Correlation measurements in small systems at the LHC

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RHIC/AGS Users meeting
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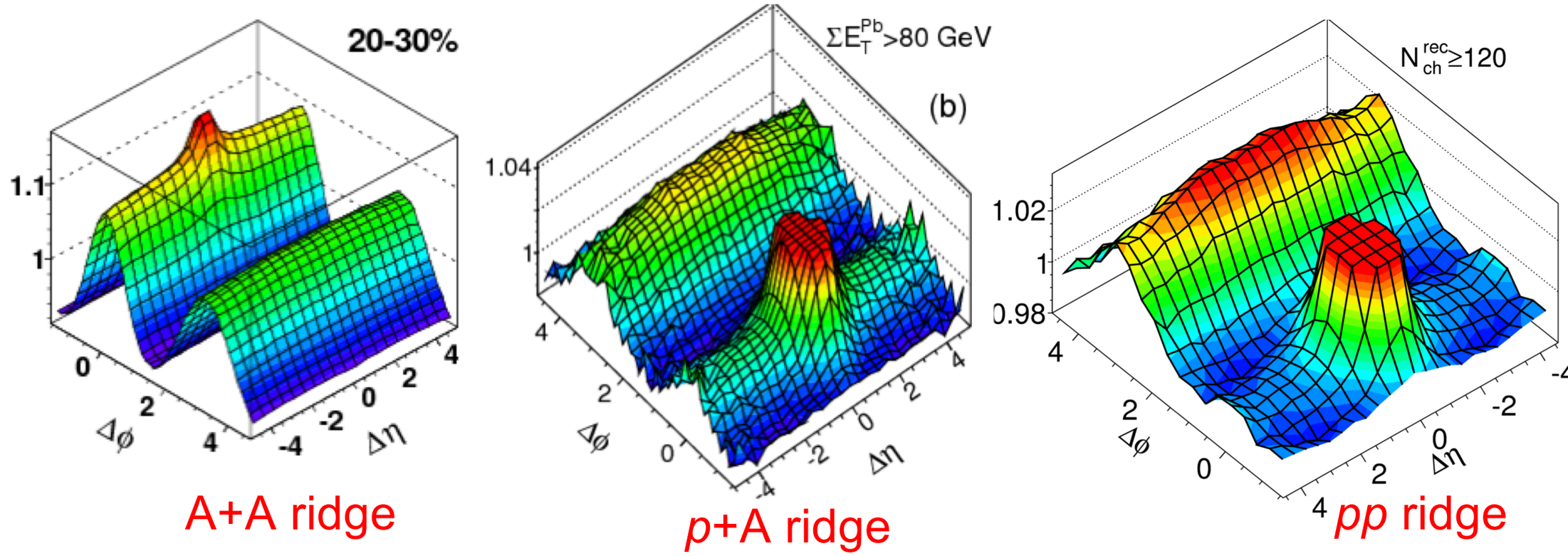
Ridges in A+A, *p*+A and *pp*



- Are they produced from the same or different mechanisms?
  - Hydro in AA and *p*+A. What about *pp*??
- If hydro, what are the implications?
  - How small can the smallest droplet of QGP be?
- If different mechanism
  - Can we find an observable that established this?

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

- Two particle hadron-hadron correlations
  - Successful extraction of v_n harmonics.
  - p_T, and N_{ch} and $\sqrt{s}$ dependence
  - Study of impact parameter dependence

Phys. Rev. C 96 (2017) 024908,
Phys. Lett. B 765 (2017) 193
ATLAS-CONF-2017-068

- Multi-particle cumulants
  - works well for *p*+A and A+A collisions
  - Can not be trusted at the typical *pp* multiplicities

Eur. Phys. J. C 77 (2017) 428,

- Sub-event cumulants
  - Much less susceptible to jet/dijet correlations
  - Suitable for measuring correlation in *pp* collisions

