Evidences for collectivity in small systems

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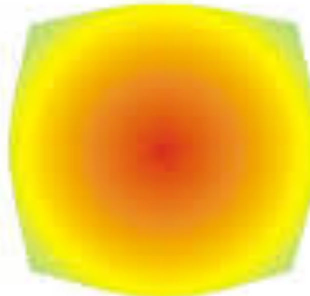
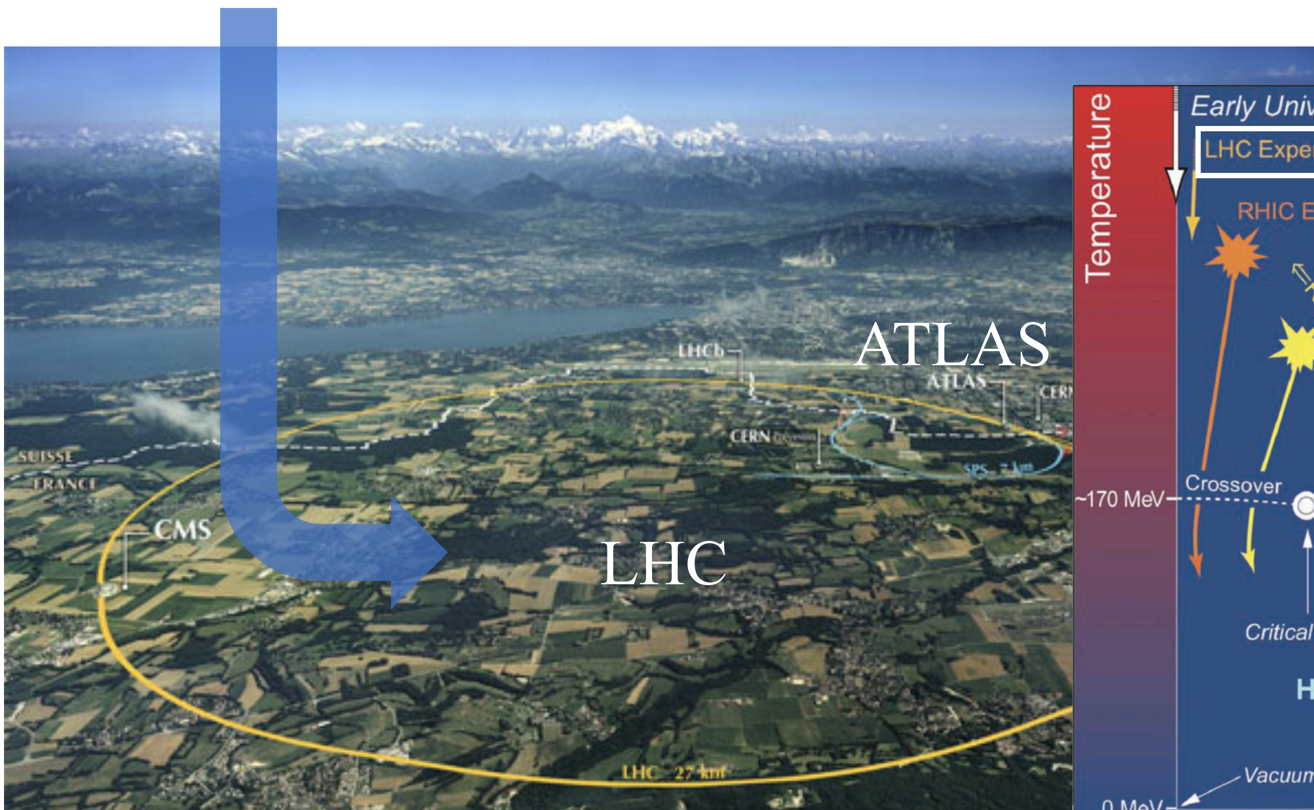
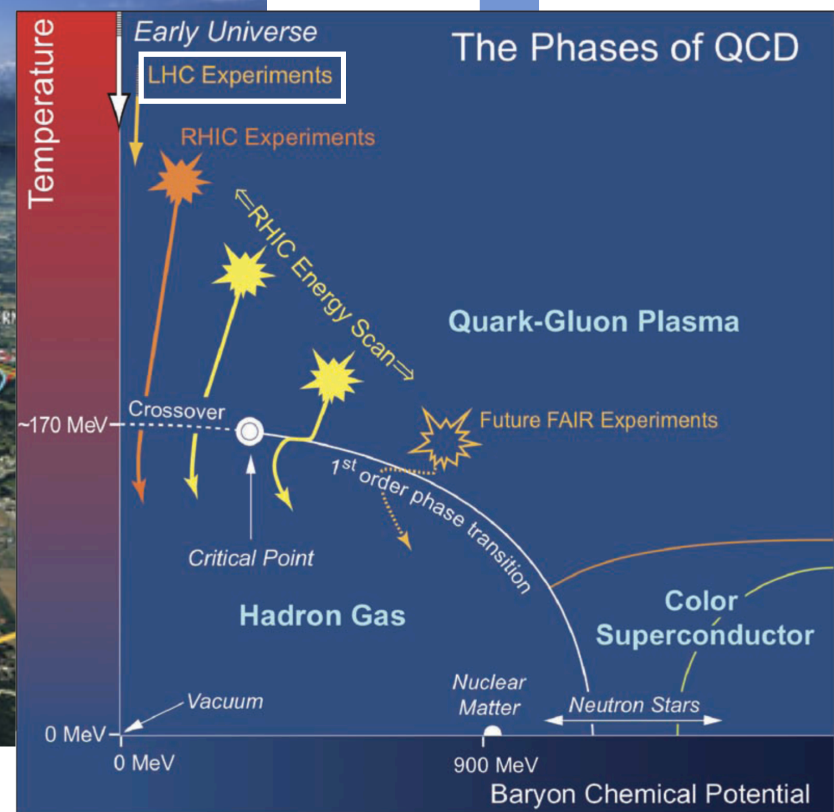
ATLAS EXPERIMENT

Stony Brook University

QGP

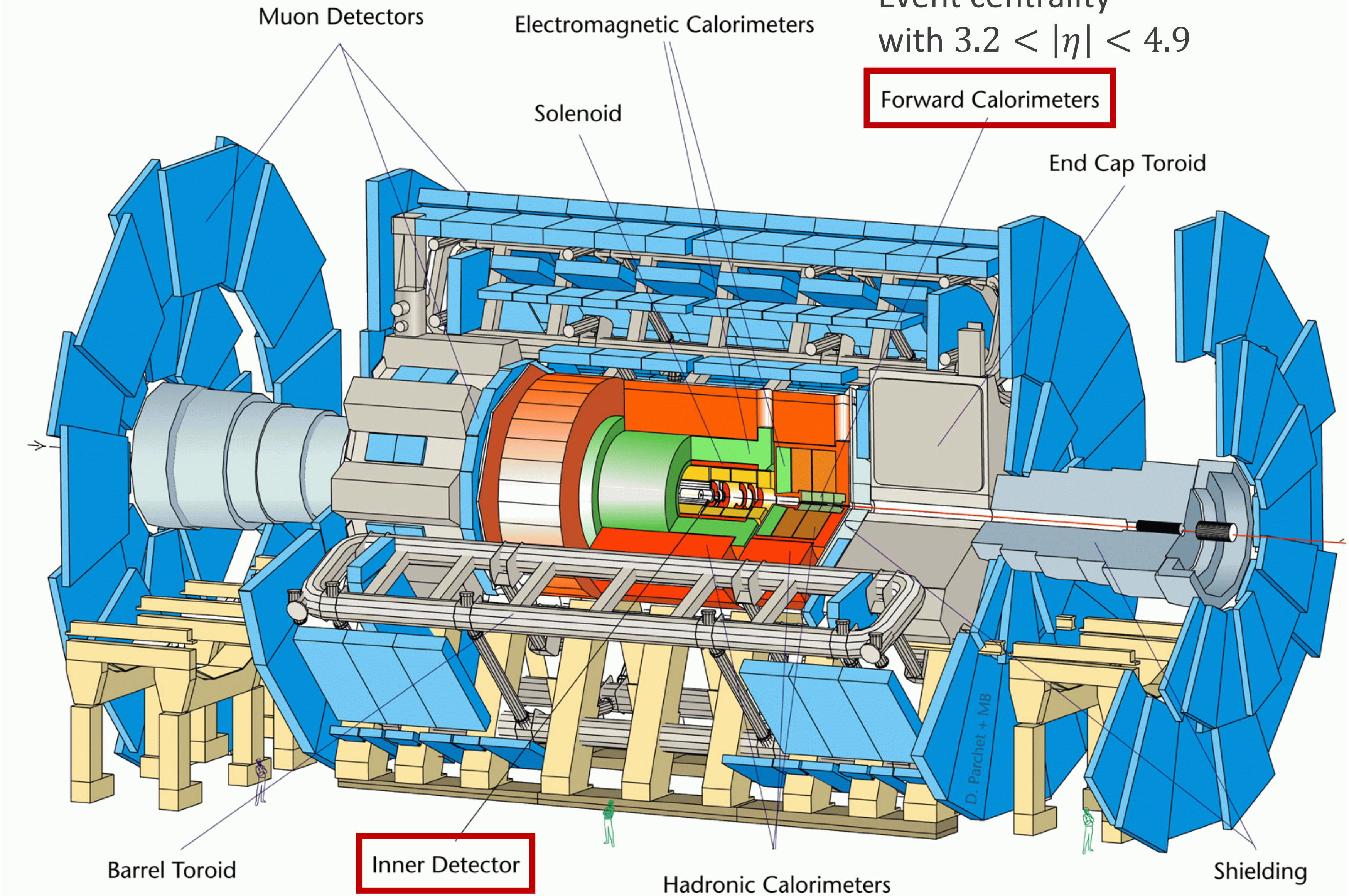



ATLAS
LHC
LHCb
ATLAS
CERN
SUISSE
FRANCE
CMS
LHC 27 km


The Phases of QCD
Temperature
Early Universe
LHC Experiments
RHIC Experiments
RHIC Energy Scan
Quark-Gluon Plasma
Future FAIR Experiments
~170 MeV
Crossover
1st order phase transition
Critical Point
Hadron Gas
Color Superconductor
Nuclear Matter
Vacuum
Neutron Stars
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential

Collectivity

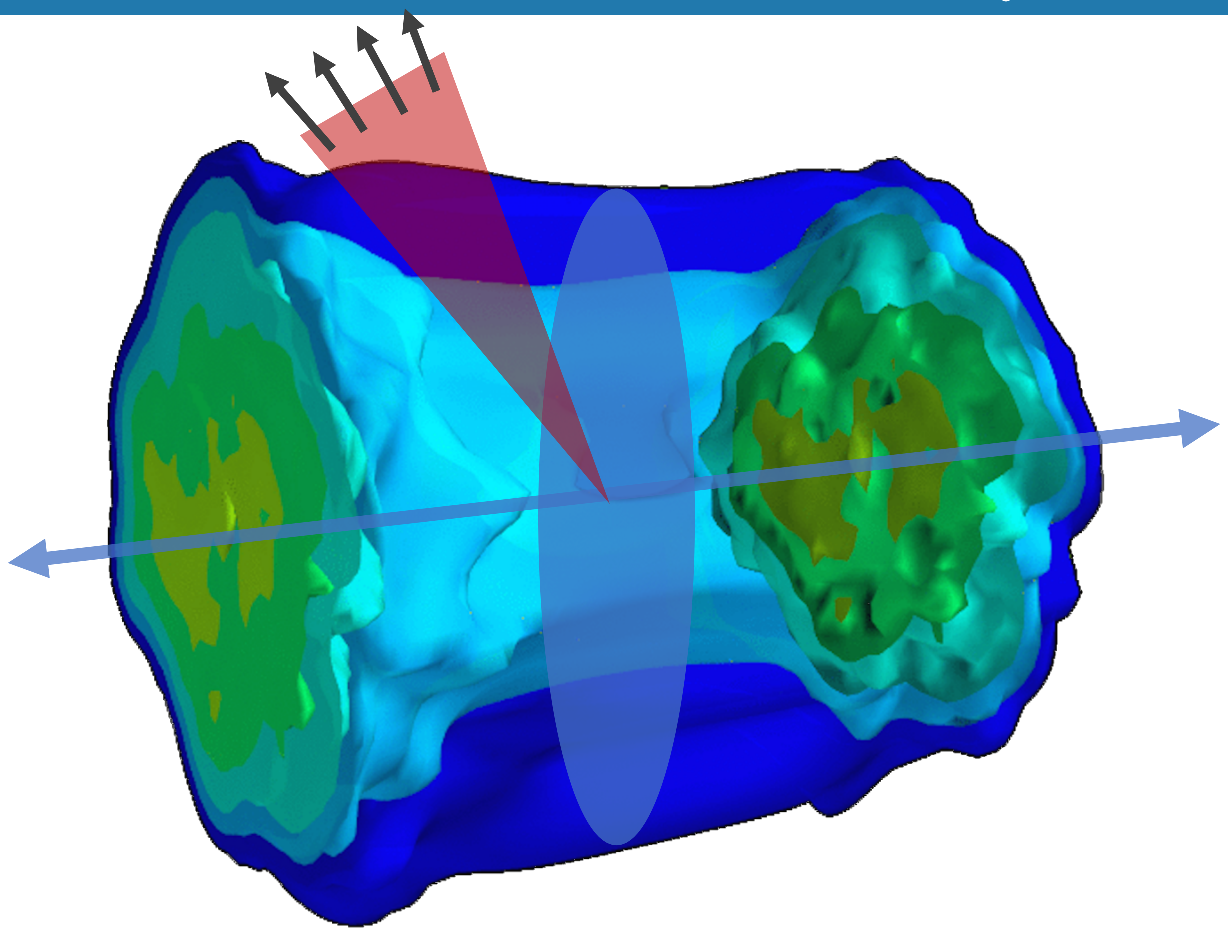
Event centrality
with $3.2 < |\eta| < 4.9$

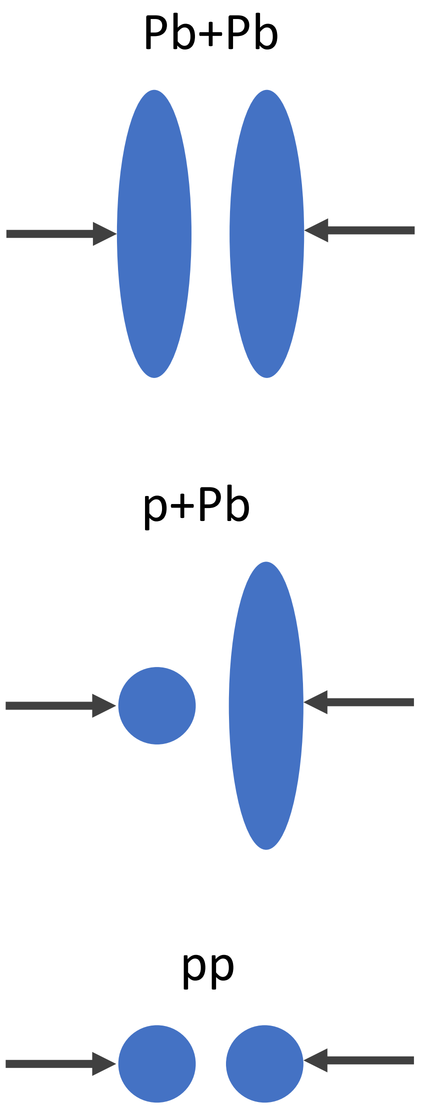


Charged hadrons
with $|\eta| < 2.5$

MBTS and ZDC for triggers

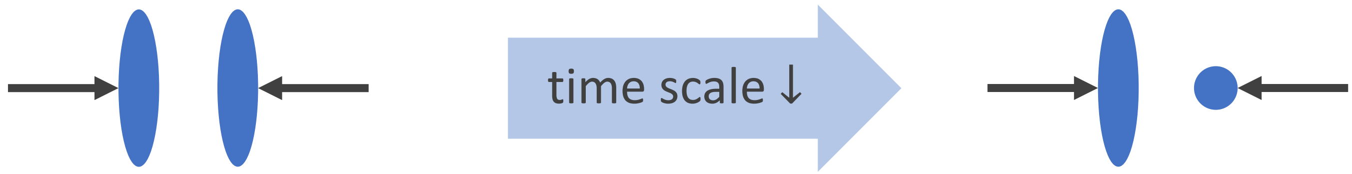
Collectivity

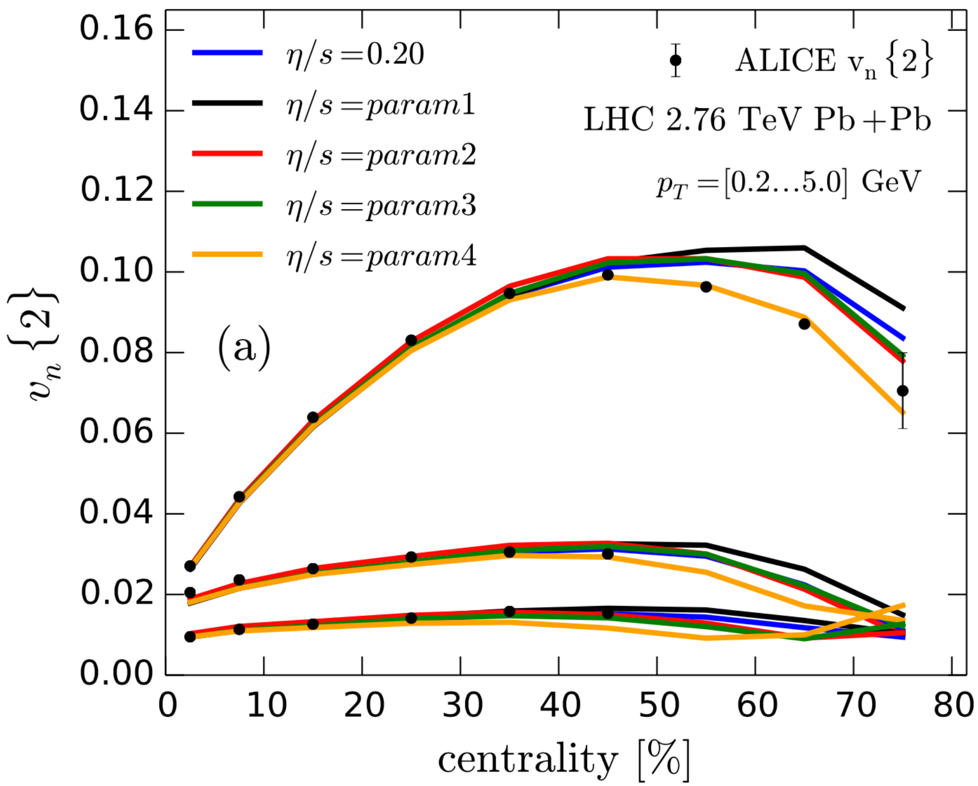


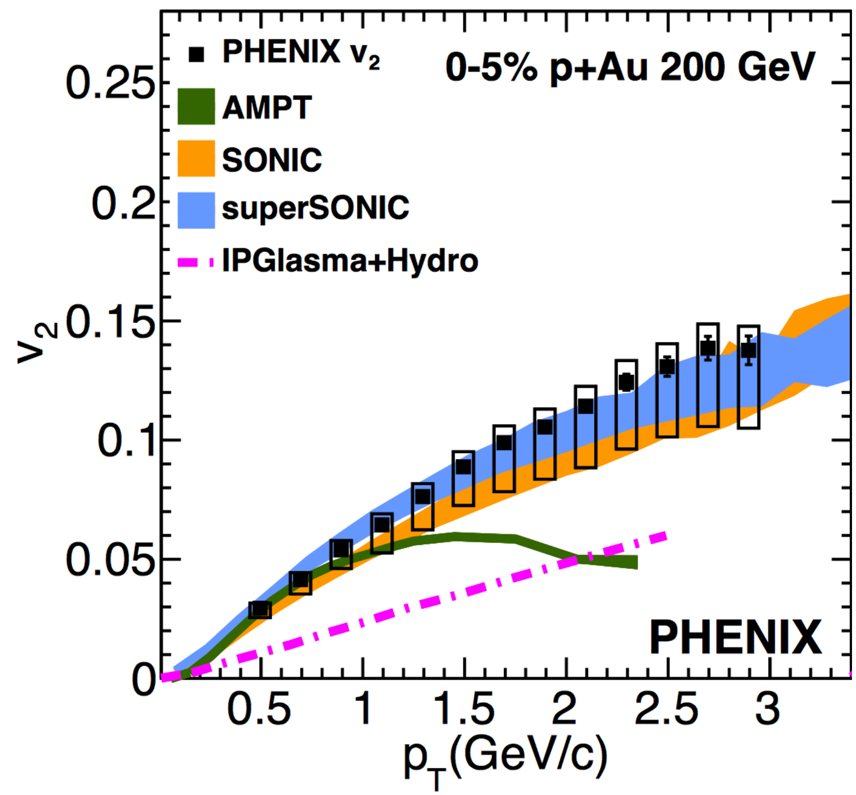


- Collectivity: how system evolve as a whole
  - Longitudinal correlation
  - Azimuthal correlation
- Short-range correlations are major background

Why small systems?







Hydro successful in A+A

Challenge hydro in p+A / pp?

Origins of collectivity?

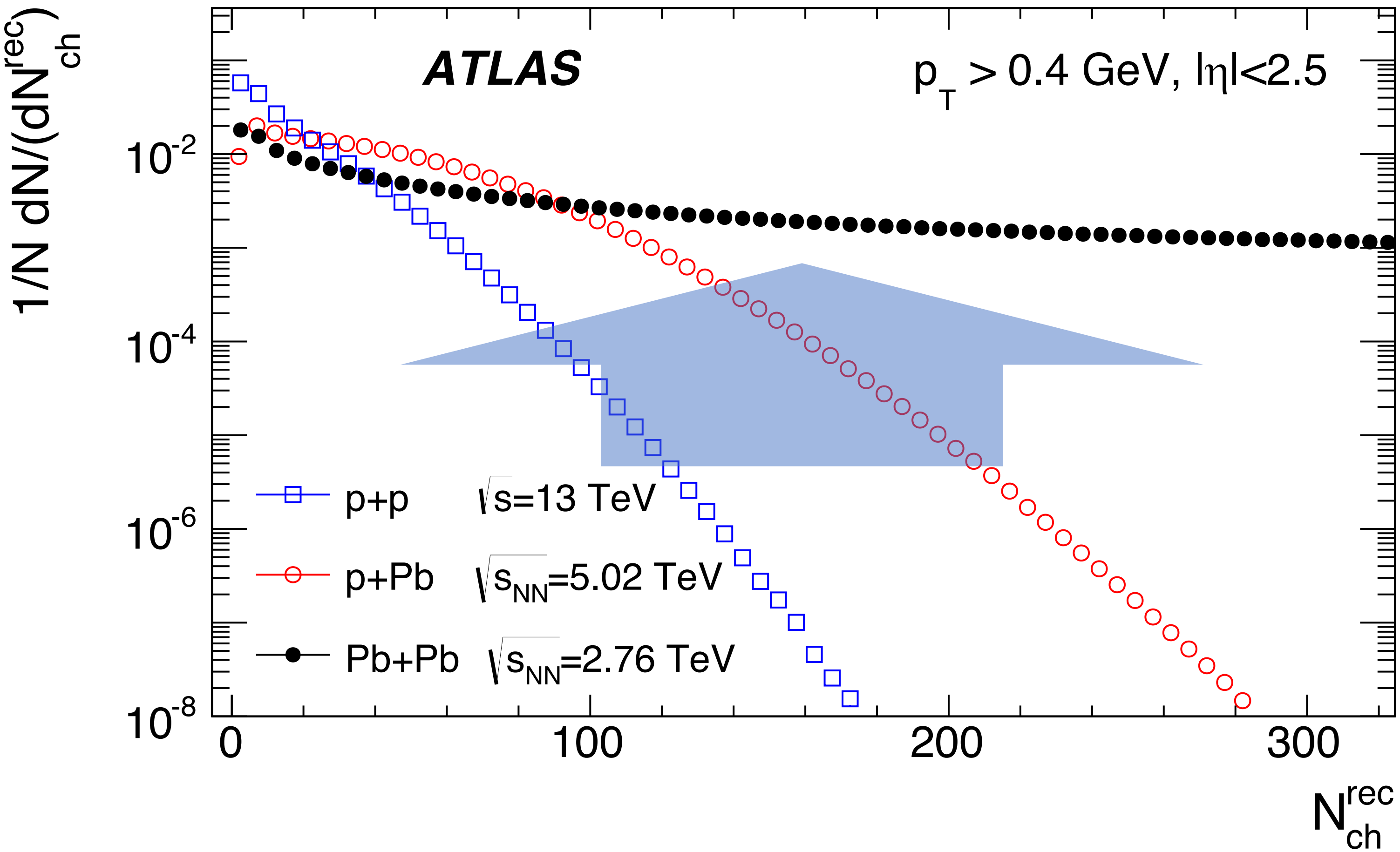
Outline

- Real-time data collection

- Longitudinal correlation

- Azimuthal correlation

Real-time data selection



LHC event rate

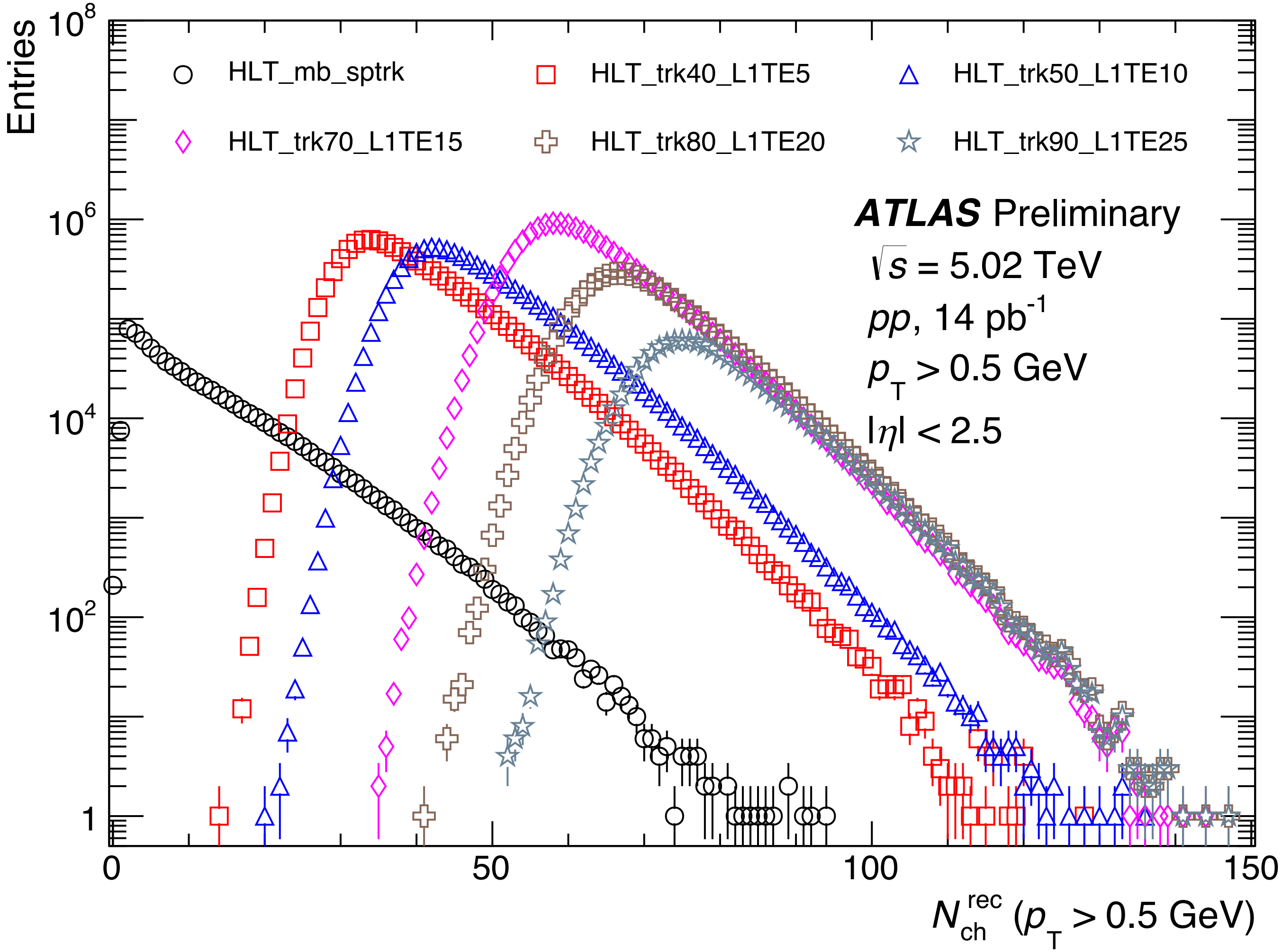
40 MHz

Triggers

Recording cap

10 kHz

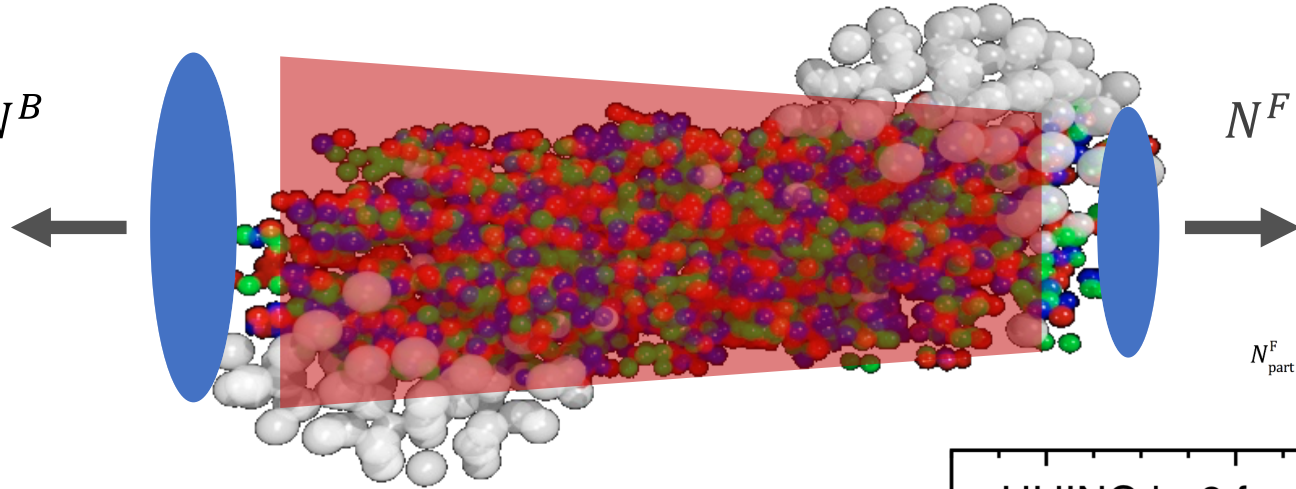
Trigger performance



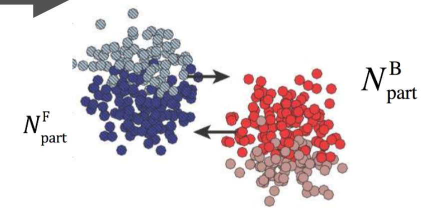
Multiple HMT triggers applied to *pp* and *p*+Pb data taking

Nature of sources seeding the long-range collective behaviors?

N^B

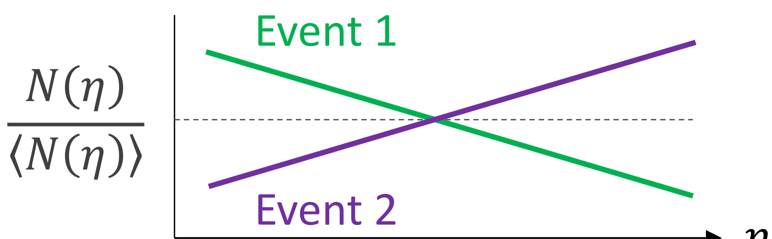


N^F participants / partons / string/tubes

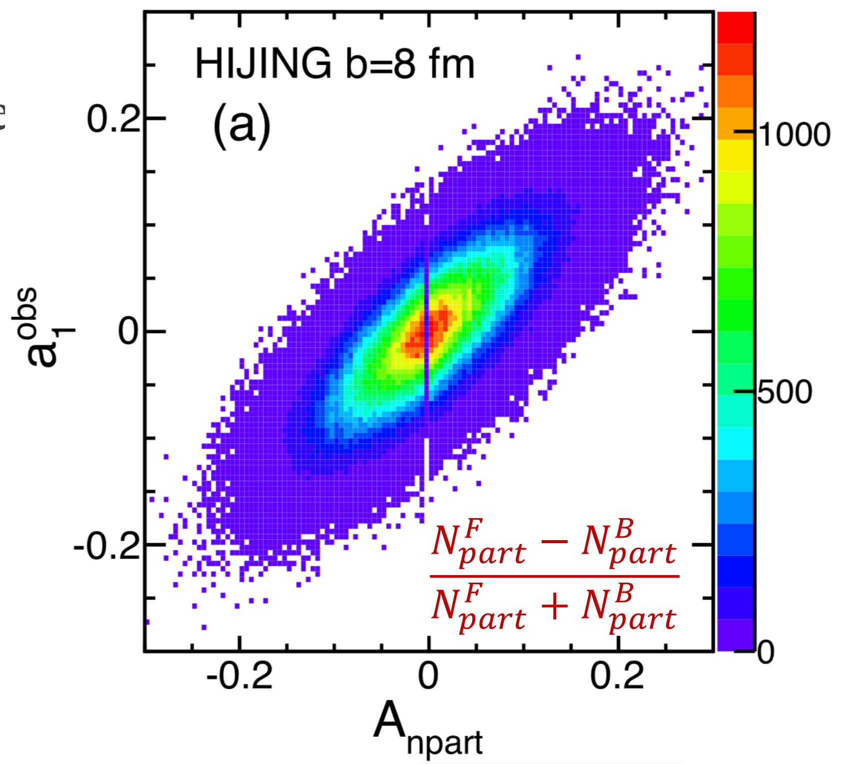


- $dN/d\eta$ shape reflects asymmetry in the numbe

Event-by-event multiplicity fluctuation?



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

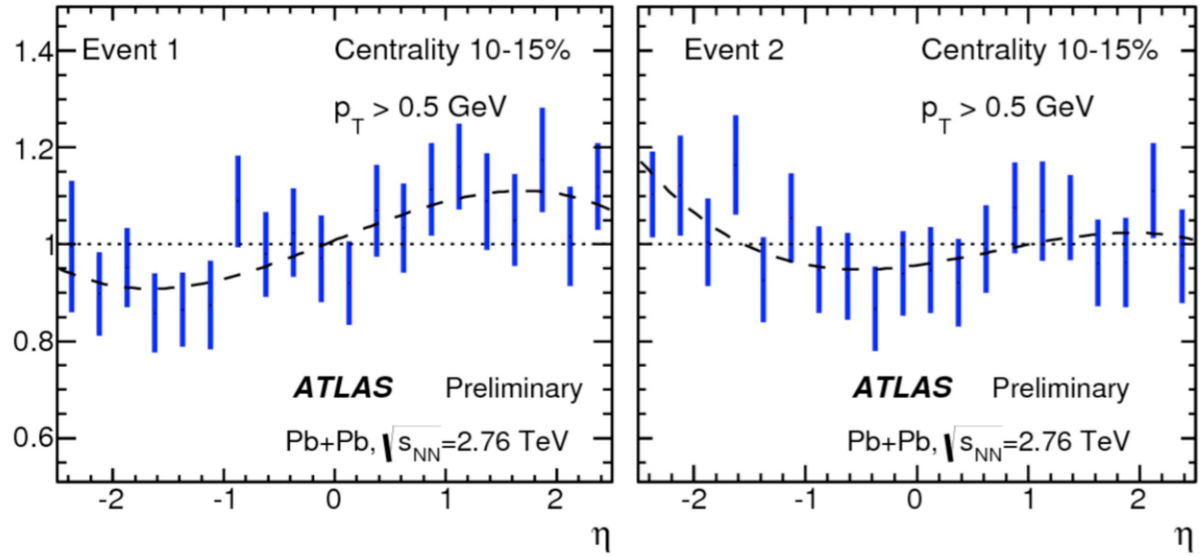


New observable

- Single particle observable

$$R_s(\eta) \equiv \frac{N(\eta)}{\langle N(\eta) \rangle}$$

- Cannot measure single particle in data!



