2025 RHIC/AGS ANNUAL USERS' MEETING

RHIC 25: A QUARTER CENTURY OF DISCOVERY

May 20-23, 2025

Workshop Report: BES

Dekrayat Almaalol, Emmy Duckworth

Experimental overview of the BES II	*Lijuan Ruan*	
Physics Large Seminar Room (LSR), 510	09:00 - 09:30	
Analysis of BES Fluctuations and cumulants (experimental)	*Zachary Sweger*	
Physics Large Seminar Room (LSR), 510	09:30 - 10:00	
UPC	*Ashik Ikbal*	
Physics Large Seminar Room (LSR), 510	10:00 - 10:30	
Flow Overview (experimental)	*MD Nassim*	
Physics Large Seminar Room (LSR), 510	13:50 - 14:20	
eToF calibration	*Mathias Labonte*	
Physics Large Seminar Room (LSR), 510	14:50 - 15:20	

Theoretical overview of the BES	*Lipei Du*
Physics Large Seminar Room (LSR), 510	11:00 - 11:30
QCD equation of state at finite density and the critical point	*Johannes Jahan*
Physics Large Seminar Room (LSR), 510	11:30 - 12:00
Cumulants and fluctuations measurement at the BES II	*volodymer vovchenko*
Physics Large Seminar Room (LSR), 510	12:00 - 12:30
Flow and Isobars Overview (theory)	*Niseem Magdy*
Physics Large Seminar Room (LSR), 510	14:20 - 14:50

The role of Neutron Stars in constraining the QCD Equation of State	*Veronica Dexheimer*
Physics Large Seminar Room (LSR), 510	15:50 - 16:20
Probing Dense Nuclear Matter: Connecting Neutron Stars and Heavy-Ion Collisions	*Nanxi Yao*
Physics Large Seminar Room (LSR), 510	16:20 - 16:50

5 Experimental Talks

4 Theoretical Talks

2 Theory talks from NS to HIC

I. Experimental measurements and Open questions

LIJUAN RUAN

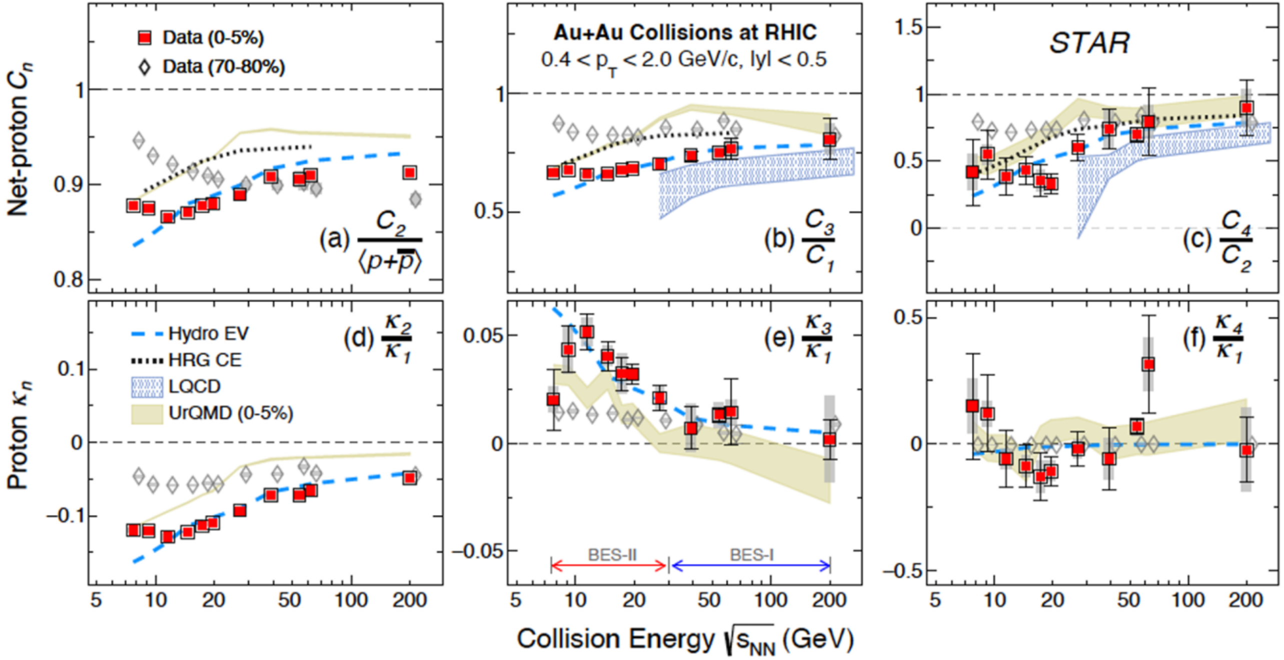
Critical needs

Theory

- Baseline calculations without critical point effects
- Dynamic calculations with critical point effects

Experiment

- Analyze 4.5 GeV and 2B 3 GeV data
- Study rapidity rapidity dependence



$156 < \mu_B < 420$ MeV

Precision results on net-proton cumulants and proton factorial cumulants from BES-II with greatly improved statistical and systematic uncertainties

Reduction factor in uncertainties on 0-5% C_4/C_2 : BES-II vs BES-I

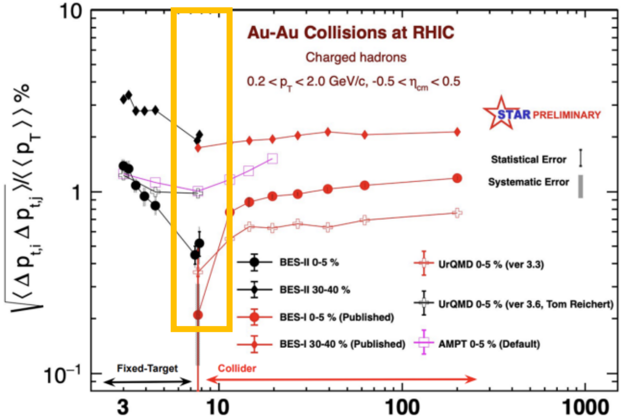
7.7 GeV		19.6 GeV	
stat. error	sys. error	stat. error	sys. error
4.7	3.2	4.5	4

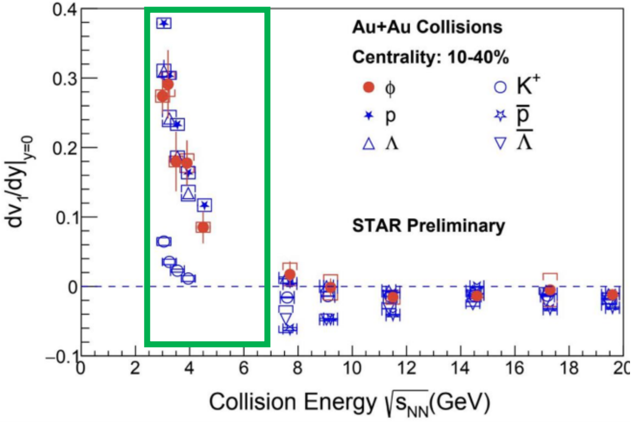
arXiv: 2504.00817

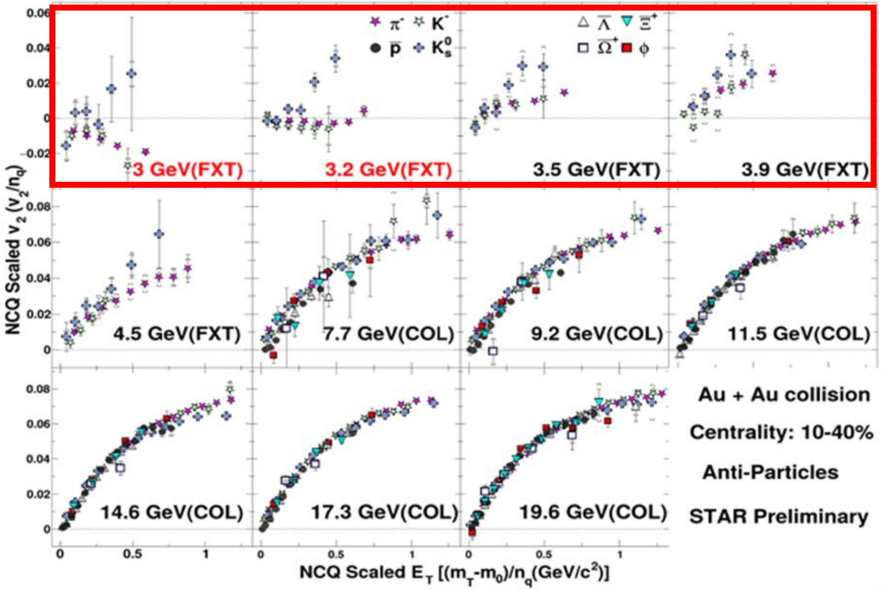
Very interesting trends observed as a function of collision energy

LIJUAN RUAN

Fixed Target: Transition regions and/or signals of critical behaviour?







- 1. Non-monotonic energy dependence of dynamical p_T fluctuations.
- 2. NCQ scaling holds breaks down at $\leq$ 3.2 GeV
  $\rightarrow$ (constraints on partonic collectivity)
- 3. What is the underlying physics mechanism?
  Momentum-dependent mean field potential at lower energies?

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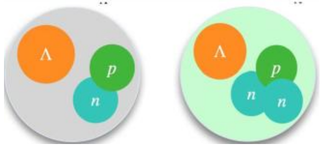
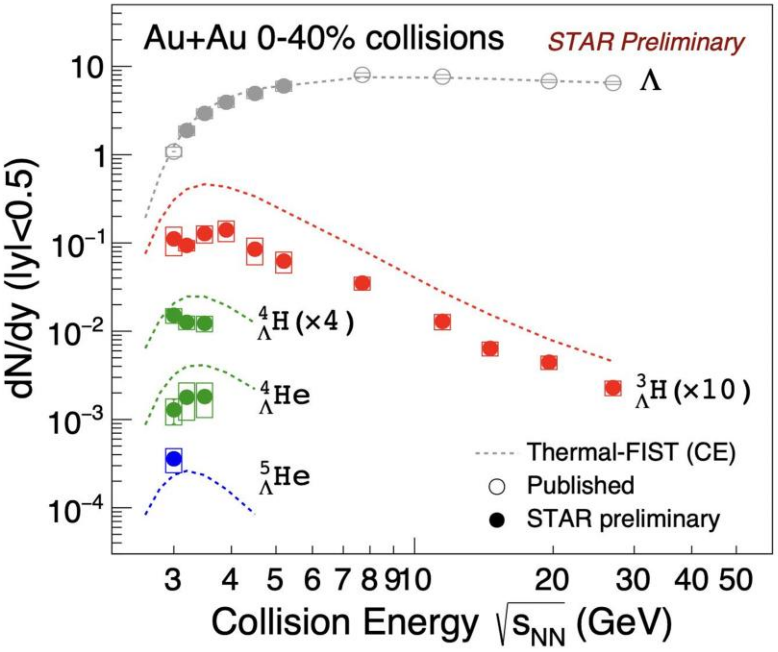
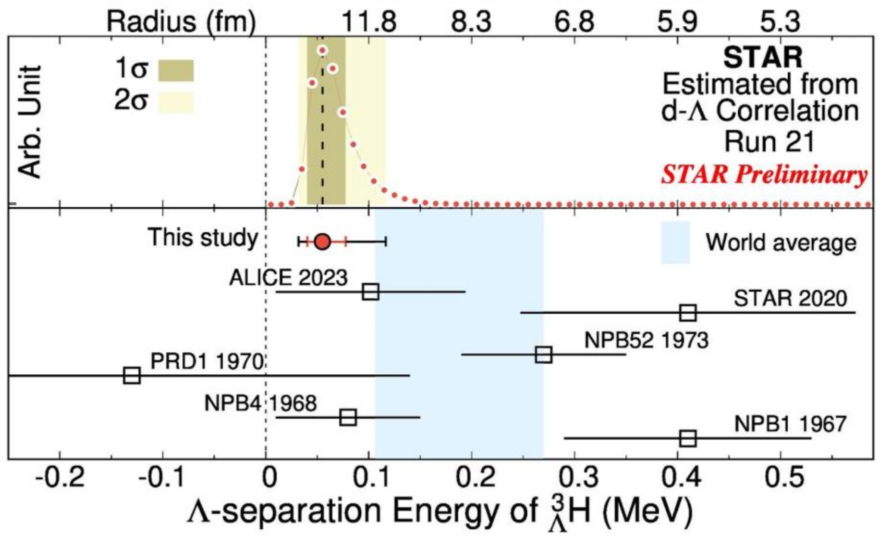
Bonus: hypernuclei production