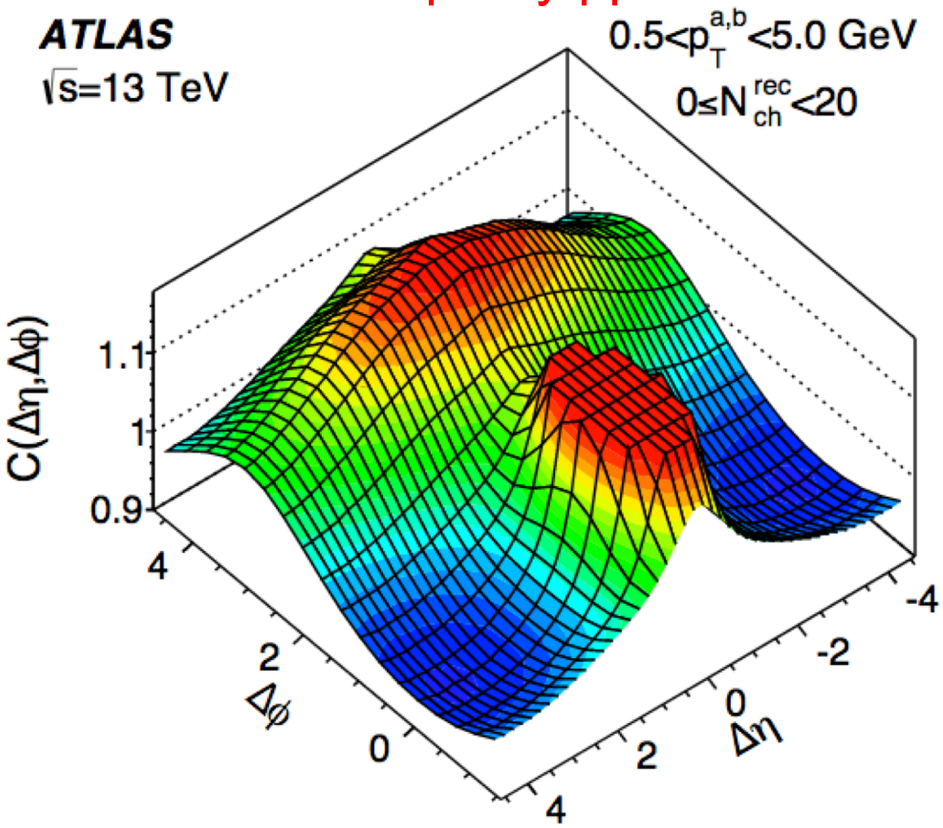
Phys. Rev. C 97 (2018) 024904,

- Asymmetric cumulants
  - Correlations between different order Fourier anisotropies

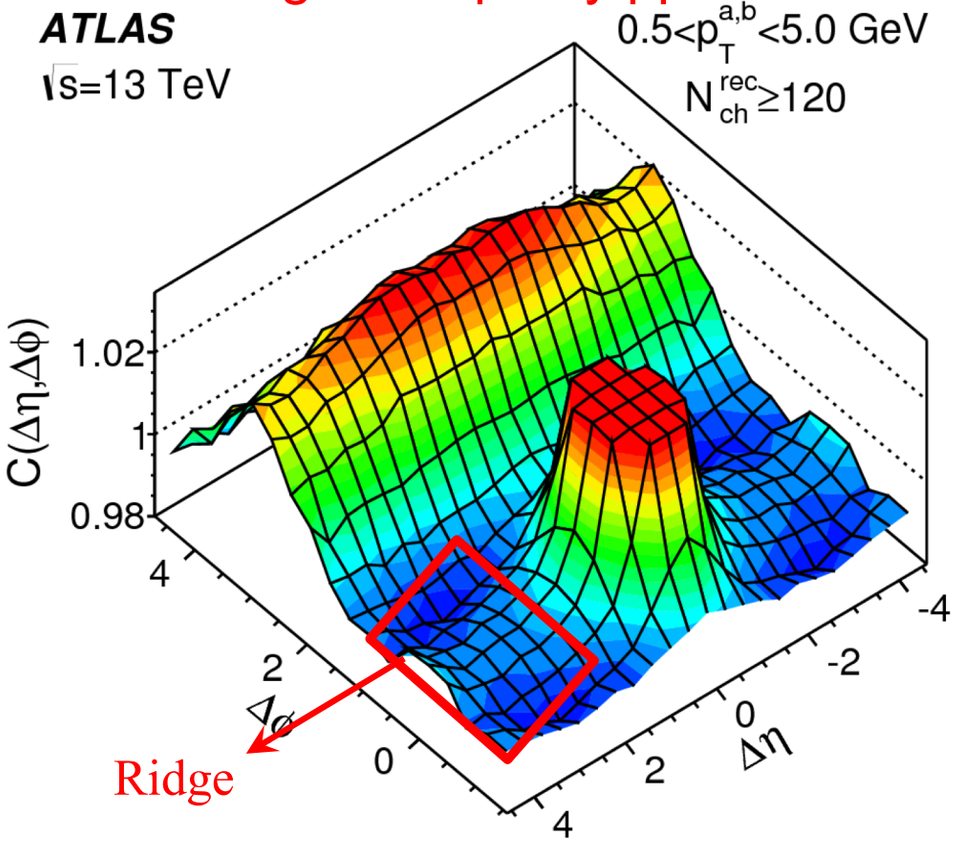
Phys. Rev. Lett. 120 (2018) 092301
Phys. Lett. B 789 (2019) 444

