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Measuring Local Parton Density Fluctuations via Proton Clustering

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for the STAR Collaboration

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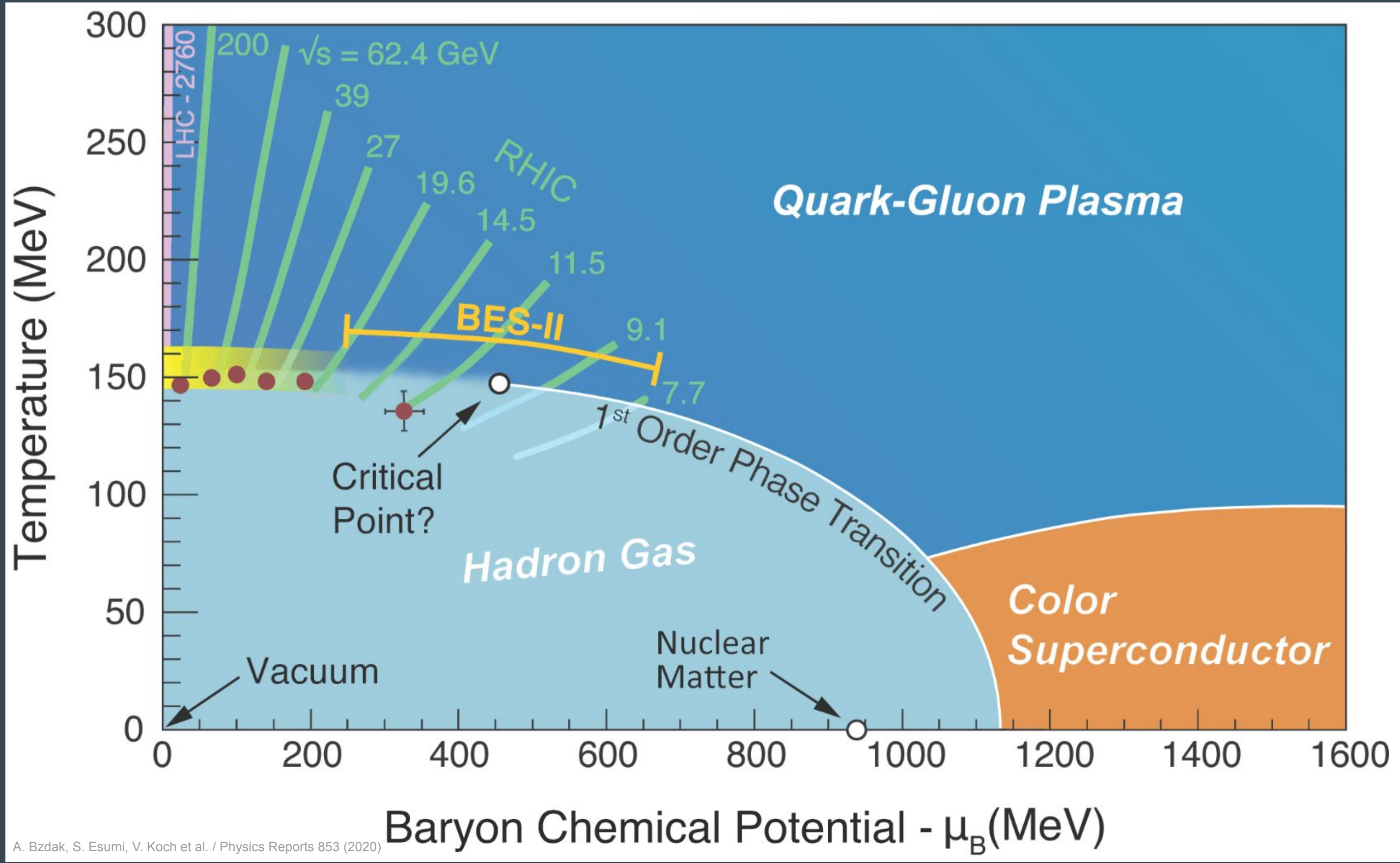
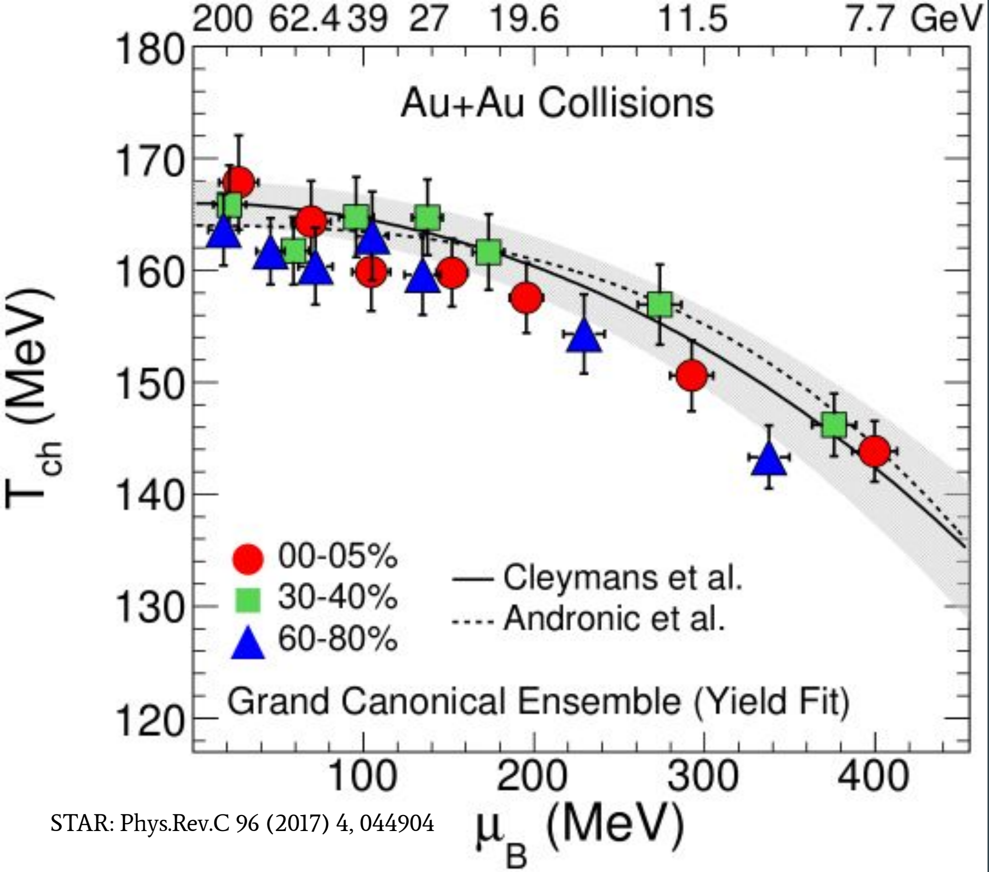
Motivation

- Map out QCD phase diagram via BES, specifically QGP to hadron gas transition
- Search for signal of clustering which may indicate a first order phase transition





STAR: Phys.Rev.C 96 (2017) 4, 044904

Data Set - Au+Au Beam Energy Scan I

$\sqrt{s_{NN}}$ (GeV)	Triggers	Minimum Bias Events (million)	0-5% Central Events (million)	AMPT 0-5% Central Events (million)
7.7	290001, 290004	3.1	0.17	1.61
11.5	310004, 310014	7.4	0.42	1.46
19.6	340001, 340011, 340021	17	0.91	1.42
27	360001	32	1.8	1.60
39	280001	88	5.7	1.56
62.4	270001, 270011, 270021	47	3.0	1.52

Proton Selection

$\lvert y \rvert < 0.5$
DCA < 1.0
$\lvert n\sigma_{proton} \rvert < 2.0$ 1.0 for 27 GeV
$0.4 < p_T < 0.8$ GeV & $p < 1.0$ GeV or $0.8 < p_T < 2.0$ GeV & $p < 3.0$ GeV & $0.6 < m^2 < 1.2$ GeV

Event Rejections Implemented:

- Pile-up
- Dca-xy Bad Events
- Bad Runs

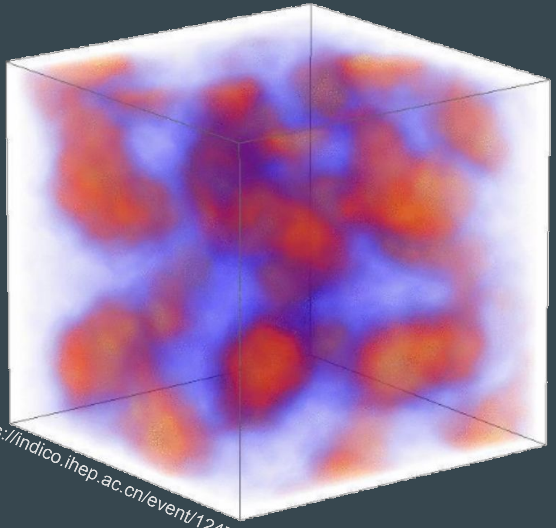
Corrections Not Implemented:

- Efficiency
- Centrality Bin Width

Centrality Definition:

Charged particles within $|\eta| < 1$ excluding protons

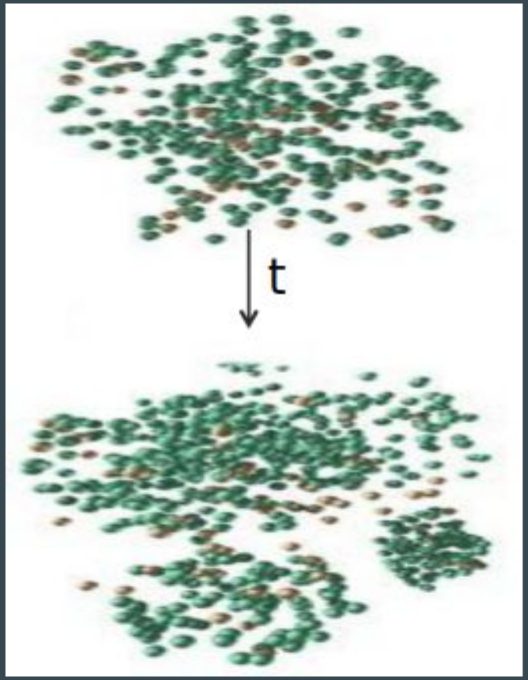
Analysis Goal

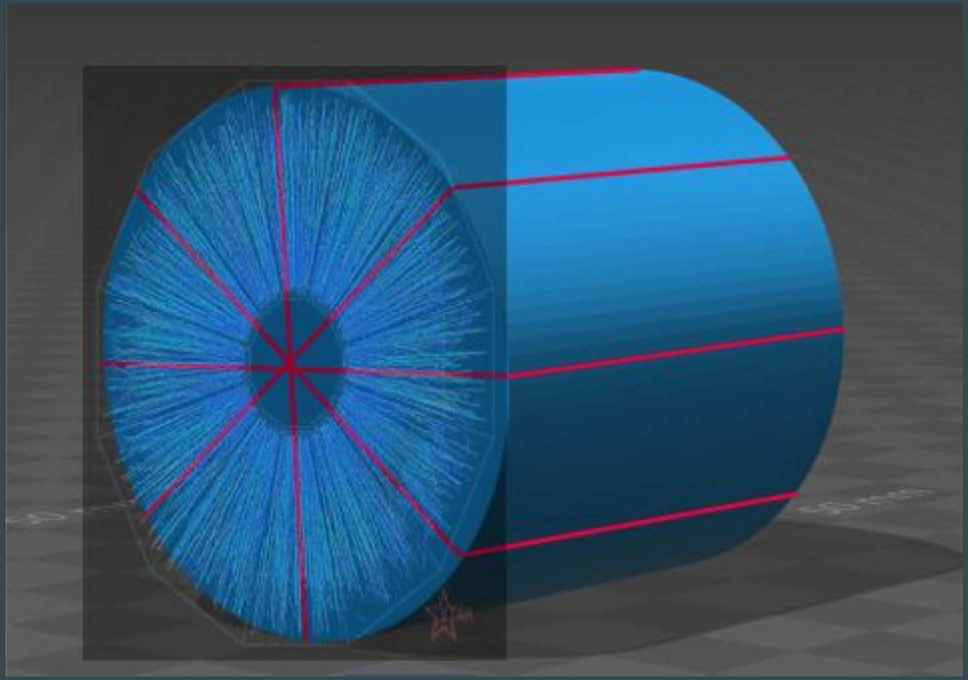


X. Luo https://indico.ihep.ac.cn/event/12478/

- Look for azimuthal correlations among protons indicative of clustering → possible sign of a first order phase transition

- Compare proton multiplicities in azimuthal partitions to uncorrelated expectation

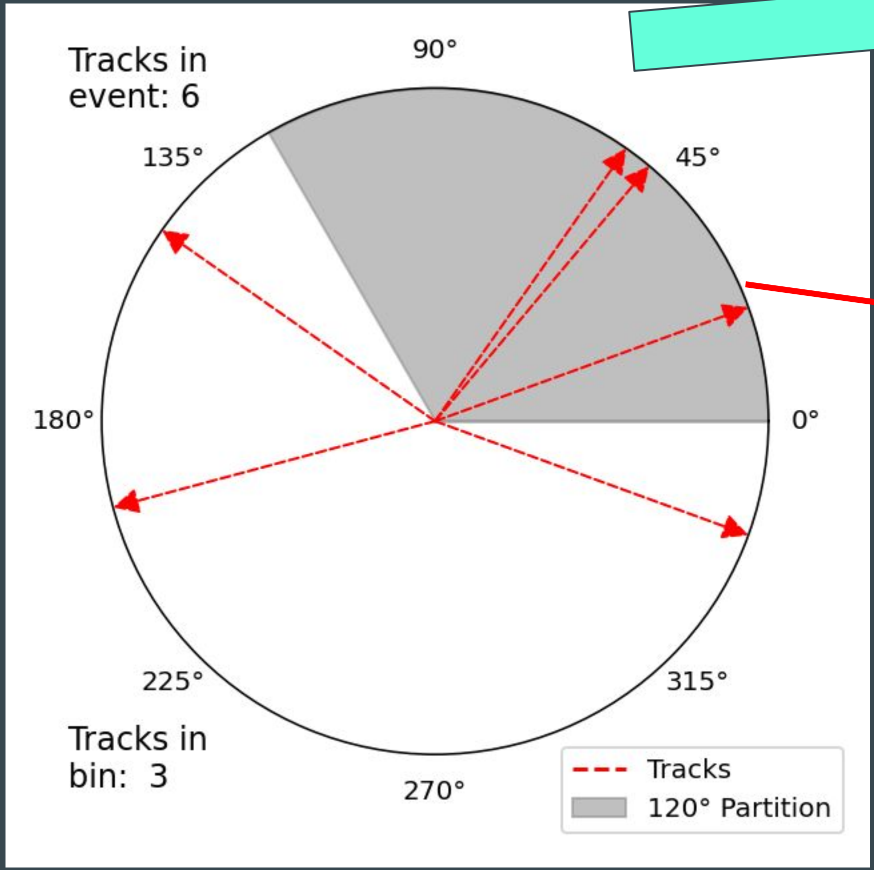


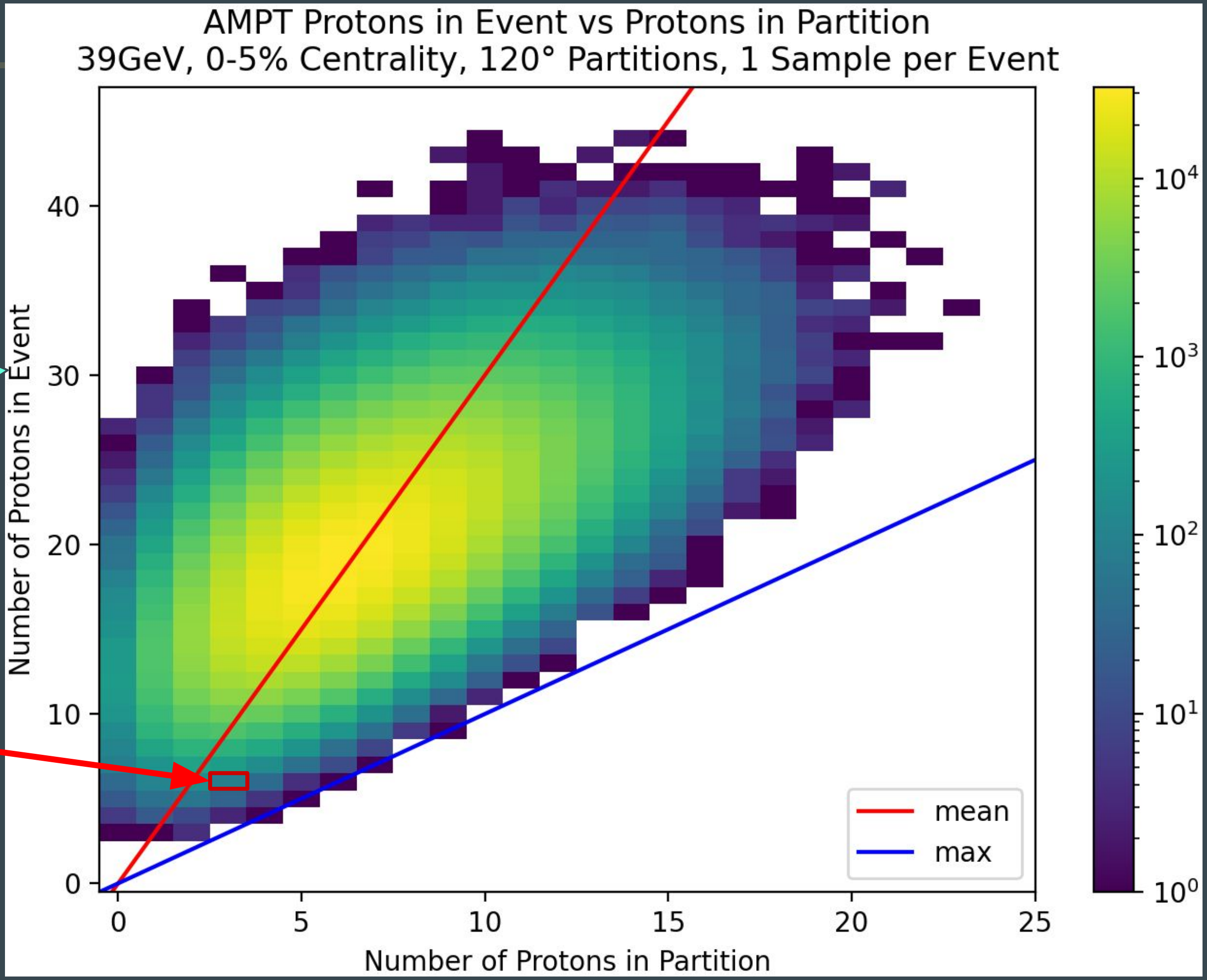


Azimuthal Partitioning

Partition the azimuth in each event and histogram particle tracks

Histogram bin contents over many events





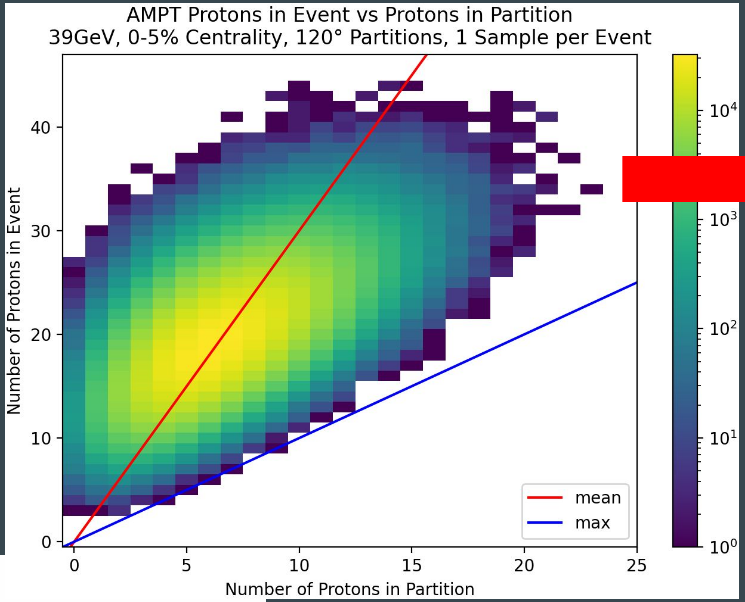
Important Dimensions:

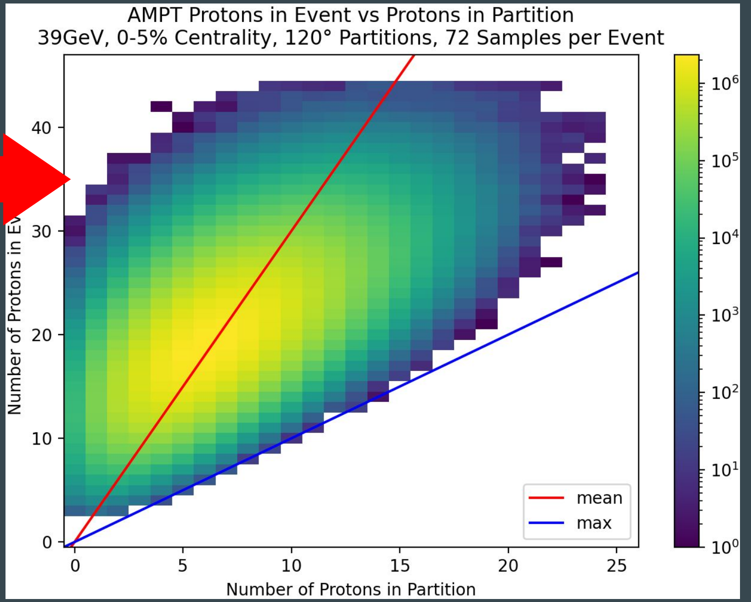
- Total Protons per Event
- Partition Width

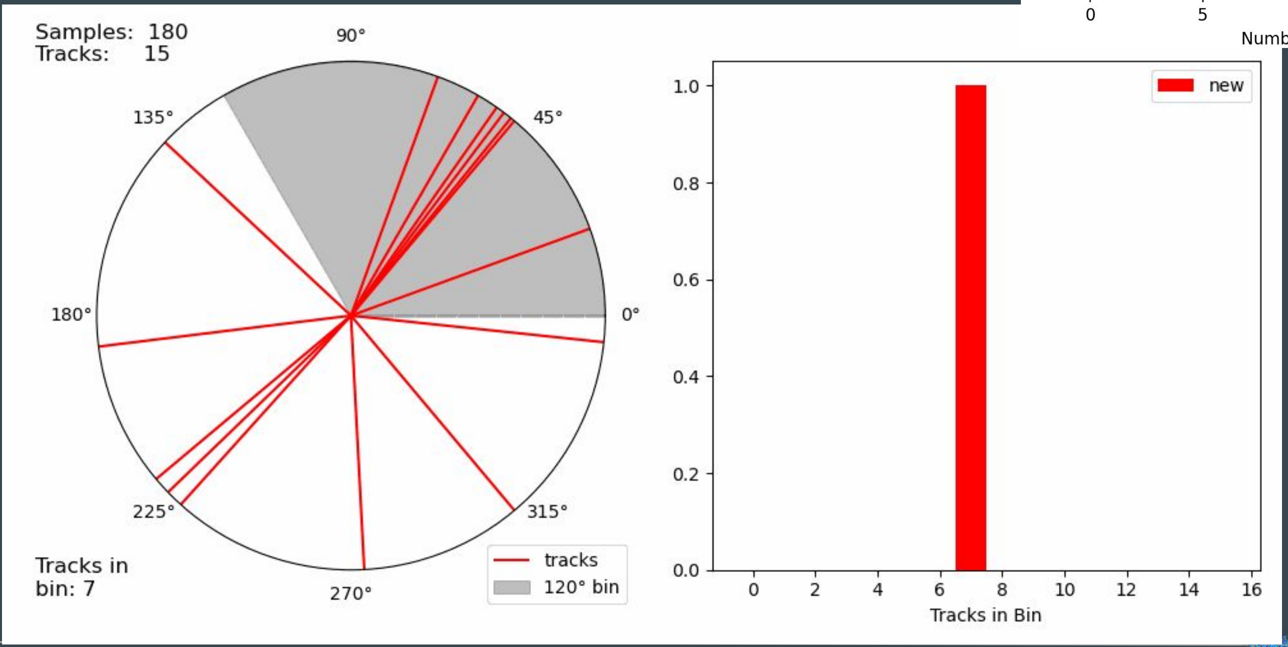
Procedure carried out identically for raw and mixed event data

Event Resampling

- Take multiple random partitions from each event (72 standard)
  - Agrees with analytical expectations for random tracks





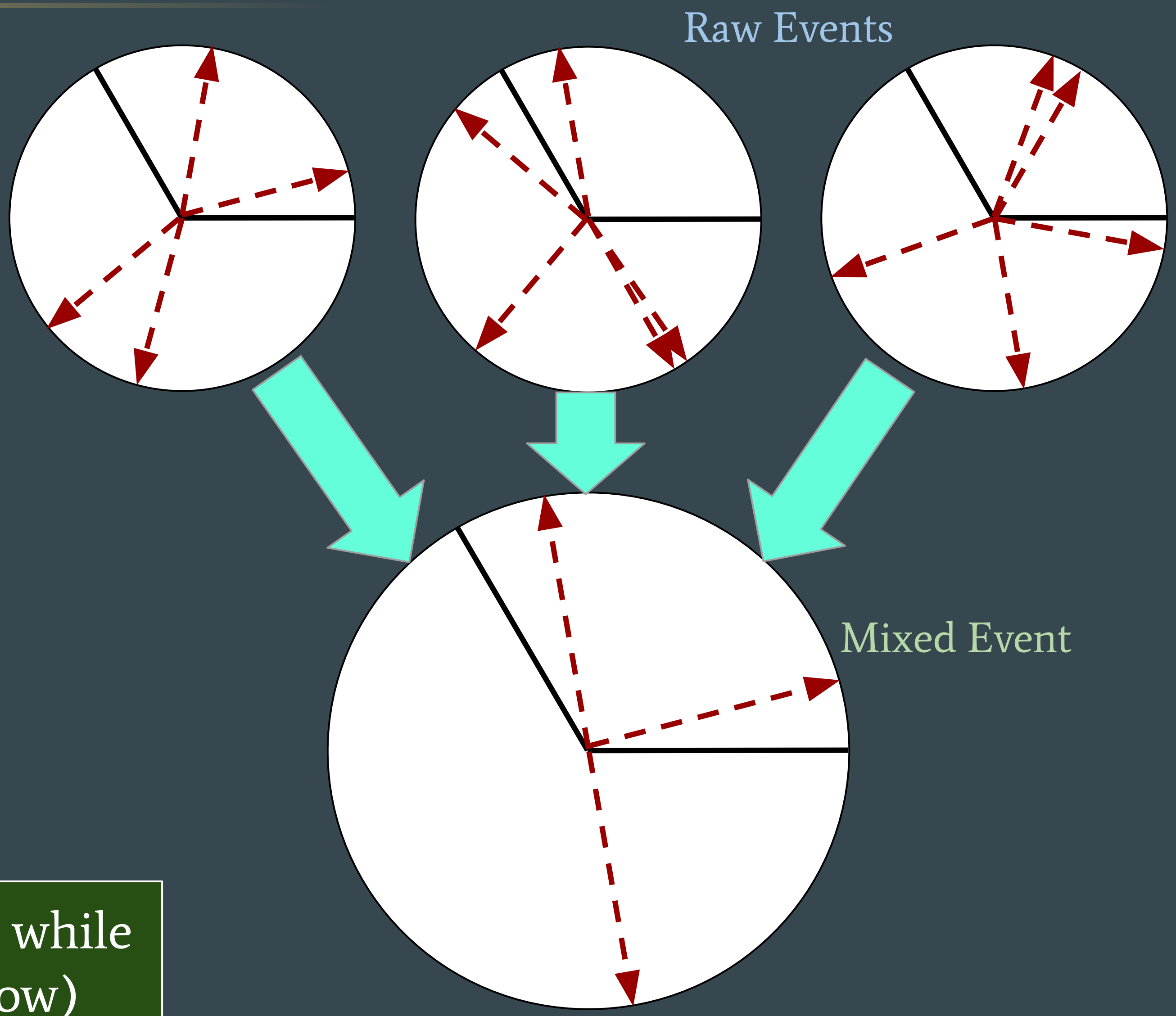


Resampling improves resolution by utilizing more information in each event

Mixed Events

Each raw event is sorted into a class based on energy, centrality, vertex z position, and event plane angle

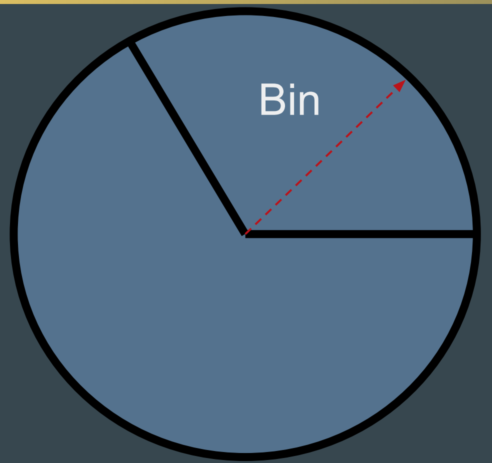
Select one particle track per event from a pool of (~150) raw events to generate mixed events



Goal:

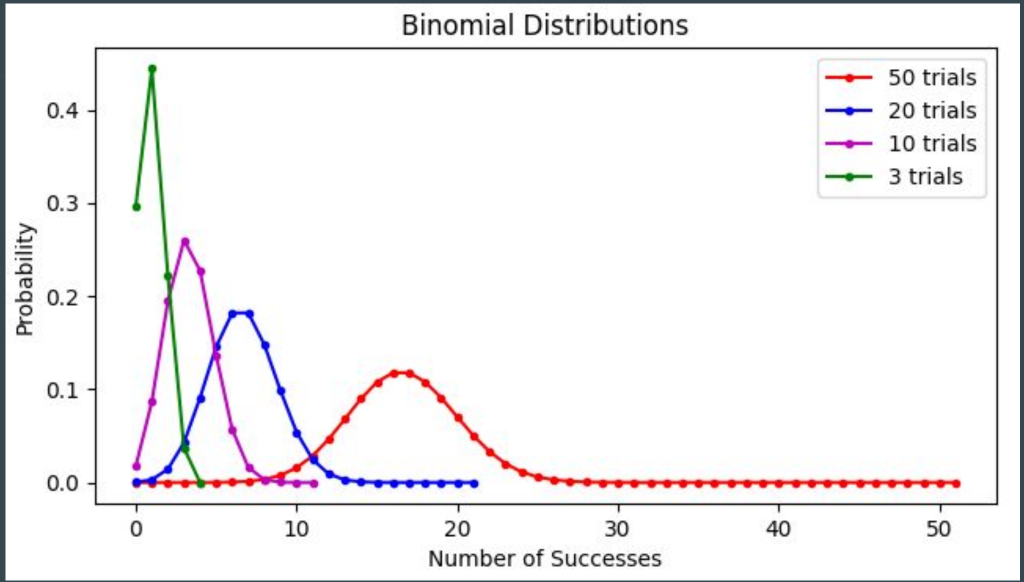
Wash out event-by-event effects (fluctuations) while capturing global effects (detector efficiency, flow)