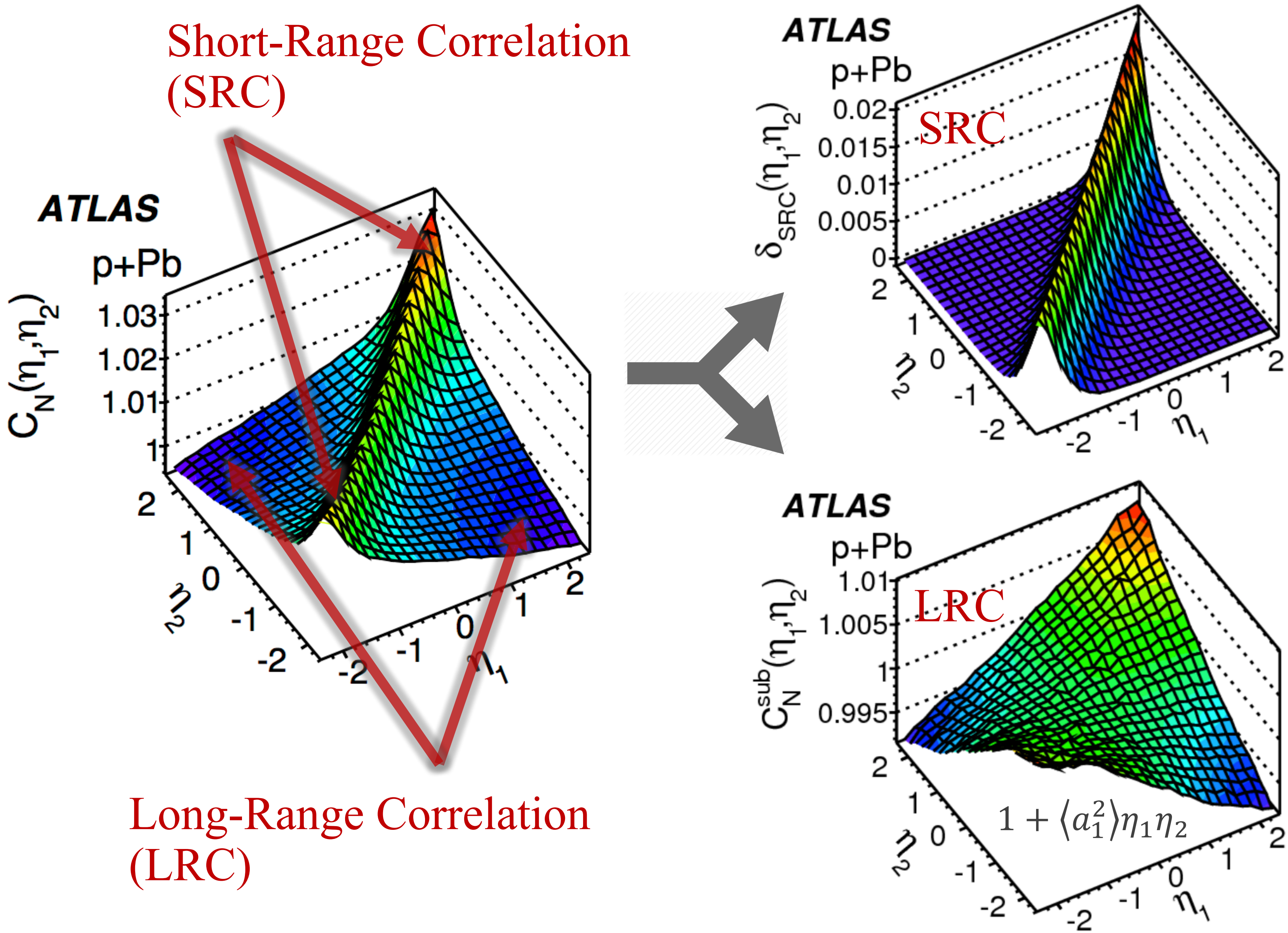
- Two particles observable (correlation function) [Derek, Phys. Rev. C 87, 024906 (2013)]

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

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

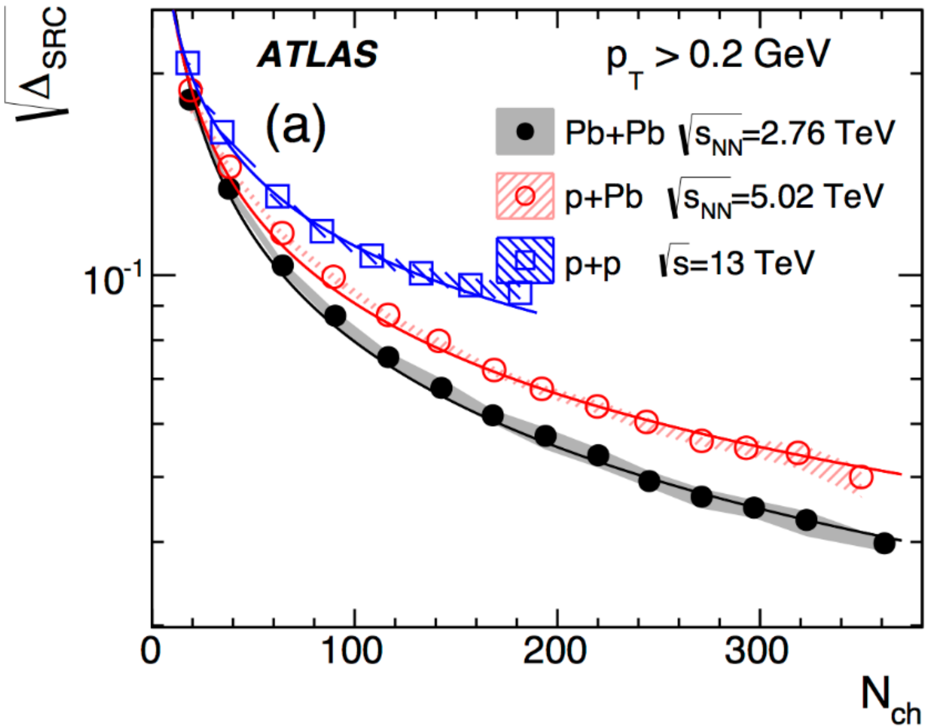
- Advantage of correlation function
  - Disentangles dynamical fluctuation from statistical fluctuation.
  - Detector effects automatically removed;

Long-range and short-range correlations



Results

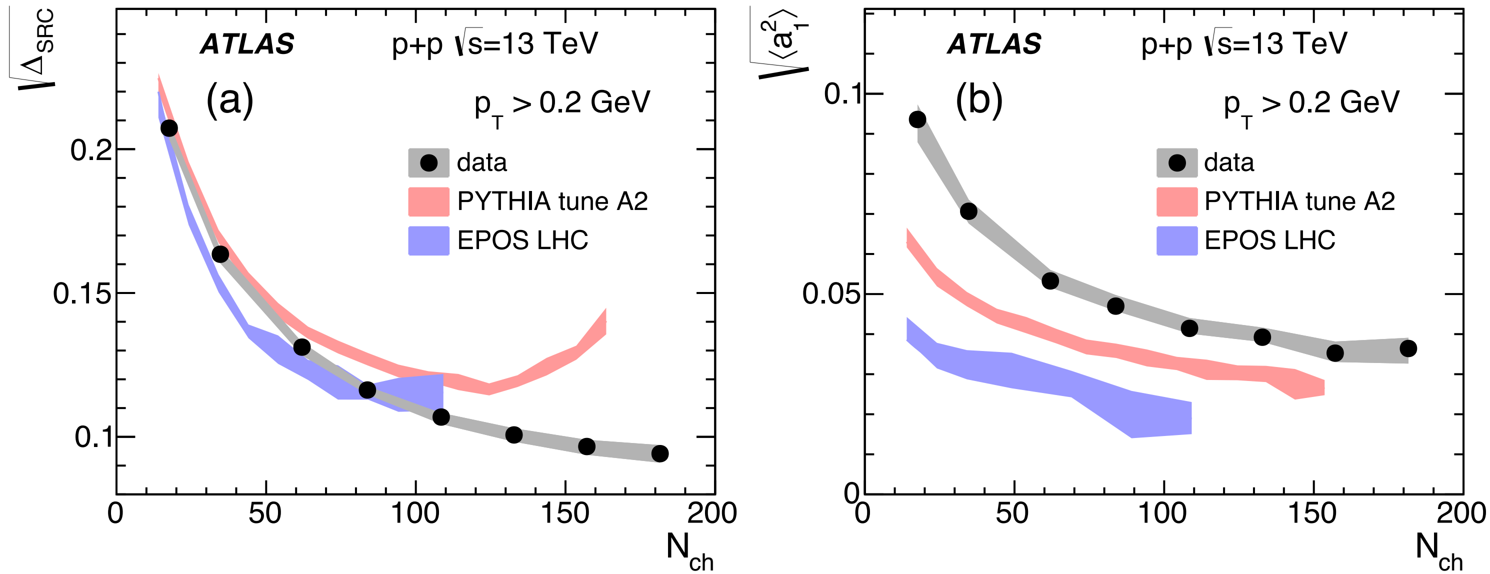
SRC



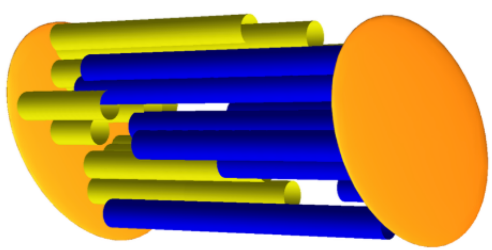
- SRC increases towards peripheral;
- SRC is stronger in small systems;

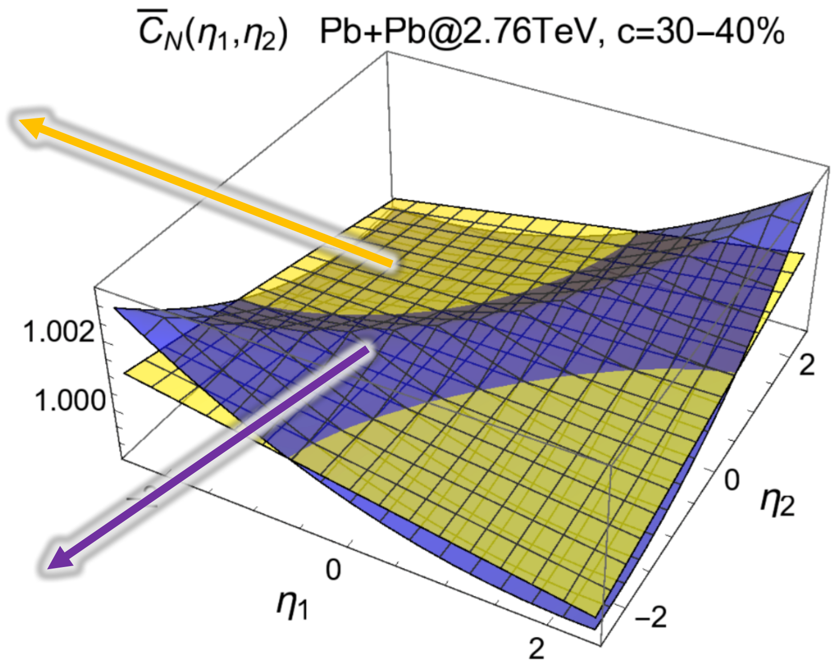
How will these new results help?

Model and data comparison



Without length fluctuation

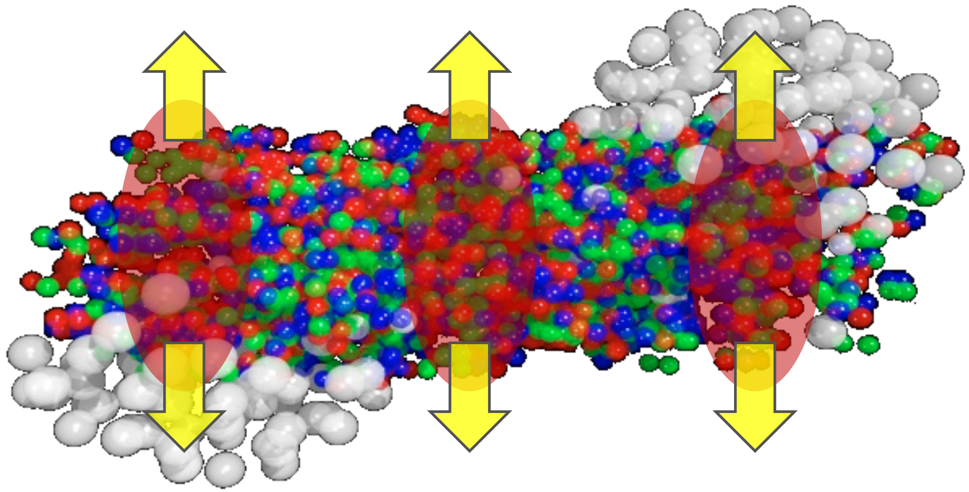




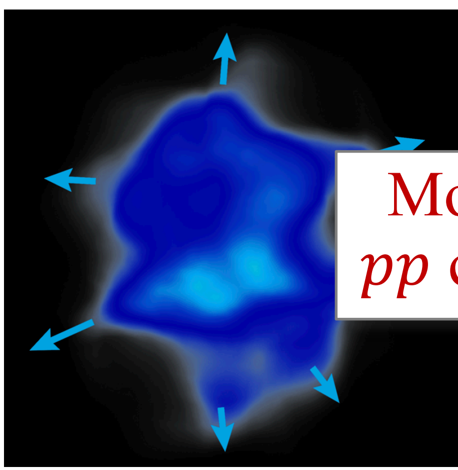
With length fluctuation

Phys. Rev. C 93, 064910 (2016)

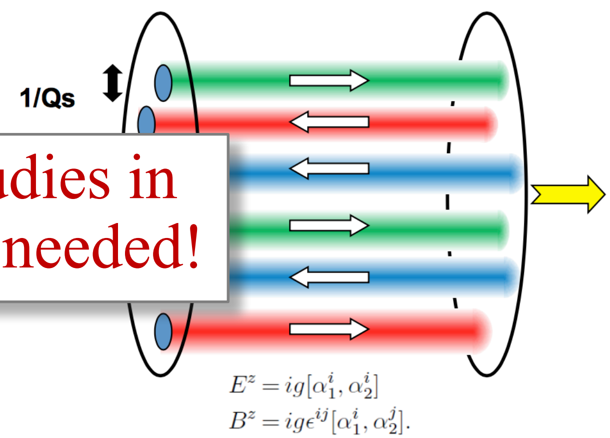
Nature of sources seeding the long-range collective behaviors?



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



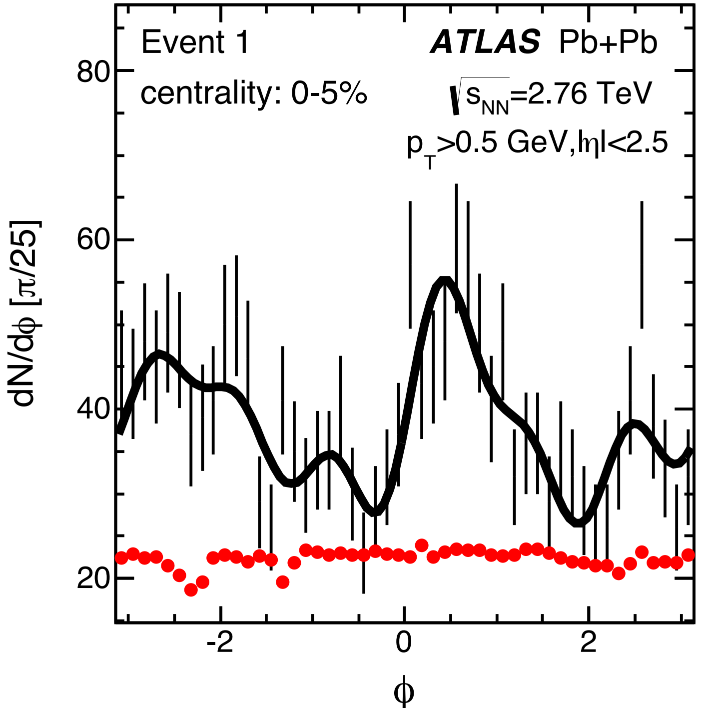
More careful studies in *pp* collisions are needed!



Final state correlations

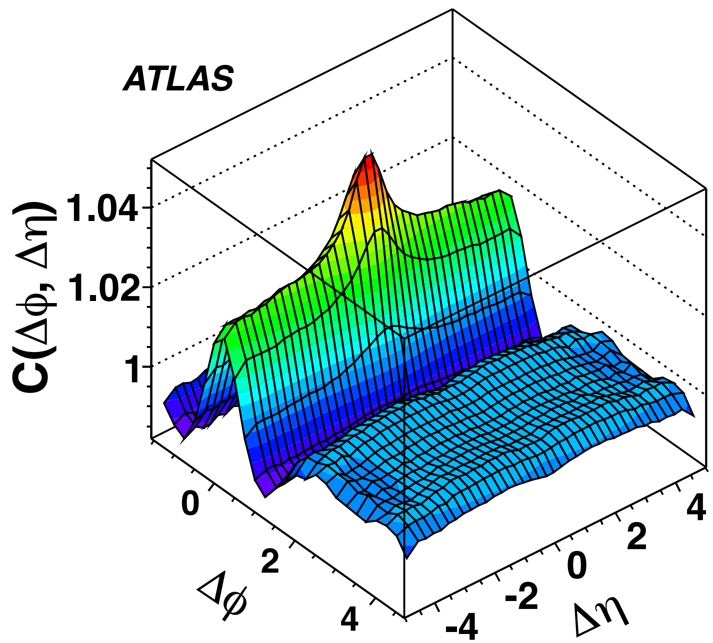
Initial state correlations

- Single particle method



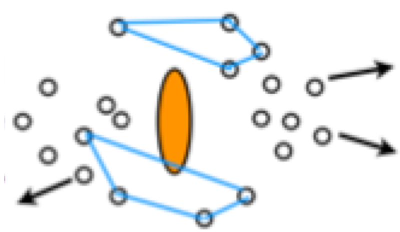
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n \cos n(\phi - \Psi)$$

- Two-particle method

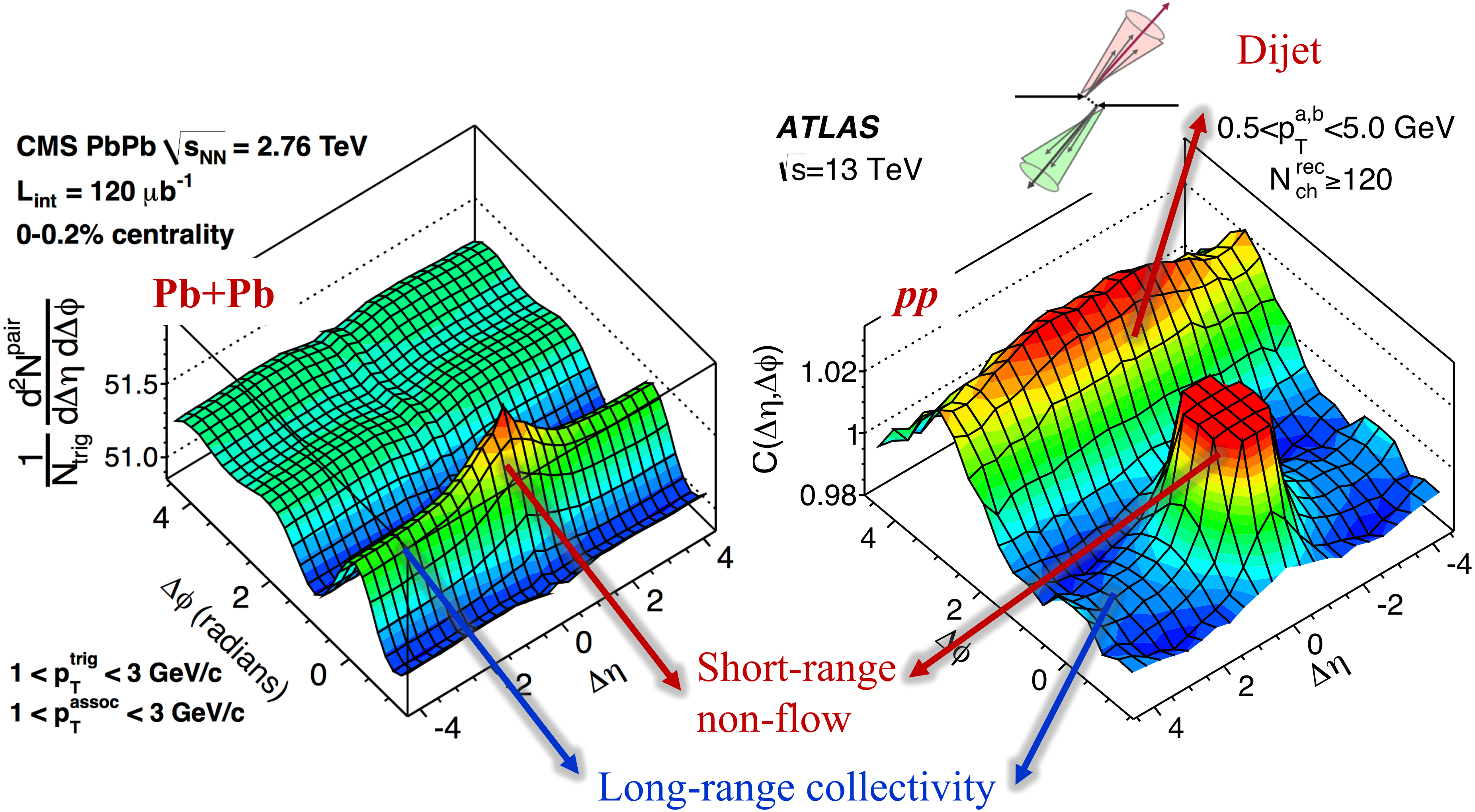


$$\frac{dN_{\text{pairs}}}{d\Delta\phi} \propto 1 + 2\sum_{n=1} v_n^2 \cos n\Delta\phi$$

- Multi-particle (cumulant) method

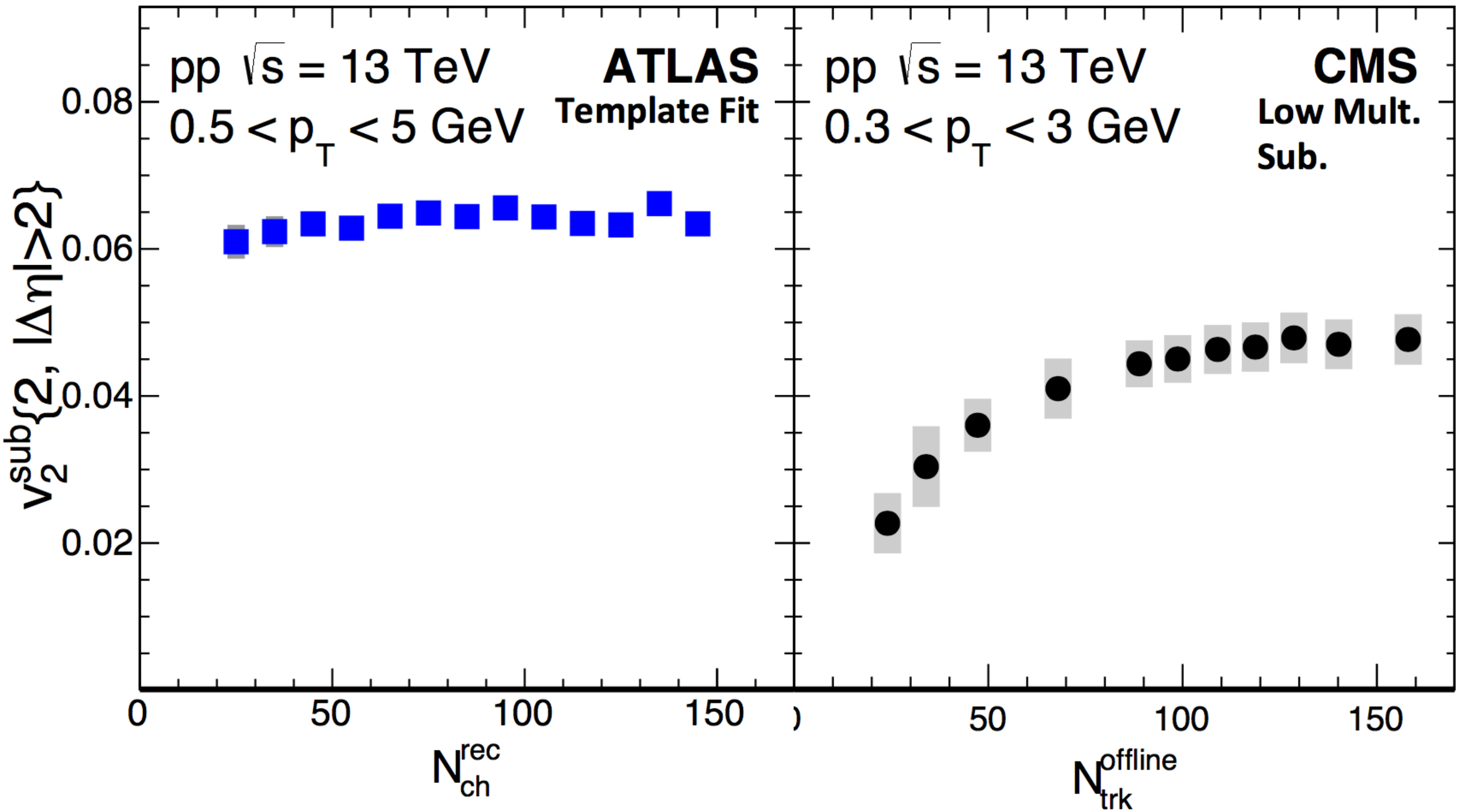


2-particle correlation

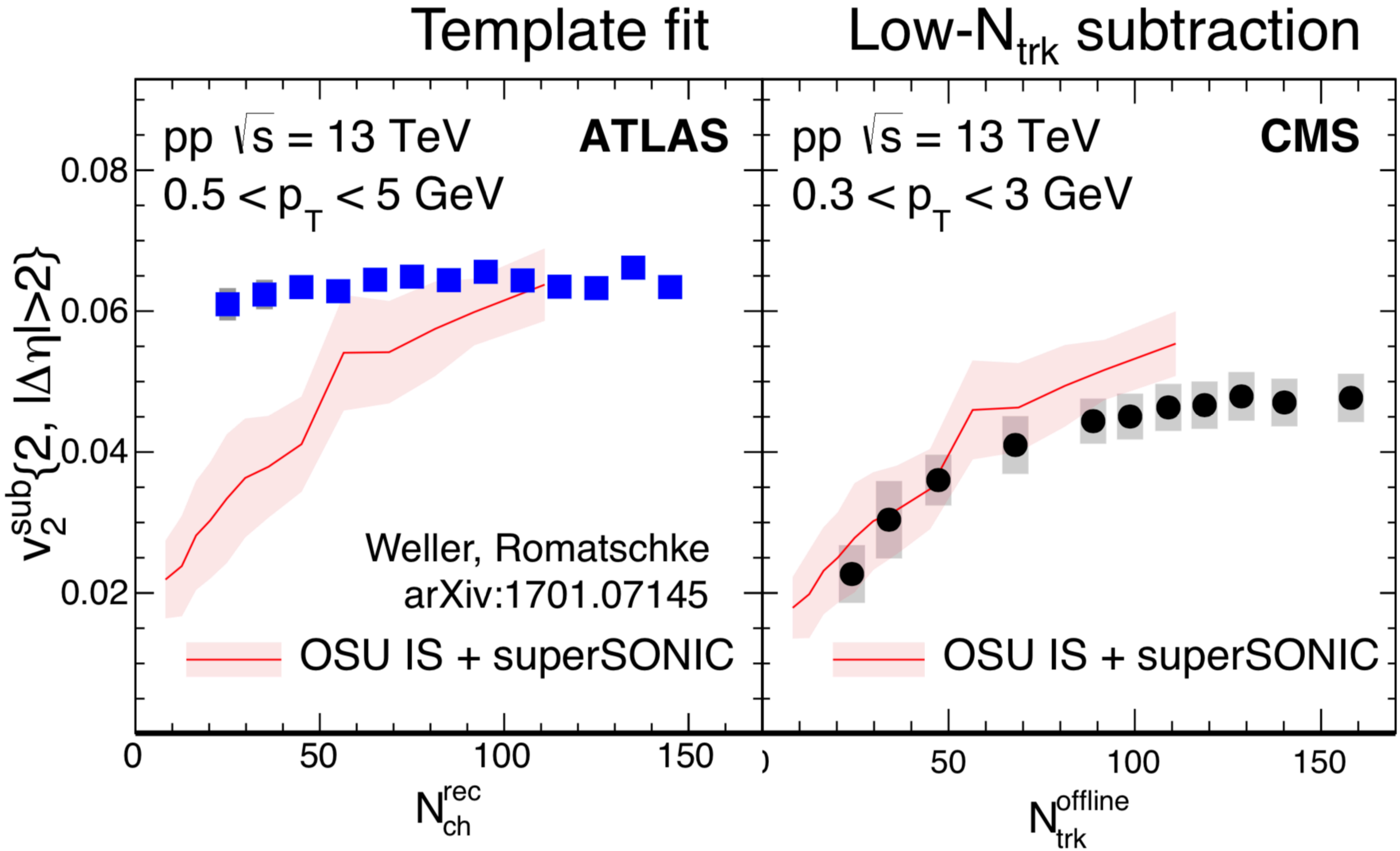


- Non-flow mainly from dijet;
- Need to remove dijet.

Non-flow removel



Different methods ⇒ Different results



- If hydro, v_2 should go down toward low N_{ch};
- New observable needed.

