Flow fluctuations in large systems (Xe and Pb) with ATLAS detector

Mingliang Zhou

for the ATLAS Collaboration

Quark Matter 2018, May 13-19, Venice

ATLAS-CONF-2017-066

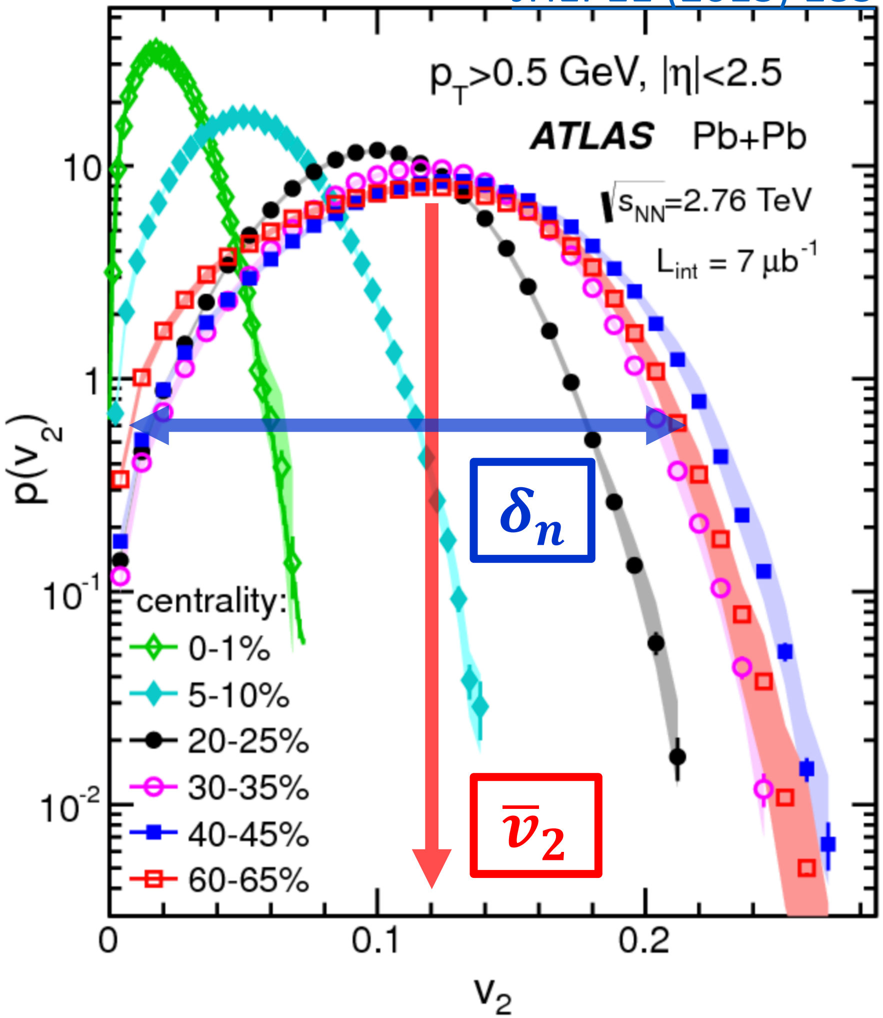
ATLAS-CONF-2018-011

ATLAS EXPERIMENT

Stony Brook University

Flow fluctuation and cumulant

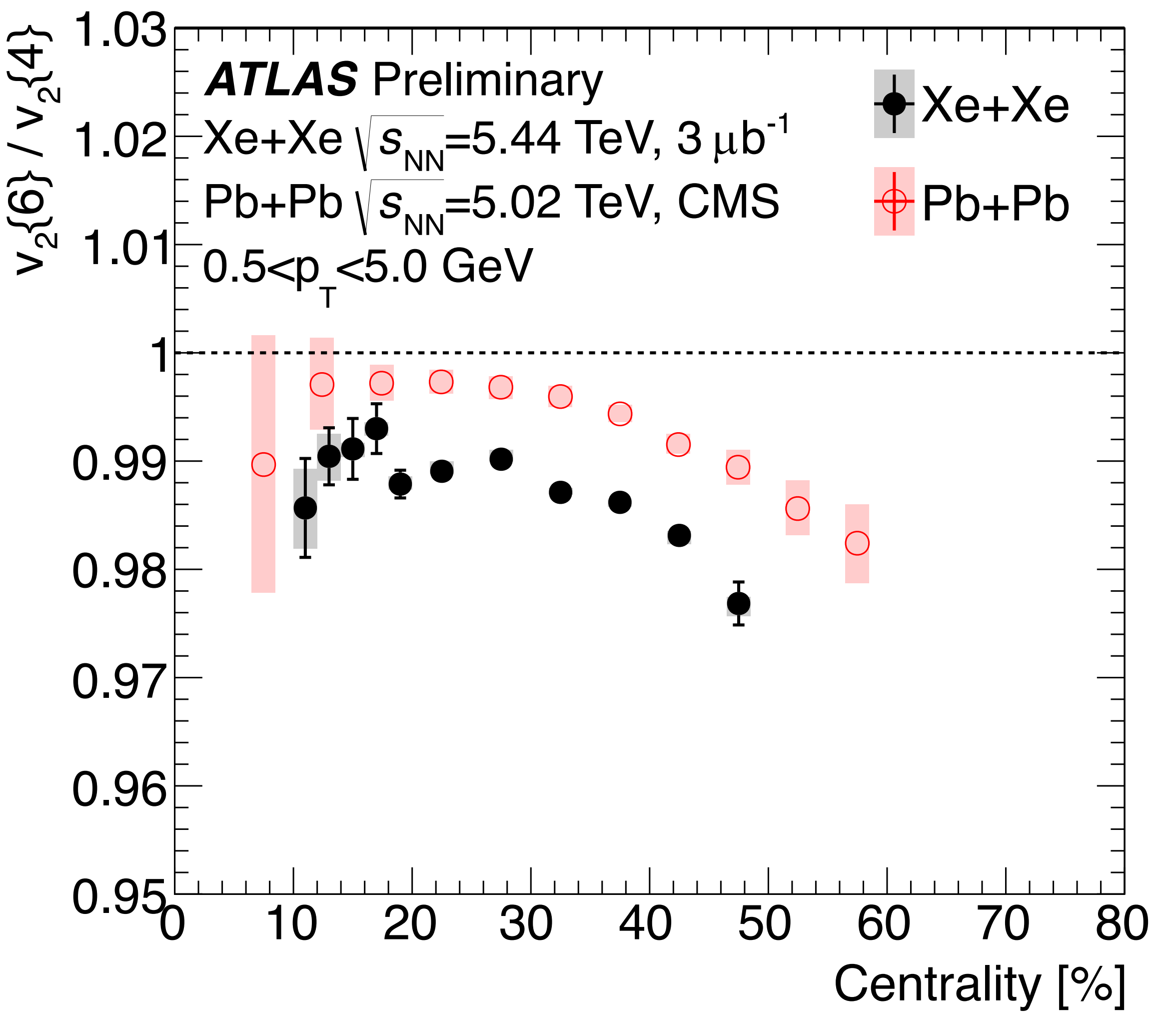
JHEP11 (2013) 183



- Flow fluctuates from event to event
  - Initial geometry
  - Hydro evolution
- Cumulant $c_n\{2k\}$ measures $p(v_n)$
  - Suppresses non-flow
  - $v_n\{4\} \equiv \sqrt[4]{-c_n\{4\}}$
- Many sources ⇒ $v_n \sim Gauss(\bar{v}_n, \delta_n)$
  - $v_n\{2\} = \sqrt{\bar{v}_n^2 + \delta_n^2}$
  - $v_n\{4\} = v_n\{6\} = \cdots = \bar{v}_n$

- System comparisons; $v_1\{4\}$ and $v_4\{4\}$ in Pb+Pb
- $v_2\{4\}$ in ultra-central: role of centrality fluctuation

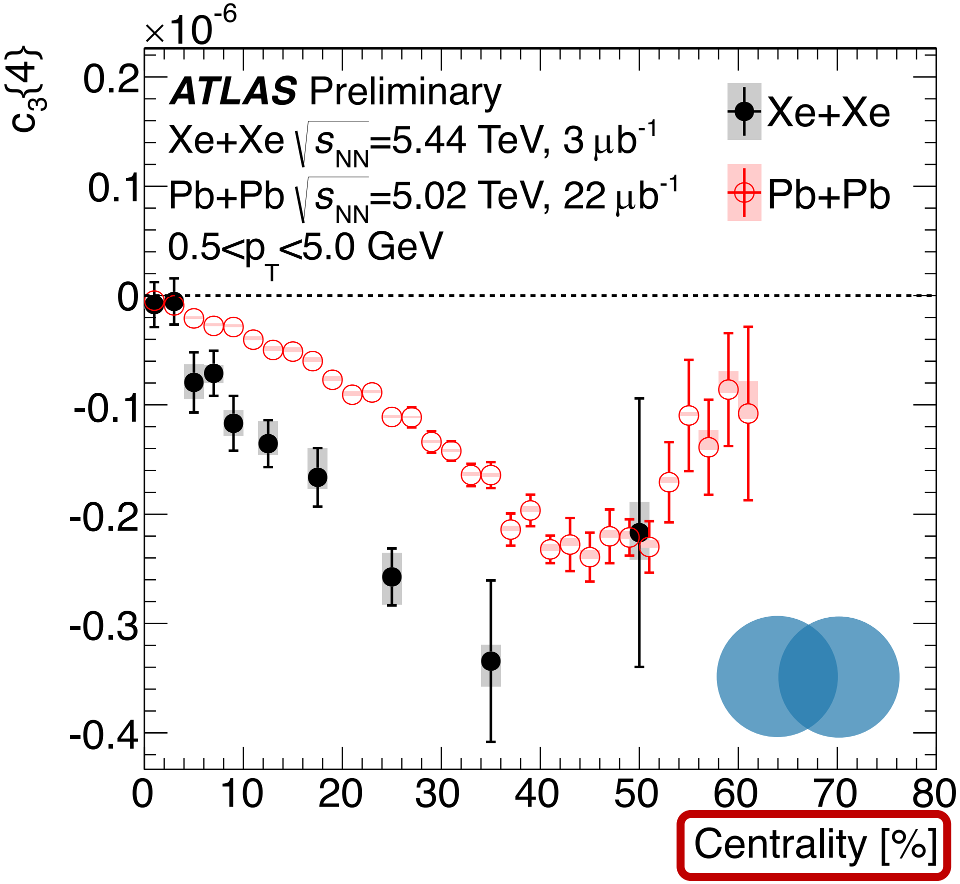
Xe+Xe and Pb+Pb: v_2



T. Bold
Tue 11:30 AM

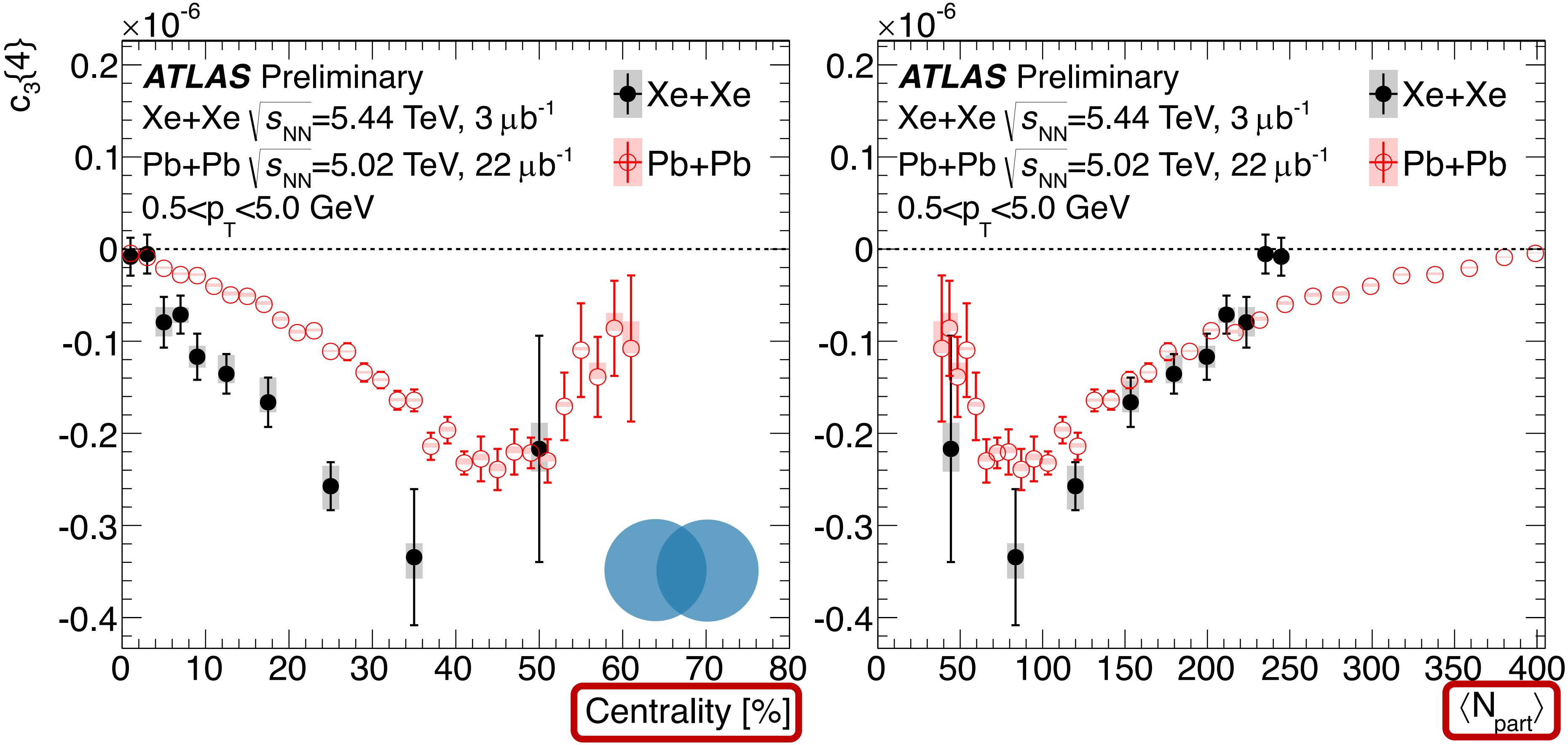
- Mass number of Xe is halfway of Pb and p;
- If $v_2 \sim Gauss(\bar{v}_n, \delta_n)$: $v_2\{6\}/v_2\{4\} = 1$
- v_2 in Xe+Xe deviates further from Gauss: deformed nucleus?

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;

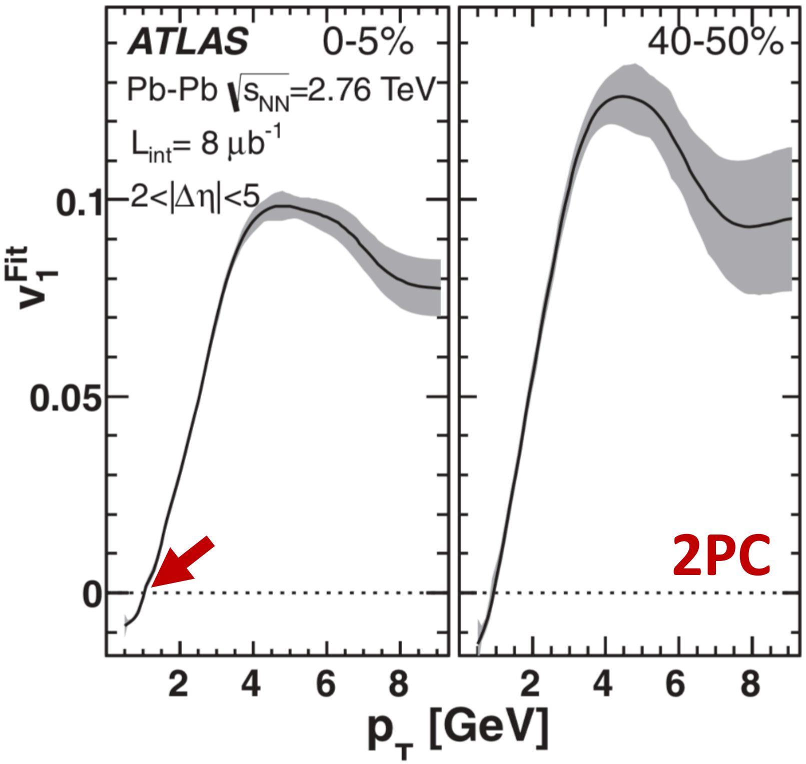
Xe+Xe and Pb+Pb: v_3



- $c_3\{4\}$ 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)

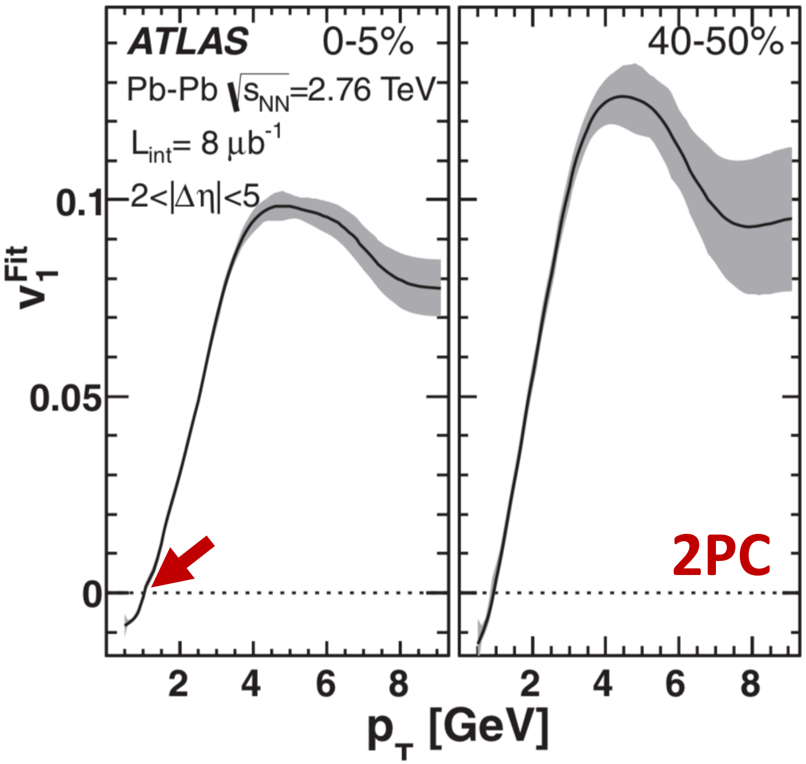
4-particle v_1

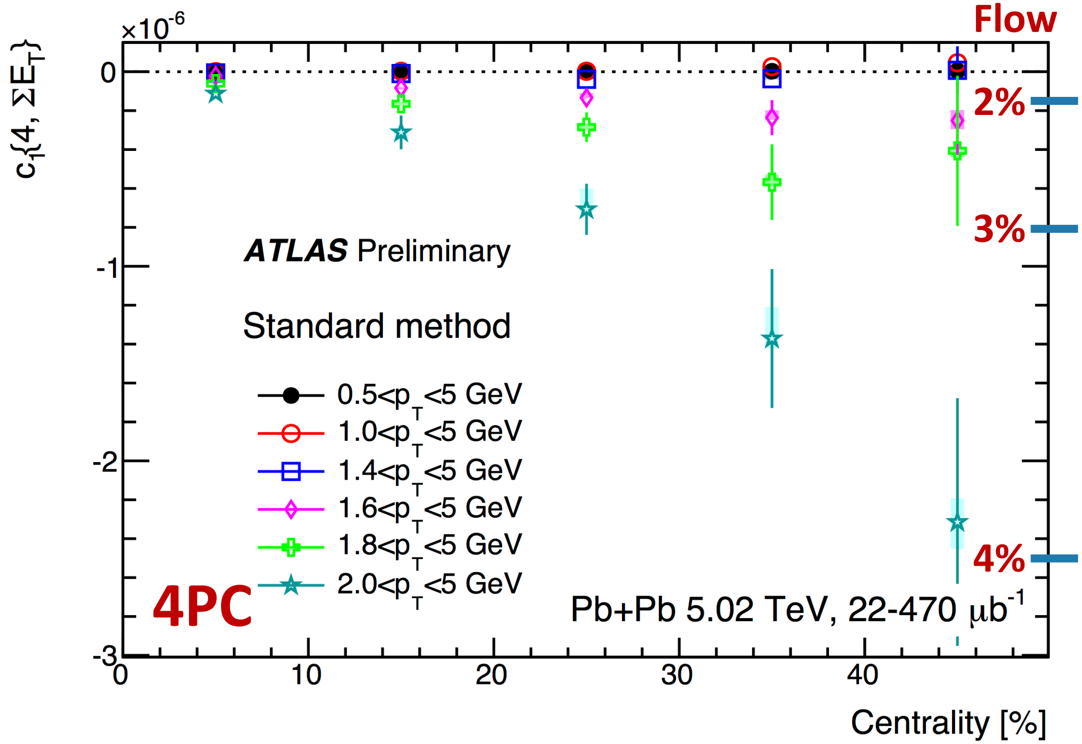
Phys. Rev. C **86**, 014907 (2012)



- To measure 4-particle v_1
  - High p_T cut needed: $v_1\{2PC\}$ changes sign at $p_T = 1.2$ GeV;
  - Free of 2PC momentum conservation: $c_1\{4\} = \langle 4\rangle - 2\langle 2\rangle^2$;

