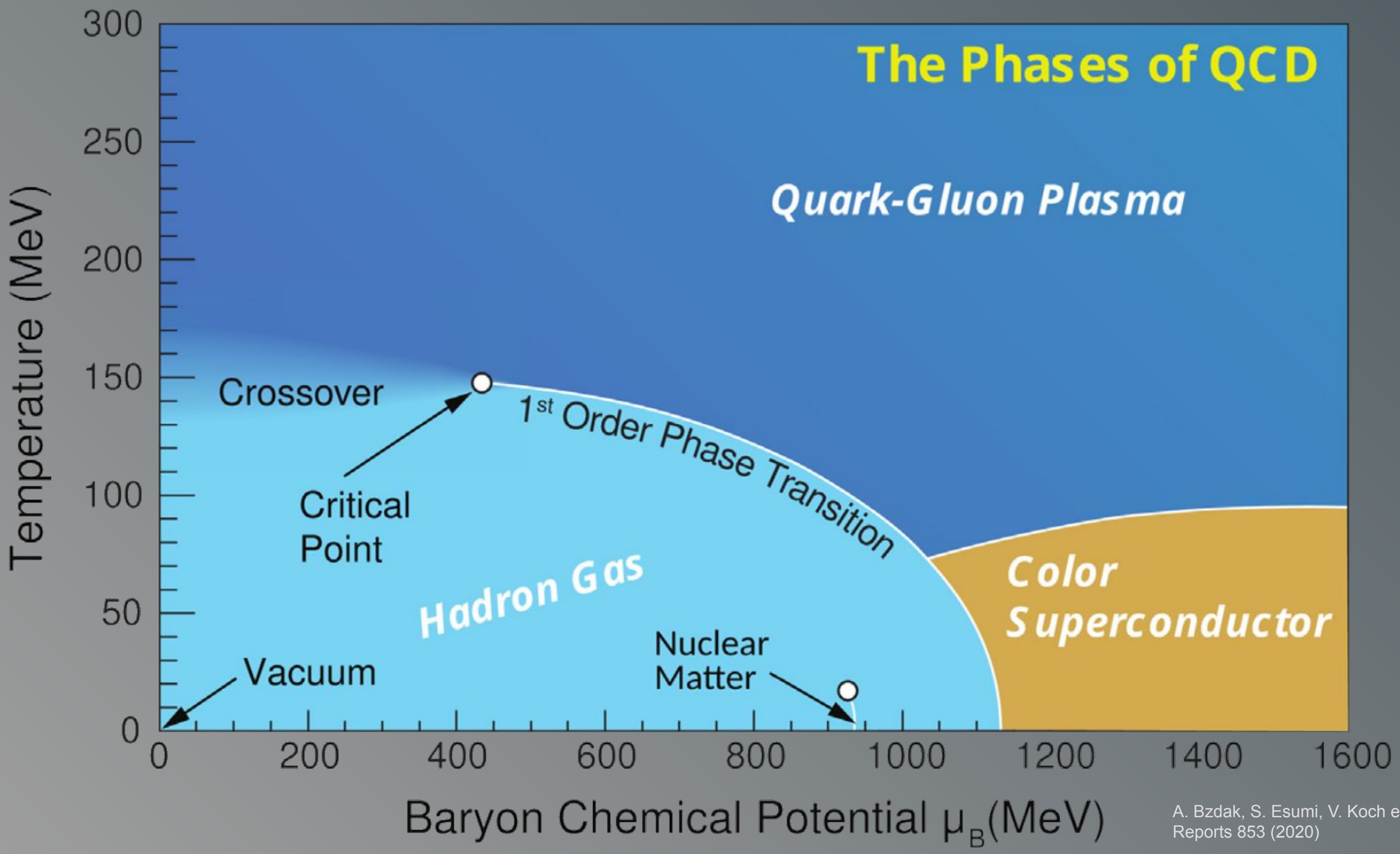
Proton Fluctuations in Azimuthal Partitions of Heavy Ion Collisions at STAR

Dylan Neff
CEA Paris-Saclay

QCD Phase Diagram

Goal: Map out phase diagram via heavy ion collisions



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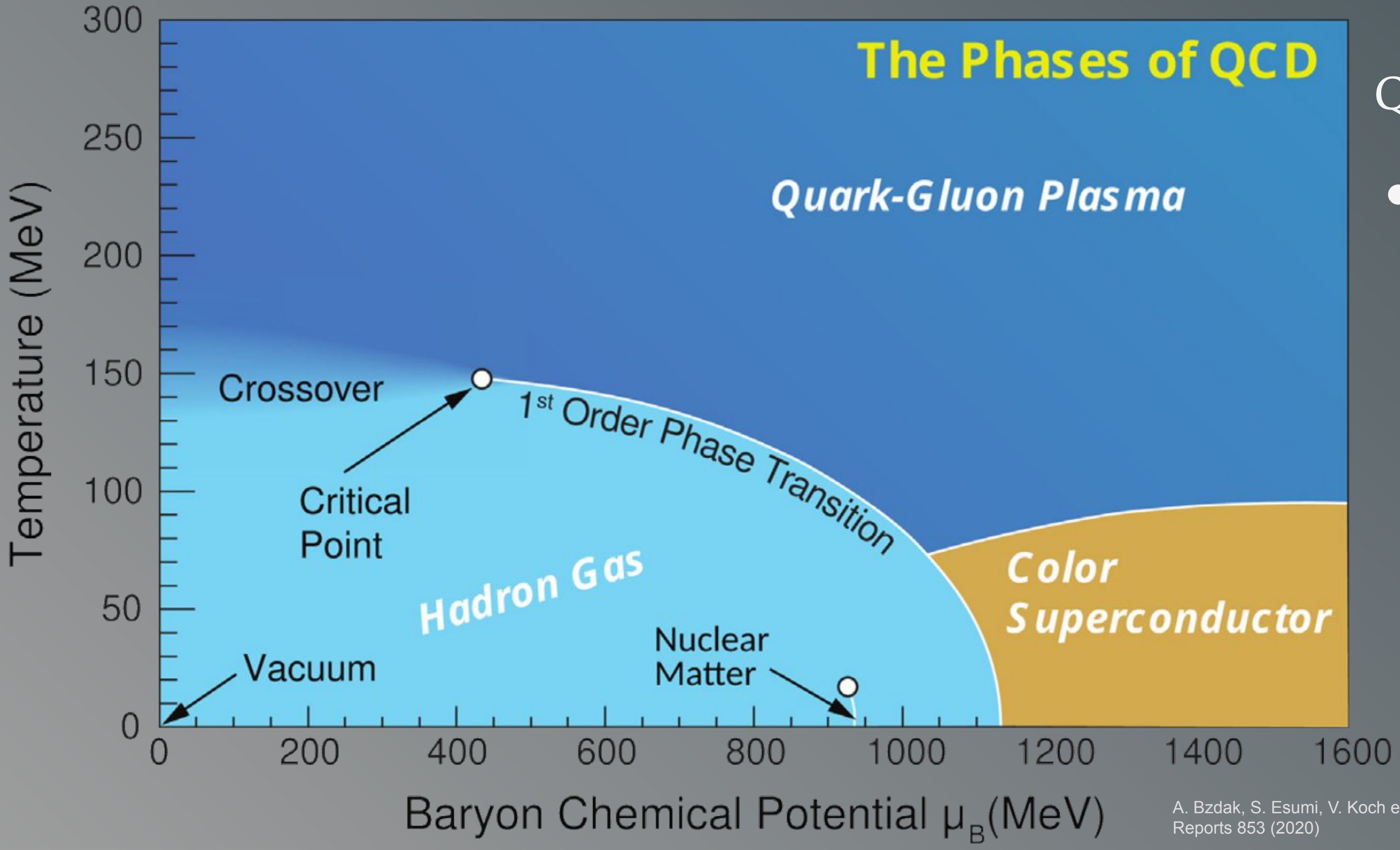

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QGP-Hadron Gas Transition

- Crossover at low μ_B ✔
  - Lattice QCD

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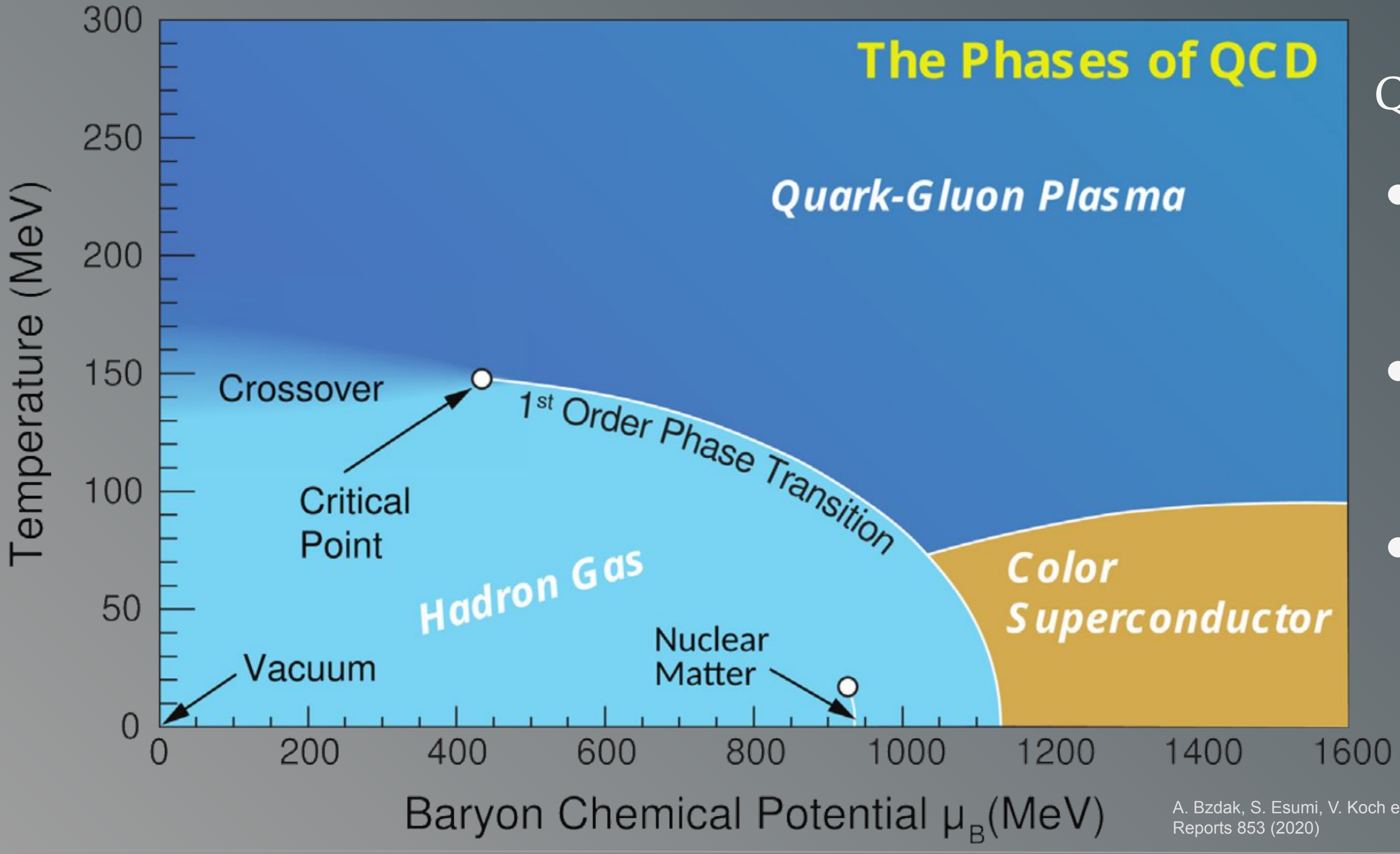

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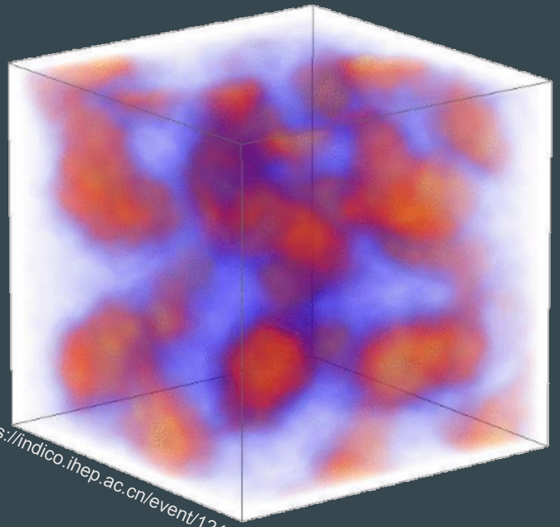
QGP-Hadron Gas Transition

- Crossover at low μ_B ✔
  - Lattice QCD
- First Order at large μ_B ?
  - Model and theory arguments
- Critical Point between ?

Analysis Goal



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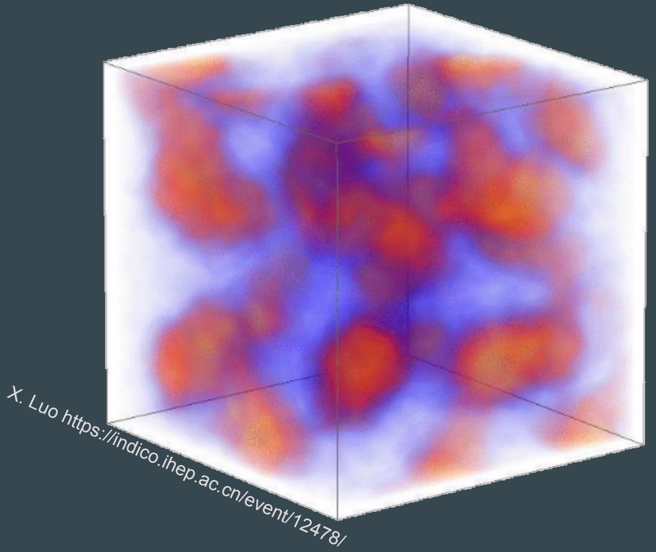
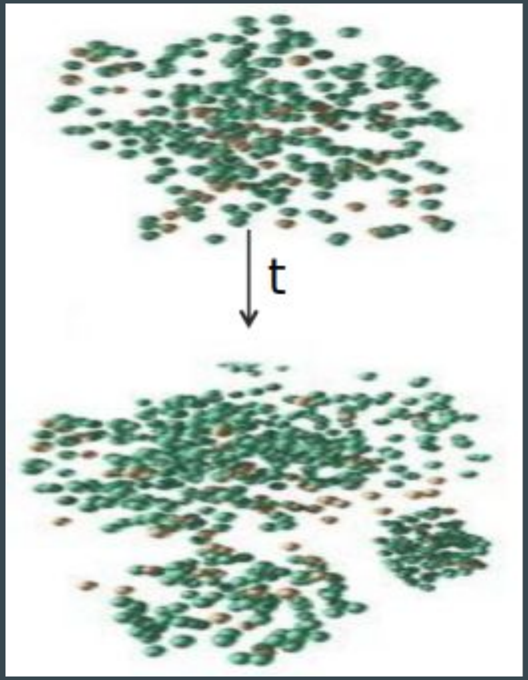
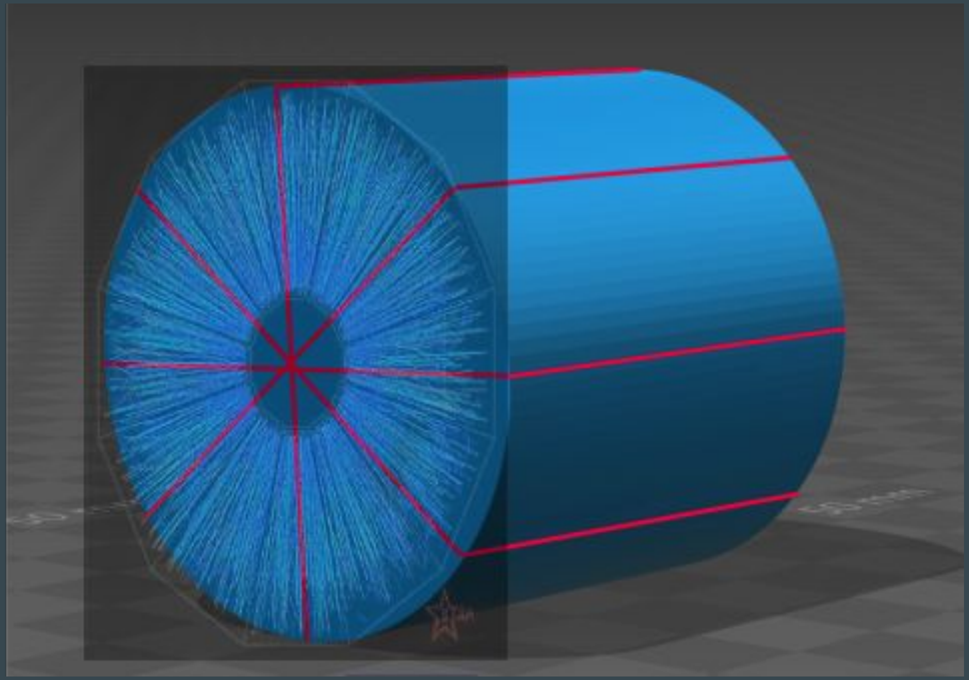


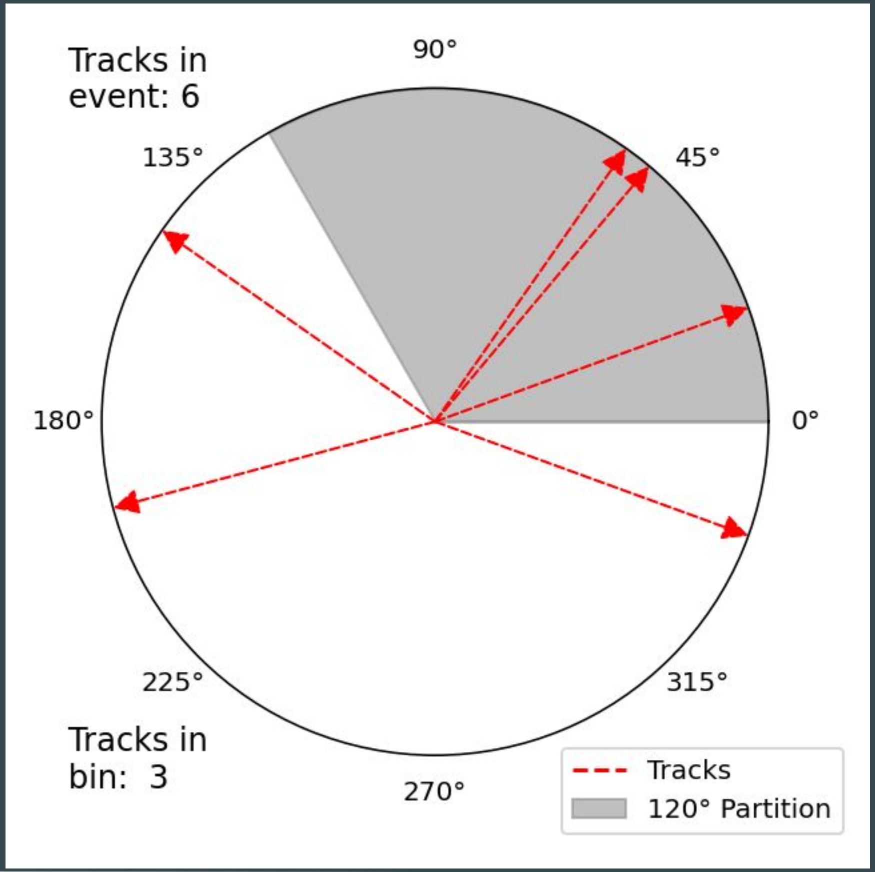
- Compare proton multiplicities in azimuthal partitions to uncorrelated expectation





Azimuthal Partitioning

Partition the azimuth in each event and histogram particle tracks



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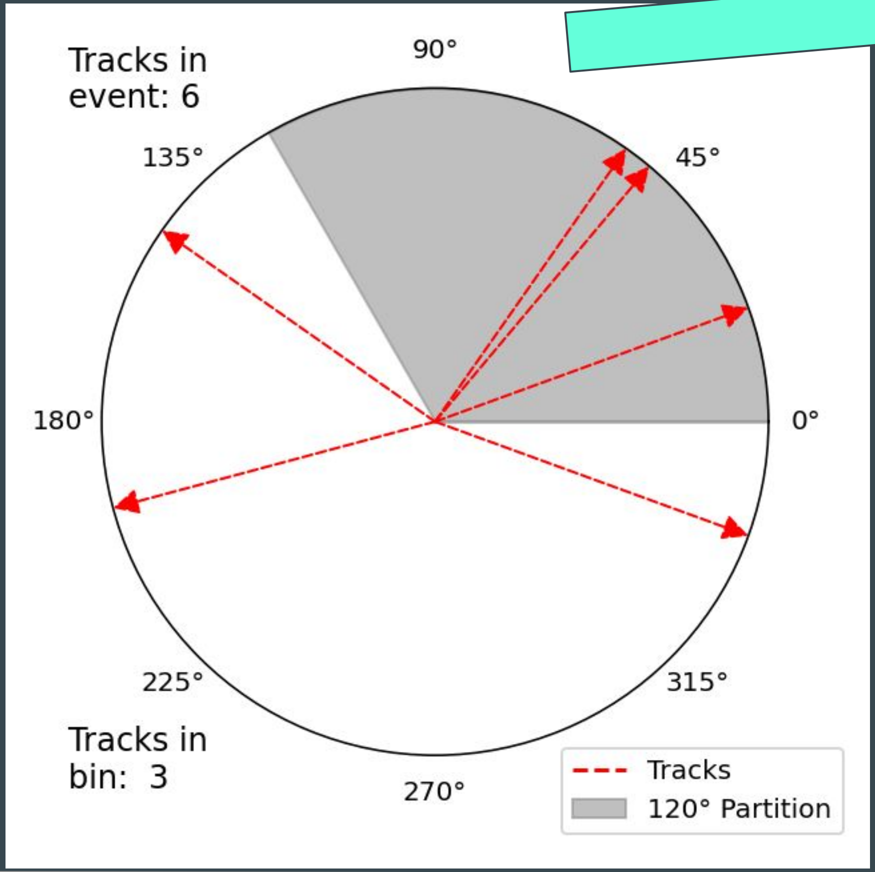
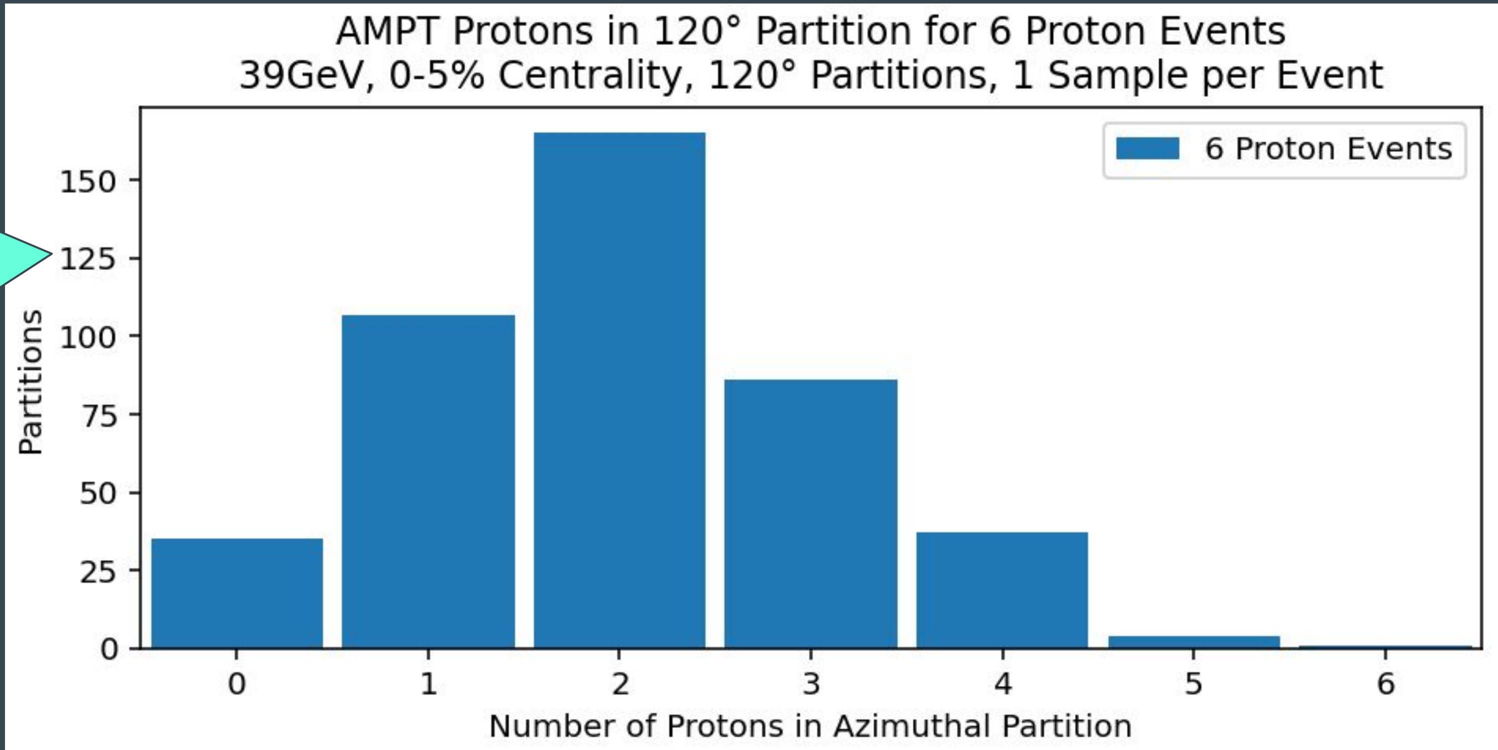


