Forward-backward multiplicity fluctuation and longitudinal harmonics in high-energy nuclear collisions

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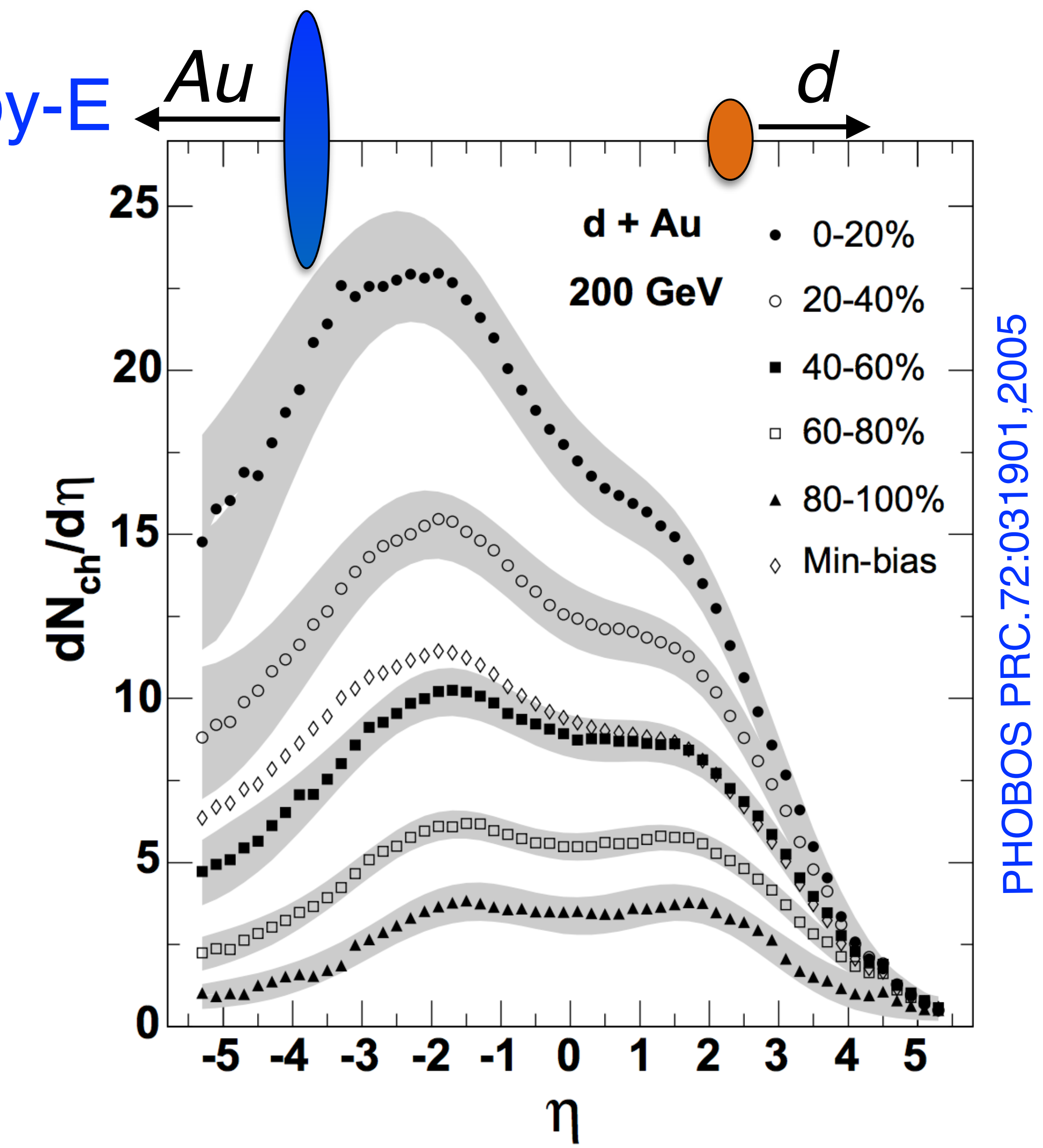
Motivation

- Multiplicity correlations in the longitudinal direction
  - sensitive to early time particle production mechanism
  - longitudinal dynamics
- $dN(\eta)/d\eta$ has forward-backward (FB) asymmetry due to $N^F_{part} \neq N^B_{part}$
  - directly seen in d+Au collisions
  - also exists in symmetric A+A collisions E-by-E
- Goal of this work
  - Develop a method which can directly measure such EbyE fluctuations
  - Apply it in HIJING and AMPT models



The analysis method (I)

- Quantify multiplicity fluc. though correlation function:
  - directly relate to the E-by-E fluctuation of $N(\eta)$ around $\langle N(\eta)\rangle$

A.Bzdak, D.Teaney, PRC.87.024906

$$R_s(\eta) \equiv \frac{N(\eta)}{\langle N(\eta)\rangle} \qquad C(\eta_1,\eta_2) = \frac{\langle N(\eta_1)N(\eta_2)\rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle} \equiv \langle R_s(\eta_1)R_s(\eta_2)\rangle$$

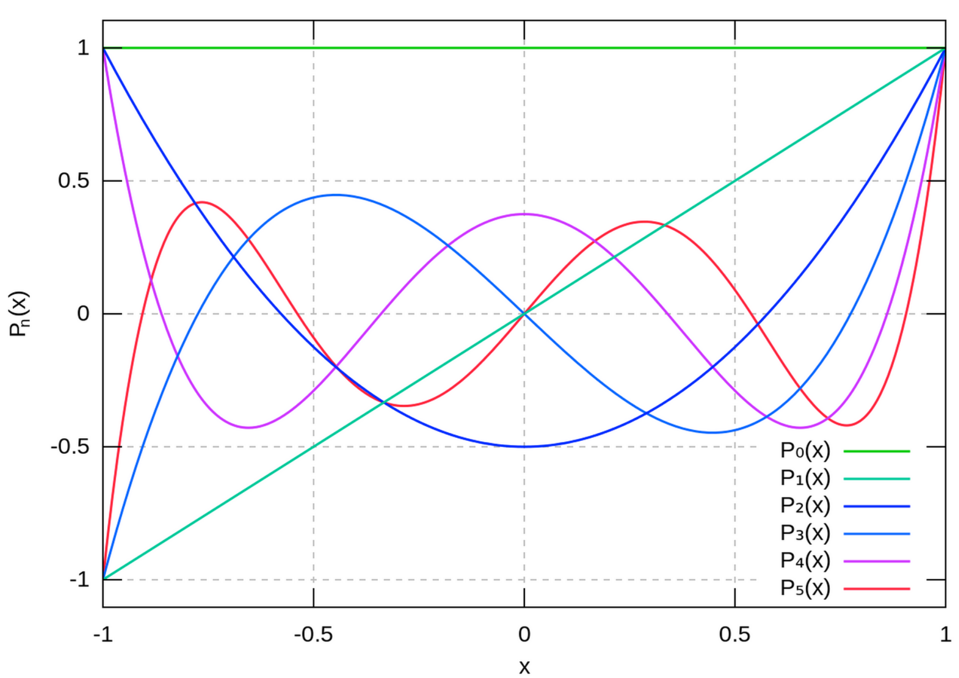
single-particle distribution

- The $R_s(\eta)$ shape fluctuation is expanded using Legendre polynomials

$$R_s(\eta) = 1 + \sum_n^{\infty} a_n T_n(\eta), \quad T_n(\eta) \equiv \sqrt{n+\frac{1}{2}}P_n(\eta/Y) \qquad \eta \in [-Y, Y]$$

longitudinal harmonics

Legendre polynomials



- a_0: rapidity independent multiplicity fluctuation
- a_1: FB fluctuation, related to $A_{part} = \frac{N^F_{part} - N^B_{part}}{N^F_{part} + N^B_{part}}$
- a_2: Quantify the fluc. of the width of $dN(\eta)/d\eta$

The analysis method (II)

- Multiplicity fluc. is quantified though the correlation function:
  - directly relate to the E-by-E fluctuation of $N(\eta)$ around $\langle N(\eta)\rangle$

$$R_s(\eta) \equiv \frac{N(\eta)}{\langle N(\eta)\rangle} \qquad C(\eta_1,\eta_2) = \frac{\langle N(\eta_1)N(\eta_2)\rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle} \equiv \langle R_s(\eta_1)R_s(\eta_2)\rangle$$

single-particle distribution

- The $R_s(\eta)$ shape fluctuation is expanded using Legendre polynomials

$$R_s(\eta) = 1 + \sum_n^{\infty} a_n T_n(\eta), \quad T_n(\eta) \equiv \sqrt{n+\frac{1}{2}}P_n(\eta/Y) \qquad \eta \in [-Y, Y]$$

longitudinal harmonics

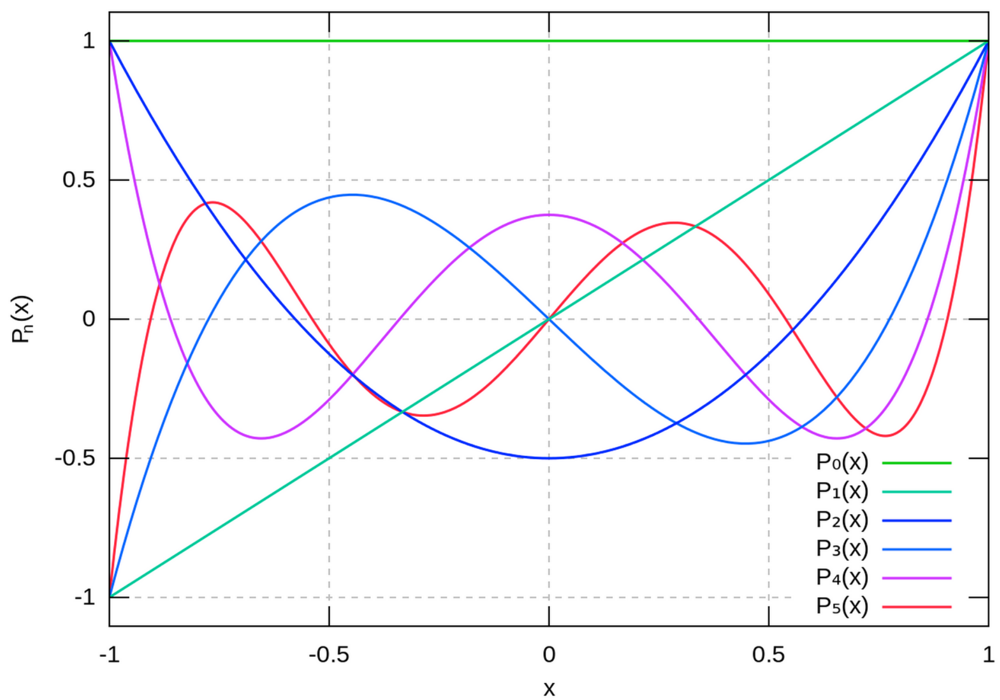
- Legendre expansion for correlation function is:

$$C(\eta_1,\eta_2) = 1 + \sum_{n,m=0}^{\infty} \langle a_n a_m\rangle \frac{T_n(\eta_1)T_m(\eta_2) + T_n(\eta_2)T_m(\eta_1)}{2}$$

