

Evidences for collectivity in small systems

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Physics Ph.D. Defense

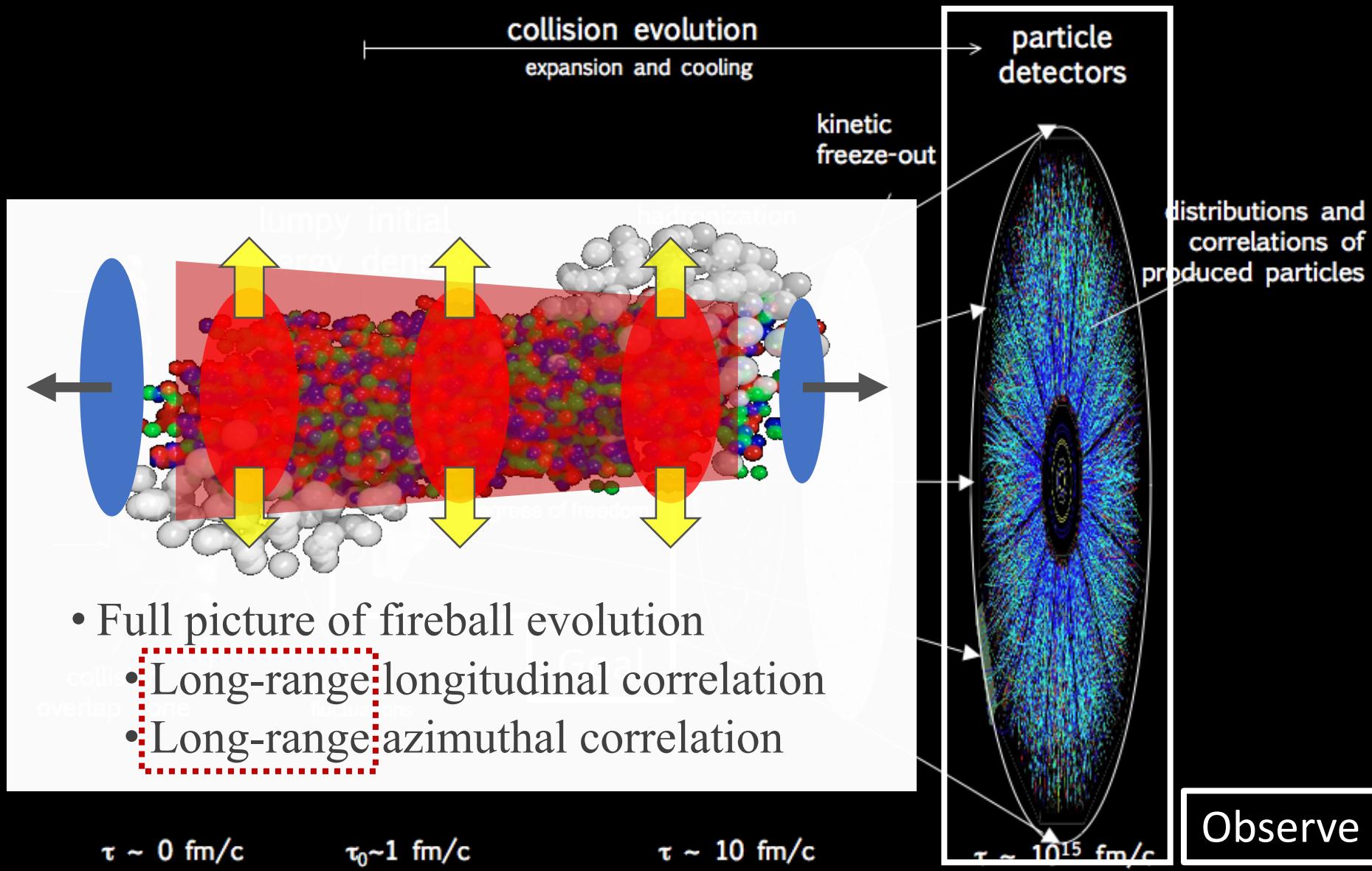
March 4th 2019



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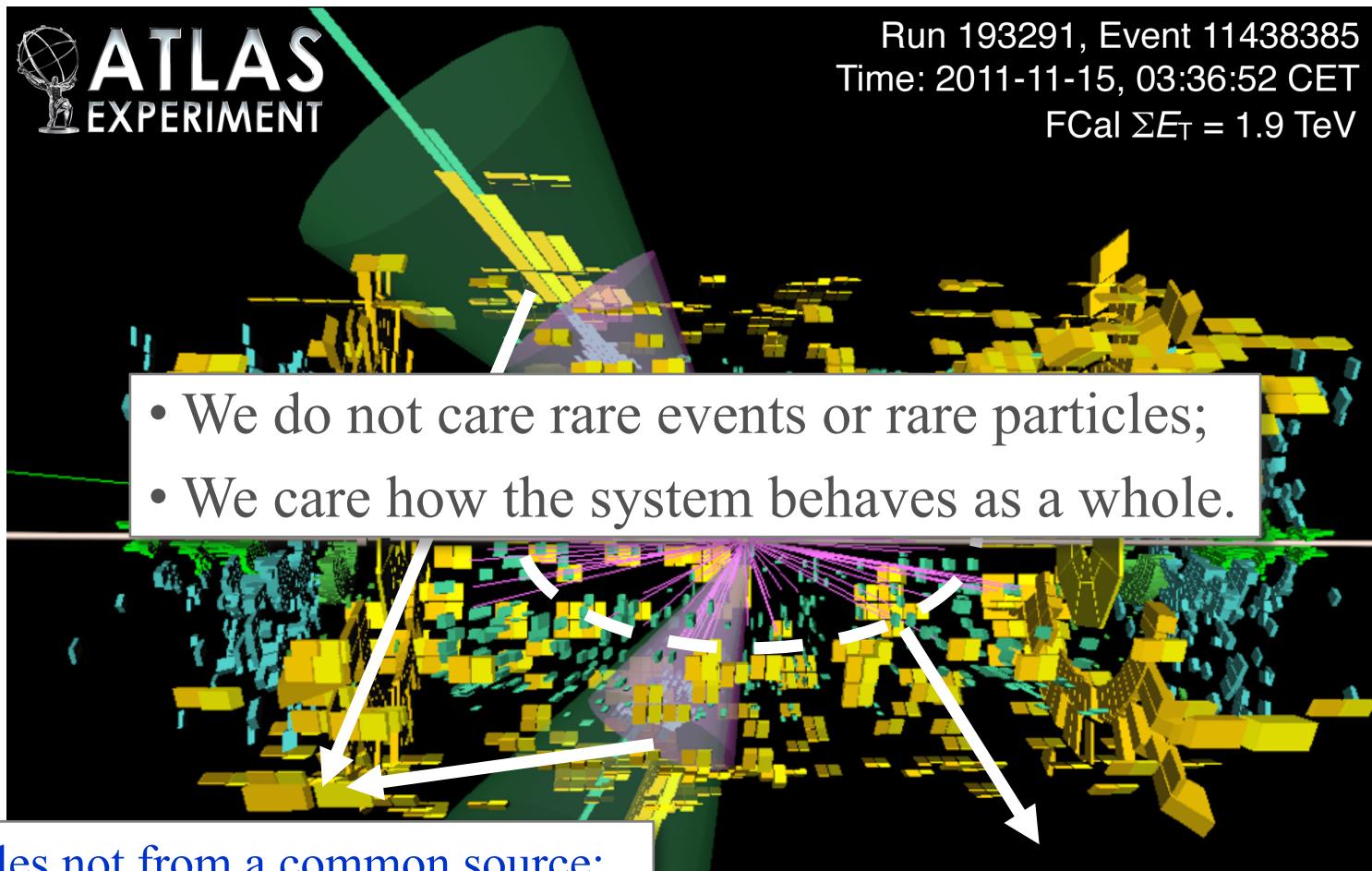
Heavy ion collision

Nuclear collisions and the QGP expansion



What is collectivity?

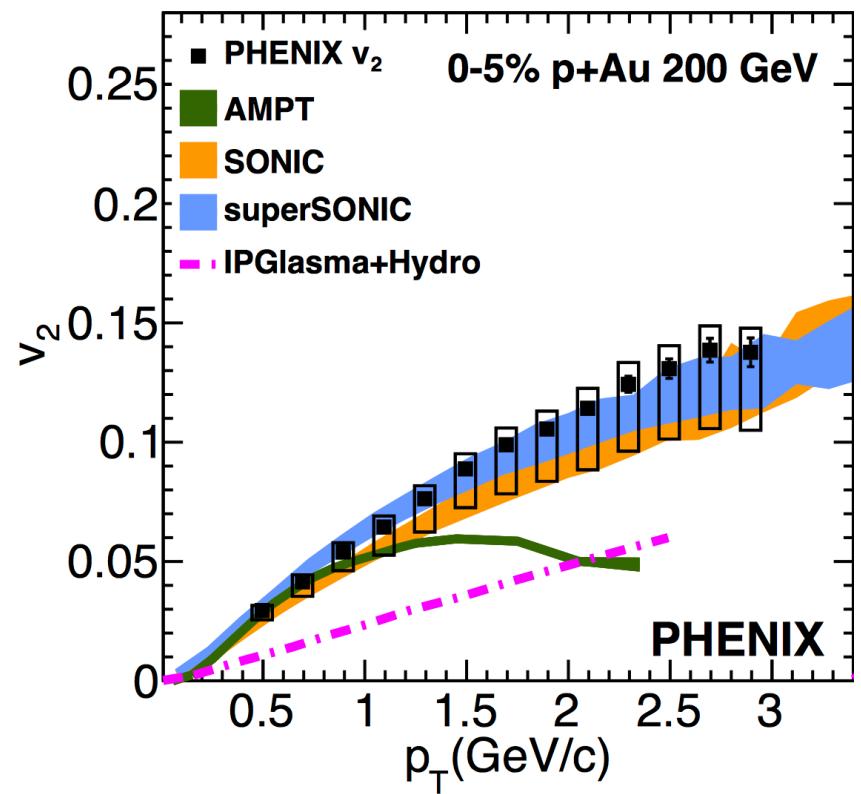
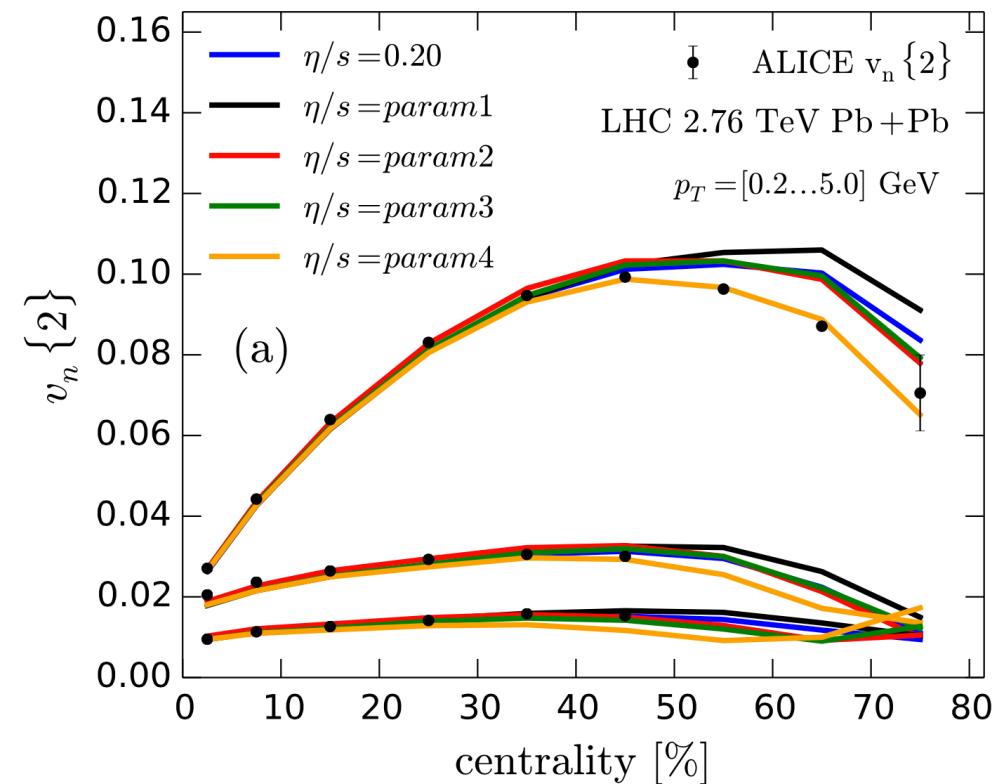
- Collectivity: condition of an entity having properties its parts do not have, due to interactions among the parts.



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?



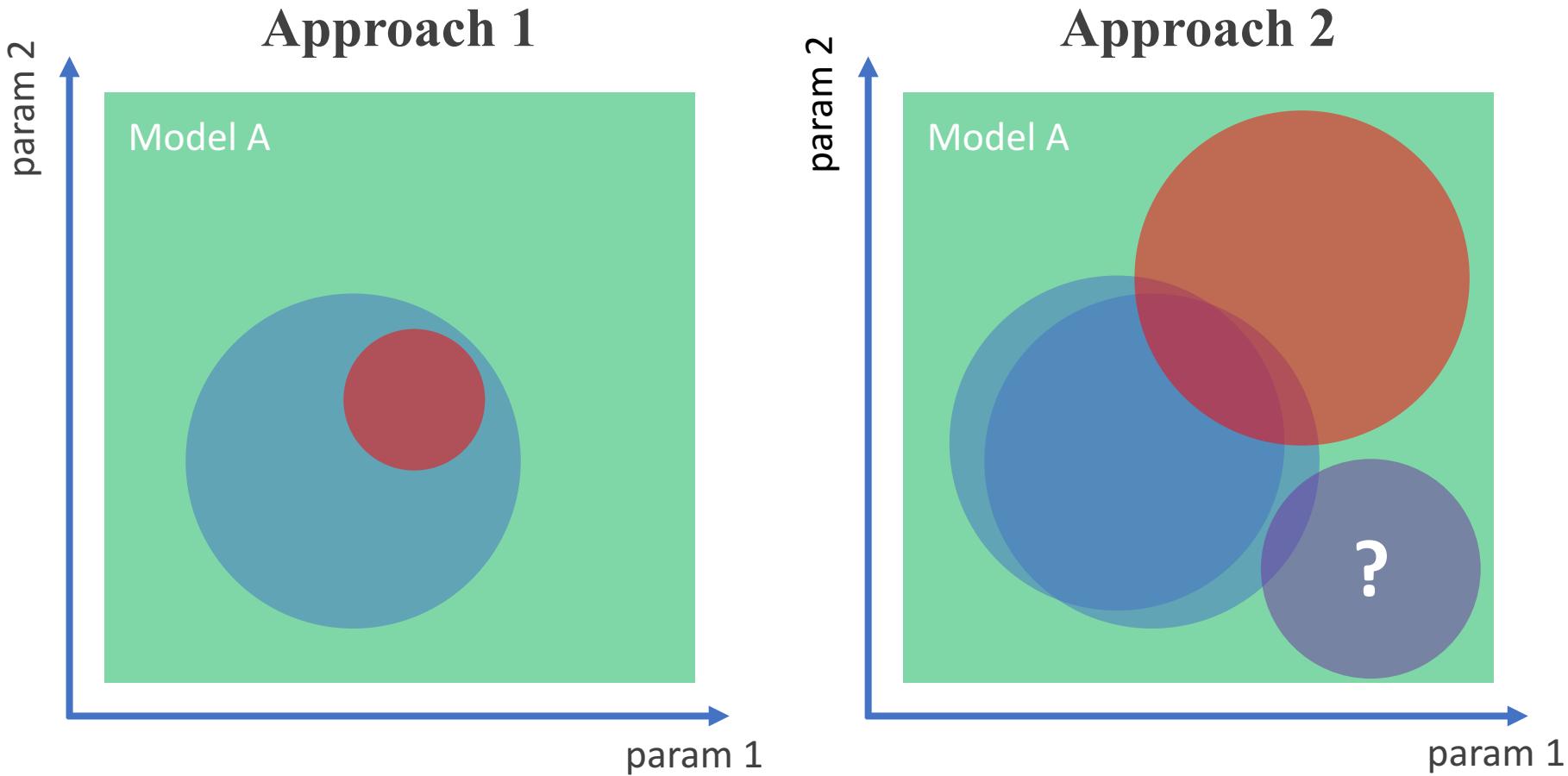
- Success of models in large systems;
- Parameters not well constrained.

- 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

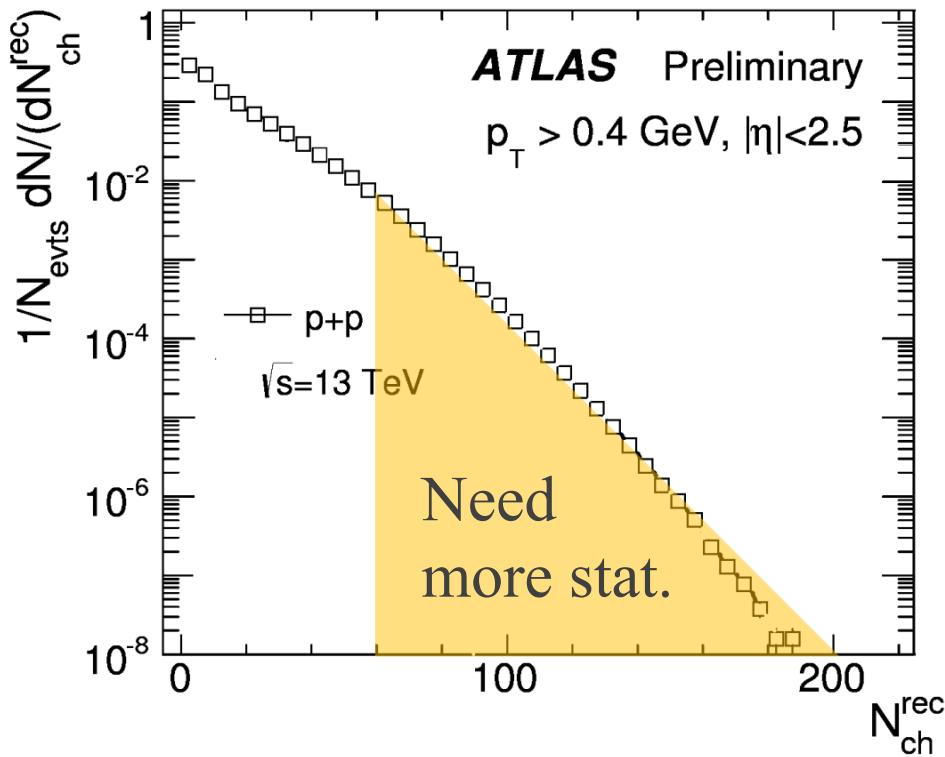


- Improve statistical significance of data

pp and $p+Pb$ events with high statistics

- Independent constraints
 - New observable
 - Collision system
 - Collision energy

Real-time data selection



LHC event rate

40 MHz



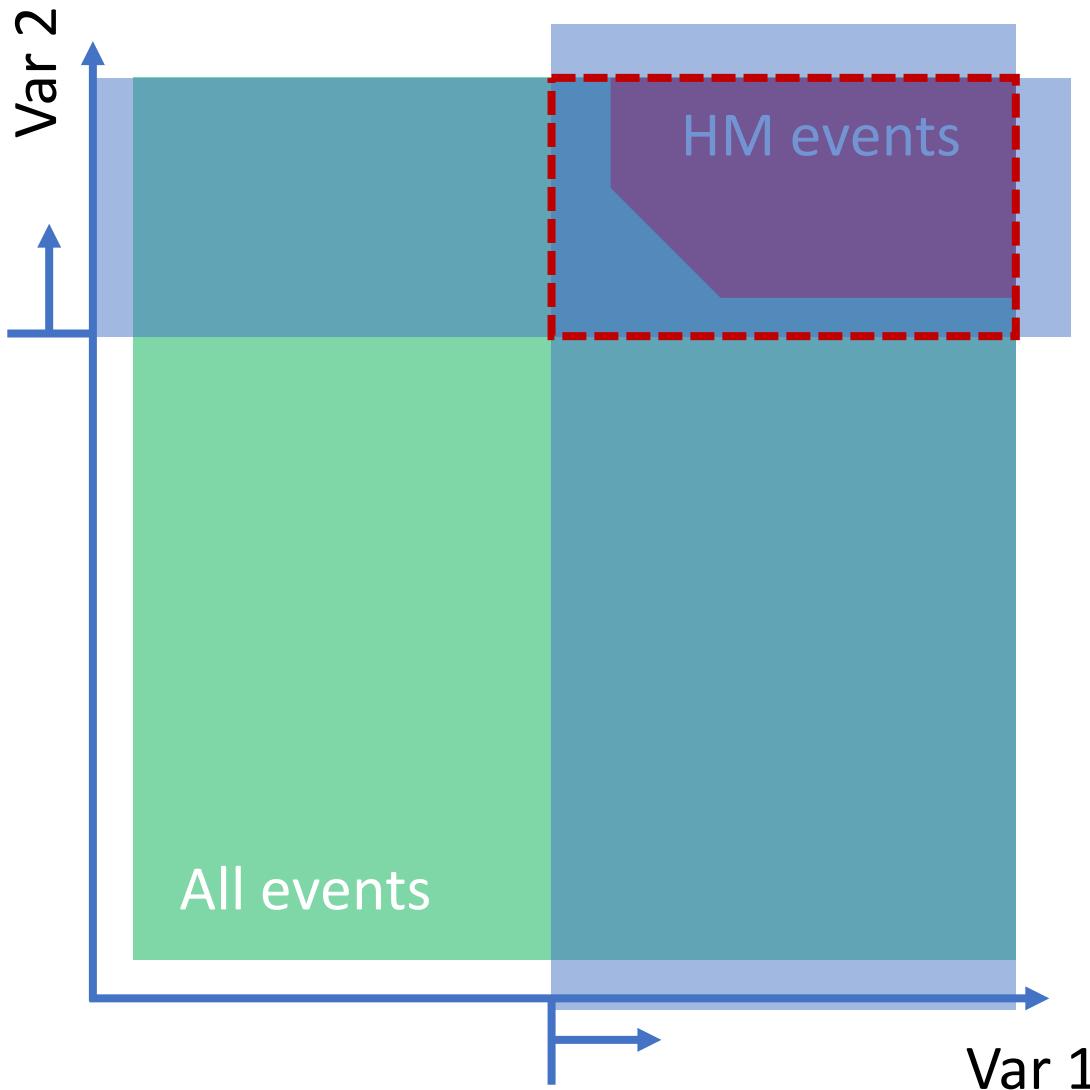
Recording cap
10 kHz



- 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

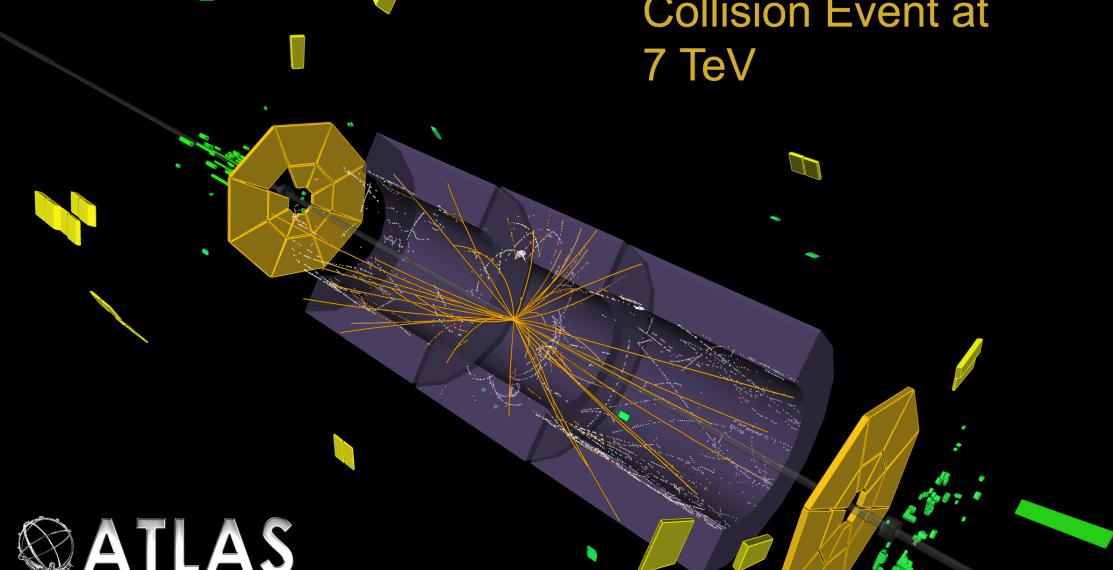
7



Sequence and thresholds of cuts designed to maximize performance.

Event display

Collision Event at
7 TeV



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

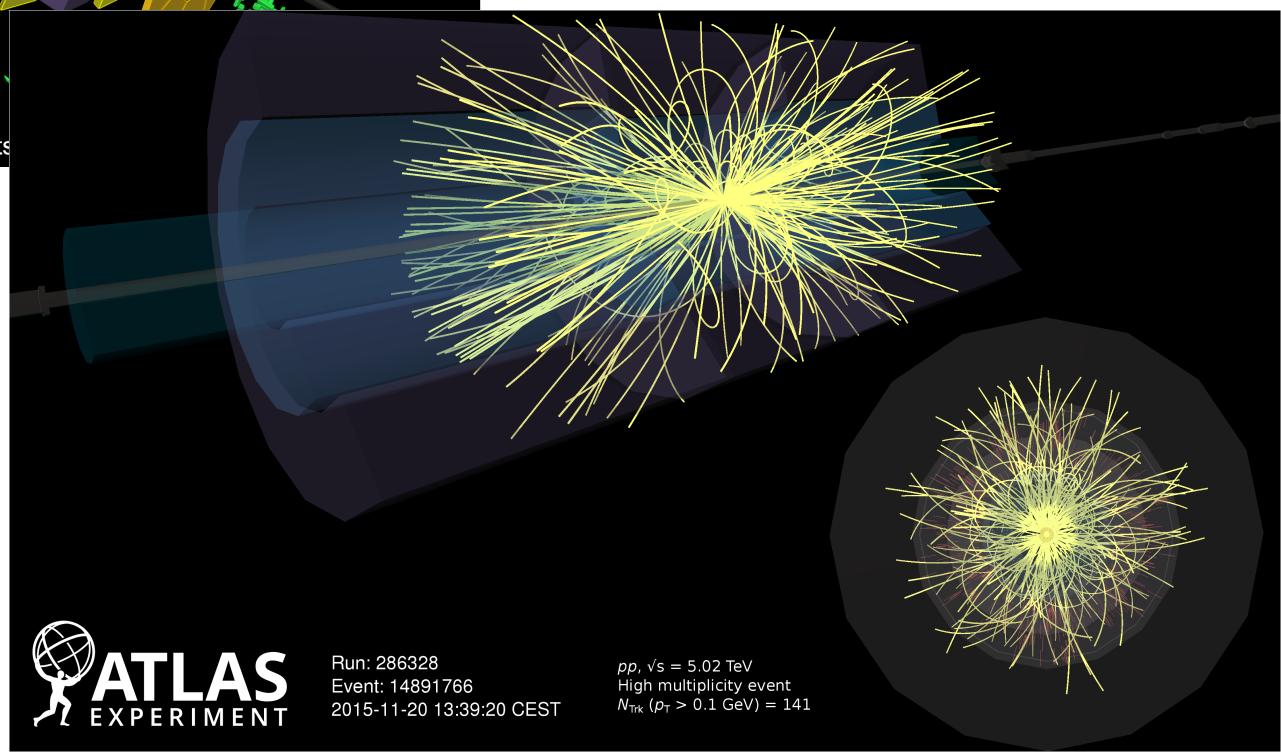
 **ATLAS**
EXPERIMENT

2010-03-30, 12:58 CEST
Run 152166, Event 316199

<http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events>

Triggered event

$N_{ch} \approx 140$



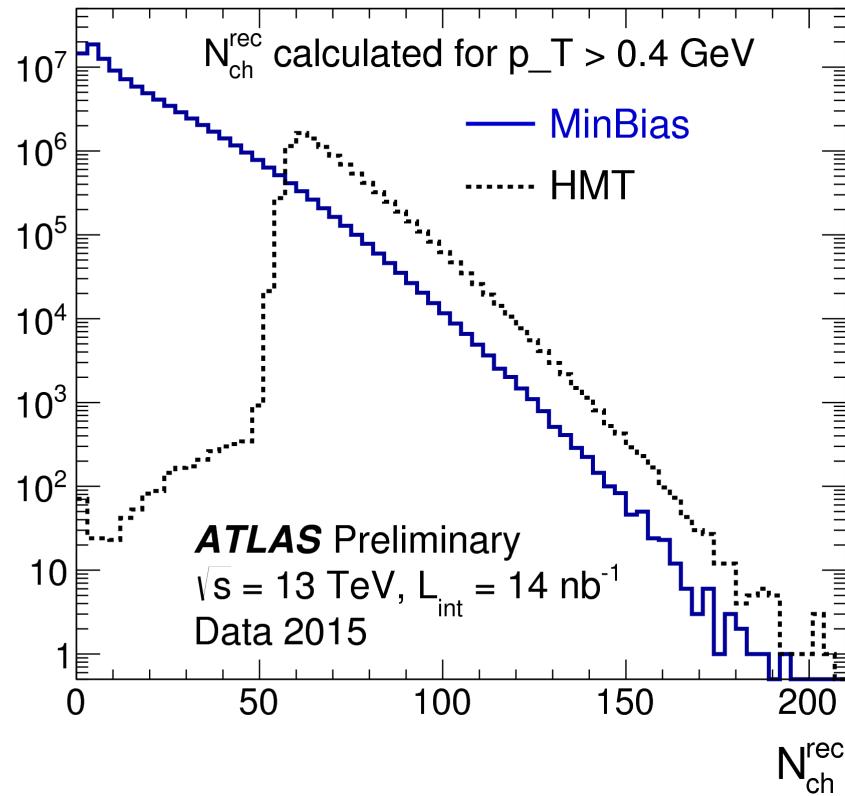
 **ATLAS**
EXPERIMENT

Run: 286328
Event: 14891766
2015-11-20 13:39:20 CEST

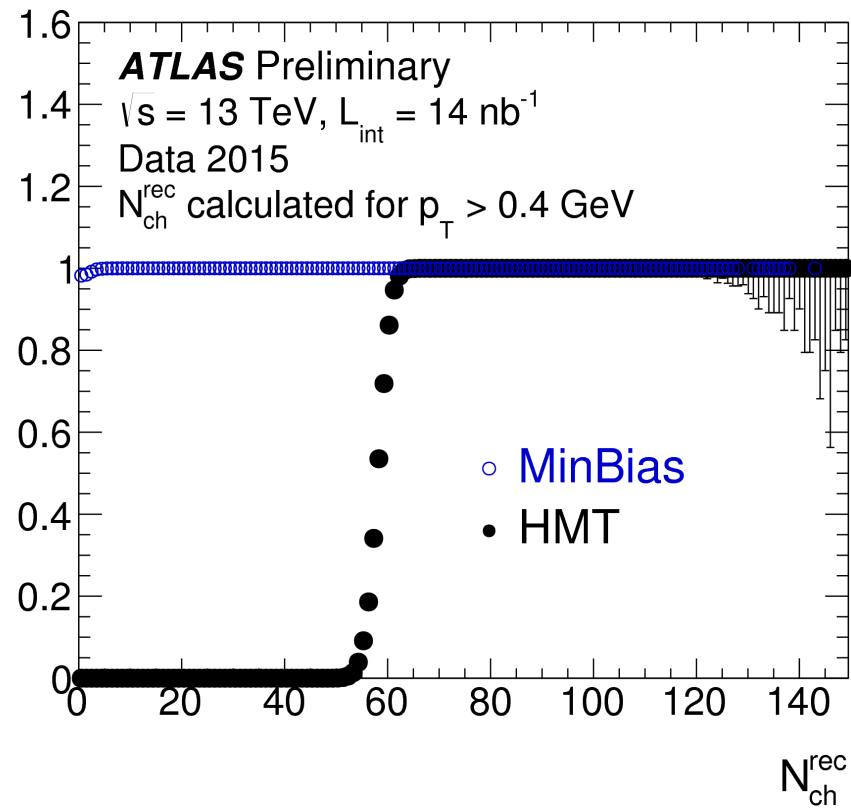
$pp, \sqrt{s} = 5.02 \text{ TeV}$
High multiplicity event
 $N_{\text{Trk}} (p_T > 0.1 \text{ GeV}) = 141$

Performance

Events / 3



Trigger efficiency

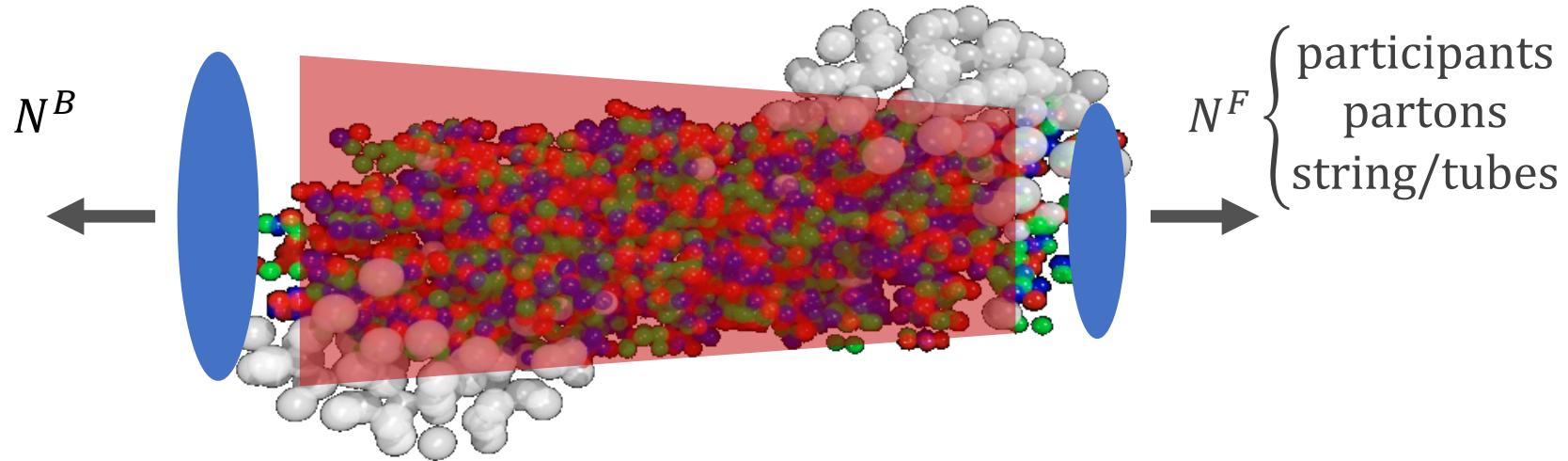


- Statistics increased by x5.

