Baryon number fluctuation in baryon rich QCD matter

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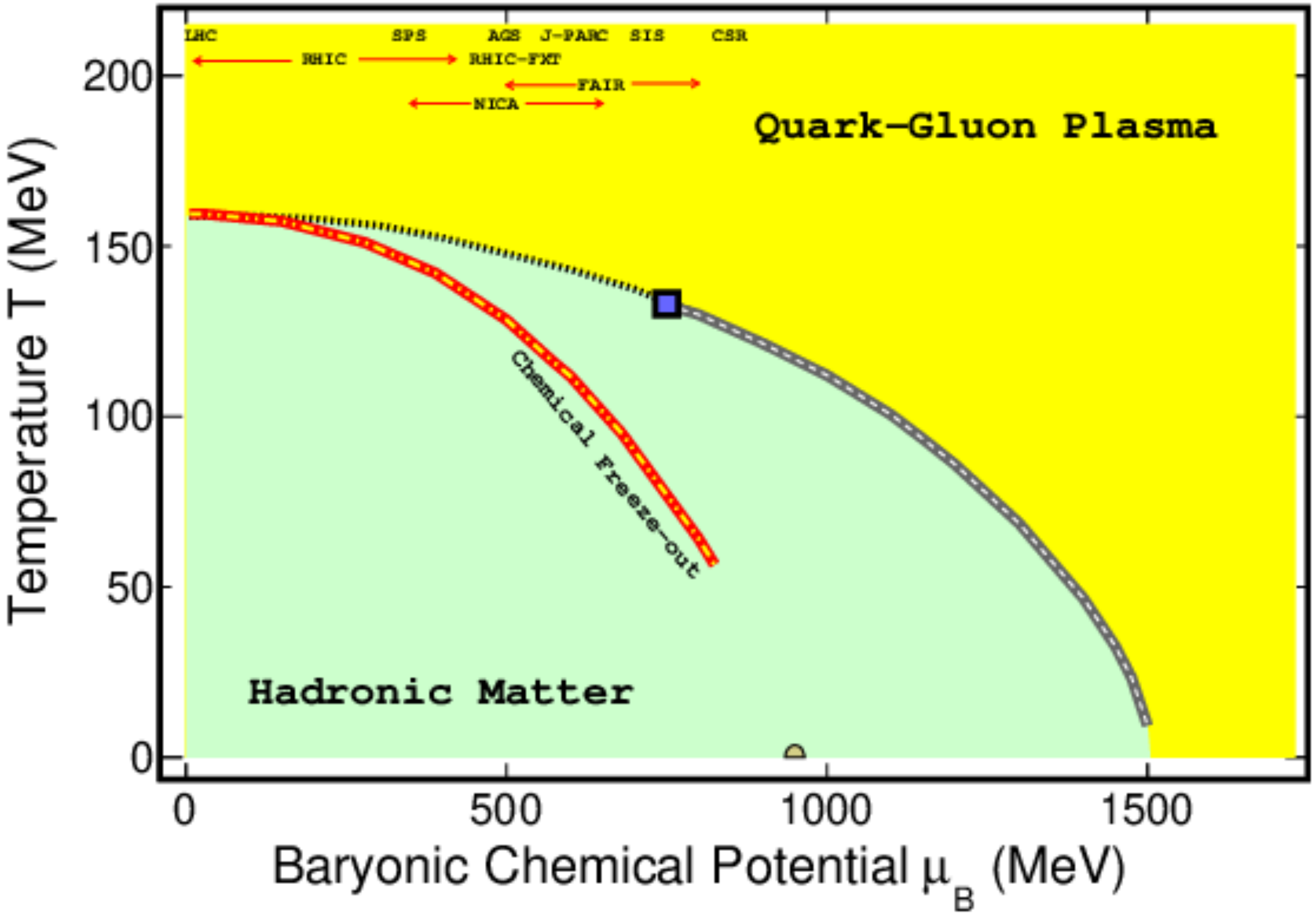
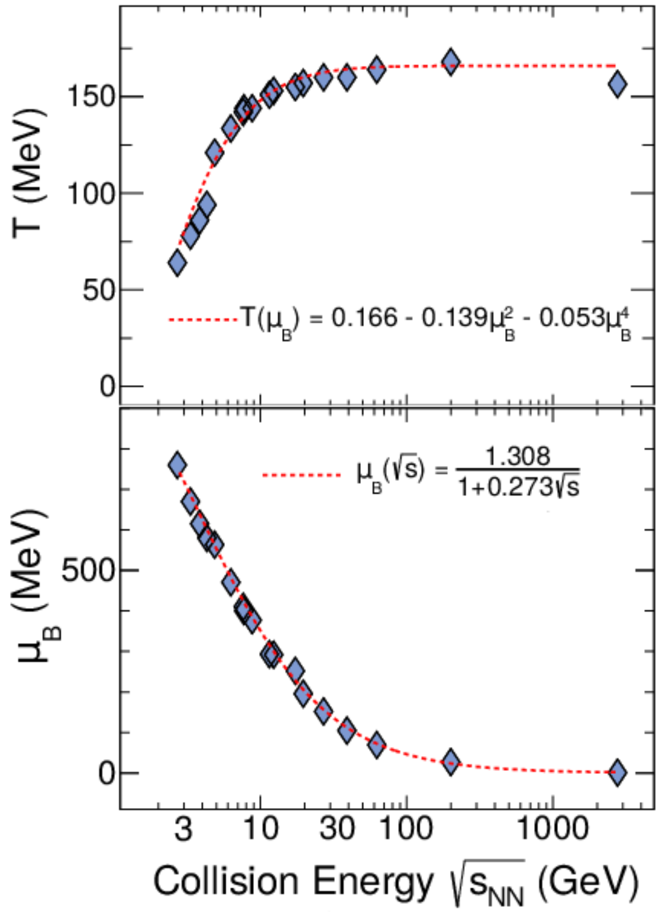
(NISER, INDIA)

24TH JANUARY 2024

QCD PHASE STRUCTURE





Prog.Part.Nucl.Phys. 125 (2022) 103960

Relativistic heavy-ion collisions allows access to the phase diagram of QCD

QCD thermodynamics and baryon fluctuations

Theory

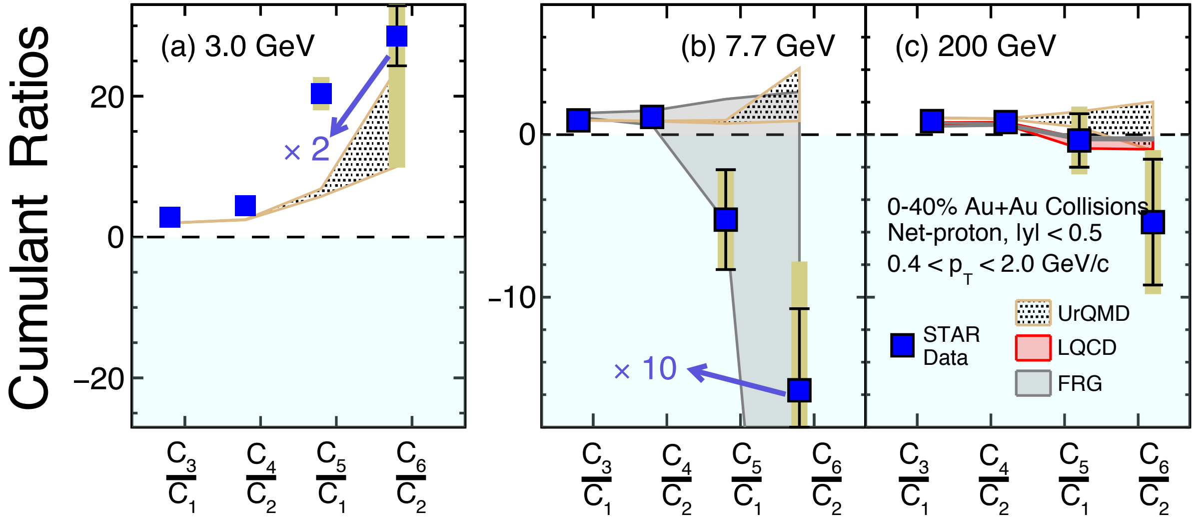
Ordering of ratios (Net-baryon): LQCD -

$$\frac{\chi_6^B(T,\vec{\mu})}{\chi_2^B(T,\vec{\mu})} < \frac{\chi_5^B(T,\vec{\mu})}{\chi_1^B(T,\vec{\mu})} < \frac{\chi_4^B(T,\vec{\mu})}{\chi_2^B(T,\vec{\mu})} < \frac{\chi_3^B(T,\vec{\mu})}{\chi_1^B(T,\vec{\mu})}$$

$$\frac{C_3}{C_1} > \frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2}$$

Susceptibility ratio ordering
PHYS. REV. D 101, 074502 (2020)