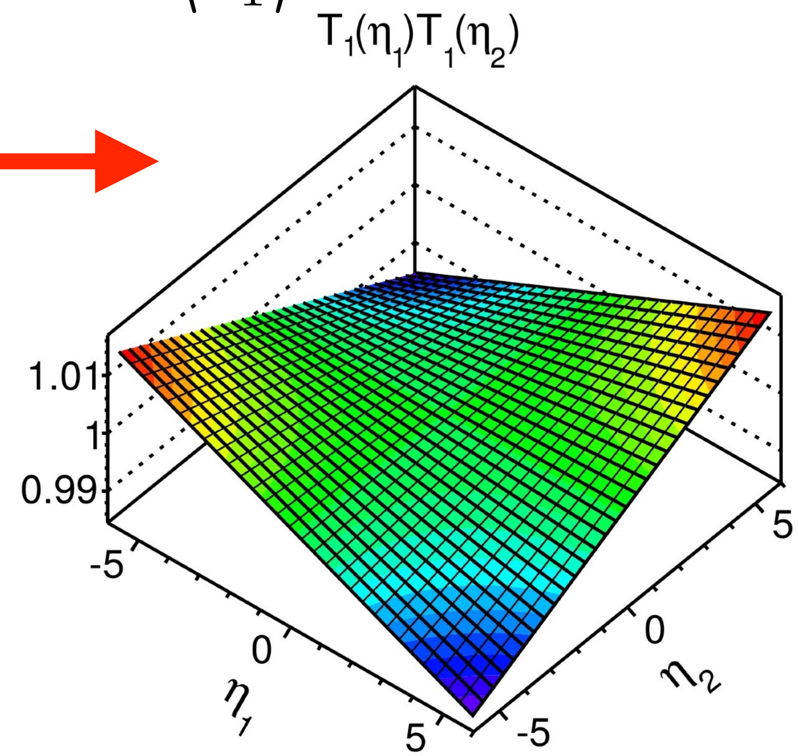
- Longitudinal fluctuations are captured by the bases and $\langle a_n a_m \rangle$

Correlation Function

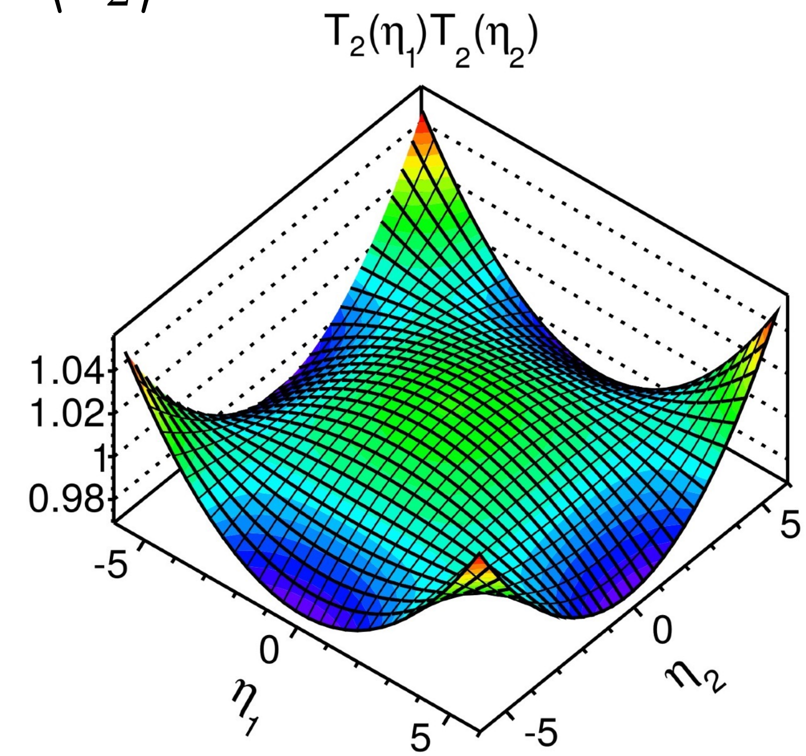
- First two shape components



$\langle a_1^2 \rangle$



$\langle a_2^2 \rangle$



- Correlation function can be obtained using mixed events technique

$$C(\eta_1, \eta_2) = \frac{\langle N(\eta_1) N(\eta_2) \rangle}{\langle N(\eta_1) \rangle \langle N(\eta_2) \rangle} \equiv \frac{\langle N(\eta_1) N(\eta_2) \rangle_{same}}{\langle N(\eta_1) N(\eta_2) \rangle_{mix}}$$

Centrality influence on CF

- Mixed events may not match perfectly!
- Centrality dependence of $\langle N(\eta) \rangle$ changes the appearance of CF

a_0, a_n correlation: $\langle a_0 a_n \rangle \neq 0$

residual centrality dependence of $\langle N(\eta) \rangle$

$$C(\eta_1,\eta_2) = 1 + \langle a_0 a_0 \rangle + \sum_{n=1}^{\infty} \langle a_0 a_n \rangle \left(T_n(\eta_2) + T_n(\eta_1) \right)$$

$$+ \sum_{n,m=1}^{\infty} \langle a_n a_m \rangle \frac{T_n(\eta_1) T_m(\eta_2) + T_n(\eta_2) T_m(\eta_1)}{2}$$

nonzero → distort → dynamical shape fluctuation

- Residual centrality dependence removed by

$$C_N(\eta_1,\eta_2) = \frac{C(\eta_1,\eta_2)}{C_p(\eta_1) C_p(\eta_2)} \approx 1 + \sum_{n,m=1}^{\infty} \langle a_n a_m \rangle \frac{T_n(\eta_1) T_m(\eta_2) + T_n(\eta_2) T_m(\eta_1)}{2}$$

$$C_p(\eta_1) = \frac{\int C(\eta_1,\eta_2) d\eta_2}{2Y}, C_p(\eta_2) = \frac{\int C(\eta_1,\eta_2) d\eta_1}{2Y}$$

- Thus isolate the dynamical shape fluctuation

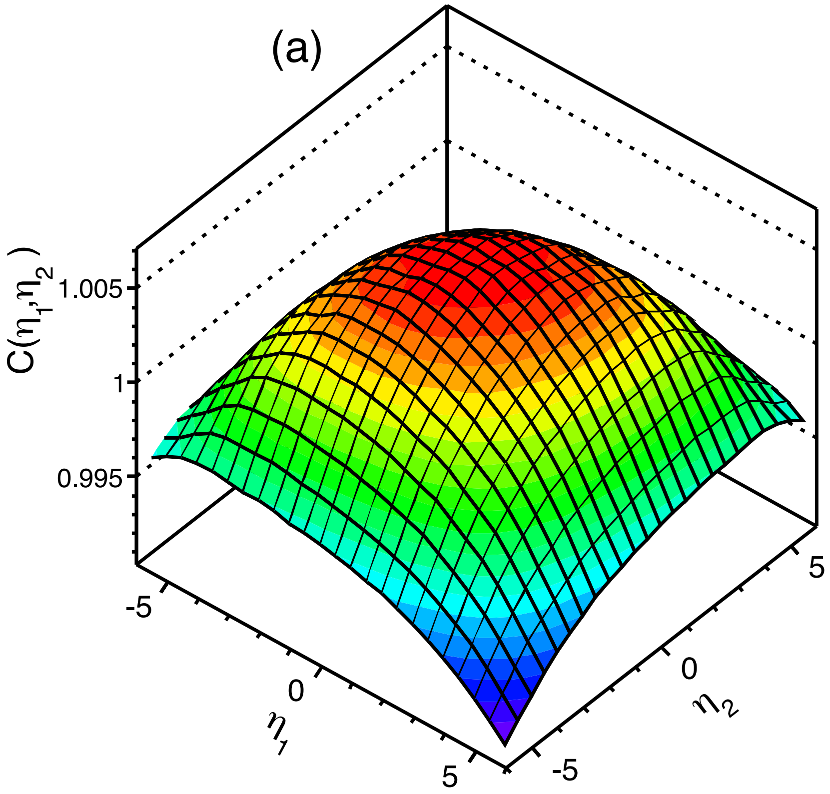
HIJING and AMPT results

Residual centrality dependence on CF in AMPT

- At fixed impact parameter, AMPT still has a large multiplicity fluctuation

$$C(\eta_1, \eta_2)$$

b=8 fm



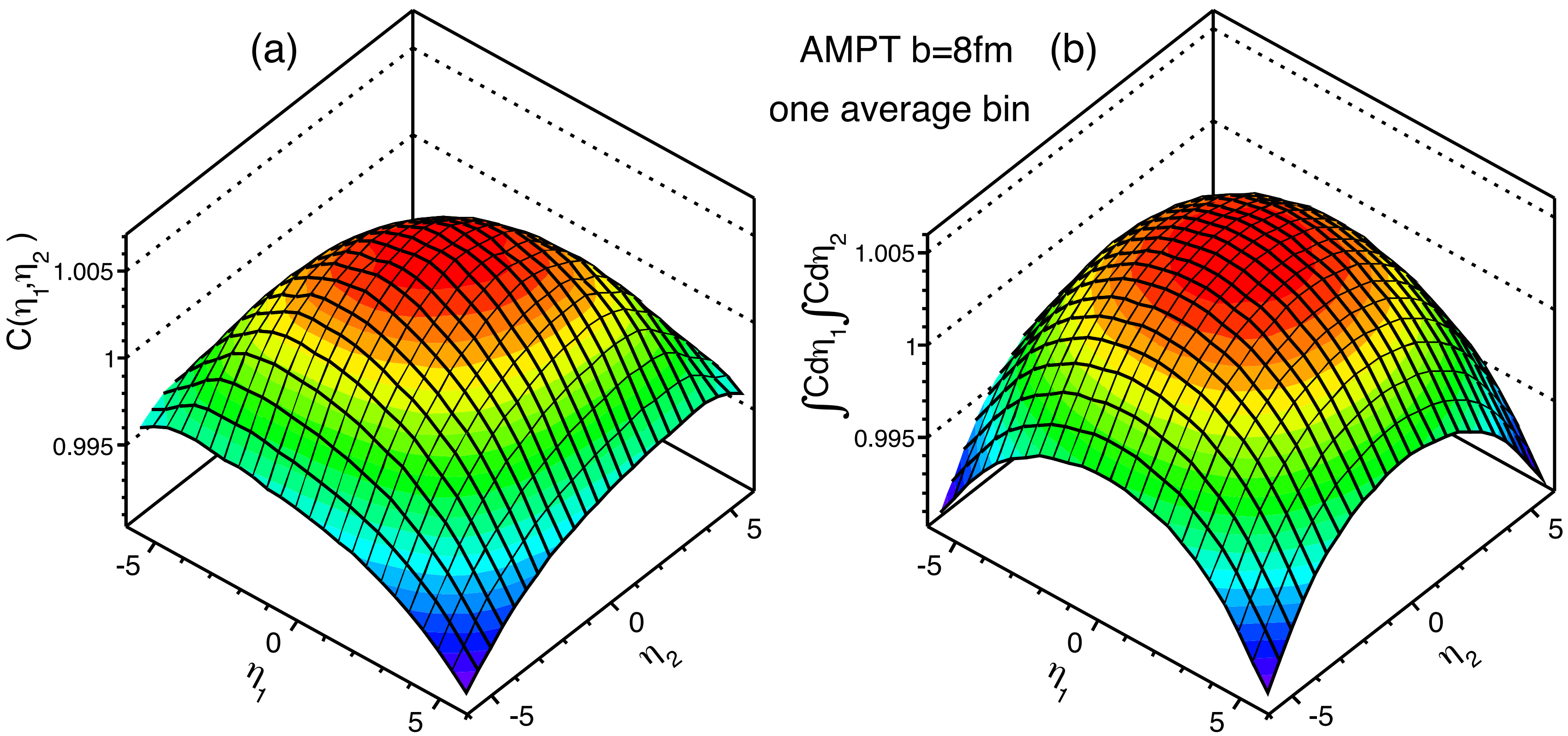
$$\eta \in [-Y, Y], \text{ Y=6}$$

Residual centrality dependence on CF in AMPT

- At fixed impact parameter, AMPT still has a large multiplicity fluctuation

$$C(\eta_1, \eta_2) \qquad C_p(\eta_1)C_p(\eta_2)$$

$$C_p(\eta_1) = \frac{\int C(\eta_1,\eta_2)d\eta_2}{2Y}, C_p(\eta_2) = \frac{\int C(\eta_1,\eta_2)d\eta_1}{2Y}$$