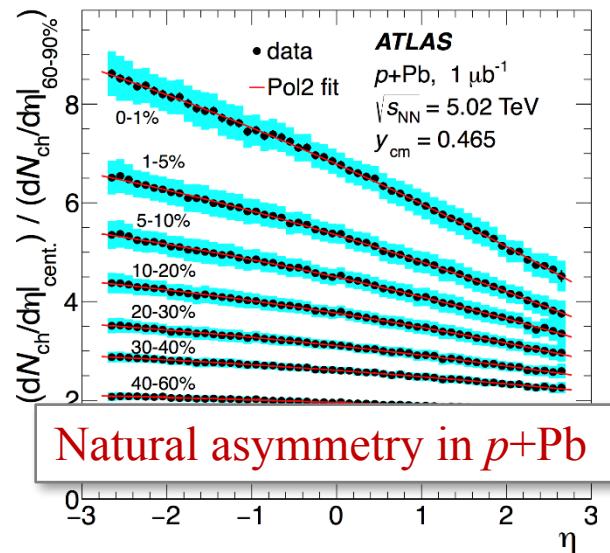
- Nominal bias introduced.

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

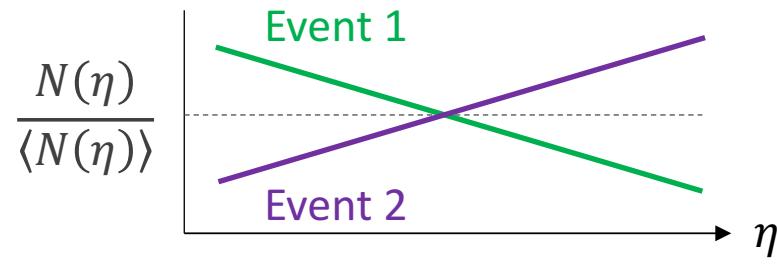
Nature of sources seeding the long-range collective behaviors?



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



Event-by-event multiplicity fluctuation?

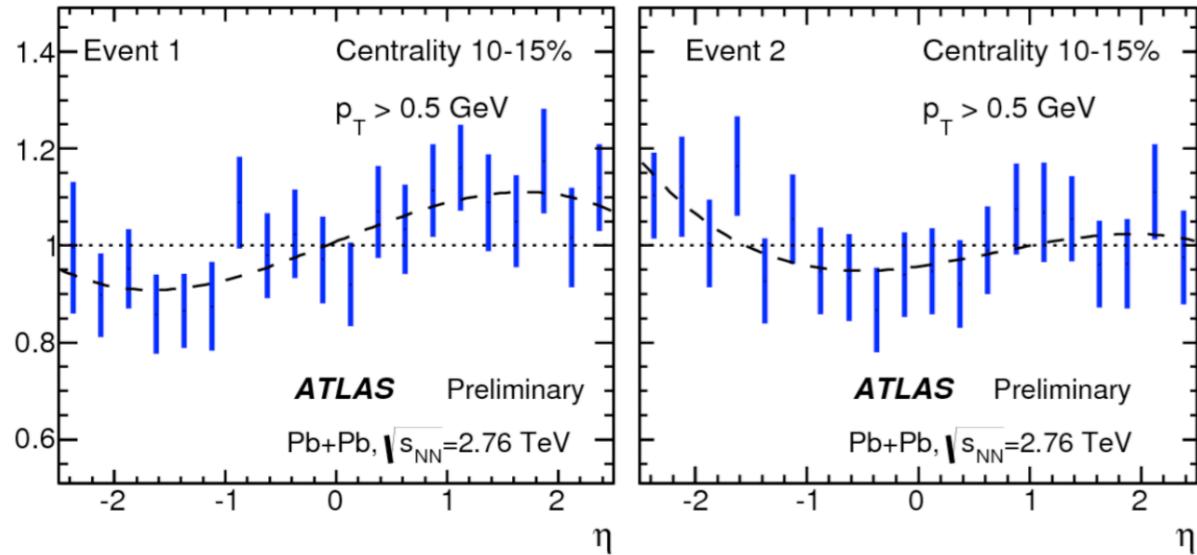


New observable

- Single particle observable

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

- Dominated by statistical fluctuations!



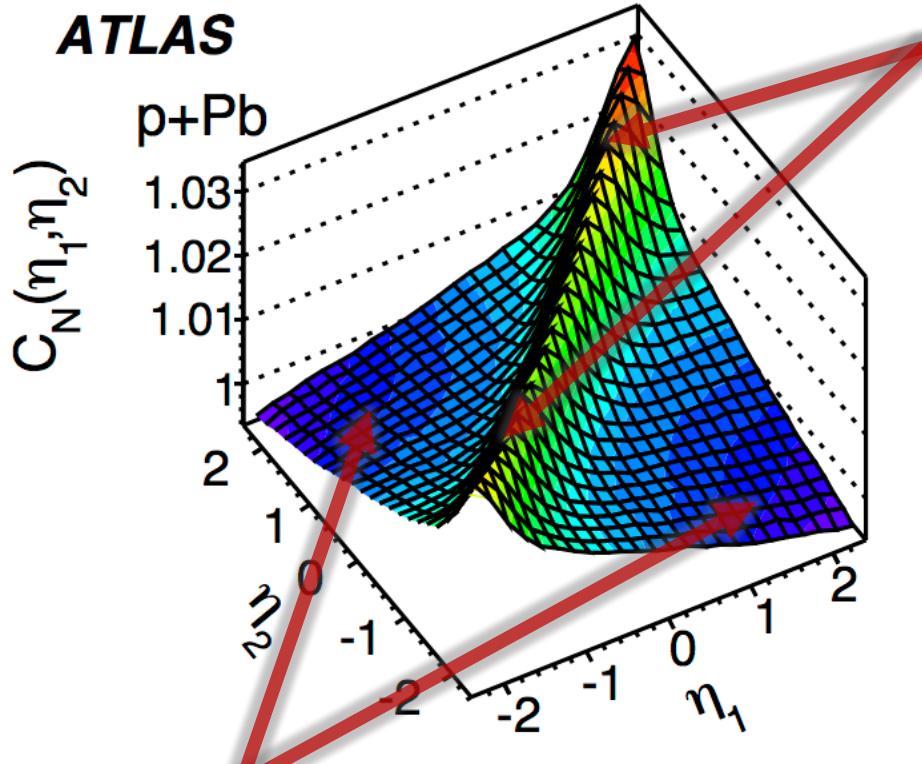
- Two particles observable (correlation function)

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

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

- Advantage of correlation function

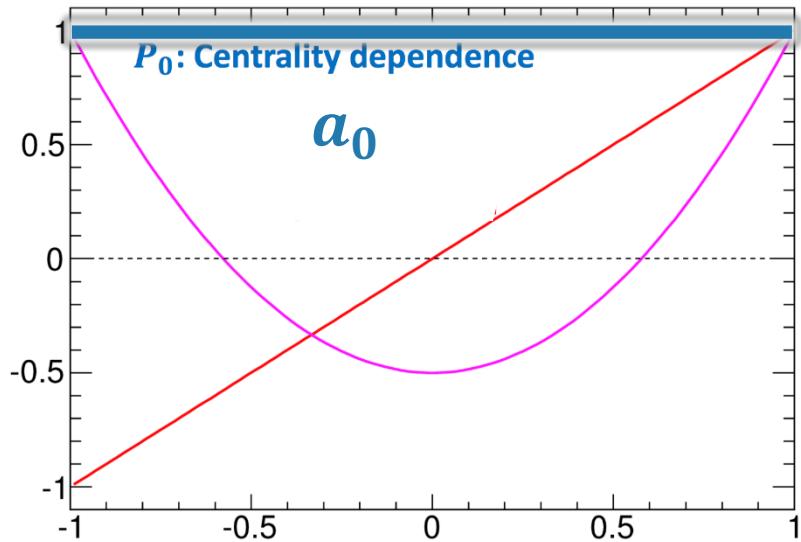
- Disentangles dynamical fluctuation from statistical fluctuation.
- Detector effects removed by mixed events;



- Long-range correlation

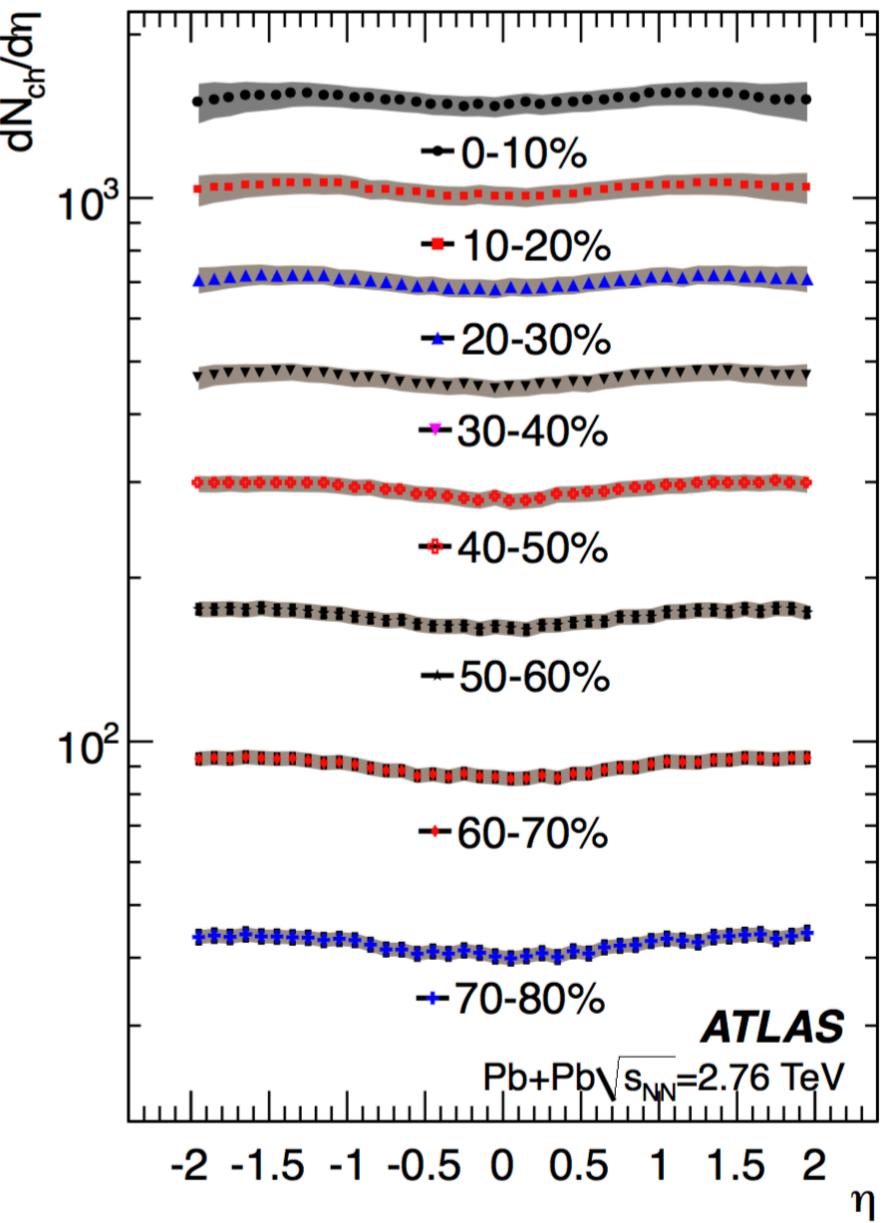
- Short-range correlation reflects correlation in the different sources: jet fragmentation, resonance decay...
- Since SRC has a strong charge dependence, a data-driven way was developed to remove the SRC (backup).
- An alternative way is through multi-particle correlation (cumulant) in η .
[Phys. Rev.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

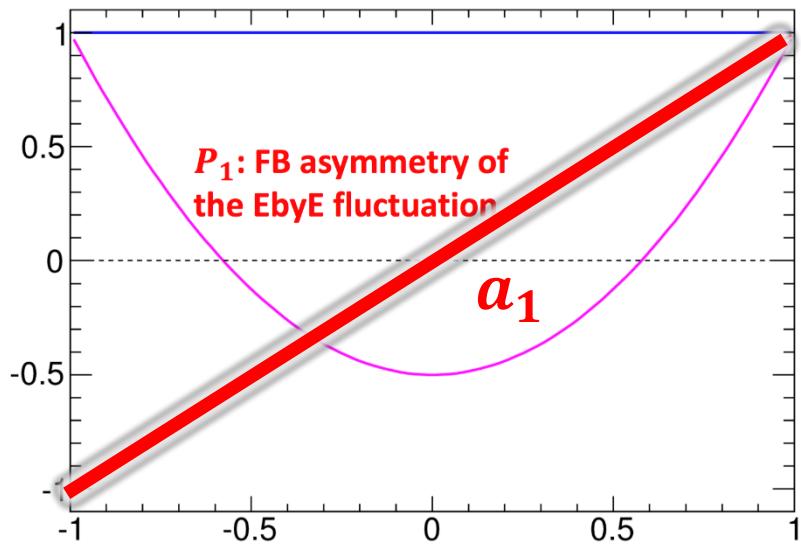
How to quantify forward-backward fluctuation?



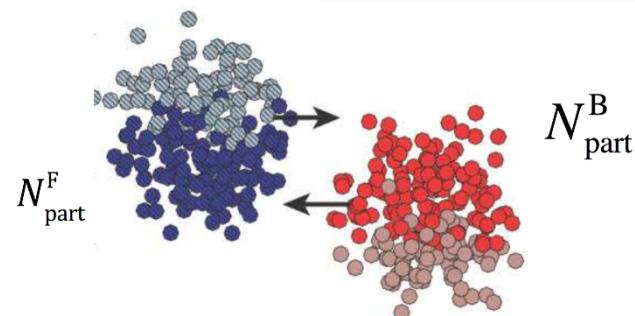
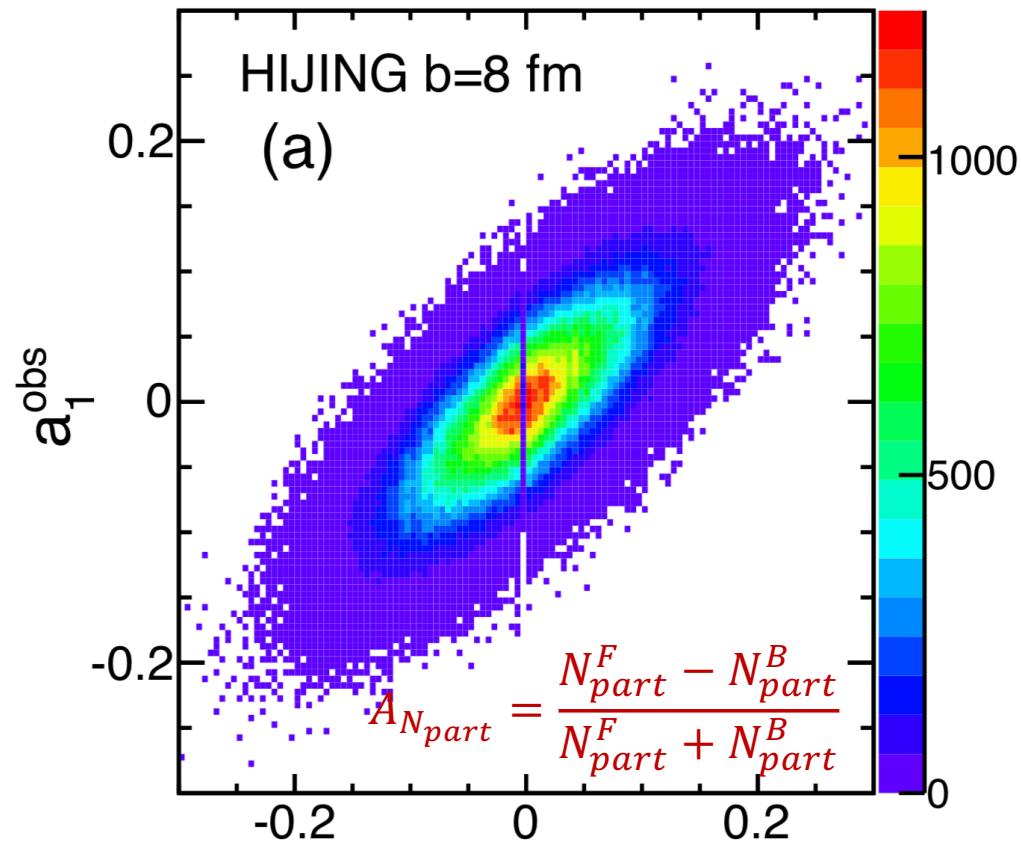
- Analysis focuses on dynamical fluctuation upon average;
- However, average multiplicity changes with centrality;
- The residual centrality dependence is removed by normalizing $C(\eta_1, \eta_2)$

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

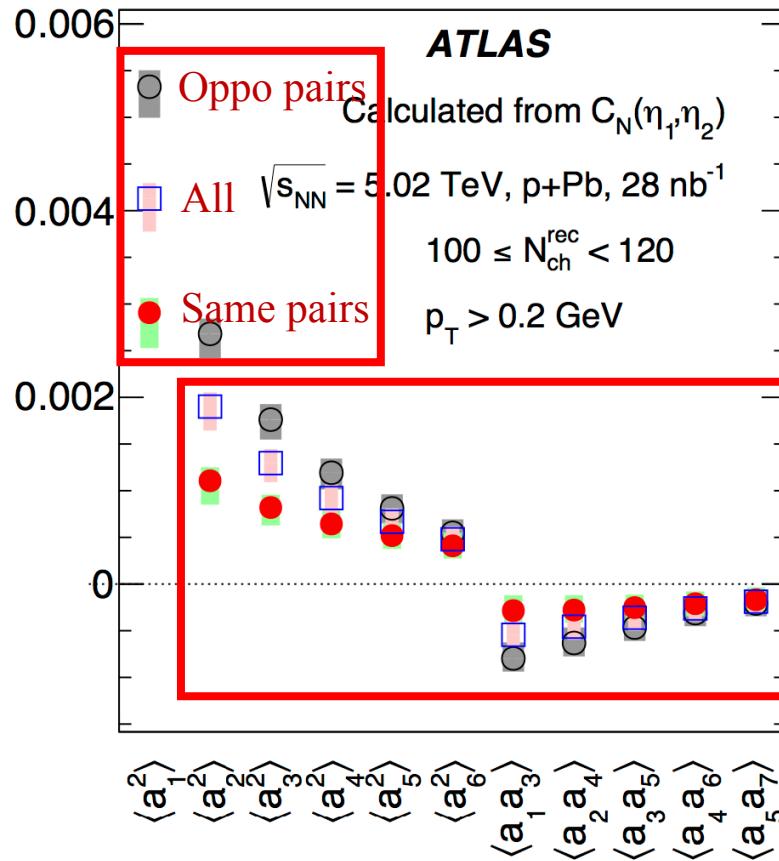




- The linear shape quantifies the FB multiplicity asymmetry;
- HIJING shows strong correlation between final multiplicity asymmetry and initial participant asymmetry;
- As will be shown later, this component dominates the shape fluctuation.



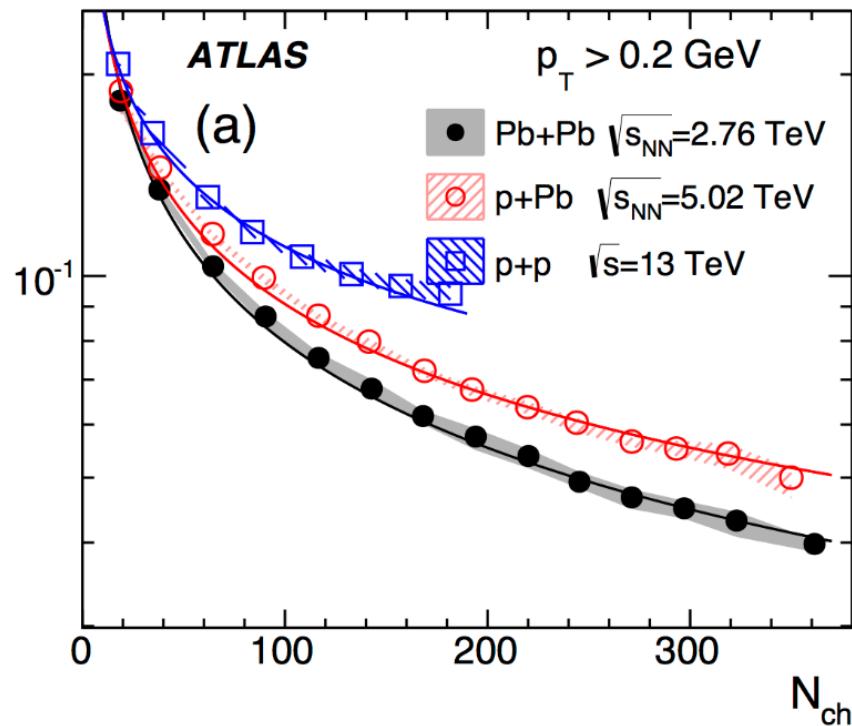
Before SRC removal



- 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.

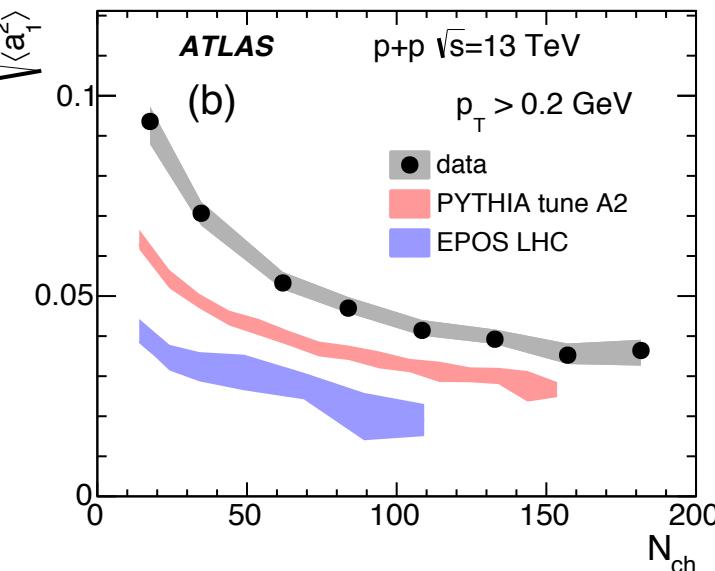
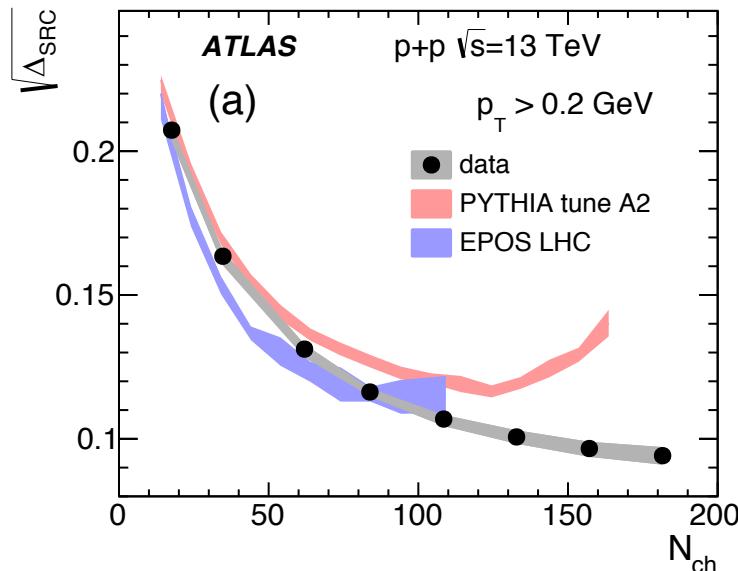
SRC



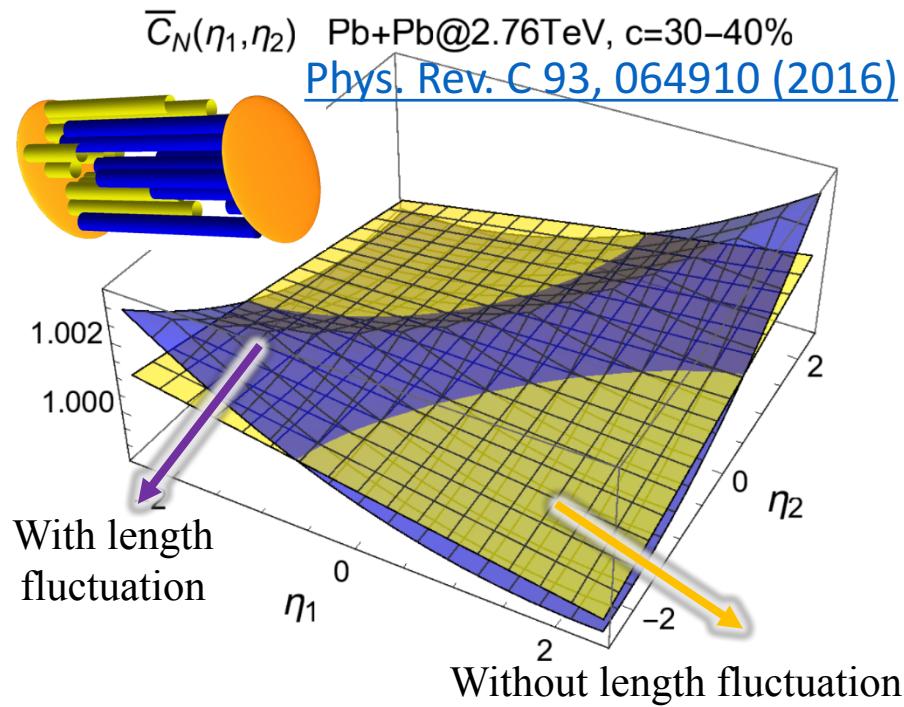
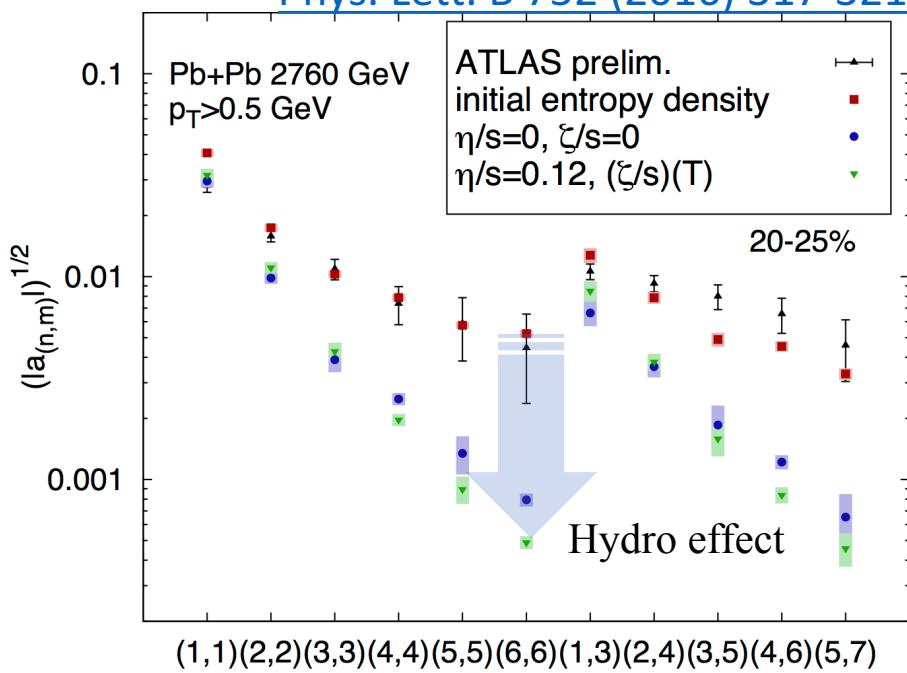
- SRC increases towards peripheral;
- SRC is stronger in small systems;

How will these new results help?

