Experimental Search for QCD Critical Point at RHIC

Bappaditya Mondal for the STAR Collaboration

National Institute of Science Education and Research, Bhubaneswar, India

9th Dec, 2023

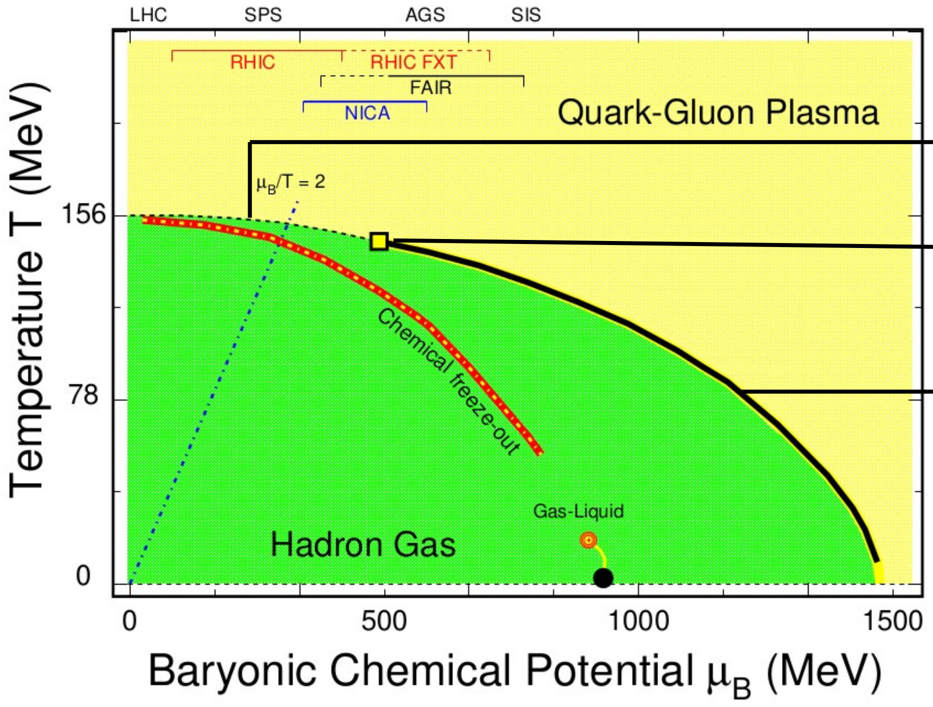
In part supported by

Outline :

1) *Introduction : QCD Phase Diagram*
2) *Results : Critical Point & Crossover Phase Transition*
3) *Future Prospects : Beam Energy Scan Phase – II*
4) *Conclusions*

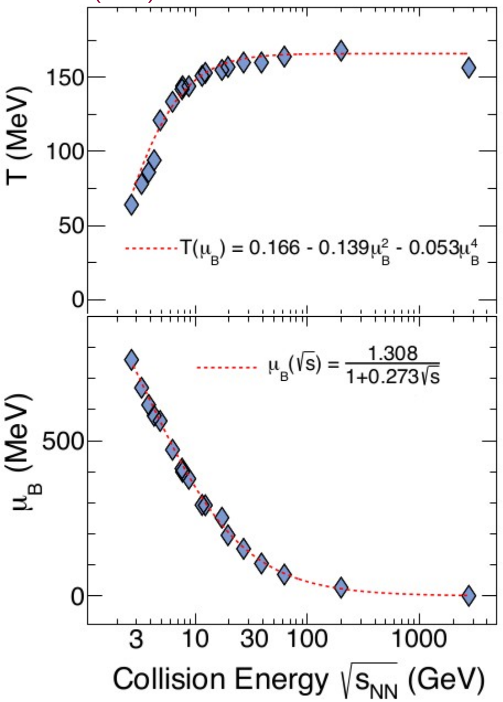
Introduction- QCD Phase Diagram

B. Mohanty, N. Xu, arXiv:2101.09210



- **Crossover transition**
  (From lattice QCD)
  Y. Aoki et al, Nature 443 (2006) 675.
- **QCD critical point (CP)**
- **1st order phase transition**
  (From model)
  S. Ejiri, Phys. Rev. D 78, 074507 (2008).

P. Braun-Munzinger, J. Stachel, Nature 448 (2007) 302
A. Pandav et. al. Prog.Part.Nucl.Phys. 125 (2022) 103960



☑ **Goal:** To study QCD phase diagram (here we focus of critical point & crossover phase transition).
☑ Varying collision energy varies Temperature (T) and Baryon Chemical Potential (μ_B).
☑ Fluctuation of conserved quatities are sensitive observables to study QCD phase structure.