Compare to Binomial



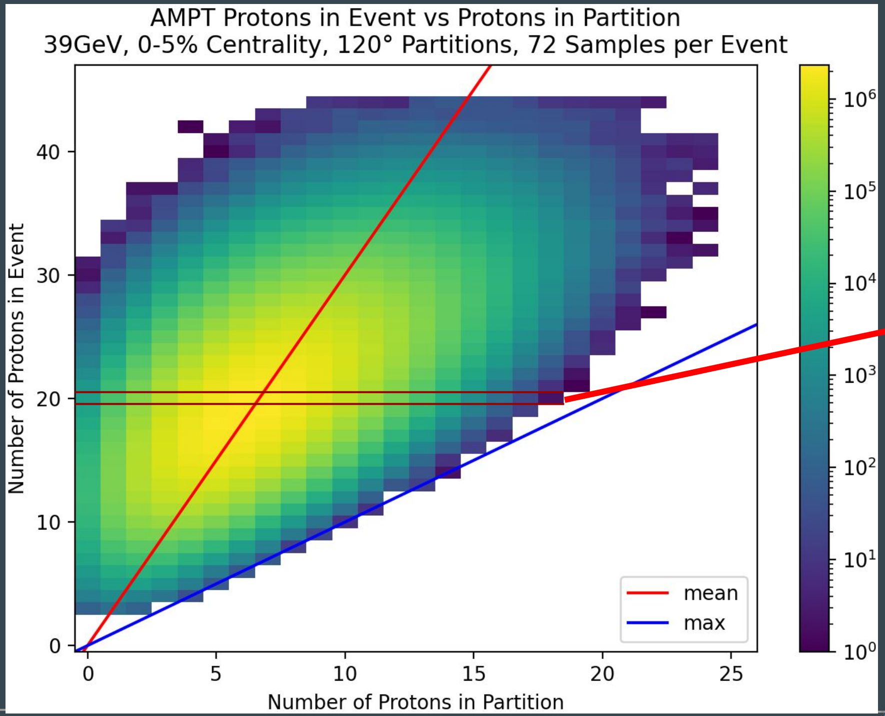
N tracks ( ) in event.
How many fall within Bin?

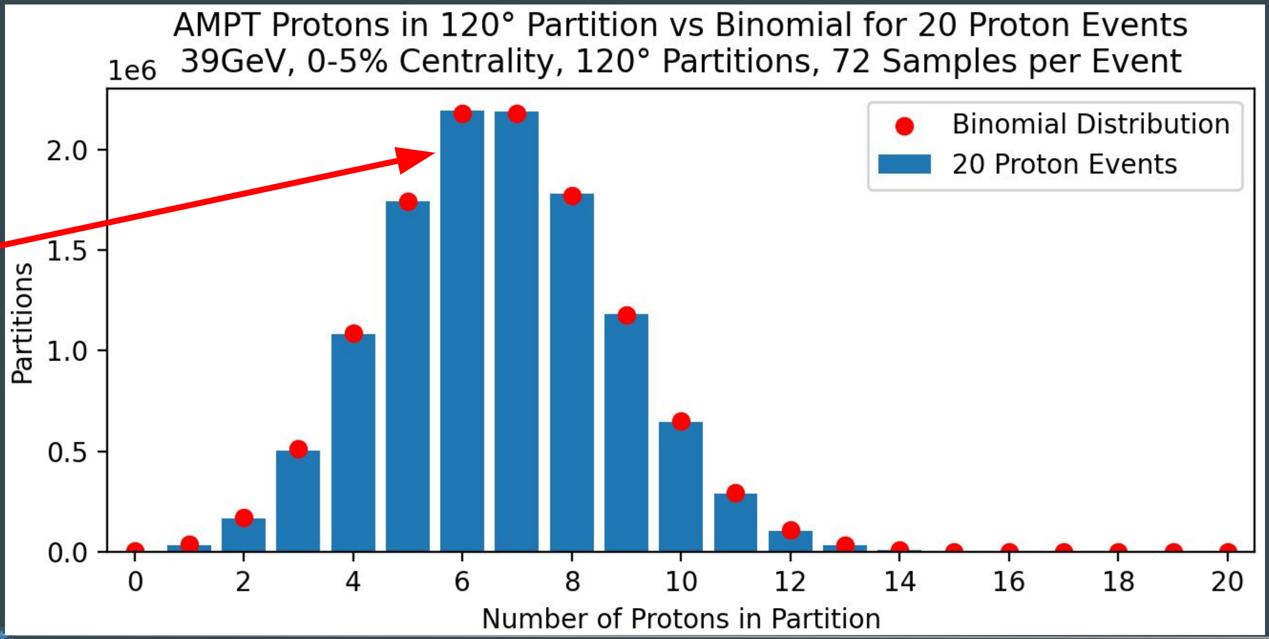
If random, expect binomial distribution



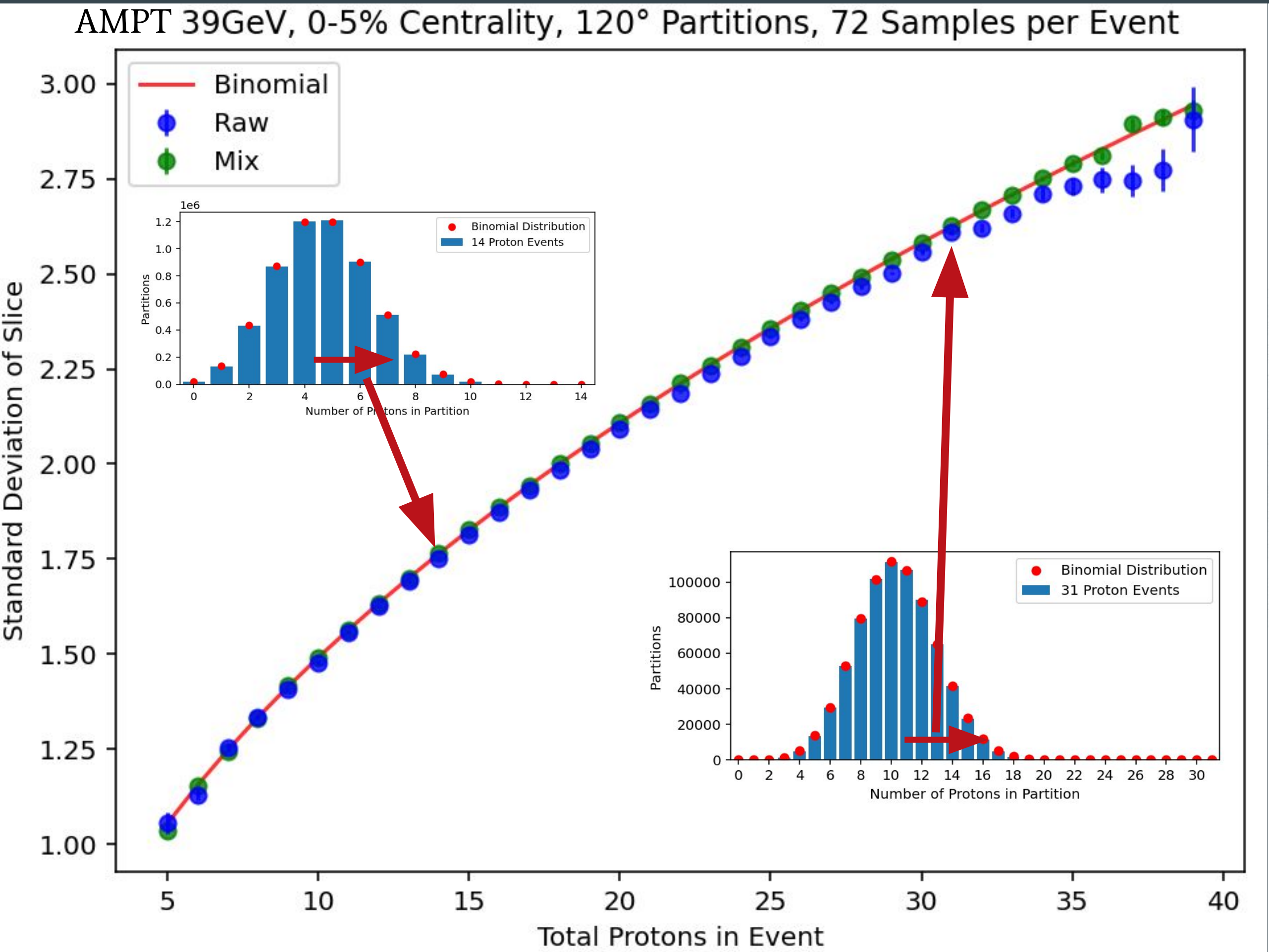
Compare 1D slices to binomial distribution

