

# Evidences for collectivity in small systems

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Physics Ph.D. Defense

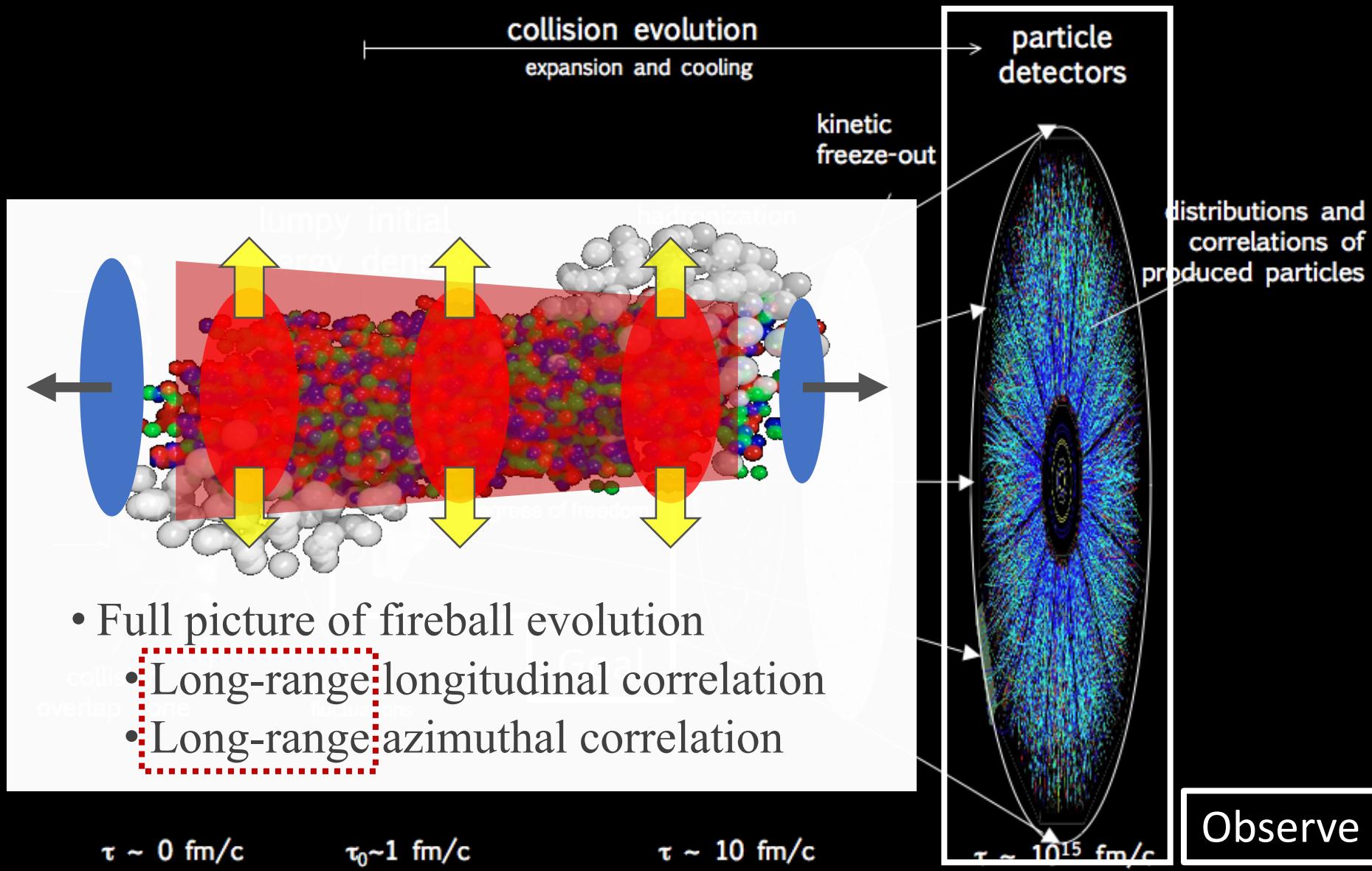
March 4<sup>th</sup> 2019



Stony Brook  
University

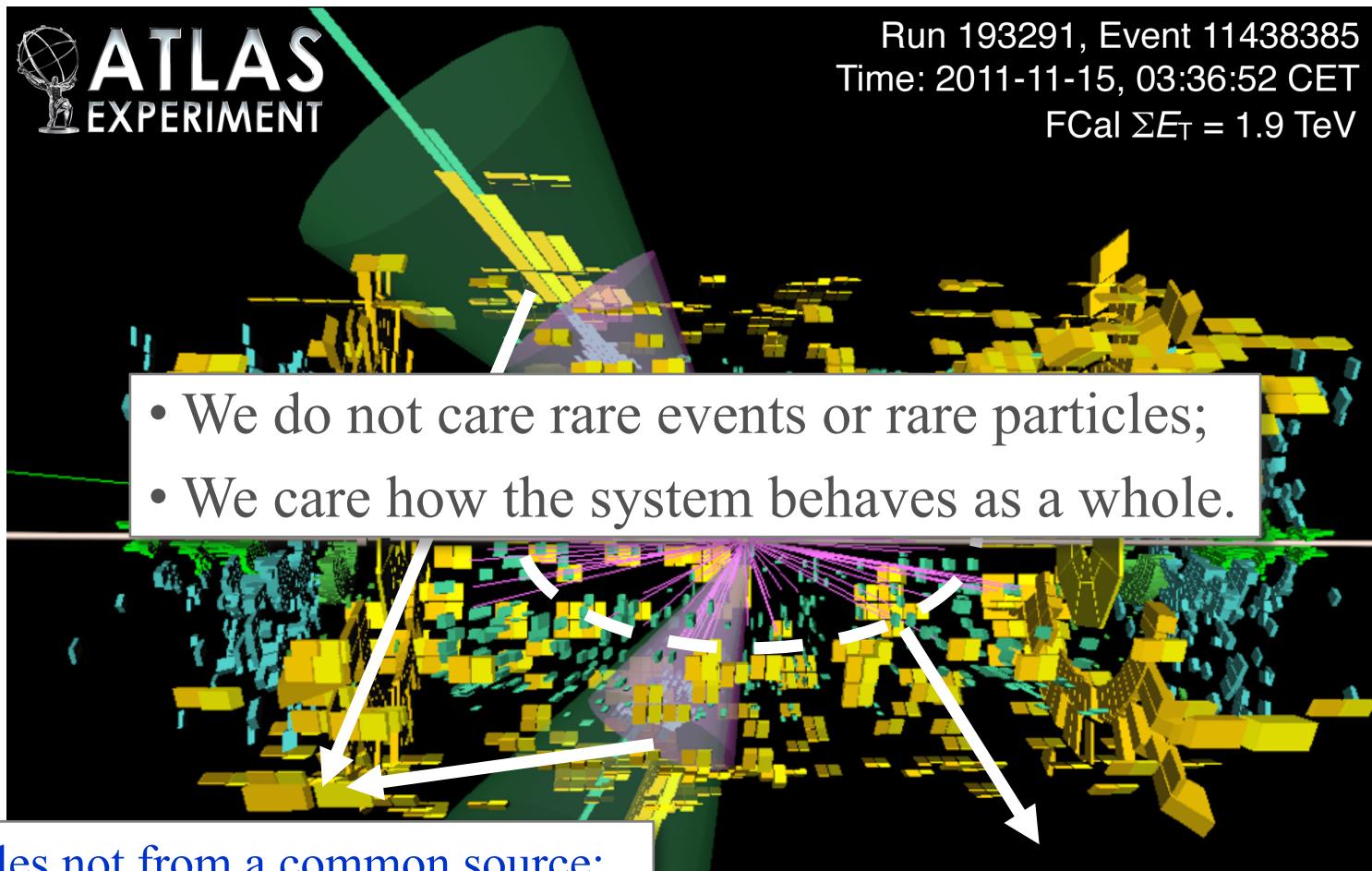
# Heavy ion collision

## Nuclear collisions and the QGP expansion



# What is collectivity?

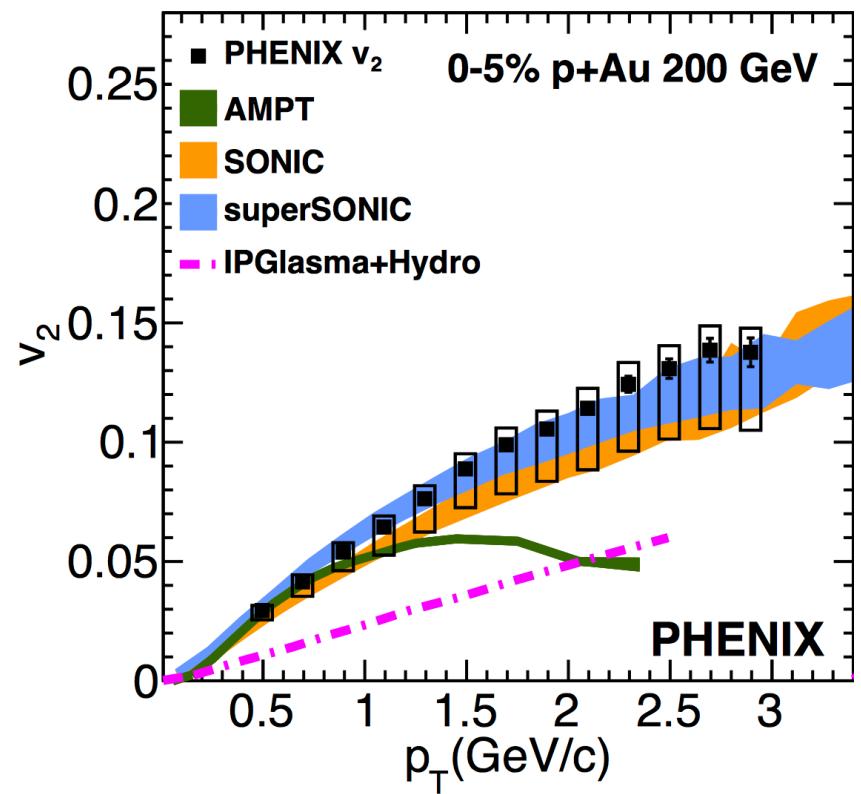
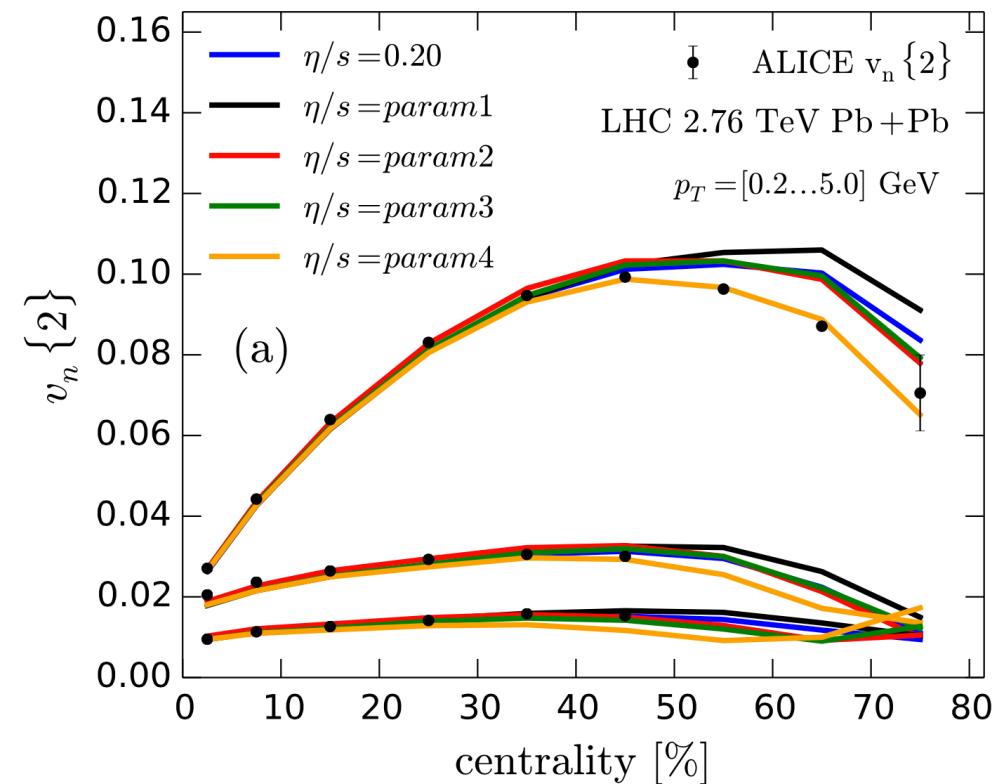
- Collectivity: condition of an entity having properties its parts do not have, due to interactions among the parts.



Particles not from a common source:  
jet, resonance decay...  
named **non-flow/short-range correlation**

Particles from a common source:  
named **(long-range) collectivity**

# Why small systems?



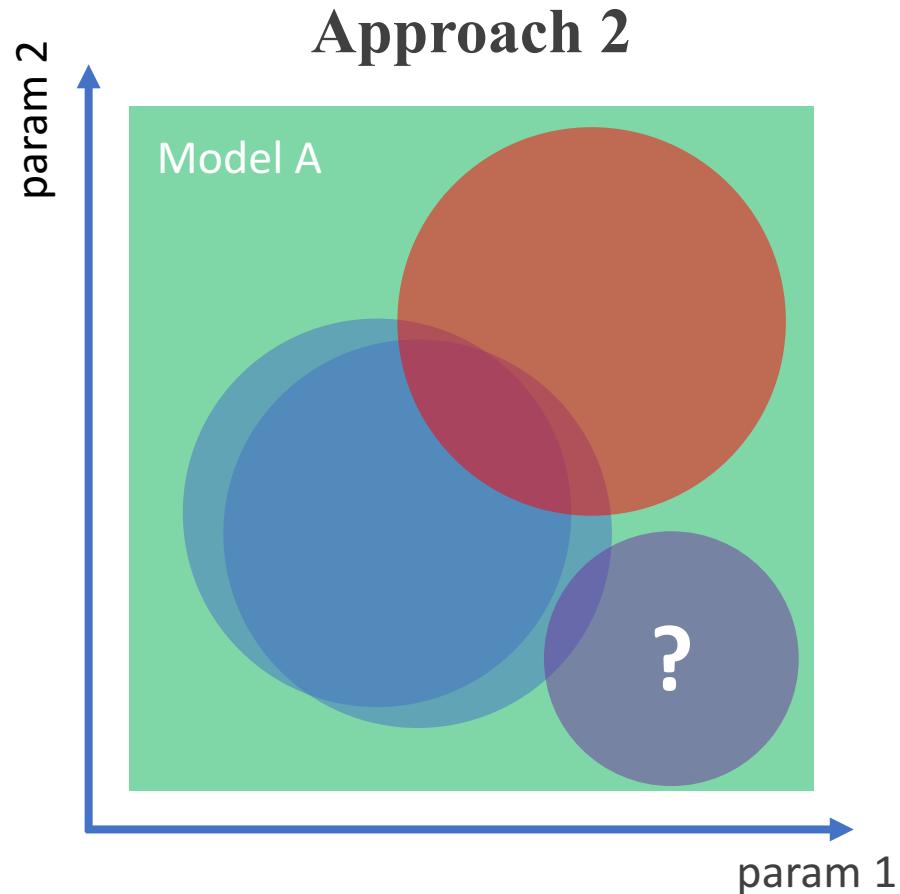
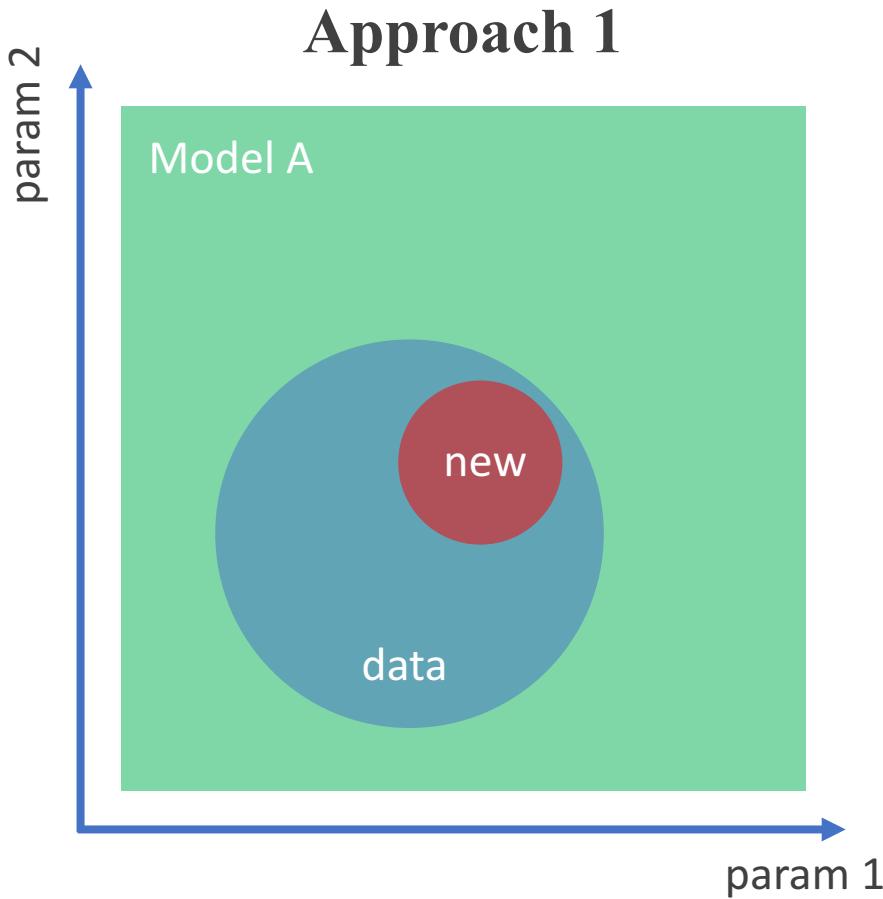
- Success of models in large systems;
- Parameters not well constrained.

- Not so good in small systems;
- QGP in small systems?

Larger proton fluctuation can better distinguish different models

# How to use data to constrain models?

5

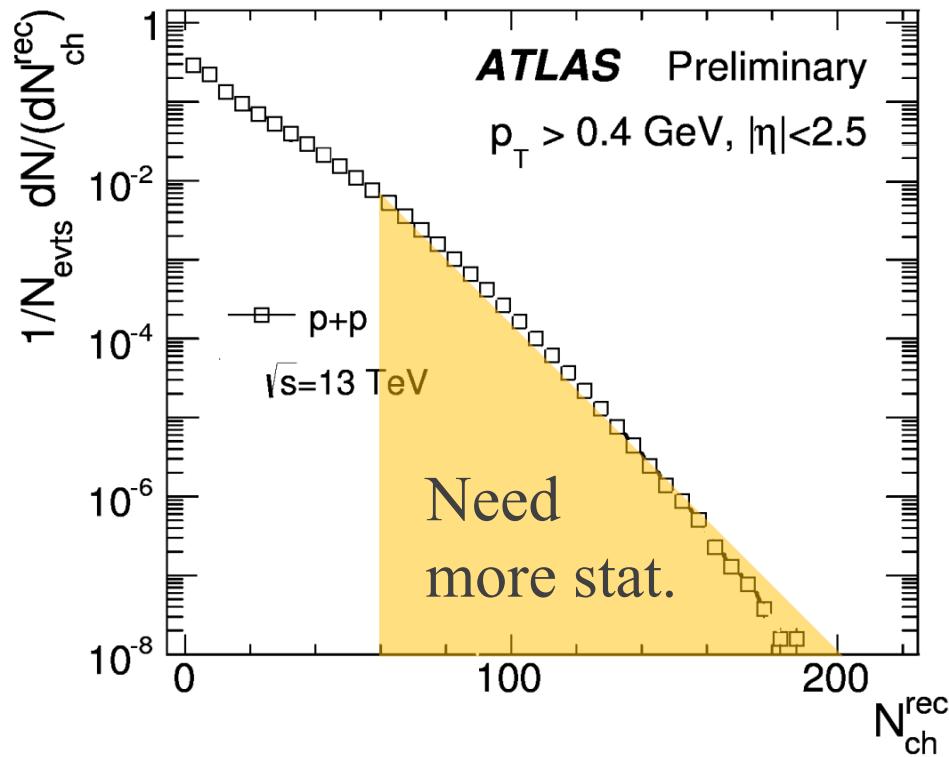


- Improve statistical significance of data

$pp$  and  $p+Pb$  events with high statistics

- Independent constrains
  - New observable
  - Collision system
  - Collision energy

# Real-time data selection



LHC event rate

40 MHz



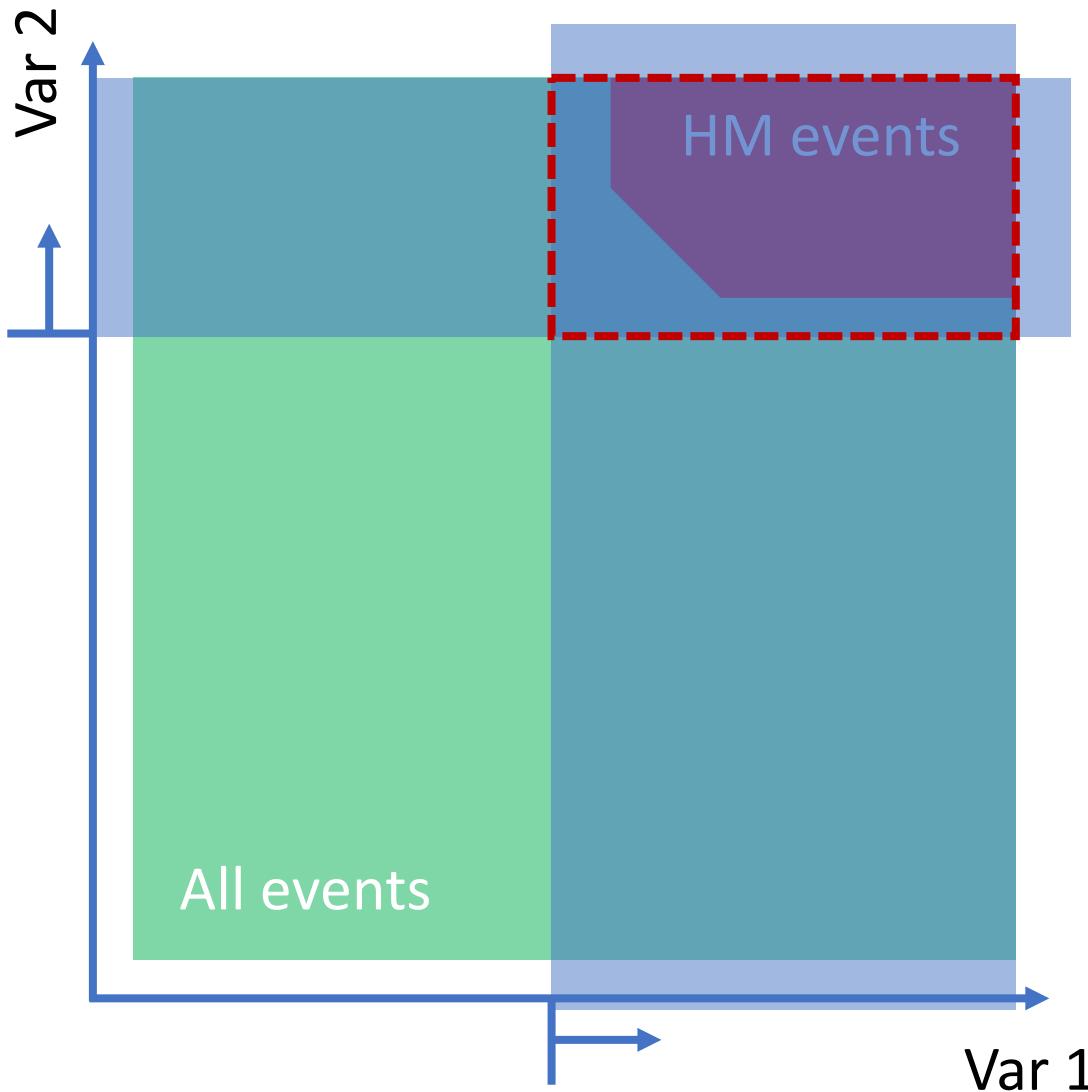
Recording cap  
10 kHz



- Design real-time data selection system (trigger)
  - Select events with  $N_{\text{ch}} > 60$  within  $10 \mu\text{s}$ ;
  - But particle reconstruction time  $\gg 10 \mu\text{s}$ .

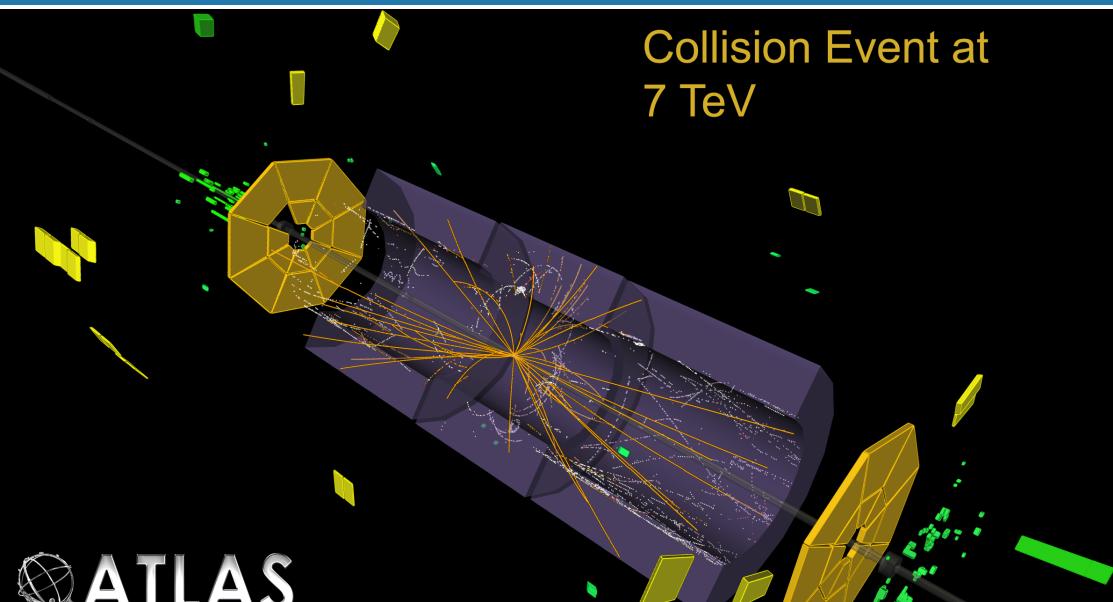
# Fast online track reconstruction

7



Sequence and thresholds of cuts designed to maximize performance.

# Event display



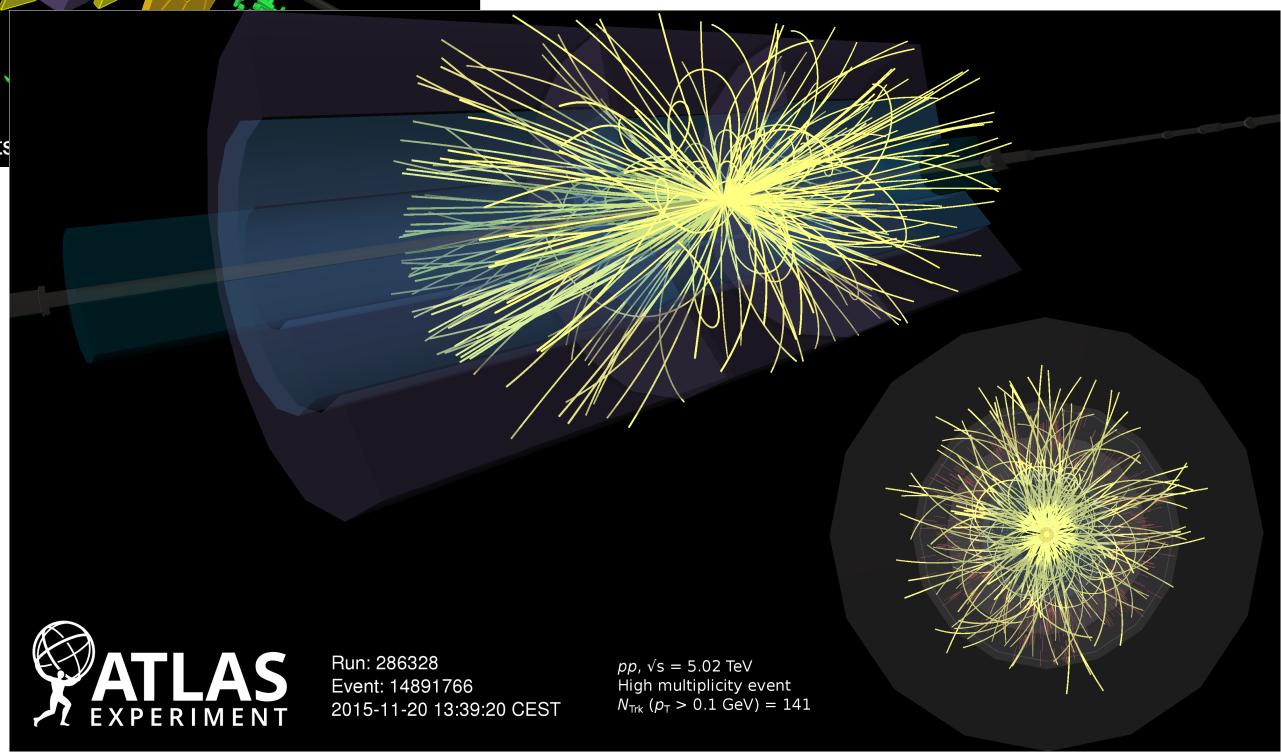
Minimum-bias event  
 $N_{ch} \approx 30$

 **ATLAS**  
EXPERIMENT

2010-03-30, 12:58 CEST  
Run 152166, Event 316199  
<http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events>

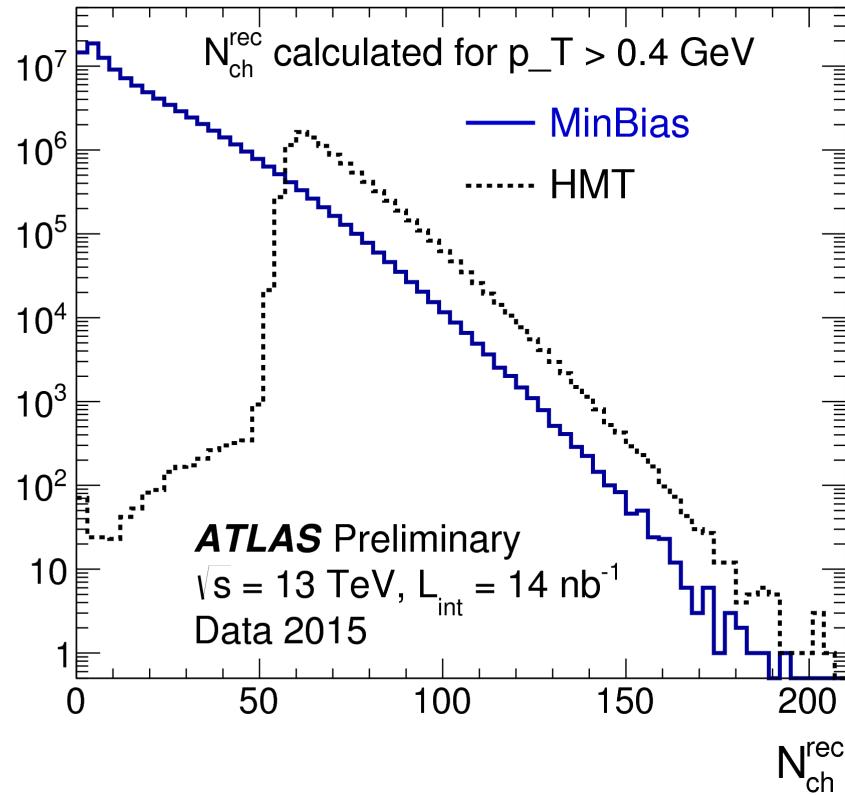
Triggered event

$N_{ch} \approx 140$

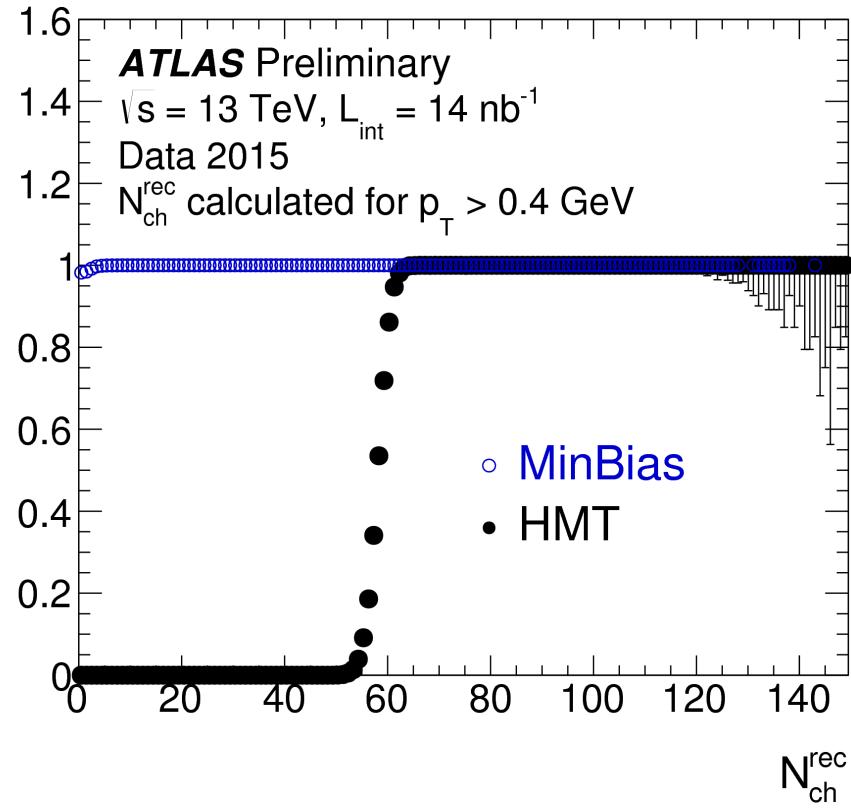


# Performance

Events / 3



Trigger efficiency

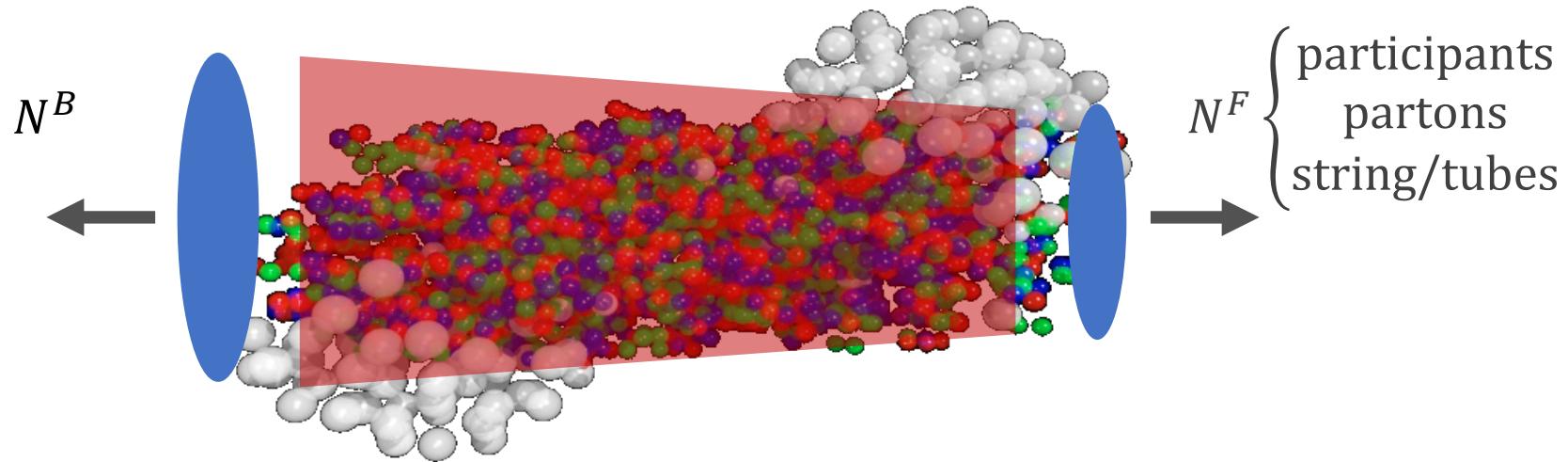


- Statistics increased by x5.

