Flow Fluctuation and Centrality Fluctuation in Pb+Pb collisions with the ATLAS Detector

arXiv:1904.04808

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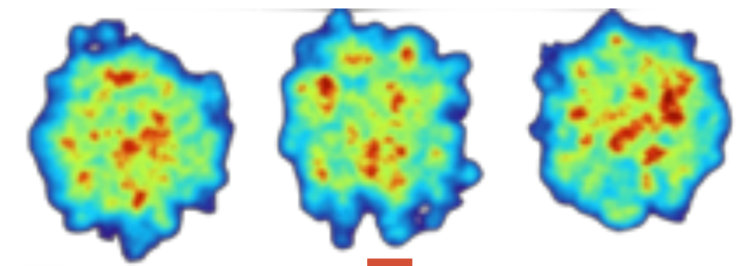
Flow Fluctuations

- Flow fluctuations arises from both initial stage and final stage
- These fluctuations affect the underlying flow probability distributions

$$p(v_n)\ ,\ p(v_n, v_m)$$

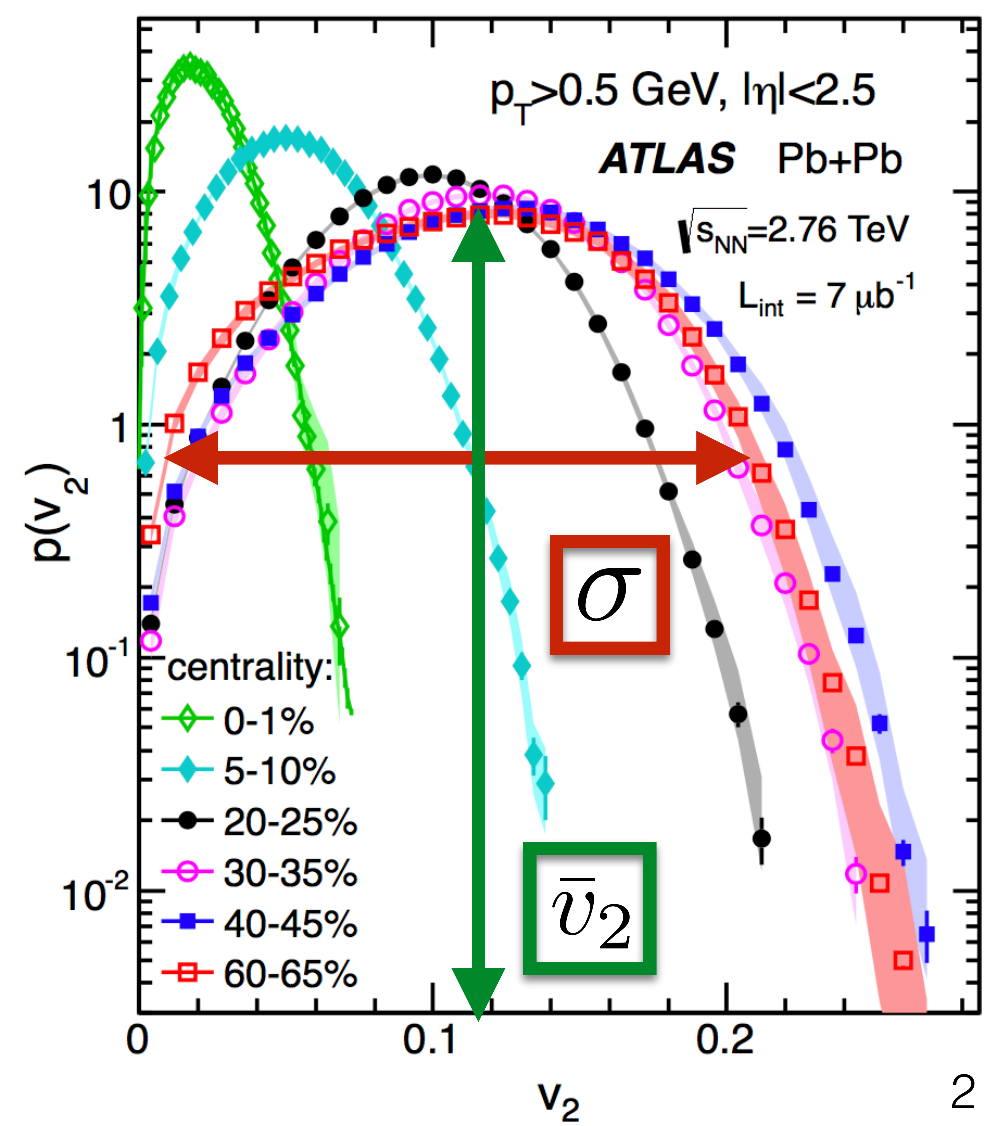
- Measuring flow fluctuations is crucial to understand space-time dynamics of HIC

EbyE IS fluct.



JHEP11(2013)183

p(v_n)



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$$p(v_n)\ ,\ p(v_n, v_m)$$

- Measuring flow fluctuations is crucial to understand space-time dynamics of HIC
- Flow fluctuations are measured using multi-particle cumulants :
  - ✦ Suppress non-flow
  - ✦ Measure $p(v_n)$, $p(v_n, v_m)$
  - ✦ Gaussian fluct. $v_n \sim Gauss(\bar{v}_n, \delta_n)$

$$v_n\{2\} = \sqrt{\bar{v}_n^2 + \delta_n}$$

$$v_n\{2\} > v_n\{4\} = v_n\{6\} = ... = \bar{v}_n$$

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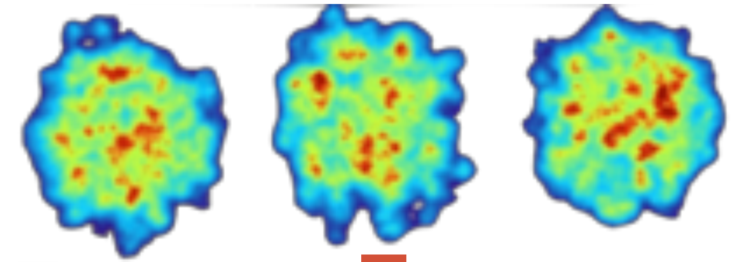

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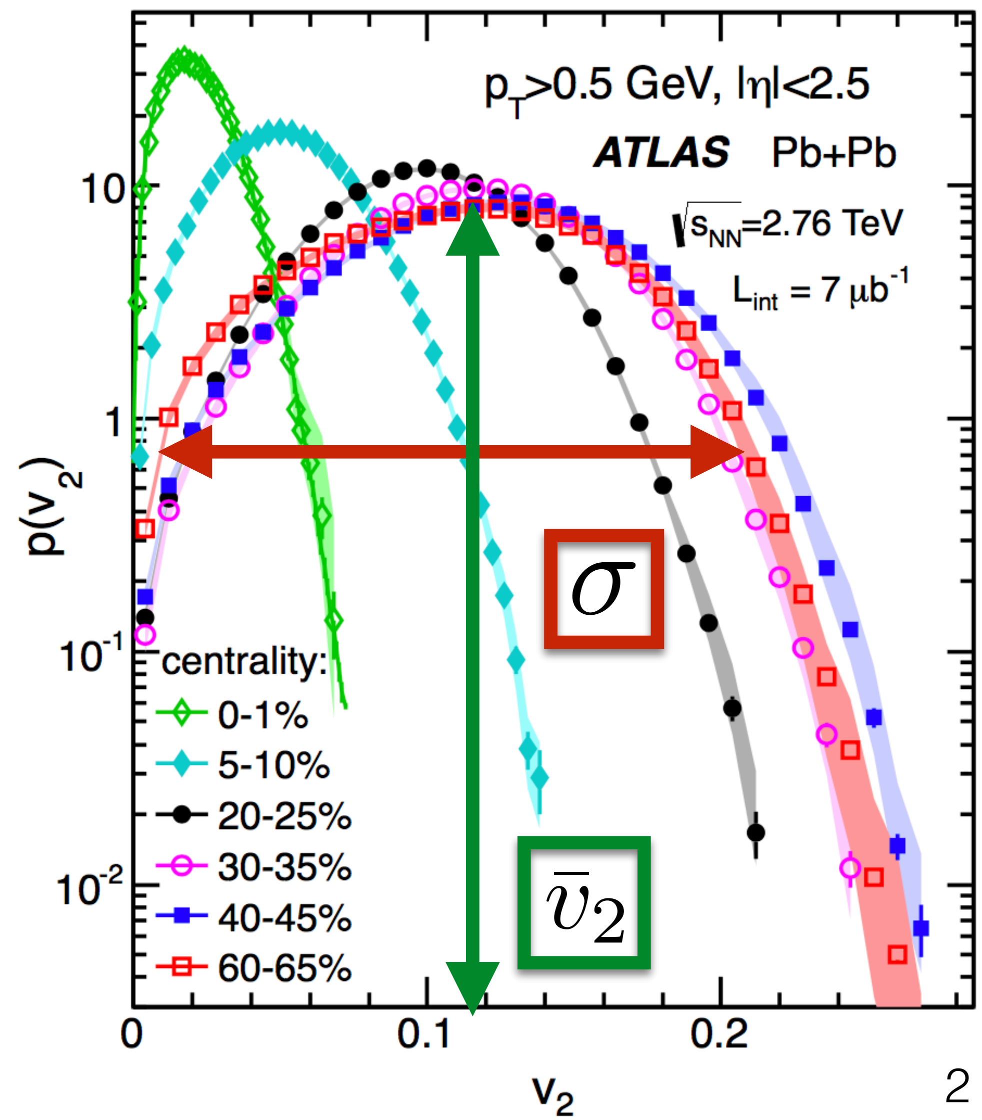

Observables for Flow Fluctuations

- Multi-particle cumulants for single harmonic - $p(v_n)$

$$c_n\{2\} = \langle v_n^2 \rangle \;, \; c_n\{4\} = \langle v_n^4 \rangle - 2\langle v_n^2 \rangle^2 \;, \; 4c_n\{6\} = \langle v_n^6 \rangle - 9\langle v_n^4 \rangle \langle v_n^2 \rangle + 12\langle v_n^3 \rangle^2$$

$$nc_n\{4\} = \frac{c_n\{4\}}{c_n\{2\}^2} = -\left(\frac{v_n\{4\}}{v_n\{2\}}\right)^4 \qquad nc_n\{6\} = \frac{c_n\{6\}}{4c_n\{2\}^3} = \left(\frac{v_n\{6\}}{v_n\{2\}}\right)^6$$

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- Symmetric cumulants for two harmonic - $p(v_n,v_m)$

$$nsc_{n,m}\{4\} = \frac{\langle v_n^2 v_m^2 \rangle}{\langle v_n^2 \rangle\langle v_m^2 \rangle} - 1$$

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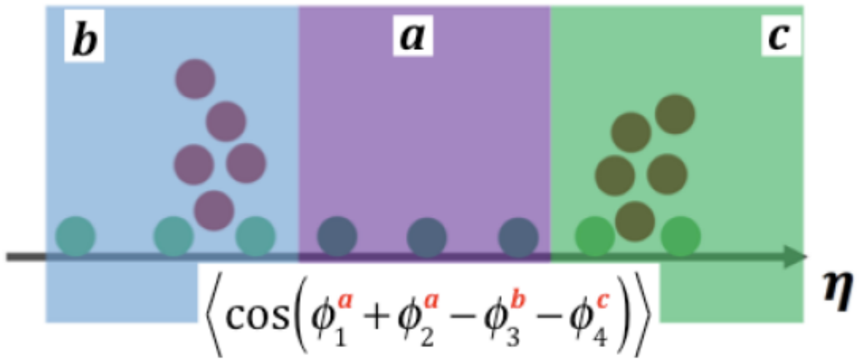
Phys. Rev. C 96, 034906

Phys. Rev. C 97, 024904

- η - subevent method - suppress non-flow
  - ✦ Cumulants from both methods - consistent
  - ✦ Only results for standard method are shown



3-subevent method

v_n from Four-particle Cumulant

- If flow is purely geometry driven : $v_n \propto \epsilon_n$ and $p(v_n)$ has same shape as $p(\epsilon_n)$

$$\frac{v_n\{4\}}{v_n\{2\}} \overset{?}{=} \frac{\epsilon_n\{4\}}{\epsilon_n\{2\}}$$

p_T independent

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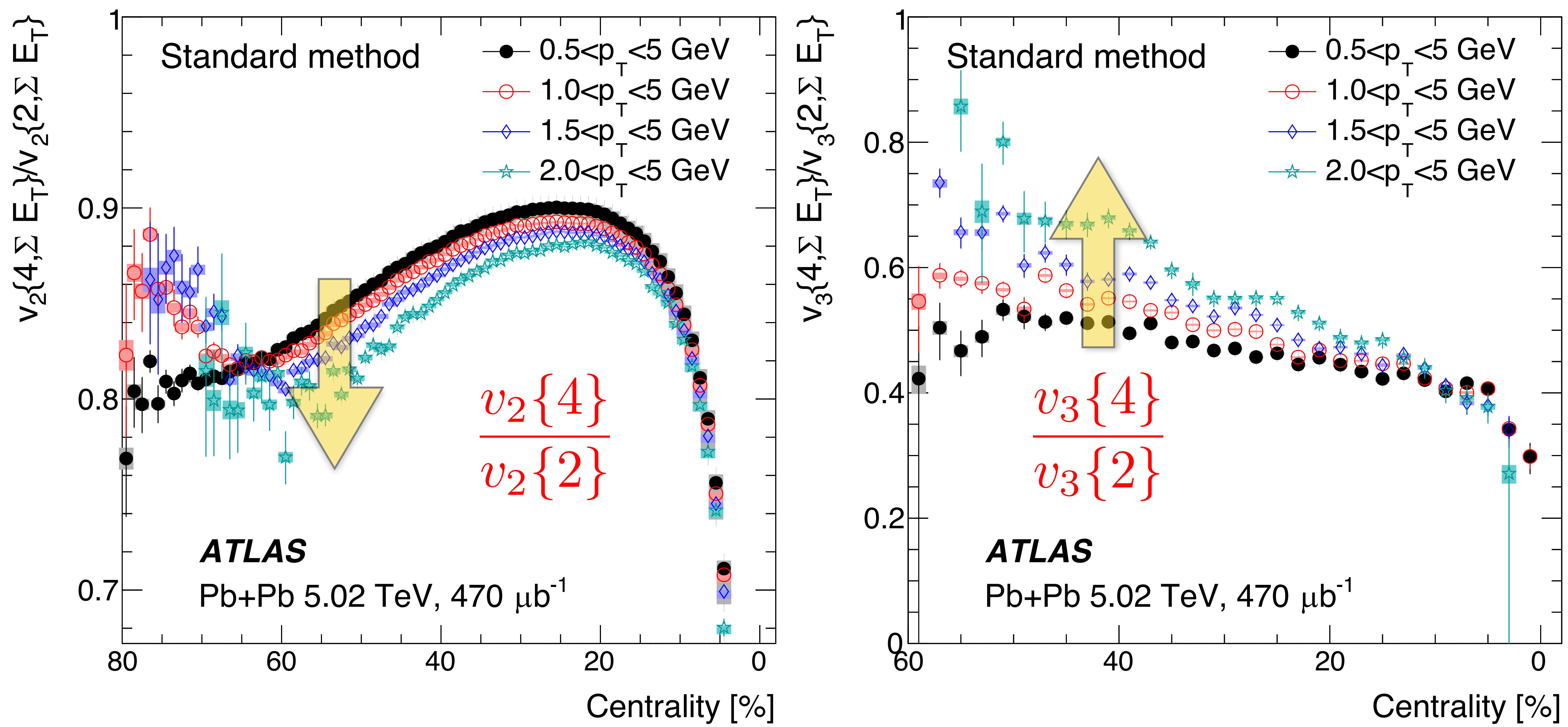

- Clear residual p_T dependence observed
- IS geometry may not be the only source
- Possibility of final state effects

$$\frac{v_n\{4\}}{v_n\{2\}} \neq \frac{\epsilon_n\{4\}}{\epsilon_n\{2\}}$$

v_2 from Six-particle Cumulant

- Due to non-gaussian fluctuations

$$\frac{v_n\{6\}}{v_n\{4\}} \neq \frac{\epsilon_n\{6\}}{\epsilon_n\{4\}} \neq 1$$

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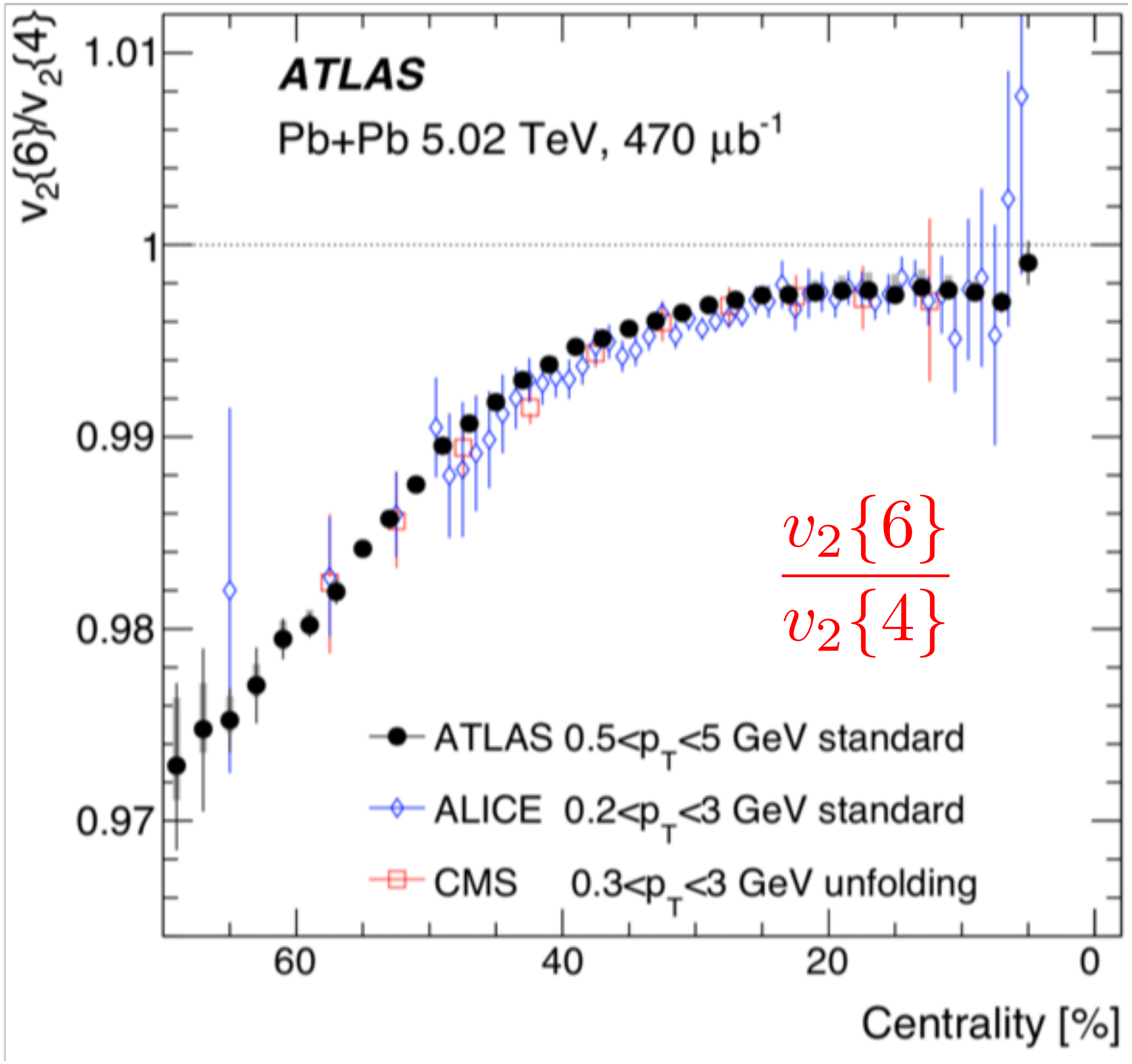
- Excellent agreement among all three experiments
  - ATLAS - much better precision
- pT dependence??



