Fluctuation measurements at RHIC-STAR

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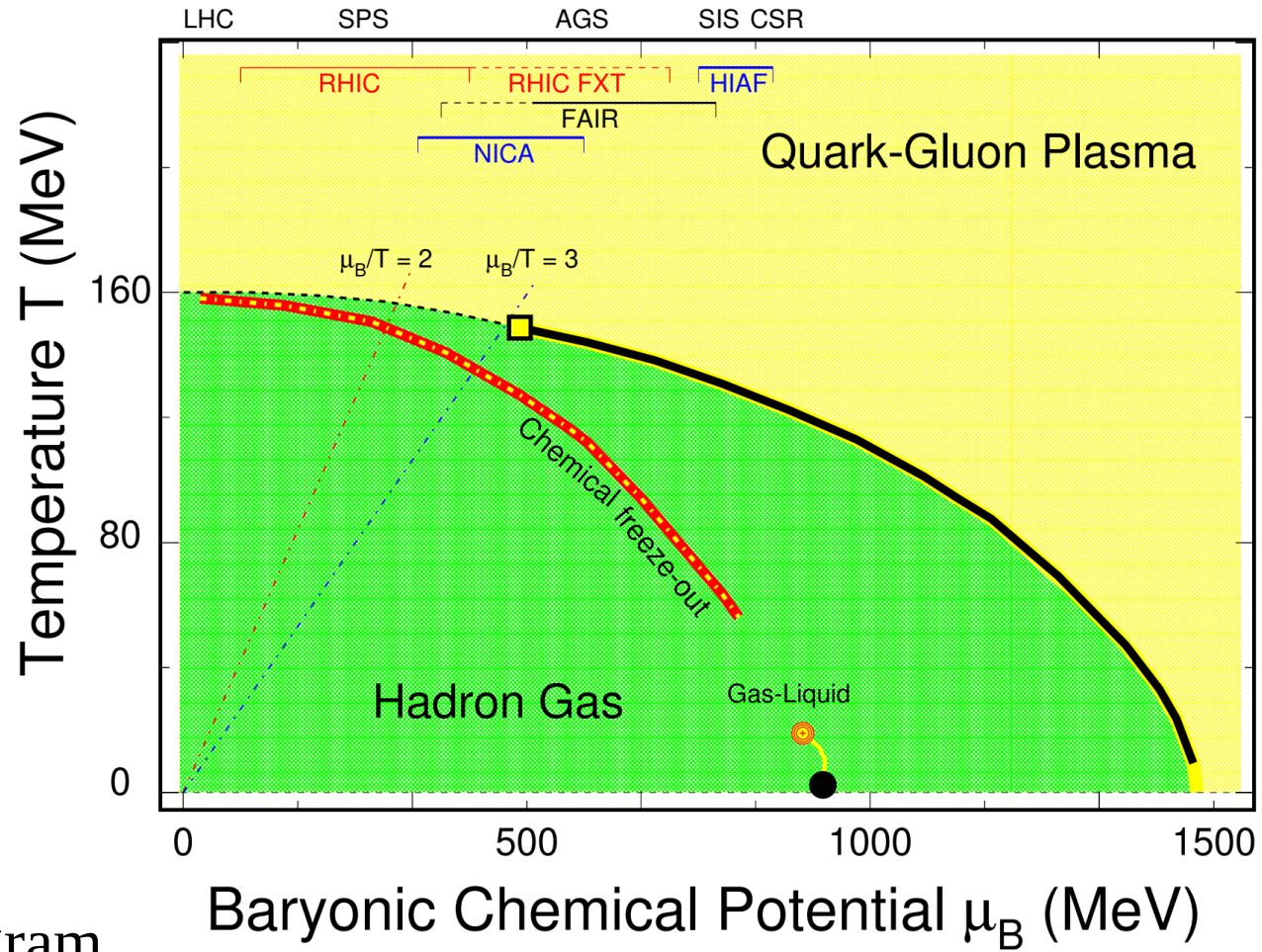
Outline

- Introduction
- Results on fluctuations from STAR
  - Search for critical point
  - Search for crossover
  - Other motivations
- Future prospects
- Summary

Introduction: QCD phase structure

- Crossover at $\mu_B = 0$
  - Predicted by lattice QCD
  - $T = (156 \pm 1.5)$ MeV
- 1st-order phase transition
  - At higher μ_B
  - Predicted by QCD-based model
- QCD critical point?
  - Existence and possible location
- Experimental scan of QCD phase diagram
  - By varying collision energy $\sqrt{s_{NN}}$

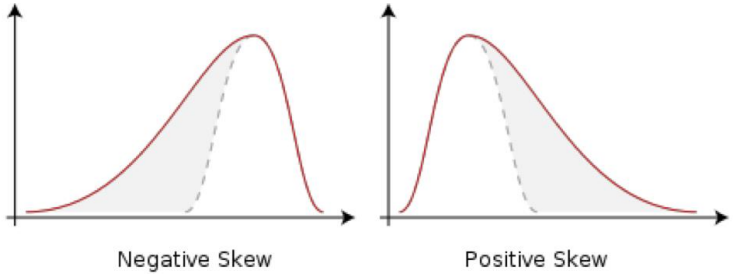


B. Mohanty, N. Xu, arXiv:2101.09210
Y. Aoki, Nature 443, 675-678 (2006)
HotQCD, PLB 795, 15-21 (2019)
M. A. Halasz, PRD 58, 096007 (1998)

Introduction: experimental observables

- Higher-order cumulants of net-particle multiplicities
  - Proxies for conserved charges (B, Q, S)
  - $\mu_r = \langle (N - \langle N \rangle)^r \rangle$: rth-order central moment
  - $C_1 = M \quad = \langle N \rangle \qquad\qquad = VT^3\chi_1^q$
  - $C_2 = \sigma^2 \quad = \mu_2 \qquad\qquad = VT^3\chi_2^q \sim \xi^2$
  - $C_3 = S\sigma^3 = \mu_3 \qquad\qquad = VT^3\chi_3^q \sim \xi^{4.5}$
  - $C_4 = \kappa\sigma^4 = \mu_4 - 3\mu_2^2 \qquad = VT^3\chi_4^q \sim \xi^7$
  - $C_5 \qquad = \mu_5 - 10\mu_3\mu_2 \qquad = VT^3\chi_5^q \sim \xi^{9.5}$
  - $C_6 = \mu_6 - 15\mu_4\mu_2 - 10\mu_3^2 + 30\mu_2^3 = VT^3\chi_6^q \sim \xi^{12}$
  - Sensitive to correlation length (ξ)

Skewness $S = \mu_3/\sigma^3$ → asymmetry

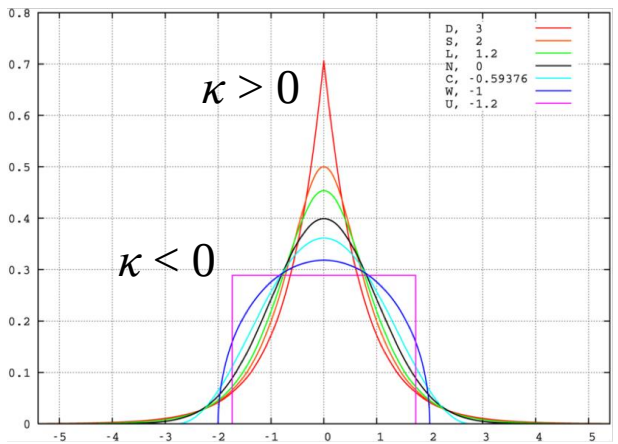


Gaussian: $C_r = 0$ ($r > 2$)

Skellam (Poisson − Poisson):

$C_3/C_1 = C_4/C_2 = C_5/C_1 = C_6/C_2 = 1$

Kurtosis $\kappa = \mu_4/\sigma^4 - 3$ → sharpness

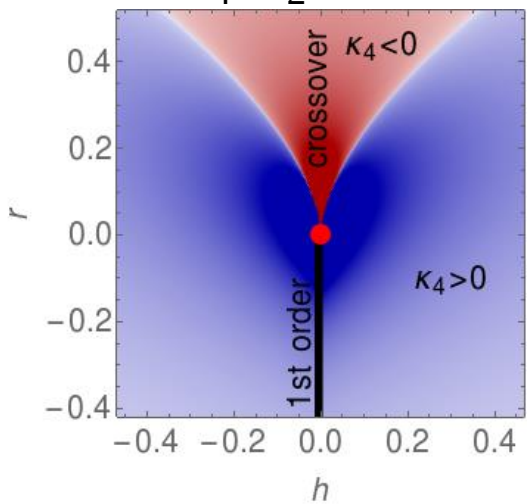


- Directly connected to susceptibilities (χ_r^q, q = B, Q, S)
  - $\frac{C_3^q}{C_2^q} = S\sigma = \frac{\chi_3^q}{\chi_2^q}, \frac{C_4^q}{C_2^q} = \kappa\sigma^2 = \frac{\chi_4^q}{\chi_2^q}$

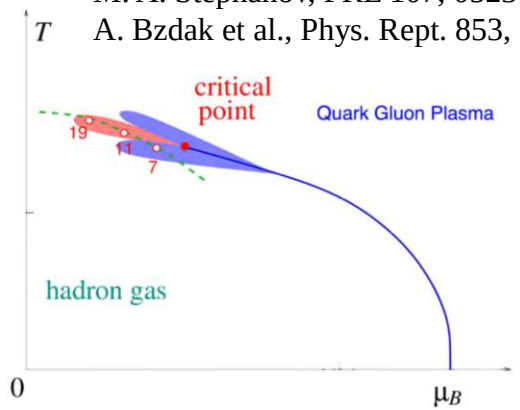
M. A. Stephanov, PRL 102, 032301 (2009)
M. Asakawa et al., PRL103, 262301 (2009)
M. A. Stephanov, PRL107, 052301 (2011)

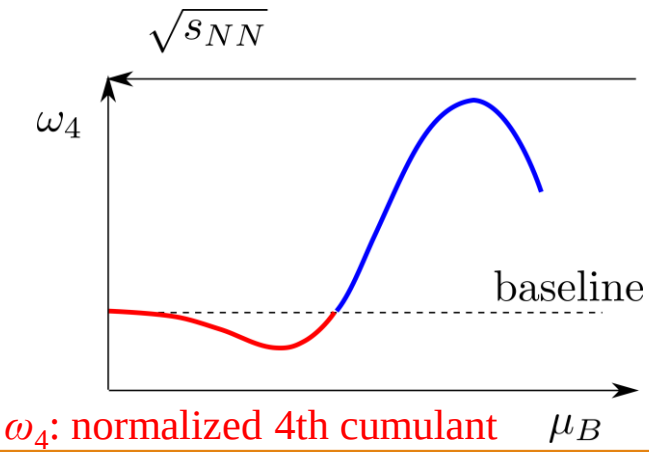
Introduction: predicted signals

- Critical point
  - Non-monotonic energy dependence of C_4/C_2 around baseline



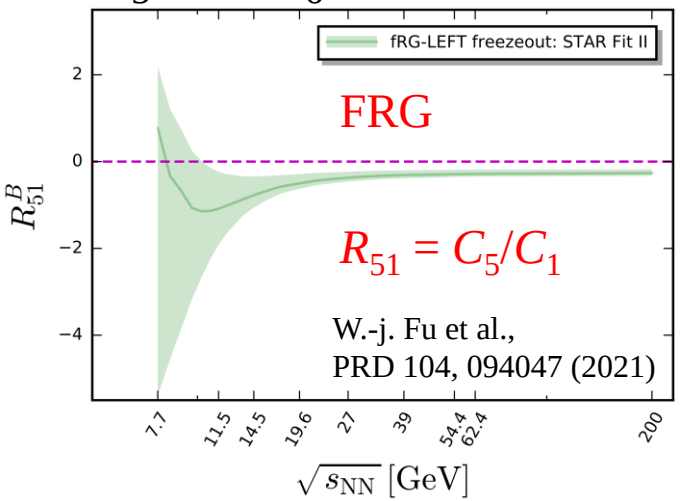
M. A. Stephanov, PRL 107, 052301 (2011)
A. Bzdak et al., Phys. Rept. 853, 1-87 (2020)