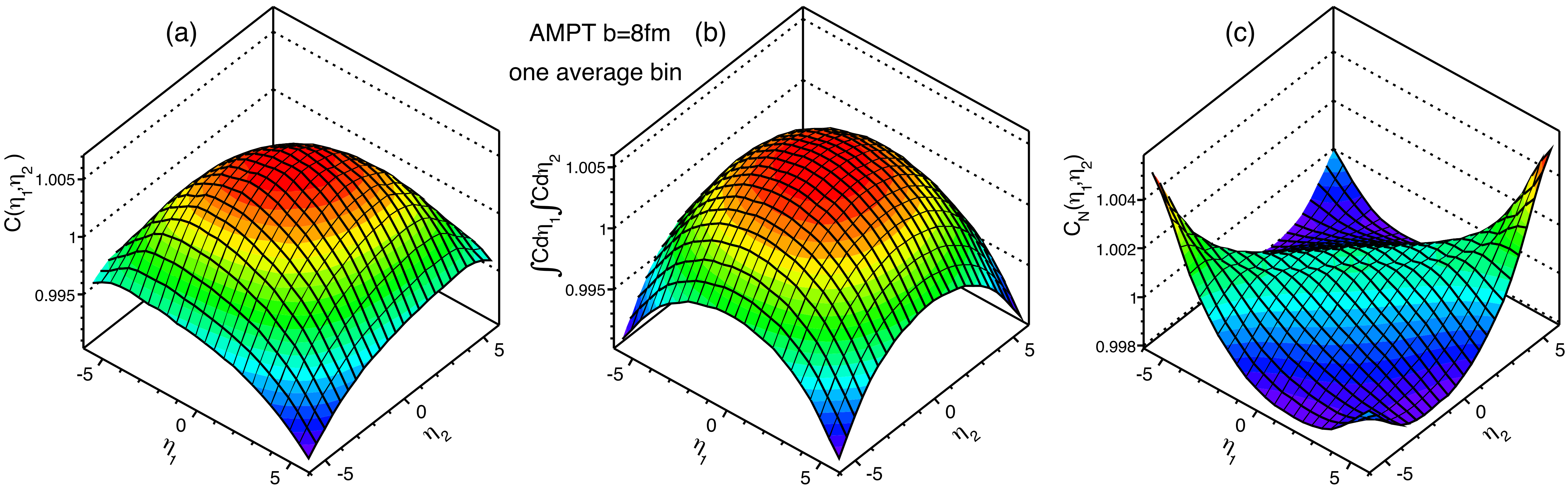


Residual centrality dependence on CF in AMPT

- At fixed impact parameter, AMPT still has a large multiplicity fluctuation

$$C(\eta_1,\eta_2) \qquad C_p(\eta_1)C_p(\eta_2) \qquad C_N(\eta_1,\eta_2)=\frac{C(\eta_1,\eta_2)}{C_p(\eta_1)C_p(\eta_2)}$$

$$C_p(\eta_1)=\frac{\int C(\eta_1,\eta_2)d\eta_2}{2Y},\ C_p(\eta_2)=\frac{\int C(\eta_1,\eta_2)d\eta_1}{2Y}$$

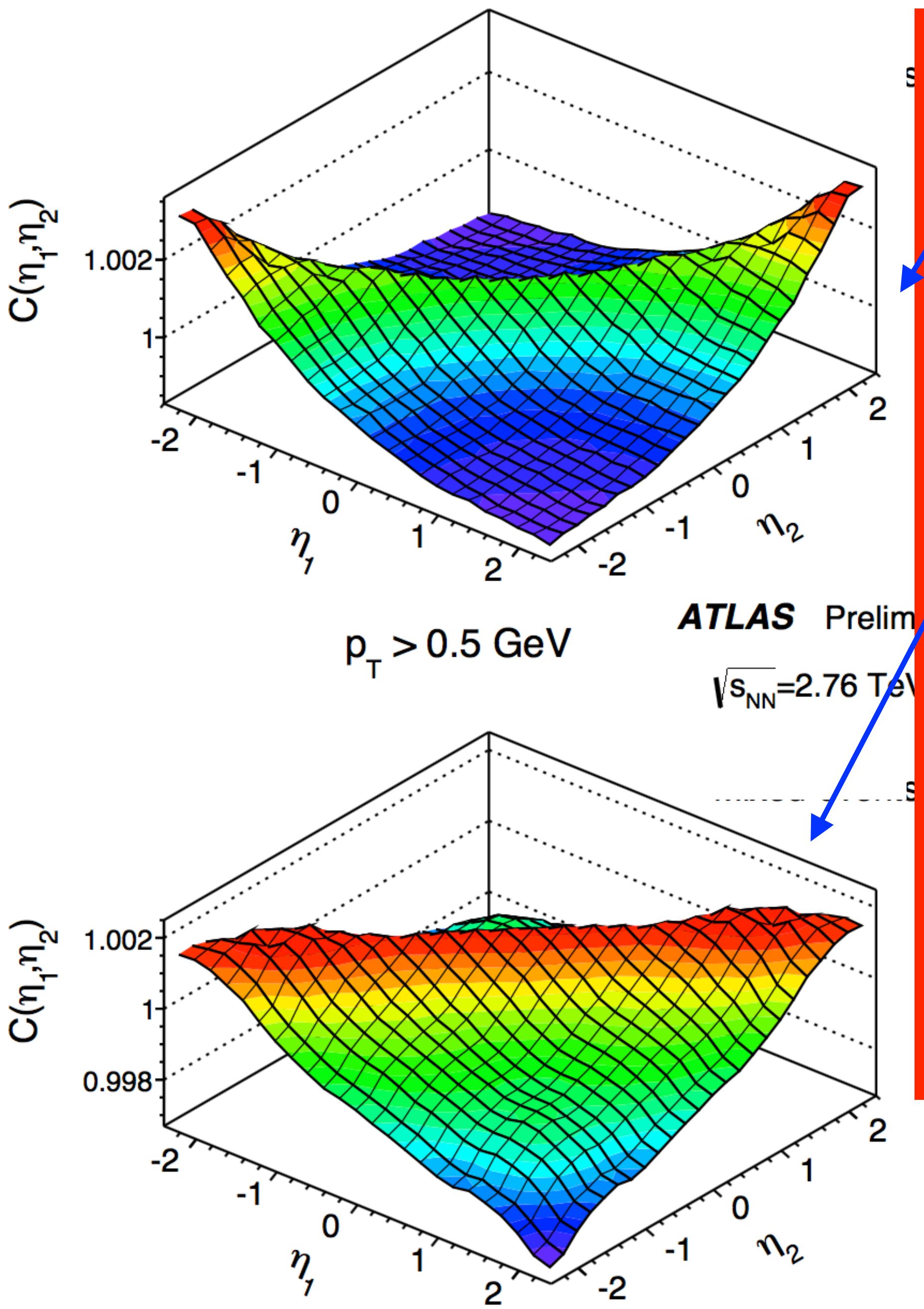


- After removal, shape fluctuation is very clear in $C_N(\eta_1,\eta_2)$

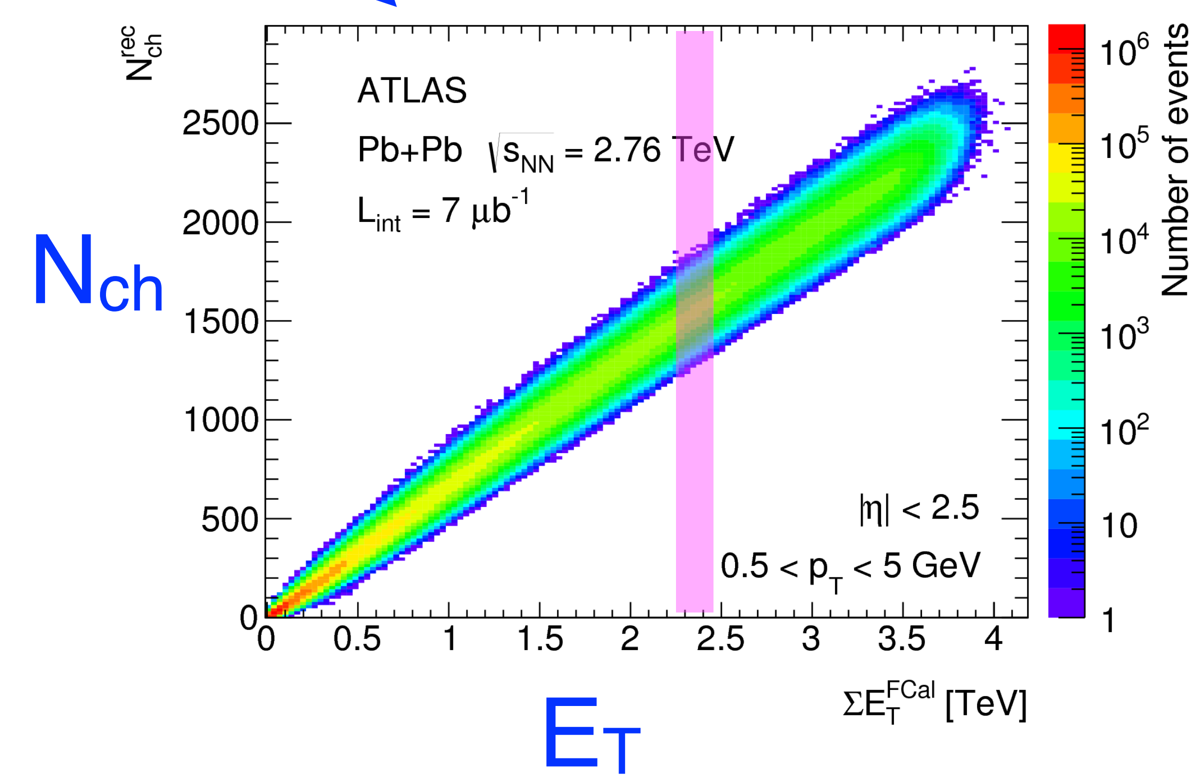
Residual centrality dependence removal(I)

- ATLAS performed this removal procedure in Pb+Pb@2.76TeV

$$C(\eta_1, \eta_2) \equiv \frac{\langle N(\eta_1)N(\eta_2)\rangle_{same}}{\langle N(\eta_1)N(\eta_2)\rangle_{mix}}$$