Histogram tracks in partition over many events



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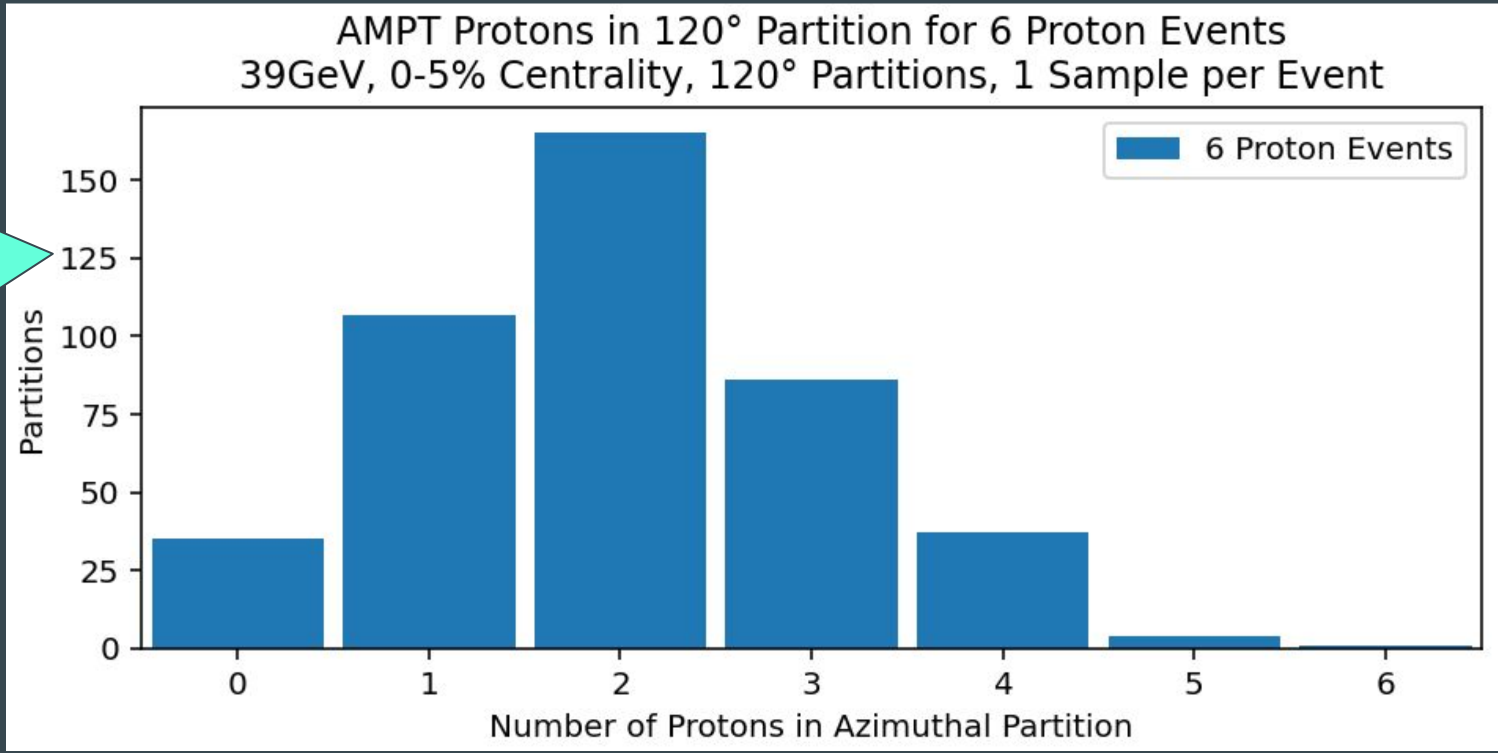
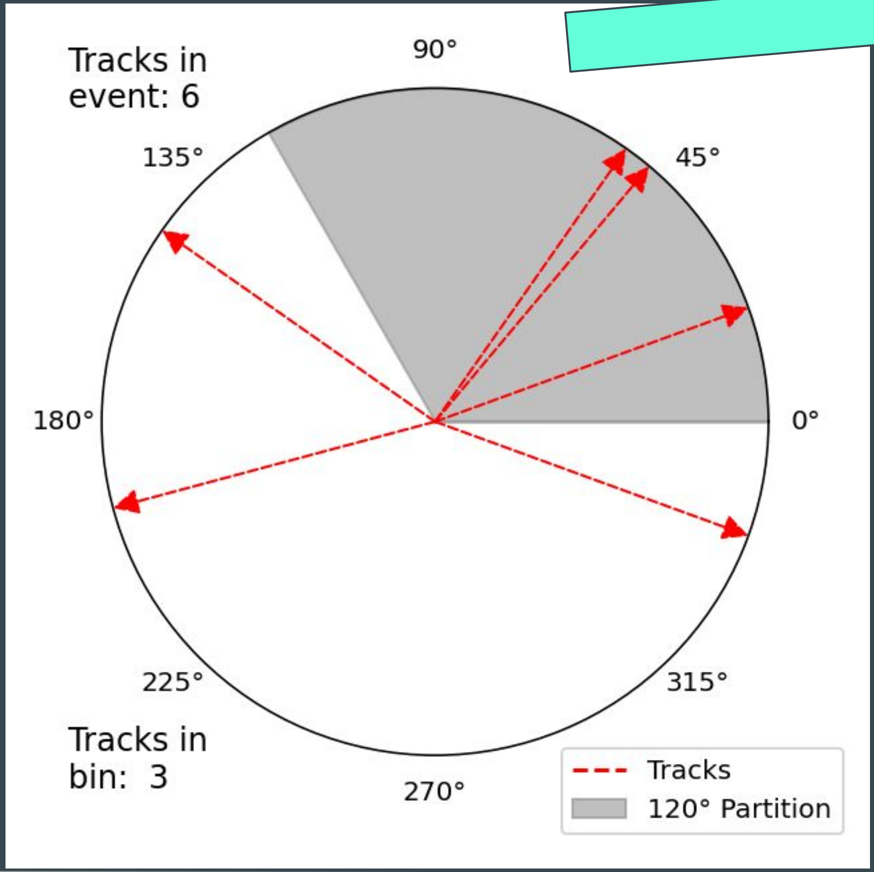
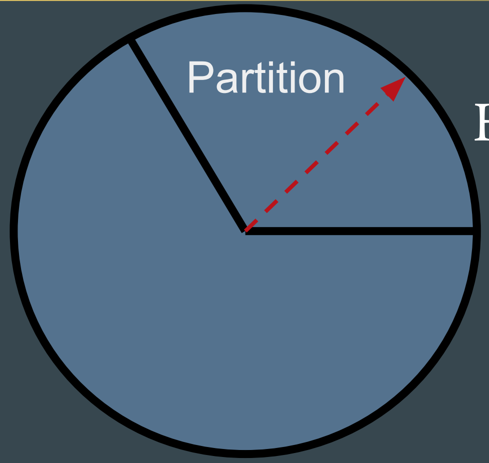




Separate histogram for each class of events:

- 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?

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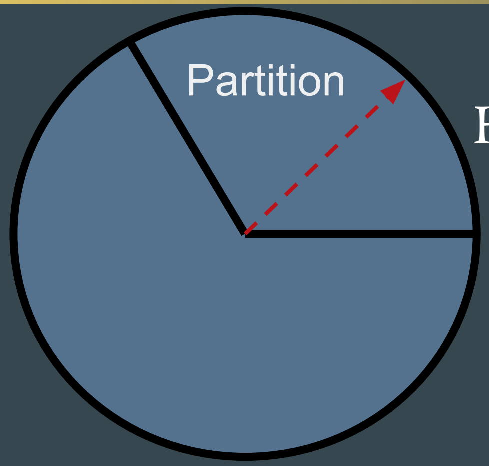

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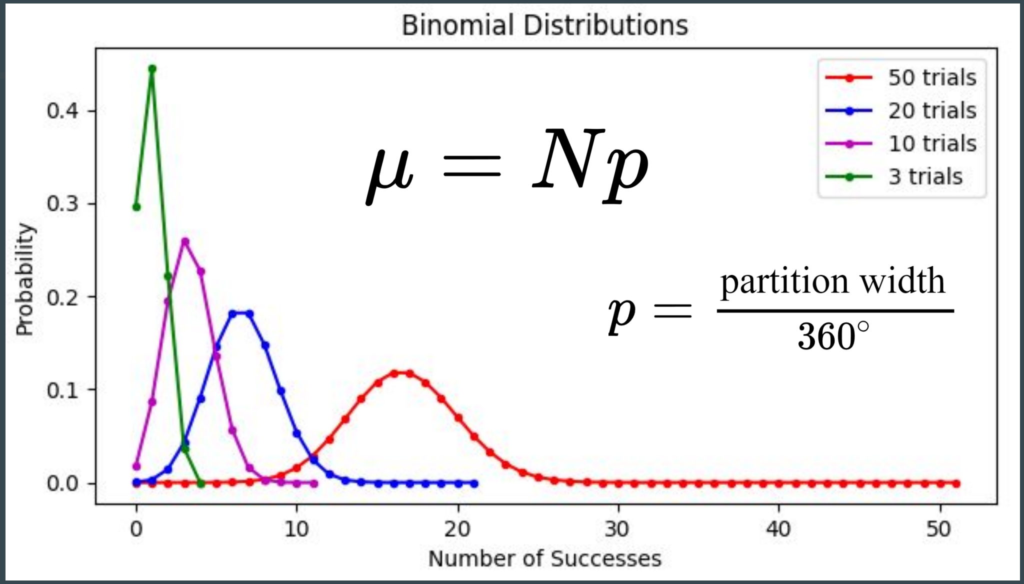

$$\mu = Np$$

$$p = \frac{\text{partition width}}{360^\circ}$$

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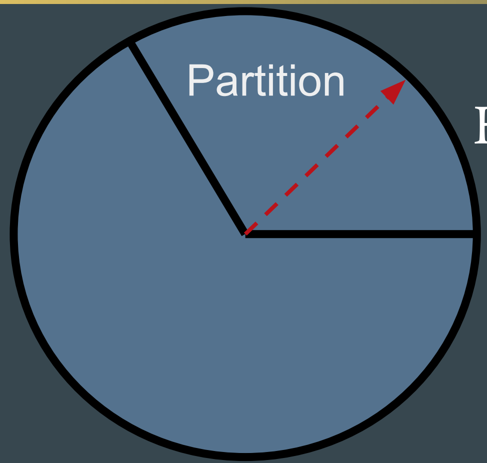

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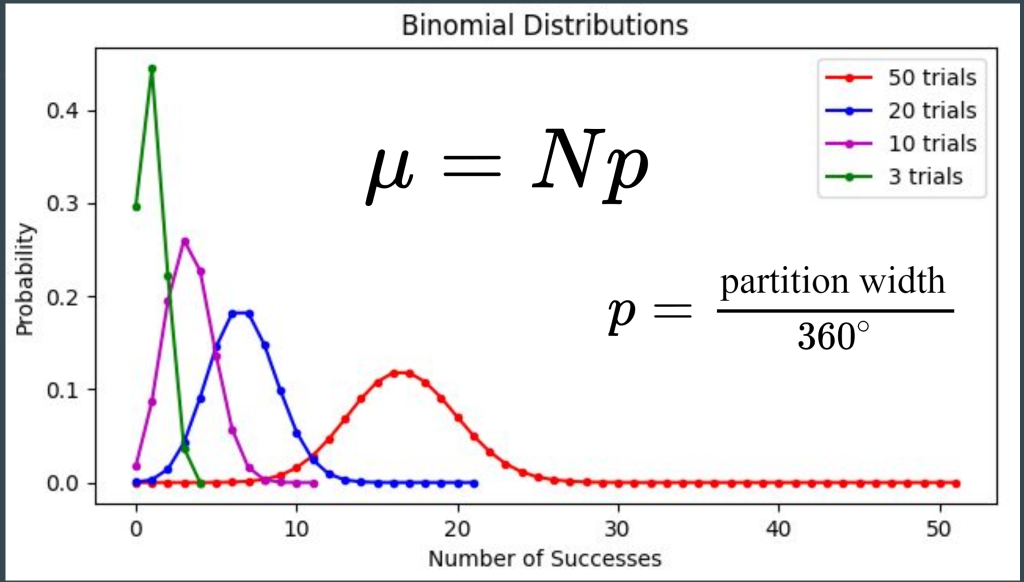

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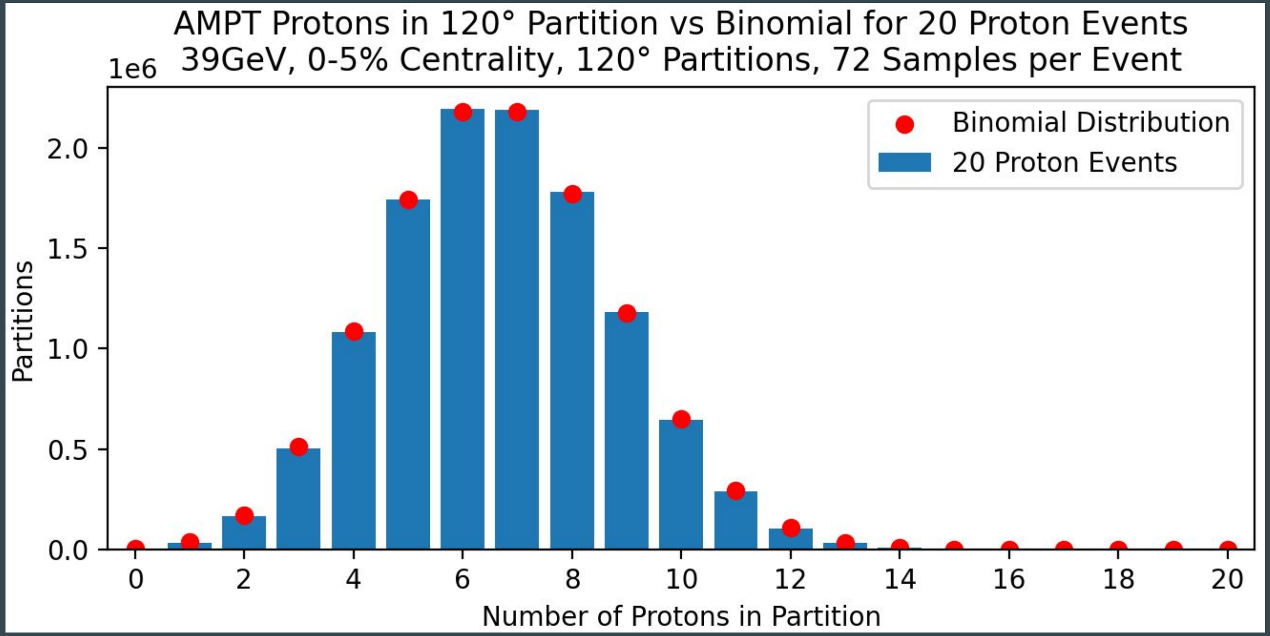
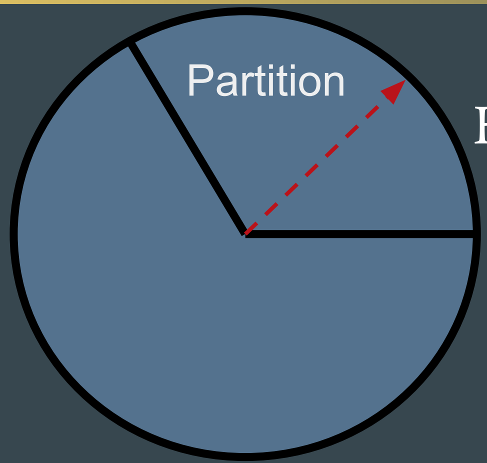
Compare measured distributions to binomial



Systematic deviations from binomial suggest correlation between proton tracks

Compare to Binomial



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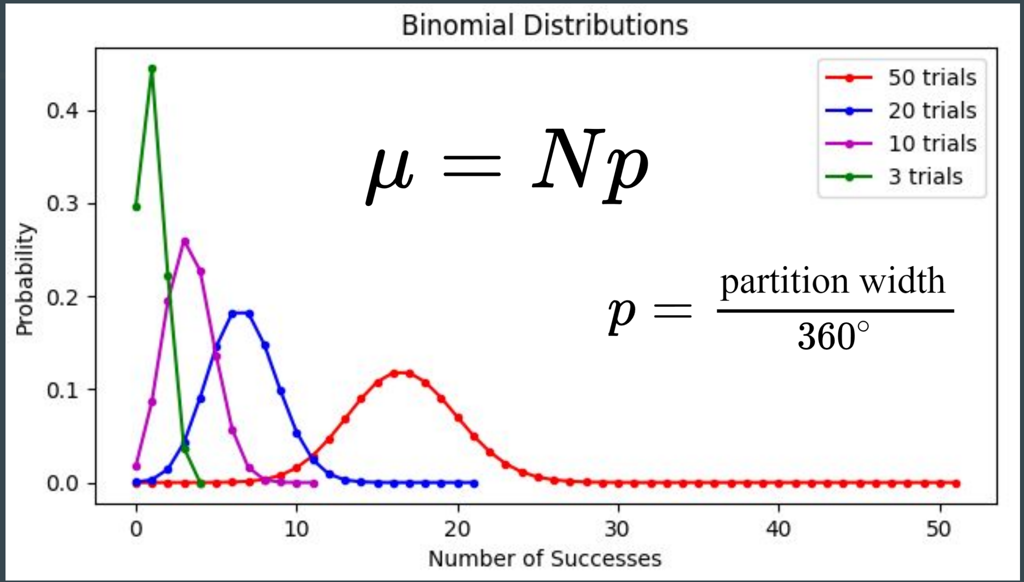

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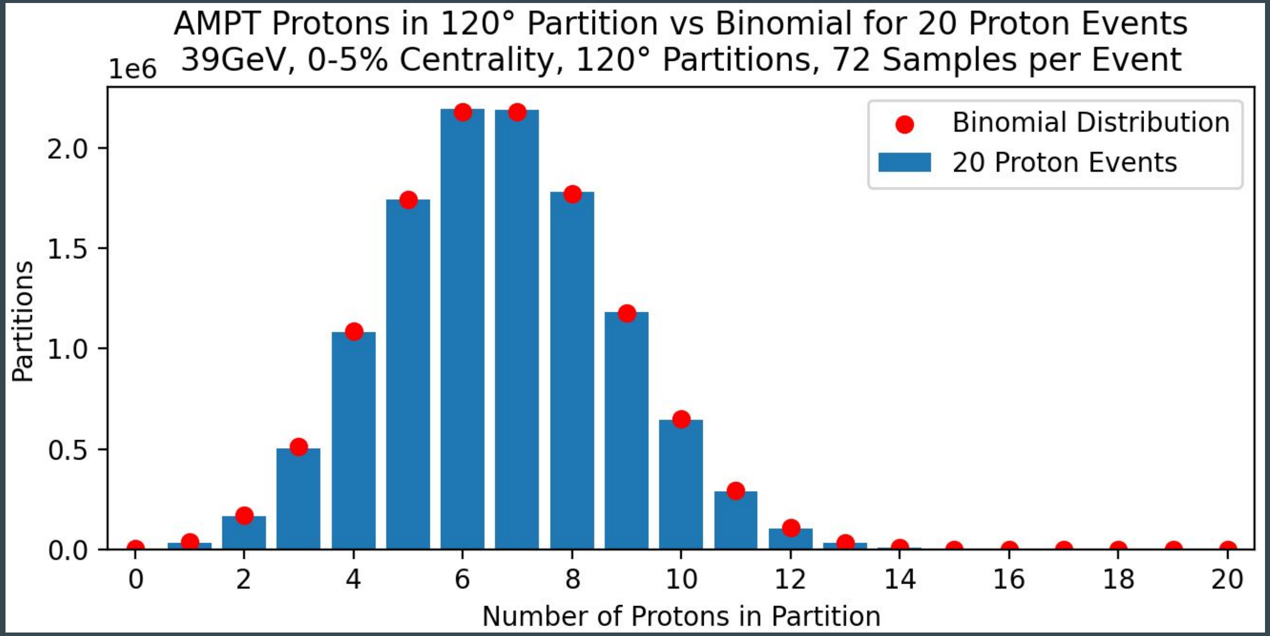


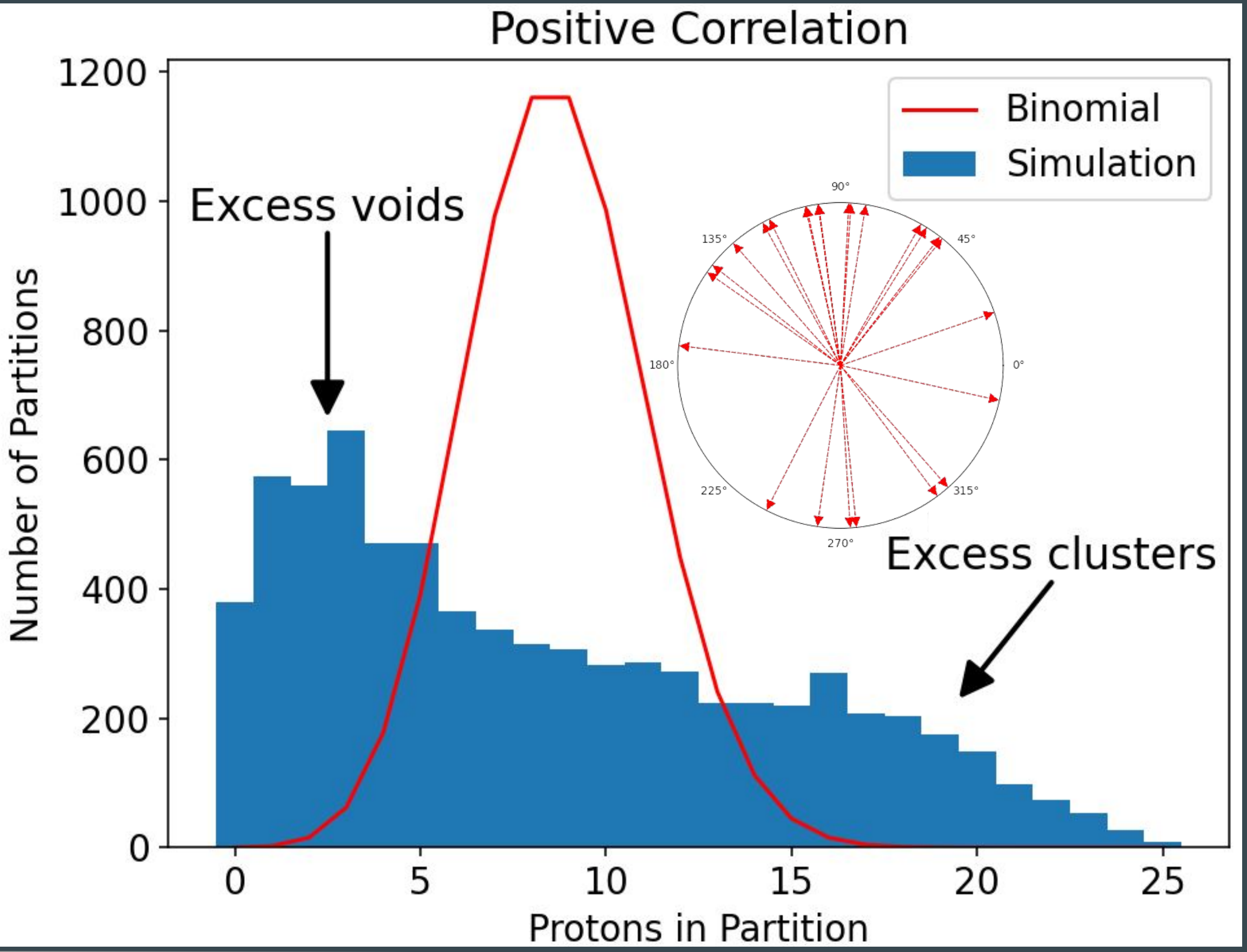
Systematic deviations from binomial suggest correlation between proton tracks

