Experimental Overview Of Critical Fluctuations

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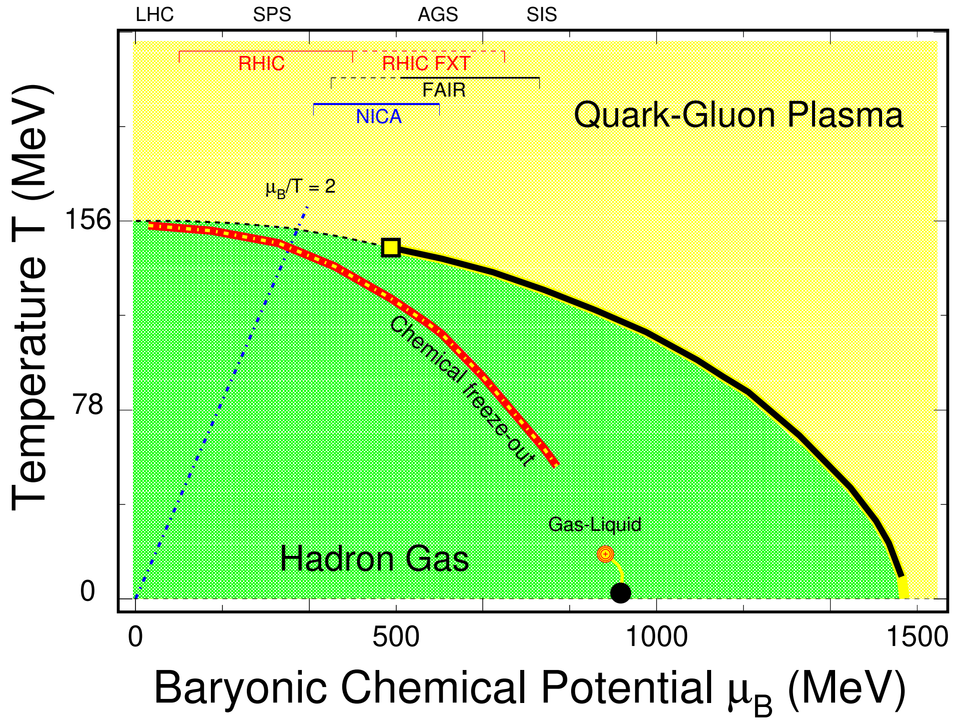
Outline
1. Introduction
2. Results
3. Future Prospects & Challenges
4. Summary

In part supported by

Probing the QCD Phase Diagram via Fluctuations

Introduction: QCD Phase Diagram



B. Mohanty, N. Xu, arXiv:2101.09210

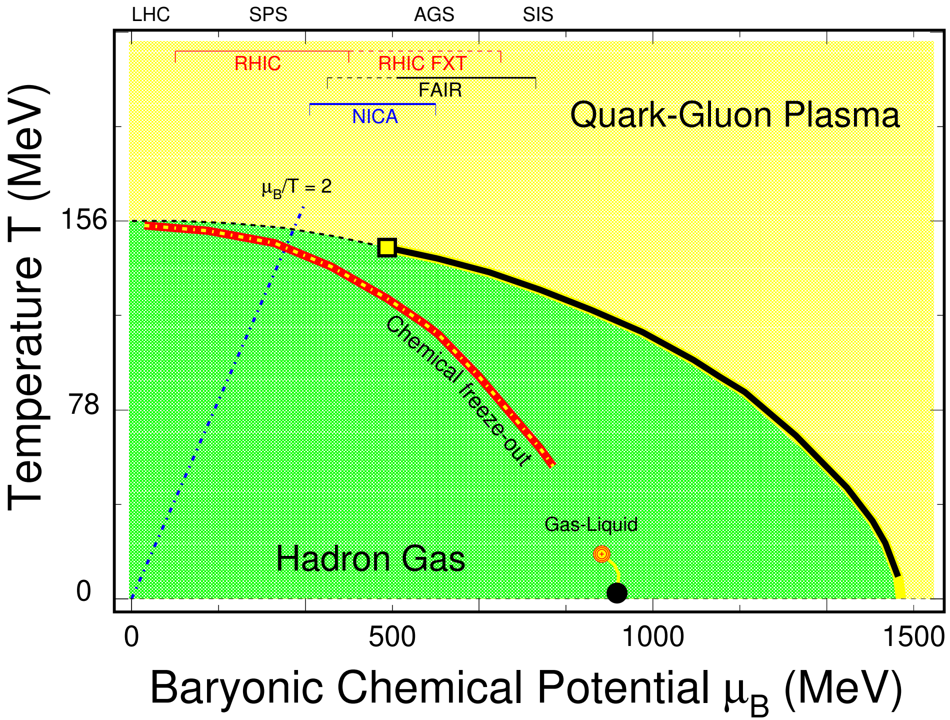
A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

Goal: Study of QCD Phase Diagram

Introduction: QCD Phase Diagram

Test of QCD Thermodynamics:
Ordering of net-baryon ratios: $\frac{C_3}{C_1} > \frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2}$

HotQCD: PRD101,074502 (2020)



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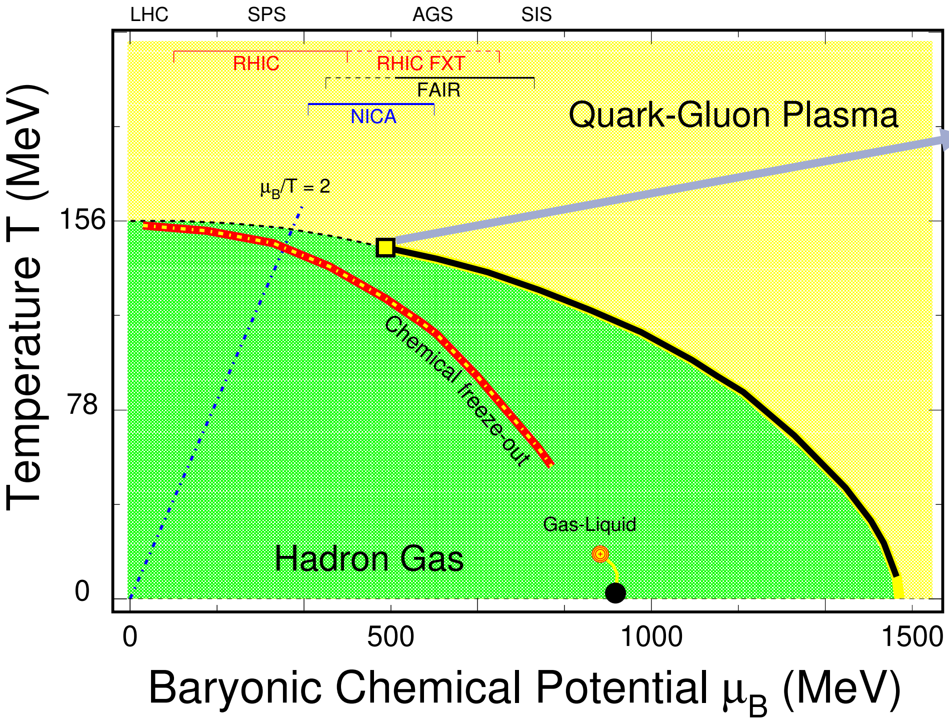

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Search for critical point (CP):
Non-monotonic trend for net-proton Kurtosis C_4/C_2 vs $\sqrt{s_{NN}}$

M. Stephanov, PRL 107 (2011) 052301

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Search for crossover:
Negative net-baryon $\frac{C_6}{C_2}$

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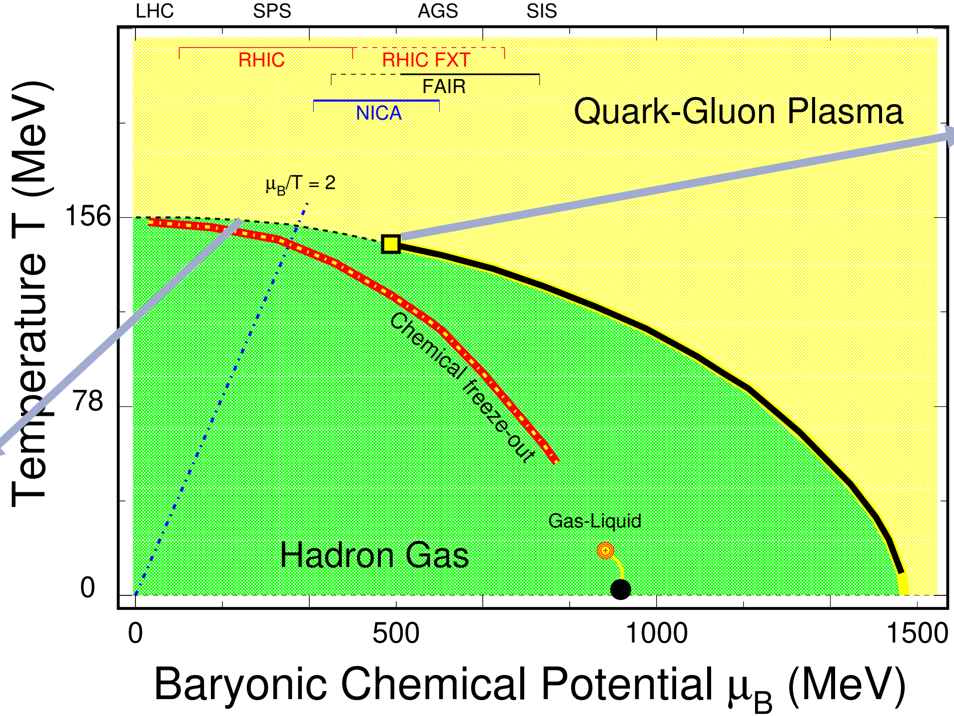