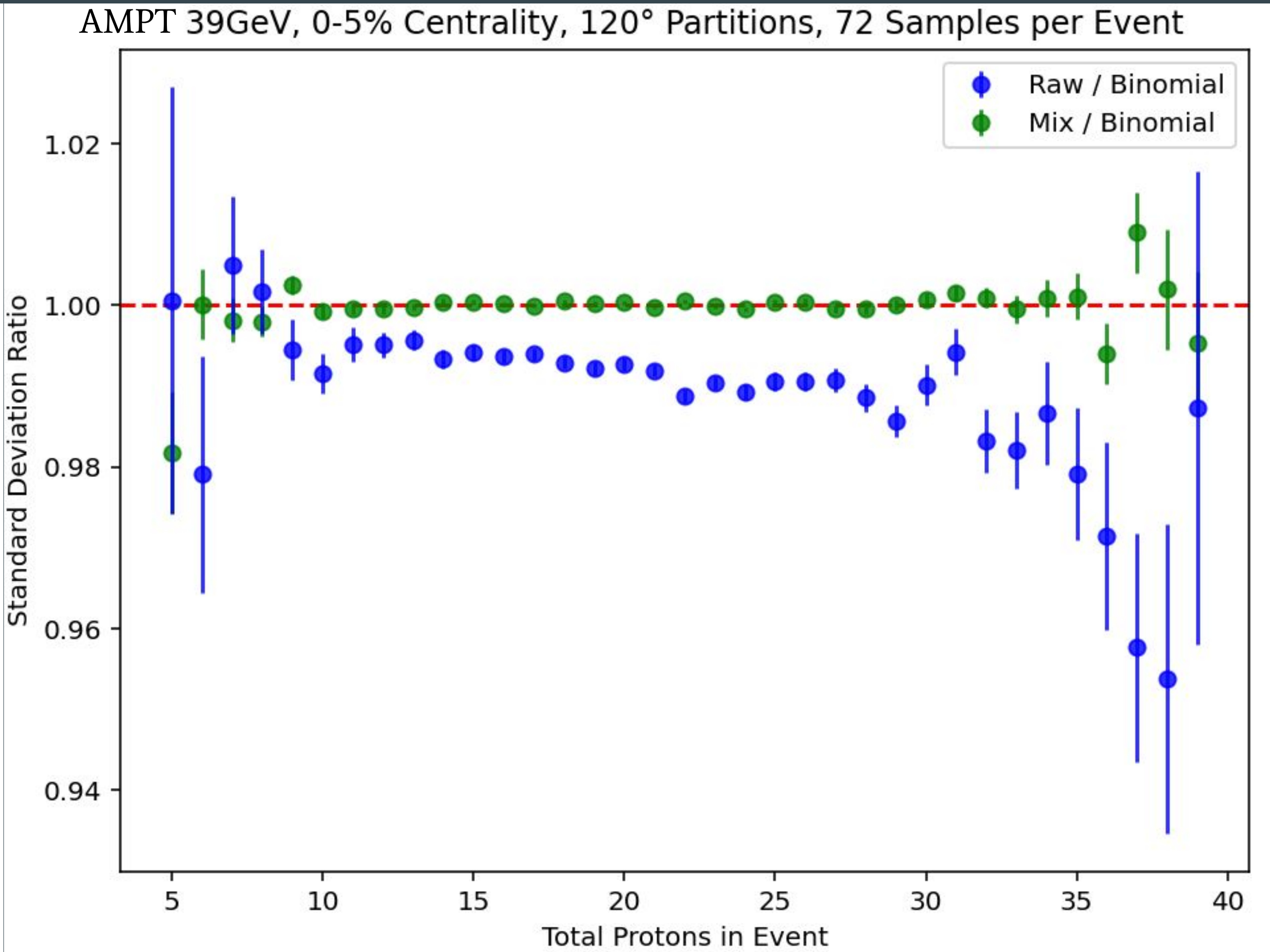
Non-binomial slices suggest correlations





Analyze Standard Deviation



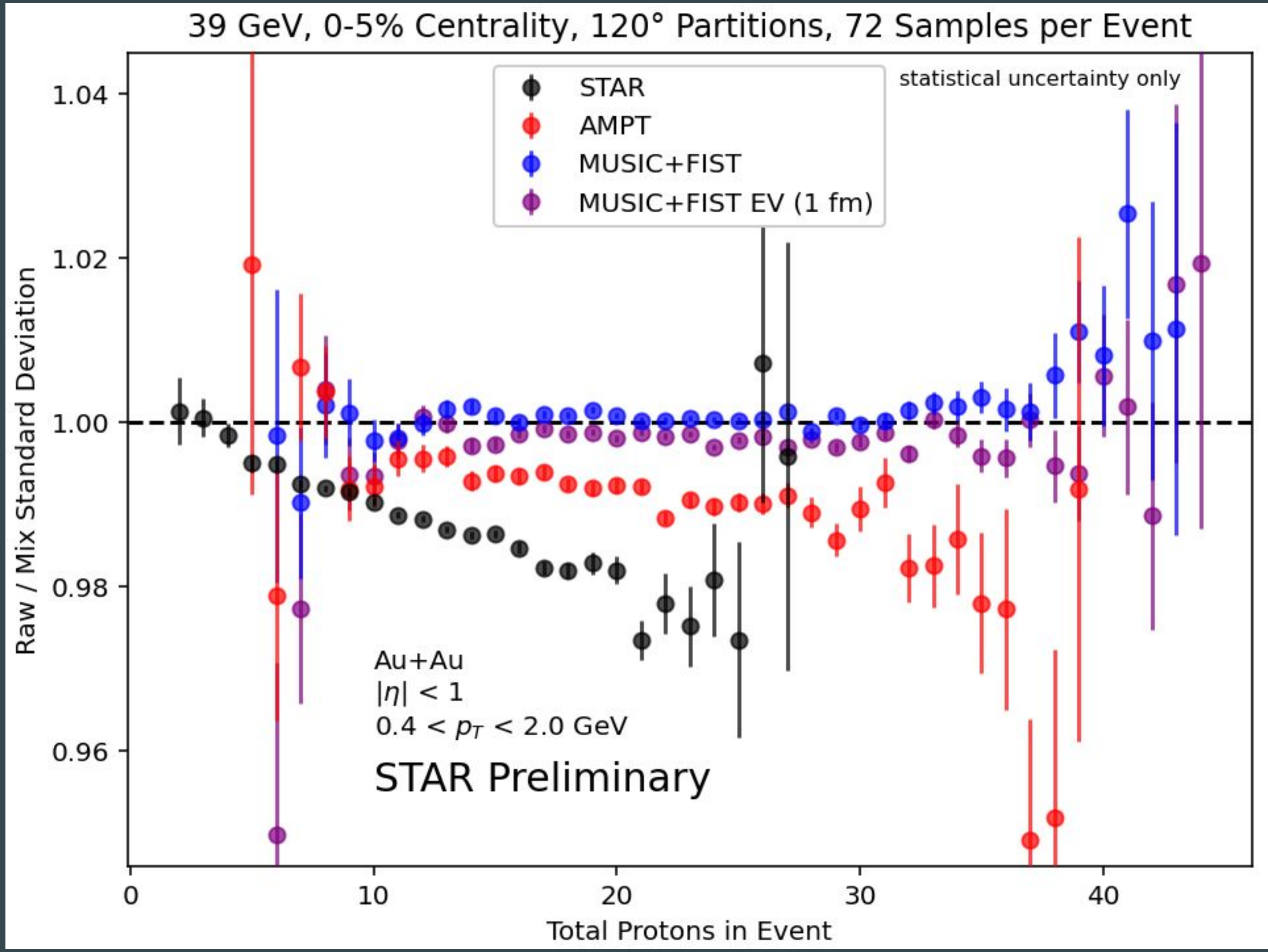


Compare standard deviation of each slice to binomial

Mixed very similar to binomial, raw data is significantly smaller

Divide by Mixed

AMPT	Lin, He	Phys. Rev. C 96, 014910
MUSIC+FIST	Vovchenko et al	Phys. Rev. C 105, 014904
MUSIC+FIST EV	Vovchenko et al	arXiv:2208.13693



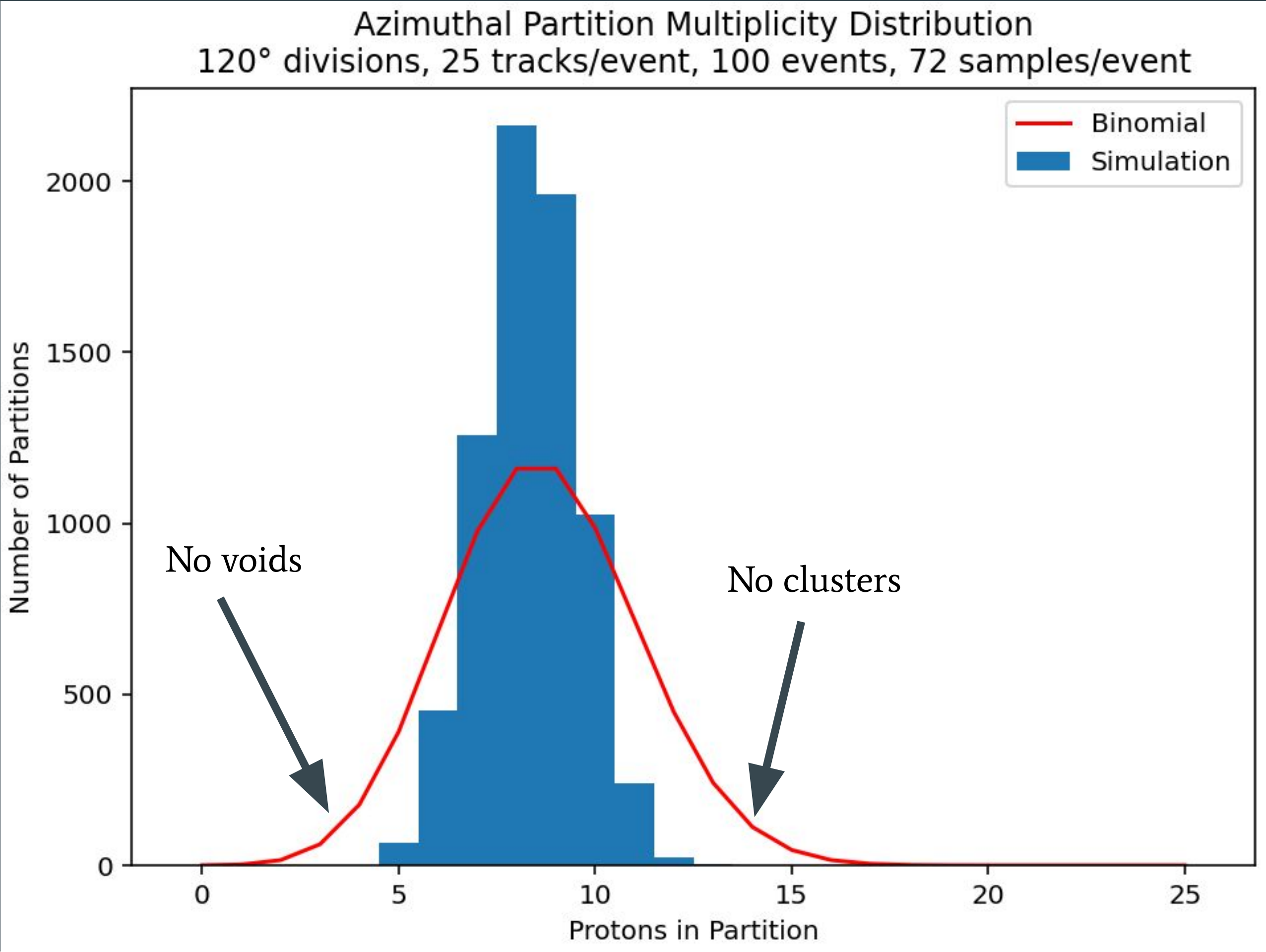
- Divide by Mixed Standard Deviation (SD) instead of binomial to wash out global effects such as efficiency dependence
- Significant deviation of raw data distribution widths from mixed data, suggesting some type of correlation

How do we interpret the SDs of these distributions?