Ridge in *pp* collisions

Low multiplicity pp events



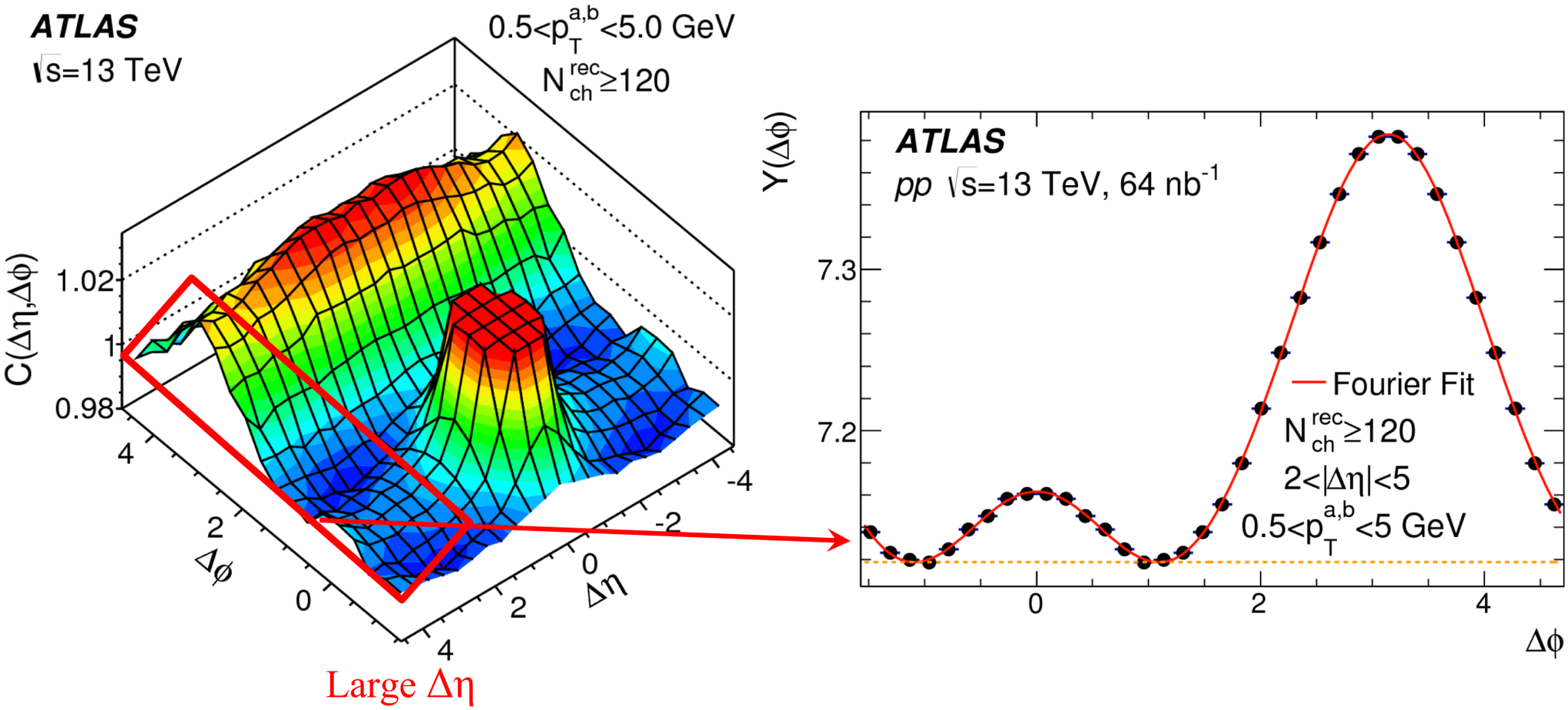
High multiplicity pp events



- Ridge "appears" at high multiplicity.
- Ridge signal much smaller compared to other features of correlation.

