Experimental overview of correlations in small collision systems : A brief History

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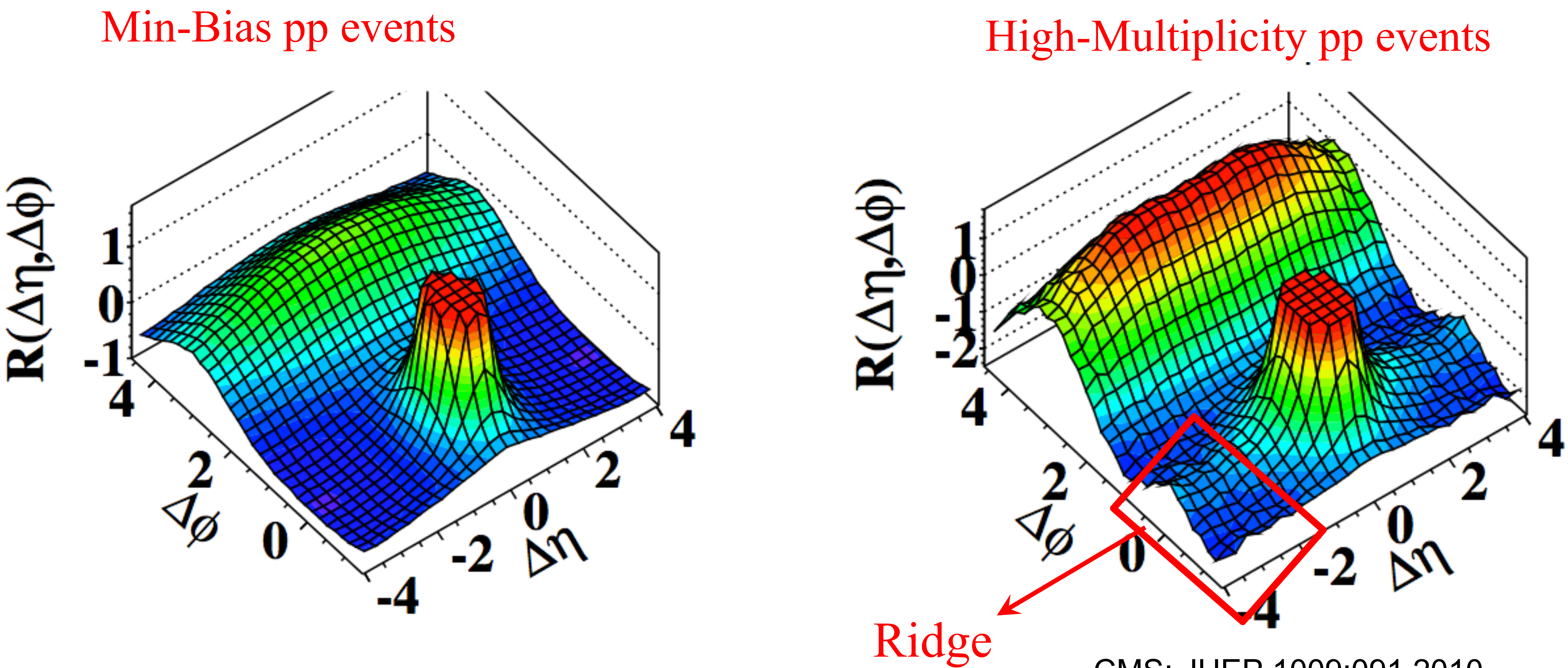
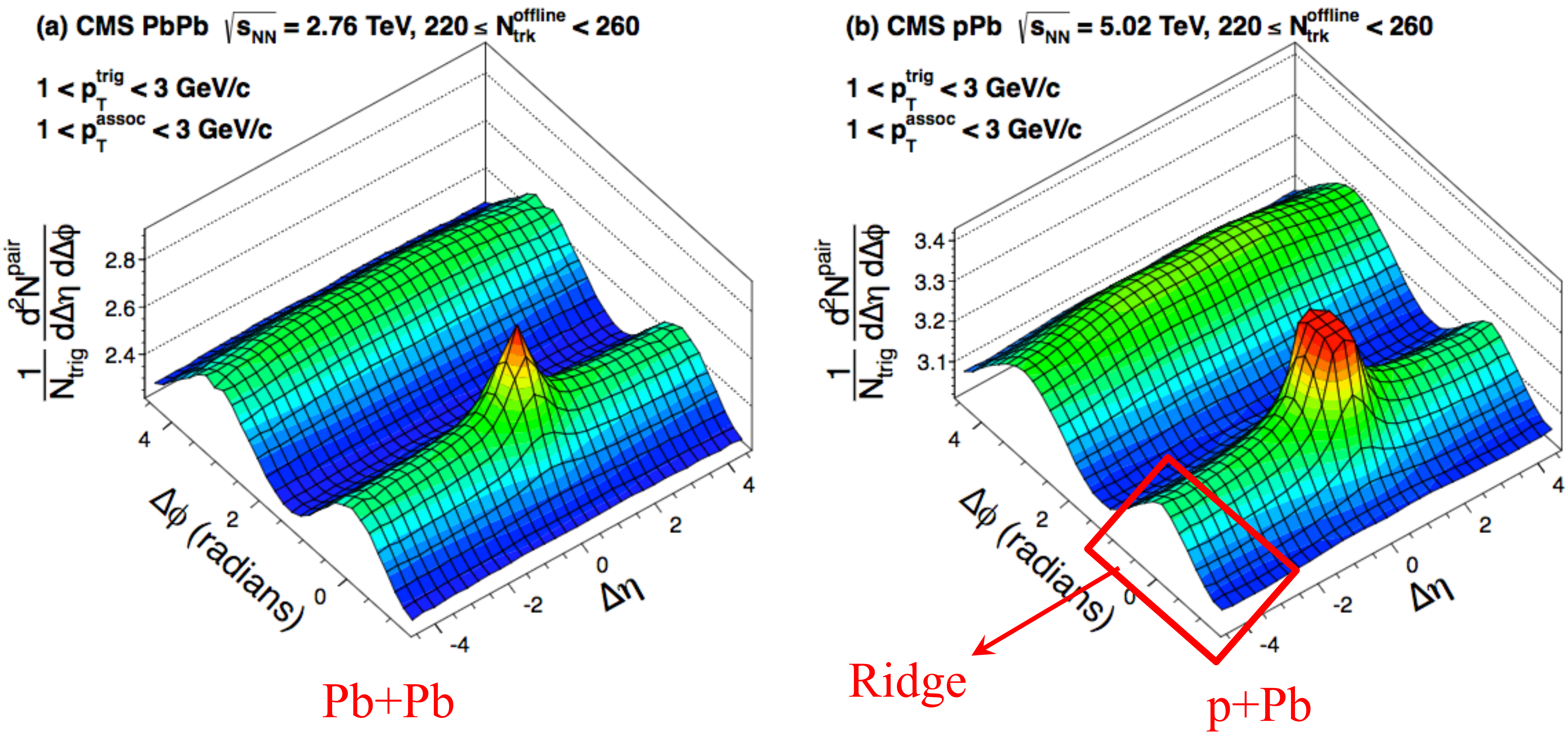
First hints of "collectivity" in pp



CMS: JHEP 1009:091,2010

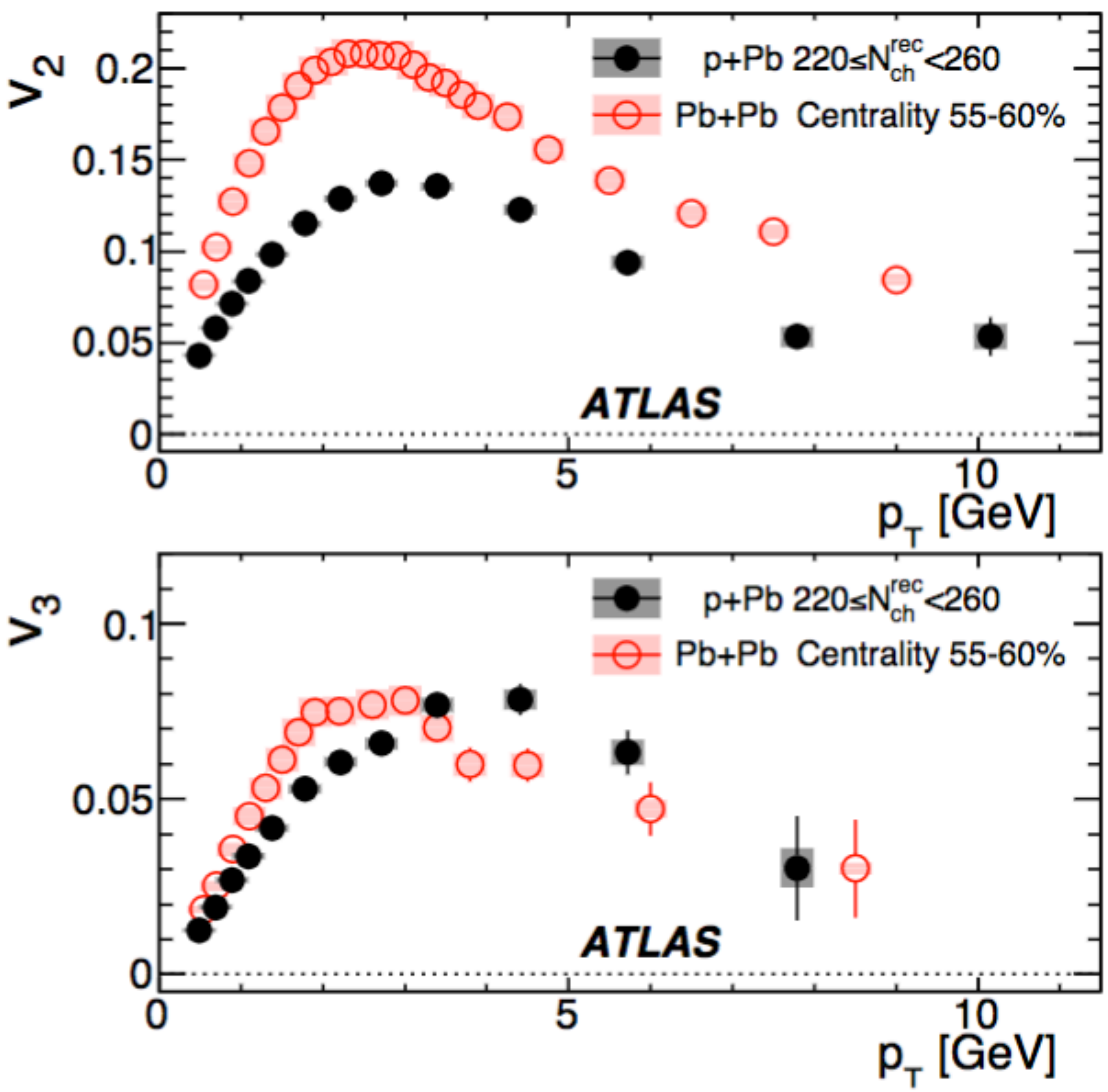
- Two-particle correlations in pp collisions by CMS in 2010.
- Long range correlation structure, "Ridge", observed along $\Delta\eta$ at $\Delta\phi=0$.
- Ridge "appears" at high multiplicity.
- Ridge signal much smaller compared to other features of correlation.
  - Not possible/no attempt made to use traditional correlation techniques used in A+A collisions
- Initial state models (CGC) able to reproduce the ridge.

The p+Pb ridge



- 2012 LHC p+Pb run
- All LHC experiments (ATLAS, ALICE, CMS) showed presence of strong long-range correlations in p+Pb.
- Correlations strong enough and multiplicities large enough to use A+A methods in p+Pb.

p+Pb: Very similar to Pb+Pb



- Azimuthal anisotropy measurements :
  - Fourier harmonics v_n extracted from the two-particle correlations

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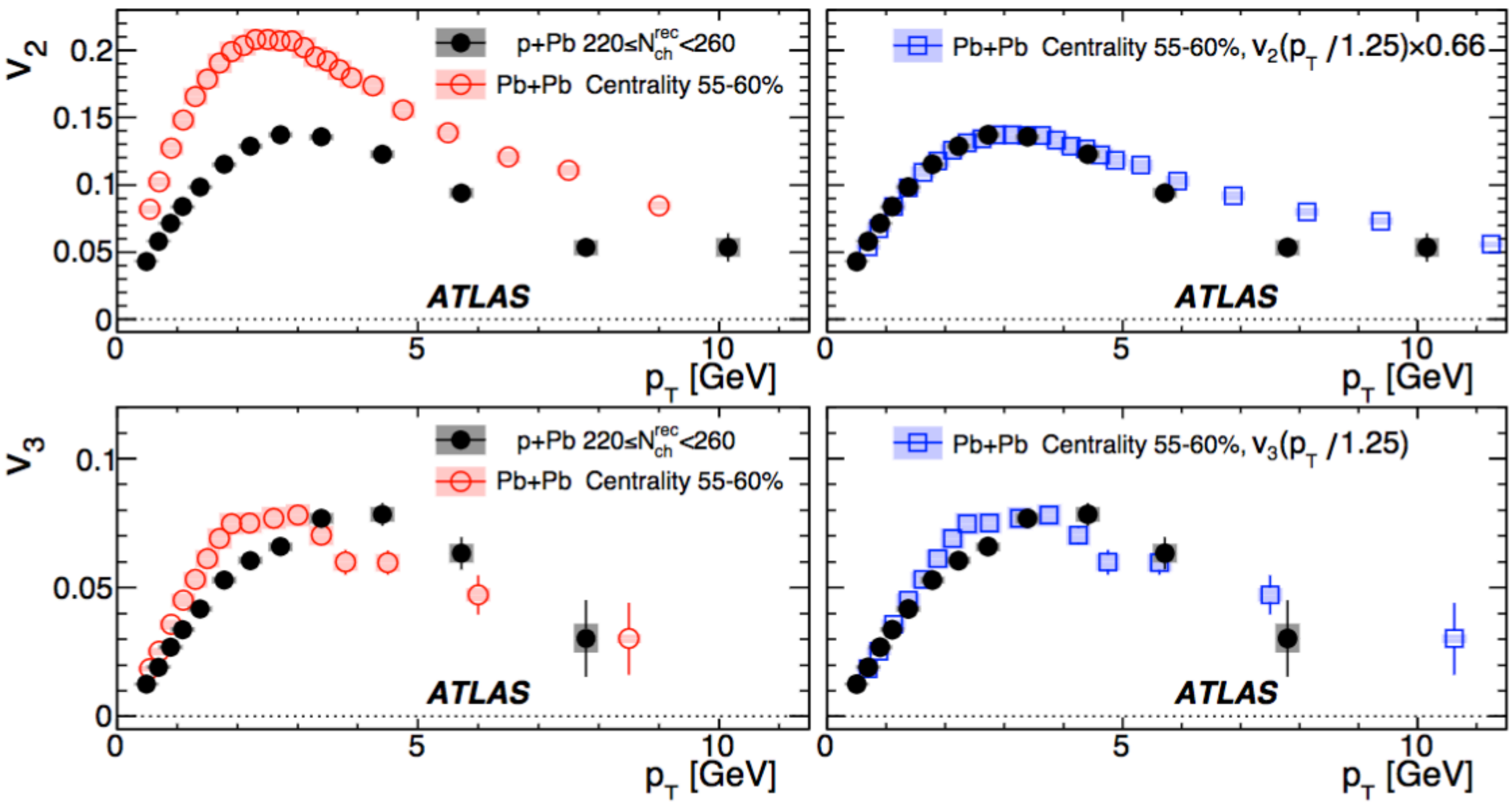
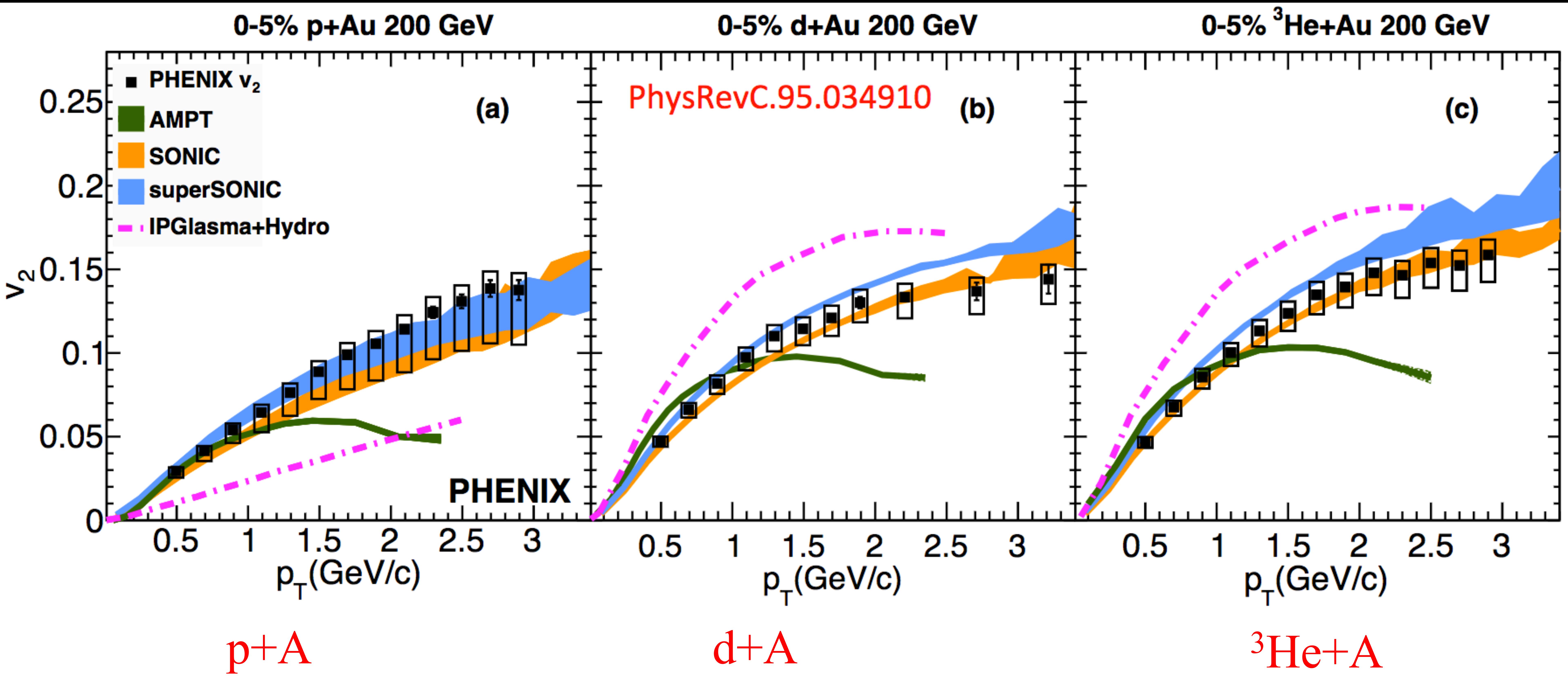


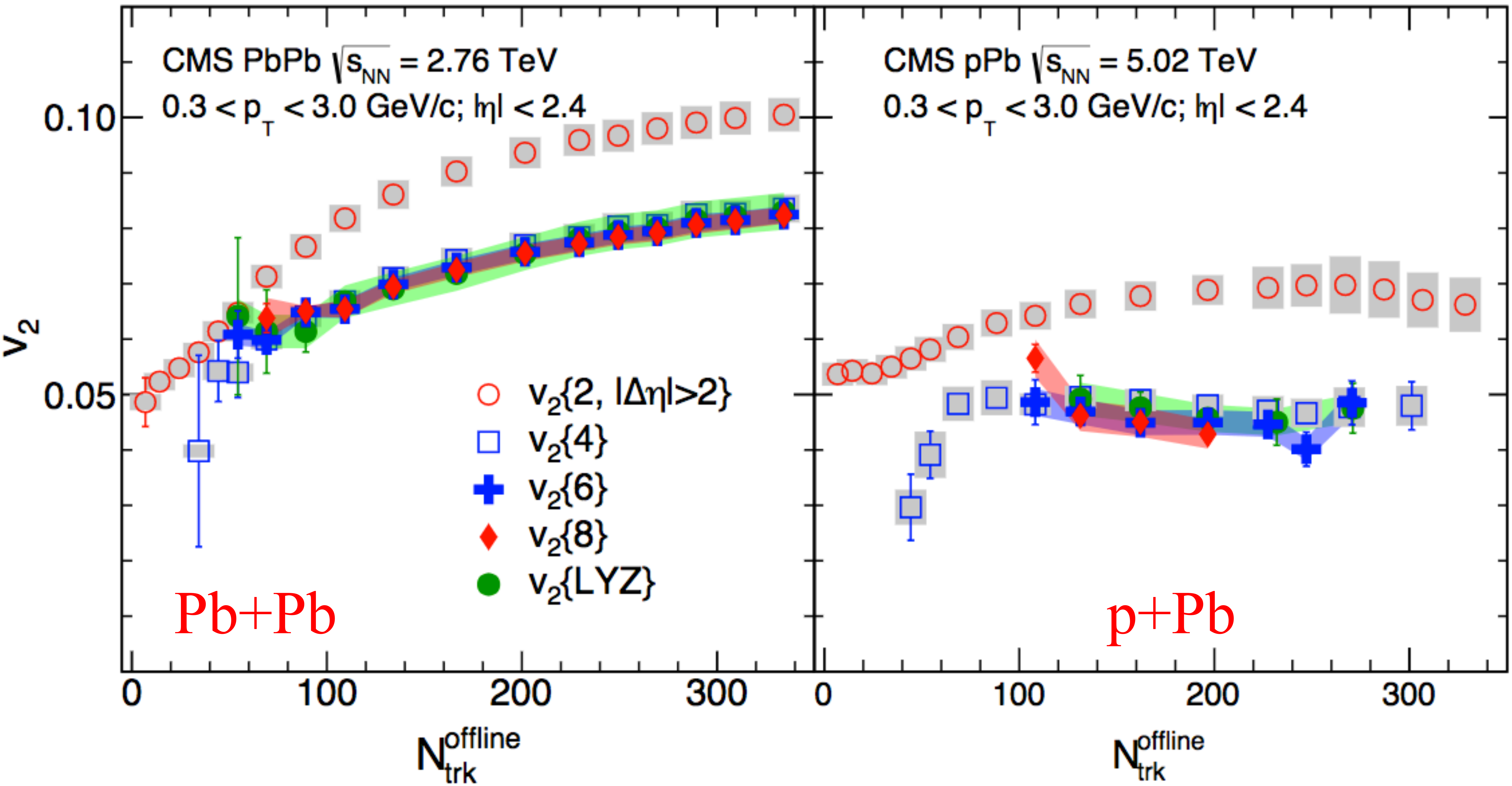
- Azimuthal anisotropy measurements :
  - Fourier harmonics v_n extracted from the two-particle correlations
- Fourier harmonics v_2-v_4 : Quite similar p_T dependence in p+Pb and Pb+Pb

p+A, d+A, ^{3}He+A



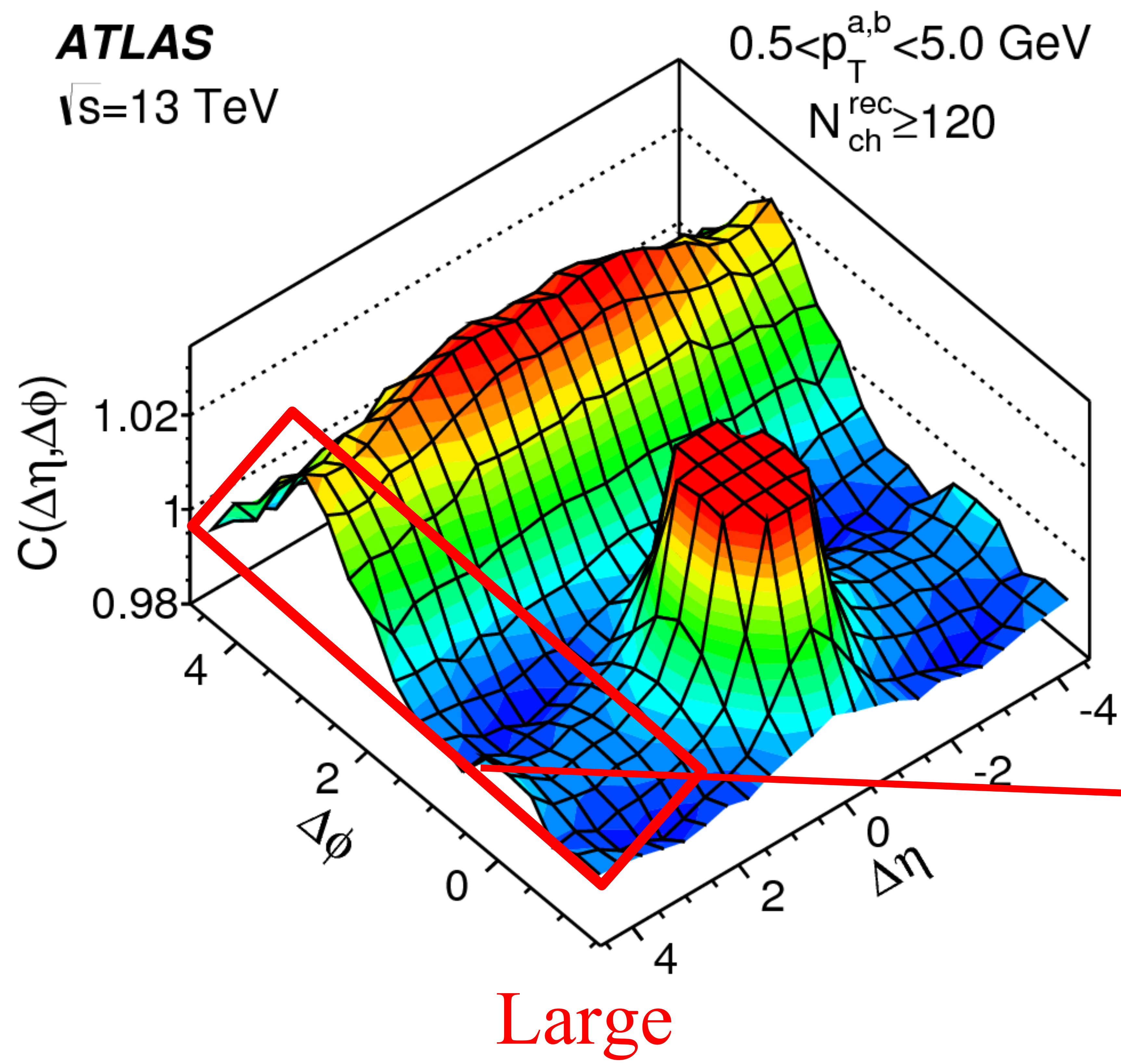
- Also similarities seen in d+A,^{3}He+A anisotropy measurements
- Reasonably well reproduced by Hydro models

