Evidences for collectivity in small systems

Mingliang Zhou

Stony Brook University

Advisor: Prof. Jiangyong Jia

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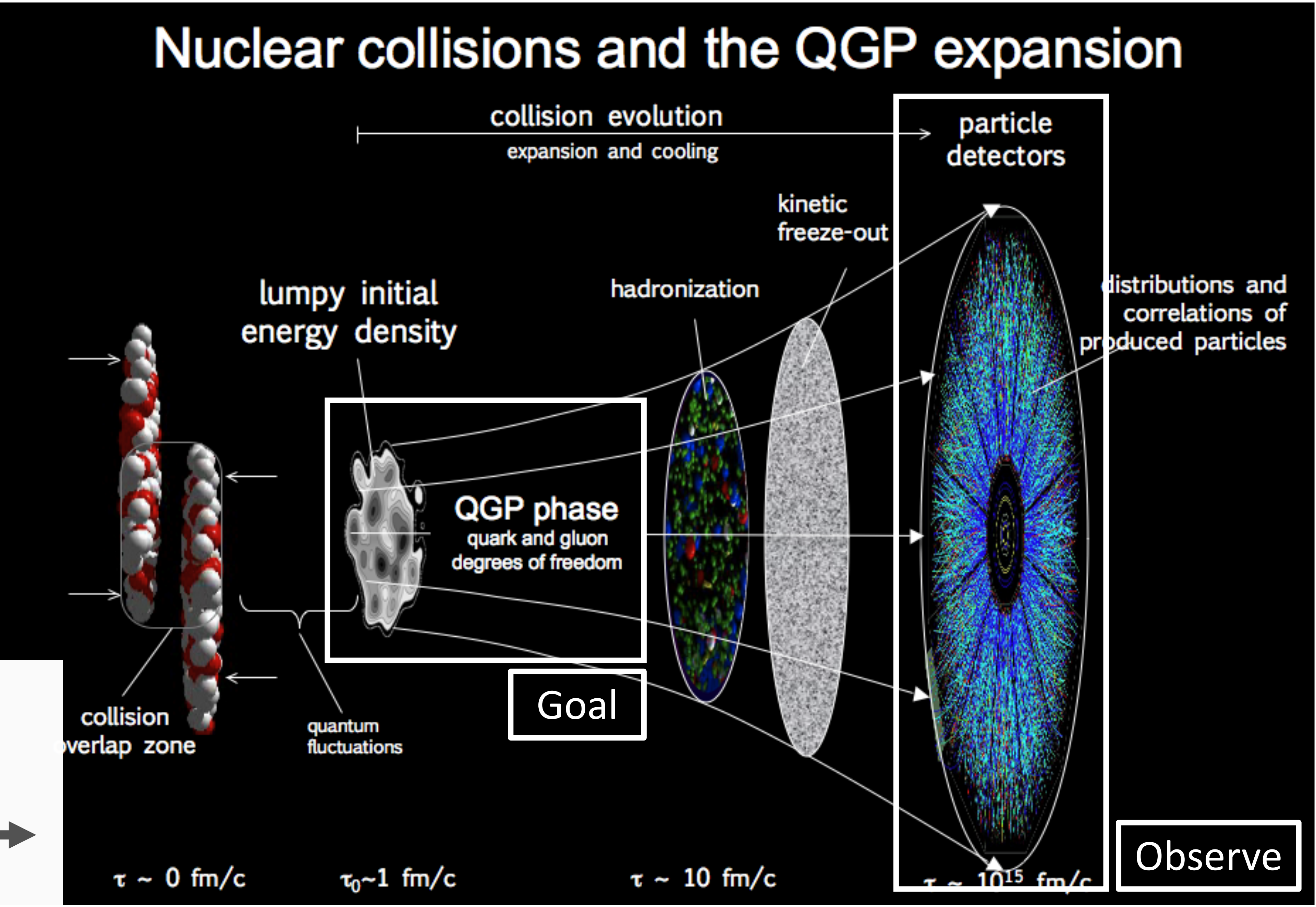
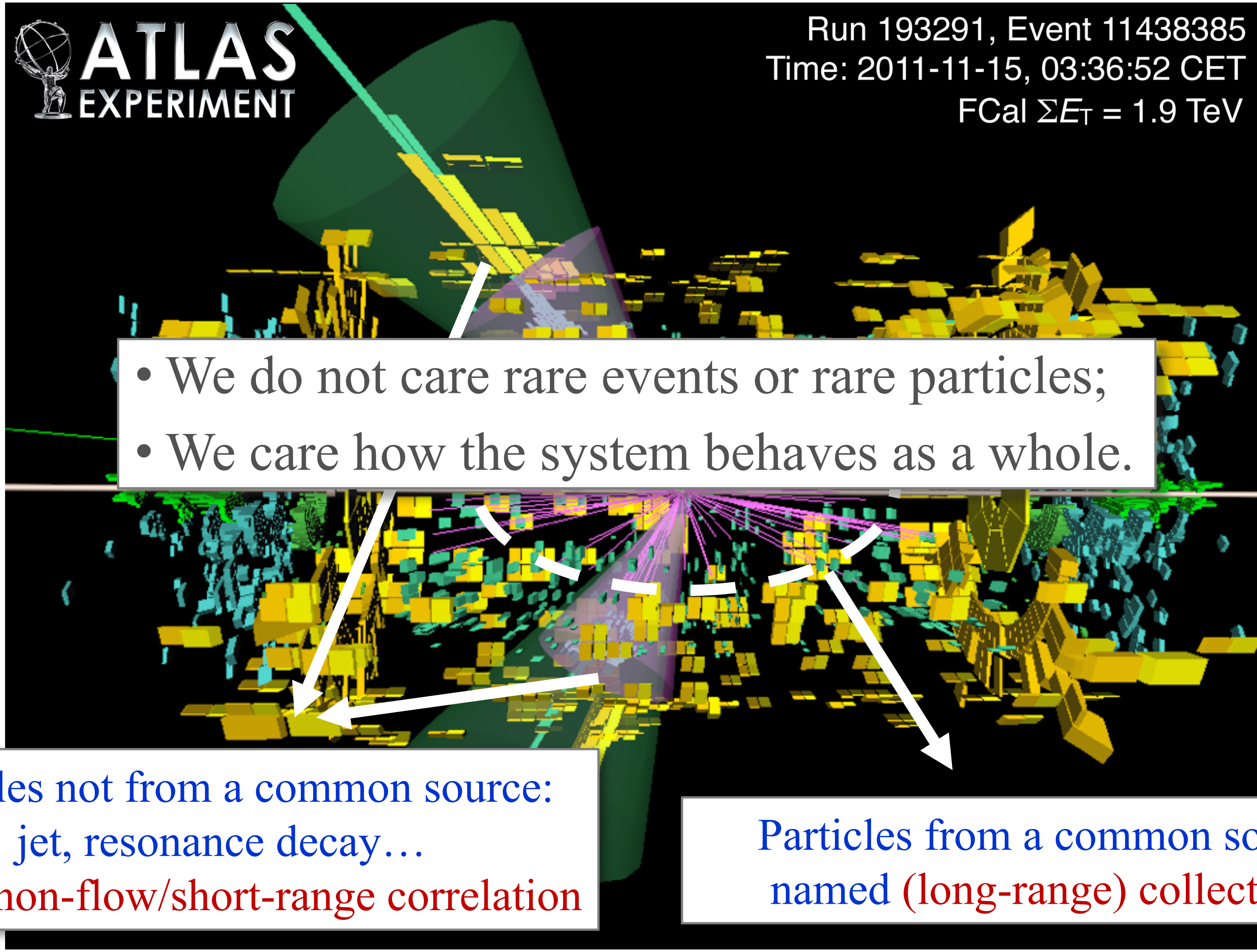

Nuclear collisions and the QGP expansion
collision evolution
expansion and cooling
particle detectors
kinetic freeze-out
hadronization
lumpy initial energy density
distributions and correlations of produced particles
QGP phase
quark and gluon degrees of freedom
Goal
collision overlap zone
quantum fluctuations
Observe
τ ~ 0 fm/c
τ0~1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

Why collectivity?

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

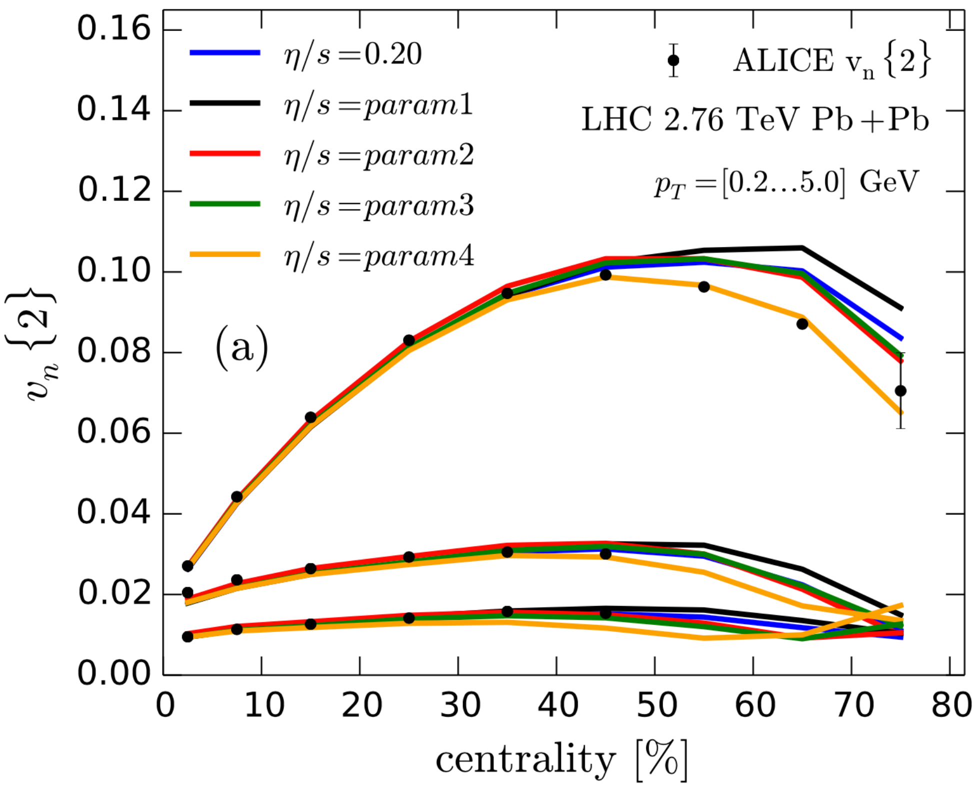


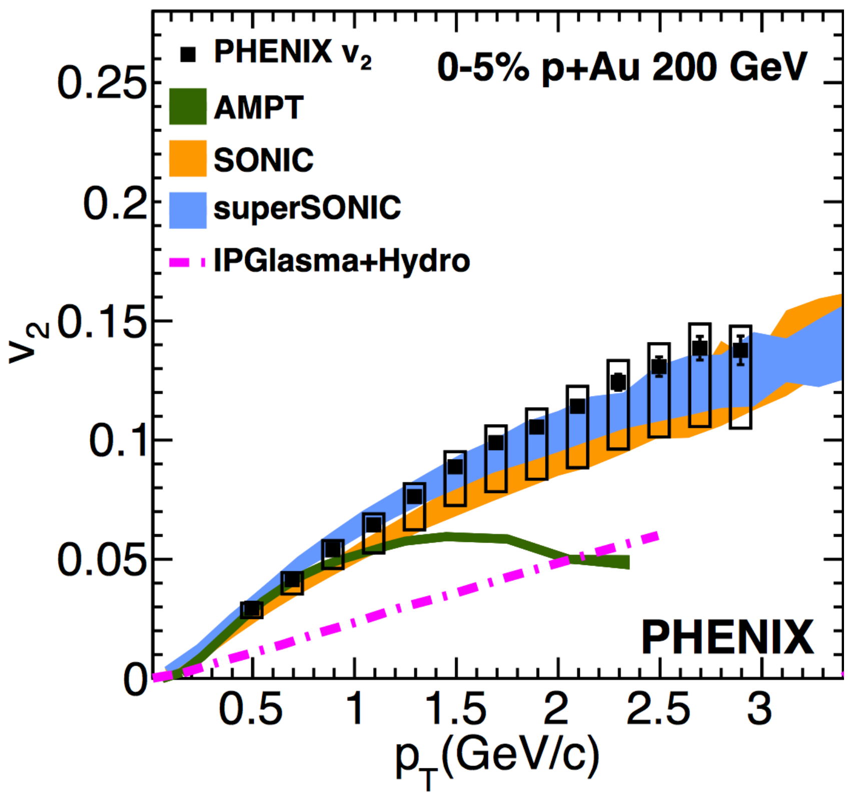
- We do not care rare events or rare particles;
- We care how the system behaves as a whole.

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?





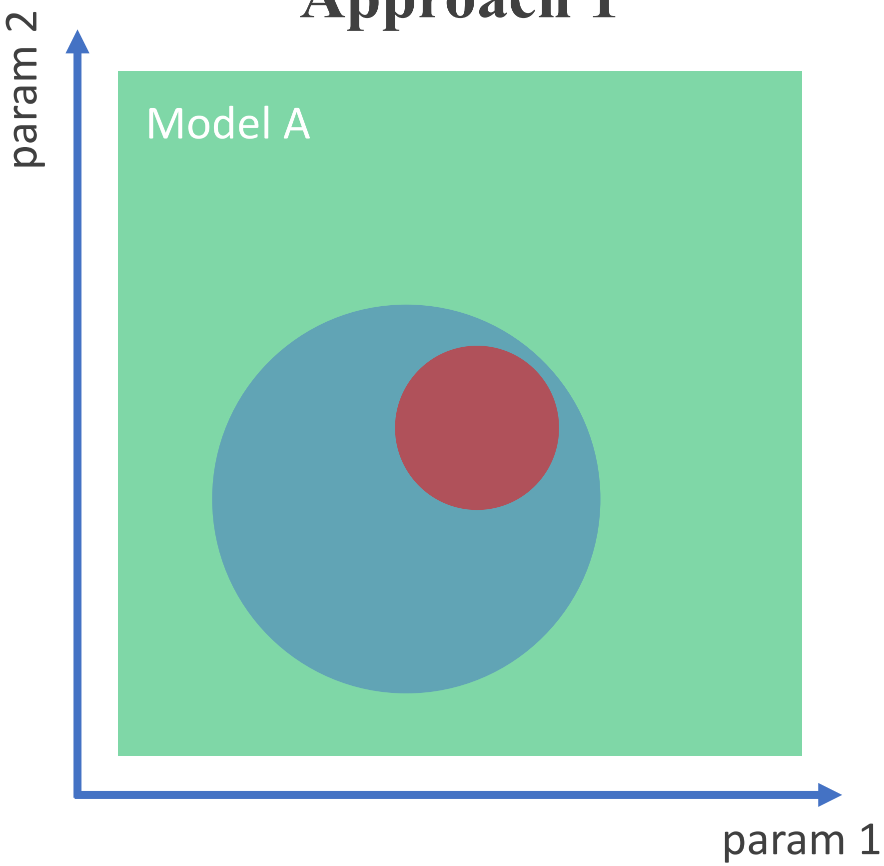
- Success of models in large systems;
- Parameters not well constrained.

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

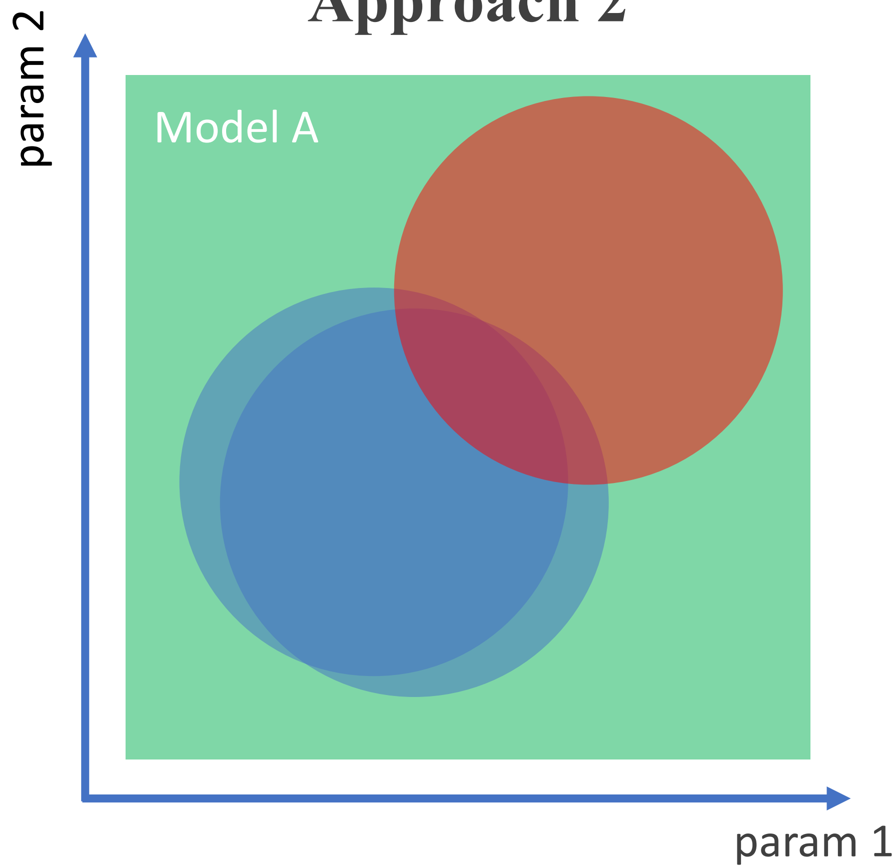
Larger proton fluctuation can better distinguish different models

How to use data to constrain models?

Approach 1



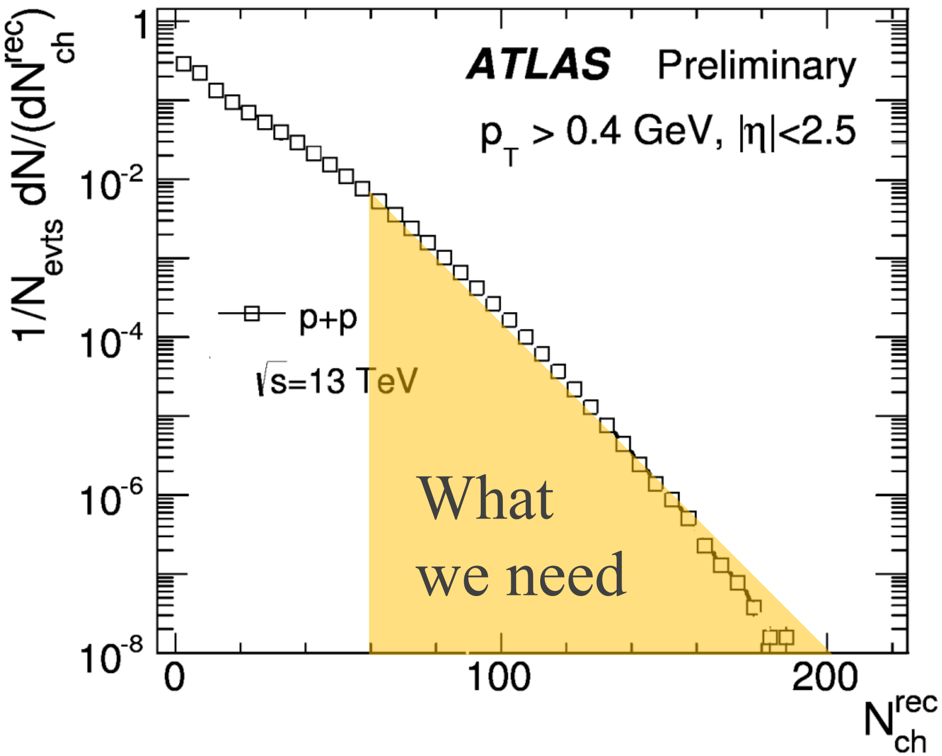
Approach 2



- Improve data statistical significance

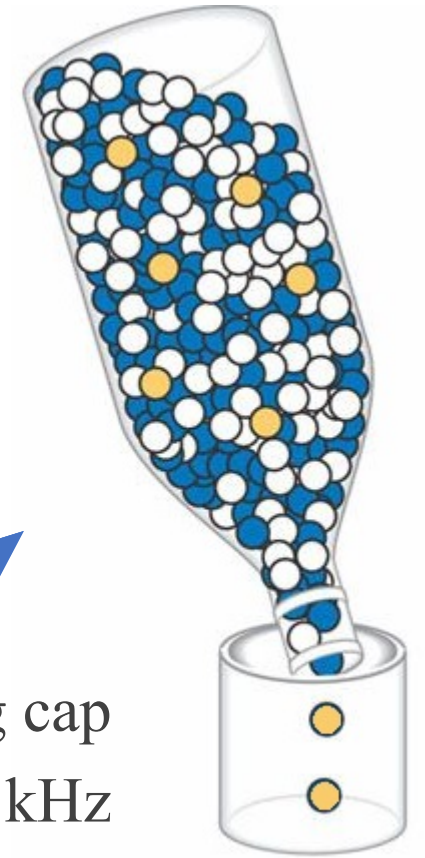
- Independent constrains
  - Observable
  - Collision system
  - Collision energy

High-multiplicity *pp* and *p*+Pb events

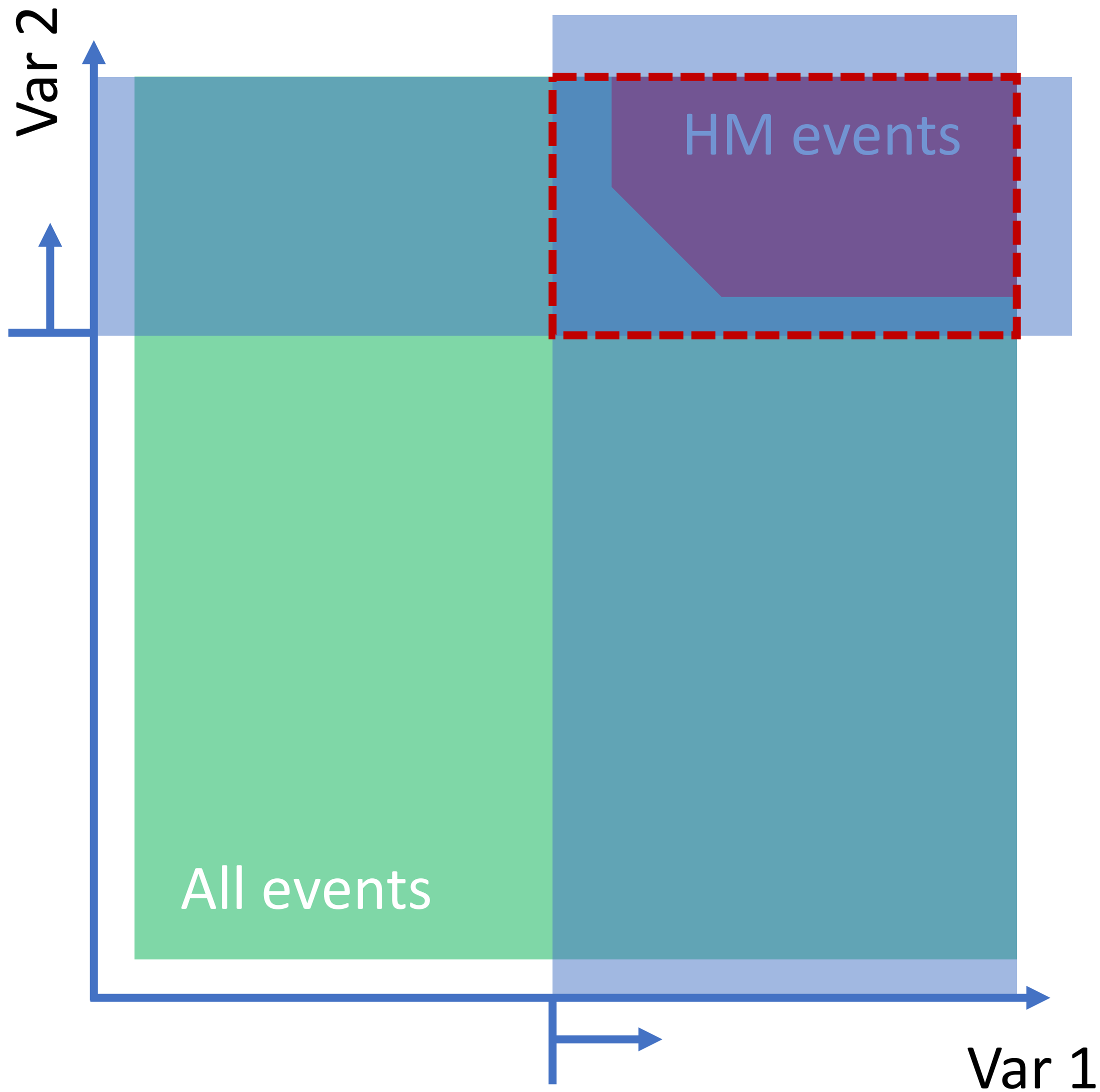


LHC event rate
40 MHz

Recording cap
10 kHz



- Need to design real-time data selection system (trigger)
  - Select events with $N_{ch} > 60$ within 1ms;
  - But particle reconstruction time $\gg$ 1ms.

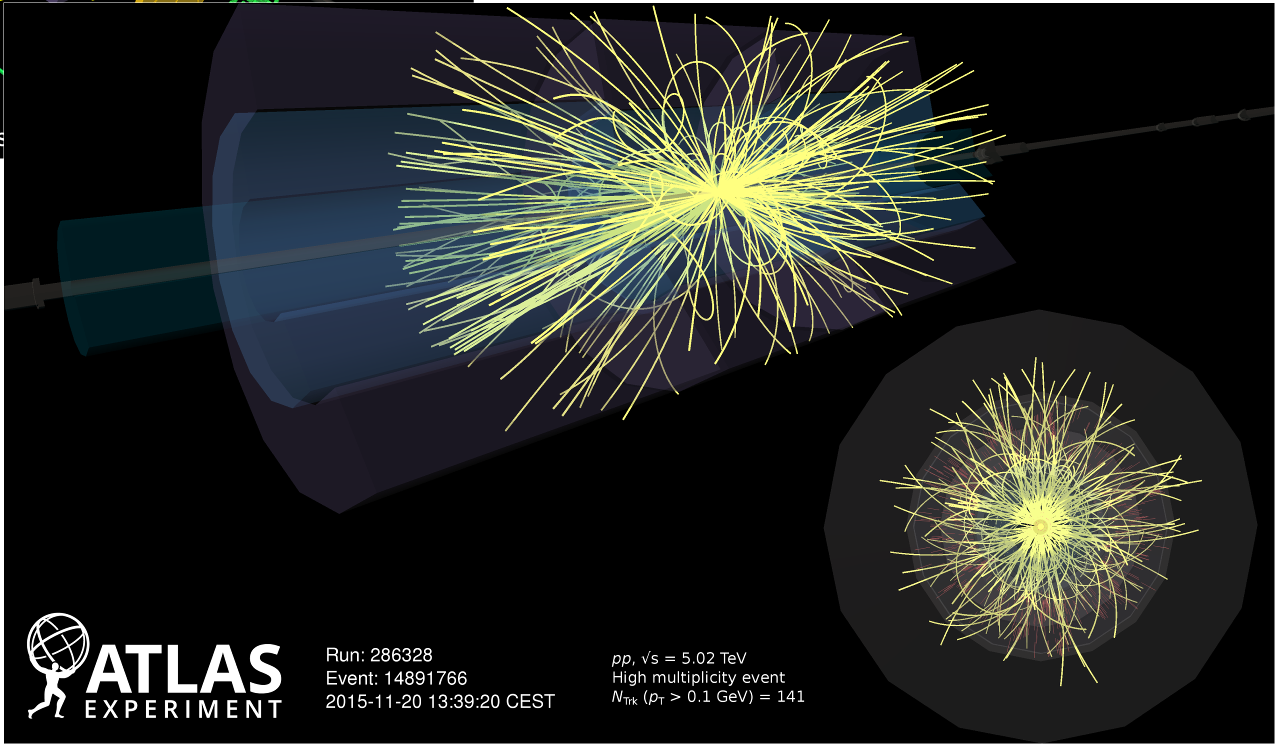


Sequence and thresholds of cuts designed to maximize performance.

Event display

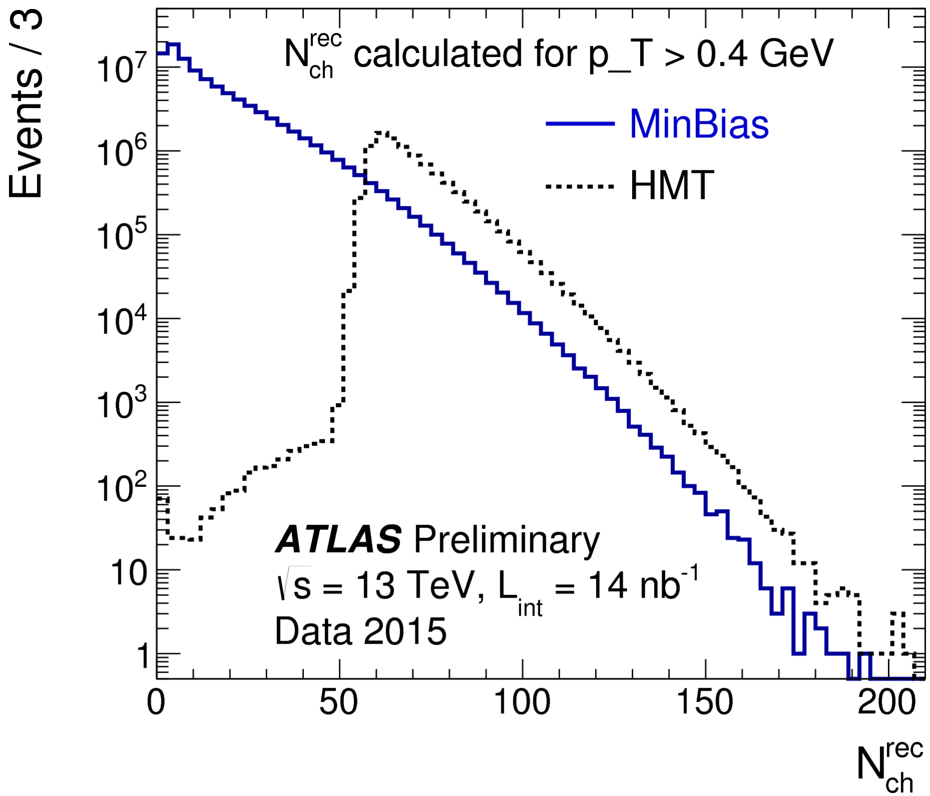
Minimum-bias event

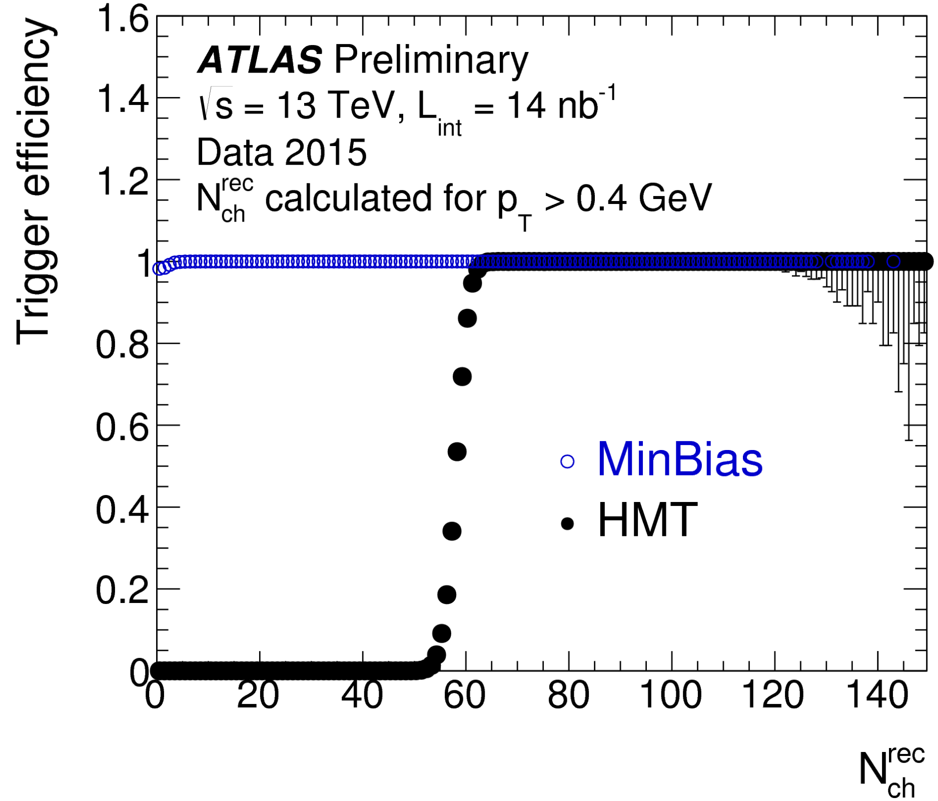
$N_{ch} \approx 30$



Triggered event

$N_{ch} \approx 140$





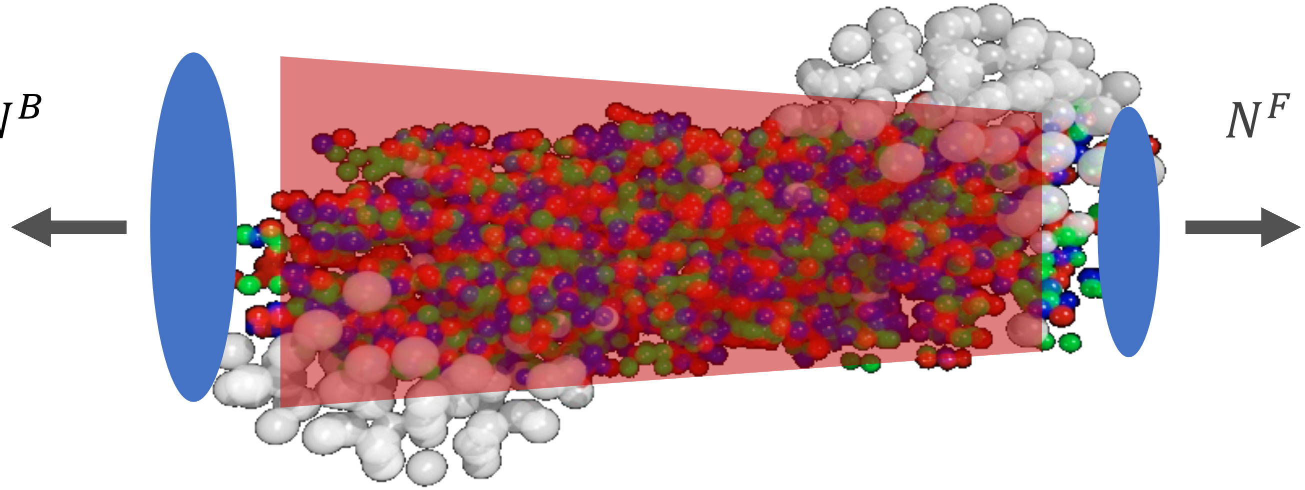
- Statistics increased by x5.
- Nominal bias introduced.

