Status Report on the Analyses of Proton-Number Cumulants in the STAR Fixed-Target Program

Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan

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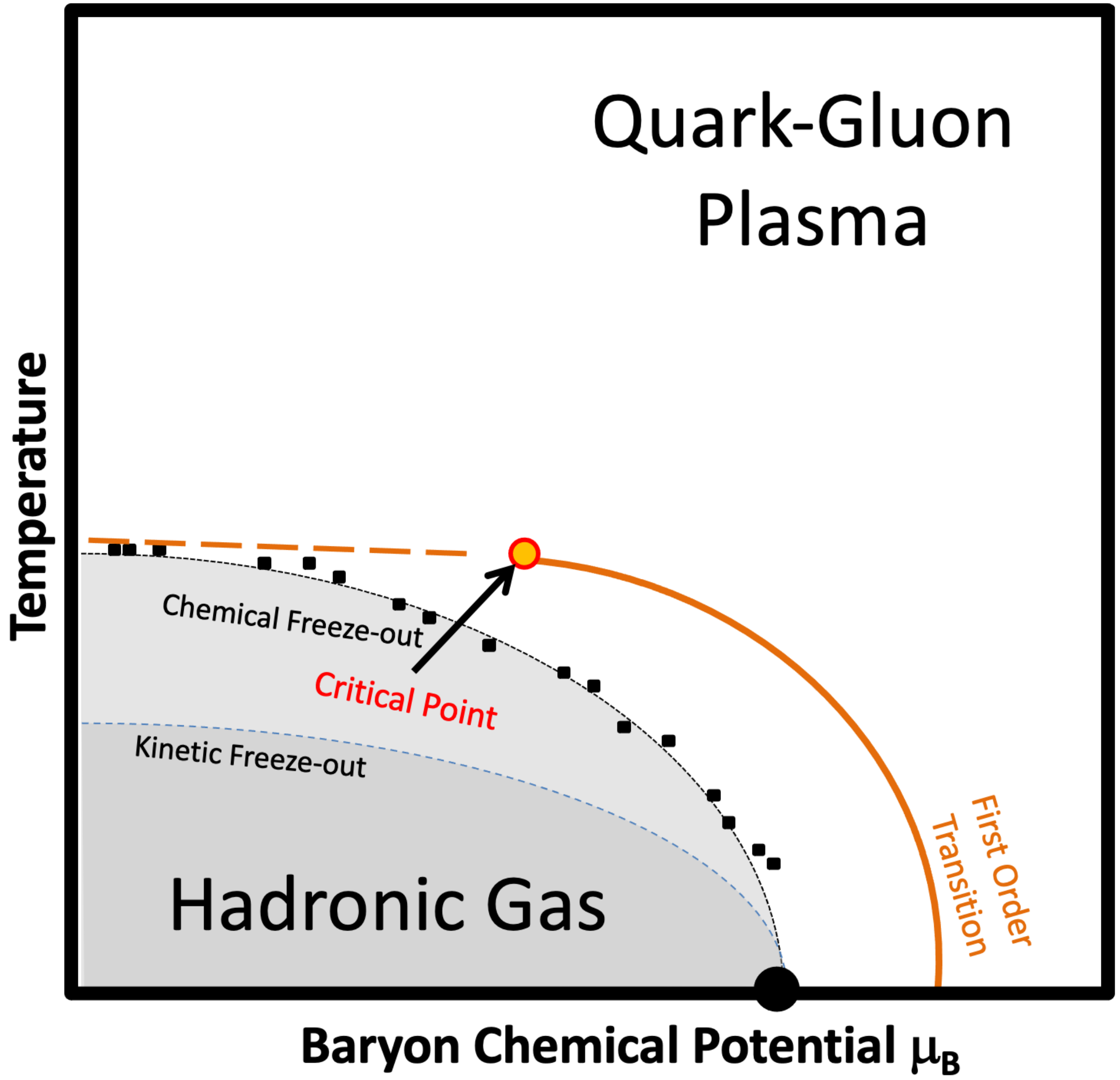
Phases of QCD Matter

QCD Phase Diagram

- Quarks and gluons experience confinement at low temperatures and densities.
- At high temperatures and densities, there is a deconfined phase, the quark-gluon plasma.

Beam Energy Scan (BES)

- BES program at the Relativistic Heavy-Ion Collider scans phase space of QCD matter by colliding gold ions at varying energies
- Seeking to map onset of deconfinement, and the predicted QCD critical point



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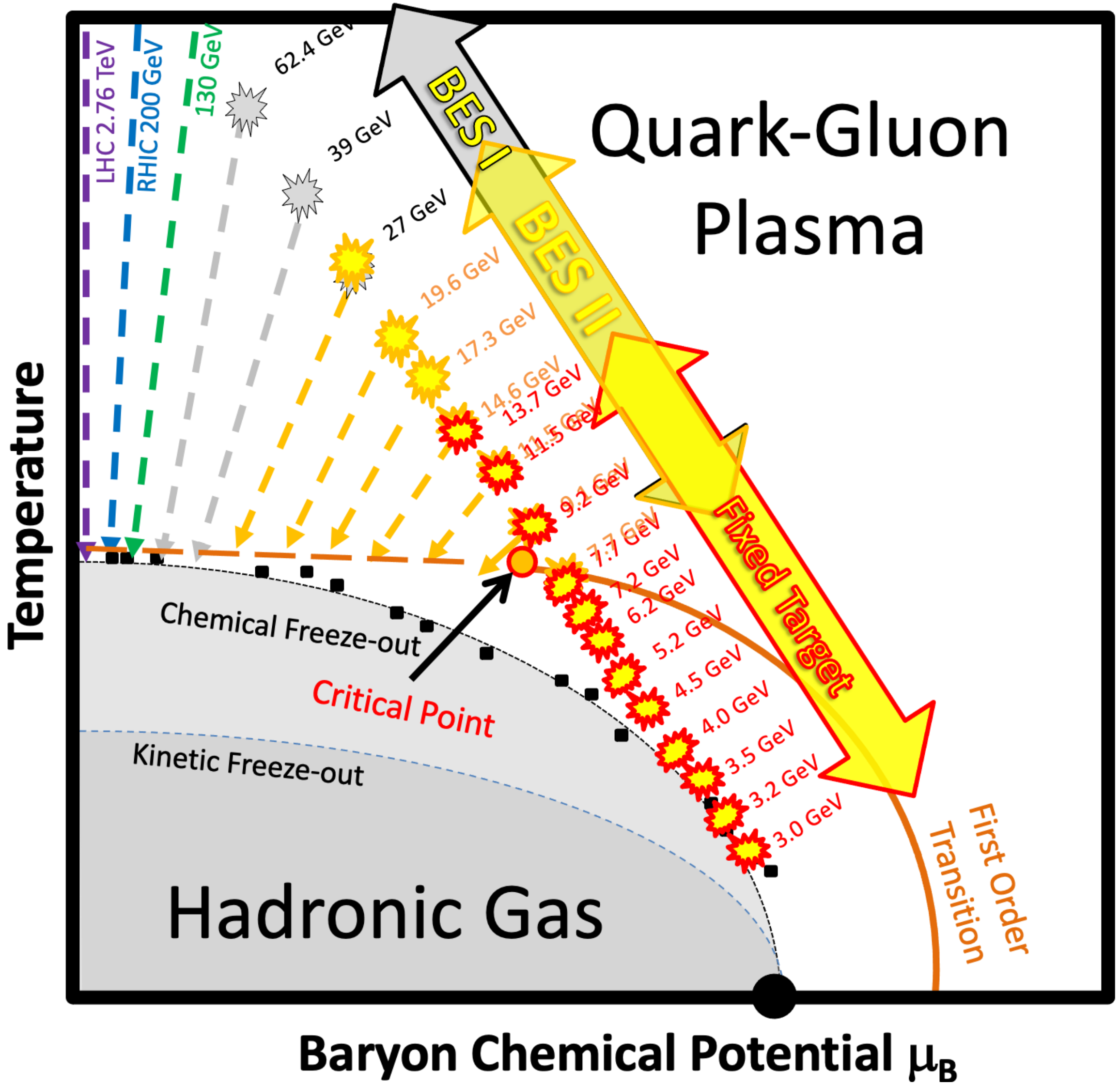