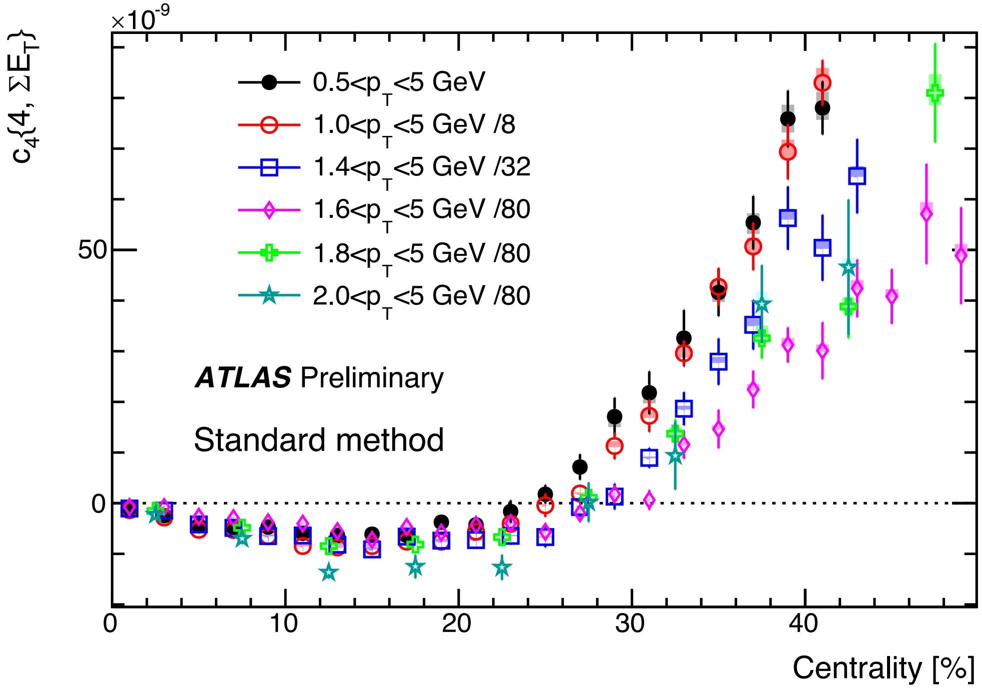
Phys. Rev. C **86**, 014907 (2012)





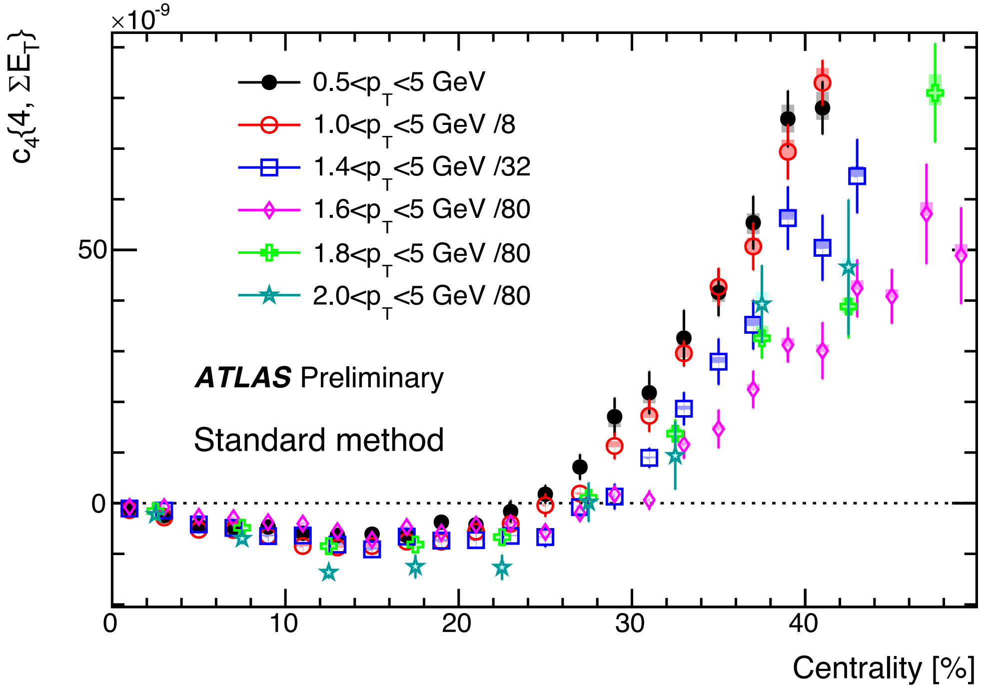
- To measure 4-particle v_1
  - High p_T cut needed: $v_1\{2PC\}$ changes sign at $p_T = 1.2$ GeV;
  - Free of 2PC momentum conservation: $c_1\{4\} = \langle 4 \rangle - 2\langle 2 \rangle^2$;
- Negative $c_1\{4\}$ observed in high p_T, peripheral collision

4-particle v_4

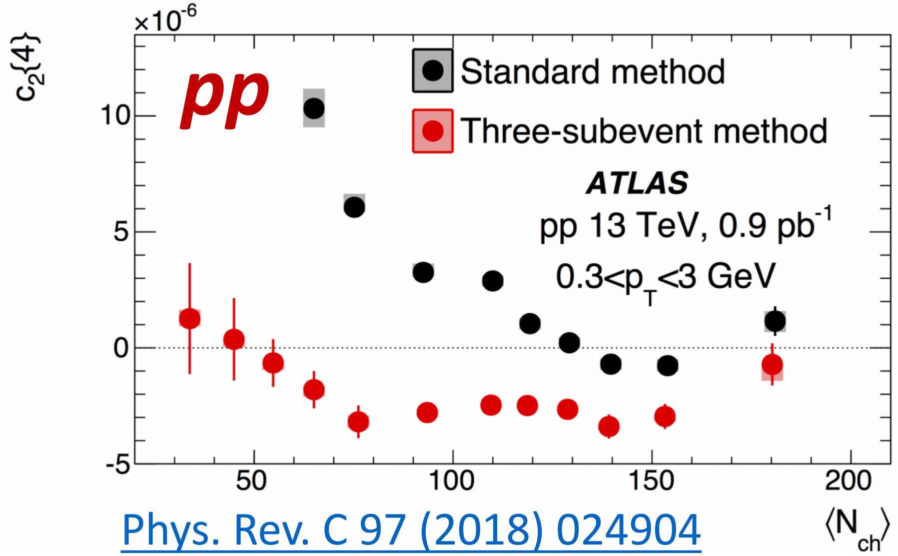


- $c_4\{4\} > 0$ and increase towards to peripheral: non-flow?

4-particle v_4



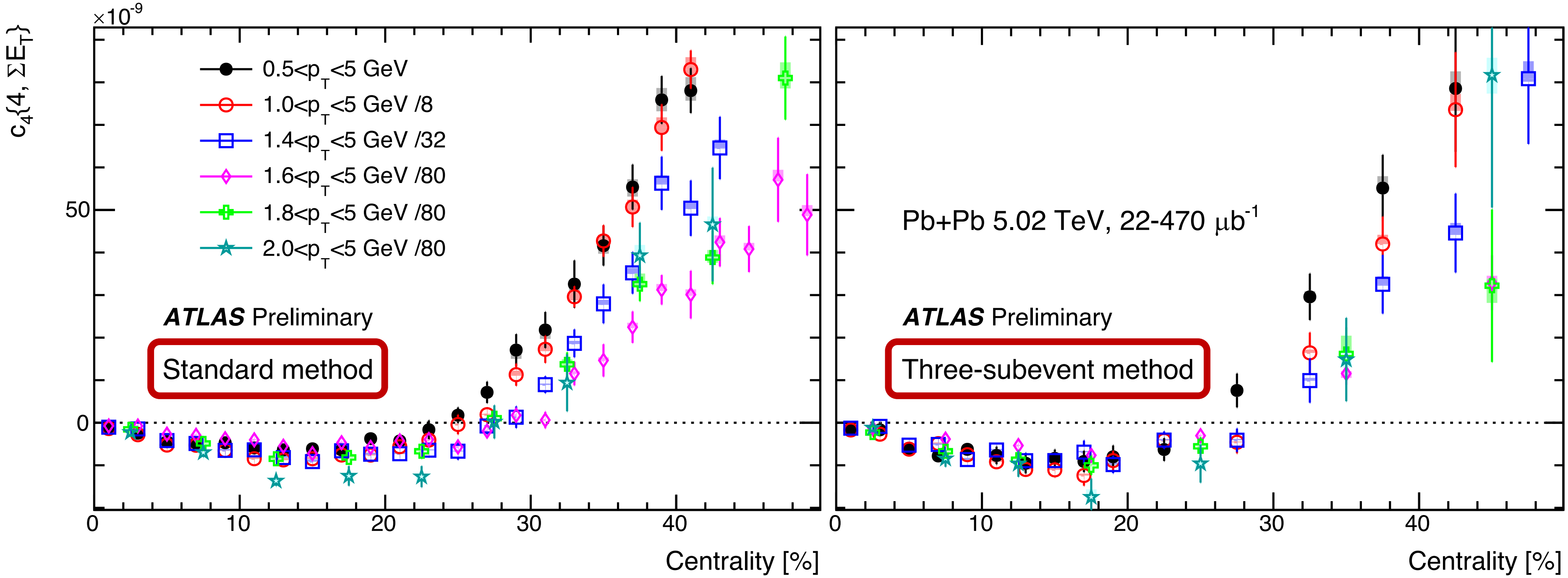
- Subevent cumulant effectively removes non-flow;



[Phys. Rev. C 97 (2018) 024904]

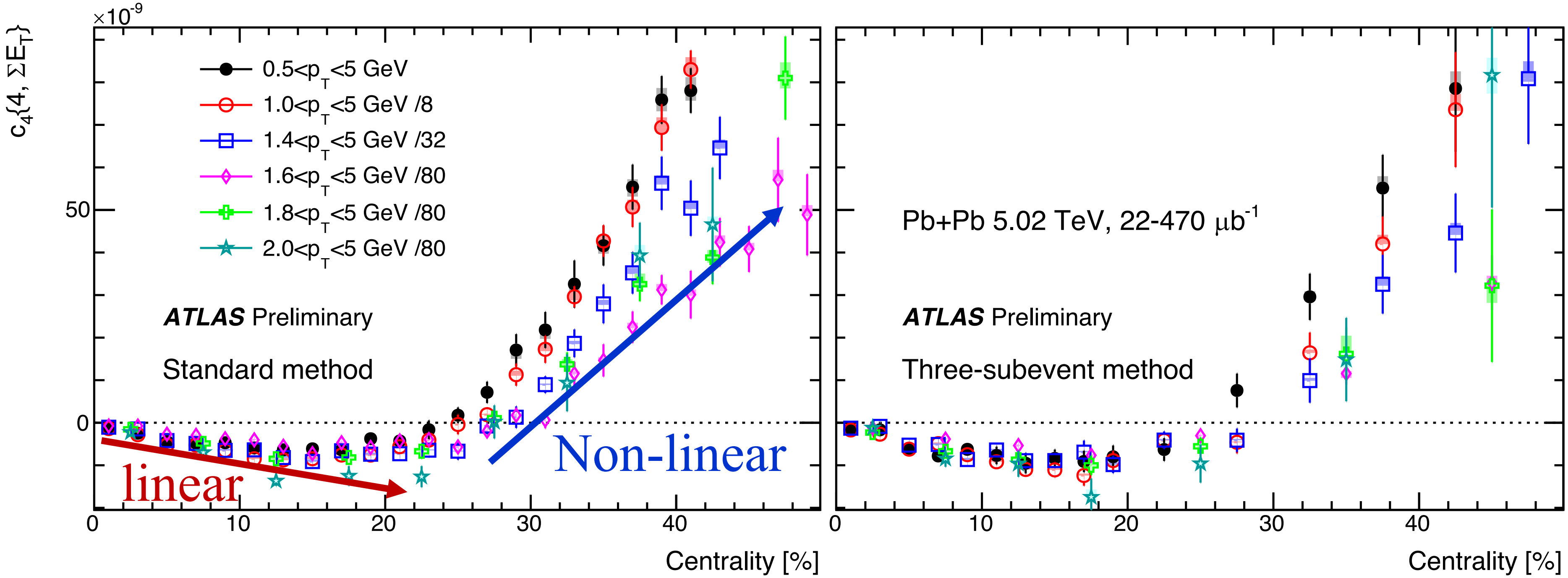
- $c_4\{4\} > 0$ and increase towards to peripheral: non-flow?

4-particle v_4



- $c_4\{4\} > 0$ and increase towards to peripheral: non-flow?
- 3-subevent measures the same: not due to non-flow.

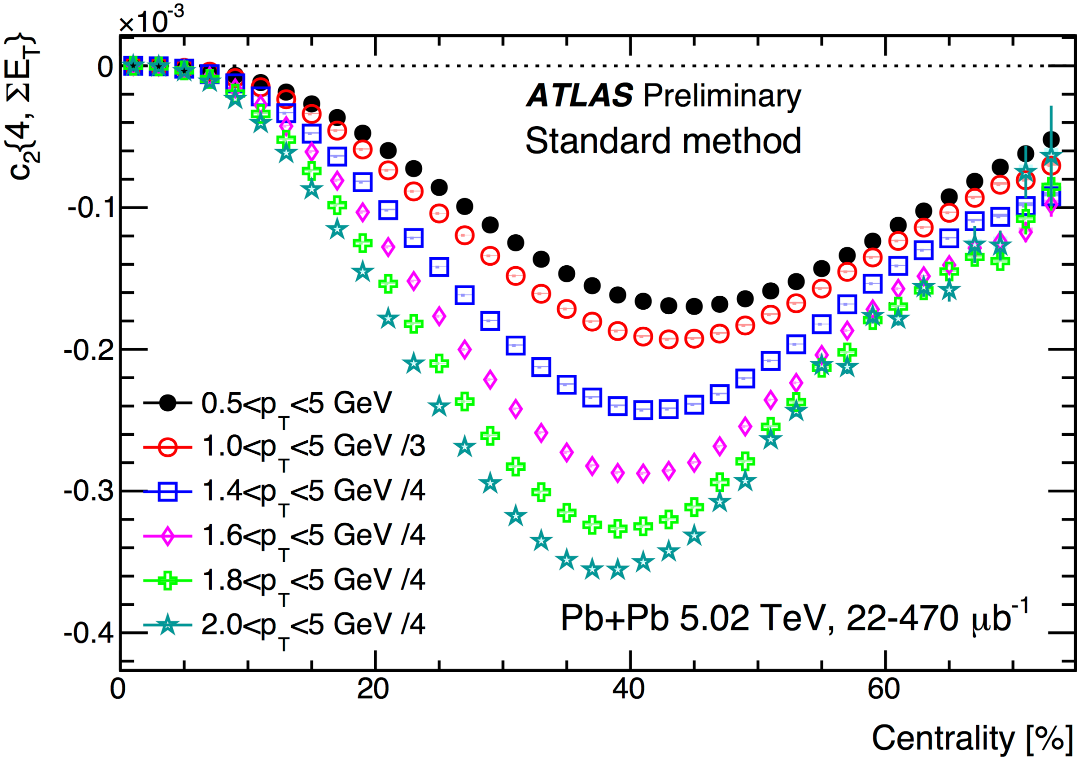
4-particle v_4



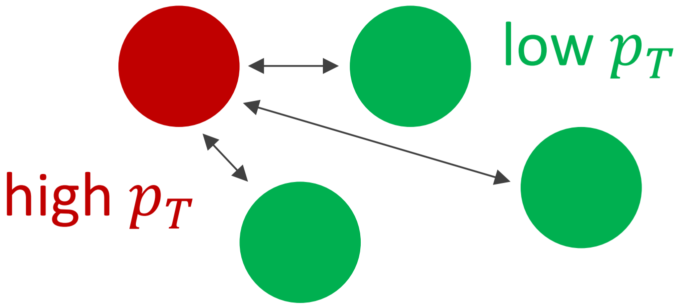
- $c_4\{4\} > 0$ and increase towards to peripheral: non-flow?
- 3-subevent measures the same: not due to non-flow.
- Linear and non-linear components: $v_4 = v_{4L} + \beta_{2,2} v_2^2$
  - $c_4\{4\} < 0$ in mid-central $\Leftarrow v_{4L}$
  - $c_4\{4\} > 0$ in peripheral $\Leftarrow v_2^2$
- Collectivity can also give $c_n\{4\} > 0$

J.Phys.Conf.Ser. 779 (2017) 012064

Centrality and p_{T} dependence of $c_2\{4\}$

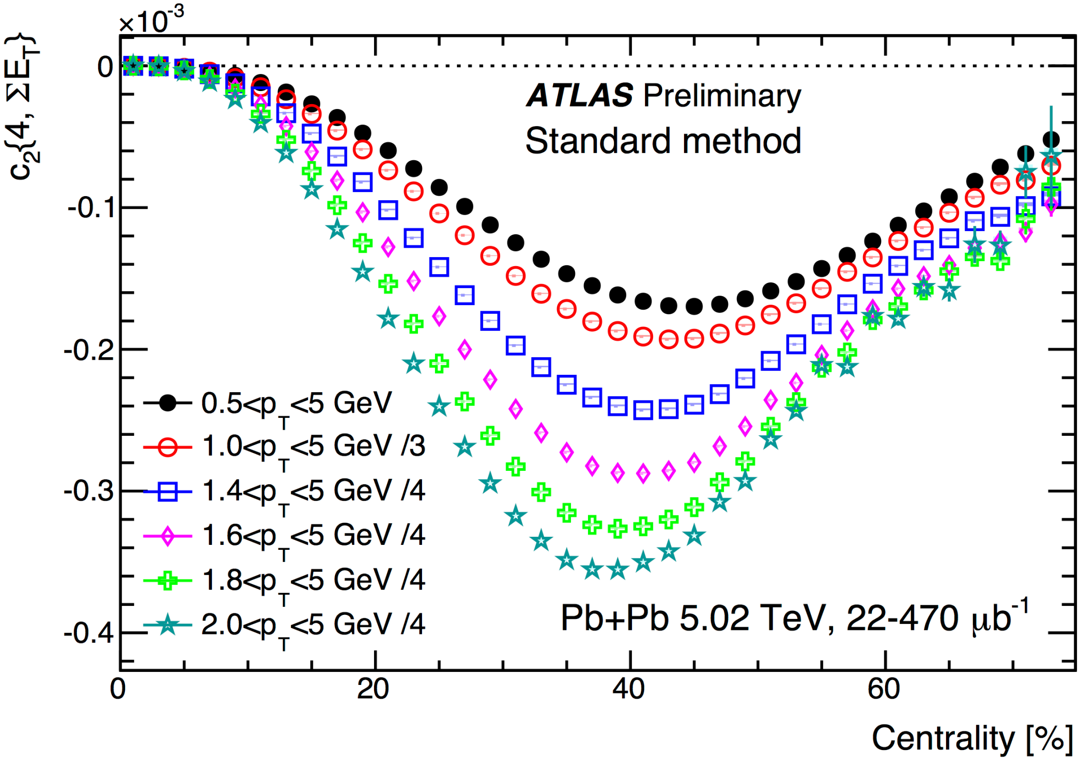


Previous measurement



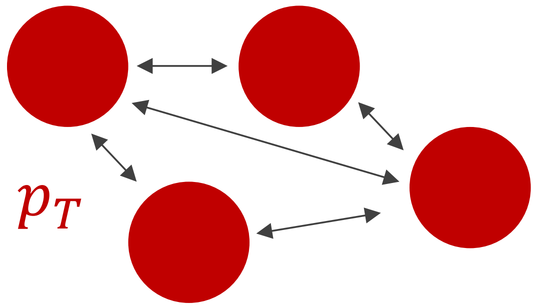
- Centrality dependence $\Leftarrow \bar{v}_2 \Leftarrow$ Geometry
- p_{T} dependence $\Leftarrow \bar{v}_2(p_{\mathrm{T}})$

