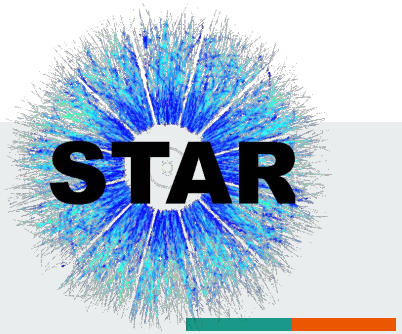


Supported in part by
U.S. DEPARTMENT OF ENERGY
Office of Science

Probing the QCD Phase Diagram at STAR

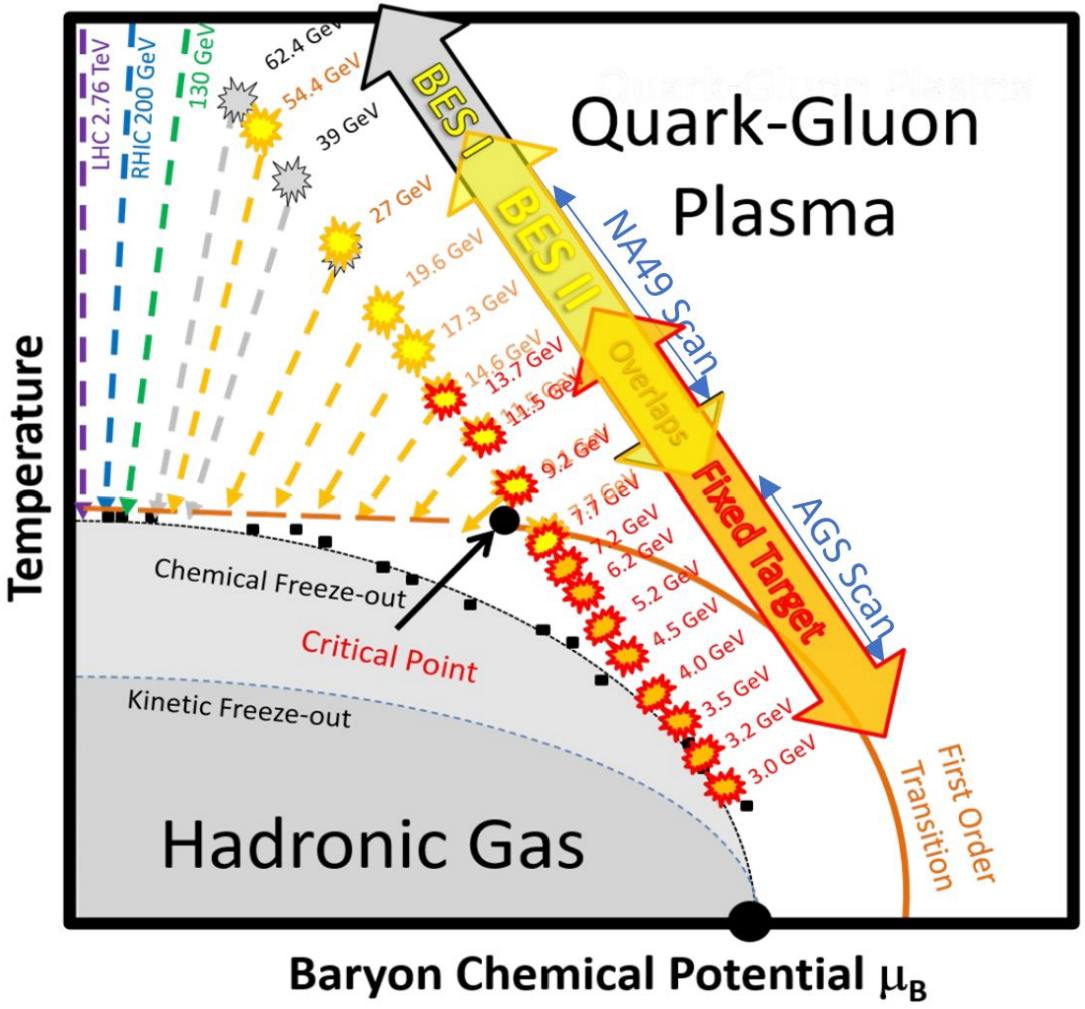
Dylan Neff (for the STAR Collaboration)
UCLA

Outline

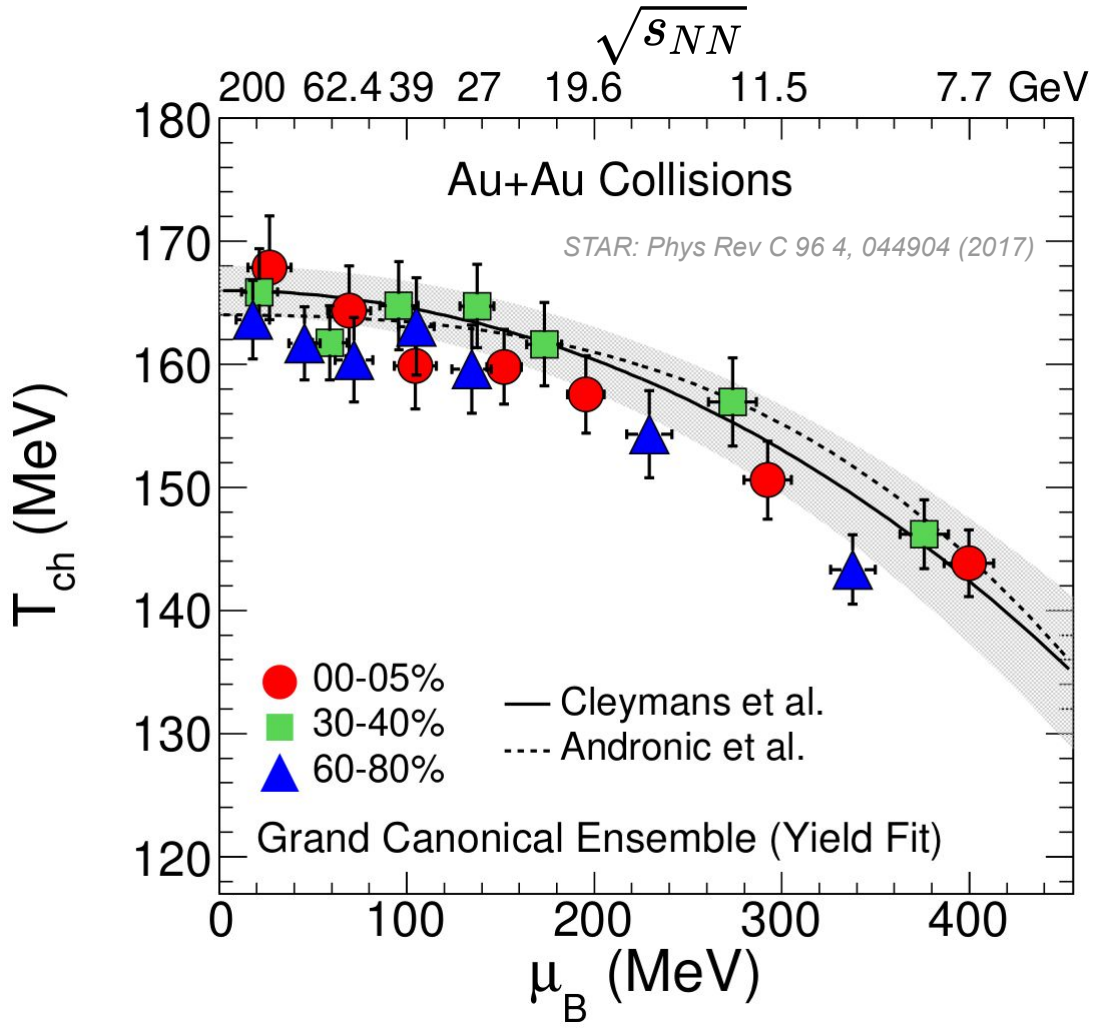
- ❑ Motivation
- ❑ Experiment
- ❑ Measurements
  - ○ Higher-Order Cumulants
  - ○ Azimuthal Partitions
- ❑ Summary

QCD Phase Diagram

Goal: Map out the QCD phase diagram with the Beam Energy Scan program

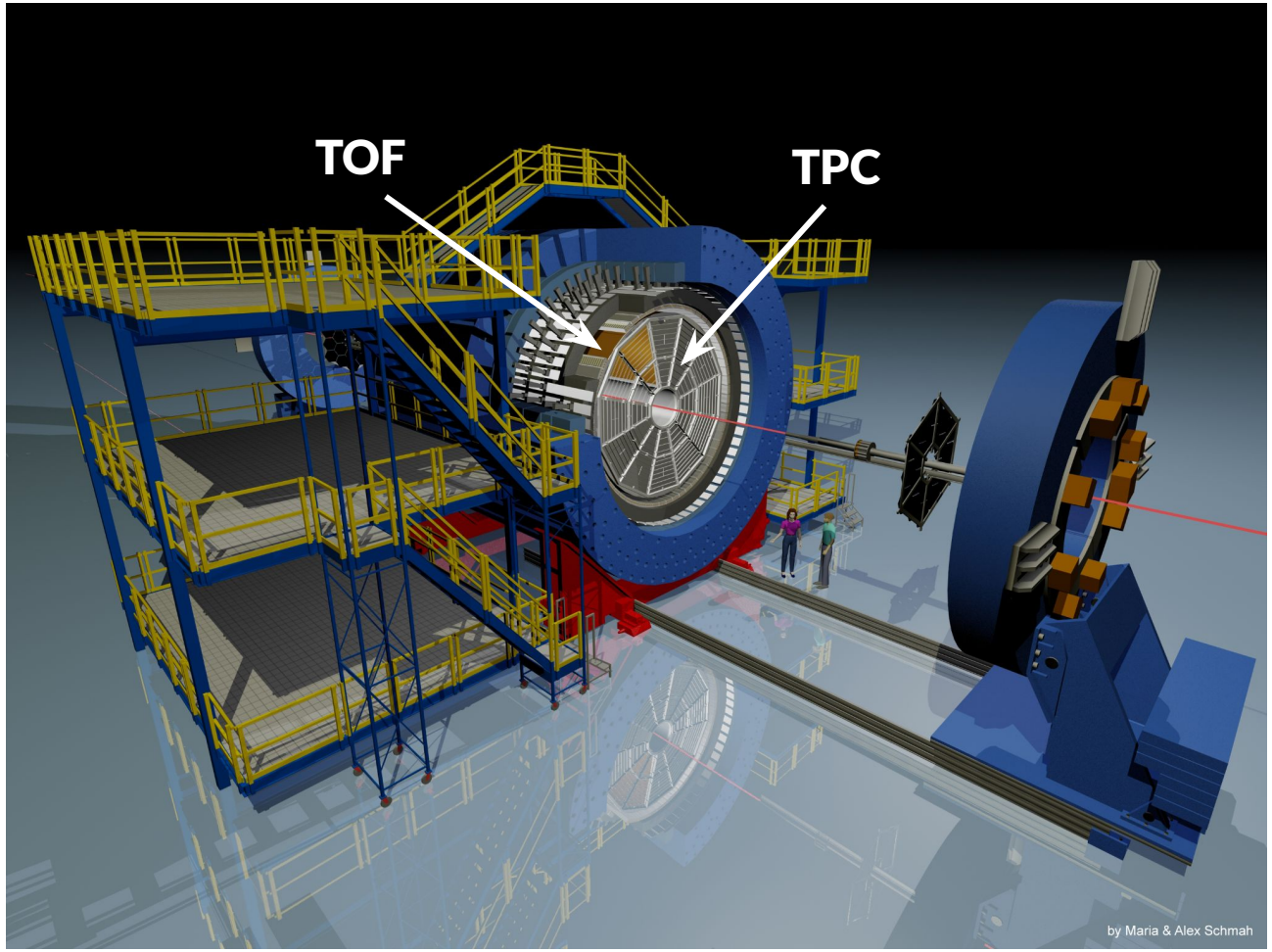


Vary beam energy to scan QCD phase space

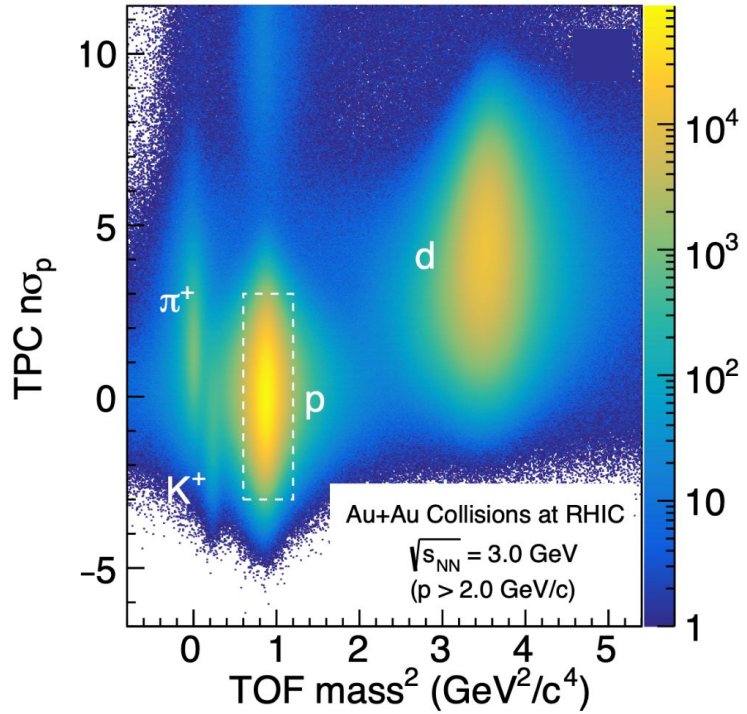


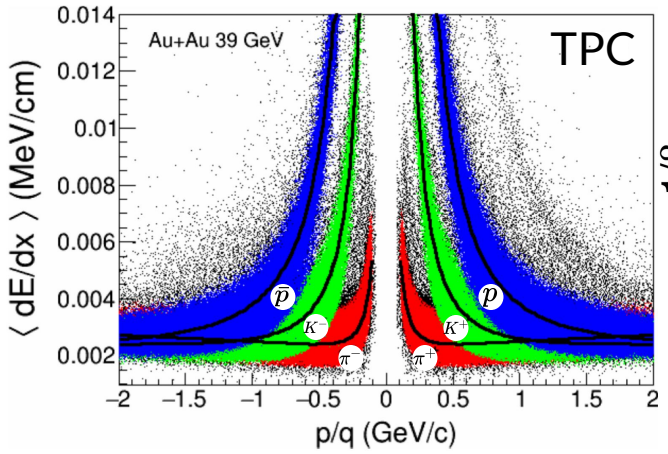
STAR Detector

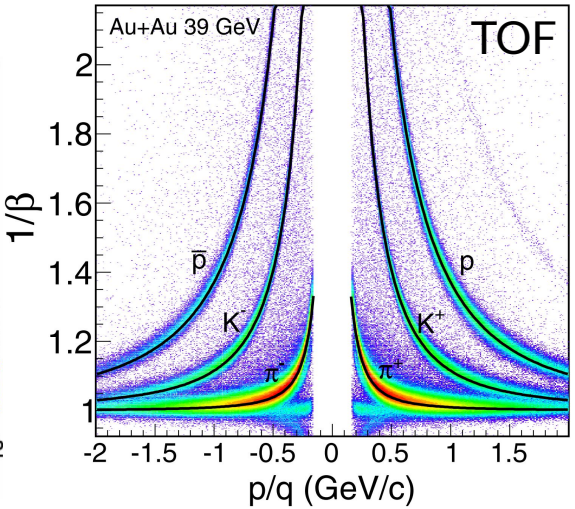
Identify (anti)protons with TPC and TOF in BES-I data