Multiple HMT triggers applied to *pp* and *p*+Pb data taking

Long-range longitudinal correlation

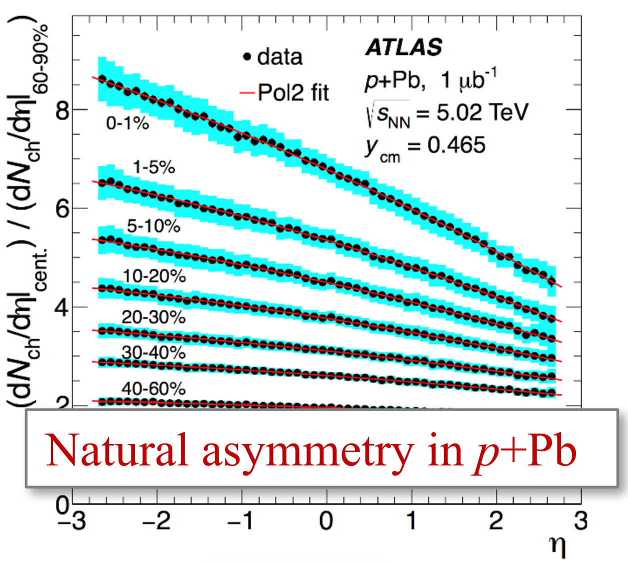
Nature of sources seeding the long-range collective behaviors?

N^B



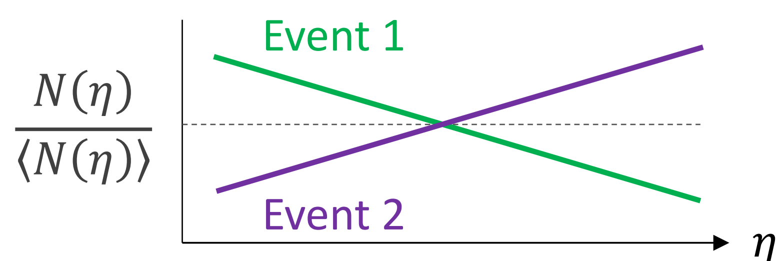
N^F $\left\{ \begin{array}{c} \text{participants} \\ \text{partons} \\ \text{string/tubes} \end{array} \right.$

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



Natural asymmetry in p+Pb

Event-by-event multiplicity fluctuation?

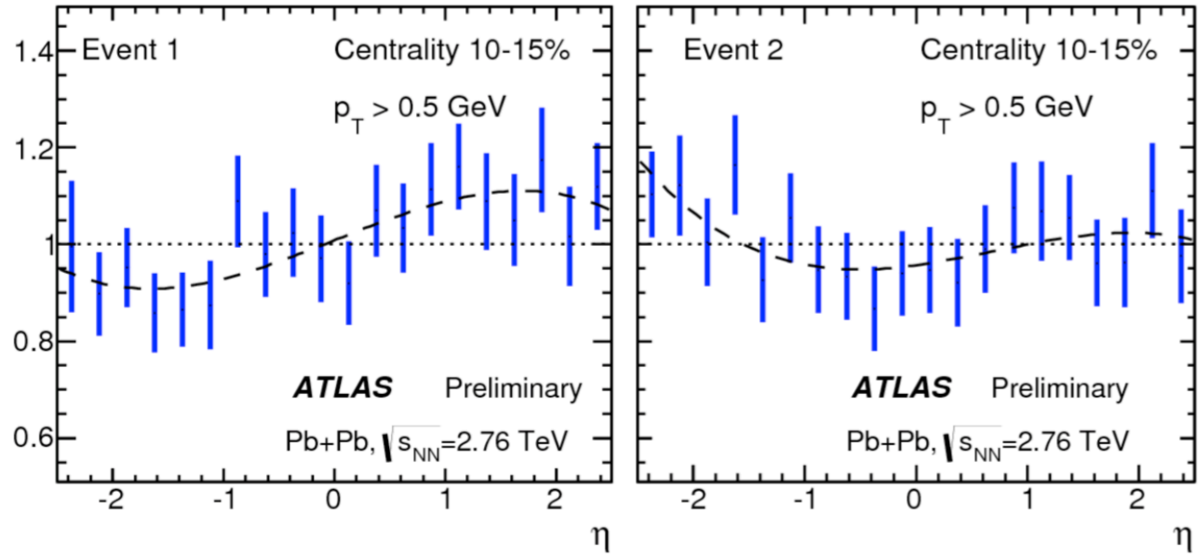


New observable

- Single particle observable

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

- Dominated by statistical fluctuations!



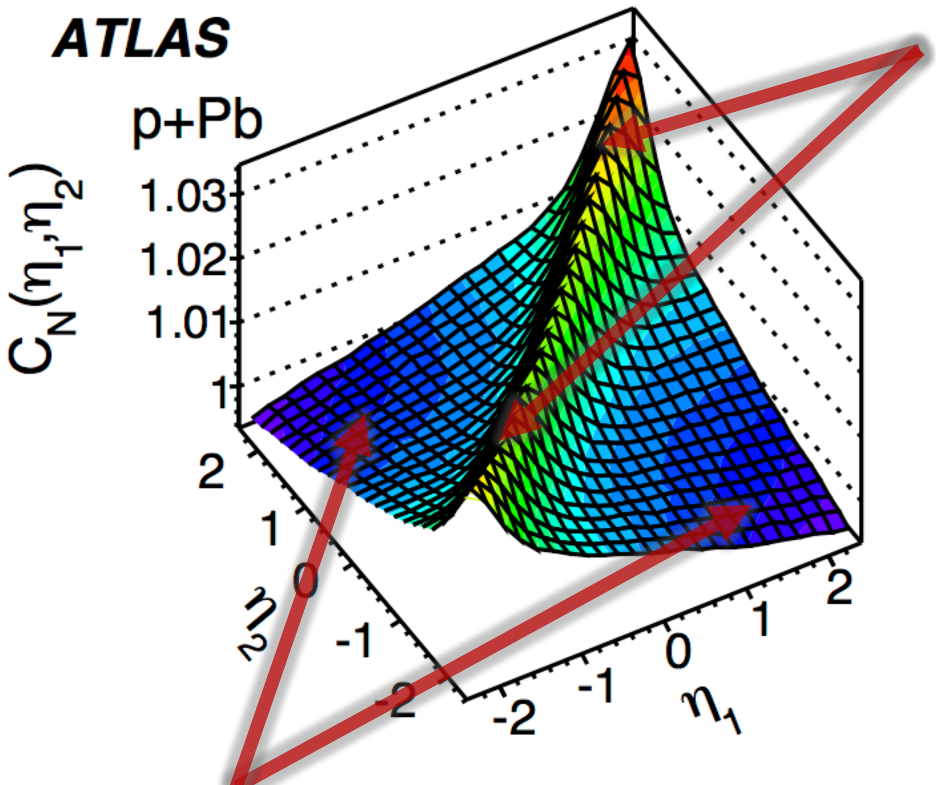
- Two particles observable (correlation function)

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

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;

Physics signal and background

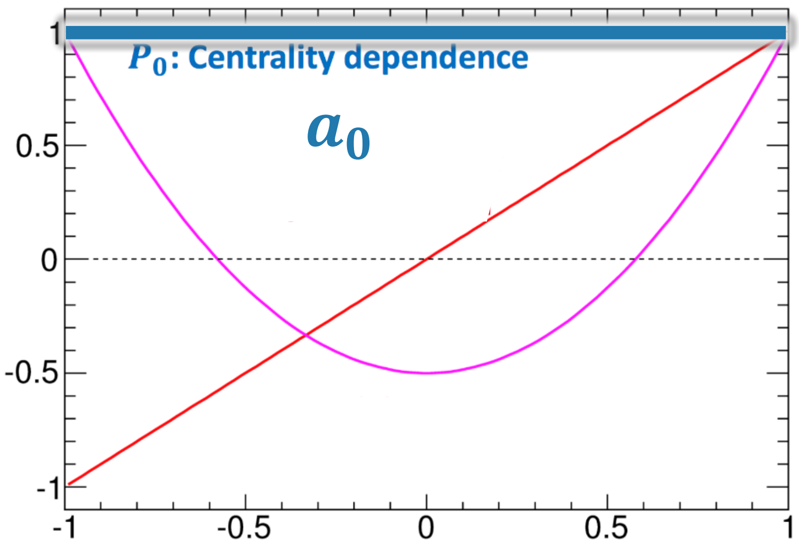


- Short-range correlation reflects correlation in the same source: jet fragmentation, resonance decay…
- Since SRC has a strong charge dependence, a data-driven way was developed to remove the SRC (backup).
- An alternative way is through multi-particle correlation (cumulant) in η. Phys. Rev. C 93, 024903 (2016)

- Long-range correlation

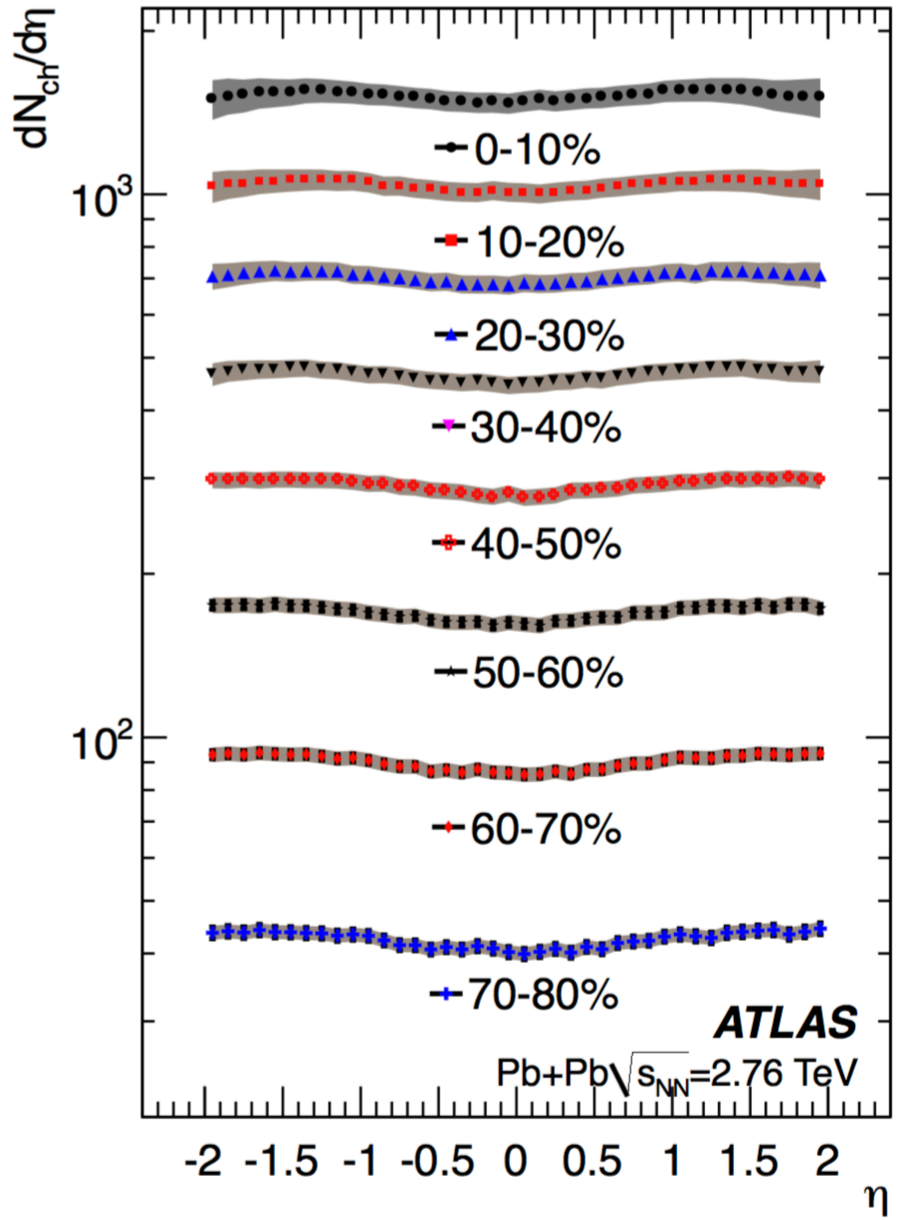
How to quantify forward-backward fluctuation?

Legendre expansion: a_0

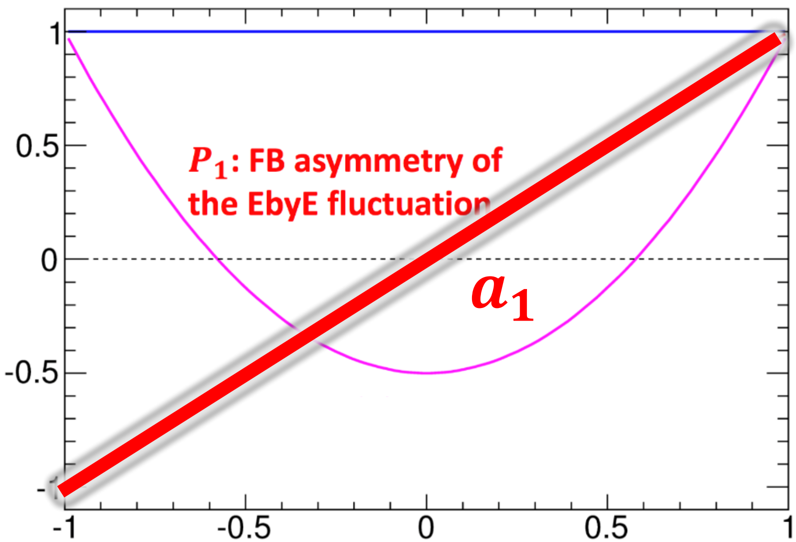


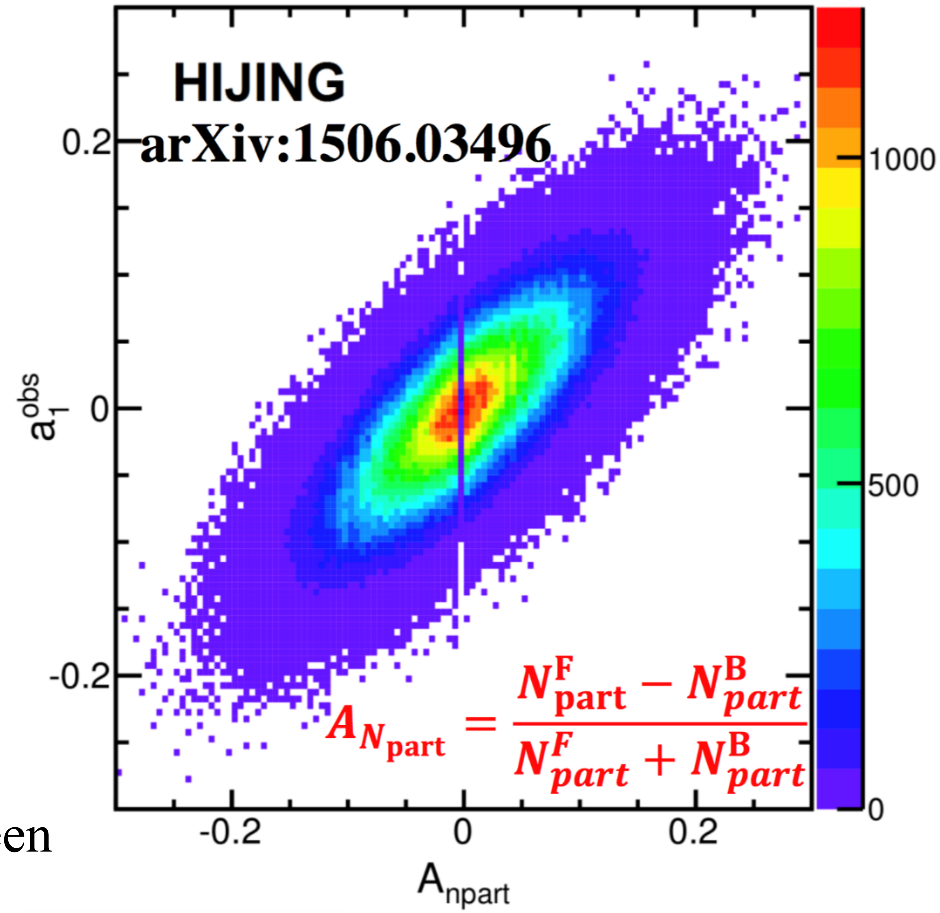
- Analysis focuses on dynamical fluctuation upon average;
- However, average multiplicity changes with centrality;
- The residual centrality dependence is removed by normalizing $C(\eta_1, \eta_2)$

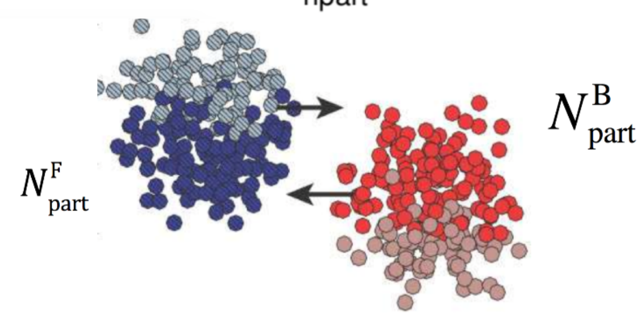
$$C_N(\eta_1, \eta_2) = \frac{C(\eta_1, \eta_2)}{C_p(\eta_1) C_p(\eta_2)}$$



Legendre expansion: a_1



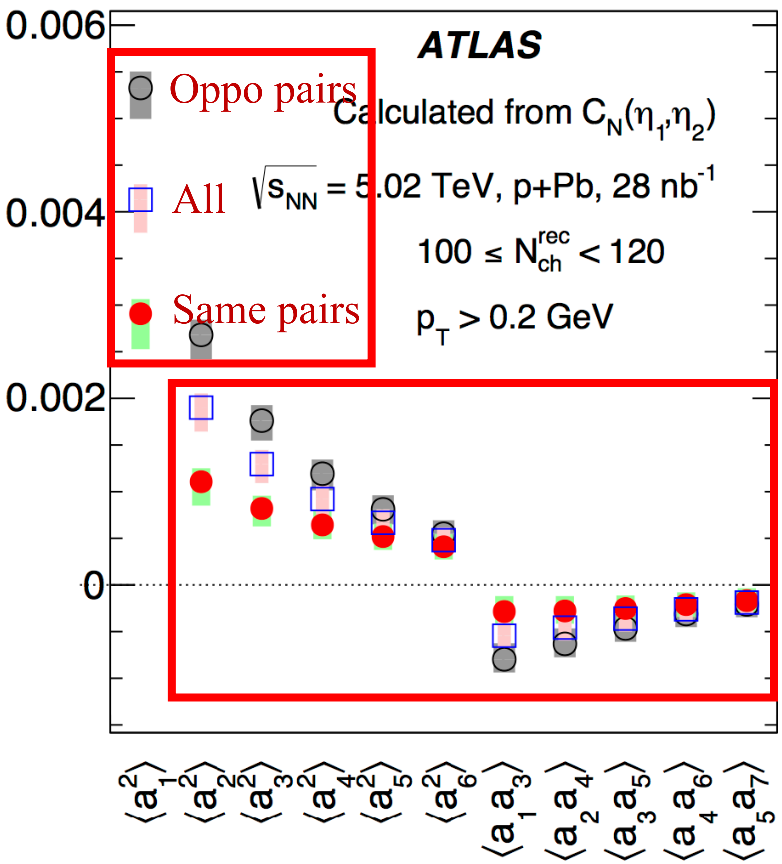




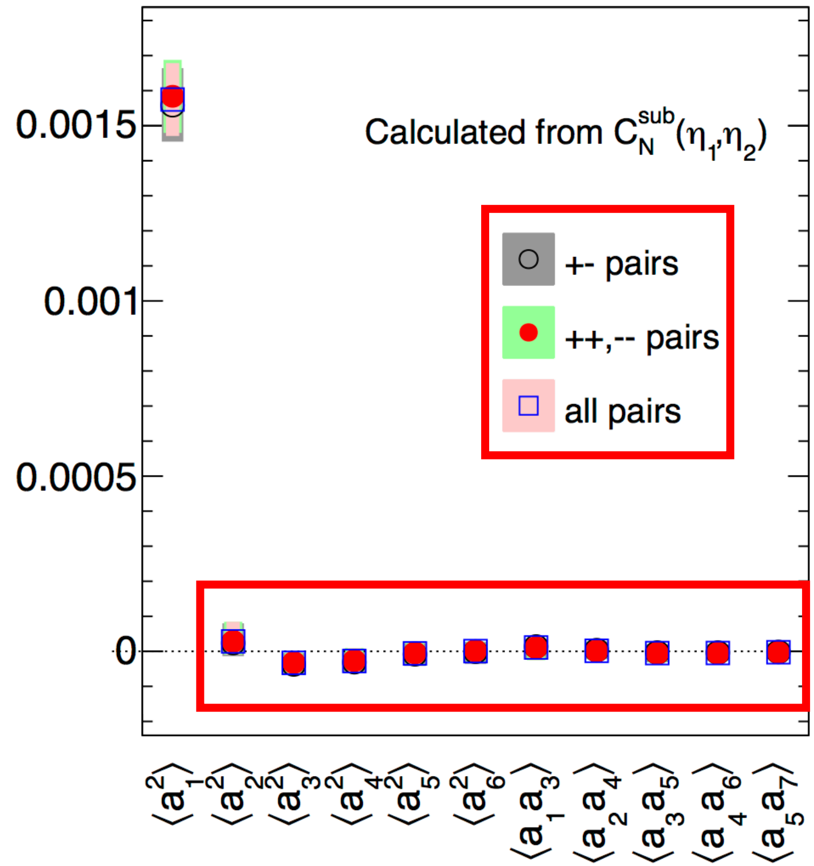
- The linear shape quantifies the FB multiplicity asymmetry;
- HIJING shows strong correlation between final multiplicity asymmetry and initial participant asymmetry;
- As will be shown later, this component dominates the shape fluctuation.

Why it is important to remove SRC?

Before SRC removal

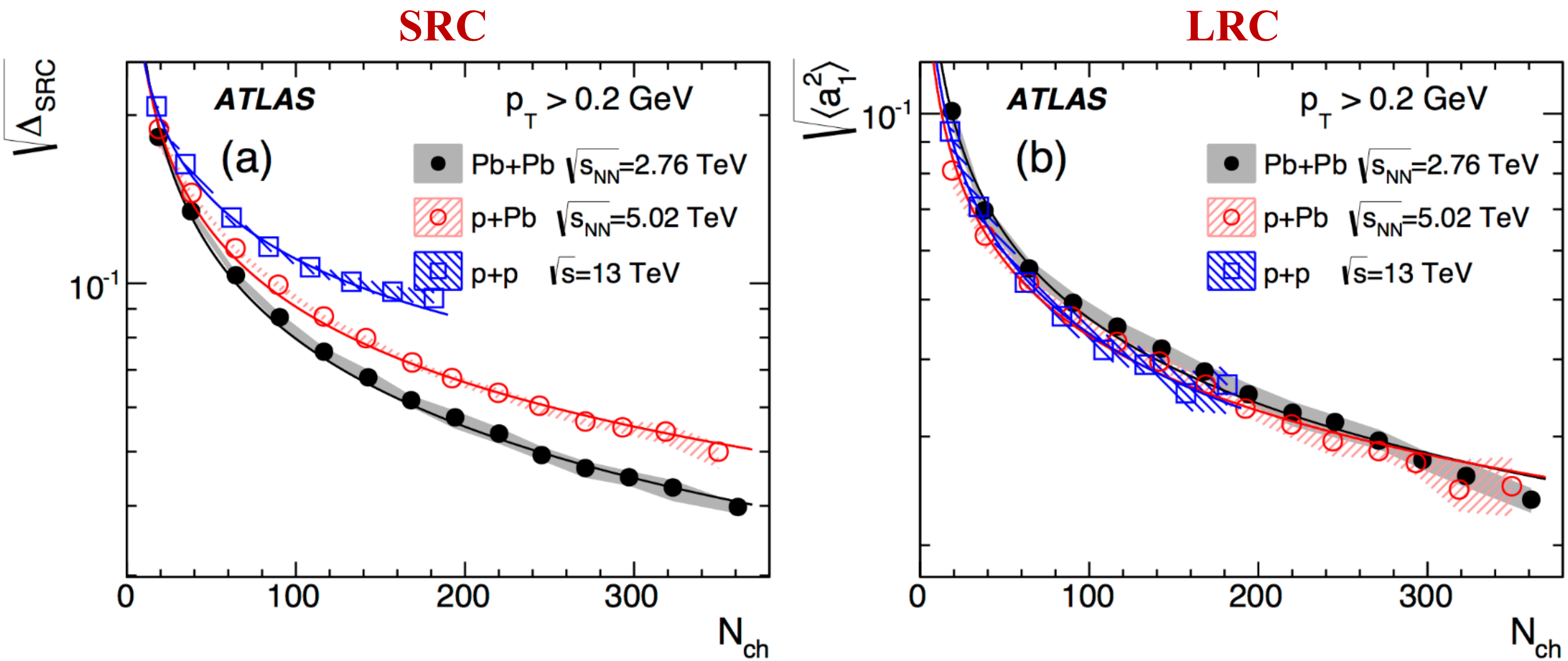


After SRC removal



- 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.



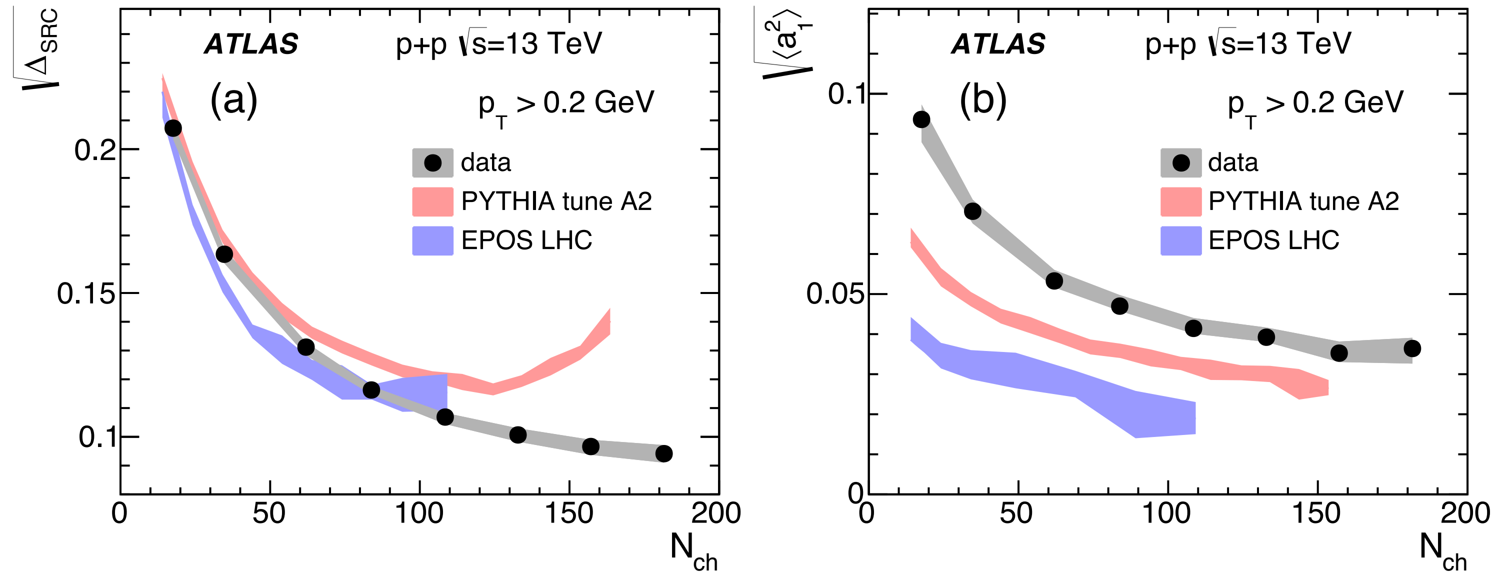
- SRC increases towards peripheral;
- SRC is stronger in small systems;

- FB fluctuation is larger in peripheral;
- Independent of system size!

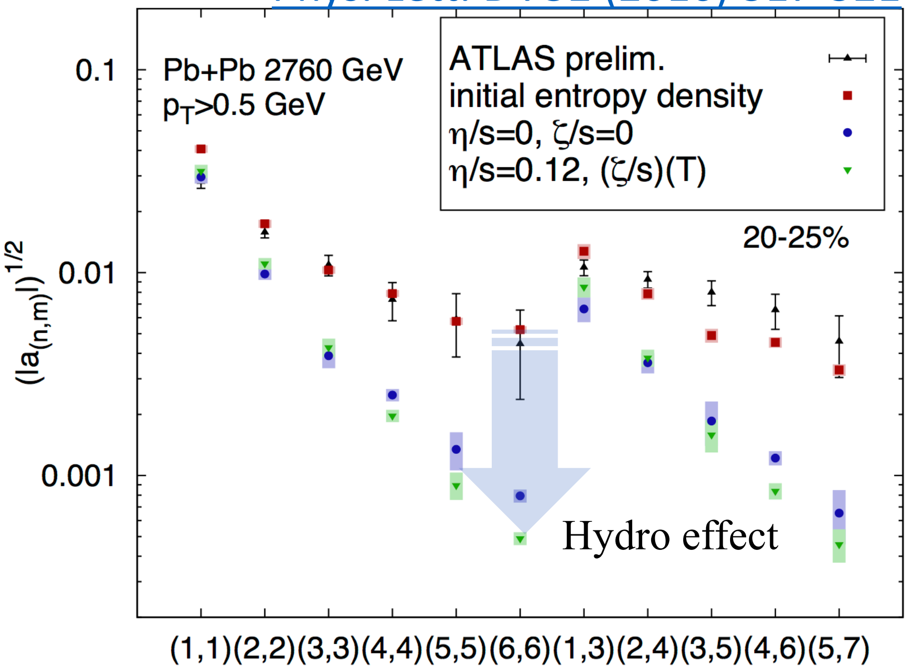
- ALICE measures the correlation between $dN/d\eta$ and ZDC energy.

How will these new results help?

