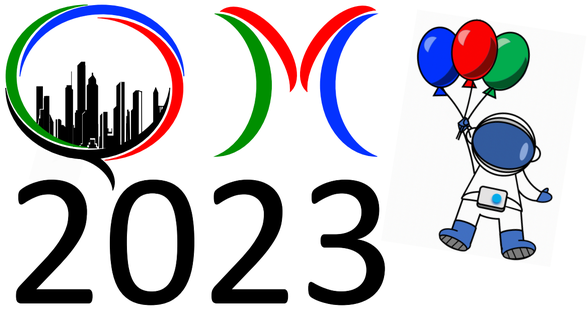
Experimental results on the search for the QCD critical endpoint

Ashish Pandav (Lawrence Berkeley National Laboratory)

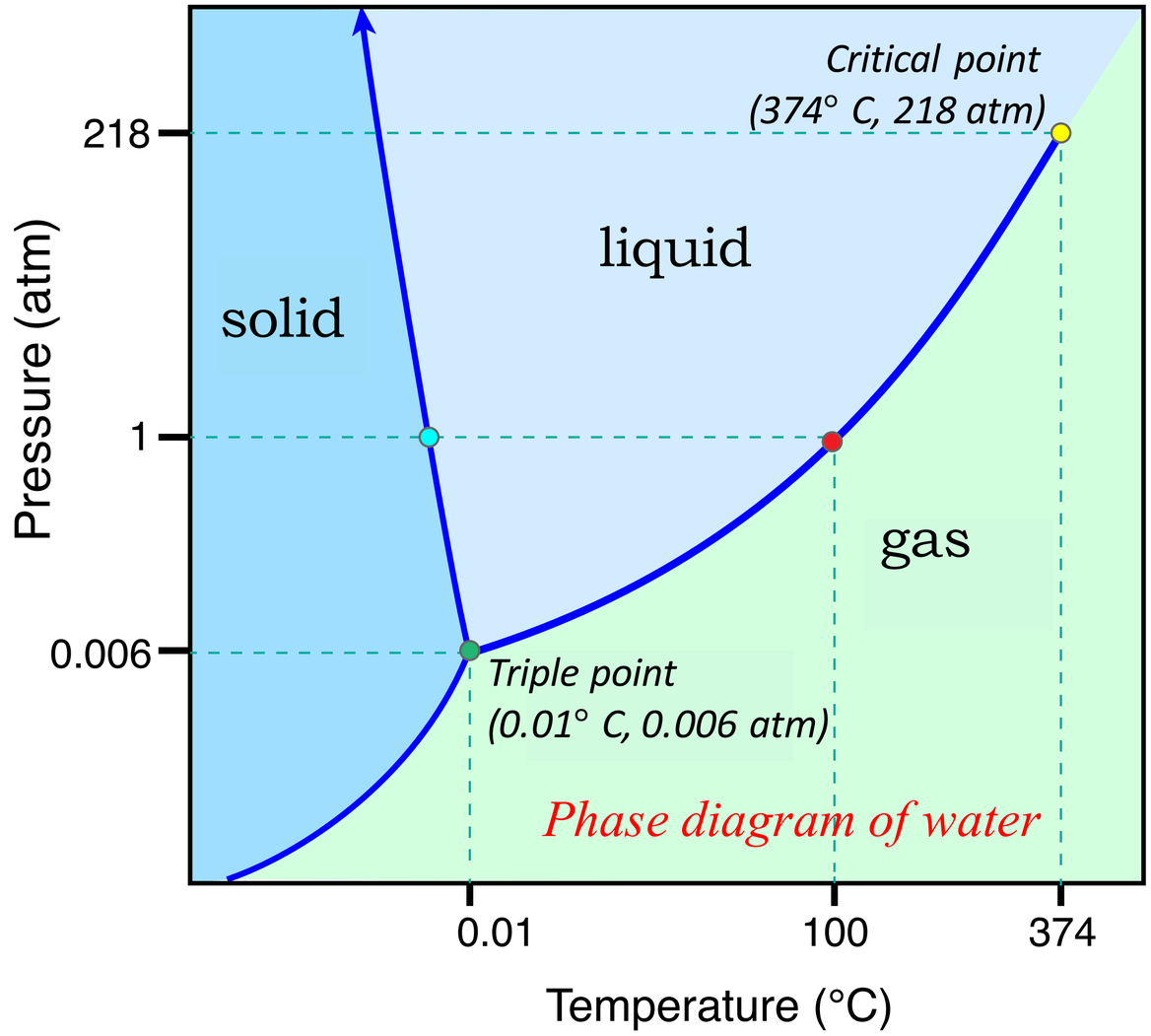
September 7, 2023



QM2023
Houston, Texas
Sep 3 -9, 2023

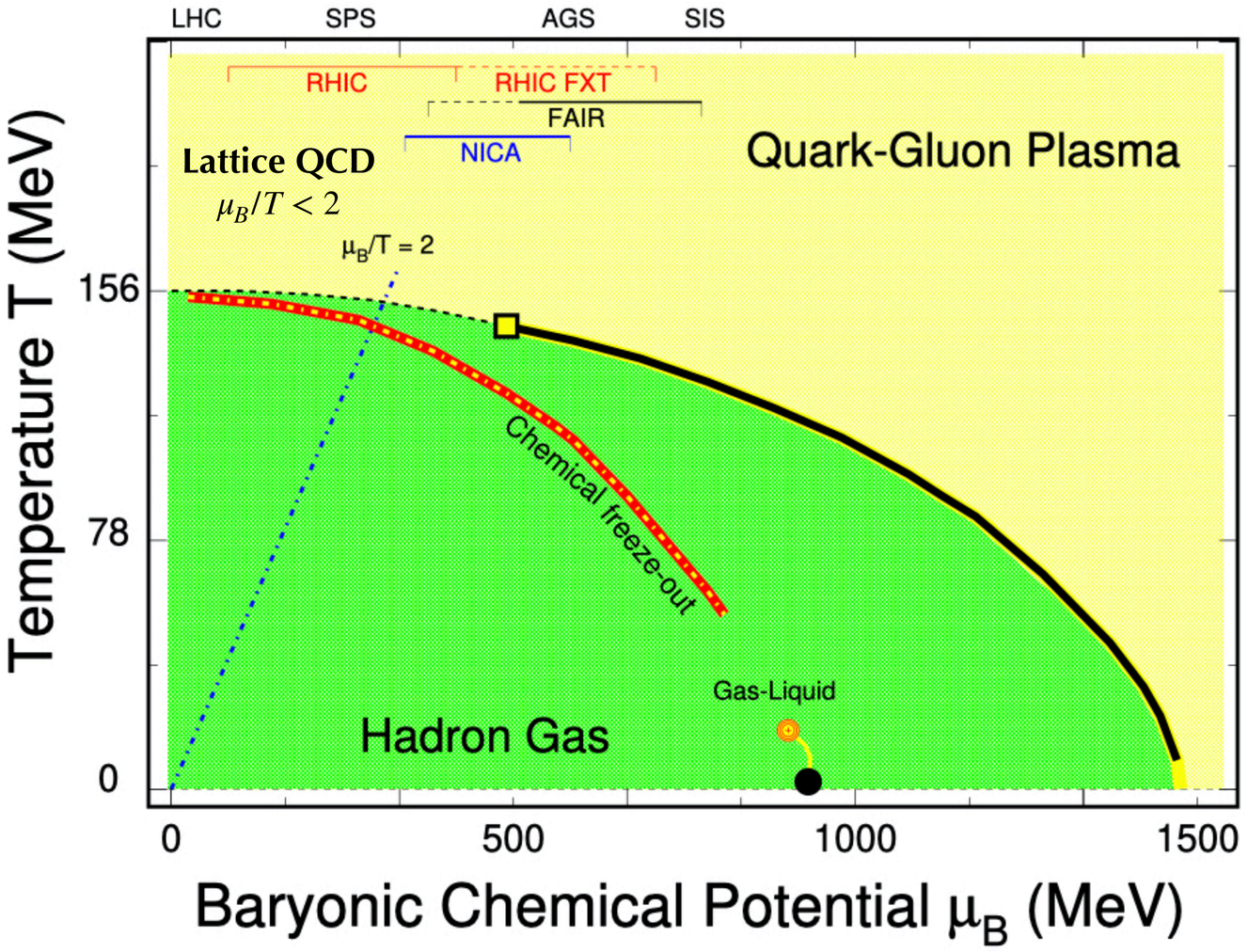
Outline

Introduction: Phase Transition



- ☐ Underlying interaction electromagnetic
- ☐ Precise understanding available

Introduction: QCD Phase Diagram



B. Mohanty, N. Xu, arXiv:2101.09210

Lattice QCD →

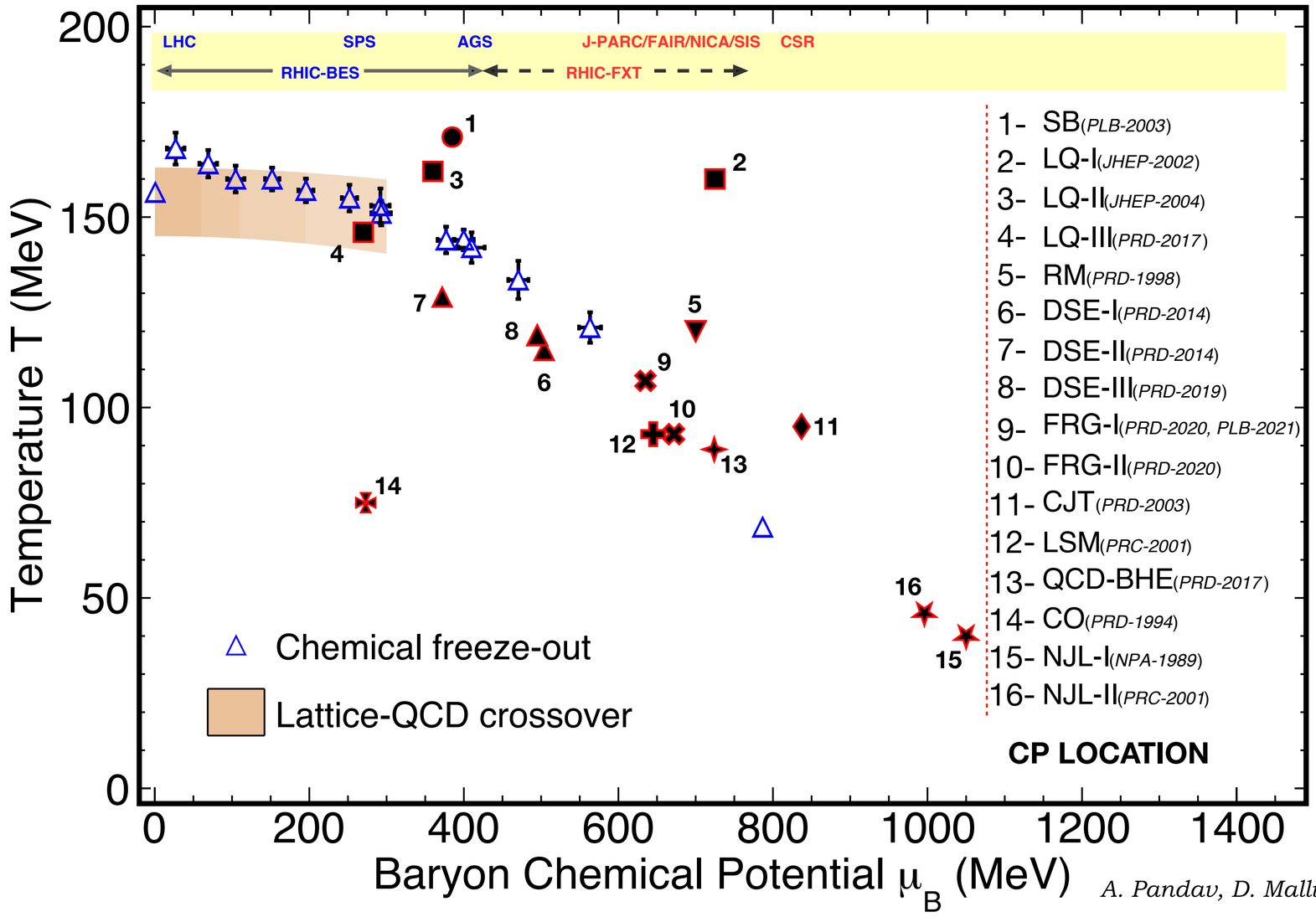
Models →

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** ?

