
# Rapidity Dependence of Multiplicity Correlations at the LHC

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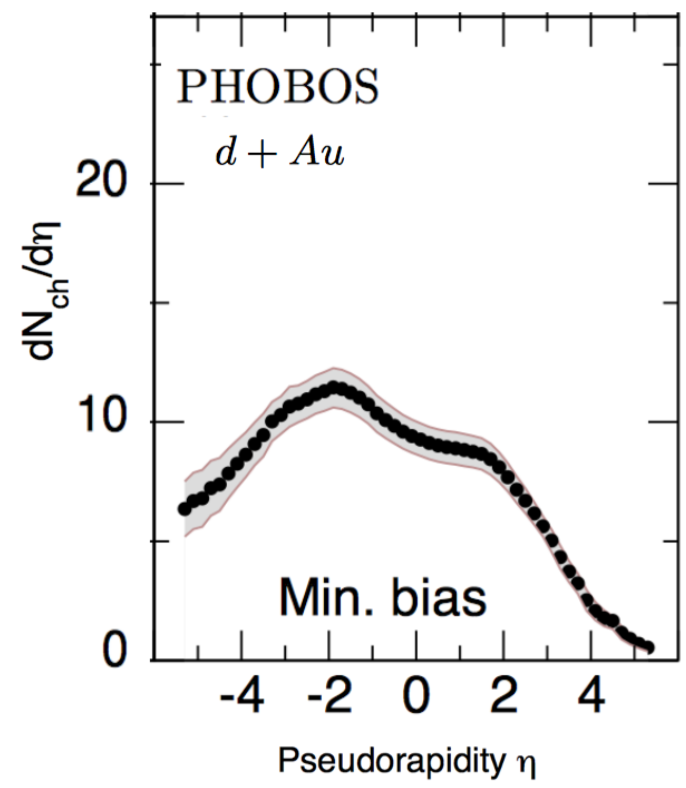
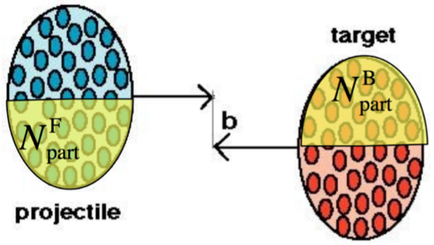
# Longitudinal correlations

- Particle production at different pseudorapidities can be correlated.
  - Can arise from initial conditions.
  - Also from long-range correlations from multi-parton interactions.
  - Can also help study hadrnozation and charge correlations and short-range correlations.

- Many measurements from RHIC and LHC of the forward-backward correlations.

arXiv:1505.06766




$N^F_{part} \neq N^B_{part}$

# Longitudinal correlations

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  - Can arise from initial conditions.
  - Also from long-range correlations from multi-parton interactions.
  - Can help study hadrnozation.

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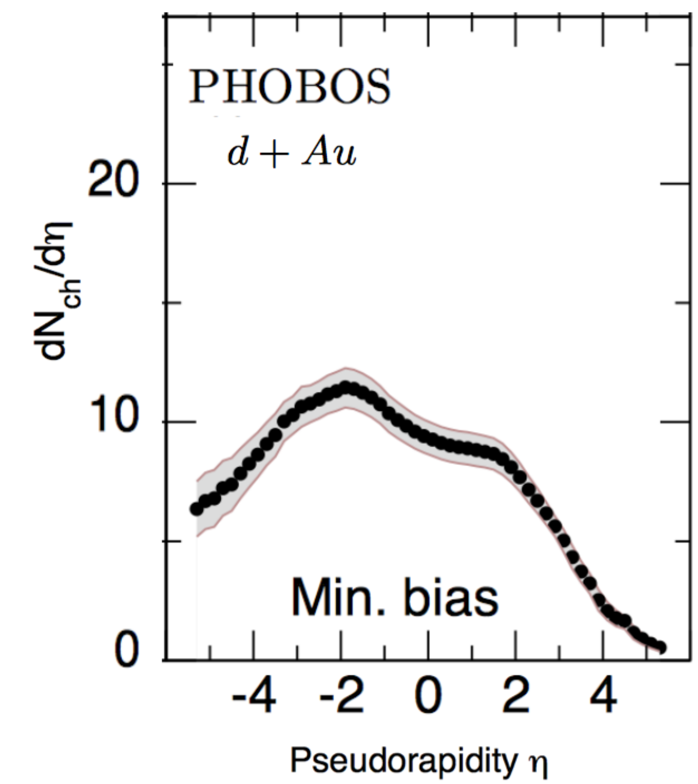
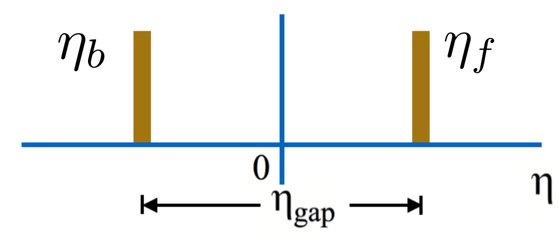
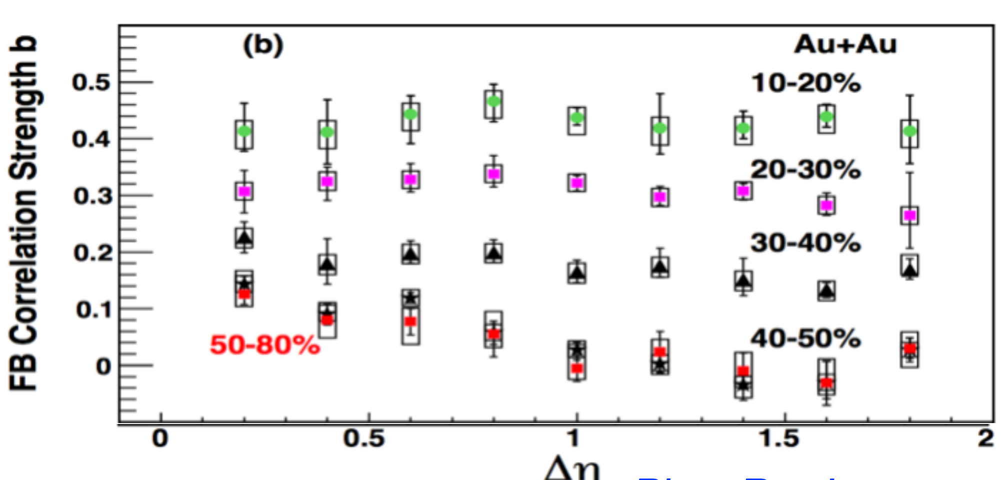


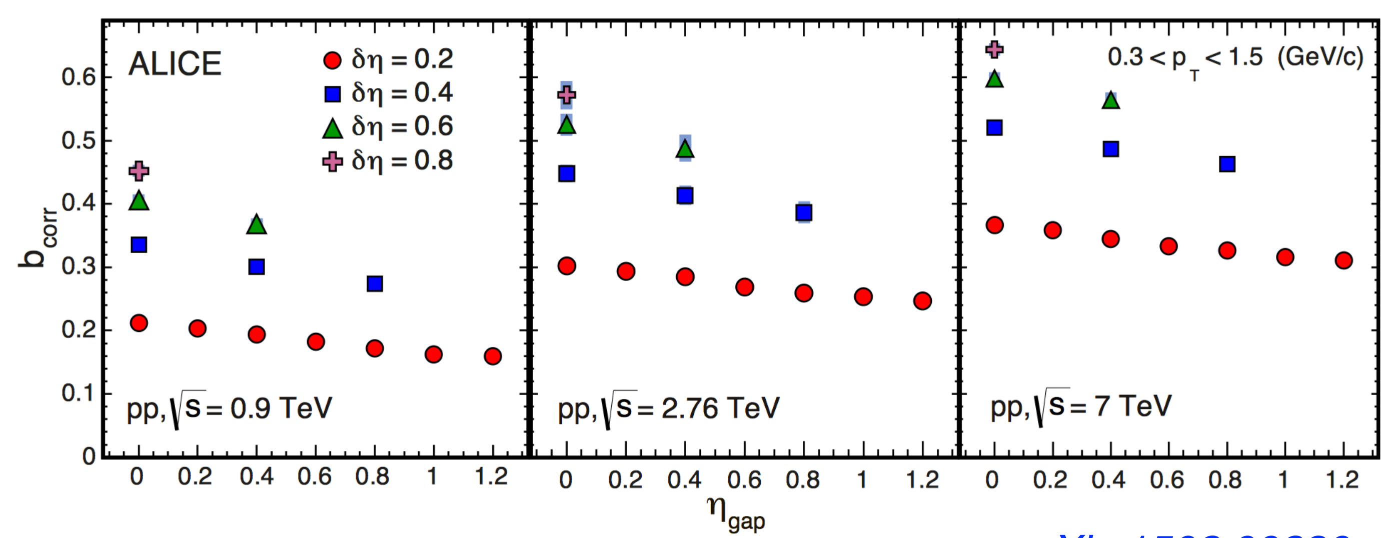

- Usually measure the correlation coefficient between multiplicities at different rapidities.
- Can be biased by statistical fluctuations.

$$b = \frac{\langle N_f N_b \rangle - \langle N_f \rangle \langle N_b \rangle}{\langle N_f^2 \rangle - \langle N_f \rangle^2}$$




Phys.Rev.Lett. 103:172301,2009



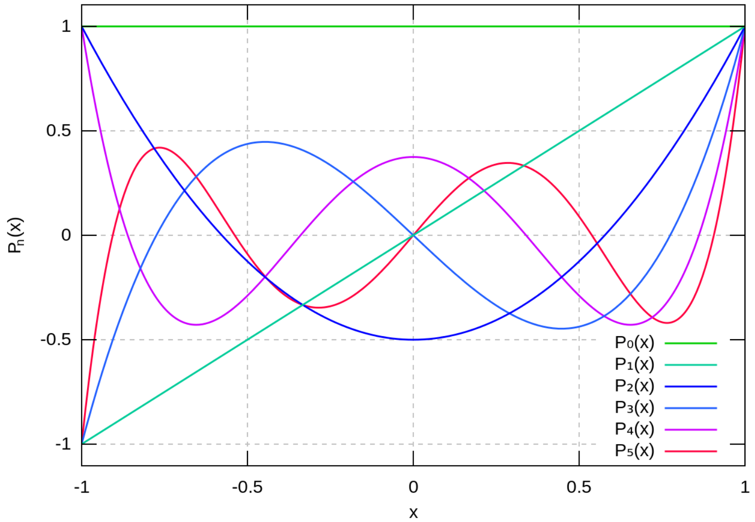

arXiv:1502.00230

# Alternate method

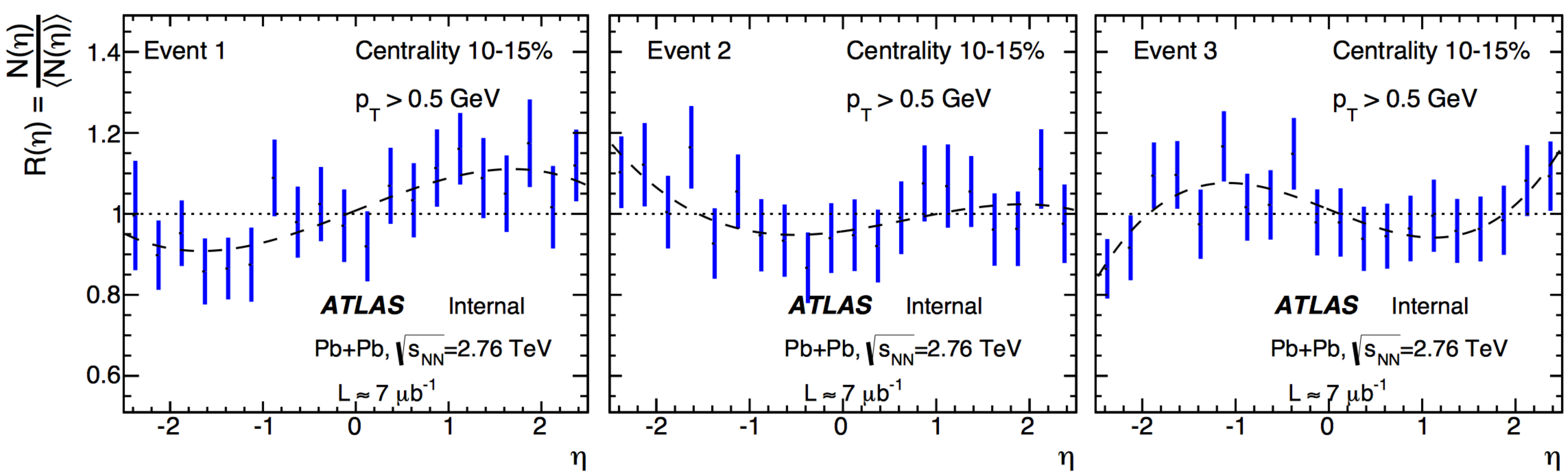
- Event-by-event shape fluctuations may be expanded in an ortho-normal set of polynomials, eg: Legendre polynomials

$$R(\eta) \equiv \frac{N(\eta)}{\langle N(\eta)\rangle} = 1 + \sum_{n=0}^{\infty} a_n T_n(\eta), \quad T_n(\eta) = \sqrt{n+\frac{1}{2}} P_n(\eta/Y)$$

$$P_0(x) = 1, \quad P_1(x) = x, \quad P_2(x) = \frac{1}{2}(3x^2 - 1) \;, \ldots.$$