Cumulants and Moments

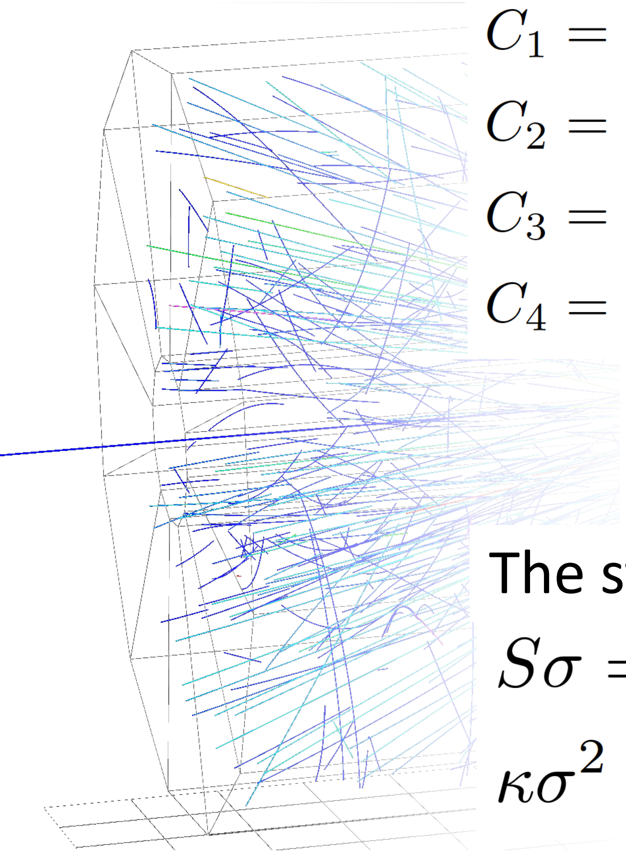
Cumulants of a distribution are defined as

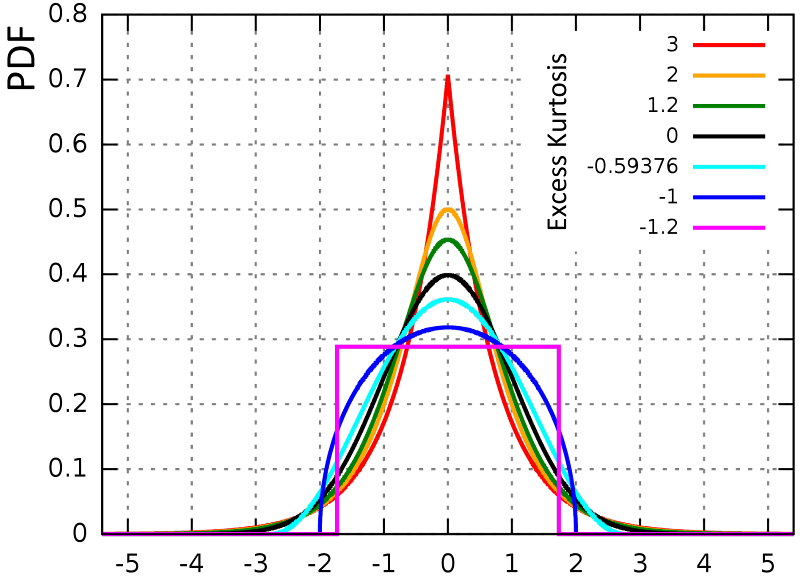
$$C_1 = \langle N \rangle \equiv \mu \text{ [mean]}$$

$$C_2 = \langle (N-\mu)^2 \rangle \equiv \sigma^2 \text{ [variance]}$$

$$C_3 = \langle (N-\mu)^3 \rangle$$

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





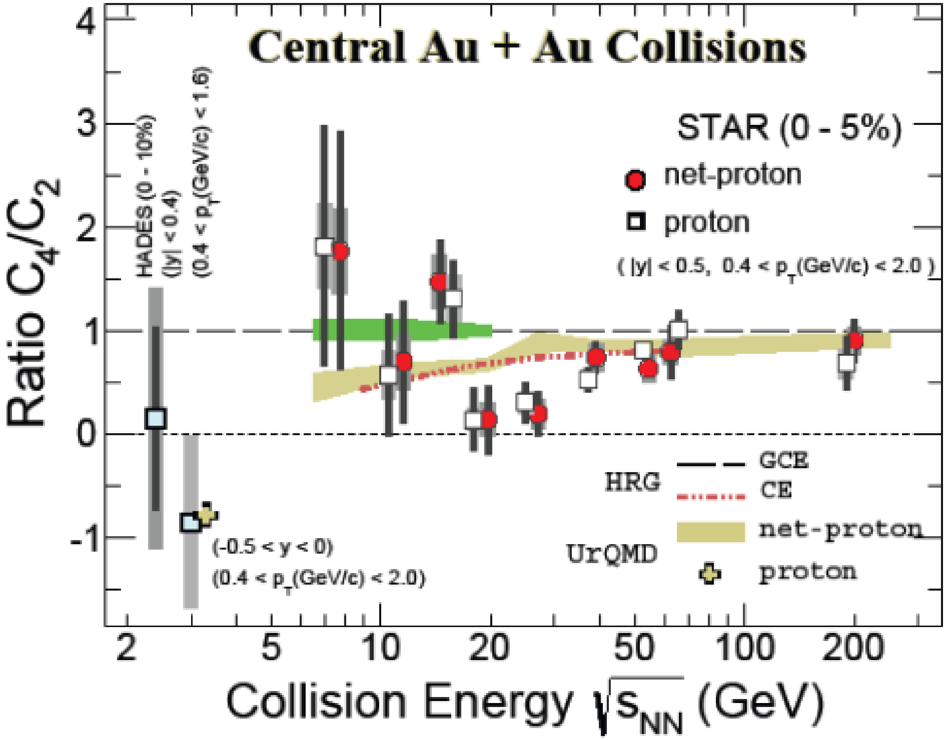
Kurtosis, Wikipedia (https://en.wikipedia.org/wiki/Kurtosis)

The standardized moments of a distribution are

$$S\sigma = C_3/C_2 \text{ [skewness]}$$ measure of distribution's asymmetry

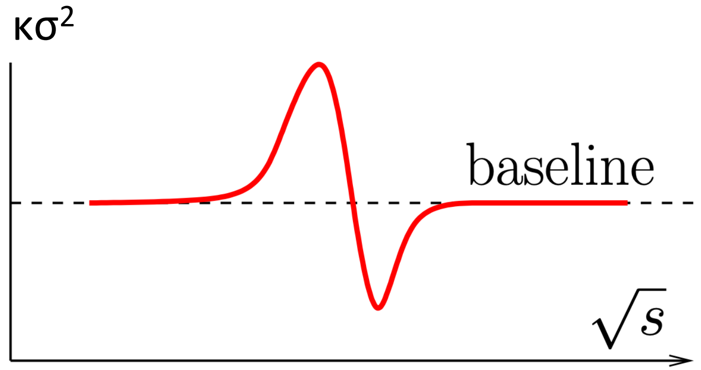
$$\kappa\sigma^2 = C_4/C_2 \text{ [excess kurtosis]}$$ measure of distribution's tails

Current Status of Cumulants Analysis



STAR, Phys. Rev. Lett. 128, 202303 (2022) ; arXiv : 2209.11940.
Phys. Rev. Lett. 126, 092301 (2021); Phys. Rev. C 104, 024902 (2021)

