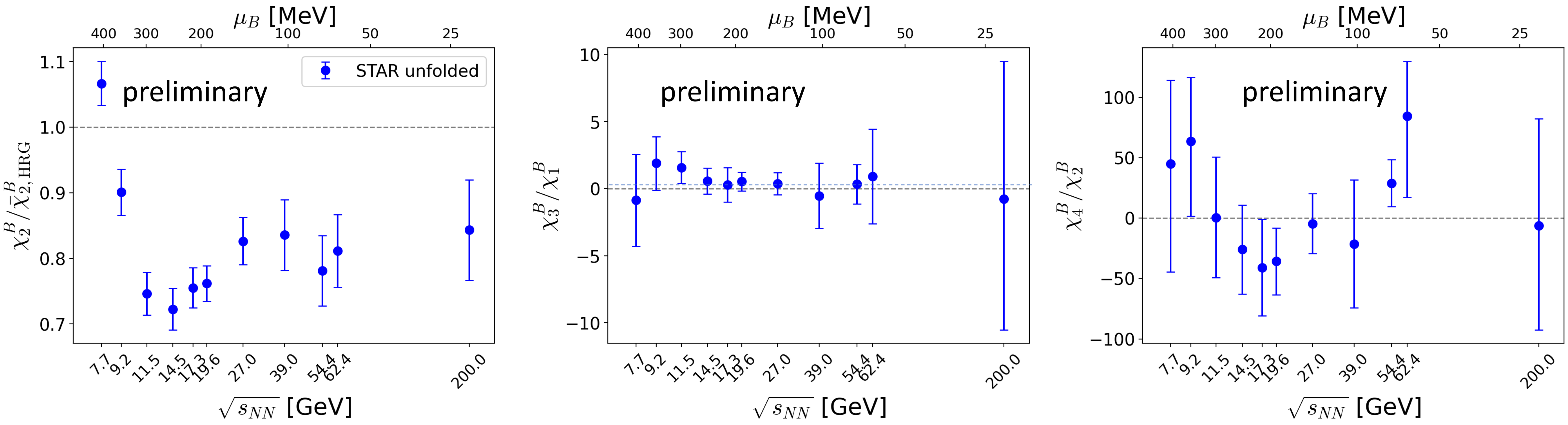


Unfolding



G. Pihan, R. Poberezhniuk, VV, to appear

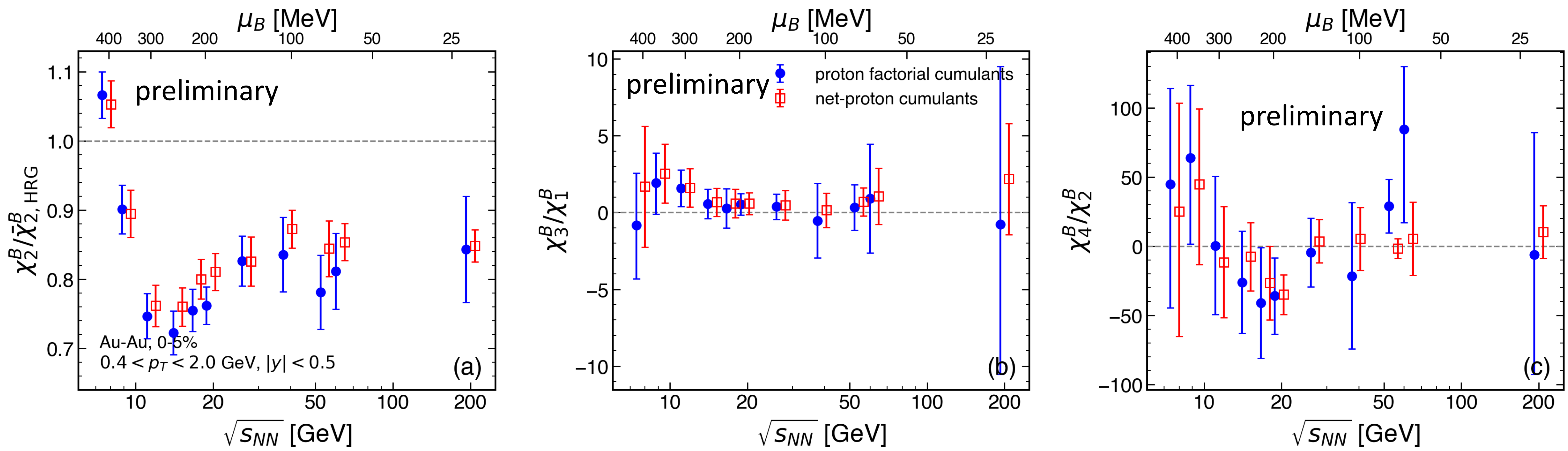
Extracted susceptibilities



- Tight constraints on χ_2^B value relative to HRG
- Uncertainties in 3rd and 4th order susceptibilities are large
  - Intermediate steps (net-B to B^+, kinematic cuts, $B^+ \rightarrow p$) act akin to efficiency correction
  - Reducing uncertainties in the data would lead to reduced extraction errors
- Results appear weakly sensitive to e_{sw}, sensitivity to other hydro parameters to be studied

