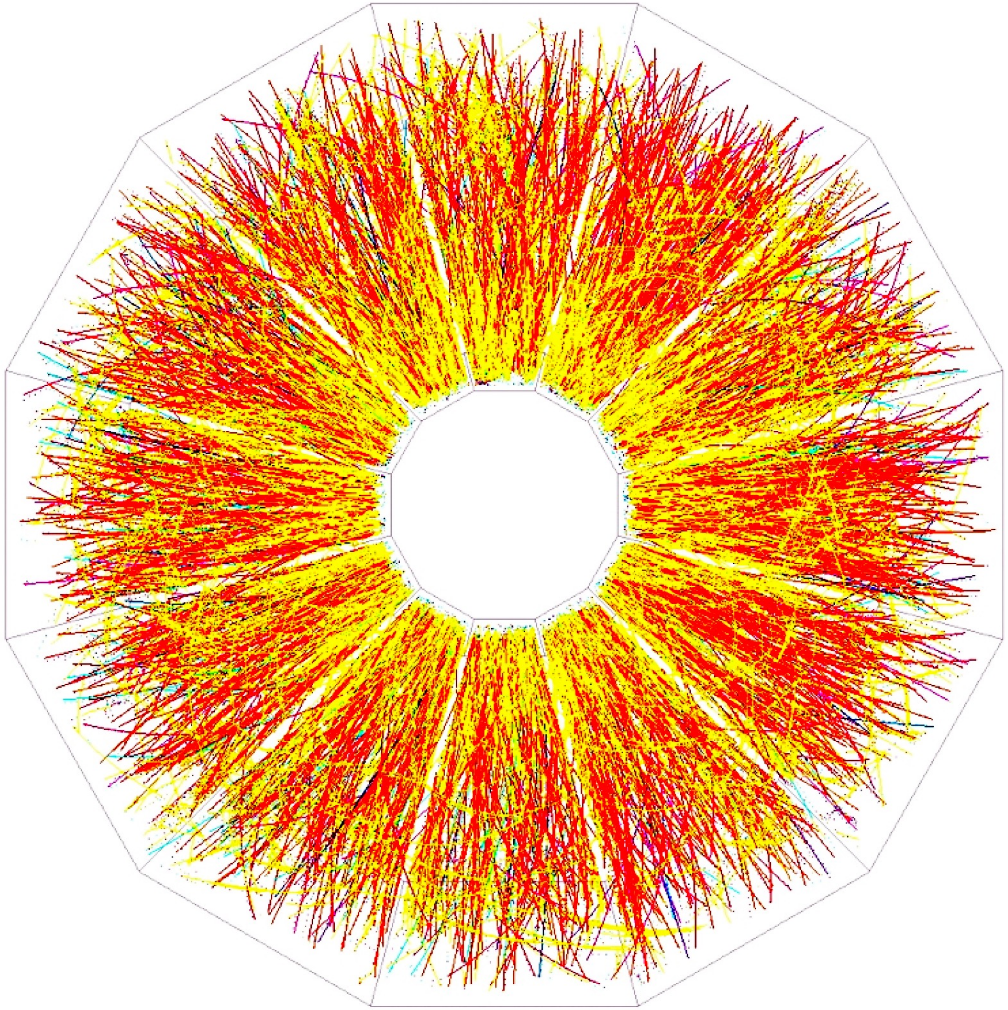


Overview of Net-particle Fluctuations from the RHIC Beam Energy Scan Program

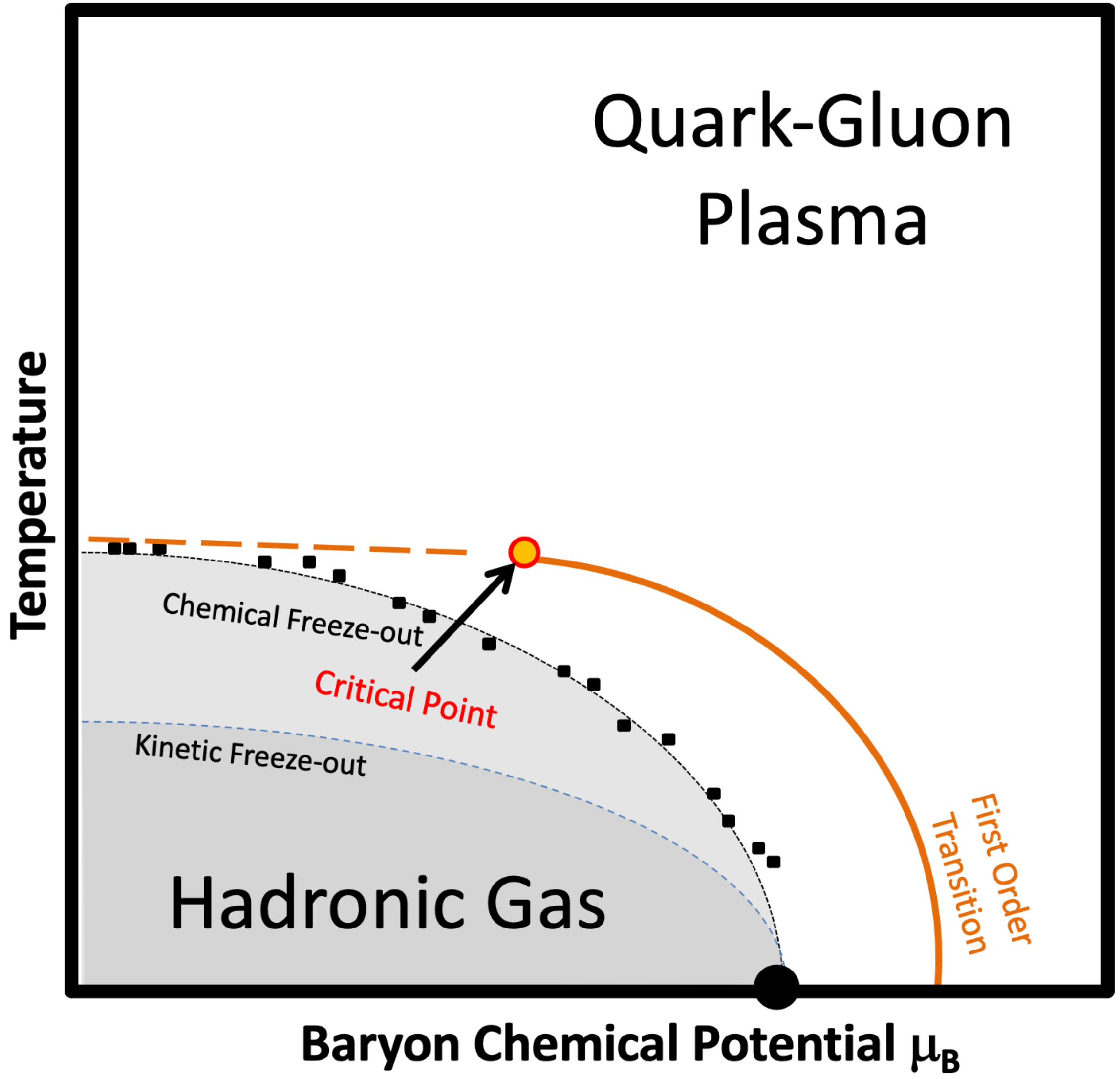
Zachary Sweger
University of California, Davis
For the STAR Collaboration

Supported in part by

Phases of QCD Matter

QCD Phase Diagram

- Cross-over transition expected at low baryon chemical potential (μ_B)
- First-order transition expected at high μ_B
- Critical point marks the location where the transition order changes



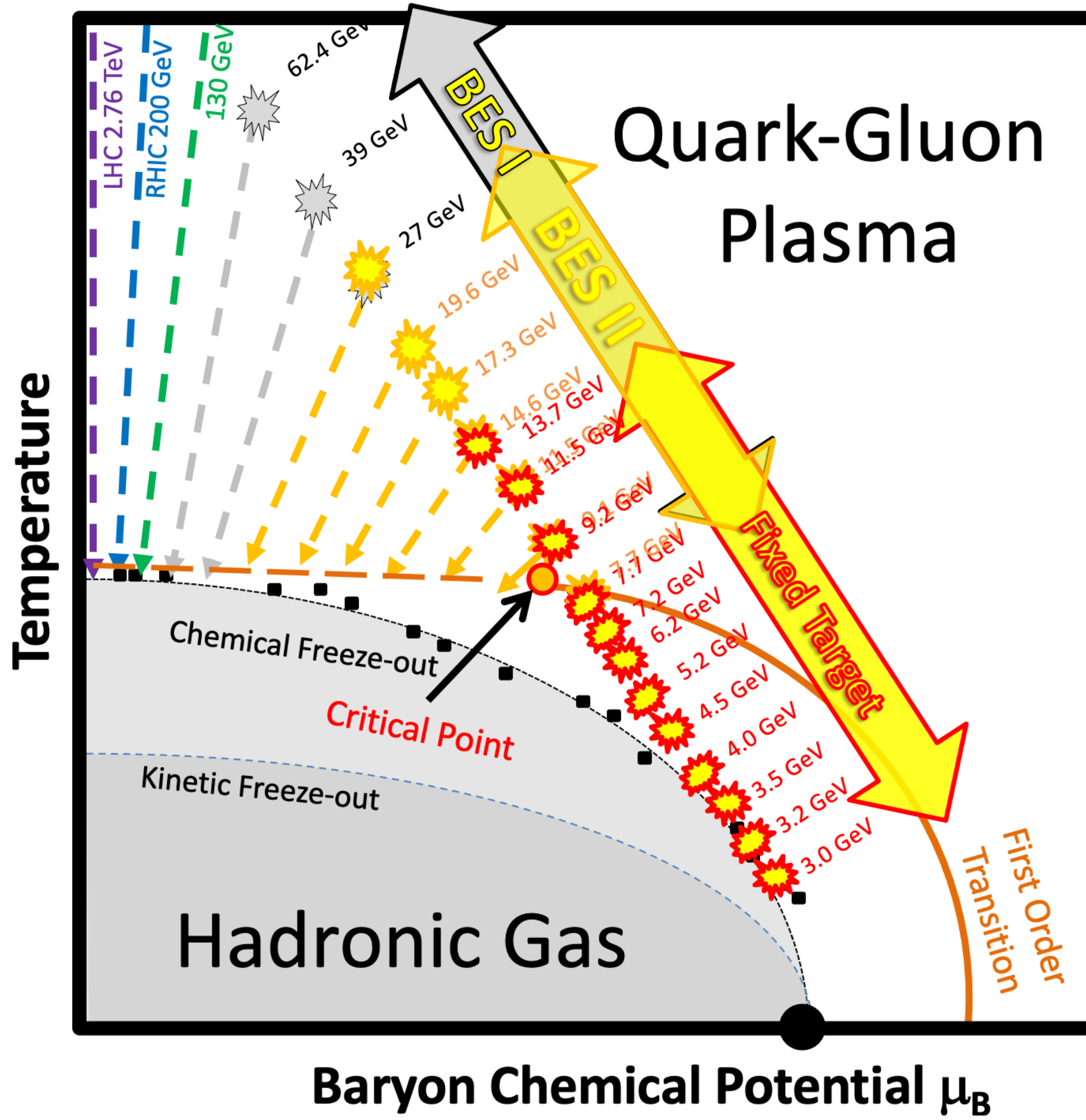
Phases of QCD Matter

QCD Phase Diagram

- Cross-over transition expected at low baryon chemical potential (μ_B)
- First-order transition expected at high μ_B
- Critical point marks the location where the transition order changes

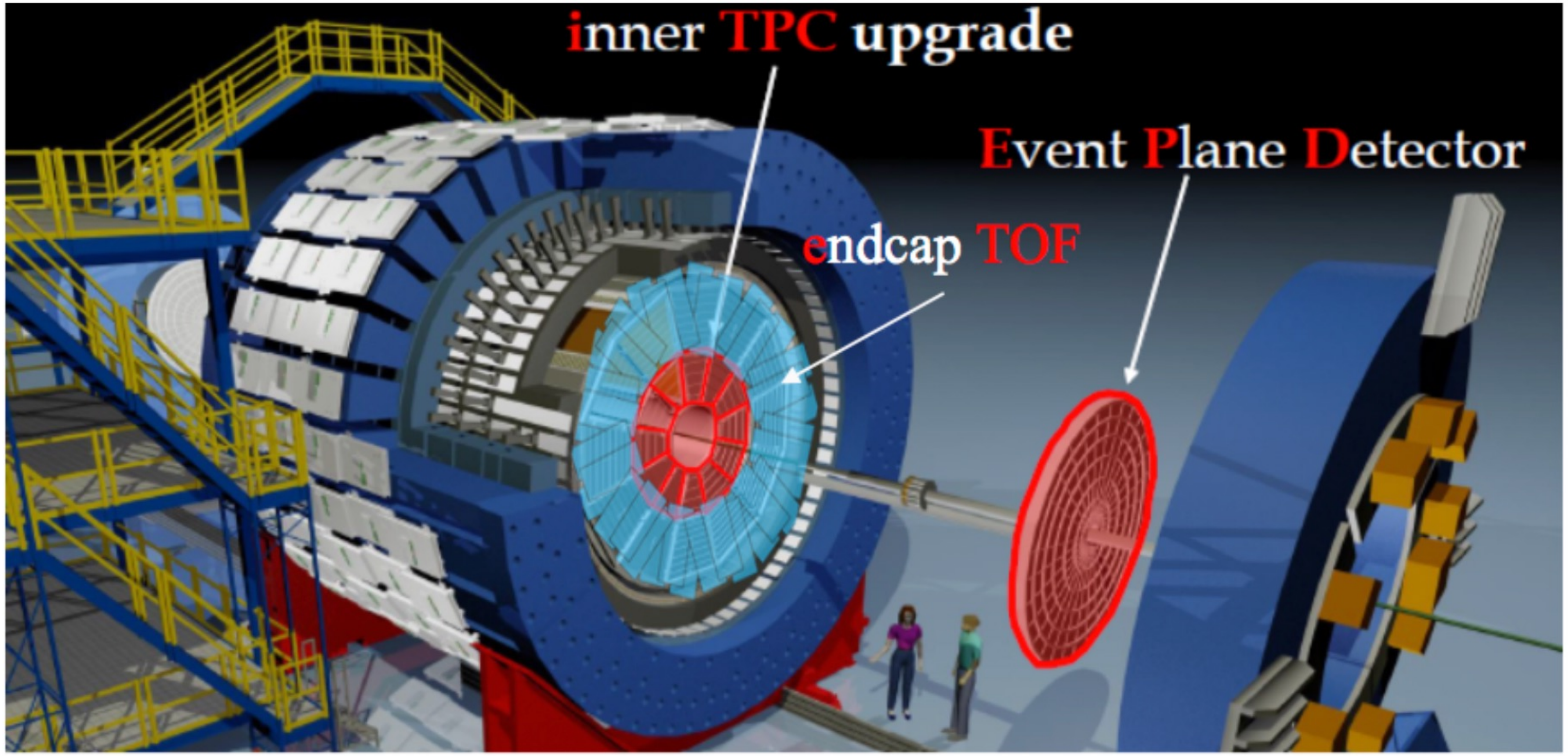
Beam Energy Scan (BES)

- 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



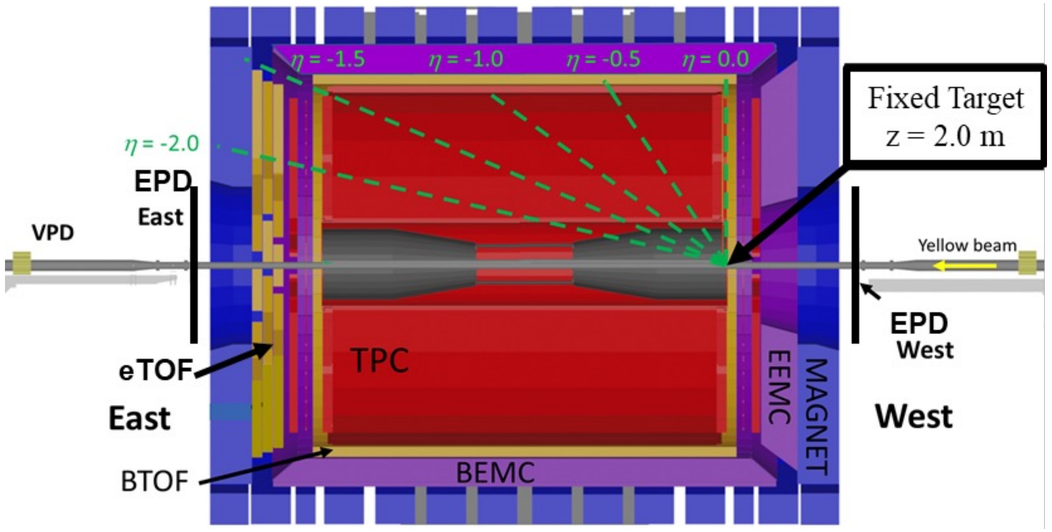
BES-II Collider Program

- Several detector upgrades following BES-I
- Endcap TOF (ETOF) extends particle identification to forward rapidity
- Inner TPC (iTPC) also extends acceptance in pT and from |η|<1 to |η|<1.5 and improves tracking
- Now have data at $\sqrt{s_{NN}}$ = 7.7, 9.2, 11.5, 14.5, 19.6, and 27 GeV



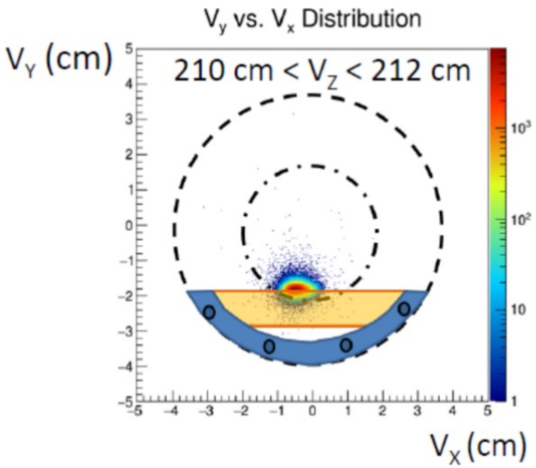
Fixed-Target (FXT) Program at STAR

- 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 wrt midrapidity
- At 7.7 GeV midrapidity moves to edge of acceptance
- Boost at higher energies shifts PID to rely more on TOF than TPC identification
- ETOF is critical for PID above 3.2 GeV!