Cumulant method

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

Genuine 4-particle correlation

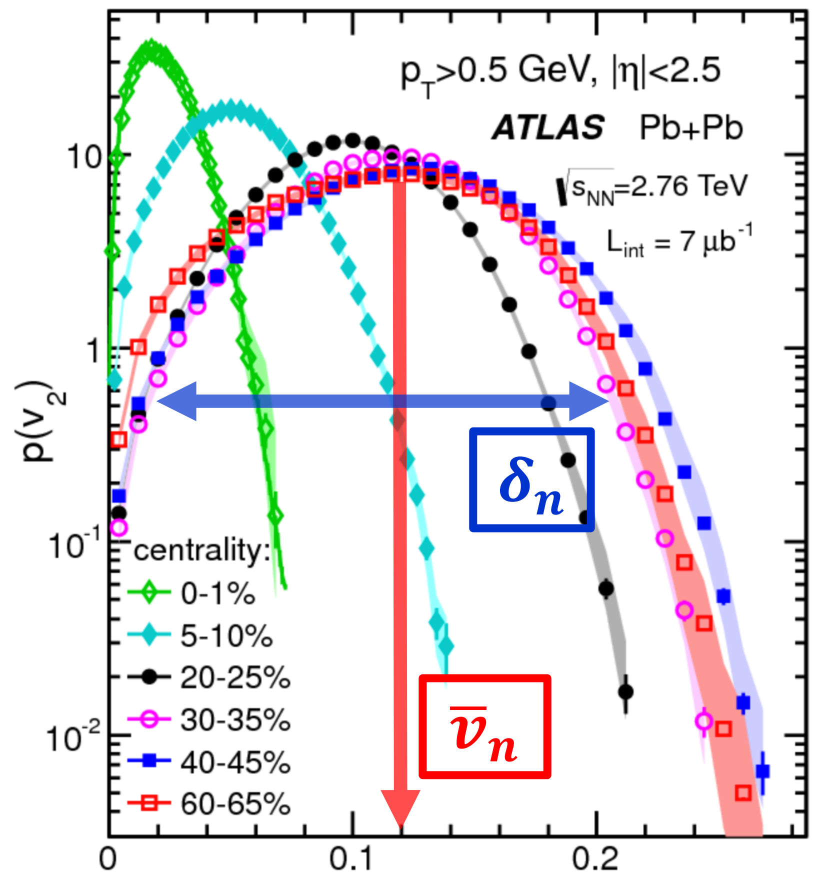
2-particle non-flow

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

- Flow fluctuates event to event $p(v_n)$;
- $v_2\{2\}, c_2\{4\} \;\Rightarrow\; \bar{v}_n, \delta_n$

- 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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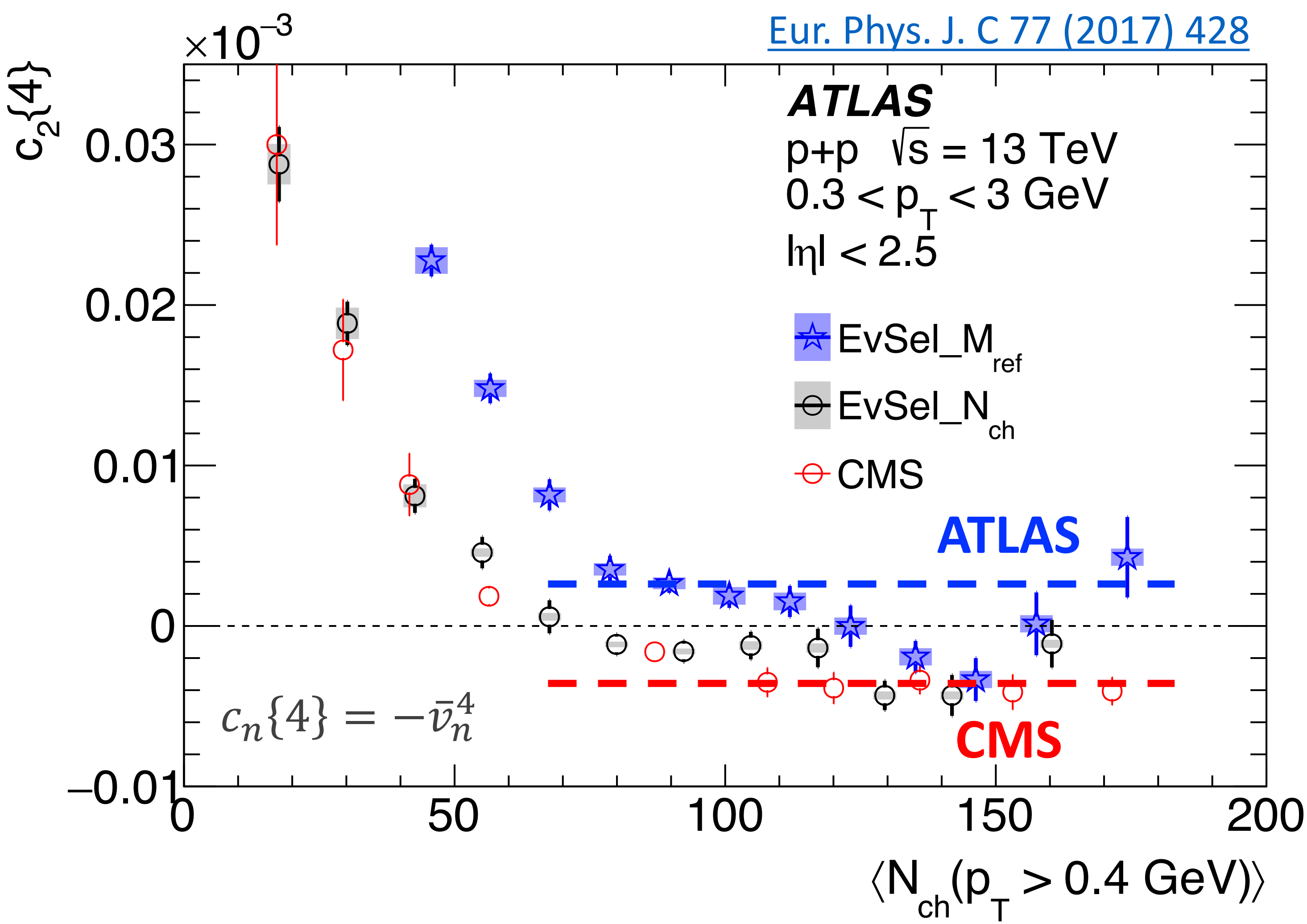
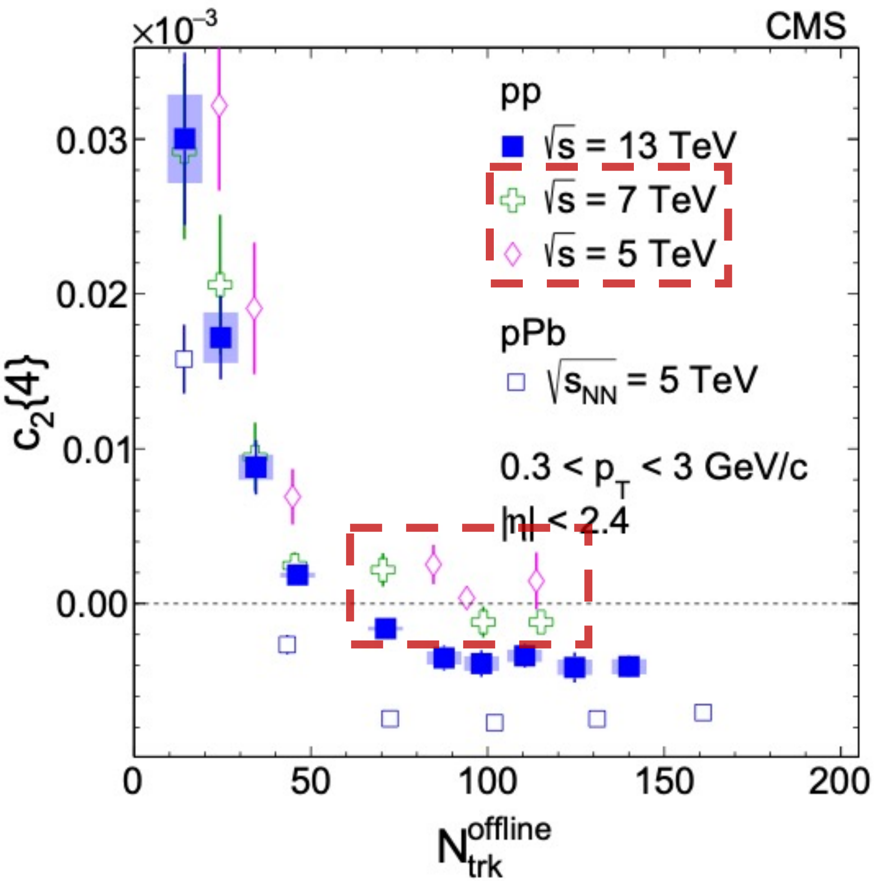
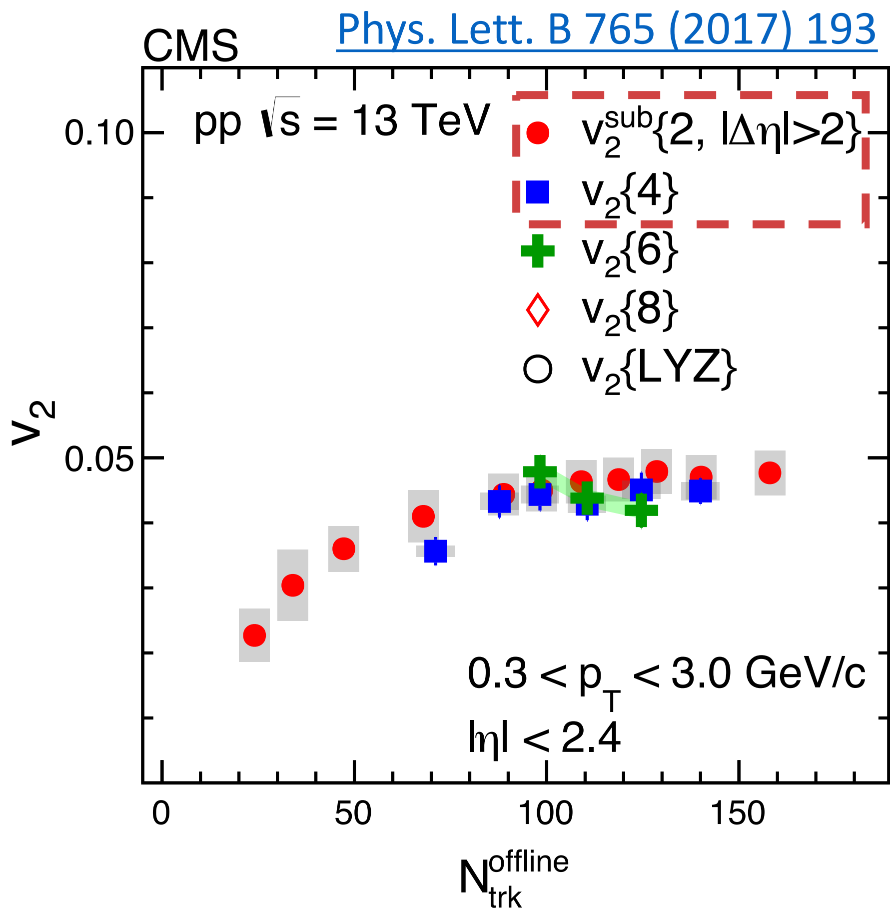
Results



To be collective, or not to be collective?

Other puzzles



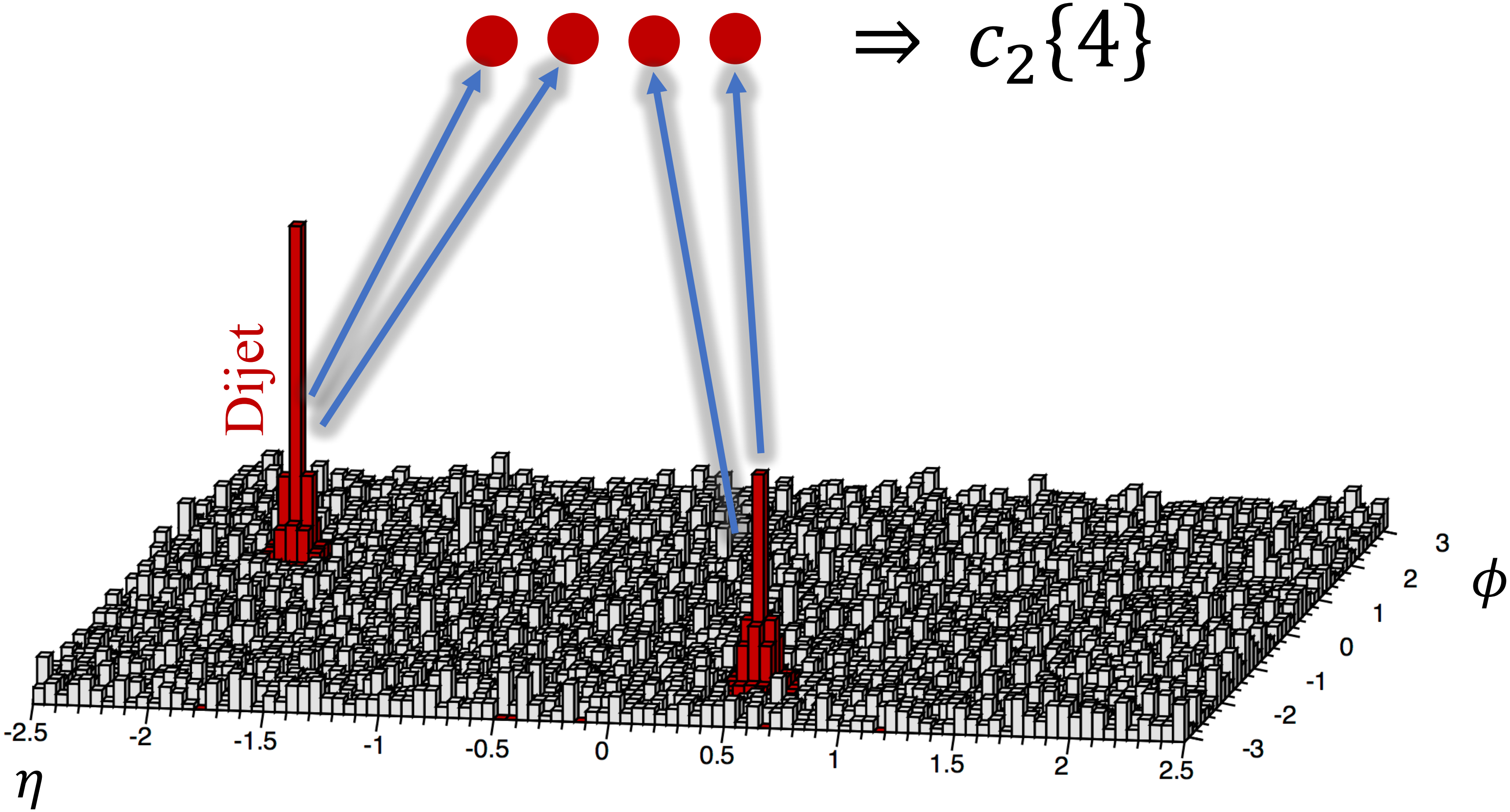


- No hint of collectivity at lower energy?

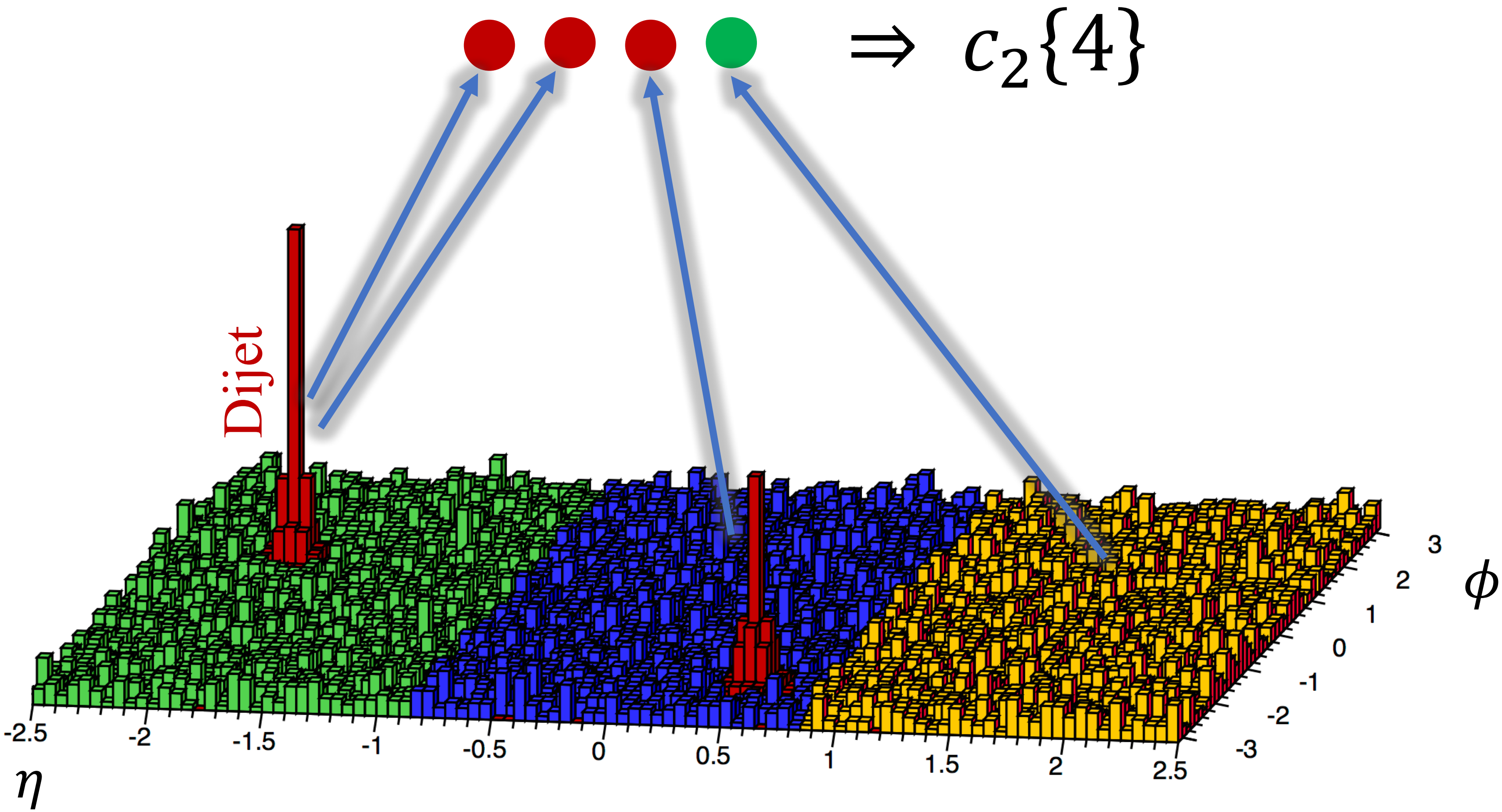
- $v_2\{2\} = v_2\{4\} +$ flow fluc
- Flow fluc ≈ 0 ?

Puzzles needs to be solved before testing models with data.

Traditional method

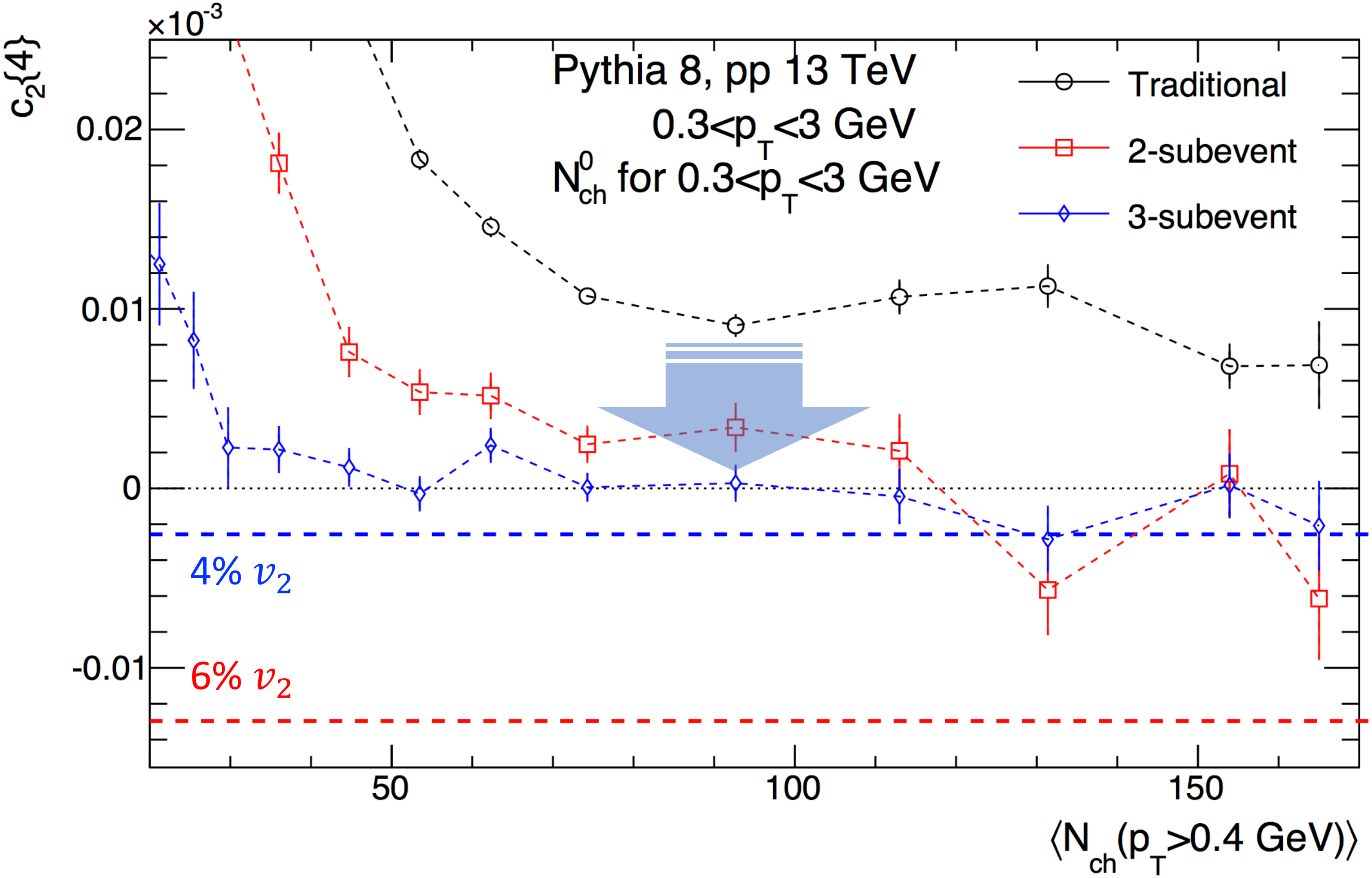


- High probability all four particles come from dijet;
- Solution: higher-order cumulant (statistical significance), or…



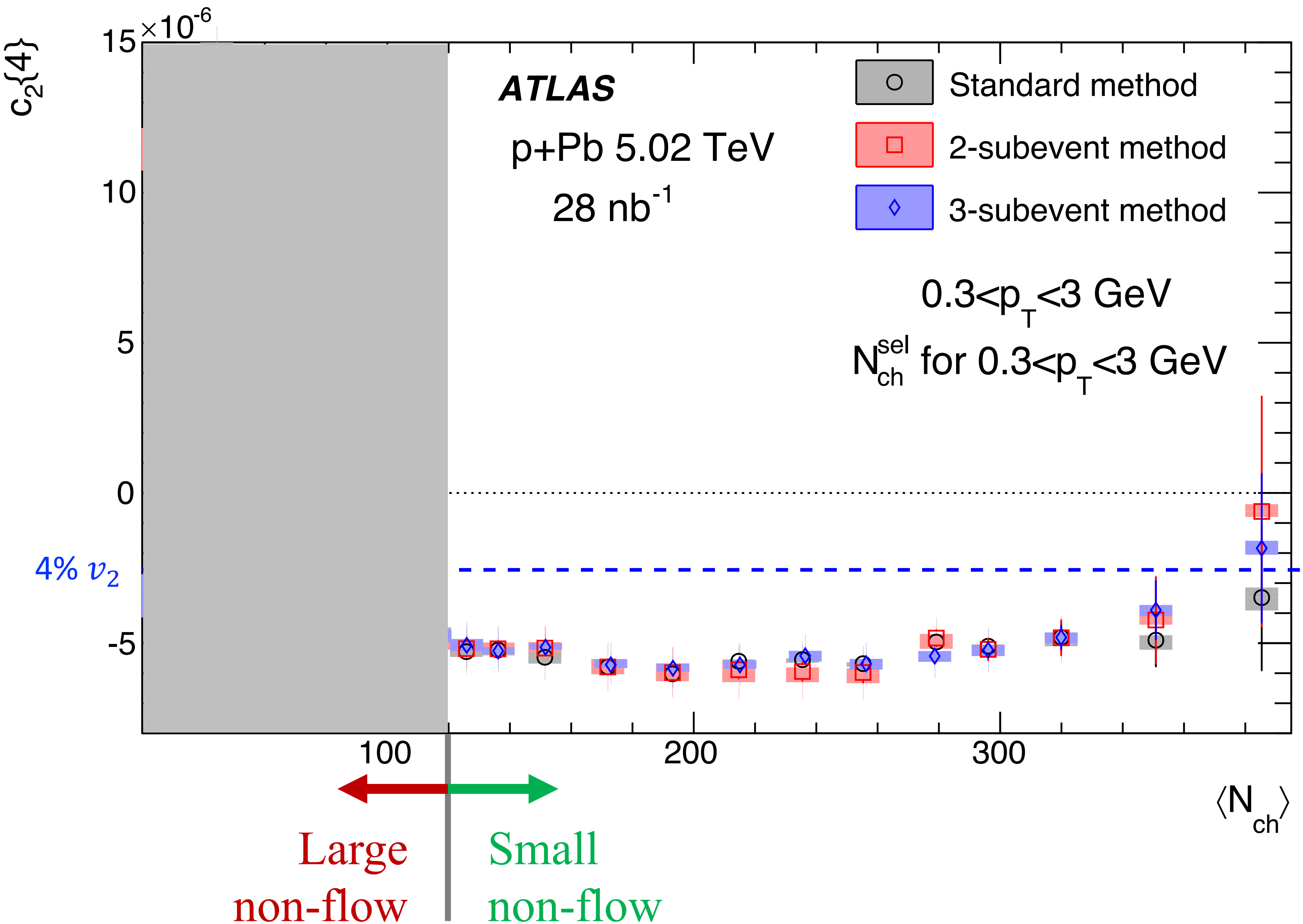
$$3 > 2$$

Validation in *pp* PYTHIA

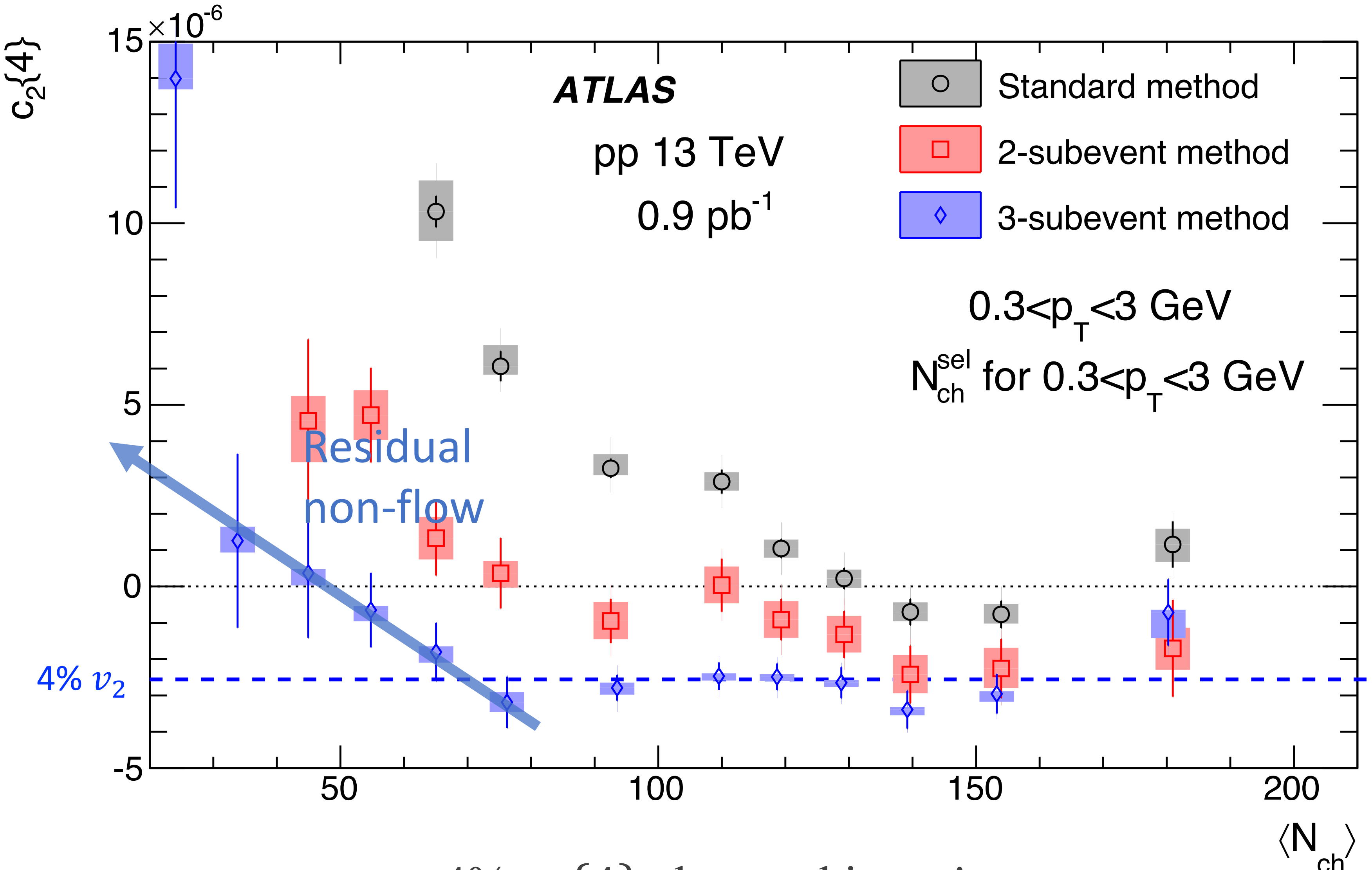


Subevent method can suppress non-flow in PYTHIA

Validation in *p*+Pb data

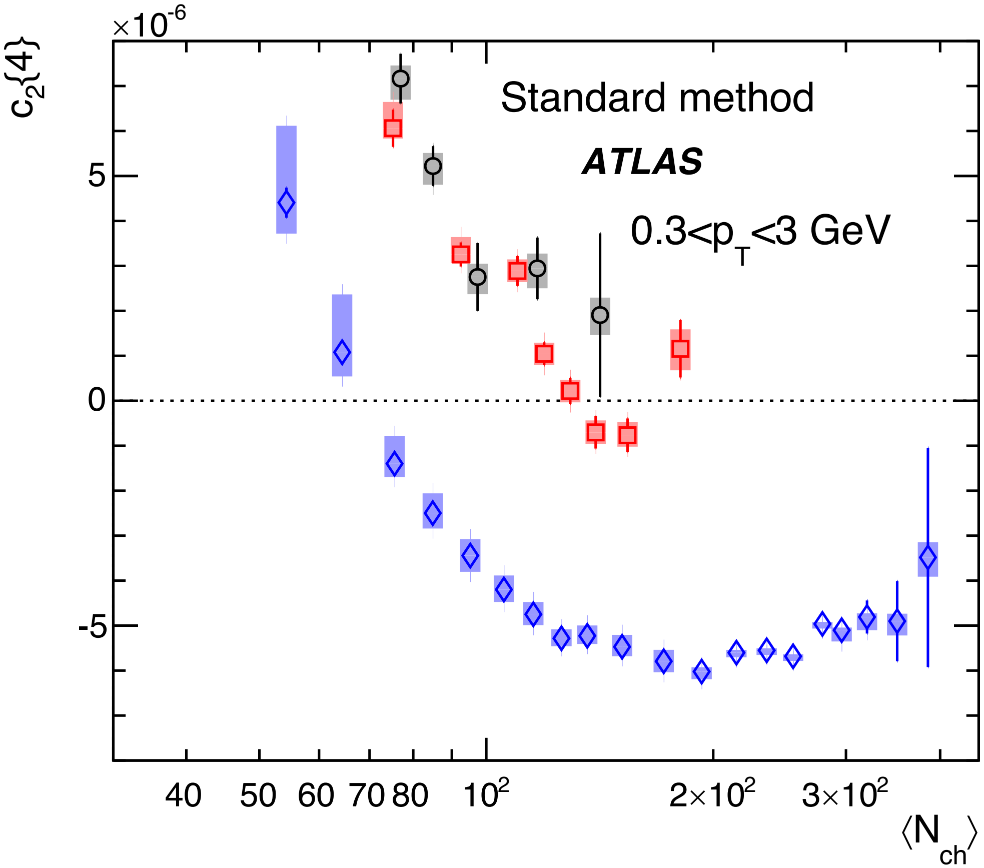


$c_2\{4\}$ in pp



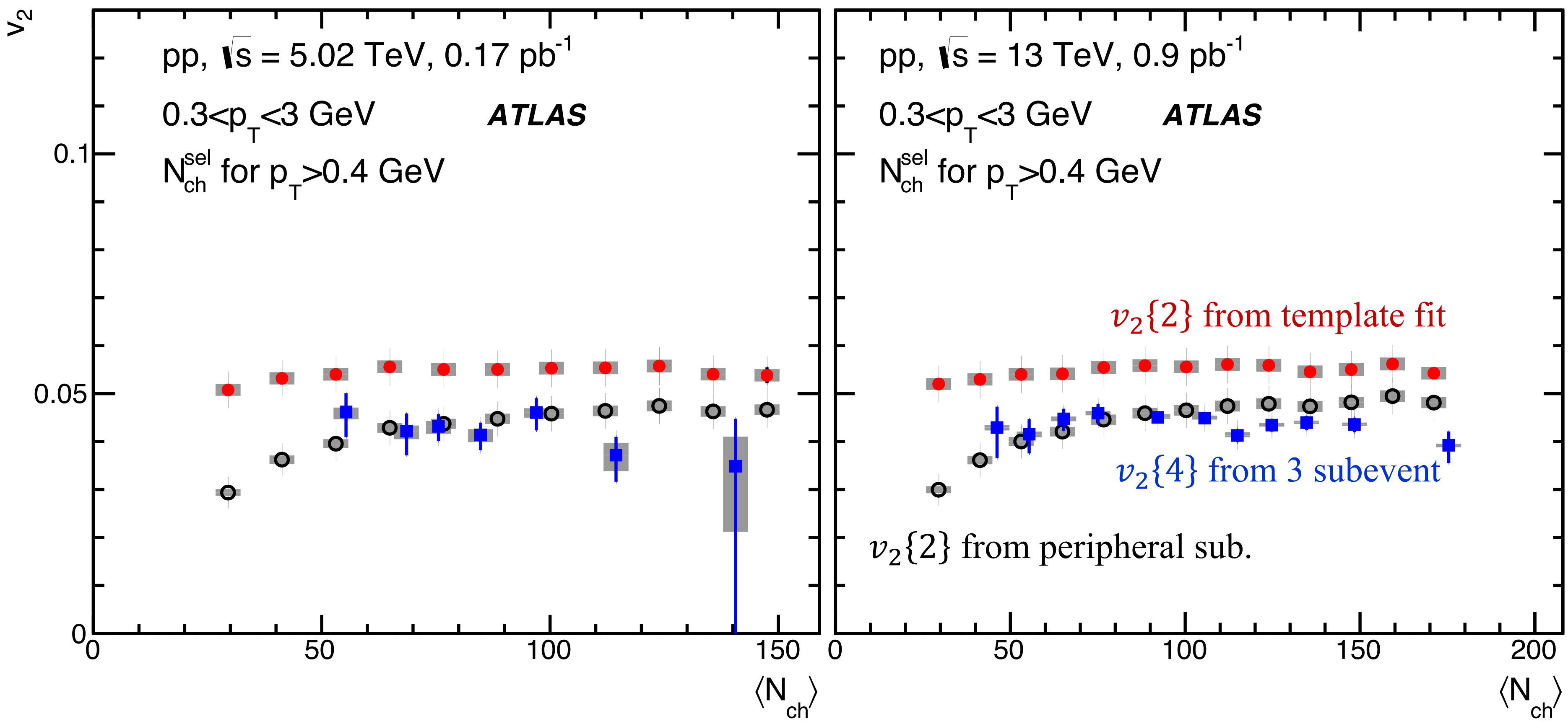
4% $v_2\{4\}$ observed in pp!

Puzzle 2: energy dependence



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

Puzzle 3: flow fluctuation

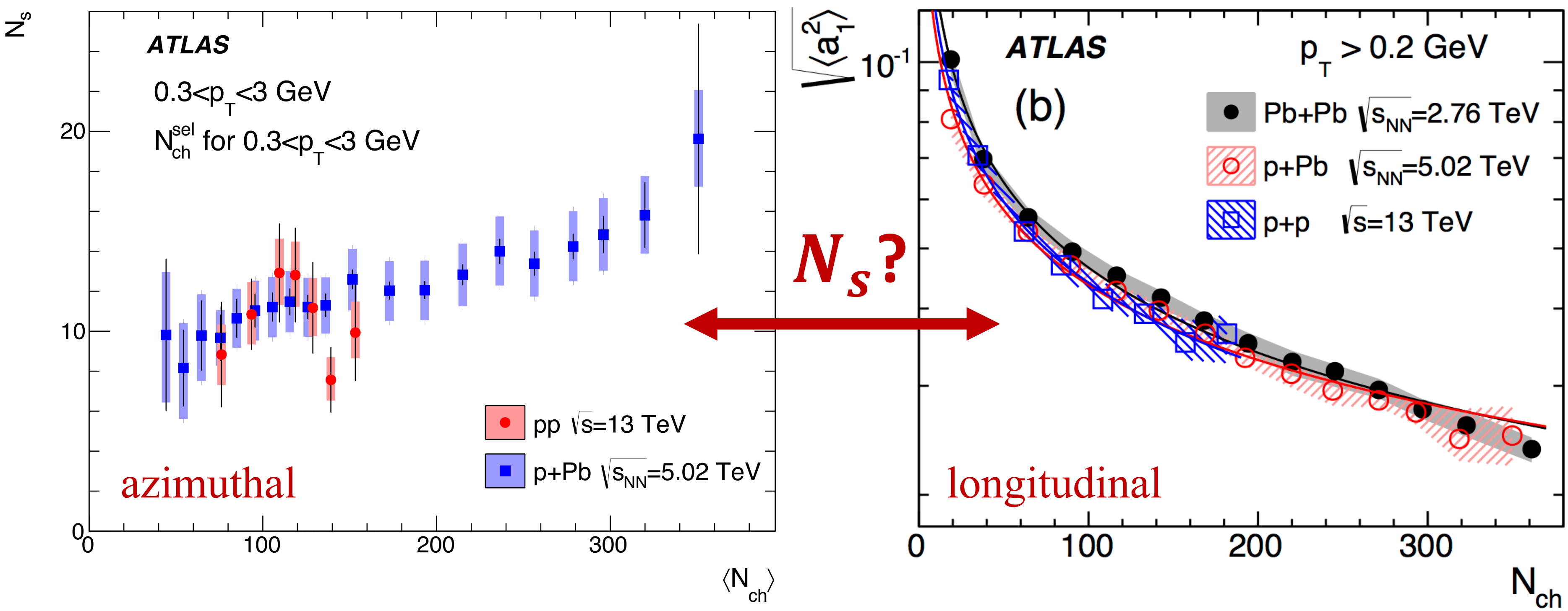


- $v_2\{4\} < v_2\{2\}$ (template fit): flow fluctuation;
- $v_2\{4\} \approx v_2\{2\}$ (peripheral sub.): underestimation of $v_2\{2\}$;
- Subevent cumulant is free of assumptions.