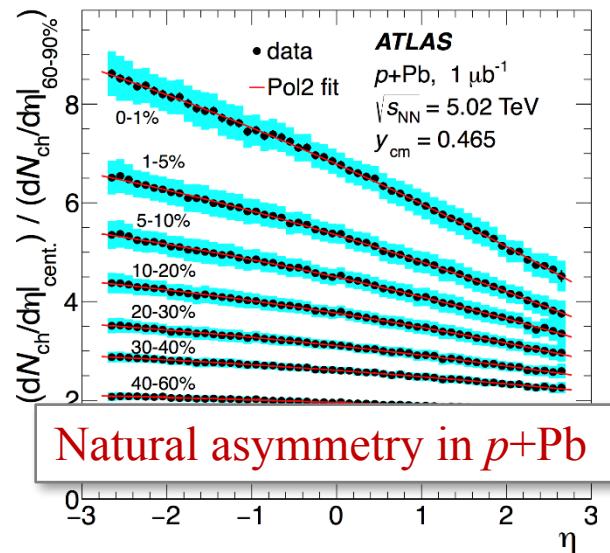
- Nominal bias introduced.

Multiple HMT triggers applied to  $pp$  and  $p+\text{Pb}$  data taking

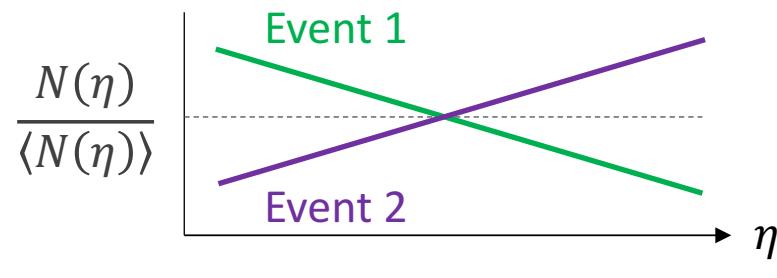
## Nature of sources seeding the long-range collective behaviors?



- $dN/d\eta$  shape reflects asymmetry in the number of forward-backward sources.



## Event-by-event multiplicity fluctuation?

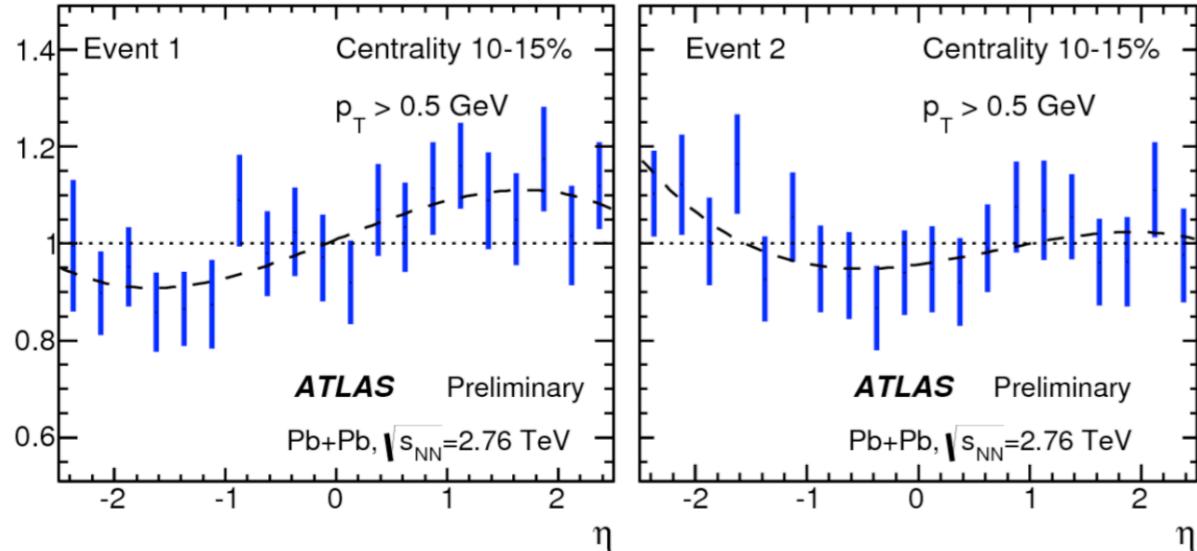


# New observable

- Single particle observable

$$R_s(\eta) \equiv \frac{N(\eta)}{\langle N(\eta) \rangle} = 1 + a_1 \eta$$

- Dominated by statistical fluctuations!



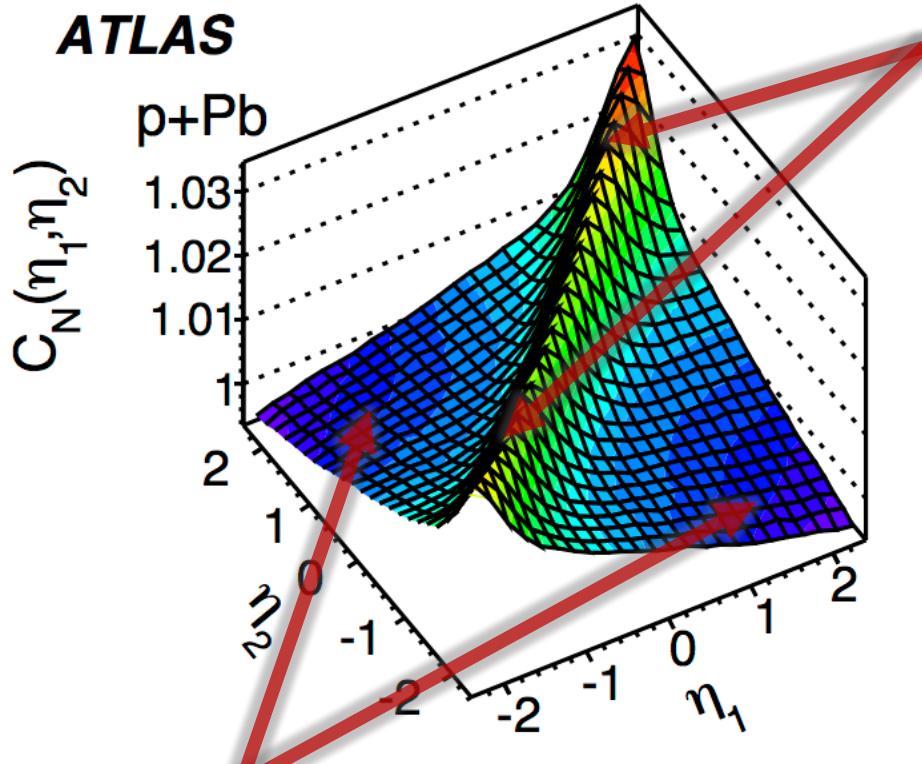
- Two particles observable (correlation function)

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

Two-particle correlation is related to single-particle distribution.

- Advantage of correlation function

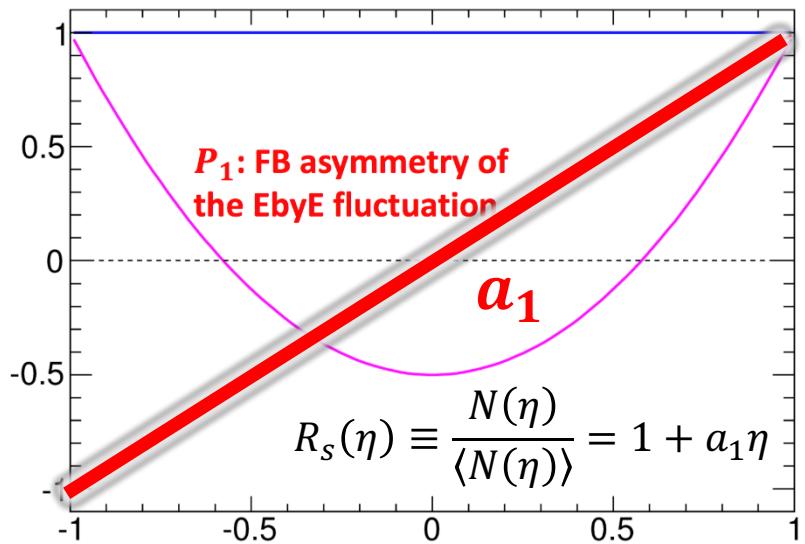
- Disentangles dynamical fluctuation from statistical fluctuation.
- Detector effects automatically removed;



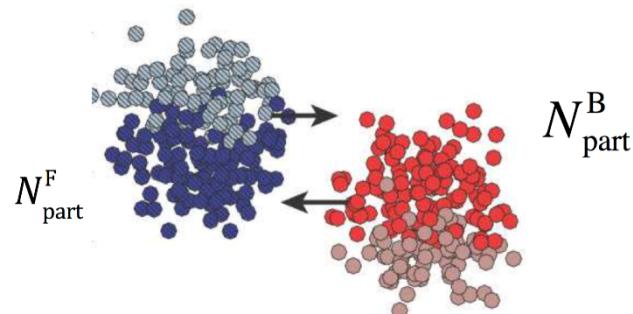
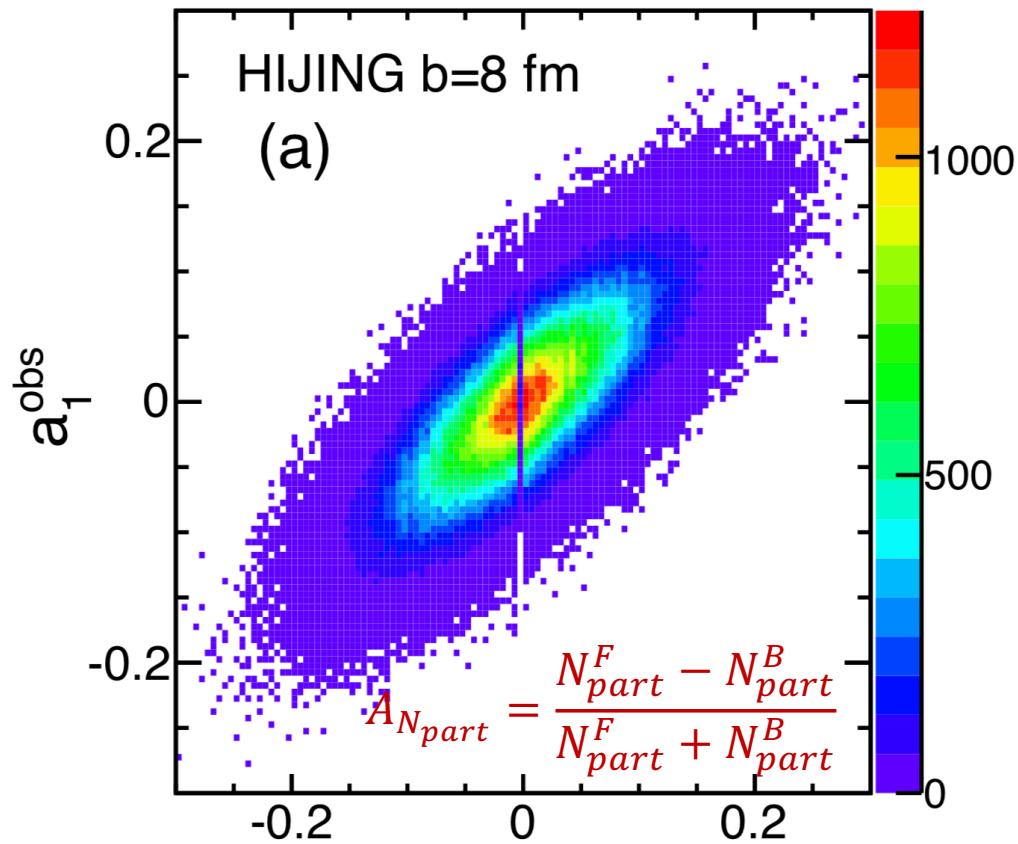
- Long-range correlation

- Short-range correlation reflects correlation in the different sources: jet fragmentation, resonance decay...
- Since SRC has a strong charge dependence, a data-driven way was developed to remove the SRC (backup).
- An alternative way is through multi-particle correlation (cumulant) in  $\eta$ .  
[Phys. Rev. C 93, 024903 \(2016\)](https://doi.org/10.1103/PhysRevC.93.024903)

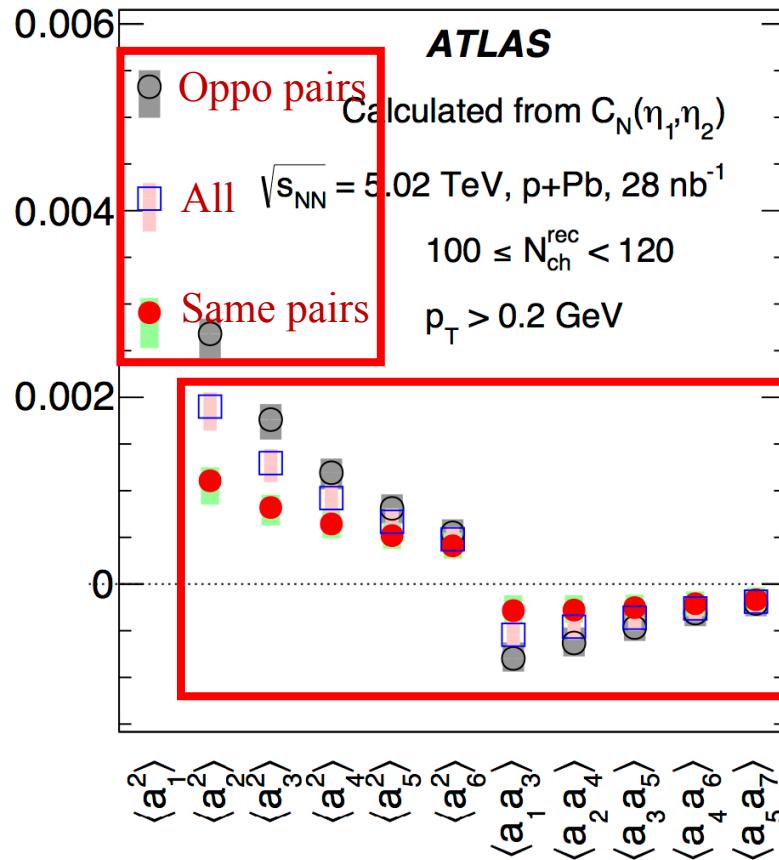
How to quantify forward-backward fluctuation?



- The linear shape quantifies the FB multiplicity asymmetry;
- HIJING shows strong correlation between final multiplicity asymmetry and initial participant asymmetry;
- As will be shown later, this component dominates the shape fluctuation.

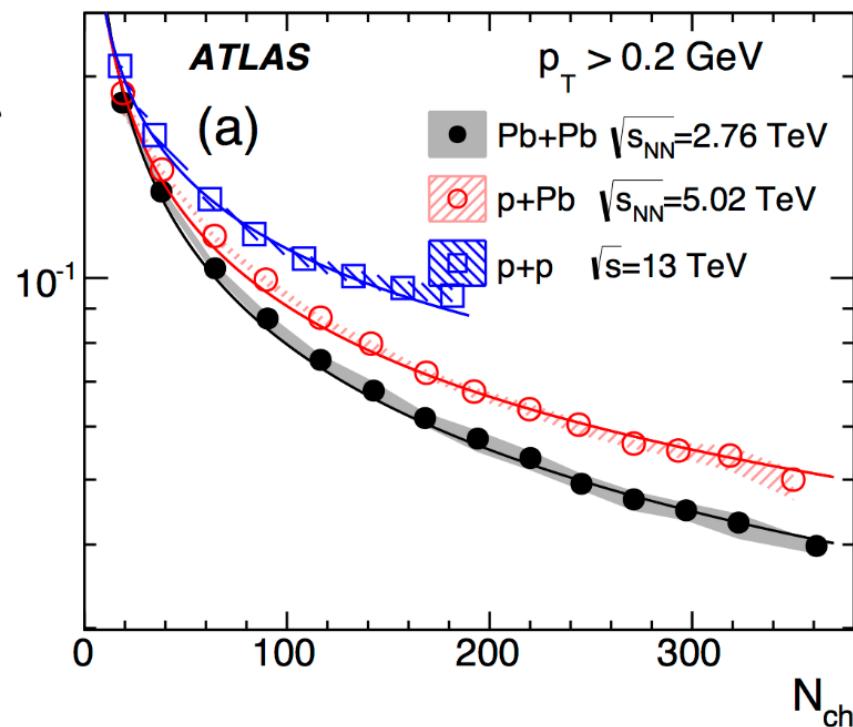


## Before SRC removal



- Higher order coefficients observed;
- Coefficients have charge dependent;
- Results hard to interpret: due to SRC!

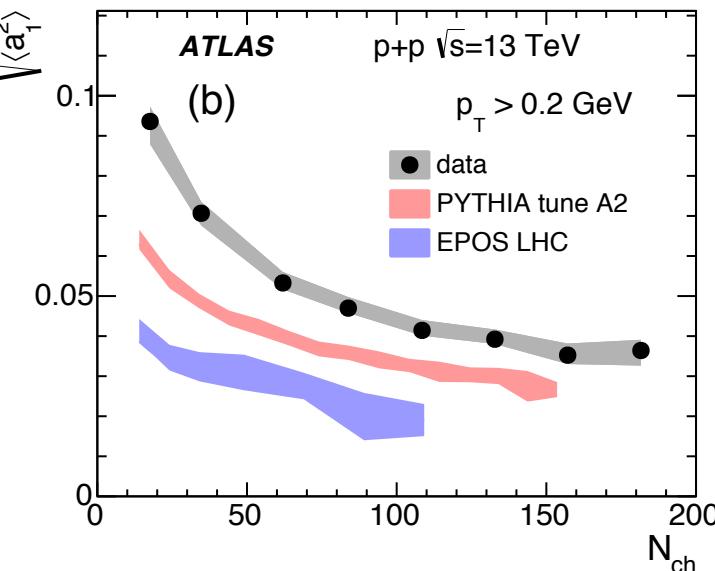
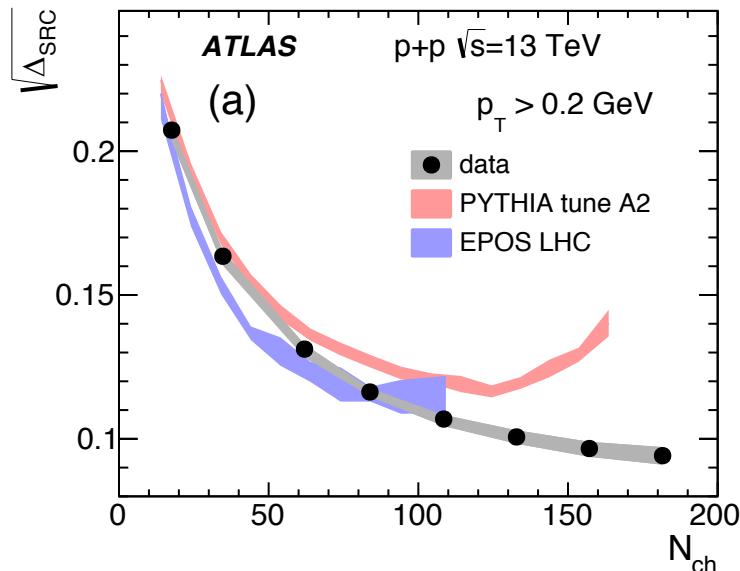
- Simpler picture after SRC removal!
- LRC dominated by linear fluctuation;
- LRC is charge independent.

**SRC**

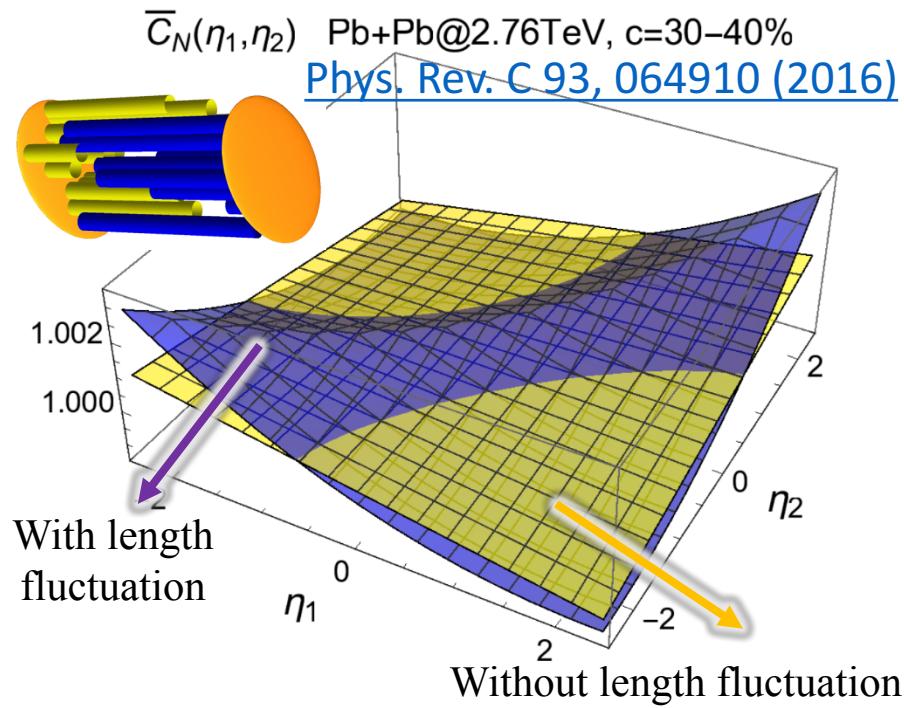
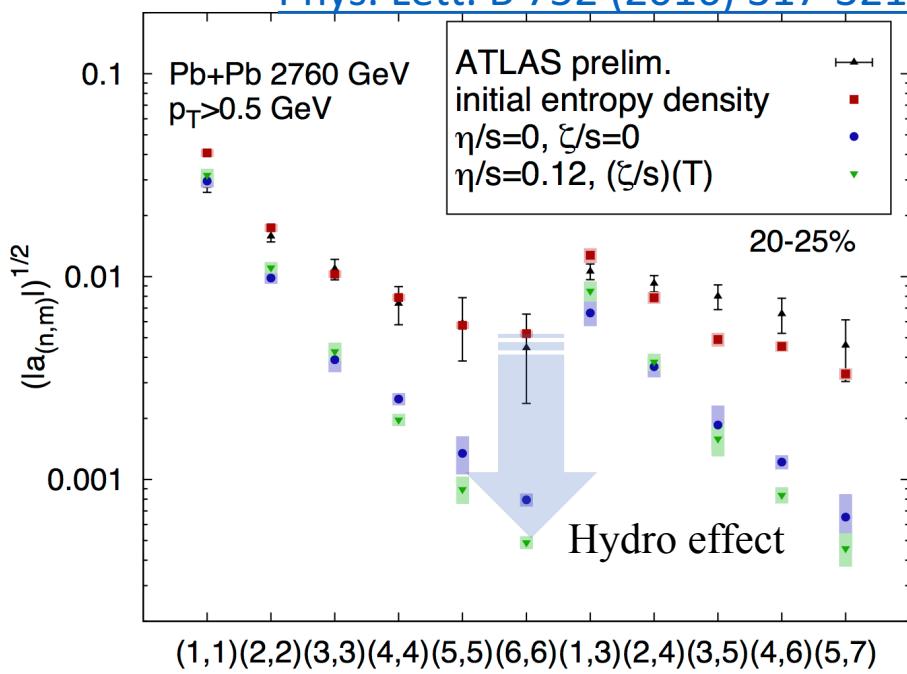
- SRC increases towards peripheral;
- SRC is stronger in small systems;

How will these new results help?

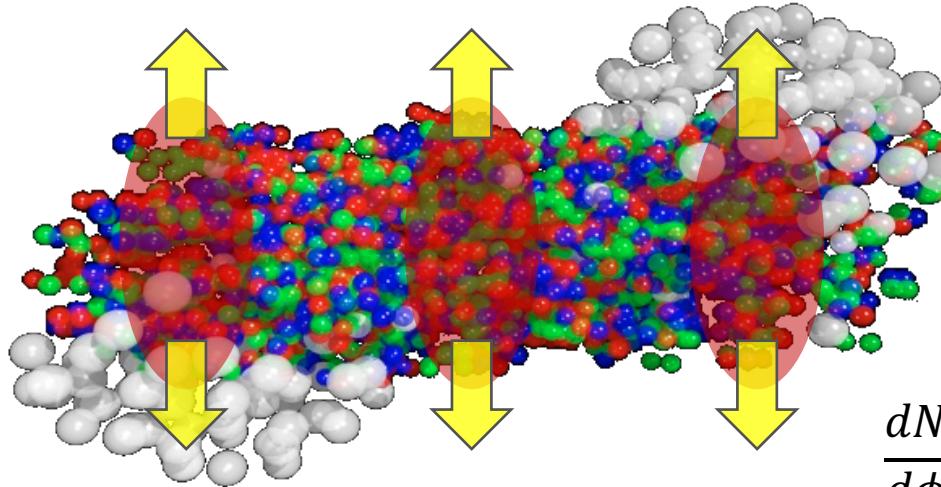
# Model and data comparison



[Phys. Lett. B 752 \(2016\) 317-321](#)

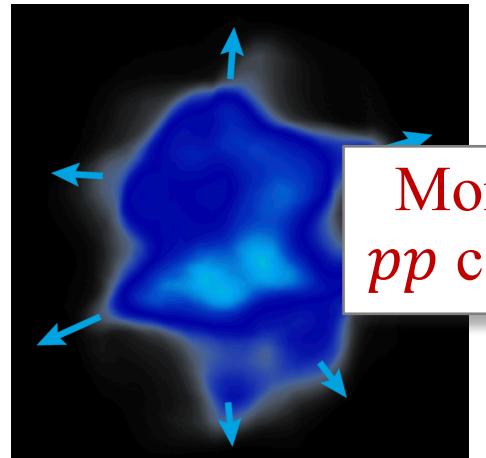


Nature of sources seeding the long-range collective behaviors?

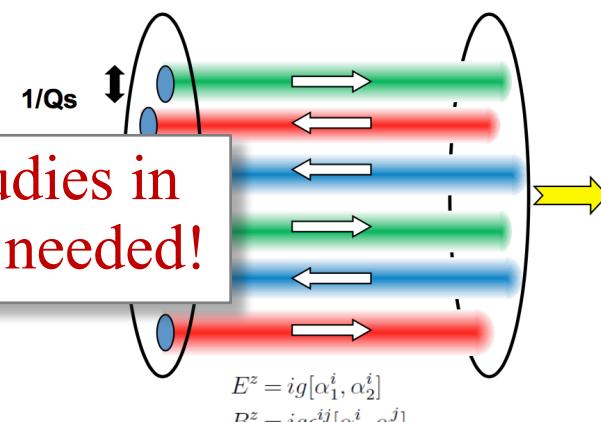


$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1} v_n \cos n\phi$$

- Azimuthal correlation in A+A: collective hydrodynamic expansion of nuclear matter;



More careful studies in  
pp collisions are needed!



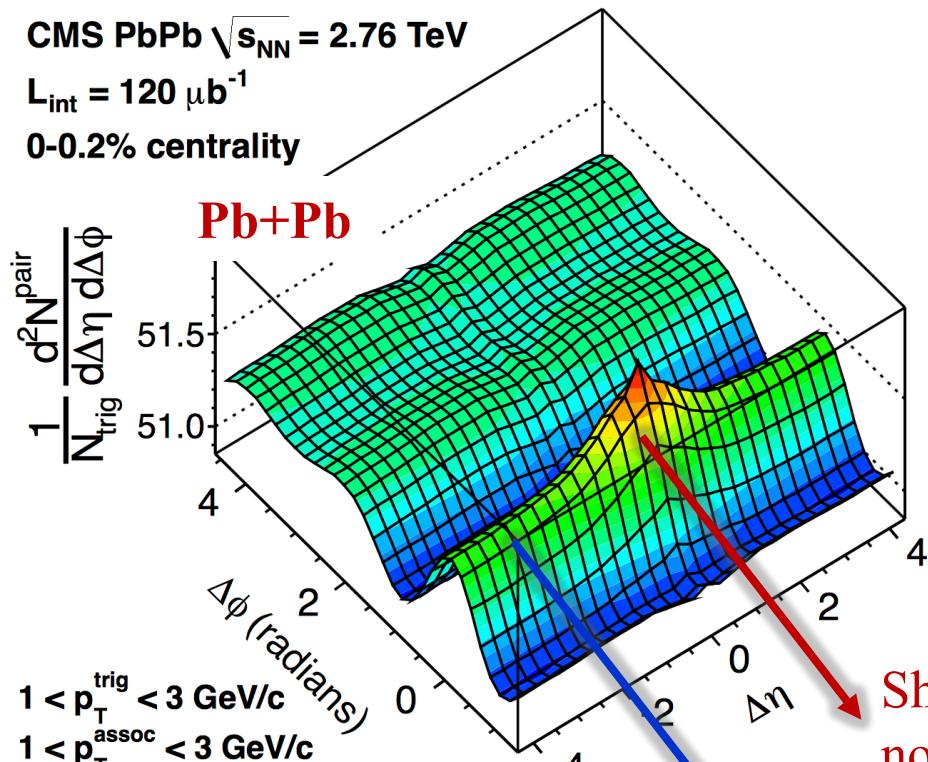
Final state correlations

Initial state correlations

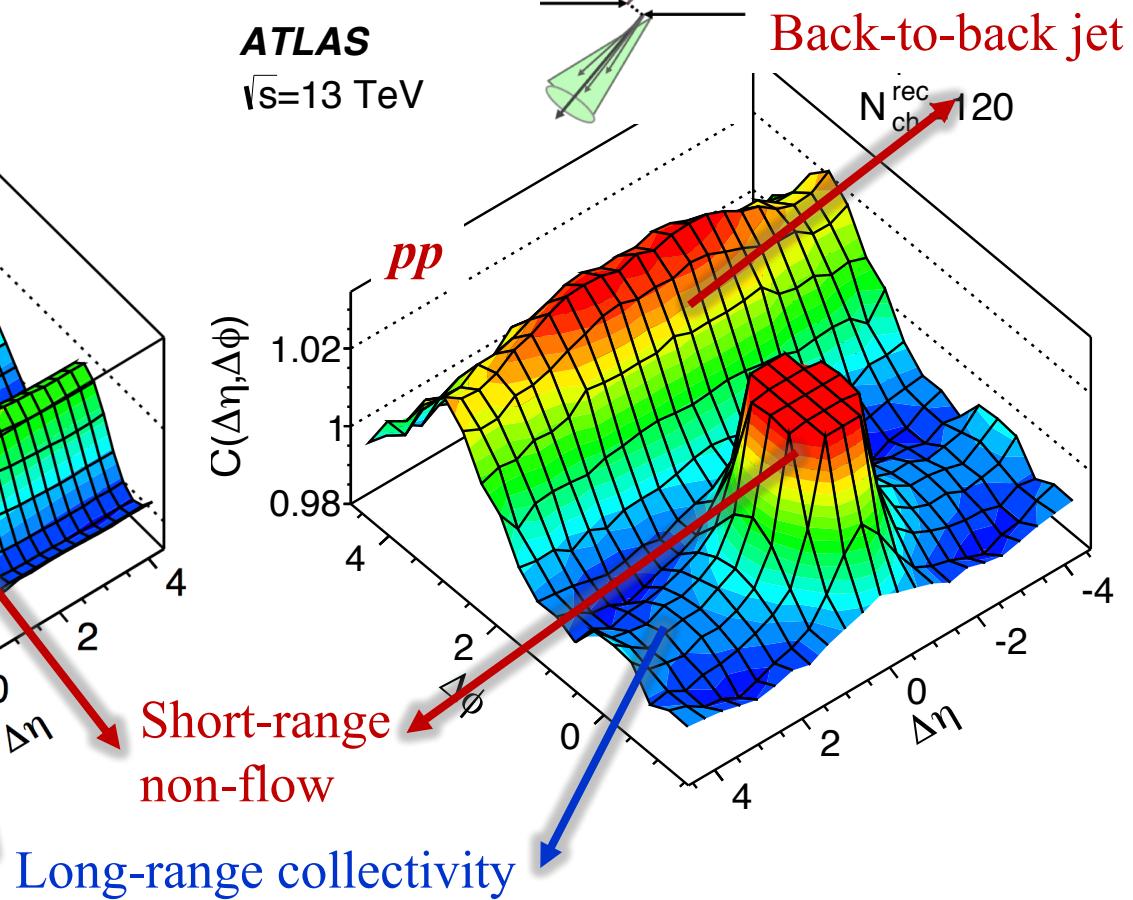
# 2-particle correlation

18

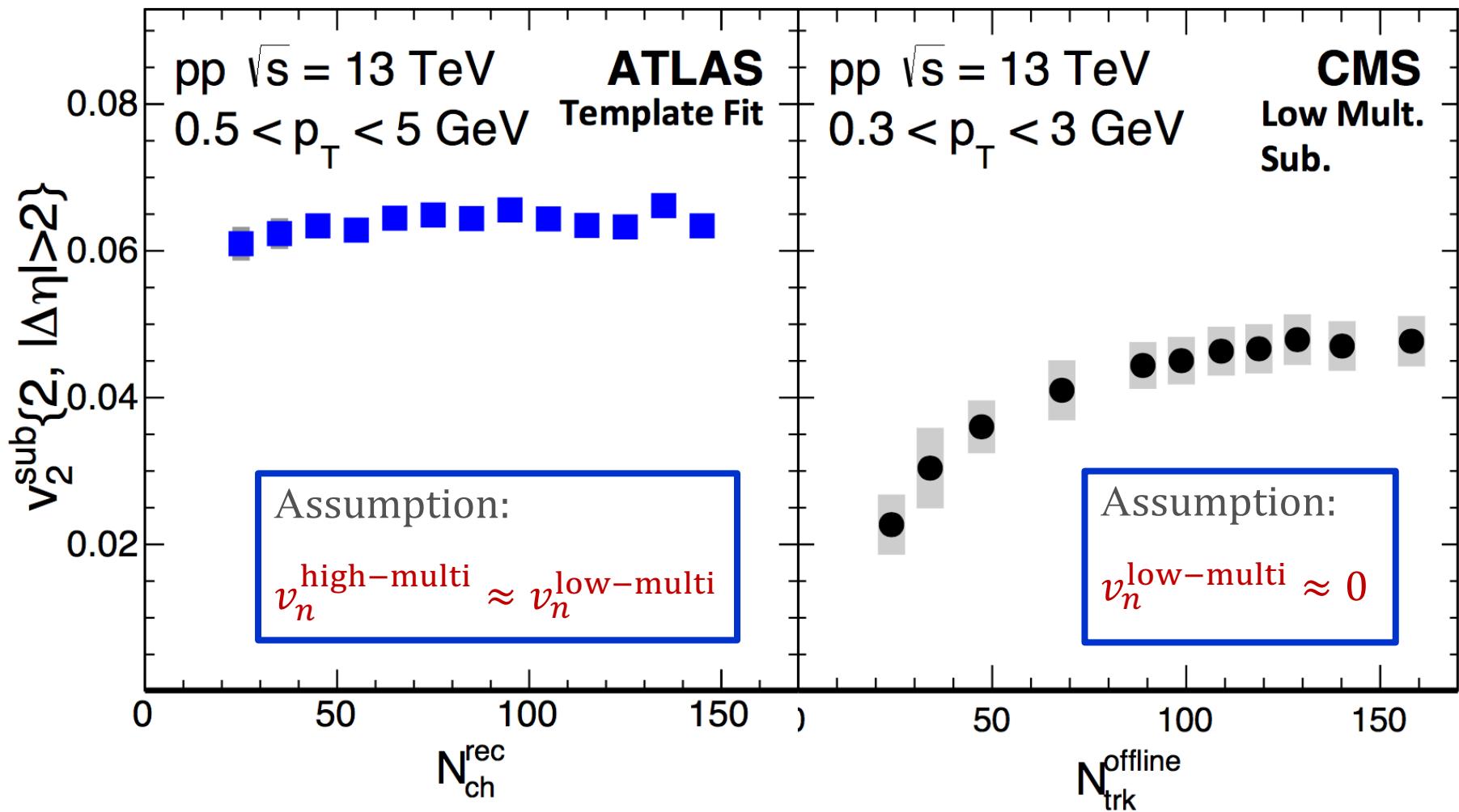
CMS PbPb  $\sqrt{s_{NN}} = 2.76 \text{ TeV}$   
 $L_{\text{int}} = 120 \mu\text{b}^{-1}$   
 0-0.2% centrality



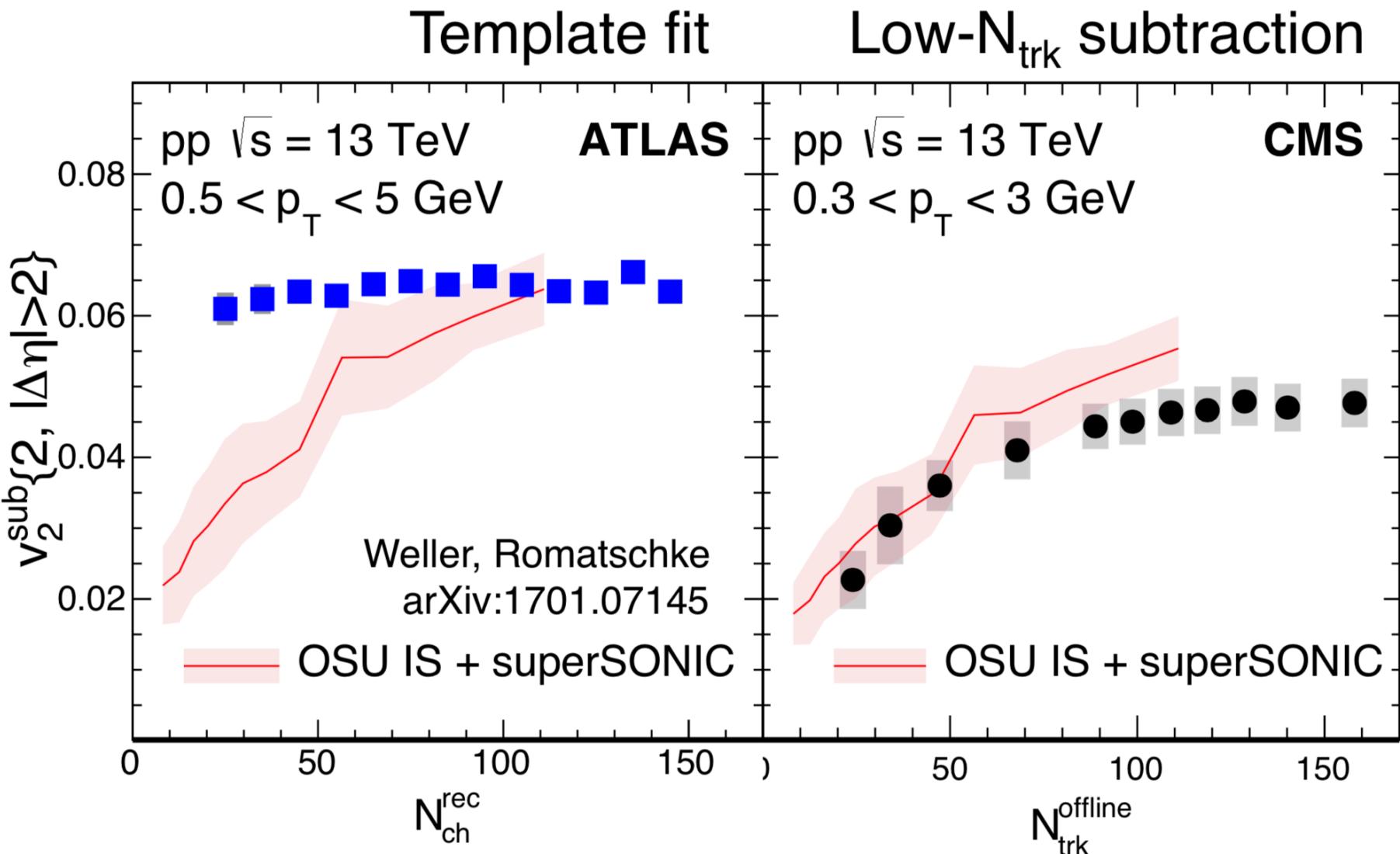
ATLAS  
 $\sqrt{s}=13 \text{ TeV}$



- Dijet behaves like long-range collectivity;
- Different methods used to remove dijet.