- Mixed-event matched in Multiplicity
- Mixed-event matched in forward rapidity energy
  - larger multiplicity fluctuation



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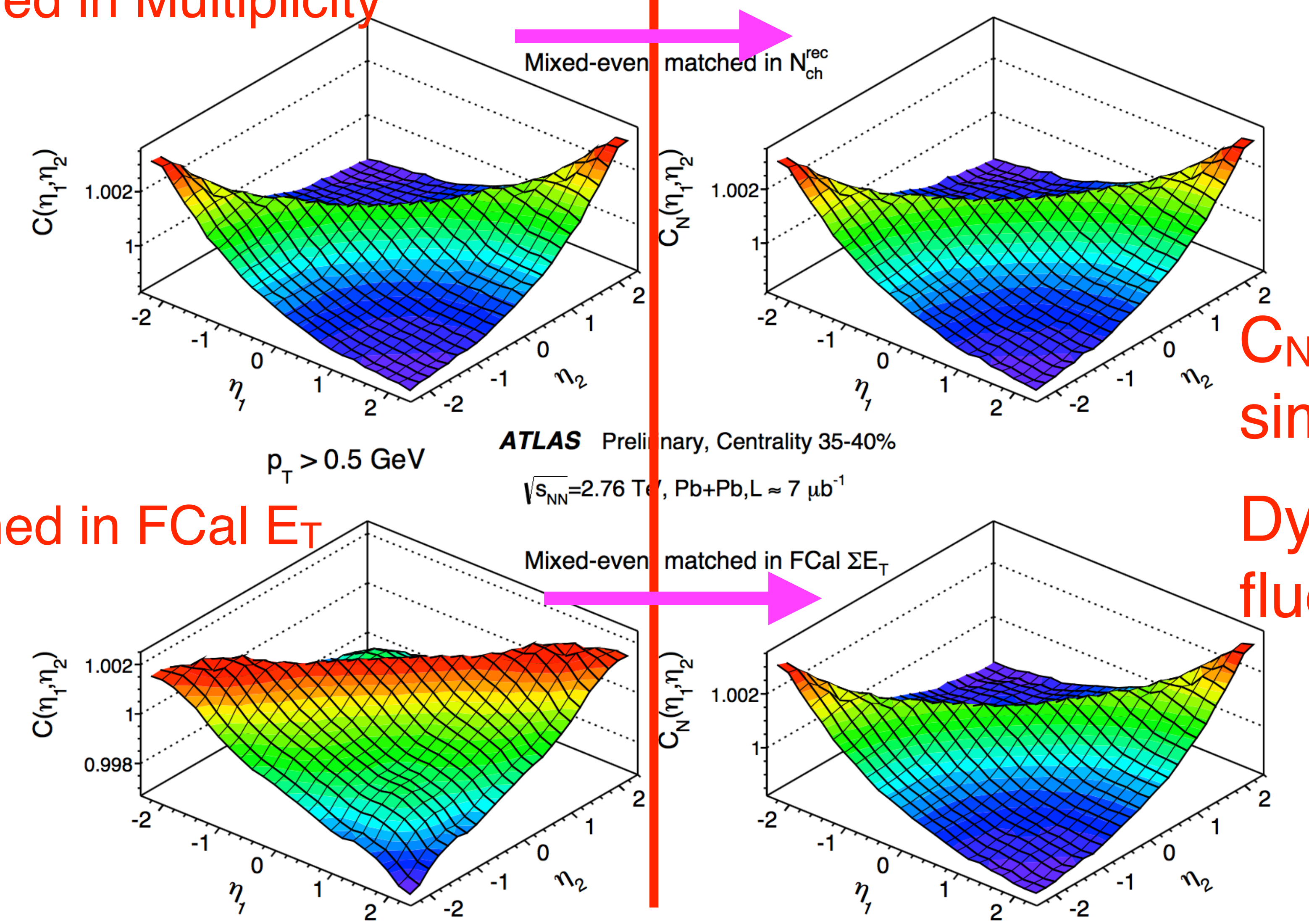
Residual centrality dependence removal(II)

$$C(\eta_1, \eta_2) \equiv \frac{\langle N(\eta_1)N(\eta_2)\rangle_{same}}{\langle N(\eta_1)N(\eta_2)\rangle_{mix}} \qquad C_N(\eta_1, \eta_2) = \frac{C(\eta_1, \eta_2)}{C_p(\eta_1)C_p(\eta_2)}$$

After removal

Mixed-event matched in Multiplicity

Mixed-event matched in FCal E_T



$C_N(\eta_1,\eta_2)$ has similar shape

Dynamical shape fluctuation is isolated

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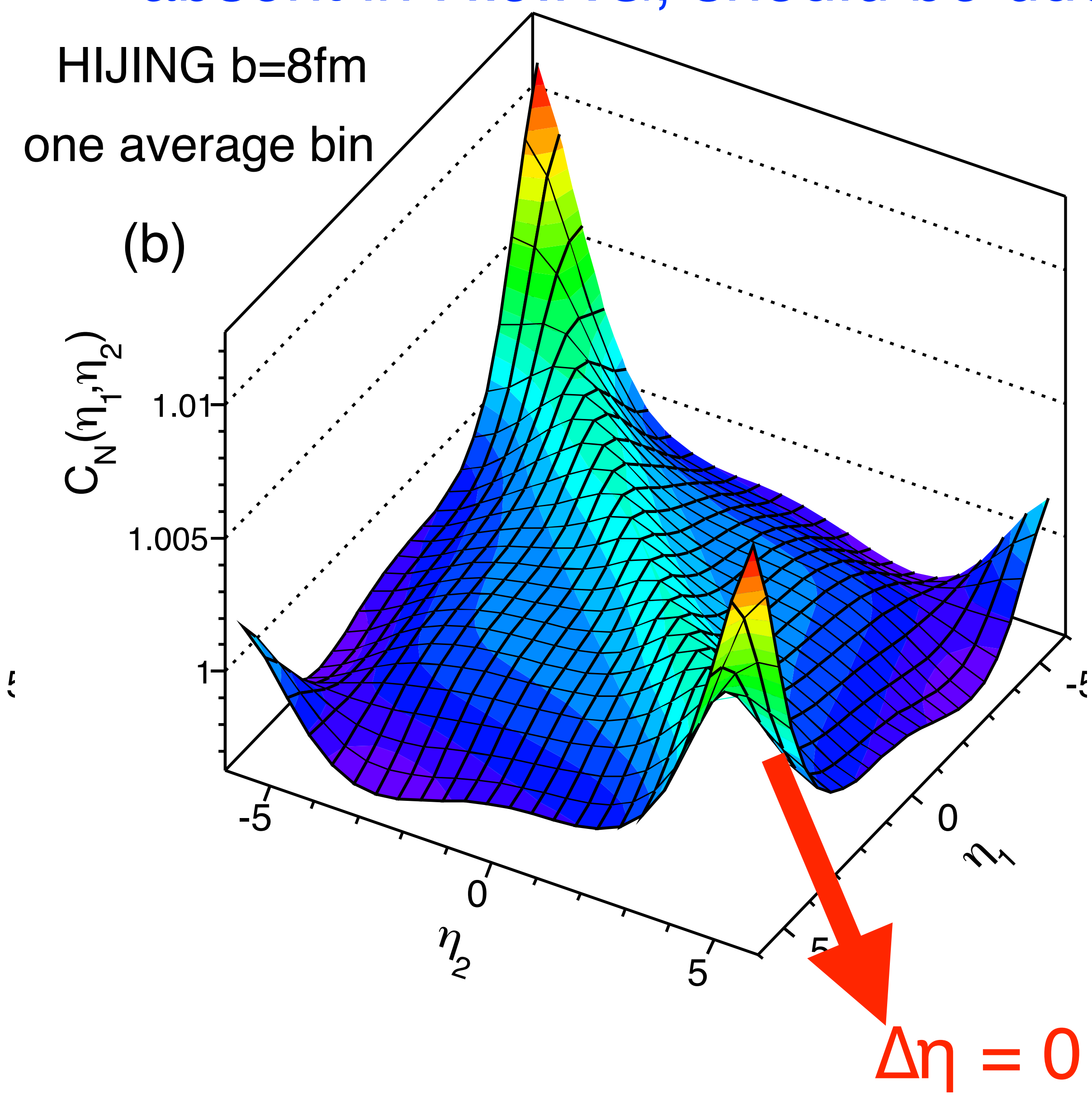
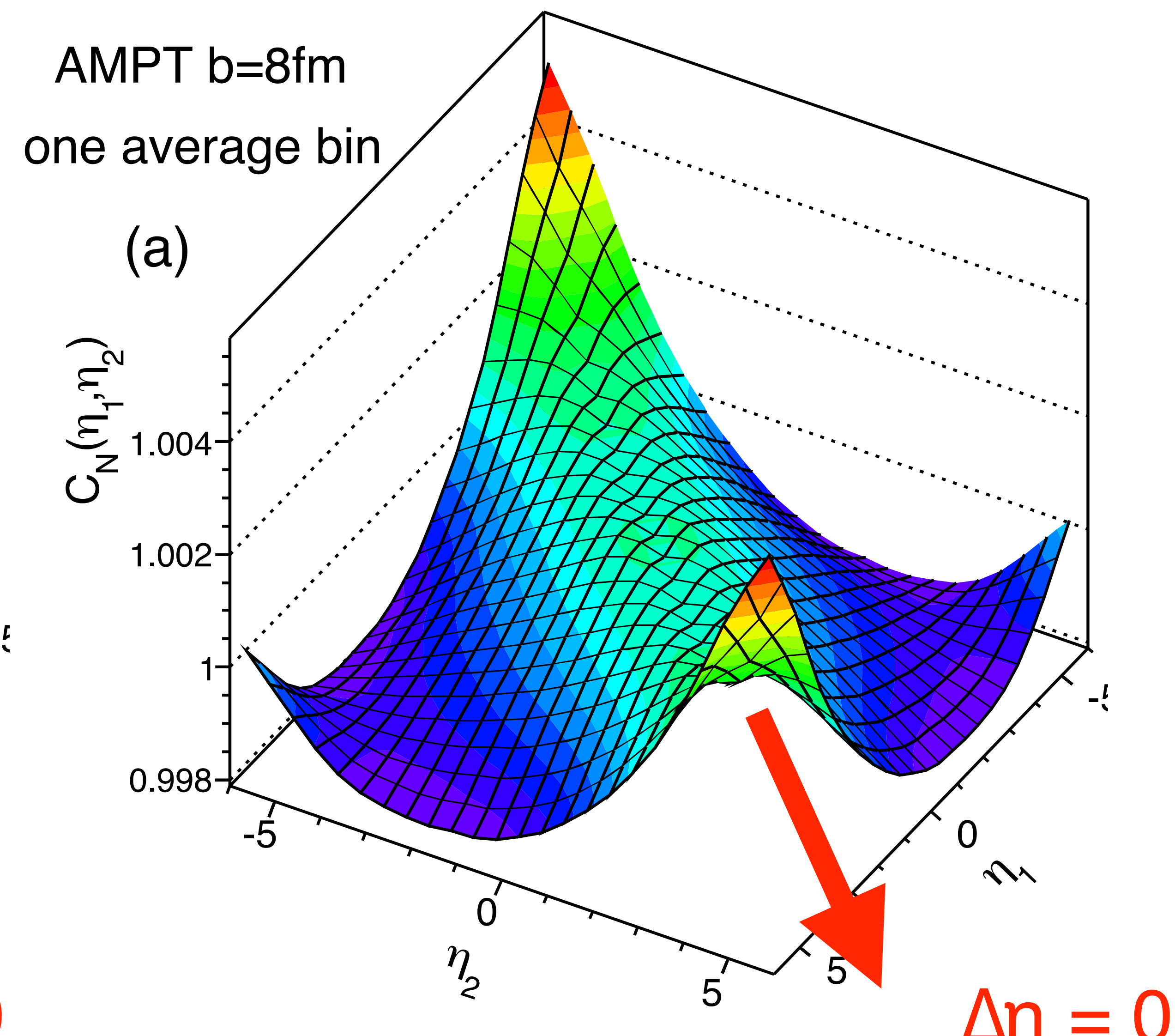
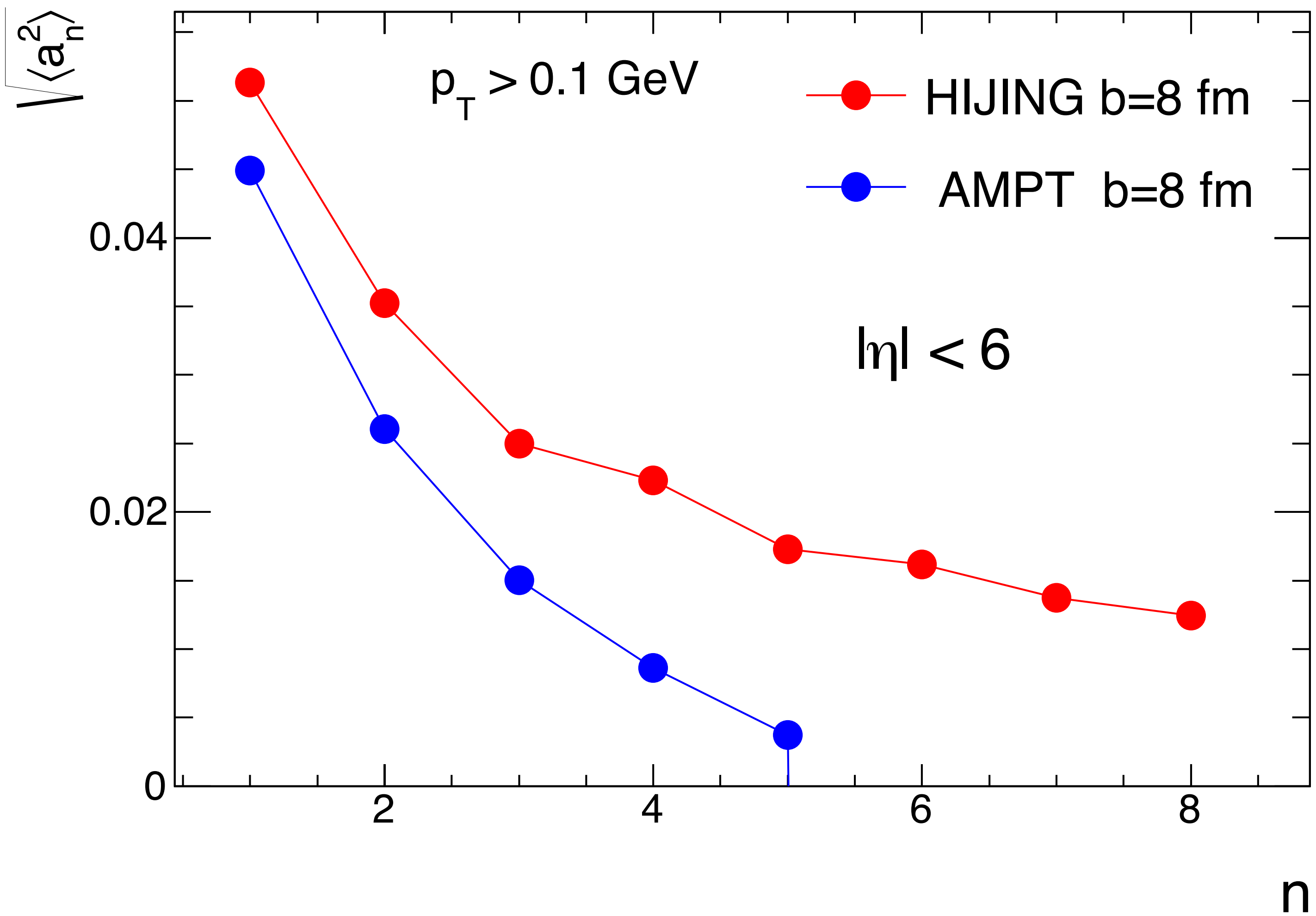
CF in HIJING and AMPT

