Multi-particle azimuthal correlation with subevent method

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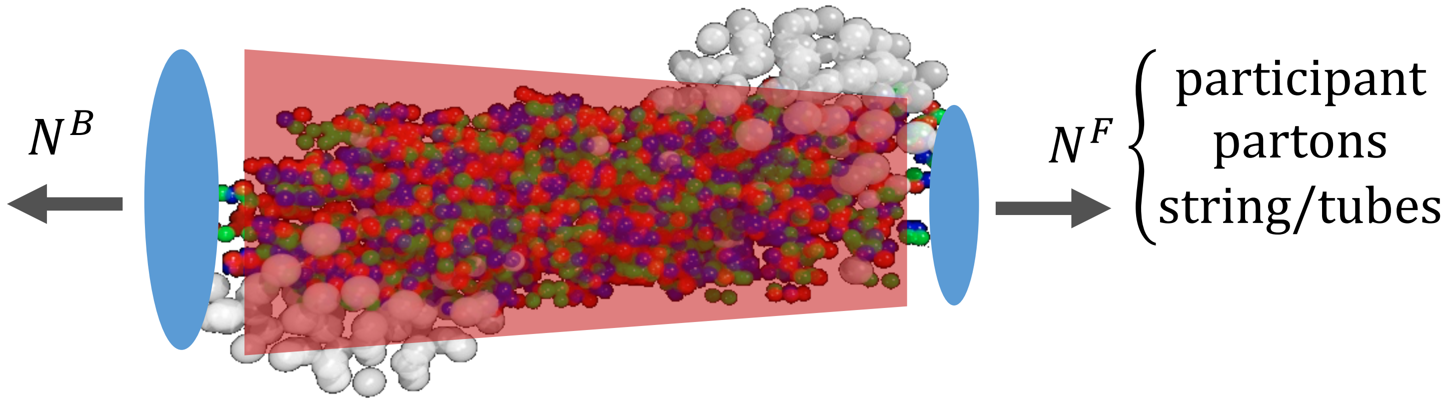
ATLAS EXPERIMENT

Quark Matter 2017

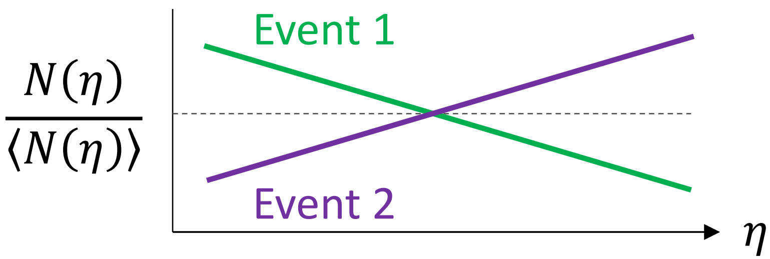
Stony Brook University

Long-range pseudo-rapidity correlation

Nature of sources seeding the long-range collective behavior?



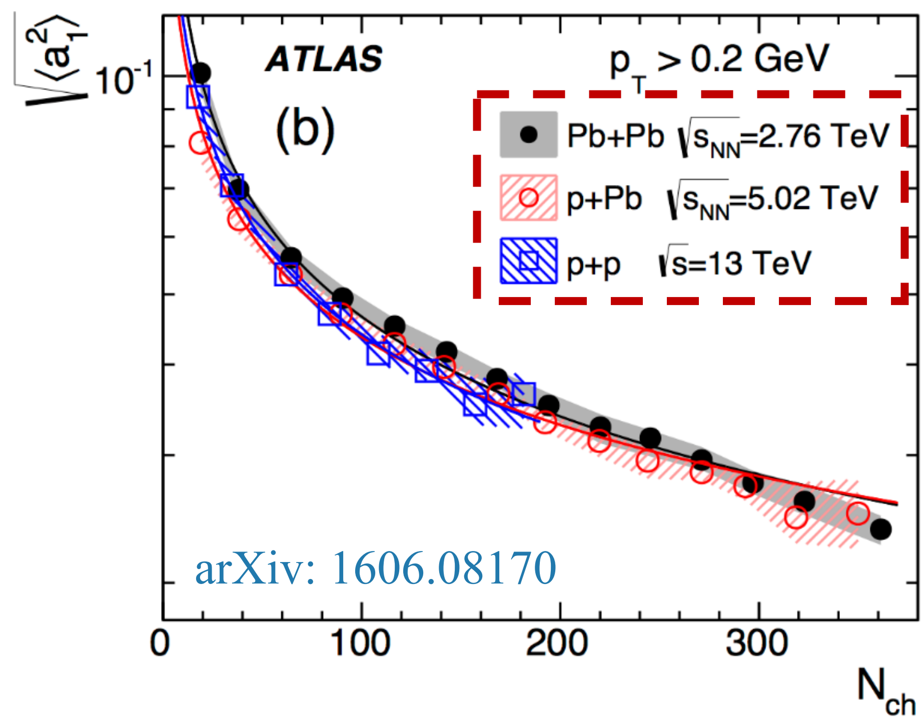
- $dN/d\eta$ shape reflects asymmetry in the number of forward-backward sources;



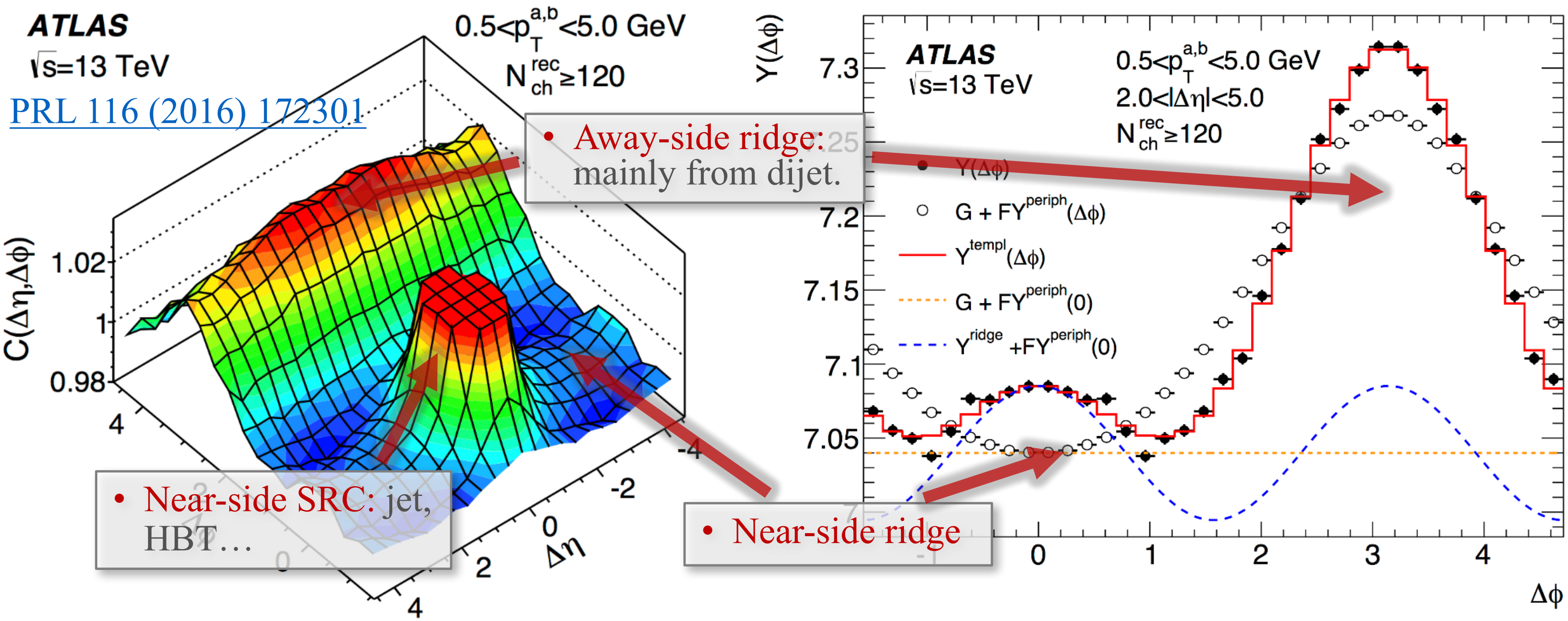
$$\boxed{\frac{N(\eta)}{\langle N(\eta)\rangle} \approx 1 + a_1\eta}$$

PRC 87, 024906 (2013)

PRC 93, 044905 (2016)



- Dominated by linear fluctuation!
- Independent of collision system!



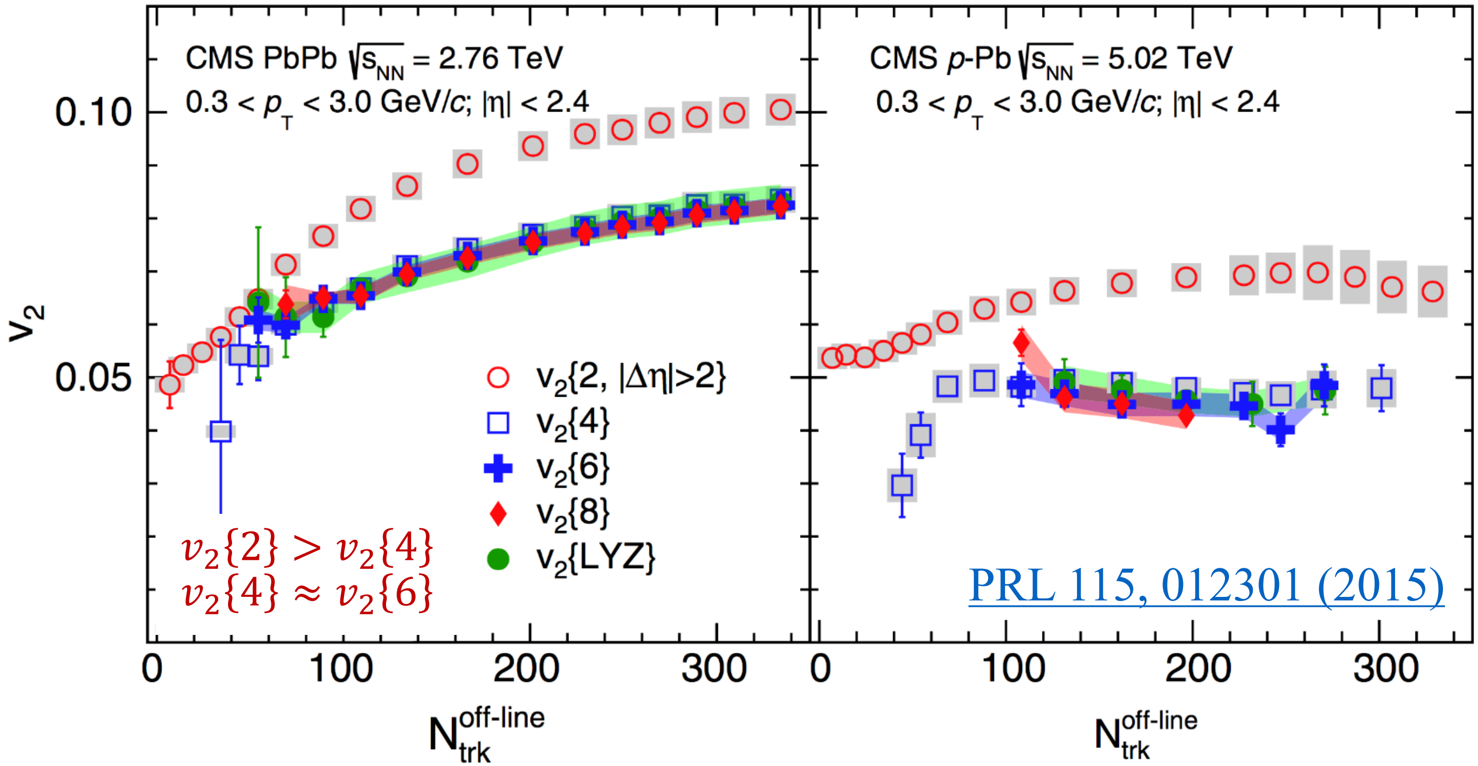
- Ridge structure also observed in small systems! Competing theories:
  - Initial stage interaction (CGC, …)? PRD 87 (2013) 094034
  - Initial stage fluctuation + final stage interaction? PRC 88 (2013) 014903
- Fluctuation in proton can be constrained in *pp* and *p*+Pb collisions.
- However, ridge hard to extract in data: larger non-flow in small system.

From the experimental perspective, central question about the ridge is whether it involves all particles (collectivity?).

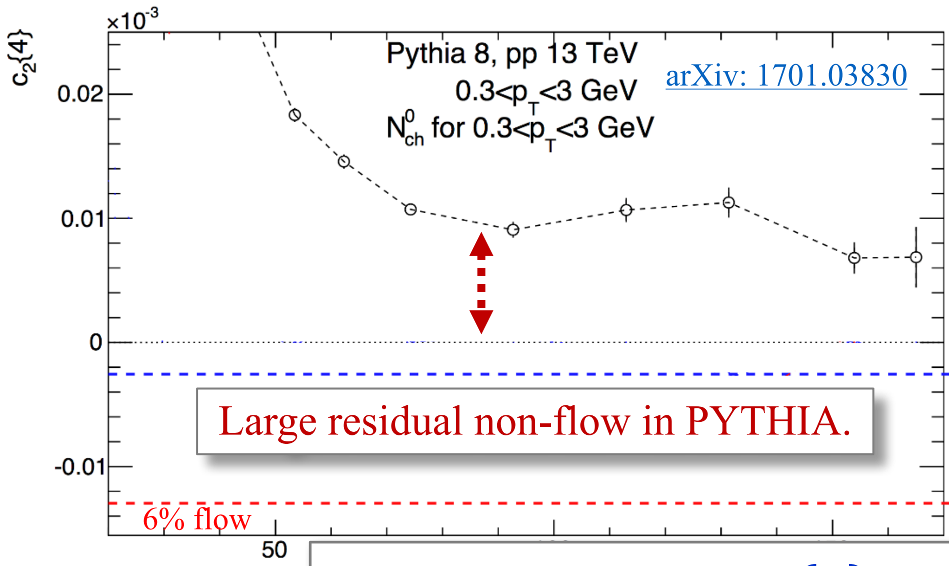
Standard cumulant

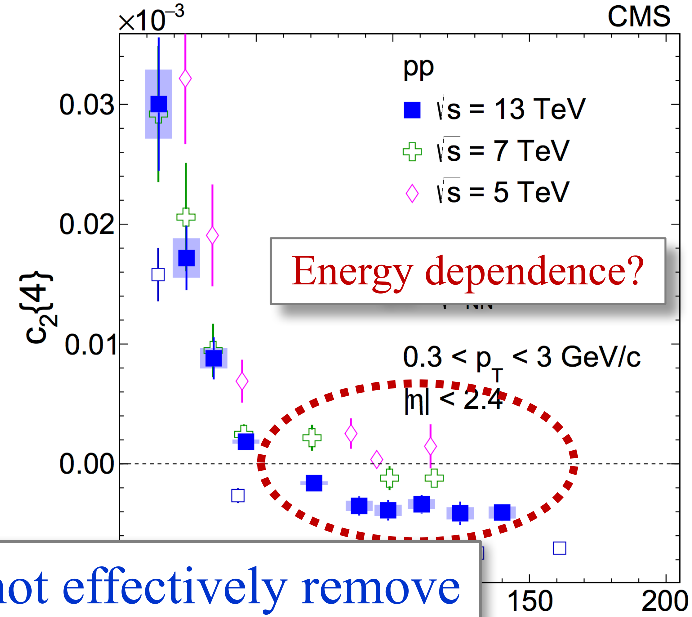
- Cumulant method: natural to probe collectivity:

$$\boxed{C_2\{4\} \equiv \langle 4\rangle - 2\langle 2\rangle^2}$$

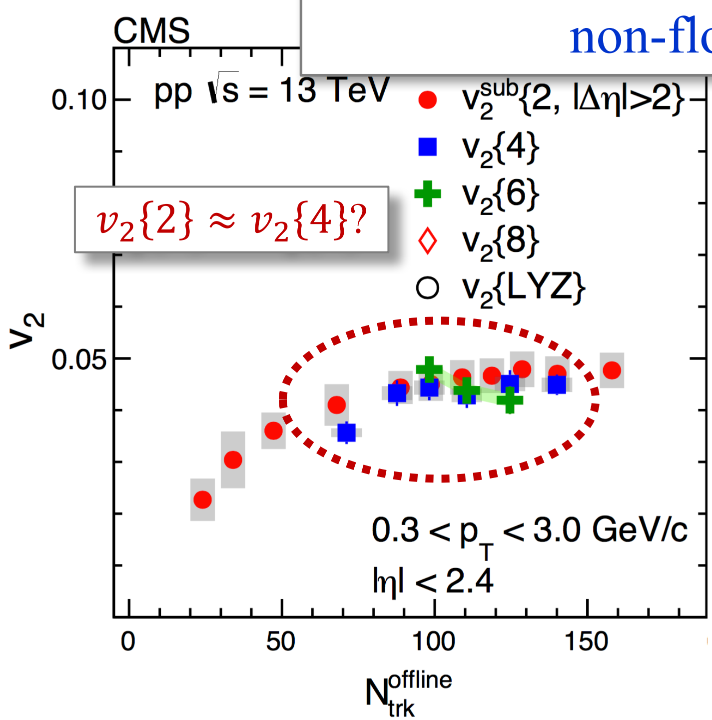


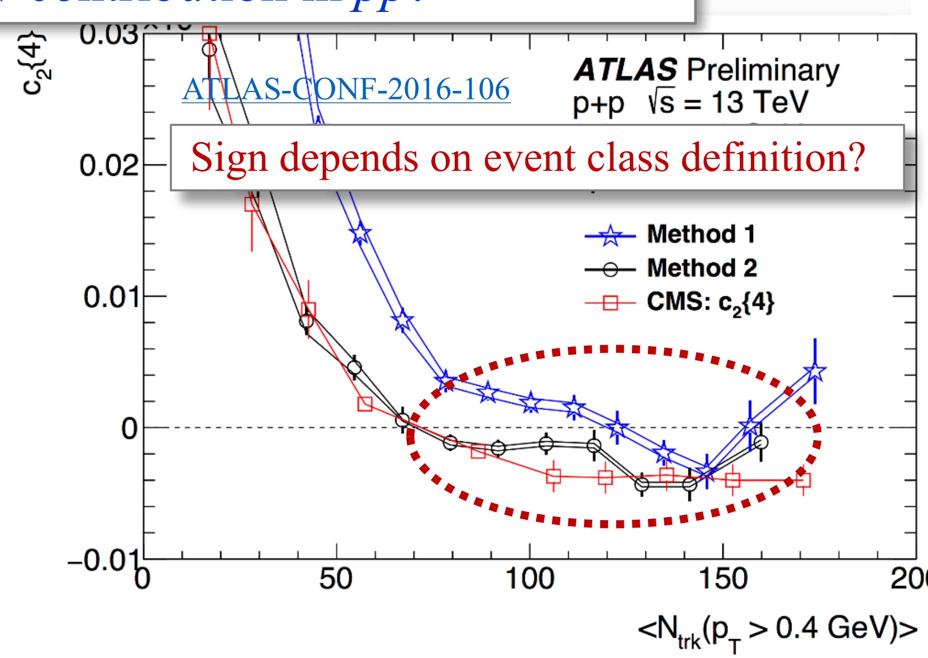
However, does cumulant work in *pp*?
N_{ch} is smaller, non-flow contribution is larger.





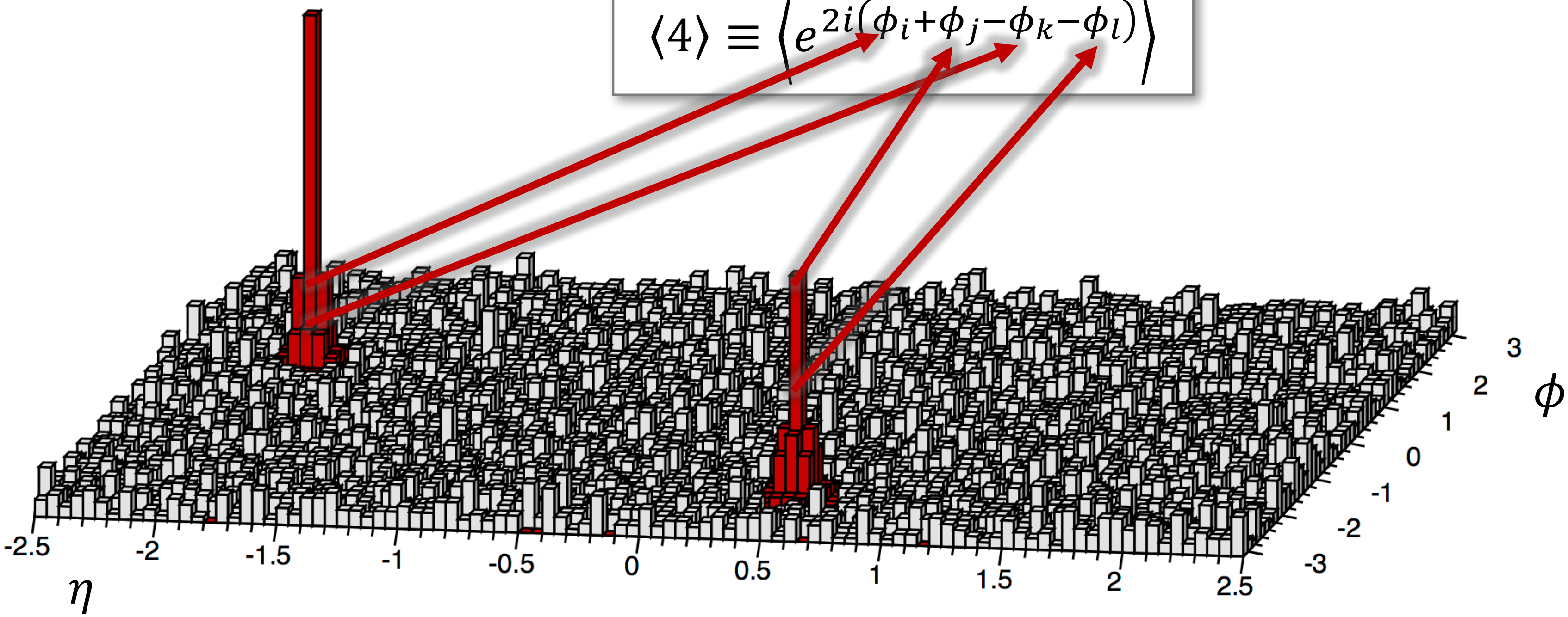
Standard cumulant $C_2\{4\}$ cannot effectively remove non-flow contribution in *pp*!





- In standard cumulant, non-flow sources contribute to four-particle correlation $\langle 4 \rangle$;

$$\langle 4 \rangle \equiv \left\langle e^{2i(\phi_i+\phi_j-\phi_k-\phi_l)} \right\rangle$$

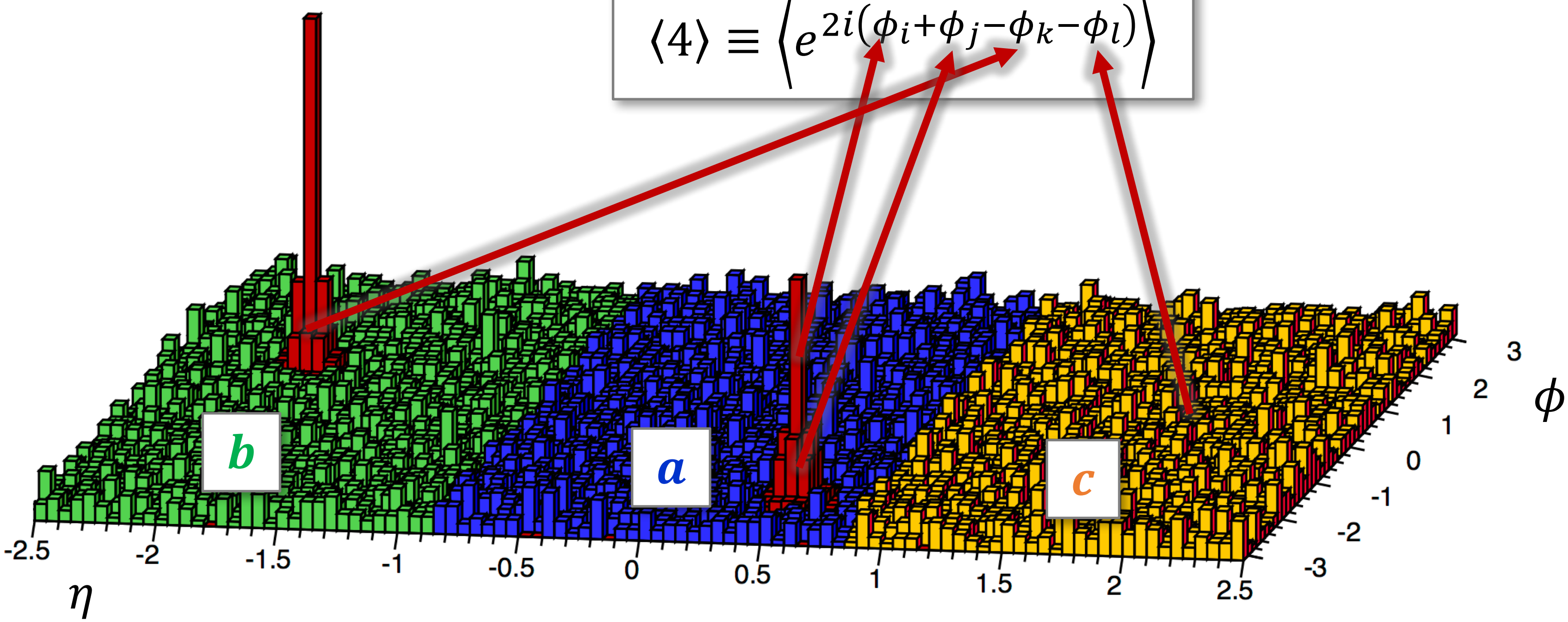


$$C_2\{4\} \equiv \langle 4 \rangle - 2\langle 2 \rangle^2 \equiv \langle 4 \rangle_{\mathrm{non-flow}} + \langle v^4 \rangle - 2\langle v^2 \rangle^2$$

Subevent cumulant

- In standard cumulant, non-flow sources contribute to four-particle correlation $\langle 4 \rangle$;
- In the subevent method, particles are correlated across all subevents (long-range).
  - 3 subevent cumulant can further suppress away-side jet contribution;
- New method validated in PYTHIA, but is there a data-driven way to check the residual non-flow in data?

$$\langle 4 \rangle \equiv \left\langle e^{2i(\phi_i+\phi_j-\phi_k-\phi_l)} \right\rangle$$



$$C_2^{2a|b,c}\{4\} \equiv \langle 4 \rangle_{2a|b,c} - 2\langle 2 \rangle_{a|b} \langle 2 \rangle_{a|c}$$

arXiv: 1701.03830

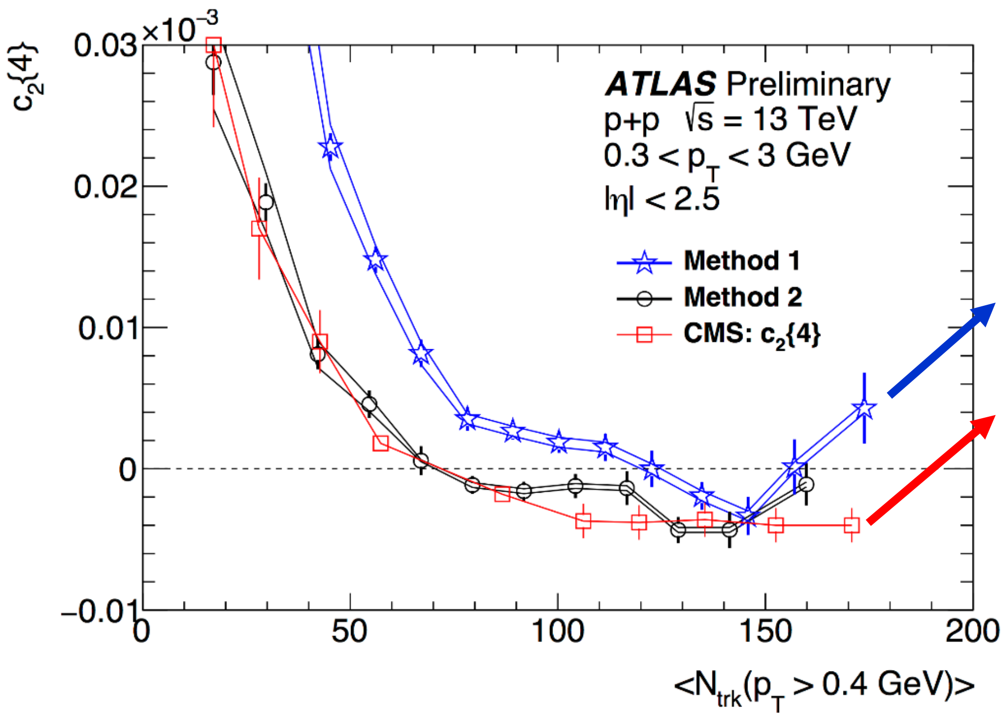
Test of residual non-flow

$$C_2\{4\} \equiv \langle \text{nonflow} + \text{flow} \rangle_{evt}$$

Non-flow changes greatly EbyE

Flow changes little EbyE

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



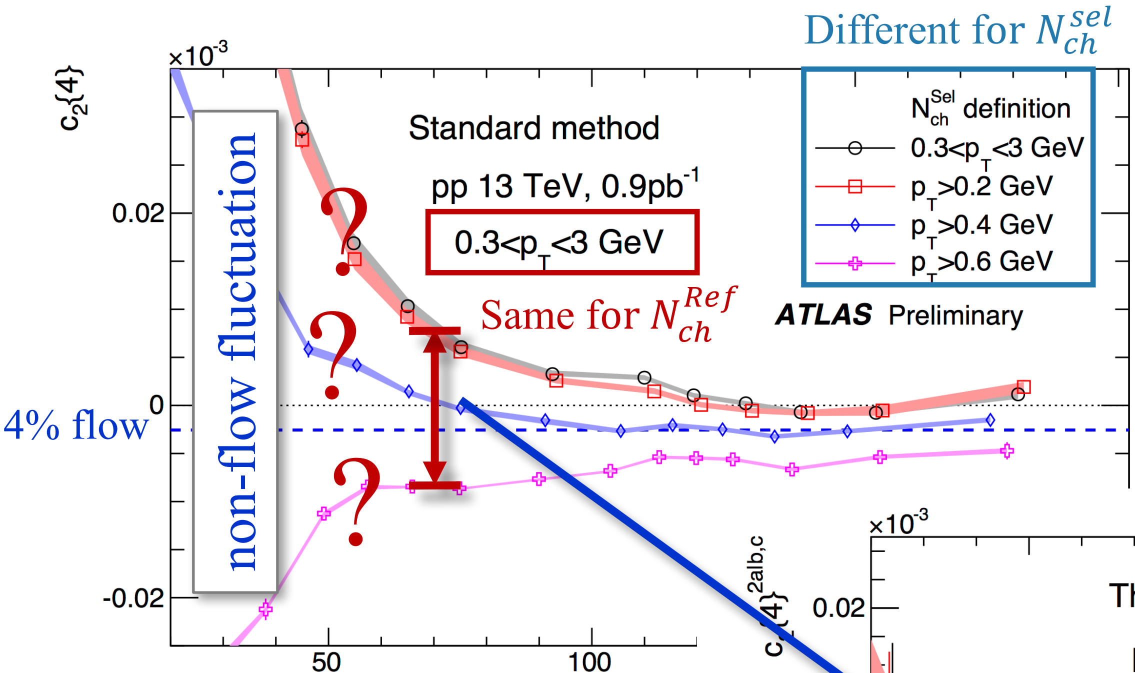
- N_{ch}^{Sel} defined with different p_T: very different non-flow fluctuation.