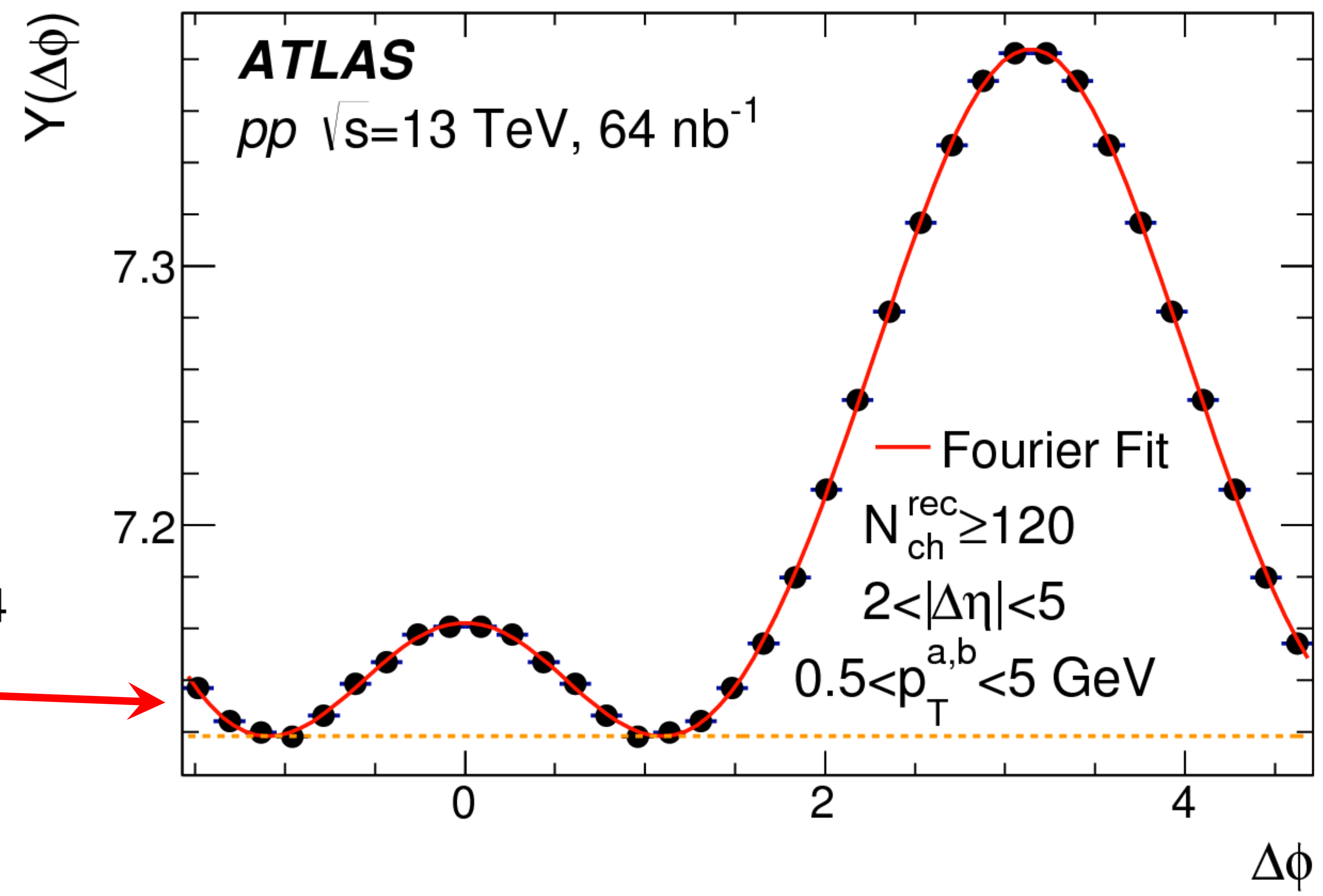
p+Pb: Very similar to Pb+Pb



- Azimuthal anisotropy measurements via multi-particle cumulants
- Similar behavior in p+Pb and Pb+Pb
  - $v_2\{2\}>v_2\{4\}\sim v_2\{6\}\sim v_2\{8\}$
- Many other measurements : mass ordering, constituent-quark scaling

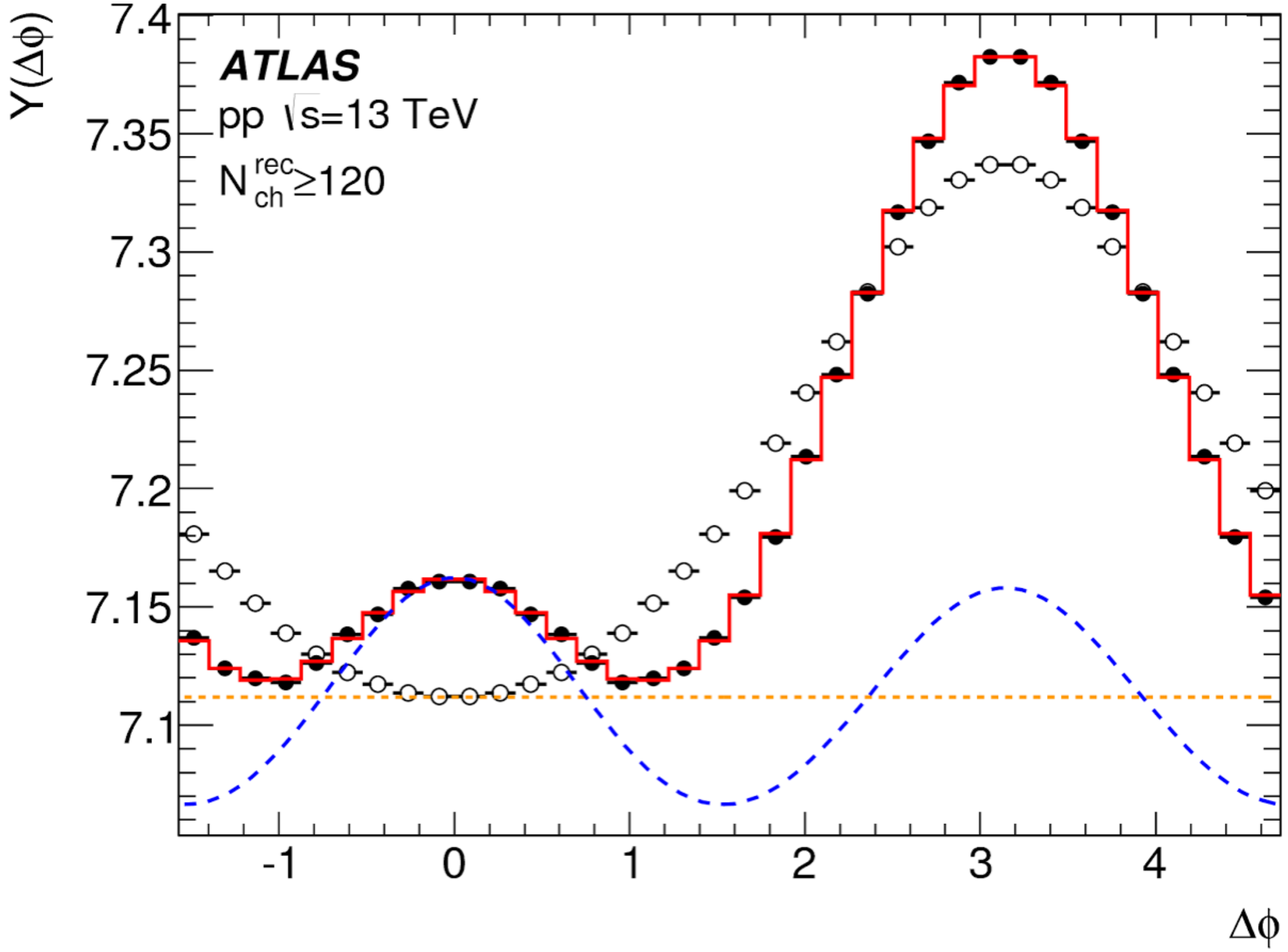
Analysis of 2PCs in pp collisions





- First step: look at long-range correlation component |Δη|>2
  - Removes near-side jet peak: same as what is done in A+A collisions
- Still dominated by away-side jet.
- Need new method to extract ridge signal.

Analysis technique: Template Fitting Procedure

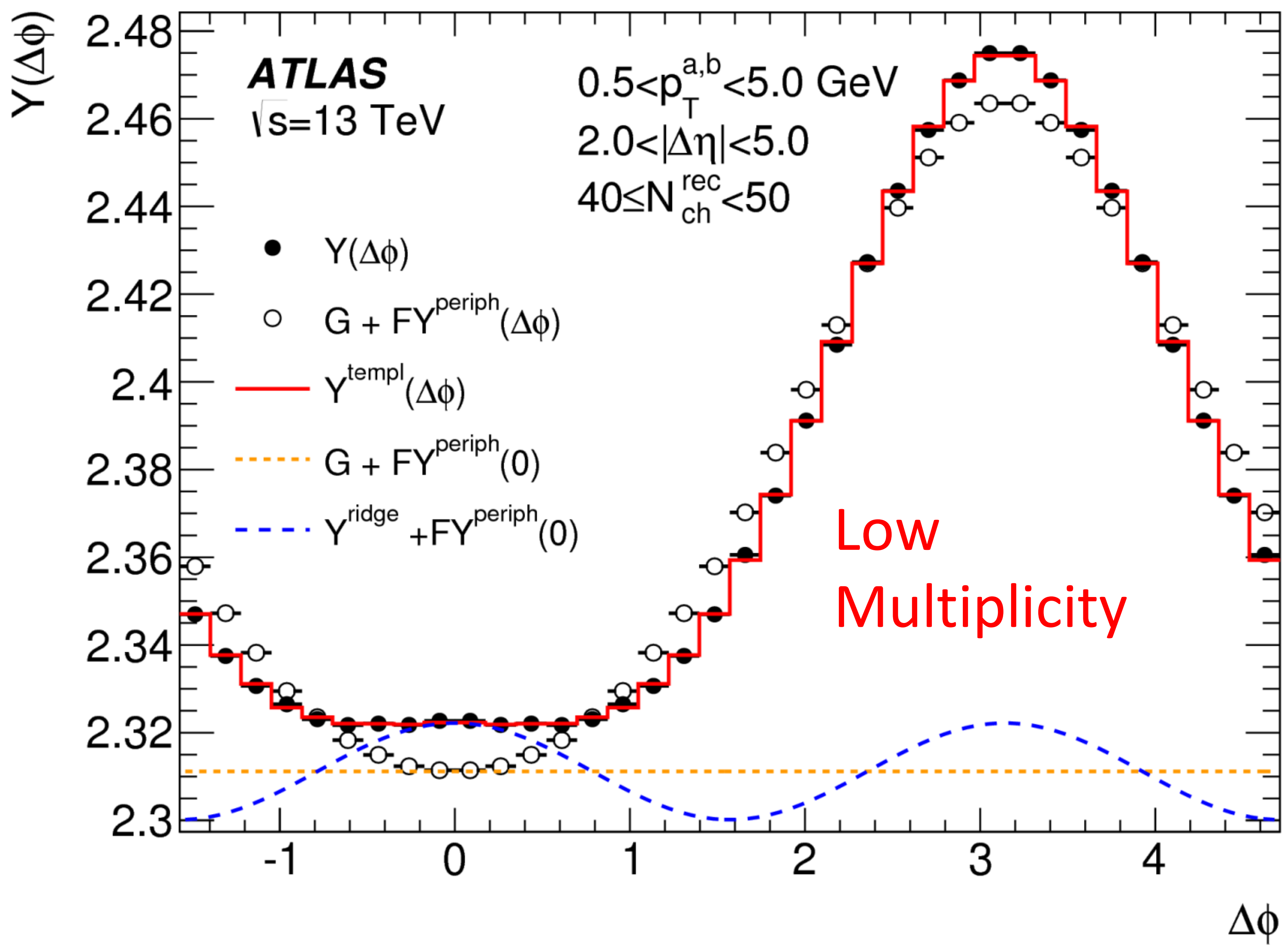


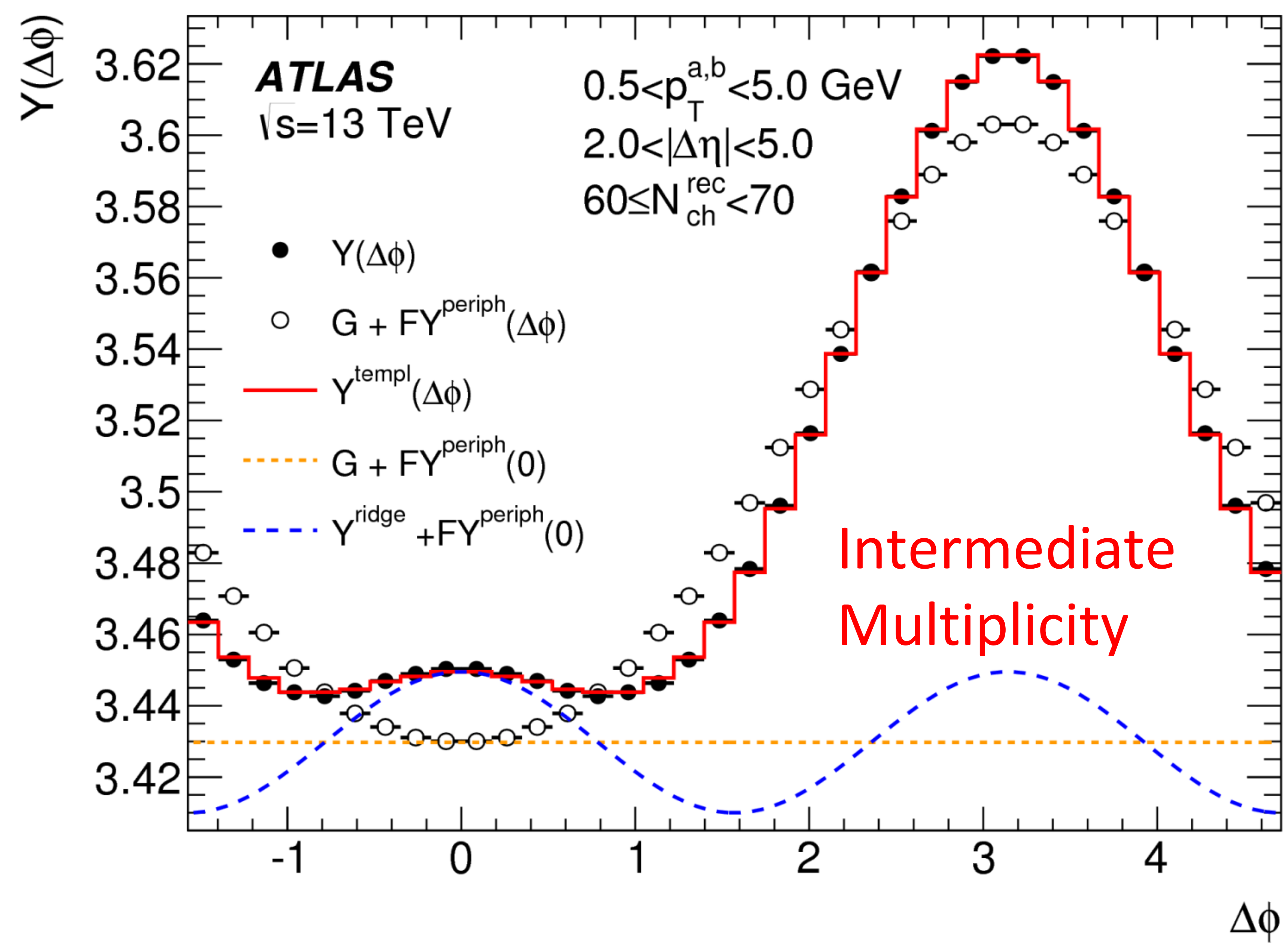
$$Y^{\mathrm{templ}}(\Delta\phi) = F\,Y^{\mathrm{periph}}(\Delta\phi) + Y^{\mathrm{ridge}}(\Delta\phi),$$
$$Y^{\mathrm{ridge}}(\Delta\phi) = G\,(1 + 2v_{2,2}\cos(2\Delta\phi))\,,$$

- A template fitting procedure used to extract long-range correlation

- Fit the correlation in high multiplicity events with Template of two components:
  - Y^{periph}: Correlation in peripheral events (N_{ch}<20)
  - Y^{ridge} : Pedestal*(1 +2v_n^2cos(nΔφ)) signal

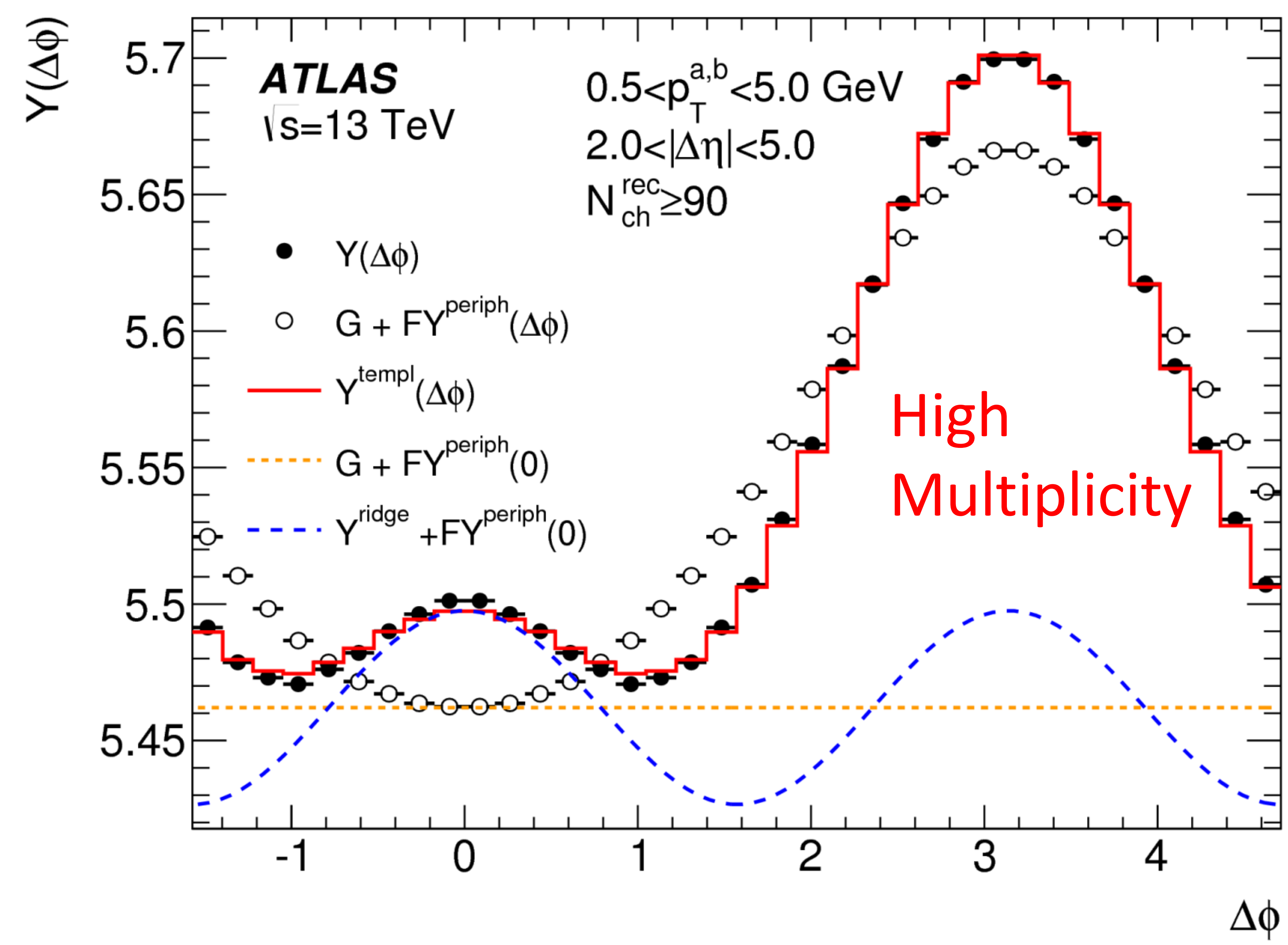
Template Fitting : Multiplicity dependence