Experiment



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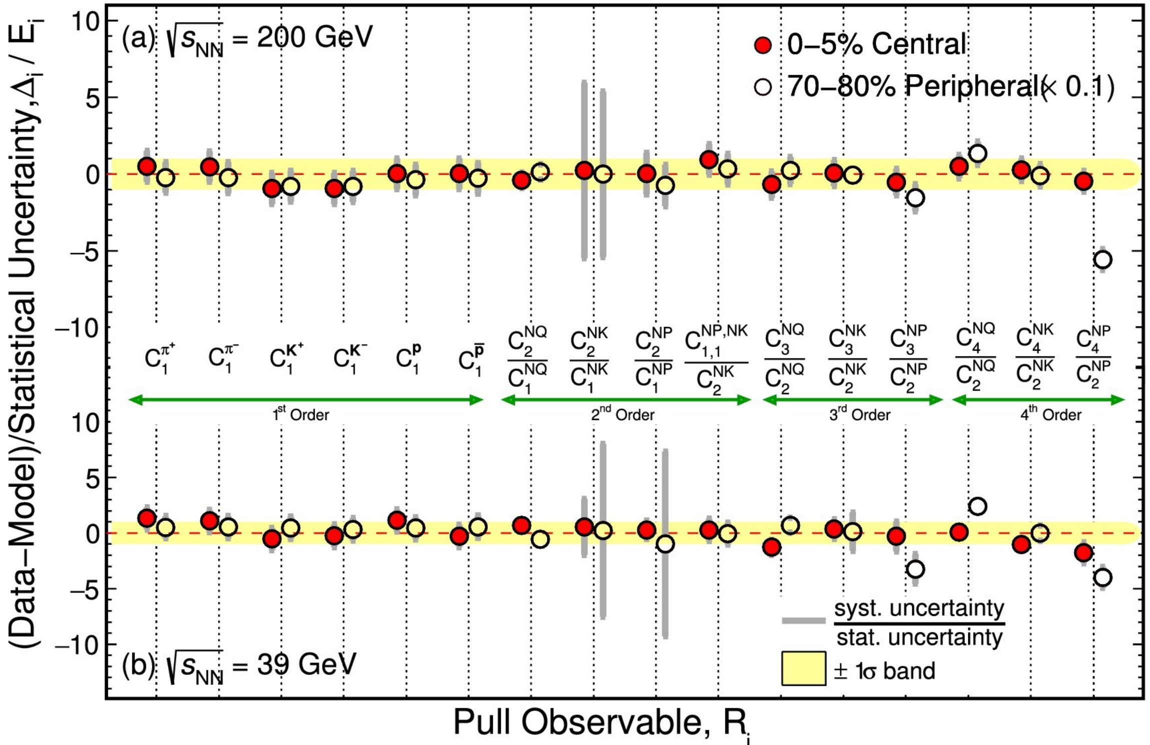
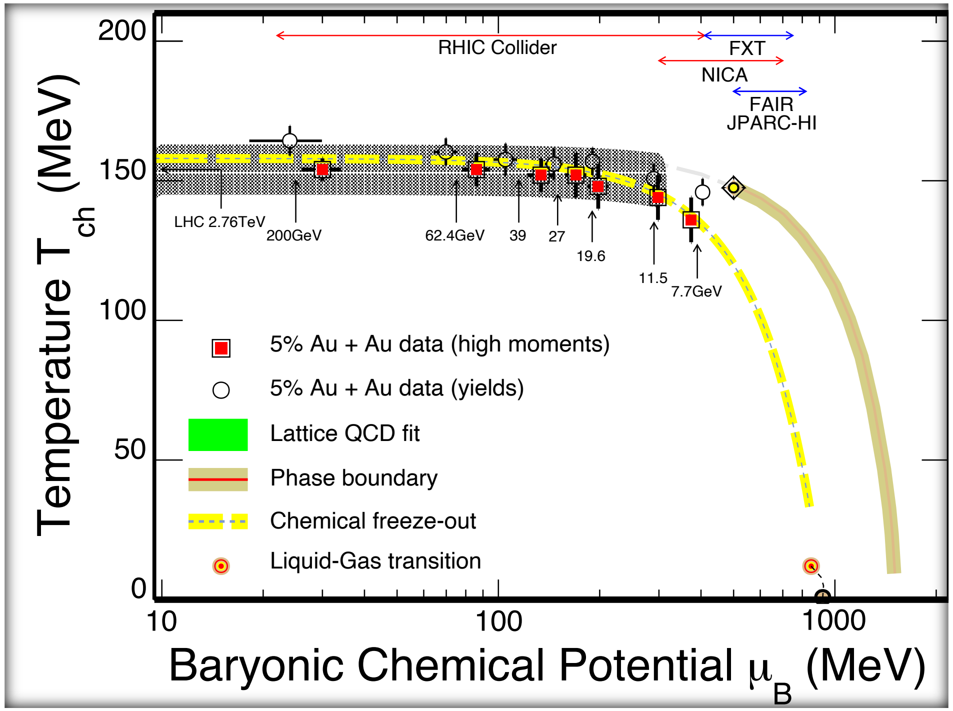
STAR: PRL128, 202303 (2022)
STAR: PRL 127, 262301 (2021)
STAR: PRL 126, 092301 (2021)
STAR: PRC 104, 024902 (2021)

- Ordering of ratios as per LQCD for collision energies < 7 GeV
- Reverse ordering observed for collision energy = 3.0 GeV.

Baryon fluctuations and thermal model

Phys.Lett.B 829 (2022) 137021



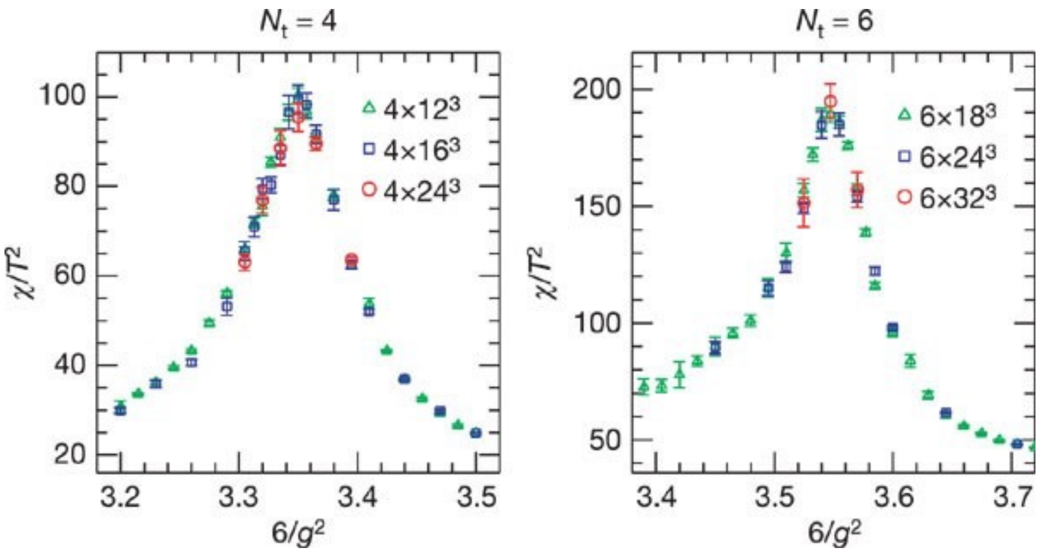


Measurements in central collisions agrees with thermal model, peripheral collisions do not.

Favors a thermal system for collision energies > 30 GeV

QCD phase structure at $\mu_B = 0$ MeV

Theory

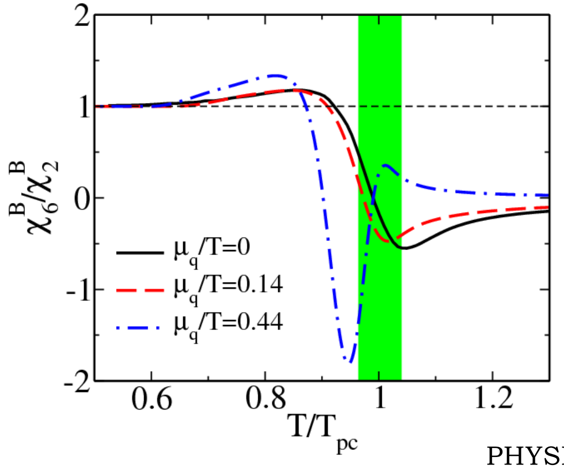


Lattice QCD: Cross over at μ_B = 0 MeV

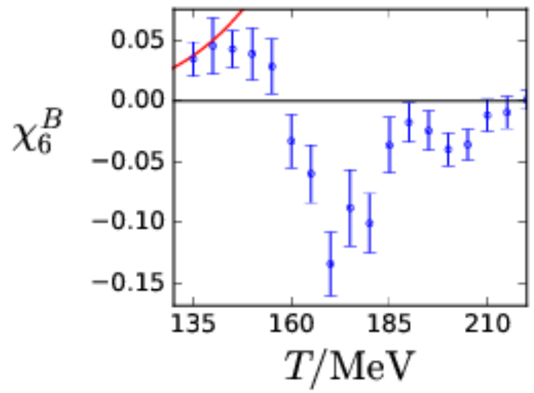
Nature 443 (2006) 675-678

Observable for experiment

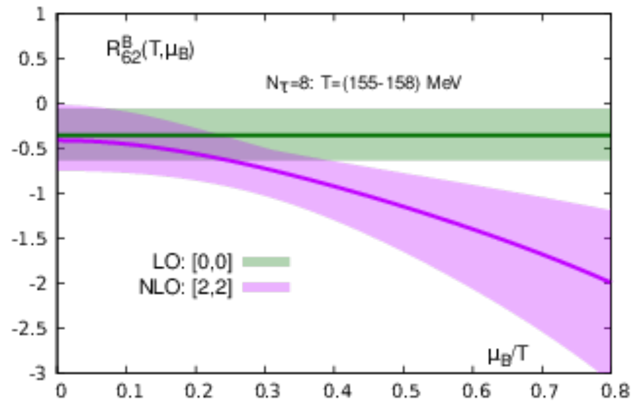
Eur. Phys. J. C 71 1694 (2011)