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 $C_2\{4\}$)!

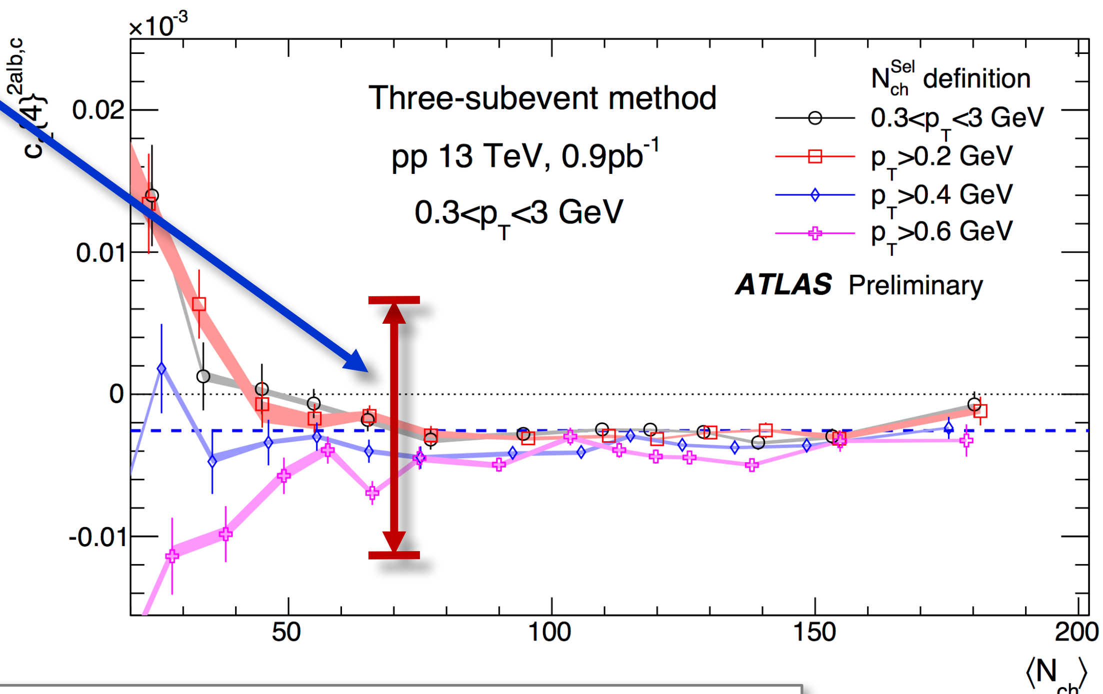
Standard cumulant v.s. Subevent cumulant



Different N_{ch}^{Sel}

Different non-flow fluctuation

Different $C_2\{4\}$



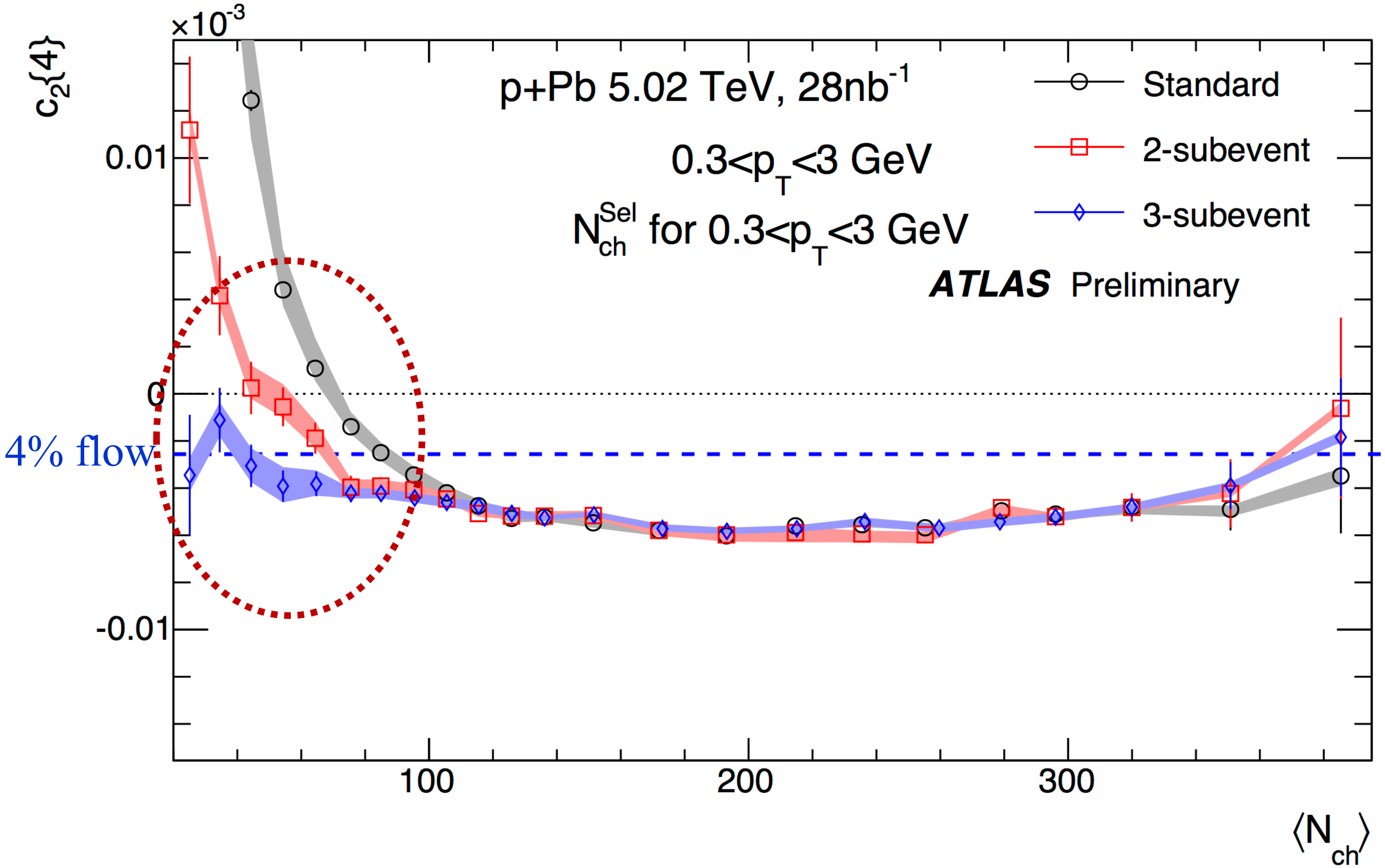
Less non-flow

Less non-flow fluctuation

Less dependence on N_{ch}^{Sel}

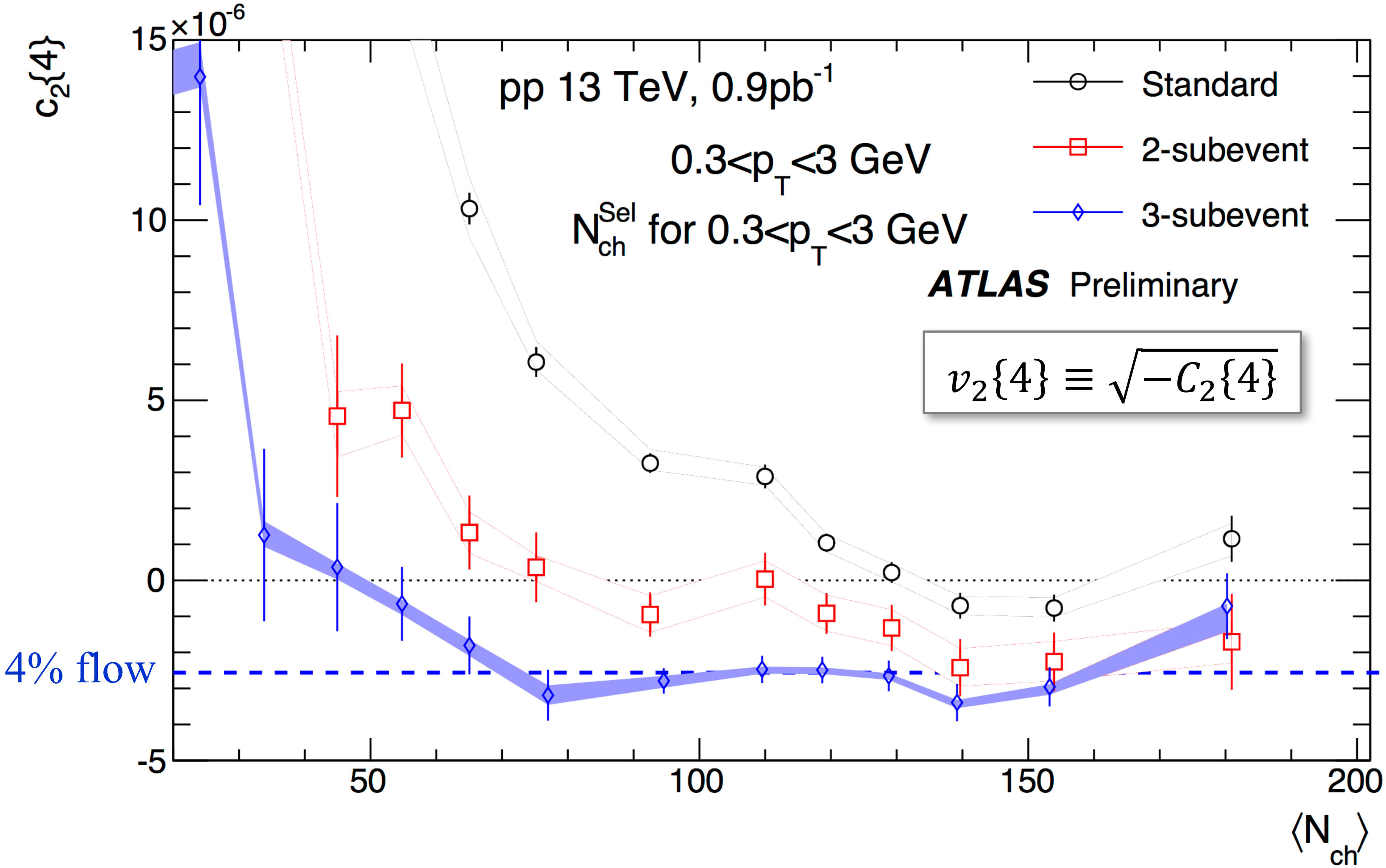
3 subevent cumulant is a more reliable method in *pp*!

New method tested in 5.02 TeV *p*+Pb



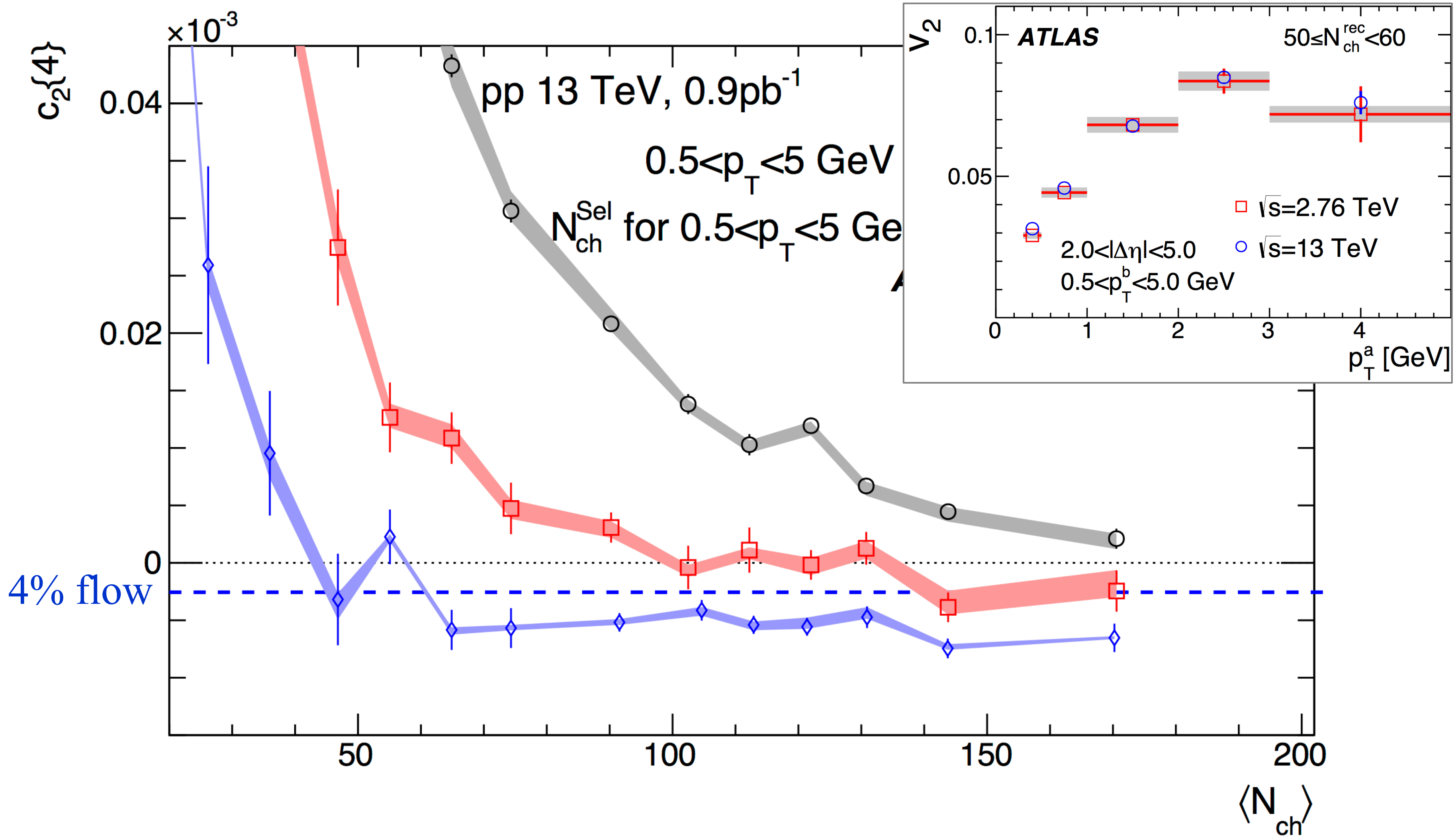
- Consistent at large N_{ch}: non-flow is smaller;
- Split observed at low N_{ch}: suppression of non-flow;