First few Legendre Polynomials




ATLAS-CONF-2015-020

*Also see: A.Bzdak,D.Teaney: 1210.1965, J.Jia,S.R,M.Zhou:1506.03496*

# Correlation Functions

$$R(\eta) \equiv \frac{N(\eta)}{\langle N(\eta)\rangle} = 1 + \sum_{n=0}^{\infty} a_n T_n(\eta), \quad T_n(\eta) = \sqrt{n+\frac{1}{2}} P_n(\eta/Y)$$

*Also see: J.Jia,S.R,M.Zhou:1506.03496*
*A.Bzdak,D.Teaney: 1210.1965*

◆ Define 2 particle correlation function: $C(\eta_1, \eta_2) = \langle R(\eta_1) R(\eta_2)\rangle = \dfrac{\langle N(\eta_1) N(\eta_2)\rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle}$

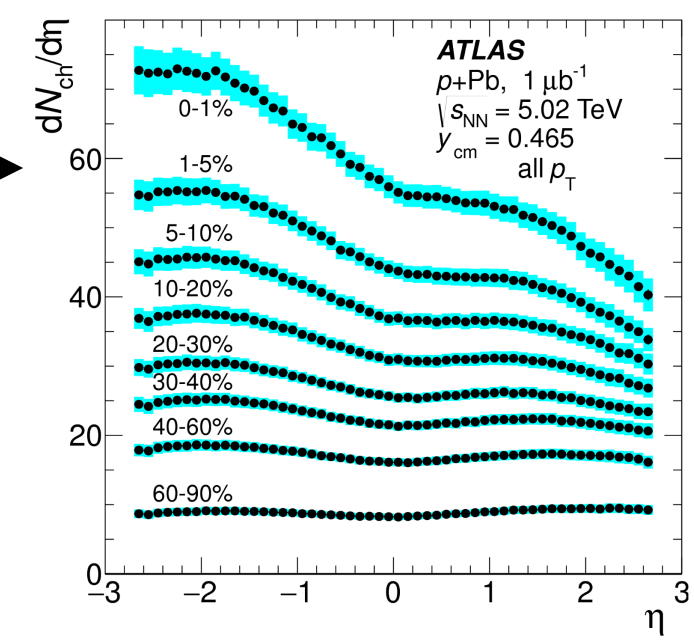
◆ Self correlations are excluded —> No bias from statistical fluctuations.
◆ Expanding the CF in the orthogonal basis gives $\langle a_n a_m\rangle$

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

◆ **Two kinds of terms:**

◉ $\langle a_0 a_n\rangle$ : shape fluctuations correlated with centrality (average multiplicity).

◉ $\langle a_n a_m\rangle : n, m > 0$ : genuine shape fluctuations at a fixed multiplicity.




◉The $\langle a_0 a_n\rangle$ terms can be removed by rescling: Has minimal influence on terms with n,m>0

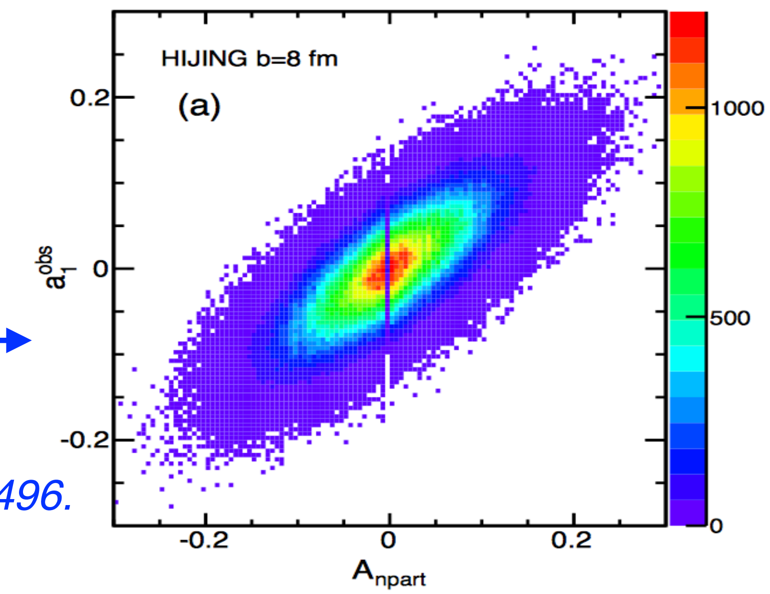
$$C_N(\eta_1, \eta_2) = \frac{C(\eta_1, \eta_2)}{C_p(\eta_1) C_p(\eta_2)}; \qquad C_p(\eta_1) = \int \frac{C(\eta_1, \eta_2)}{2Y} d\eta_2, C_p(\eta_2) = \int \frac{C(\eta_1, \eta_2)}{2Y} d\eta_1; Y = 2.4$$

# Studies on HIJING and AMPT

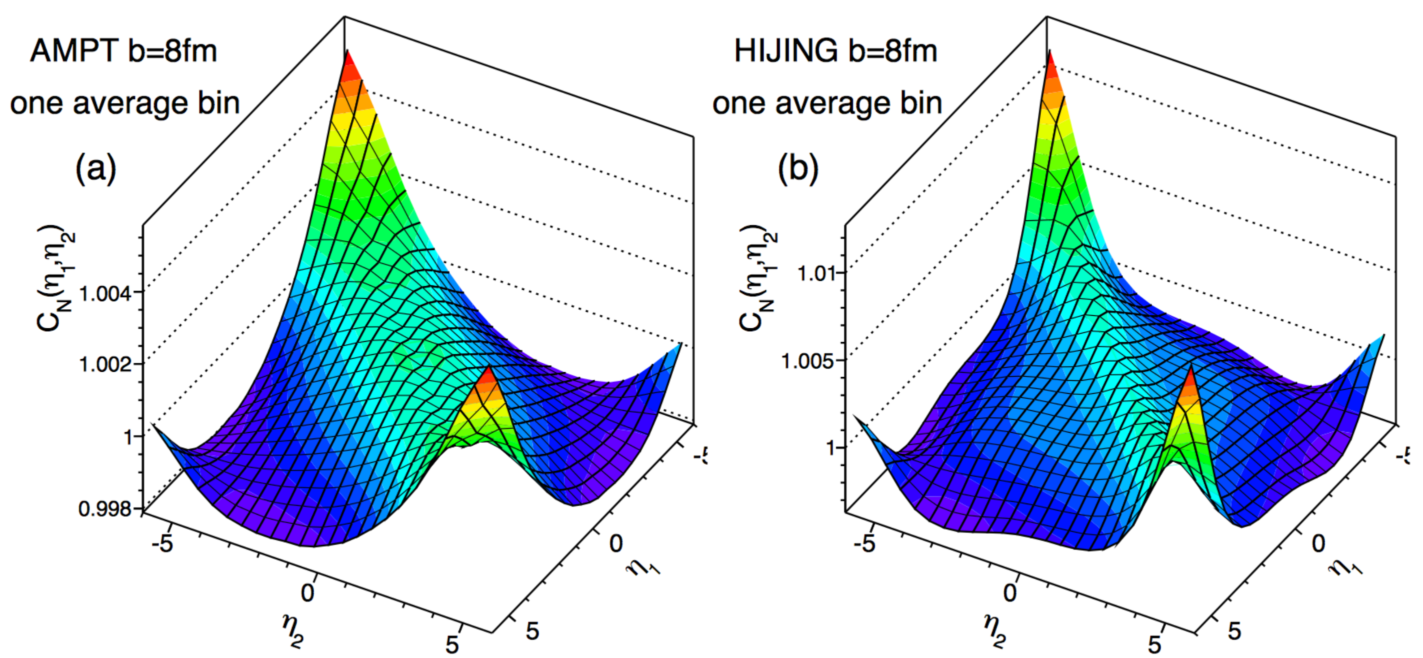
$$R(\eta) \equiv \frac{N(\eta)}{\langle N(\eta)\rangle} = 1 + \sum_{n=0}^{\infty} a_n T_n(\eta)$$

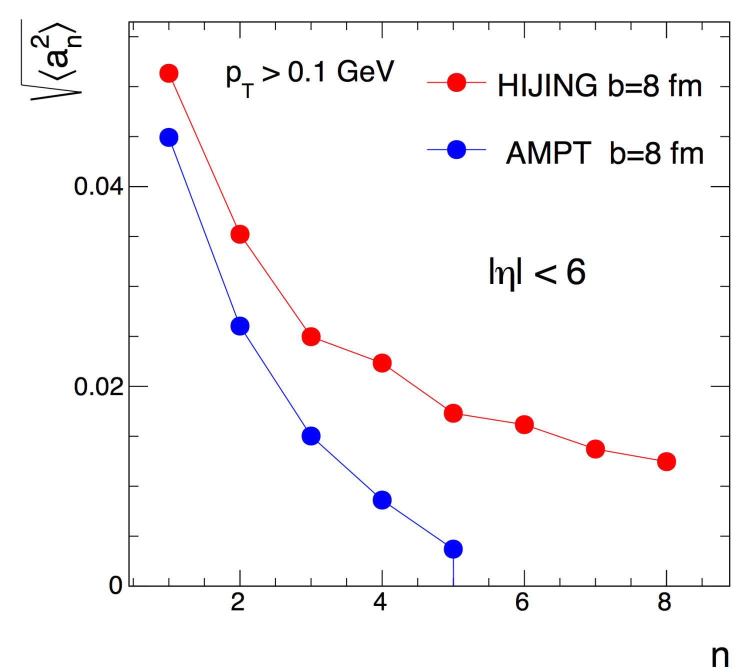
$$A_{N_{\rm part}} = \frac{N_{\rm part}^{\rm F} - N_{\rm part}^{\rm B}}{N_{\rm part}^{\rm F} + N_{\rm part}^{\rm B}}.$$

- Strong correlation of event-by-event $a_1$ with participant asymmetry is seen in HIJING.