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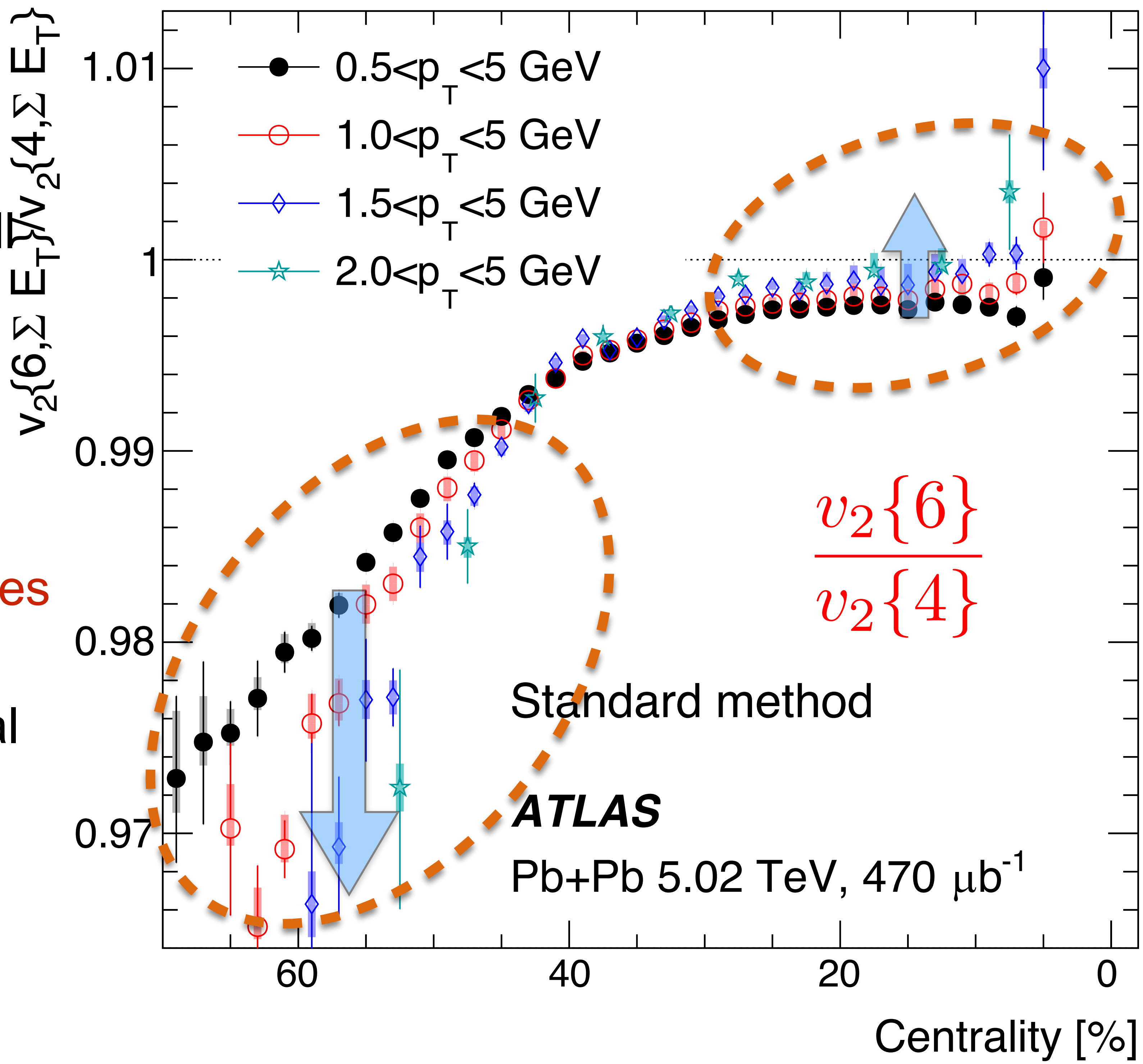
$$\frac{v_n\{6\}}{v_n\{4\}} \neq \frac{\epsilon_n\{6\}}{\epsilon_n\{4\}} \neq 1$$

- Excellent agreement among all three experiments
  - ATLAS - much better precision
- Changes with different p_T ranges
  - Increases with pT at central
  - Decreases with pT at peripheral
- Possibility of final state effects



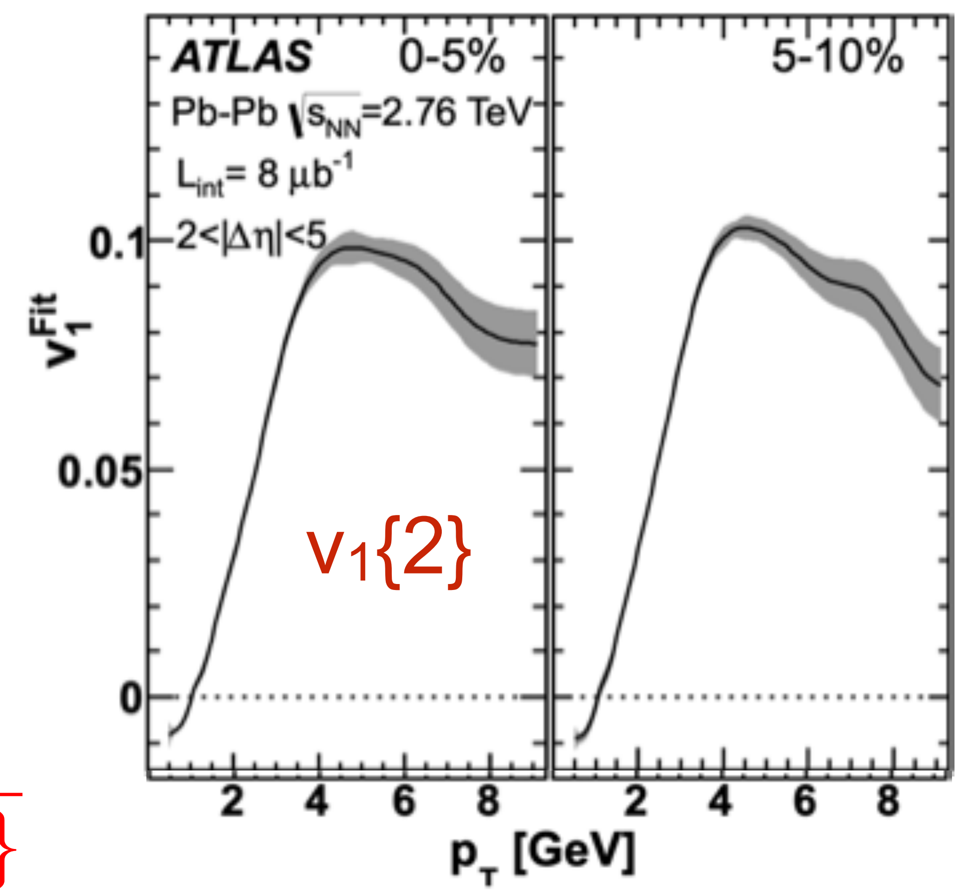
Four-particle cumulant for v_1

Phys.Rev. C86 (2012) 014907

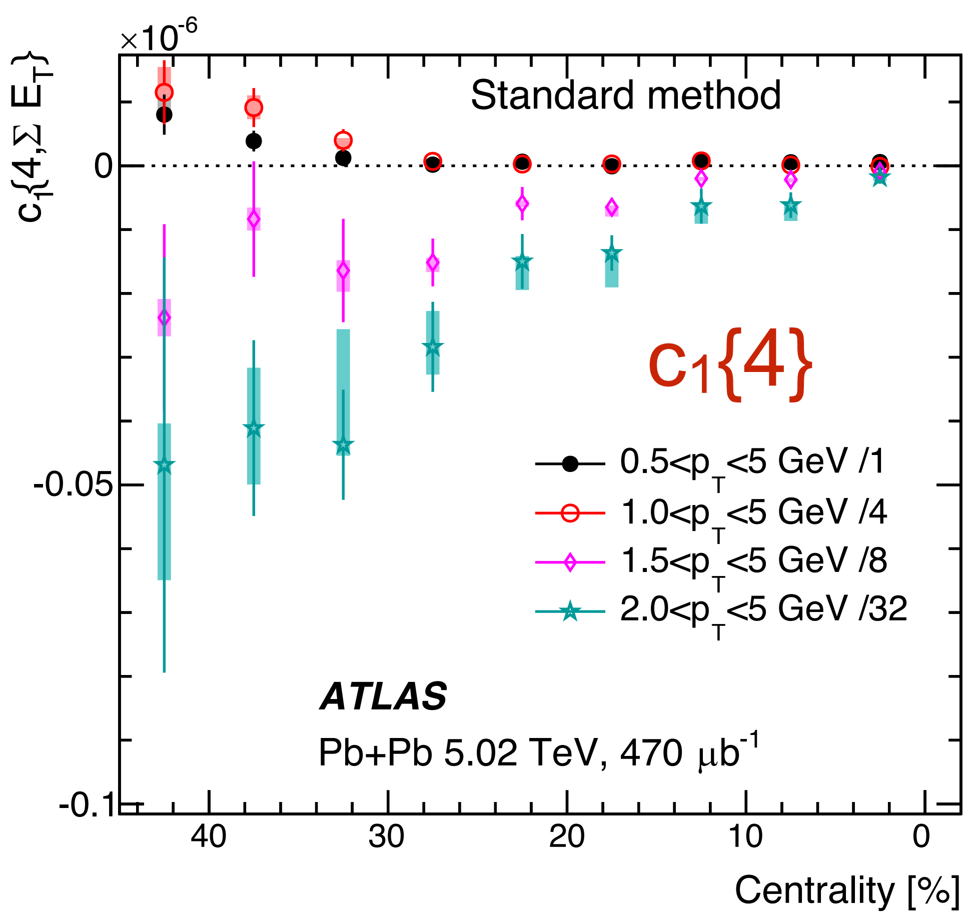
- $v_1\{2\}$ changes sign at low p_T~1.2GeV
- $c_1\{4\}$: -ve observed for higher p_T

$$c_1\{4\} = \langle v_1^4 \rangle - 2\langle v_1^2 \rangle^2$$

- $v_1\{4\}$ - taking only high p_T (larger signal)



$$v_1\{4\} = \sqrt[4]{-c_1\{4\}}$$



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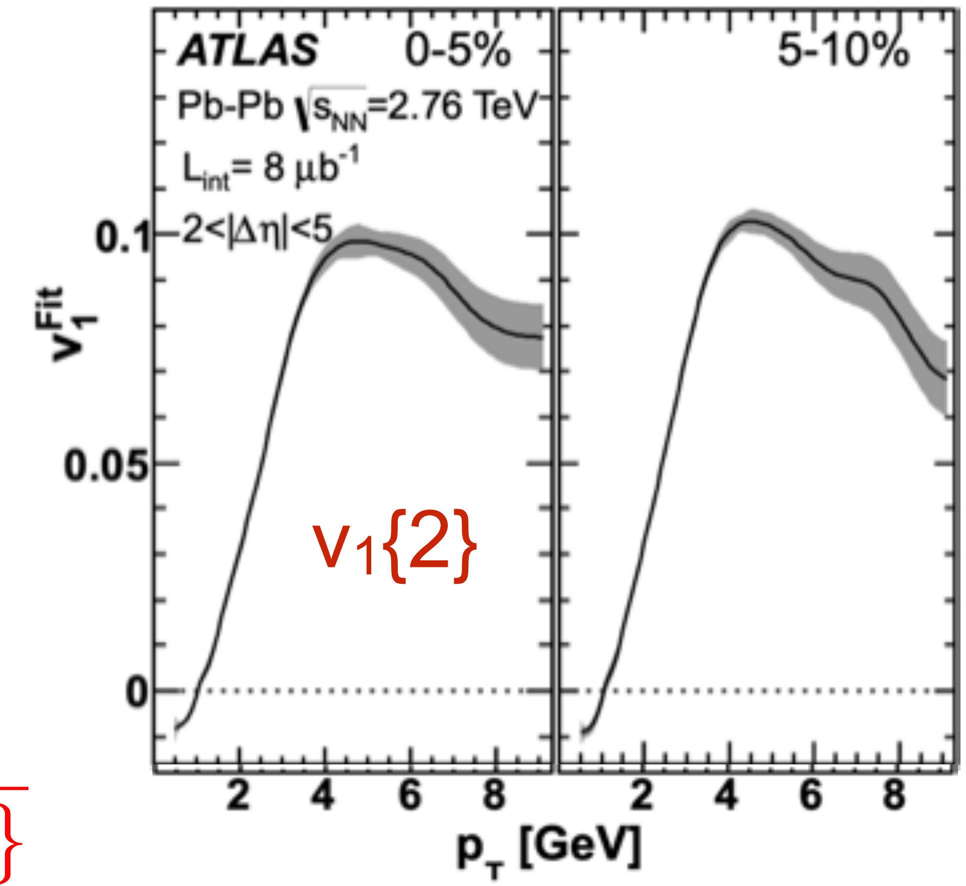
- $v_1\{4\}$ - taking only high p_T (larger signal)
- First measurement of $v_1\{4\}$ - signal increases from central to peripheral
- Consistent with 3SE results



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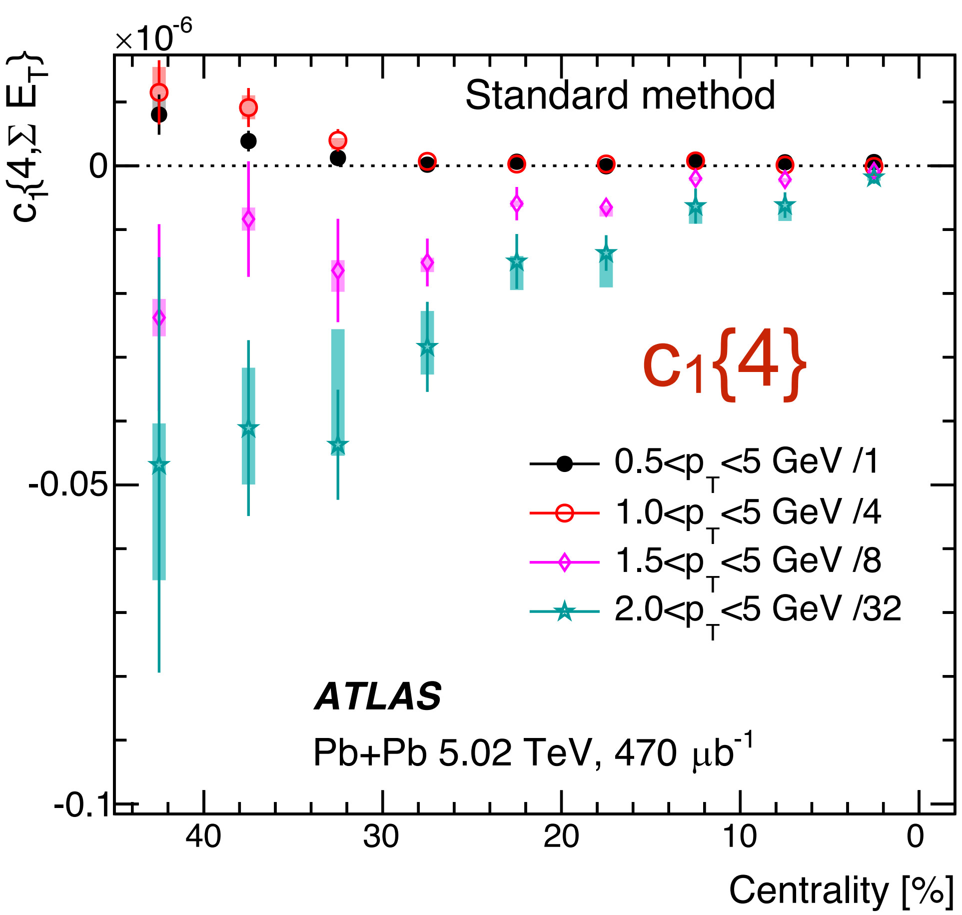
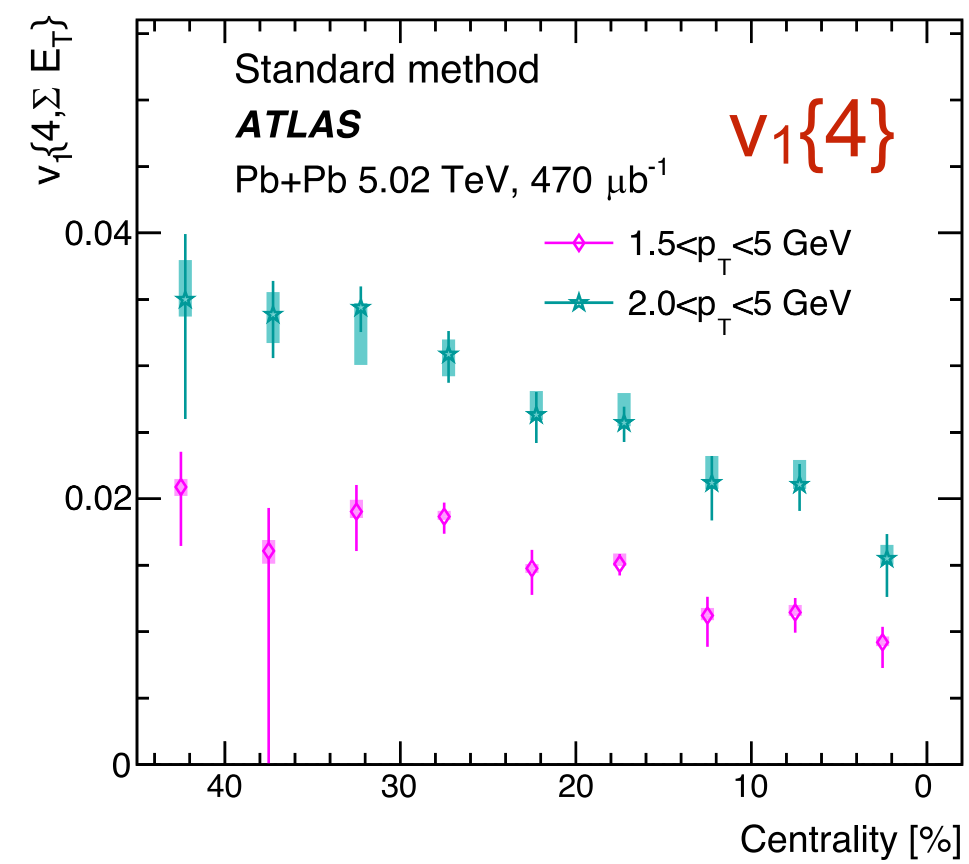
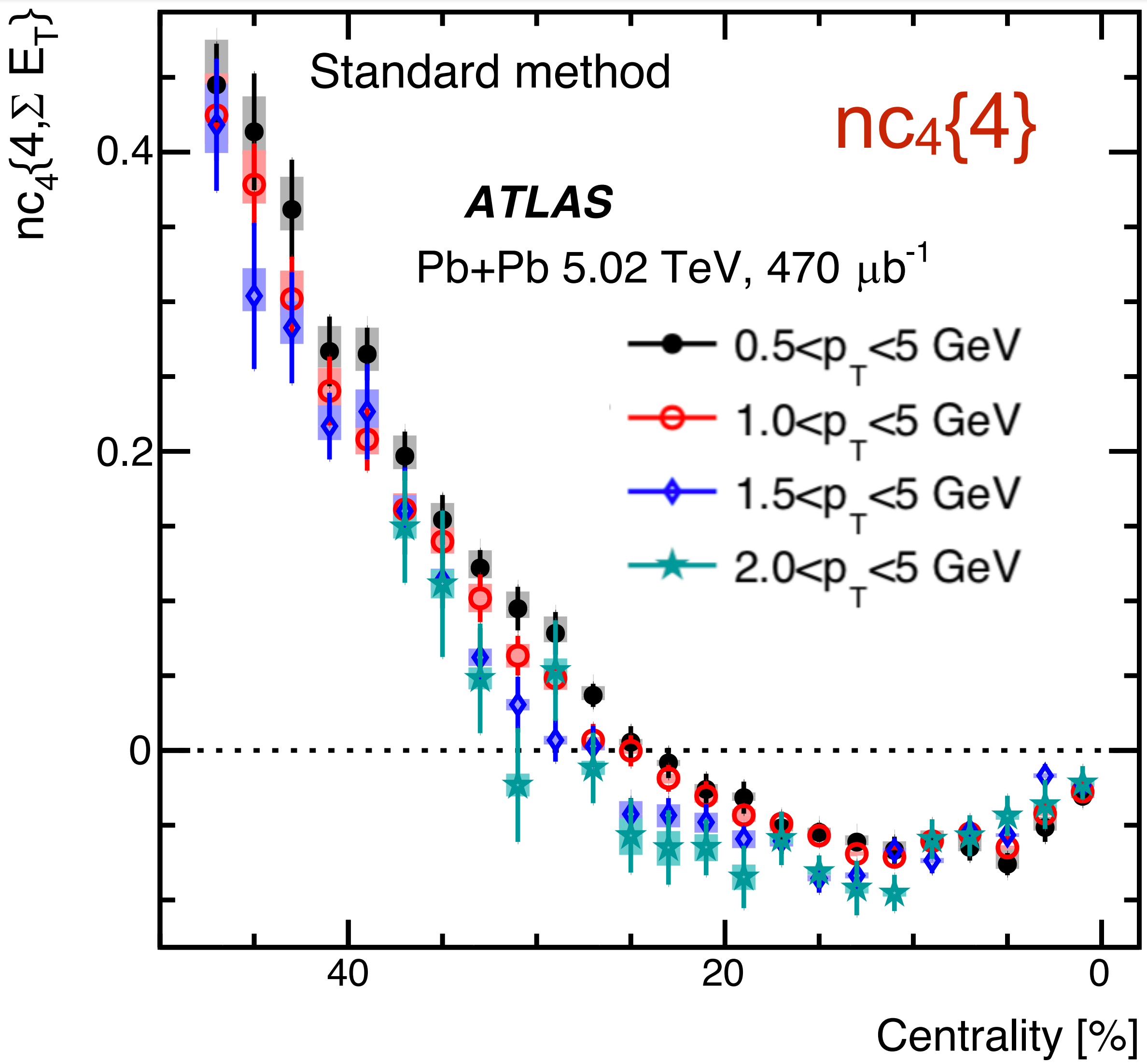




