Experimental Status of QCD Phase Diagram

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Jan 13, 2024

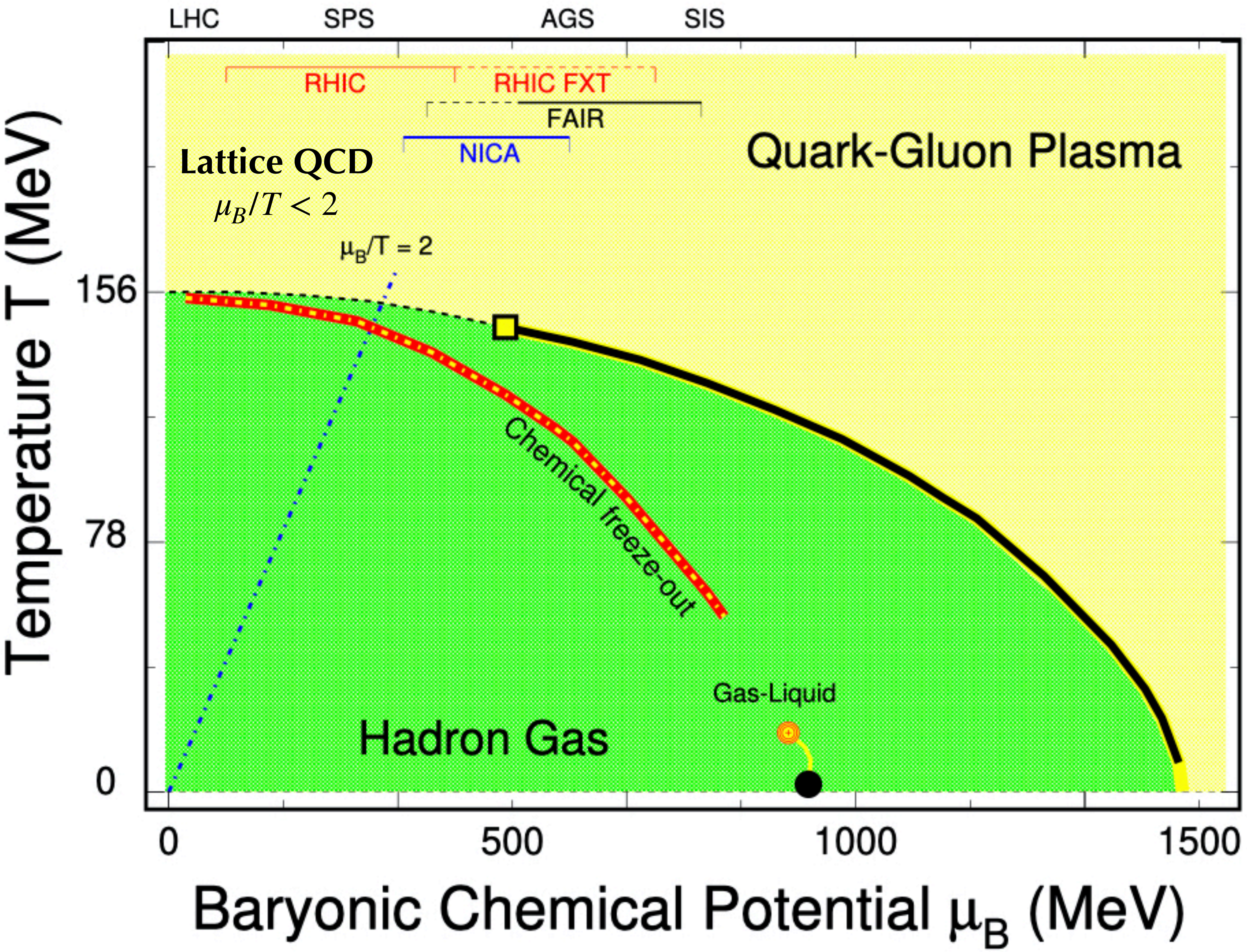
Outline

1. Introduction
2. Experimental analysis
3. Results
4. Summary

ATHIC 2025
January 13-16, 2025

BERKELEY LAB

Introduction: QCD Phase Diagram



B. Mohanty, N. Xu, arXiv:2101.09210

Lattice QCD →

Models →

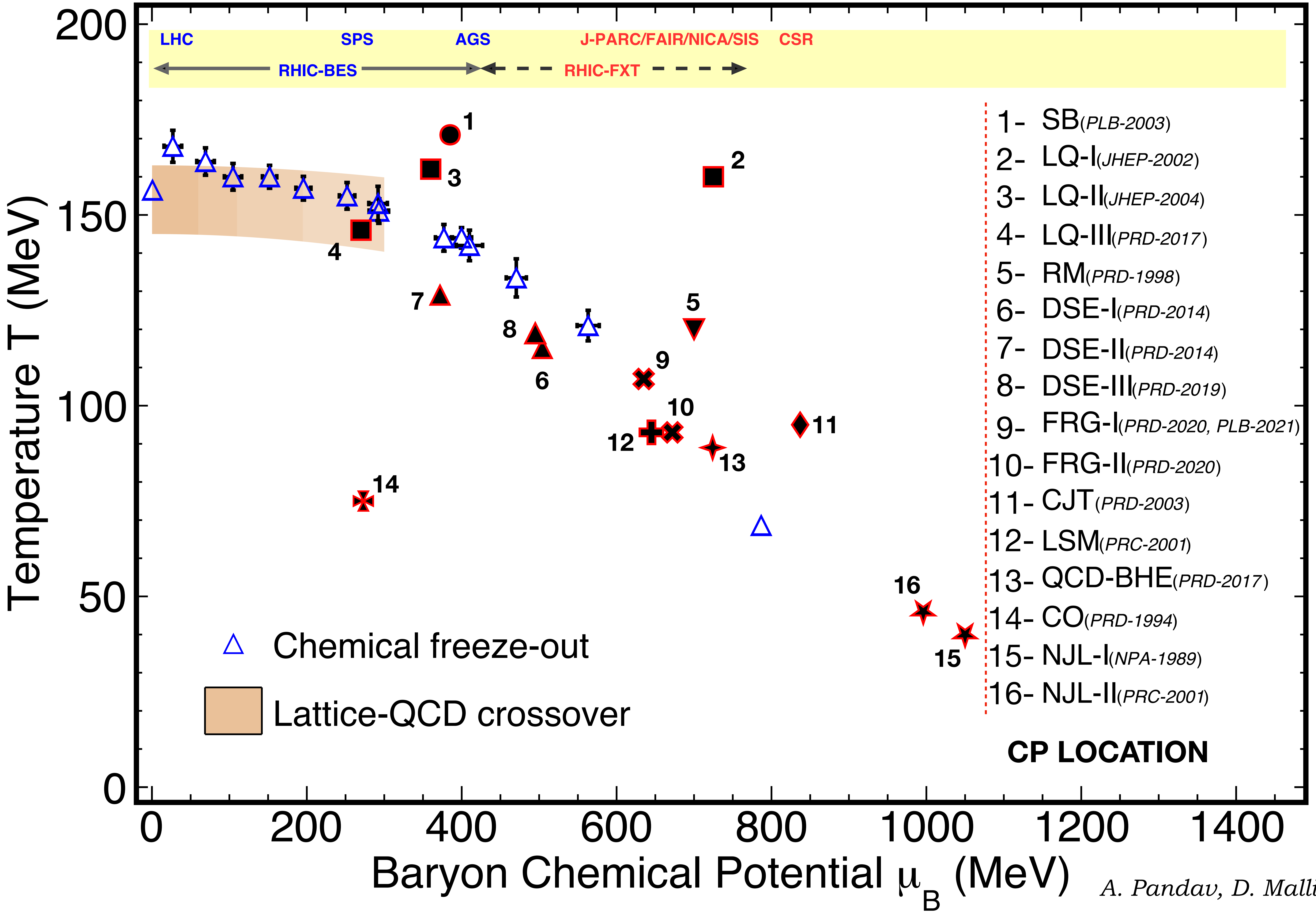
Phase structure:

- QGP and hadronic phase ✓
- Transition temperature (T_c) ✓
- Crossover at small μ_B ($\frac{\mu_B}{T} < 2$) ✓
- 1st order P.T. at large μ_B ?
- **Critical end point** ?

☐ Phase diagram of strongly interacting matter

☐ Largely conjectured

Introduction: QCD Phase Diagram



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 predictions in $\mu_B - T$ plane. **Experimental search very important.**

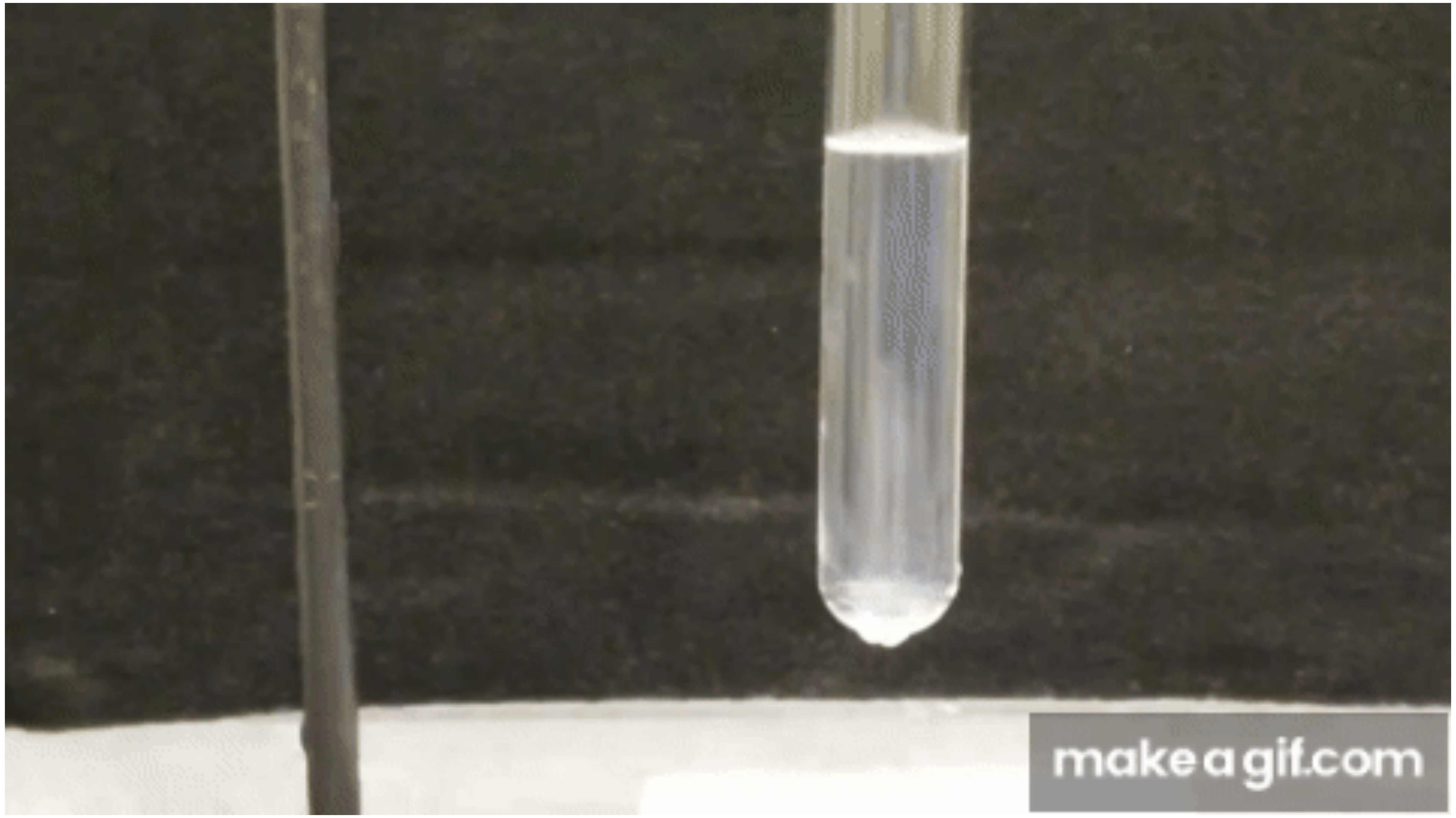
Observables (Selected):

Observable	Definition	Comments
Particle ratio fluctuation ν_{dyn}	$\frac{<N_x(N_x-1)>}{<N_x>^2}+\frac{<N_y(N_y-1)>}{<N_y>^2}-2\frac{<N_xN_y>}{<Nx><N_y>}$	**For CP search:** Look for non-monotonic collision energy dependence
Momentum correlation $<\Delta p_{T,i}\Delta p_{T,j}>$	$\frac{1}{N_{ev}}\sum_{k=1}^{N_{ev}}\frac{C_k}{N_k(N_k-1)}$ $C_k=\sum_{i=1}^{N_k}\sum_{j=1,j\neq i}^{N_k}(p_{T,i}-<M(p_T)>)(p_{T,j}-<M(p_T)>)$	Look for non-monotonic collision energy dependence
Intermittency: Scaled factorial mom. $F_q(M)$	$\frac{<\frac{1}{M^2}\sum_{i=1}^{M^2}n_i(n_i-1)..(n_i-q+1)>}{<\frac{1}{M^2}\sum_{i=1}^{M^2}n_i>}$	Look for scaling behavior of factorial moments w.r.t bin size M
Femtoscopic correlation function $C(k*)$	$N\frac{A(k*)}{B(k*)}$	Look for power law scaling of correlation function
Fluctuations/Cumulants of conserved charge C_n	$C_1=<n>, C_2=<\delta n^2>$ $C_3=<\delta n^3>$ $C_4=<\delta n^4>-3<\delta n^2>^2$	Look for non-monotonic collision energy dependence

Observables (Selected):

Observable	Definition	Comments
Particle ratio fluctuation ν_{dyn}	$\frac{< N_x(N_x-1) >}{< N_x >^2} + \frac{< N_y(N_y-1) >}{< N_y >^2} - 2\frac{< N_x N_y >}{< Nx > < N_y >}$	**For CP search:** Look for non-monotonic collision energy dependence
Momentum correlation $< \Delta p_{T,i} \Delta p_{T,j} >$	$\frac{1}{N_{ev}} \sum_{k=1}^{N_{ev}} \frac{C_k}{N_k(N_k-1)}$ $C_k = \sum_{i=1}^{N_k} \sum_{j=1,j\neq i}^{N_k} (p_{T,i} - < M(p_T) >)(p_{T,j} - < M(p_T) >)$	Look for non-monotonic collision energy dependence
Intermittency: Scaled factorial mom. $F_q(M)$	$\frac{< \frac{1}{M^2} \sum_{i=1}^{M^2} n_i(n_i-1)..(n_i-q+1) >}{< \frac{1}{M^2} \sum_{i=1}^{M^2} n_i >}$	Look for scaling behavior of factorial moments w.r.t bin size M
Femtoscopic correlation function $C(k^*)$	$N\frac{A(k^*)}{B(k^*)}$	Look for power law scaling of correlation function
Fluctuations/Cumulants of conserved charge C_n	$C_1 = < n >, C_2 = < \delta n^2 >$ $C_3 = < \delta n^3 >$ $C_4 = < \delta n^4 > - 3 < \delta n^2 >^2$	**Theory calculation available** Look for non-monotonic collision energy dependence

FLUCTUATIONS NEAR CP:



Development of long range density fluctuations,

Divergence of correlation length, thermodynamic response functions (susceptibility, compressibility etc)

Enhanced fluctuations expected near CP.