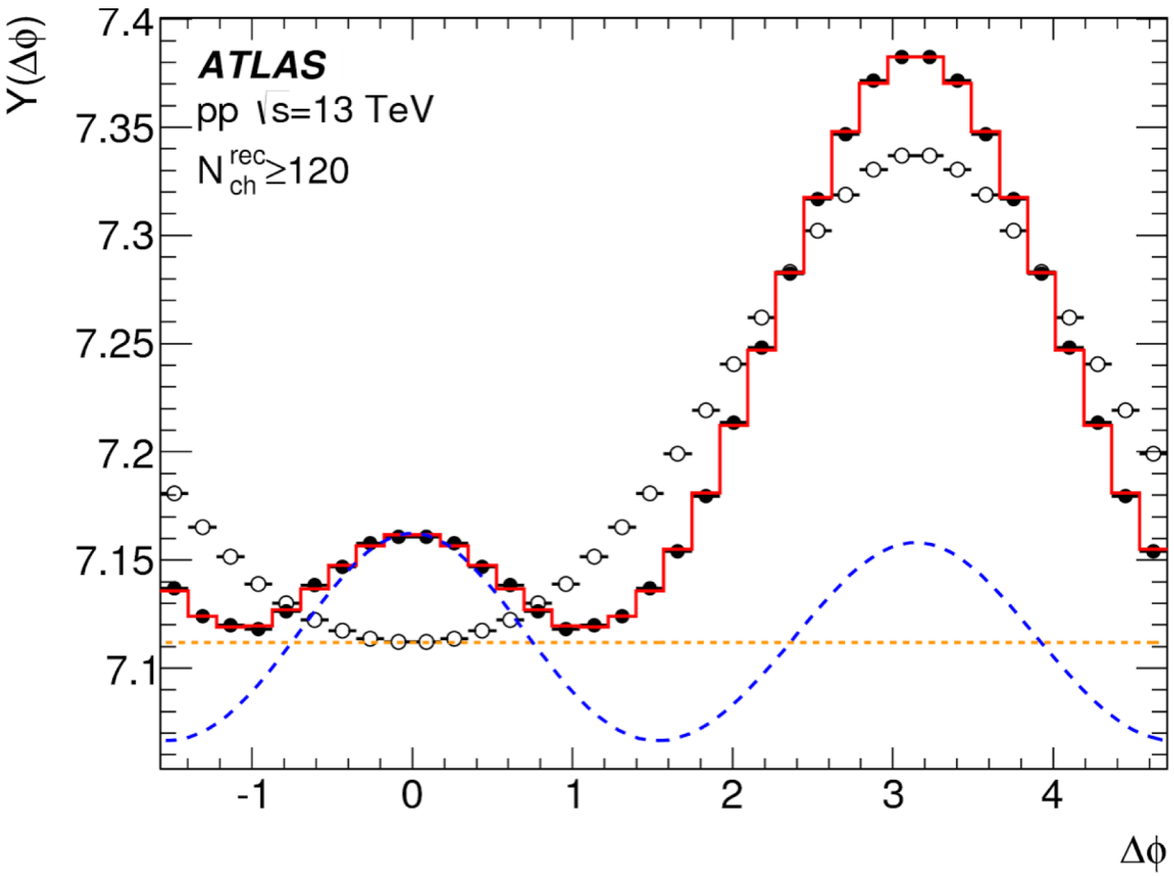
Phys. Rev. C 96 (2017) 024908

Analysis of 2PCs in *pp* collisions



- First step: look at long-range correlation component $|\Delta\eta|>2$
  - 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.