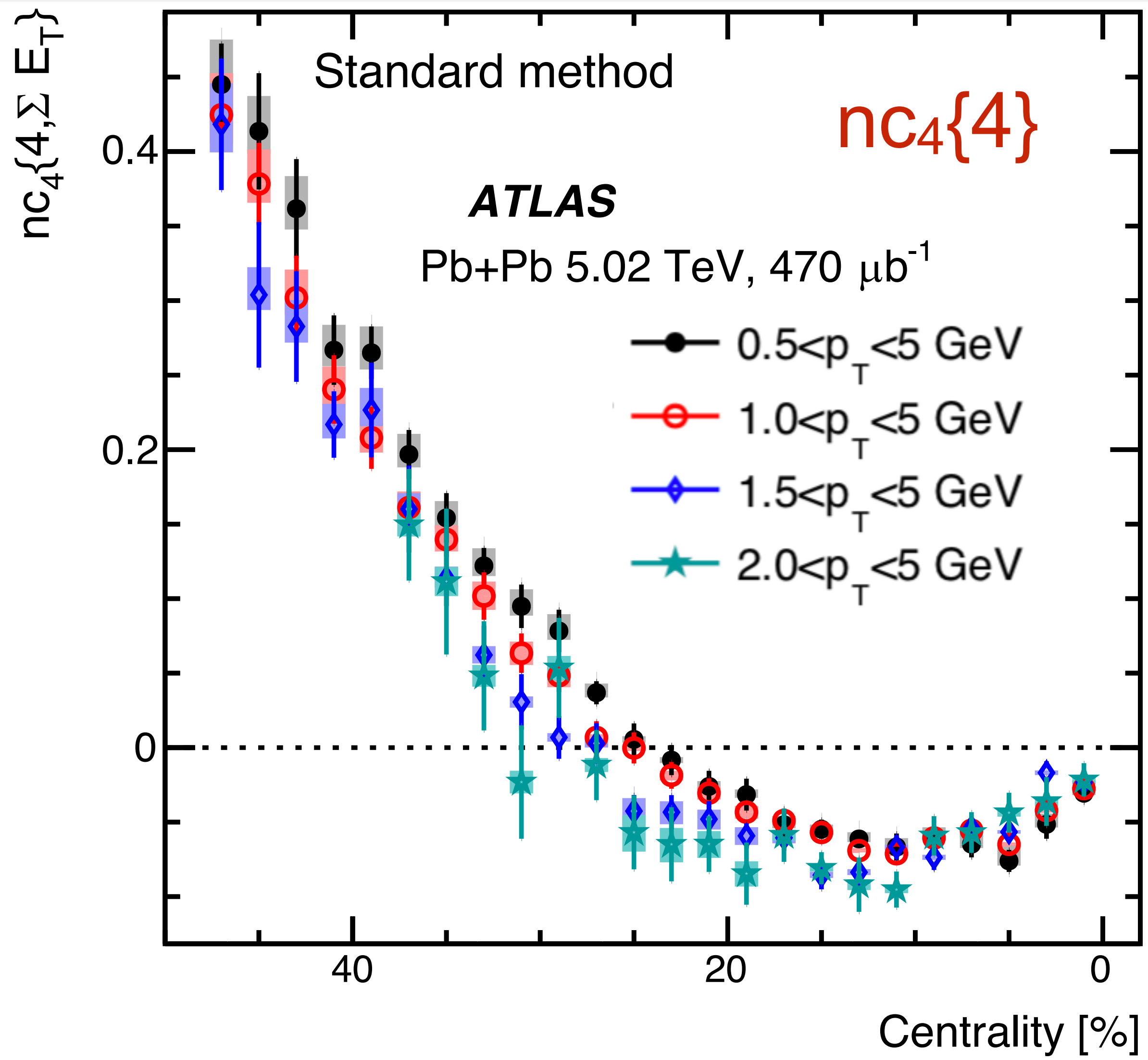
Four-particle cumulant for v_4

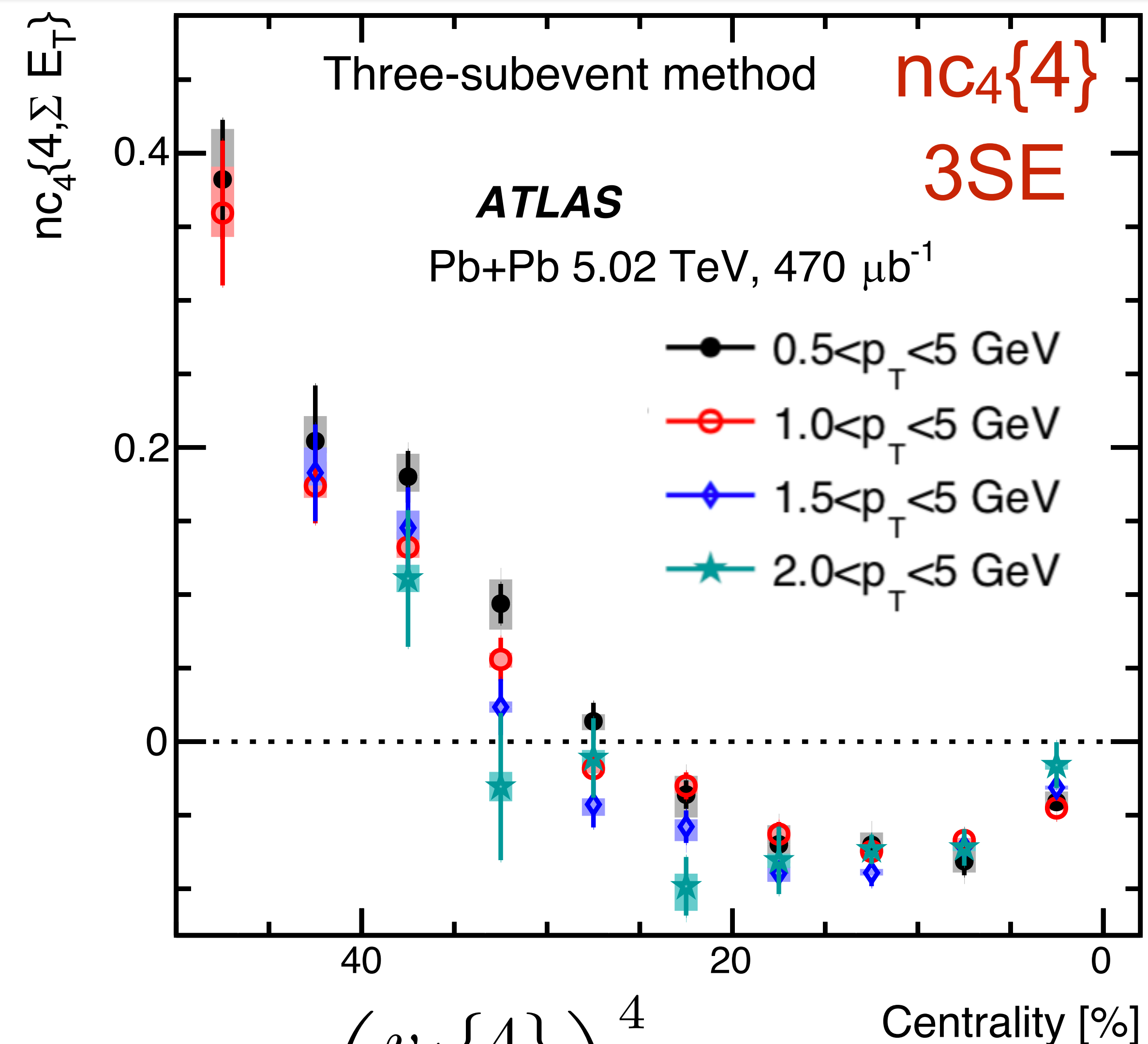


$$nc_4\{4\} = -\left(\frac{v_4\{4\}}{v_4\{2\}}\right)^4$$

- Sign change for $nc_4\{4\}$ at mid-central, non-linear increase in peripheral
- Is it due to non-flow?

Four-particle cumulant for v_4





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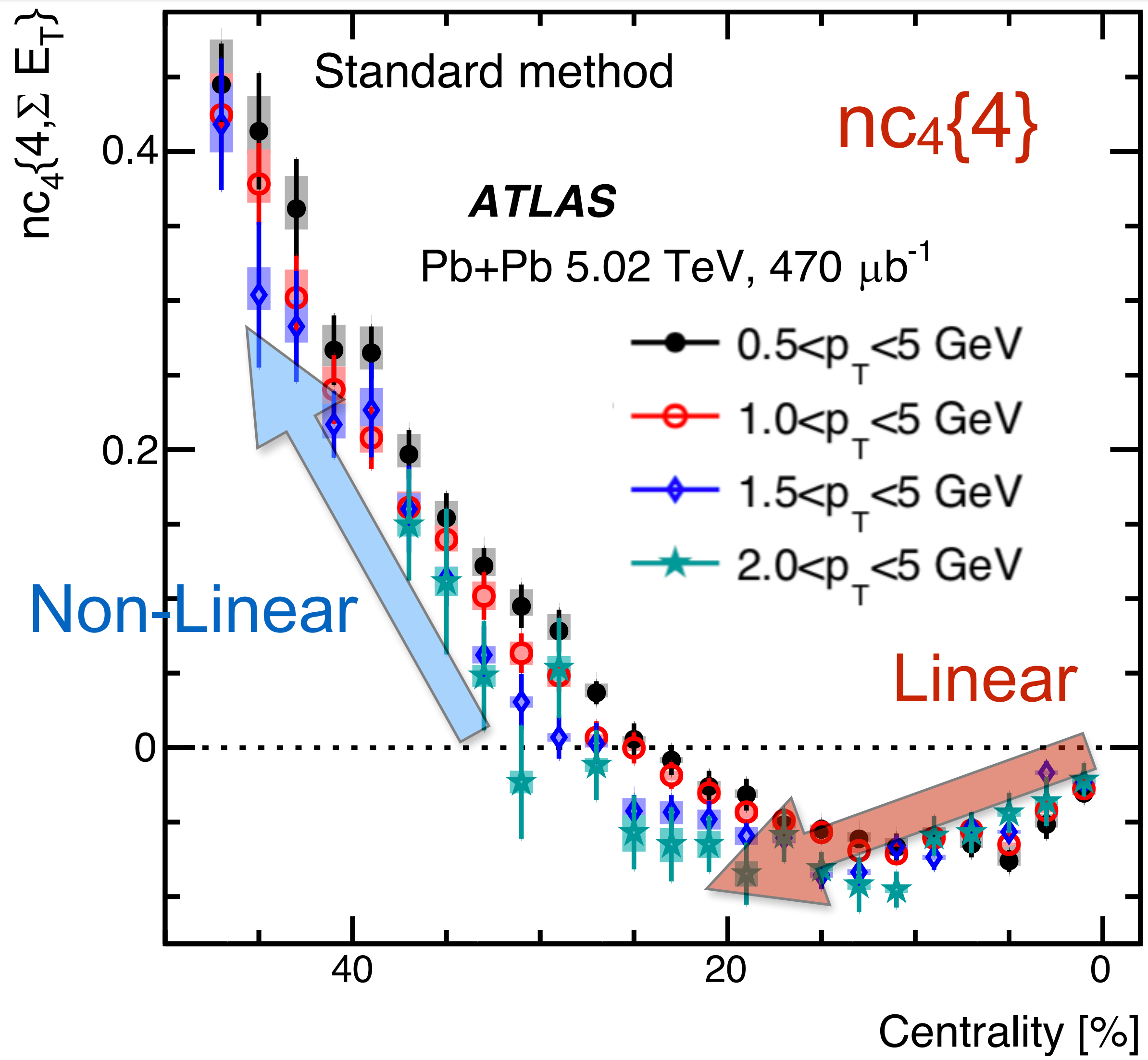

