TCHoU Workshop (Quark-Nuclear Matters)

# Fluctuation analysis in STAR BES-II

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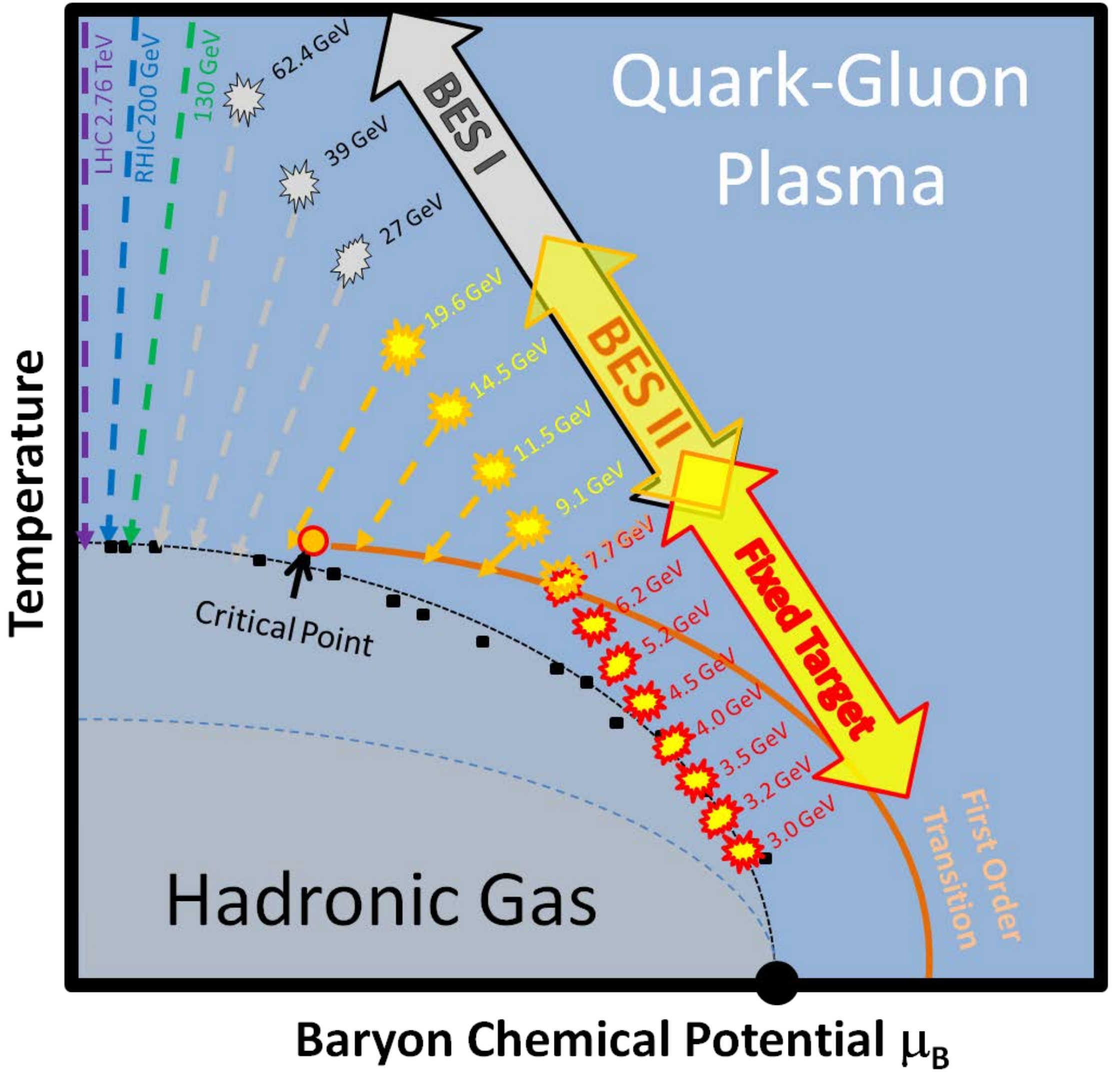
# Outline

- Introduction
- STAR BES and results
- Upgrades in BES-II
- Challenges in FXT
- Summary

# Introduction: QCD phase structure

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

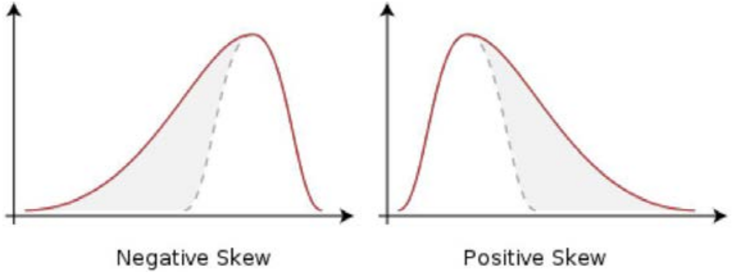



STAR and CBM, arXiv:1609.05102; Y. Aoki, Nature 443, 675-678 (2006); HotQCD, PLB 795, 15-21 (2019)

# Introduction: experimental observables

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

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

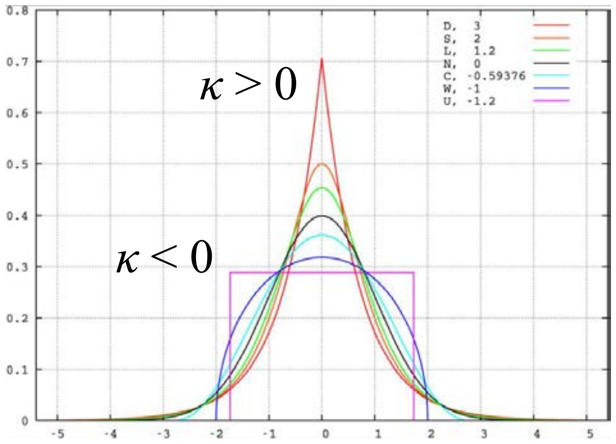



Gaussian: $C_r = 0$ ($r > 2$)

Skellam (Poisson − Poisson):

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

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



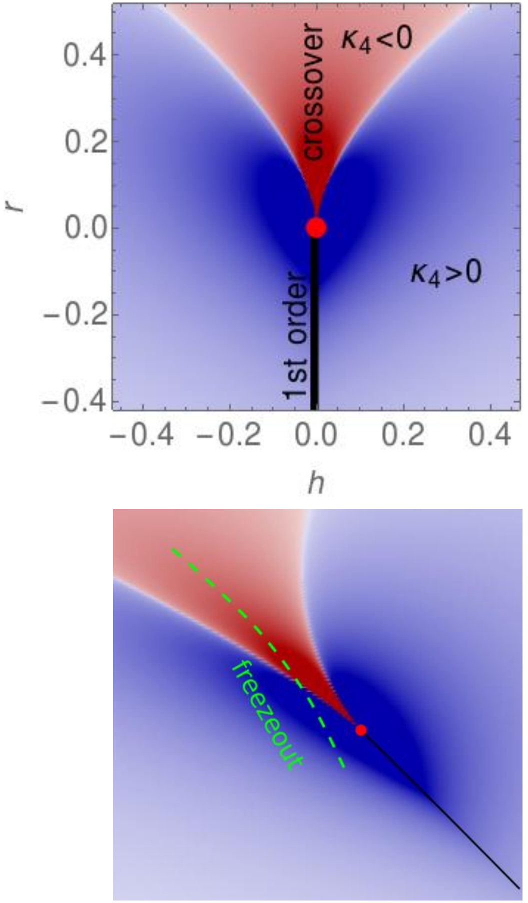

- Directly connected to susceptibilities ($\chi_r^q$, $q = B, Q, S$)
  - $\frac{C_3^q}{C_2^q} = S\sigma = \frac{\chi_3^q}{\chi_2^q}$, $\frac{C_4^q}{C_2^q} = \kappa\sigma^2 = \frac{\chi_4^q}{\chi_2^q}$

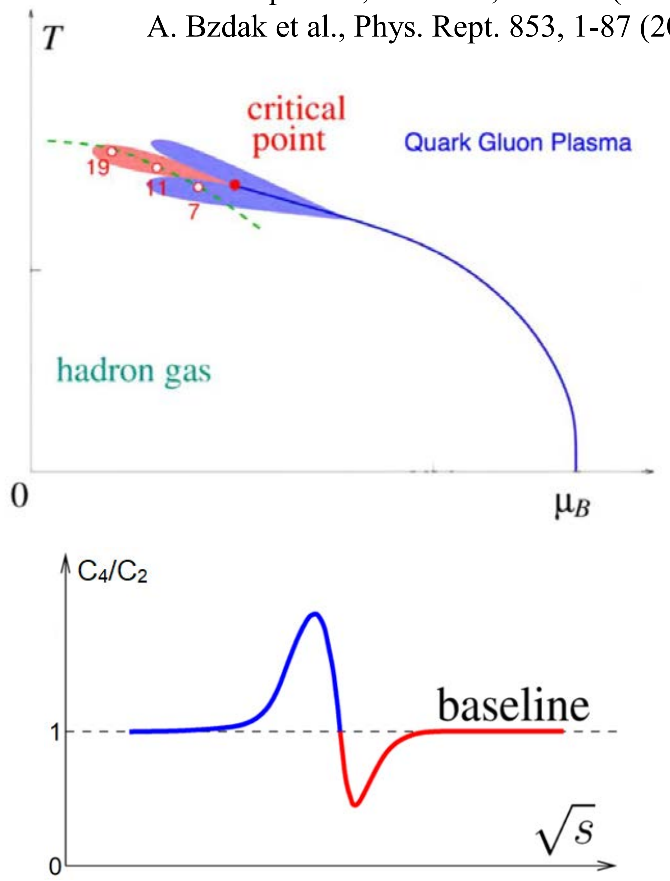
M. A. Stephanov, PRL 102, 032301 (2009)
M. Asakawa et al., PRL103, 262301 (2009)
M. A. Stephanov, PRL107, 052301 (2011)