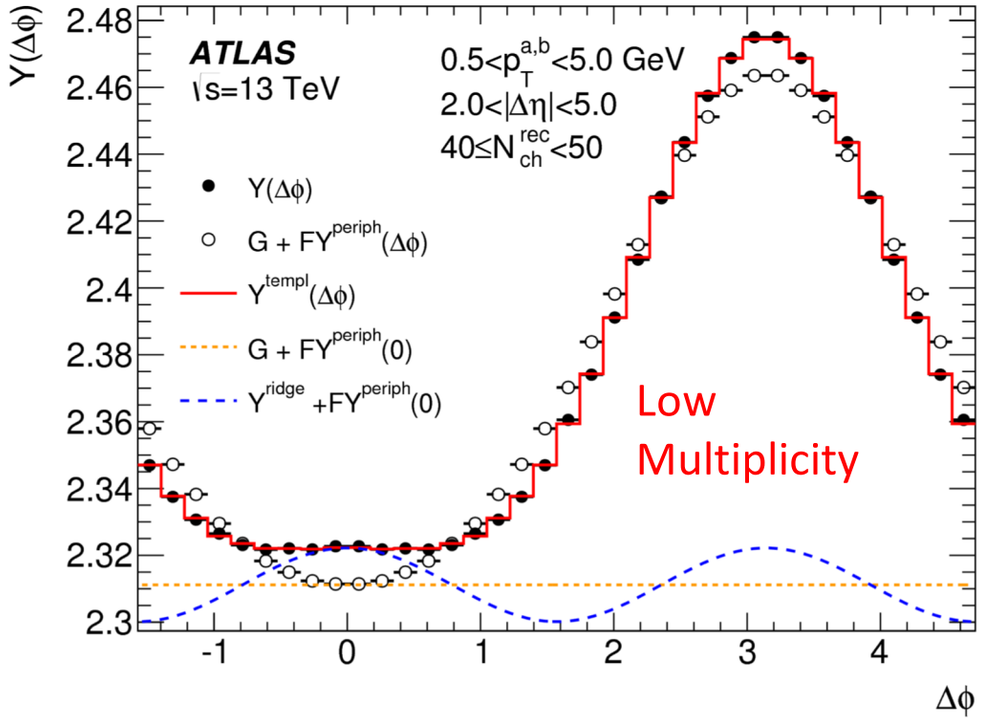
Analysis technique: Template Fitting Procedure