G. Pihan, R. Poberezhniuk, VV, to appear

Extracted susceptibilities: using net-proton cumulants



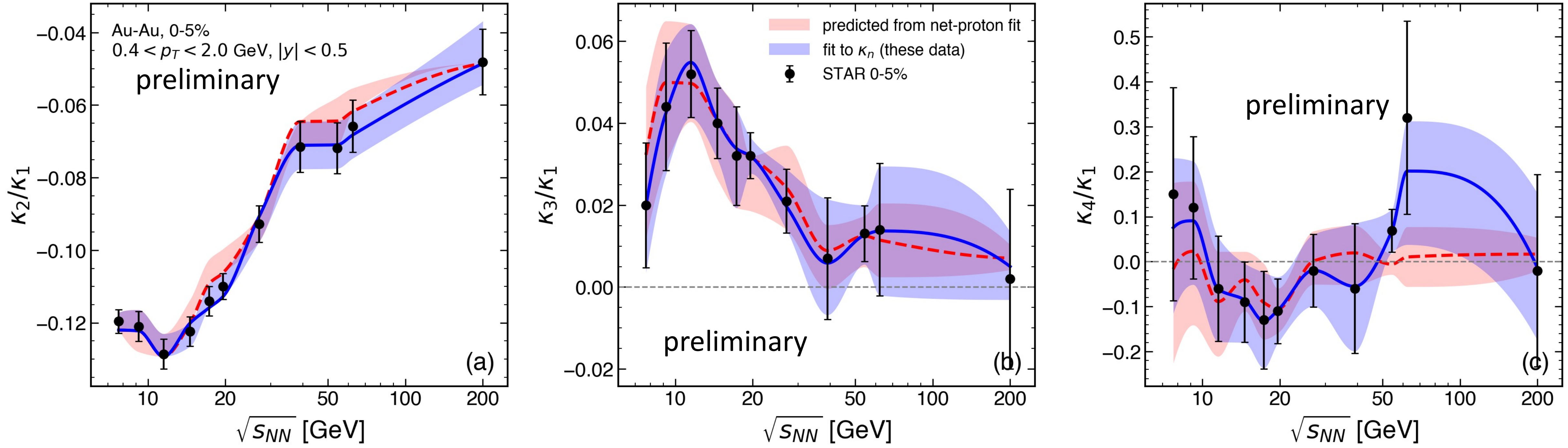
- Red points: extraction using net-proton cumulants rather than proton factorial cumulants
- Generally smaller error at larger $\sqrt{s_{\mathrm{NN}}}$, this is due to preserving antiproton correlations
- Results consistent with factorial cumulant extraction
  - Notably: $\chi_4^B/\chi_2^B = -35 \pm 14$
- But beware of the antiproton puzzle (based on BES-I data)