Does collectivity turn off at lower  $N_{ch}$ ?



- If hydro,  $v_2$  should go down toward low  $N_{ch}$ ;
- Methods free of assumptions?

- Multi-particle correlation  $\text{corr}_n\{4\} \equiv \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle$

Genuine 4-particle correlation

2-particle non-flow

- Multi-particle cumulant  $c_n\{4\} \equiv \langle \text{corr}_n\{4\} \rangle - 2\langle \text{corr}_n\{2\} \rangle^2$

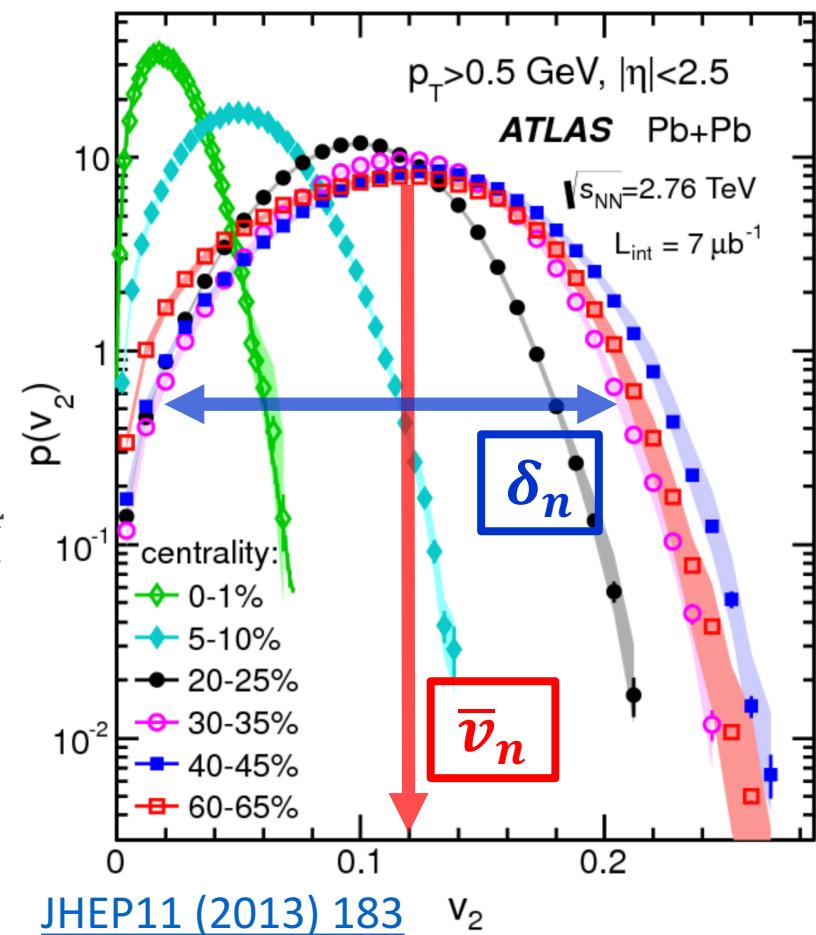
- Flow fluctuates from event to event;

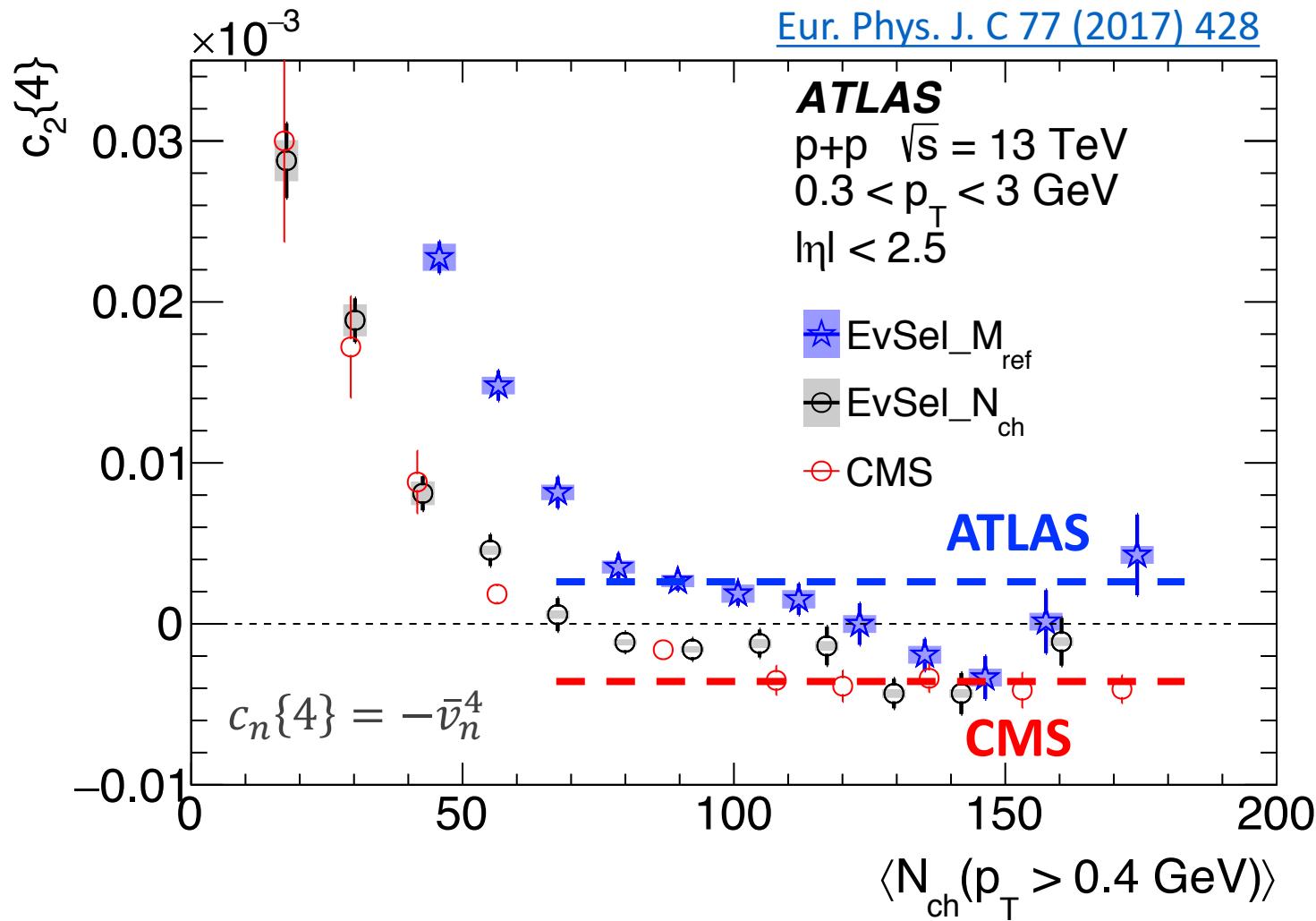
- Cumulant probes  $p(v_n)$ .

- Features of cumulant method

- Suppress non-flow (< 4 particles);
- If  $p(v_n) \sim \text{Gauss}$ , then  $c_n\{4\} = -\bar{v}_n^4$

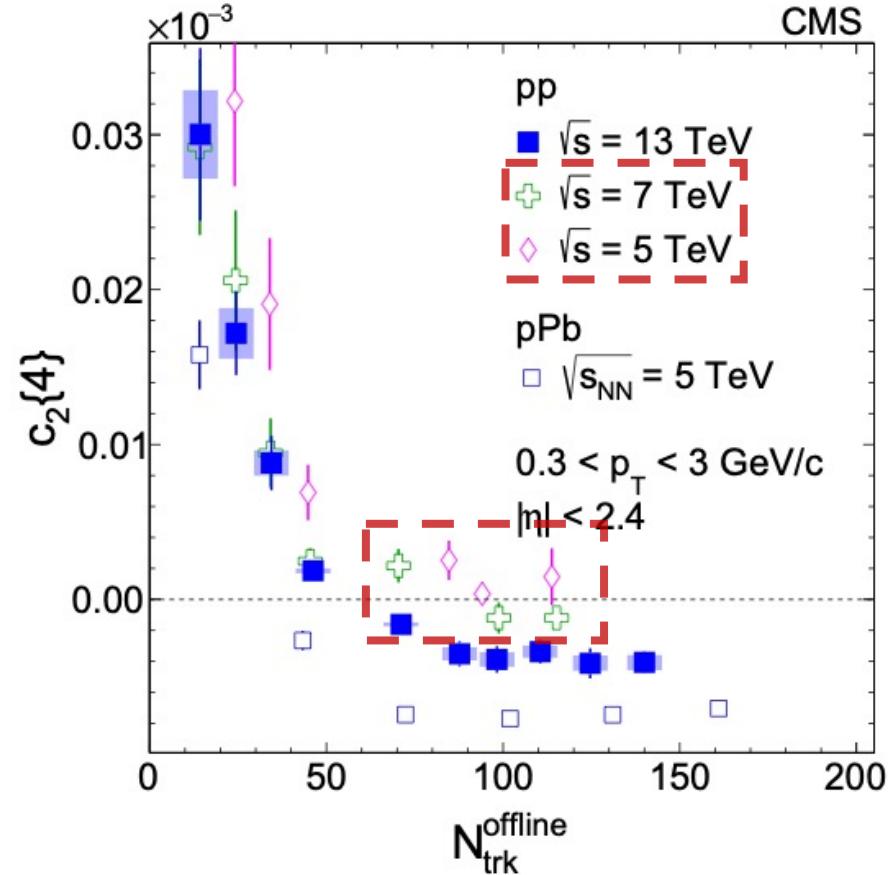
Cumulant proved successful in large systems, how about small systems?



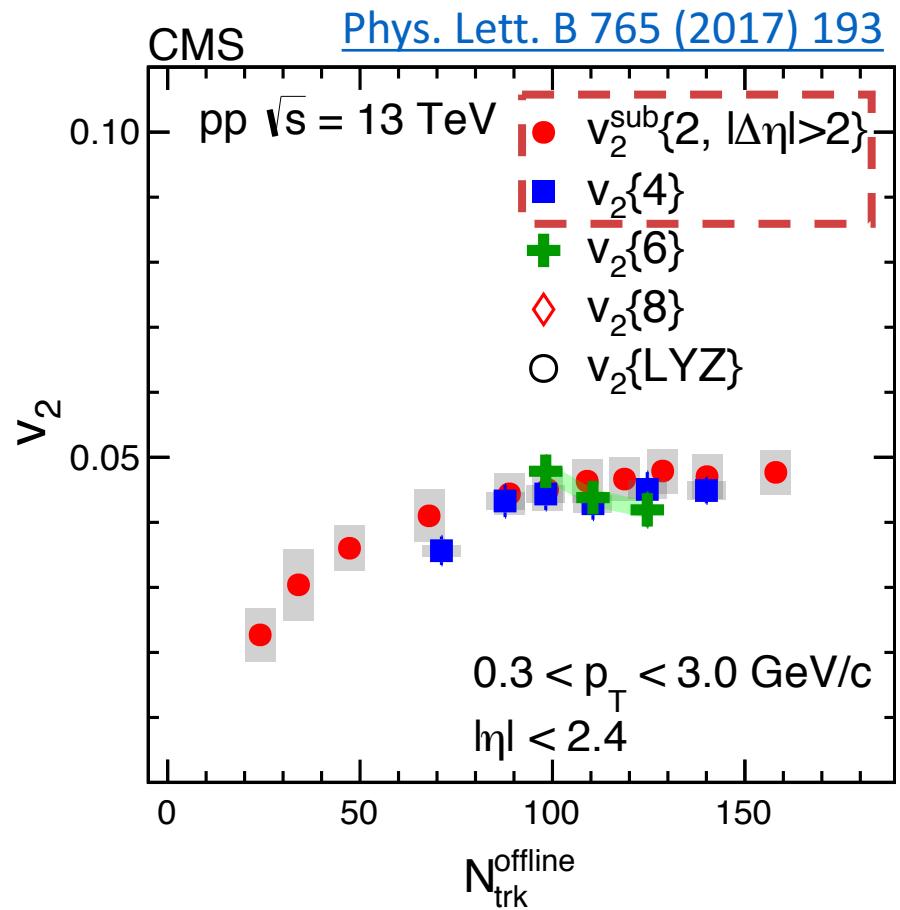


To be **collective**, or not to be **collective**?

# Other puzzles



- No hint of collectivity at lower energy?

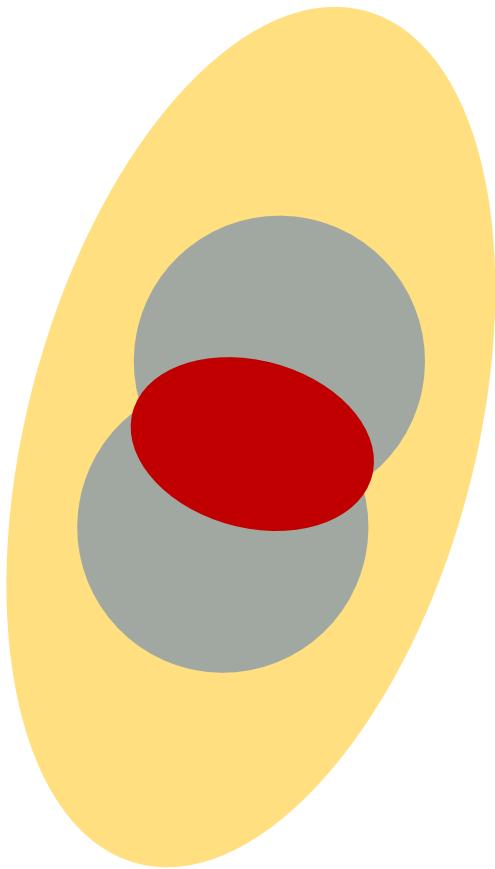


- $v_2\{2\} = v_2\{4\} + \text{flow fluc}$
- Flow fluc  $\approx 0$  ?

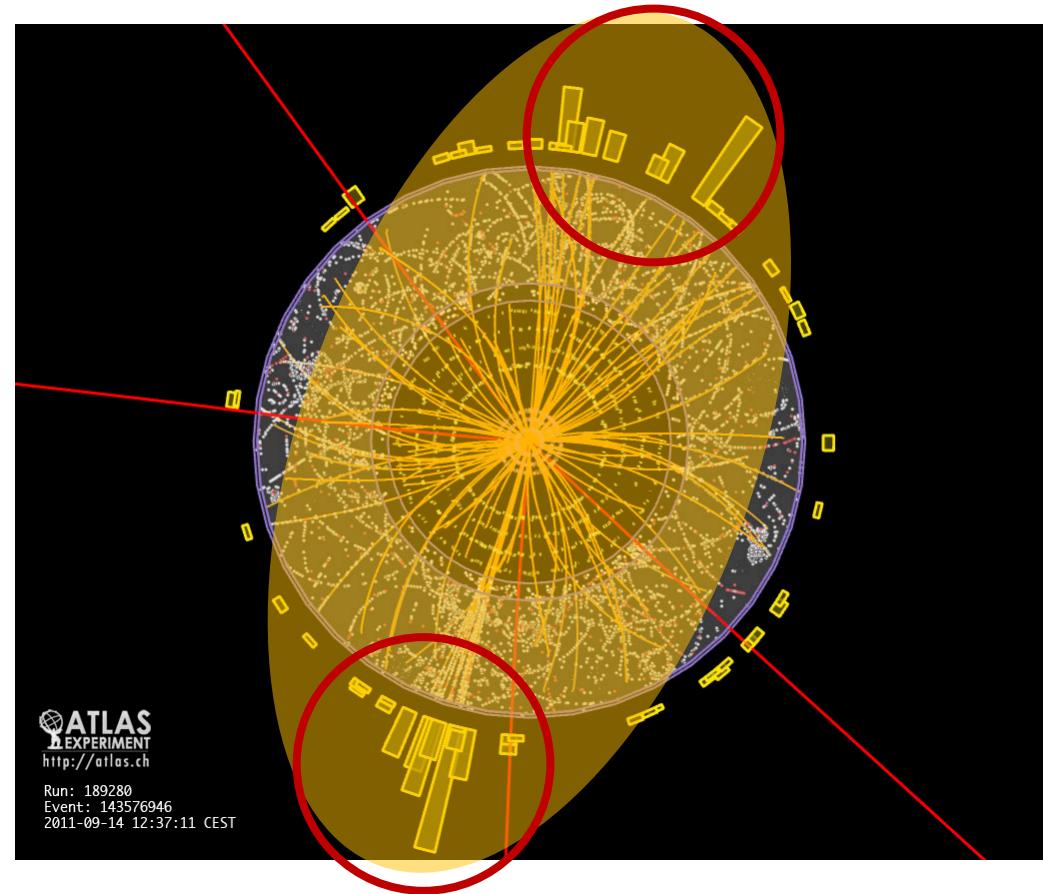
Puzzles needs to be solved before testing models with data.

# Signal or background?

24



Signal: collectivity

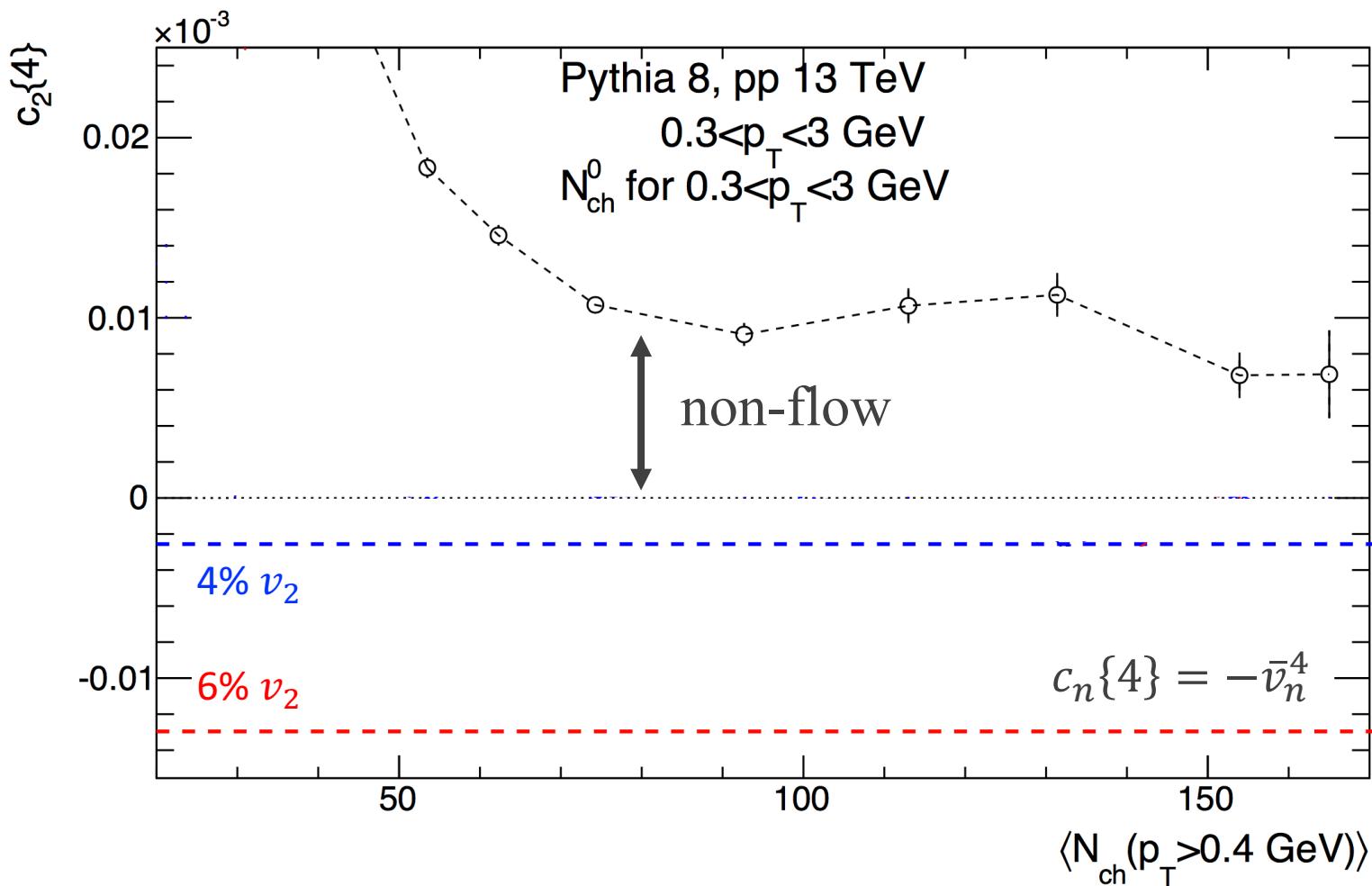


Background: dijets

Maybe background is the one to blame?

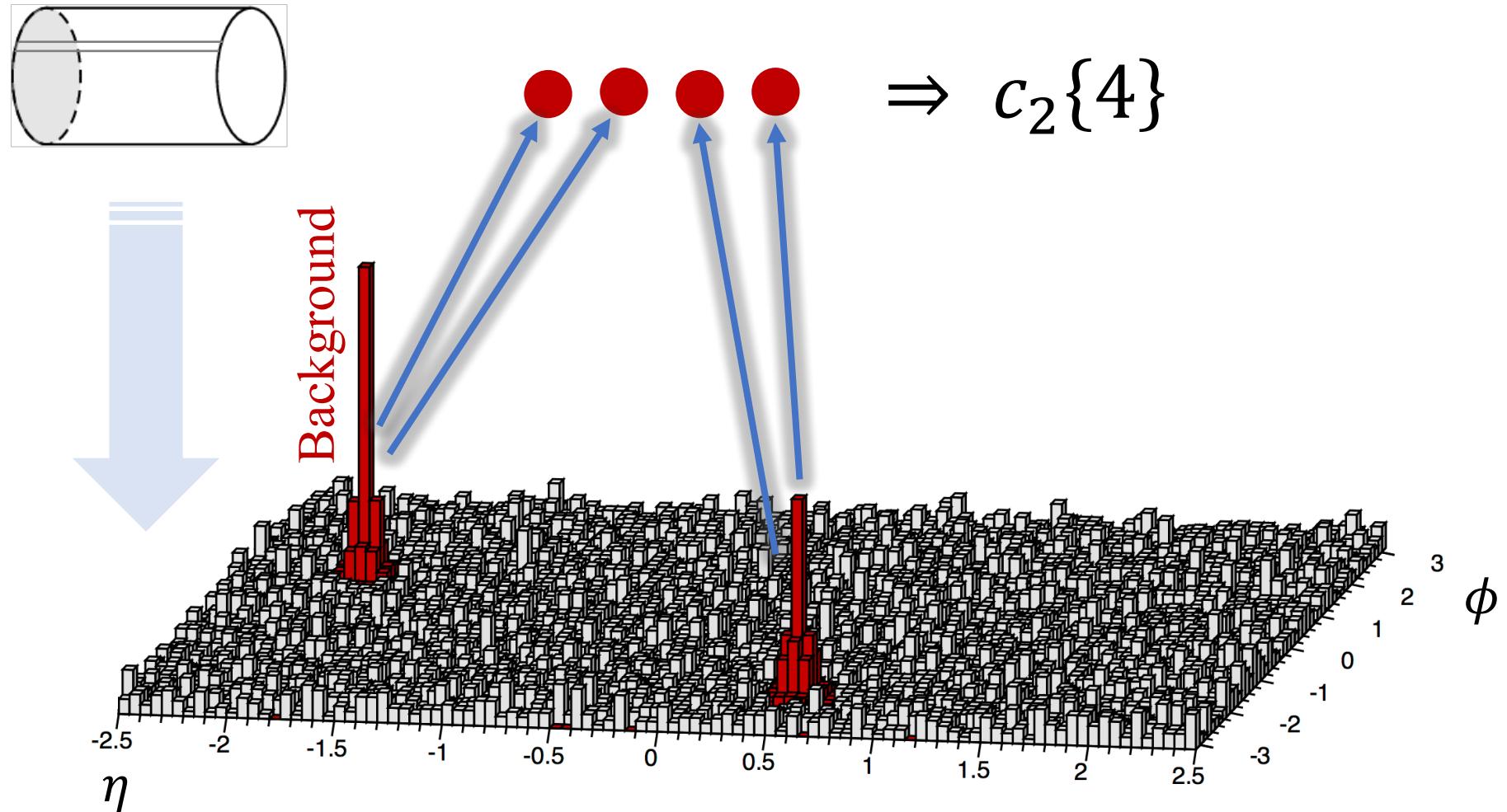
# Test of background

25

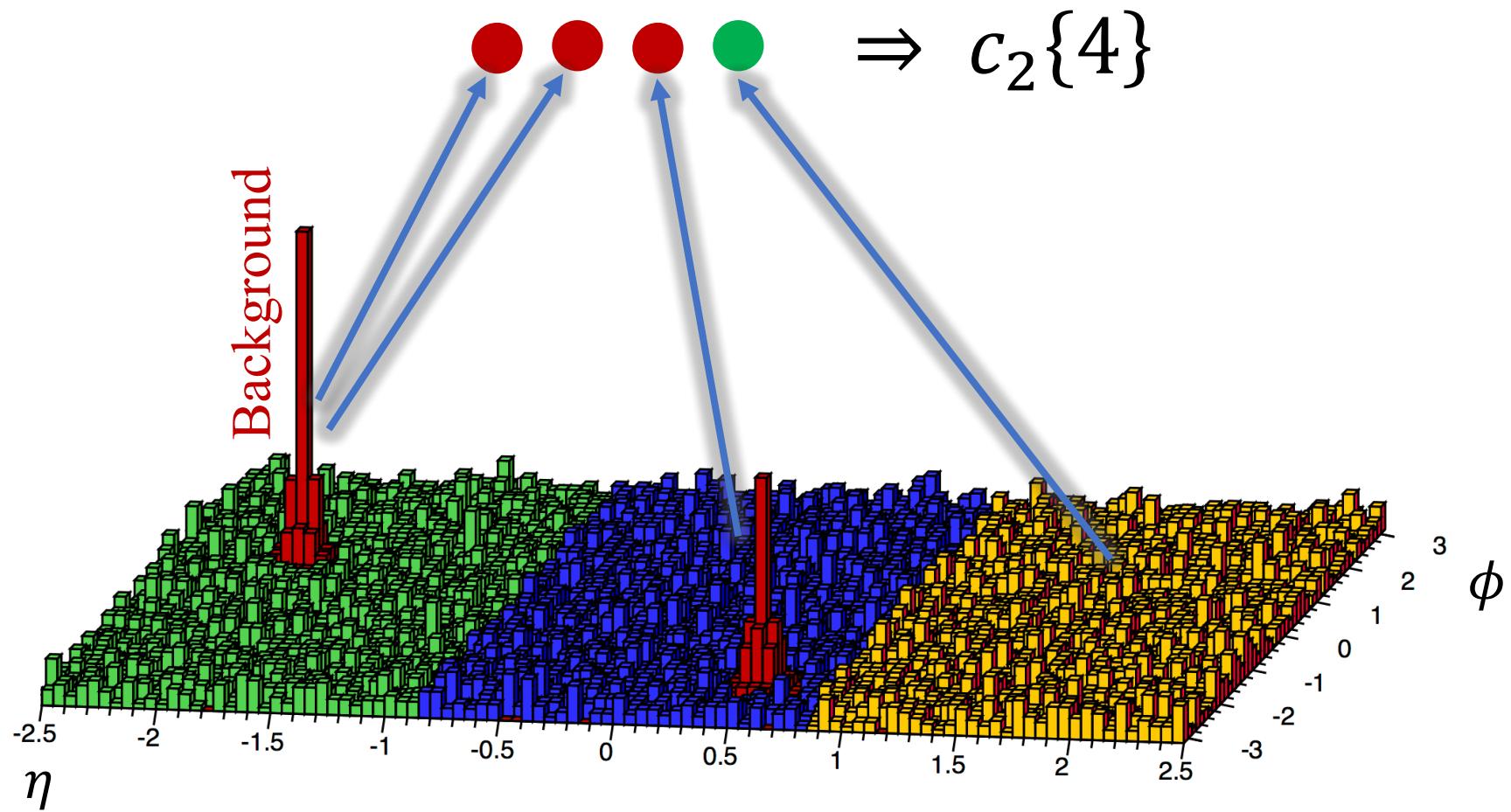


Traditional cumulant cannot remove non-flow in  $pp$

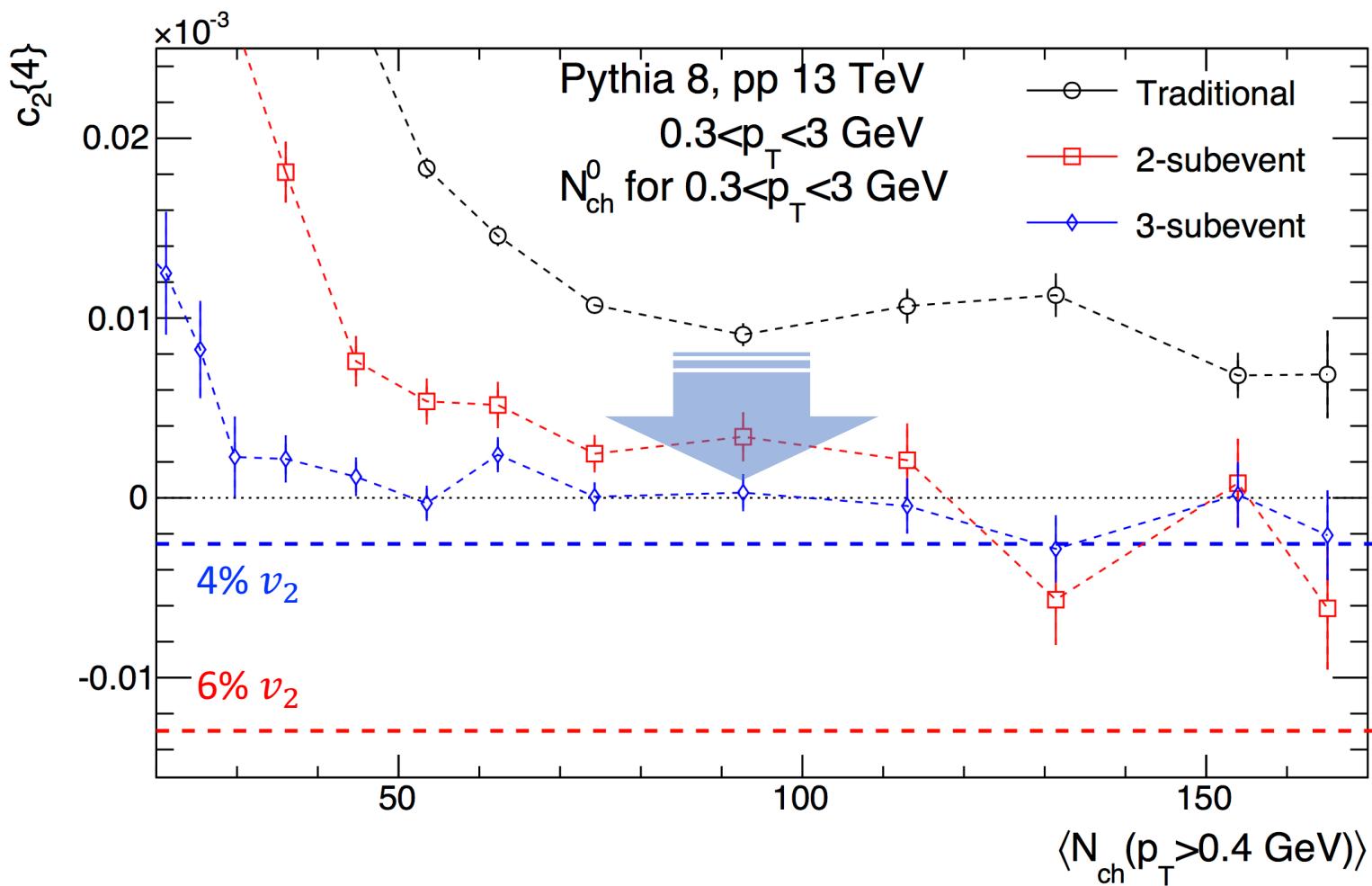
# Traditional method



- High probability all four particles come from background;
- Solution: higher-order cumulant (statistical significance), or...