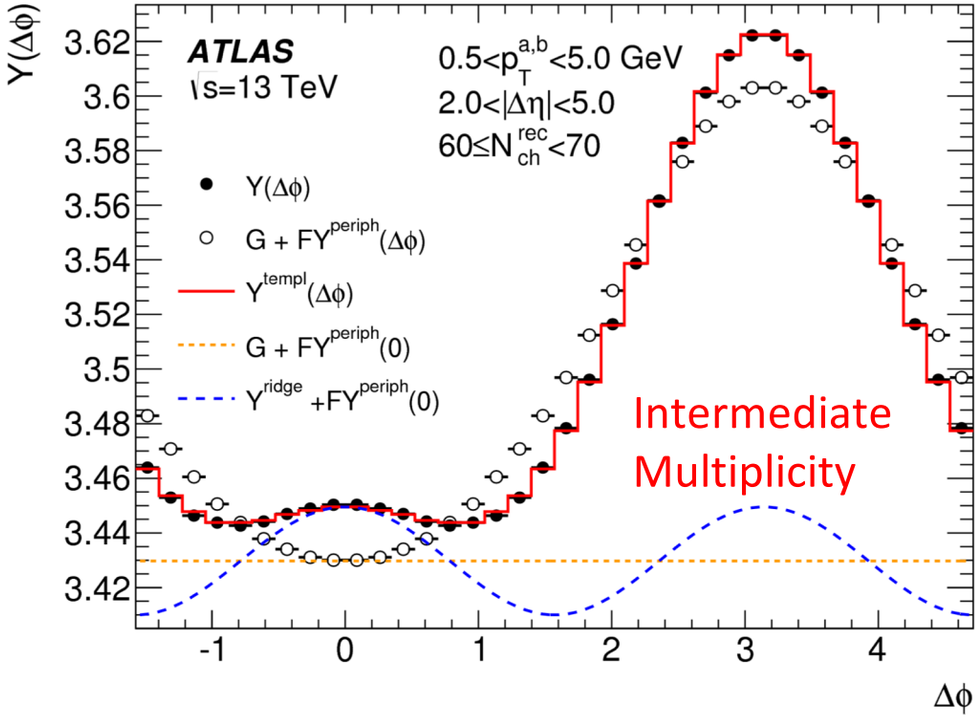


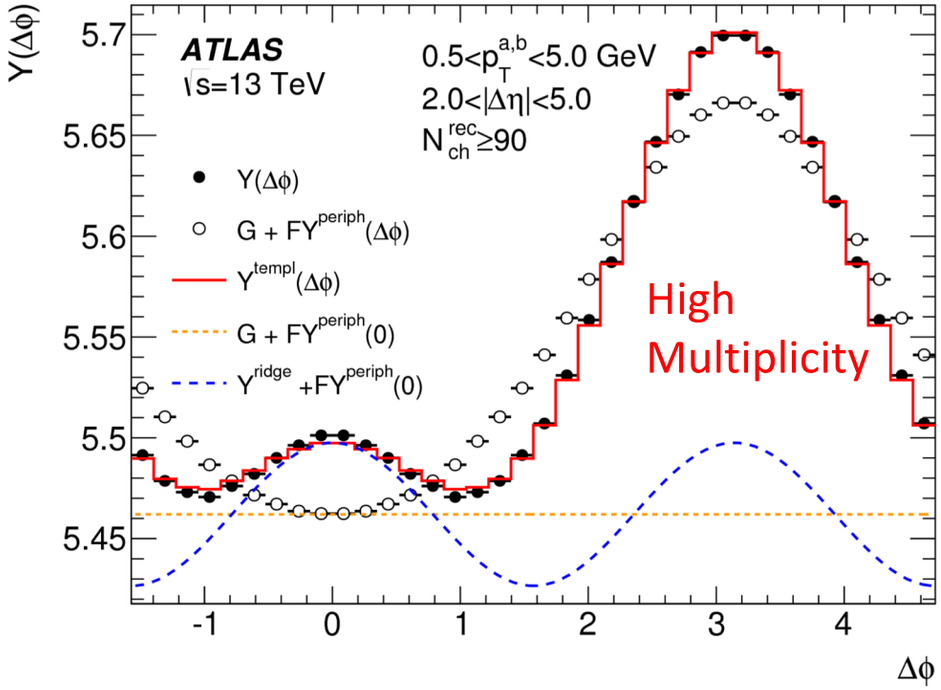
Phys. Rev. C 96 (2017) 024908

- A template fitting procedure used to extract long-range correlation.
- Fit the correlation in high multiplicity events with Template of two components:
  - C^{periph}: Correlation in peripheral events (N_{ch}<20) : Jet background
  - C^{ridge} : Pedestal*(1 +2v_n^2cos(nΔφ)) : True signal