# Introduction: predicted signals

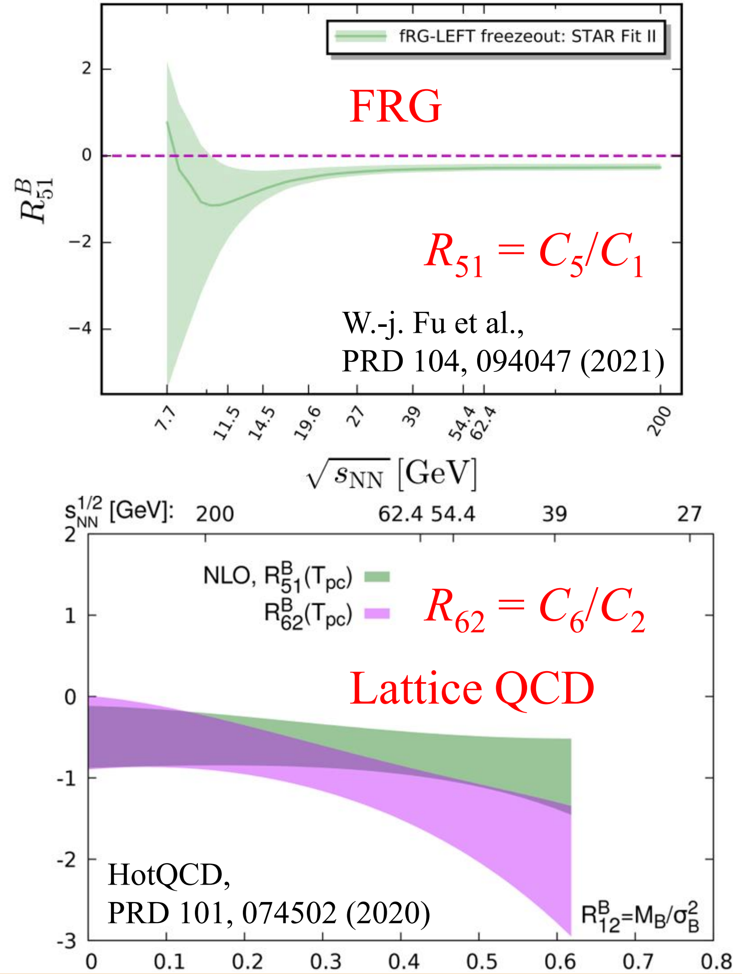
- Critical point
  - Non-monotonic energy dependence of $C_4/C_2$ around baseline

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




- Crossover
  - Negative $C_5$ and $C_6$



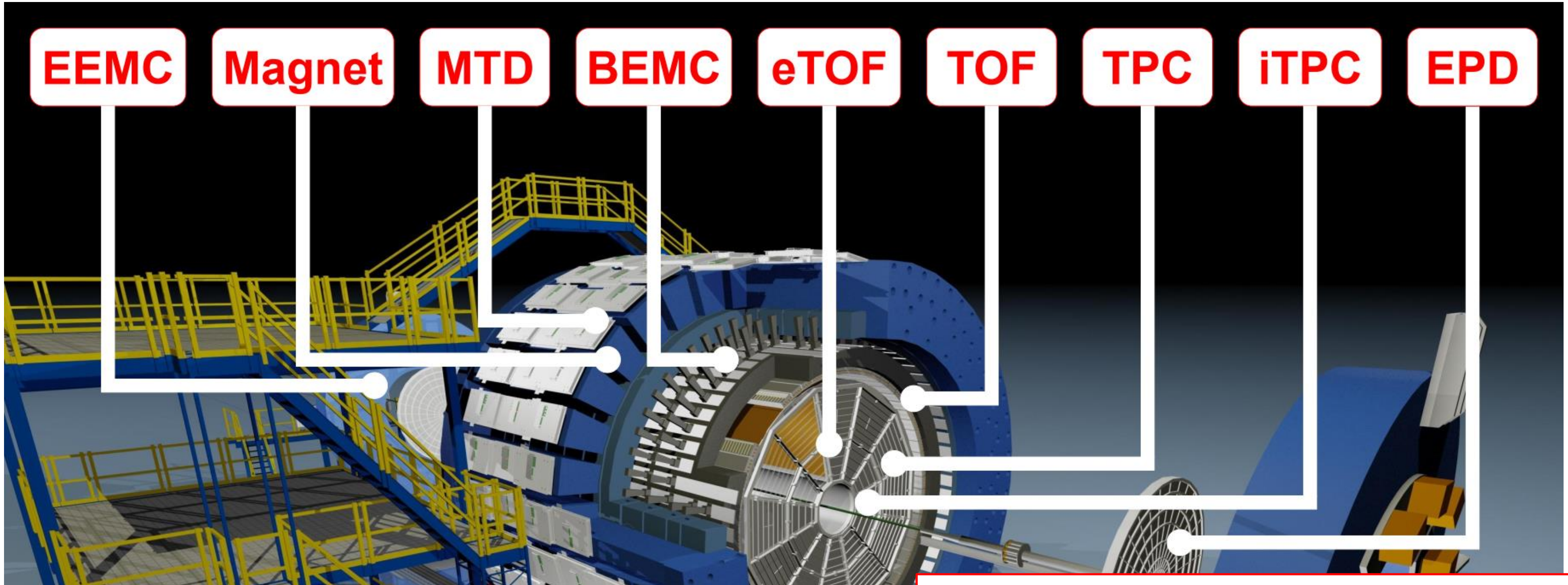
# Beam Energy Scan program

- To map QCD phase diagram: BES-I 2010 – 2017; BES-II (including FXT) 2018 – 2021

| $\sqrt{s_{NN}}$ (GeV) | # Events | Year 20xx (BES-I/**II**) | $\mu_B$ (MeV) |
|---|---|---|---|
| 200 | 238M/**138M/20B** | 10/**19/23–25** | 25 |
| 62.4 | 47M | 10 | 73 |
| 54.4 | 550M | 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 | 20M | 14 | 264 |
| 11.5 | 6.6M/**235M** | 10/**20** | 315 |
| 9.2 | **162M** | **20** | 373 |
| 7.7 | 3M/**101M** | 10/**21** | 420 |

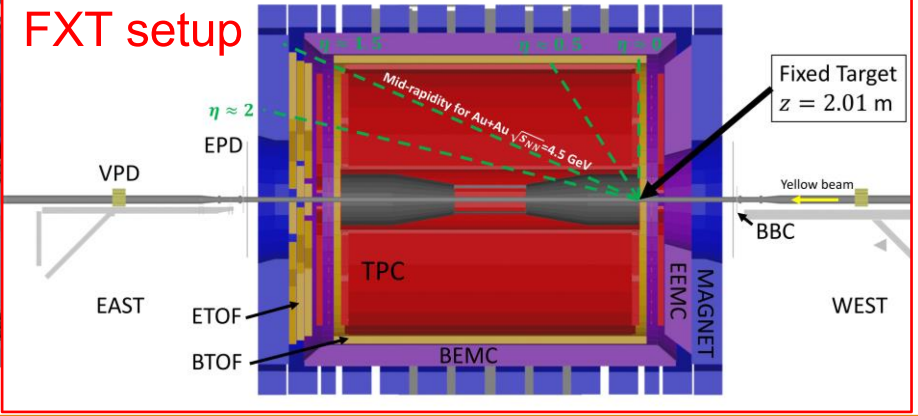
| $\sqrt{s_{NN}}$ (GeV) | # Events | Year 20xx (FXT) | $\mu_B$ (MeV) |
|---|---|---|---|
| 13.7 | 51M | 21 | 276 |
| 11.5 | 52M | 21 | 315 |
| 9.2 | 54M | 21 | 373 |
| 7.7 | 51M/112M | 19/20 | 420 |
| 7.2 | 155M/317M/89M | 18/20/21 | 440 |
| 6.2 | 118M | 20 | 487 |
| 5.2 | 103M | 20 | 541 |
| 4.5 | 108M | 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 | 720 |

# STAR detector system



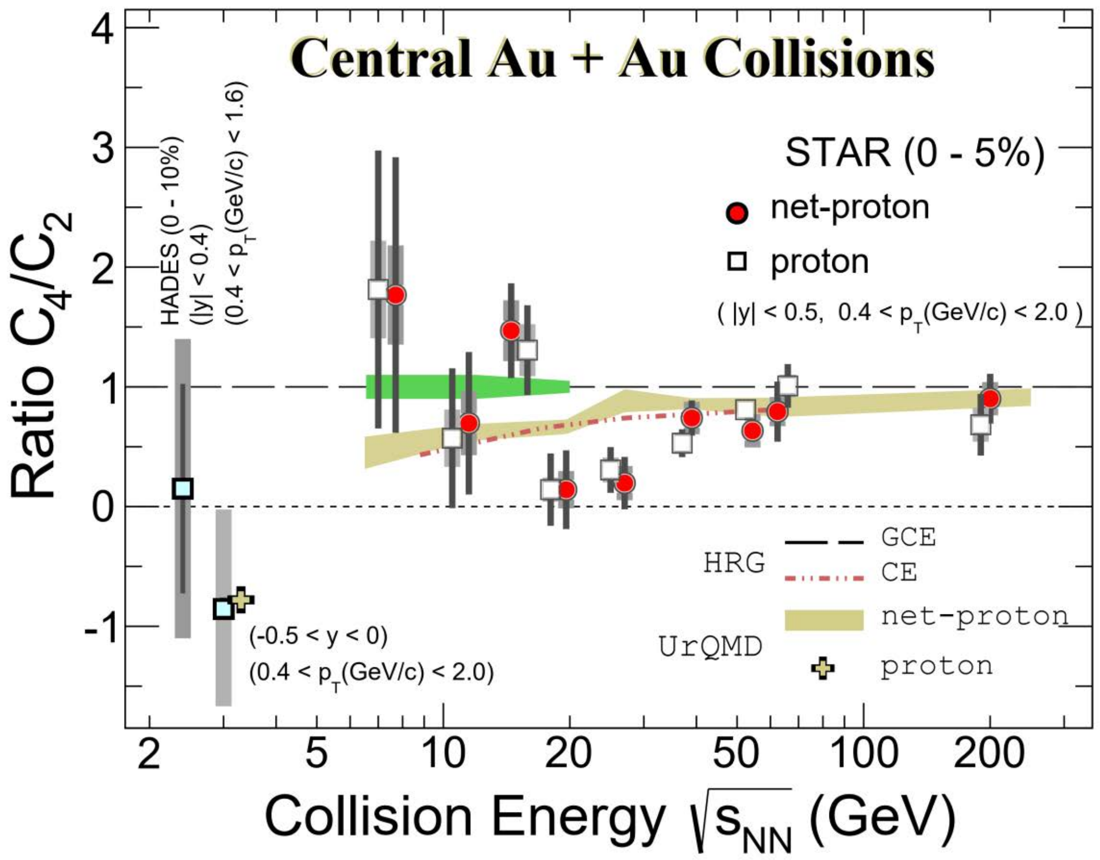

- Large acceptance
- Excellent PID
- Uniform efficiency
- Upgraded since 2018
  - iTPC, eTOF, EPD