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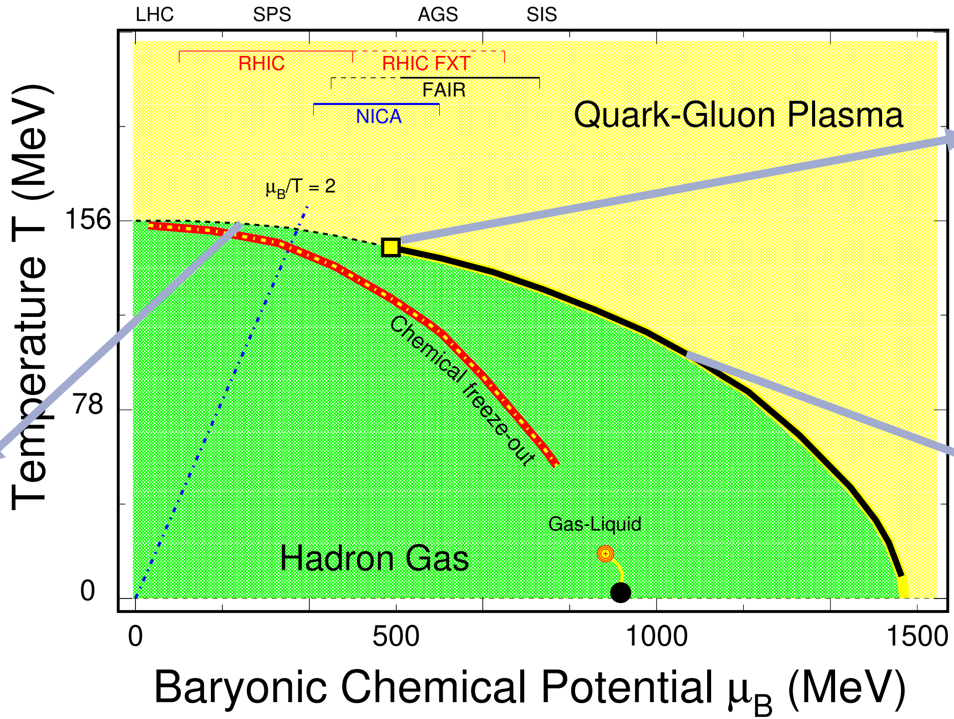

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M. Stephanov, PRL 107 (2011) 052301

Search for 1^{st} order:
Bimodal proton distribution:
Large proton factorial cumulants (κ_5 and κ_6) with alternating sign.

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

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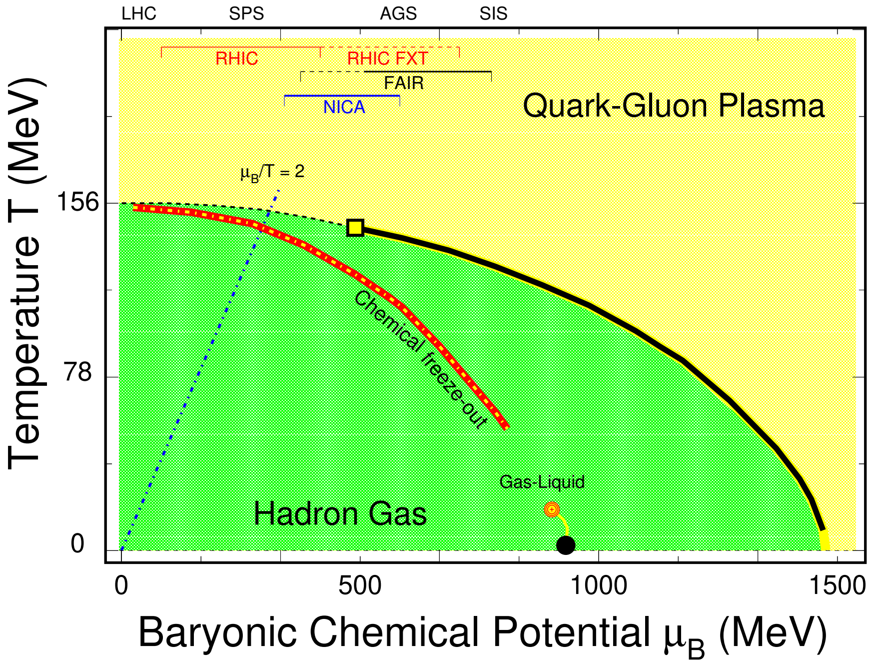
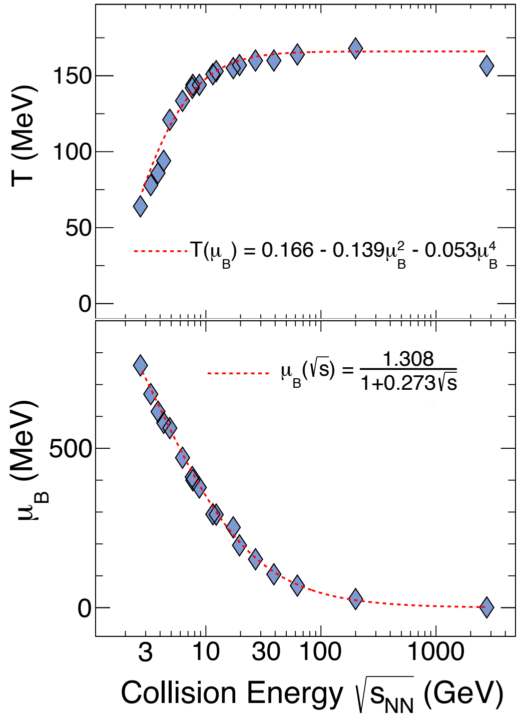


B. Mohanty, N. Xu, arXiv:2101.09210
A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

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



Varying beam energy varies Temperature (T) and Baryon Chemical Potential (μ_B).
Fluctuations of conserved quantities are sensitive to phase transition and critical point.

Observables

- Higher-order cumulants of net-particle distributions (proxy for **conserved charges**).

$C_1 = \langle N \rangle$

$C_2 = \langle (\delta N)^2 \rangle$

$C_3 = \langle (\delta N)^3 \rangle$

$C_4 = \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2$

$C_5 = \langle (\delta N)^5 \rangle - 10 \langle (\delta N)^3 \rangle \langle (\delta N)^2 \rangle$

$C_6 = \langle (\delta N)^6 \rangle - 15 \langle (\delta N)^4 \rangle \langle (\delta N)^2 \rangle - 10 \langle (\delta N)^3 \rangle^2 + 30 \langle (\delta N)^2 \rangle^3$

Here, $\delta N = N - \langle N \rangle$

- Higher order cumulants sensitive probe for the CP and nature of phase transition.

  Crossover (small μ_B)

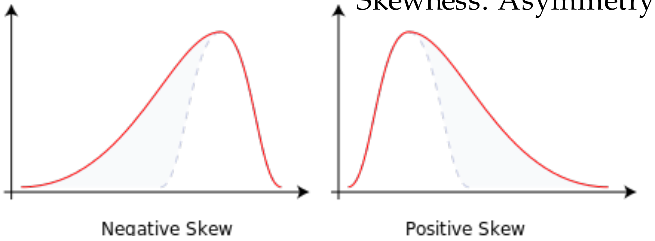
  First order (large μ_B)

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

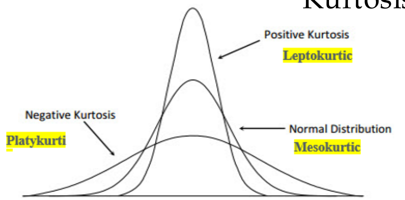
$C_2 \sim \xi^2$ $\quad C_4 \sim \xi^7$ *Quantitative numbers - Model dependent

$$\frac{\chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^{(3)}}{\chi_q^{(2)}} = S\sigma = \frac{C_{3,q}}{C_{2,q}}$$

Skewness: Asymmetry

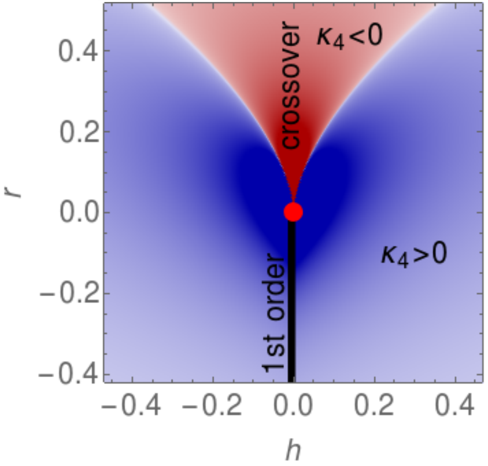


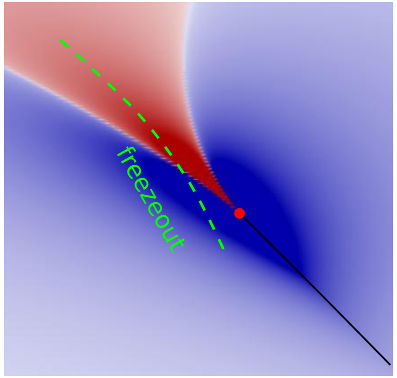
Kurtosis: Peakedness



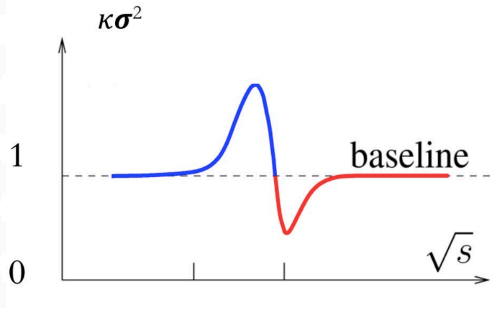
Search for QCD Critical Point

Ising Model Analogy





Kurtosis of net-proton in the presence of CP



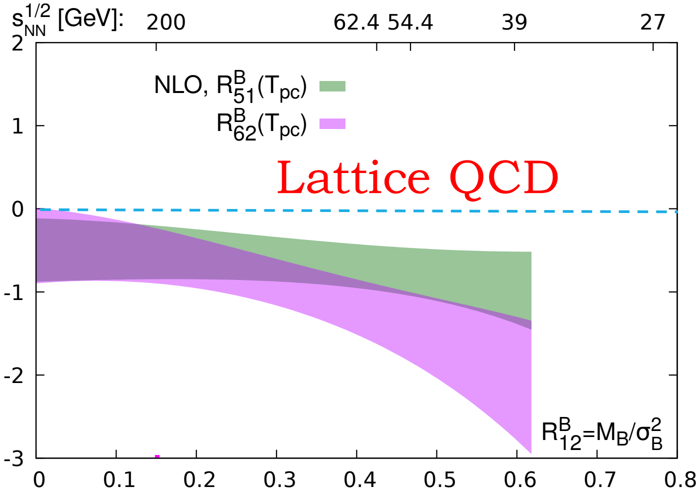
Non-monotonic collision energy dependence with deviation below and above baseline fluctuations.
→ Existence of critical region