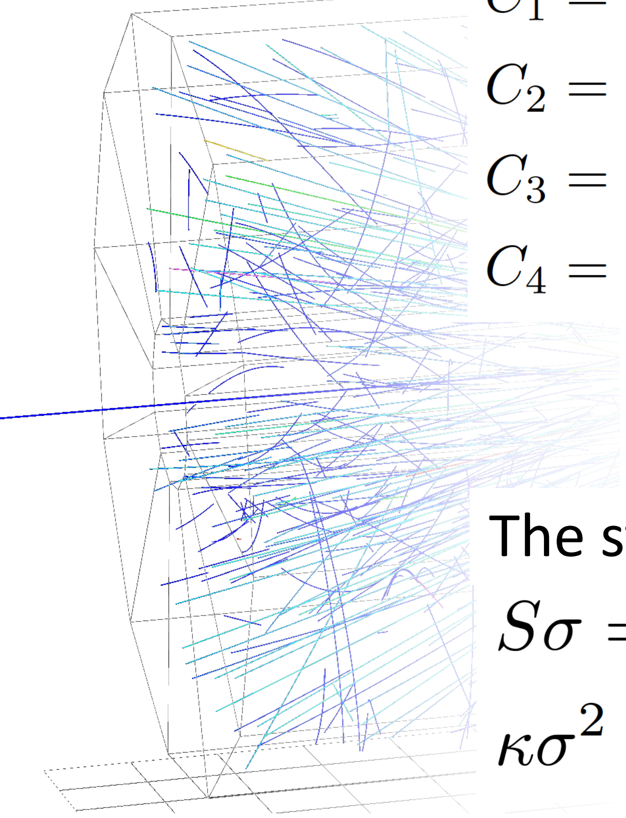
Endcap Time-of-Flight Detector

ETOF Details

- CBM-TOF group provided ETOF system
- Provides particle identification over $1.55<\eta<2.2$
- Collected data for the Fixed-Target Program
- Calibrations still in progress.

Net-particle Fluctuations

Cumulants and Moments



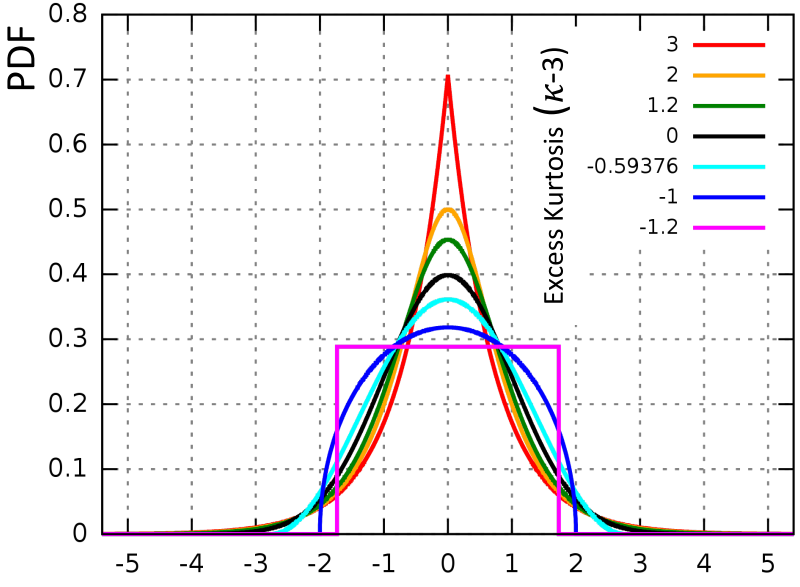
Cumulants of a distribution are defined as

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

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

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

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



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

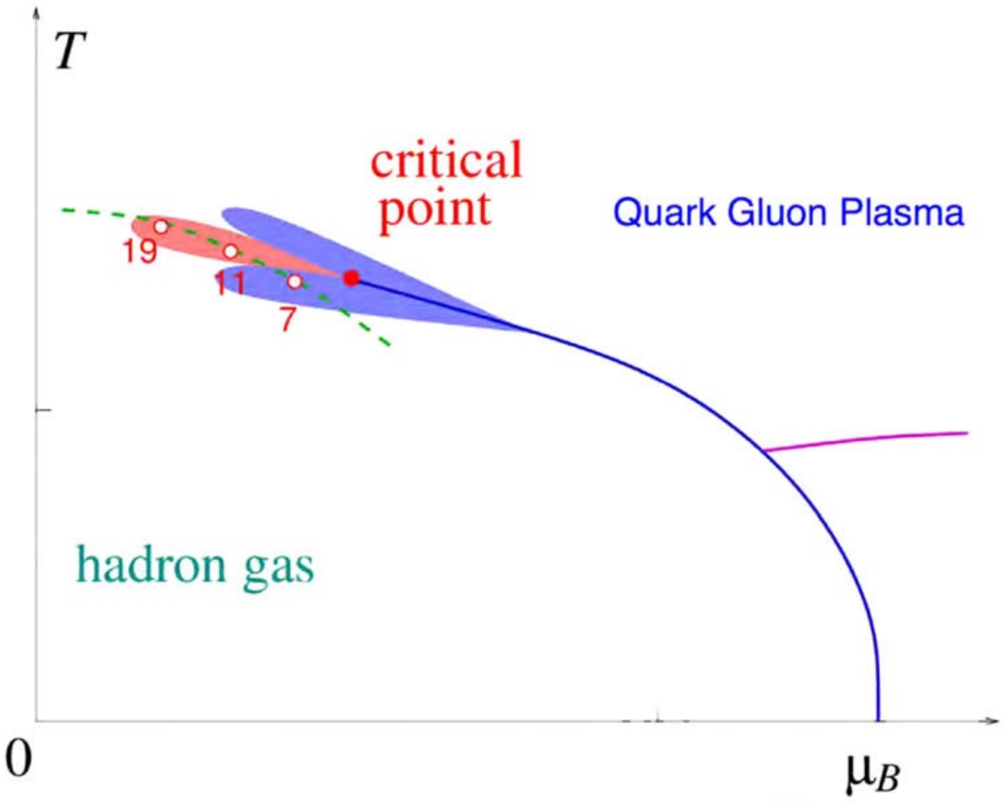
The standardized moments of a distribution are

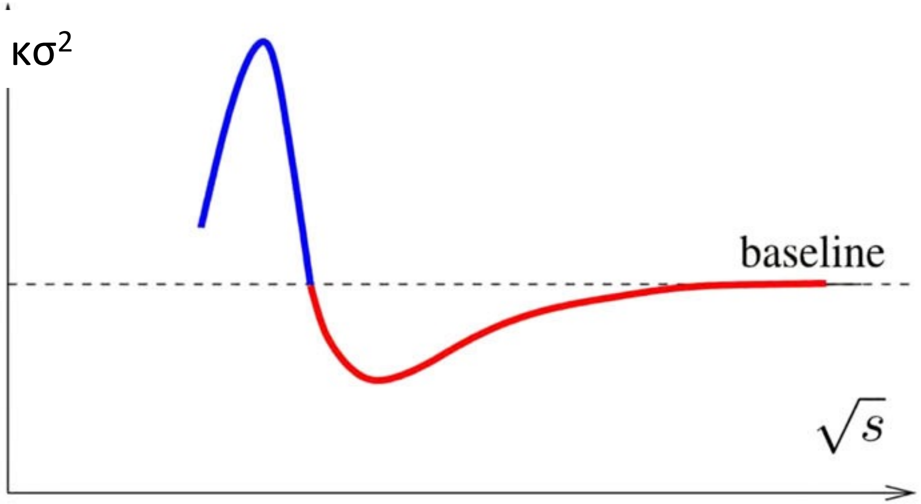
$S\sigma = C_3/C_2$ measure of distribution's asymmetry

$\kappa\sigma^2 = C_4/C_2$ measure of distribution's tails

Proximity to Critical Point → Fluctuations

Predicted Fluctuation in C_4/C_2 Near Critical Point



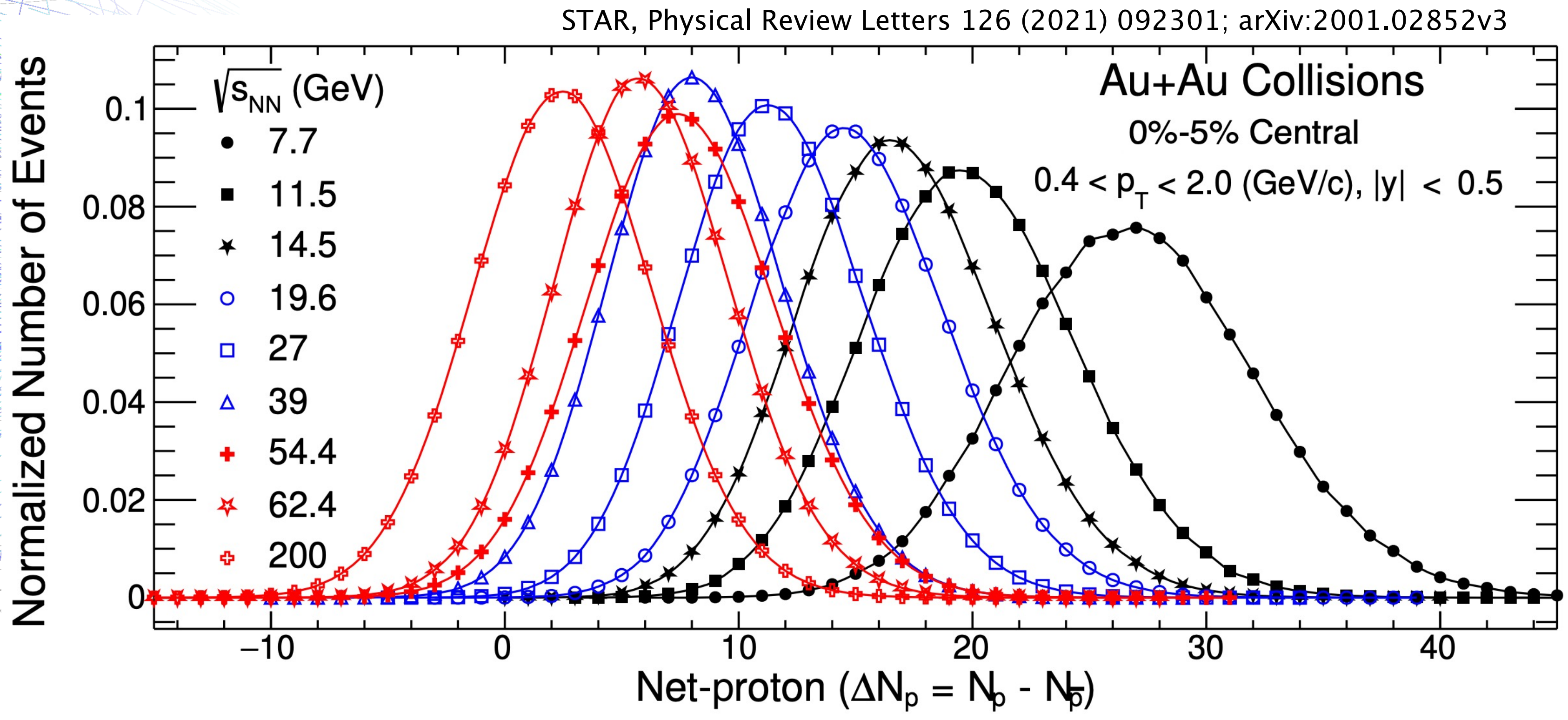


X. Luo, N. Xu, Nucl Sci Tech (2017) 28:112. DOI: 10.1007/s41365-017-0257-0

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

BES-I Protons

- In BES-I, STAR measured net-proton number distributions from $\sqrt{s_{NN}}$ of 7.7 to 200 GeV

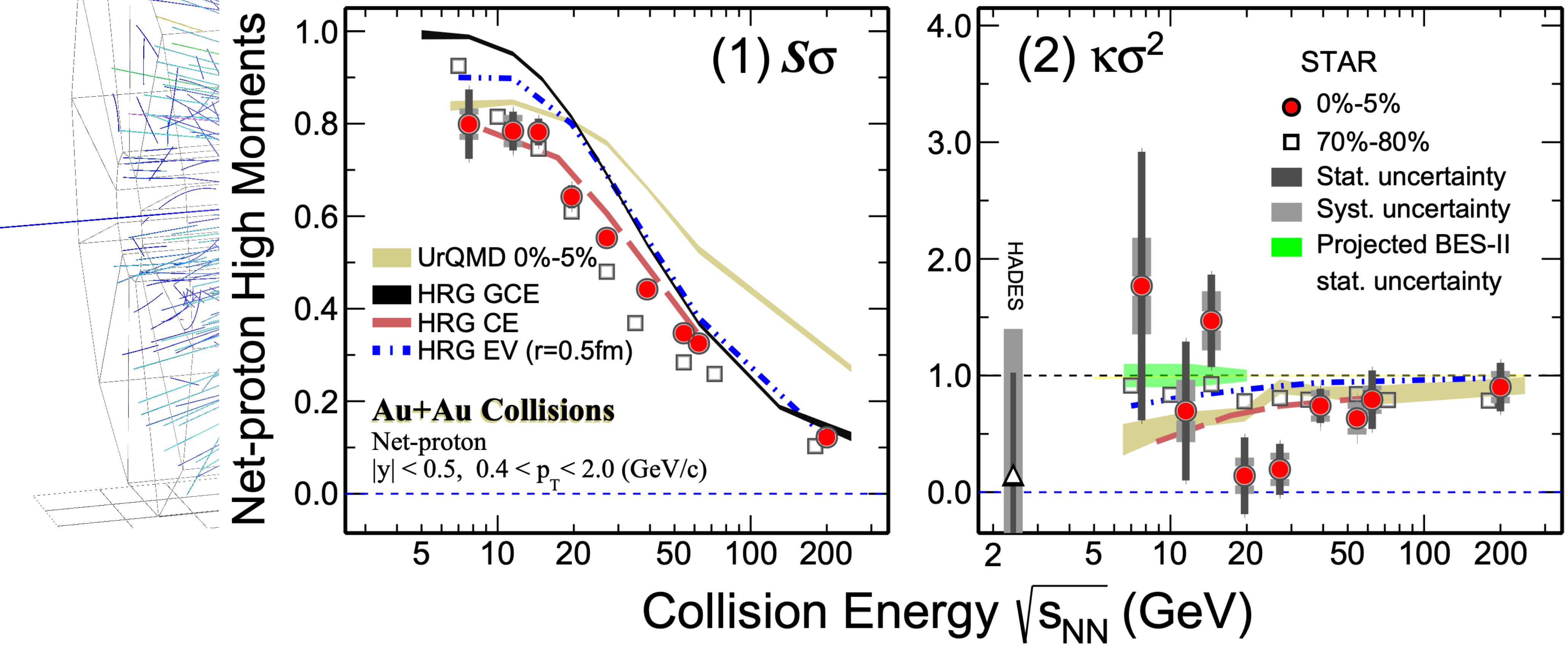


BES-I Protons

- From these distributions, STAR measured cumulants C_1-C_4 and their ratios

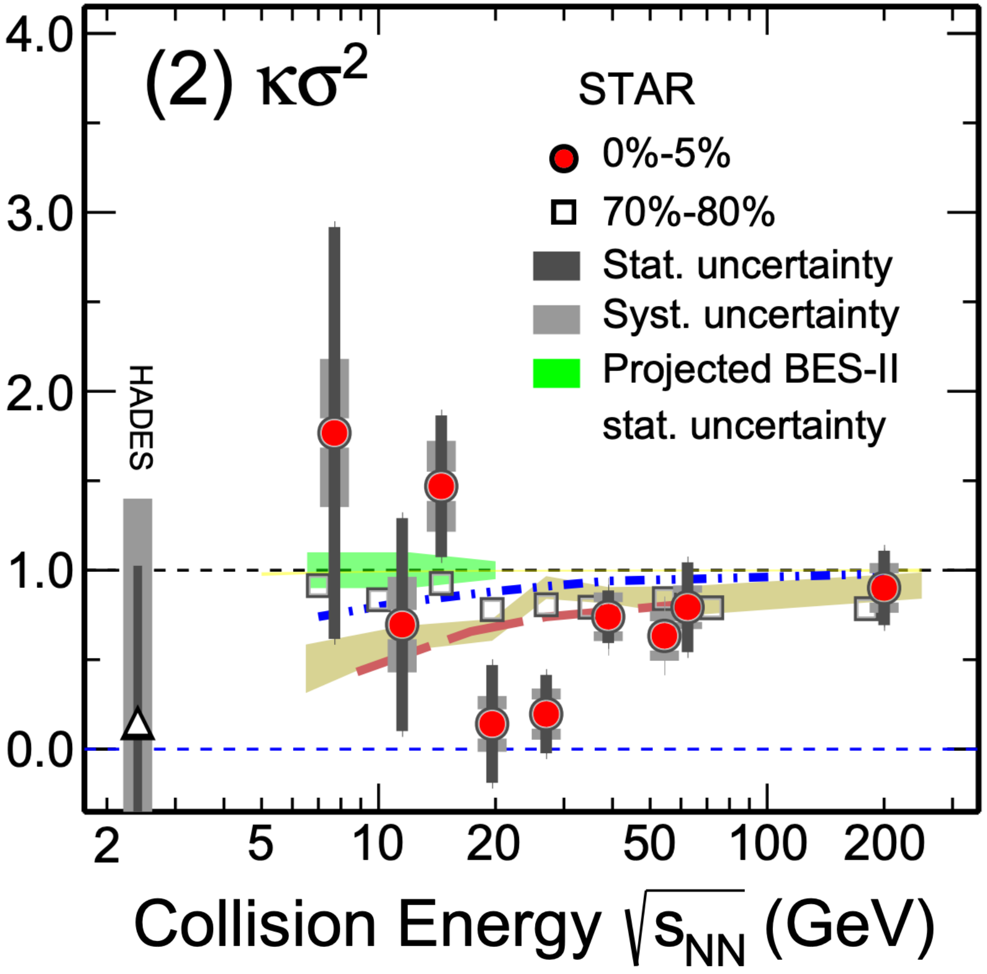
STAR Physical Review Letters 126 (2021) 092301; arXiv:2001.02852v3

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



Current Status of Cumulants Analysis

STAR Physical Review Letters 126 (2021) 092301; arXiv:2001.02852v3



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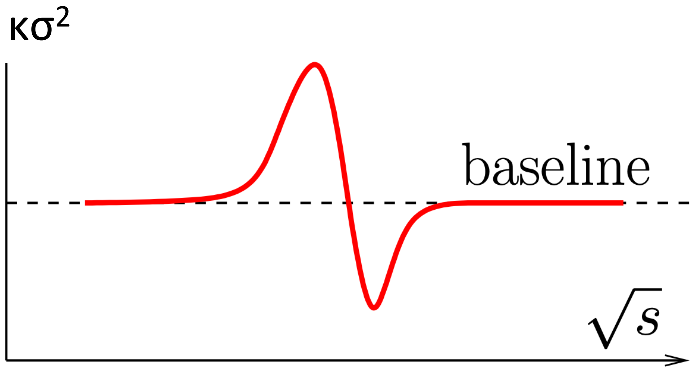

M. Stephanov. J. Physics G.: Nucl. Part. Phys. **38** (2011) 124147

- Non-monotonic energy dependence was observed in BES-I data with a 3.1 sigma significance.
- High-statistics data (BES-II collider mode) with detector improvements have been taken from 7.7 GeV to 27 GeV.