Number of sources

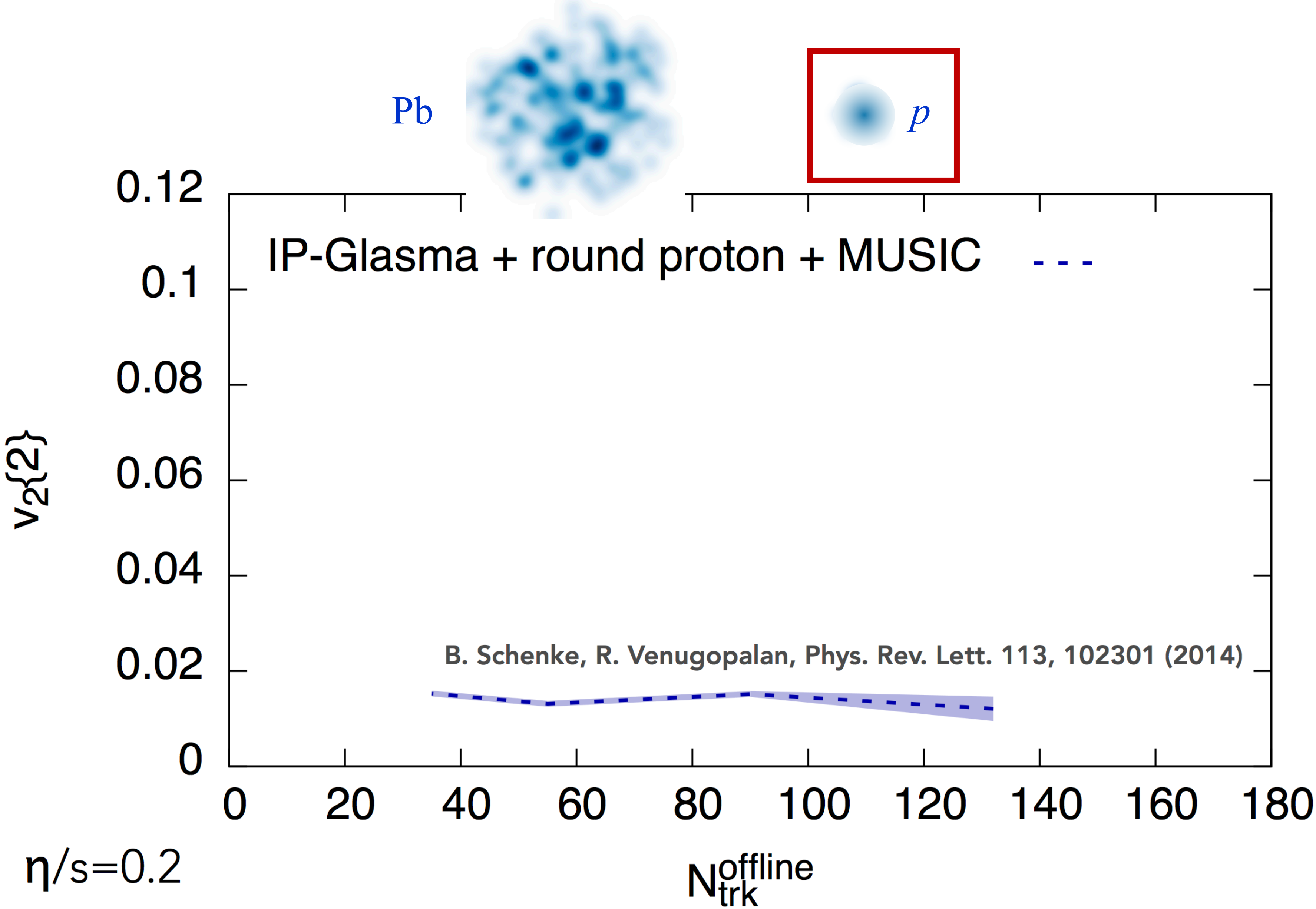
- $v_2\{2\} \neq v_2\{4\}$: EbyE flow fluctuations associated with fluctuating initial conditions. Phys. Rev. Lett. 112, 082301 (2014)
- Fluctuation can be quantified to the number of sources N_s in the initial stage:

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

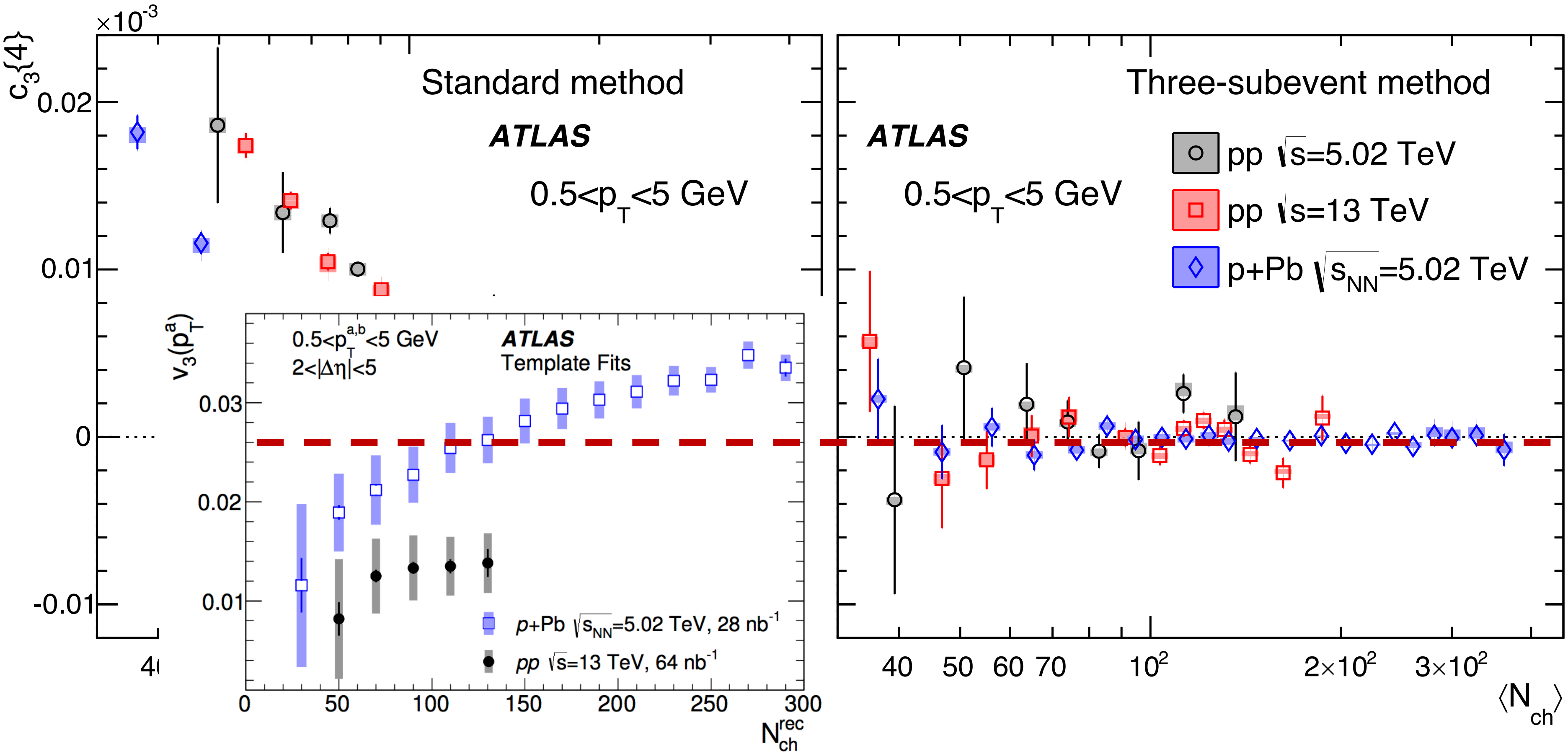


- N_s for p+Pb goes up to 20 at high multiplicity;
- N_s for pp approximately consistent with p+Pb at comparable $\langle N_{ch}\rangle$ value.

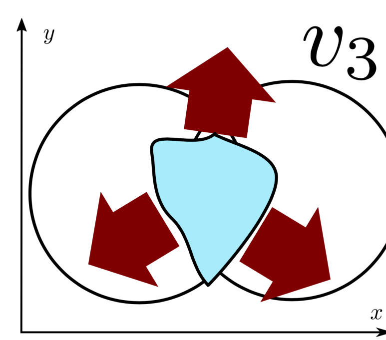
Nucleon substructure fluctuation



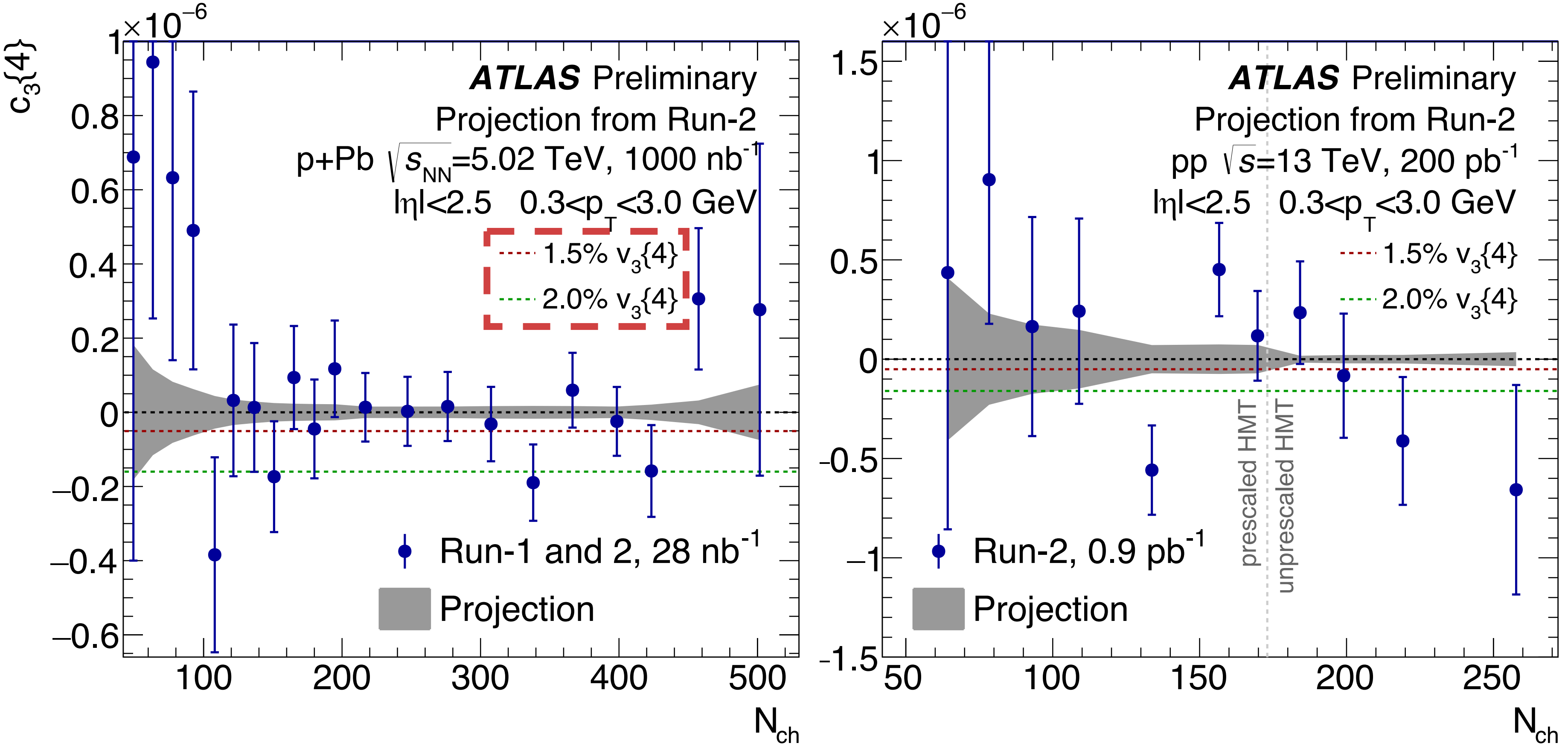
$\eta/s=0.2$



- $c_3\{4\}$ 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



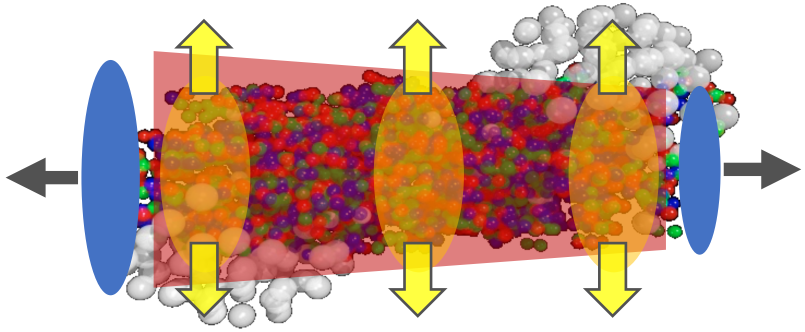
- Opportunity luminosity increase in Run 3;
- Challenges trigger, pileup, tracking...

Non-non-flow $\neq$ Flow!

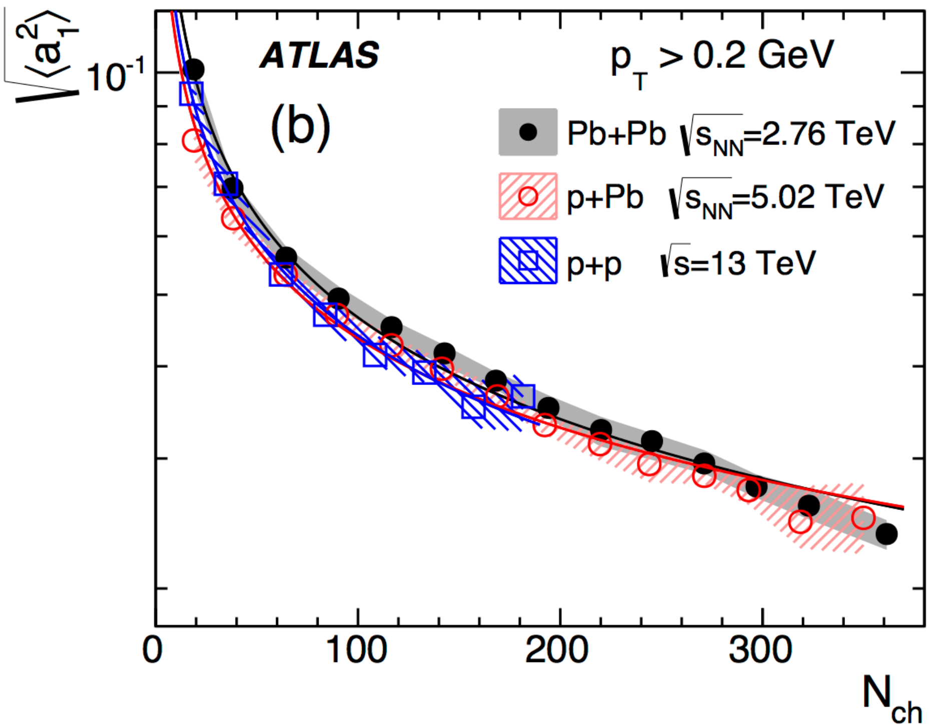
Summary

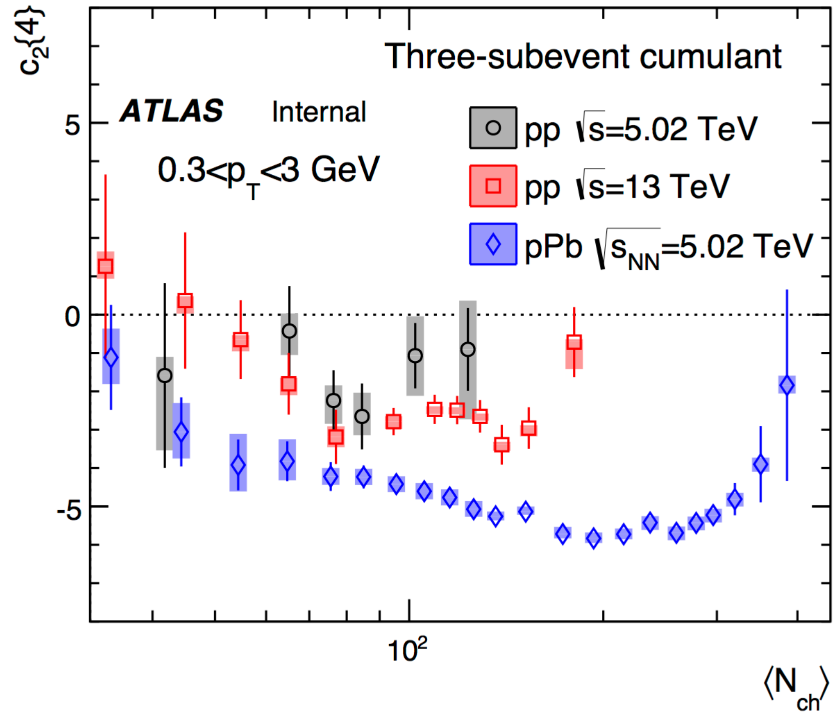
Nature of sources seeding the long-range collective behavior?

Longitudinal correlation



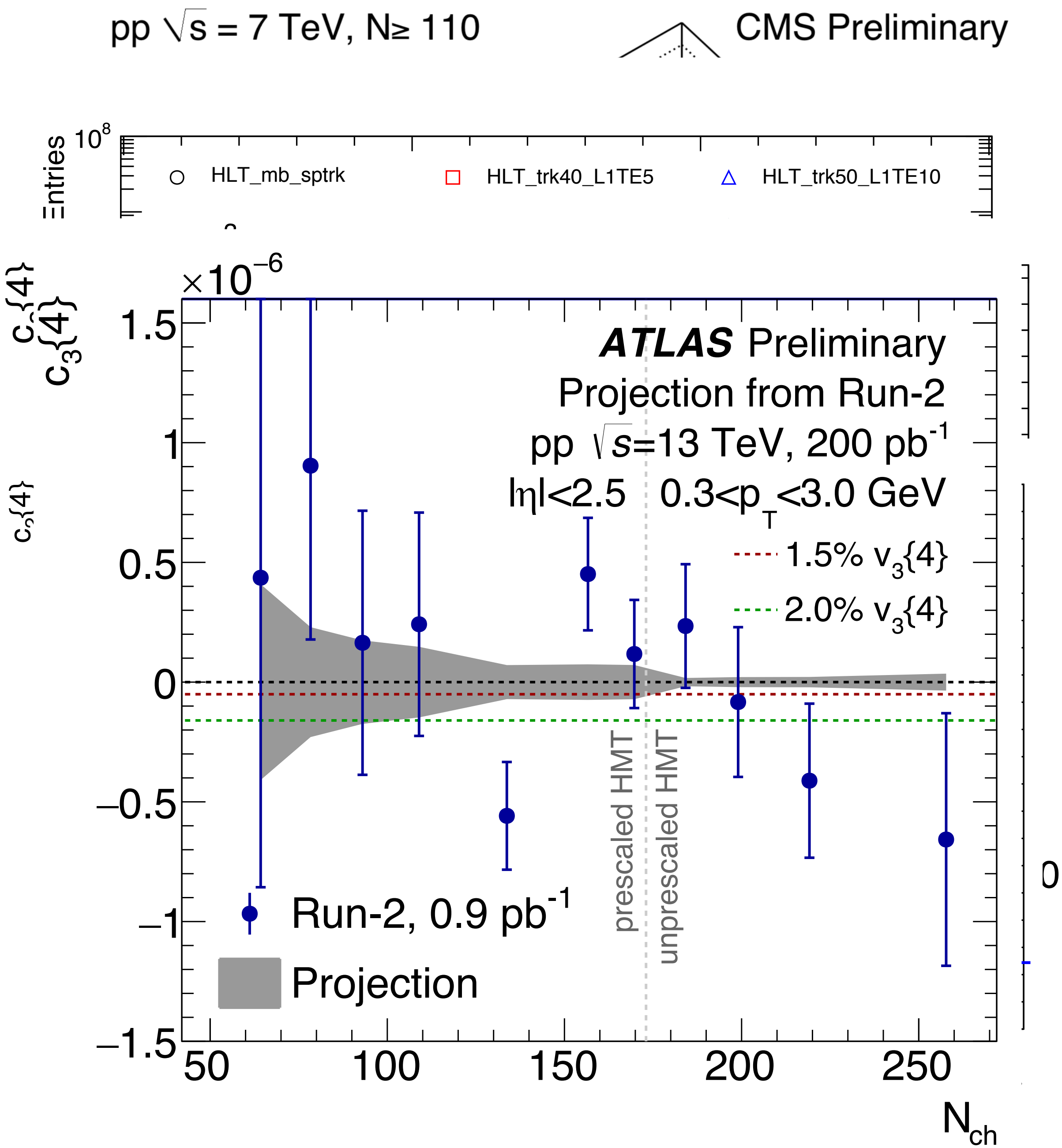
Azimuthal correlation





Evidence of collectivity in small systems!

Summary



Hypothesis
Collectivity in *pp*?

Data Gather
Real-time selection

Data Analysis
Large background

New Algorithm
3 > 2

Conclusion
Collectivity in *pp*!

Outlook
More statistics

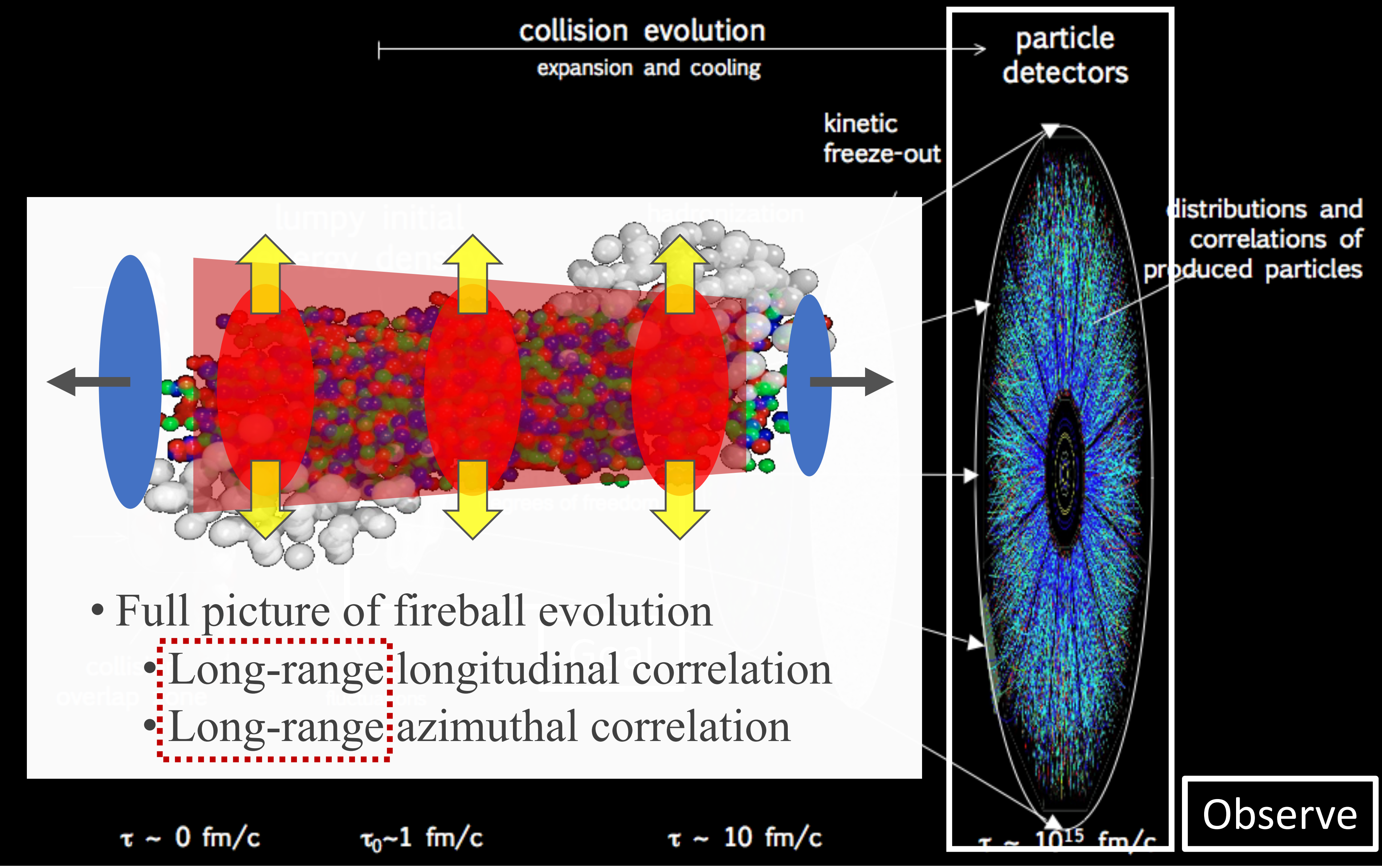
List of publications

- Longitudinal correlation
  - Phys. Rev. C 93, 044905 (2016) (method)
  - Phys. Rev. C 95, 064914 (2017) (ATLAS)
  - Nucl. Phys. A 956, 769 (2016) (ATLAS proc)
- Subevent cumulant in small systems
  - Phys. Rev. C 96, 034906 (2017) (method)
  - Phys. Rev. C 97, 024904 (2018) (ATLAS)
  - Nucl. Phys. A 967, 472 (2017) (ATLAS proc)
- Centrality fluctuation in large systems
  - Phys. Rev. C 98, 044903 (2018) (method)
  - Submitted to JHEP (2019) (ATLAS)
  - Nucl. Phys. A 982, 323 (2019) (ATLAS proc)
- Cumulants in novel system Xe+Xe
  - Nucl. Phys. A 982, 391 (2019) (ATLAS proc)

Backup

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

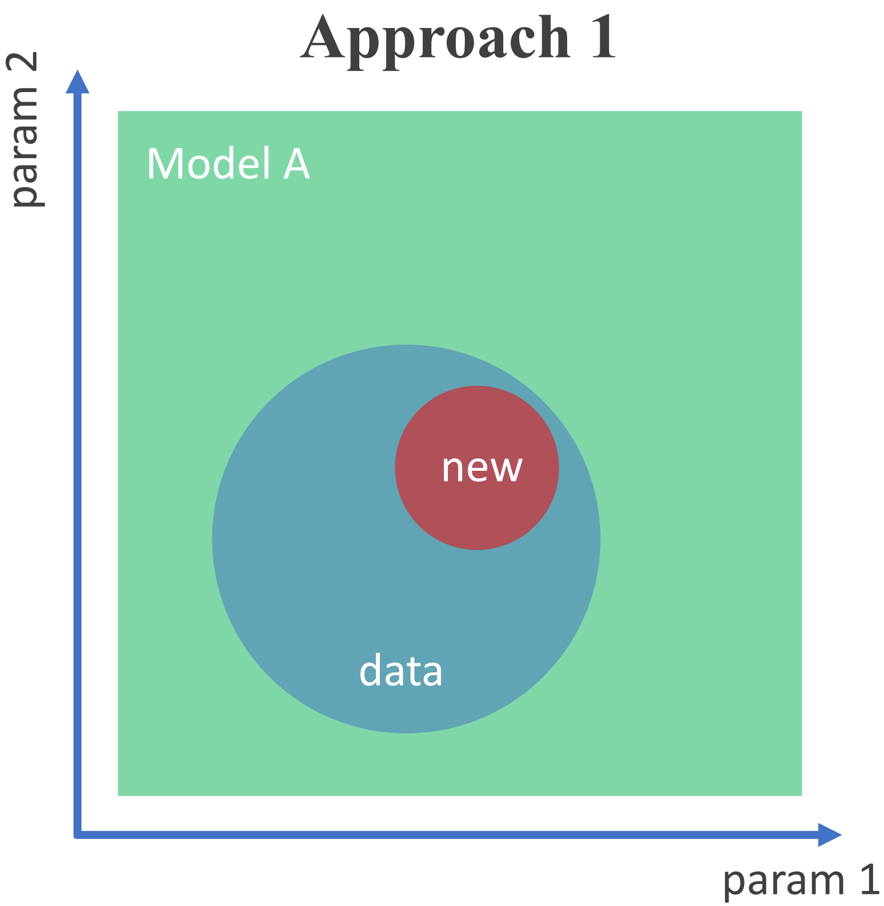
Nuclear collisions and the QGP expansion



- Full picture of fireball evolution
  - Long-range longitudinal correlation
  - Long-range azimuthal correlation

How to use data to constrain models?

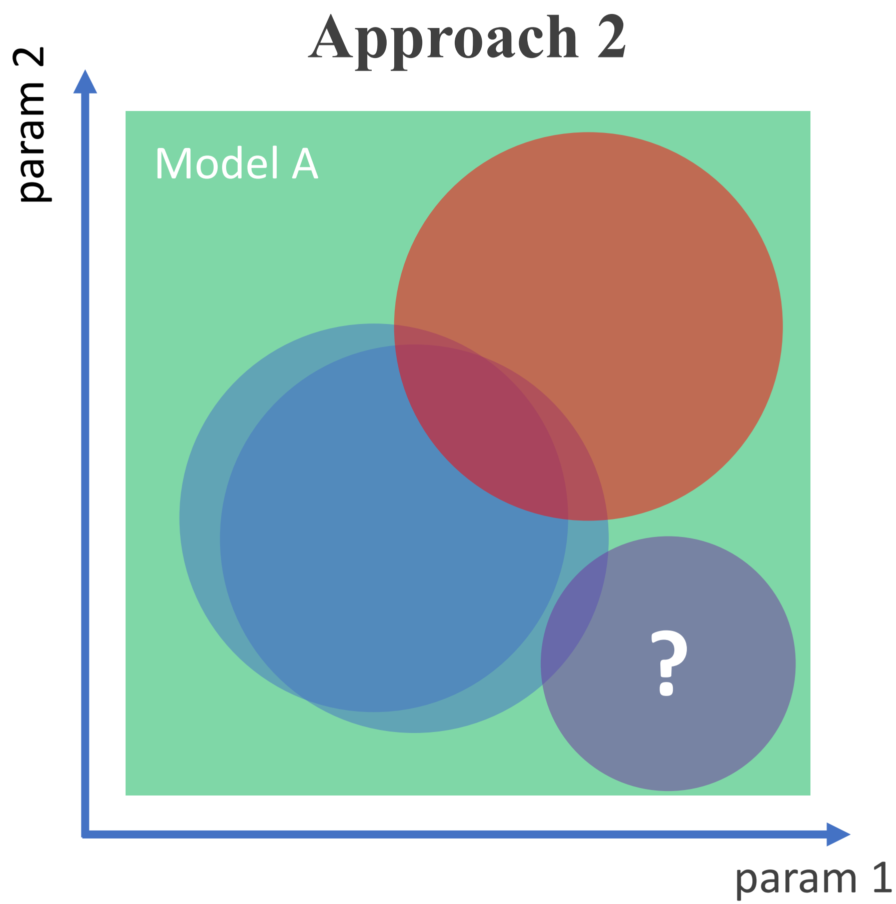
Approach 1



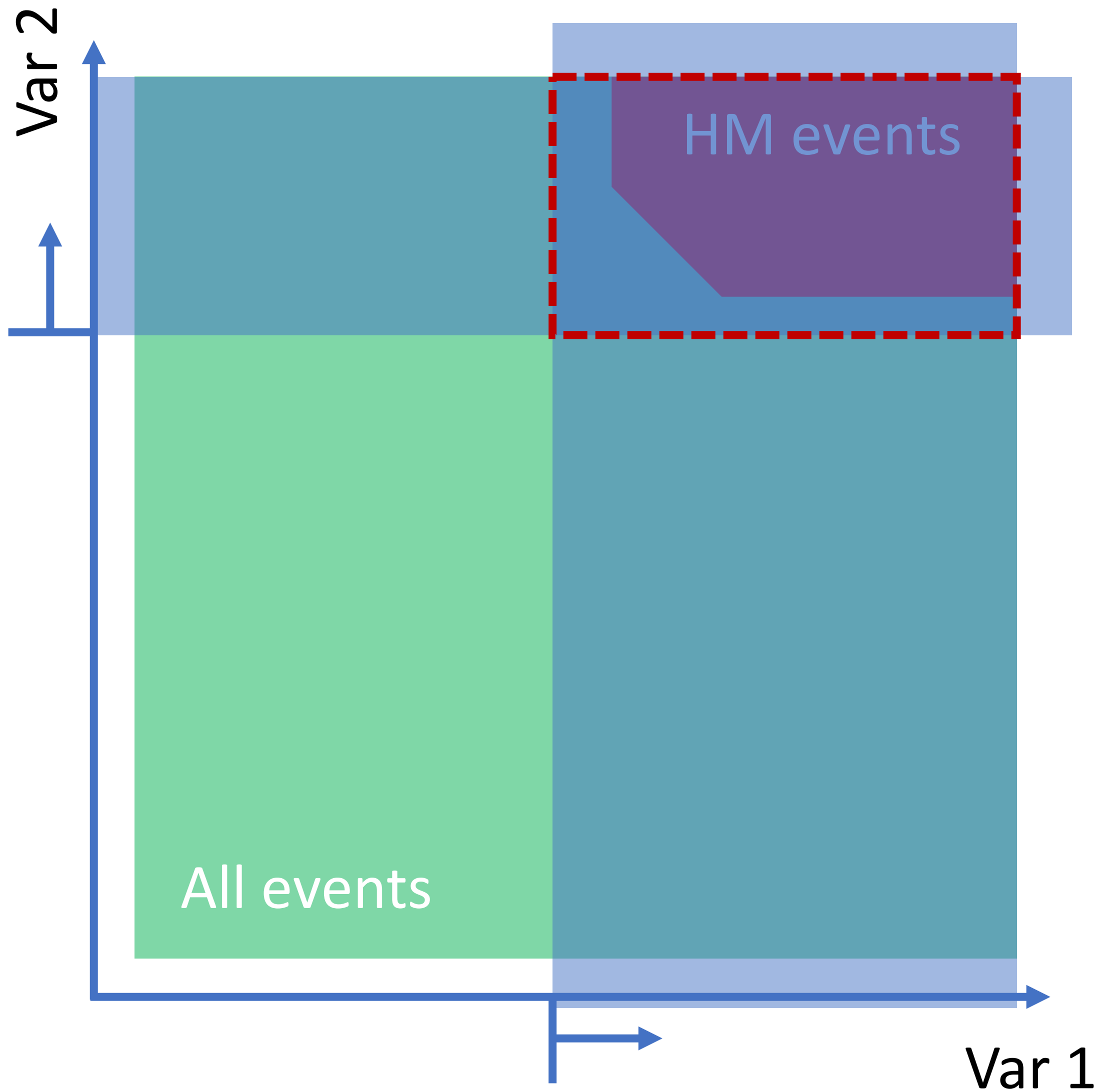
- Improve statistical significance of data

pp and *p*+Pb events with high statistics

Approach 2



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

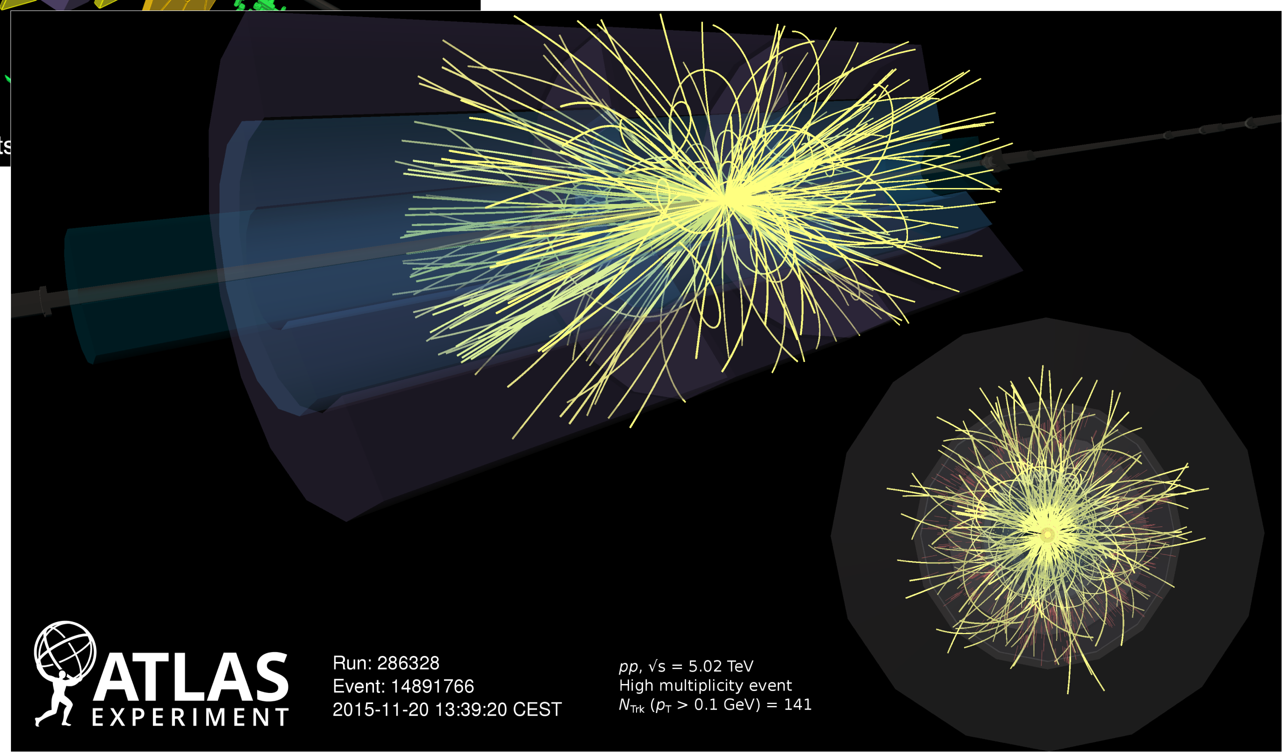


Sequence and thresholds of cuts designed to maximize performance.