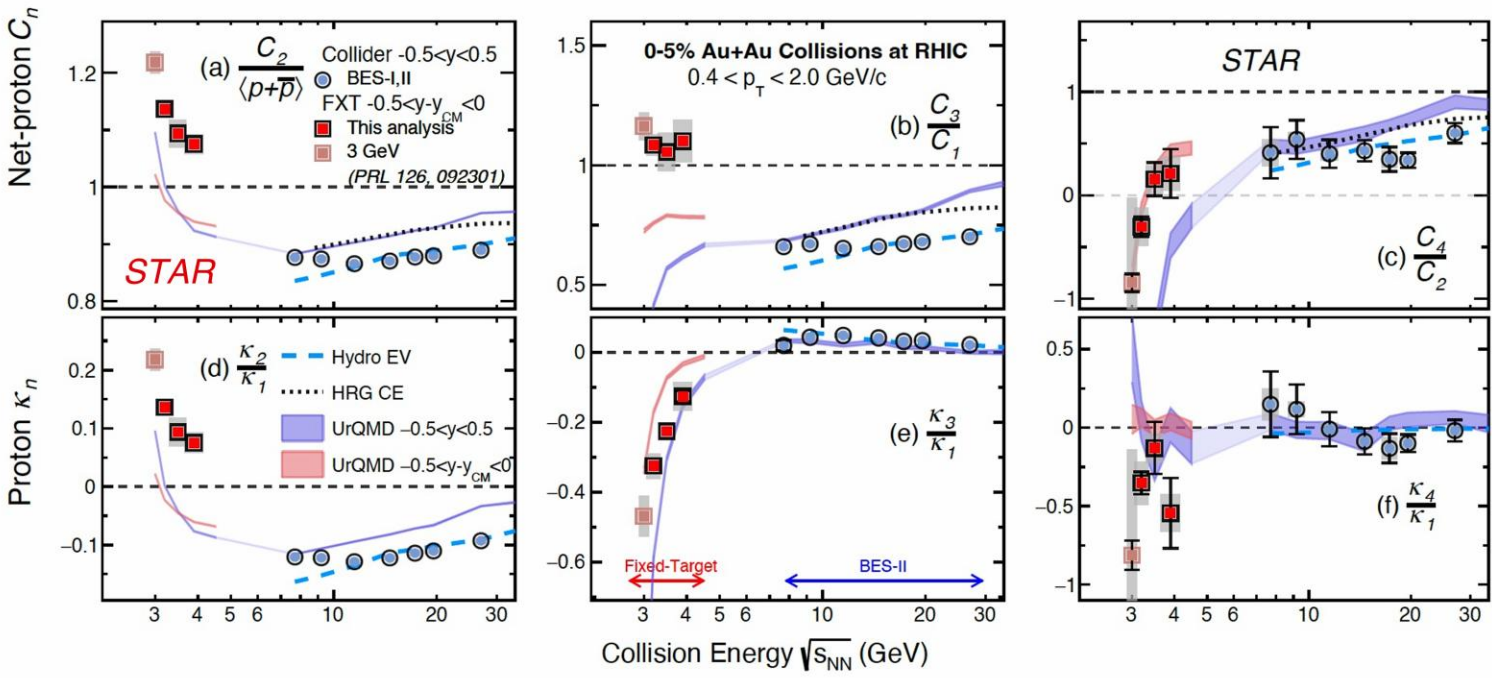
- Most precise hypertriton lifetime measurement via d-Lambda correlations

- Constrain hyperon– nucleon and hyperon-hyperon interaction Connection to neutron stars

ZACHARY SWEGER

Analysis: Cumulant Results

- C_2/C_1 and κ_2/κ_1 monotonically decrease as predicted by UrQMD
- C_3/C_1 shows no strong energy dependence, similar to UrQMD, κ_3/κ_1 monotonically increases as predicted
- Central C_4/C_2 is consistent with UrQMD $-0.5 < y - y_{CM} < 0, \kappa_4/\kappa_1$ shows no strong energy dependence within uncertainties

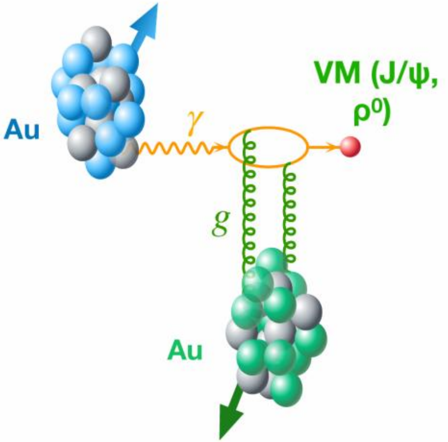


ASHIK IKBAL SHEIKH

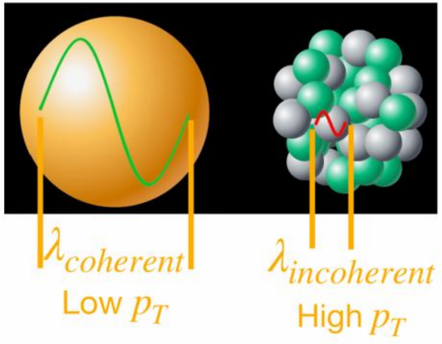
Vector meson production in UPCs

constraints on theoretical models related to nuclear geometry

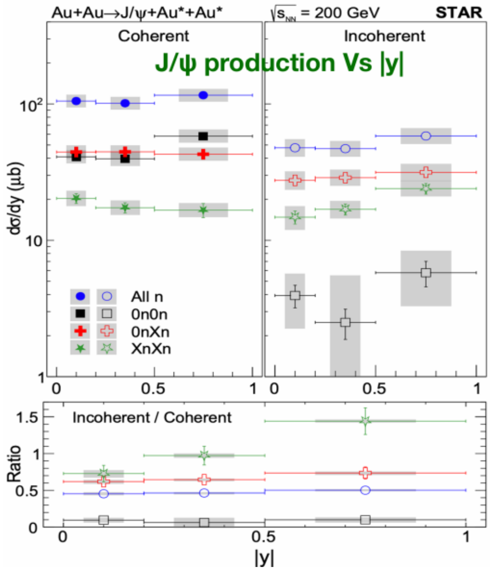
STAR, *Phys Rev Lett* 133 (2024) 5, 052301

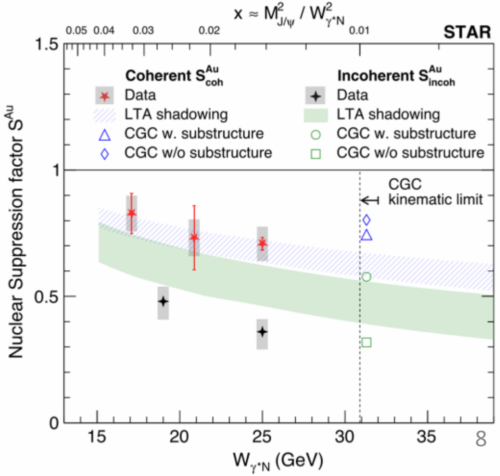


In UPC, vector mesons are photo-produced



Coherent and incoherent vector mesons probe different momentum/ length scale





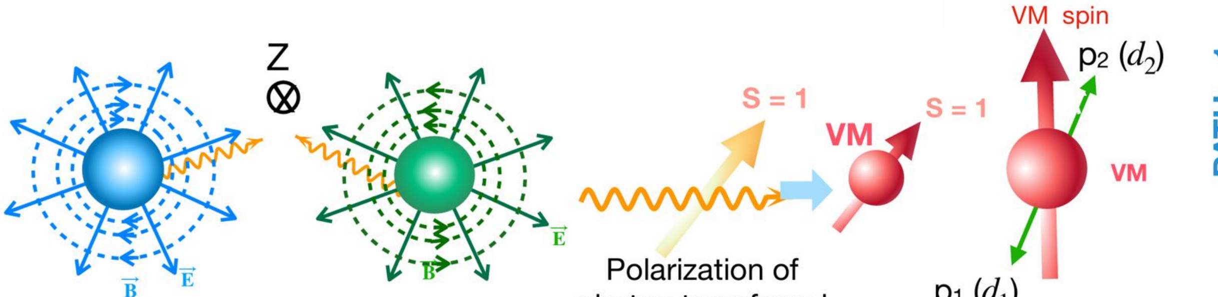
=> Coh/Incoh x-sec measurements sensitive to nuclear structure and deformation

=> Coh and Incoh x-sec suppressed by ~30% and ~65% (at $W_{\gamma^*N} = 25$ GeV), respectively — does not directly support the CGC with subnucleonic fluctuations

ASHIK IKBAL SHEIKH

Vector meson spin interference in UPCs

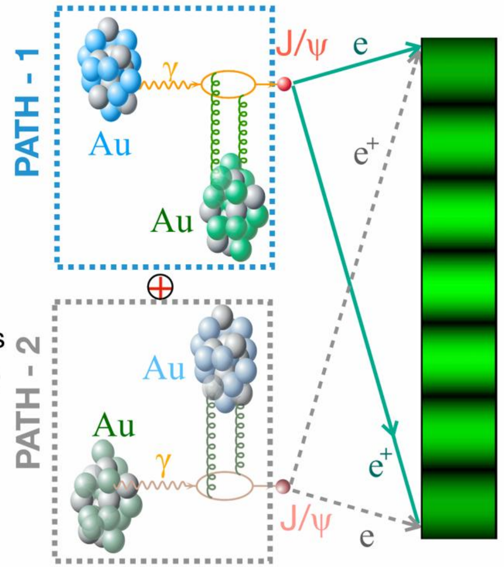
constraints to the parton density and baseline for EIC



UPC photons are linearly polarized

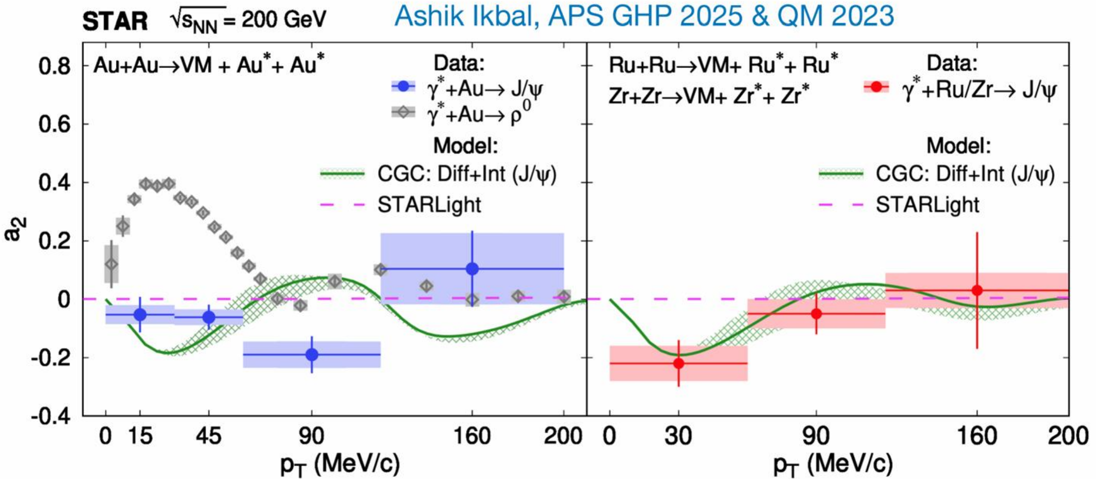
Polarization of photon transferred to VM