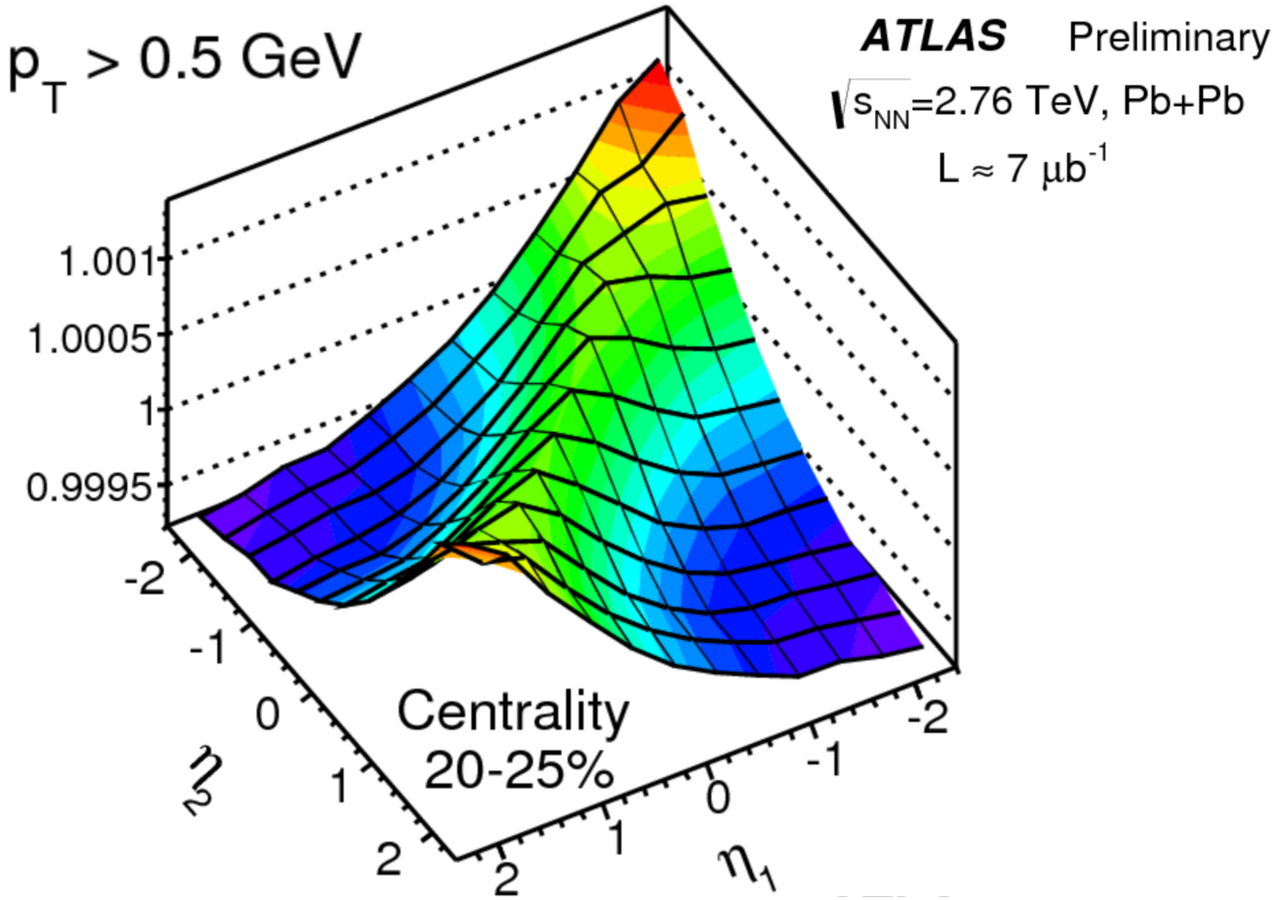

*More results in J.Jia,S.Radhakrishnan,M.Zhou, arXiv:1506.03496.*

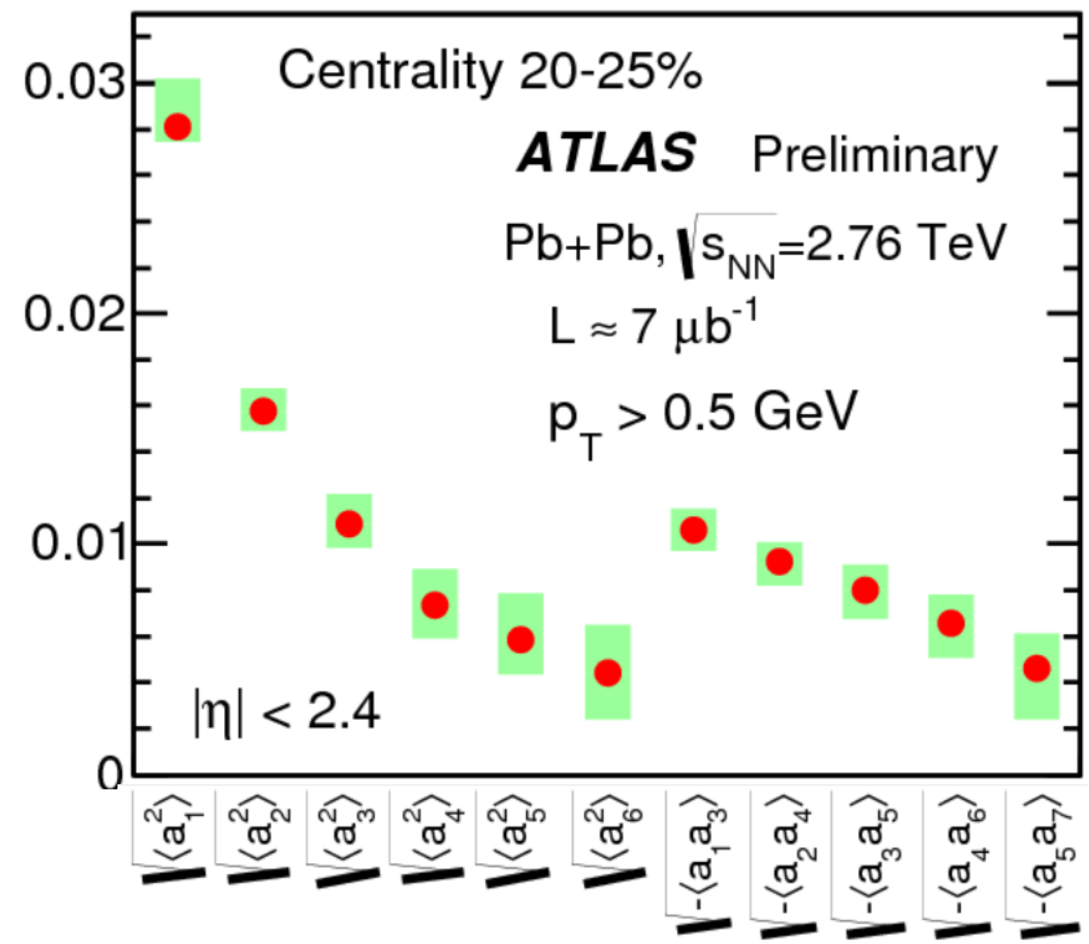



- CFs and $a_n$ differ between AMPT and HIJING.
- Narrower and larger short-range correlation in HIJING than AMPT.
- $\sqrt{\langle a_n^2\rangle}$ in HIJING larger than in AMPT, also AMPT values drop faster.
  - Part of this difference can be from difference in the short-range correlation.

# Longitudinal Correlations in Pb+Pb - I



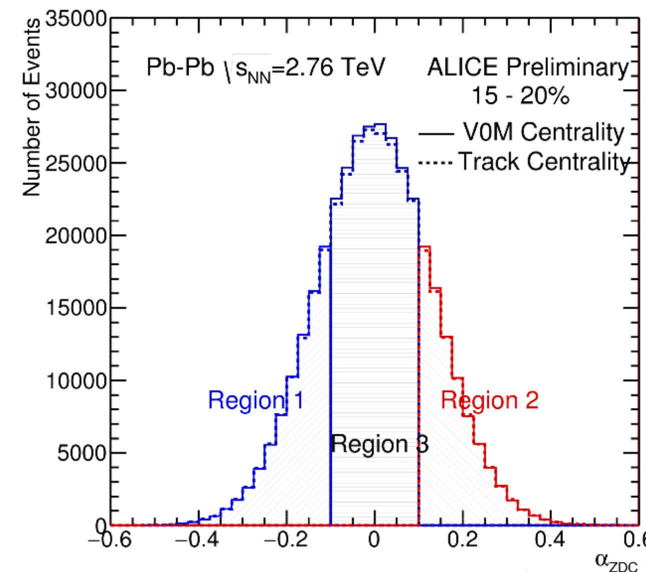

***From ATLAS-CONF-2015-020***

- Much smaller short-range correlation than in HIJING.
- $a_n$ values decrease with increasing n, as in AMPT and HIJING.
- Rate of decrease is similar to AMPT than HIJING, again, could be reflection of different short-range correlation.

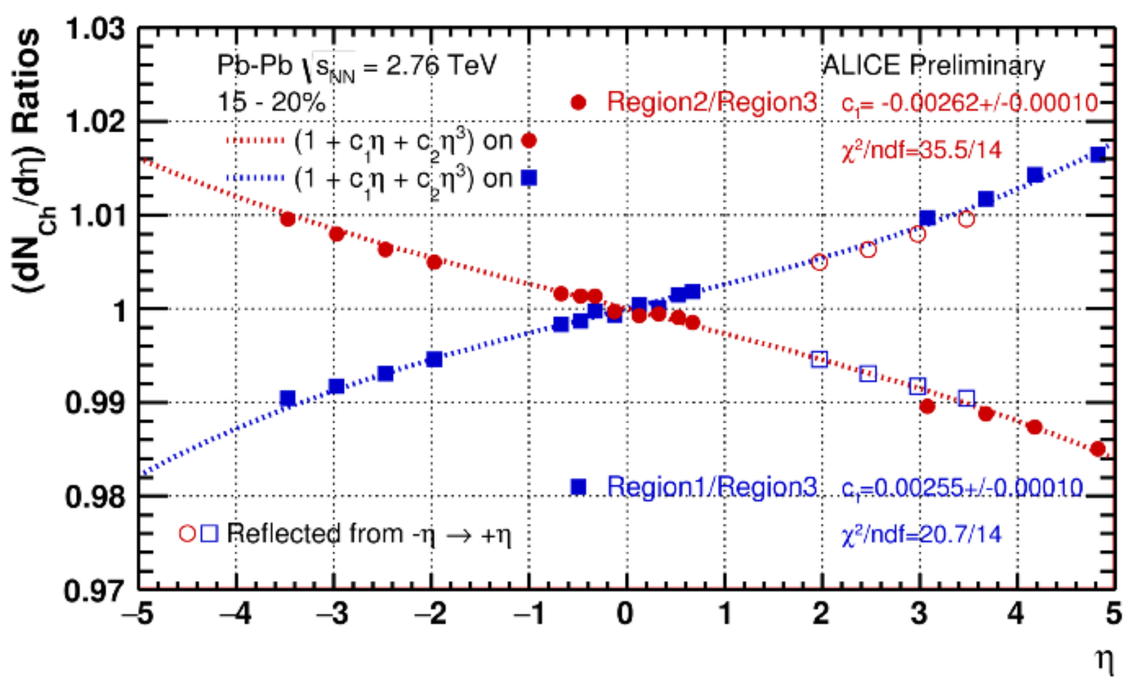
# Longitudinal Correlations in Pb+Pb - II

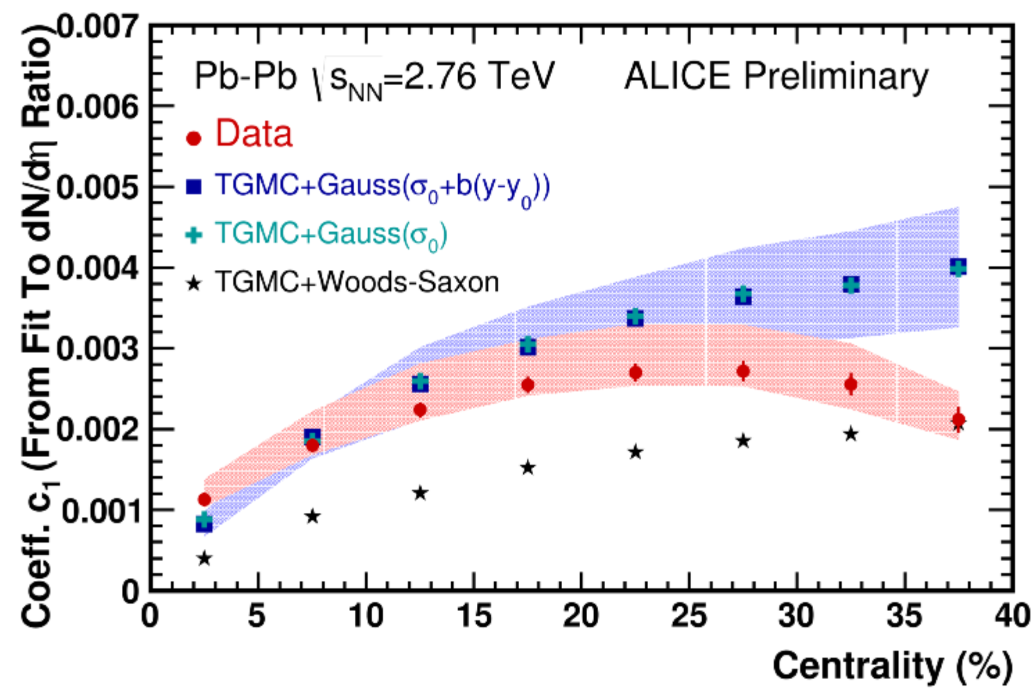
- Events with participant asymmetry can be slected using spectators meausred in ZDC.
- Ratio of rapidity distributions for cases with asymmetry to that without asymmetry can be studied.