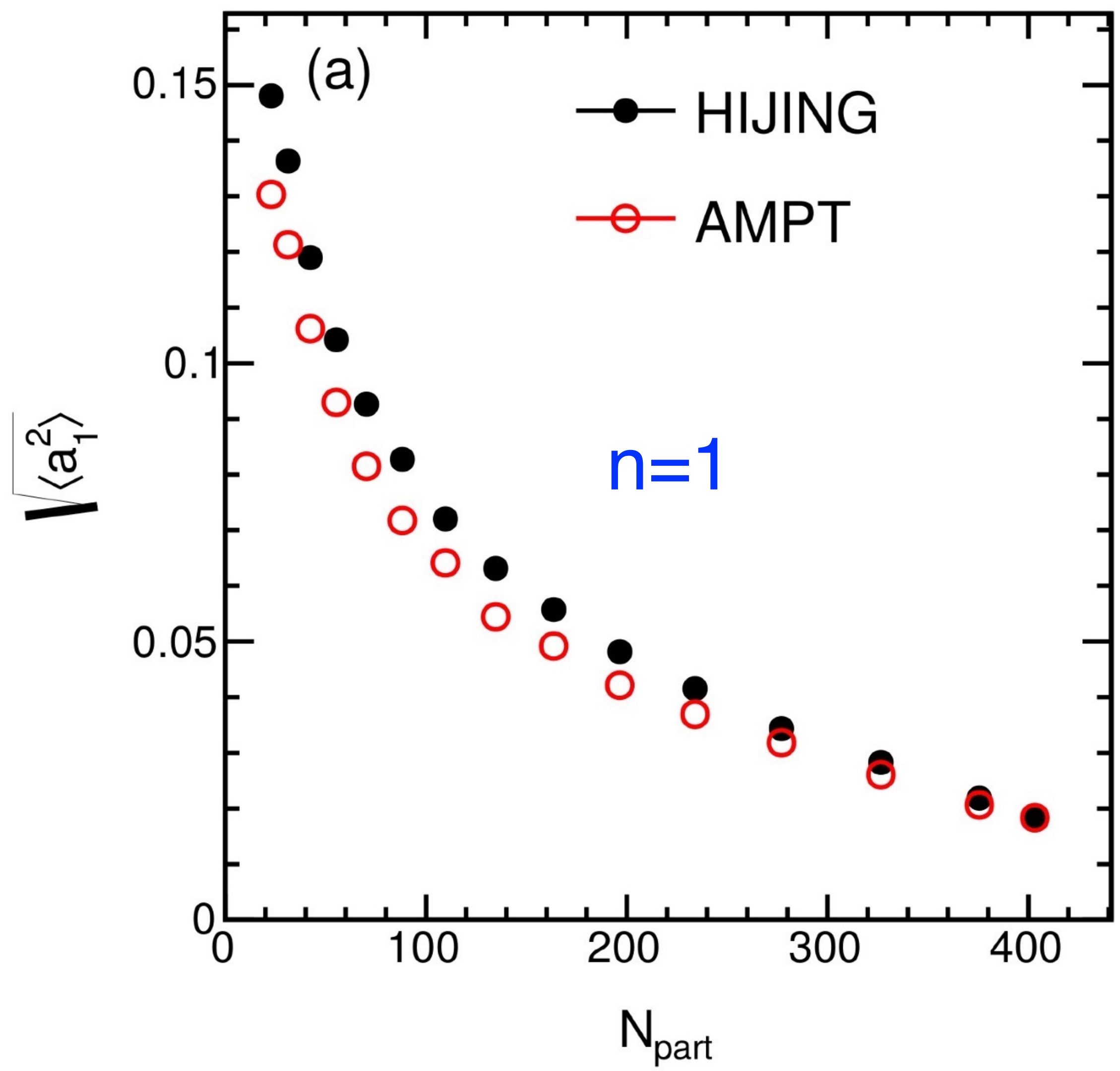
- AMPT and HIJING has same initial condition, but AMPT has final state interaction
- AMPT results show an shallow minimum around $\Delta\eta = 0$ with a width of about ±0.4.
  - absent in HIJING, should be due to final state effects





$\sqrt{\langle a_n^2 \rangle}$ in HIJING and AMPT



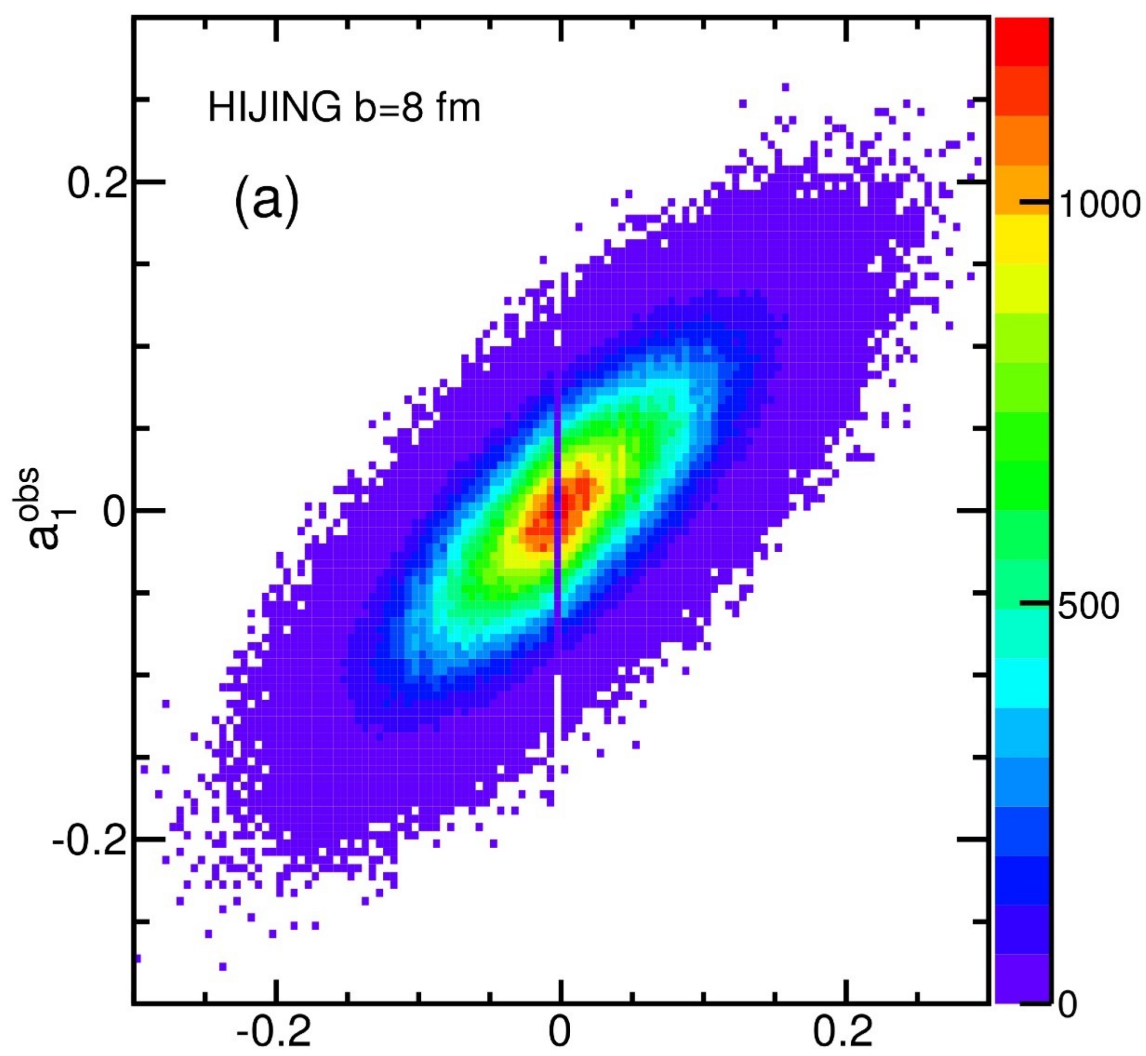


- $\sqrt{a_n^2}$ is consistently smaller in AMPT than those from HIJING
  - the final state interaction have more damping effects on the coefficients
- a_1 signal strength increases toward peripheral collisions
  - peripheral events has smaller multiplicity, thus larger relative fluctuations

Is a_1 driven by N_{part} FB asymmetry?