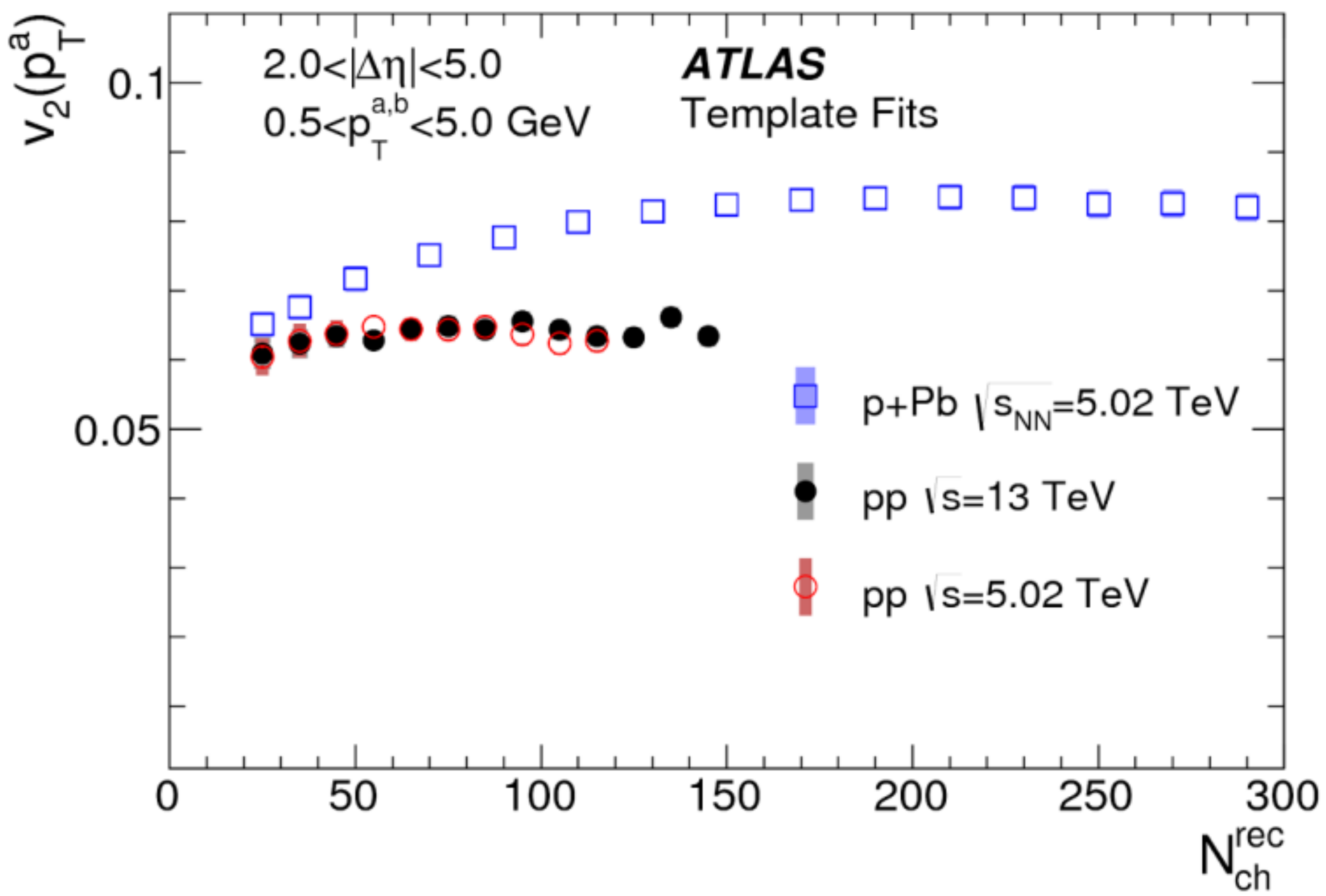


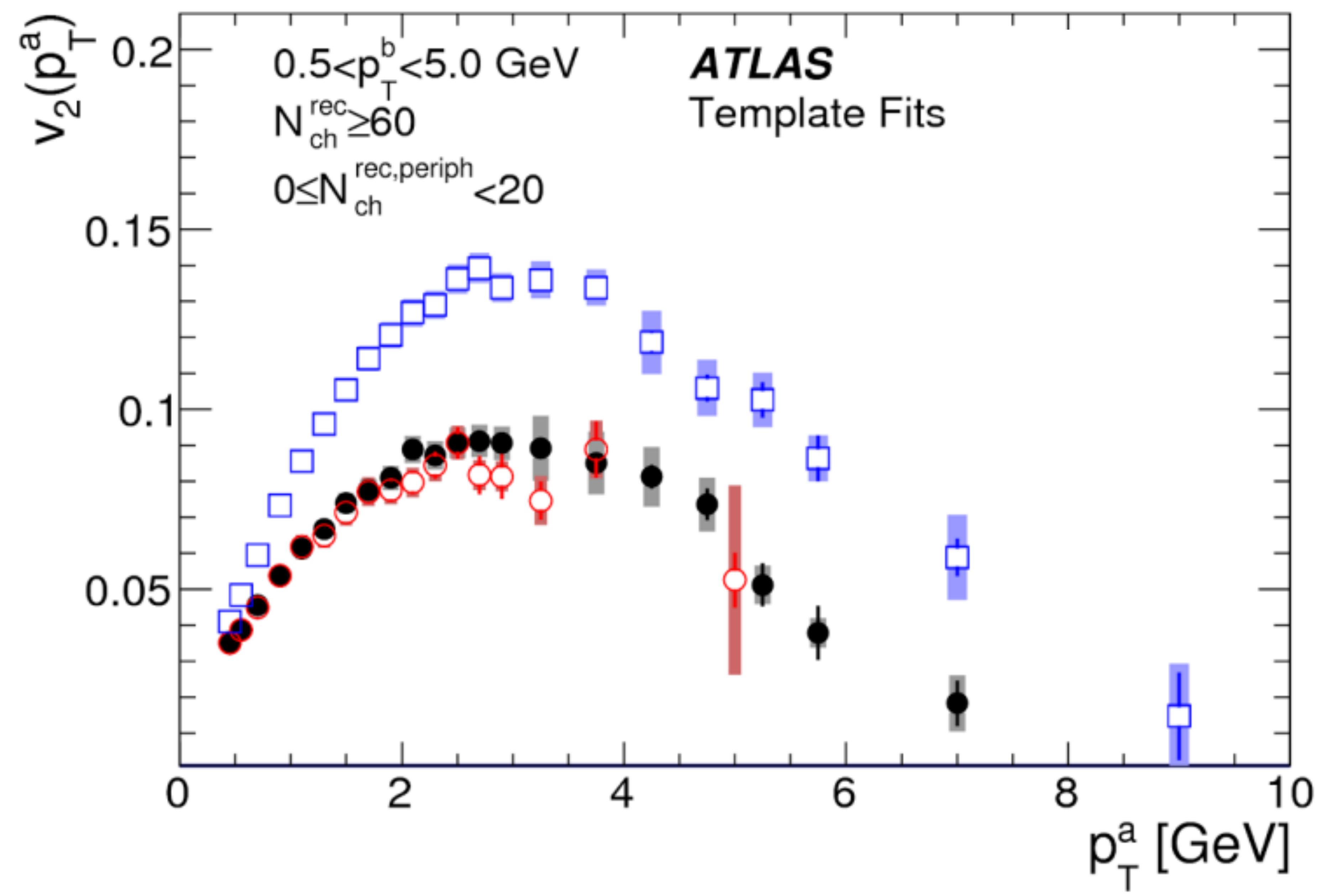
Considerable long-range correlation even in low & intermediate multiplicity events.

Broadening of away-side and emergence of peak on near-side well described.



Comparison of systems & energies : pp and p+Pb

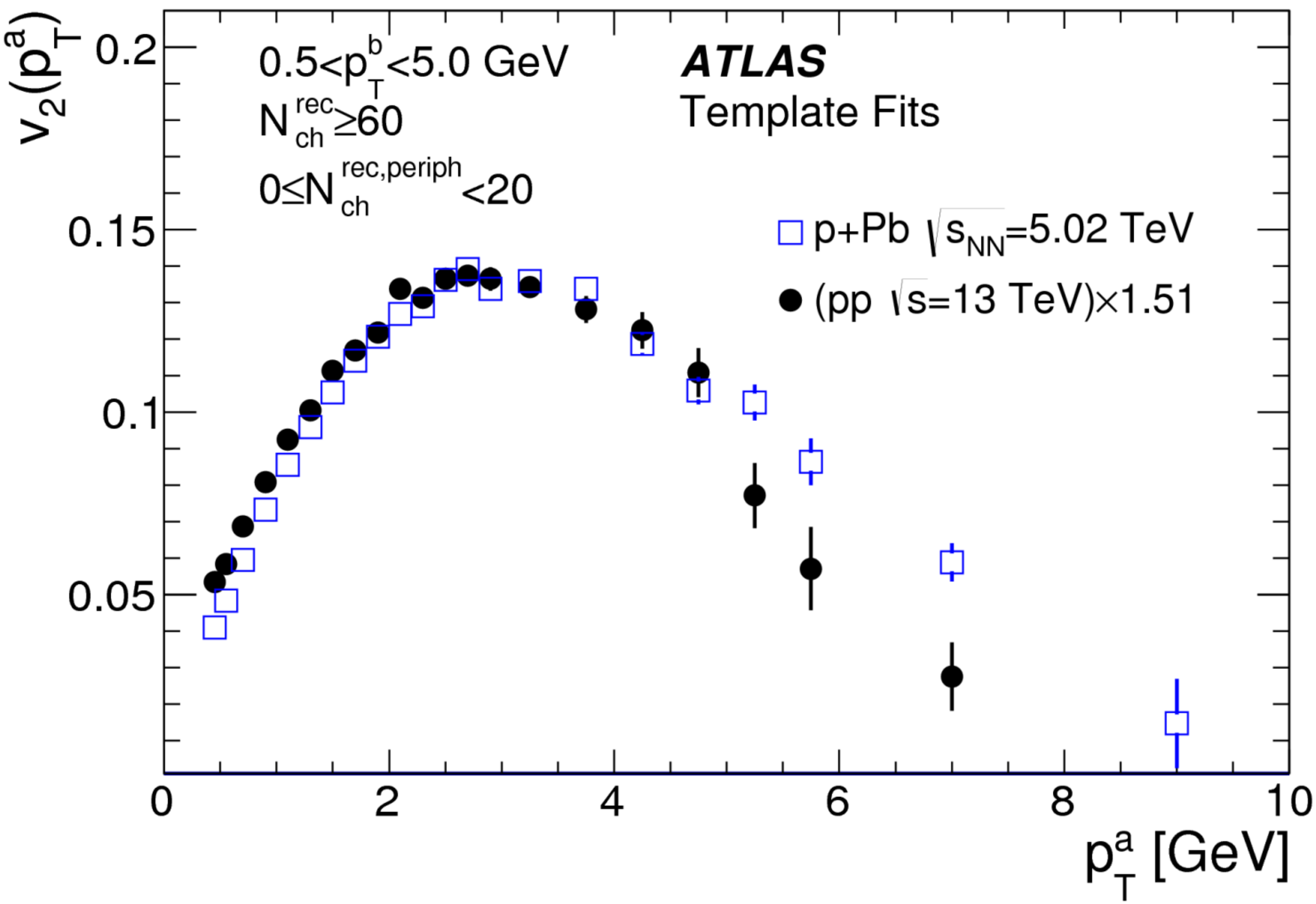




- Only a weak dependence on multiplicity seen for pp v_2
- For p+Pb clear multiplicity dependence is seen for v_2
- p+Pb v_2 is larger than pp v_2.

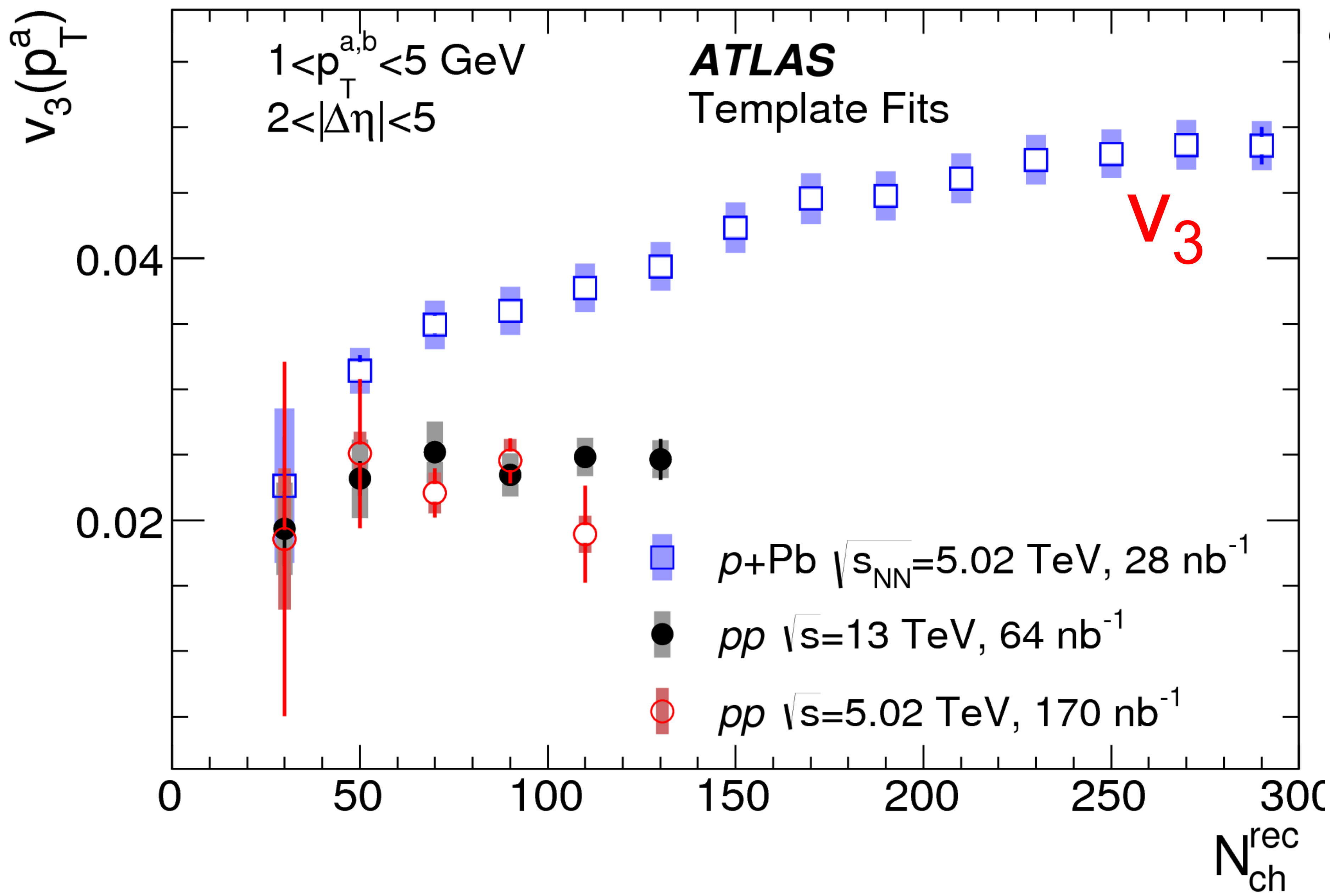
- Consistent values for v_2 between 5.02 TeV and 13 TeV pp collisions.
  - No dependence of v_2 on collision energy

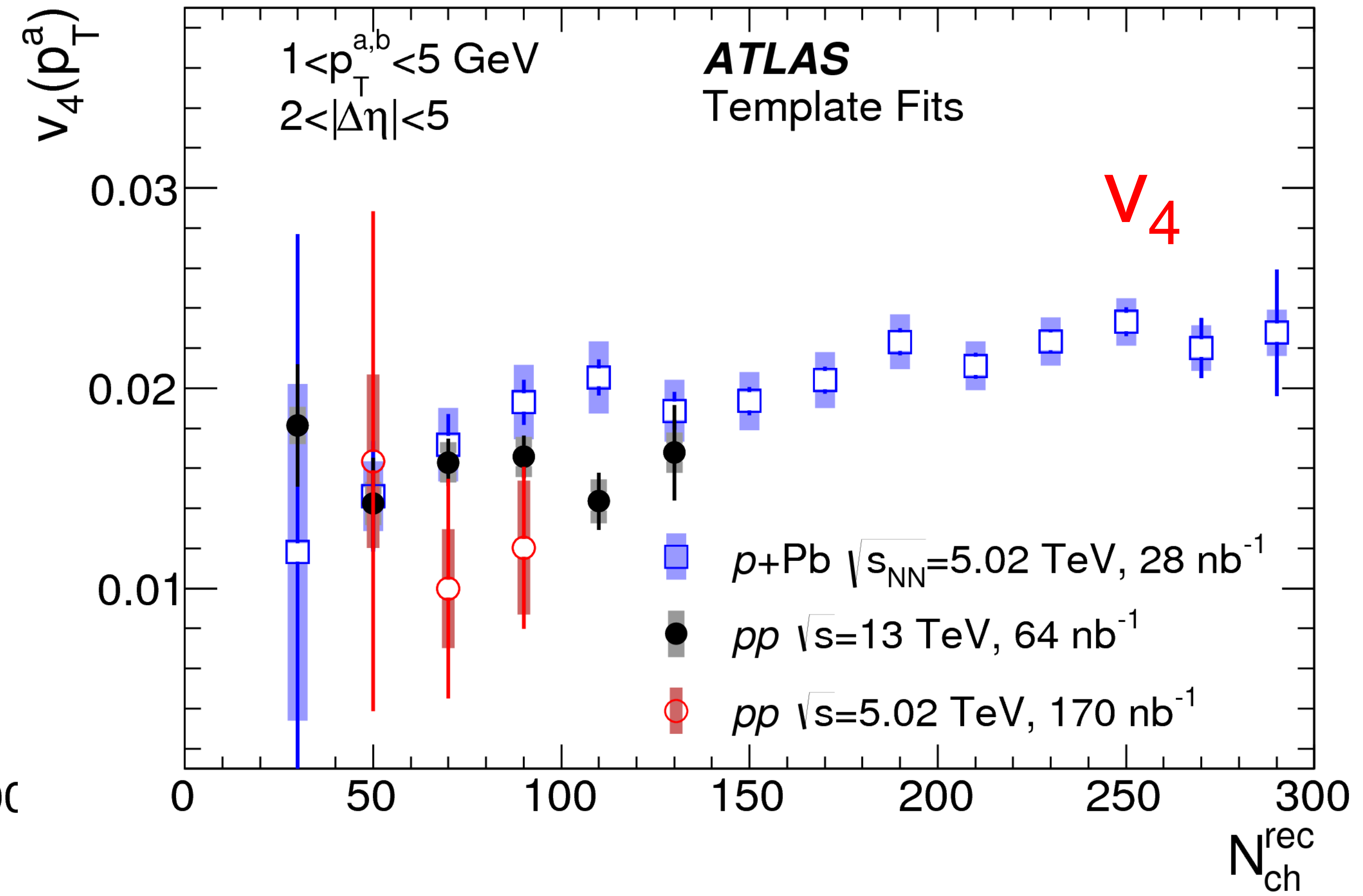
Shape of $v_2(p_T)$ in pp and p+Pb



- Very similar shape of $v_2(p_T)$ between pp and pPb
- At higher p_T, pp v_2 decreases faster
  - possibly larger contribution from hard processes?

Comparison of systems & energies : higher order v_n



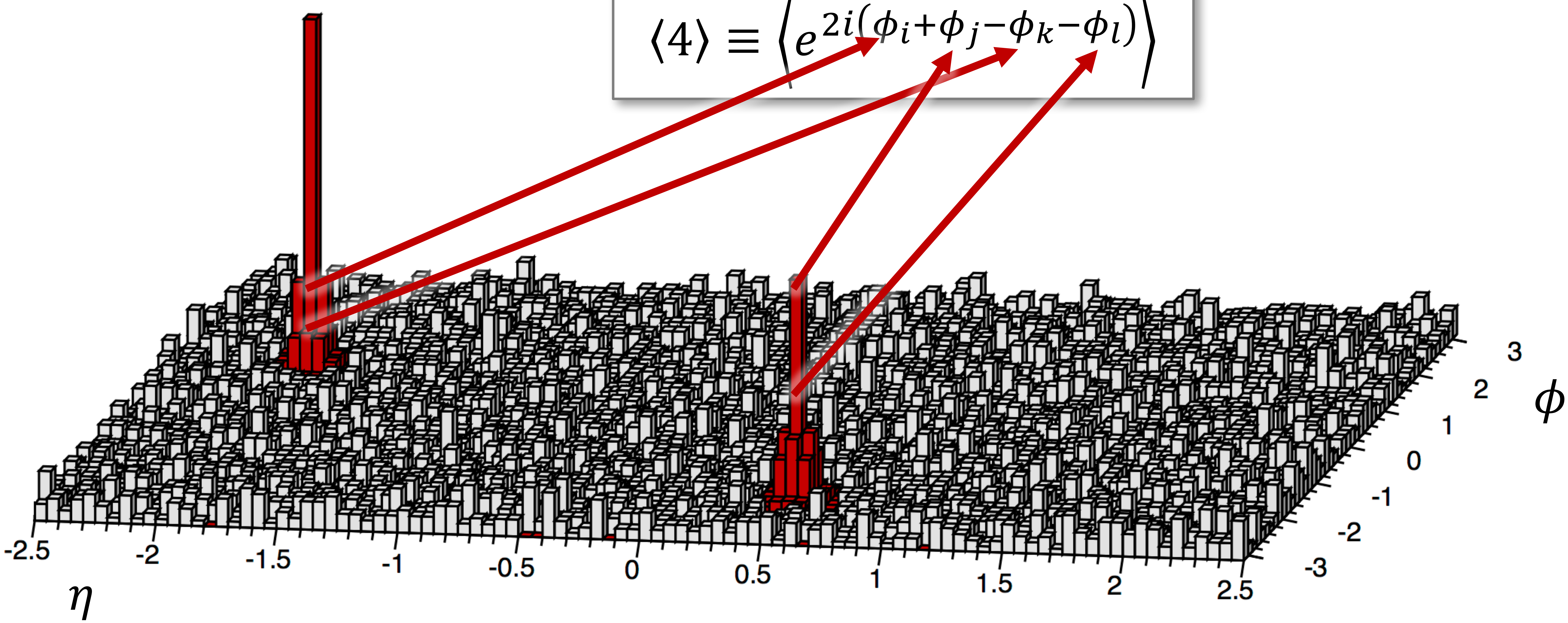


- Comparison for higher order harmonics: v_3 and v_4
- No multiplicity dependence seen in all *pp* v_n.
- Consistent between 5.02 and 13 TeV results

What about multi-particle cumulants?

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

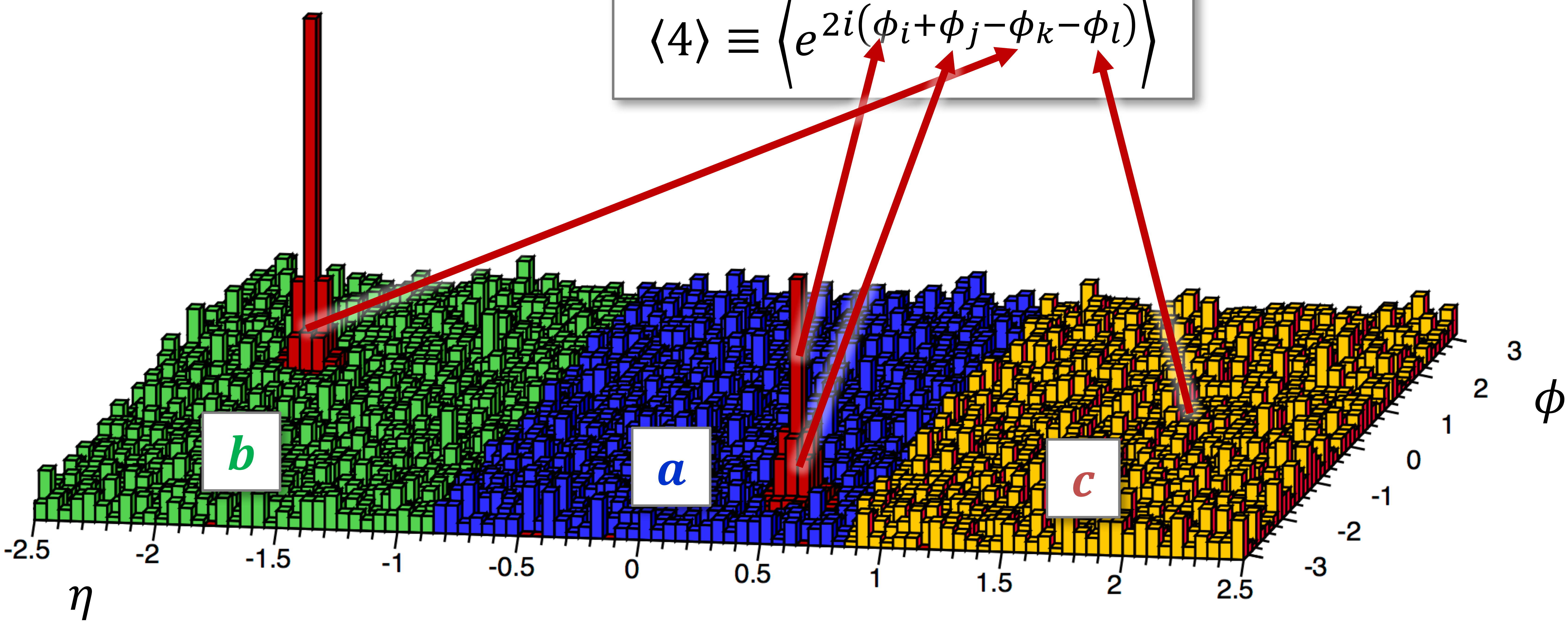
$$\langle 4\rangle \equiv \left\langle e^{2i(\phi_i+\phi_j-\phi_k-\phi_l)}\right\rangle$$



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

Subevent cumulants

- 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:



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

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

[arXiv: 1701.03830]