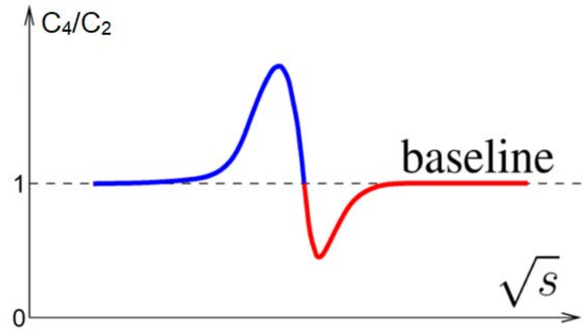
FXT setup



# STAR published measurements (BES-I)

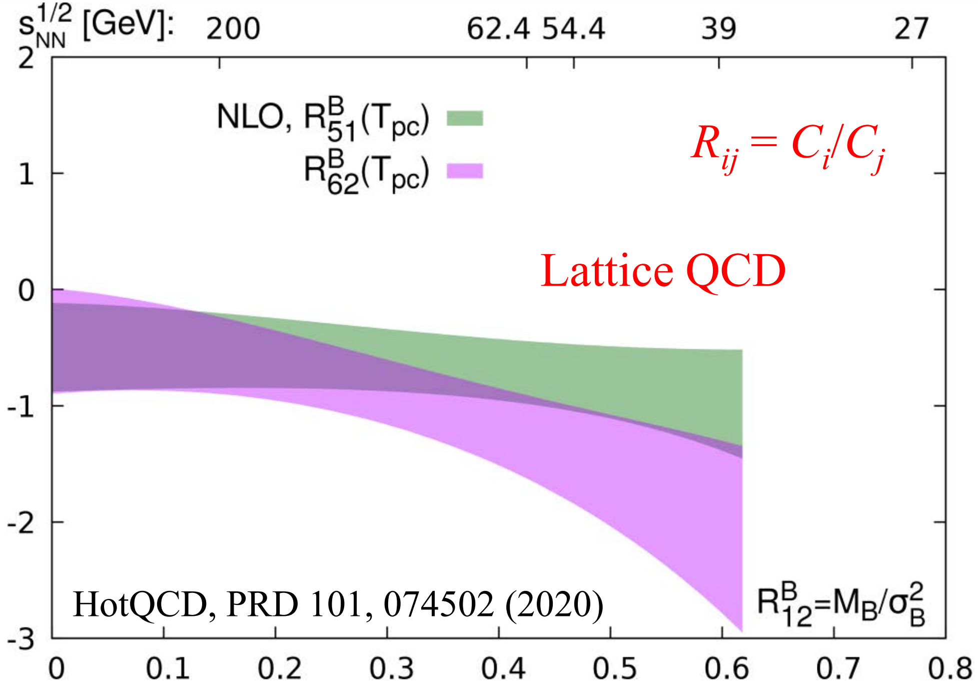
- Non-monotonic energy dependence ($3.1\sigma$)
  - Qualitatively consistent with prediction considering critical point
  - Deviates from non-critical models
- Significant suppression at $\sqrt{s_{NN}} = 3.0$ GeV
  - Reproduced by UrQMD model (baryon-conservation driven)
  - Predominantly hadronic matter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

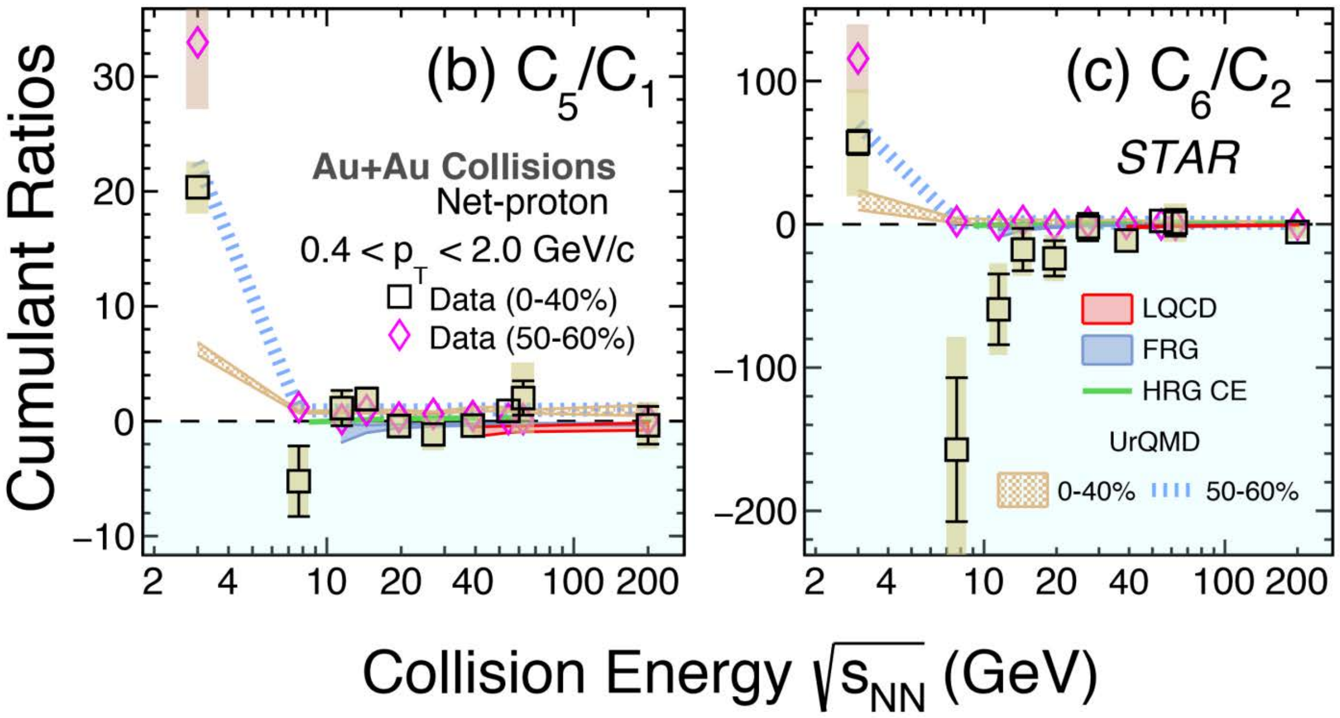



STAR, PRL 126, 092301 (2021)
STAR, PRC 104, 024902 (2021)
STAR, PRL 128, 202303 (2022)
STAR, PRC 107, 024908 (2023)