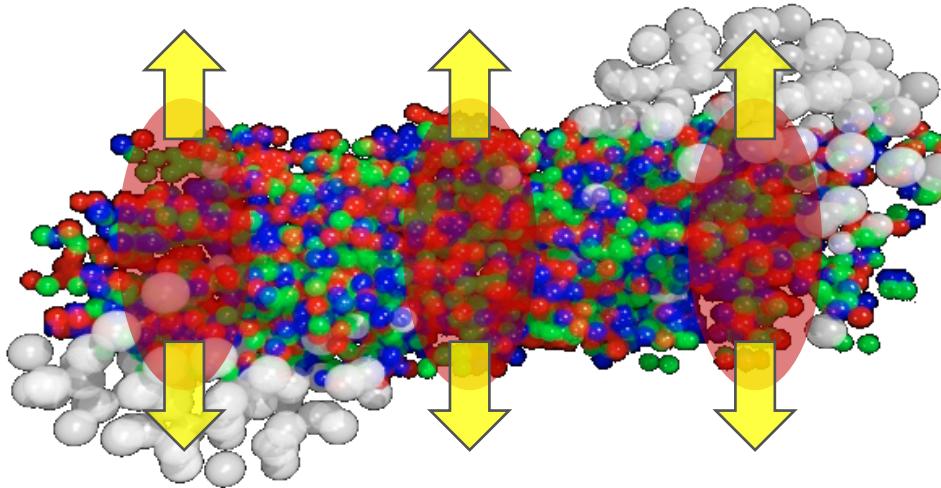
Model and data comparison



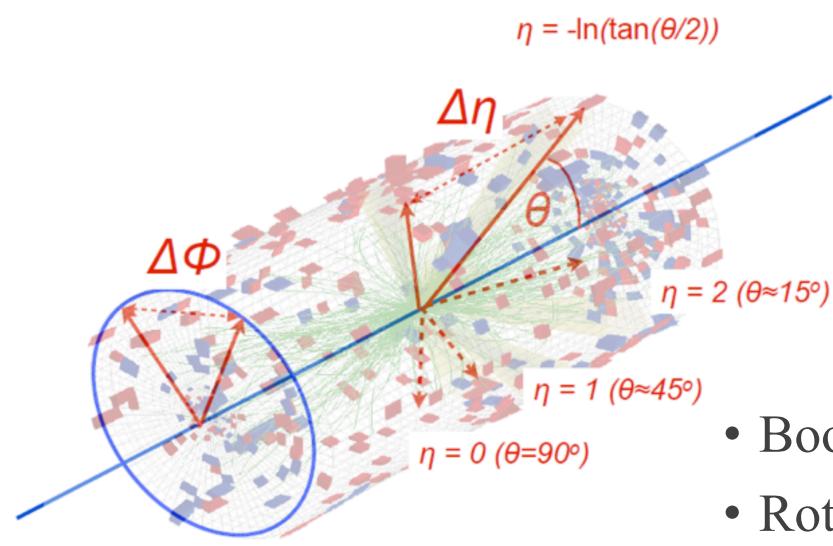
[Phys. Lett. B 752 \(2016\) 317-321](#)



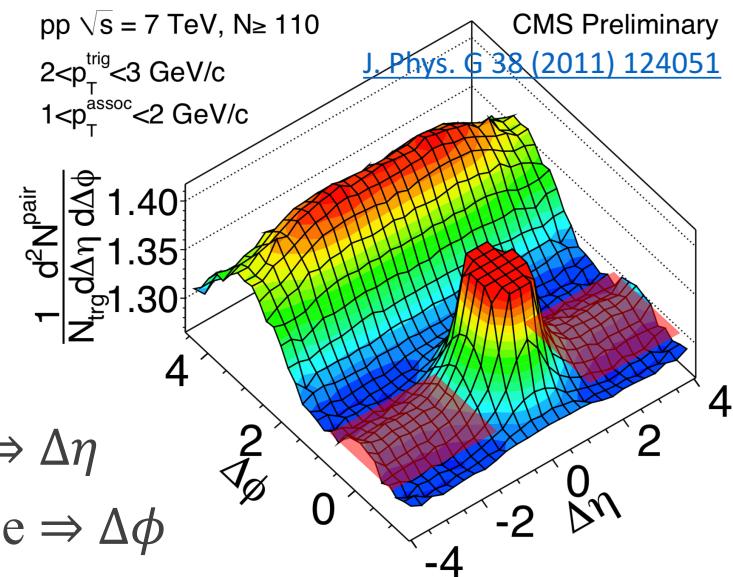
Nature of sources seeding the long-range collective behaviors?



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

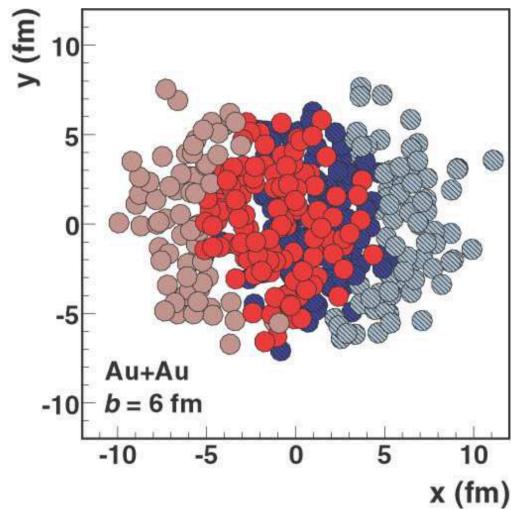


- Boost invariance $\Rightarrow \Delta\eta$
- Rotation invariance $\Rightarrow \Delta\phi$



Origins of collectivity

- Final state correlations

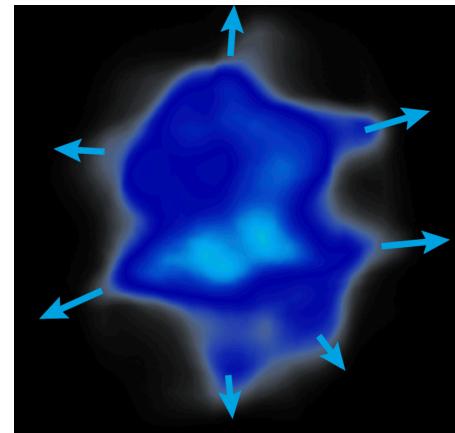


Spatial structure from initial condition

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

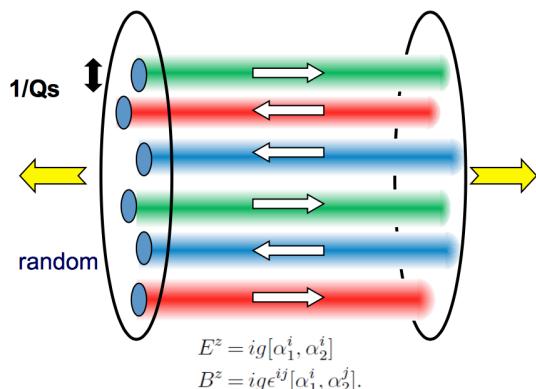


Hydrodynamic flow



Momentum correlations

- Initial state correlations



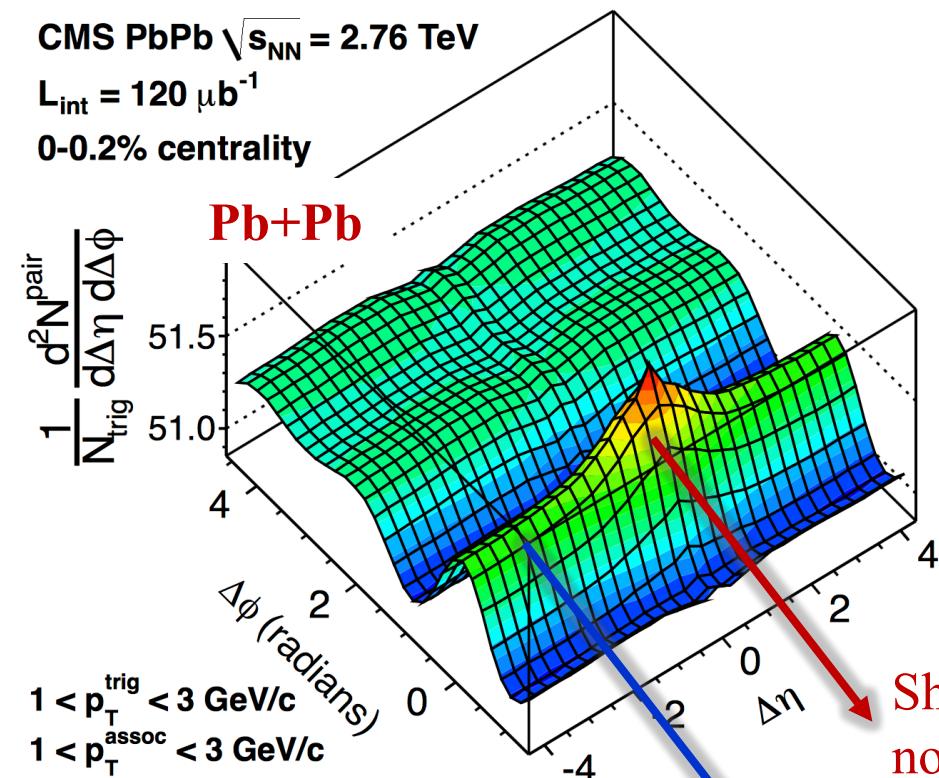
More careful studies in pp collisions are needed!

Particles are produced with momentum space correlations

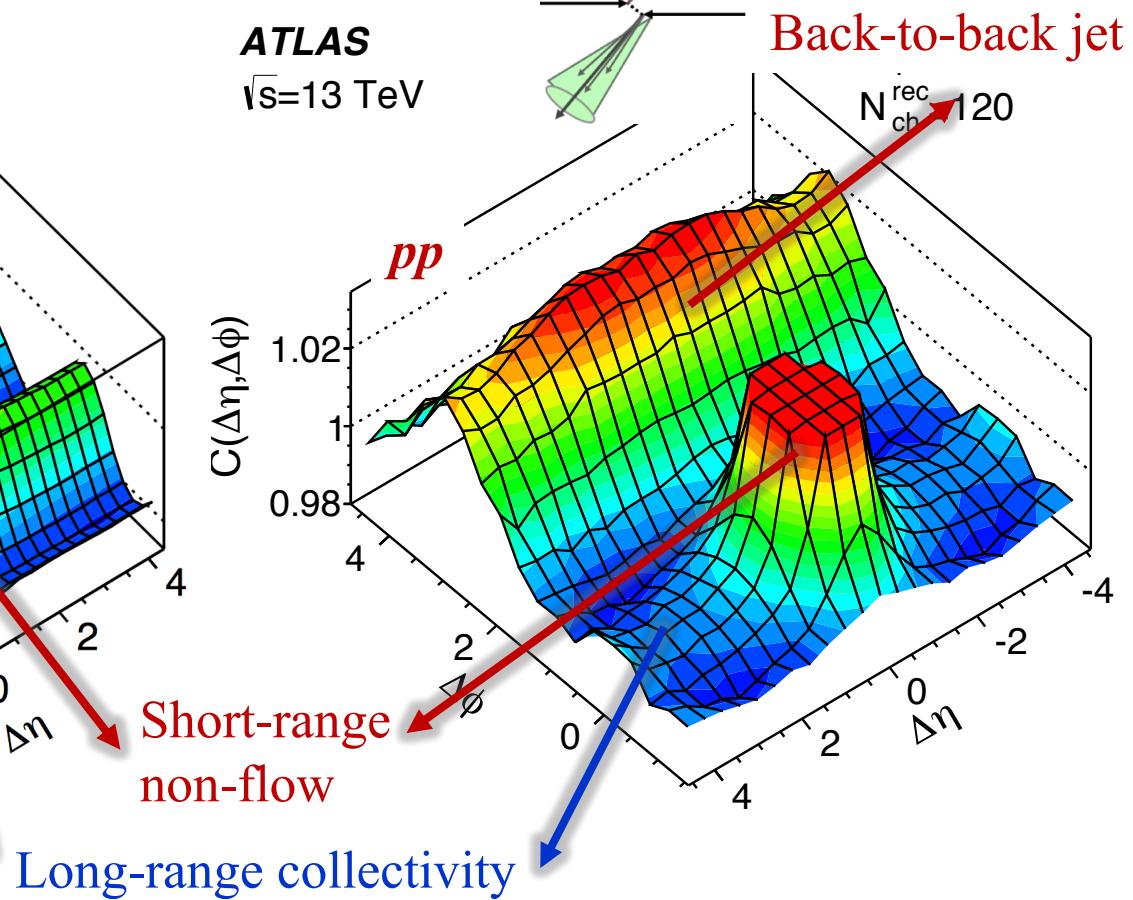
2-particle correlation

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



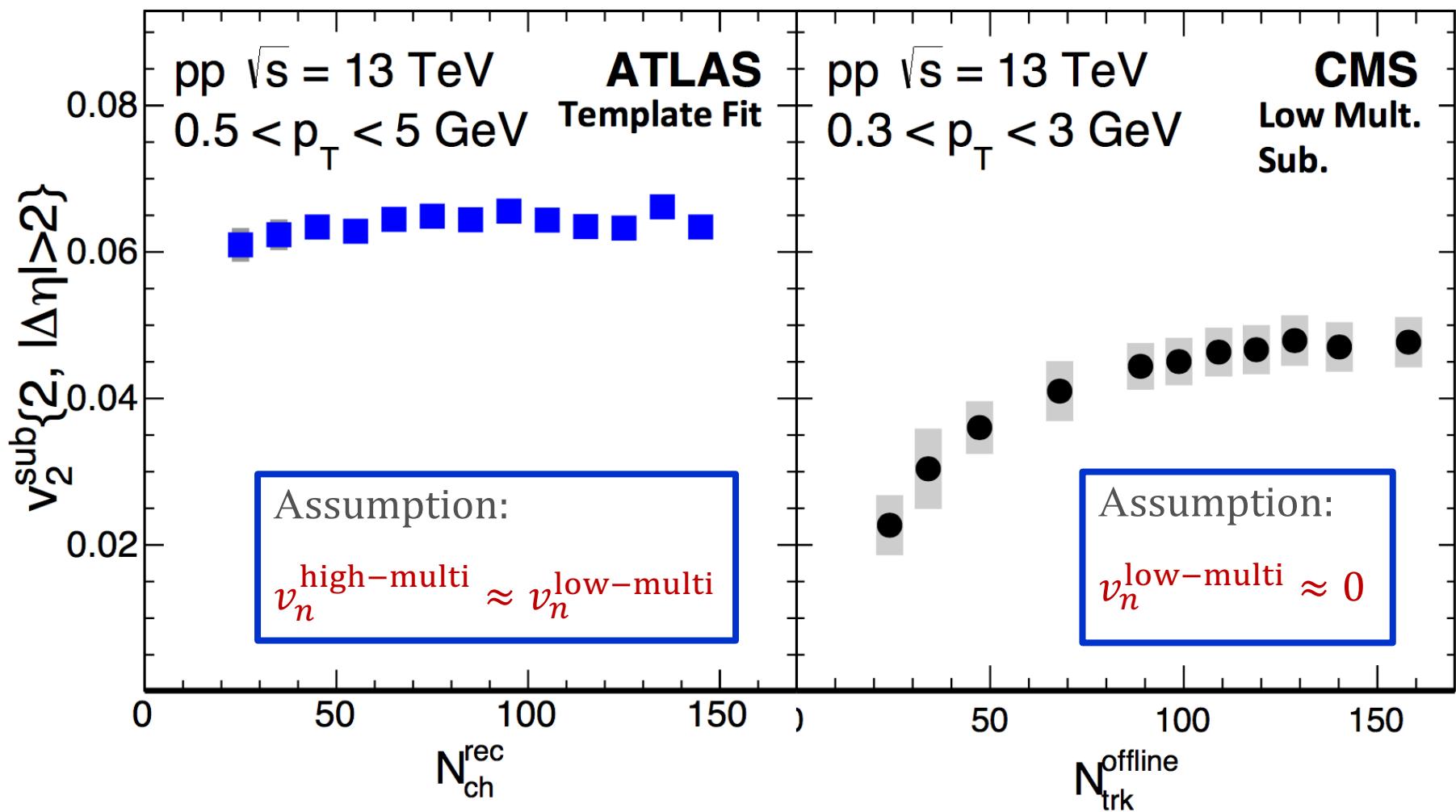
ATLAS
 $\sqrt{s}=13 \text{ TeV}$



Short-range non-flow

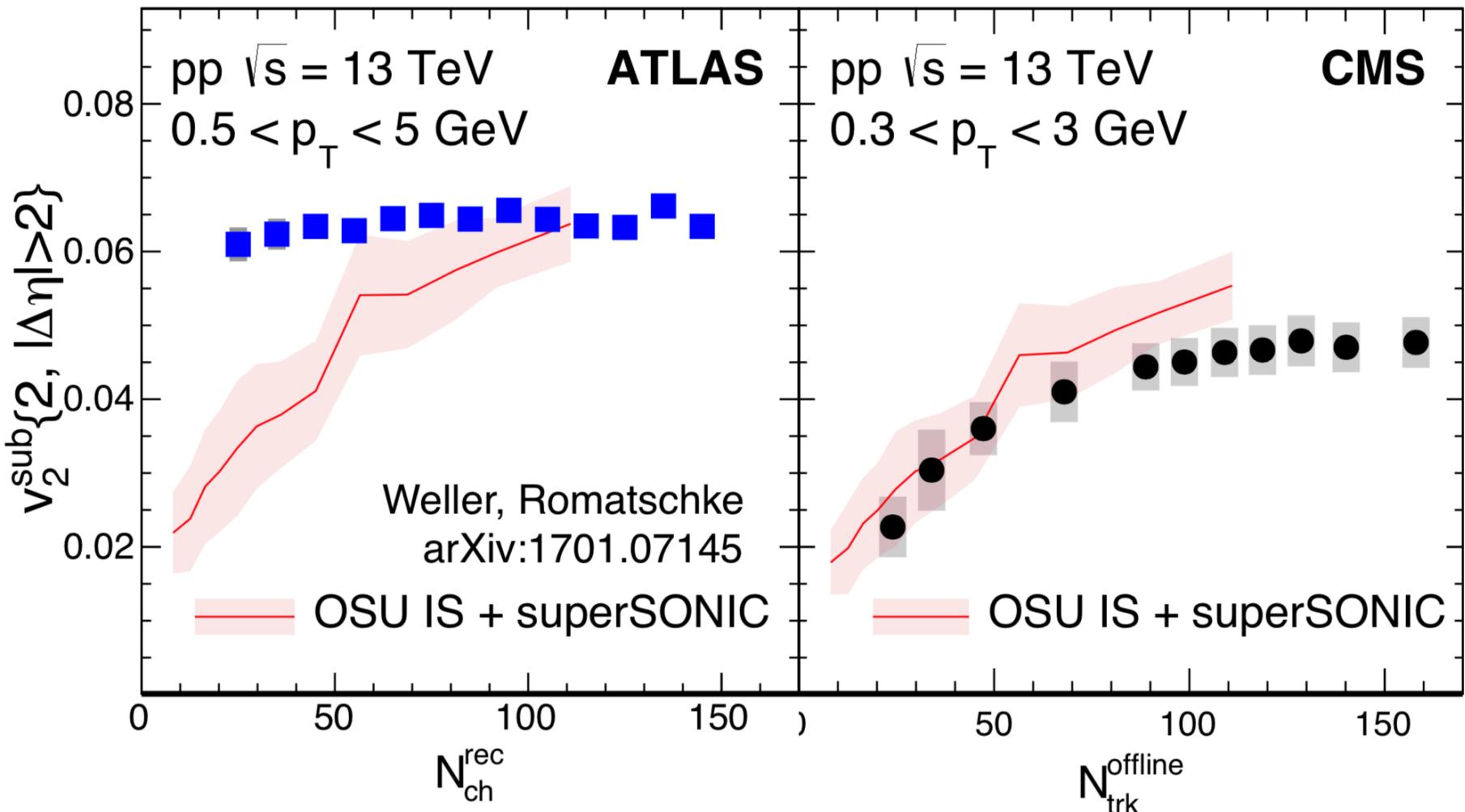
Long-range collectivity

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



Does collectivity turn off at lower N_{ch} ?

Template fit

Low- N_{trk} subtraction

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

Cumulant method

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

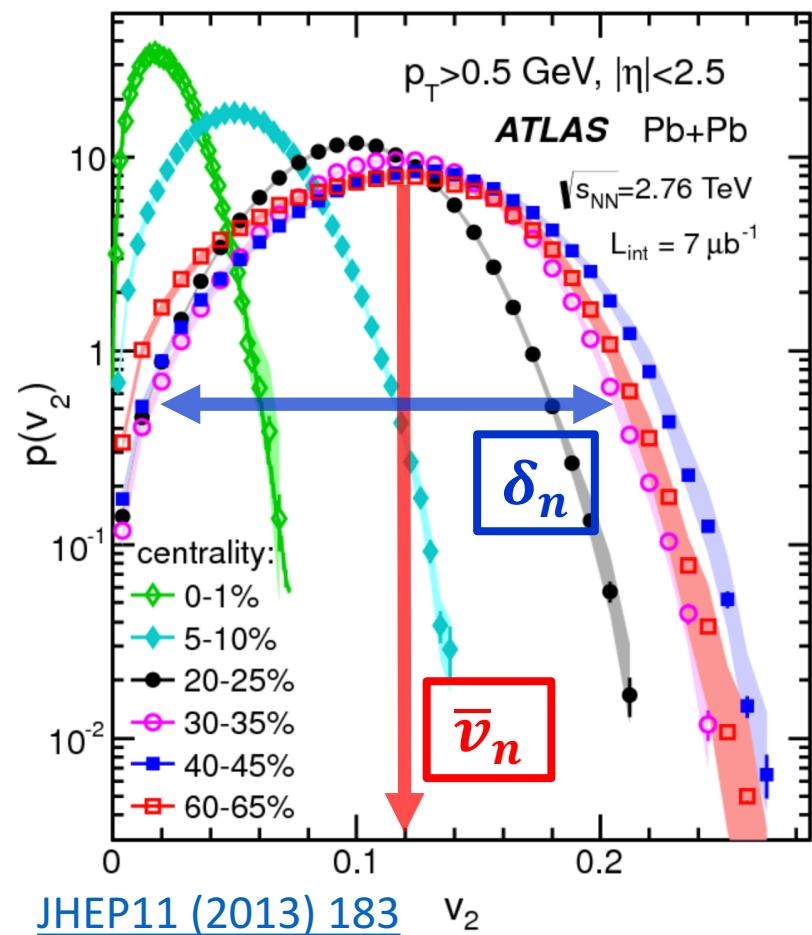
- Flow fluctuates from event to event;

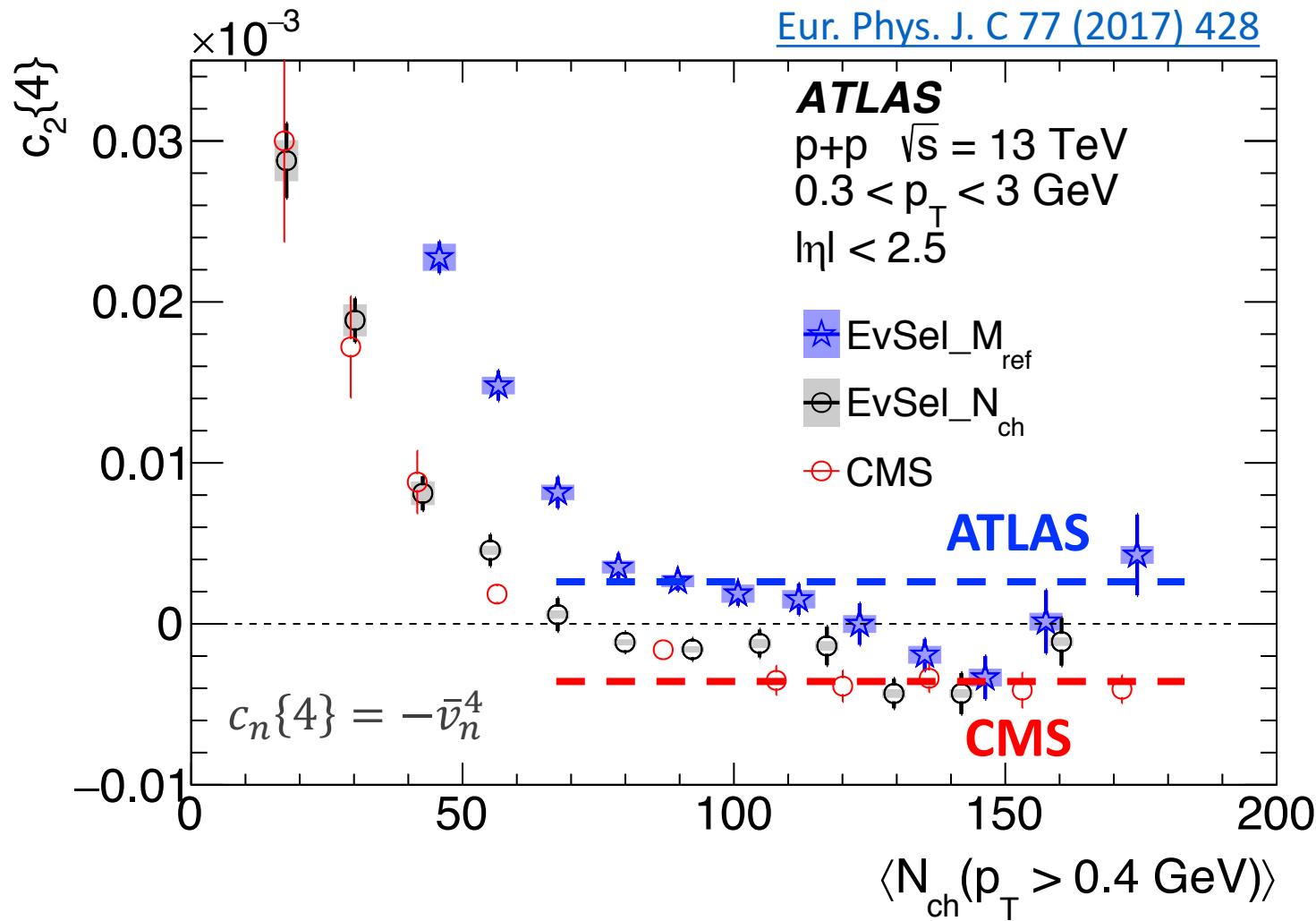
- Cumulant probes $p(v_n)$.

- Features of cumulant method

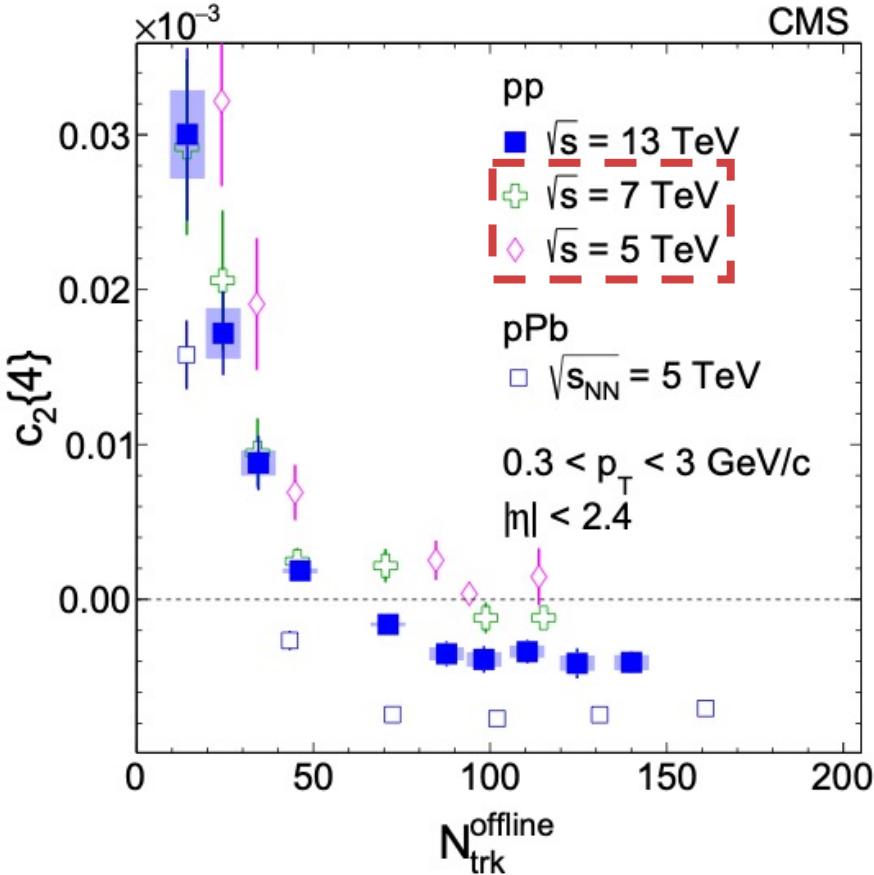
- Suppress non-flow (< 4 particles);
- If $p(v_n) \sim \text{Gauss}$, then $c_n\{4\} = -\bar{v}_n^4$

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

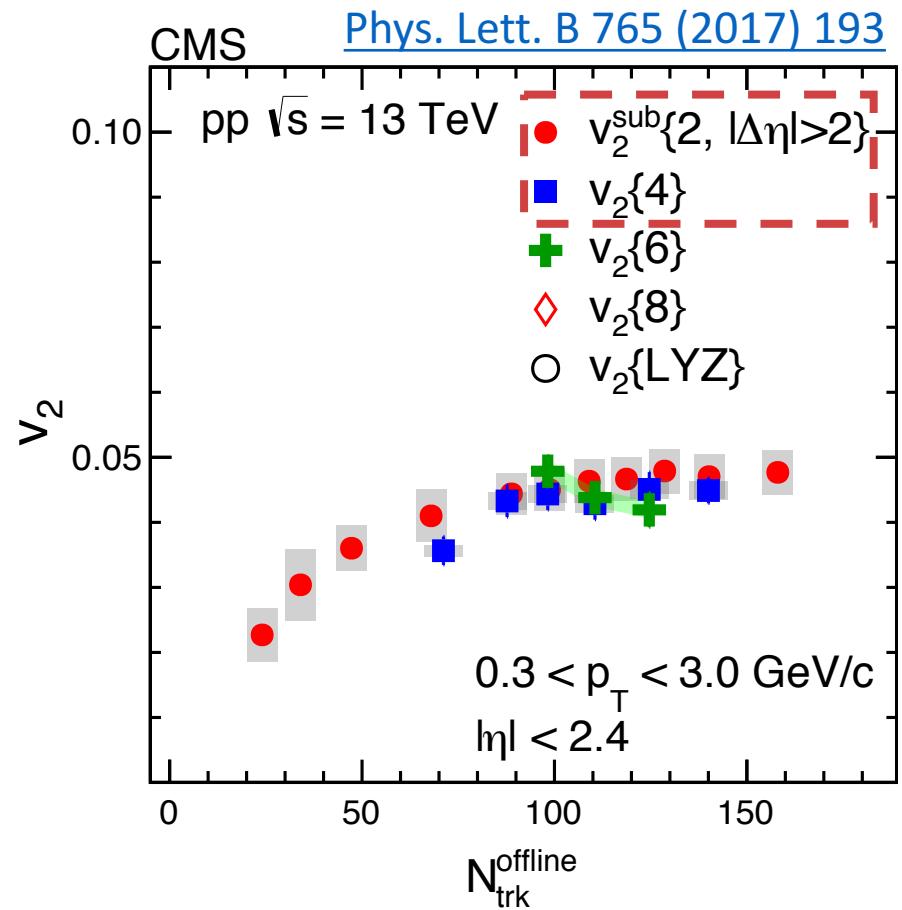




To be **collective**, or not to be **collective**?



- No hint of collectivity at lower energy?

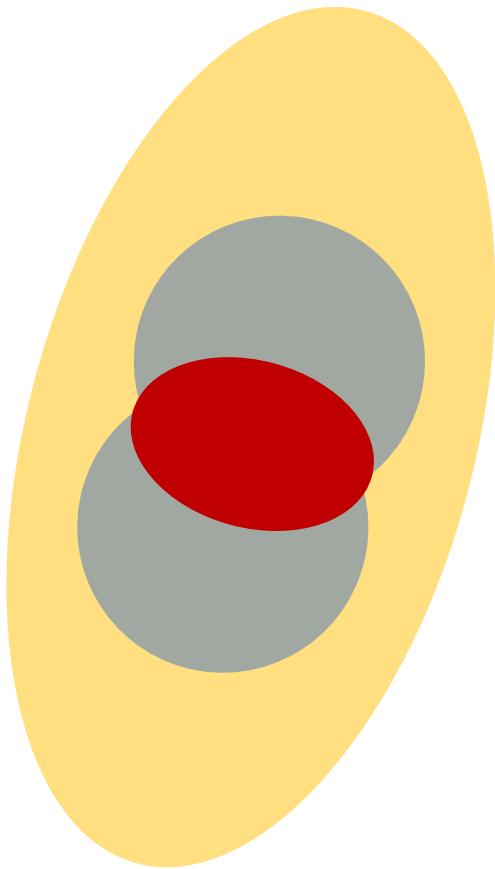


- $v_2\{2\} = v_2\{4\} + \text{flow fluc}$
- Flow fluc ≈ 0 ?