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

Large variance → excess clustering



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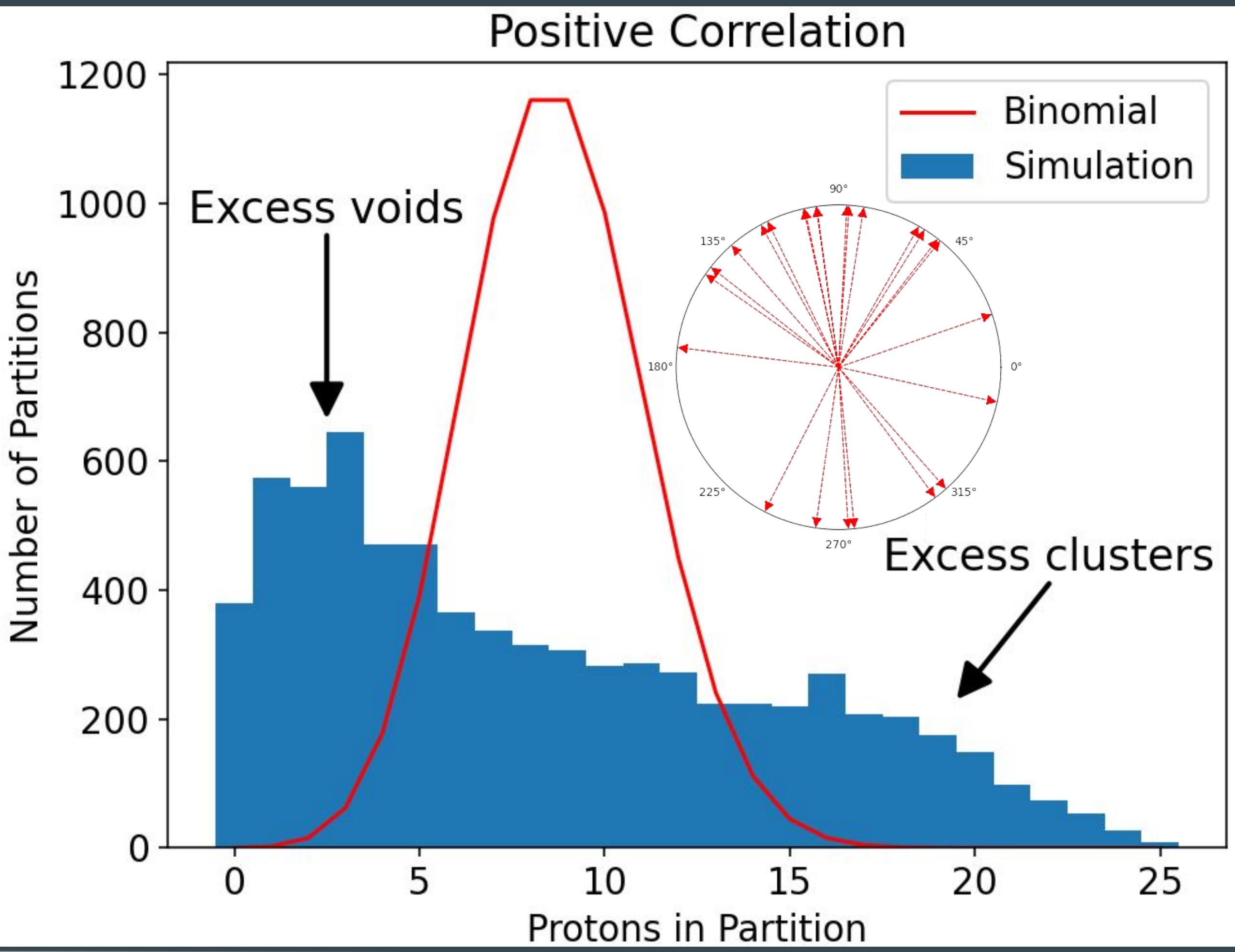
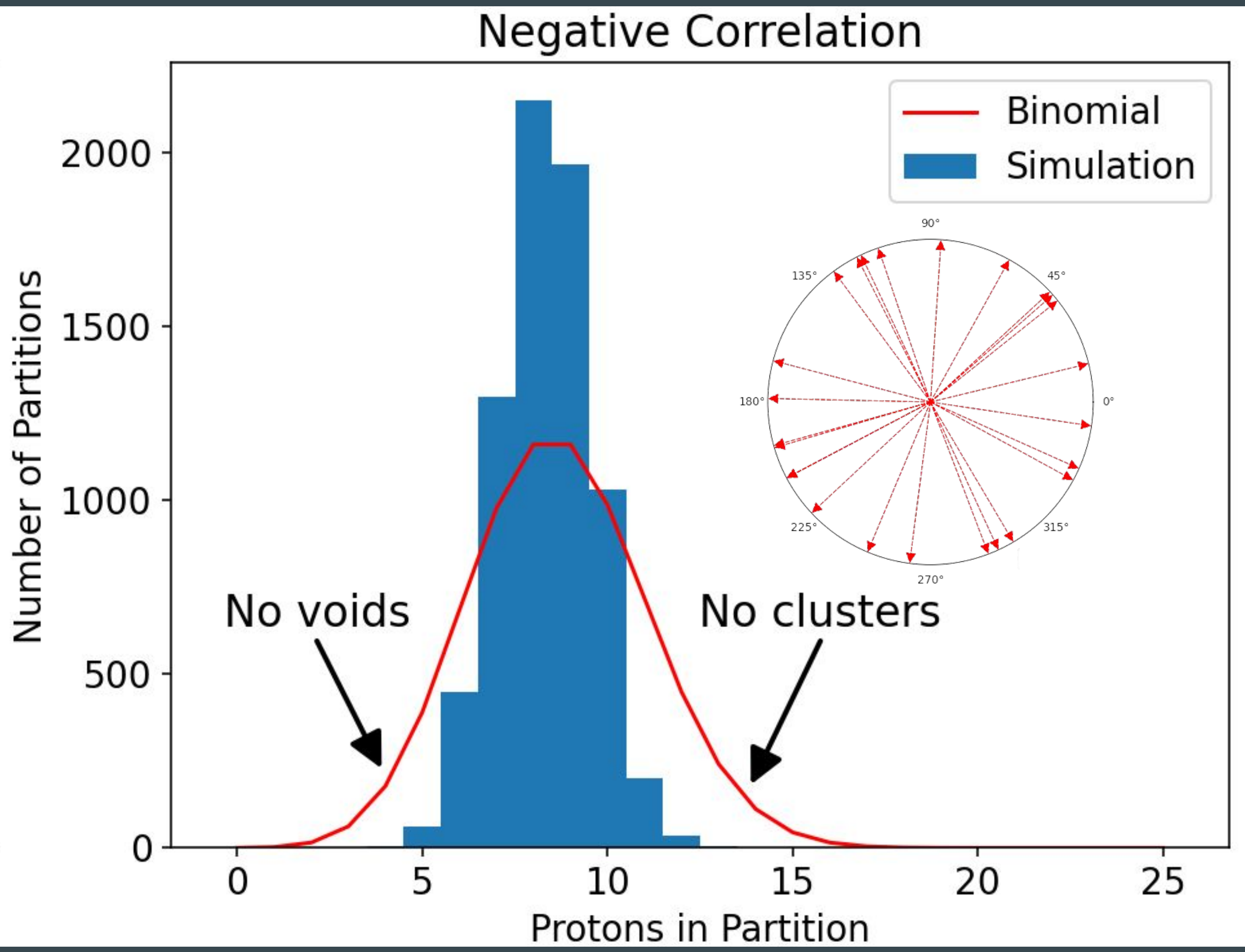
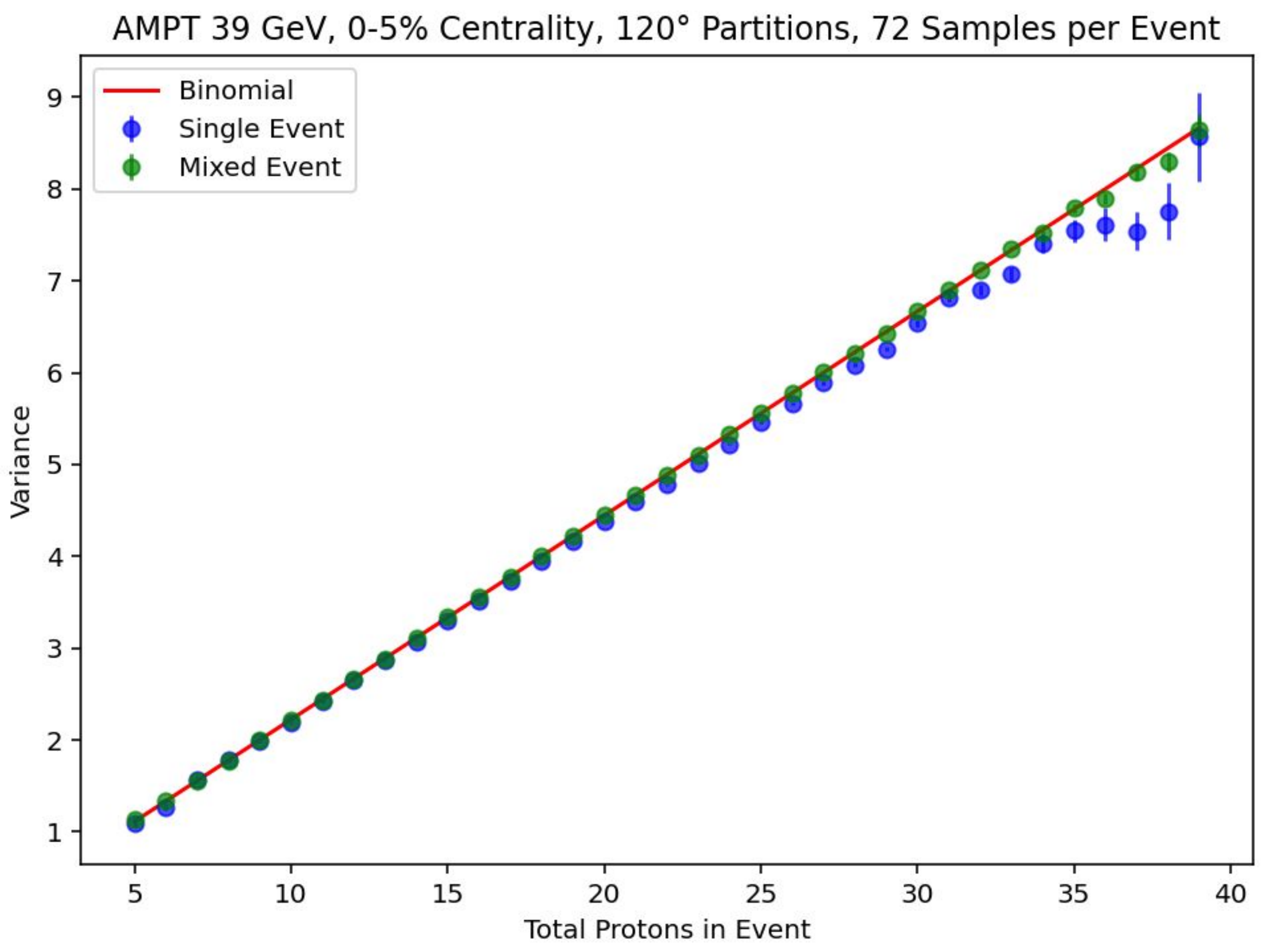


Small variance → lack of clustering



Compare Variance to Binomial



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

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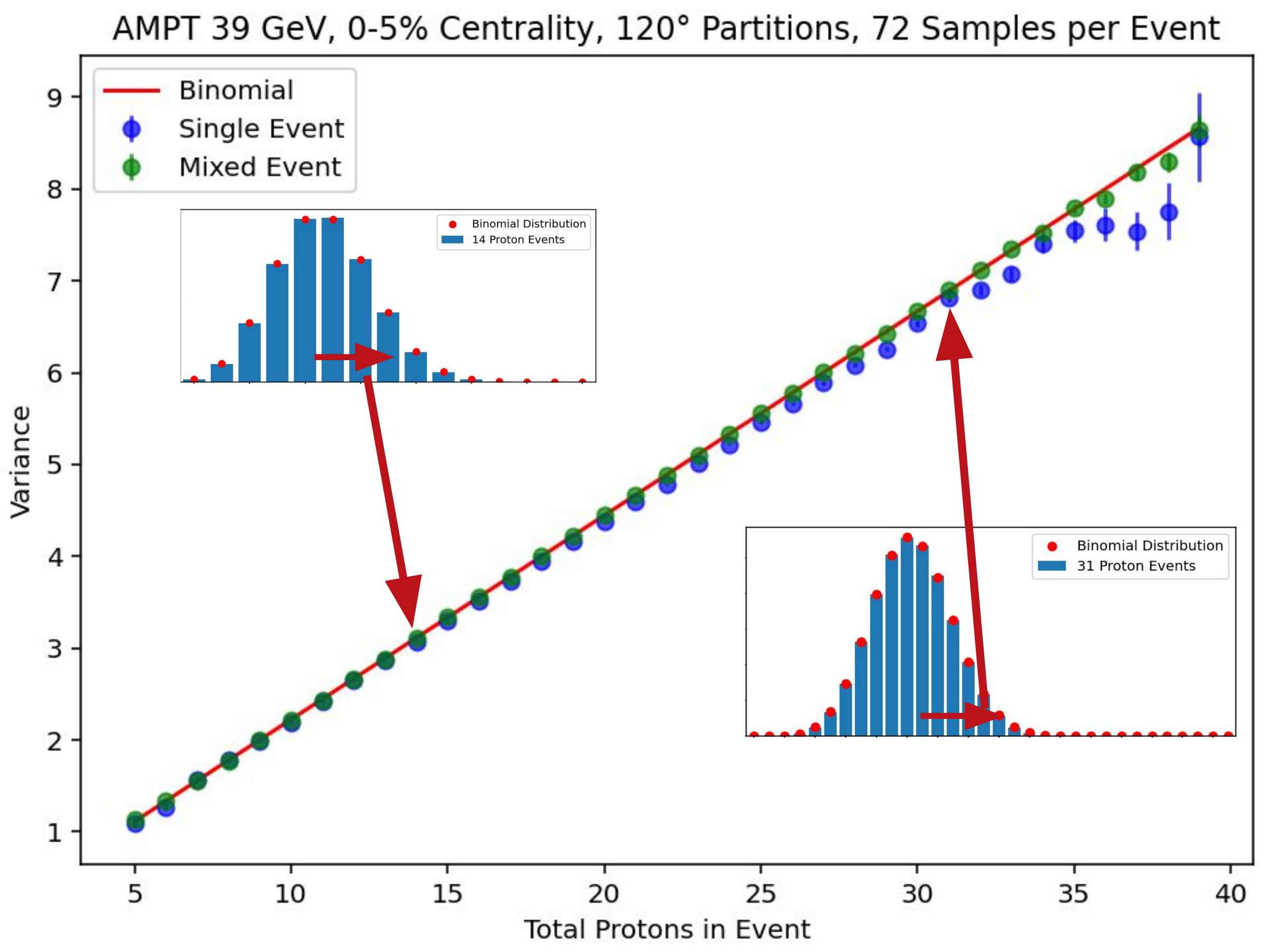

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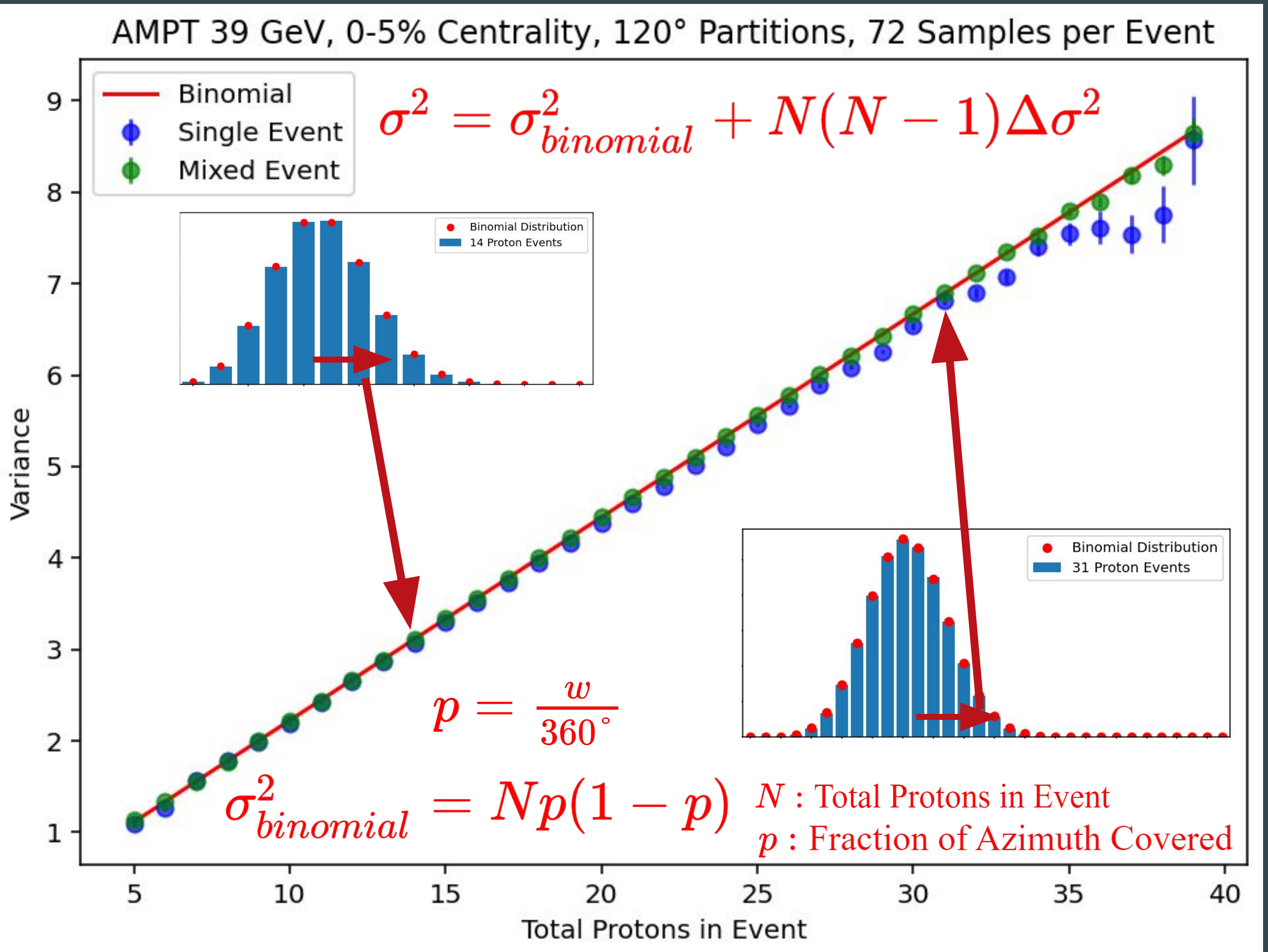

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Define observable as normalized deviation from binomial

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

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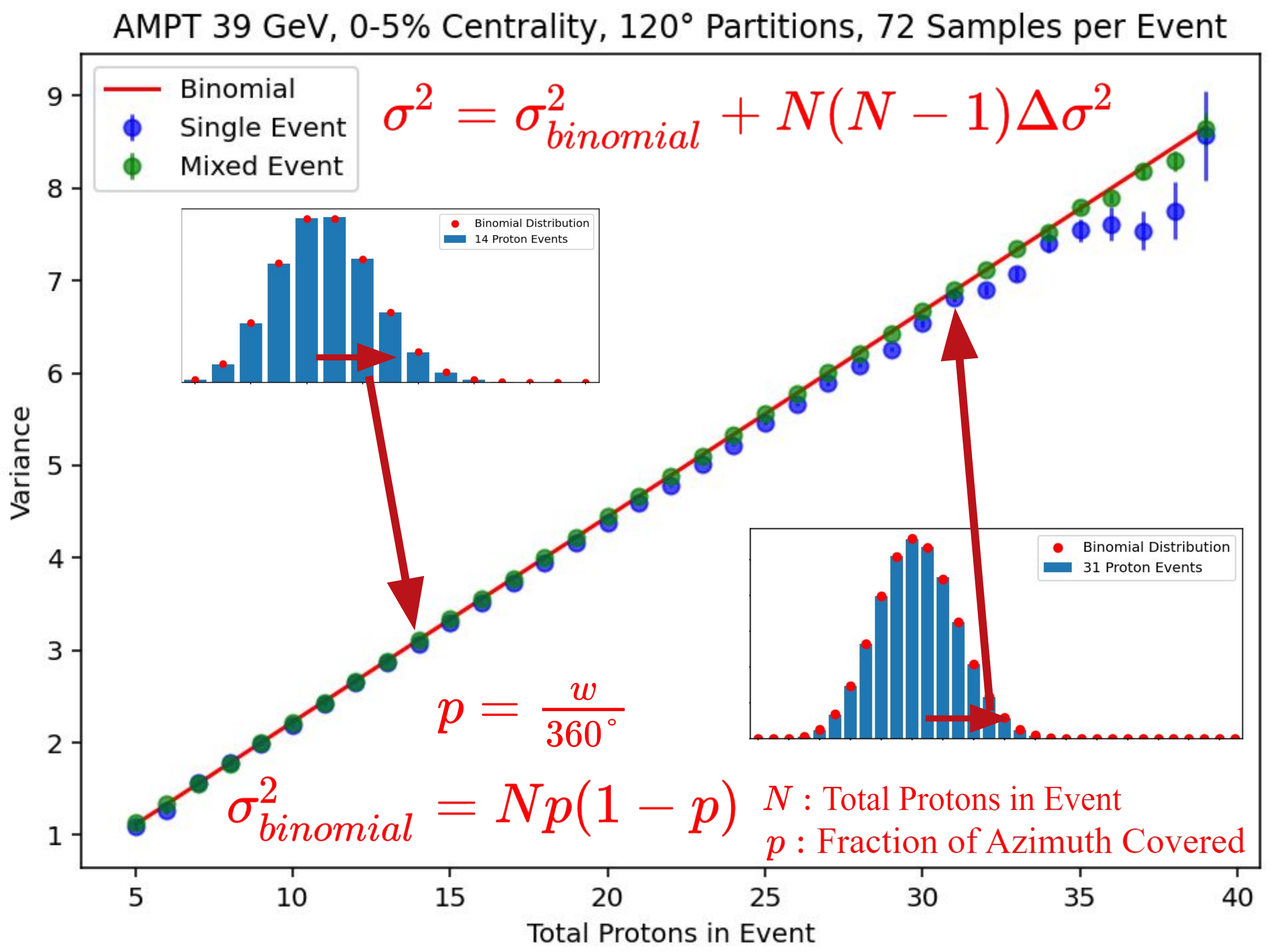
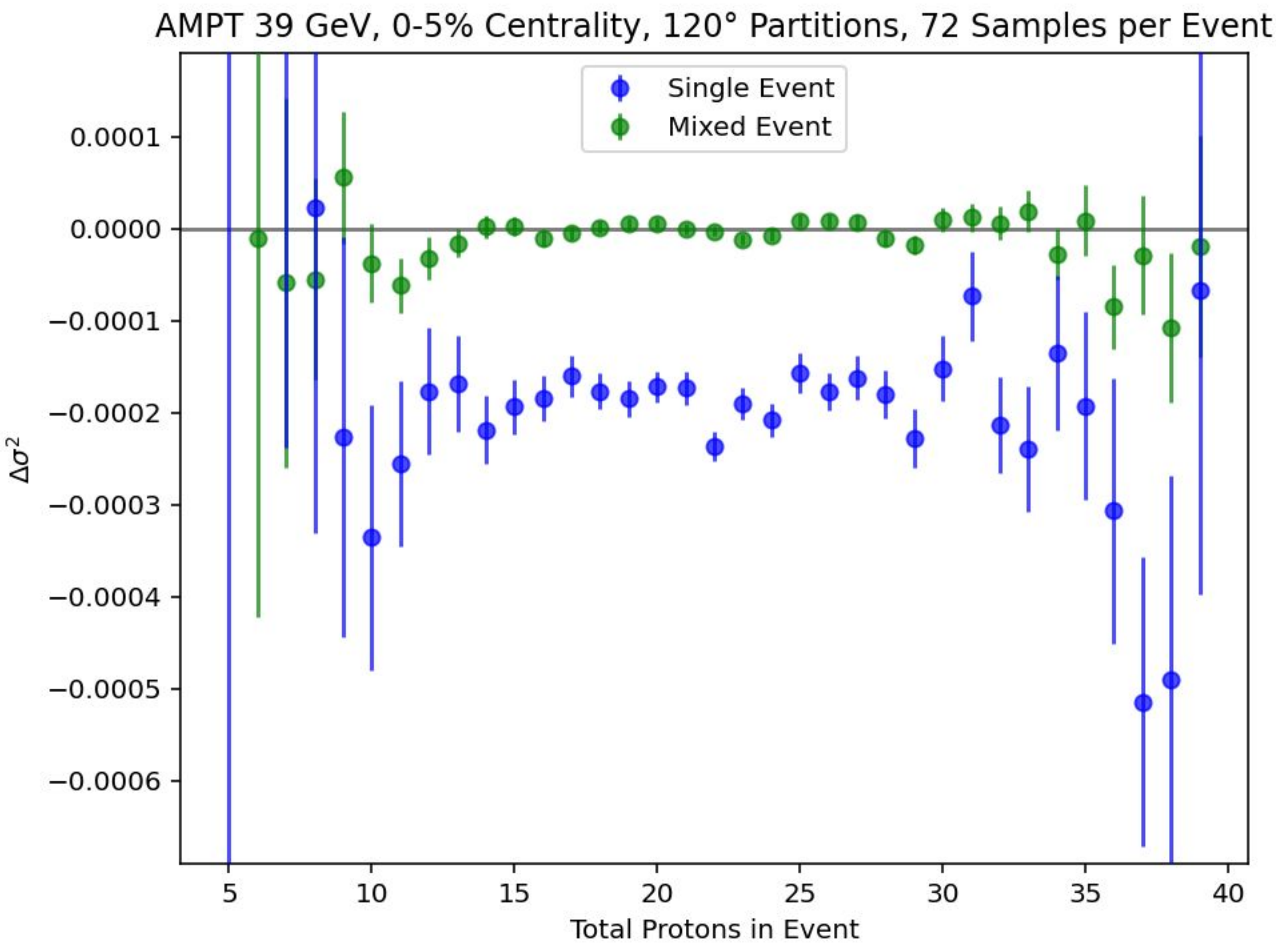


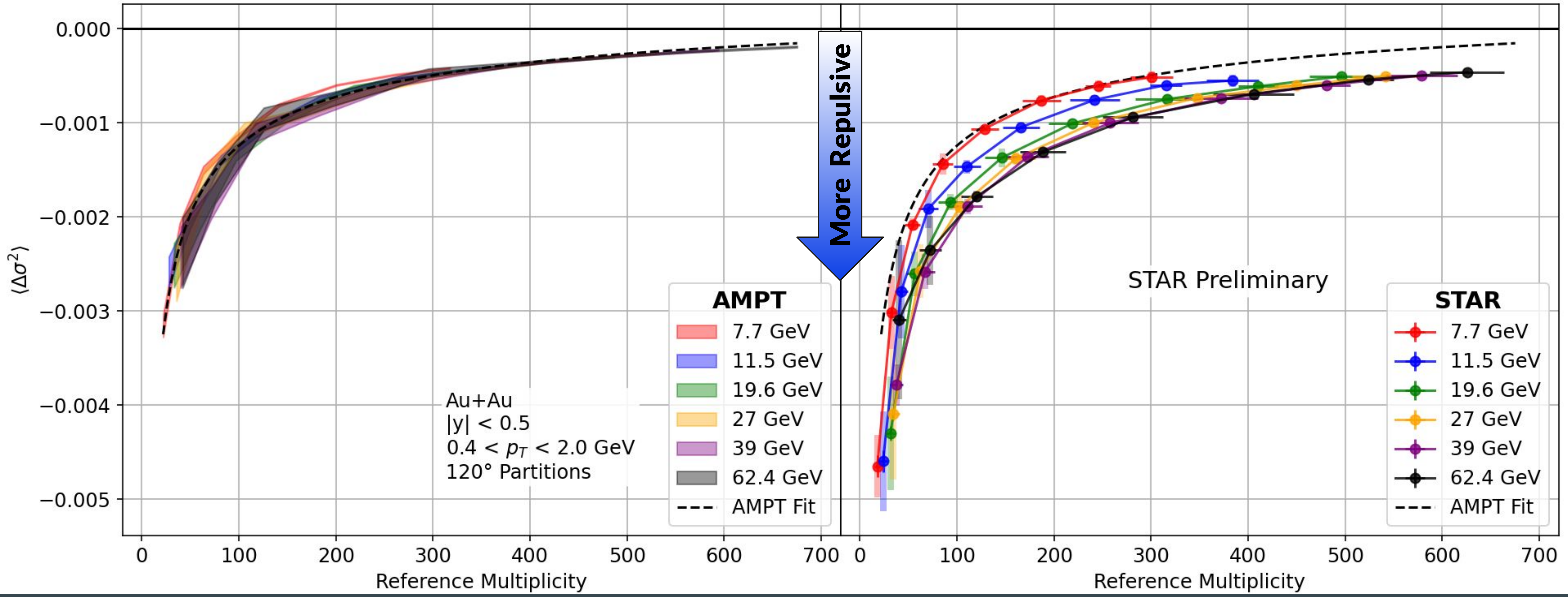


Single and Mixed Event variances very similar to binomial, though slight deviations apparent