Centrality and p_T dependence of $c_2\{4\}$



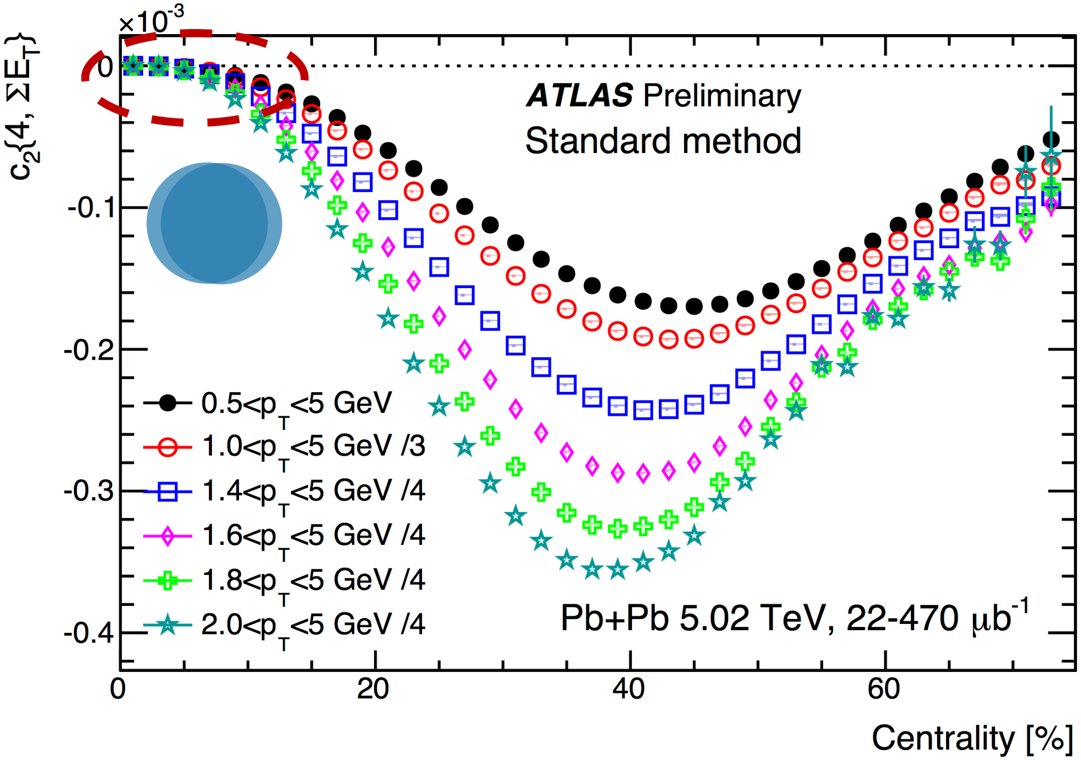
This measurement

high p_T



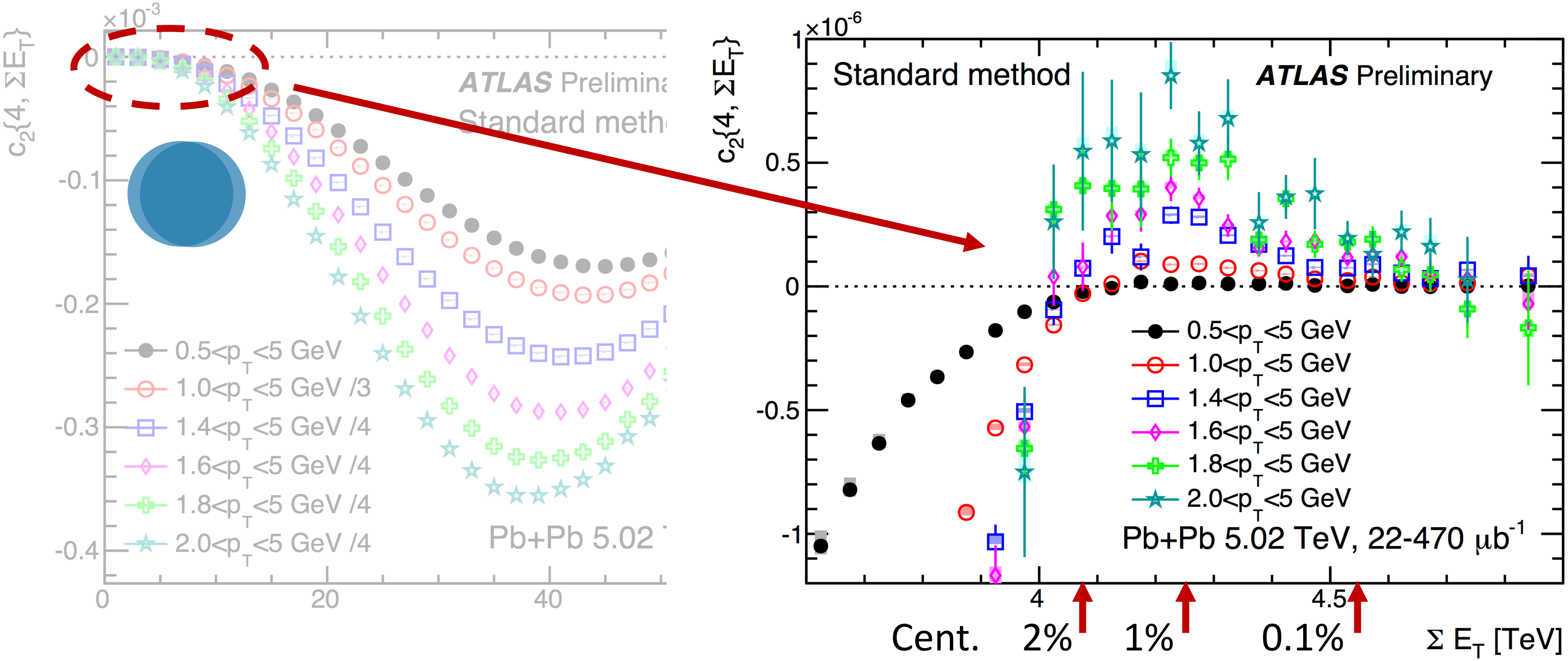
- Centrality dependence $\Leftarrow \bar{v}_2 \Leftarrow$ Geometry
- p_T dependence $\Leftarrow \bar{v}_2(p_T)$
  - Require all particles in the same p_T range;
  - Not affected by flow p_T-decorrelation;
- But how about flow fluctuation? Need to suppress $\bar{v}_2$.

Ultra-Central Collision (UCC)



- In UCC: $\bar{v}_2 \to 0$, largest relative flow fluctuation;
- ATLAS applied UCC triggers: ×20 statistics over MinBias;

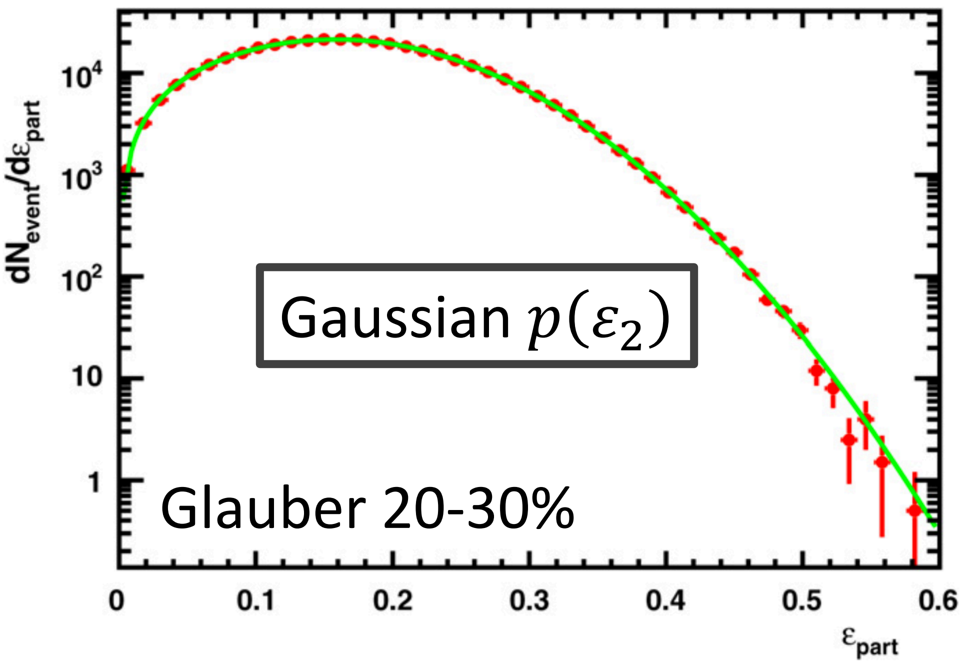
Ultra-Central Collision (UCC)



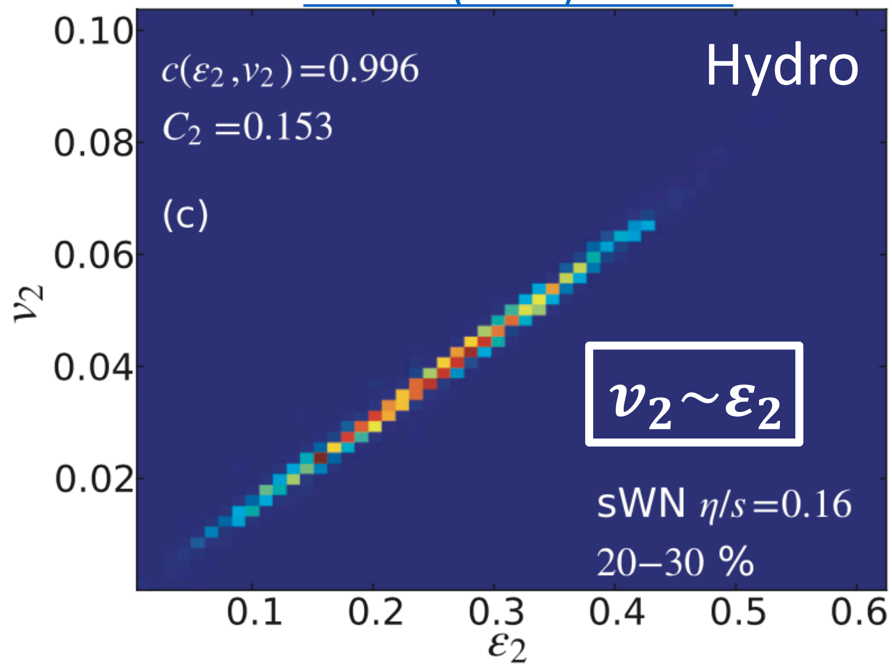
- In UCC: $\bar{v}_2 \rightarrow 0$, largest relative flow fluctuation;
- ATLAS applied UCC triggers: ×20 statistics over MinBias;
- $c_2\{4\} > 0$ in UCC ⇒ non-Gaussian flow fluctuation
  - Why?

Initial stage and hydro response

PLB 659 (2008) 537-541



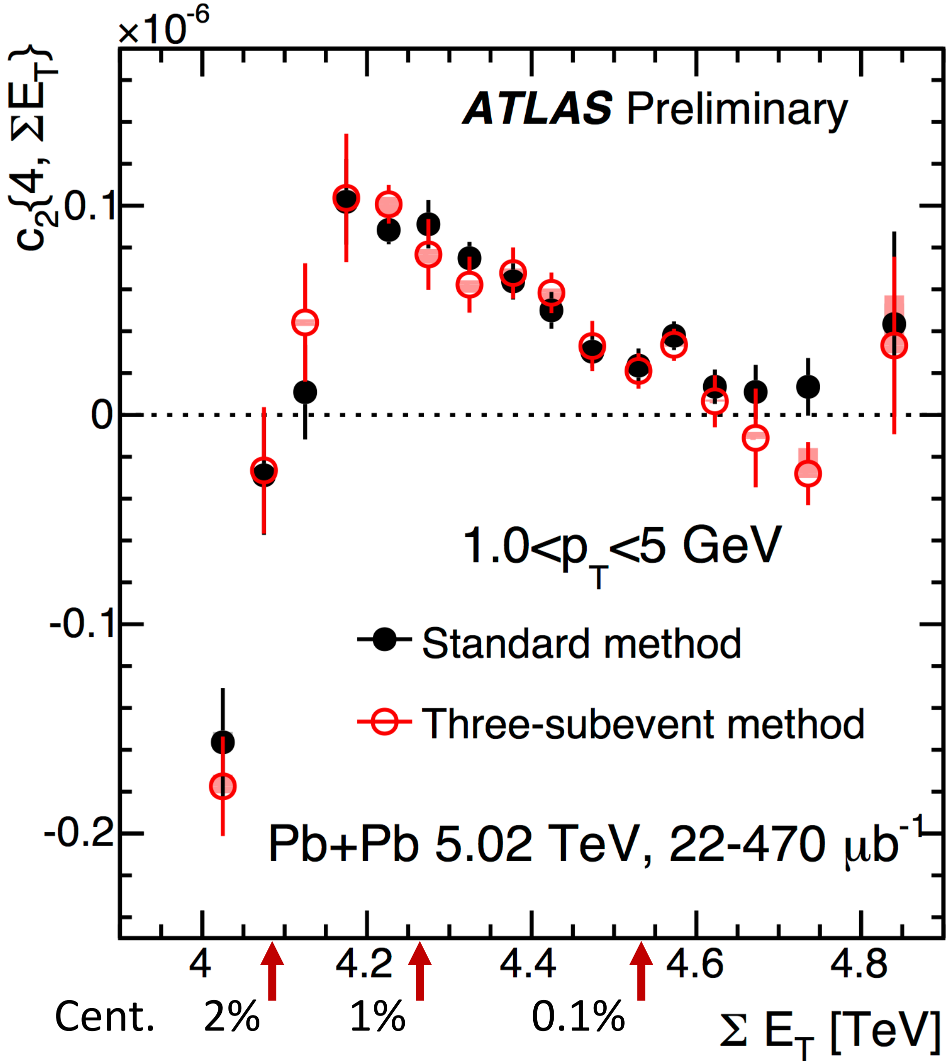
PRC 87 (2013) 054901



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

- 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?

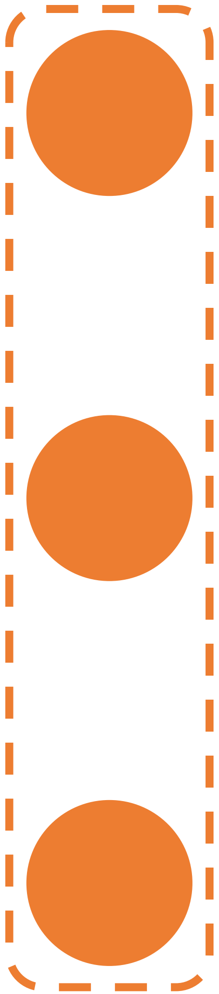
Non-flow contribution?



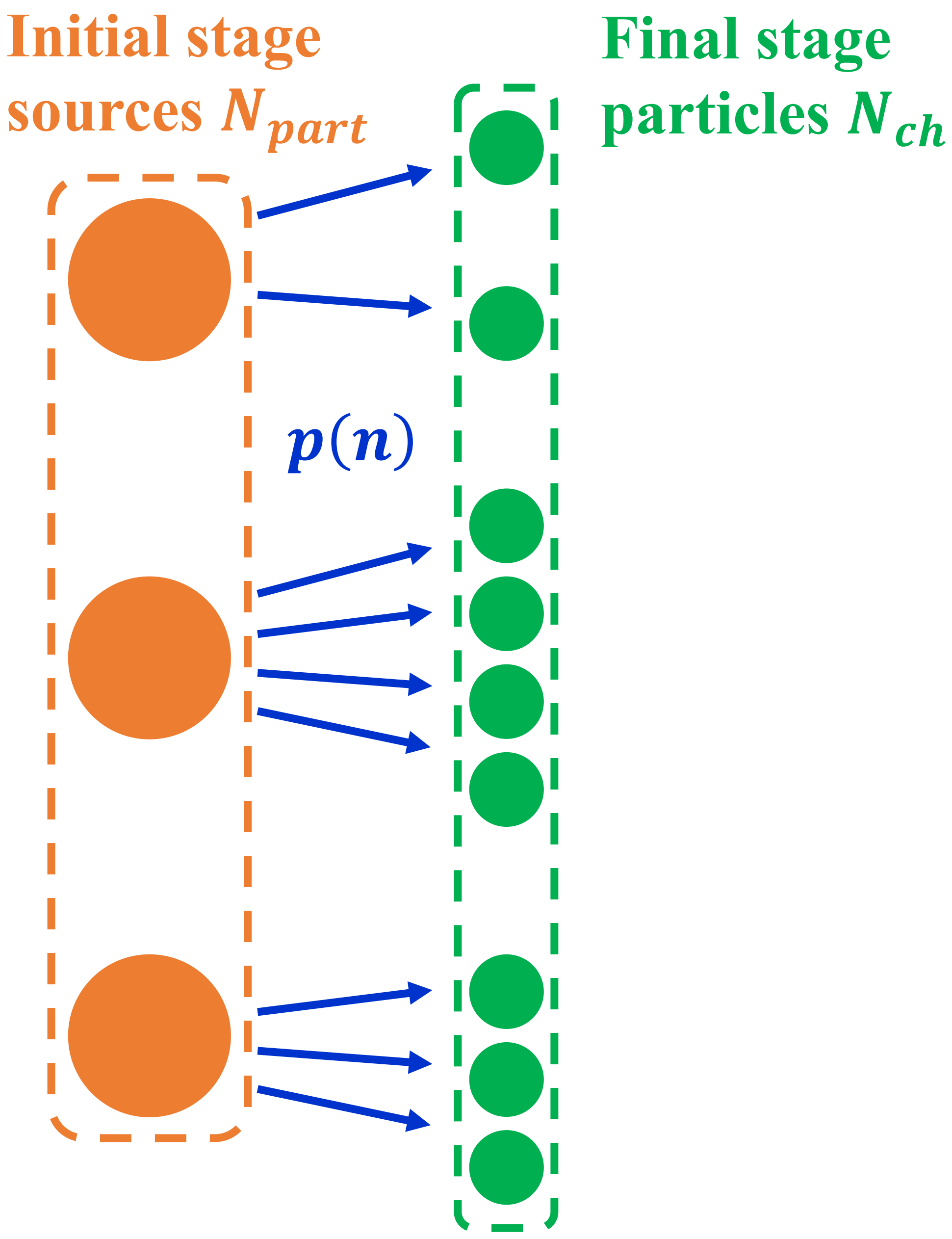
- Two methods consistent: not due to non-flow.
- Pileup effects have also been suppressed.

Centrality (volume) Fluctuation (CF)

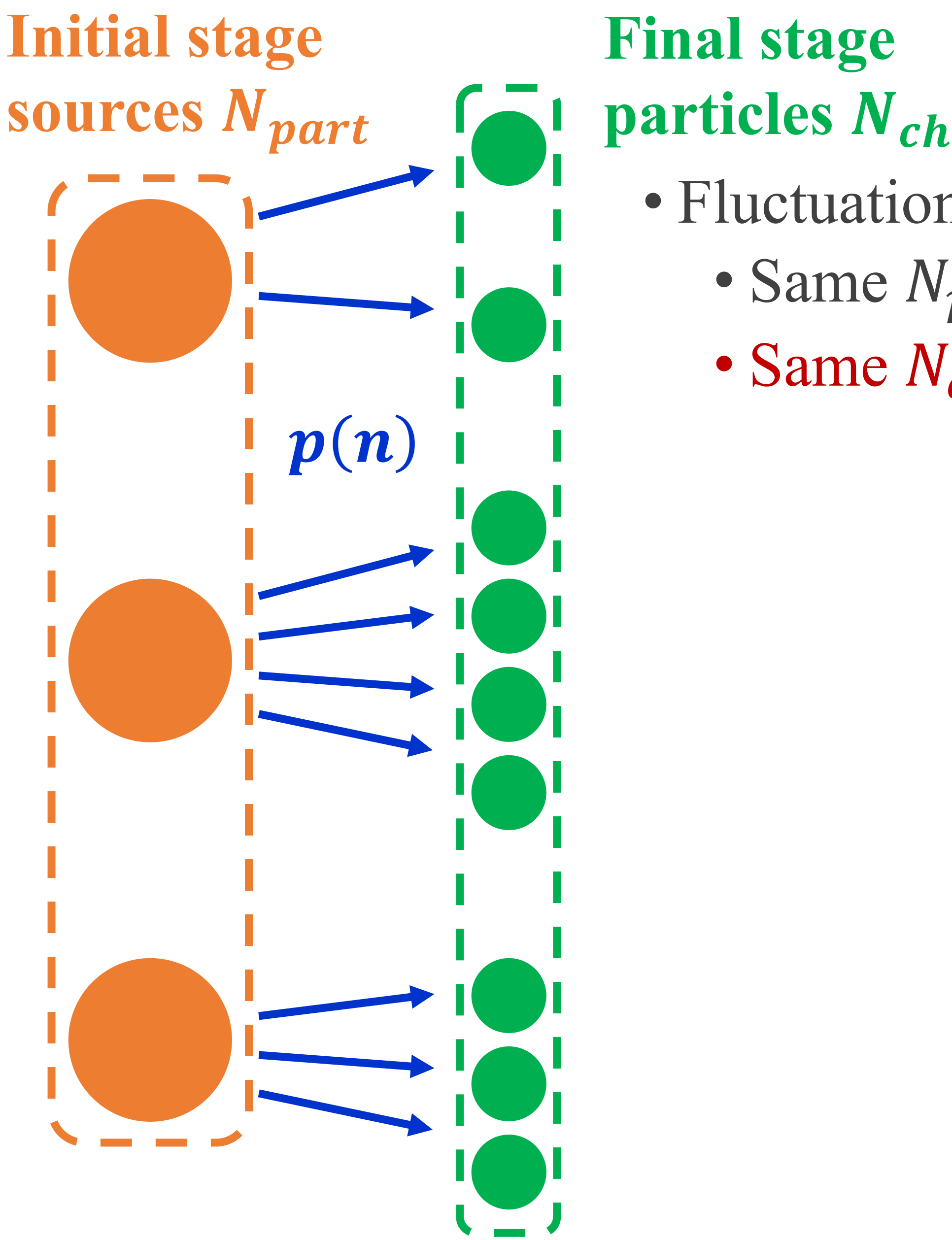
Initial stage sources N_{part}



Centrality (volume) Fluctuation (CF)



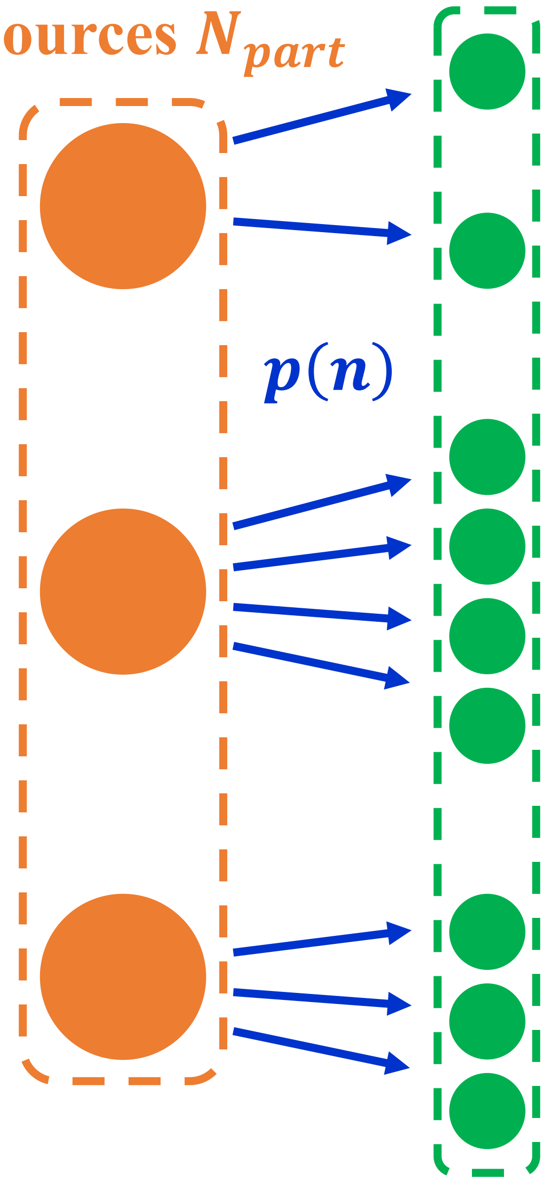
Centrality (volume) Fluctuation (CF)



Not detector effect!

- Fluctuation of particle production $p(n)$
  - Same $N_{part} \Rightarrow$ different N_{ch}
  - Same $N_{ch} \Rightarrow$ different N_{part}

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 $\mathcal{O}bs(N_{ch})$
  - 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?

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

Calculated event-by-event

Averaged over many events

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

Calculated event-by-event

Averaged over many events

Binning defined by	Observable
FCal: $3.2 < \|\eta\| < 4.9$	$c_2\{4, \Sigma E_{\mathrm{T}}\}$
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}

How to test centrality fluctuation in data?