Event display

Minimum-bias event

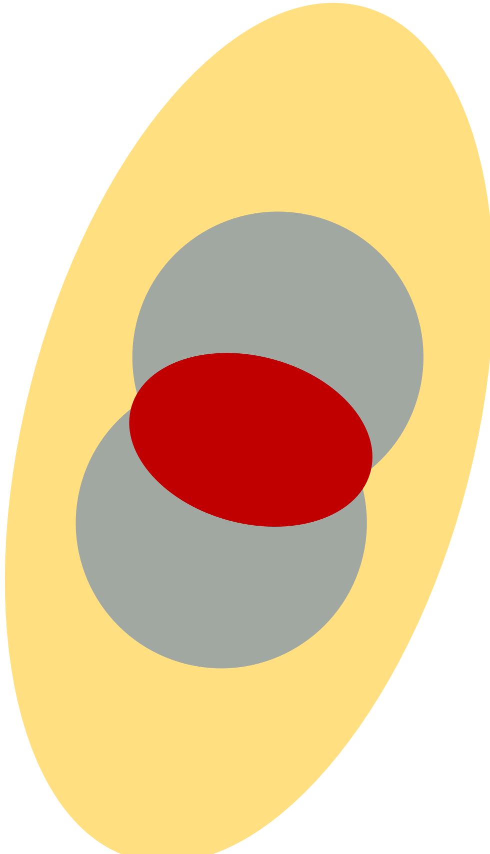
$N_{ch} \approx 30$



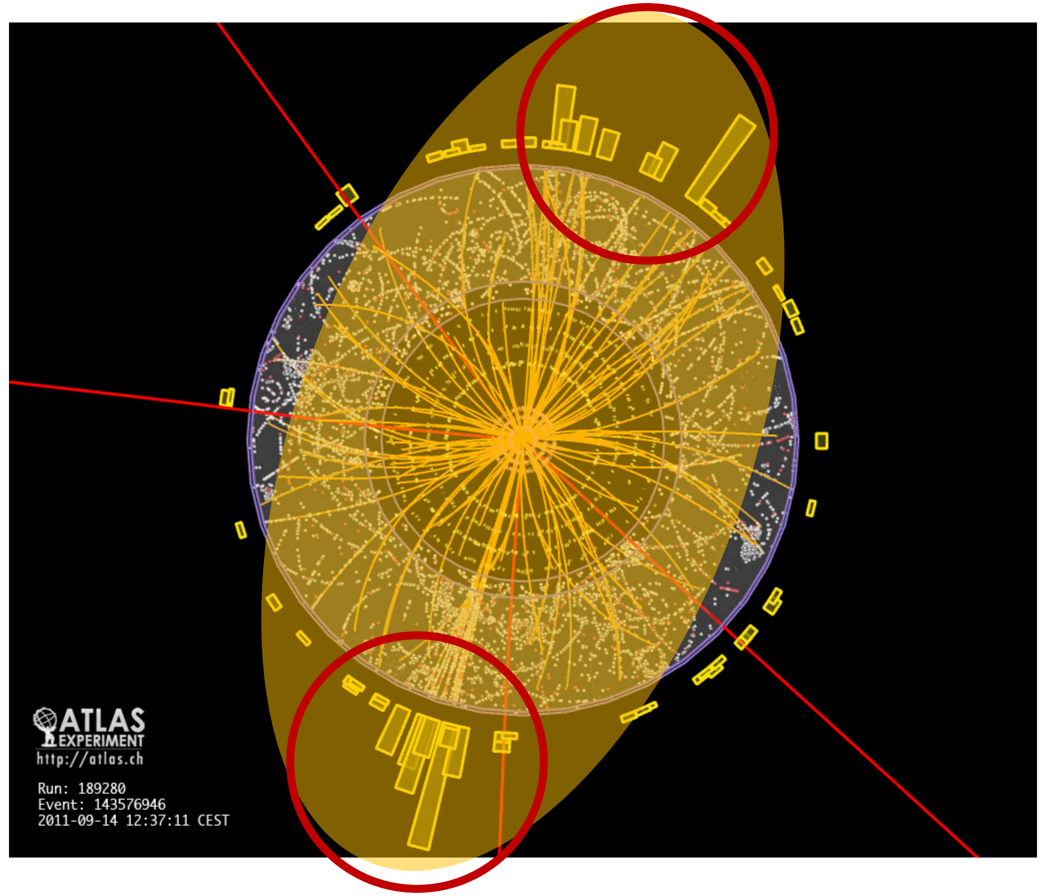
Triggered event

$N_{ch} \approx 140$

Signal or background?



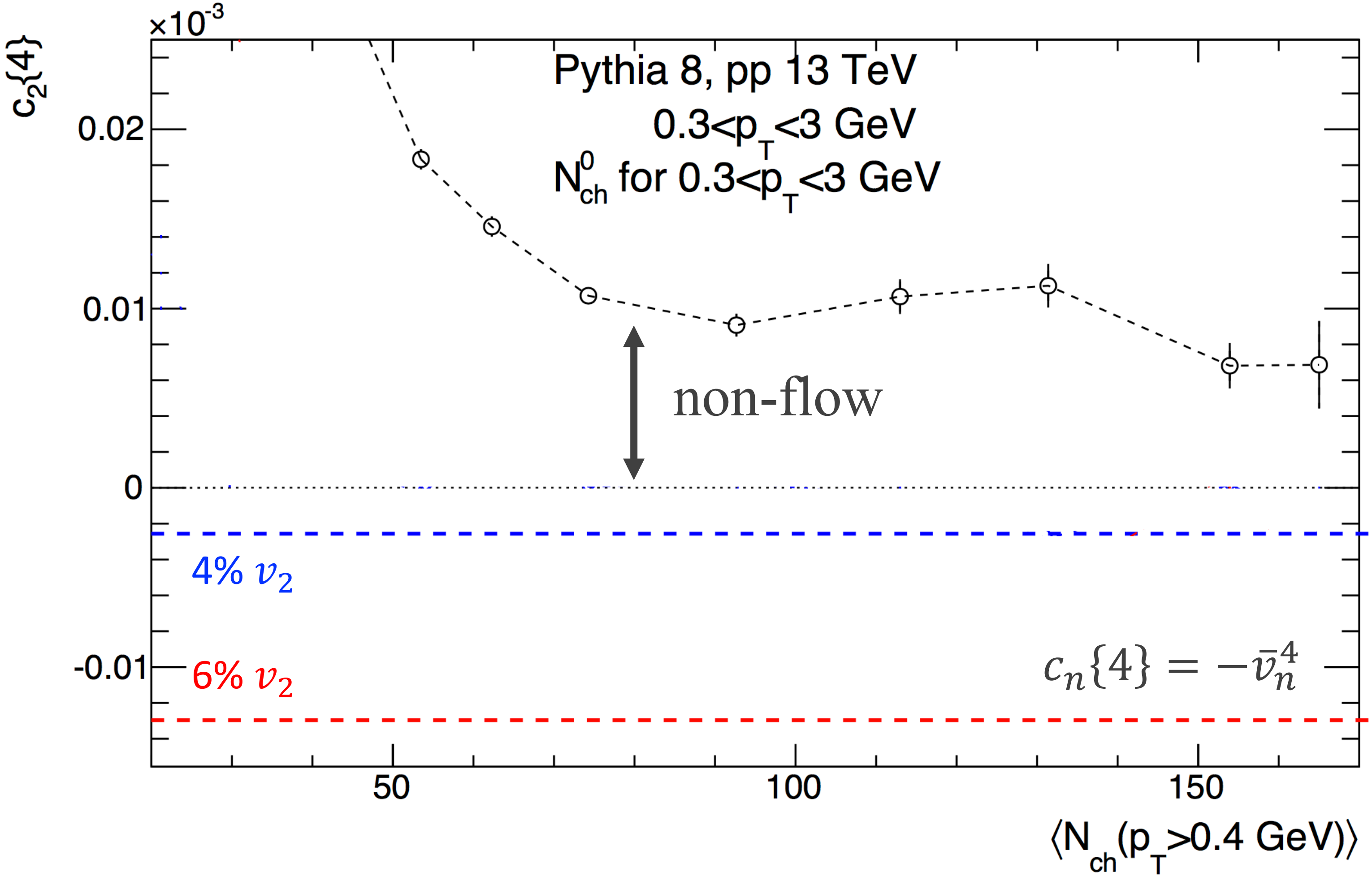
Signal: collectivity



Background: dijets

Maybe background is the one to blame?

Test of background



Traditional cumulant cannot remove non-flow in *pp*

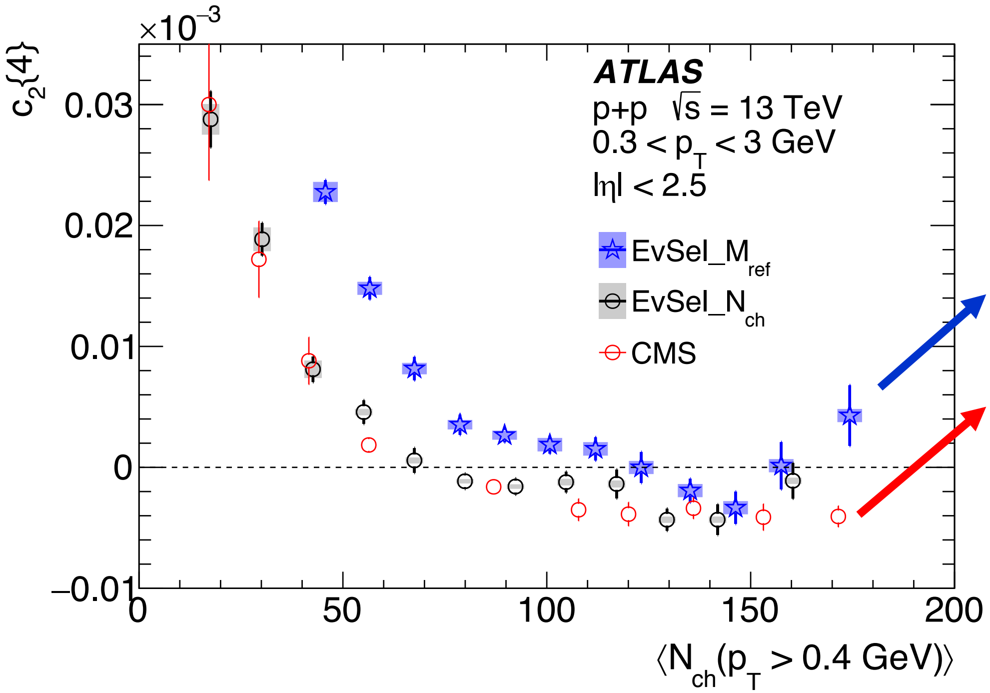
Test of residual non-flow

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

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.

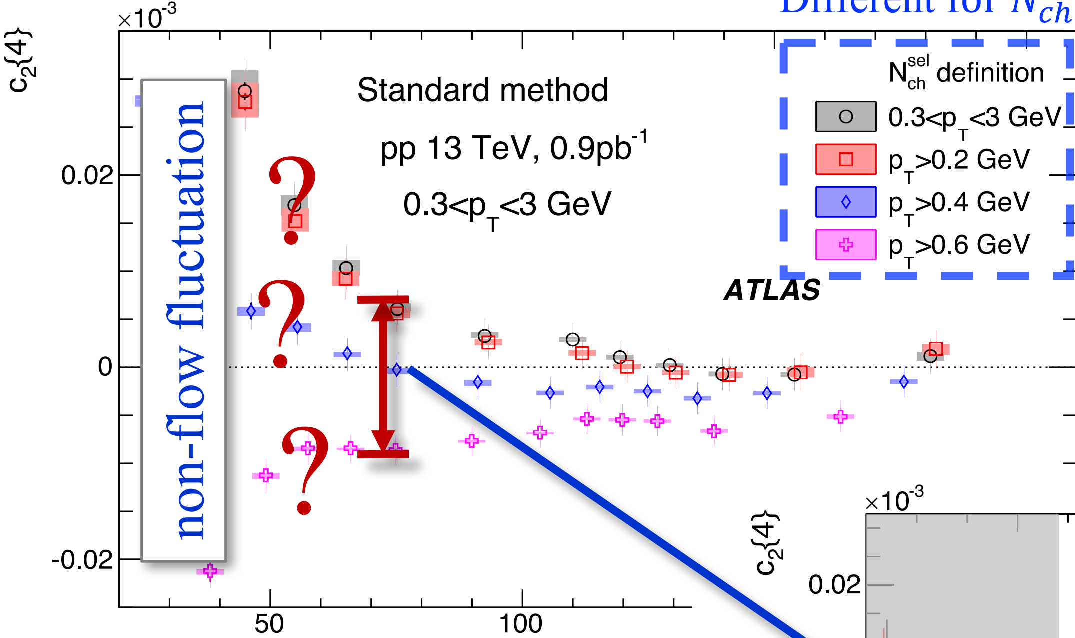
N_{ch}^{Sel} defined with $0.3 < p_T < 3.0$ GeV

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}

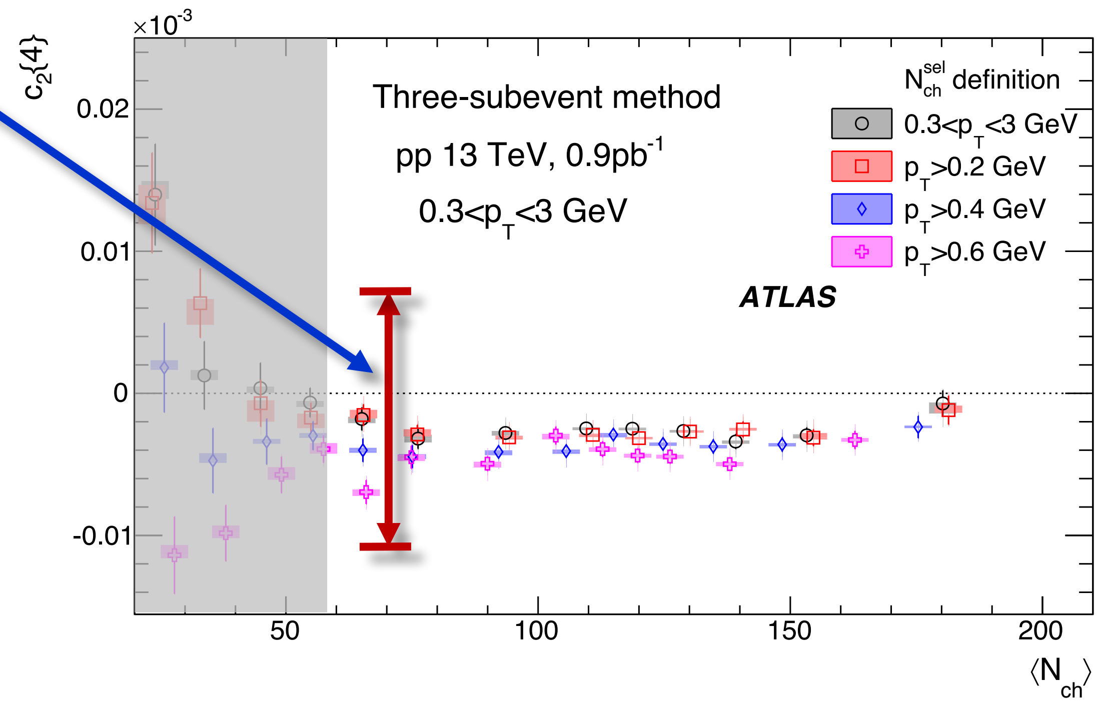
Different non-flow fluctuation

Different $c_2\{4\}$

Less non-flow

Weaker non-flow fluctuation

Weaker N_{ch}^{Sel} dependence



Data-driven method to test residual non-flow

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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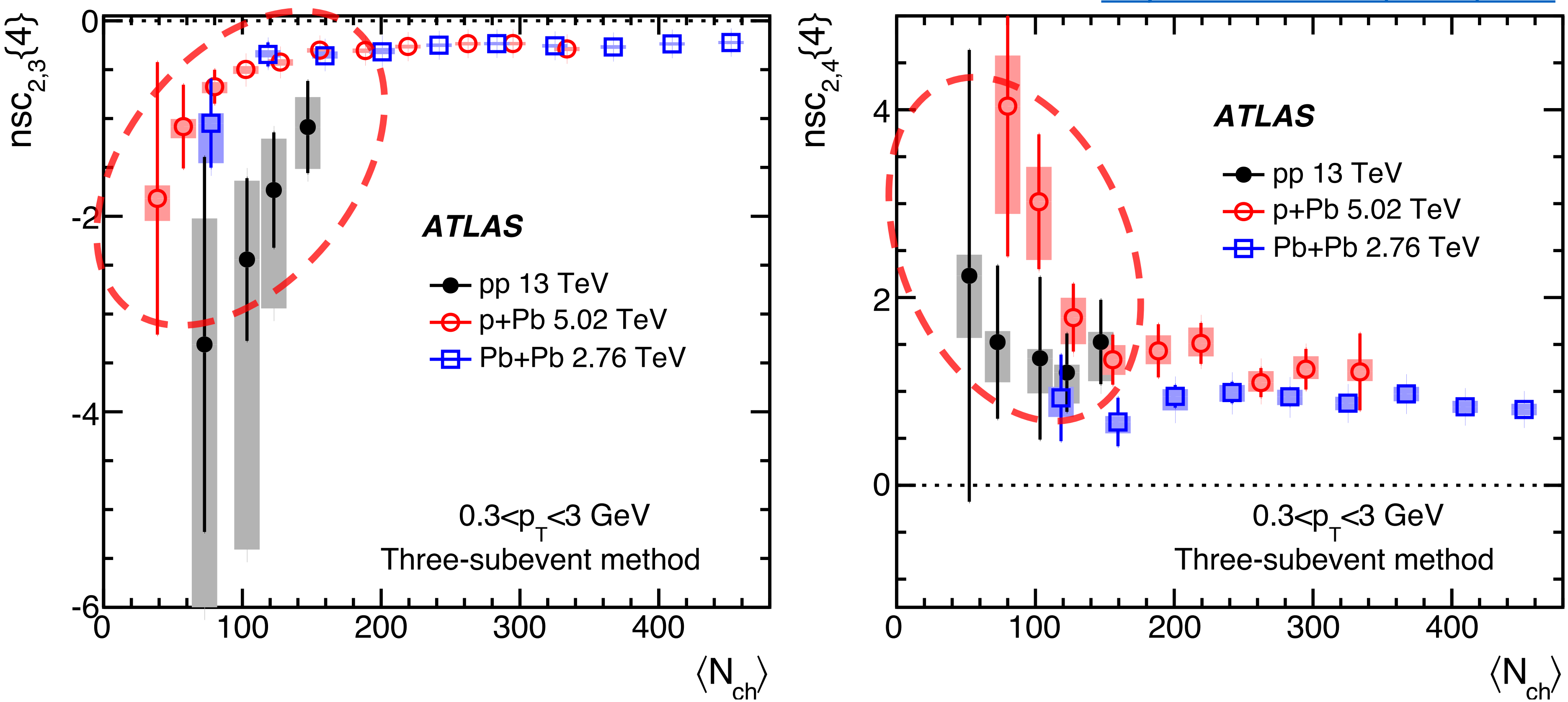


- Same sign, different magnitudes across systems;
- Independent constrains on models.

Forward-backward multiplicity fluctuation

Motivation: a historical view

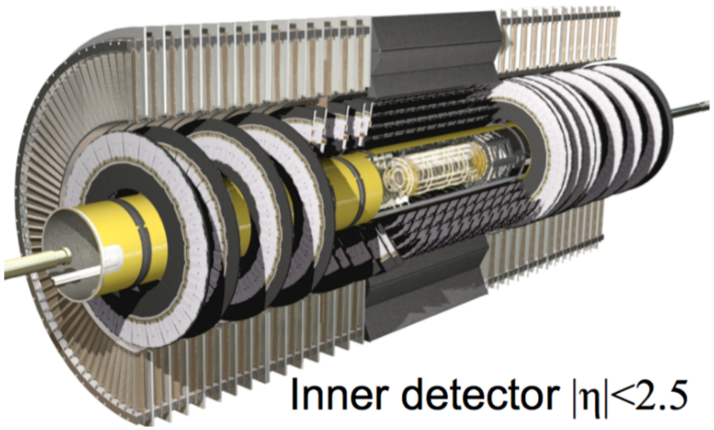
- Rapidity correlations is an old story

- Physics goal: understand production mechanism in early stage.
  - More details see the thesis.

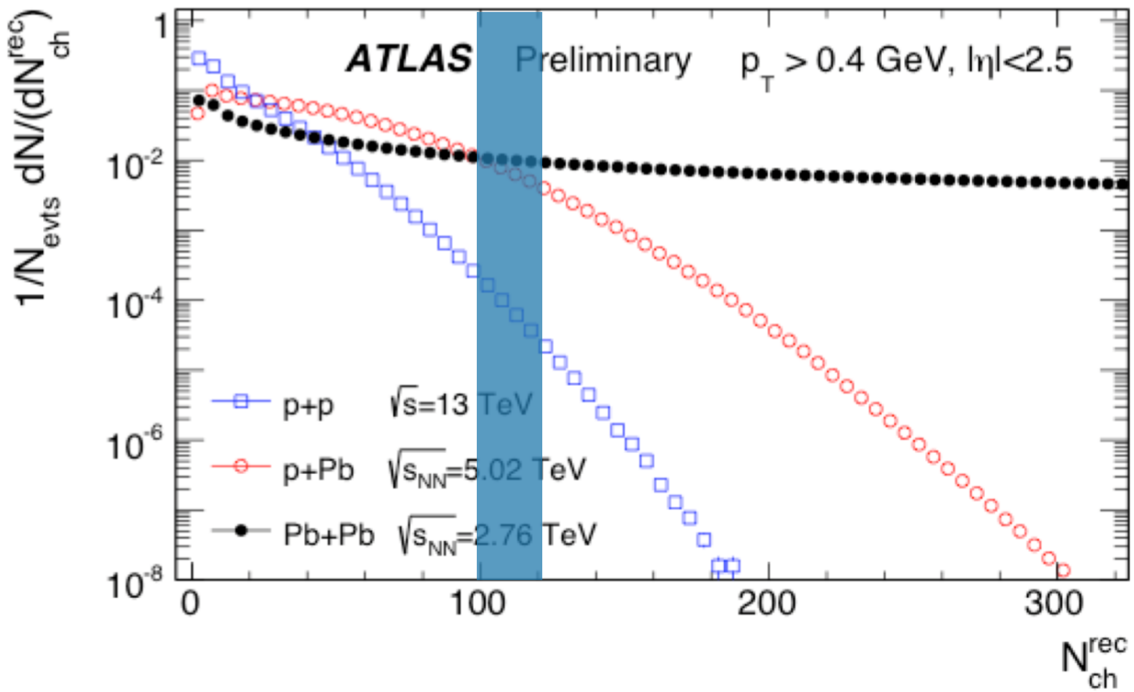
- Why we come back to this analysis?
  - Previous methods focused on limited phase space: η and $-\eta$;
  - We used a new observable that covers full η space;
  - Short-range correlation and statistical dilution;
  - We estimated short-range correlation;
  - Few direct comparisons among different systems;
  - 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;



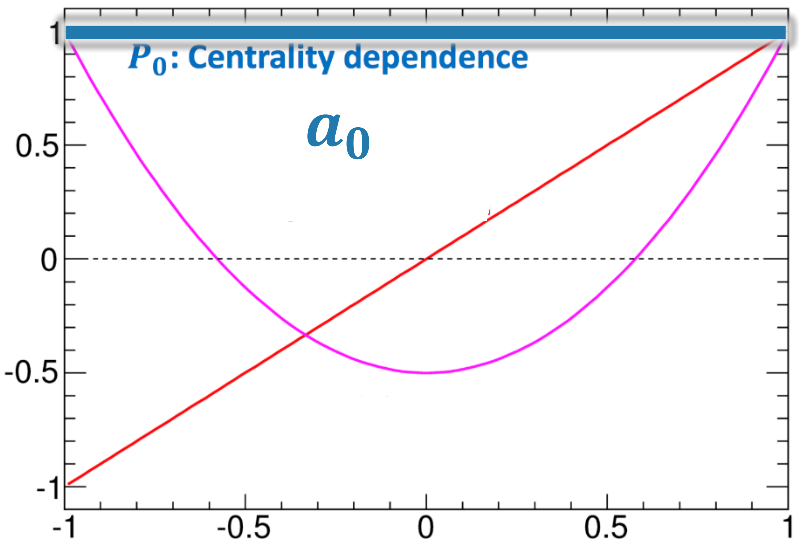
Pb+Pb 2.76 TeV, 2010, MB
p+Pb 5.02 TeV, 2013, MB+HMT
p+p 13 TeV, 2015, MB+HMT



- Analysis carried out in many bins over $10 \leq N_{ch}^{rec} < 300$;
- Results presented as a function efficiency-corrected values N_{ch}.

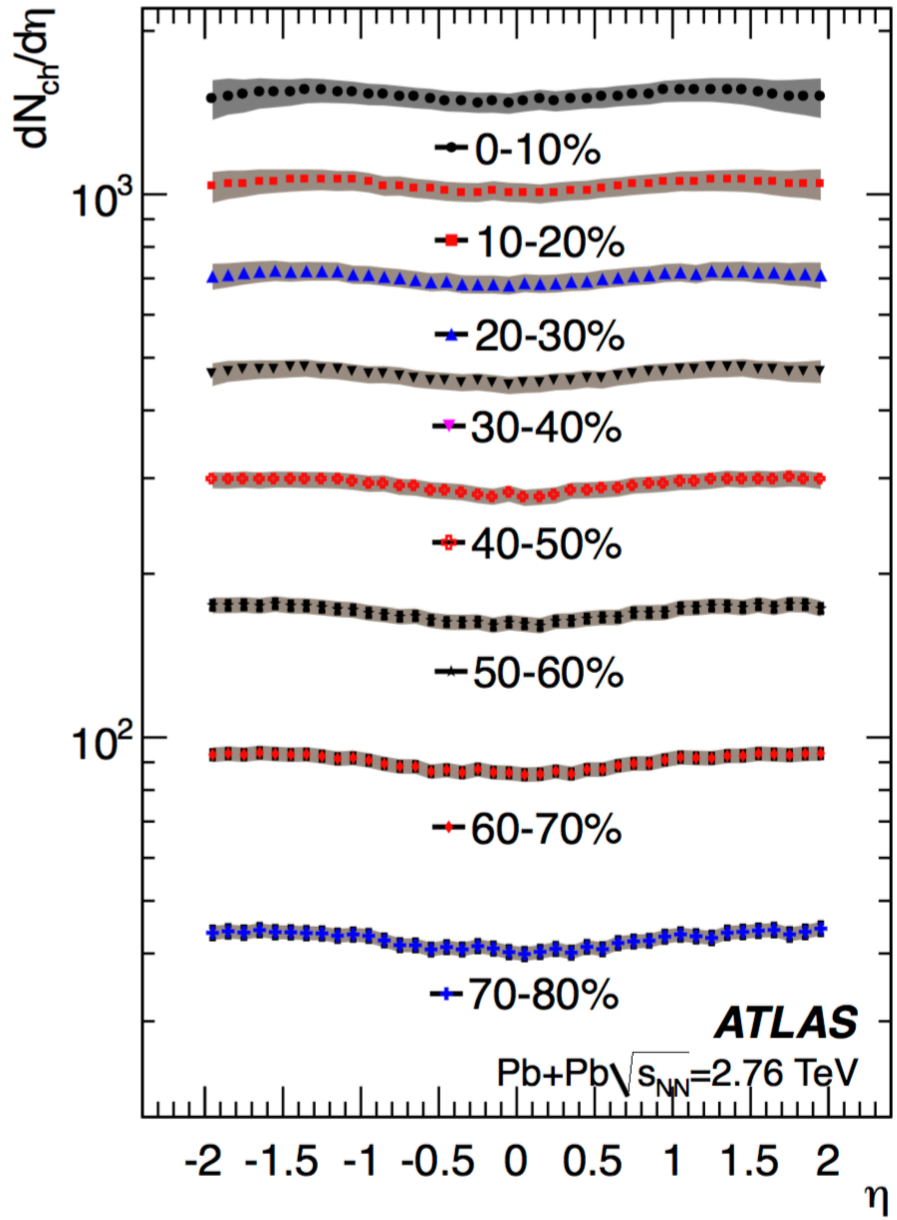
  - How long-range correlation compare among three systems, at the same N_{ch}?

Legendre expansion: a_0



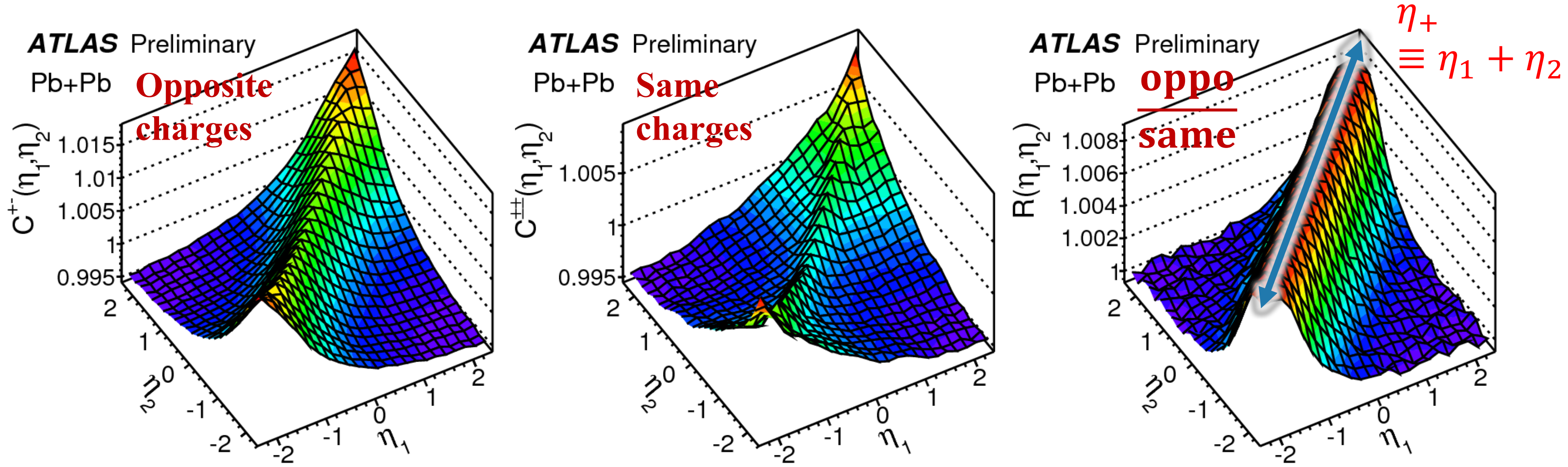
- Analysis focuses on dynamical fluctuation upon average;
- However, average multiplicity changes with centrality;
- The residual centrality dependence is removed by normalizing $C(\eta_1, \eta_2)$

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

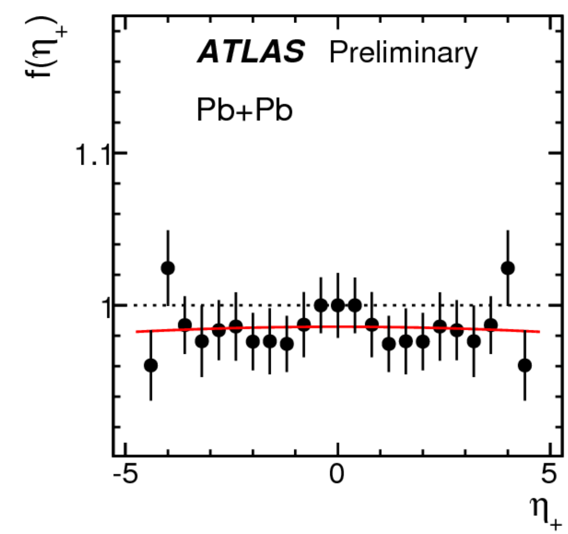


Charge dependence of $C(\eta_1, \eta_2)$

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

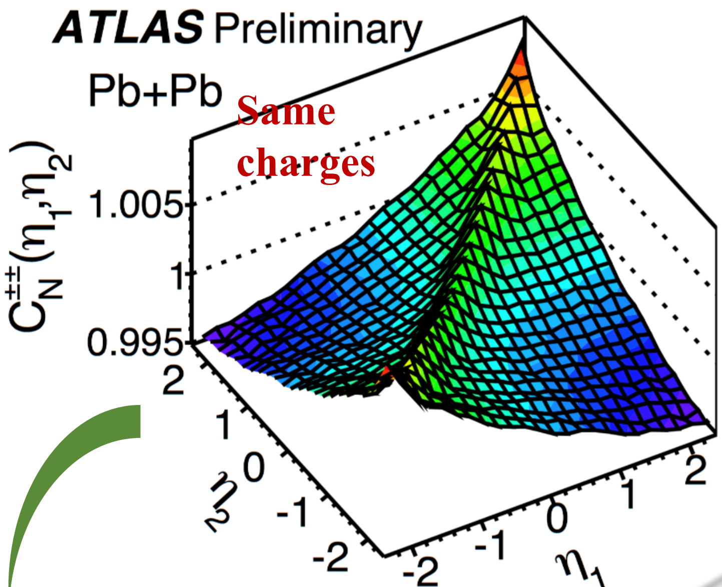


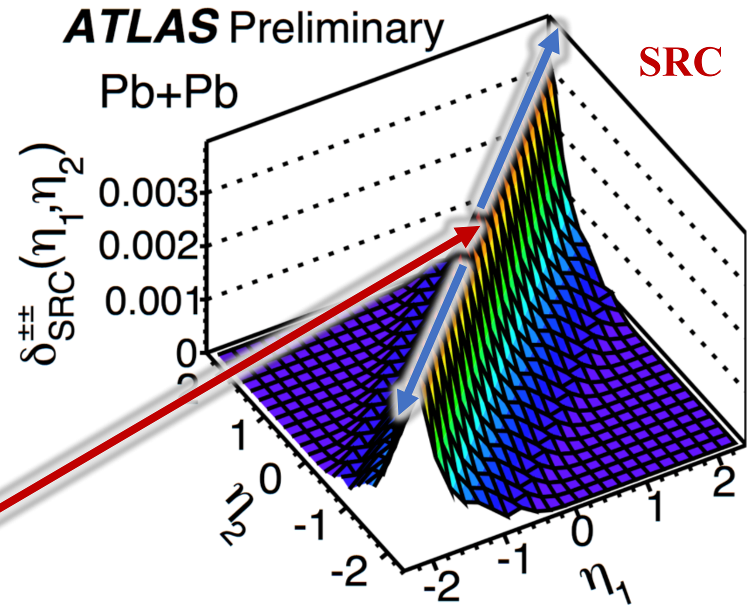
- Ratio of opposite to same charges $R(\eta_1, \eta_2)$
  - Very strong Gaussian-like SRC;
  - Very weak LRC: charge-independent;
- Amplitude of $R(\eta_1, \eta_2)$ along η_+: $f(\eta_+)$, reflects the strength of SRC in the longitudinal direction;
- Assumption: strength of SRC along η_+ is same for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

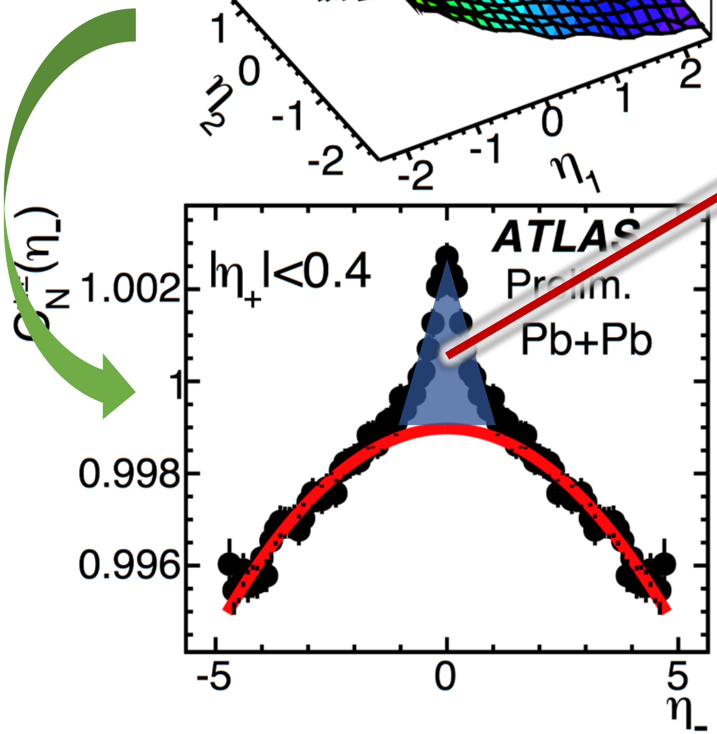


Estimation of short-range correlation

- To estimate SRC, LRC pedestal is estimated first.