- Data have been collected to fill the large gap between 3.0 and 7.7 GeV.

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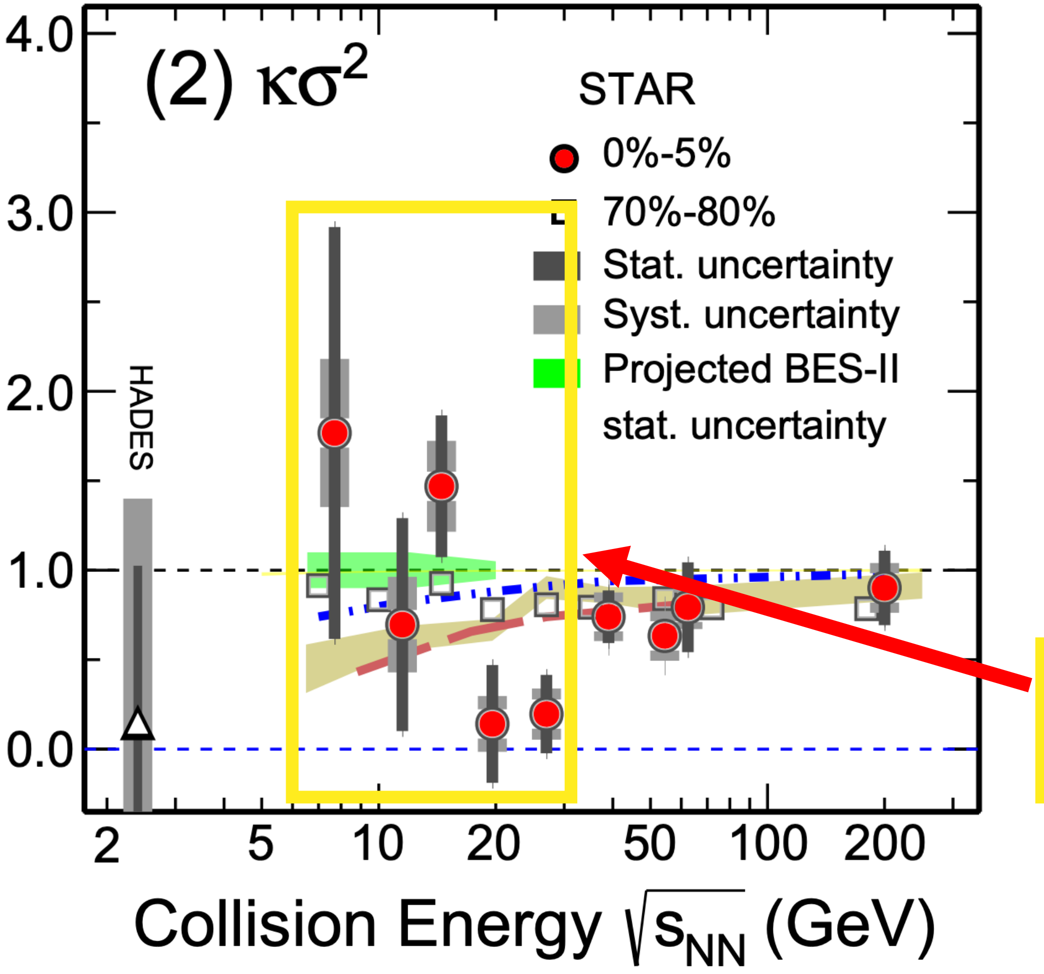

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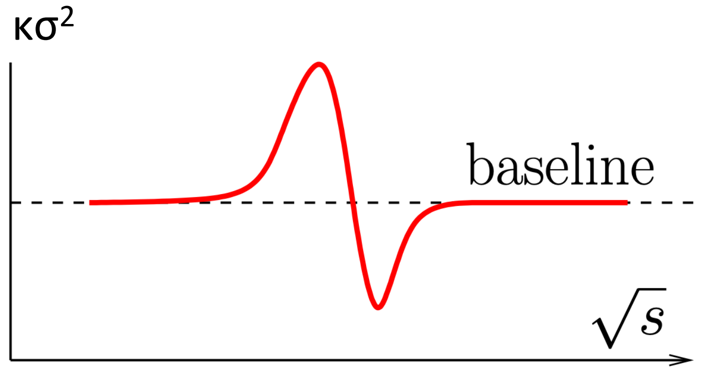

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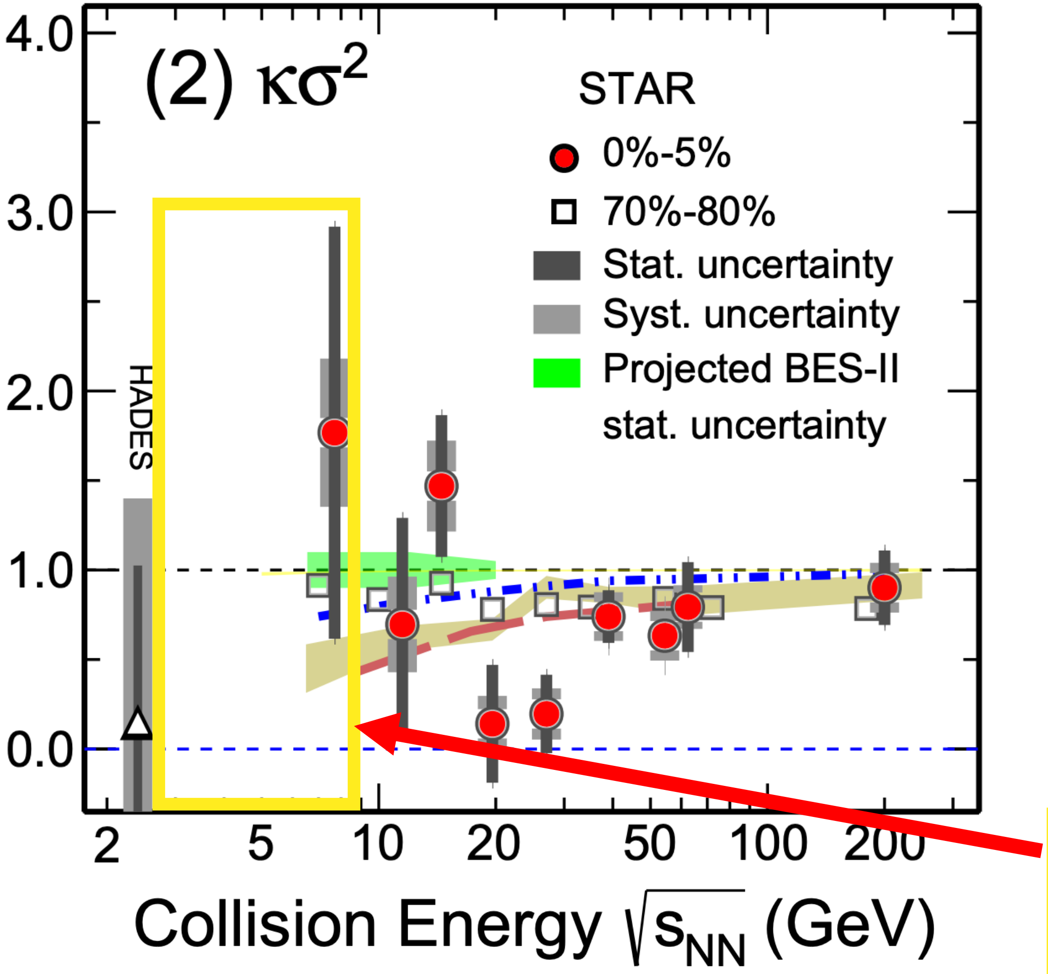

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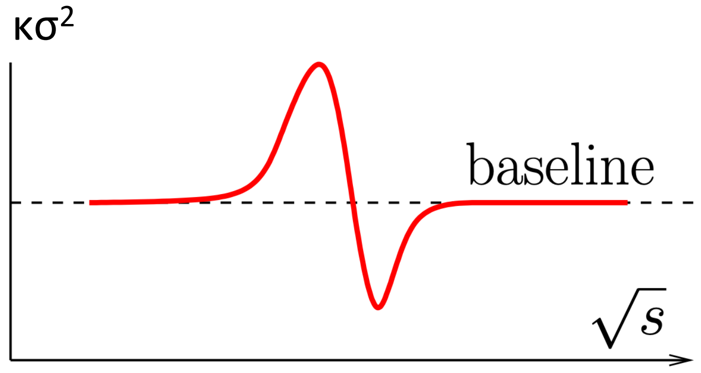

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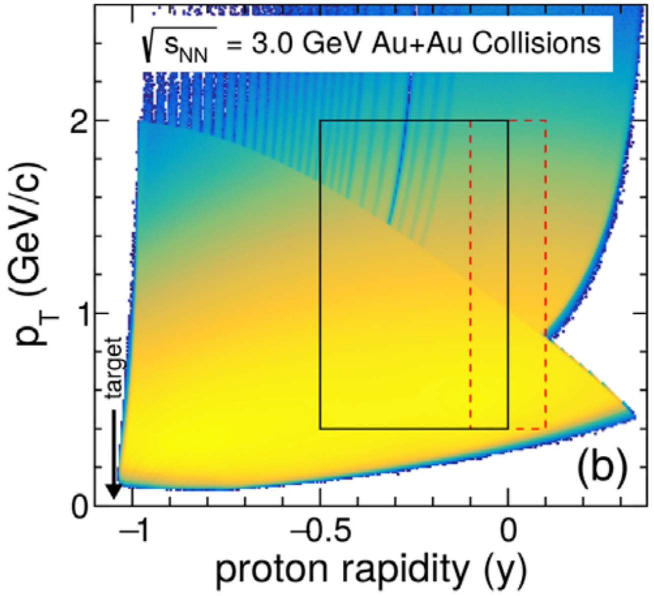
Highlights from Recent Publications

Highlights: Proton Cumulants at 3.0 GeV

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

- In 2022, FXT 3 GeV cumulants were published up to C_4.
- This was first FXT proton moments analysis
- Used asymmetric acceptance window $-0.5<y-y_{cm}<0$



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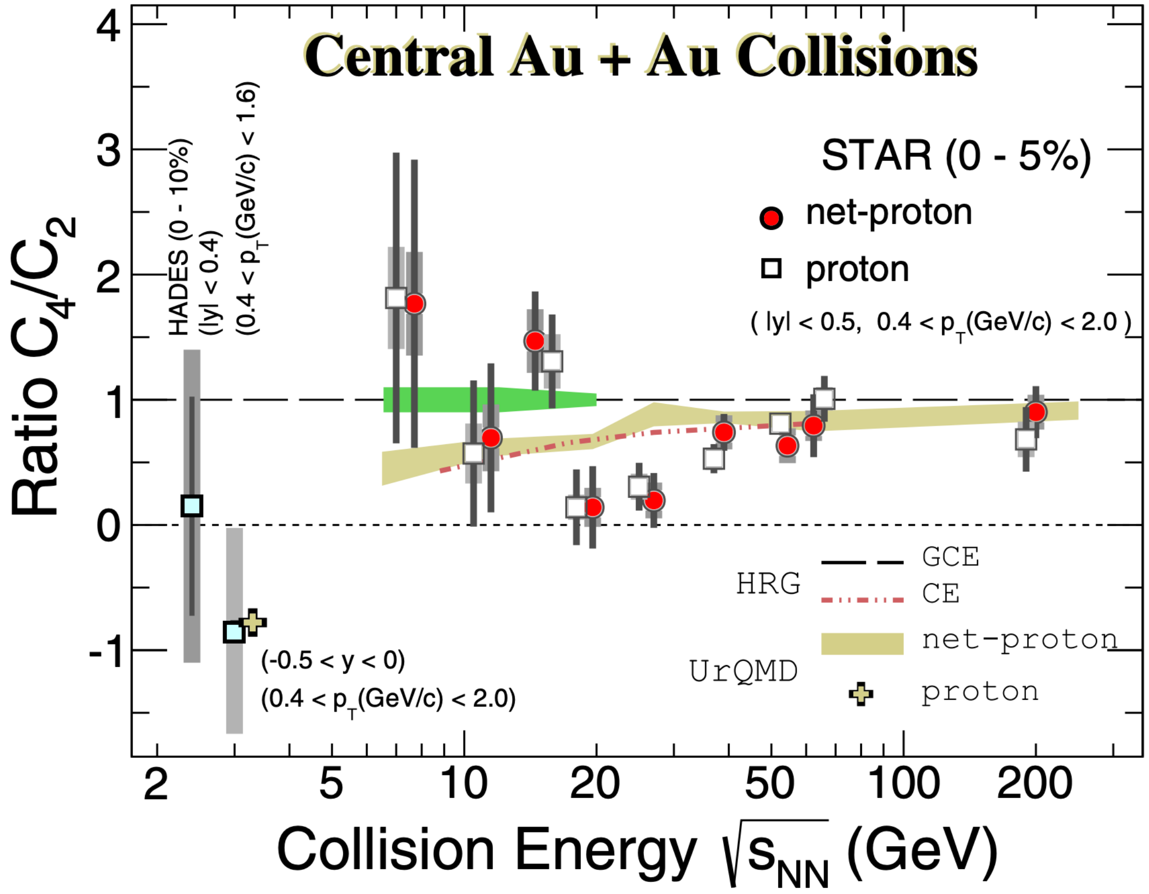

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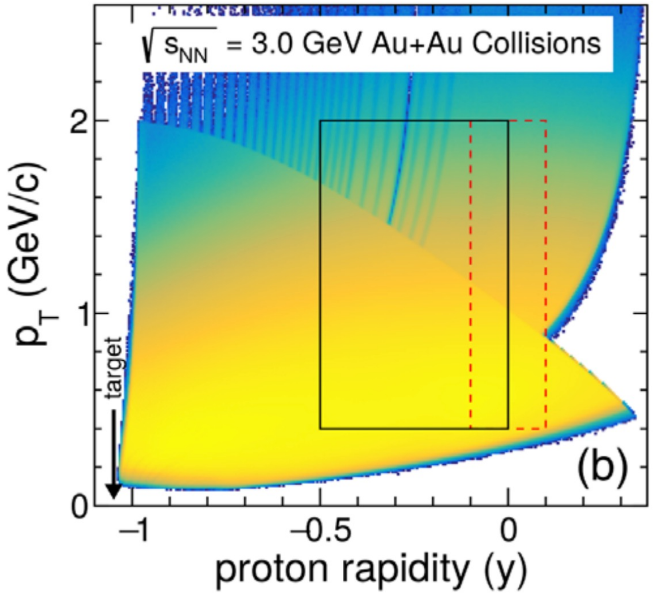

- C_4/C_2 at 3 GeV added to energy scan

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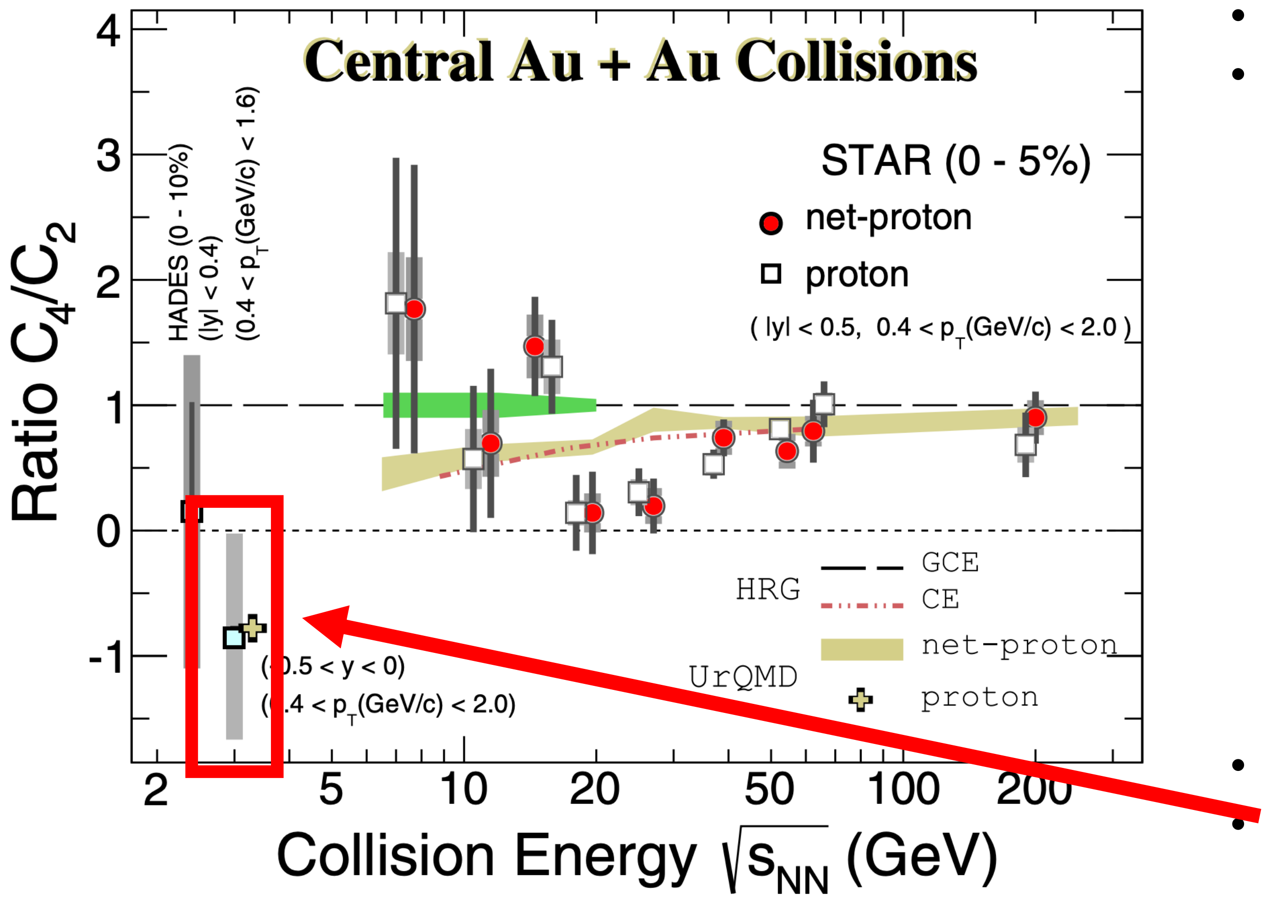