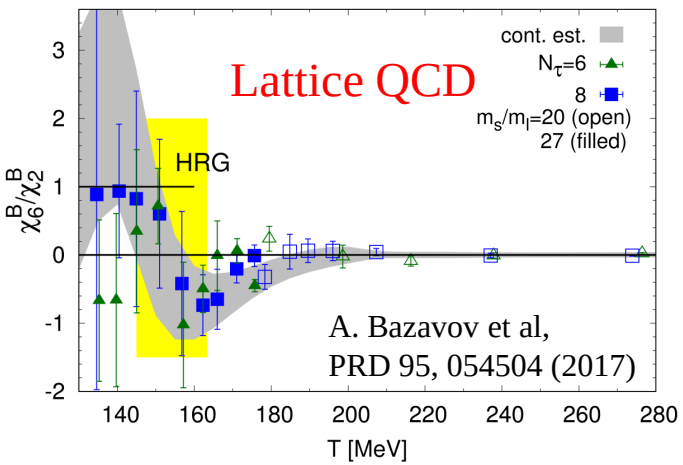


ω_4: normalized 4th cumulant

- Crossover
  - Negative C_5 and C_6



W.-j. Fu et al.,
PRD 104, 094047 (2021)



A. Bazavov et al,
PRD 95, 054504 (2017)

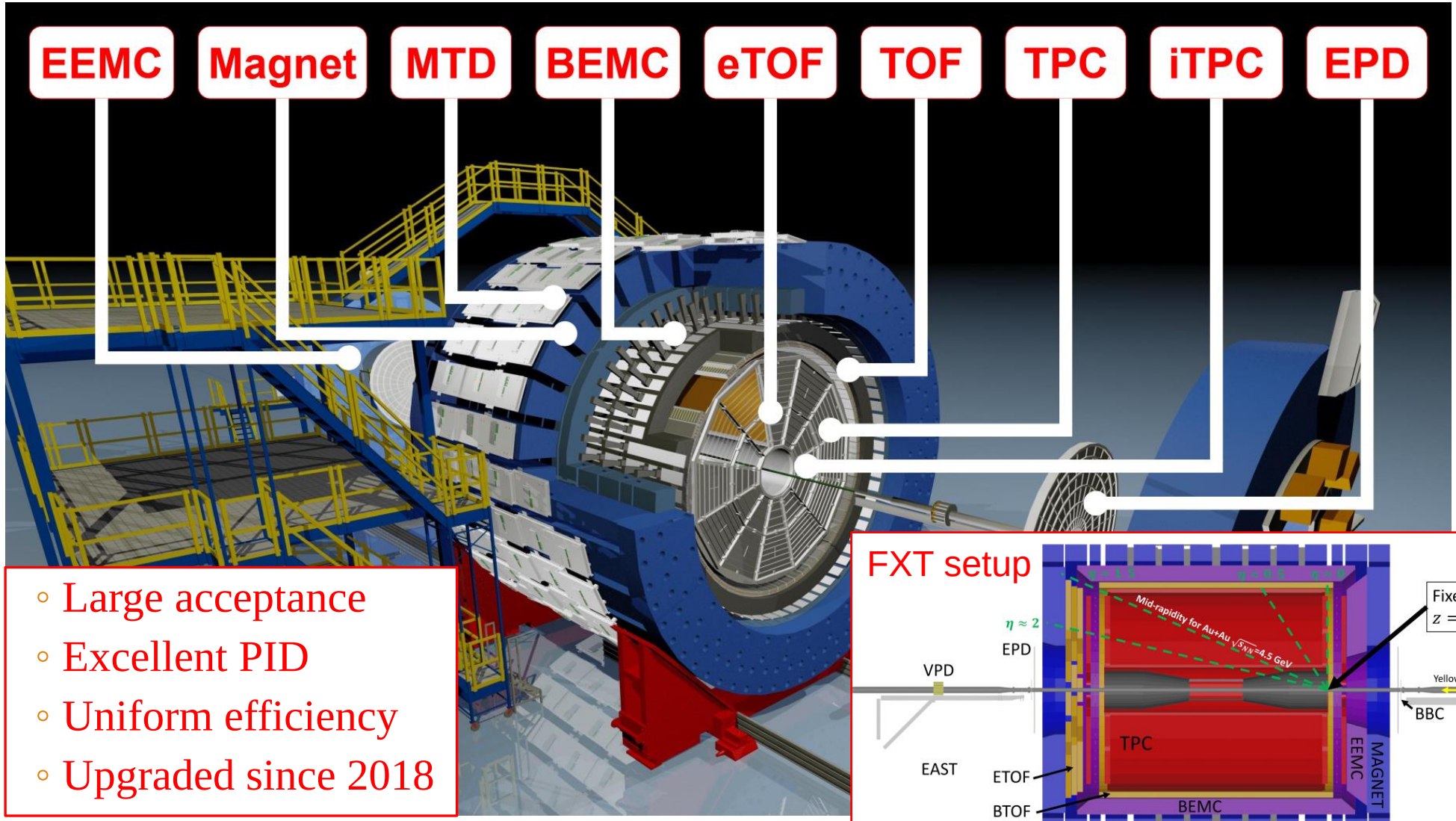
RHIC Beam Energy Scan program

- To map the QCD phase diagram: wide μ_B range (25 – 750 MeV), high statistics

$\sqrt{s_{NN}}$ (GeV)	# Events	Year 20xx (BES-I/**II**)	μ_B (MeV)
200	238M/**138M/20B**	10/**19/23–25**	25
62.4	46M	10	73
54.4	1.2B	17	83
39	86M	10	112
27	30M/**555M**	11/**18**	156
19.6	15M/**478M**	11/**19**	206
17.3	**256M**	**21**	230
14.6	**324M**	**19**	262
14.5	13M	14	264
11.5	7M/**235M**	10/**20**	315
9.2	**162M**	**20**	373
7.7	3M/**101M**	10/**21**	420

$\sqrt{s_{NN}}$ (GeV)	# Events	Year 20xx (**FXT**)	μ_B (MeV)
13.7	**51M**	**21**	276
11.5	**52M**	**21**	315
9.2	**54M**	**21**	373
7.7	**51M/112M**	**19/20**	420
7.2	**155M/317M/89M**	**18/20/21**	440
6.2	**118M**	**20**	487
5.2	**103M**	**20**	541
4.5	**108M**	**20**	589
3.9	**53M/117M**	**19/20**	633
3.5	**116M**	**20**	666
3.2	**201M**	**19**	699
3.0	**258M/2.1B**	**18/21**	750

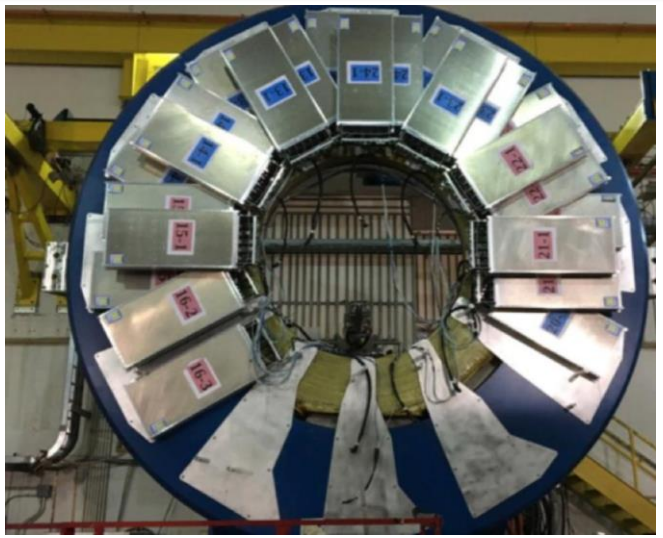
STAR detector system



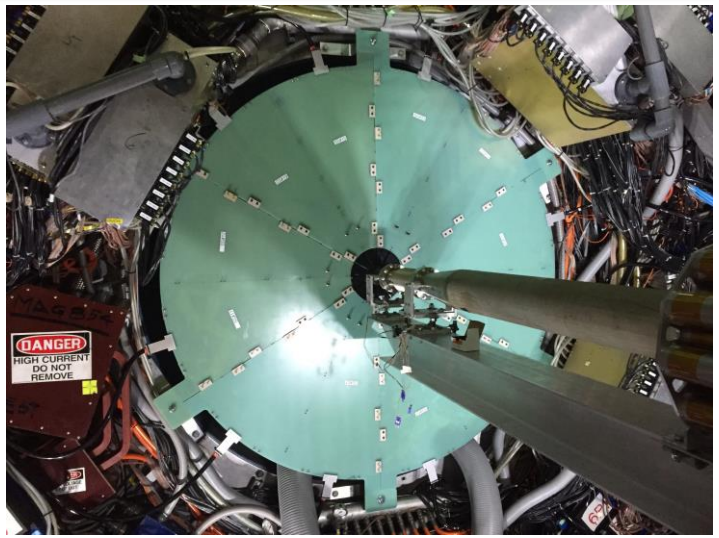
- Large acceptance
- Excellent PID
- Uniform efficiency
- Upgraded since 2018

STAR detector upgrades

- iTPC (since 2019)
  - Improves dE/dx measurement
  - Extends η_{max} from 1.0 to 1.5
    - For FXT, η_{max} from 2.0 to 2.5
  - Lowers p_T cut-in from 125 to 60 MeV/c