A. Bzdak, V. Koch, VV, PRC 112, 024901 (2025)

G. Pihan, R. Poberezhniuk, VV, to appear

Cross-checking the fits

UNIVERSITY OF HOUSTON



- Fit to net-proton cumulants, then compute proton factorial cumulants
- The results are consistent

A. Bzdak, V. Koch, VV, PRC 112, 024901 (2025)

G. Pihan, R. Poberezhniuk, VV, to appear

Attraction vs repulsion

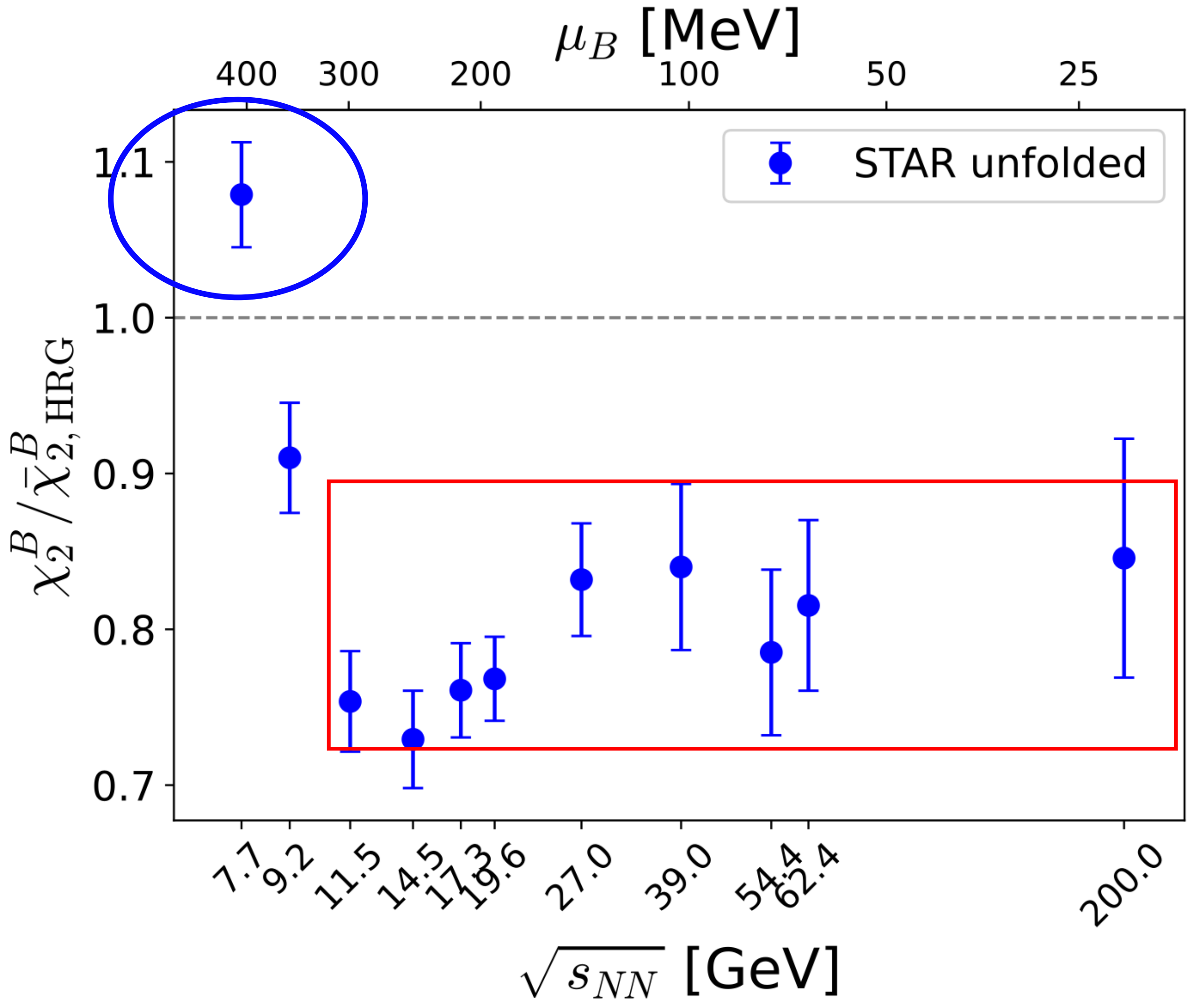
G. Pihan, R. Poberezhniuk, VV, to appear

