Update:
Proton Fluctuations in Azimuthal Partitions

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Updates Since March Collaboration Meeting

- Observable reparameterized

- Resolved background subtraction worries
    - Mixed Events
    - Elliptic Flow

- Systematics checked and incorporated

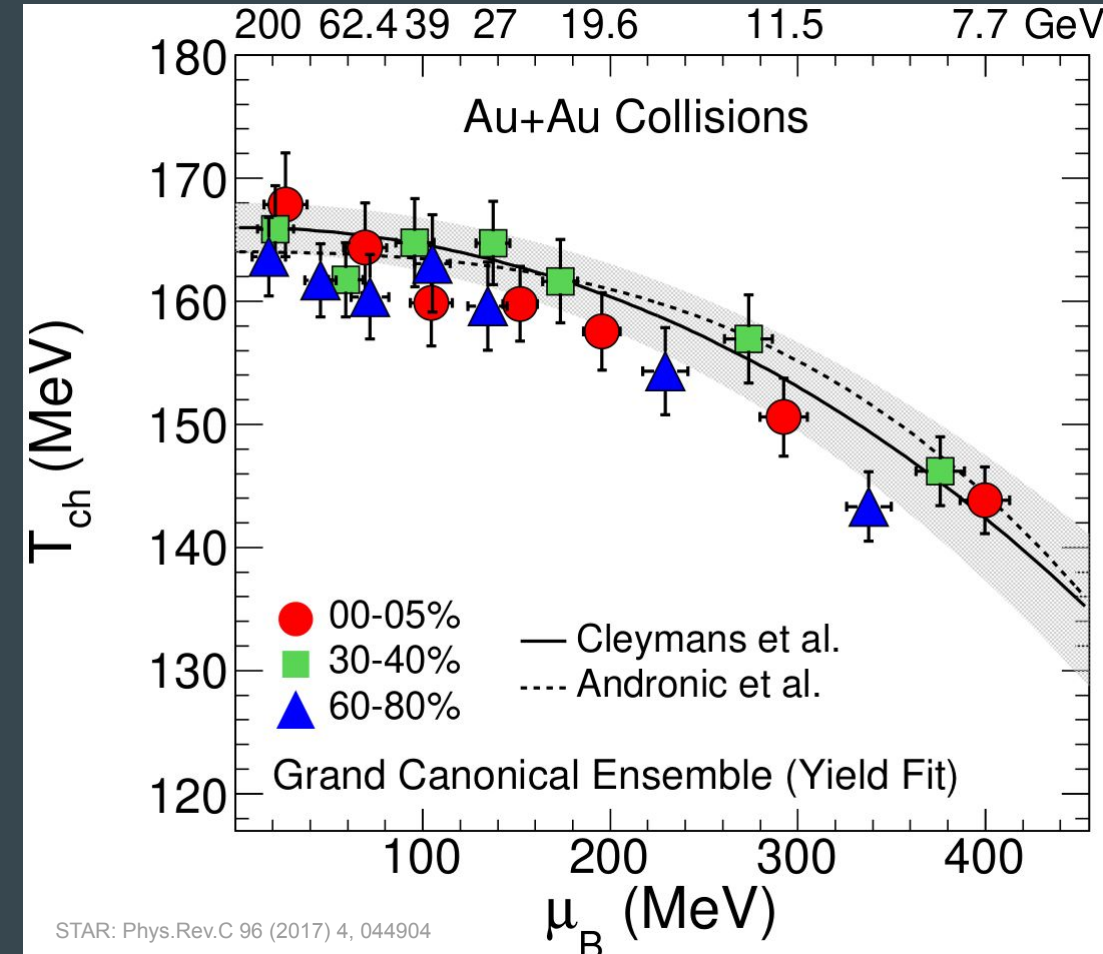- Plots vs partition width and reference multiplicity

QCD Phase Diagram

Goals:

- Experimentally verify the cross-over transition at low μ_B
- Look for observables sensitive to a first order transition

A. Bzdak, S. Esumi, V. Koch et al. / Physics Reports 853 (2020)
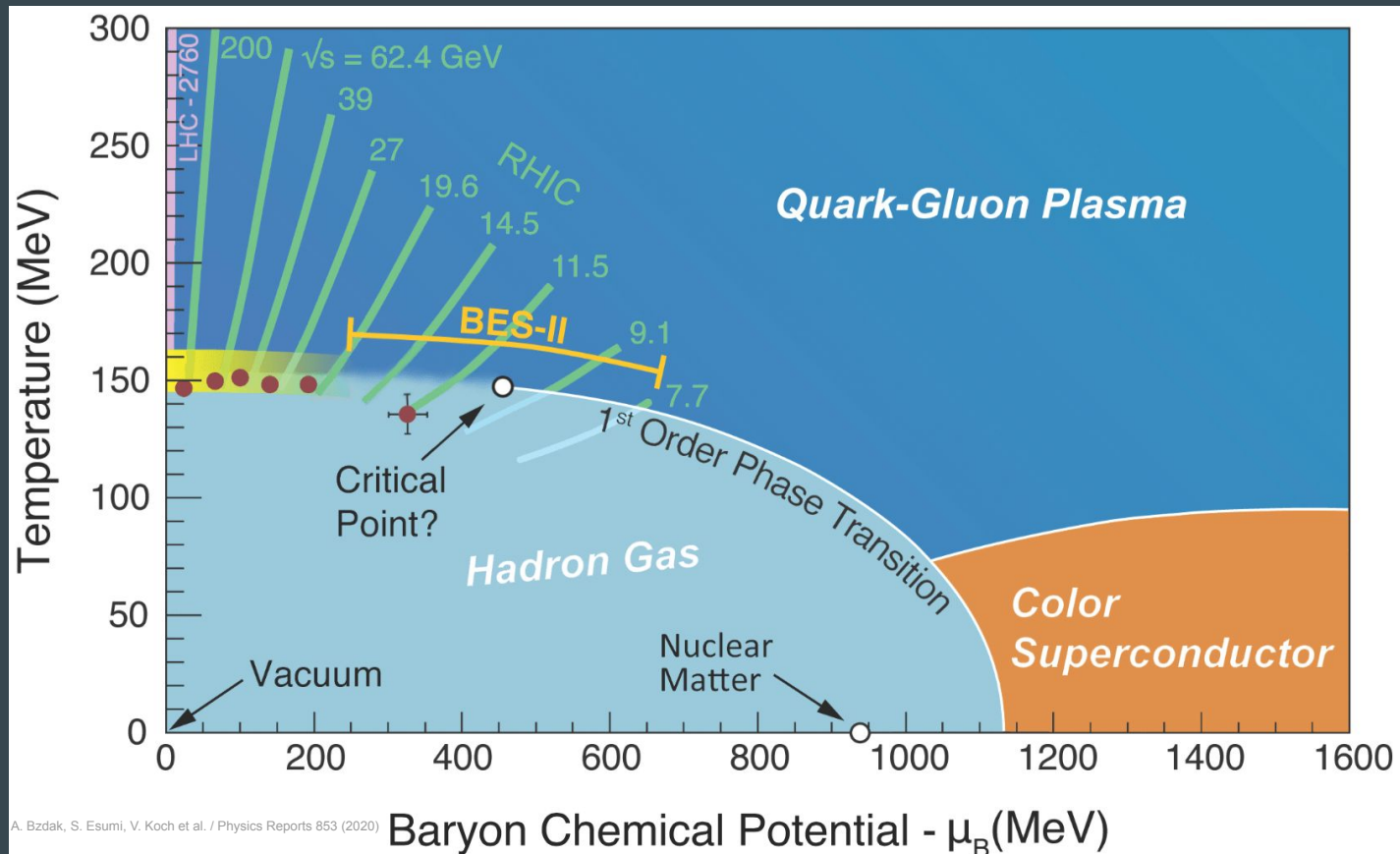
Vary beam energy to scan QCD phase space

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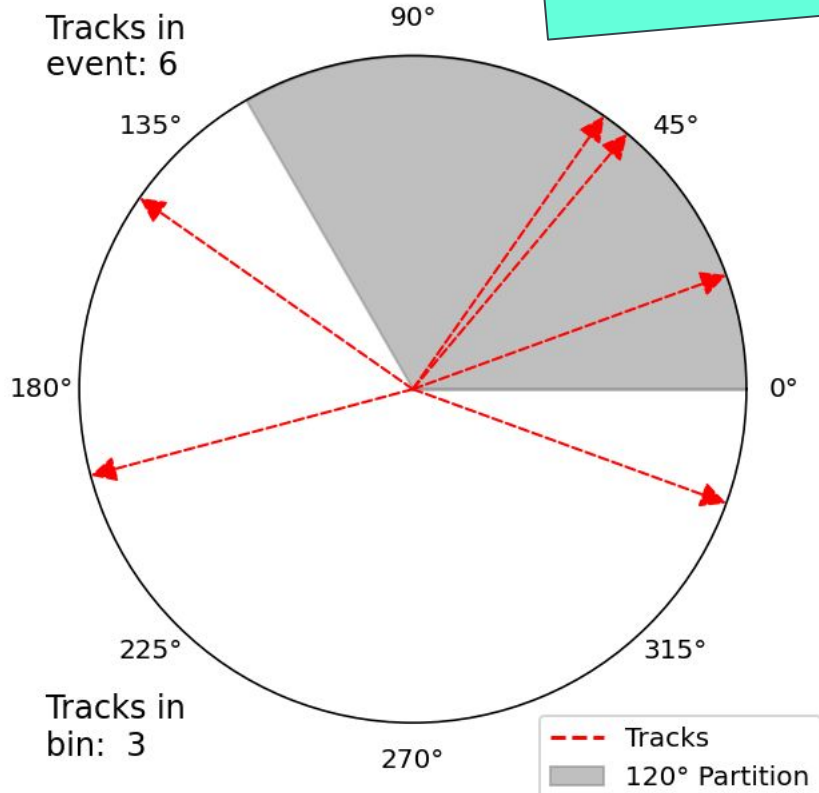
Analysis Goal

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

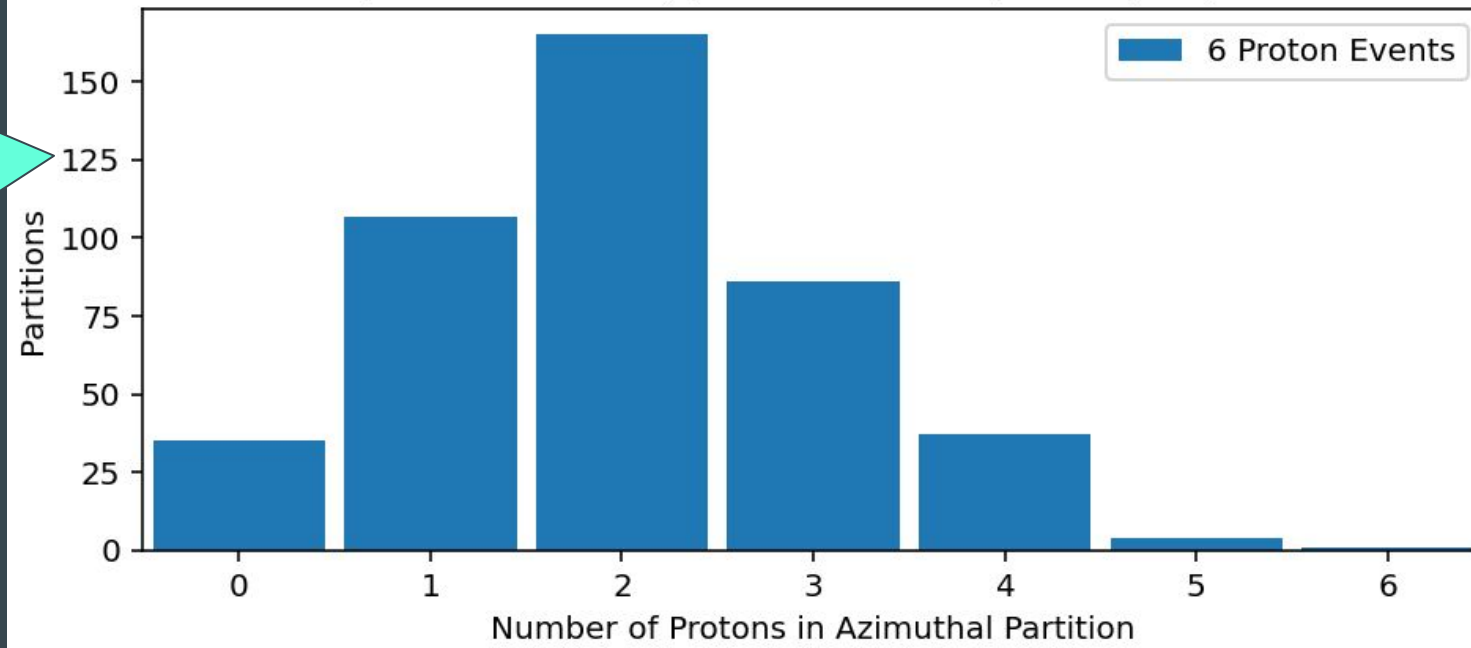- Compare proton multiplicities in azimuthal partitions to uncorrelated expectation
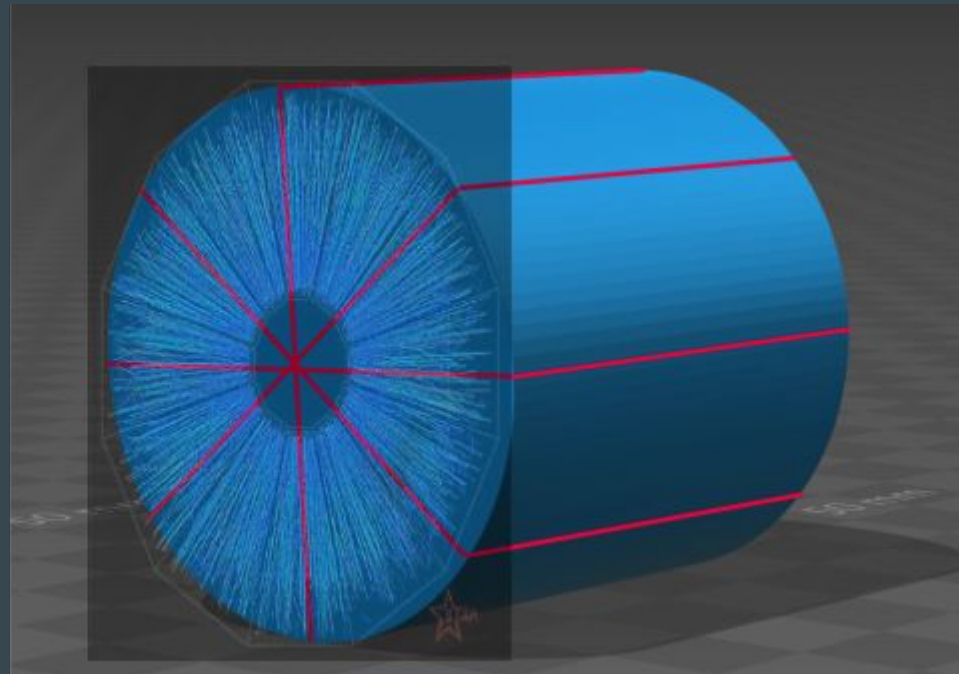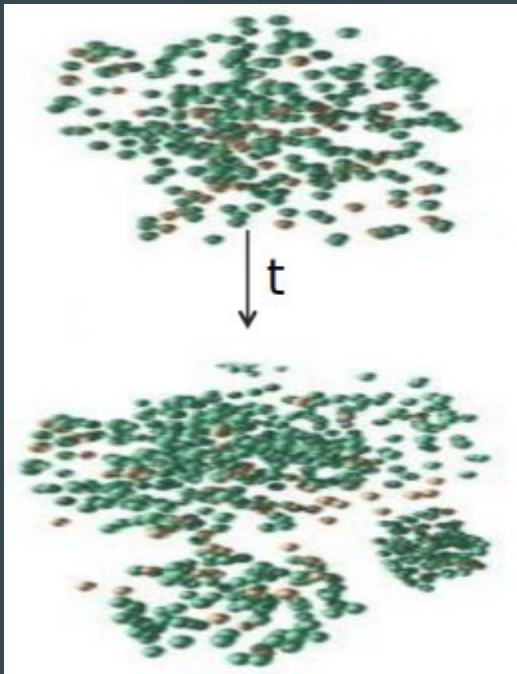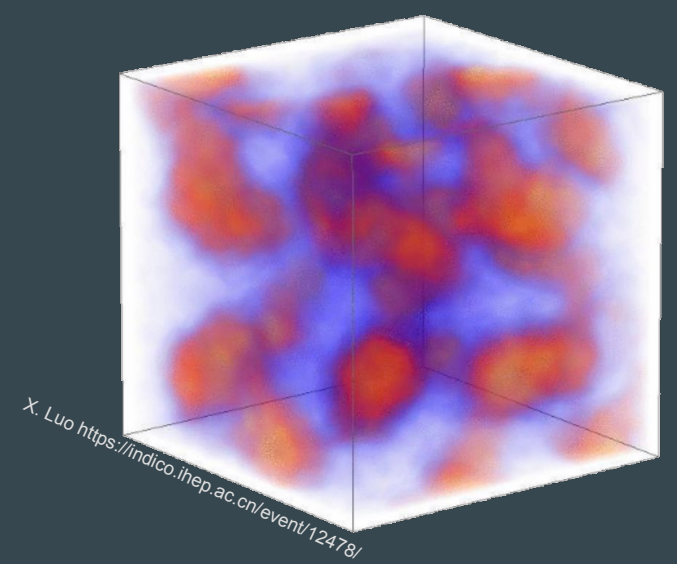
Azimuthal Partitioning