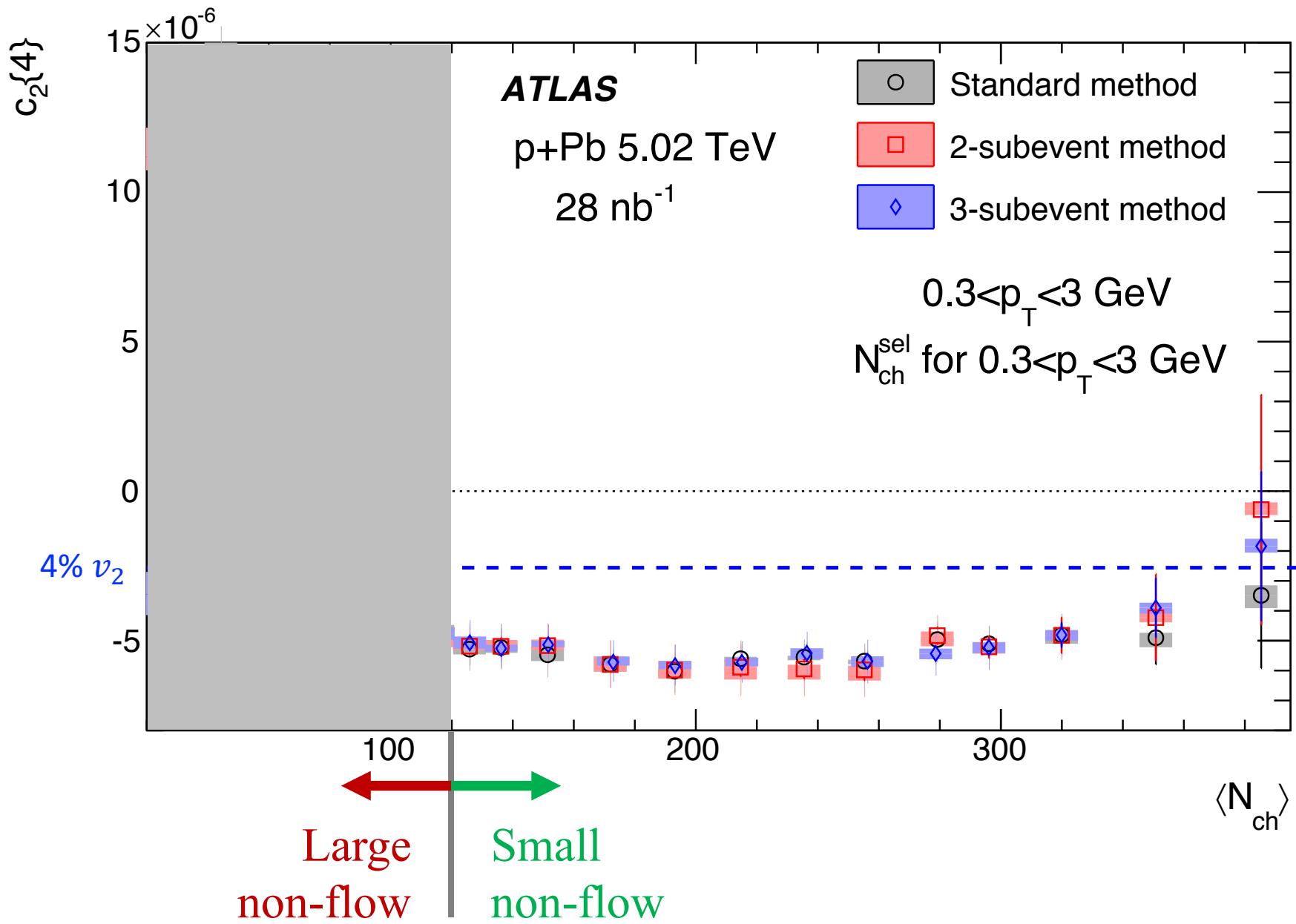
$$3 > 2$$

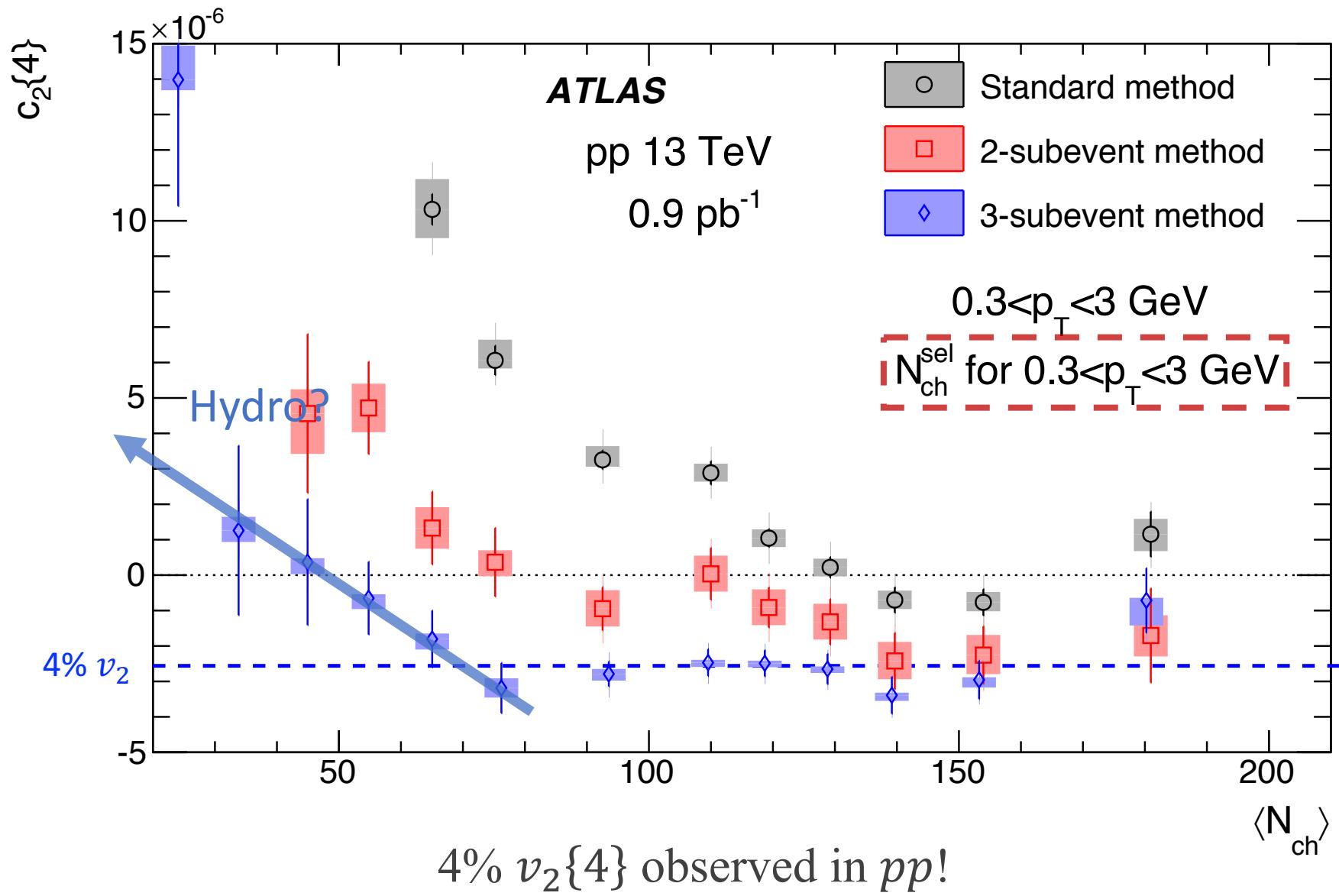


Subevent method can suppress non-flow in PYTHIA

# Validation in $p+\text{Pb}$ data

29



$c_2\{4\}$  in  $pp$ 

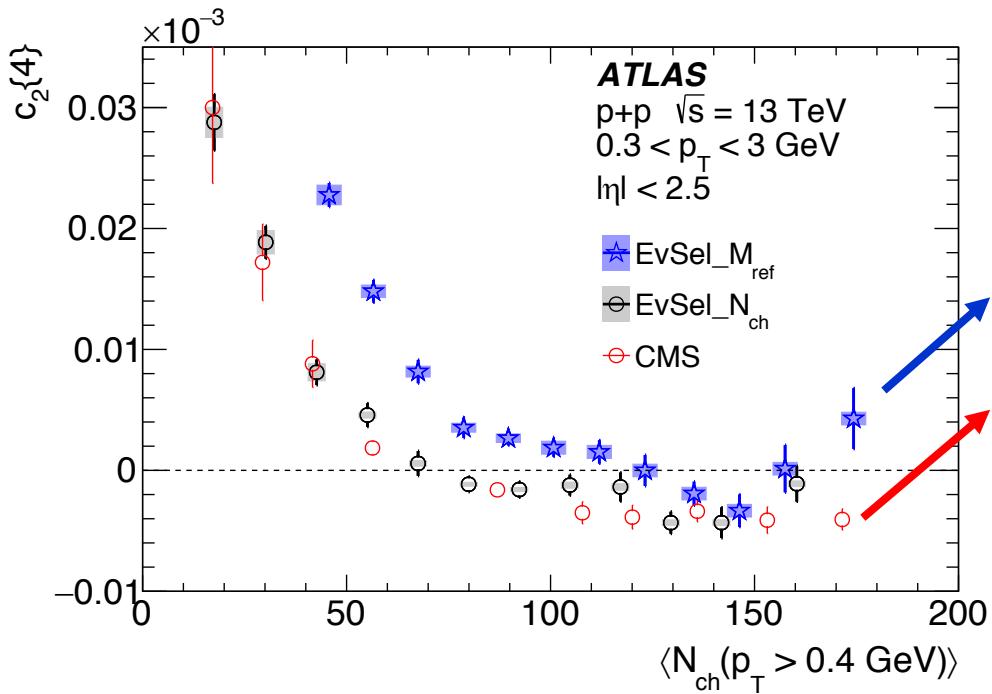
# Test of residual non-flow

$$c_2\{4\} \equiv \langle \text{nonflow} + \text{flow} \rangle_{evt}$$

Non-flow changes greatly EbyE

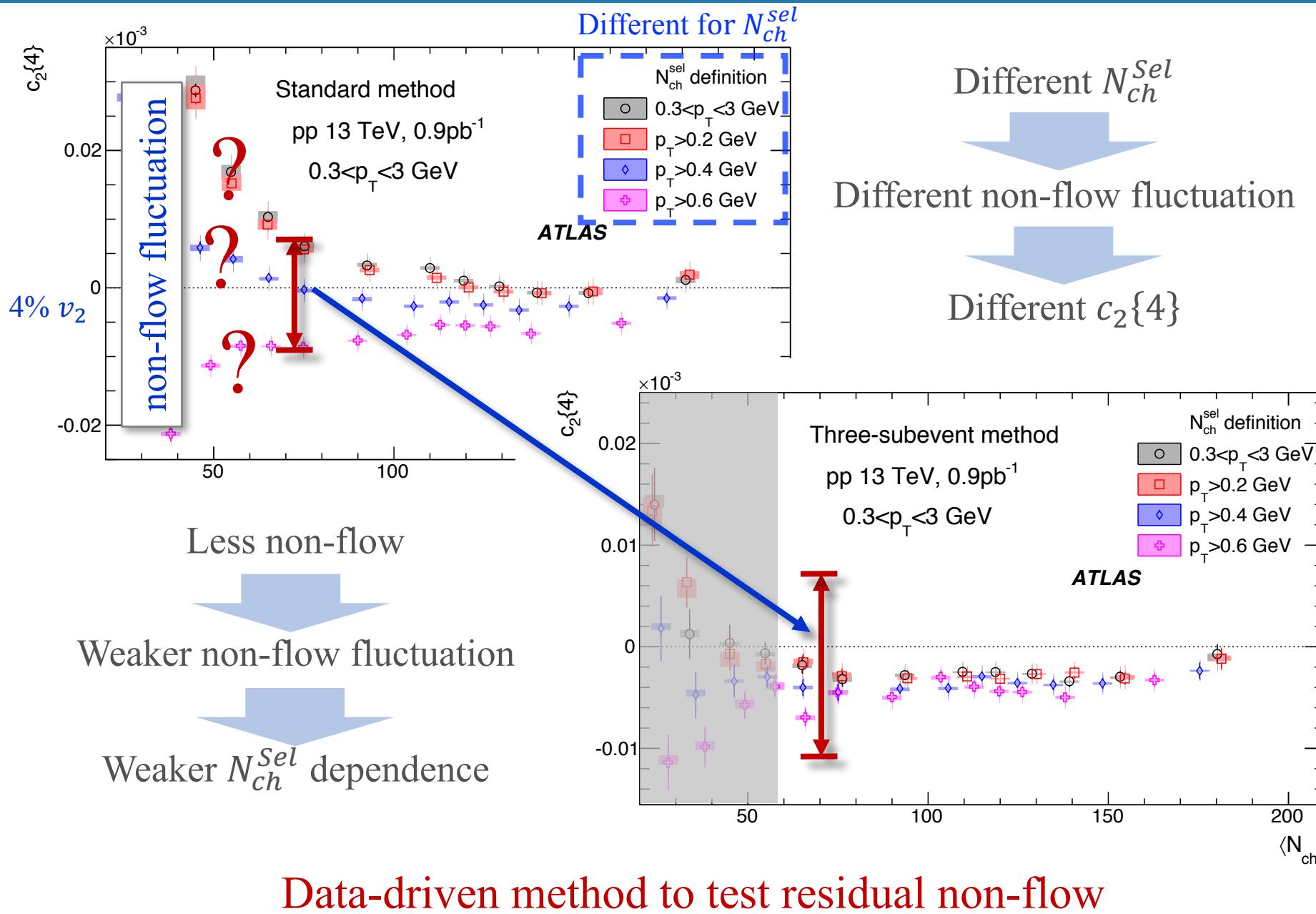
Flow changes little EbyE

**non-flow fluc. ← multiplicity fluc. ← how  $\langle \dots \rangle_{evt}$  is defined:  $N_{ch}^{Sel}$**



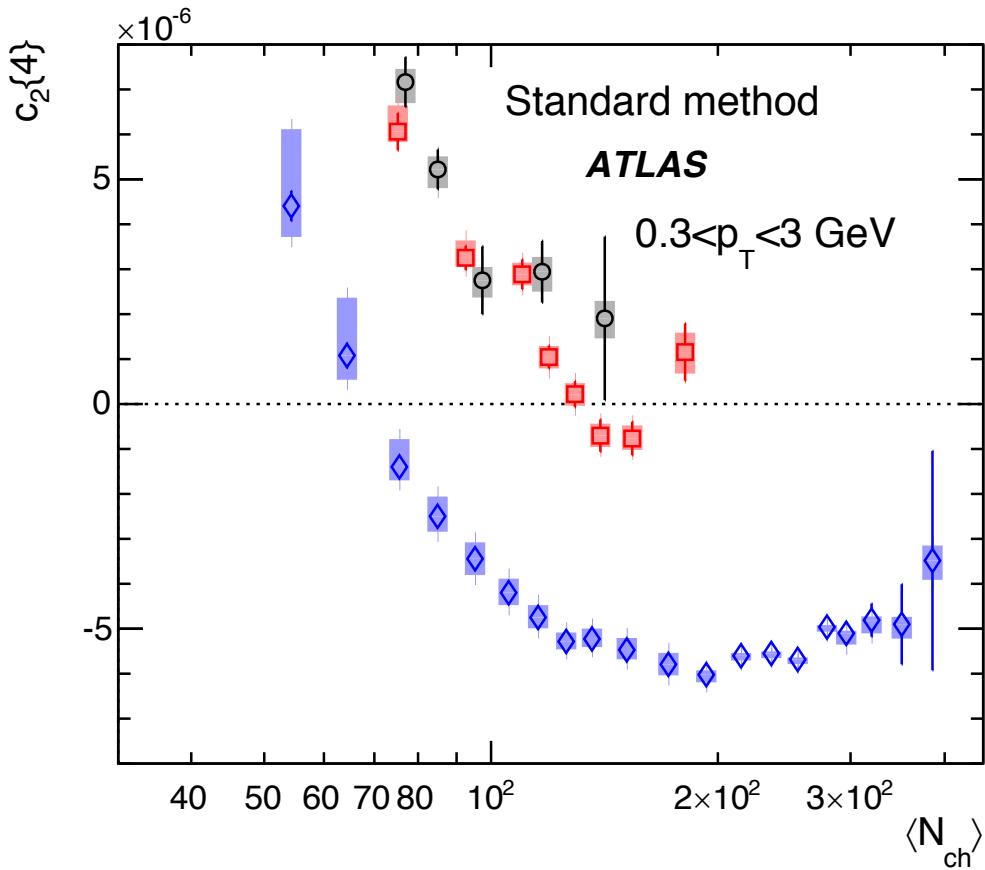
- $N_{ch}^{Sel}$  defined with different  $p_T$ : very different non-flow fluctuation.
- $N_{ch}^{Sel}$  defined with  $0.3 < p_T < 3.0 \text{ GeV}$
- $N_{ch}^{Sel}$  defined with  $p_T > 0.4 \text{ GeV}$
- Non-flow fluctuation might mimic the flow signal (negative  $c_2\{4\}$ )!

# Puzzle 1: $N_{ch}^{sel}$ dependence



## Puzzle 2: energy dependence

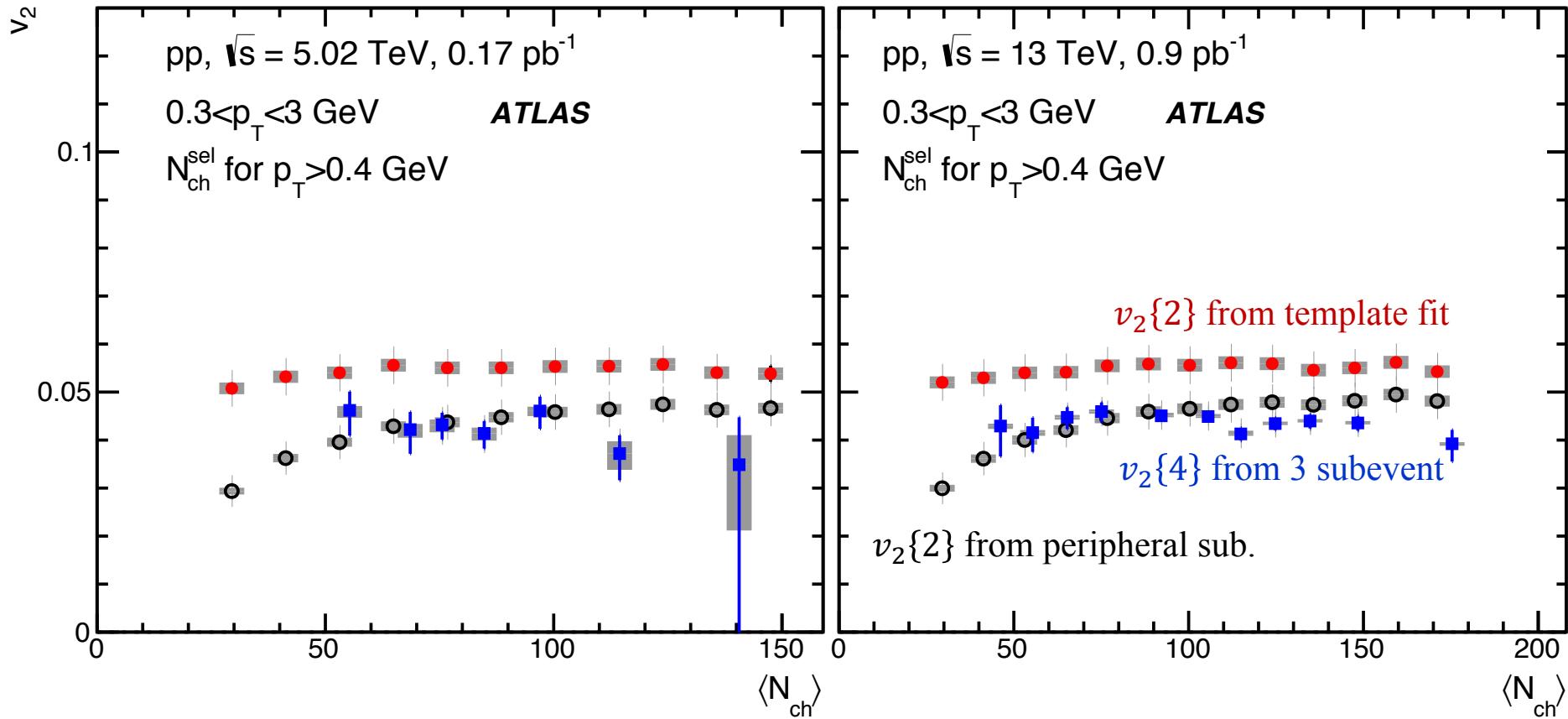
33



- Weak energy dependence in  $pp$ ;
- $p+Pb$  has larger flow than  $pp$ ;

# Puzzle 3: flow fluctuation

34

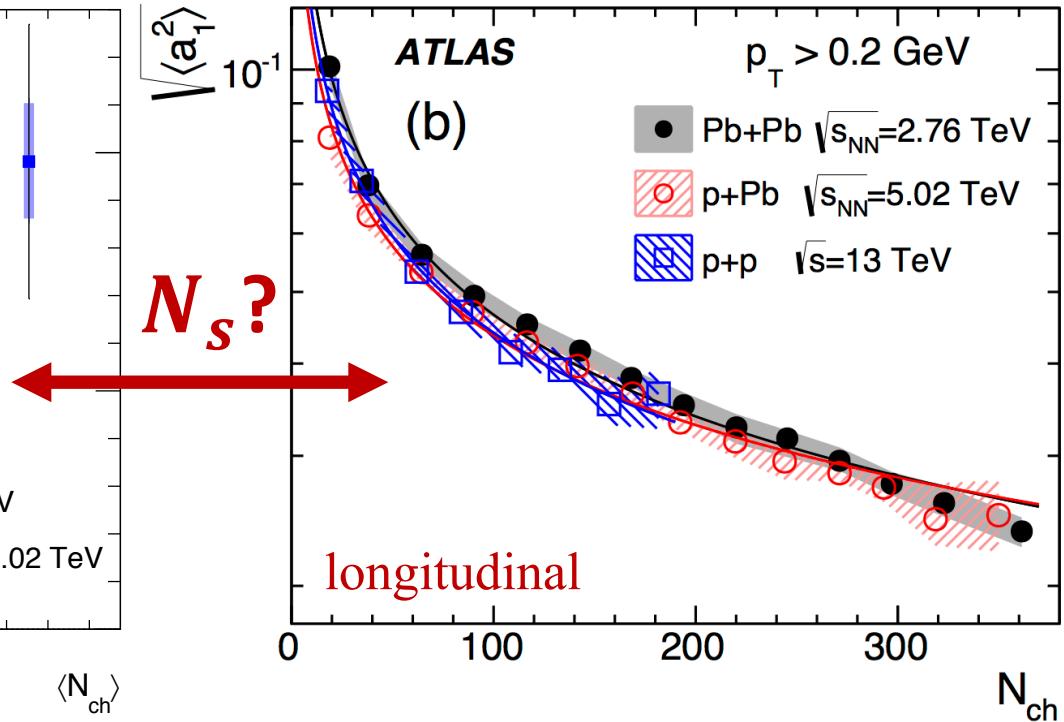
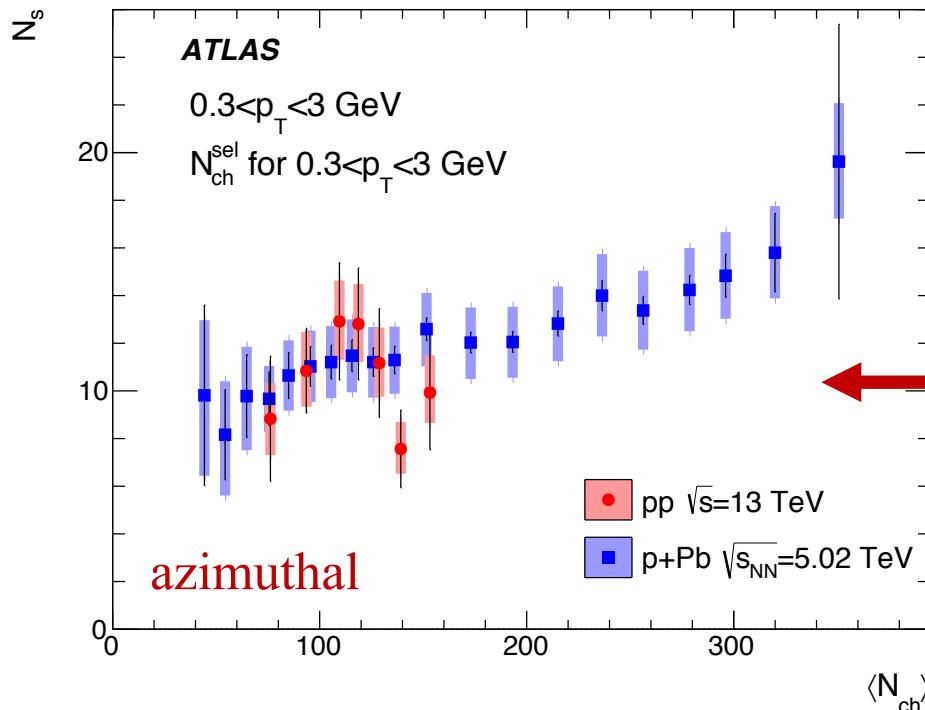


- $v_2\{4\} < v_2\{2\}$  (template fit): flow fluctuation;
- $v_2\{4\} \approx v_2\{2\}$  (peripheral sub.): underestimation of  $v_2\{2\}$ ;
- Subevent cumulant is free of assumptions.

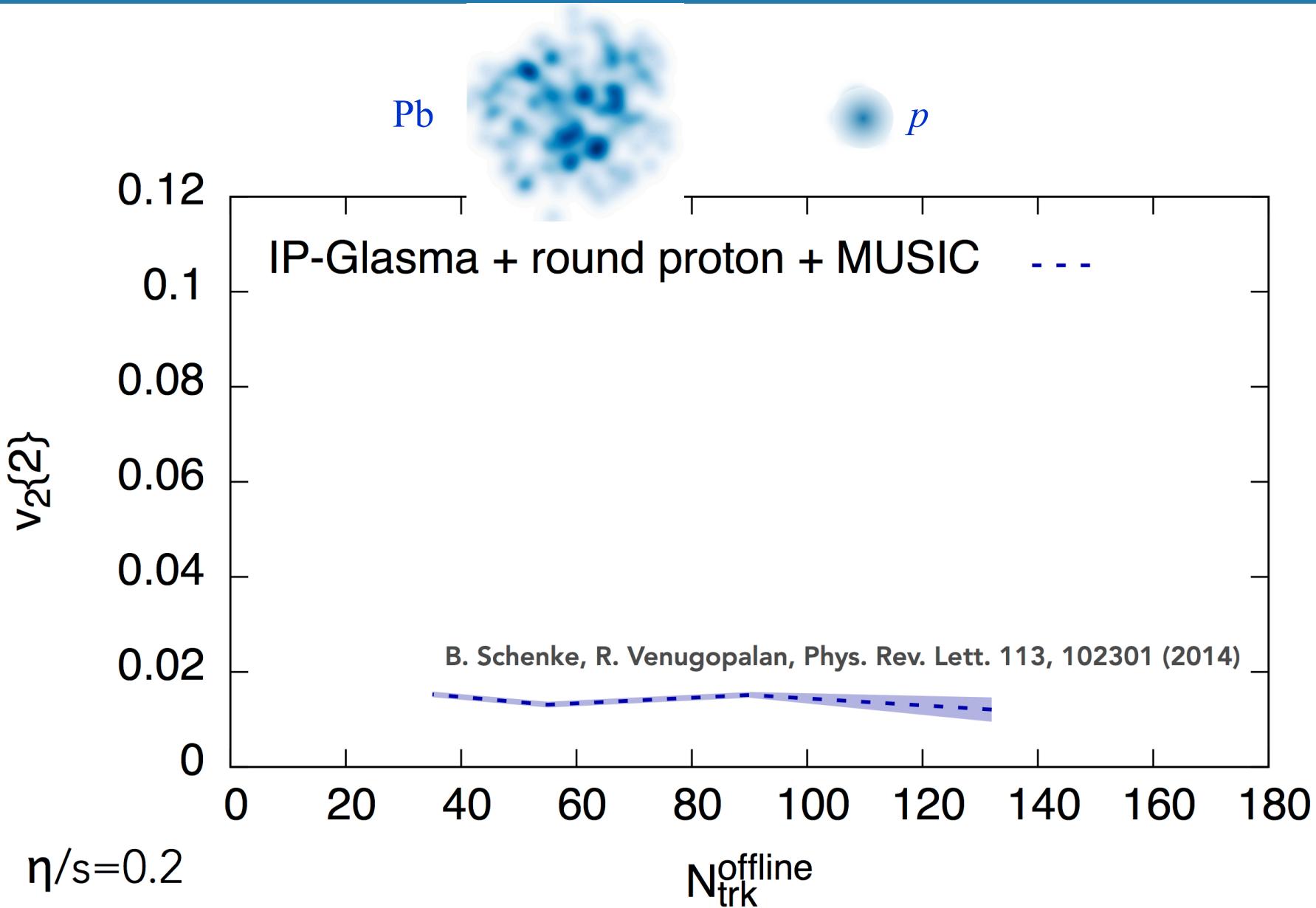
- $\nu_2\{2\} \neq \nu_2\{4\}$ : EbyE flow fluctuations associated with fluctuating initial conditions. [Phys. Rev. Lett. 112, 082301 \(2014\)](#)
- Fluctuation can be quantified to the number of sources  $N_s$  in the initial stage:

$$\frac{\nu_2\{4\}}{\nu_2\{2\}} = \left( \frac{4}{3 + N_s} \right)^{1/4}$$

$$\frac{N(\eta)}{\langle N(\eta) \rangle} \approx 1 + a_1 \eta, \quad a_1 \propto \frac{1}{\sqrt{N_s}}$$



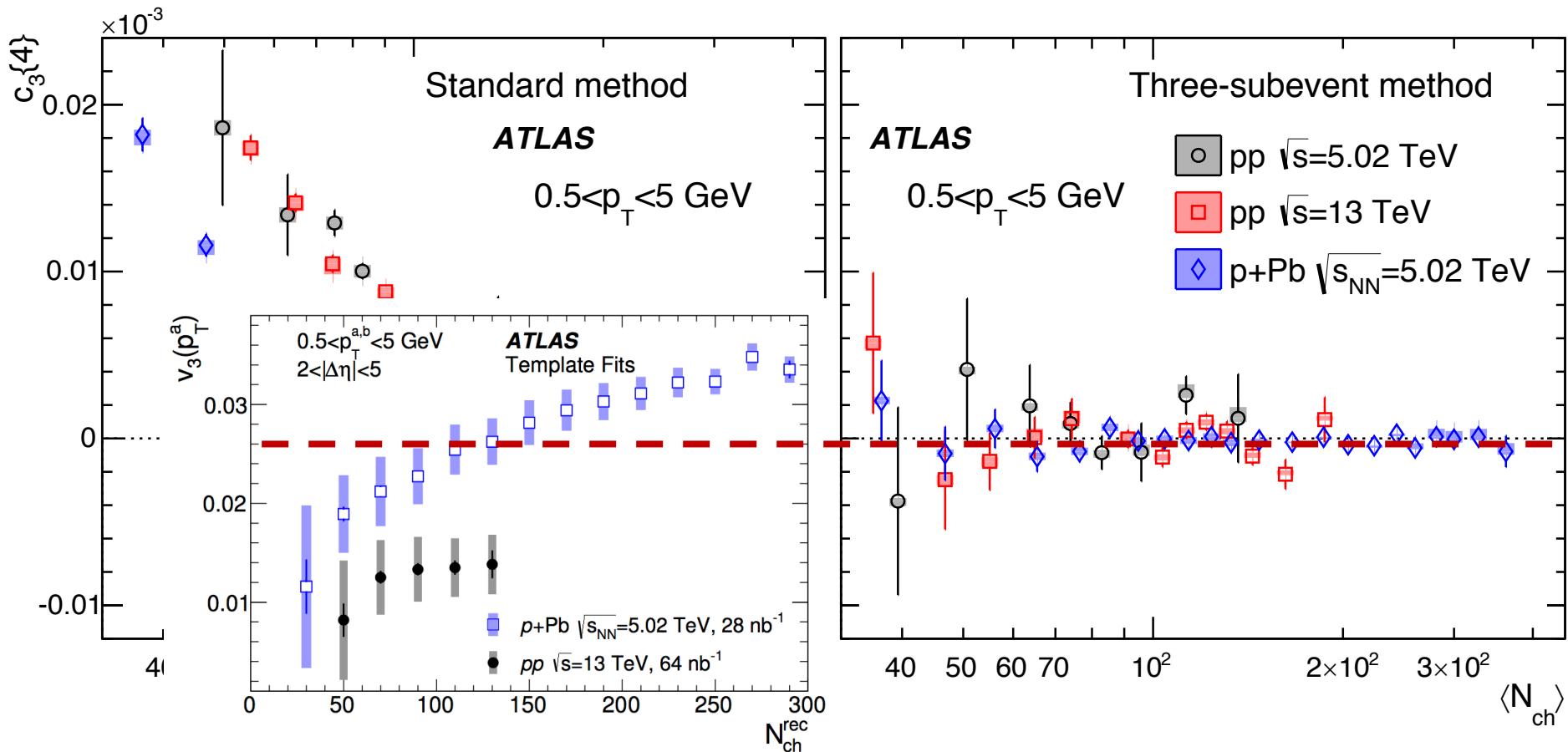
- $N_s$  for  $p+Pb$  goes up to 20 at high multiplicity;
- $N_s$  for  $pp$  approximately consistent with  $p+Pb$  at comparable  $\langle N_{ch} \rangle$  value.



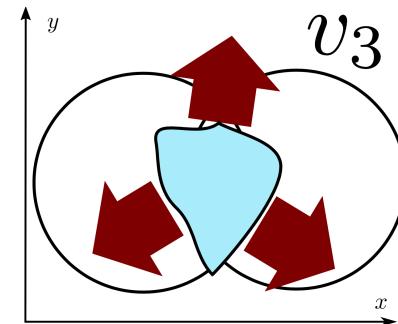


Non-non-flow  $\neq$  Flow!