STAR: Phys Rev Lett 130, 082301 (2023)







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

Observables - Cumulants

N: Net-proton multiplicity

C_n: n^{th} order cumulant

$\delta N = N - \langle N \rangle$

$$C_1 = \langle N \rangle$$
$$C_2 = \langle (\delta N)^2 \rangle$$
$$C_3 = \langle (\delta N)^3 \rangle$$

$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$$
$$C_5 = \langle (\delta N)^5 \rangle - 10\langle (\delta N)^3 \rangle \langle (\delta N)^2 \rangle$$
$$C_6 = \langle (\delta N)^6 \rangle - 15\langle (\delta N)^4 \rangle \langle (\delta N)^2 \rangle - 10\langle (\delta N)^3 \rangle^2 + 30\langle (\delta N)^2 \rangle^3$$

Stephanov, Phys Rev Lett 107, 052301 (2011)

Higher-order cumulants are more sensitive to the correlation length

Cumulants ratios cancel trivial volume dependence

$$\frac{C_5}{C_1} = \frac{\chi_5}{\chi_1}$$
$$\frac{C_6}{C_2} = \frac{\chi_6}{\chi_2}$$

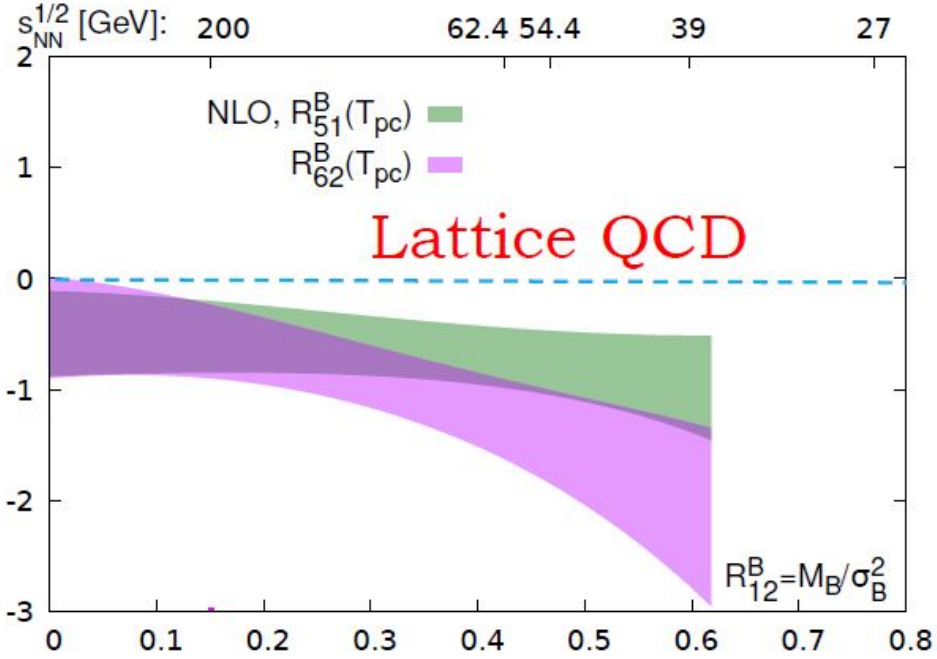
χ_n: n^{th} order cumulant

- Cumulant ratios are directly related to susceptibilities from theory
- Sensitive probes for the nature of the QCD phase transition

Predicted Features of Crossover

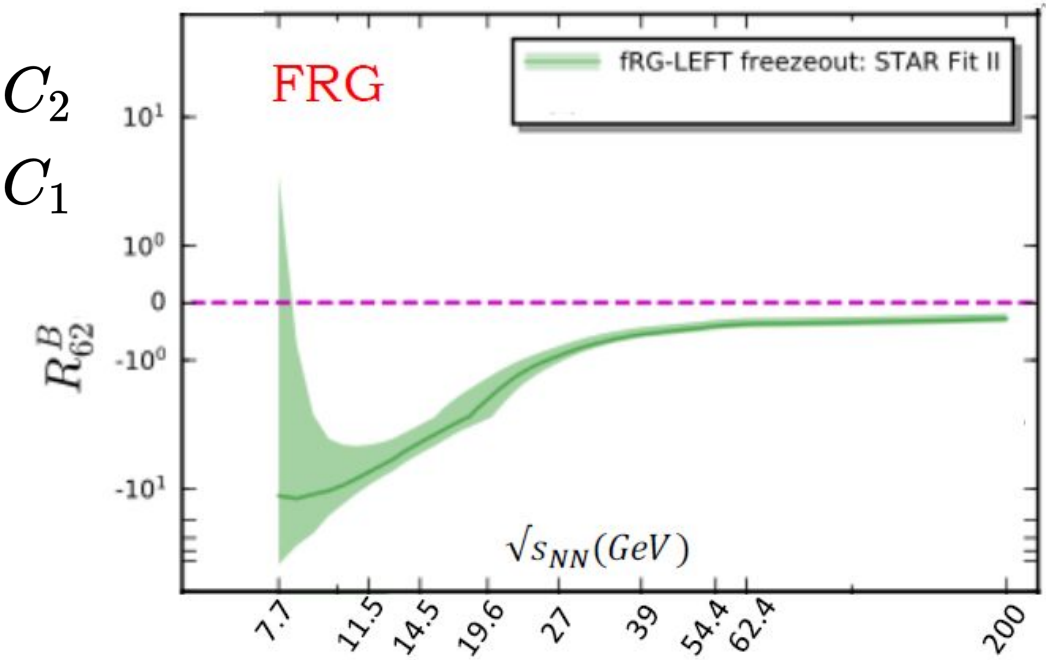
C_5 and C_6

- **Negative** for LQCD, FRG (Functional Renormalization Group) – crossover
- **Positive** for HRG (GCE) and UrQMD (no QCD transition)



HotQCD, Phys Rev D 101,074502 (2020)

$$R_{62} = C_6/C_2$$
$$R_{51} = C_5/C_1$$



Wei-jie Fu et. al, Phys Rev D 104, 094047 (2021)

Ordering of ratios (Net-baryon): $\frac{C_3}{C_1} > \frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2}$ - LQCD, FRG

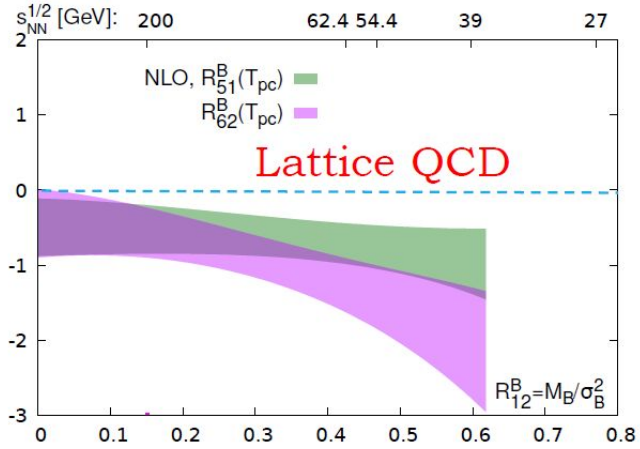
Hyper-Order Cumulant Ratios

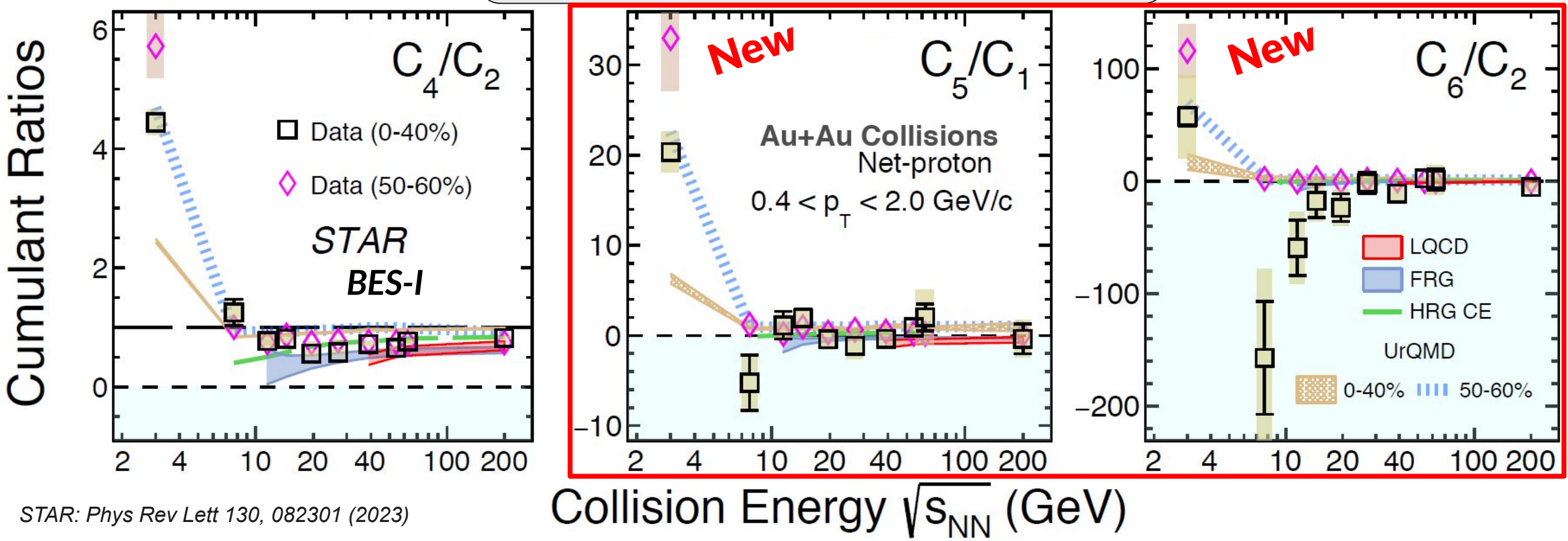
C_4/C_2 → Positive at 0-40%

C_5/C_1 → Weak trend with energy

C_6/C_2

- **Increasingly negative** with decreasing energy
  - ➪ Qualitatively matches trend of lattice calculations
- $\sqrt{s_{NN}}$ = 3 GeV positive and consistent with UrQMD

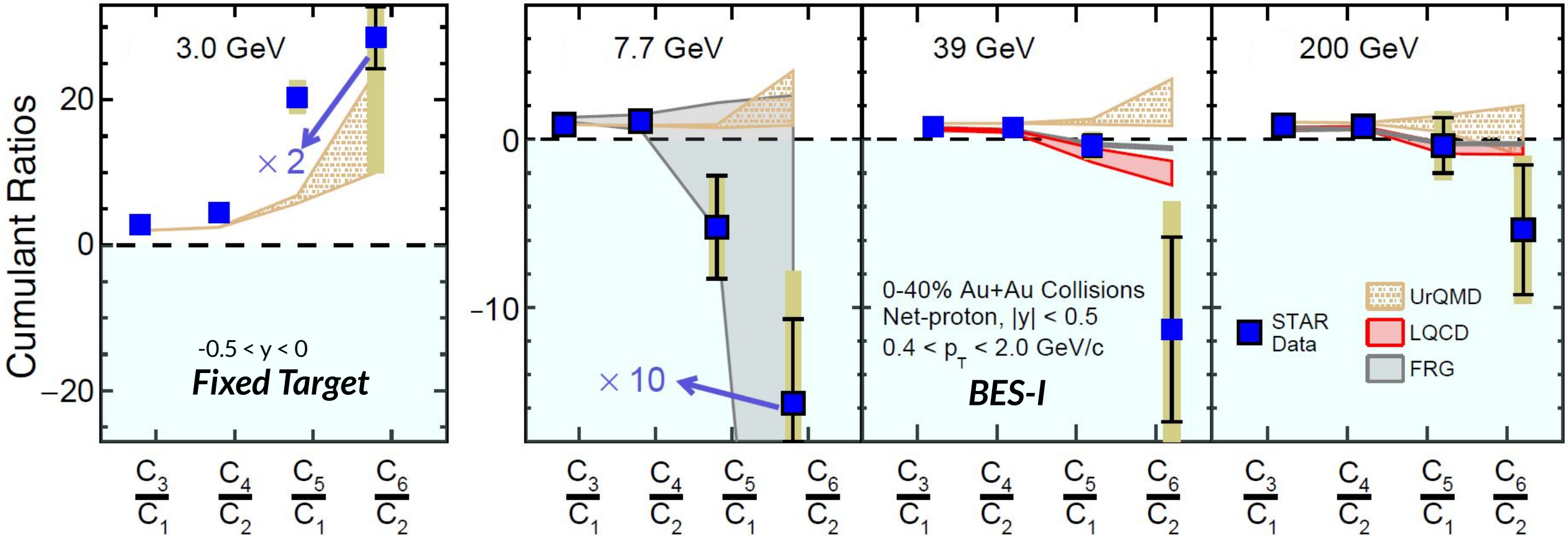




STAR: Phys Rev Lett 130, 082301 (2023)