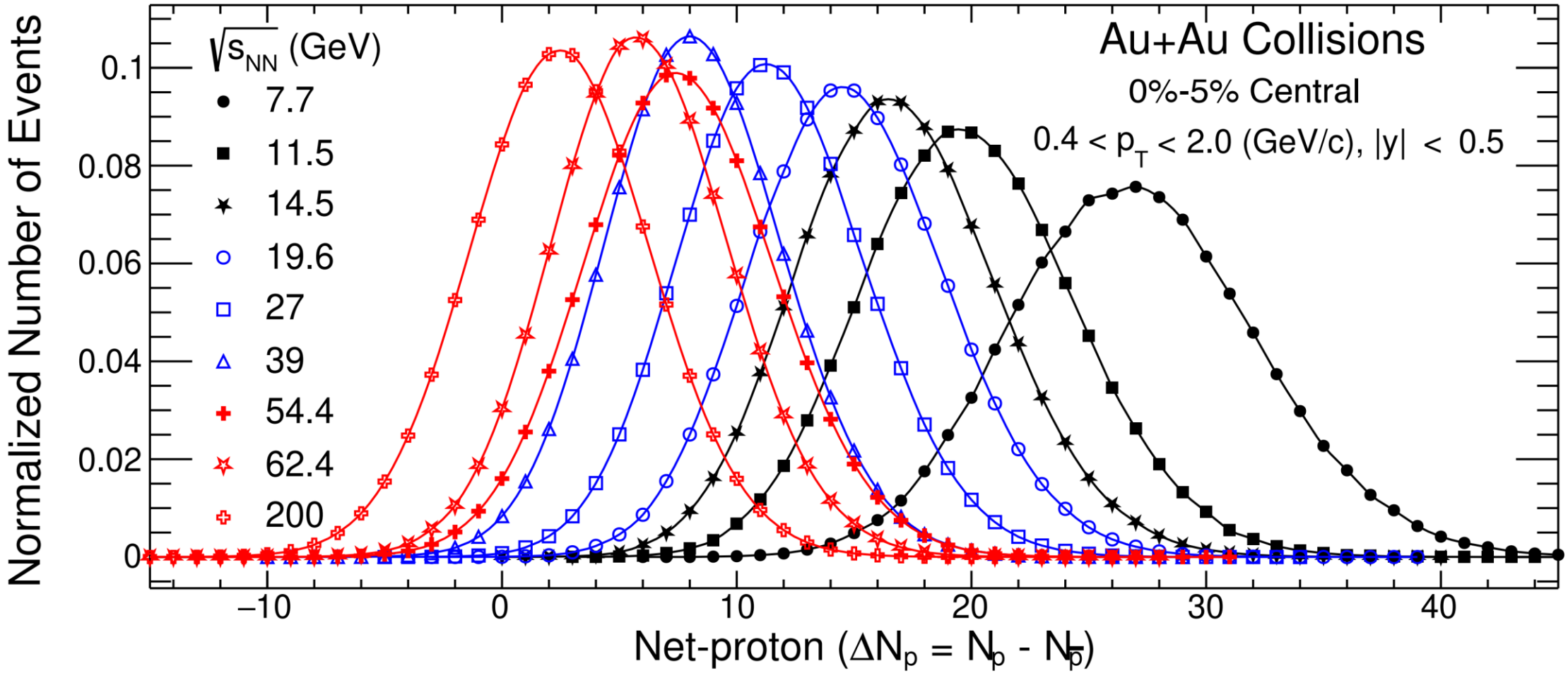
- eTOF (since 2019)
  - Forward rapidity coverage
    - Crucial in fixed-target program
  - PID at $0.9 < \eta < 1.5$
    - For FXT, $1.5 < \eta < 2.5$
  - Provided by FAIR-CBM



- EPD (since 2018)
  - $2.14 < |\eta| < 5.09$
  - Improves trigger
  - Better event plane reconstruction
  - Better centrality determination

iTPC: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
eTOF: STAR and CBM eTOF Group, arXiv:1609.05102
EPD: J. Adams et al., NIMA 968, 163970 (2020)

Raw net-proton multiplicity distributions

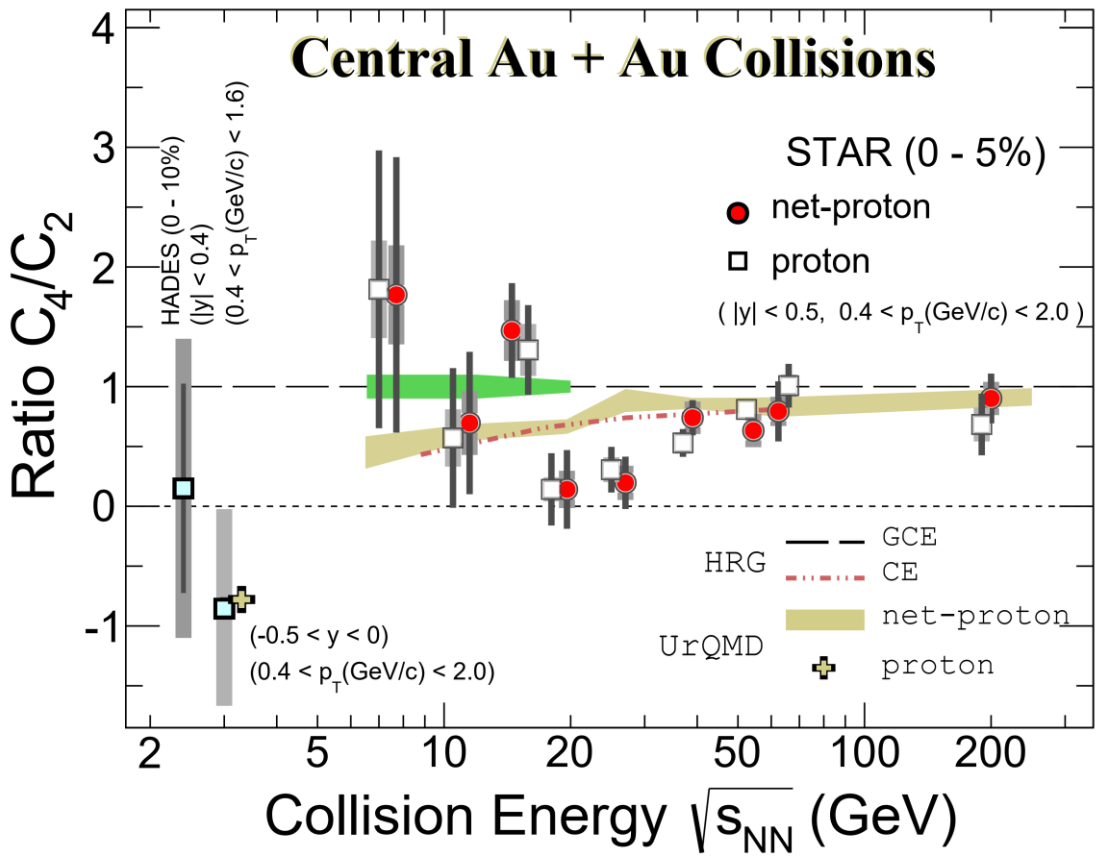


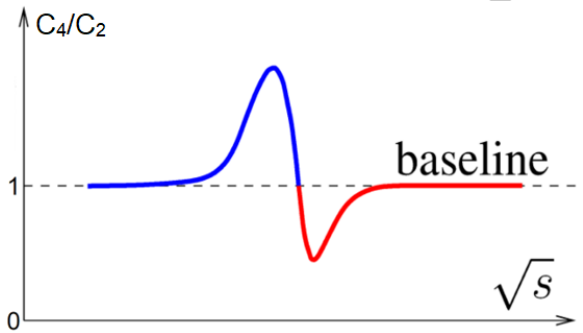
- Efficiency-uncorrected in top 5% central collisions at $\sqrt{s_{\mathrm{NN}}}$ = 7.7 – 200 GeV (BES-I)
- Decreasing mean values as collision energy increases

STAR, PRL 126, 092301 (2021)

Critical point search: net-proton C_4/C_2

- Non-monotonic energy dependence (3.1σ)
  - Qualitatively consistent with prediction considering critical point
  - Deviates from non-critical models
- Significant suppression at $\sqrt{s_{NN}}$ = 3.0 GeV
  - Reproduced by UrQMD model (baryon-conservation driven)
  - Predominantly hadronic matter
- Critical region could only exist at $\sqrt{s_{NN}}$ > 3.0 GeV if created in HIC



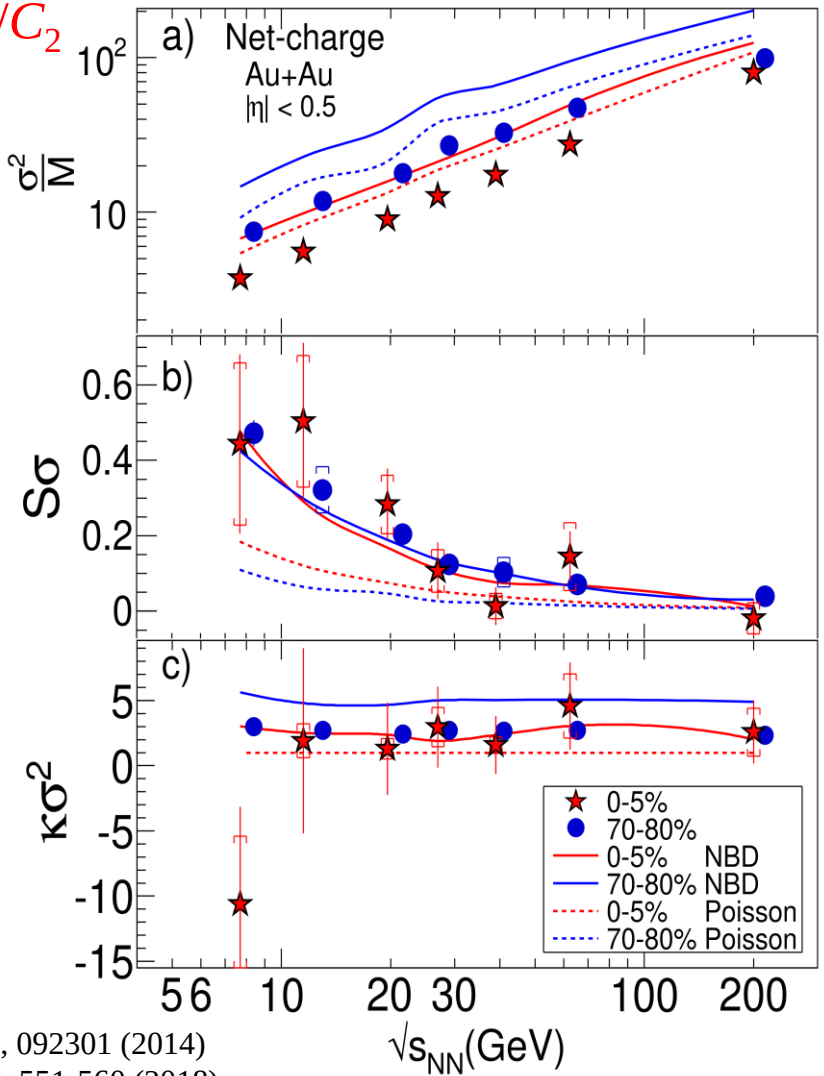


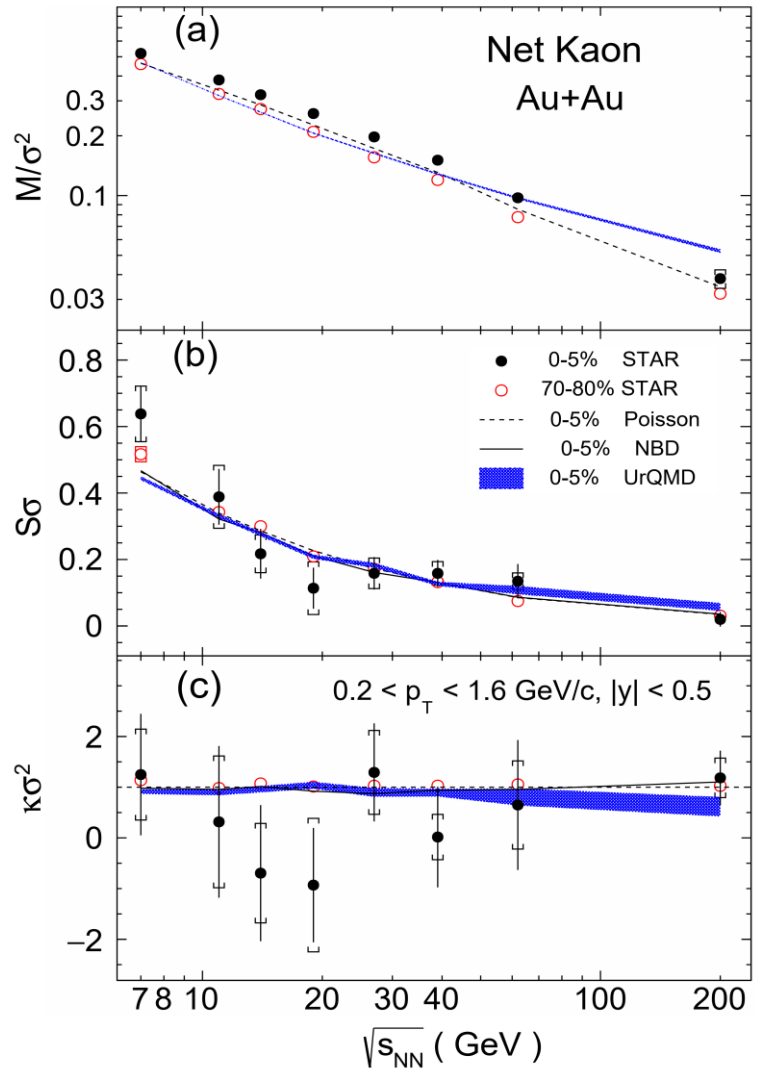
STAR, PRL 126, 092301 (2021)
STAR, PRC 104, 024902 (2021)
STAR, PRL 128, 202303 (2022)
STAR, PRC 107, 024908 (2023)