Predicted Fluctuation in C_4/C_2 Near Critical Point



M. Stephanov. J. Physics G.: Nucl. Part. Phys. **38** (2011) 124147

- Non-monotonic collision-energy dependence of baryon-number kurtosis predicted near critical point
- Non-monotonicity was observed in BES-I
- Recent measurement at 3 GeV demonstrates a return to the UrQMD baseline.
- High-statistics data with detector improvements have been taken from 7.7 GeV to 27 GeV in collider mode and 3.0 to 7.7 GeV with the Fixed Target program from BES-II

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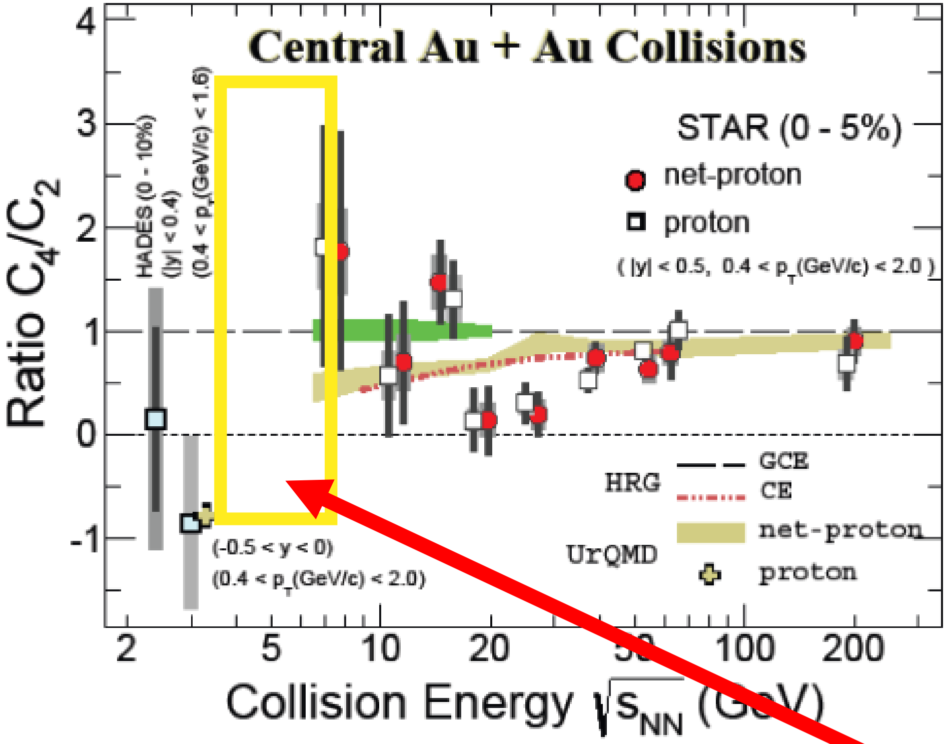

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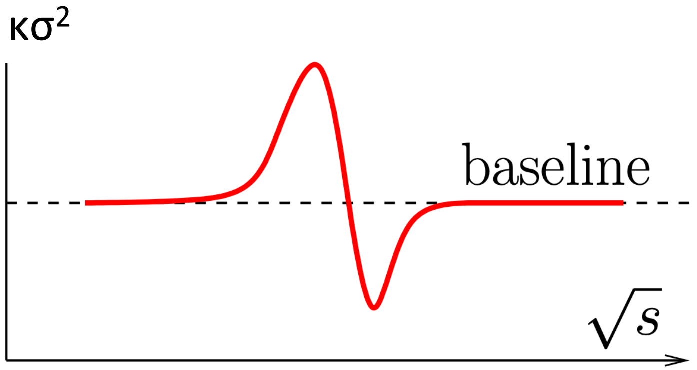

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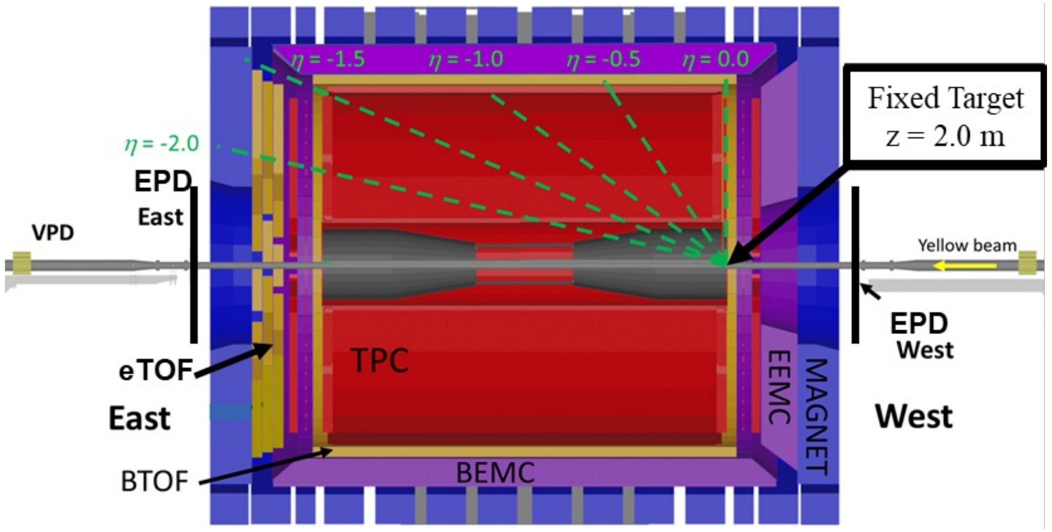
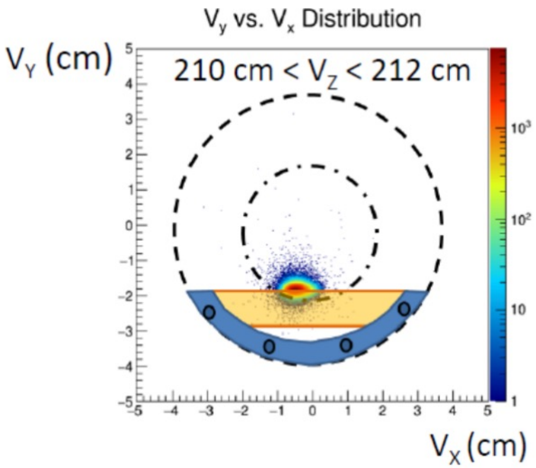
Fixed-Target (FXT) Program at STAR

- Test run with gold target in 2015
- First physics runs at $\sqrt{s_{NN}}$ = 3.0 GeV and 7.2 GeV in 2018
- Now have data at $\sqrt{s_{NN}}$ of 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.2, and 7.7 GeV