***From ALICE-PREL-98164***




$$\alpha_{ZDC} = \frac{ZNC - ZNA}{ZNC + ZNA}$$




- The ratios are fit with $R(\eta) = 1 + c_1\eta + c_2\eta^3$
- The $c_1$ values from data are compared to different models of particle production at mid-rapity.

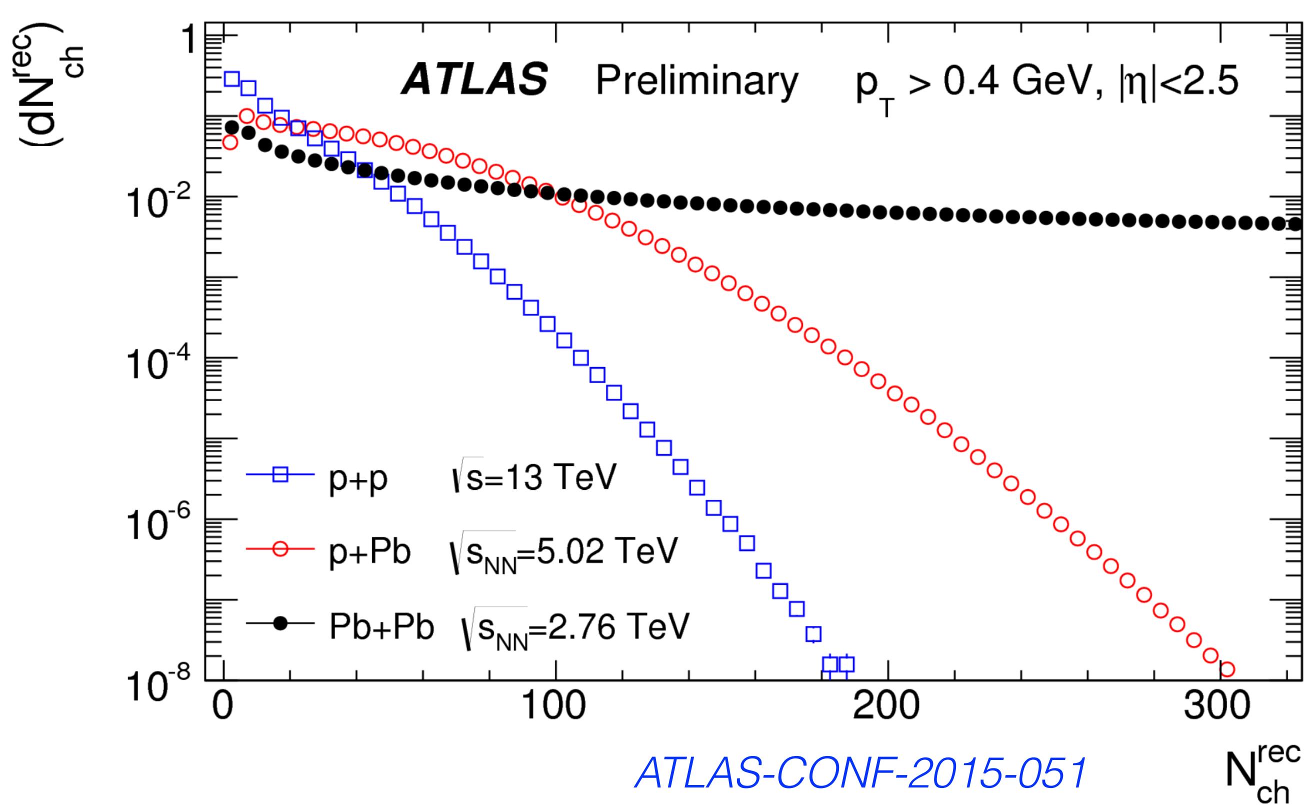
# How about different collision systems?

- How does the longitudinal correlations compare between different collision systems?
- Study the correlations in p+p, p+Pb and peripheral Pb+Pb systems at similar multiplicity.
- Short-range correlations could be different between the three systems.
- Can the short-range correlations be separated? How do they compare between the systems?
- How does the coefficients from long-range correlations compare?

Pb+Pb 2.76 TeV, 2010,

p+Pb 5.02 TeV, 2013,

p+p 13 TeV, 2015,




ATLAS-CONF-2015-051

# Small systems: Short-range correlations

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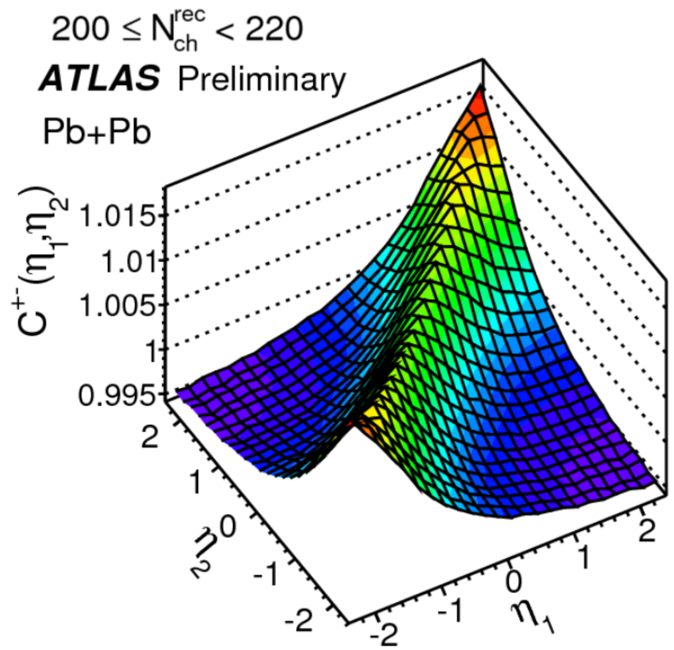
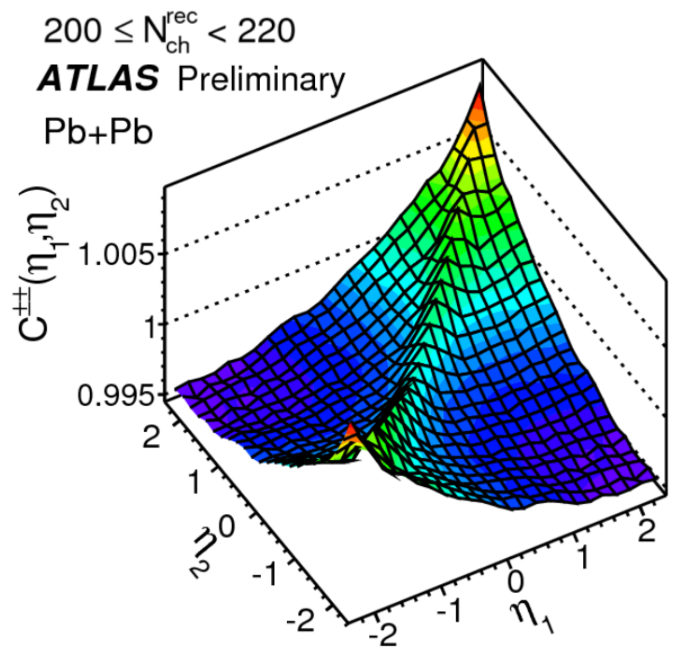
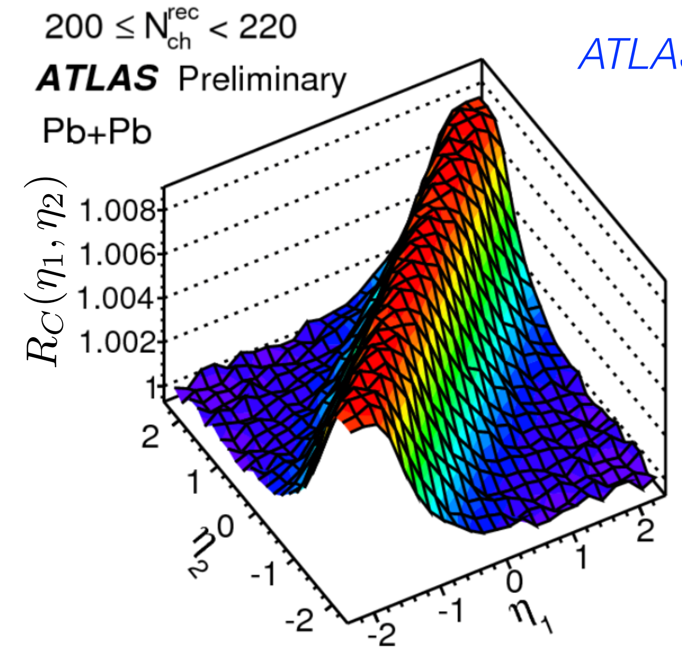
**Oppo. charge pairs**




**Same charge pairs**



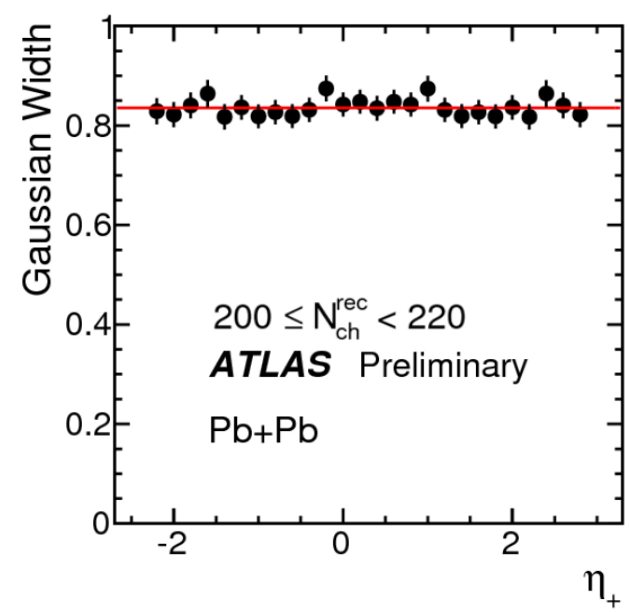

**Ratio. Long-range cancels out**

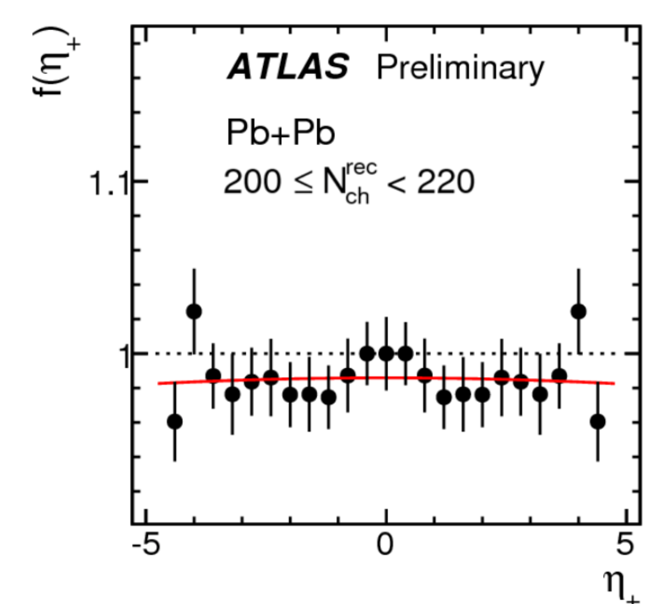



$$R_C(\eta_1,\eta_2) = \frac{C^{+-}(\eta_1,\eta_2)}{C^{\pm\pm}(\eta_1,\eta_2)}$$

$$\approx 1 + \delta_{SRC}^{+-}(\eta_1,\eta_2) - \delta_{SRC}^{\pm\pm}(\eta_1,\eta_2)$$

$$f(\eta_+) = \frac{\int_{-0.4}^{0.4} R(\eta_+,\eta_-)/0.8\, d\eta_- - 1}{\int_{-0.4}^{0.4} R(0,\eta_-)/0.8\, d\eta_- - 1}$$