Cumulant Ratio Ordering

Ordering of ratios (Net-baryon): $\frac{C_3}{C_1} > \frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2}$ - LQCD, FRG



- Violation of ordering found at fixed target $\sqrt{s_{NN}}$ = 3 GeV
  - Trend reproduced by UrQMD
  - Suggests hadronic matter
- Data trends appear consistent with predicted hierarchy between $\sqrt{s_{NN}}$ = 7.7 and 200 GeV

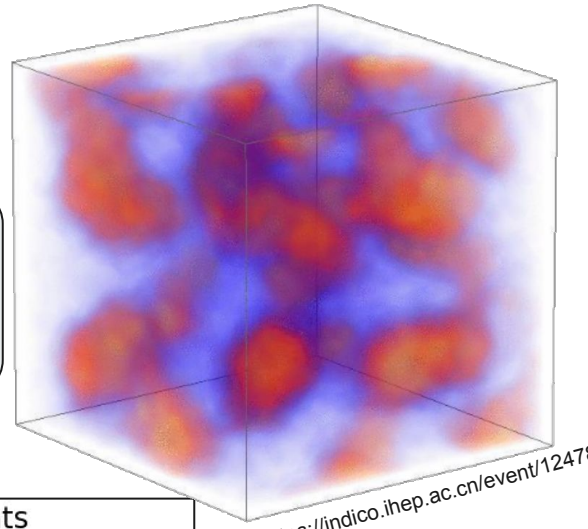
STAR: Phys Rev Lett 130, 082301 (2023)

Azimuthal Partitioning

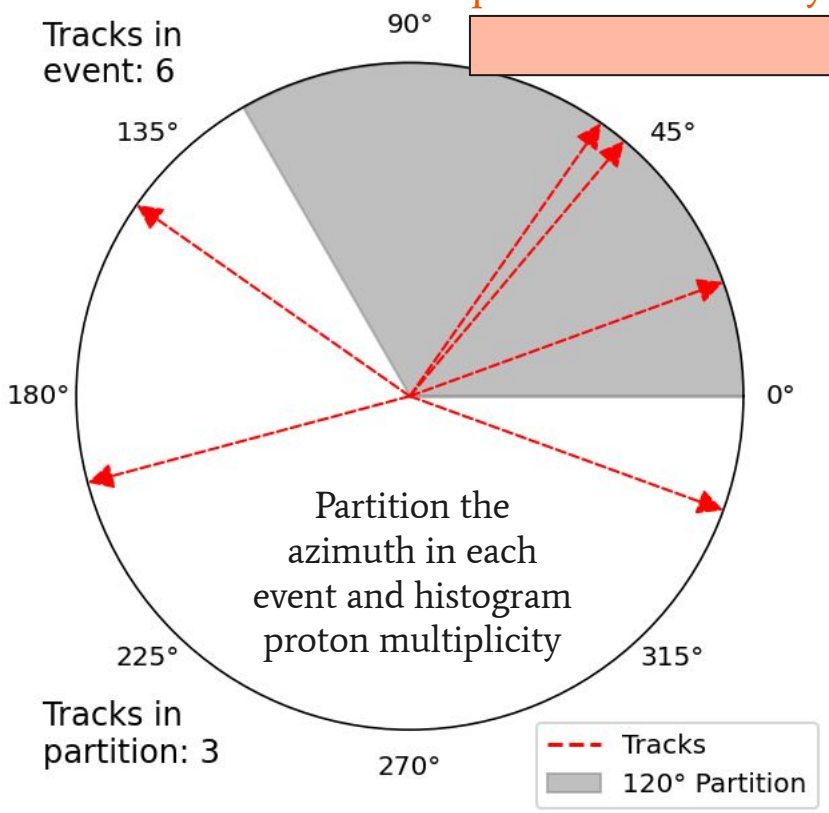
Analysis Goal

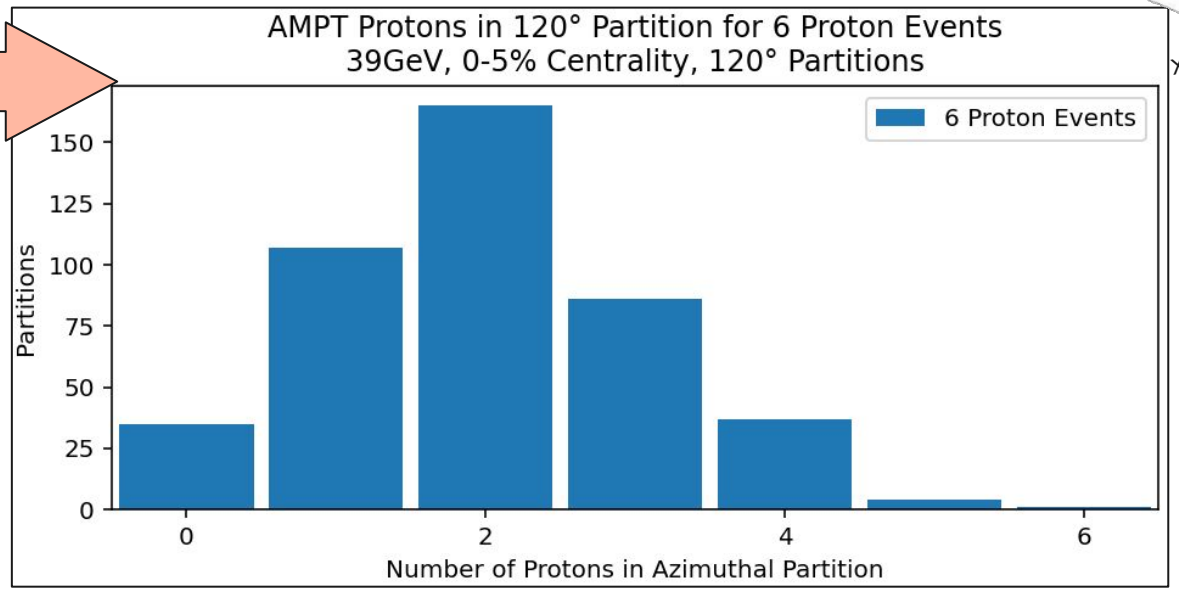
Look for azimuthal correlations among protons indicative of clustering
➔ possible sign of a first order phase transition

J Steinheimer, J Randrup Phys Rev C 87, 054903 (2013)



Histogram tracks in partition over many events

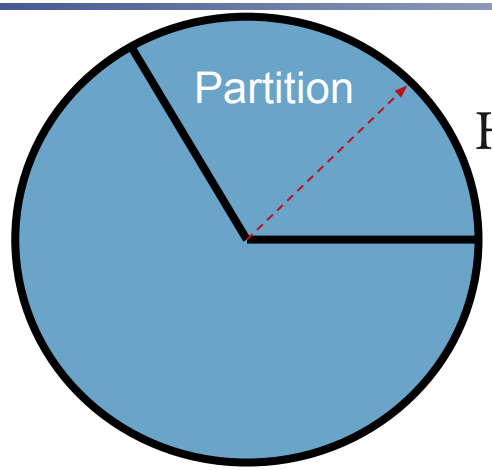




Separate histogram for each class of events:

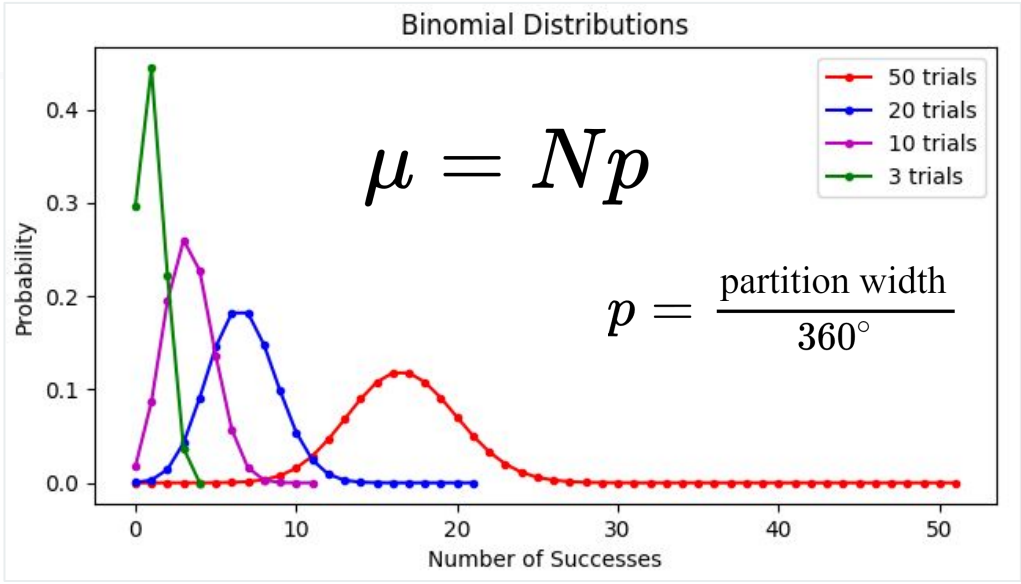
- ❑ Total Protons in Event (N)
- ❑ Partition Width (w)
- ❑ Single Event and Mixed Event Data

Compare to Binomial

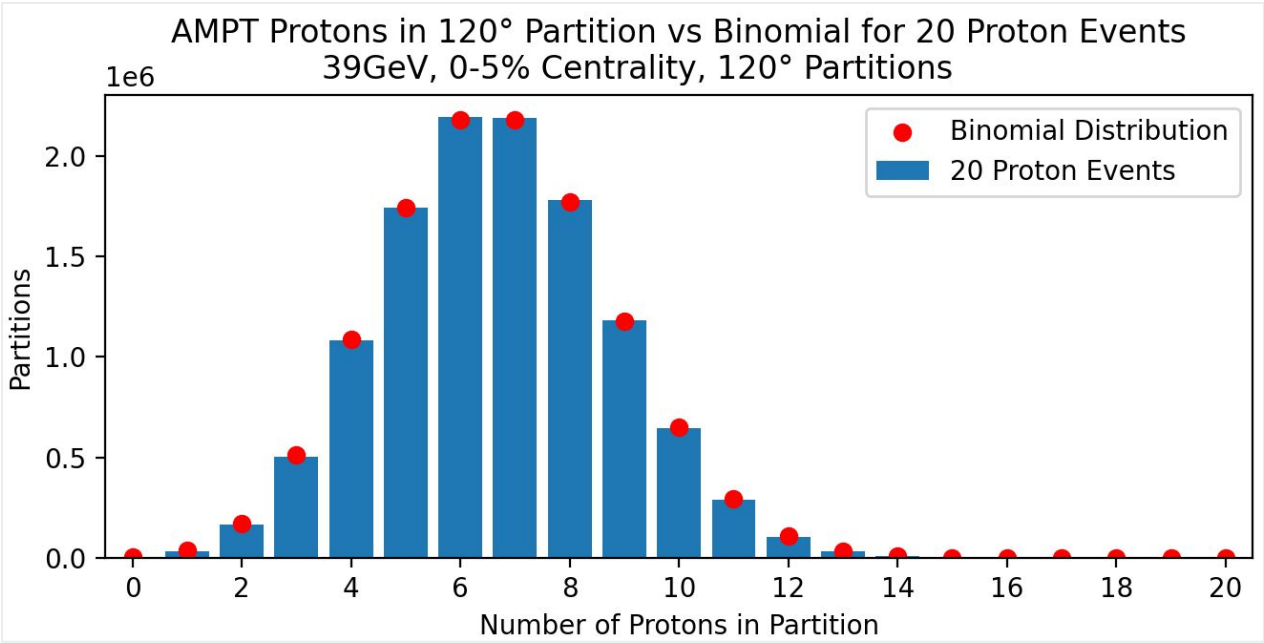


N tracks ( ) in event.
How many fall within Partition?