Challenges for FXT

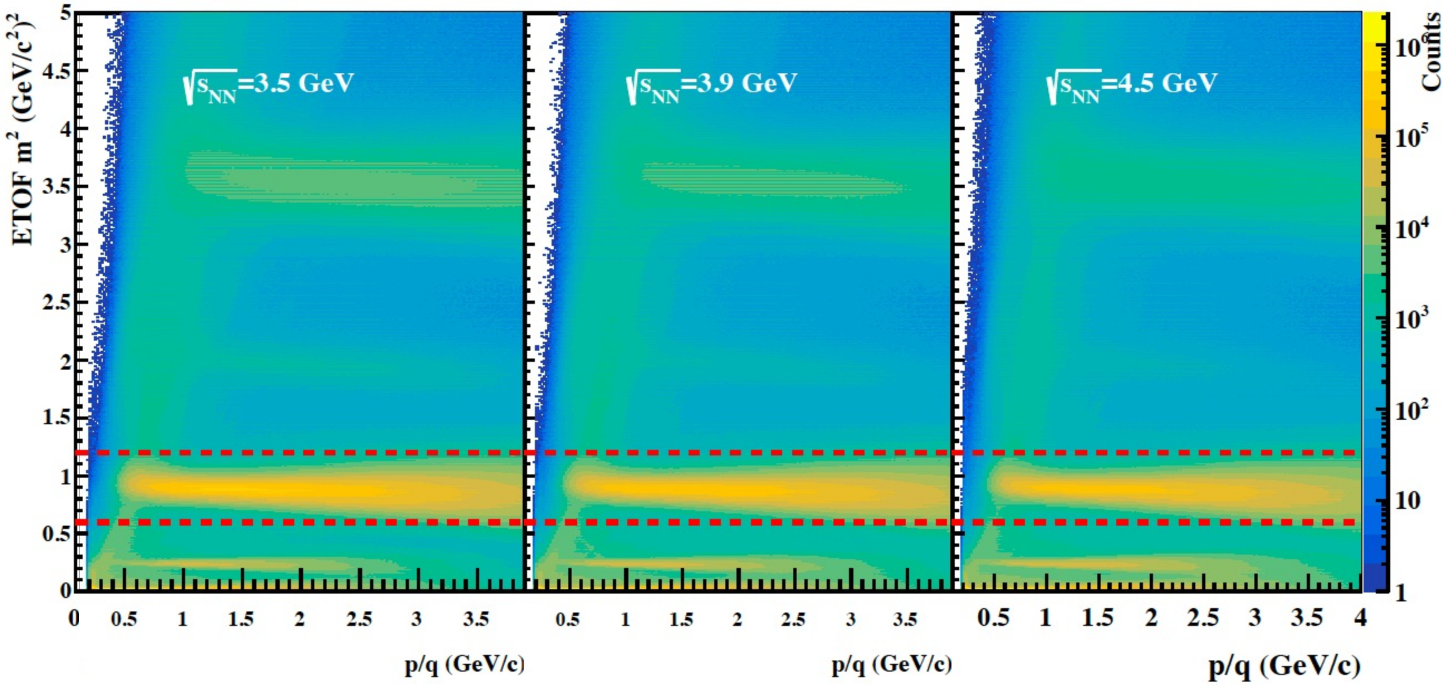
- Shifting asymmetric acceptance with respect to midrapidity with collision energy
- At 7.7 GeV, the midrapidity moves to edge of Time Projection Chamber (TPC) acceptance
- Boost at higher energies shifts particle identification (PID) to rely more on TOF than TPC

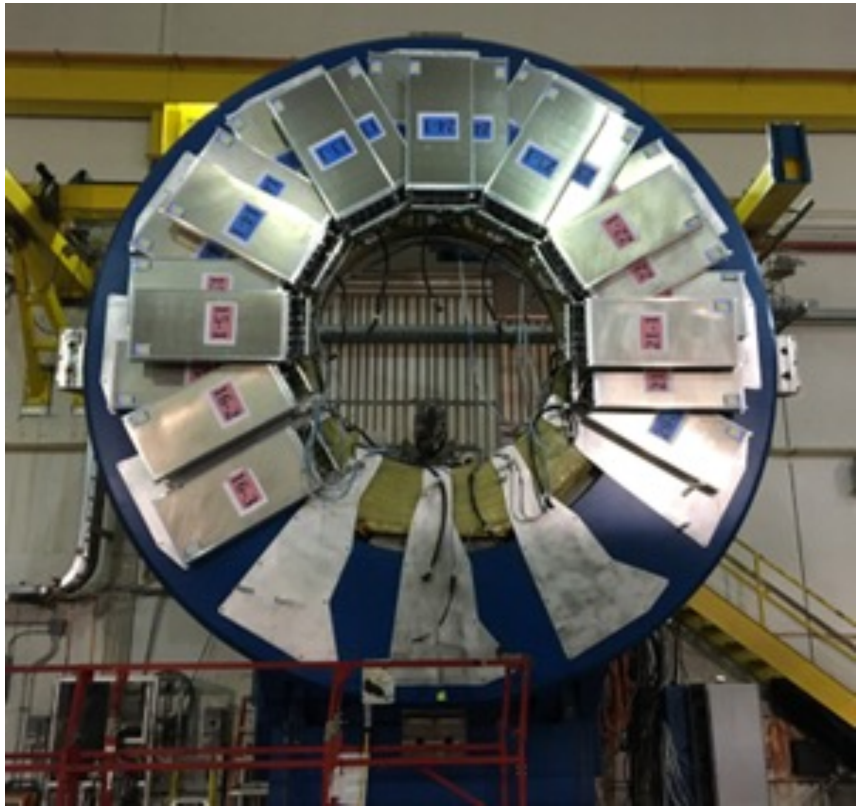


Endcap Time-of-Flight Detector

ETOF Details

- CBM-TOF group provided ETOF system
- Provides particle identification over 1.55<η<2.2
- Collected data for the Fixed-Target Program
- Calibrations completed at $\sqrt{s_{NN}}$ = 3.5, 3.9, 4.5 GeV



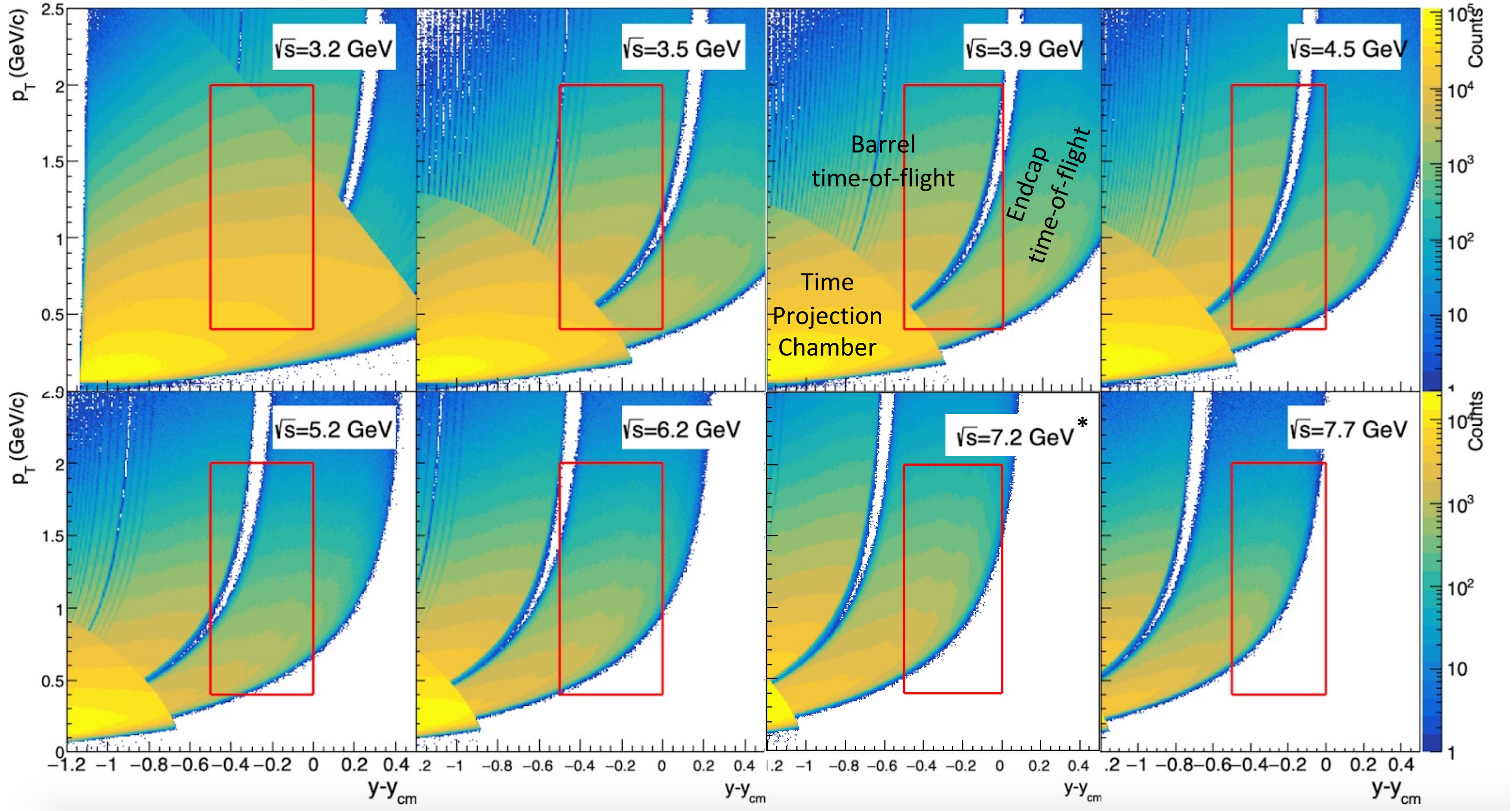


Analysis Strategy

- Midrapidity analyses will be performed at $\sqrt{s_{NN}}$ = 3.2, 3.5, 3.9, 4.5 GeV since we have near-full coverage over $-0.5<y-y_{CM}<0$ and $0.4<p_T<2$ GeV/c
- At $\sqrt{s_{NN}}$ = 5.2, 6.2, 7.2, and 7.7 GeV proton cumulants will be analyzed away from midrapidity
  - We can map proton cumulants as a function of μ_B