Observables (Net-proton Cumulants)

☑ Higher order cumulants of net proton (proxy for net-baryon) distribution.

$$C_1 = \langle N \rangle \qquad here, N = number\ of\ net\ proton$$

$$C_2 = \langle (\delta N)^2 \rangle \qquad here, \delta N = N - \langle N \rangle$$

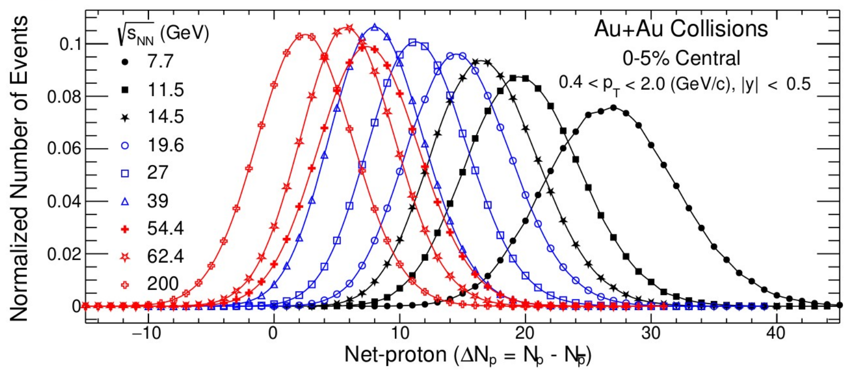
$$C_3 = \langle (\delta N)^3 \rangle$$

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

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

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

PhysicalL Review Letters 126, 092301 (2021)

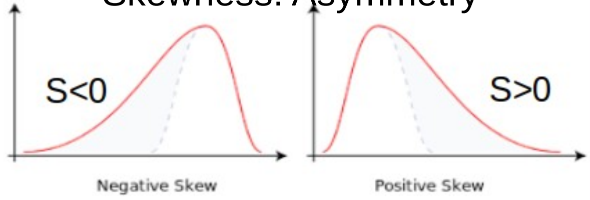


☑ Higher order cumulants are sensitive probes for the CP and nature of phase transition.

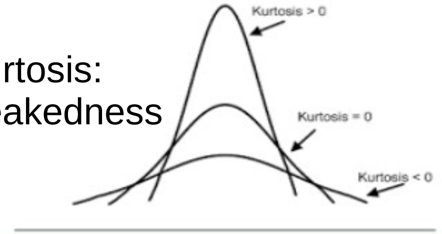
☑ Direct comparison with lattice QCD, HRG, QCD-based model calculations.

$$\frac{C_3}{C_2} = S\sigma \qquad \frac{C_4}{C_2} = \kappa\sigma^2 \qquad S = Skewness, \kappa = Kurtosis$$

Skewness: Asymmetry



Kurtosis: Peakedness



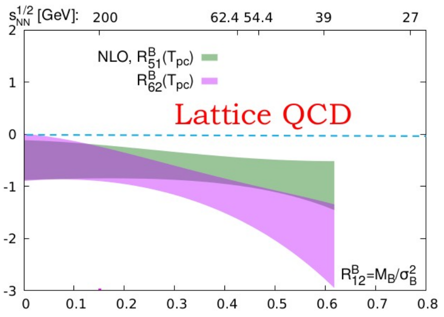
M. A. Stephanov, Phys.Rev.Lett. 107 (2011) 052301
Y. Hatta ,M. A. Stephanov, Phys.Rev.Lett. 91 (2003) 102003

Result: Experimental Evidence of Crossover Transition

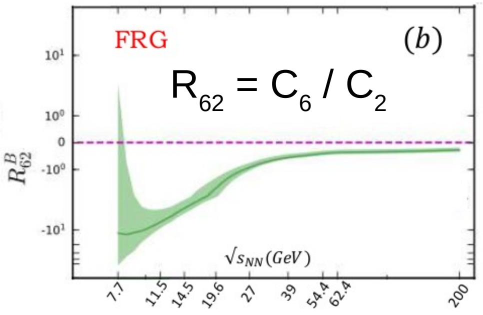
Theory prediction

- ☑ Signal for crossover search: Negative sign of C_5, C_6 that increase in magnitude with decreasing collision energy.

- ☑ Results from Lattice QCD and Funtional renormalization Group (FRG) are shown here.