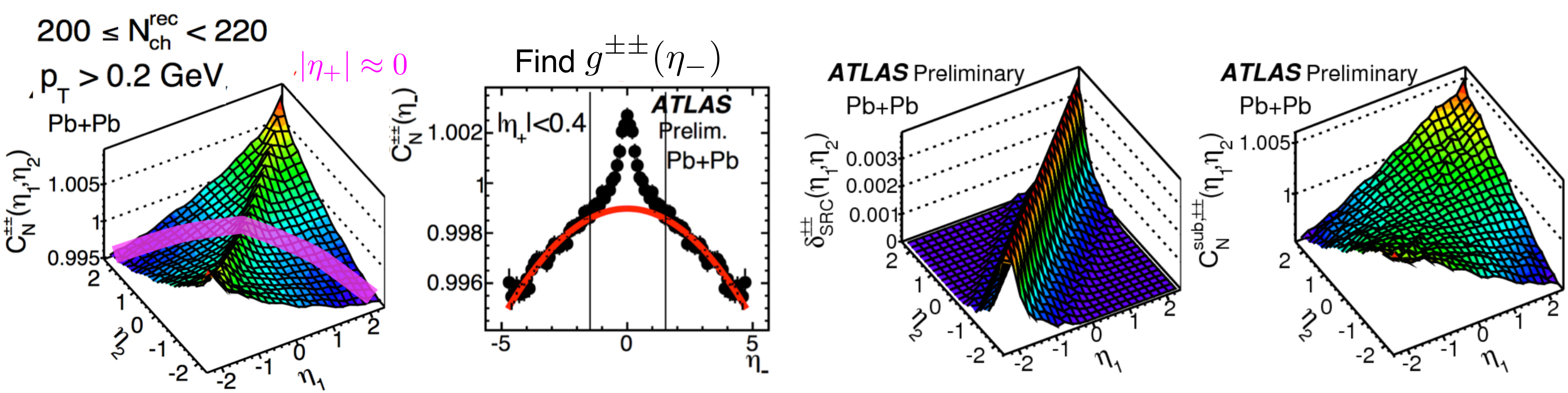




$$\eta_+ = \eta_1 + \eta_2$$
$$\eta_- = \eta_1 - \eta_2$$

- Difference between opposite charge and same charge correlations is in the short-range contribution.
- Width and magnitude of SR peak independent of $\eta_+$

# Small systems: Estimation of SRC

- SRC in a narrow slice around $|\eta_+| \approx 0$ is evaluated by fitting a polynomial to the LR region ( $|\eta_-| > 1.5$), and subtracting the fit.
- Extend in $\eta_+$ based on the $\eta_+$ dependence of $R_C(\eta_1, \eta_2)$

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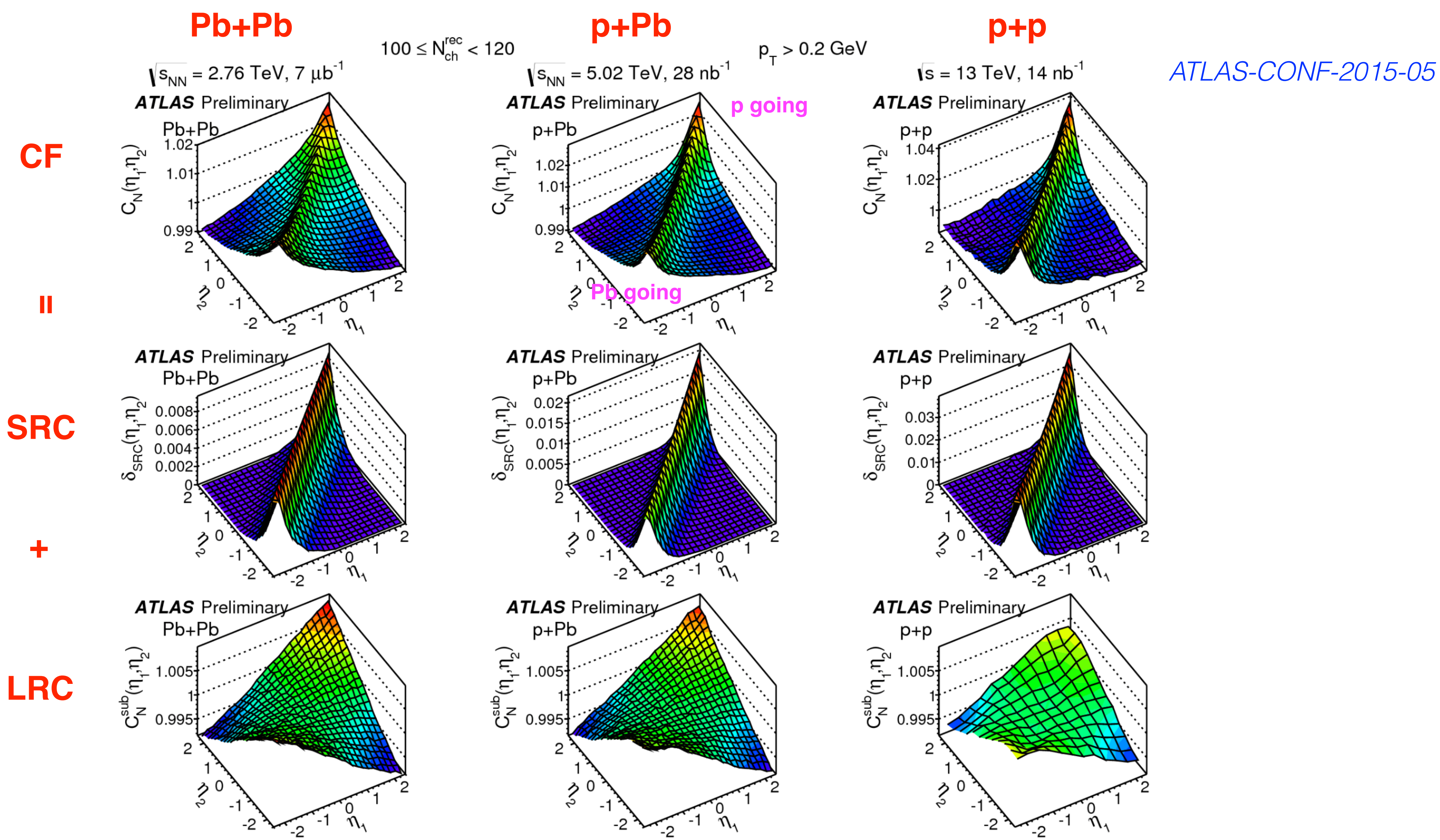
- SRC estimated as,

$$\delta_{\rm SRC}^{+-} = f(\eta_+)g^{+-}(\eta_-)$$

$$\delta_{\rm SRC}^{\pm\pm} = f(\eta_+)g^{\pm\pm}(\eta_-)$$

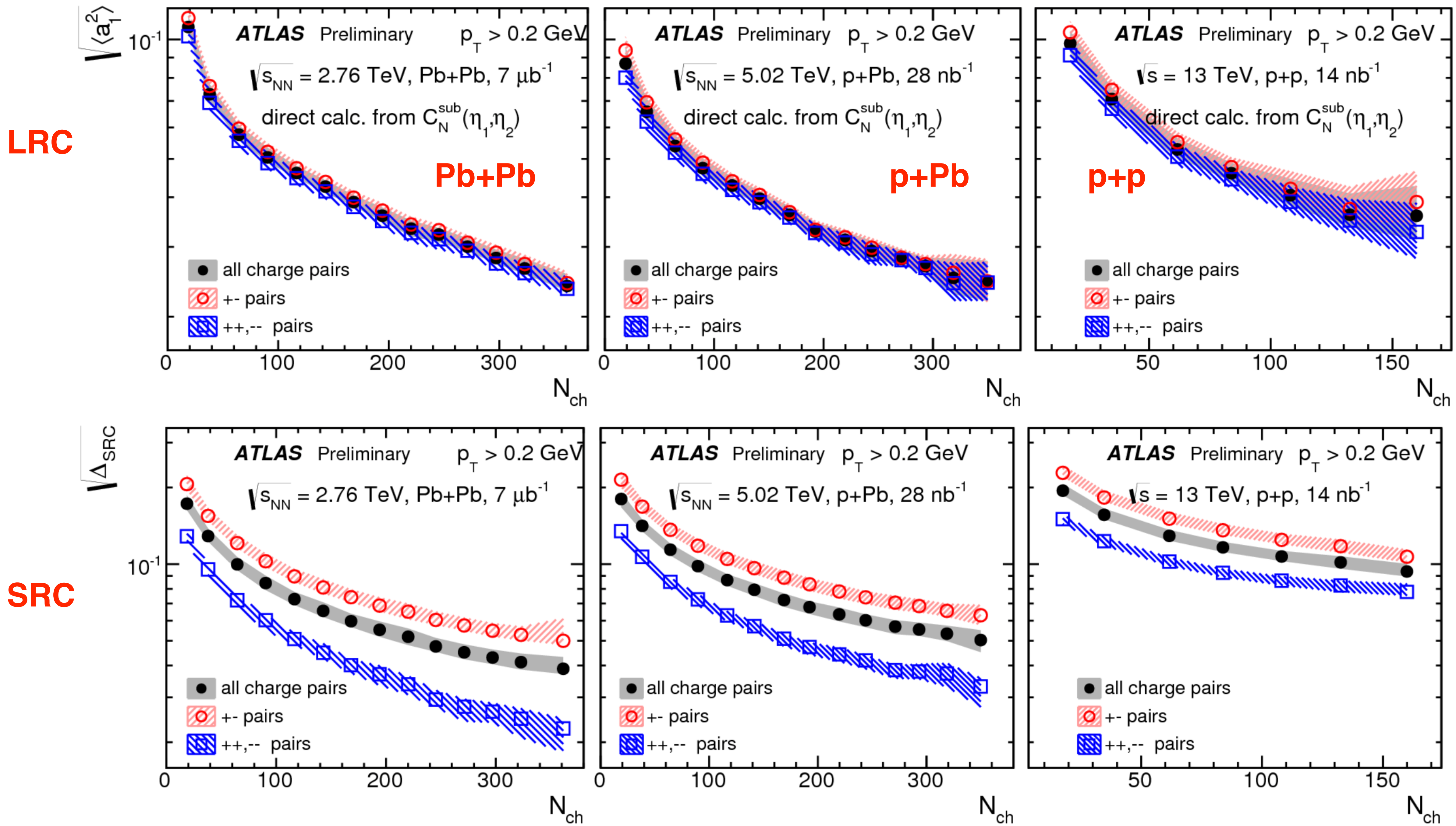
- Evaluated separately for oppo. and same charged pairs and for different collision systems and multiplicity classes.

# Small systems: SR and LR components




- Difference in CFs is mostly from difference in the SR region.
- LR component is similar in three systems and dominated by $a_1$ modulation.
- SRC is asymmetric in p+Pb (larger in p going side), but LRC is symmetric.