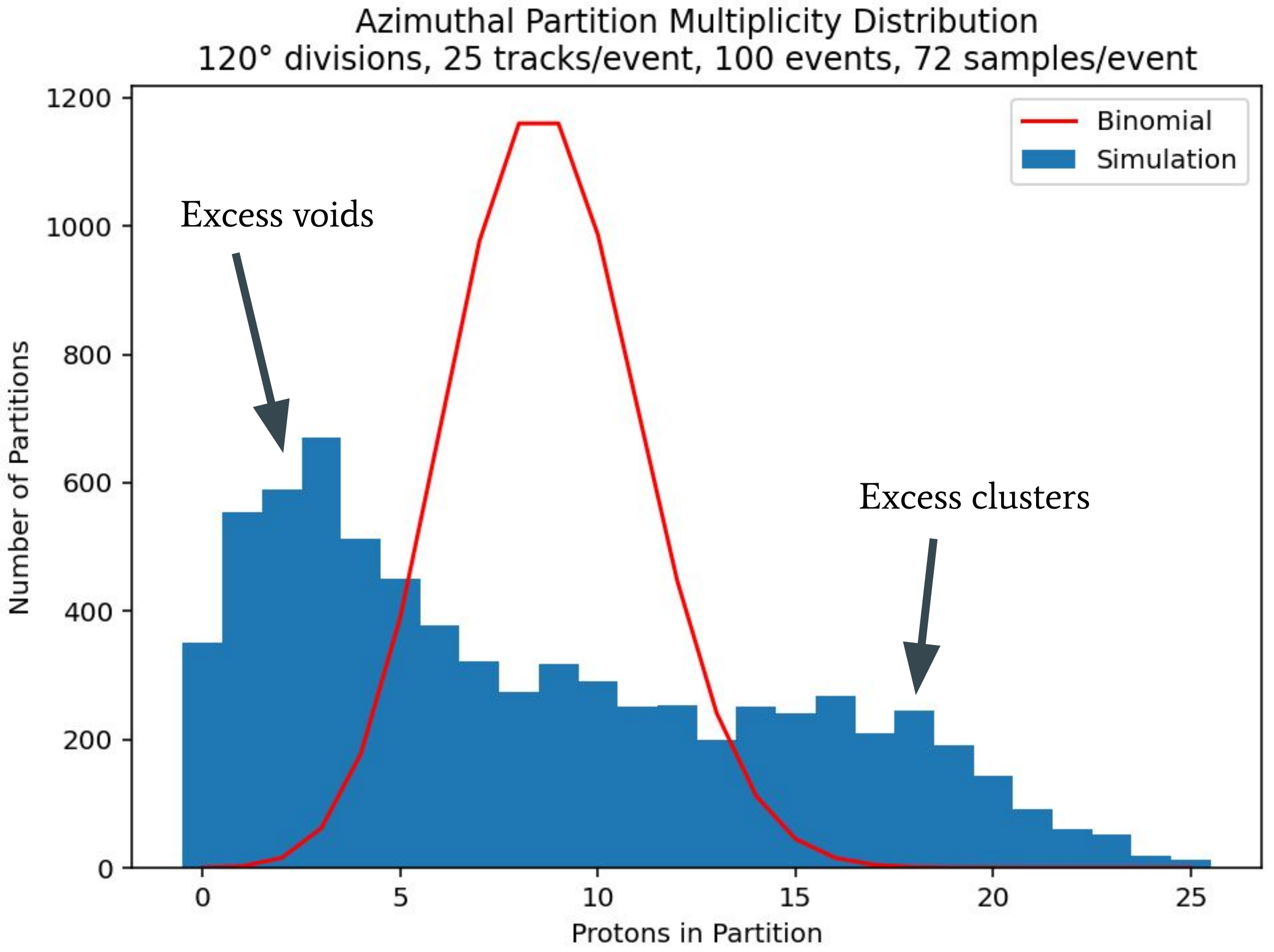
Distribution Width Interpretation

- Standard deviation proxy for degree of clustering
- Total tracks per event fixed → clusters and voids are a packaged deal

Small standard deviation → lack of clustering (repulsion)



Large standard deviation → excess clustering



Correlation in Data

AMPT	Lin, He	Phys. Rev. C 96, 014910
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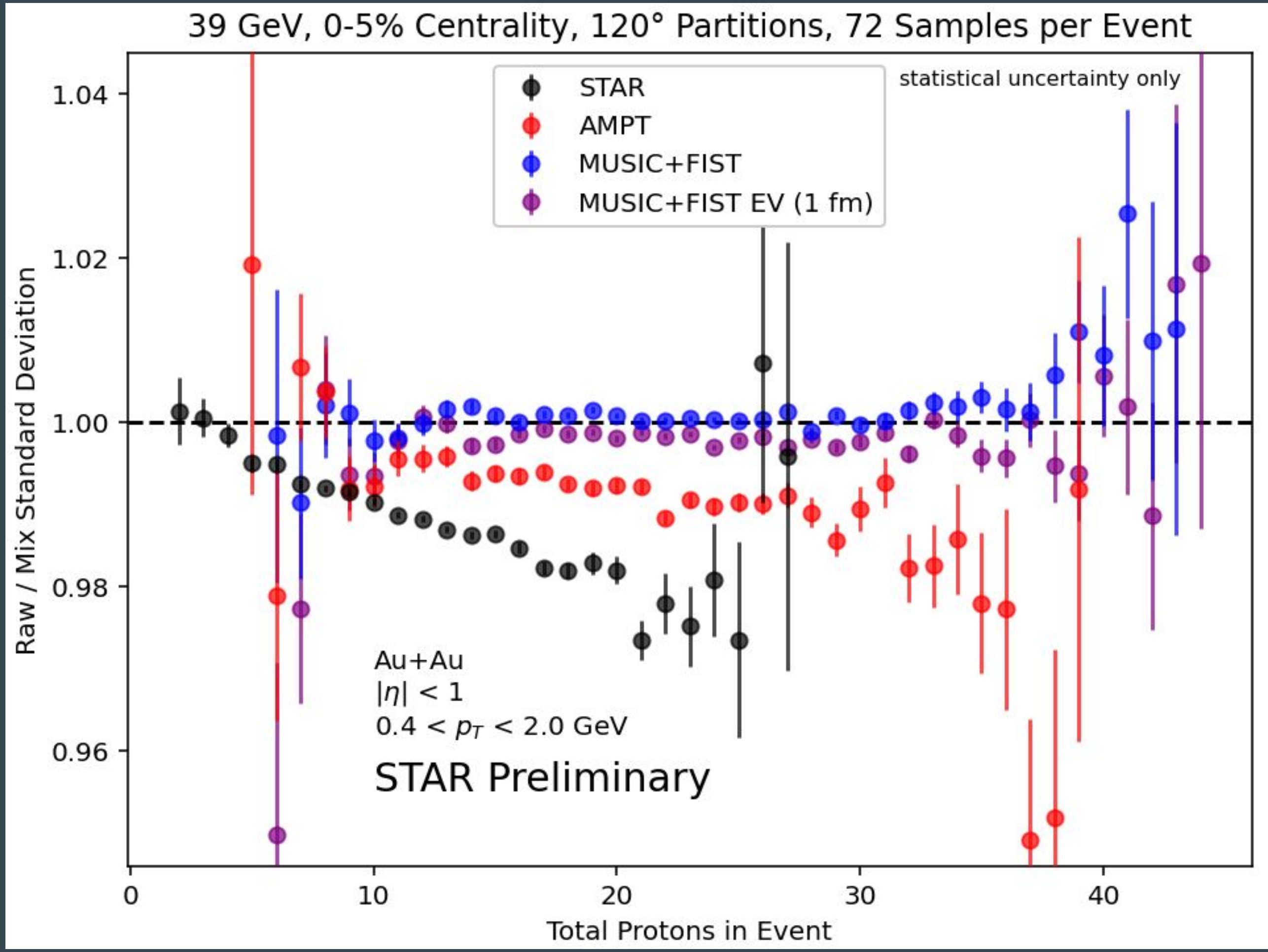


- Divide by Mixed Standard Deviation instead of binomial to wash out global effects

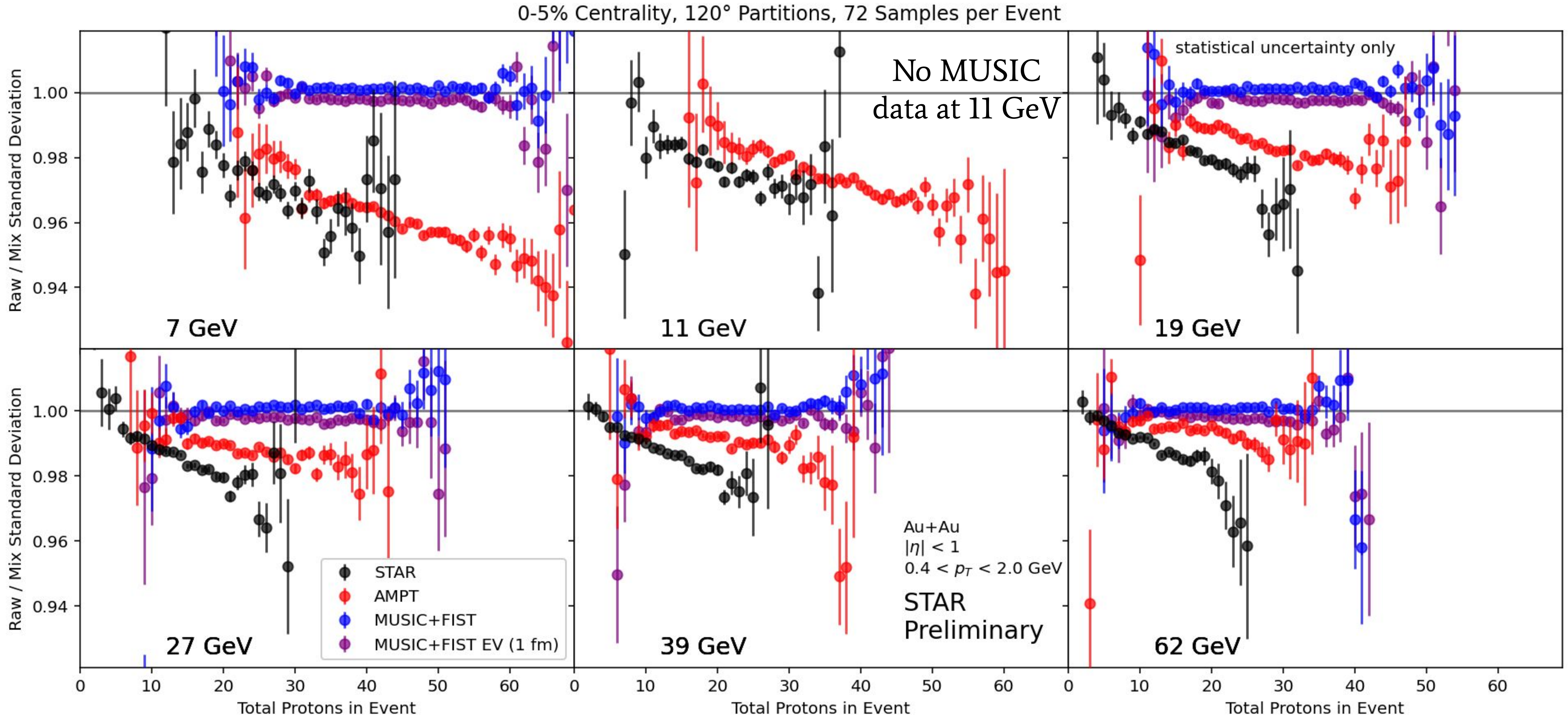
- Values less than 1 → repulsion
- Values greater than 1 → clustering