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

Introduction: QCD Critical Point (CP) From Theory

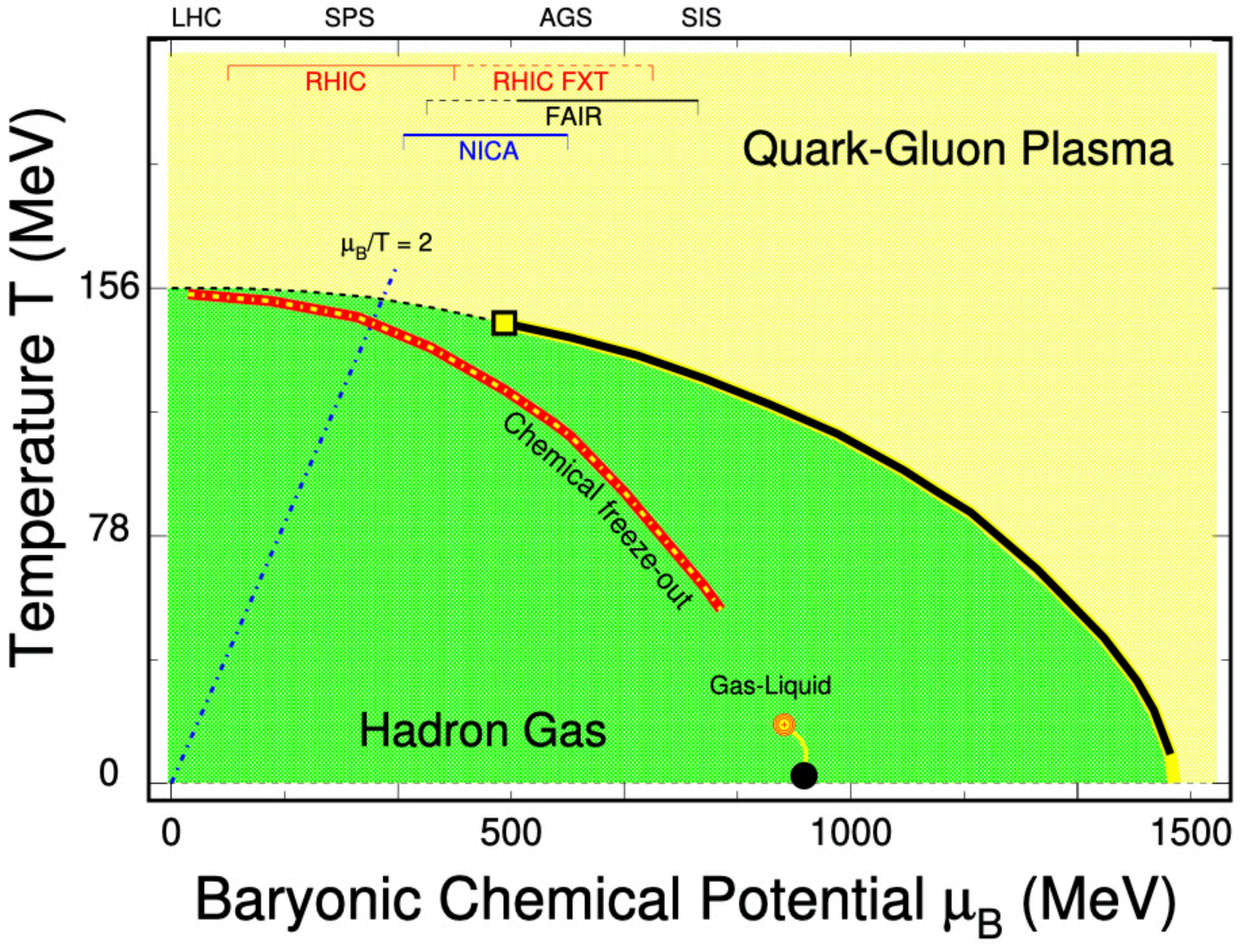


- Lattice calculations at high μ_B suffer from sign problem
- Effective models have several underlying assumptions/ approximations

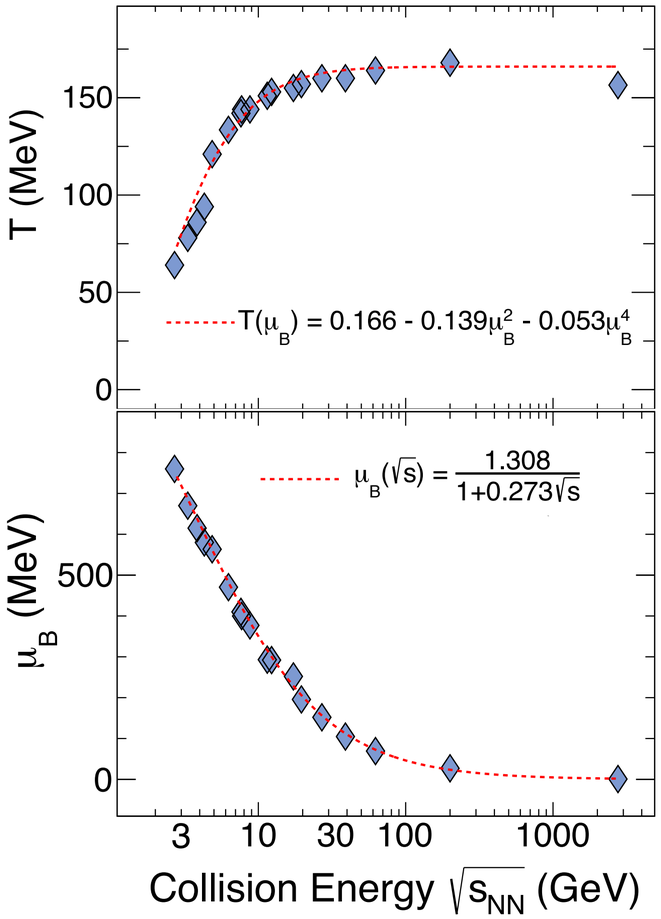
A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

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

Introduction: Experimentally accessing Phase Diagram



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



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

- 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

Observables For CP Search (Selected):

Observable	Definition	Comments
Particle ratio fluctuation ν_{dyn}	$\frac{< N_x(N_x-1) >}{< N_x >^2} + \frac{< N_y(N_y-1) >}{< N_y >^2} - 2\frac{< N_x N_y >}{< Nx >< N_y >}$	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
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

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New data on $F_q(M)$, $C(k^*)$

B.Porfy (NA61/SHINE): Talk (Wednesday):

Observables For CP Search (Selected):

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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
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

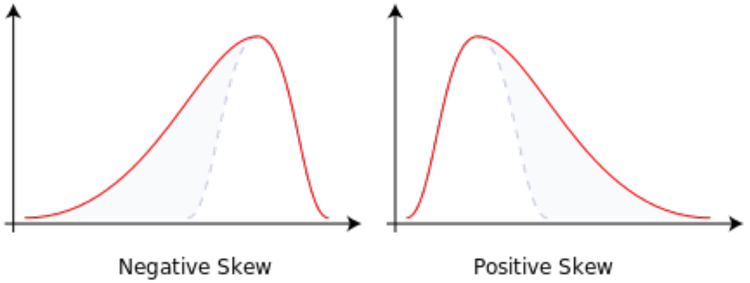
Cumulants:

- Cumulants: n = *conserved charge number (net-baryon) in an event*

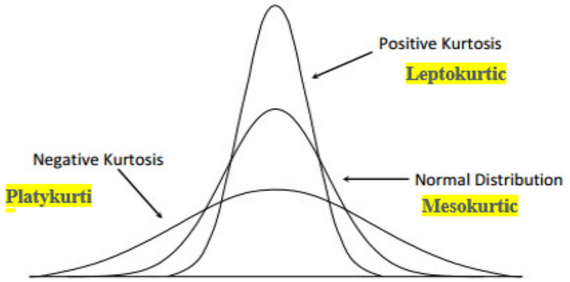
$$C_1 = < n >$$
$$C_2 = < \delta n^2 >$$
$$C_3 = < \delta n^3 >$$
$$C_4 = < \delta n^4 > - 3 < \delta n^2 >$$
$$C_5 = < \delta n^5 > - 10 < \delta n^3 > < \delta n^2 >$$
$$C_6 = < \delta n^6 > - 15 < \delta n^4 > < \delta n^2 > - 10 < \delta n^3 >^2 + 30 < \delta n^2 >^3$$

$*\delta n = n - < n >$

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: STAR experiment:
Cumulants (C_n) and Factorial cumulants (κ_n)
Theory and other experiments:
Cumulants (κ_n) and Factorial cumulants (C_n)

More on comparison of factorial cumulants vs theory:

V. Vovchenko: Plenary talk (Today)

Cumulants and CP Search:

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

Finite size/time effects reduces ξ

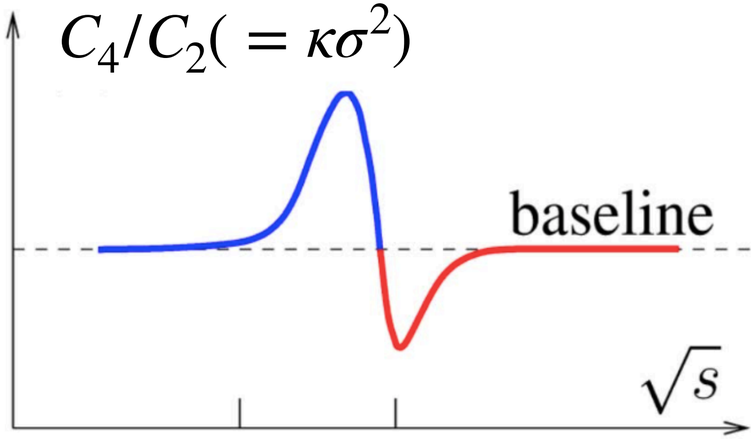
Higher order ➞ more sensitivity

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

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

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

CP search

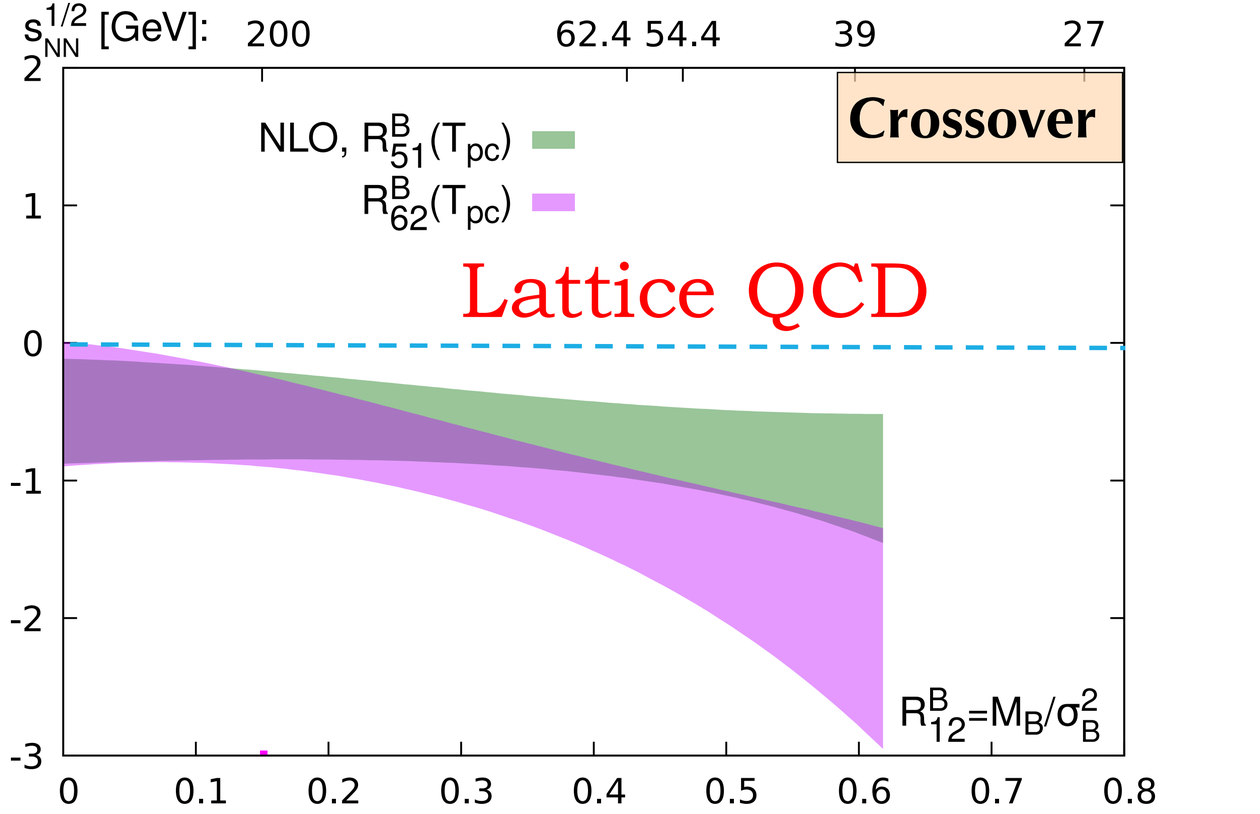


Assumption: Thermodynamic equilibrium

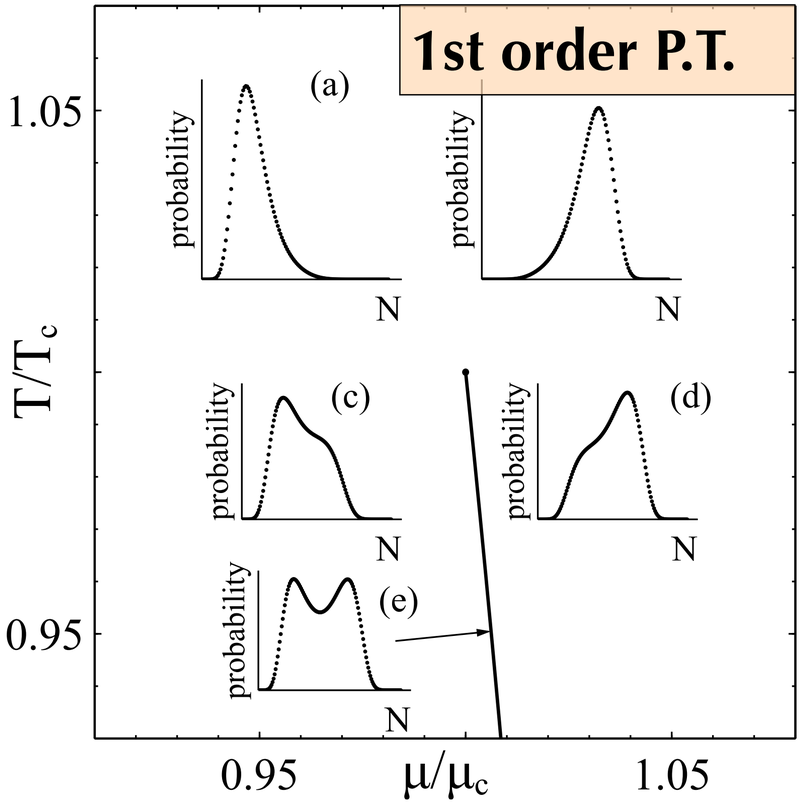
Non-monotonic $\sqrt{s_{NN}}$ dependence of C_4/C_2 of conserved quantity - **existence of a critical region**

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

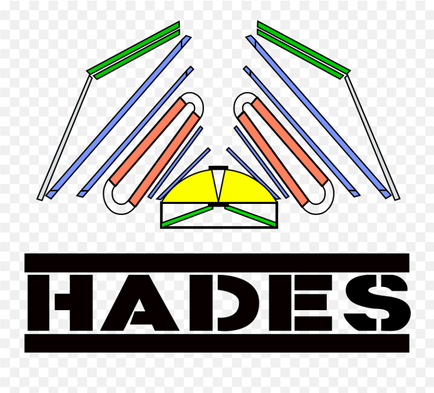
Bimodal multiplicity distribution near **1st order P.T.** - Large factorial cumulants κ_n alternating sign with increasing order

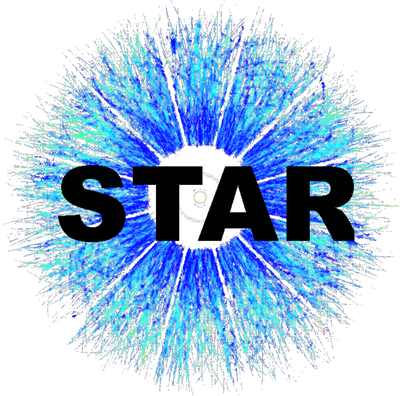
Strategy:

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

Active Experiments for CP Search:



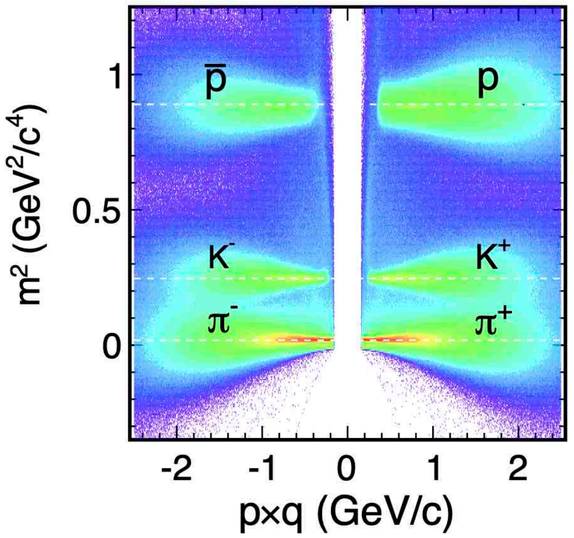


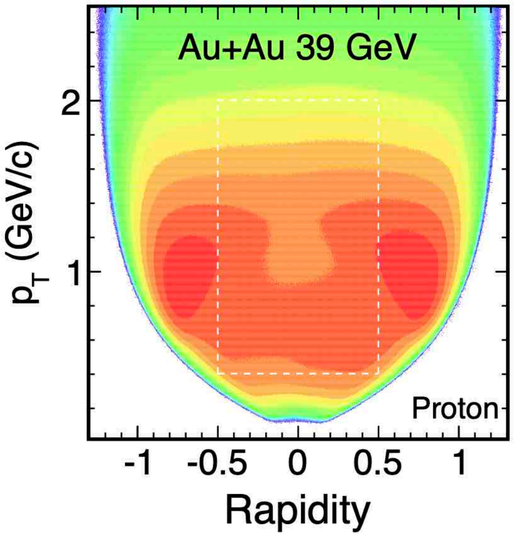
Overview talks:

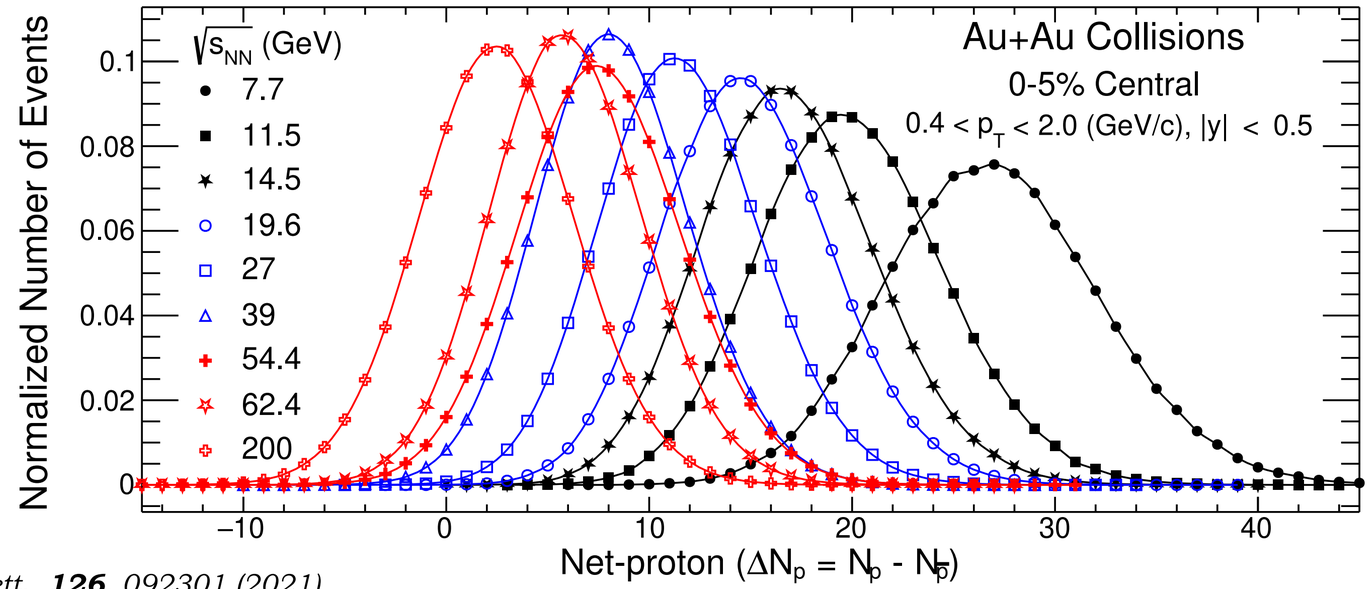
S. Spies (HADES)
P. Podlaski (NA61/SHINE)
R. Reed (STAR)
I.C. Arsene (ALICE)

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)

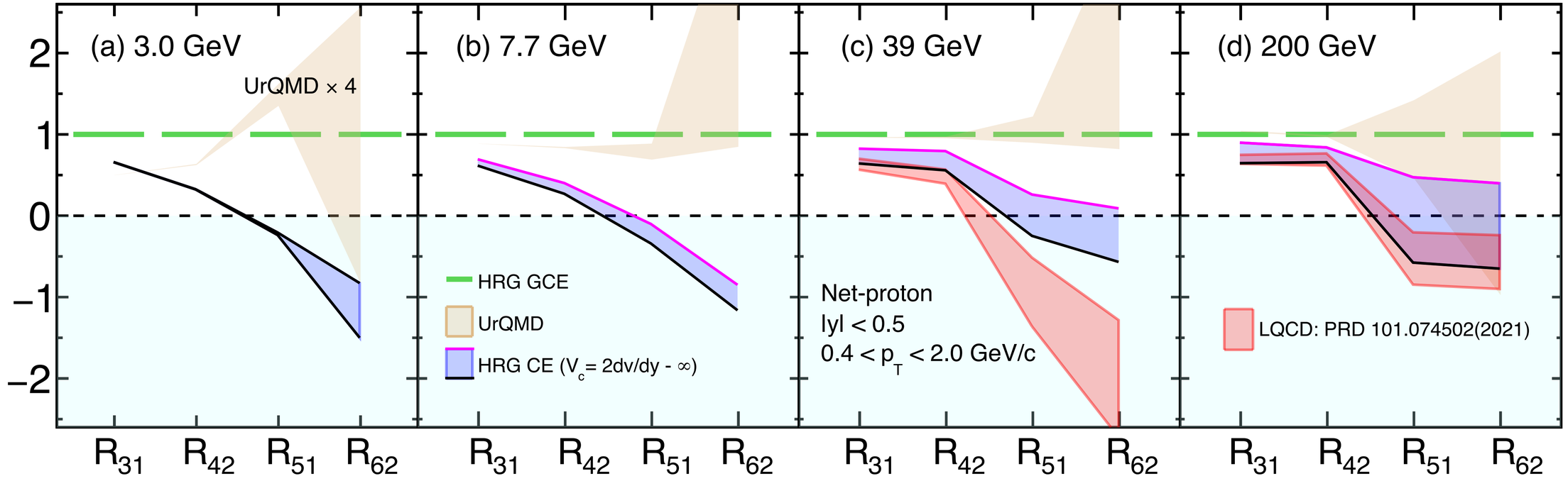
☐ Measure statistical and systematic uncertainties: stat.err. $C_r \propto \frac{\sigma^r}{\sqrt{N}}$

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: 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



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

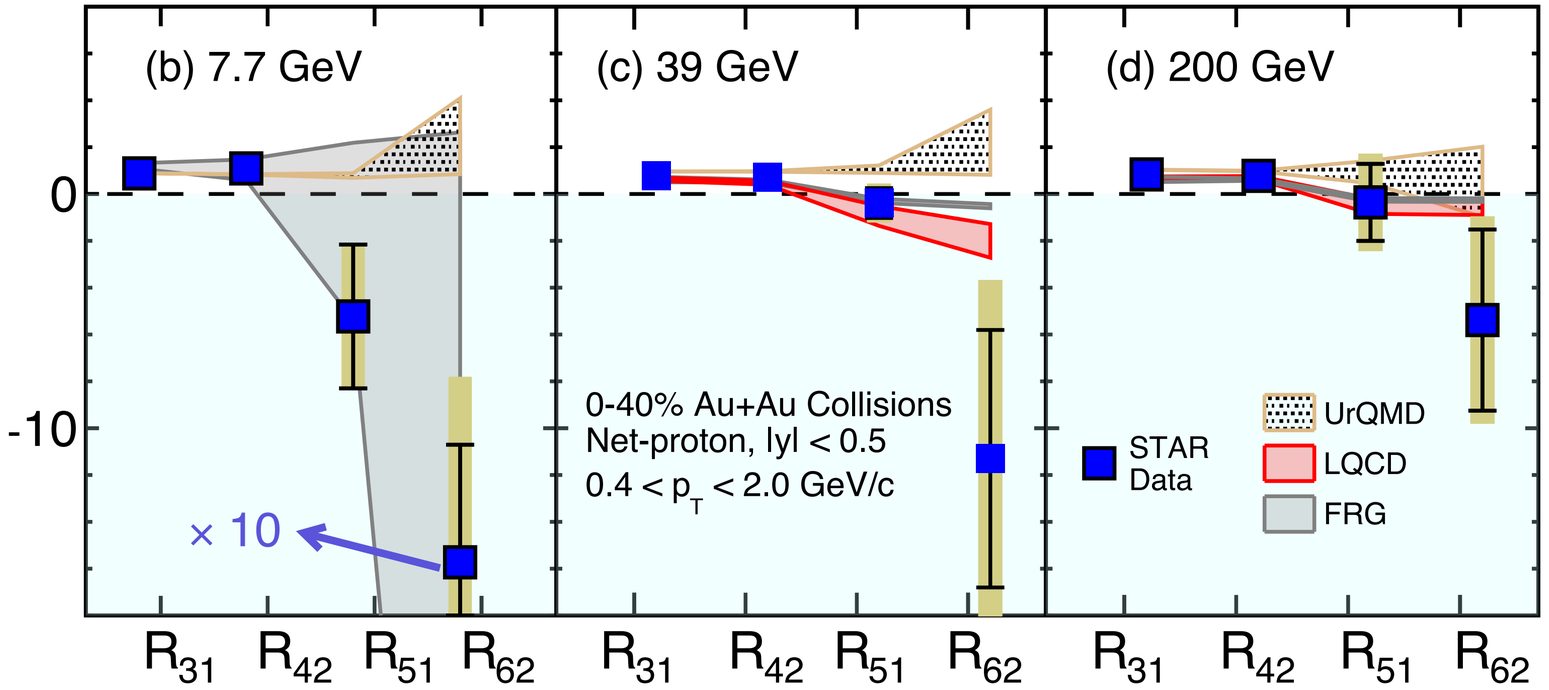
Thermal FIST : V.Vovchenko, H. Stoecker, Comp. Phys. Comm. 244, 295-301 (2019)