# STAR published measurements (BES-I)

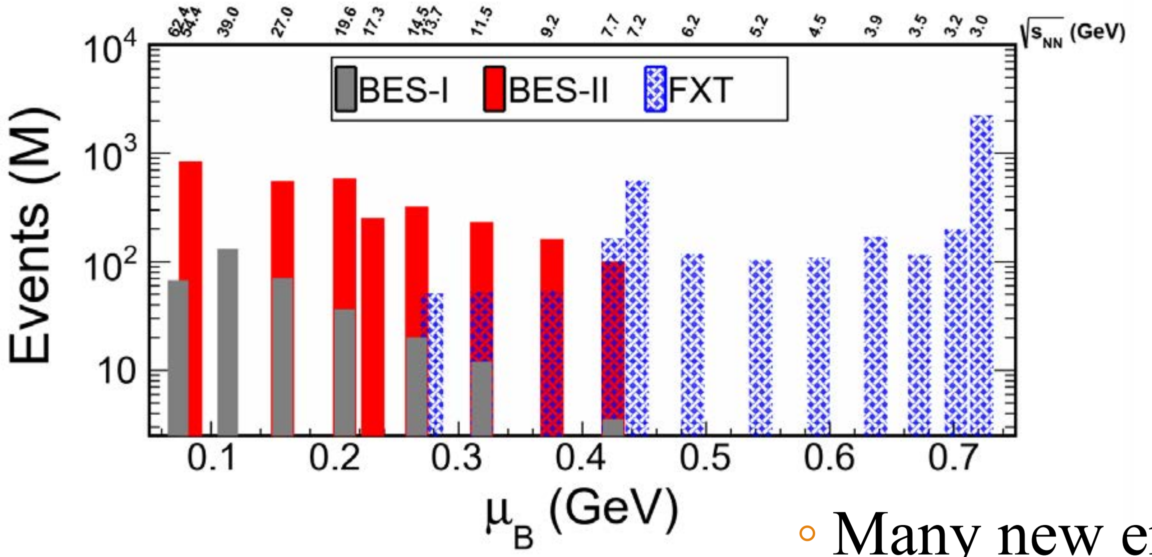


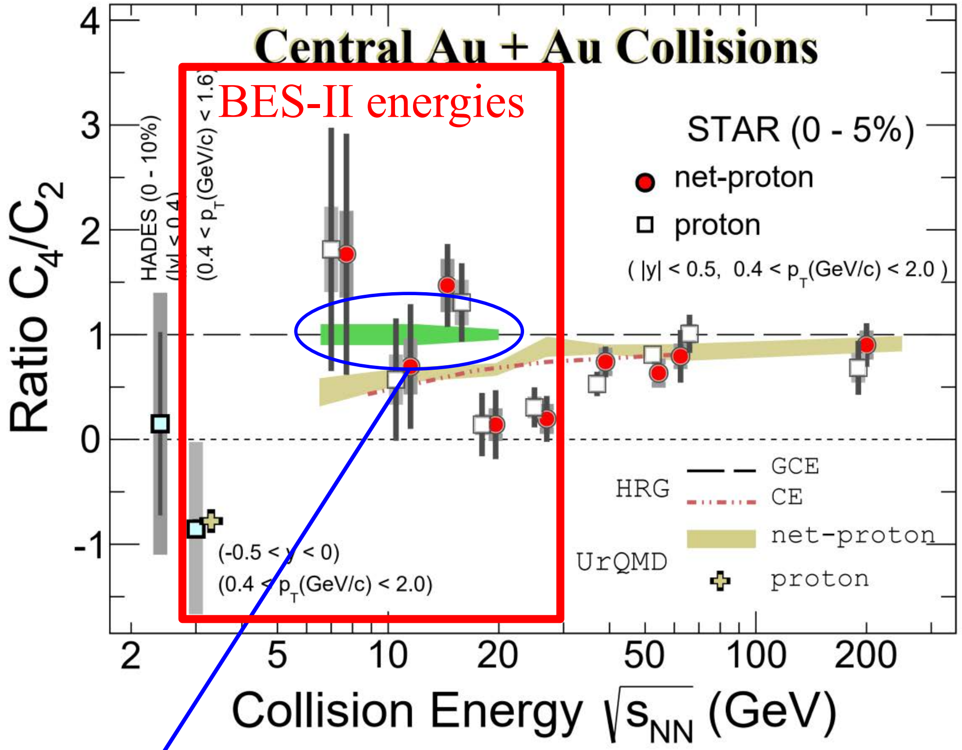



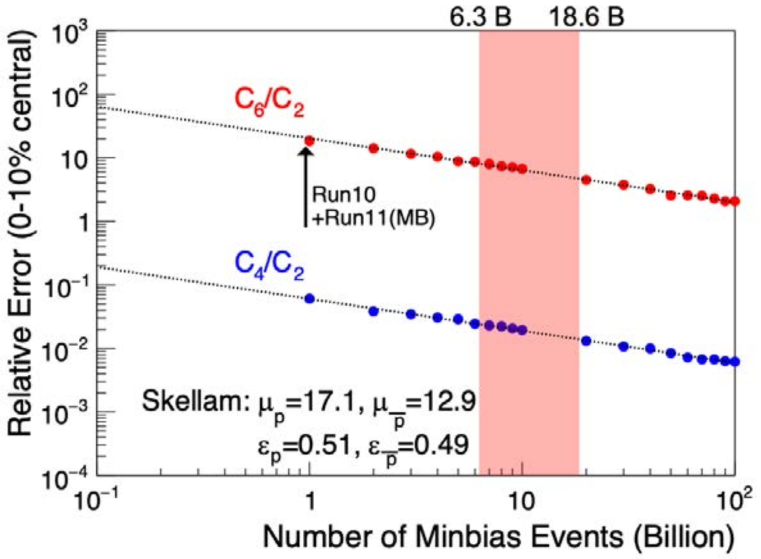

- $C_5/C_1$ (0-40% at $\sqrt{s_{NN}} = 7.7 - 200$ GeV) fluctuates around zero at all energies
- Increasingly negative $C_6/C_2$ (0-40%) as collision energy $\sqrt{s_{NN}}$ decreases down to 7.7 GeV
  - Trend consistent with LQCD calculation (UrQMD always positive or ~ 0)
- Positive $C_5/C_1$ & $C_6/C_2$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

STAR, PRL 130, 082301 (2023)

# Upgrades in BES-II: energies and statistics



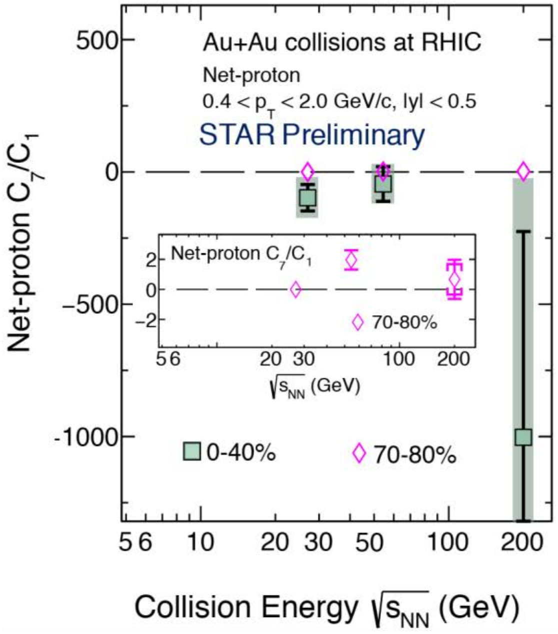



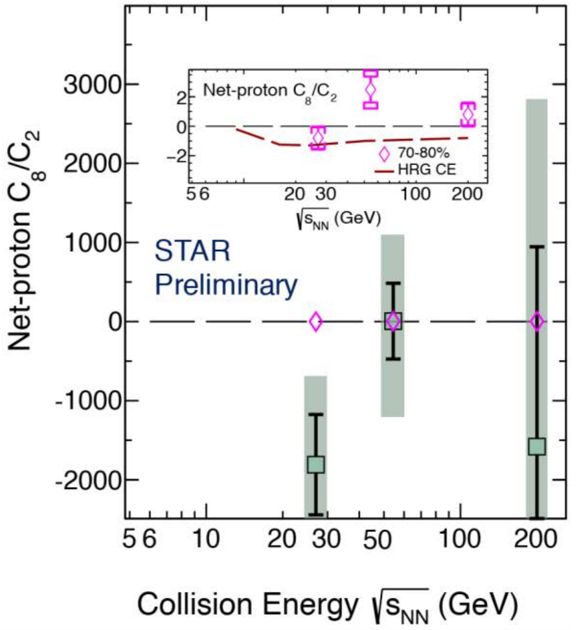

- Many new energies
  - From 3 to 27 GeV
  - Fine scan of $\mu_B$
- Much higher statistics
  - Smaller uncertainties expected in BES-II
  - Precision measurement for $C_4$ and even higher orders

STAR Beam Use Request SN0773, SN0793

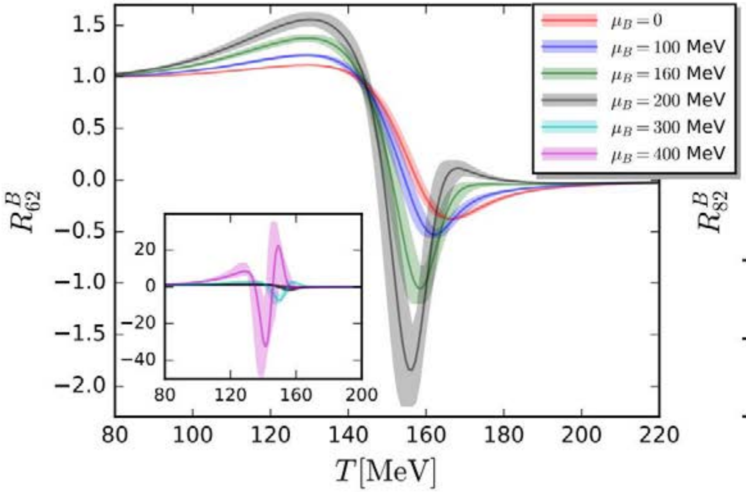
# Hyper-order cumulants: search for crossover

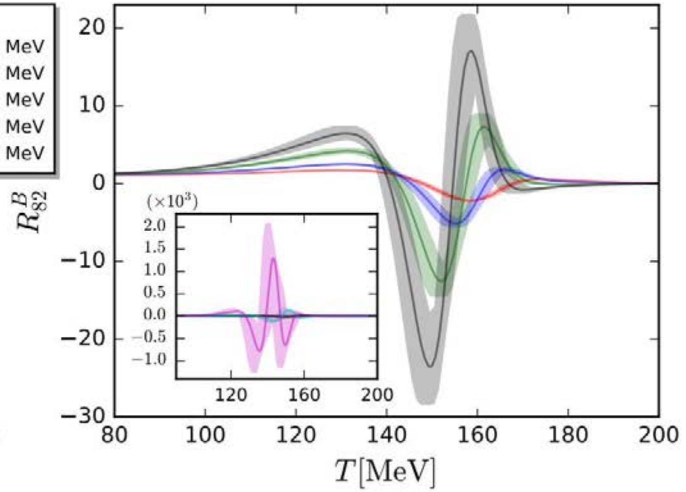
- Hyper-order cumulants $C_5 - C_8$
  - Sensitive to crossover
  - Vulnerable to backgrounds
  - Hungry for statistics
    - 2.1B events at $\sqrt{s_{\mathrm{NN}}} = 3.0$ GeV (2021)
    - 20B events at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV (2023–2025)



