Experimental search for QCD critical point using fluctuation of conserved charges

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INT Workshop
20r-1c
Seattle

Outline

1. Introduction
2. Results
3. Future prospects and challenges
4. Summary

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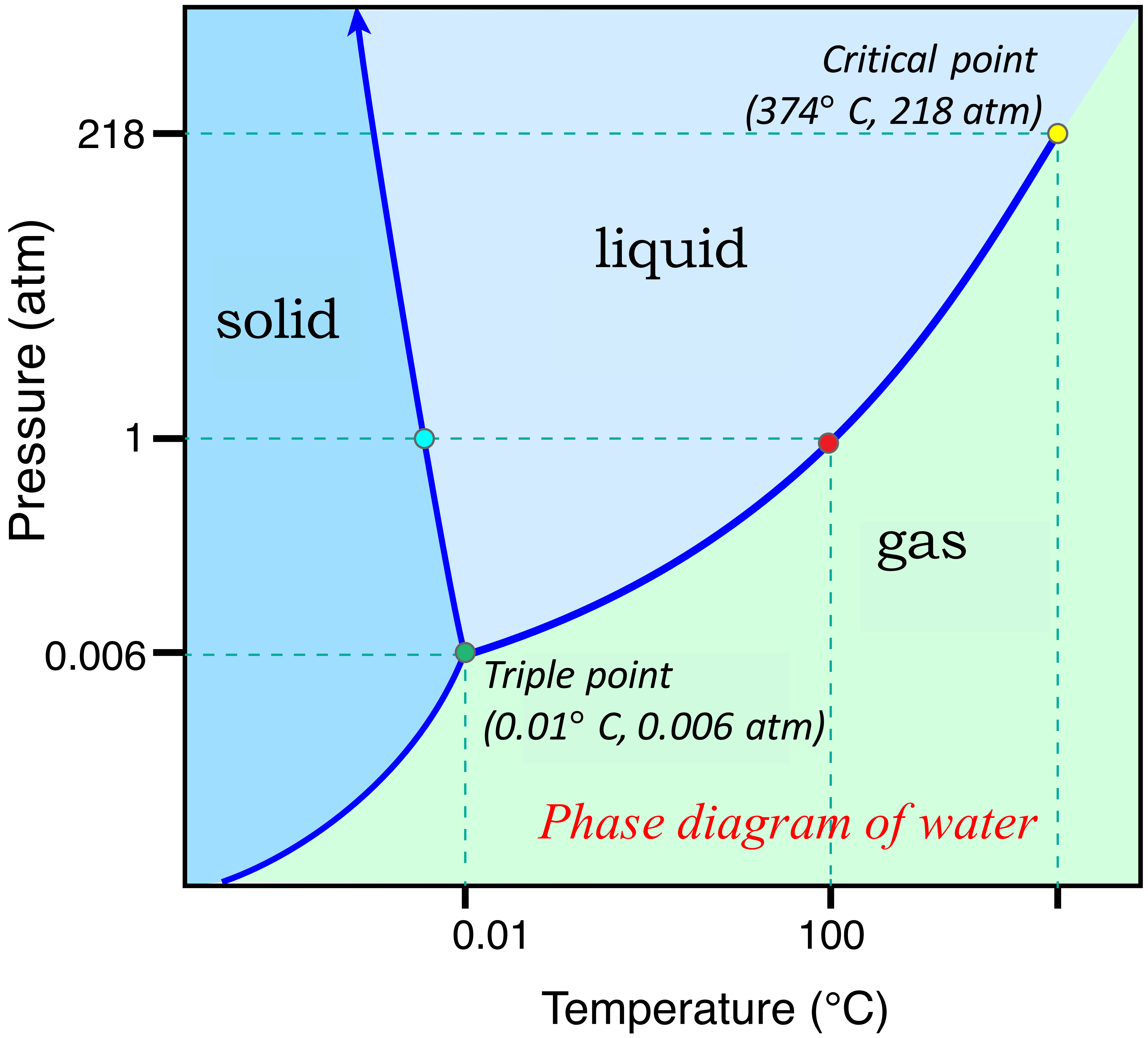
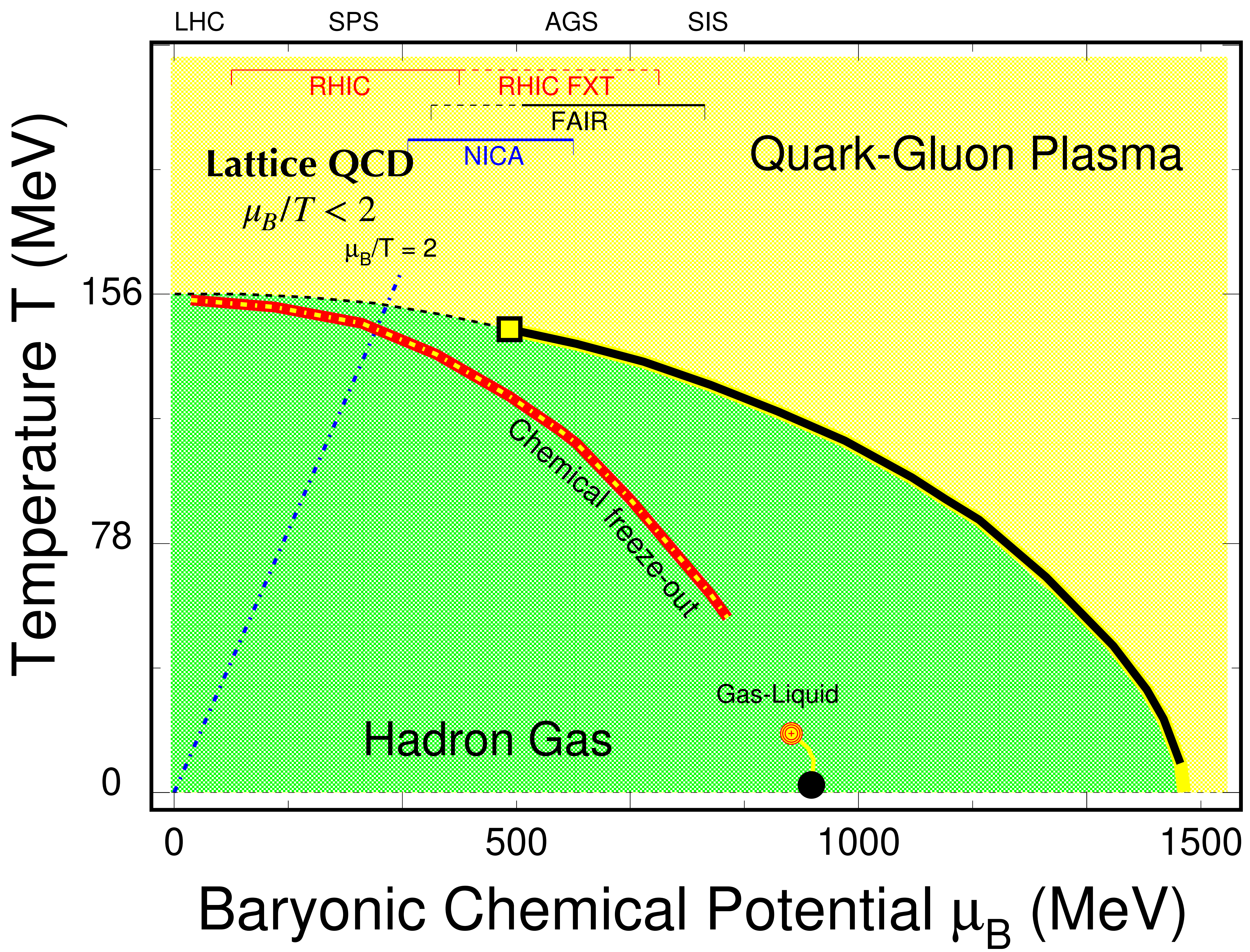
Introduction: Phase Transition



- Underlying interaction electromagnetic
- Precise understanding available

Introduction: QCD Phase Diagram



(Baryon doping)

Phase structure:

- QGP and hadronic phase ✓

Lattice QCD:

- Transition temperature (T_c) ✓
- Crossover at small μ_B ($\frac{\mu_B}{T} < 2$) ✓

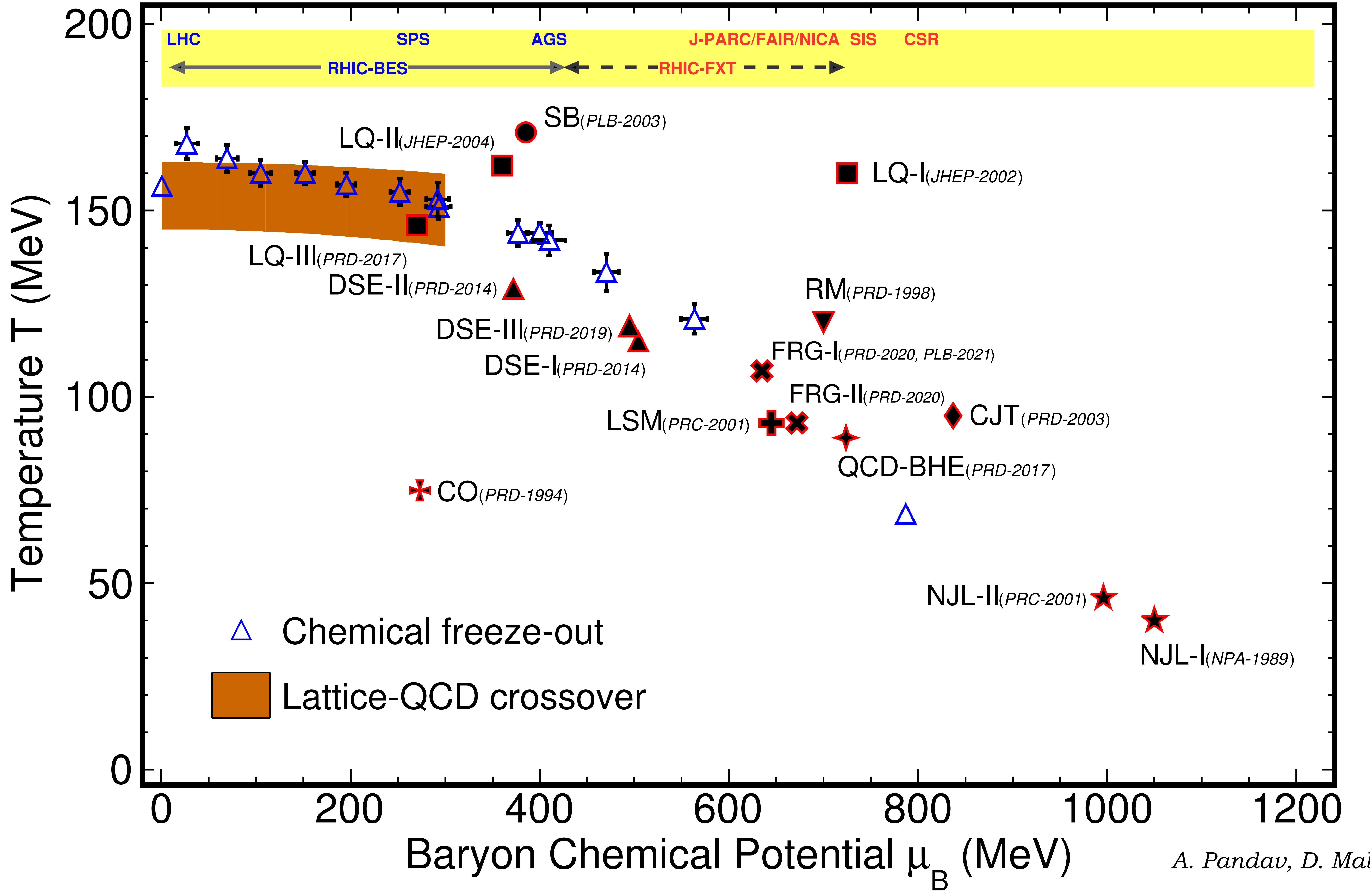
Models:

- 1st order P.T. at large μ_B ?
- **Critical end point** ?