Decay $VM \to d_1 d_2$ daughters correlated (L+S conservation)



Interference of two independent paths

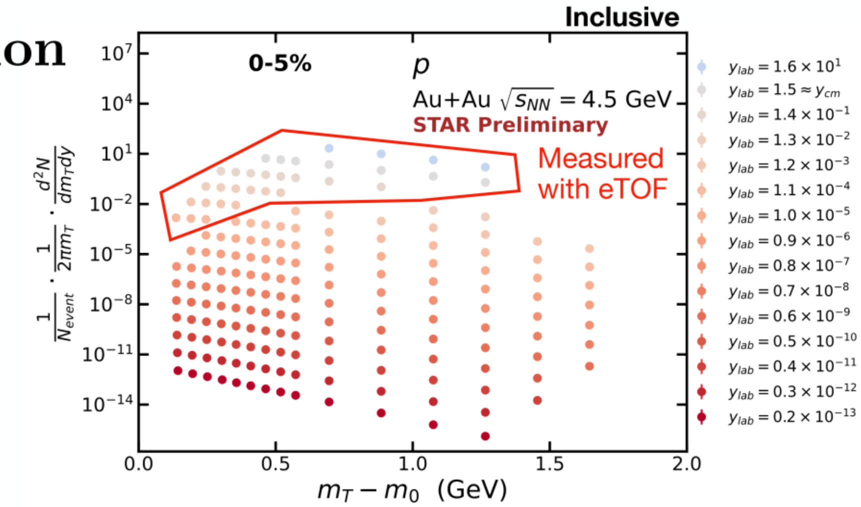
Ashik Ikbal, APS GHP 2025 & QM 2023



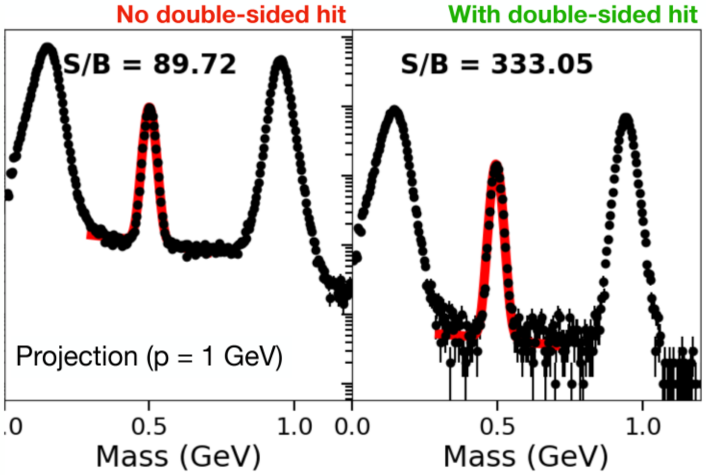
=> Positive modulation for ρ and negative for J/ψ — Bosonic interference for ρ and fermionic interference for J/ψ

=> CGC cannot describe the dat

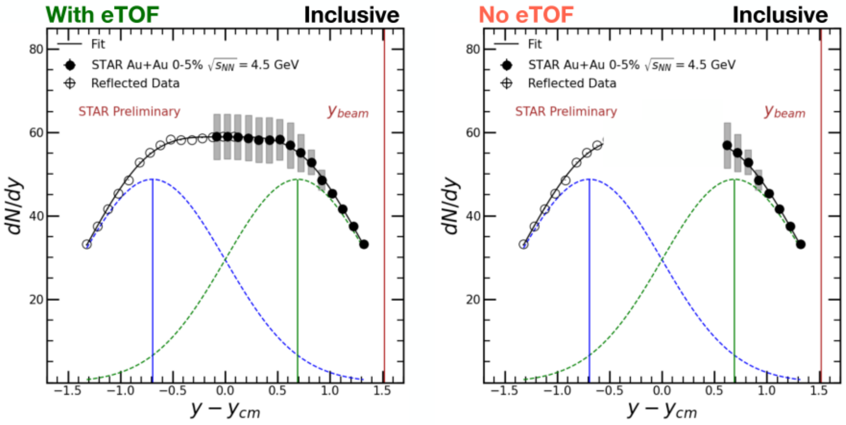
eTOF Calibration



- Calibration efforts have yielded results!
- Allows us to constrain proton yield near mid rapidity
- Rapidity coverage is critical (PID at $\eta = 1 - 1.5$)



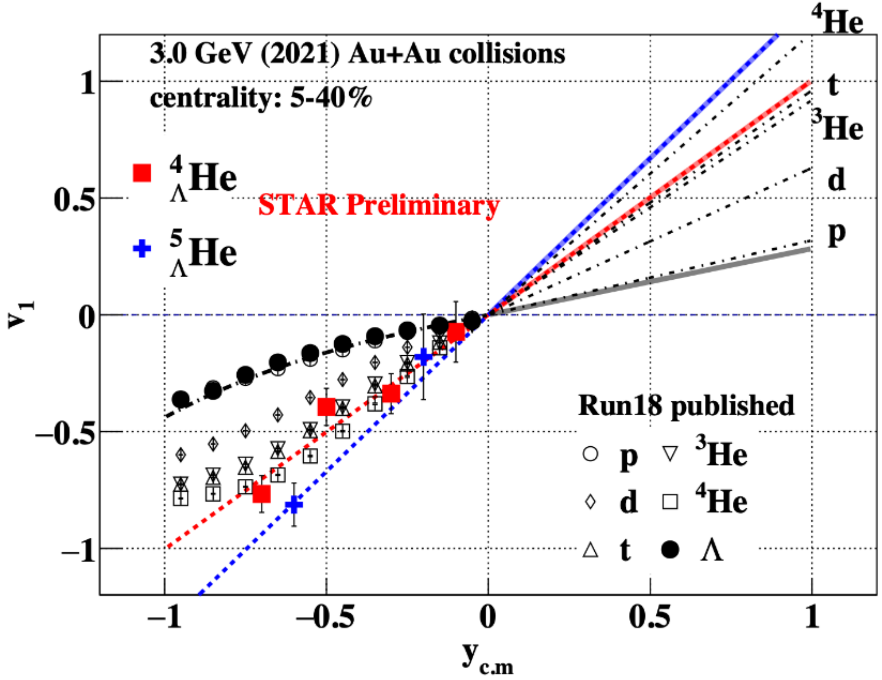
- Signal to background ratio

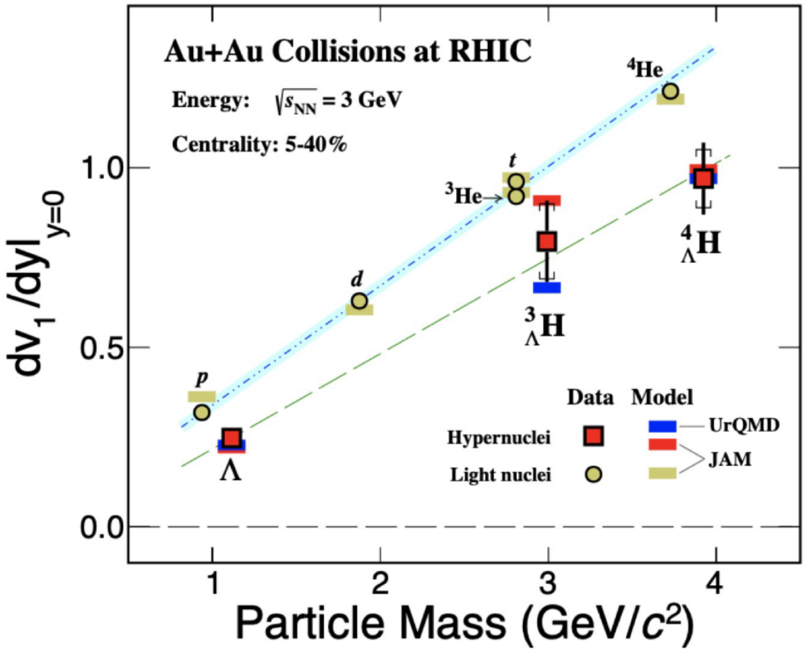


MD NASIM

Hyper nuclei flow

- Significant directed flow of (hyper-)nuclei is observed
- Hyper nuclei flow indicates coalescence behavior

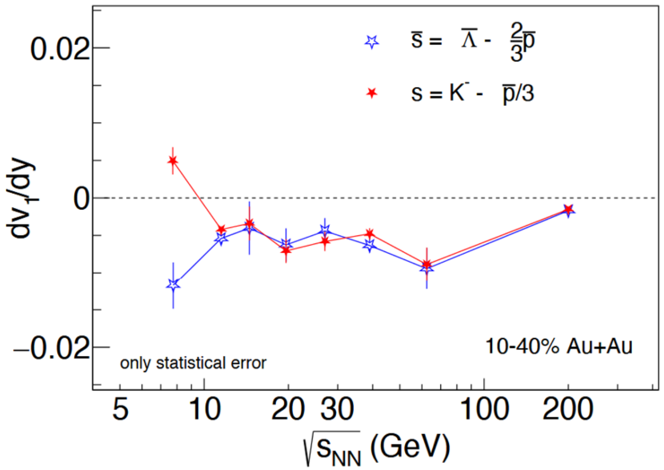


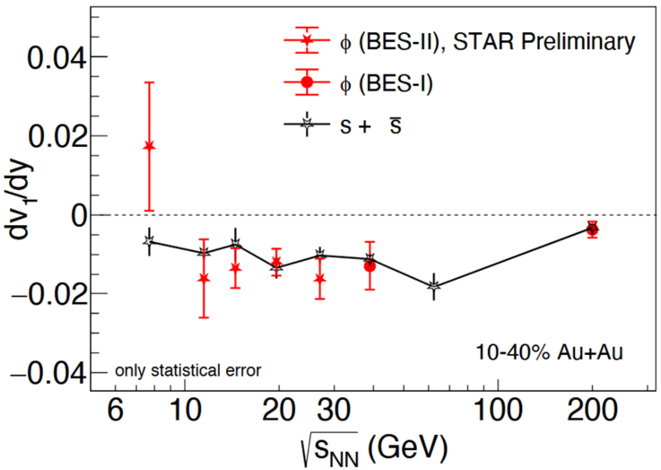


JAM based coalescence model explain the data

MD NASIM

The v_1 of s and s-bar quarks is obtained using STAR BES-II (Preliminary) and BES-I (Published) data under the framework of coalescence sum rule.





- Splitting between s and s-bar v_1 at $\sqrt{s_{NN}} = 7.7 GeV$. May indicates significant role of associated strangeness production at this lower energies
- $\sqrt{s_{NN}} \geq 7.7 GeV$: The v_1 of ϕ meson consistent with **coalescence picture**

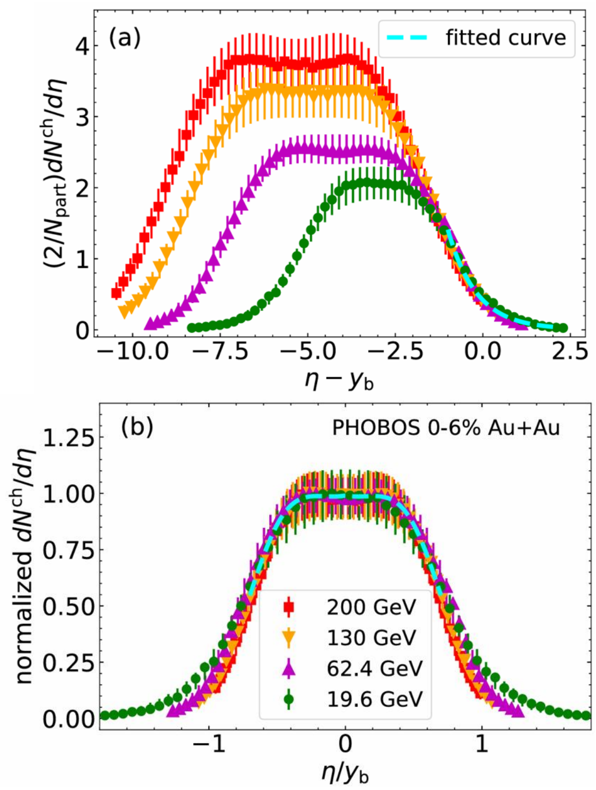
STAR: PRL 120, 062301 (2018)

II. Theoretical developments, phenomenology, and challenges

DIPEI DU

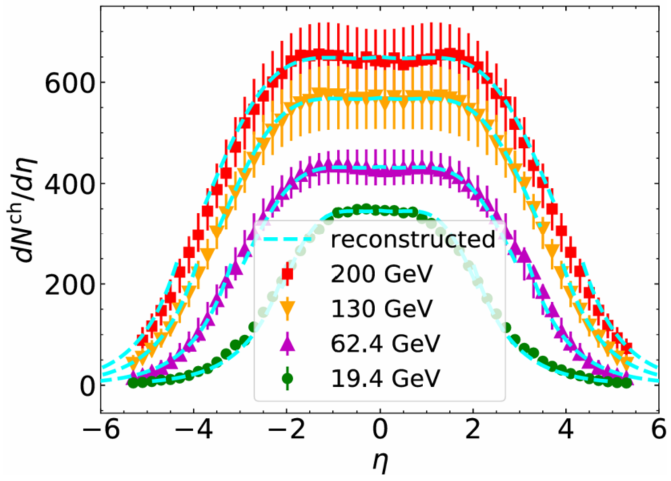
Theoretical constraints on IS and dynamics of BES

universal scaling properties



Fit two regions separately:

- forward-rapidity: limiting fragmentation
- mid-rapidity: central plateau
- The fitted curves can be used to reconstruct $dN_{ch}/d\eta$, even at energies that were not directly measured.