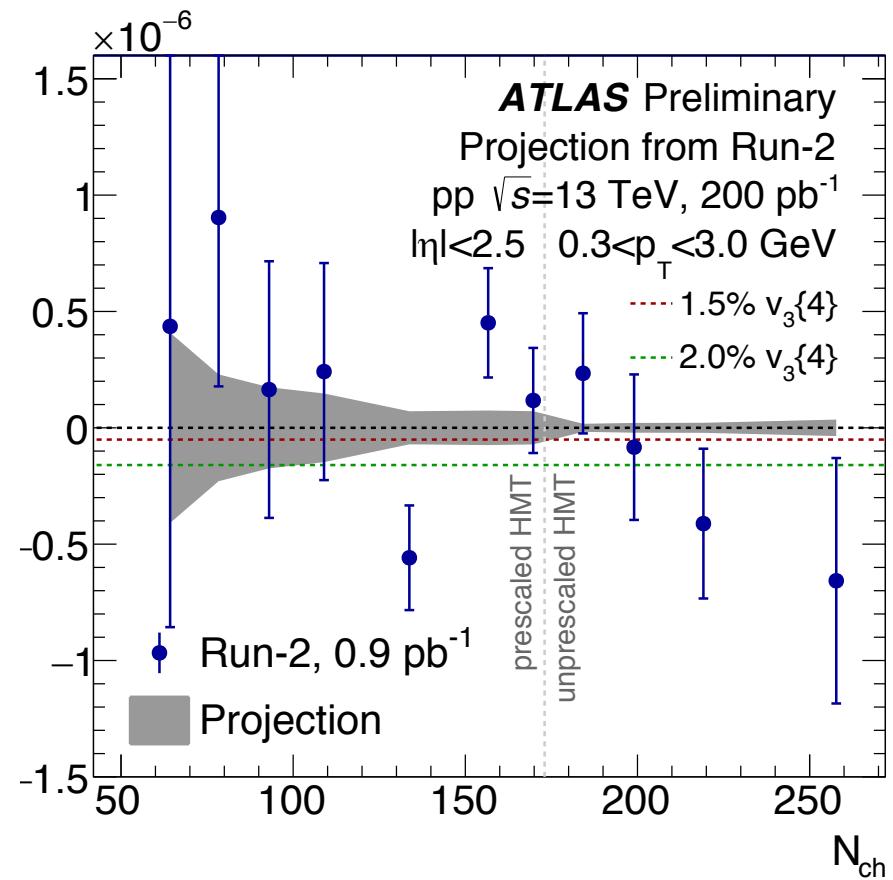
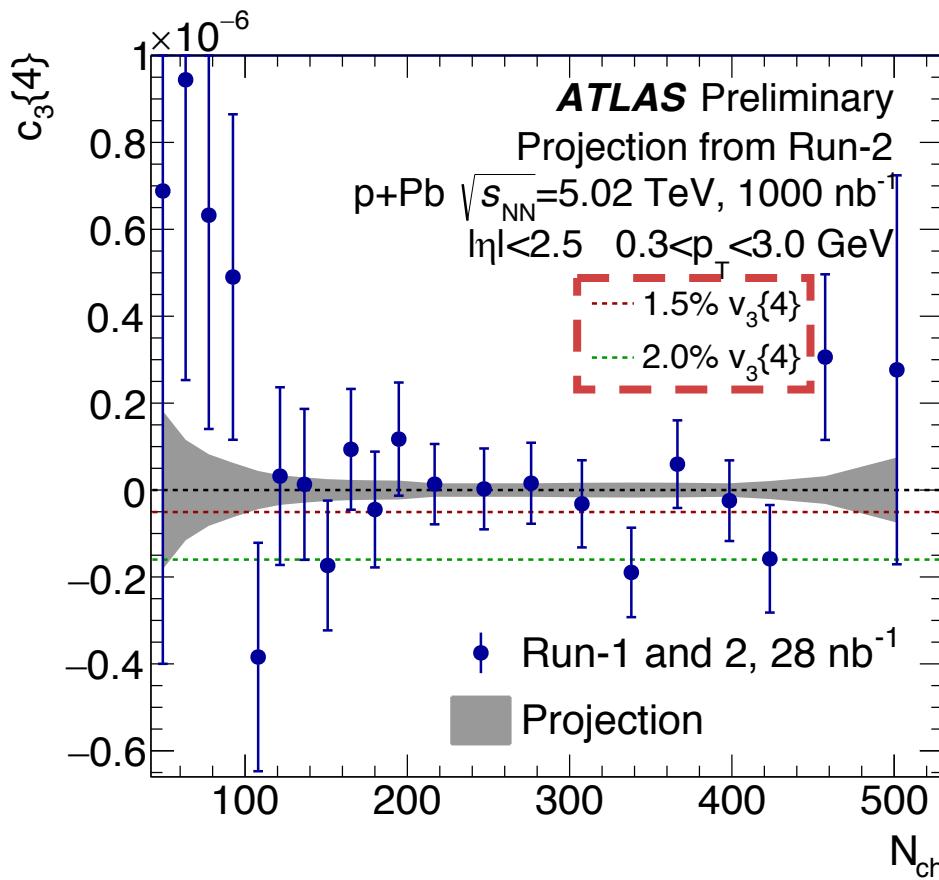
# Third harmonic $v_3$



- $c_3\{4\}$  is consistent with 0
  - $\bar{v}_3 \ll \bar{v}_2$ ?
  - Fluctuation kills  $v_3\{4\}$ ?
  - More statistics needed.



# $v_3$ projected in Run 3



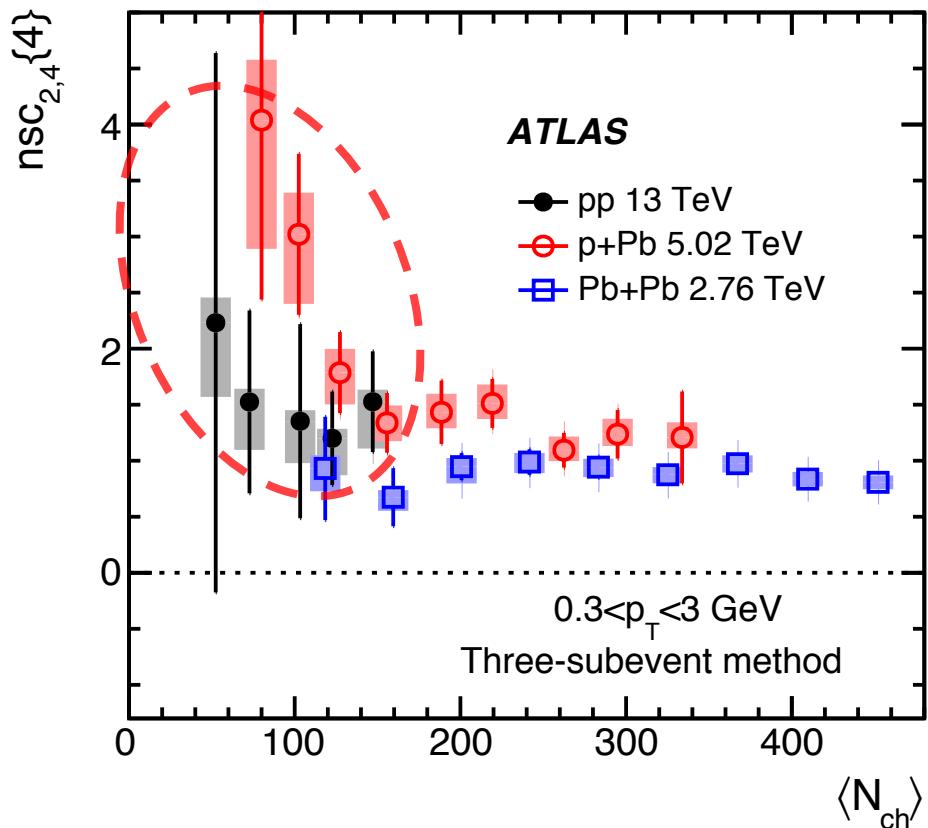
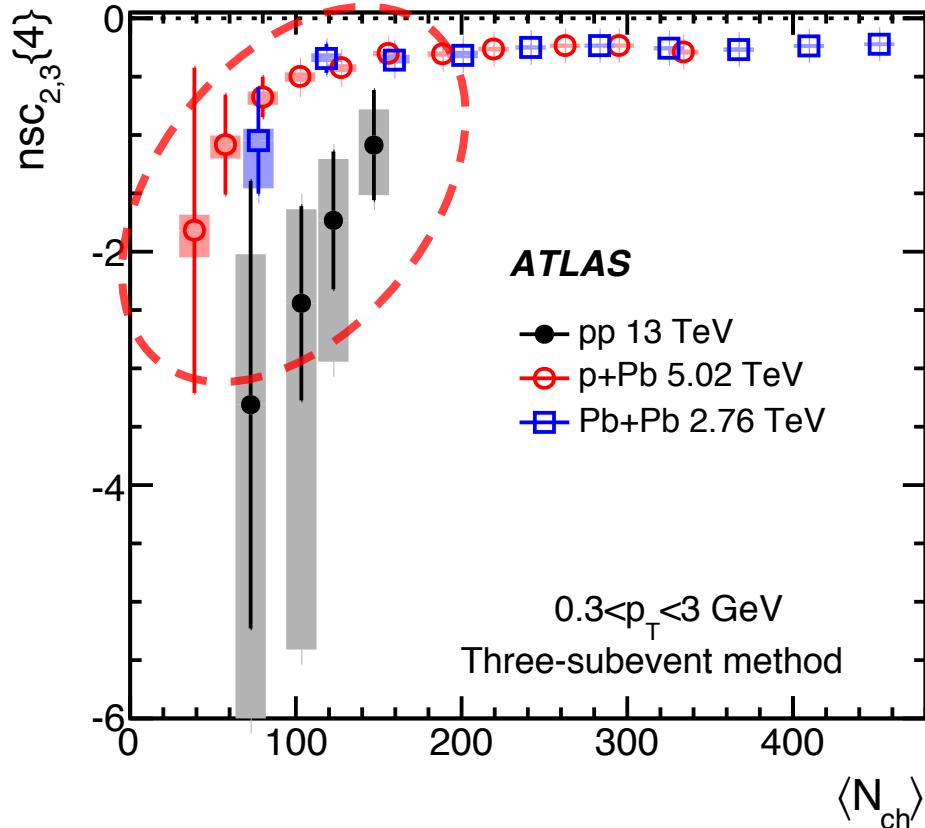
- Opportunity luminosity increase in Run 3;
- Challenges trigger, pileup, tracking...

# Correlation between $v_n$ and $v_m$

40

$$nsC_{n,m}\{4\} = \frac{\langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle}{\langle v_n^2 \rangle \langle v_m^2 \rangle}$$

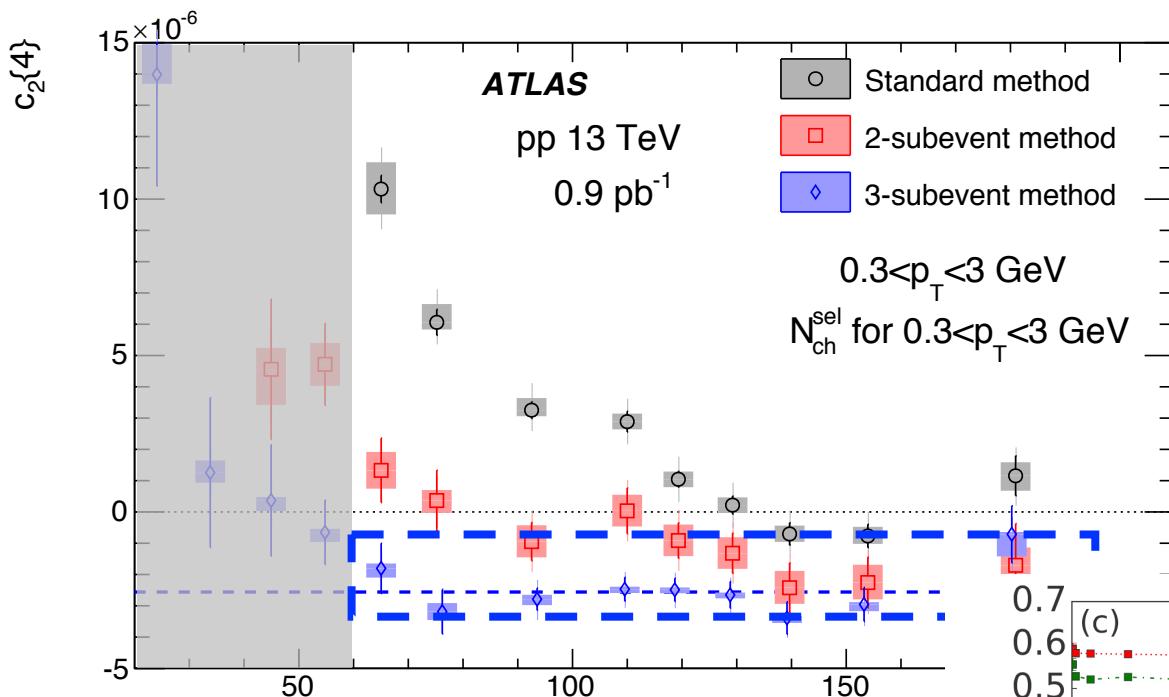
[Phys. Lett. B 789 \(2019\) 444](#)



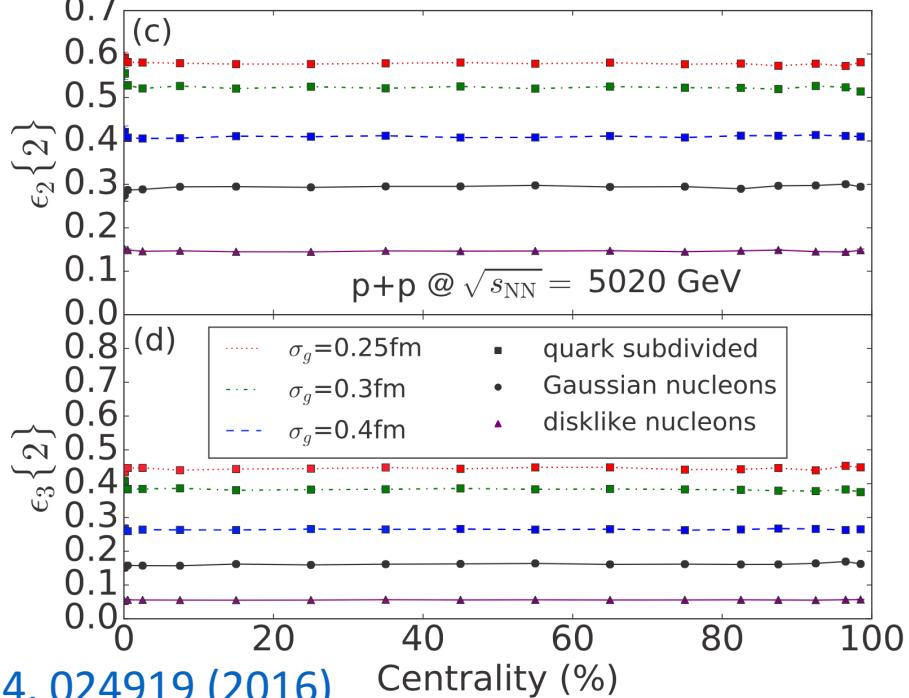
- Same sign, different magnitudes across systems;
- Independent constraints on models.

# Last puzzle: $N_{ch}$ dependence

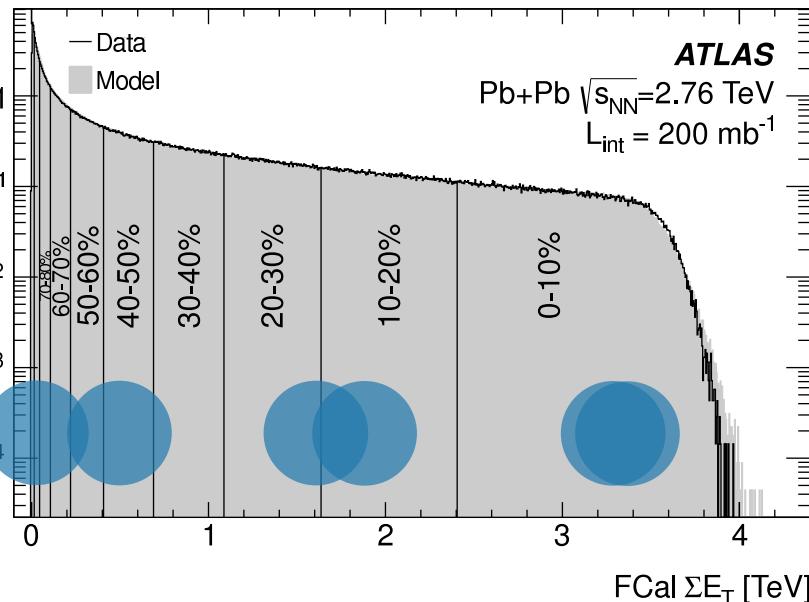
41



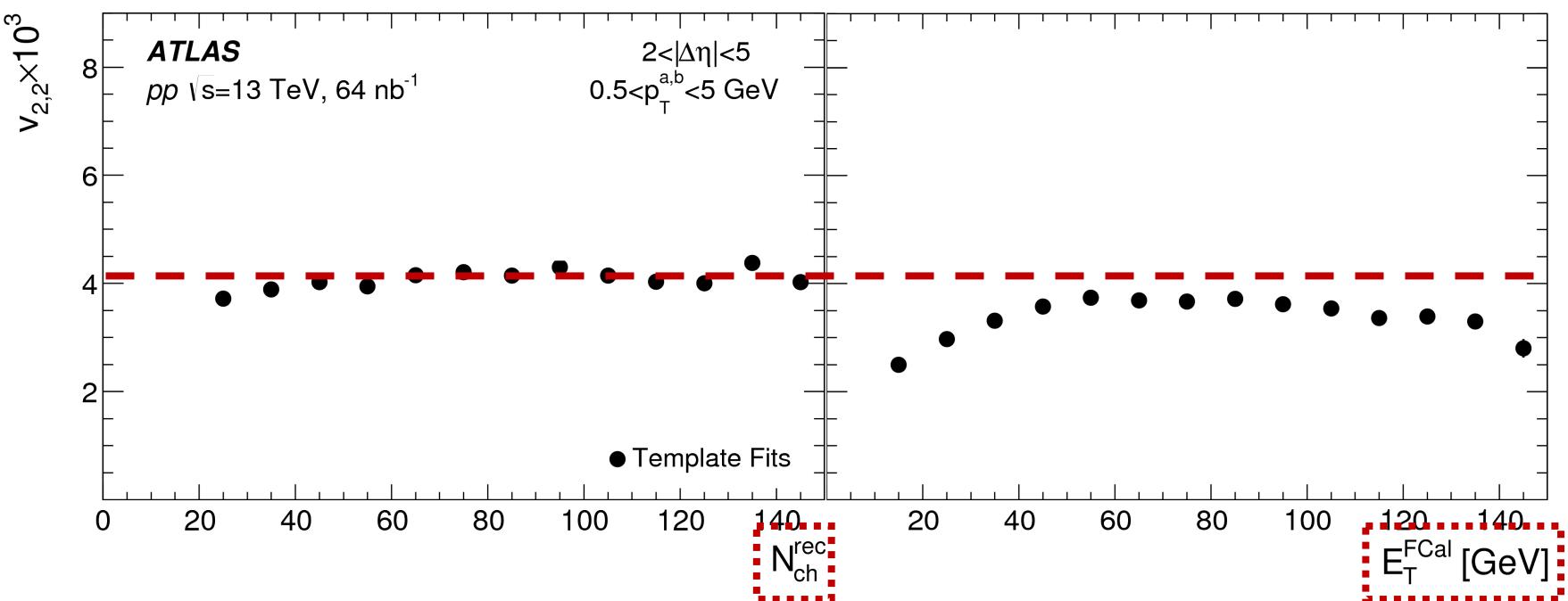
- Weak independence of  $N_{ch}$ ;
- Similar observation in model
  - No “geometry” in  $pp$ ?
  - $N_{ch}$  not a good indicator for centrality?



# Centrality fluctuation



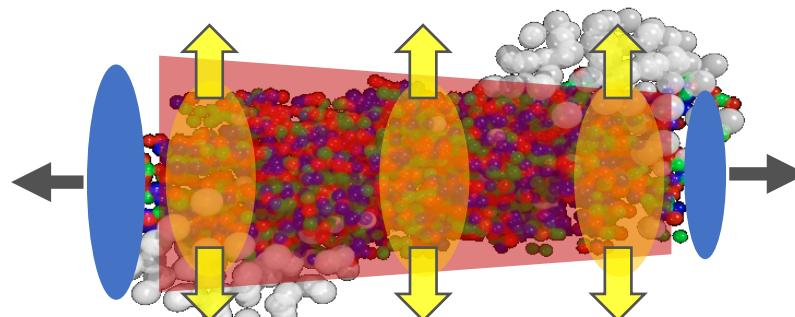
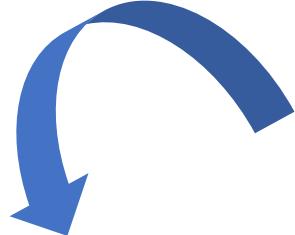
- Centrality quantifies the overlap region of the collision;
- The mapping replies on model and is on the average level;
- Different centrality definitions gives different dependence.



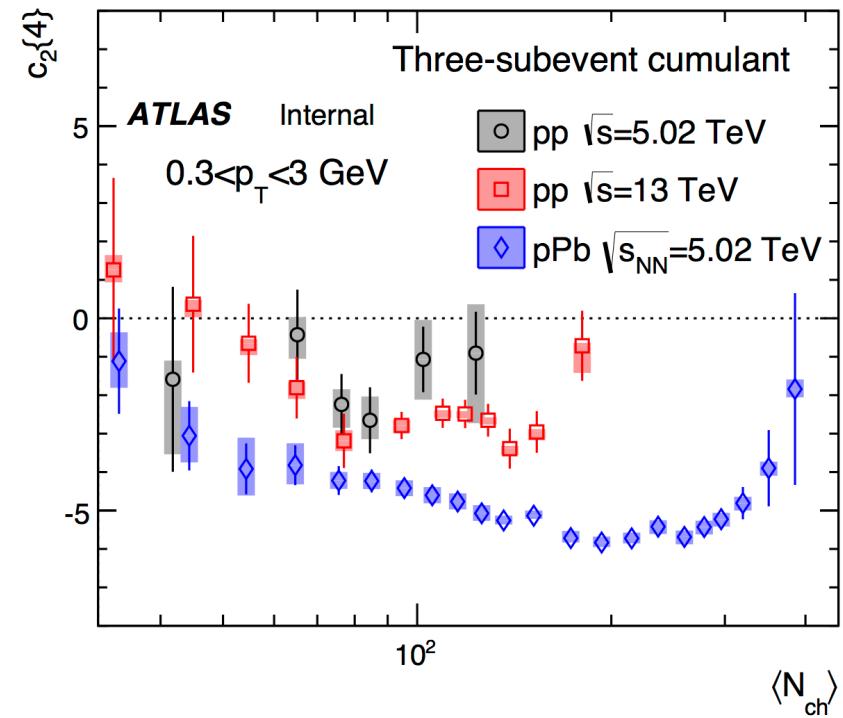
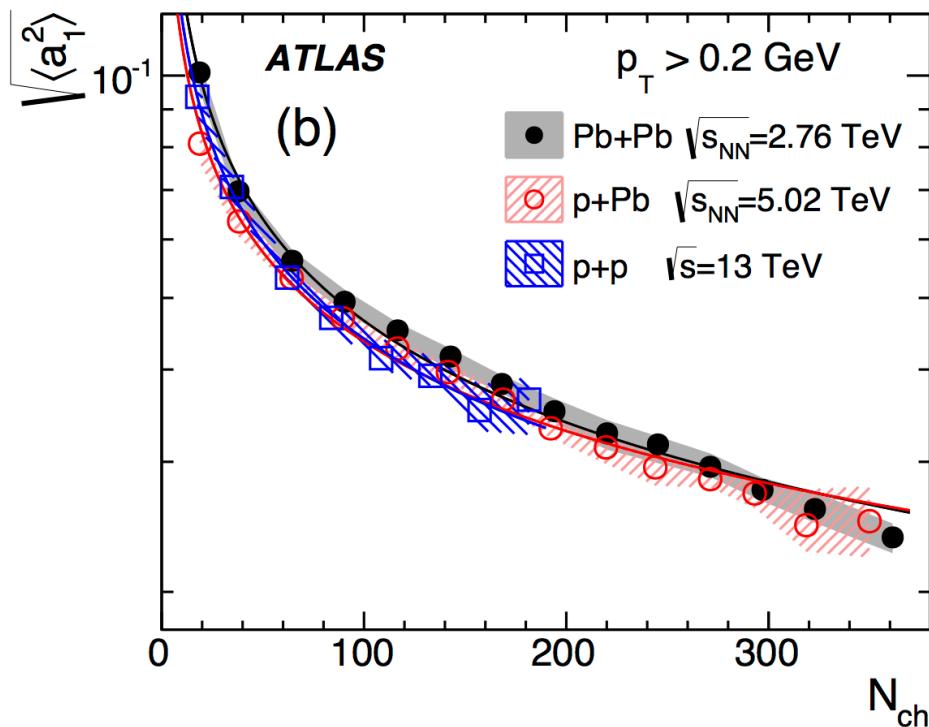
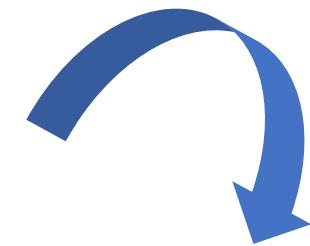
# Summary

Nature of sources seeding the long-range collective behavior?

Longitudinal correlation



Azimuthal correlation



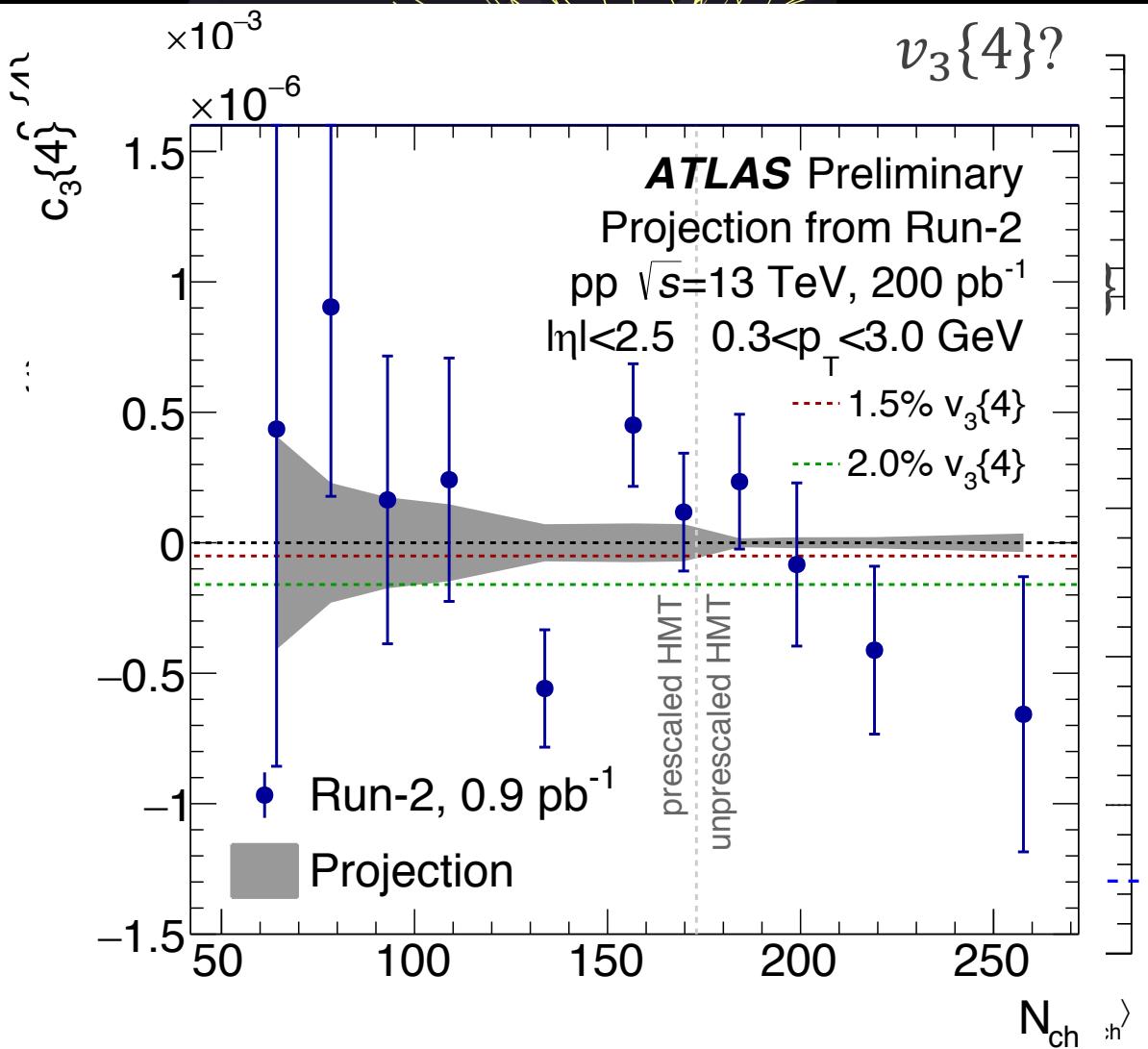
Evidence of collectivity in small systems!

# Summary

pp  $\sqrt{s} = 7$  TeV,  $N \geq 110$

$2 < p_T^{\text{trig}} < 3$  GeV/c

CMS Preliminary



**Hypothesis**  
Collectivity in  $pp$ ?

**Data Gather**  
Real-time selection

**Data Analysis**  
Large background

**New Algorithm**  
 $3 > 2$

**Conclusion**  
Collectivity in  $pp$ !

**Outlook**  
Other observables

## Backup

- Forward-backward multiplicity correlation;
- Flow and centrality fluctuation;
- Novel collision system Xe+Xe.

# **Forward-backward multiplicity fluctuation**

- Rapidity correlations is an old story



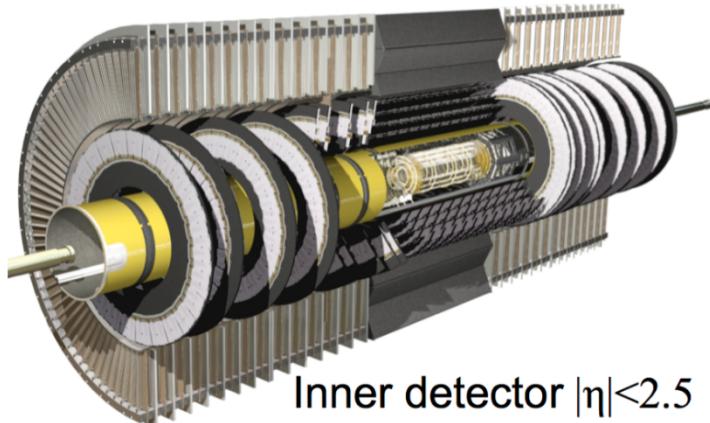
- Physics goal: understand production mechanism in early stage.

- More details see the thesis.

- Why we come back to this analysis?

- Previous methods focused on limited phase space:  $\eta$  and  $-\eta$ ;
  - We used a new observable that covers full  $\eta$  space;
  - Short-range correlation and statistical dilution;
  - We estimated short-range correlation;
  - Few direct comparisons among different systems;
  - We compared from large to small systems.

- Correlation functions calculated using charged particles  $p_T > 0.2$  GeV;
- High-multiplicity track (HMT) trigger used to increase statistics;

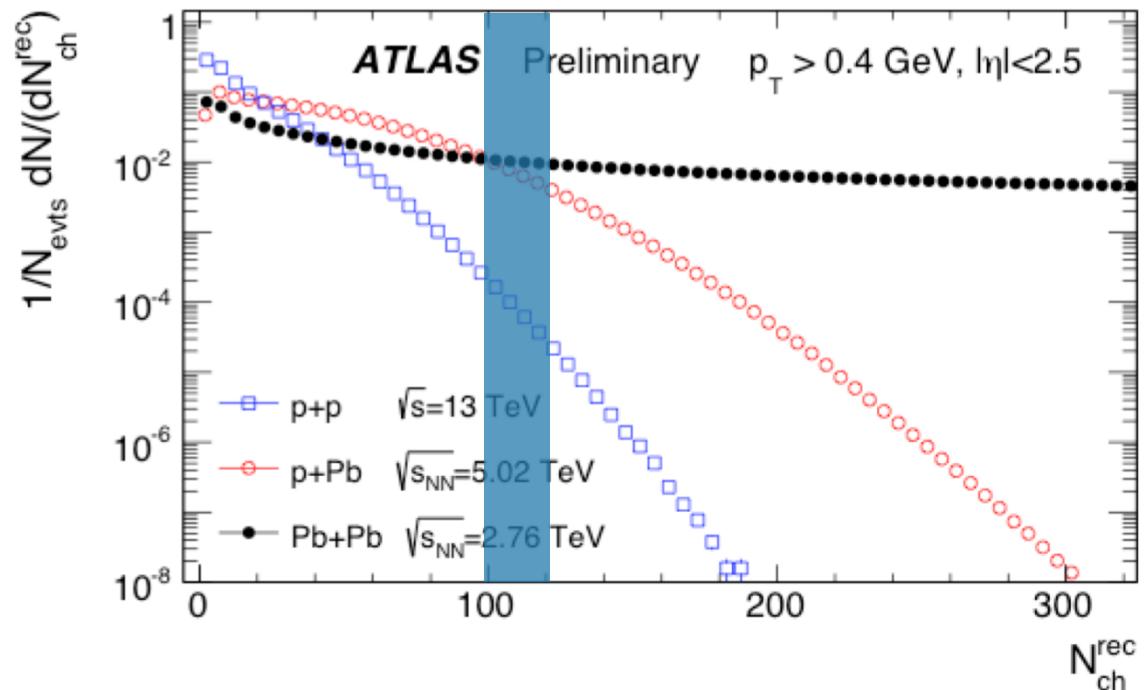


Inner detector  $|\eta| < 2.5$

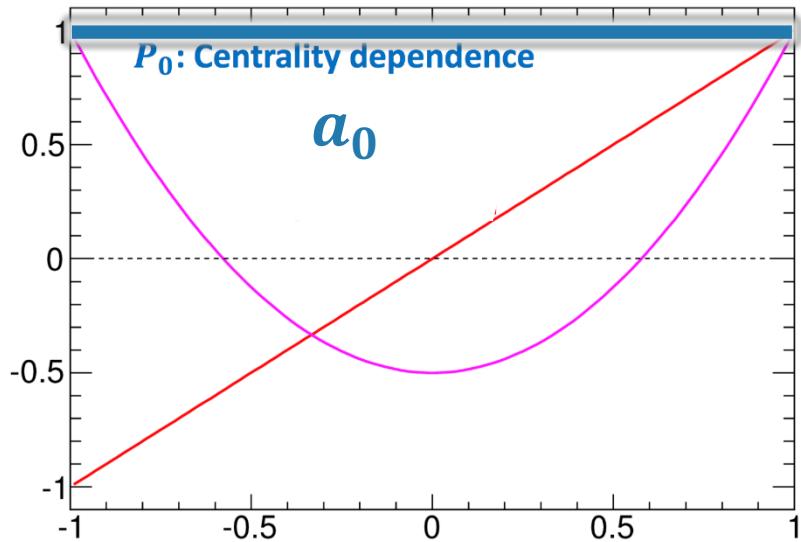
Pb+Pb 2.76 TeV, 2010, MB

$p$ +Pb 5.02 TeV, 2013, MB+HMT

$p$ + $p$  13 TeV, 2015, MB+HMT

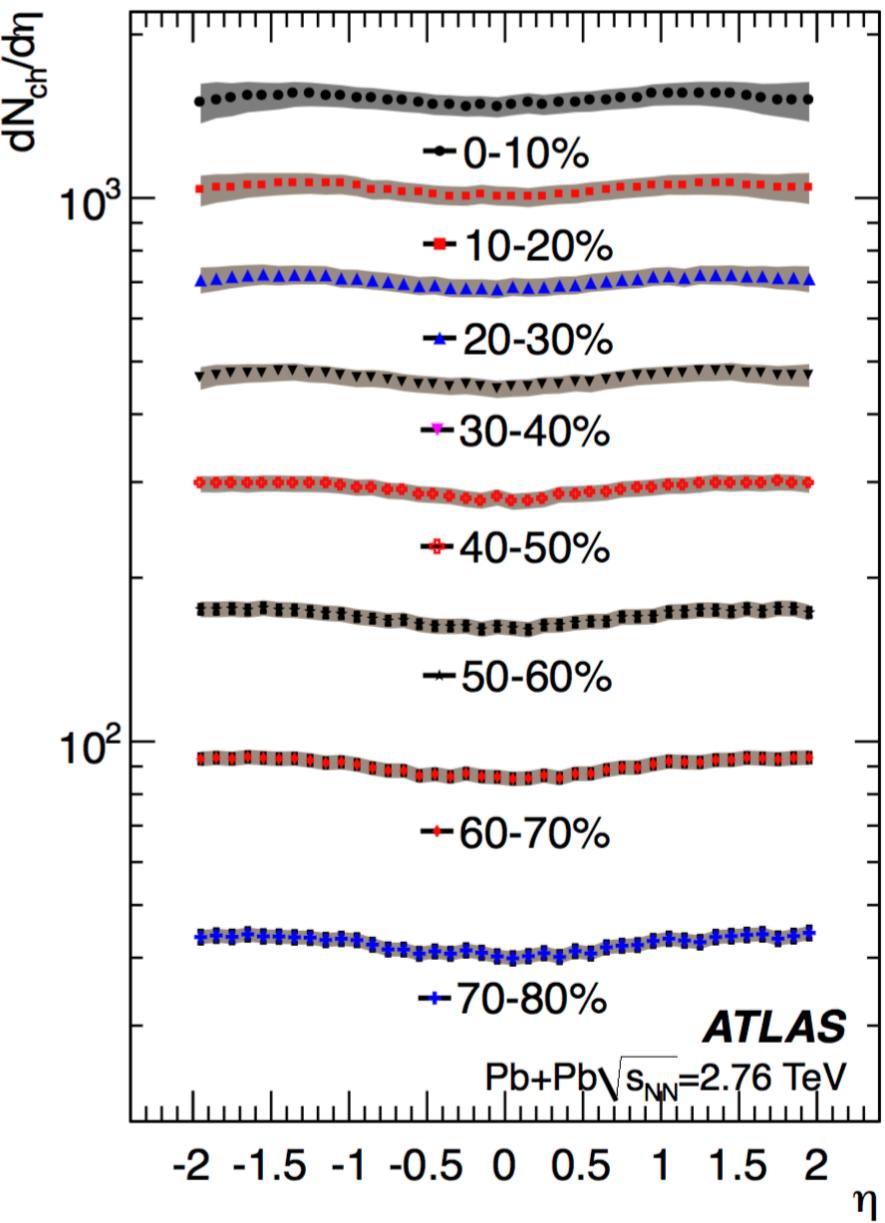


- Analysis carried out in many bins over  $10 \leq N_{ch}^{rec} < 300$ ;
- Results presented as a function efficiency-corrected values  $N_{ch}$ .
  - How long-range correlation compare among three systems, at the same  $N_{ch}$ ?