13 TeV *pp*: comparison of three methods



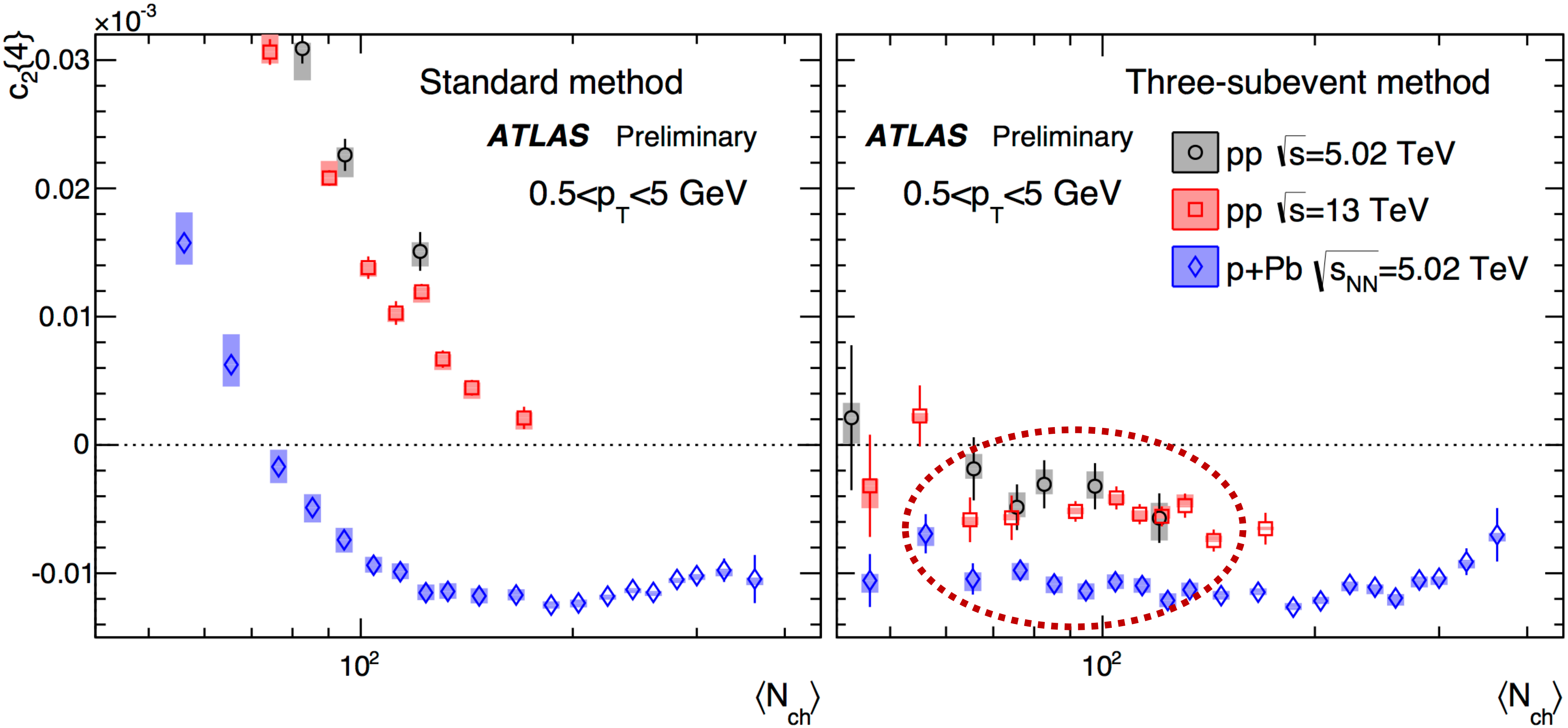
- Standard cumulant has positive $C_2\{4\}$: large residual non-flow;
- 2 subevent cumulant already suppresses non-flow;
- 3 subevent cumulant measures 4% flow down to 70 tracks.

13 TeV pp: higher p_T region



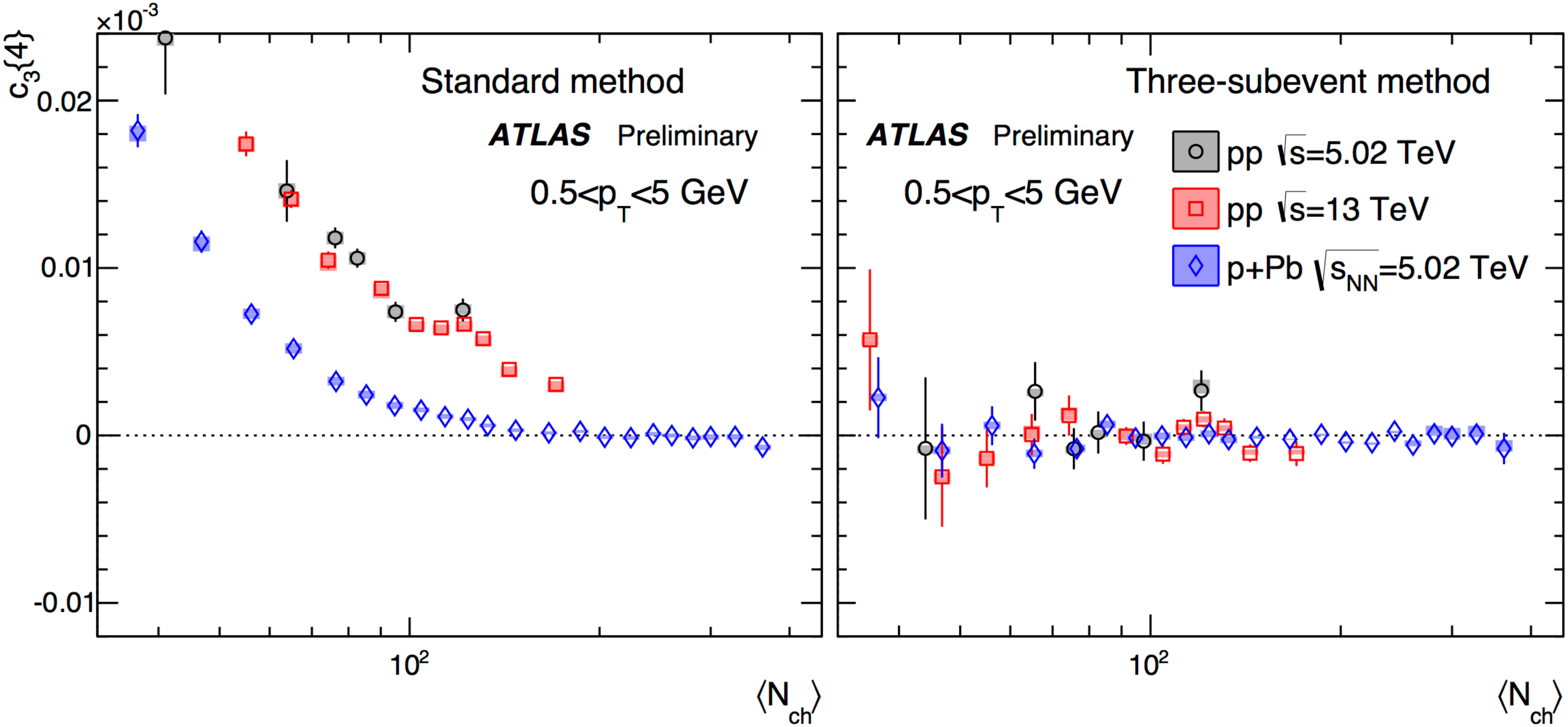
- Higher p_T range: higher fraction of non-flow;
- ONLY 3 subevent method gives larger flow signal;

Comparison among three collision systems



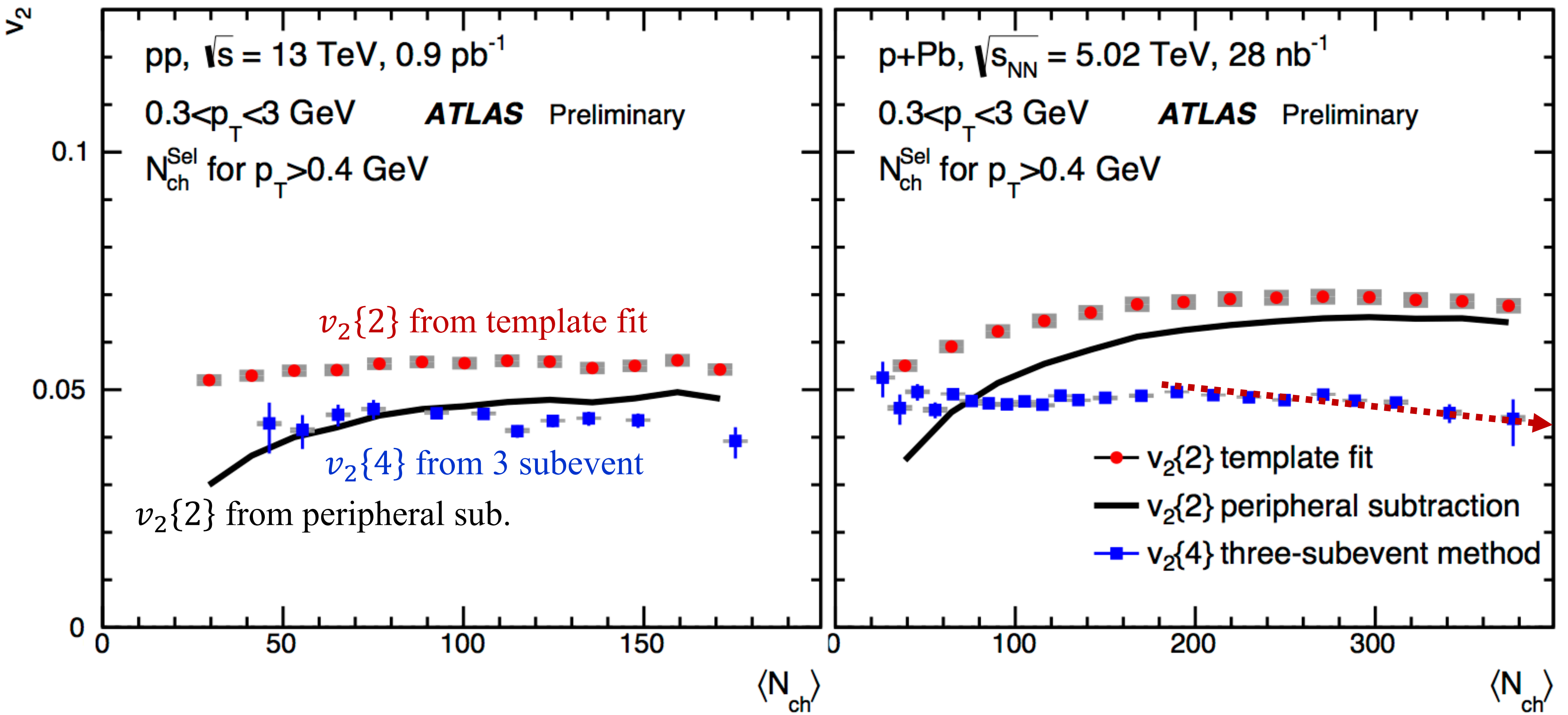
- *pp* results from standard cumulant unable to compare with *p*+Pb;
- With 3 subevent, negative $C_2\{4\}$ observed in 5.02 TeV *pp*;
- Weak energy dependence in *pp*: more data for 5.02 TeV *pp* in 2017?
- *p*+Pb has larger flow than *pp* in the comparable N_{ch} region;

Third harmonic $C_3\{4\}$



- $C_3\{4\}$ still has residual non-flow in standard method;
- $C_3\{4\}$ from 3 subevent is consistent with 0:
    - $\bar{v}_3 \ll \bar{v}_2$
    - Fluctuation kills $C_3\{4\}$?

Comparison with 2-particle correlation method

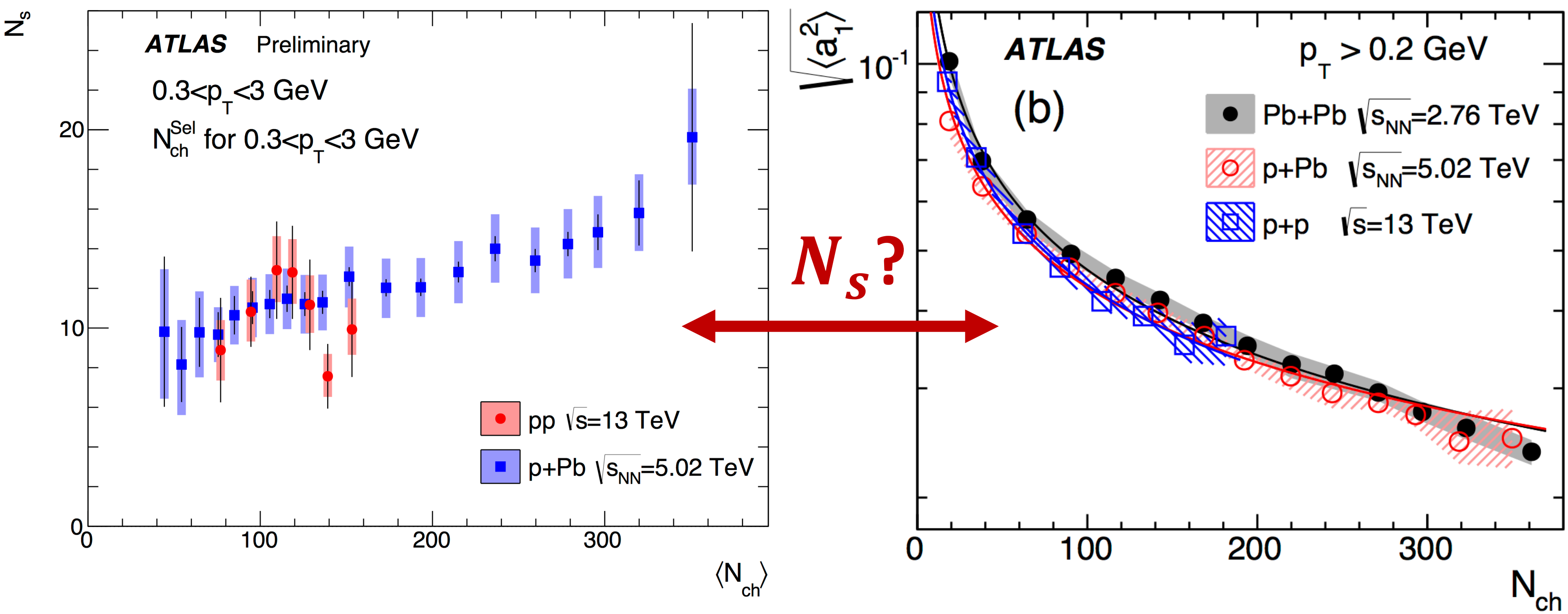


- $v_2\{4\} < v_2\{2\}$ (template fit): flow fluctuation;
- $v_2\{4\} \approx v_2\{2\}$ (peripheral subtraction): underestimation of $v_2\{2\}$;
- Decreasing trend of $C_2\{4\}$ for central p+Pb:
  - Many sources in central p+Pb?