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

A. Bzdak et al, Phys. Rept. 853, 1-87 (2020)

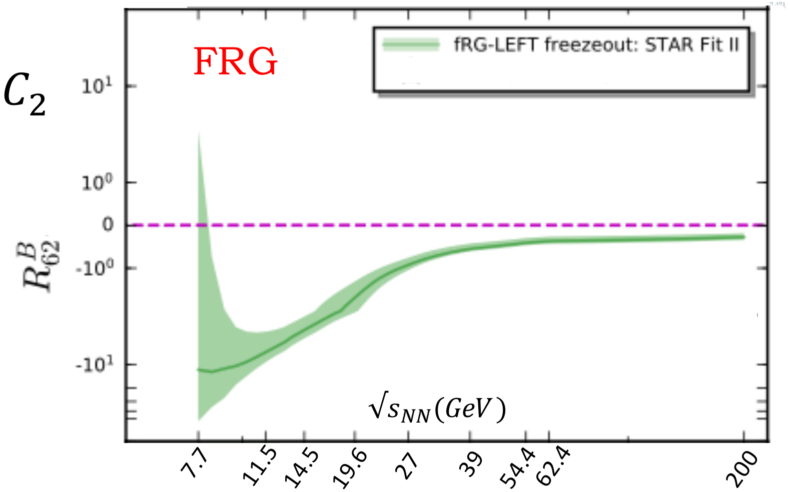
Search for Crossover

C_5, C_6: negative for LQCD, FRG (Functional Renormalization Group) – crossover
C_5, C_6: positive for HRG (GCE) and UrQMD (No QCD transition)



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

$$R_{62} = C_6/C_2$$



Wei-jie Fu et. al, PRD 104, 094047(2021)

Ordering of ratios : $\frac{C_3}{C_1} > \frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2}$ - LQCD, FRG

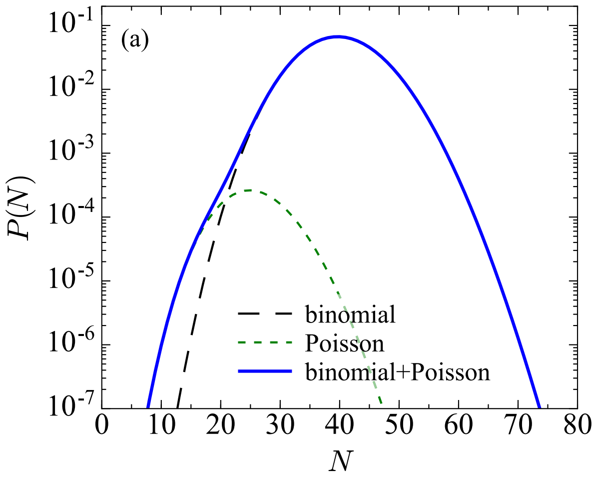
Search for 1st order Phase Transition

Multiplicity distribution bi-modal (contribution from two phases)

Proton factorial cumulants κ_n: with increasing order, increase rapidly in magnitude with alternating sign

$$\kappa_1 = C_1$$
$$\kappa_2 = -C_1 + C_2$$
$$\kappa_3 = 2C_1 - 3C_2 + C_3$$
$$\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4$$
$$\kappa_5 = 24C_1 - 50C_2 + 35C_3 - 10C_4 + C_5$$
$$\kappa_6 = -120C_1 + 274C_2 - 225C_3 + 85C_4 - 15C_5 + C_6$$

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



$P(N) = (1-\alpha)P_a(N) + \alpha P_b(N)$: Two Component/Bimodal Distribution

Analysis Procedure

1/ Event and track selections, centrality selection

2/ Construct net-particle multiplicity distributions

3/ Perform measurement of cumulants

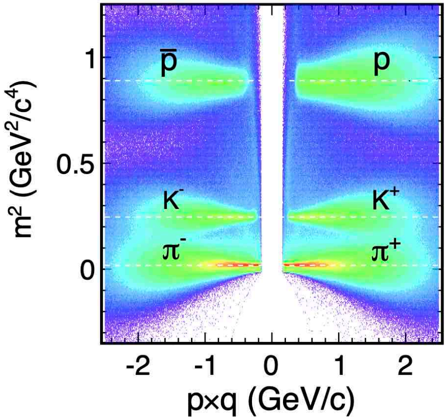
4/ Correct for volume fluctuation effect: perform centrality bin-width correction (CBWC) / VFC

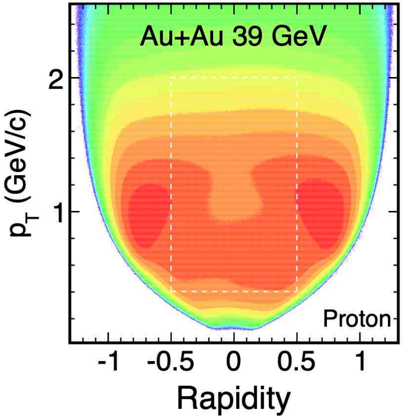
5/ Correct for detector efficiency

6/ Comparison with models to draw conclusion

Analysis Methods and Corrections

Particle Identification





- ❑ Ensure high purity

Correction for Efficiency and Volume Fluctuation

- ❑ Binomial Efficiency correction
- ❑ Check for non-binomial effects: unfolding

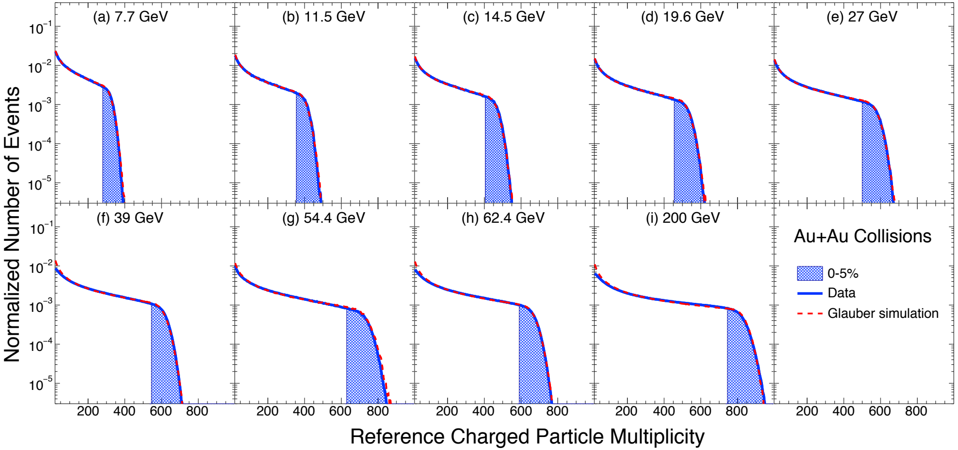
X. Luo , PRC 91, (2015) 034907, T. Nonaka et al, PRC 95, (2017) 064912,
X. Luo et al, PRC 99 (2019), 044917 , T. Nonaka et al, NIMA906 10-17(2018)

- ❑ Centrality Bin Width Correction – data driven
- ❑ Volume Fluctuation Correction – model dependent

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

Centrality Definition

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



- ❑ Maximize resolution and minimize self correlation effects.

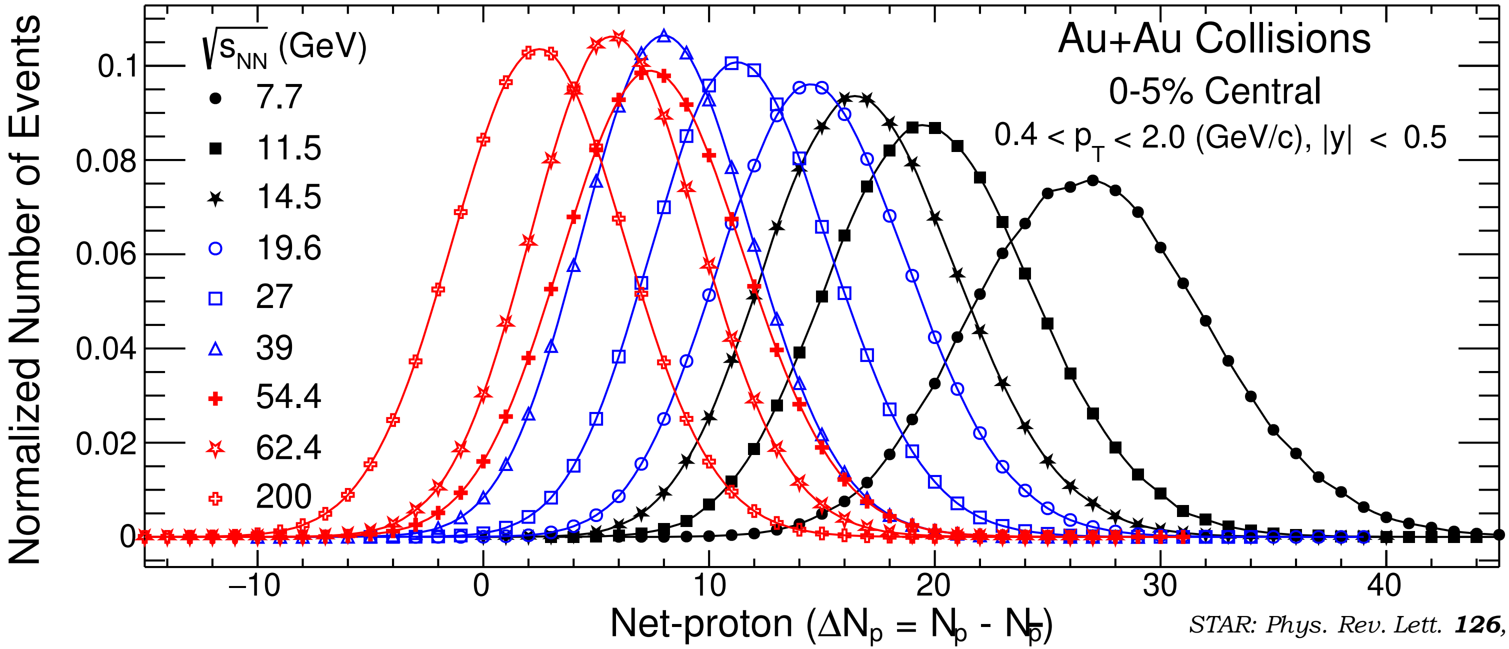
Statistical and Systematic Uncertainties