- Analysis focuses on dynamical fluctuation upon average;
- However, average multiplicity changes with centrality;
- The residual centrality dependence is removed by normalizing  $C(\eta_1, \eta_2)$

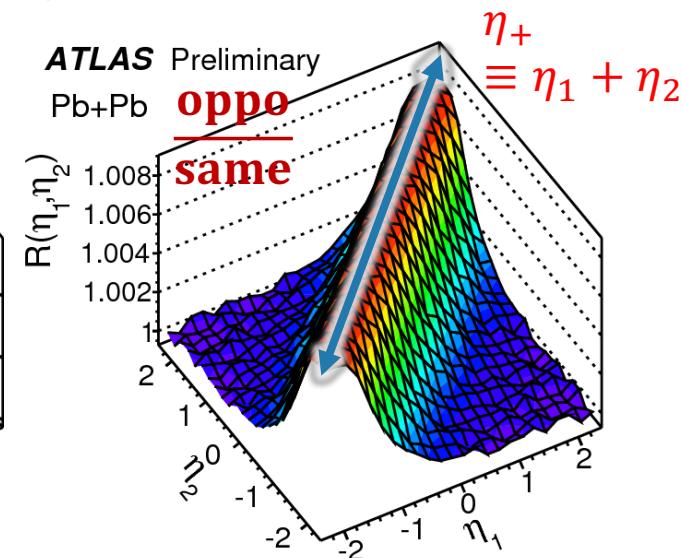
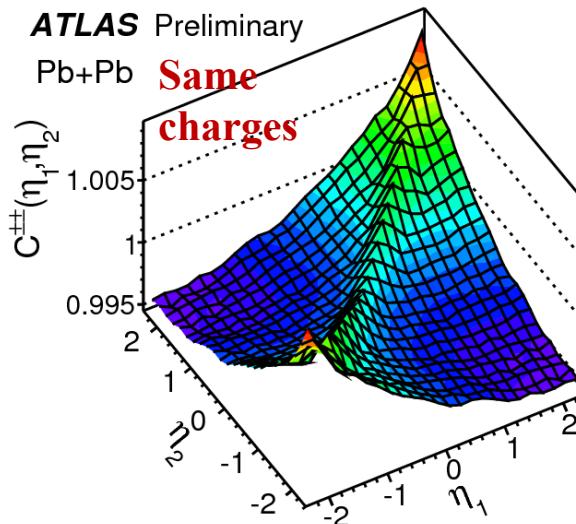
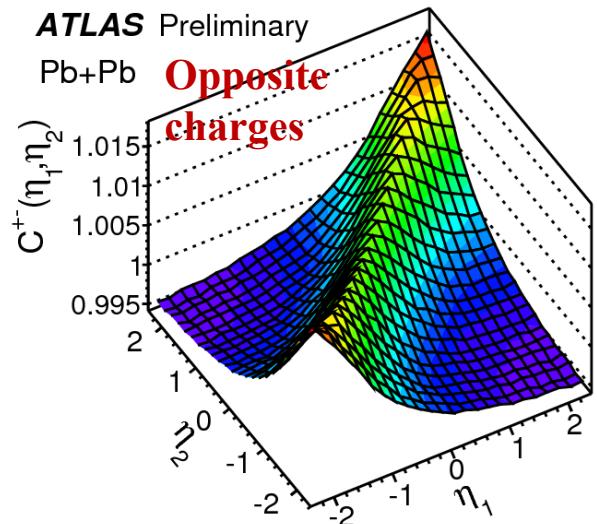
$$C_N(\eta_1, \eta_2) = \frac{C(\eta_1, \eta_2)}{C_p(\eta_1)C_p(\eta_2)}$$



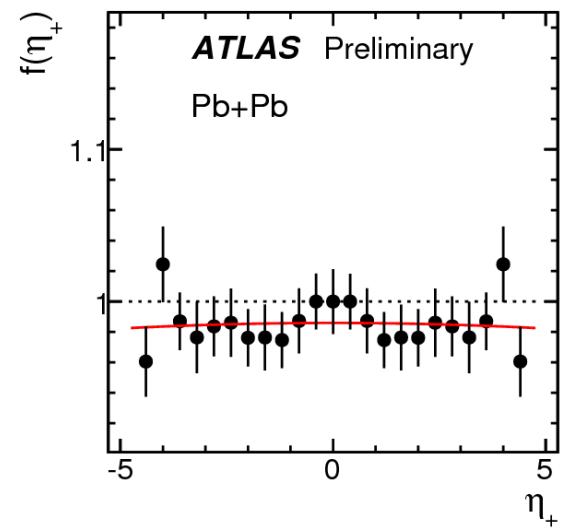
# Charge dependence of $C(\eta_1, \eta_2)$

50

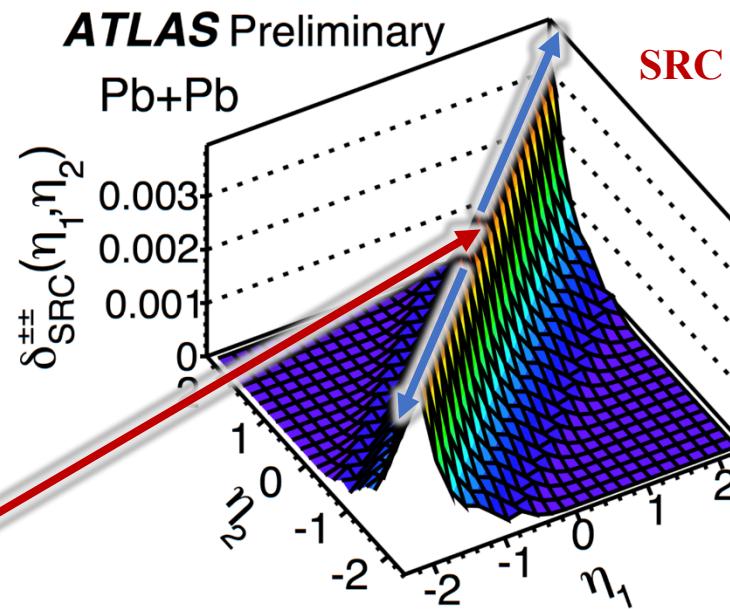
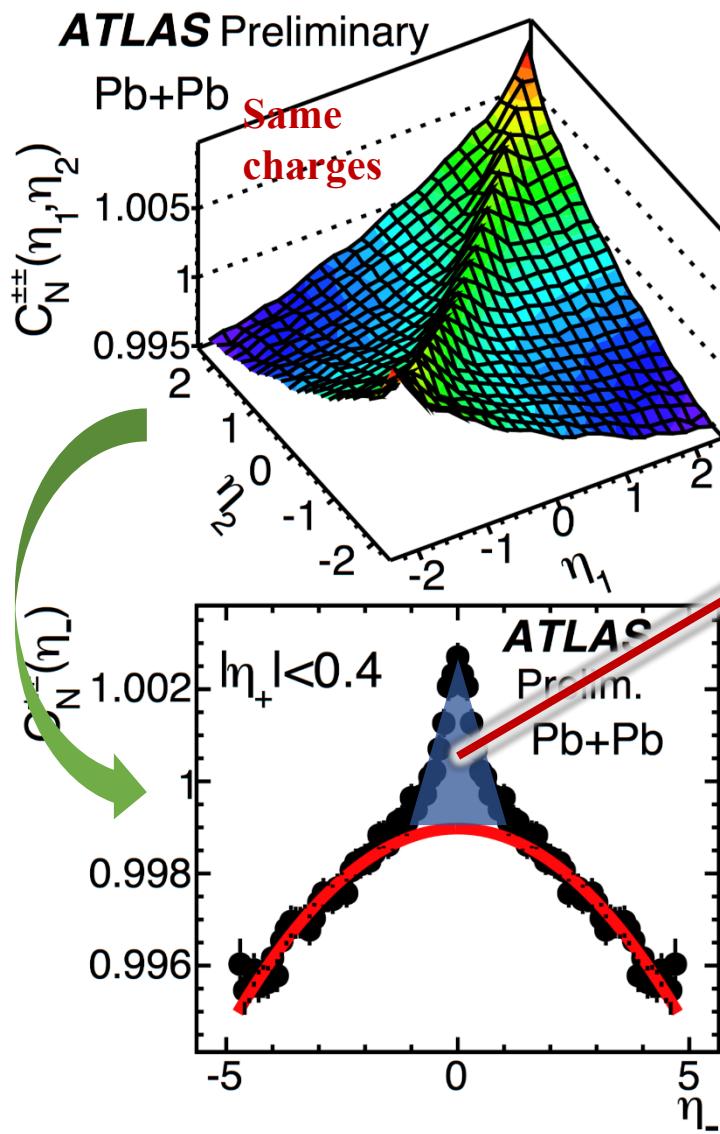
- Particles from the same source (SRC) have strong charge dependence.



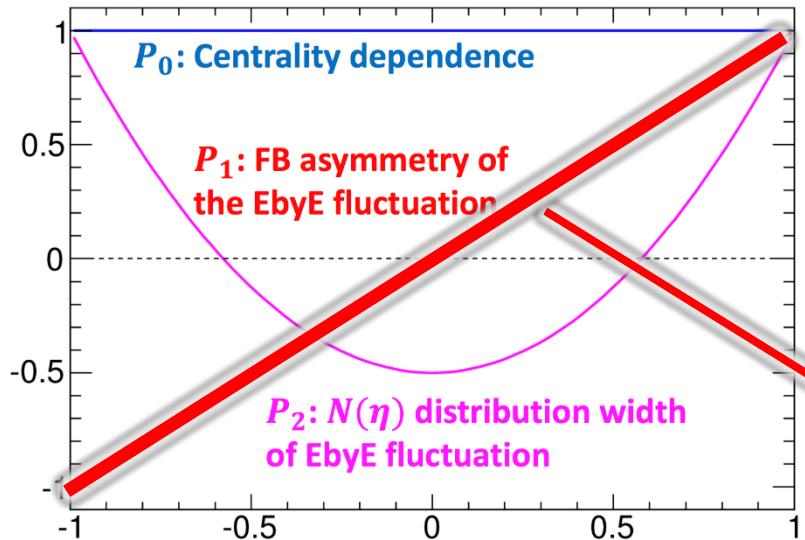
- Ratio of opposite to same charges  $R(\eta_1, \eta_2)$ 
  - Very strong Gaussian-like SRC;
  - Very weak LRC: charge-independent;
- Amplitude of  $R(\eta_1, \eta_2)$  along  $\eta_+$ :  $f(\eta_+)$ , reflects the strength of SRC in the longitudinal direction;
- Assumption: strength of SRC along  $\eta_+$  is same for same charge and opposite charge.



- To estimate SRC, LRC pedestal is estimated first.

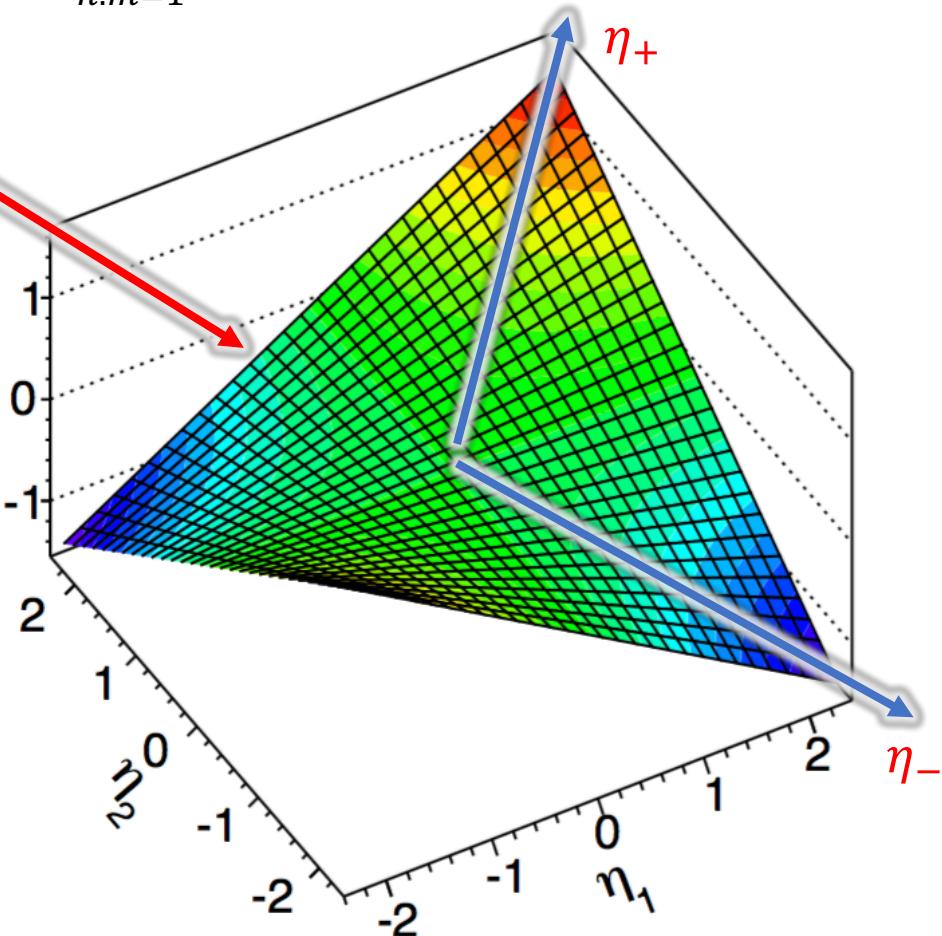


- $C(\eta_1, \eta_2)$  from same charge used to estimate LRC pedestal because of small SRC;
- LRC pedestal is fitted with quadratic function;
- The additional structure upon LRC pedestal determines the shape of SRC;
- The full  $\delta_{SRC}(\eta_1, \eta_2)$  is then populated using  $f(\eta_+)$  scaling.



- Expansion of correlation function  $C_N(\eta_1, \eta_2)$

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



- If linear shape dominates:

$$C_N(\eta_1, \eta_2) = 1 + \langle a_1^2 \rangle \eta_1 \eta_2$$

- Expressed as  $\eta_+$  and  $\eta_-$ :

$$C_N(\eta_1, \eta_2) = 1 + \frac{\langle a_1^2 \rangle}{4} (\eta_+^2 - \eta_-^2)$$

# Results: correlation function

53

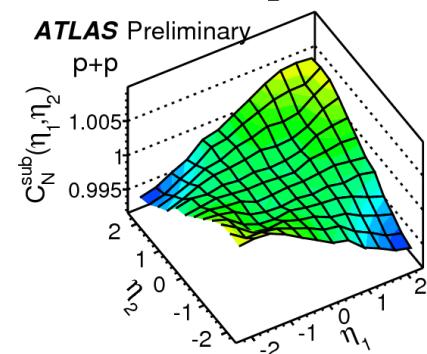
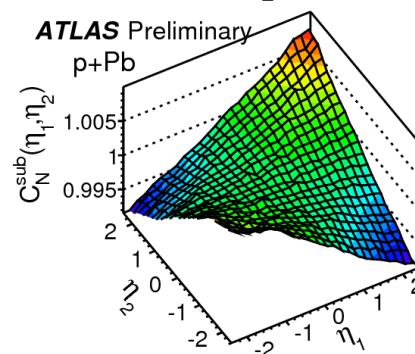
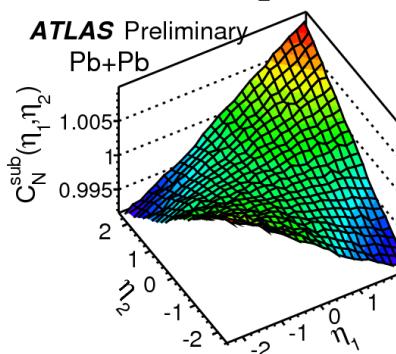
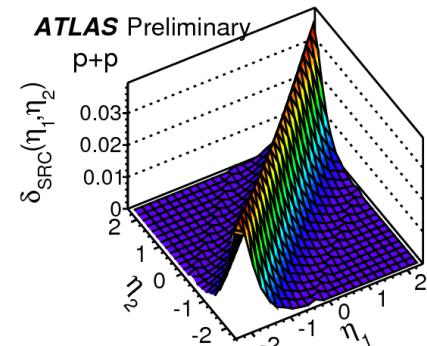
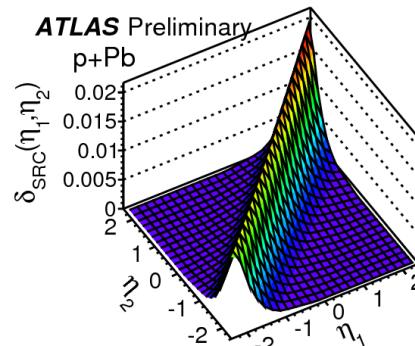
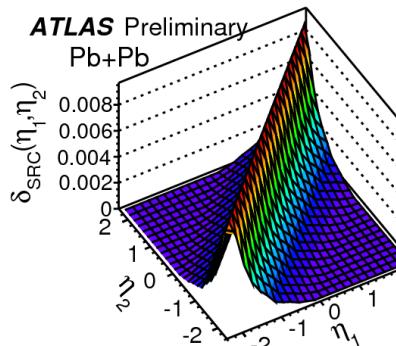
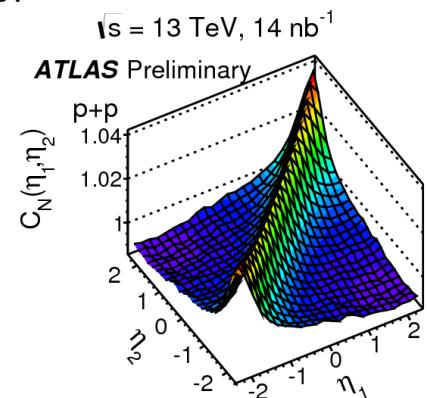
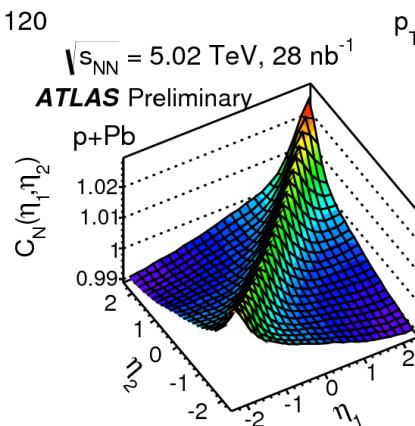
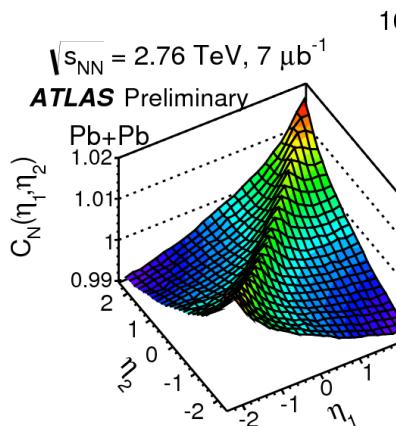
Raw  
 $C_N(\eta_1, \eta_2)$

||

Short-range  
 $\delta_{SRC}(\eta_1, \eta_2)$

+

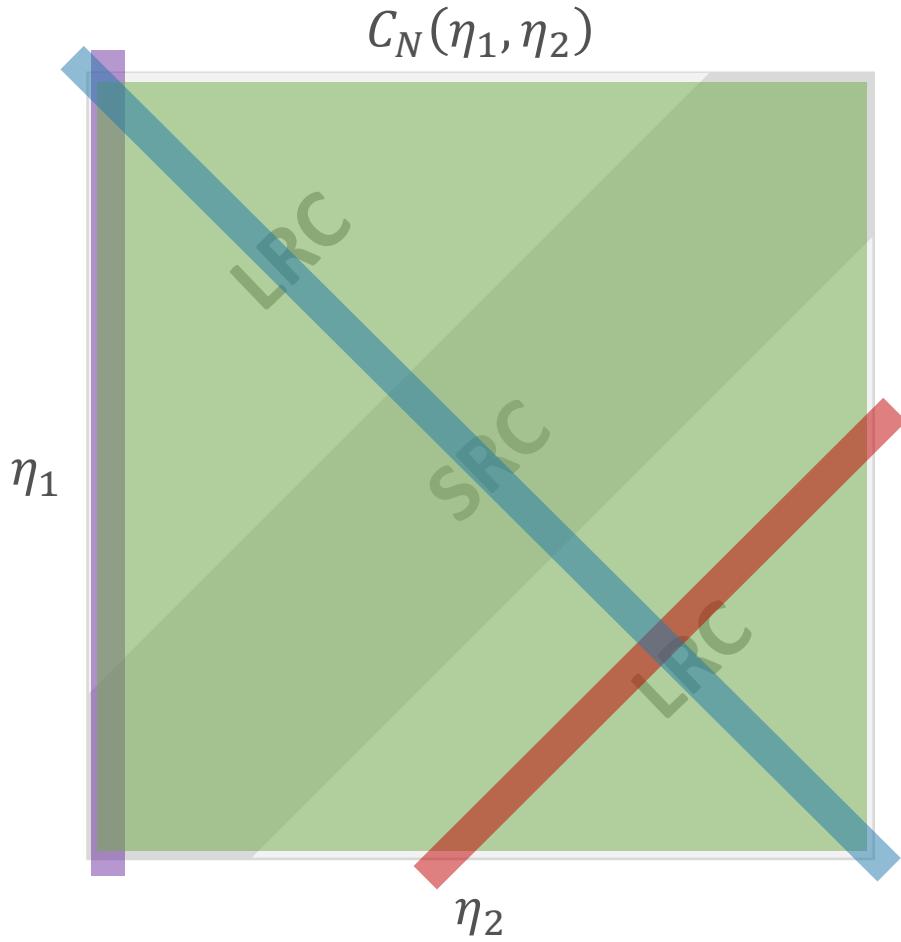
Long-range  
 $C_N^{sub}(\eta_1, \eta_2)$



Pb+Pb

p+Pb

pp



- Four methods have different responses of the analysis procedures, and are largely independent.

- Expansion of  $C_N^{sub}(\eta_1, \eta_2)$

$$C_N^{sub}(\eta_1, \eta_2) = 1 + \langle a_1^2 \rangle \eta_1 \eta_2$$

- Quadratic fit along  $C_N^{sub}(\eta_-)$

$$C_N^{sub}(\eta_-) = 1 + \frac{\langle a_1^2 \rangle}{4} (\eta_+^2 - \eta_-^2)$$

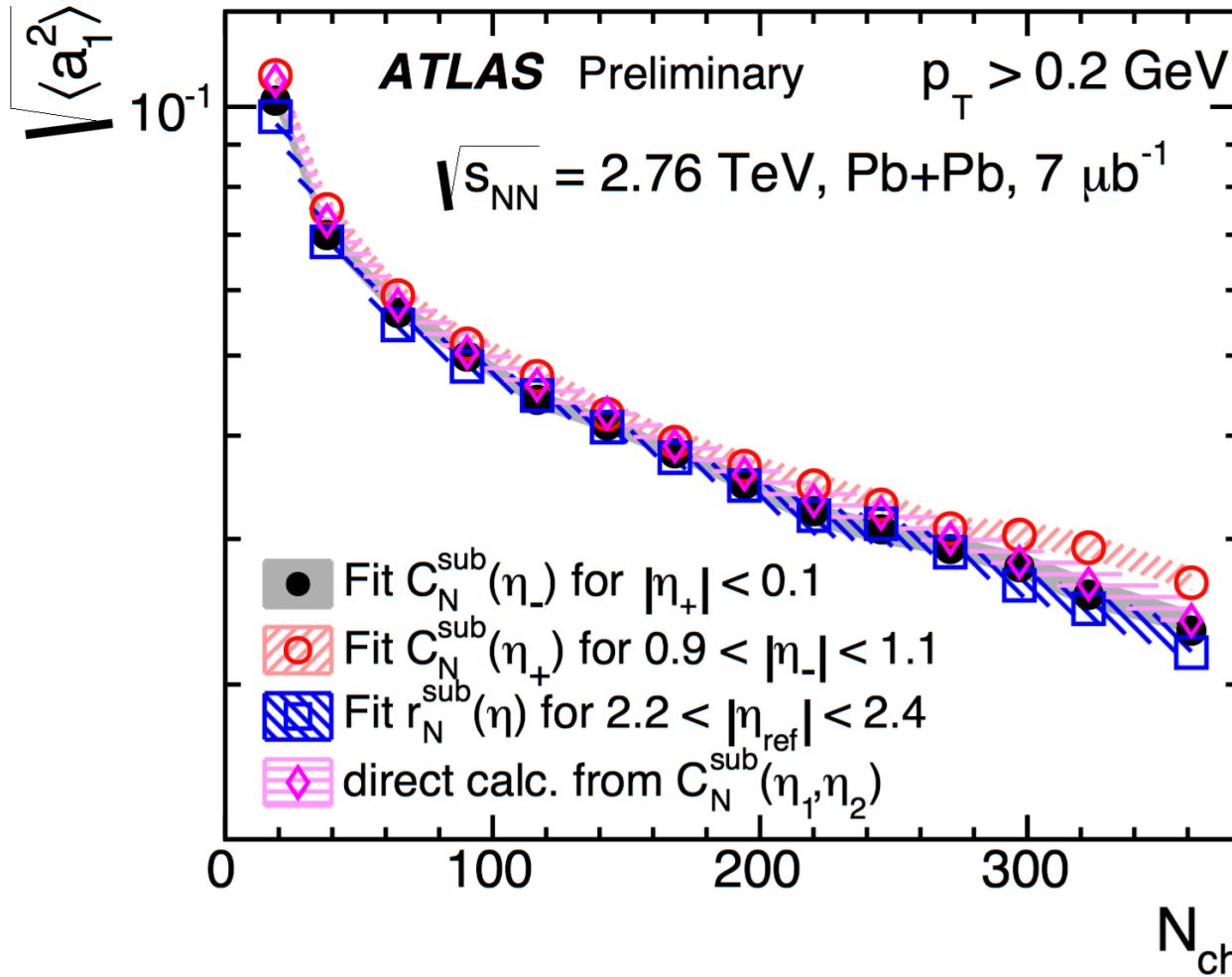
- Quadratic fit along  $C_N^{sub}(\eta_+)$

$$C_N^{sub}(\eta_+) = 1 + \frac{\langle a_1^2 \rangle}{4} (\eta_+^2 - \eta_-^2)$$

- Linear fit of  $r_N^{sub}(\eta, \eta_{ref}) \equiv \frac{C_N^{sub}(-\eta, \eta_{ref})}{C_N^{sub}(\eta, \eta_{ref})}$

$$r_N^{sub}(\eta, \eta_{ref}) = 1 - 2\langle a_1^2 \rangle \eta \eta_{ref}$$

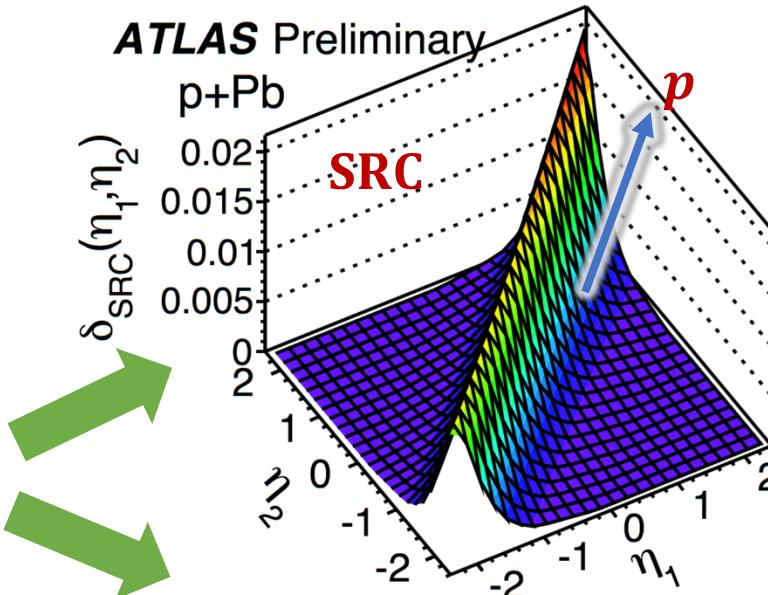
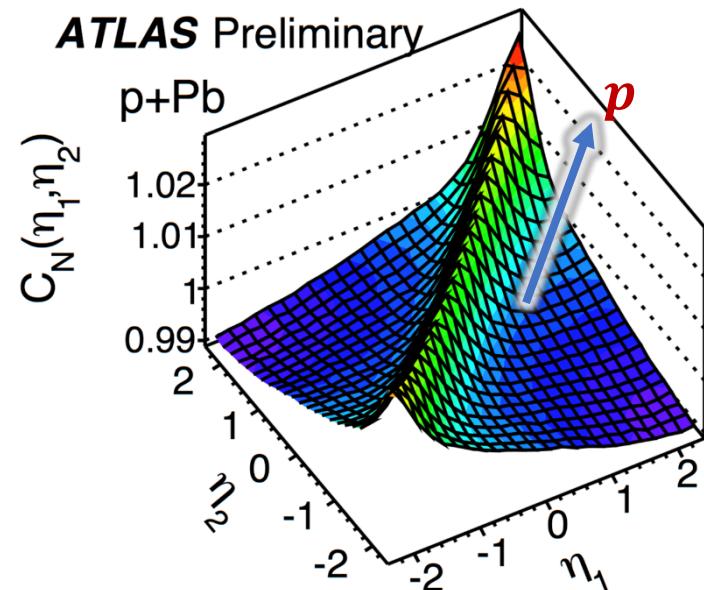
- Four largely independent methods are applied to determine  $\langle a_1^2 \rangle$ ;
- Different methods have different sensitivity to the analysis procedures;



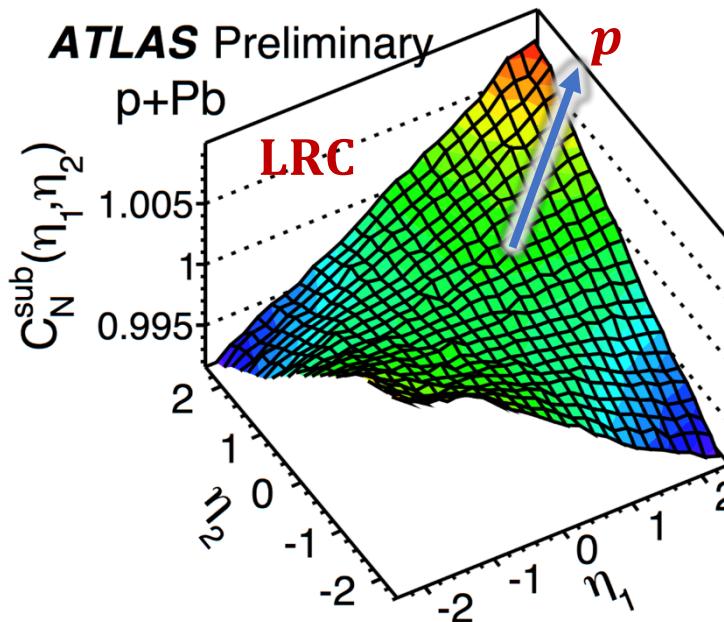
- Four methods give consistent  $a_1$ : conclusions are insensitive to the procedure.

# Asymmetry in $p+Pb$ collision

56

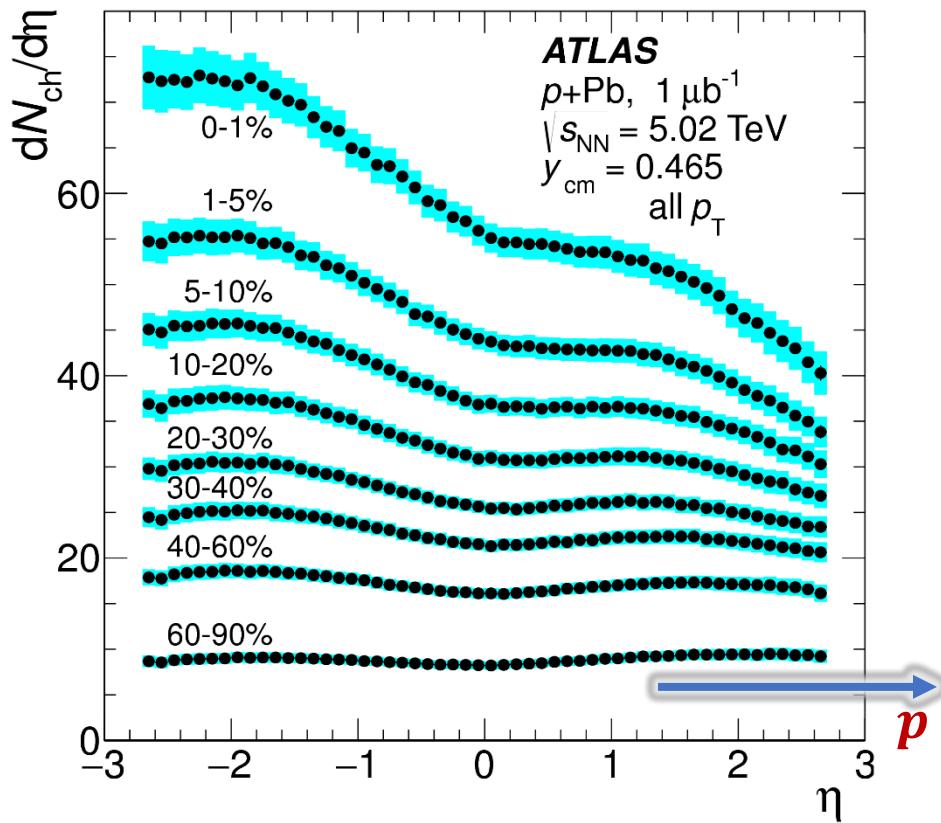
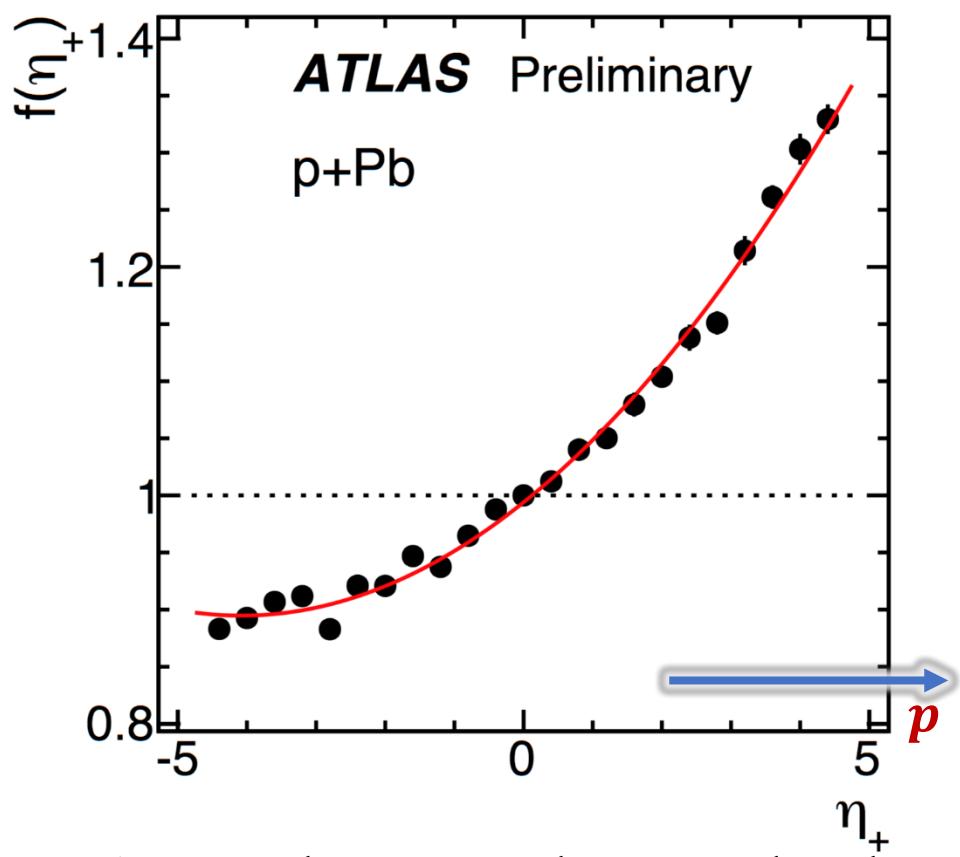


- Asymmetry entirely due to SRC!