Top priority for publication →

Secondary for publication →



*7.2 GeV acceptance map comes from 6.2 GeV, shifted to the appropriate rapidity

Theory Predictions for Critical Point Location

Nominal $\sqrt{s}$ (GeV)	Chemical Potential μ_B (MeV)
3.2	697
3.5	666
3.9	632
4.5	589
5.2	541
6.2	487
7.2	443
7.7	420

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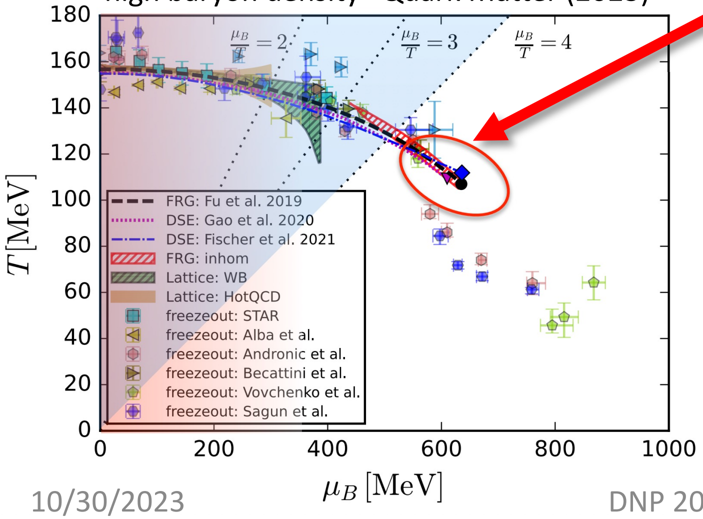

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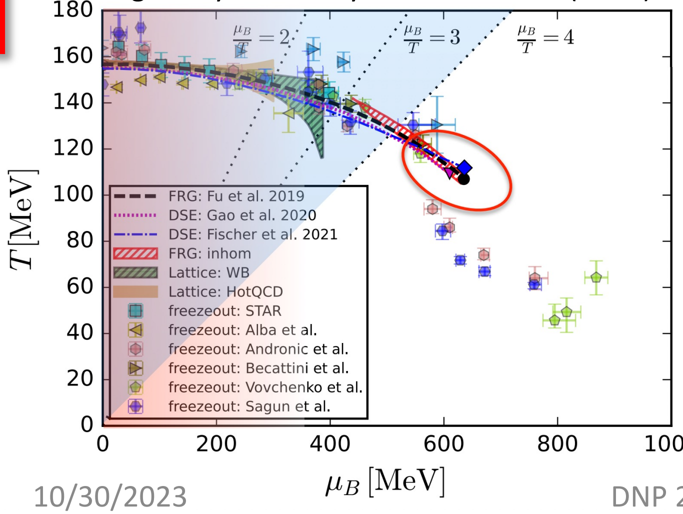

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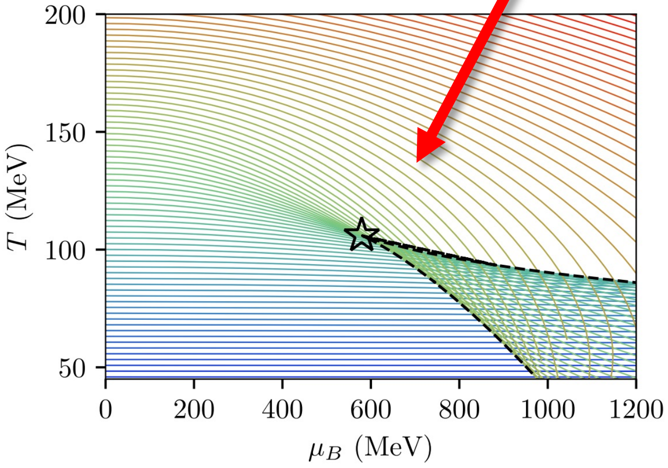

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- Maurício Hippert: holographic Bayesian analysis gives $560 \lesssim \mu_B \lesssim 625$ MeV
- Jishnu Goswami: extrapolation using machine-learning model from hot QCD: $\mu_B \cong 600 \pm 80$ MeV

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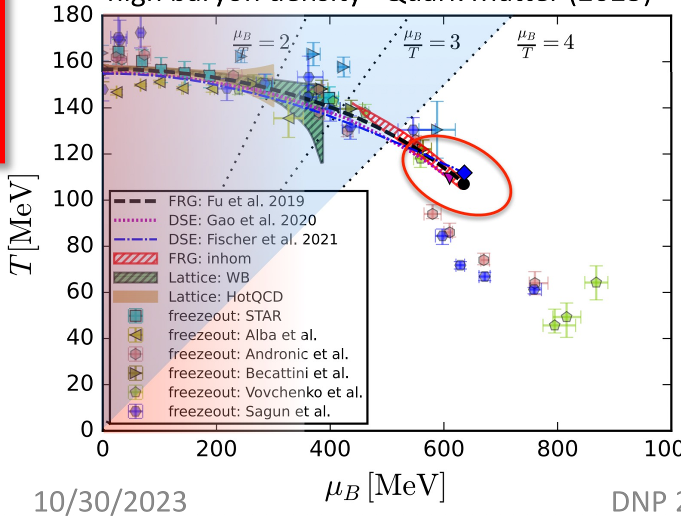