- ❑ Delta Theorem and Bootstrap method

X. Luo, J. Phys. G39, 025008 (2012), A. Pandav et al, NPA991, 121608 (2019)

- ❑ Vary PID, track selection cuts, background contamination

Event-by-event Raw Net-proton Distributions

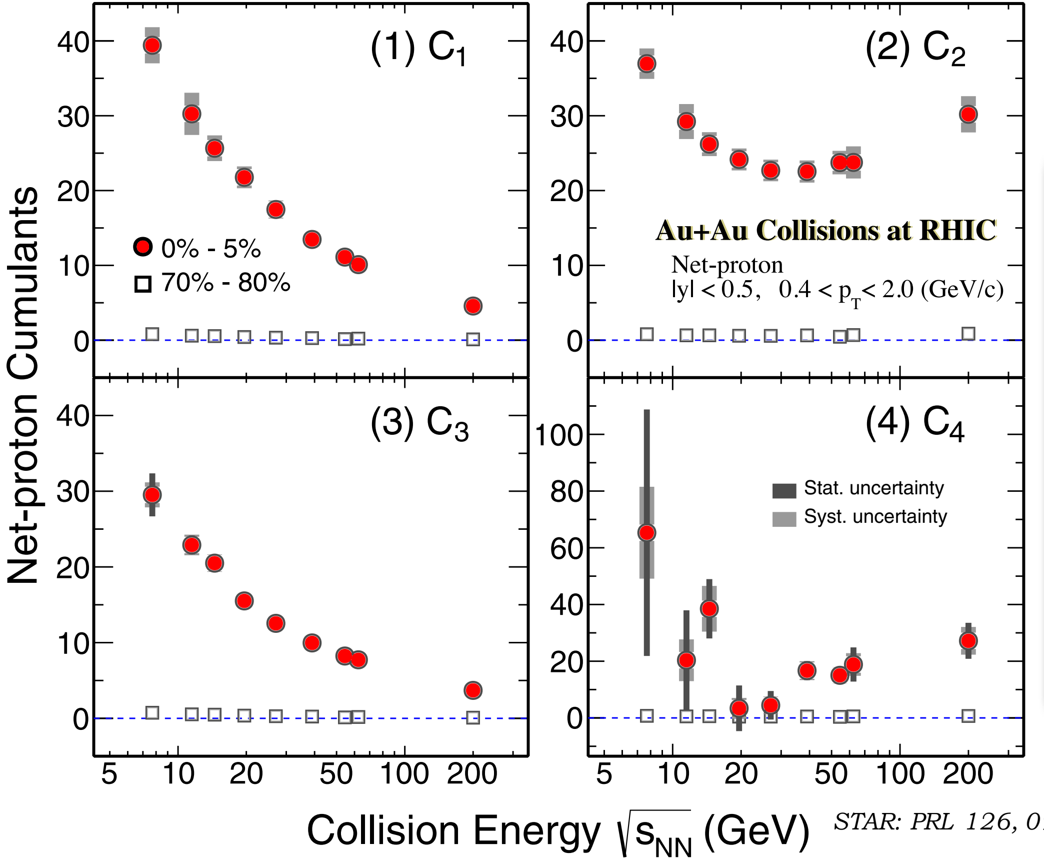


STAR: Phys. Rev. Lett. ***126****, 092301 (2021)*

1) Net-proton distributions, top 5% central collisions, efficiency uncorrected.

2) Values of the mean increase as energy decreases, effect of baryon stopping.

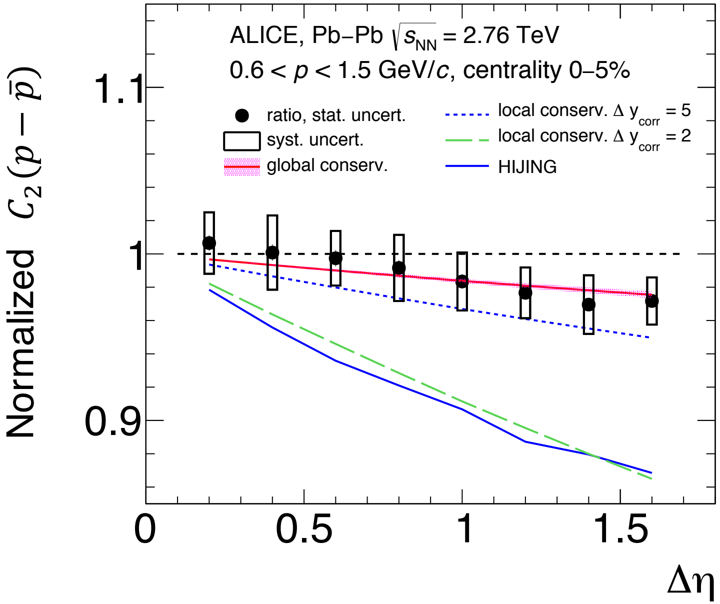
Net-proton Cumulant Measurements

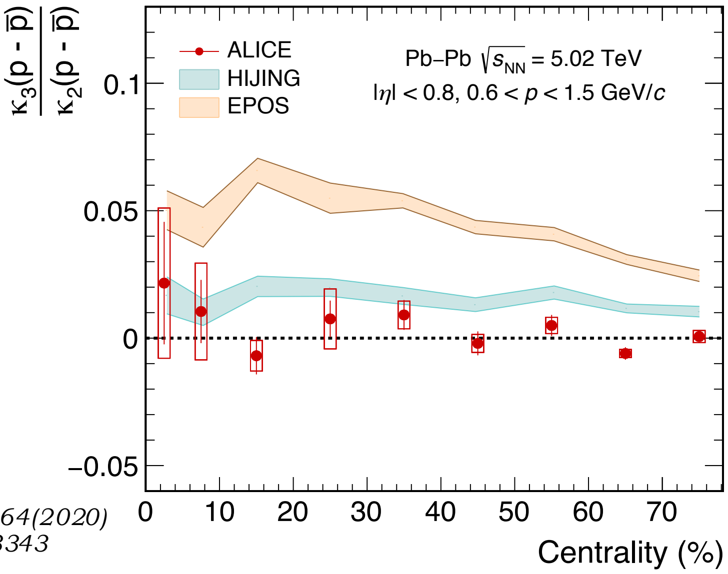


STAR: PRL 126, 092301 (2021)

- Cumulants C_1 and C_3 decrease with collision energy for 0-5% centrality.
- C_2 and C_4 (0-5%) show non-monotonic collision energy dependence.
- Peripheral measurements close to zero.

Cumulant Measurements at vanishing μ_B

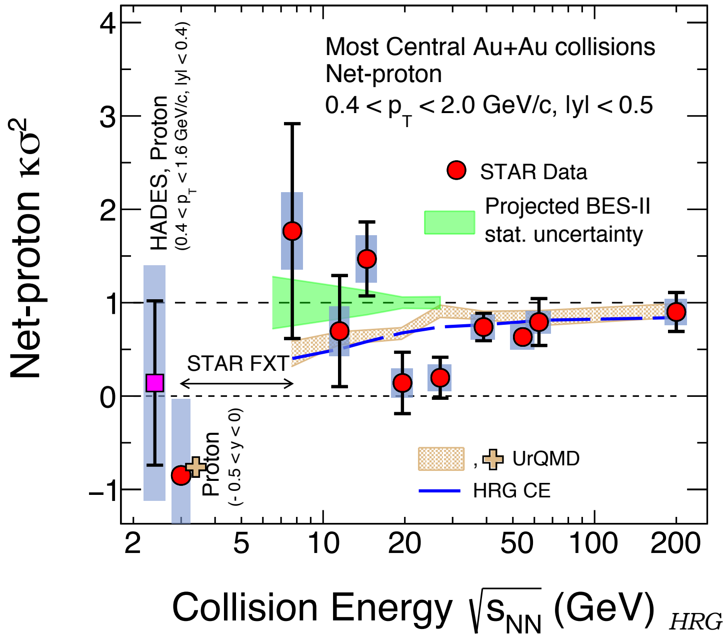




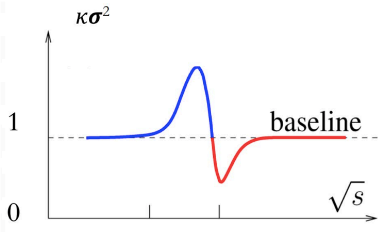
ALICE: PLB807, 135564(2020)
ALICE: arXiv:2206.03343

- Presence of long-range rapidity correlations ($\Delta y_{corr} > 0.5$) between protons and antiprotons. HIJING and EPOS reproduces qualitative trend but show quantitative differences.
- Vanishing third order cumulant observed – consistent with LQCD and HRG calculations.