- AMPT and STAR see proton repulsion. MUSIC+FIST model serves as baseline which shows weak clustering while the Excluded Volume version shows weak repulsion

MUSIC+FIST EV includes Excluded Volume effects - no two baryons coalesce within the same 1 fm volume on the hypersurface

Repulsion at All Energies

Effect appears to manifest as a function of the total number of protons per event



Summary

- Search for signals of clustering in azimuthally partitioned proton multiplicity distributions

- Strong signal of proton repulsion found
  - Present in STAR data as well as AMPT and, to a smaller degree, MUSIC+FIST
  - STAR repulsion magnitude significantly greater than models
  - Further study needed to identify source and quantify magnitude of repulsion

Thanks for your attention!

Backup

Simulating Correlated Tracks

- Built simple model of correlation to test analysis

- *n* tracks in event placed one at a time
  - First track has flat probability distribution in ϕ
  - Each track placed produces Gaussian distortion in P(ϕ) for all subsequent tracks

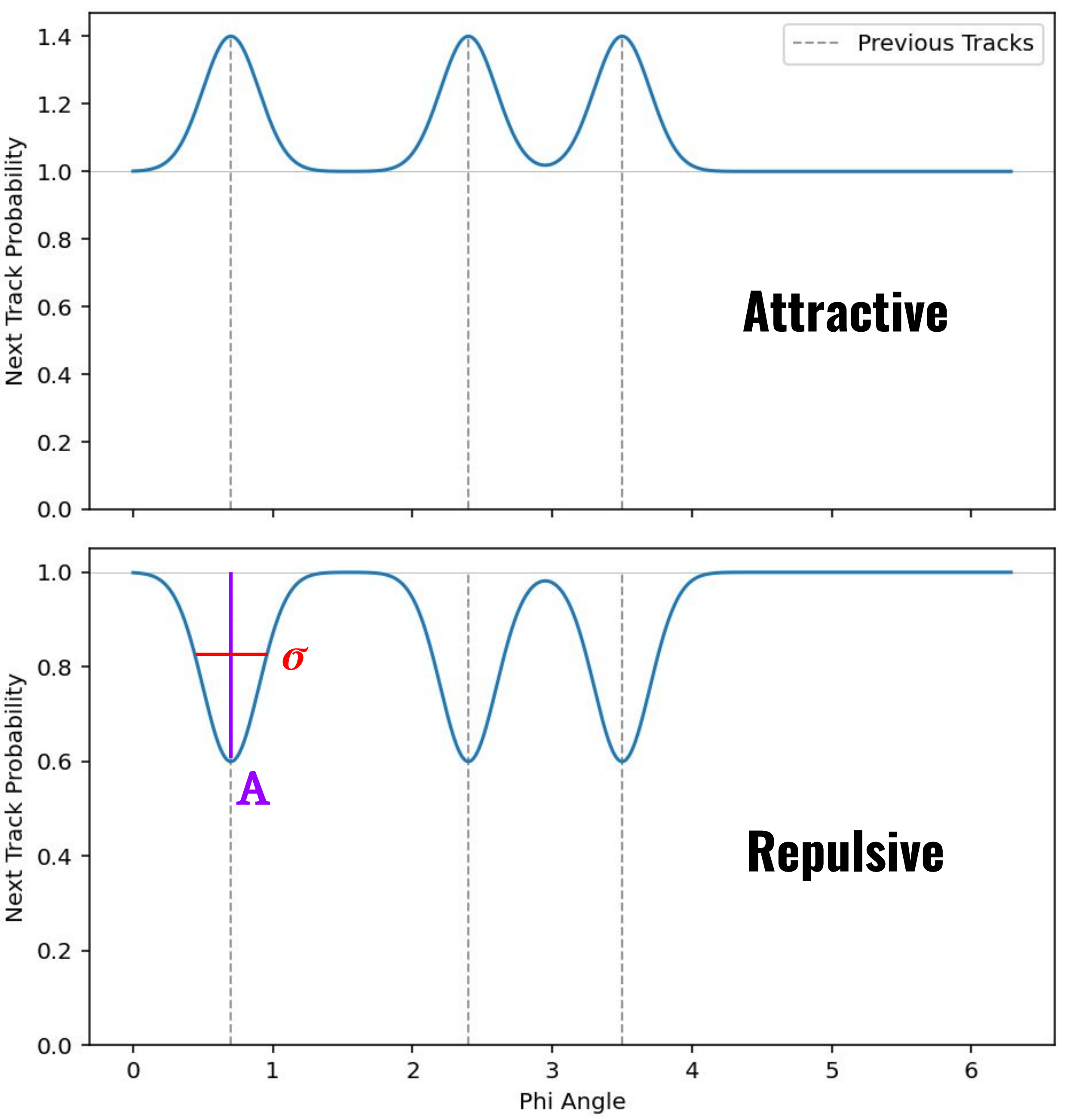
- Can model attraction (A>0) and repulsion (A<0)

2 Parameter Model:
- Amplitude (A)
- Width (σ)

baseline

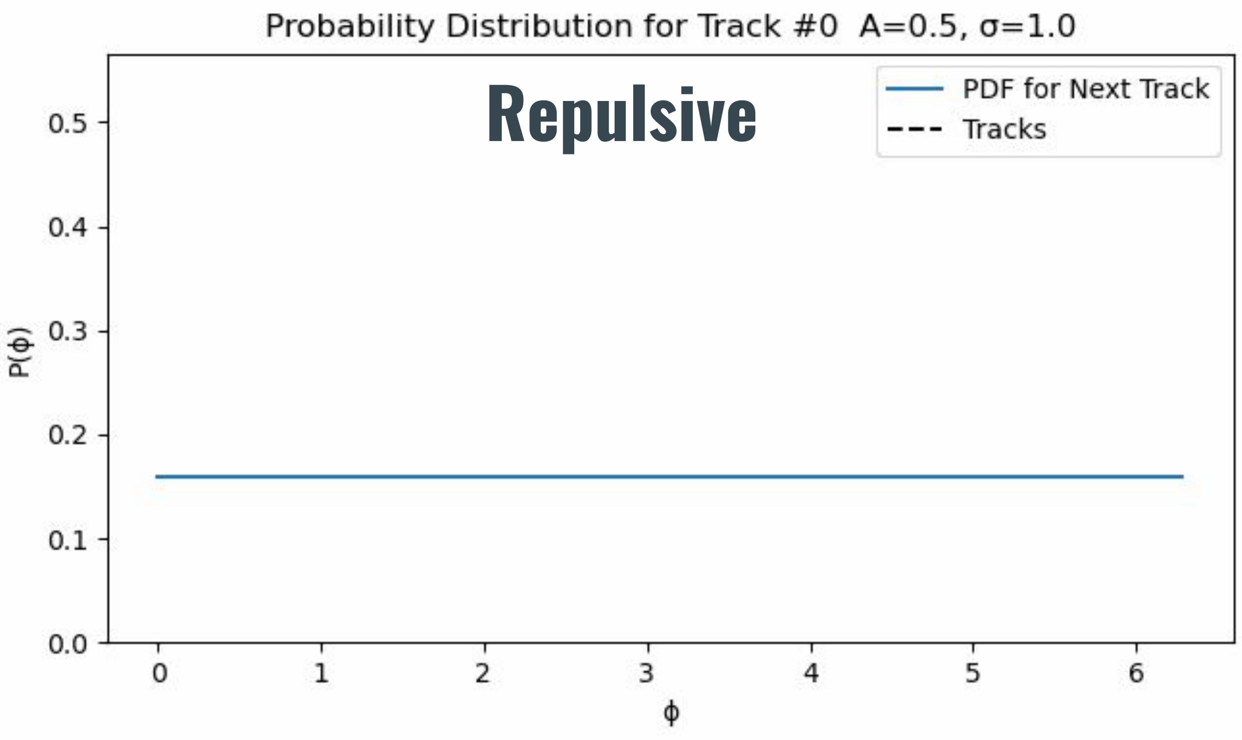
$$P(\phi) \propto \prod_{i=i}^{n} 1 + \frac{A}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\phi-\phi_i}{\sigma}\right)^2}$$