Partition the azimuth in each event
and histogram particle tracks

Histogram tracks in partition
over many events

Important Dimensions:
- Total Protons in Event
- Partition Width

Procedure carried out identically for
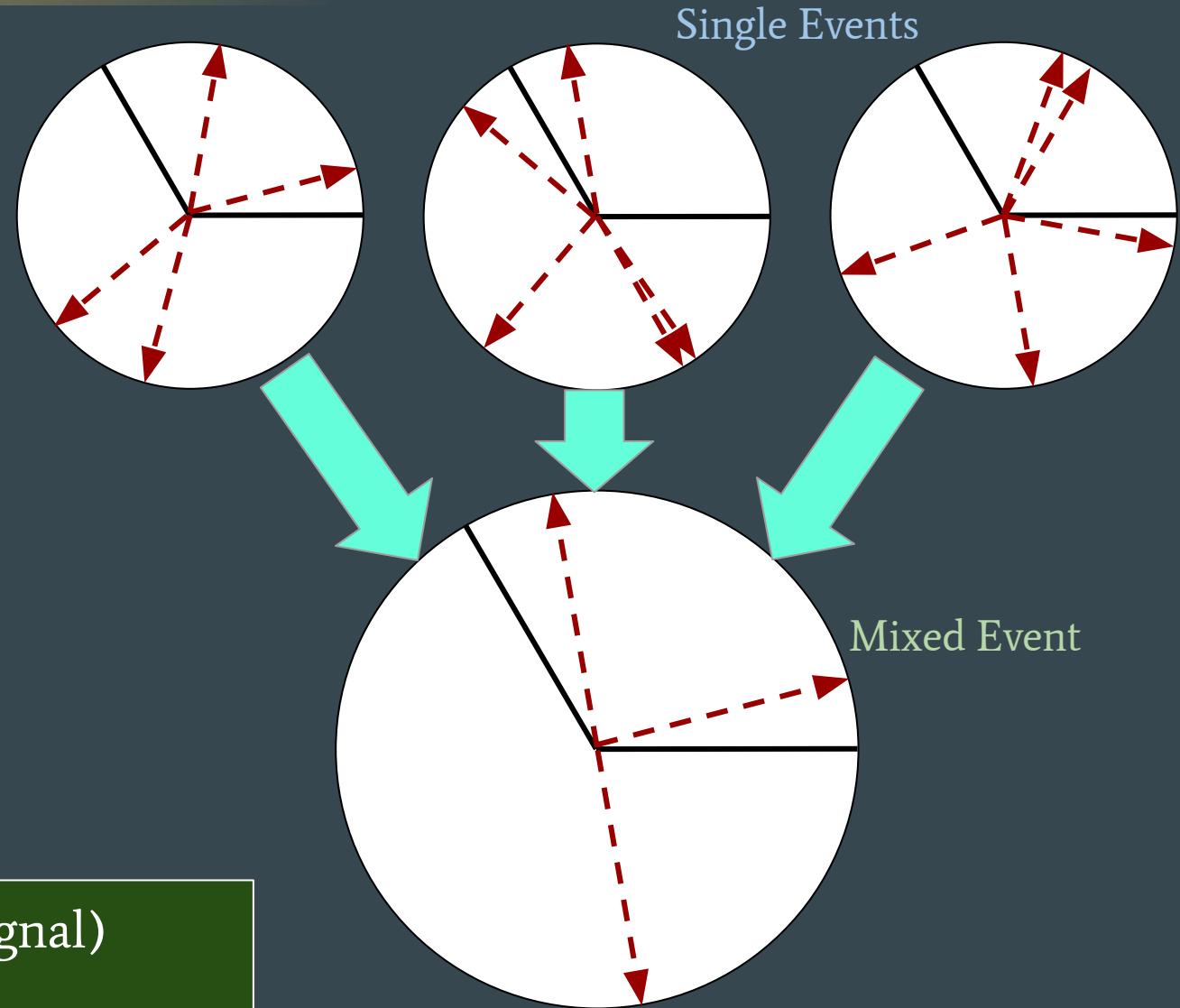raw and mixed event data

Mixed Events

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

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

Goal:

Wash out correlated event-by-event effects (signal) while capturing detector effects (background)

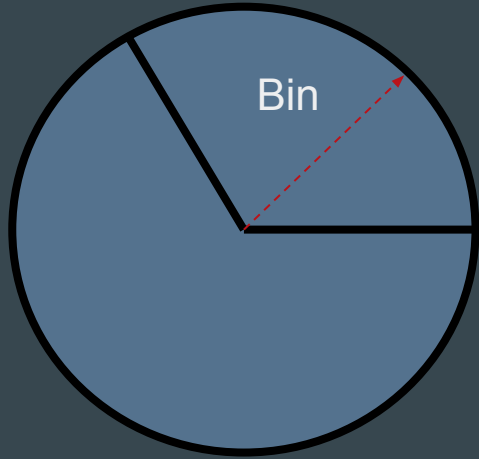Single Events

Mixed Event

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
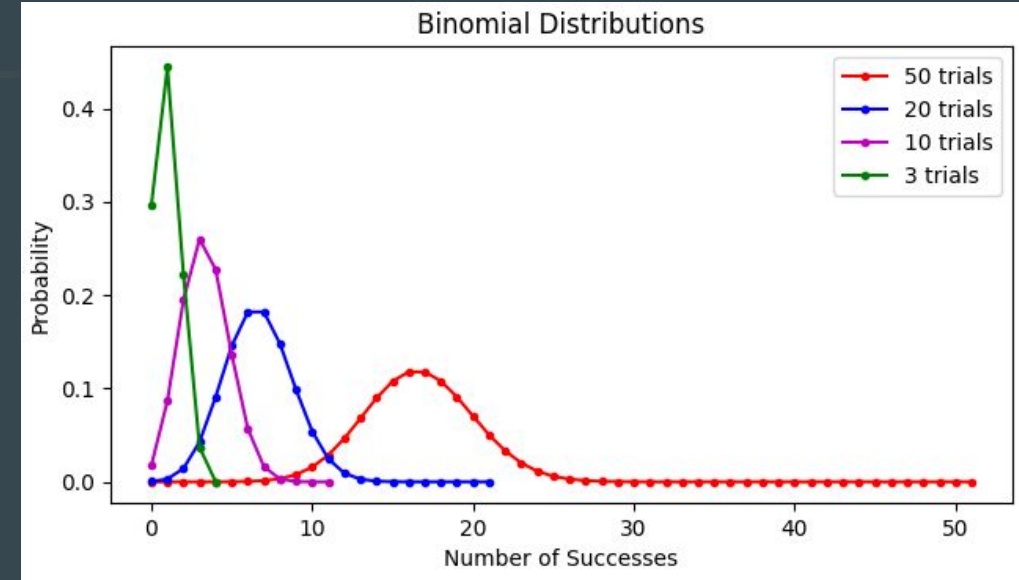

Few entries poor resolution

Distribution better resolved
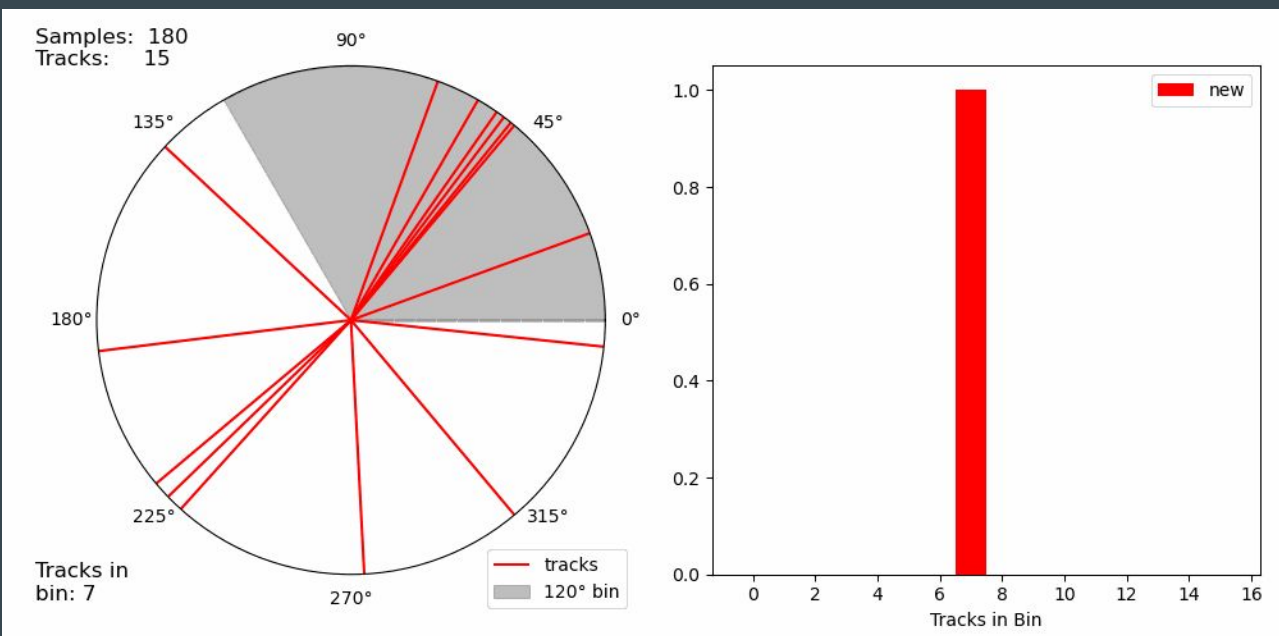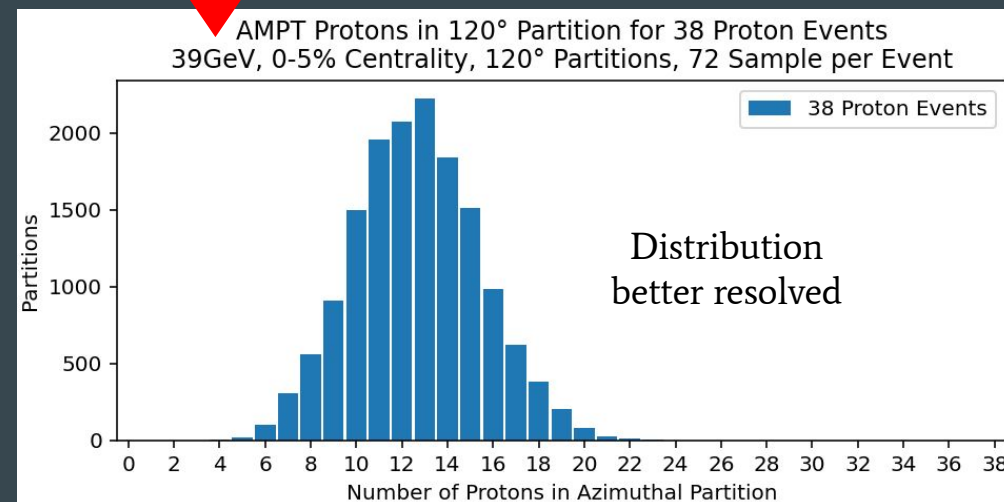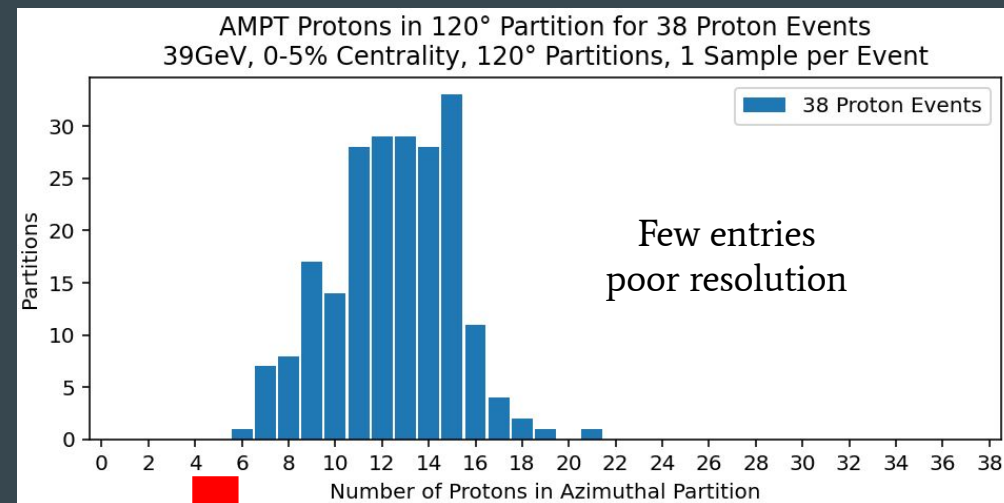
Compare to Binomial