B. Mohanty, N. Xu, arXiv:2101.09210
A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

- Underlying interaction: strong force (QCD)
- Largely conjectured

Introduction: QCD Critical Point (CP) From Theory

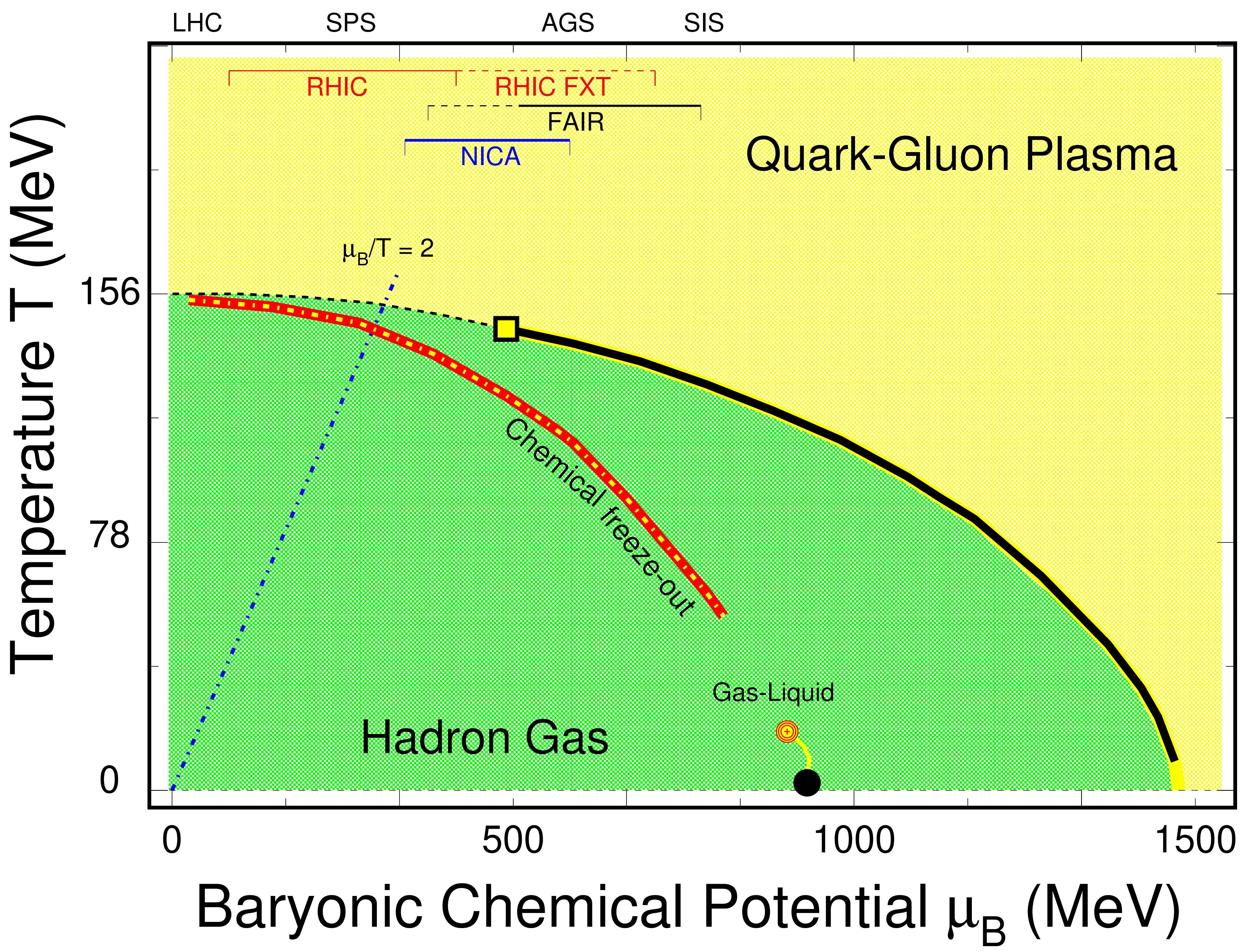


A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

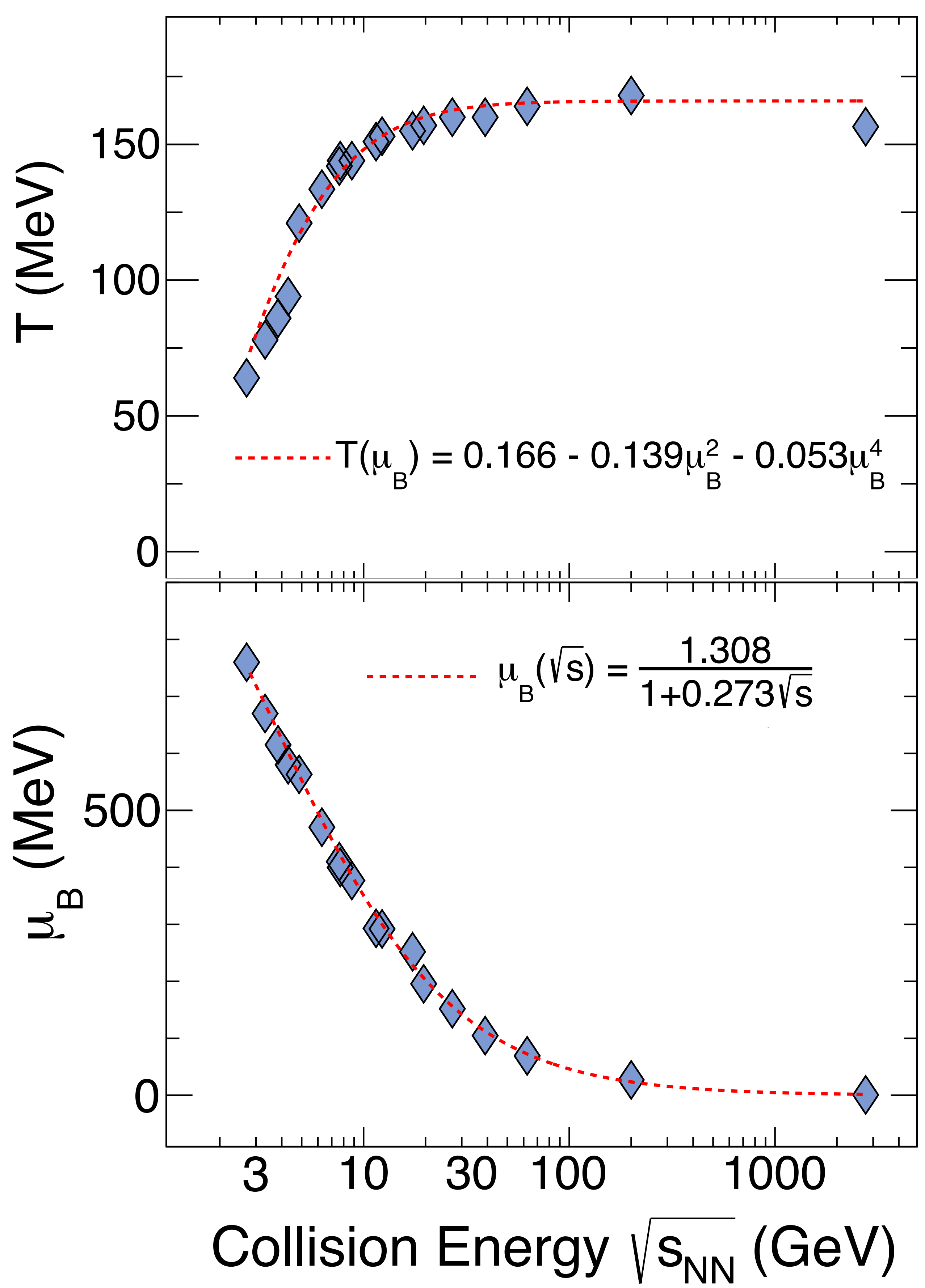
- Lattice calculations at high μ_B suffer from sign problem
- Effective models have several underlying assumptions/ approximations

Theory prediction vary wildly in $\mu_B - T$ plane. **Experimental search very important.**

Introduction: Experimentally accessing Phase Diagram



P. Braun-Munzinger, J. Stachel, Nature 448 (2007) 302



B. Mohanty, N. Xu, arXiv:2101.09210, A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

- Varying collision energy, impact parameter, rapidity acceptance, collision species, varies T and μ_B of system created
- Study energy/centrality/rapidity/species dependence of CP sensitive observables

Cumulants:

- Cumulants:

$$C_1 = < n > \quad n = \textit{conserved charge number in an event}$$

$$C_2 = < \delta n^2 > \qquad {}^*\delta n = n - < n >$$

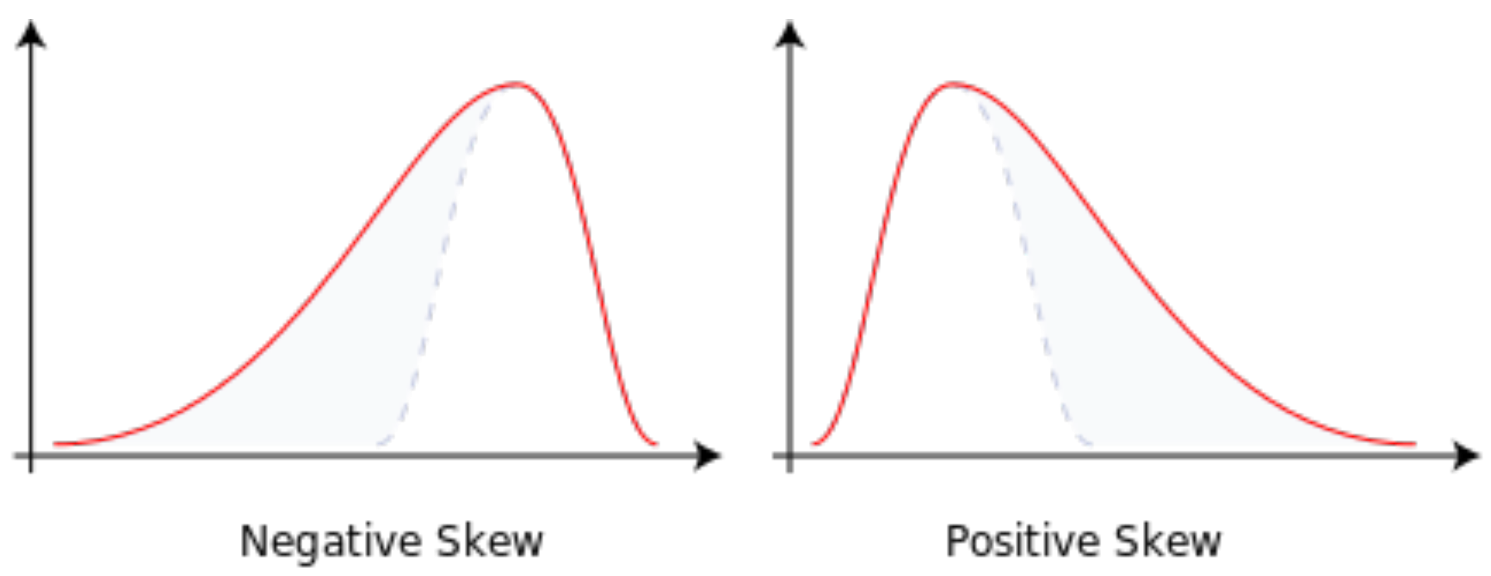
$$C_3 = < \delta n^3 >$$

$$C_4 = < \delta n^4 > - 3 < \delta n^2 >$$

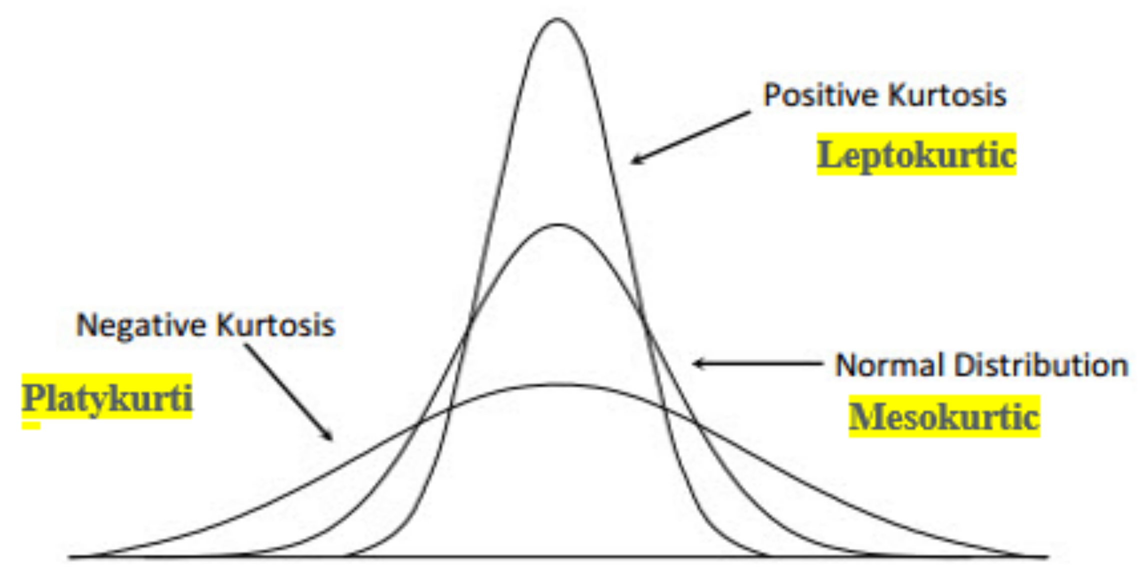
$$C_5 = < \delta n^5 > - 10 < \delta n^3 > < \delta n^2 >$$

$$C_6 = < \delta n^6 > - 15 < \delta n^4 > < \delta n^2 > - 10 < \delta n^3 >^2 + 30 < \delta n^2 >^3$$

Skewness: Asymmetry



Kurtosis: Peakedness



- Factorial cumulants (irreducible correlation function):

$$\kappa_1 = C_1$$

$$\kappa_2 = - C_1 + C_2$$

$$\kappa_3 = 2C_1 - 3C_2 + C_3$$

$$\kappa_4 = - 6C_1 + 11C_2 - 6C_3 + C_4$$

$$\kappa_5 = 24C_1 - 50C_2 + 35C_3 - 10C_4 + C_5$$

$$\kappa_6 = - 120C_1 + 274C_2 - 225C_3 + 85C_4 - 15C_5 + C_6$$

Note: Convention for STAR:
Cumulants (C_n) and Factorial cumulants (κ_n)
Theories and ALICE:
Cumulants (κ_n) and Factorial cumulants (C_n)

Cumulants and CP Search:

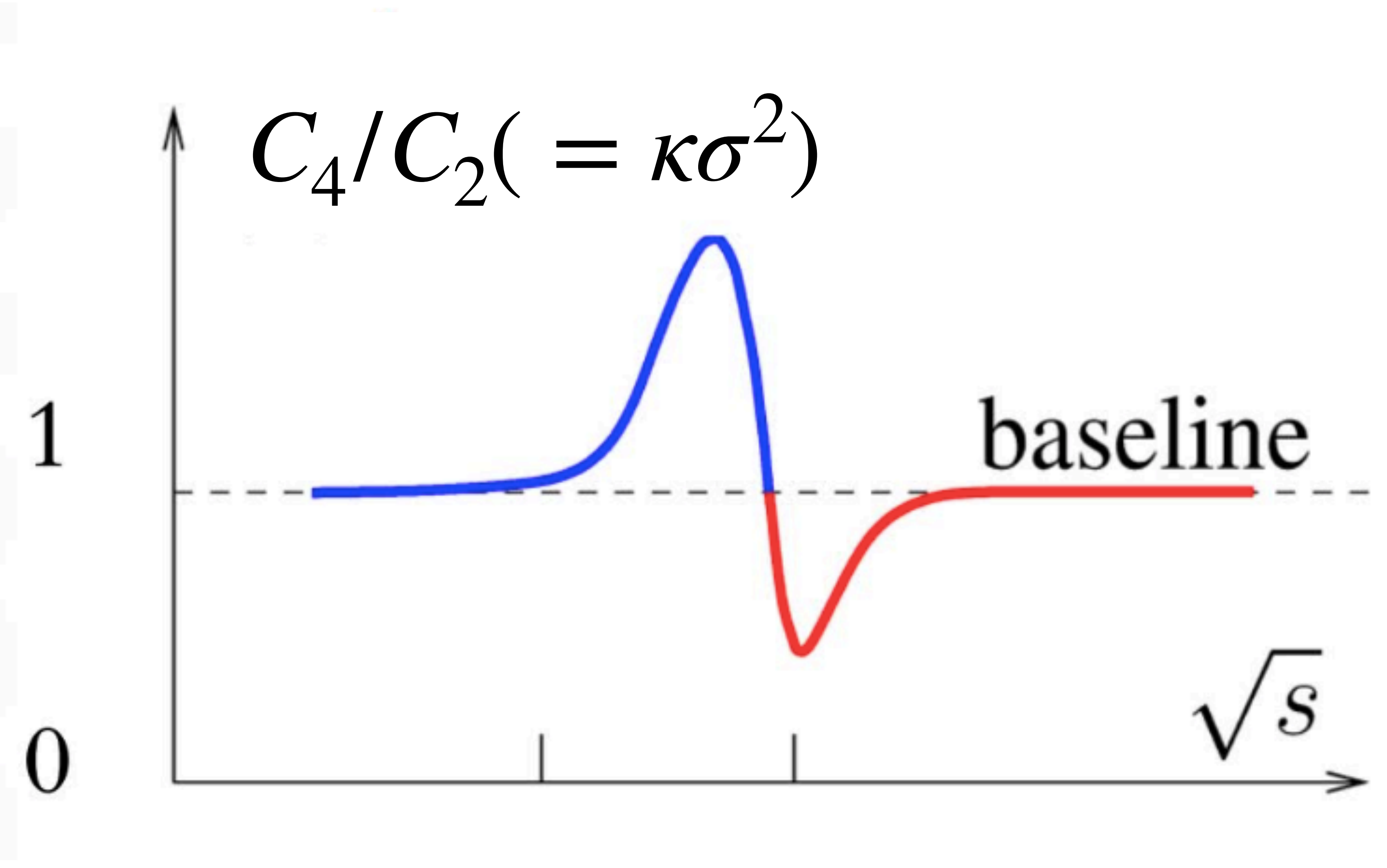
Related to correlation length: $C_2 \sim \xi^2, C_4 \sim \xi^7$