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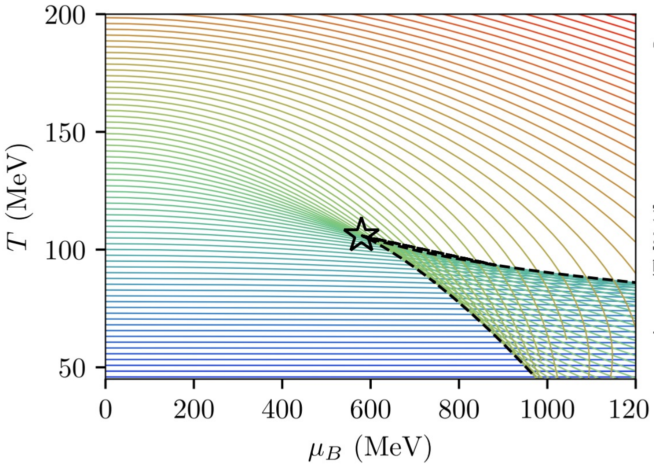
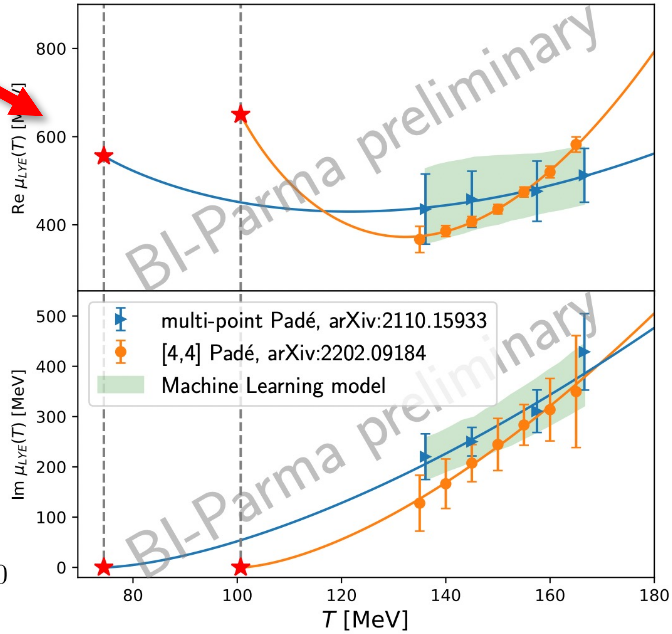
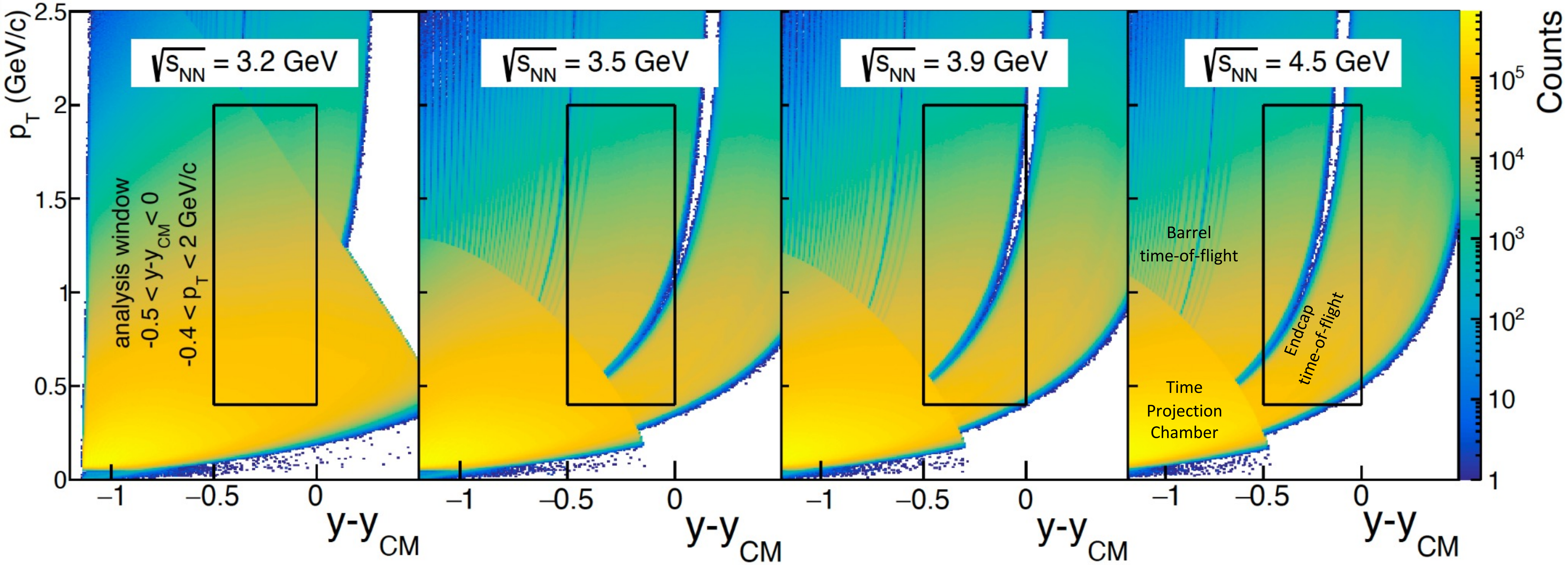


Jishnu Goswami, "Exploring the Critical Points in QCD with Multi-Point Padè and Machine Learning Techniques in (2+1)-flavor QCD" Quark Matter (2023)



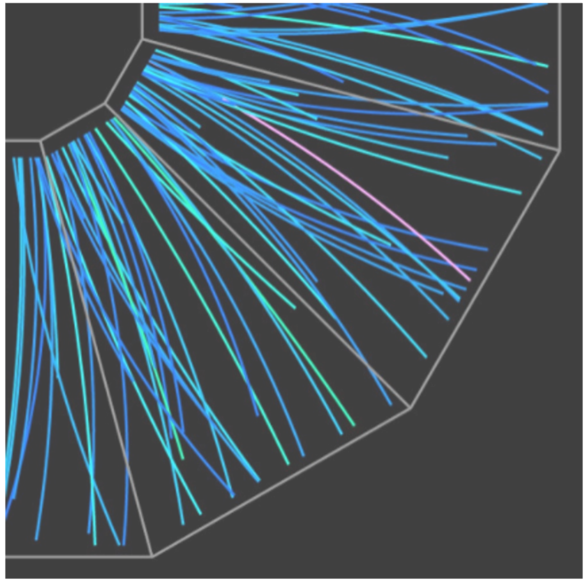
Detector Acceptances

- We have near full acceptance in our analysis window ($-0.5<y-y_{CM}<0$, $0.4<p_T<2$ GeV/c) up to 4.5 GeV
- We rely on much more time-of-flight for particle identification for $\sqrt{s_{NN}}$ = 3.5, 3.9, 4.5 GeV



Lessons: FXT and Timing Fluctuations

- STAR TPC has 40 μs drift time



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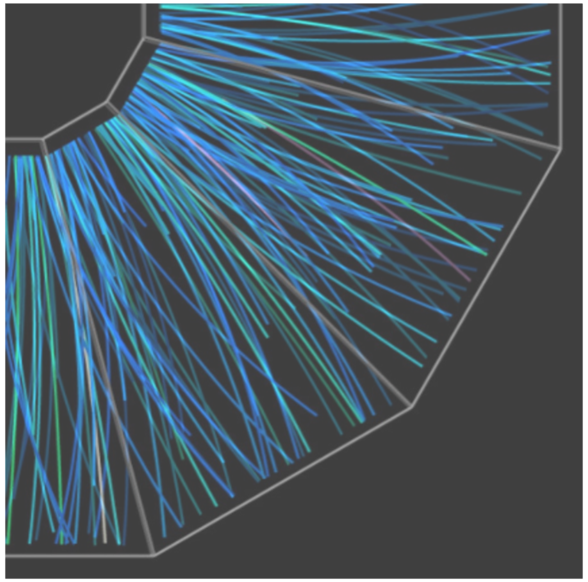
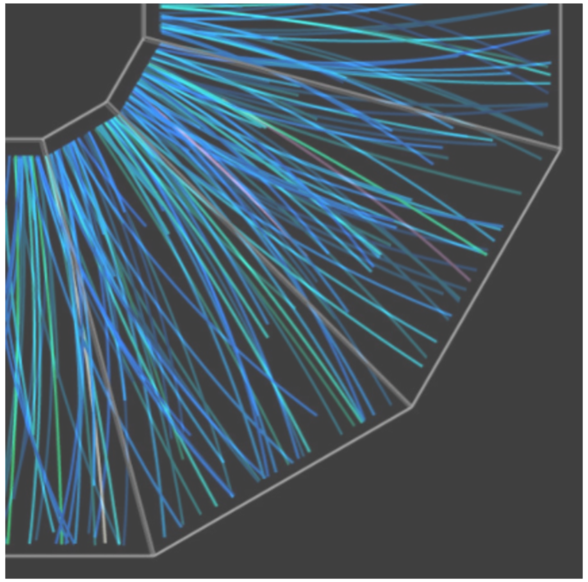