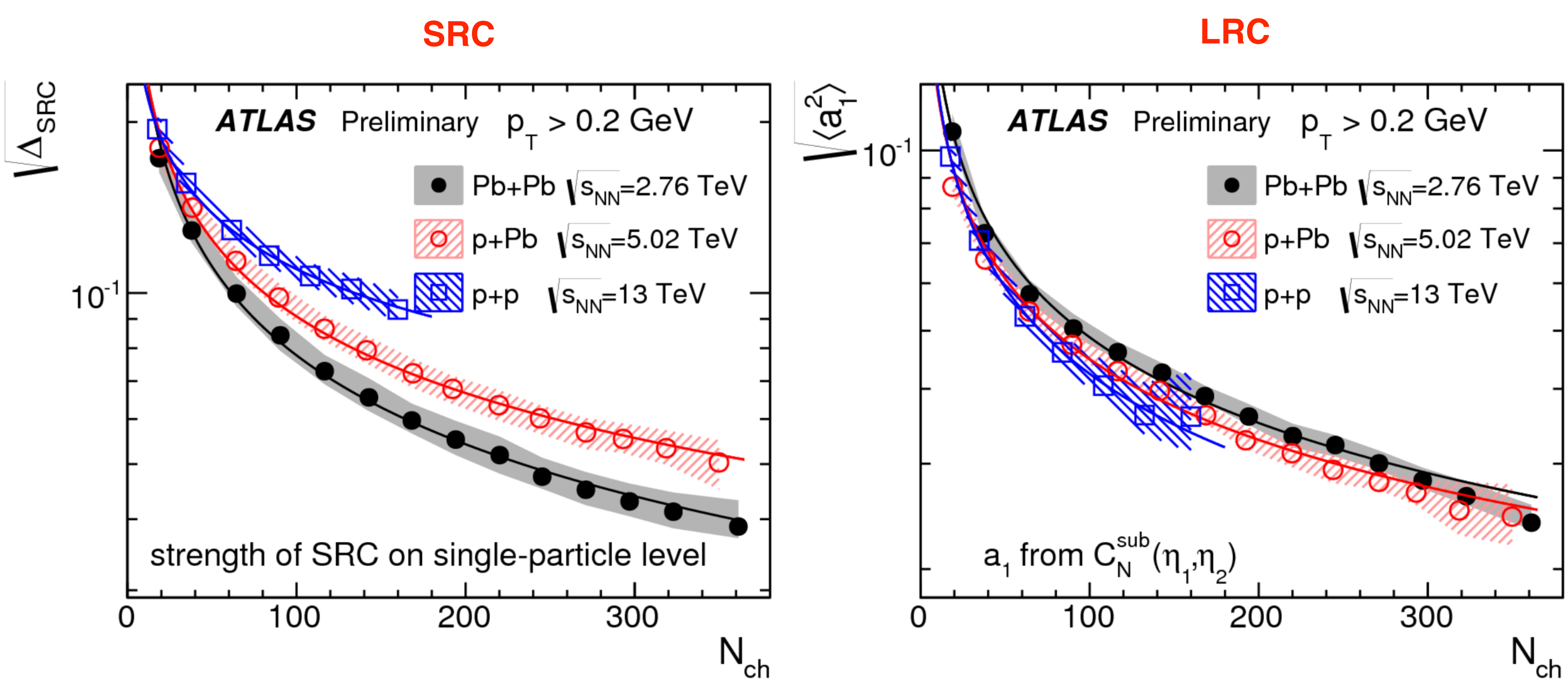
# Small systems: Charge dependence




From ATLAS-CONF-2015-051

- $$\Delta_{SRC} = \frac{\int \delta_{SRC}(\eta_1,\eta_2)d\eta_1 d\eta_2}{4Y^2}, \quad Y = 2.4\cdot$$
- LRC is independent of charge combination, SRC has strong dependece.

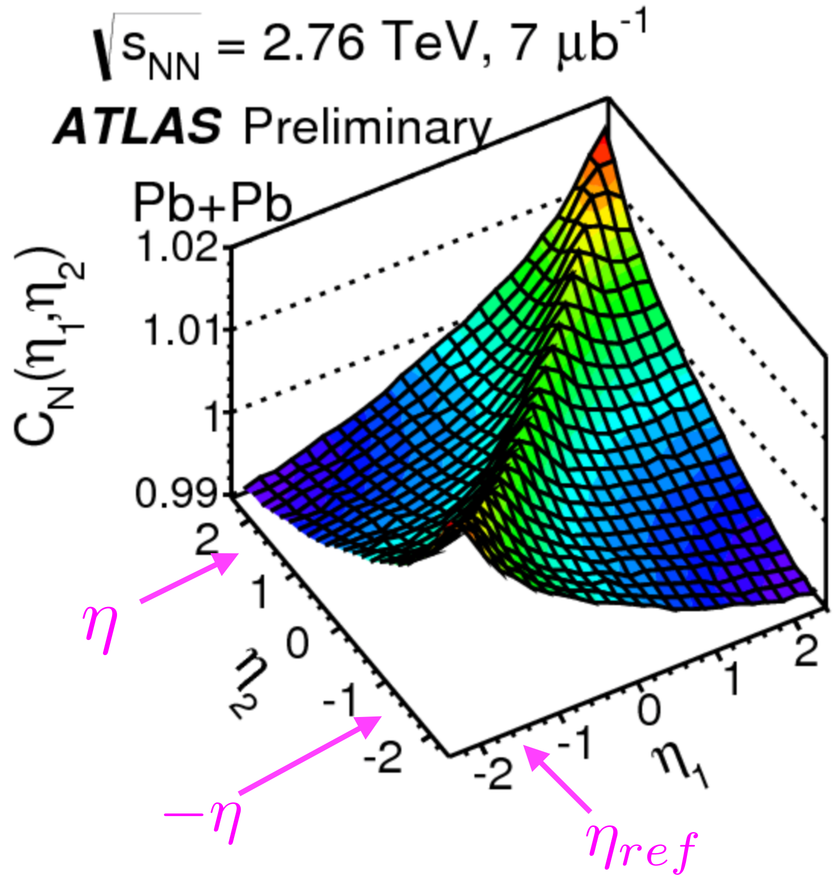
# Small systems: System dependence




*From ATLAS-CONF-2015-051*

- At given $N_{ch}$, LRC is independent of the collision system.
- SRC has strong system size dependence, largest in smallest system.
- $\sqrt{\langle a_1^2 \rangle} \sim \frac{1}{N^\alpha}, \quad \alpha \approx 0.5$

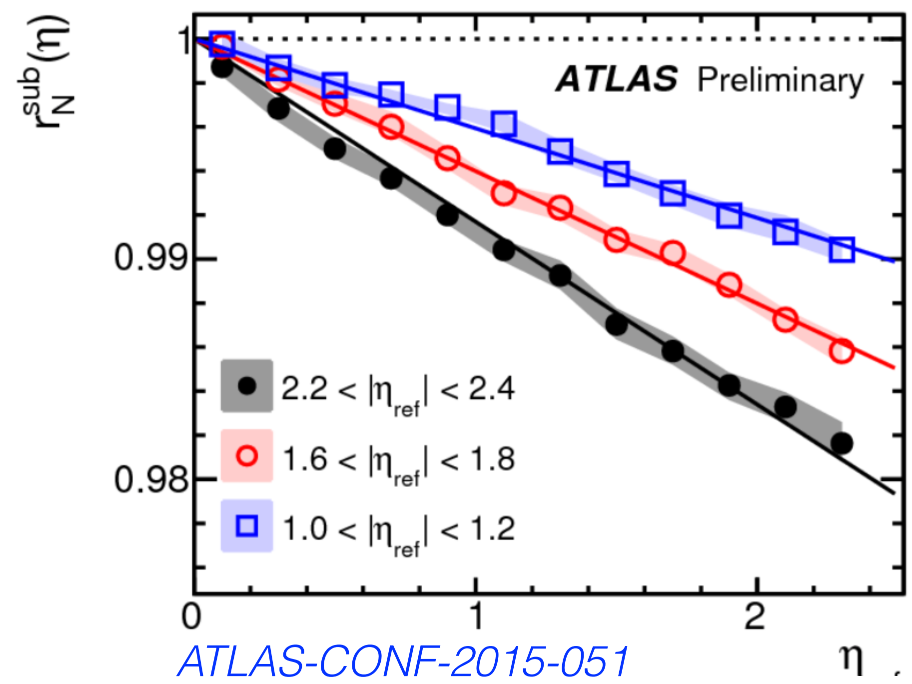
# Further studies




- Define the ratio,

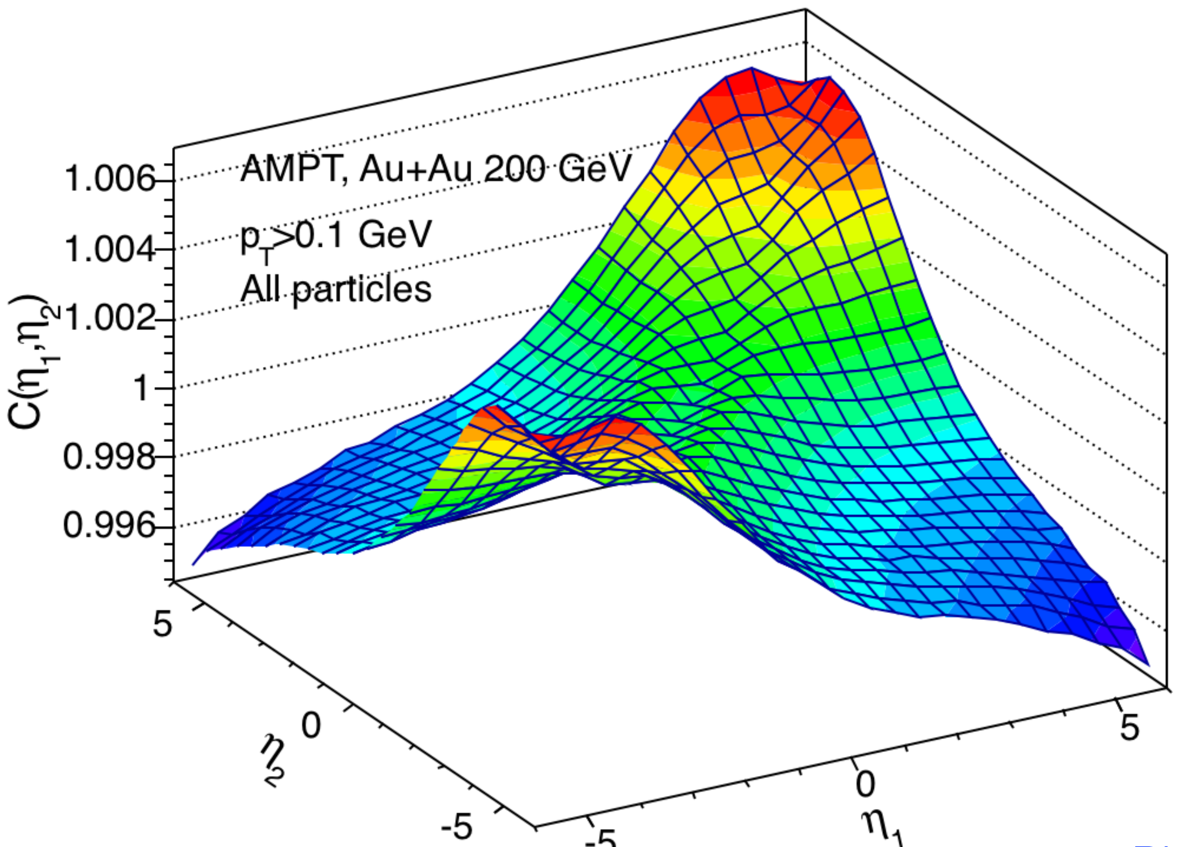
$$r_N^{sub}(\eta,\eta_{ref}) = \begin{cases} C_N^{sub}(-\eta,\eta_{ref})/C_N^{sub}(\eta,\eta_{ref}) & ,\ \eta_{ref}>0 \\ C_N^{sub}(\eta,-\eta_{ref})/C_N^{sub}(-\eta,-\eta_{ref}) & ,\ \eta_{ref}<0 \end{cases}$$
$$\approx 1-2\langle a_1^2\rangle \eta\eta_{ref} \,,$$