DIPEI DU

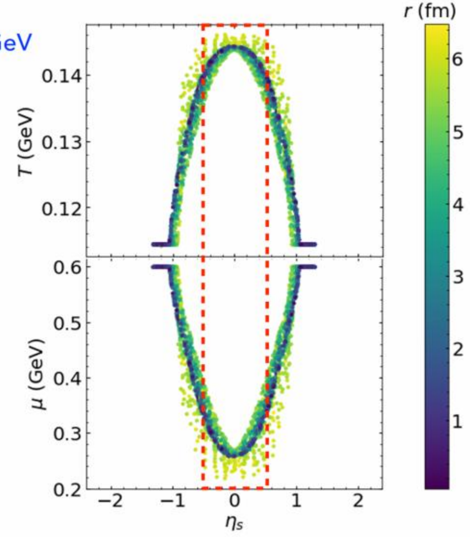
Predictions on the thermodynamics and dynamical evolution?

Longitudinal property variation at freezeout

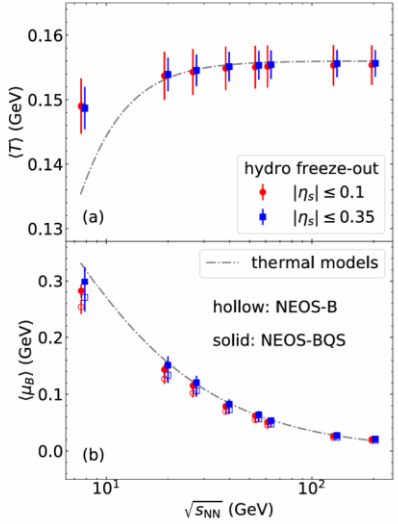
0-5% 7.7 GeV

$\Delta T/T_{\mathrm{mid}} \sim 20\,\%$

$\Delta\mu/\mu_{\mathrm{mid}} \gtrsim 100\,\%$

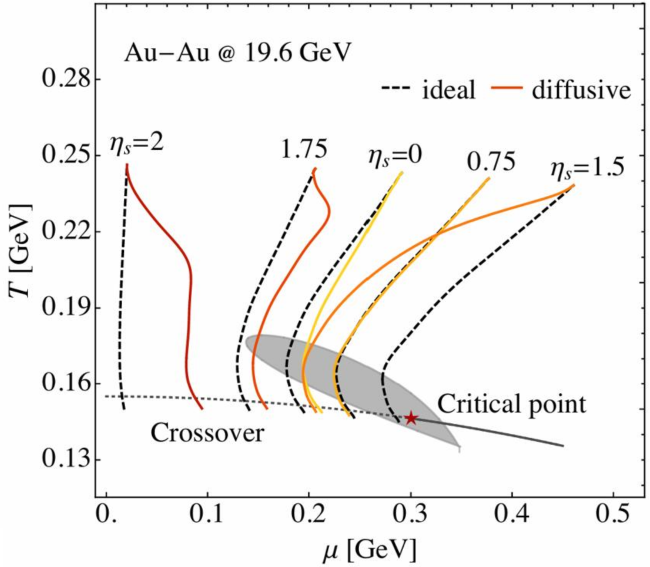


LD, H. Gao, S. Jeon & C. Gale, PRC 109, 014907 (2024)



L. Du, PRC 110 (2024) 1, 014904

0-10% BES



LD, X. An and U. Heinz, PRC 104, 064904 (2021); CPOD21, 2109.06918

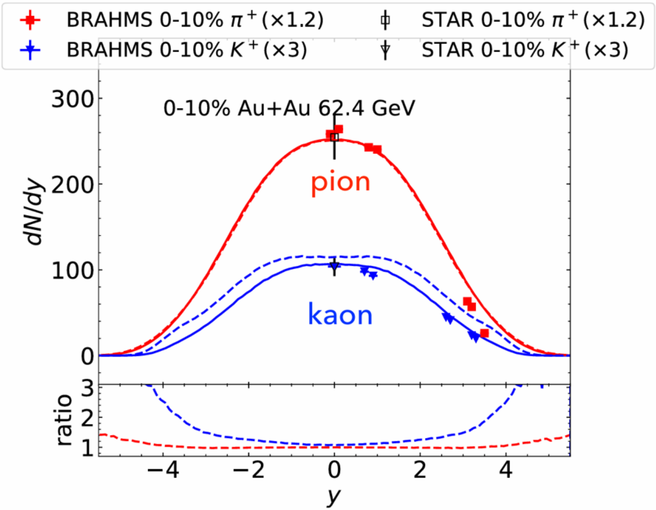
Variation of dynamical expansion trajectories for different rapidities

- The variation in thermodynamic properties across spacetime rapidity is strong for collisions 10 GeV.
- Due to thermal smearing, thermal models extract (T, μ_B) averaged over a broader window

LIPEI DU

Constraints on the QCD EoS at finite densities

NEOS: Monnai et al, PRC 100, 024907 (2019)

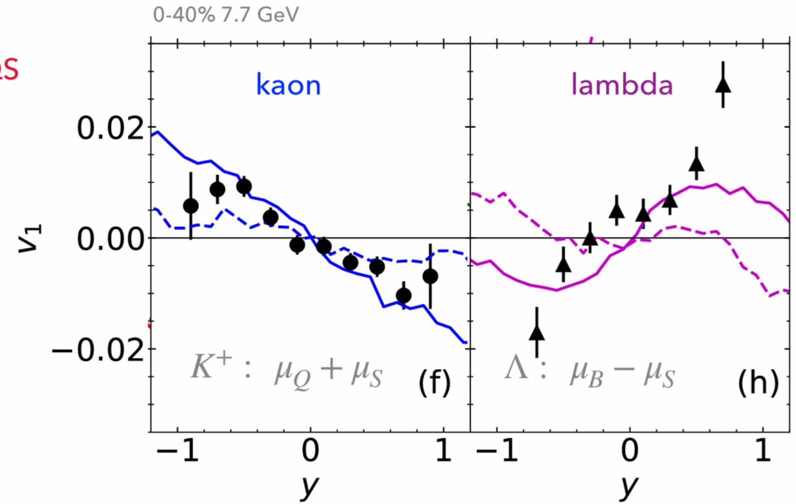


L. Du, PRC 110 (2024) 1, 014904

Dashed: NEOS-BQS

Solid: NEOS-B

Data: STAR, PRL 112, 162301 (2014); PRL 120, 062301 (2018)



LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

- Rapidity-dependent measurements of identified particles provide valuable insights into the EoS at finite chemical potentials.
- The directed flow of identified particles offers significant constraining power on the properties of the EoS.

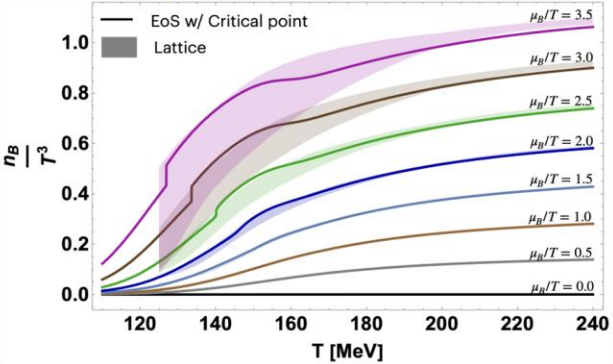
JOHANNAS JAHAN

New regimes μ_i can be reached with LQCD + critical region!

Finite (T, μB)

- New lattice T-Expansion Scheme (TExS) + tunable CEP from 3D Ising model

Kahangirwe *et al., PRD* 109 (2024) 9, 094046



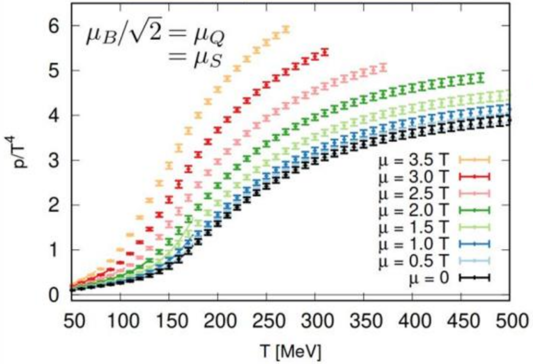
$\mu_B/T < 3.5$

- First finite μ_B results from:
  - EMD Holographic approach $\mu_B < 1100$ MeV (sQGP only)
    Grefa et al., *PRD* 104 (2021) 3, 034002
  - functional Renormalization Group $\mu_B/T < 4$
    Lu et al., arXiv:2504.05099

Finite ($T + \mu_B, \mu_Q, \mu_S$ / μ_I / eB)

- Generalization of the TExS in 4D (T, μ_B, μ_Q, μ_S) based on new set of continuum-estimated lattice $\chi_{2/4}^{BQS}$

Abuali *et al.,* arXiv:2504.01881



For this case:

$\mu_B \leq 670$ MeV

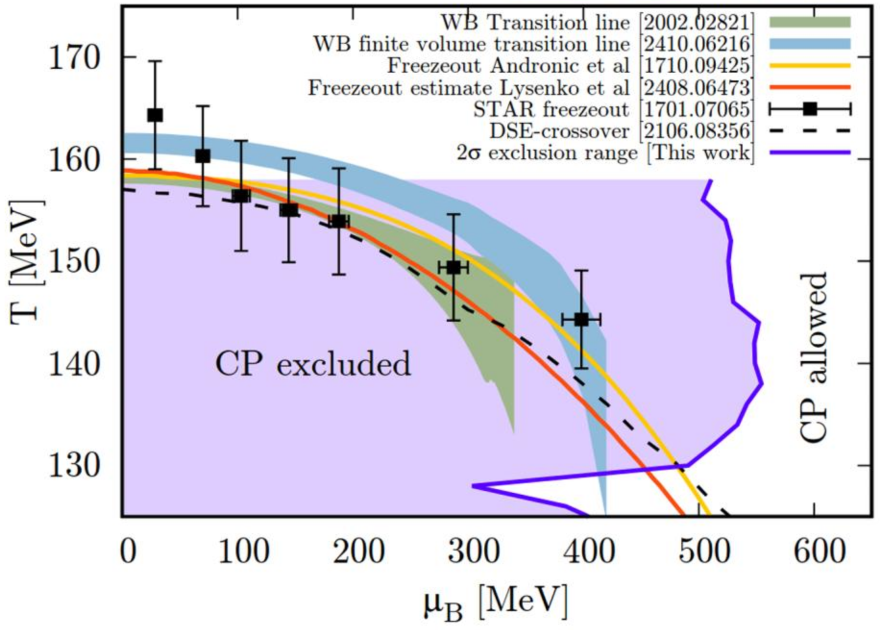
$\mu_Q \leq 475$ MeV

$\mu_S \leq 475$ MeV

- Lattice fermion sign problem circumvented for:
  - finite eB thermodynamics + observe CP at eB=4-9 GeV^2
    D'Elia *et al.,* 105 (2022) 3, 034511
  - finite μ_I thermodynamics + pion condens° at $\mu_I > m_\pi/2$
    Brandt *et al., JHEP* 07 (2023) 055