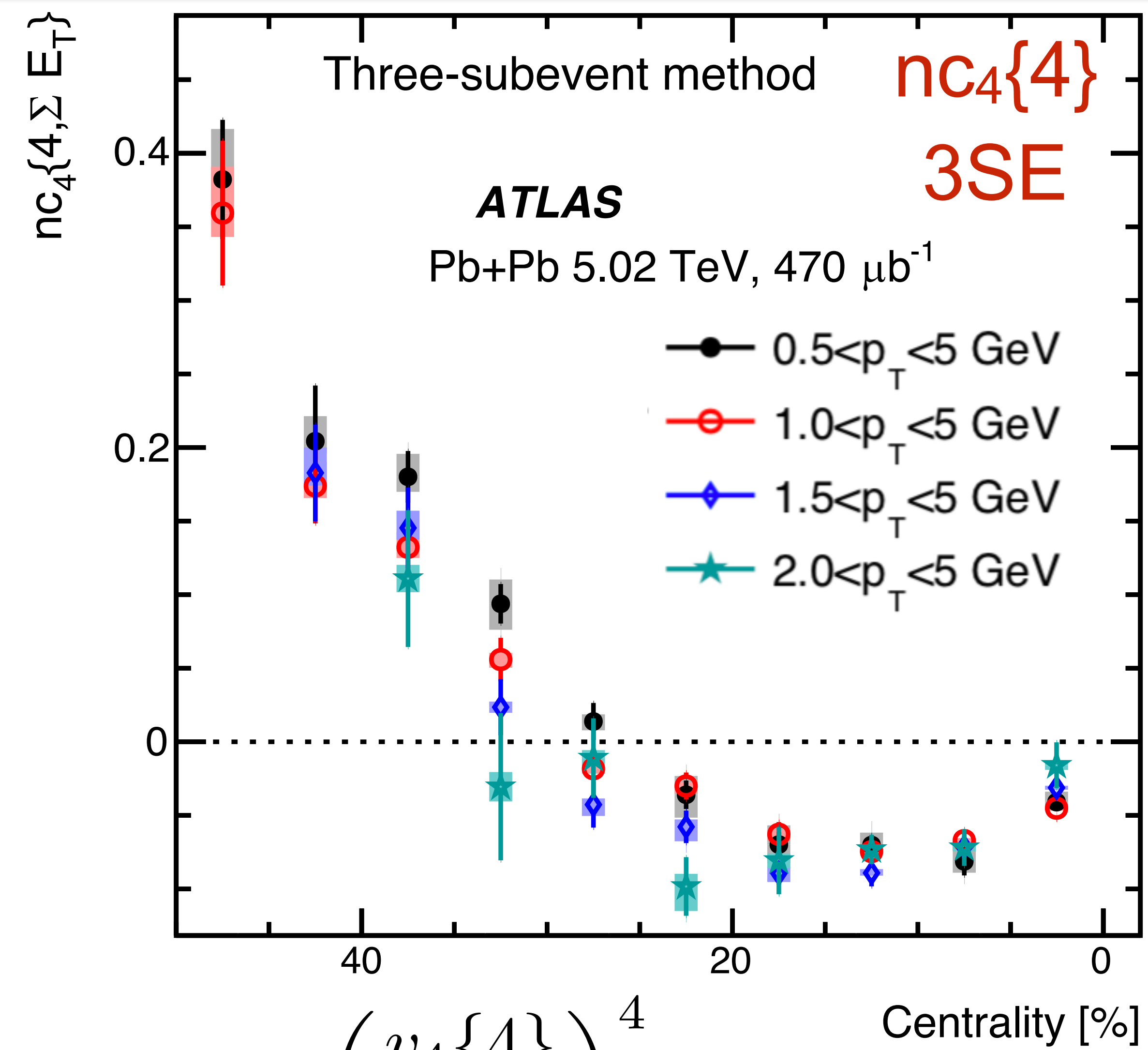

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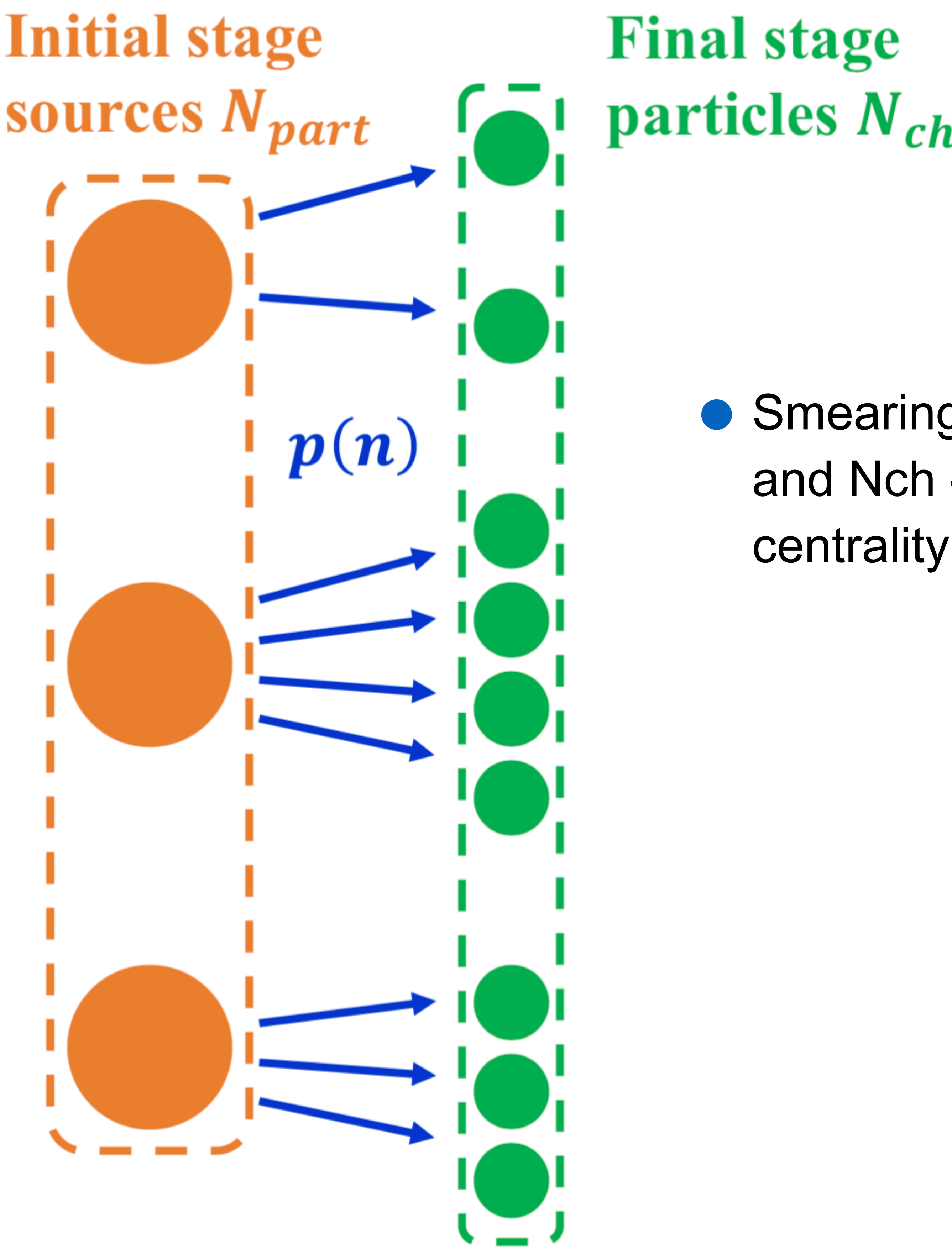
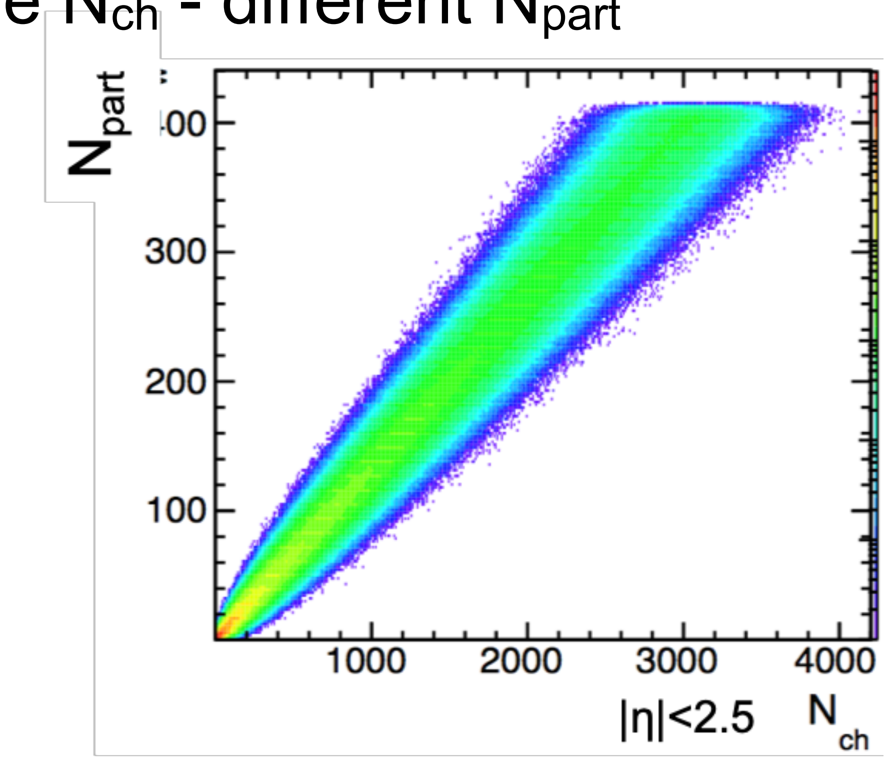
- Is it due to non-flow? Not non-flow! Similar behaviour in 3SE method
- Possible reason : Mode mixing in v4: $v_4 = v_{4L} + \beta_{2,2} v_2^2$
  - ✦ v_{4L} - $nc_4\{4\} < 0$ in central
  - ✦ v_2^2 - $nc_4\{4\} > 0$ in peripheral

Role of Centrality Fluctuation



- Fluctuation in particle production p(n) :
  - ✦ Same N_{part} - different N_{ch}
  - ✦ Same N_{ch} - different N_{part}



- Smearing b/w Npart and Nch - gives centrality fluctuation

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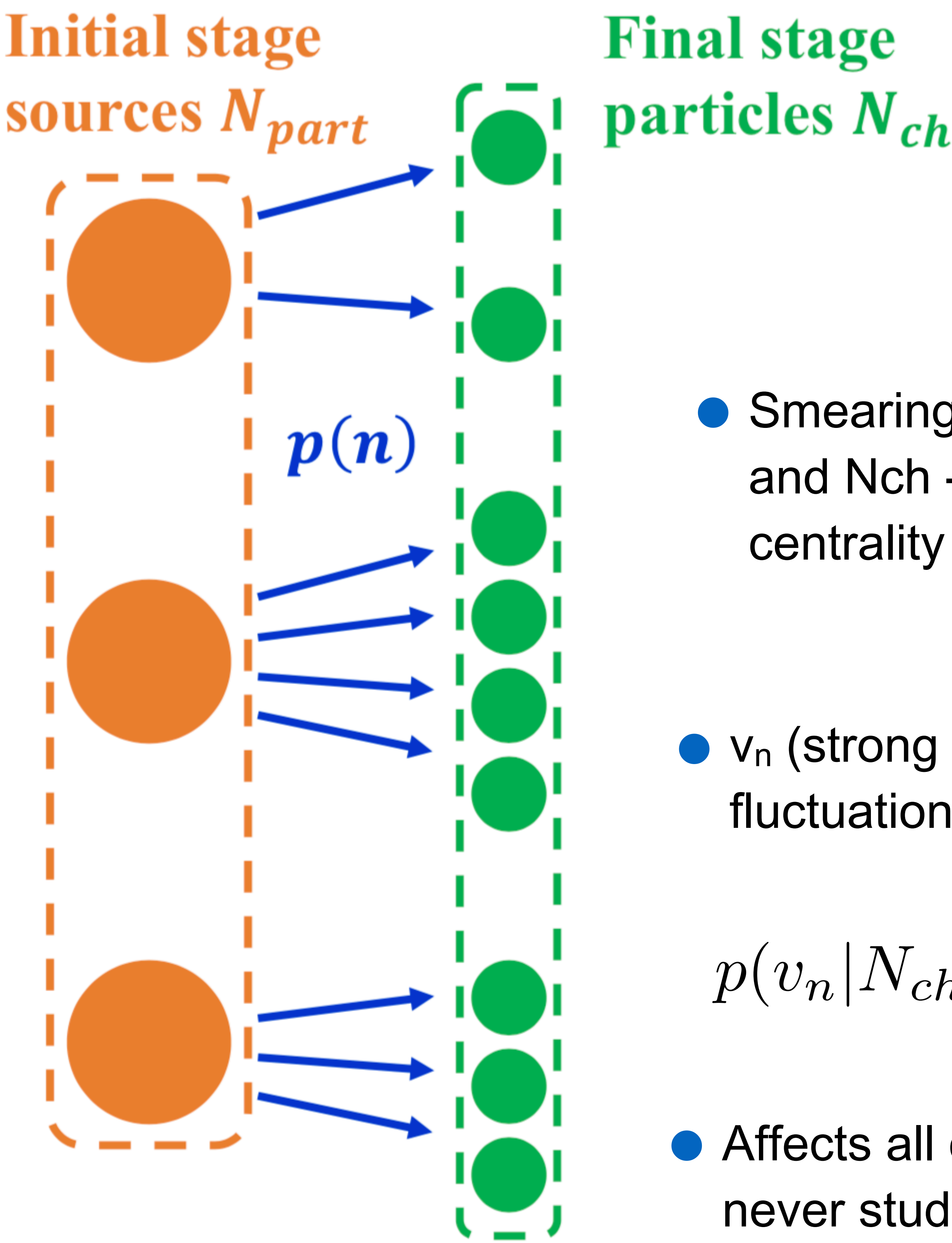

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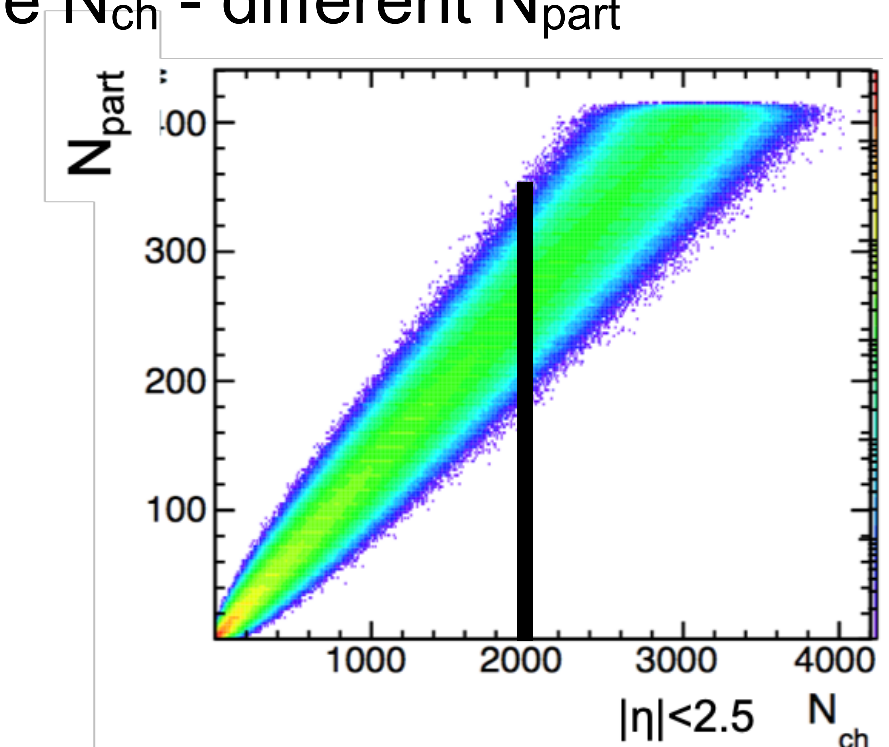

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- v_n (strong centrality dependence) - centrality fluctuation can add additional smearing

$$p(v_n|N_{ch}) = \sum_{cent} p(v_n|cent) \otimes p(cent|N_{ch})$$

- Affects all observables that change with centrality - never studied in flow before

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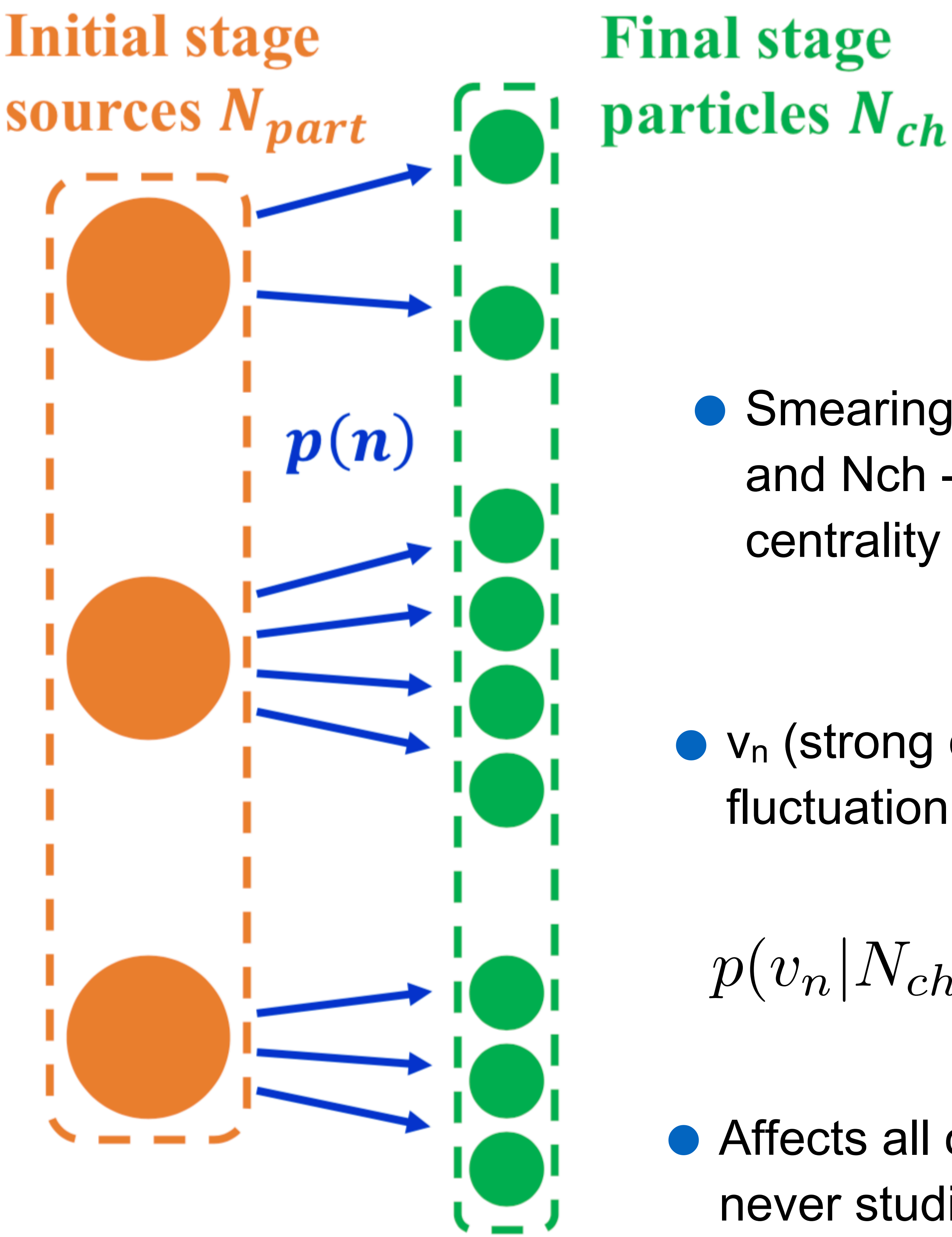

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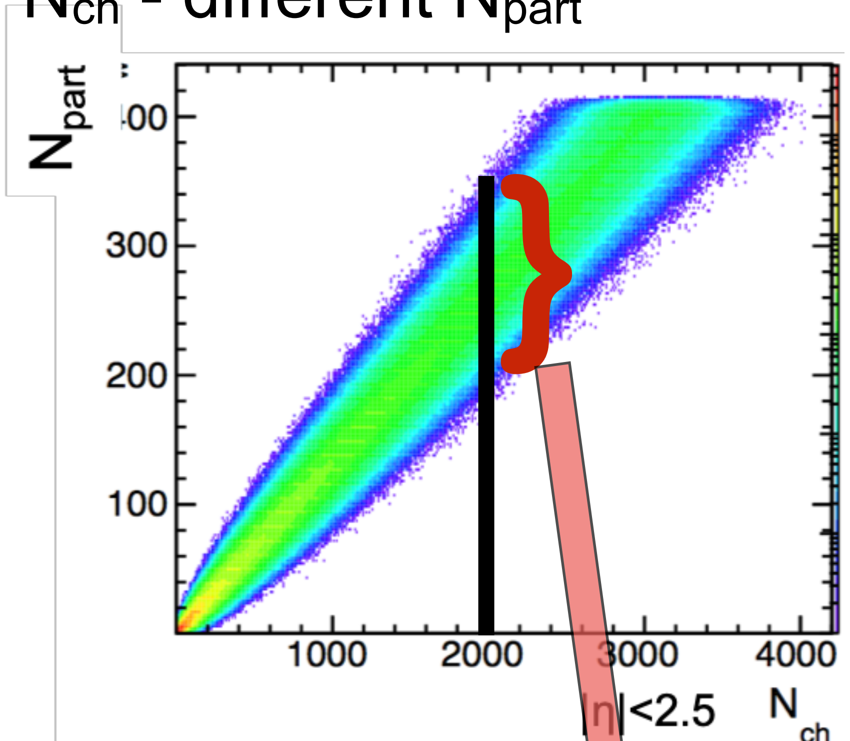

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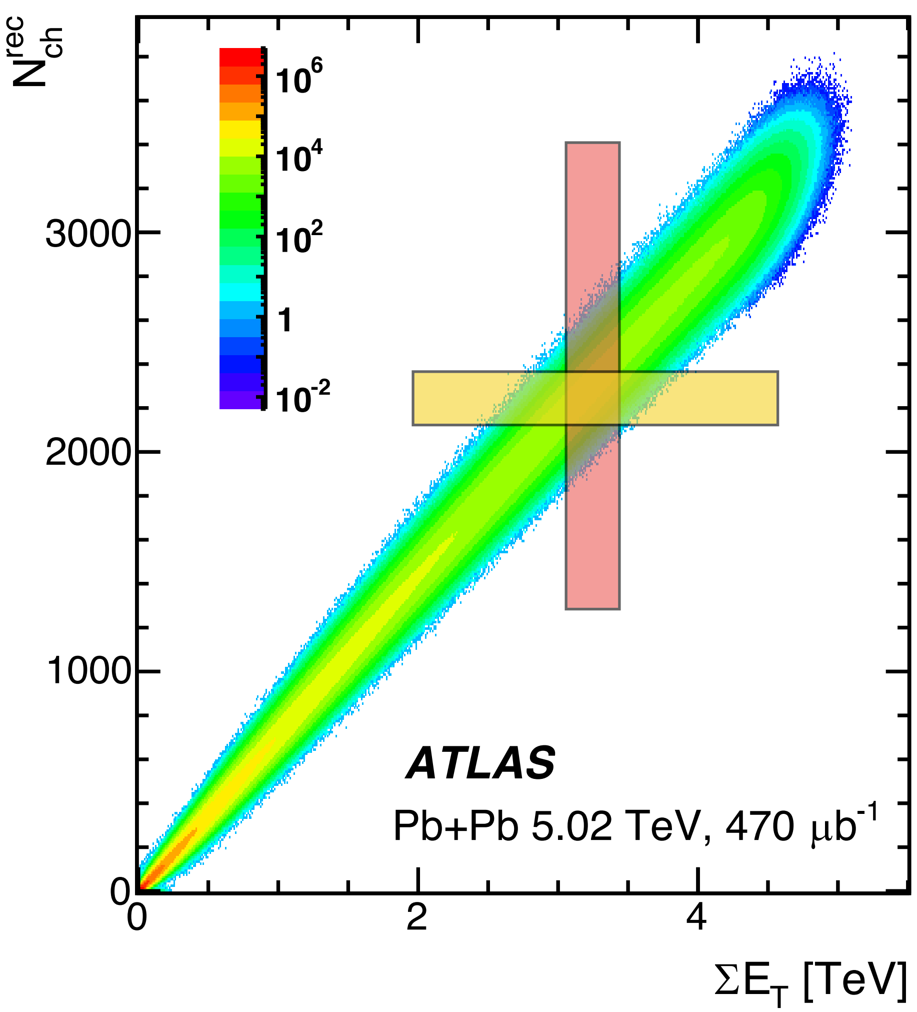
How to probe Centrality Fluctuation