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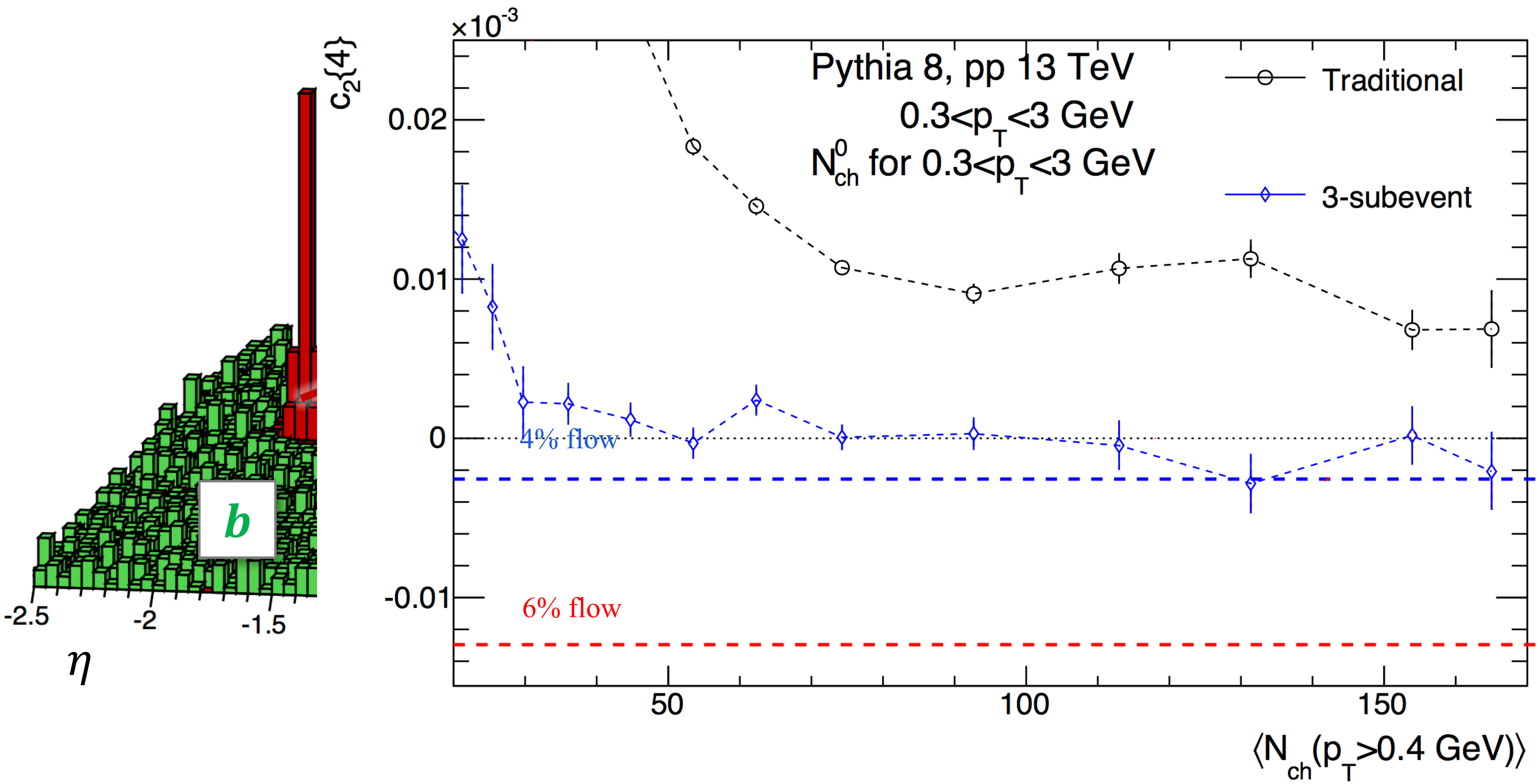
- New method validated in PYTHIA



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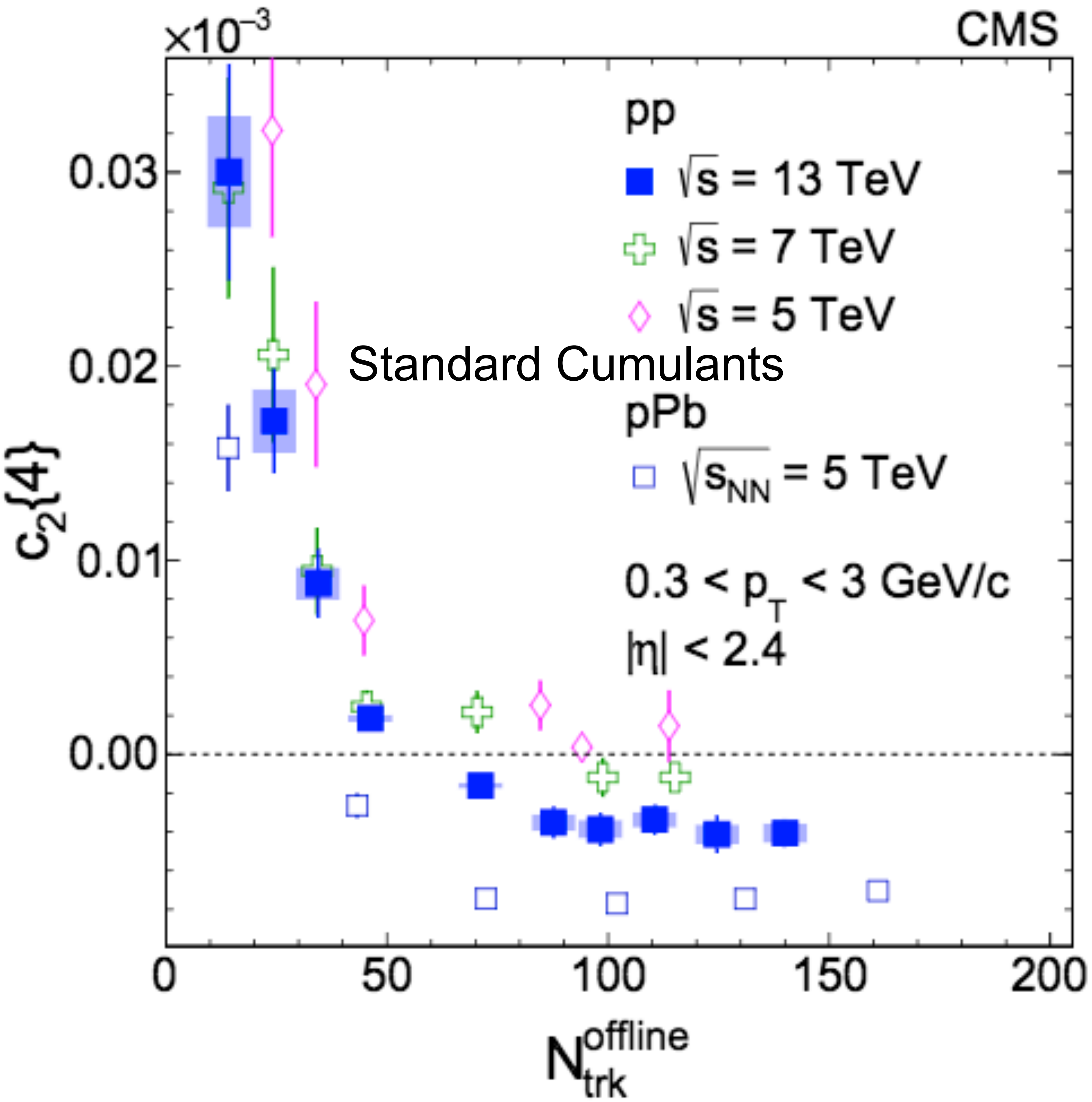
Cumulants: Energy dependence



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  - No such dependence was seen in the Template (or 2PC) v_2
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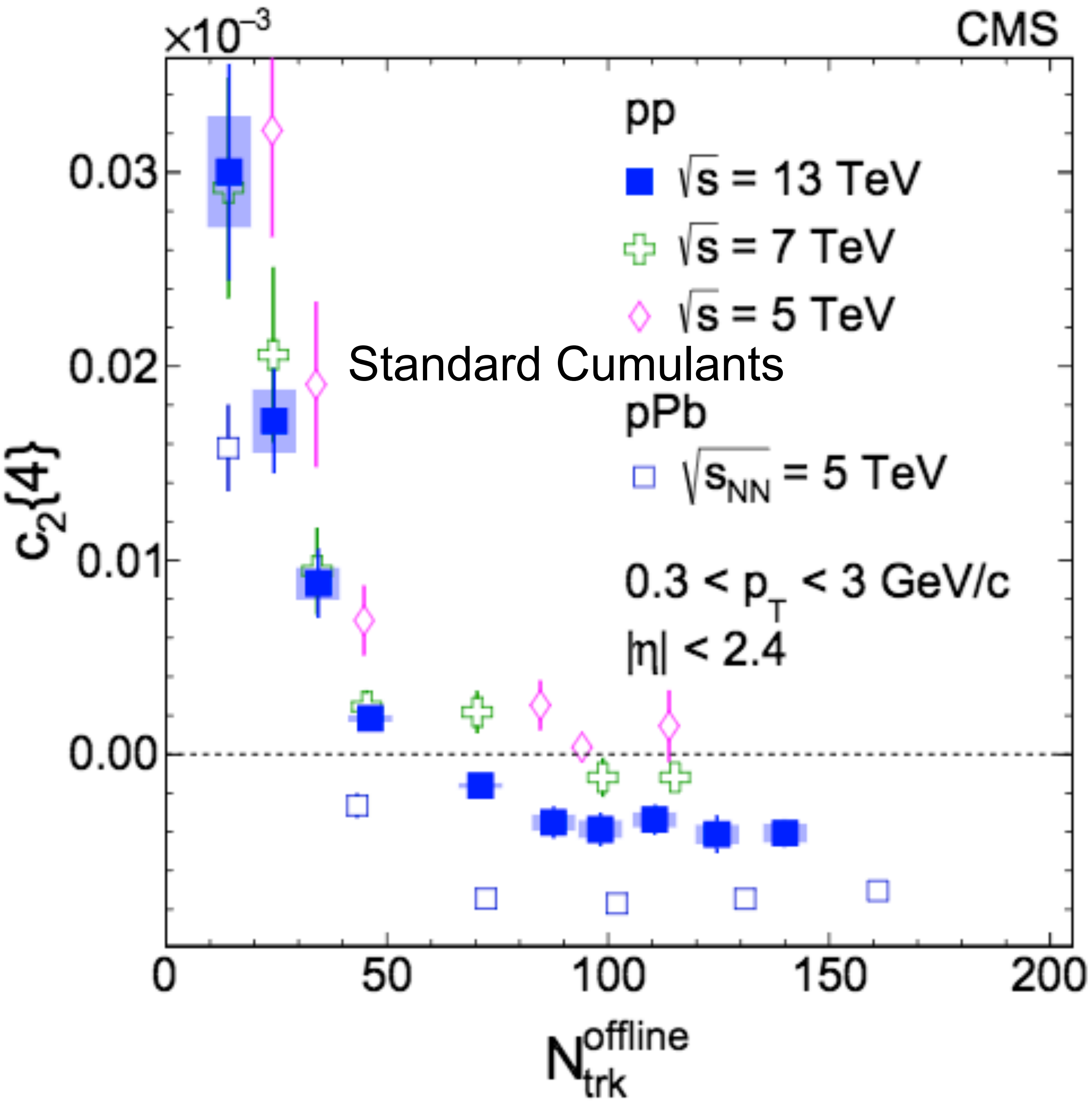

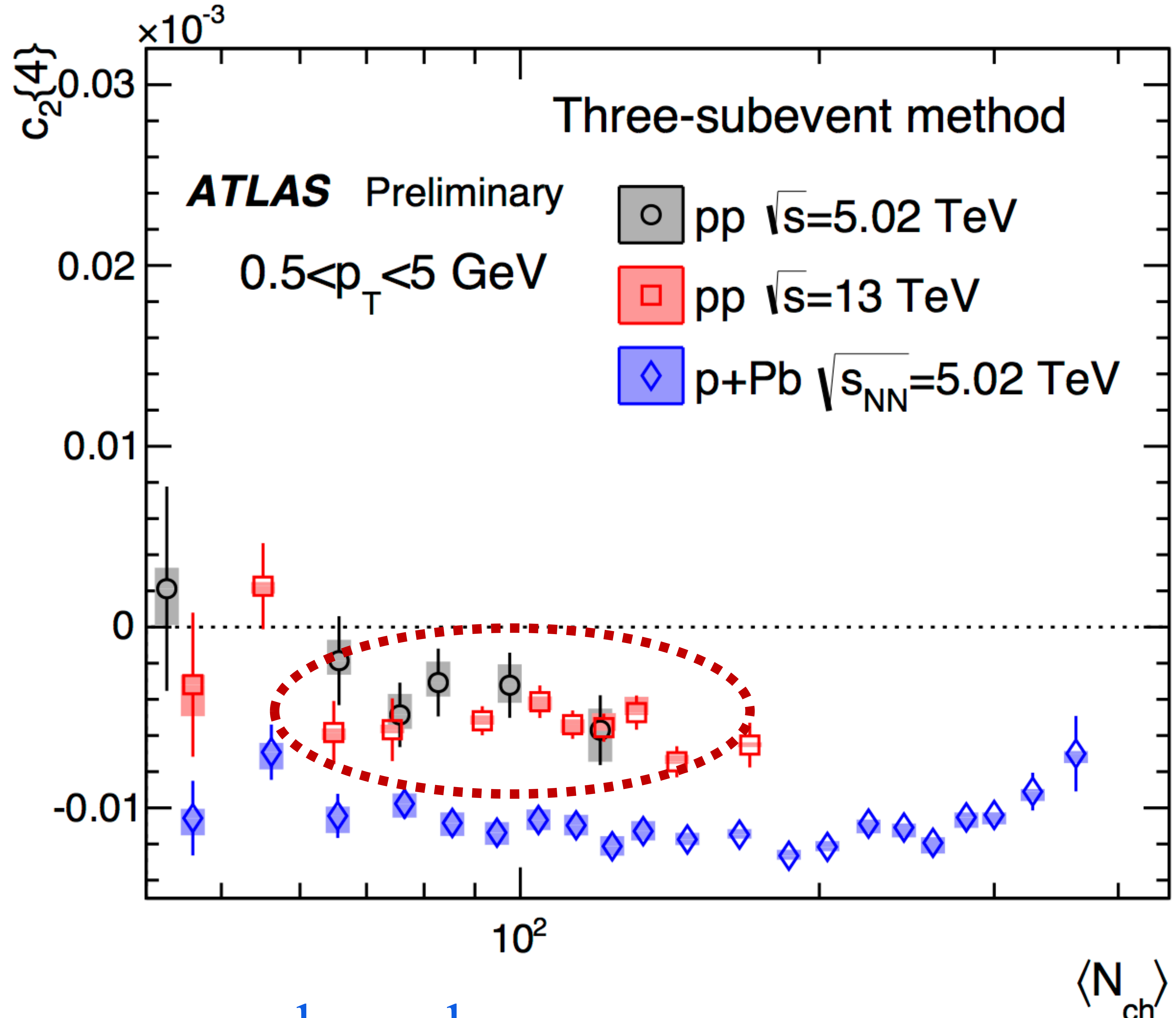

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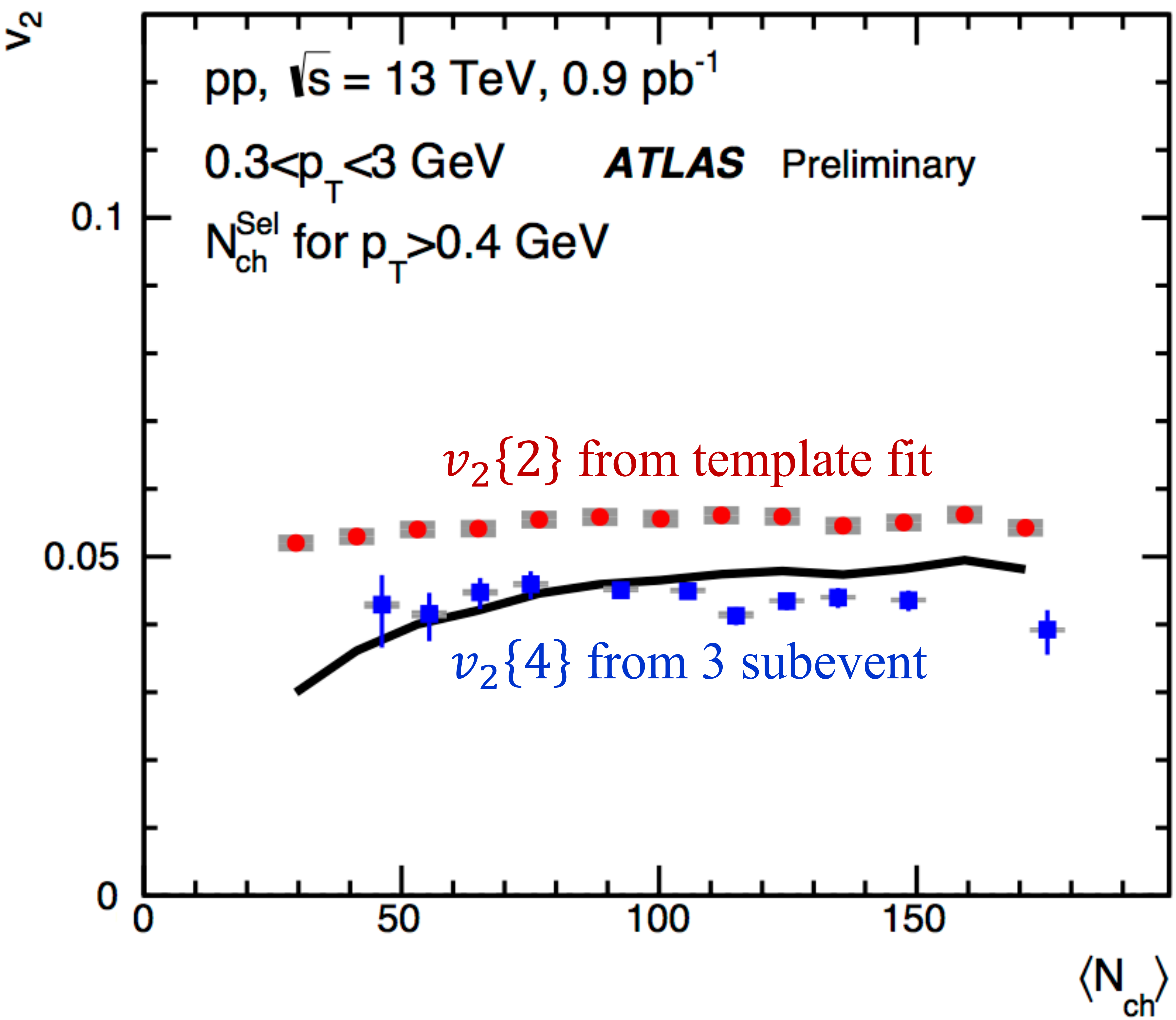
  - No such dependence was seen in the Template (or 2PC) v_2
  - $c_2\{4\}$ is +ve at 5TeV
- With 3 subevent, negative $C_2\{4\}$ observed in 5.02 TeV *pp*;
- Weak energy dependence in *pp* restored.
- *p*+Pb has larger flow than *pp* in the comparable N_{ch} region;

pp $v_2\{4\}$: Multiplicity dependence

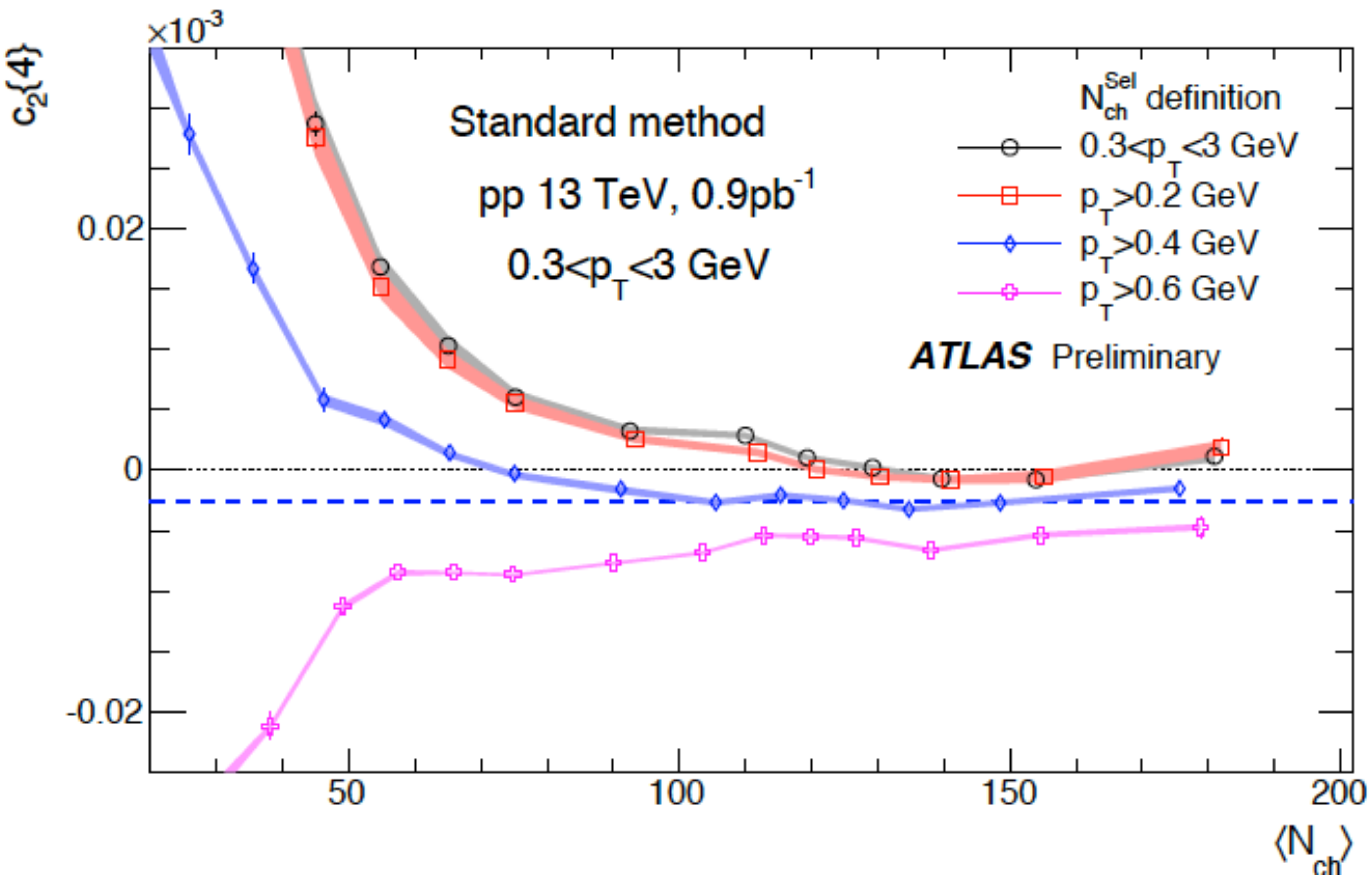


- $v_2\{4\}$ consistent with no. multiplicity dependence (For $N_{ch}>50$)
- $v_2\{4\} < v_2\{2\}$ (template fit): flow fluctuation;

Summary-I : Experimental perspective

- Jet/dijet correlation removal is the critical step in interpreting pp collisions

- Standard cumulant measurements not capable of removing non-flow
  - Can not be blindly used in pp collisions (PYTHIA non-closure)
  - Multiplicity fluctuations mimic correlation