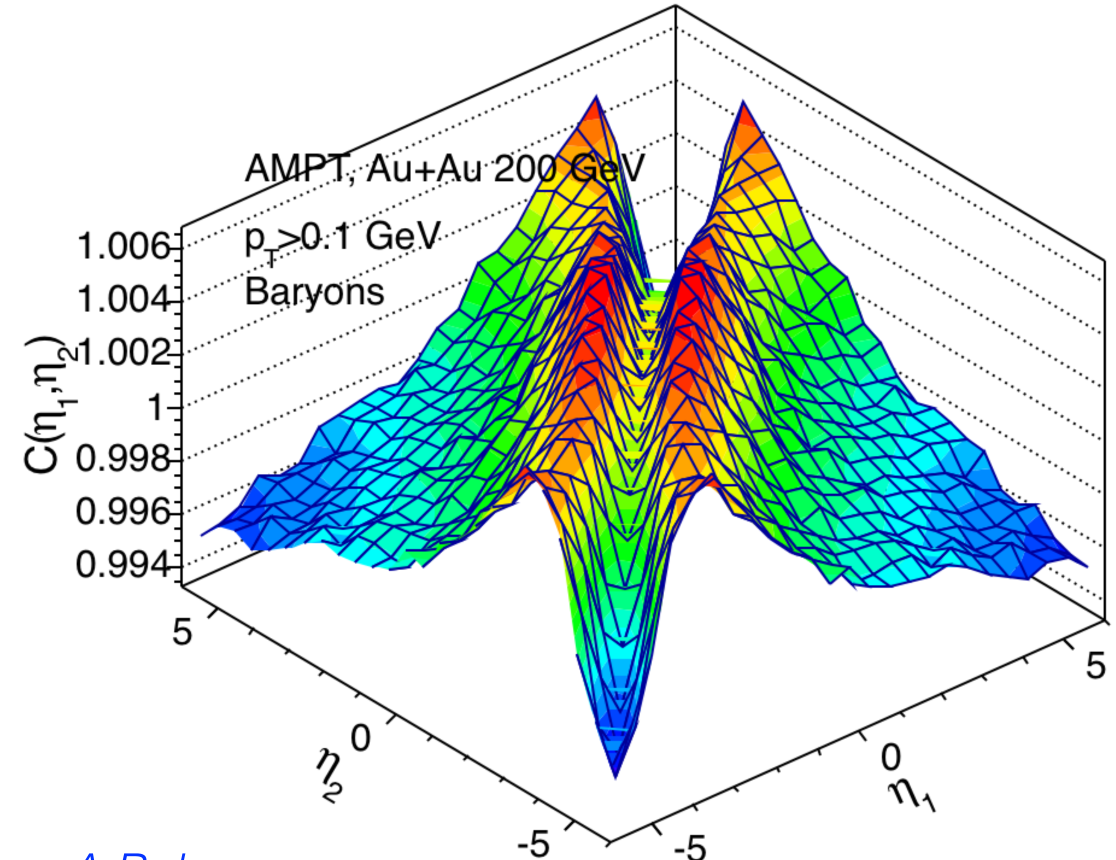
- $a_1$ can obtained from a linear fit.



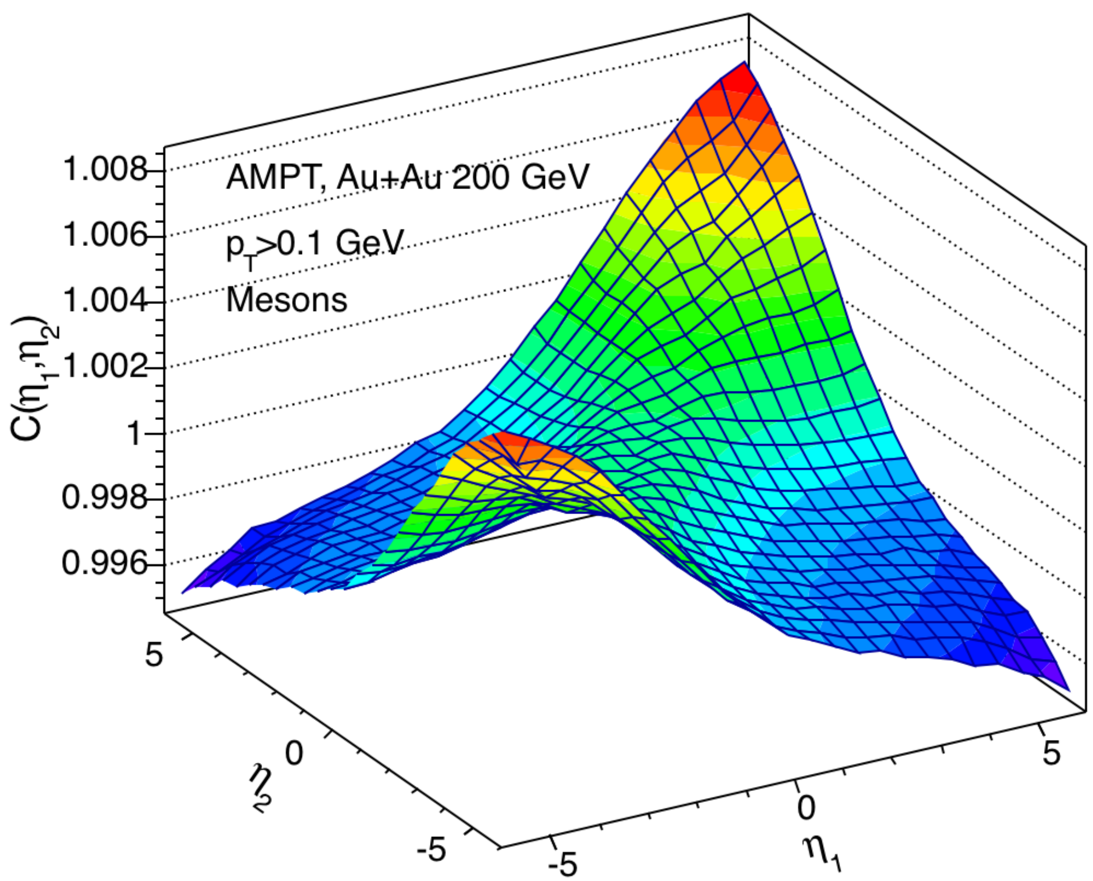

- ◆ Useful for detectors with smaller acceptance.
- ◆ Can construct the ratio by correlating the mid-rapidity detector with a forward detector.

# Further studies




*Plots from A.Behera*




- Can study CFs for identified particles.
- Baryons show a strong depletion in the short range region.
- Long-range correlations are consistent.

# Summary and Conclusions

- Longitudinal correlations are typically studied using F-B correlation coefficienct. New studies use correlation functions.
- Can study both shape fluctuations correlated with centrality and genuine shape fluctuations.

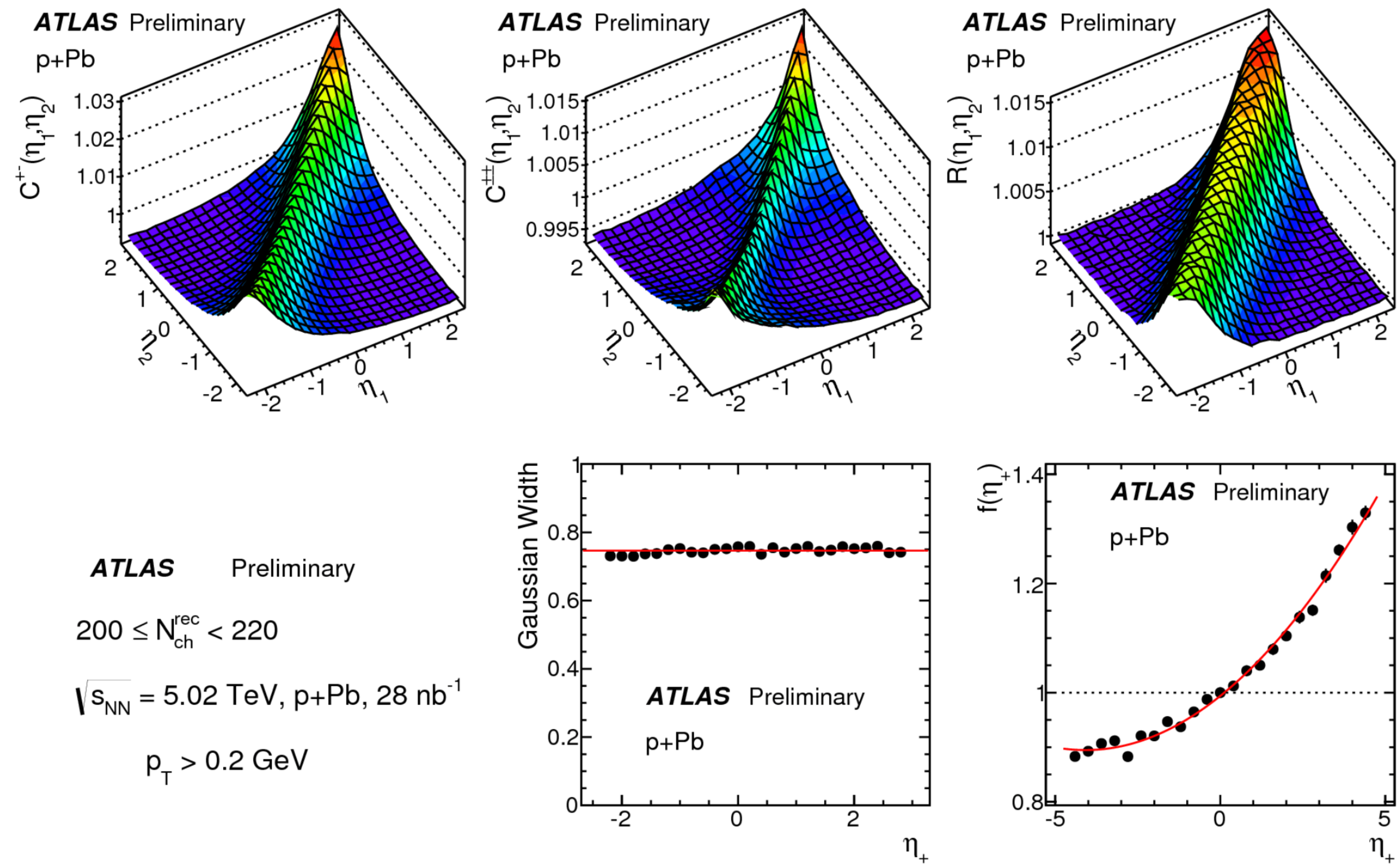
- $a_1$ and participant aymmetry show strong correlation in HIJING.
- LR correlations in Pb+Pb collisions at LHC is dominated by $a_1$ modulation.

- SRC contribute to the CF and $a_n$.
- SRC has strong system size and charge dependence.
- LRC for different collision systems at same $N_{ch}$ have similar magnitude.

- Future prospects:
  - Similar measurements can be done at RHIC at different beam energies.
  - Can construct a ratio to overcome lack of large acceptance.
  - Study of conserved charges and particle identified correlations can help studies of hadronization.
  - LRC important for realistic non boost invariant simulation of initial conditions.