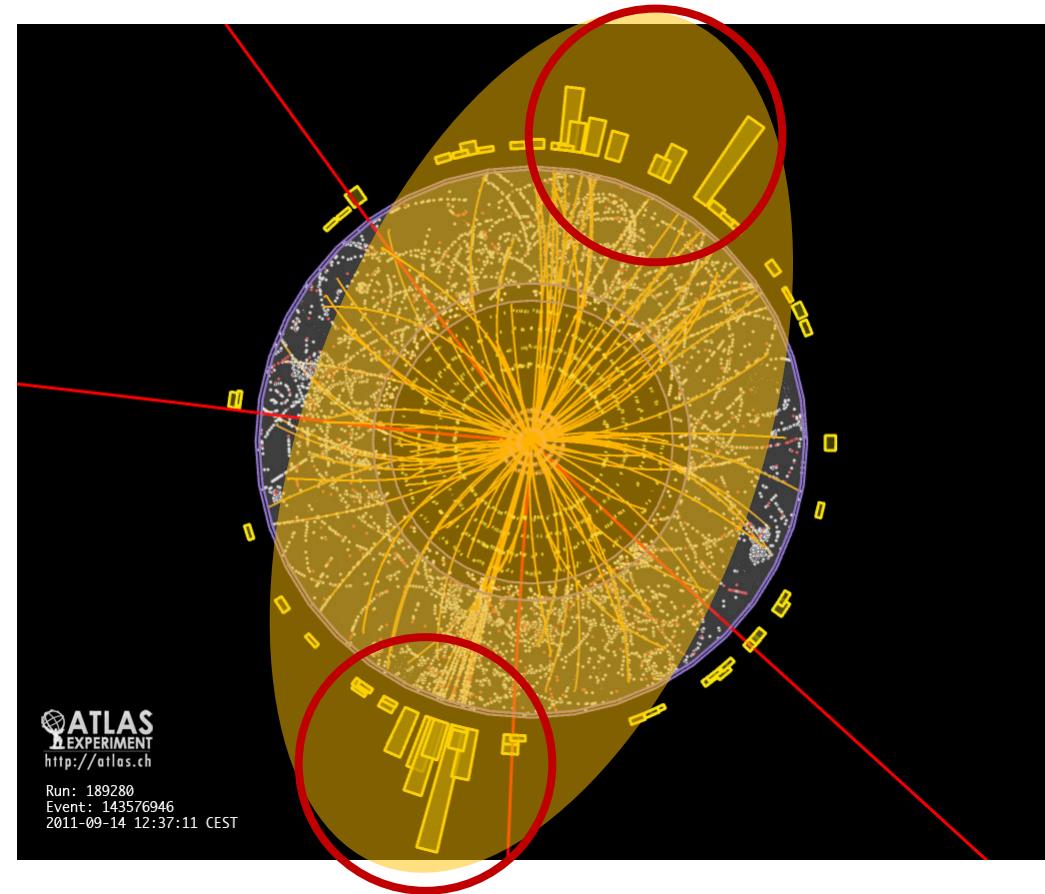
Puzzles needs to be solved before testing models with data.

Signal or background?

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Signal: collectivity

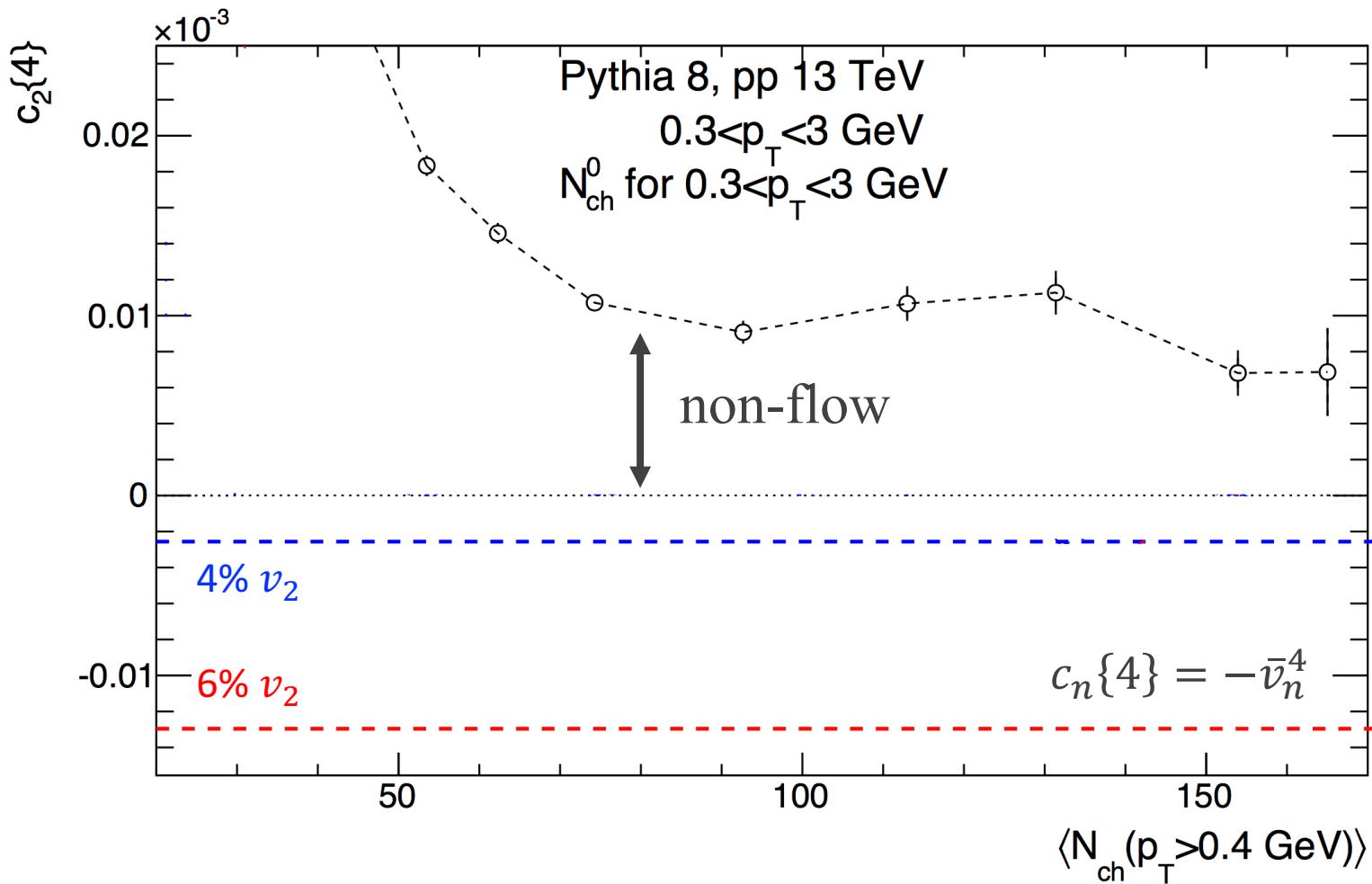


Background: dijets

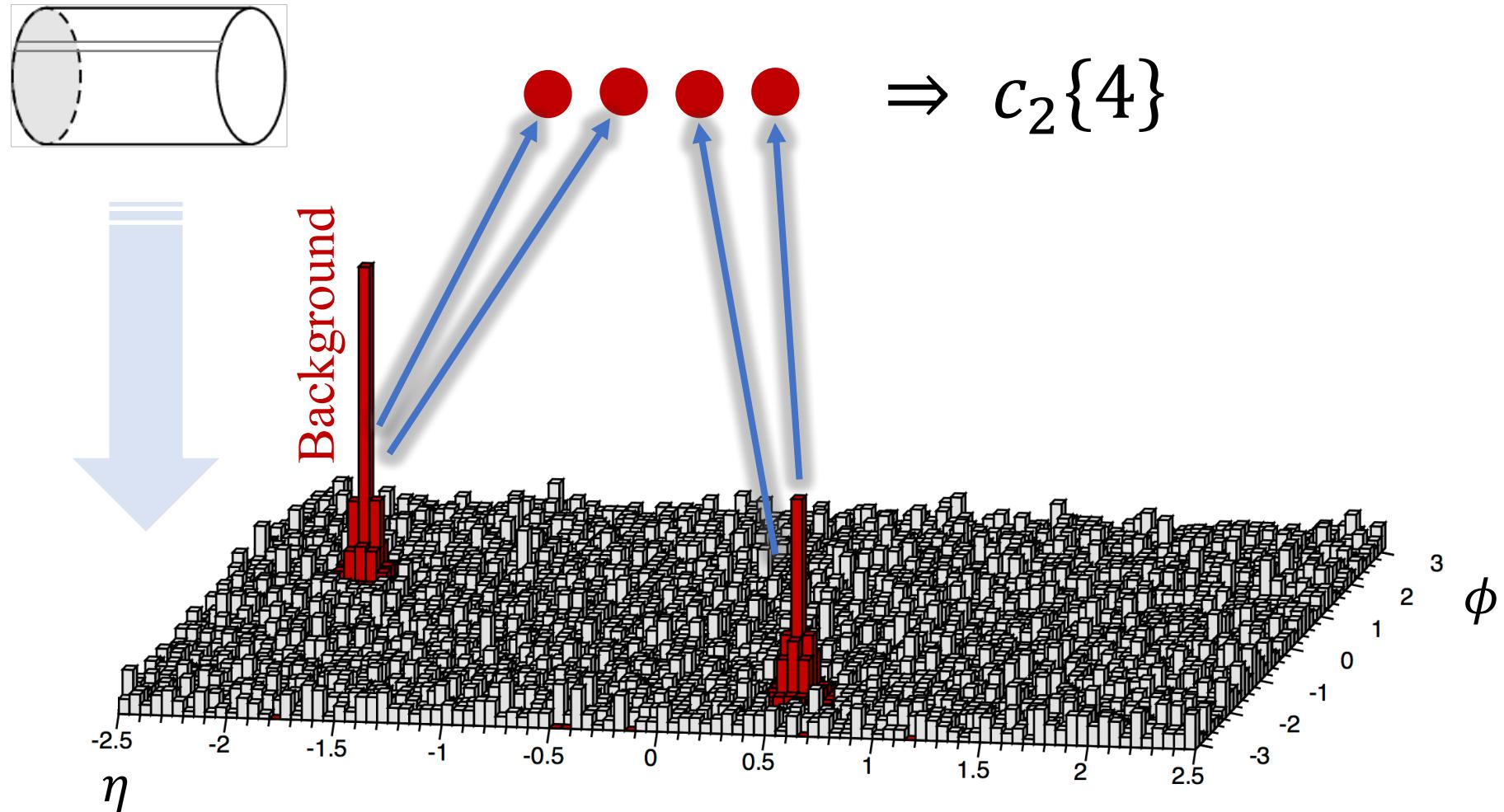
Maybe background is the one to blame?

Test of background

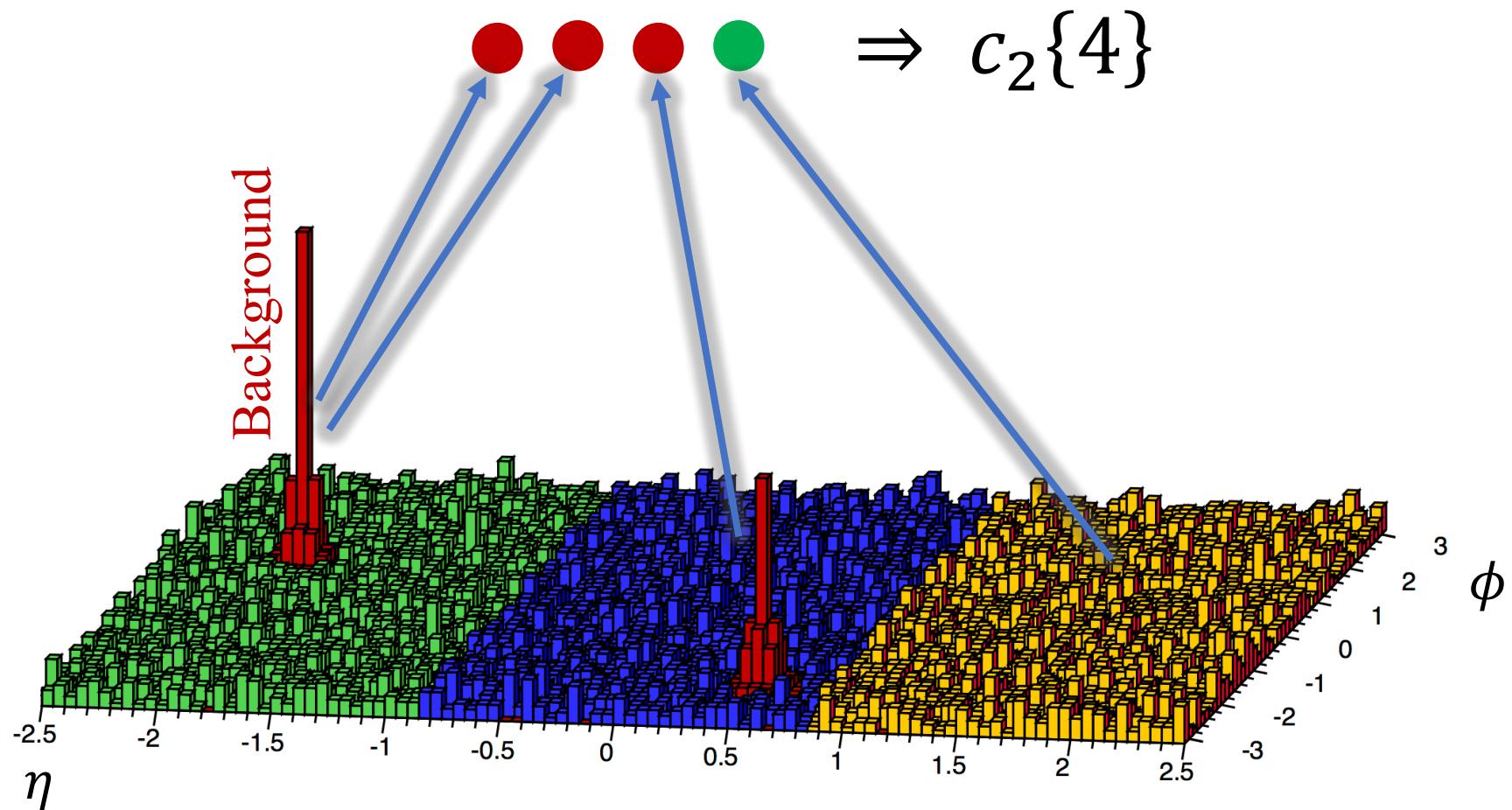
27



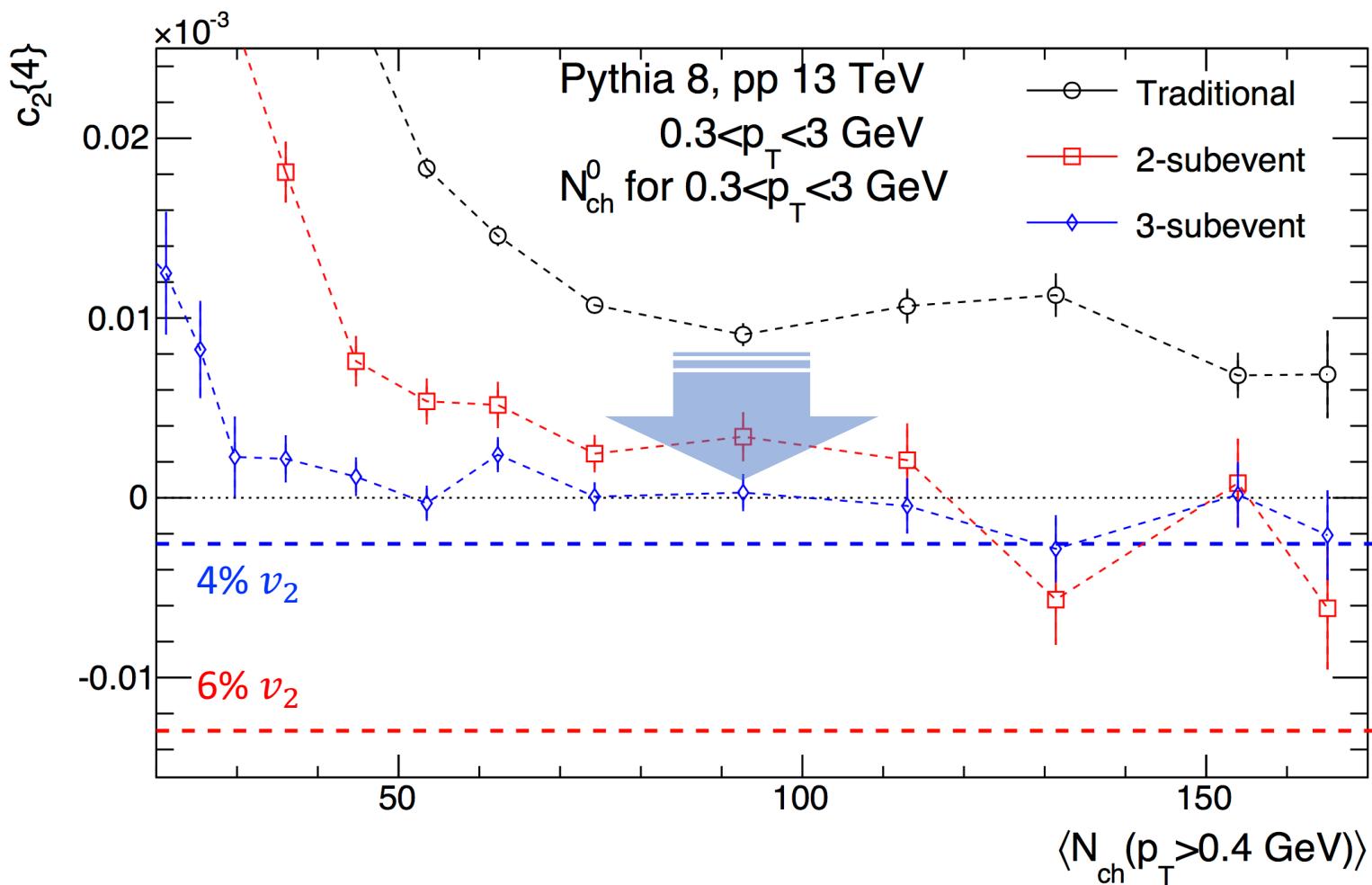
Traditional cumulant cannot remove non-flow in pp



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



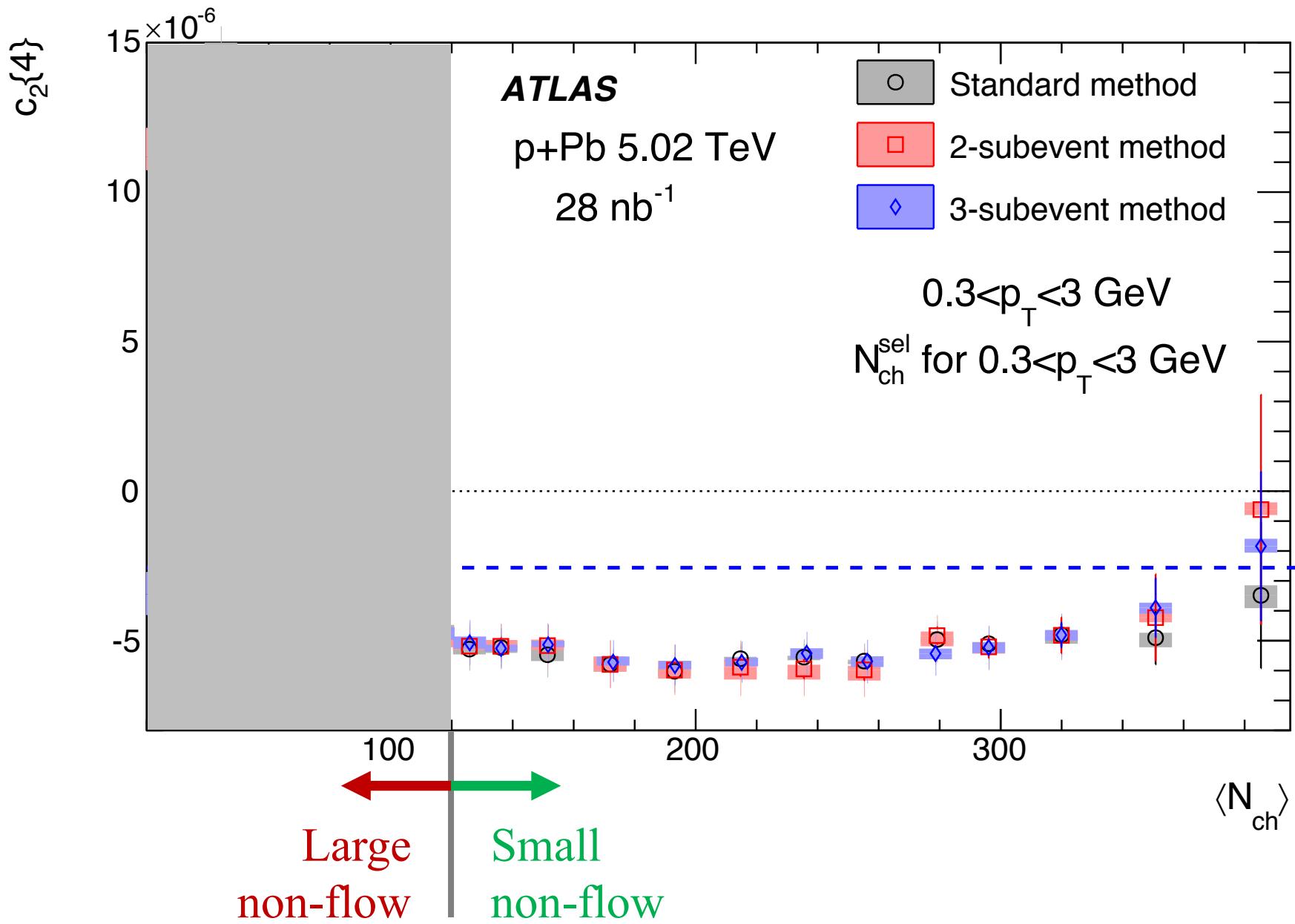
$$3 > 2$$

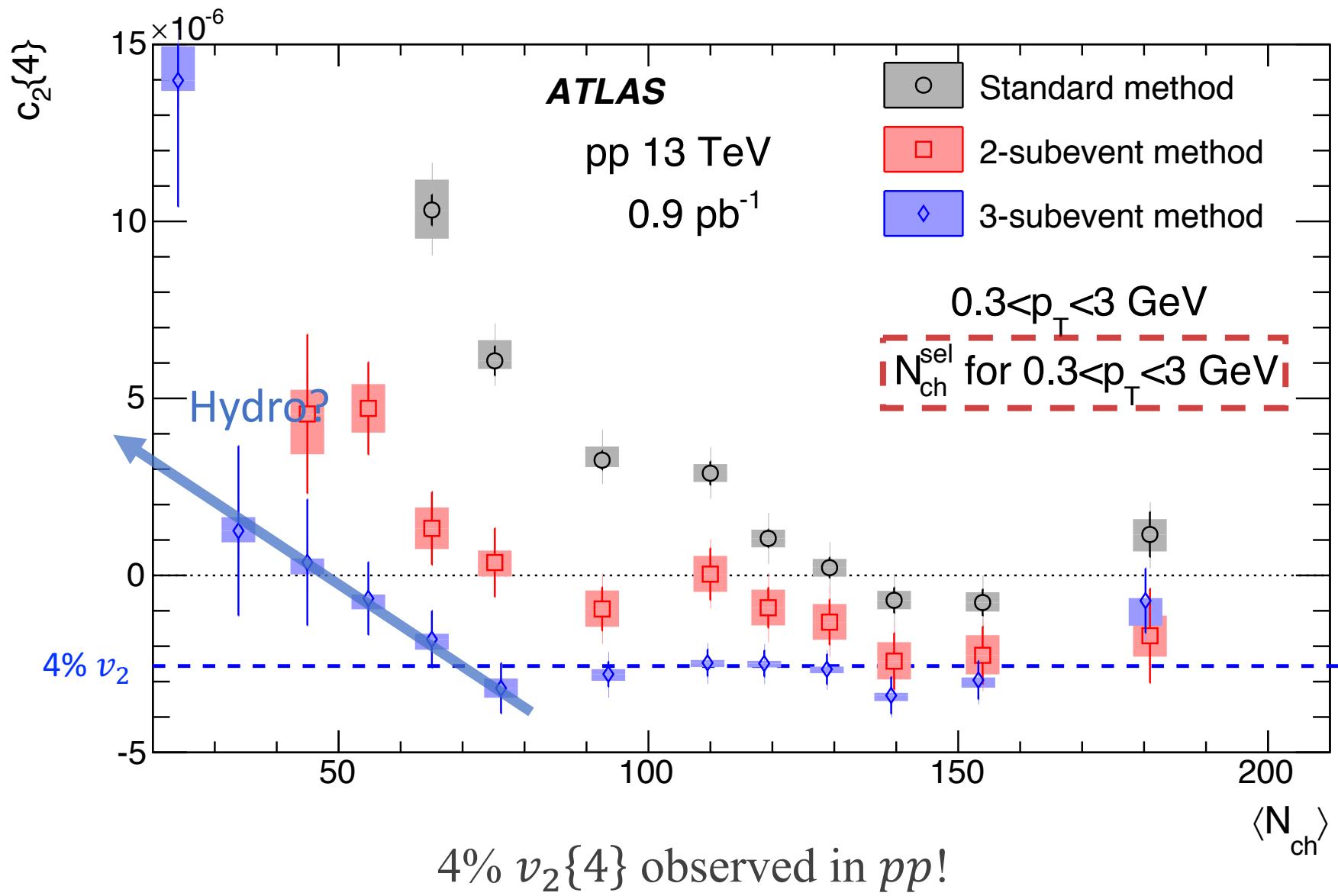


Subevent method can suppress non-flow in PYTHIA

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

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$c_2\{4\}$ in pp 

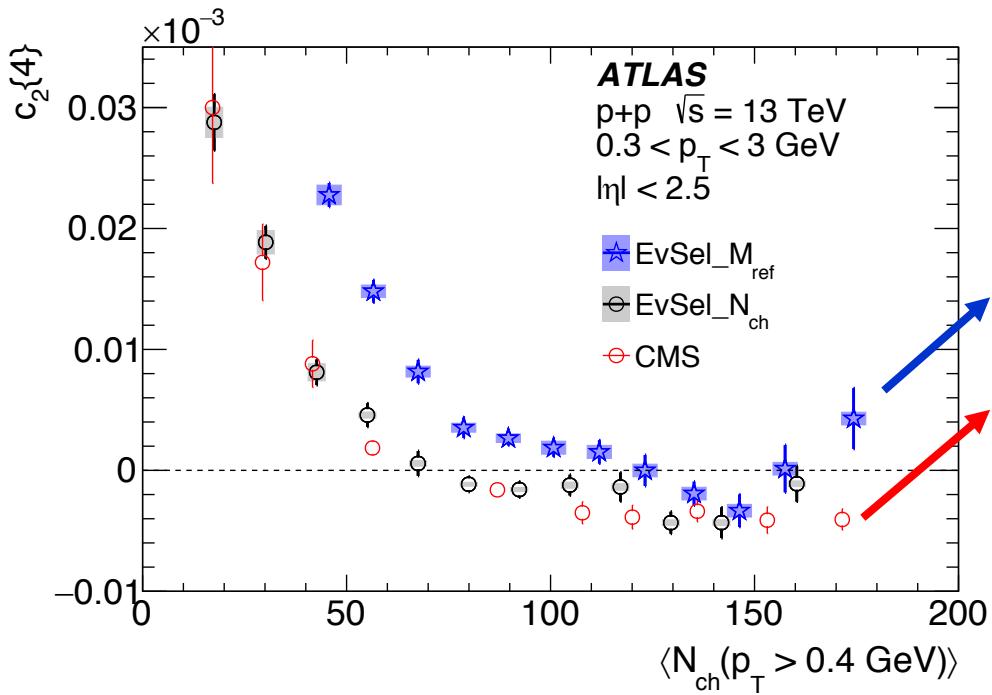
Test of residual non-flow

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

Non-flow changes greatly EbyE

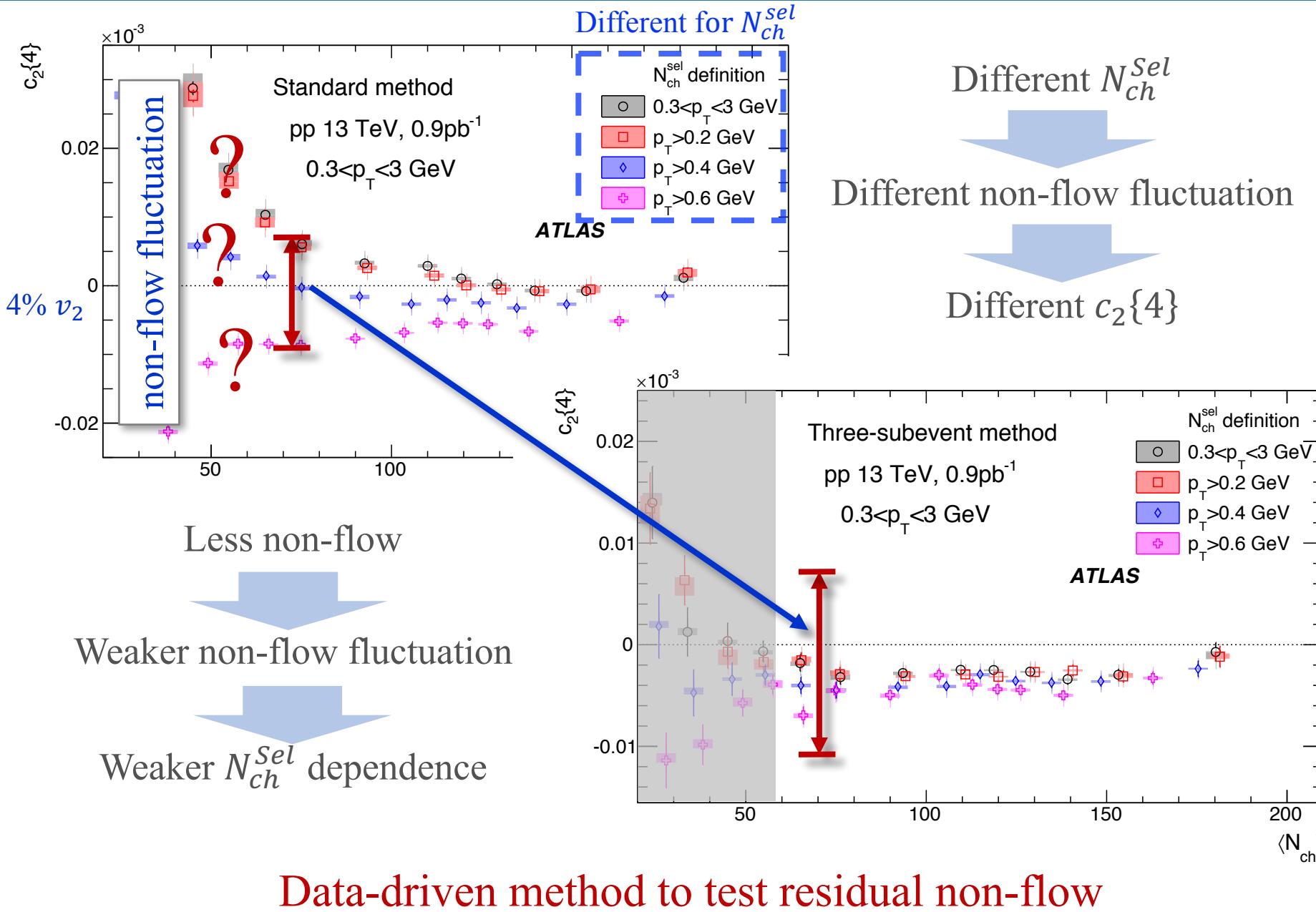
Flow changes little EbyE

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



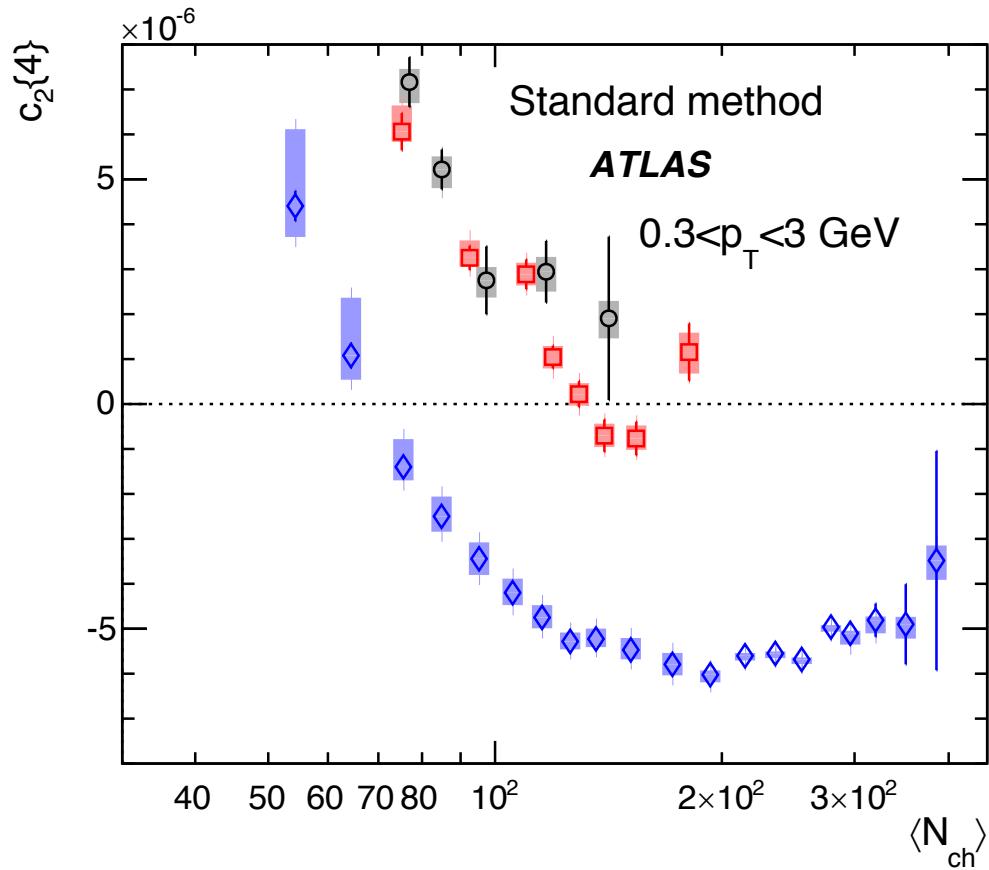
- N_{ch}^{Sel} defined with different p_T : very different non-flow fluctuation.
- N_{ch}^{Sel} defined with $0.3 < p_T < 3.0 \text{ GeV}$
- N_{ch}^{Sel} defined with $p_T > 0.4 \text{ GeV}$
- Non-flow fluctuation might mimic the flow signal (negative $c_2\{4\}$)!