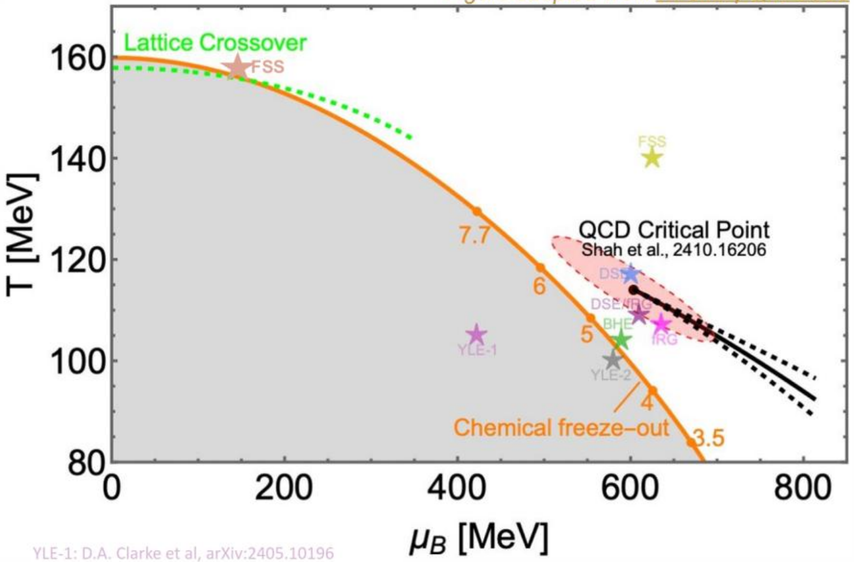
Significant theory developments in prediction of the CP

Borsányi et al., arXiv:2502.10267



→ Existence of a **critical point excluded at 2σ** for **μ_B < 450 MeV** by new lattice QCD analysis

Figure adapted from H. Shah, QM 2025



YLE-1: D.A. Clarke et al, arXiv:2405.10196

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: P.J. Gunkel et al., PRD 104, 052202 (2021)

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

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

FSS: Roy Lacey, arXiv:2411.09139

Compared with **new HRG chemical freeze-out line** calculated at $\mu_Q = \mu_S = 0$

→ **Lower bound for CEP existence**

Lysenko et al., arXiv:2408.06473

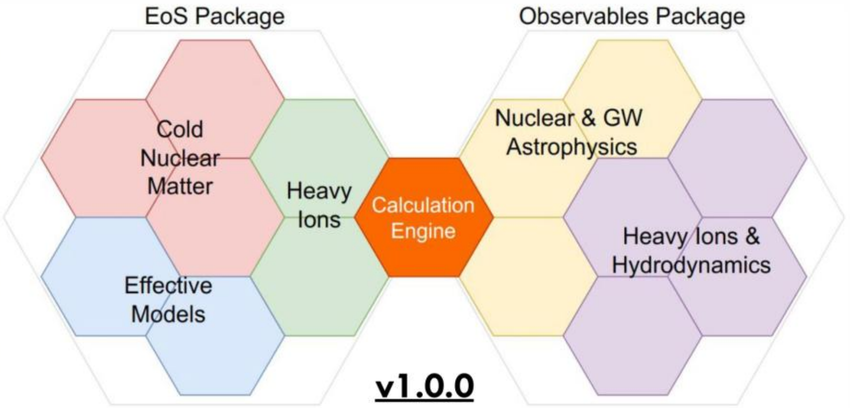
JOHANNAS JAHAN

Click here for more

MODULAR UNIFIED SOLVER OF THE EQUATION OF STATE

Public release of the calculation engine early 2025!

Pelicer *et al.*, *PRD* 111 (2025) 10, 103037 Manning *et al.*, DOI:10.5281/zenodo.14721911



A.T. Manning, MUSES Collaboration Meeting 2023

- 4D Taylor expansion
- Ising – 2D TExS
- Chiral EFT
- Crust DFT
- CMF++
- Holographic

- (Pseudo) universal QLIMR relations
- Beta equilibrium
- 1D EoS merger

Next to come (v1.x.x):

- HRG vdW EoS
- 4D TExS EoS
- …
- Partial pressures
- Thermal fits

Stay tuned & feel free to join the MUSES workshop next week! *(Tuesday, May 27)*

MUSES Collaboration Meeting

May 27, 2025, 9:00 AM → May 30, 2025, 4:00 PM US/Central

Loomis Physics Building, University of Illinois Urbana-Champaign

Scaled factorial cumulants and the antiproton puzzle

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

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

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

integrated correlation function in rapidity

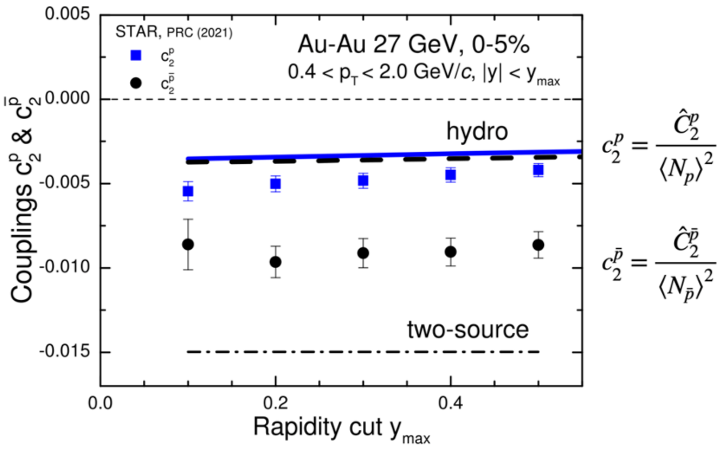
Long-range correlations lead to acceptance-independent $\hat{c}_k$, including any combination of global baryon conservation and volume fluctuations (no need for CBWC)!

Standard hydro predicts:

$\hat{c}_2^p \approx \hat{c}_2^{\bar{p}} = const.$ at a given $\sqrt{s_{NN}}$

Experiment:

$|\hat{c}_2^p| < |\hat{c}_2^{\bar{p}}|$ **the antiproton puzzle**

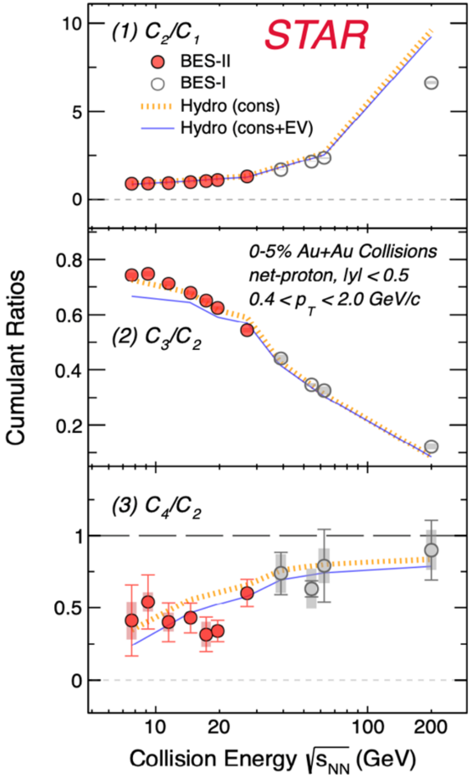


Possible explanation: stopped and produced matter do not thermalize (no single fluid)

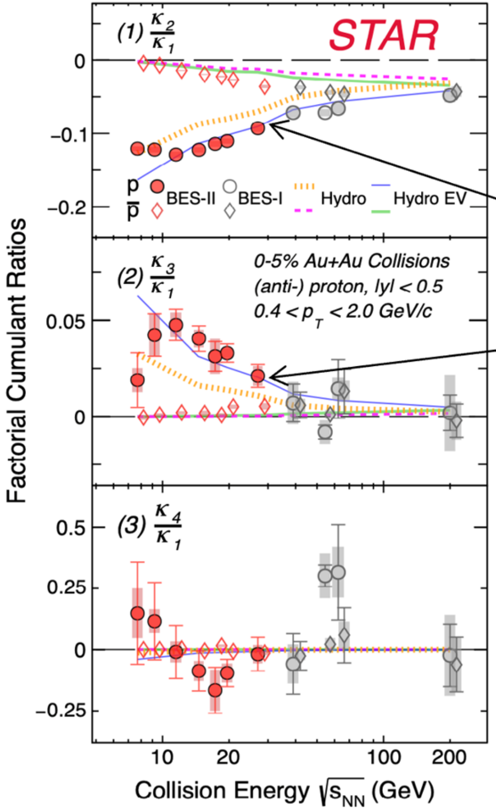
A. Bzdak, V. Koch, V. Vovchenko, arXiv:2503.16405

Understanding proton cumulants from RHIC-BES-II data

Net-proton cumulant ratios

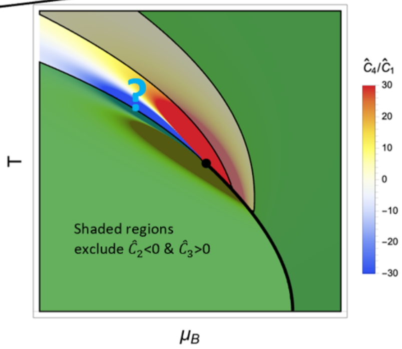


Proton/antiproton factorial cumulant ratios



- Factorial cumulants may be more instructive than ordinary cumulants
- Deviations from available non-critical baseline at $\sqrt{s_{NN}} < 10$ GeV

$\hat{C}_2$ −baseline > 0 & $\hat{C}_3$ −baseline < 0



- Need precise handle on non-critical contributions

VOLODYA VOVCHENKO

Mean p_T fluctuations

Mean p_T fluctuations:

$$\langle \Delta p_{T,i} \Delta p_{T,i} \rangle \sim \langle \Delta \langle p_T \rangle^2 \rangle$$

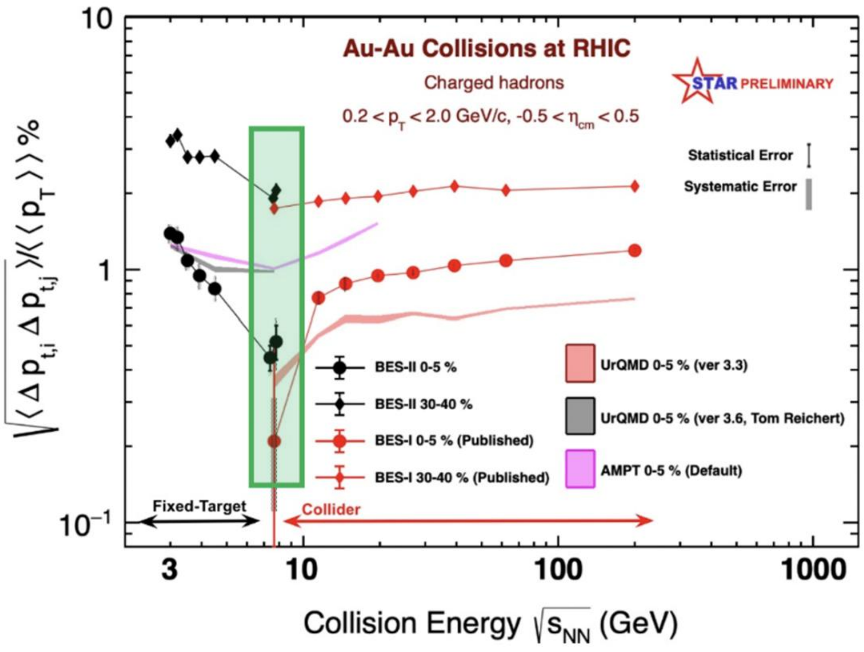
Mean p_T probes the temperature

Gardim et al, Nature Phys. (2020)

$$\langle p_T \rangle \propto Teff$$

$$\langle \Delta p_{T,i} \Delta p_{T,i} \rangle \sim \langle \Delta T^2 \rangle$$