Binnings defined by	Observable
$\sum E_T$: $3.2 < \lvert\eta\rvert < 4.9$	$c_n\{2k, \sum E_T\}$
N_{ch} : $\lvert\eta\rvert < 2.5$	$c_n\{2k, N_{ch}\}$

- Define event ensembles in narrow . ΣE_T and N_{ch}^{rec}



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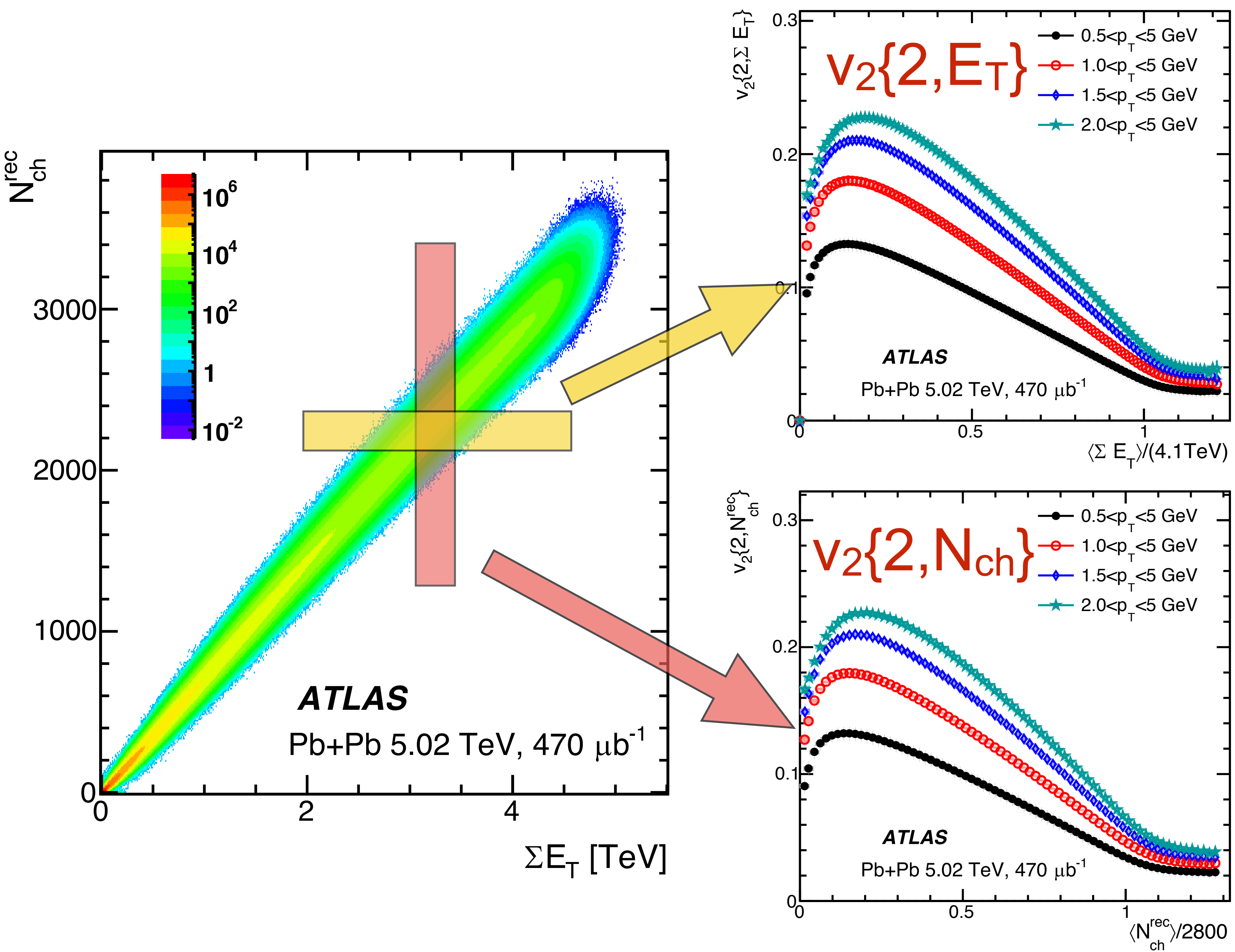

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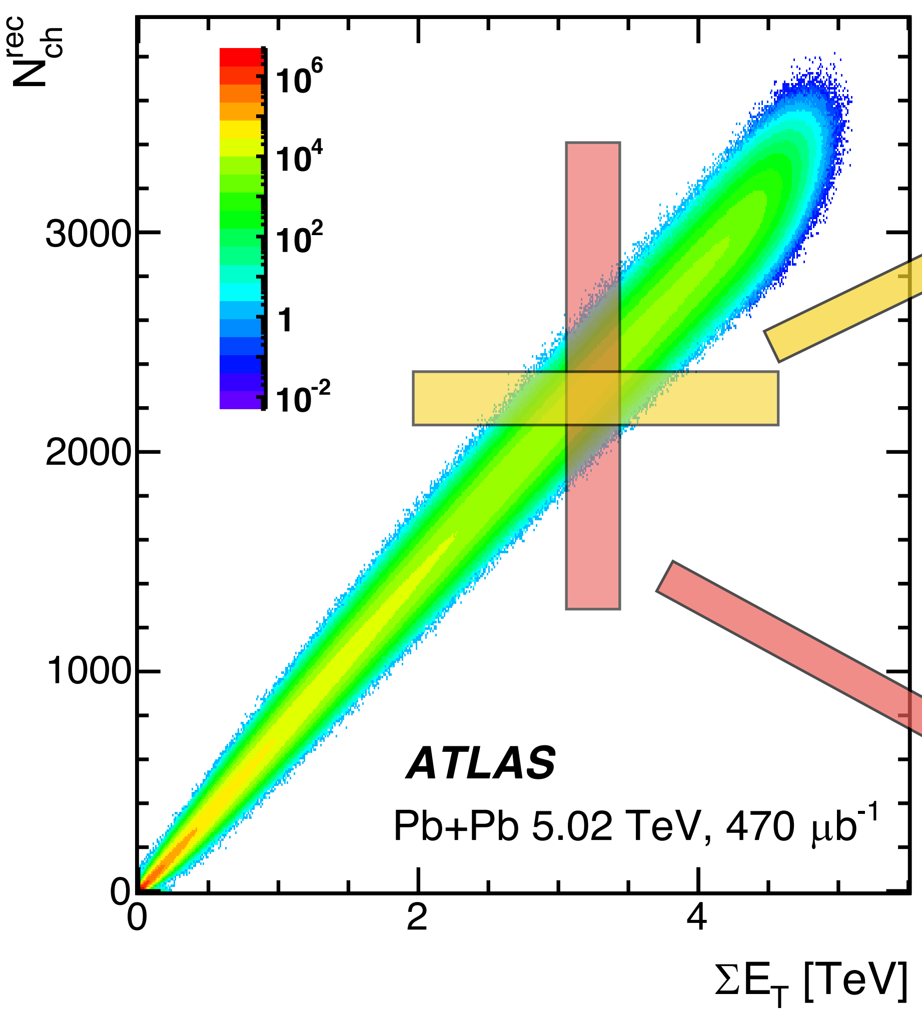

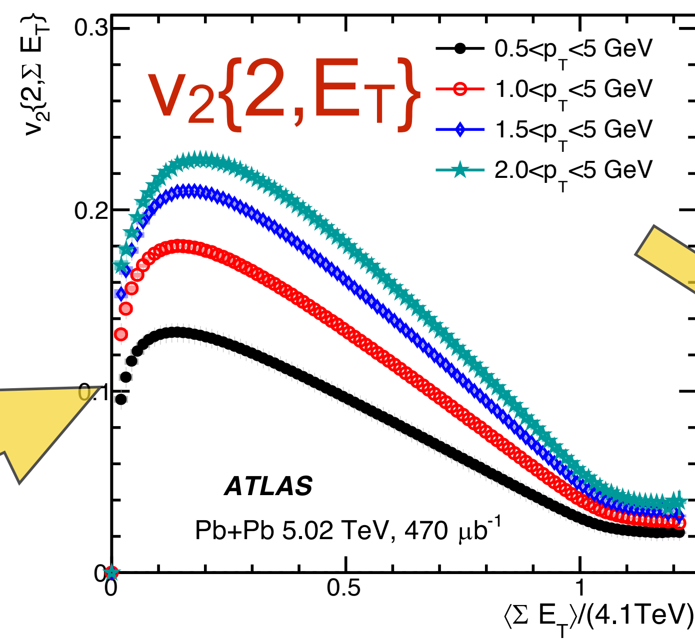

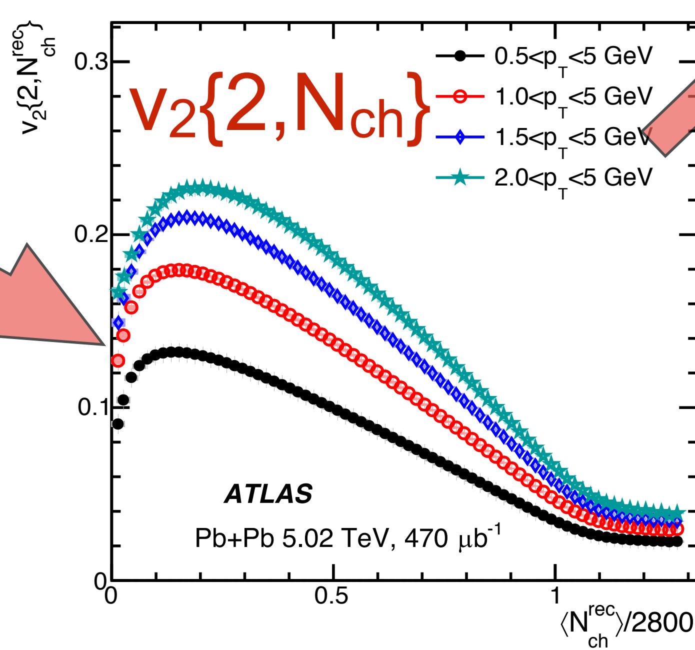

Relative CF

Diff. at same $\langle \Sigma E_T \rangle$ or same $\langle N_{Ch}^{rec} \rangle$

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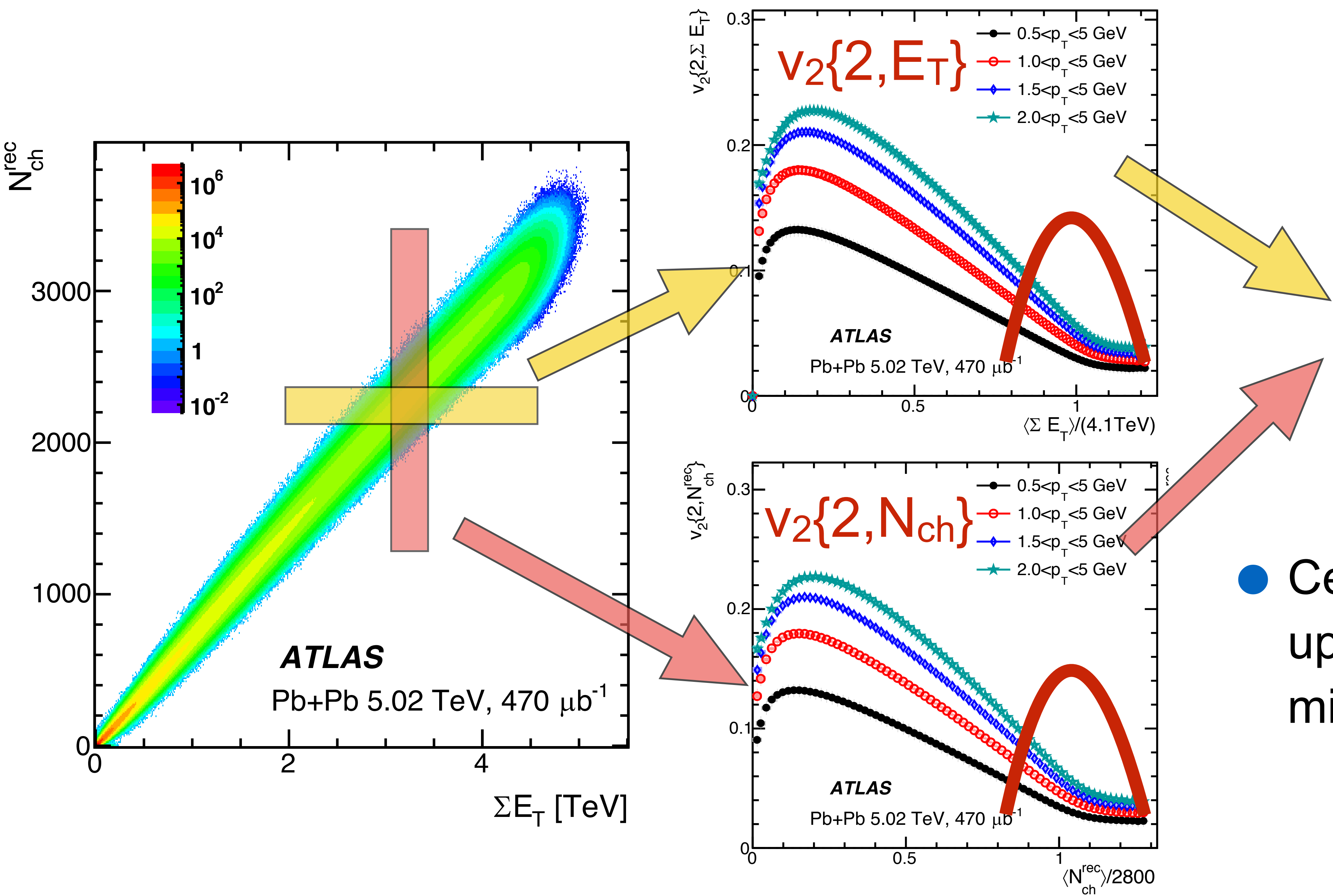

Relative CF

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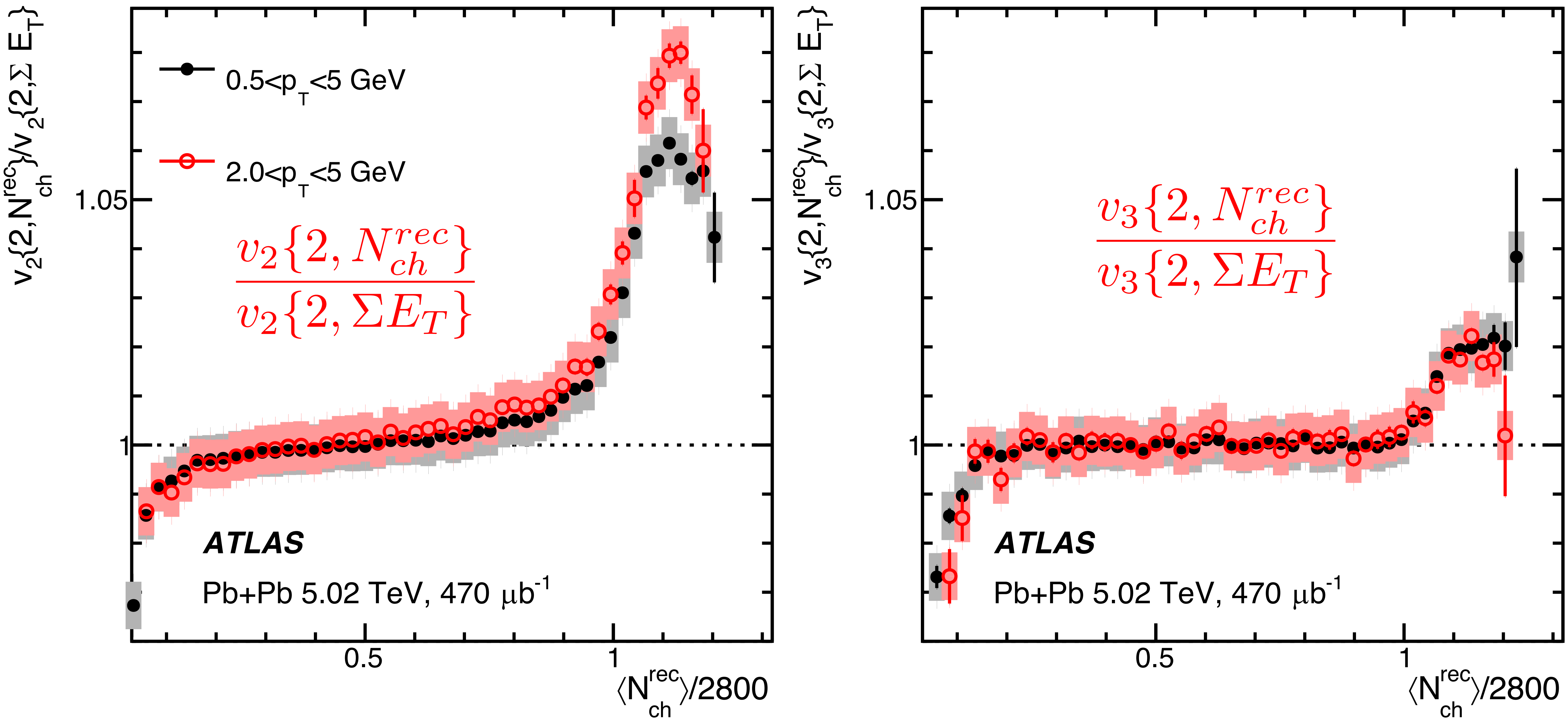
- Central region - v_2 will go up due to smearing from mid-central