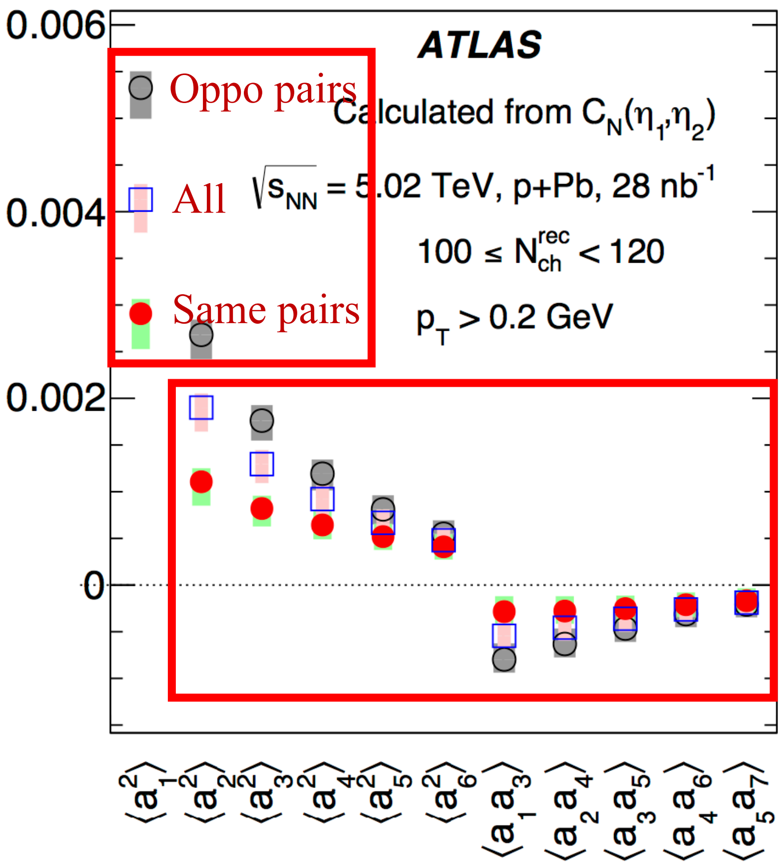




- $C(\eta_1, \eta_2)$ from same charge used to estimate LRC pedestal because of small SRC;
- LRC pedestal is fitted with quadratic function;
- The additional structure upon LRC pedestal determines the shape of SRC;
- The full $\delta_{SRC}(\eta_1, \eta_2)$ is then populated using $f(\eta_+)$ scaling.

Why it is important to remove SRC?

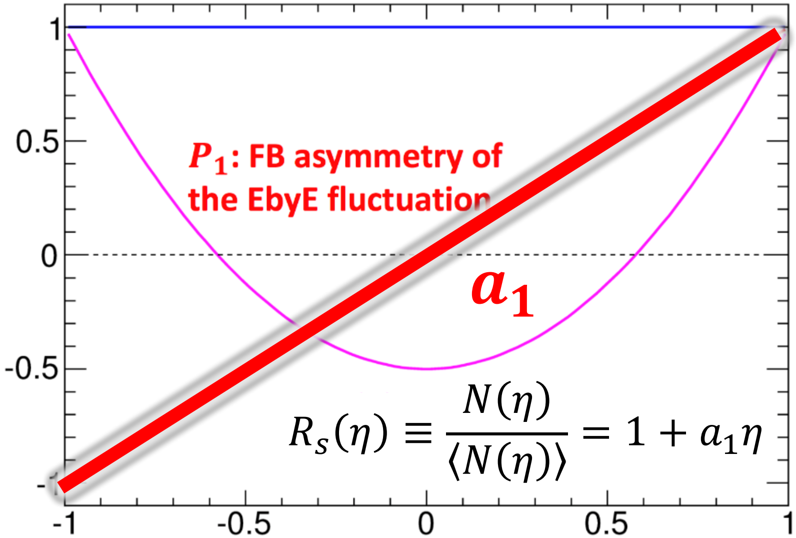
Before SRC removal

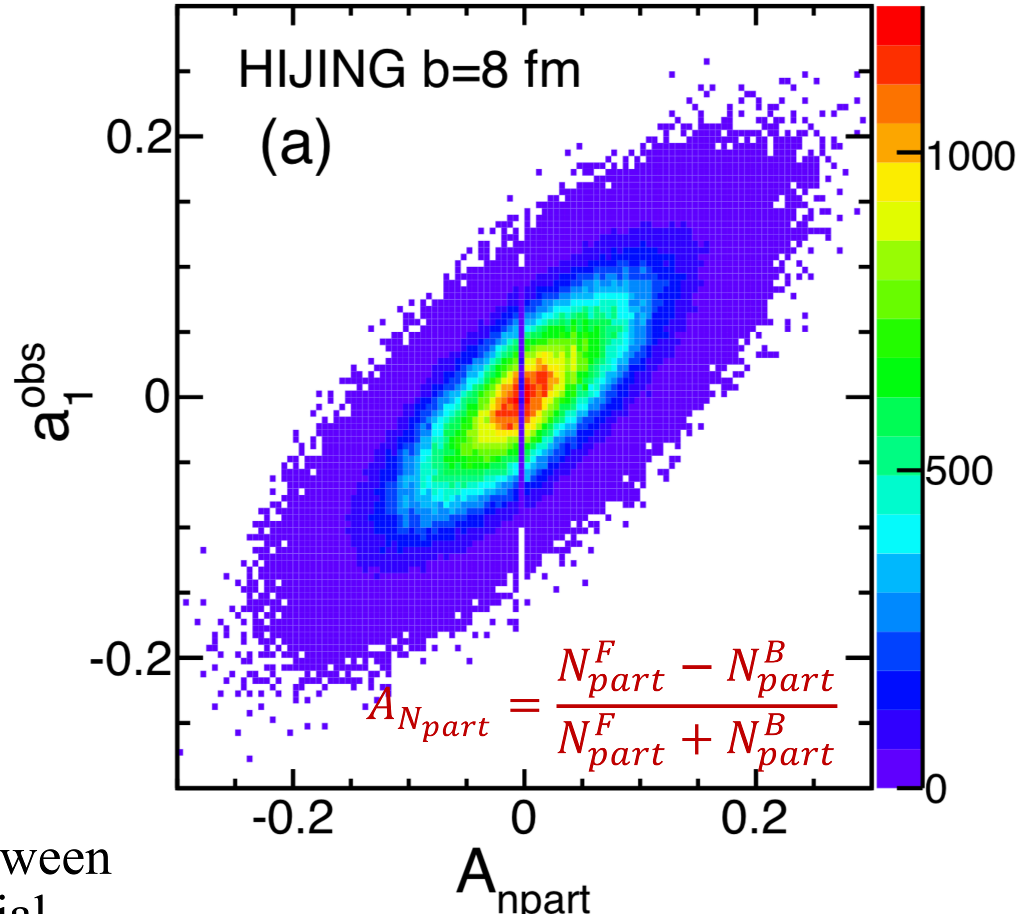


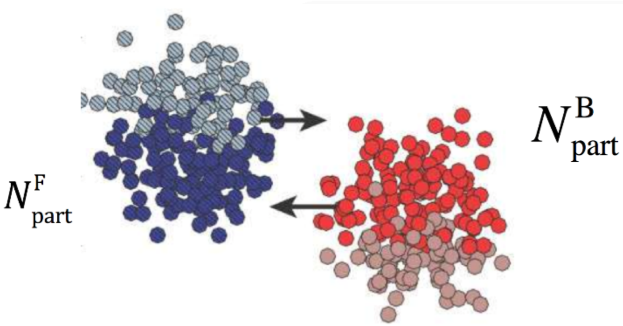
- Higher order coefficients observed;
- Coefficients have charge dependent;
- Results hard to interpret: due to SRC!

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

Legendre expansion: a_1

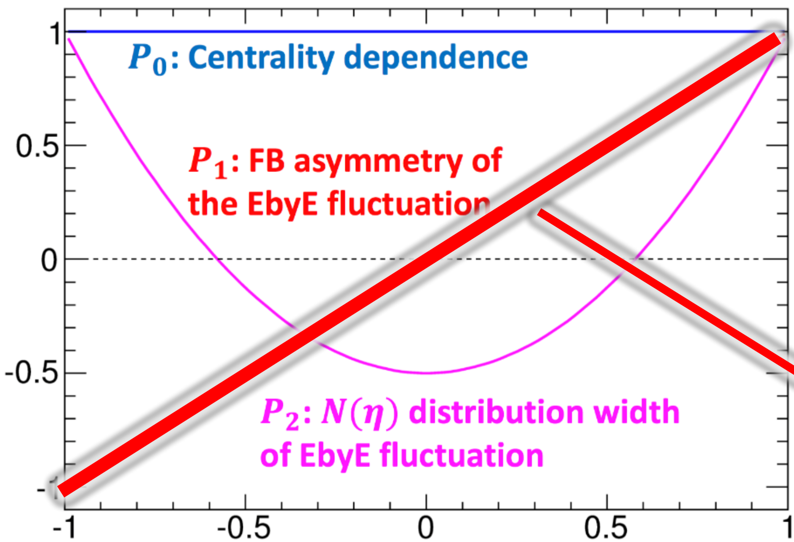






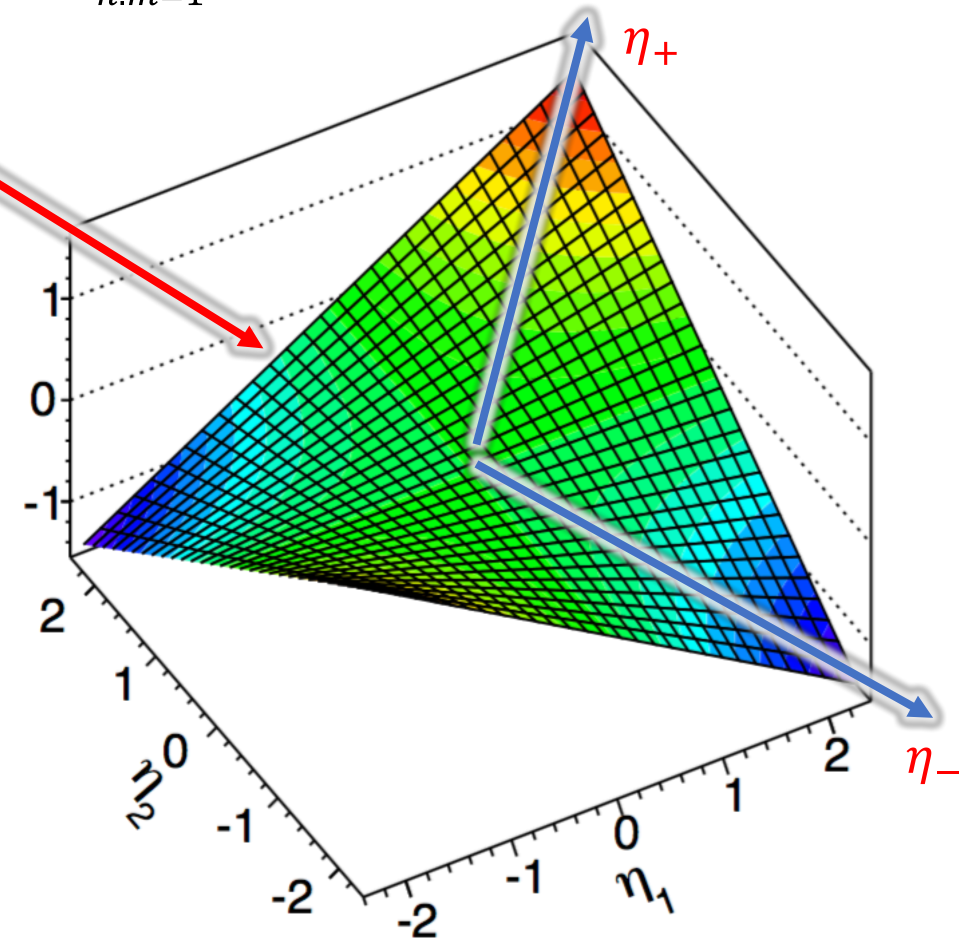
- The linear shape quantifies the FB multiplicity asymmetry;
- HIJING shows strong correlation between final multiplicity asymmetry and initial participant asymmetry;
- As will be shown later, this component dominates the shape fluctuation.

Legendre expansion: from a_n to $\langle a_n a_m \rangle$



- 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

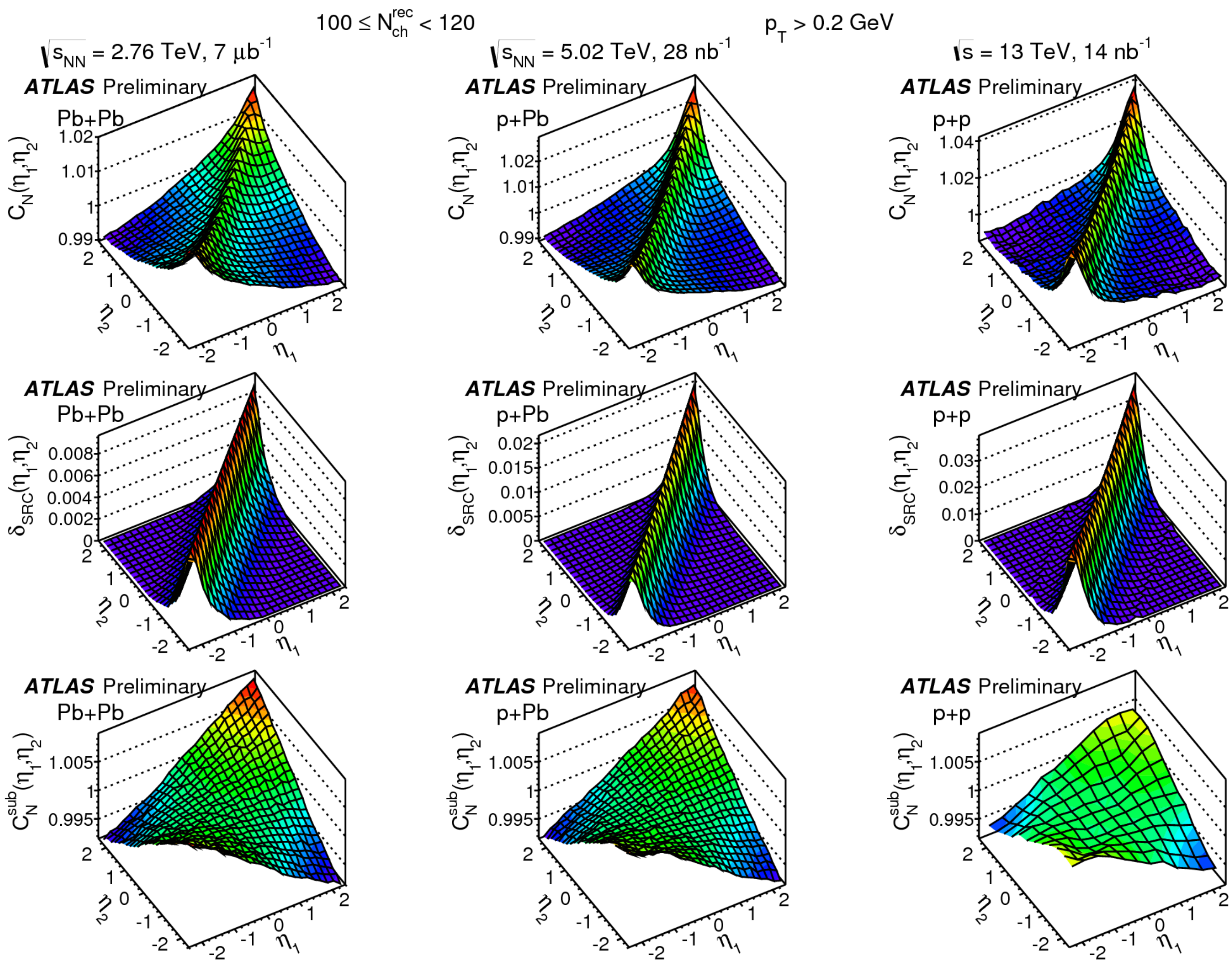
Raw
$C_N(\eta_1, \eta_2)$

=

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

+

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

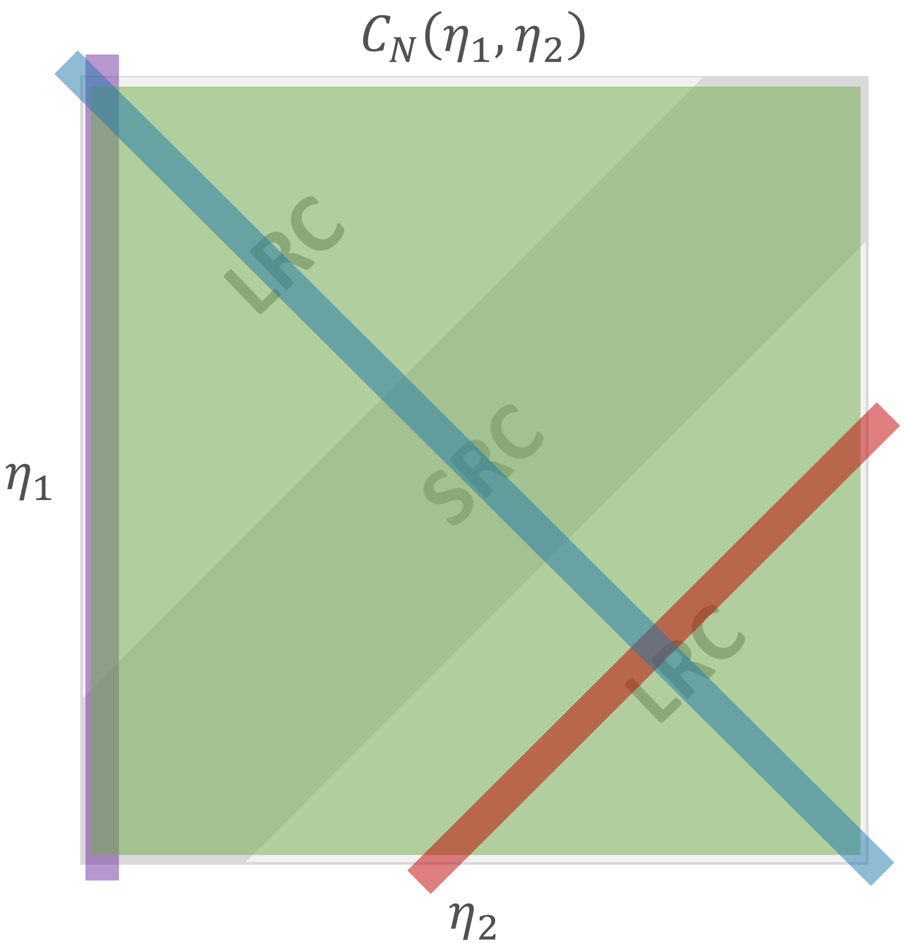


Pb+Pb

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

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

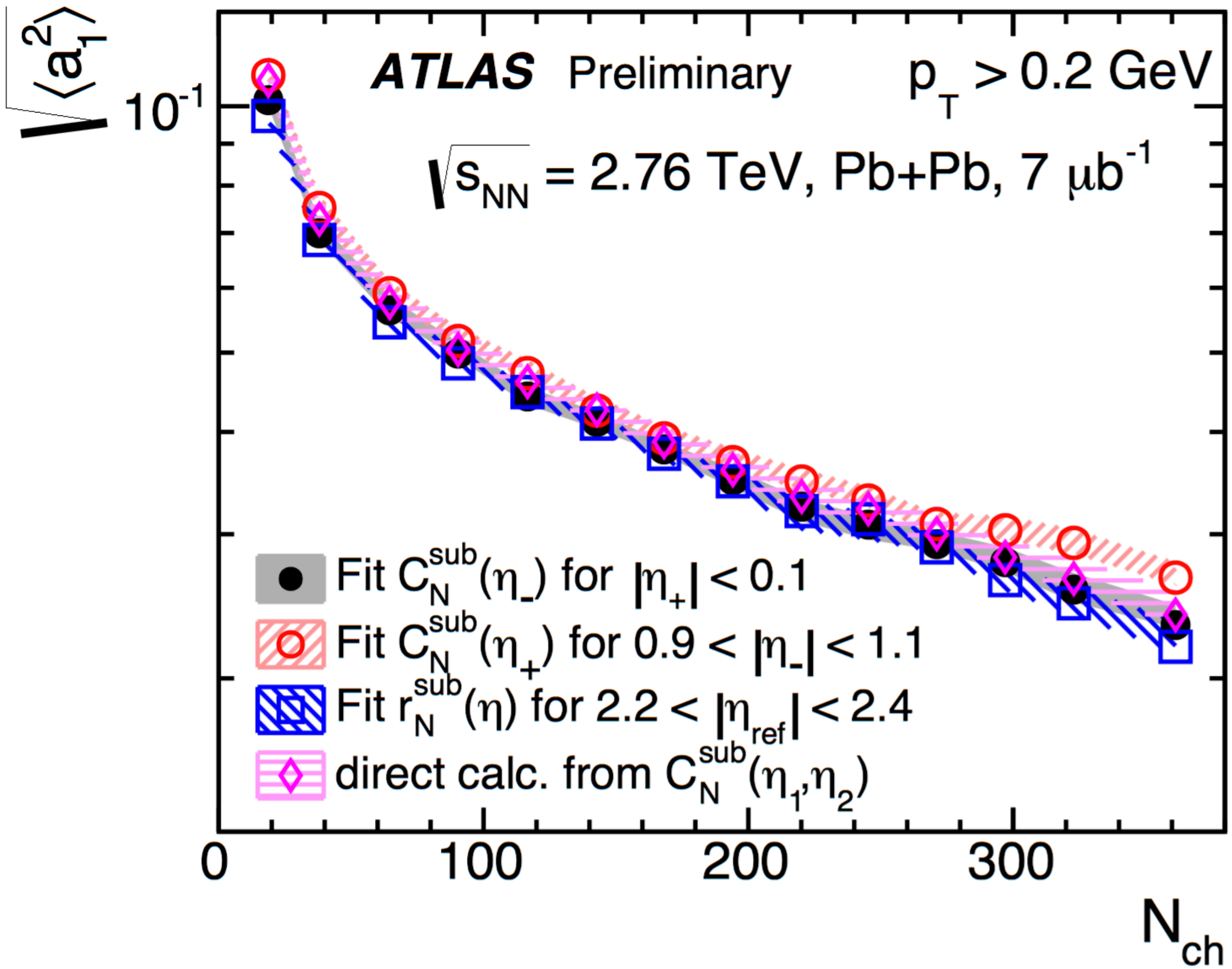
- Linear fit of $r_N^{sub}(\eta,\eta_{ref}) \equiv \frac{C_N^{sub}(-\eta,\eta_{ref})}{C_N^{sub}(\eta,\eta_{ref})}$

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

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

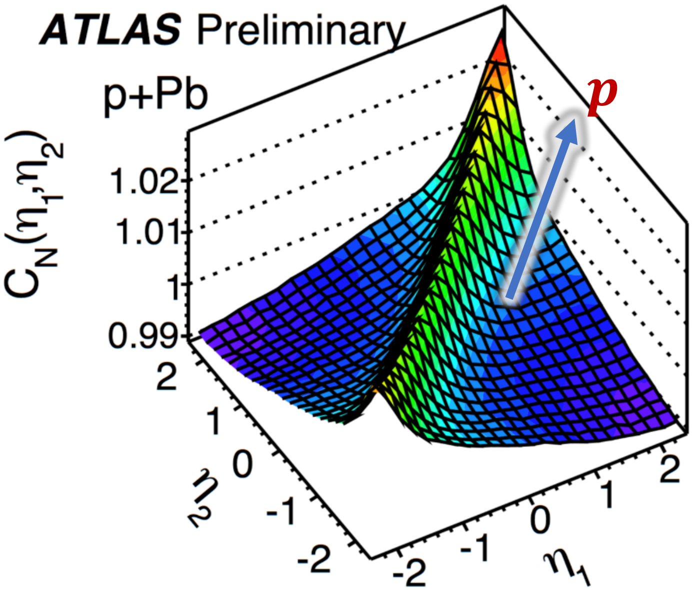
How stable are the results?

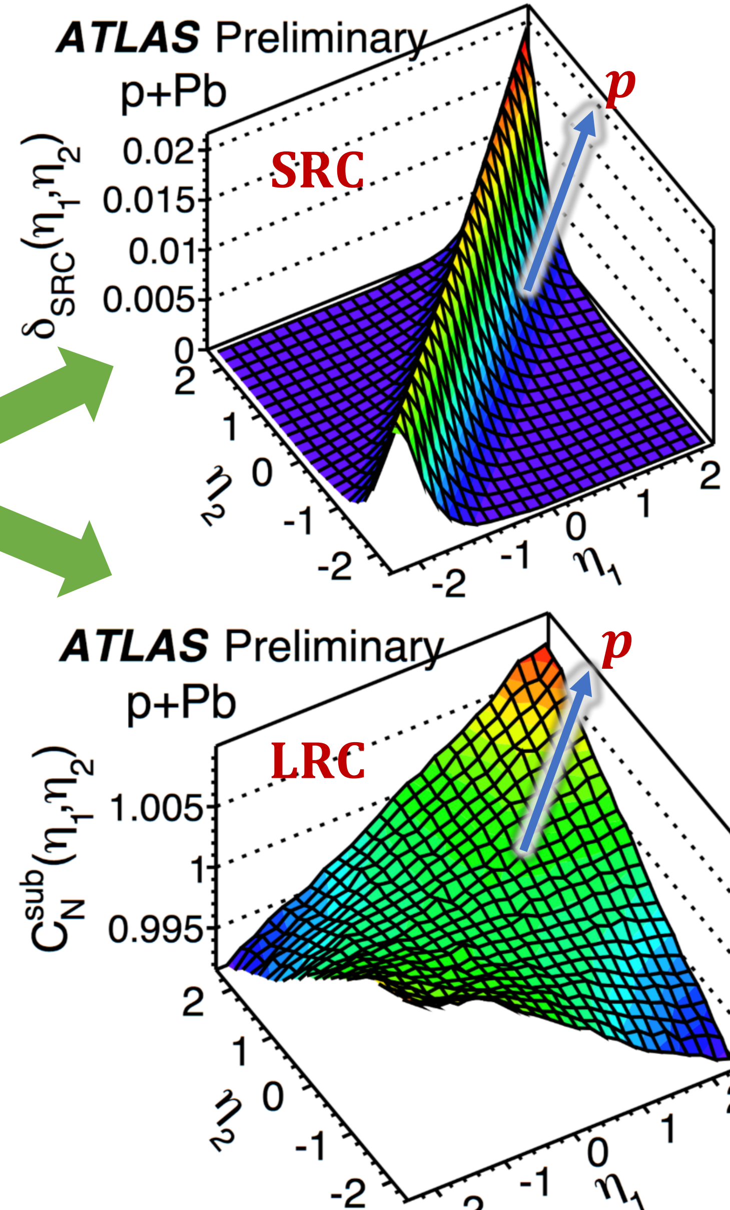
- Four largely independent methods are applied to determine $\langle a_1^2 \rangle$;
- Different methods have different sensitivity to the analysis procedures;



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

Asymmetry in *p*+Pb collision





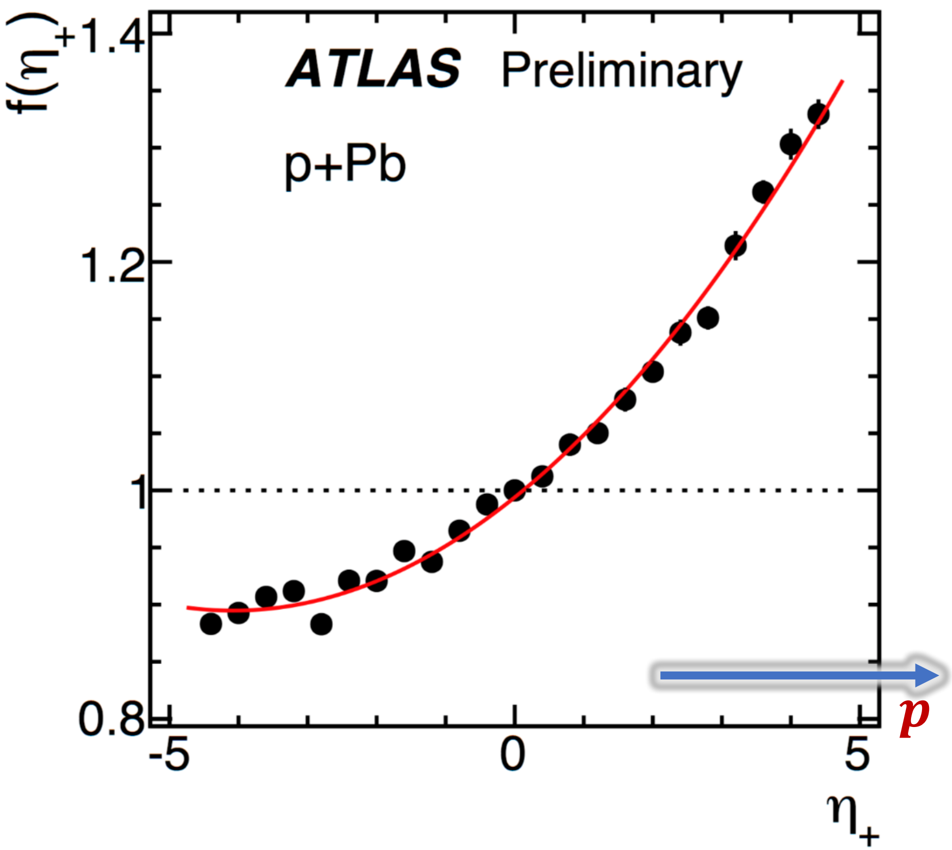
- Asymmetry entirely due to SRC!

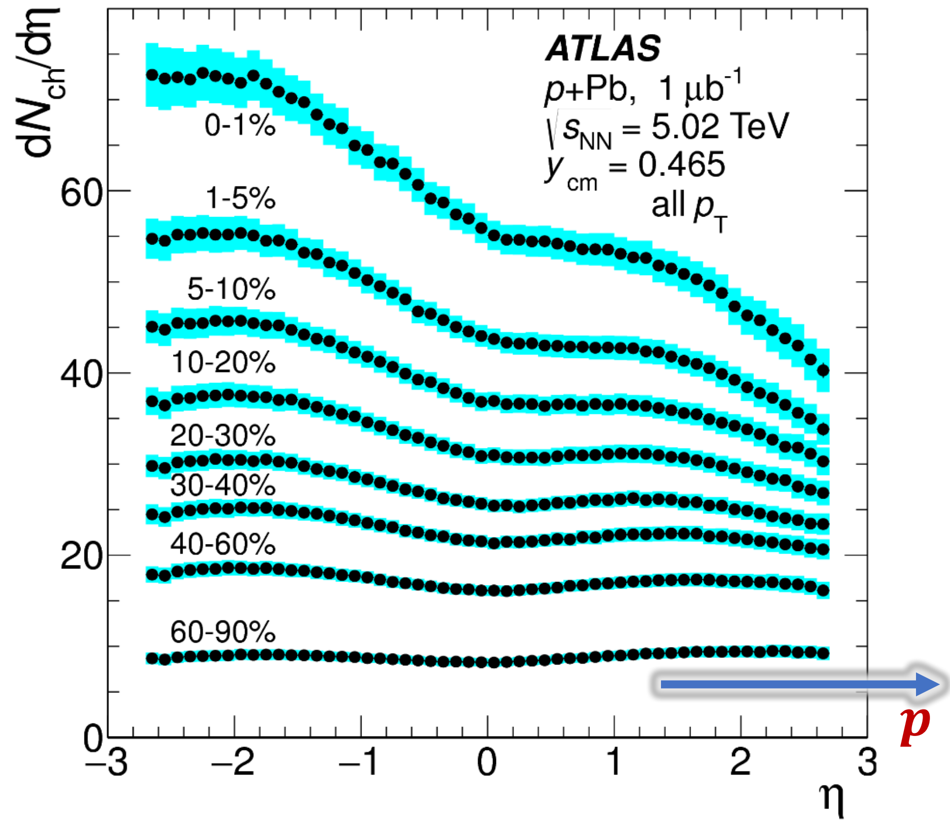
- Asymmetry observed in *p*+Pb collision: stronger correlation in the proton-going side.