HRG CE (Vc = ∞, global cons.): P. B Munzinger et al, NPA 1008, 122141 (2021)
UrQMD: STAR: PRL 130, 082301 (2023)

- Ideal HRG GCE (non-interacting): no ordering
- UrQMD - no thermal equilibrium: no ordering within uncertainties
- HRG CE with baryon conservation: ordering observed at all energies
- **Equilibrium+Interaction necessary for ordering of cumulant ratios**

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



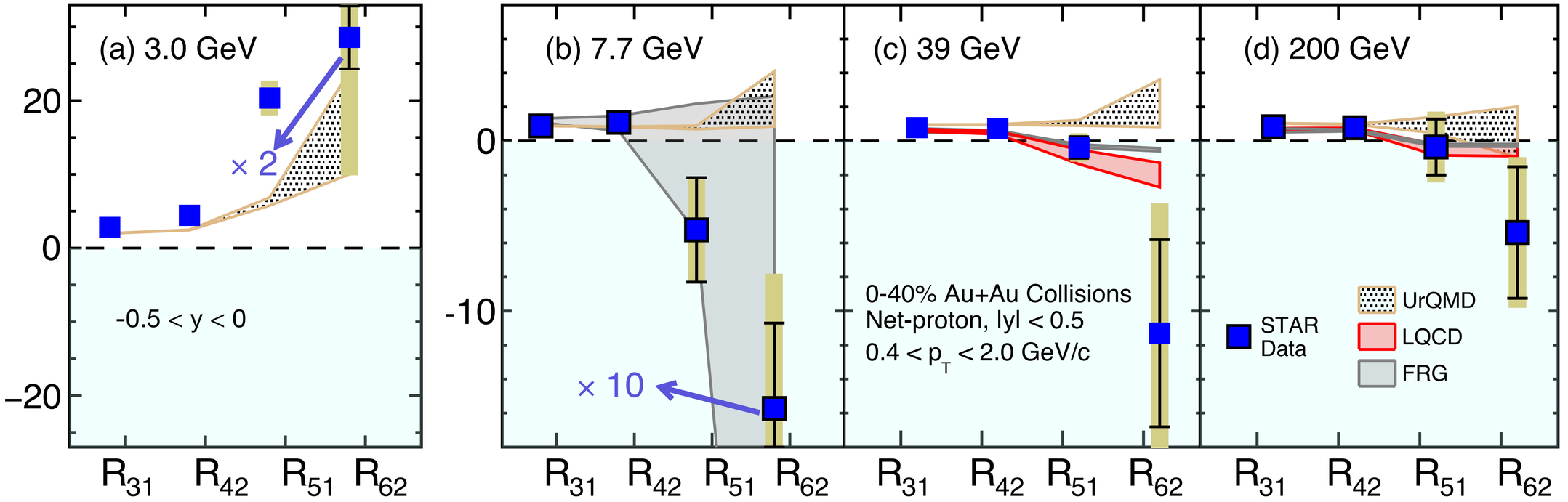
$R_{31} = C_3/C_1$ $R_{42} = C_4/C_2$ $R_{51} = C_5/C_1$ $R_{62} = C_6/C_2$

☐ Within uncertainties, 7.7 - 200 GeV data consistent with lattice predicted hierarchy.

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

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

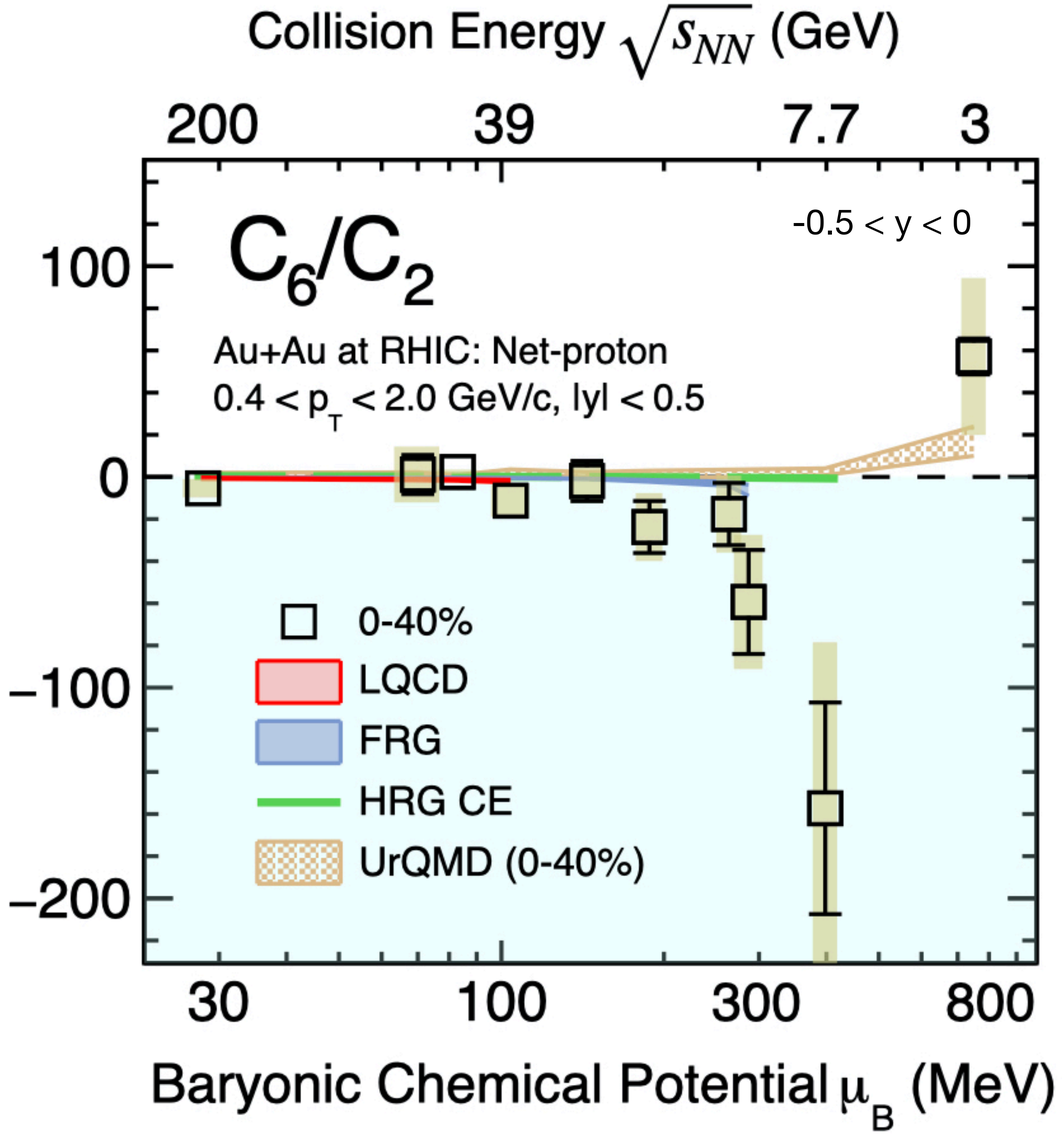
D.Neff (STAR): Talk (Tuesday)

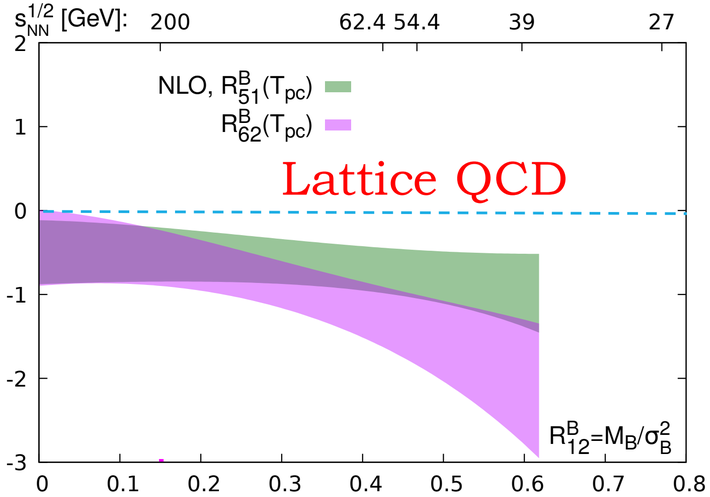
Strategy:

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





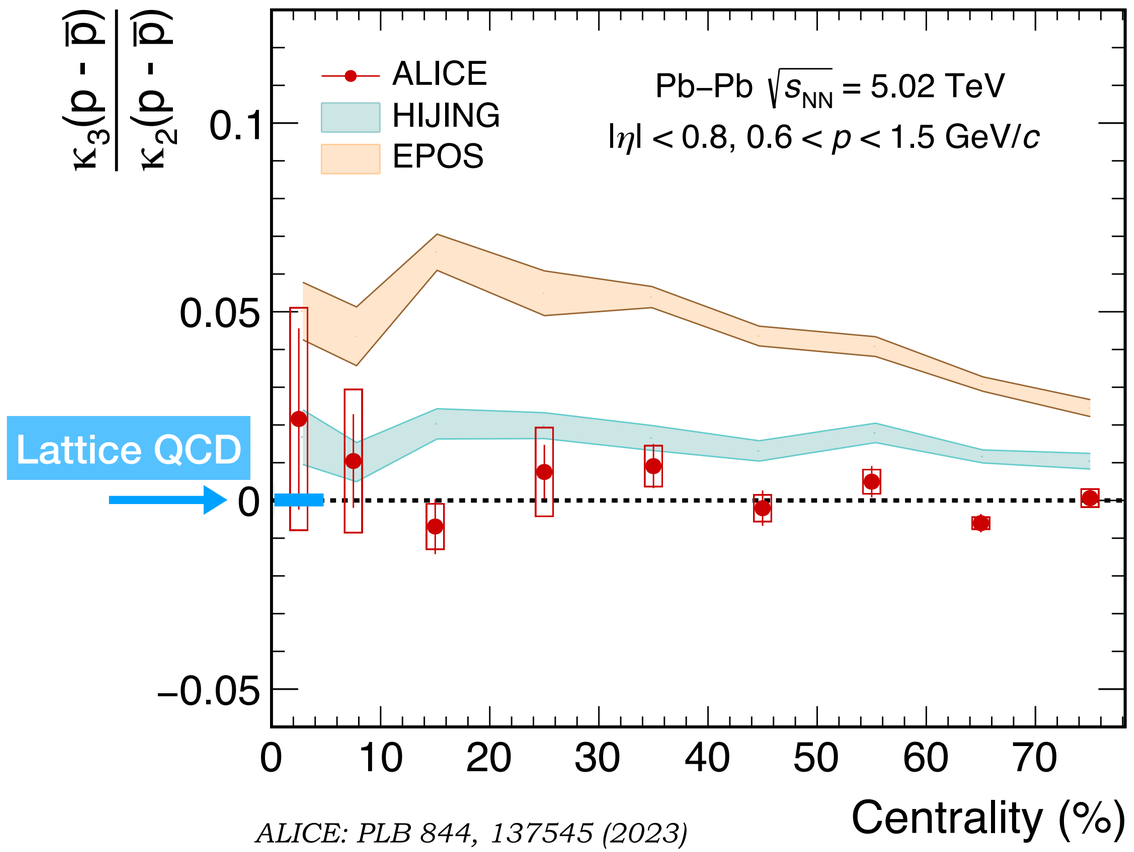
- Increasingly negative C_6/C_2 (down to 7.7 GeV) with decreasing $\sqrt{s_{NN}}$ (1.7σ significance) - sign and trend consistent with lattice QCD
- $C_6/C_2 > 0$ at 3 GeV, sign reproduced by UrQMD. Peripheral data > 0