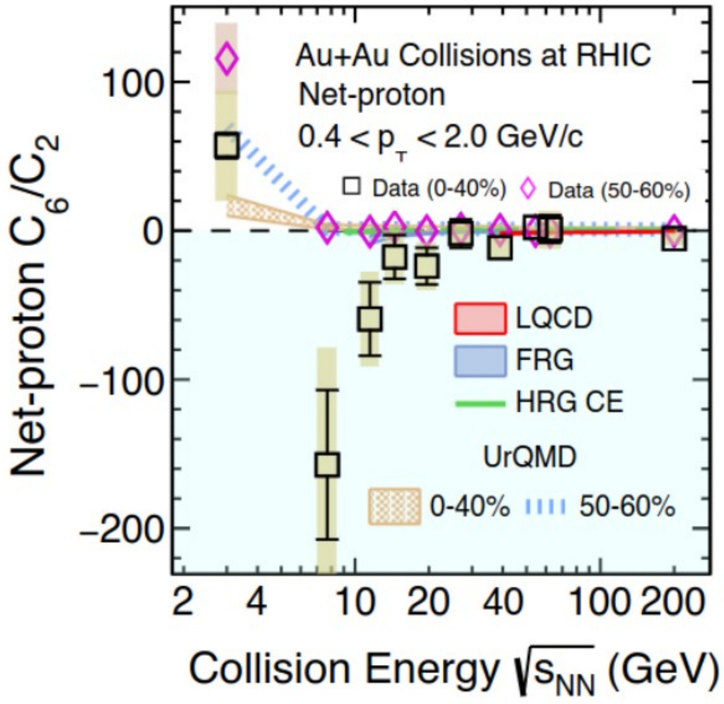
HotQCD, Phys. Rev. D101,074502 (2020)



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

- ☑ C_5, C_6 positive from UrQMD, HRG (no QCD transition).

Experimental result



M. S. Abdallah et al, [STAR] PRL 127, 262301 (2021).

B. E. Aboona et al, [STAR], PRL 130, 082301 (2023).

200 - 7.7 GeV are from BES-I and 3 GeV is from BES-II

- ☑ Increasing negative C_6/C_2 with decreasing energy (200 – 7 GeV) for 0-40% centrality class ($\leq 1.7\ \sigma$).
- ☑ Consistent trend with LQCD expectation.
- ☑ Large positive value at 3 GeV.
- ☑ C_6/C_2 (50-60%), UrQMD ≥ 0 for all energies.

Result: Search for Critical Point (CP)

Theory prediction

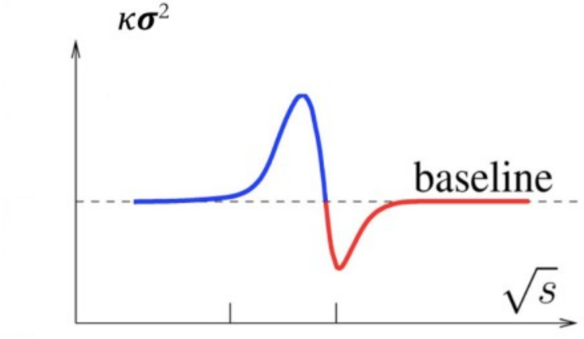
☑ Related to correlation length: $C_2 \sim \xi^2 \quad C_4 \sim \xi^7$.

☑ Correlation length diverges near critical point.

☑ Finite size/time effects reduces ξ .

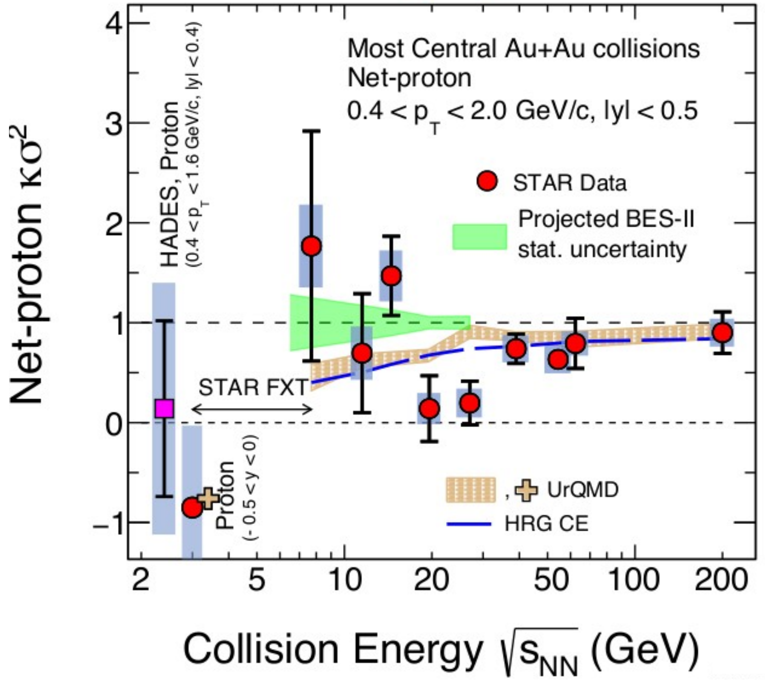
☑ Higher order cumulants more sensitive to CP.