- Why the asymmetric collision causes asymmetric SRC?

- LRC is symmetric.

SRC asymmetry in p+Pb collision



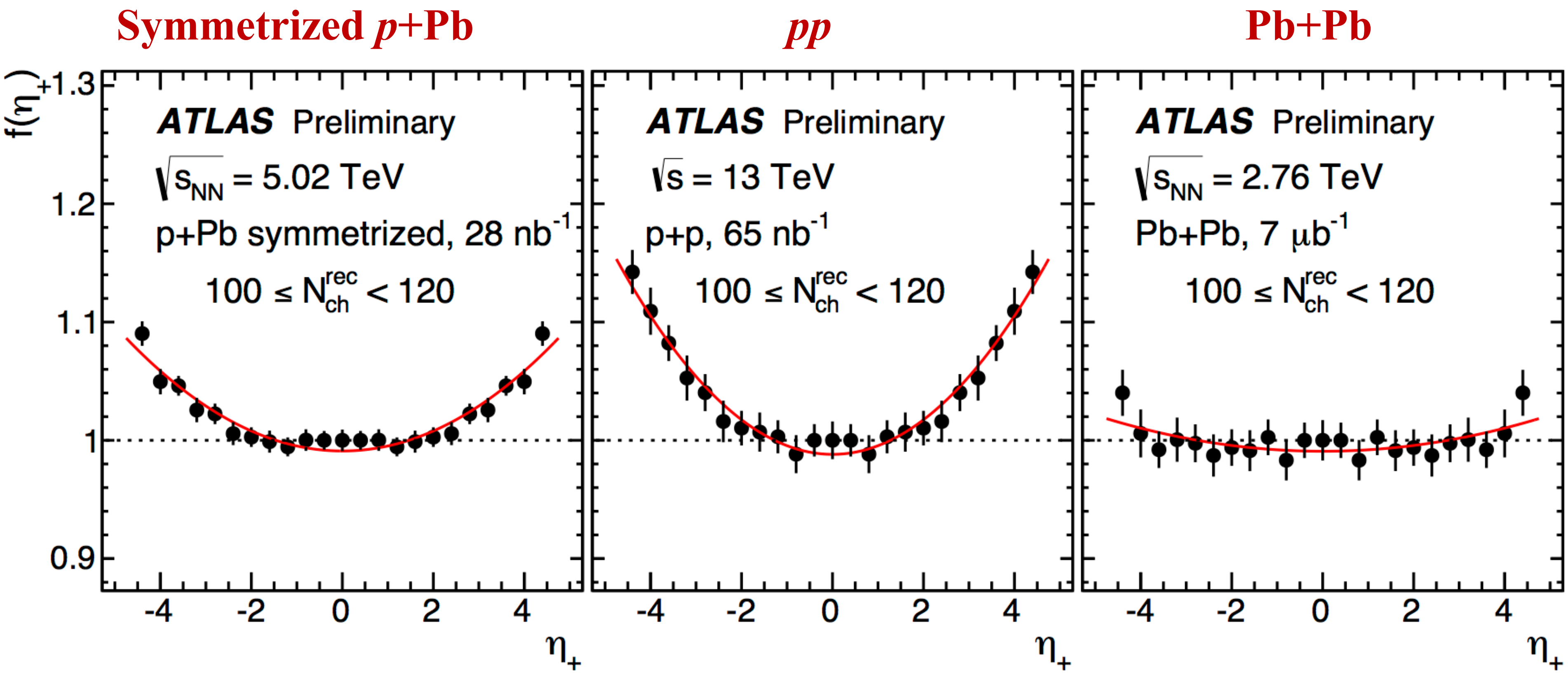


- Assume there are n clusters and each one emits m particles on average;
- Assume n is proportional to local particle density $dN_{ch}/d\eta$;

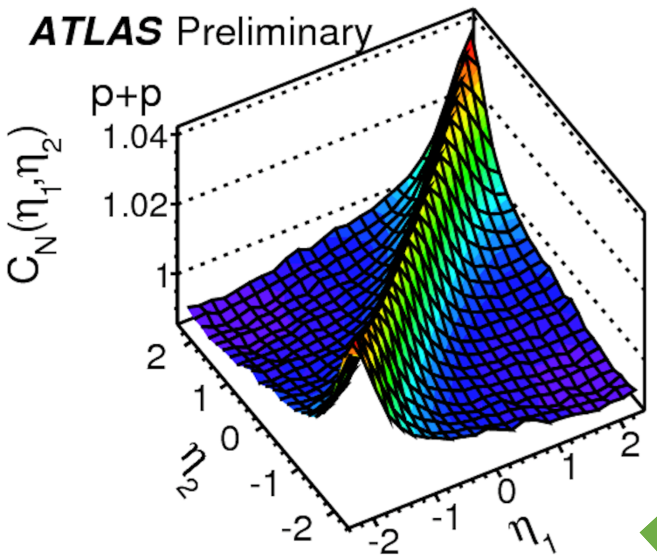
$$\delta_{SRC} \propto \frac{n\langle m(m-1)\rangle}{(n\langle m\rangle)^2} = \frac{1}{n} \propto \frac{1}{dN_{ch}/d\eta}$$

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.

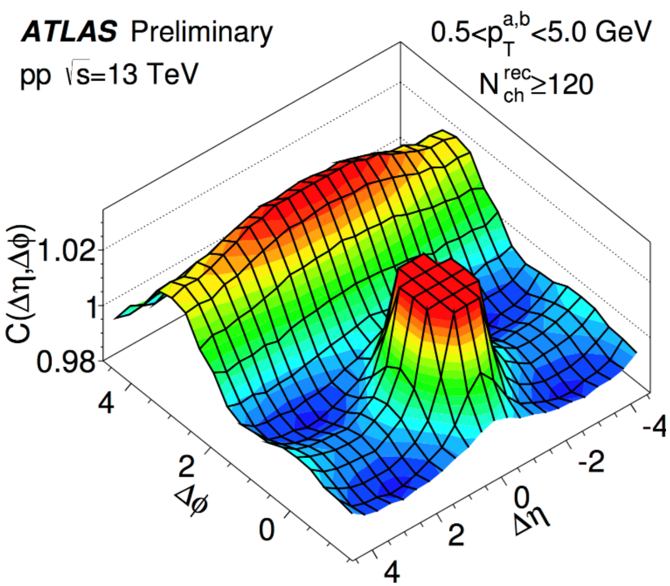


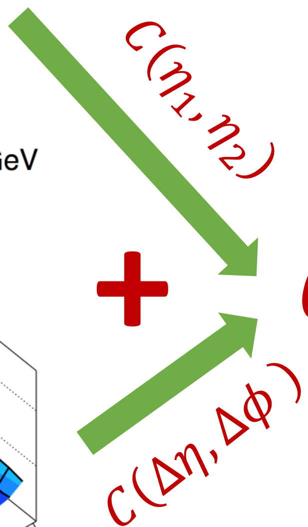
- $C(\eta_1,\eta_2)$ is a very comprehensive observable.
- Reconstruct balance function

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

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

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



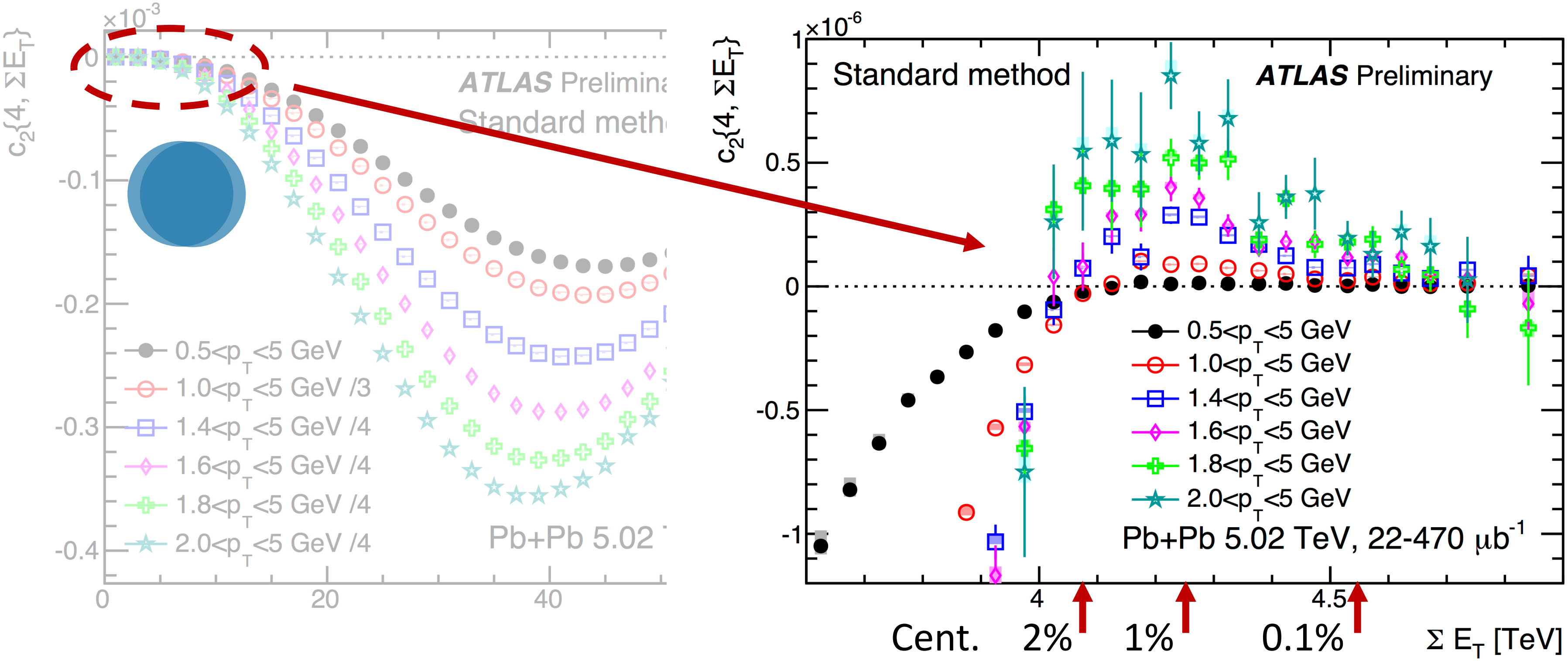


+

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

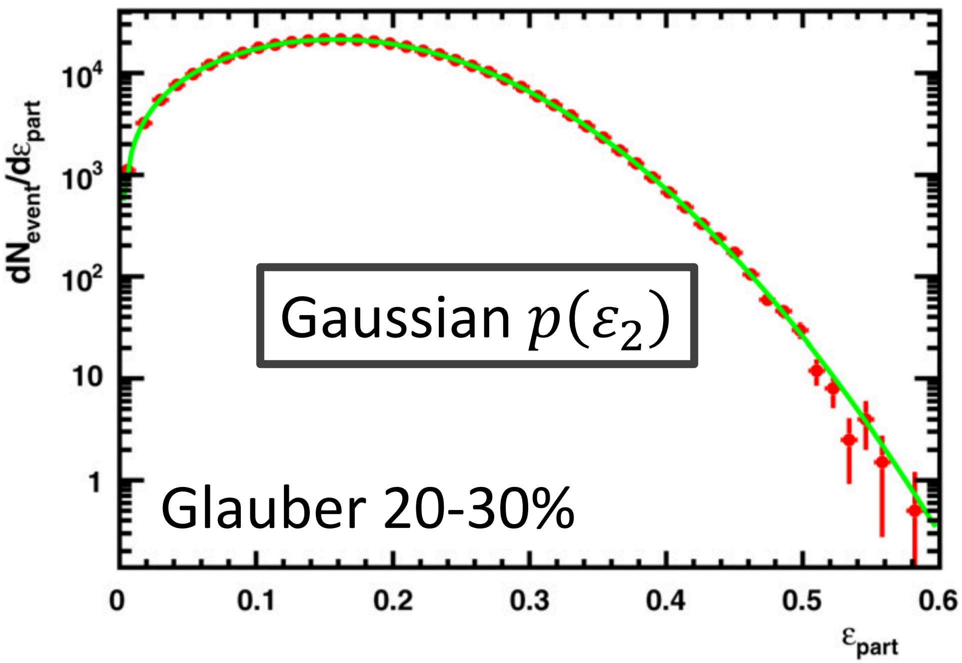
Centrality fluctuation

Ultra-Central Collision (UCC)



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

PLB 659 (2008) 537-541



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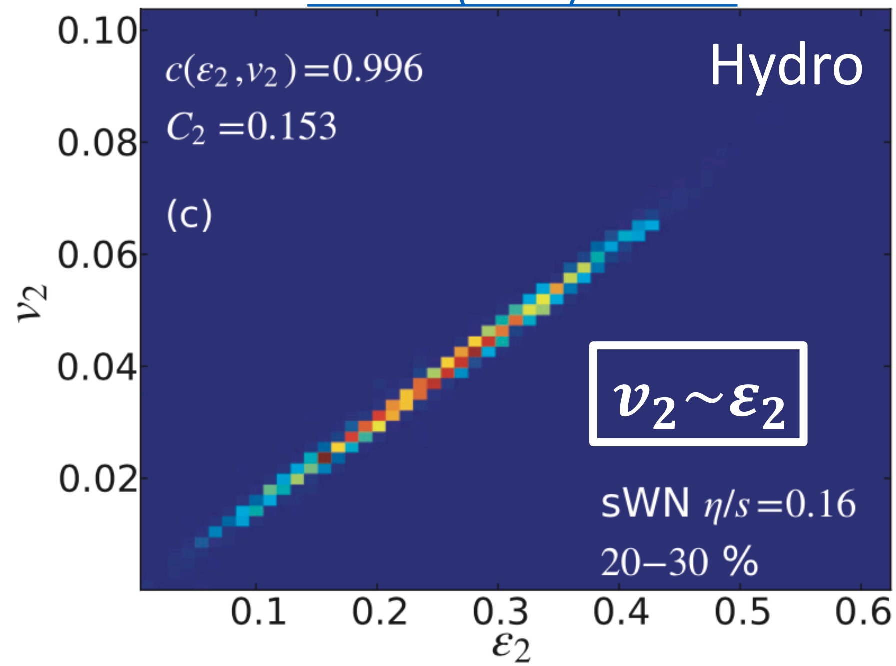
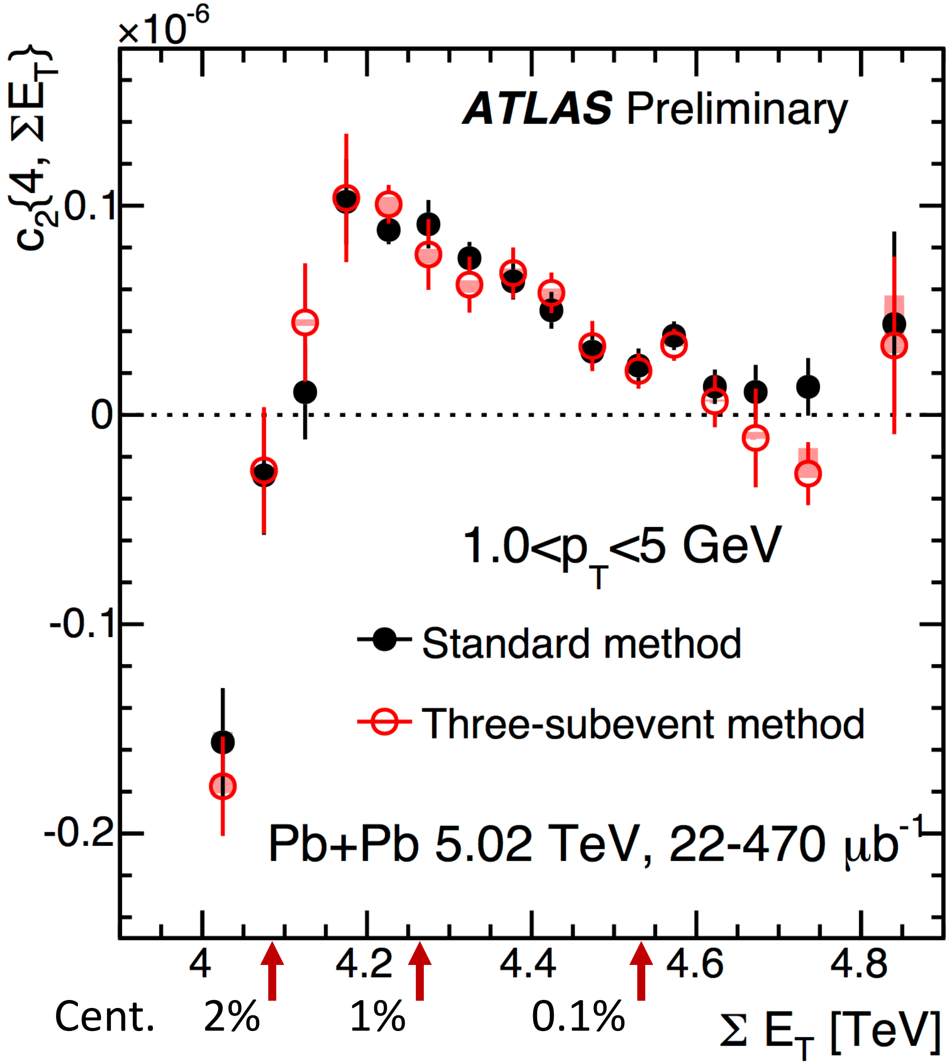


$$\boxed{v_n\{4\} = \bar{v}_n = \sqrt[4]{-c_n\{4\}}}$$

- 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?

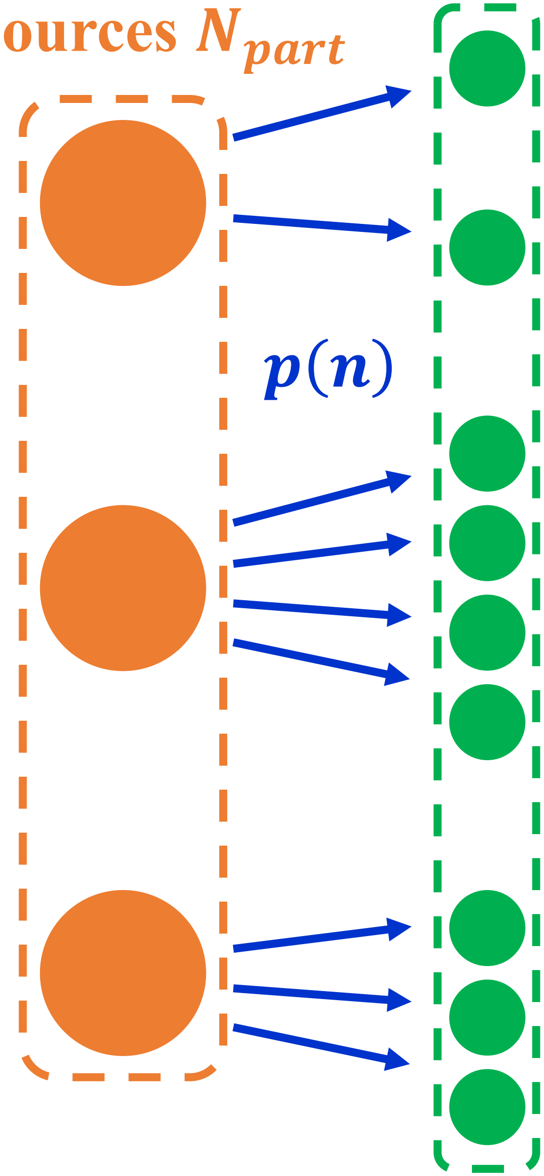
Non-flow contribution?



- 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?

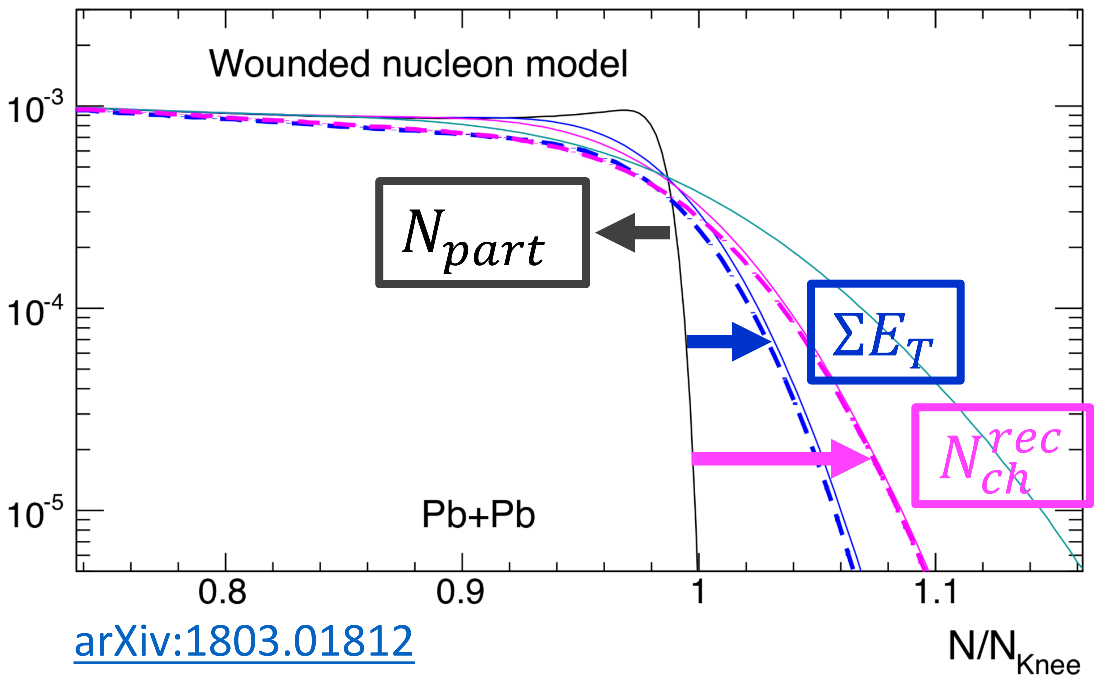
$$c_n\{4\} \equiv \langle\underbrace{\langle 4 \rangle}_{\text{Calculated event-by-event}}\rangle - 2\langle\langle 2 \rangle\rangle^2$$

Averaged over many events

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

- **Particle production depends on η**

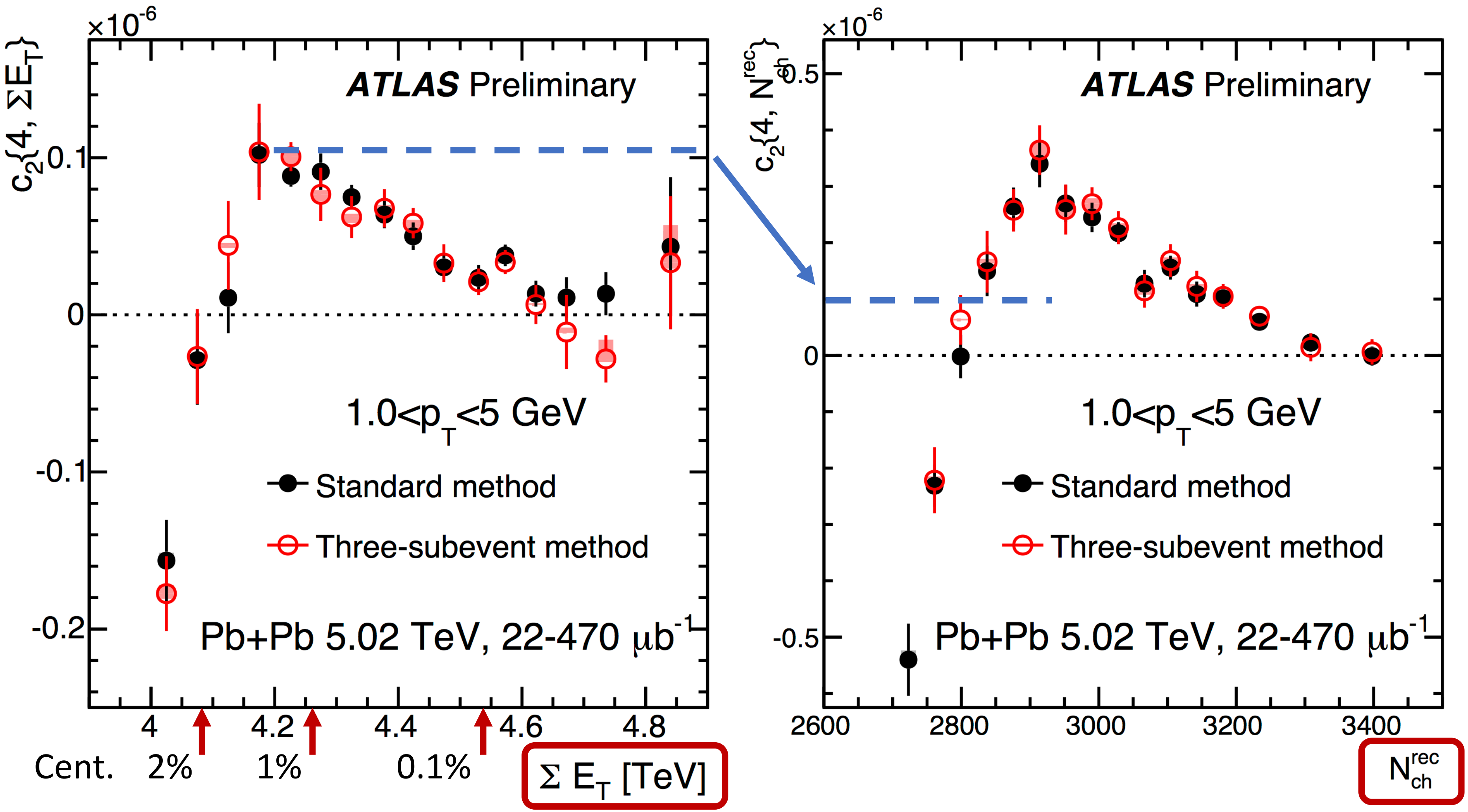
$\boxed{\text{Test relative CF by comparing } c_2\{4\} \text{ binned by } \Sigma E_{\mathrm{T}} \text{ and } N_{ch}^{rec}}$



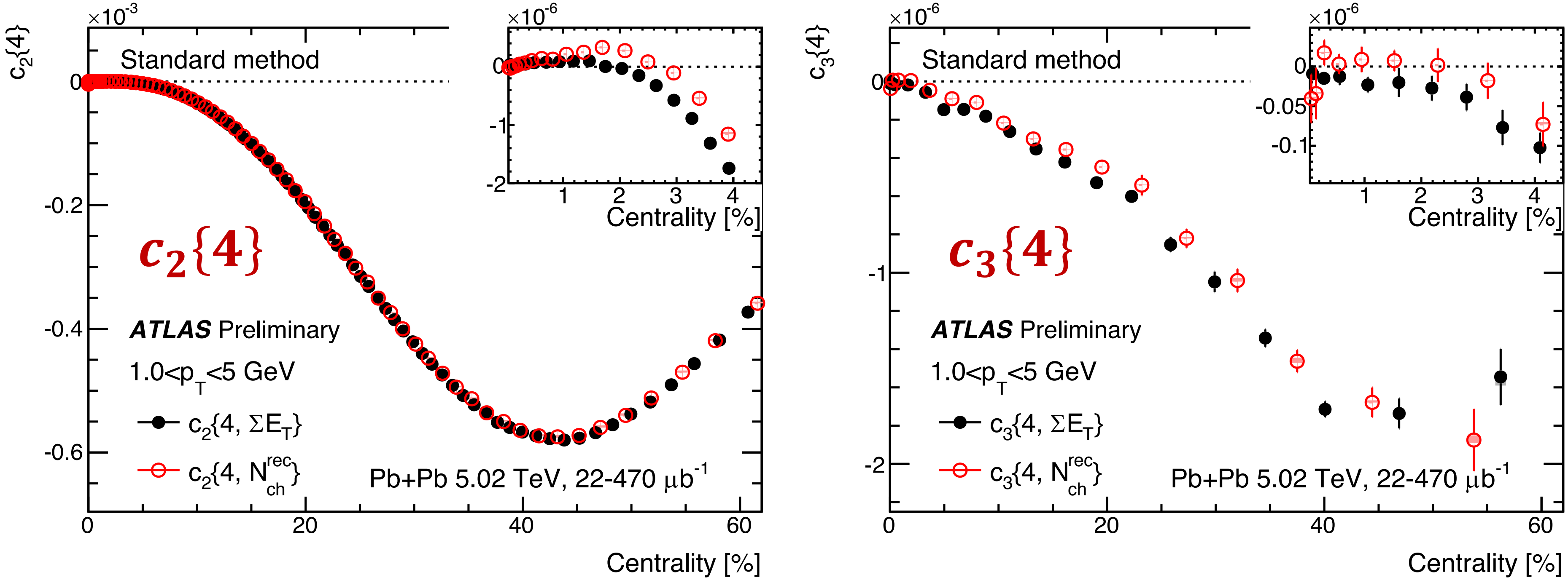
arXiv:1803.01812

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

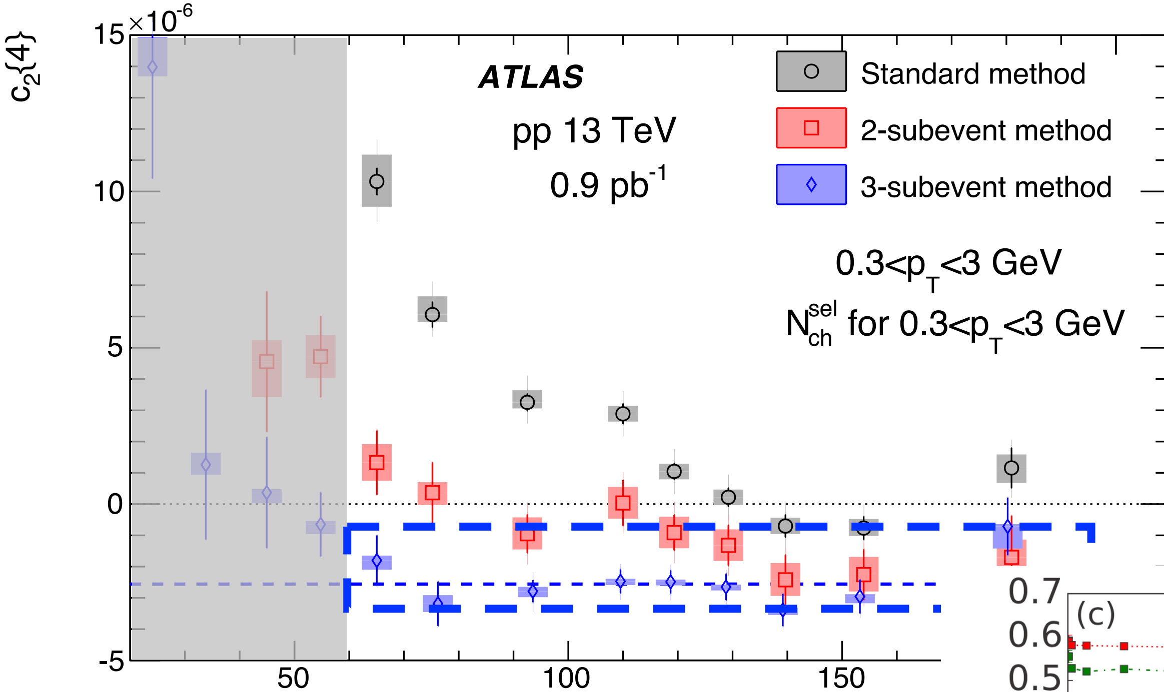
$c_2\{4\}$ and centrality fluctuation

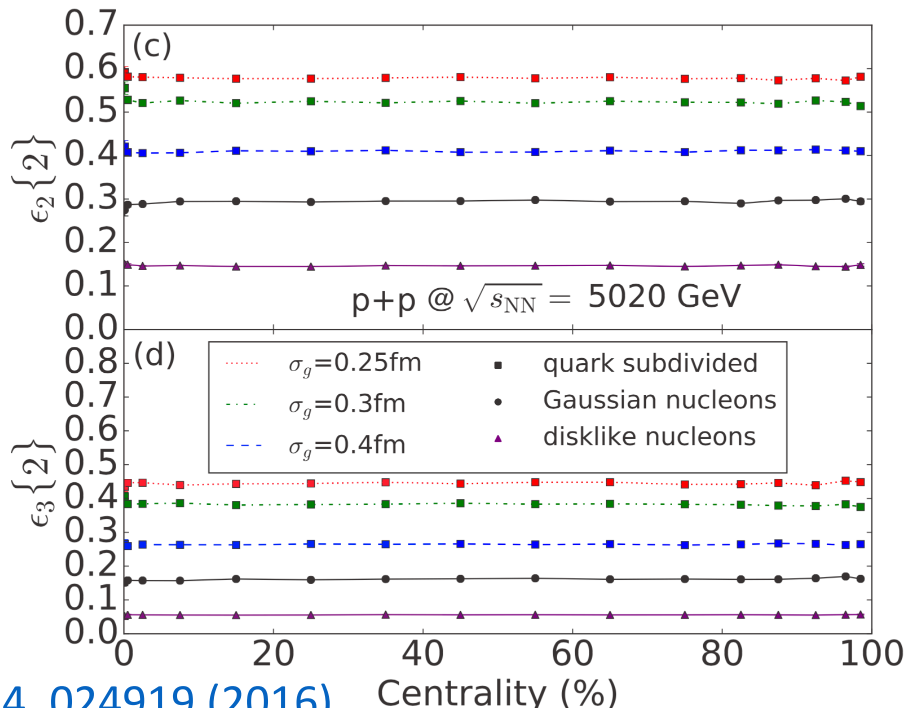


- $c_2\{4, \Sigma E_{\mathrm{T}}\} < c_2\{4, N_{ch}^{rec}\}$: CF affects flow cumulant;
- $c_2\{4\} \rightarrow 0$ in very most-central: smaller CF effect;