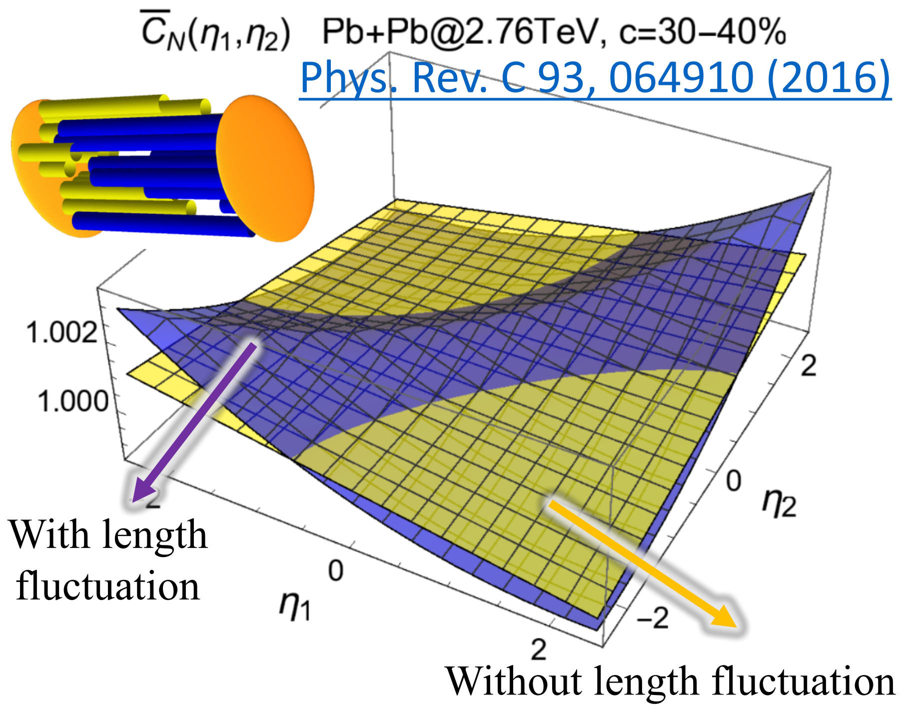
Model and data comparison



Phys. Lett. B 752 (2016) 317-321

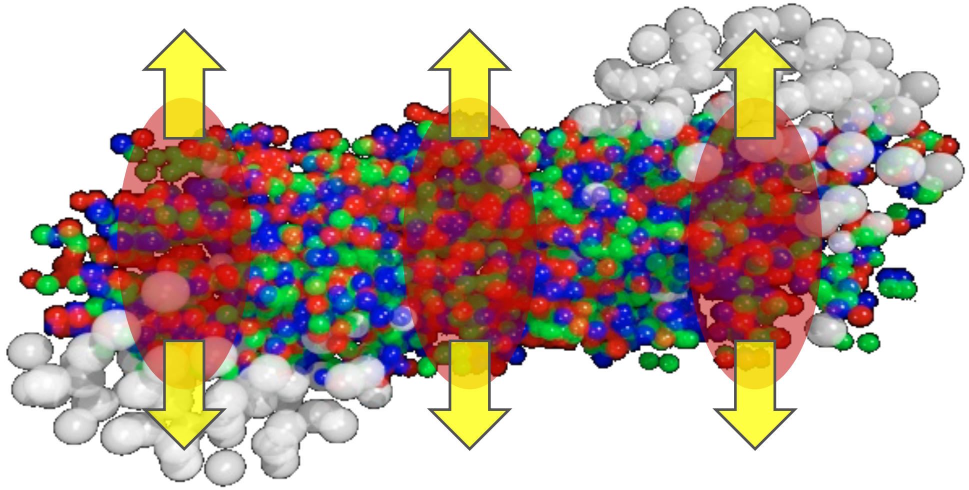


Phys. Rev. C 93, 064910 (2016)

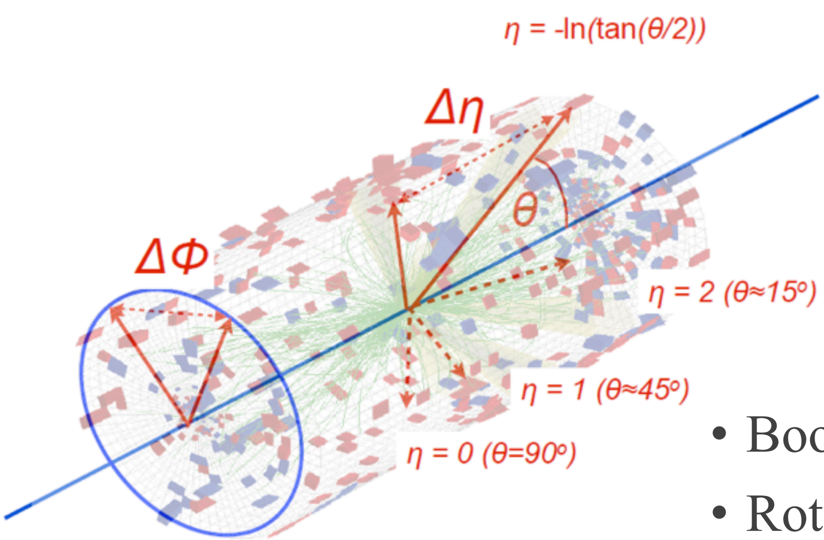


Long-range azimuthal correlation

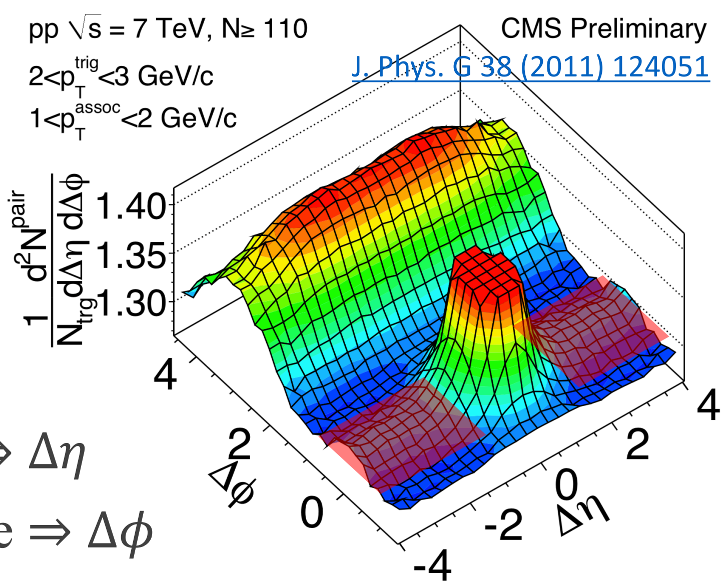
Nature of sources seeding the long-range collective behaviors?



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



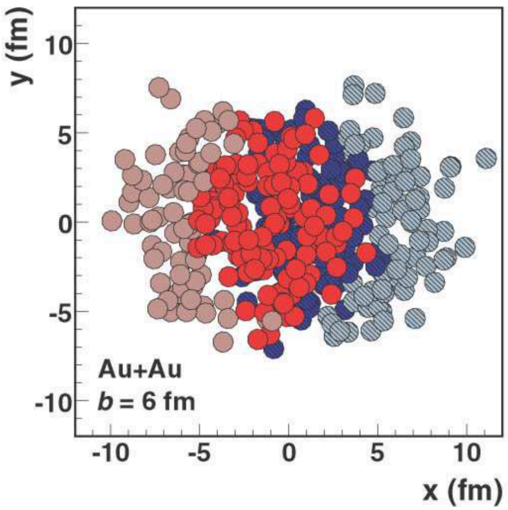
- Boost invariance ⇒ $\Delta\eta$
- Rotation invariance ⇒ $\Delta\phi$



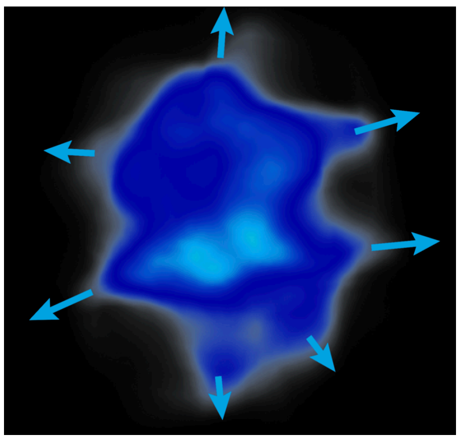
Origins of collectivity

- **Final state correlations**

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



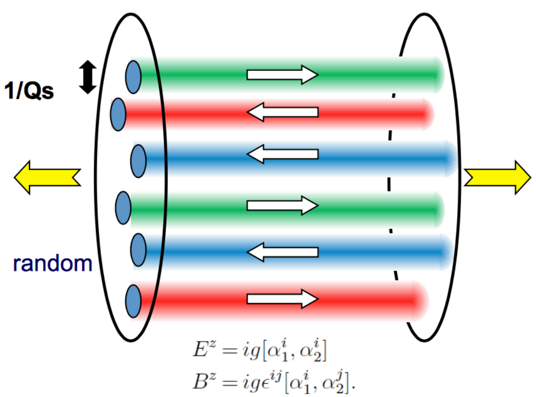
Hydrodynamic flow



Spatial structure from initial condition

Momentum correlations

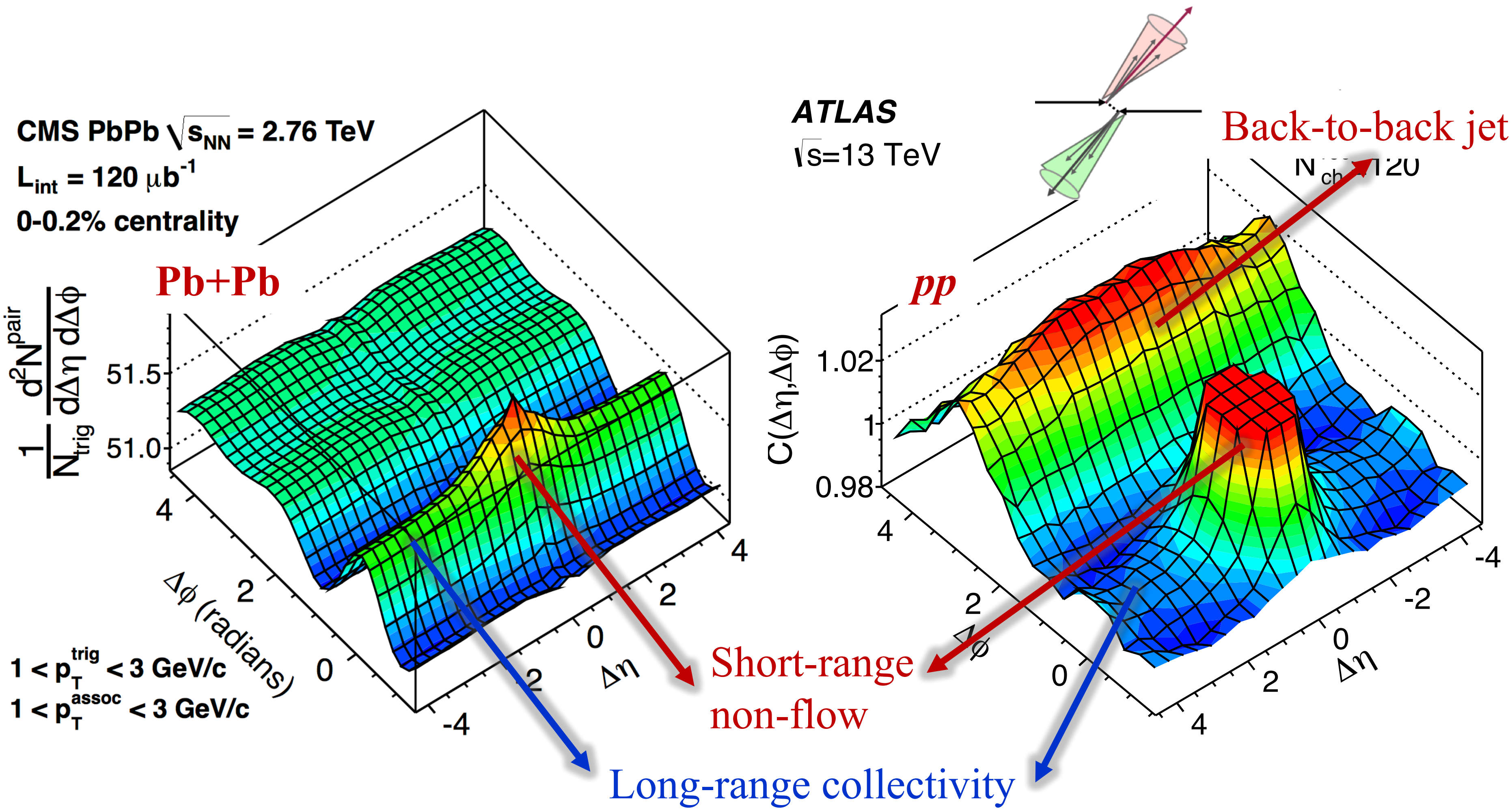
- **Initial state correlations**



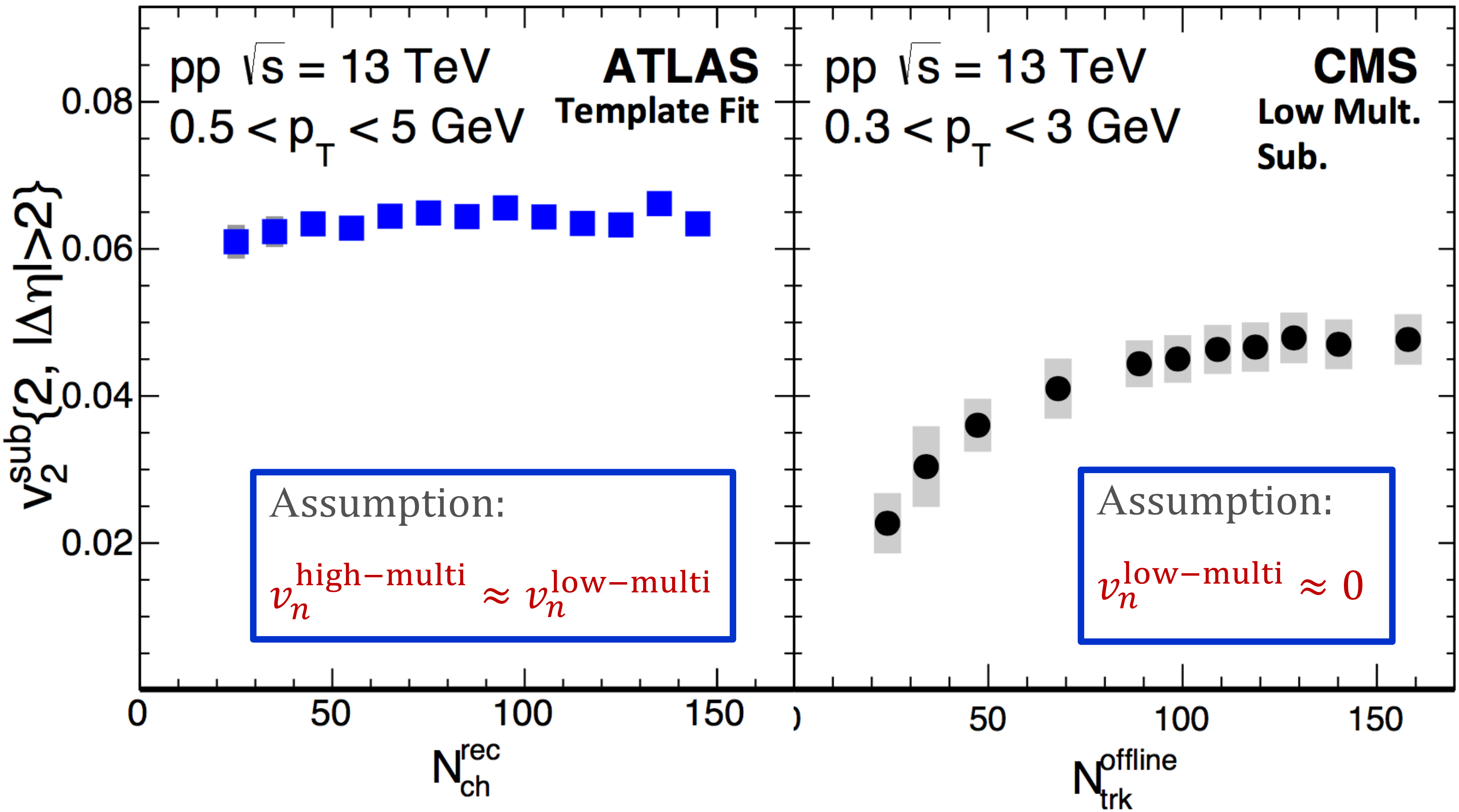
More careful studies in *pp* collisions are needed!

Particles are produced with momentum space correlations

2-particle correlation

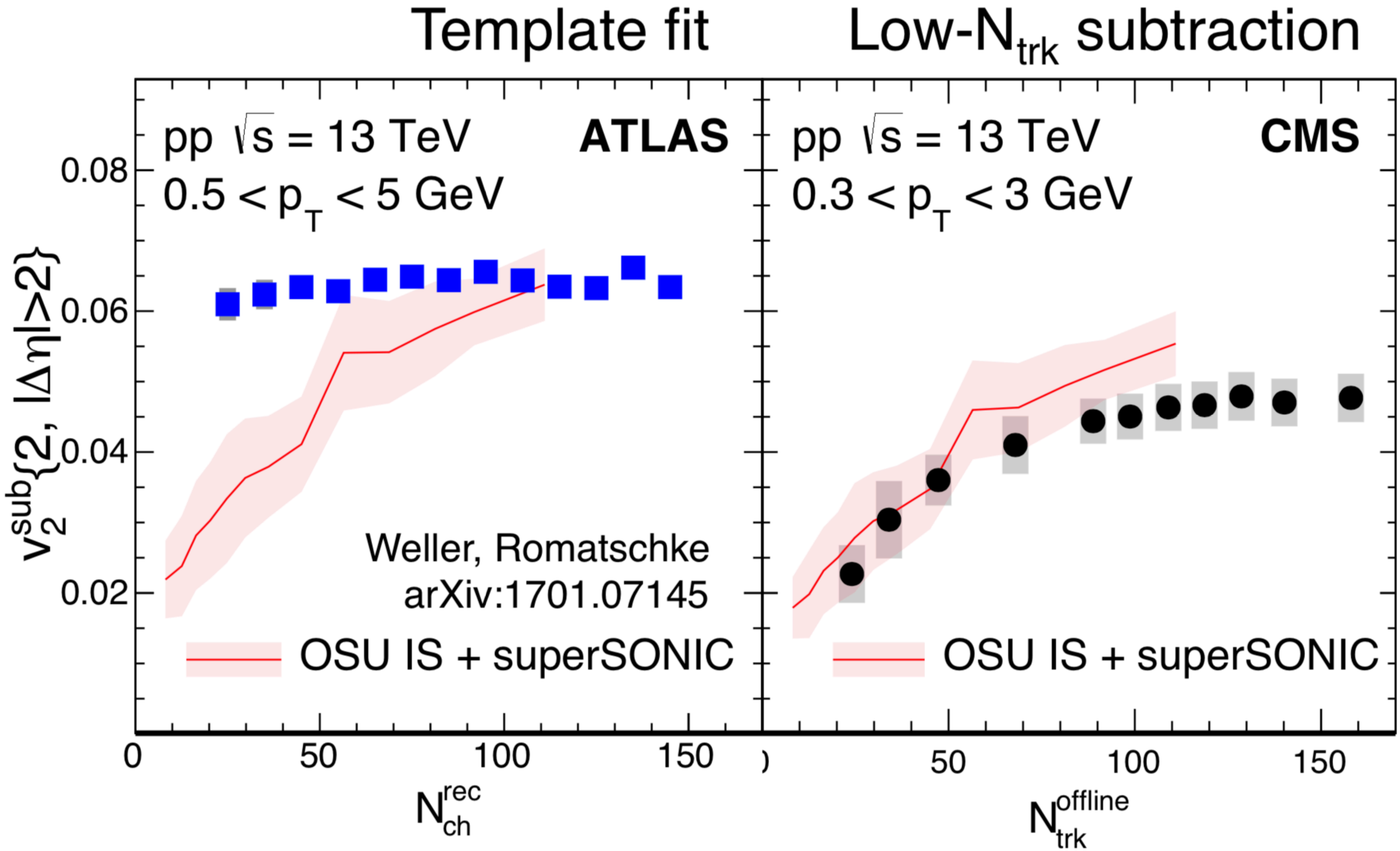


- Dijet behaves like long-range collectivity;
- Different methods used to remove dijet.



Does collectivity turn off at lower N_{ch}?

Hydro prediction



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

Cumulant method

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

Genuine 4-particle correlation

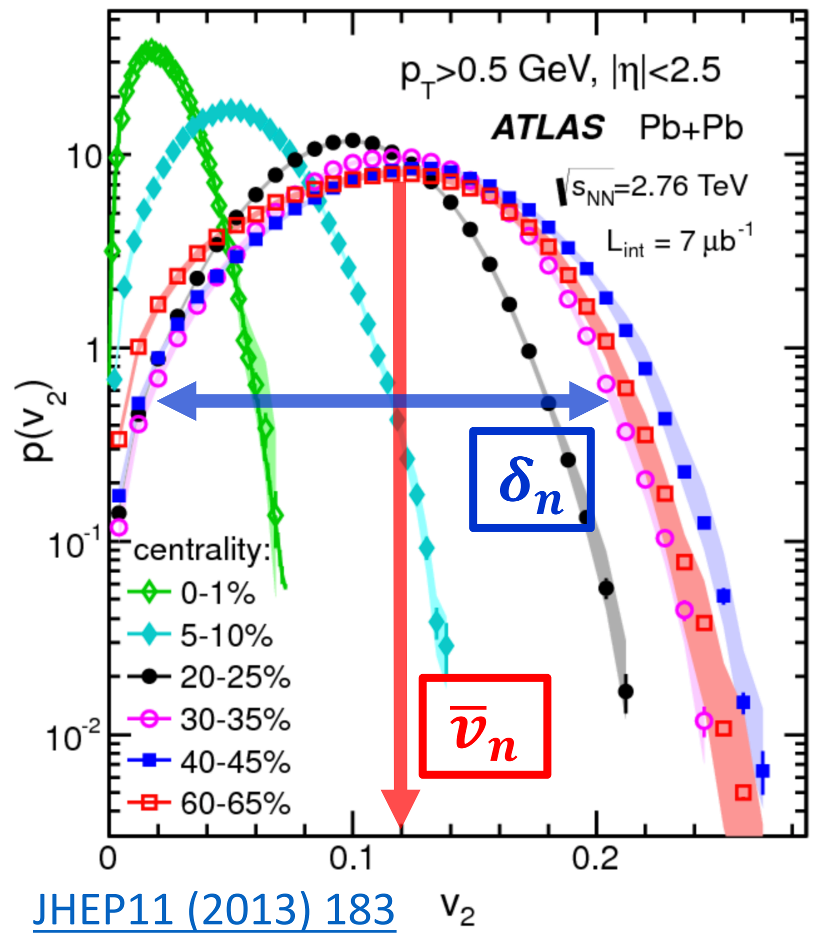
2-particle non-flow

- Multi-particle cumulant $c_n\{4\} \equiv \langle corr_n\{4\} \rangle - 2\langle corr_n\{2\} \rangle^2$

- Flow fluctuates from event to event;
- Cumulant probes $p(v_n)$.

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

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



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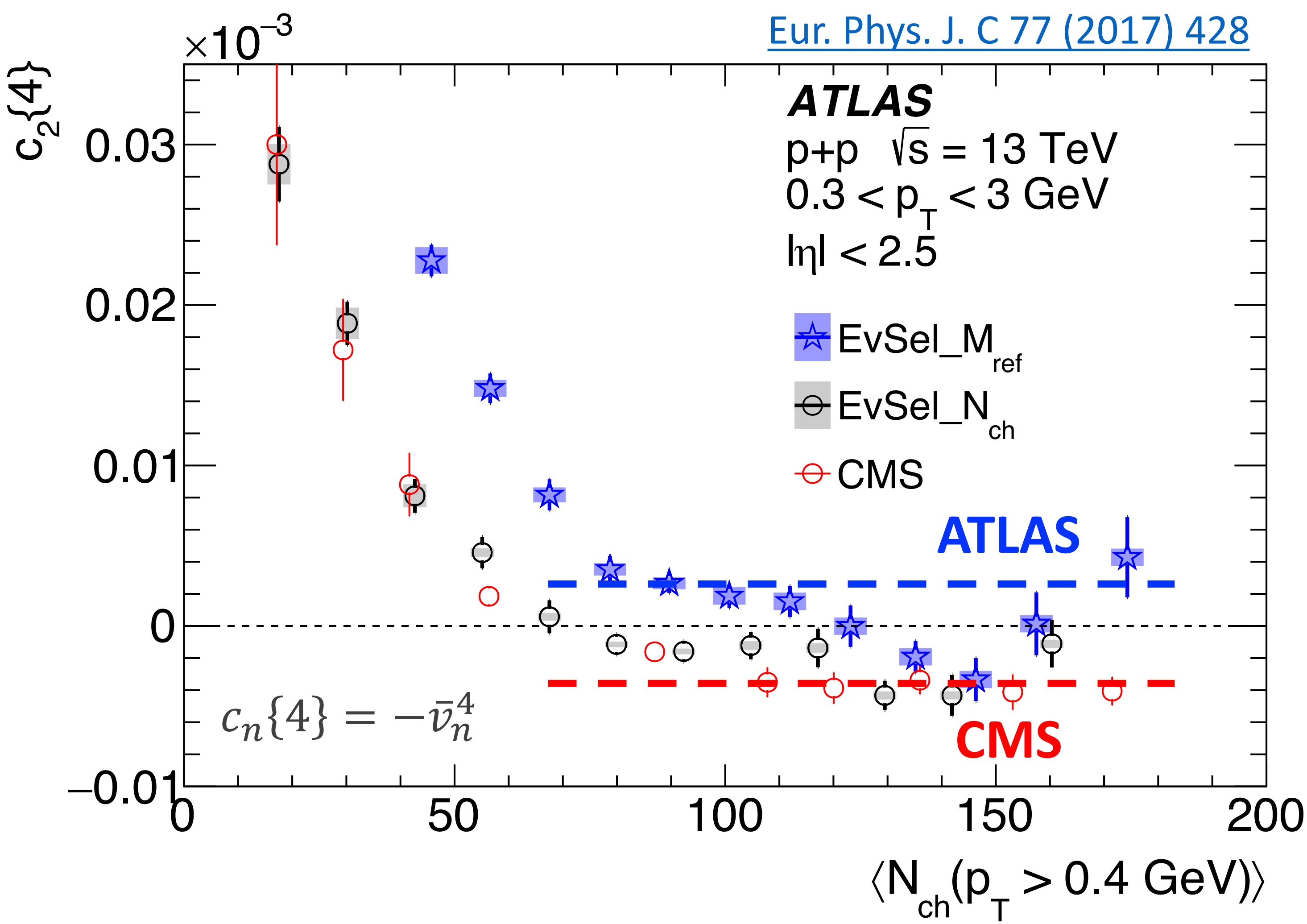
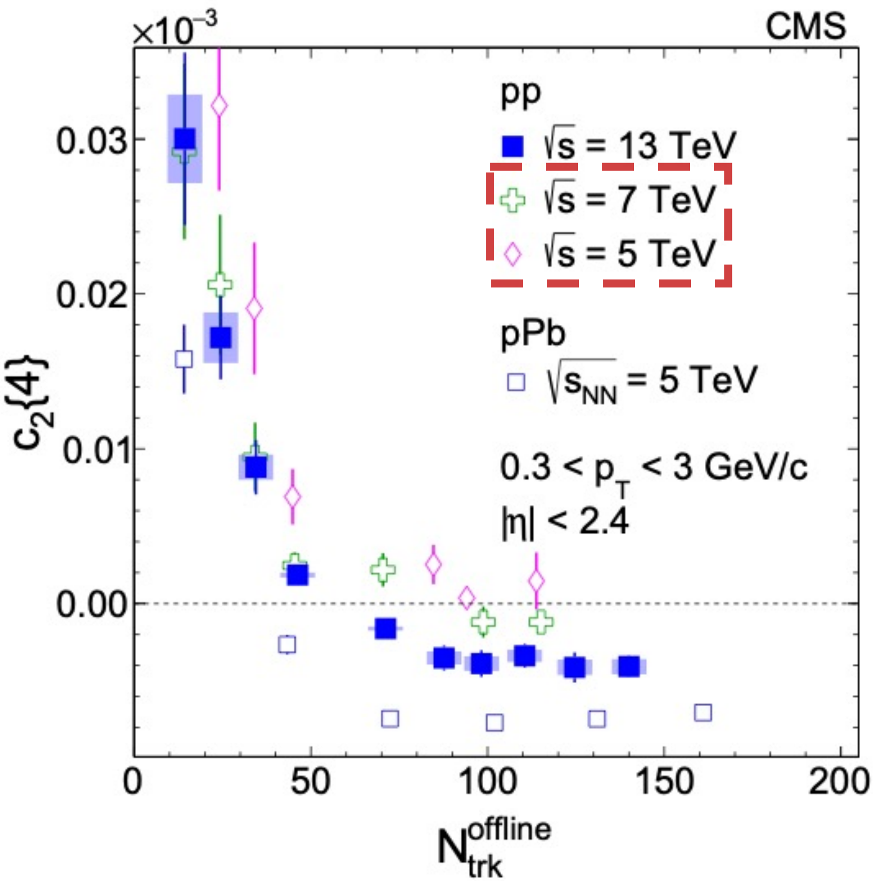
Results

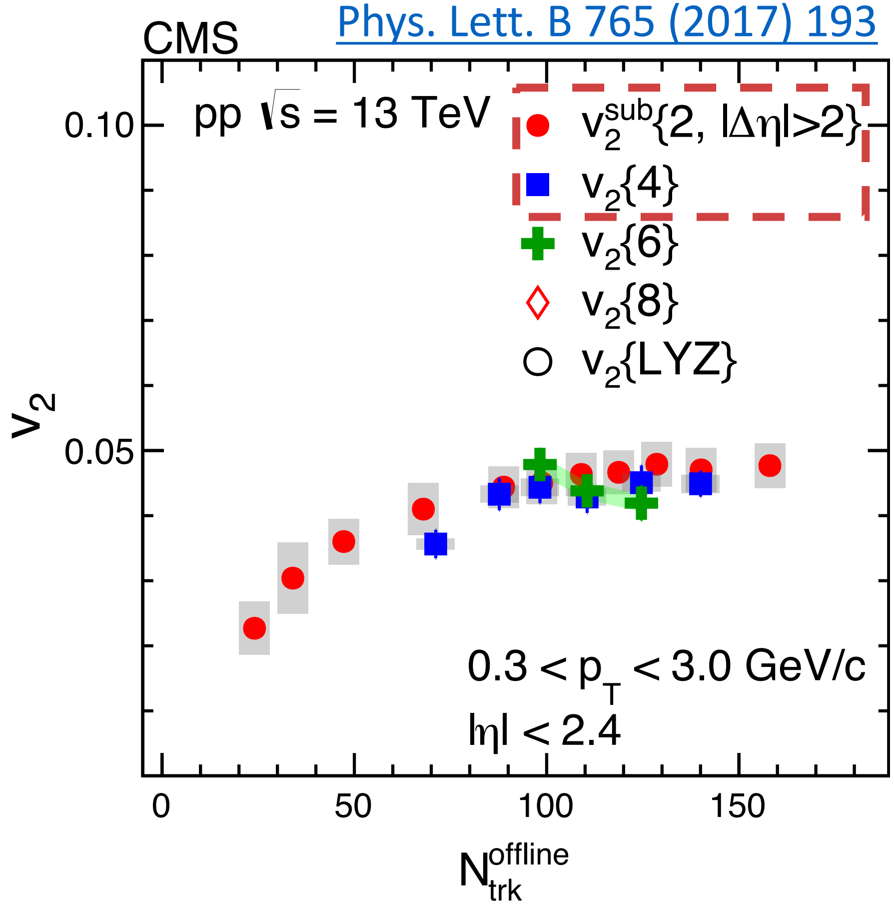


To be collective, or not to be collective?

Other puzzles



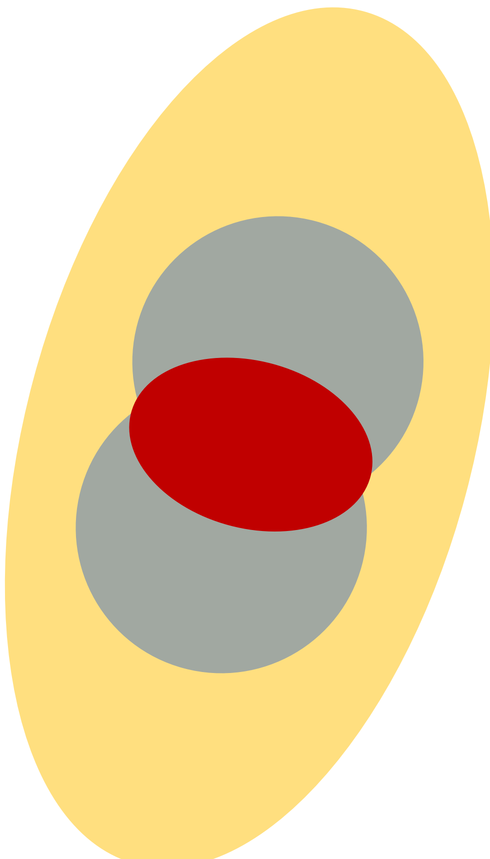
Phys. Lett. B 765 (2017) 193

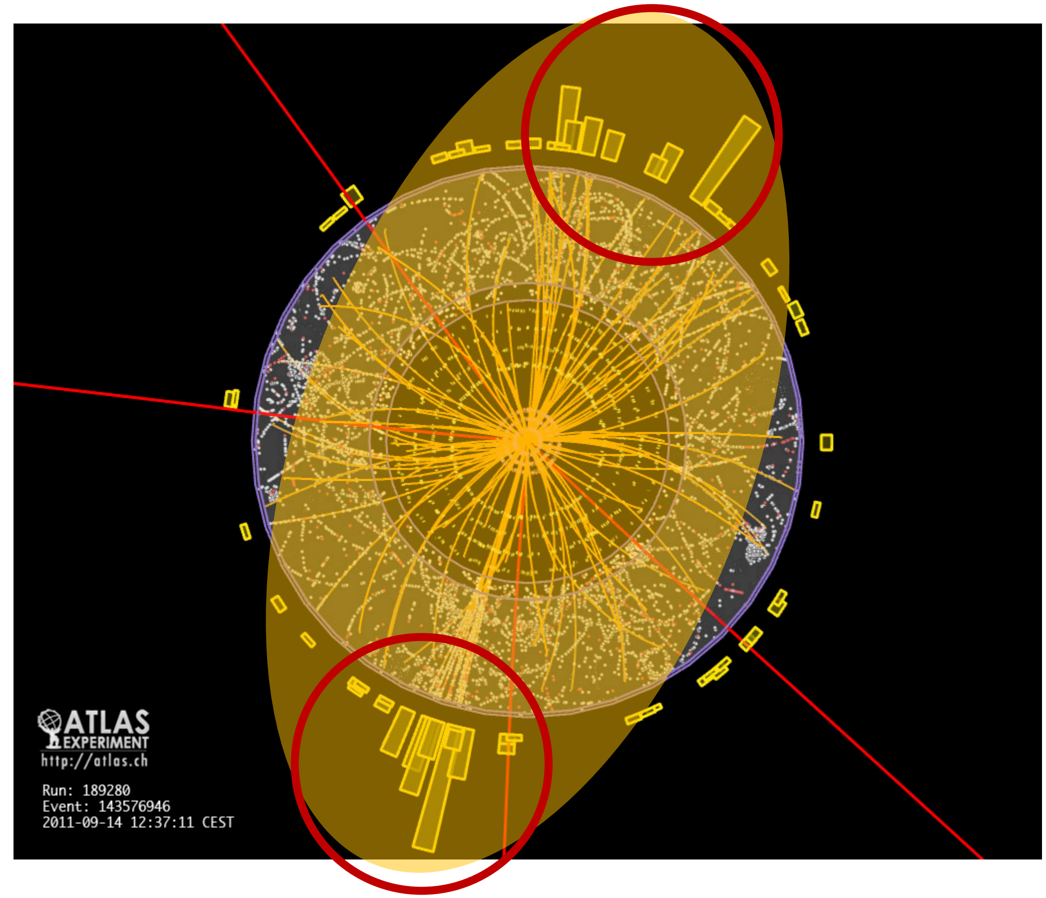


- No hint of collectivity at lower energy?