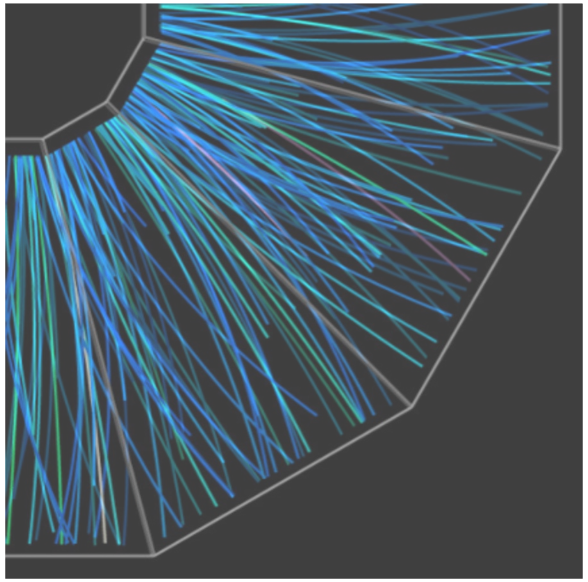
Lessons: FXT and Timing Fluctuations

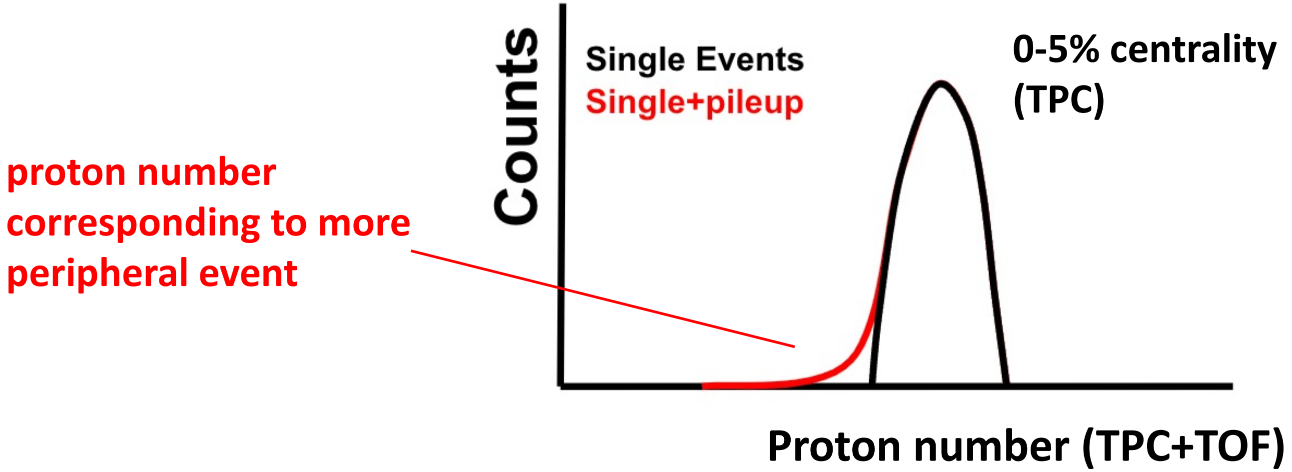
- STAR TPC has 40 μs drift time → occasionally a second collision will occur within that time
- Tracks from a second collision that are included in the event are known as pileup
- Time-of-flight (TOF) detectors use nanosecond-scale timing resolution to identify particles
- Pileup tracks which are out-of-time will often not be well-identified by TOF



Lessons: FXT and Timing Fluctuations

- When we use the time-of-flight for particle ID, protons from out-of-time pileup are not counted by the fast TOF
- The TPC still identifies all the pileup tracks
- Centrality is determined by the TPC multiplicity
- A pileup event may be classified as very central, but have few protons
- For each centrality bin, this leads to a low-proton-number tail





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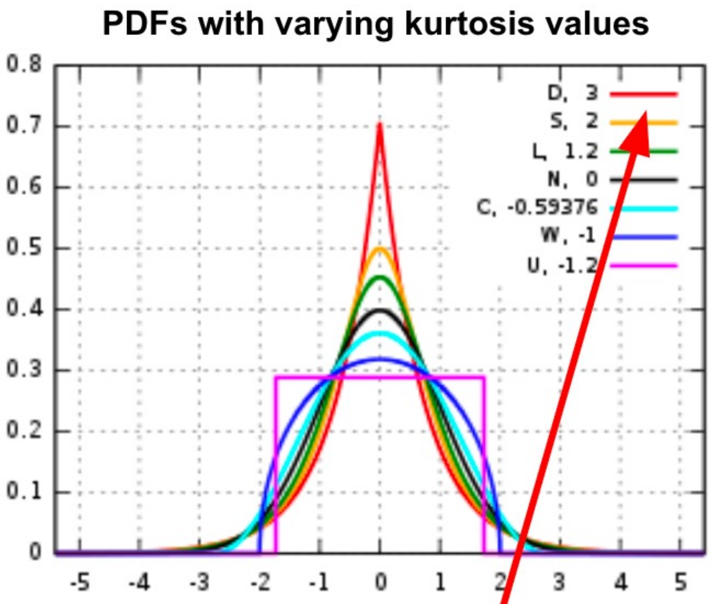
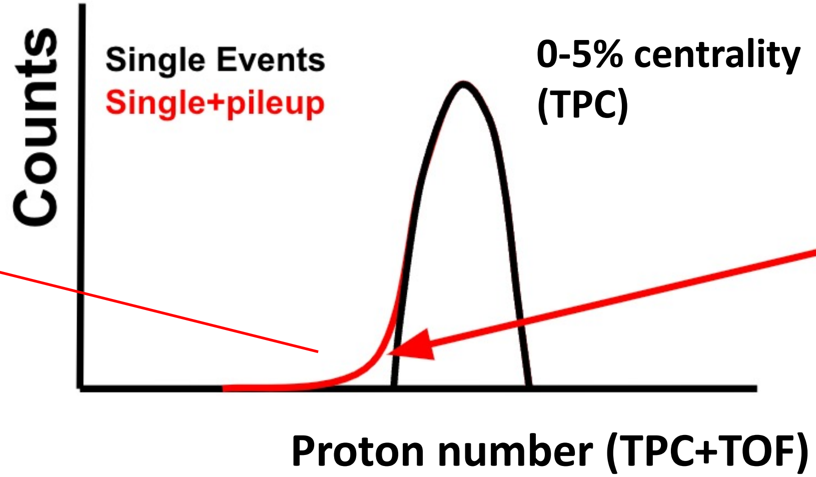
- For each centrality bin, this leads to a low-proton-number tail
- Long tails mean large kurtosis



proton number corresponding to more peripheral event



Large tails → large kurtosis

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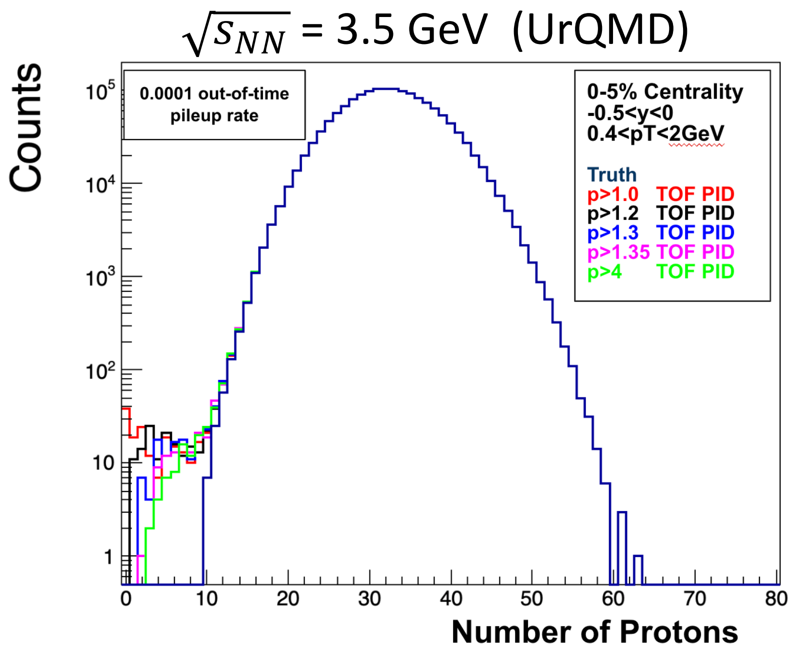
- We can simulate this in UrQMD by sampling two events at a rate of 0.0001
- In the experiment we use TOF PID for tracks above a certain momentum
- We can simulate this by only including pileup tracks with momenta below the threshold for using TOF
- The more TOF PID we use, the more the pileup causes a tail