Critical point search: net-charge & net-kaon cumulants

$\sigma^2/M = C_2/C_1$, $S\sigma = C_3/C_2$, $\kappa\sigma^2 = C_4/C_2$

- No clear centrality dependence of C_3/C_2 and C_4/C_2
- Monotonic energy dependence of all three cumulant ratios observed
- Large C_4/C_2 uncertainties
  - High statistics in BES-II required for further measurements

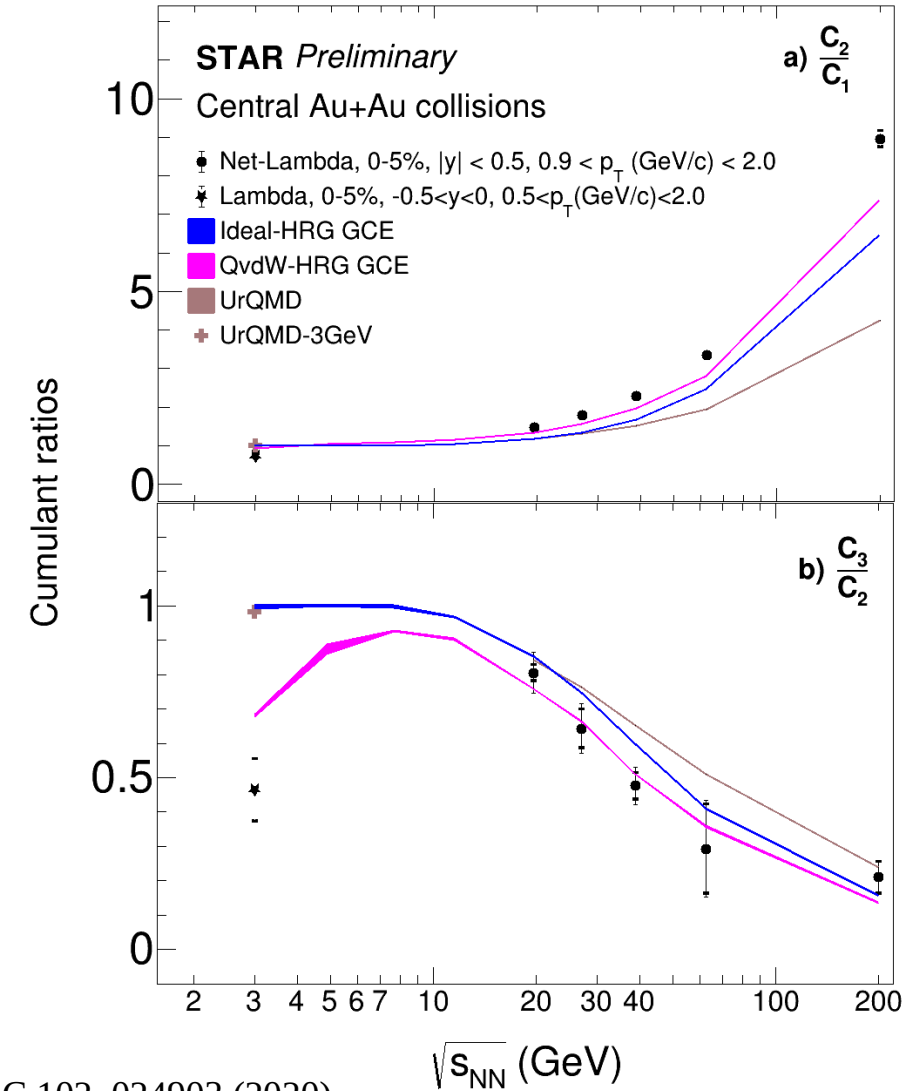




STAR, PRL 113, 092301 (2014)
STAR, PLB 785, 551-560 (2018)

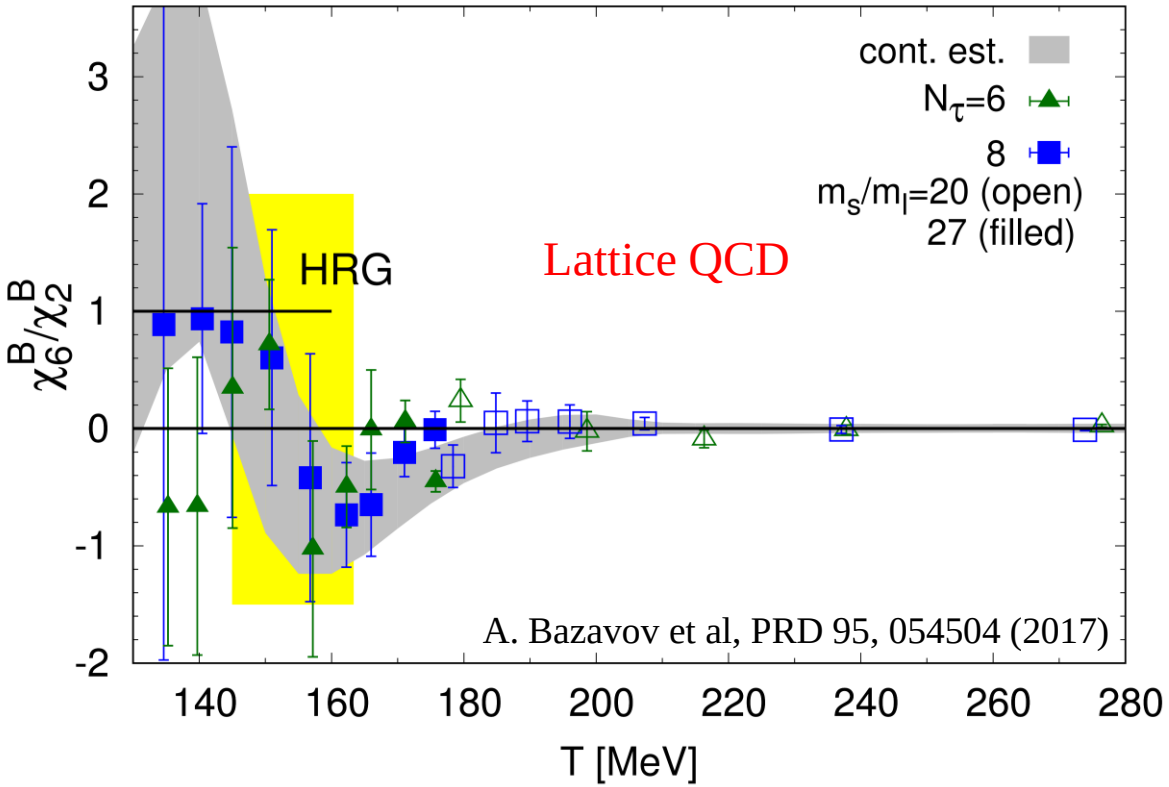
Critical point search: net-Λ cumulants

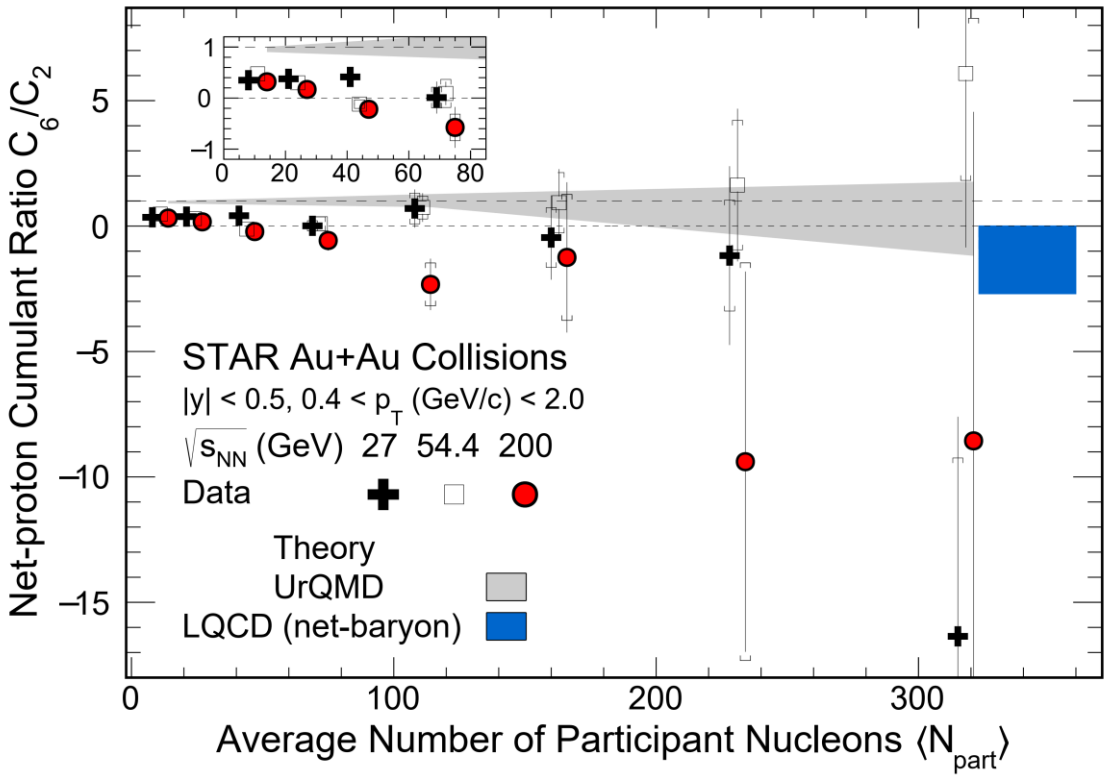
- Both baryon and strangeness in Λ-hyperons
  - Net-Λ fluctuations driven by *B* and *S* conservations
- Monotonic energy dependence of C_2/C_1 & C_3/C_2 at $\sqrt{s_{NN}}$ = 19.6 – 200 GeV
  - Qualitatively predicted by models
- Clear suppression of C_3/C_2 at $\sqrt{s_{NN}}$ = 3.0 GeV
- QvdW-HRG shows better agreement with data
  - Quantum Van der Waals interaction included
  - Effect of hadronic interactions at low energy



STAR, PRC 102, 024903 (2020)