Bin

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

⟹

If random, expect binomial
distribution

Binomial Distributions
- 50 trials
- 20 trials
- 10 trials
- 3 trials

Compare measured
distributions to binomial

AMPT Protons in 120° Partition vs Binomial for 20 Proton Events
39GeV, 0-5% Centrality, 120° Partitions, 72 Samples per Event
- Binomial Distribution
- 20 Proton Events
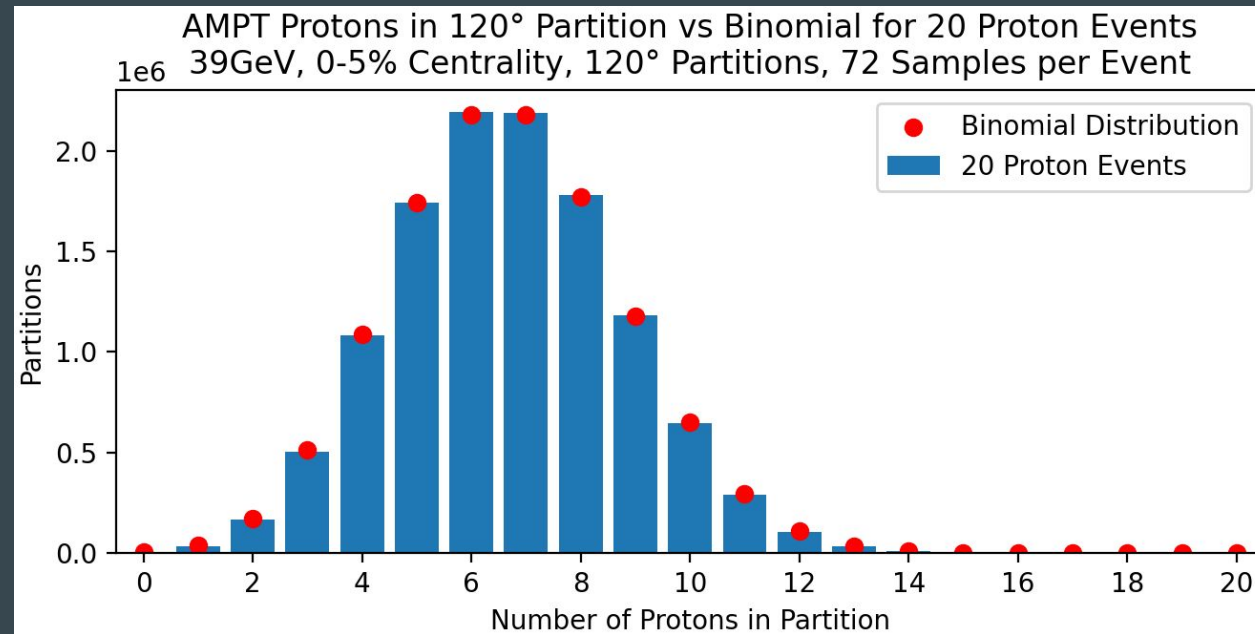
Systematic deviations from
binomial suggest correlation
between proton tracks

Compare Variance to Binomial

AMPT 39 GeV, 0-5% Centrality, 120° Partitions, 72 Samples per Event
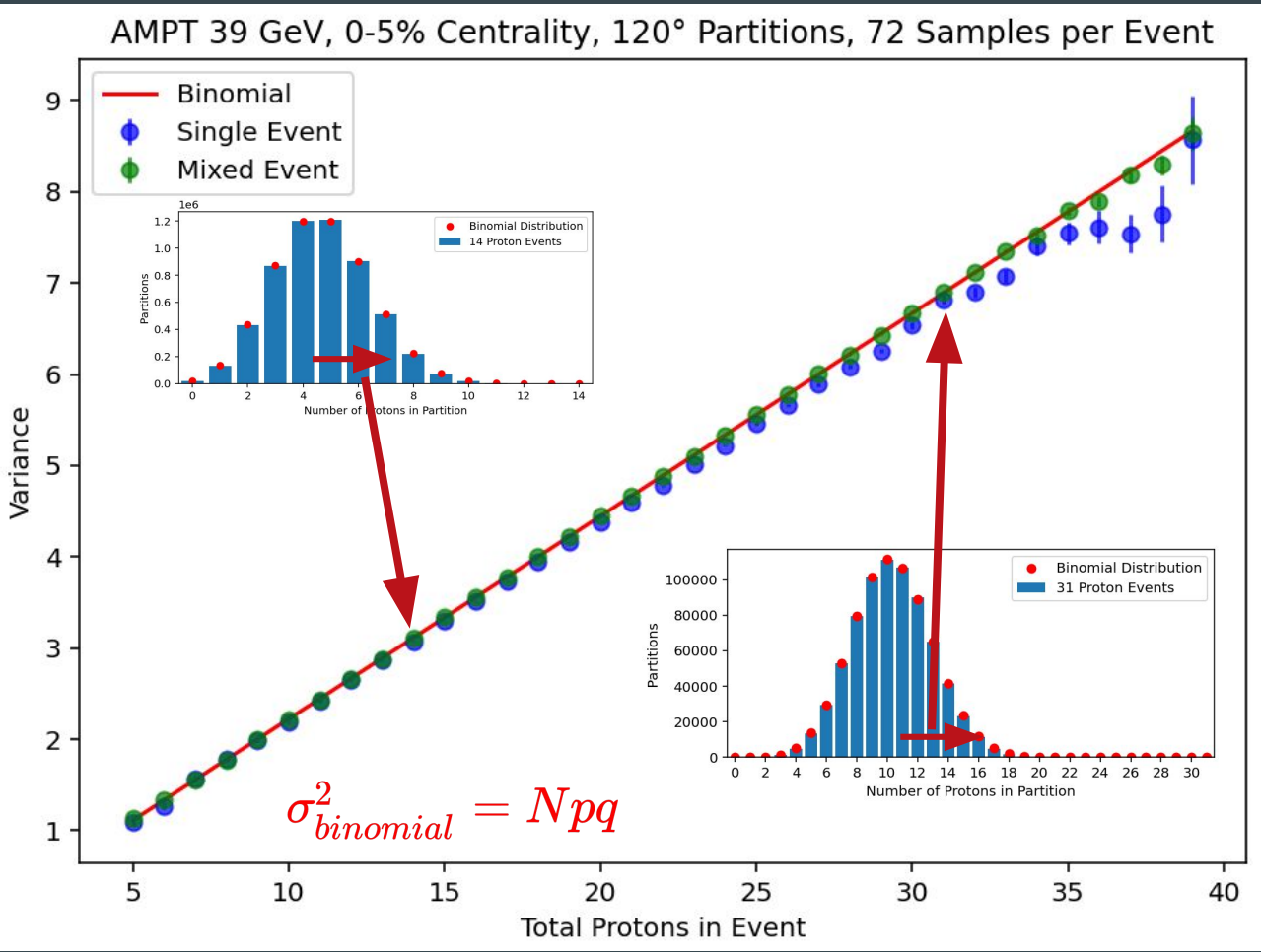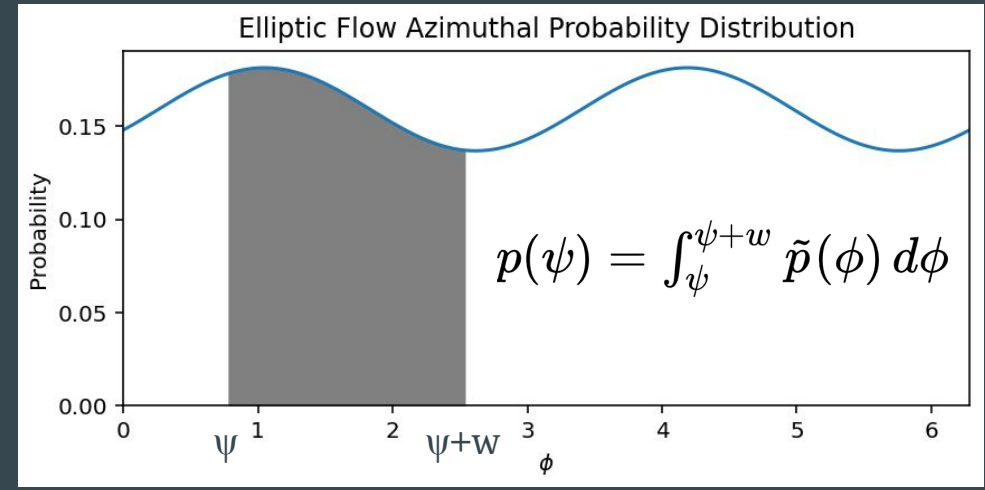
$$\sigma^2_{binomial} = Npq$$

Single and Mixed Event variances very similar to binomial, though slight deviations apparent

Elliptic Flow Azimuthal Probability Distribution

$$p(\psi) = \int_{\psi}^{\psi+w} \tilde{p}(\phi)\, d\phi$$

When tracks distributed on azimuth according to a static PDF (iid), we can calculate variance exactly

$$\sigma^2 = \sigma^2_{binomial} + N(N-1)\left[\frac{1}{2\pi}\int_0^{2\pi} p(\psi)^2\, d\psi - p^2\right]$$

Define observable as normalized deviation from binomial

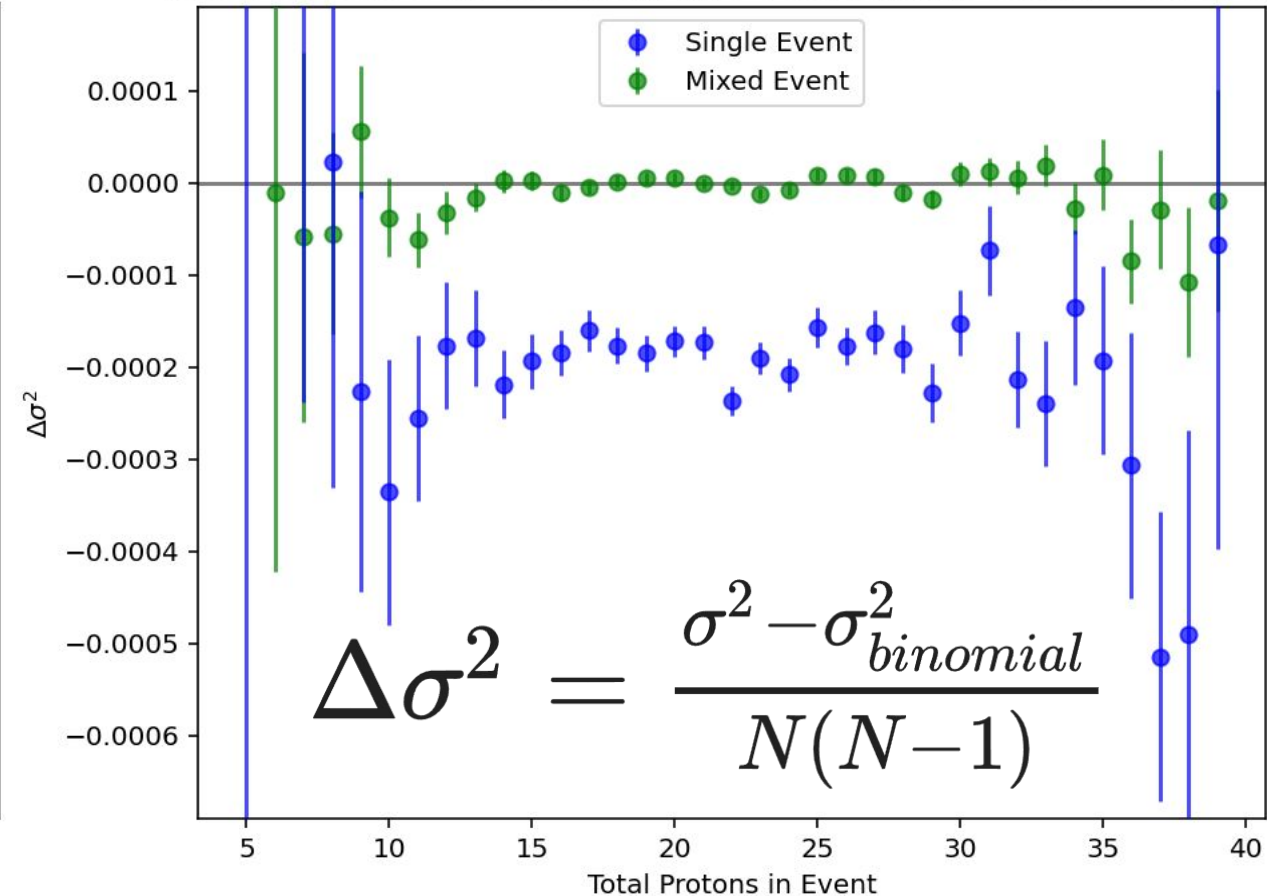$$\Delta\sigma^2 = \frac{\sigma^2 - \sigma^2_{binomial}}{N(N-1)}$$