JHEP 10 (2018) 205



PHYSICAL REVIEW D 101, 074502 (2020)

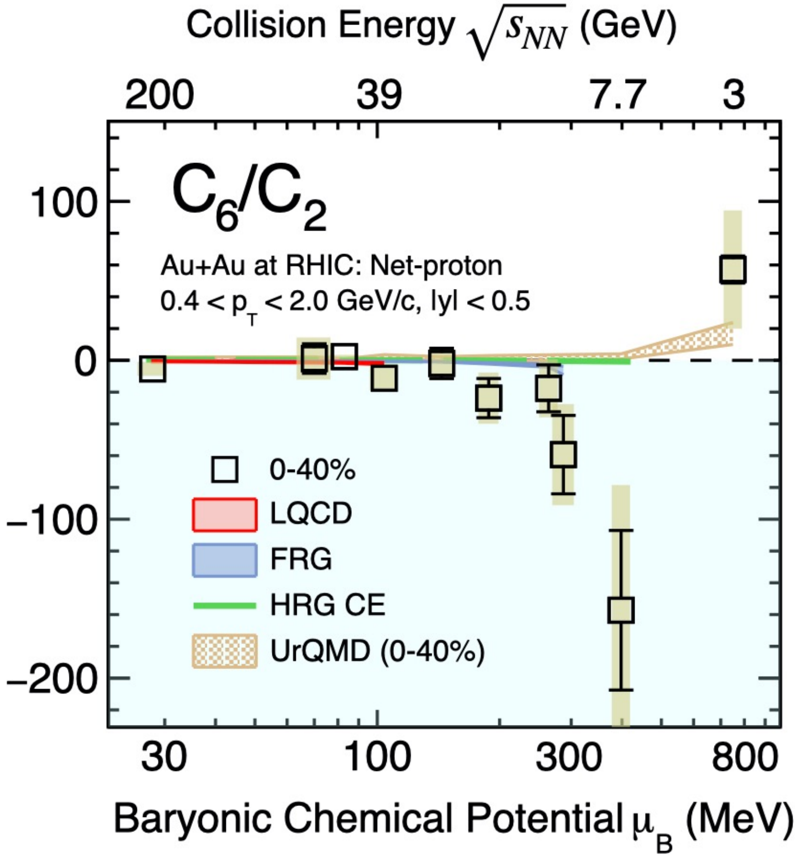


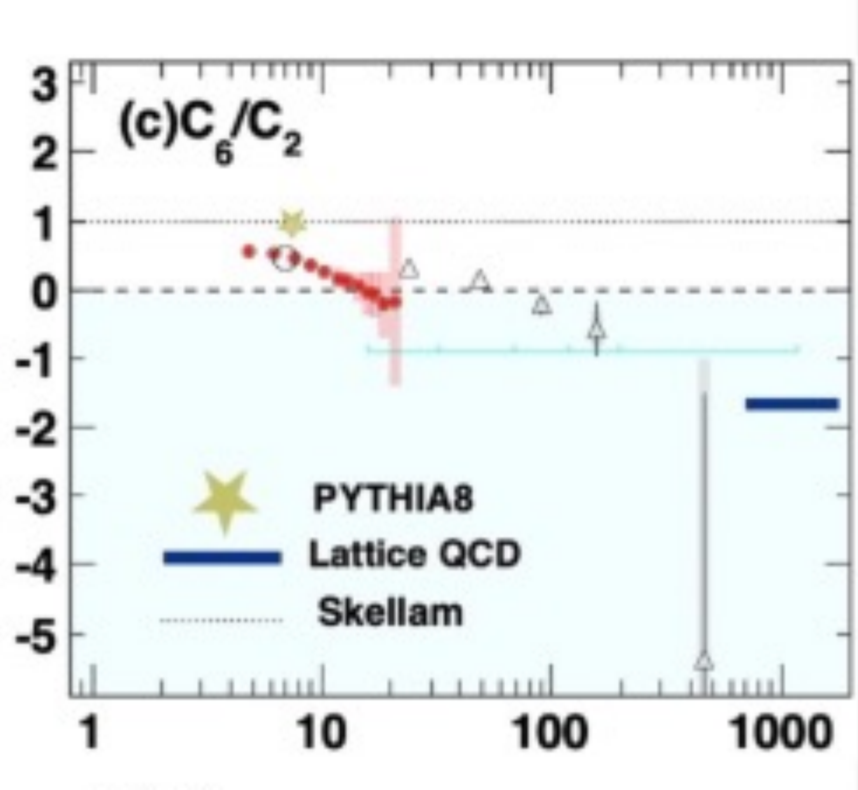
$\chi^B{}_6/\chi^B{}_2$ or $C^B{}_6/C^B{}_2 < 0$

Study the sign of high order baryon correlations

Search for signals of cross over

Net-proton proxy for net-baryon



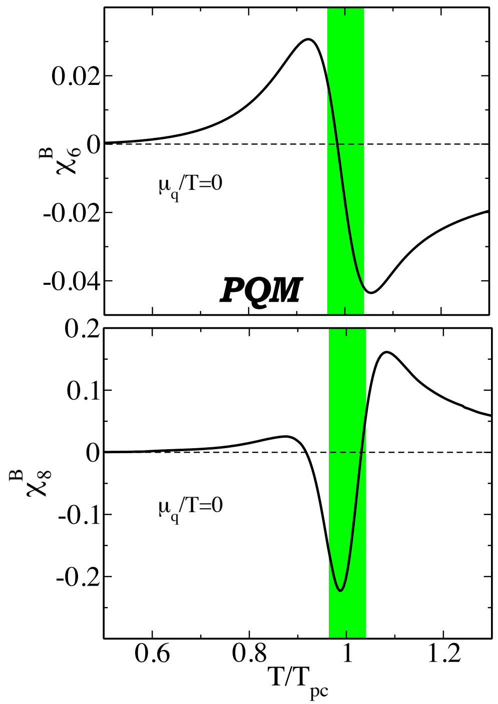


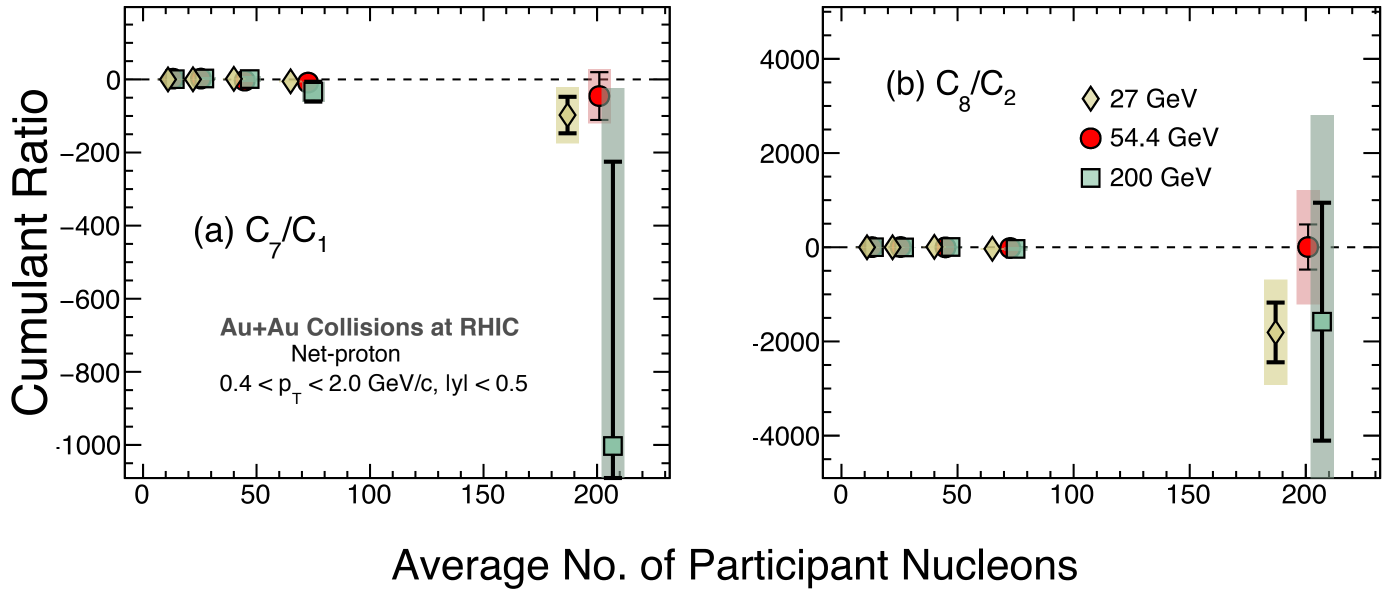
STAR: PRL 130 , 82301 (2023)
STAR: PRL 127, 262301 (2021)
arxiv: 2311.00934 [nucl-ex]

Sixth order cumulant ratios sign consistent with lattice QCD calculation with a crossover except at collision energy ~ 3 GeV