If random, expect binomial distribution



Compare measured distributions to binomial



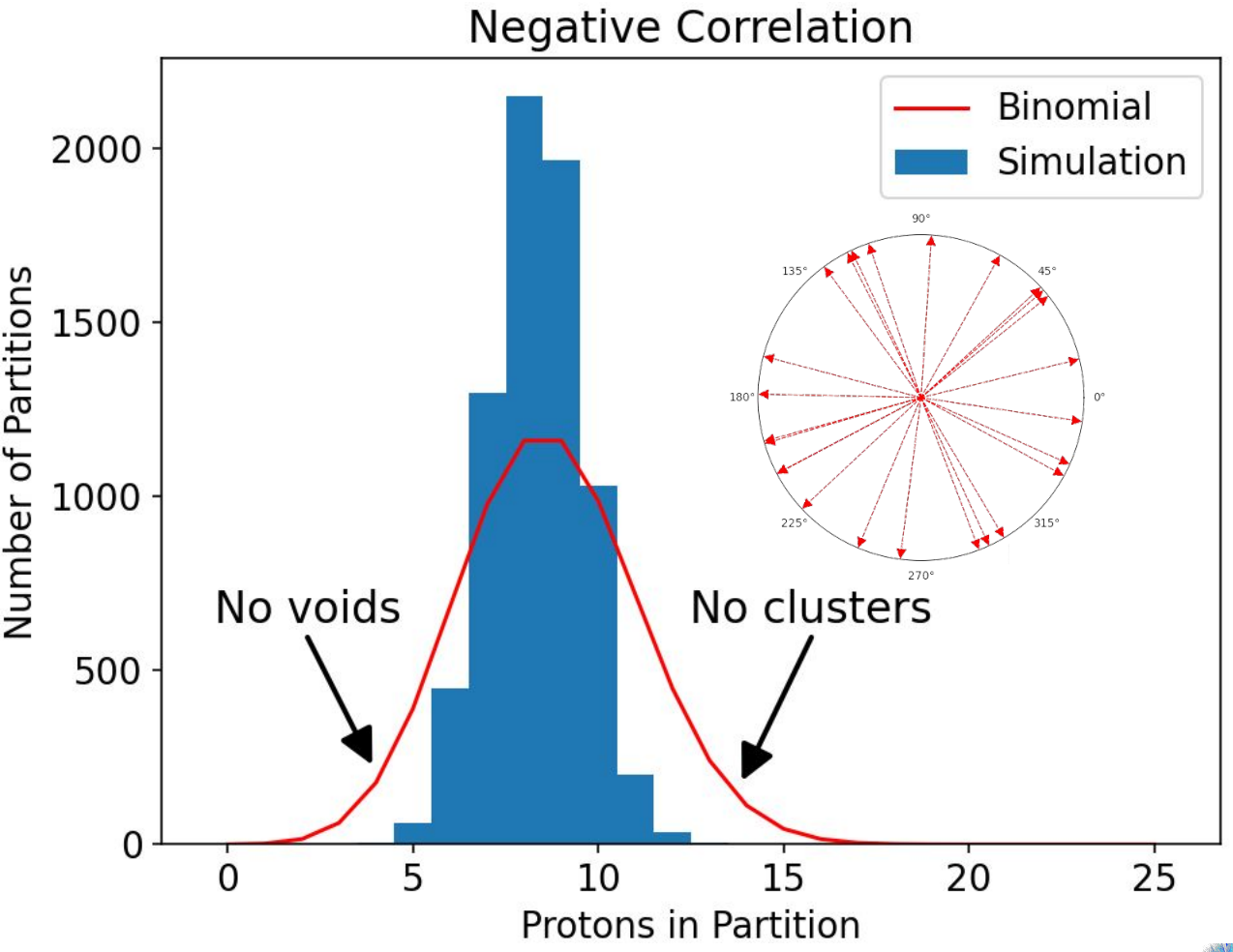
Systematic deviations from binomial suggest correlation between proton tracks