- Finite size/time effects reduces ξ
- Higher order → more sensitivity

$q = B, Q, S$

Related to susceptibilities: $\frac{C_{4q}}{C_{2q}} = \frac{\chi_4^q}{\chi_2^q}, \frac{C_{6q}}{C_{2q}} = \frac{\chi_6^q}{\chi_2^q}$

- Direct comparison with lattice QCD, HRG, QCD-based model calculations



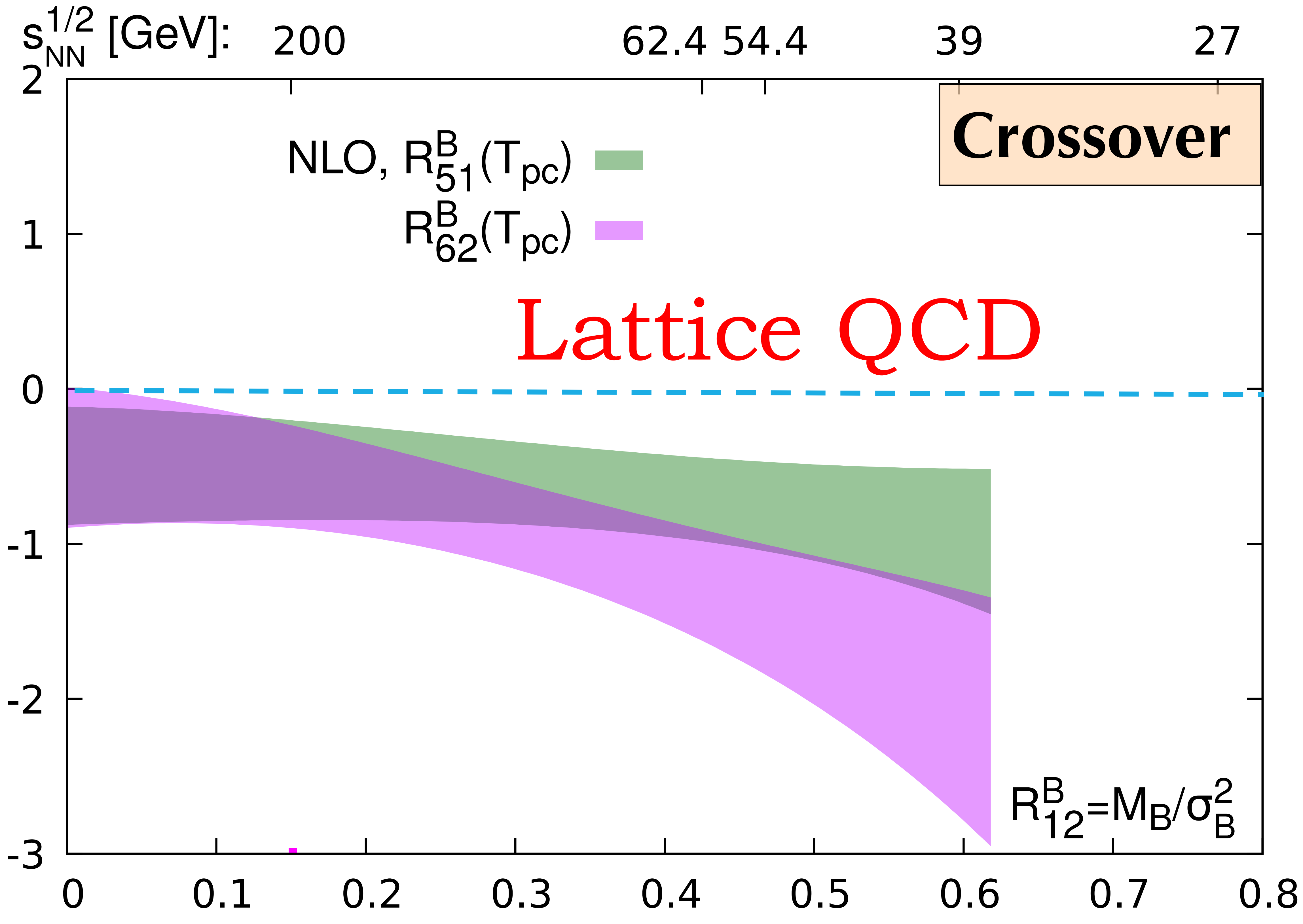
Assumption: Thermodynamic equilibrium

Non-monotonic $\sqrt{s_{NN}}$ dependence of net-proton C_4/C_2 - existence of a critical region

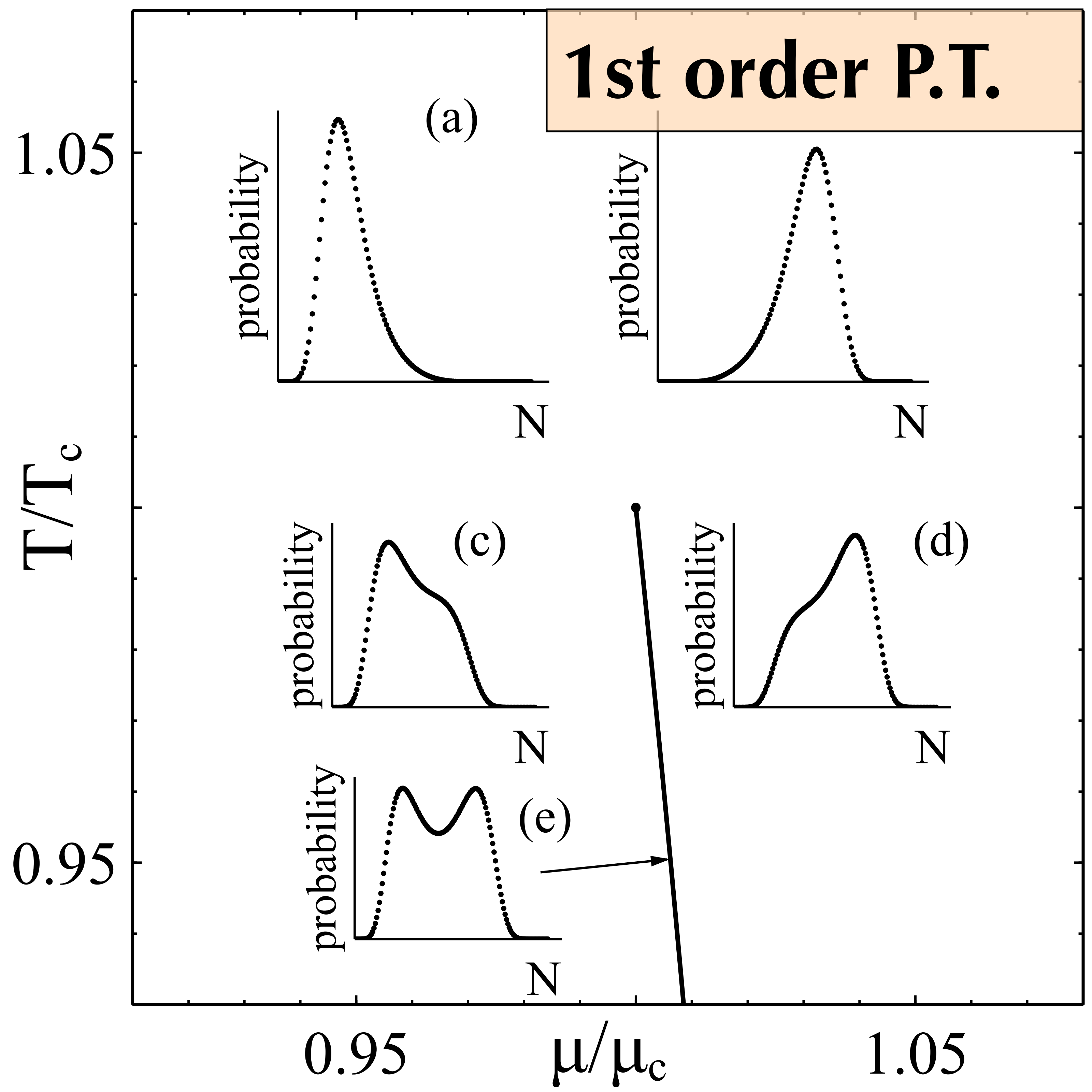
M. A. Stephanov, Phys.Rev.Lett. 107 (2011) 052301,
Y. Hatta ,M. A. Stephanov, Phys.Rev.Lett. 91 (2003) 102003

Cumulants and CP Search:

Establish crossover and first-order P.T. -> CP exists



HotQCD, Phys. Rev. D101,074502 (2020), Wei-jie Fu et. al, PRD 104, 094047 (2021)



A. Bzdak and V. Koch, PRC100, 051902(R) (2019)

Sign of net-baryon C_5/C_1 and C_6/C_2:
<0 - Lattice QCD/FRG - **includes crossover**
>0 - HRG and UrQMD - no QCD transition

Bimodal multiplicity distribution near **1st order P.T.** - Large factorial cumulants κ_n alternating sign with increasing order

Strategy:

Towards making the QCD phase diagram a reality

- **Perform collisions of nuclei to produce and study QCD matter**
- Check if produced system is governed by thermodynamics
- Experimentally establish crossover at small μ_B
- Search for signs of 1st order P.T. at large μ_B
- Search for signs of QCD critical point

Currently Active Experiments for CP Search:

HADES: S. Harabasz, QM2022

SHINE: A. Laszlo, CPOD2022

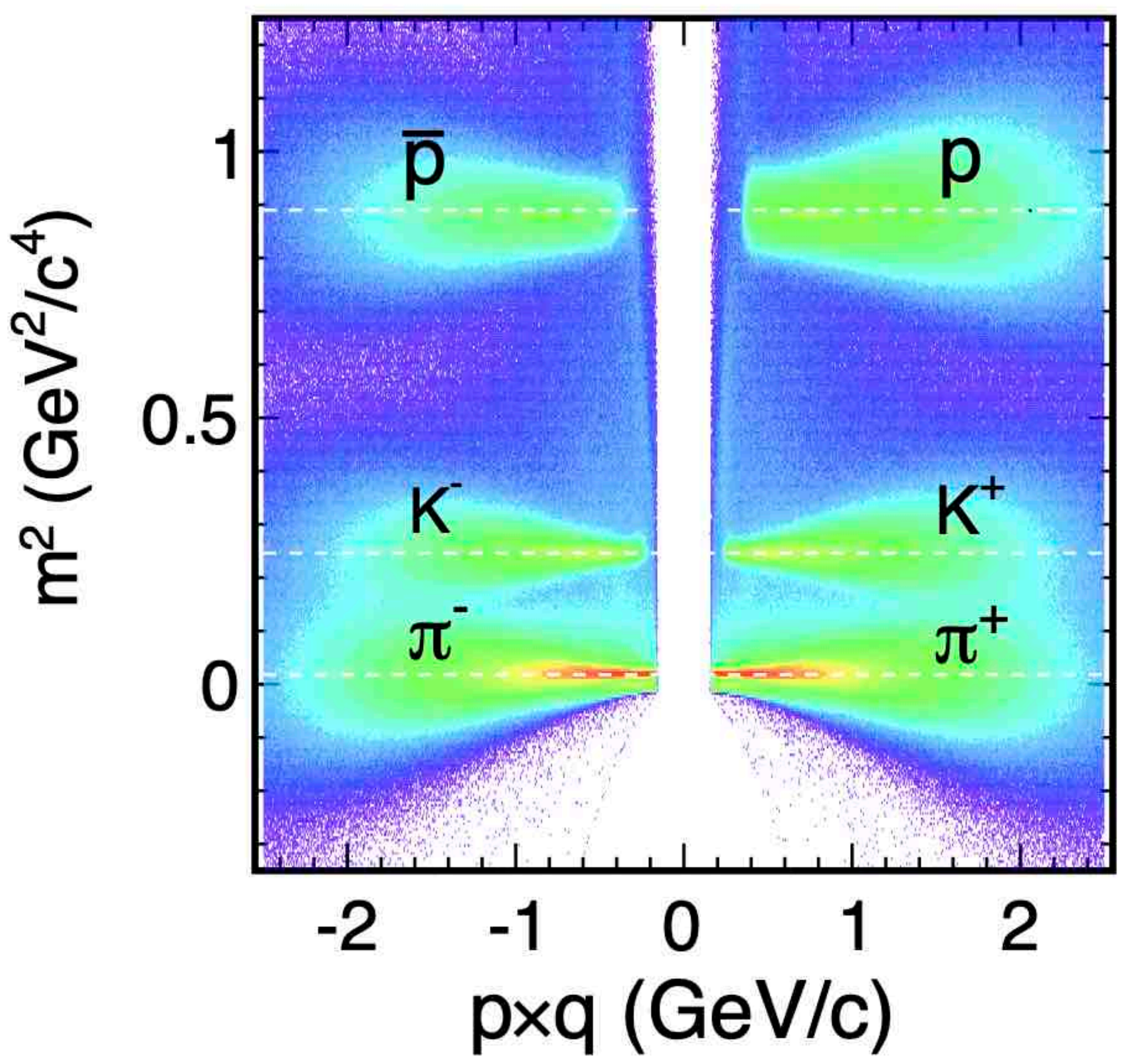
STAR: starnotes : sn0598

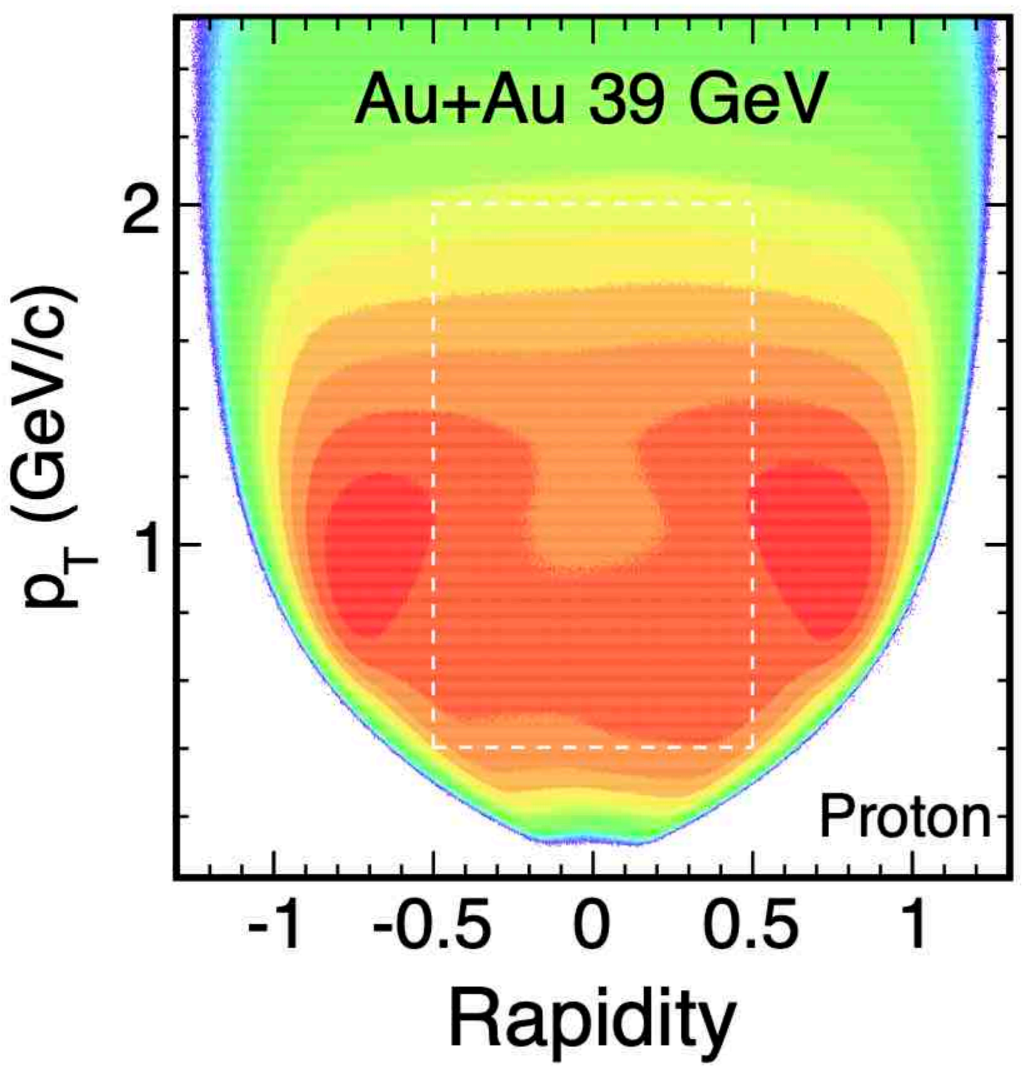
ALICE: CERN-EP-2022-227

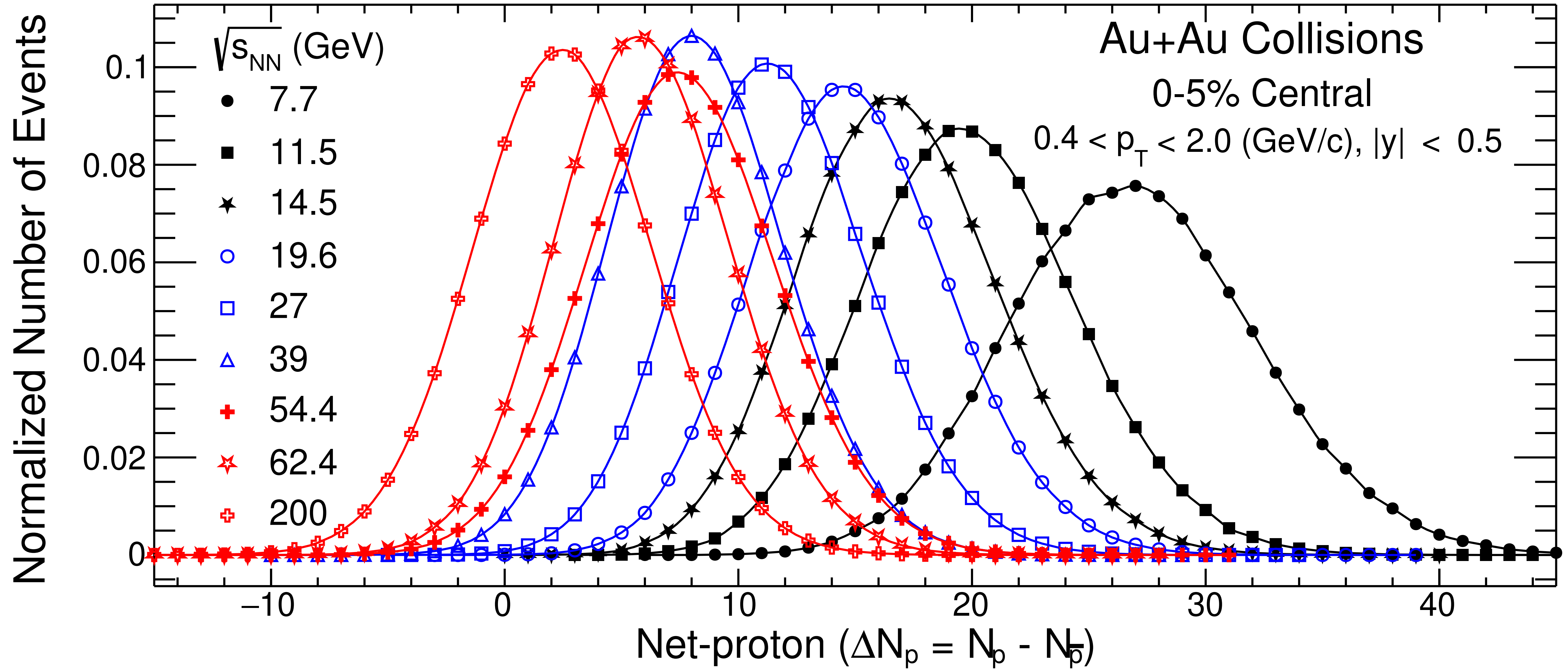
Experiment	Facility	Mode	Colliding energy ($\sqrt{s_{NN}}$)	Systems* *Not all are listed
HADES	SIS18	FXT	2.32 - 2.7 GeV	Au+Au, Ag+Ag, C+C, p+p
NA61/ SHINE	SPS	FXT	5.1 - 17.3 GeV	Pb+Pb, Be+Be, Ar+Sc, p+p
STAR	RHIC	COL/ FXT	3 - 200 GeV	Au+Au, U+U, Zr+Zr, Ru+Ru, Cu+Cu, d+Au, He3+Au, p+Au, p+p
ALICE	LHC	COL	2.76 - 13 TeV	Pb+Pb, Xe+Xe, p+Pb, p+p

Analysis Details:

STAR: Phys. Rev. Lett. ***126****, 092301 (2021)*







- Use net-proton as proxy for net-baryon fluctuation

Event-by-event raw net-proton distribution

- Correct for volume fluctuation effects: CBWC and VFC method (Both methods consistent for sufficiently high centrality resolution)

  X. Luo et al, J.Phys. G 40, 105104 (2013), V. Skokov et al., Phys. Rev. C88 (2013) 034911
  P. Braun-Munzinger et al, NPA 960 (2017)114-130

- Correct for detector efficiency: Binomial efficiency correction / unfolding

  X. Luo , PRC 91, (2015) 034907, T. Nonaka et al, PRC 95, (2017) 064912,
  X. Luo et al, PRC 99 (2019), 044917 , T. Nonaka et al, NIMA906 10-17(2018)

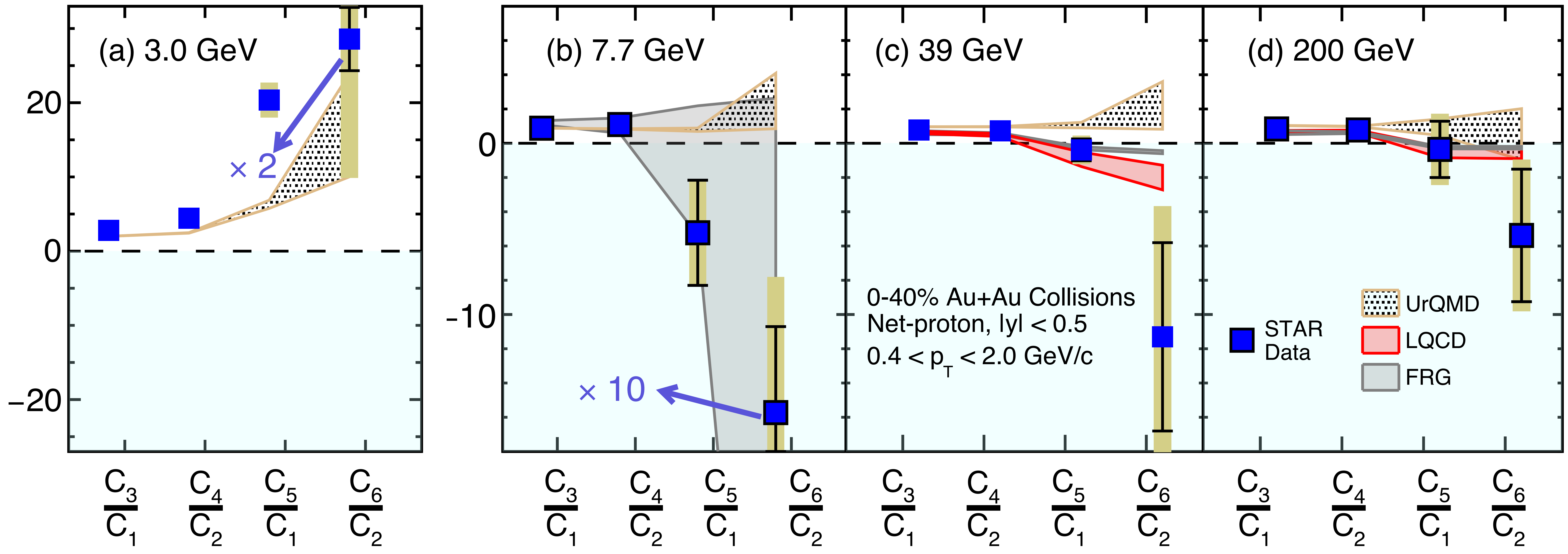
- Measure statistical and systematic uncertainties: stat.err. $C_r \propto \frac{\sigma^r}{\sqrt{N}}$

Strategy:

- Perform collisions of nuclei to produce and study QCD matter
- **Check if produced system is governed by thermodynamics**
- Experimentally establish crossover at small μ_B
- Search for signs of 1st order P.T. at large μ_B
- Search for signs of QCD critical point

Results: *Test Of Thermodynamics*

Test of thermodynamics: Net-baryon $C_3/C_1 > C_4/C_2 > C_5/C_1 > C_6/C_2$ - Lattice QCD



STAR: PRL 130, 082301 (2023)
STAR: PRL 127, 262301 (2021)
STAR: PRL 126, 092301 (2021)
STAR: PRC 104, 024902 (2021)

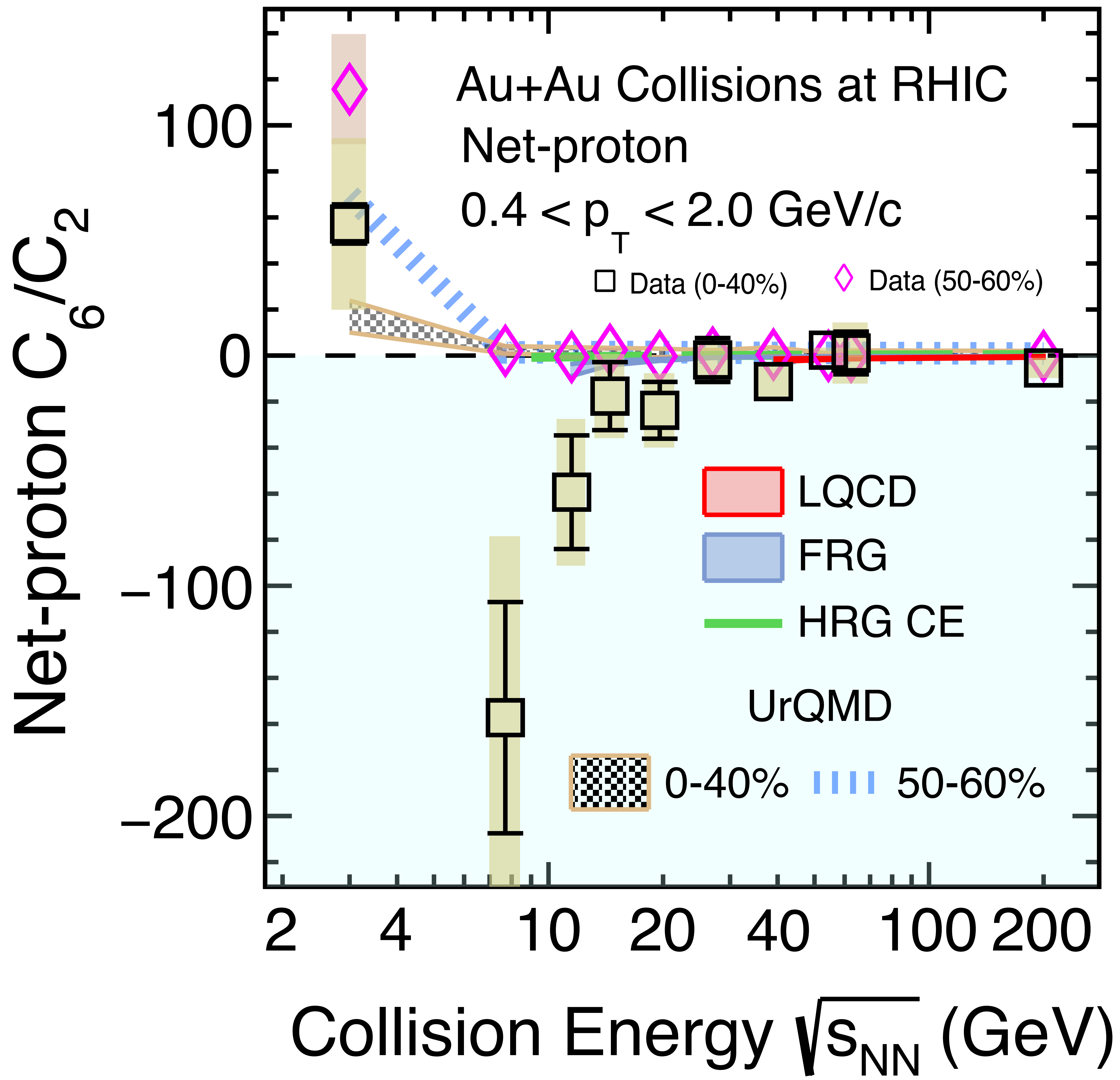
Within uncertainties, 7.7 and 200 GeV data consistent with predicted hierarchy. No clear ordering observed from UrQMD.