How to quantify fluctuations? measure cumulants.

Critical Opalescence: CO_2 appears milky white

T. Andrews. Phil. Trans. Royal Soc.,1869, 159:575.

CUMULANTS:

- **Cumulants:** $n =$ ***net-proton multiplicity in an event***

$$C_1 = < n >$$

$$C_2 = < \delta n^2 > \quad *\delta n = n - < n >$$

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

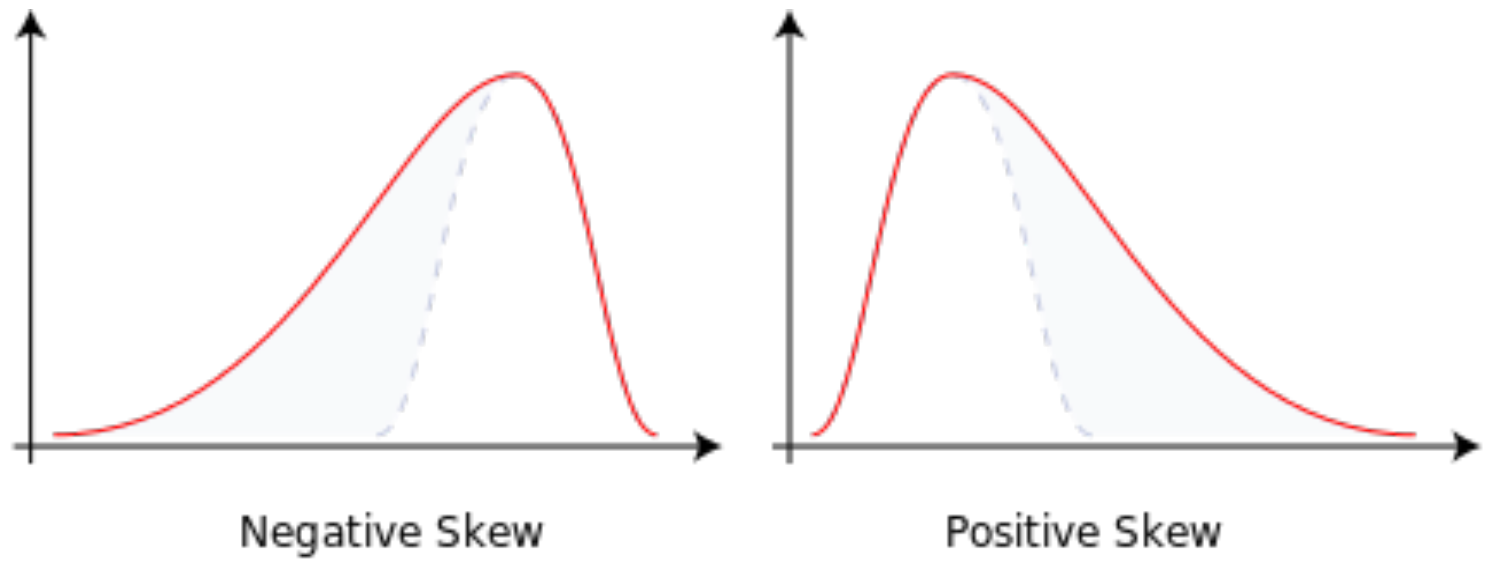
$$C_4 = < \delta n^4 > - 3 < \delta n^2 >$$

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

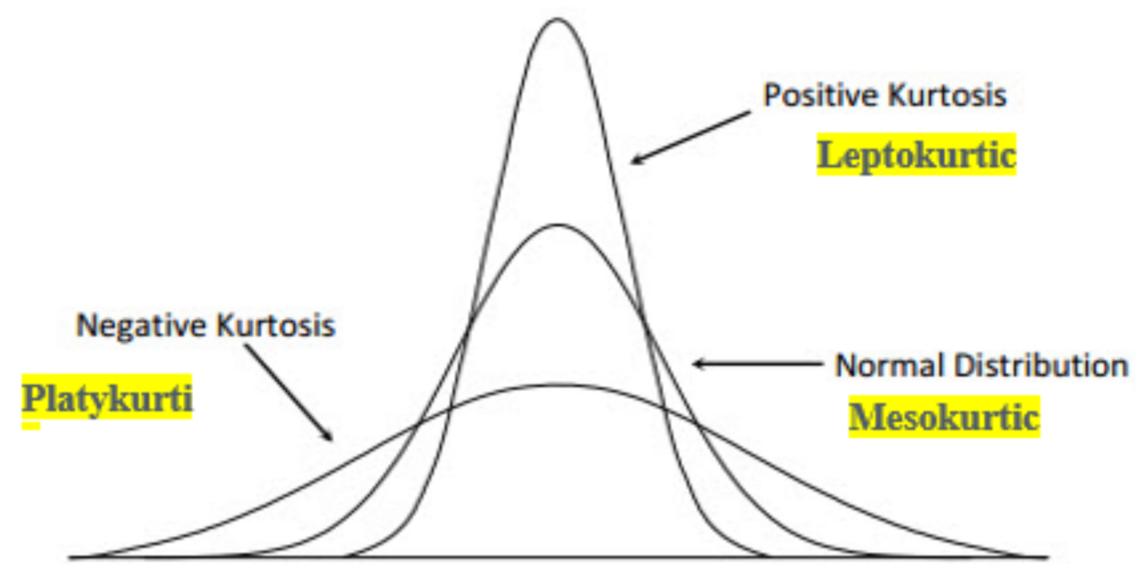
$$C_6 = < \delta n^6 > - 15 < \delta n^4 > < \delta n^2 > \; - 10 < \delta n^3 >^2 + 30 < \delta n^2 >^3$$

M. A. Stephanov, PRL 107 (2011) 052301

Skewness: Asymmetry



Kurtosis: Peakedness



R.V. Gavai and S. Gupta, PLB696, 459(11)
S. Ejiri, F. Karsch, K. Redlich, PLB633, 275(06)
A. Bazavov et al., PRL109, 192302(12)
S. Borsanyi et al., PRL111, 062005(13)

- **Factorial cumulants:**

$$\kappa_1 = C_1$$

$$\kappa_2 = -C_1 + C_2$$

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

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

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

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

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

Finite size/time effects reduces ξ

Higher order→more sensitivity

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

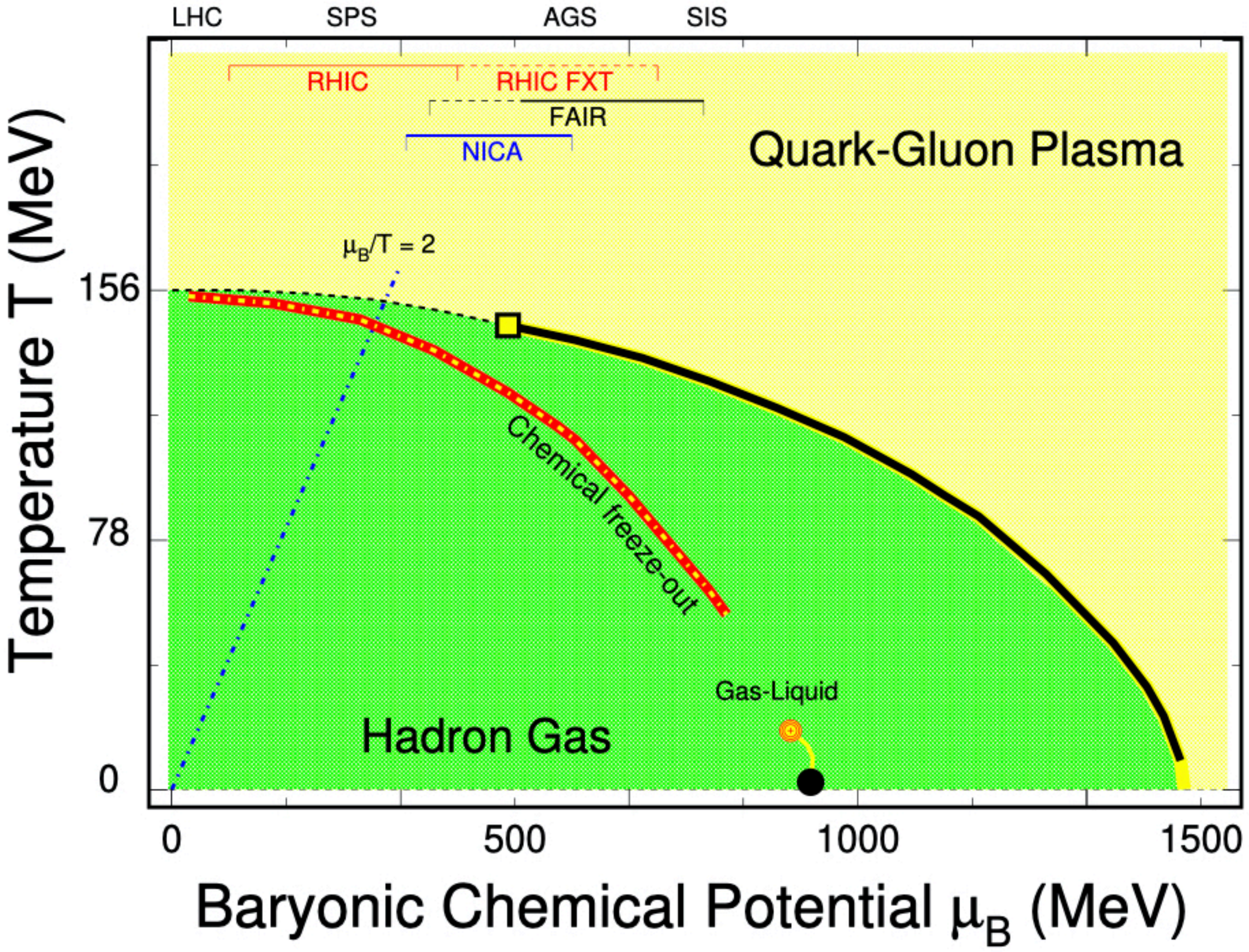
Comparison with lattice QCD,
HRG, QCD-based model calculations

Strategy:

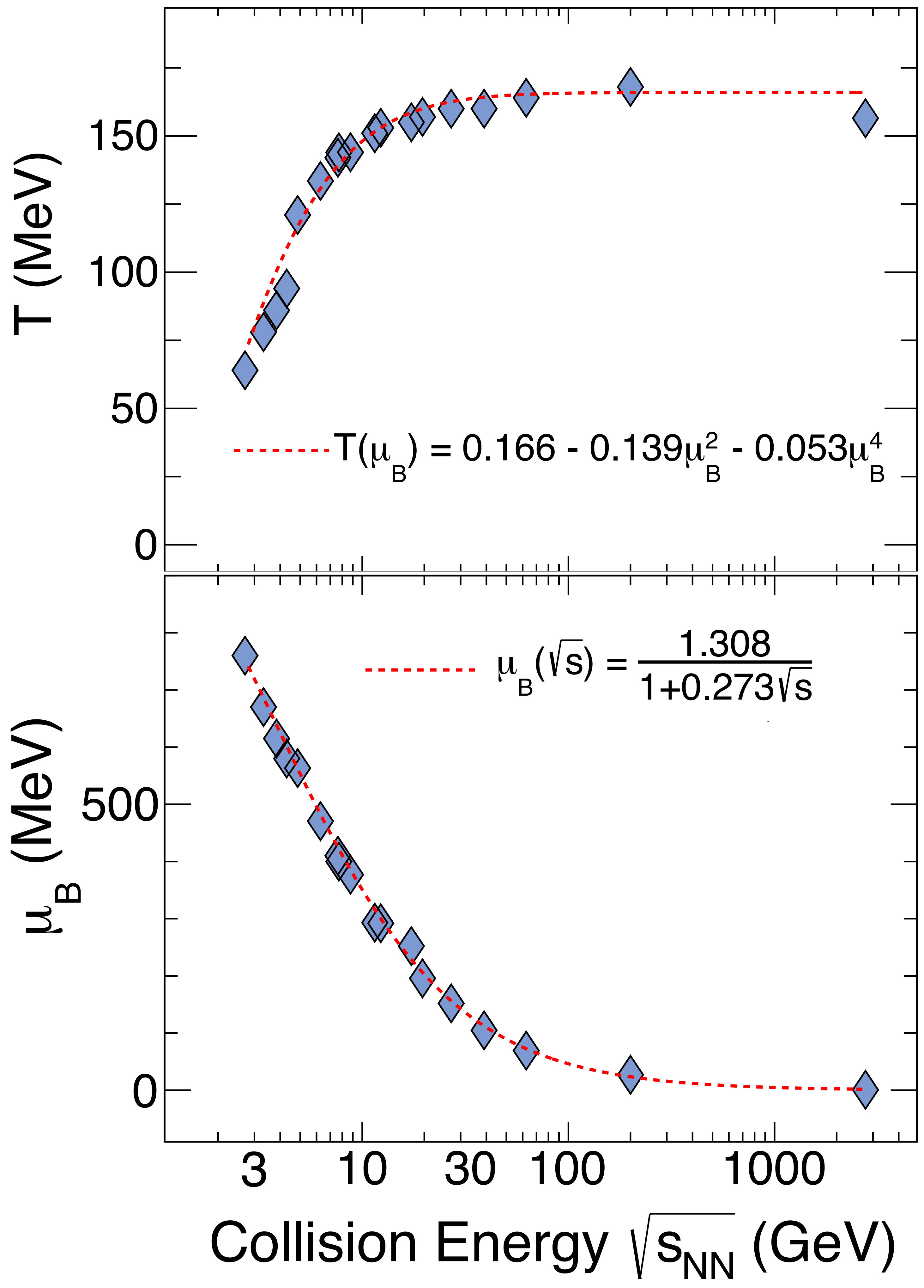
Towards making the QCD phase diagram a reality

- ☐ **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 signatures of 1st order P.T. at large μ_B
- ☐ Search for signatures of QCD critical point