attraction

$\chi_2^B / \overline{\chi_2^B} > 1$

VDW: $\dfrac{1}{1 - \dfrac{2an}{T}}$

$a > 0$ – attraction



repulsion

$\chi_2^B / \overline{\chi_2^B} < 1$

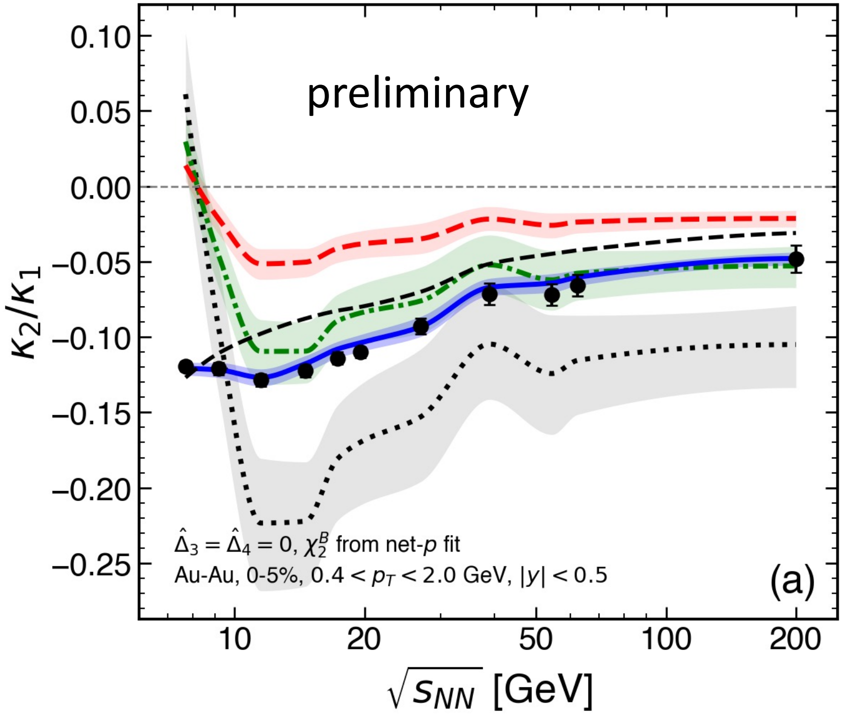
VDW: $(1 - \mathrm{bn})2$

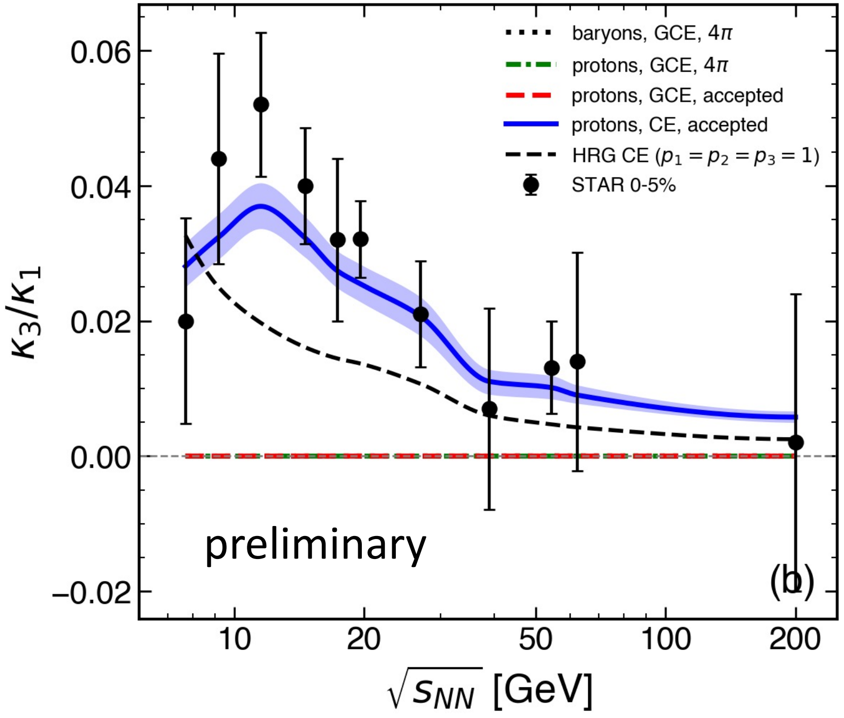
$\mathrm{b} > 0$ – repulsion

Interplay of repulsive (high $\sqrt{s_{NN}}$) and attractive (low $\sqrt{s_{NN}}$) interactions?

Is everything driven by 2-particle correlations?

- Assume that only 2-baryon correlations are non-zero in the EoS
- This corresponds to setting irreducible relative cumulants $\widehat{\Delta}\chi_3^B = 0$ and $\widehat{\Delta}\chi_4^B = 0$