STAR: PRL 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)

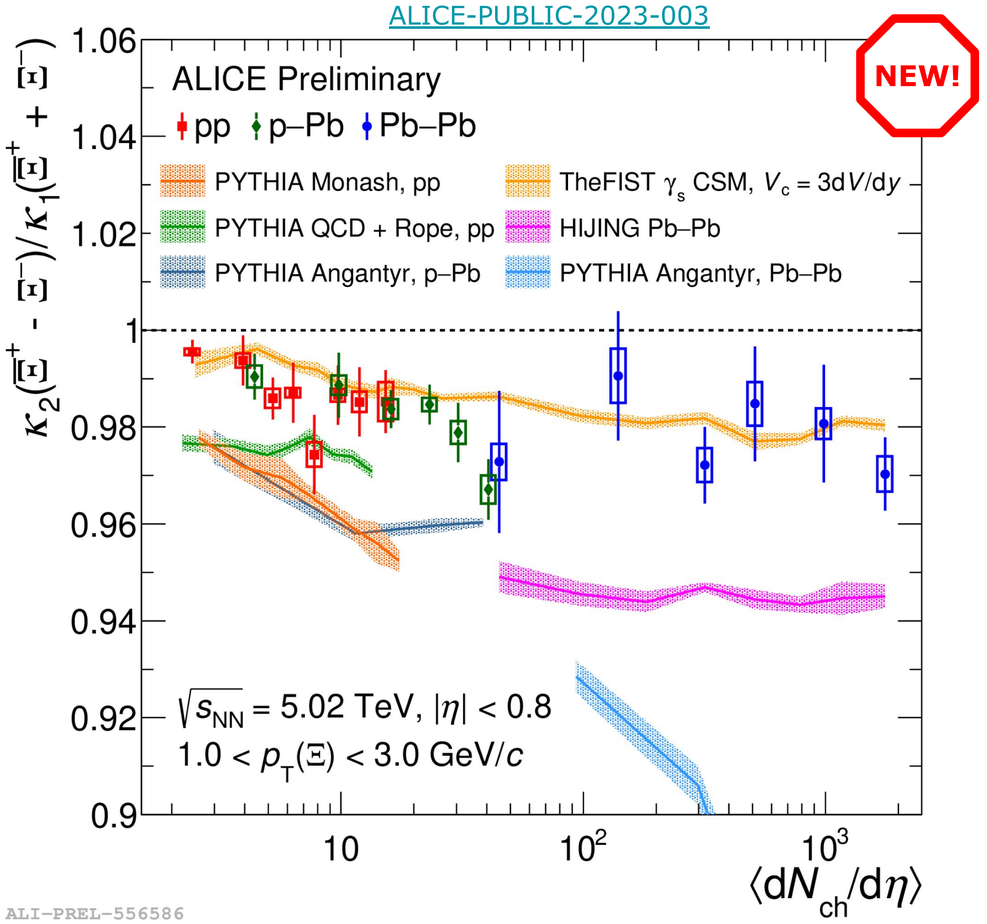
D. Neff (STAR): Talk (Tuesday)

Results: Measurements at Vanishing μ_B



ALICE: PLB 844, 137545 (2023)

ALICE-PUBLIC-2023-003



ALI-PREL-556586

M. Ciacco (ALICE): Talk (Tuesday)

- Vanishing third order cumulant ratio – consistent with LQCD and HRG calculations

- Cascade fluctuations: string fragmentation model fails, data explained by HRG with conservation $V_c = 3dV/dy$. Presence of long-range rapidity correlations.

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

- ☐ Experimentally establish crossover at small μ_B

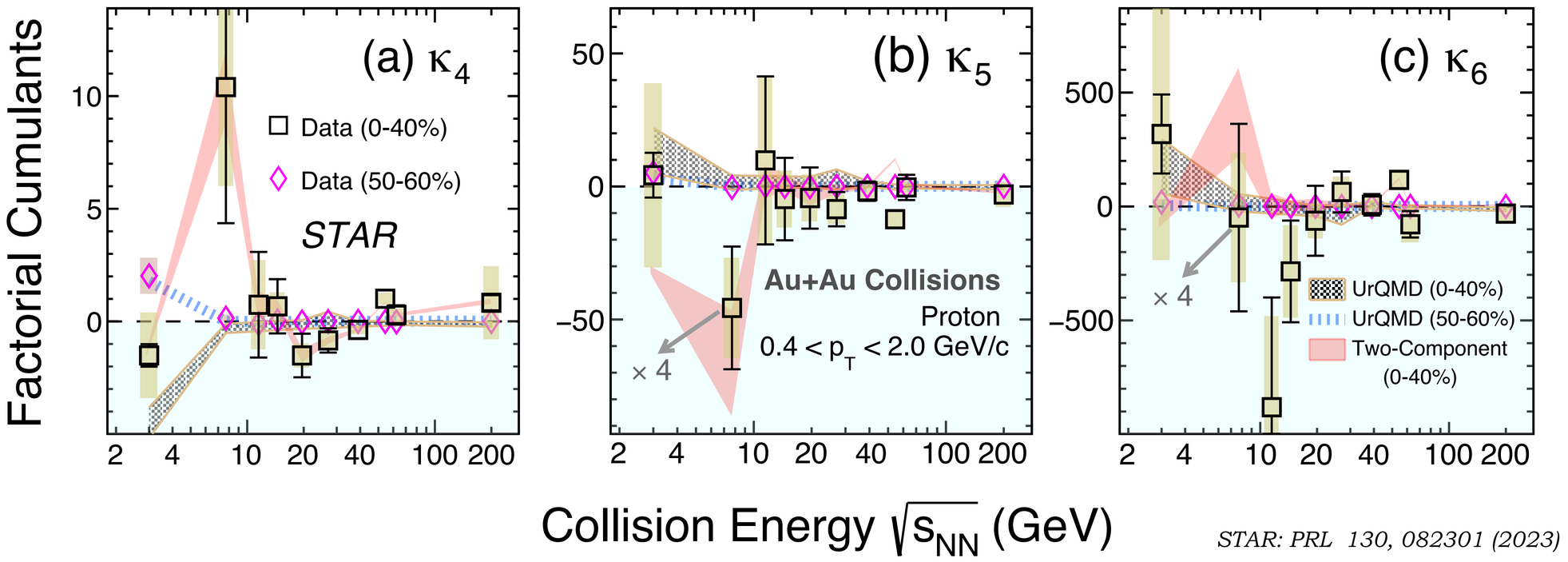
  Observed sign and trend in data ($\sqrt{s_{NN}} \geq 7.7$ GeV) consistent with calculations from lattice QCD ($\mu_B < 110$ MeV) with a crossover at $O(\sim 1\sigma)$ significance level.

- ☐ **Search for signs of 1st order P.T. at large μ_B**

- ☐ 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.

- Precision measure necessary to see trends clearly at low energies.

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 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.

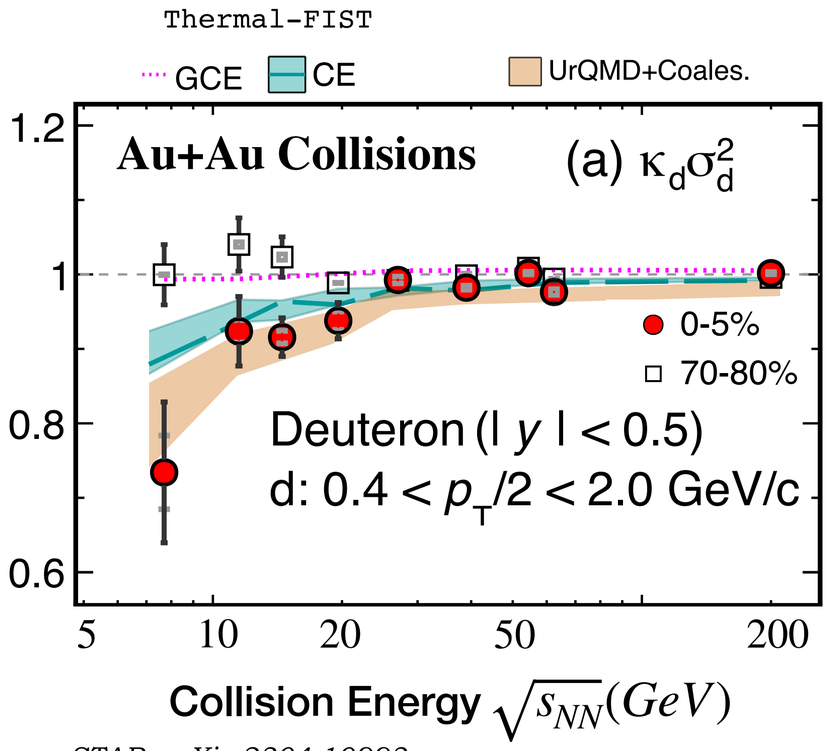
- ☐ Search for signs of 1st order P.T. at large μ_B

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

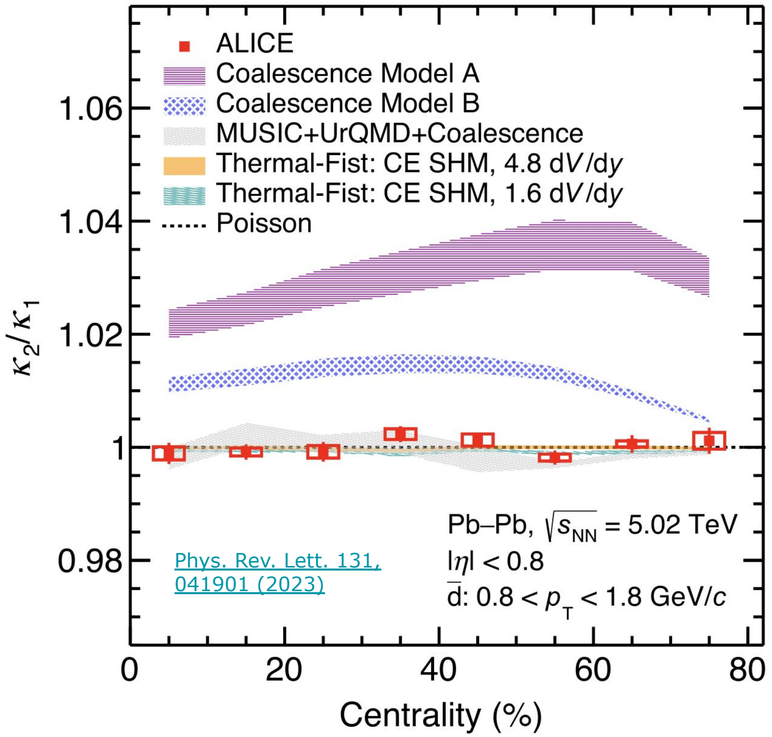
- ☐ **Search for signs of QCD critical point**

Results: Light Nuclei Fluctuation

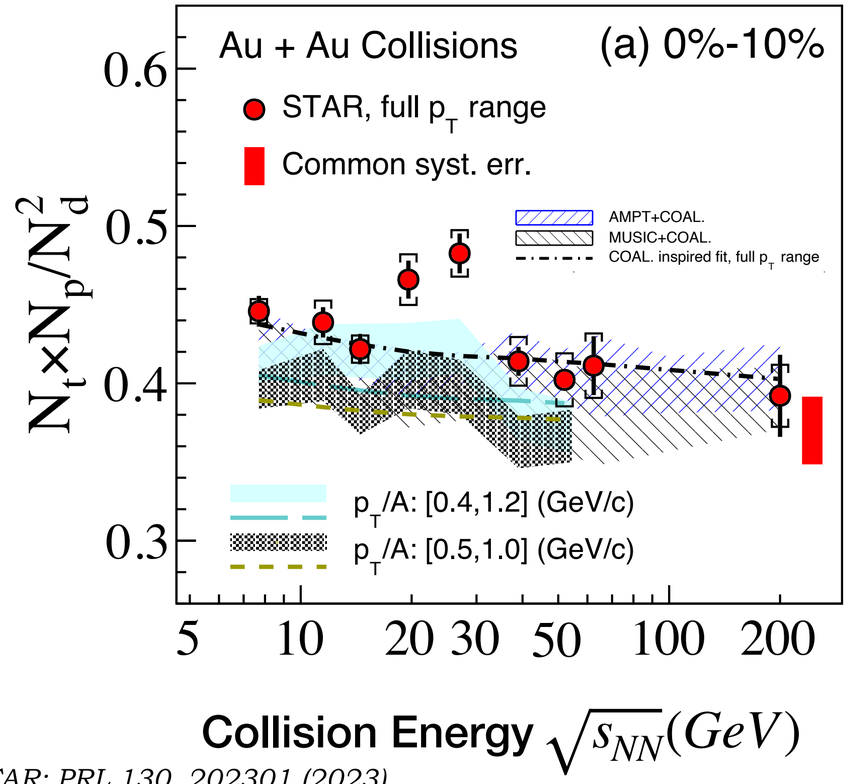
Light nuclei yield and fluctuations: sensitive to local density fluctuation near CP