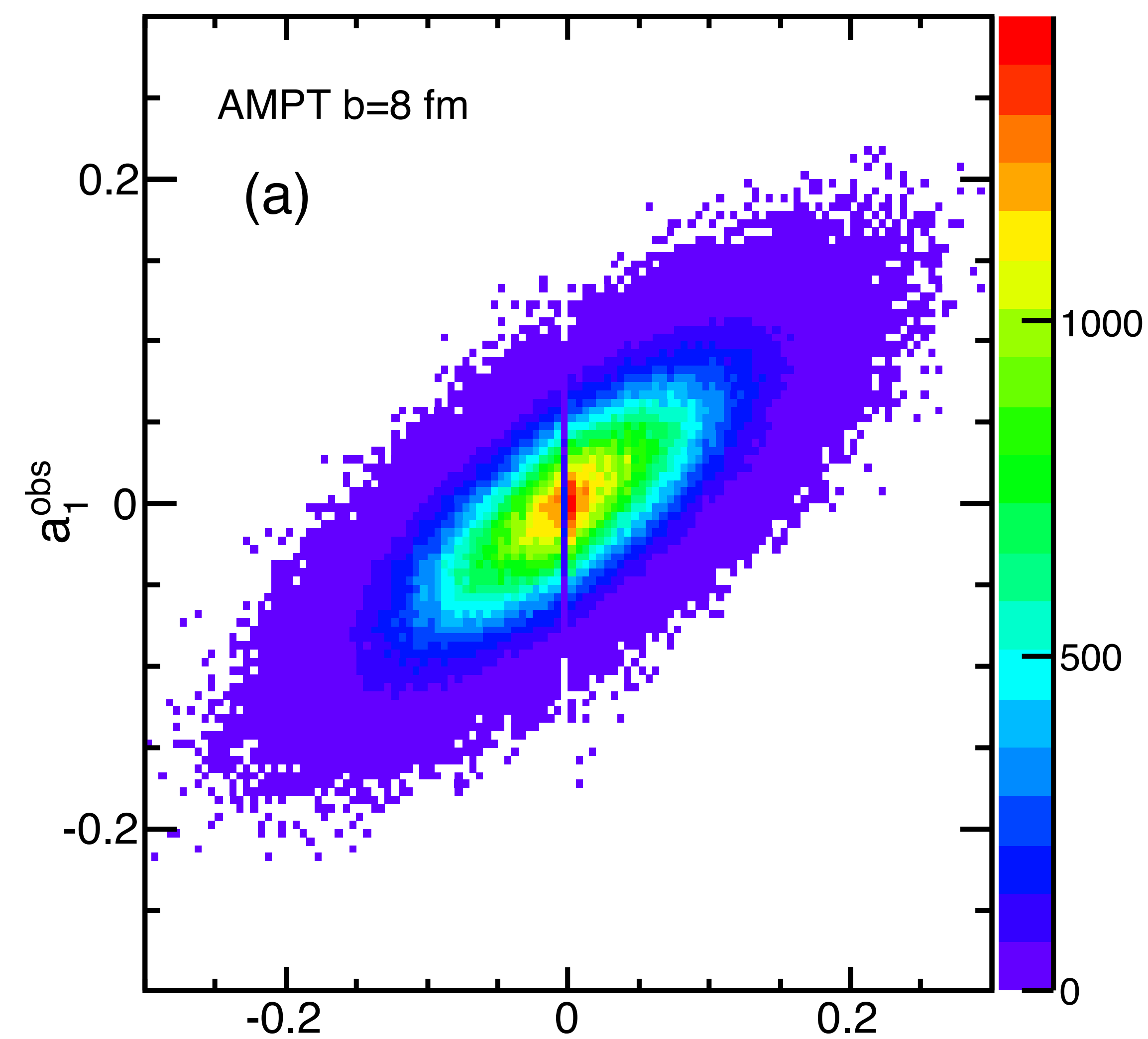
- Strong correlation between a_1 and $A_{part} = \frac{N^F_{part} - N^B_{part}}{N^F_{part} + N^B_{part}}$ is observed!