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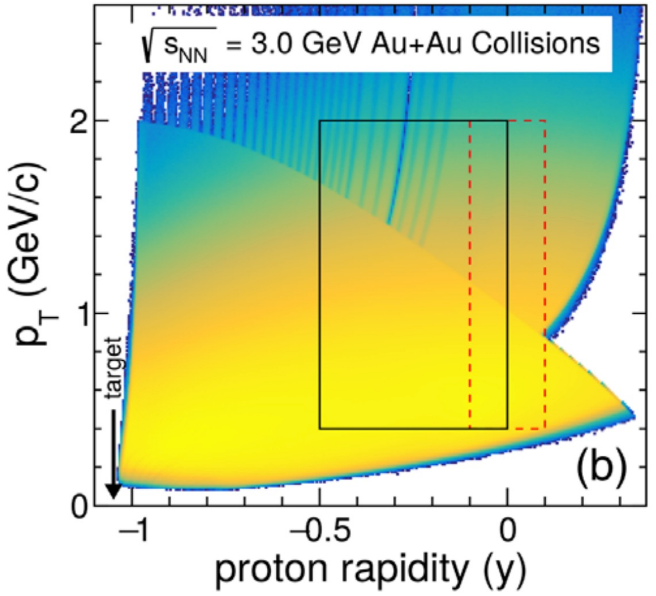
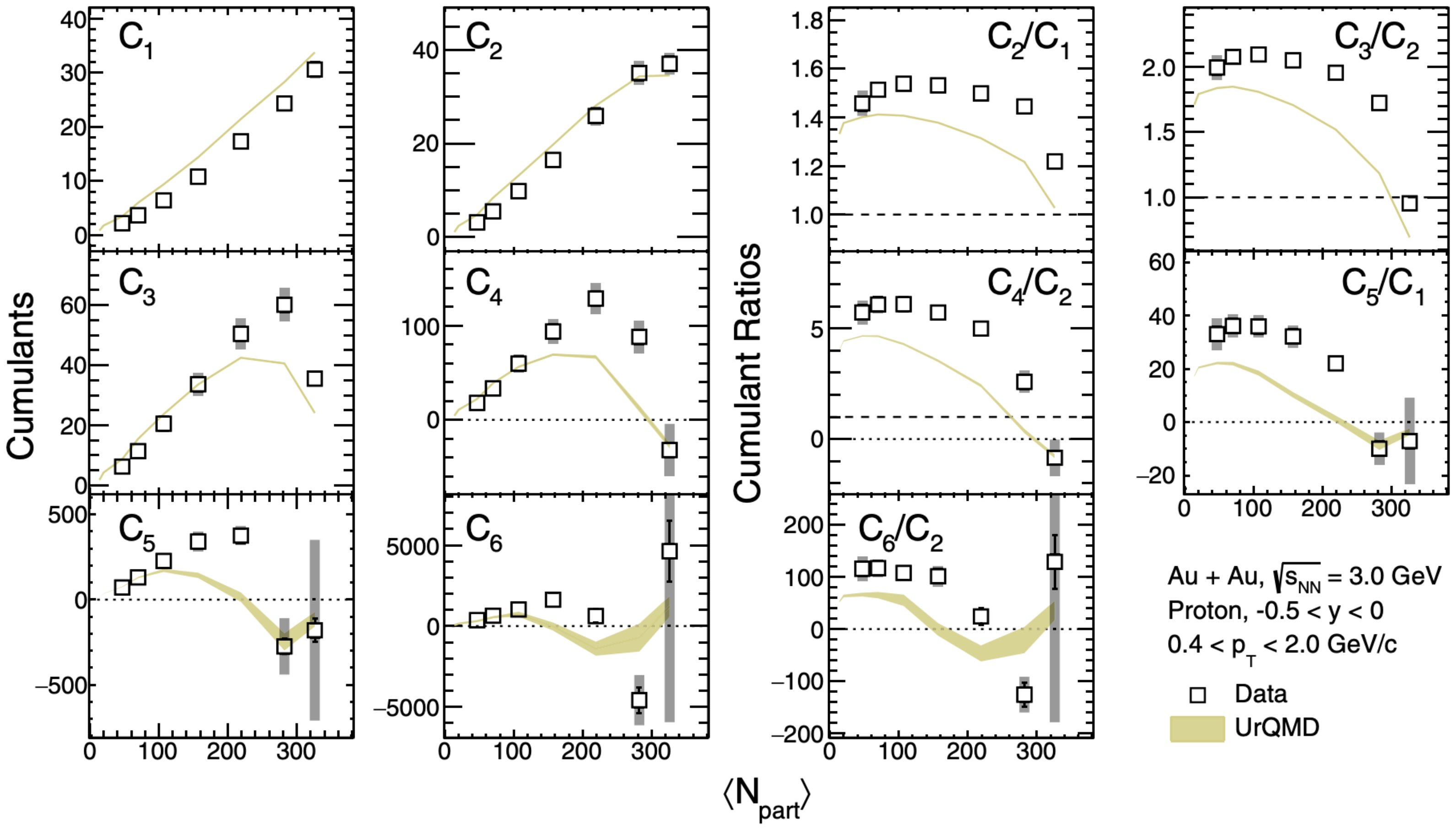


- C_4/C_2 at 3 GeV added to energy scan
- Result is consistent with UrQMD calculations

Highlights: Proton Higher-Order Cumulants at 3.0 GeV

- This year the 3 GeV cumulants up to C_6 and their ratios were published

STAR, Phys. Rev. C 107, 024908 (2023)



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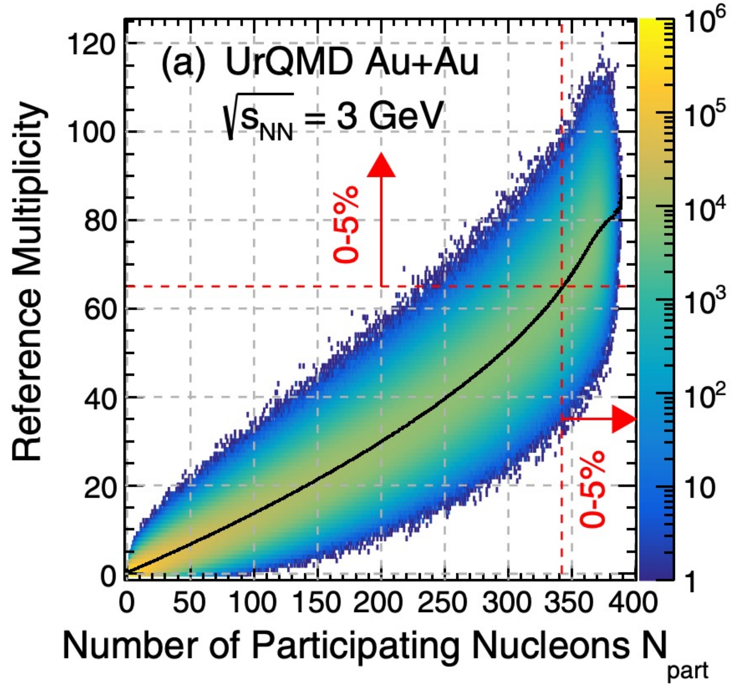
- Paper included discussion and simulations of initial volume fluctuations (IVF)



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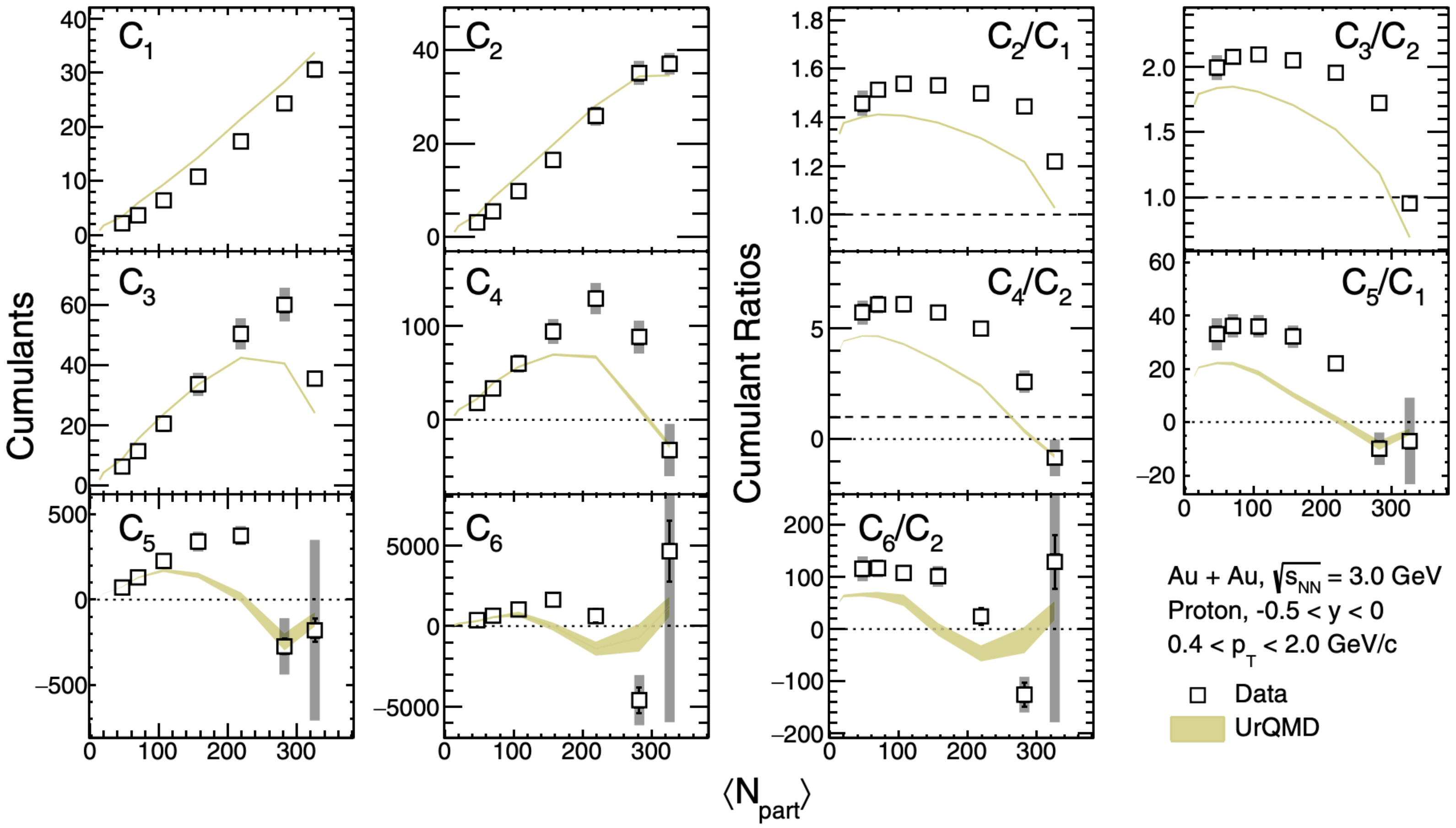

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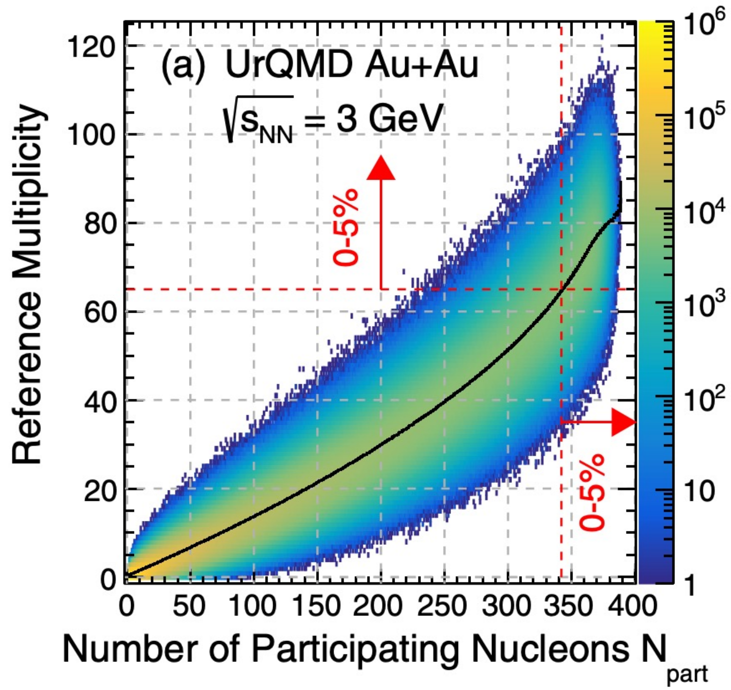