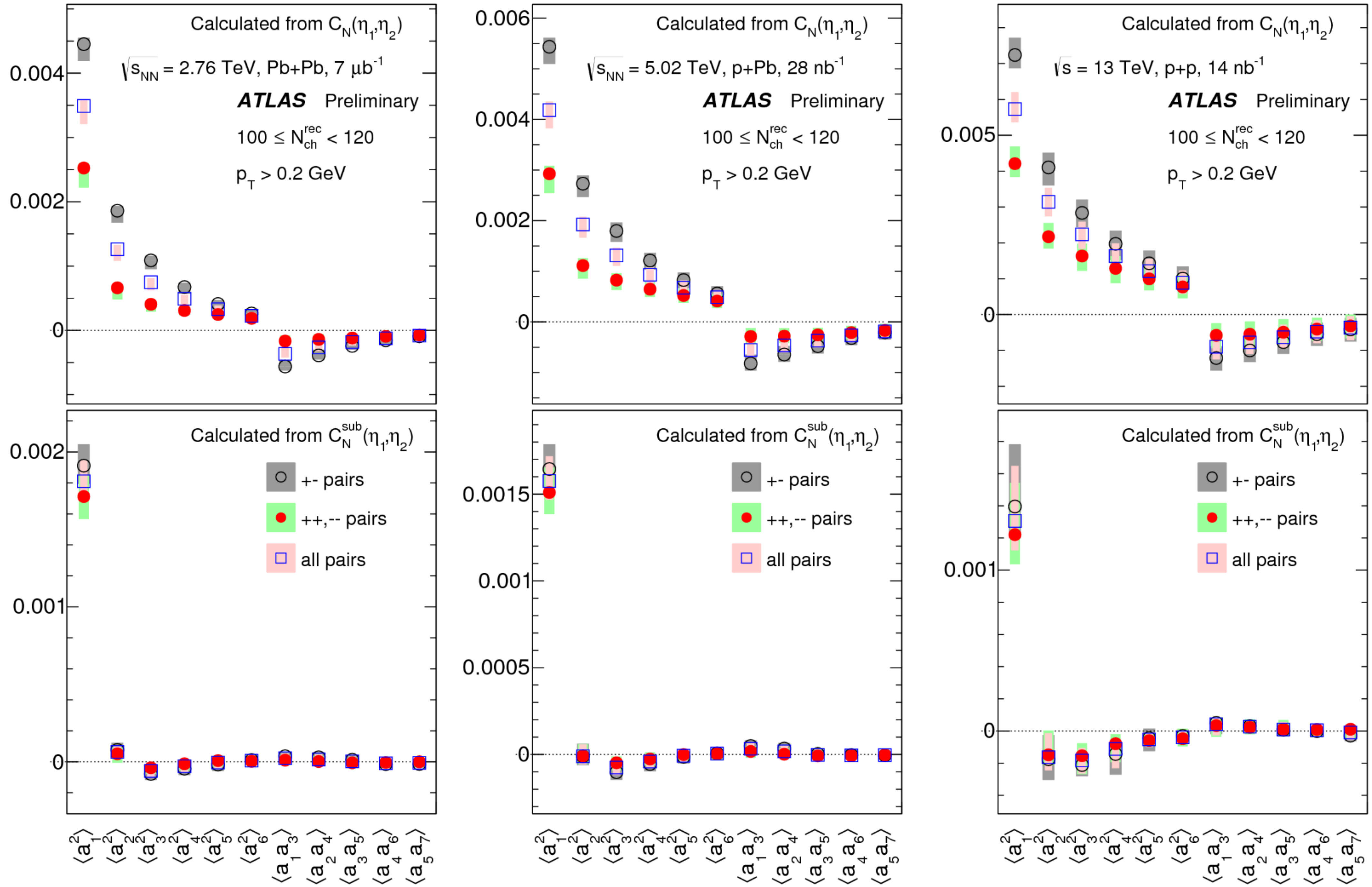
# Back Up

# SRC in p+Pb




- Same width for all $\eta_+$ but strong enhancement towards the p-going side.

# Spectra before and after subtraction




- Strong charge dependence before subtraction.
- Independent of charge combunation after subtraction.

# Longitudinal CFs in Pb+Pb - II

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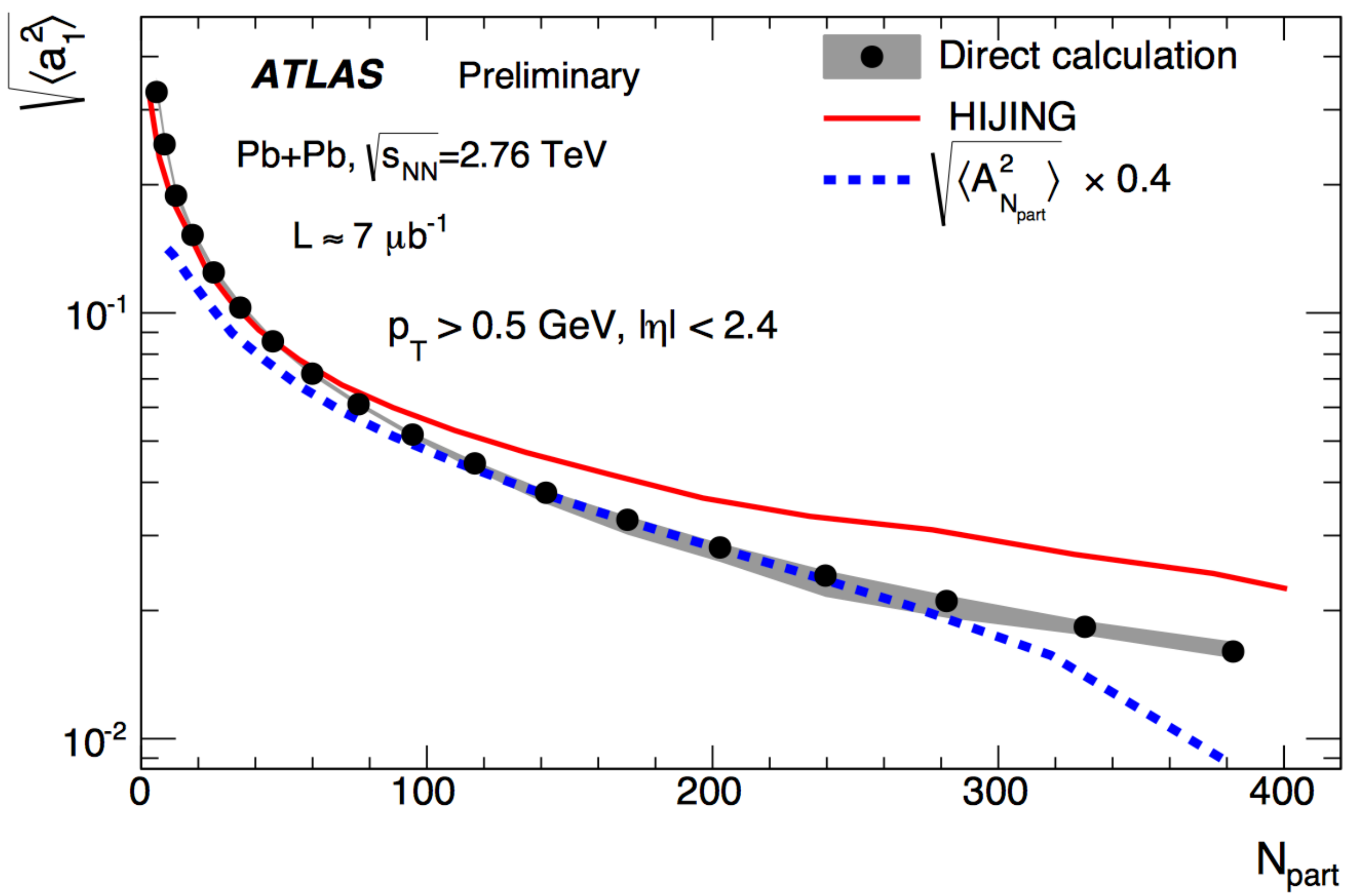
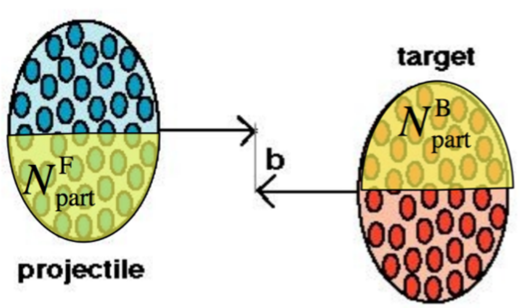
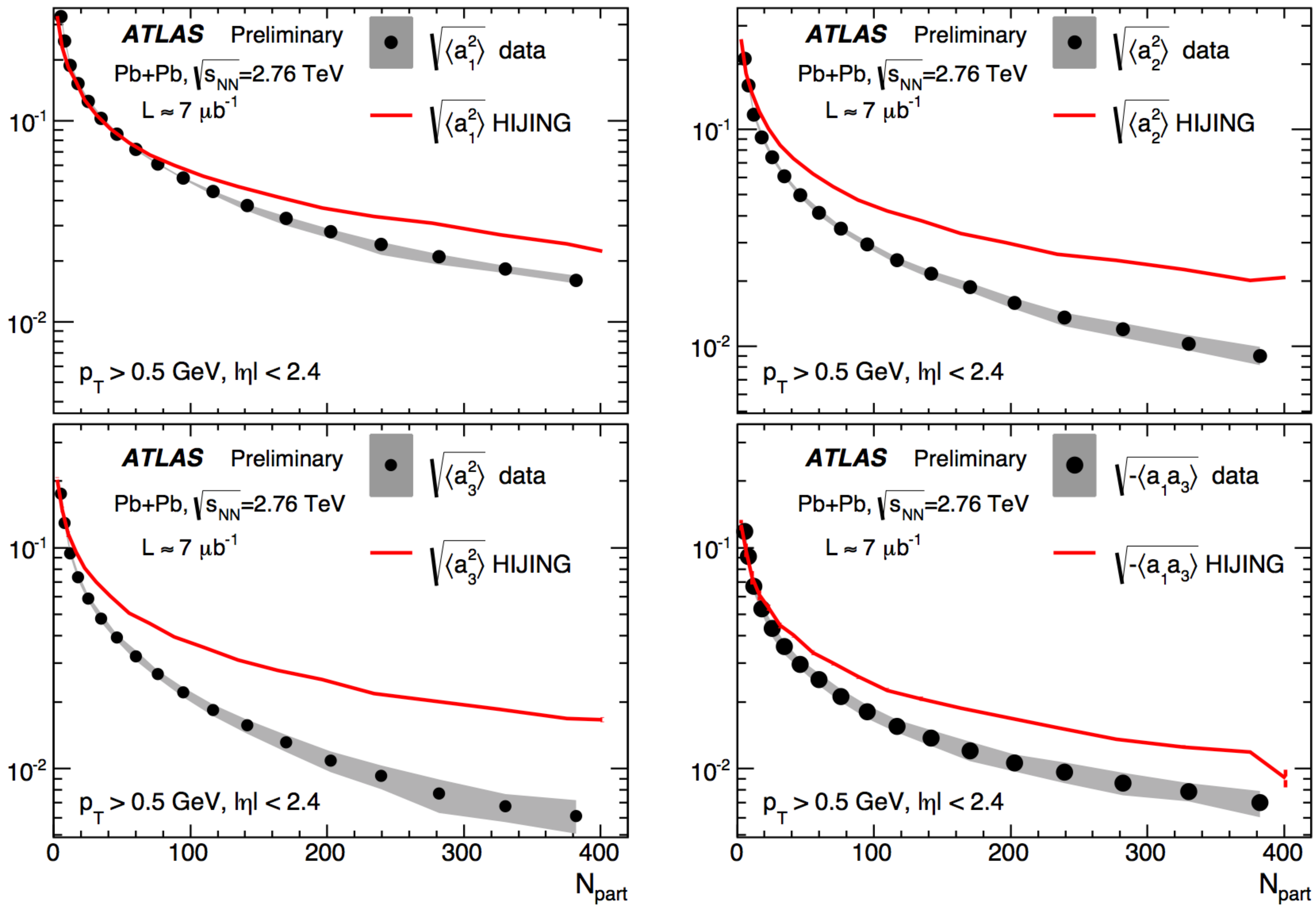



- Glauber model captures the centrality dependence of $\sqrt{\langle a_1^2 \rangle}$ in mid-central collisions.
- Fails in most central and peripheral classes, larger fluctuation than predicted by Glauber —> sub-nucleonic level fluctuations?
- Also shown are $\sqrt{\langle a_1^2 \rangle}$ from HIJING
- HIJING over-estimates $\sqrt{\langle a_1^2 \rangle}$ in mid-central and central collisions.




$$A_{N_{\text{part}}} = \frac{N_{\text{part}}^{\text{F}} - N_{\text{part}}^{\text{B}}}{N_{\text{part}}^{\text{F}} + N_{\text{part}}^{\text{B}}} \, .$$

# Comparison with HIJING - II



# Statistical fluctuations

- Event by event modulations can also arise from statistical noise

$$N(\eta) = \langle N(\eta) \rangle \left( 1 + \sum_{n=0}^{\infty} a_n T_n(\eta) \right), \quad T_n(\eta) = \sqrt(n + \frac{1}{2}) P_n(\eta/Y)$$

- But these should average to zero in the CF, $C(\eta_1, \eta_2) = \frac{\langle N(\eta_1) N(\eta_2) \rangle}{\langle N(\eta_1) \rangle \langle N(\eta_2) \rangle}$

- since
  a) Statistical fluctuations in two different $\eta$ are uncorrelated
  b) Self correlations are not counted in the CF
  when $\eta_1 = \eta_2$, statistical fluctuations dont average to zero and equals $\langle N(\eta) \rangle$
  which is same as the number of self-correlations.

- So the $\langle a_n a_m \rangle$ from CFs are quantities unfolded for statistical noise.