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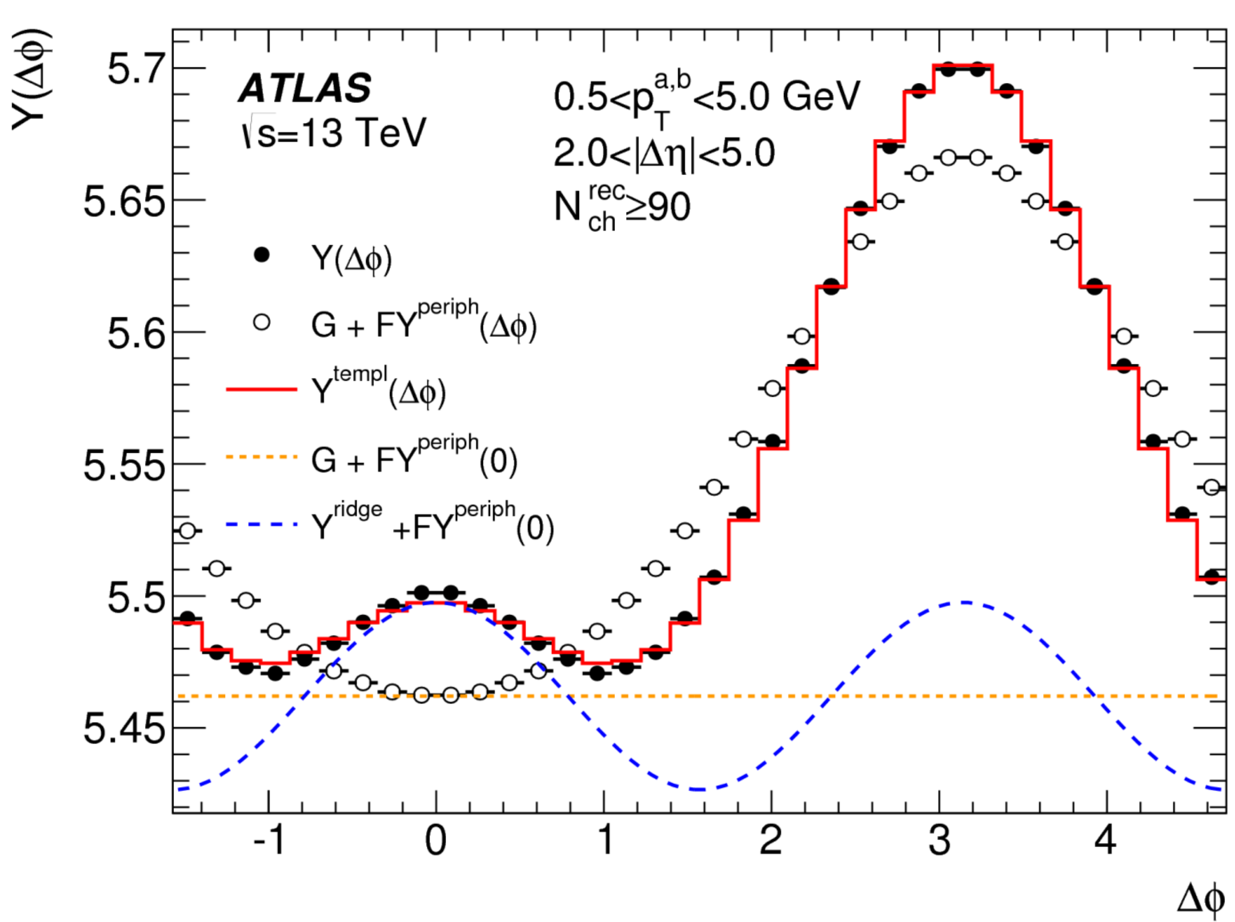
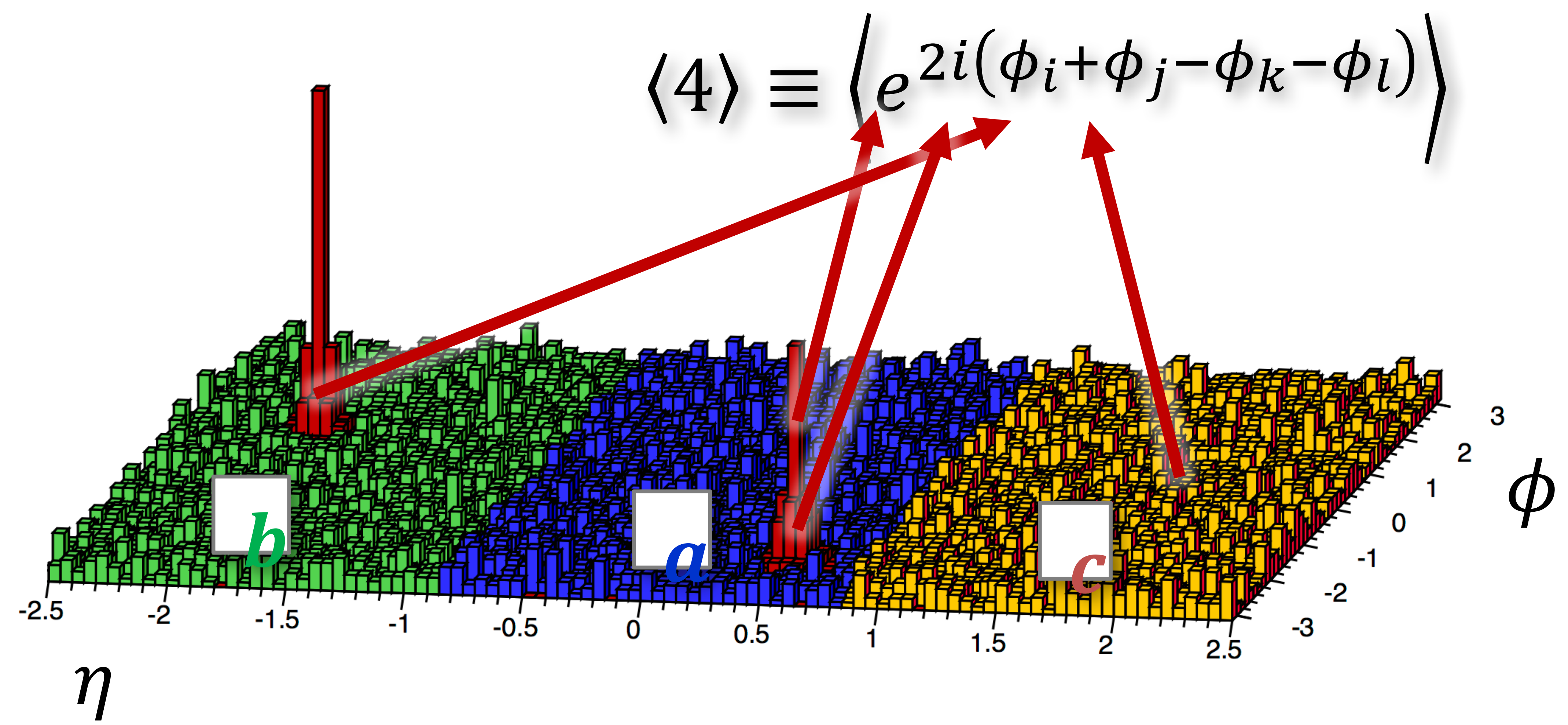
- Non-flow removal
  - Sub-event cumulants
  - Template fitting in 2PC





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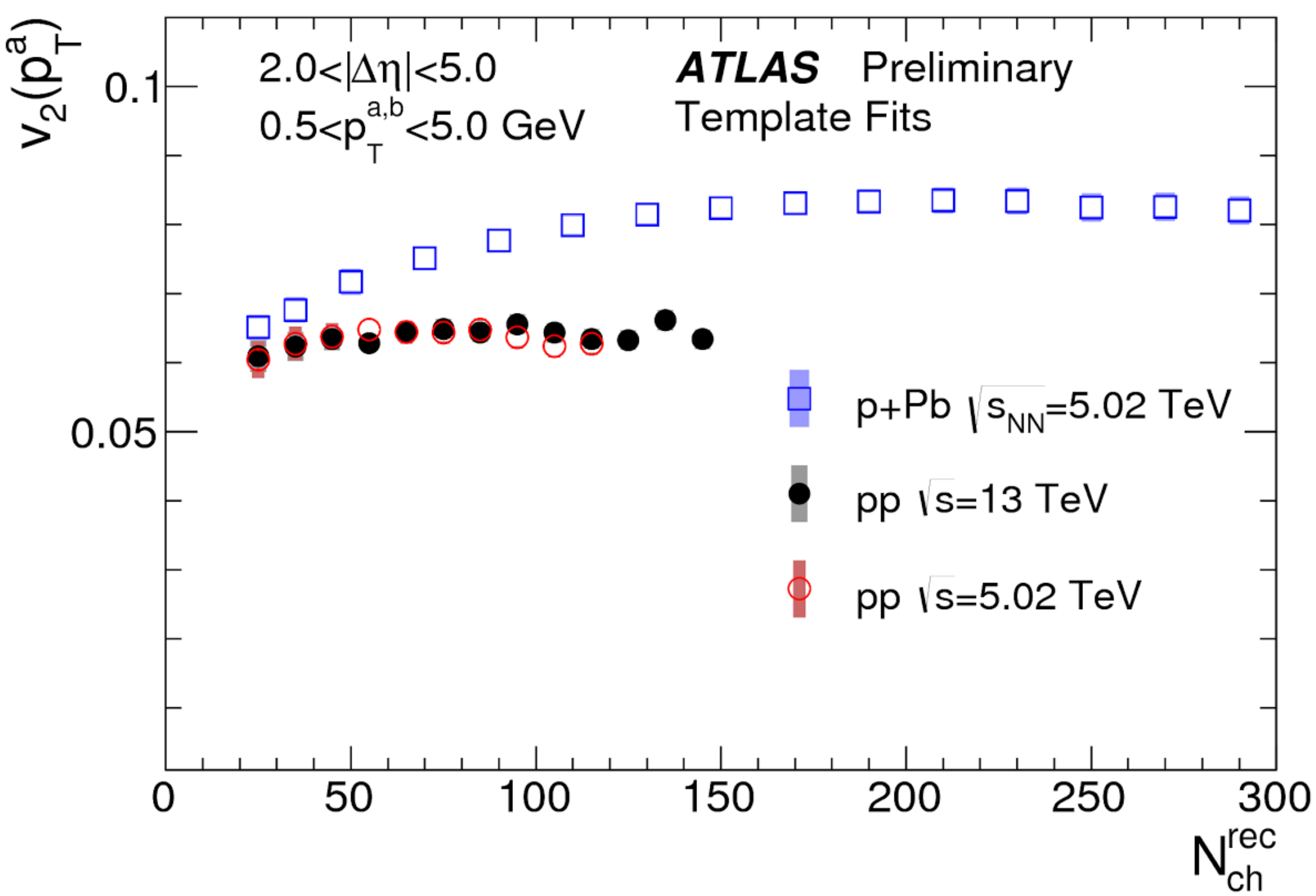

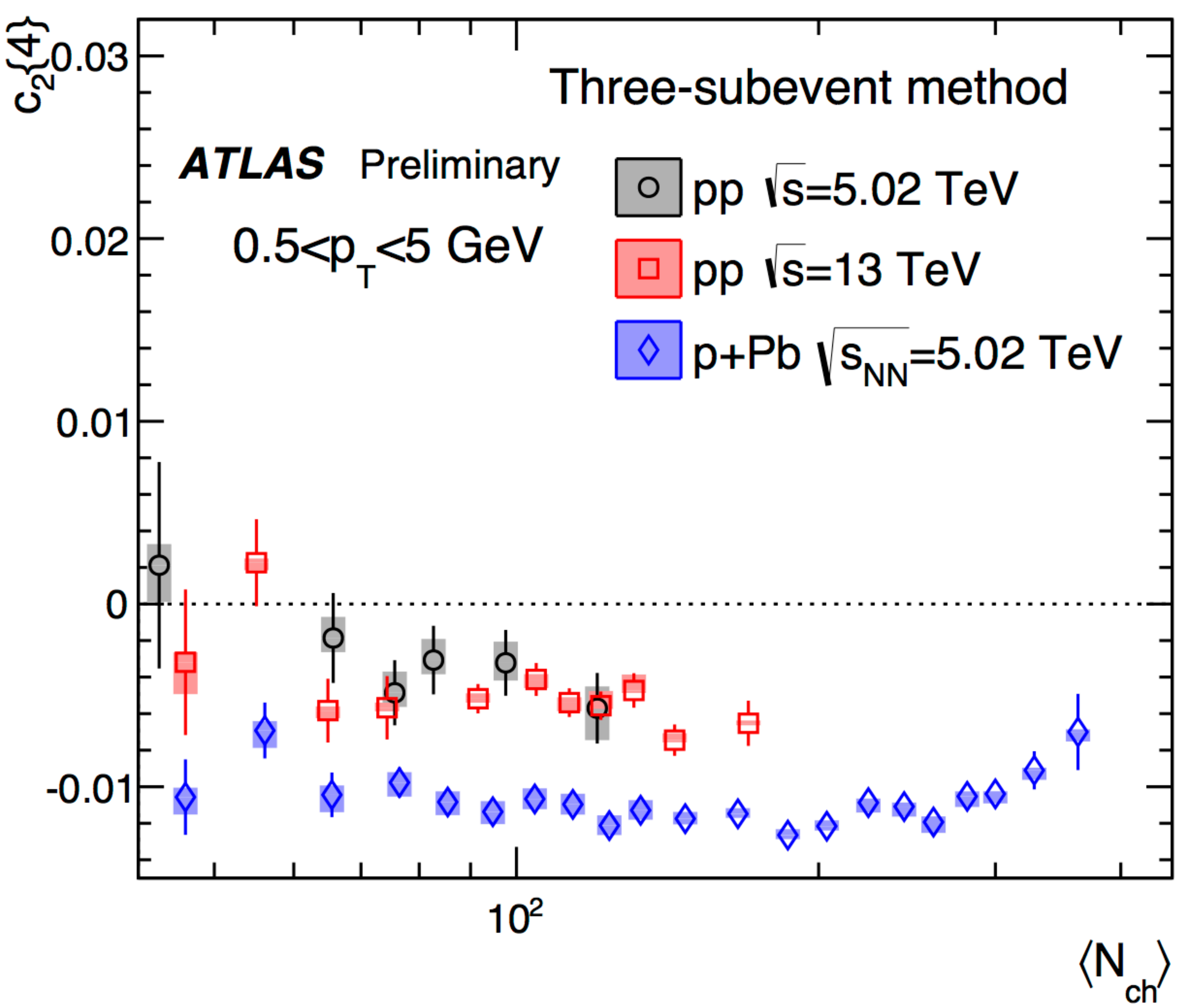

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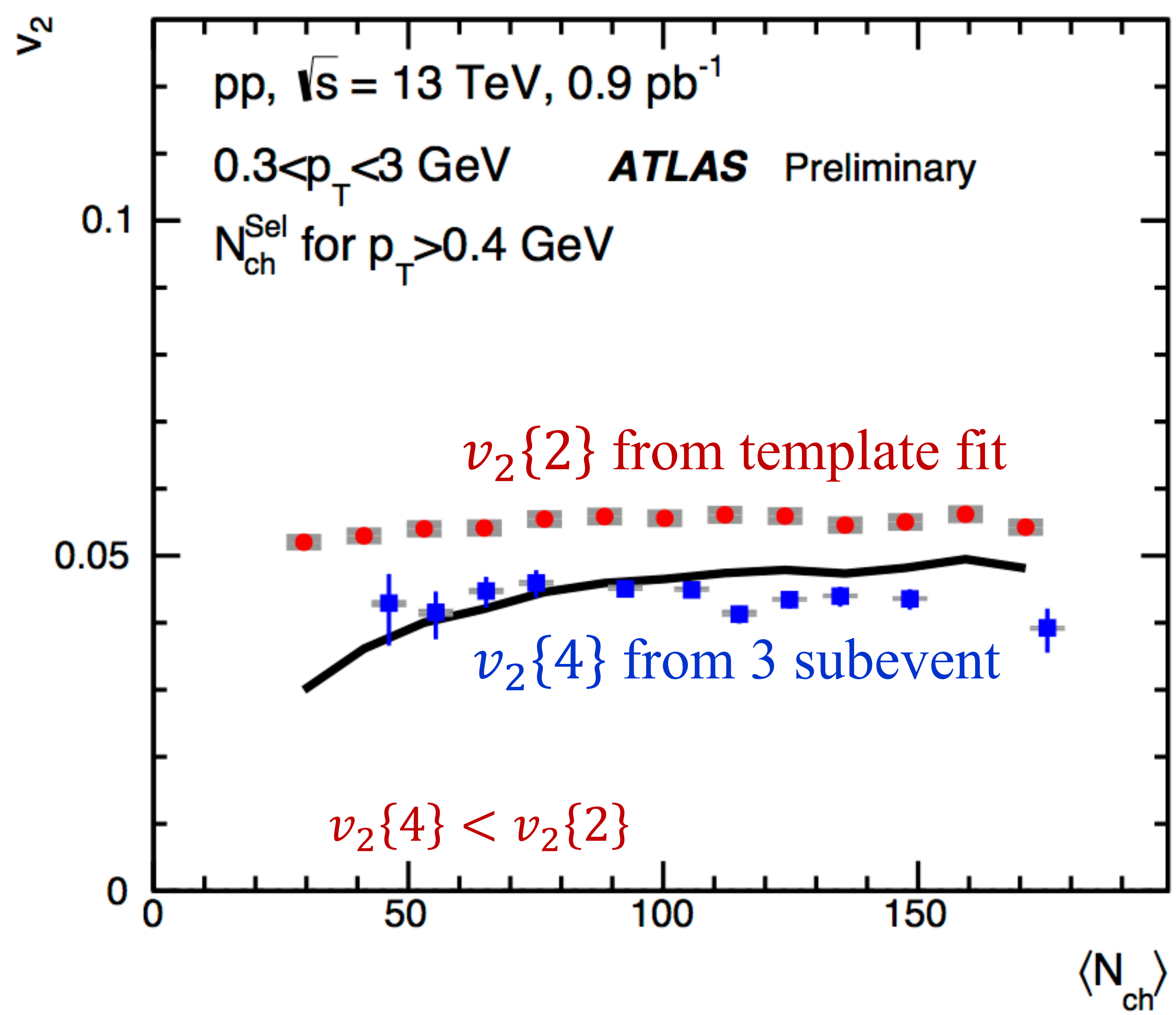

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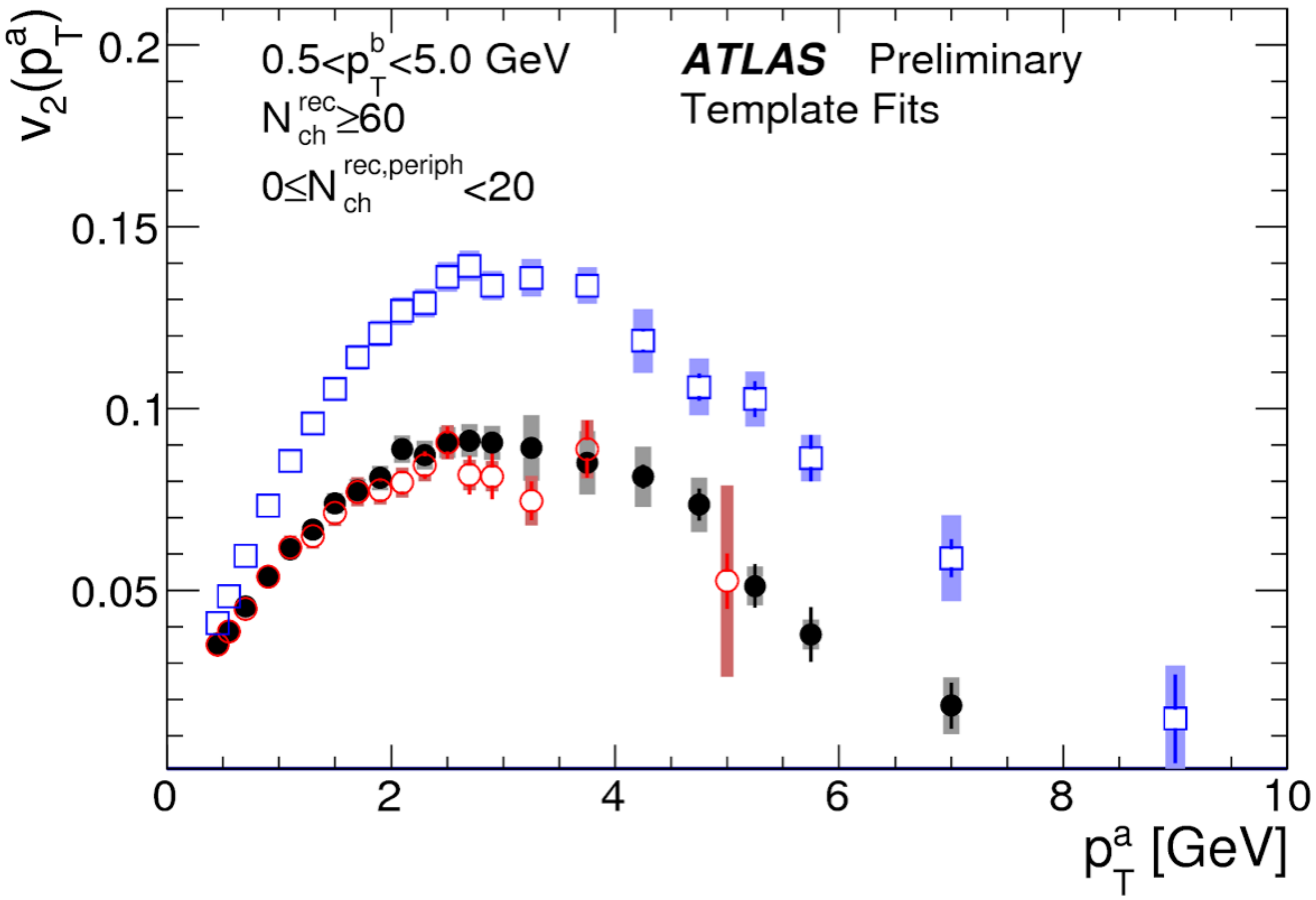

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  - $v_2\{4\}<v_2\{2\}$
  - Event by event v_2 fluctuations
- p_T dependence qualitatively similar between AA, p+Pb and pp collisions
- Global nature of collision does not imply hydrodynamic behavior
  - Energy, multiplicity dependence and fluctuations may be key to understanding origin
  - Relics of measurement technique may still be present!

Backups

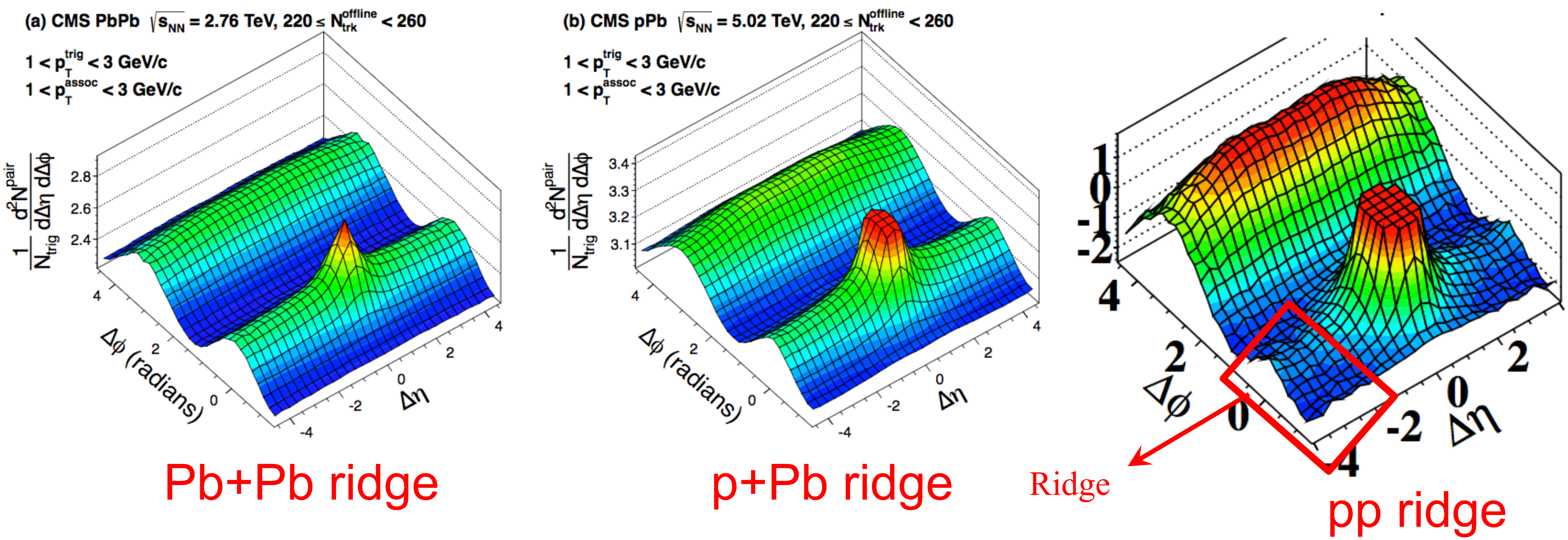
Large set of new measurements in pp (and p+Pb)

- Two particle inclusive hadron-hadron correlations
  - Account for the "jet"-contamination to 2PCs
  - First successful extraction of v_n harmonics.
  - Detailed p_T, and multiplicity and energy dependence of long-range correlations

- Multi-particle cumulants
  - In principle suppresses correlations: works well for p+A and A+A collisions
  - Will show that it can not be trusted at the typical pp multiplicities
  - Multiplicity fluctuations can mimic correlation signal

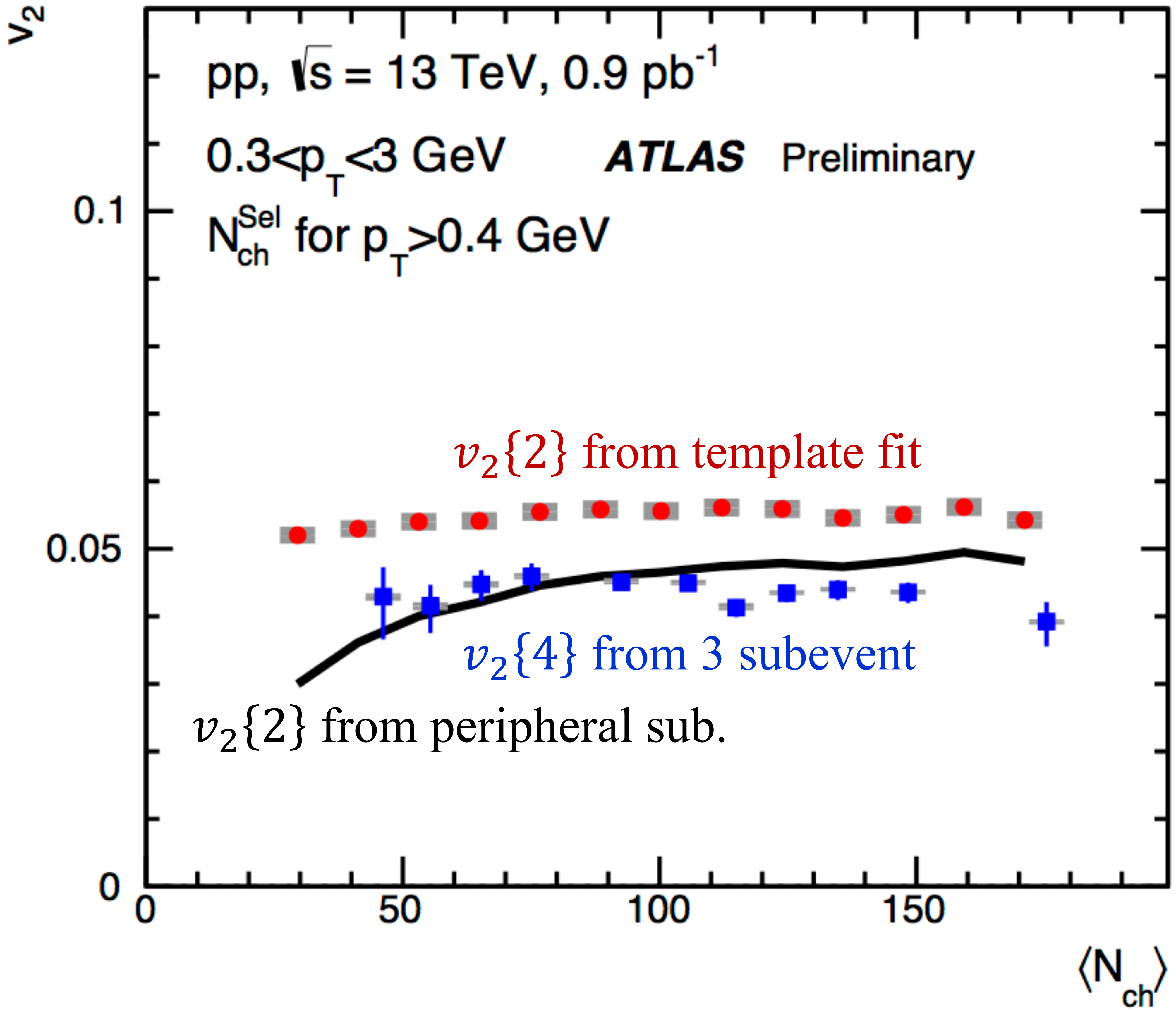
- Sub-event cumulants
  - Much less susceptible to jet/dijet correlations
  - Can be trusted for measuring correlation in *pp* collisions, except at very low multiplicities