Compare Variance to Binomial

AMPT 39 GeV, 0-5% Centrality, 120° Partitions, 72 Samples per Event

$$\sigma^2 = \sigma^2_{binomial} + N(N-1)\Delta\sigma^2$$

$$\sigma^2_{binomial} = Npq$$

AMPT 39 GeV, 0-5% Centrality, 120° Partitions, 72 Samples per Event

$$\Delta\sigma^2 = \frac{\sigma^2 - \sigma^2_{binomial}}{N(N-1)}$$
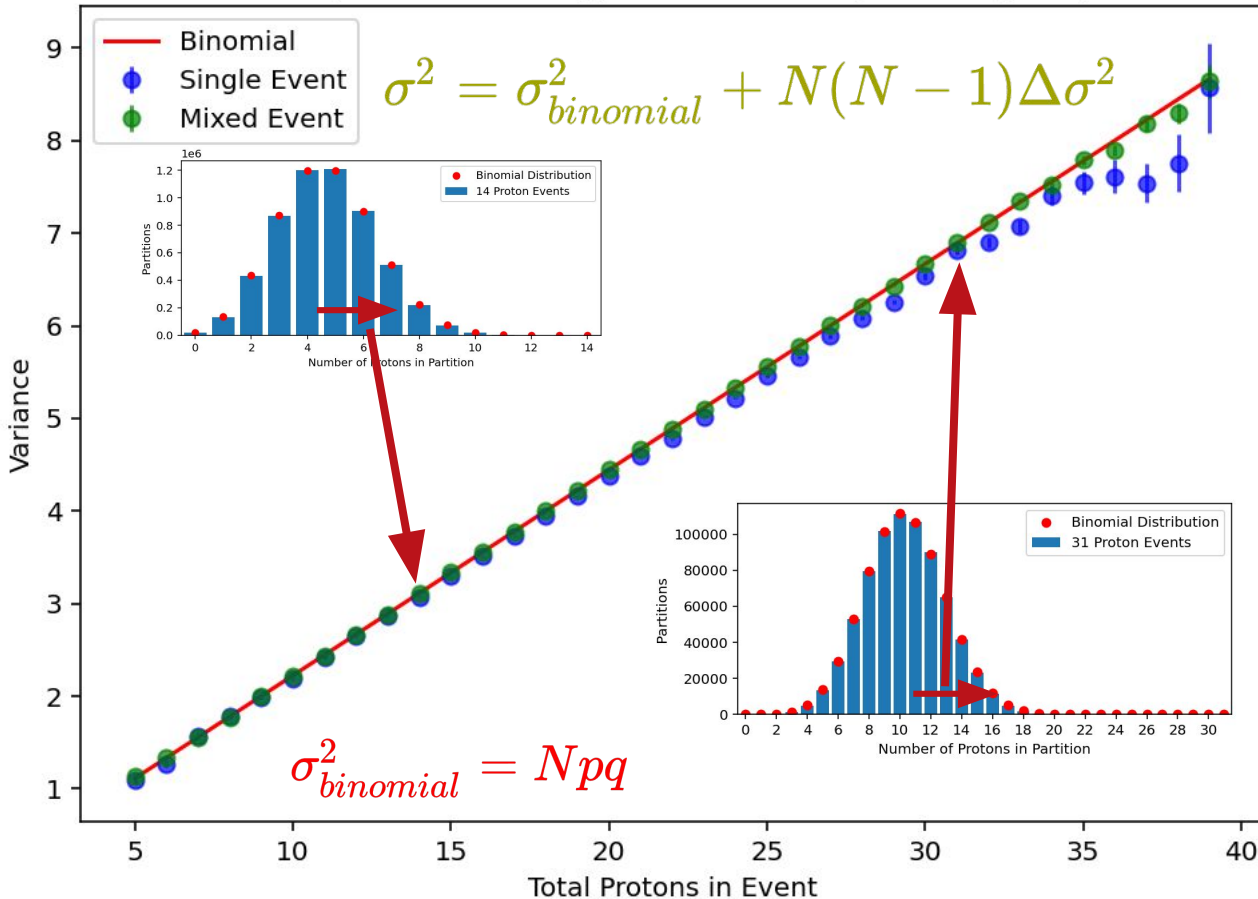
Single and Mixed Event variances very similar to binomial, though slight deviations apparent

Mixed Event variance very similar to binomial, Single Event is significantly smaller

Correct by Mixed

39 GeV, 0-5% Centrality, 120° Partitions, 72 Samples per Event
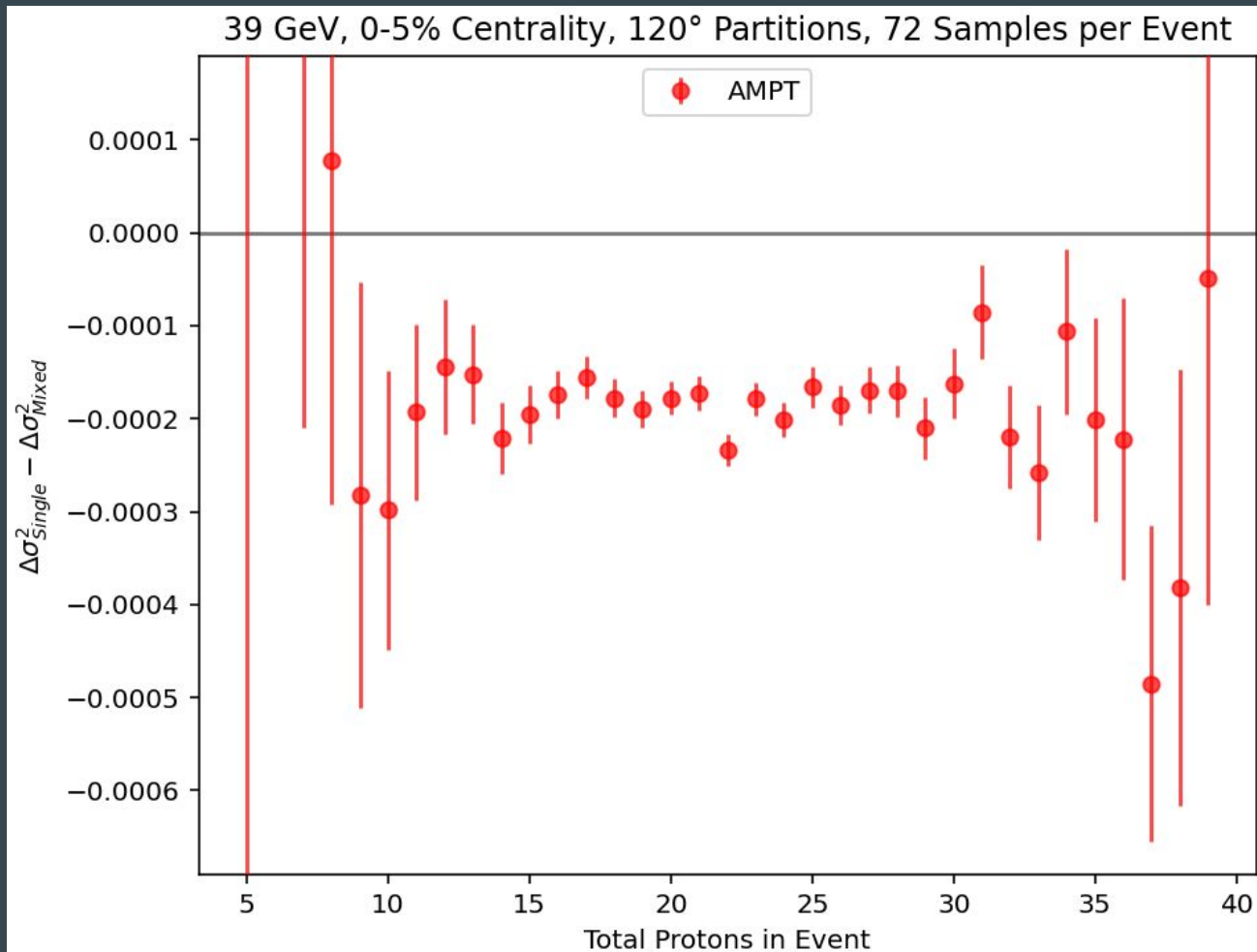
- Subtract Mixed to wash out detector effects

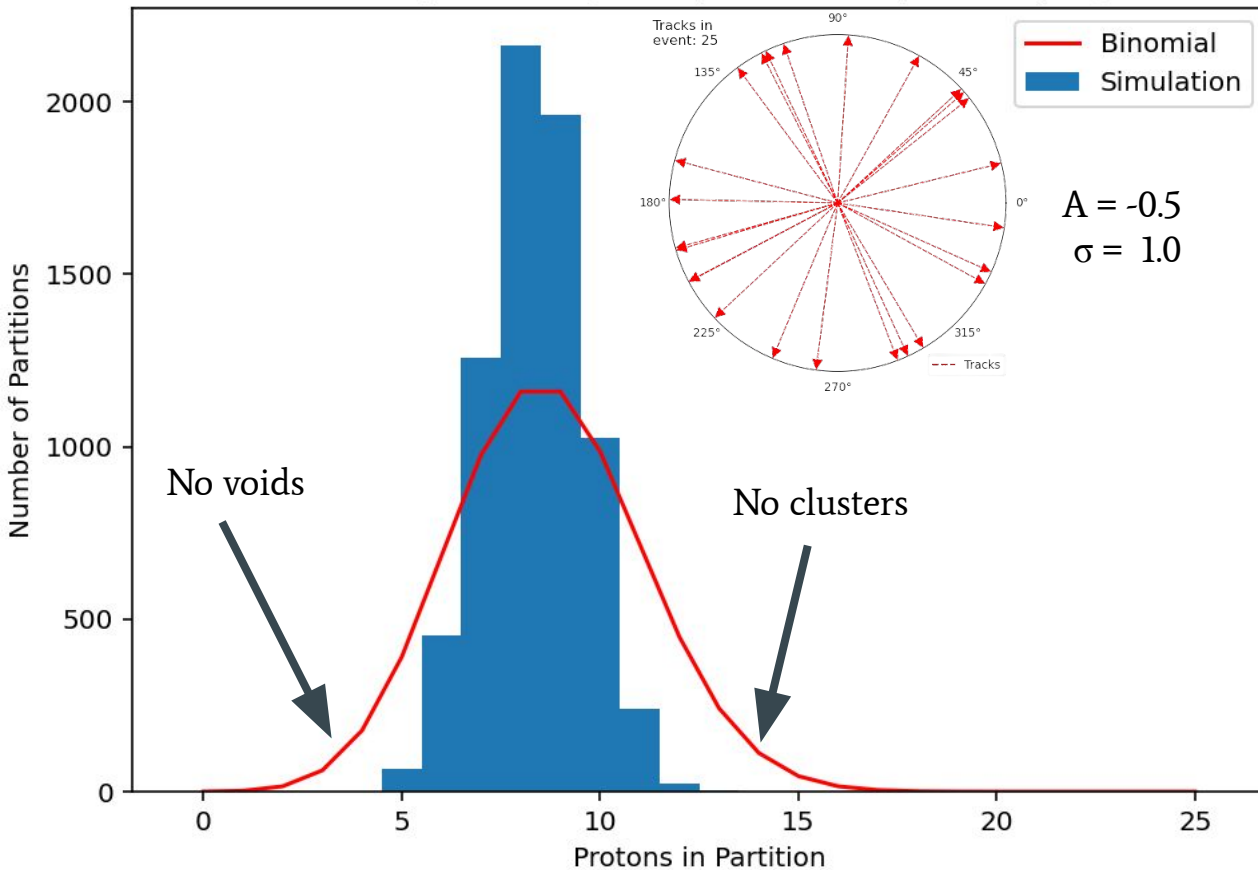- Significantly negative deviation from binomial, suggesting some type of correlation

How do we interpret the variance of these distributions?