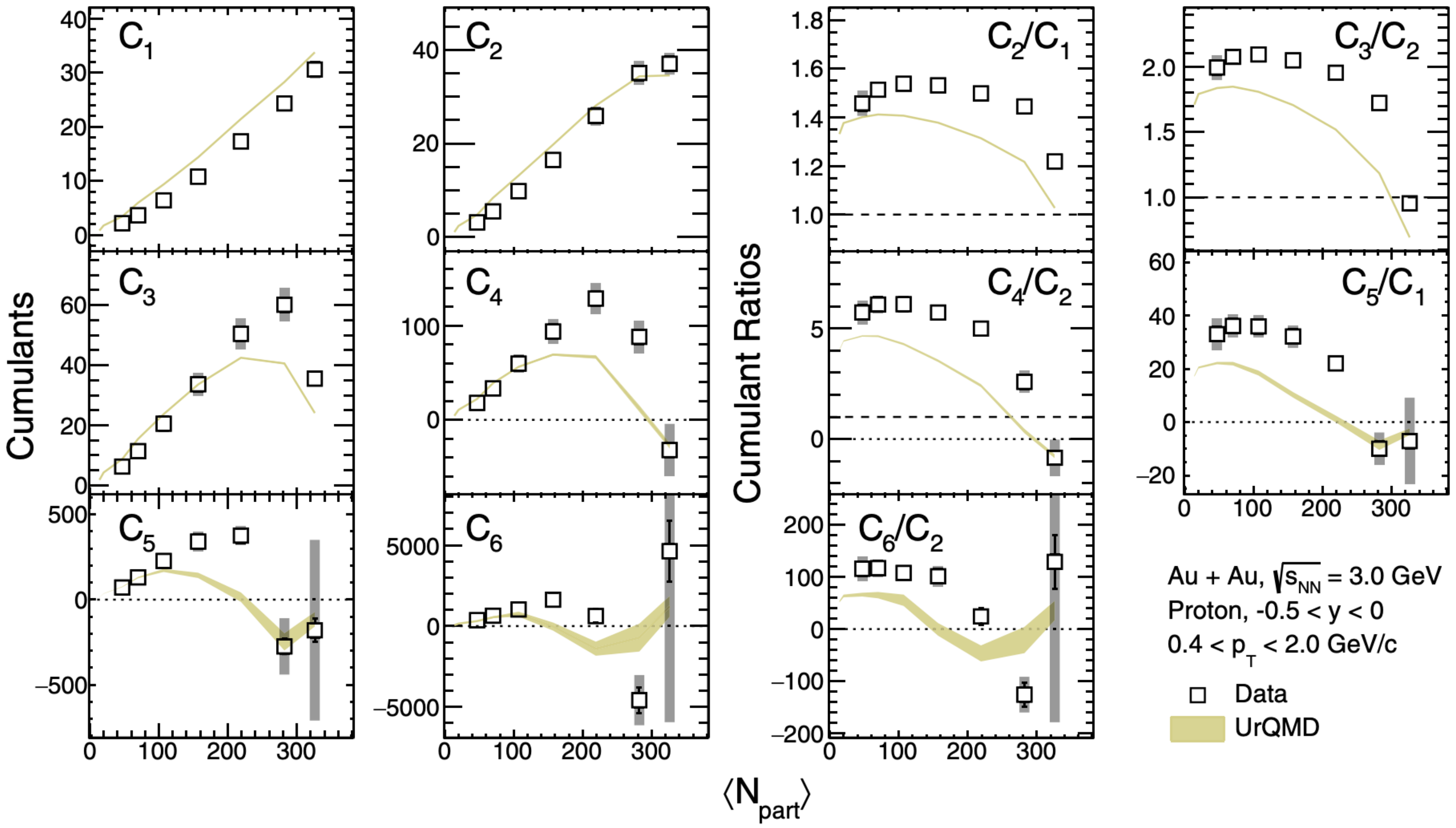

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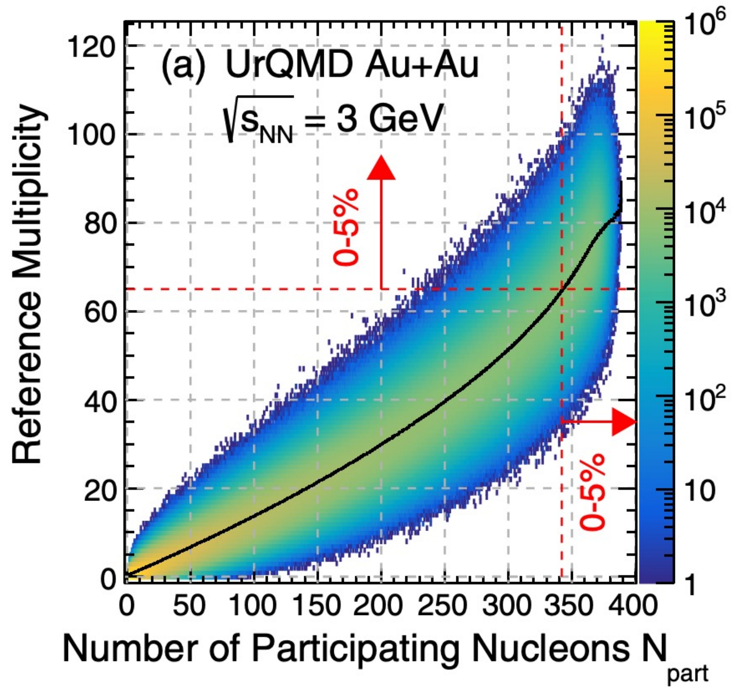
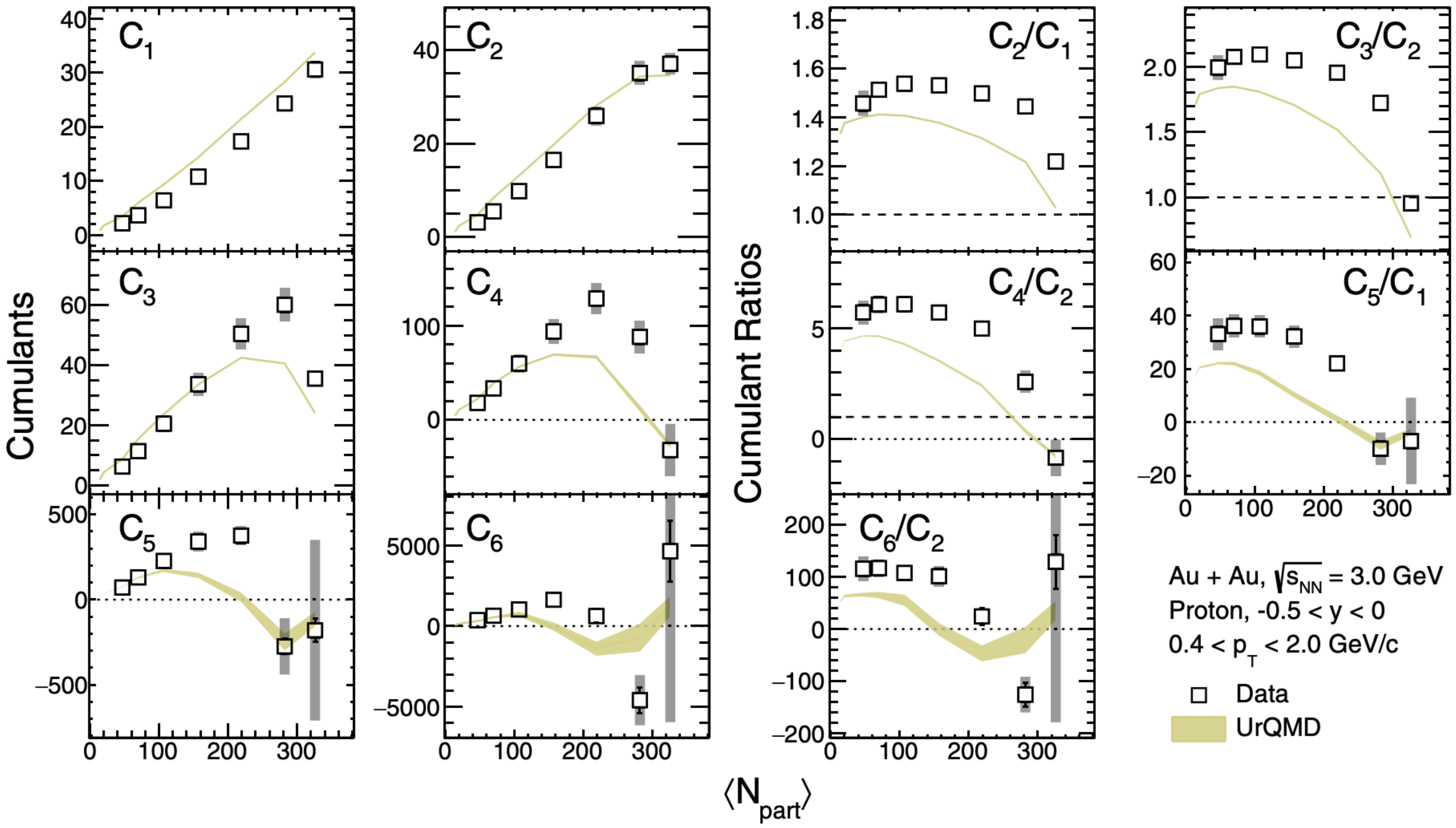
- This year the 3 GeV cumulants up to C_6 and their ratios were published
- Paper included discussion and simulations of initial volume fluctuations (IVF)
- Most central cumulants were consistent with UrQMD
- It is crucial to understand IVF in FXT

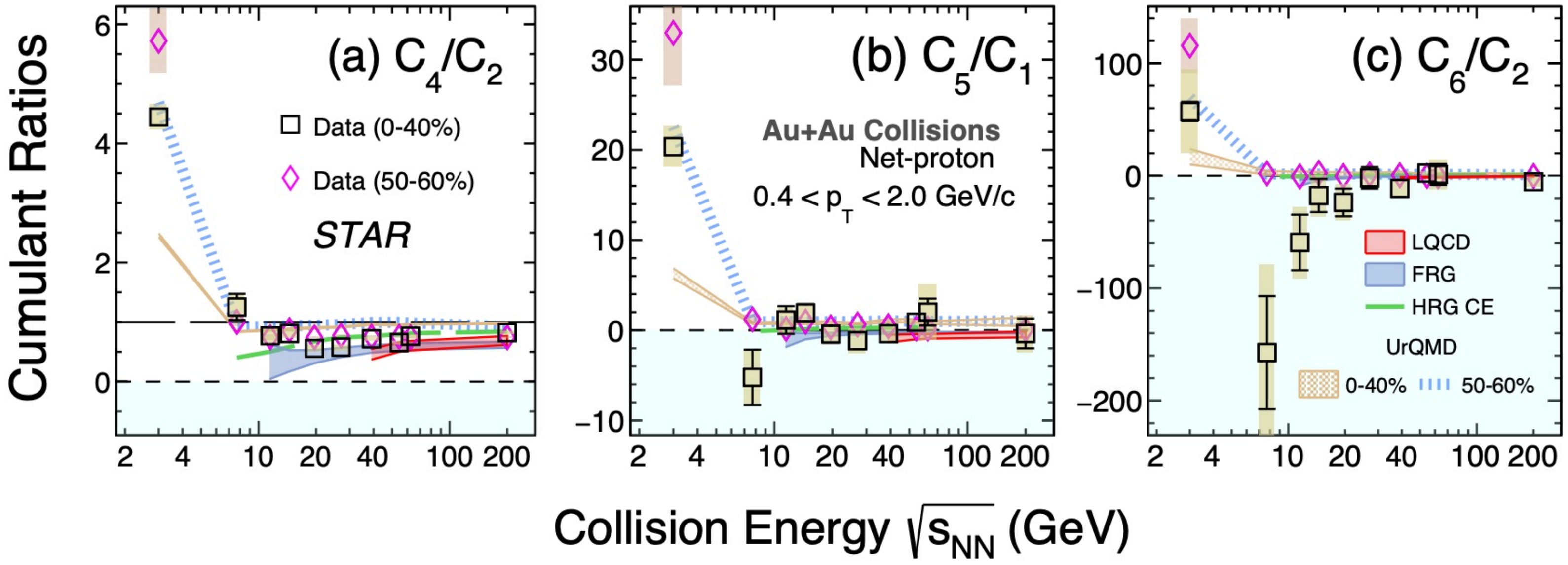




Highlights: Energy Scan of Net-Proton Higher Cumulants

- This year STAR published higher-order cumulants up to C_6 for 0-40% and 50-60% centrality from BES-I data from $\sqrt{s_{NN}}$ of 7.7 to 200 GeV and FXT data at $\sqrt{s_{NN}}$ = 3 GeV

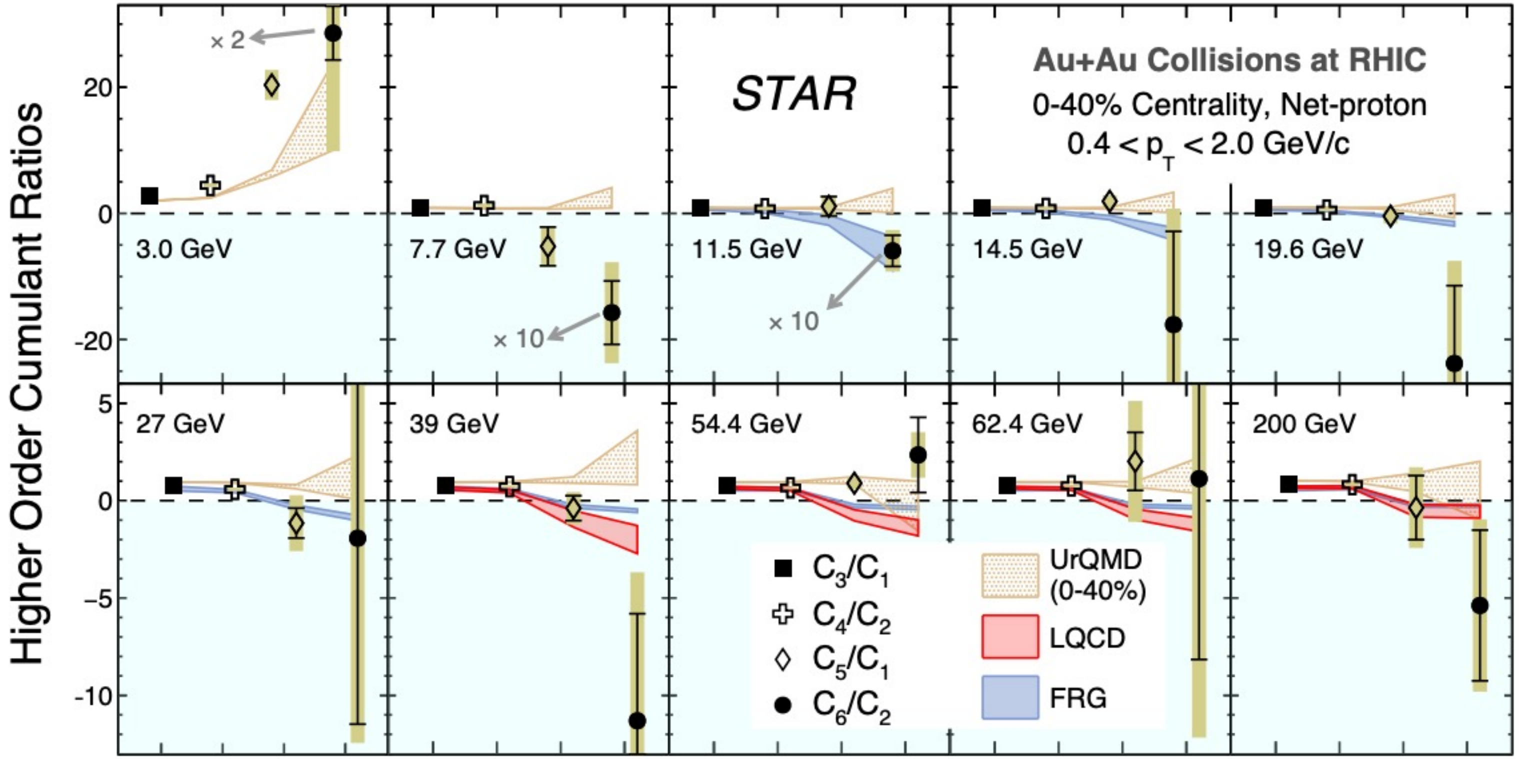
STAR, Phys. Rev. Lett. 130, 082301 (2023); arXiv:2207.09837v2



Highlights: Energy Scan of Net-Proton Higher Cumulants

- These higher-order cumulants allow us to compare the hierarchy of different orders
- LQCD predicts $C_3/C_1 > C_4/C_2 > C_5/C_1 > C_6/C_2$
- This holds (within uncertainties) at each energy except 3 GeV!
- 3 GeV shows reverse ordering which is predicted by UrQMD suggesting hadronic interactions

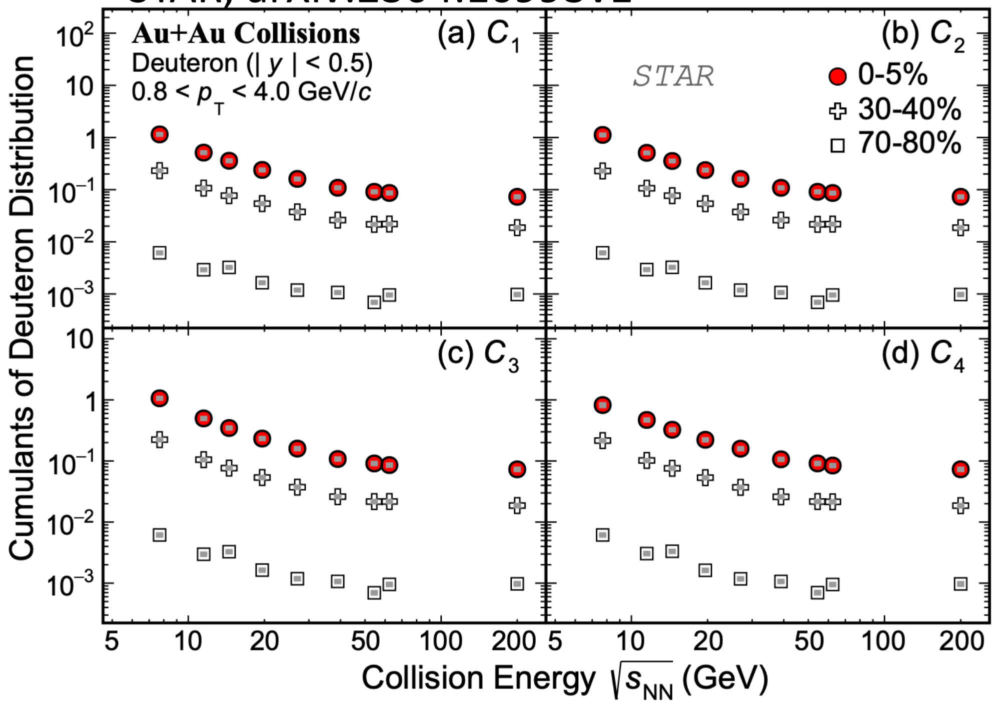
STAR, Phys. Rev. Lett. 130, 082301 (2023); arXiv:2207.09837v2



Highlights: Deuteron Cumulants

- This year STAR also posted to arXiv an energy scan of the deuteron-number cumulants up to C_4 and their ratios

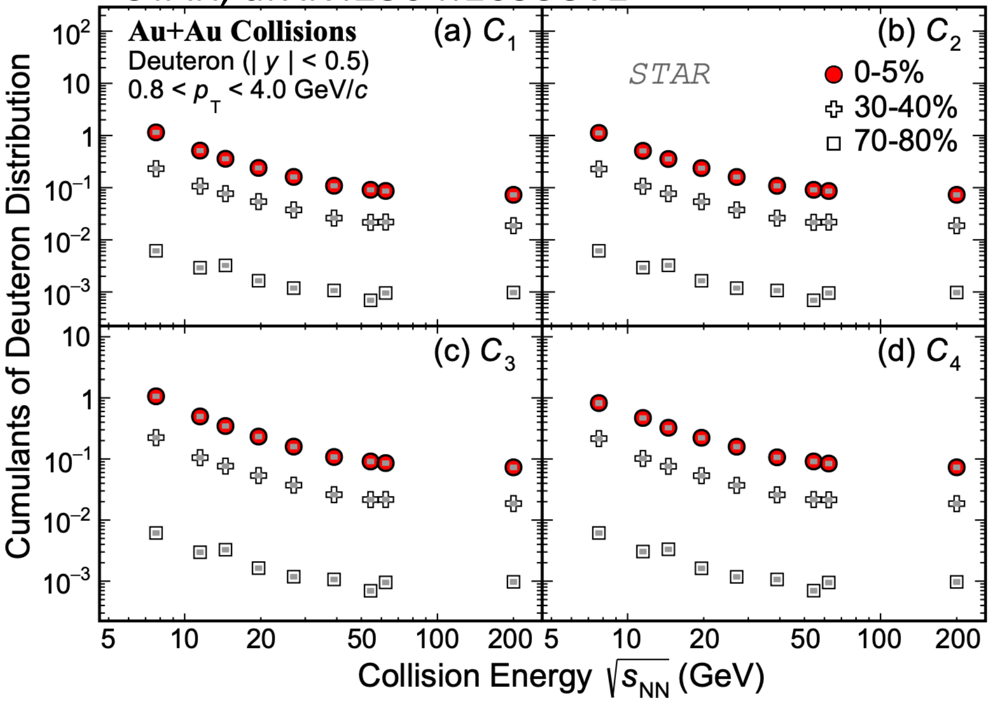
STAR, arXiv:2304.10993v1

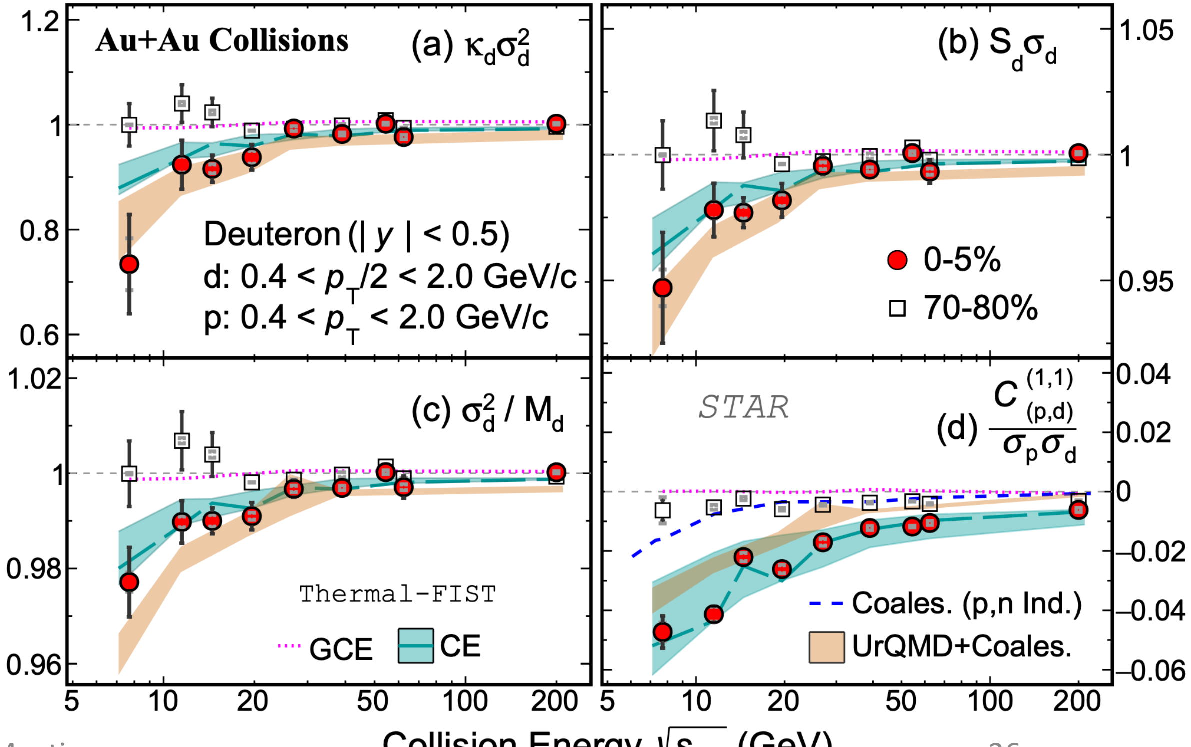


Highlights: Deuteron Cumulants

- This year STAR also posted to arXiv an energy scan of the deuteron-number cumulants up to C_4 and their ratios
- It had previously been thought that the deuteron cumulant ratios could distinguish between thermal deuteron production and production by coalescence
- The results were consistent with both Canonical Ensemble thermal model predictions and with the latest coalescence model of formation