Crossover search: net-proton C_6/C_2

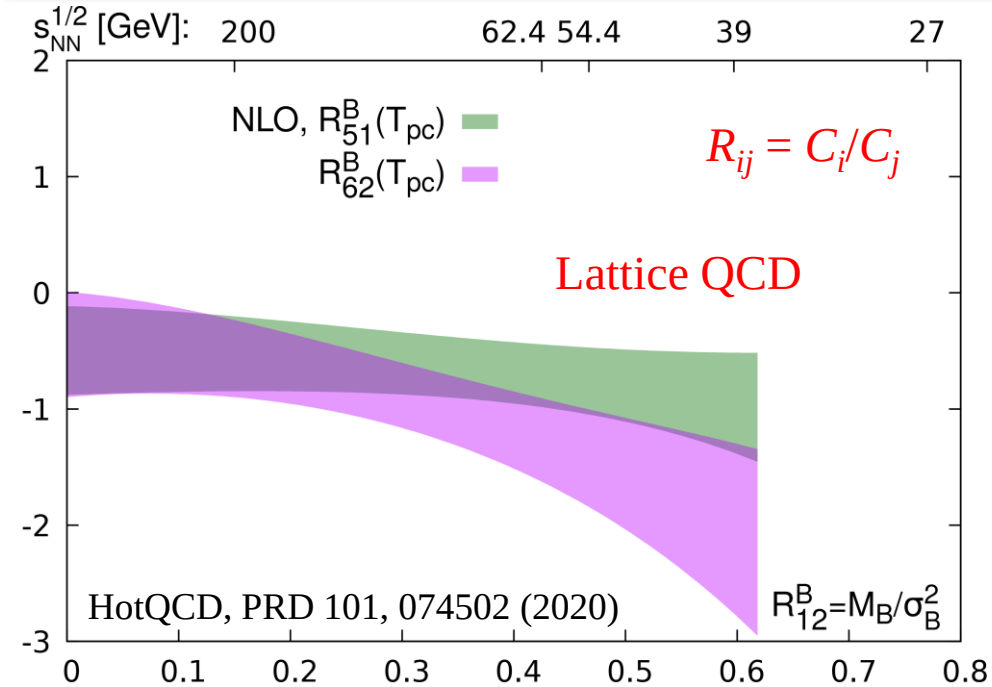


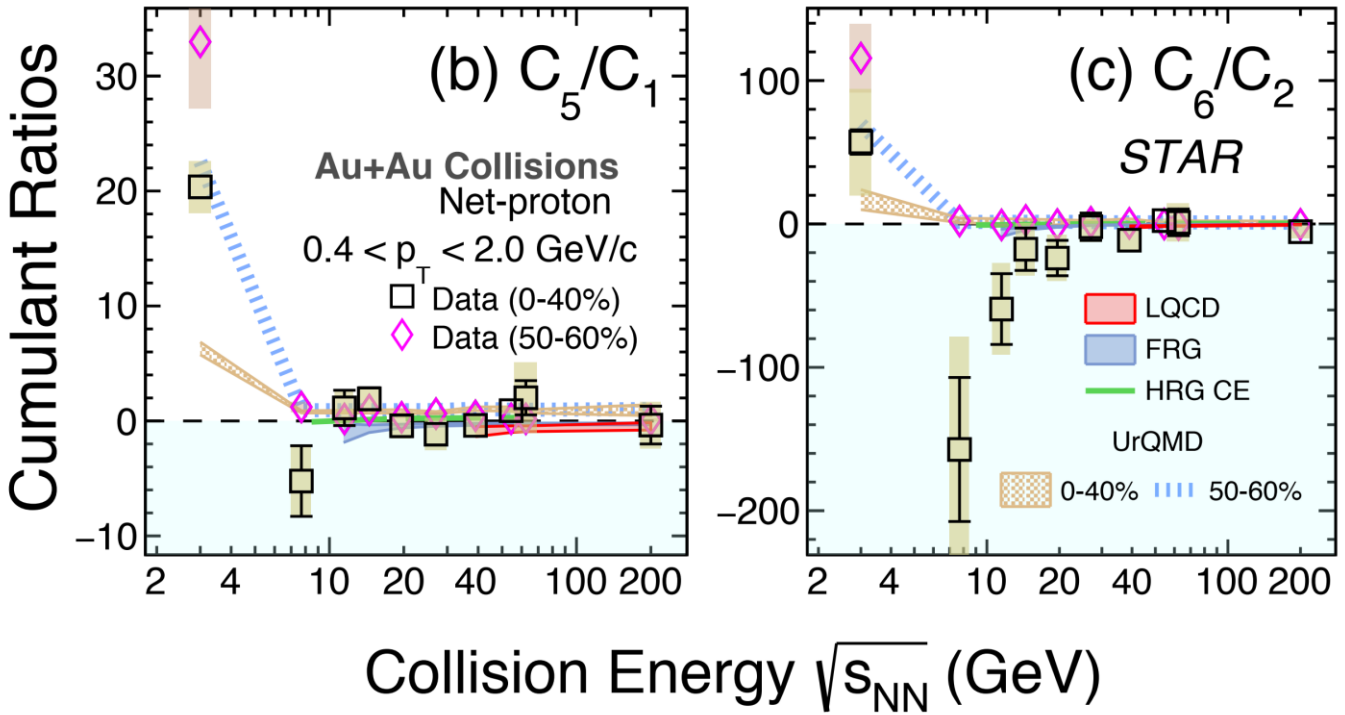


- Progressively negative C_6/C_2 from peripheral to central collisions at $\sqrt{s_{NN}}$ = 200 GeV
- Consistent with lattice QCD calculation in $\sqrt{s_{NN}}$ = 200 GeV central collisions
  - Hint of smooth crossover at top RHIC energy
- UrQMD prediction always around unity (statistical baseline)

STAR, PRL 127, 262301 (2021)

Crossover search: net-proton C_5/C_1 & C_6/C_2

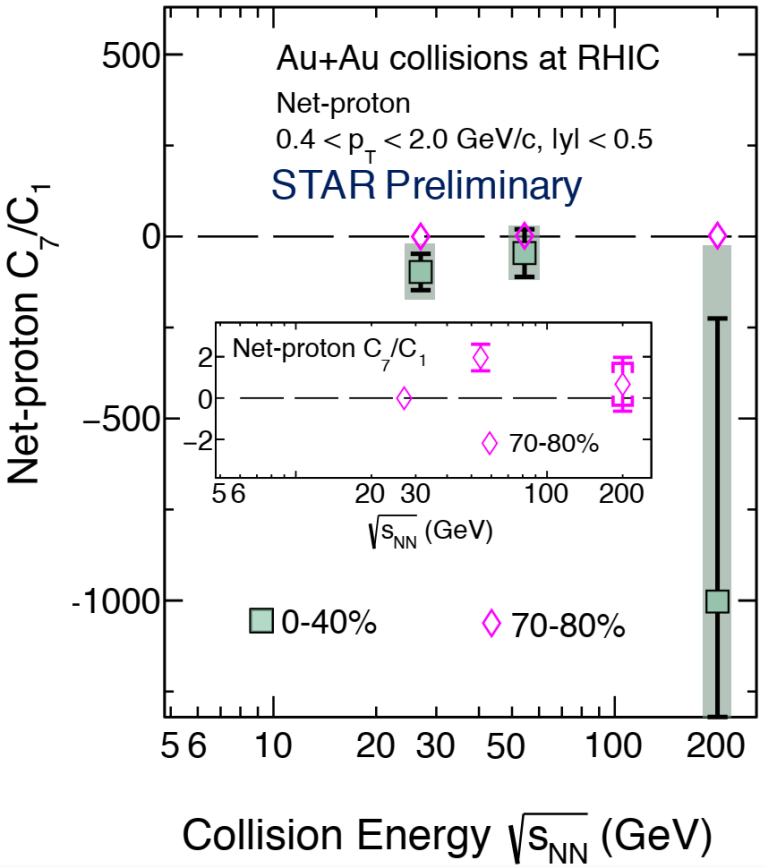


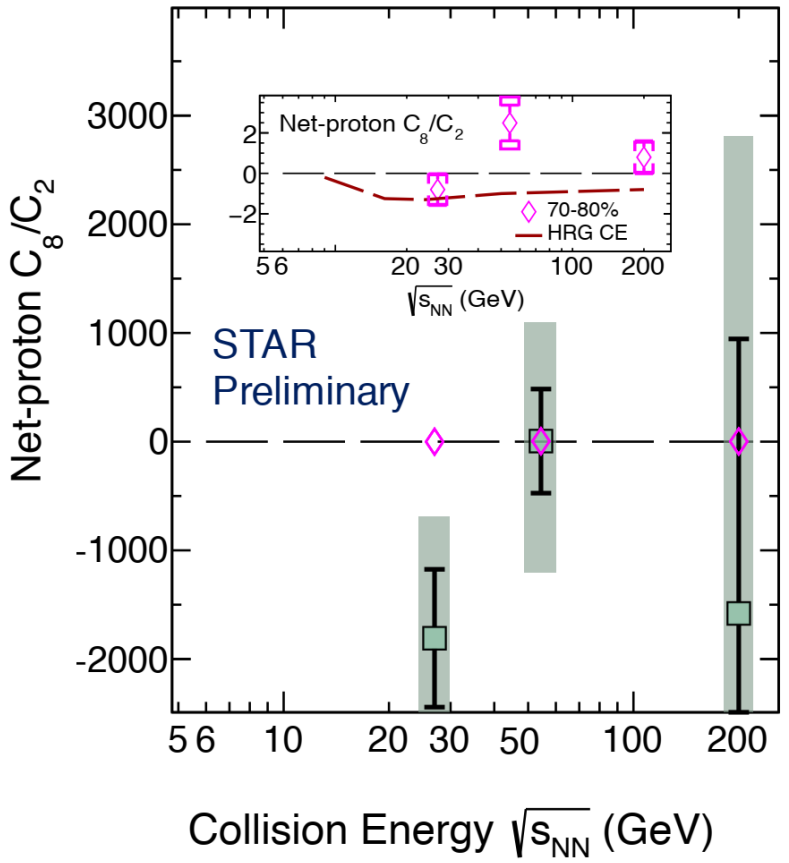


- C_5/C_1 (0-40% at $\sqrt{s_{NN}}$ = 7.7 – 200 GeV) fluctuates around zero at all energies
- Increasingly negative C_6/C_2 (0-40%) as collision energy $\sqrt{s_{NN}}$ decreases down to 7.7 GeV
  - Trend consistent with LQCD calculation (UrQMD always positive or ~ 0)
- Positive C_5/C_1 & C_6/C_2 at 3.0 GeV, obviously different trend

STAR, PRL 130, 082301 (2023)

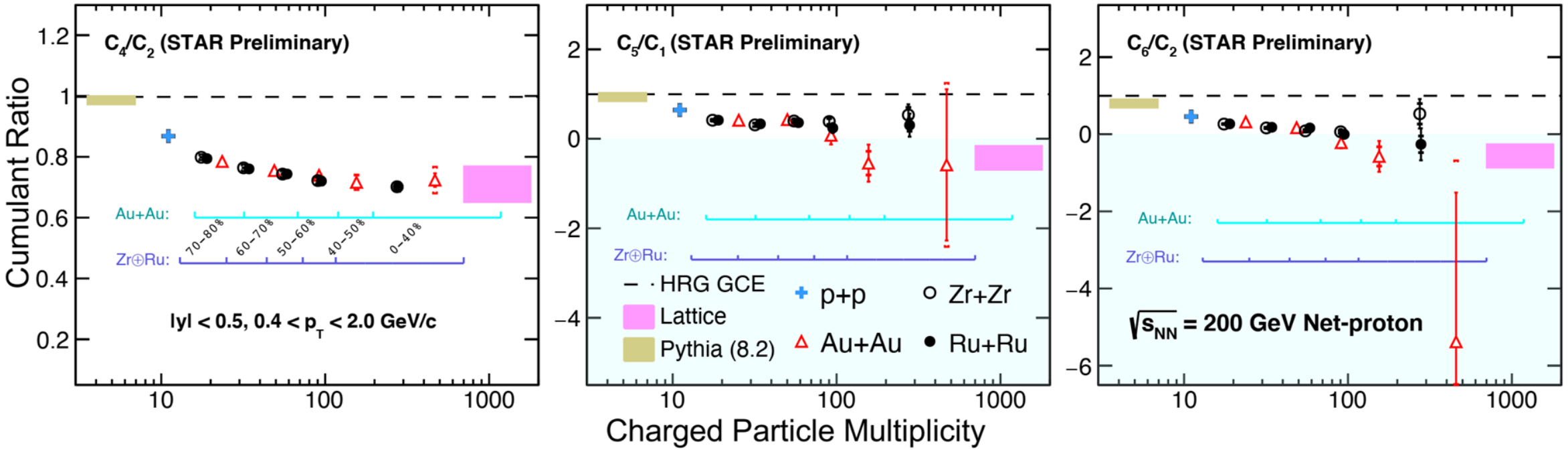
Crossover search: net-proton C_7/C_1 & C_8/C_2