STAR: arXiv 2304.10993



ALICE: PRL 131, 041901 (2023)

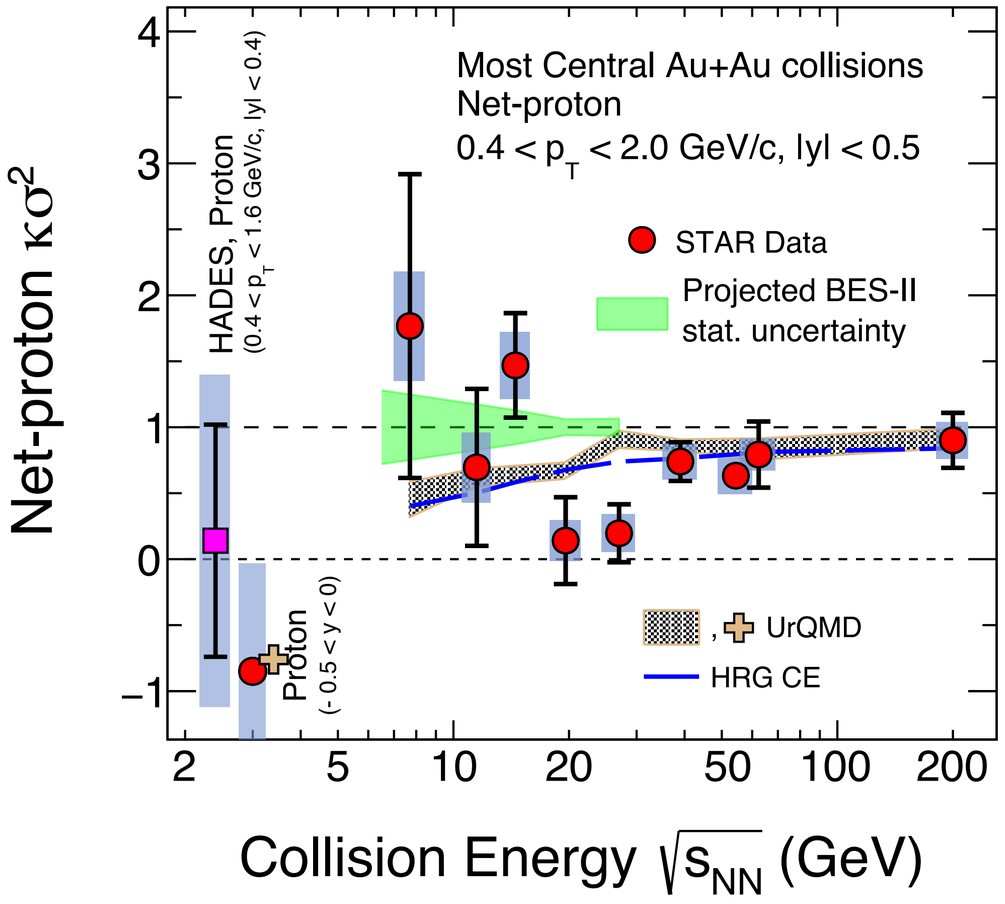


STAR: PRL 130, 202301 (2023)

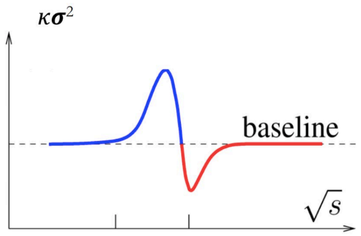
- Fluctuations of deuteron explained by HRG CE and UrQMD+Coalescence model
- Light nuclei ratio: $N_t \times N_p/N_d^2$ shows deviations around $\sqrt{s_{NN}} = 19$ and 27 GeV

  Investigation ongoing to link the observation in regards CP search

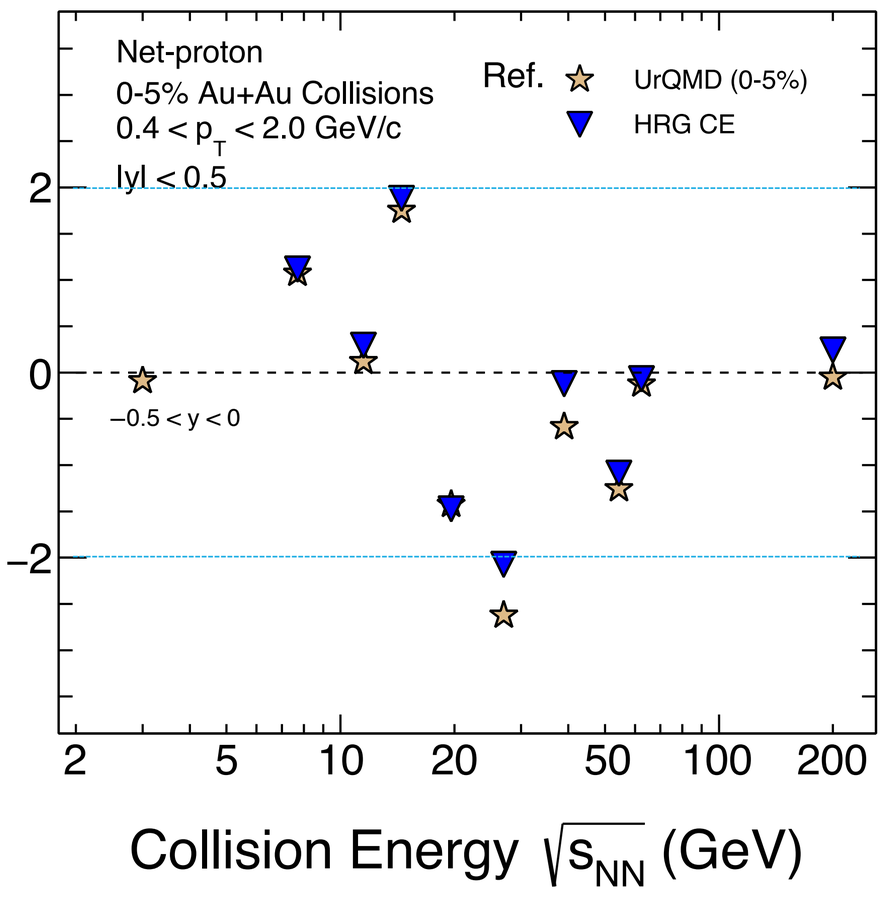
Results: Net-proton Fluctuations



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



$$\frac{\kappa\sigma^2\,(\text{Data}) - \text{Ref.}}{\text{Total Uncertainties}}$$



HADES: PRC 102, 024914 (2020)
STAR: PRL 127, 262301 (2021)
STAR: PRL 128, 202302 (2022)
HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)

- 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
- Precision measurement from BES-II ongoing

Strategy:

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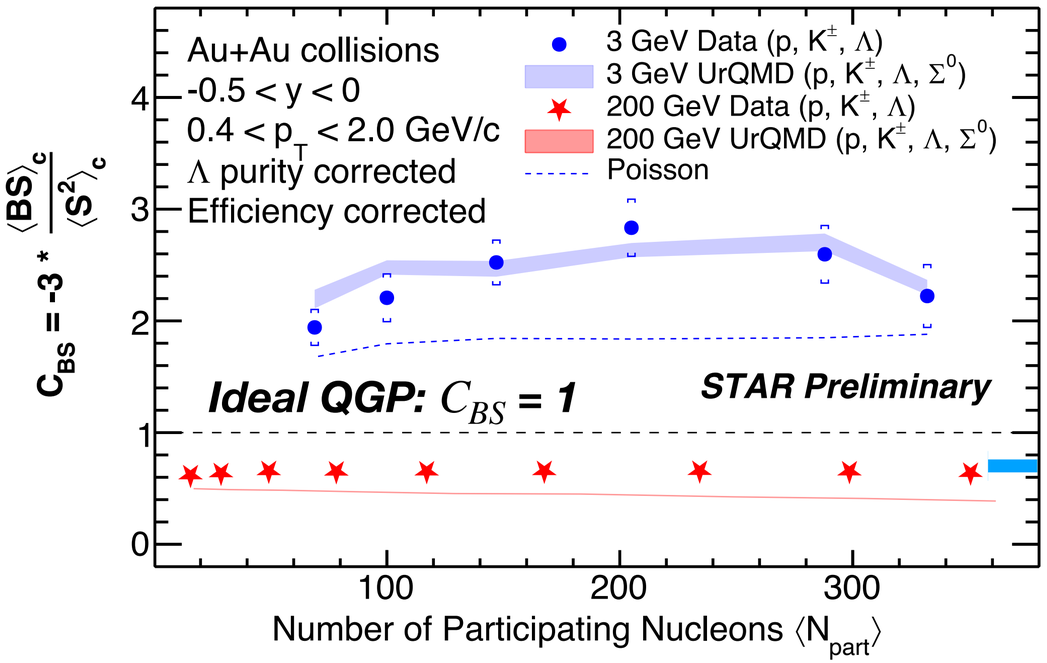
  Data ($\sqrt{s_{NN}} > 7.7$ GeV) within uncertainties suggest absence of any bimodal structure expected near 1st order phase transition.

- ☐ Search for signs of QCD critical point

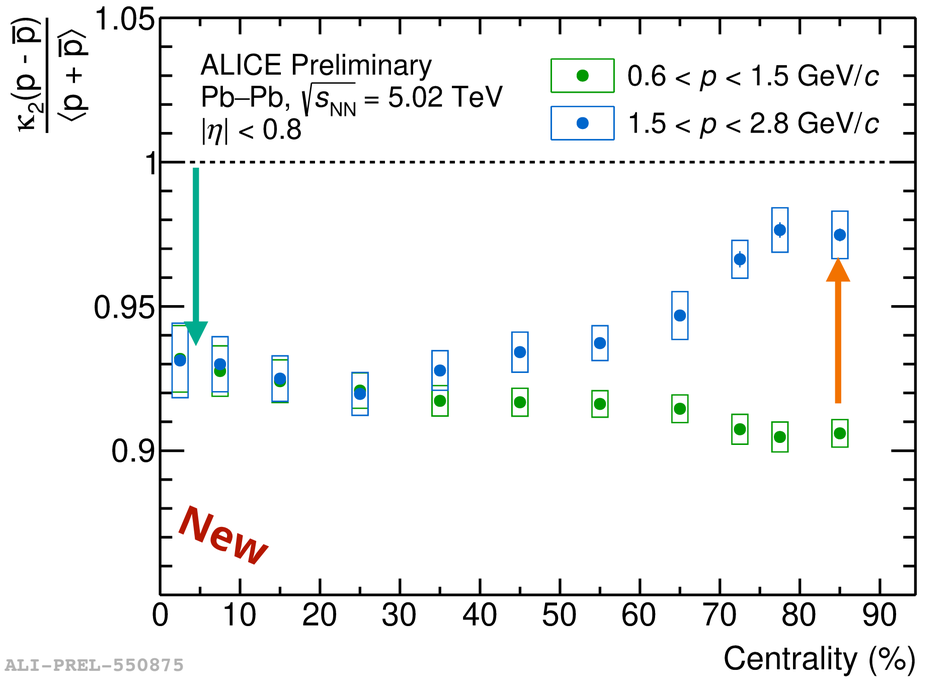
  Non-monotonic energy dependence observed in data around (7.7 - 27 GeV) within $\lesssim 3\sigma$ level, consistent with model expectation with a CP. Precision measurement ongoing

New measurements at QM:

Study QGP formation and initial magnetic field in HI collisions: off diagonal cumulants