HIJING



$$A_{part} = \frac{N^F_{part} - N^B_{part}}{N^F_{part} + N^B_{part}}$$

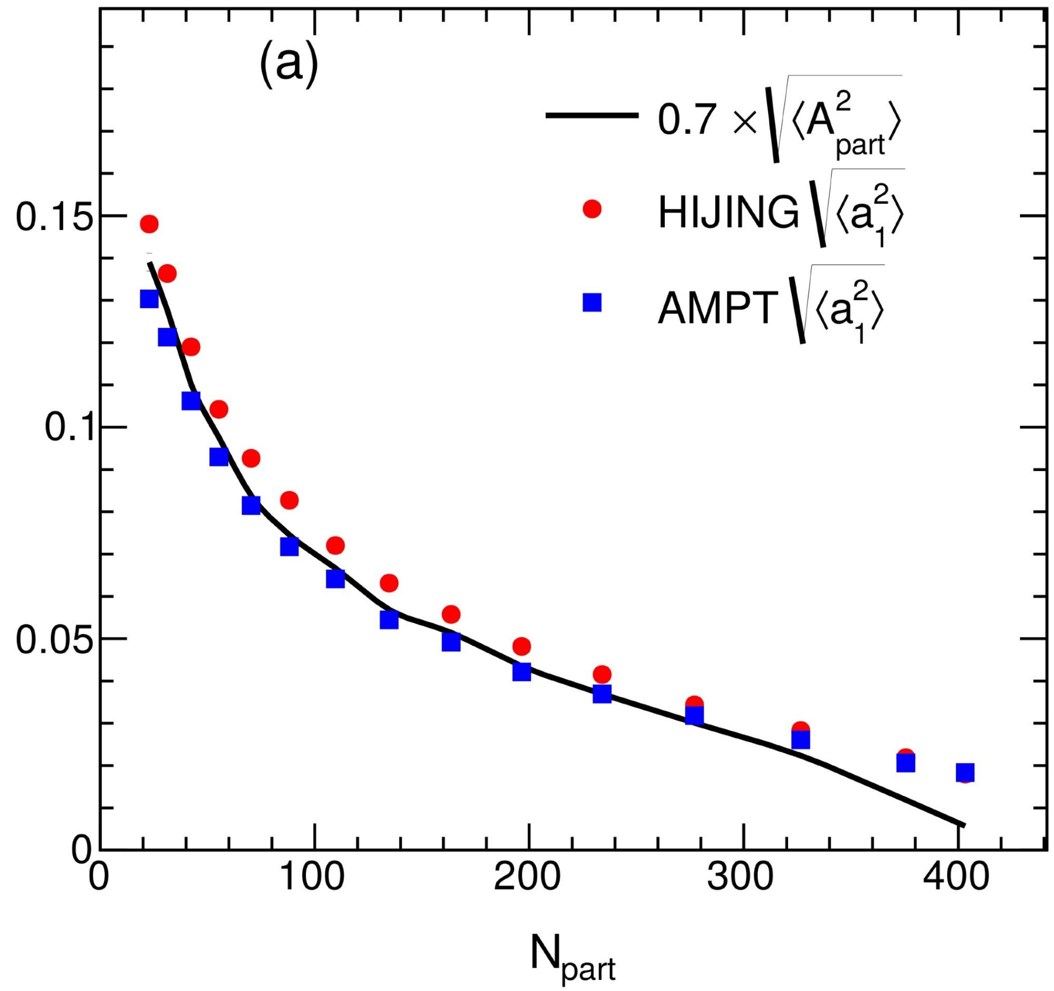
AMPT



$$A_{part} = \frac{N^F_{part} - N^B_{part}}{N^F_{part} + N^B_{part}}$$

A_{part} in Glauber, a_1 in HIJING and AMPT

1. $a_1 \propto N^F_{part} - N^B_{part}$

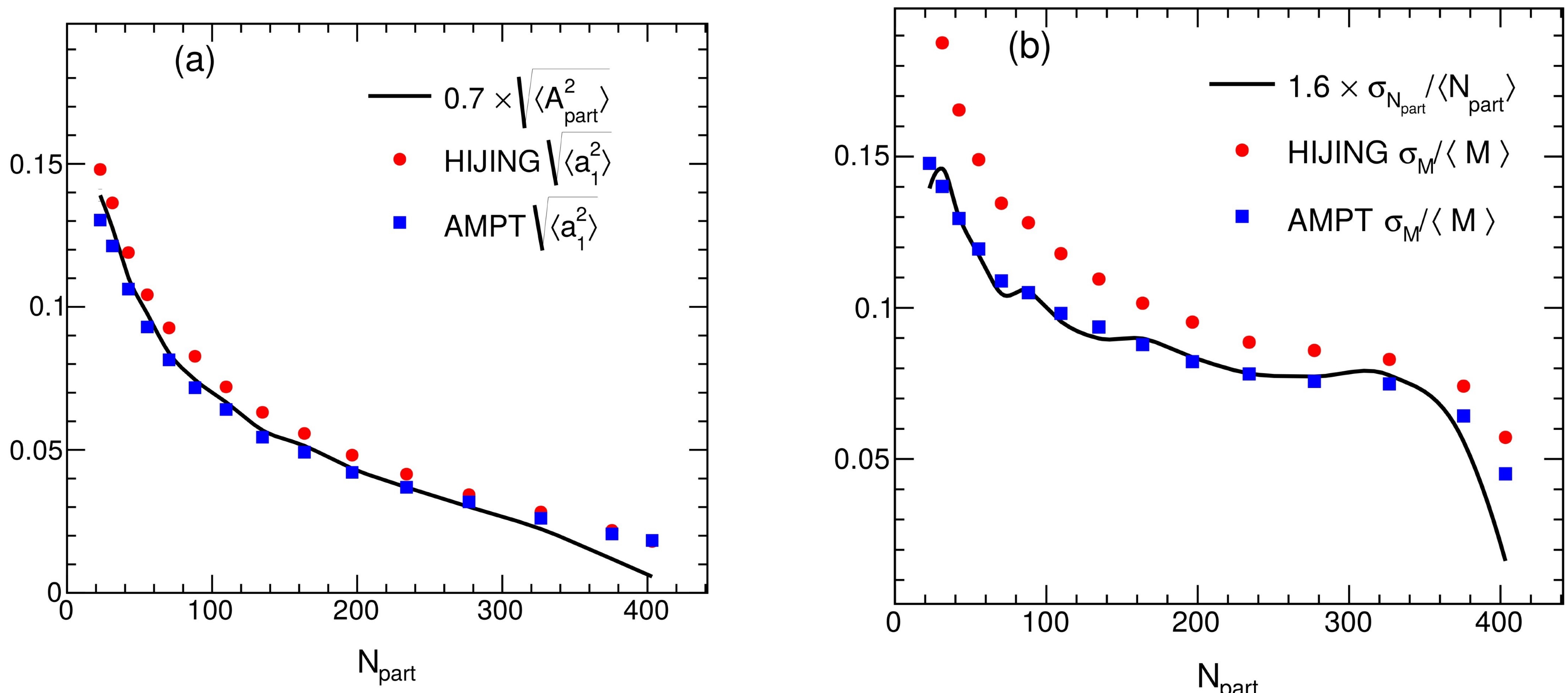


- Fig(a). Similar centrality dependence of a_1 and A_{part} in three models

  → a_1 is driven by N_{part} asymmetry

A_{part} in Glauber, a_1 in HIJING and AMPT

1. $a_1 \propto N^F_{part} - N^B_{part}$
2. $Mul \propto N^F_{part} + N^B_{part}$



- Fig(a). Similar centrality dependence of a_1 and A_{part} in three models

  ⟶ a_1 is driven by N_{part} asymmetry
- Fig(b). Similar centrality dependence of M fluc. with N_{part} fluc.

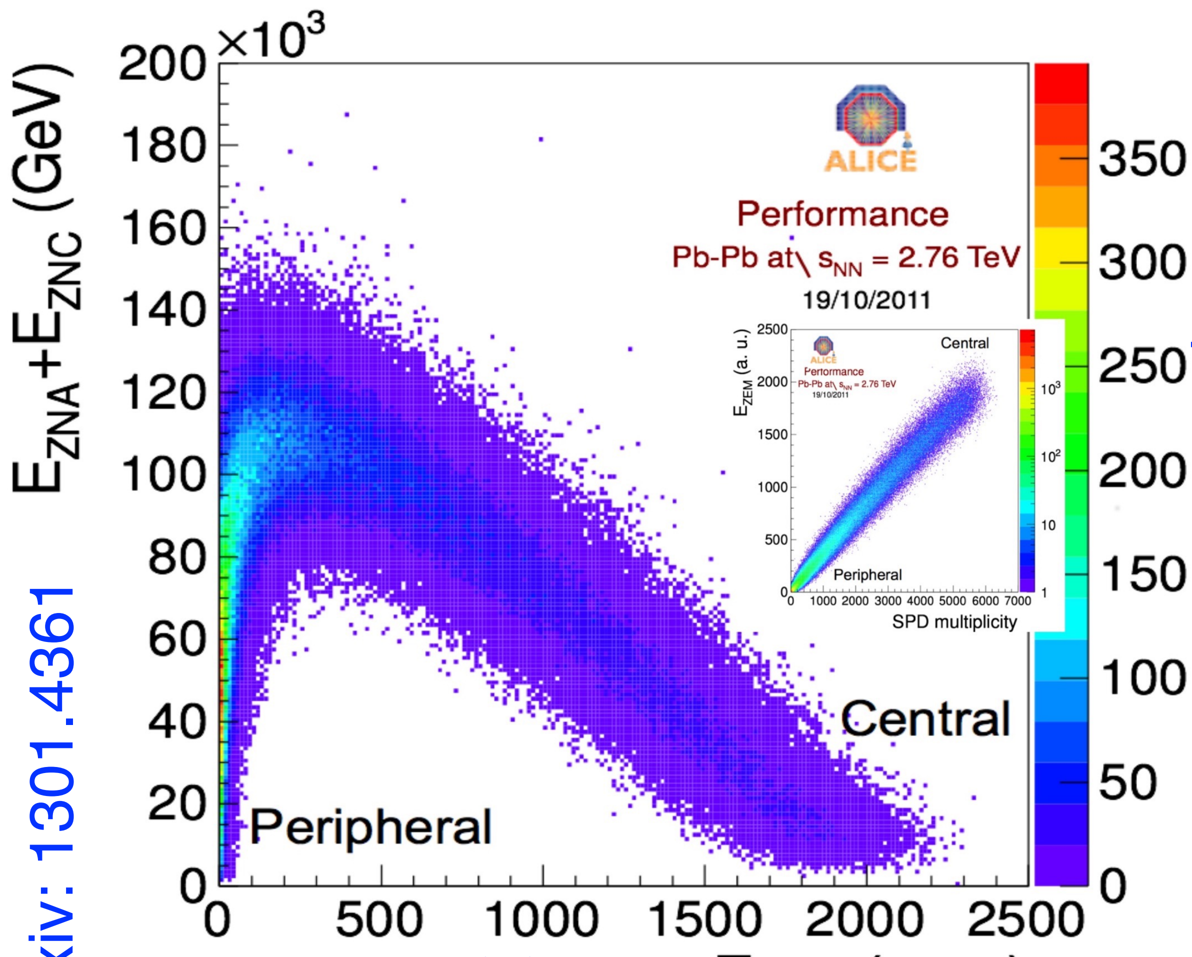
a_1 with spectator asymmetry

- a_1 also should be anti-correlated with N_{spec} FB asymmetry

$$N^F_{part} - N^B_{part} = -(N^F_{spec} - N^B_{spec})$$

- Zero Degree Calorimeters measure a fraction F/B-going $N_{neutron}$
  - also expect some anti-correlation with spectator neutrons in ZDC