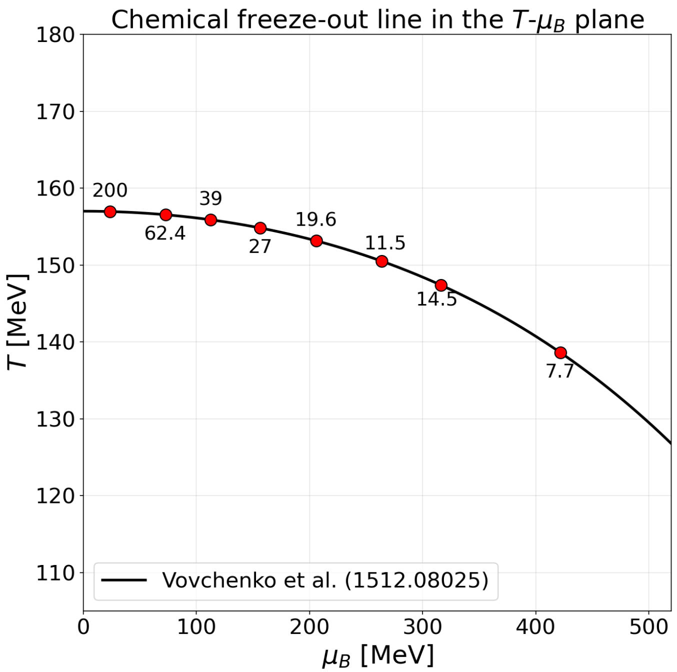


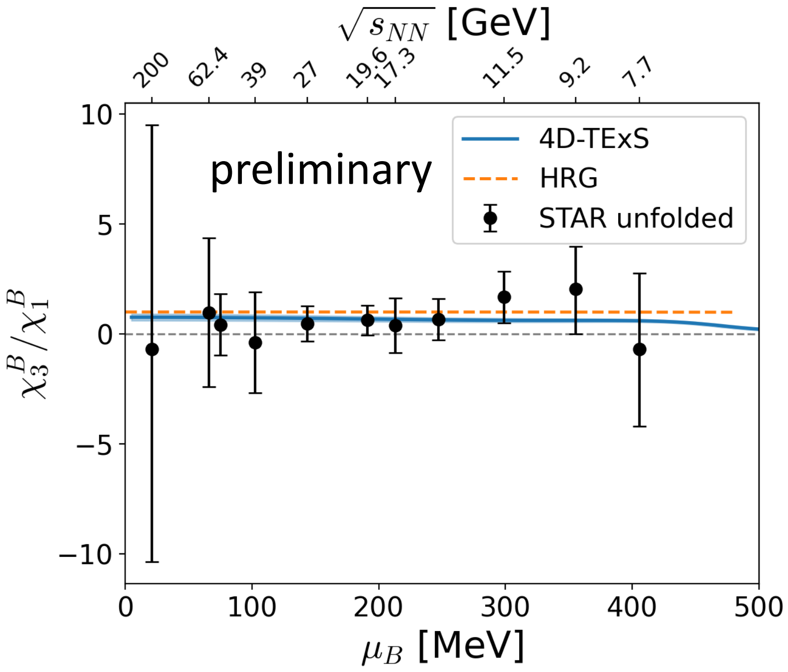
Non-monotonic third-order factorial cumulant is generated by interplay of that of equilibrium 2-particle correlations and baryon conservation correction