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

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

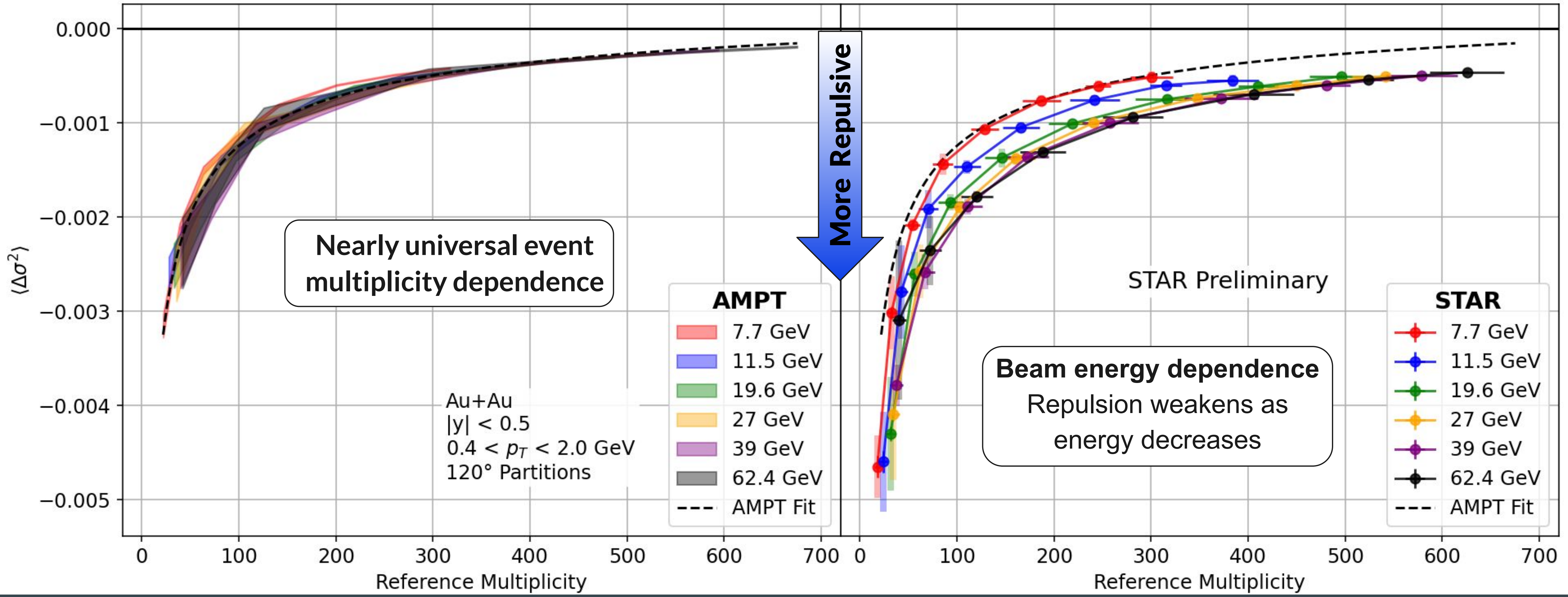
Magnitude of repulsive interaction increases with decreasing multiplicity per event



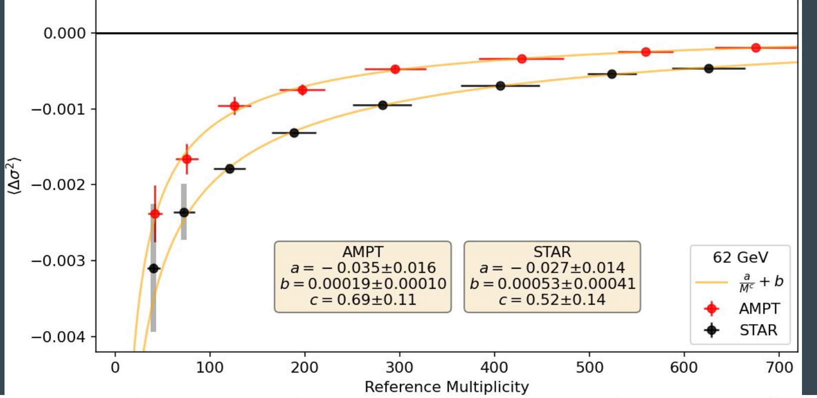
⟨$\Delta\sigma^2$⟩ vs Event Multiplicity

Magnitude of repulsive interaction increases with decreasing multiplicity per event

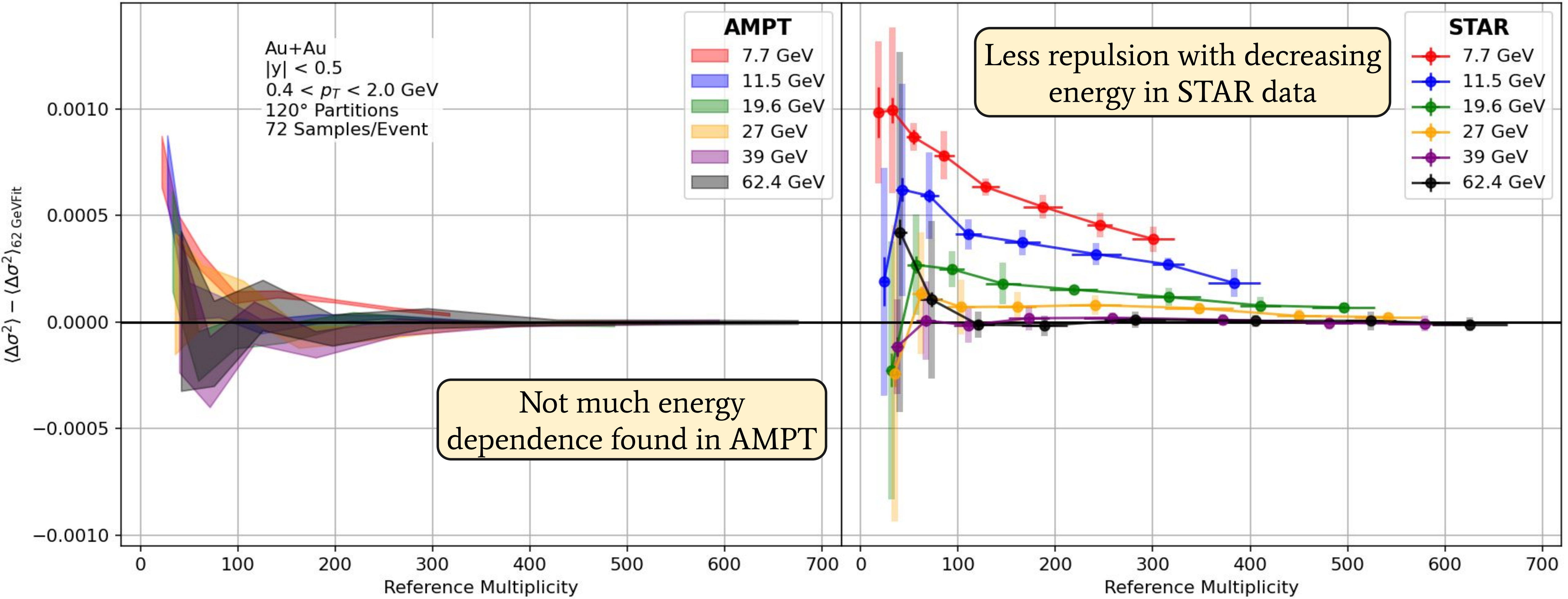
Multiplicity dependence likely dominated by global momentum conservation



Subtract 62 GeV Baseline



Subtract the 62.4 GeV fits to highlight the STAR energy dependence



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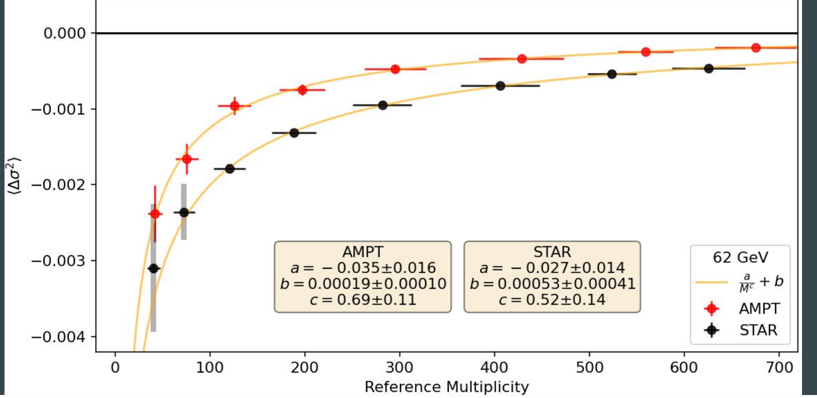
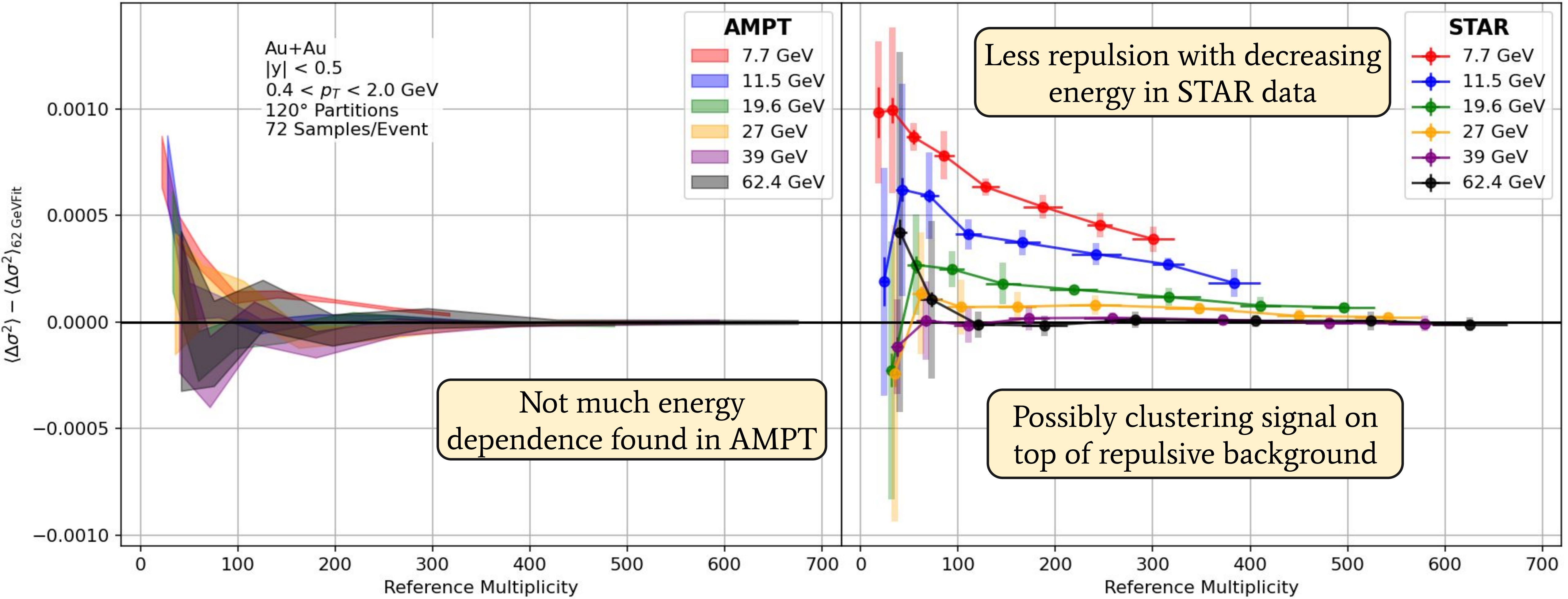
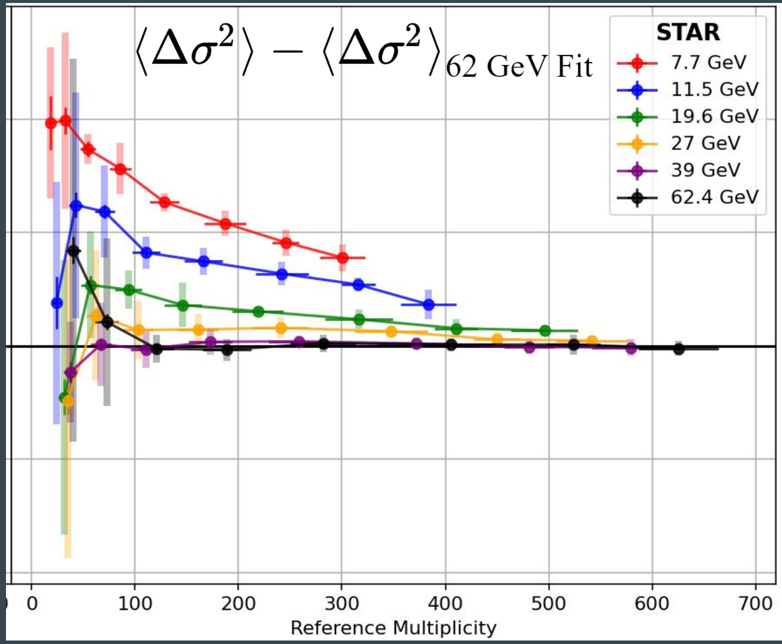




Summary

- Phase diagram of QCD probed with the Beam Energy Scan at RHIC
  - Look for clustering of protons as signal for first-order transition
- Strong proton repulsion observed
  - Likely momentum conservation background
  - Need to correct this background to measure possible superimposed clustering signal



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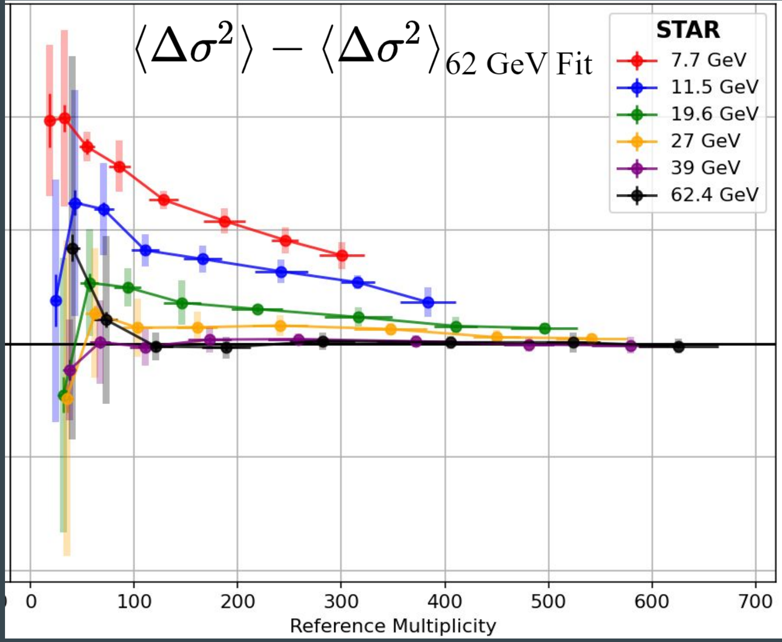

Thanks for your attention!

Backup

RHIC Beam Energy Scan (BES)

$\uparrow \sqrt{s_{NN}} \leftrightarrow \mu_B \downarrow$

Collision energy is directly related to baryon density at mid rapidity

- Initial state nuclei made of baryons
- More baryons transported to mid-rapidity at lower beam energies
- Pair production at higher energy dilutes baryon density

$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	T_{CH} (MeV)
200	25	166
62.4	73	165
54.4	83	165
39	112	164
27	156	162
19.6	206	160
14.5	264	156
11.5	315	152
9.2	355	140
7.7	420	140

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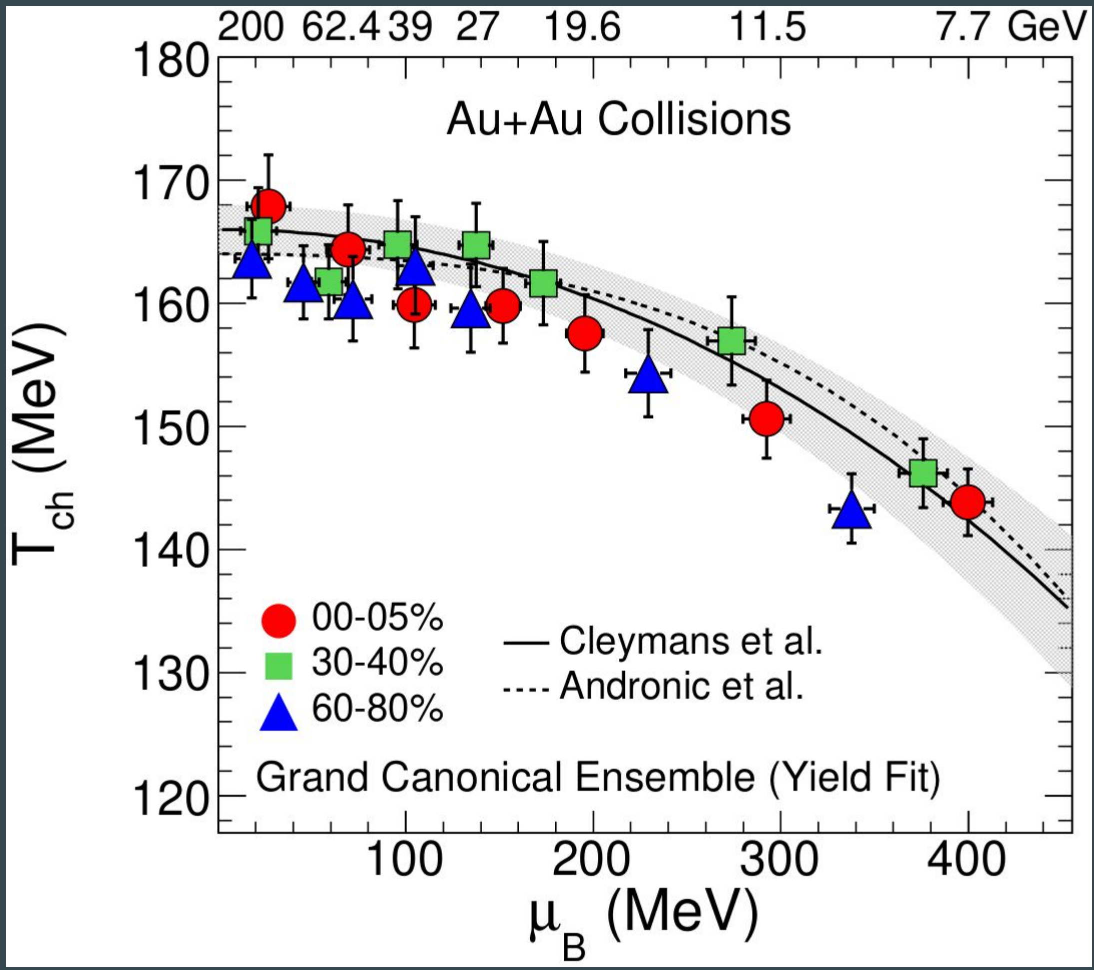
Vary beam energy to scan QCD phase space



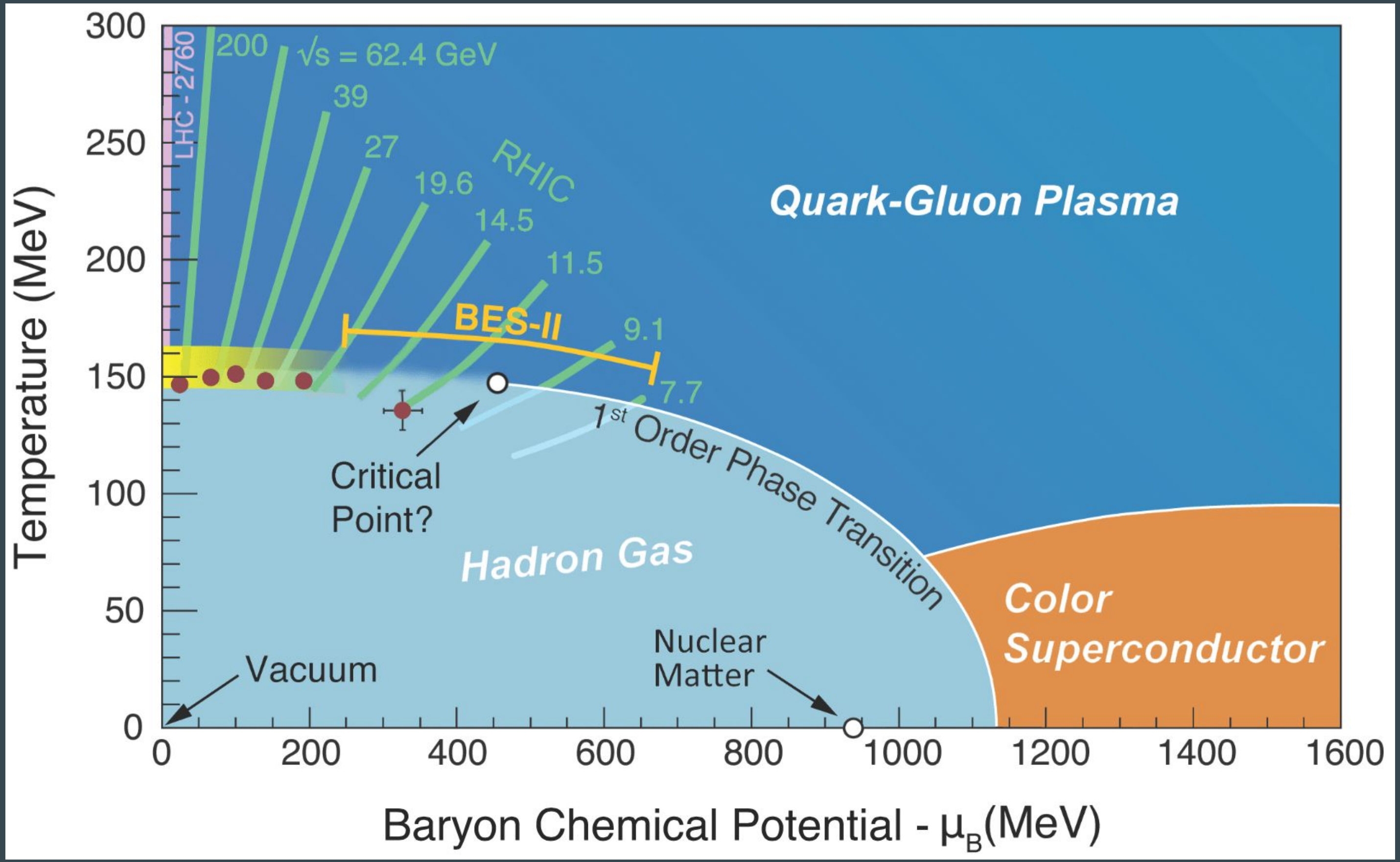
STAR: Phys.Rev.C 96 (2017) 4, 044904

RHIC Beam Energy Scan (BES)

Experimental signature of critical point?

Fluctuations ⟶ Critical Point ⟶ STAR Net Proton Analysis

Clustering ⟶ First Order ⟶ Azimuthal Partition Analysis



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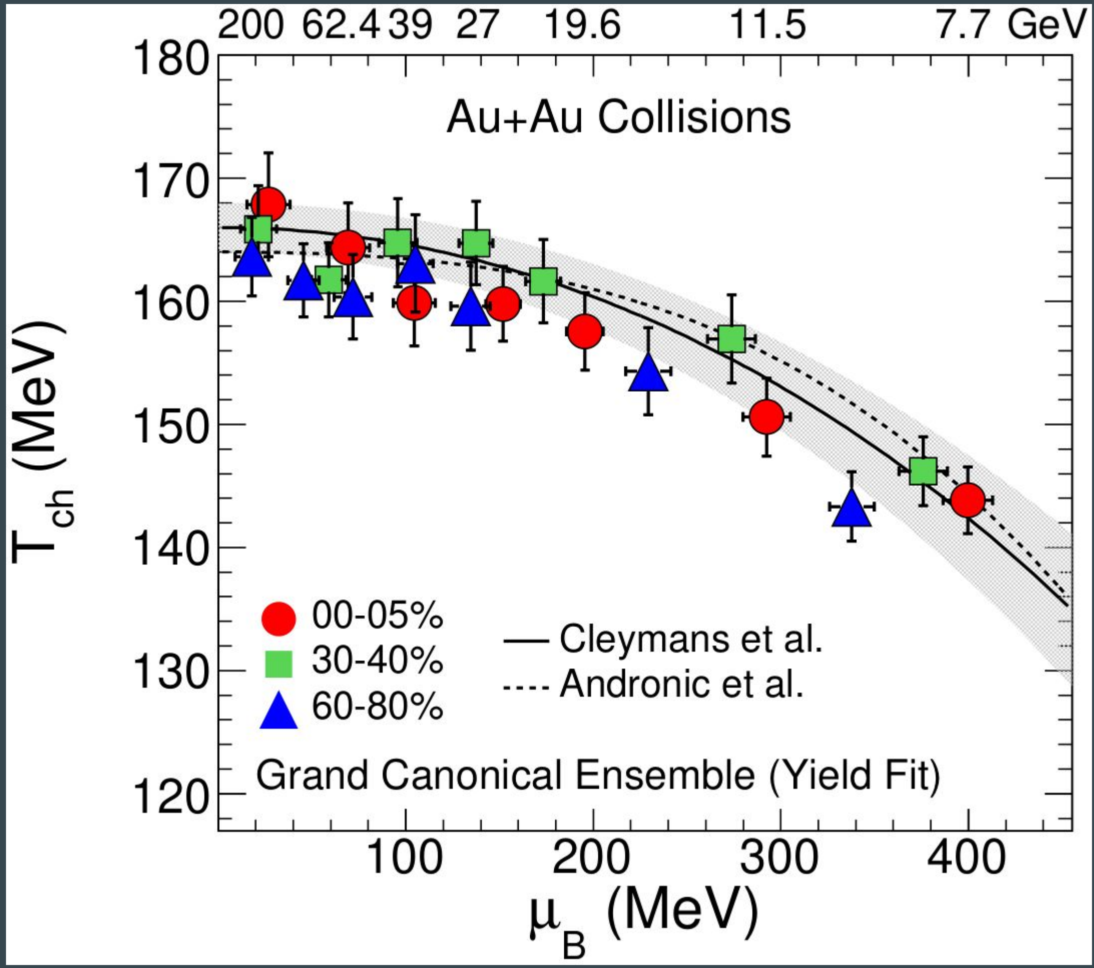

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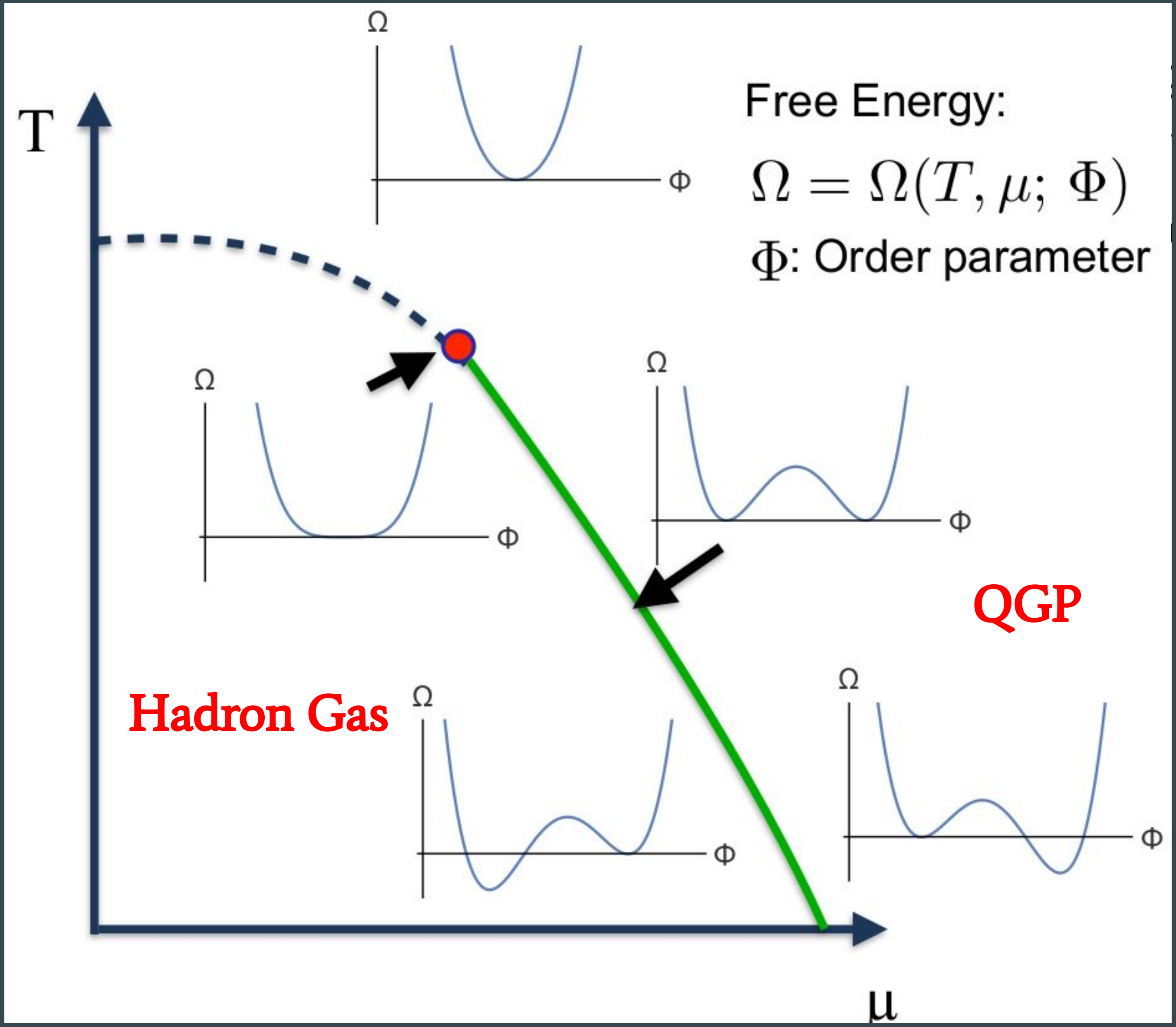
Phase Transitions of QCD