Experimentally accessing QCD Phase Diagram



B. Mohanty, N. Xu, arXiv:2101.09210



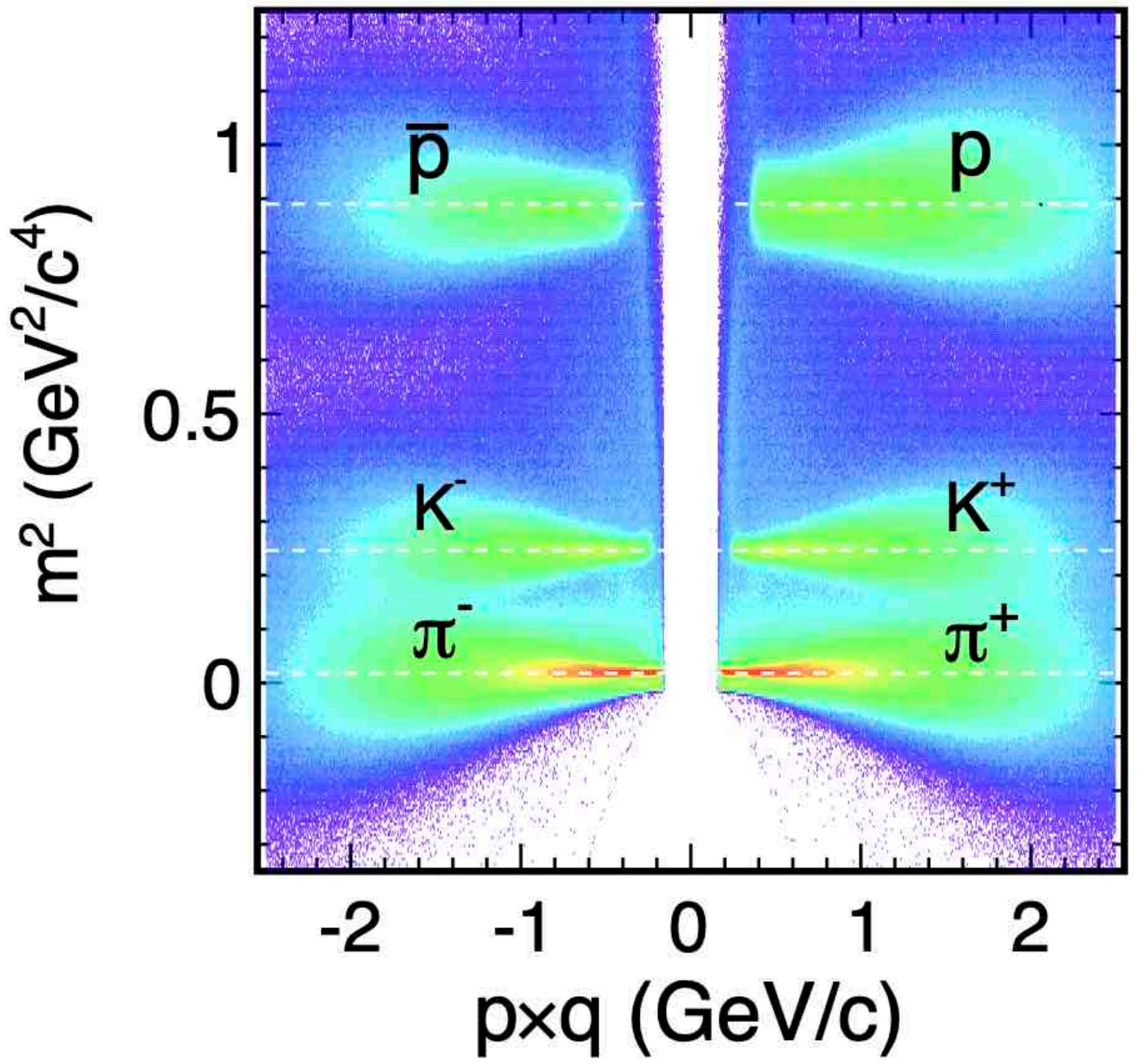
A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

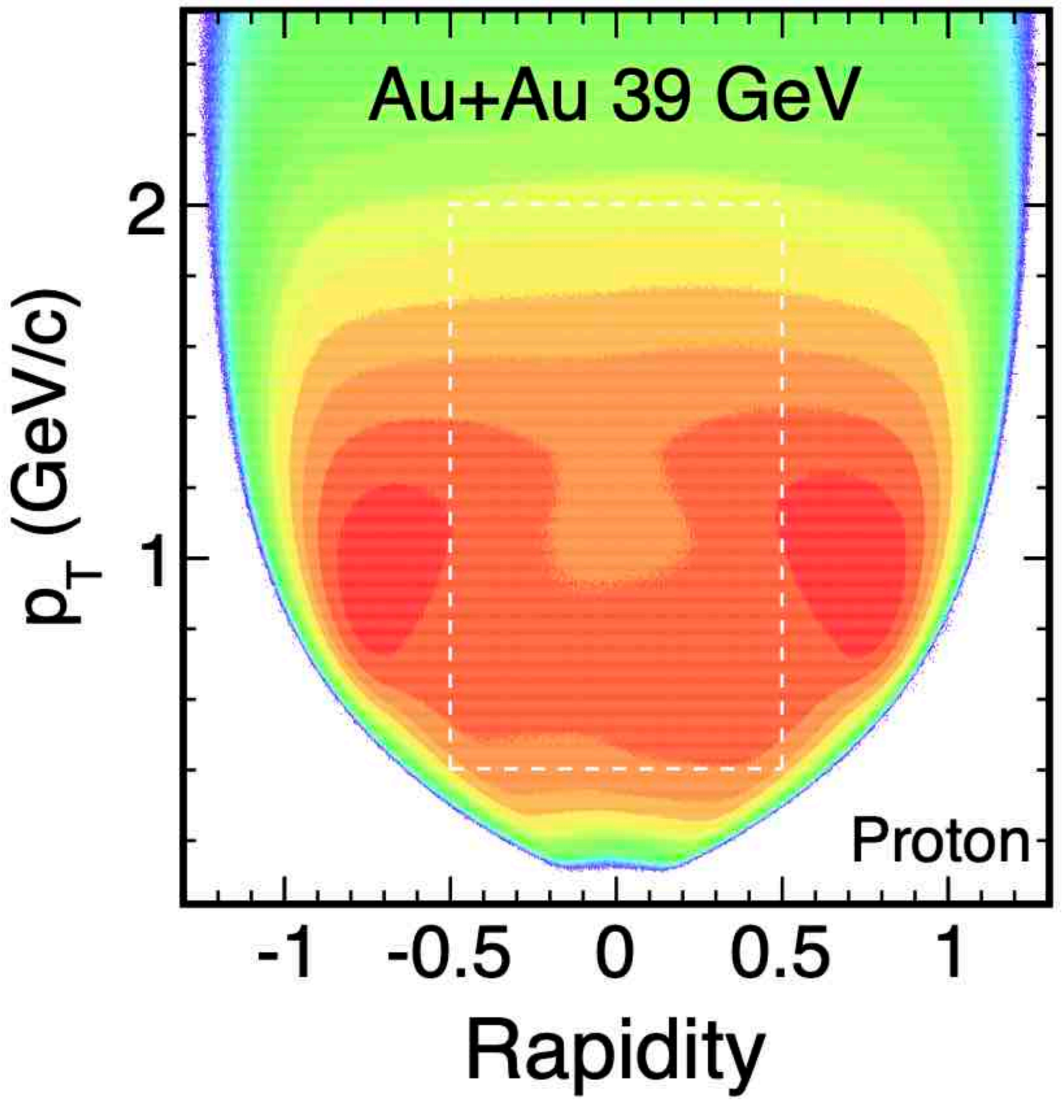
- Varying collision energy, impact parameter varies T and μ_B of system created
- Study energy/centrality dependence of cumulants

Active Experiments Studying QCD Phase Diagram:

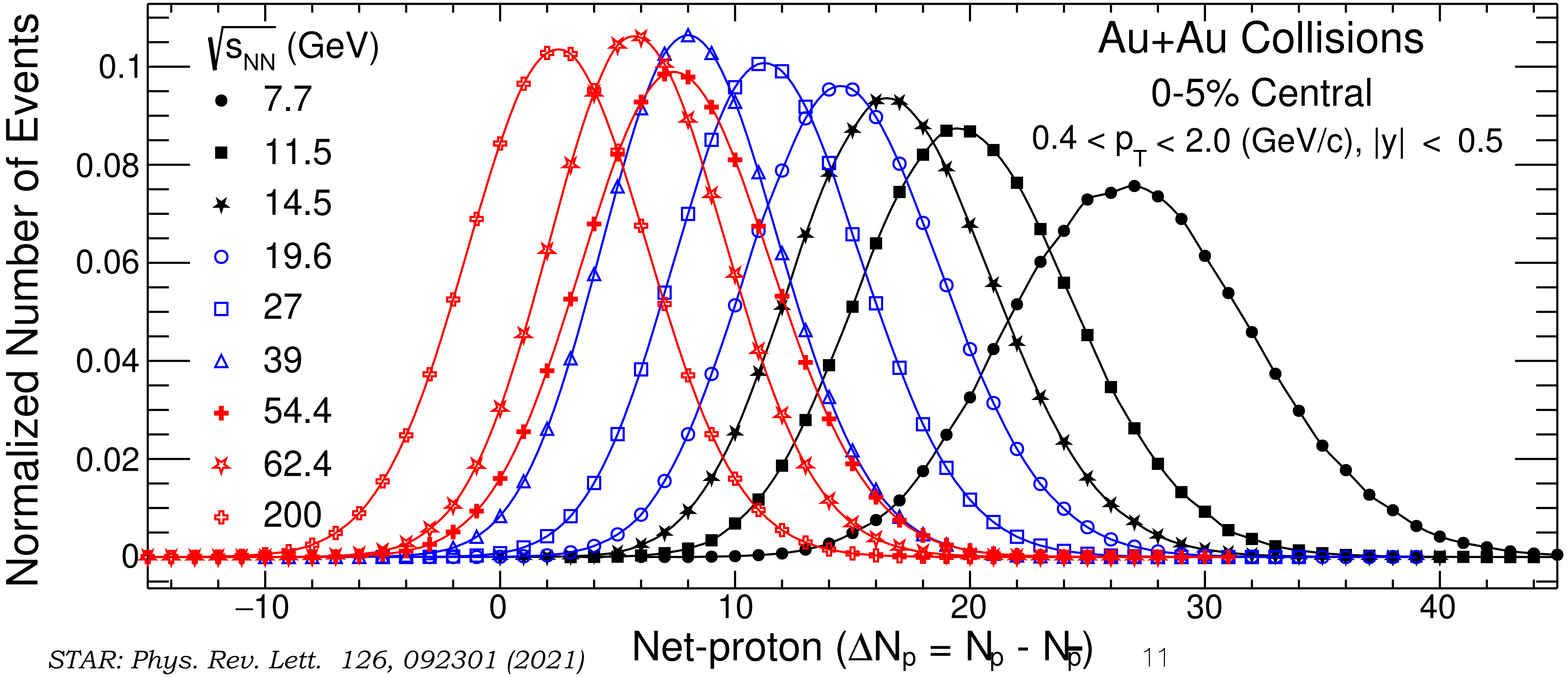
Experiment	Facility	Mode	Colliding energy ($\sqrt{s_{NN}}$)	Systems* *Not all are listed
HADES	SIS18	FXT	2.32 - 2.7 GeV	Au+Au, Ag+Ag, C+C, p+p
NA61/ SHINE	SPS	FXT	5.1 - 17.3 GeV	Pb+Pb, Be+Be, Ar+Sc, p+p
STAR	RHIC	COL/ FXT	3 - 200 GeV	Au+Au, U+U, Zr+Zr, Ru+Ru, Cu+Cu, d+Au, He3+Au, p+Au, p+p
ALICE	LHC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

Analysis:





Identifying and selecting protons and antiprotons within a kinematic phase space.



Construct net-proton distributions, obtain cumulants of these distributions.

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

Strategy:

Towards making the QCD phase diagram a reality

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- ☐ **Check if produced system is governed by thermodynamics**
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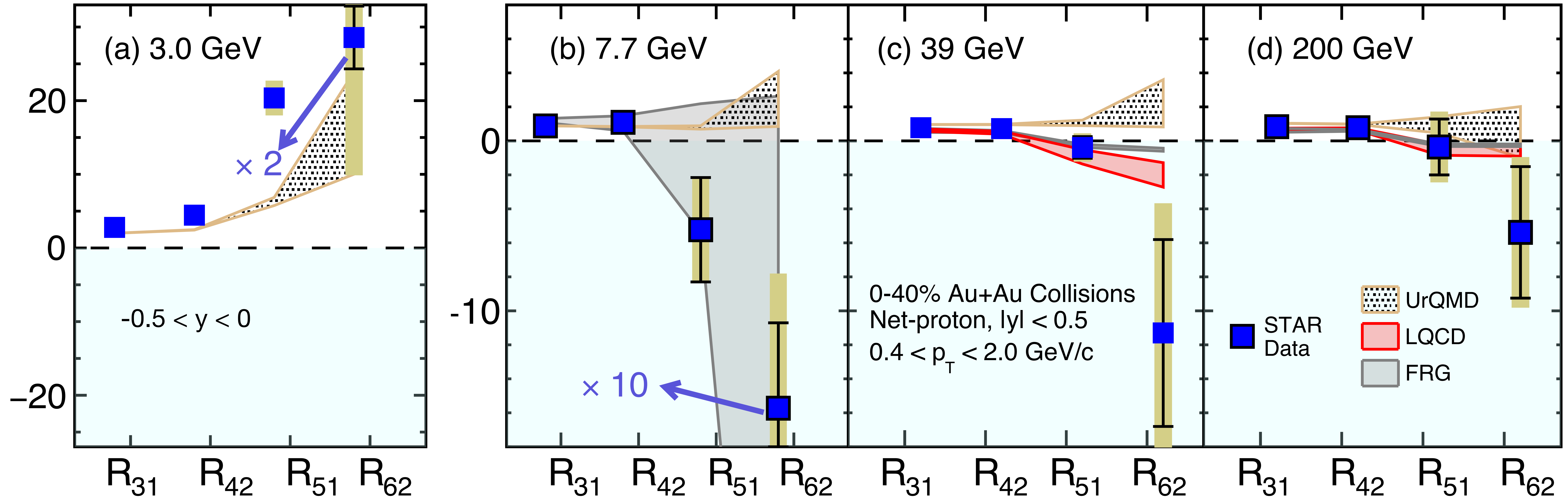
- ☐ Search for signatures of QCD critical point

RESULTS: STUDY OF THERMODYNAMICS

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



$R_{31} = C_3/C_1$ $R_{42} = C_4/C_2$ $R_{51} = C_5/C_1$ $R_{62} = C_6/C_2$

- ☐ Within uncertainties, 7.7 - 200 GeV data consistent with lattice predicted hierarchy.
- ☐ At 3 GeV, violation of ordering is seen. Observed ordering reproduced by UrQMD.