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

Puzzles needs to be solved before testing models with data.

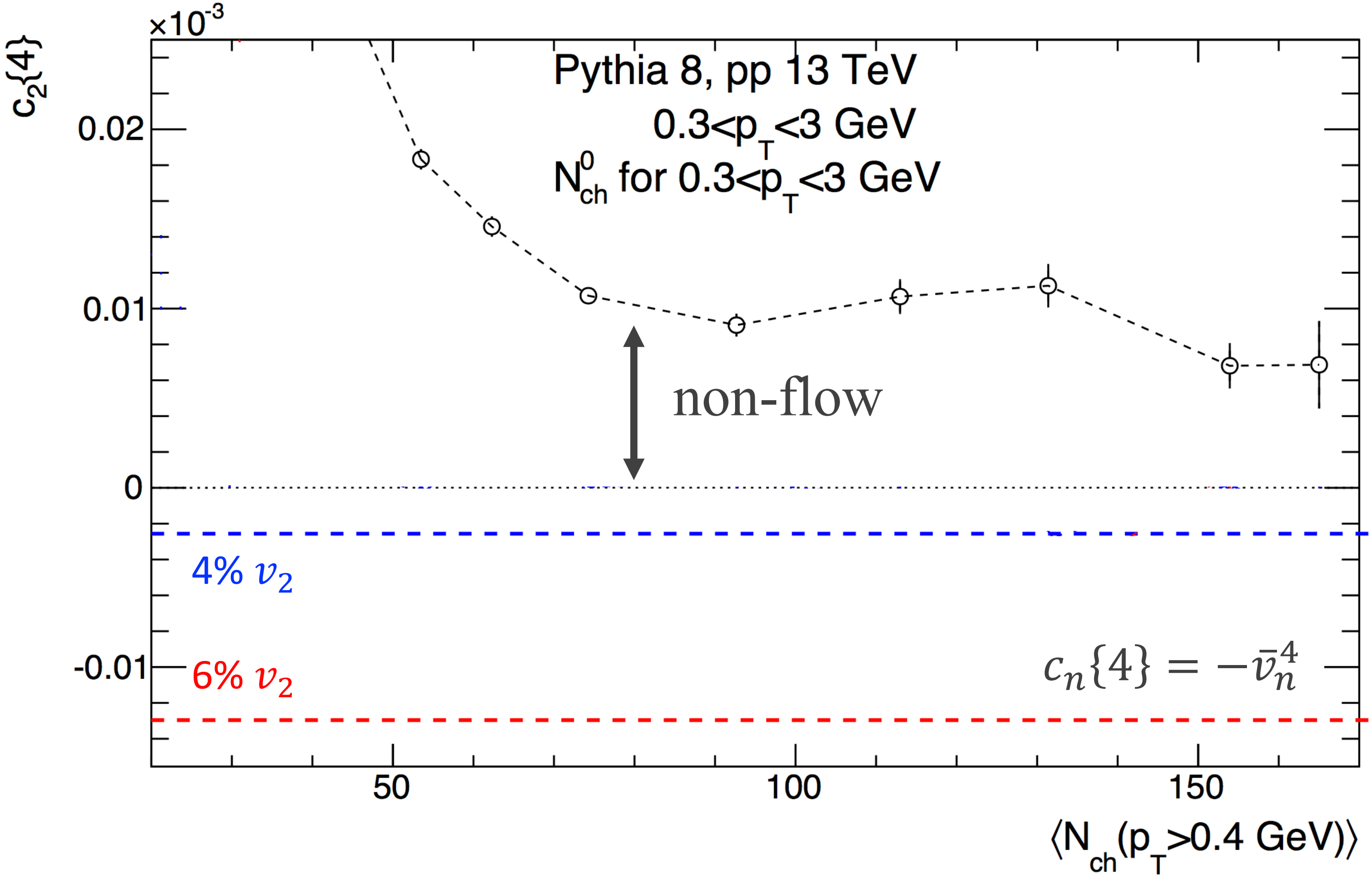




Signal: collectivity

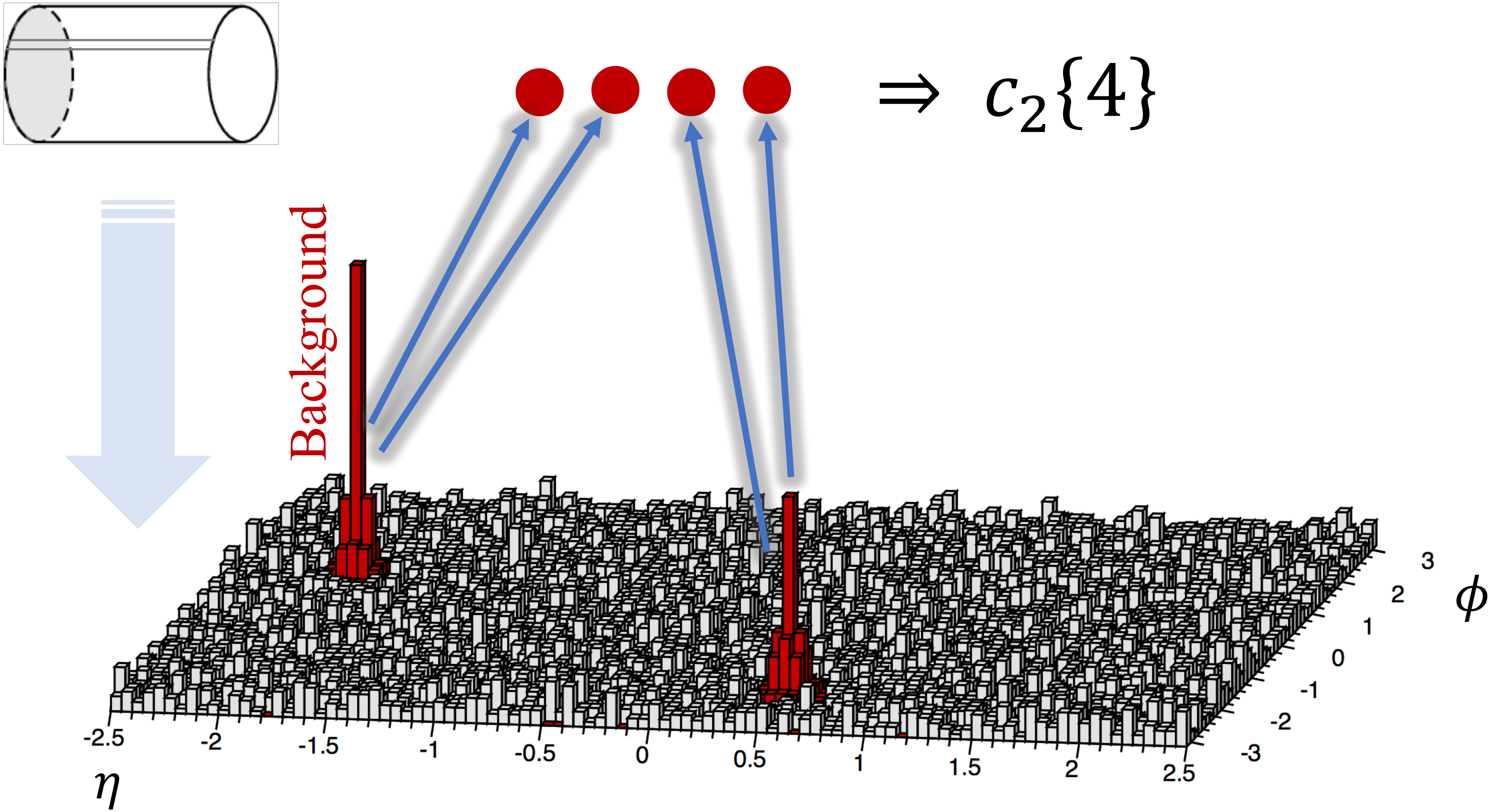
Background: dijets

Maybe background is the one to blame?



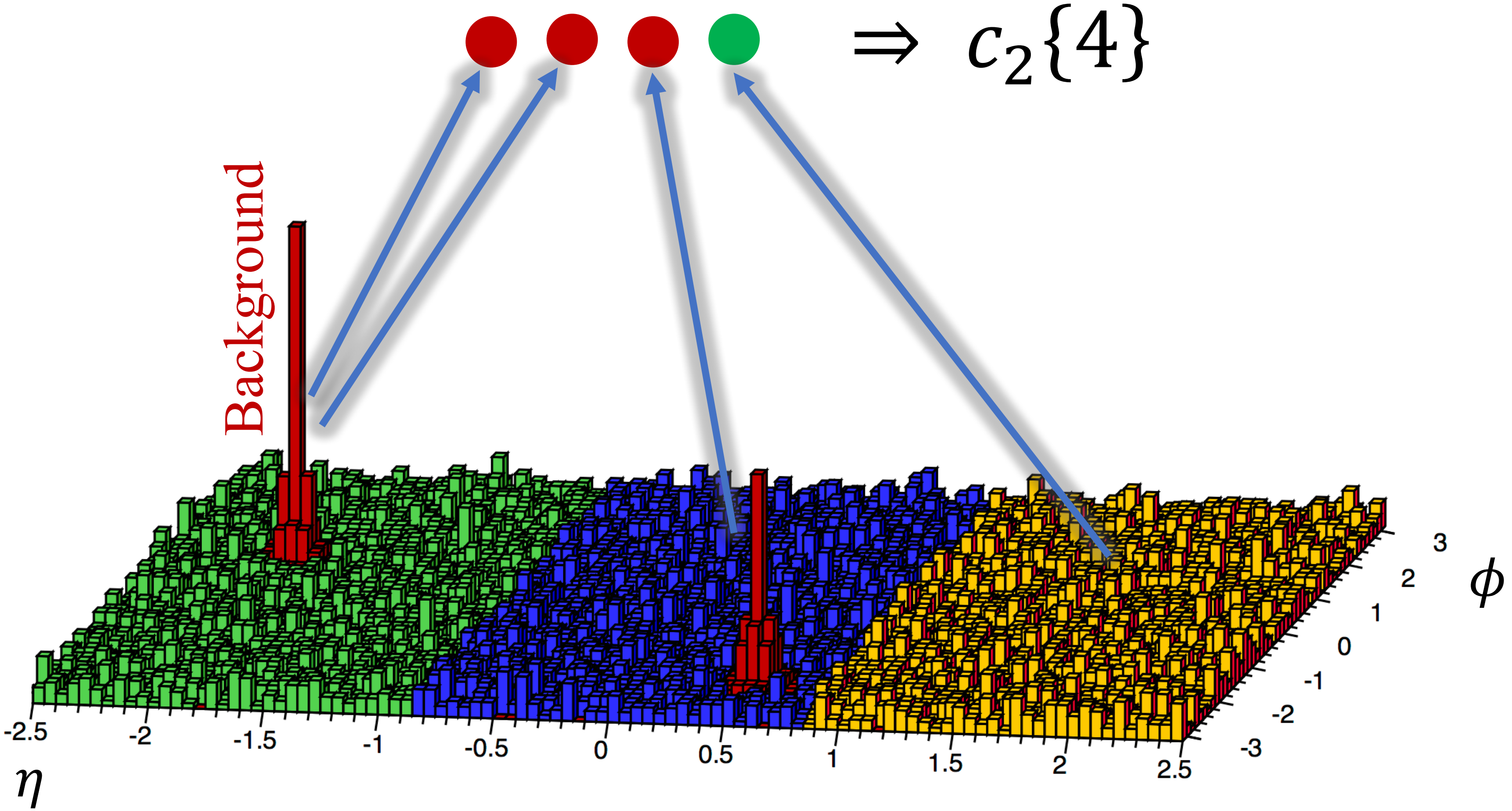
Traditional cumulant cannot remove non-flow in *pp*

Traditional method



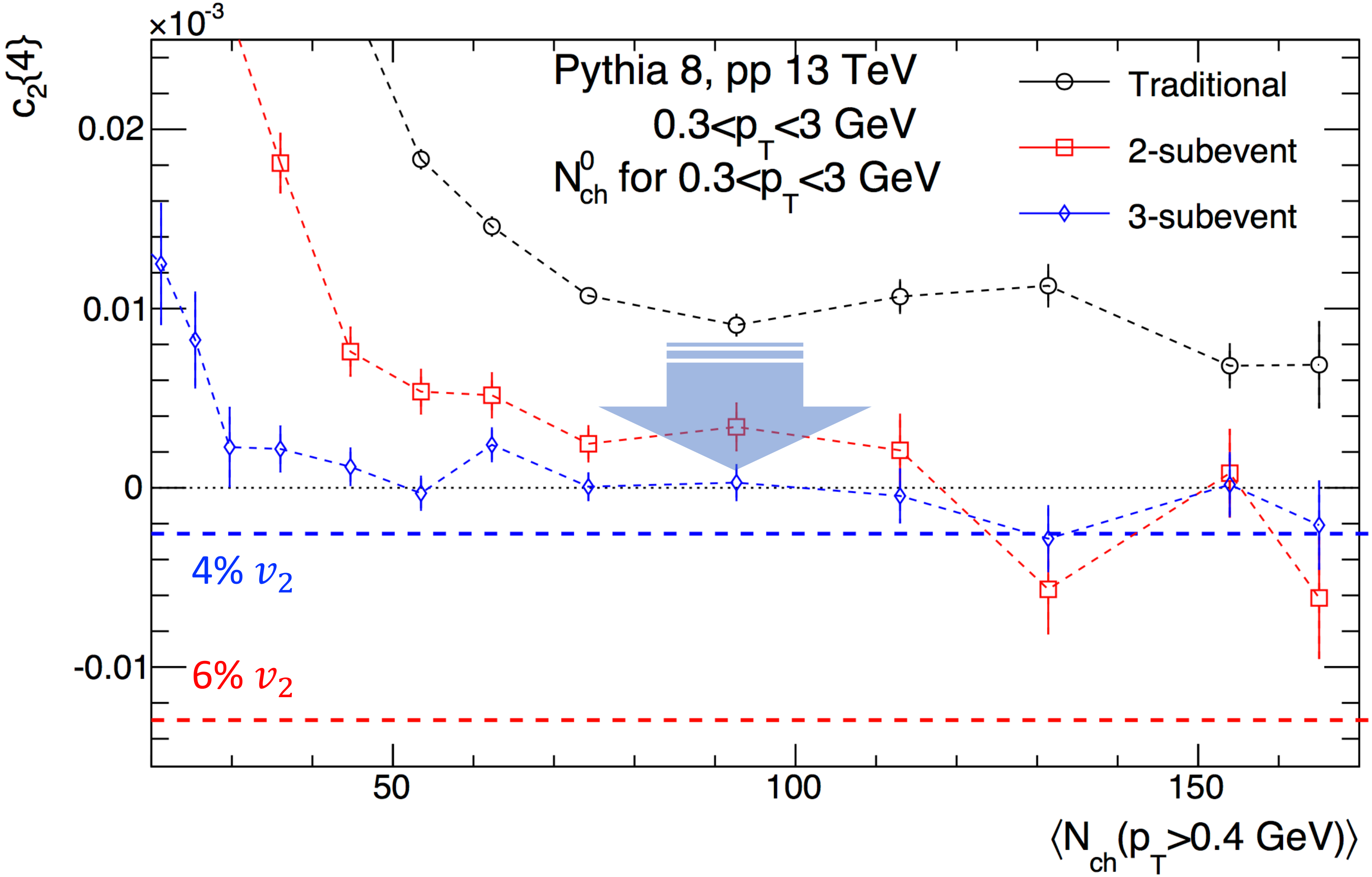
- High probability all four particles come from background;
- Solution: higher-order cumulant (statistical significance), or…

Subevent method



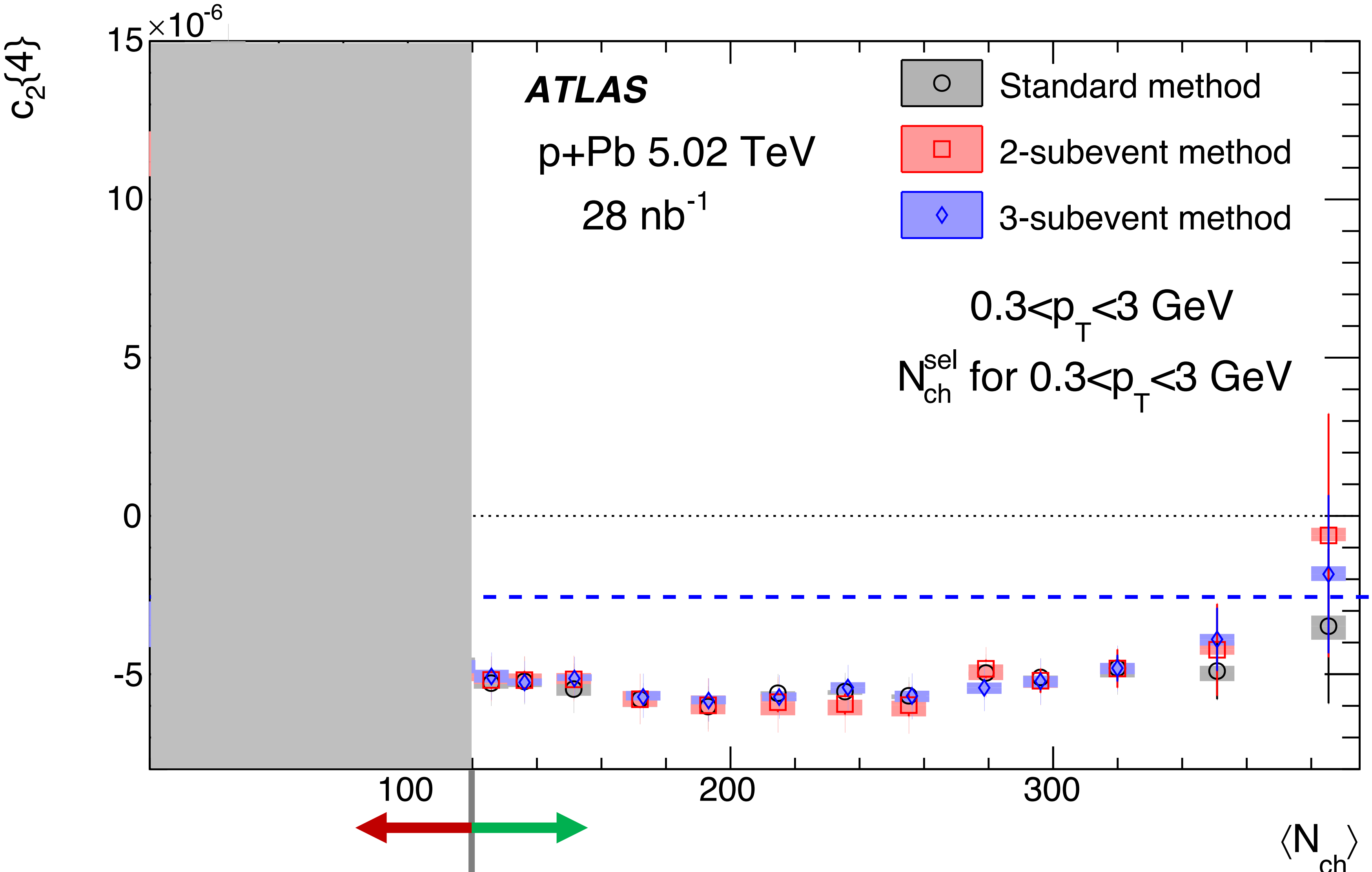
$3 > 2$

Validation in *pp* PYTHIA



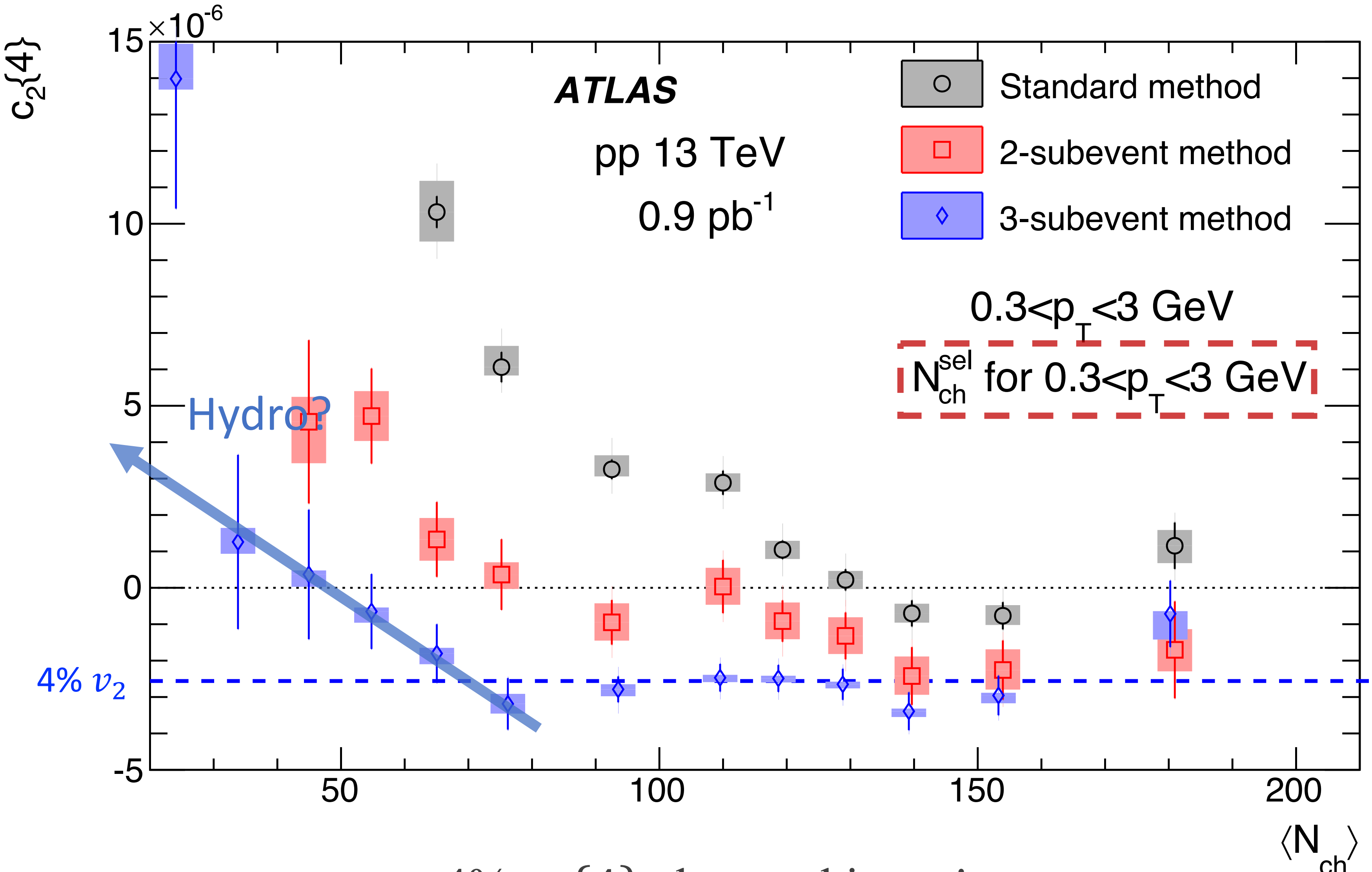
Subevent method can suppress non-flow in PYTHIA

Validation in *p*+Pb data



Large non-flow

Small non-flow



4% $v_2\{4\}$ observed in pp!

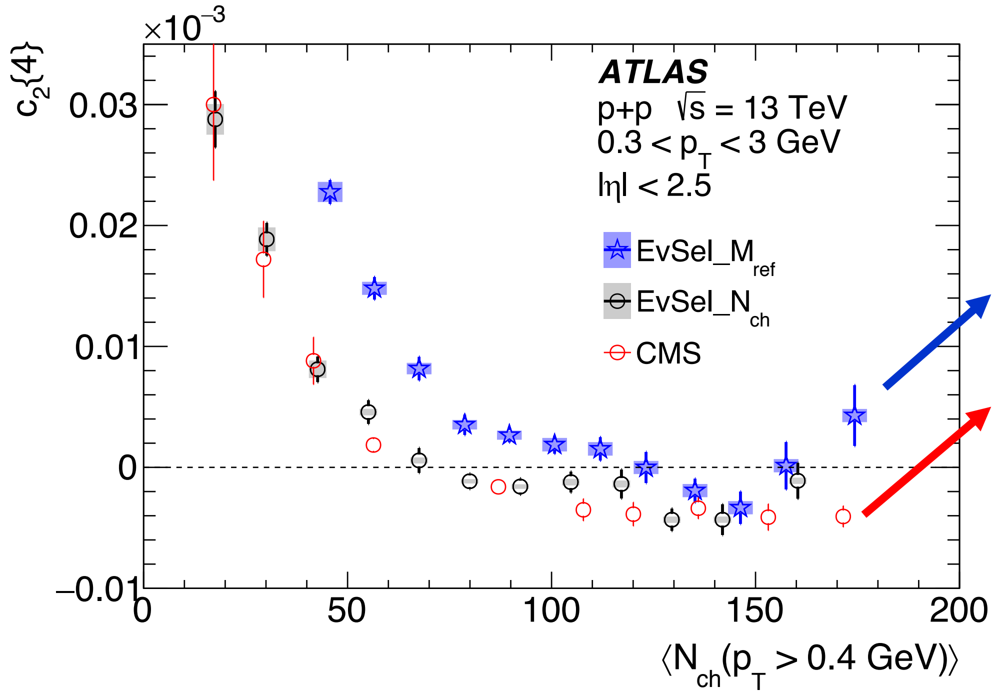
Test of residual non-flow

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

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.

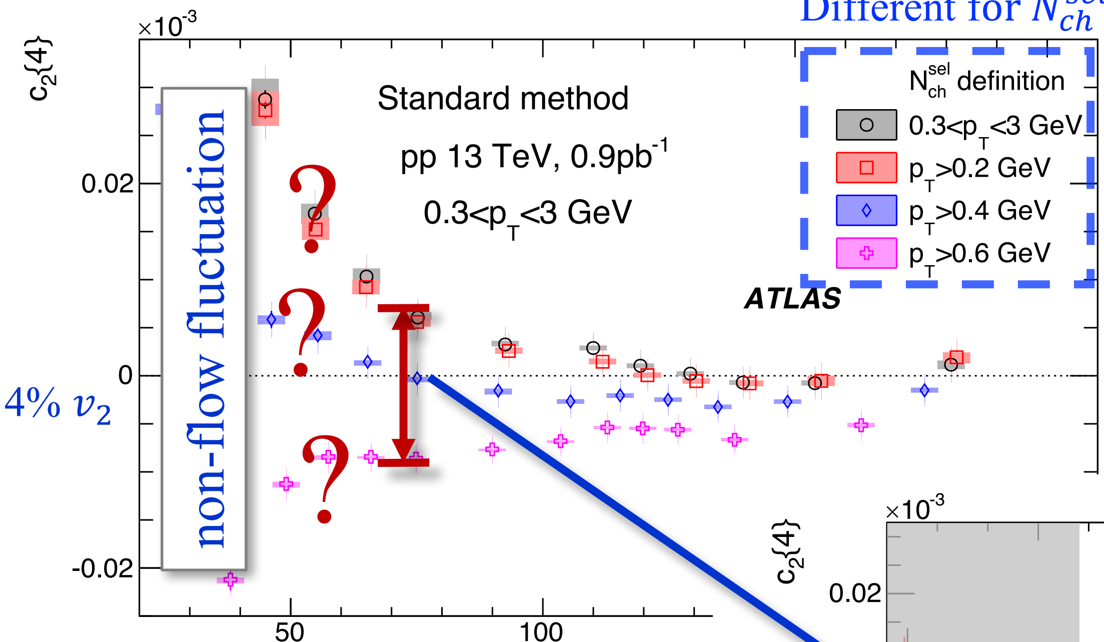
N_{ch}^{Sel} defined with $0.3 < p_T < 3.0$ GeV

N_{ch}^{Sel} defined with $p_T > 0.4$ GeV

- Non-flow fluctuation might mimic the flow signal (negative $c_2\{4\}$)!