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

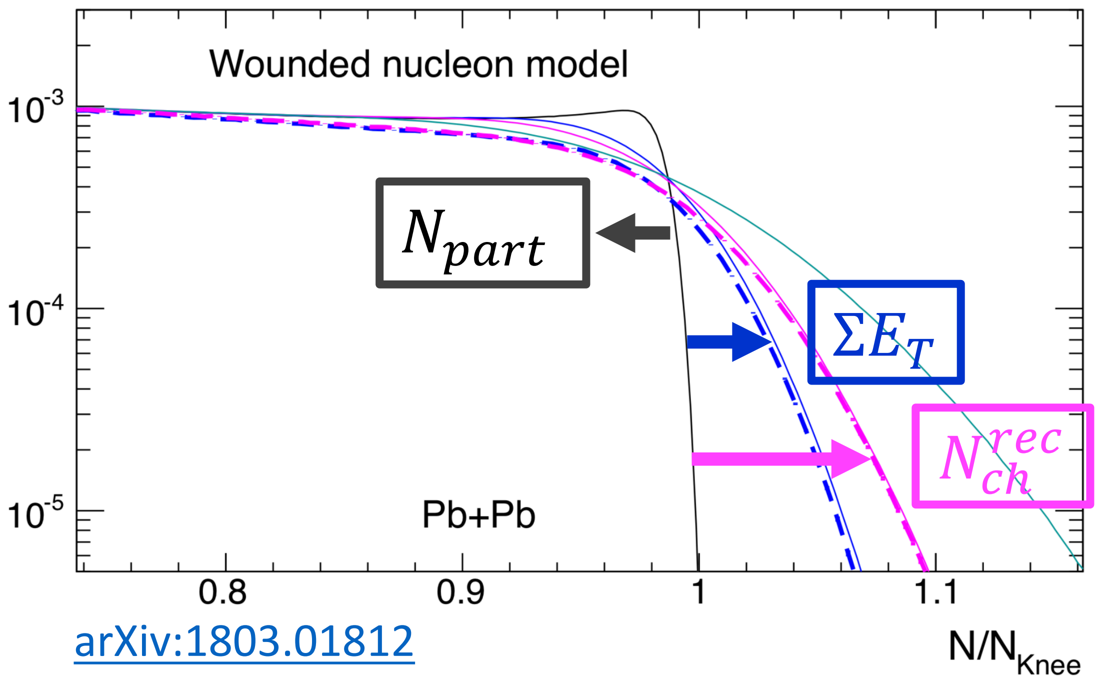
Calculated event-by-event

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**

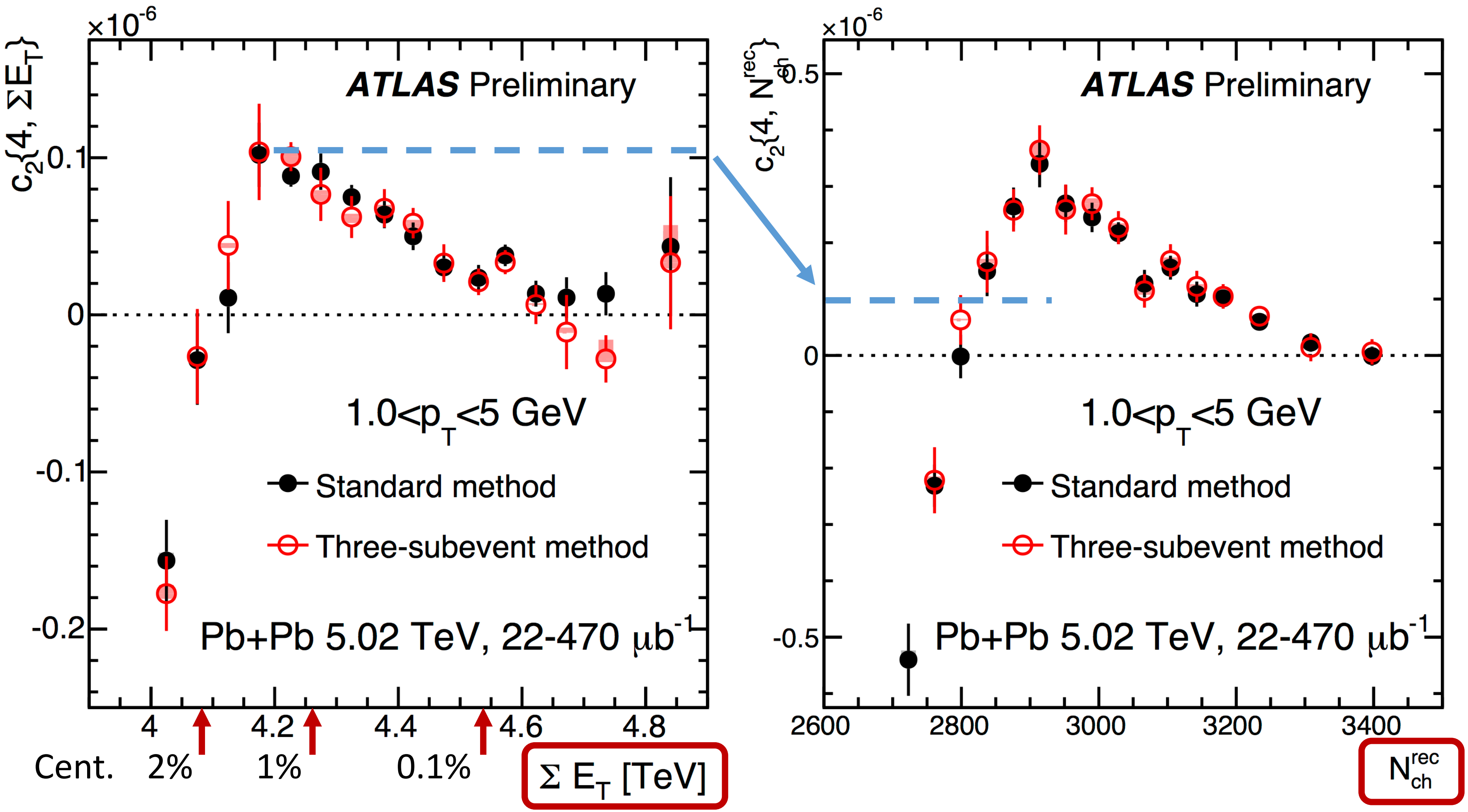
Test relative CF by comparing $c_2\{4\}$ binned by ΣE_T and N_{ch}^{rec}



arXiv:1803.01812

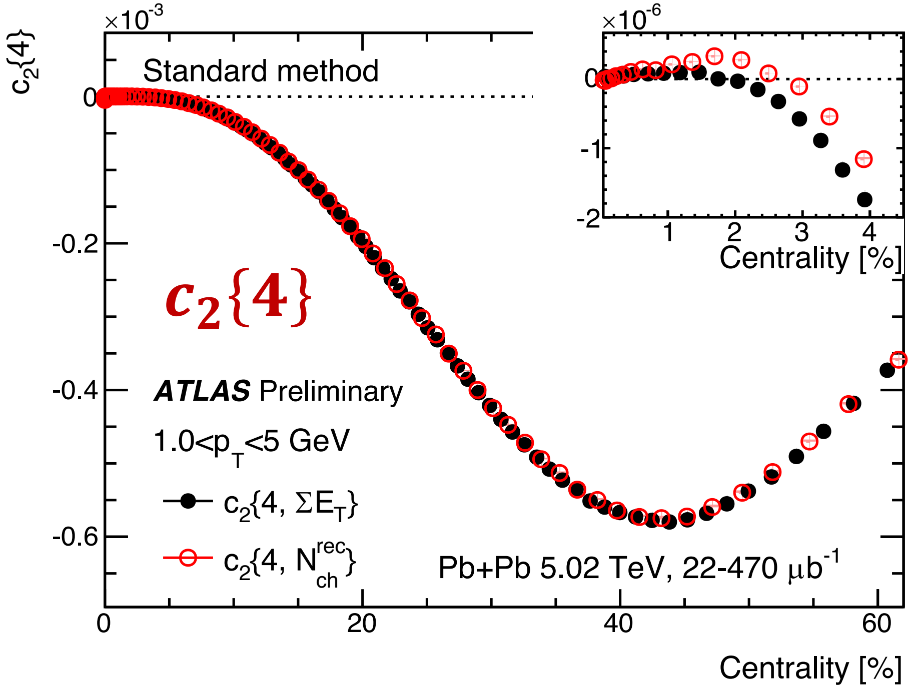
- $p(N_{ch}^{rec})$ broader than $p(\Sigma E_T)$
- CF effect: $\Sigma E_T < N_{ch}^{rec}$
- Prediction
  - $c_2\{4, \Sigma E_T\} < c_2\{4, N_{ch}^{rec}\}$

$c_2\{4\}$ and centrality fluctuation



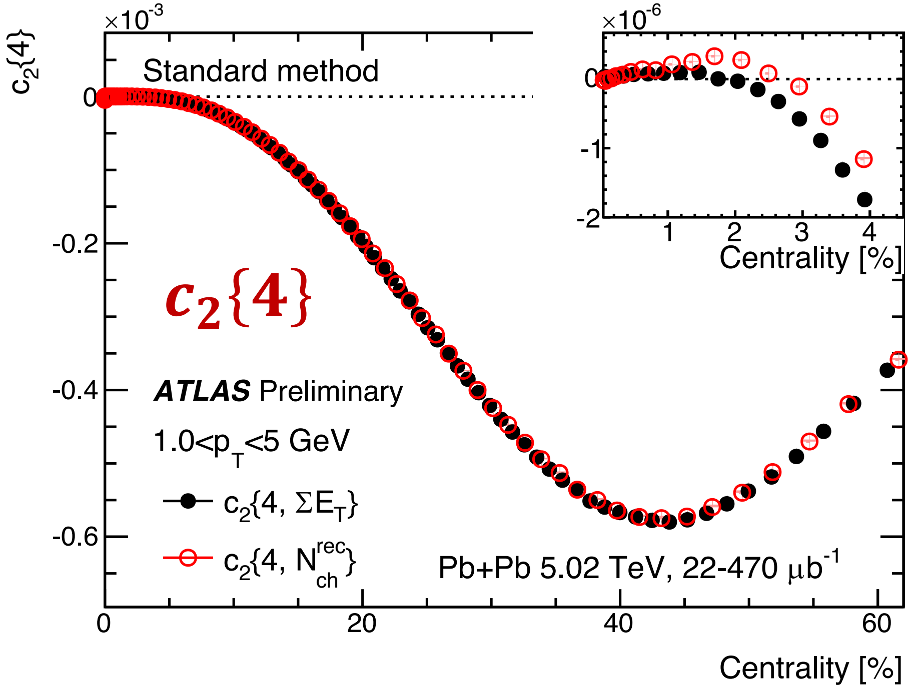
- $c_2\{4, \Sigma E_{\mathrm{T}}\} < c_2\{4, N_{ch}^{rec}\}$: CF affects flow cumulant;
- $c_2\{4\} \rightarrow 0$ in very most-central: smaller CF effect;

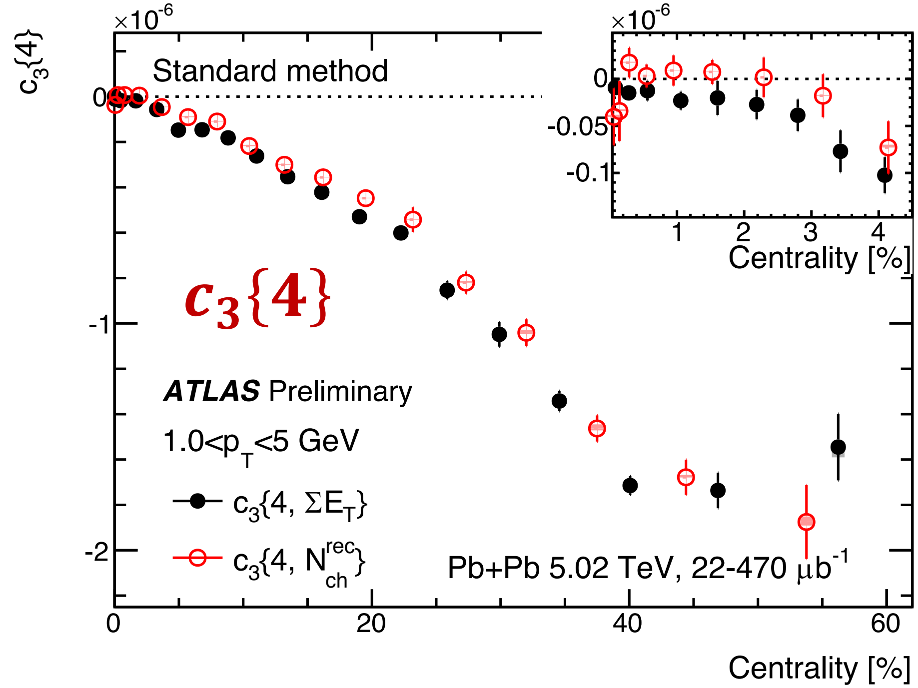
From ultra-central to full centrality



- $c_2\{4\}$: CF mostly affects central;

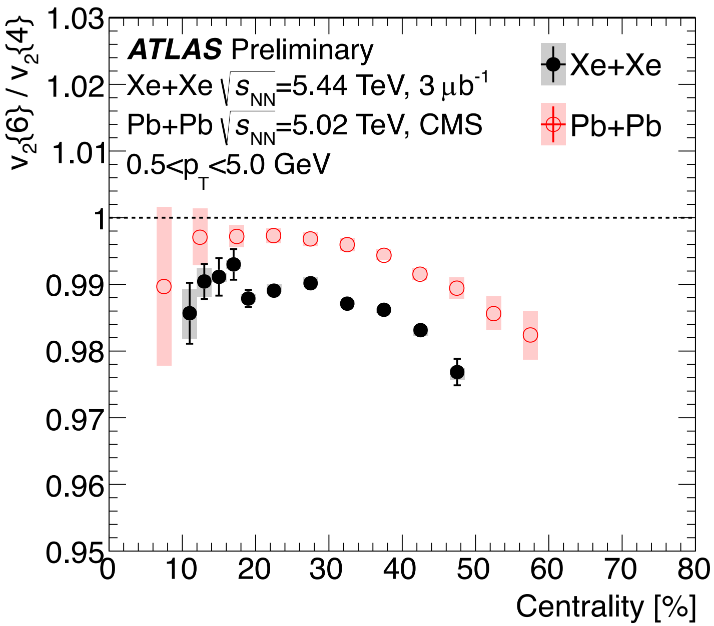
From ultra-central to full centrality

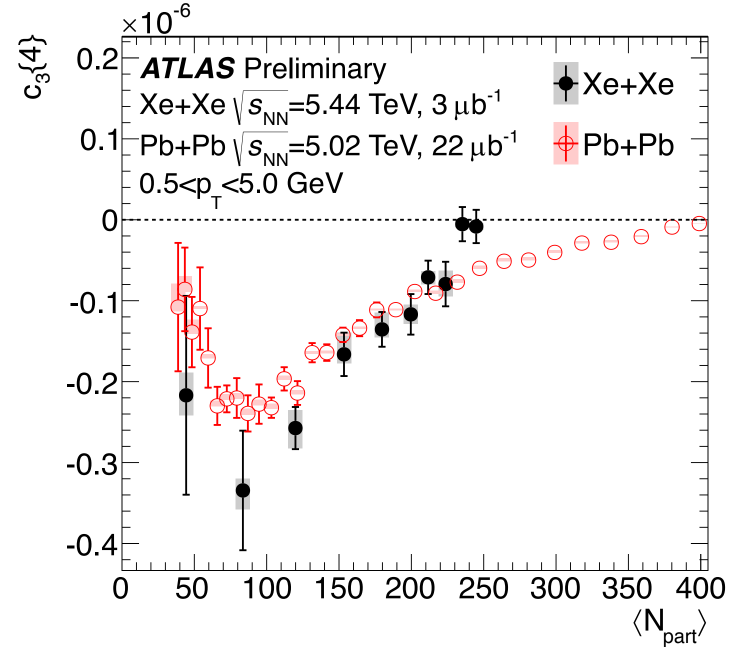




- $c_2\{4\}$: CF mostly affects central;
- $c_3\{4\}$: CF affects most centralities.