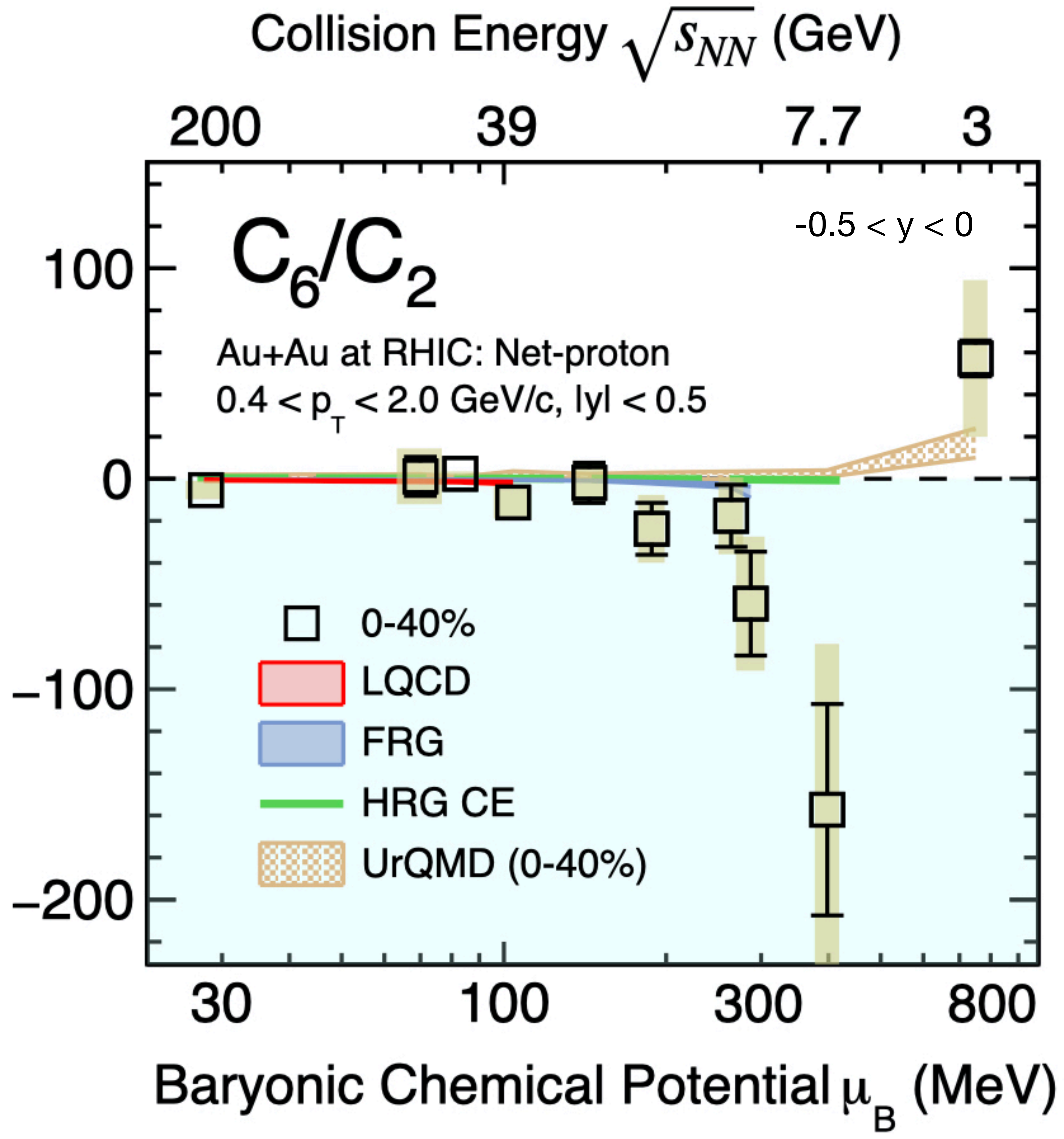
LQCD: HotQCD, PRD101,074502 (2020)
FRG: Wei-jie Fu et. al, PRD 104, 094047 (2021)
STAR: PRL 130, 082301 (2023)
: PRL 127, 262301 (2021)
STAR: PRL 126, 092301 (2021)
: PRC 104, 024902 (2021)

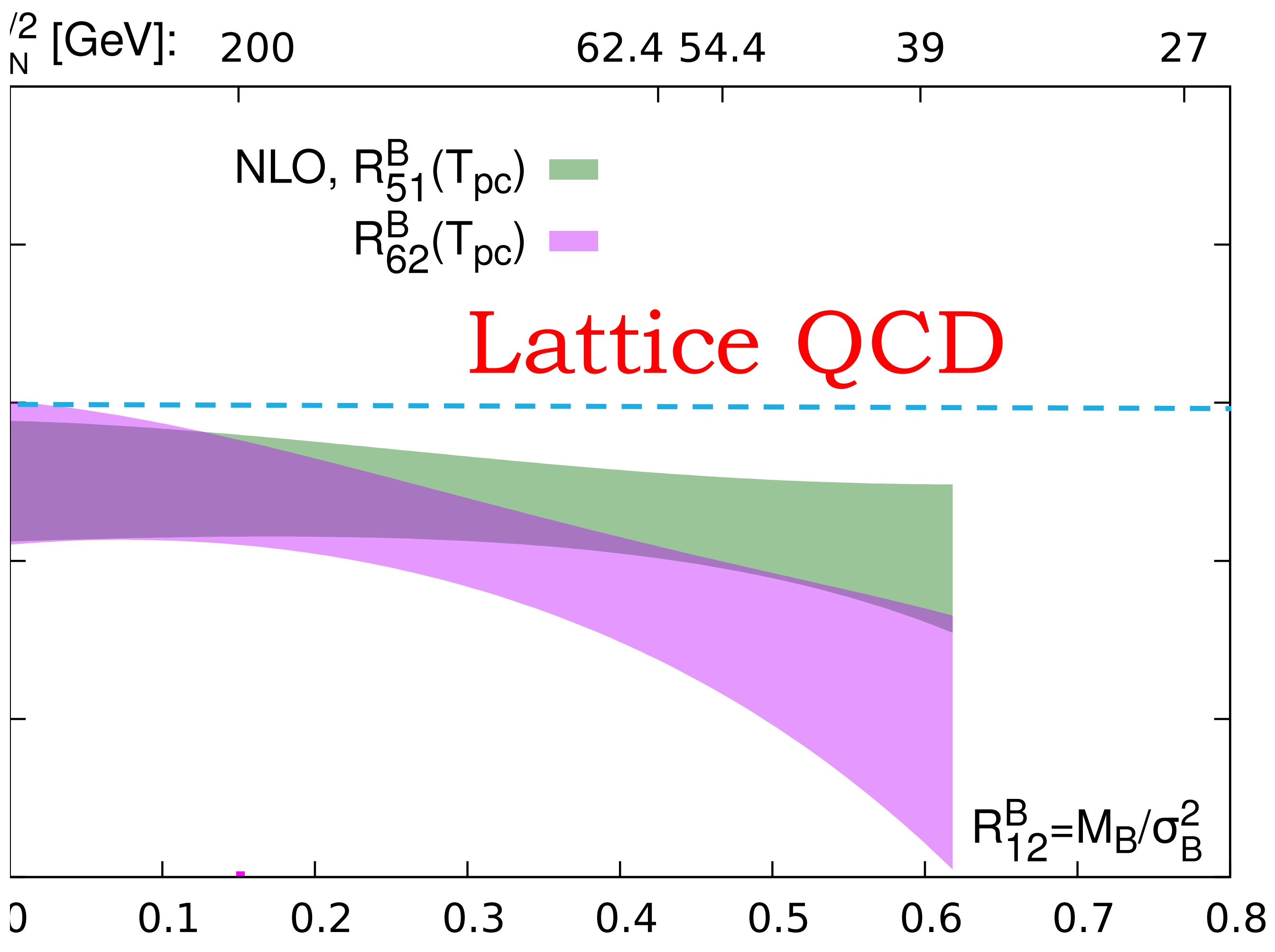
Strategy:

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 signatures of 1st order P.T. at large μ_B
- ☐ Search for signatures of QCD critical point

Results: Hyper-order Fluctuation



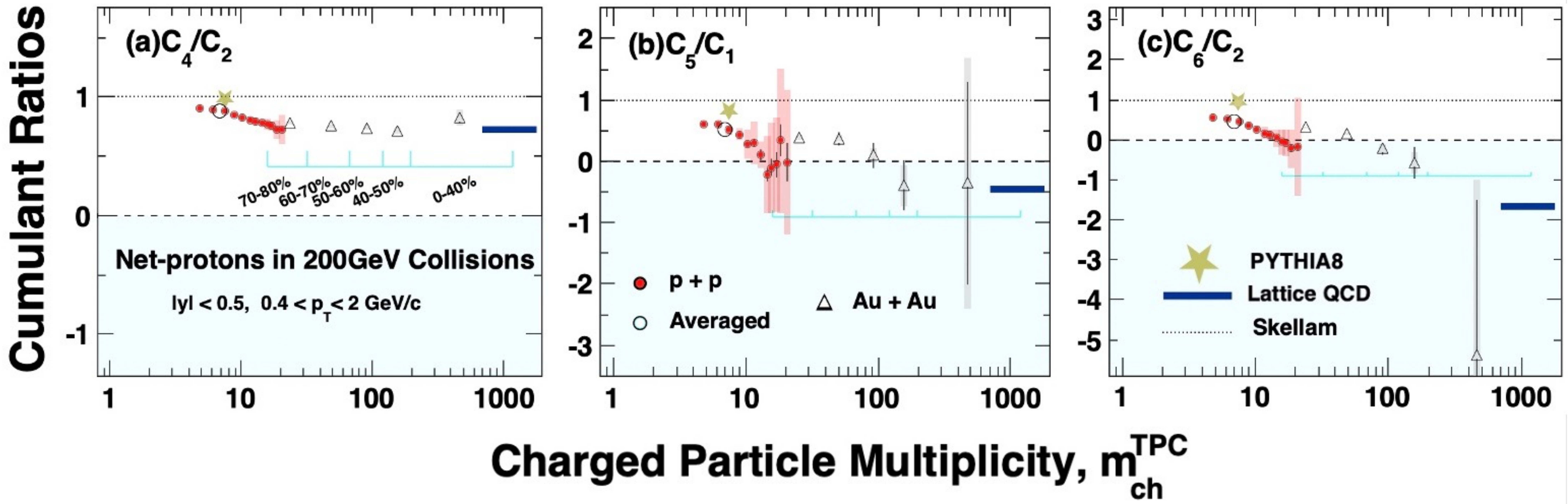


- Increasingly negative C_6/C_2 (down to 7.7 GeV) with decreasing $\sqrt{s_{NN}}$ (1.7σ significance) - a trend consistent with lattice QCD

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

STAR: PRL 127, 262301 (2021)
STAR: PRL 130, 082301 (2023)
HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
LQCD: HotQCD, PRD 101, 074502 (2020)
FRG: Wei-jie Fu et. al, PRD 104, 094047 (2021)

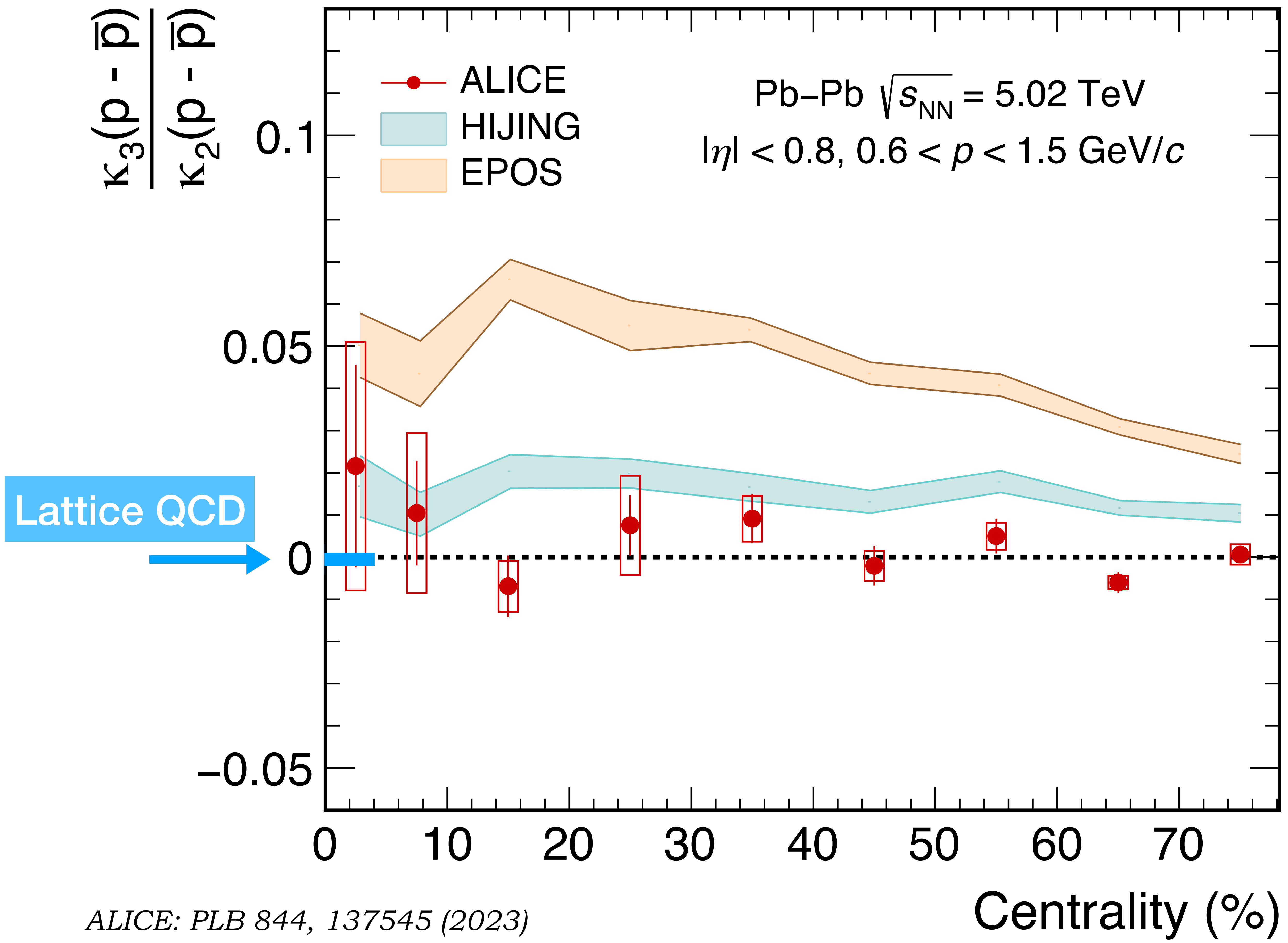
Results: Hyper-order Fluctuations in Small system



STAR: PRL 127, 262301 (2021)
STAR: arXiv:2311.00934

- ☐ Fifth and sixth order cumulant ratios progressively negative towards higher charged particle multiplicity– approaching lattice calculation that includes a crossover.

Results: Data at vanishing μ_B



ALICE: PLB 844, 137545 (2023)

- ☐ Vanishing third order cumulant ratio – consistent with LQCD and HRG calculations
- ☐ HIJING, EPOS does not describe the data well.