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



Puzzle 2: energy dependence

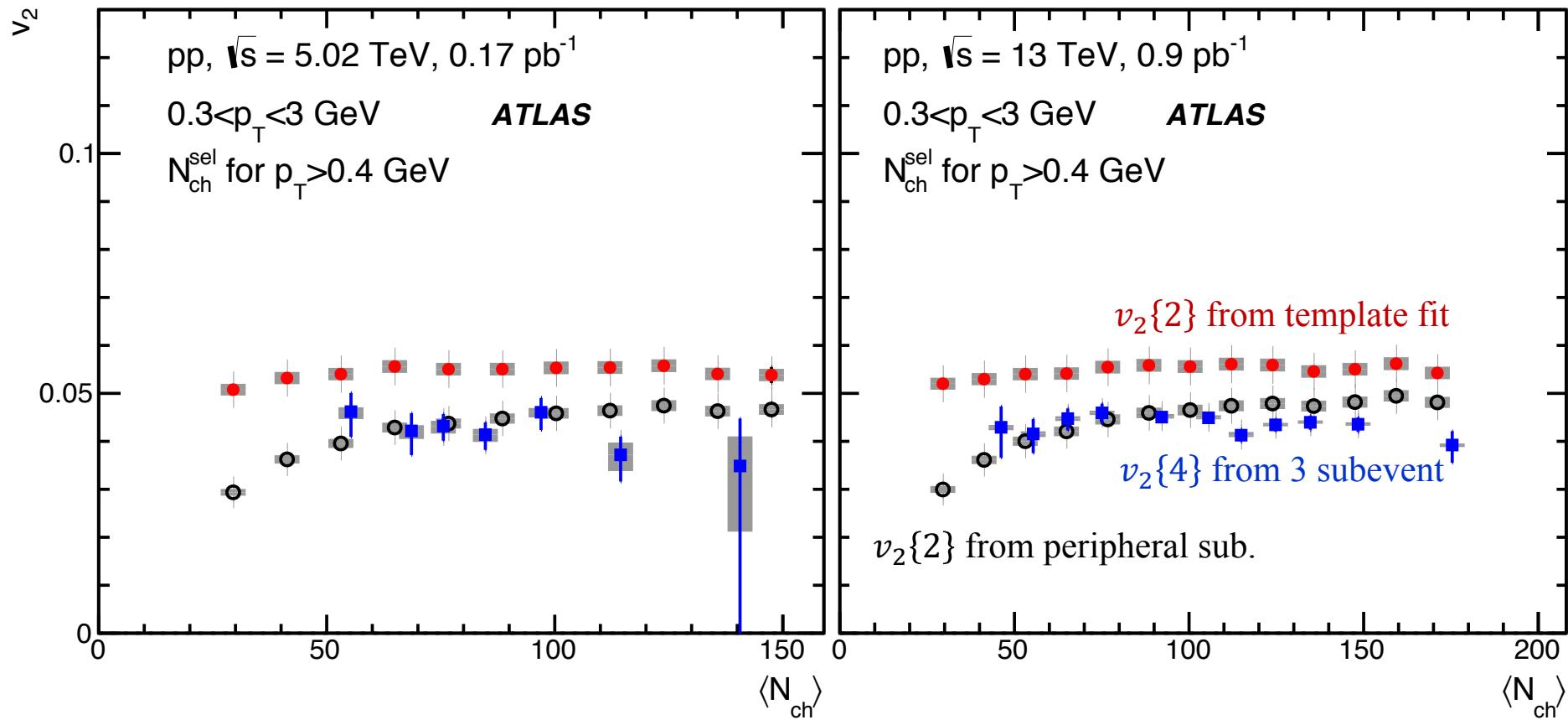
35



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

Puzzle 3: flow fluctuation

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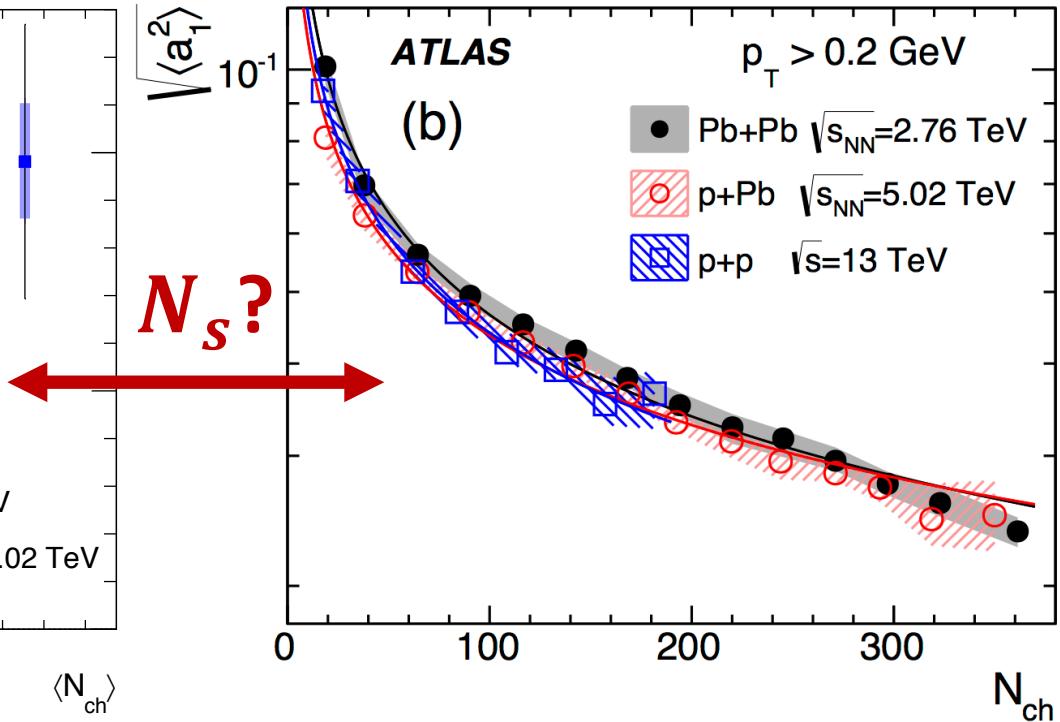
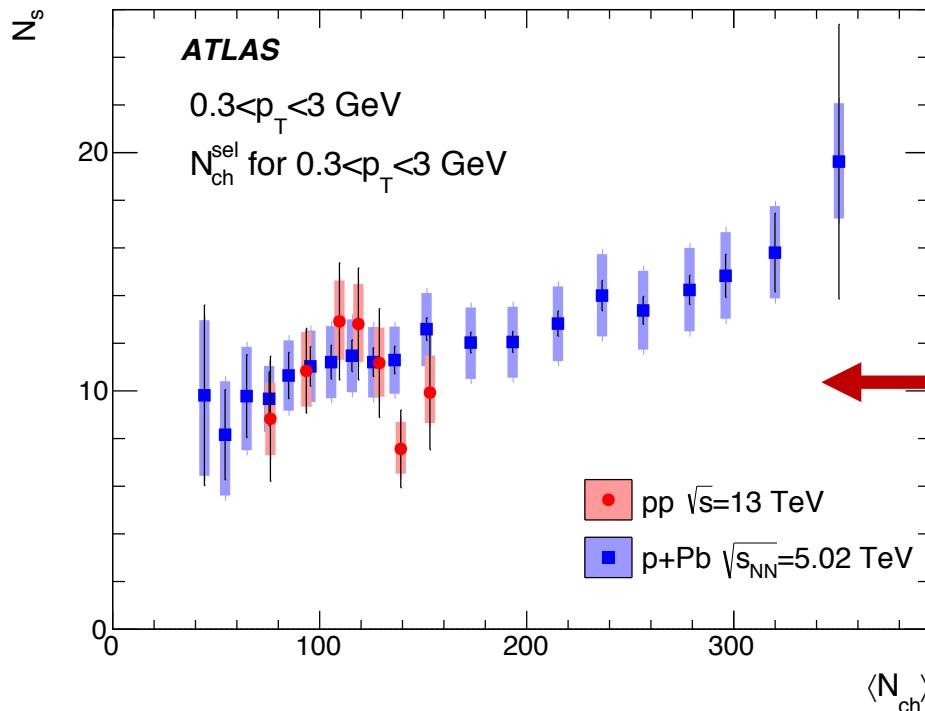
- $v_2\{4\} < v_2\{2\}$ (template fit): flow fluctuation;
- $v_2\{4\} \approx v_2\{2\}$ (peripheral sub.): underestimation of $v_2\{2\}$;
- Subevent cumulant is free of assumptions.

Number of sources

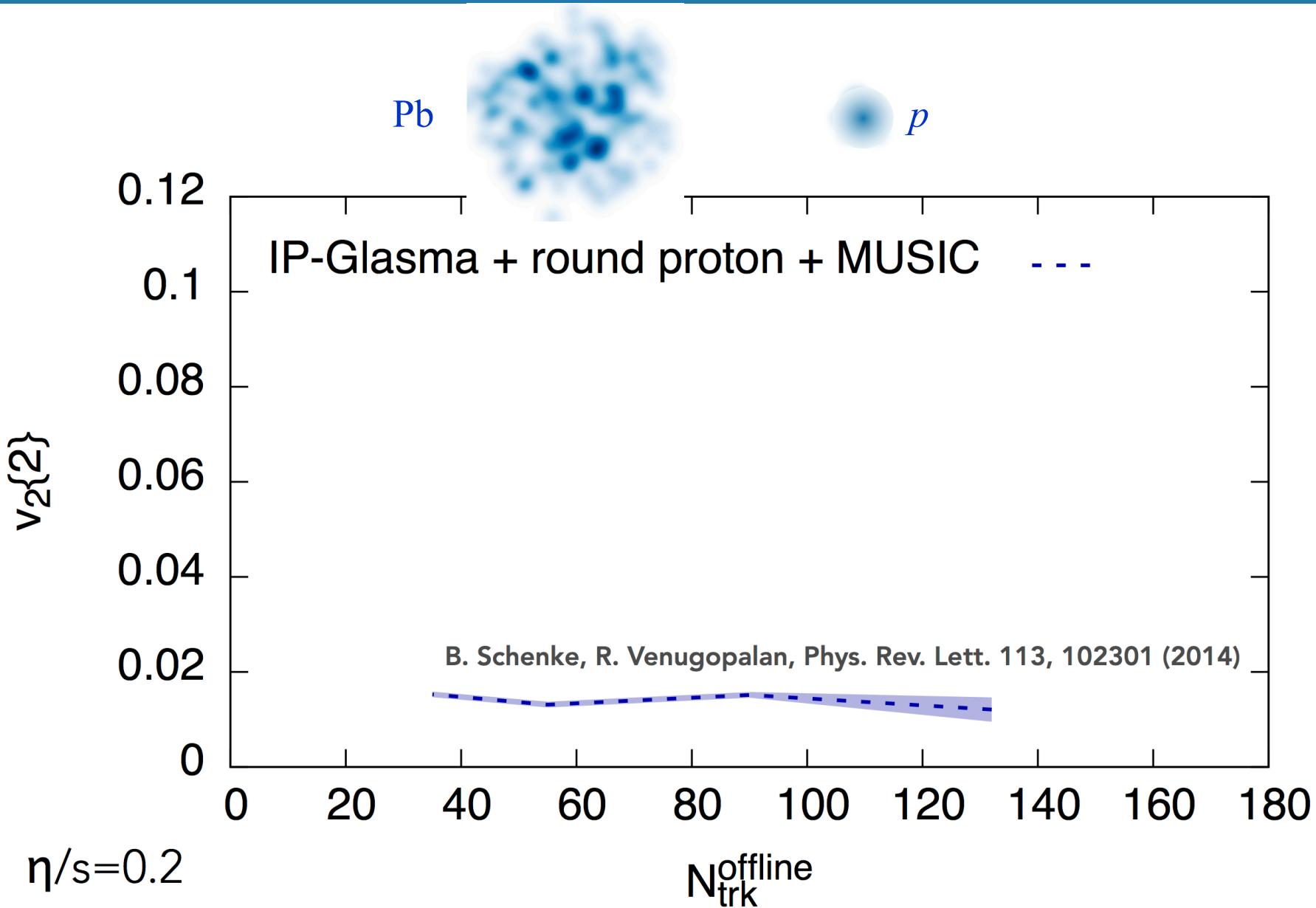
- $\nu_2\{2\} \neq \nu_2\{4\}$: EbyE flow fluctuations associated with fluctuating initial conditions. [Phys. Rev. Lett. 112, 082301 \(2014\)](#)
- Fluctuation can be quantified to the number of sources N_s in the initial stage:

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

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



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

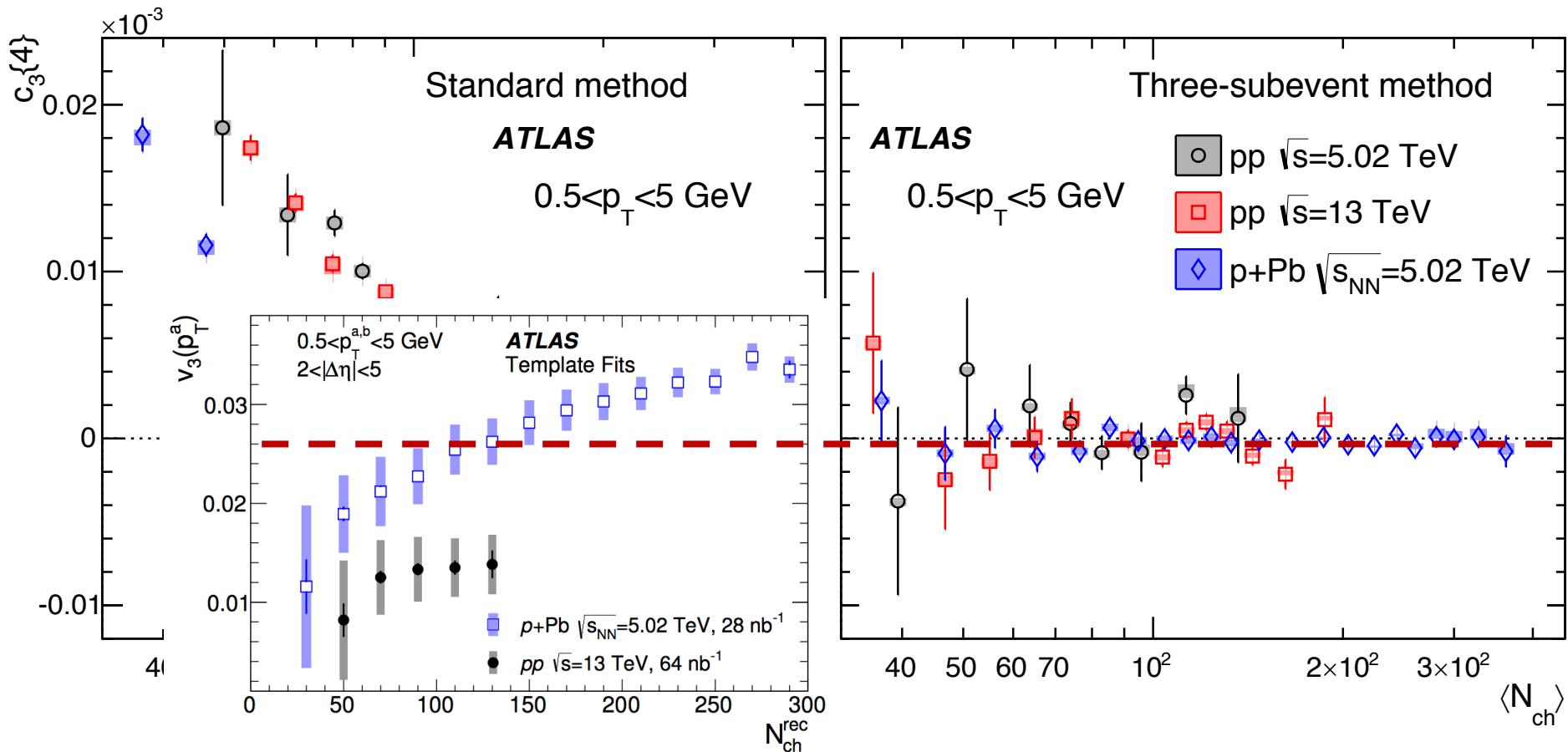




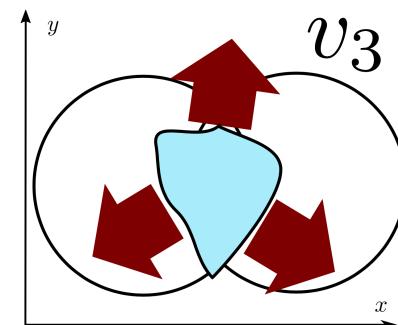
Non-non-flow \neq Flow!

Third harmonic v_3

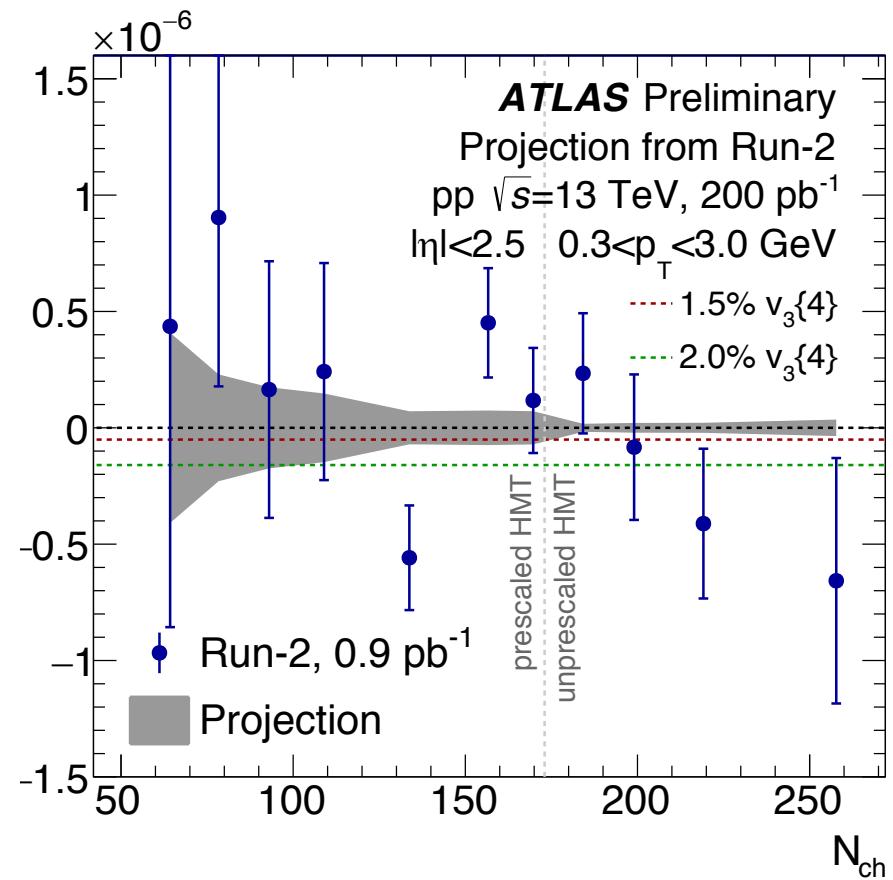
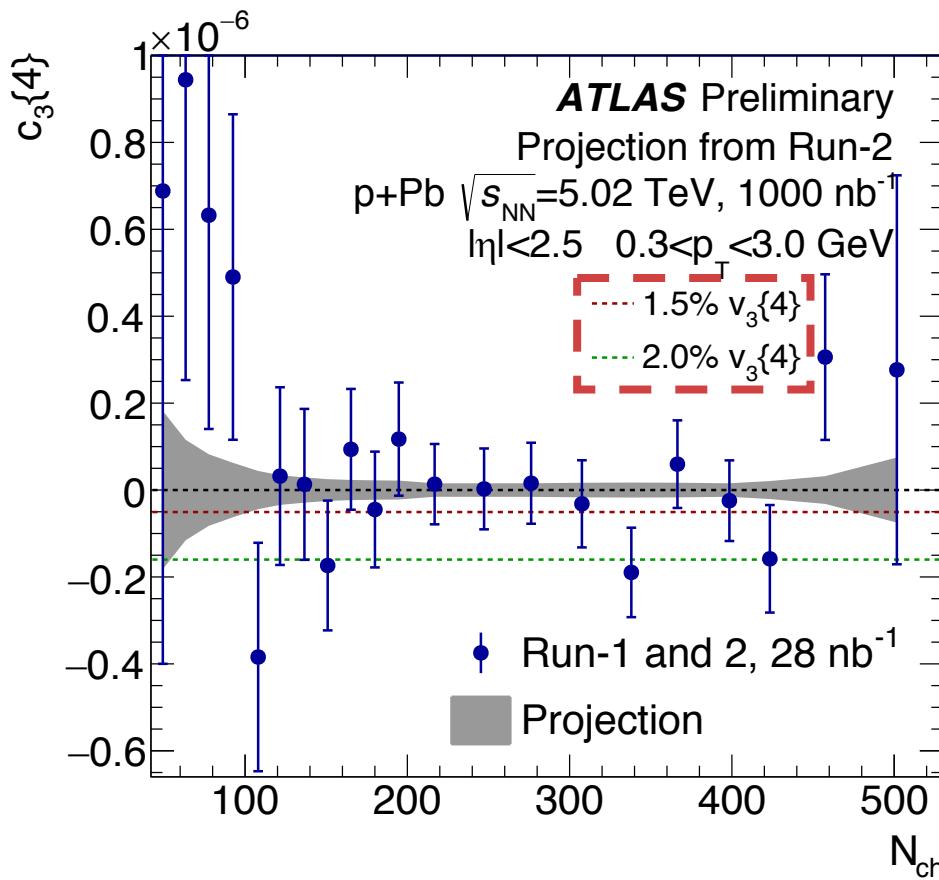
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- $c_3\{4\}$ is consistent with 0
 - $\bar{v}_3 \ll \bar{v}_2$?
 - Fluctuation kills $v_3\{4\}$?
 - More statistics needed.



v_3 projected in Run 3



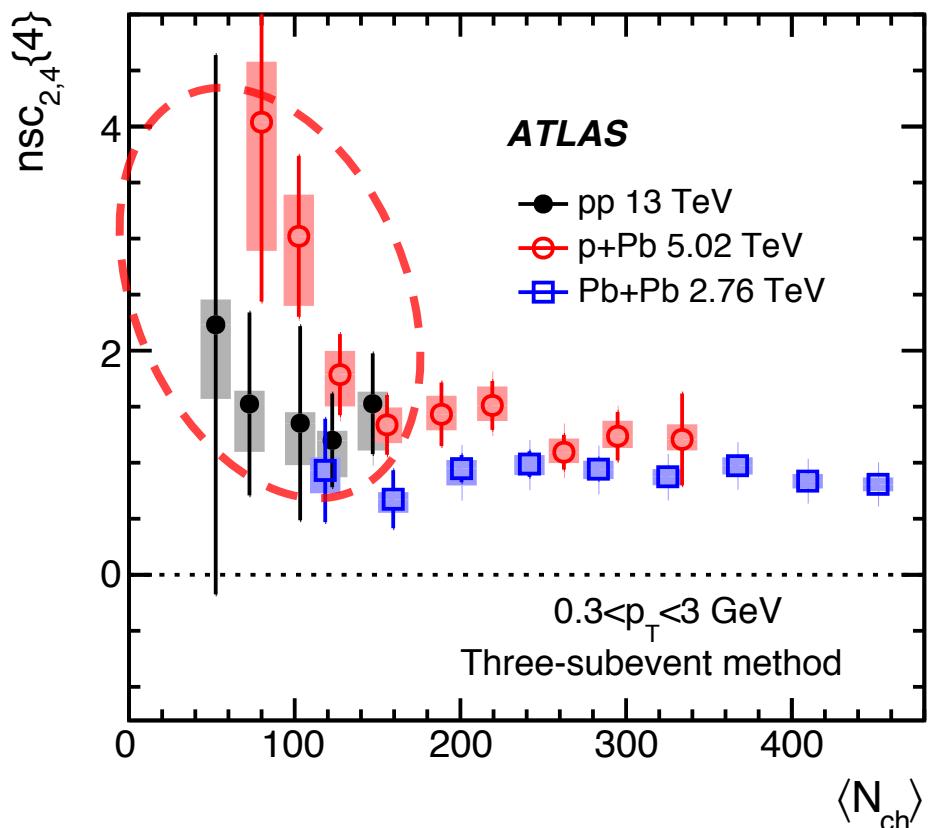
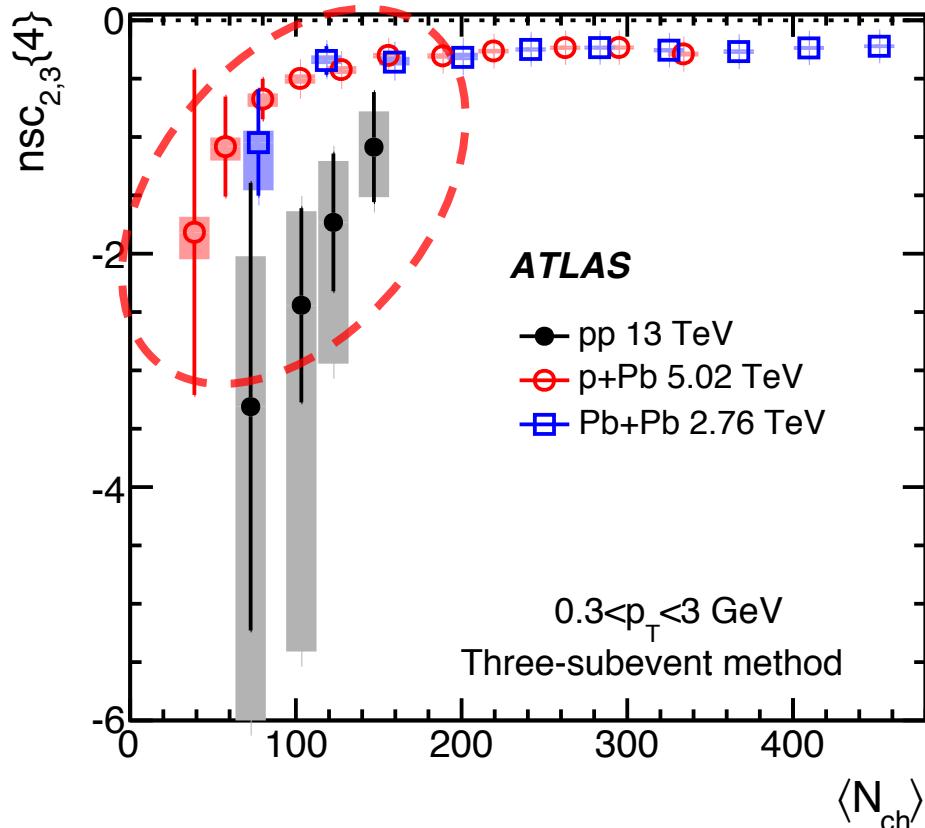
- Opportunity luminosity increase in Run 3;
- Challenges trigger, pileup, tracking...

Correlation between v_n and v_m

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

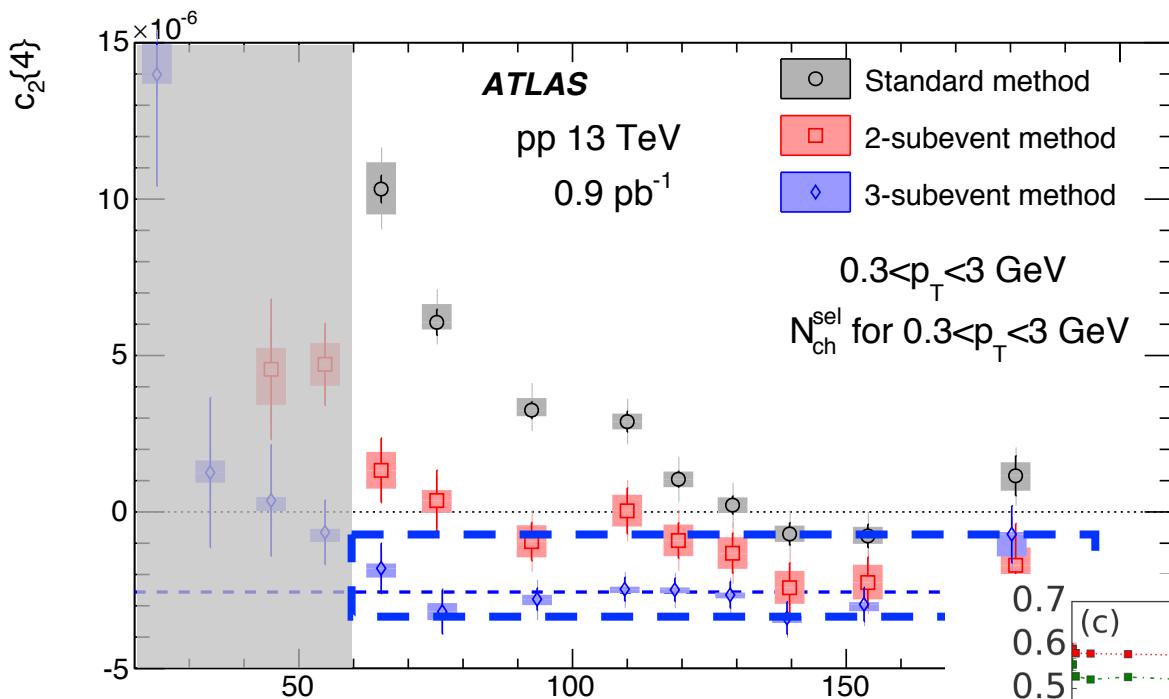
[Phys. Lett. B 789 \(2019\) 444](#)



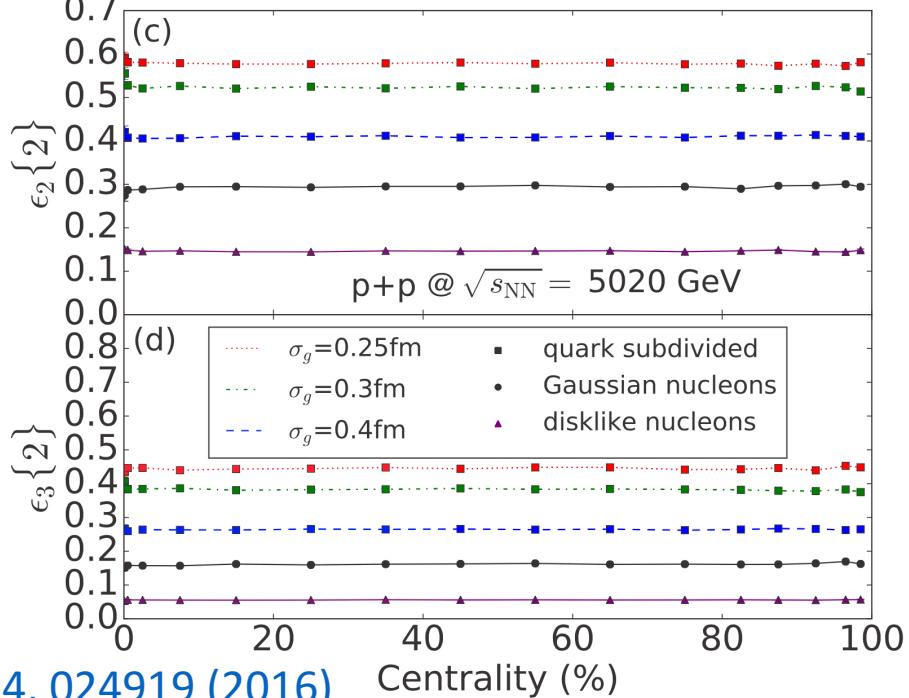
- Same sign, different magnitudes across systems;
- Independent constraints on models.