- Peripheral: fluctuates around zero
- Central: negative (~1.4σ) at $\sqrt{s_{\rm NN}}$ = 27 GeV, consistent with zero at 54.4 & 200 GeV
  - No clear energy dependence within large uncertainties

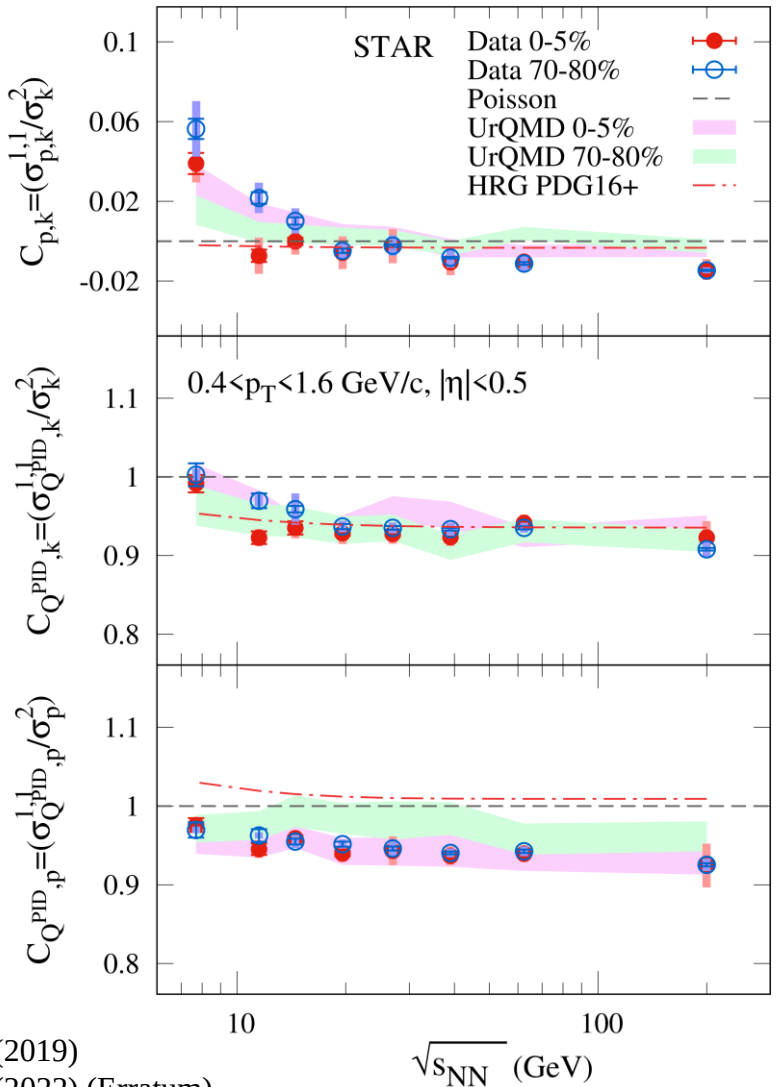
Crossover search: net-proton C_n in different systems



- Results in different systems follow a decreasing trend as multiplicity increases
  - Smoothly connect each other in p+p, Zr+Zr, Ru+Ru and Au+Au collisions
- Cumulant ratios in most central Au+Au collisions agree with lattice QCD calculations
  - Hint of smooth crossover at top RHIC energy

B, *Q*, *S* correlations: net-p,Q,K off-diagonal C_2

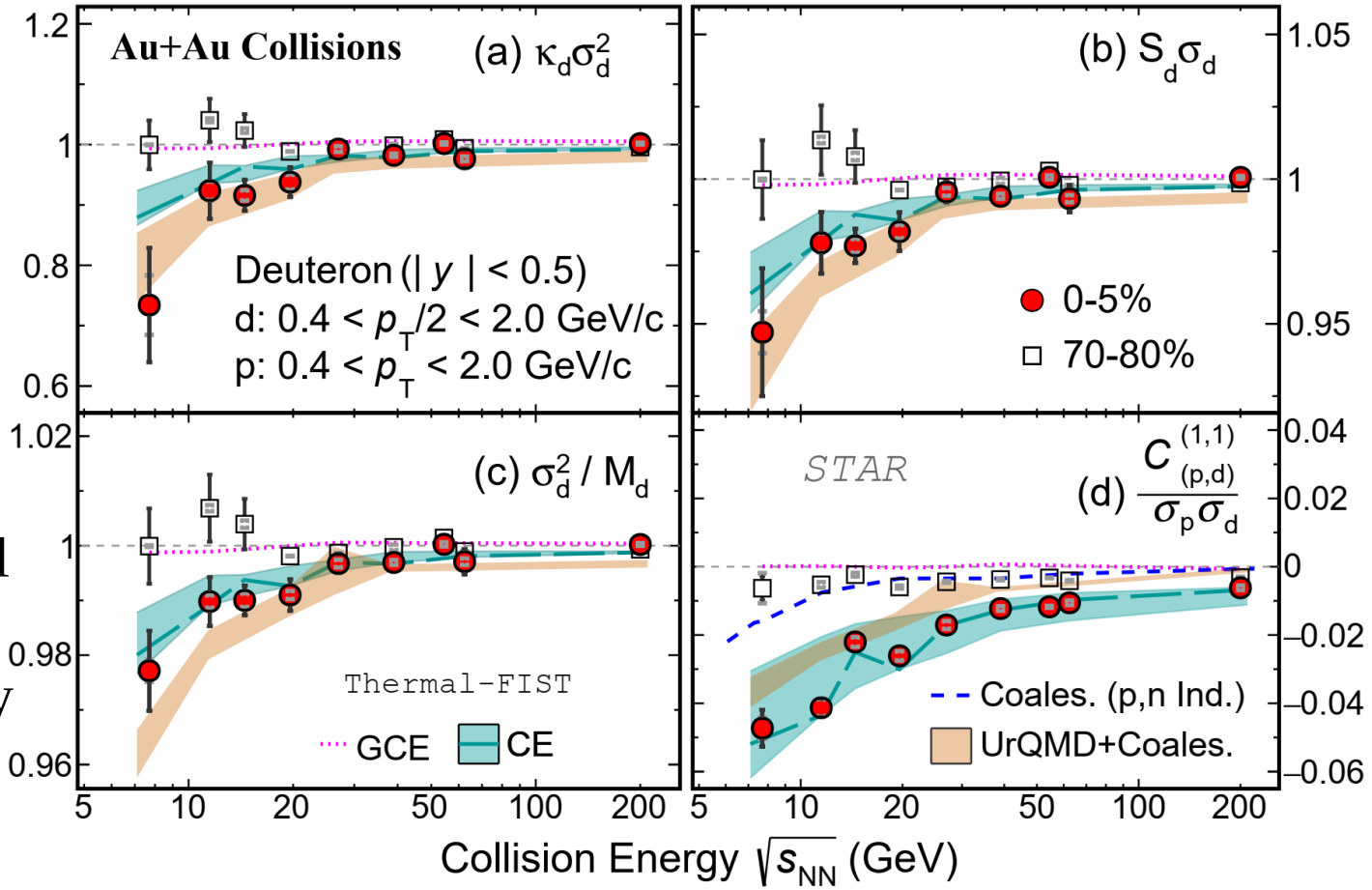
- Second-order off-diagonal to diagonal cumulant ratios between
  - Net-proton and net-kaon
  - Net-charge and net-kaon
  - Net-charge and net-proton
- Roughly reproduced by UrQMD
- No strong dependence on centrality or collision energy
- Possible measurements of *B*, *Q*, *S* correlations including hyperons in BES-II



STAR, PRC 100, 014902 (2019)
STAR, PRC 105, 029901 (2022) (Erratum)

Deuteron production mechanism: deuteron cumulants

- Deuteron cumulant ratios
  - Central: monotonically decrease as energy decreases
  - Peripheral: fluctuate around unity, weak energy dependence
- Proton-deuteron correlations
  - Below zero (anti-correlation) at all centralities and energies
  - At top 5% centrality, progressively negative at lower energy

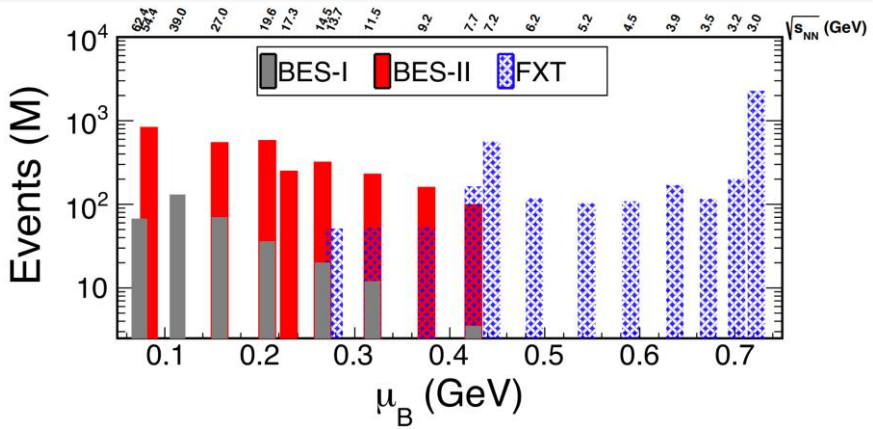


- Energy dependence qualitatively reproduced by UrQMD+Coalescence model and CE Thermal-FIST model

STAR, arXiv:2304.10993

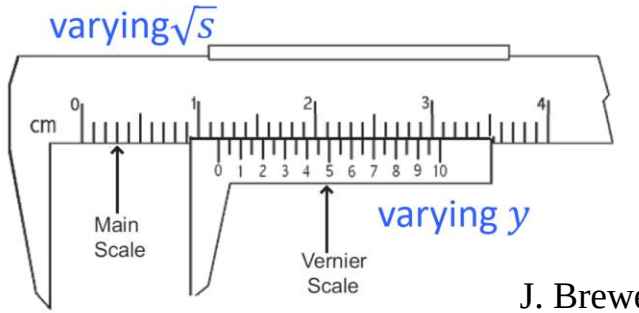
Future prospects: search for critical point

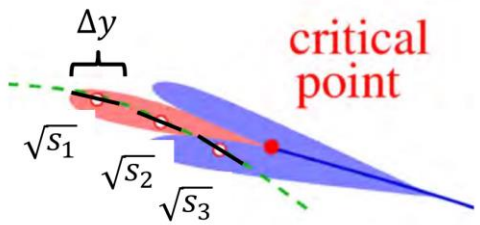
- BES-II collision energies from $\sqrt{s_{NN}}$ = 3.0 to 27 GeV
  - Map QCD phase diagram up to μ_B = 750 MeV
  - Fill in energy gap in $\sqrt{s_{NN}}$ = 3.0 – 7.7 GeV