Distribution Width Interpretation

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

Small variance → lack of clustering

Large variance → excess clustering

Azimuthal Partition Multiplicity Distribution
120° divisions, 25 tracks/event, 100 events, 72 samples/event

A = -0.5
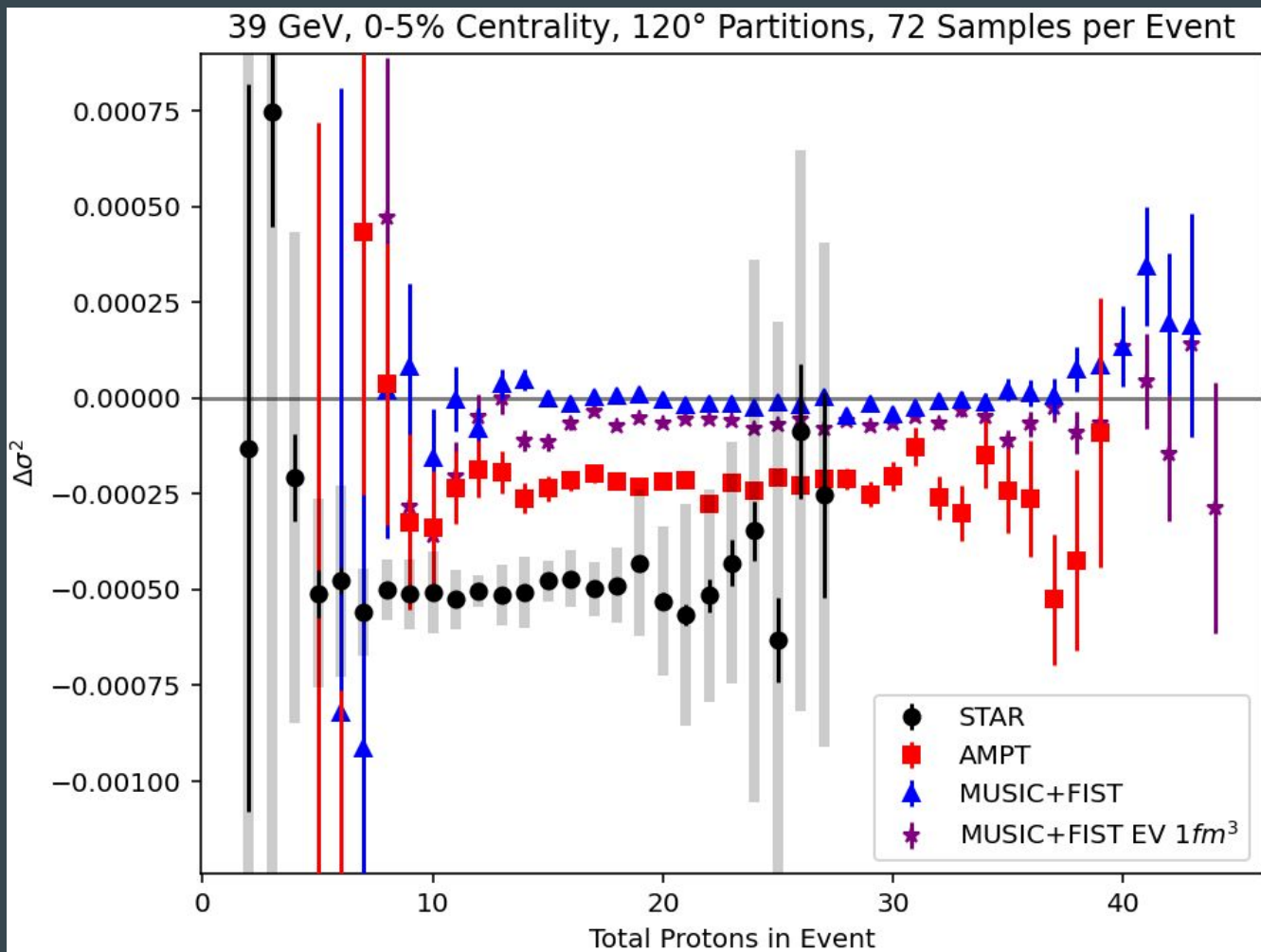σ = 1.0

No voids

No clusters

Azimuthal Partition Multiplicity Distribution
120° divisions, 25 tracks/event, 100 events, 72 samples/event

Excess voids

Excess clusters

A = +0.5
σ = 1.0
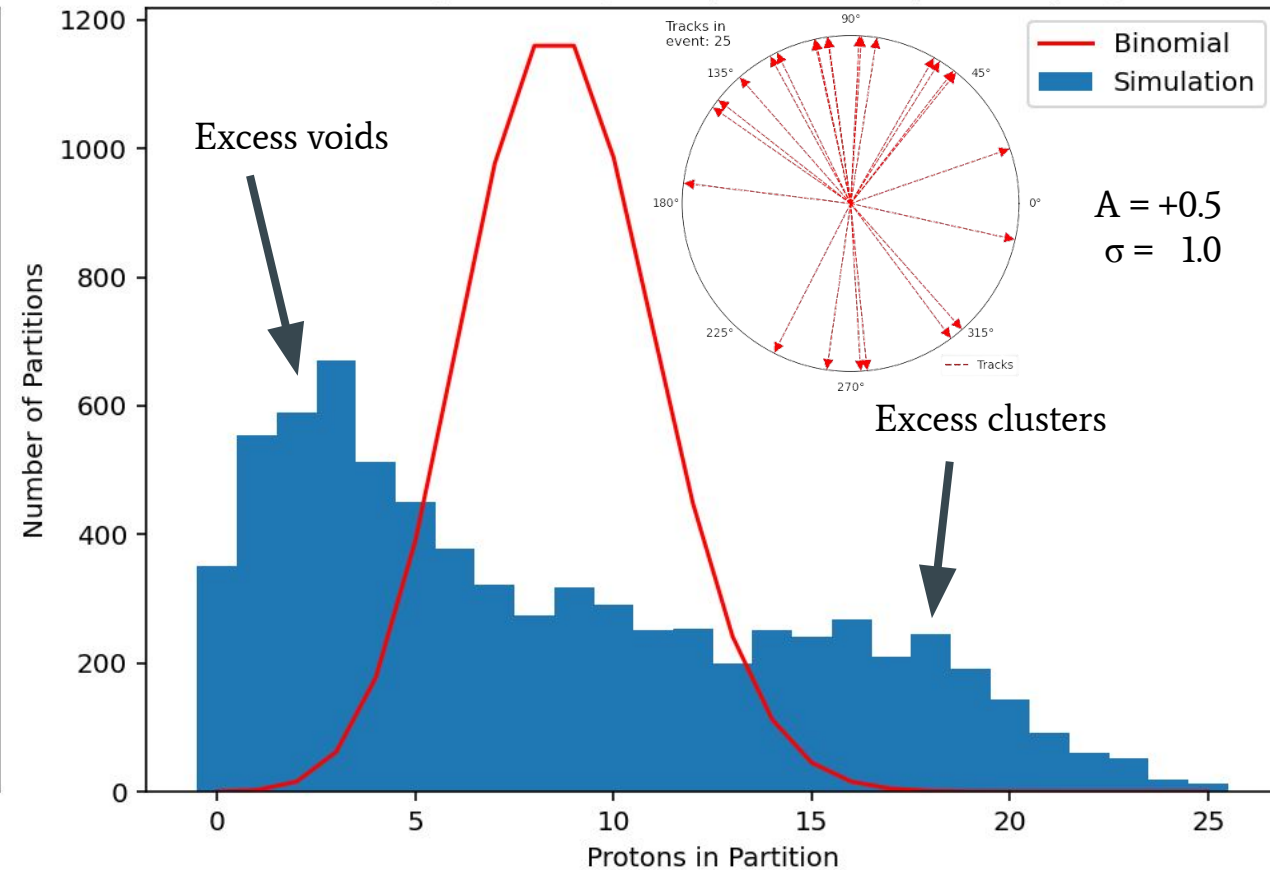
Correlation in Data

Corrected by mixed events and elliptic flow

39 GeV, 0-5% Centrality, 120° Partitions, 72 Samples per Event

- Positive   →   clustering
- Negative   →   repulsion

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

- Relatively large systematics in STAR data but still significant repulsion

MUSIC+FIST EV includes Excluded Volume effects - no two baryons coalesce within the same 1 fm volume on the freezeout hypersurface
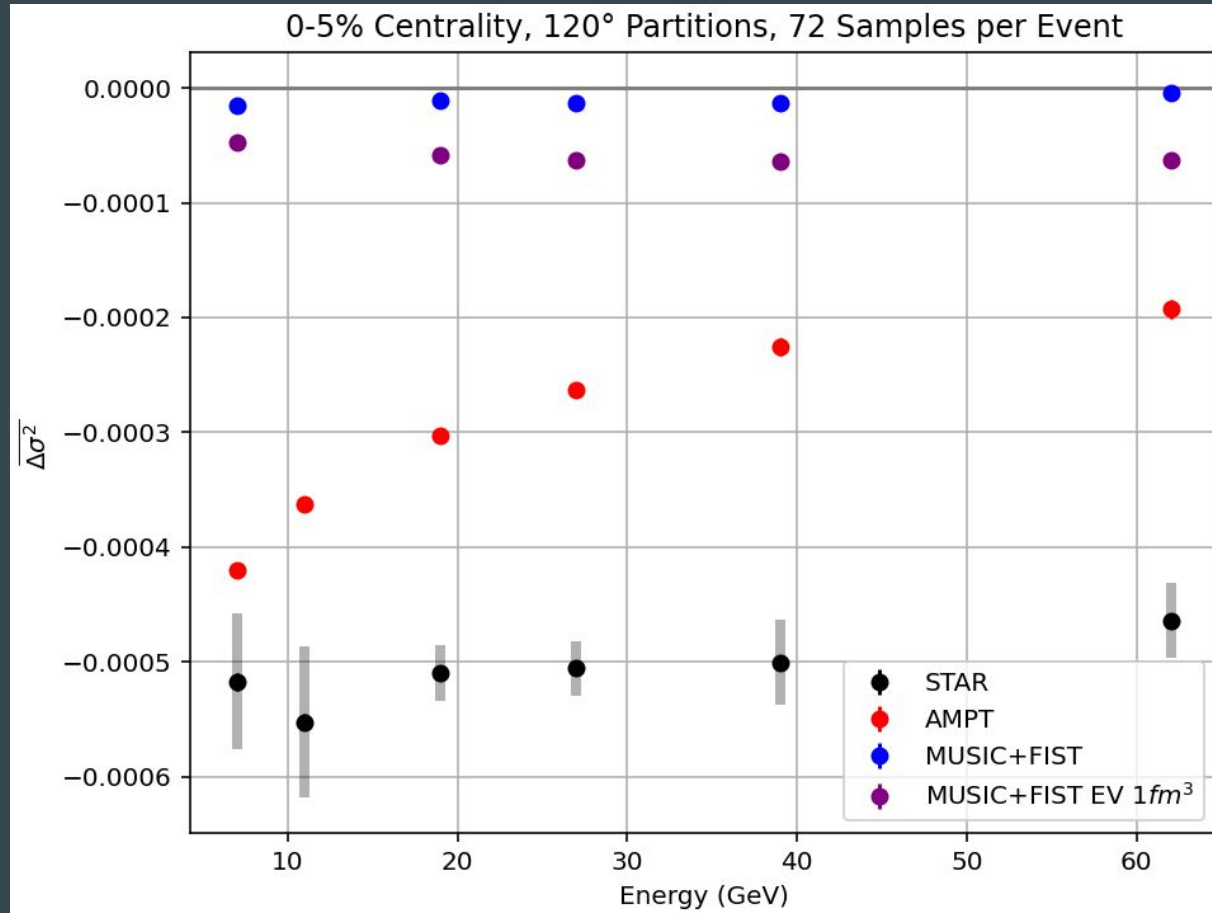
0-5% Centrality, 120° Partitions, 72 Samples per Event
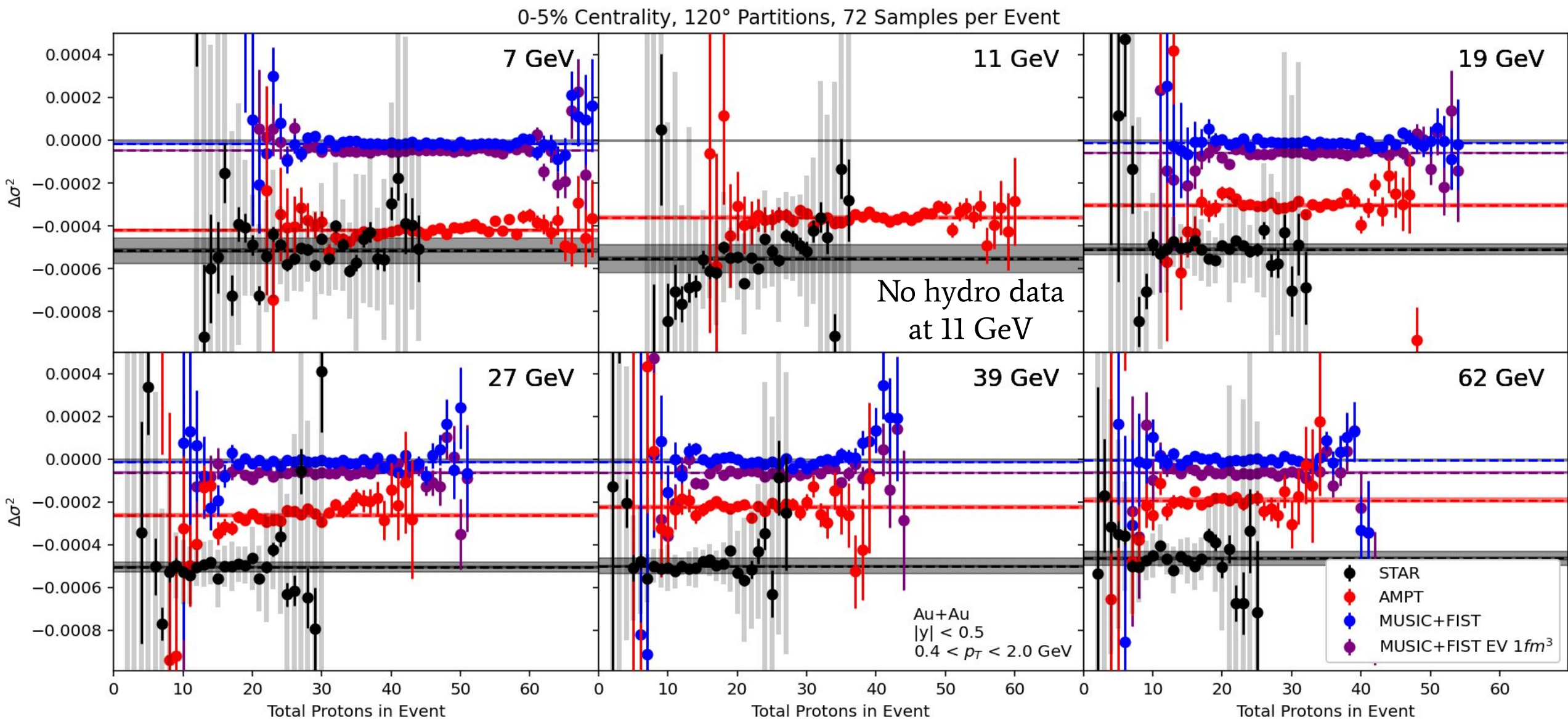
Correlation Strength vs Energy