Focus on width of distributions

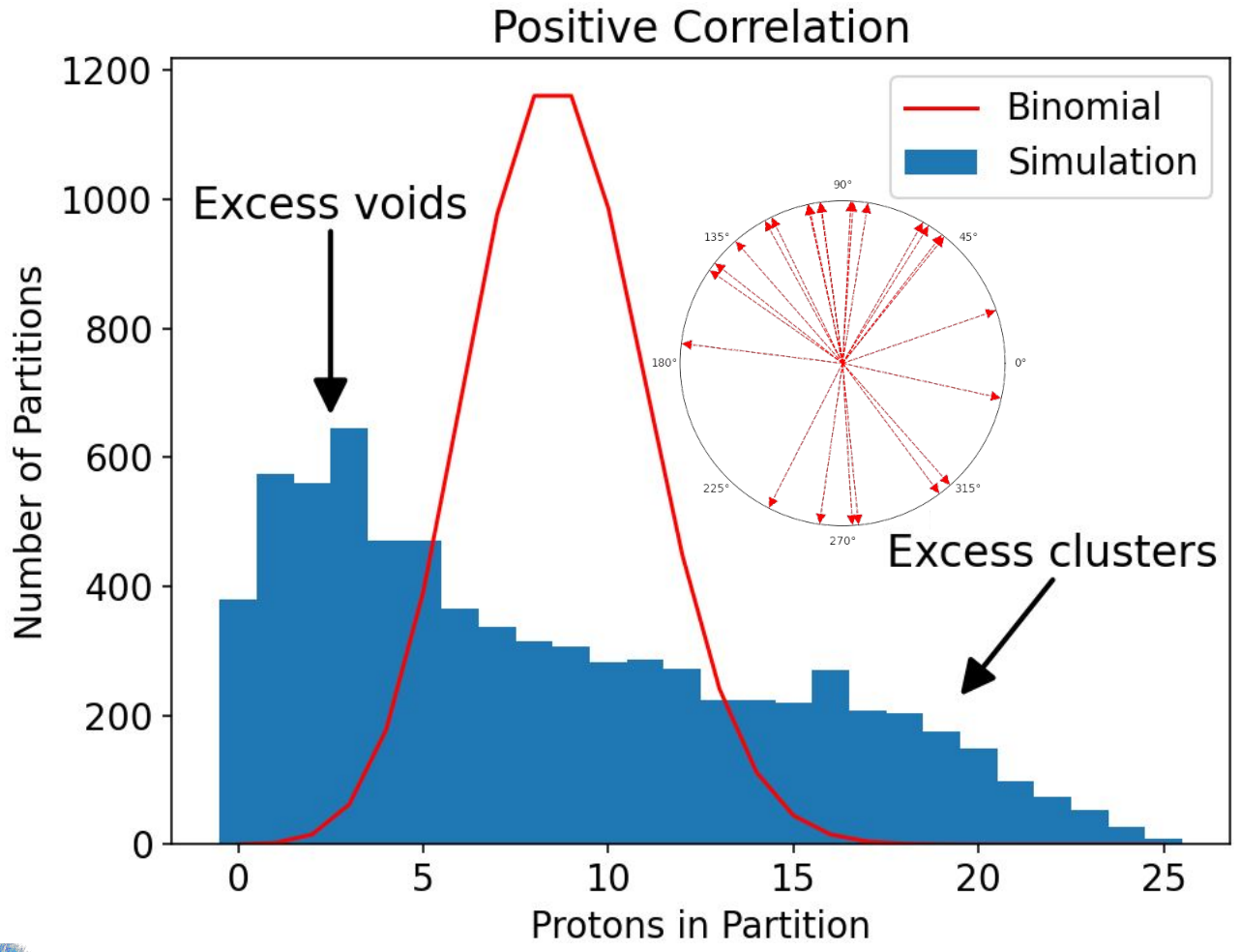
Distribution Width Interpretation

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

Small variance → lack of clustering



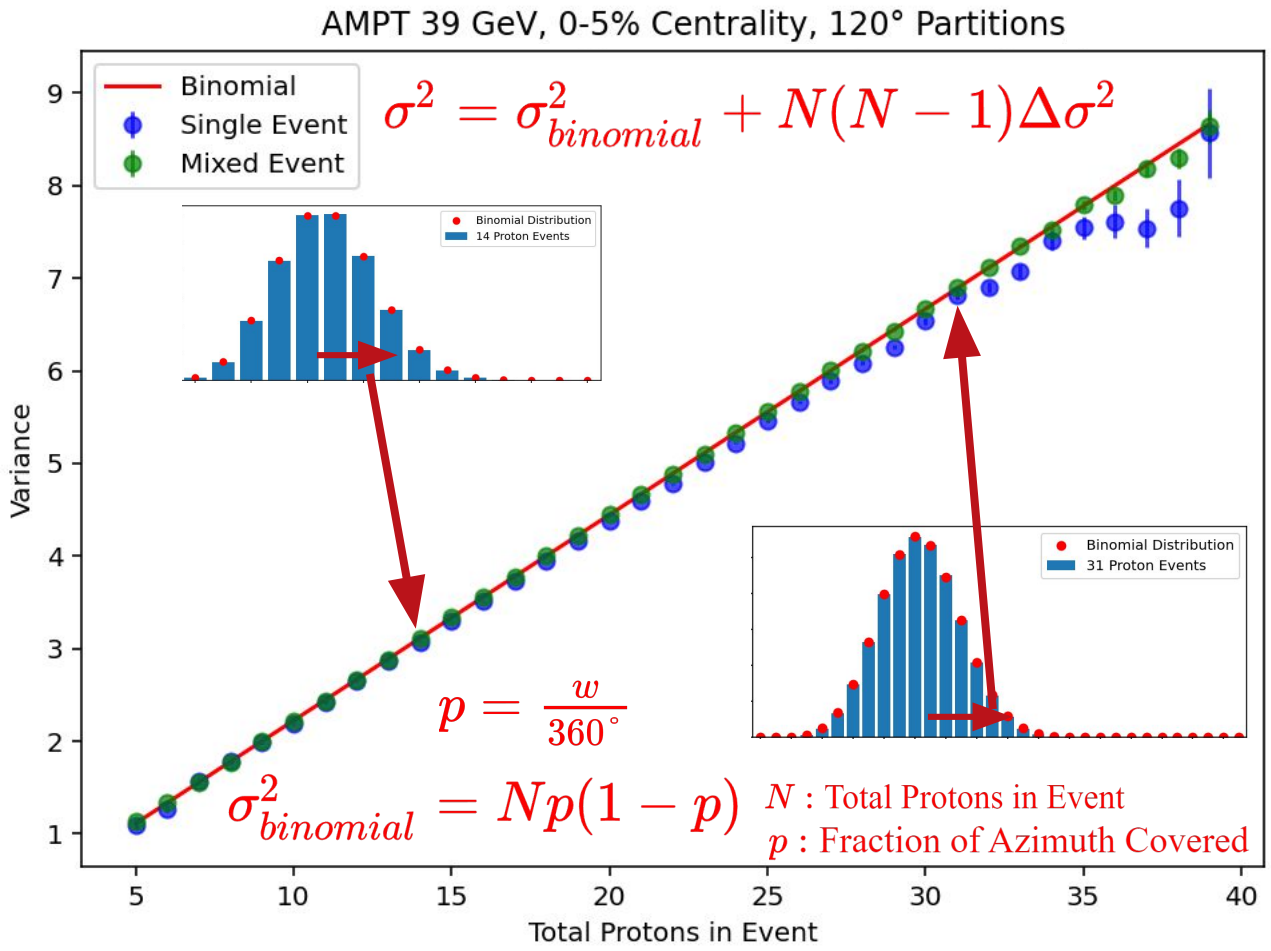
Large variance → excess clustering

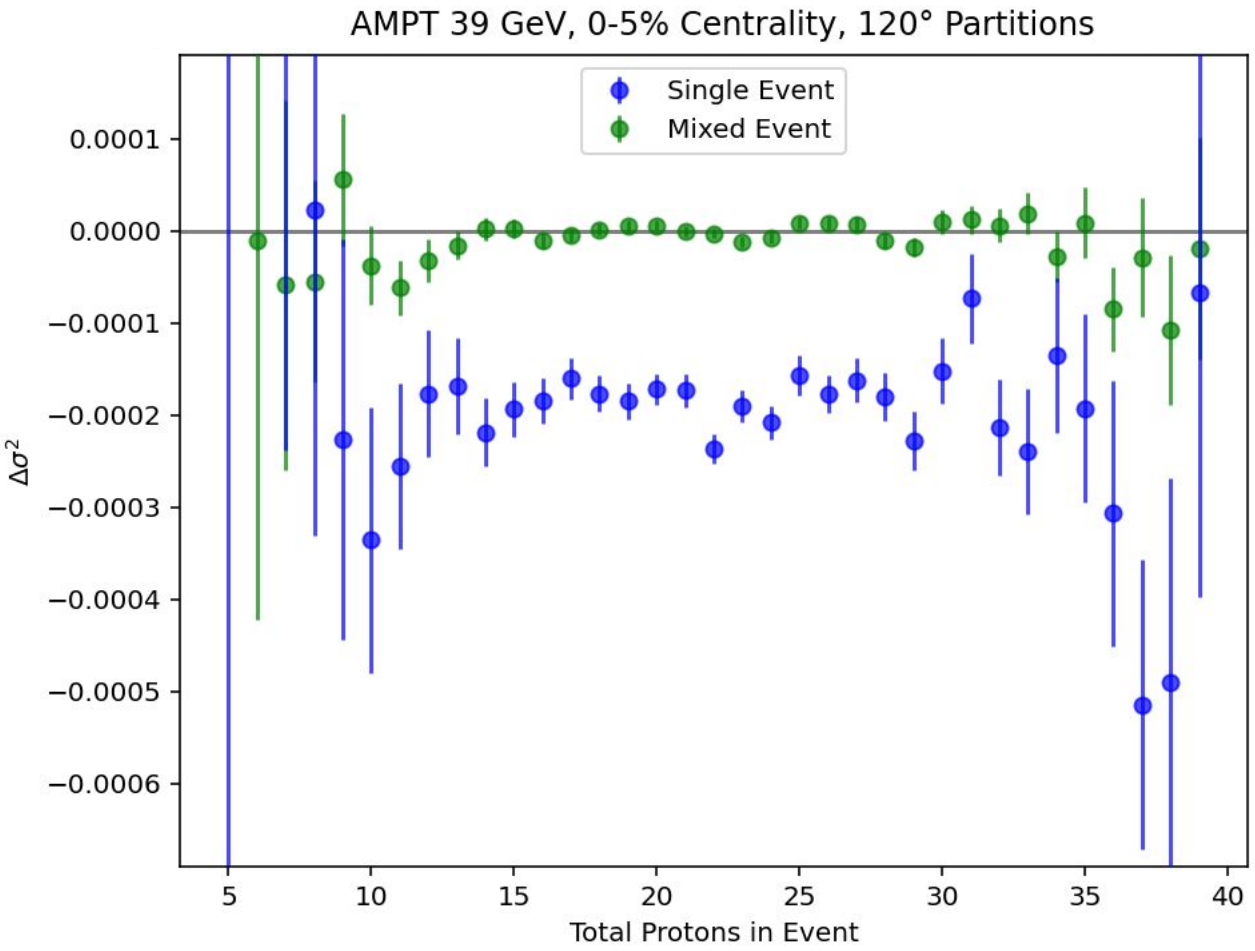


Compare Variance to Binomial

Define observable as normalized deviation from binomial

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



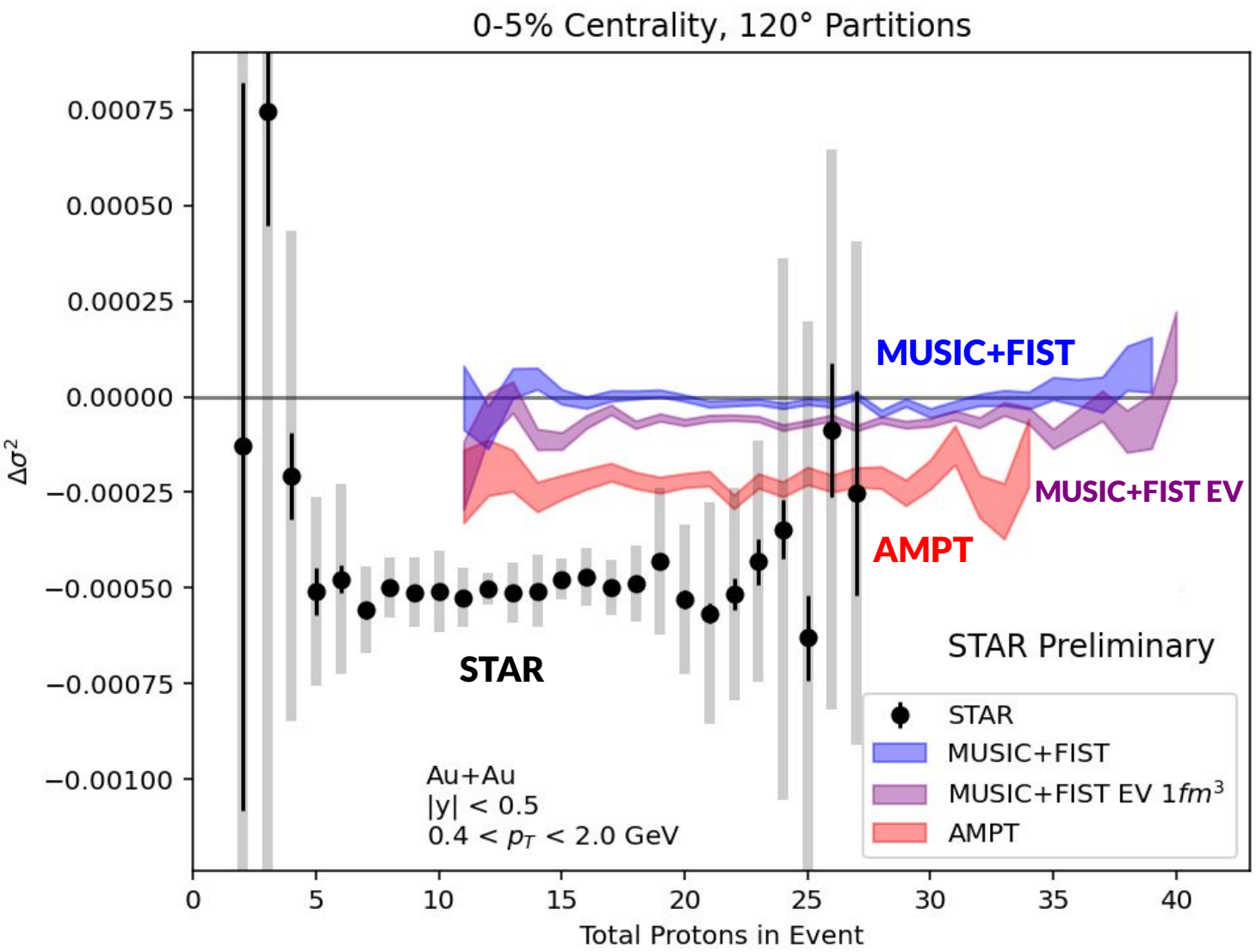


Single and Mixed Event variances very similar to binomial, though slight deviations apparent

Mixed Event $\langle\Delta\sigma^2\rangle \approx 0 \rightarrow$ very similar to binomial, Single Event is significantly smaller variance

Repulsion Observed

AMPT	Lin, He	Phys. Rev. C 96, 014910	(2017)
MUSIC+FIST	Vovchenko et al	Phys. Rev. C 105, 014904	(2022)
MUSIC+FIST EV	Vovchenko et al	Phys. Rev. C 106, 064906	(2022)



Positive $\Delta\sigma^2$ → Clustering

Negative $\Delta\sigma^2$ → Repulsion

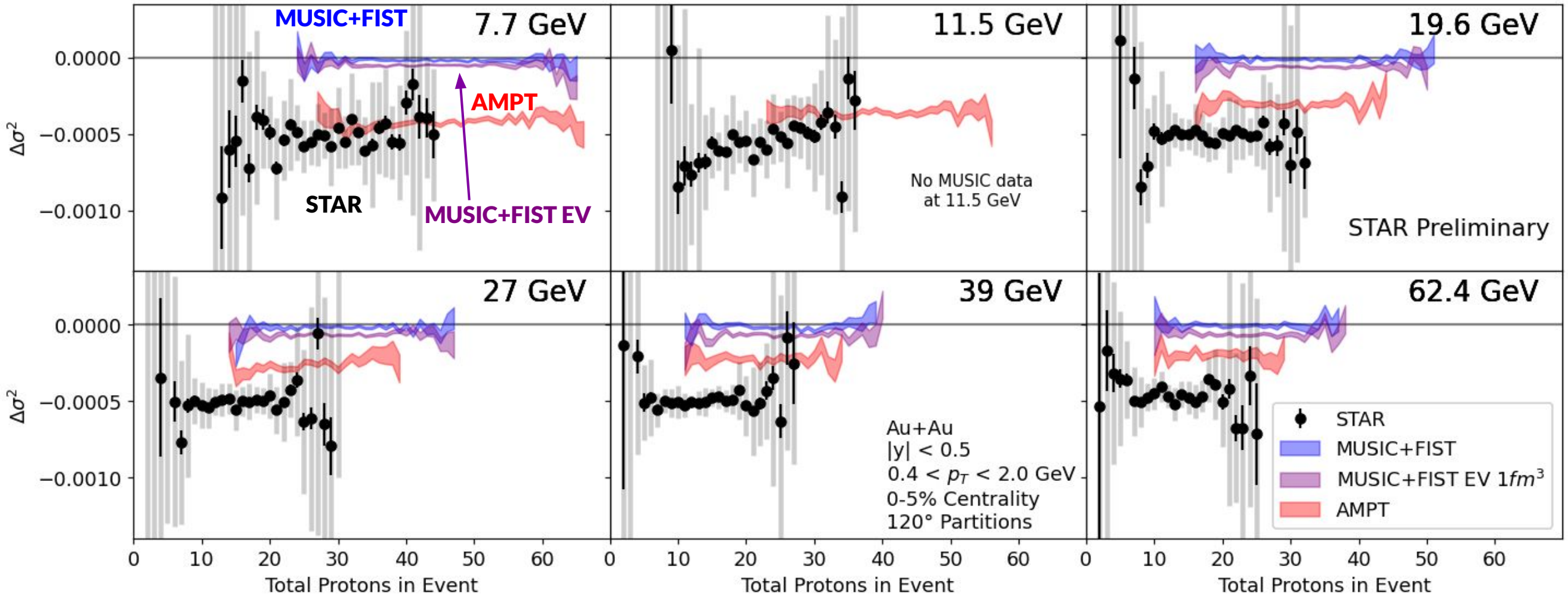
- Significant repulsion observed in STAR data
- MUSIC+FIST with Excluded Volume more repulsive than base model which sees little correlation
- AMPT calculations show stronger repulsion than MUSIC+FIST models

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

Repulsion Found at All Energies

Negative $\Delta\sigma^2$ observed at all energies for STAR and AMPT

Dependence on proton event multiplicity flat



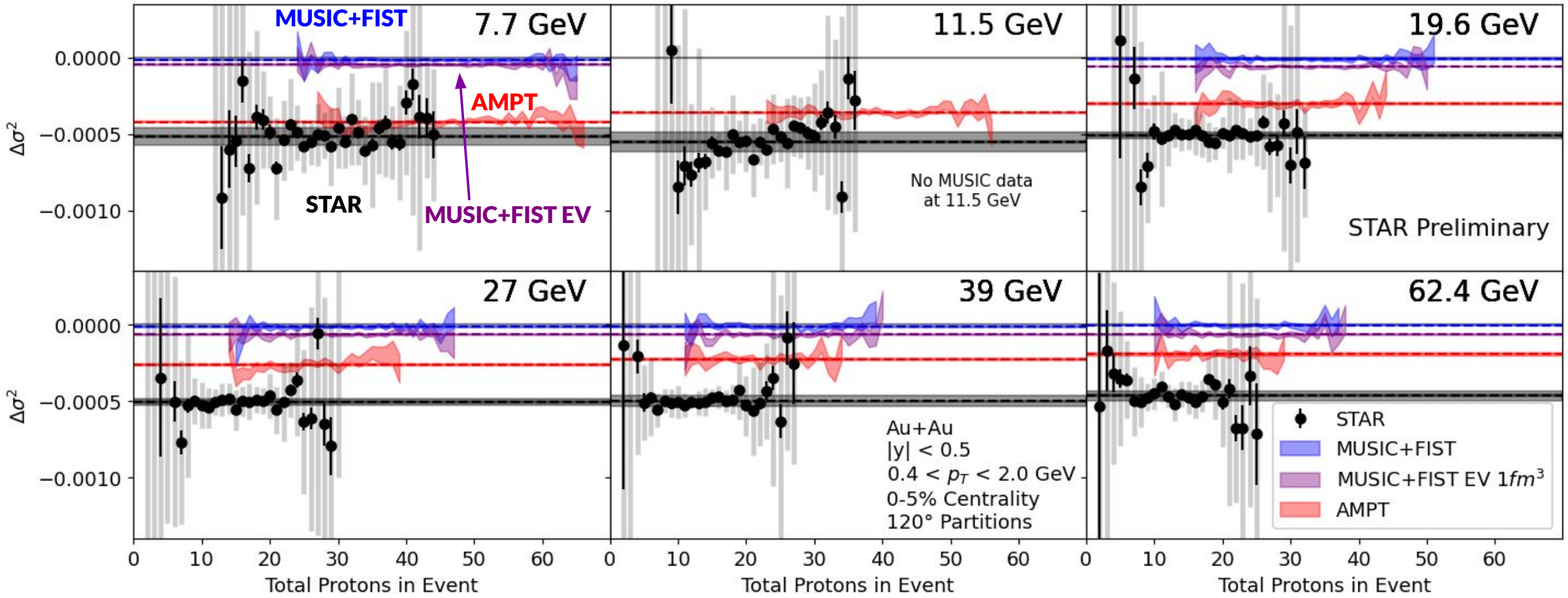
Repulsion Found at All Energies

Negative $\Delta\sigma^2$ observed at all energies for STAR and AMPT

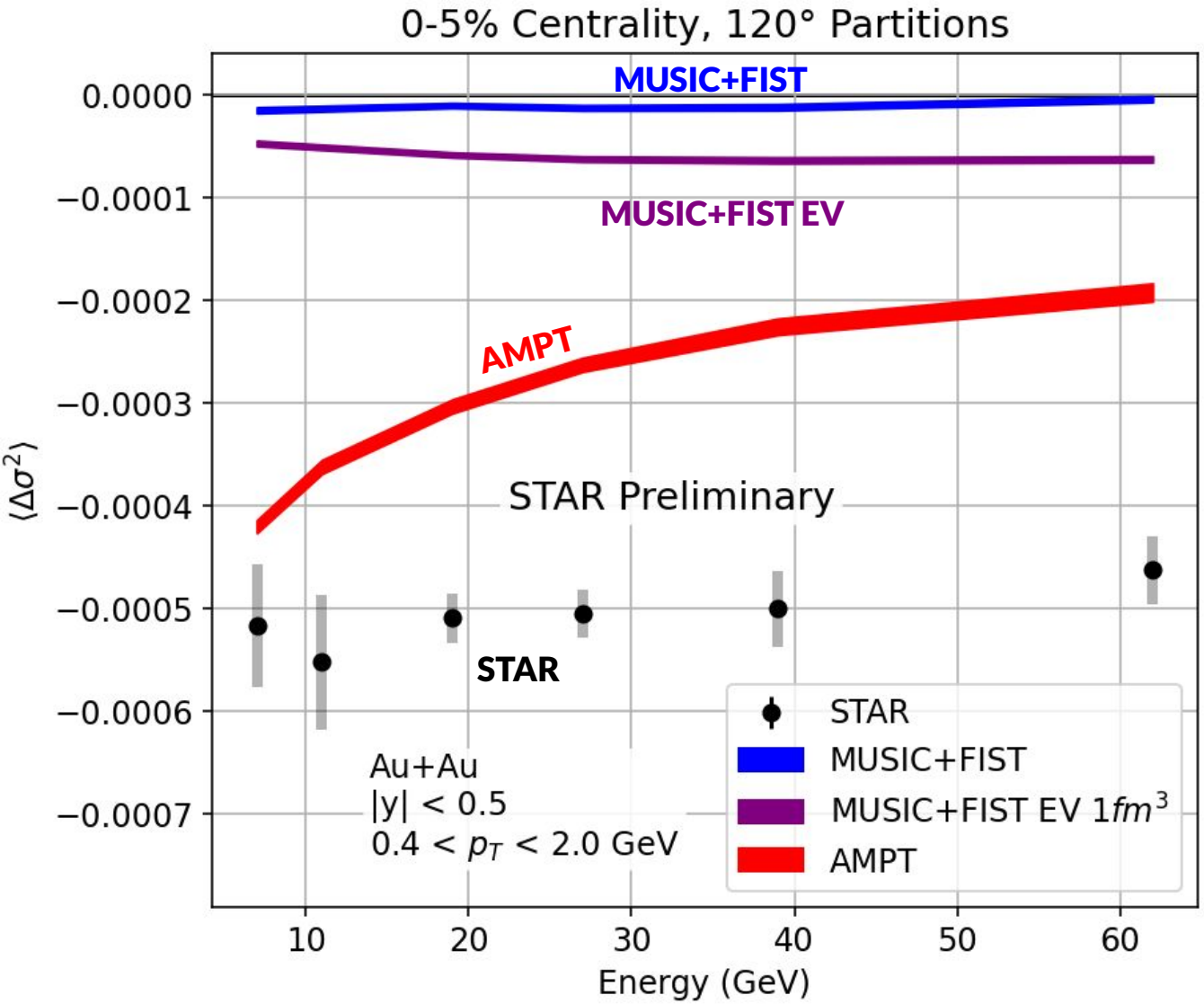
Dependence on proton event multiplicity flat