Strategy:

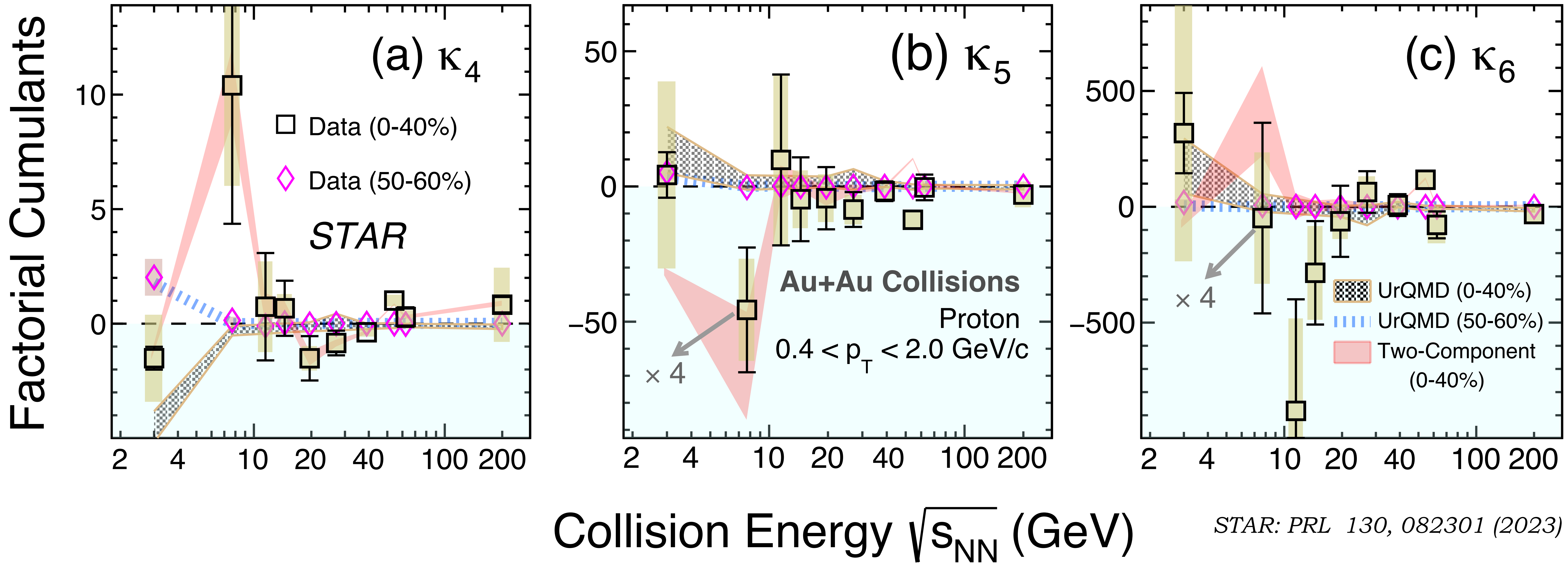
Towards making the QCD phase diagram a reality

- ☐ 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 signatures of 1st order P.T. at large μ_B**
- ☐ Search for signatures of QCD critical point

Results: Search for the First-order Phase Transition

Two-component distribution: Large factorial cumulants with alternating sign

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



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.

- Precision measurement needed.

STRATEGY:

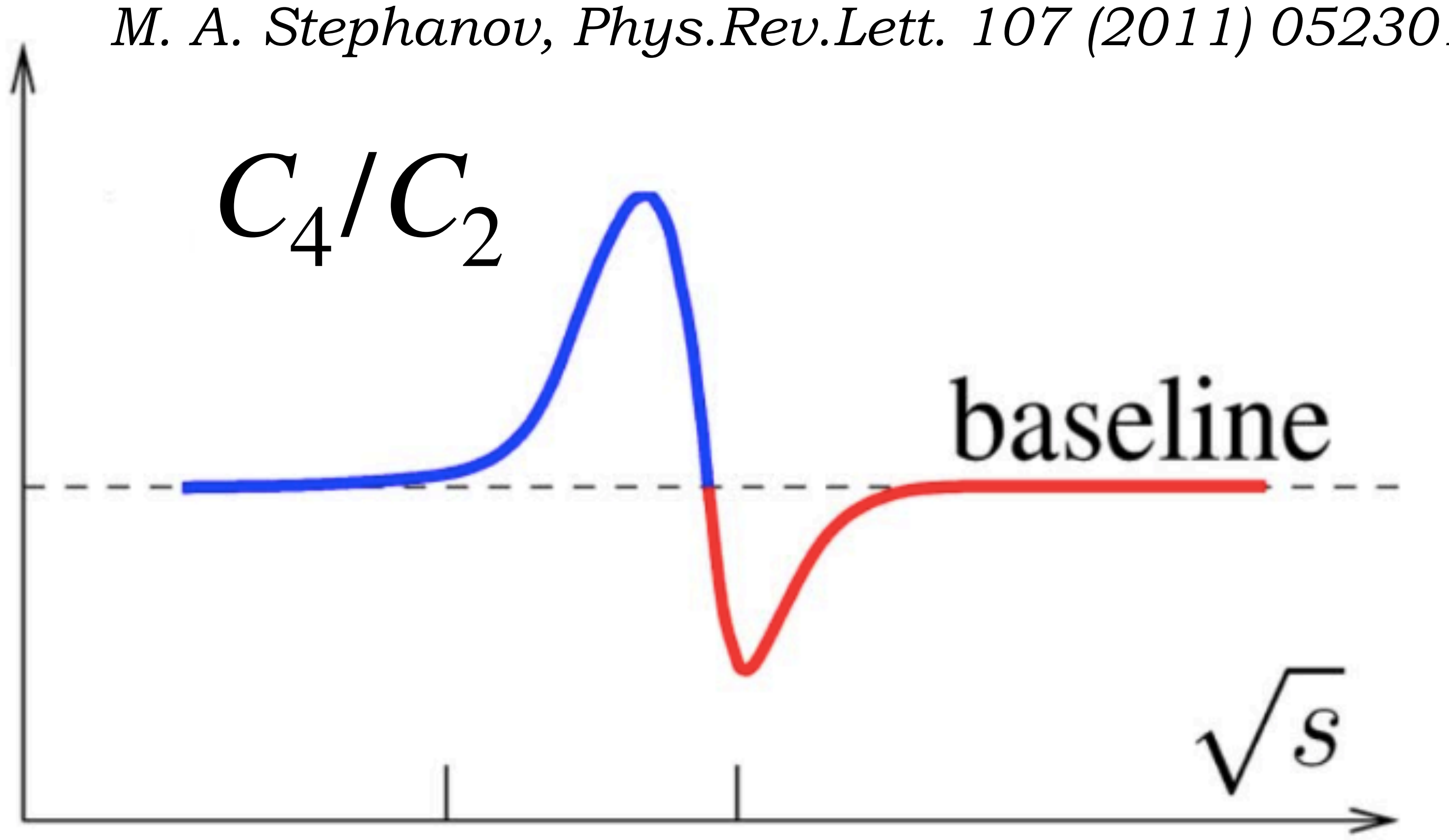
Towards making the QCD phase diagram a reality

- ☐ 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 signatures of 1st order P.T. at large μ_B
- ☐ **Search for signatures of QCD critical point**

Results: Search for the Critical Point

CP search

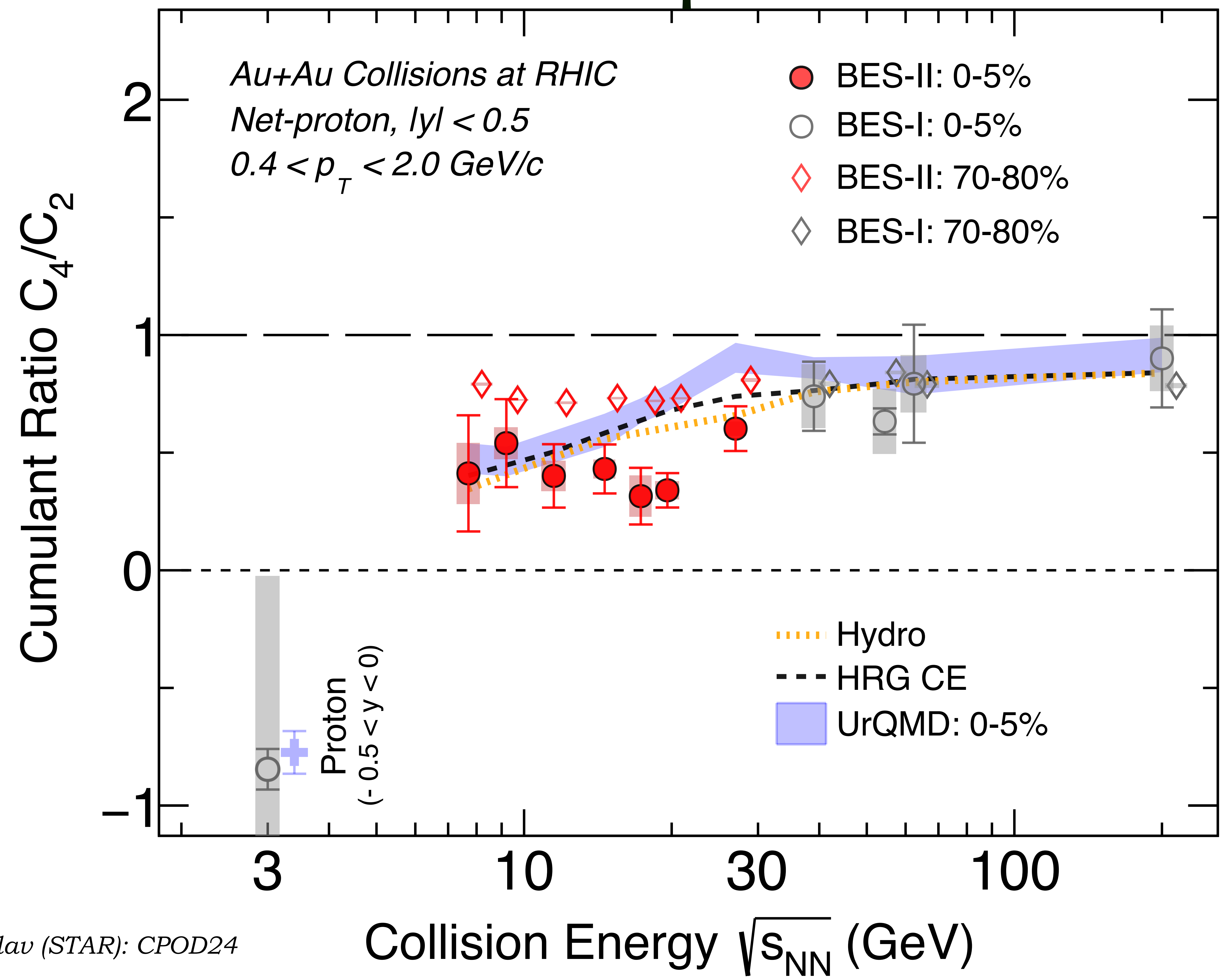
M. A. Stephanov, Phys.Rev.Lett. 107 (2011) 052301



Non-monotonic $\sqrt{s_{NN}}$ dependence of C_4/C_2 of conserved quantity - **existence of a critical region**

Assumption: Thermodynamic equilibrium

BES-II: 1st set of precision data out.



A. Pandav (STAR): CPOD24

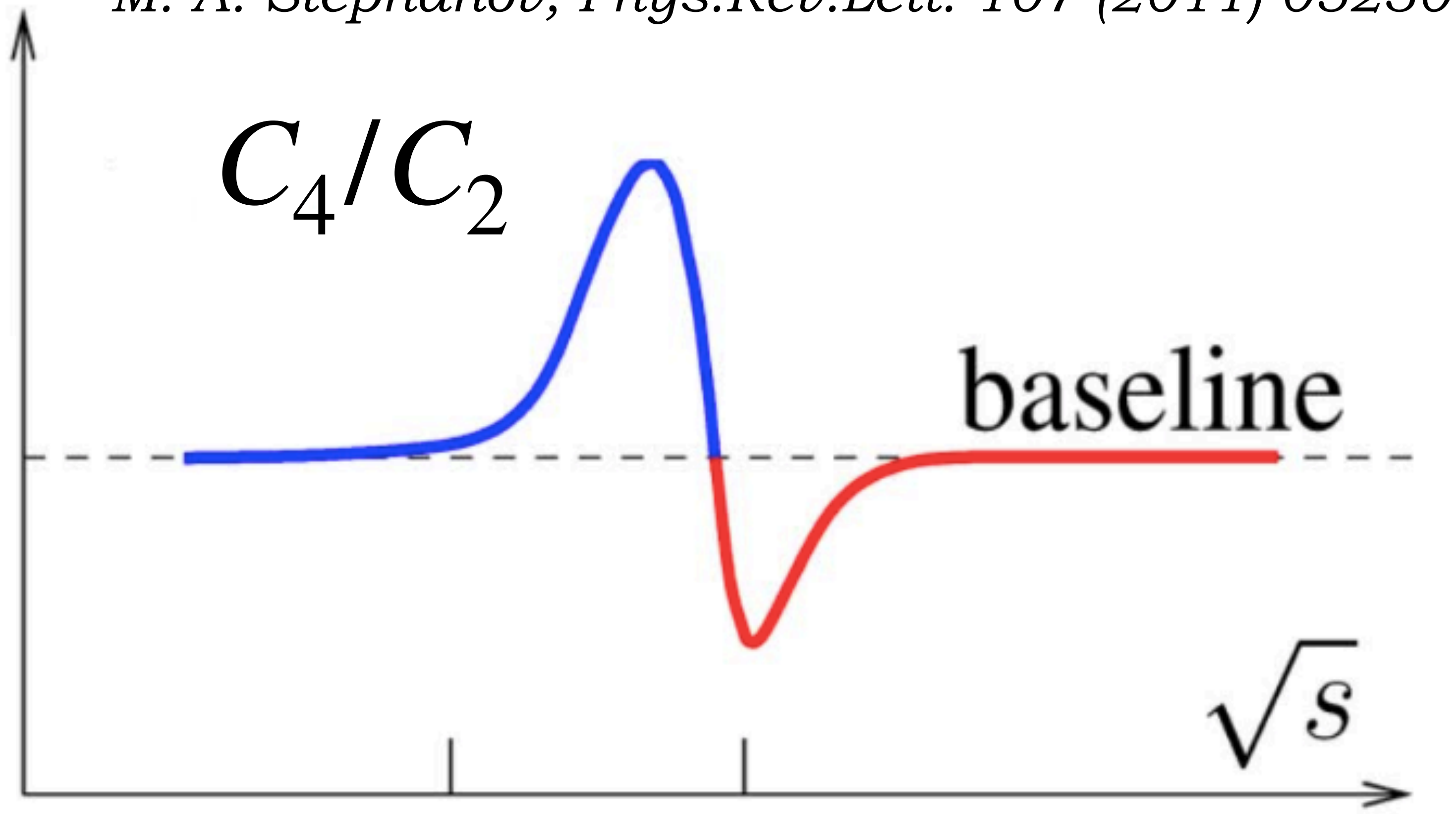
STAR: PRL 128, 202302 (2022)
STAR: PRL 127, 262301 (2021)
HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
Hydro: V. Vovchenko et al, PRC 105, 014904 (2022)

- BES-II at RHIC: ~10-20 fold increase in statistics and important detector upgrades and a new fixed target program. About factor 4 reduction in stat. and sys errors. More measurement ongoing.