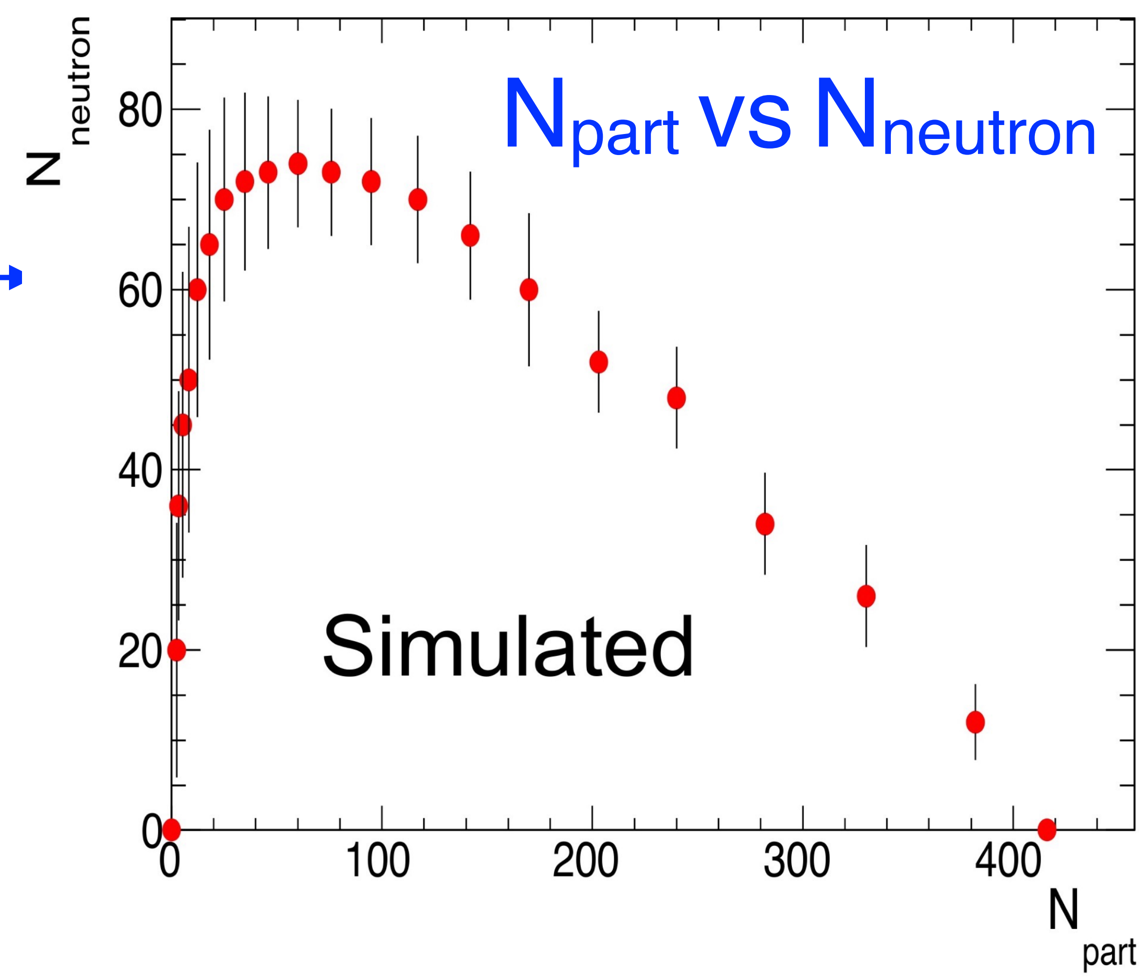
$N_{neutron}$



arxiv: 1301.4361

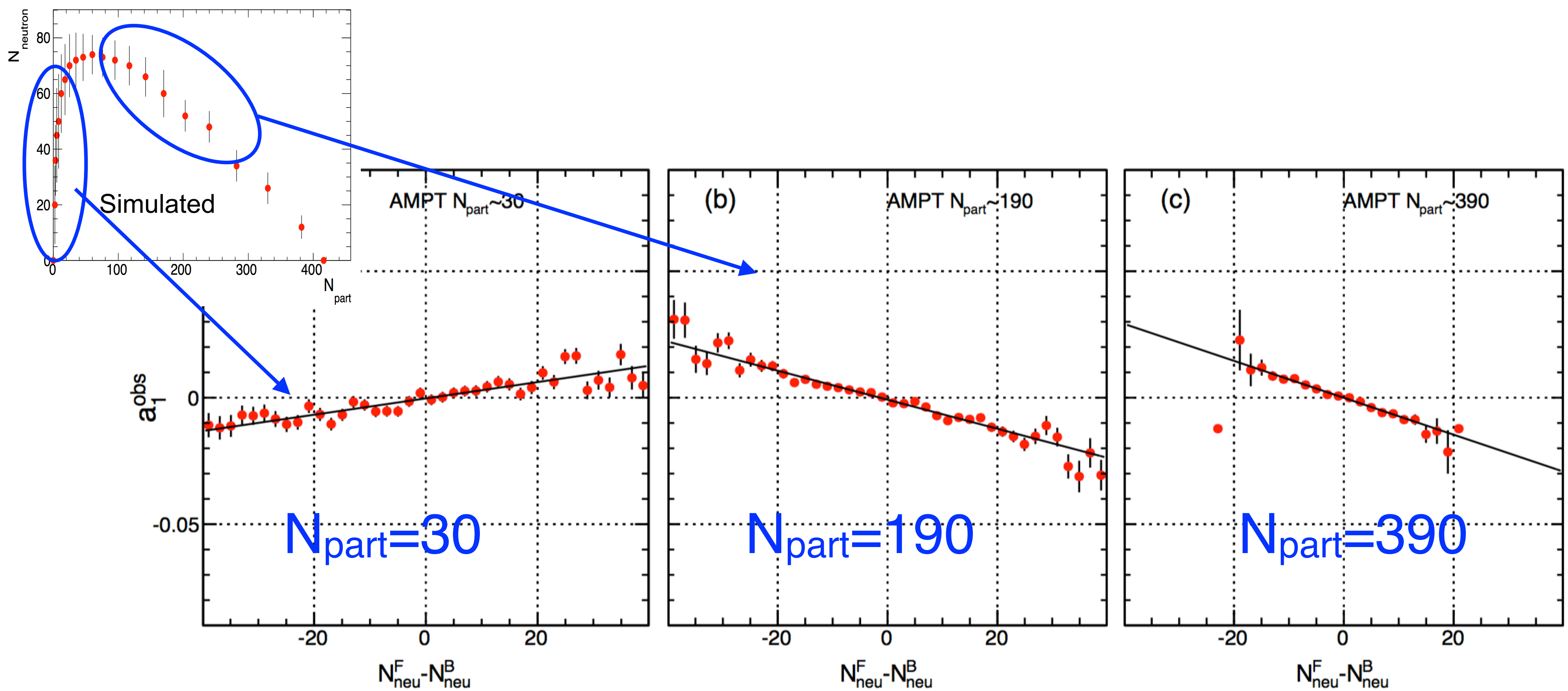
$4.8 < |\eta| < 5.8$

centrality



a_1 with $N_{neutron}$ asymmetry

- We predict the correlation strength in experimental measurement
  - we see signal strength of a few percent

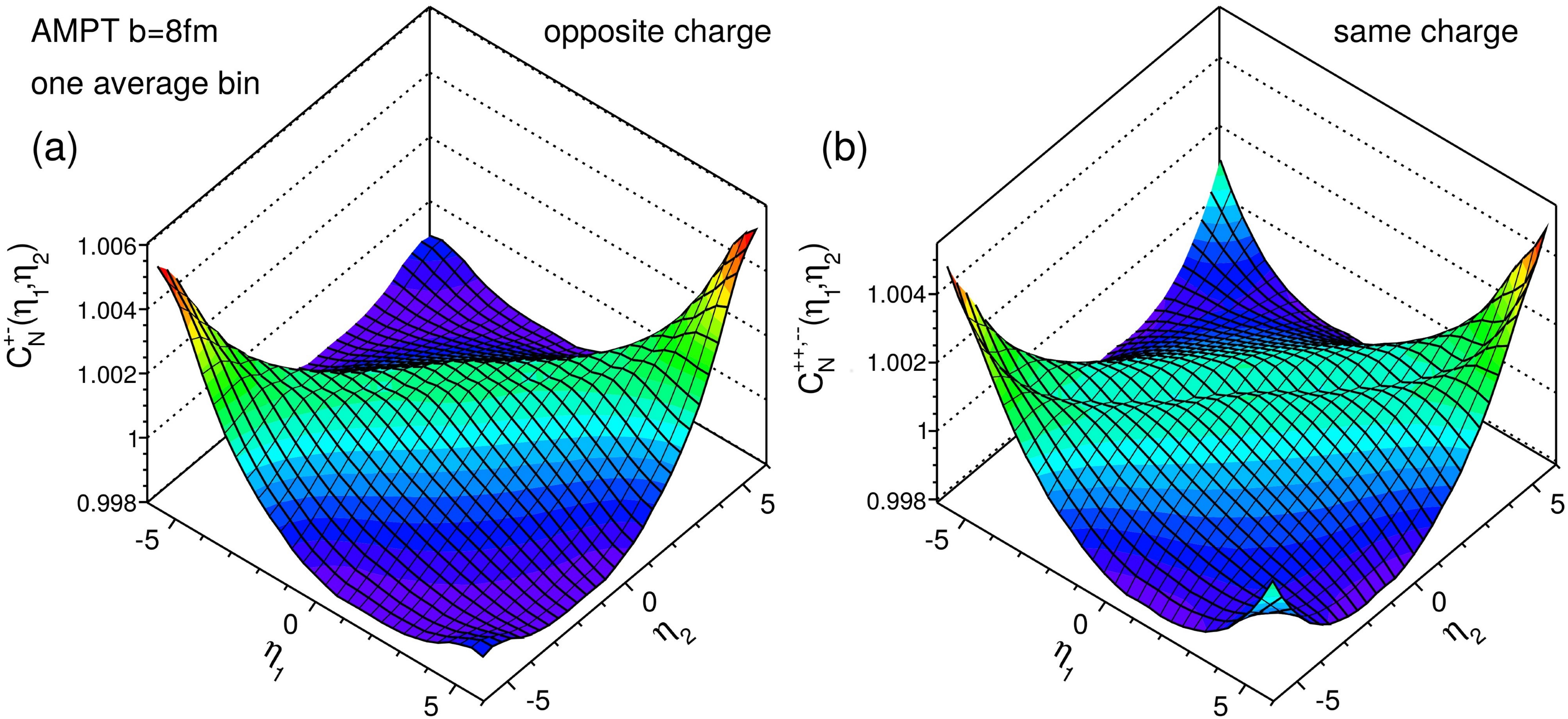


- a_1 and $N^F_{neu} - N^B_{neu}$ are experimental observables
  - this correlation can be measured directly in experiments

Charge dependence of CF in AMPT

- Correlations between different charge combinations
  - same long-range structure, charge-dependent short range structure

$$C_N^{+,-}(\eta_1,\eta_2) = \frac{\langle N^+(\eta_1)N^-(\eta_2)\rangle}{\langle N^+(\eta_1)\rangle\langle N^-(\eta_2)\rangle} \qquad C_N^{++,--}(\eta_1,\eta_2) = \frac{\langle N^\pm(\eta_1)N^\pm(\eta_2)\rangle}{\langle N^\pm(\eta_1)\rangle\langle N^\pm(\eta_2)\rangle}$$



Summary

- A method is proposed to study the longitudinal multiplicity correlations
  - suitable for p+p, p+A, A+A collisions
  - residual centrality effect can be removed from correlation function
  - short range correlation subtraction possible *(see next talk of ALTAS measurement)*
- Physics in HIJING and AMPT model is revealed using this method:
  - $\langle a_n a_n \rangle$ has been observed for different oder n
  - coefficients are damped more in AMPT than HIJING
  - a_1 and N_{part} asymmetry: strong correlation
  - a_1 direct related to $N^F_{neu} - N^B_{neu}$: anti-correlation, measurable in experiments
  - charge dependence of CF in AMPT also shows the final state hardonization affects the CF
- These study shows that pseudo rapidity correlation function provide a tool to understand the early particle production mechanism and longitudinal dynamics in heavy-ion collisions

Back up

a_n from fitting single particle distribution

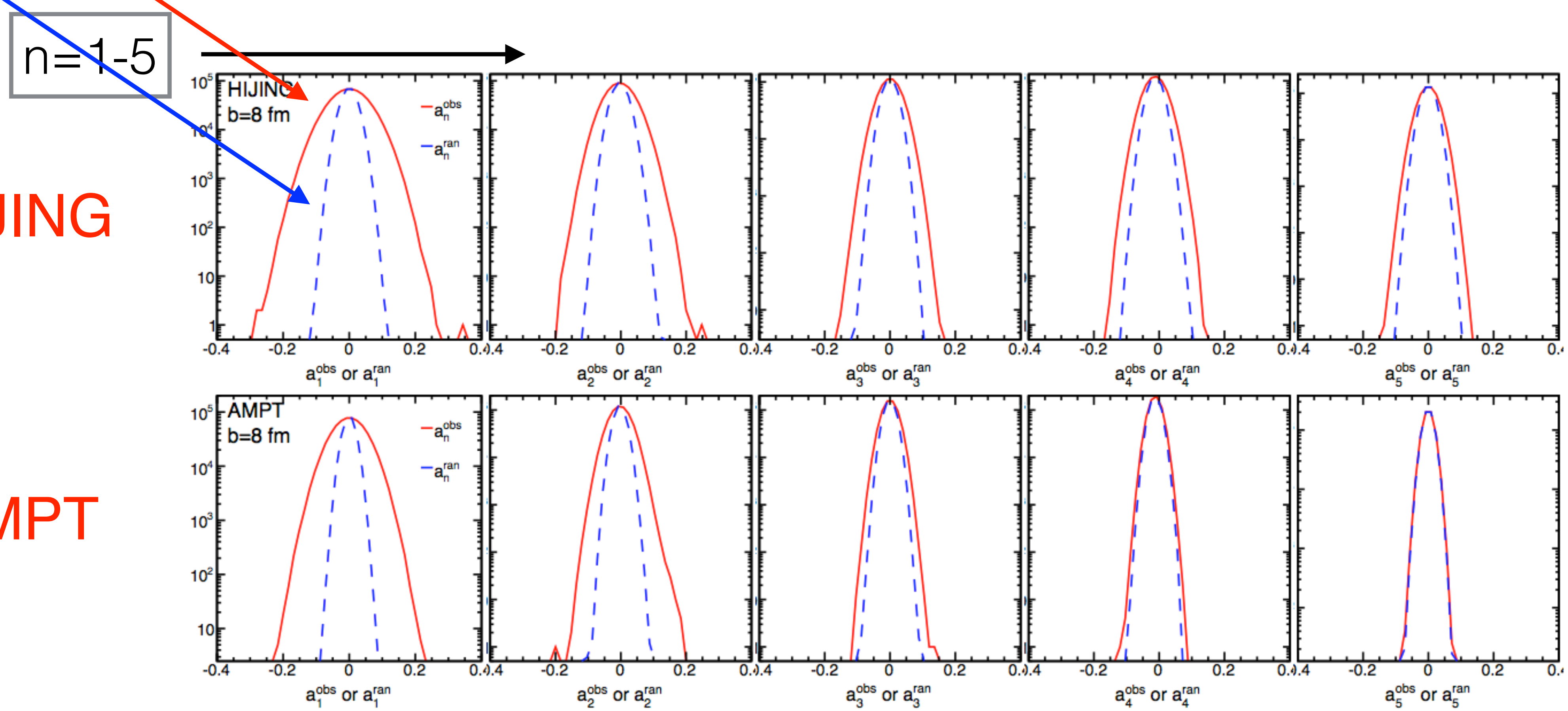
- We run HIJING and AMPT simulation data in Pb+Pb @2.76TeV
- Events are binned in narrow event activities based on total multiplicity M

a_n^{obs} directly fit $R(\eta)$

a_n^{ran} fit from a random event with M particles sampled to $\langle R(\eta) \rangle$, to account for the signal from statistical noise

HIJING

AMPT



- Guassian distribution observed, so we can calculate true signal by

$$\langle a_n^2 \rangle = \left\langle \left(a_n^{\text{obs}}\right)^2 \right\rangle - \left\langle \left(a_n^{\text{ran}}\right)^2 \right\rangle$$