Lattice QCD



V. Koch et al: PRL95, 182301 (2005)
LQCD: PRD 104, 074512 (2021)

T. Nonaka (ISMD 2023)

C_{BS} (200 GeV) < 1, close to lattice QCD

C_{BS} (3 GeV) > 1, reproduced by UrQMD

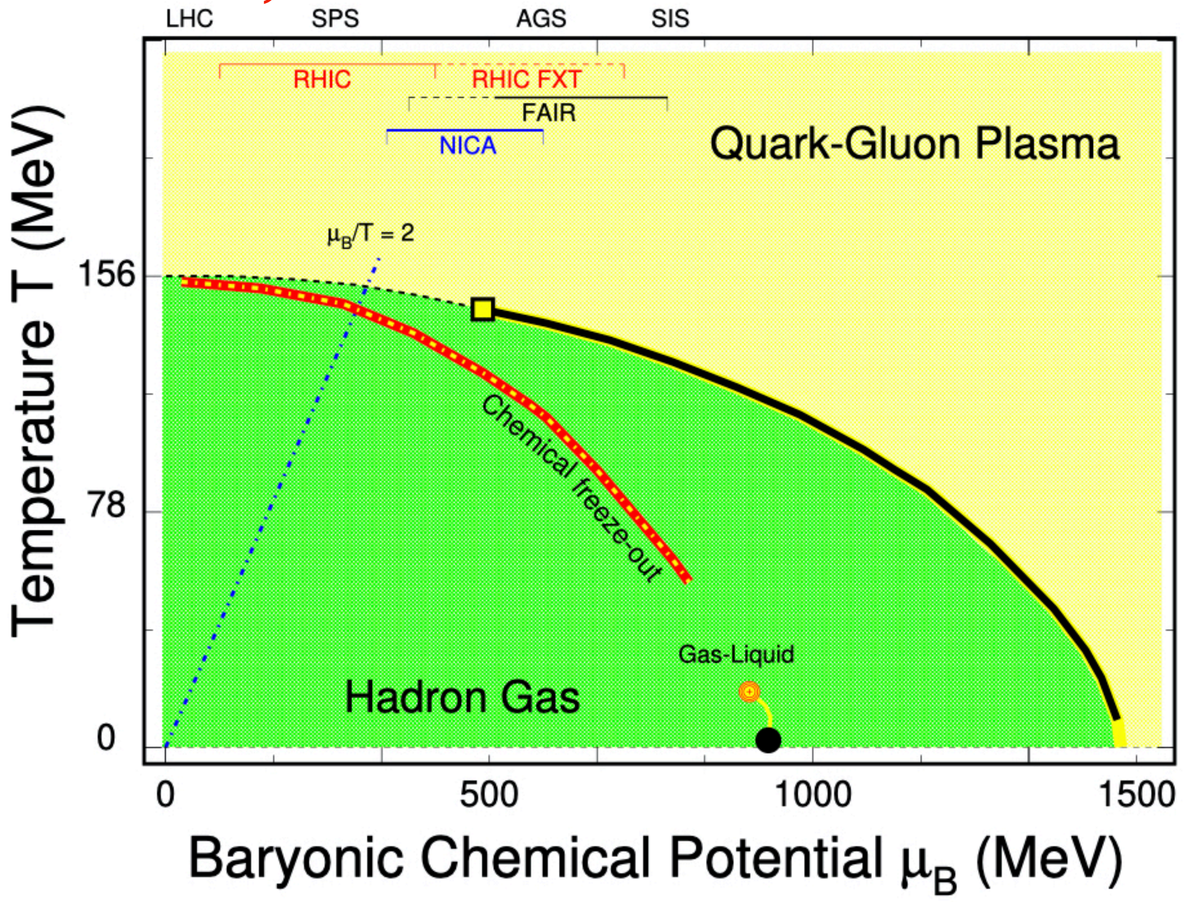
Y. Zhang (STAR): Poster (Tuesday)

Presence of B field: Look for increasing trend (peak structures) in centrality dependence of diagonal (off diagonal) cumulants *H.T. Ding et al, EPJA 57.202 (2021), arXiv:2208.07285*

Net-proton data in line with lattice expectation. Model studies needed. Off-diagonal cumulants also measured: trend reproduced by HRG CE.

I. Fokin (ALICE): Poster (Tuesday) ***S. Saha (ALICE): Poster (Tuesday)***

Status Thus Far,



Recent lattice studies at finite μ_B:

A. Pasztor (Lattice overview)

NCQ scaling:

R. Reed (STAR): overview
I.C. Arsene (ALICE): overview
A. Angerami (CMS):overview

- Hint of non-monotonic trend (3.1 σ level) around $\sqrt{s_{NN}}$ = 7.7 - 27 GeV **(BES-II data to confirm)**
- Crossover at $\sqrt{s_{NN}} \geq$ 39 GeV ($\mu_B \leq$ 110 MeV): Lattice QCD, interesting trends also seen in 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)
- **CP (if present and accessible in collisions) is expected between $\sqrt{s_{NN}} = 3 - 39$ GeV**

Future Prospects

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: $|\eta| < 4$

Wide acceptance- **Rapidity scan for CP search**

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

J. Brewer et. al., PRC 98, 061901 (2018)

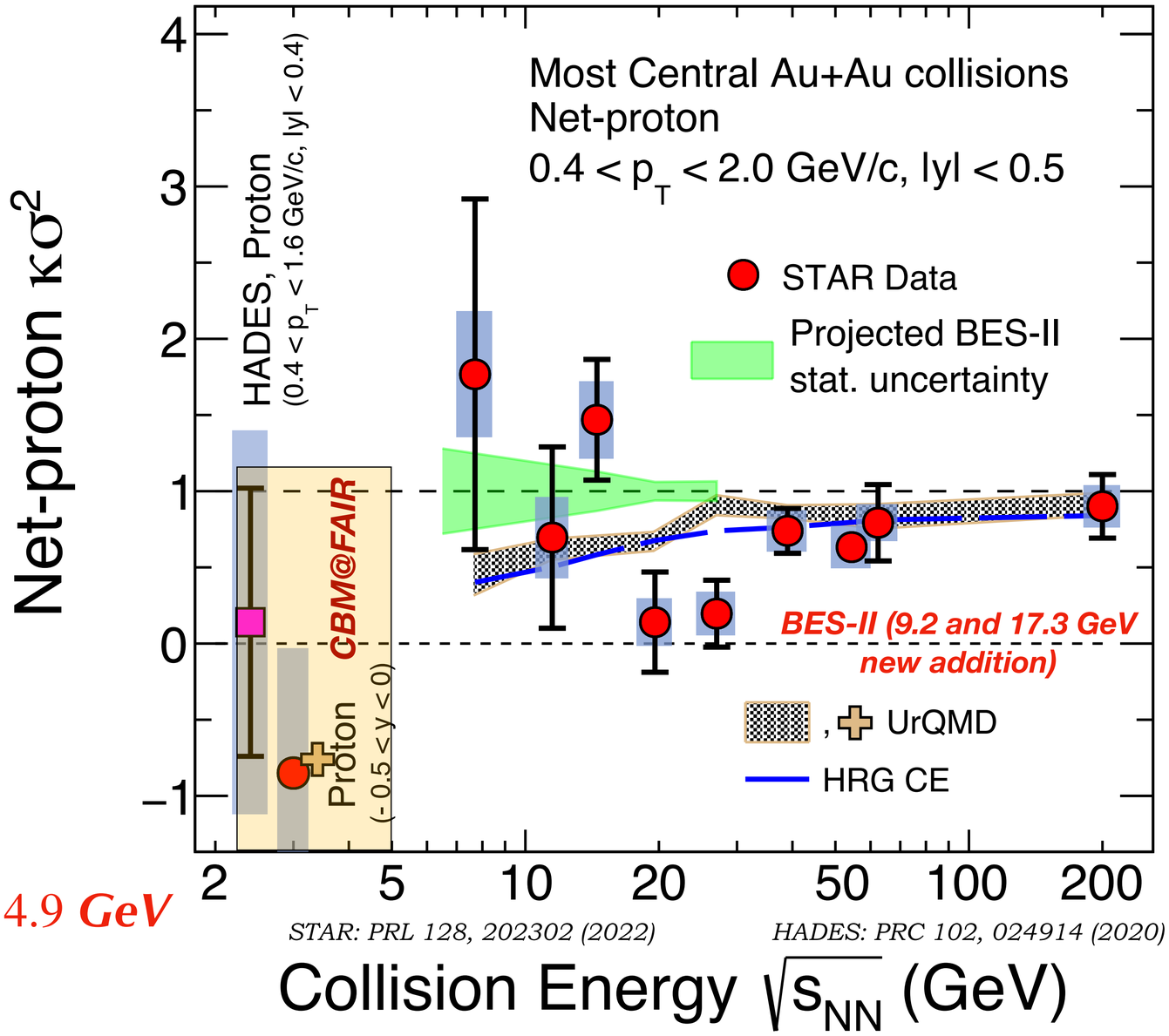
CBM to take Au+Au data (2028): $\sqrt{s_{NN}} = 2.4 - 4.9$ ***GeV***

C. Hohne (CBM): Talk (Wednesday)

NA60+: ***G. Alocco (NA60+): Talk (Wednesday)***

STAR-FXT: ***Z. Sweger (STAR): Poster (Tuesday)***

acceptance at mid rapidity challenging at high $\sqrt{s_{NN}}$



2. Study crossover at STAR and LHC with C_6 and C_8

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

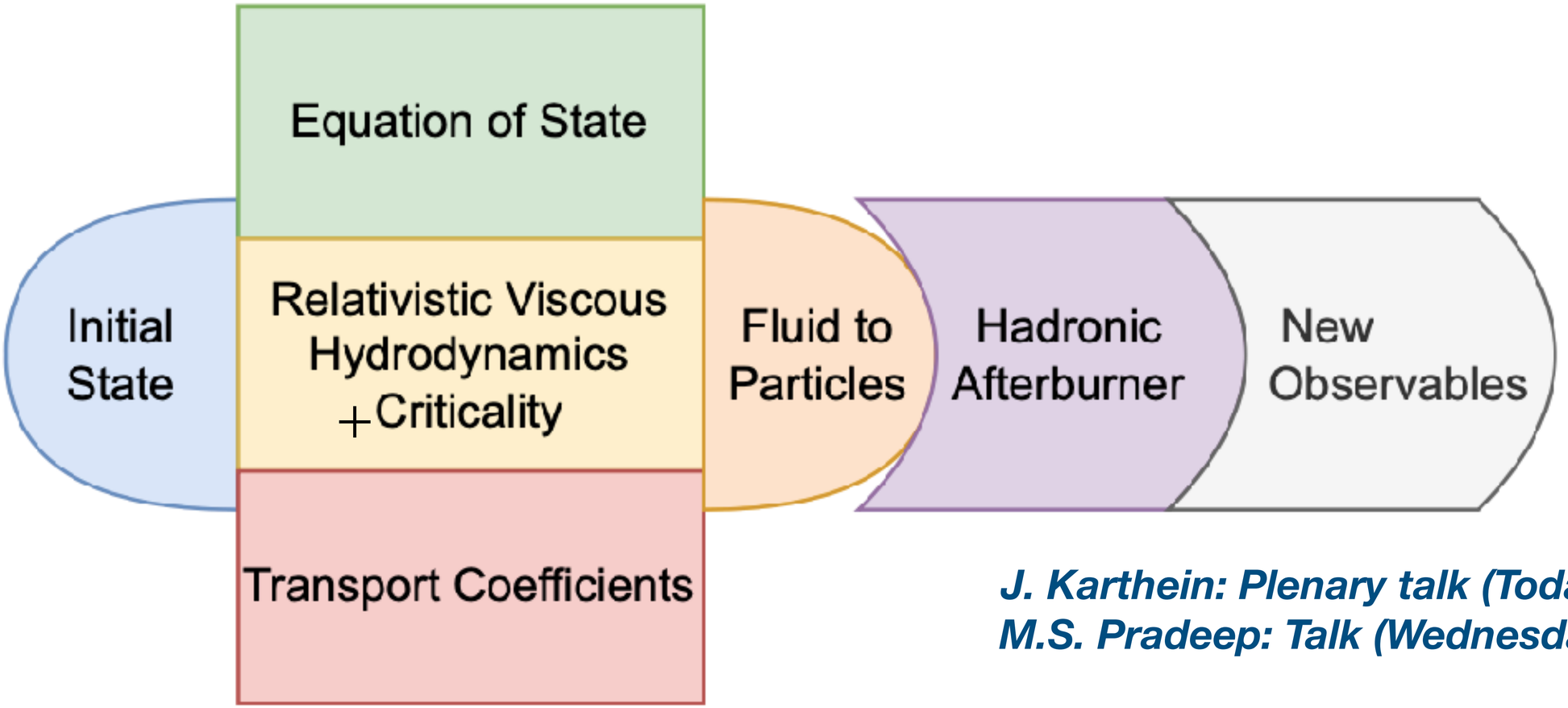
Au+Au at $\sqrt{s_{NN}}$ = 3 GeV: ~ 2 billion events collected

ALICE : Higher order measurements possible with high statistic LHC Run3

HotQCD: PRD101, 074502 (2020),
S. Borsanyi et al, JHEP10 (2018) 205, B. Friman et al, EPJC 71, 1694 (2011)