Results: Search for the Critical Point

CP search

M. A. Stephanov, Phys.Rev.Lett. 107 (2011) 052301

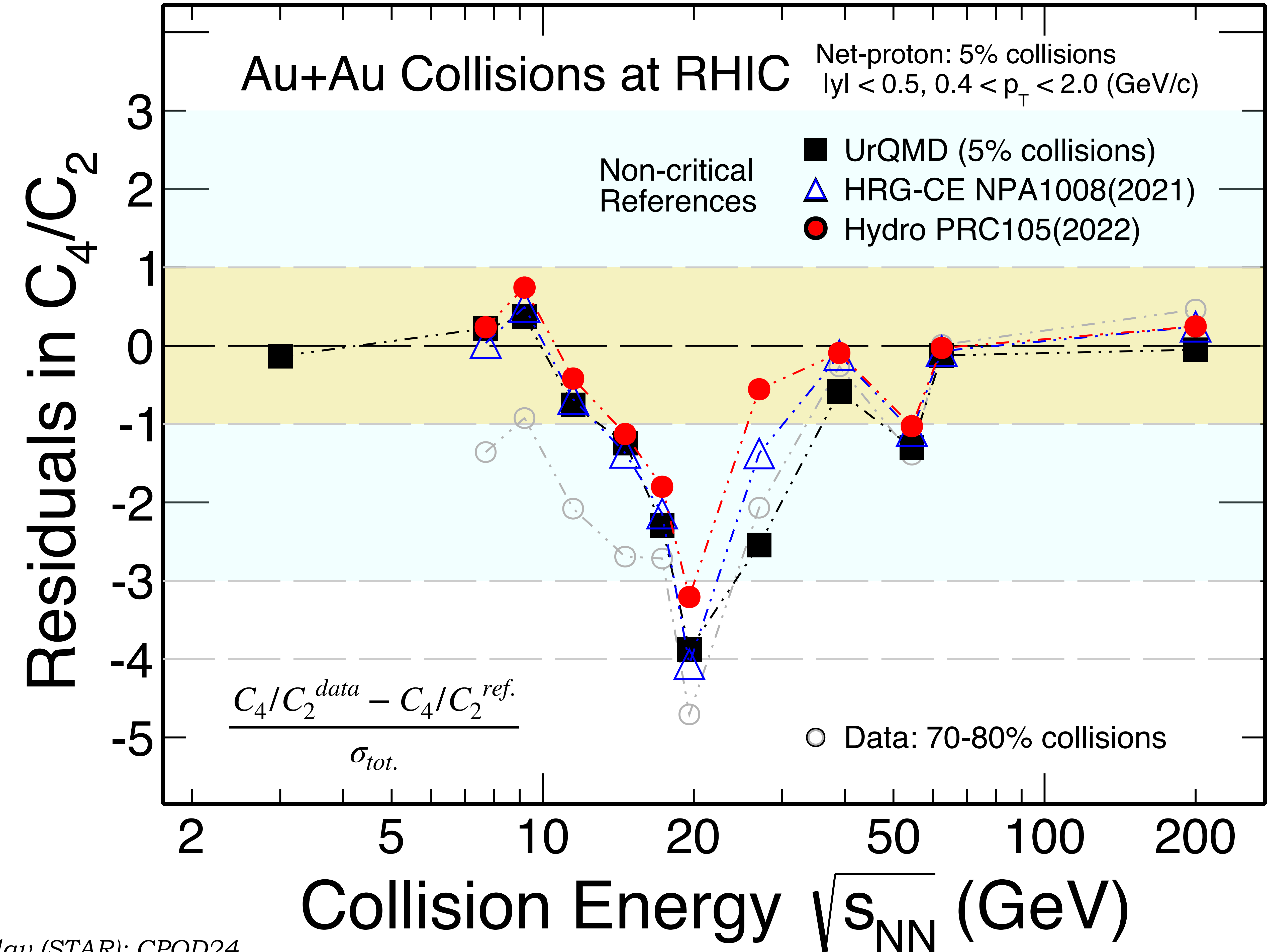


Non-monotonic $\sqrt{s_{NN}}$ dependence of C_4/C_2 of conserved quantity - **existence of a critical region**

Assumption: Thermodynamic equilibrium

See talk from Bappa Mondal (Wed)

BES-II: 1st set of precision data out.



A. Pandav (STAR): CPOD24

STAR: PRL 128, 202302 (2022)
STAR: PRL 127, 262301 (2021)
HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
Hydro: V. Vovchenko et al, PRC 105, 014904 (2022)

- ☐ Minimum seen in C4/C2 (0-5%) w.r.t. non-CP baselines around 20 GeV at ~3-5σ significance.

Findings:

- ☐ 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 lattice thermodynamics. 3 GeV data violates. QCD matter out of equilibrium at 3 GeV?

- ☐ 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

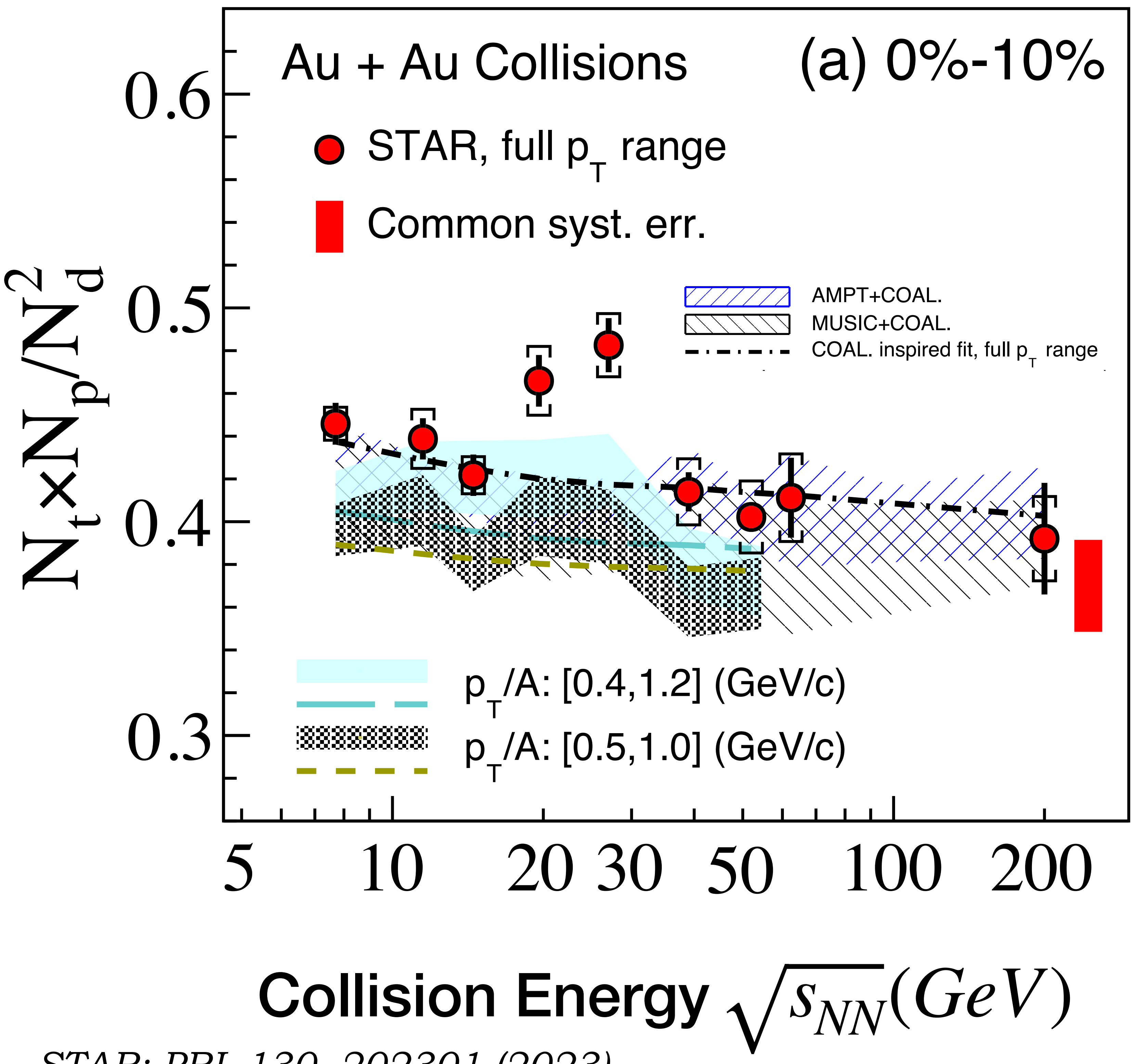
  Data ($\sqrt{s_{NN}} > 7.7$ GeV) within uncertainties suggest absence of any bimodal structure expected near 1st order phase transition.

- ☐ Search for signs of QCD critical point

  Minimum seen in net-proton C4/C2 (0-5%) w.r.t. non-CP baselines around 20 GeV at ~3-5σ significance - a feature of the proposed signal of the CP.

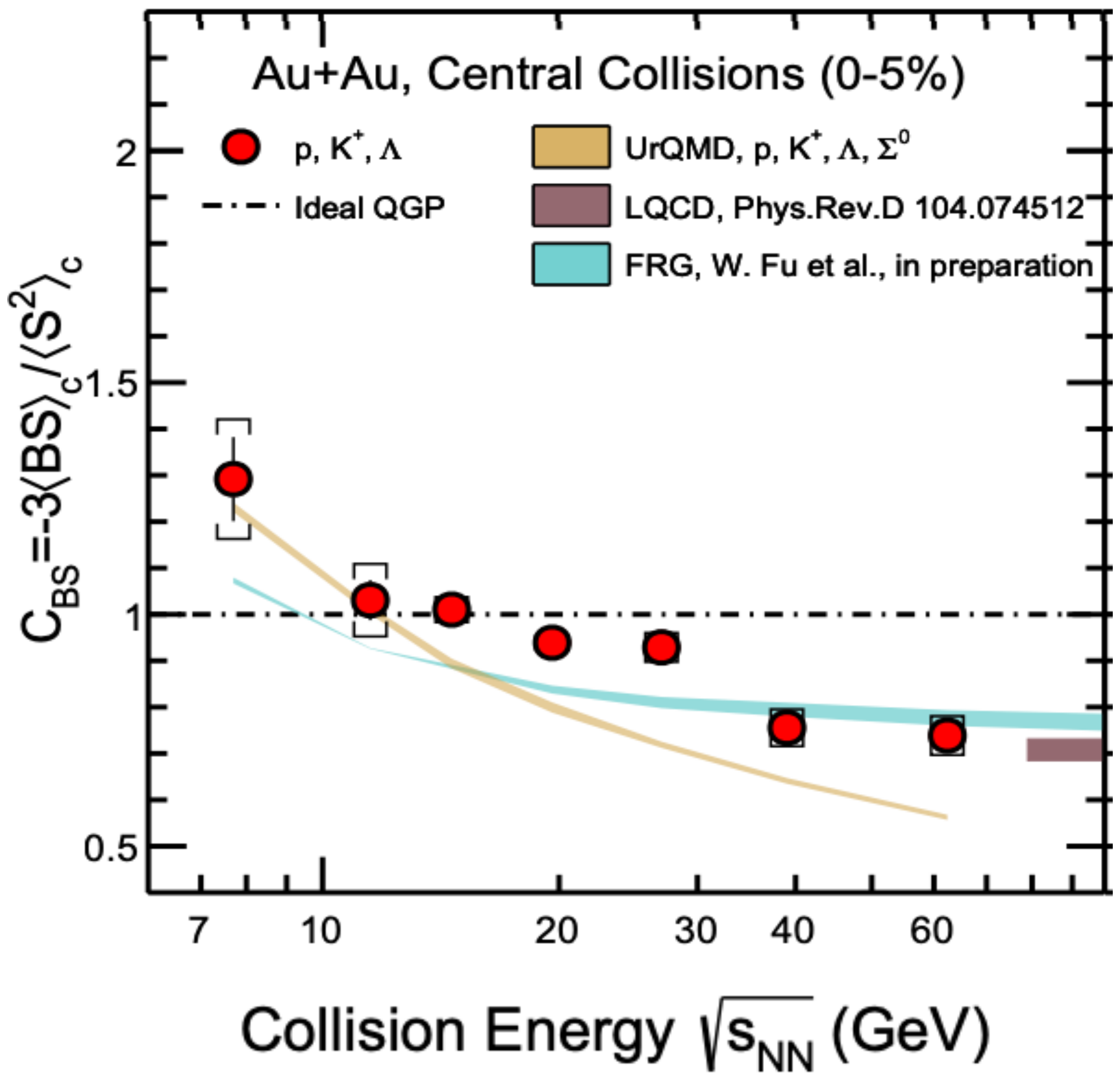
Interesting Trends in Other Observables

Light nuclei ratio



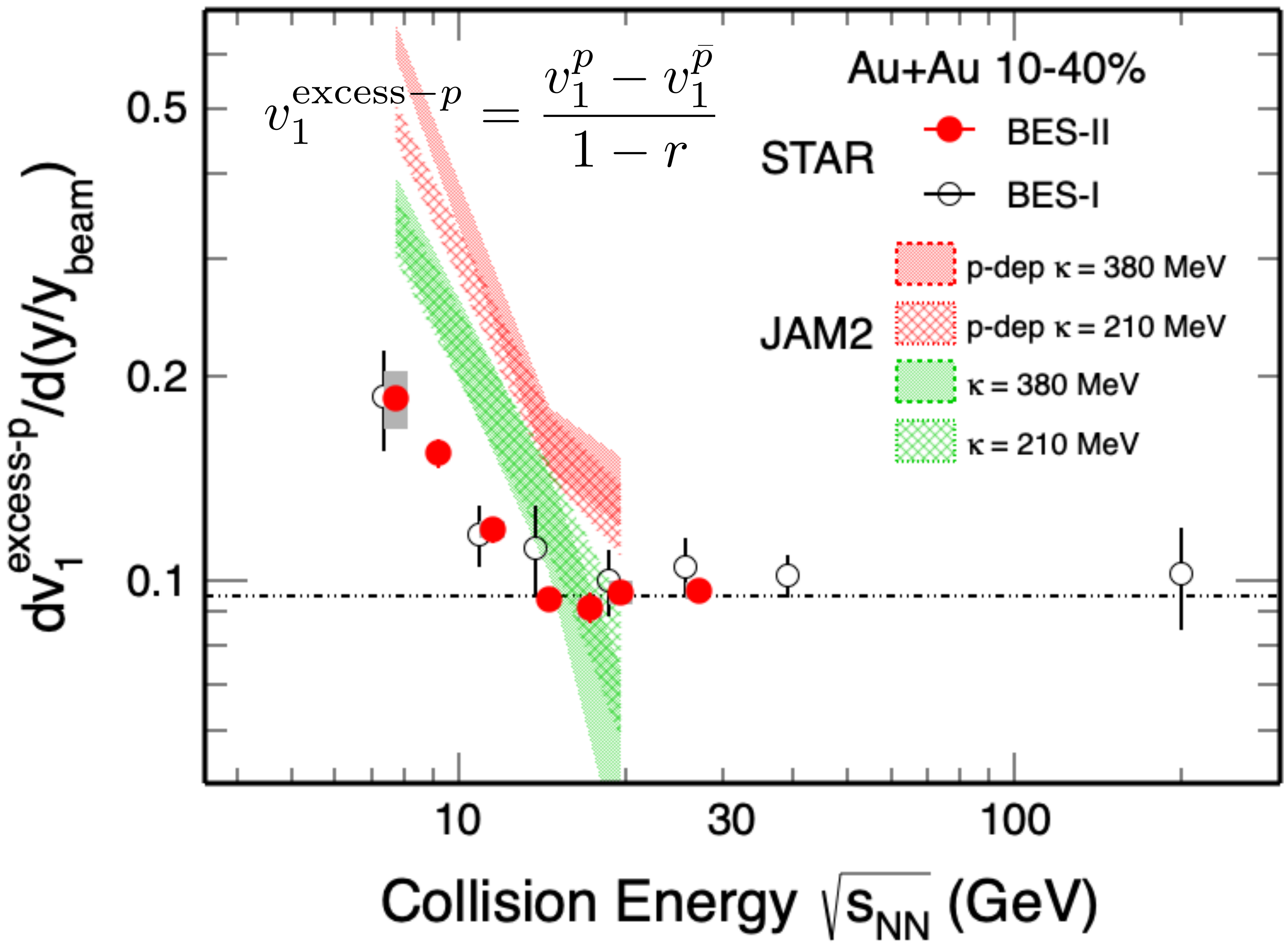
STAR: PRL 130, 202301 (2023)