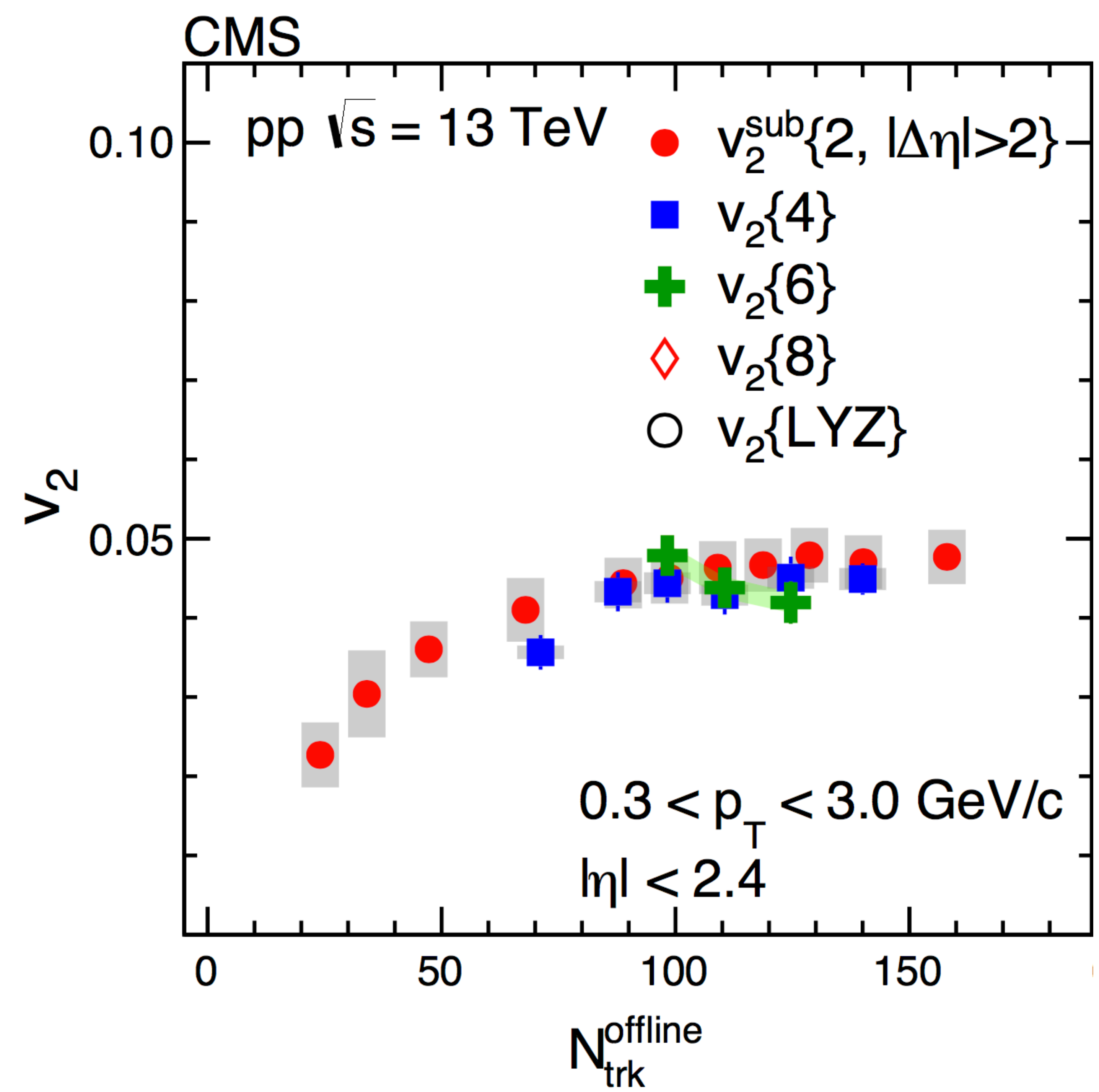
Ridges in Pb-Pb, p-p and p+Pb



- Two-particle correlations show long range correlation structure along $\Delta\eta$ at $\Delta\phi=0$.
- Is there an effective mechanism that rules them all? Is it initial state effect, final state effect or both?
- Final state effect may not imply hydro.
- Is there an away-side ridge in pp and pPb?
- What is its detailed p_T, η, and centrality dependence?

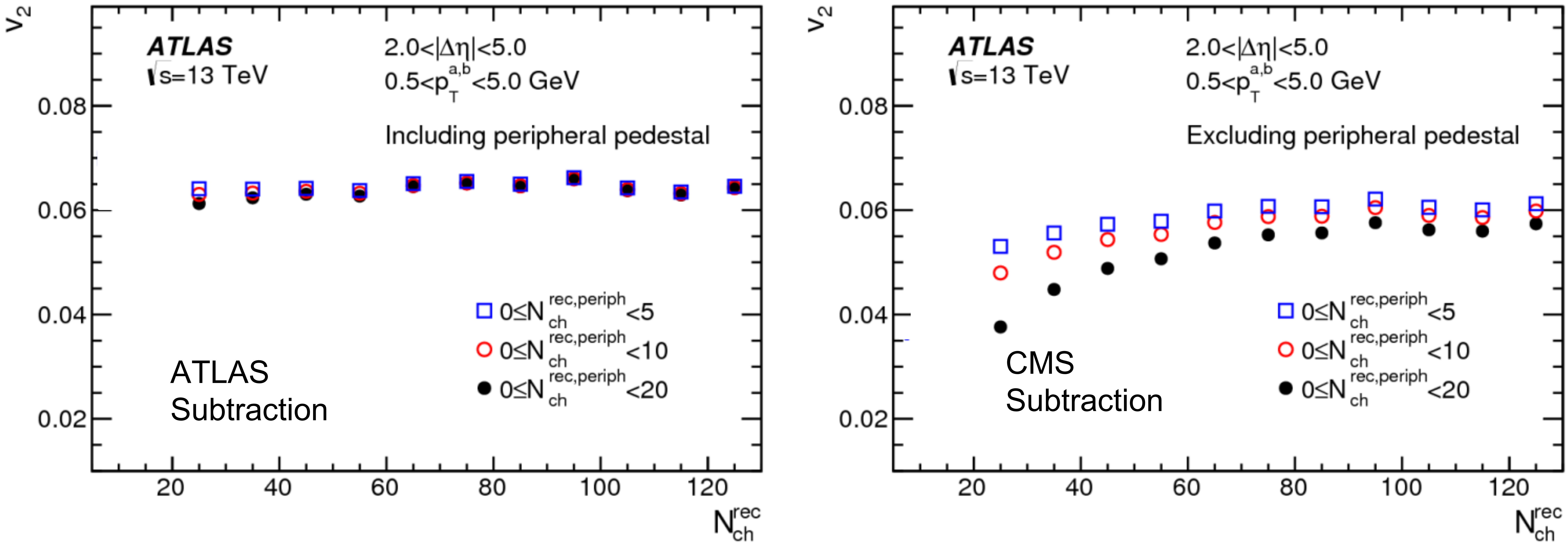
$v_2\{4\}$: Multiplicity dependence





- $v_2\{4\}$ consistent with no. multiplicity dependence (For $N_{ch}>50$)
- $v_2\{4\} < v_2\{2\}$ (template fit): flow fluctuation;
- $v_2\{4\} \approx v_2\{2\}$ (peripheral subtraction): underestimation of $v_2\{2\}$;

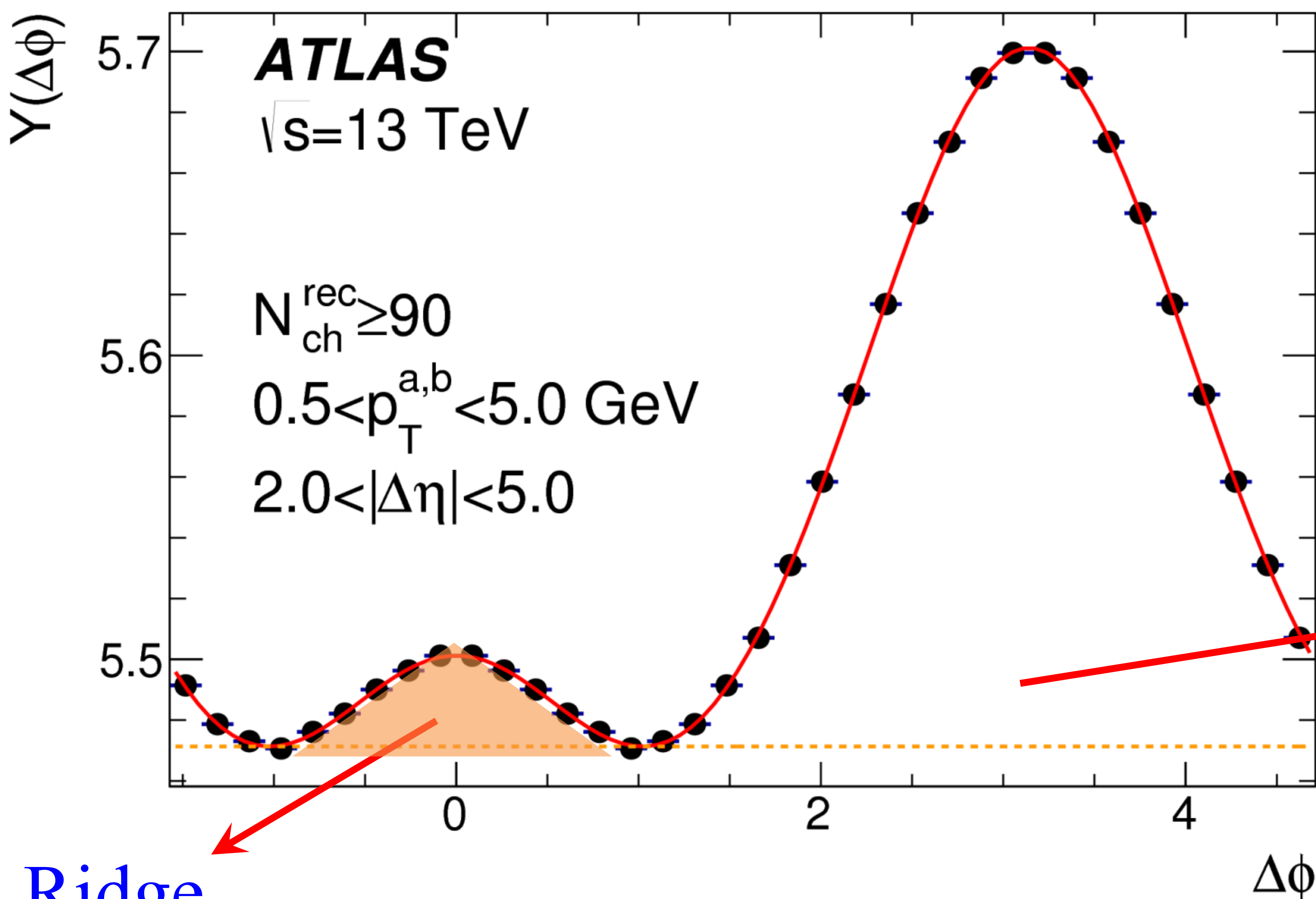
CMS-like subtraction



Template procedure assumes that the “jet” component of the long-range correlation in higher multiplicity is identical to that in lower multiplicity up to scale factor

Can test assumption by changing choice of low-multiplicity interval and repeating measurements.

Prior status of ridge measurements in pp



Previous measurements extracted the integrated yields on the near-side only.

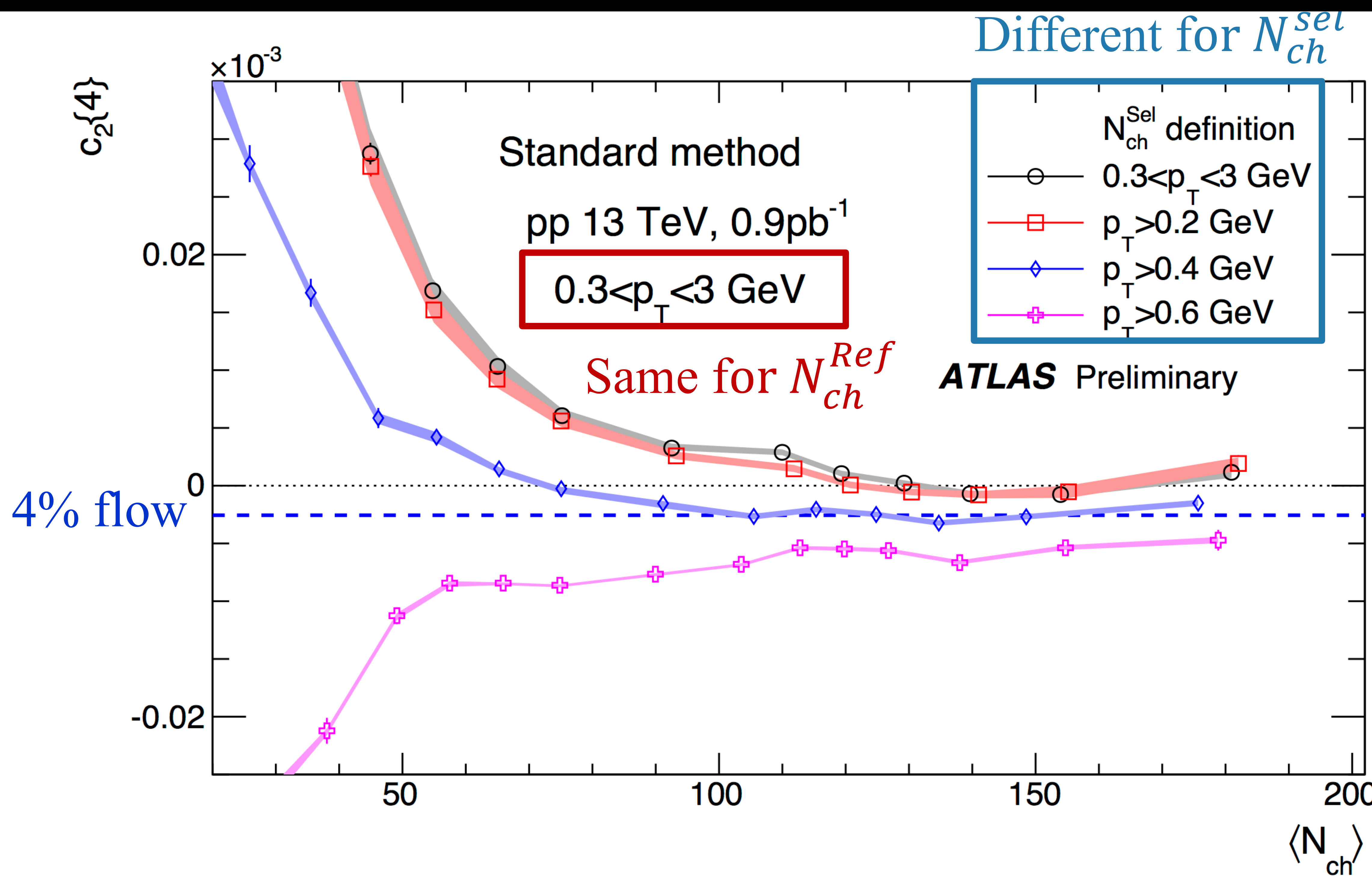
No idea if there are long-range correlations on away-side, hidden under the jet peak.

Ridge

No attempts made to study full Δφ dependence of long-range correlation

Ridge strength quantified by the (flawed) ZYAM procedure

Cumulants: Event-activity dependence



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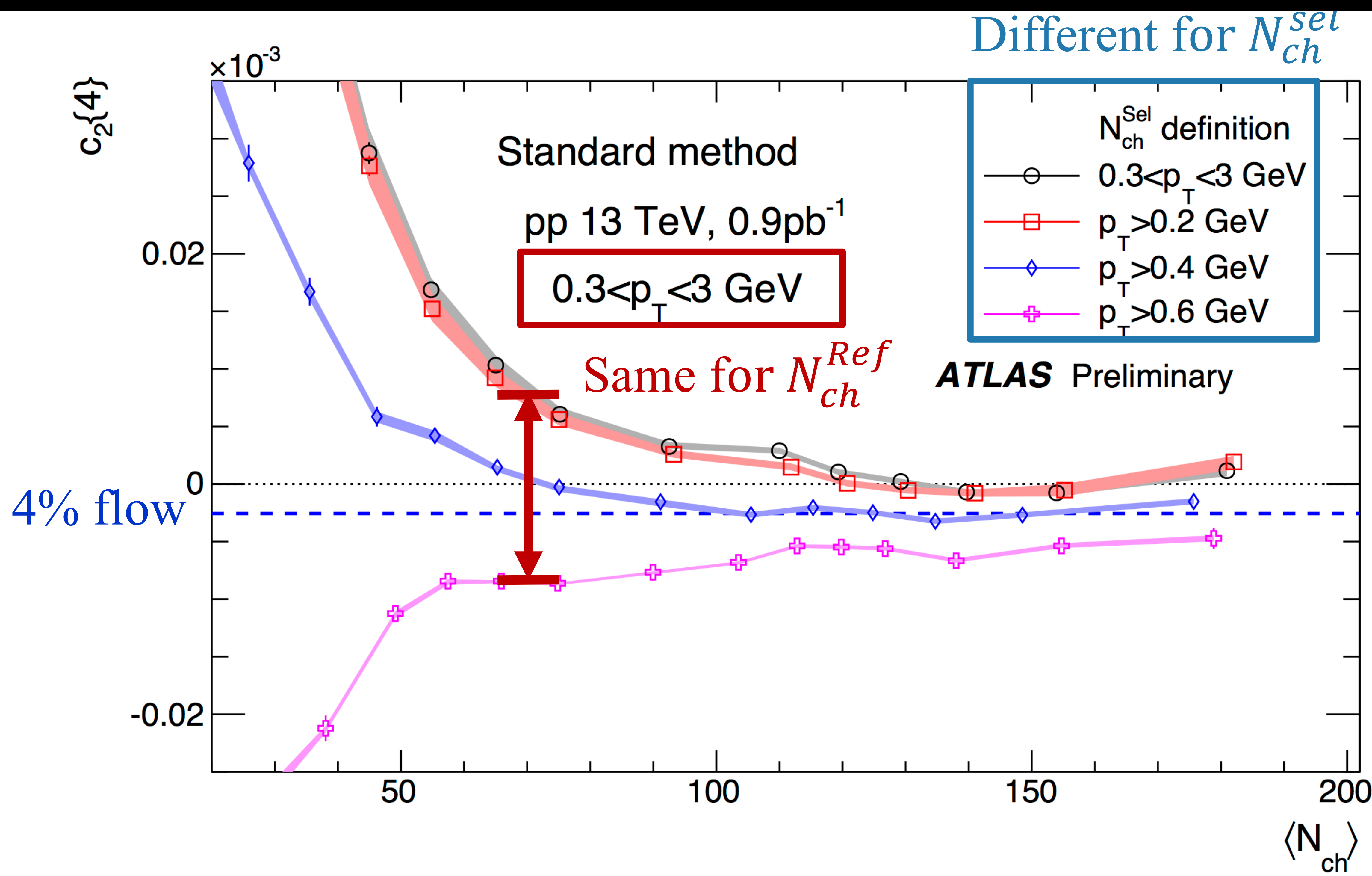

Different N_{ch}^{Sel}

Different non-flow fluctuation

Different $C_2\{4\}$

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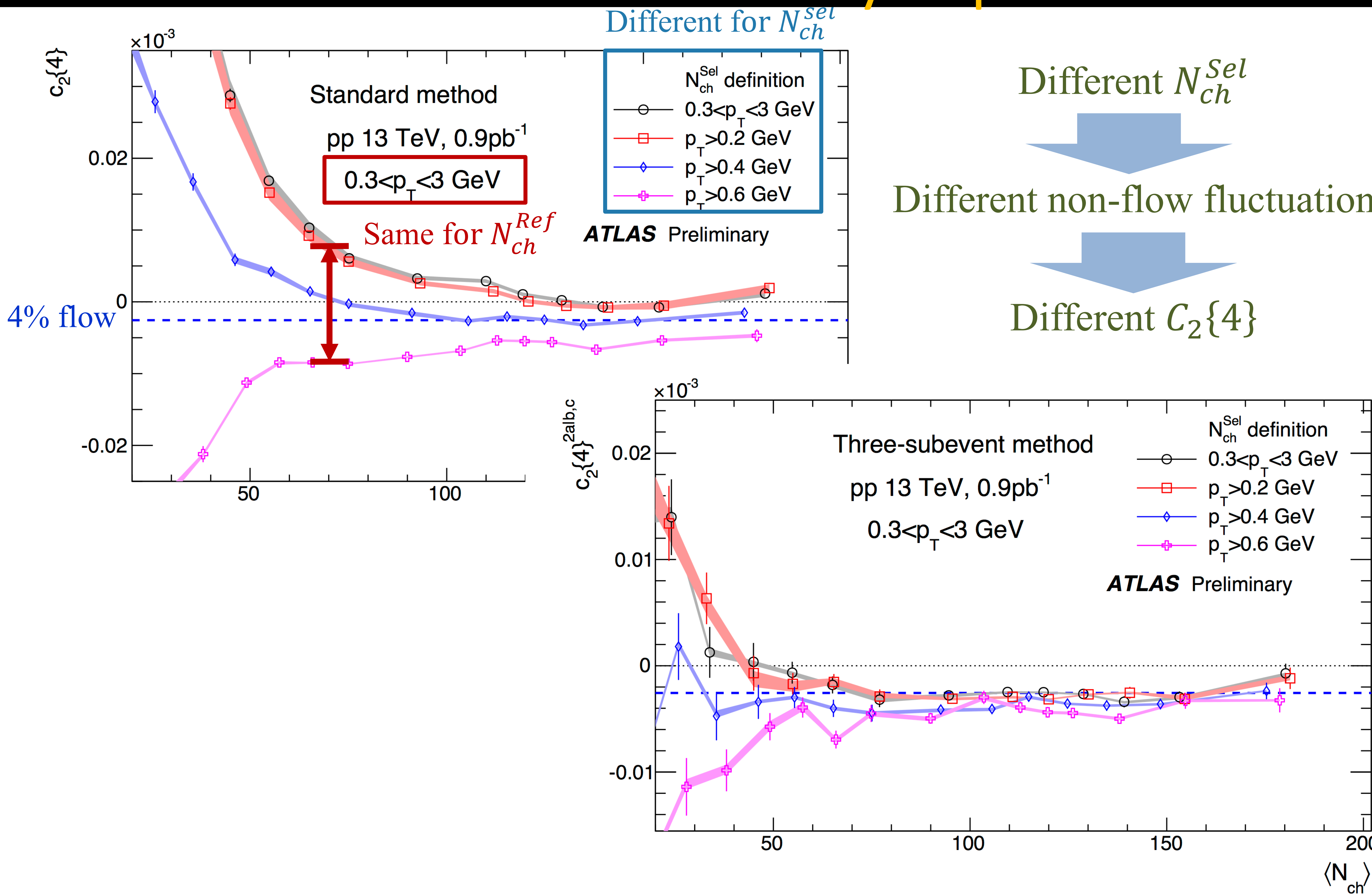