Net-Proton C_4/C_2 – Critical Point Search

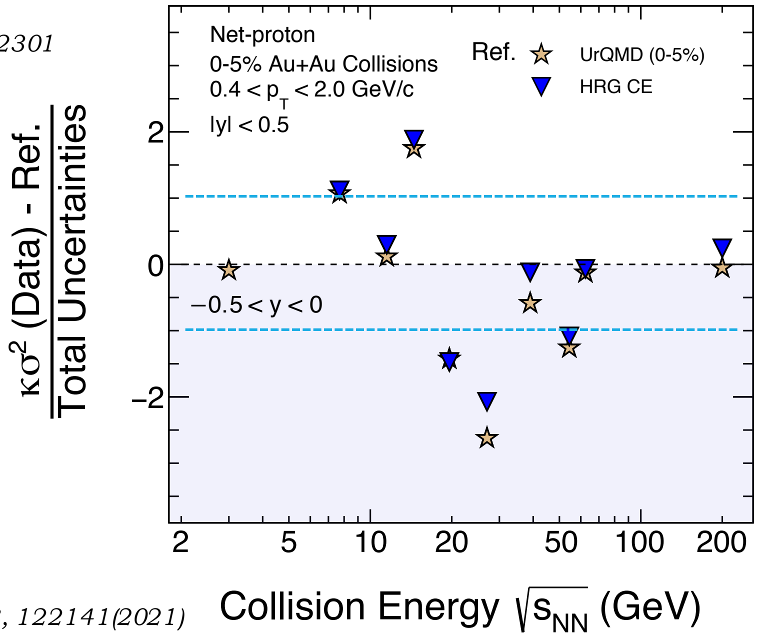


M. A. Stephanov, Phys.Rev.Lett. 107 (2011) 052301



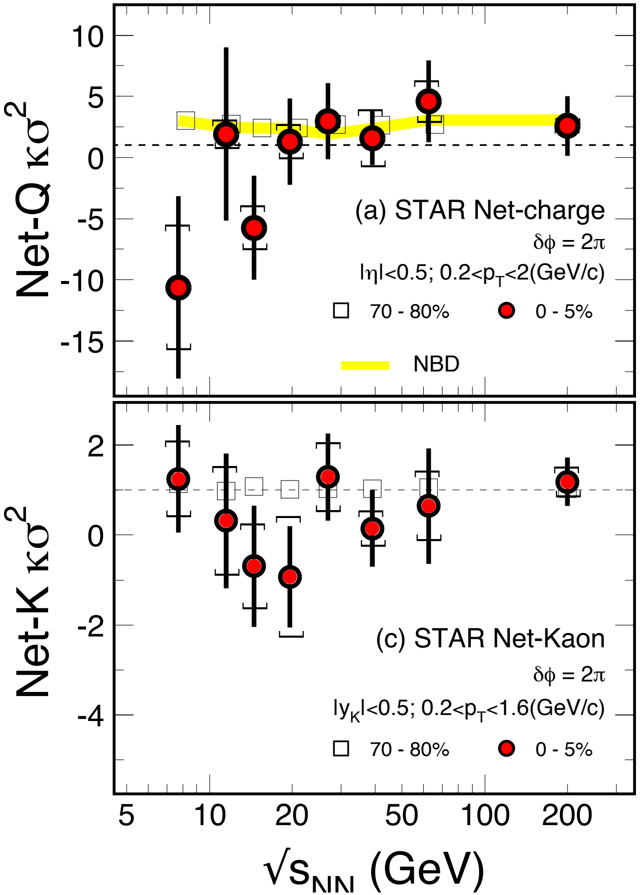
HADES: PRC 102,024914(20)
STAR: PRL 126, 092301 (2021)
HRG CE: P. B Munzinger et al, NPA1008, 122141(2021)

Deviation from baseline



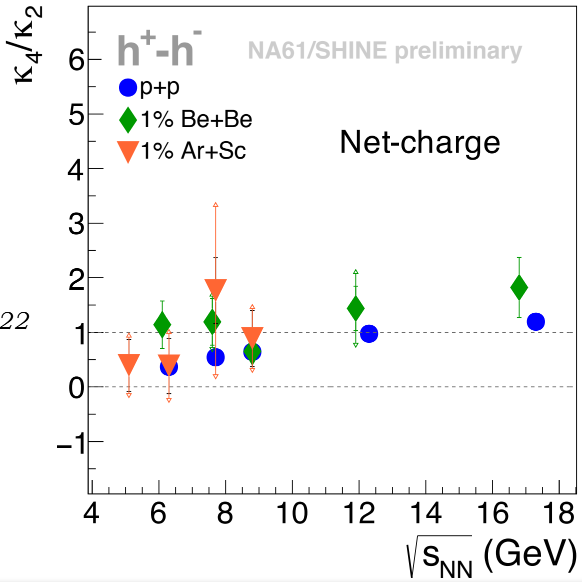
- Non-monotonic collision energy dependence observed for net-proton C_4/C_2 – consistent with CP expectation. Non-CP models fail to reproduce the observed trend.
- Suppression observed at $\sqrt{s_{NN}}$ = 3GeV (μ_B = 750 MeV), consistent with UrQMD – QCD matter created is dominantly hadronic.

Net-Particle C_4/C_2 – Critical Point Search



STAR: PRL. 113 (2014) 092301
STAR: PLB 785 (2018) 551-560

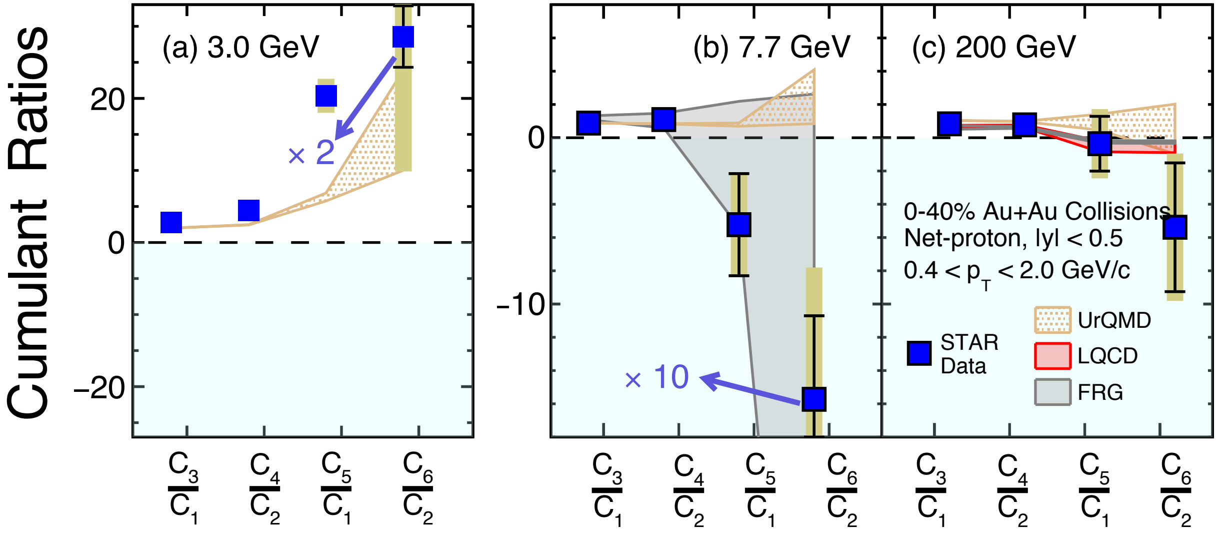
A. Marcinek, NA61/SHINE Collaboration, QM22



- ❑ Within large uncertainties monotonic energy dependence trend observed for net-charge and net-kaon fluctuations.
- ❑ The statistical uncertainty: $\sim \frac{\sigma^m}{\sqrt{N}\,\varepsilon^k}$

Measurements and QCD Thermodynamics

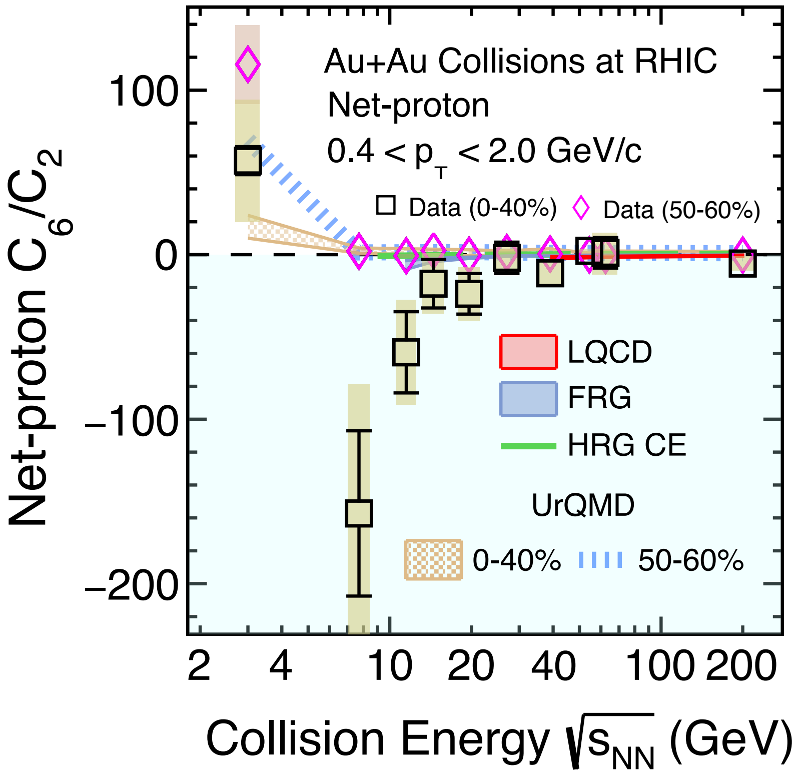
Ordering of ratios (Net-baryon): $\frac{C_3}{C_1} > \frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2}$ - LQCD, FRG

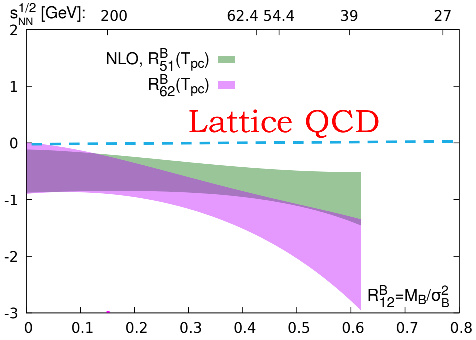


STAR: arXiv:2207.09837
STAR: PRL 127, 262301 (2021)
STAR: PRL 126, 092301 (2021)
STAR: PRC 104, 024902 (2021)

- ❑ Within uncertainties, 7.7 and 200 GeV data consistent with predicted hierarchy. UrQMD does not follow the ordering. Positive for all the ratios.
- ❑ **At 3 GeV, violation of ordering is seen.** Observed ordering reproduced by UrQMD.