STAR, arXiv:2304.10993v1





Highlights: Net-Charge/Net-Kaon Cumulants

- In 2019 STAR published a beam-energy scan ($\sqrt{s_{NN}}$=7.7-200 GeV) of second-order off-diagonal and diagonal cumulants of net-charge, net-proton, and net-kaon distributions in Au+Au collisions

STAR, Phys. Rev. C 100, 014902 (2019);
Erratum: Phys. Rev. C 105, 029901 (2022)

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- Off-diagonal cumulants sensitive to off-diagonal thermodynamic susceptibilities relating correlations of conserved charges
- Off-diagonal thermodynamic susceptibilities expected to have abrupt change with deconfinement onset
- **Conclusion: Cumulant ratios show no strong centrality/energy dependence. Results consistent with UrQMD simulations**

STAR, Phys. Rev. C 100, 014902 (2019);
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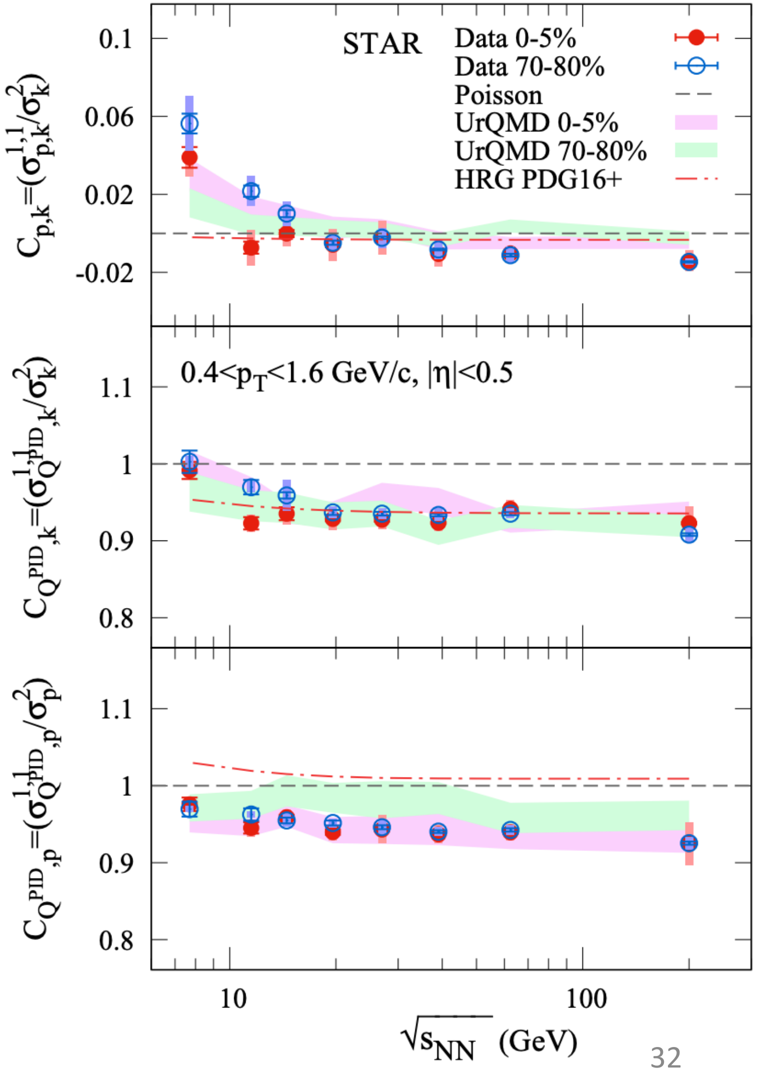


Upcoming Results

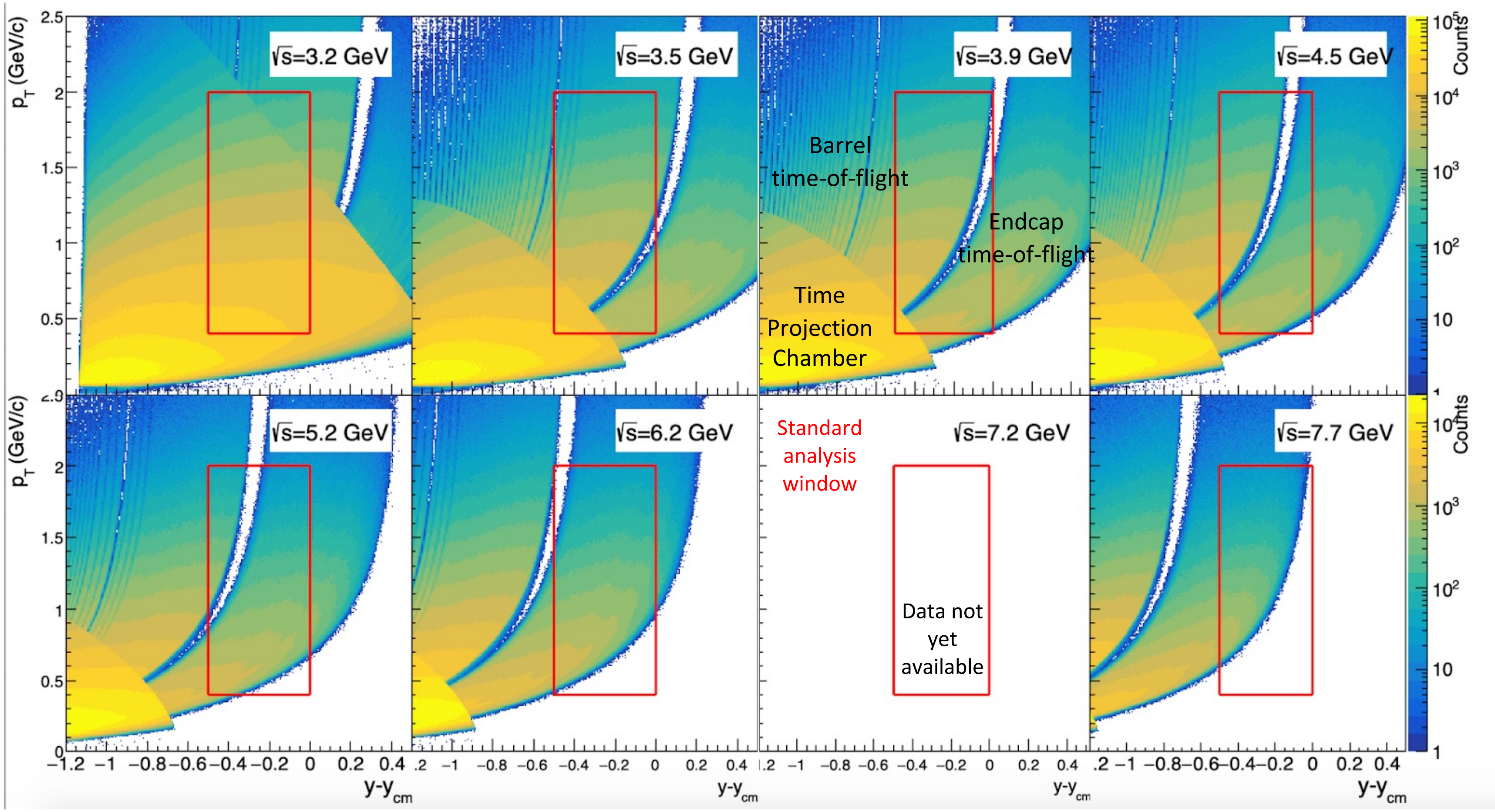
Data from the Fixed-Target Program

Nominal $\sqrt{s}$ (GeV)	Chemical Potential μ_B	Year	Number of Good events	Precise y_{cm}	Status of Production	ETOF Calibration Status	Efficiency Calibration Status	Bad Runs Analysis
3.2	0.70	2019	200.6M	1.139	Produced	Not needed	Completed	Completed
3.5	0.67	2020	115.6M	1.254	Reproduction pending	Completed	Pending	Completed
3.9	0.63	2020	117M	1.375	Reproduction pending	Completed	Pending	Completed
4.5	0.59	2020	108M	1.522	Produced	Pending	Pending	Completed
5.2	0.54	2020	103M	1.683	Produced	Pending	Pending	Completed
6.2	0.49	2020	118M	1.867	Produced	Pending	Pending	Completed
7.2	0.44	2020	316.9M	2.021	Not yet Produced	Pending	Pending	Pending
7.7	0.42	2020	112.5M	2.102	Reproduction pending	Completed	Pending	Completed

Data from BES-II Collider Program

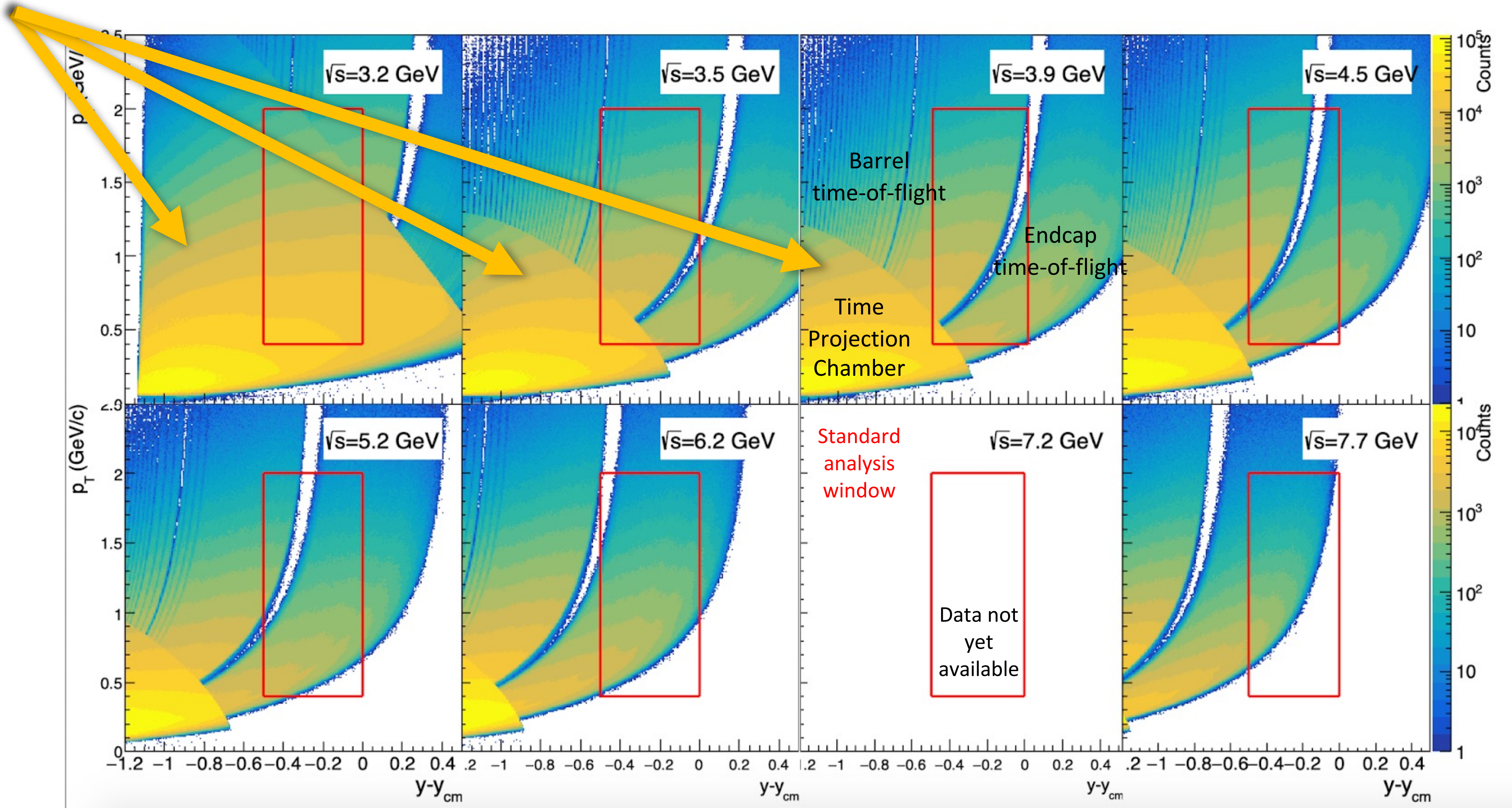
Nominal $\sqrt{s}$ (GeV)	Chemical Potential μ_B	Year	Number of Good events	Precise y_{cm}	Status of Production	ETOF Calibration Status	Efficiency Calibration Status	Bad Runs Analysis
7.7	0.42	2021	101M	0	Produced	Not needed	Completed	Pending
9.2	0.37	2020	162M	0	Produced	Not needed	Pending	Pending
11.5	0.32	2020	235M	0	Produced	Not needed	Pending	Pending
14.6	0.26	2019	324M	0	Produced	Not needed	Completed	Completed
19.6	0.21	2019	478M	0	Produced	Not needed	Completed	Completed
27	0.16	2018	555M	0	Produced	Not needed	Completed	Completed

FXT Proton Moments: Detector Acceptances



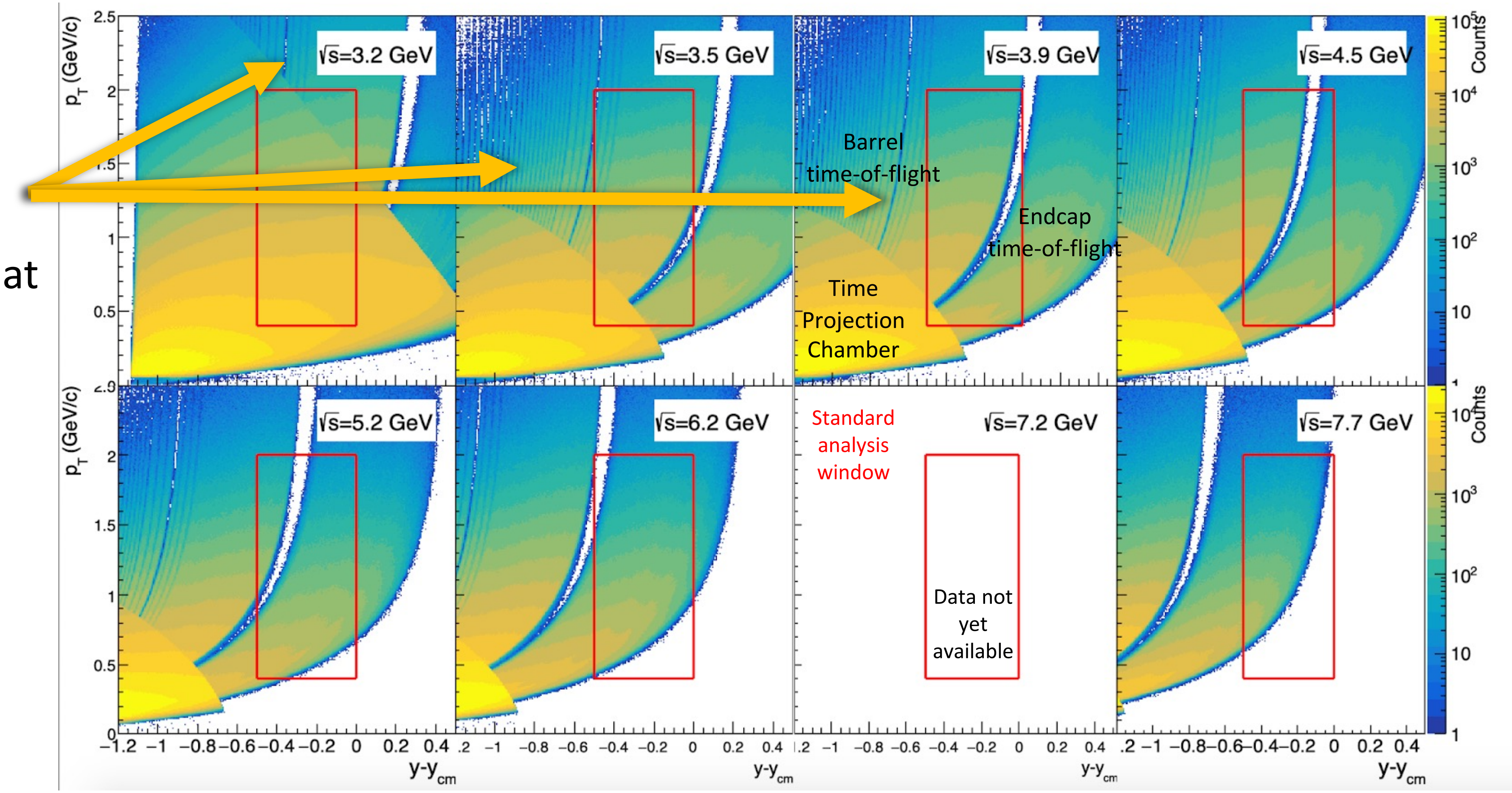
FXT Proton Moments: Detector Acceptances

- At low momenta and low rapidities, the time-projection chamber is used to identify protons
- Pion contamination starts to become significant as momentum increases.