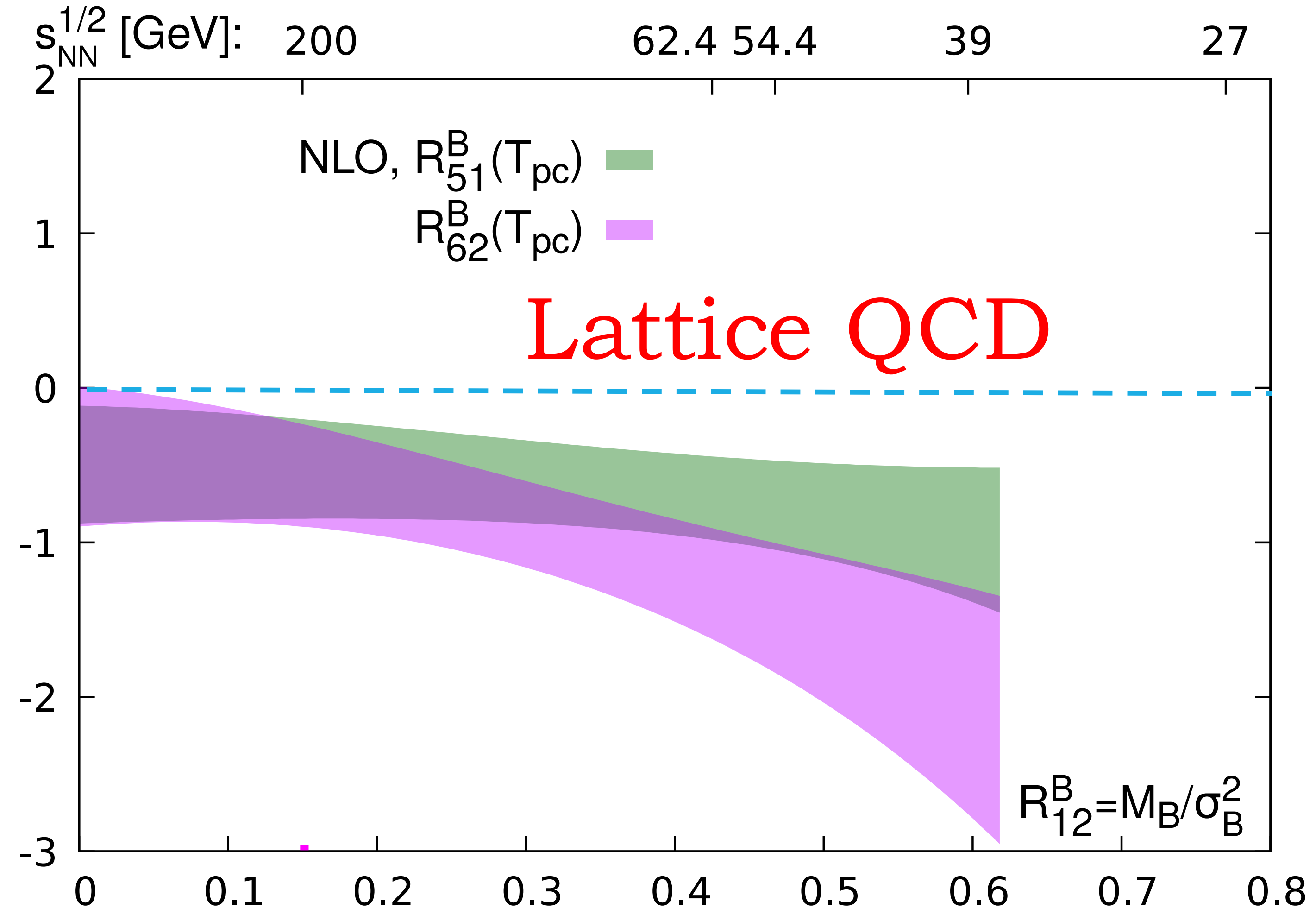
At 3 GeV, violation of ordering is seen. Observed ordering reproduced by UrQMD.

Strategy:

- Perform collisions of nuclei to produce and study QCD matter
- Check if produced system is governed by thermodynamics
  - Data ($\sqrt{s_{NN}} \geq 7.7$ GeV or $\mu_B < 420$ MeV) within uncertainties favors ordering expected from thermodynamics
- **Experimentally establish crossover at small μ_B**
- Search for signs of 1st order P.T. at large μ_B
- Search for signs of QCD critical point

Results: Energy Dependence of C_6/C_2





HotQCD, Phys. Rev. D101,074502 (2020)

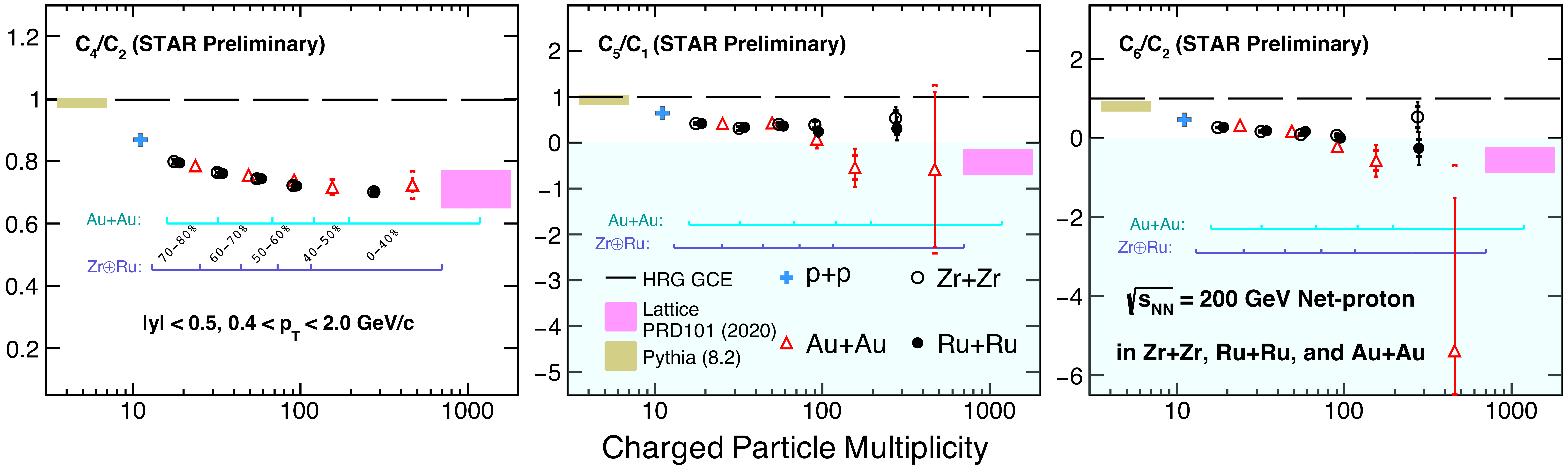
- Increasingly negative C_6/C_2 (down to 7.7 GeV) with decreasing $\sqrt{s_{NN}}$ (1.7σ significance) - sign and trend consistent with lattice QCD

- $C_6/C_2 > 0$ at 3 GeV, sign reproduced by UrQMD. Peripheral data > 0

STAR: PRL 130, 082301 (2023)

STAR: PRL 127, 262301 (2021), HRG CE: P. B Munzinger et al, NPA1008, 122141(2021)

Results: Multiplicity Dependence of C_6/C_2

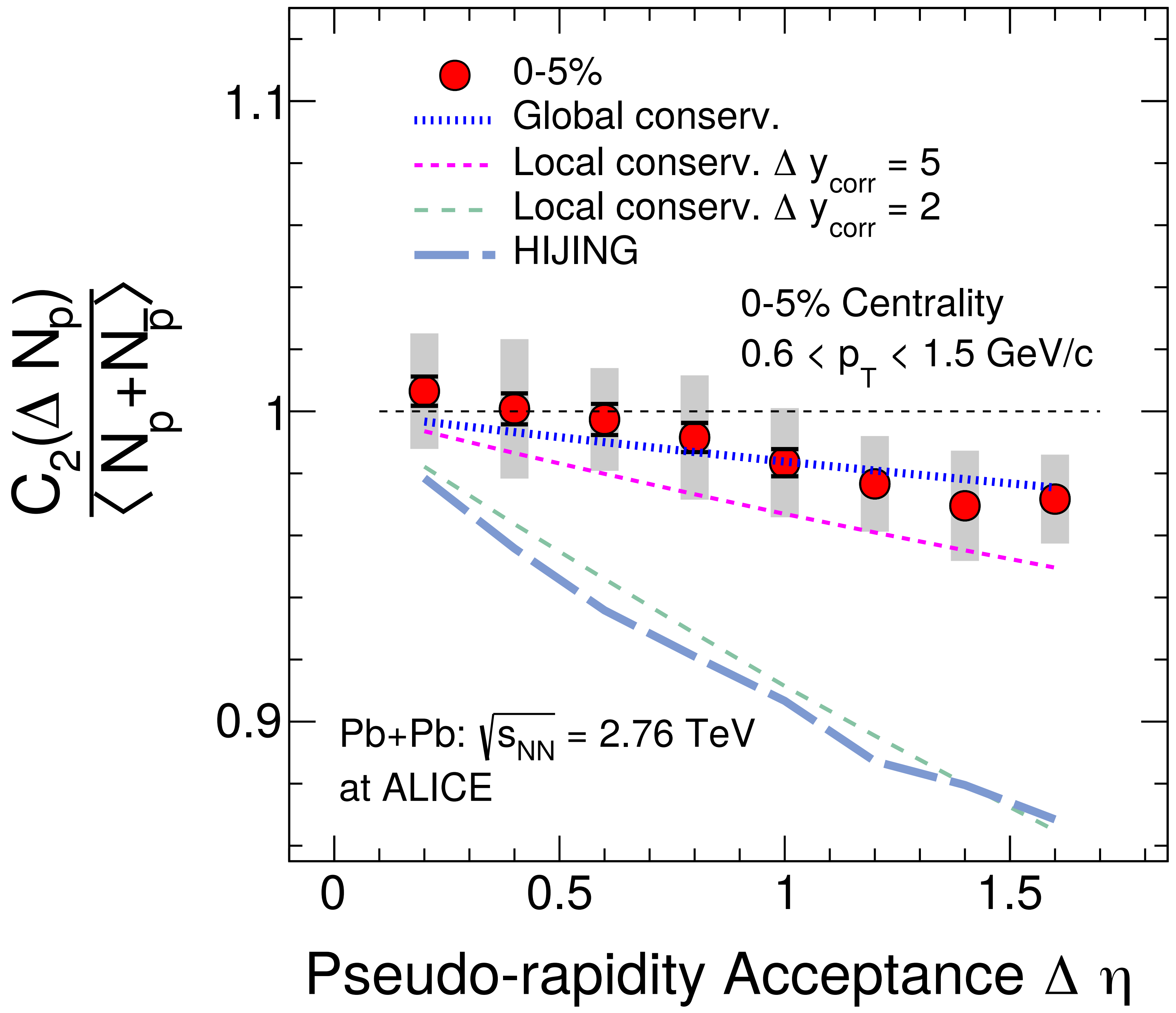


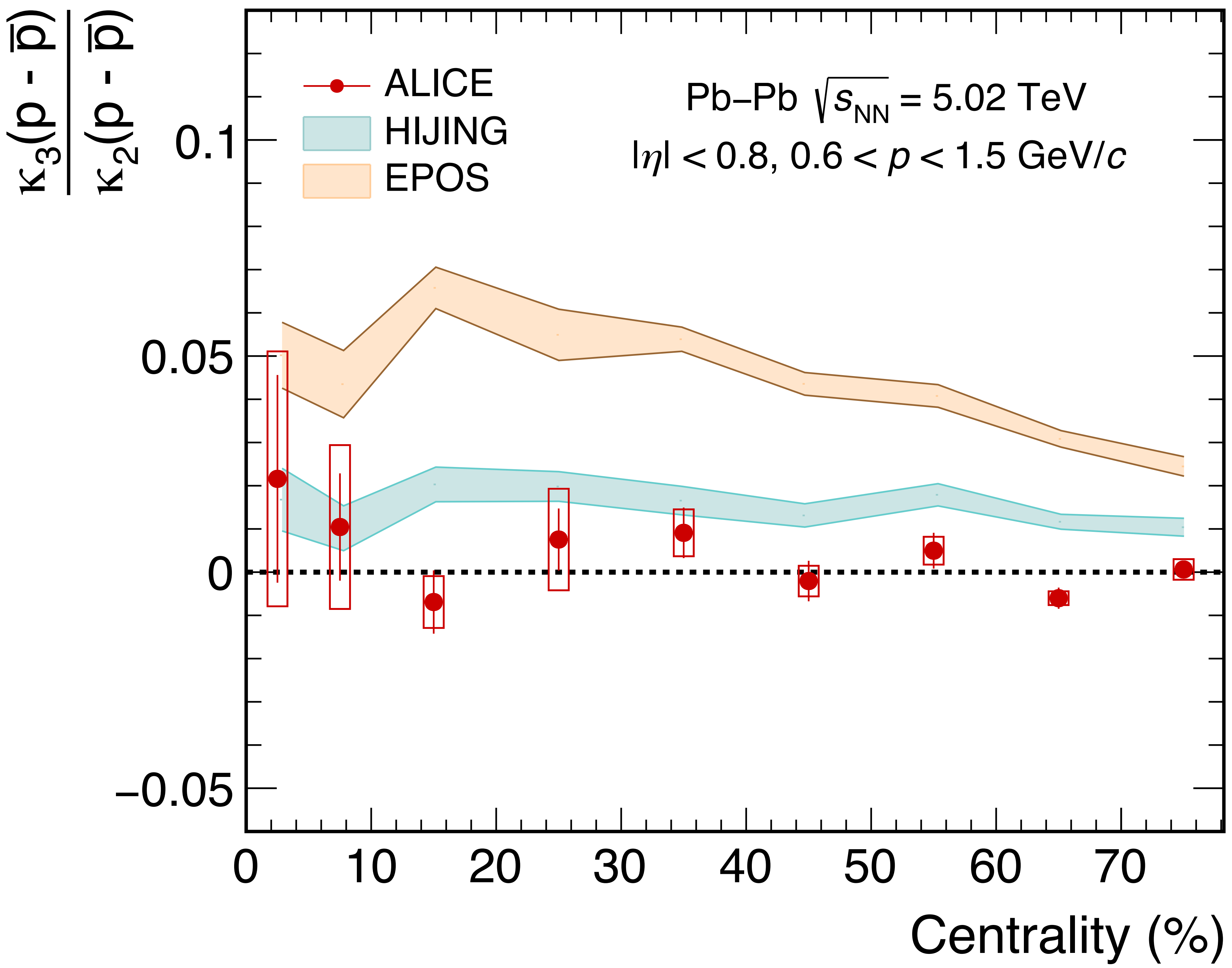
STAR: PRL 127, 262301 (2021)
H.-S. Ko, STAR Collaboration, QM22

Measurements at $\sqrt{s_{NN}}$ = 200 GeV ($\mu_B \sim 20$ MeV)

- Fifth and sixth order cumulant ratios progressively negative towards higher charged particle multiplicity– sign consistent with lattice QCD calculation with a crossover

Results: Measurements at Vanishing μ_B





ALICE: PLB807, 135564(2020)
ALICE: PLB844, 137545(2023)