Template Fitting : Multiplicity dependence



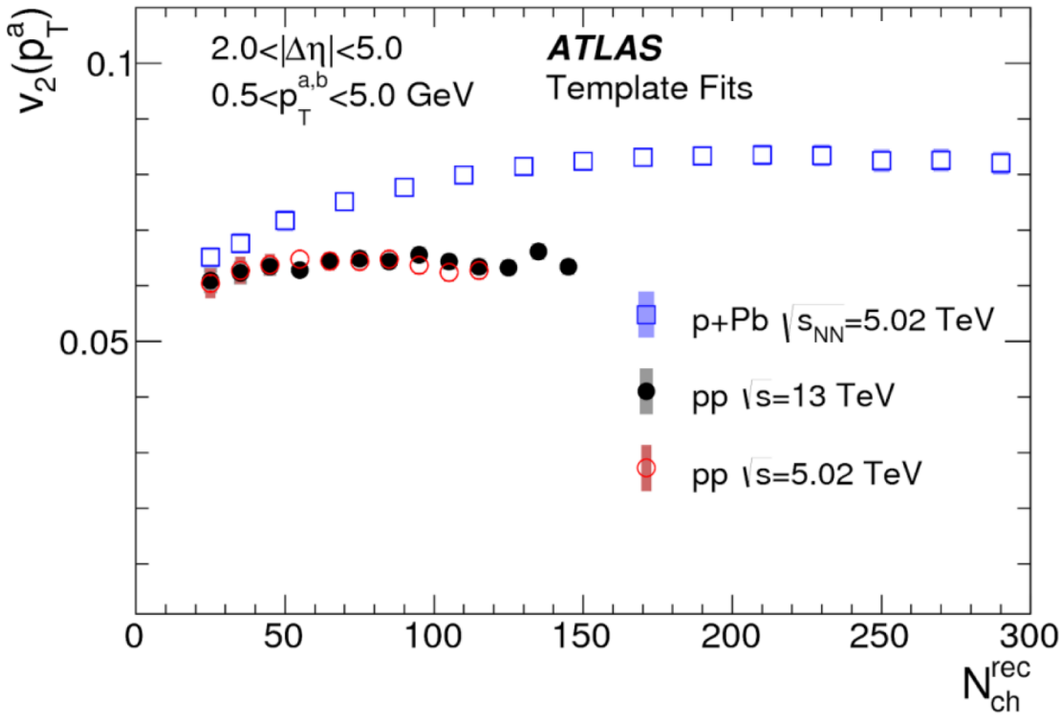


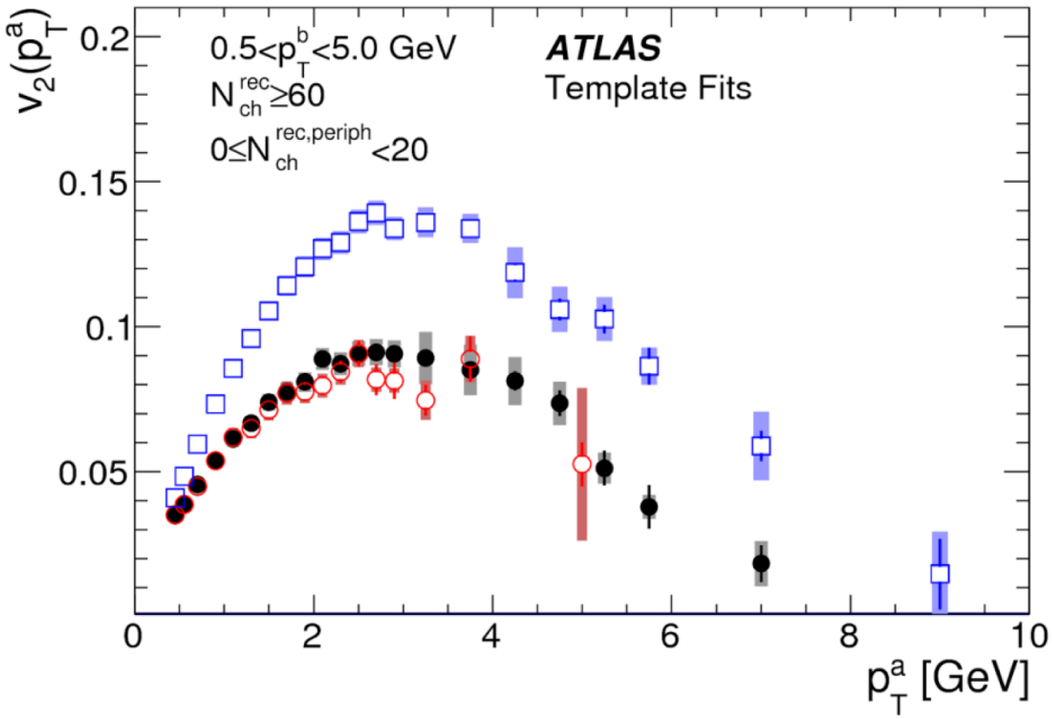


Considerable long-range correlation even in low & intermediate multiplicity events.