- LRC is symmetric.

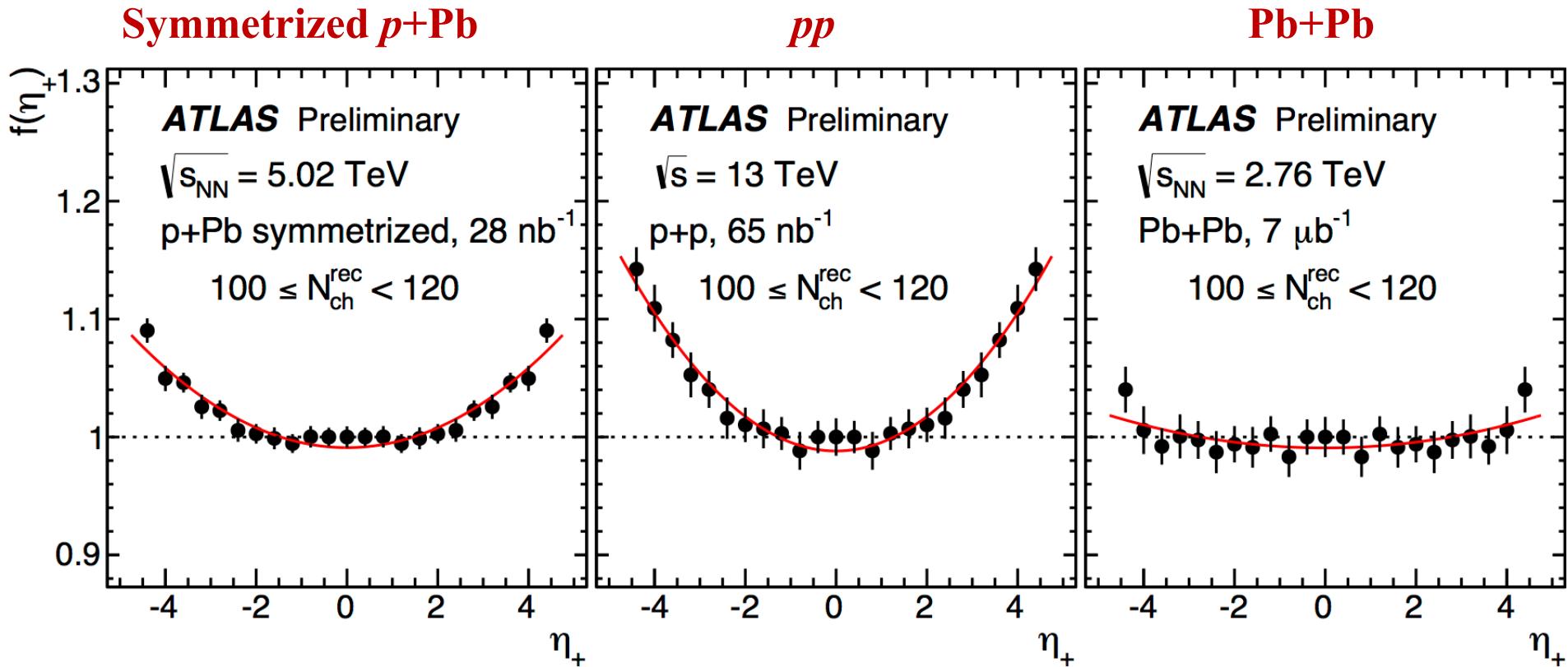
- Asymmetry observed in  $p+Pb$  collision: stronger correlation in the proton-going side.
- Why the asymmetric collision causes asymmetric SRC?



- Assume there are  $n$  clusters and each one emits  $m$  particles on average;
- Assume  $n$  is proportional to local particle density  $dN_{ch}/d\eta$ ;

$$\delta_{SRC} \propto \frac{n \langle m(m-1) \rangle}{(n \langle m \rangle)^2} = \frac{1}{n} \propto \frac{1}{dN_{ch}/d\eta}$$

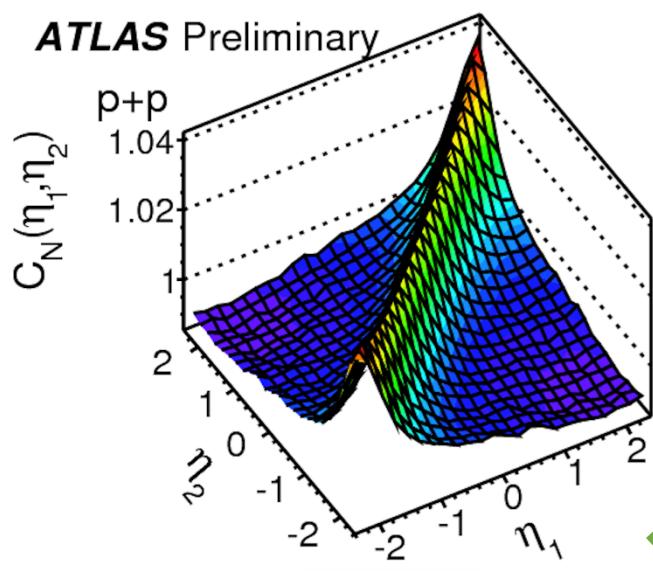
Inverse to multiplicity distribution



- For better comparison with  $pp$  and  $\text{Pb}+\text{Pb}$ ,  $p+\text{Pb}$  is symmetrized;
- In high-multiplicity  $pp$ , SRC shape is slightly larger than  $p+\text{Pb}$ ;
- However in  $\text{Pb}+\text{Pb}$ , SRC shape is more flat.
- EbyE asymmetry of multiplicity (relative to average multiplicity) in high-multiplicity  $pp$  is larger than  $p+\text{Pb}$  while  $\text{Pb}+\text{Pb}$  collision is more symmetric.

# Outlook

**ATLAS** Preliminary



- $C(\eta_1, \eta_2)$  is a very comprehensive observable.

- Reconstruct balance function

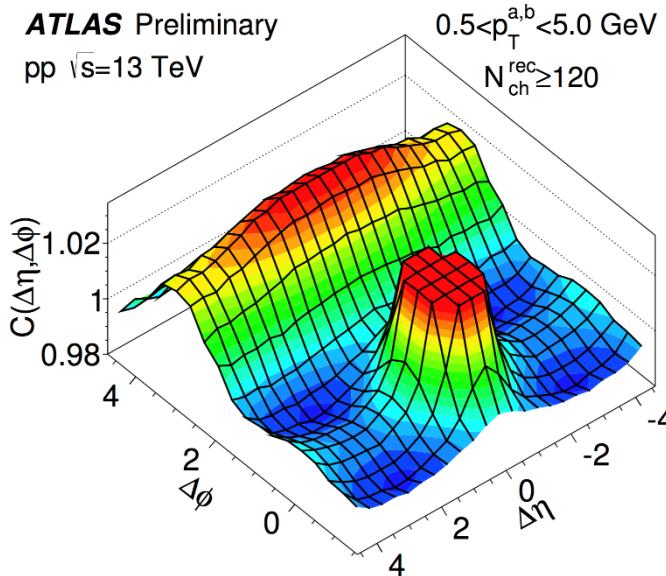
$$2B(\Delta\eta) \equiv 2C^{+-}(\Delta\eta) - C^{++}(\Delta\eta) - C^{--}(\Delta\eta)$$

- Test factorization: high- $p_T$   $a_n^H$  and low- $p_T$   $a_n^L$

$$r_n \equiv \frac{\langle a_n^H a_n^L \rangle}{\sqrt{\langle a_n^H a_n^H \rangle} \sqrt{\langle a_n^L a_n^L \rangle}}$$

**ATLAS** Preliminary

pp  $\sqrt{s}=13$  TeV



$C(\eta_1, \eta_2)$

+

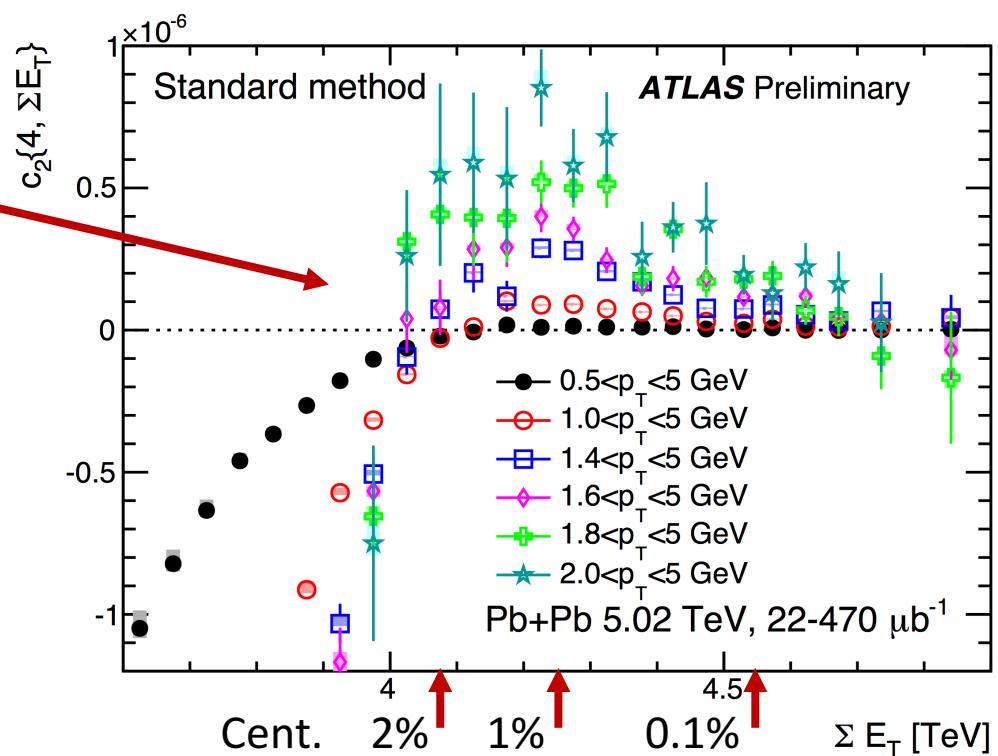
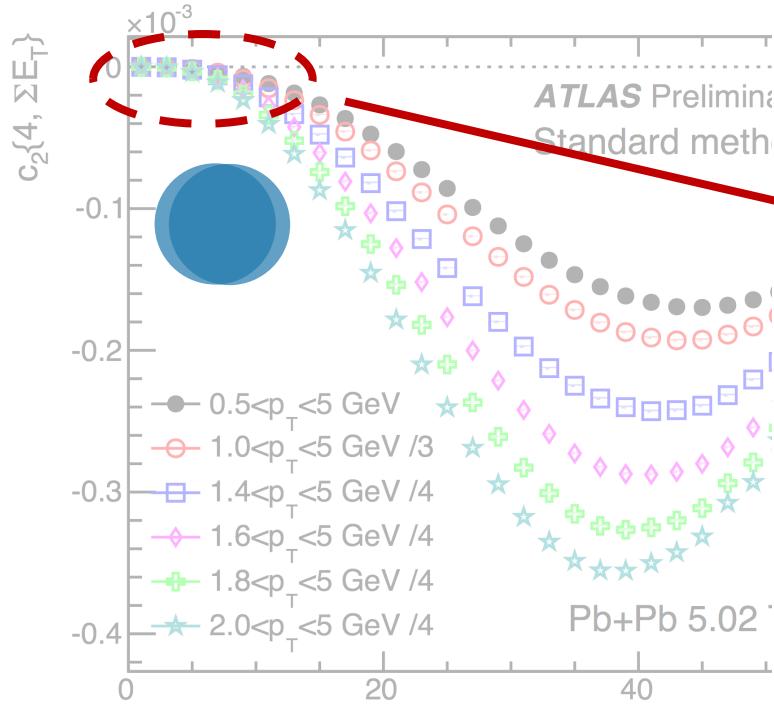
$C(\Delta\eta, \Delta\phi)$

$C(\eta_1, \eta_2, \Delta\phi) !$

# Centrality fluctuation

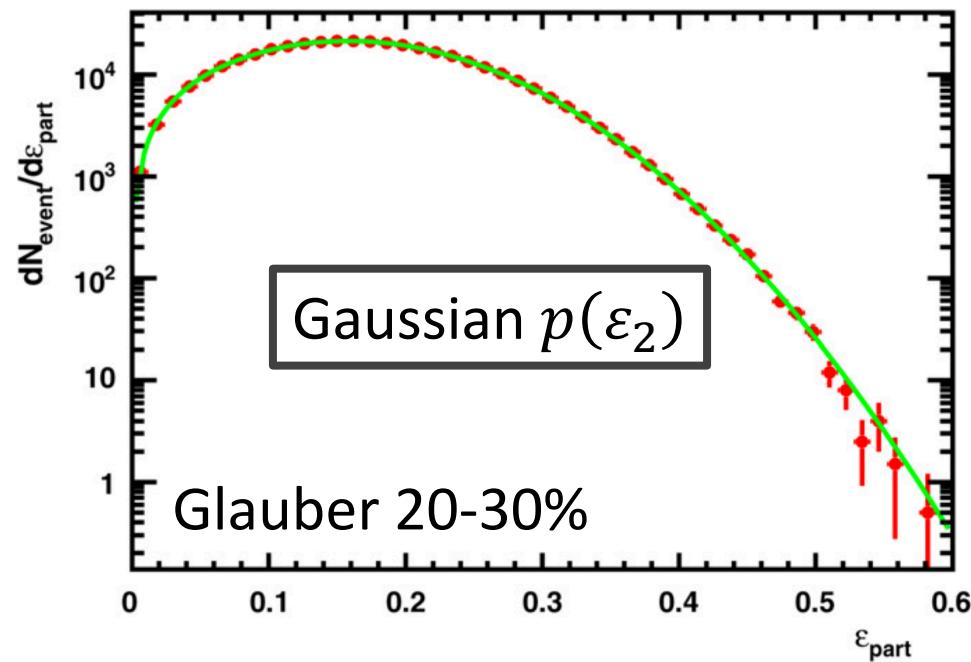
# Ultra-Central Collision (UCC)

61

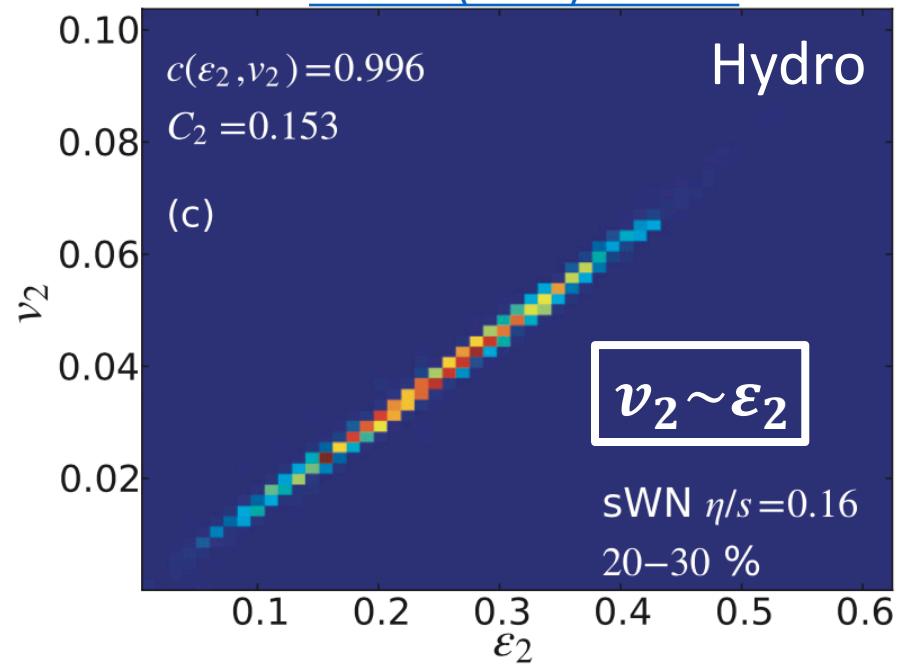


- In UCC:  $\bar{v}_2 \rightarrow 0$ , largest relative flow fluctuation;
- ATLAS applied UCC triggers:  $\times 20$  statistics over MinBias;
- $c_2\{4\} > 0$  in UCC  $\Rightarrow$  non-Gaussian flow fluctuation
  - Why?

[PLB 659 \(2008\) 537-541](#)



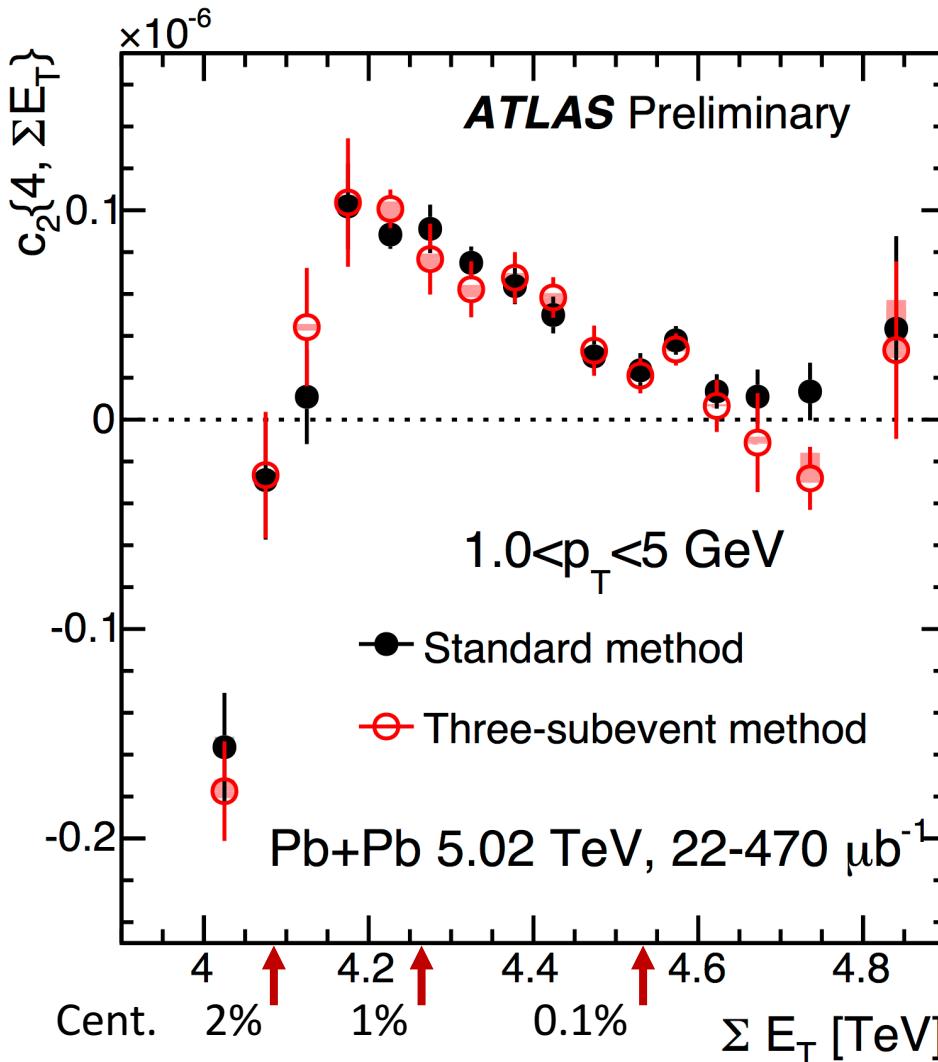
[PRC 87 \(2013\) 054901](#)



- On the model side
  - Gaussian  $p(\varepsilon_2) \Rightarrow$  Gaussian  $p(v_2) \Rightarrow c_2\{4\} \leq 0$
- But we observed  $c_2\{4\} > 0$ 
  - Non-flow contribution?

$$v_n\{4\} = \bar{v}_n = \sqrt[4]{-c_n\{4\}}$$

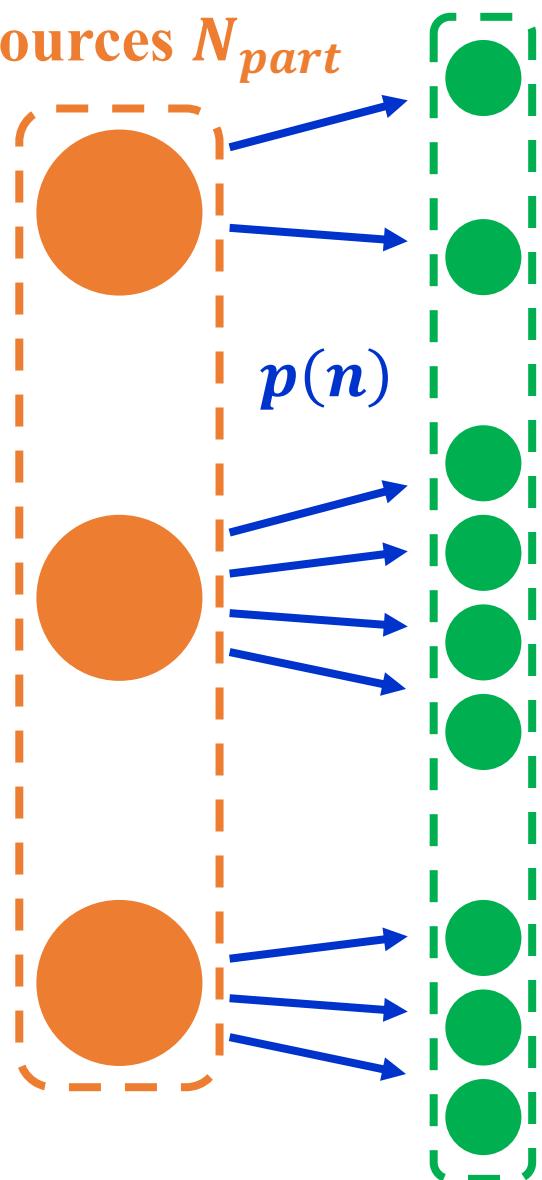
# Non-flow contribution?



- Two methods consistent: **not due to non-flow**.
- Pileup effects have also been suppressed.

### Initial stage

**sources  $N_{part}$**



### Final stage

**particles  $N_{ch}$**

Not detector effect!

- Fluctuation of particle production  $p(n)$ 
  - Same  $N_{part}$   $\Rightarrow$  different  $N_{ch}$
  - Same  $N_{ch}$   $\Rightarrow$  different  $N_{part}$
- In the experiment
  - First calculate  $Obs(N_{ch})$
  - Then map to  $\langle N_{part} \rangle$
- Flow is driven by initial stage  $N_{part}$
- $Obs(\langle N_{part} \rangle)$  introduces CF
- CF affects all fluctuation measurements, but never been studied in flow

$$c_n\{4\} \equiv \langle \langle 4 \rangle \rangle - 2 \langle \langle 2 \rangle \rangle^2$$

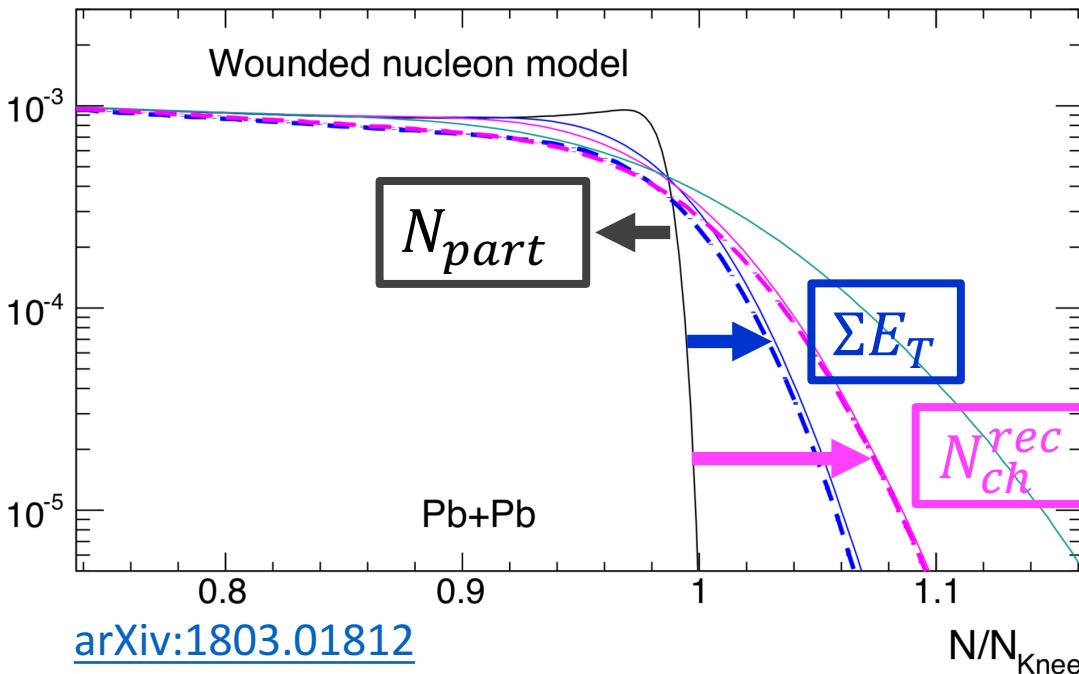
Calculated  
event-by-event

Averaged over many events

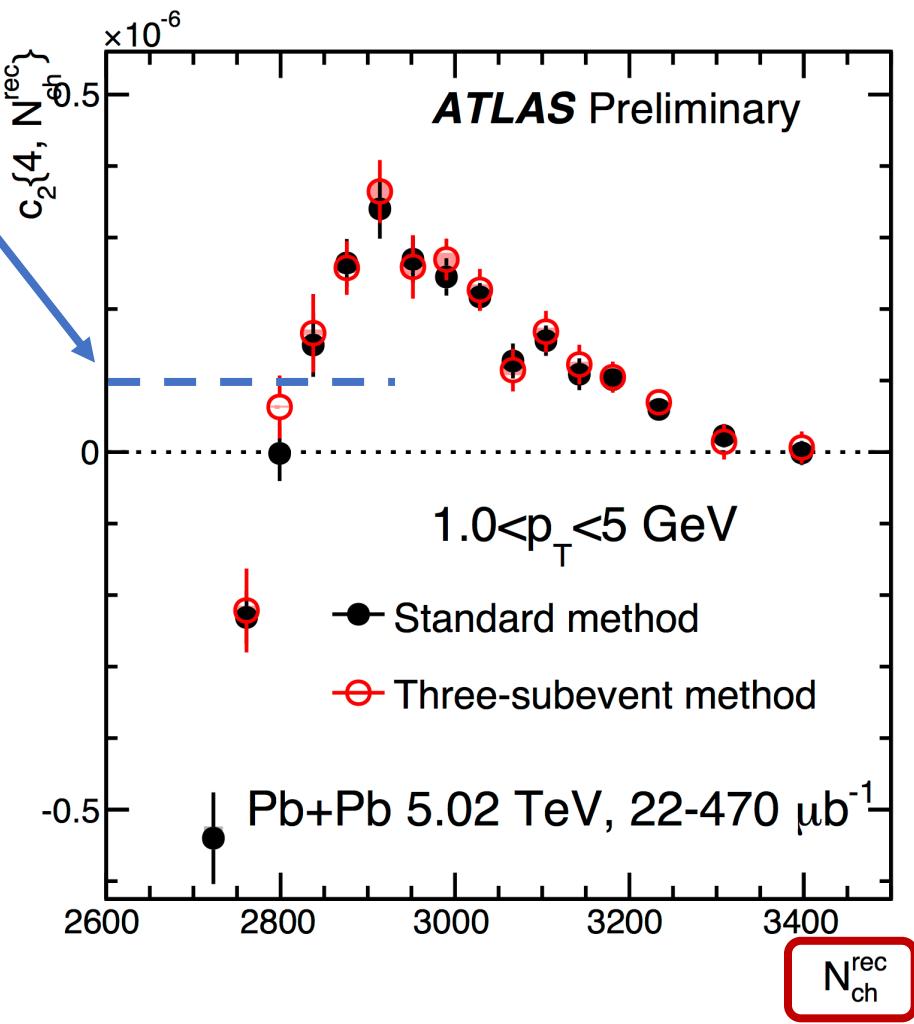
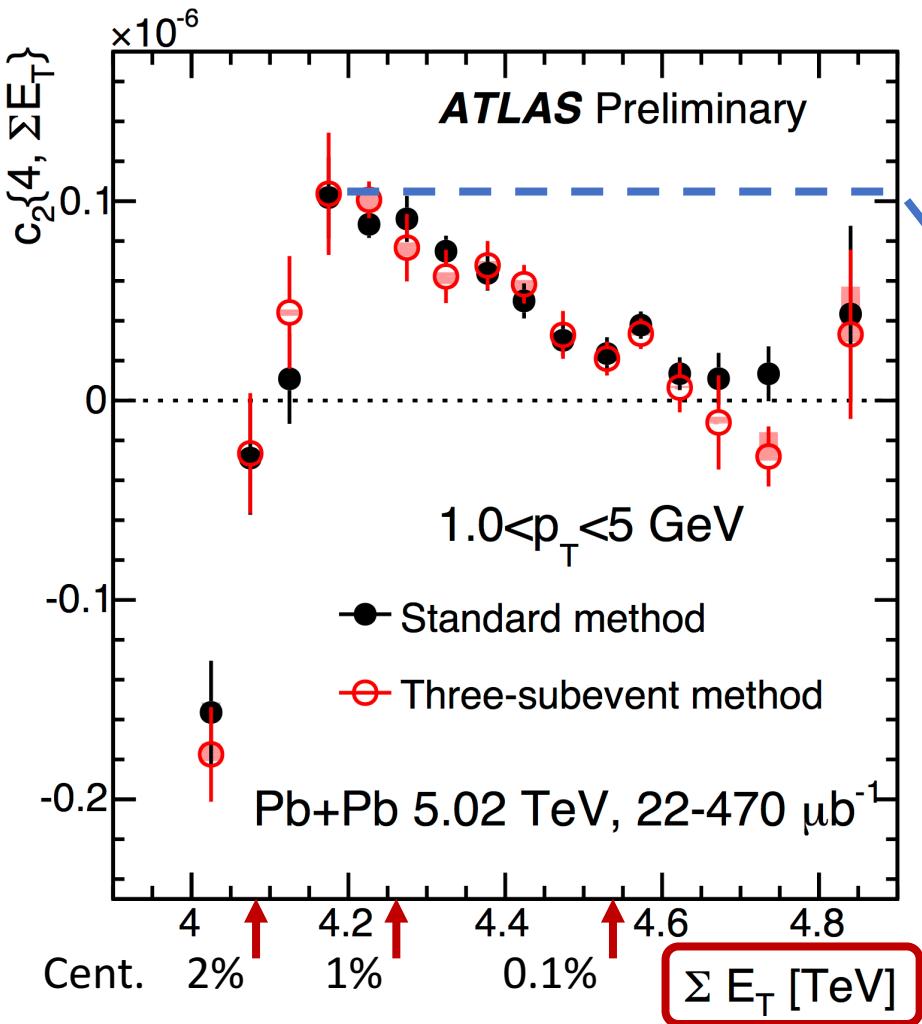
Binning defined by	Observable
FCal: $3.2 <  \eta  < 4.9$	$c_2\{4, \Sigma E_T\}$
ID: $ \eta  < 2.5, p_T$ cut	$c_2\{4, N_{ch}^{rec}\}$

- Particle production depends on  $\eta$

Test relative CF by comparing  $c_2\{4\}$  binned by  $\Sigma E_T$  and  $N_{ch}^{rec}$



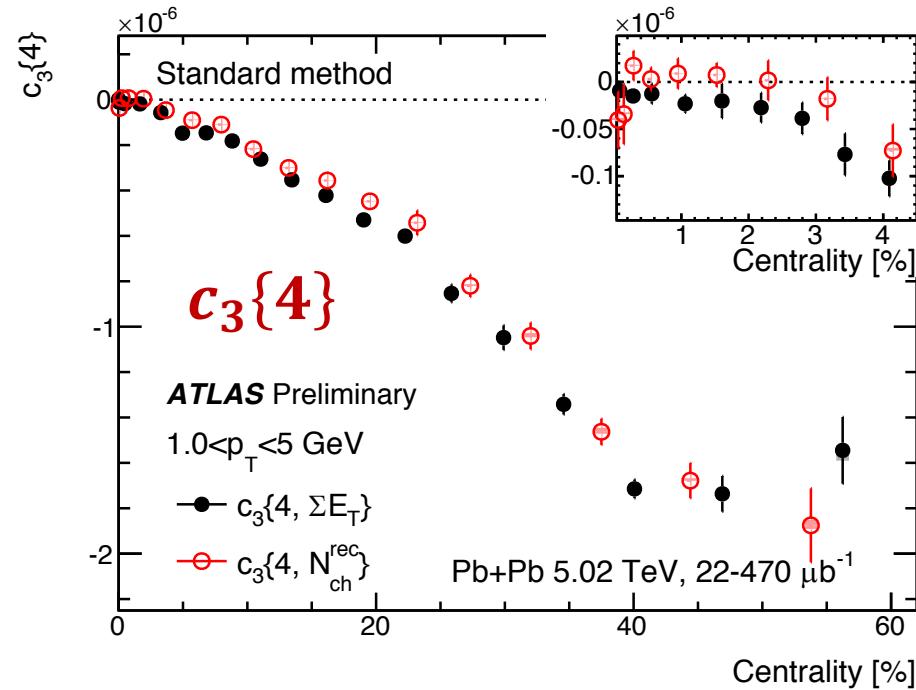
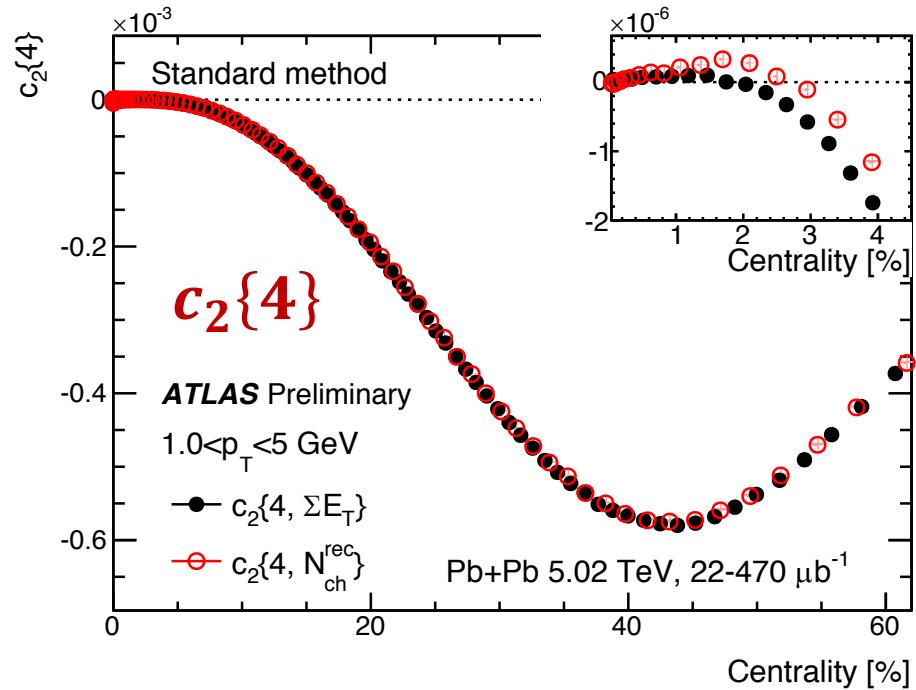
- $p(N_{ch}^{rec})$  broader than  $p(\Sigma E_T)$
- CF effect:  $\Sigma E_T < N_{ch}^{rec}$
- Prediction
  - $c_2\{4, \Sigma E_T\} < c_2\{4, N_{ch}^{rec}\}$



- $c_2\{4, \Sigma E_T\} < c_2\{4, N_{\text{ch}}^{\text{rec}}\}$ : CF affects flow cumulant;
- $c_2\{4\} \rightarrow 0$  in very most-central: smaller CF effect;

# From ultra-central to full centrality

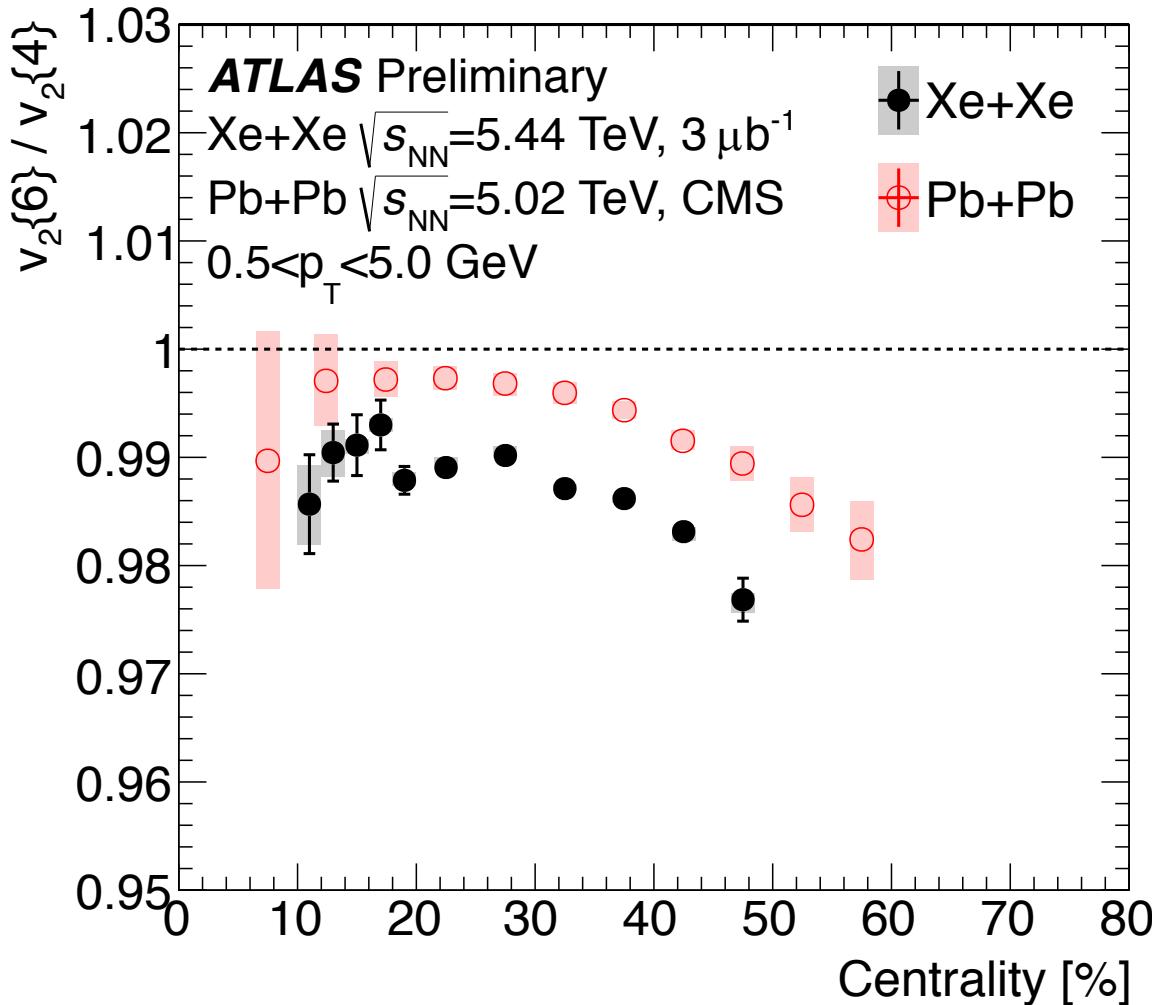
67



- $c_2\{4\}$ : CF mostly affects central;
- $c_3\{4\}$ : CF affects most centralities.