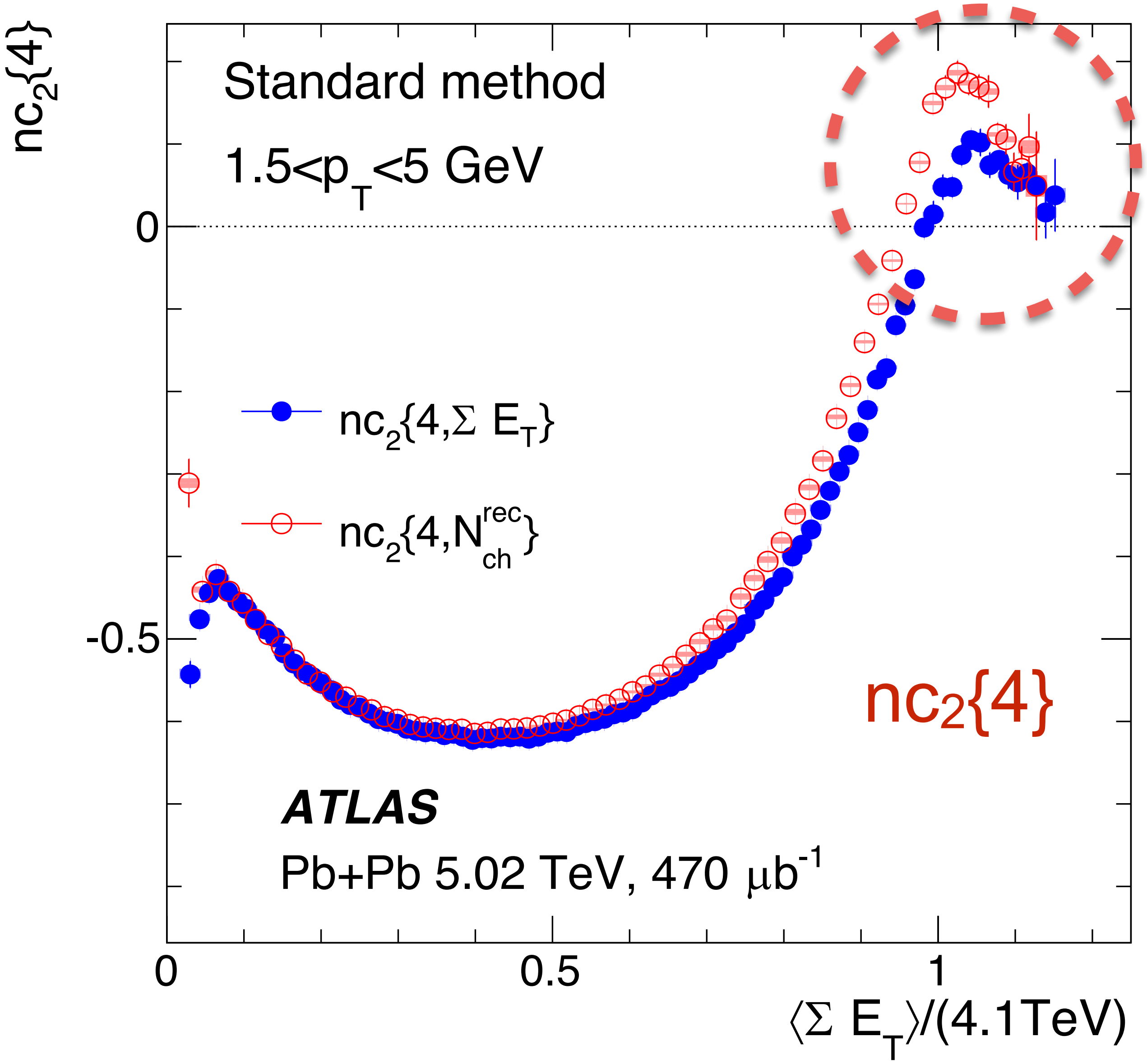
Centrality Fluctuation effect on $v_n\{2\}$

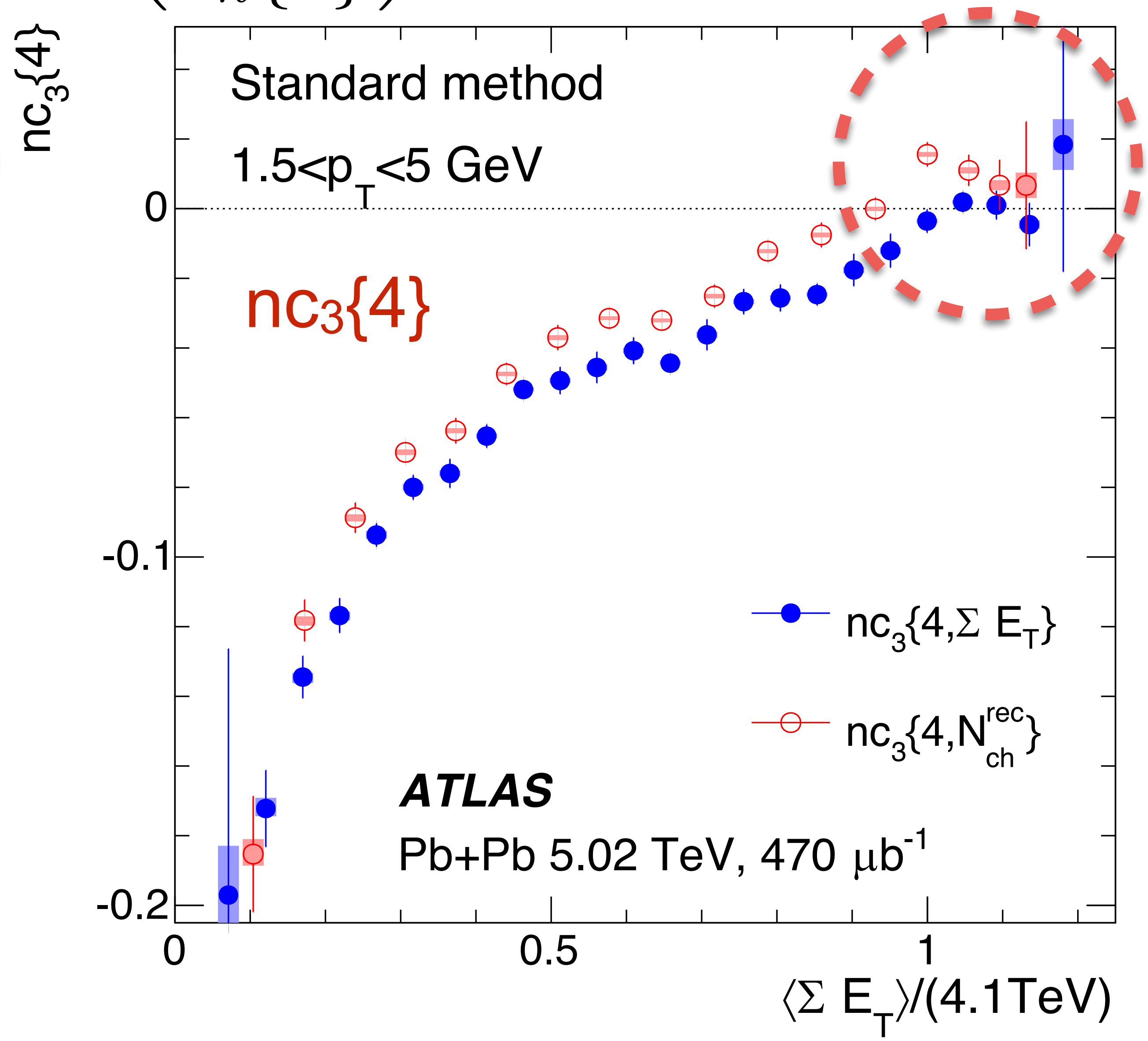


- $v_n\{2, N_{ch}^{rec}\} > v_n\{2, \Sigma E_T\}$, when matched to same $\langle N_{Ch}^{rec} \rangle$
  - ✦ N_{ch}^{rec} has larger centrality fluctuation and poorer resolution than ΣE_T
- Centrality fluctuation for $v_2\{2\}$ is larger than for $v_3\{2\}$ - $v_2\{2\}$ has stronger centrality dependence than $v_3\{2\}$

Centrality Fluctuation effect on $nc_n\{4\}$

$$nc_n\{4\} = -\left(\frac{v_n\{4\}}{v_n\{2\}}\right)^4$$





- Direct comparison - CF largest in UCC persists to midcentral
- Sign change in UCC - due to centrality fluctuation - ref.

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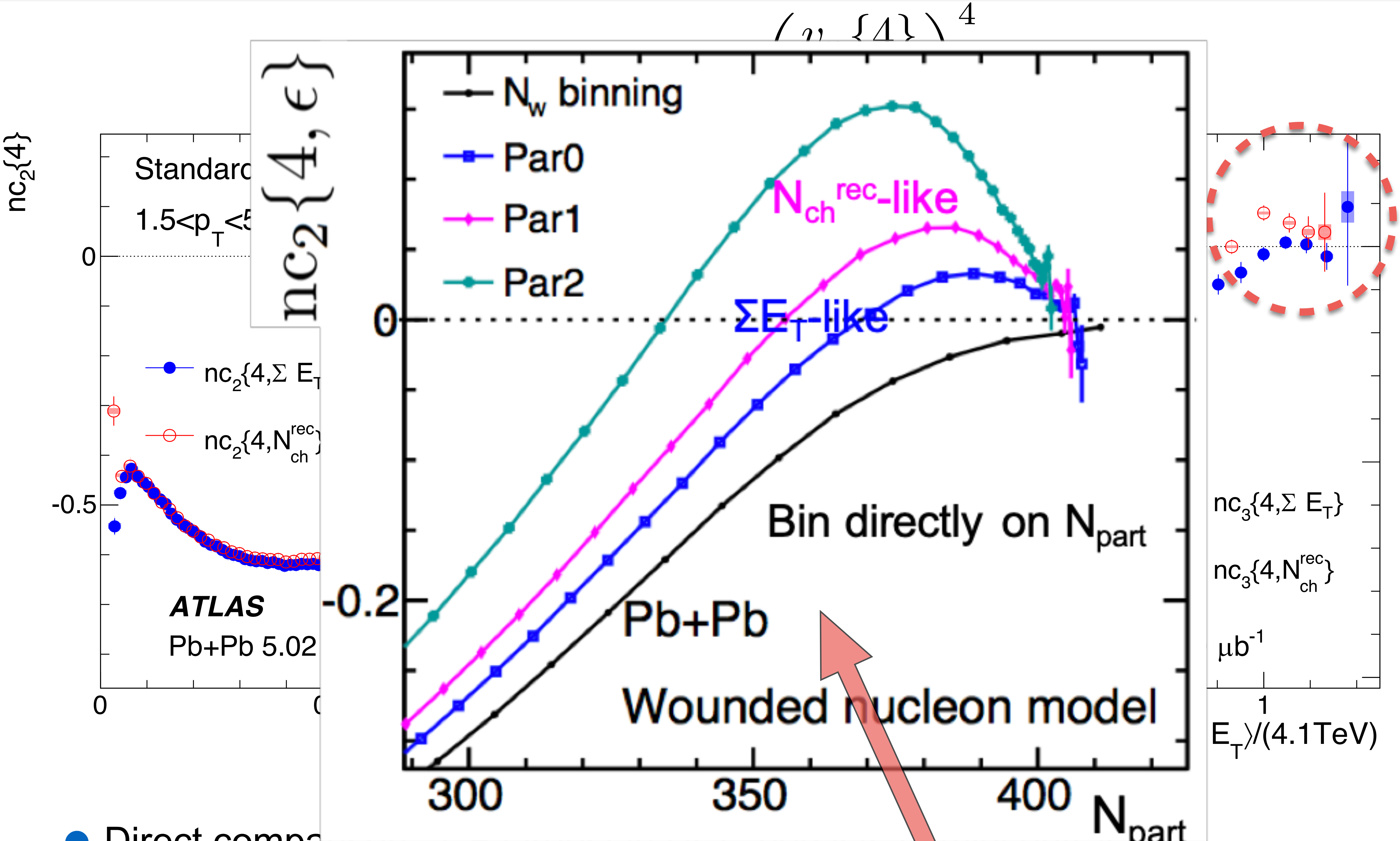

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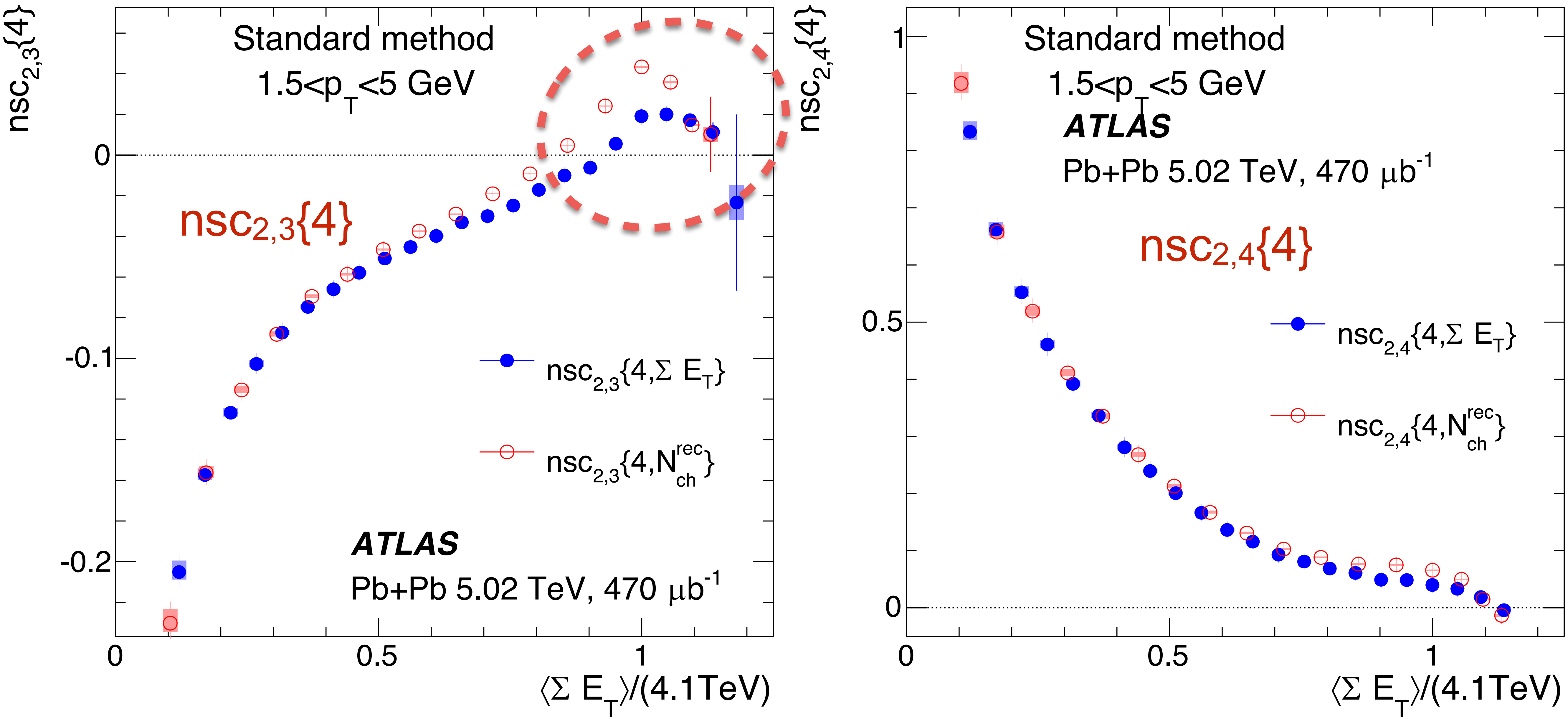
Centrality fluctuation effect on $nsc_{n,m}\{4\}$

$$nsc_{2,3}\{4\} = \frac{\langle v_2^2 v_3^2 \rangle}{\langle v_2^2 \rangle \langle v_3^2 \rangle} - 1 \qquad nsc_{2,4}\{4\} = \frac{\langle v_2^2 v_4^2 \rangle}{\langle v_2^2 \rangle \langle v_4^2 \rangle} - 1$$



- Expected anti-correlation for (v_2,v_3) and +ve correlation for (v_2-v_4) observed
- Centrality fluctuation is less for $nsc_{2,4}\{4\}$ compared to $nsc_{2,3}\{4\}$
- Sign change in UCC - due to CF

Summary

arXiv:1904.04808

- Flow fluctuations
  - ✦ Significant p_T dependence for cumulants - possible final state effects
    - ✦ Also affects Non-gaussianity of $p(v_n)$ - $v_2\{6\}/v_2\{4\}$
  - ✦ First measurement of $v_1\{4\}$
  - ✦ Observed sign change in $v_4\{4\}$ - may be due to non-linear mode-mixing
- Centrality fluctuations
  - ✦ Centrality fluctuation smears flow fluctuations - $nc_n\{4\}$, $nsc_{n,m}\{4\}$
  - ✦ N_{ch} has larger CF and poorer centrality resolution than E_T
  - ✦ Leads to sign change of four particle cumulants in ultracentral collisions
  - ✦ Important for small system which have larger centrality fluctuation

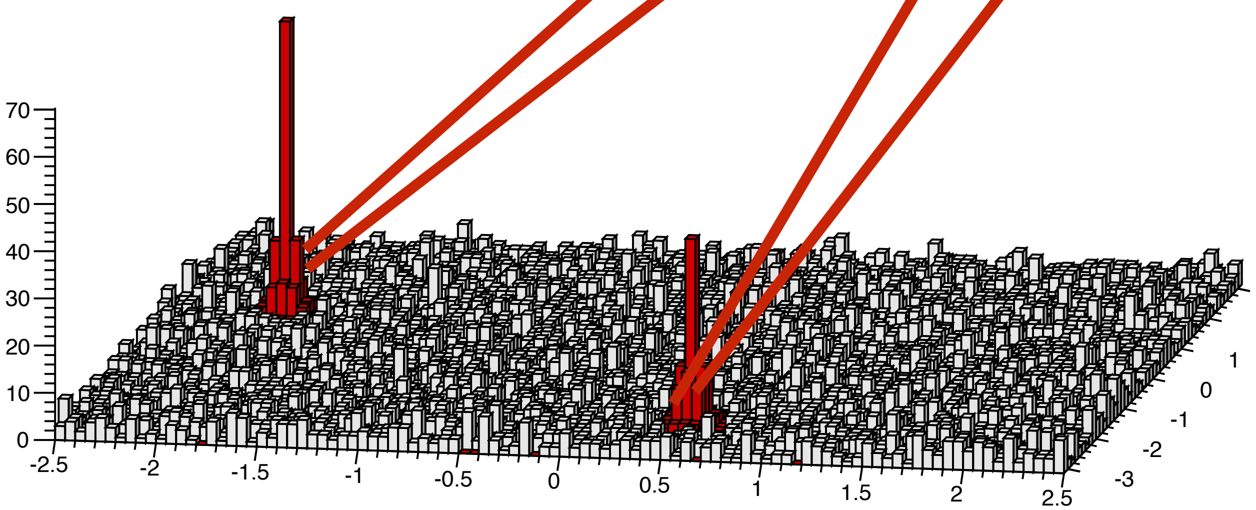
Backup

Subevent Method for Cumulants

- Subevents in pseudorapidity used to remove non-flow correlations

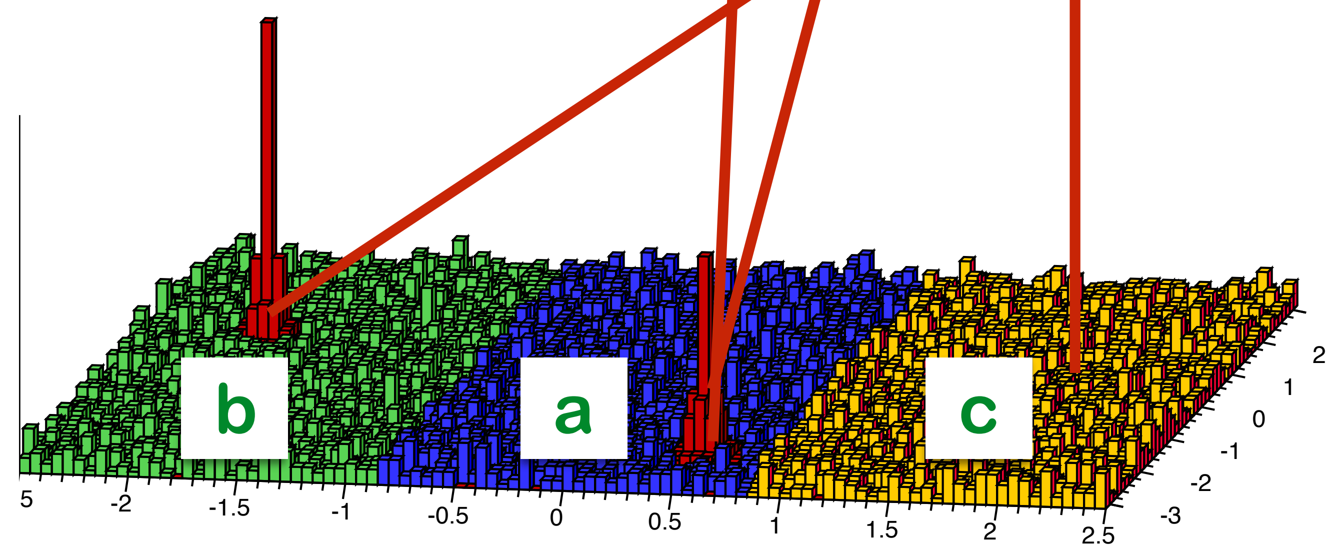
Standard

$$\langle\{4\}_n\rangle = \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle$$