Number of sources in initial stage

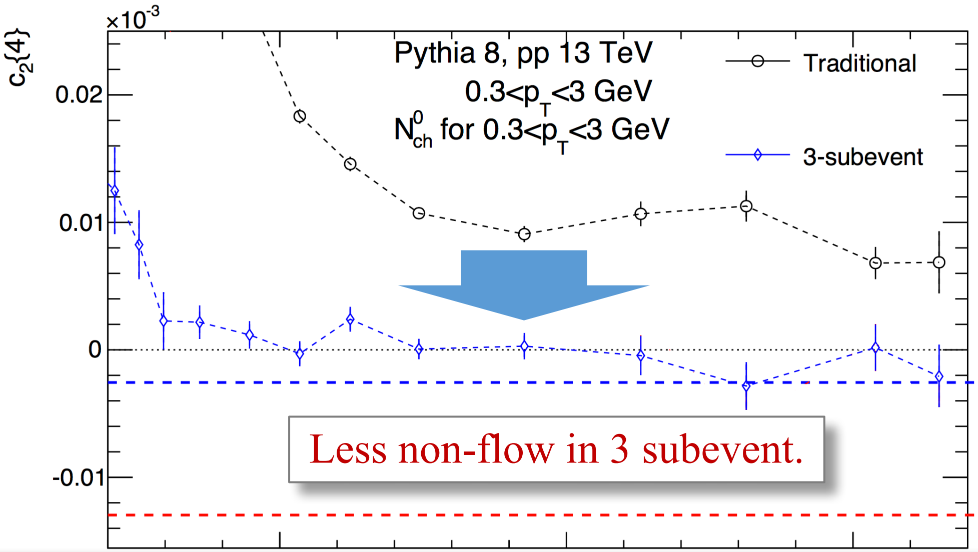
- $v_2\{2\} \neq v_2\{4\}$: EbyE flow fluctuations associated with fluctuating initial conditions. [PRL 112, 082301 (2014)]
- Fluctuation can be quantified to the number of sources N_s in the initial stage:

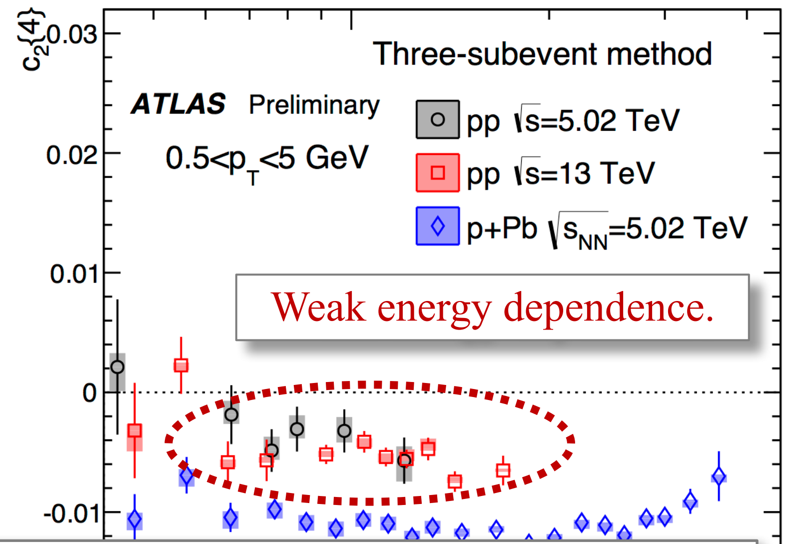
$$\frac{v_2\{4\}}{v_2\{2\}} = \left(\frac{4}{3+N_s}\right)^{1/4} \qquad\qquad \frac{N(\eta)}{\langle N(\eta)\rangle} \approx 1 + a_1\eta, \qquad a_1 \propto 1/\sqrt{N_s}$$



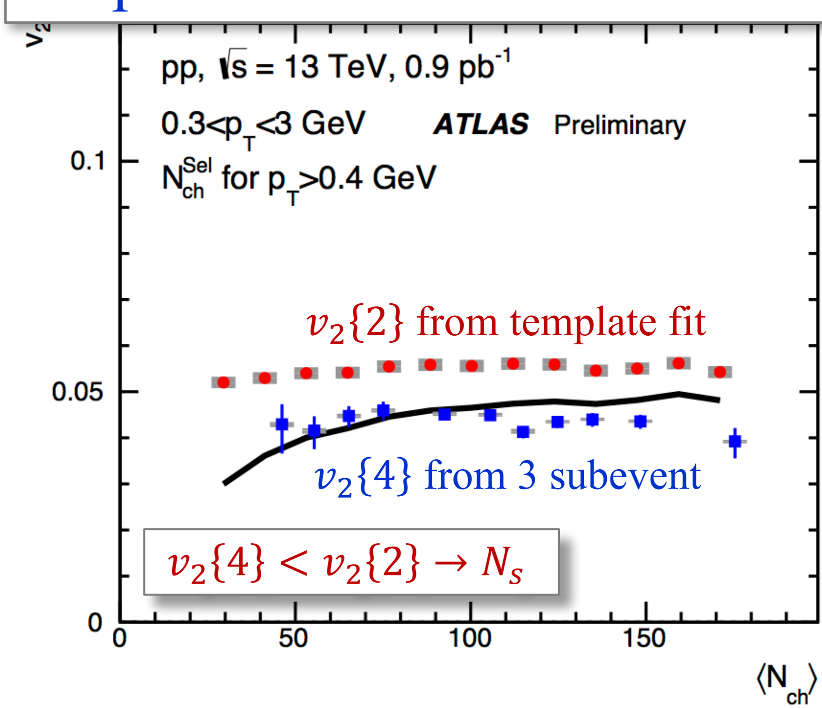
- N_s for p+Pb goes up to 20 at high multiplicity;
- N_s for pp approximately consistent with p+Pb at comparable $\langle N_{ch}\rangle$ value.

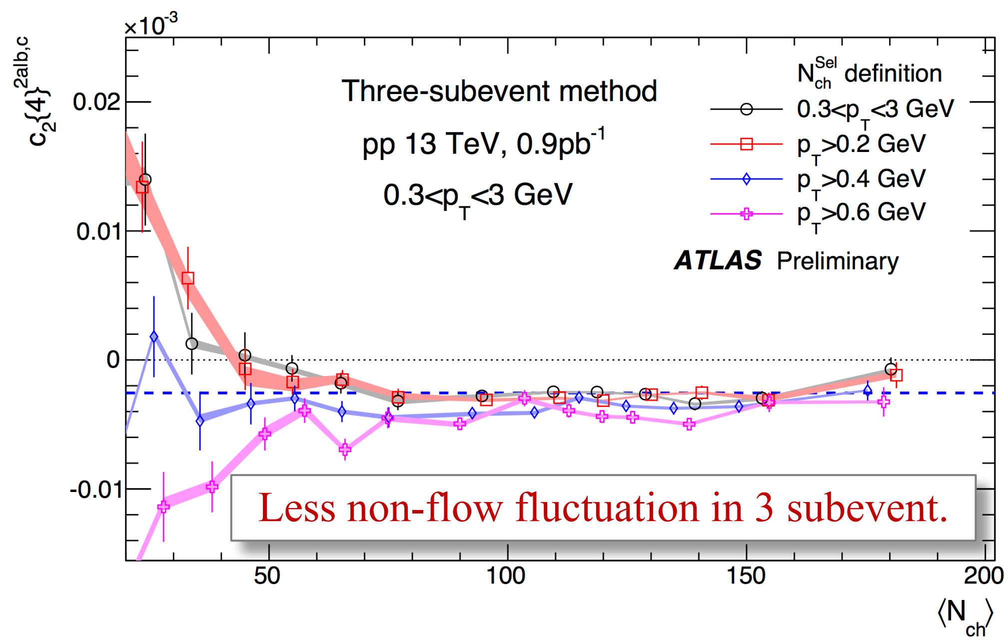
Summary





Hope the new results can better constrain models in small systems.

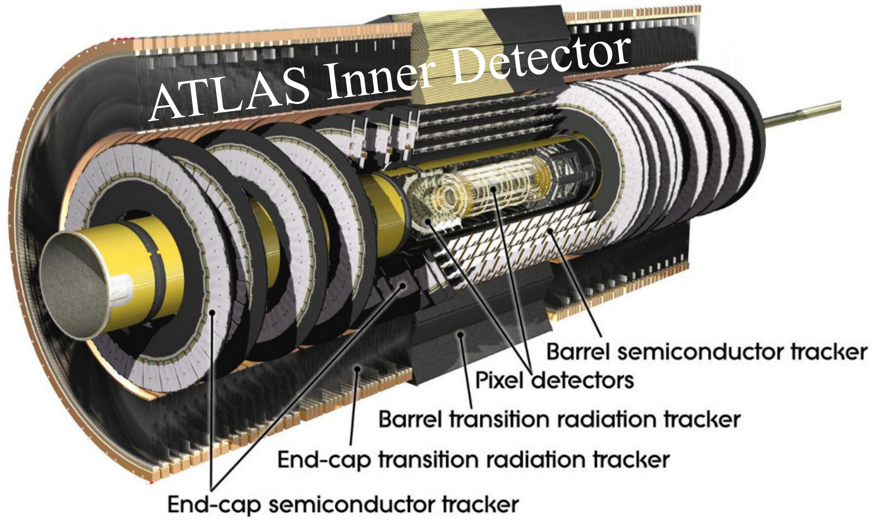




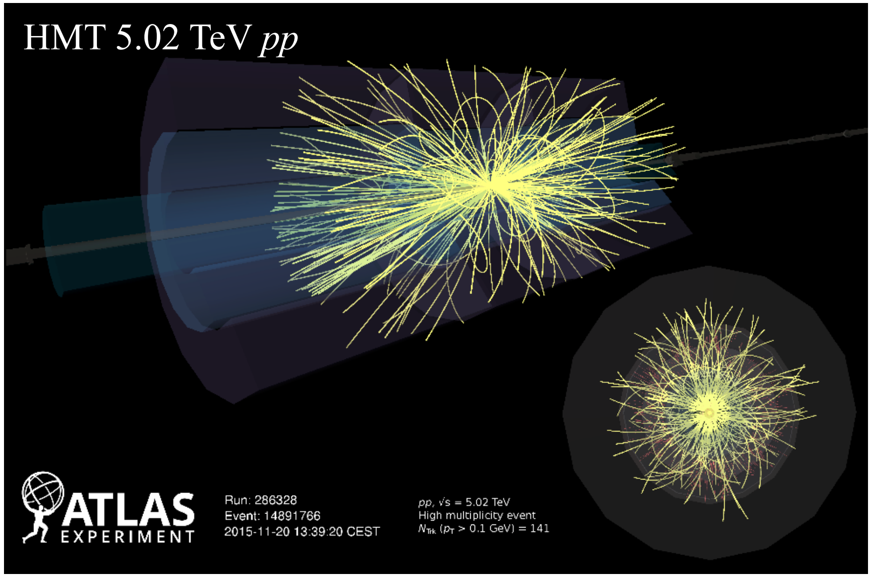
Back Up

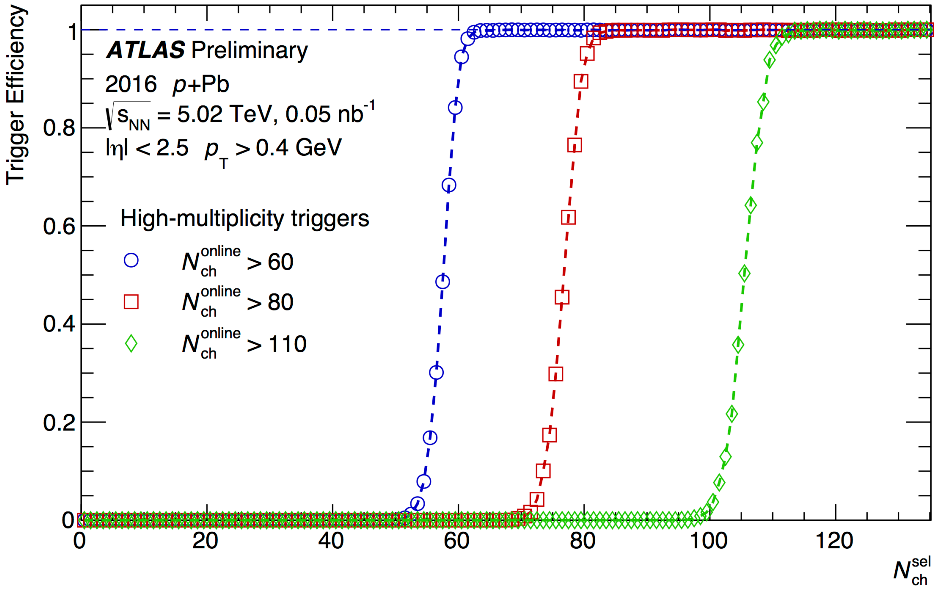
Data sets

- Studied in this analysis:
  - Energy dependence of $C_2\{4\}$ in pp;
  - Comparison between pp and p+Pb;
- 3 collision systems included:
  - 13 TeV pp (2015+2016)
  - 5.02 TeV pp (2015)
  - 5.02 TeV p+Pb (2013+2016)



- Two p_T ranges: $0.3 < p_T < 3.0$ GeV and $0.5 < p_T < 5.0$ GeV;
- High-multiplicity track triggers developed to enhance statistics at large N_{ch}:





Formulas without particle weight

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

$$\langle 2\rangle \equiv \frac{Q_n^2 - M}{M(M-1)}$$

$$\langle 4\rangle \equiv \frac{Q_n^4 + Q_{2n}^2 - 2Q_{2n}Q_n^* Q_n^* - 4(M-2)Q_n^2 + 2M(M-3)}{M(M-1)(M-2)(M-3)}$$

$$C_n^{a,a|b,b}\{4\} \equiv \langle 4\rangle_{a.a|b,b} - 2\langle 2\rangle_{a|b}^2$$

$$\langle 2\rangle_{a|b} \equiv \frac{Q_{n,a}Q_{n,b}}{M_a M_b}$$

$$\langle 4\rangle_{a,a|b,b} \equiv \frac{(Q_{n,a}^2 - Q_{2n,a})(Q_{n,b}^2 - Q_{2n,b})^*}{M_a(M_a-1)M_b(M_b-1)}$$

$$C_n^{a,a|b,c}\{4\} \equiv \langle 4\rangle_{a,a|b,c} - 2\langle 2\rangle_{a|b}\langle 2\rangle_{a|c}$$