FXT Proton Moments: Detector Acceptances

- At high momenta and low rapidities, the barrel TOF provides better proton ID, but at lower efficiency



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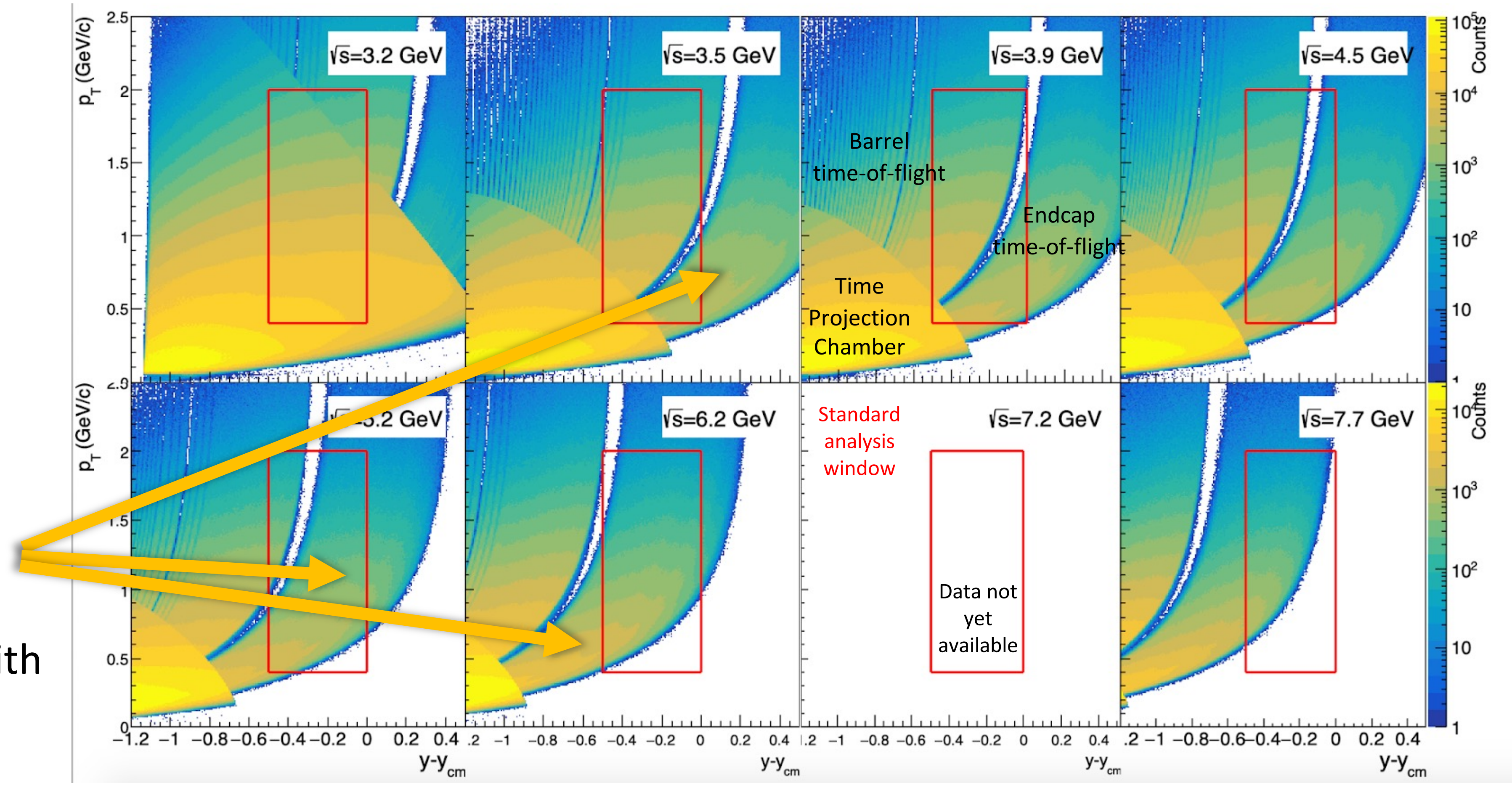
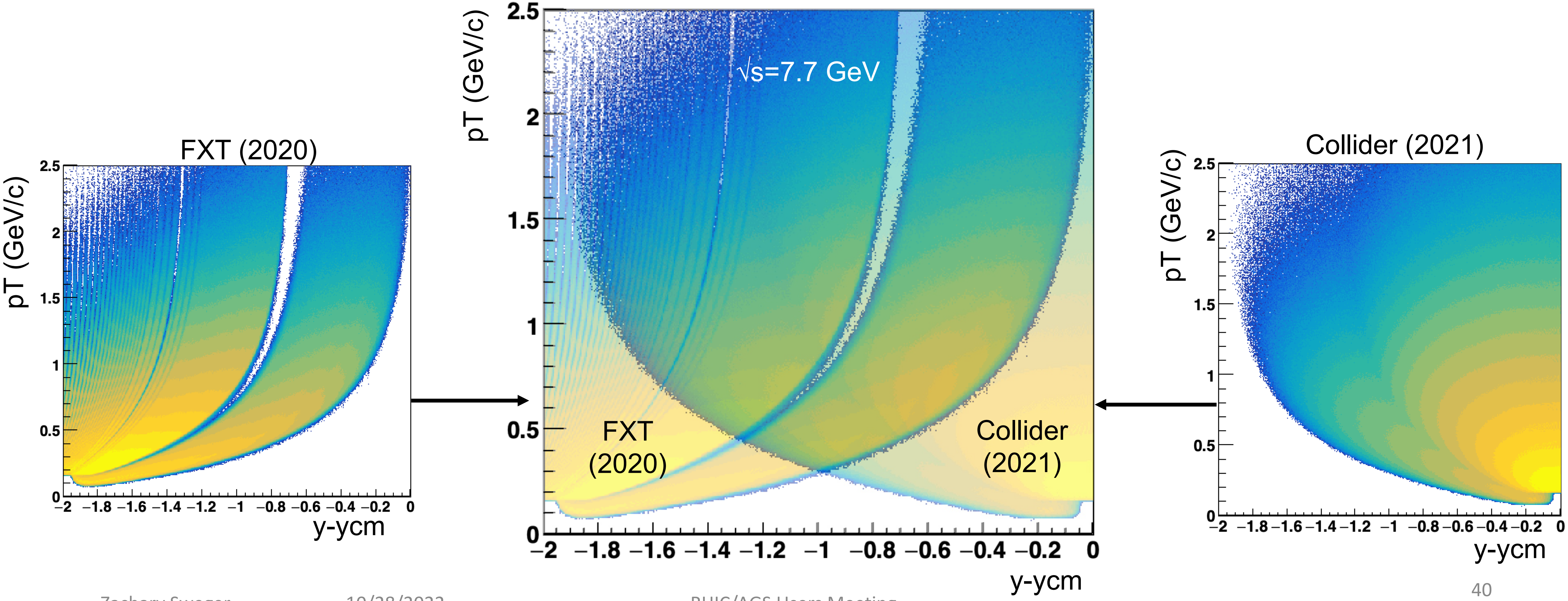


- At high momenta and high rapidities, the endcap TOF provides good resolution, with lower efficiency.

Important Check: FXT & Collider Overlap at 7.7 GeV

- Acceptance overlap at 7.7 GeV for FXT and collider data provides a unique opportunity to benchmark our understanding of FXT methodologies against collider data
- This will not be a standard fluctuation analysis window, and will not be a part of the cumulant energy scan, but is important for building confidence in comparisons between the fixed-target program and collider results



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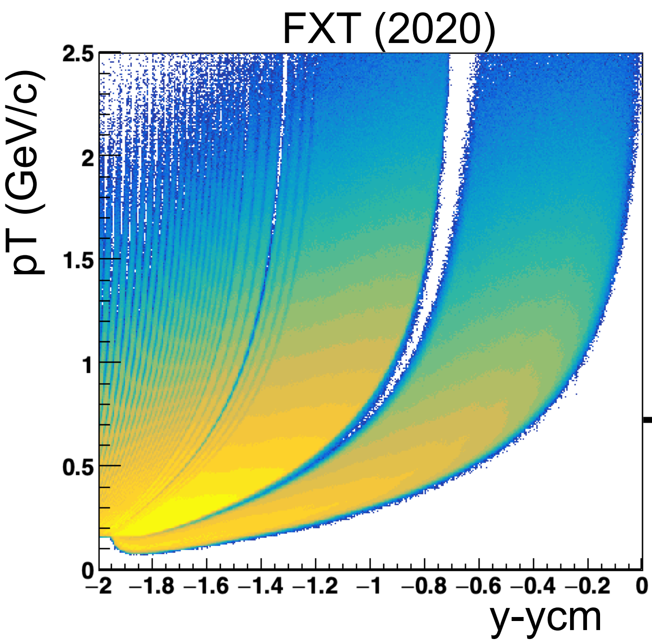

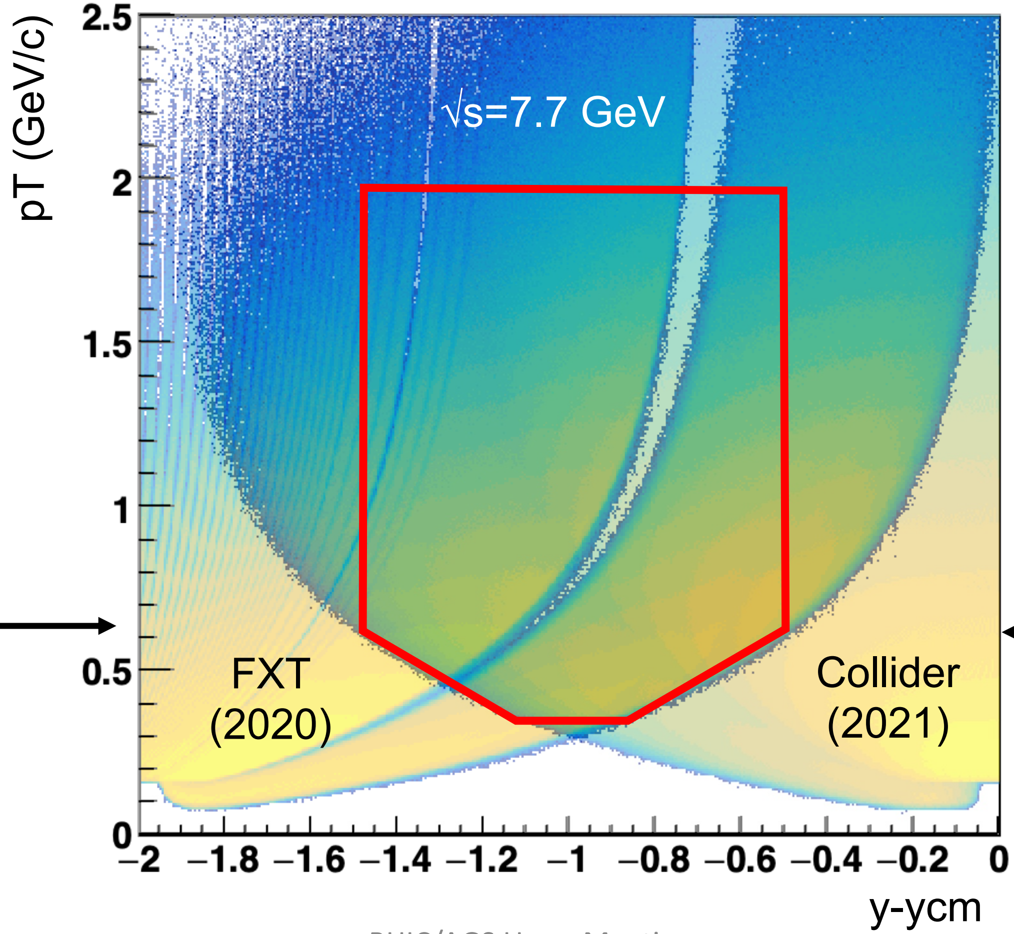

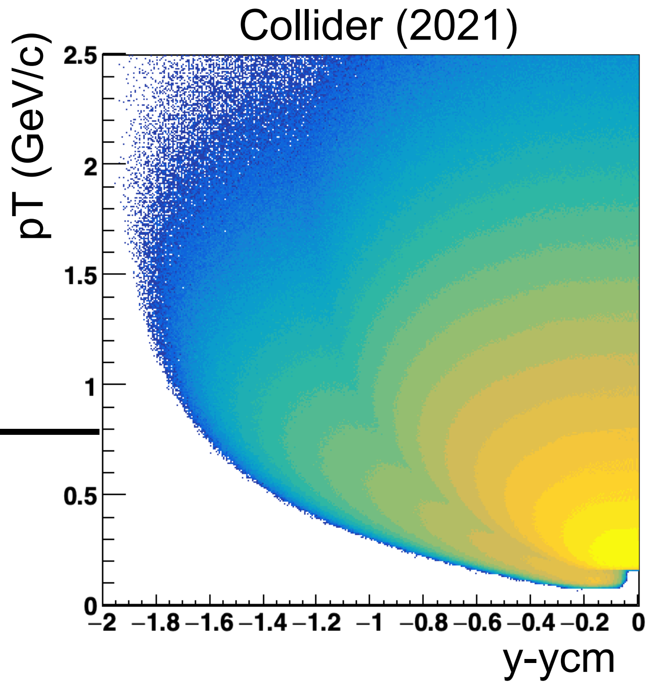

Lessons from BES-II and FXT

Lessons: FXT and Timing Fluctuations

Using TOF for PID

- The Fixed-Target Program, relies on TOF much more than collider analyses
- This has meant that we need to intimately understand the TOF
- Luckily TPC and TOF acceptances overlap, so we can check that the TPC and TOF results agree in certain regions

Lessons: FXT and Timing Fluctuations

The question: what does pileup look like to the TOF?

- If a second collision happens slightly after the first, the pileup particles will have incorrect timing information and cannot be identified by their mass
- So the precision timing of the TOF means that the extra protons from a pileup event will not be detected by the TOF, while the charged particle multiplicity is measured by TPC including pileup events.
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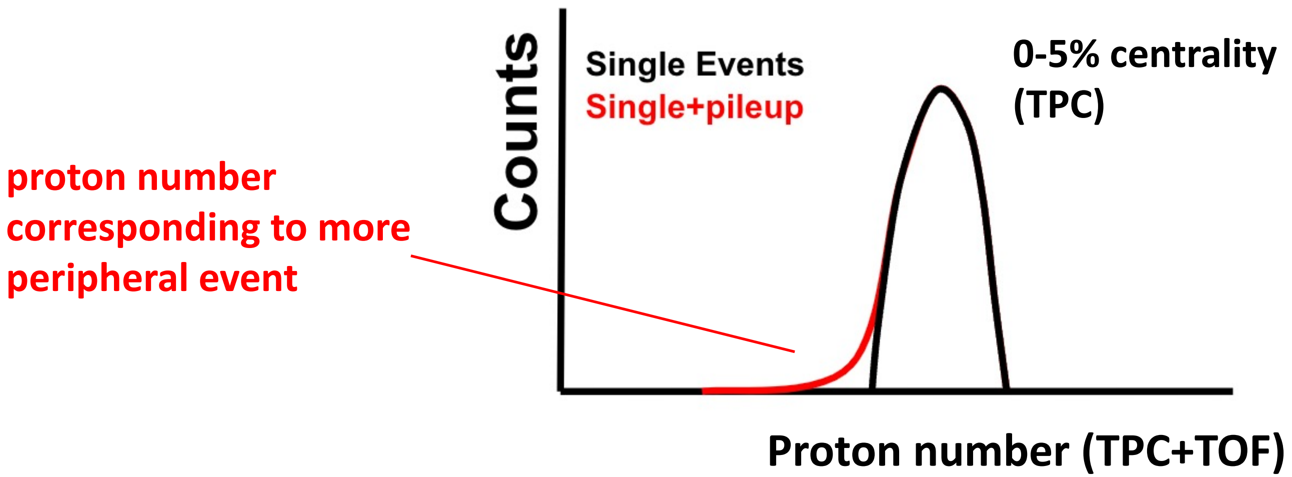

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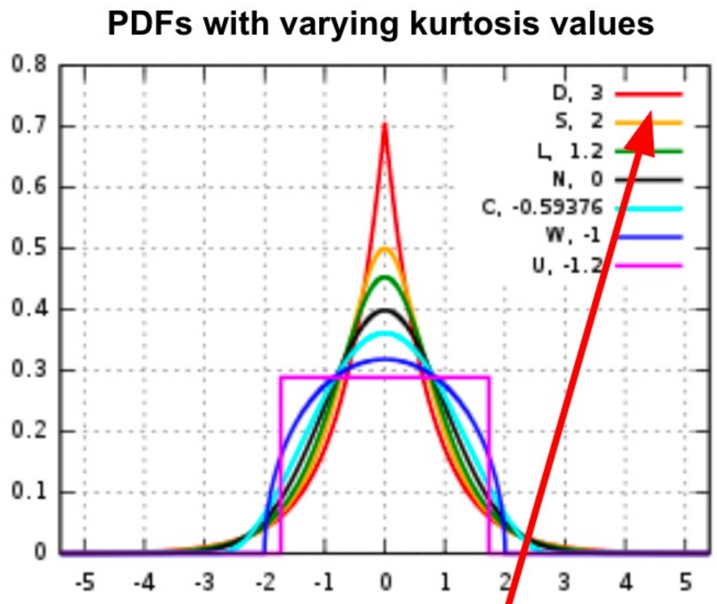
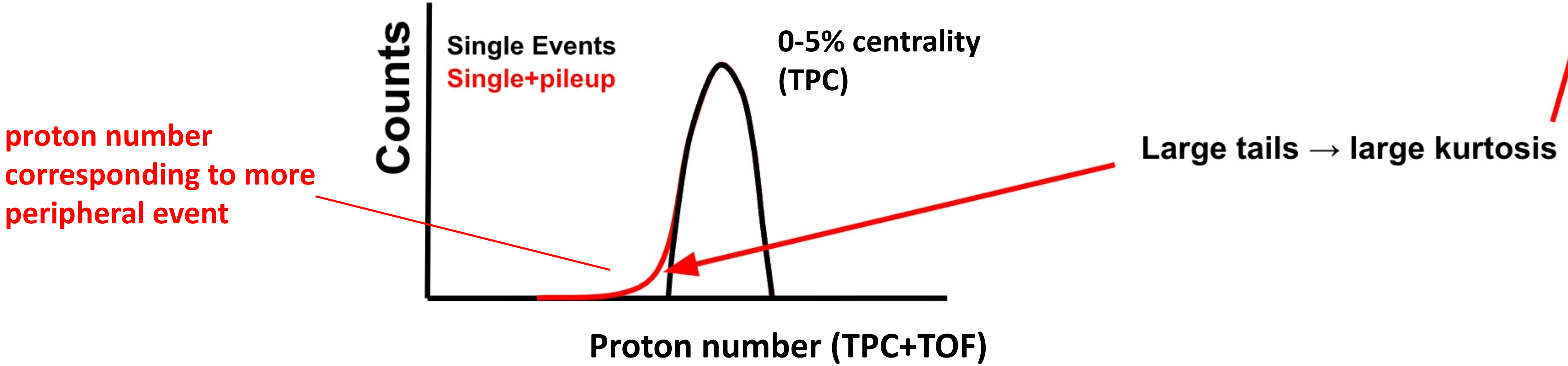
- Long tails mean large kurtosis