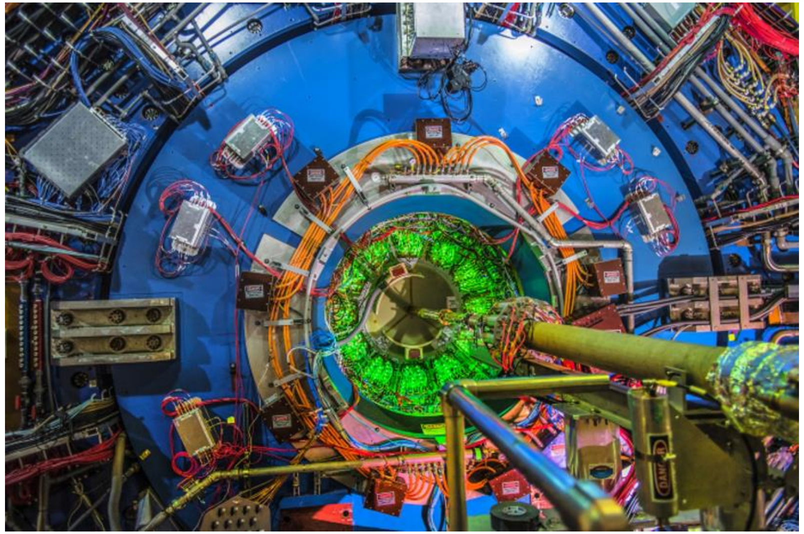

- May have precision measurements in BES-II



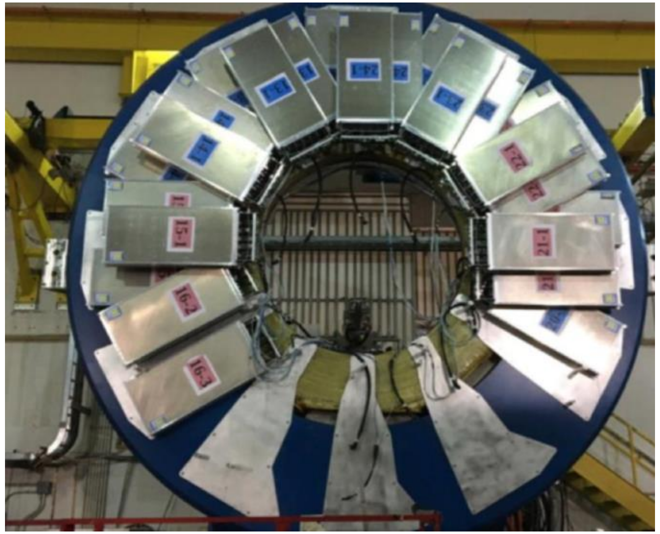




STAR talk, sQM 2022
W.-j. Fu et al. PRD 104, 094047 (2021)

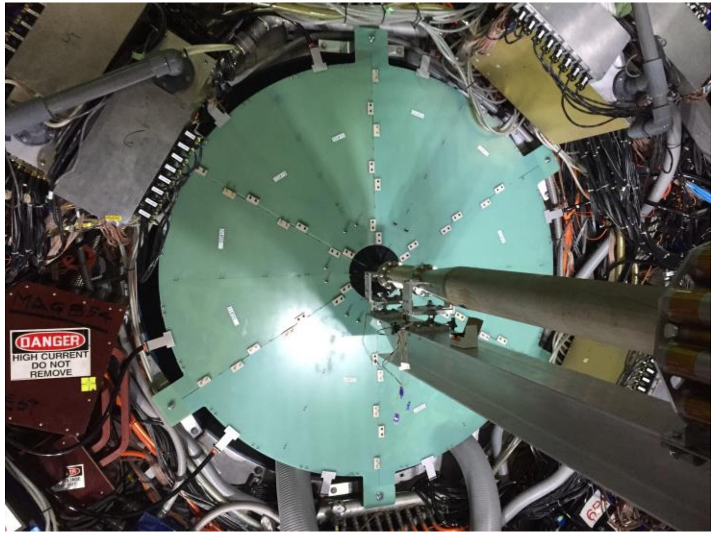
# Upgrades in BES-II: new detectors



- iTPC (since 2019)
  - Improves d$E$/d$x$ measurement
  - Extends $\eta_{\mathrm{max}}$ from 1.0 to 1.5
    - For FXT, $\eta_{\mathrm{max}}$ from 2.0 to 2.5
  - Lowers $p_{\mathrm{T}}$ cut-in from 125 to 60 MeV/$c$



- eTOF (since 2019)
  - Forward rapidity coverage
    - Crucial in fixed-target program
  - PID at $1.05 < \eta < 1.50$
    - For FXT, $1.52 < \eta < 2.24$
  - Provided by FAIR-CBM

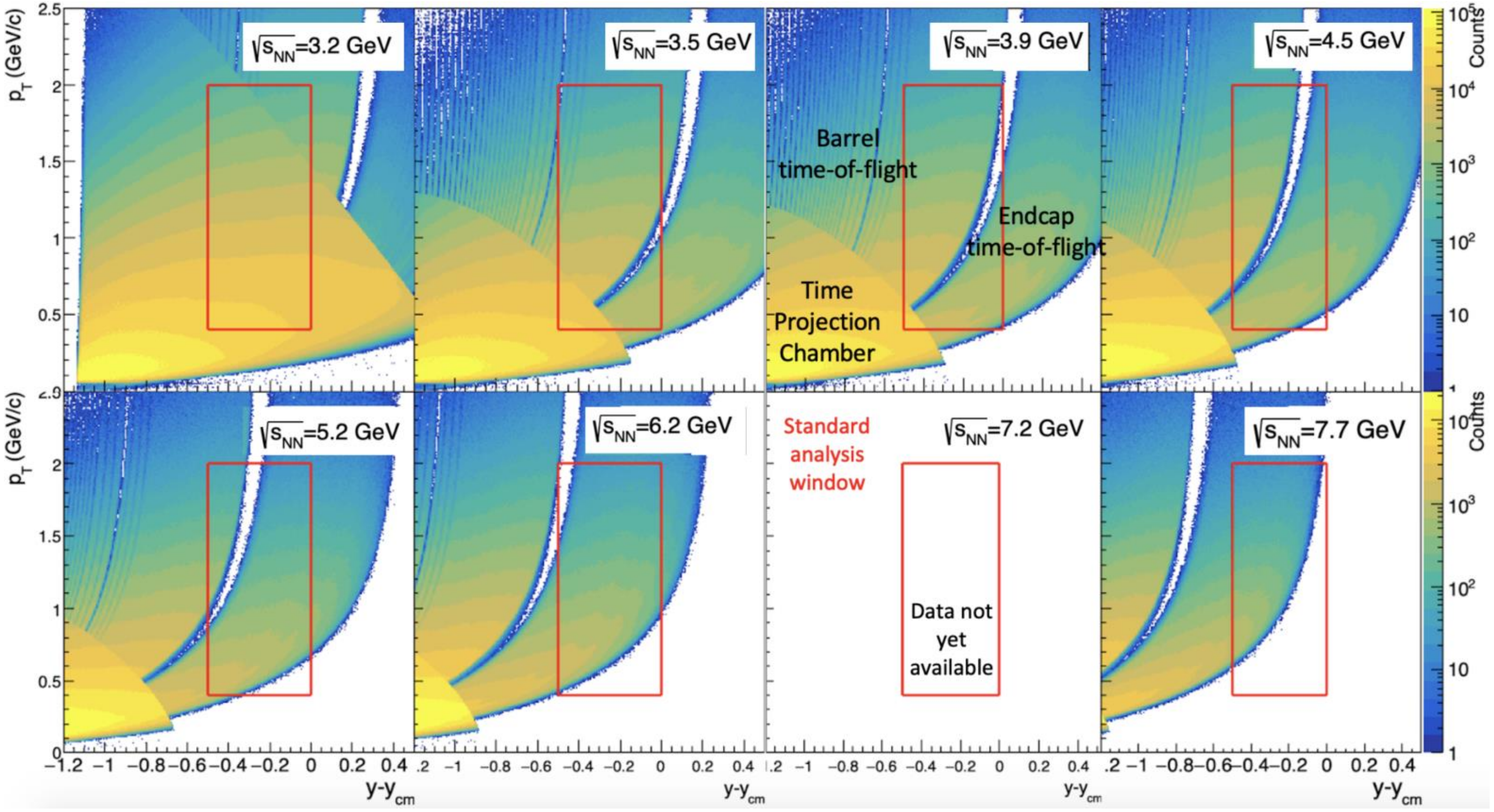



- EPD (since 2018)
  - $2.14 < |\eta| < 5.09$
  - Improves trigger
  - Better event plane reconstruction
  - Better centrality determination

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)

# Proton acceptance plots in FXT mode

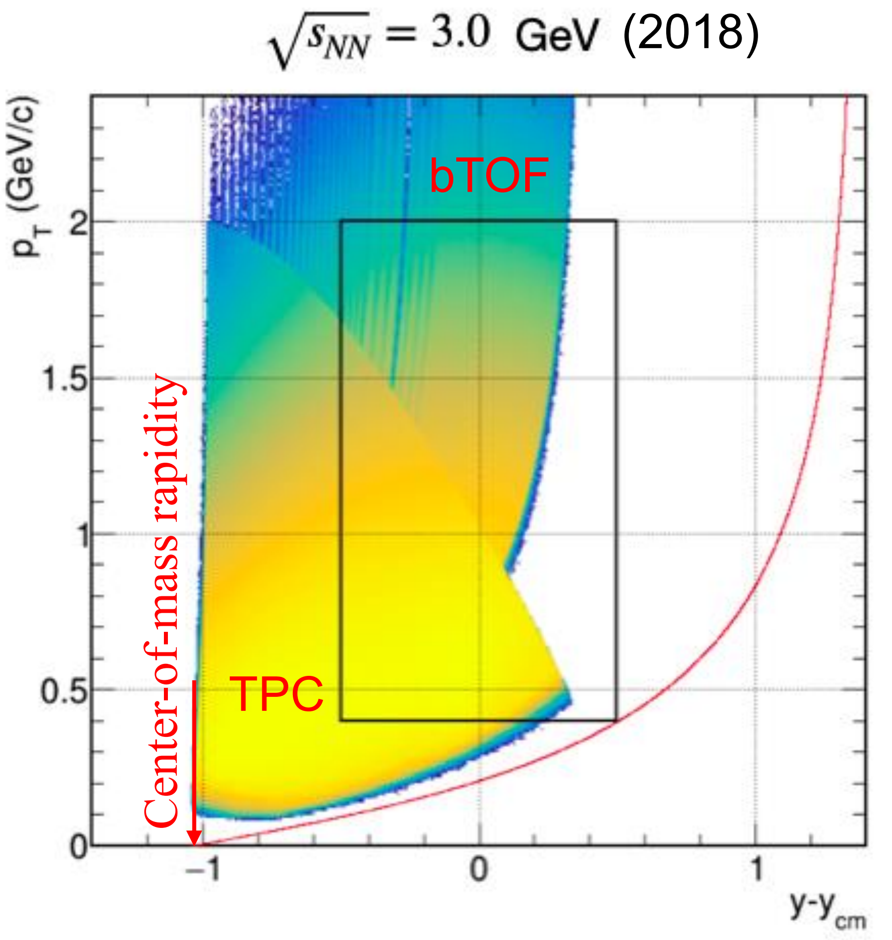
- Standard analysis window (red box)
  - $0.4\ \mathrm{GeV}/c < p_T < 2\ \mathrm{GeV}/c$
  - $-0.5 < y < 0$
- TOF is required at high momenta where proton purity < 90%
- Nearly full acceptance at $\sqrt{s_{NN}}$ up to 4.5 GeV
  - Limited mid-rapidity coverage at higher energies
- Crucial eTOF for proton identification at $\sqrt{s_{NN}}$ from 3.5 GeV