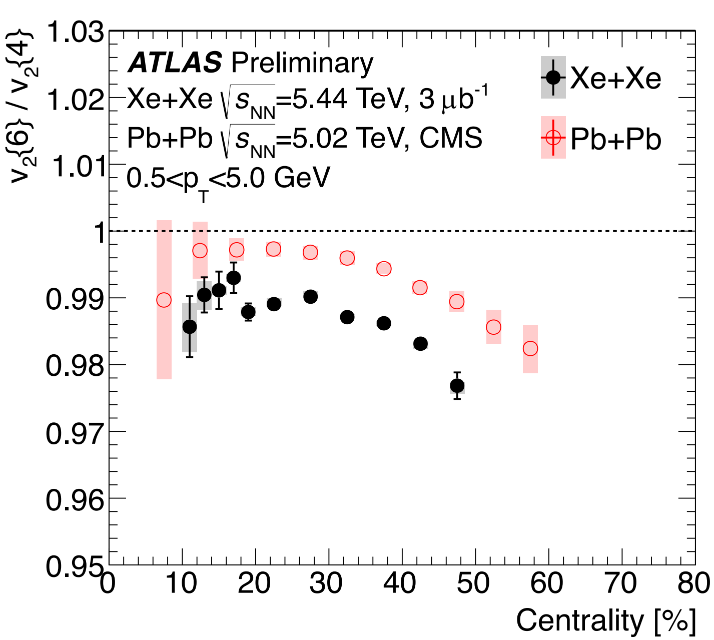
Summary I



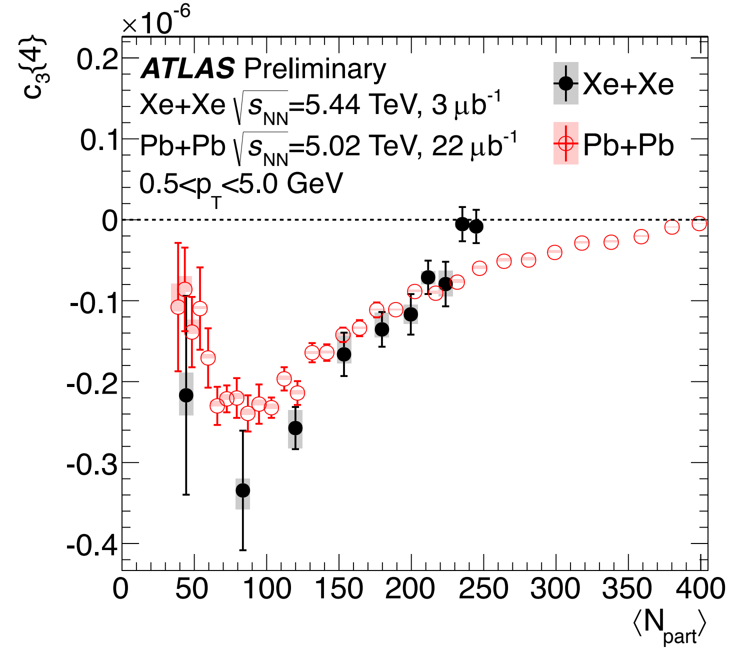


- Non-Gauss: Xe and Pb
- N_{part} scaling between Xe and Pb

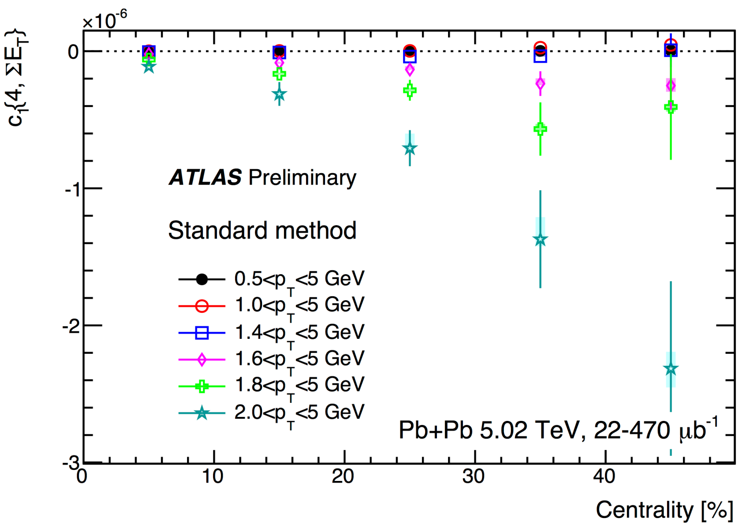
Summary I



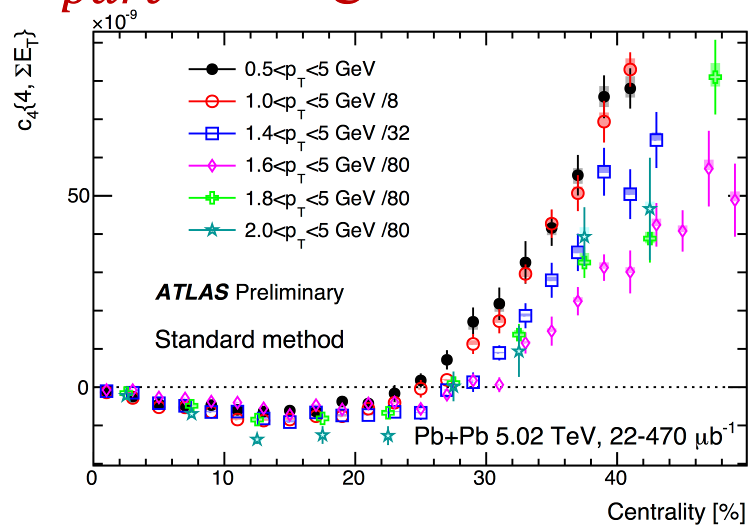
- Non-Gauss: Xe and Pb



- N_{part} scaling between Xe and Pb



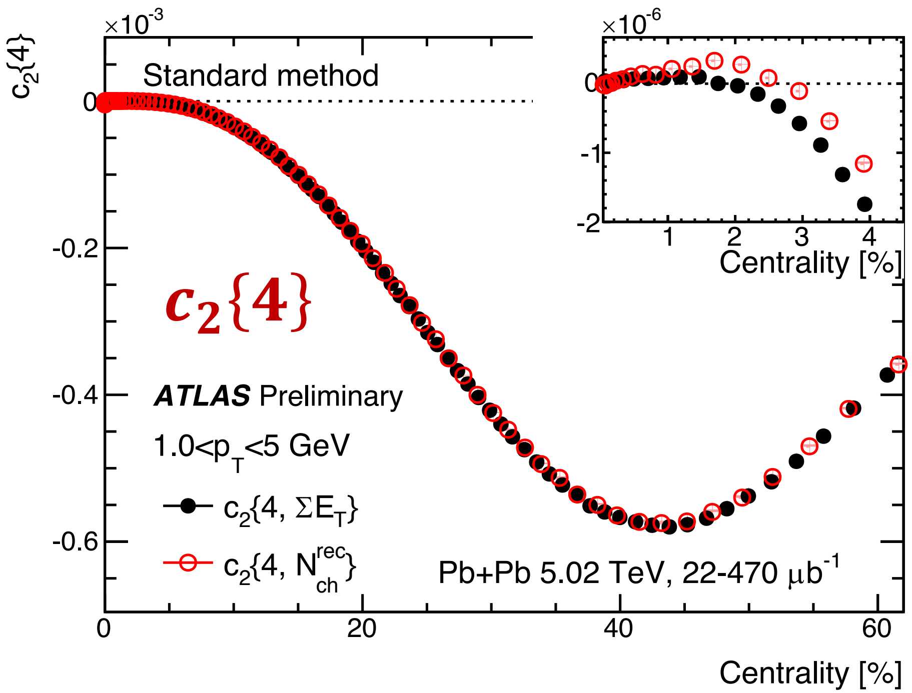
- $c_1\{4\} < 0$: dipolar fluctuation

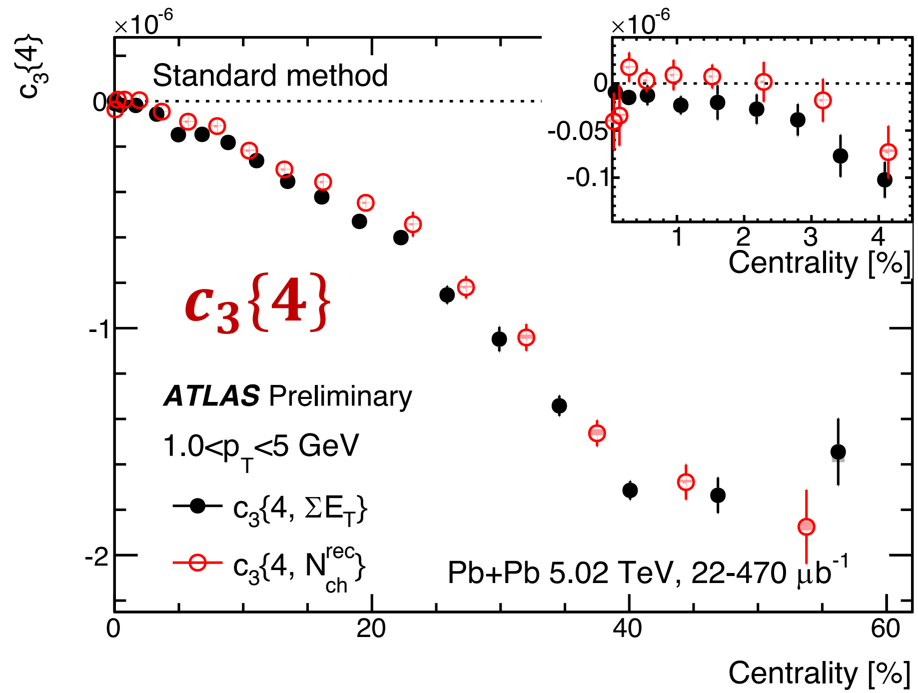


- $c_4\{4\} > 0$: non-linear

Summary II

- Ultra-central collision: perfect to study flow fluctuation
  - $c_2\{4\} > 0$ in ultra-central;
  - CF probably causes $c_2\{4\} > 0$;
  - CF affects $c_3\{4\}$ in most centralities;





Summary II

- Ultra-central collision: perfect to study flow fluctuation
  - $c_2\{4\} > 0$ in ultra-central;
  - CF probably causes $c_2\{4\} > 0$;
  - CF affects $c_3\{4\}$ in most centralities;

- Suggestions to minimize centrality fluctuation
  1. Choose observables insensitive to CF (use models);
  2. Define centrality by observables with small CF (forward η?);
  3. Model-data comparison requires same binning $\Rightarrow$ CF cancels;

Outlook

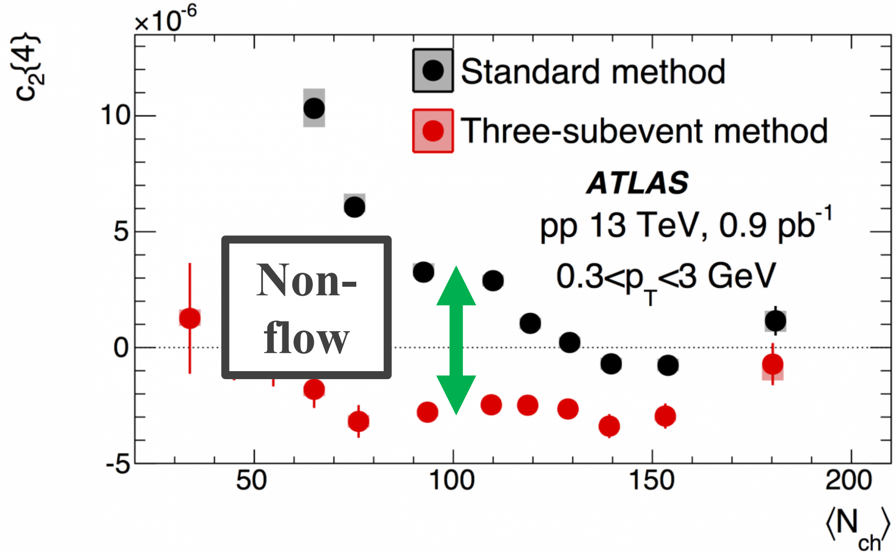
- Cumulant is sensitive to fluctuation: easy to extract signal;

Outlook

- Cumulant is sensitive to fluctuation: easy to extract signal;
- But sometimes it is too sensitive: significant other effects…

- Cumulant is sensitive to fluctuation: easy to extract signal;
- But sometimes it is too sensitive: significant other effects…

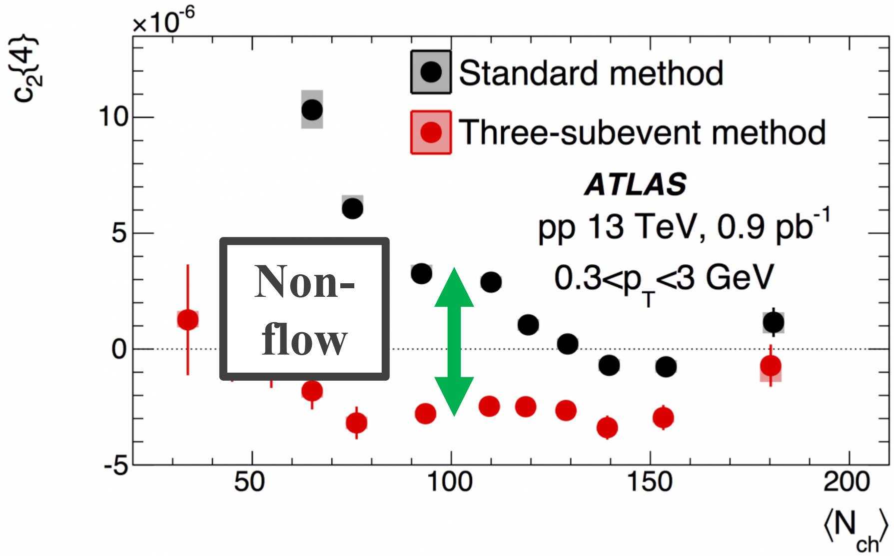
QM17



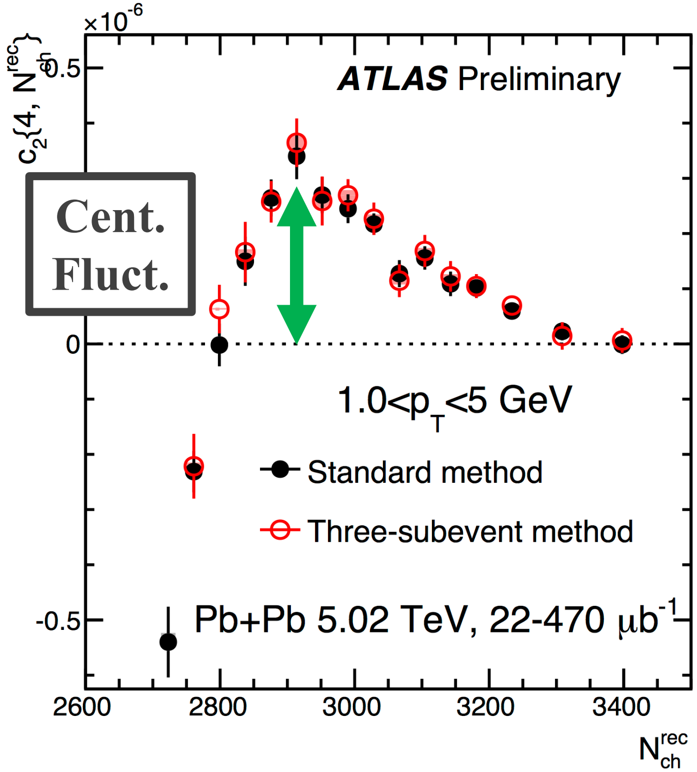
Outlook

- Cumulant is sensitive to fluctuation: easy to extract signal;
- But sometimes it is too sensitive: significant other effects…

QM17



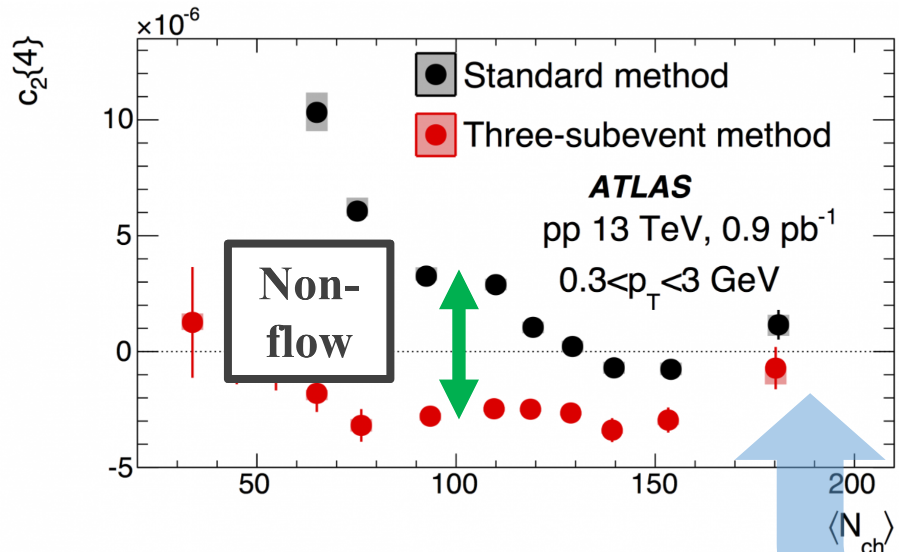
QM18



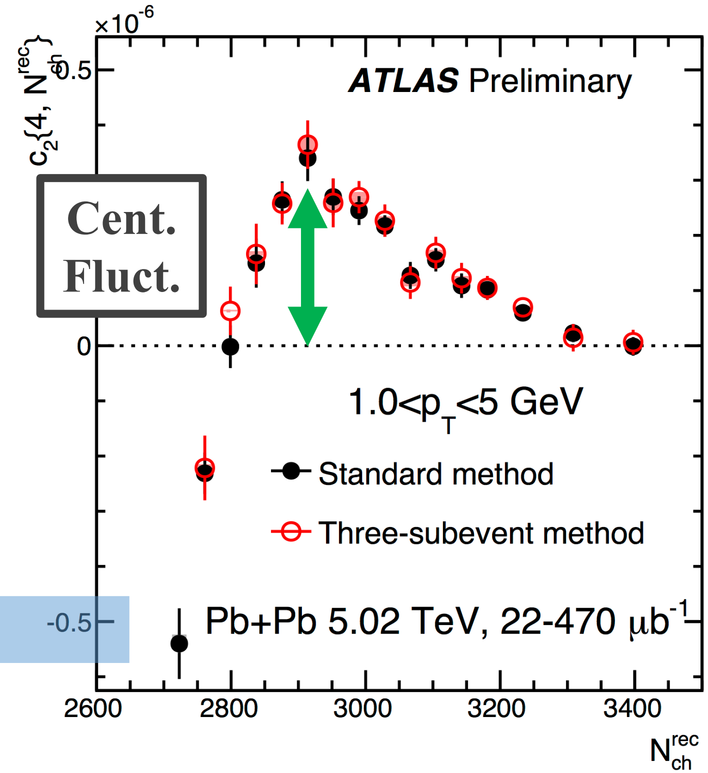
Outlook

- Cumulant is sensitive to fluctuation: easy to extract signal;
- But sometimes it is too sensitive: significant other effects...

QM17

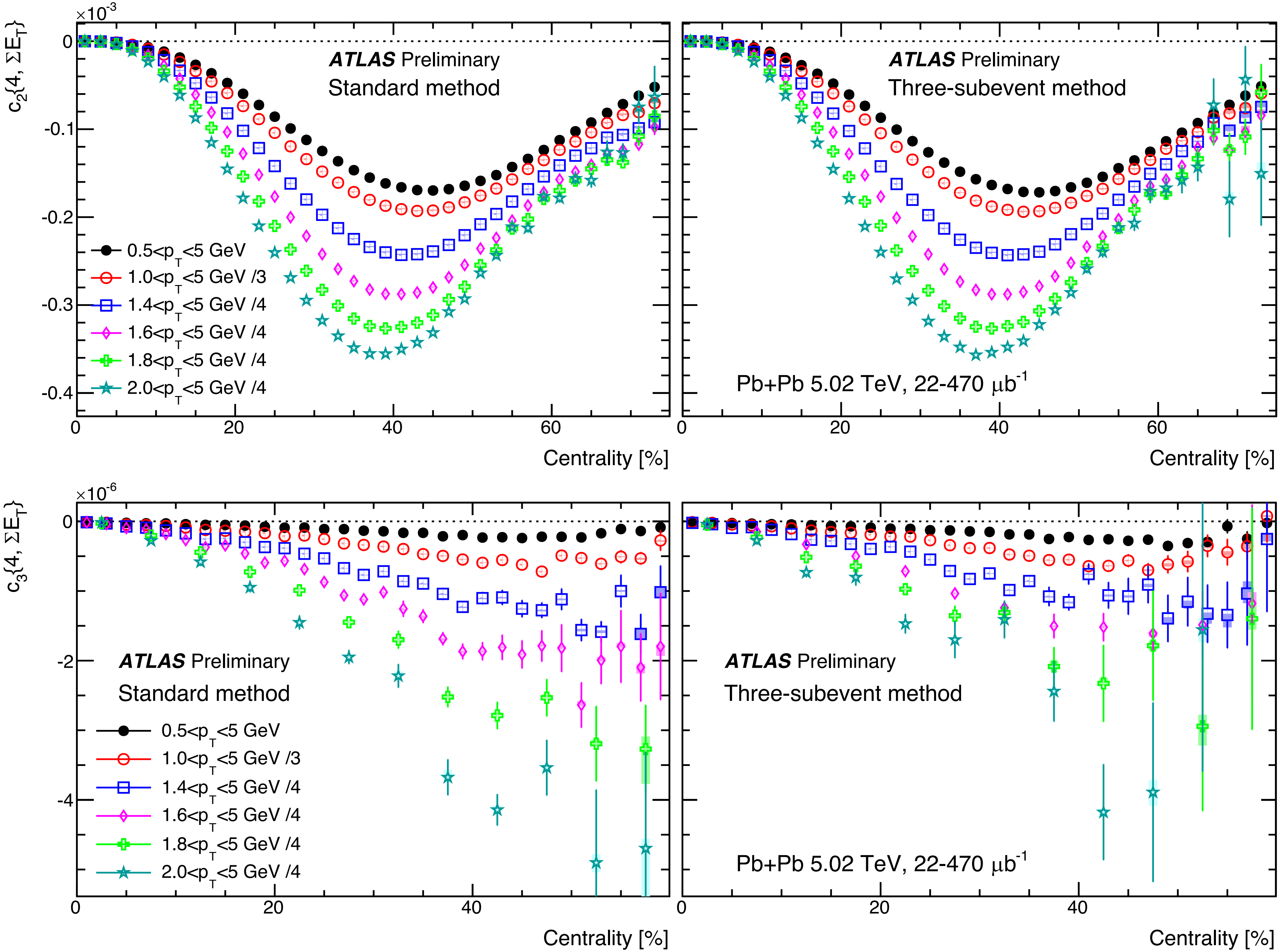


QM18

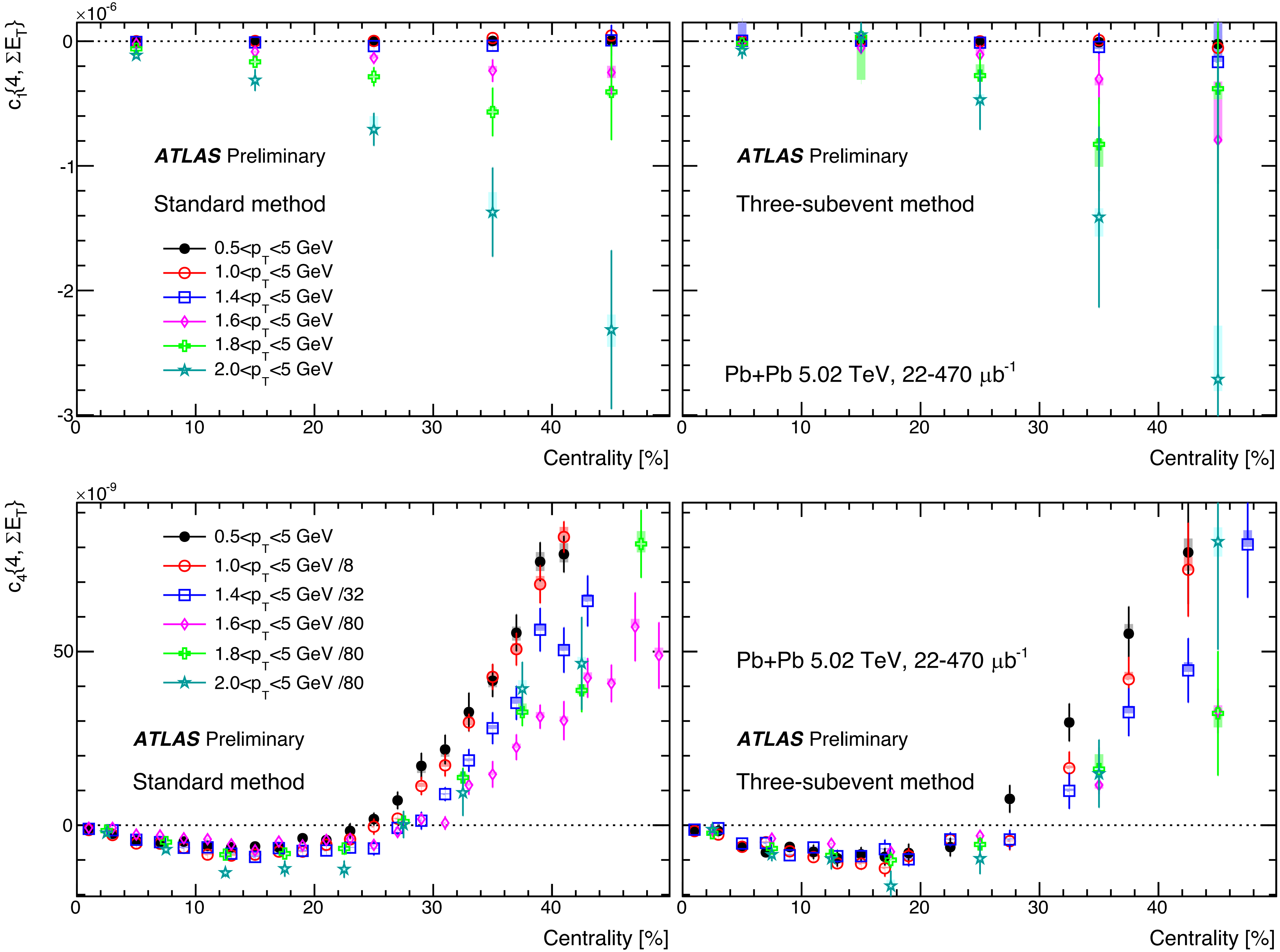


- $c_2\{4\}$ independent of N_{ch}?
  - Larger CF in small system
  - N_{ch} not a good indicator for "centrality"?