Average over Total Protons in Event

$$\Delta\sigma^2(N) \longrightarrow \langle \Delta\sigma^2 \rangle$$



Correlation Strength vs Energy



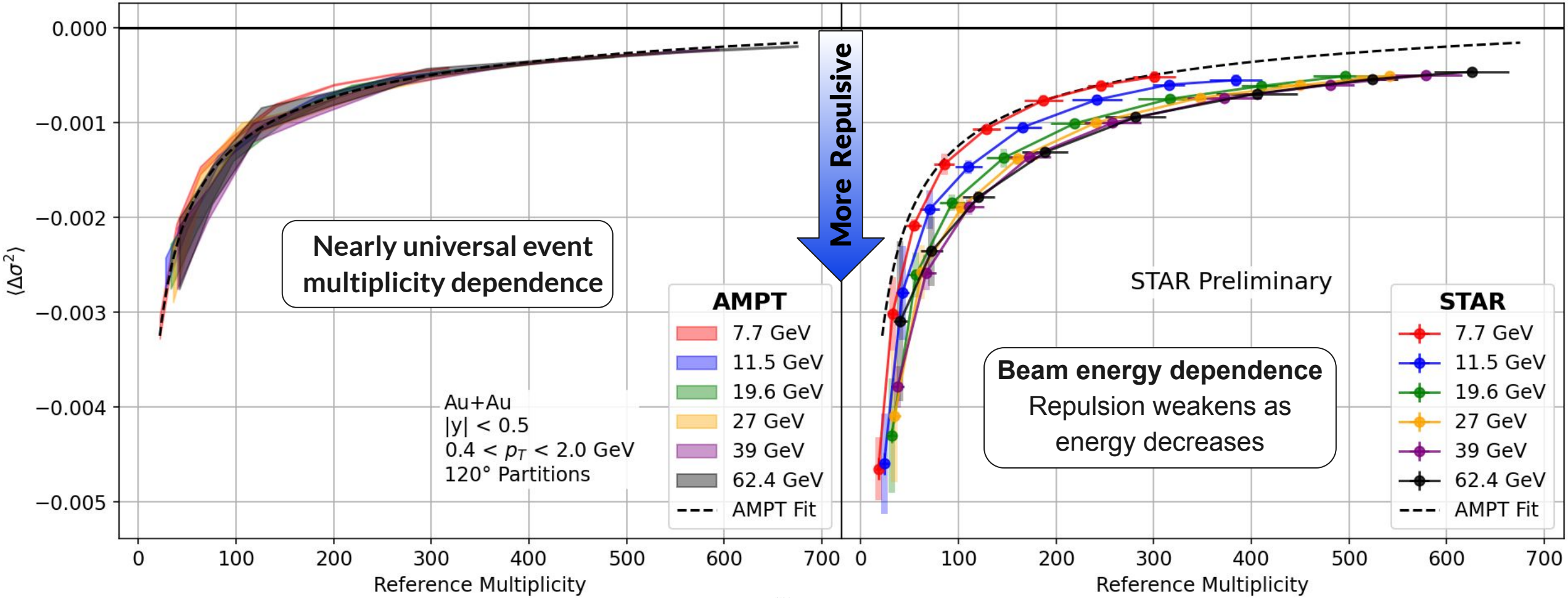
Negative $\Delta\sigma^2$ → Repulsion

- Repulsion observed between proton tracks in STAR data and all models
- STAR correlations from most central 0-5% centrality showed no significantly beam energy dependence and larger strength in correlation than AMPT. In addition, AMPT showed a moderate beam energy dependence.

$\langle \Delta\sigma^2 \rangle$ vs Event Multiplicity

Magnitude of repulsive interaction increases with decreasing multiplicity per event

Multiplicity dependence likely dominated by global momentum conservation

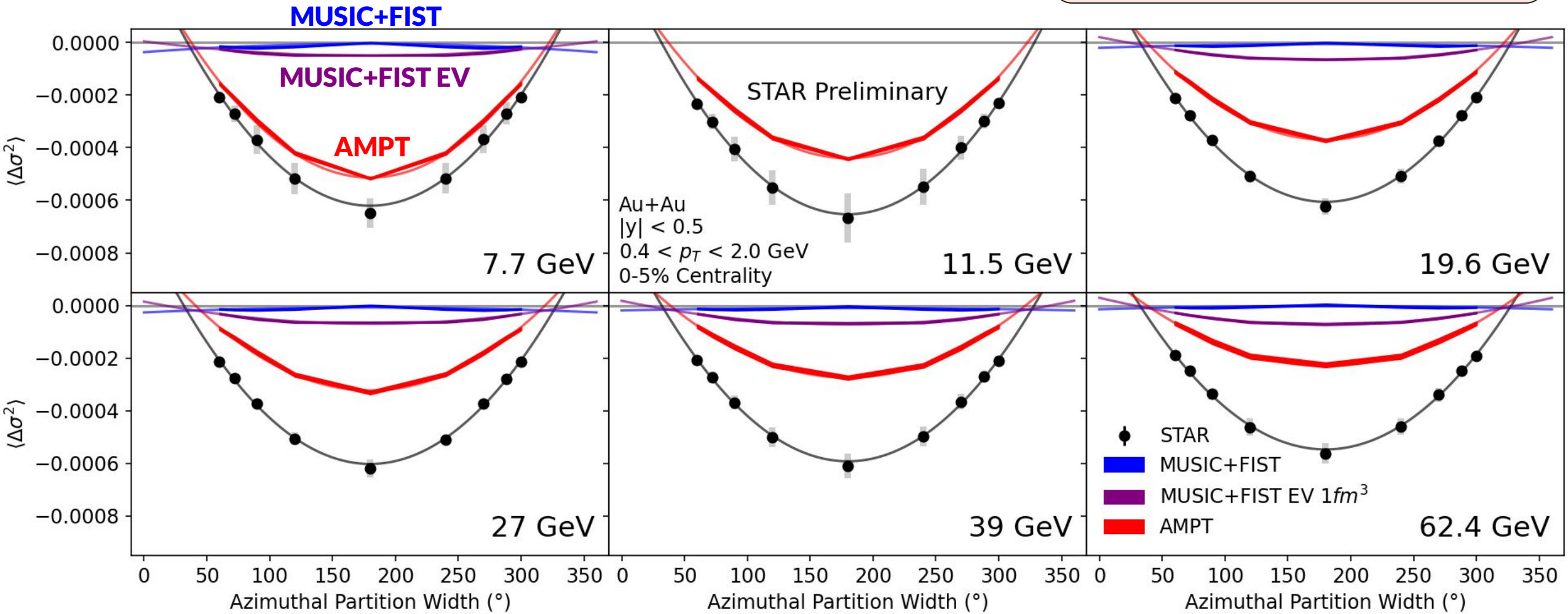


$\langle \Delta\sigma^2 \rangle$ vs Partition Width

Partition width dependence may encode information about range of correlation

Evidenced by toy model simulations

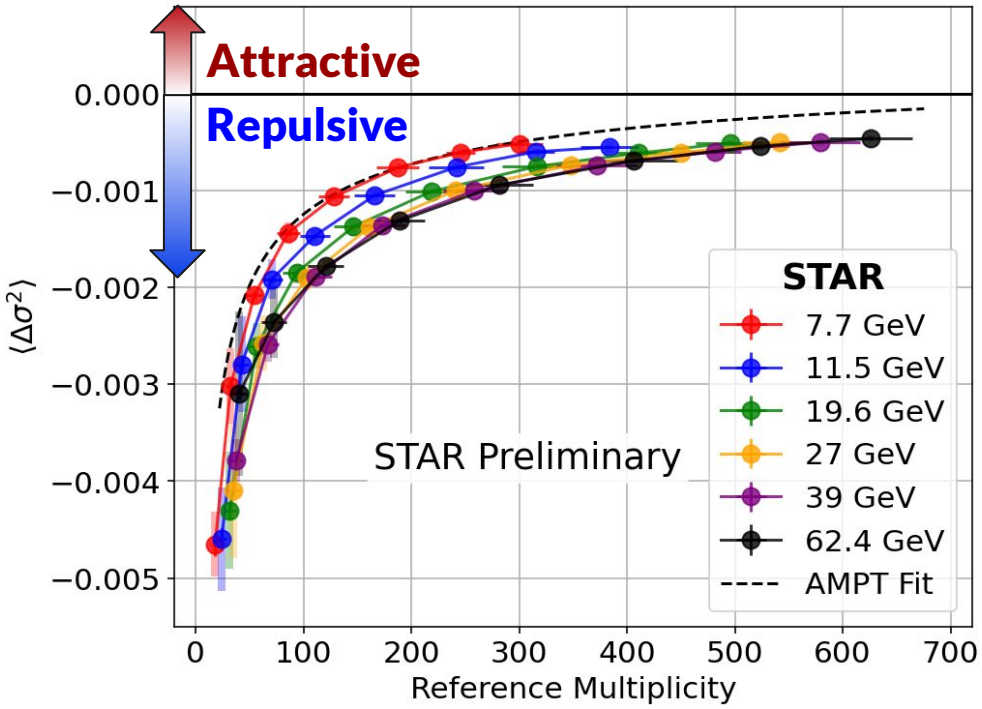
Trends well described by quadratic
Curvature related to range of correlation



Summary

Thanks for your attention!

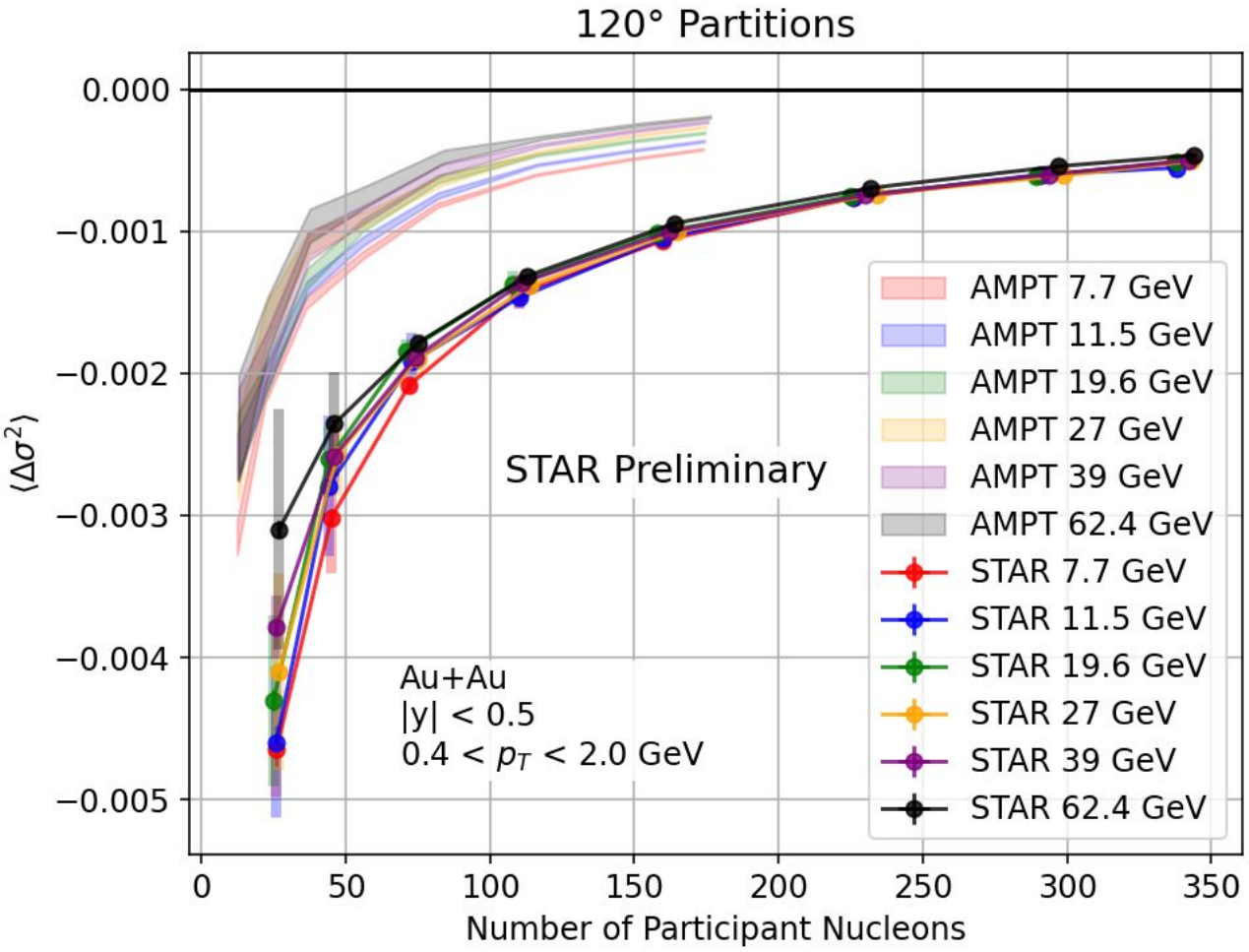
- Observed increasingly negative $\frac{C_6}{C_2}$ with decreasing energy within uncertainty $\mathcal{O}(1\sigma)$
  Trend consistent with lattice QCD calculations from $\sqrt{s_{NN}}$ = 7.7 GeV - 200 GeV
- Within uncertainty, data from $\sqrt{s_{NN}}$ = 7.7 GeV - 200 GeV seem to favor ordering expected from lattice
- C6>0 and ordering violated at $\sqrt{s_{NN}}$ = 3GeV - reproduced by UrQMD
  - Suggests hadronic matter dominant
- Strong proton repulsion observed
  - Stronger at lower event multiplicity
    - Likely momentum conservation background, obscuring any possible clustering signal
  - Trend with multiplicity is energy dependent in STAR data while energy independent for AMPT. To be further explored in the future.