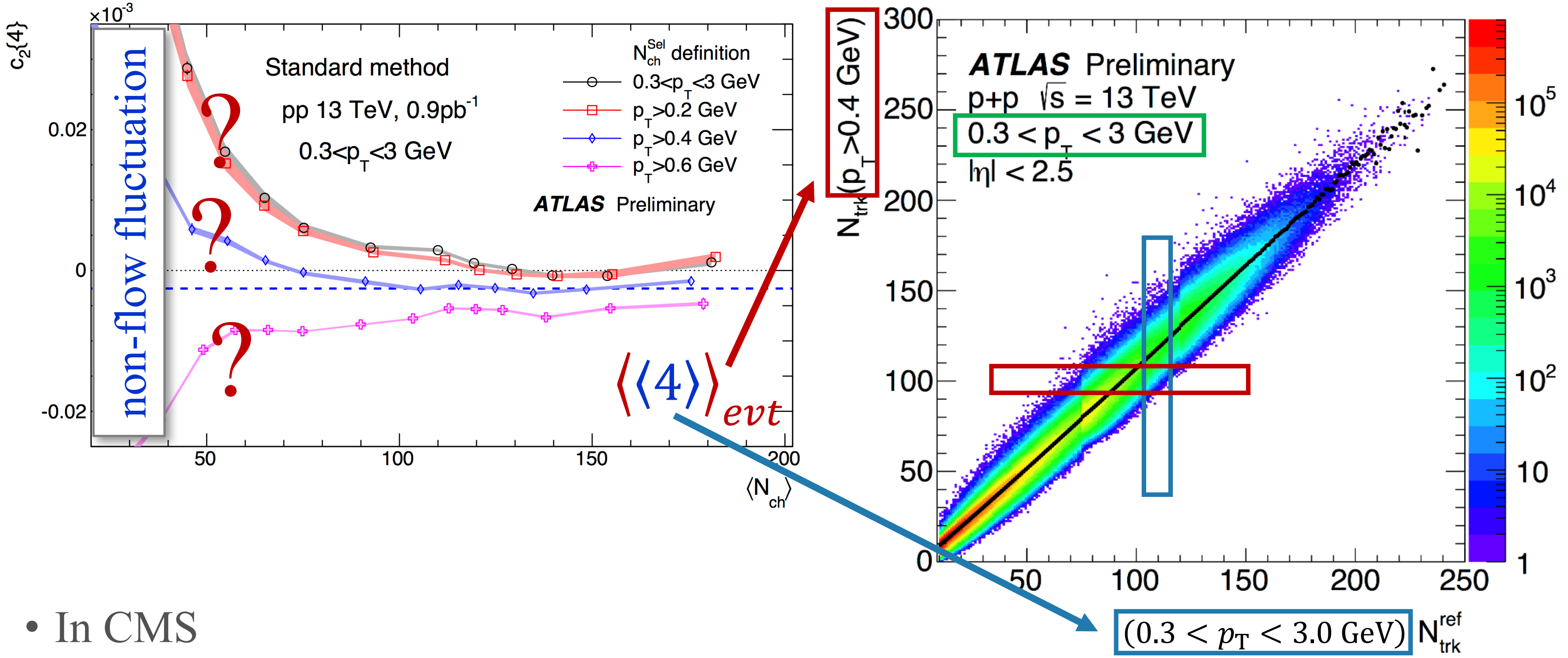
$$\langle 2\rangle_{a|b} \equiv \frac{Q_{n,a}Q_{n,b}}{M_a M_b}$$

$$\langle 2\rangle_{a|c} \equiv \frac{Q_{n,a}Q_{n,c}}{M_a M_c}$$

$$\langle 4\rangle_{a,a|b,c} \equiv \frac{(Q_{n,a}^2 - Q_{2n,a})Q_{n,b}^* Q_{n,c}^*}{M_a(M_a-1)M_b M_c}$$

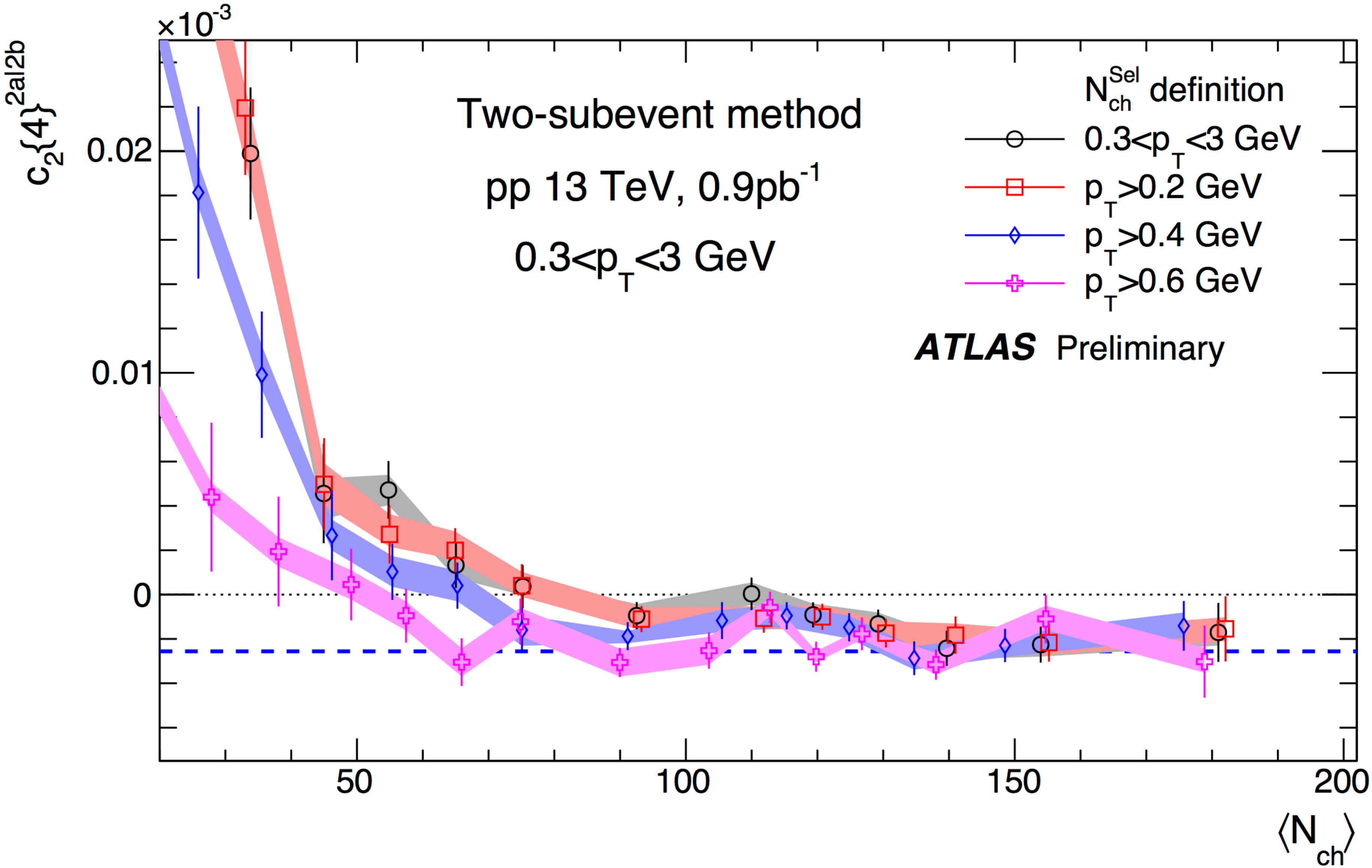
$$= \left\langle e^{in(\phi_1^a+\phi_2^b-\phi_3^a-\phi_4^c)}\right\rangle_c + \left\langle \boldsymbol{v}_{n,a}^2 \boldsymbol{v}_{n,b}^* \boldsymbol{v}_{n,c}^*\right\rangle - \left\langle v_{n,a}^2\right\rangle\left\langle \boldsymbol{v}_{n,b}\boldsymbol{v}_{n,c}^*\right\rangle - \left\langle \boldsymbol{v}_{n,a}\boldsymbol{v}_{n,b}^*\right\rangle\left\langle \boldsymbol{v}_{n,a}\boldsymbol{v}_{n,c}^*\right\rangle$$

Multiplicity fluctuation

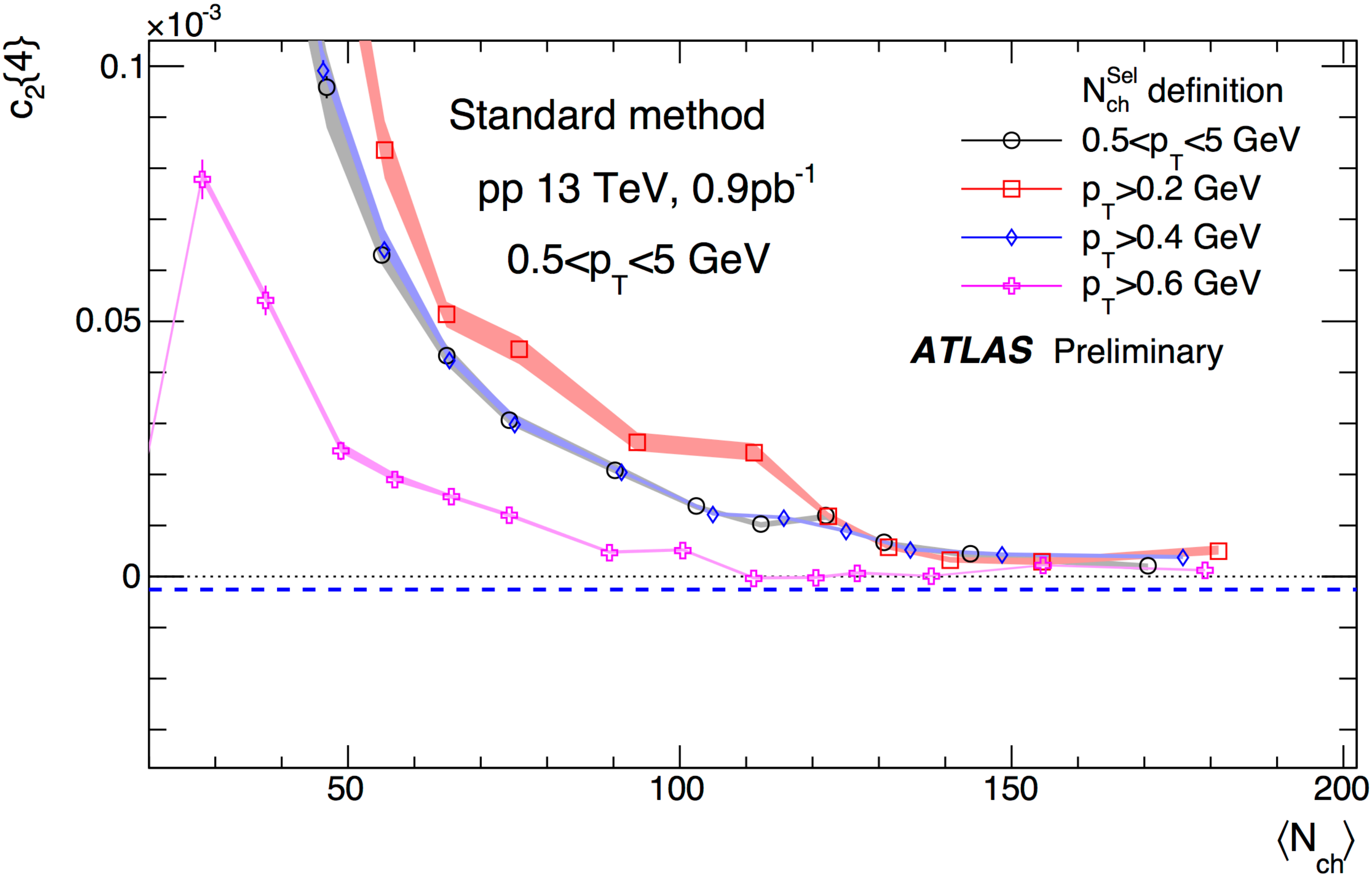


- In CMS
  - $\langle 4\rangle$ is calculated in $0.3 < p_T < 3.0$ GeV;
  - $\langle \dots \rangle_{evt}$ is binned with N_{ch}^{Sel} of $p_T > 0.4$ GeV;
- In ATLAS
  - $\langle 4\rangle$ is calculated in $0.3 < p_T < 3.0$ GeV;
  - $\langle \dots \rangle_{evt}$ is binned with N_{ch}^{Sel} of $0.3 < p_T < 3.0$ GeV;
  - X-axis of $C_2\{4\}$ is projected to $\langle N_{ch}\rangle$ with $p_T > 0.4$ GeV;