Last puzzle: N_{ch} dependence

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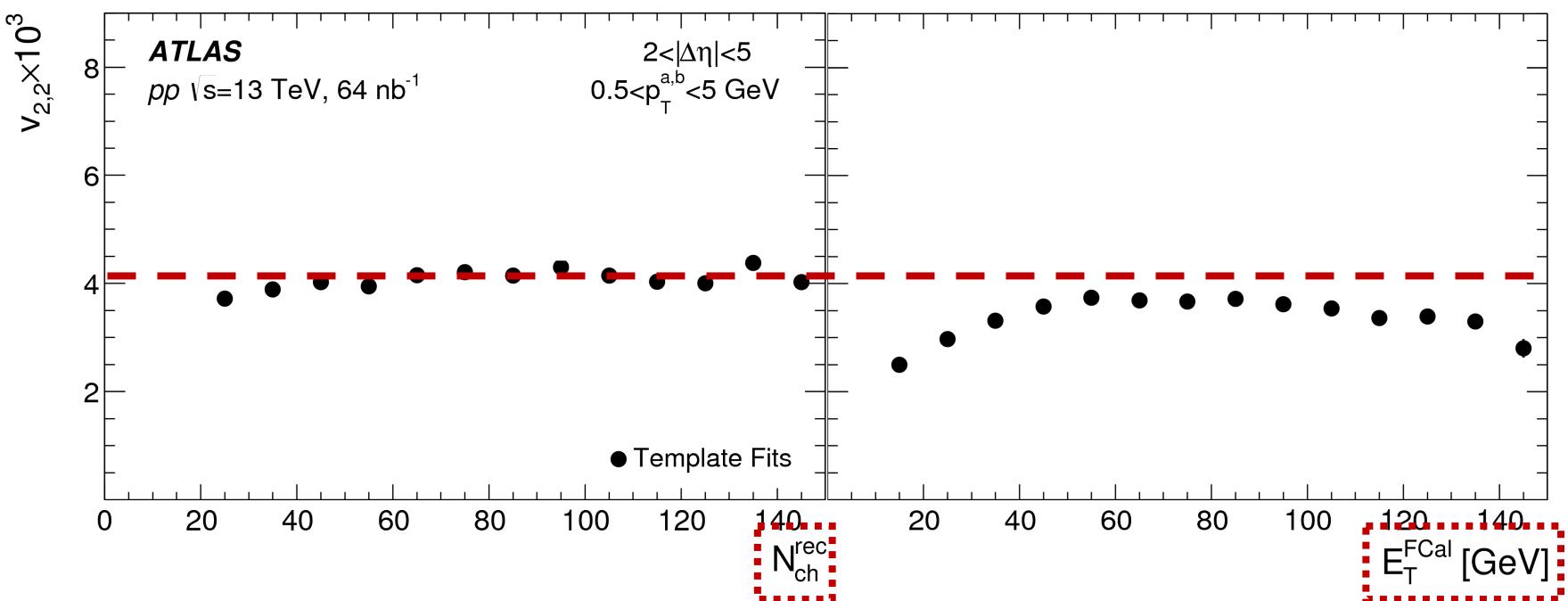
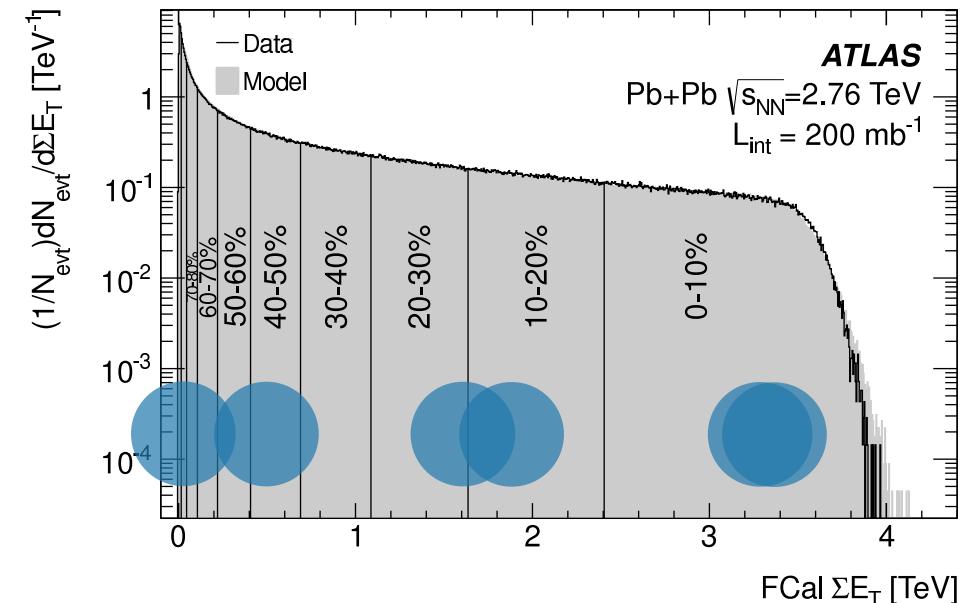


- Weak independence of N_{ch} ;
- Similar observation in model
 - No “geometry” in pp ?
 - N_{ch} not a good indicator for centrality?



Centrality fluctuation

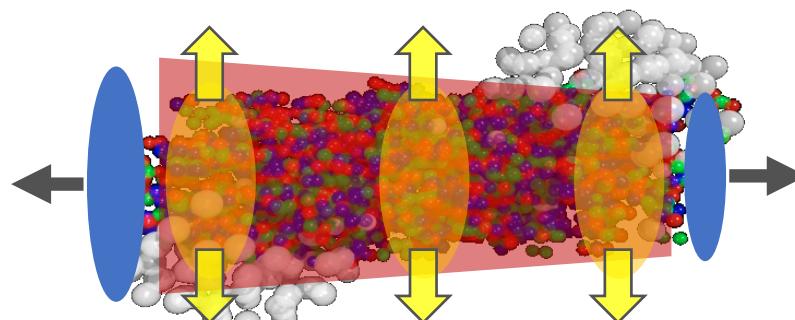
- Centrality quantifies the overlap region of the collision;
- The mapping replies on model and is on the average level;
- Different centrality definitions gives different dependence.



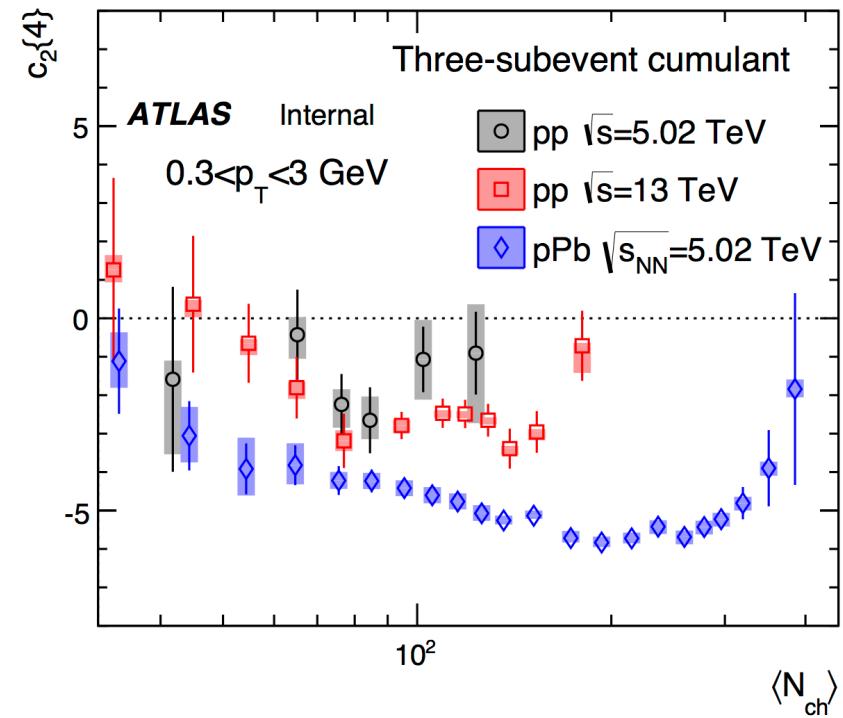
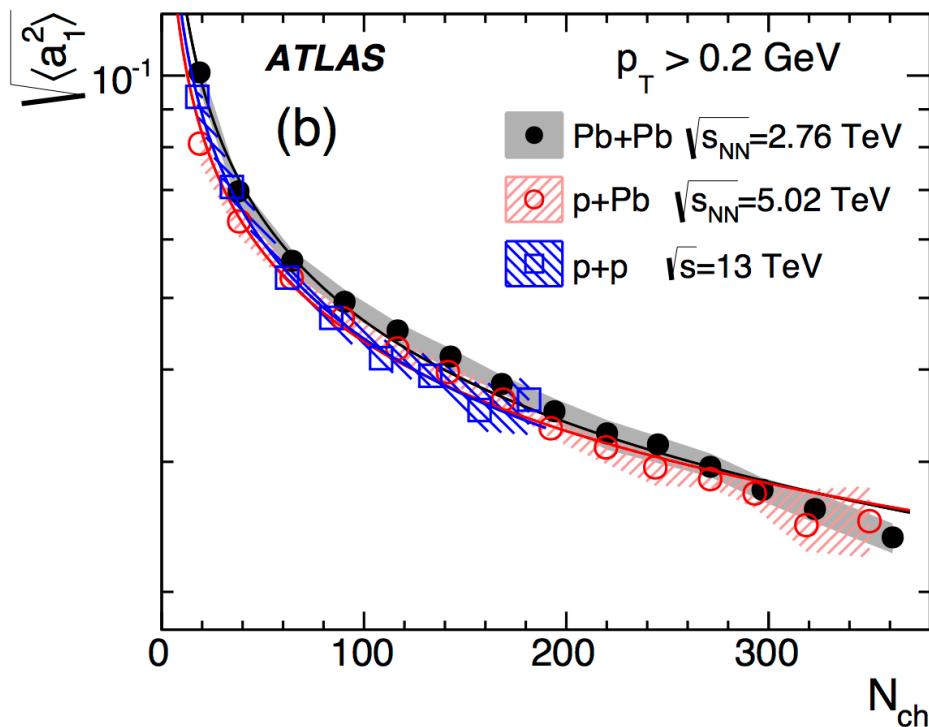
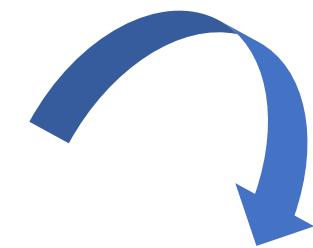
Summary

Nature of sources seeding the long-range collective behavior?

Longitudinal correlation



Azimuthal correlation



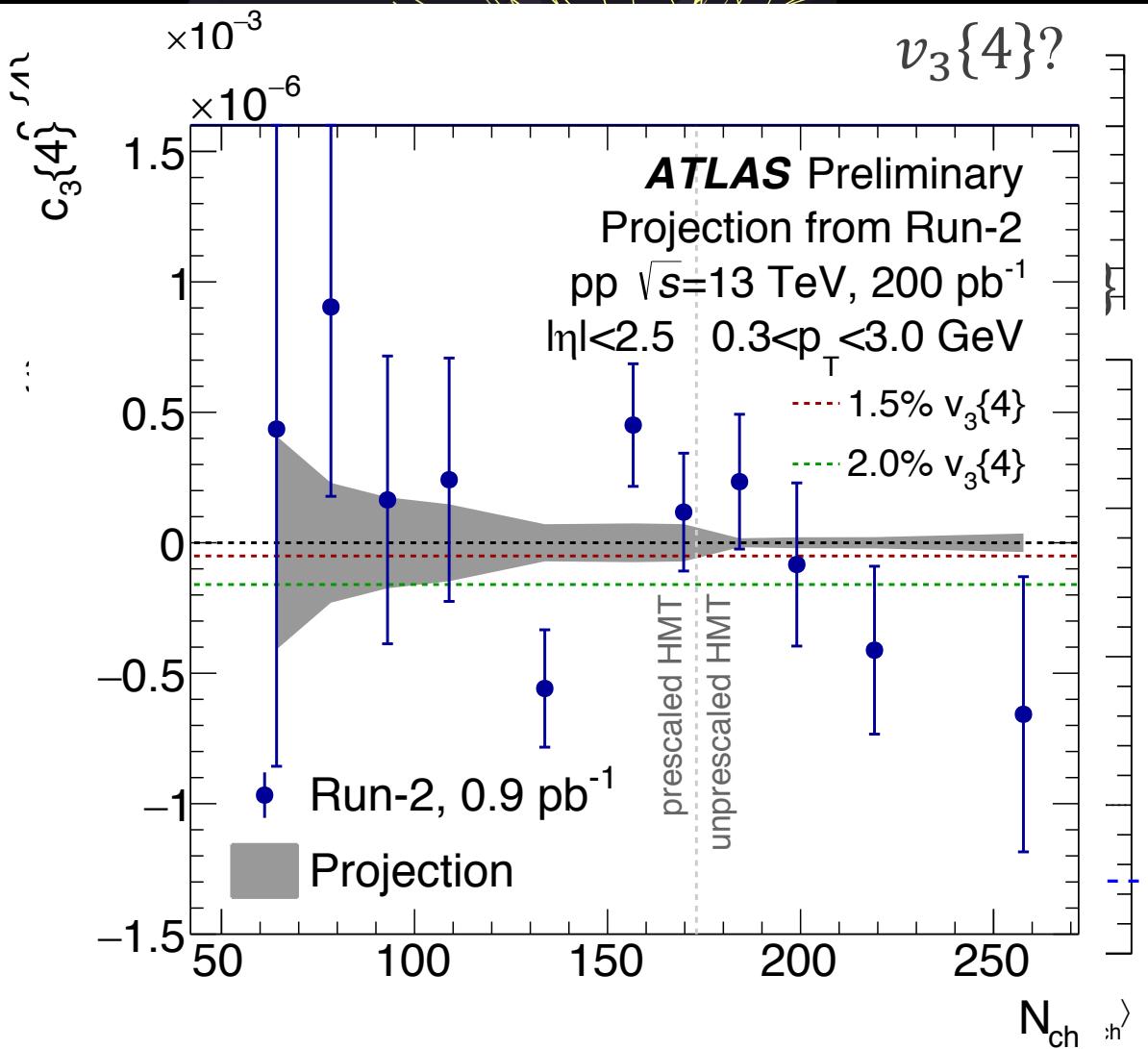
Evidence of collectivity in small systems!

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

- O+O to O+O

Backup

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

Forward-backward multiplicity fluctuation

- Rapidity correlations is an old story



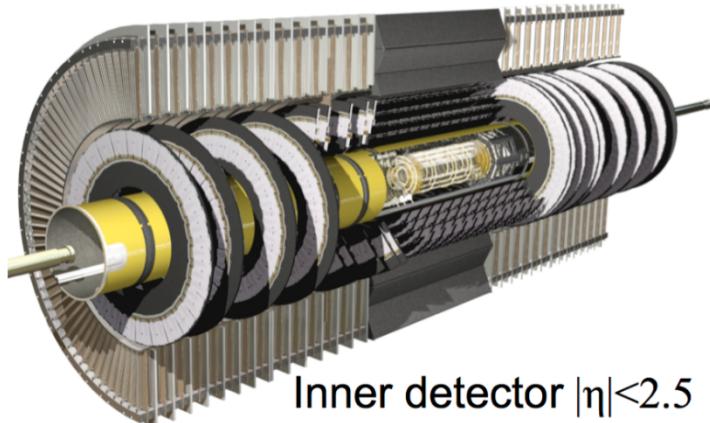
- Physics goal: understand production mechanism in early stage.

- More details see the thesis.

- Why we come back to this analysis?

- Previous methods focused on limited phase space: η and $-\eta$;
 - We used a new observable that covers full η 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;

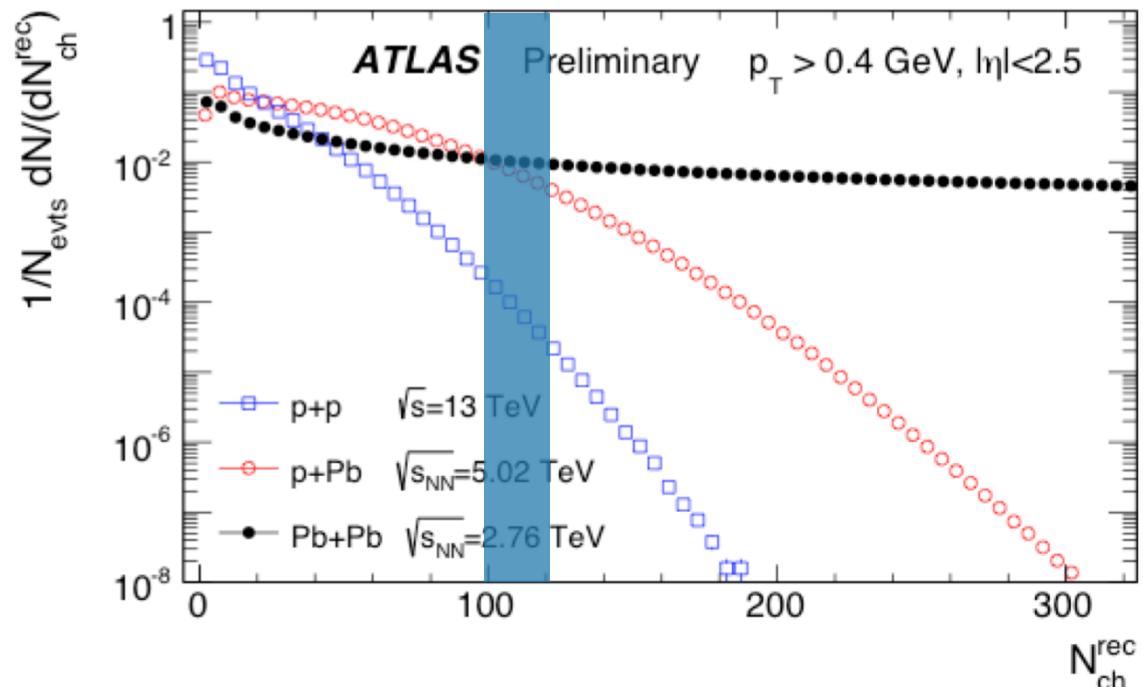


Inner detector $|\eta| < 2.5$

Pb+Pb 2.76 TeV, 2010, MB

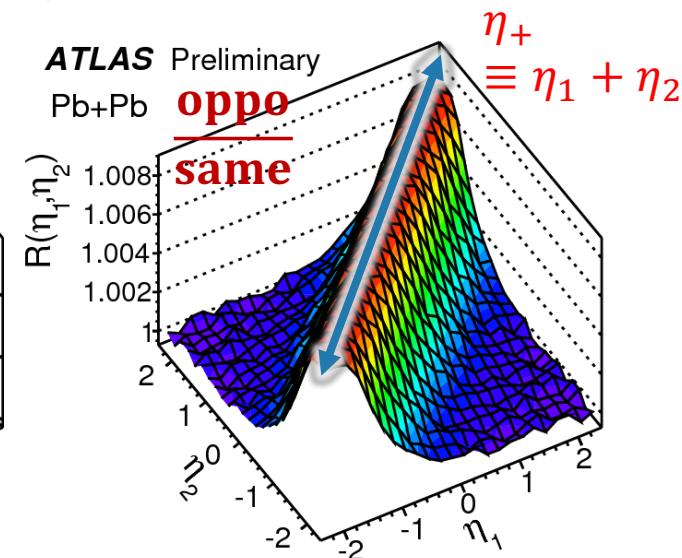
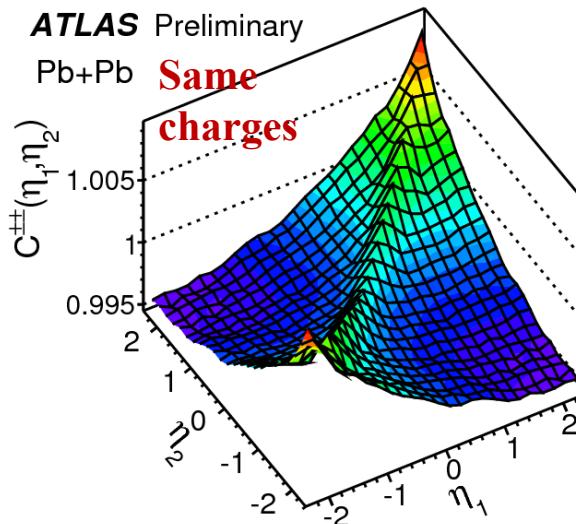
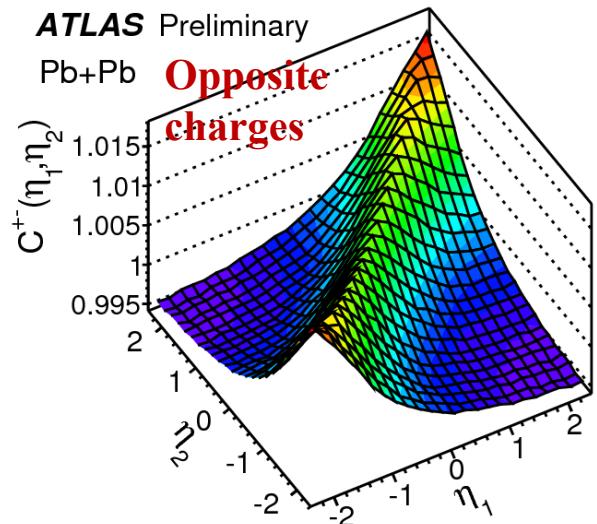
p +Pb 5.02 TeV, 2013, MB+HMT

p + p 13 TeV, 2015, MB+HMT

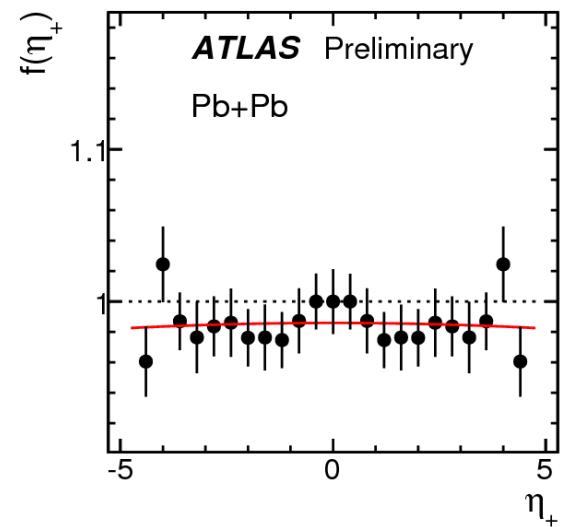


- Analysis carried out in many bins over $10 \leq N_{ch}^{rec} < 300$;
- Results presented as a function efficiency-corrected values N_{ch} .
 - How long-range correlation compare among three systems, at the same N_{ch} ?

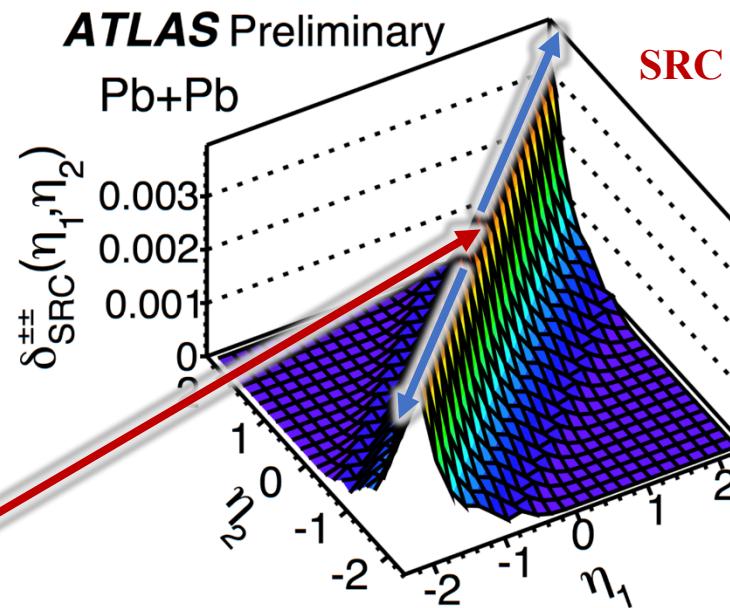
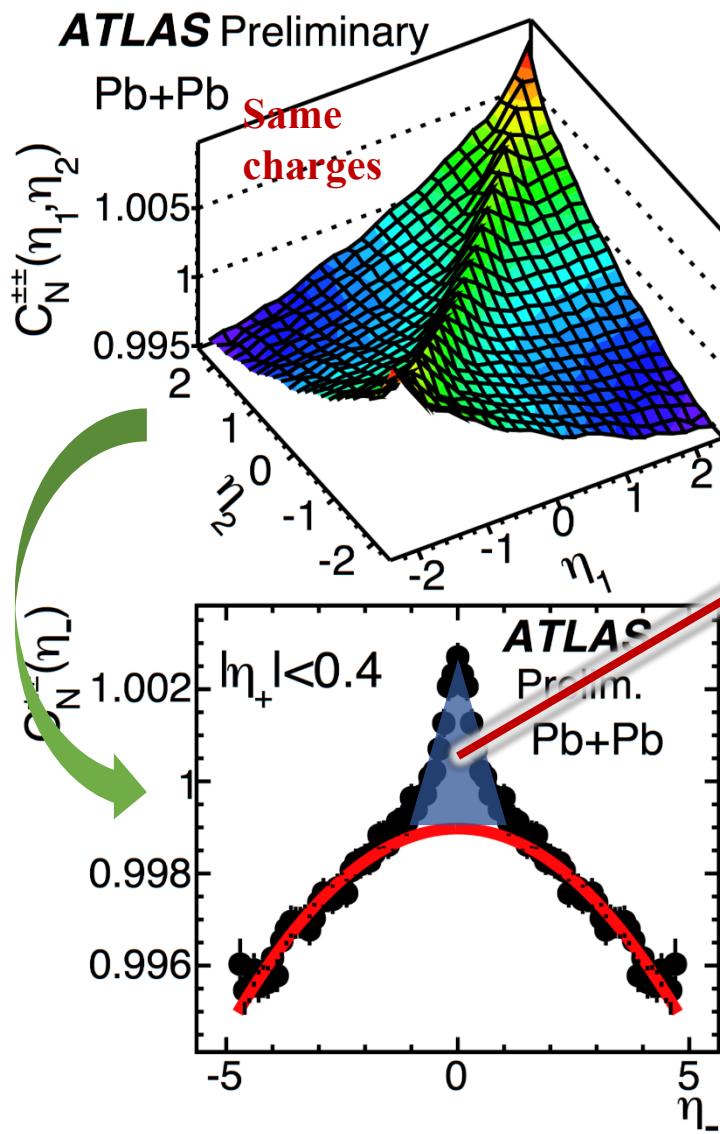
- Particles from the same source (SRC) have strong charge dependence.



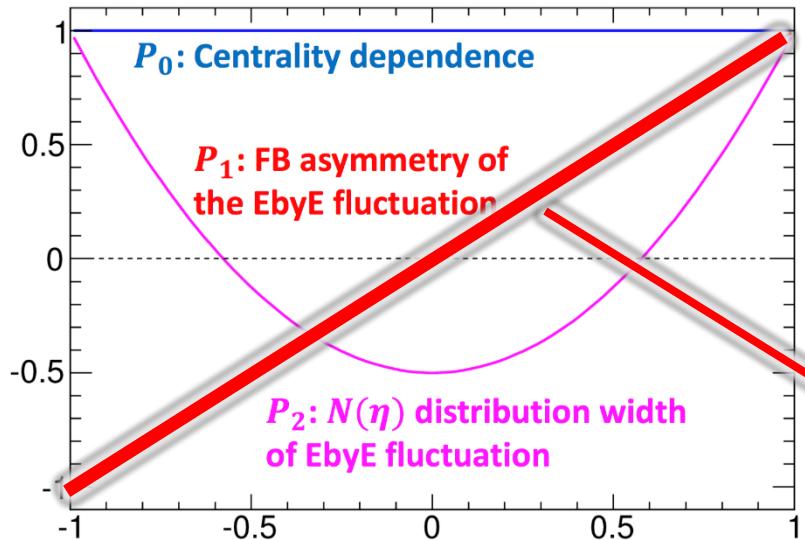
- Ratio of opposite to same charges $R(\eta_1, \eta_2)$
 - Very strong Gaussian-like SRC;
 - Very weak LRC: charge-independent;
- Amplitude of $R(\eta_1, \eta_2)$ along η_+ : $f(\eta_+)$, reflects the strength of SRC in the longitudinal direction;
- Assumption: strength of SRC along η_+ is same for same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



- To estimate SRC, LRC pedestal is estimated first.