Baryon-Strangeness Correlation



STAR: Hanwen's CPOD2024 talk

Proton Directed flow



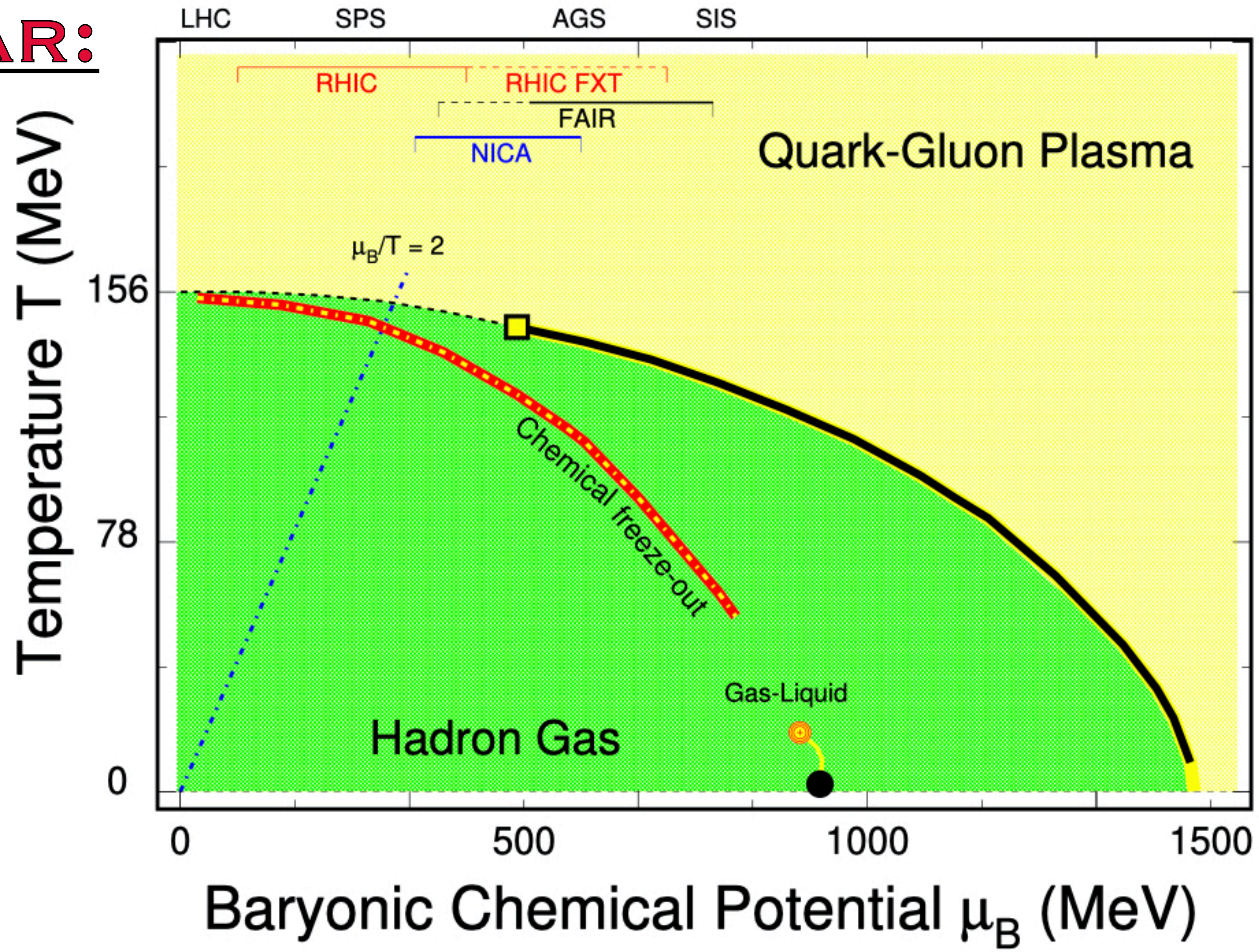
STAR: Emmy's CPOD2024 talk

Light nuclei ratio show deviation around $\sqrt{s_{NN}}$ = 19.6 and 27 GeV.

C_{BS} deviates from lattice/FRG at $\sqrt{s_{NN}} \leq 27$ GeV, consistent at higher energies.

Slope of Excess-p v_1 follows a scaling at $\sqrt{s_{NN}} \geq 14.6$ GeV. Scaling broken at lower energies.

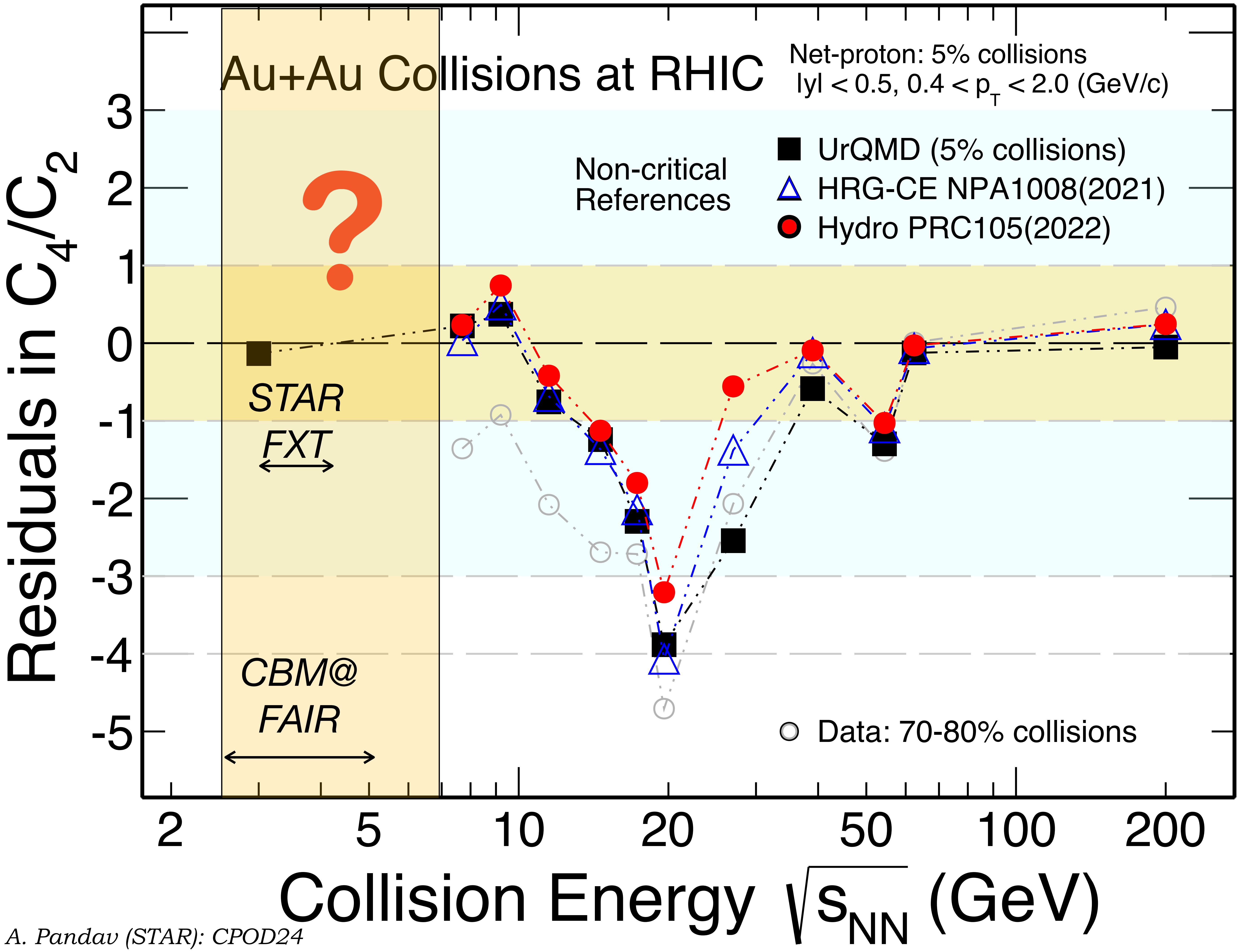
Status so far:



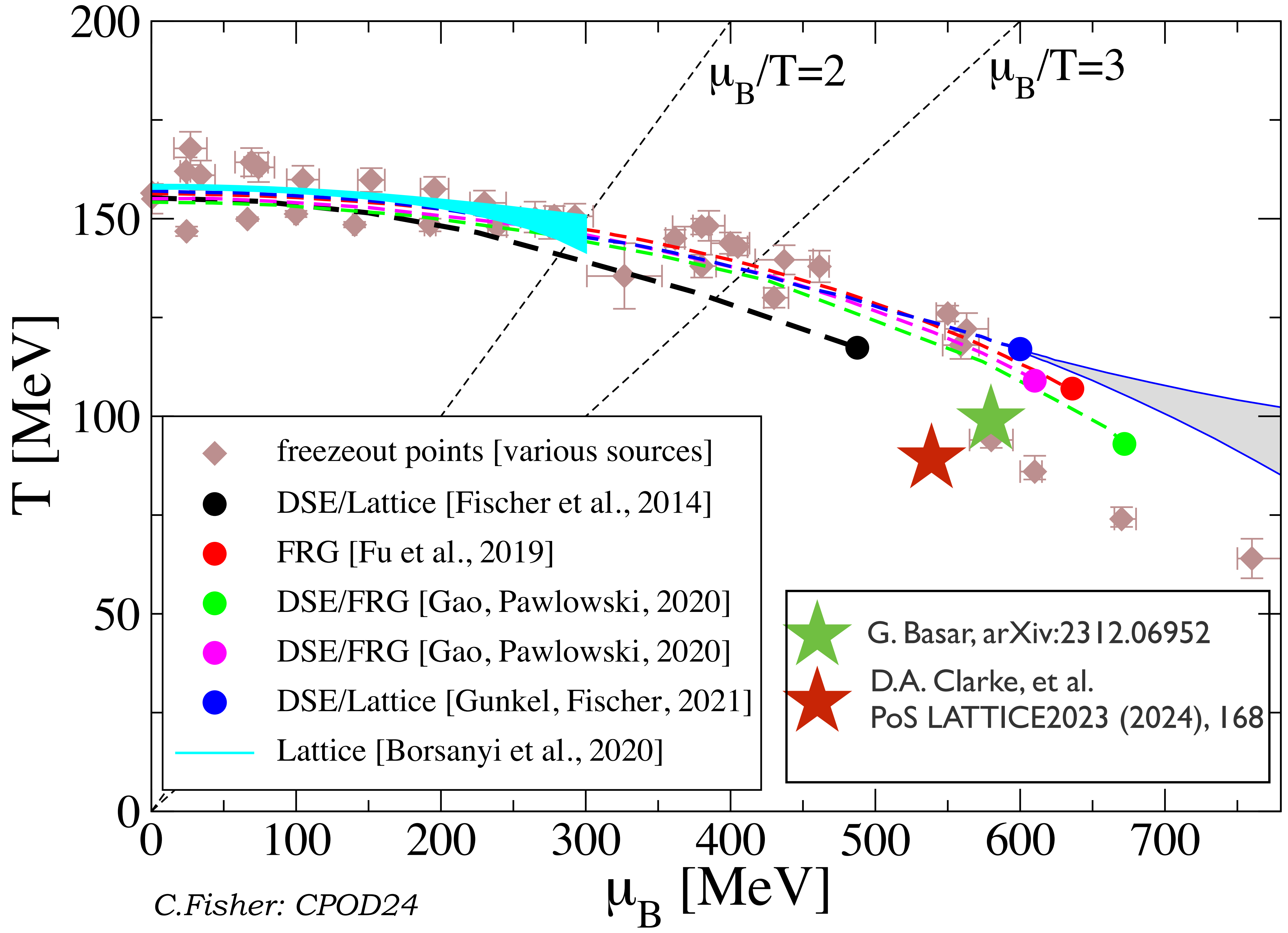
- Minimum seen in C4/C2 (0-5%) precision BES-II data w.r.t. non-critical baselines (~3-5 σ) around $\sqrt{s_{NN}}$ = 20 GeV. Theoretical insights needed for interpretation of data in regards to CP.
- Crossover for $\sqrt{s_{NN}} >$ 27 GeV ($\mu_B \leq$ 110 MeV): Lattice QCD, interesting trends also seen in BES-I data
- Data falling to hadronic baseline at $\sqrt{s_{NN}}$ = 3 GeV (μ_B = 720 MeV): hadronic interactions dominant (observation supported by breakdown of NCQ scaling)
- **Extensive BES-II measurements ongoing from $\sqrt{s_{NN}} = 3 - 27$ GeV.**

OUTLOOK: EXTENDING TO HIGHER μ_B

HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021) Hydro: V. Vovchenko et al, PRC 105, 014904 (2022)