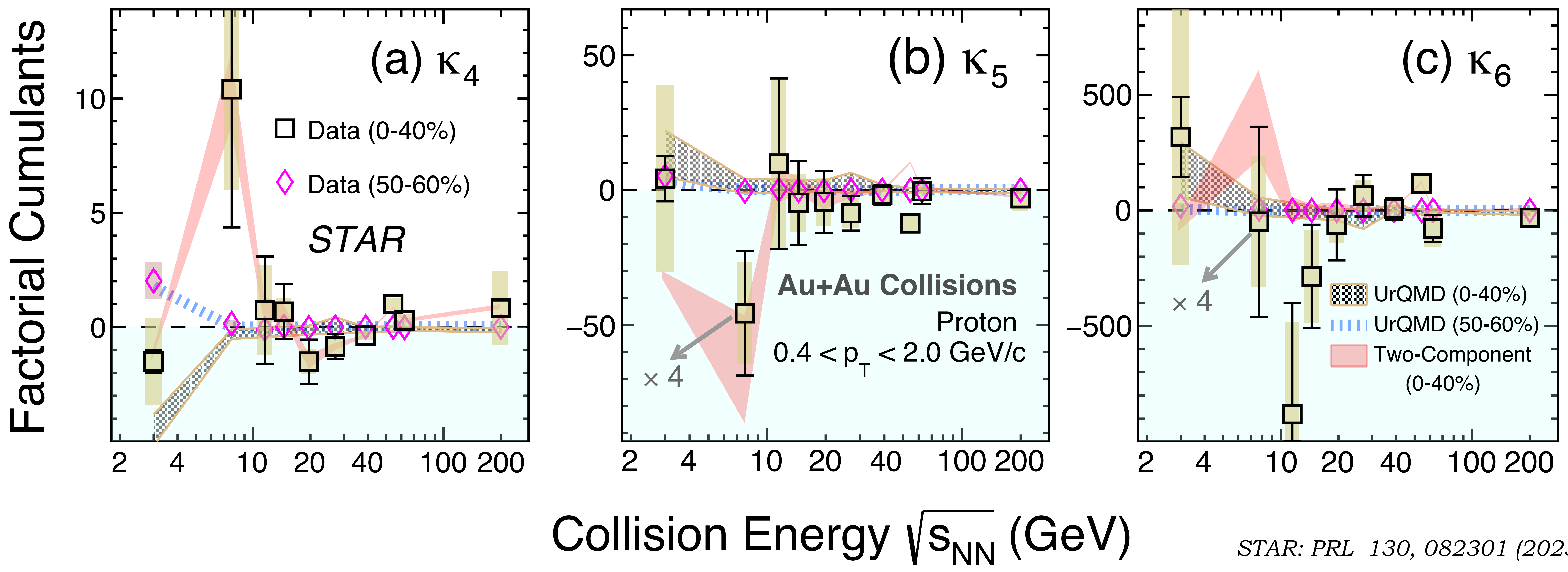
- Presence of long-range rapidity correlations ($\Delta y_{corr} > 0.5$) between protons and antiprotons
- Vanishing third order cumulant ratio – consistent with LQCD and HRG calculations

Strategy:

- Perform collisions of nuclei to produce and study QCD matter
- Check if produced system is governed by thermodynamics
  - Data ($\sqrt{s_{NN}} \geq 7.7$ GeV or $\mu_B < 420$ MeV) within uncertainties favors ordering expected from thermodynamics
- Experimentally establish crossover at small μ_B
  - Observed sign and trend in data ($\sqrt{s_{NN}} \geq 7.7$ GeV) consistent with calculations from lattice QCD ($\mu_B < 110$ MeV) with a crossover at $O(\sim 1\sigma)$ significance level
- **Search for signs of 1st order P.T. at large μ_B**
- Search for signs of QCD critical point

Results: Proton Factorial Cumulants

Two-component distribution: Large factorial cumulants with alternating sign



STAR: PRL 130, 082301 (2023)

- For $\sqrt{s_{NN}} \geq 11.5$ GeV, the proton κ_n within uncertainties does not support the two-component shape of proton distributions expected near a 1st order P.T.
- Possibility of sign change at low energy.

Strategy:

- Perform collisions of nuclei to produce and study QCD matter
- Check if produced system is governed by thermodynamics
  - Data ($\sqrt{s_{NN}} \geq 7.7$ GeV or $\mu_B < 420$ MeV) within uncertainties favors ordering expected from thermodynamics
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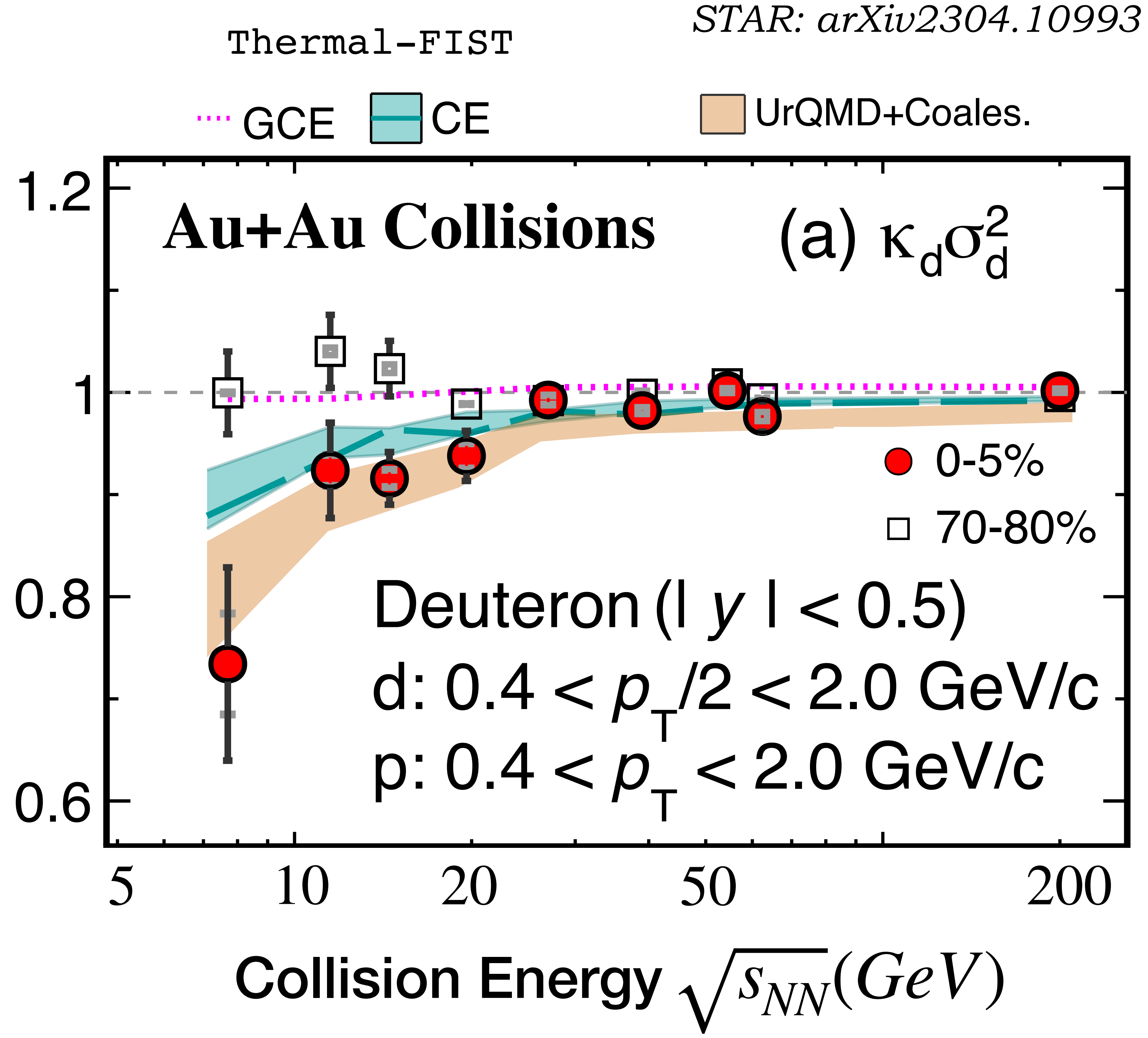
- Search for signs of 1st order P.T. at large μ_B
  - Data ($\sqrt{s_{NN}} \geq 7.7$ GeV) within uncertainties suggest absence of any bimodal structure expected near 1st order phase transition
- **Search for signs of QCD critical point**

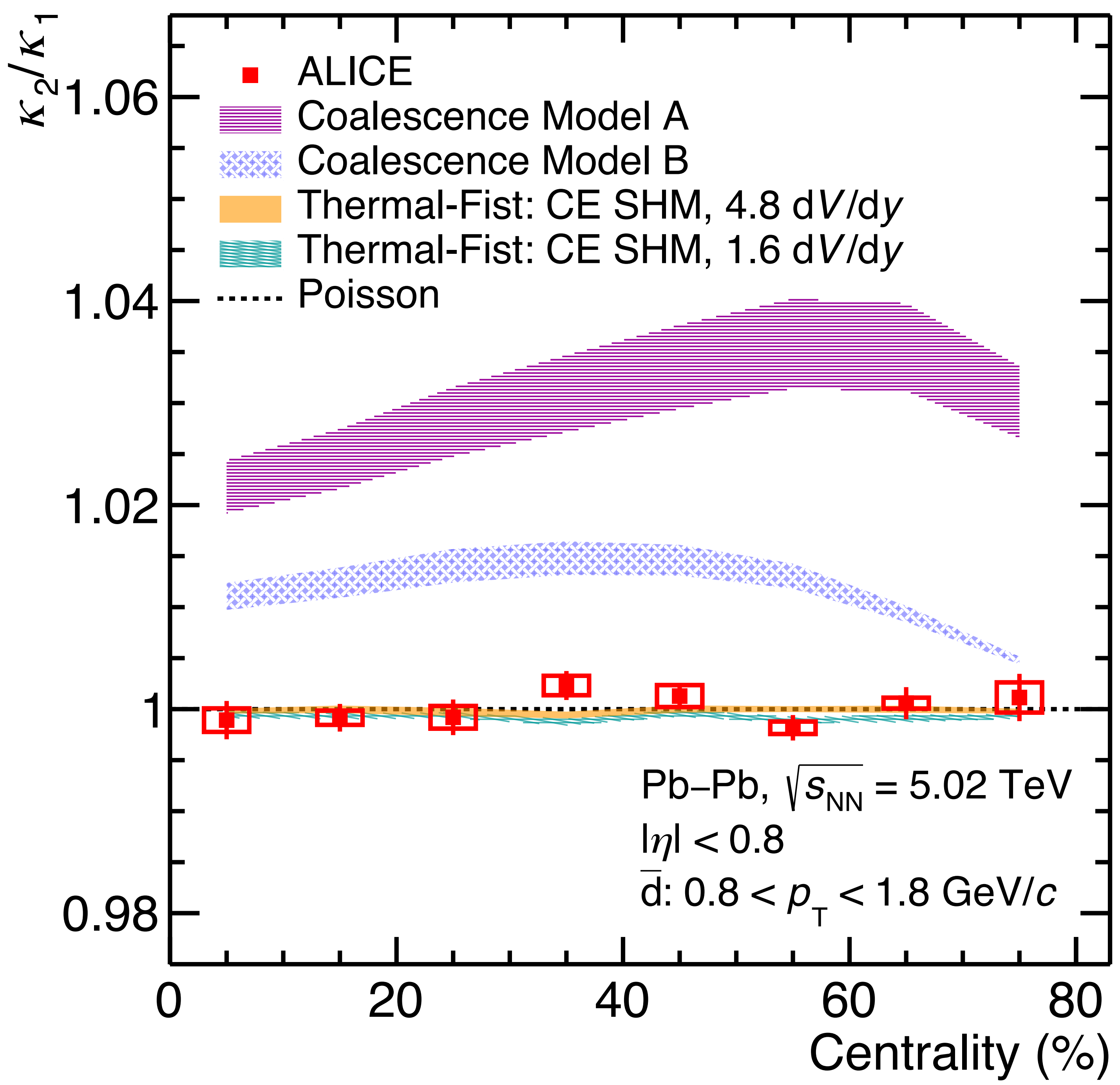
Results: *Light Nuclei Fluctuation*

Light nuclei yield and fluctuations: sensitive local density fluctuation near CP

STAR: arXiv2304.10993

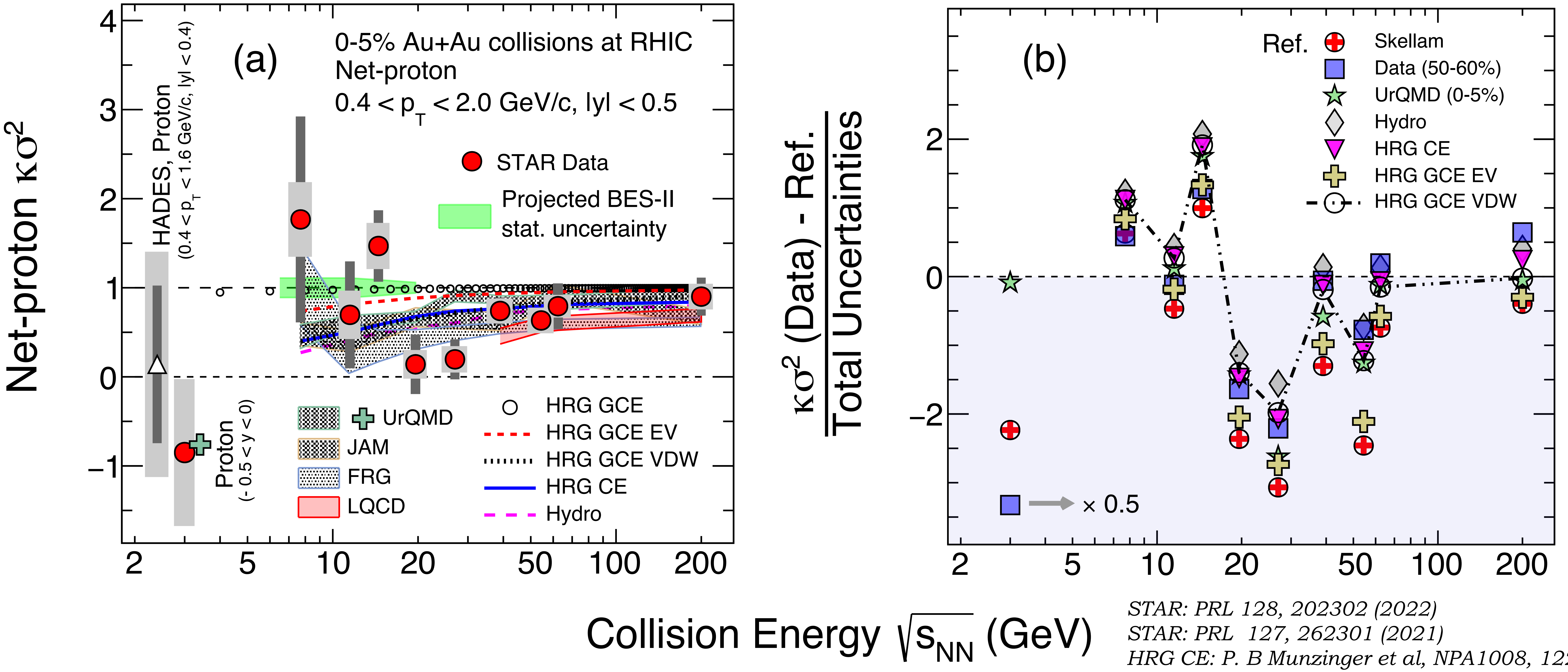


ALICE: PRL 131, 041901 (2023)



- Fluctuations of deuteron explained by HRG and UrQMD+Coalescence model

Results: Net-proton Fluctuations



STAR: PRL 128, 202302 (2022)
STAR: PRL 127, 262301 (2021)
HRG CE: P. B Munzinger et al, NPA1008, 122141(2021)
Hydro: Vovchenko et al, PRC 105, 014904 (2022)

- Non-monotonic collision energy dependence observed for net-proton C_4/C_2 at 3.1σ level – consistent with CP expectation. Non-CP models fail to reproduce the observed trend
- Suppression observed at $\sqrt{s_{NN}} =$ 3GeV (μ_B = 750 MeV), consistent with hadronic baseline

Strategy:

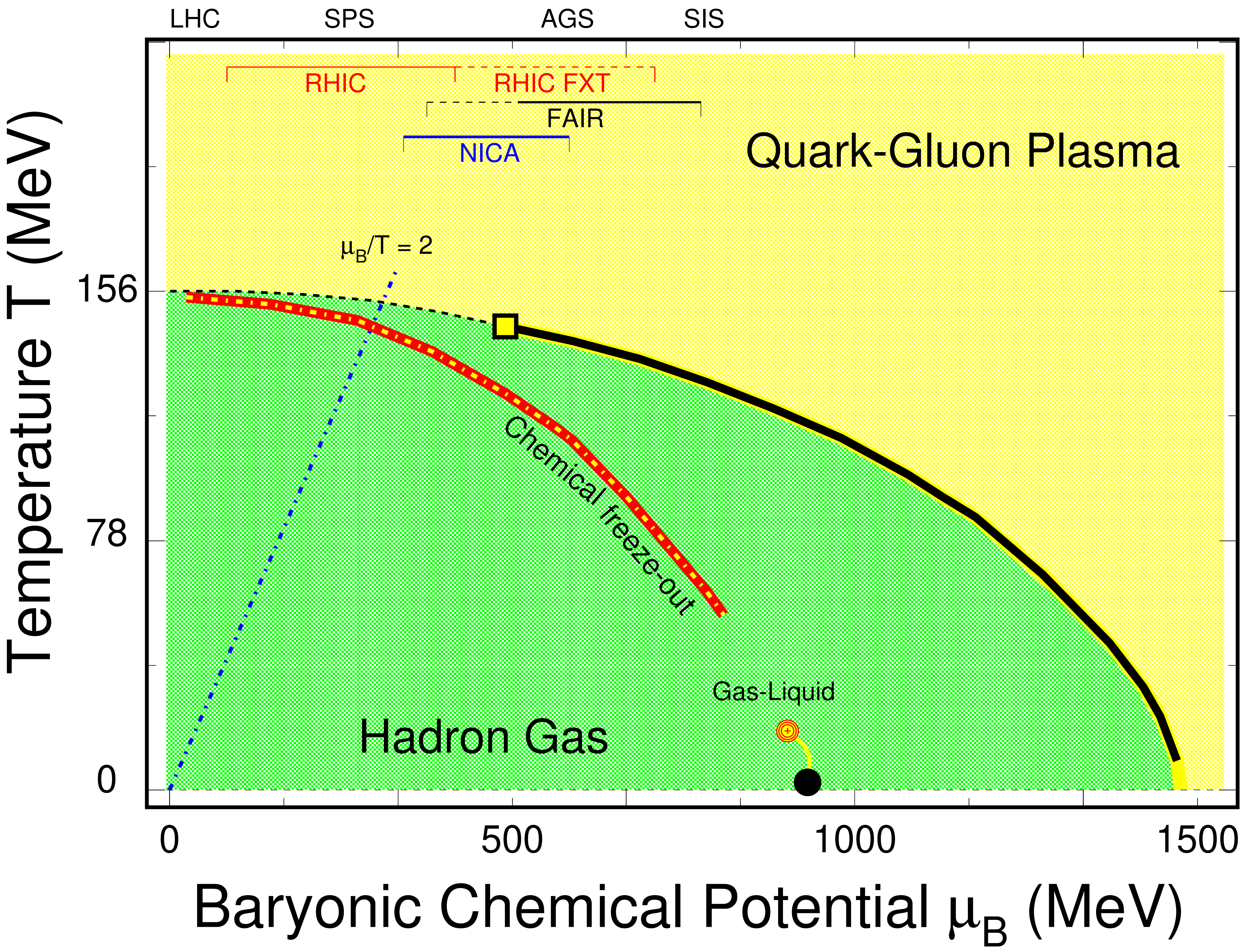
- Perform collisions of nuclei to produce and study QCD matter
- Check if produced system is governed by thermodynamics
  - Data ($\sqrt{s_{NN}} \geq 7.7$ GeV or $\mu_B < 420$ MeV) within uncertainties favors ordering expected from thermodynamics

- Experimentally establish crossover at small μ_B
  - Observed sign and trend in data ($\sqrt{s_{NN}} \geq 7.7$ GeV) consistent with calculations from lattice QCD ($\mu_B < 110$ MeV) with a crossover at $O(\sim 1\sigma)$ significance level

- Search for signs of 1st order P.T. at large μ_B
  - Data ($\sqrt{s_{NN}} > 7.7$ GeV) within uncertainties suggest absence of any bimodal structure expected near 1st order phase transition

- Search for signs of QCD critical point
  - Non-monotonic energy dependence observed in data at $\sim 3\sigma$ level, consistent with expectation from model with CP. Precision measurement necessary

Status So Far:



- Hint of non-monotonic trend (3.1 σ level) around μ_B = 140 - 420 MeV **(BES-II data to confirm)**
- Indication of crossover at $\mu_B \leq$ 110 MeV (Lattice QCD)
- Data falling to hadronic baseline at $\sqrt{s_{NN}}$ = 3 GeV (μ_B = 750 MeV)

- **CP (if present and accessible in collisions) is expected between μ_B = 110 - 750 MeV ($\sqrt{s_{NN}} = 3 - 39$ GeV)**

Future Prospects and challenges

Precision Measurements

BES-II upgrade *https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598*

10-20X increase in statistics for Au+Au ($\sqrt{s_{NN}} = 3 - 27$ GeV)

Detector upgrades: iTPC, EPD, eTOF

Wide acceptance: $|\eta| < 1.6$

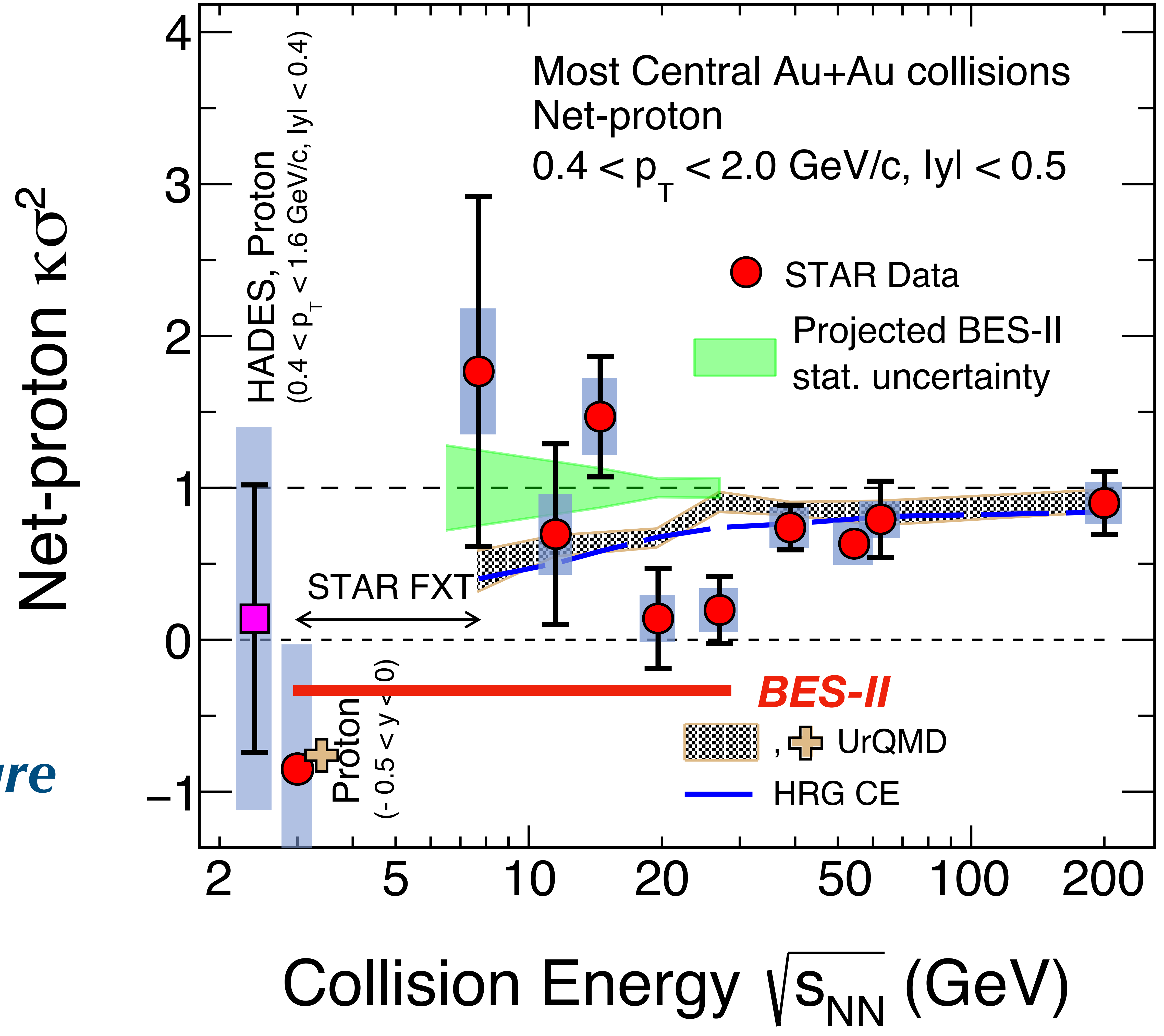
LHC Run3 upgrade *CERN-LHCC-2022-009*

More than 50X increase in statistics

Detector upgrades: TPC, ITS, FIT

Wide acceptance: $|\eta| < 4$

CBM and NICA also to take data for CP search in future



STAR: PRL 128, 202302 (2022)

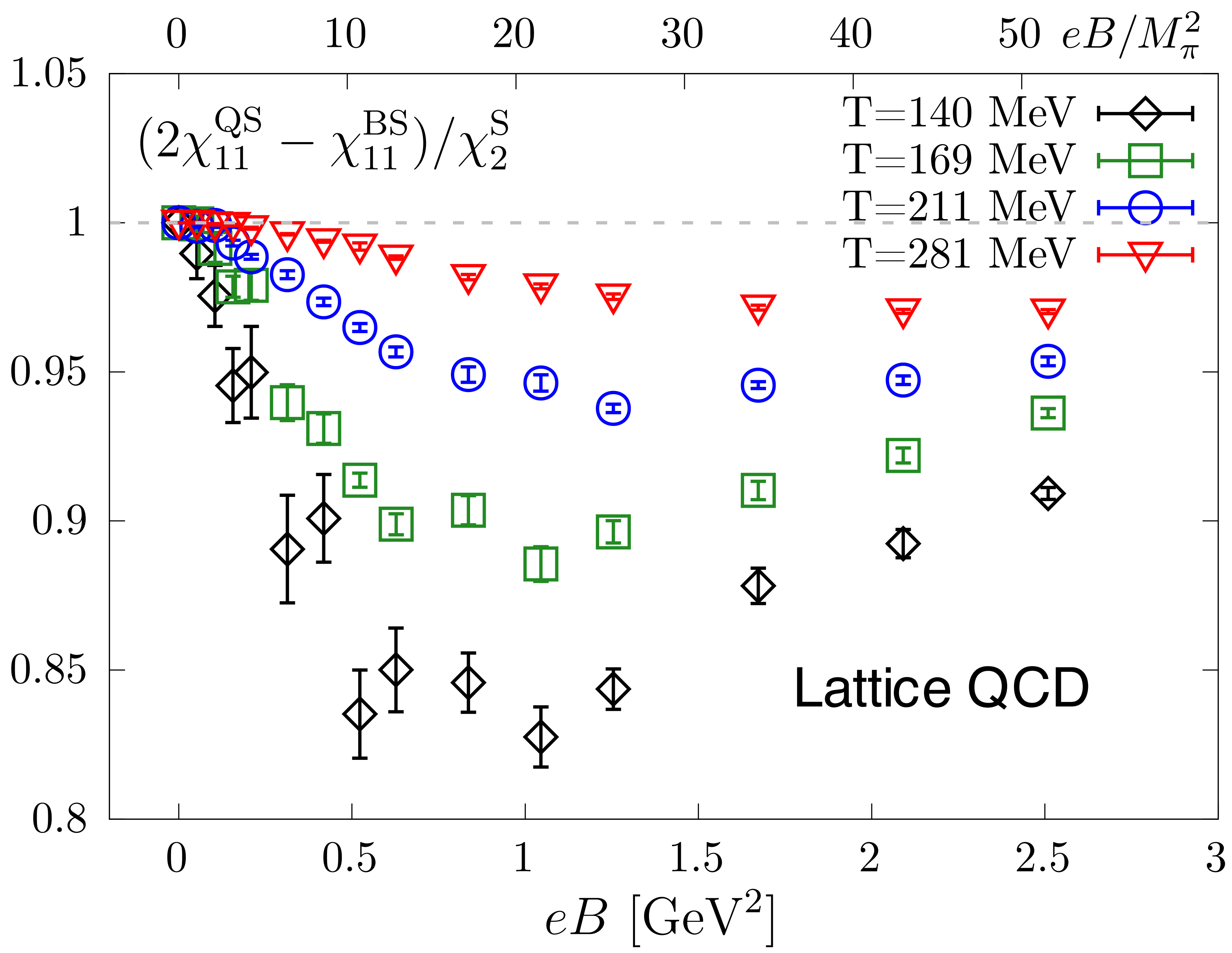
Rapidity is a finer-resolution probe of the critical regime than $\sqrt{s_{NN}}$

- **Rapidity scan for CP search**

J. Brewer et. al., Phys.Rev.C 98 (2018) 6, 061901

New measurements

1. Probing magnetic field: Off diagonal cumulants



Isospin symmetry broken due to magnetic field: Measure centrality dependence of mixed cumulants to verify its presence

H.T. Ding et al, EPJA 57.202 (2021)