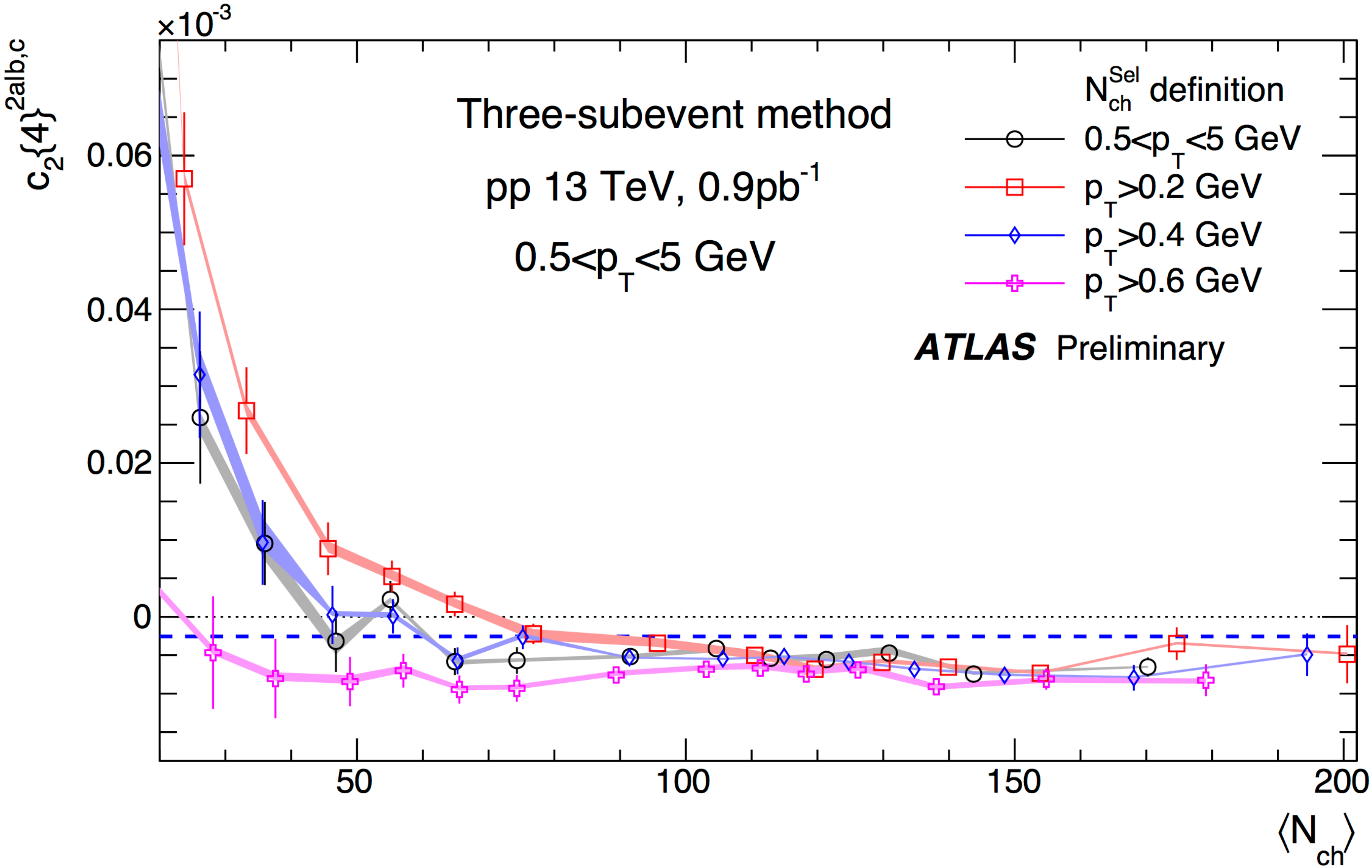
Residual non-flow check in 2 subevent



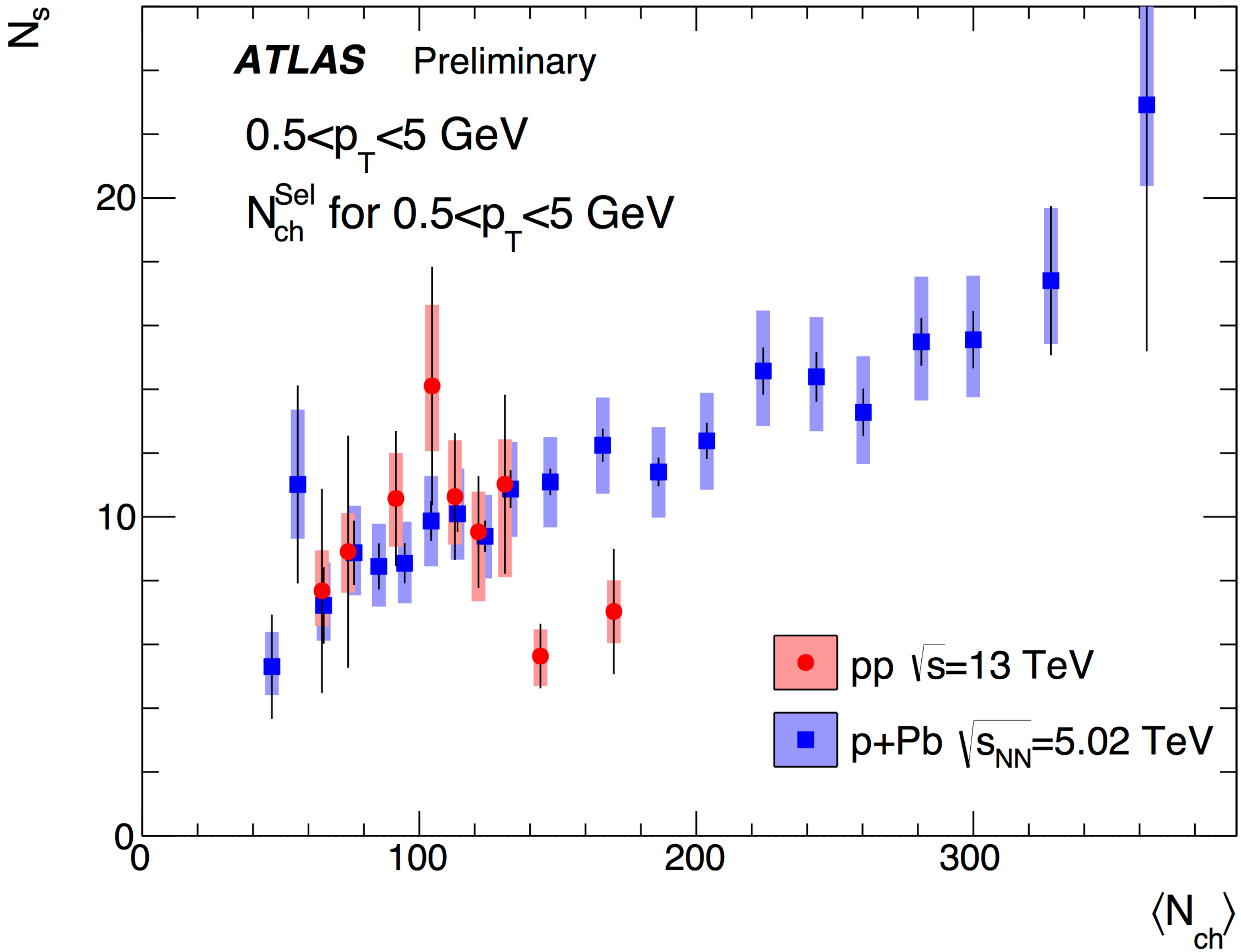
Residual non-flow check in higher p_T



Residual non-flow check in higher p_T



N_s in $0.5 < p_T < 5.0$ GeV

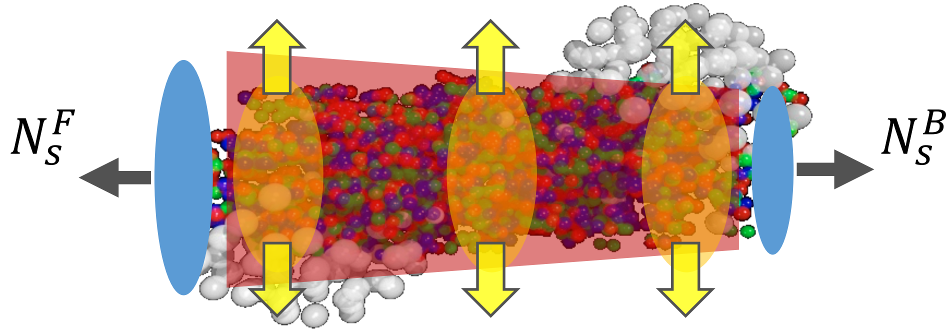


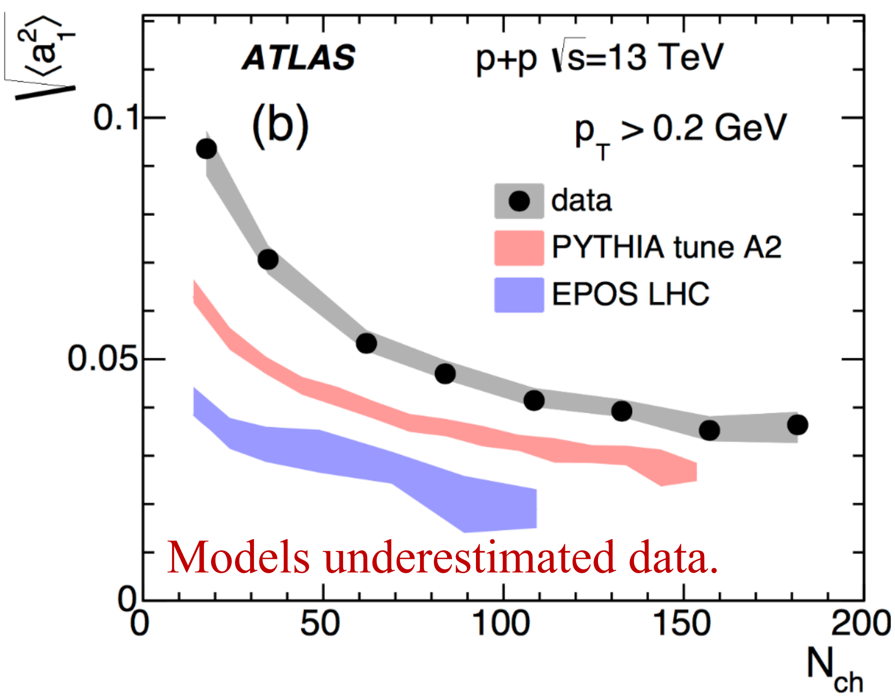
Summary

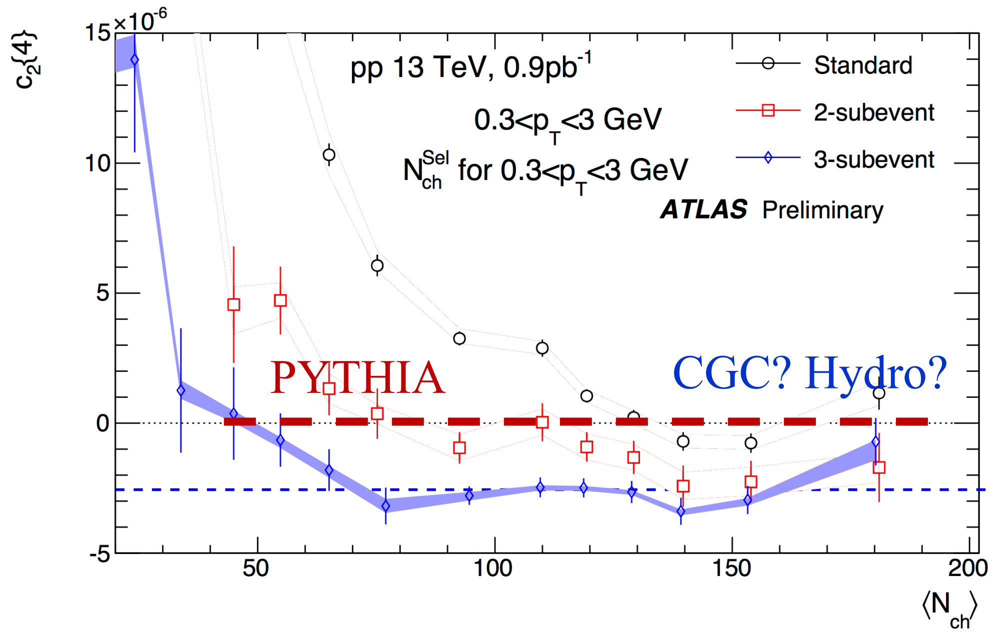
Nature of sources seeding the long-range collective behavior?

Longitudinal correlation

Azimuthal correlation

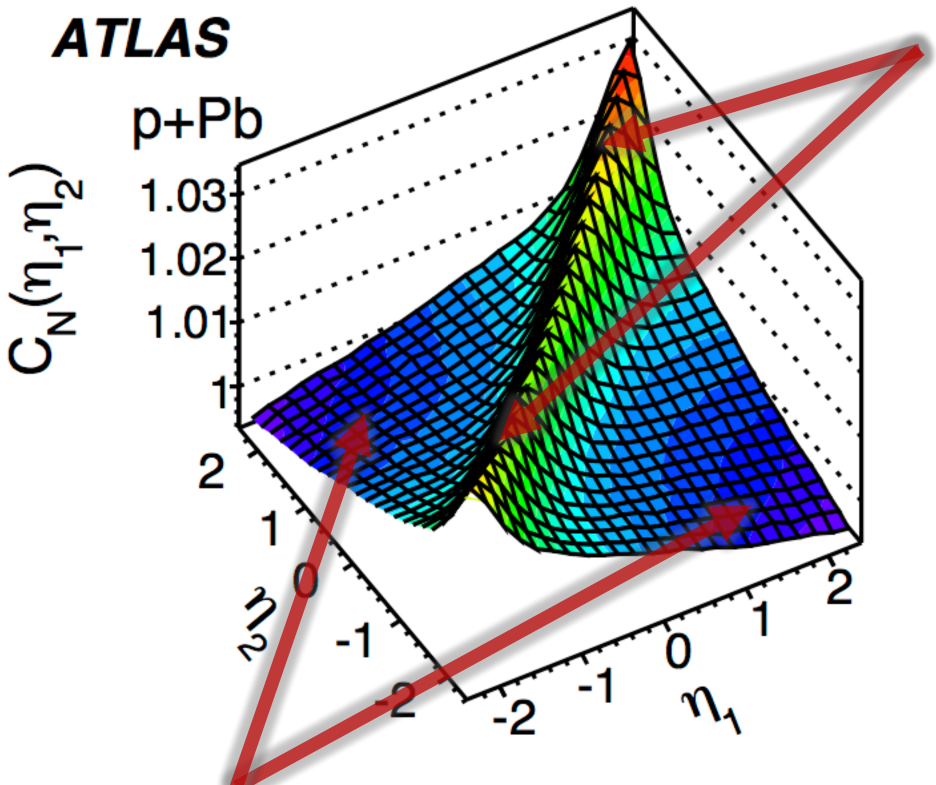






Physics signal and background

- 2-particle pseudo-rapidity correlation: $$C(\eta_1, \eta_2) \equiv \frac{\langle N(\eta_1)N(\eta_2)\rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle}$$



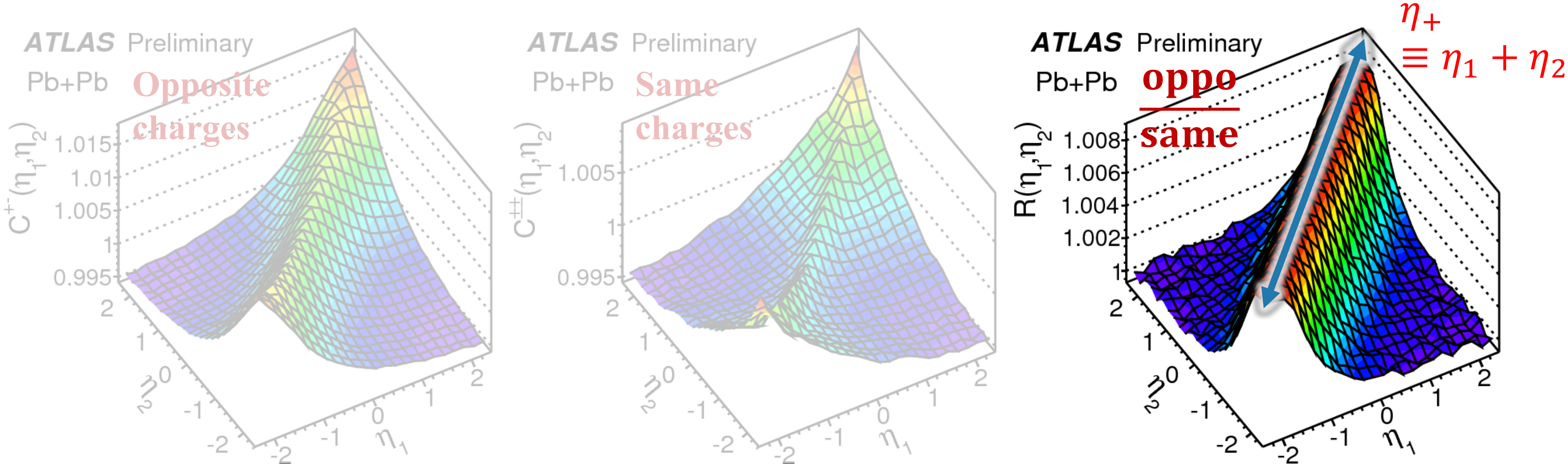
- Short-range correlation (SRC) reflects correlation in the same source: jet fragmentation, resonance decay…
- Since SRC has a strong charge dependence, a data-driven way was developed to remove the SRC.
- An alternative way is through multi-particle correlation (cumulant) in pseudo-rapidity. [PRC.93.024903]

- Long-range correlation (LRC)

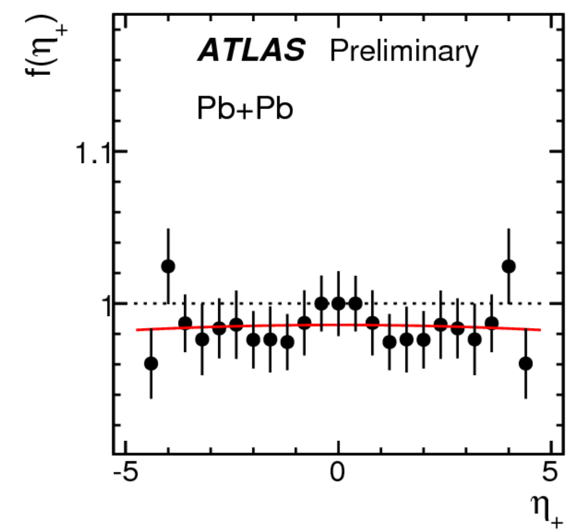
From the experimental perspective, the key is to extract the physics signal from the background.