0-5% Centrality, 120° Partitions, 72 Samples per Event
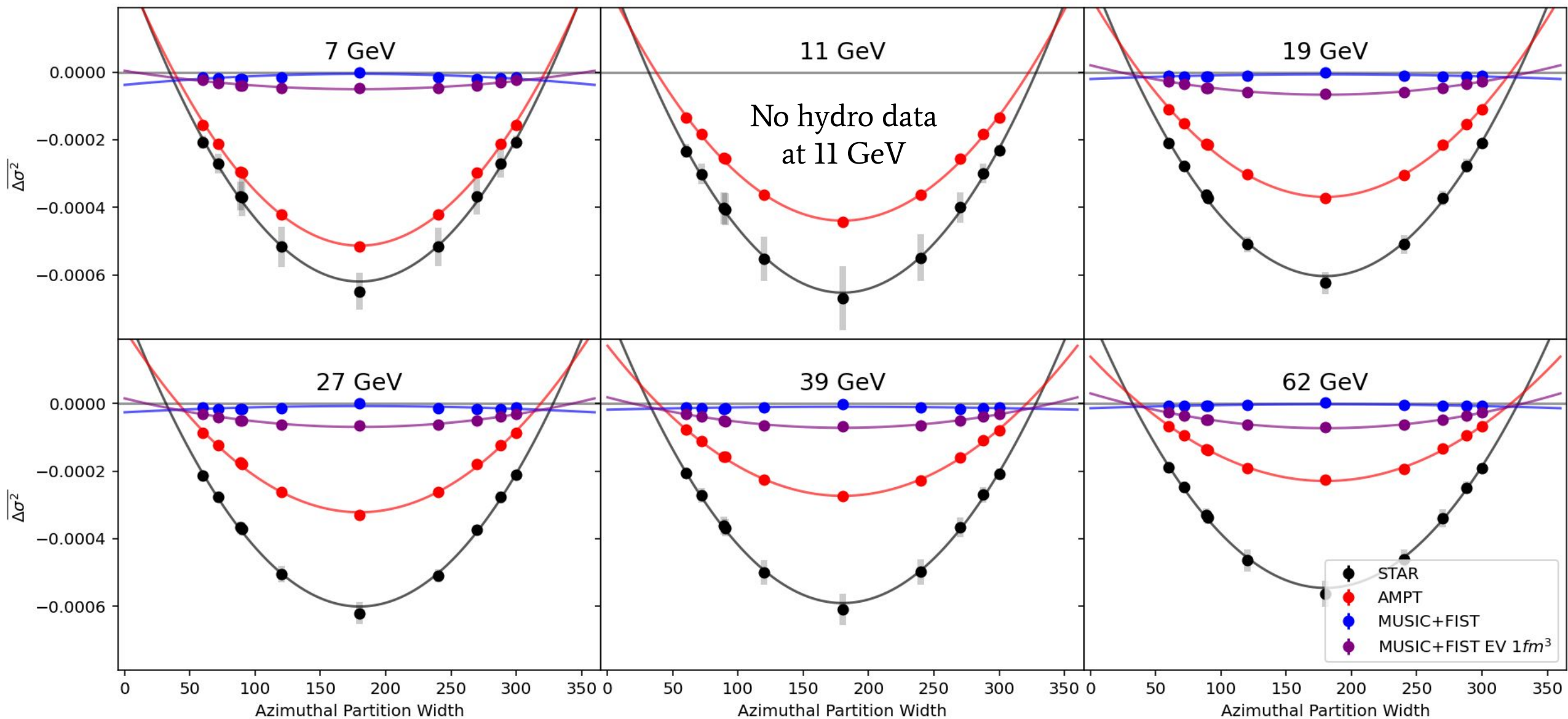
- Variance is related to strength of correlation

- All models except the original MUSIC+FIST show repulsion between proton tracks

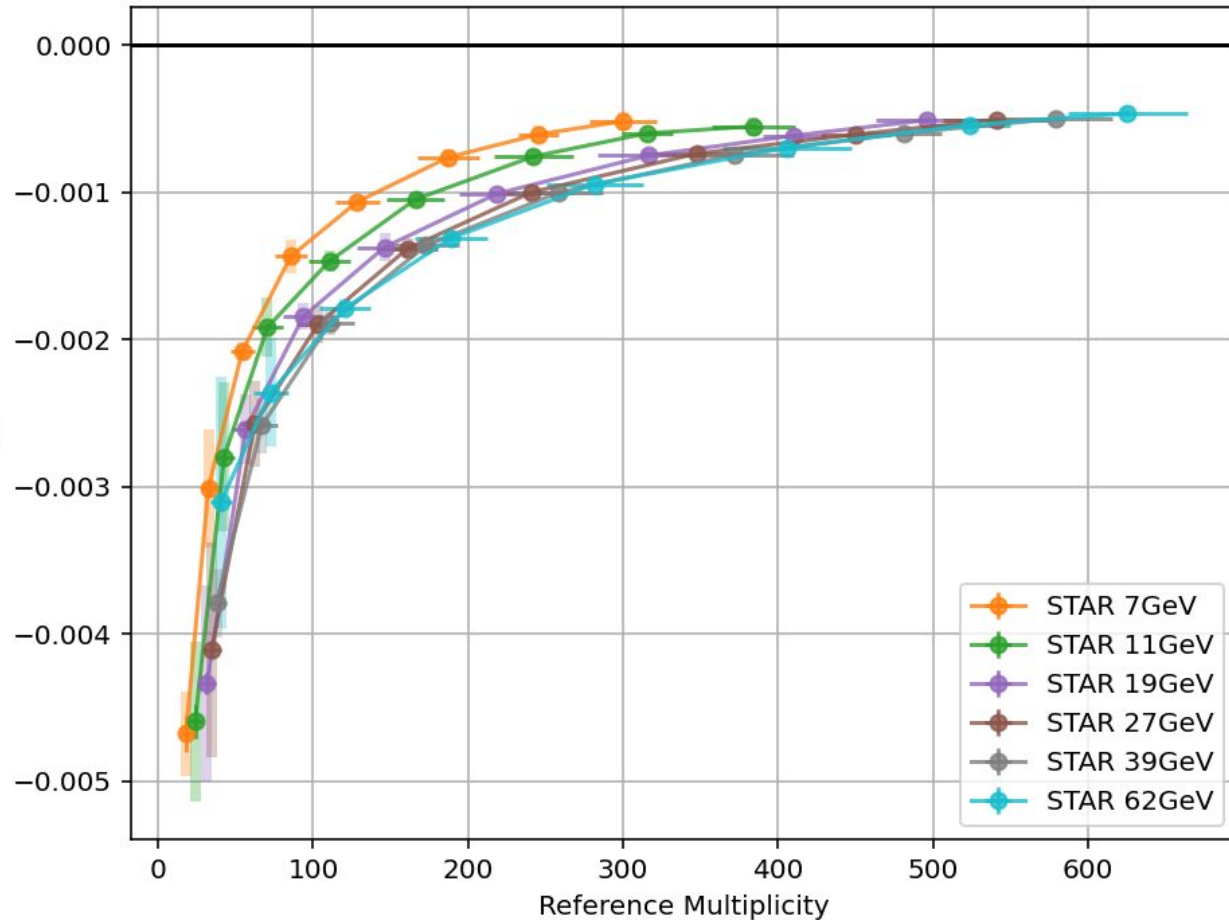- STAR correlation considerably stronger than MUSIC+FIST or AMPT

Curvature may provide information
about range of correlation

Correlation Strength vs Reference Multiplicity

120° Partitions, 72 Samples per Event

- Plotting all centralities vs their average reference multiplicity reveals a strong multiplicity dependence

- Refmult dependence relatively independent of energy
  - Possible trend toward universal curve at high energy
  - Lower energies deviate slightly from high energy curve - somewhat weaker repulsion at same refmult

- Suggests effect may be due to radial flow or momentum conservation

Summary

- New today
  - Reparameterized observable
  - Data with systematic error bars
  - Partition width dependence
  - Refmult dependence

$$\Delta\sigma^2 = \frac{\sigma^2 - \sigma^2_{binomial}}{N(N-1)}$$

- Putting together results for a paper proposal

- Can present in future if interested
  - Mixed and elliptic flow corrections
 - Systematic checks

Thanks for your attention!

Backup

Stochastic Partitions

- With evenly spaced partitions, the distribution tends to oscillate at high number of samples

- With stochastic partitions, the distribution doesn't converge quite as nicely
  - This is also partially due to the way the plot on the right is generated. Entirely new random partitions each time
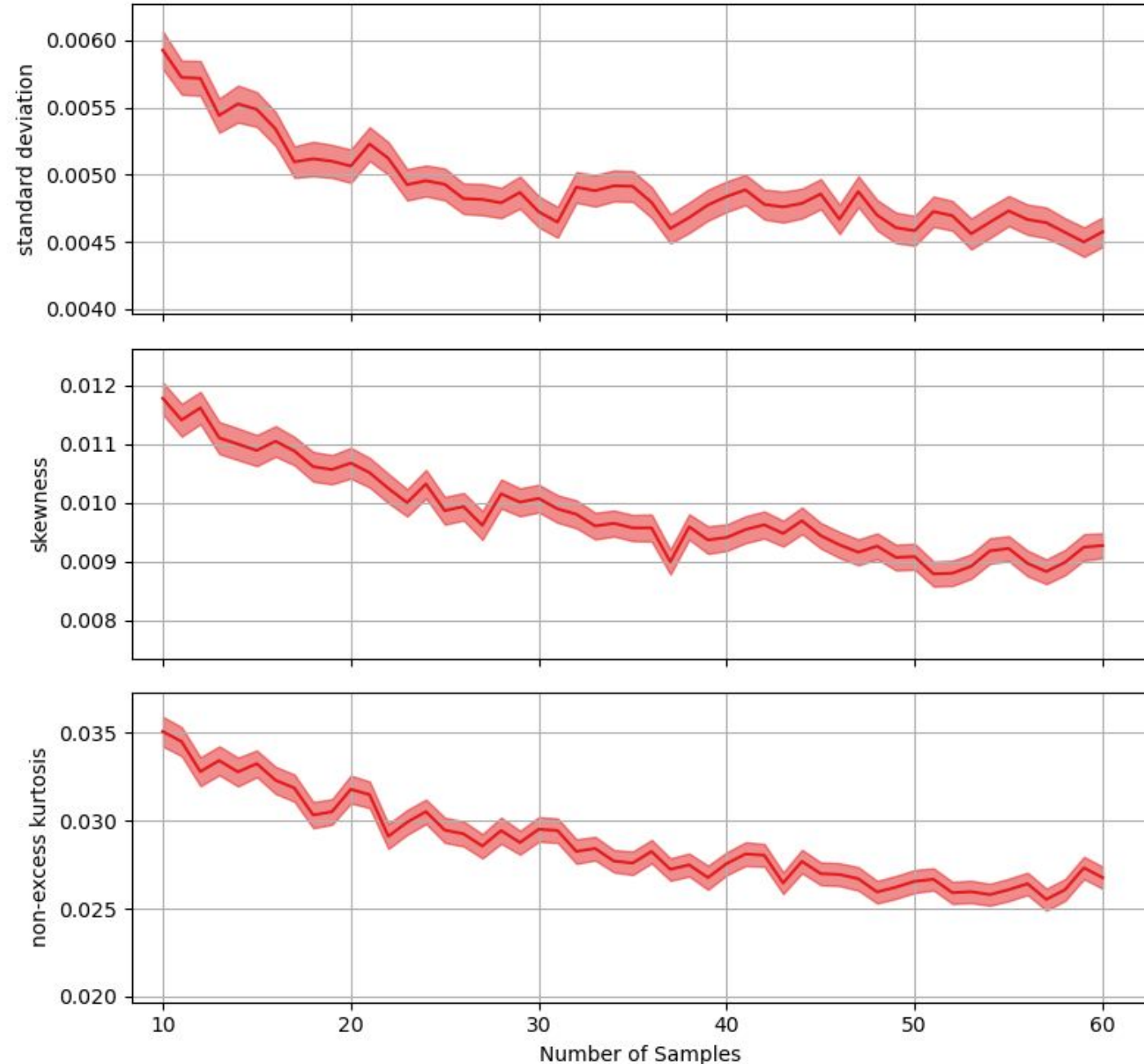
Evenly Spaced Partitions
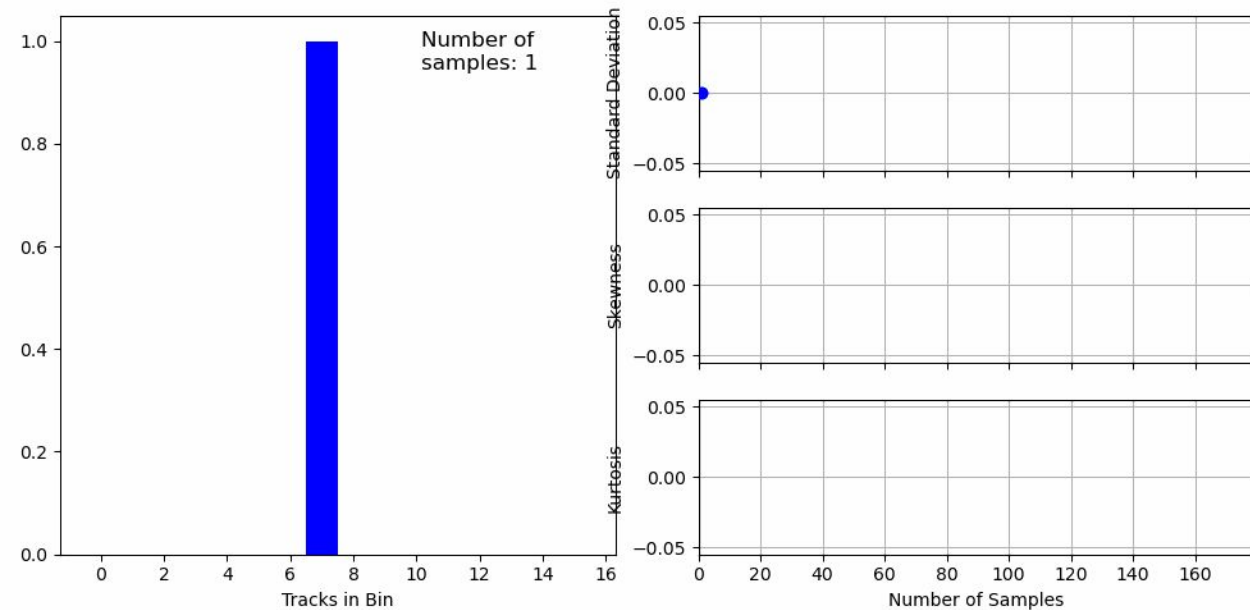
Stochastically Spaced Partitions