Search for signals of cross over – future

A. Pandav, STAR Collaboration, SQM22



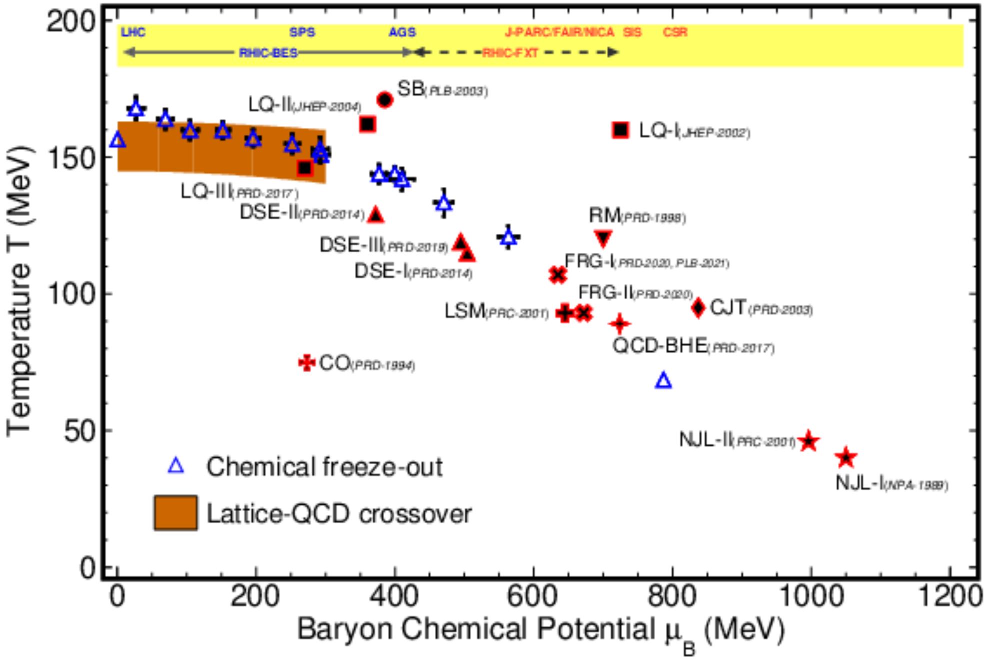


STAR BUR Run22, STAR note 0773, ALICE: arXiv1812.06772

Future: Extending measurements to C_7 and C_8 - more sensitive probes for crossover

- ❑ STAR: Au+Au at $\sqrt{s_{NN}}$ = 200 GeV: ~ 20 billion event (2023+2025); $\sqrt{s_{NN}}$ = 3 GeV: ~ 2 billion events collected
- ❑ ALICE: Higher order measurements possible with high statistics LHC Run 3 data.

Baryon fluctuations & QCD Critical point



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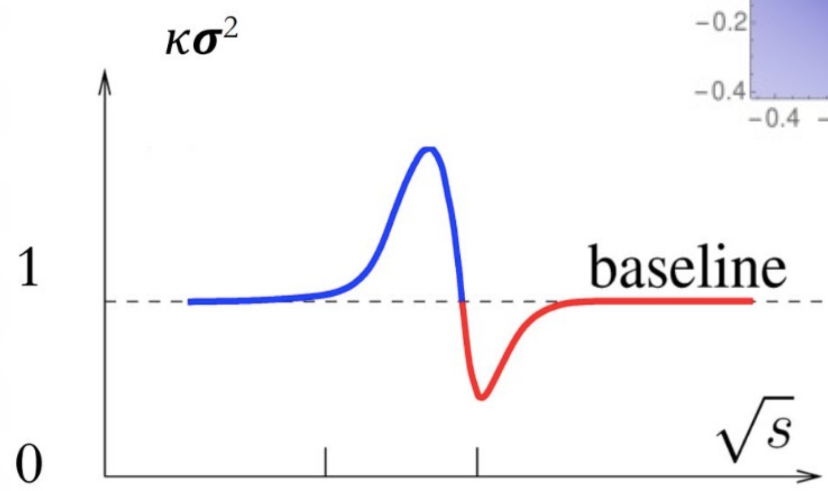
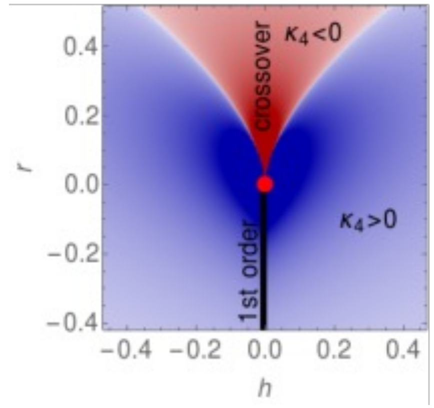
If present, beyond μ_B = 200 MeV

Theory expectations

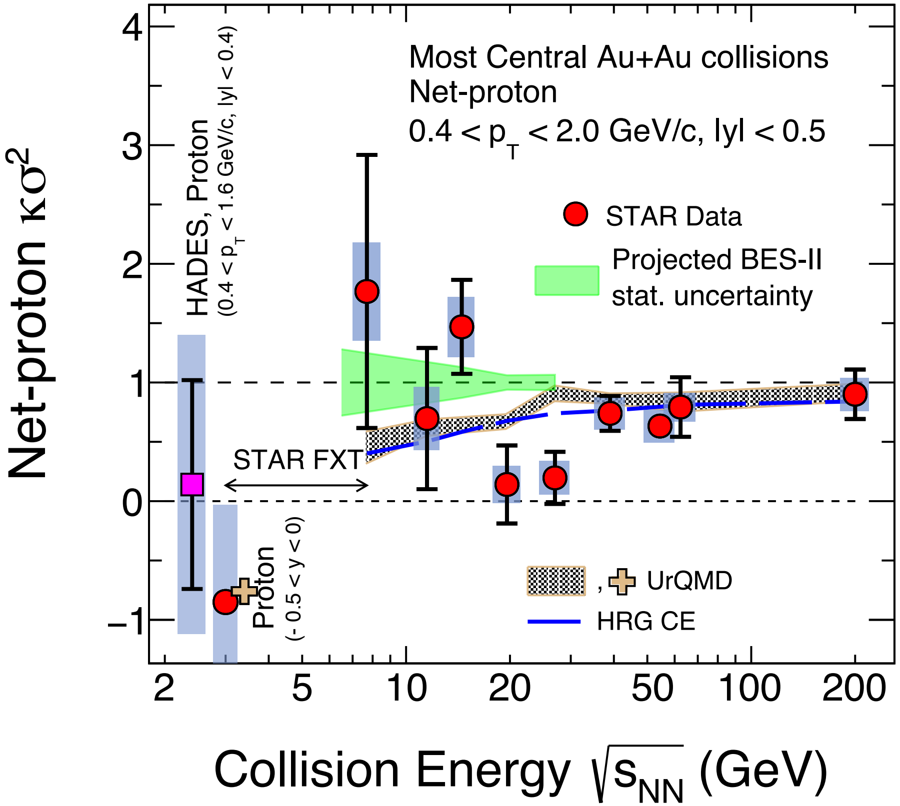




M. A. Stephanov, Phys.Rev.Lett. 107 (2011) 052301

Expected signature: Non-monotonic variations of 4th order proton number fluctuations as a function of collision energy.

Search for signals of QCD Critical Point



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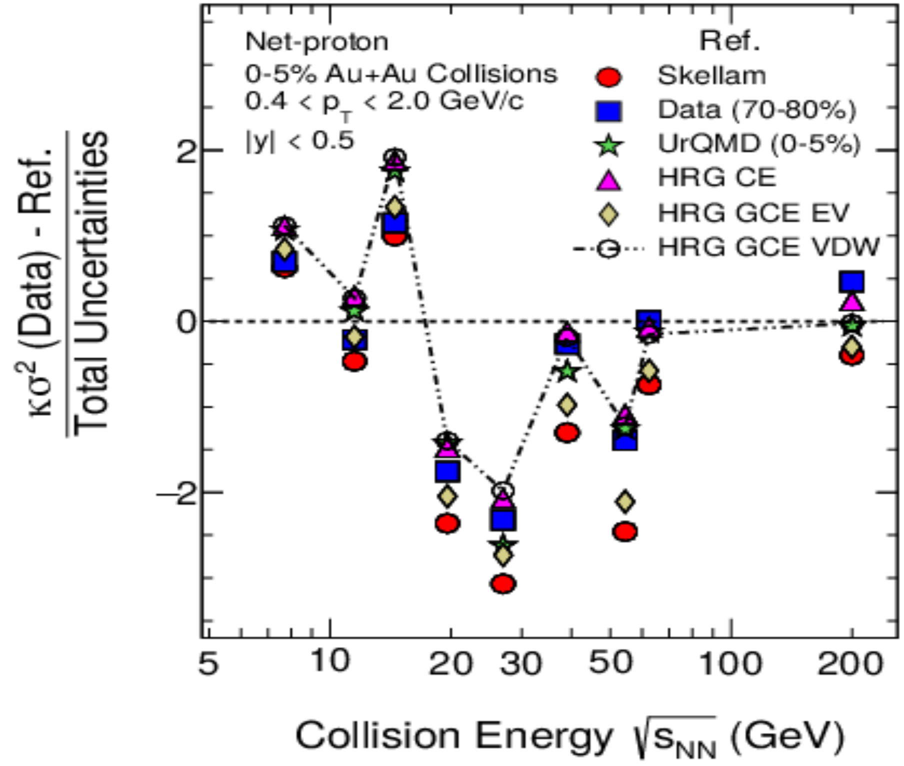
STAR: PRL128, 202303 (2022)
STAR: PRL 127, 262301 (2021)
STAR: PRL 126, 092301 (2021)
STAR: PRC 104, 024902 (2021)
HADES: RC 102,024914(20)