In equilibrium: $\langle \Delta T^2 \rangle = \frac{T^2}{V c_V}$



R. Manikandhan (STAR), QM2025

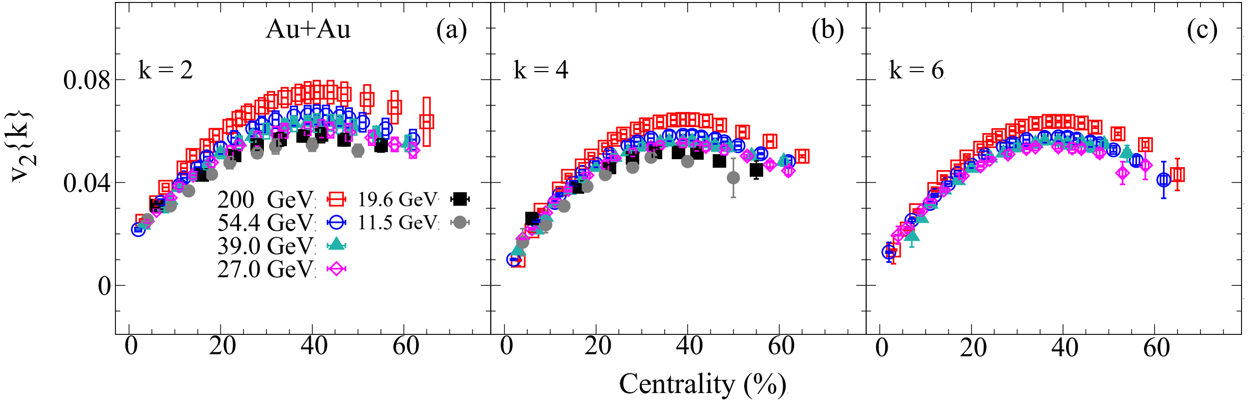
At the critical point $c_V \to \infty$ → Minimum in $\sqrt{s_{NN}}$ dependence?

NISSEM MAGDY

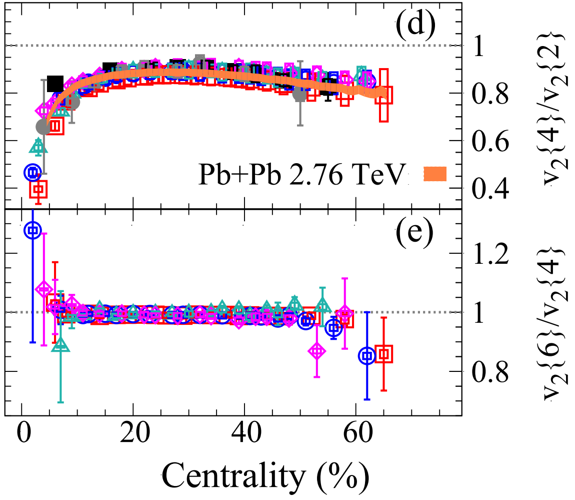
Systematic control over the effects of the IS and medium response

Symmetric Correlations

STAR Collaboration PRL 129 (2022)



Normalized Symmetric Correlations



- Symmetric correlations $v_2\{k\}$ show characteristic energy dependence.
  Sensitive to the interplay between initial- and final-state effects.

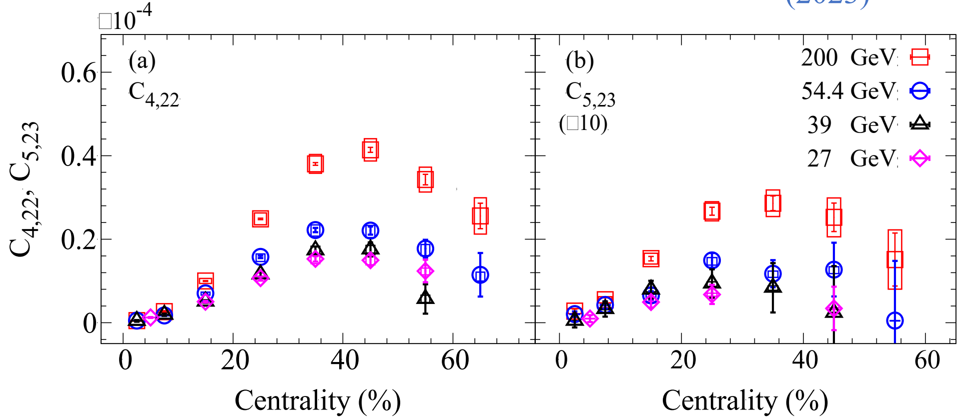
- Normalized symmetric correlations,
  $v_2\{4\}/v_2\{2\}$ show weak dependence on beam energy.
  Sensitive to the initial state effects.

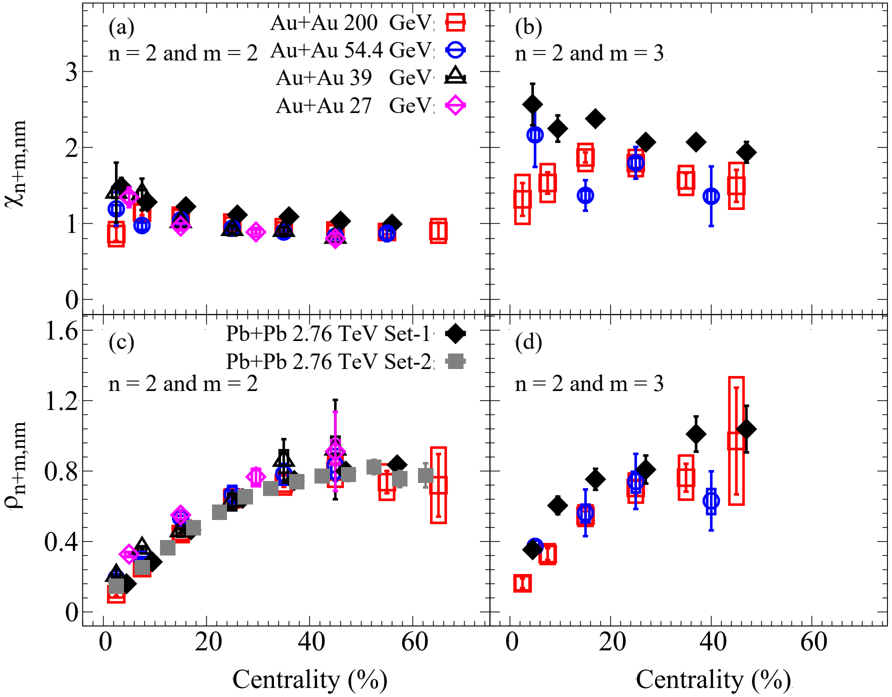
NISSEM MAGDY

Asymmetric Correlations

STAR Collaboration PLB 839 (2023)

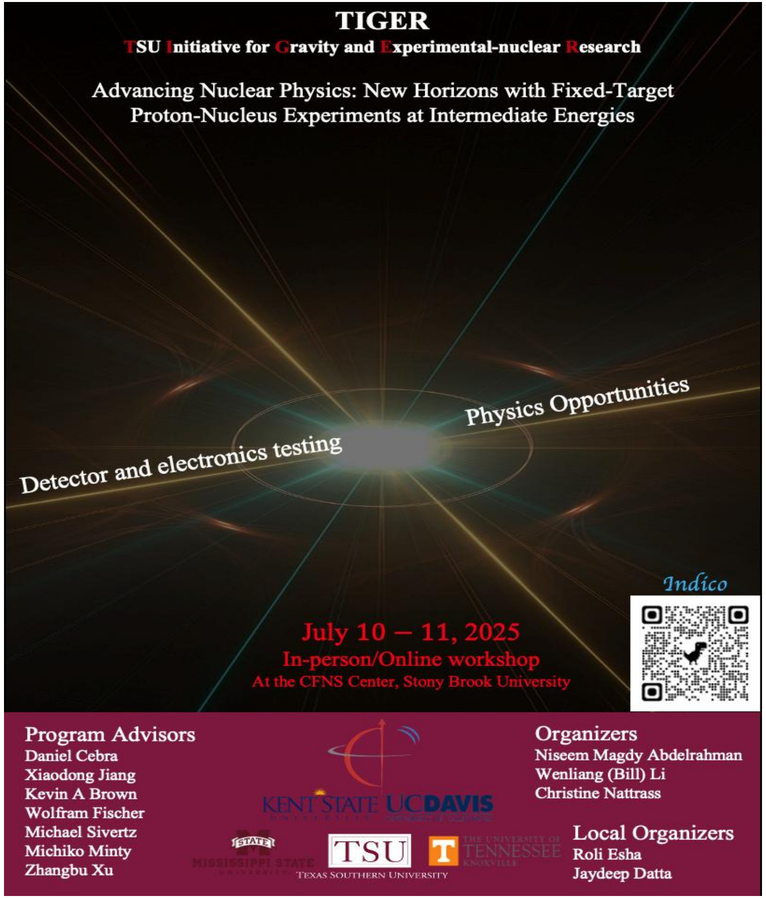
Normalized Symmetric Correlations





- Asymmetric correlations, $C_{n,m,n+m}$ show characteristic energy dependence.
  Sensitive to the interplay between initial- and final-state effects.
- Normalized asymmetric correlations, show weak dependence on beam energy.
  Sensitive to the initial state effects.

NISSEM MAGDY



Journal of Physics G: Nuclear and Particle Physics

Quantum Chromodynamics Evolution: The Current Legacy and the Electron-Ion Collider's Pioneering Horizons

Guest Editors

Niseem Magdy Abdelrahman, *Texas Southern University, USA*
Wenliang Li, *Mississippi State University, USA*
Wenbin Zhao, *Lawrence Berkeley National Laboratory, USA*

Celebrating 25 Years of RHIC:
Honoring Experimental and Theory Collaborations and Individual Contributions

Laying the Roadmap to the Electron-Ion Collider

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Inspire-hep: 1305036
ORCID: 0000-0002-6458-6552

IV. Connections to NS and constraints on the HIC EoS

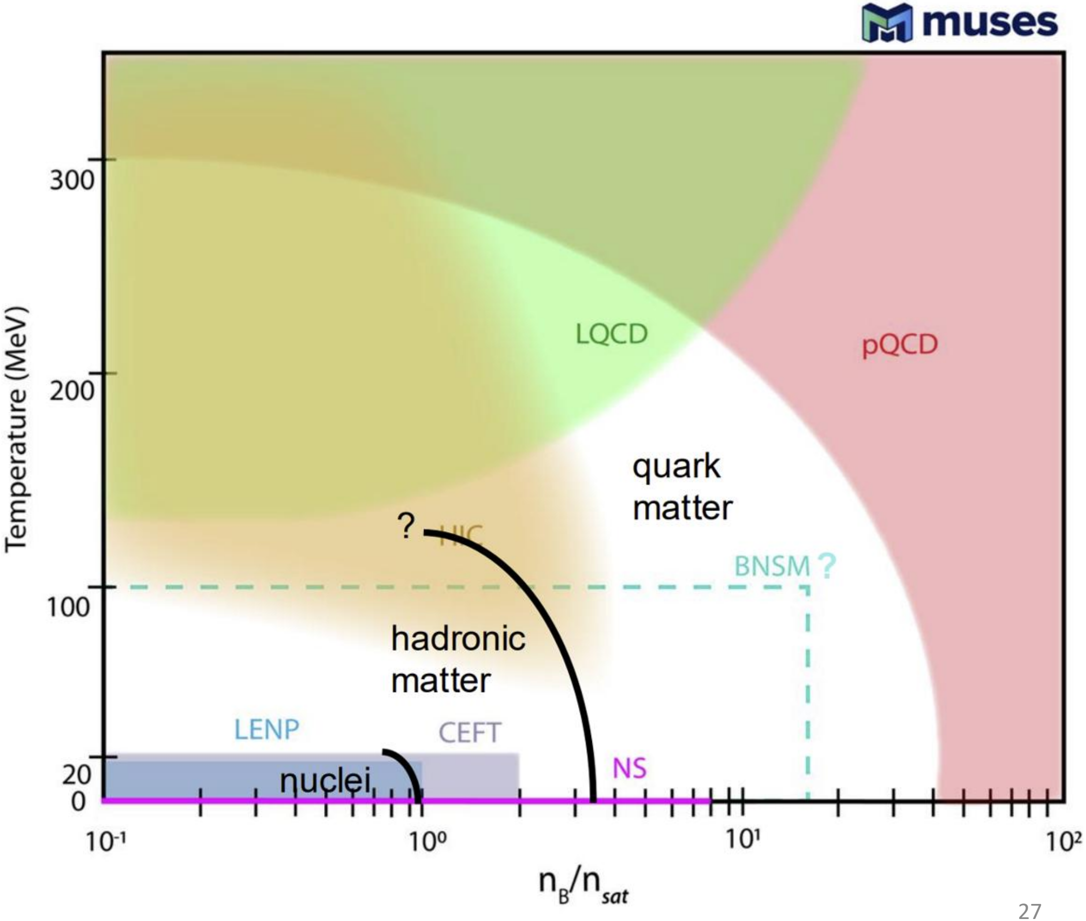
Veronica Dexheimer

Current input from different (first-principle and effective) theories and experiments