V. Koch Quark Matter 2019

Order parameters for QCD are conserved charge densities



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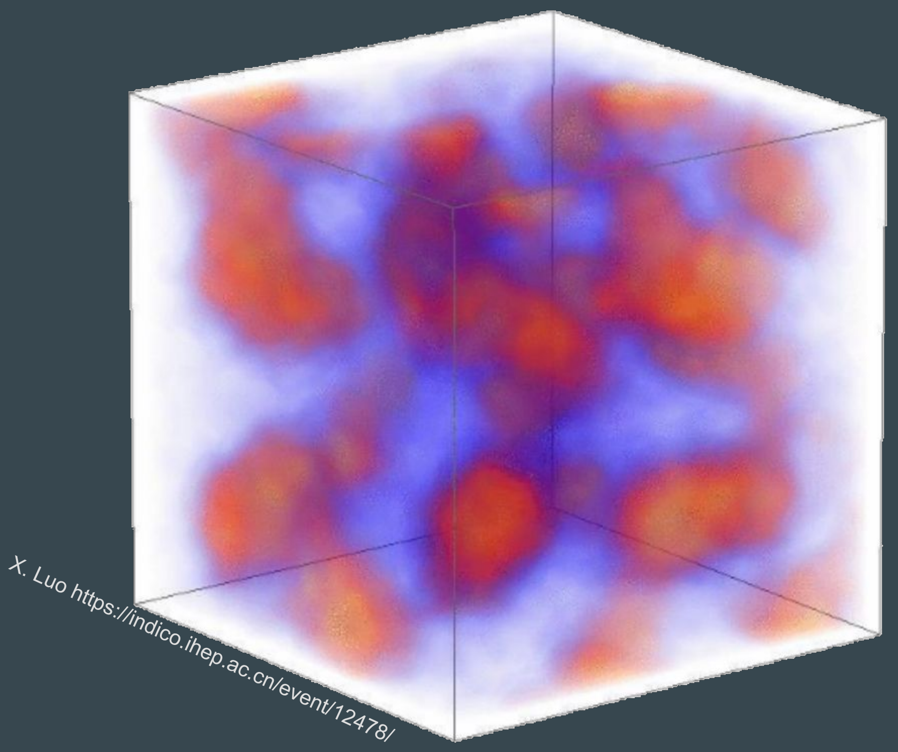

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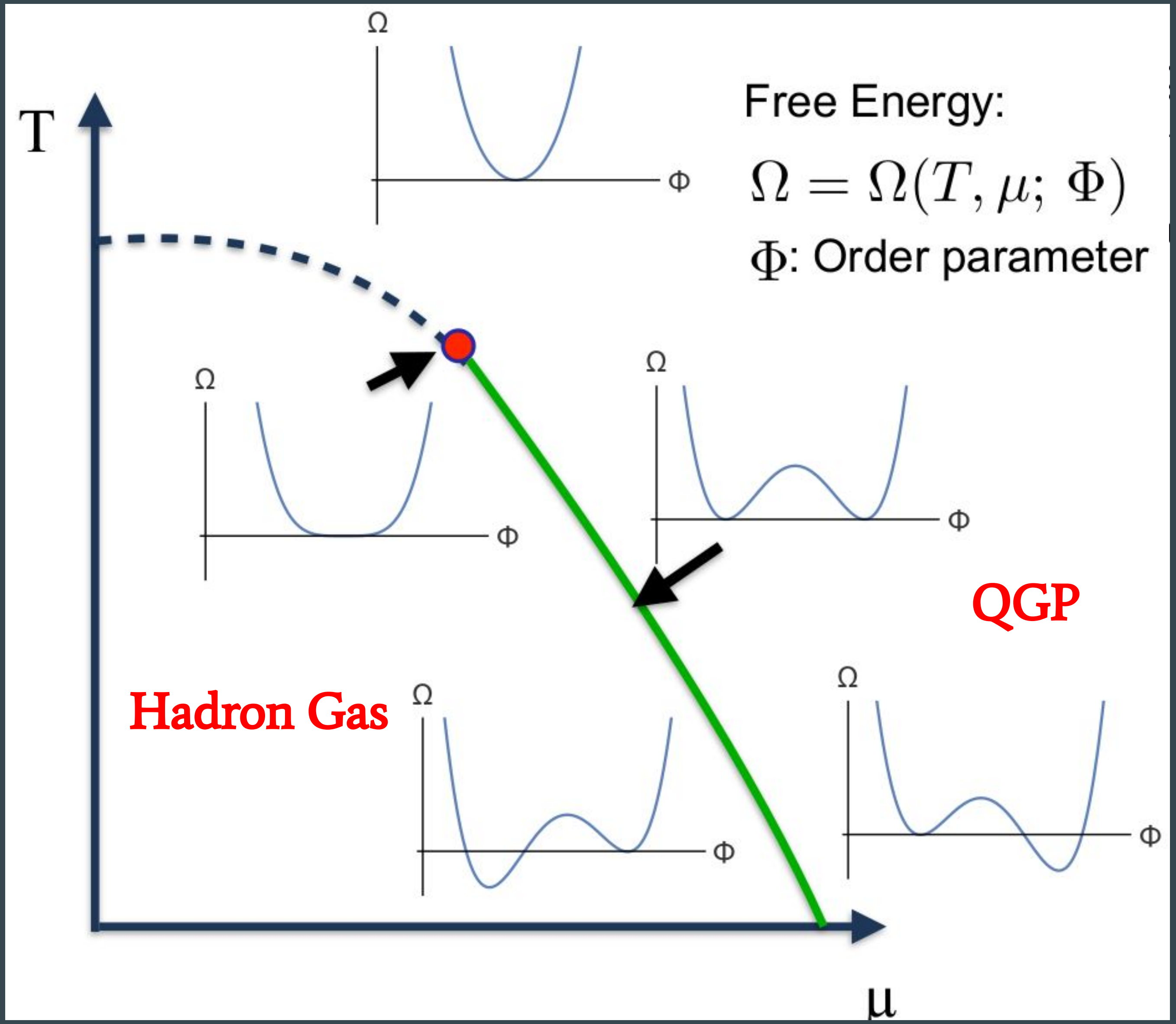
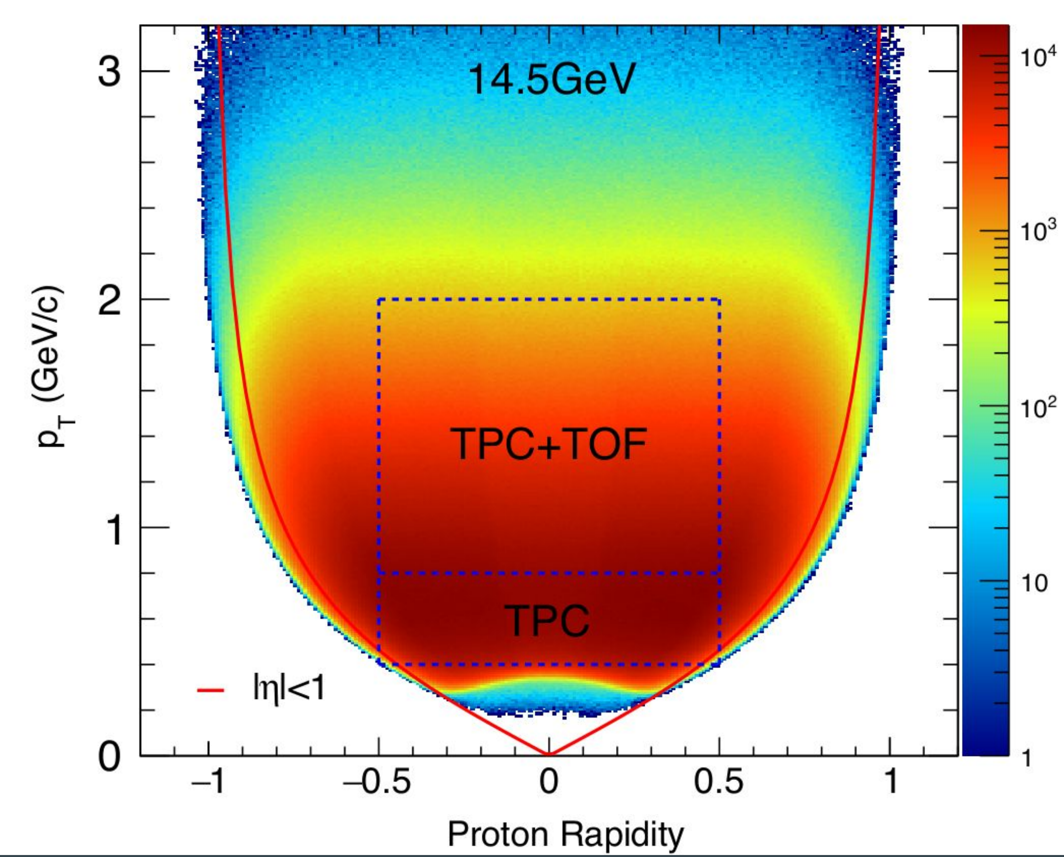


Local density fluctuations expected in 1st order transition, larger as critical point is approached → clustering

STAR Tracking and PID

Particle identification via two detectors

- Time Projection Chamber (**TPC**)
- Time of Flight (**TOF**)



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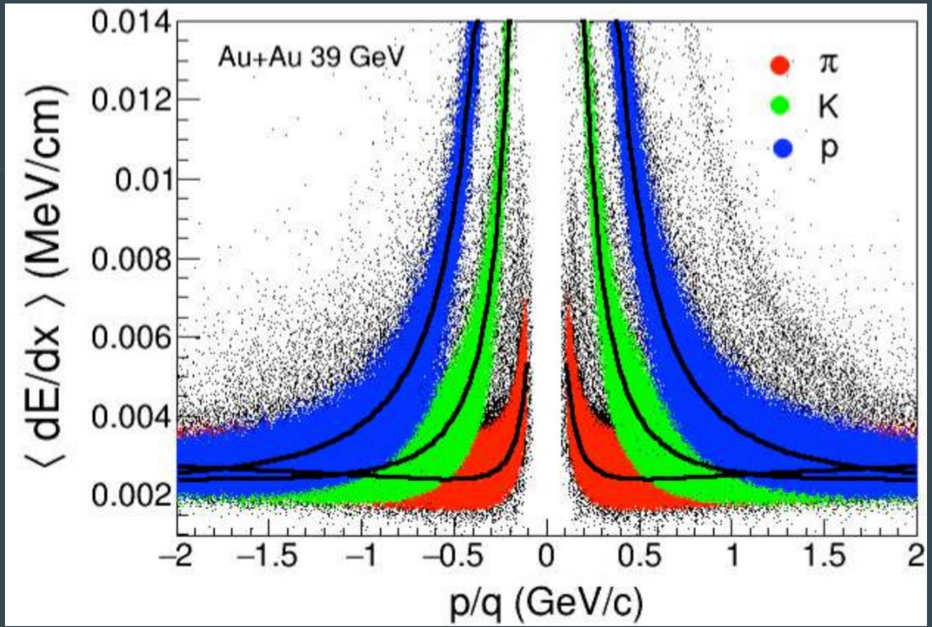
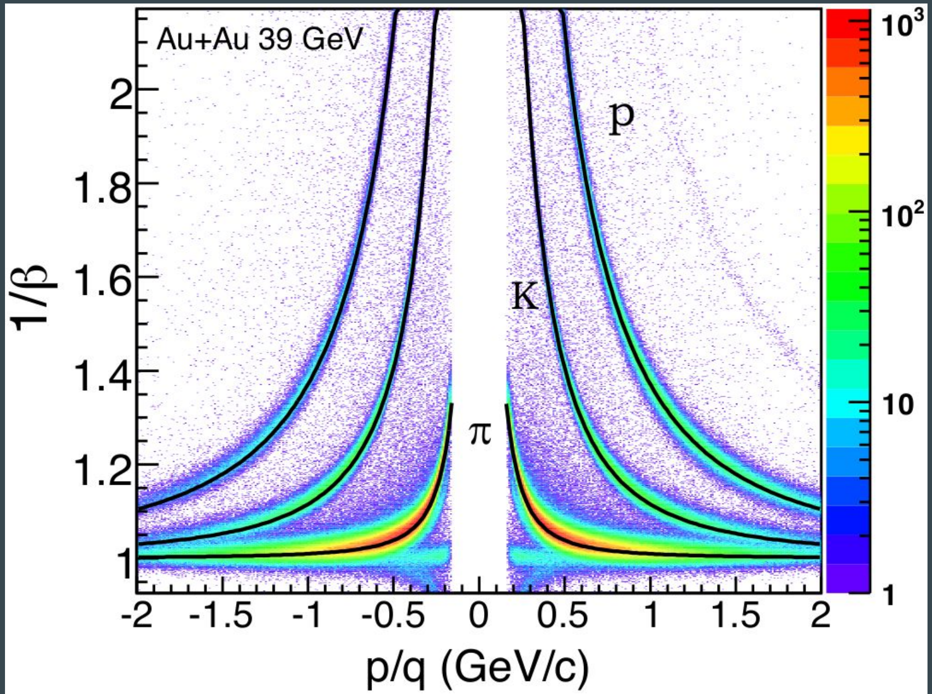
TPC

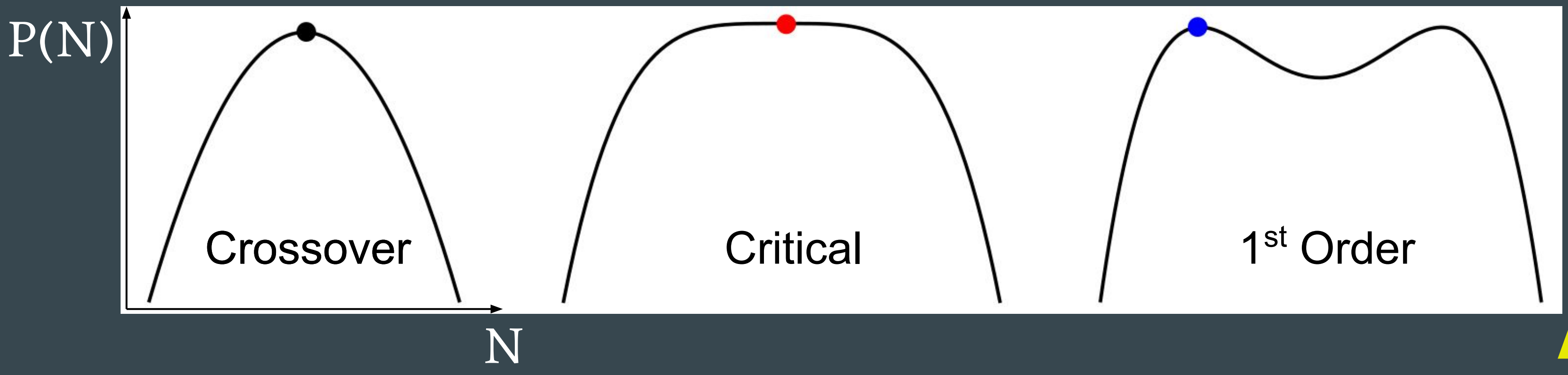


TOF



B. Mohanty https://indico.ihep.ac.cn/event/12164/

Fluctuations of Conserved Quantities



Multiplicity (N) distribution of conserved charge changes along phase transition line

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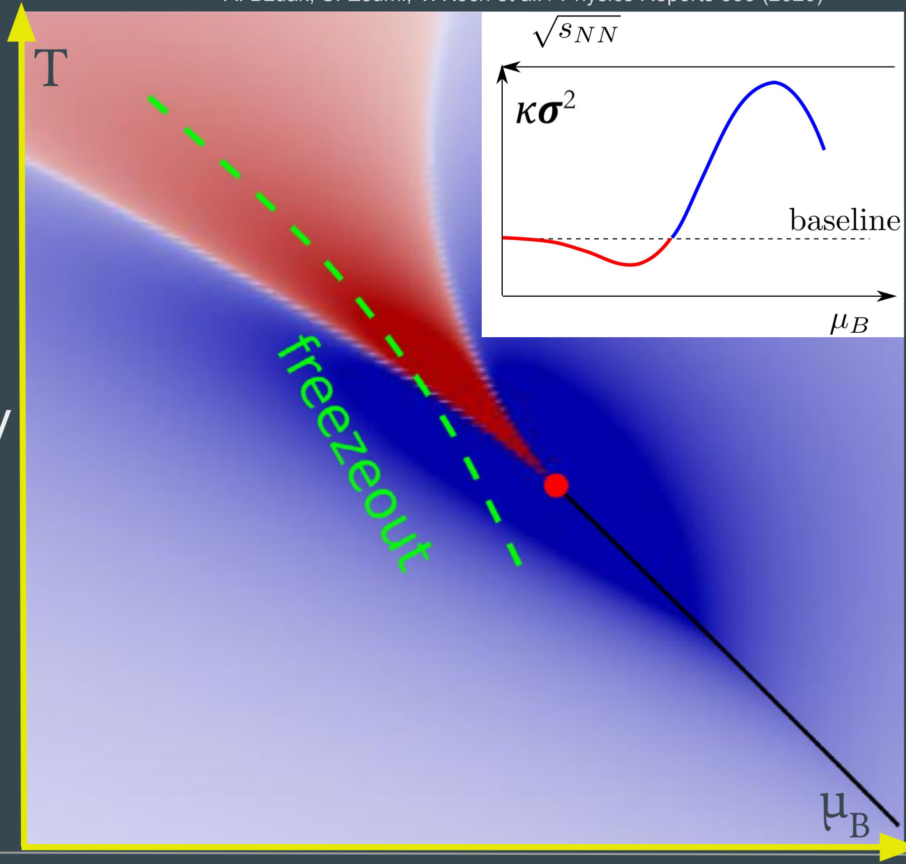
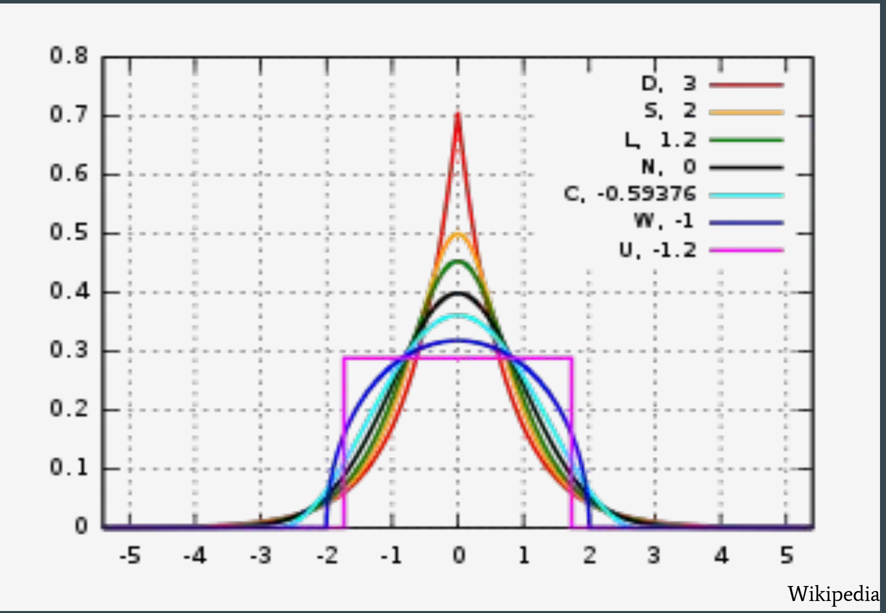


Calculate kurtosis → measure of peakedness

$$\kappa = \frac{\mu_4}{\mu_2^2}$$

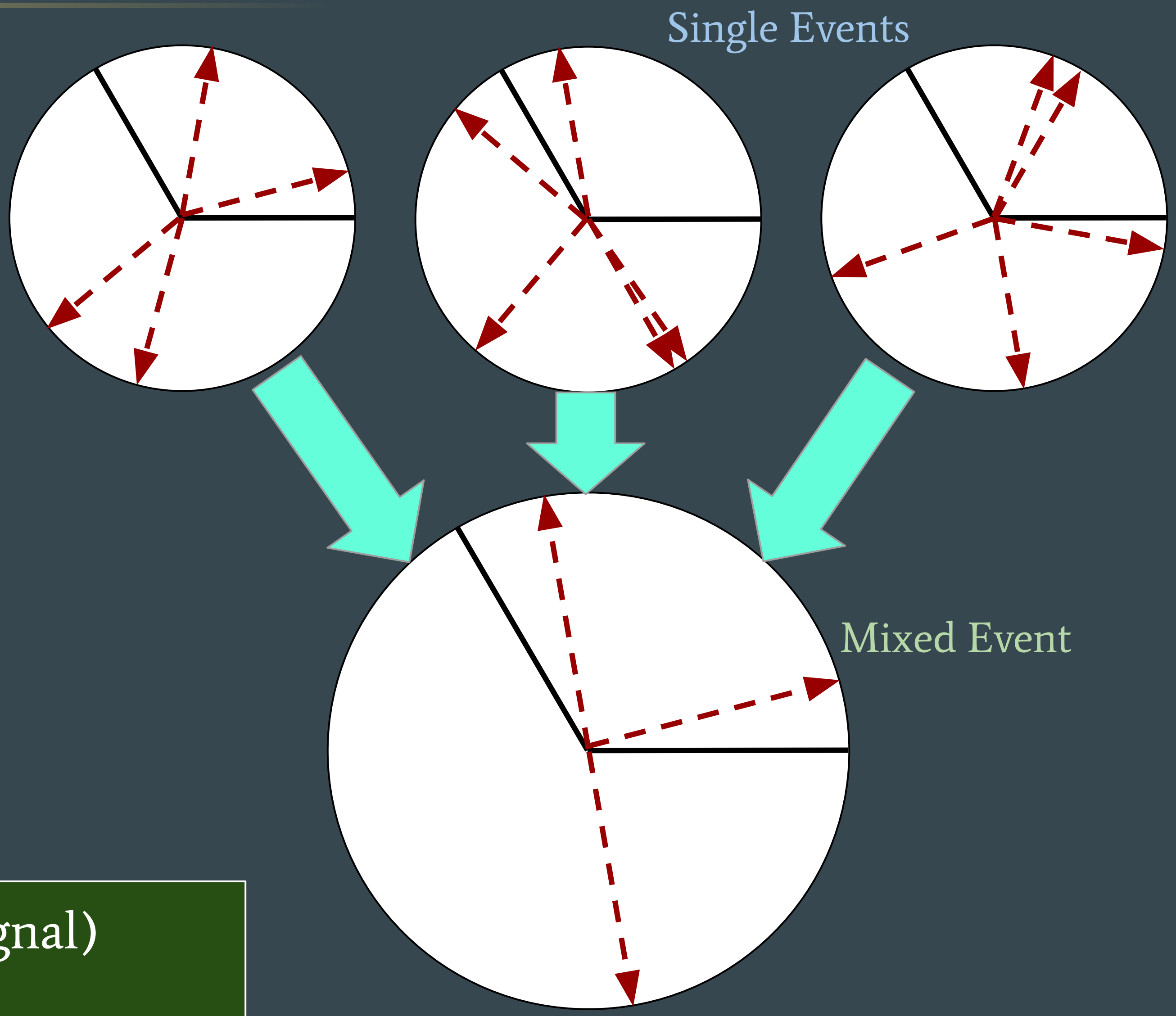


Kurtosis of net-proton multiplicity distribution expected to be non-monotonic as a function of energy if critical point exists

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

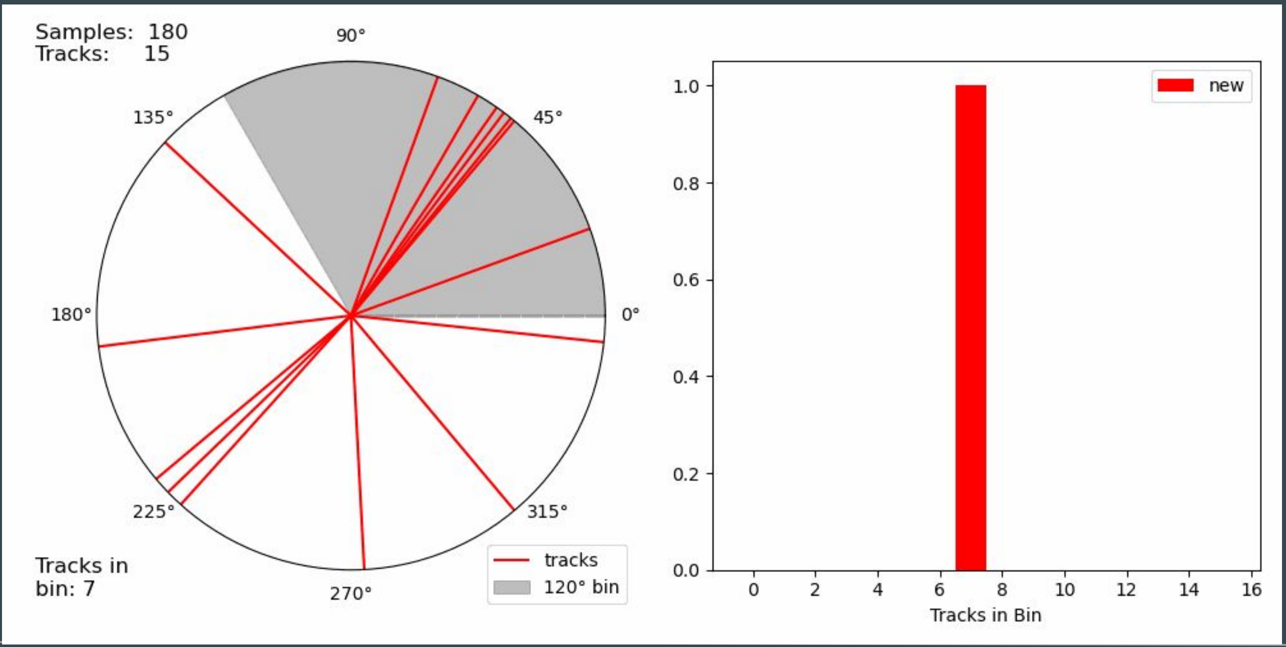


Goal:

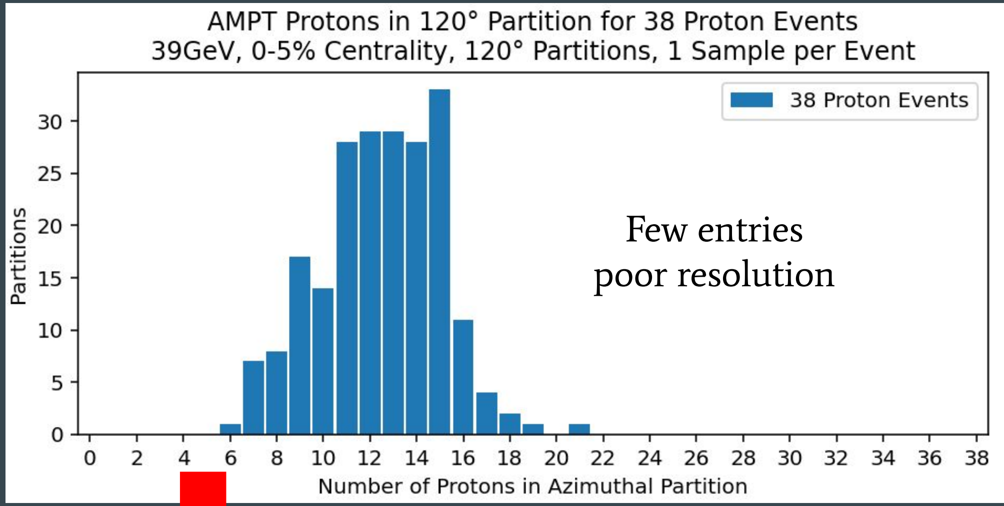
Wash out correlated event-by-event effects (signal) while capturing detector effects (background)

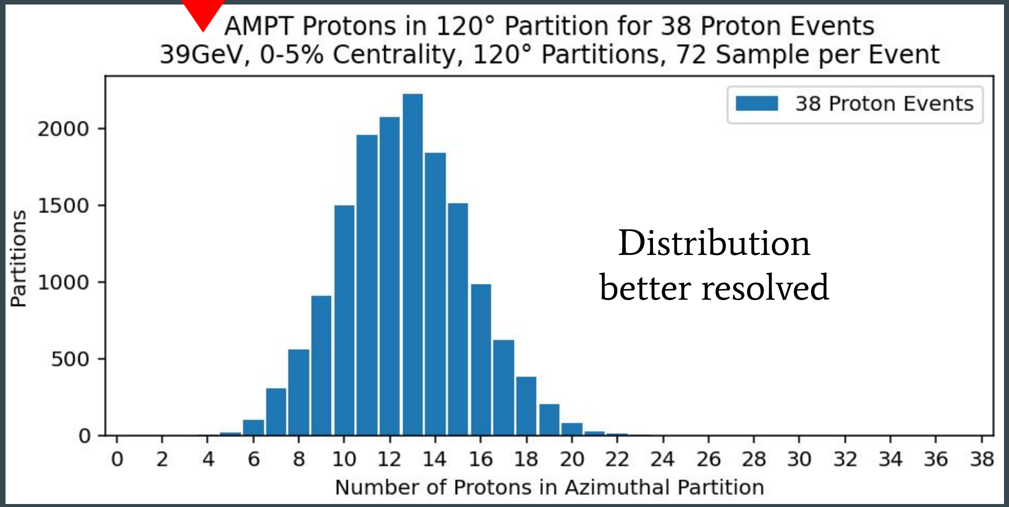
Event Resampling

- Take multiple random partitions (72) from each event
- Agrees with analytical expectations for random tracks
- Entries no longer independent → Block Bootstrap



Resampling improves resolution by utilizing more information in each event

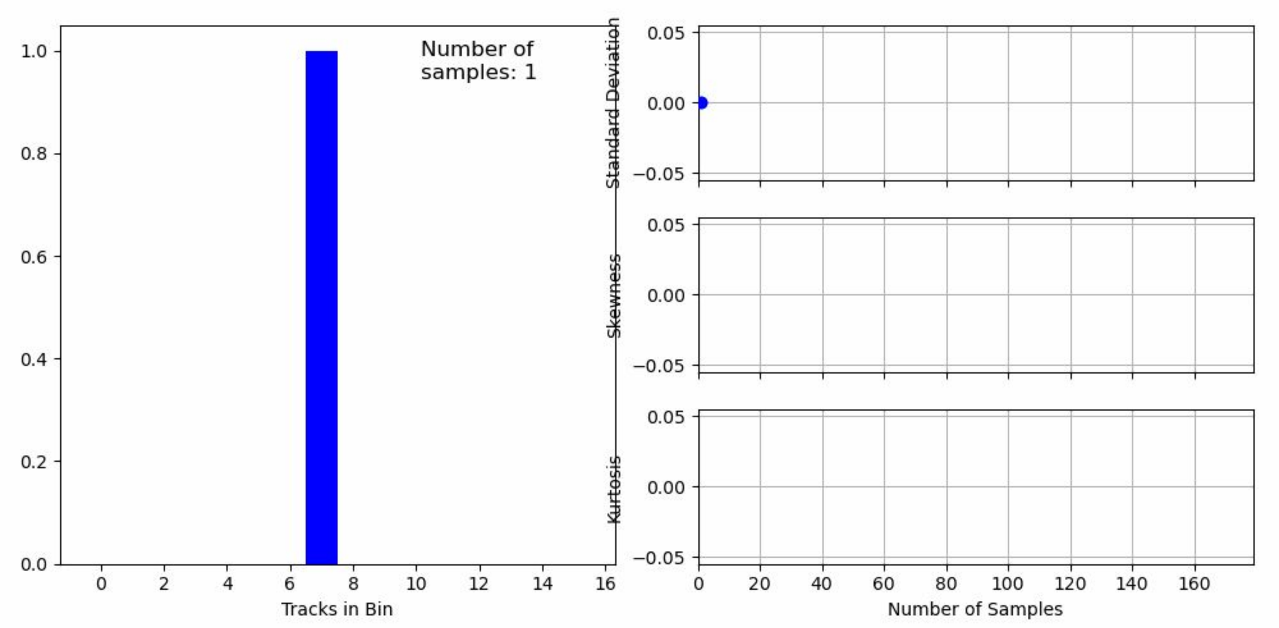




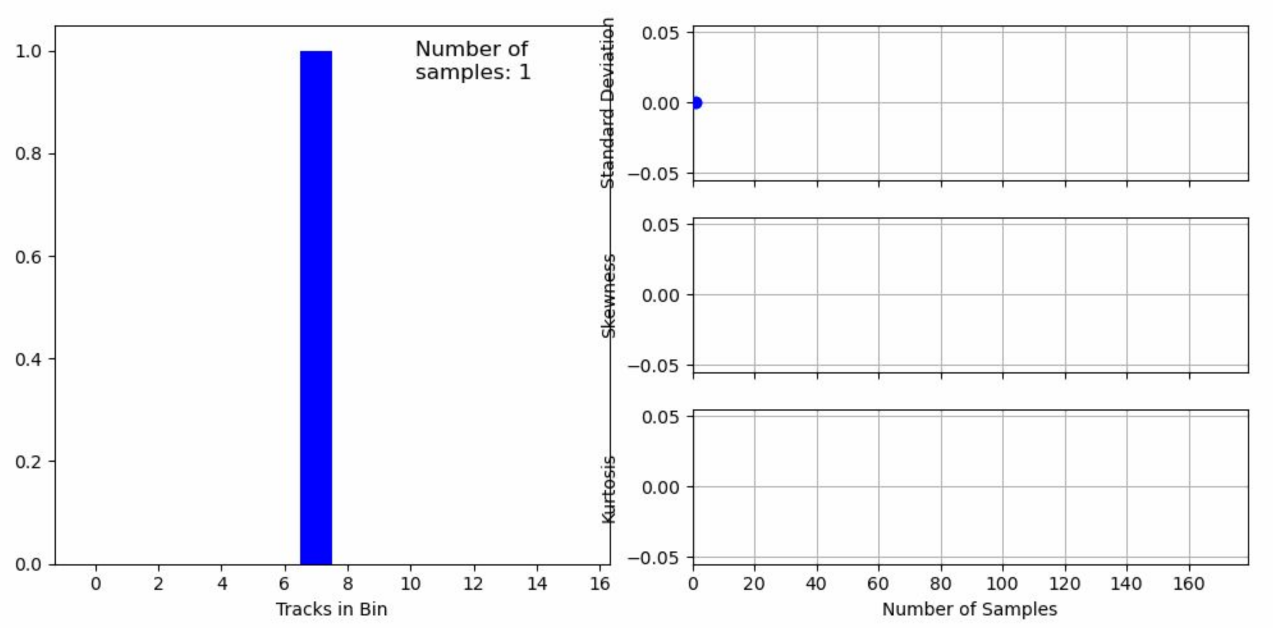
Stochastic Partitions

- 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

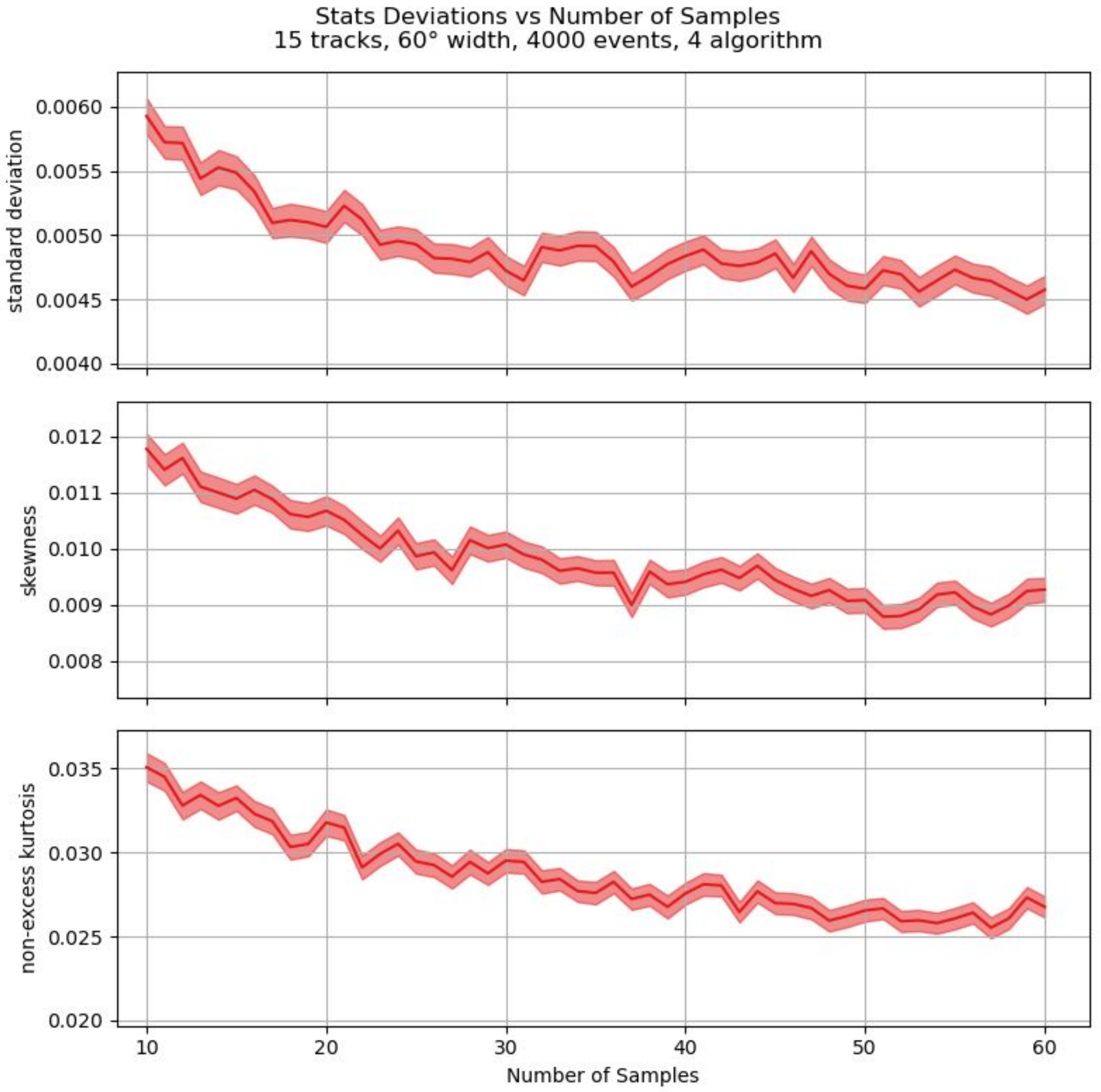


Stochastically Spaced Partitions

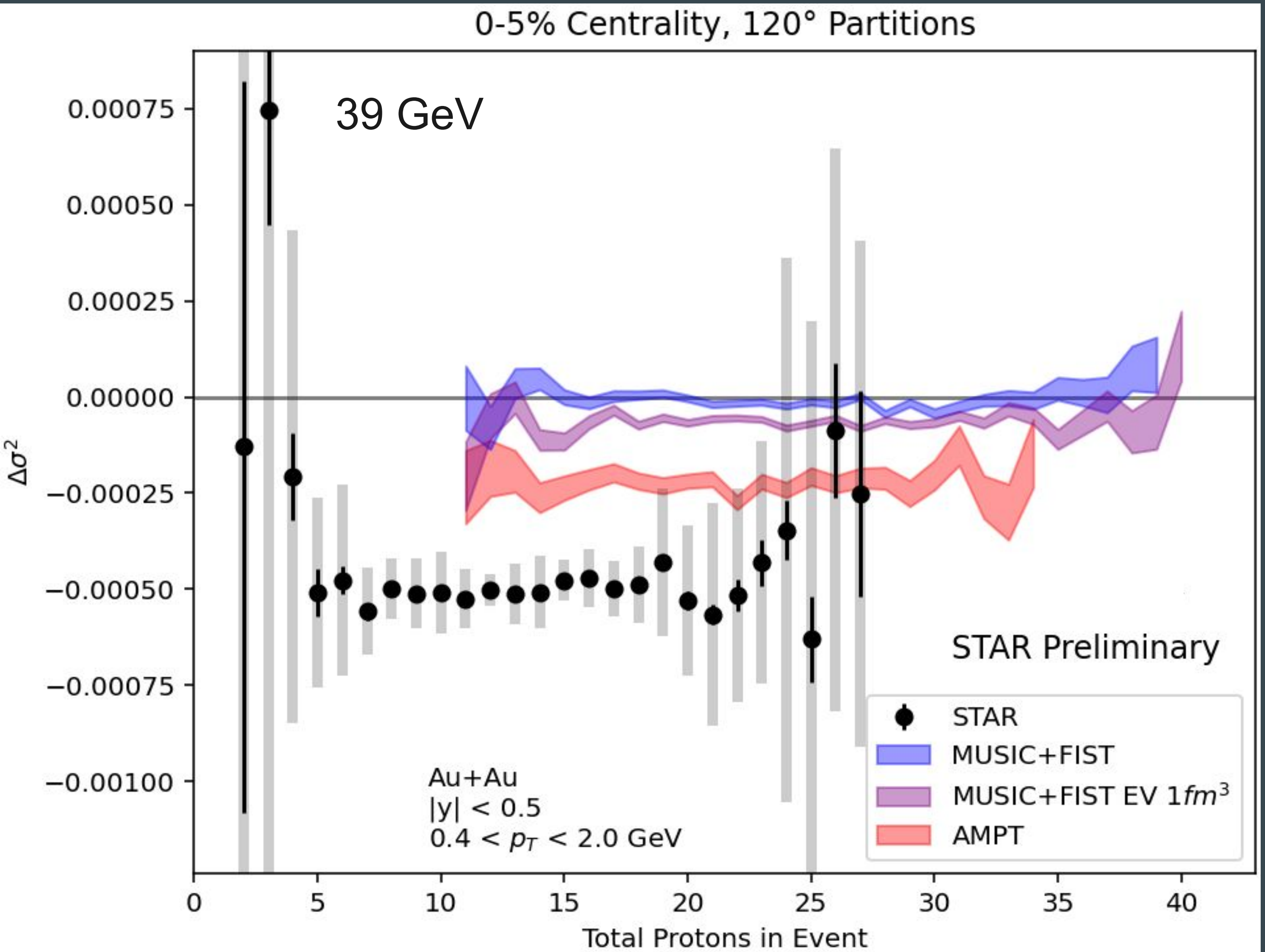


Optimal Samples

- 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

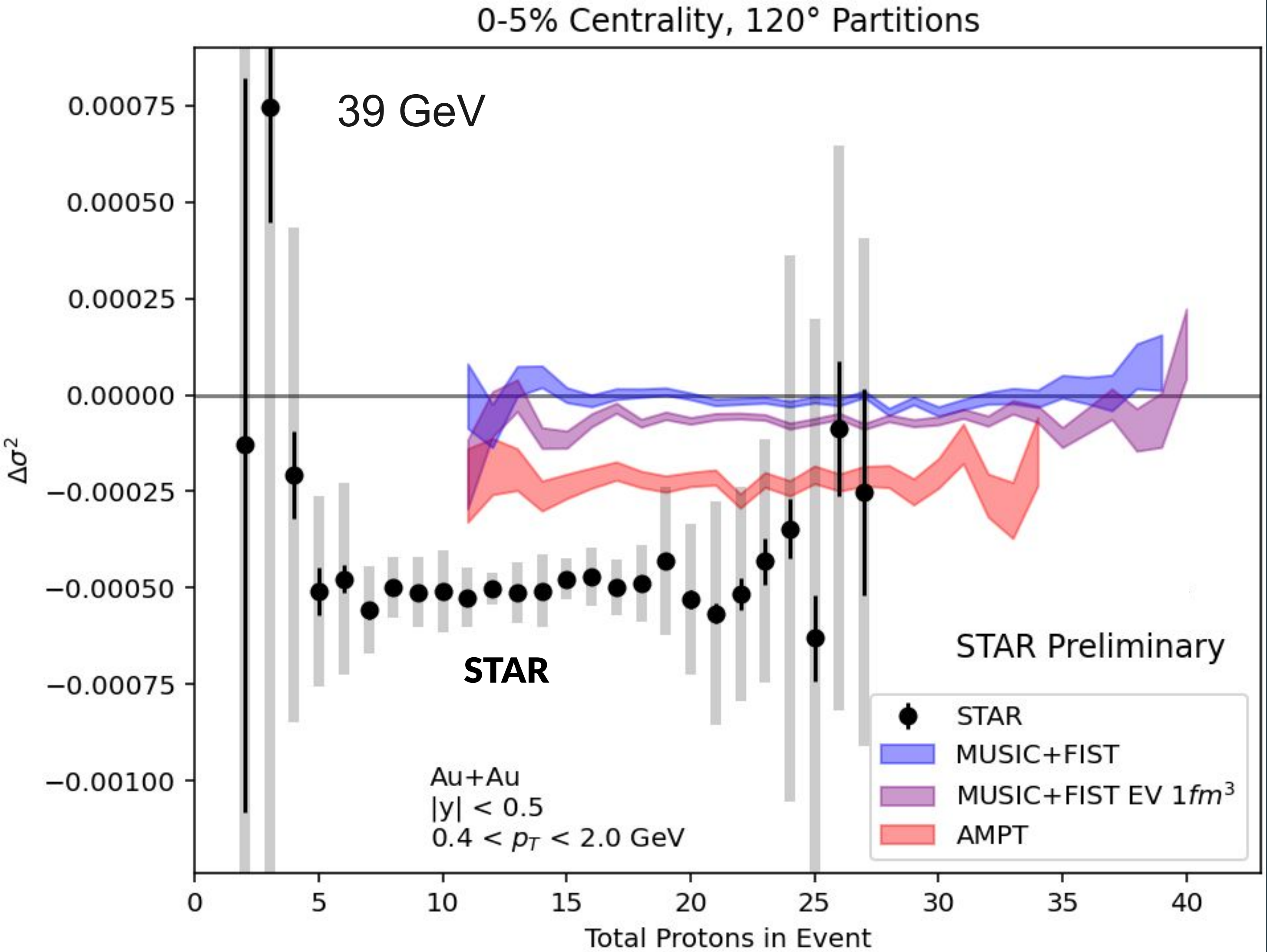


Repulsion Observed



Positive $\Delta\sigma^2$	→	Clustering
Negative $\Delta\sigma^2$	→	Repulsion

Repulsion Observed



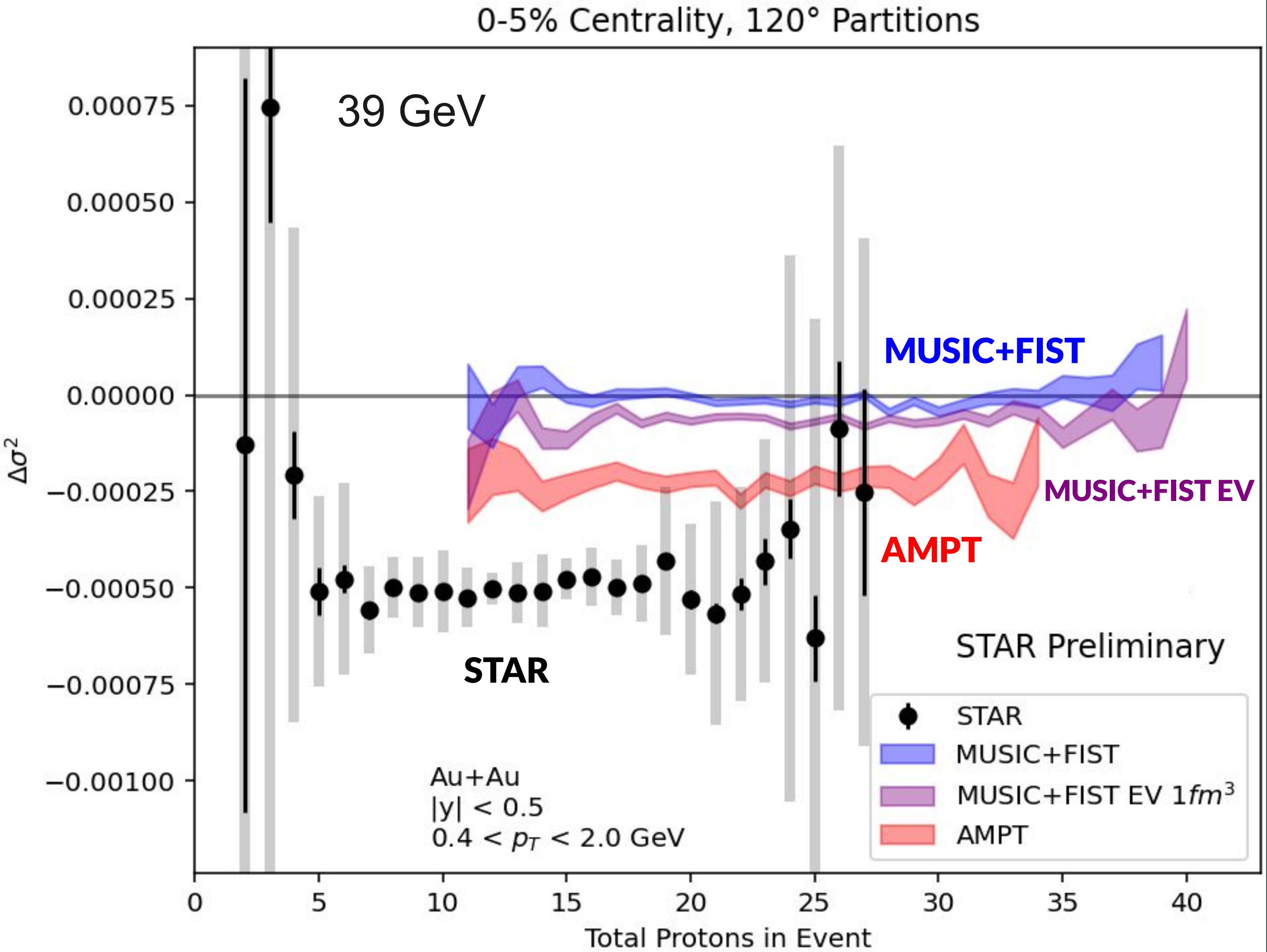
Positive $\Delta\sigma^2$ → Clustering

Negative $\Delta\sigma^2$ → Repulsion

- Significant repulsion observed in STAR data

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

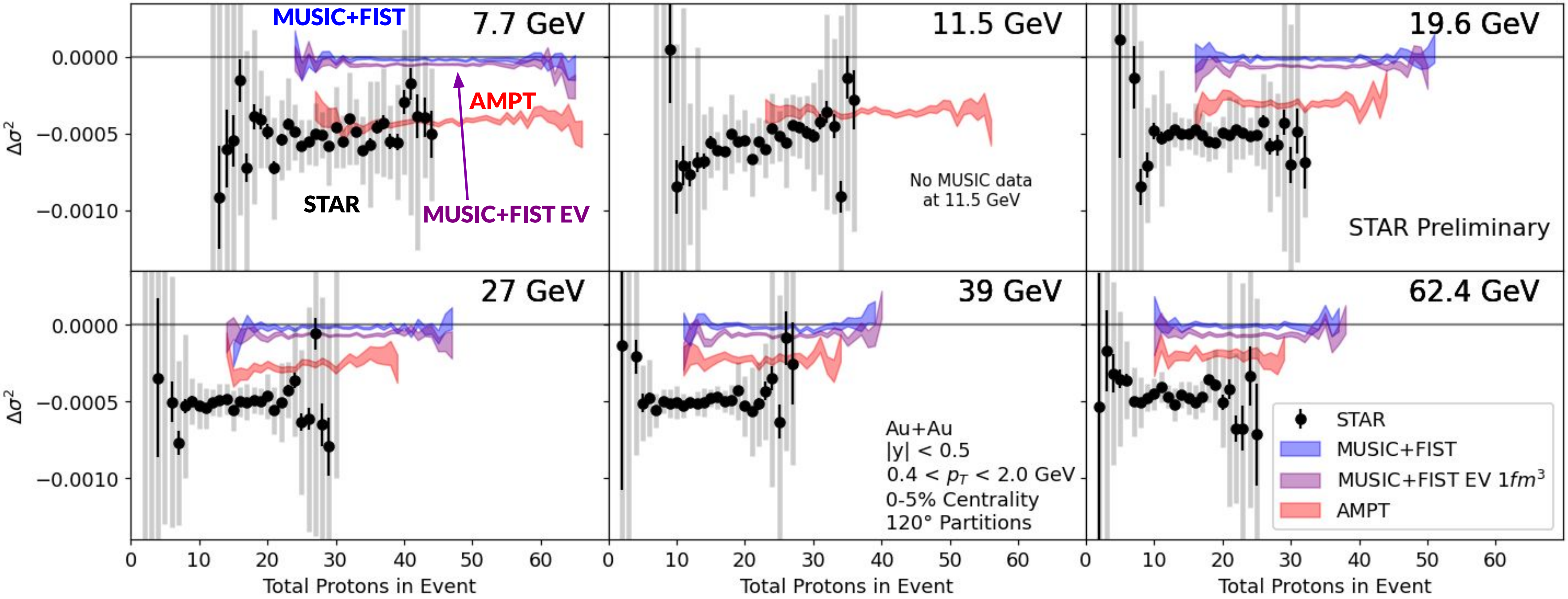
- ❑ Significant repulsion observed in STAR data
- ❑ MUSIC+FIST with Excluded Volume more repulsive than base model which sees little correlation
- ❑ AMPT calculations show stronger repulsion than MUSIC+FIST models