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

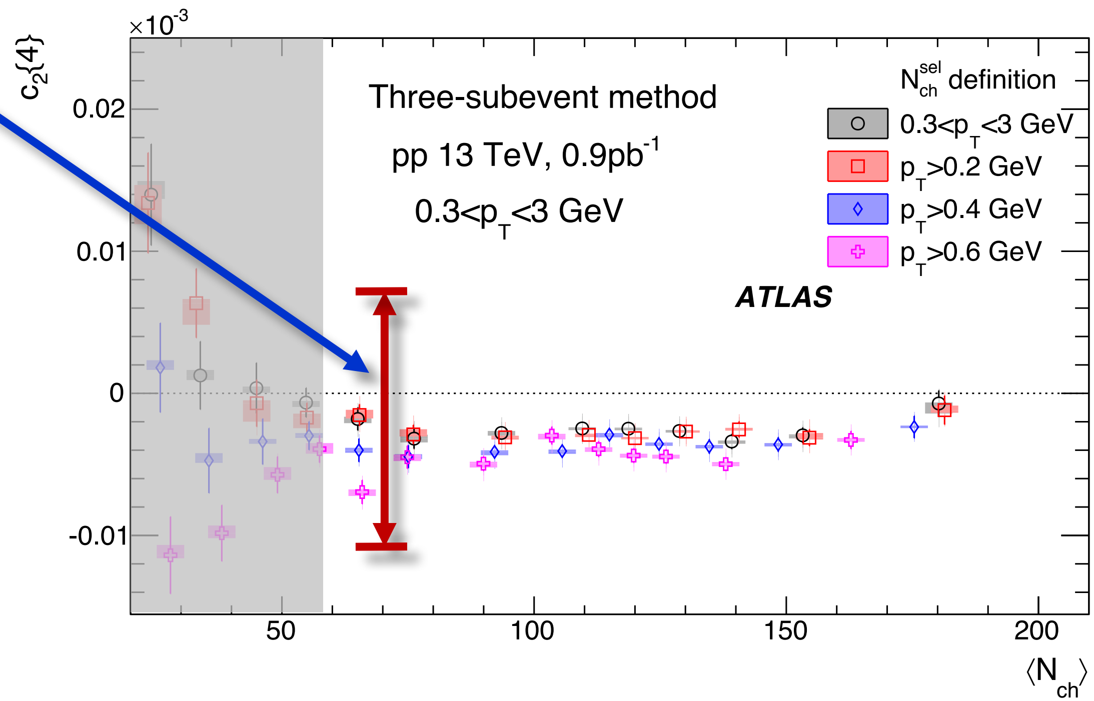
Different for N_{ch}^{sel}



Different N_{ch}^{Sel}

Different non-flow fluctuation

Different $c_2\{4\}$

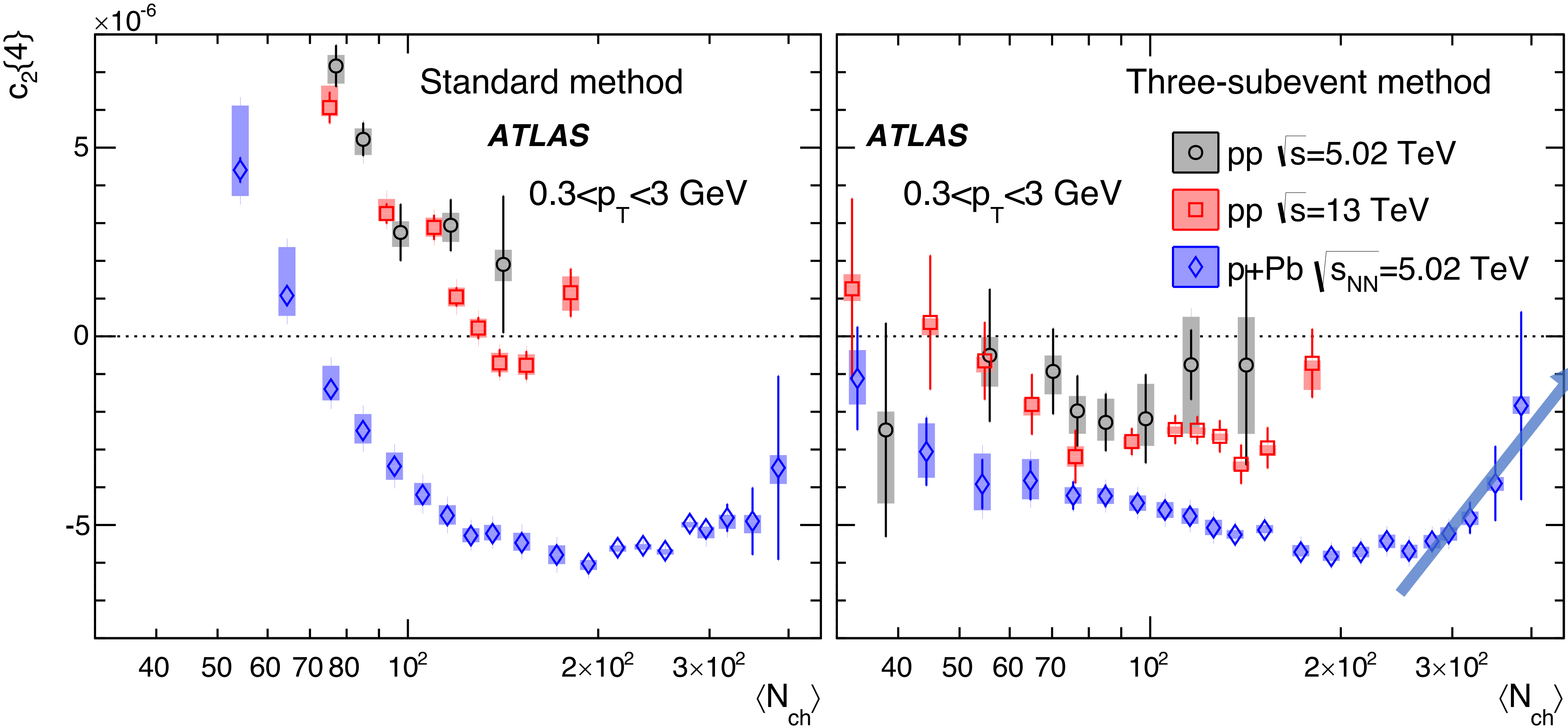


Less non-flow

Weaker non-flow fluctuation

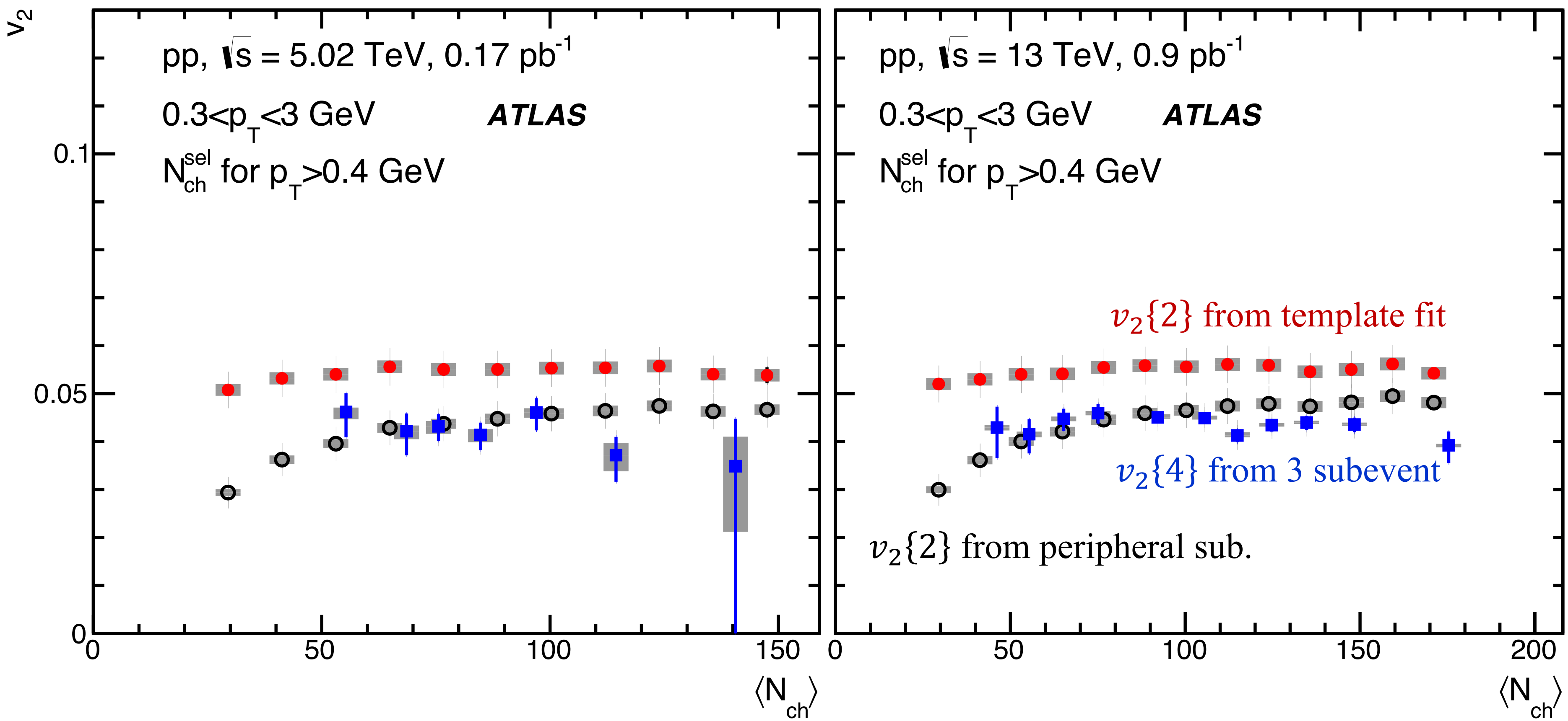
Weaker N_{ch}^{Sel} dependence

Data-driven method to test residual non-flow



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

Puzzle 3: flow fluctuation

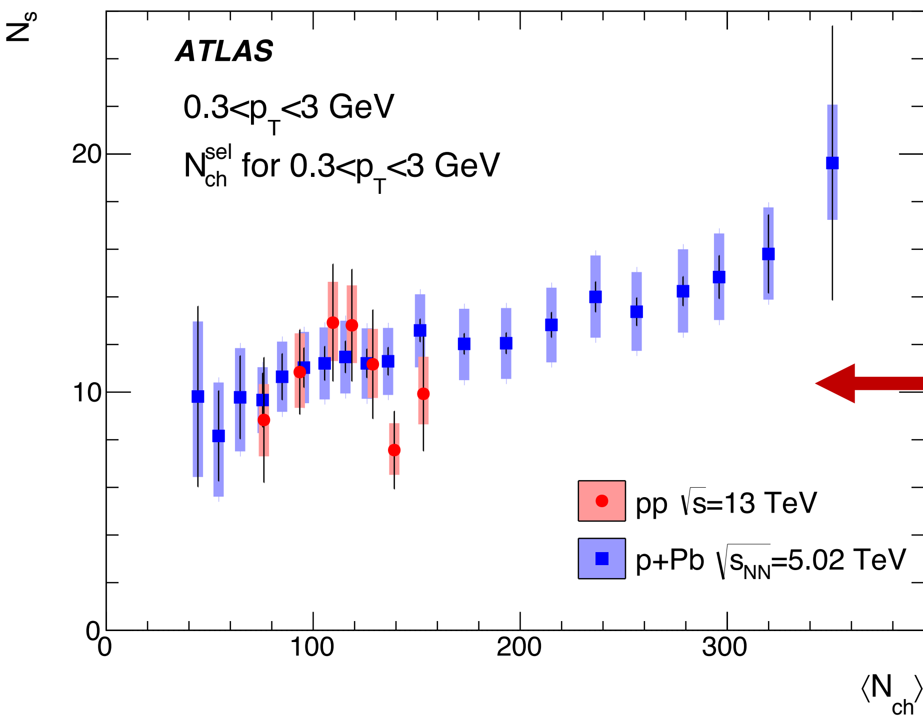


- $v_2\{4\} < v_2\{2\}$ (template fit): flow fluctuation;
- $v_2\{4\} \approx v_2\{2\}$ (peripheral sub.): underestimation of $v_2\{2\}$;
- Subevent cumulant is more robust.

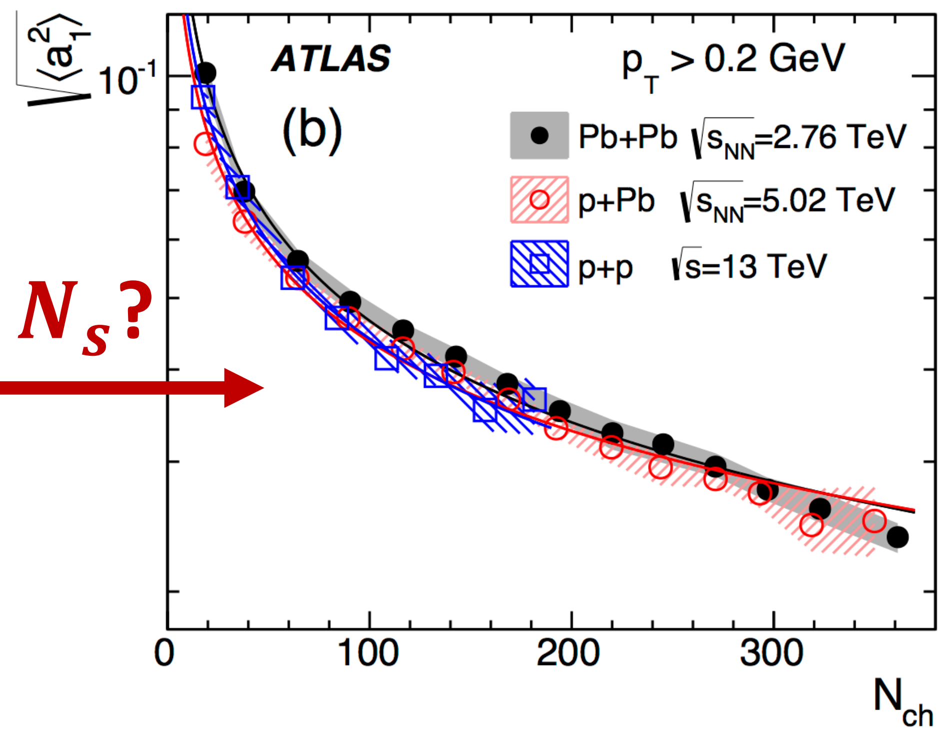
Number of sources

- $v_2\{2\} \neq v_2\{4\}$: 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:

$$\frac{v_2\{4\}}{v_2\{2\}} = \left(\frac{4}{3 + N_s}\right)^{1/4} \qquad \frac{N(\eta)}{\langle N(\eta)\rangle} \approx 1 + a_1\eta, \qquad a_1 \propto 1/\sqrt{N_s}$$

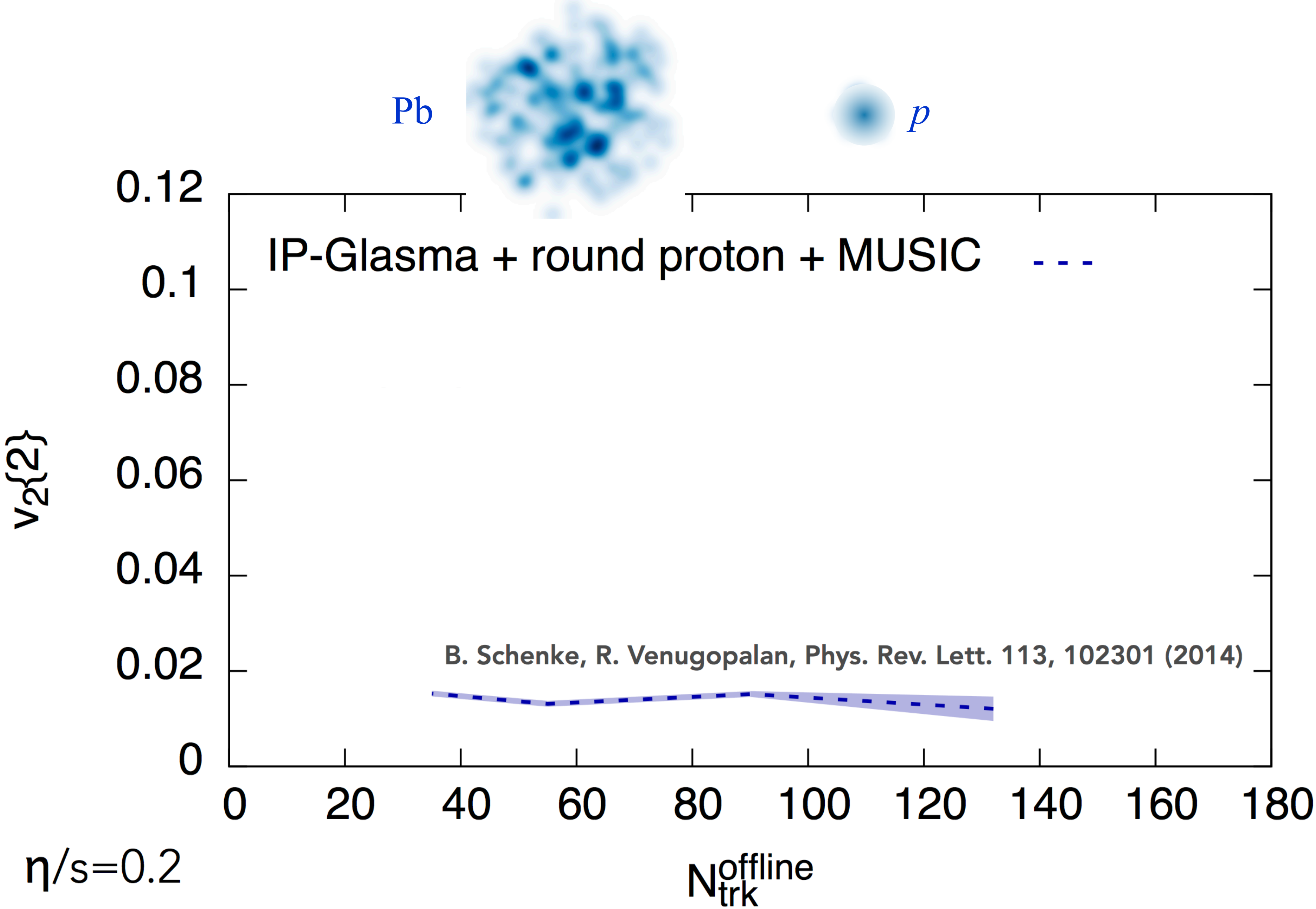


N_s?



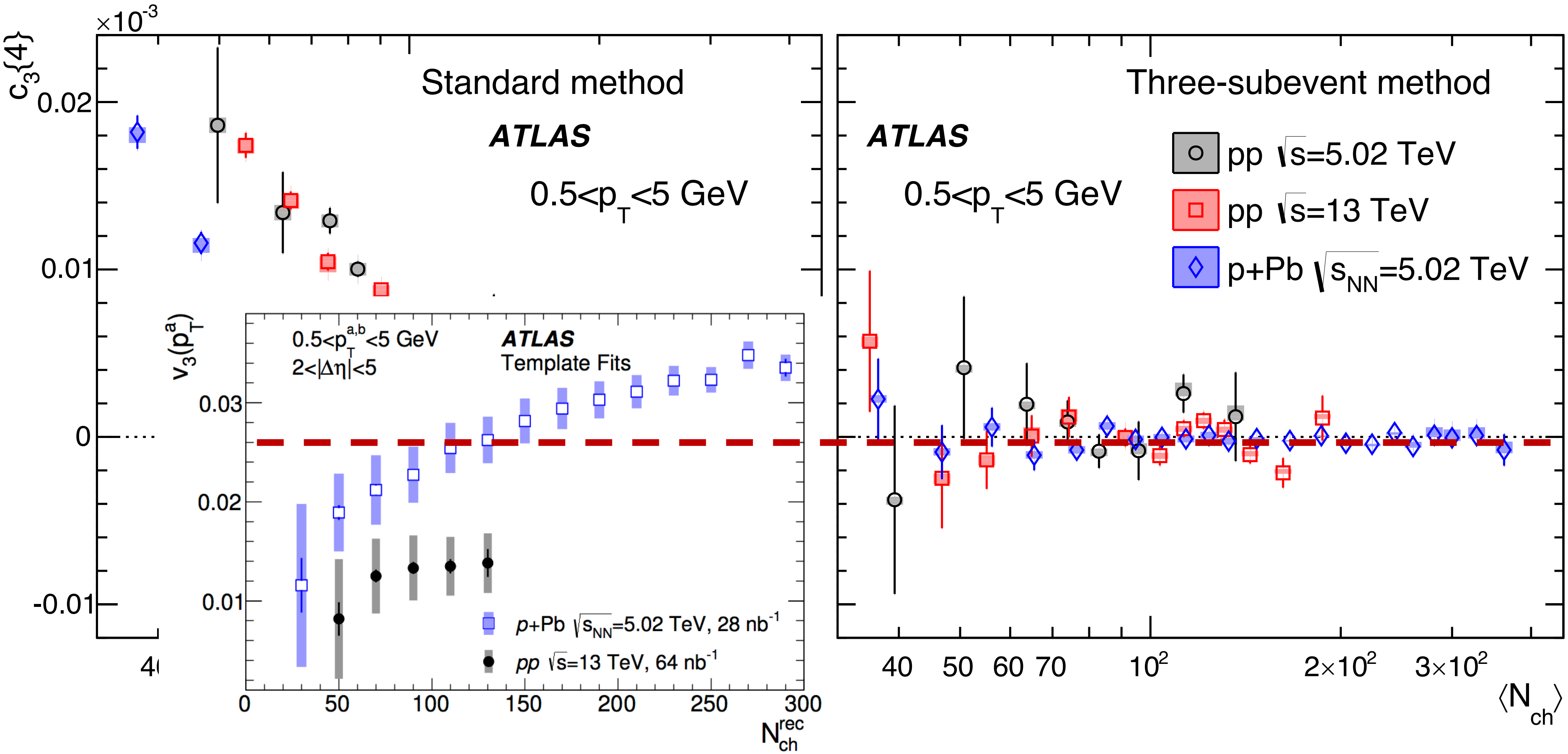
- N_s for p+Pb goes up to 20 at high multiplicity;
- N_s for pp approximately consistent with p+Pb at comparable $\langle N_{ch}\rangle$ value.

Nucleon substructure fluctuation

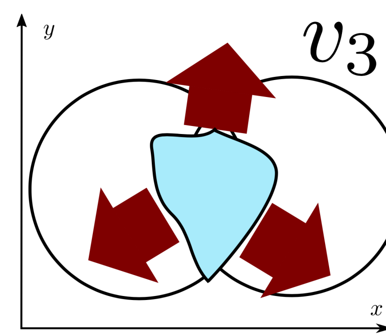


$\eta/s=0.2$

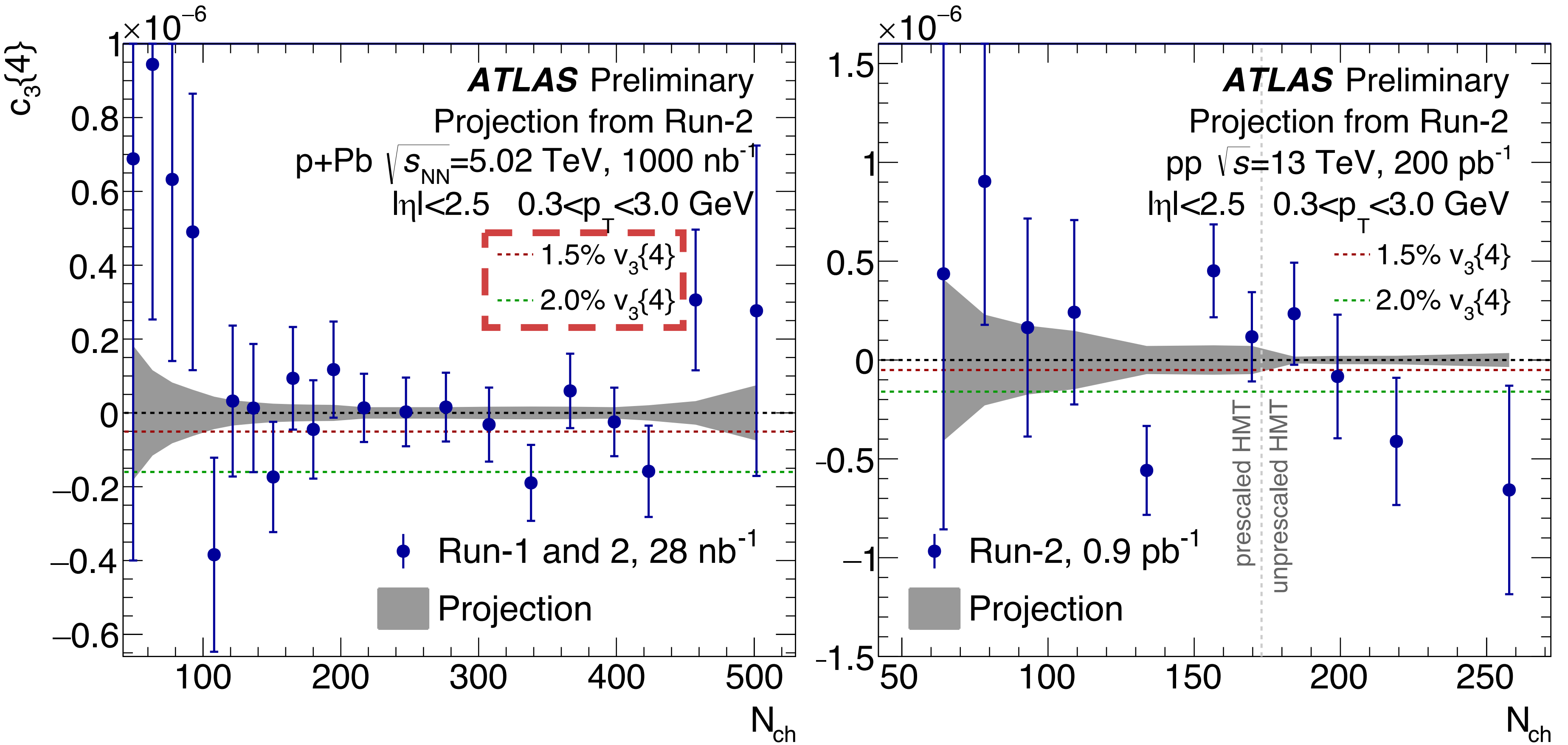
Non-non-flow $\neq$ Flow!



- $c_3\{4\}$ 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

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

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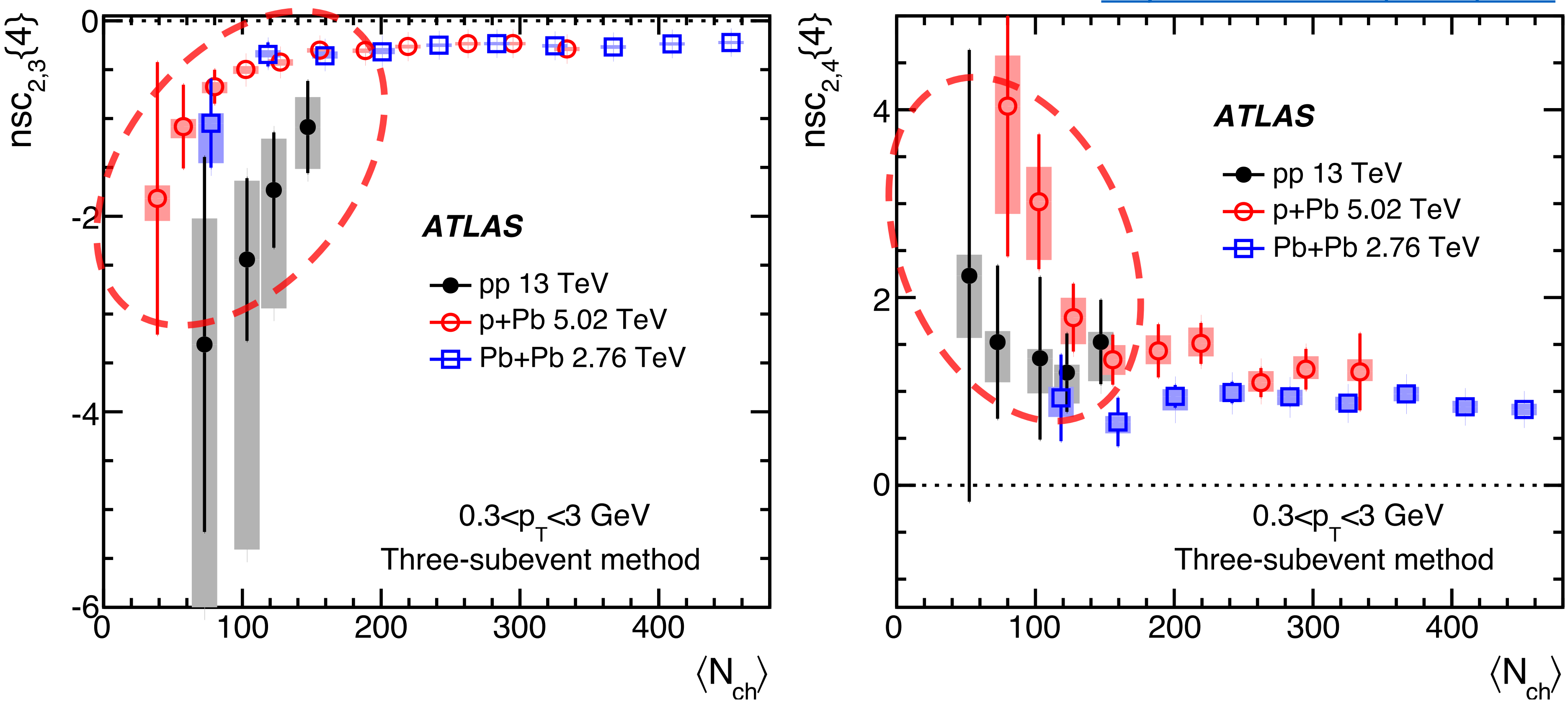
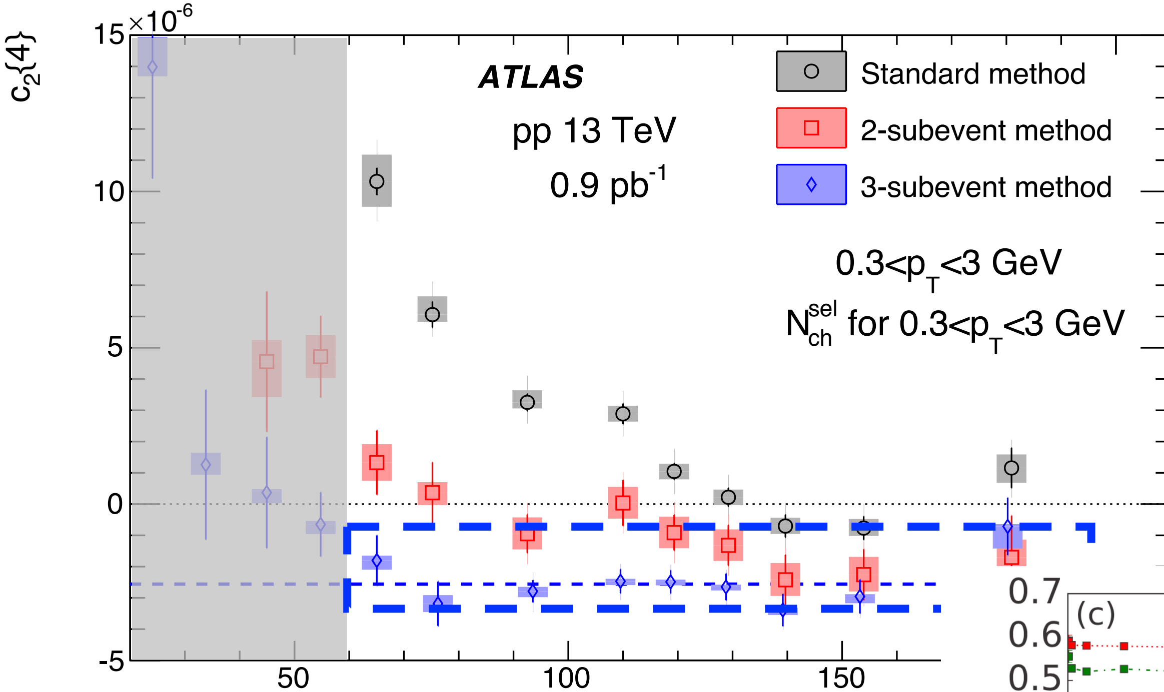
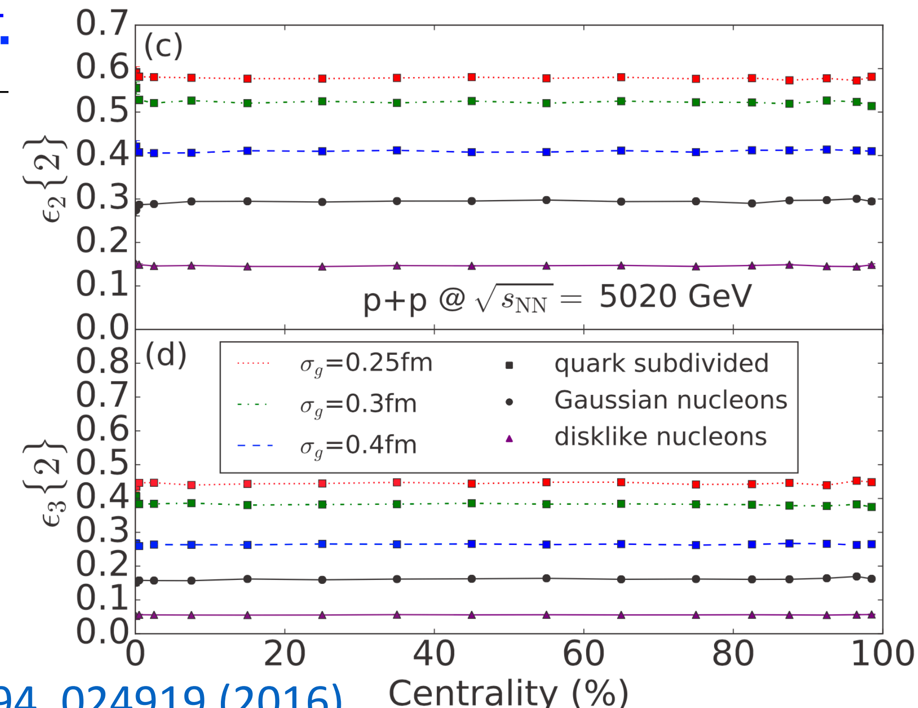


- Same sign, different magnitudes across systems;
- Additional constrains on models.

Last puzzle: N_{ch} dependence





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

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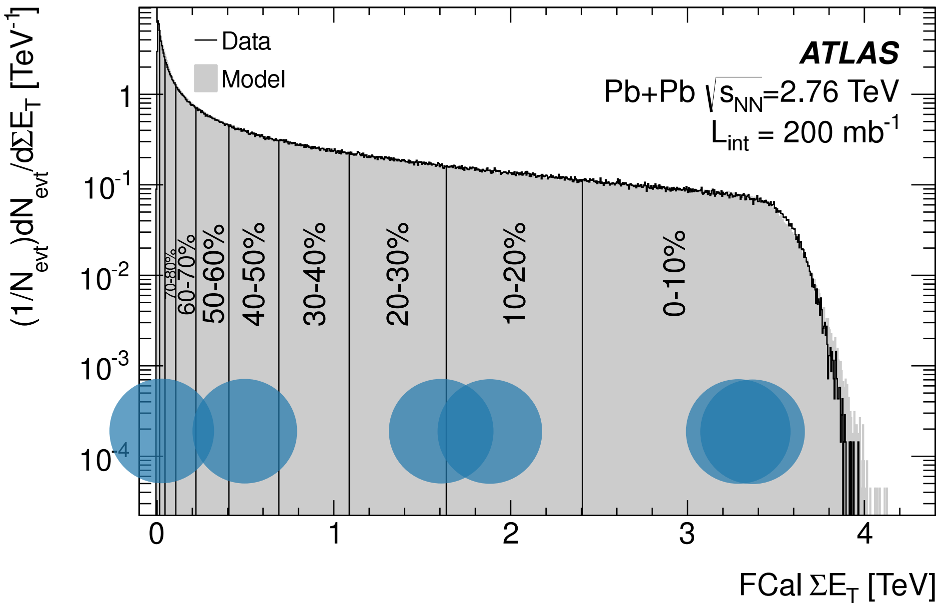
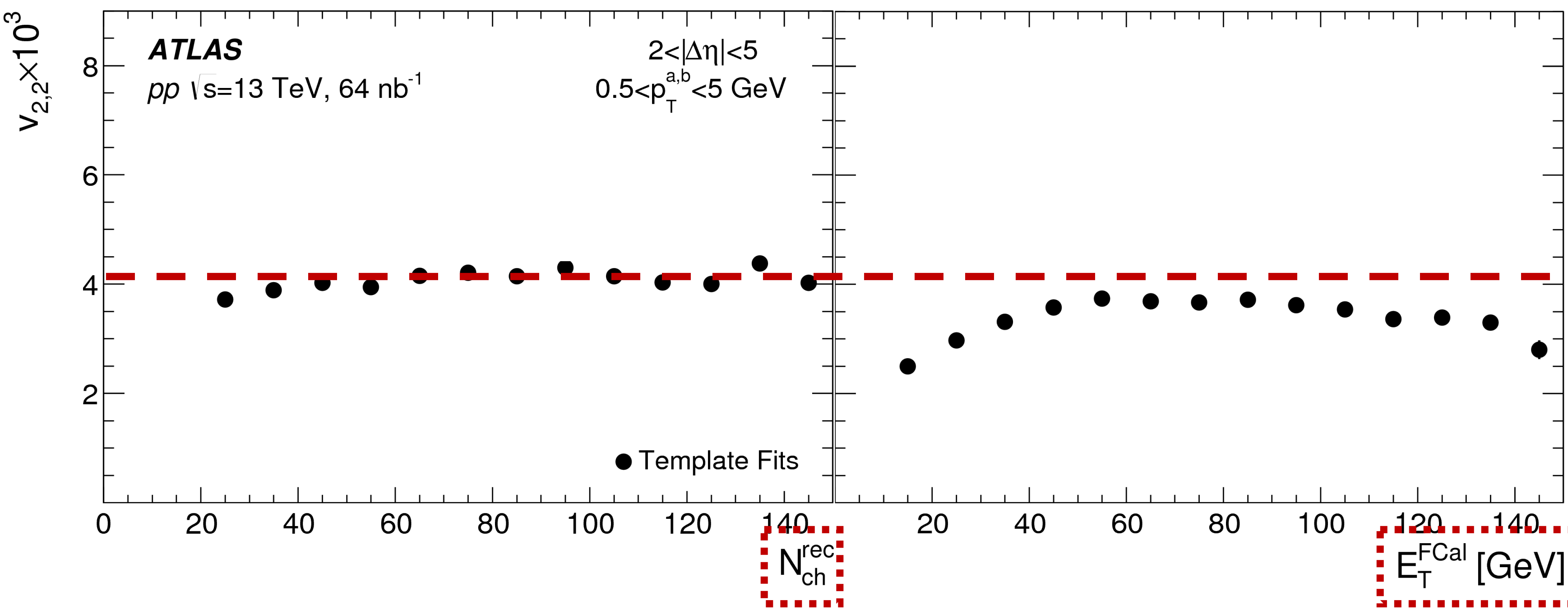
Centrality fluctuation



- 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.