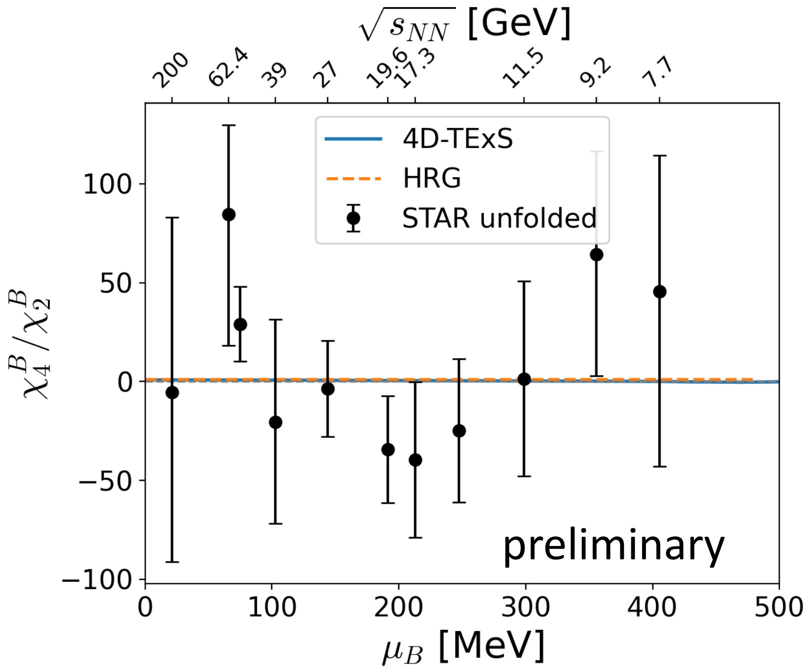
G. Pihan, R. Poberezhniuk, VV, to appear

Comparing to lattice QCD

To map the results to QCD phase diagram use chemical freeze-out parametrization [VV et al., PRC 93, 064906 (2016)]