STAR poster, QM 2023

# Upgrades in BES-II: larger acceptance

- For FXT $\sqrt{s_{NN}} = 3.0$ GeV in 2018 (published)
  - No iTPC installed
  - TPC coverage: $-2.0 < \eta_{lab} < 0$
  - Proton acceptance: $-0.5 < y < 0$
    - Only half mid-rapidity window covered
- For FXT since 2019 (analysis ongoing)
  - Both iTPC and eTOF are installed
  - TPC including iTPC: $-2.5 < \eta_{lab} < 0$
- For FXT $\sqrt{s_{NN}} = 3.0$ GeV in 2021 (2.1B events)
  - Possible proton measurement within $-0.5 < y < 0.5$
  - Red curve: expected acceptance boundary with iTPC and eTOF

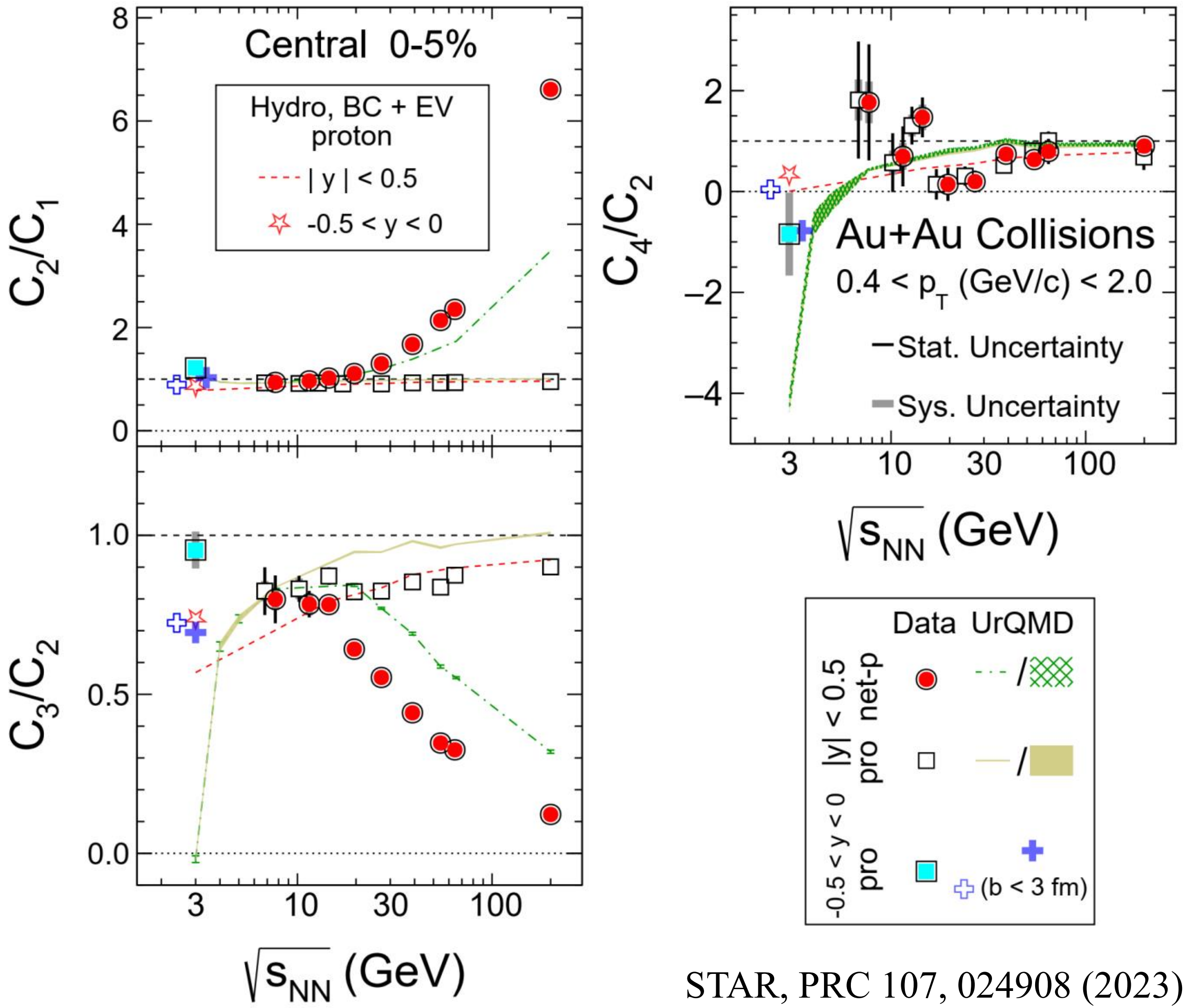



STAR Beam Use Request SN0755

# Comparison between half/full mid-rapidity

- From models for 3.0 GeV, clear difference between calculations in half and full mid-rapidity windows
- Necessary to learn the difference between $-0.5 < y < 0$ and $|y| < 0.5$ in experiments

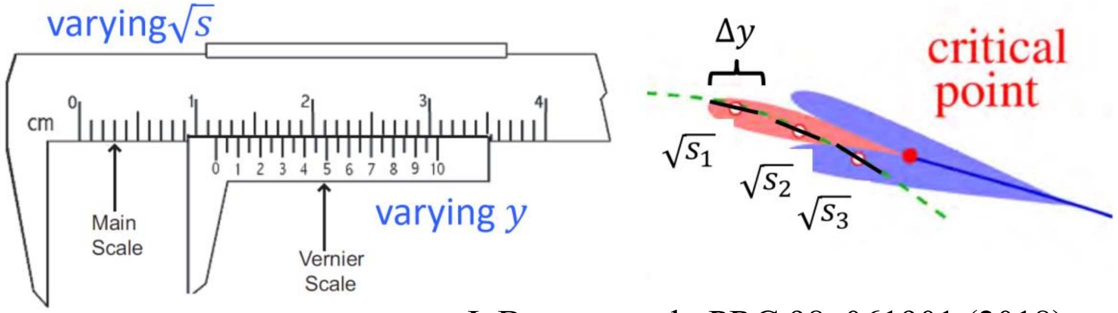
| | $C_4/C_2$ |
|---|---|
| Data ($-0.5 < y < 0$) | $\sim -1$ |
| UrQMD ($-0.5 < y < 0$) | $\sim -1$ |
| UrQMD ($|y| < 0.5$) | $\sim -4$ |
| Hydro ($-0.5 < y < 0$) | $\sim 1$ |
| Hydro ($|y| < 0.5$) | $\sim 0$ |



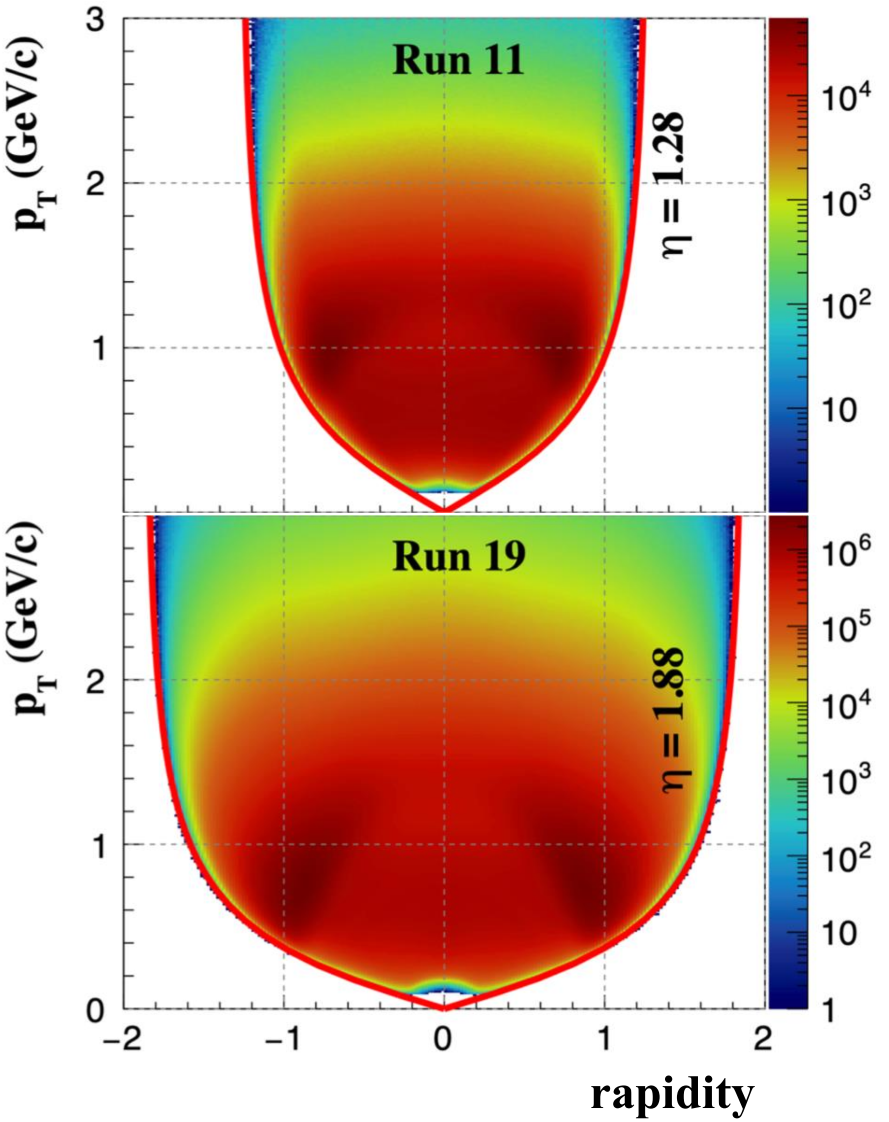

STAR, PRC 107, 024908 (2023)