Measurements



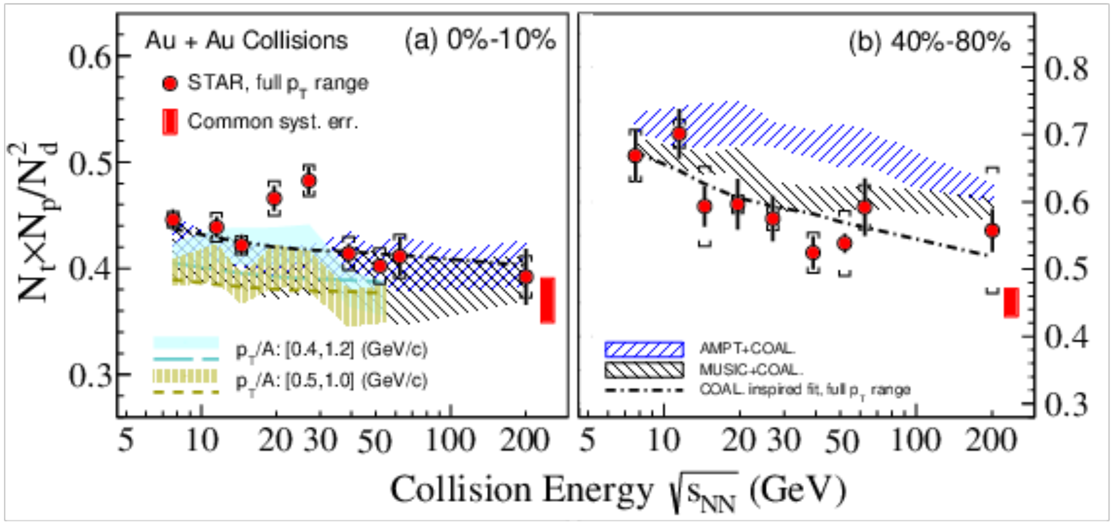
HRG CE: P. B Munzinger et al, NPA1008, 122141(2021)

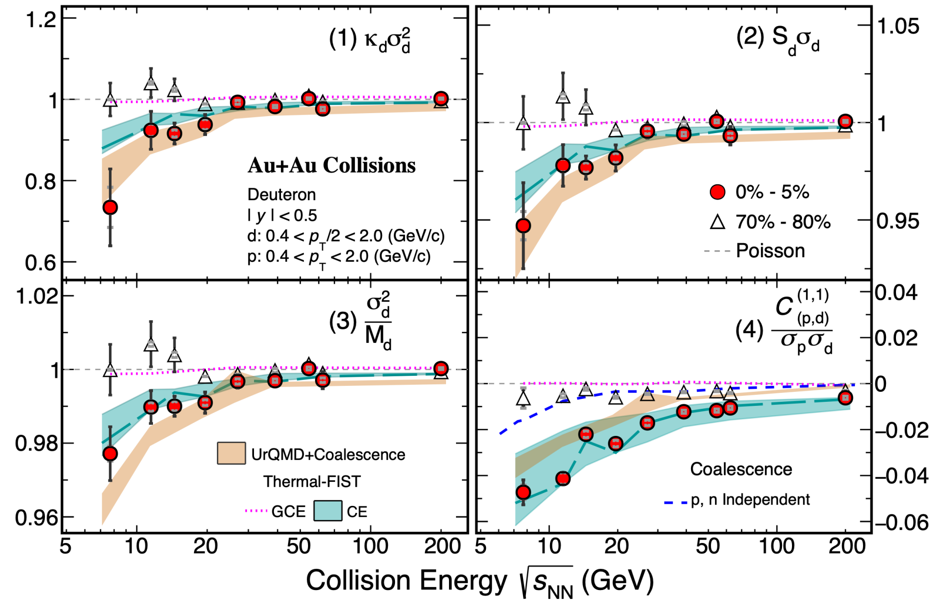
Deviations from baseline

Search for CP with higher baryon number carrying (nuclei) objects

STAR: e-Print: 2304.10993 [nucl-ex]

STAR: Phys.Rev.Lett. 130 (2023) 202301

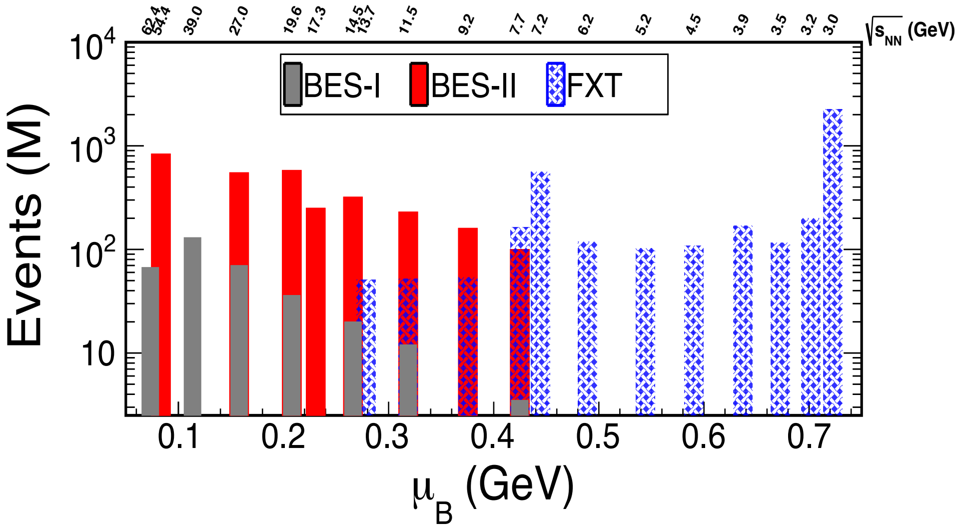


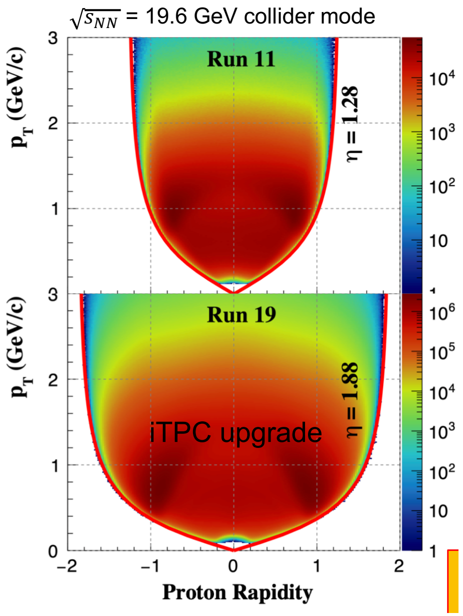


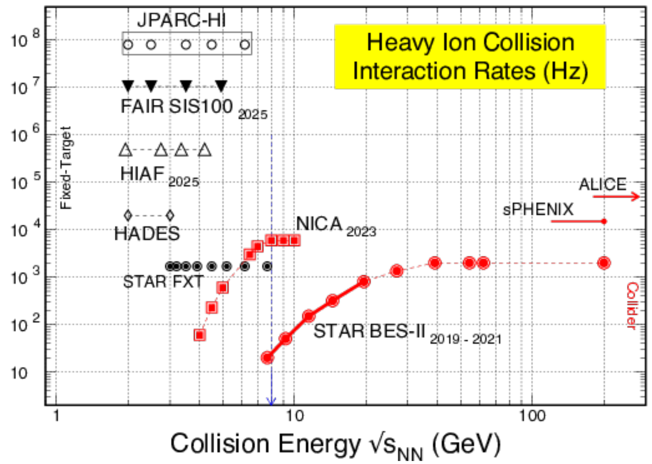
Sensitive to the neutron density fluctuations

CE thermal model and UrQMD + Coalescence qualitatively agree with data
Large acceptance for nuclei needed for CP search

Search for QCD CP - Future







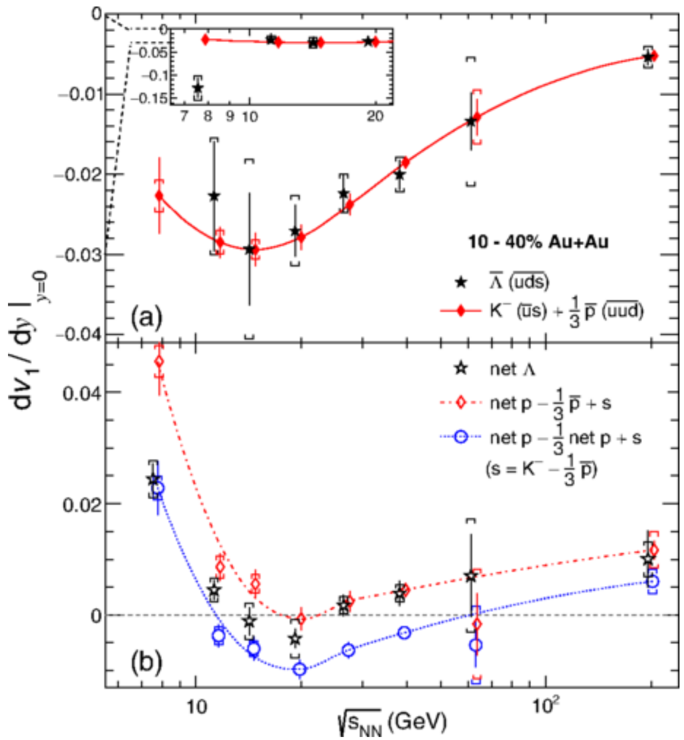
e-Print: 2209.05009 [nucl-ex]