☑ In presence of critical point: non-monotonic collision energy dependence of C_4 / C_2 .



M.A. Stephanov, Phys.Rev.Lett. 107 (2011) 052301
A. Bzdak et al, Phys. Rept. 853, 1-87 (2020)

Experimental result



HADES: PRC 102,024914(20)

STAR: PRL 126, 092301 (2021)

HRG CE: P. B Munzinger et al, NPA1008, 122141(2021)

200 - 7.7 GeV are from BES-I and 3 GeV is from BES-II

☑ Non-monotonic collision energy dependence observed for net-proton C_4 / C_2 .

☑ Consistent with model expectation with a CP.

☑ Non-CP model fails to explain.

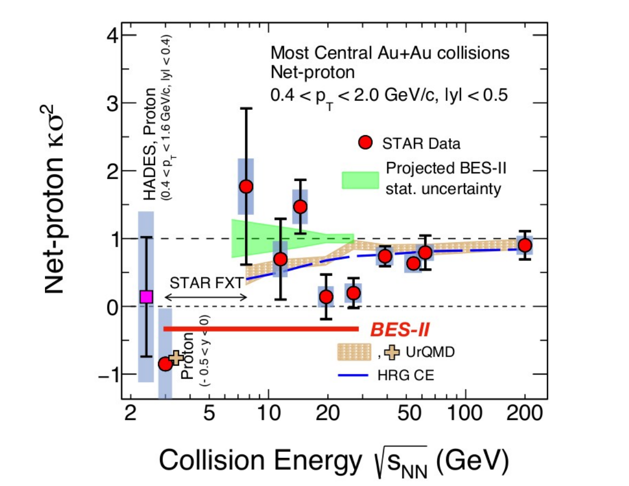
☑ At 3 GeV, value consistent with UrQMD calculations -> hadronic matter.

Future Prospects: Beam Energy Scan Phase - II

STAR: PRL 126, 092301 (2021)
A. Pandav et. al. Prog.Part.Nucl.Phys. 125 (2022) 103960

BES-I result interesting but large statistical uncertainties -> BES-II needed.

- ☑ 10 – 20 times increase in statistics for Au + Au collision (7.7 – 27 GeV).
- ☑ Two new collider energy: 9.2 & 17.3 GeV, important for CP search.
- ☑ FXT program can reach $\sqrt{s_{NN}} = 3\,GeV$ (μ_B = 750 MeV).

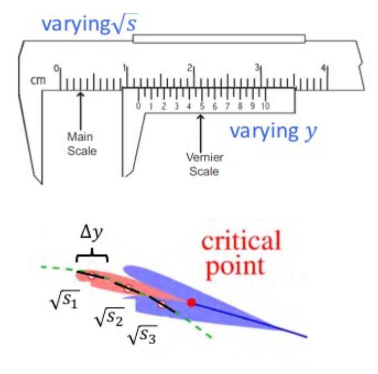


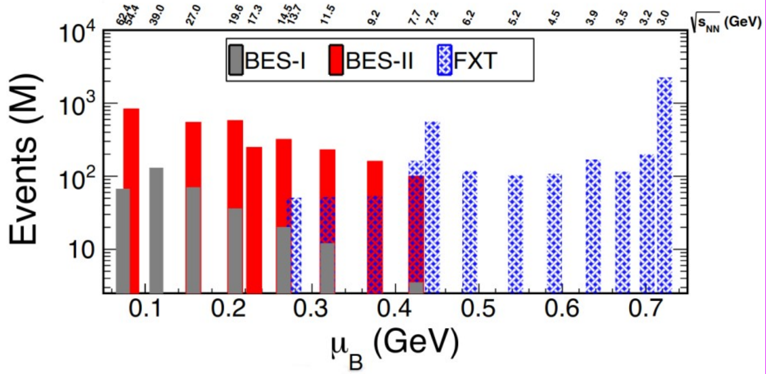
- ☑ Detector Upgrades (iTPC, eTOF, EPD) :
  - Enlarged kinematic coverage (|η| < 1.6).
  - Improve centrality definition.
  - Crucial for acceptance dependence study.