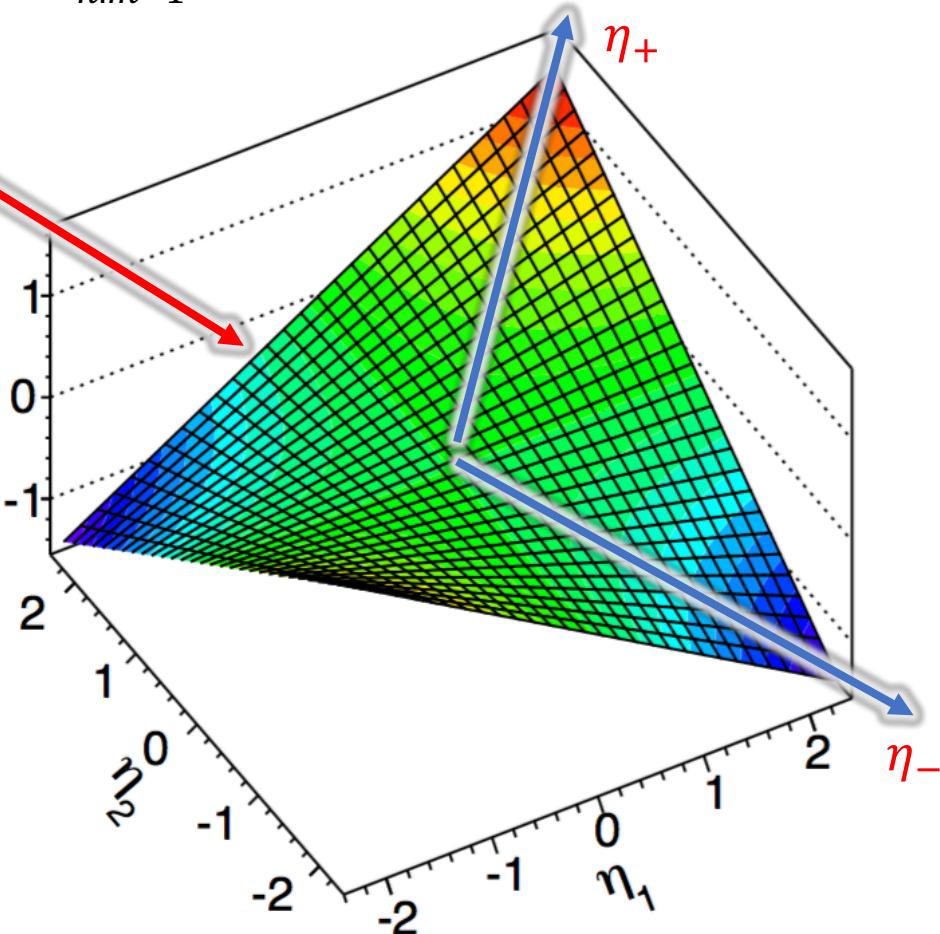


- $C(\eta_1, \eta_2)$ from same charge used to estimate LRC pedestal because of small SRC;
- LRC pedestal is fitted with quadratic function;
- The additional structure upon LRC pedestal determines the shape of SRC;
- The full $\delta_{SRC}(\eta_1, \eta_2)$ is then populated using $f(\eta_+)$ scaling.



- 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 η_+ and η_- :

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

Results: correlation function

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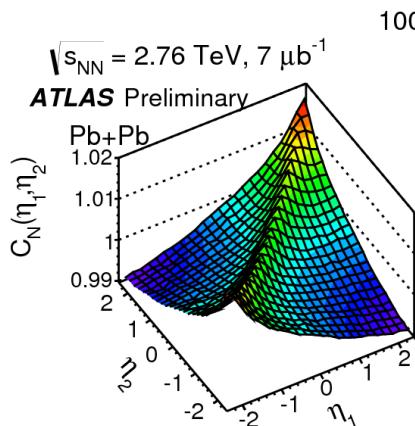
Raw
 $C_N(\eta_1, \eta_2)$

||

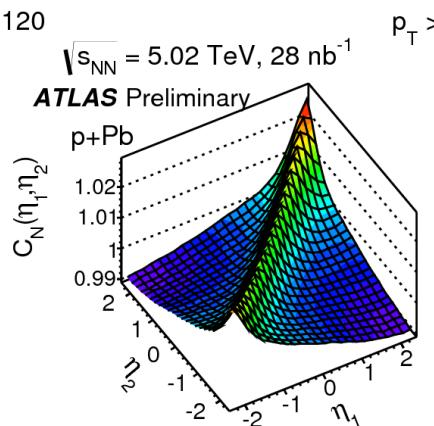
Short-range
 $\delta_{SRC}(\eta_1, \eta_2)$

+

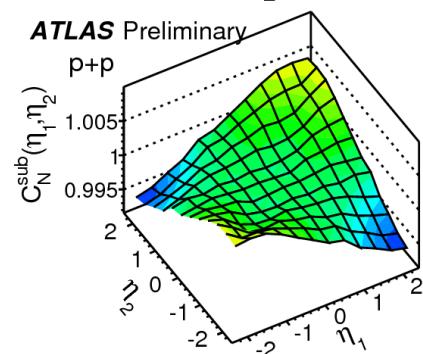
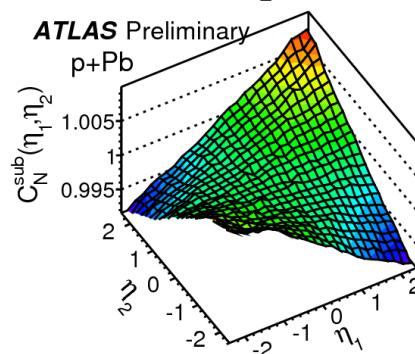
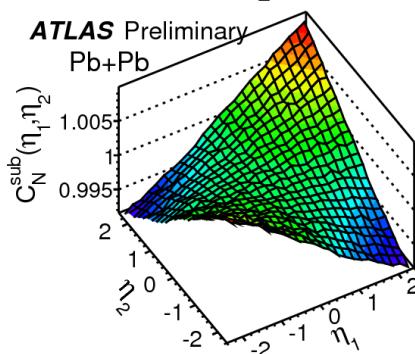
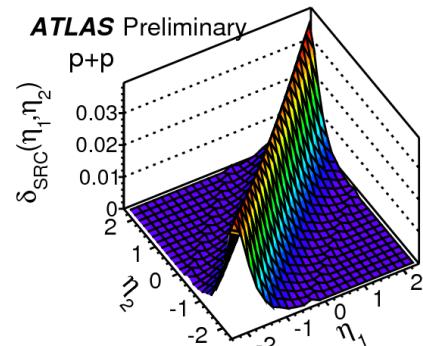
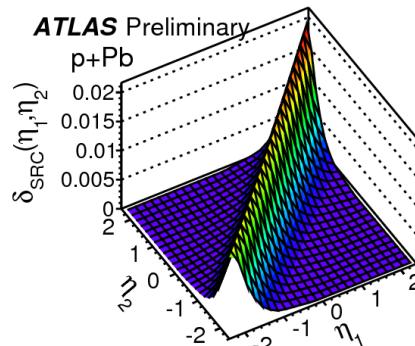
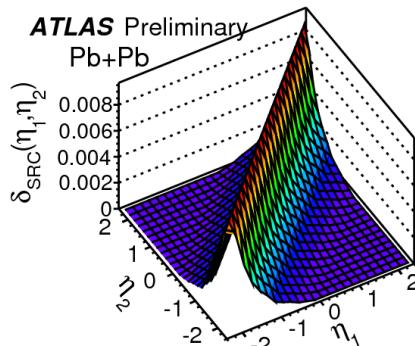
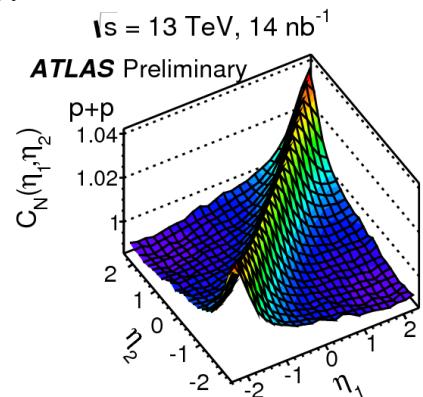
Long-range
 $C_N^{sub}(\eta_1, \eta_2)$



$100 \leq N_{ch}^{\text{rec}} < 120$



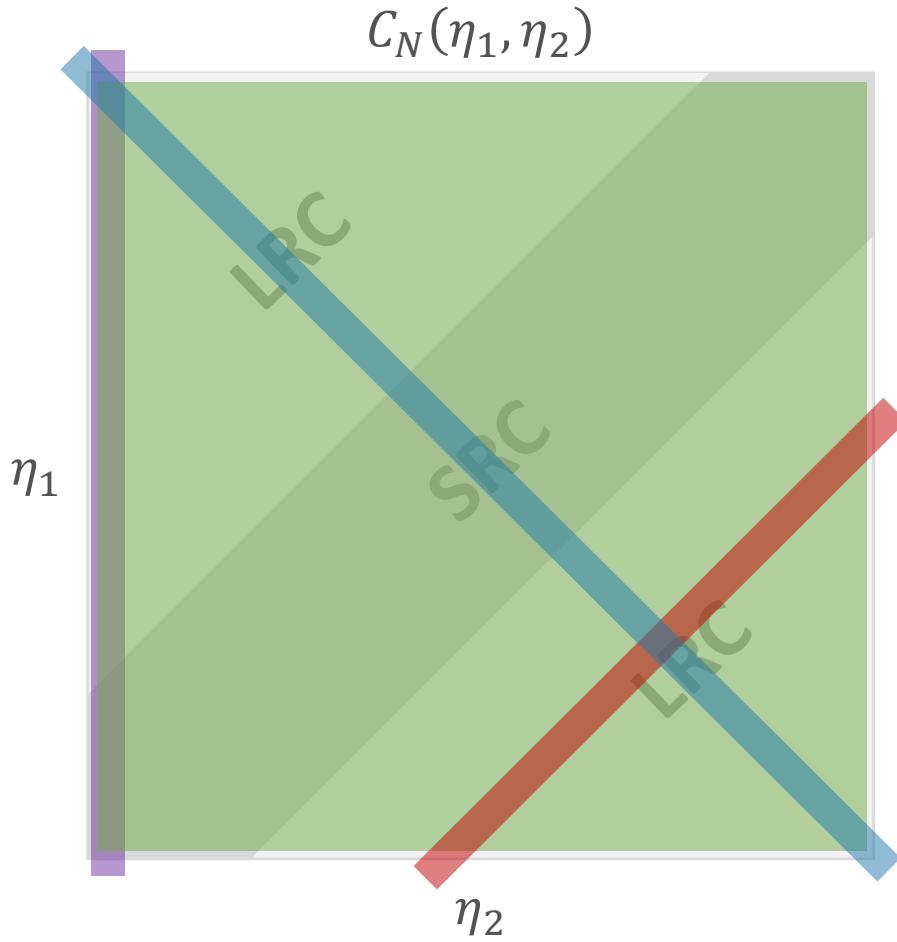
$p_T > 0.2 \text{ GeV}$



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 $C_N^{sub}(\eta_+)$

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

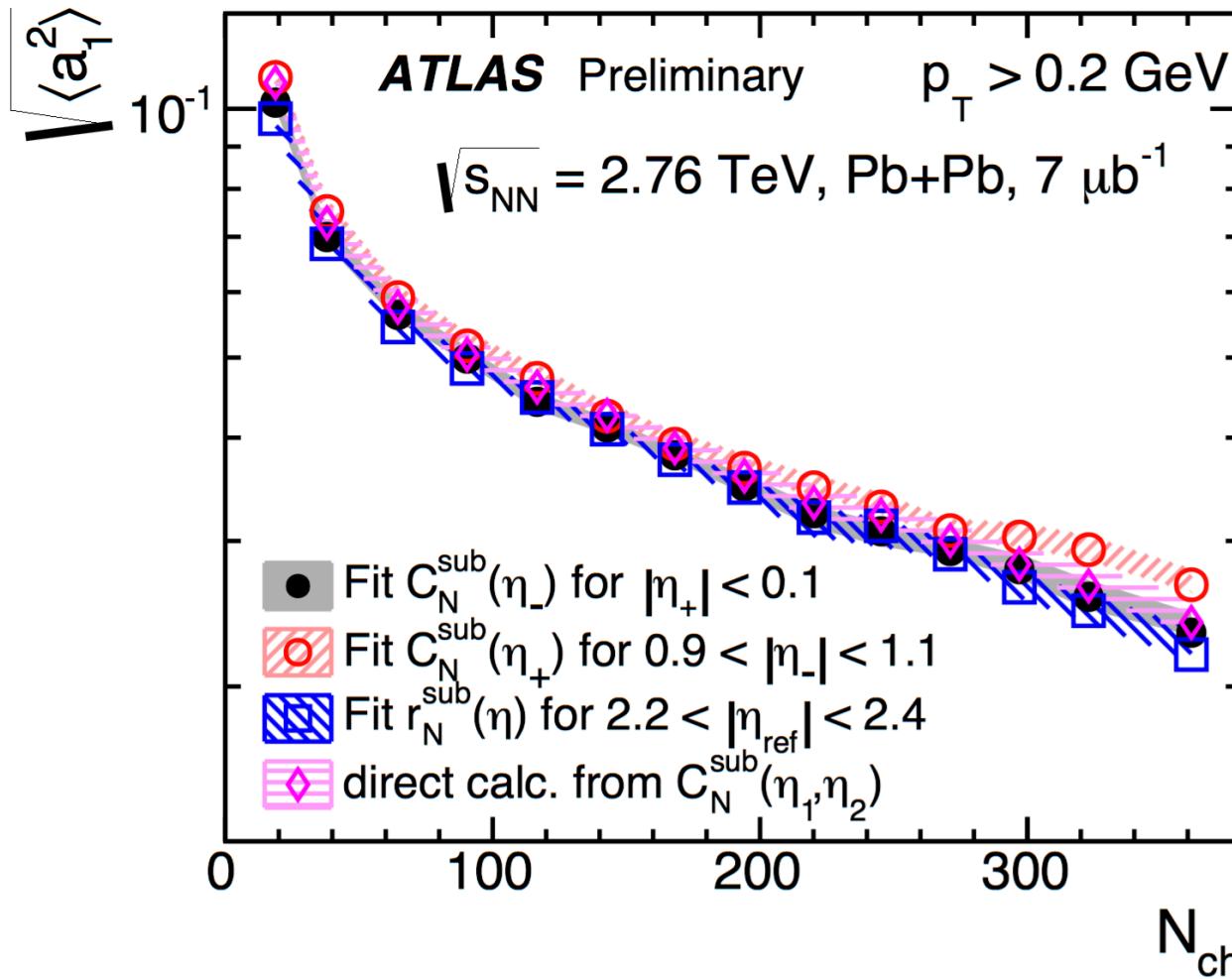
- Linear fit of $r_N^{sub}(\eta, \eta_{ref}) \equiv \frac{C_N^{sub}(-\eta, \eta_{ref})}{C_N^{sub}(\eta, \eta_{ref})}$

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

How stable are the results?

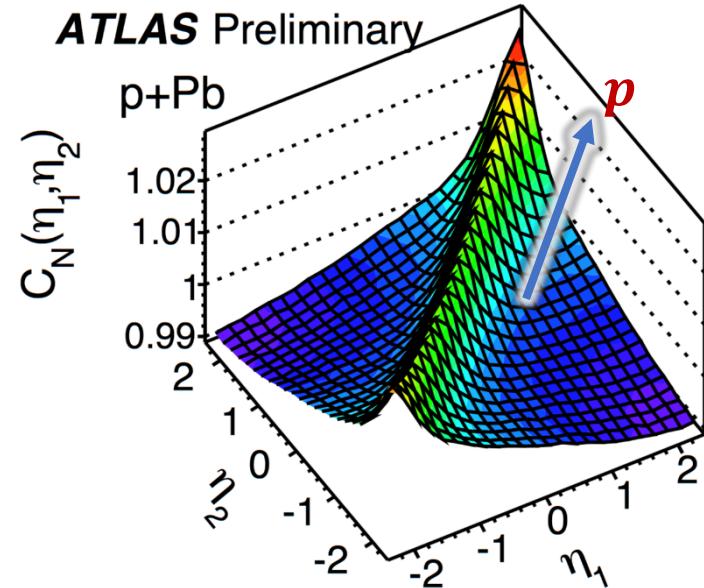
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- Four largely independent methods are applied to determine $\langle a_1^2 \rangle$;
- Different methods have different sensitivity to the analysis procedures;

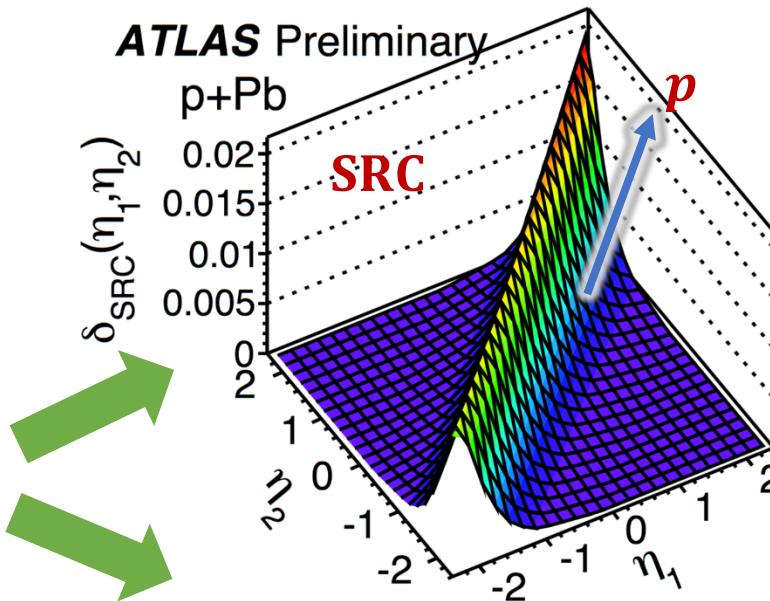


- Four methods give consistent a_1 : conclusions are insensitive to the procedure.

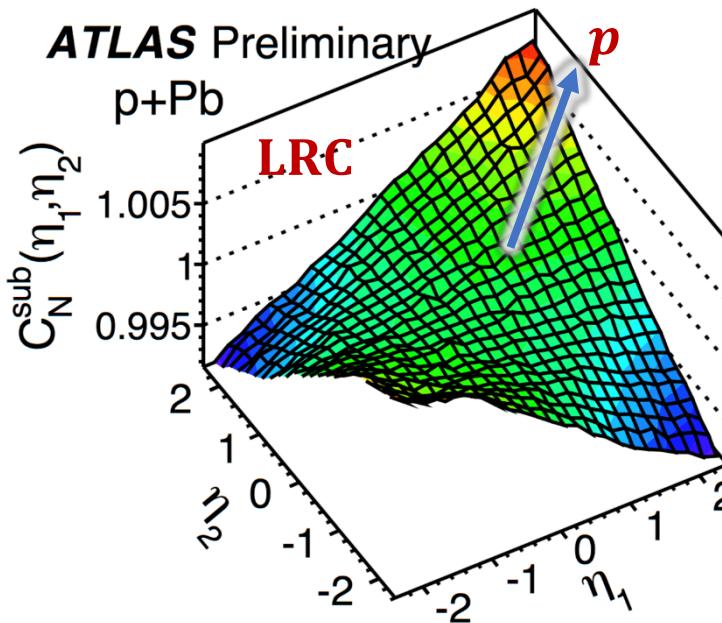
Asymmetry in $p+\text{Pb}$ collision



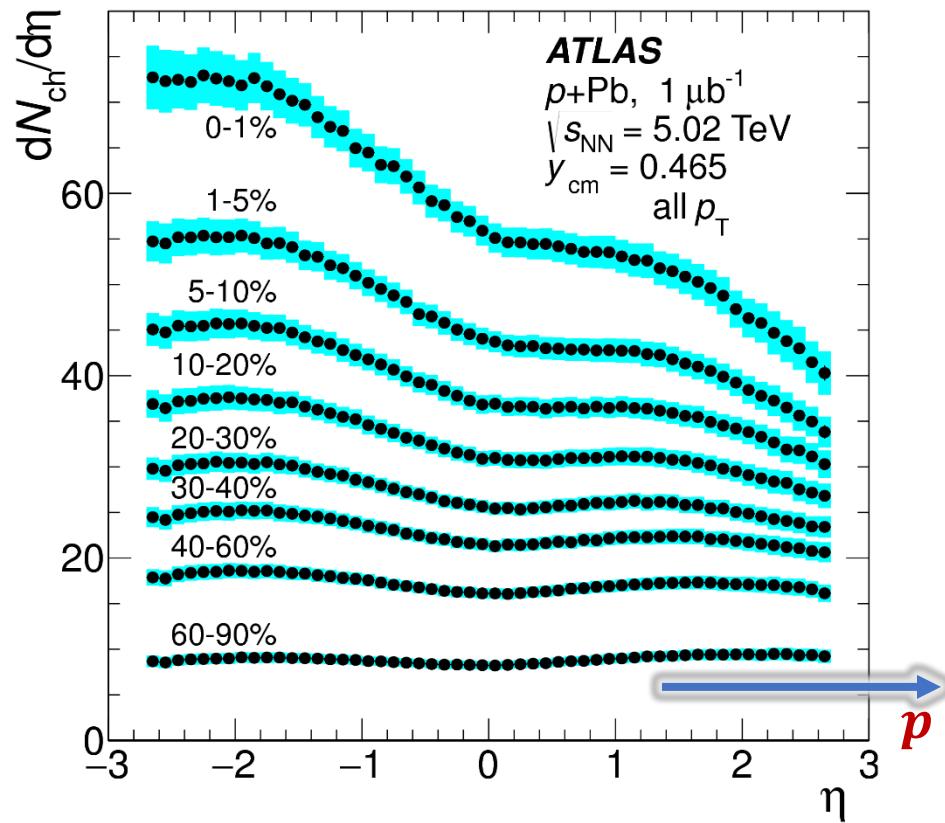
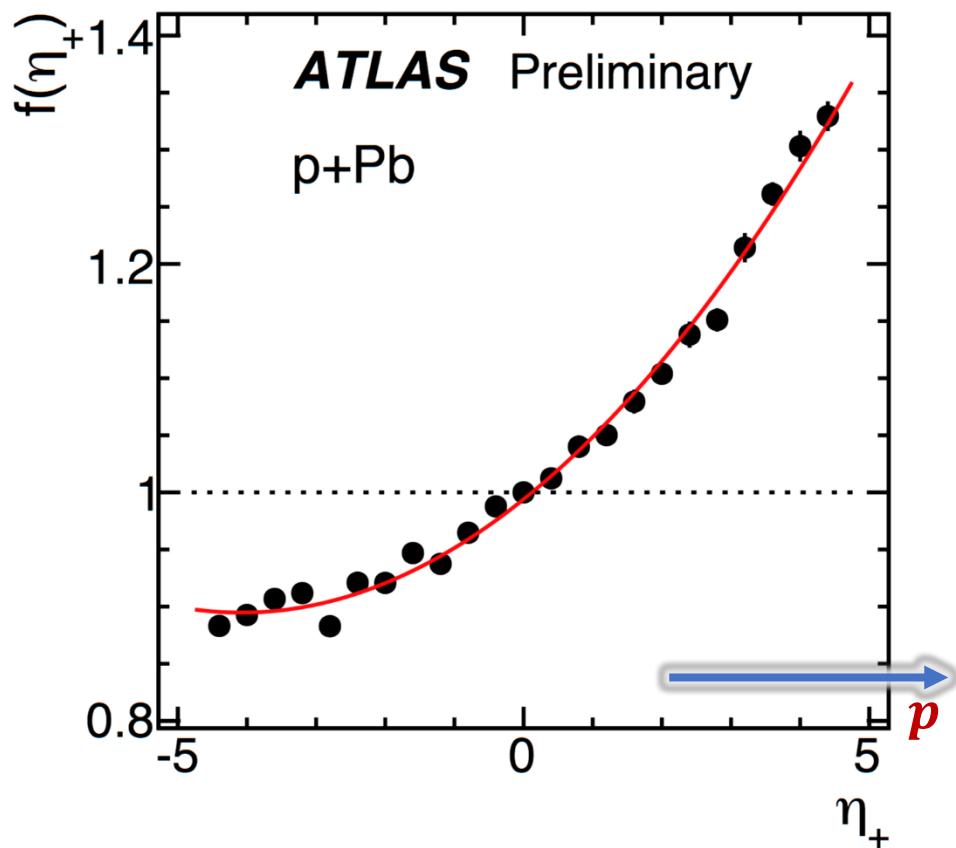
- Asymmetry observed in $p+\text{Pb}$ collision: stronger correlation in the proton-going side.
- Why the asymmetric collision causes asymmetric SRC?



- Asymmetry entirely due to SRC!



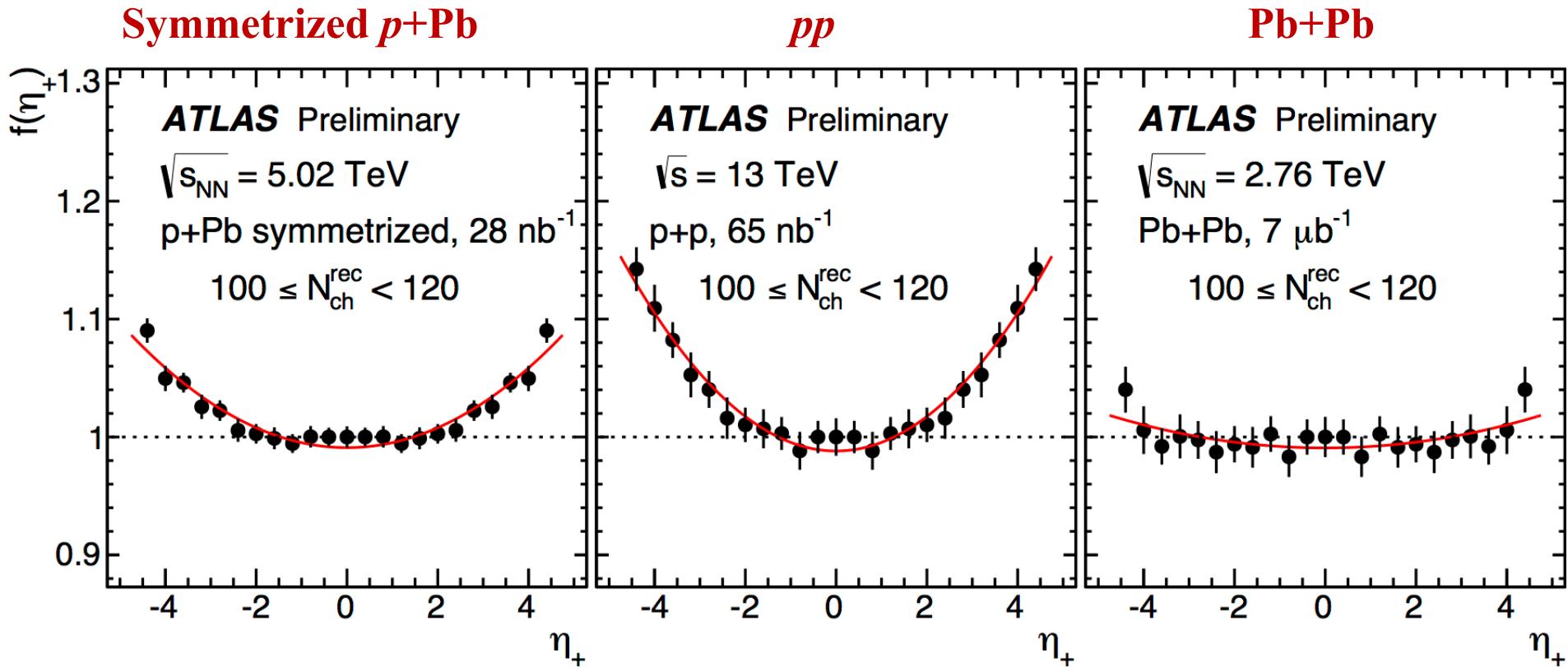
- LRC is symmetric.



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

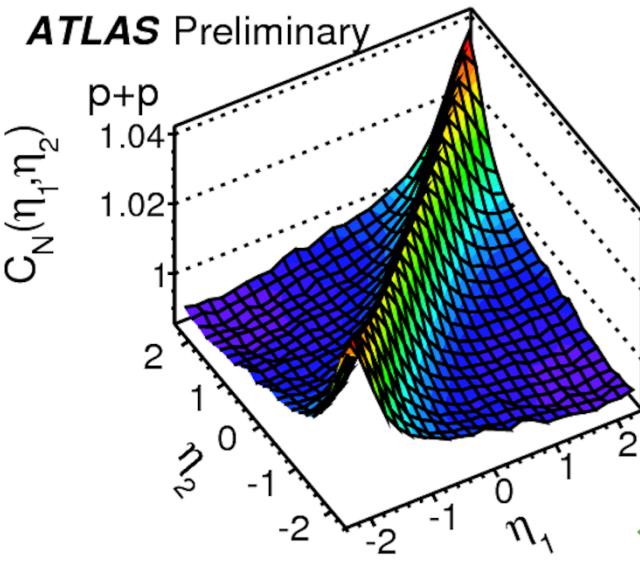
$$\delta_{SRC} \propto \frac{n \langle m(m-1) \rangle}{(n \langle m \rangle)^2} = \frac{1}{n} \propto \frac{1}{dN_{ch}/d\eta}$$

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



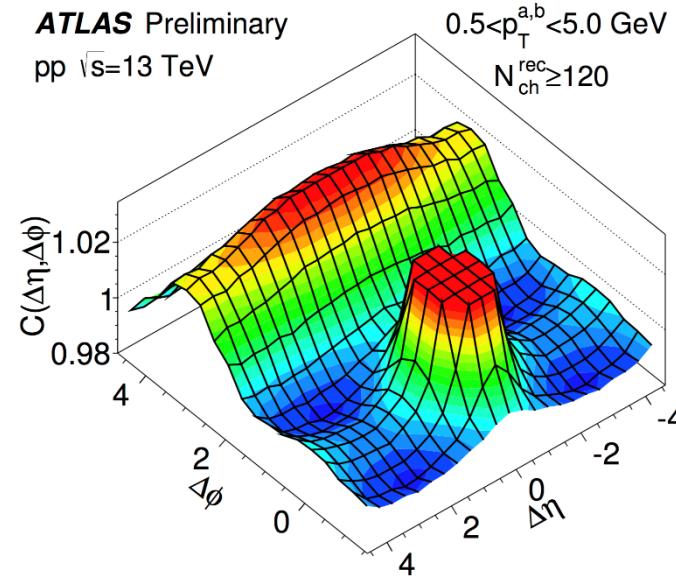
- $C(\eta_1, \eta_2)$ is a very comprehensive observable.