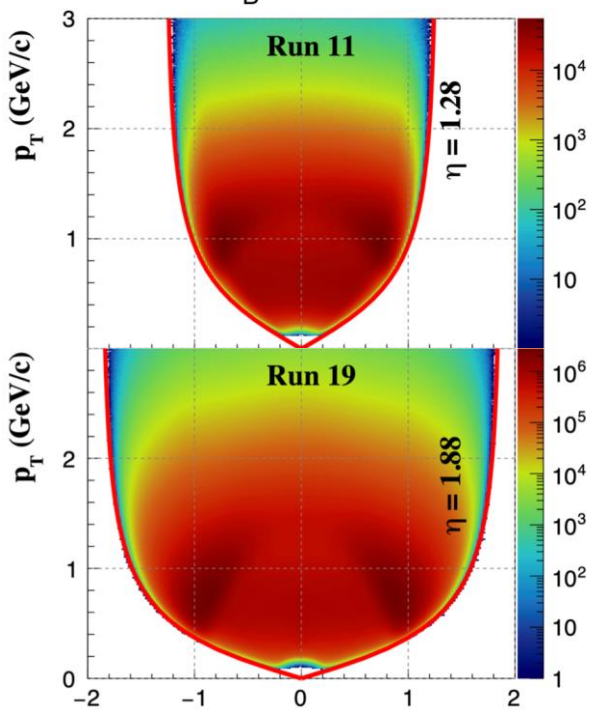
- Much more statistics than BES-I
  - Precision measurements for higher-order fluctuations

- Enlarged rapidity coverage after detector upgrades
  - Rapidity scan: sensitive probe for critical region



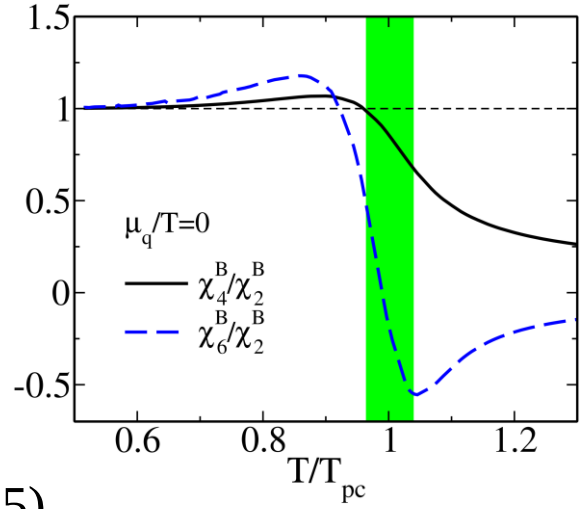


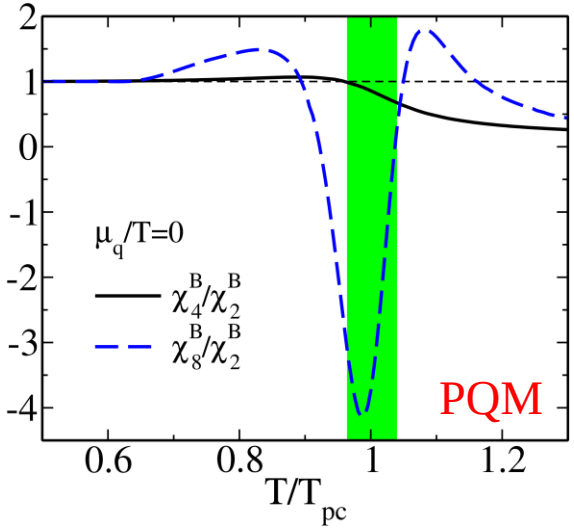
J. Brewer et al., PRC 98, 061901 (2018)

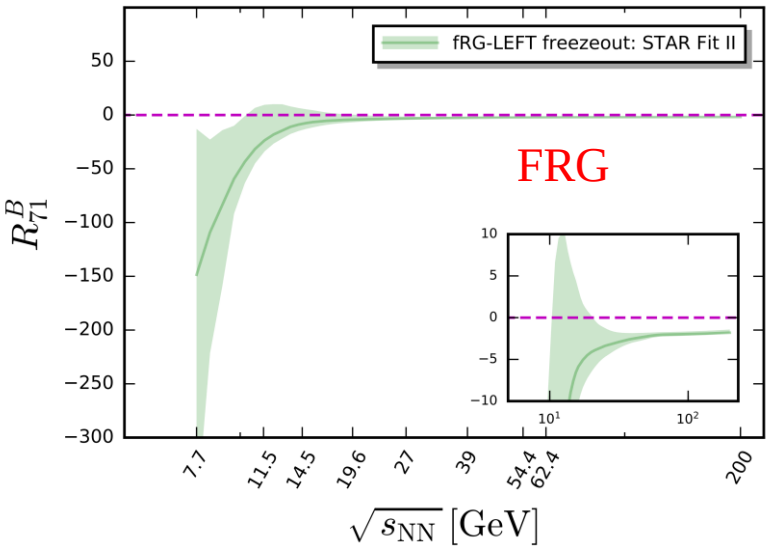


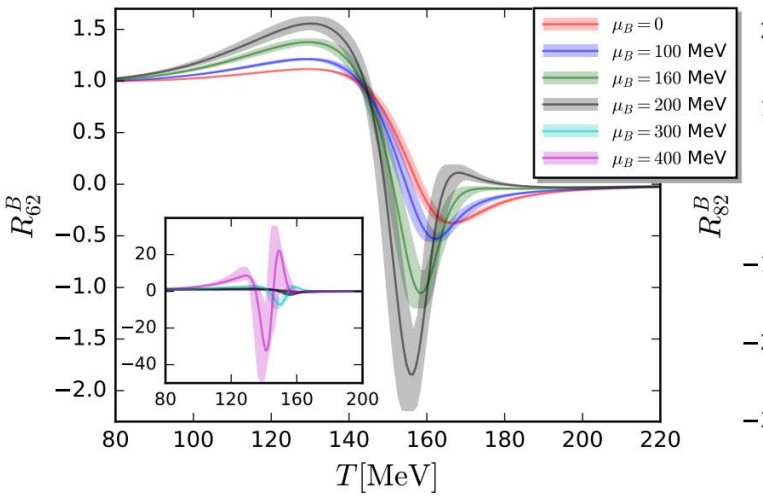
Future prospects: search for crossover

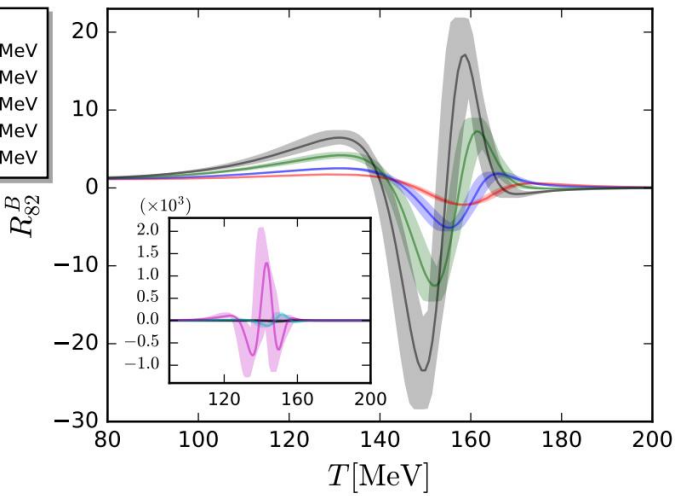
- Precision measurement of hyper-order cumulants $C_5 - C_8$
  - Sensitive probes for crossover
  - Vulnerable to backgrounds
  - Statistics hungry
    - 2.1B events at $\sqrt{s_{\rm NN}}$ = 3.0 GeV (2021)
    - 20B events at $\sqrt{s_{\rm NN}}$ = 200 GeV (2023–2025)







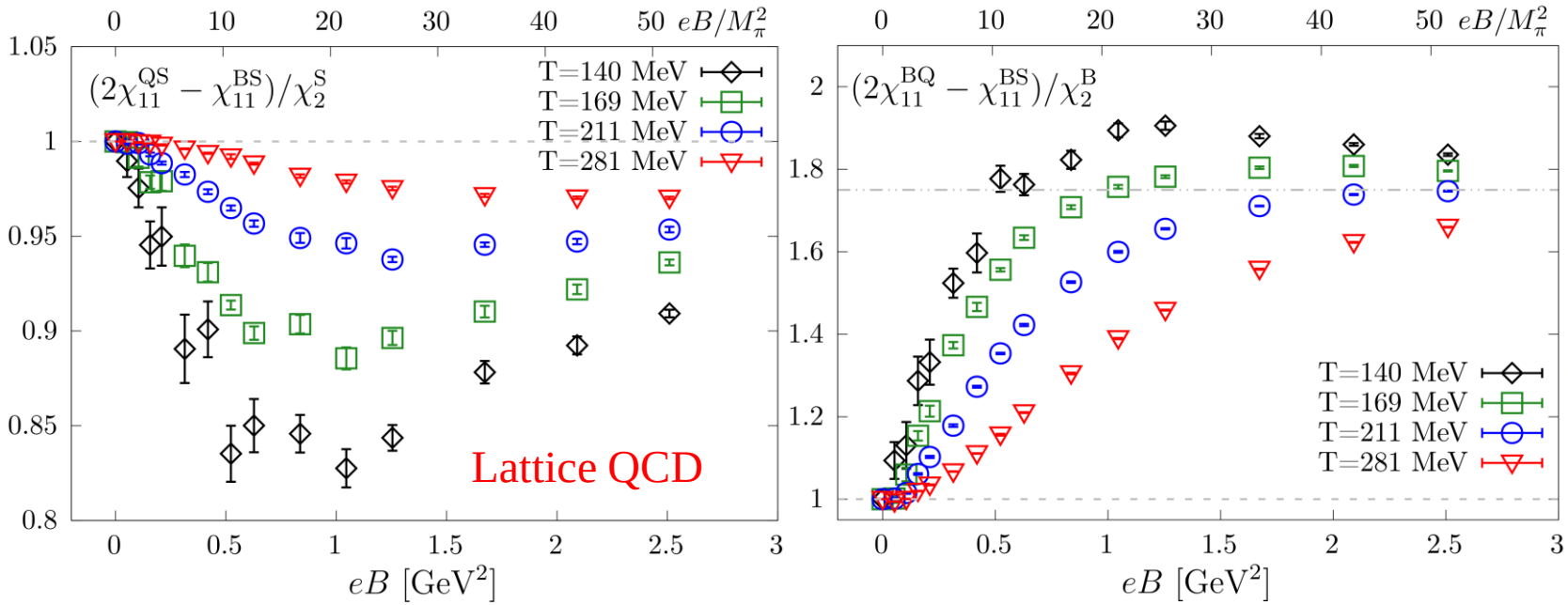




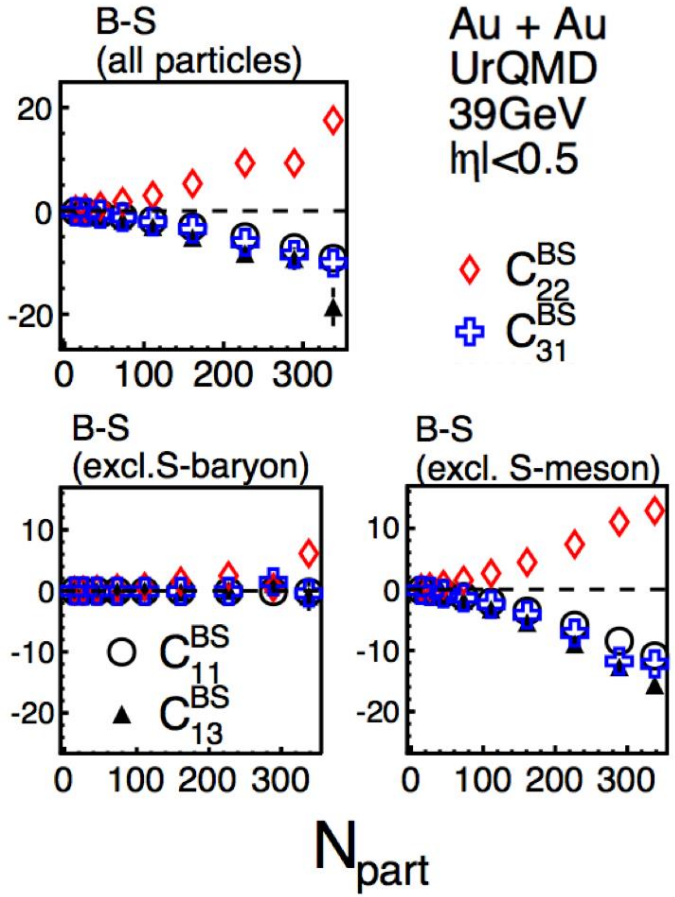
B. Friman et al., EPJC 71, 1694 (2011)
W.-j. Fu et al. PRD 104, 094047 (2021)