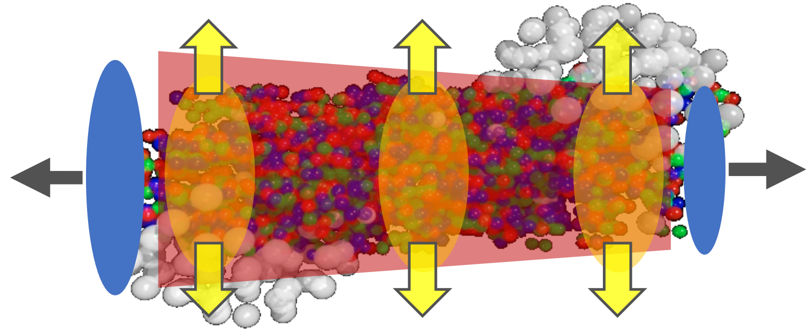


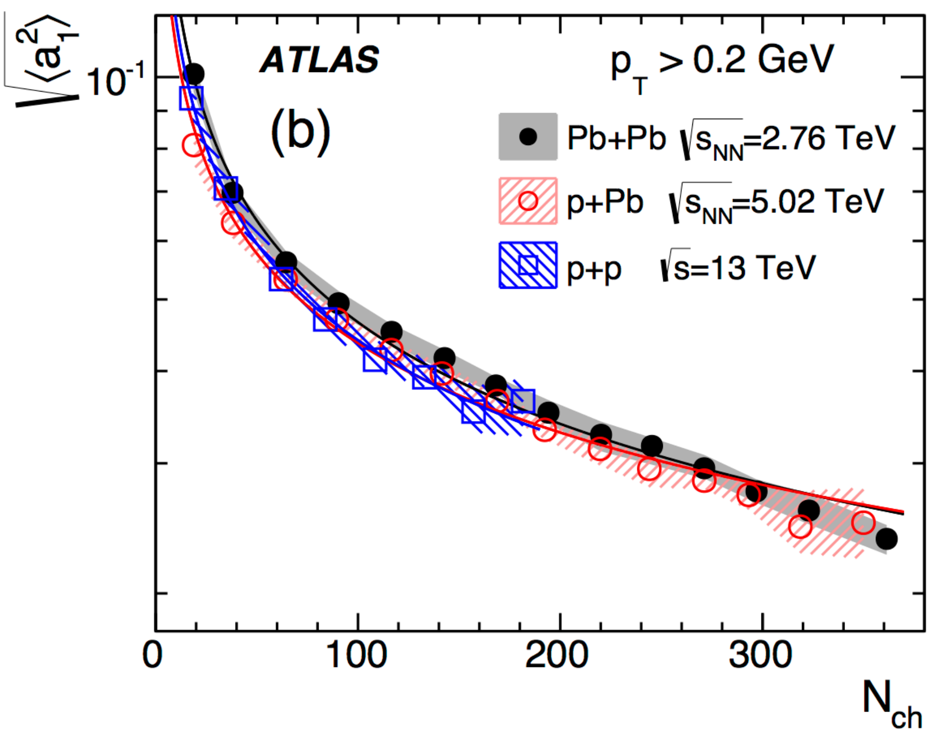
Summary

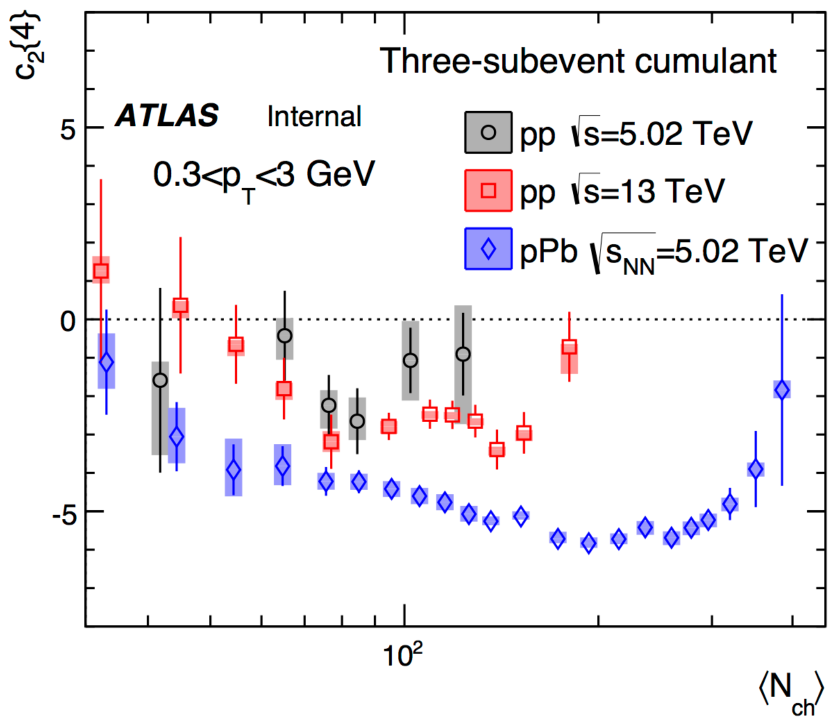
Nature of sources seeding the long-range collective behavior?

Longitudinal correlation

Azimuthal correlation







Evidence of collectivity in small systems!

Hypothesis
Collectivity in pp?

Data Gather
Real-time selection

Data Analysis
Large background

New Algorithm
$3 > 2$

Conclusion
Collectivity in pp!

Outlook
Other observables

Final note

- O+O to O+O

Backup

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

Forward-backward multiplicity fluctuation

Motivation: a historical view

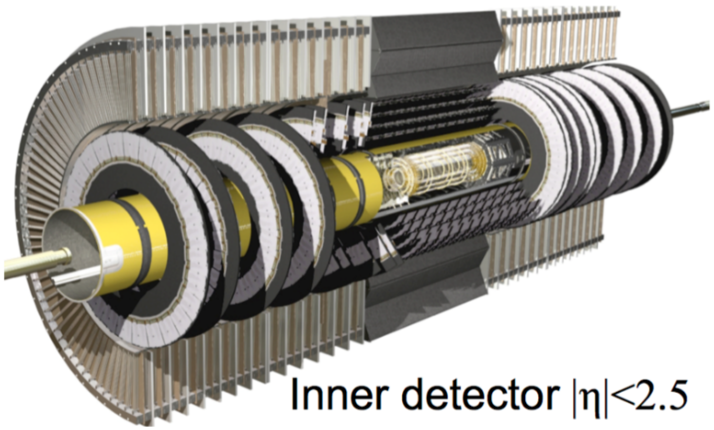
- Rapidity correlations is an old story

- 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.

Pb+Pb, *p*+Pb and *pp* datasets

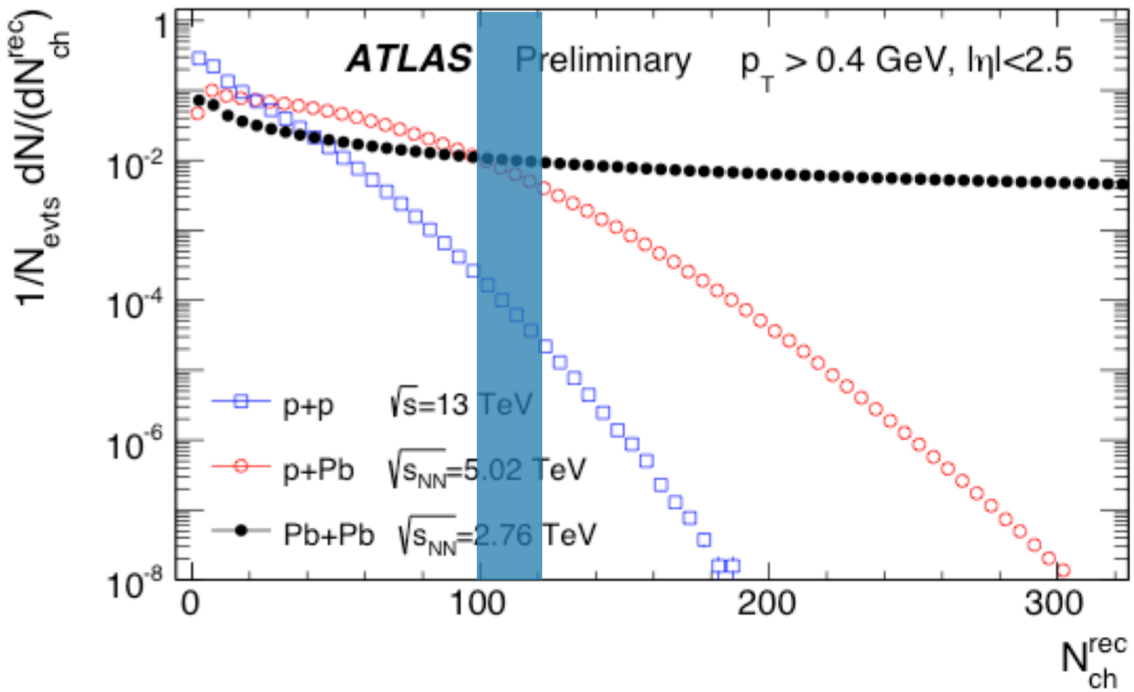
- Correlation functions calculated using charged particles $p_T > 0.2$ GeV;
- High-multiplicity track (HMT) trigger used to increase statistics;



Pb+Pb 2.76 TeV, 2010, MB

p+Pb 5.02 TeV, 2013, MB+HMT

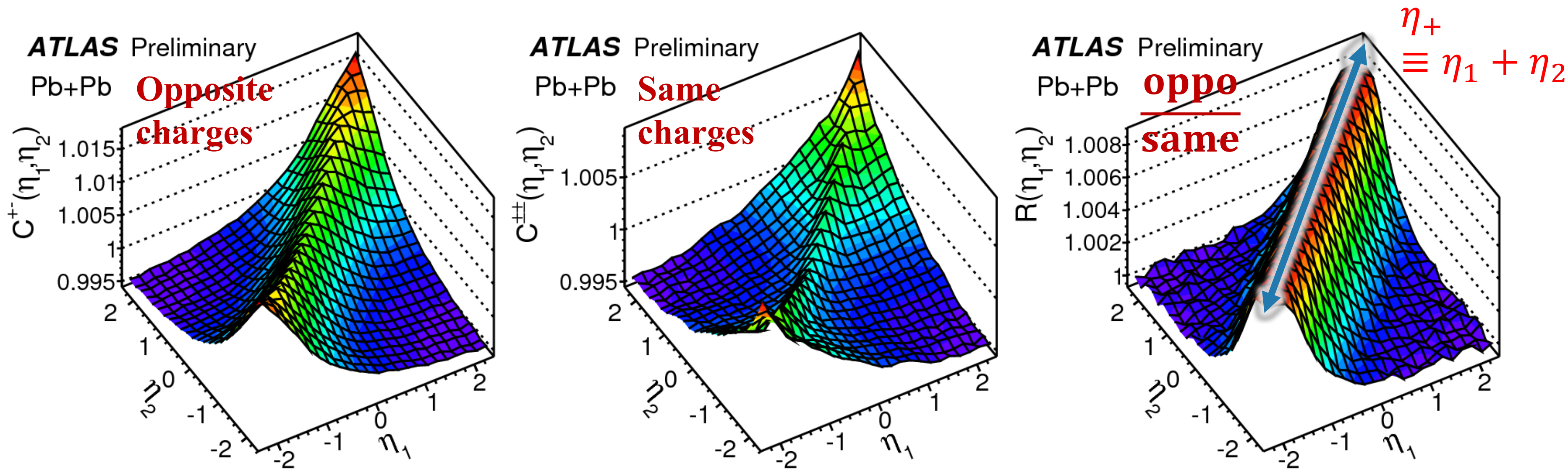
p+p 13 TeV, 2015, MB+HMT



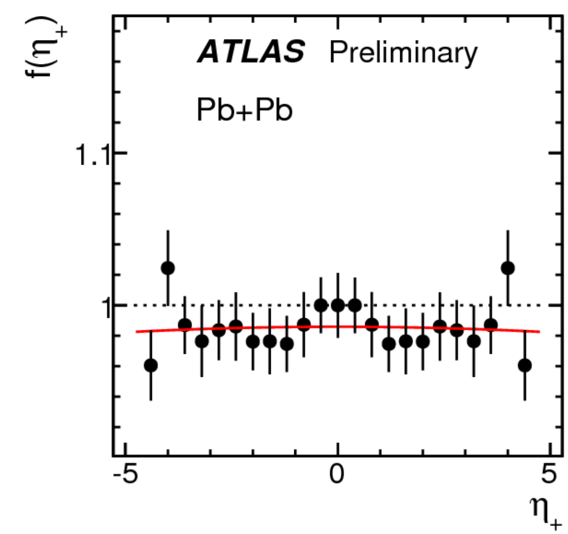
- Analysis carried out in many bins over $10 \leq N_{ch}^{rec} < 300$;
- Results presented as a function efficiency-corrected values N_{ch}.
  - How long-range correlation compare among three systems, at the same N_{ch}?

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

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

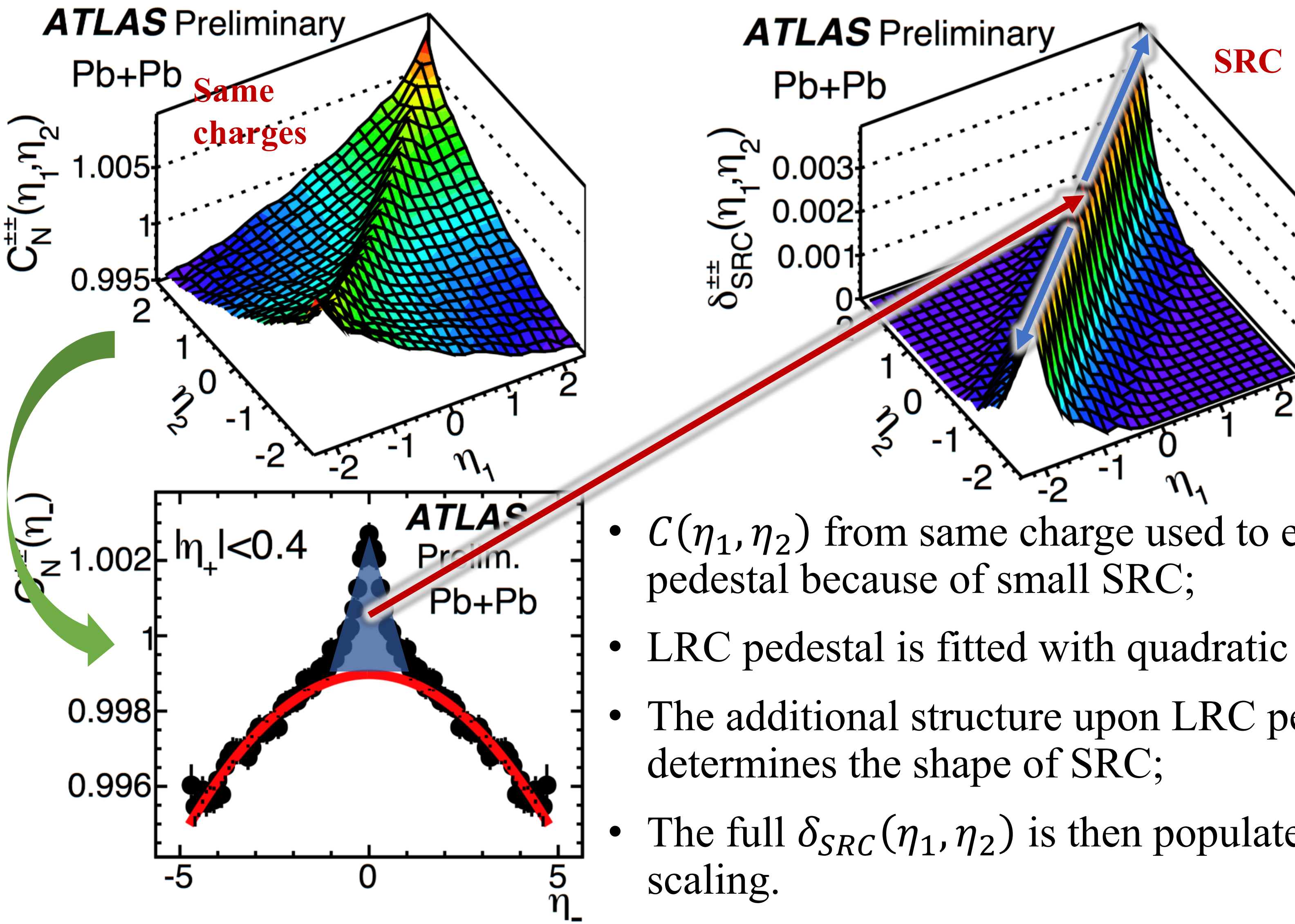


- Ratio of opposite to same charges $R(\eta_1, \eta_2)$
  - Very strong Gaussian-like SRC;
  - Very weak LRC: charge-independent;
- Amplitude of $R(\eta_1, \eta_2)$ along η_+: $f(\eta_+)$, reflects the strength of SRC in the longitudinal direction;
- Assumption: strength of SRC along η_+ is same for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

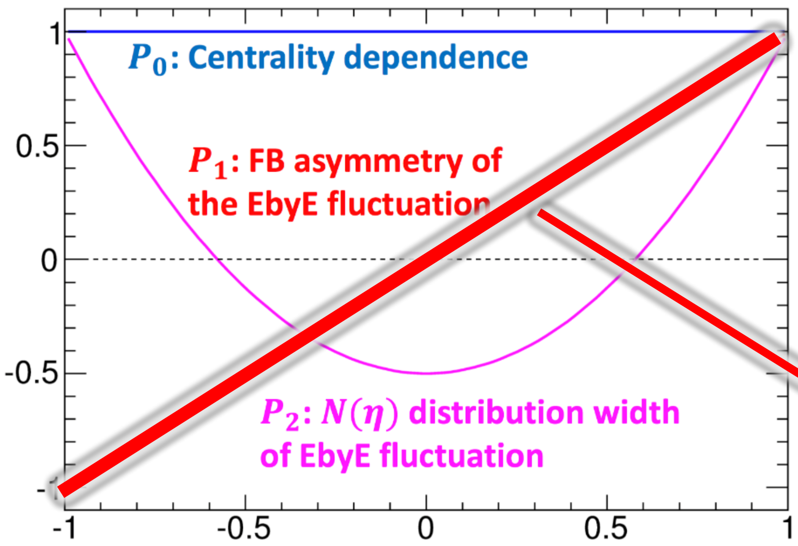


Estimation of short-range correlation

- To estimate SRC, LRC pedestal is estimated first.

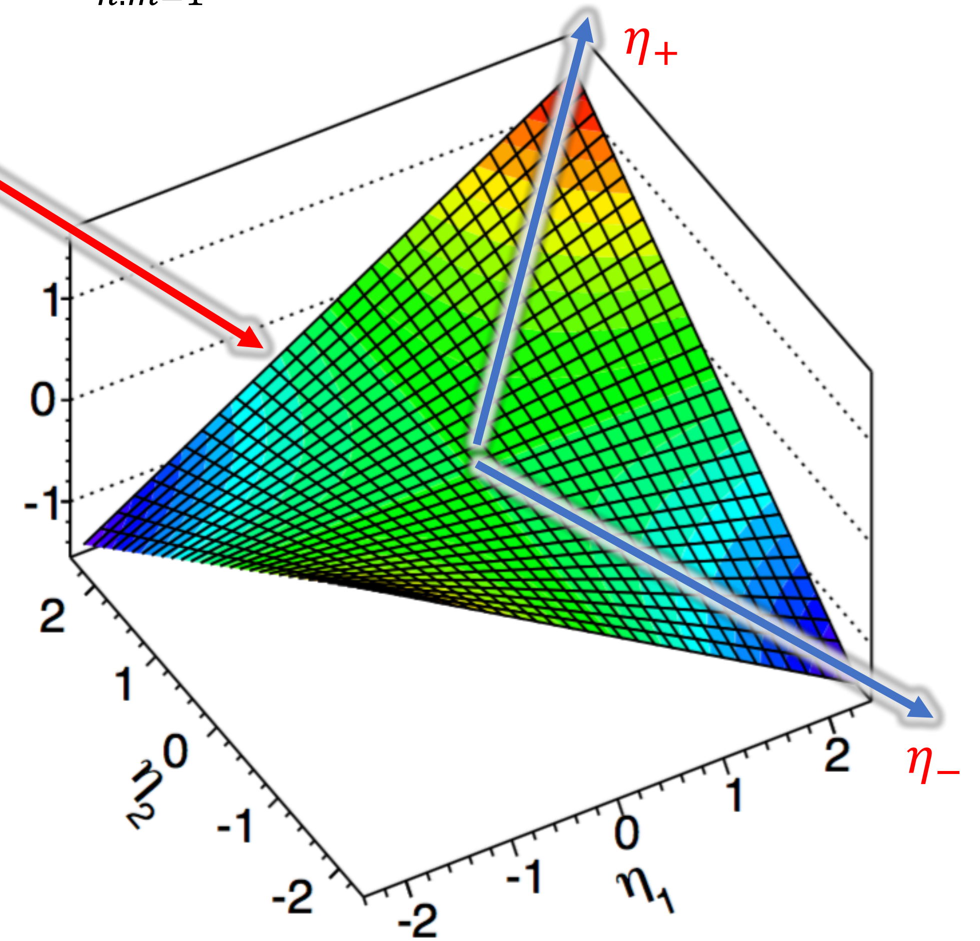


- $C(\eta_1, \eta_2)$ from same charge used to estimate LRC pedestal because of small SRC;
- LRC pedestal is fitted with quadratic function;
- The additional structure upon LRC pedestal determines the shape of SRC;
- The full $\delta_{SRC}(\eta_1, \eta_2)$ is then populated using $f(\eta_+)$ scaling.



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

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



- 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

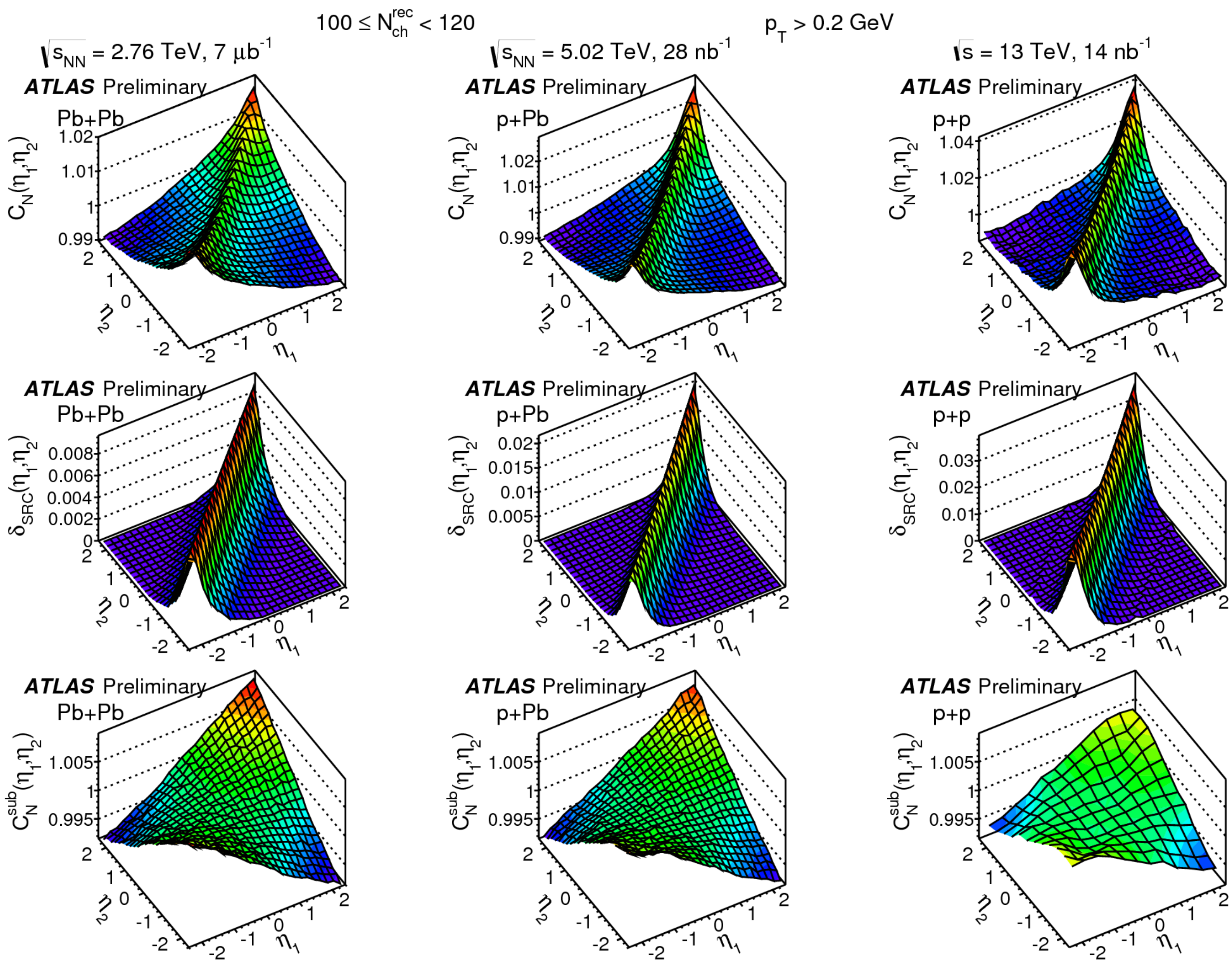
Raw
$C_N(\eta_1, \eta_2)$

=

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

+

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

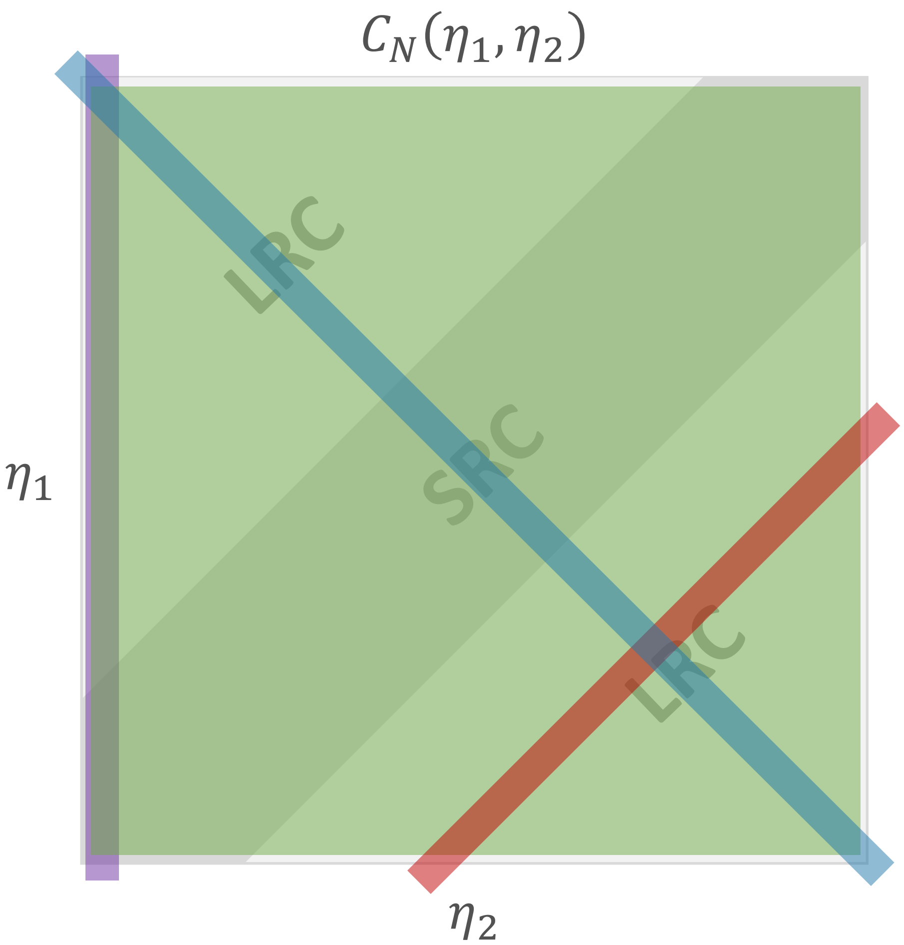


Pb+Pb

p+Pb

pp

Other methods to measure $\langle a_1^2 \rangle$



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

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

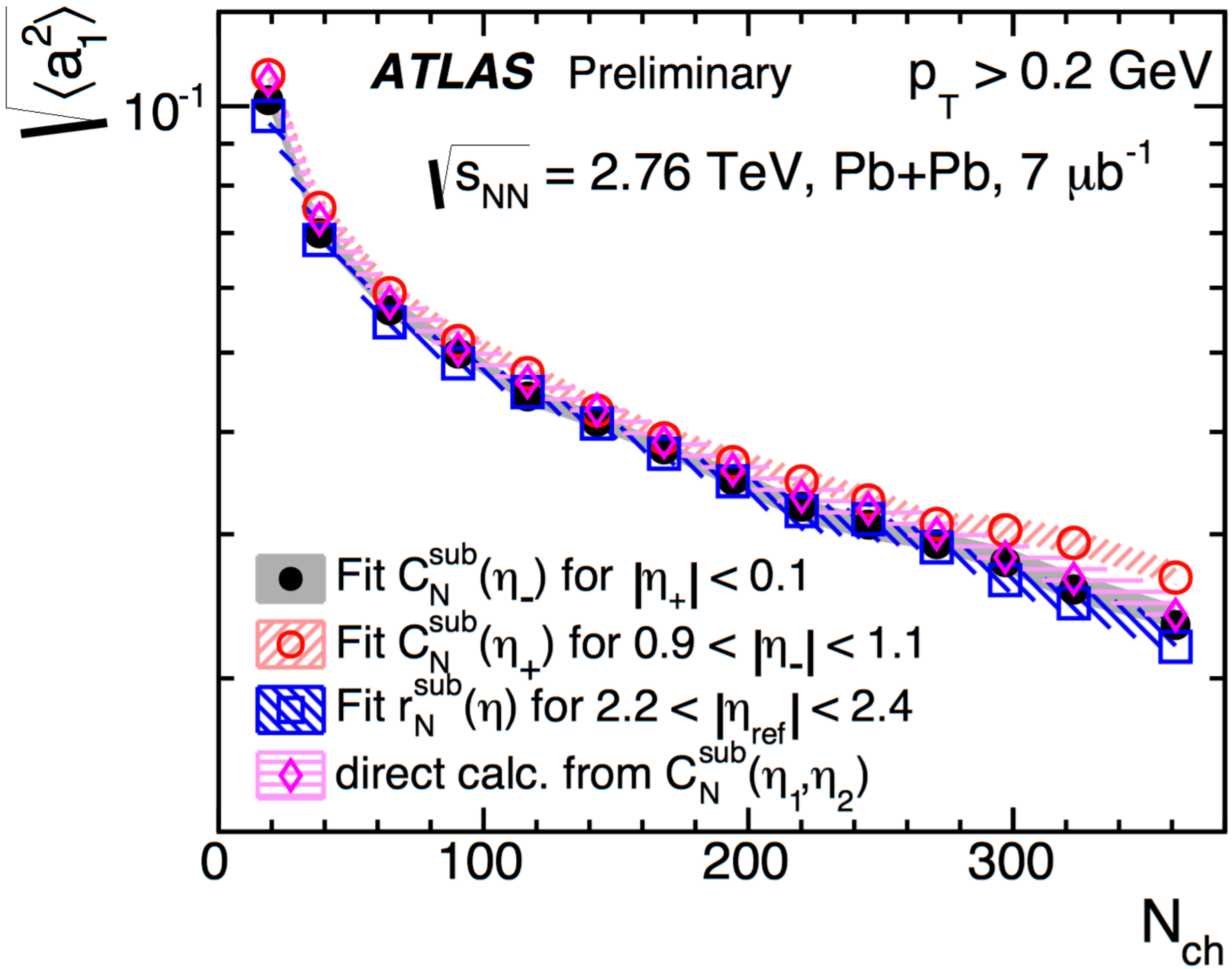
- Linear fit of $r_N^{sub}(\eta,\eta_{ref}) \equiv \frac{C_N^{sub}(-\eta,\eta_{ref})}{C_N^{sub}(\eta,\eta_{ref})}$

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

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

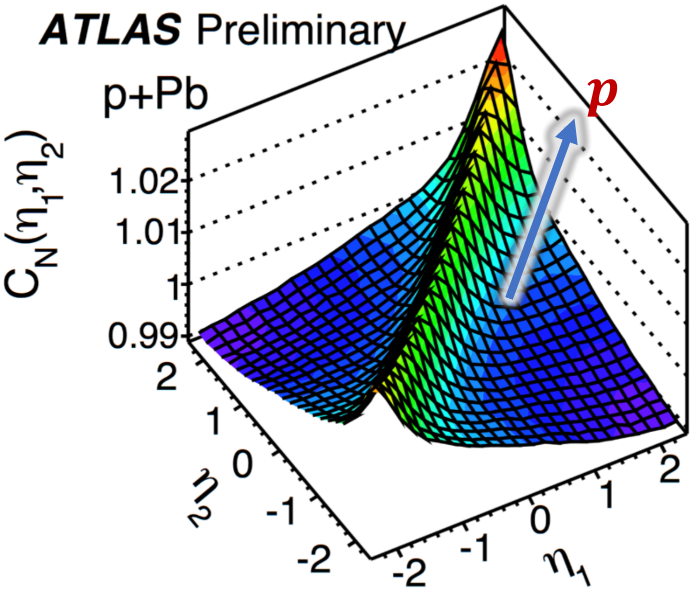
How stable are the results?