- ☑ Rapidity scan for CP search:
  Rapidity scan is a finer probe of critical regime than energy scan.

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

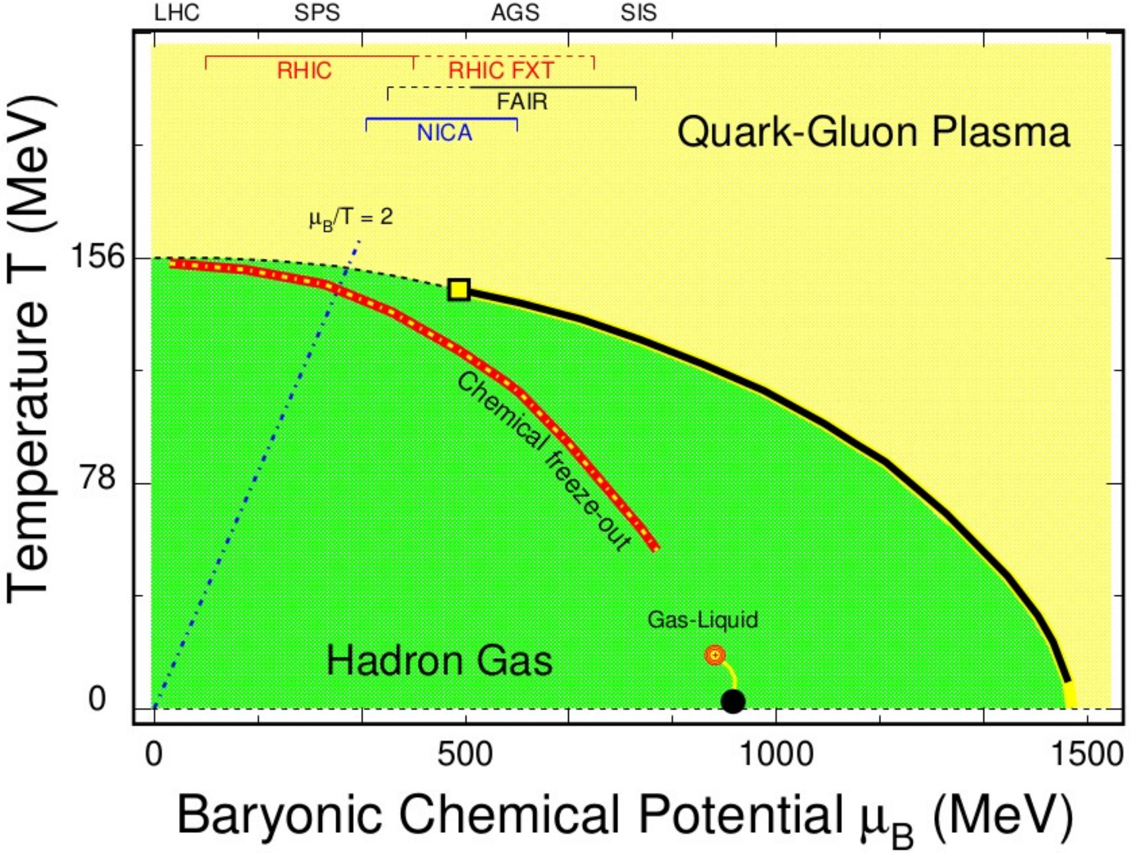
STAR BES-II White paper 2014 [STAR]
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598





Current Status and Conclusions

B. Mohanty, N. Xu, arXiv:2101.09210



- ☑ Consistent with crossover prediction at $\sqrt{s_{NN}} \geq 39$ GeV or $\mu_B \leq 110$ MeV -Lattice QCD.
- ☑ Hint of non-monotonic trend (3.1 σ level) between $\sqrt{s_{NN}}$ = 7.7 – 27 GeV around μ_B = 140 - 420 MeV, (BES-II will confirm).
- ☑ Low energy region $\sqrt{s_{NN}}$ = 3.0 – 39 GeV (μ_B = 110 - 750 MeV) would be interesting for CP search.

- ☑ Analysis for BES-II is ogoing.
- ☑ Stay tuned for new exciting result.

➔ We thank the STAR focus group and STAR collaboration for opportunity and support.

Thank You