Net-Proton C_6/C_2 – Crossover Search





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

- Increasingly negative C_6/C_2 (7.7 – 200 GeV) with decreasing energy at a level of $\lesssim 1.7\sigma$ observed for 0-40% centrality – lattice QCD calculations are consistent with observed trend in data.
- At 3 GeV, 0-40% measurement positive.
- C_6/C_2(50-60%), UrQMD ≥ 0 for all energies.

STAR: arXiv:2207.09837

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

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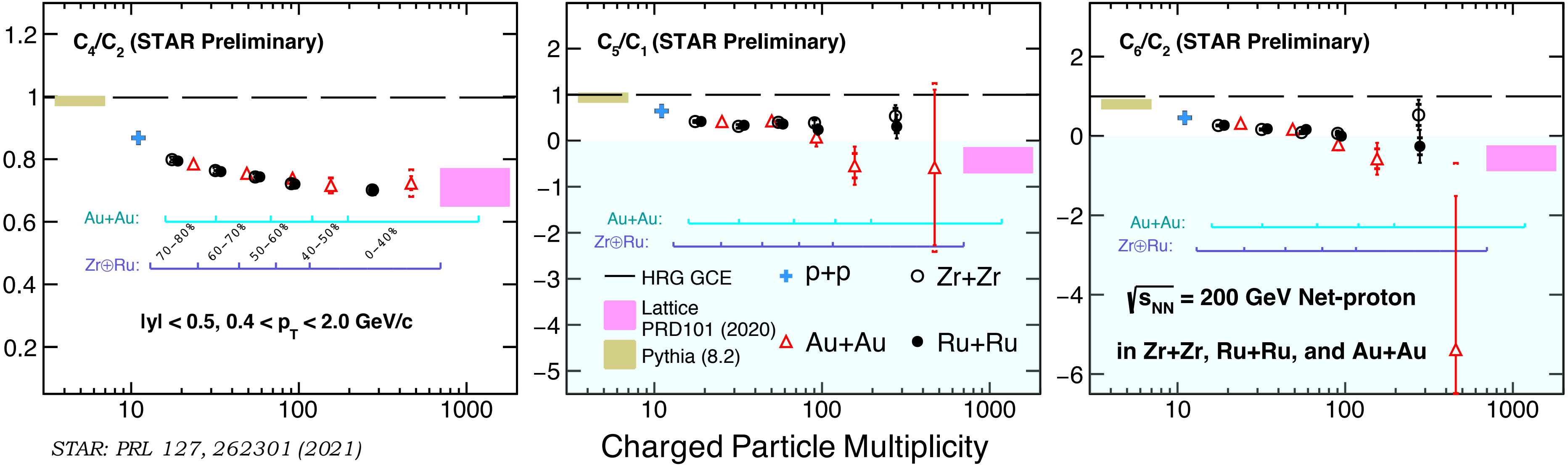
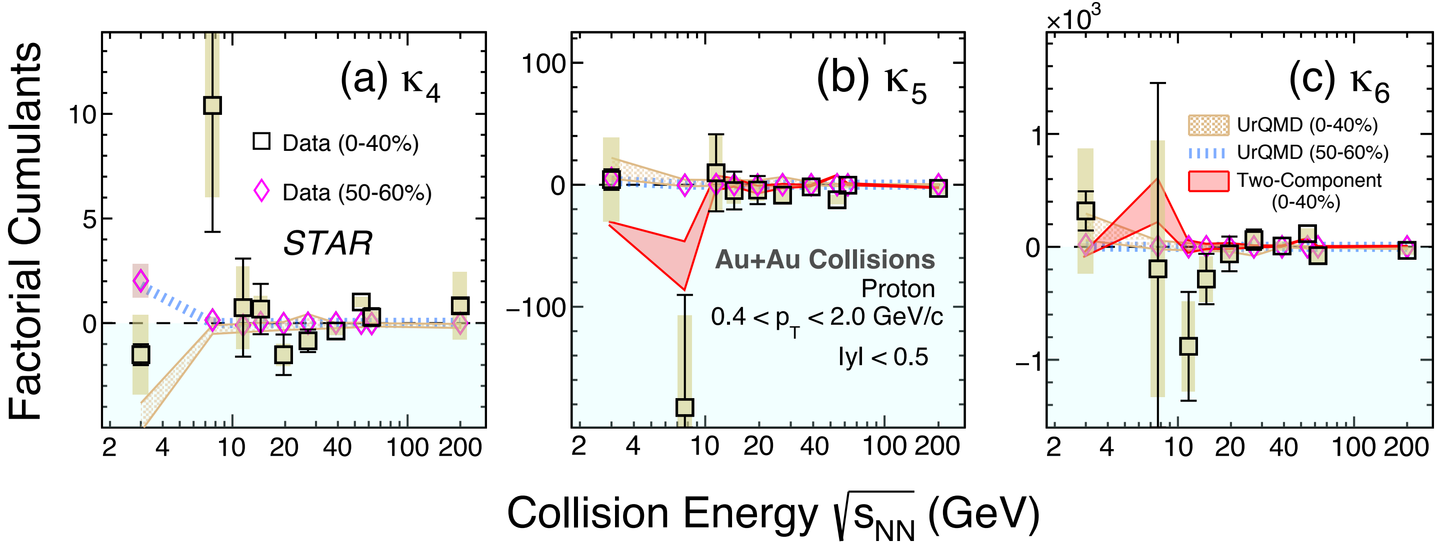


STAR: PRL 127, 262301 (2021)

H.-S. Ko, STAR Collaboration, QM22

- ❑ Decreasing trend of cumulant ratios observed with increase in system size. (p+p, Zr+Zr, Ru+Ru, and Au+Au collisions)
- ❑ Measurements at high charged multiplicity consistent with lattice QCD.
- ❑ Fifth and sixth order cumulant ratios grow progressively negative towards higher charged particle multiplicity – sign consistent with lattice QCD calculation with a crossover.

Proton κ_5 and κ_6 – 1st order Phase Transition Phase Transition



STAR: arXiv:2207.09837

STAR: PRC 104, 024902 (2021)

Multiplicity distribution two-component near a 1st order transition.

Large factorial cumulants with alternating sign.

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

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

- Peripheral data and UrQMD calculations consistent with zero at all energies.

Summary

Test of QCD Thermodynamics:
Lattice predicted ordering: $\frac{C_3}{C_1} > \frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2}$ observed in data

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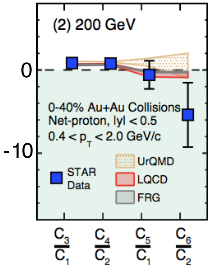
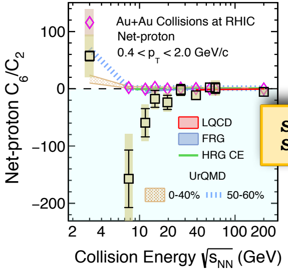


Search for crossover:
Negative sign of C6/C2 observed



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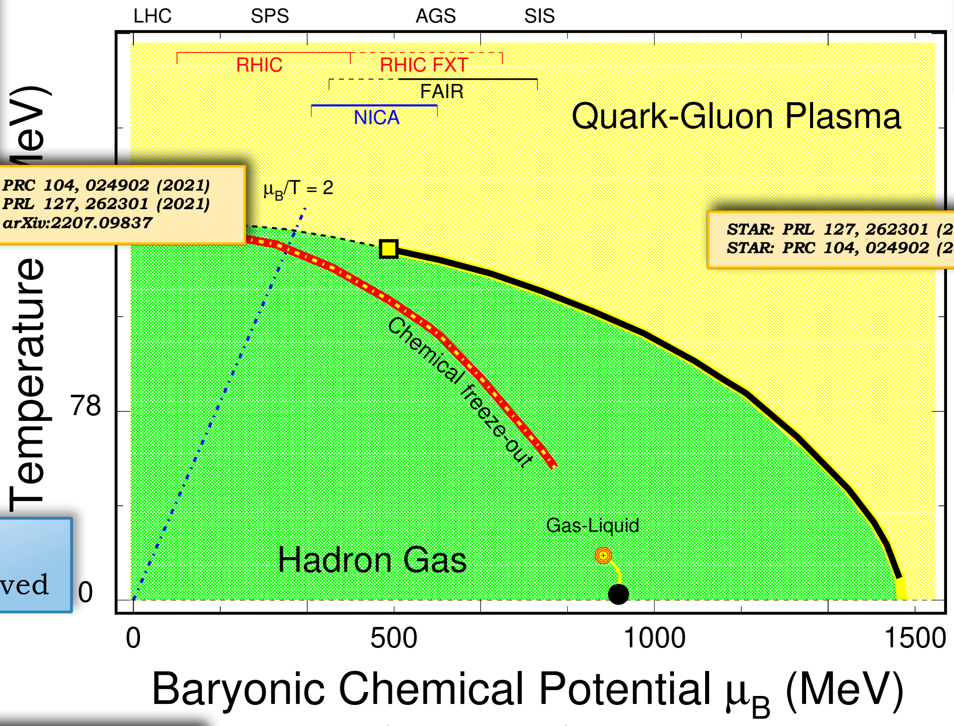