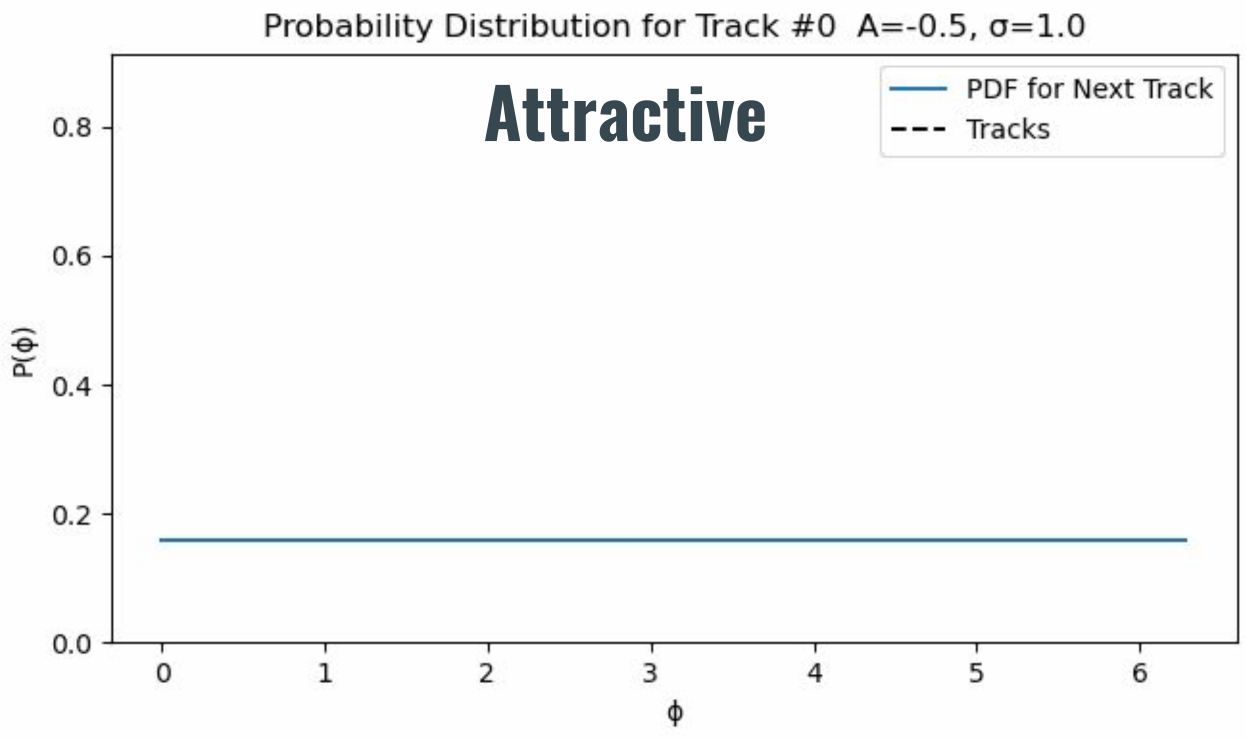
Parameters not directly comparable between attractive and repulsive



Toy Model Visualization

- Model visualized here for a single event with large correlation A to demonstrate an exaggerated effect
- Tracks in the Repulsive model tend to spread out while those in the Attractive model cluster together
  - Always finite probability for any ϕ due to baseline of +1 in Gaussian kernel

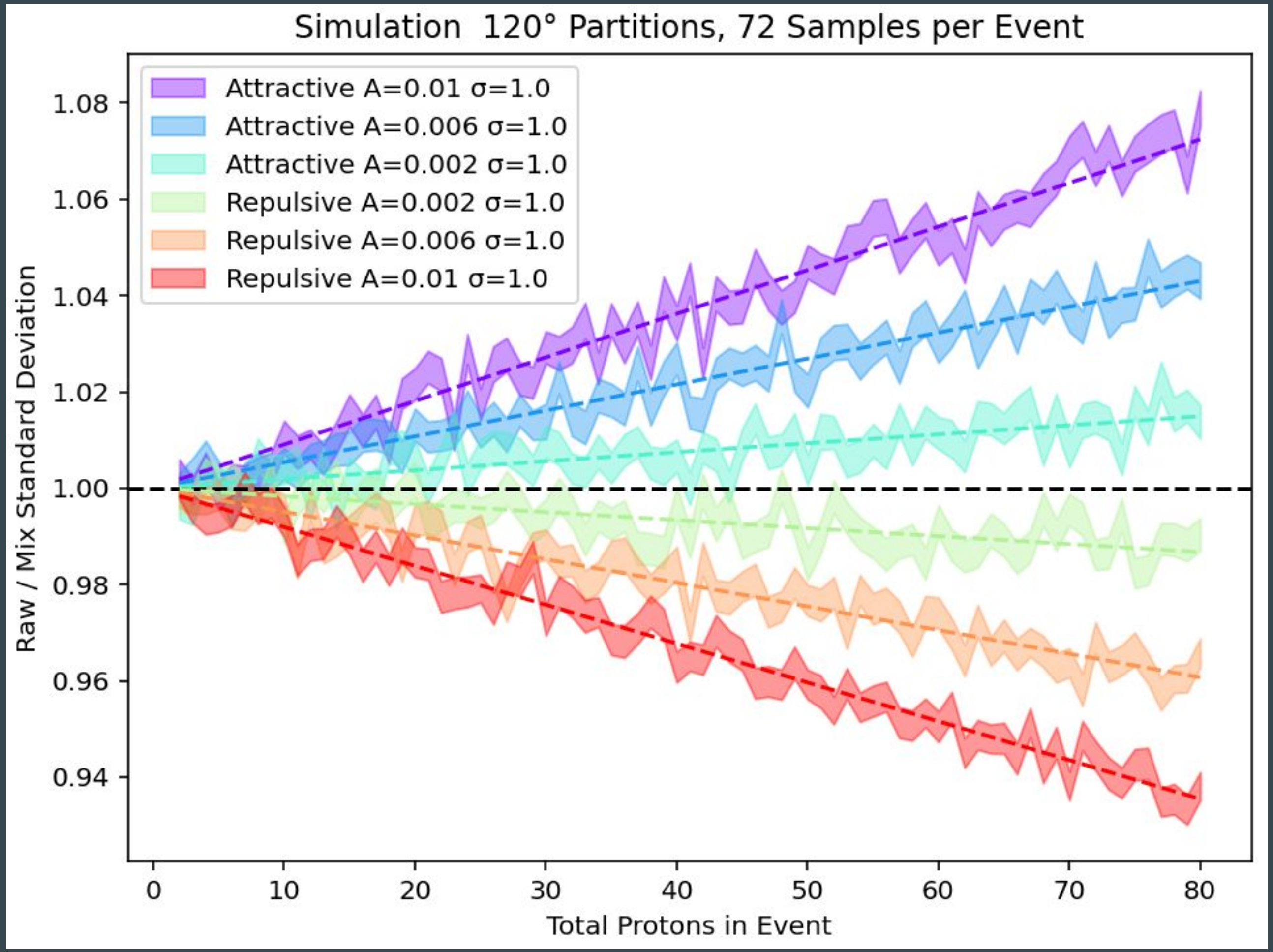




Width vs Total Protons

$$y = mx + 1$$

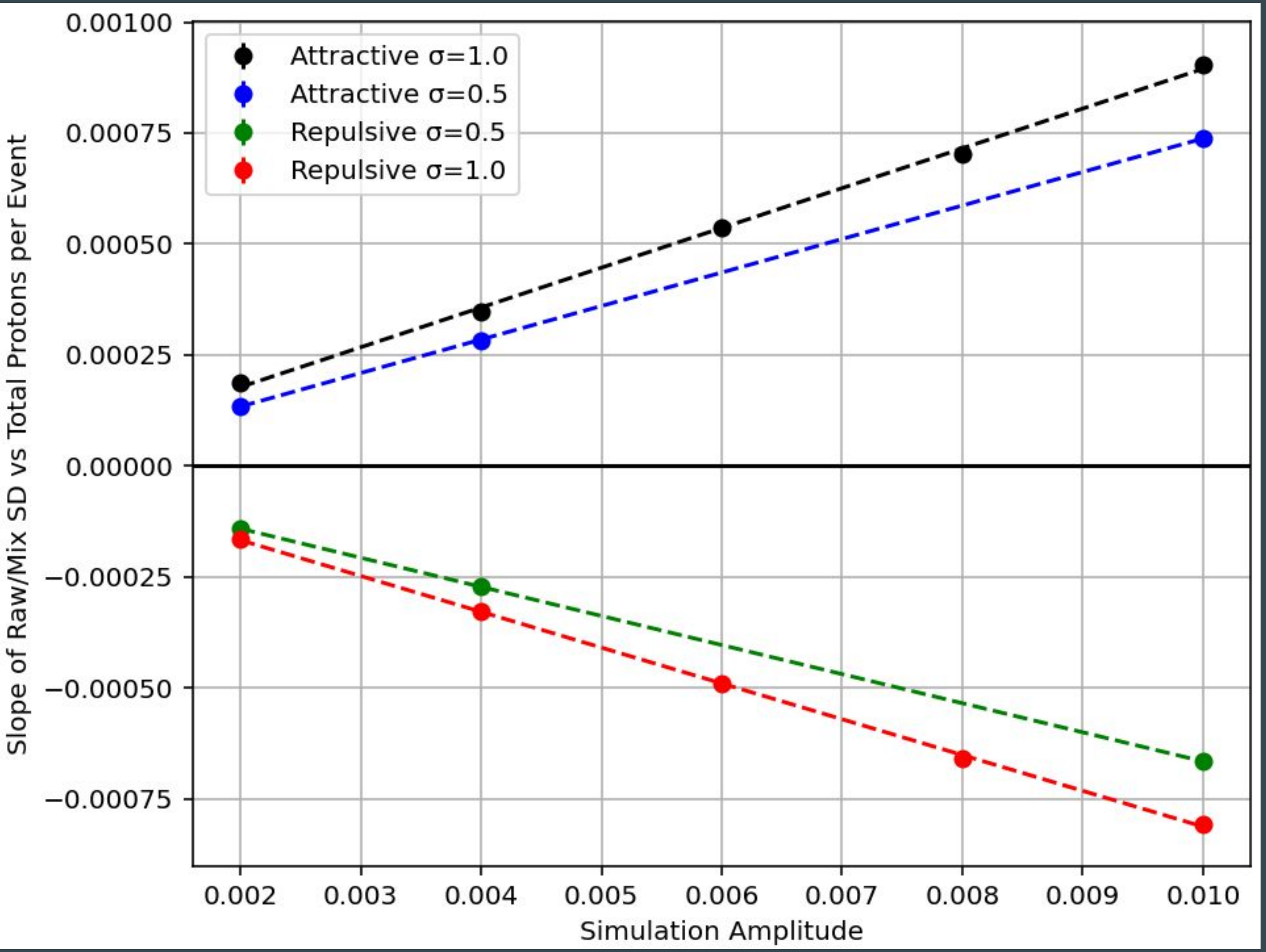
- Plot the standard deviation of distributions vs the total number of protons in each event for a handful of simulation *A*mplitudes
- Observe consistent linear trends with magnitude of slope correlated with *A*
- Fit each simulation to line with y-intercept fixed at 1



Mixed distributions for toy model are statistically identical to binomial

Can Reliably Extract Correlation

- Plotting the slope of the widths of the distributions vs the total number of protons, get good linear relationship with input simulation *Amplitude*
- This suggests the analysis can reliably extract the input correlation in the case of this simple model
- Changing Gaussian correlation width lead to different but still linear relationship



Slope vs Partition Width Simulation

- Dependence appears quadratic
- Curvature switches at slope=0
- Different σ different x-intercept