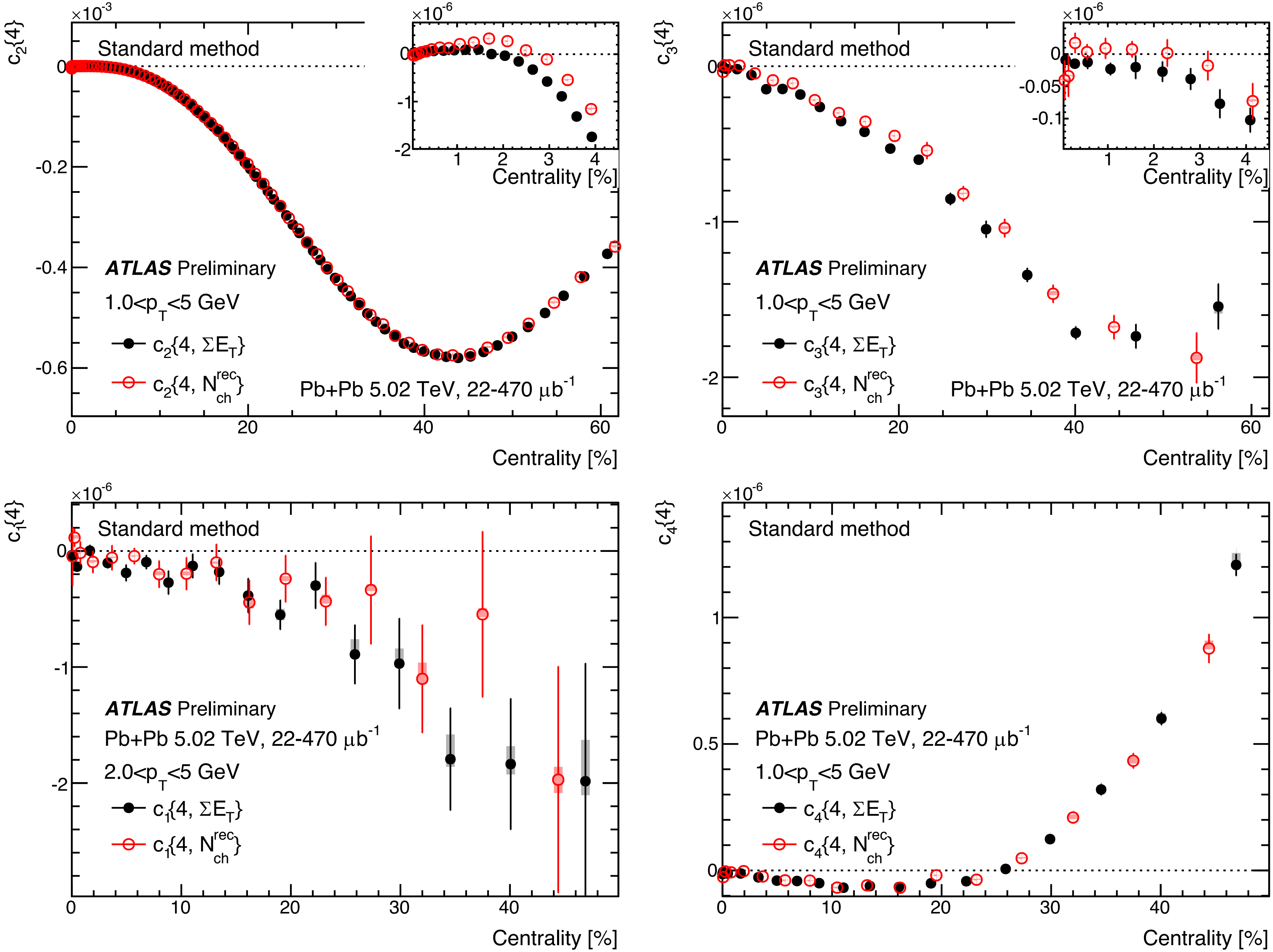
Backup



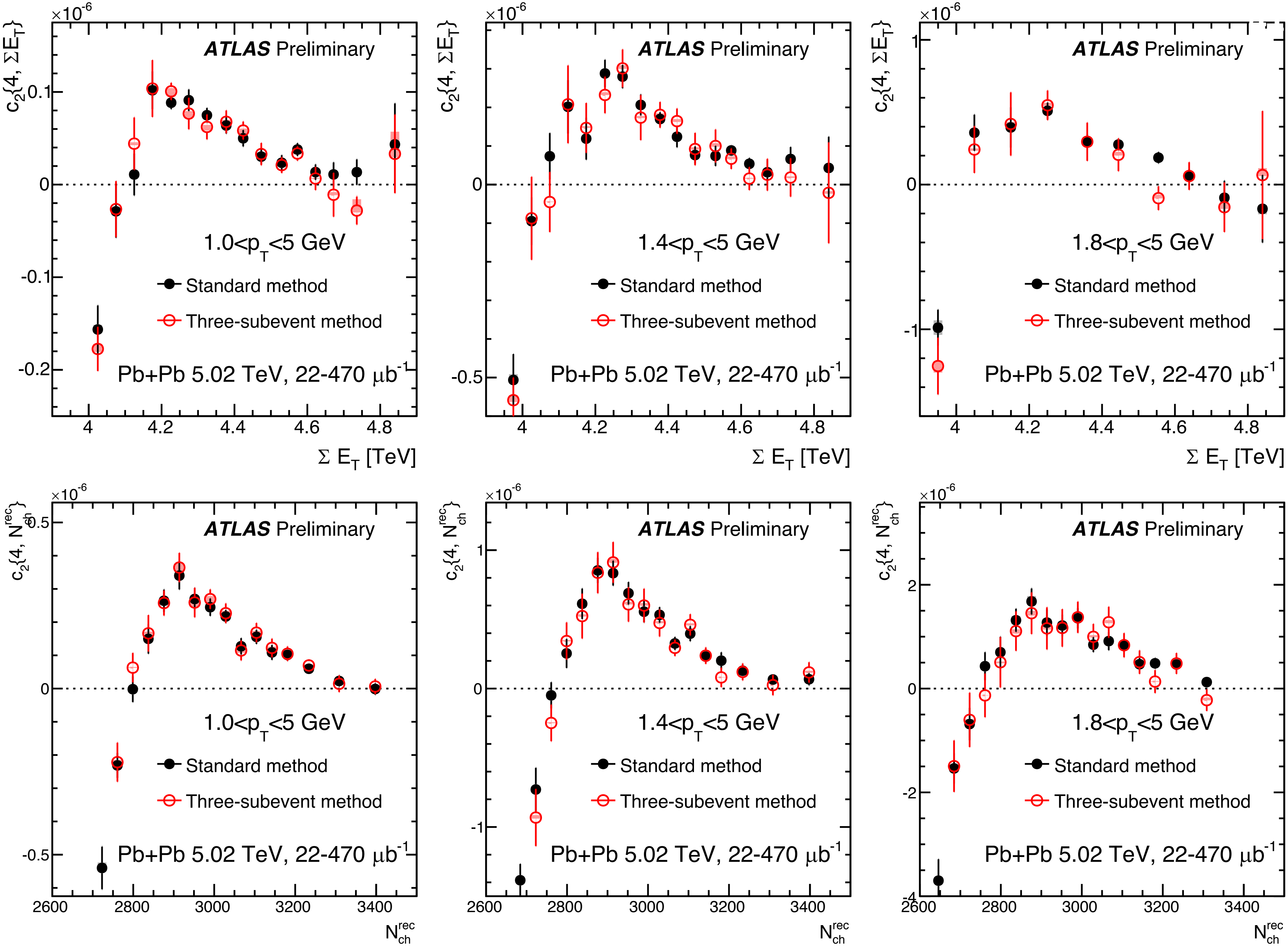
×10⁻³
c₂{4, ΣE_T}
0
-0.1
-0.2
-0.3
-0.4
ATLAS Preliminary
Standard method
0.5<p_T<5 GeV
1.0<p_T<5 GeV /3
1.4<p_T<5 GeV /4
1.6<p_T<5 GeV /4
1.8<p_T<5 GeV /4
2.0<p_T<5 GeV /4
0
20
40
60
Centrality [%]
ATLAS Preliminary
Three-subevent method
Pb+Pb 5.02 TeV, 22-470 μb⁻¹
0
20
40
60
Centrality [%]
×10⁻⁶
c₃{4, ΣE_T}
0
-2
-4
ATLAS Preliminary
Standard method
0.5<p_T<5 GeV
1.0<p_T<5 GeV /3
1.4<p_T<5 GeV /4
1.6<p_T<5 GeV /4
1.8<p_T<5 GeV /4
2.0<p_T<5 GeV /4
0
20
40
Centrality [%]
ATLAS Preliminary
Three-subevent method
Pb+Pb 5.02 TeV, 22-470 μb⁻¹
0
20
40
Centrality [%]

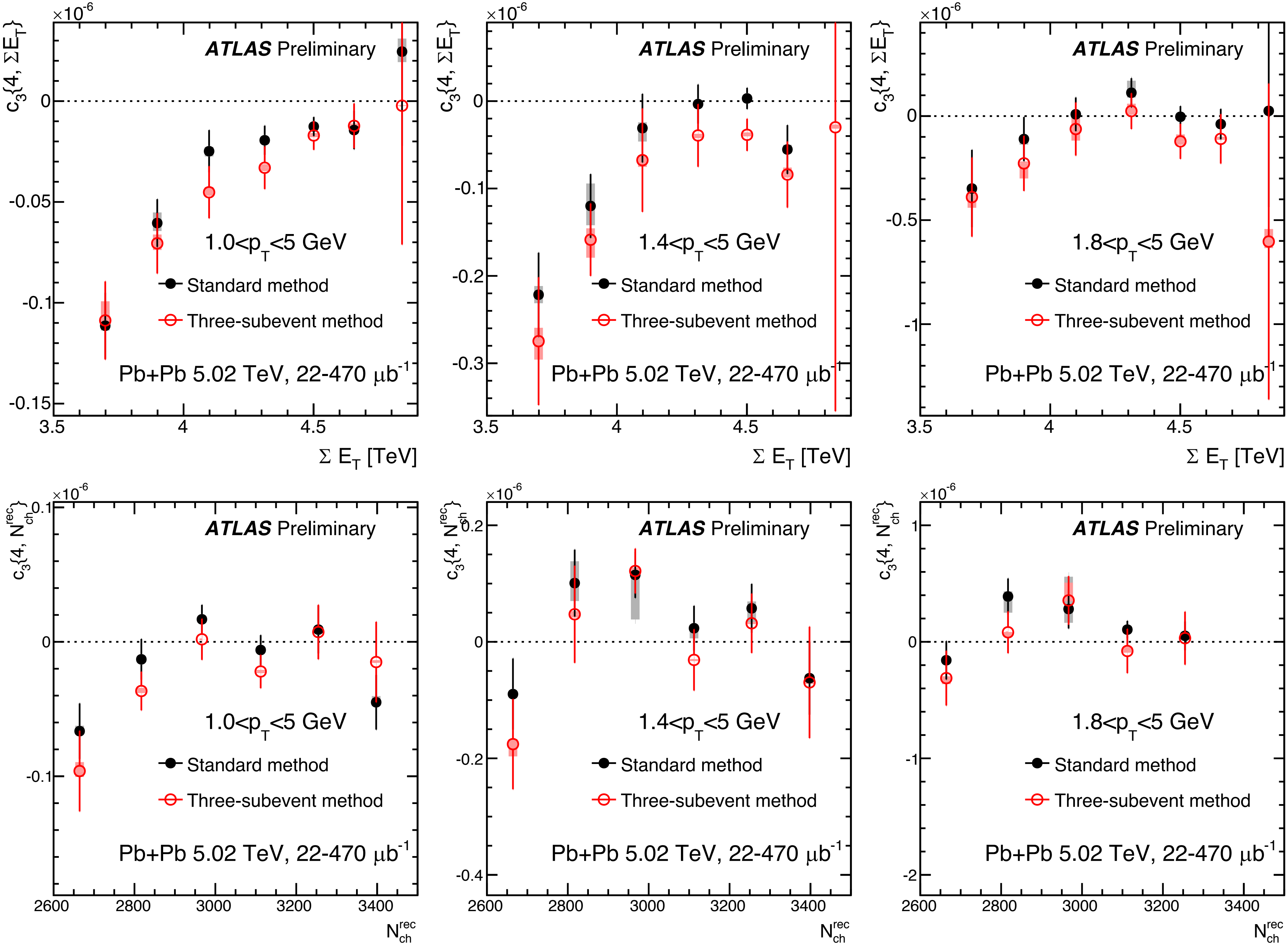


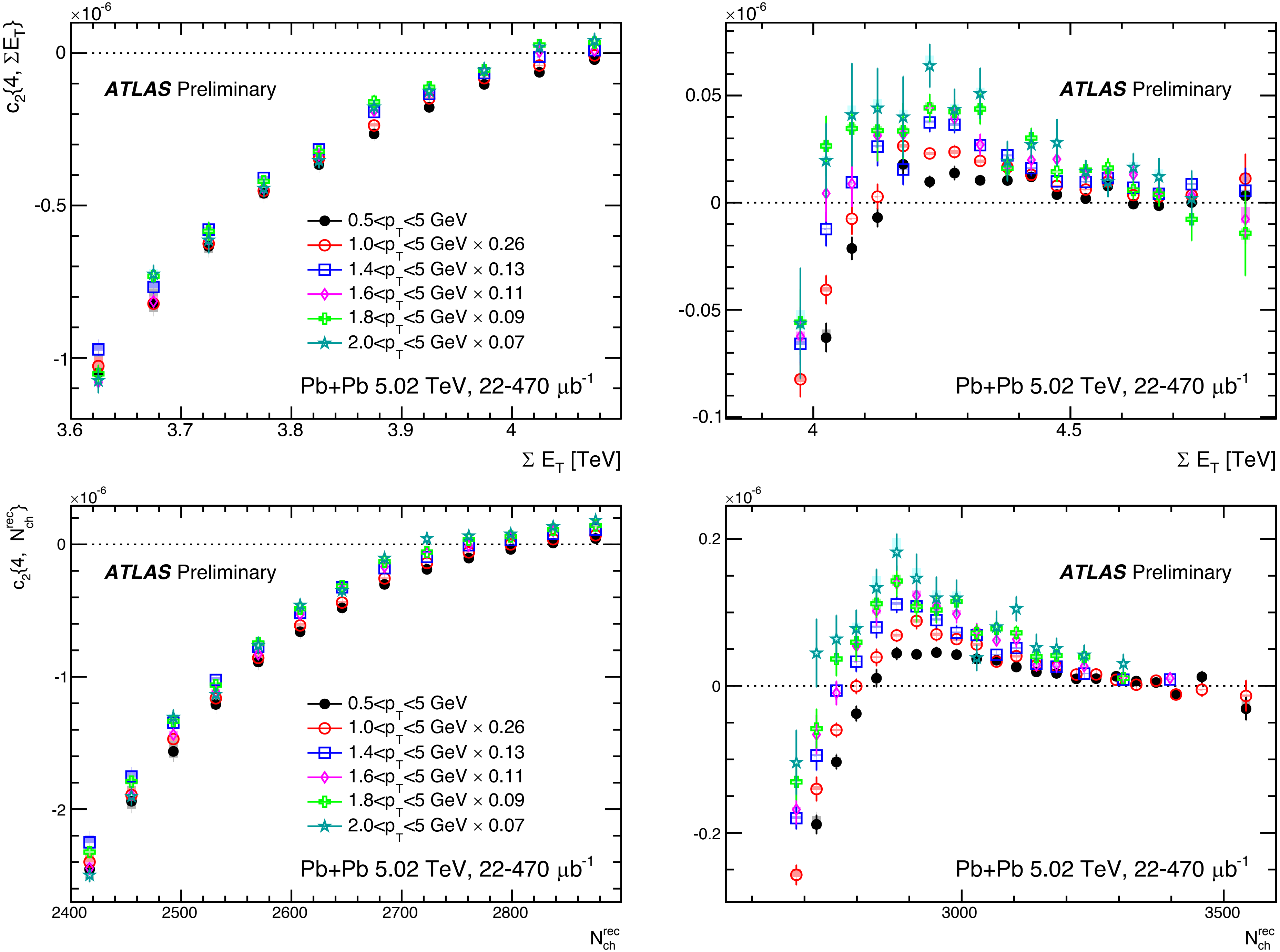
×10^-6
c_1{4, ΣE_T}
ATLAS Preliminary
Standard method
0.5<p_T<5 GeV
1.0<p_T<5 GeV
1.4<p_T<5 GeV
1.6<p_T<5 GeV
1.8<p_T<5 GeV
2.0<p_T<5 GeV
Centrality [%]
ATLAS Preliminary
Three-subevent method
Pb+Pb 5.02 TeV, 22-470 μb^-1
Centrality [%]
×10^-9
c_4{4, ΣE_T}
0.5<p_T<5 GeV
1.0<p_T<5 GeV /8
1.4<p_T<5 GeV /32
1.6<p_T<5 GeV /80
1.8<p_T<5 GeV /80
2.0<p_T<5 GeV /80
ATLAS Preliminary
Standard method
Centrality [%]
Pb+Pb 5.02 TeV, 22-470 μb^-1
ATLAS Preliminary
Three-subevent method
Centrality [%]



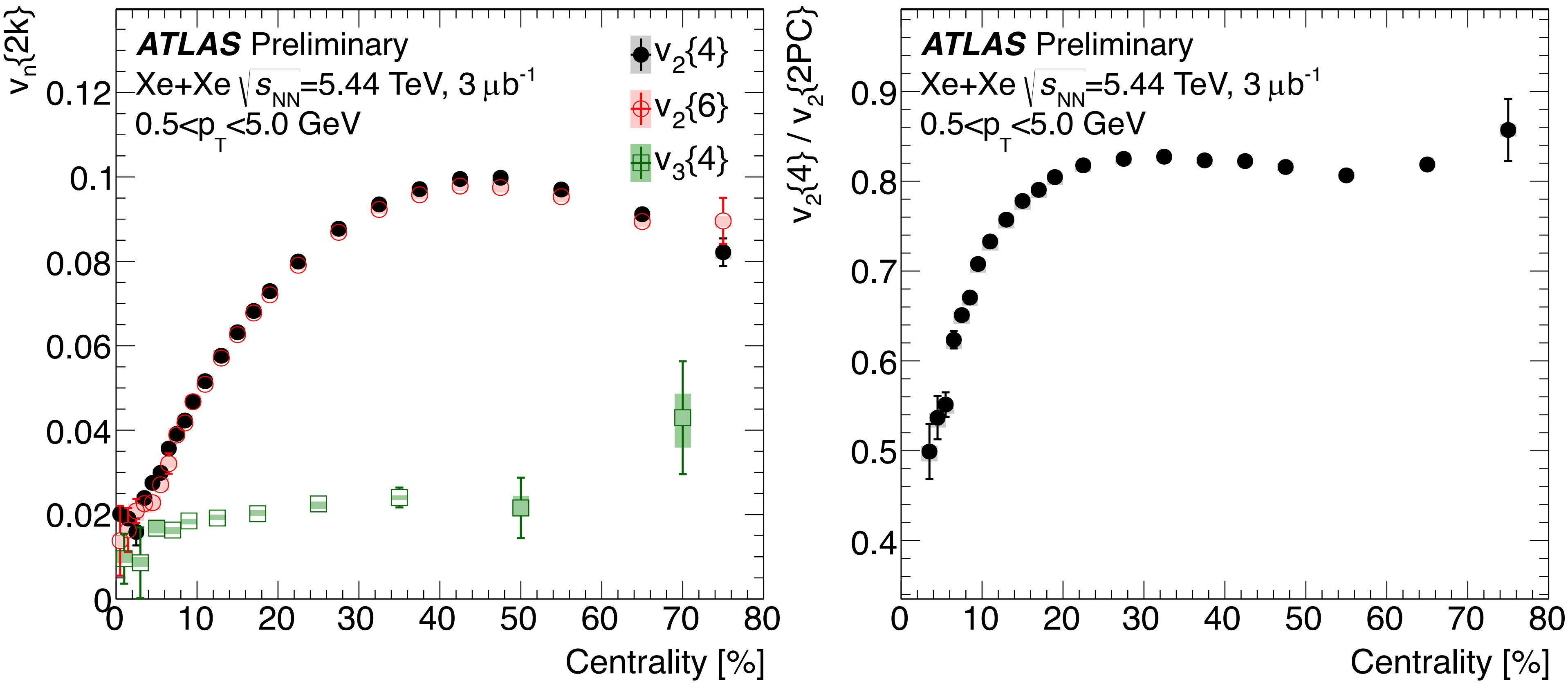
Standard method
ATLAS Preliminary
1.0<p_T<5 GeV
c_2{4, ΣE_T}
c_2{4, N_ch^rec}
Pb+Pb 5.02 TeV, 22-470 μb^-1
c_2{4}
×10^-3
×10^-6
Centrality [%]
Standard method
ATLAS Preliminary
1.0<p_T<5 GeV
c_3{4, ΣE_T}
c_3{4, N_ch^rec}
Pb+Pb 5.02 TeV, 22-470 μb^-1
c_3{4}
×10^-6
Centrality [%]
Standard method
ATLAS Preliminary
Pb+Pb 5.02 TeV, 22-470 μb^-1
2.0<p_T<5 GeV
c_1{4, ΣE_T}
c_1{4, N_ch^rec}
c_1{4}
×10^-6
Centrality [%]
Standard method
ATLAS Preliminary
Pb+Pb 5.02 TeV, 22-470 μb^-1
1.0<p_T<5 GeV
c_4{4, ΣE_T}
c_4{4, N_ch^rec}
c_4{4}
×10^-6
Centrality [%]