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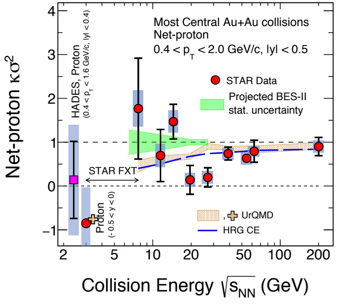
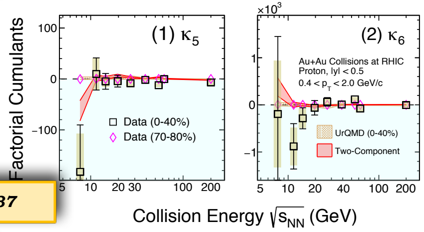


Search for 1^{st} order:
Absence of bimodal structure at $\sqrt{s_{NN}} \geq 11.5$ GeV



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Precision measurement at BES-II ongoing

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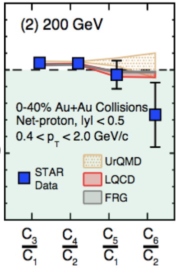
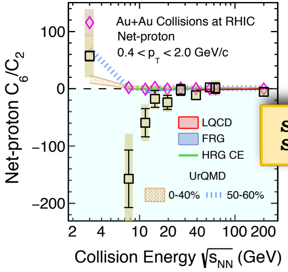
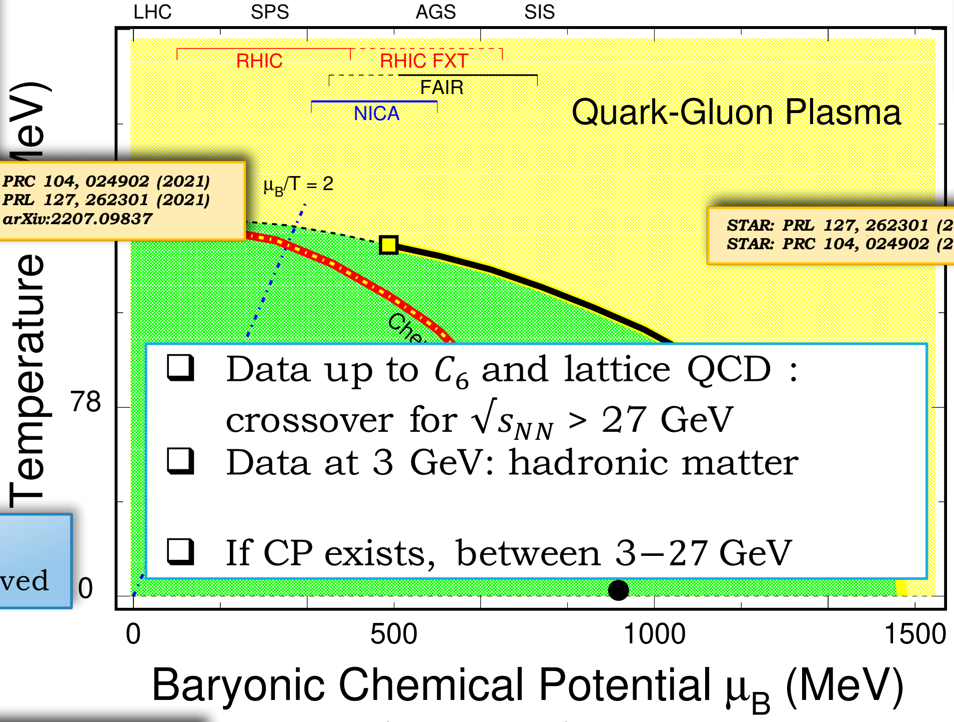
STAR: PRL 127, 262301 (2021)
STAR: arXiv:2207.09837



Search for crossover:
Negative sign of C6/C2 observed



STAR: PRL 127, 262301 (2021)
STAR: arXiv:2207.09837

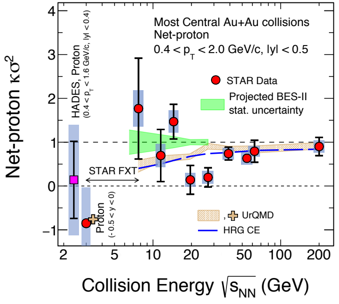


- Data up to C_6 and lattice QCD : crossover for $\sqrt{s_{NN}}$ > 27 GeV
- Data at 3 GeV: hadronic matter
- If CP exists, between 3–27 GeV

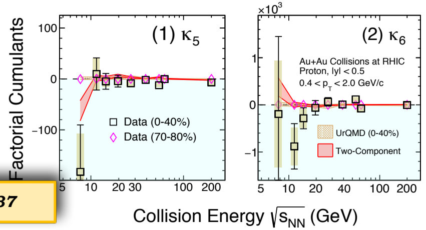
B. Mohanty, N. Xu, arXiv:2101.09210
A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

Search for critical point (CP):
Non-monotonic trend for net-proton Kurtosis C_4/C_2 observed.

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



Search for 1^{st} order:
Absence of bimodal structure at $\sqrt{s_{NN}} \geq 11.5$ GeV



STAR: arXiv:2207.09837

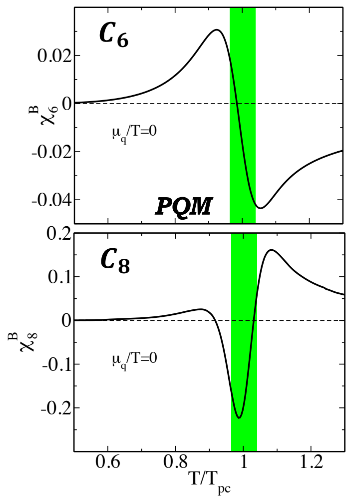
Precision measurement at BES-II ongoing

Future Prospects and Upcoming Experiments

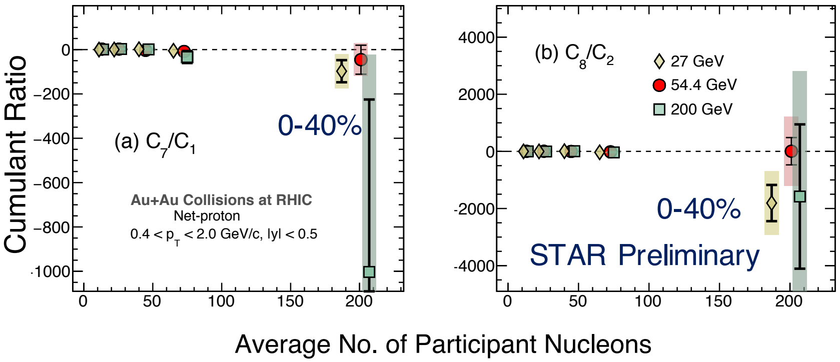
Crossover Search and Probing Magnetic field in HIC

Extending fluctuations to C_7 and C_8 - more sensitive probes for crossover

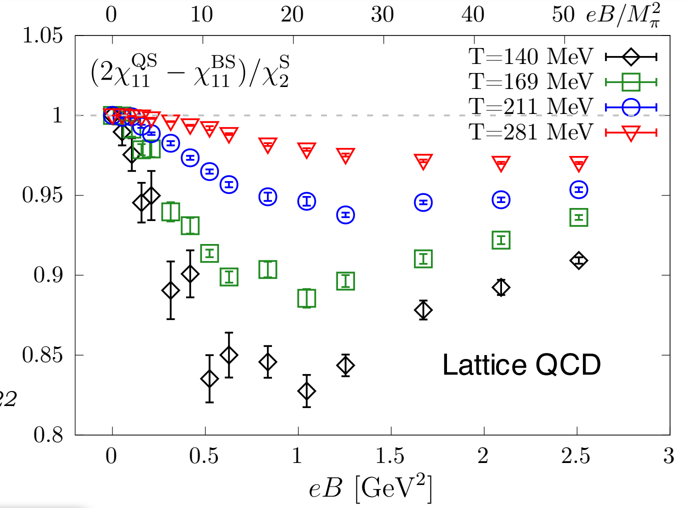
Measuring BS, BQ, QS correlations to probe magnetic field in HIC



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



A. Pandav, STAR Collaboration, SQM22



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

- 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

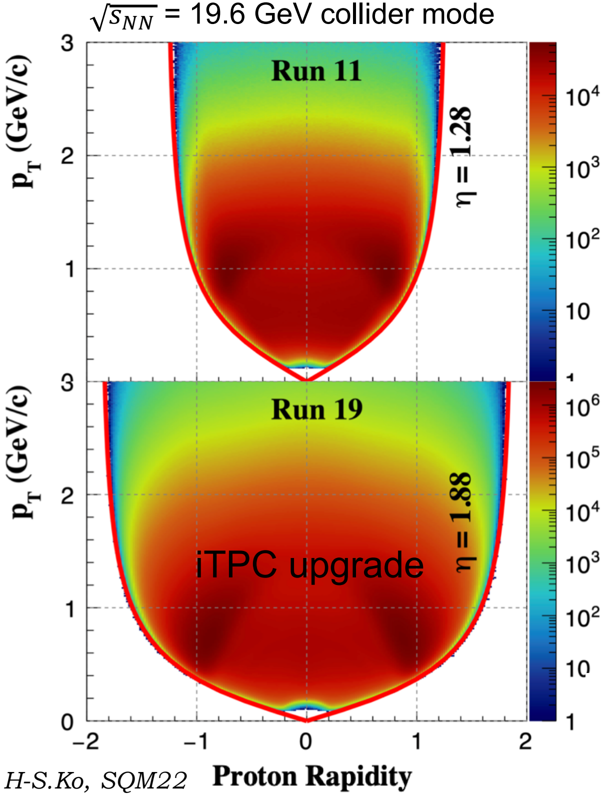
Isospin symmetry broken due to magnetic field.