Larger statistics, larger acceptance and more differential measurements

Future experiments like CBM and NICA will probe high baryon density regime

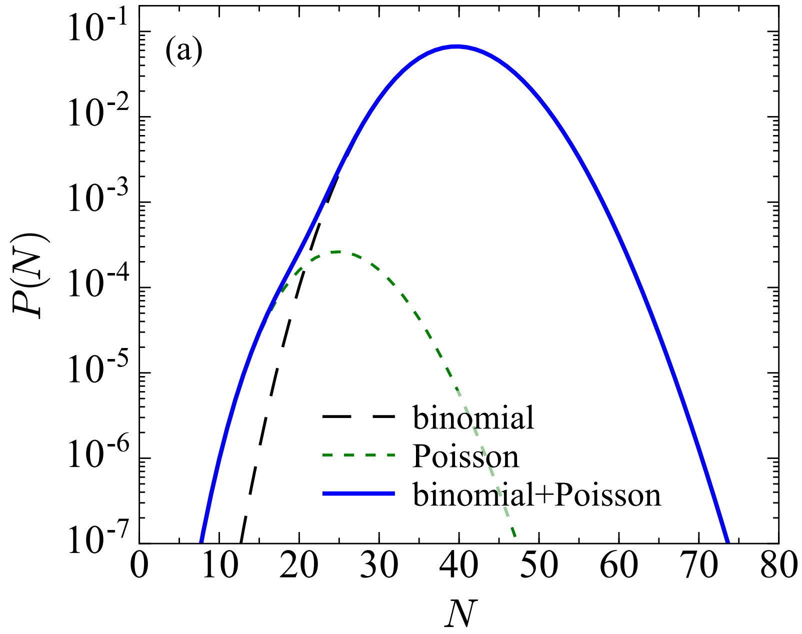
Baryon fluctuation and 1st order phase transition

STAR: *Phys.Rev.Lett.* 120 (2018) 6, 062301



Non-monotonic variation of slope of directed flow of baryons with collision energy

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

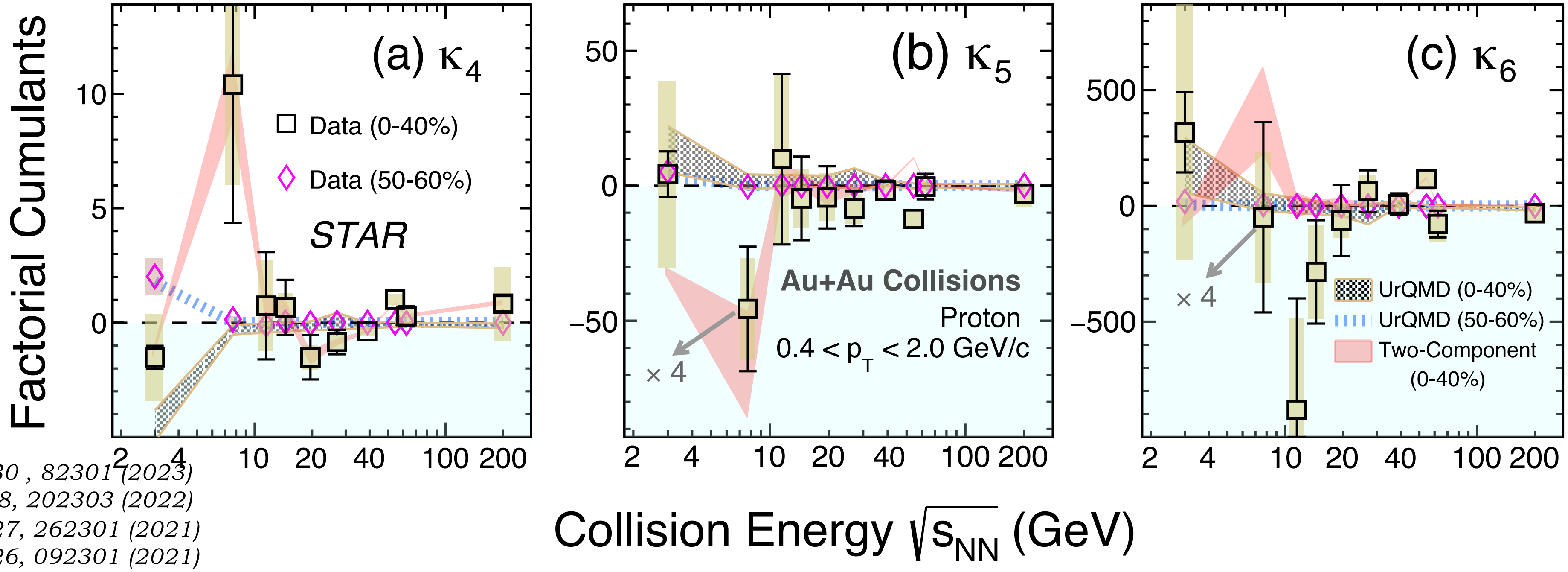


Multiplicity distribution bi-modal (two phases)

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

Search for signals of 1st order phase transition

Proton



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

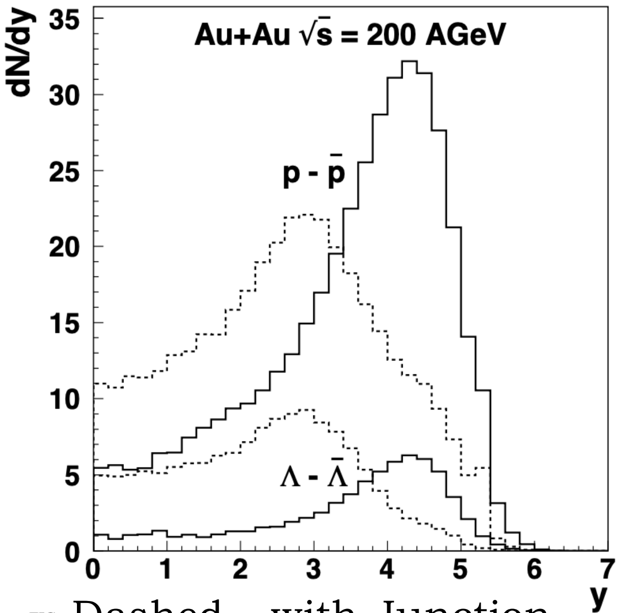
- For $\sqrt{s_{NN}} \geq 11.5$ GeV, κ_n within uncertainties does not support the two-component shape of proton distributions. Possibility of sign change at low energy.
- Peripheral data and UrQMD results consistent with zero.

Role of Baryon Junction in Baryon number Fluctuation

Idea: Phys. Lett. B 378 (1996) 238-246: Can Gluons trace Baryon Numbers ? "the traces of baryon number in a high-energy process can reside in a non-perturbative configuration of gluon fields, rather than in the valence quarks.

MODEL: Phys.Lett.B443:45-50,1998: Baryon Number Transport via Gluonic Junctions: A novel non-perturbative gluon junction mechanism is introduced within the HIJING/B nuclear collision event generator to calculate baryon number transport. ...In HIJING/B, we implement Kharzeev's model through a "Y" string configuration for the excited baryon.