Living Rev.Rel. 27 (2024) 1, 3
e-Print: [2303.17021](2303.17021)

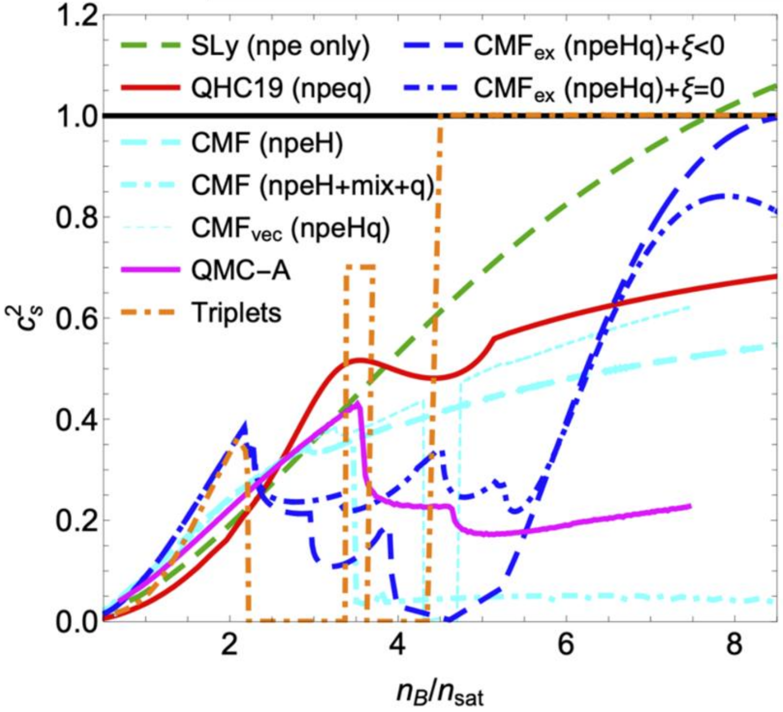
Astrophysics input only at T∼0 for now …

but finite T input is coming soon

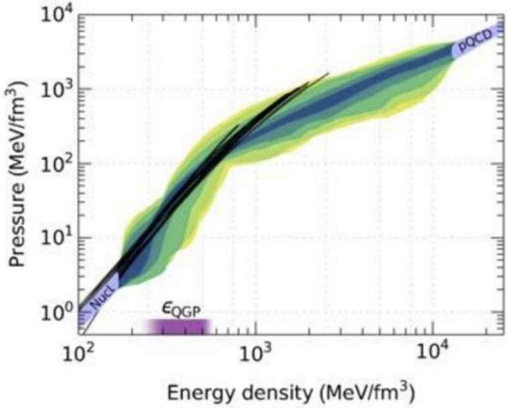


Structure associated with different particles, interactions, phase transitions, …

PRD 105 (2022) 2, 023018 e-Print: [2106.03890](2106.03890)



- ✶ Structure needed to reproduce nuclear + astrophysics data

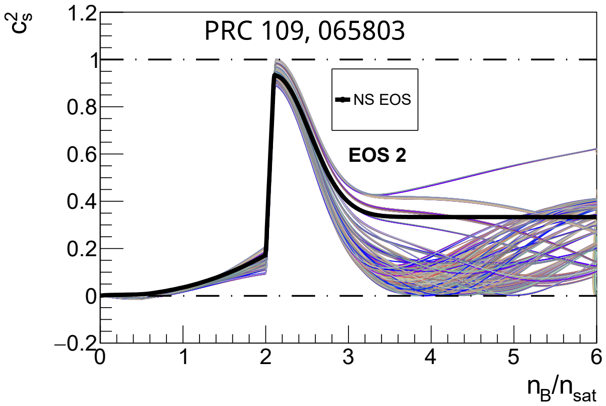


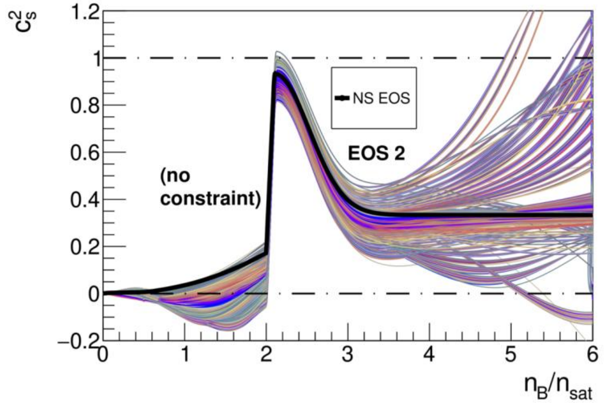
Nature Phys. 16 (2020) 9, 907-910 e-Print: [1903.09121](1903.09121)

NANXI YAO

Converted EOS Band

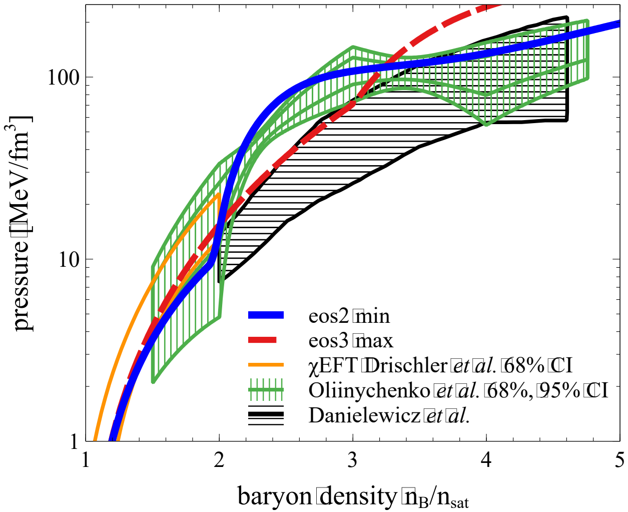
- Converted at $Y_{Q,QCD}^{const}$ = 0.5
- Same location of the peak, shifted magnitude
- Constraints on the converted EOS:
  - Stability and causality ($c_s^2 > 0$ for $n_B \geq 0.9 n_{sat}$ and $c_s^2 < 1$)
  - Saturation properties
    - $0.14\ fm^{-3} < n_{sat} < 0.18\ fm^{-3}$
    - -18 MeV < B < -14 MeV



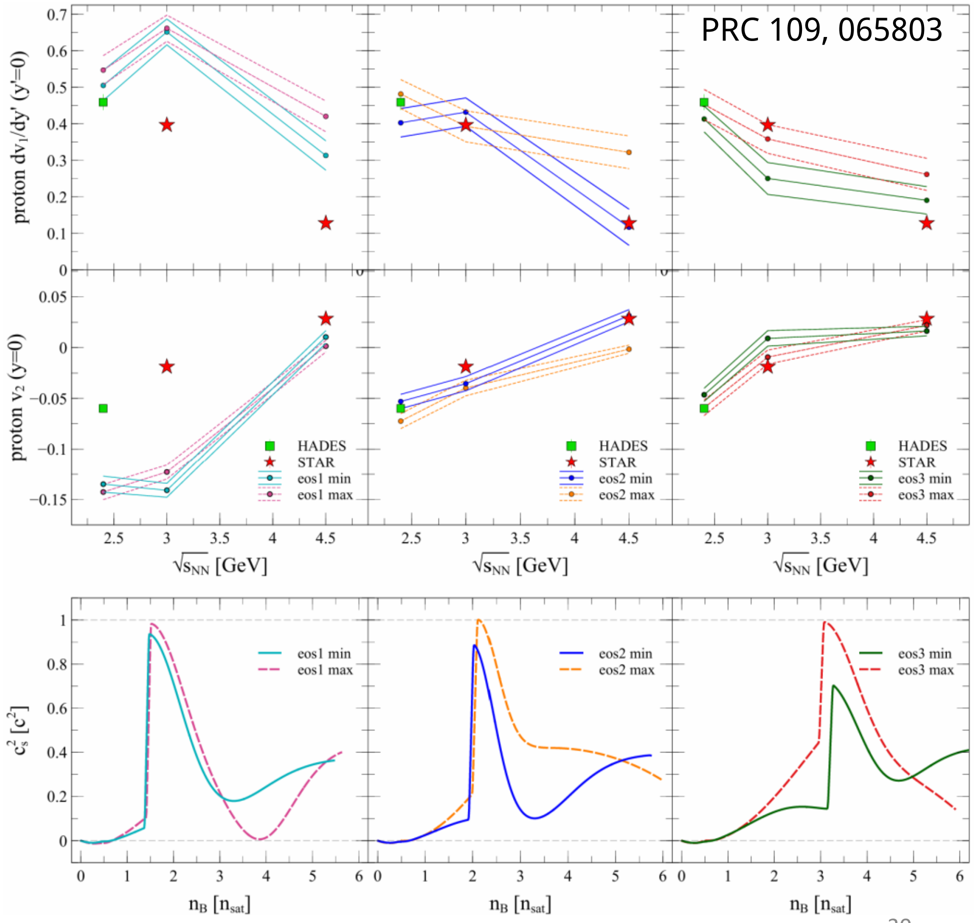


NANXI YAO

- To ensure $\varepsilon/n_B \to m_N$ and $c_s^2 \to 0$ as $n_B \to 0$, match the converted EOS to an EOS obtained from the density functional (VDF) model.
- **EOS with sharp rise at $2n_B$ is favored by the flow data**



Connecting NS with HIC experimental data



Experimental overview of the BES II	*Lijuan Ruan*	
Physics Large Seminar Room (LSR), 510	09:00 - 09:30	
Analysis of BES Fluctuations and cumulants (experimental)	*Zachary Sweger*	
Physics Large Seminar Room (LSR), 510	09:30 - 10:00	
UPC	*Ashik Ikbal*	
Physics Large Seminar Room (LSR), 510	10:00 - 10:30	
Flow Overview (experimental)	*MD Nassim*	
Physics Large Seminar Room (LSR), 510	13:50 - 14:20	
eToF calibration	*Mathias Labonte*	
Physics Large Seminar Room (LSR), 510	14:50 - 15:20	

Theoretical overview of the BES	*Lipei Du*
Physics Large Seminar Room (LSR), 510	11:00 - 11:30
QCD equation of state at finite density and the critical point	*Johannes Jahan*
Physics Large Seminar Room (LSR), 510	11:30 - 12:00
Cumulants and fluctuations measurement at the BES II	*volodymer vovchenko*
Physics Large Seminar Room (LSR), 510	12:00 - 12:30
Flow and Isobars Overview (theory)	*Niseem Magdy*
Physics Large Seminar Room (LSR), 510	14:20 - 14:50

The role of Neutron Stars in constraining the QCD Equation of State	*Veronica Dexheimer*
Physics Large Seminar Room (LSR), 510	15:50 - 16:20
Probing Dense Nuclear Matter: Connecting Neutron Stars and Heavy-Ion Collisions	*Nanxi Yao*
Physics Large Seminar Room (LSR), 510	16:20 - 16:50

Thank you for an amazing workshop!