A. Pandav (STAR): CPOD24

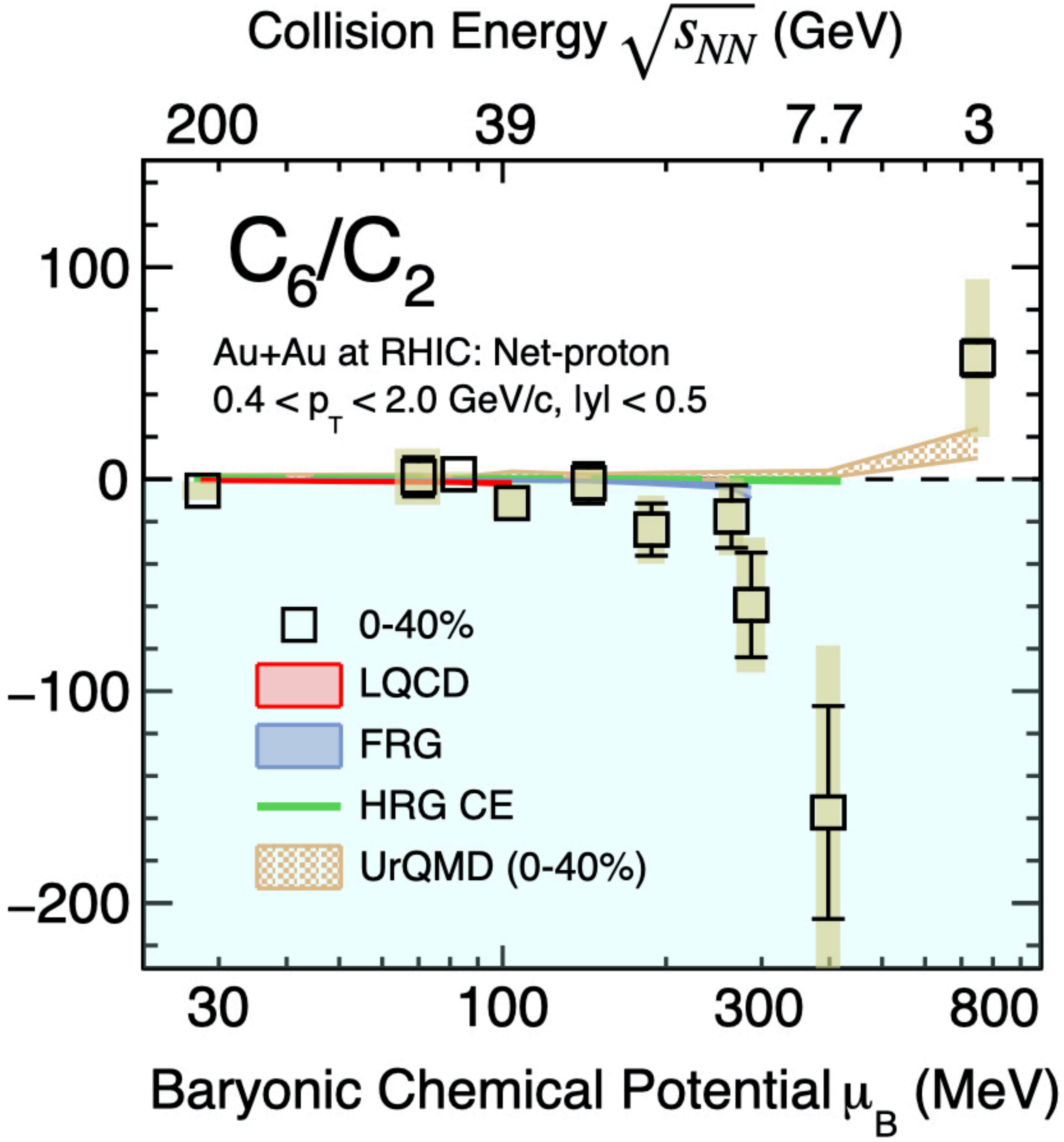


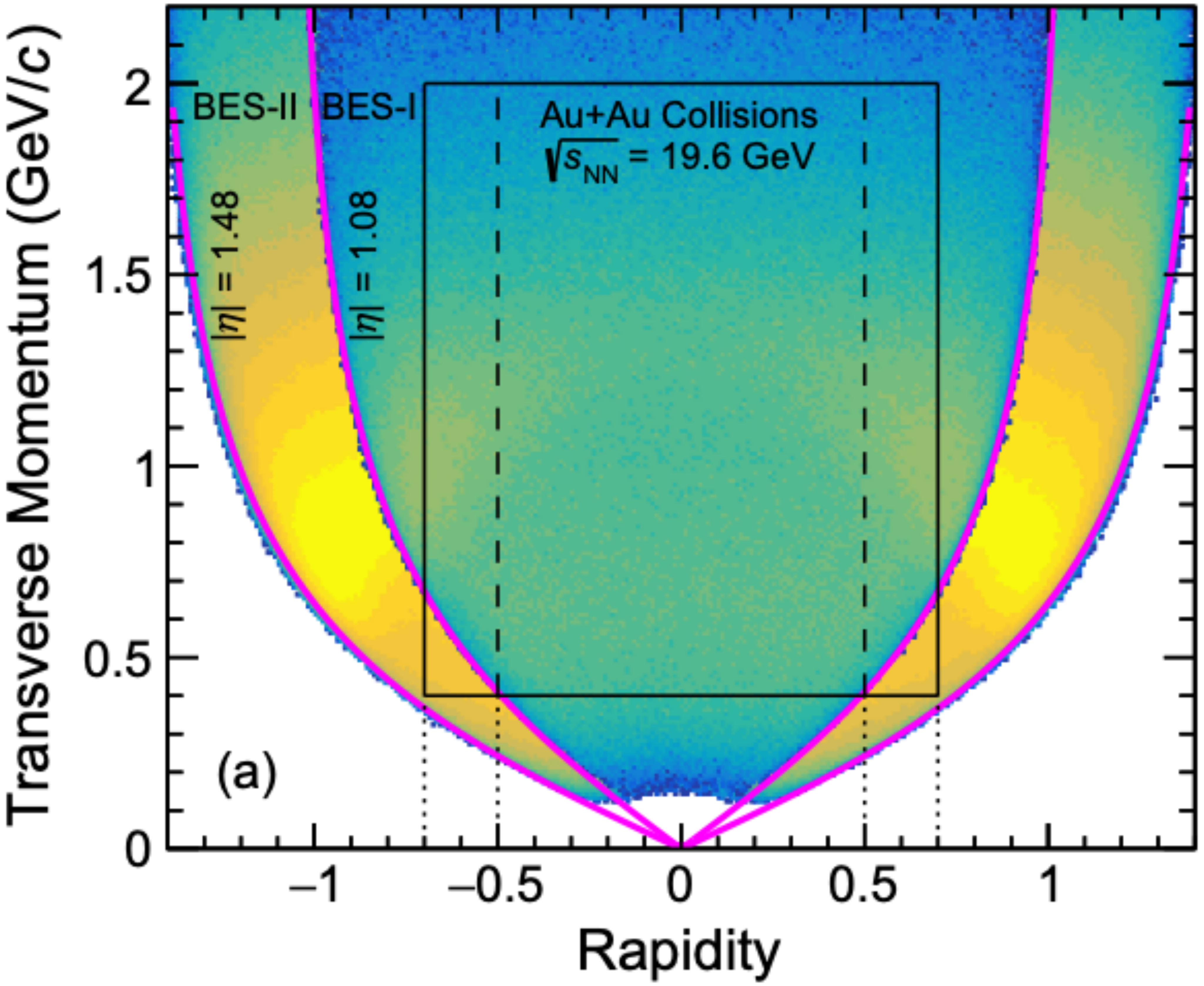
C.Fisher: CPOD24

Latest theory predictions for CP: *μ_B^{CP}: ~ 420 – 750 MeV, T^{CP}: ~ 90 – 120 MeV*

STAR-FXT ($\sqrt{s_{NN}}$ = 3 – 3.9 GeV) analysis ongoing , CBM ($\sqrt{s_{NN}}$ = 2.4 – 4.9 GeV) to take data 2028

Outlook: Hyper-order data and Acceptance Scan



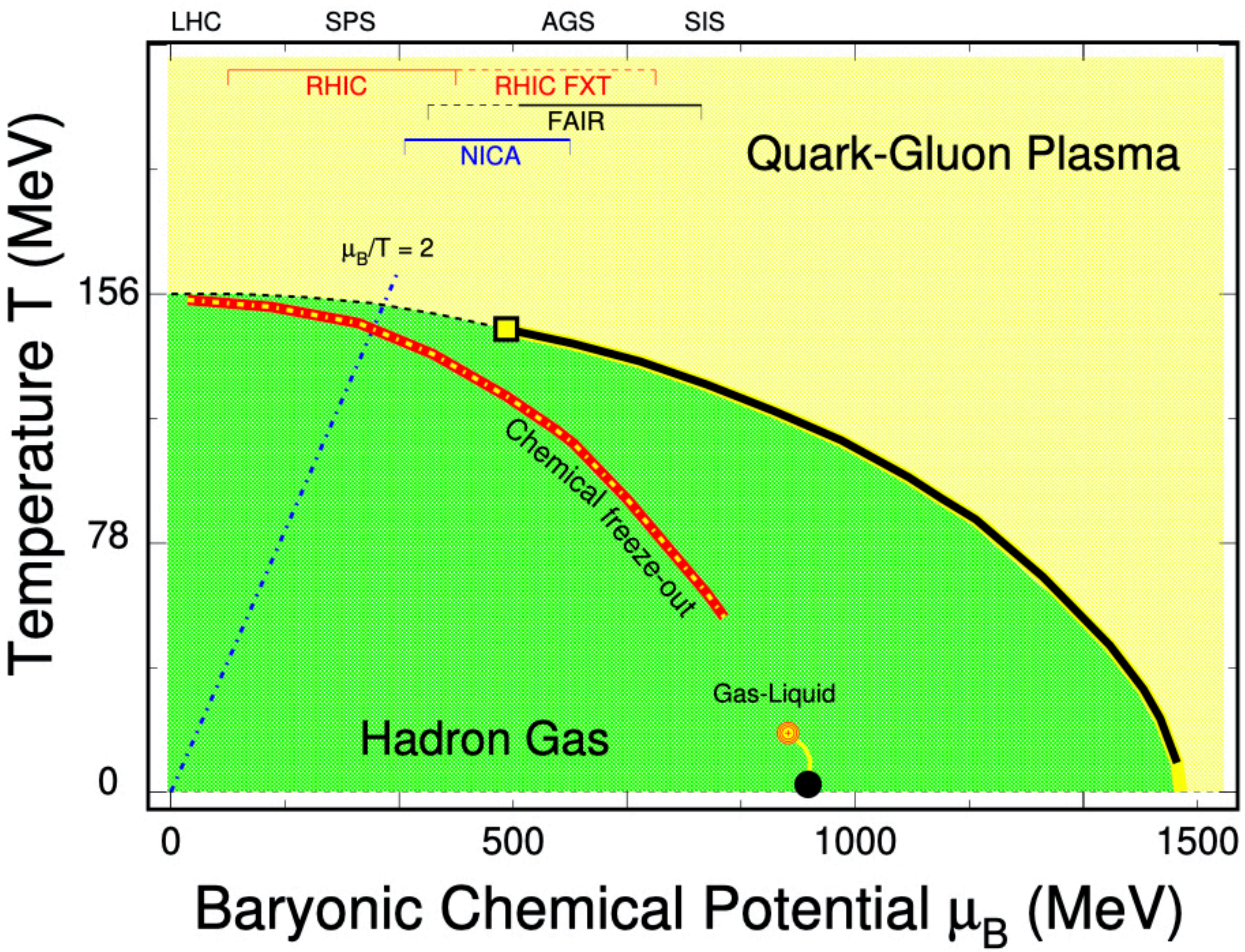


Hyper-order data: probes for crossover. STAR: BES-II, Au+Au at $\sqrt{s_{NN}}$ = 200 GeV: ~ 20 billion event (2023+2025) and $\sqrt{s_{NN}}$ = 3 GeV: ~ 2 billion events collected. Precision measurement ongoing.

ALICE : Higher order measurements to come with high statistic LHC Run3

Acceptance scan: Stronger CP signals expected with wider rapidity/p_T acceptance.

Conclusion:



- Several intriguing observations made from currently available data. Lot of new precise experimental data to come.
- Detailed theoretical studies on QCD phase structure ongoing.
- New experimental facilities at high baryon density to come in upcoming years: CBM@FAIR, NICA@JINR, J-PARC, HIAF.

Exciting times ahead. Stay tuned.

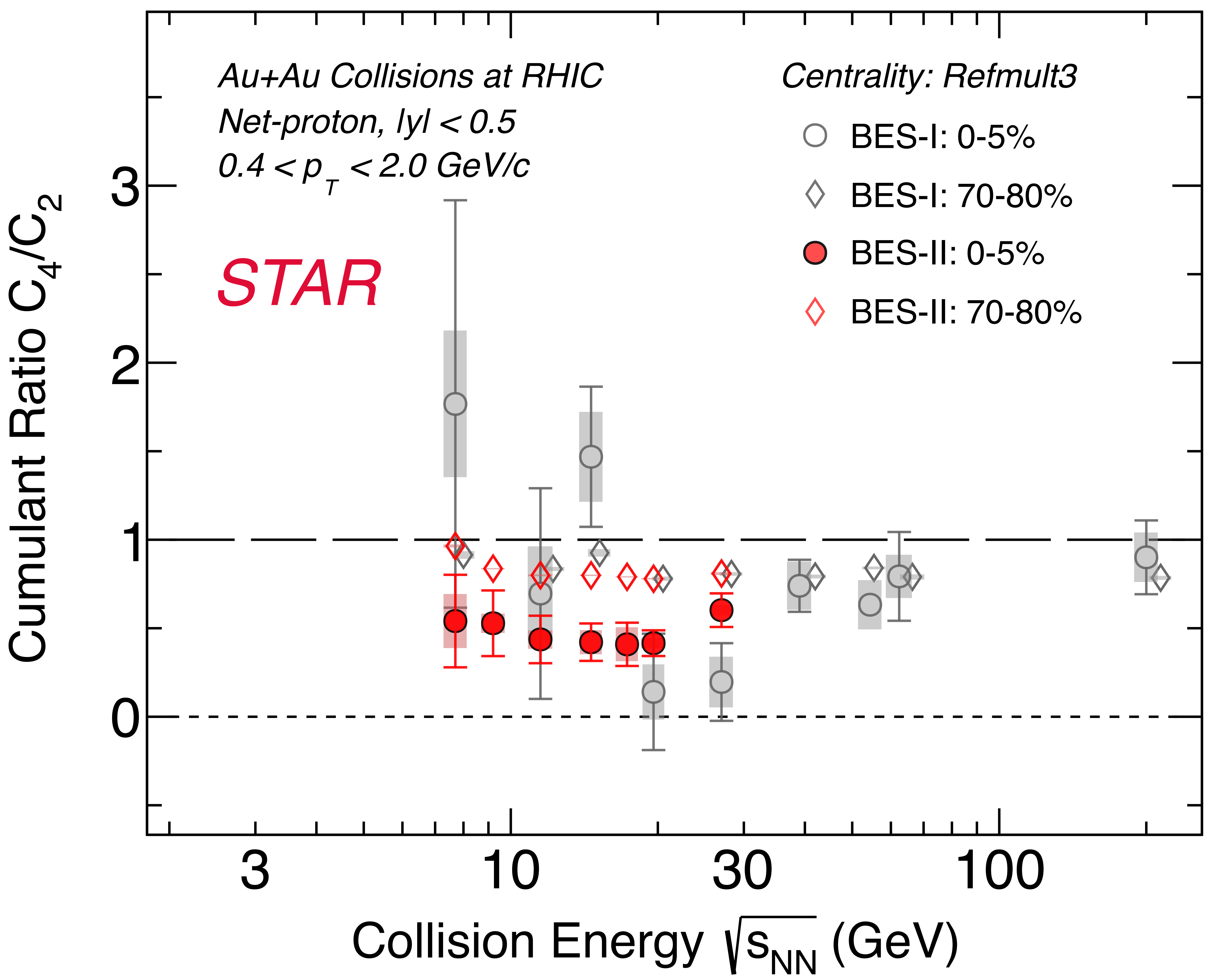
Acknowledgements:

Alphabetically: Xin Dong, ShinIchi Esumi, Yige Huang, Ho-San Ko*, Xiaofeng Luo, Debasish Mallick*, Bedanga Mohanty, Dylan Neff*, Risa Nishitani*, Bappaditya Mondal*, Toshihiro Nonaka, Fan Si*, Zachary Sweger*, Zhaohui Wang*, Yongcong Xu*, Nu Xu, Xin Zhang*, Xiuxian Wang*, Yifei Zhang, Yu Zhang.*

RHIC operation, STAR Collaboration members, and RNC group.
Organizers for the opportunity. ***Thank you all.***

Backup:

Energy Dependence of C_4/C_2: Comparison with BES-I



Deviation between BES-II and BES-I data

$\sqrt{s_{NN}}$ (GeV)	0-5%	70-80%
7.7	1.0σ	0.9σ
11.5	0.4σ	1.3σ
14.6	2.2σ	2.5σ
19.6	0.7σ	0.1σ
27	1.4σ	0.2σ

- BES-II results consistent with BES-I within uncertainties.