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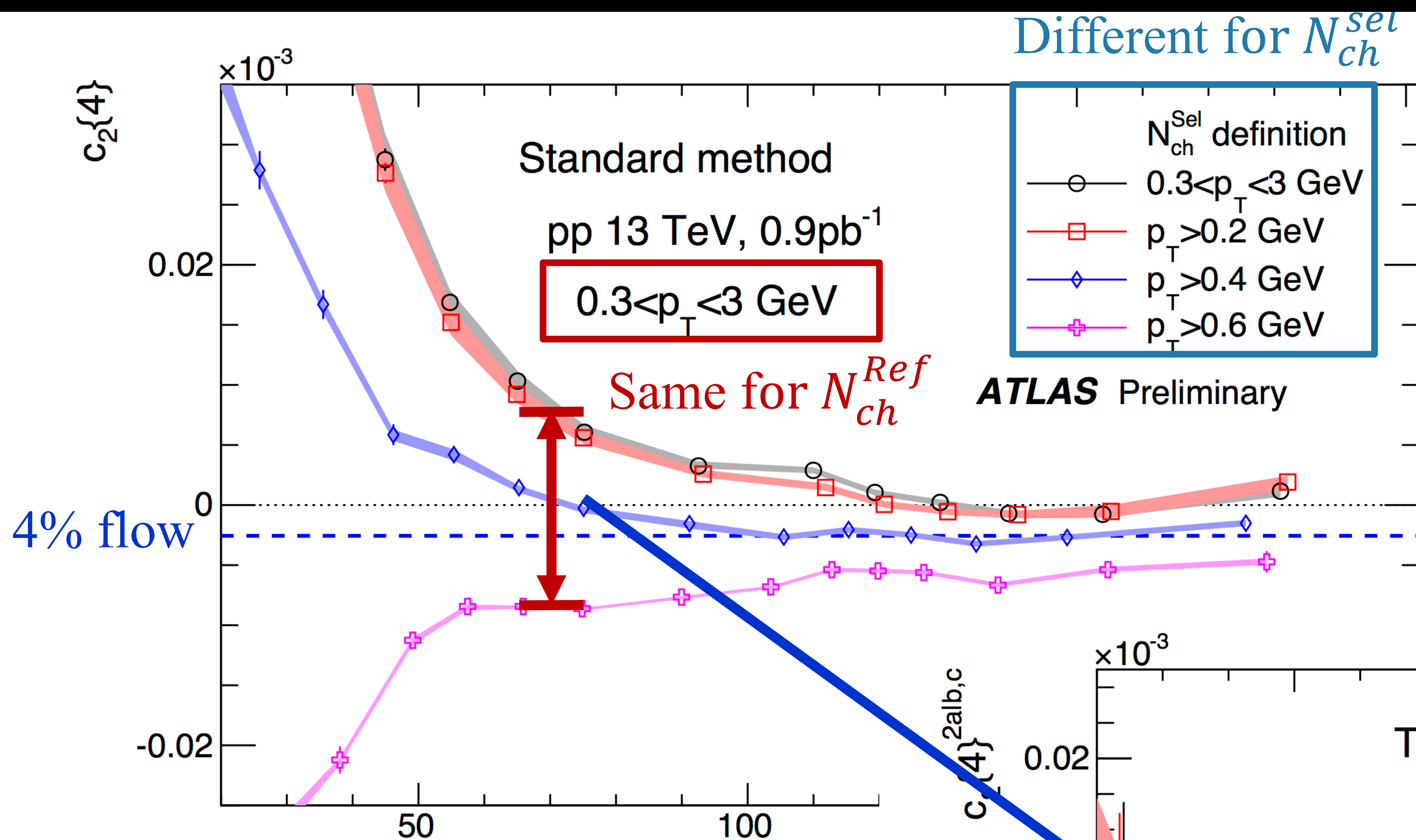


Different N_{ch}^{Sel}

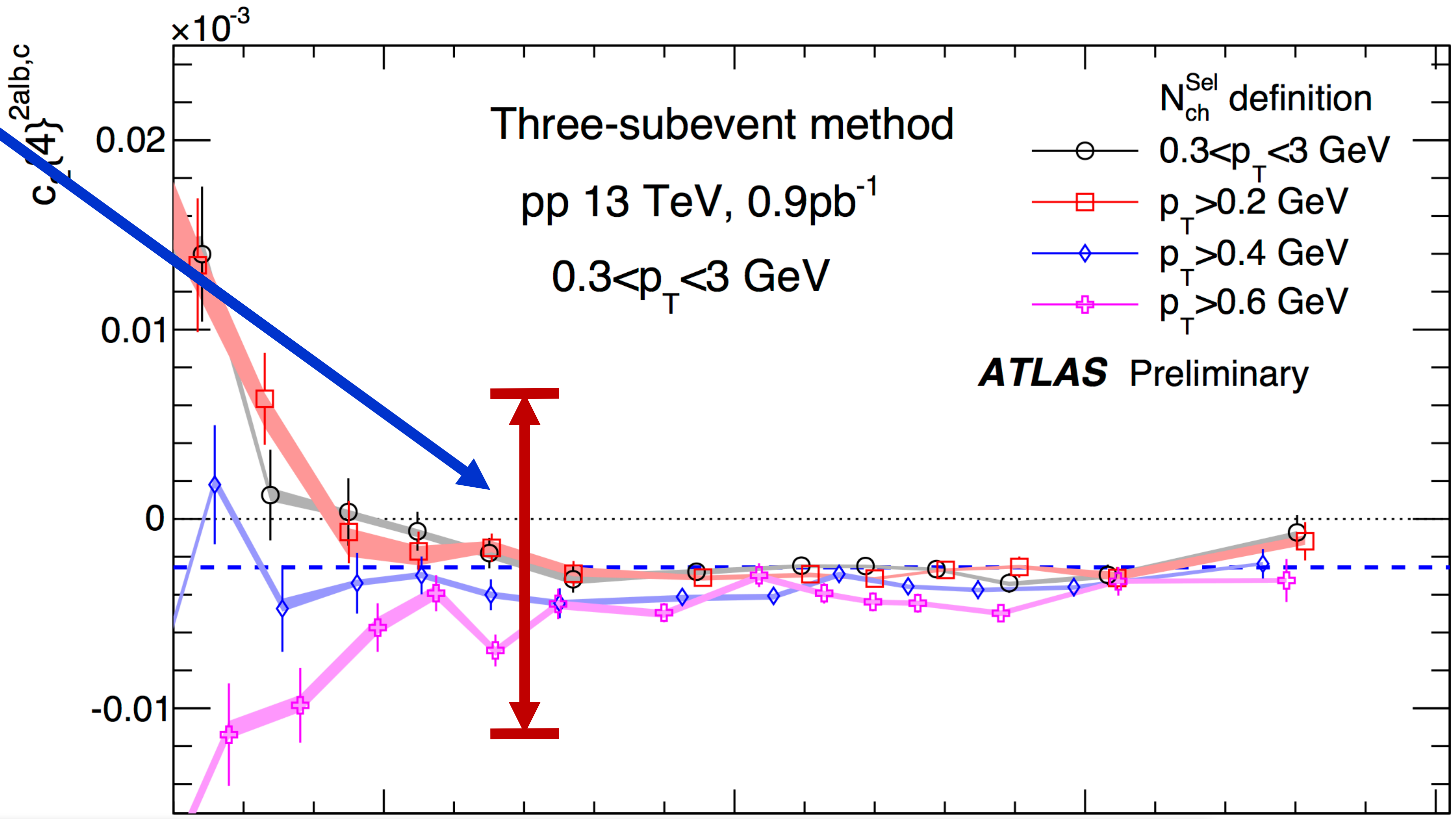
Different non-flow fluctuation

Different $C_2\{4\}$

Less non-flow

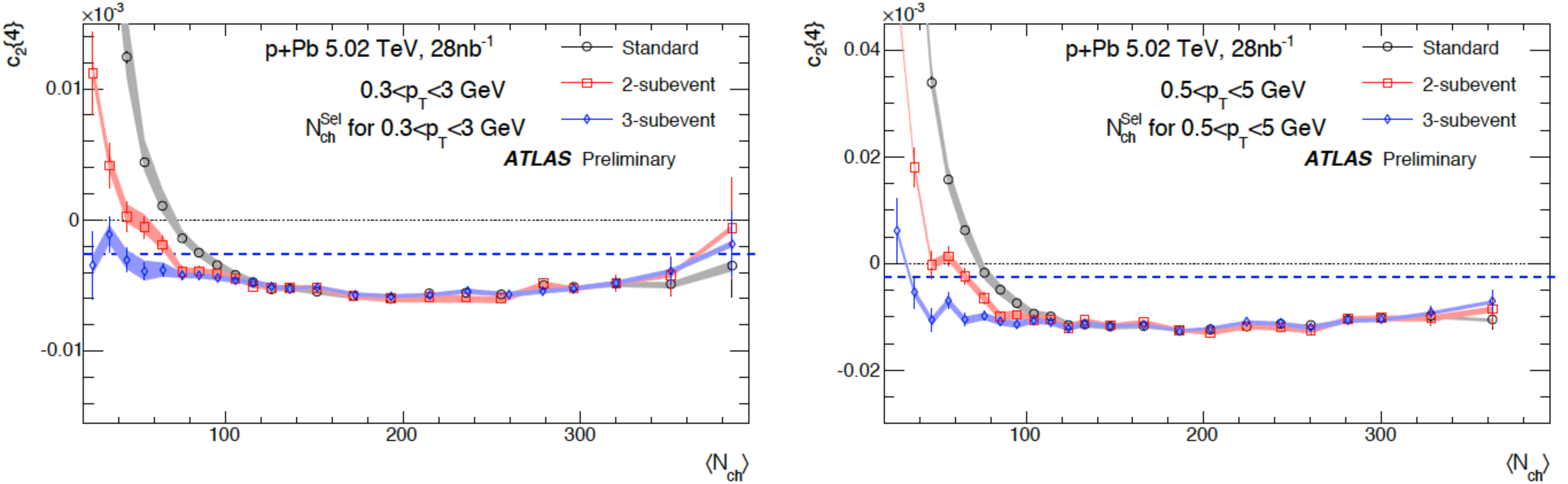
Less non-flow fluctuation

Less dependence on N_{ch}^{Sel}



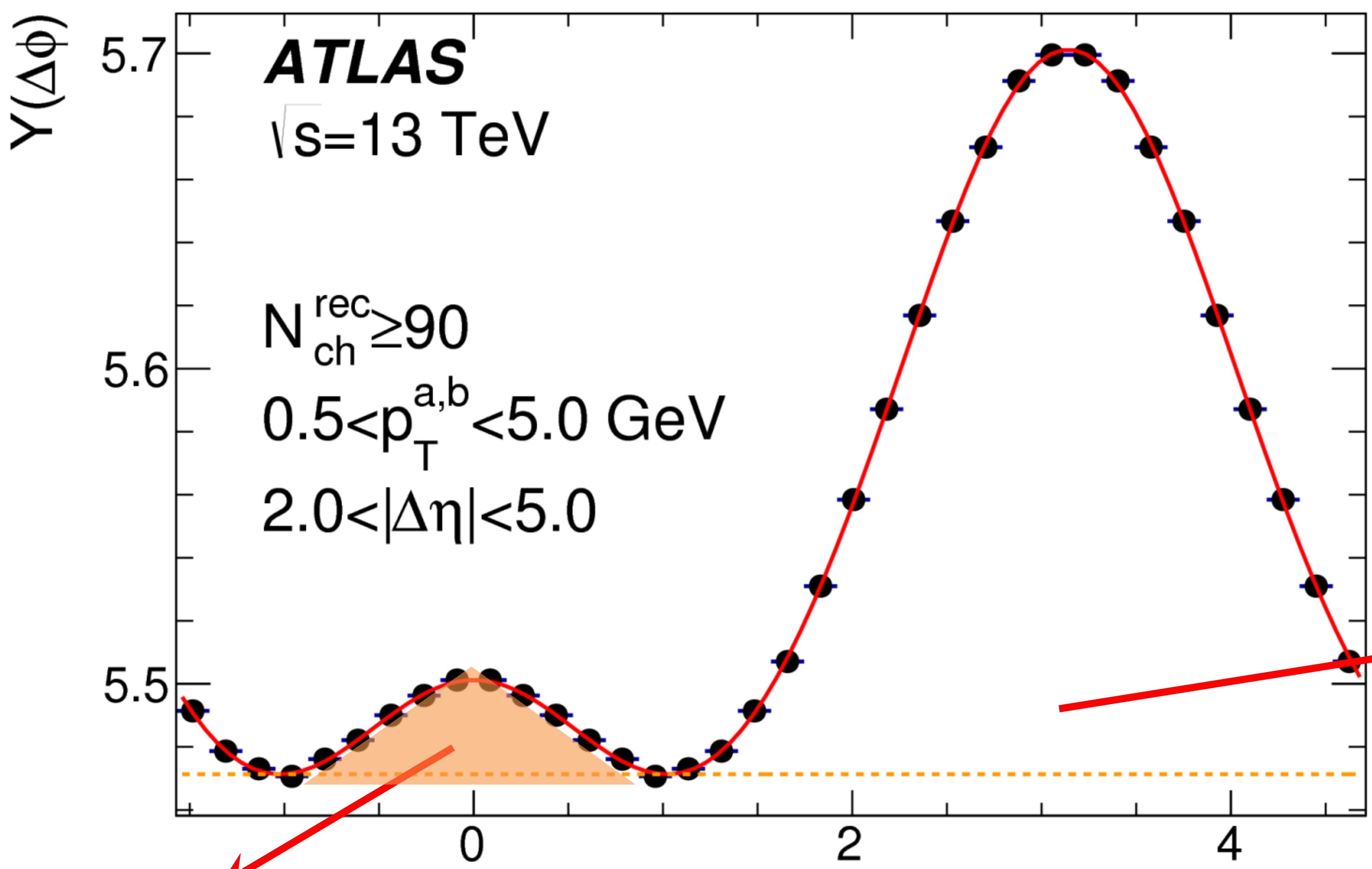
- 3 subevent cumulant is a more reliable method in *pp*!
- 3-subevent cumulant is –ve to much lower multiplicities

Subevent cumulants in p+Pb



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

Prior status of ridge measurements in pp



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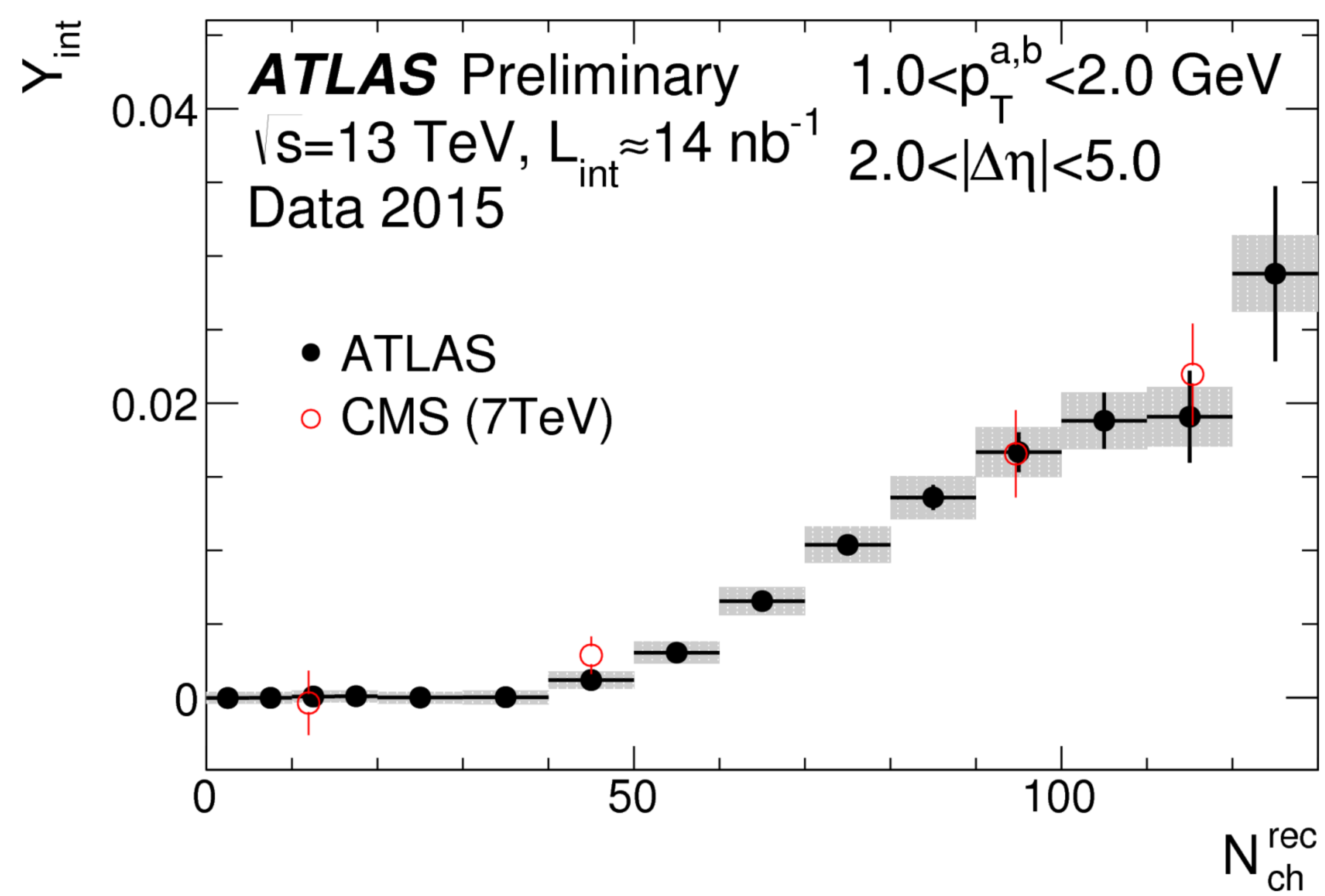

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Ridge strength quantified by the (flawed) ZYAM procedure

Factorization of $v_{2,2}$

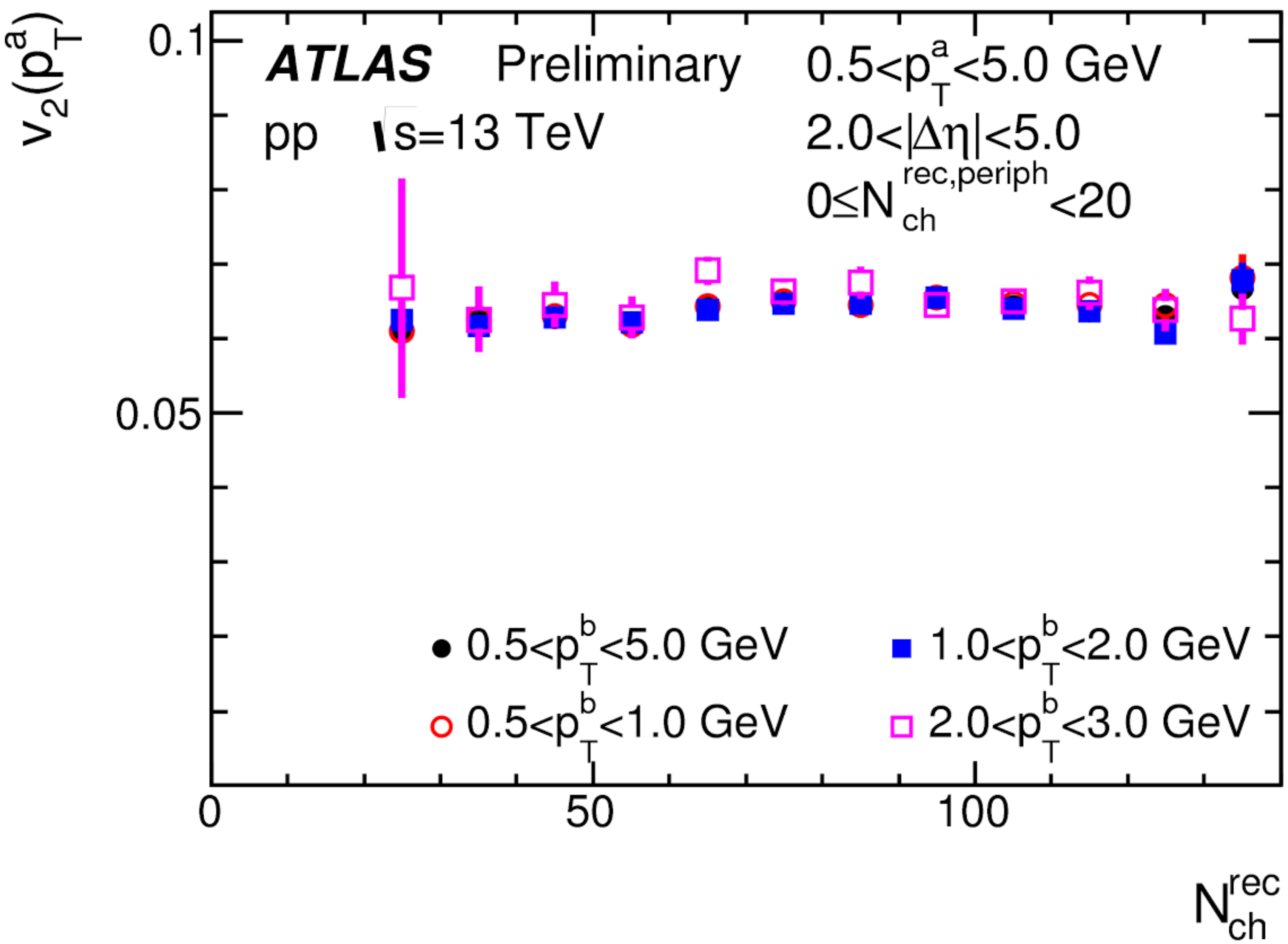
- Can extract Fourier coefficients $v_{2,2}$, $v_{3,3}$ of LRC etc from Template Fit

- If correlation arises from single particle $v_n(p_T)$, then the $v_{n,n}$ should factorize

$$v_{2,2}(p_T^a,p_T^b)=v_2(p_T^a)v_2(p_T^b)$$

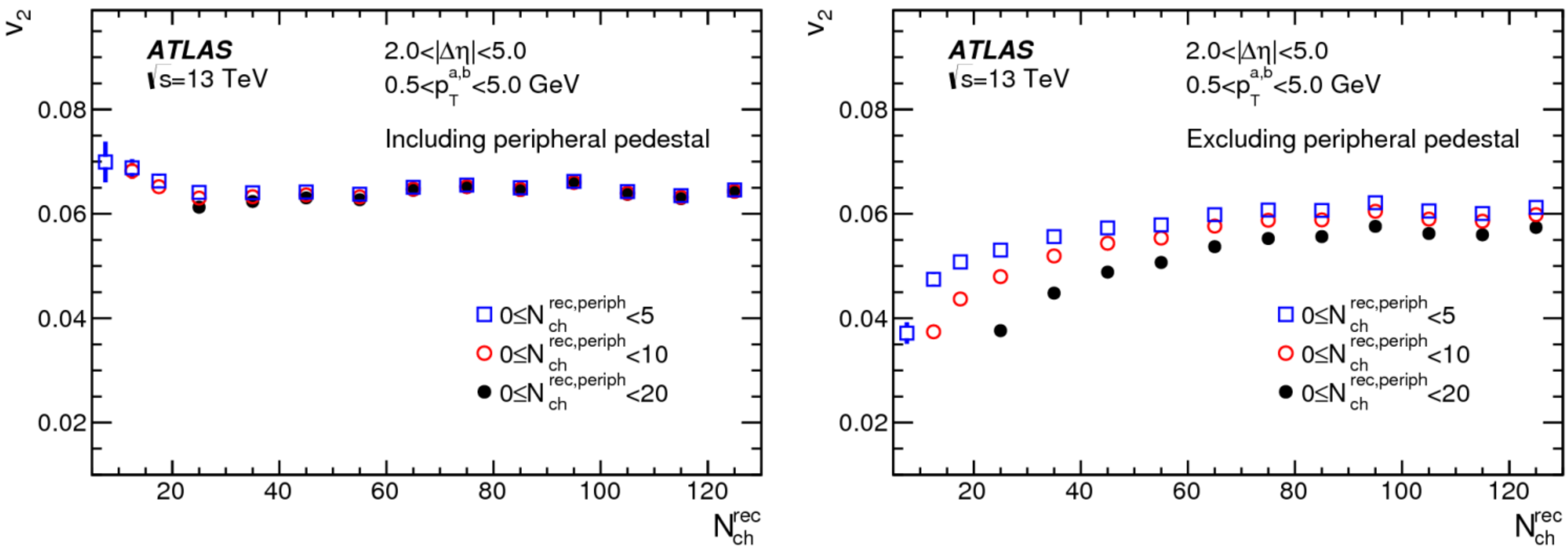
OR

$$v_2(p_T^a)=v_{2,2}(p_T^a,p_T^b)/v_2(p_T^b)$$



$v_2(p_T^a)$ is independent of choice of associated (p_T^b) particle.