Dylan Neff
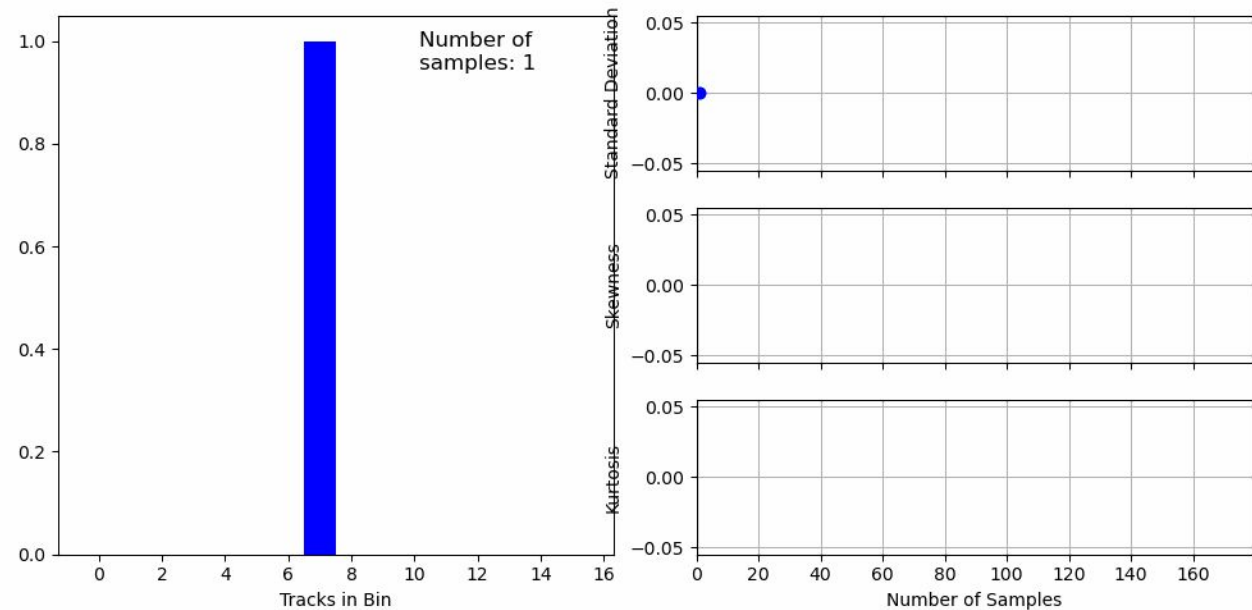
Optimal Samples

- Need to optimize the number of samples per event
  - More samples → more accurate moments
  - More samples → slower analysis

- Decided on 72 samples per event
  - 5° spacing on average

Stats Deviations vs Number of Samples
15 tracks, 60° width, 4000 events, 4 algorithm

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 $P(\phi)$ for all subsequent tracks

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

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

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

baseline

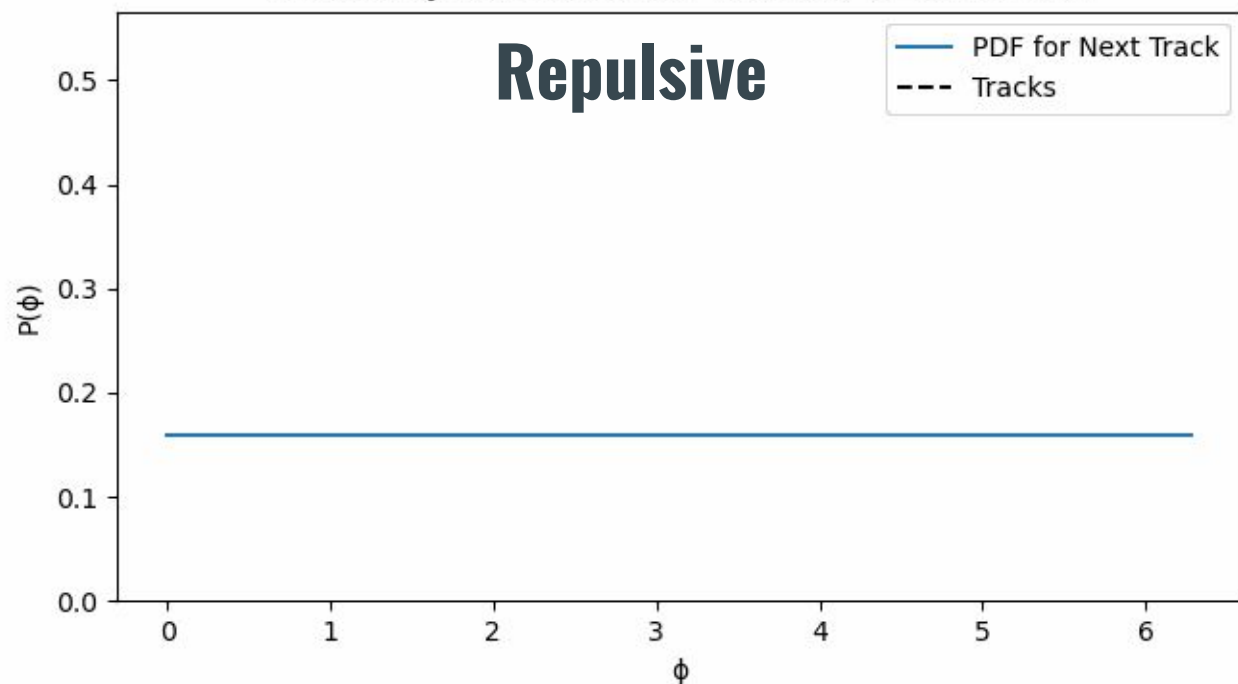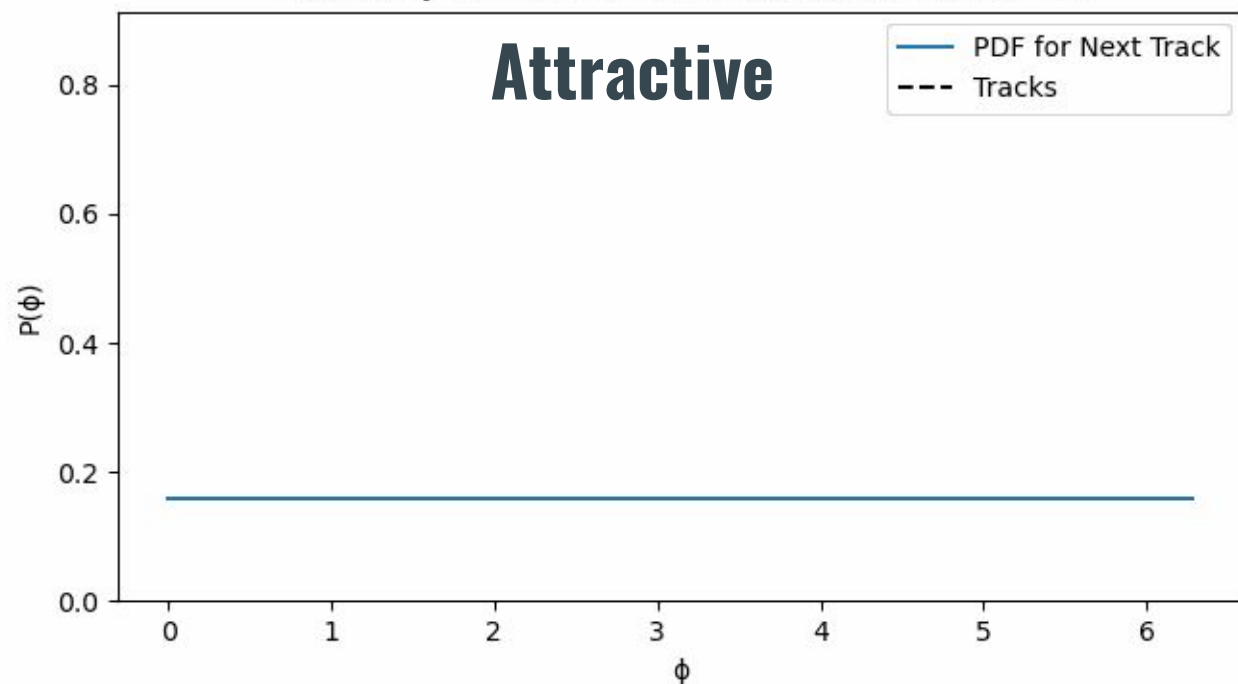Attractive
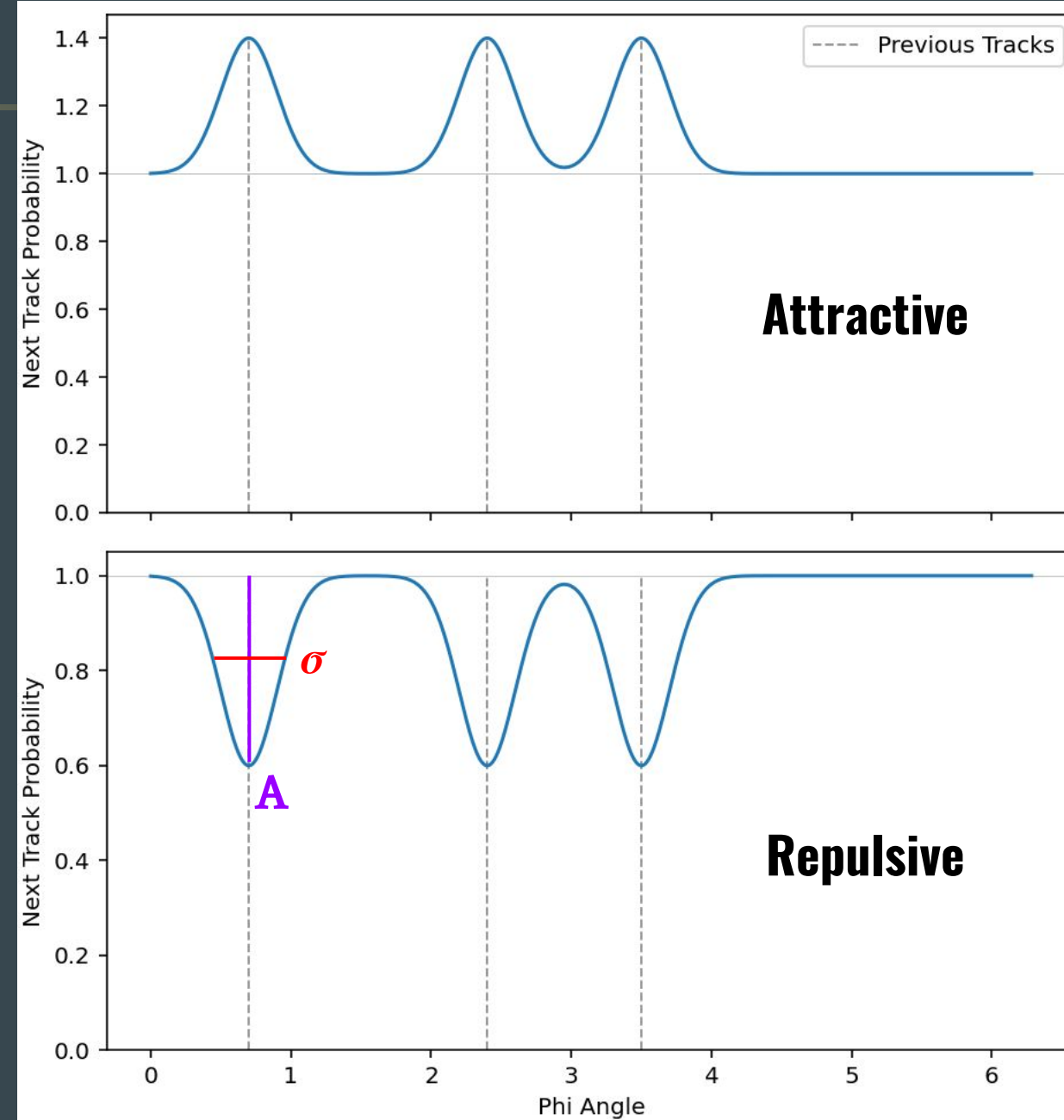
Repulsive