$\varepsilon_{\rm SW} \approx 0.35 - 0.40$ GeV/fm^3

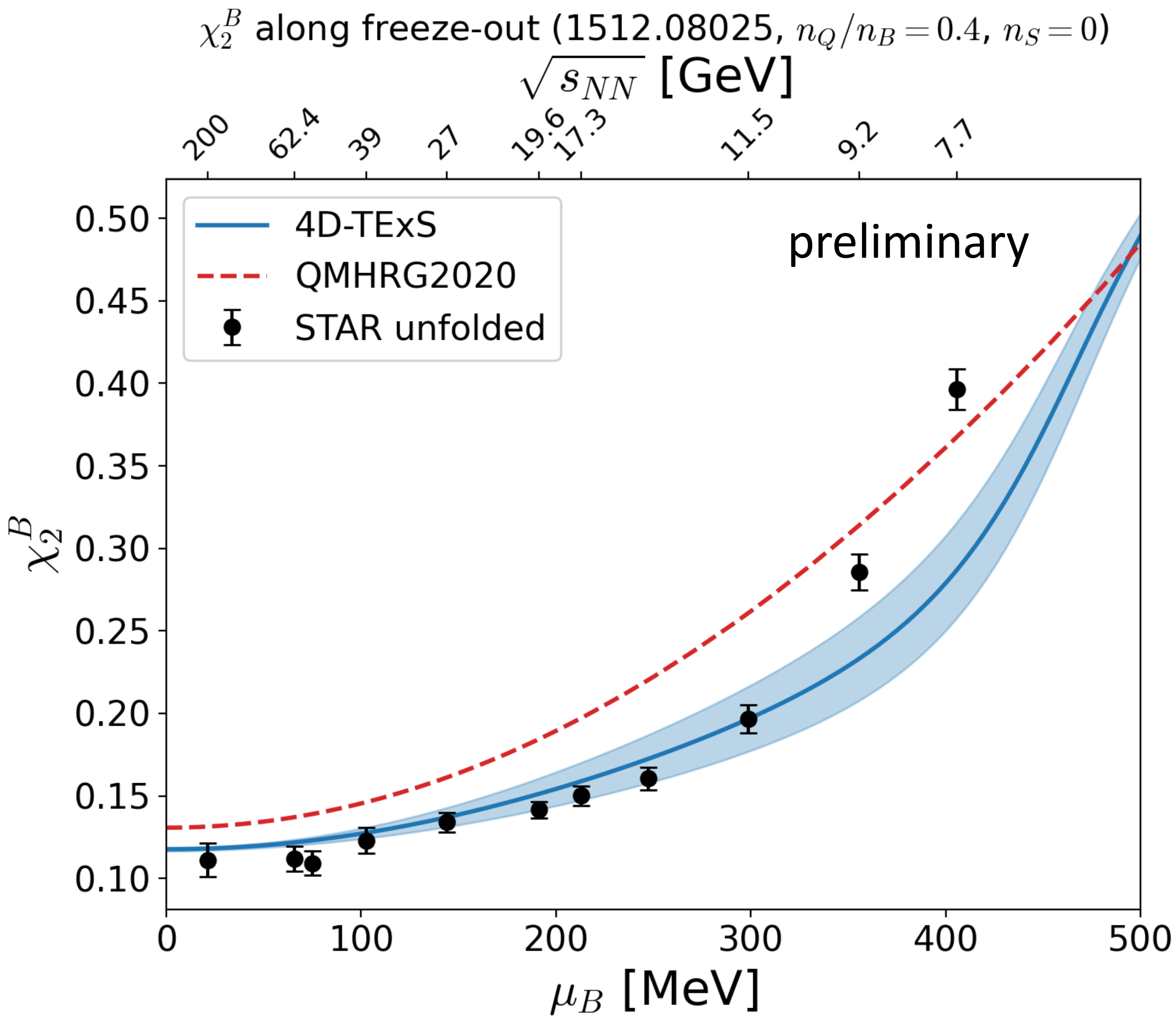
4D-TExS: [A. Abuali et al., Phys. Rev. D 112, 054502 (2025)]

- Lattice-based EoS at finite baryon density
- Computed under HIC conditions ($n_Q/n_B = 0.4, n_S = 0$)

Given large errors on extracted higher-order susceptibilities, essentially any scenario (from baseline to CP) is possible

G. Pihan, R. Poberezhniuk, VV, to appear

Baryon susceptibility χ_2^B



4D-TExS: [A. Abuali et al., Phys. Rev. D 112, 054502 (2025)]

- To obtain absolute χ_2^B multiply by HRG value
  - QMHRG motivated by lattice QCD studies at $\mu_B = 0$ [HotQCD, PRD 104, 074512 (2021)]
- Agreement with lattice QCD at $\mu_B < 300$ MeV
- Enhancement relative to lattice QCD at $\mu_B > 300$ MeV