# Upgrades in BES-II: larger acceptance

- Acceptance is much larger thanks to iTPC
- Proton rapidity extension
  - $|y| < 0.5$ in BES-I, 0.7 may be available in BES-II
  - To observe correlations in larger system size
- Rapidity scan
  - Sensitive probe for critical region
  - Detailed scan for the QCD phase diagram




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



# Upgrades in BES-II: better centrality resolution

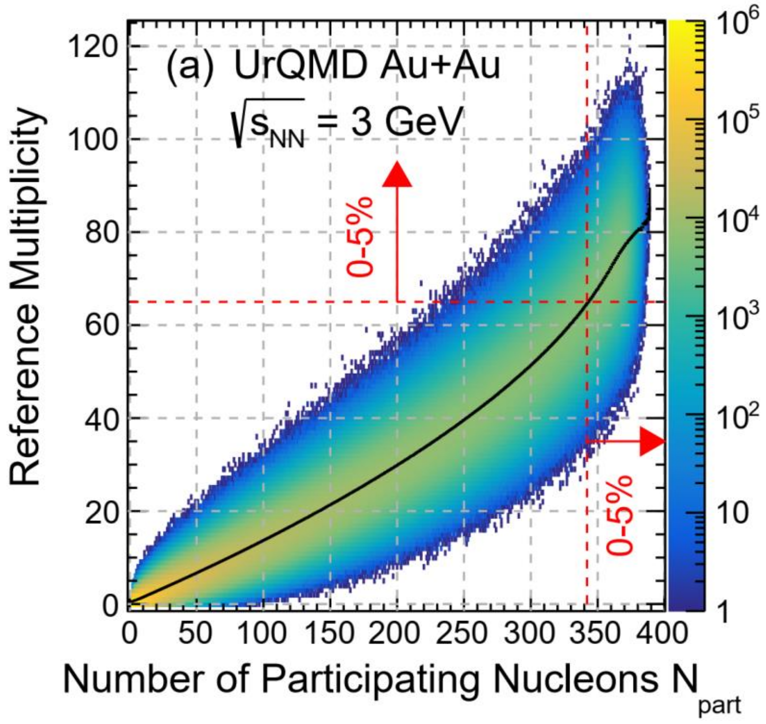
- For net-proton fluctuation measurements, centrality is determined by the reference multiplicity excluding (anti)protons
  - To avoid auto-correlation

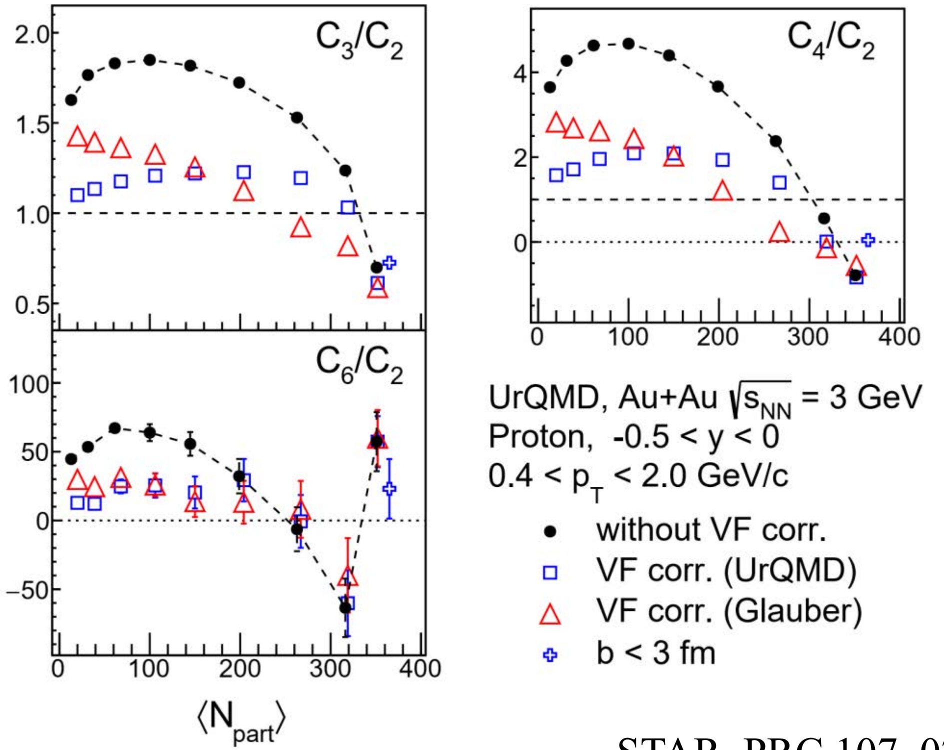
- In BES-I, multiplicity (called RefMult3) is defined by $\pi^{\pm}$ and $K^{\pm}$ within $|\eta| < 1.0$

- With the extended acceptance, RefMult3X is defined by $\pi^{\pm}$ and $K^{\pm}$ within $|\eta| < 1.6$
  - Better centrality resolution => smaller volume fluctuation => contribution to cumulants

- Effect should be checked both in experiments and models

# UrQMD simulation: volume fluctuation effect

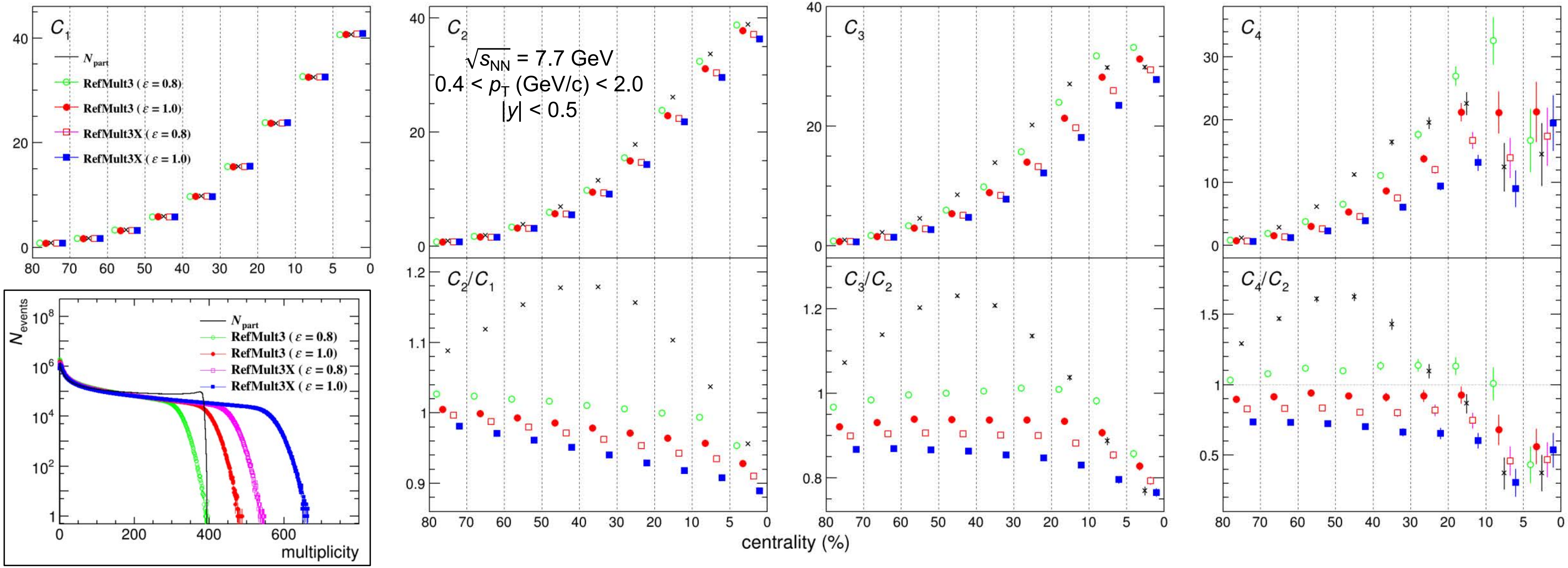



STAR, PRC 107, 024908 (2023)

- $N_{part}$ is a characterization of the system volume
- Effect of volume fluctuation
  - The centrality by reference multiplicity selects different events from the centrality by $N_{part}$
  - $N_{part}$ varies even in each reference multiplicity bin

# UrQMD simulation: centrality resolution effect



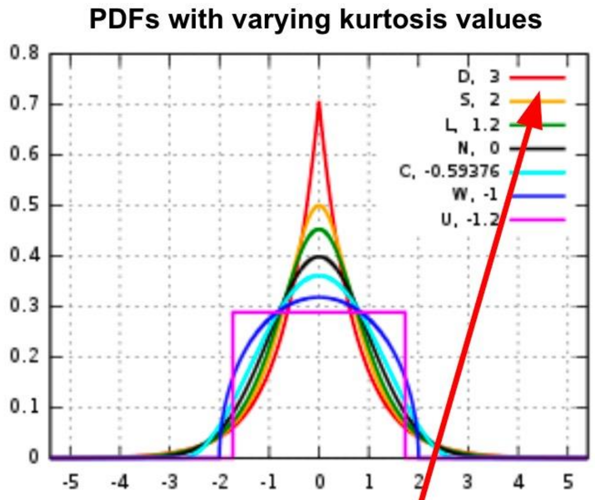

- Centrality resolution from worst to best: ○ < ● < □ < ■
  - Clear ordering: better resolution => lower cumulants/ratios (except $C_4/C_2$ at 0-5%)
- Comparisons needed in experimental measurements