- 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

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



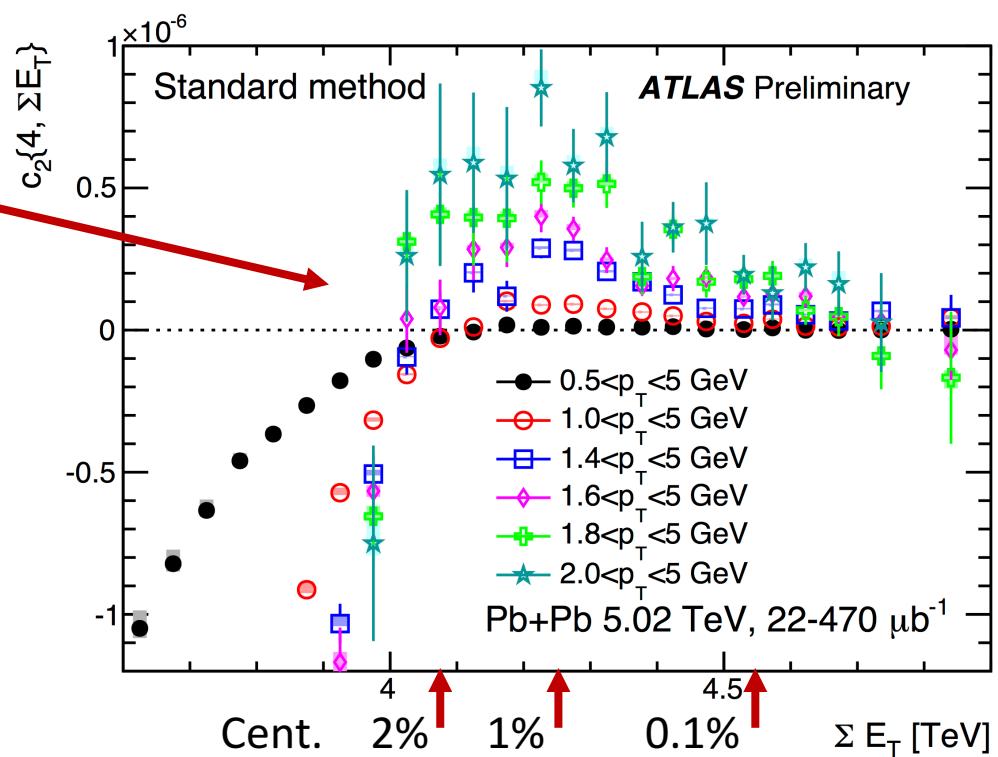
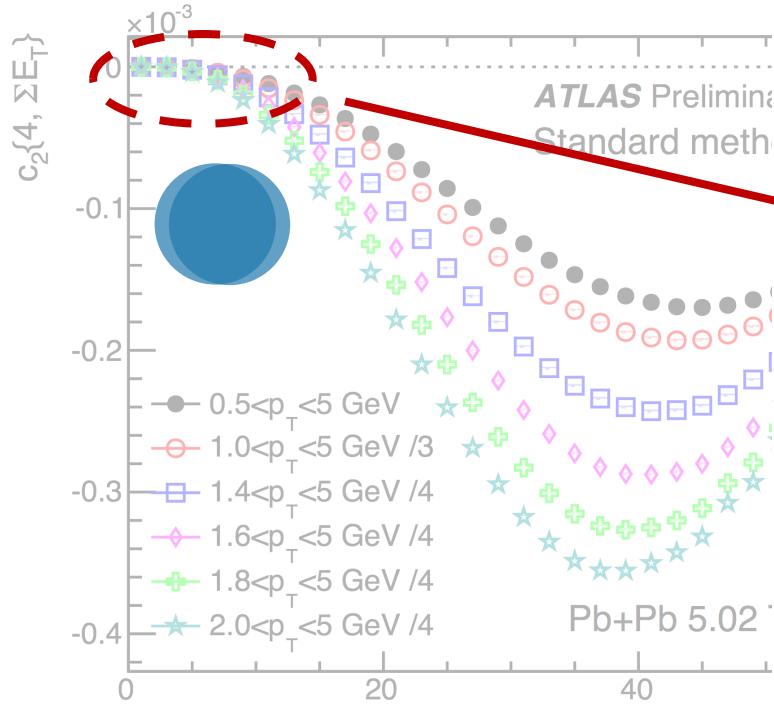
$C(\eta_1, \eta_2)$ 
 $+ C(\Delta\eta, \Delta\phi)$ 

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

Centrality fluctuation

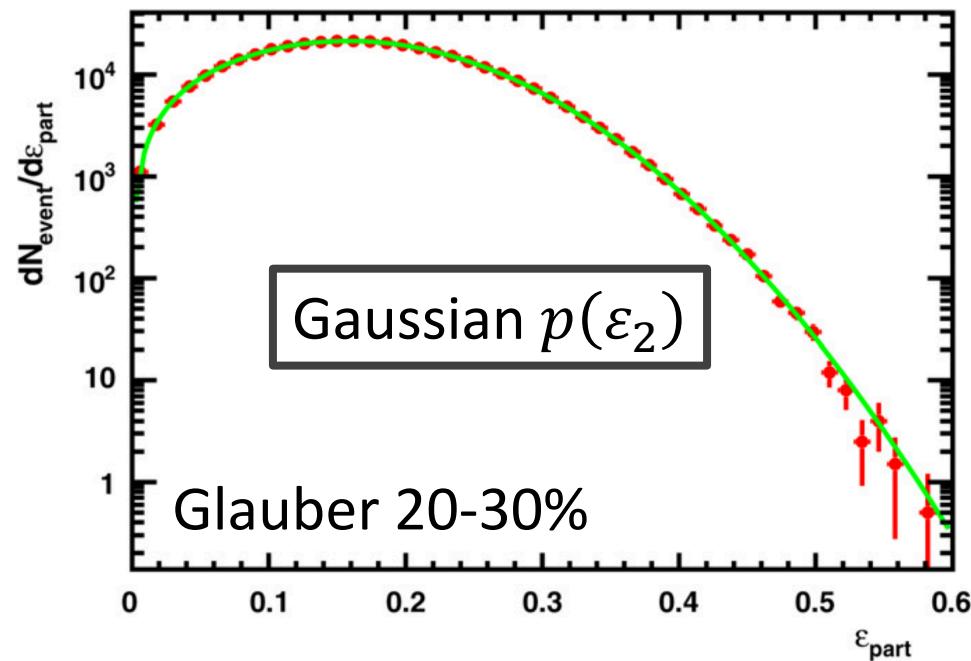
Ultra-Central Collision (UCC)

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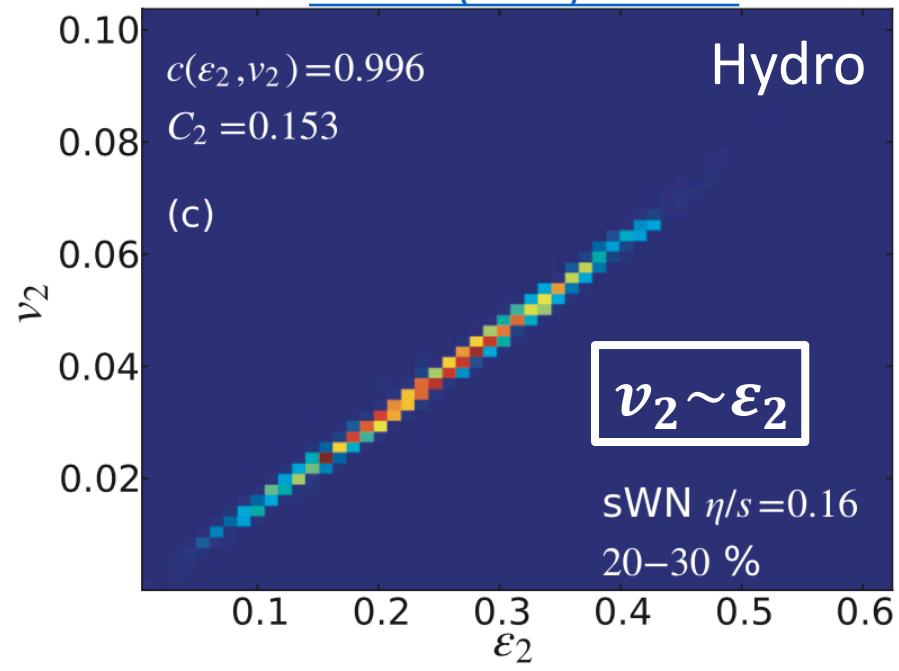


- In UCC: $\bar{v}_2 \rightarrow 0$, largest relative flow fluctuation;
- ATLAS applied UCC triggers: $\times 20$ statistics over MinBias;
- $c_2\{4\} > 0$ in UCC \Rightarrow non-Gaussian flow fluctuation
 - Why?

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



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

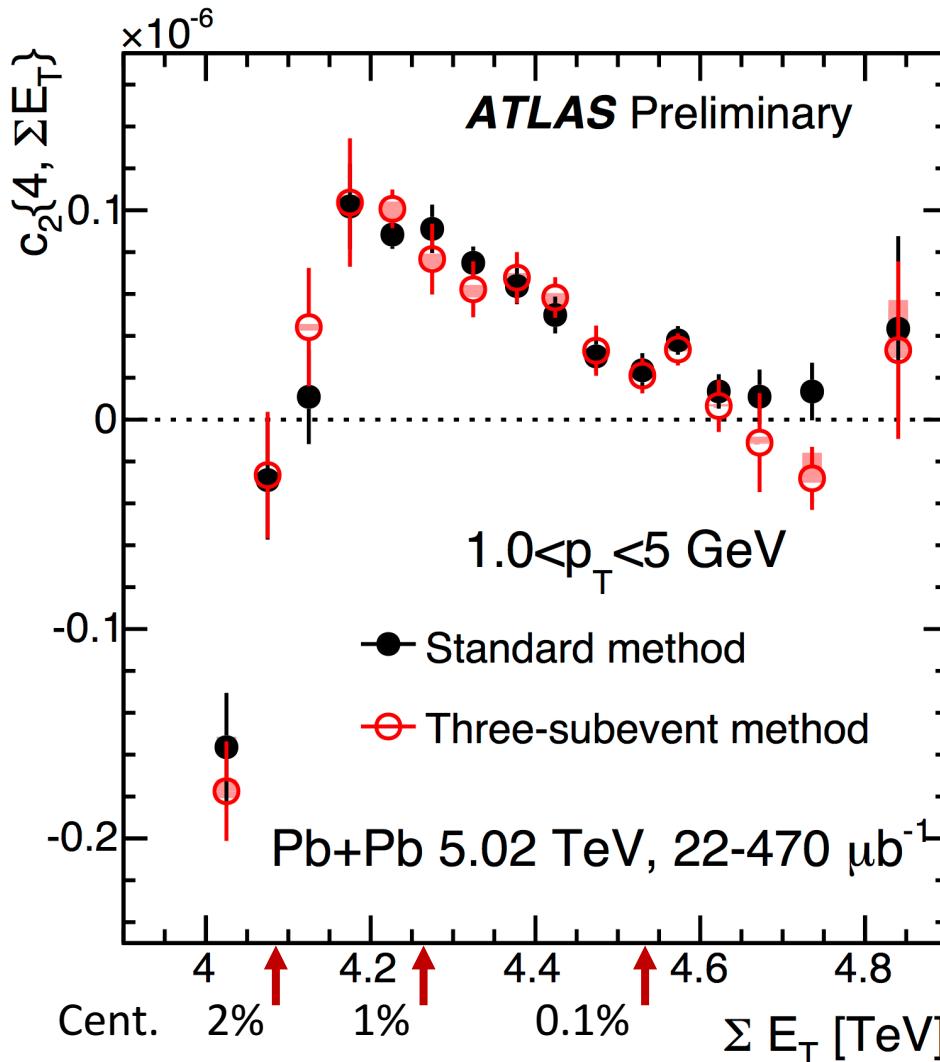


- On the model side
 - Gaussian $p(\varepsilon_2) \Rightarrow$ Gaussian $p(v_2) \Rightarrow c_2\{4\} \leq 0$
- But we observed $c_2\{4\} > 0$
 - Non-flow contribution?

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

Non-flow contribution?

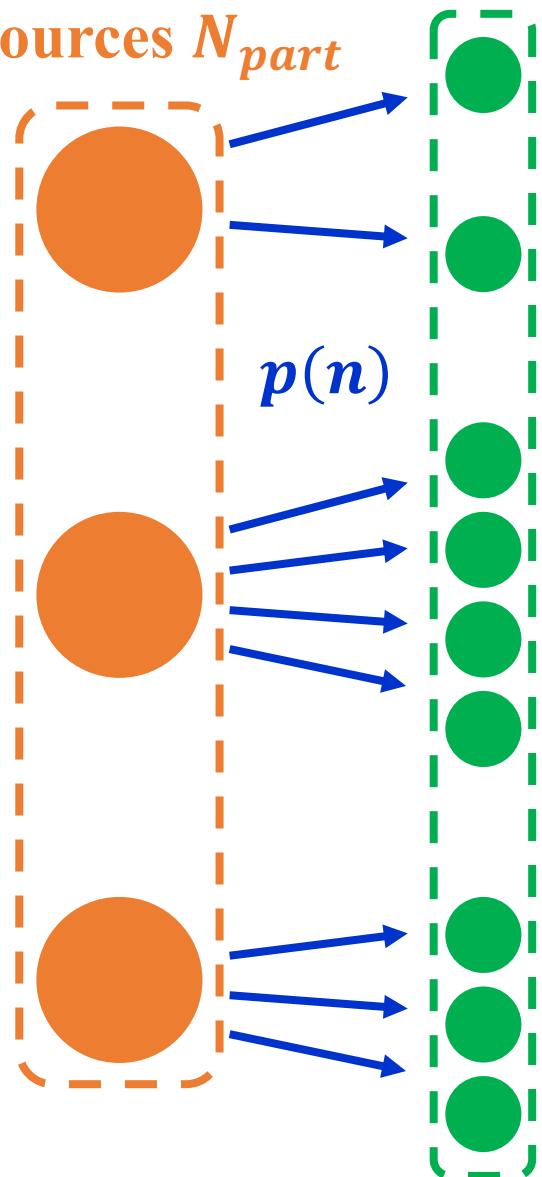
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- Two methods consistent: **not due to non-flow**.
- Pileup effects have also been suppressed.

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

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

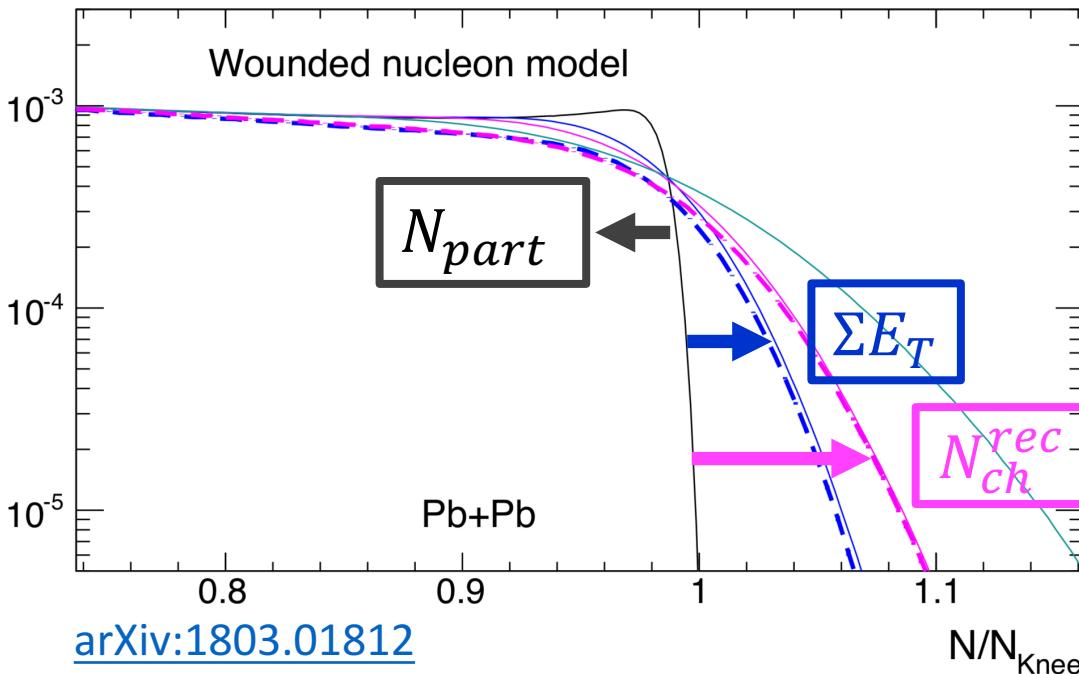
Calculated
event-by-event

Averaged over many events

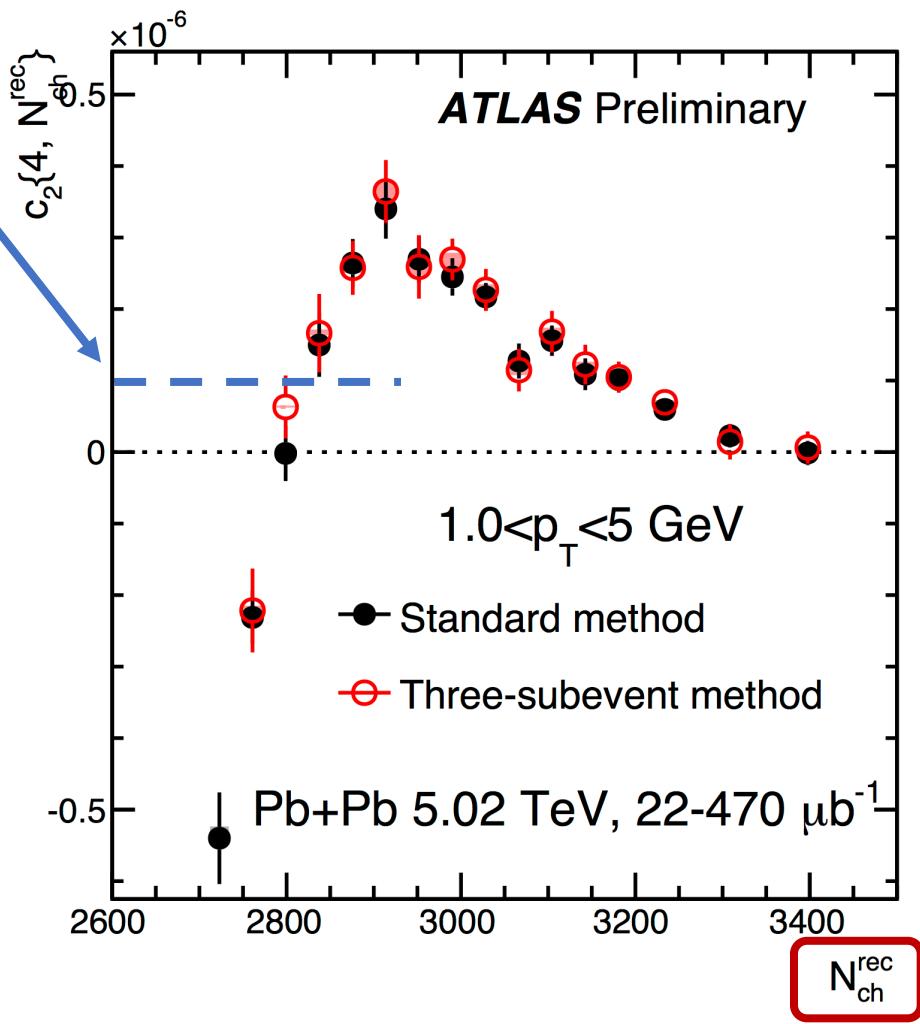
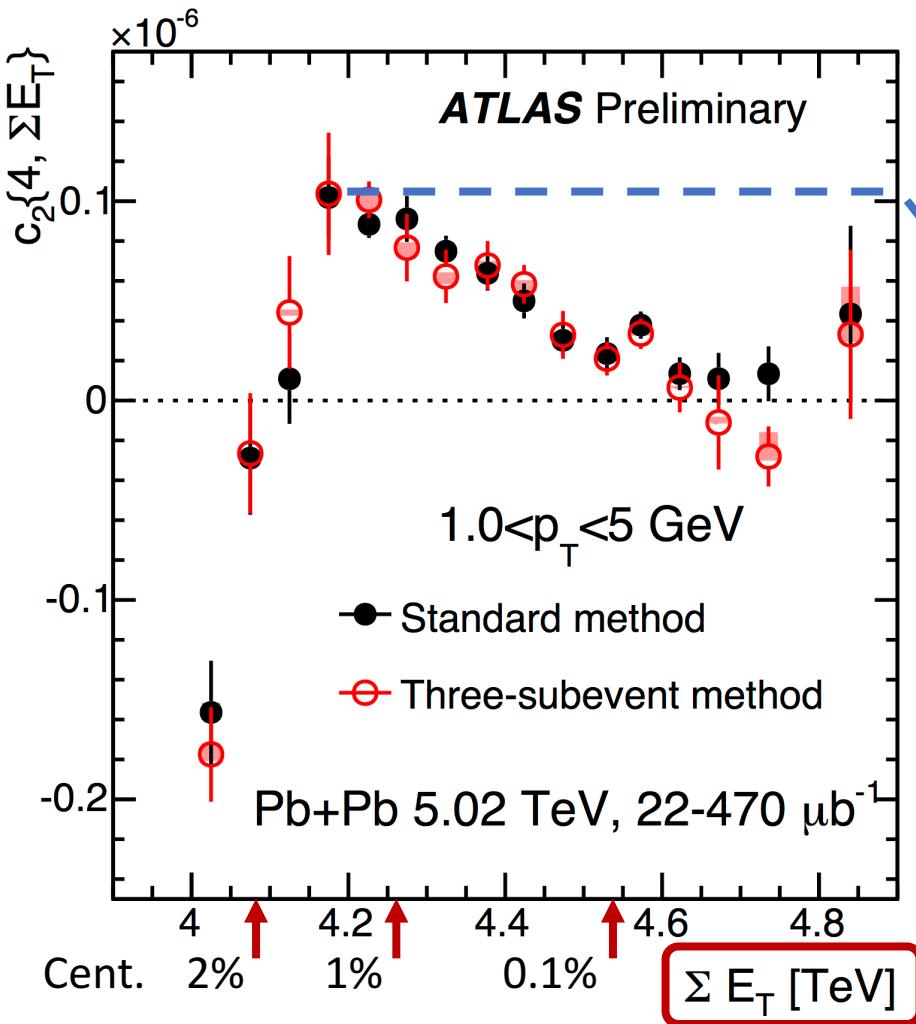
Binning defined by	Observable
FCal: $3.2 < \eta < 4.9$	$c_2\{4, \Sigma E_T\}$
ID: $ \eta < 2.5, p_T$ cut	$c_2\{4, N_{ch}^{rec}\}$

- Particle production depends on η

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



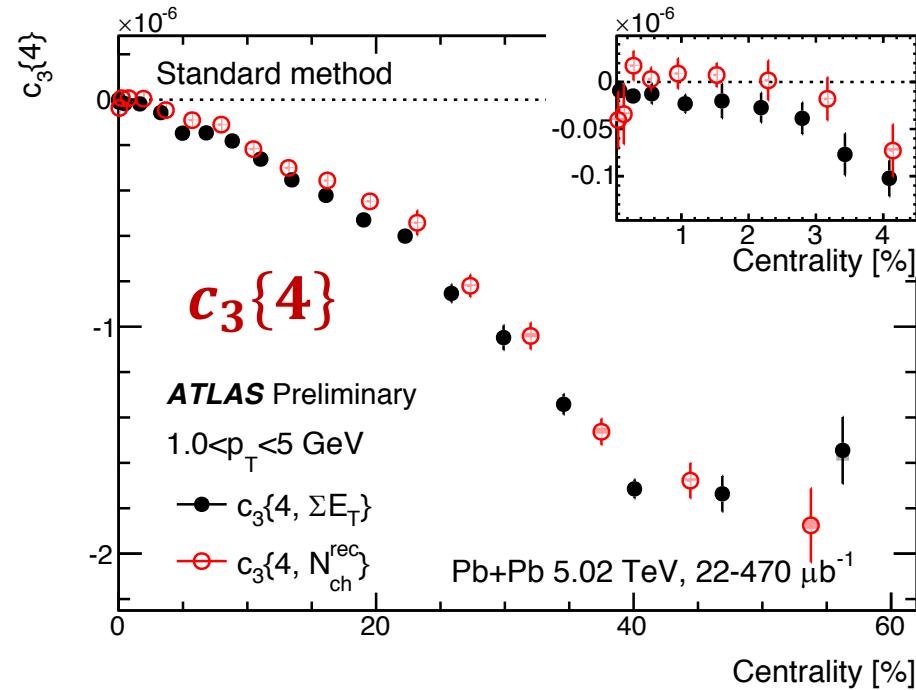
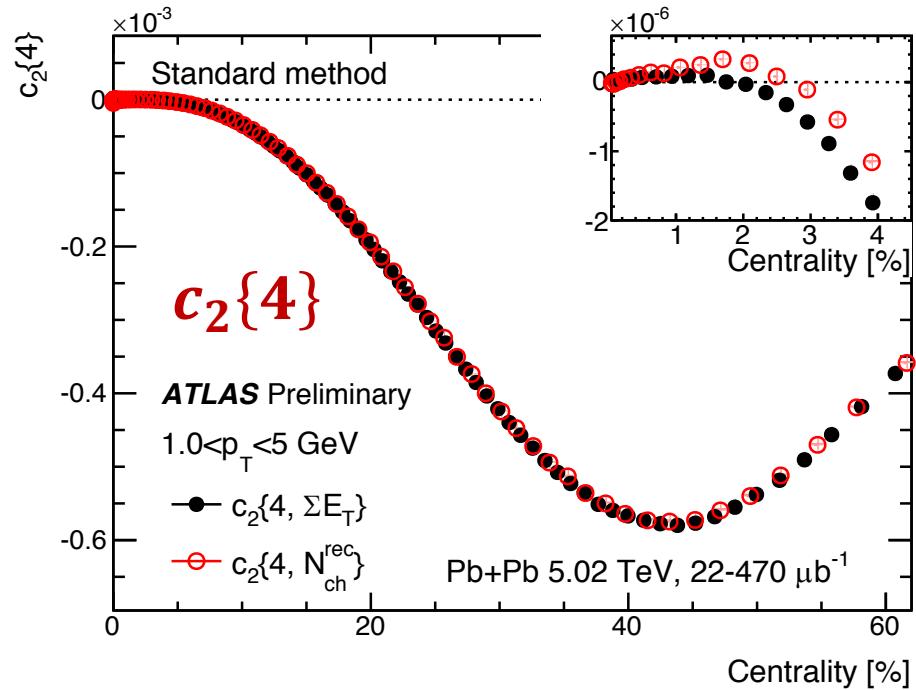
- $p(N_{ch}^{rec})$ broader than $p(\Sigma E_T)$
- CF effect: $\Sigma E_T < N_{ch}^{rec}$
- Prediction
 - $c_2\{4, \Sigma E_T\} < c_2\{4, N_{ch}^{rec}\}$



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

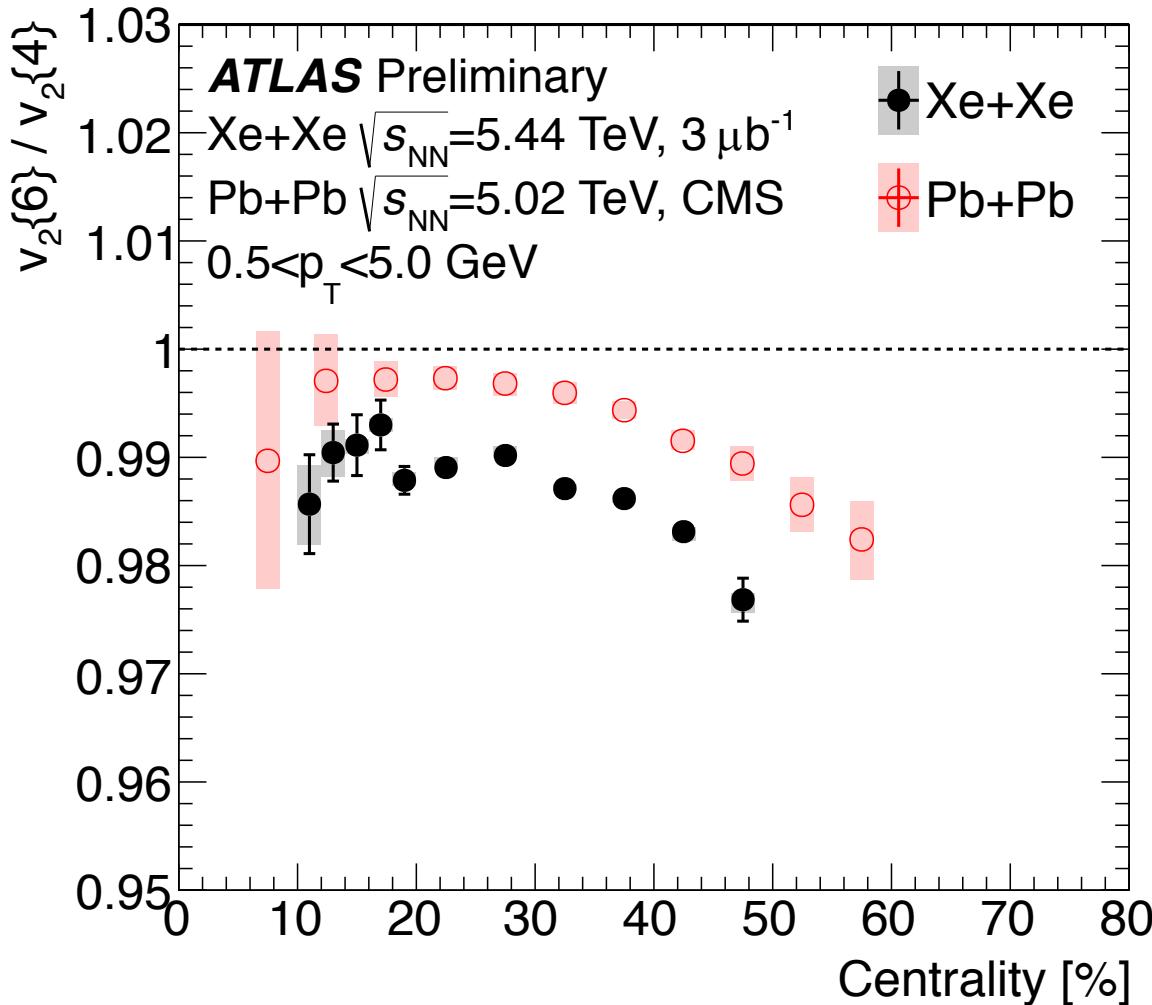
From ultra-central to full centrality

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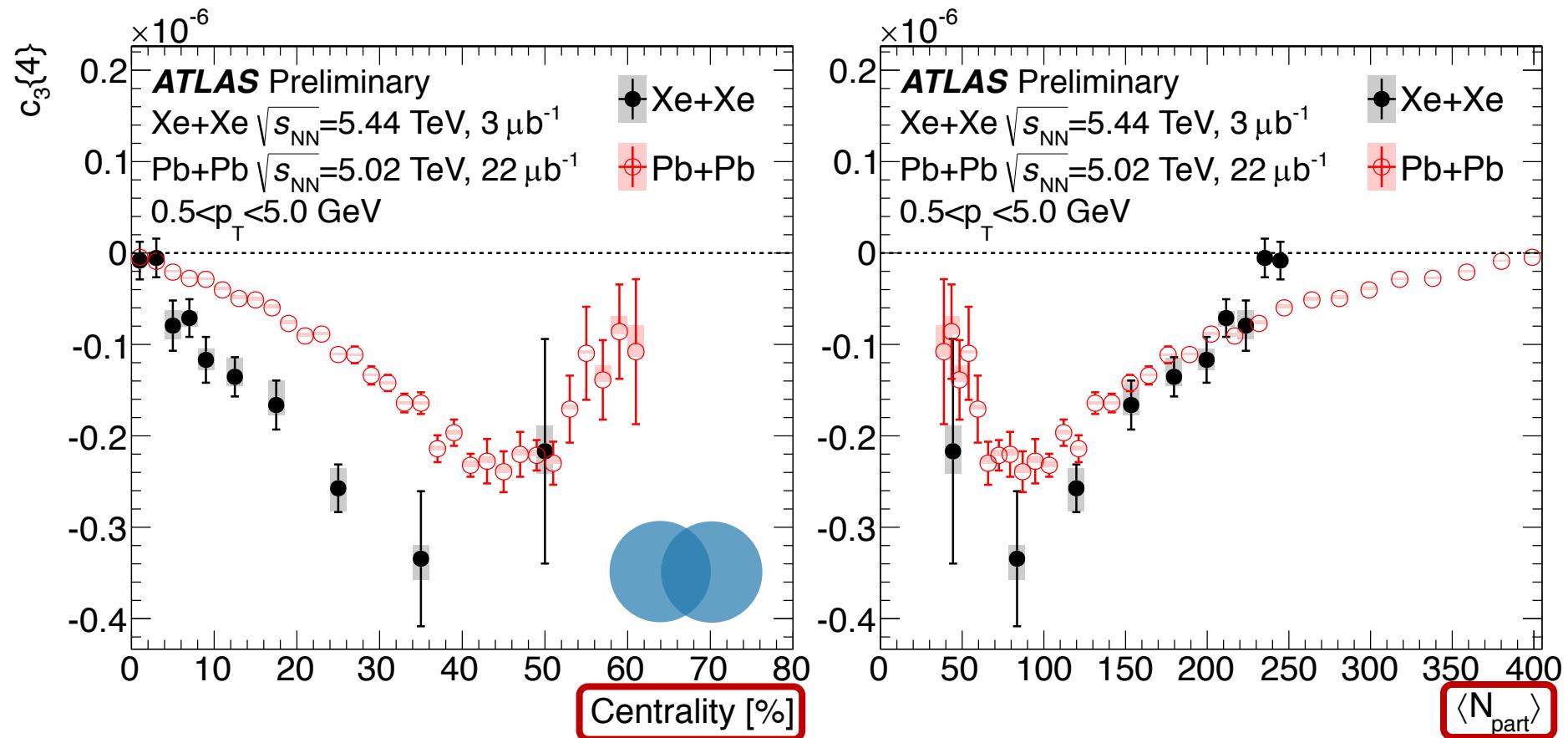
- $c_2\{4\}$: CF mostly affects central;
- $c_3\{4\}$: CF affects most centralities.

Comparison between Pb+Pb and Xe+Xe



- 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 $\langle N_{part} \rangle$
 - Fluctuation driven by # of sources N_{part}
 - Similar observation for $c_4\{4\}$ (see backup)

Multi-particle cumulant

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