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





- 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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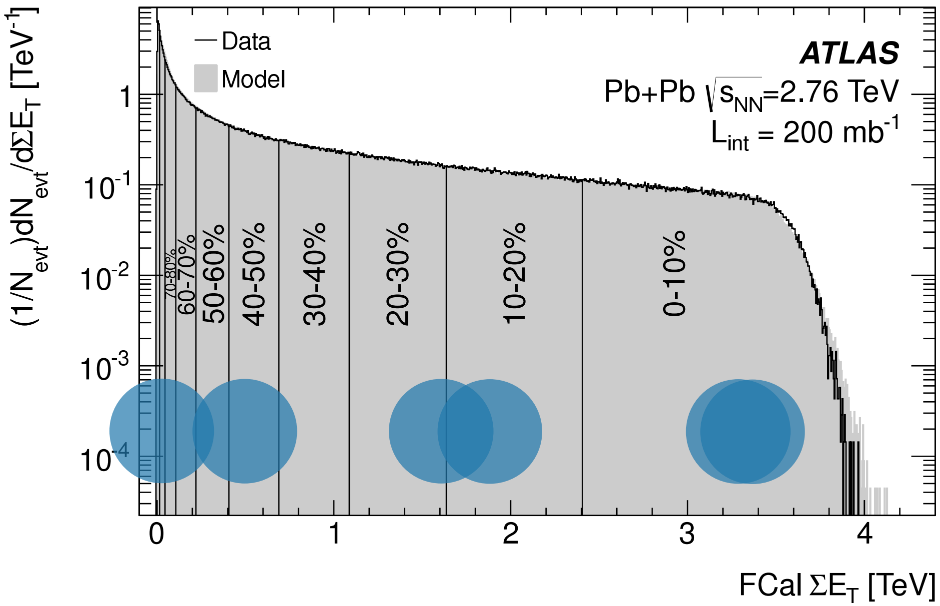
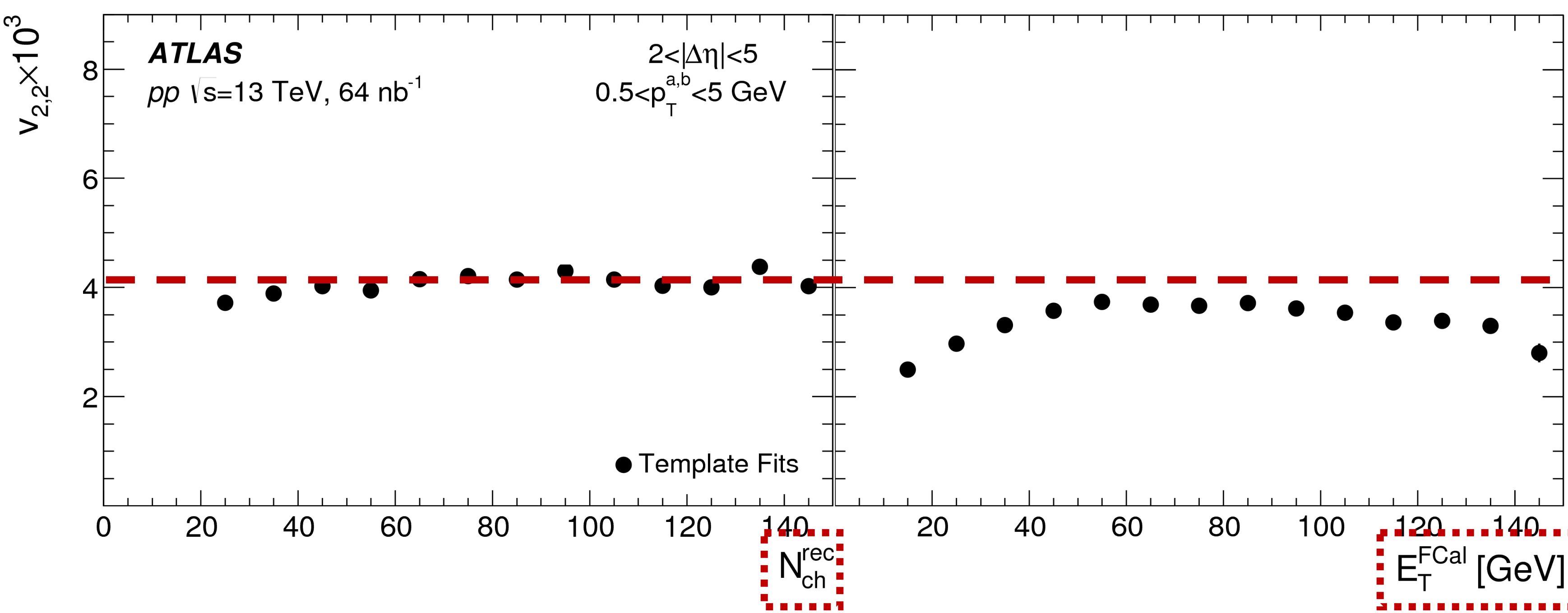
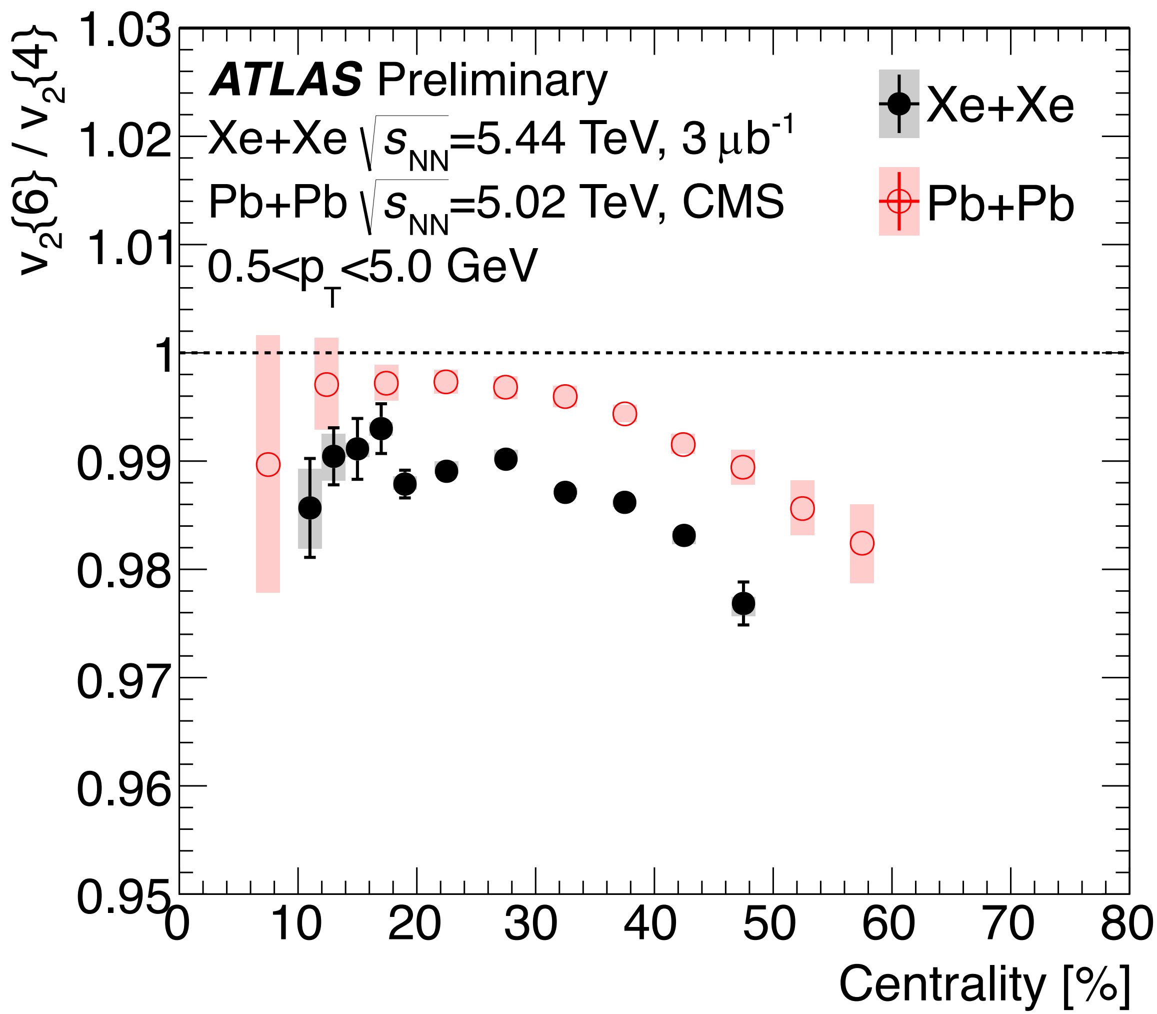


- Centrality quantifies the overlap region of the collision;
- The mapping replies on model and is on the average level;
- Different centrality definitions gives different dependence.



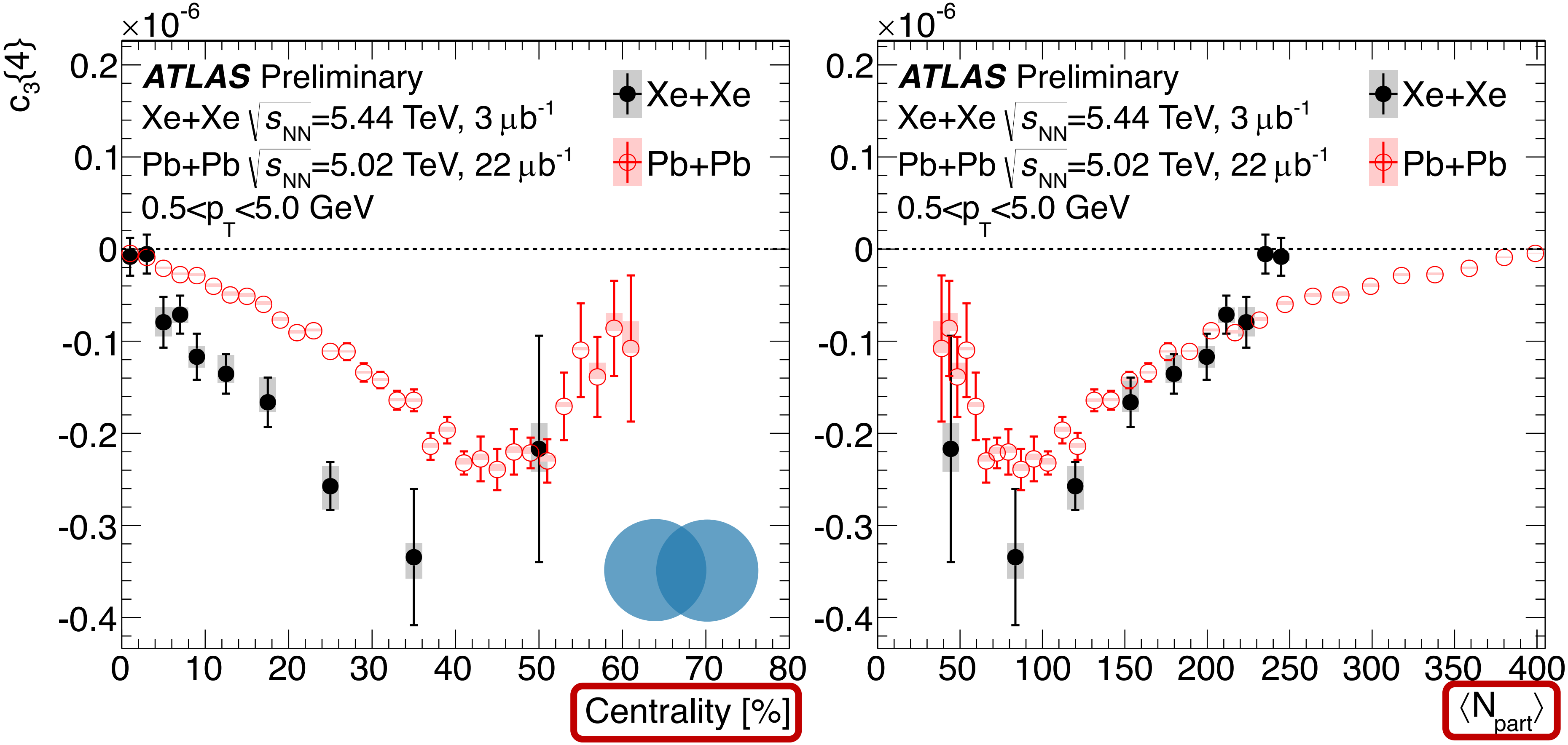
Comparison between Pb+Pb and Xe+Xe

Xe+Xe and Pb+Pb: v_2



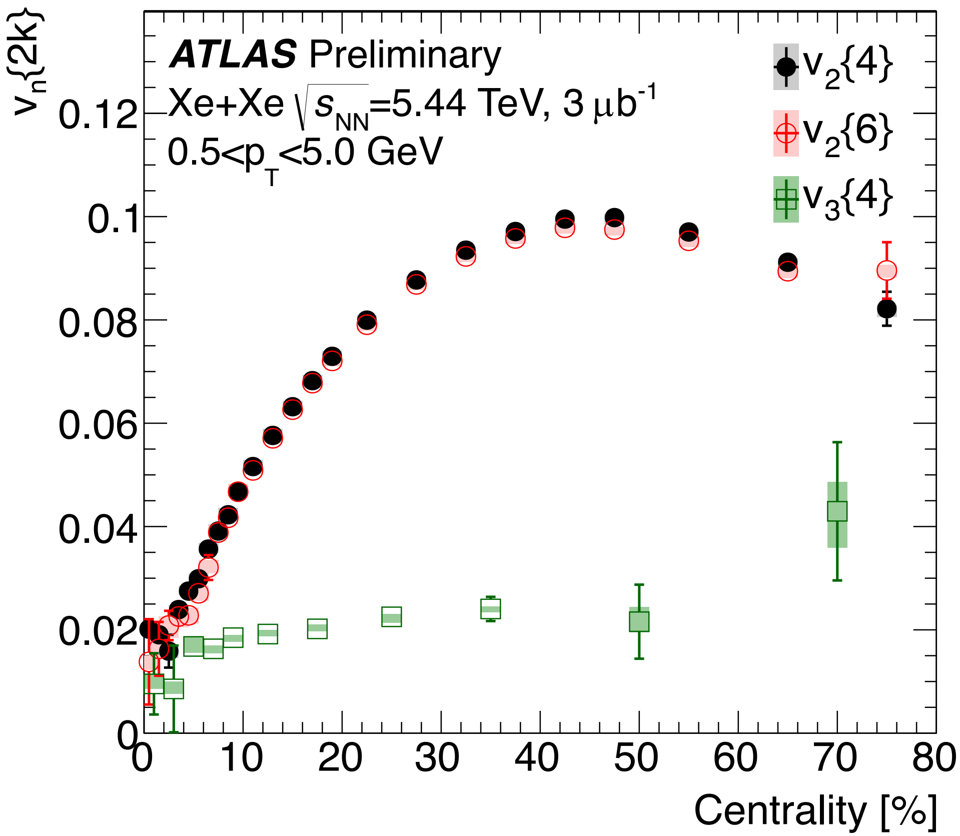
- Mass number of Xe is halfway of Pb and p;
- If $v_2 \sim Gauss(\bar{v}_n, \delta_n)$: $v_2\{6\}/v_2\{4\} = 1$
- v_2 in Xe+Xe deviates further from Gauss: deformed nucleus?

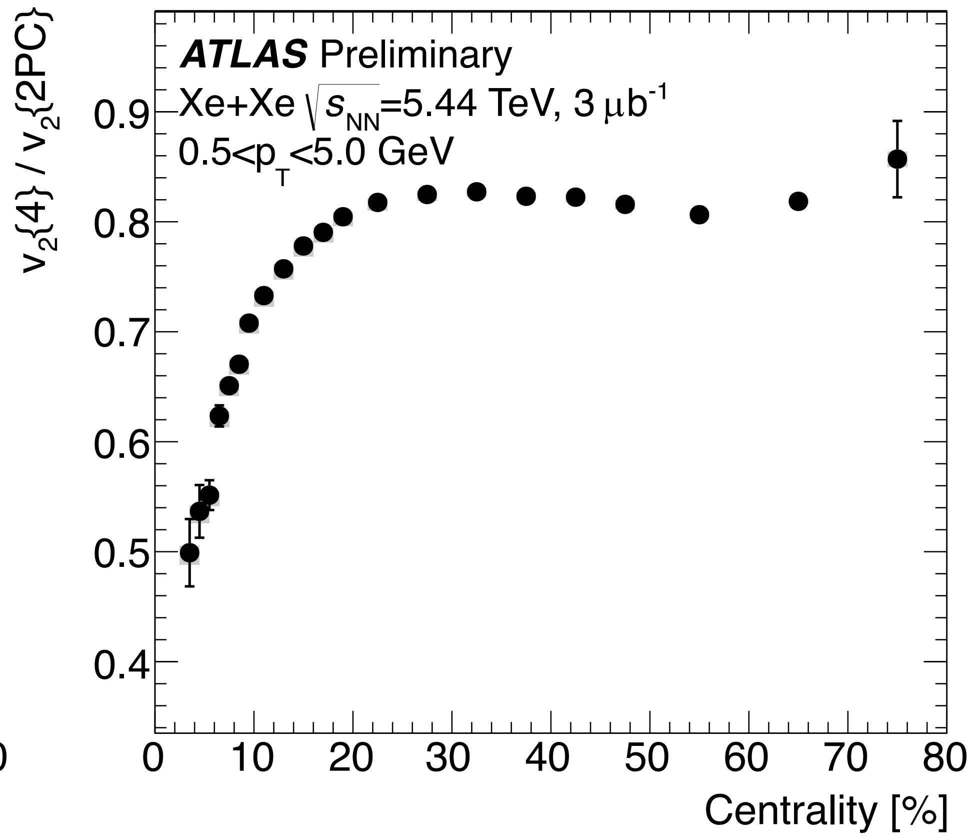
Xe+Xe and Pb+Pb: v_3

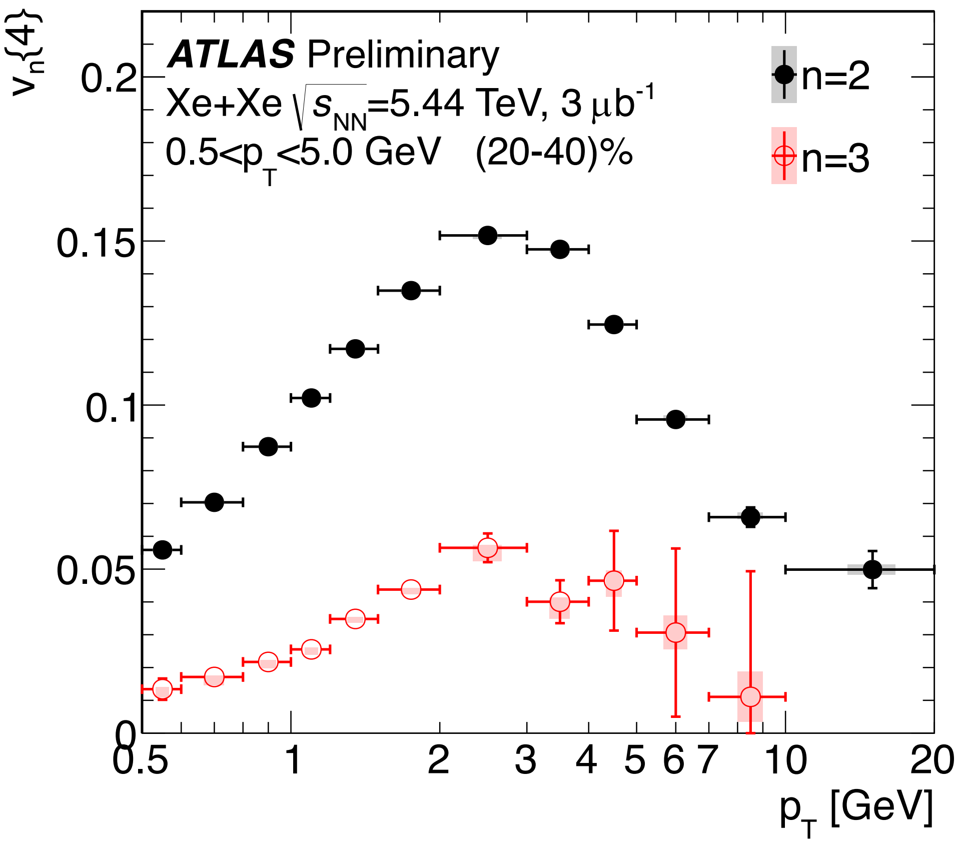


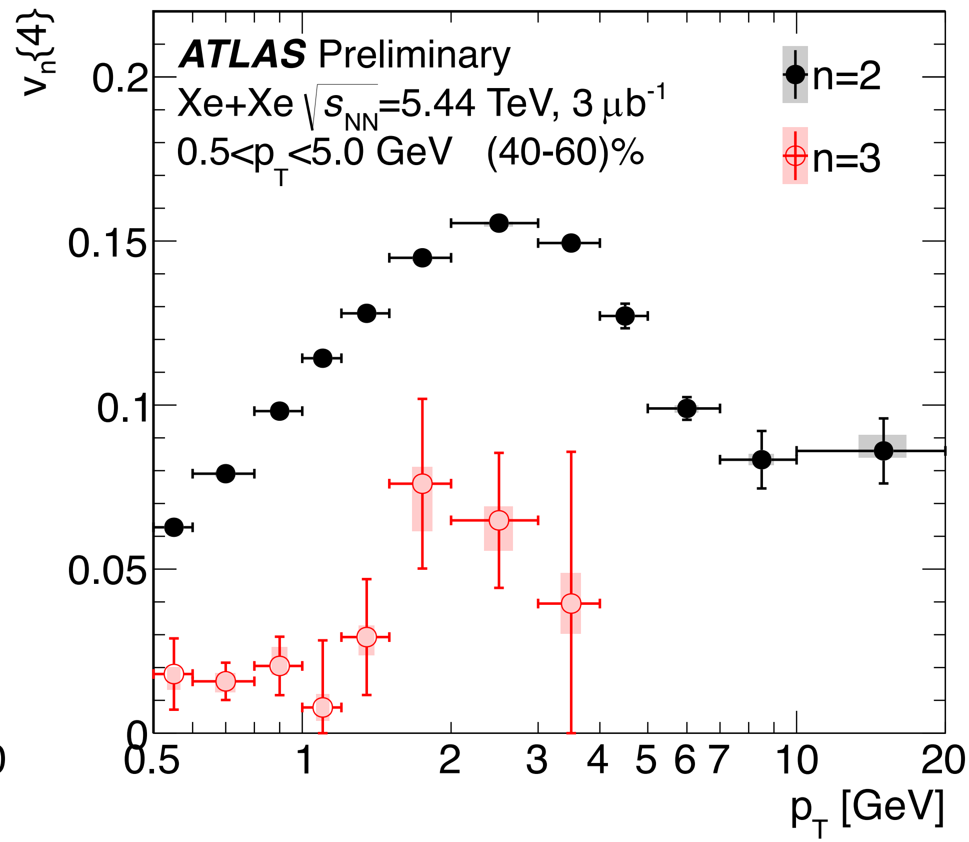
- $c_3\{4\}$ doesn't scale with centrality between Xe and Pb
  - No avg. geometry for v_3;
- $c_3\{4\}$ scales with $\langle N_{part} \rangle$
  - Fluctuation driven by # of sources N_{part}
- Similar observation for $c_4\{4\}$ (see backup)

Multi-particle cumulant

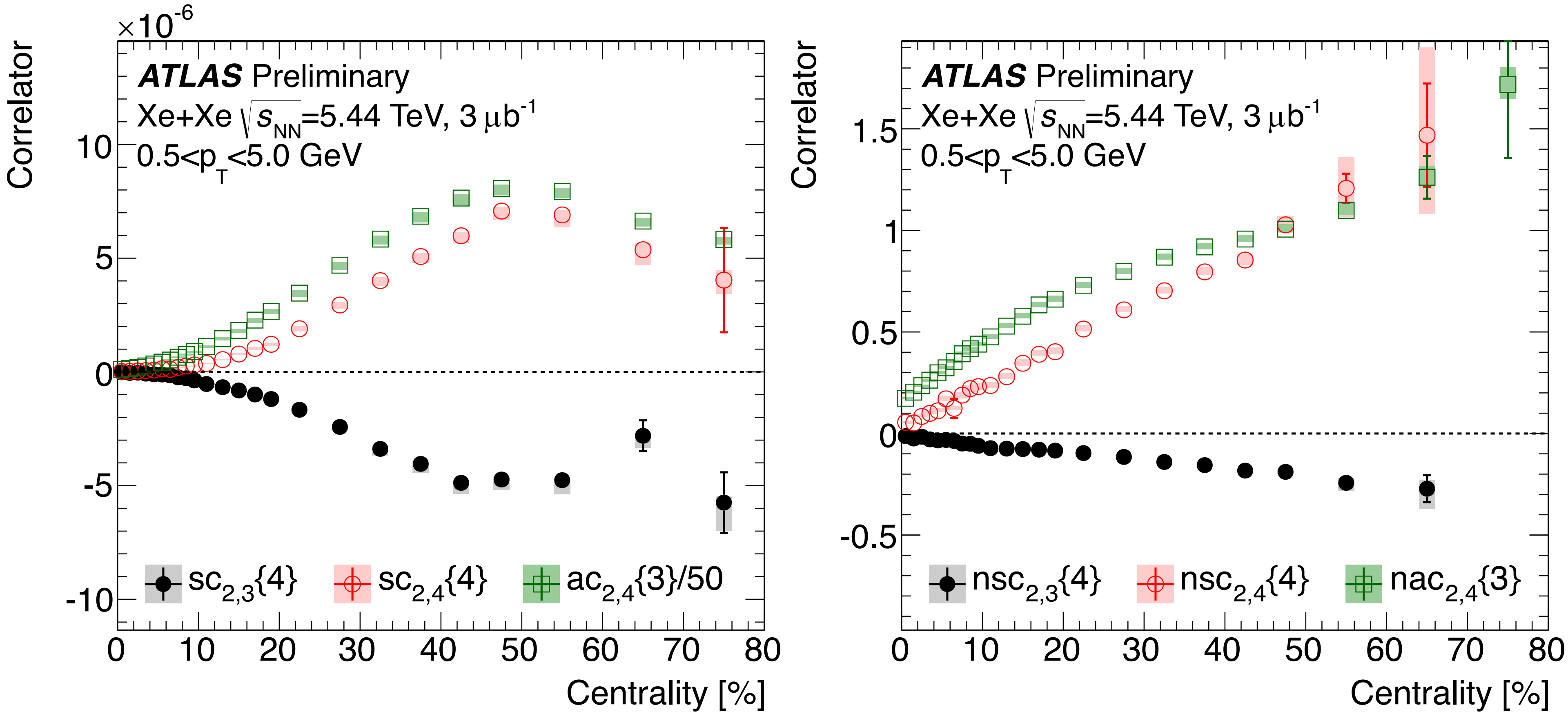


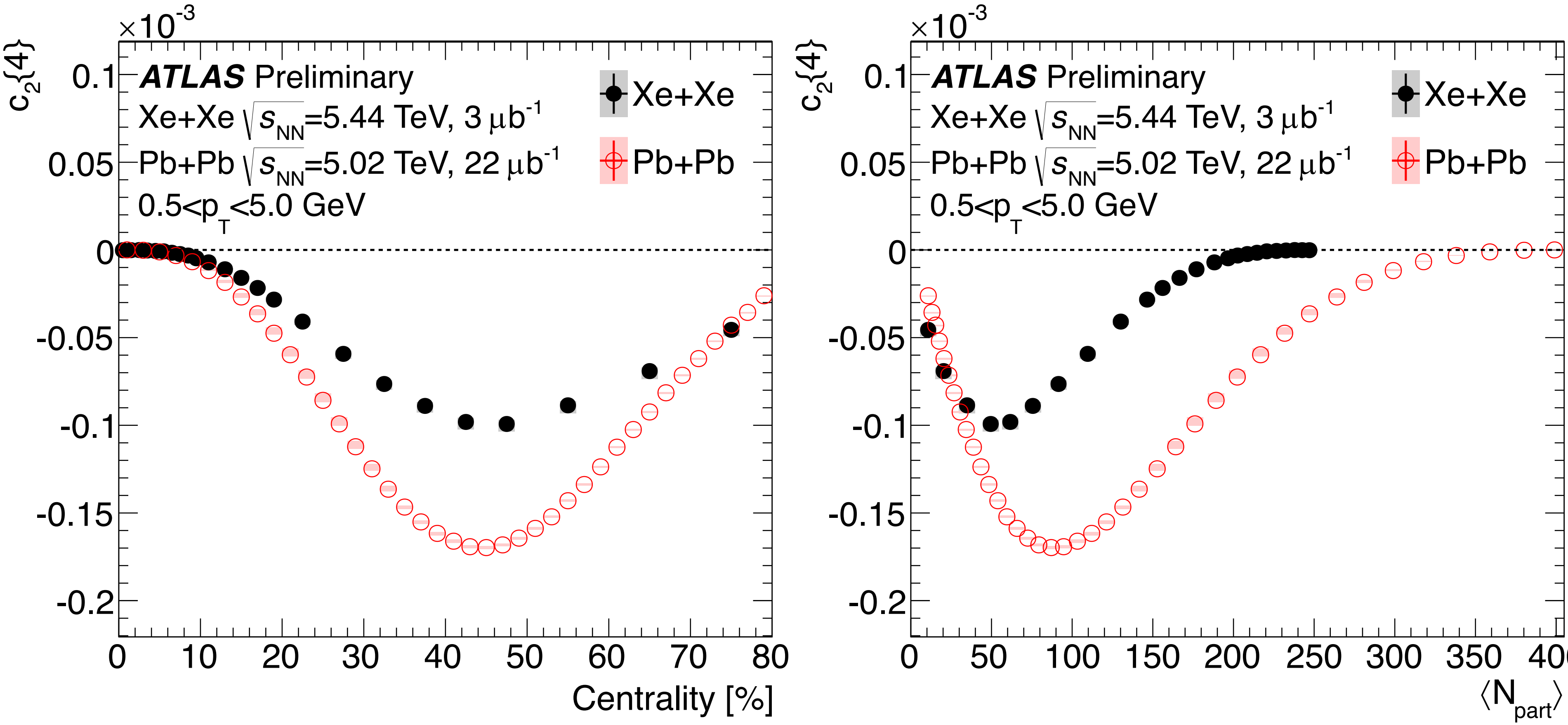



ATLAS Preliminary
Xe+Xe √s_NN=5.44 TeV, 3 μb^-1
0.5<p_T<5.0 GeV (20-40)%
n=2
n=3
v_n{4}
p_T [GeV]


ATLAS Preliminary
Xe+Xe √s_NN=5.44 TeV, 3 μb^-1
0.5<p_T<5.0 GeV (40-60)%
n=2
n=3
v_n{4}
p_T [GeV]

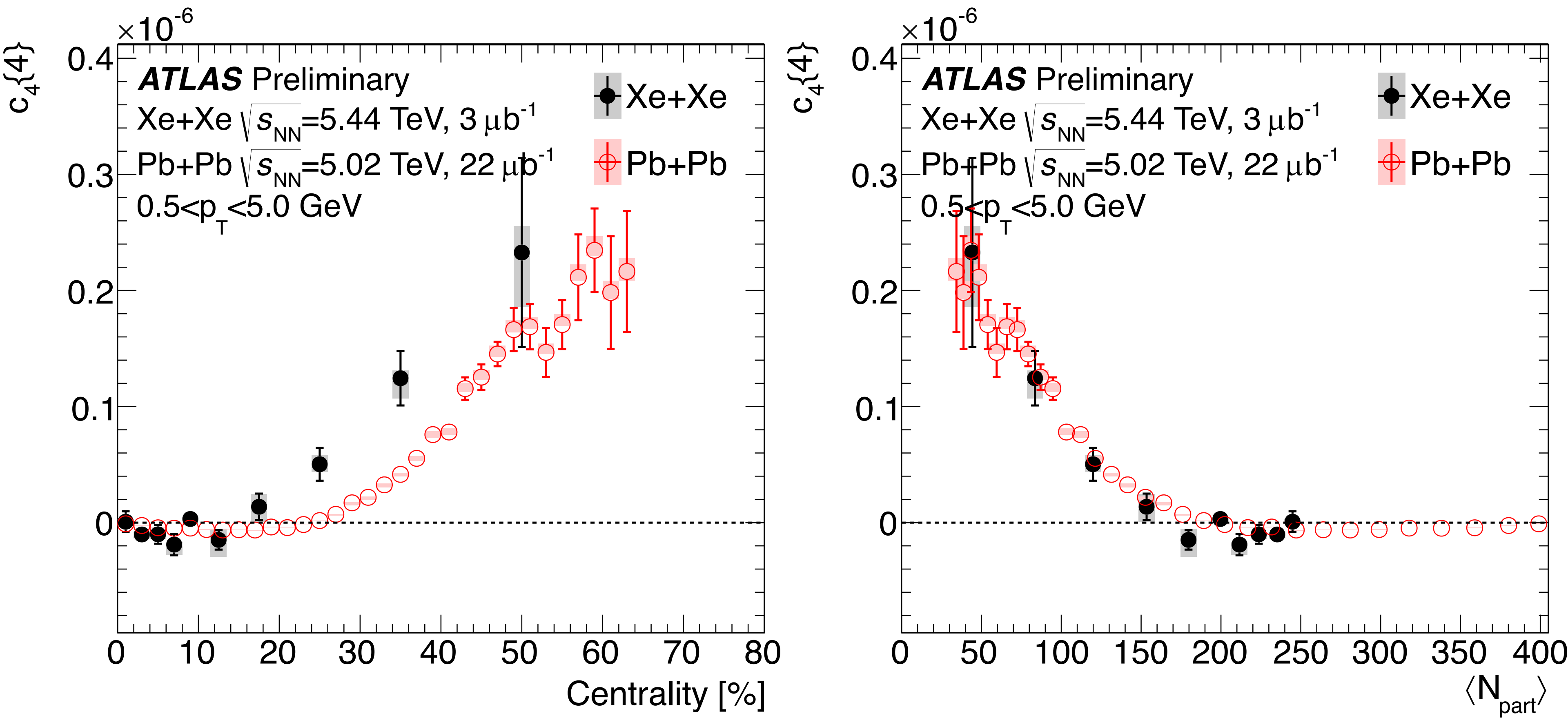
Symmetric cumulant





×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⟩

$c_3\{4\}$

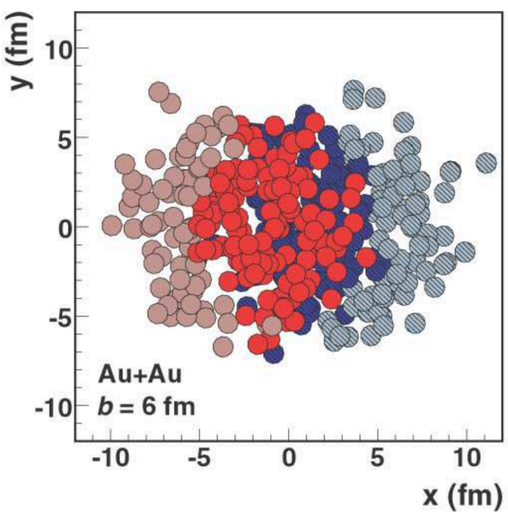

$\times 10^{-6}$
$c_4\{4\}$
ATLAS Preliminary
Xe+Xe $\sqrt{s_{NN}}$=5.44 TeV, 3 μb^{-1}
Pb+Pb $\sqrt{s_{NN}}$=5.02 TeV, 22 μb^{-1}
0.5<p_T<5.0 GeV
Xe+Xe
Pb+Pb
Centrality [%]
$\langle N_{part} \rangle$

Title

Origins of collectivity

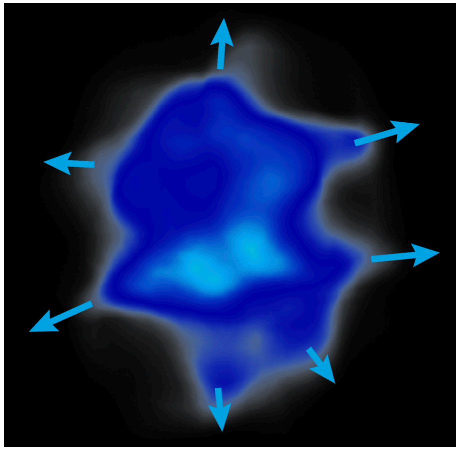
- **Final state correlations**

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



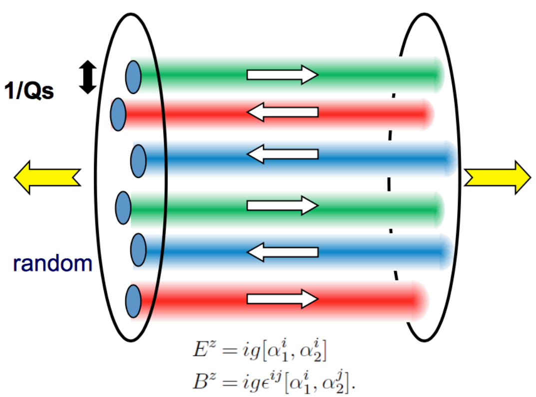
Spatial structure from initial condition

Hydrodynamic flow



Momentum correlations

- **Initial state correlations**



More careful studies in *pp* collisions are needed!

Particles are produced with momentum space correlations