ZYAM based subtraction



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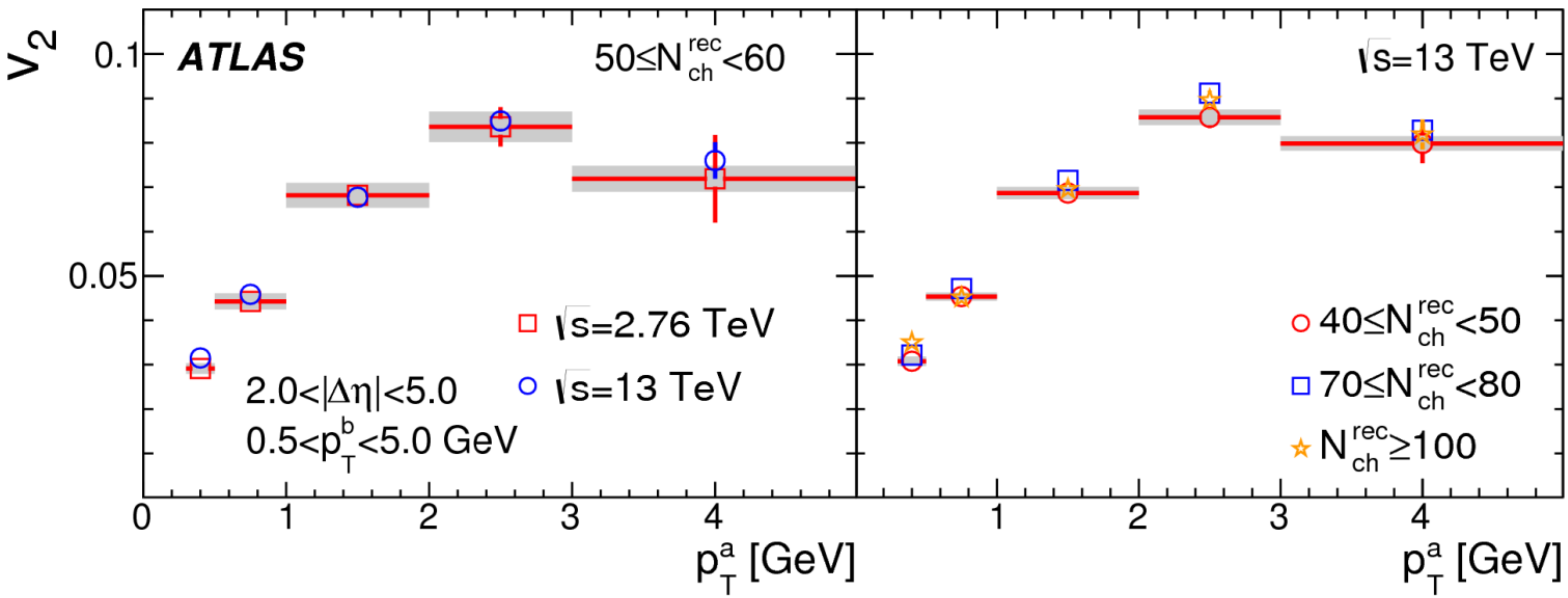
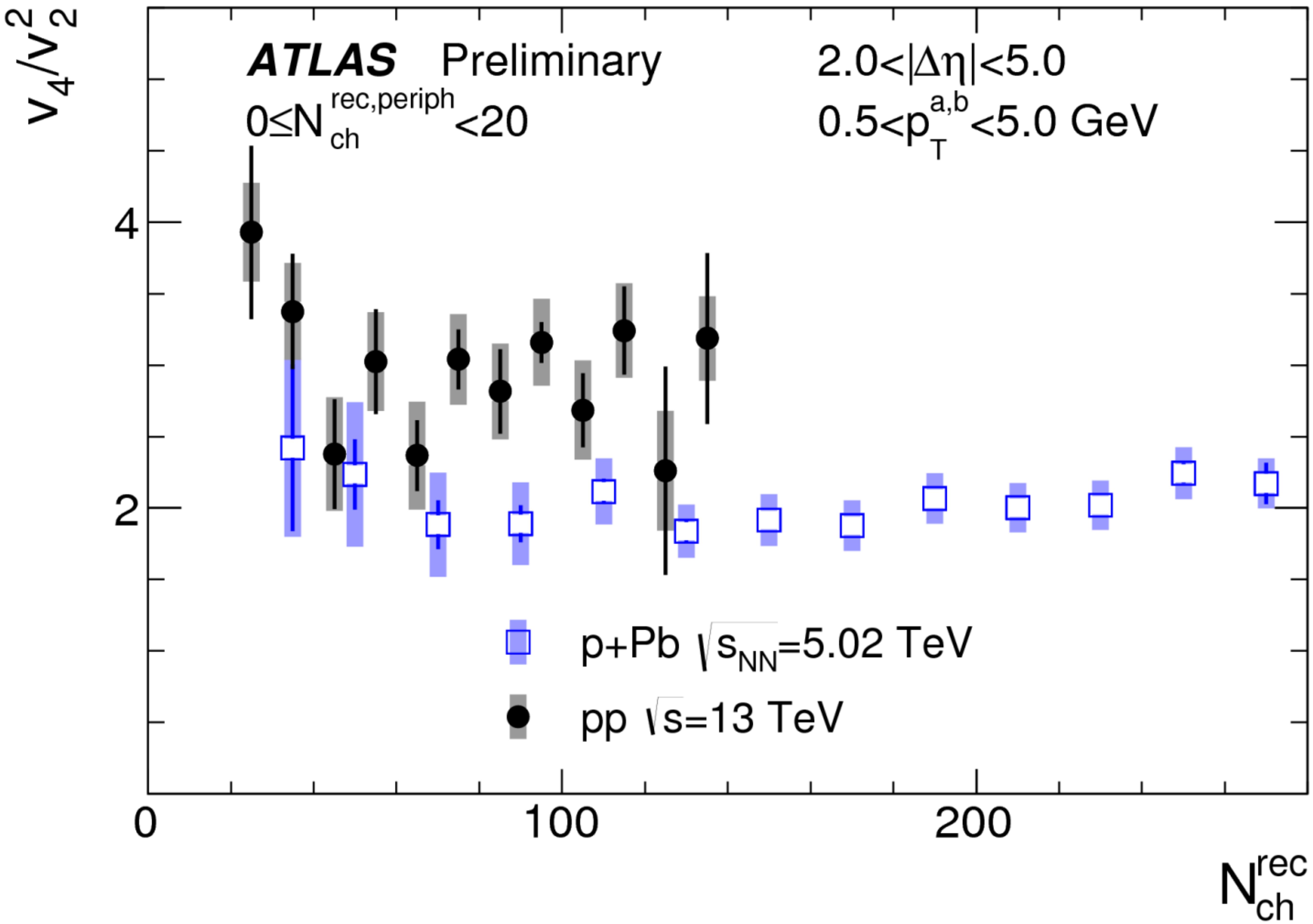


- Comparison of 2.76 TeV and 13 TeV v_2 values as function of p_T
  - Values consistent independent of p_T

Scaling of v_2 and v_4 in pp and p+Pb



- Ratio v_4/v_2^2 is independent of multiplicity in pp and p+Pb collisions.
- Value is larger in pp collisions.

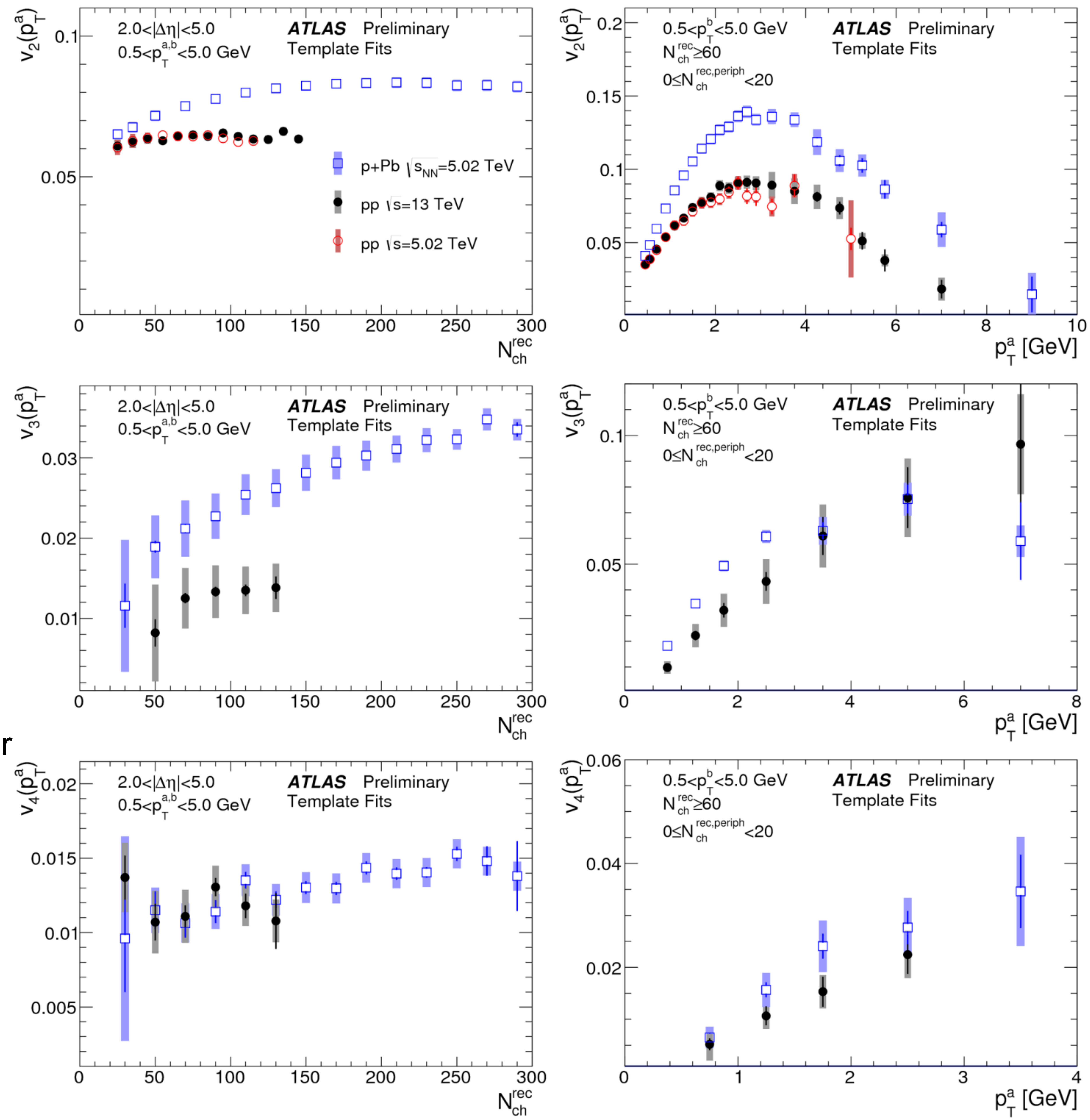
Comparison of systems : pp and p+Pb

Very consistent results between 5TeV and 13TeV pp v2.

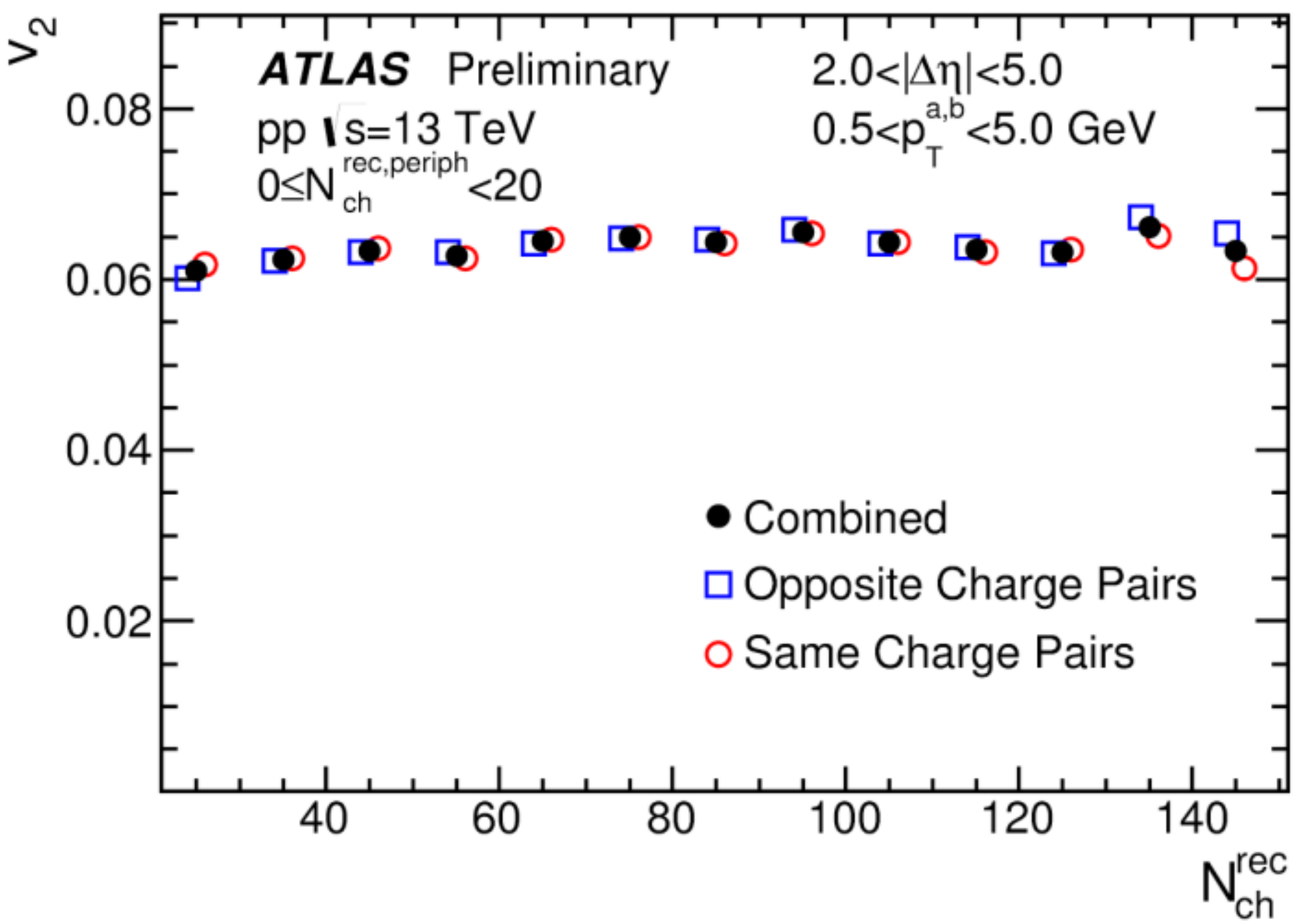
Weak dependence on multiplicity seen for pp v2

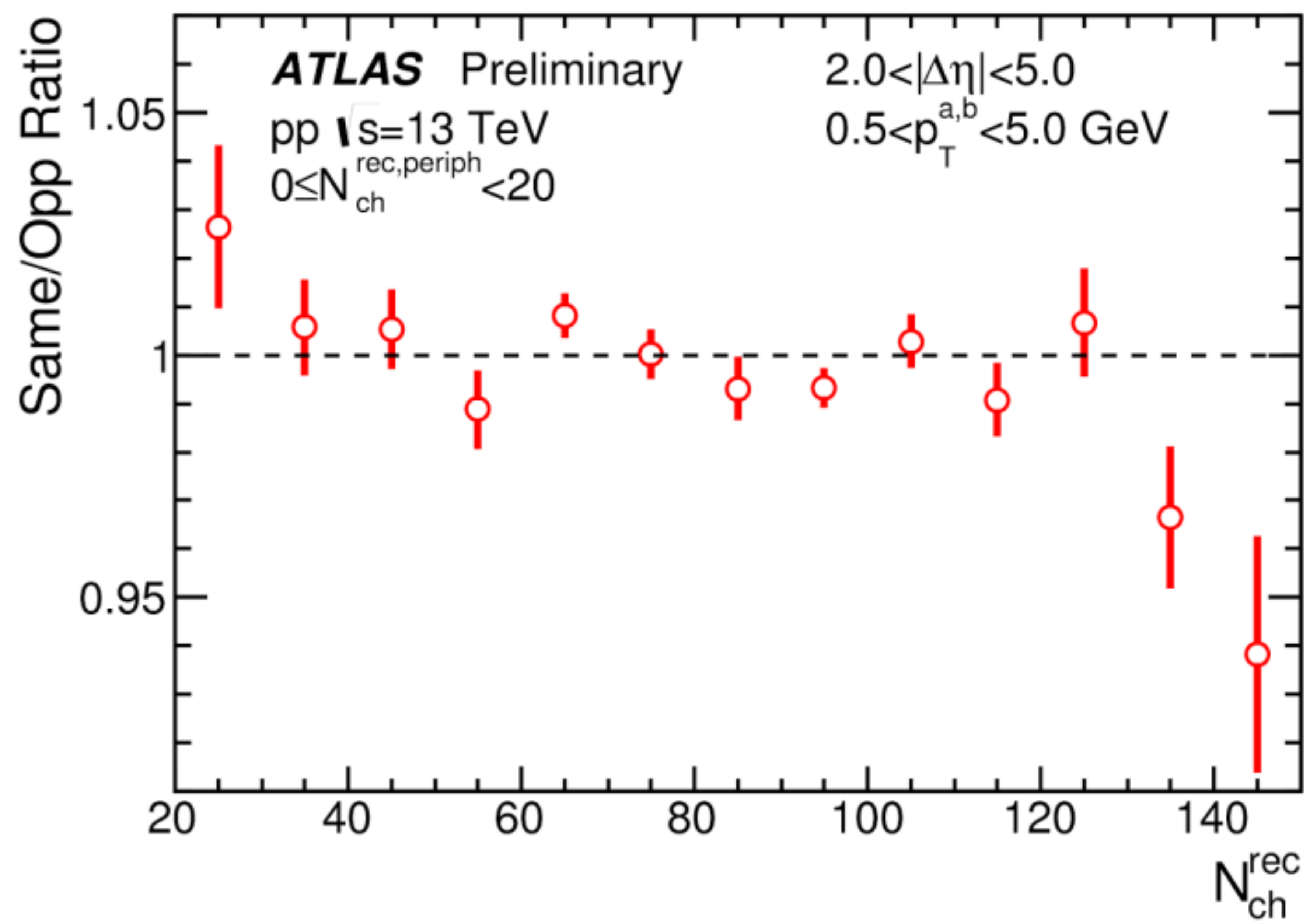
Higher order harmonics for pp consistent with no multiplicity dependence as well

For p+Pb clear multiplicity dependence is seen for v2 and v3, and slightly weaker dependence for v4

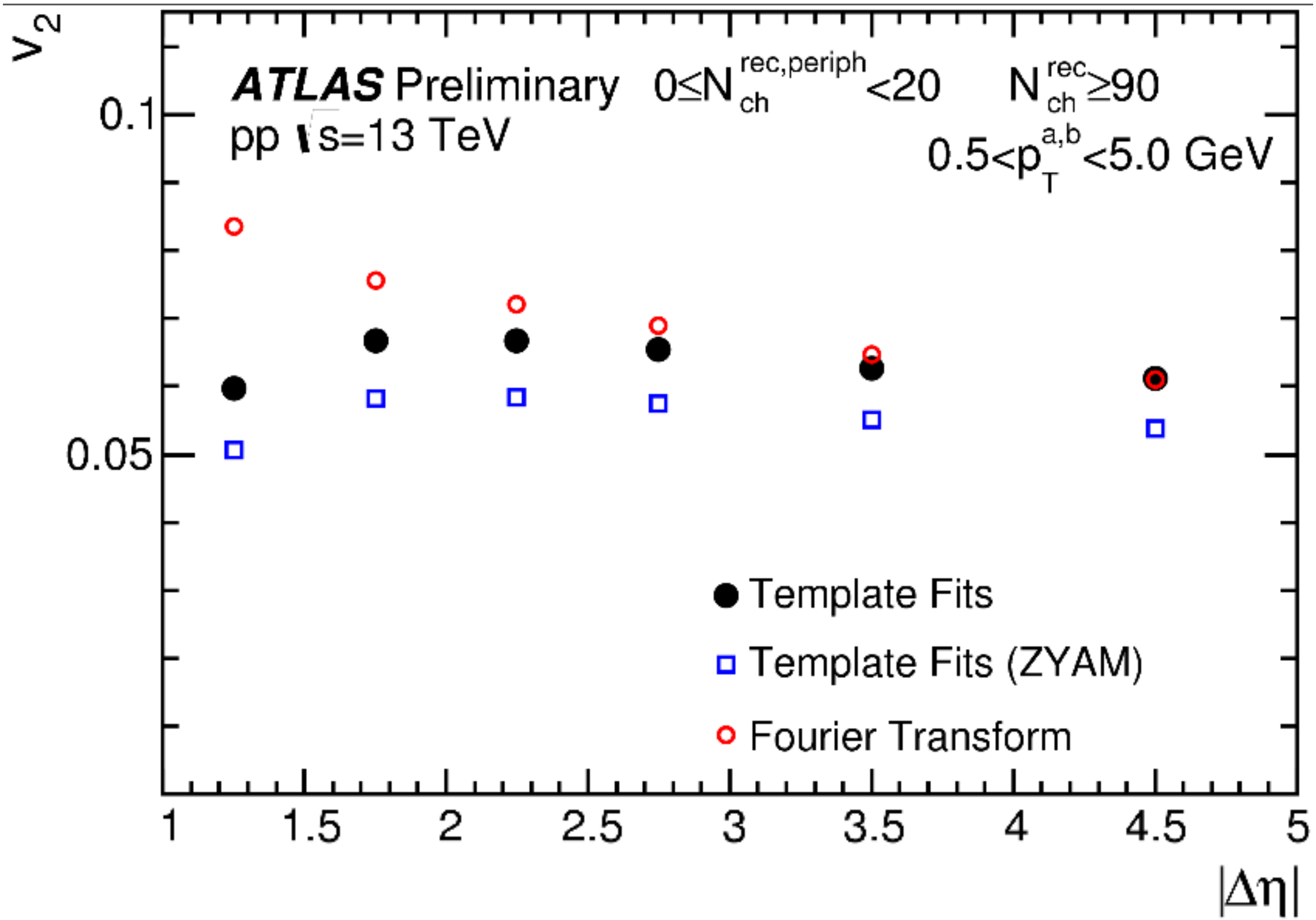


Charge dependence

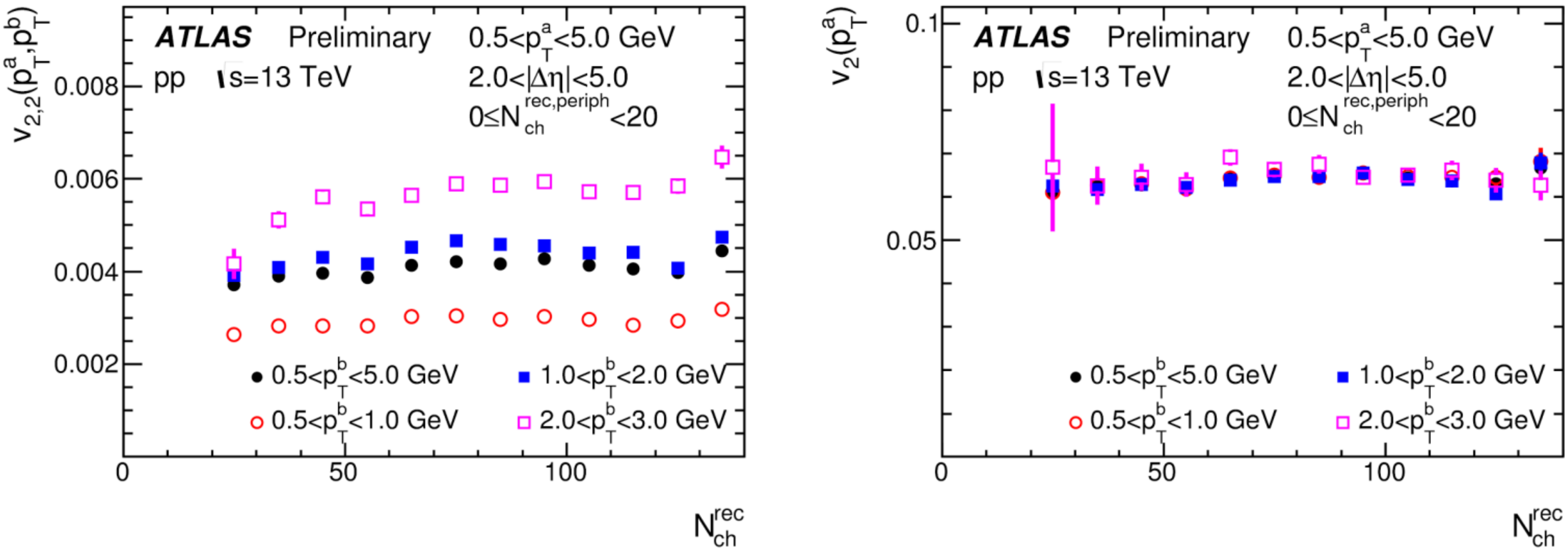




Δη dependence



Factorization of pp $v_{2,2}$



Peripheral scaling factor