3 Subevents

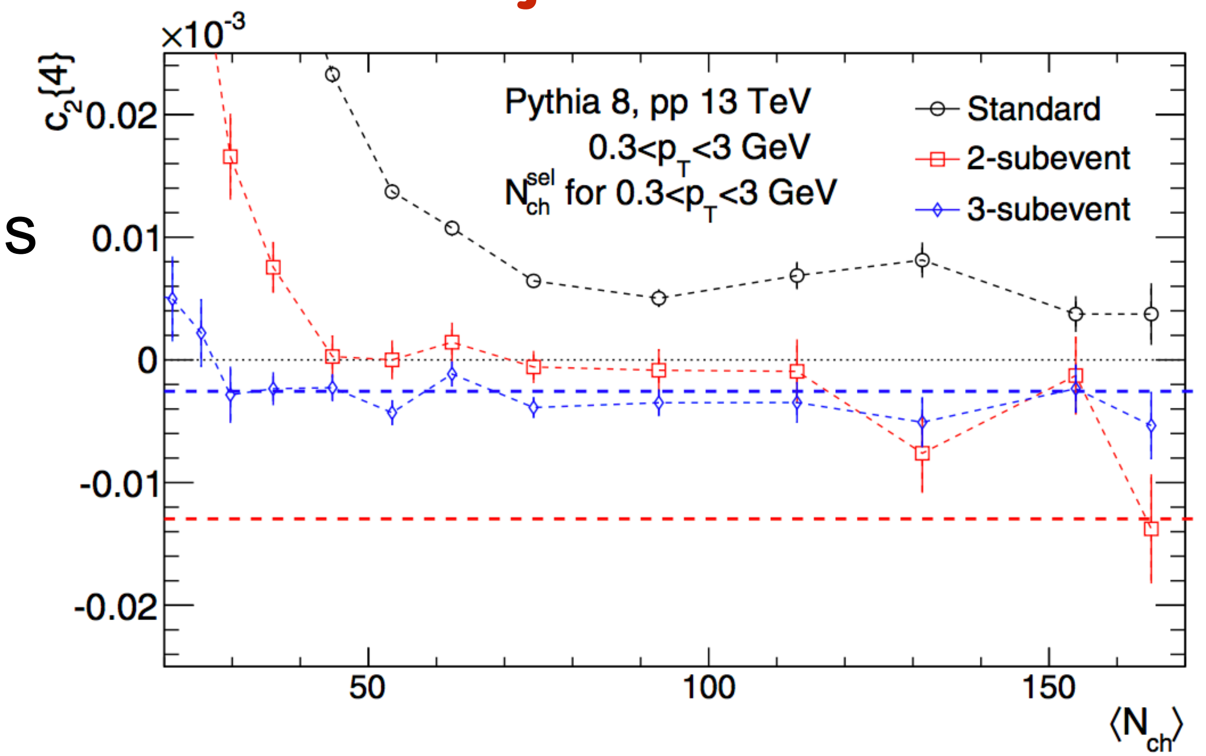
$$\langle\{4\}_n\rangle_{2a|b,c} = \langle e^{in(\phi_1^a+\phi_2^a-\phi_3^b-\phi_4^c)}\rangle$$



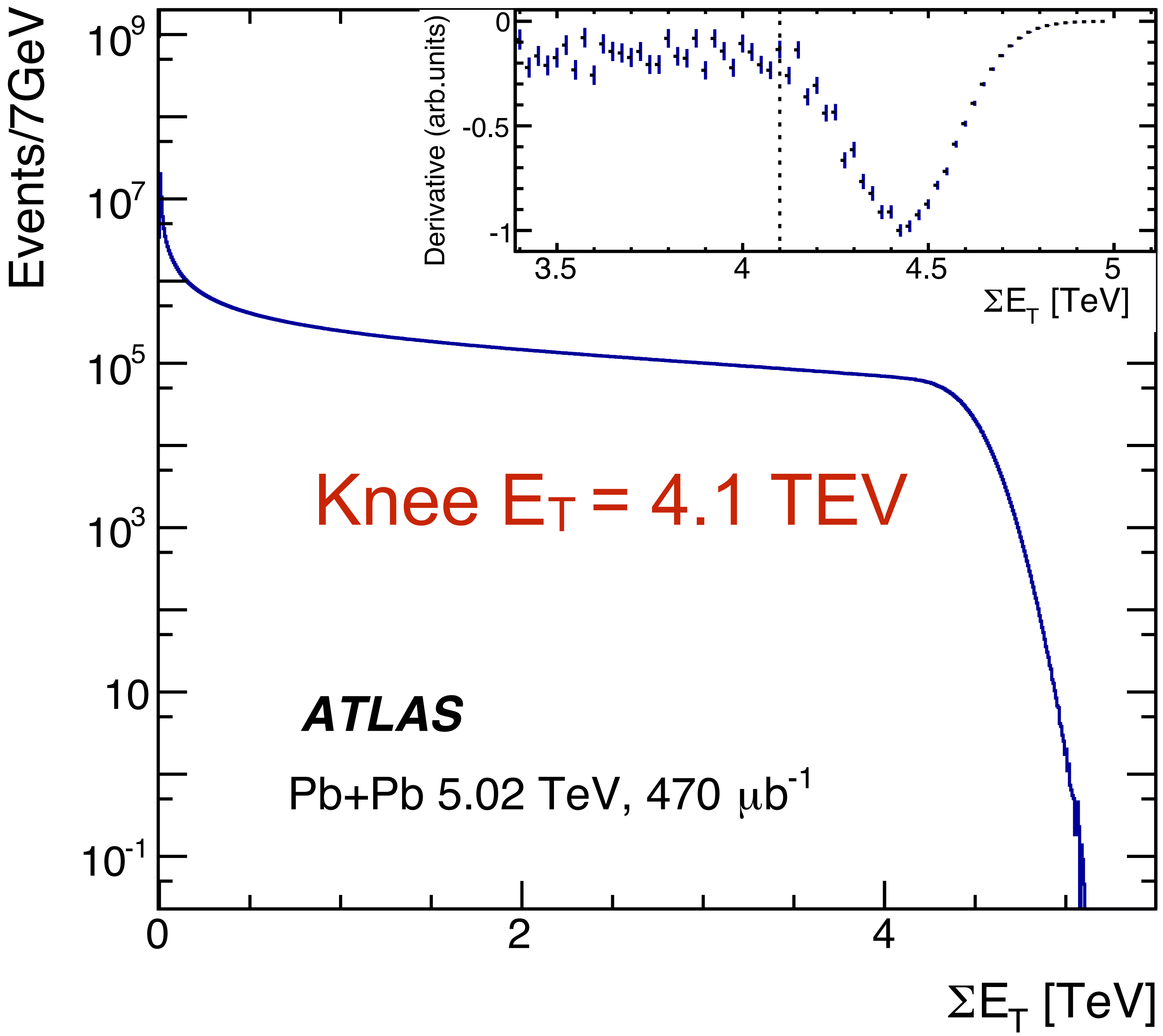
- 2-subevent removes **intra-jet** and 3-subevent removes **inter-jet** correlations

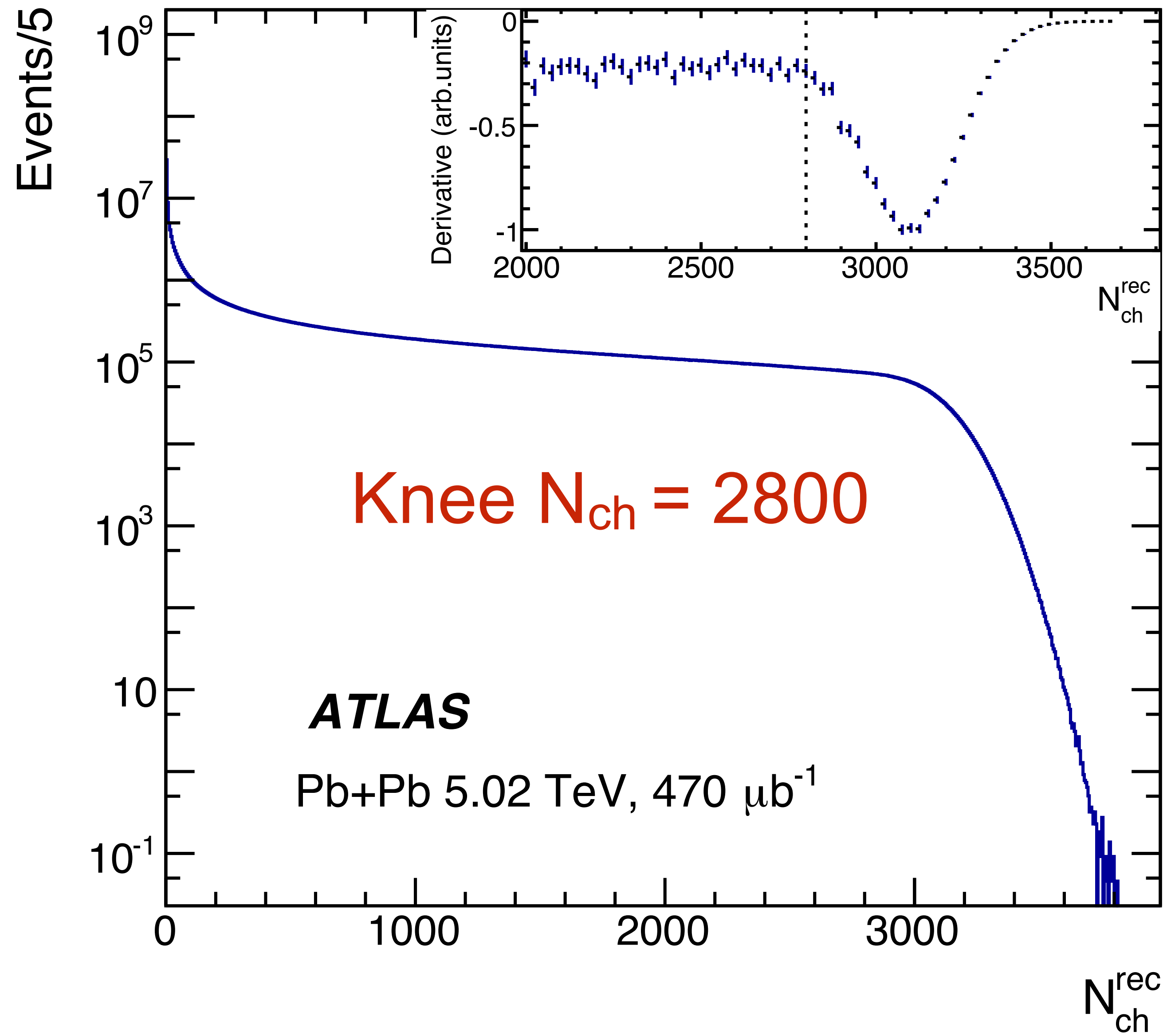
- Performance in Pythia - standard method fails to suppress non-flow

Phys. Rev. C 96, 034906



Knee Values for N_{ch} and E_T





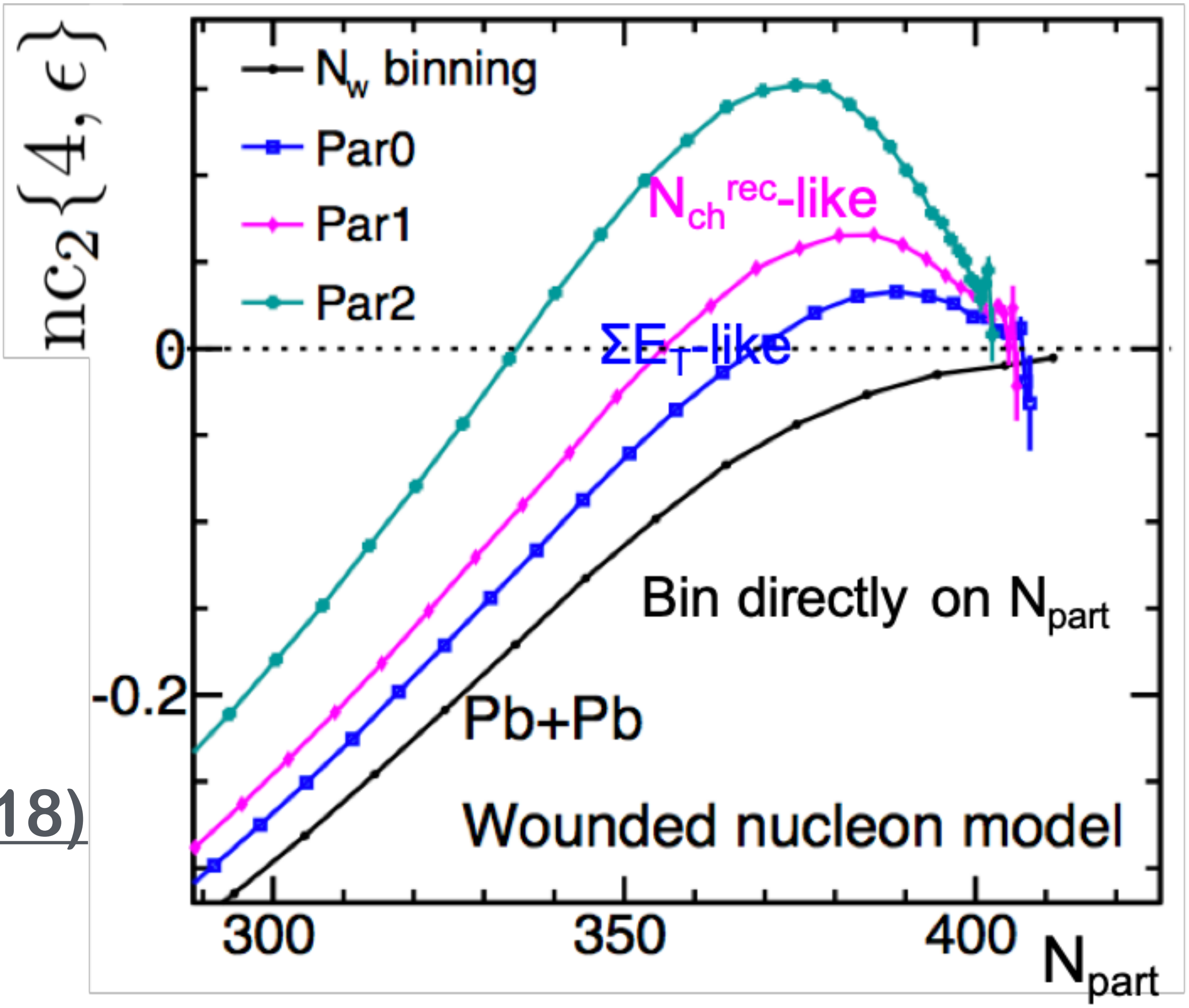
- Knee - Point at which Derivatives start to deviate from constant value
- Knee E_T = 4.1 TeV
- Knee N_{ch} = 2800

Glauber study of Centrality Fluctuation

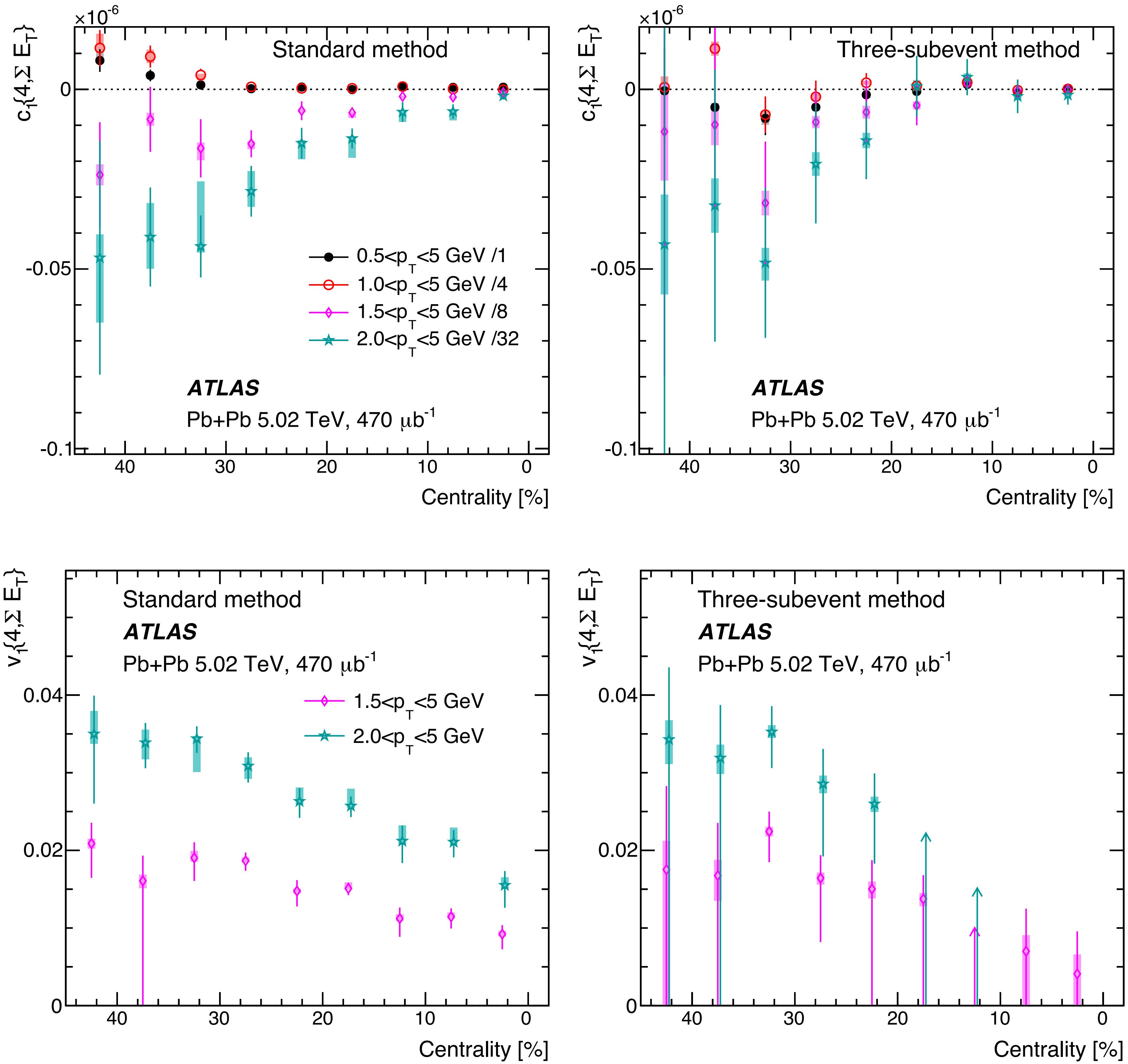
- Cumulants calculated from eccentricity
- Final multiplicity = Npart + NBD convolution for each participant
- Event class based on Npart - no sign change

- Event class based on final N_{ch} - clear sign change
- Event class based on final E_T - clear sign change