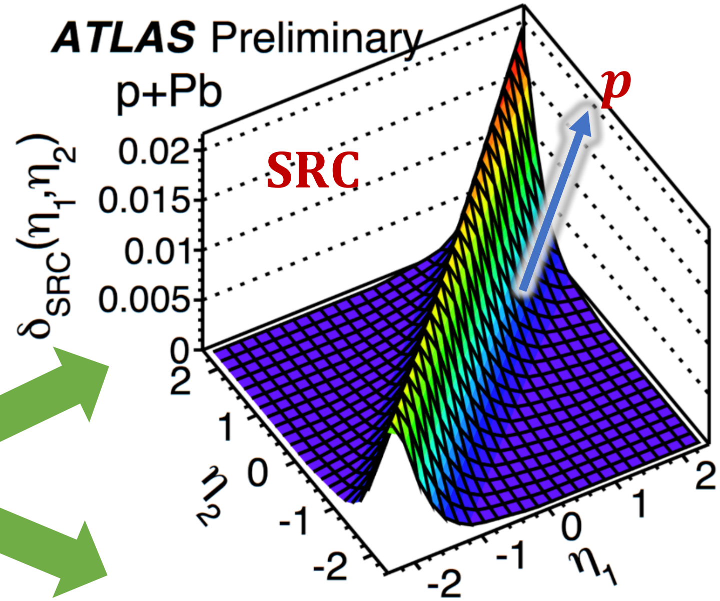
- Four largely independent methods are applied to determine $\langle a_1^2 \rangle$;
- Different methods have different sensitivity to the analysis procedures;



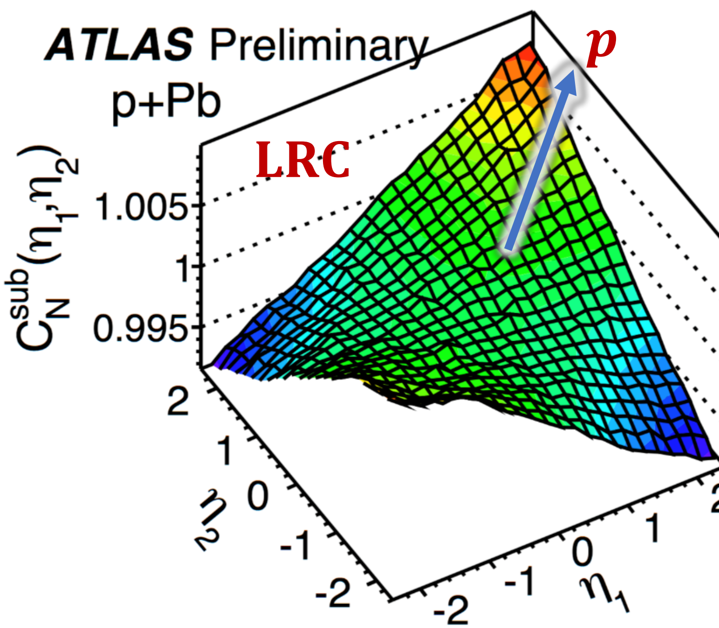
- Four methods give consistent a_1: conclusions are insensitive to the procedure.

Asymmetry in p+Pb collision





- Asymmetry entirely due to SRC!

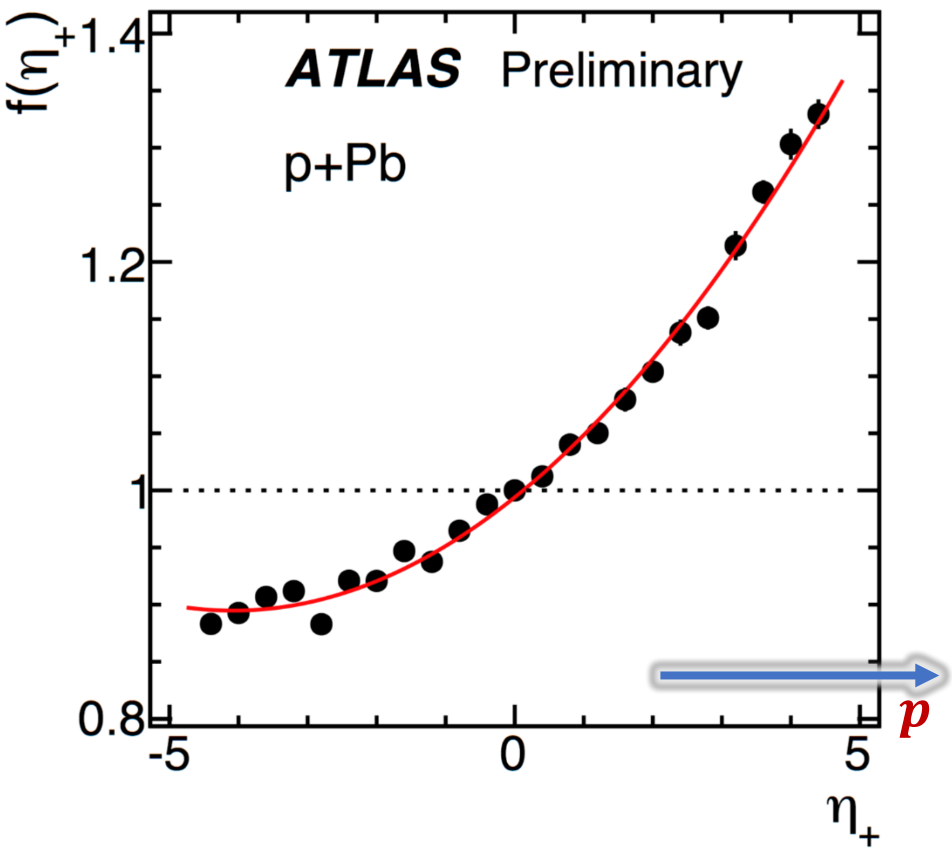


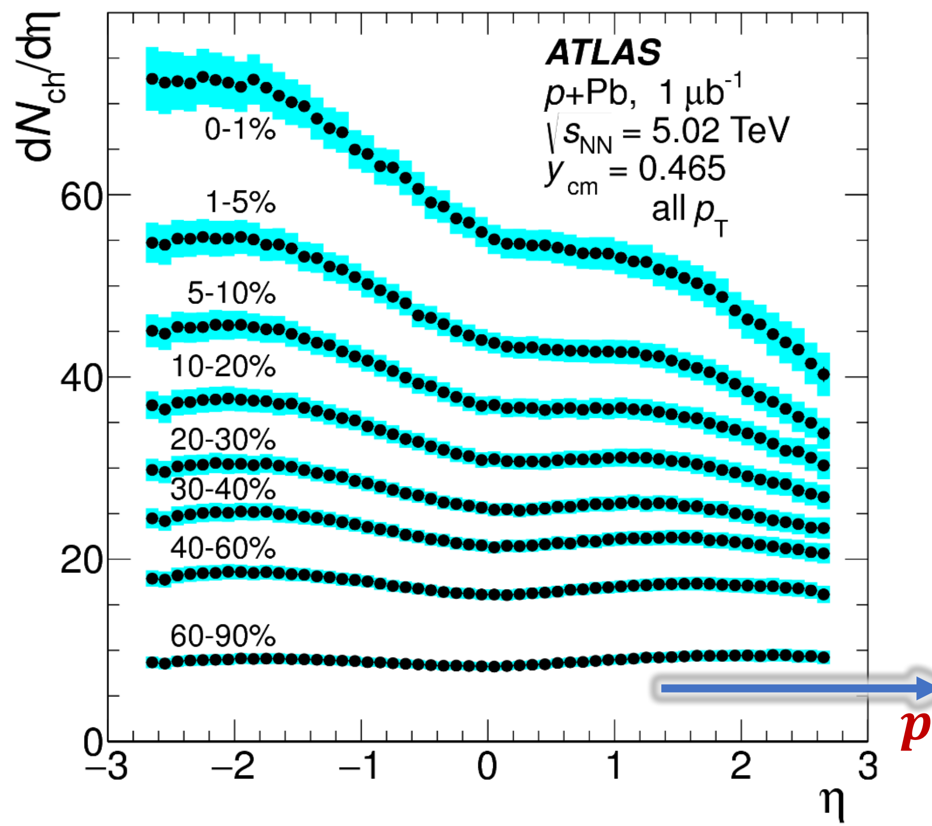
- LRC is symmetric.

- Asymmetry observed in p+Pb collision: stronger correlation in the proton-going side.

- Why the asymmetric collision causes asymmetric SRC?

SRC asymmetry in p+Pb collision



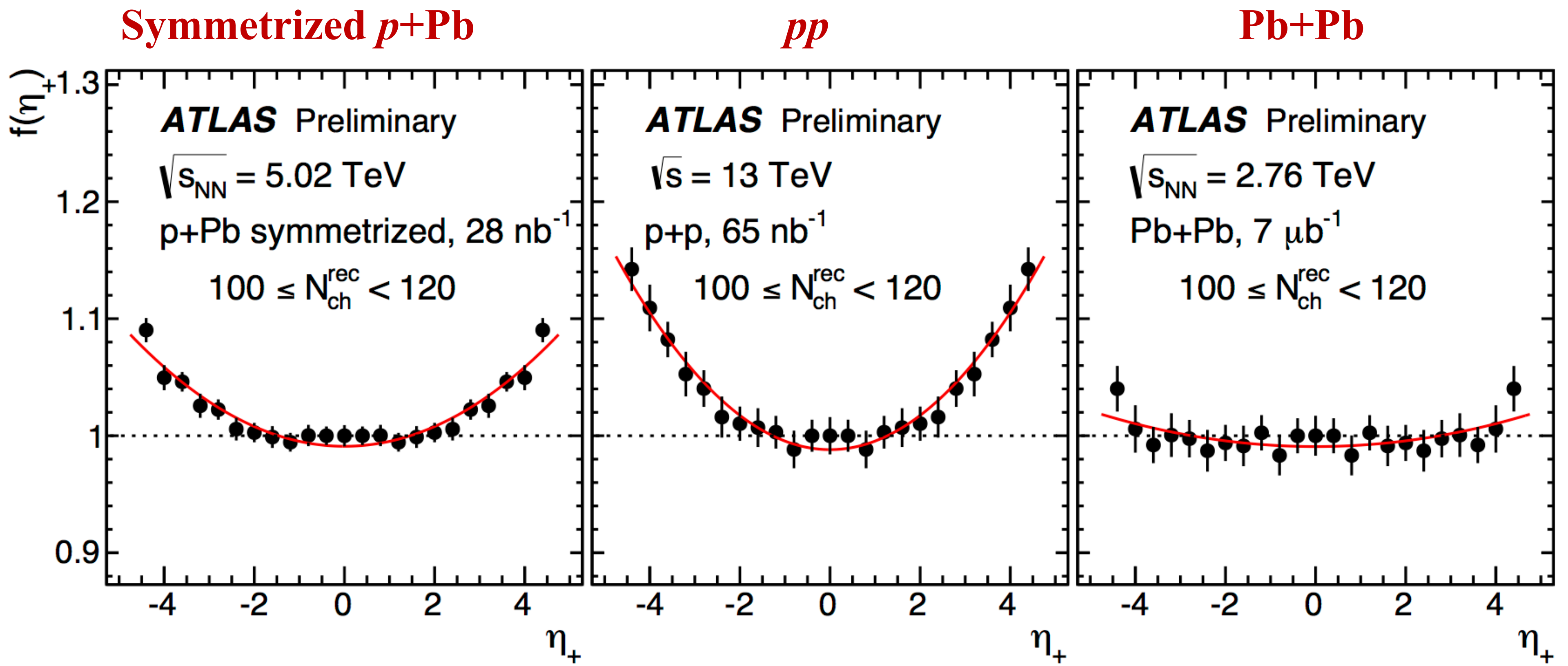


- Assume there are n clusters and each one emits m particles on average;
- Assume n is proportional to local particle density $dN_{ch}/d\eta$;

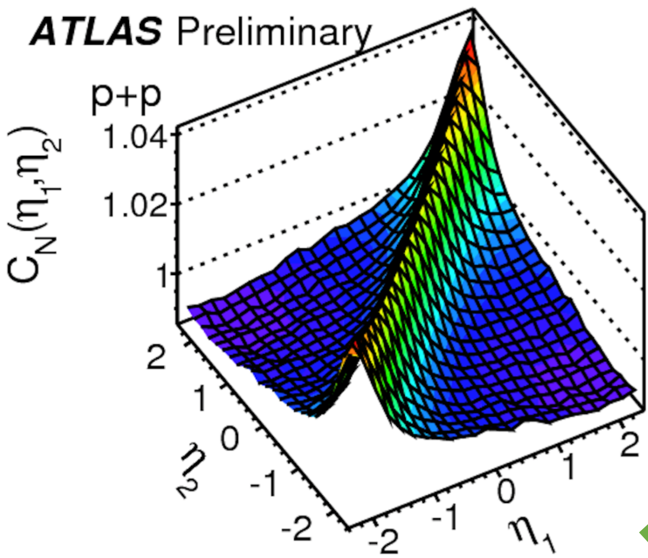
$$\delta_{SRC} \propto \frac{n\langle m(m-1)\rangle}{(n\langle m\rangle)^2} = \frac{1}{n} \propto \frac{1}{dN_{ch}/d\eta}$$

Inverse to multiplicity distribution

Compare SRC shape in three systems



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

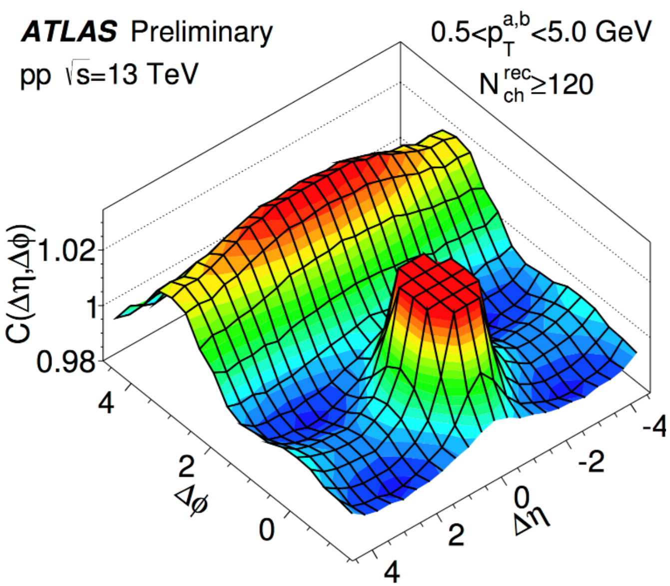


- $C(\eta_1,\eta_2)$ is a very comprehensive observable.
- Reconstruct balance function

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

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

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



$C(\eta_1,\eta_2)$

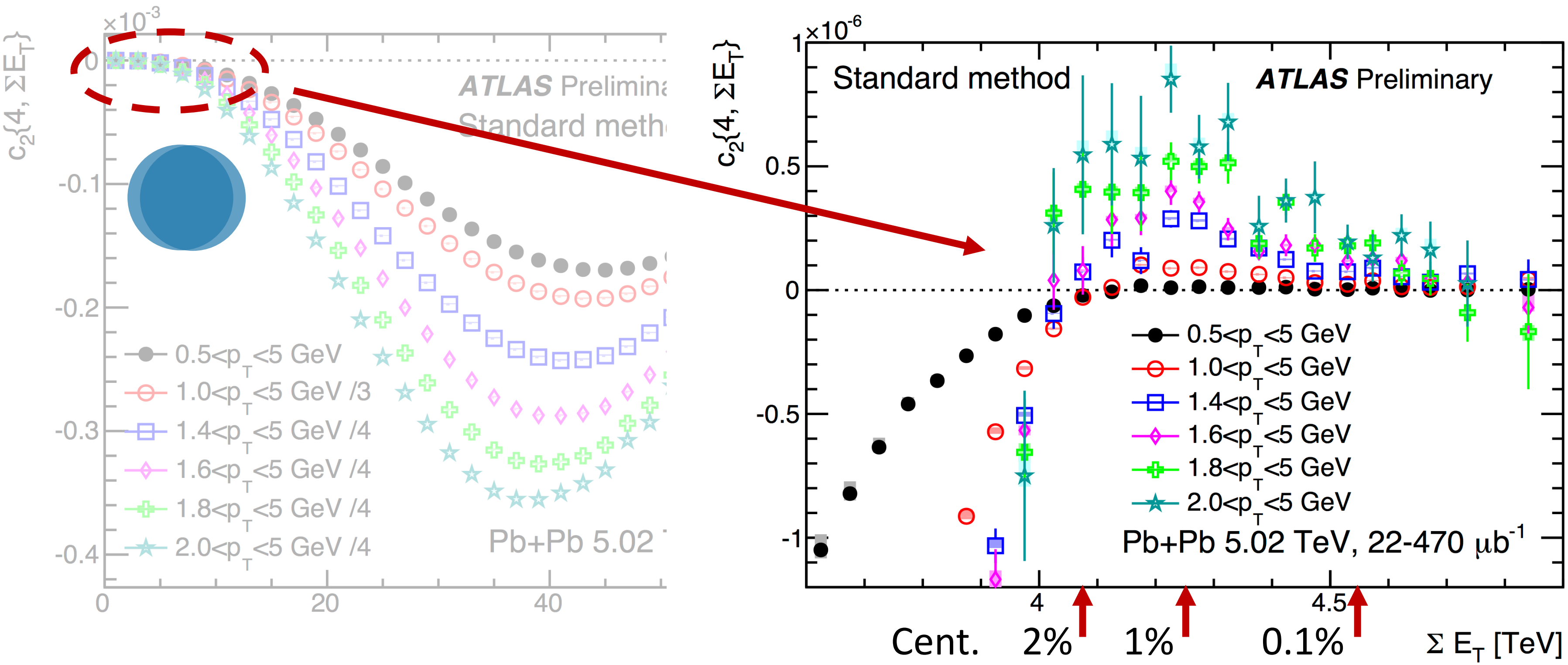
$C(\Delta\eta,\Delta\phi)$

+

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

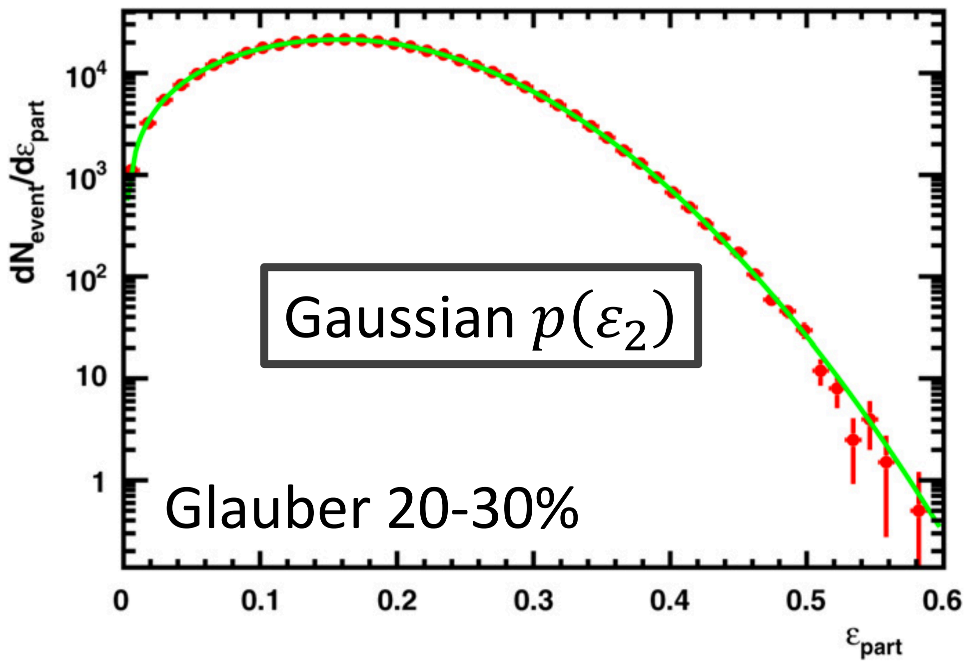
Centrality fluctuation

Ultra-Central Collision (UCC)



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

PLB 659 (2008) 537-541



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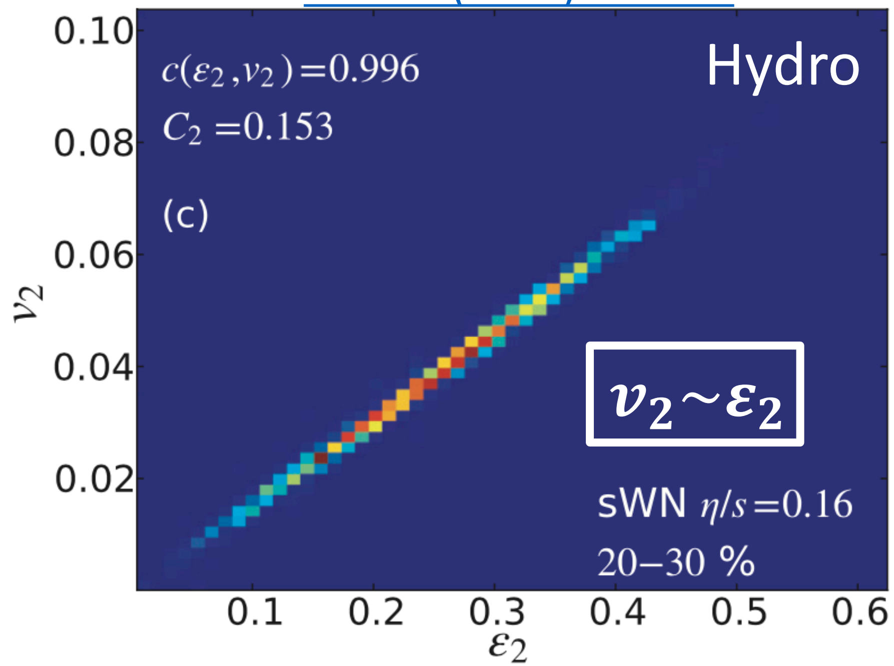
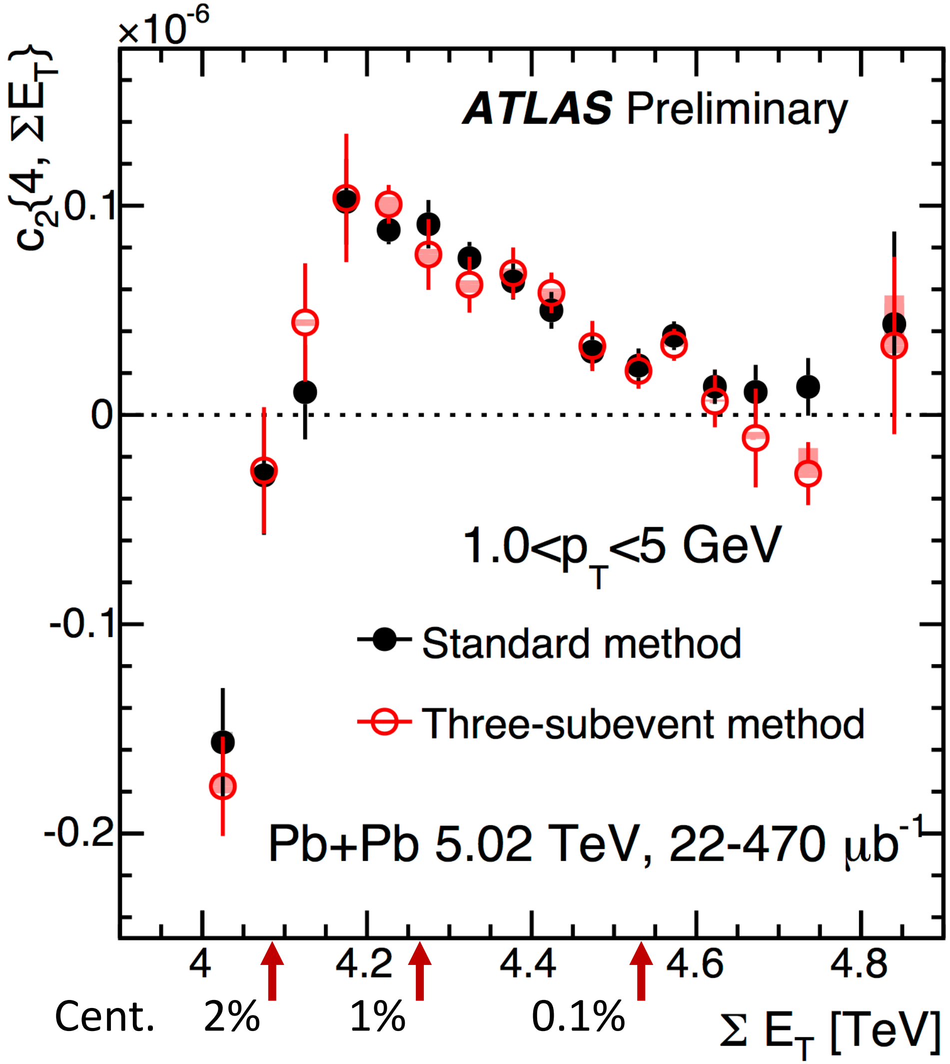


$$v_n\{4\} = \bar{v}_n = \sqrt[4]{-c_n\{4\}}$$

- 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?

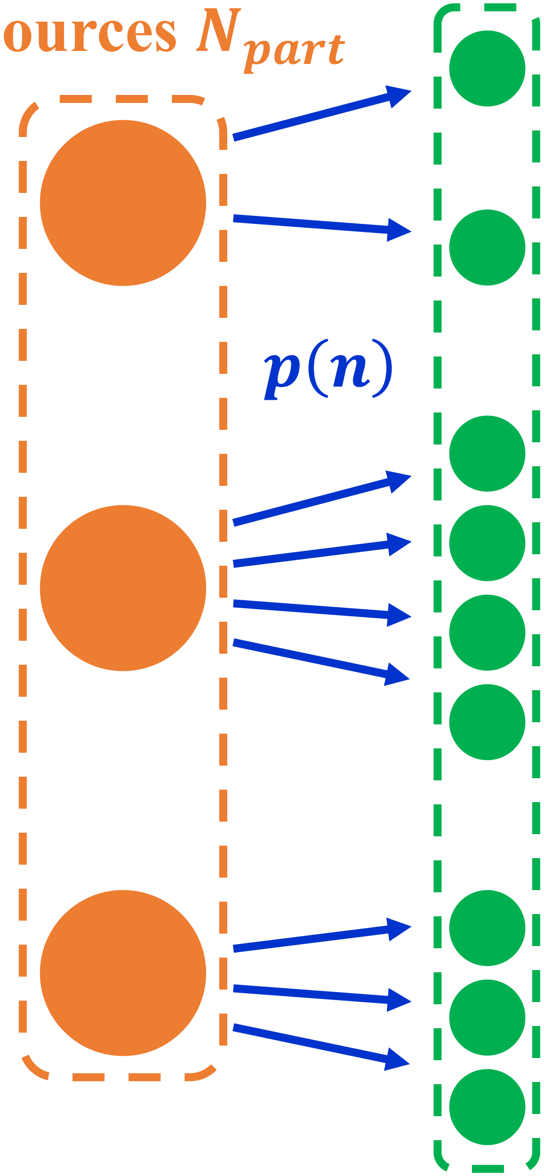
Non-flow contribution?



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

Centrality (volume) Fluctuation (CF)

Initial stage sources N_{part}



Final stage particles N_{ch}

Not detector effect!

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

How to test centrality fluctuation in data?

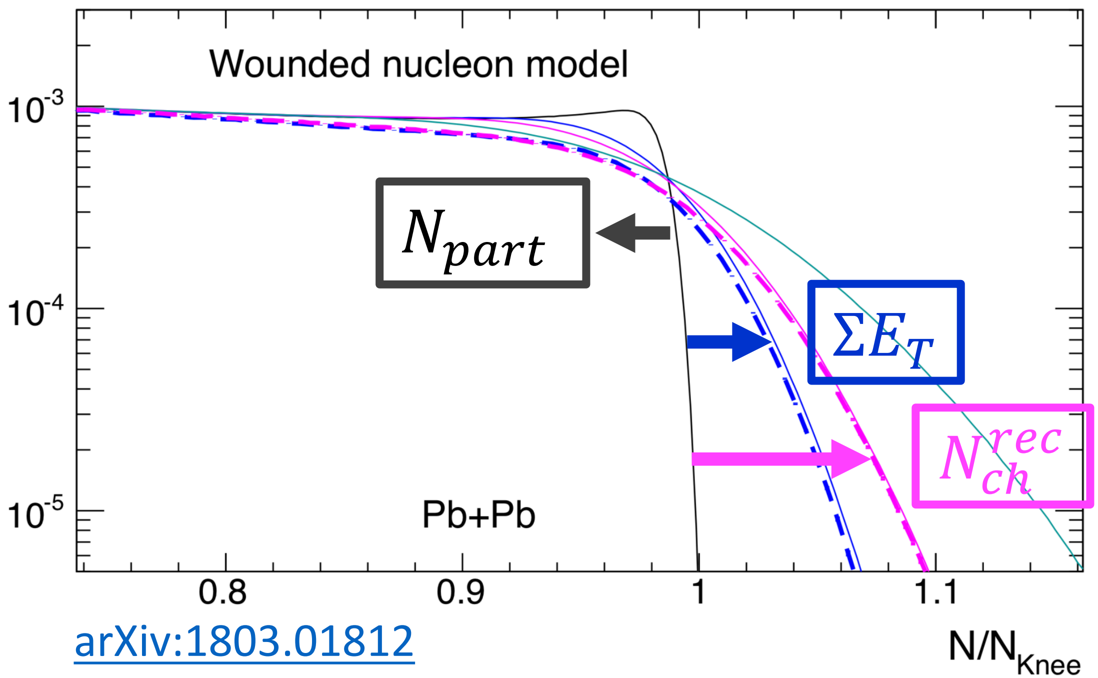
$$c_n\{4\} \equiv \langle\underbrace{\langle 4\rangle}_{\text{Calculated event-by-event}}\rangle - 2\langle\langle 2\rangle\rangle^2$$