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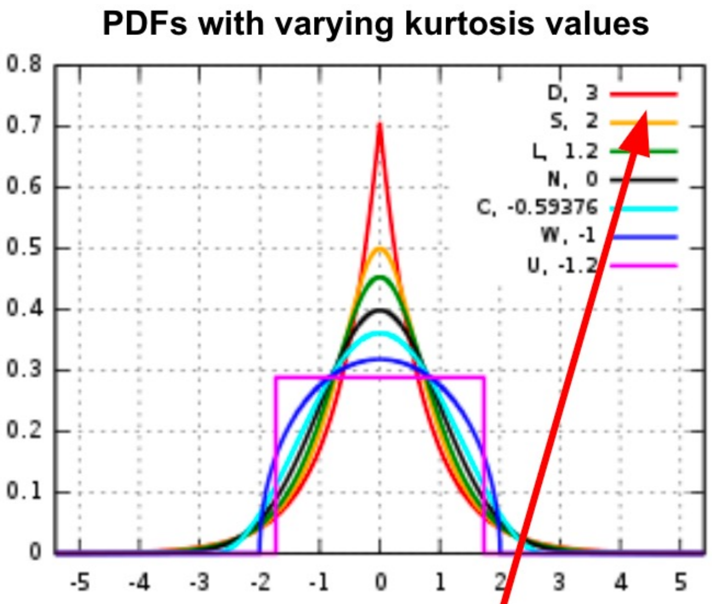
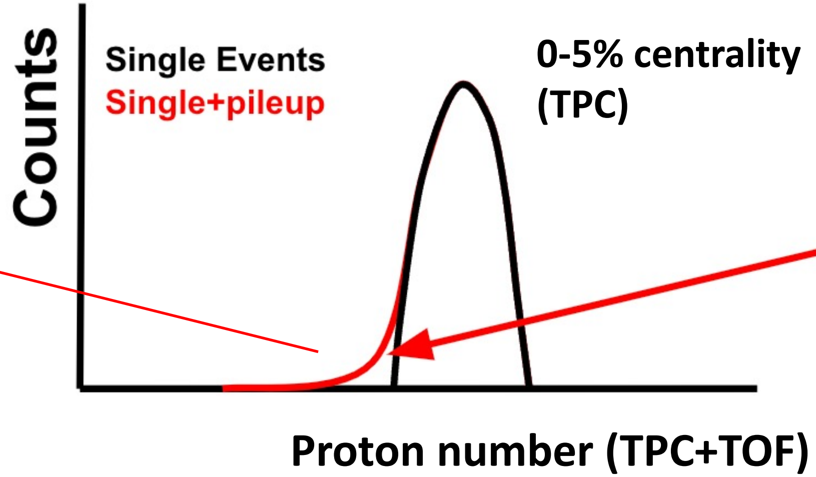


The PID difference between analyzed protons (TPC+TOF) and centrality definition (TPC) leads to few protons for pileup events classified as very central events

proton number corresponding to more peripheral event

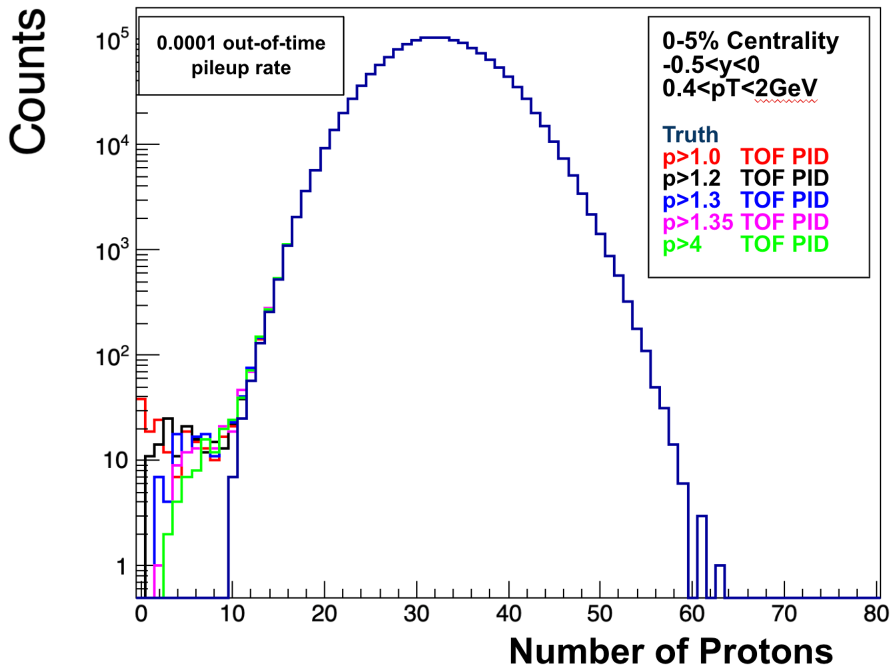


Large tails → large kurtosis

Lessons: FXT and Timing Fluctuations

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

$\sqrt{s_{NN}}$ = 3.5 GeV (UrQMD)



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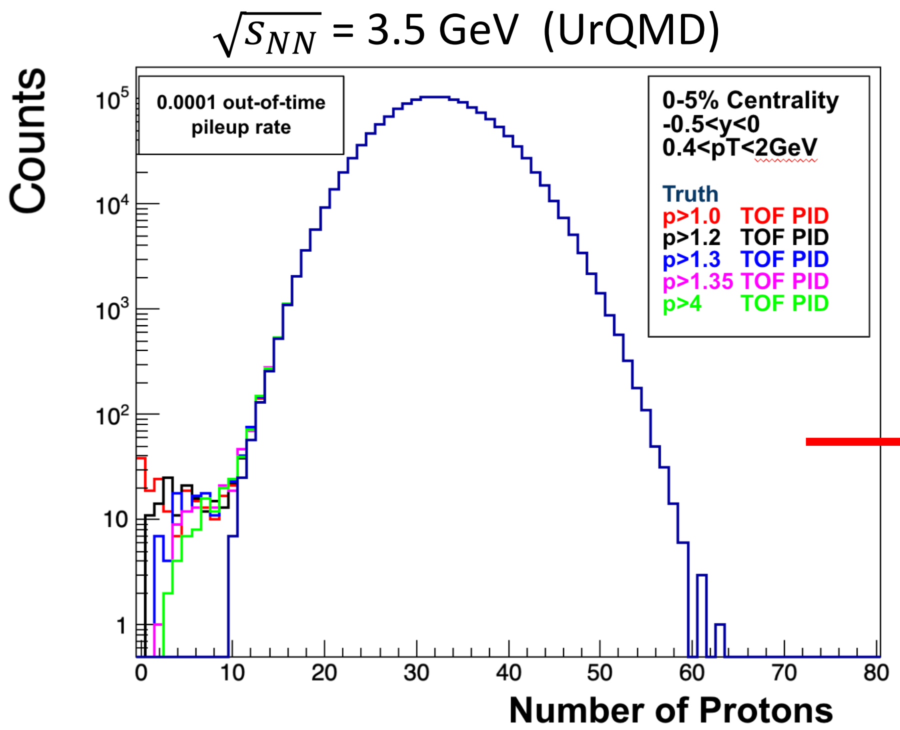
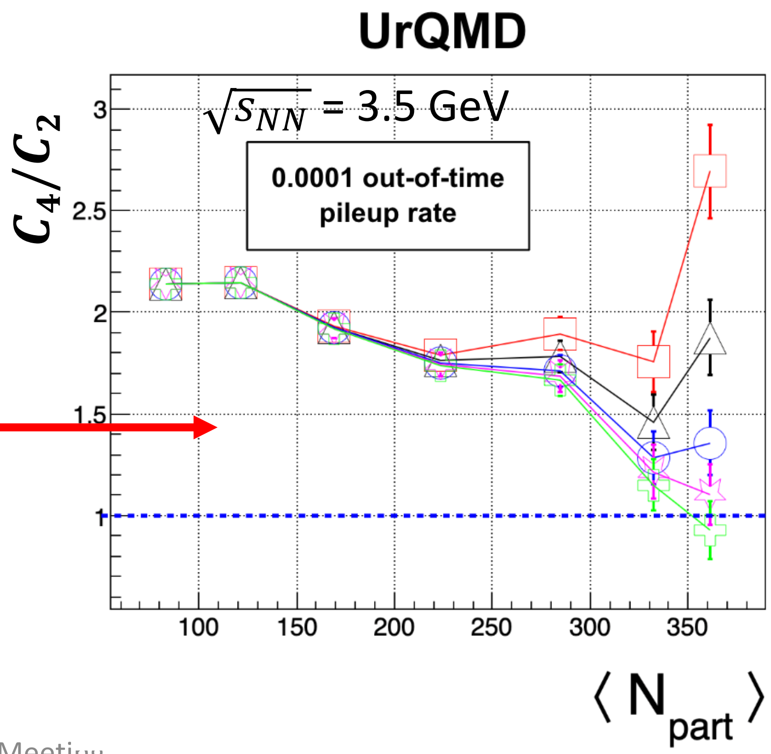
- This causes instability in C_4/C_2 and other cumulants

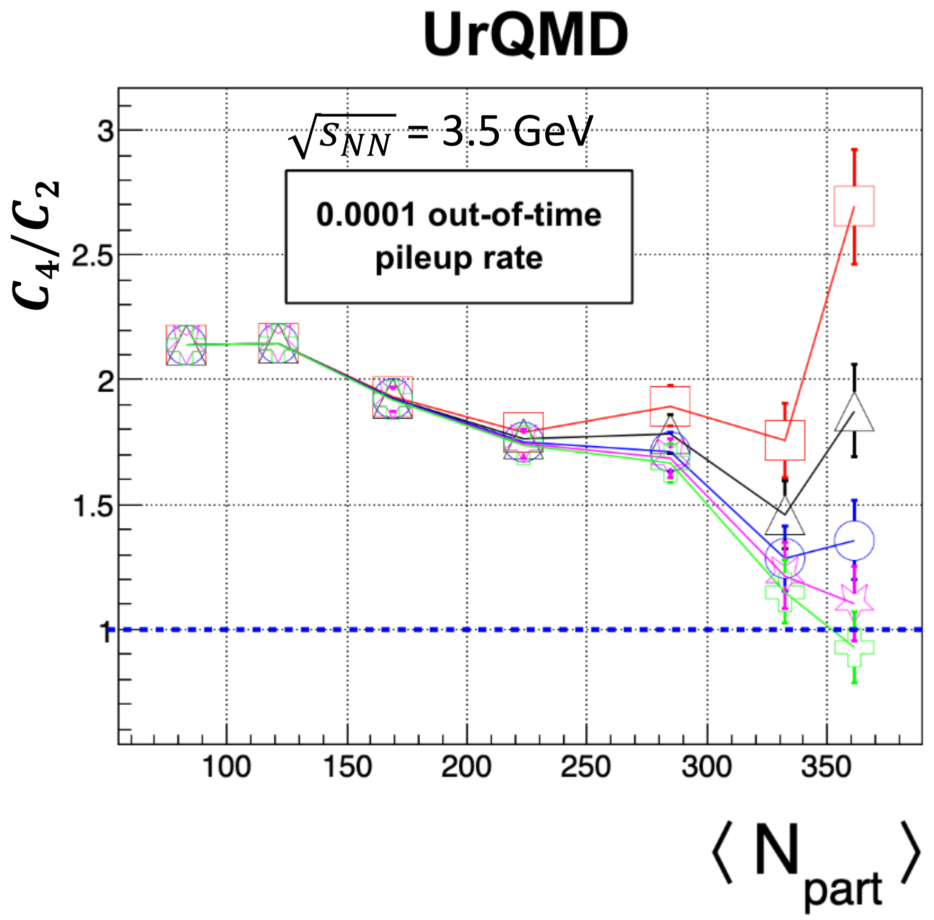




Lessons: FXT and Timing Fluctuations

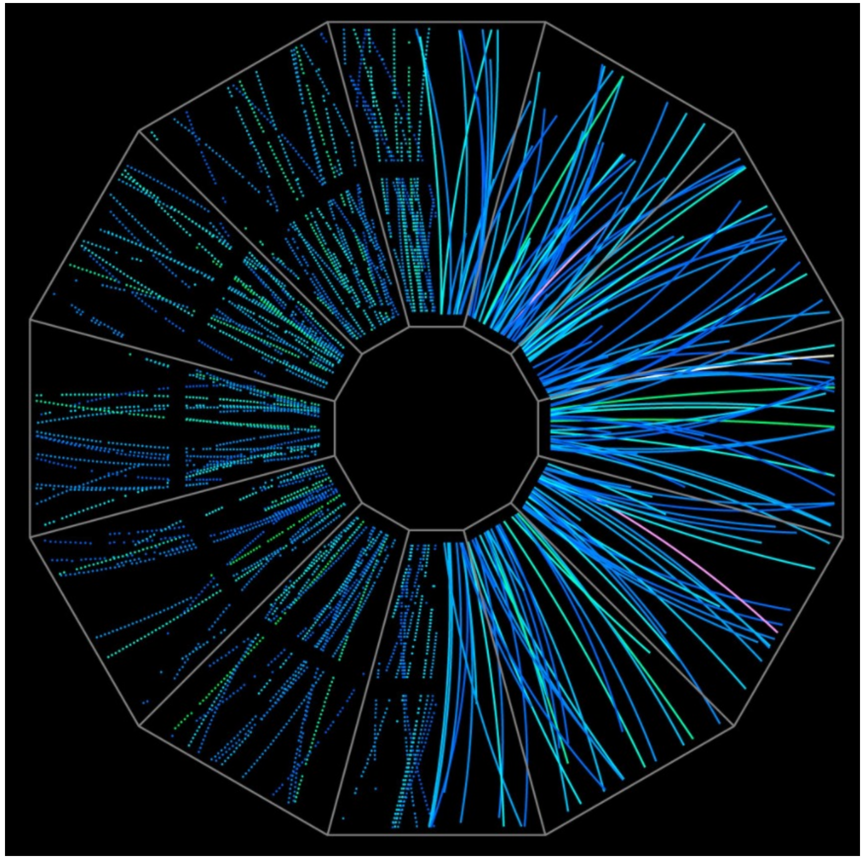
Conclusions from this study

- Differences in TOF and TPC timing precision can cause fluctuations
- When using TOF for PID, pileup may have a larger effect on cumulants than previously understood
- It is best to remove pileup, NOT correct for it



Lessons: Collider Data and Tracking

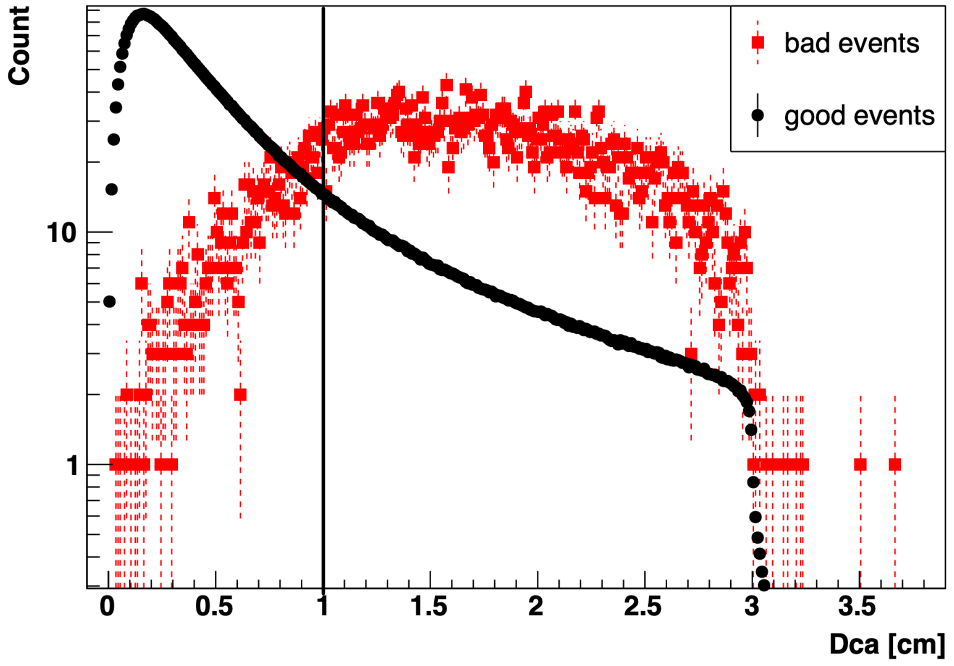
- STAR's tracking algorithm uses tracks to identify a vertex
- Each track is then assigned a "distance of closest approach" (DCA) to the vertex
- We only want primary particles, so we take tracks with DCA<1cm
- If, in some small number of events, the vertexing algorithm fails, then those events will have an oddly-low number of protons
- This can also lead to a low-proton-number tail



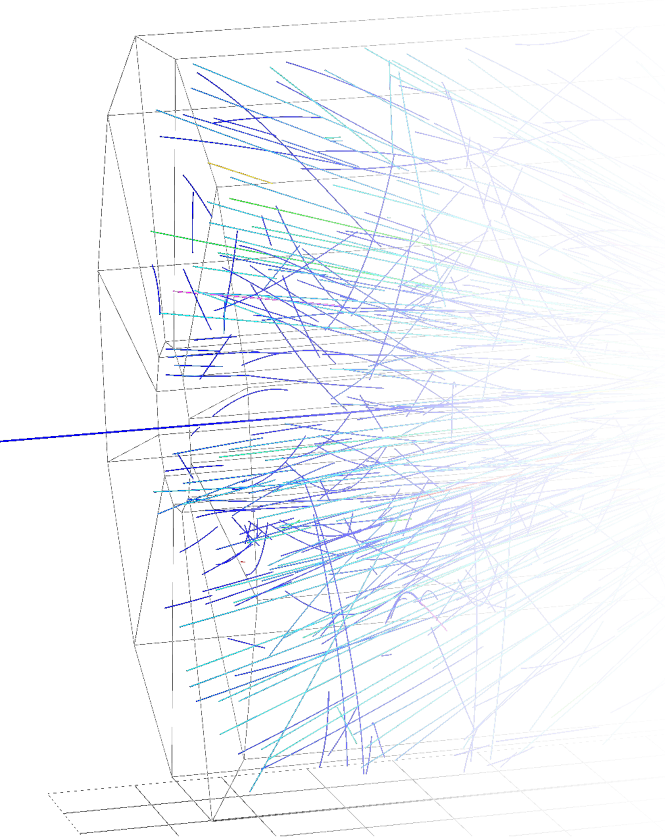
https://www.bnl.gov/newsroom/news.php?a=214492

Lessons: Collider Data and Tracking

- These events are identifiable by their distinct DCA distribution
- We can find these by looking event-by-event at the average DCA in the x, y, and z directions
- By rejecting outliers as bad events, we can minimize the effect of this vertexing issue on fluctuations analyses



Conclusions and Outlook



What We've Learned

- Data taken in BES-I shows non-monotonic behavior of net-proton cumulant ratios which suggests proximity to the critical point.
- STAR has published net-proton high-order cumulants up to C_6 at $\sqrt{s_{NN}}$ = 3 GeV and between 7.7 and 200 GeV
- Newly-published deuteron cumulants agree with both thermal and coalescence models

Outlook

- Recent data from the Fixed–Target Program will extend our knowledge of the (net-)proton cumulants at low energies (3.2-7.7 GeV)
- The BES-II Collider Program is providing high-statistics data between 7.7 and 27 GeV
- We are working to understand the unique challenges associated with fluctuations analyses
- BES-II and FXT analyses are in progress