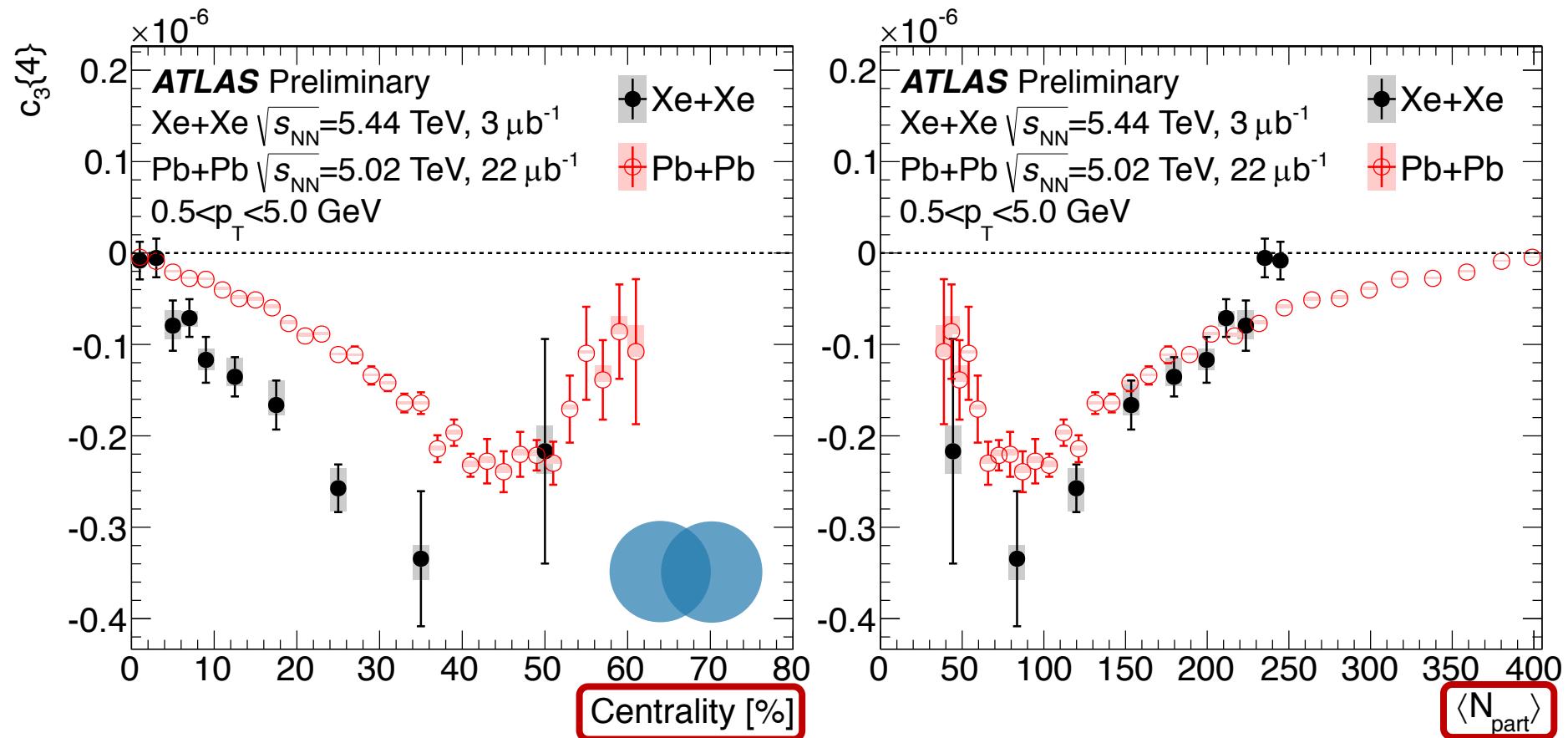
## **Comparison between Pb+Pb and Xe+Xe**

# Xe+Xe and Pb+Pb: $v_2$



- Mass number of Xe is halfway of Pb and  $p$ ;
- If  $v_2 \sim \text{Gauss}(\bar{v}_n, \delta_n)$ :  $v_2\{6\}/v_2\{4\} = 1$
- $v_2$  in Xe+Xe deviates further from Gauss: deformed nucleus?

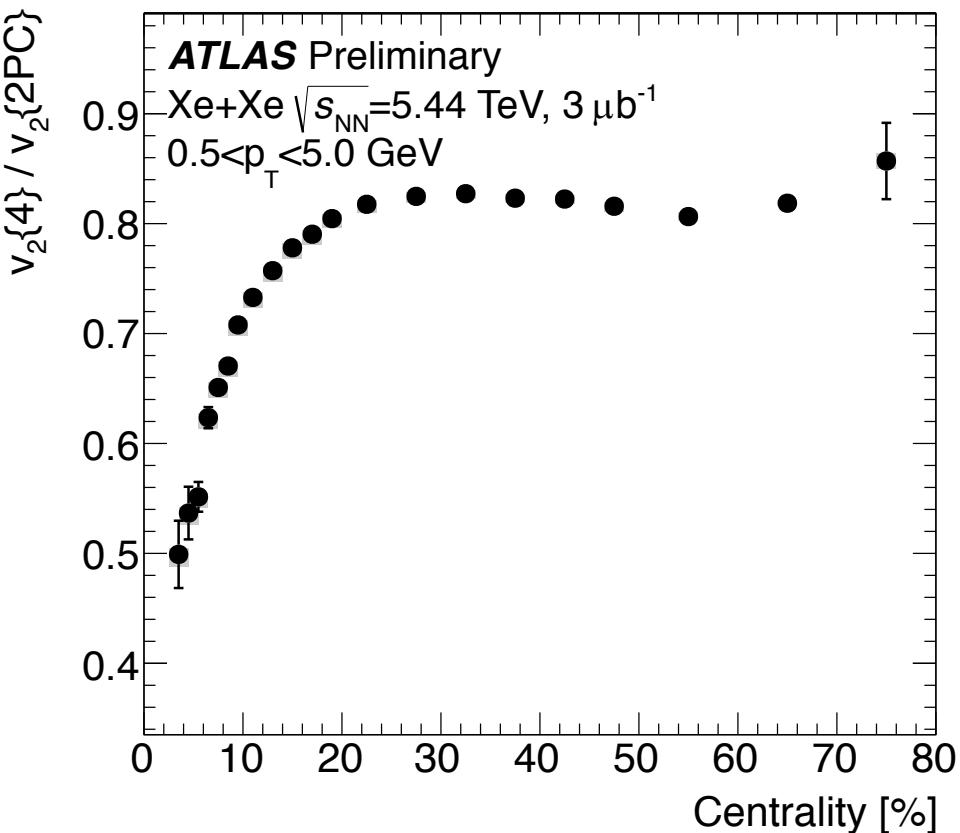
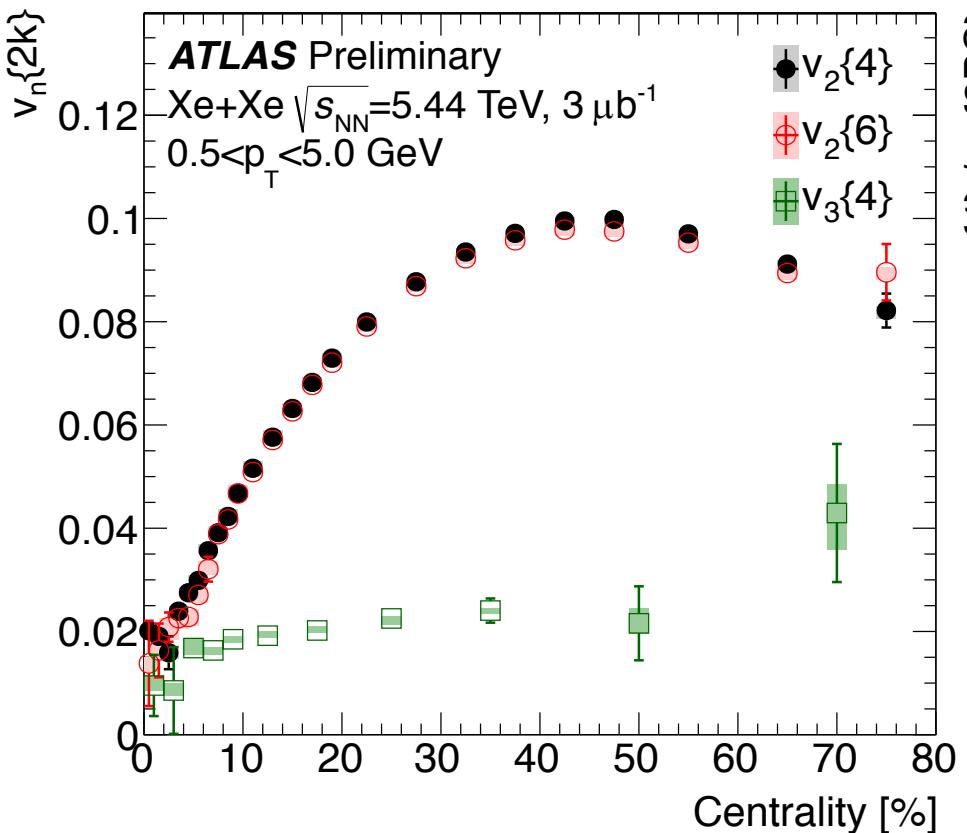
# Xe+Xe and Pb+Pb: $v_3$

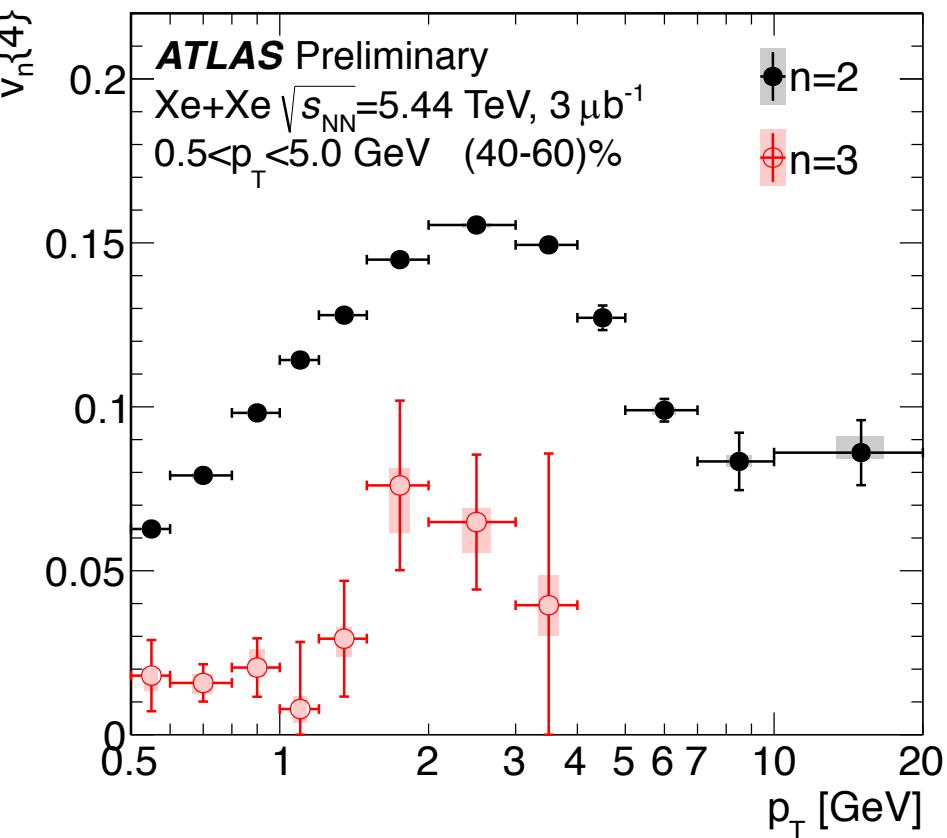
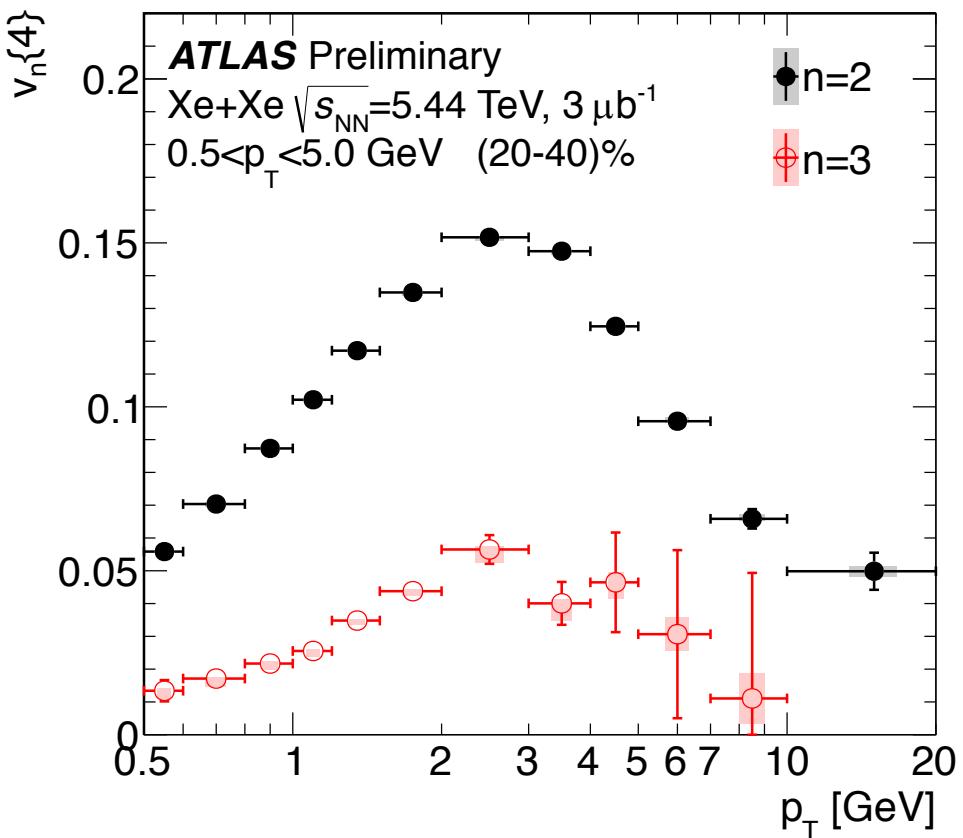


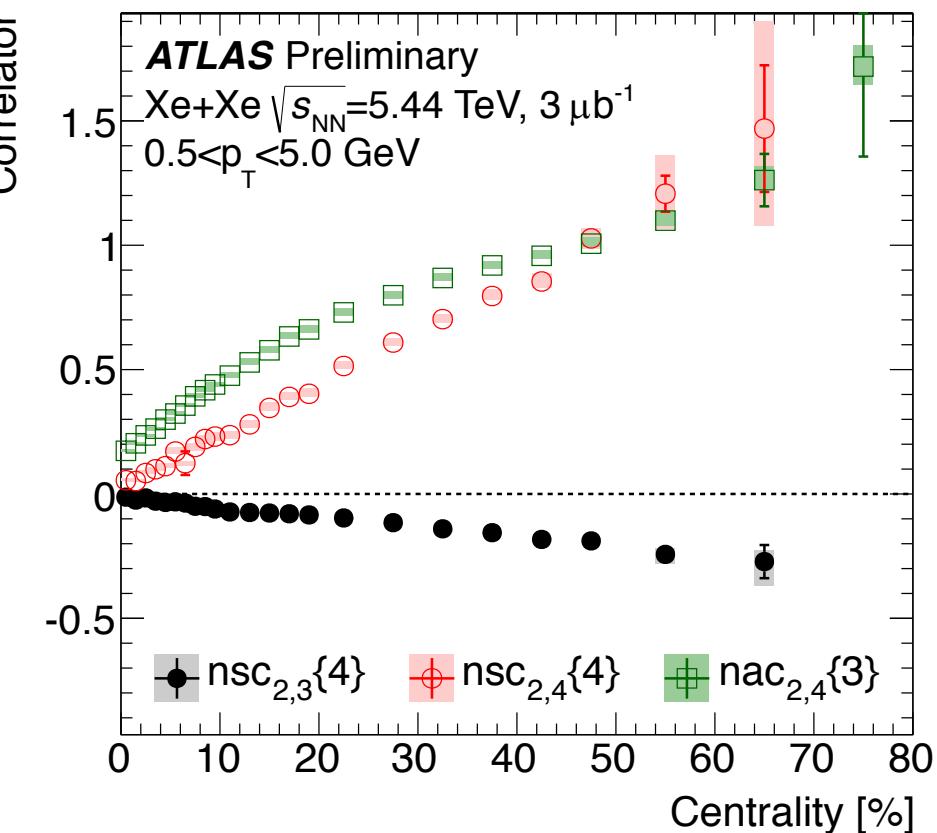
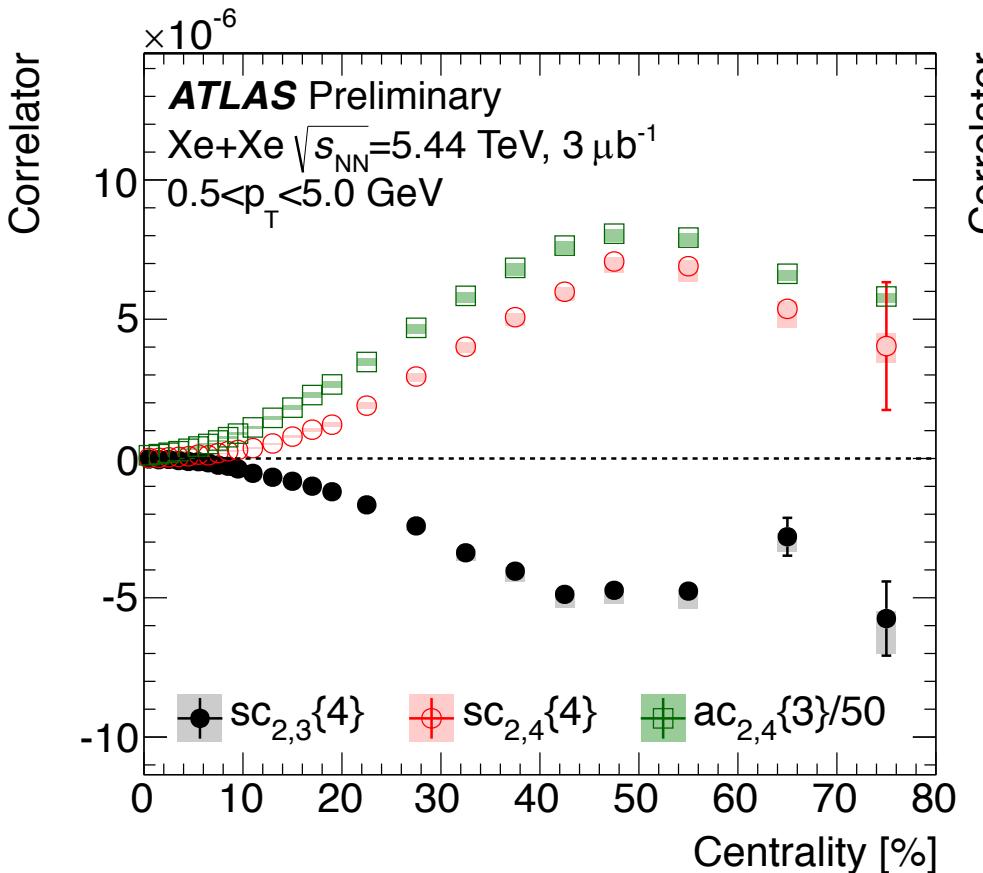
- $c_3\{4\}$  doesn't scale with centrality between Xe and Pb
  - No avg. geometry for  $v_3$ ;
- $c_3\{4\}$  scales with  $\langle N_{\text{part}} \rangle$ 
  - Fluctuation driven by # of sources  $N_{\text{part}}$
  - Similar observation for  $c_4\{4\}$  (see backup)

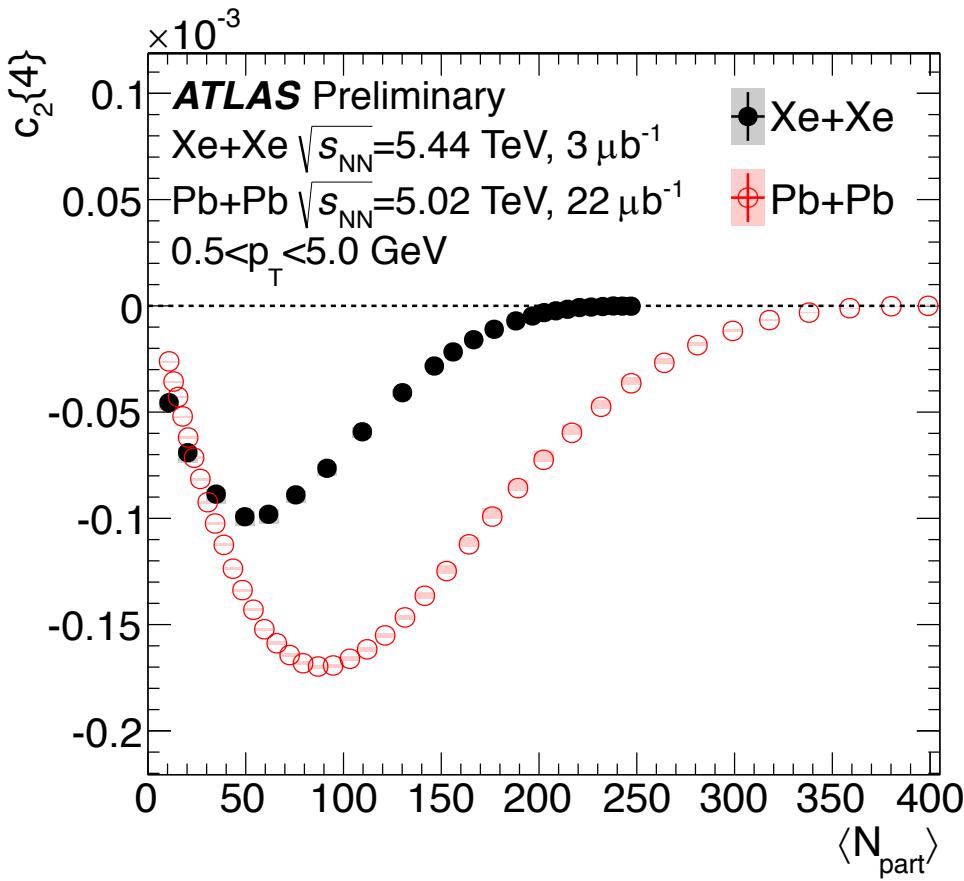
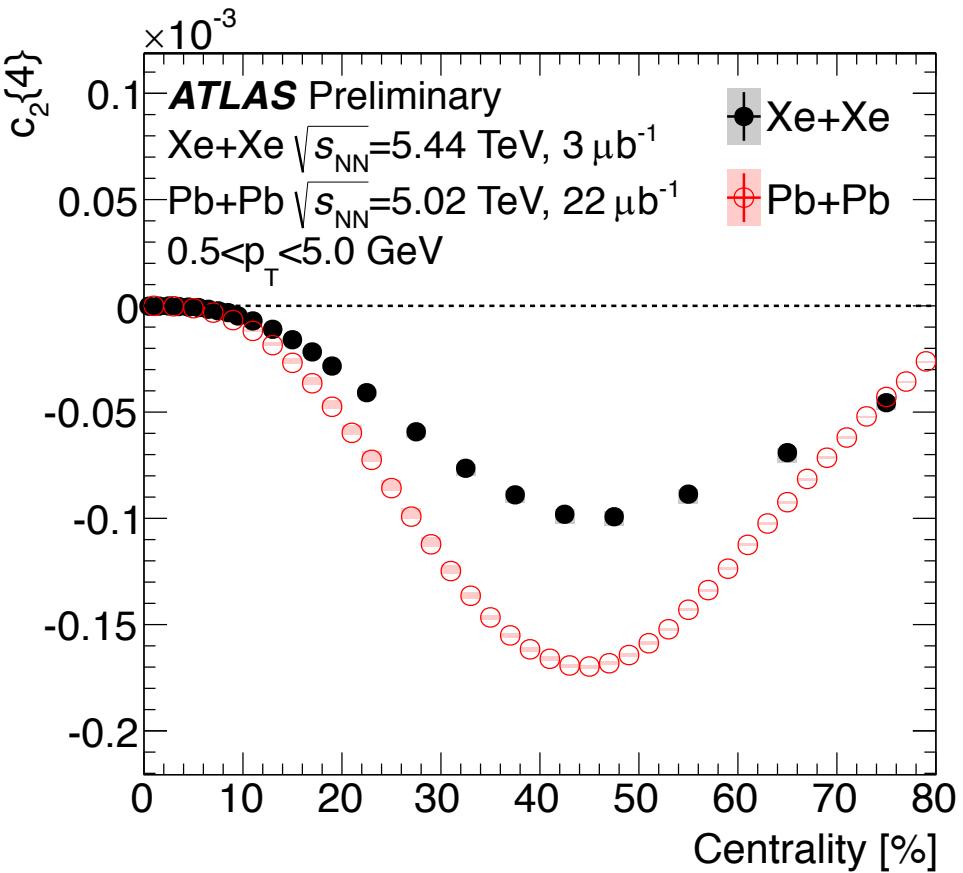
# Multi-particle cumulant

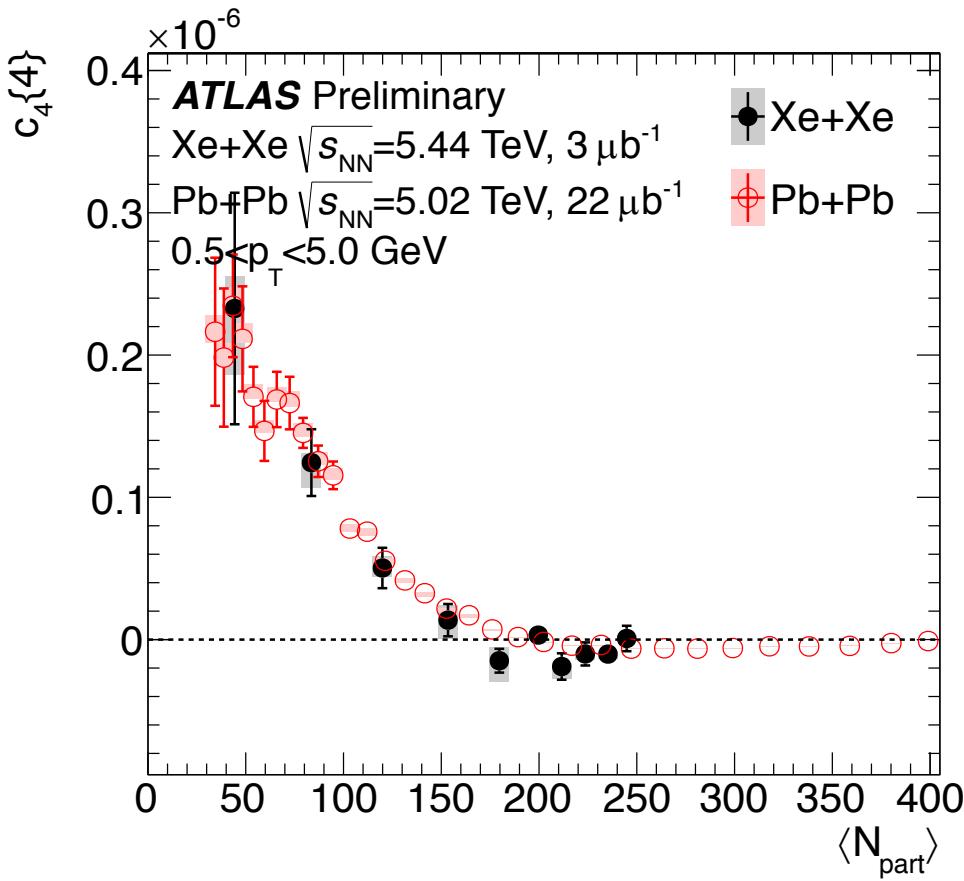
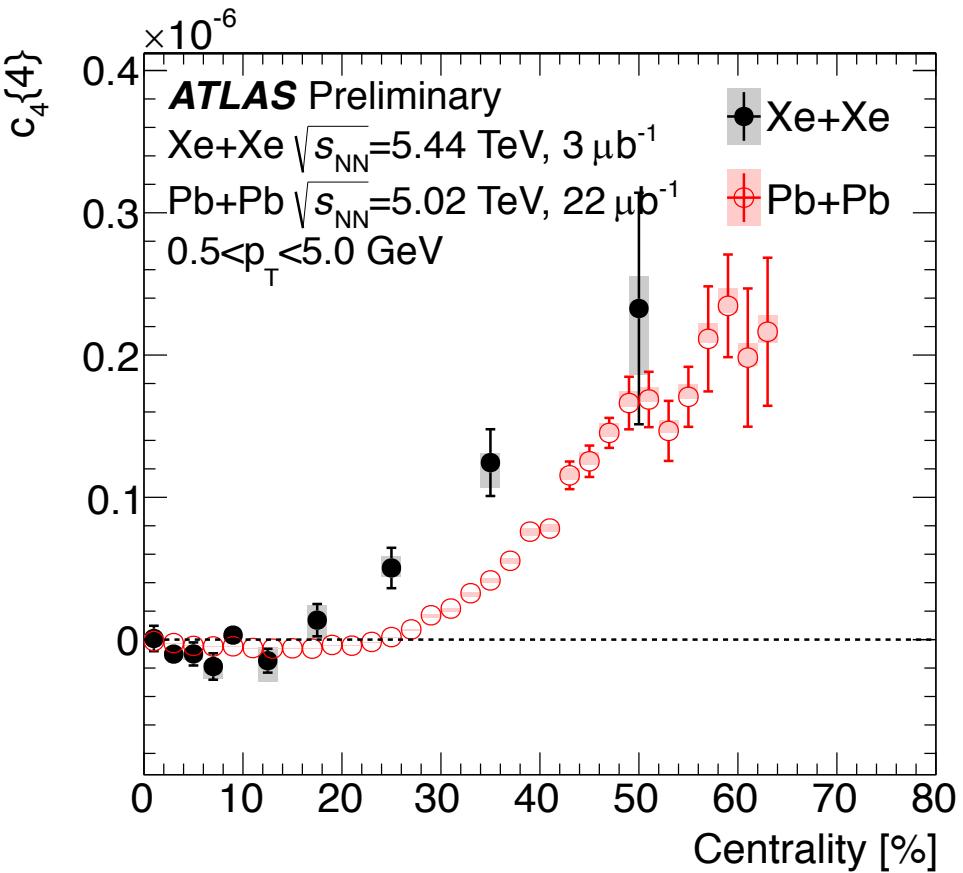
71







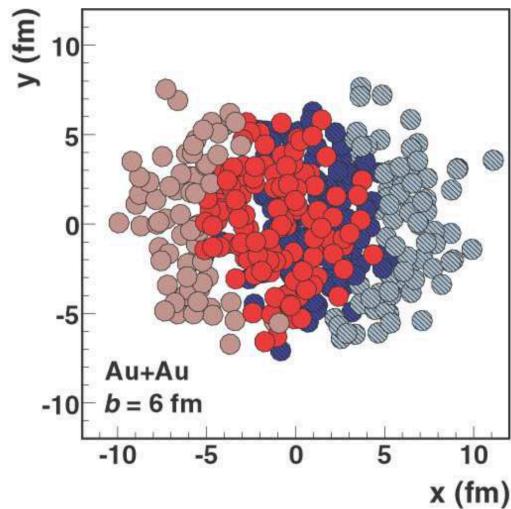






# Origins of collectivity

- Final state correlations

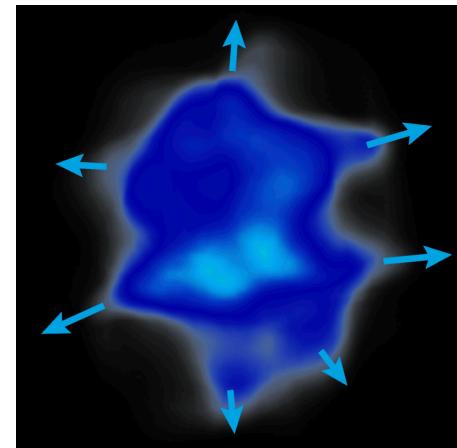


Spatial structure from initial condition

$$\frac{dN}{d\phi} = G \left( 1 + 2 \sum_{n=1} v_n \cos n\phi \right)$$

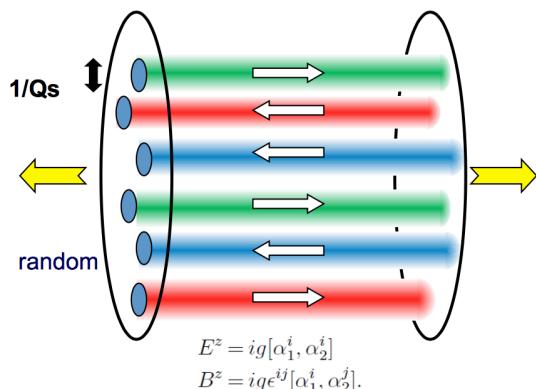


Hydrodynamic flow



Momentum correlations

- Initial state correlations



More careful studies in  $pp$  collisions are needed!

Particles are produced with momentum space correlations

- O+O to O+O