⚠ **Caveats:**

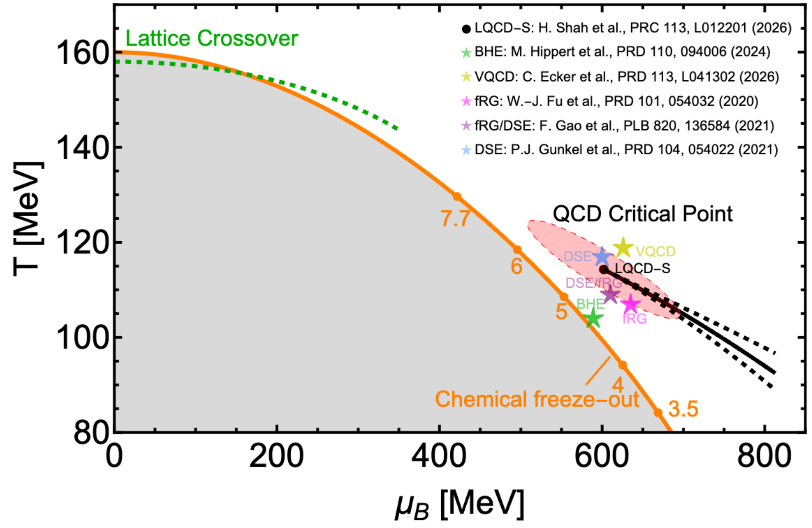
- Sensitive to the hadron list
- Sensitive to assumed freeze-out line
- Lattice EoS (4D-TExS) is an extrapolation (no truncation error included)

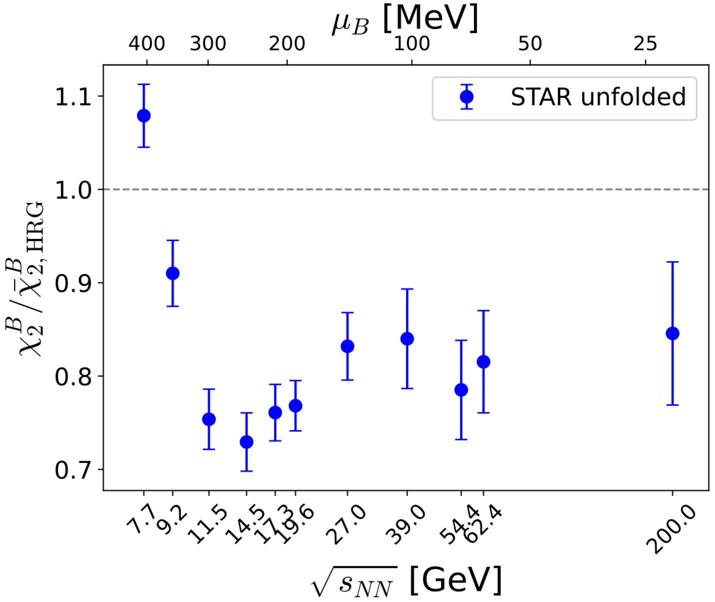
G. Pihan, R. Poberezhniuk, VV, to appear

Summary

- **Entropy contours method**
  - Suggests a candidate critical region near $T \sim 110$ MeV, $\mu_B \sim 600$ MeV conditional on the low order extrapolation.
  - Strangeness neutrality (HICs) moves the candidate CP to larger μ_B
  - Beta equilibrium (neutron stars) changes it only mildly
  - Sufficiently large isospin asymmetry (early Universe) removes it
- **Inference from heavy-ion data**
  - The inferred χ_2^B agrees with lattice-based EoS at lower μ_B and shows enhancement at higher μ_B
  - 2-particle equilibrium correlations appear to drive non-monotonic third-order factorial cumulants observed by STAR
  - Large uncertainties keep higher orders weakly constrained.

Outlook: Fixed-target energies and LHC, other centralities.





Thanks for your attention