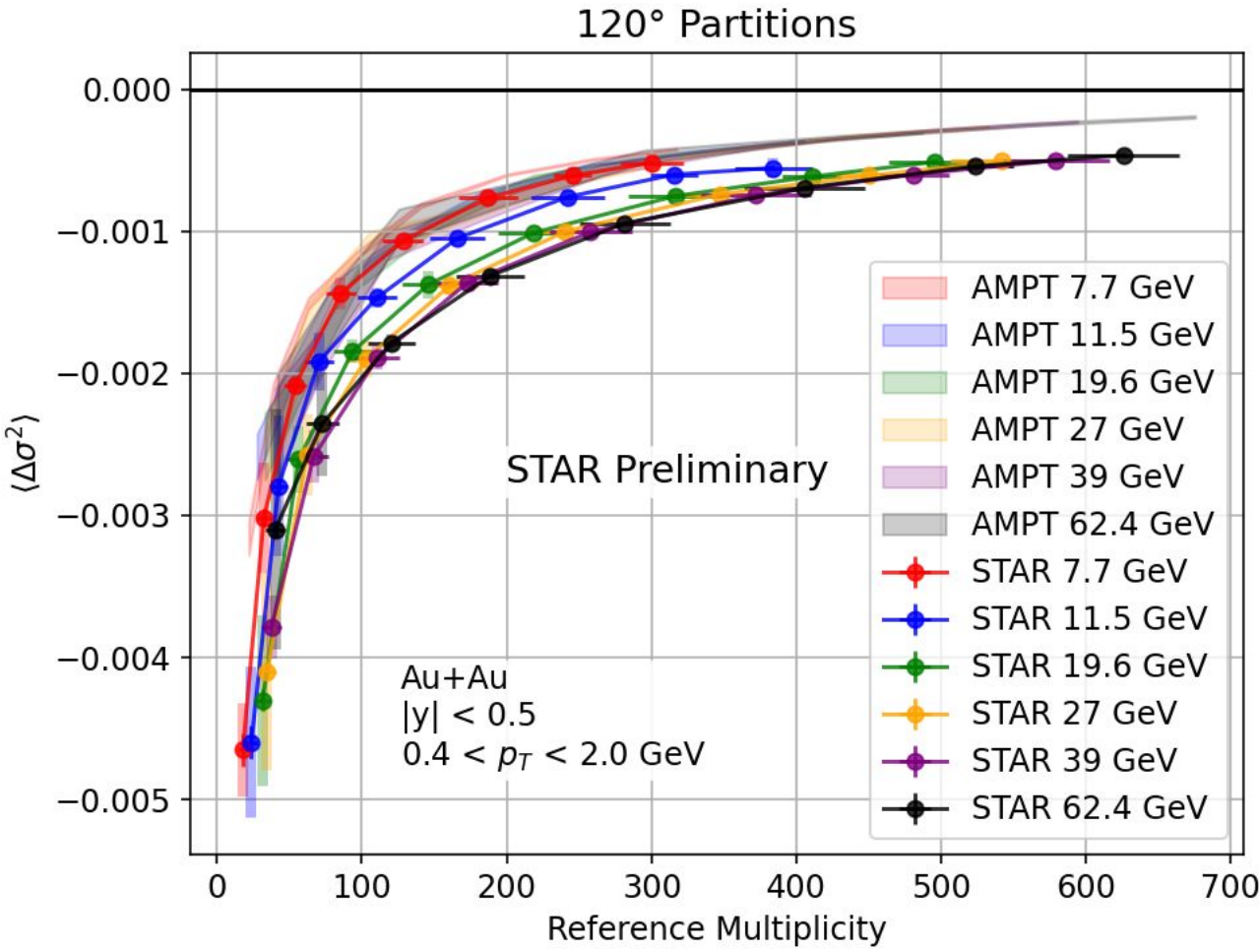


Backup

$\langle \Delta\sigma^2 \rangle$ vs Event Multiplicity

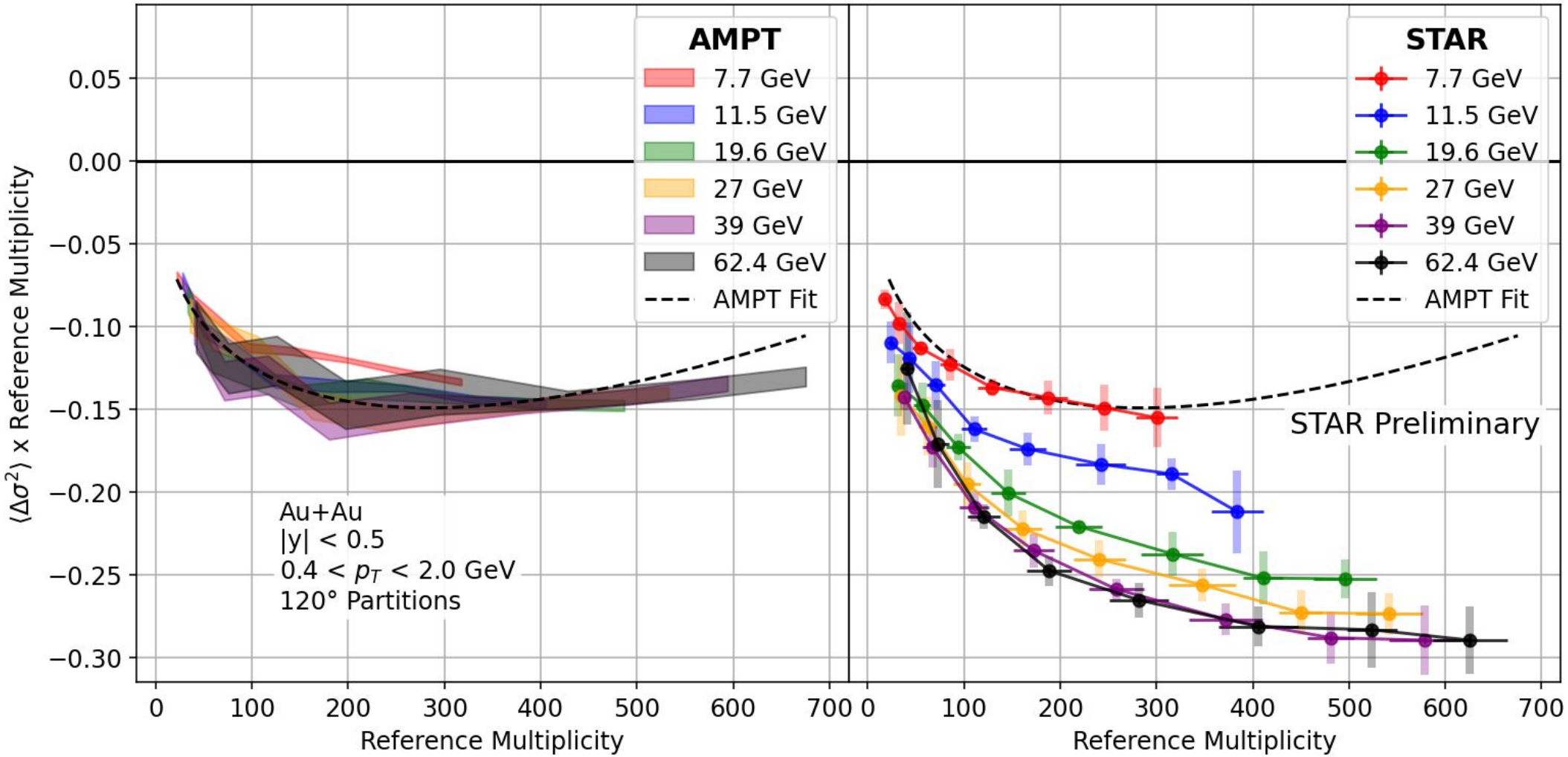
Magnitude of repulsive interaction increases with decreasing multiplicity per event





$\langle \Delta\sigma^2 \rangle$ vs Event Multiplicity

Divide out the naively expected 1/N multiplicity dependence from global momentum conservation to better see STAR energy dependence



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

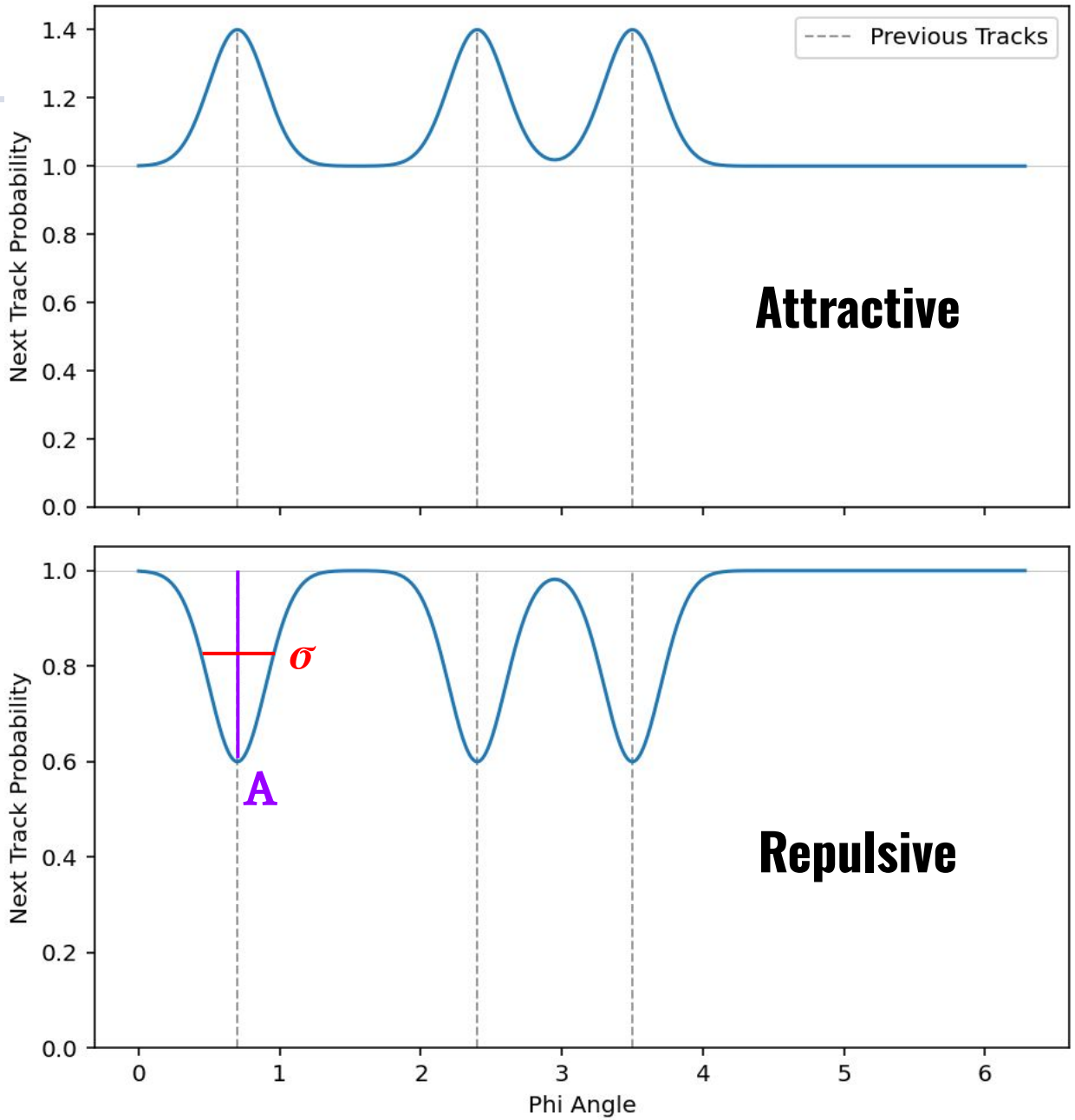
- Can model attraction (A>0) and repulsion (A<0)

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

baseline

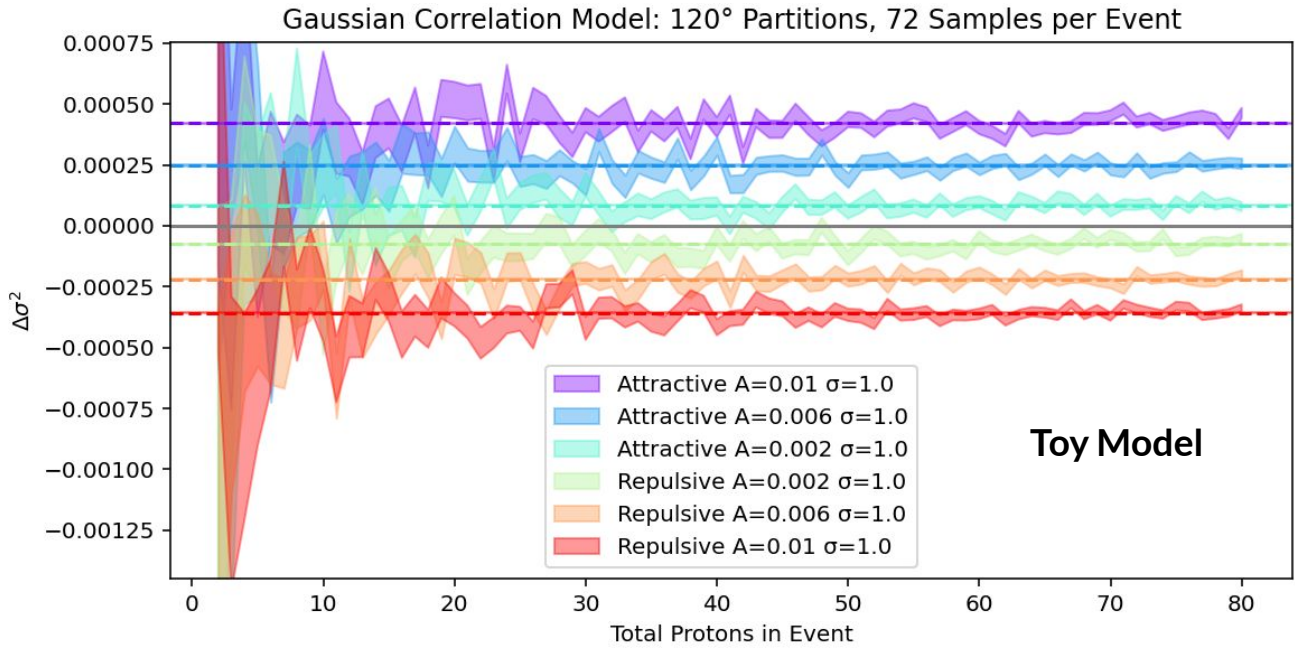
$$P(\phi) \propto \prod_{i=i}^{n} 1 + \frac{A}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\phi-\phi_i}{\sigma}\right)^2}$$