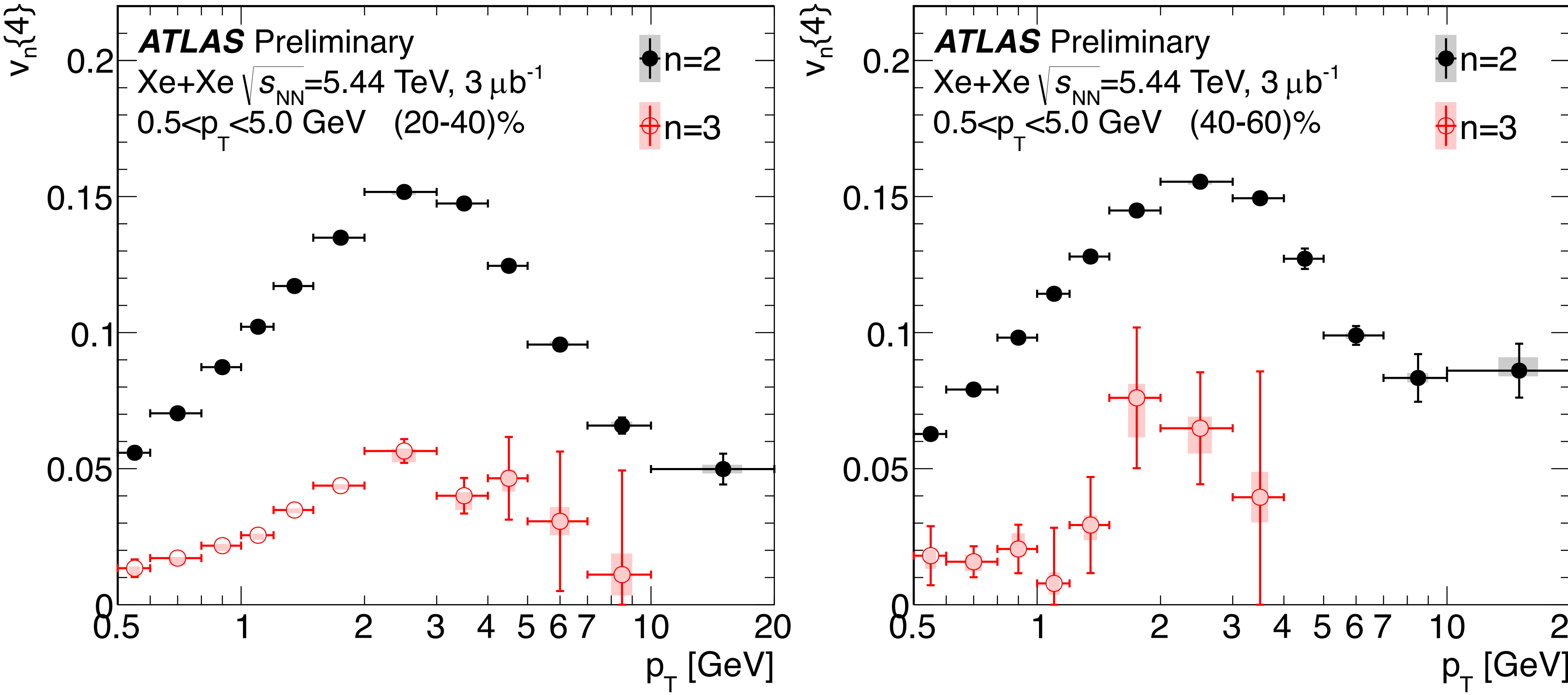

ATLAS Preliminary
1.0<p_T<5 GeV
1.4<p_T<5 GeV
1.8<p_T<5 GeV
Standard method
Three-subevent method
Pb+Pb 5.02 TeV, 22-470 μb^-1
c_2{4, ΣE_T}
ΣE_T [TeV]
c_2{4, N_ch^rec}
N_ch^rec
×10^-6

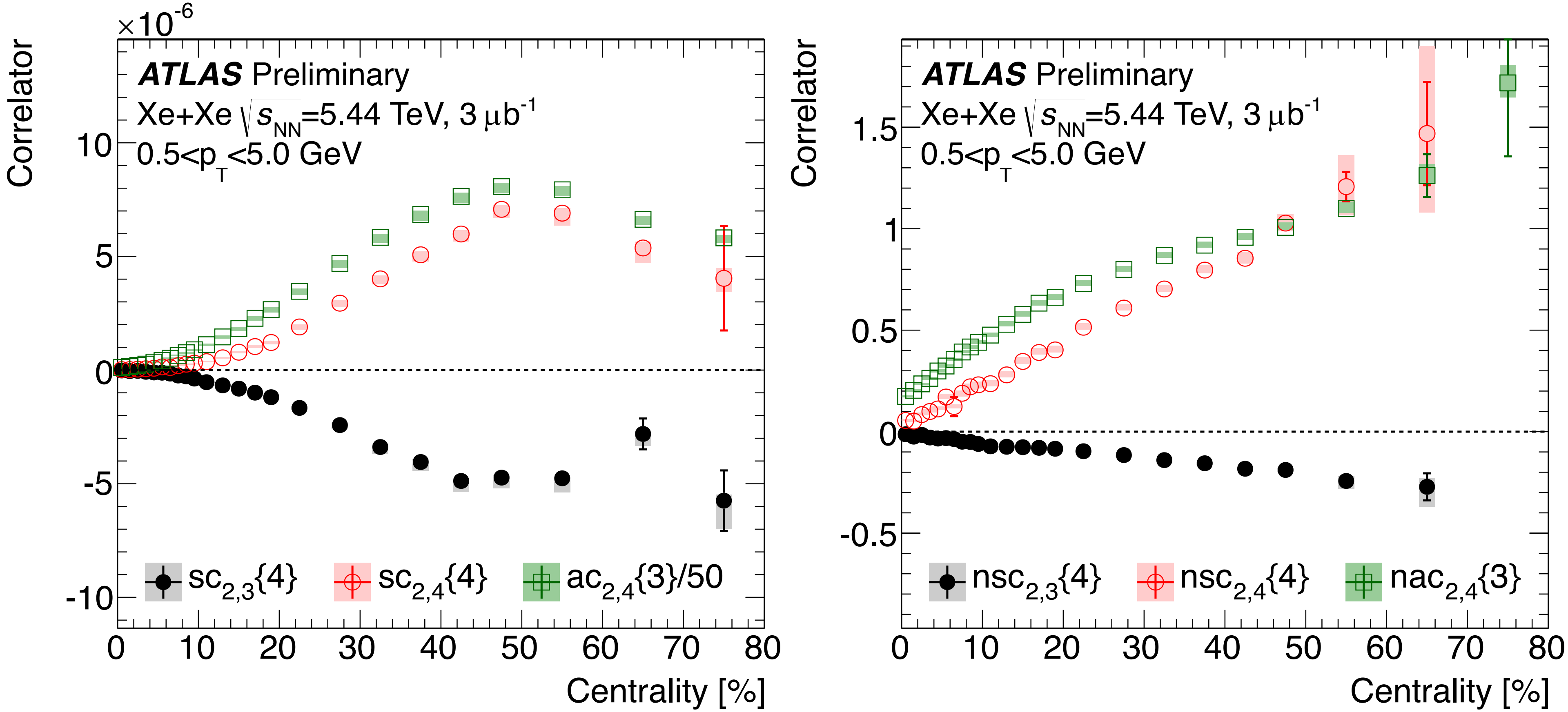

ATLAS Preliminary
1.0<p_T<5 GeV
1.4<p_T<5 GeV
1.8<p_T<5 GeV
Standard method
Three-subevent method
Pb+Pb 5.02 TeV, 22-470 μb^-1
c_3{4, ΣE_T}
c_3{4, N_ch^rec}
×10^-6
Σ E_T [TeV]
N_ch^rec



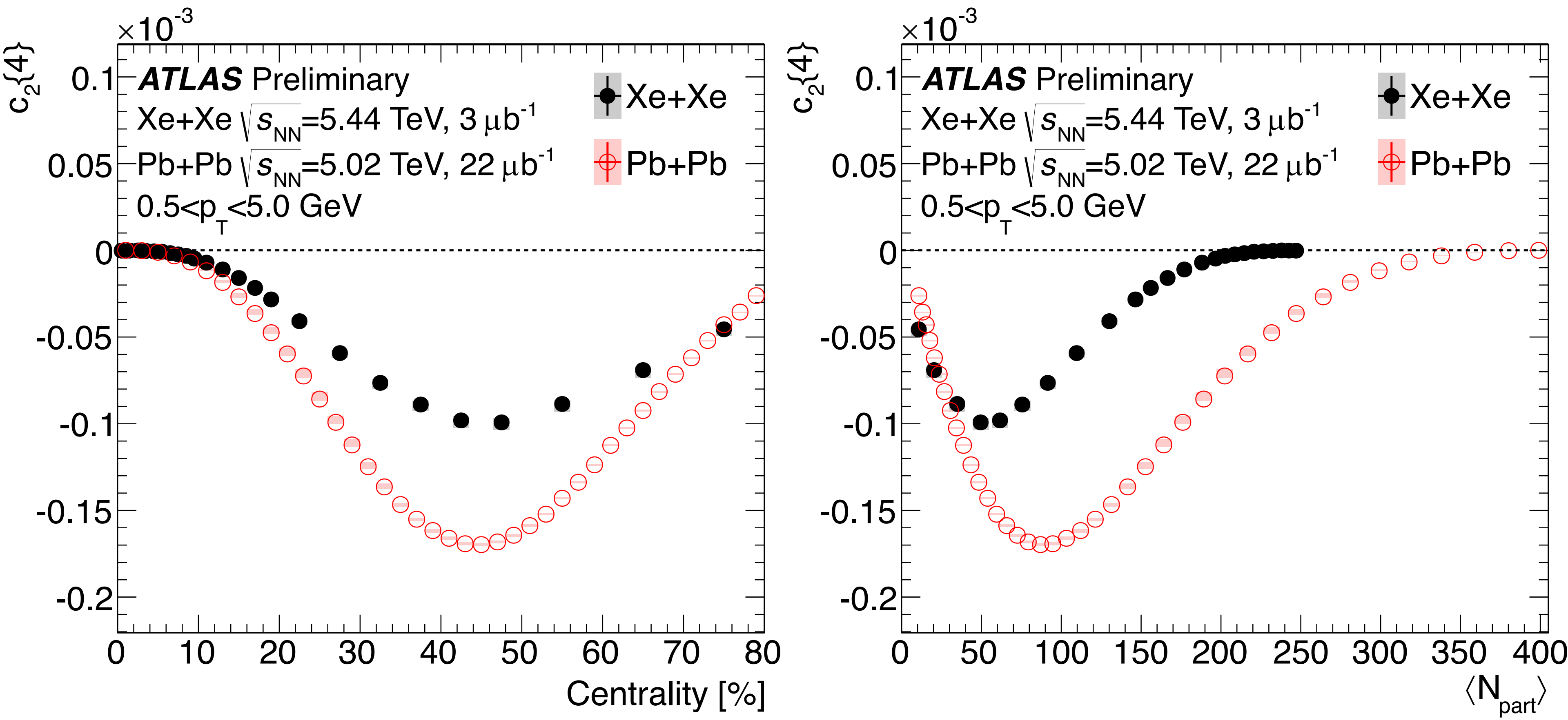
$\times10^{-6}$
$c_2\{4, \Sigma E_T\}$
ATLAS Preliminary
0.5<p_T<5 GeV
1.0<p_T<5 GeV × 0.26
1.4<p_T<5 GeV × 0.13
1.6<p_T<5 GeV × 0.11
1.8<p_T<5 GeV × 0.09
2.0<p_T<5 GeV × 0.07
Pb+Pb 5.02 TeV, 22-470 μb^{-1}
0
-0.5
-1
3.6
3.7
3.8
3.9
4
ΣE_T [TeV]
$\times10^{-6}$
ATLAS Preliminary
0.05
0
-0.05
-0.1
4
4.5
Pb+Pb 5.02 TeV, 22-470 μb^{-1}
ΣE_T [TeV]
$\times10^{-6}$
$c_2\{4, N_{ch}^{rec}\}$
ATLAS Preliminary
0.5<p_T<5 GeV
1.0<p_T<5 GeV × 0.26
1.4<p_T<5 GeV × 0.13
1.6<p_T<5 GeV × 0.11
1.8<p_T<5 GeV × 0.09
2.0<p_T<5 GeV × 0.07
Pb+Pb 5.02 TeV, 22-470 μb^{-1}
0
-1
-2
2400
2500
2600
2700
2800
N_{ch}^{rec}
$\times10^{-6}$
ATLAS Preliminary
0.2
0
-0.2
3000
3500
Pb+Pb 5.02 TeV, 22-470 μb^{-1}
N_{ch}^{rec}


ATLAS Preliminary
Xe+Xe $\sqrt{s_{NN}}$=5.44 TeV, 3 μb^{-1}
0.5<p_T<5.0 GeV
$v_2\{4\}$
$v_2\{6\}$
$v_3\{4\}$
$v_n\{2k\}$
Centrality [%]
ATLAS Preliminary
Xe+Xe $\sqrt{s_{NN}}$=5.44 TeV, 3 μb^{-1}
0.5<p_T<5.0 GeV
$v_2\{4\}$ / $v_2\{2PC\}$
Centrality [%]

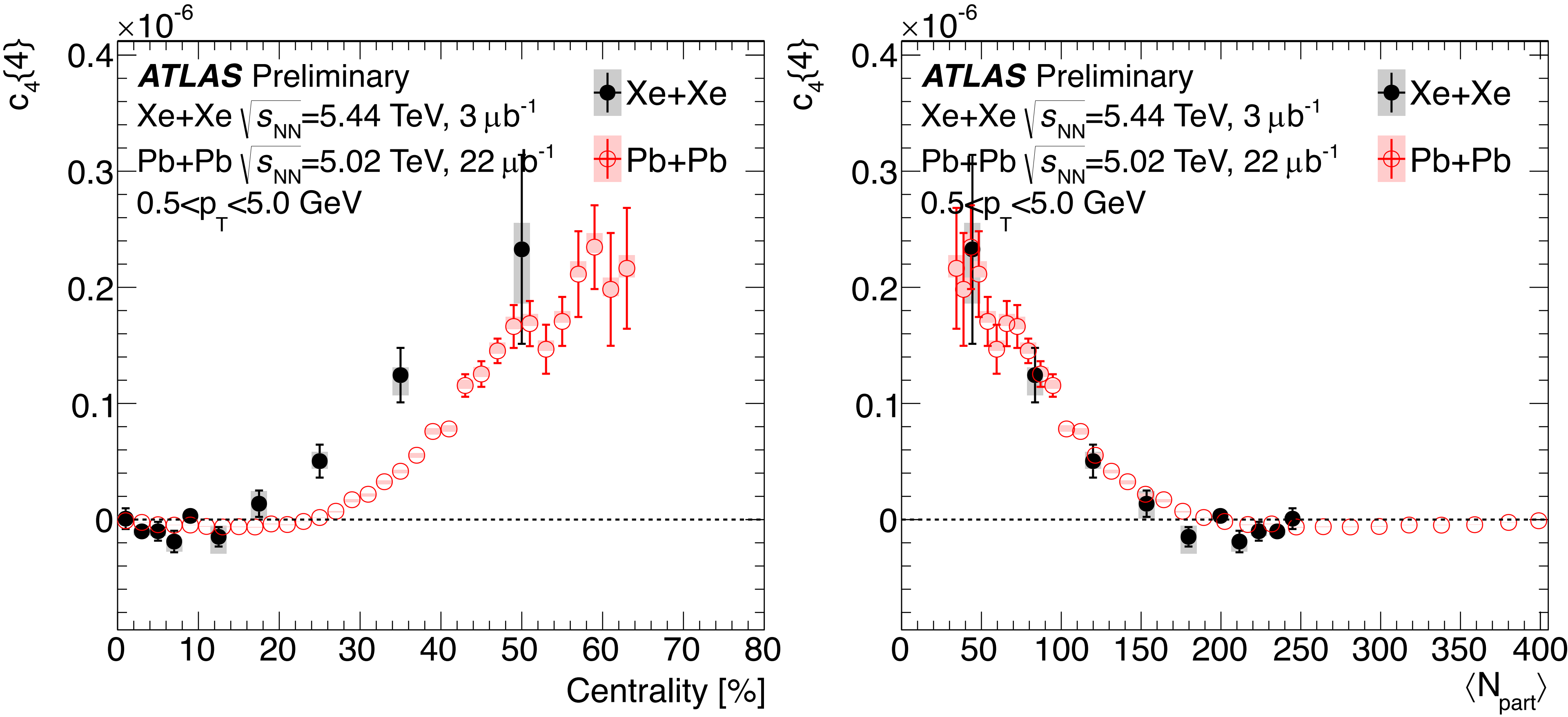

ATLAS Preliminary
Xe+Xe $\sqrt{s_{NN}}$=5.44 TeV, 3 μb^{-1}
0.5<p_T<5.0 GeV (20-40)%
n=2
n=3
$v_n\{4\}$
p_T [GeV]
ATLAS Preliminary
Xe+Xe $\sqrt{s_{NN}}$=5.44 TeV, 3 μb^{-1}
0.5<p_T<5.0 GeV (40-60)%
n=2
n=3
$v_n\{4\}$
p_T [GeV]



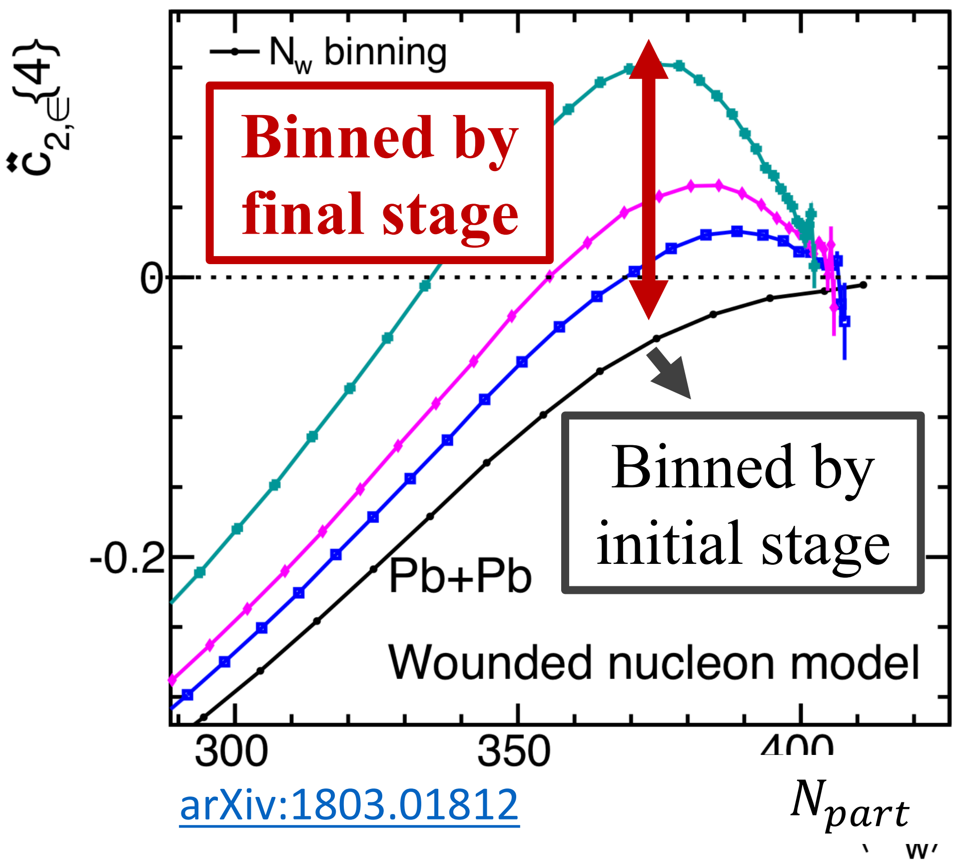
×10^-6
ATLAS Preliminary
Xe+Xe √sNN=5.44 TeV, 3 μb-1
0.5<pT<5.0 GeV
Correlator
10
5
0
-5
-10
sc2,3{4}
sc2,4{4}
ac2,4{3}/50
0
10
20
30
40
50
60
70
80
Centrality [%]
ATLAS Preliminary
Xe+Xe √sNN=5.44 TeV, 3 μb-1
0.5<pT<5.0 GeV
Correlator
1.5
1
0.5
0
-0.5
nsc2,3{4}
nsc2,4{4}
nac2,4{3}
0
10
20
30
40
50
60
70
80
Centrality [%]



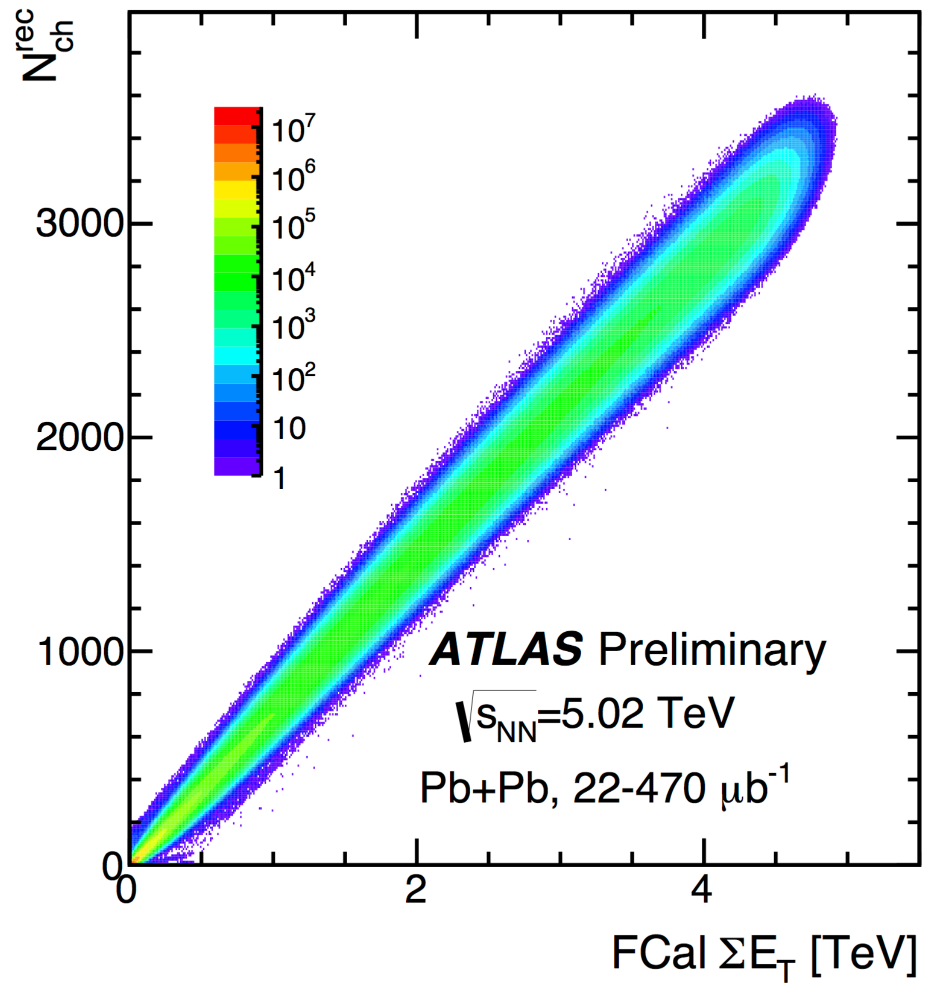
ATLAS Preliminary
Xe+Xe $\sqrt{s_{NN}}$=5.44 TeV, 3 μb^{-1}
Pb+Pb $\sqrt{s_{NN}}$=5.02 TeV, 22 μb^{-1}
0.5<p_T<5.0 GeV
Xe+Xe
Pb+Pb
$c_2\{4\}$
$\times 10^{-3}$
Centrality [%]
$\langle N_{part} \rangle$