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

Repulsion at All Energies

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

Dependence on proton event multiplicity flat

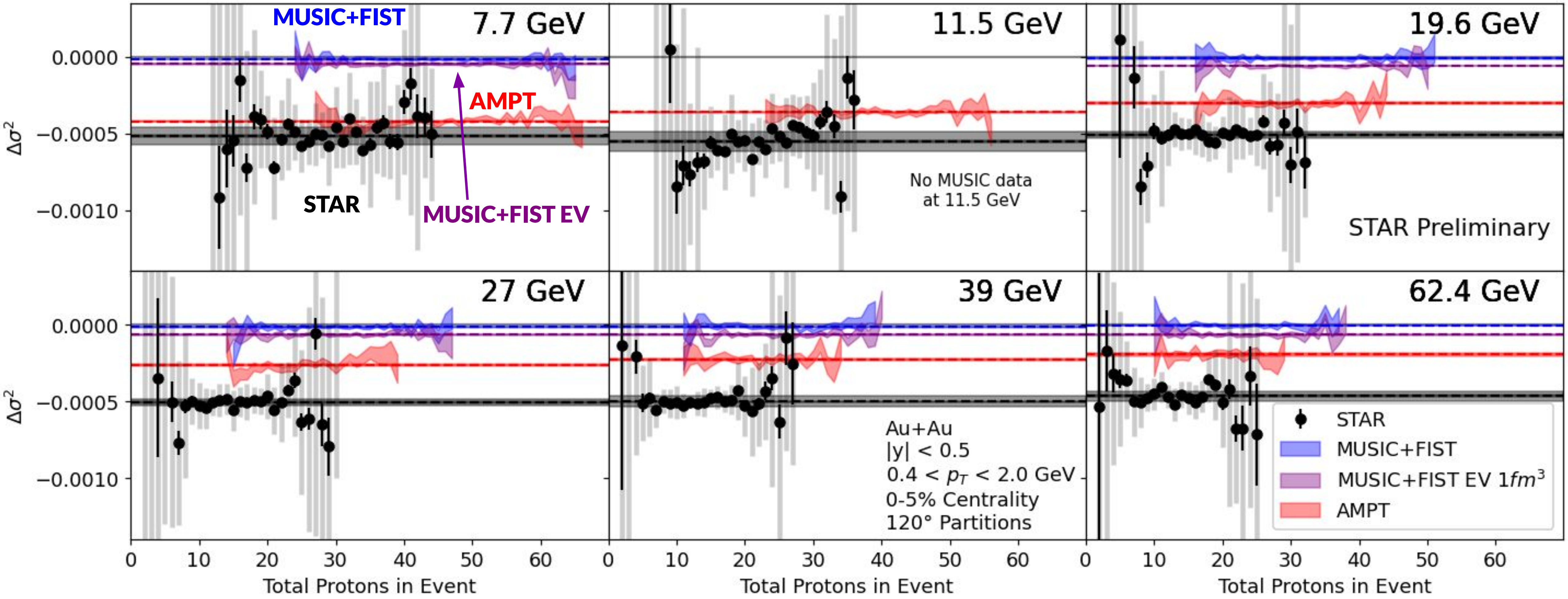


Repulsion at All Energies

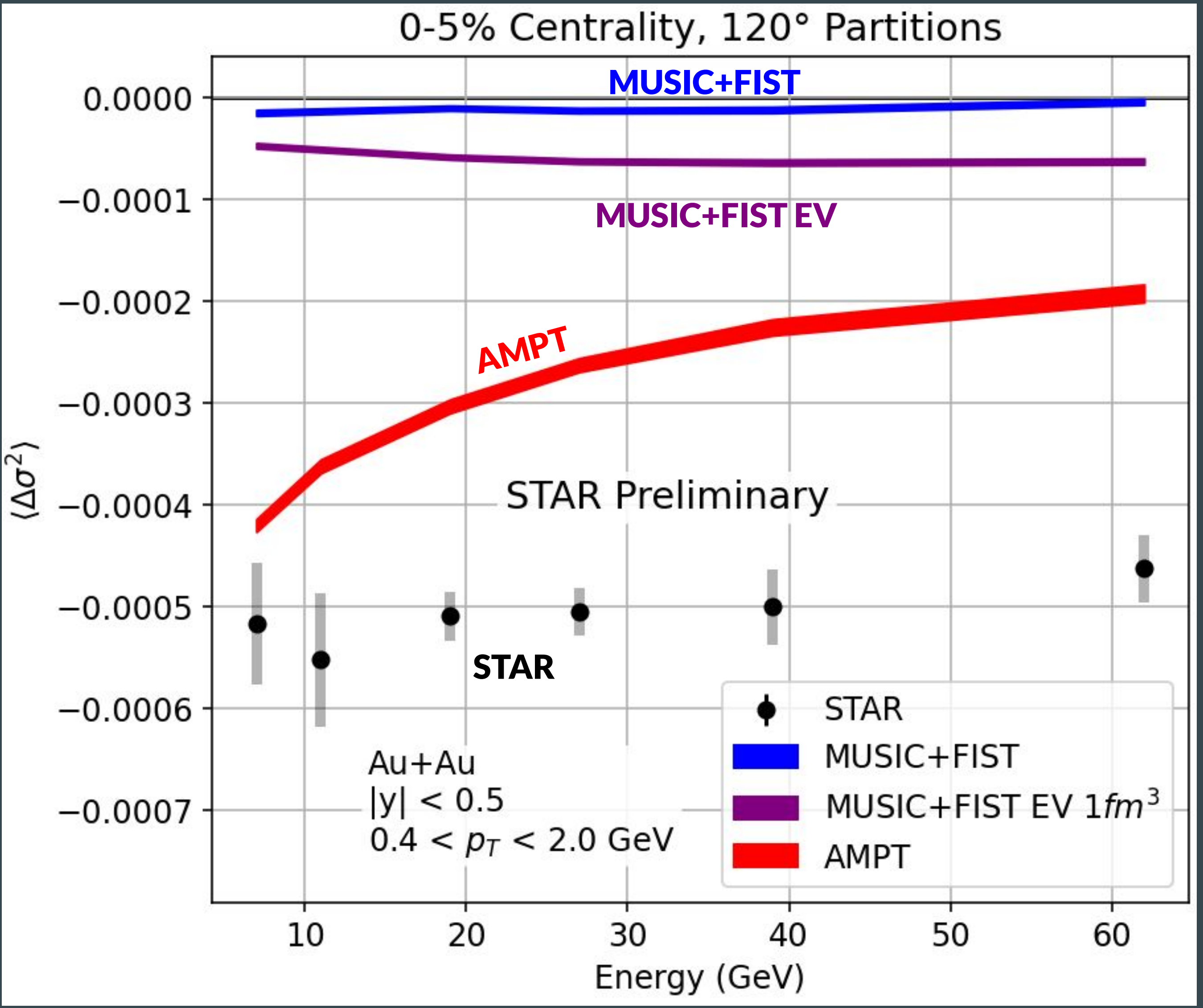
Negative $\Delta\sigma^2$ observed at all energies for STAR and AMPT

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

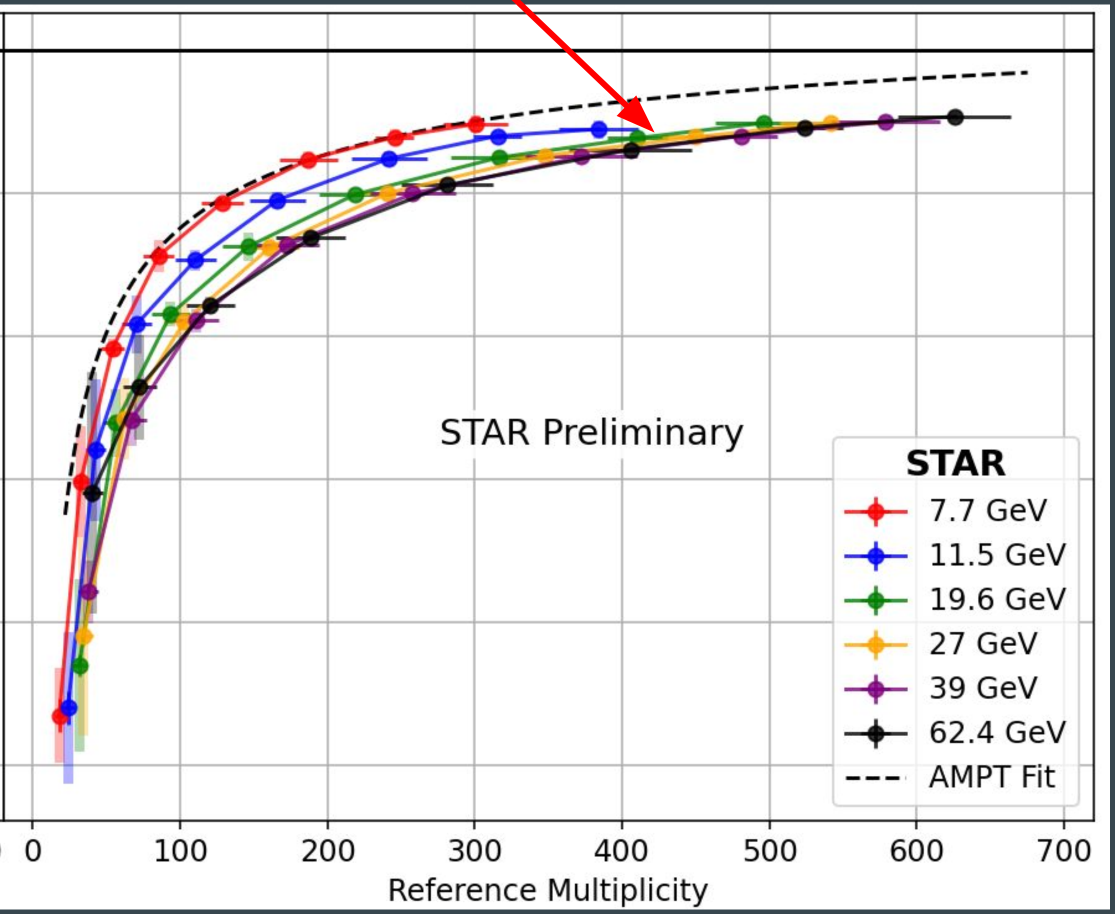


Negative $\Delta\sigma^2$ → Repulsion

- 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.

Use 62 GeV as Baseline

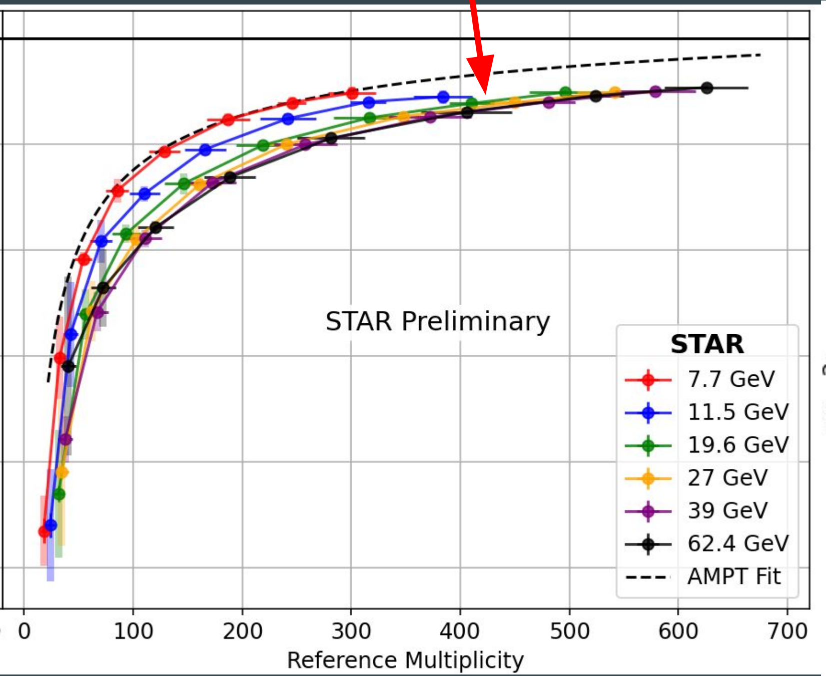
STAR data seem to converge at high energy

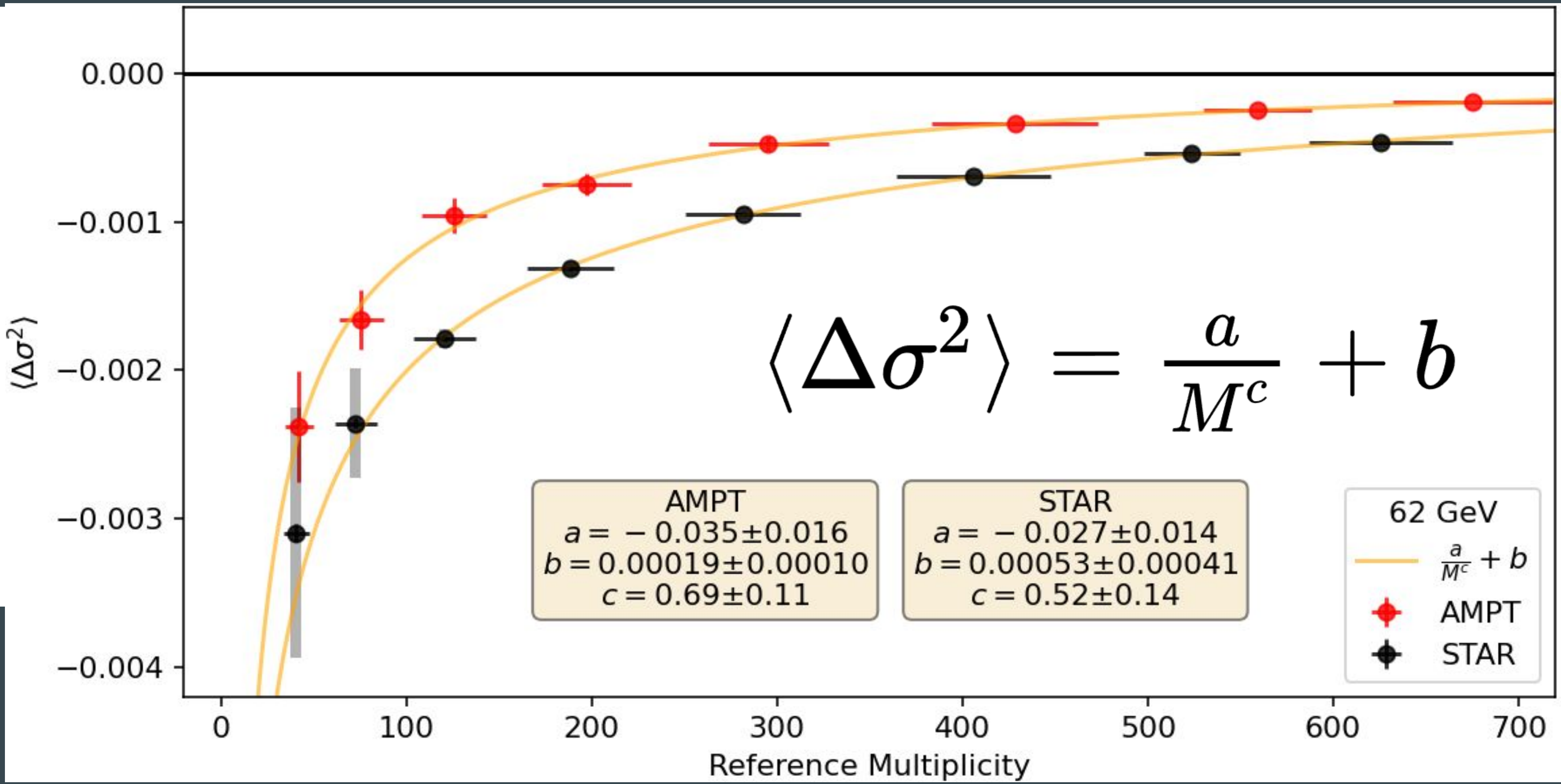


Use 62 GeV as Baseline

STAR data seem to converge at high energy

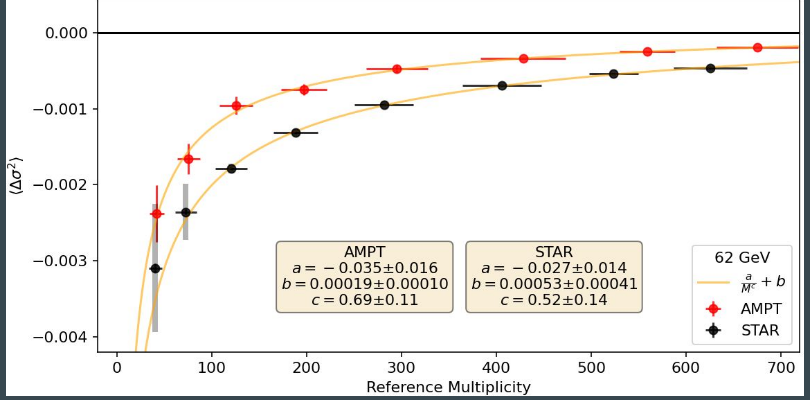
Find an adequate fit for 62.4 GeV and use as a baseline

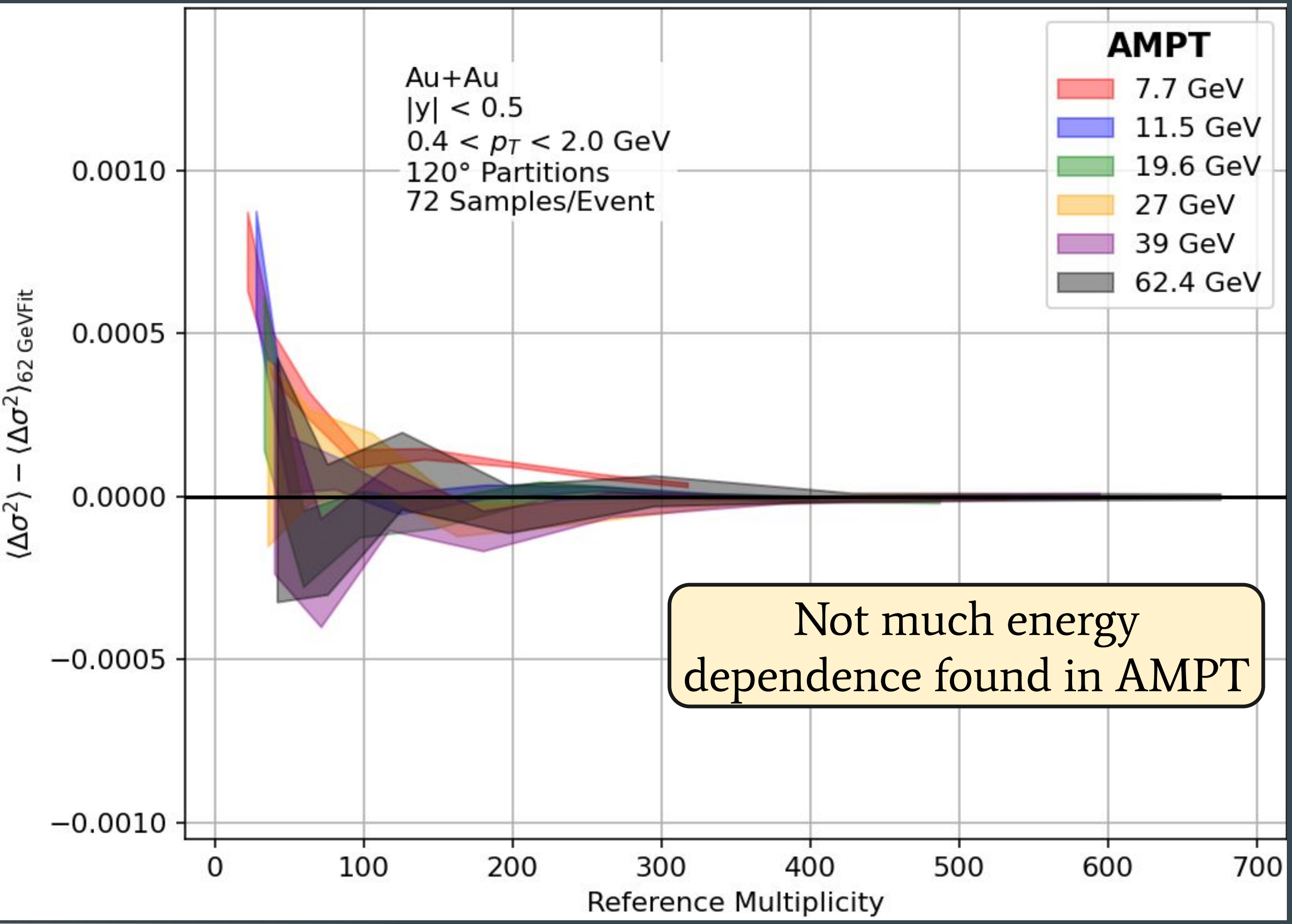




Subtract 62 GeV Baseline

Subtract the 62.4 GeV fits to highlight the STAR energy dependence





Models

AMPT

A Multi-Phase Transport Model

String melting mode - Excited strings melt into interacting partons

HIJING
Initial Conditions

↓

ZPC
Parton Interactions

↓

Coalescence
Hadronization

↓

ART
Elastic Scattering

MUSIC+FIST

Glauber
Initial Conditions

↓

MUSIC
Hydro Evolution

↓

FIST Sampler
Hadronization

Cooper-Frye like particlization with Thermal-FIST on freezeout hypersurface

Excluded Volume ensures no two baryons are formed within 1 fm

Neither model contains critical phenomena and serve to establish a baseline for STAR data

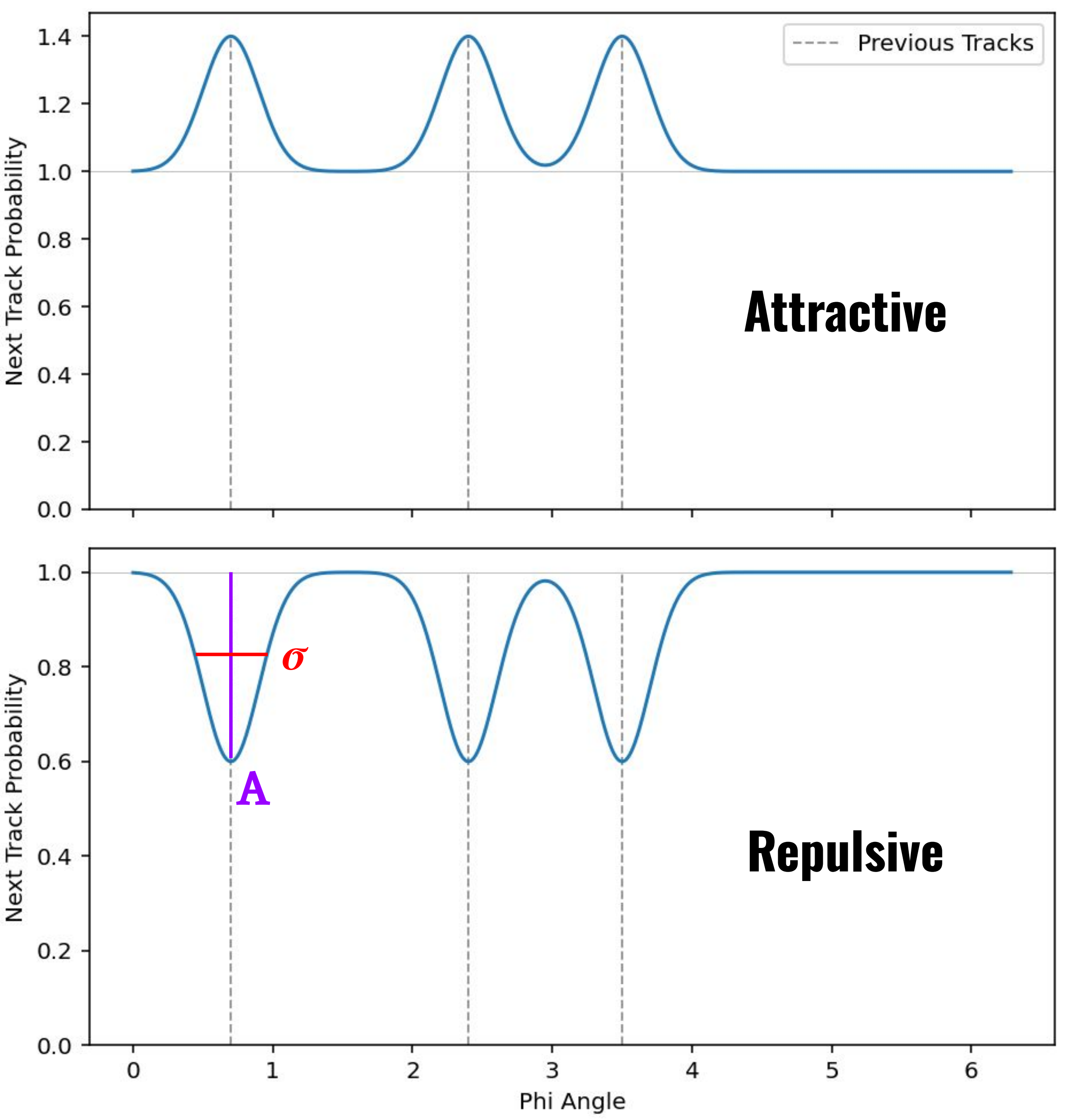
Simulating Correlated Tracks

- 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)