Parameters not directly comparable between attractive and repulsive



Simulations vs Total Protons

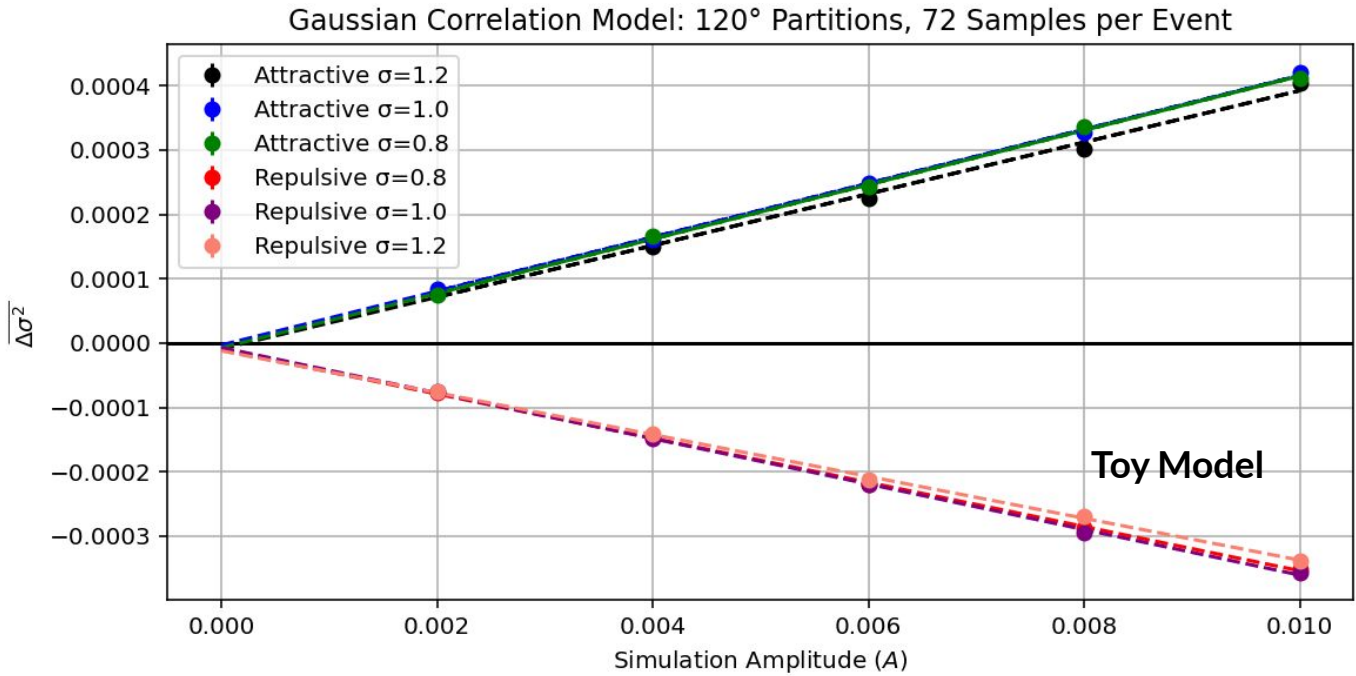
- Plot $\Delta\sigma^2$ vs the total number of protons in each event for a handful of simulation *A*mplitudes
- Observe consistently flat trends with average value correlated with *A*



Mixed distributions for toy model are statistically identical to binomial

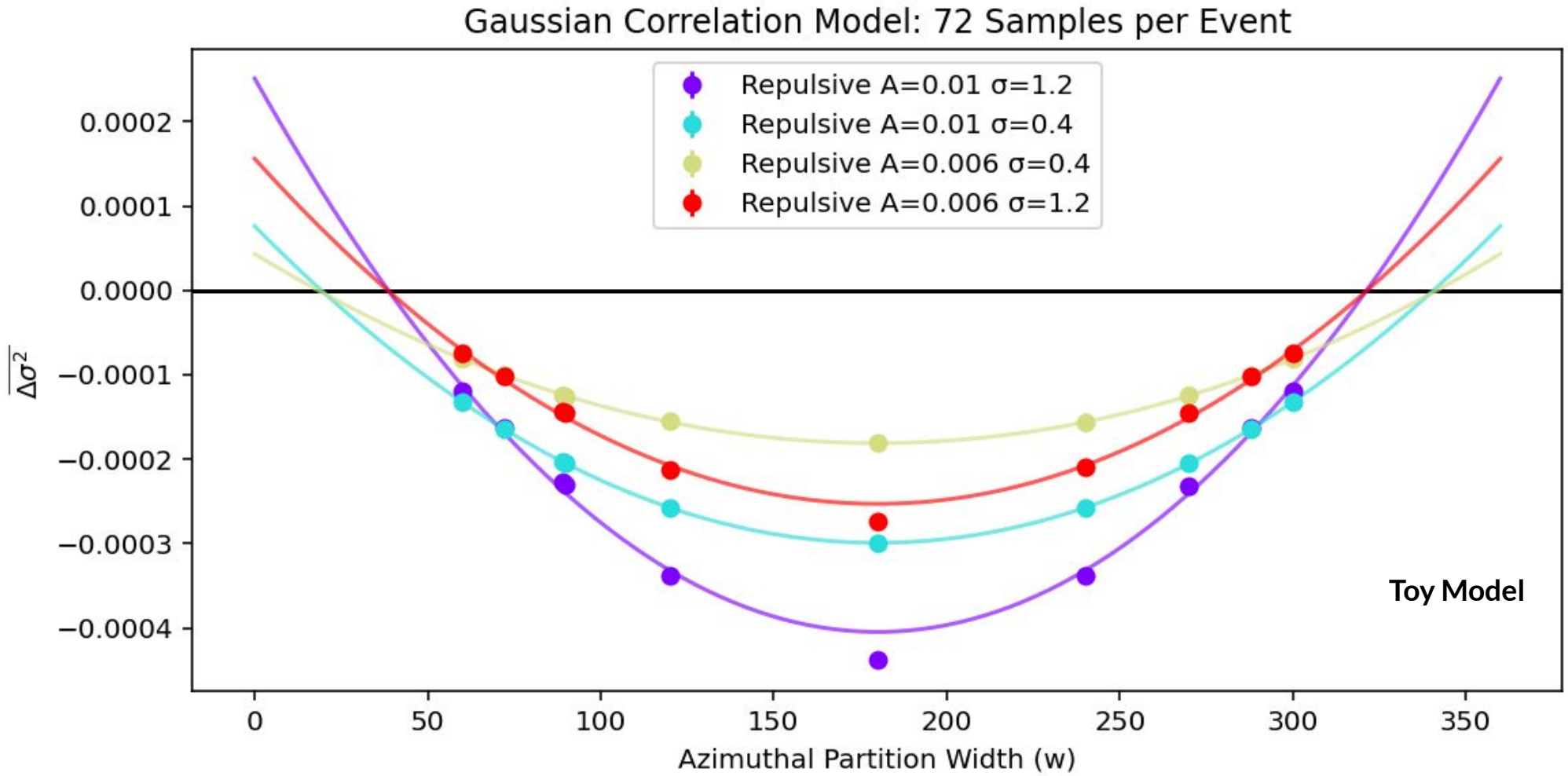
Can Reliably Extract Correlation

- Plotting $\Delta\sigma^2$ vs the total number of protons, get good linear relationship with input simulation *A*mplitude
- This suggests the analysis can reliably extract the input correlation in the case of this simple model
- Changing Gaussian correlation width leads to different but still linear relationship



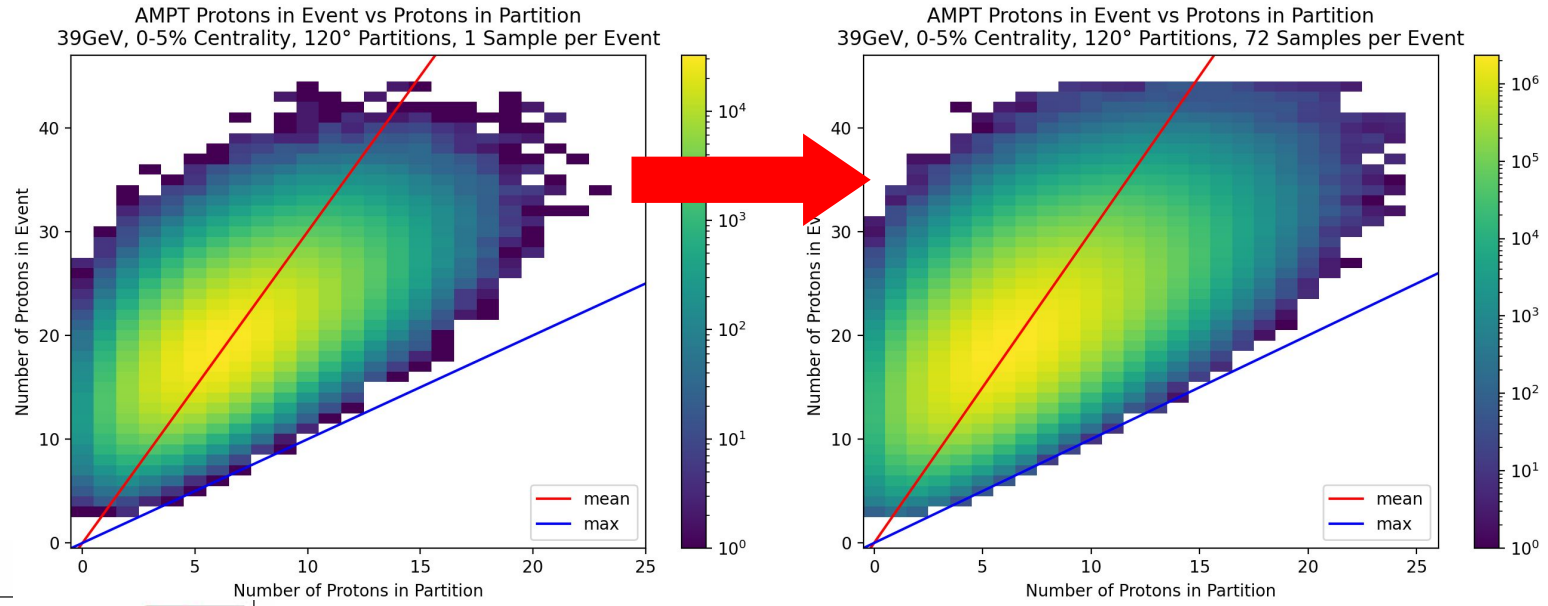
Slope vs Partition Width Simulation

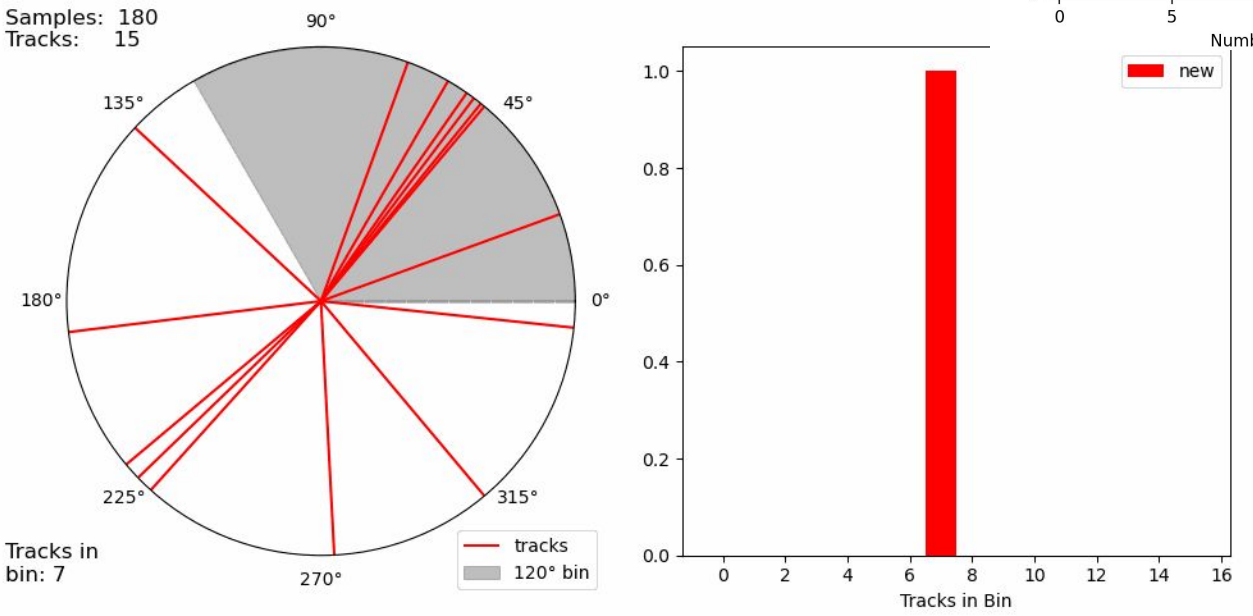
- Dependence appears quadratic
- Different σ different x-intercept



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