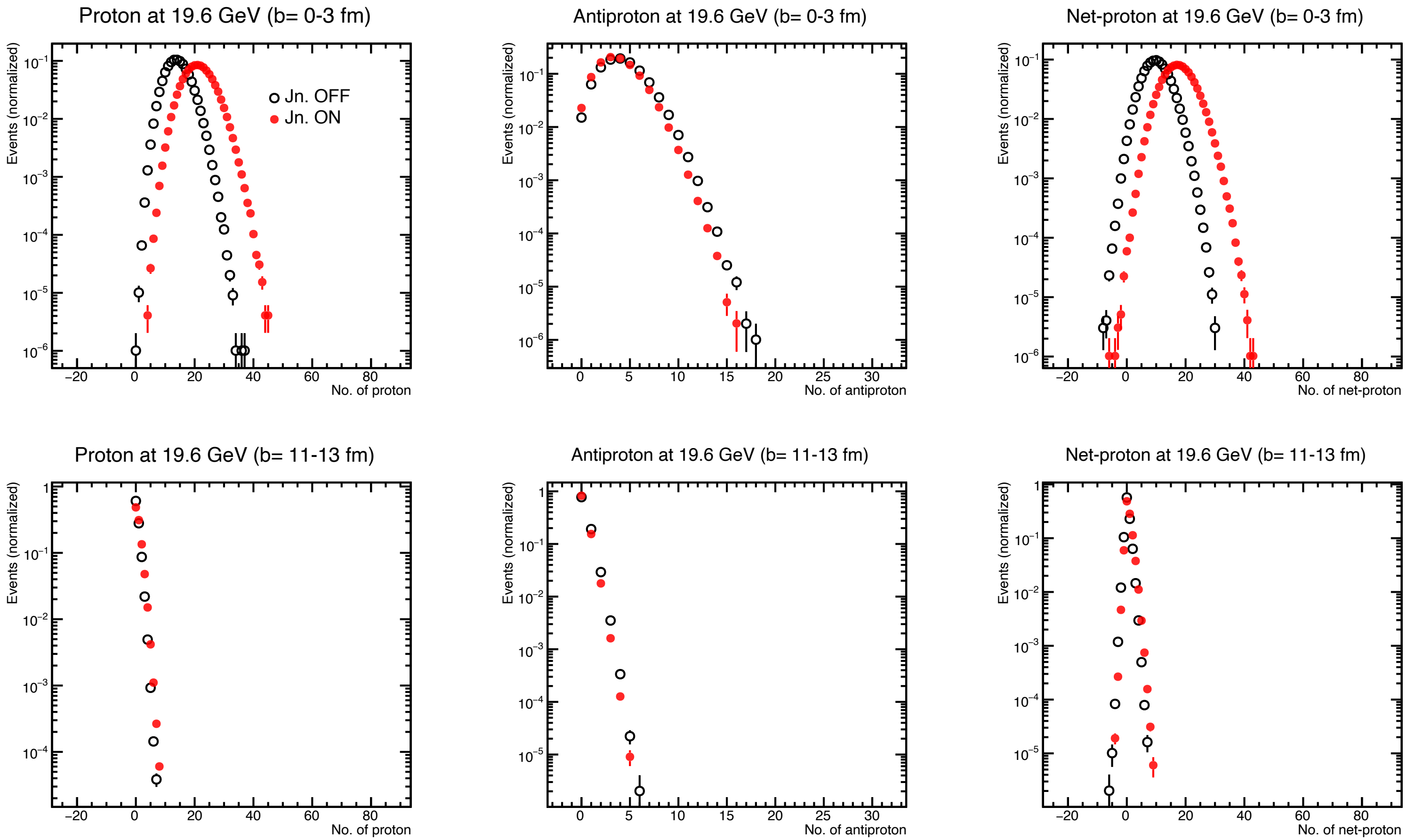
PHYSICAL REVIEW LETTERS 83, 1735 (1999)
PHYSICAL REVIEW C **68**, 054902 (2003)
PHYSICAL REVIEW C **70**, 064906 (2004)
PHYSICAL REVIEW C **72**, 054901 (2005)
PHYSICAL REVIEW C **81**, 054911 (2010)
PHYSICAL REVIEW C **83**, 024902 (2011)
PHYSICAL REVIEW C **98**, 064903 (2018)



Dashed – with Junction

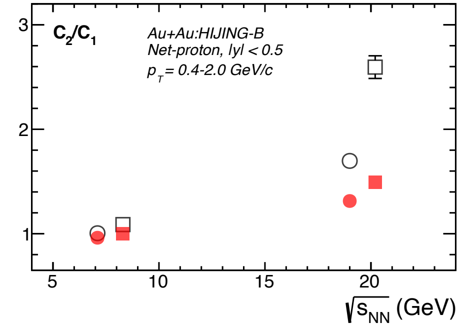
HIJING Bbar (v. 1.0) Model based study

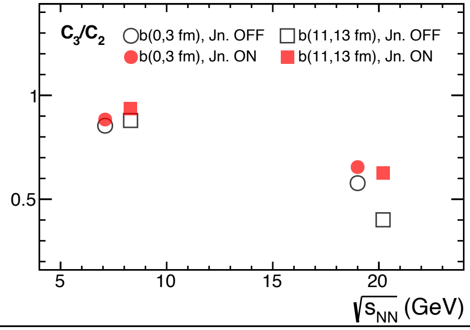
Distributions & Cumulants of proton, anti-proton and net-protons w/w.o baryon junction

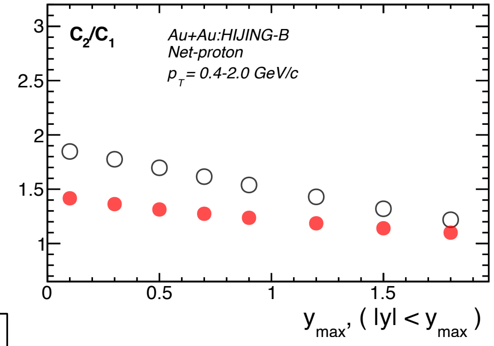


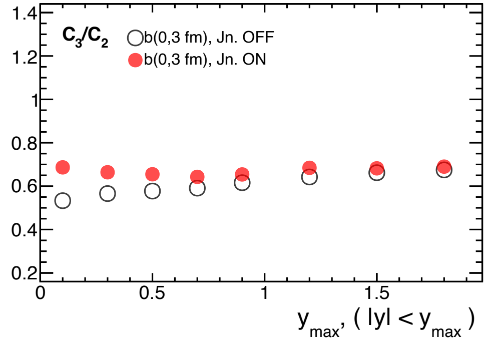
Differences in net-proton distributions with and without baryon junction observed in central collisions

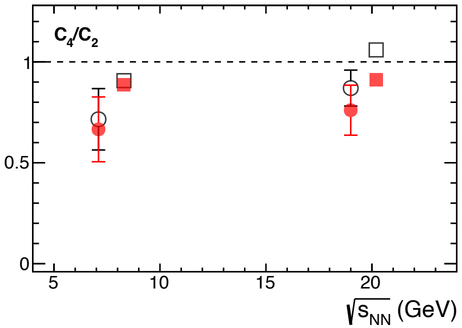
Cumulants of net-proton distributions w/w.o baryon junction





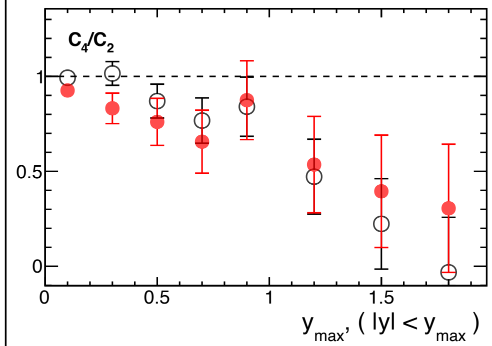






Baryon Junction:

- Effect at higher collision energy.
- 2nd order normalized fluctuations are suppressed.
- Distribution gets more skewed.



19.6 GeV

Baryon Junction:

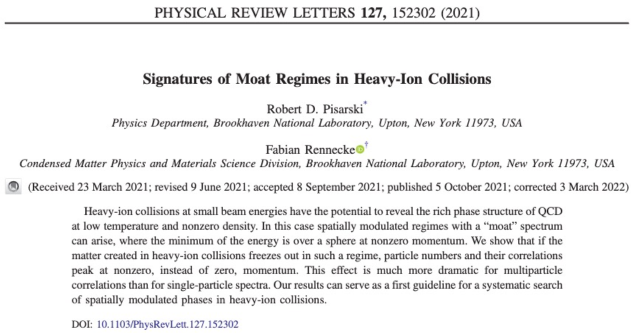
Normalized 2nd order fluctuations more suppressed towards mid-rapidity

Exotic phases: Moat regime

Experimental observable

Theory

Region in phase diagram


PHYSICAL REVIEW LETTERS **127,** 152302 (2021)

Signatures of Moat Regimes in Heavy-Ion Collisions

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Heavy-ion collisions at small beam energies have the potential to reveal the rich phase structure of QCD at low temperature and nonzero density. In this case spatially modulated regimes with a “moat” spectrum can arise, where the minimum of the energy is over a sphere at nonzero momentum. We show that if the matter created in heavy-ion collisions freezes out in such a regime, particle numbers and their correlations peak at nonzero, instead of zero, momentum. This effect is much more dramatic for multiparticle correlations than for single-particle spectra. Our results can serve as a first guideline for a systematic search of spatially modulated phases in heavy-ion collisions.

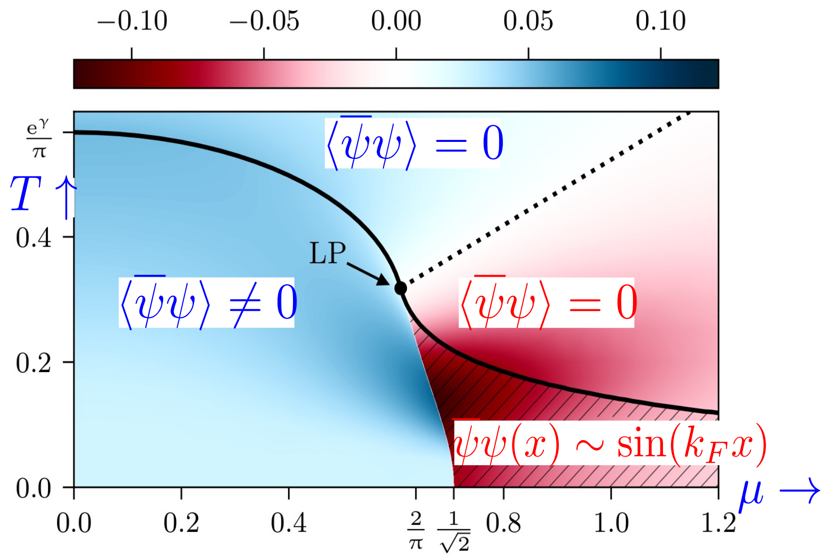
DOI: 10.1103/PhysRevLett.127.152302

$$\mathcal{L} = \frac{1}{2}(\partial_0\vec{\phi})^2 - \frac{Z}{2}(\partial_i\vec{\phi})^2 - \frac{W}{2}(\partial_i^2\vec{\phi})^2 - \frac{m_{\rm eff}^2}{2}\vec{\phi}^2 + \cdots$$

$$E_\phi(\mathbf{p}^2) = \sqrt{Z\mathbf{p}^2 + W(\mathbf{p}^2)^2 + m_{\rm eff}^2}$$