2. Crossover search at STAR and LHC with C_6 and C_8

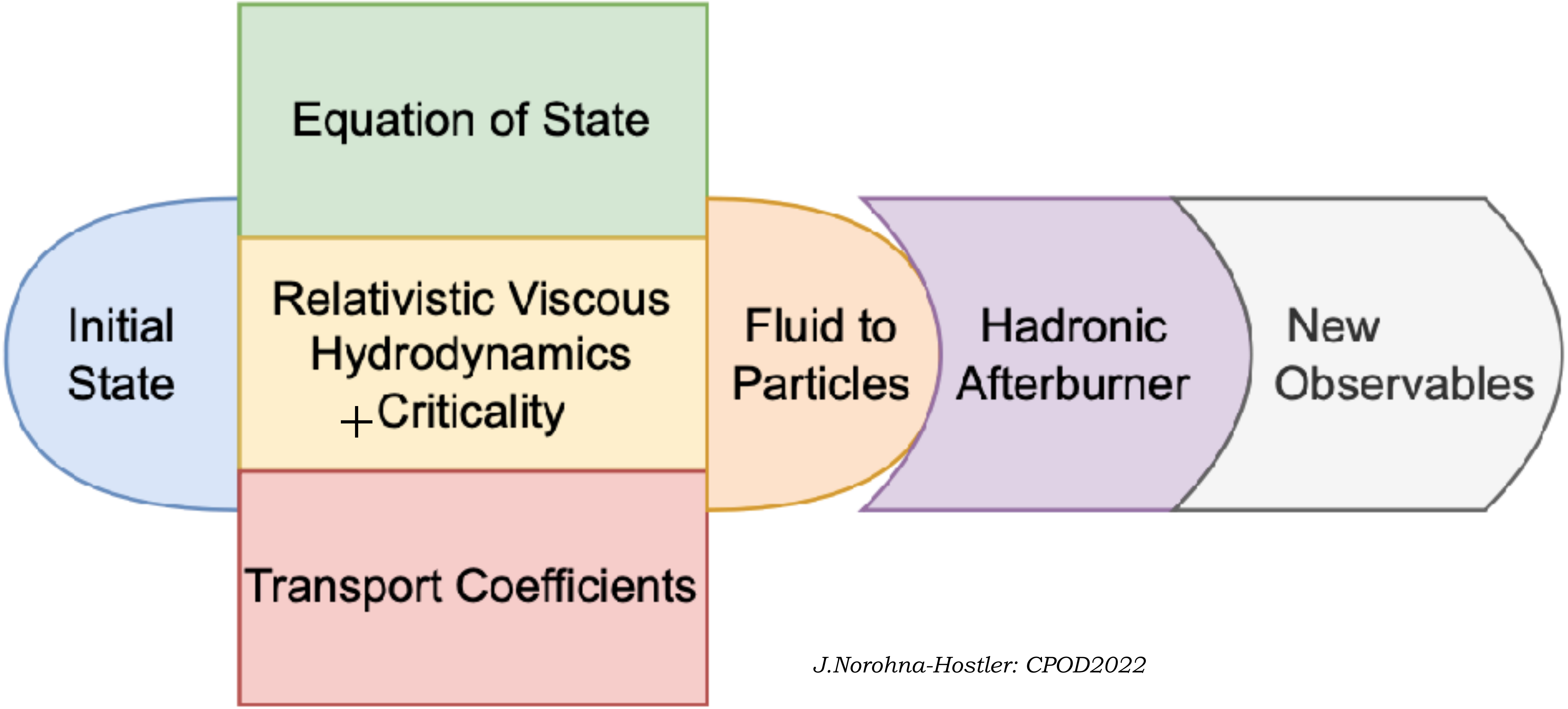
HotQCD: PRD101, 074502 (2020),
S. Borsanyi et al, JHEP10 (2018) 205, B. Friman et al,EPJC71, 1694(2011)

STAR: Au+Au at $\sqrt{s_{NN}}$ = 200 GeV: ~ 20 billion event (2023+2025)

Au+Au at $\sqrt{s_{NN}}$ = 3 GeV: ~ 2 billion events collected

ALICE : Higher order measurements possible with high statistic LHC Run3

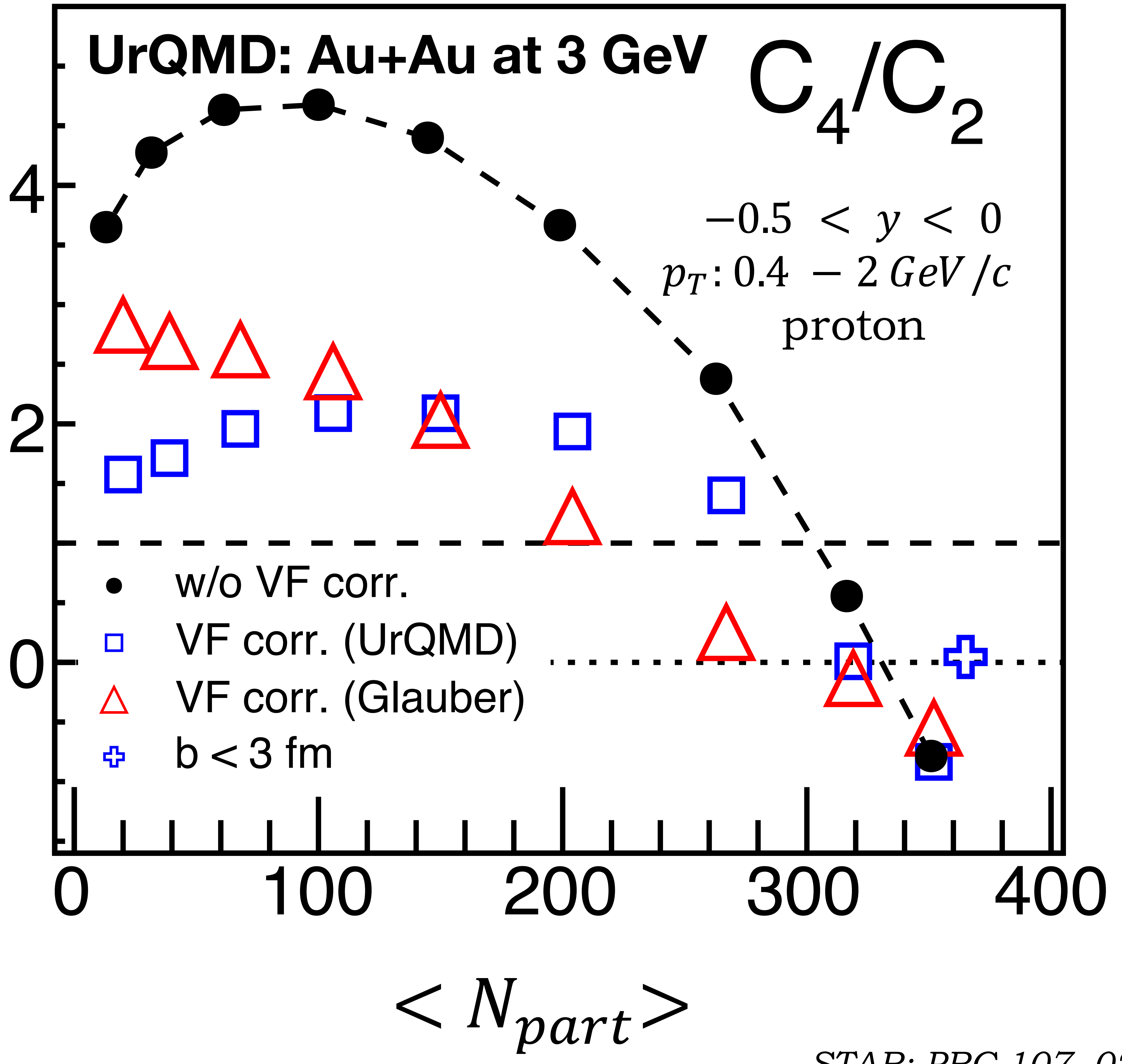
Understanding Dynamics of System in Hi Collisions

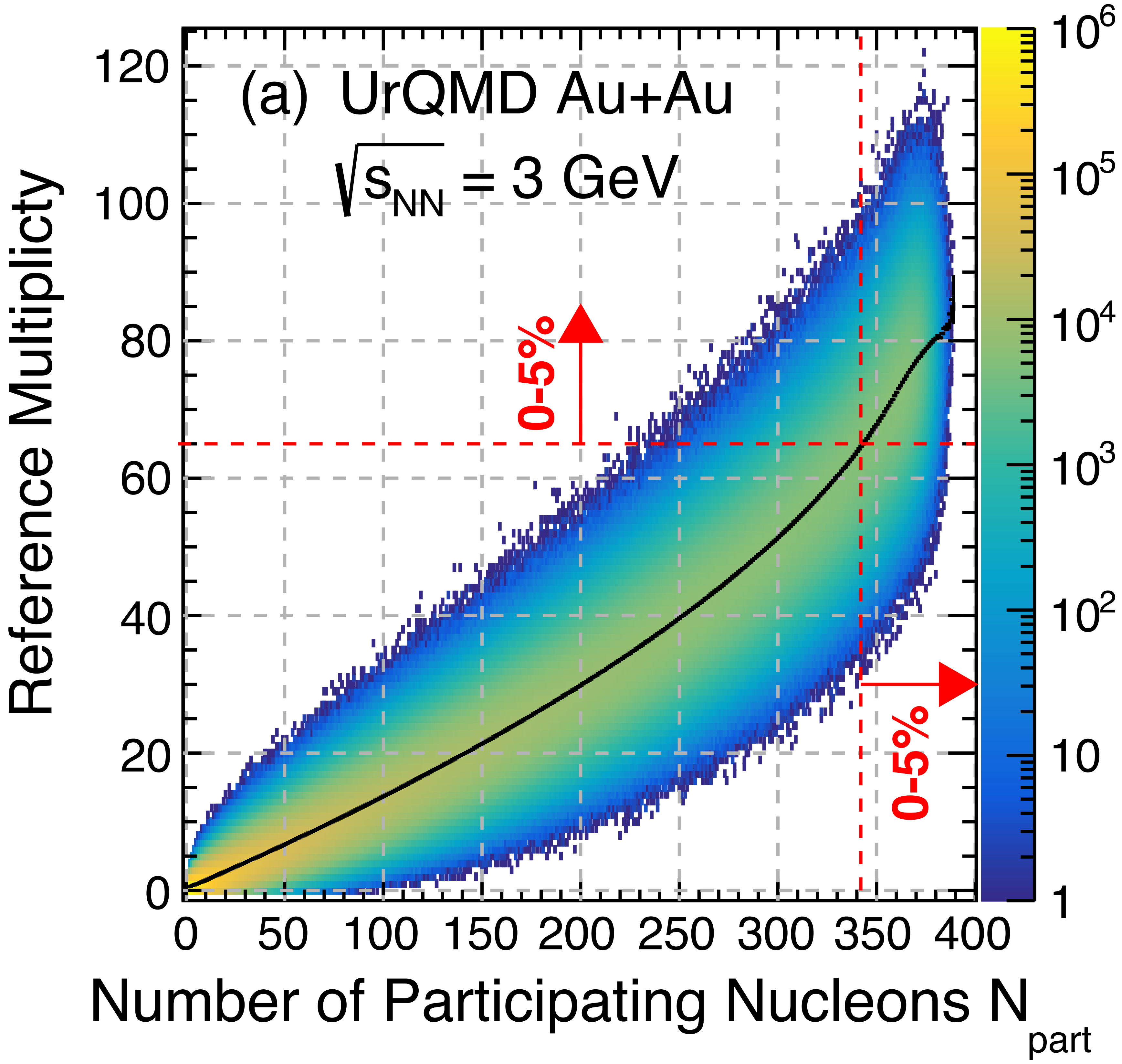


J.Norohna-Hostler: CPOD2022

System near CP not in equilibrium due to finite time and size effects - could lead to suppression of critical signals
Hydrodynamic calculations with critical point considering non-equilibirum effects

Initial Volume Fluctuation Effects:





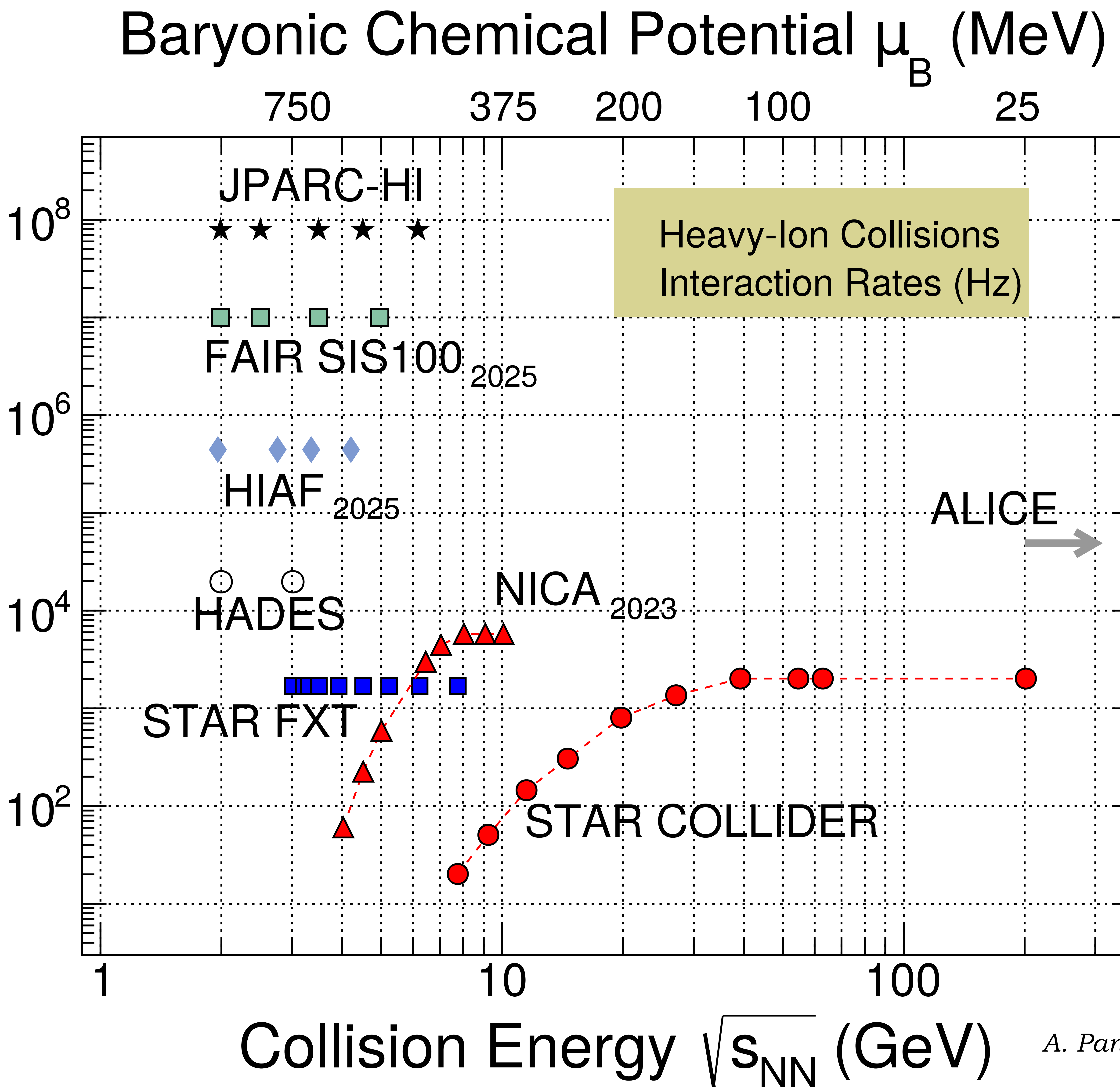
STAR: PRC 107, 024908 (2023)

Initial volume fluctuation effect significant at low $\sqrt{s_{NN}}$

Low collision energy: low charged particle multiplicity - poor centrality resolution

Look for alternate way to obtain $< N_{part} >$ in experiments.

Conclusion:



A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

- Significant effort has been put from experiment/theory for CP search
- More to come in near future:

-Theory calculations considering non-equilibrium effects
-Lattice QCD calculations at large μ_B
-Precision data and new experimental facilities

Stay tuned.

Acknowledgements:

Alphabetically: Xin Dong, ShinIchi Esumi, Yige Huang, Ho-San Ko*, Xiaofeng Luo, Debasish Mallick*, Bedanga Mohanty, Dylan Neff*, Risa Nishitani*, Bappaditya Mondal*, Toshihiro Nonaka, Grazyna Odyniec, Zachary Sweger*, Volodya Vovchenko, Yongcong Xu*, Nu Xu, Xin Zhang*, Yu Zhang*.* * PhDs/postdocs

STAR Collaboration, EHEP group at NISER and RNC group at LBNL

And organizers for the opportunity. ***Thank you.***

Backup