STAR BUR Run22, STAR note 0773, ALICE: arXiv1812.06772

CP Search: BES-II at RHIC and CBM at FAIR

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

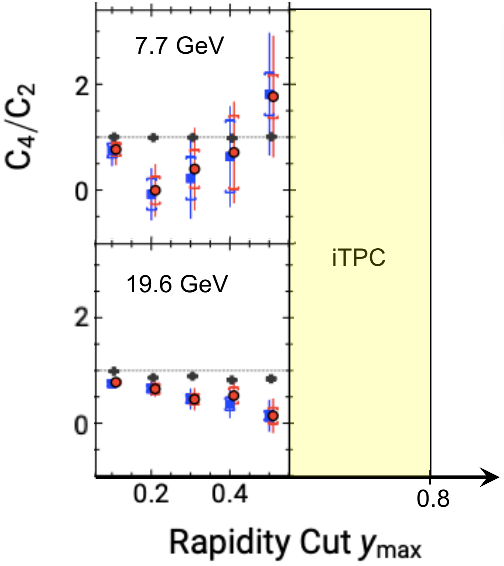
Enlarged Phase Space



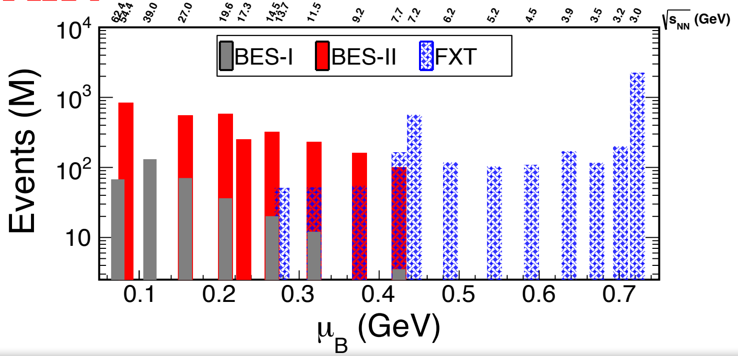
H-S.Ko, SQM22

BES-II: Precision measurement up to μ_B = 750 MeV

Full rapidity coverage at high μ_B region

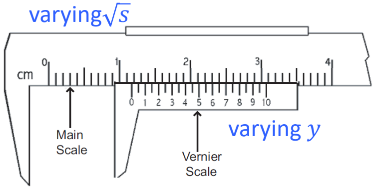


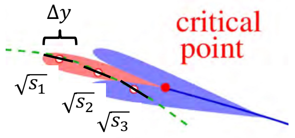
X.Dong, QCD Town Hall Meeting



CBM: 2.7 < $\sqrt{s_{NN}}$ < 4.9 GeV
High interaction rates – large statistics

Energy scan and rapidity scan



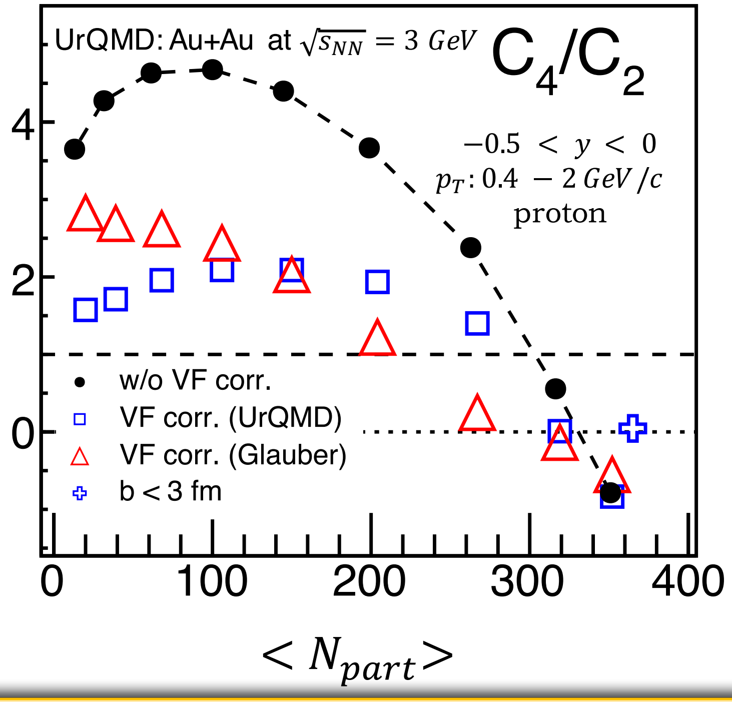


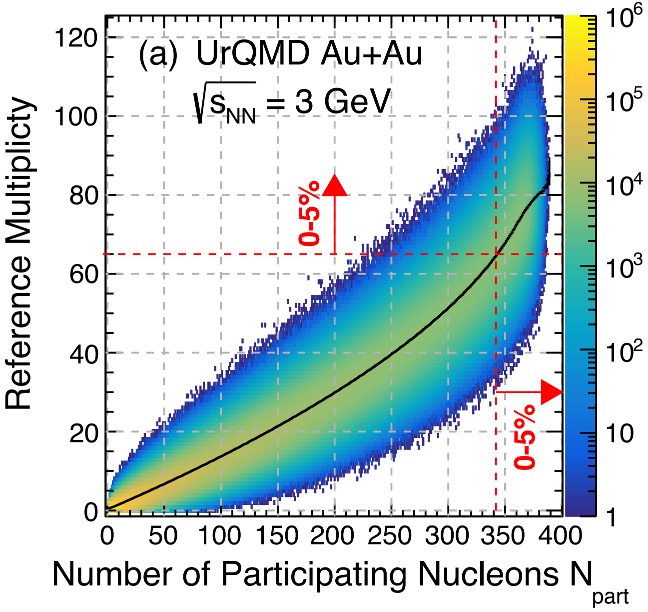
Rapidity is a finer-resolution probe of the critical regime than $\sqrt{s_{NN}}$

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

Initial Volume Fluctuation Effect at High Baryonic Density Region

STAR: arXiv:2209.11940

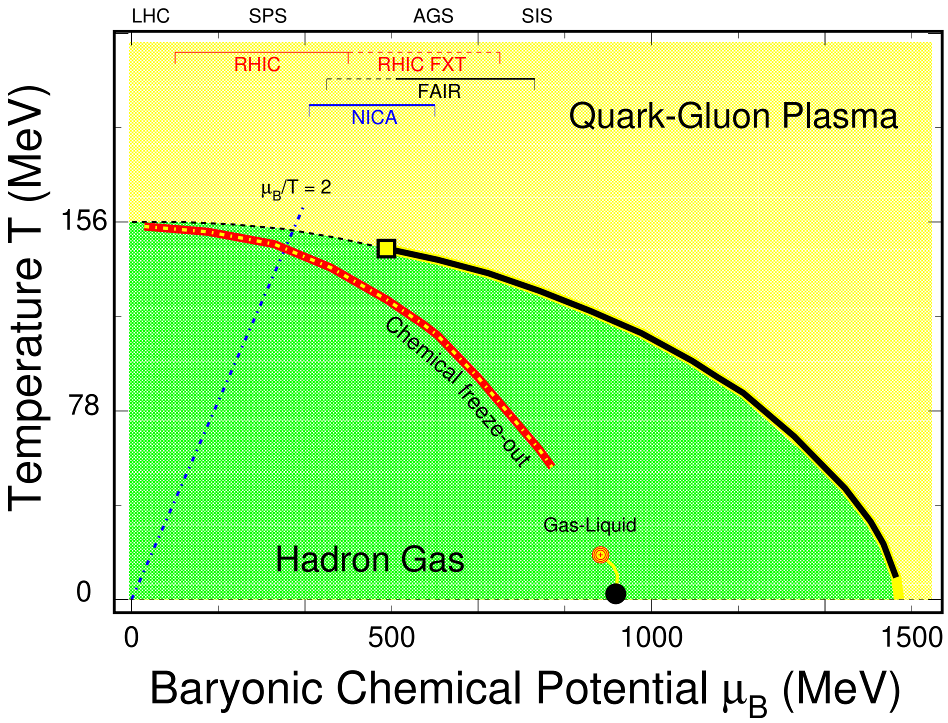




A new method: *A. Rustamov et al, arXiv:2211.14849*

- ❑ 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.

Current Status of CP and Conclusion



B. Mohanty, N. Xu, arXiv:2101.09210

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

Critical point unlikely to exist below $\frac{\mu_B}{T} < 2.5$ ($\sqrt{s_{NN}} > 27$ GeV) - lattice QCD

Measurements at $\sqrt{s_{NN}}$ = 3 GeV – strongly suggest QCD matter created is hadronic.

Critical region, if created in HIC is likely to be between $\sqrt{s_{NN}}$ = 3 – 27 GeV.

Measurements from BES-II, upcoming experiments: CBM at FAIR will be crucial.

Acknowledgements

*Alphabetically: Xin Dong, ShinIchi Esumi, **Yige Huang**, **Ho-San Ko**, Xiaofeng Luo, **Debasish Mallick**, Bedangadas Mohanty, **Dylan Neff**, Risa Nishitani, Toshihiro Nonaka, **Zachary Sweger**, Nu Xu, **Xin Zhang**, **Yu Zhang**, and other STAR colleagues.*

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

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THANK YOU FOR YOUR ATTENTION