Future prospects: probing magnetic field in HIC

- Second-order off-diagonal cumulants of net-baryon, net-charge, net-strangeness
  - Sensitive observable for magnetic field
  - Hyperons (Λ, Ξ, …) should be taken into account
    - Play an important role in *B*-*S* correlations
  - Could be measured in BES-II and isobar (Zr+Zr & Ru+Ru) data

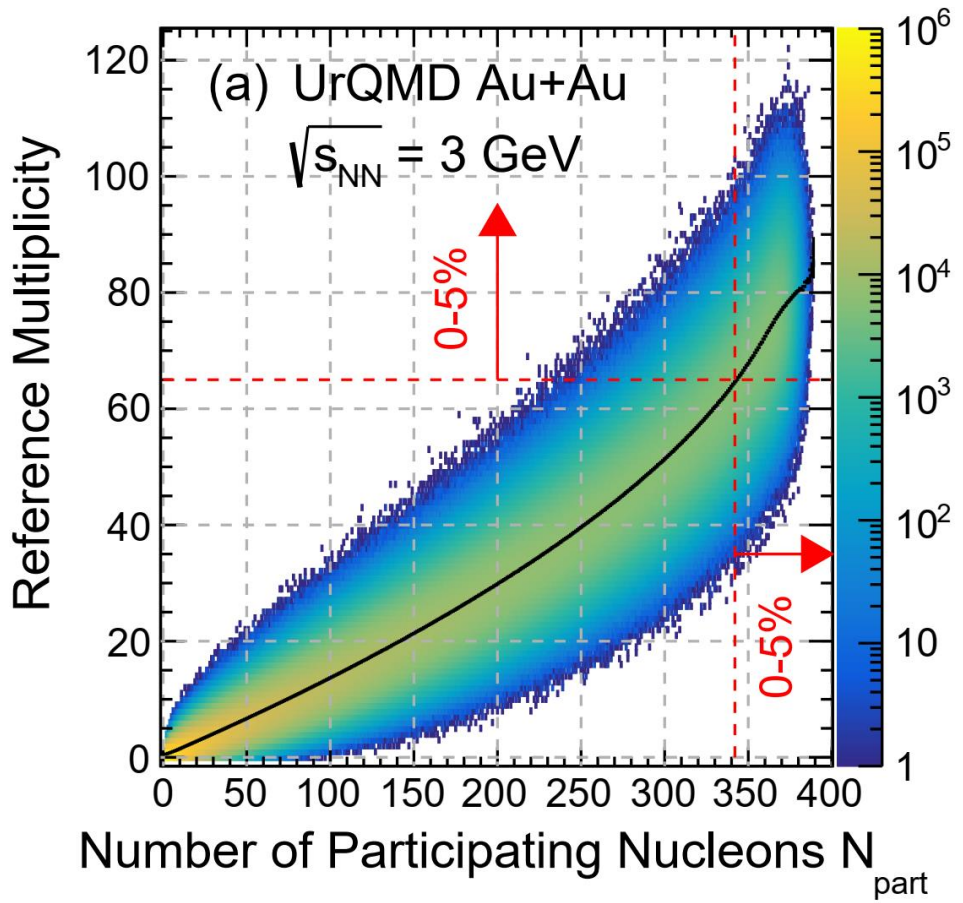


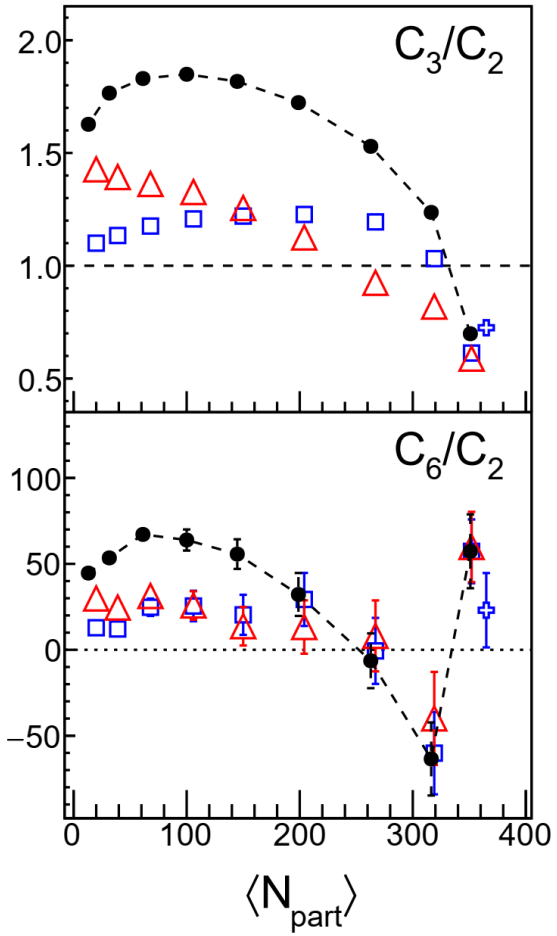
H.-T. Ding et al., EPJA 57, 202 (2021)

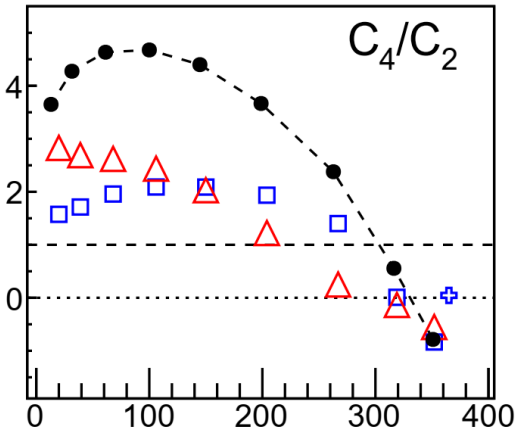


Z. Yang et al., PRC 95, 014914 (2017)

Future prospects: initial volume fluctuation







UrQMD, Au+Au $\sqrt{s_{NN}}$ = 3 GeV
Proton, -0.5 < y < 0
0.4 < p_T < 2.0 GeV/c

- without VF corr.
- VF corr. (UrQMD)
- VF corr. (Glauber)
- b < 3 fm

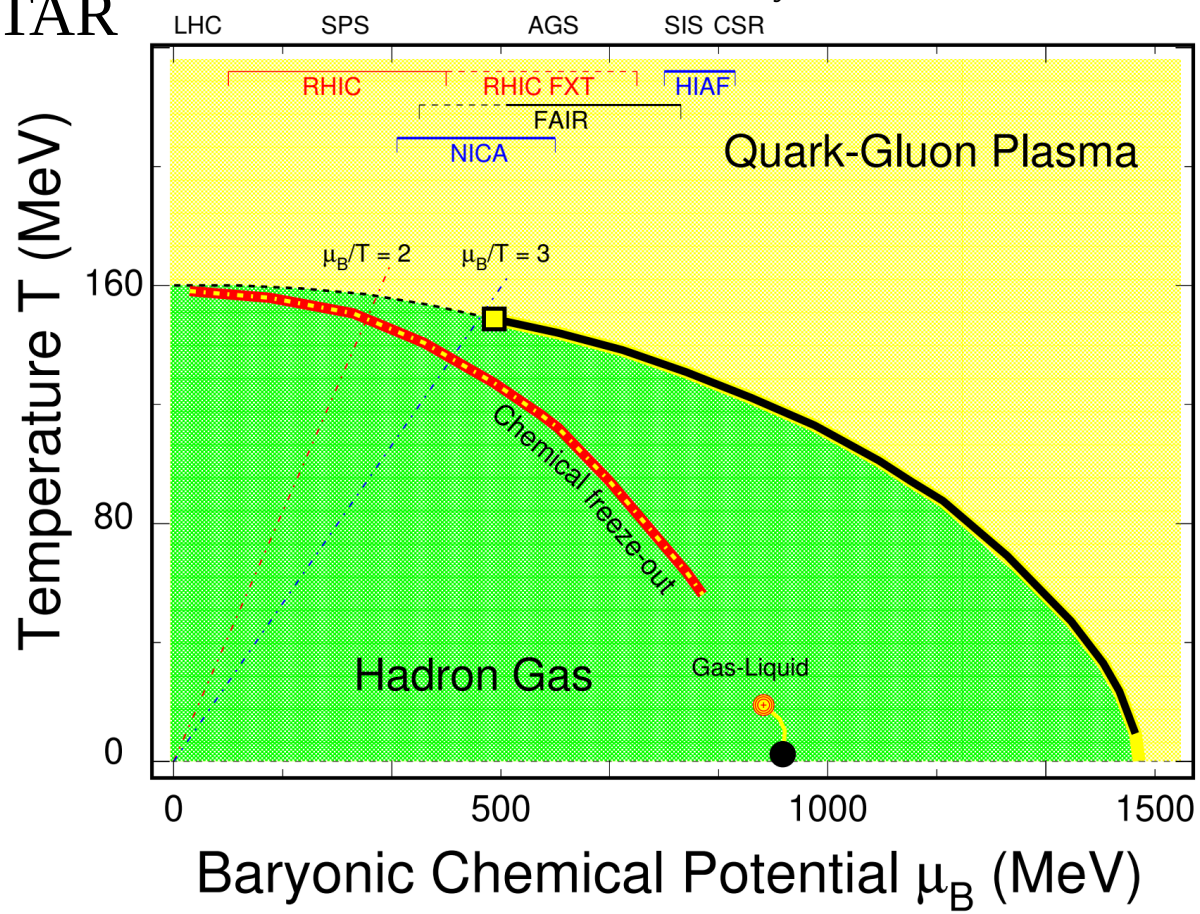
STAR, PRC 107, 024908 (2023)

- Lower multiplicity at lower energy −> worse centrality resolution
- Significant effect of initial volume fluctuation in low-energy collisions

Summary

- Lots of fluctuation measurements from STAR
  - Net-proton, net-charge, net-kaon, …
- Several hints on QCD phase structures
  - Hint of smooth crossover at top RHIC energy
  - Predominantly hadronic matter at $\sqrt{s_{NN}}$ = 3.0 GeV
  - Critical region could only exist at $\sqrt{s_{NN}}$ > 3.0 GeV if created in HIC
- BES-II fluctuation measurements at high baryon density are ongoing!

B. Mohanty, N. Xu, arXiv:2101.09210



Thank you for your attention!