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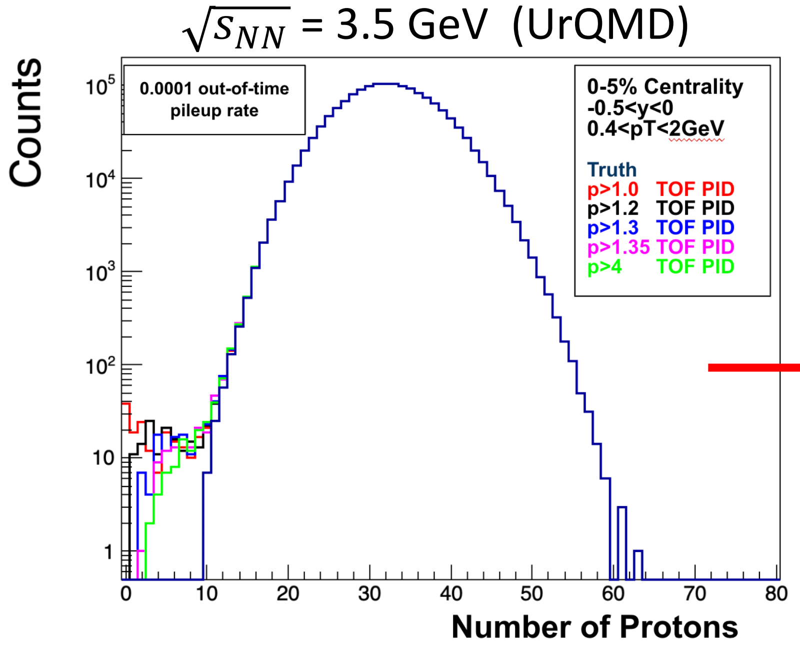
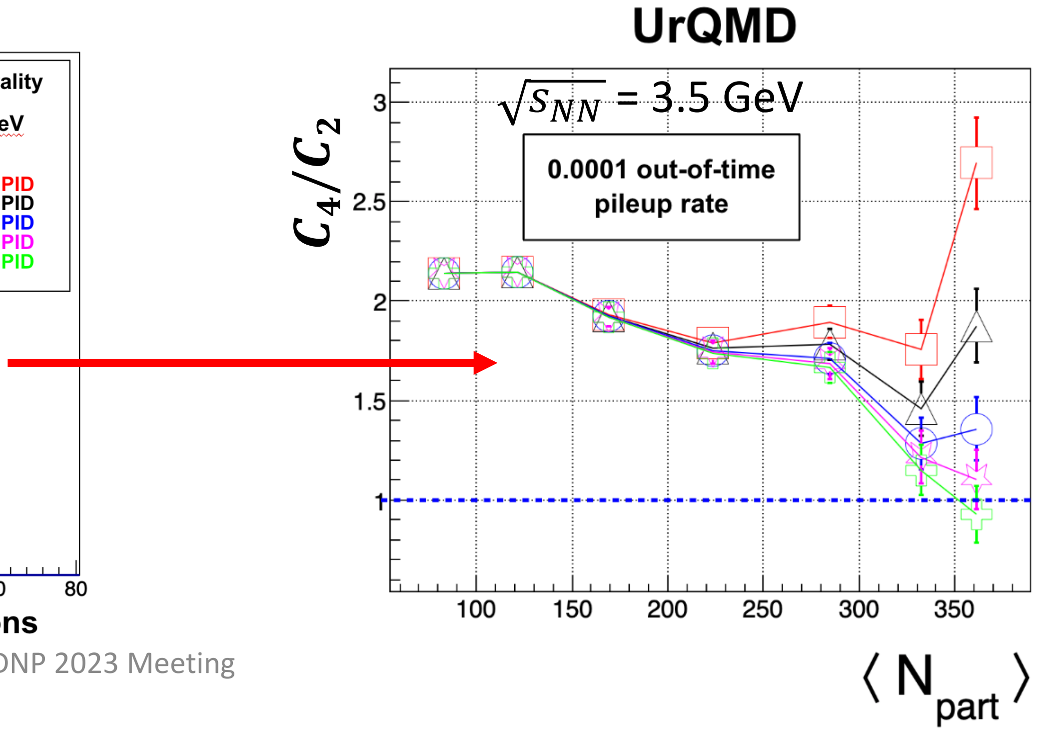
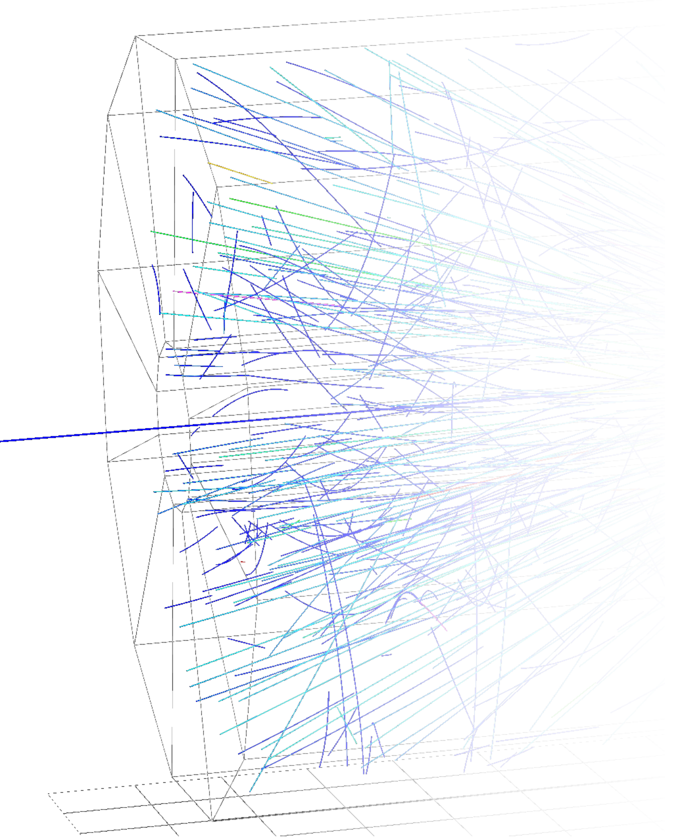
- We can simulate this by only including pileup tracks with momenta below the threshold for using TOF
- The more TOF PID we use, the more the pileup causes a tail
- This causes instability in C_4/C_2 and other cumulants
- **Conclusion:** remove pileup when using TOF for proton ID. *Do not* correct for it.
- We can remove pileup by rejecting events with discrepant TOF and TPC multiplicities





Conclusions and Outlook



- Recent data from the Fixed–Target Program will extend our knowledge of the proton cumulant ratios at low energies (3.2-7.7 GeV)
- Non-monotonic variation in proton higher moments would suggest proximity to a critical point in the QCD phase diagram
- Many theoretical approaches now suggest critical point is accessible in the STAR Fixed-Target regime
- Midrapidity measurements will be performed at $\sqrt{s_{NN}}$ = 3.2, 3.5, 3.9, and 4.5 GeV
- Rapidity-dependent study will be done at $\sqrt{s_{NN}}$ = 5.2, 6.2, 7.2, and 7.7 GeV.
- The Fixed-Target analysis comes with unique challenges which we are working to understand