Challenges

Understanding Dynamics of System in Hi Collisions



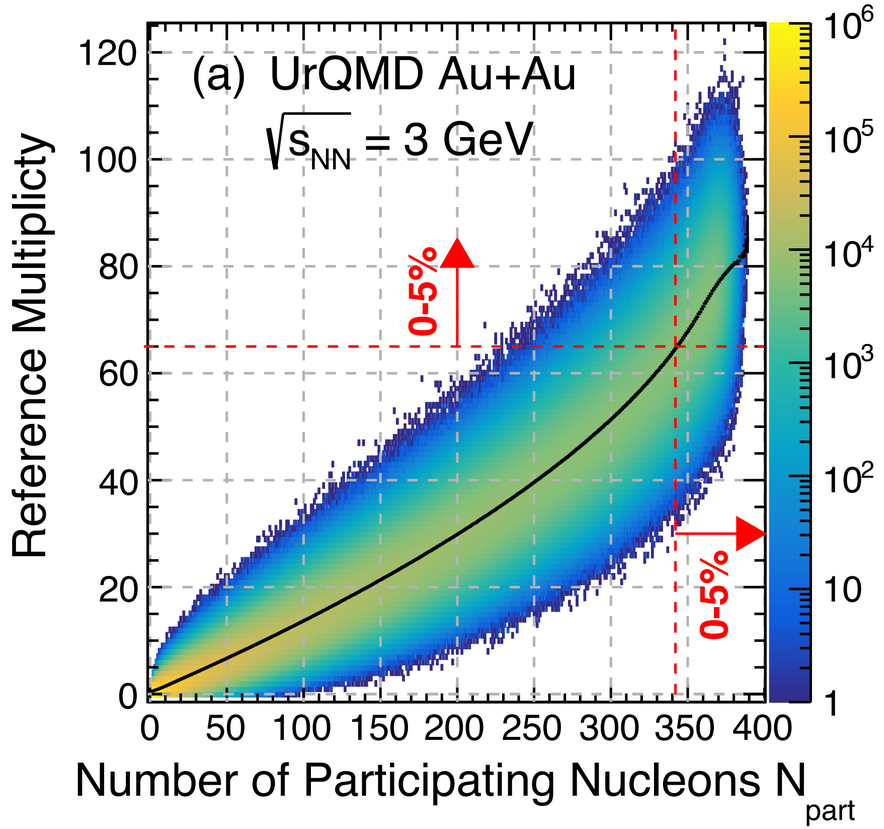
J.Norohna-Hostler: CPOD2022

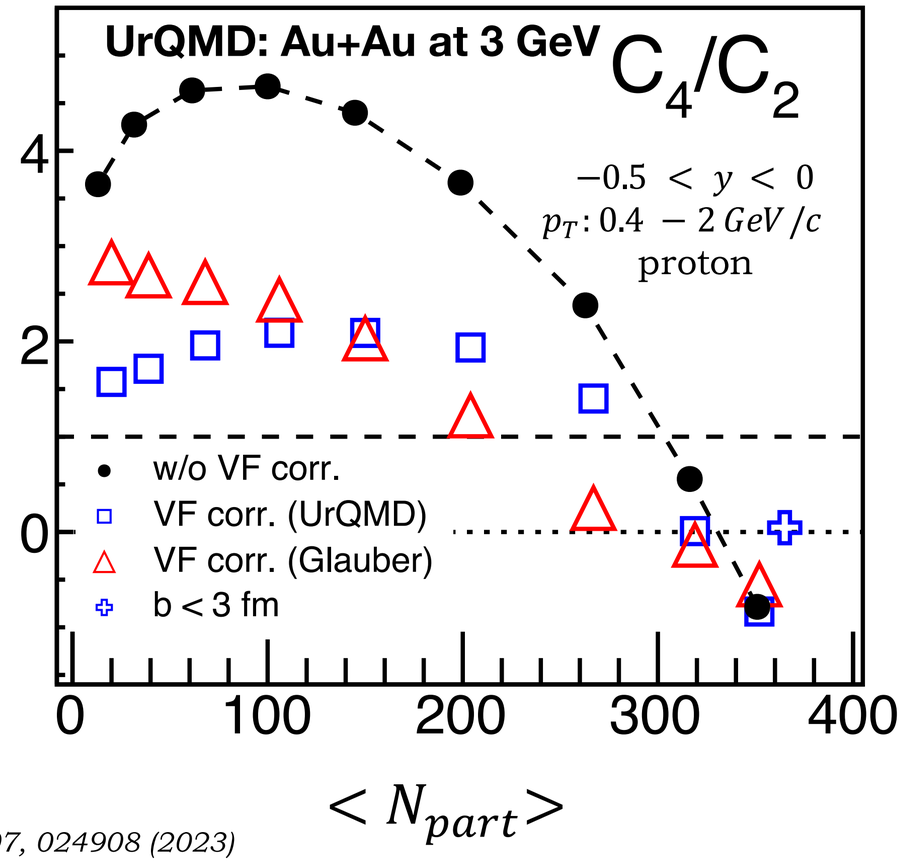
J. Karthein: Plenary talk (Today)
M.S. Pradeep: Talk (Wednesday)

(Work ongoing at BEST, MUSES Collaboration)

- ☐ Hydrodynamic calculations with critical point considering non-equilibirum effects ongoing
- ☐ System near CP not in equilibrium - could lead to suppression of critical signals

Initial Volume Fluctuation Effects:





STAR: PRC 107, 024908 (2023)

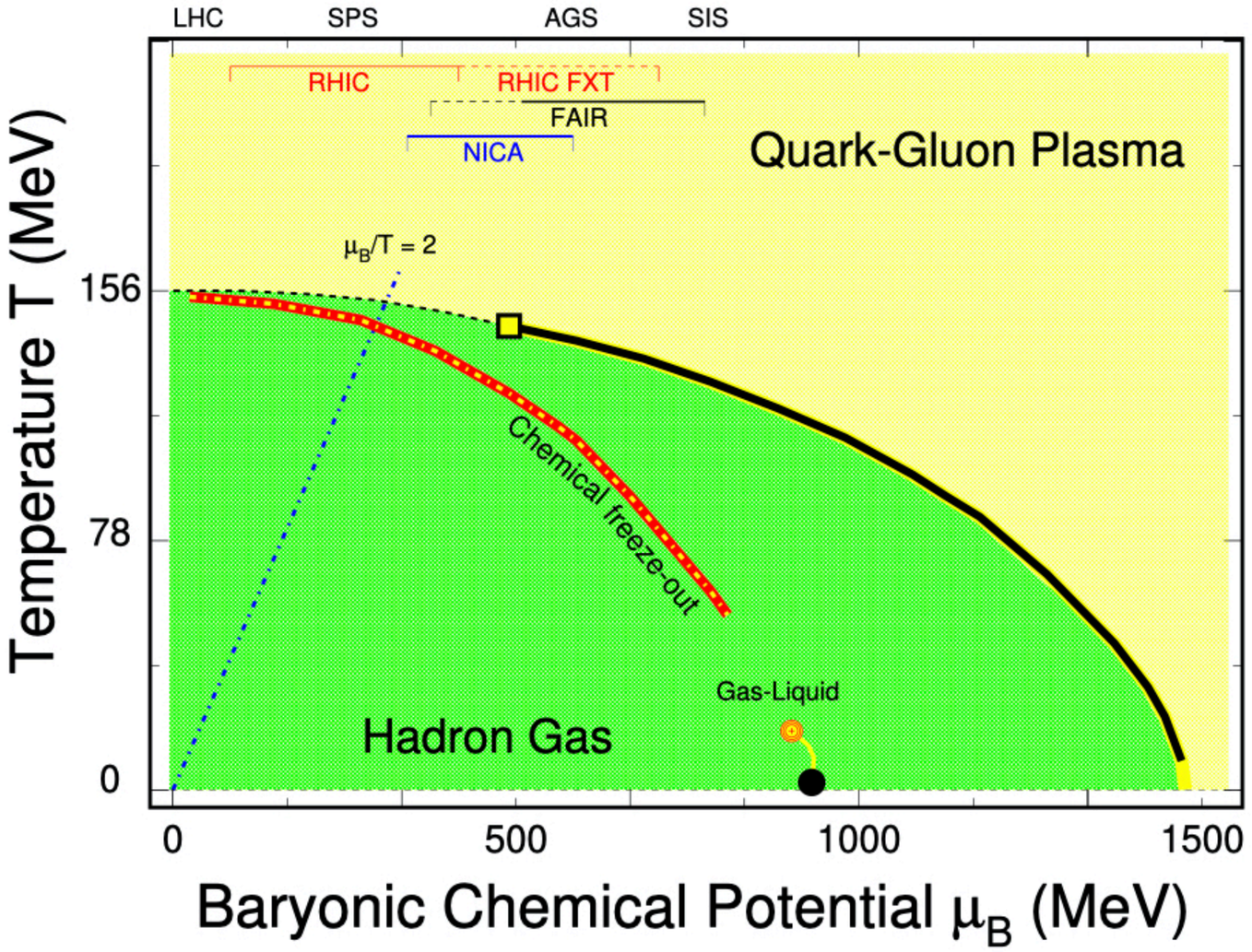
- Initial volume fluctuation effect significant at low $\sqrt{s_{NN}}$

  Low collision energy: low charged particle multiplicity - poor centrality resolution
- Look for alternate way to obtain $< N_{part} >$ in experiments.

A. Rustamov: Poster (Tuesday)

A new method for correcting VF

Conclusion:



- Currently available data and theories suggest CP could be within $\sqrt{s_{NN}}$ = 3 - 39 GeV (subjected to its existence and accessibility in nuclear collision)
- BES-II analysis and upcoming experimental programs at high baryon density underway
- 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, Grazyna Odyniec, Zachary Sweger*, Volodya Vovchenko, Yongcong Xu*, Nu Xu, Xin Zhang*, Yu Zhang*.* * PhDs/postdocs

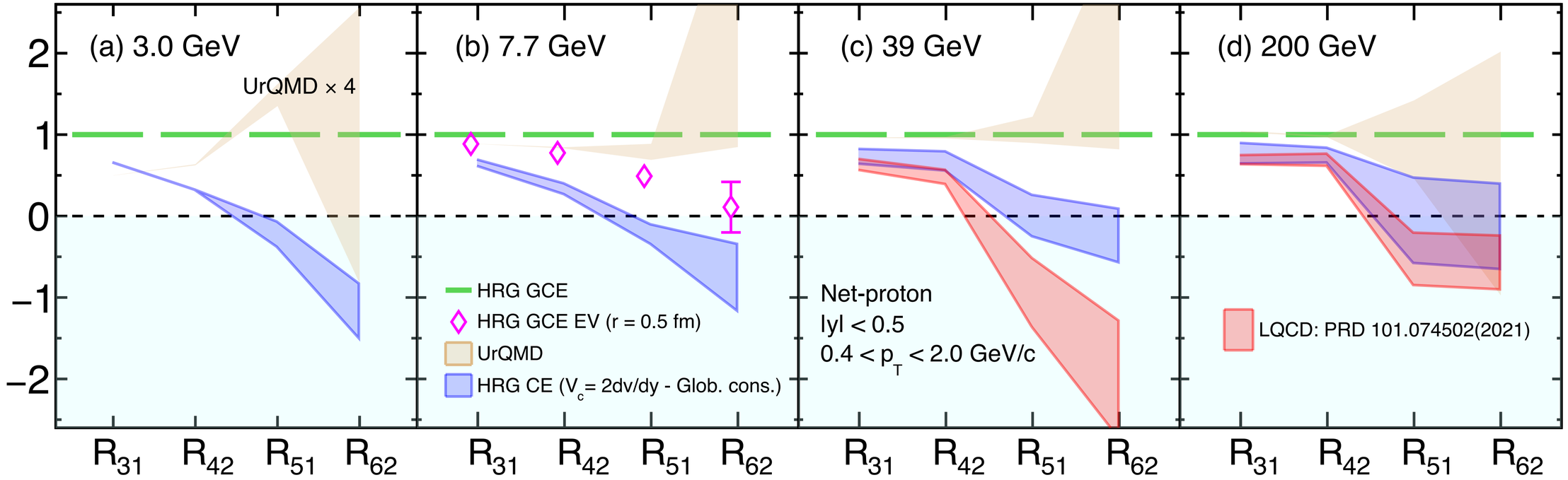
STAR Collaboration members, RNC group at LBNL

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

Back up

Results: Study Of Thermalization

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



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

Thermal FIST : V.Vovchenko, H. Stoecker, Comp. Phys. Comm. 244, 295-301 (2019)

HRG CE Global conservation: P. B Munzinger et al, NPA 1008, 122141 (2021)
UrQMD: STAR: PRL 130, 082301 (2023)

- Ideal HRG GCE (non-interacting): no ordering
- UrQMD - no thermal equilibrium: no ordering within uncertainties
- HRG GCE EV and HRG CE with baryon conservation: ordering observed at all energies
- **Equilibrium+Interaction necessary for ordering of cumulant ratios**