Phys. Rev. C **109**, 065803

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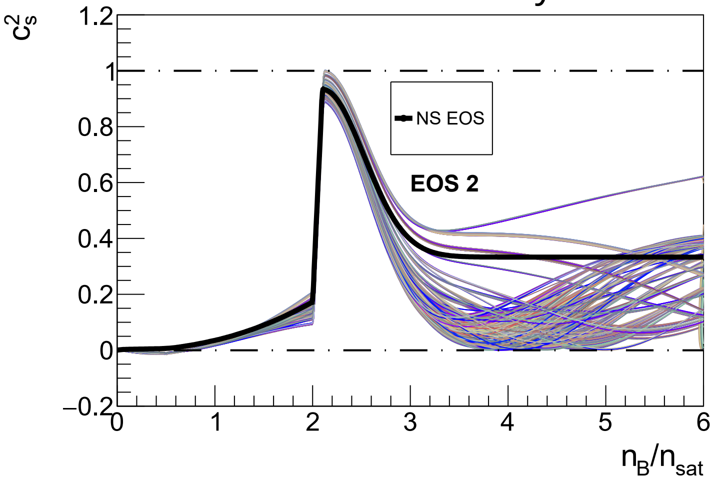
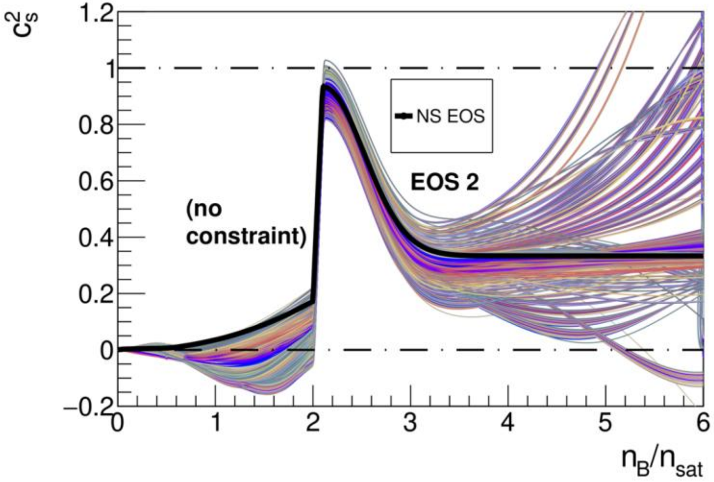
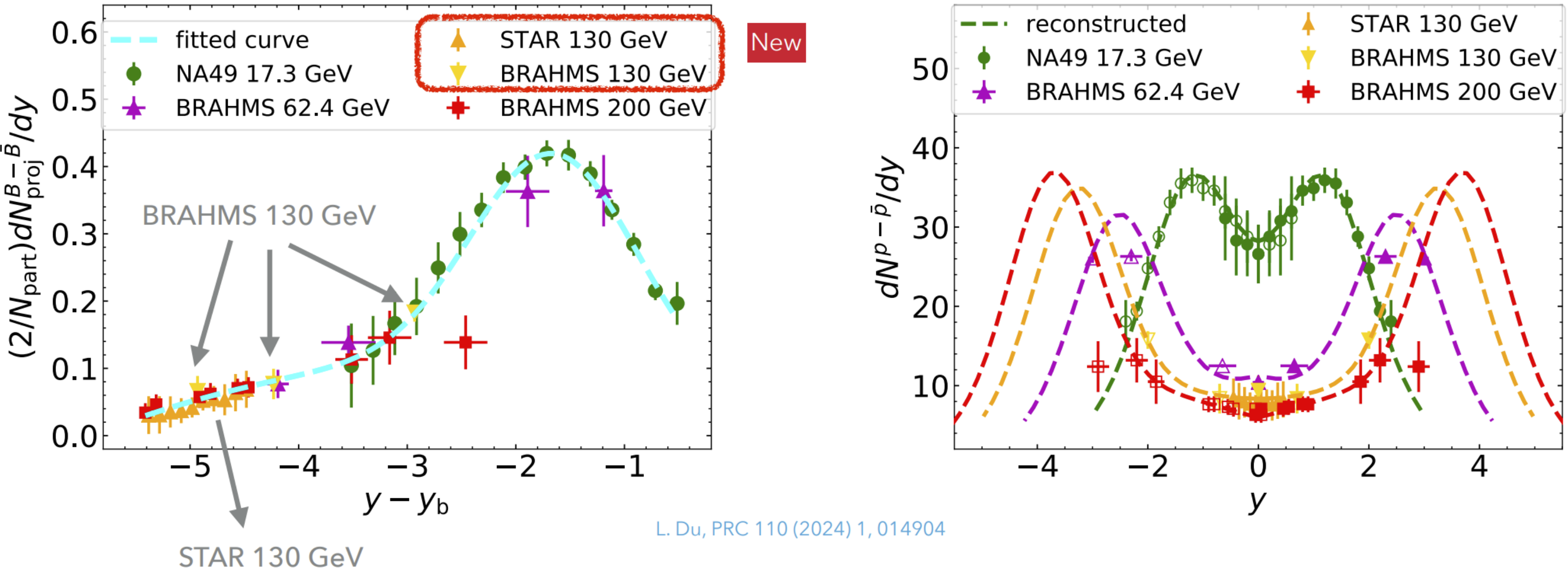




CONSTRUCT RAPIDITY-DISTRIBUTION: $dN^{p-\bar{p}}/dy$

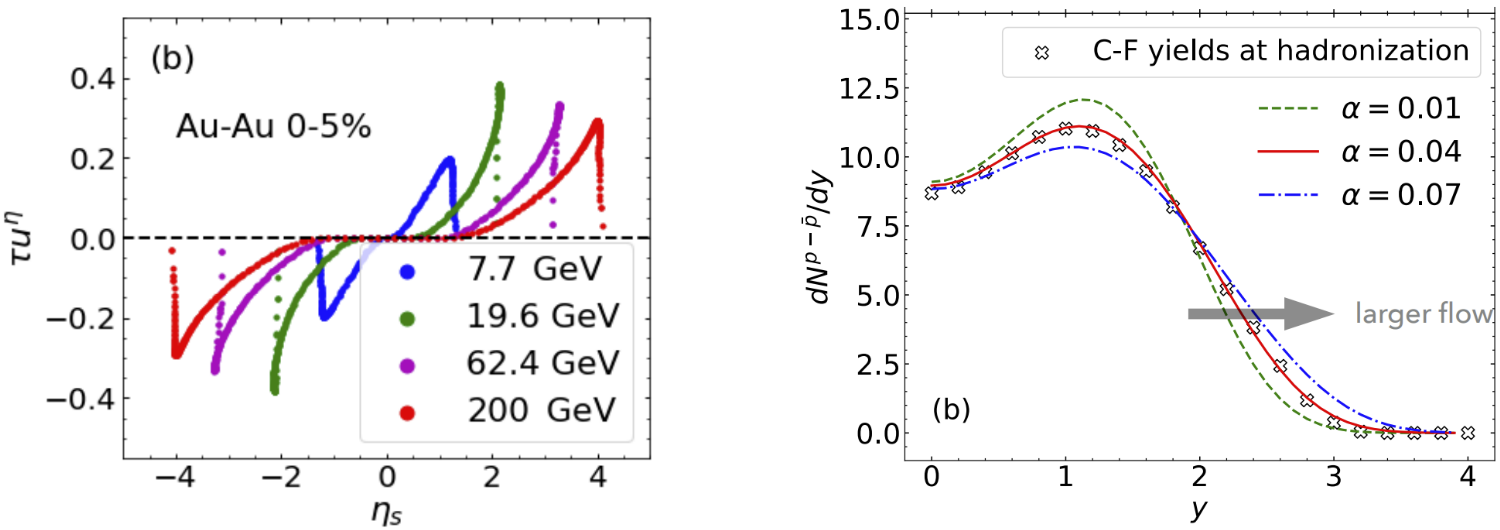


L. Du, PRC 110 (2024) 1, 014904

- Fit the net baryon rapidity density attributed to the projectile after subtraction of the target contribution.
- The reconstructed distributions can help constrain models at BES.

BRAHMS, PLB 677, 267-271(2009); Braun-Munzinger, Friman, Redlich, Rustamov, and Stachel, NPA 1008 (2021) 122141; Hoelck, Hiyama, and Wolschin, PLB 840, 137866 (2023)

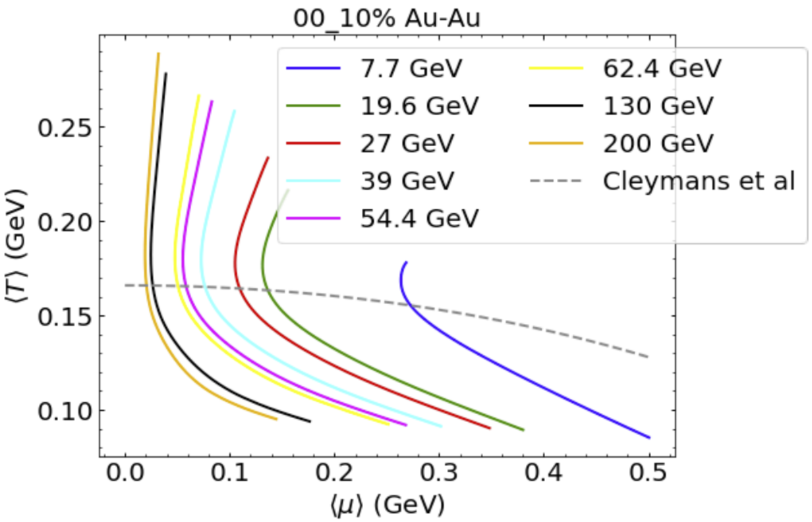
LONGITUDINAL FLOW AT FREEZE-OUT



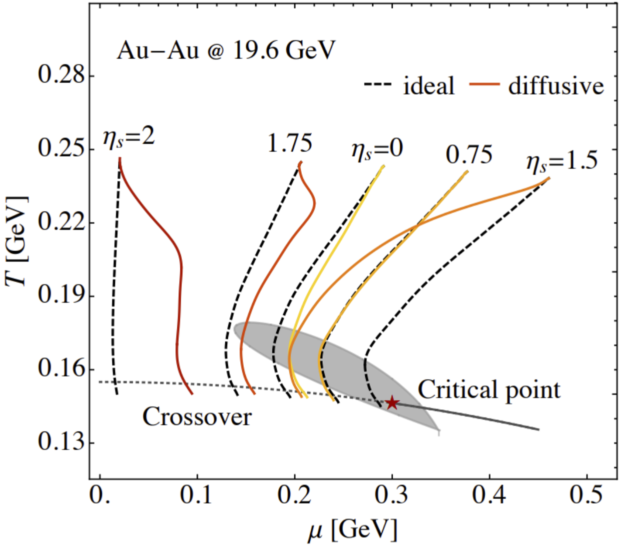
LD, H. Gao, S. Jeon & C. Gale, PRC 109, 014907 (2024)

- Boost invariance is strongly broken, especially at forward-/backward- rapidities;
- Starting from the same profiles, the rapidity distributions are stretched with increased longitudinal flow, with heavier particles experiencing greater stretching;
- Rapidity distributions of various species can be used to constrain the longitudinal flow.

BEAM ENERGY SCAN VS. RAPIDITY SCAN



properties averaged over a rapidity window



LD, X. An and U. Heinz, PRC 104, 064904 (2021); CPOD21, 2109.06918

- Left: expansion trajectories at midrapidity in heavy-ion collisions with different beam energies;
- Right: expansion trajectories for different rapidities of the fireball in a collision at a fixed beam energy