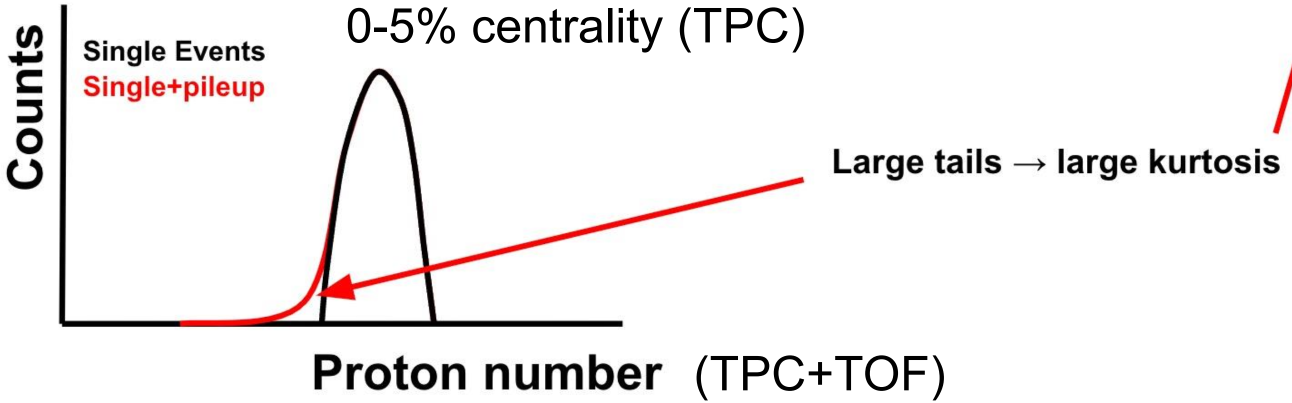
# Challenges in FXT: pileup and timing issue

- Pileup events: formed by multiple collisions in a short time (not separated by detector)
  - Higher pileup fraction in FXT than collider experiments

- TOF has better timing precision and is faster than TPC
  - TPC reconstructs tracks from pileup events, but TOF often misses them due to timing offset

- TPC multiplicity for centrality
- TPC+TOF for proton ID
  - A tail on the left-hand side of proton number distribution in central events



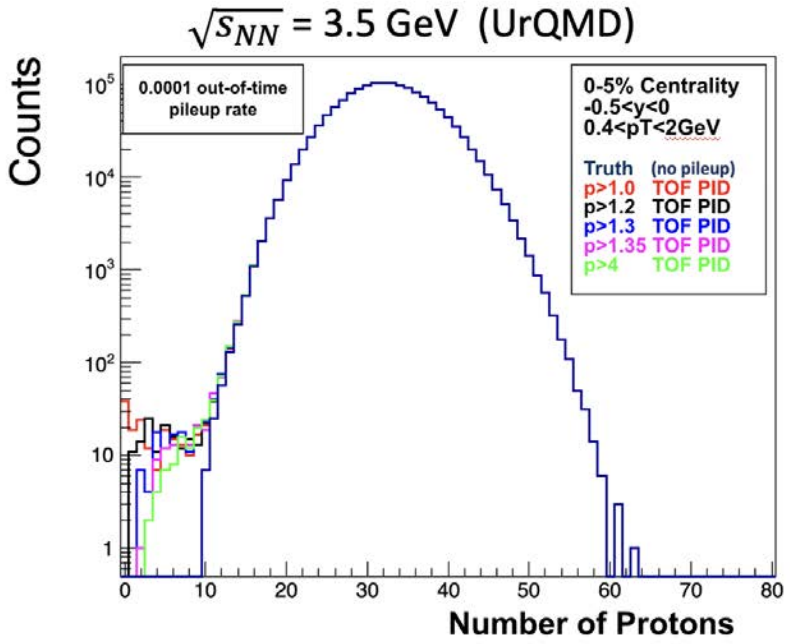

STAR talk, DNP 2023

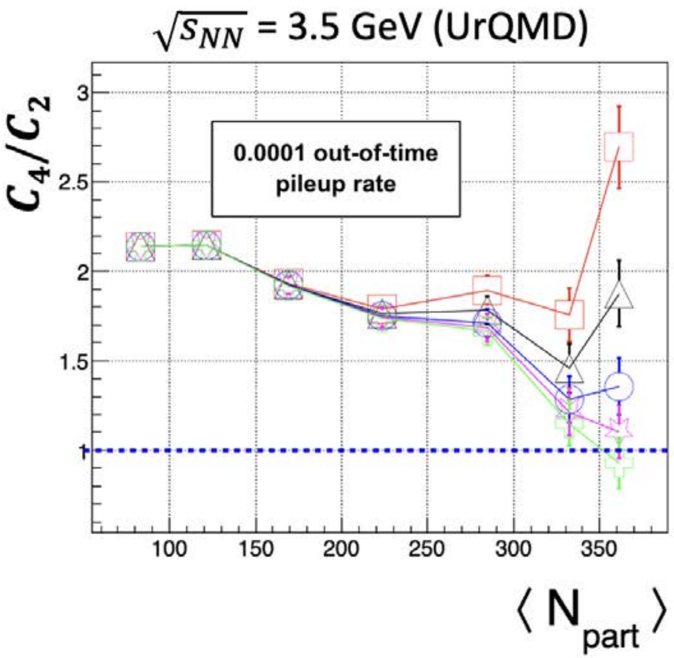
# UrQMD simulation: pileup and timing issue

- In experiments, we require TOF PID for tracks above a certain momentum

- In UrQMD, we simulate pileup process and TOF PID
- Instability of cumulants observed during variation of momentum threshold for TOF PID

- Pileup events should be carefully rejected if we require TOF for PID



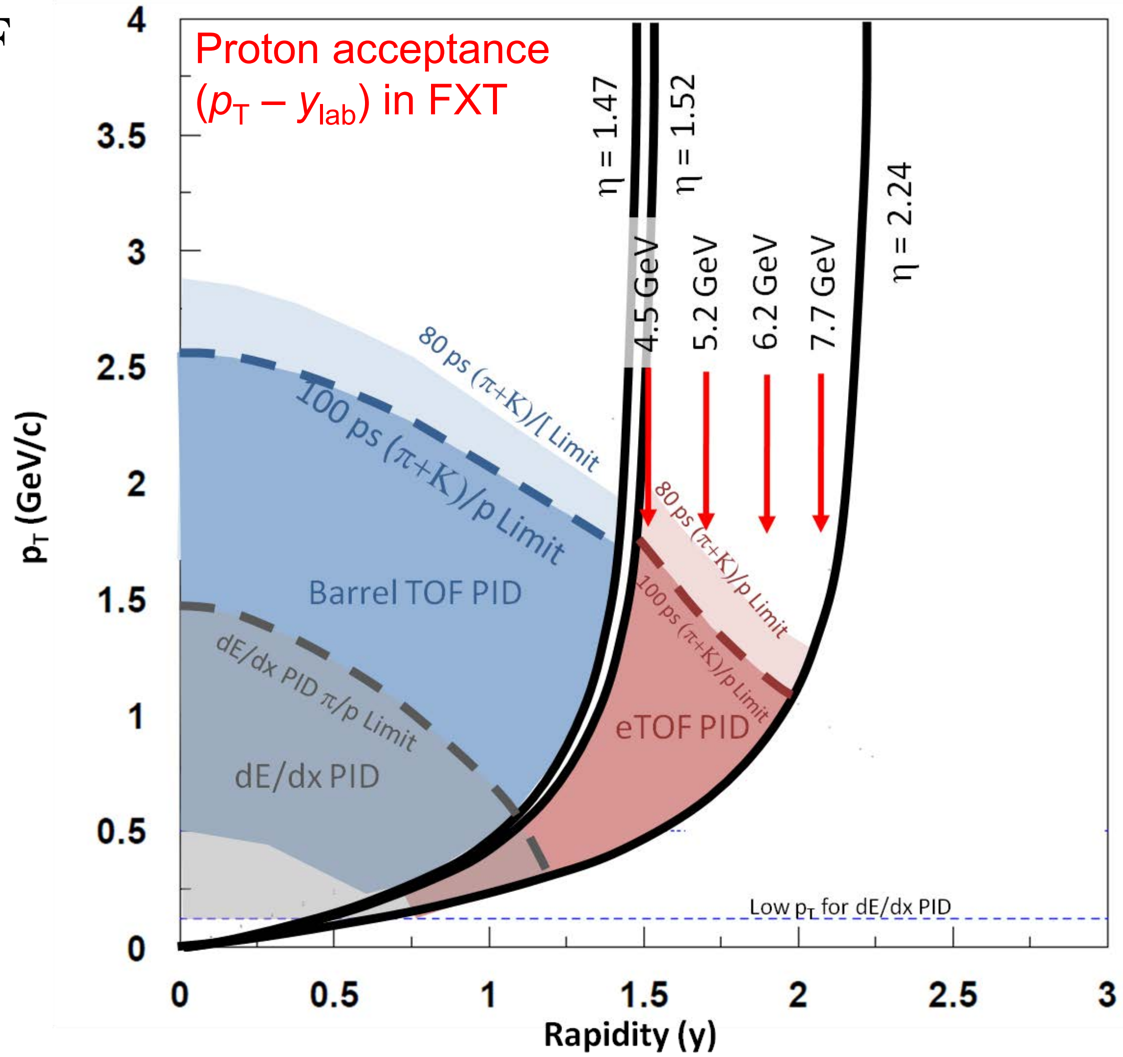

STAR talk, DNP 2023

# Challenges in FXT: $\eta$ gap between b/eTOF

- An acceptance gap between bTOF and eTOF
  - $1.45 \lesssim \eta_{\mathrm{lab}} \lesssim 1.55$
  - No TOF available for PID

- Solutions
  - Check TPC proton purity in the gap
  - Test removing the gap from the acceptance

- Model studies also needed for the effect




STAR and CBM, arXiv:1609.05102

# Summary

- In BES-II, STAR has collected lots of data from $\sqrt{s_{\rm NN}}$ = 3.0 to 27 GeV
  - FXT mode: 3.0 – 13.7 GeV; collider mode: 7.7 – 27 GeV
- Several upgrades in BES-II
  - New energies: 3.2 – 7.2, 9.2, 17.3 GeV; much higher statistics
  - New detectors, larger acceptance, and better centrality resolution
- A few challenges in FXT
- BES-II fluctuation measurements are ongoing.

*Thank you for your attention!*