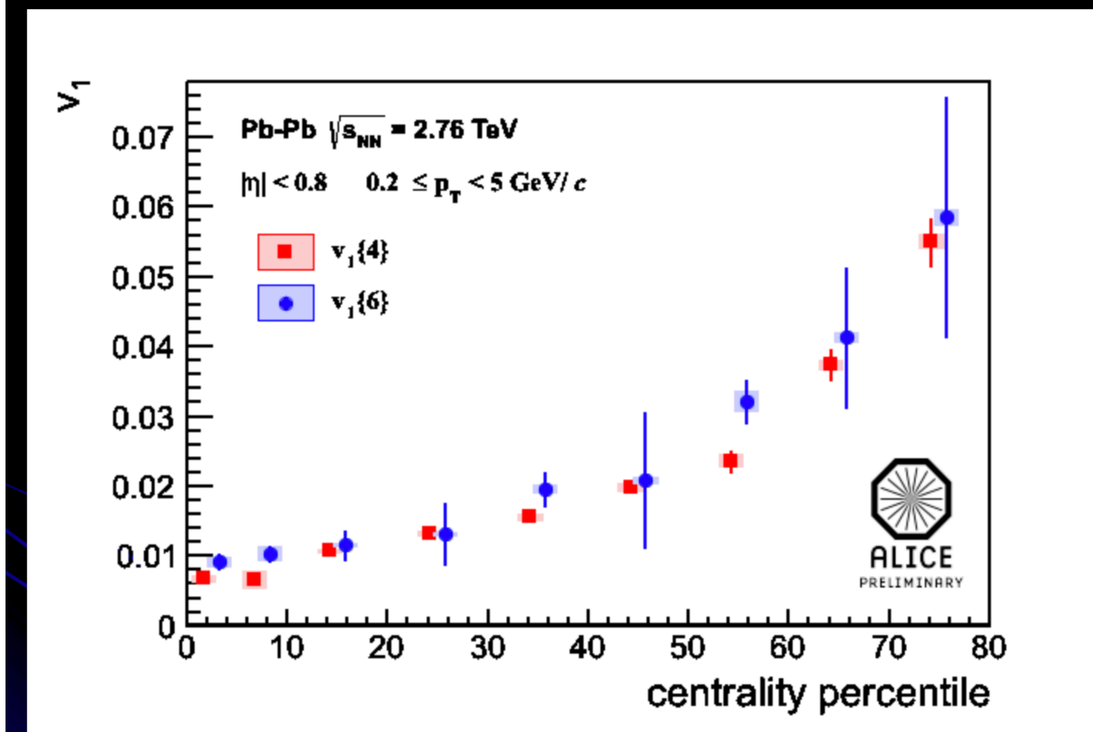
Phys. Rev. C 98, 044903 (2018)



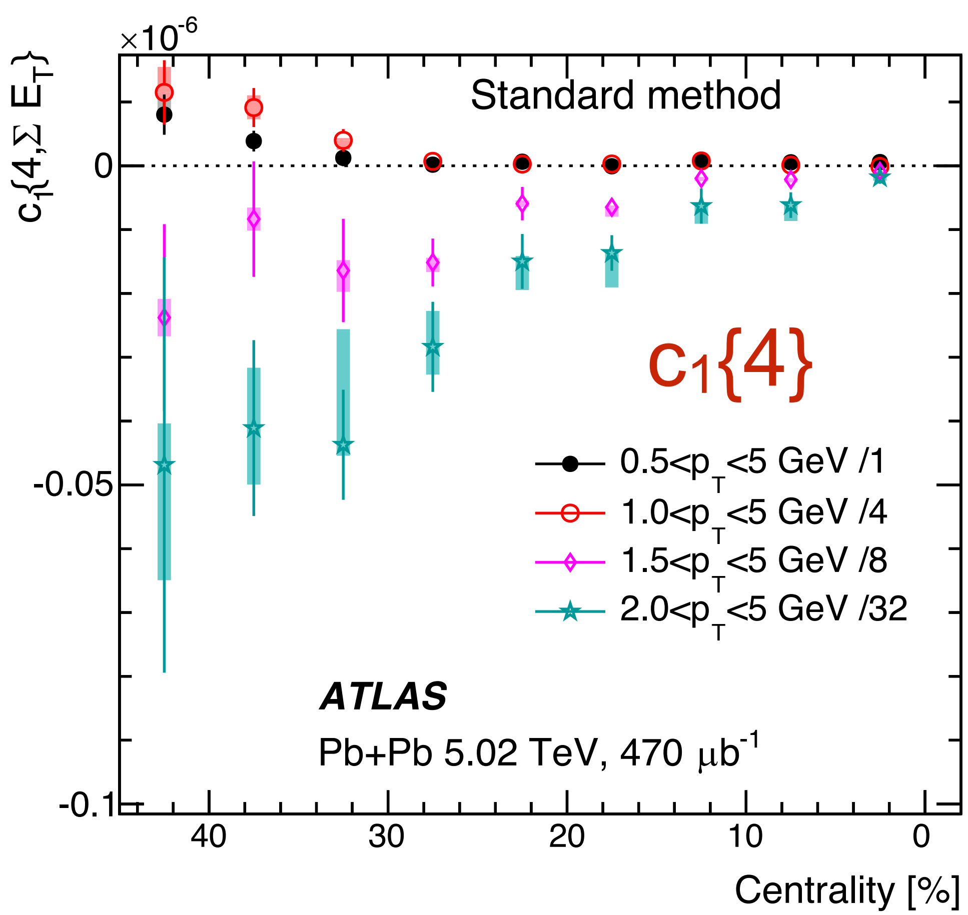
v₁{4} - Both methods

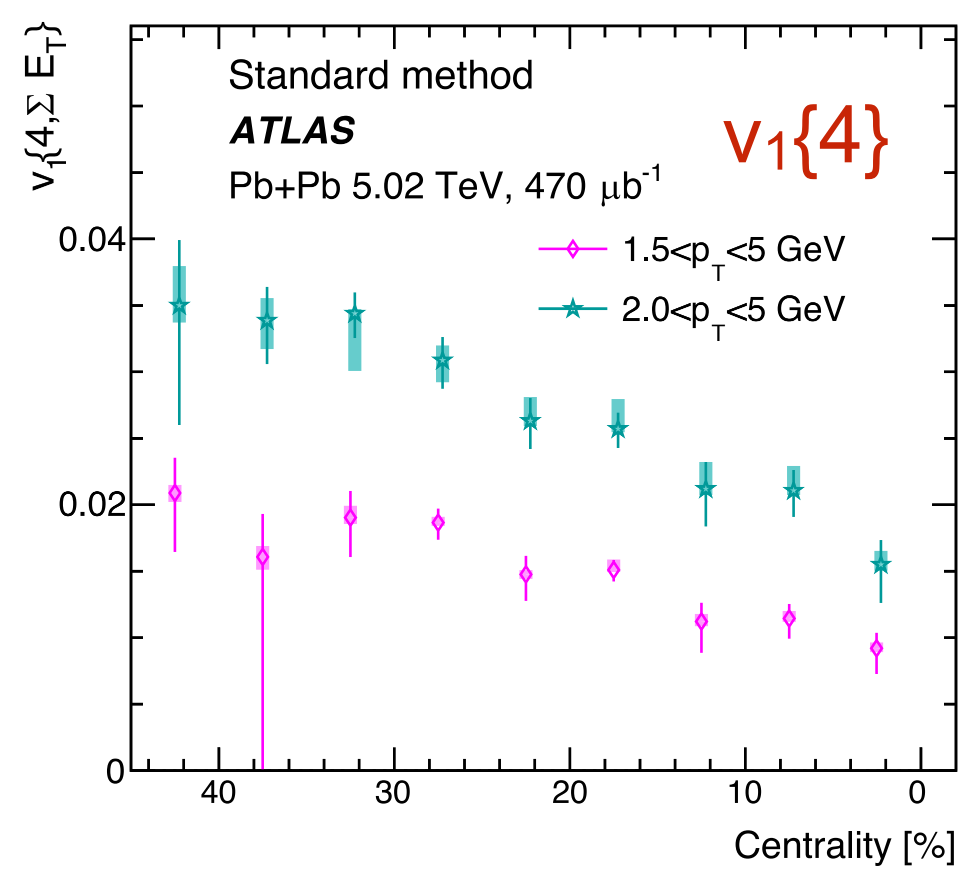


ALICE v1{4}

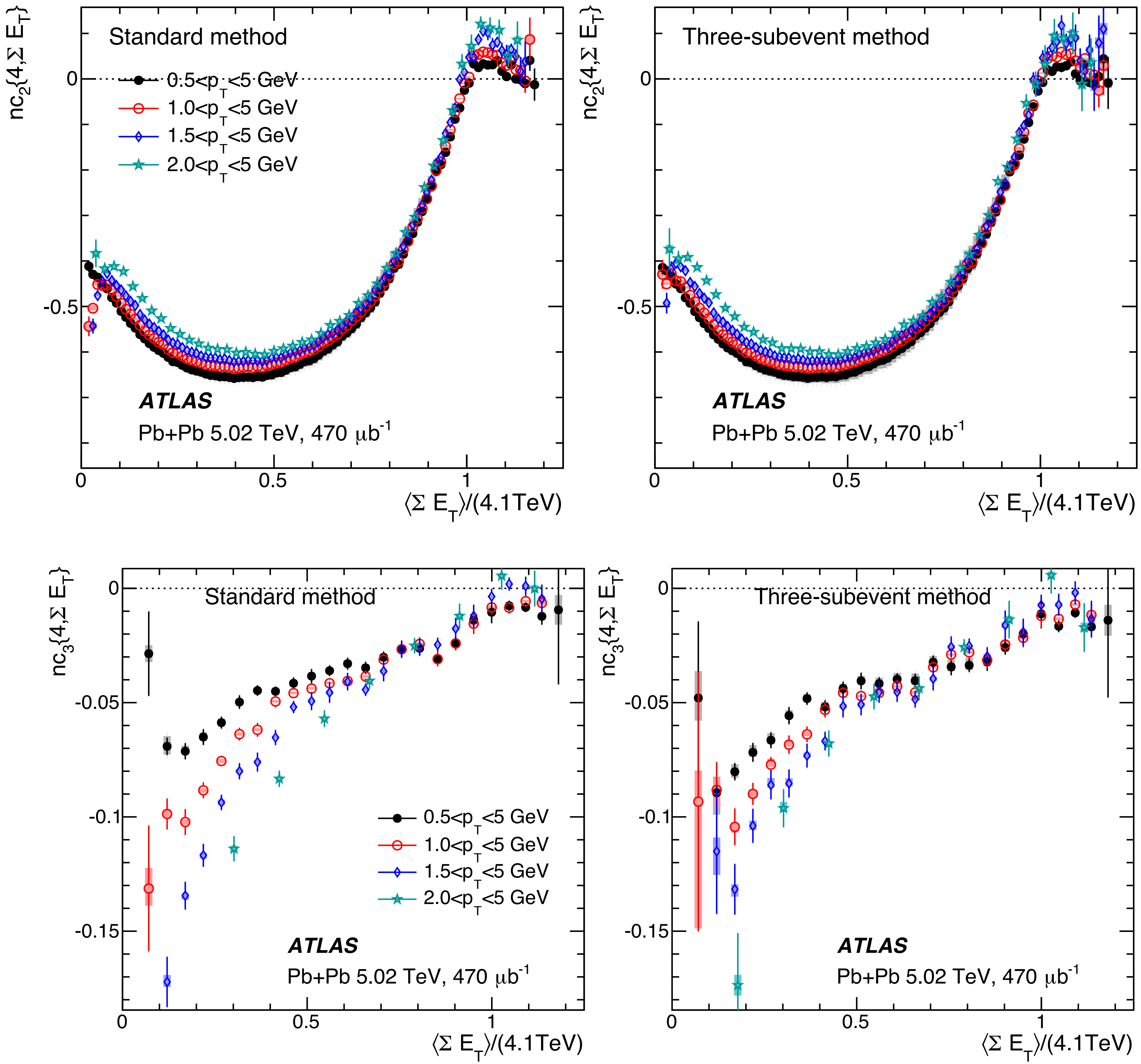


$v_1\{4\}$ and $v_1\{6\}$ are similar within the uncertainties

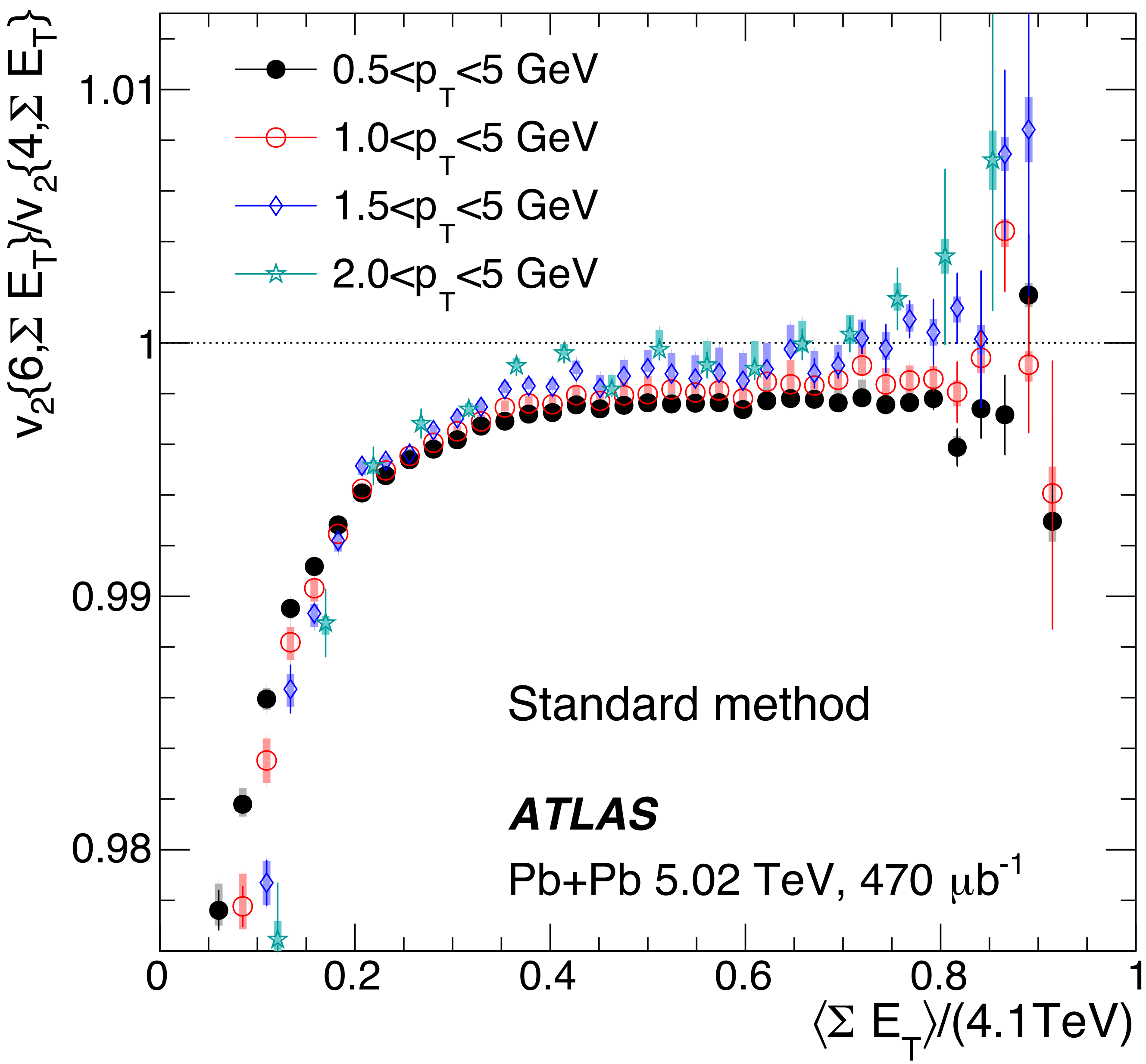


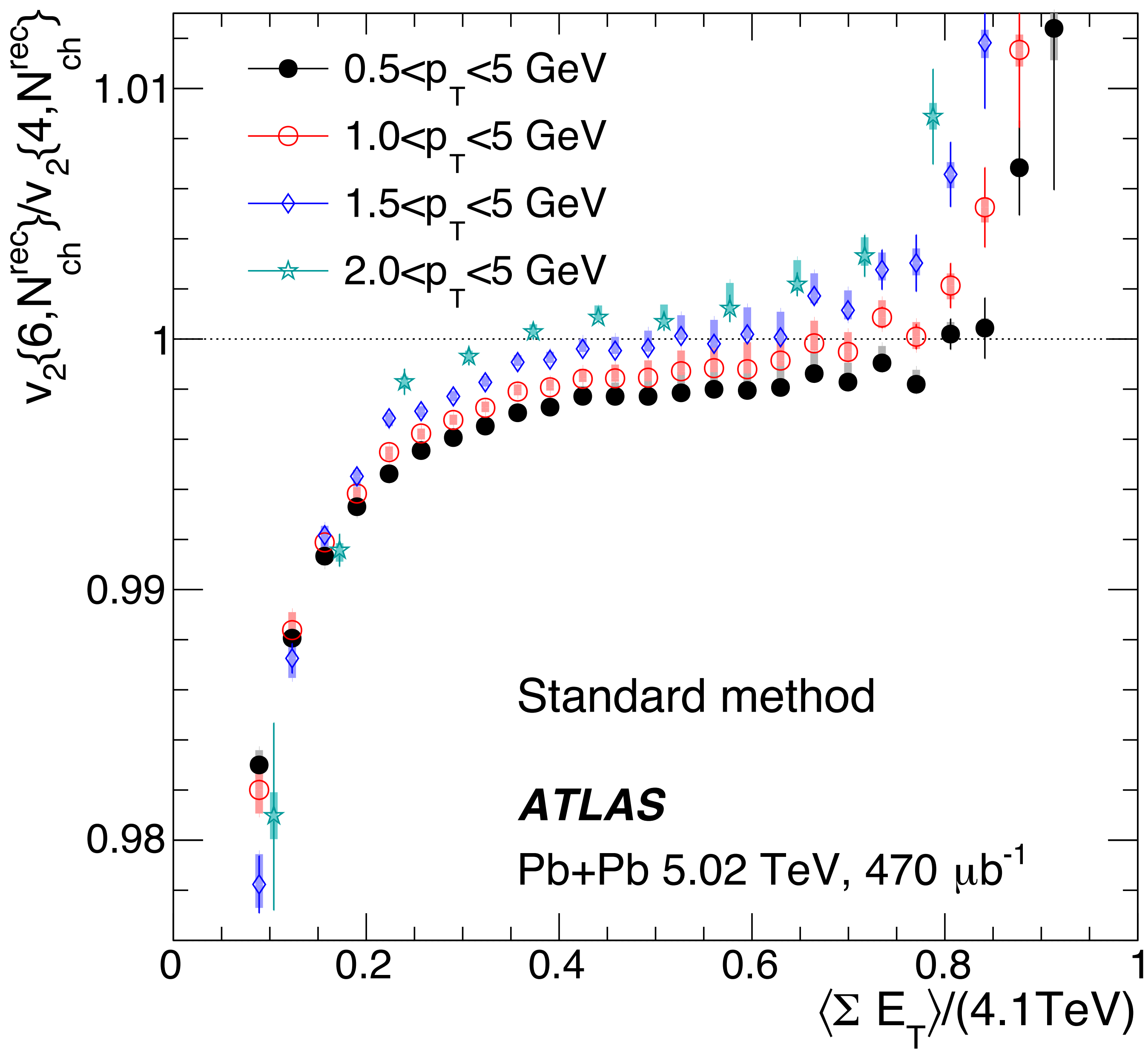


$nc_n\{4\}$ - Both Methods



$v_2\{6\}/v_2\{4\}$ - Cent. Fluct.





- Dependence on p_T is stronger for N_{ch} based event class due to poorer centrality resolution

$v_n\{4\}$ - Cent, E_T and N_{ch}