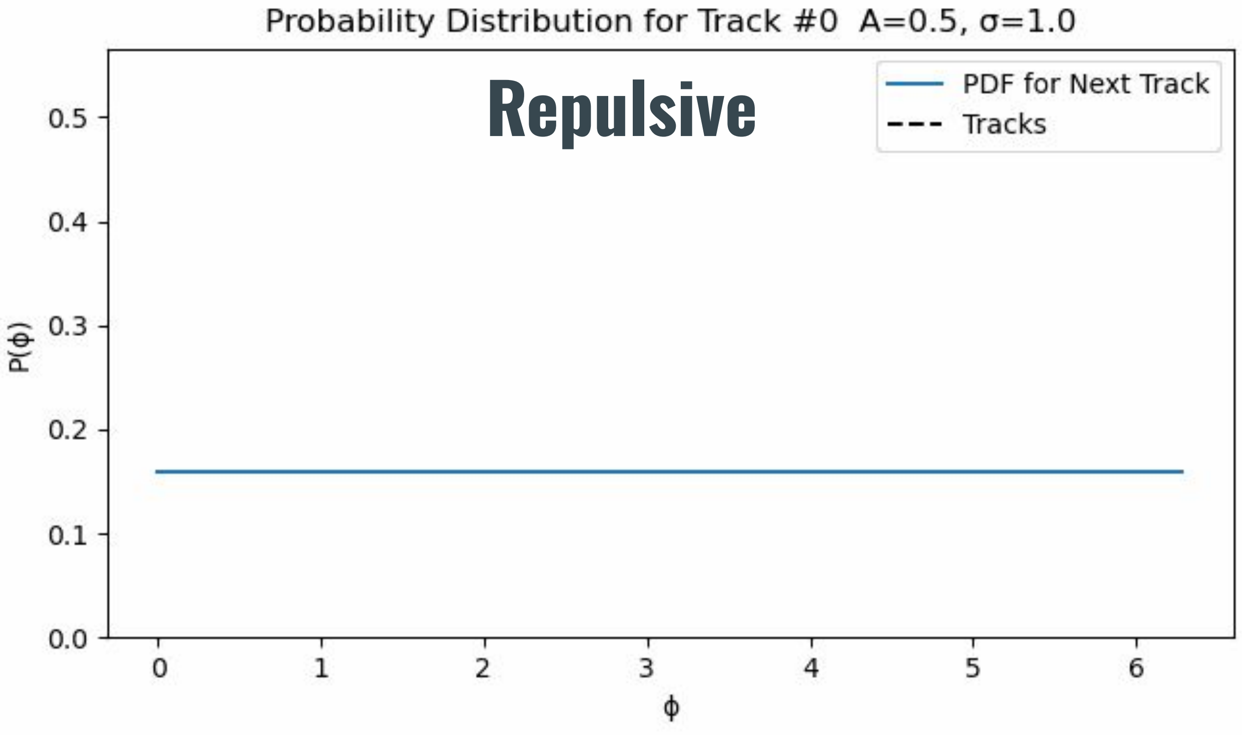
baseline

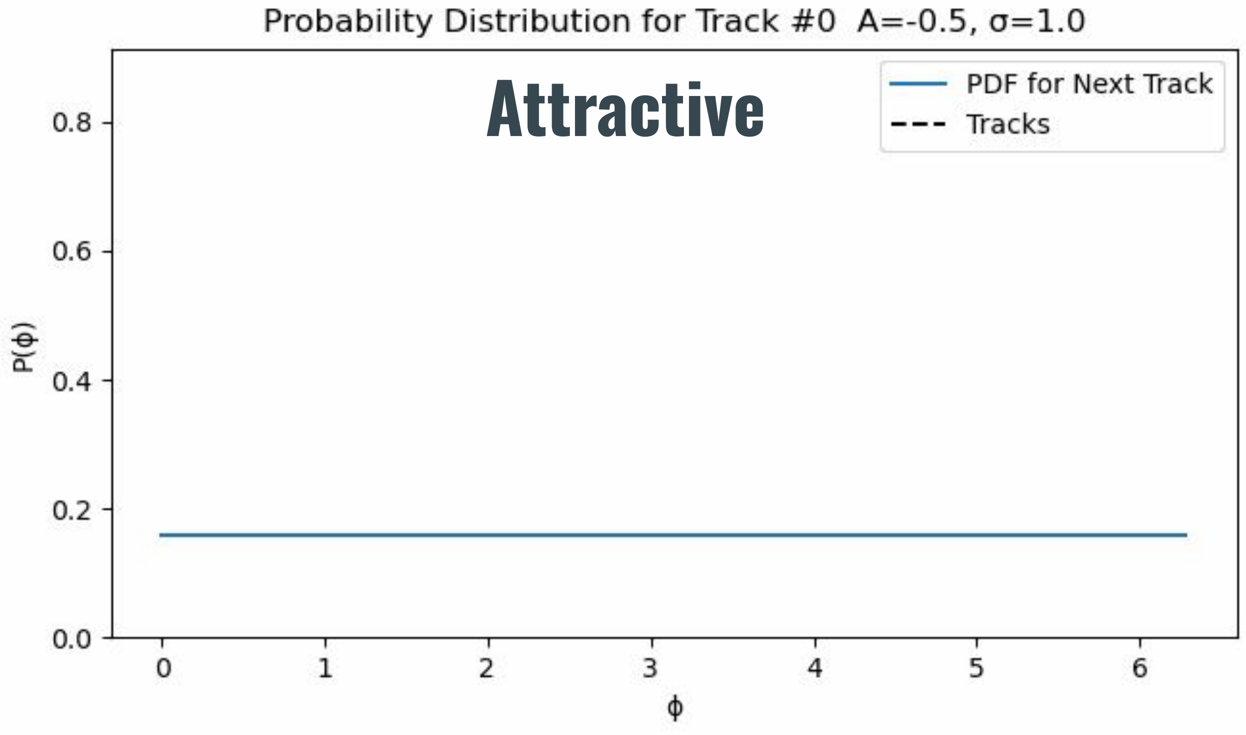
$$P(\phi) \propto \prod_{i=i}^{n} 1 + \frac{A}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\phi-\phi_i}{\sigma}\right)^2}$$



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

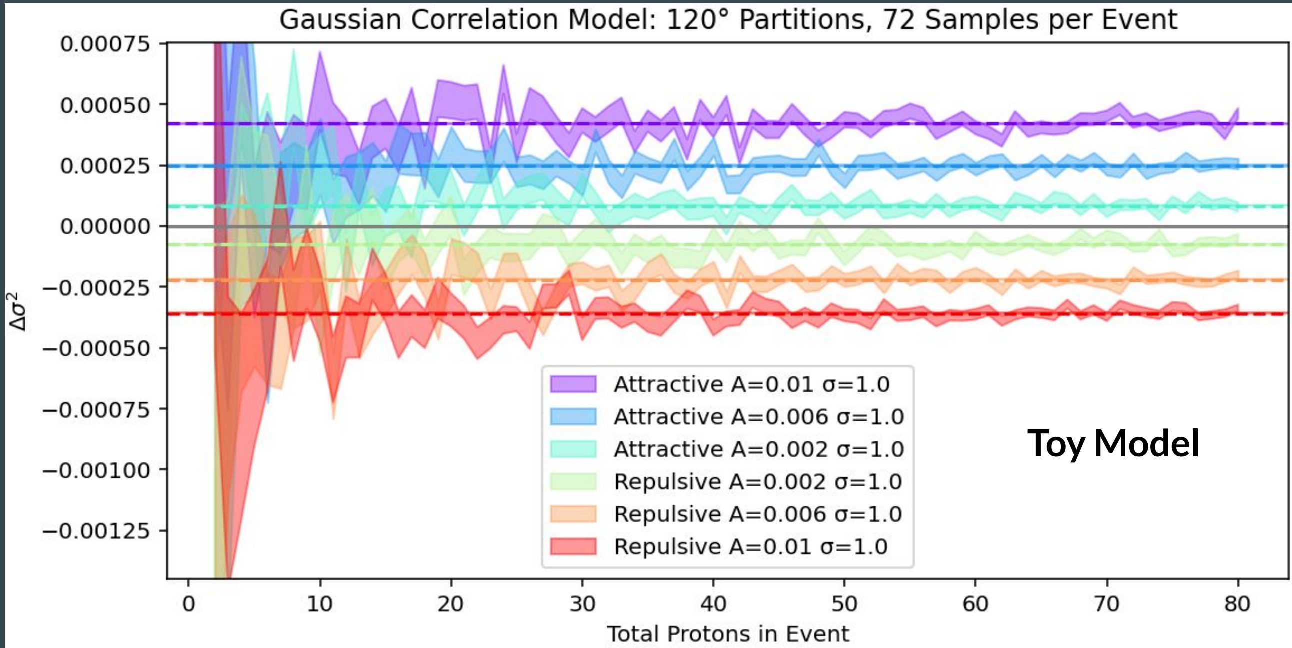




Simulations vs Total Protons

- 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*



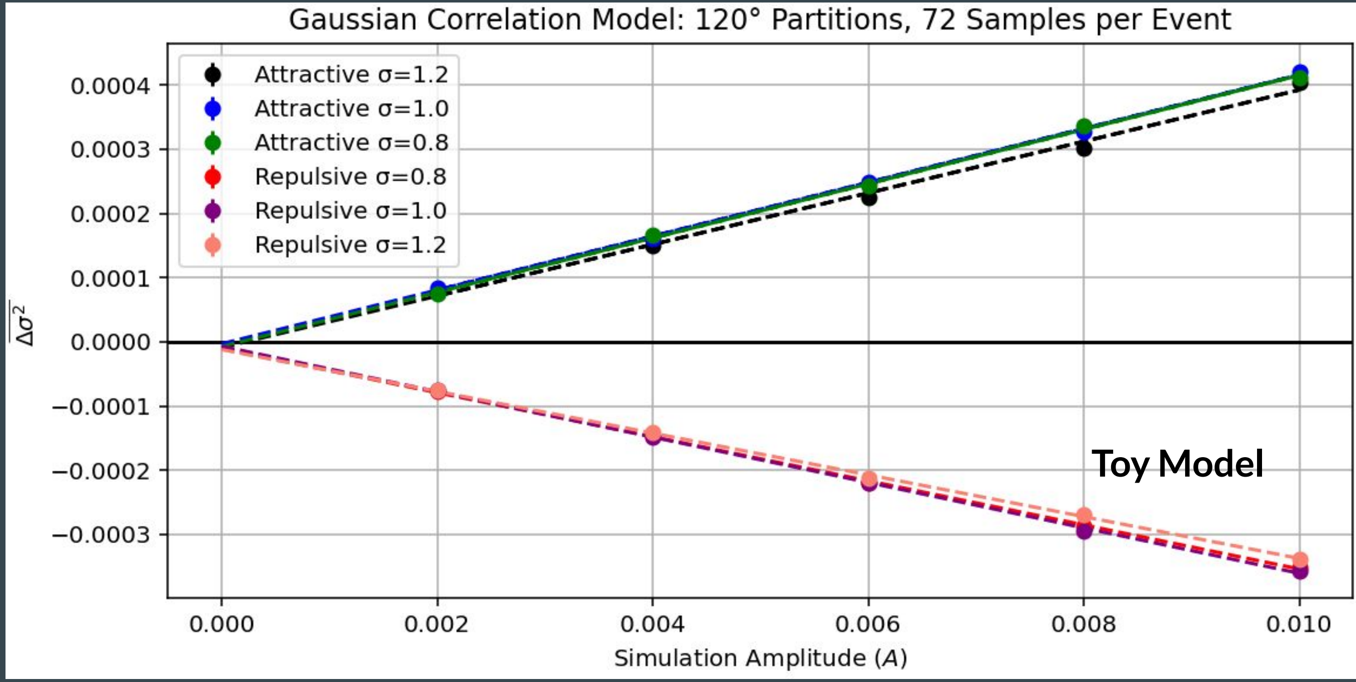
Mixed distributions for toy model are statistically identical to binomial

Can Reliably Extract Correlation

- Plotting $\Delta\sigma^2$ vs the total number of protons, get good linear relationship with input simulation *Amplitude*

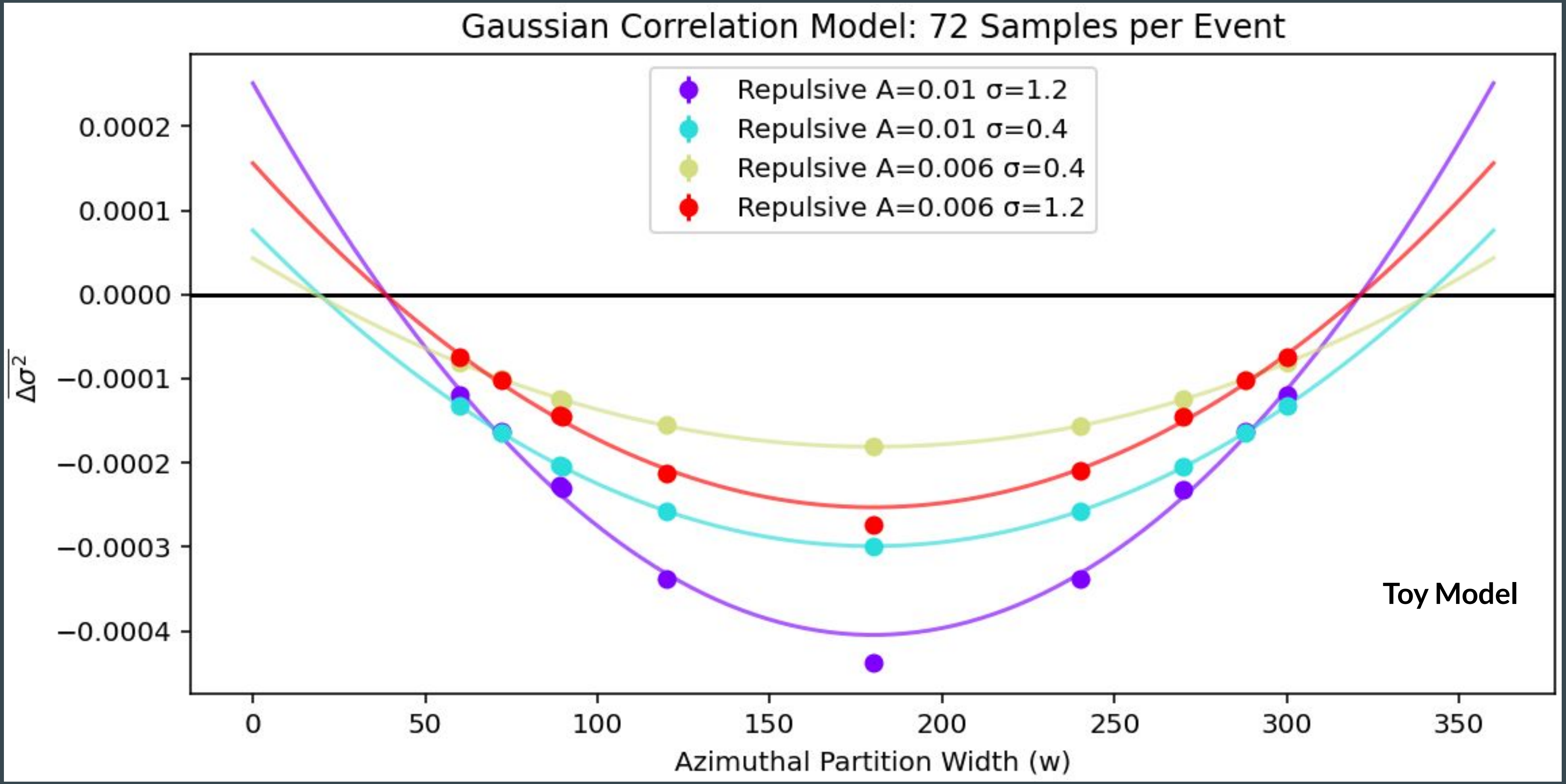
- This suggests the analysis can reliably extract the input correlation in the case of this simple model

- Changing Gaussian correlation width leads to different but still linear relationship



Slope vs Partition Width Simulation

- Dependence appears quadratic
- Different σ different x-intercept

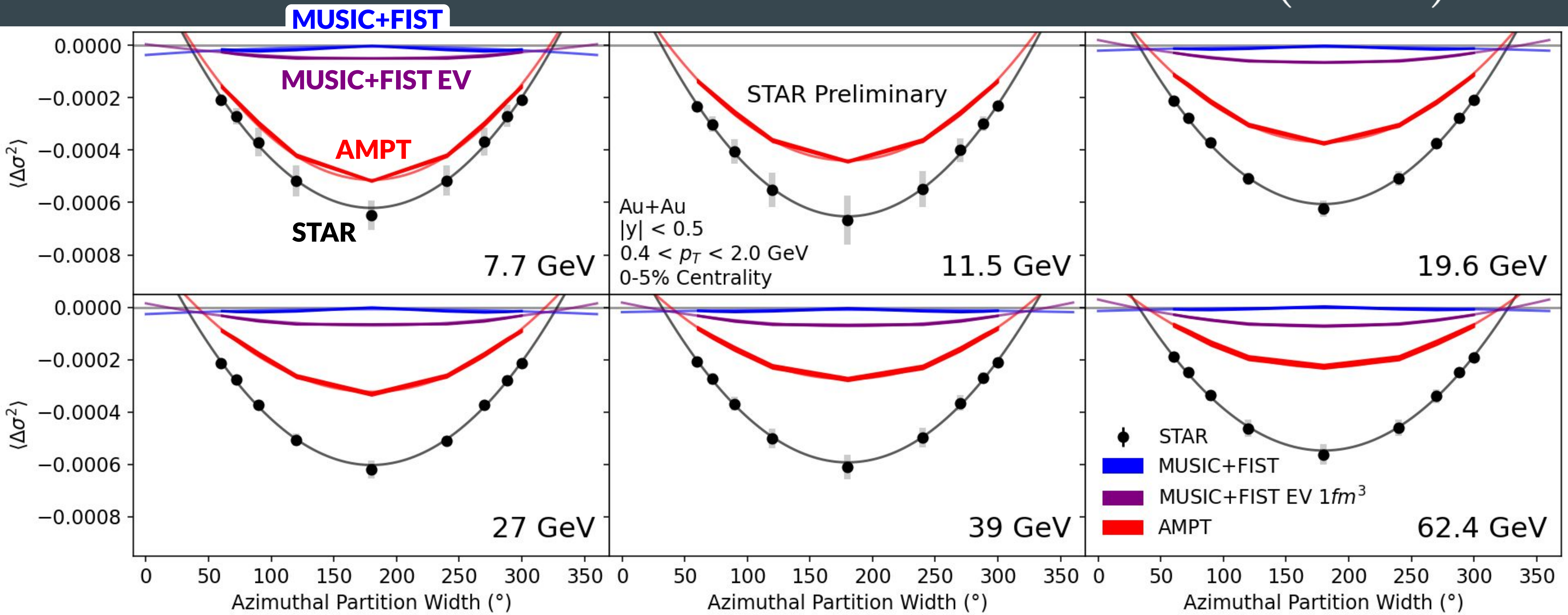


⟨Δσ²⟩ vs Partition Width

Trends well described by quadratic
Curvature related to range of correlation

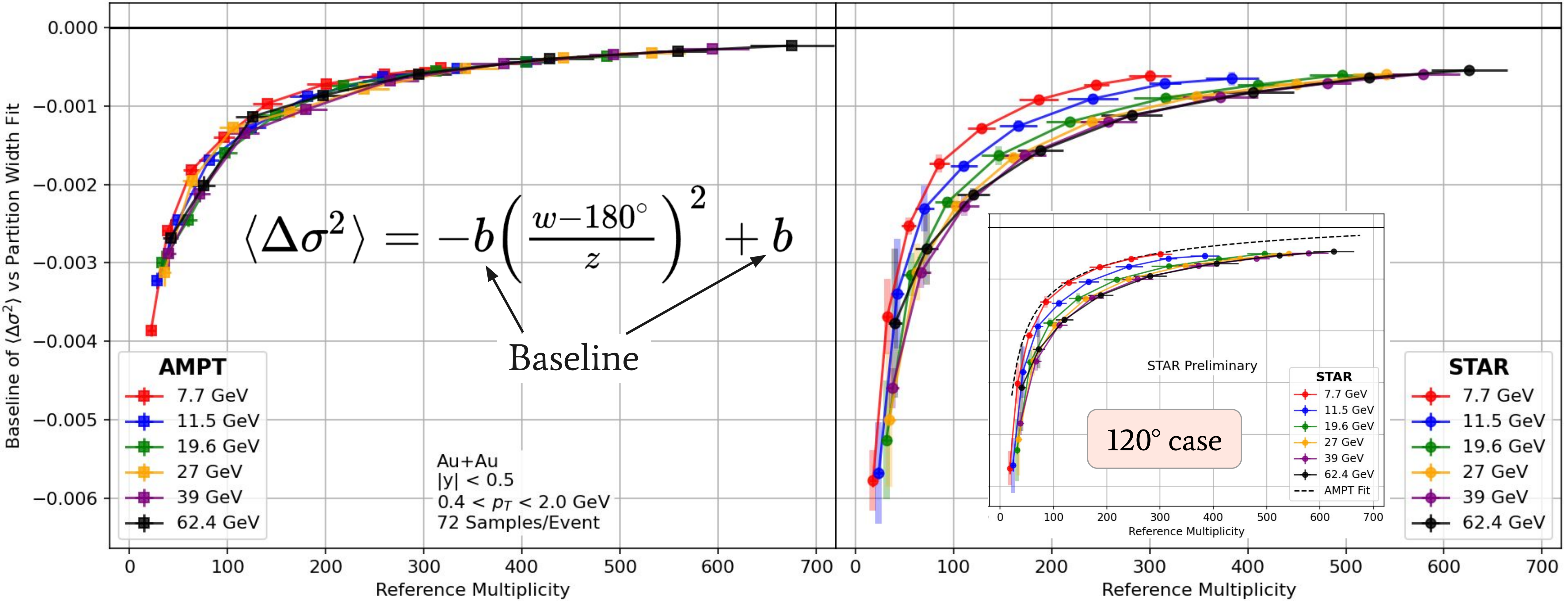
Partition width dependence may encode information about range of correlation → Evidenced by toy model simulations

$$\langle \Delta\sigma^2 \rangle = -b\left(\frac{w-180^\circ}{z}\right)^2 + b$$

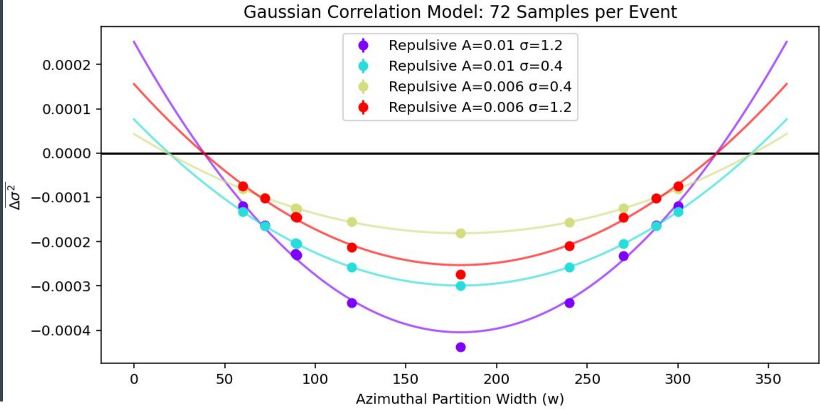


Baseline vs Event Multiplicity

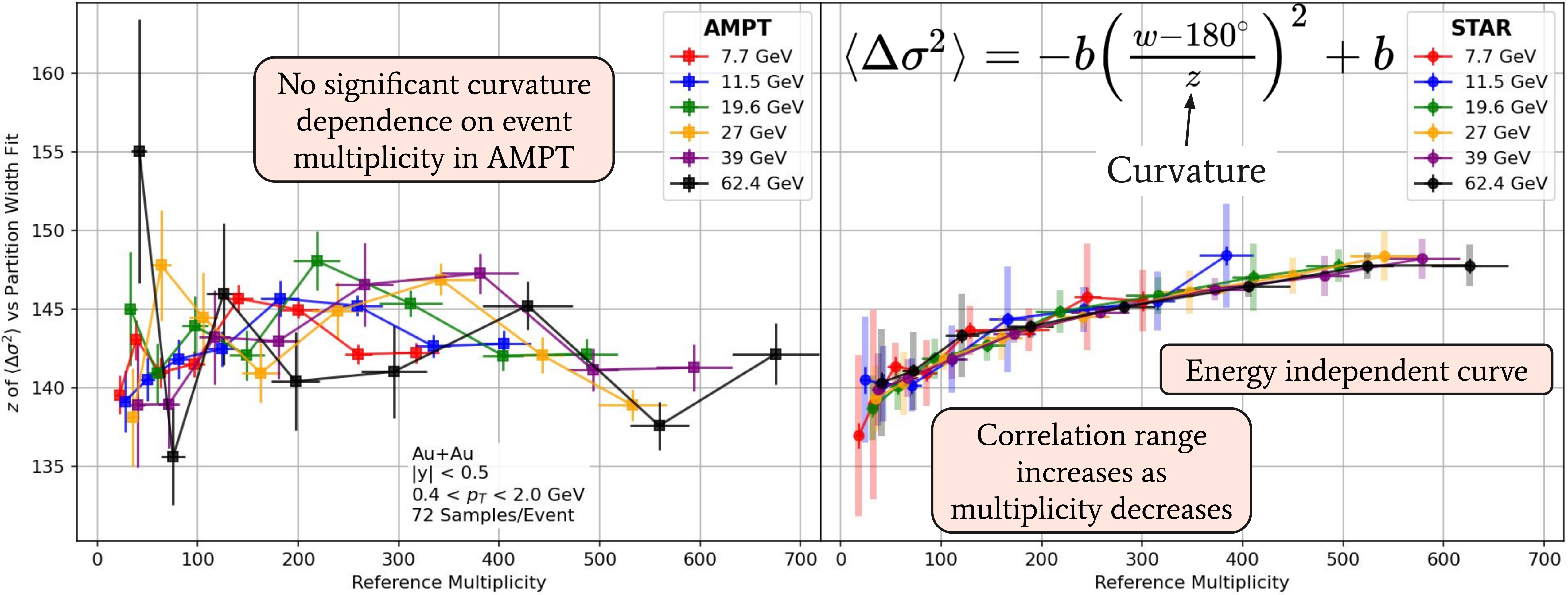
Same message as 120° case, better statistics



Curvature vs Event Multiplicity



Clear difference in correlation range between STAR data and AMPT model



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 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

$DCA_{max} \in (0.8, 1.2)$
$\lvert n\sigma_{proton}\rvert_{max} \in (1.8, 2.2)$ (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 $\lvert\eta\rvert < 1$ excluding protons

Corrections Implemented:

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

Corrections Not Implemented:

- Efficiency Correction
- Centrality Bin Width Correction