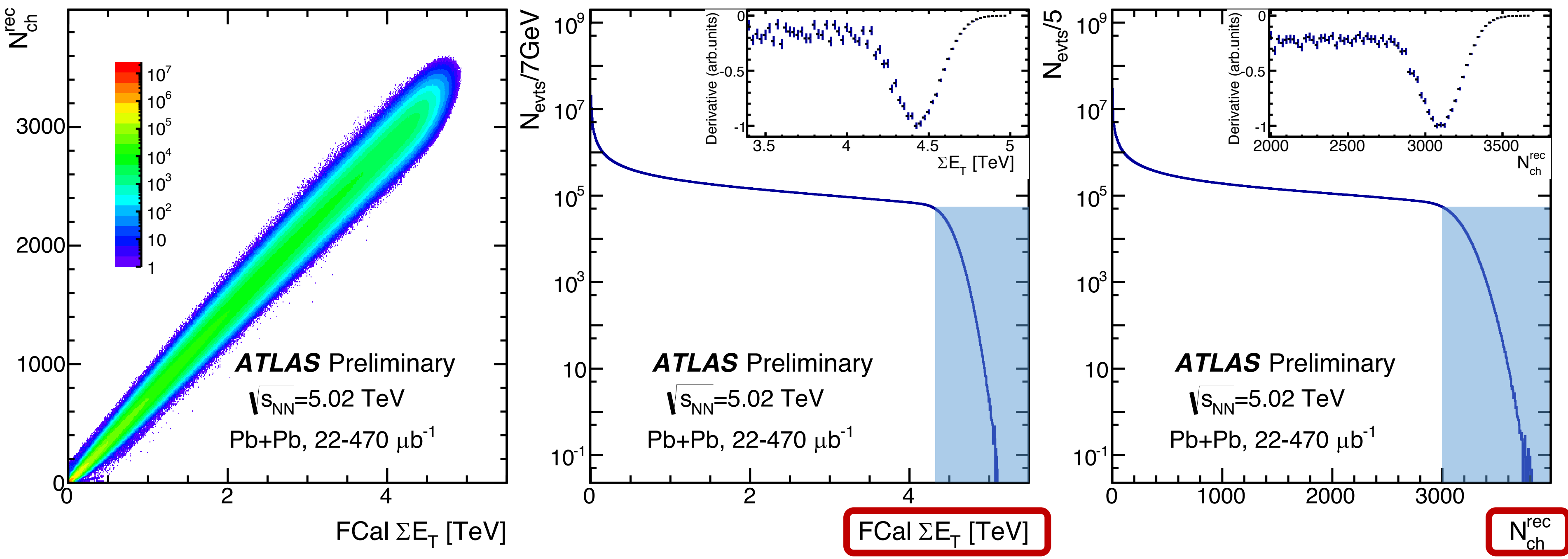


ATLAS Preliminary
Xe+Xe √sNN=5.44 TeV, 3 μb-1
Pb+Pb √sNN=5.02 TeV, 22 μb-1
0.5<pT<5.0 GeV
Xe+Xe
Pb+Pb
c4{4}
×10-6
Centrality [%]
⟨Npart⟩



arXiv:1803.01812





N_{ch}^{rec}
3000
2000
1000
0
0
2
4
FCal ΣE_T [TeV]
10^7
10^6
10^5
10^4
10^3
10^2
10
1
ATLAS Preliminary
√s_NN=5.02 TeV
Pb+Pb, 22-470 μb^-1
N_evts/7GeV
Derivative (arb.units)
ΣE_T [TeV]
FCal ΣE_T [TeV]
N_evts/5
N_{ch}^{rec}

- Definitions of centrality
  - Ideally, defined by initial stage: N_{part} or b;
  - In experiment, defined by final stage: E_T or N_{ch};
- To compare data with models, map $\langle N_{ch} \rangle$ to $\langle N_{part} \rangle$;
- But it does NOT always work for cumulant.

Cumulant is sensitive to flow fluctuation, but sometimes it is TOO sensitive…

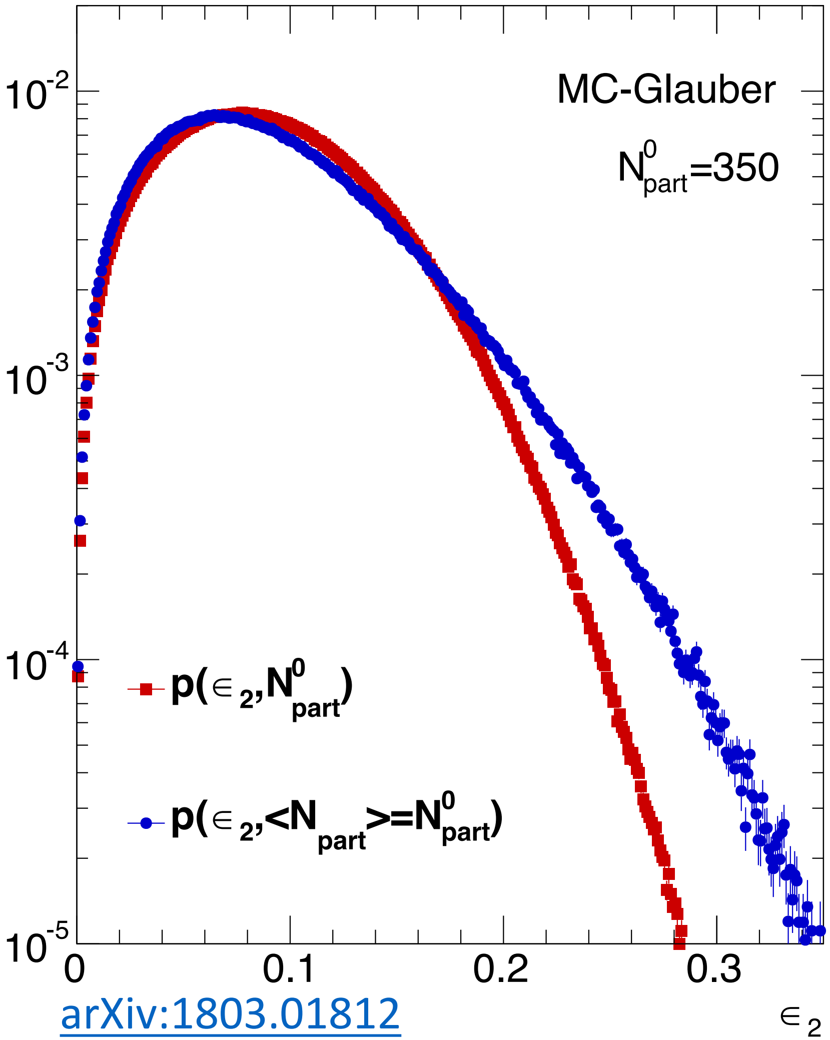
- 4-particle cumulant: $c_n\{4\} \equiv \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2$

Averaged over many events in each centrality

Calculated event-by-event

Centrality definition ⇒ flow fluctuation ⇒ $c_2\{4\}$

- Since $p(v_2)$ depends on N_{part}: $p(v_2, N_{part}^0) \neq p(v_2, \langle N_{part} \rangle = N_{part}^0)$



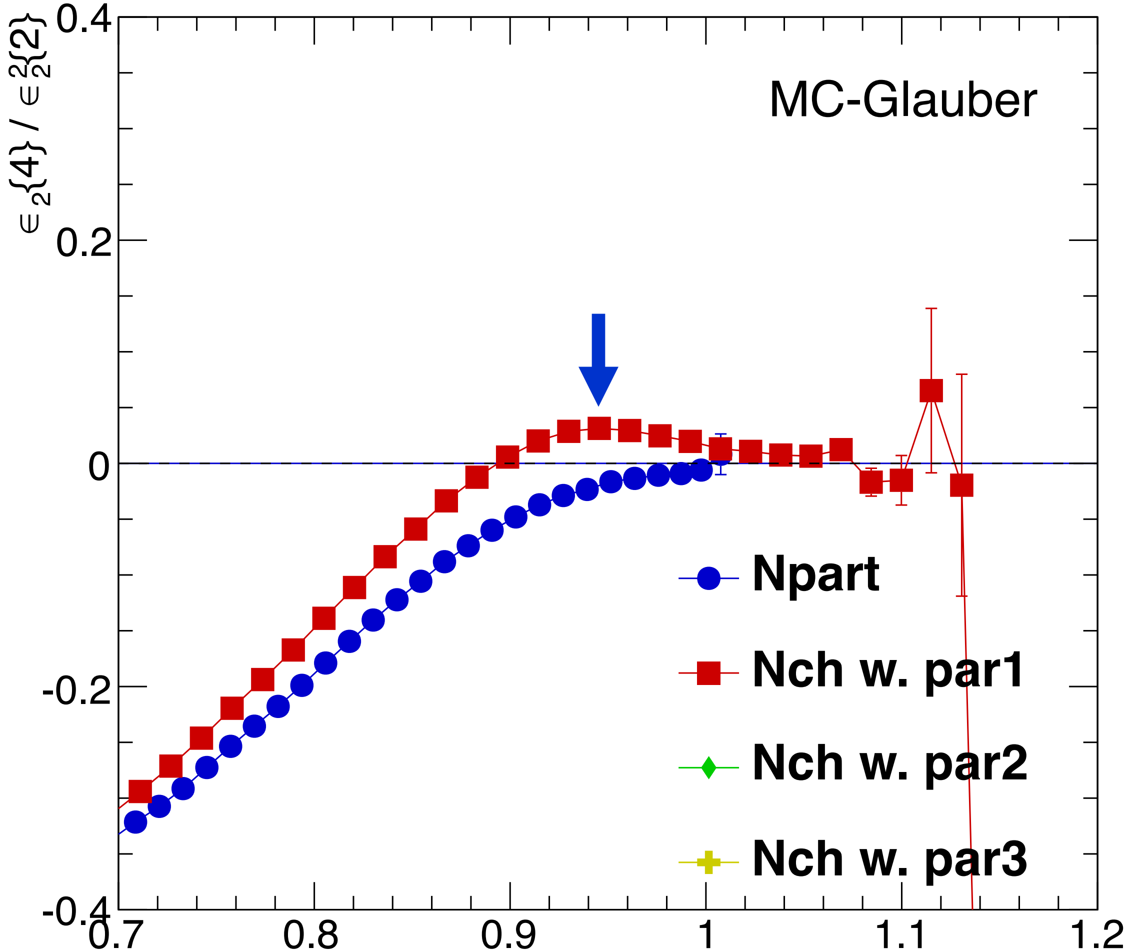
arXiv:1803.01812

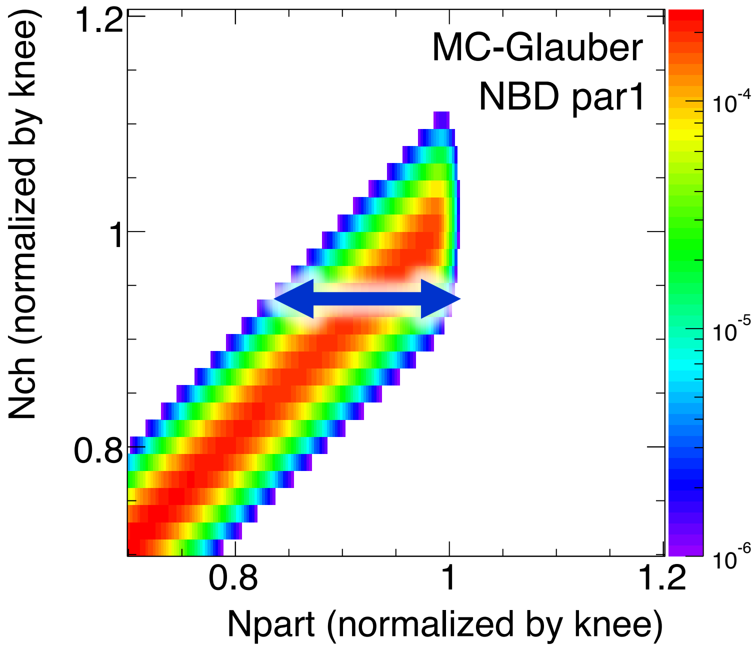
$$c_2\{4, N_{part}^0\} \neq c_2\{4, \langle N_{part} \rangle = N_{part}^0\}$$

Centrality resolution has potential effects on cumulants.

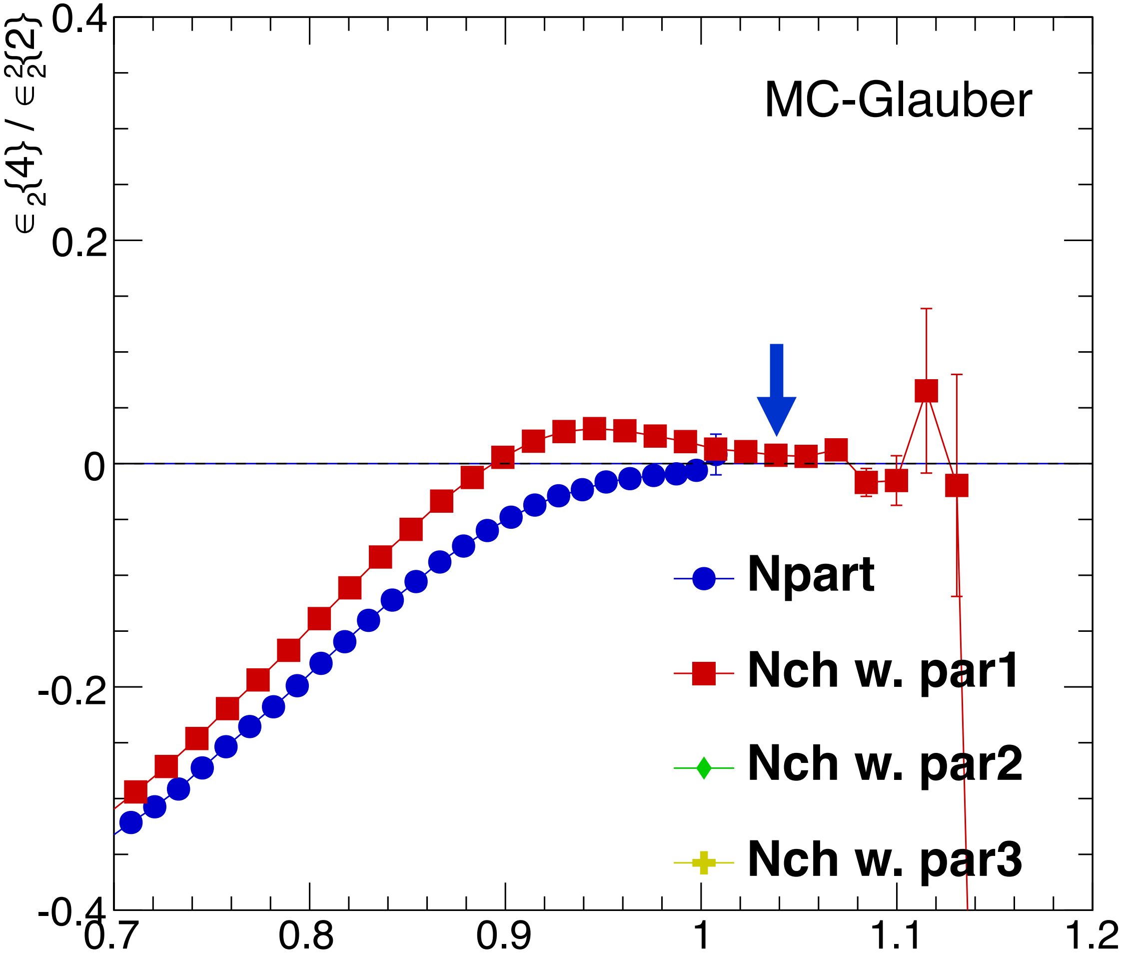
- Assume $v_2 \sim \epsilon_2$, such effects can be shown in MC-Glauber

$$\epsilon_2\{4, N_{part}^0\} \neq \epsilon_2\{4, \langle N_{part} \rangle = N_{part}^0\}$$

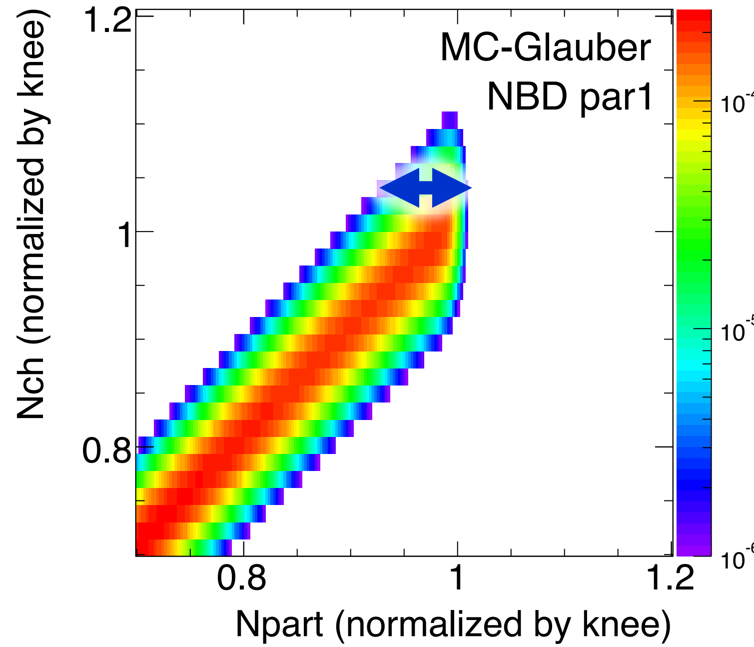




arXiv:1803.01812

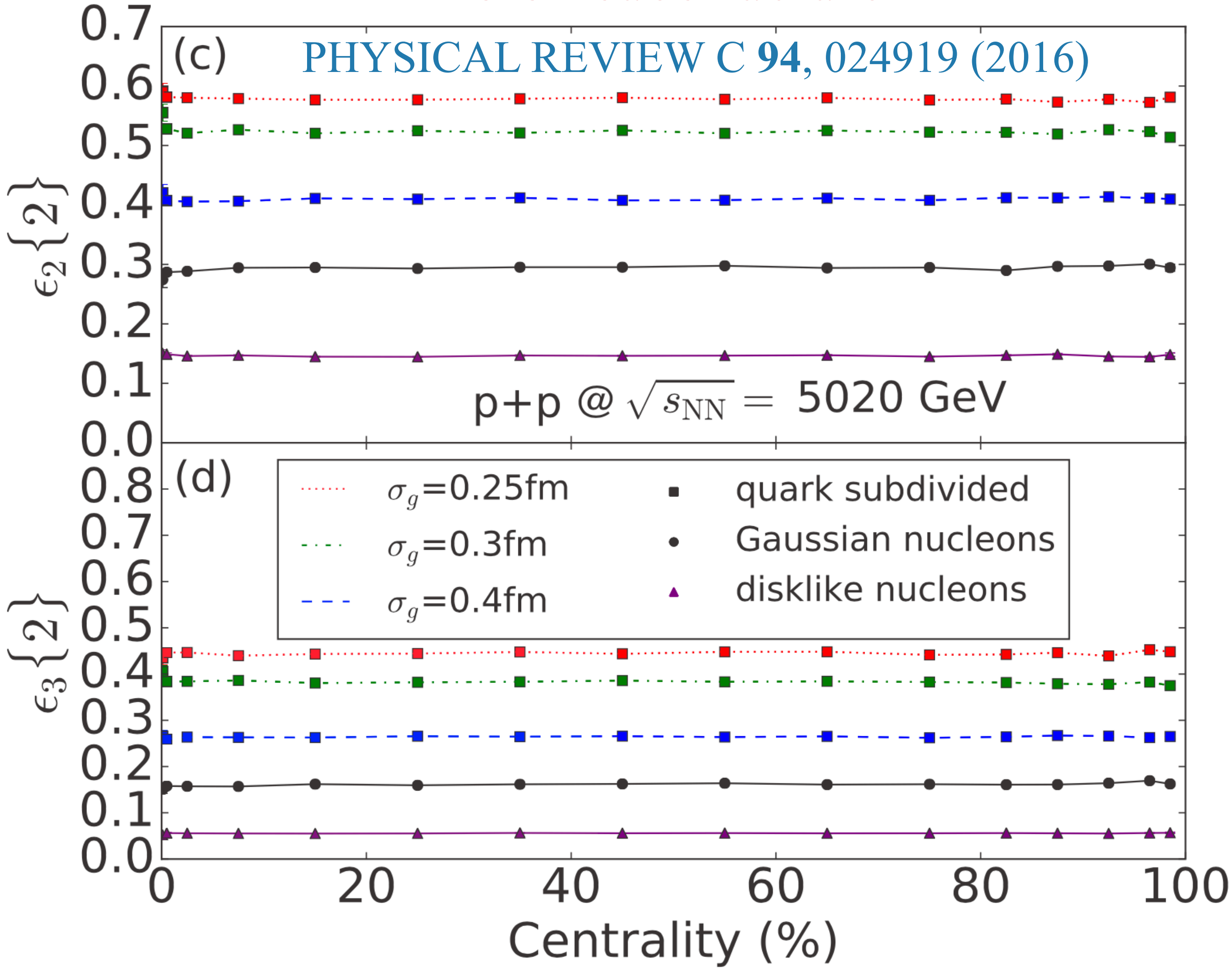


arXiv:1803.01812



- In very central collision, centrality resolution becomes better.

Proton substructure



- Centrality resolution too poor: N_{ch} not a good indicator for geometry?