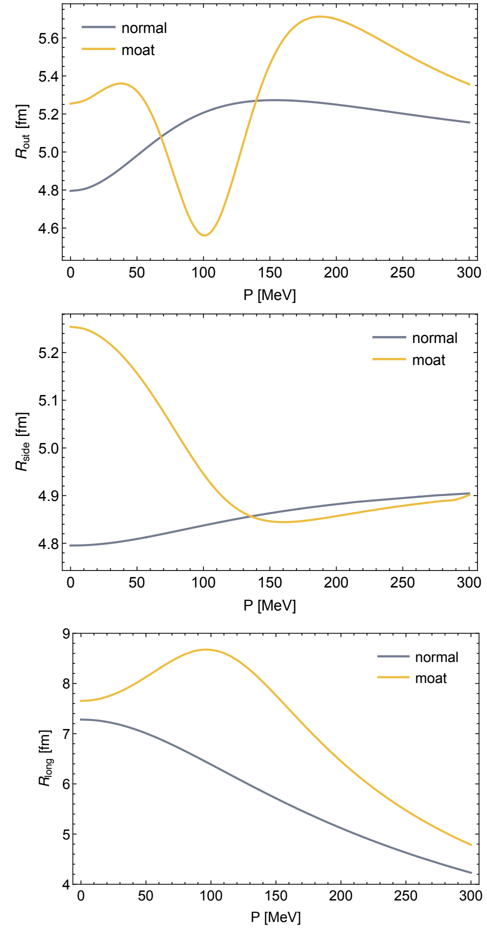
Z < 1 and W > 0

Arxiv: 21120: 07024



Low temperature and high baryon density

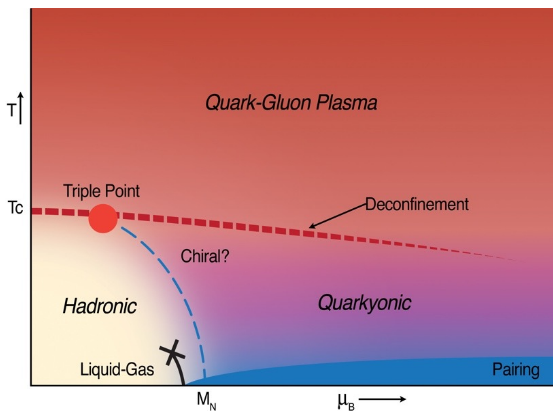
e-Print: 2301.11484 [hep-ph]



New feature in QCD phase diagram that high baryon density experiments could search

Exotic phases: Quarkyonic matter

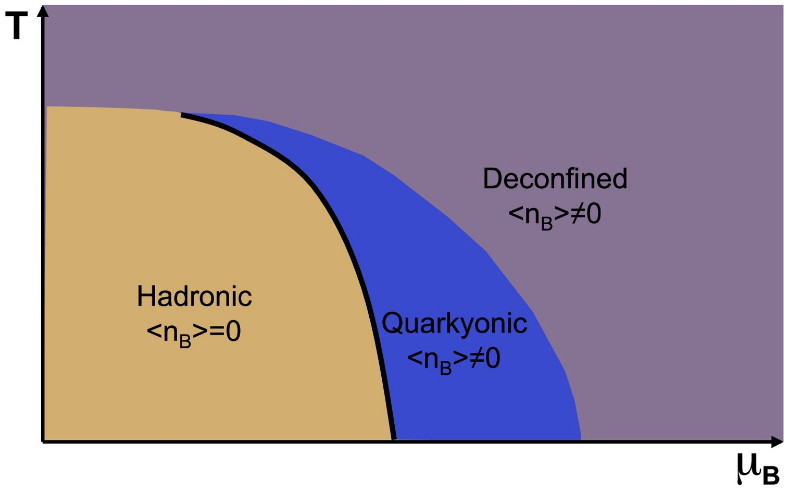
QCD-like Theory



Phases at large N_c - *dense* nuclear matter but *confined* phase.
Baryon number is the order parameter for transition.

L. McLerran, R.D. Pisarski
Nucl. Phys. A, 796 (2007), p. 83
Y. Hidaka, L.D. McLerran, R.D. Pisarski
Nucl. Phys. A, 808 (2008), p. 117

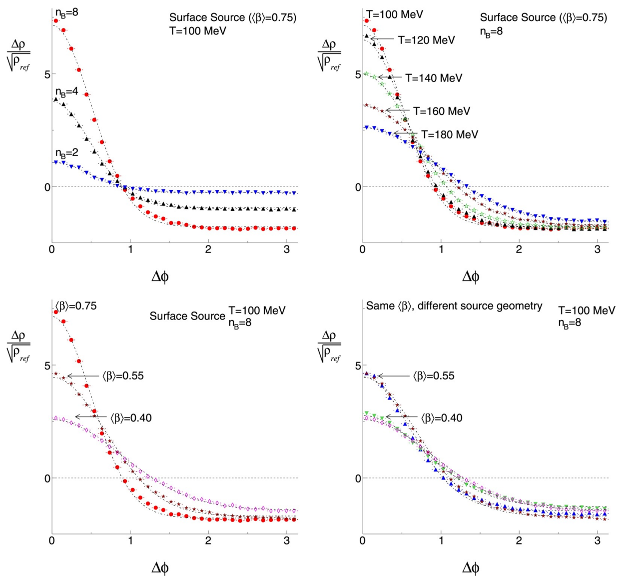
Region in phase diagram



Large *Nc*, baryon mass $M_B \sim N_c \Lambda_{QCD}$. *For* $T \sim \Lambda_{QCD}$, baryon number is $n_B \sim \exp(\mu_B/T - M_B/T) \sim e^{-Nc}$ (negligibly small) and it remains that way as long as $\mu_B < M_B$. For larger μ_B the n_B becomes non-zero. In the deconfined quark–gluon plasma phase there are no baryon masses, so that there is no baryon-number suppression.

Experimental signature

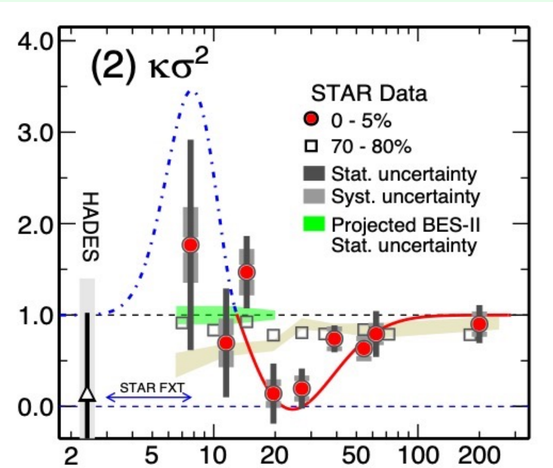
Phys.Lett.B 690 (2010) 135-140

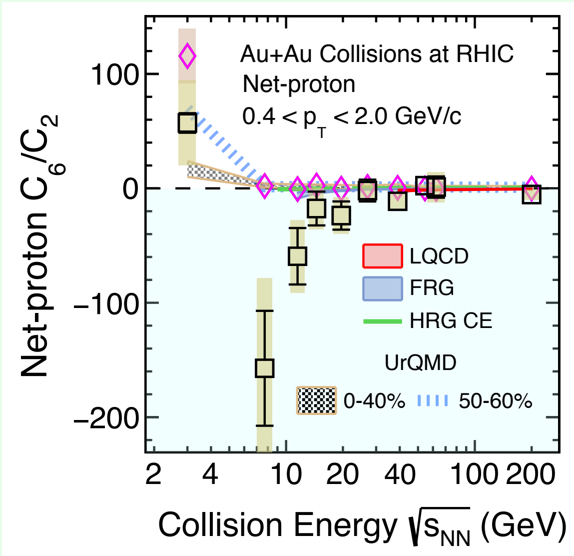


$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}} = \frac{d^2N/(d\phi_1\, d\phi_2) - (dN/d\phi_1)\cdot(dN/d\phi_2)}{\sqrt{(dN/d\phi_1)\cdot(dN/d\phi_2)}}$$

Baryon-Baryon correlations to look for nucleation of baryon rich bubbles surrounded by baryon free regions

Summary – QCD phase structure





- Programs to carry out systematic study of the phase structure of QCD phase diagram through relativistic heavy ion collisions underway. Baryons play a crucial role.
- Higher moments measurements seem to follow QCD thermodynamics except at 3 GeV
- Experimental evidences of signatures related to critical point observed at a 3 σ level
- Lattice QCD clearly shows cross over at $\mu_B = 0$.
- Experimental indications of cross over at μ_B = 20 MeV observed at < 2 σ level
- Hints of change of equation of state at high μ_B
- First study of role of baryon junction on fluctuation observable presented.

- Need to continue the dedicated programs in the high baryon density regime to unfold the QCD phase diagram. This includes looking for Moat and Quarkyonic matter regimes

- Experiments: STAR@RHIC BES-II, CBM@FAIR, NICA@JNIR, SHINE@CERN-SPS, J-PARC-HI and CEE-HIAF complementary to each other

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Zhangbu Xu and Nu Xu for discussions

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