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

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

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

Systematic Cuts

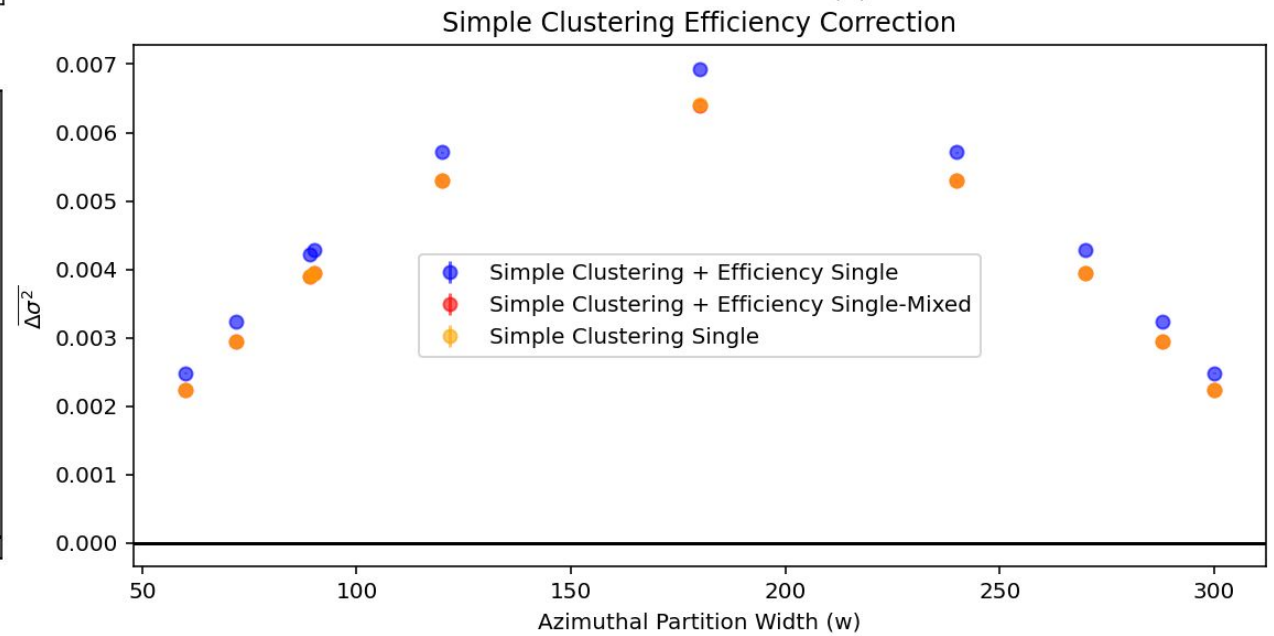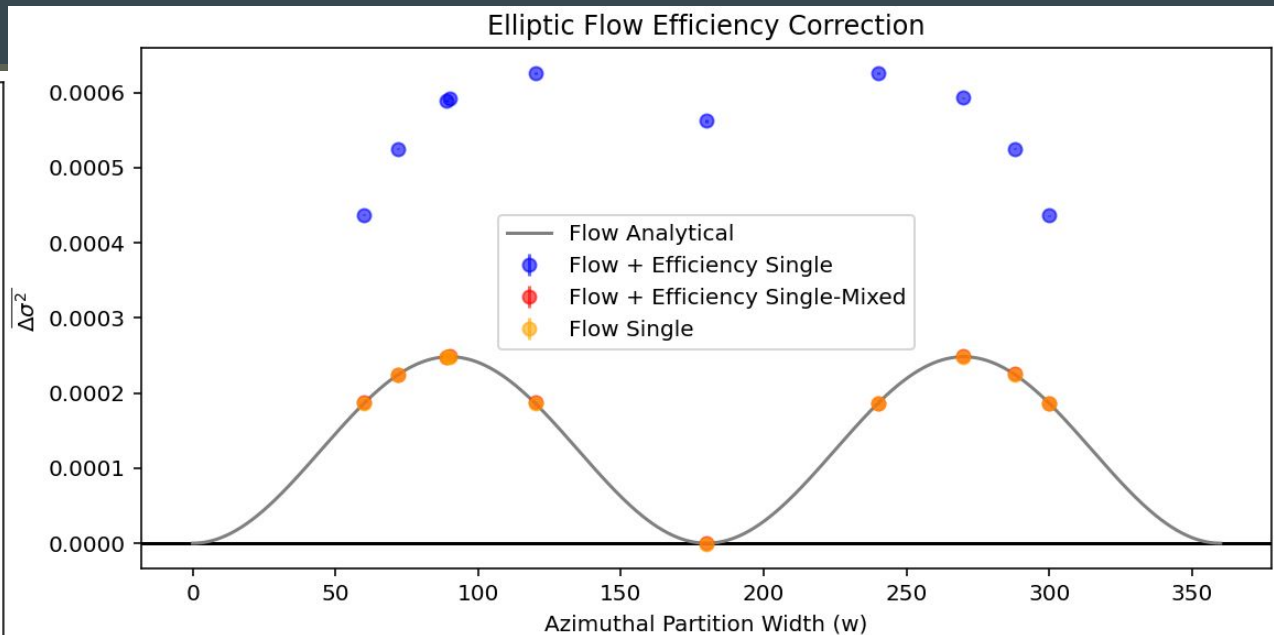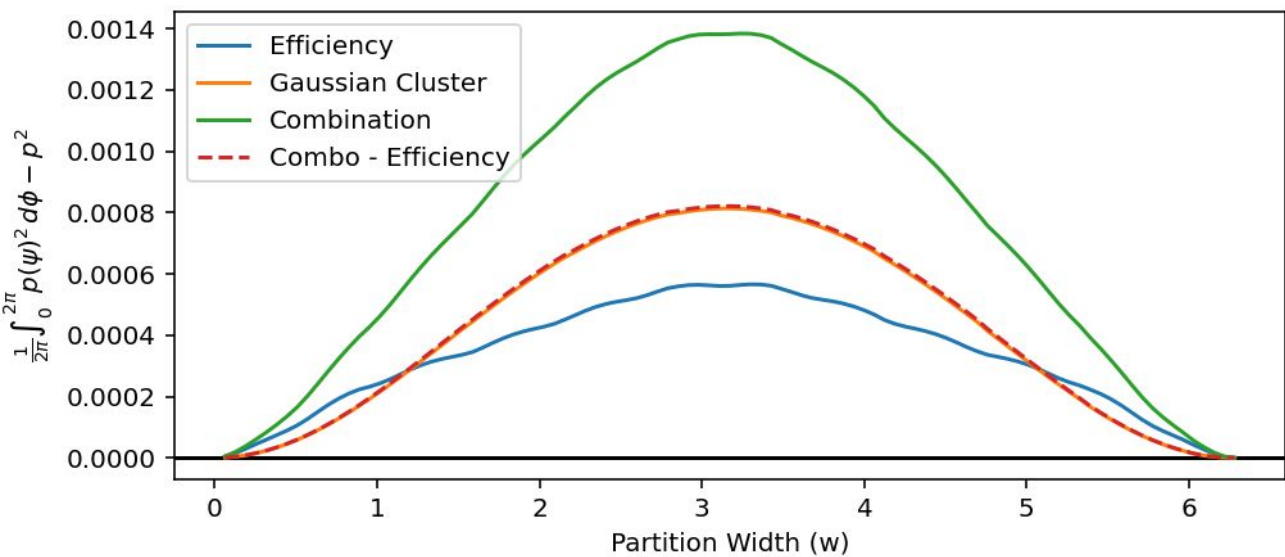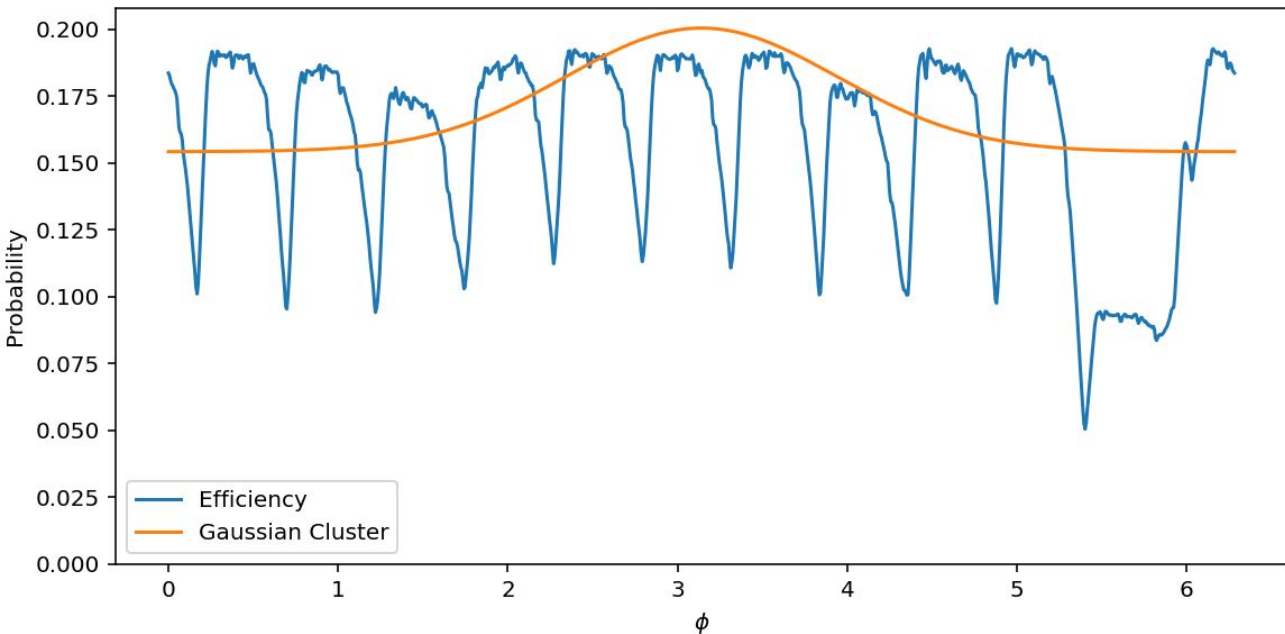| |
|---|
| $DCA_{max} \in (0.8, 1.2)$ |
| $|n\sigma_{proton}|_{max} \in (1.8, 2.2)$ (0.9, 1.1) for 27GeV |
| $m^2_{range} \in (0.2, 0.6)$ centered on 0.9 |
| nHitsFit $\in [15, 25]$ |

Centrality Definition: refmult3
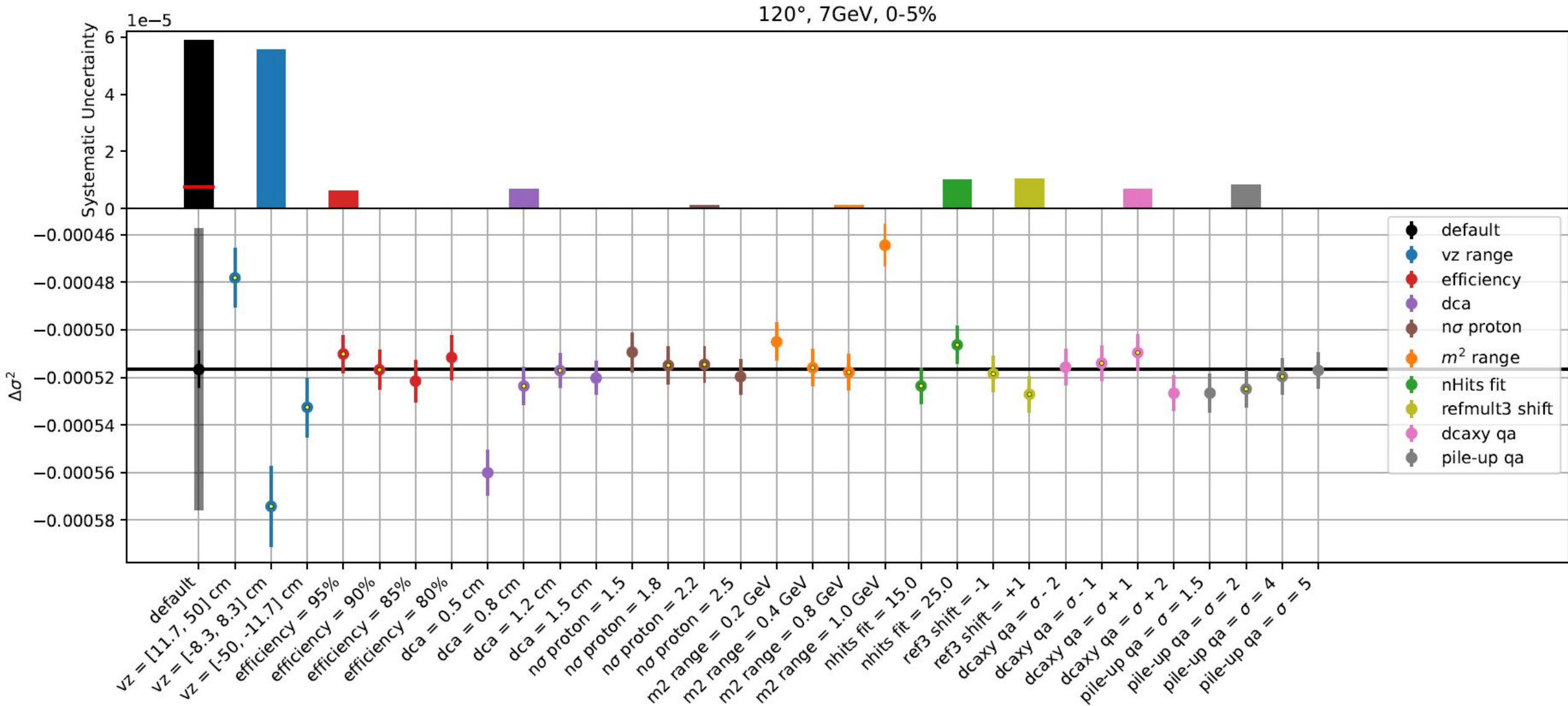
Charged particles within $|\eta| < 1$ excluding protons

Corrections Implemented:

- Pile-up Rejection
- Dca-xy Bad Events Cut
- Bad Runs Removed

Corrections Not Implemented:

- Efficiency Correction
- Centrality Bin Width Correction

Correct for Elliptic Flow

Dylan Neff

Mixed Event Correction

Dylan Neff

120°, 7GeV, 0-5%

120°, 7GeV, 0-5%