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

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

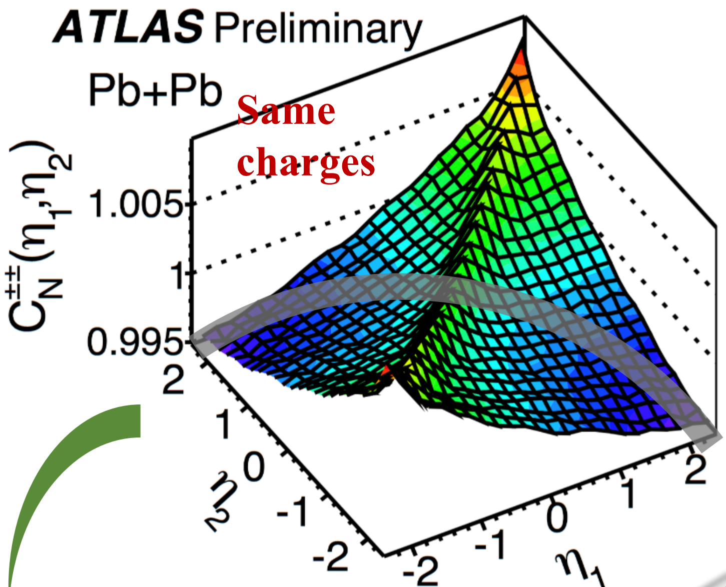


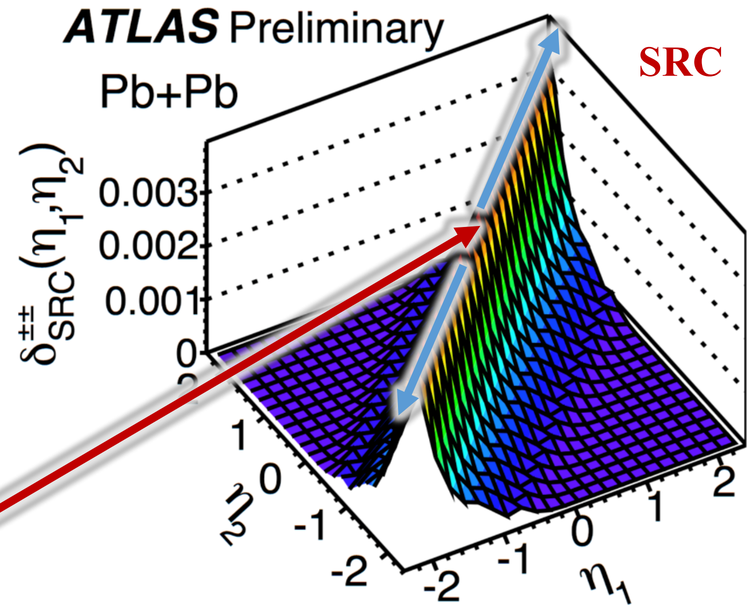
- Ratio of opposite to same charges $R(\eta_1, \eta_2)$
  - Very strong Gaussian-like SRC;
  - Very weak LRC: charge-independent;
- Amplitude of $R(\eta_1, \eta_2)$ along η_+: $f(\eta_+)$, reflects the strength of SRC in the longitudinal direction;
- Assumption: strength of SRC along η_+ is same for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

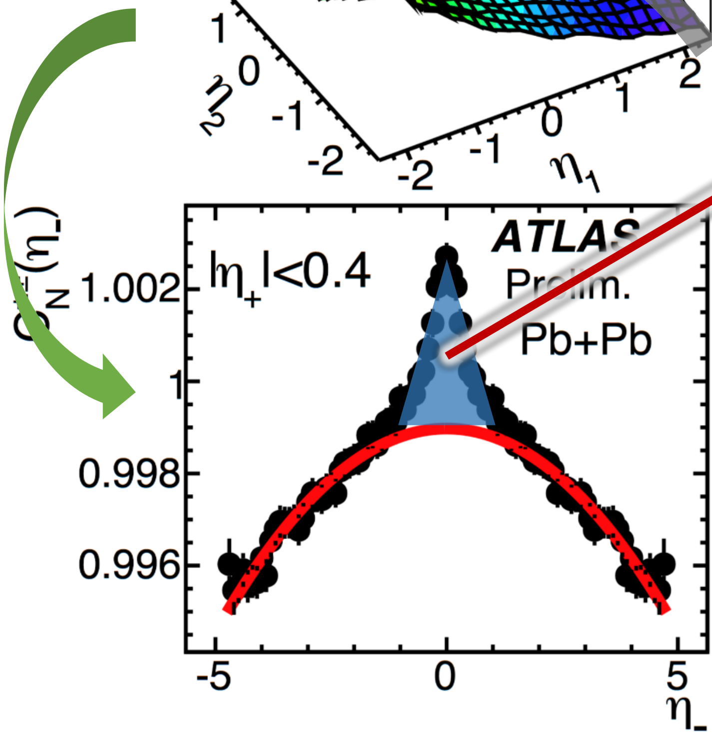


Estimation of short-range correlation

- To estimate SRC, LRC pedestal is estimated first.



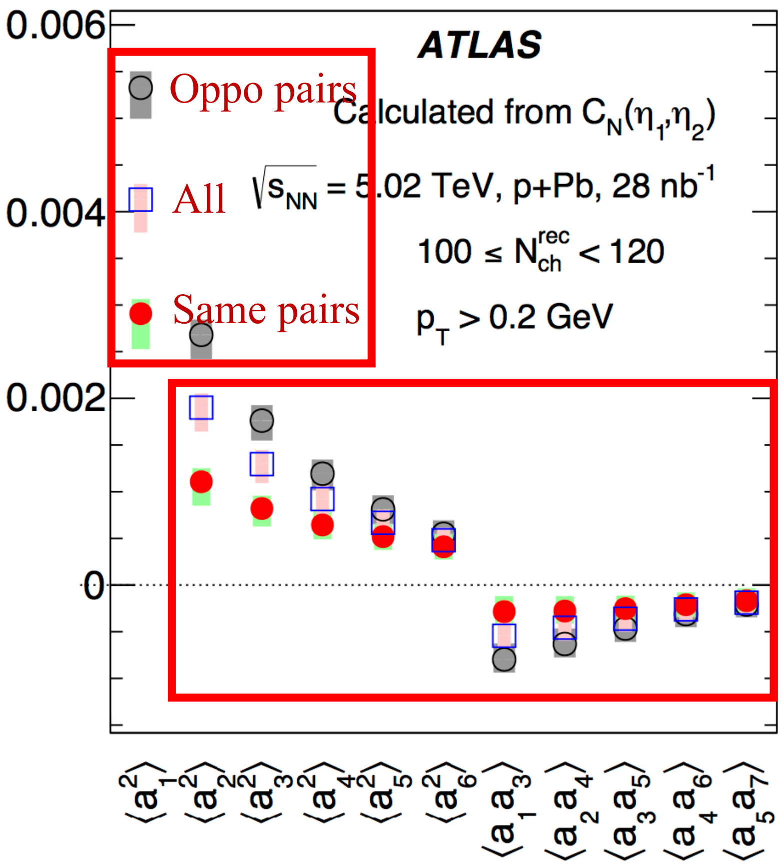




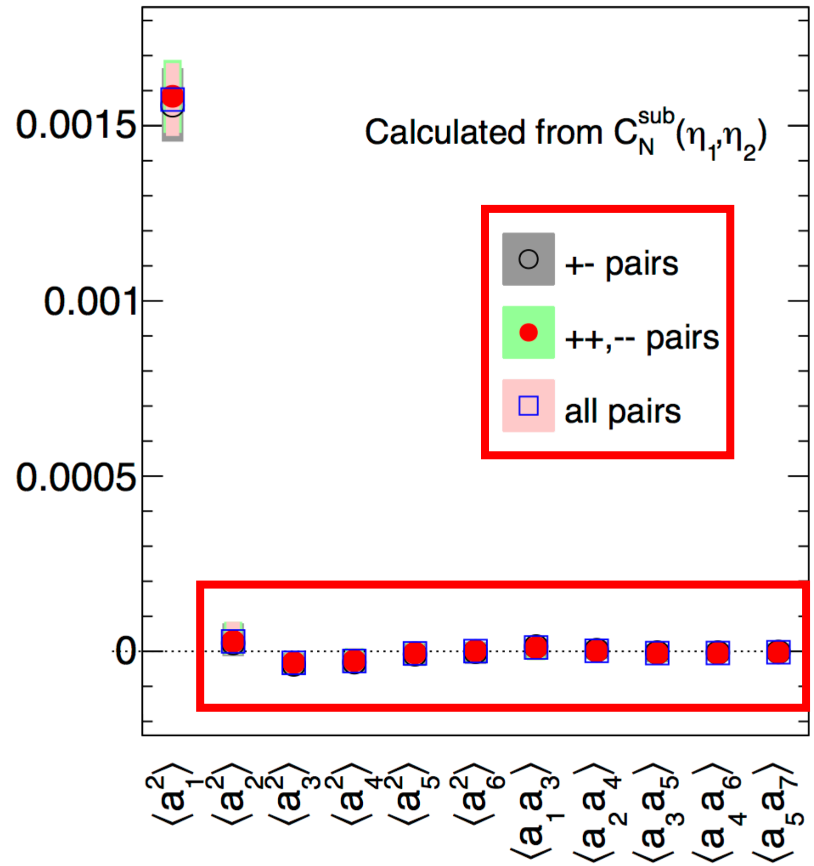
- $C(\eta_1, \eta_2)$ from same charge used to estimate LRC pedestal because of small SRC;
- LRC pedestal is fitted with quadratic function;
- The additional structure upon LRC pedestal determines the shape of SRC;
- The full $\delta_{SRC}(\eta_1, \eta_2)$ is then populated using $f(\eta_+)$ scaling.

Why it is important to remove SRC?

Before SRC removal



After SRC removal

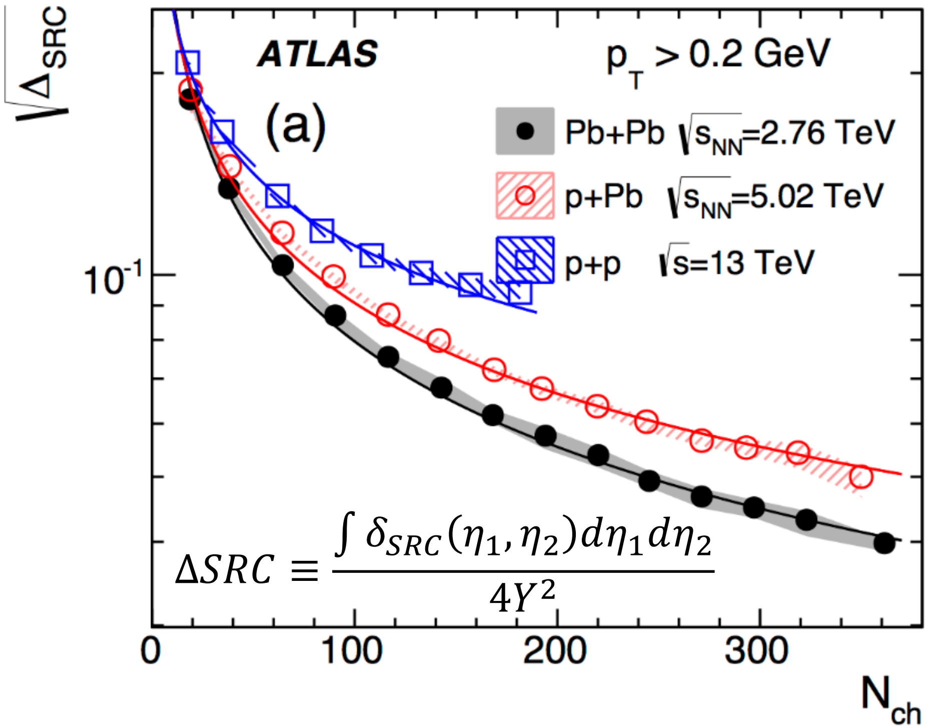


- Higher order coefficients observed;
- Coefficients have charge dependent;
- Results hard to interpret: due to SRC!

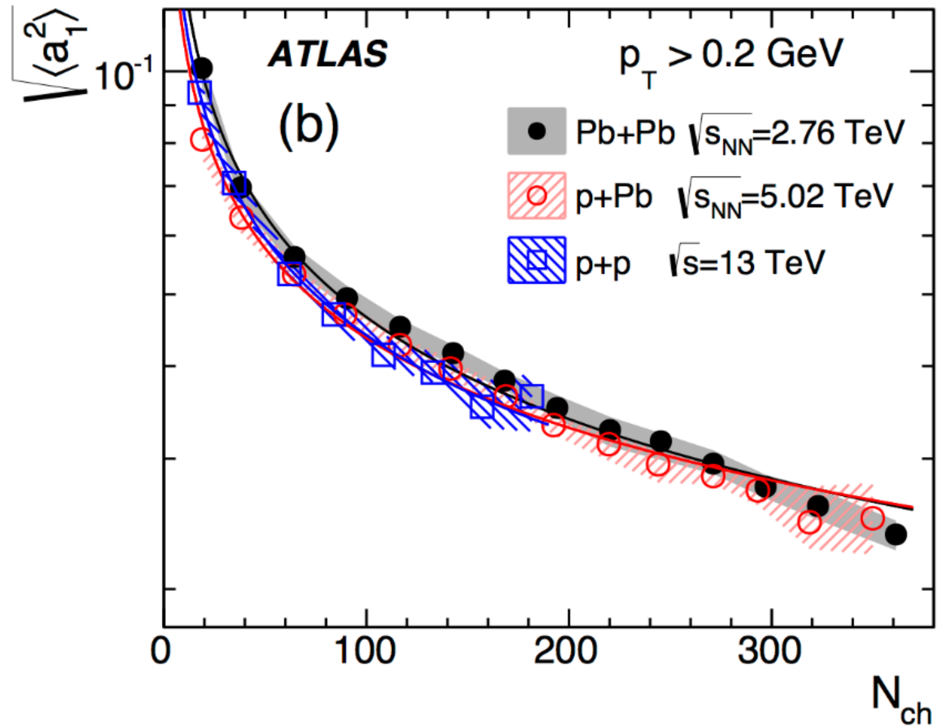
- Simpler picture after SRC removal!
- LRC dominated by linear fluctuation;
- LRC is charge independent.

Why it is important to remove SRC?

Short-range correlation



Long-range correlation



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

- Dominated by linear fluctuation!
- Independent of collision system!

- Follow-up model studies
  - Viscous hydro: [PLB 2015.11.063]
  - Length of sources fluctuation: [PRC 93, 064910 (2016)]
  - Saturation scale fluctuation: [PRC 94, 044918 (2016)]