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**

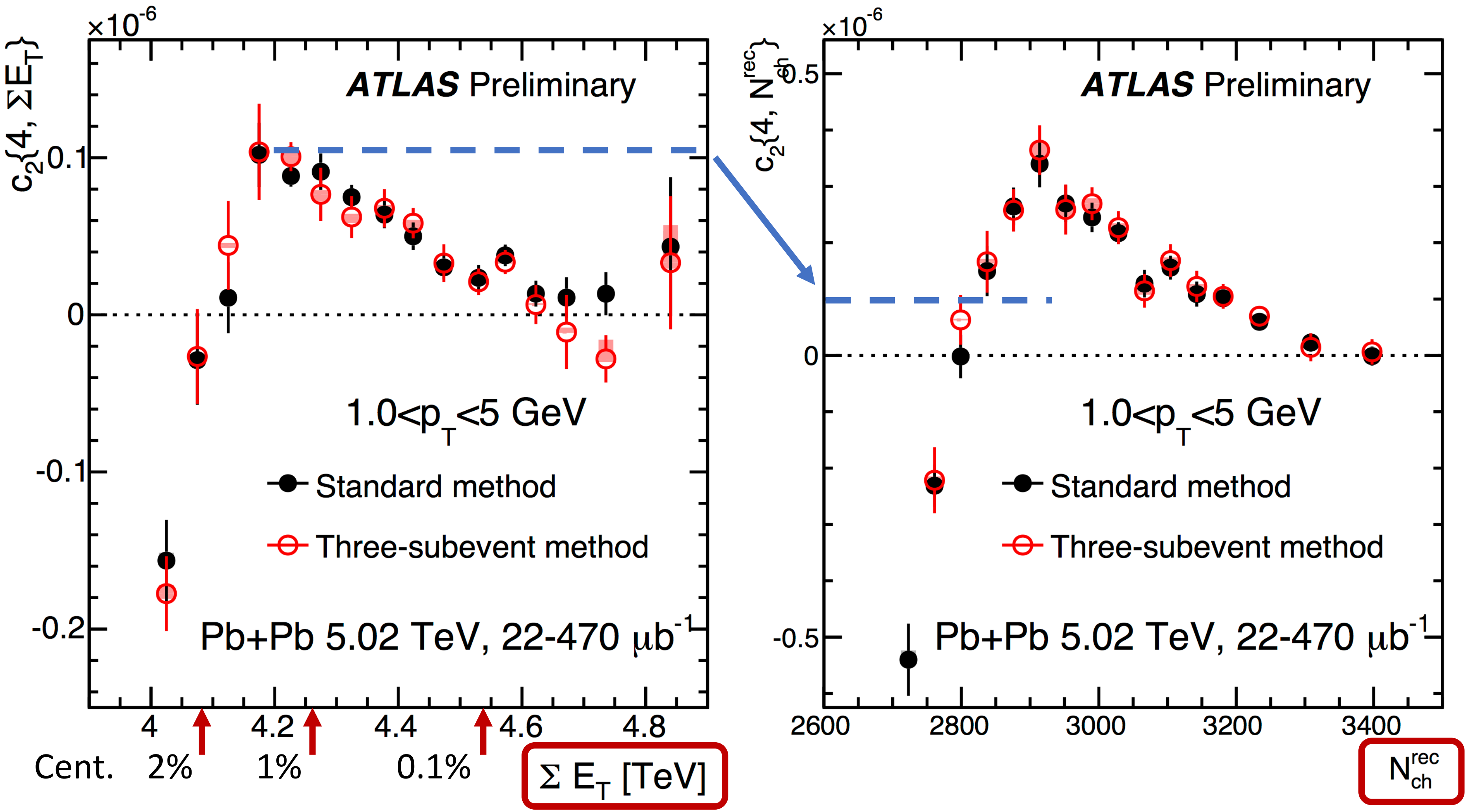
Test relative CF by comparing $c_2\{4\}$ binned by ΣE_T and N_{ch}^{rec}



arXiv:1803.01812

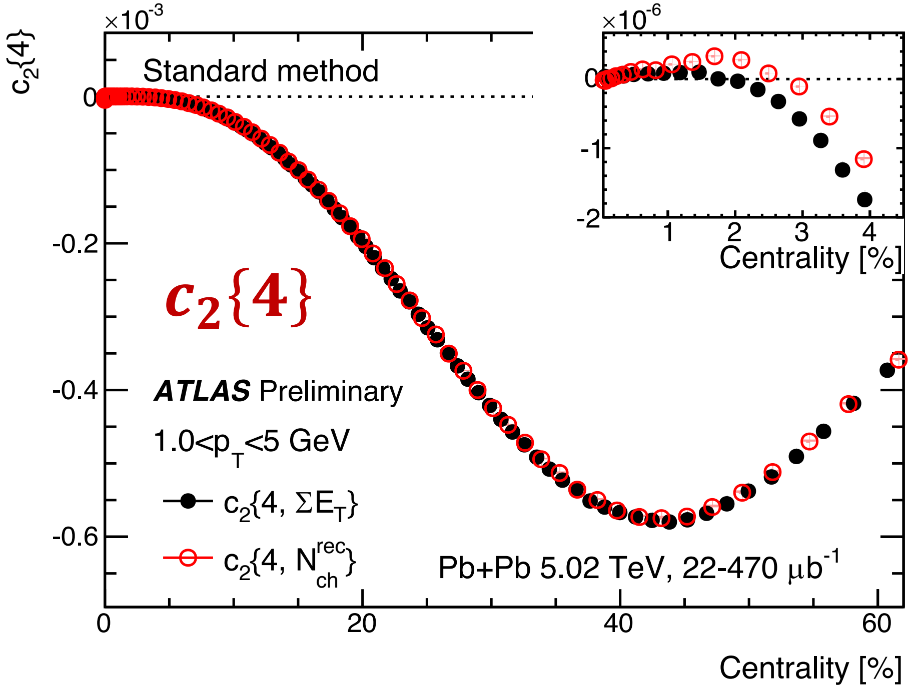
- $p(N_{ch}^{rec})$ broader than $p(\Sigma E_T)$
- CF effect: $\Sigma E_T < N_{ch}^{rec}$
- Prediction
  - $c_2\{4, \Sigma E_T\} < c_2\{4, N_{ch}^{rec}\}$

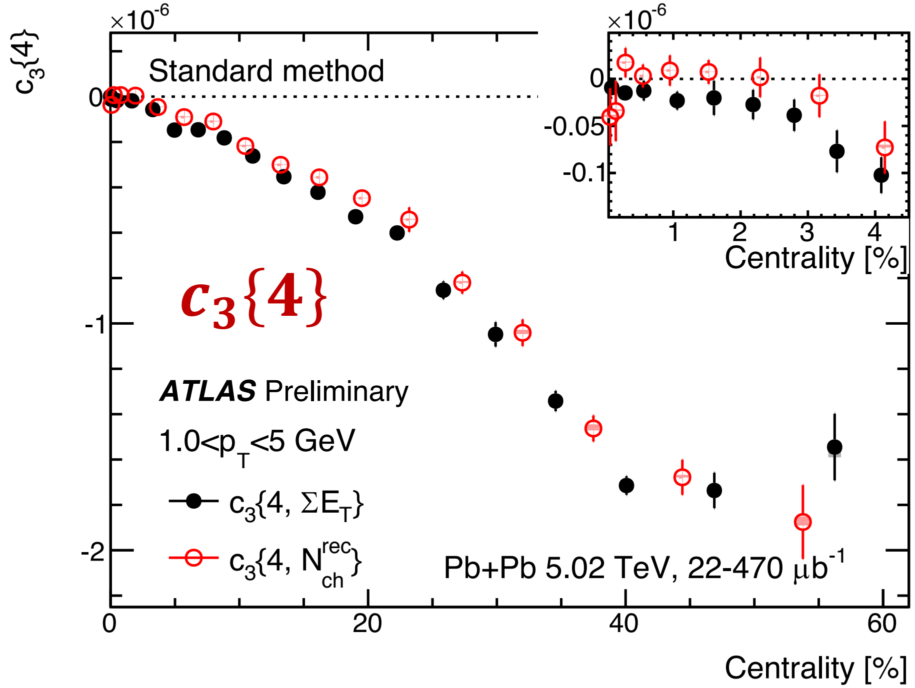
$c_2\{4\}$ and centrality fluctuation



- $c_2\{4, \Sigma E_{\mathrm{T}}\} < c_2\{4, N_{ch}^{rec}\}$: CF affects flow cumulant;
- $c_2\{4\} \to 0$ in very most-central: smaller CF effect;

From ultra-central to full centrality

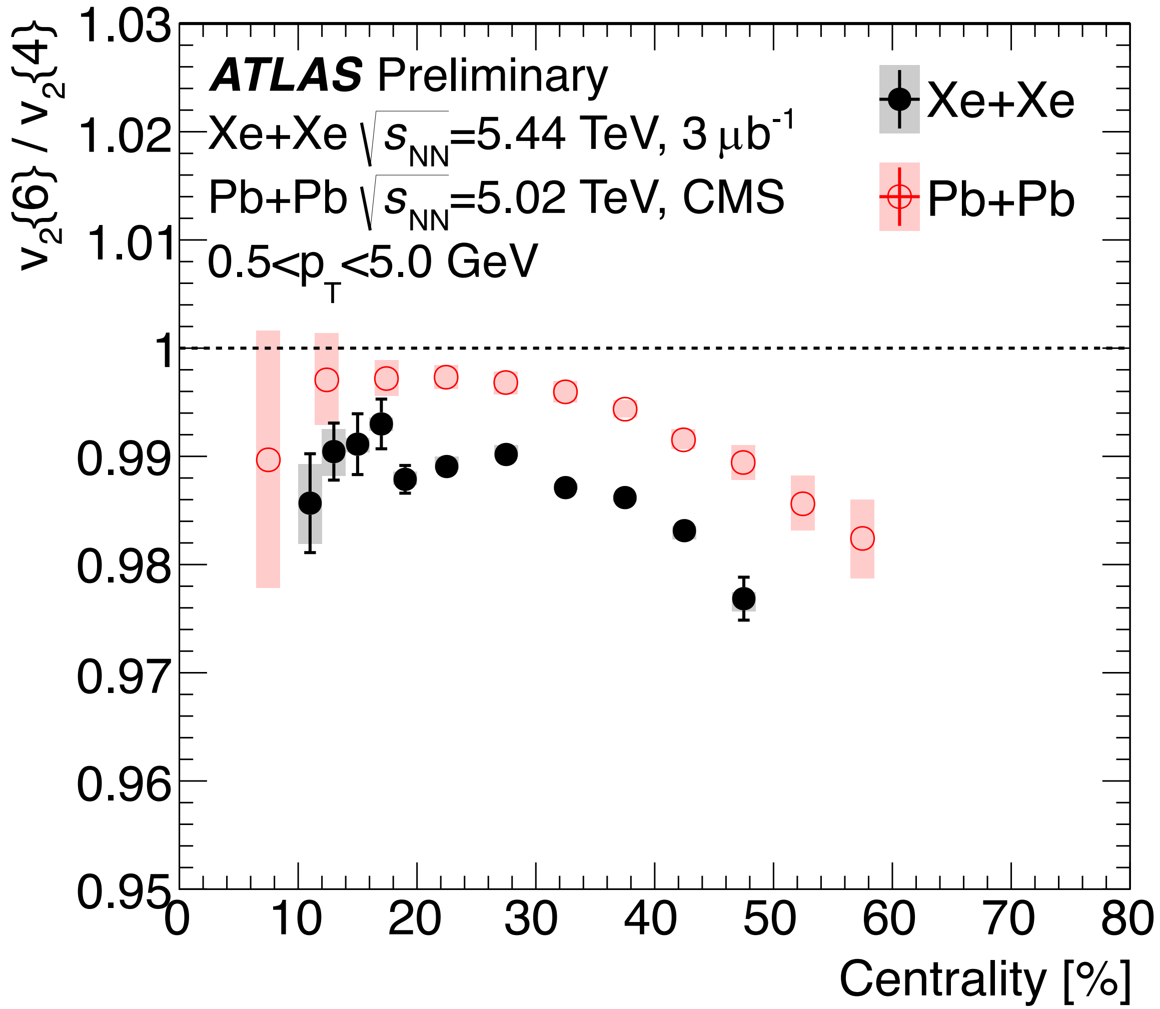




- $c_2\{4\}$: CF mostly affects central;
- $c_3\{4\}$: CF affects most centralities.

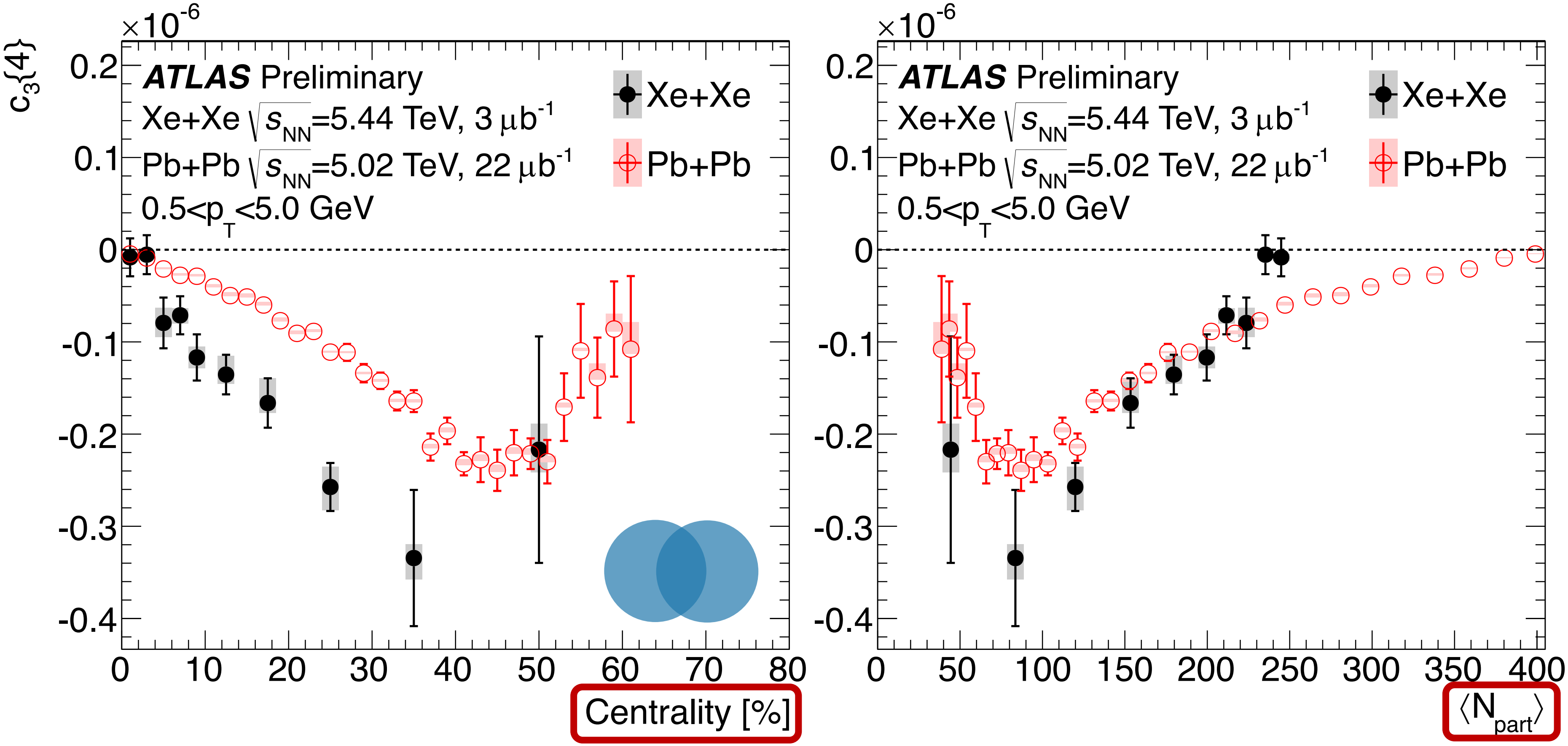
Comparison between Pb+Pb and Xe+Xe

Xe+Xe and Pb+Pb: v_2



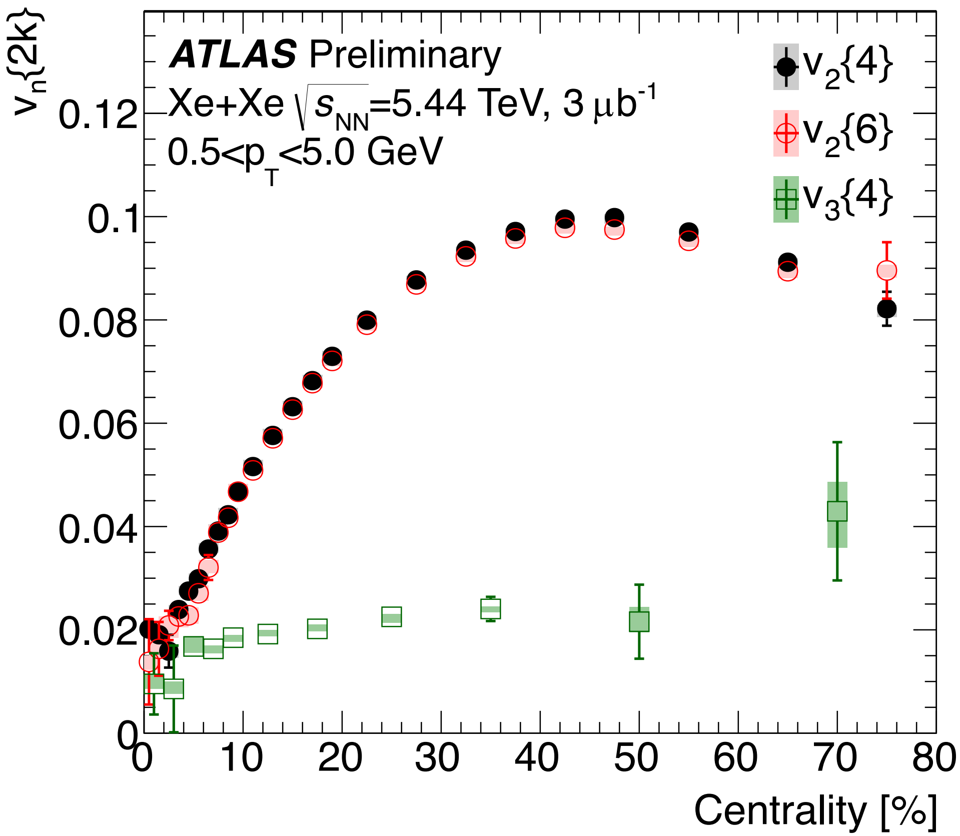
- Mass number of Xe is halfway of Pb and p;
- If $v_2 \sim Gauss(\bar{v}_n, \delta_n)$: $v_2\{6\}/v_2\{4\} = 1$
- v_2 in Xe+Xe deviates further from Gauss: deformed nucleus?

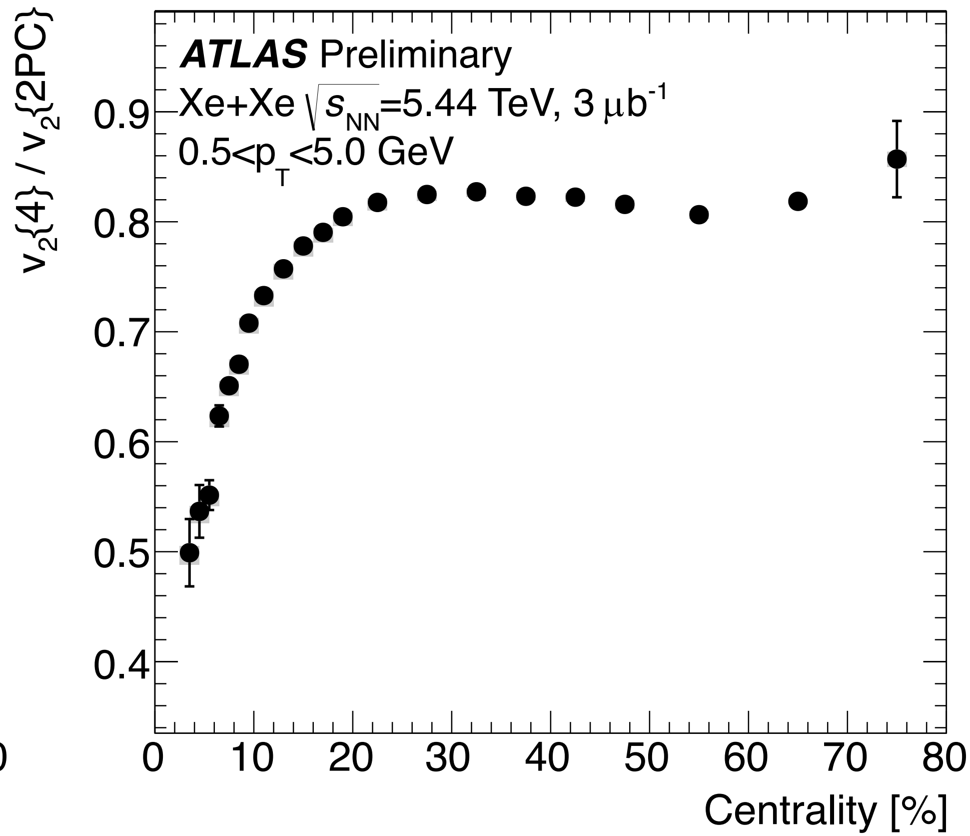
Xe+Xe and Pb+Pb: v_3



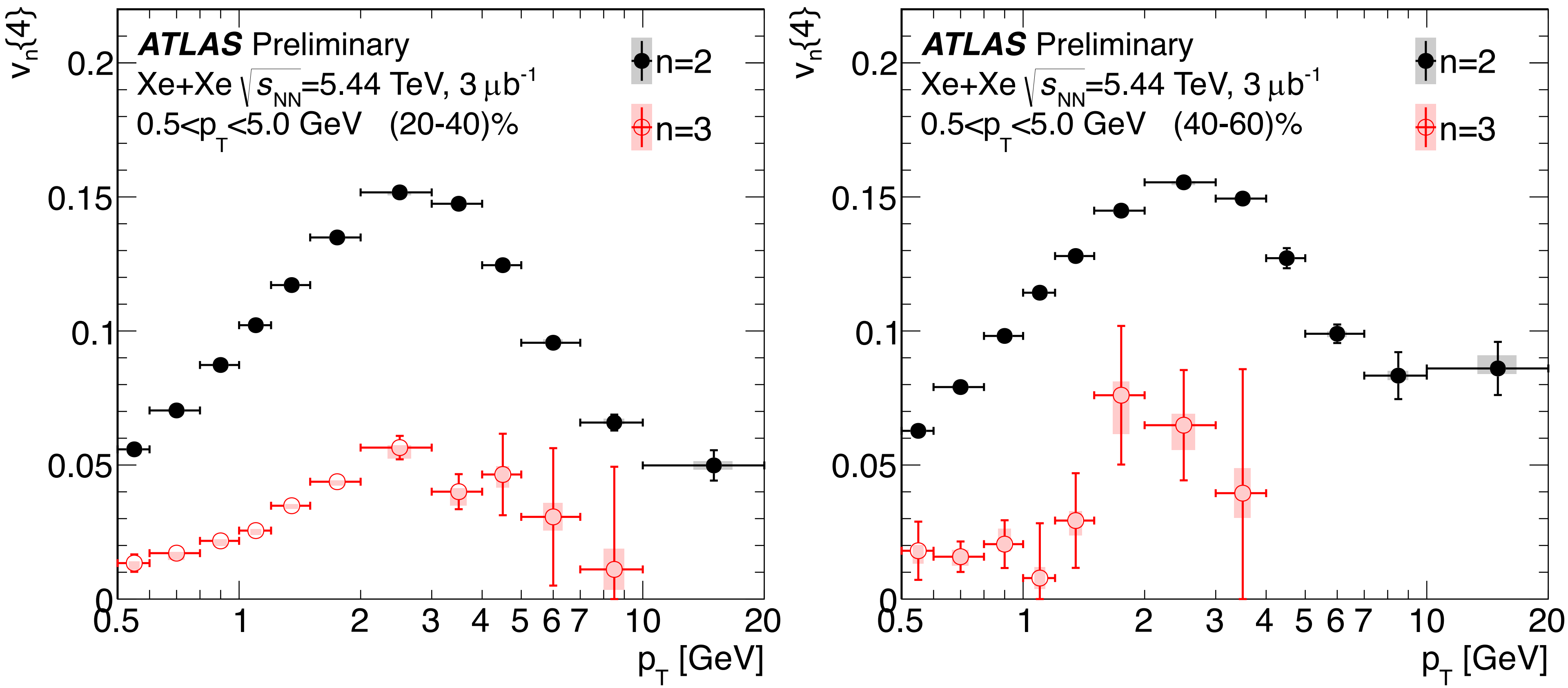
- $c_3\{4\}$ doesn't scale with centrality between Xe and Pb
  - No avg. geometry for v_3;
- $c_3\{4\}$ scales with $\langle N_{part} \rangle$
  - Fluctuation driven by # of sources N_{part}
- Similar observation for $c_4\{4\}$ (see backup)

Multi-particle cumulant

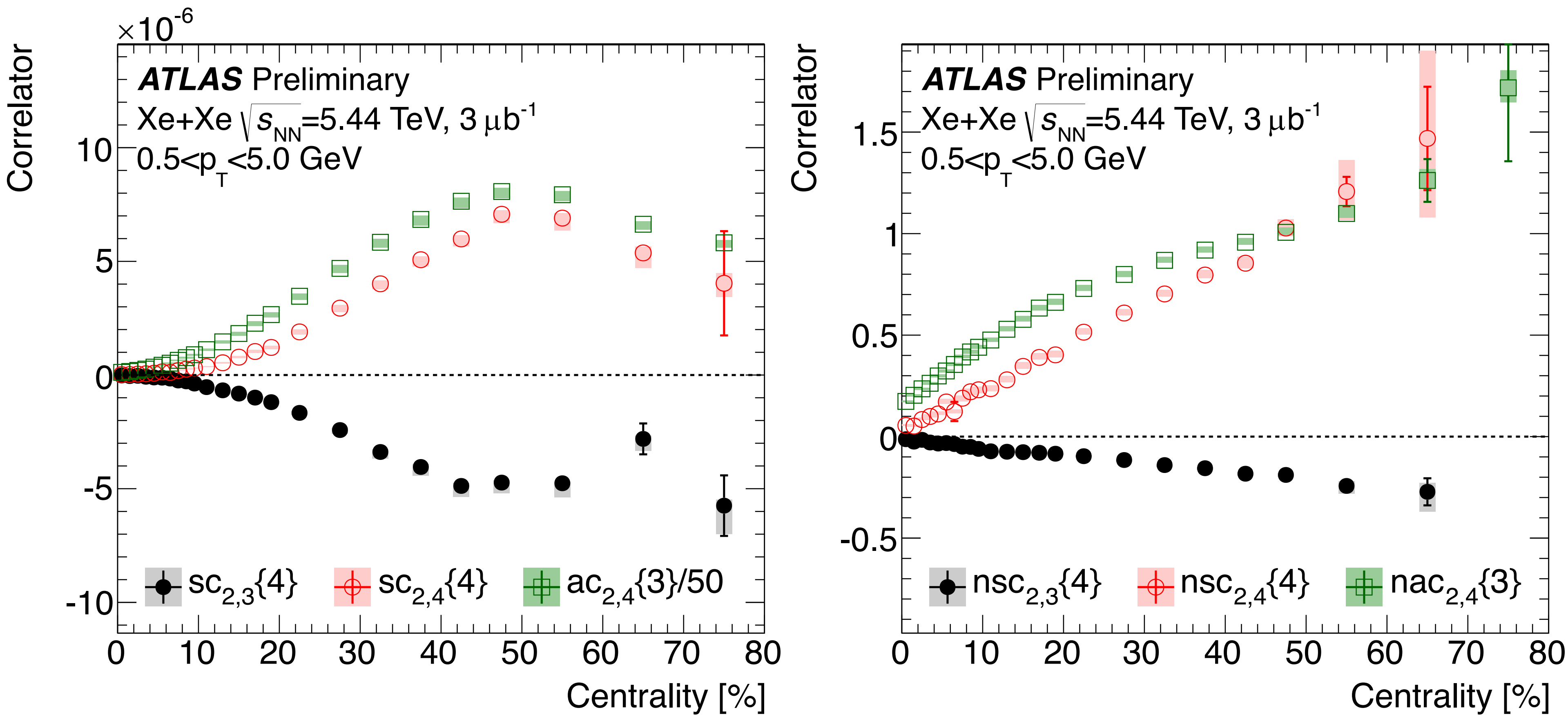




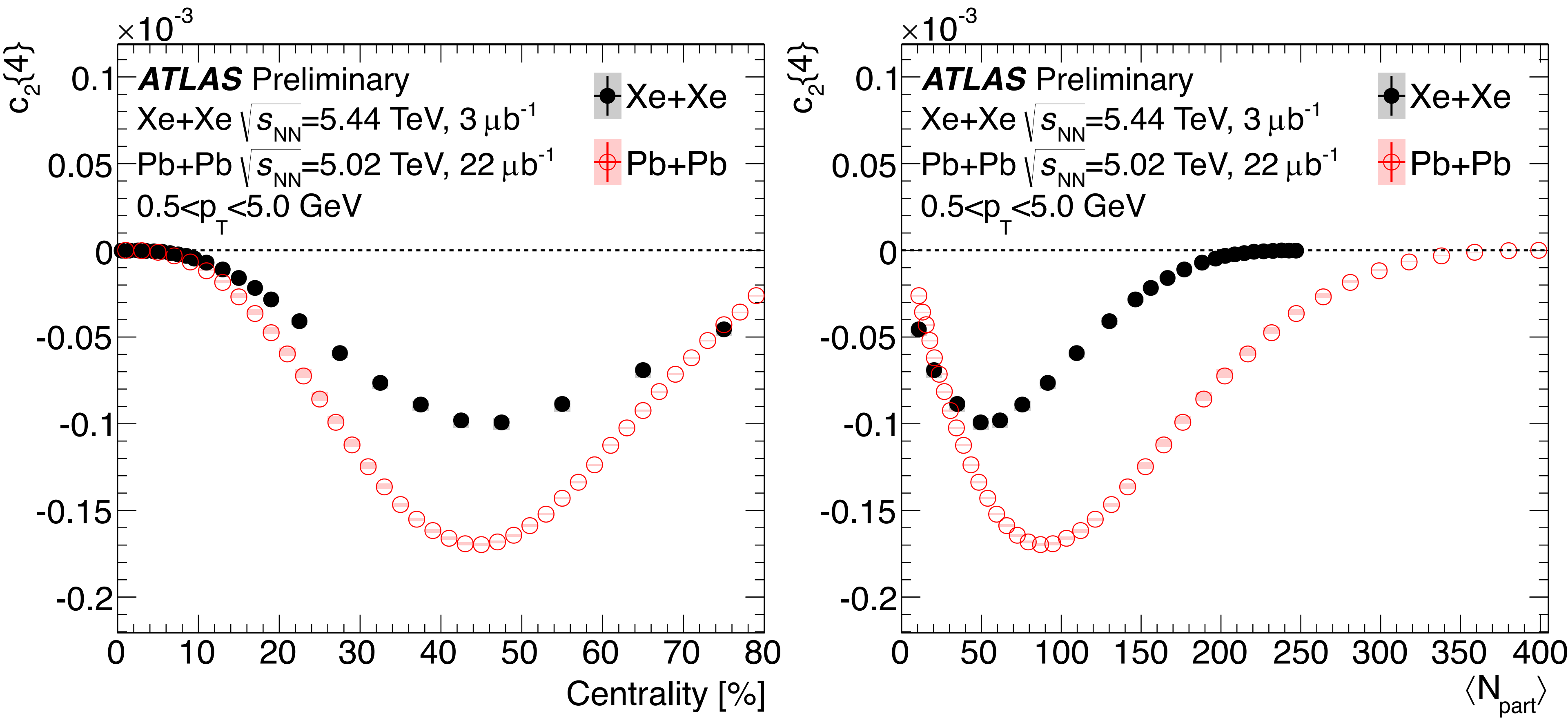
Differential cumulant



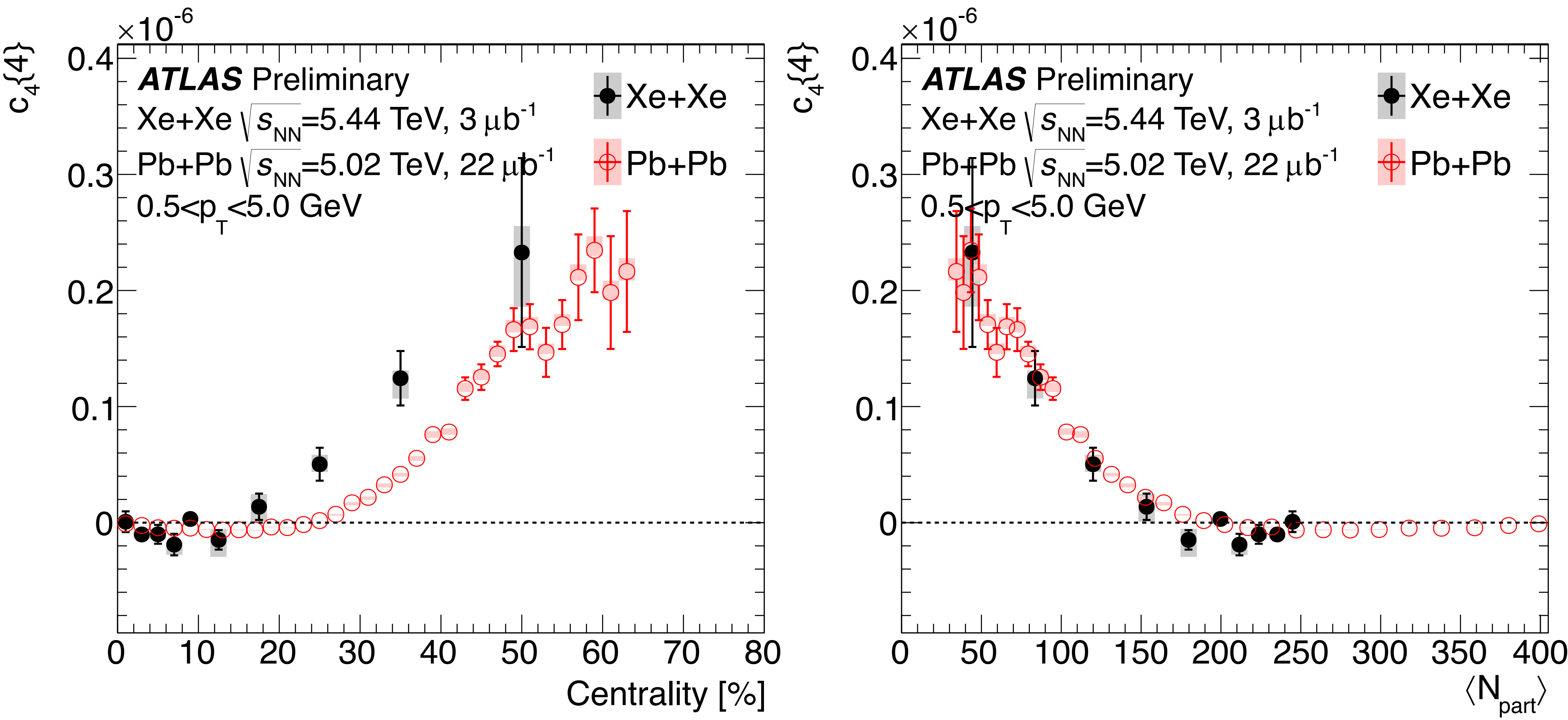
Symmetric cumulant



$c_2\{4\}$



×10^-3
c2{4}
ATLAS Preliminary
Xe+Xe √sNN=5.44 TeV, 3 μb^-1
Pb+Pb √sNN=5.02 TeV, 22 μb^-1
0.5<pT<5.0 GeV
Xe+Xe
Pb+Pb
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0 10 20 30 40 50 60 70 80
Centrality [%]
0 50 100 150 200 250 300 350 400
⟨Npart⟩


×10^-6
c_4{4}
ATLAS Preliminary
Xe+Xe √s_NN=5.44 TeV, 3 μb^-1
Pb+Pb √s_NN=5.02 TeV, 22 μb^-1
0.5<p_T<5.0 GeV
Xe+Xe
Pb+Pb
Centrality [%]
⟨N_part⟩
0
0.1
0.2
0.3
0.4
0
10
20
30
40
50
60
70
80
0
50
100
150
200
250
300
350
400