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

Comparison of systems & energies : *pp* and *p*+Pb

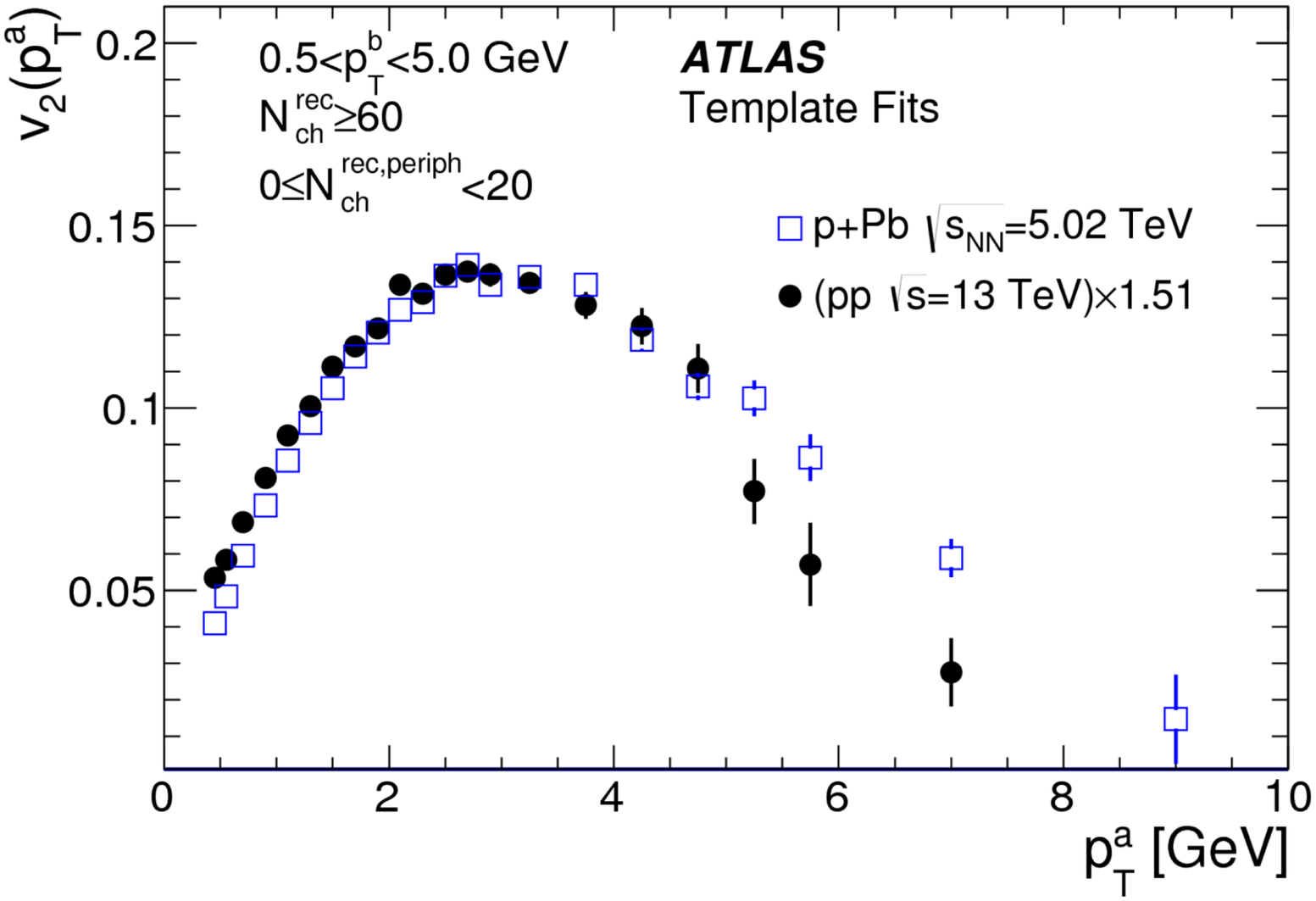




- For *p*+Pb clear multiplicity dependence is seen for v_2
- Only a weak dependence on multiplicity seen for *pp* v_2
- *p*+Pb v_2 is larger than *pp* v_2.

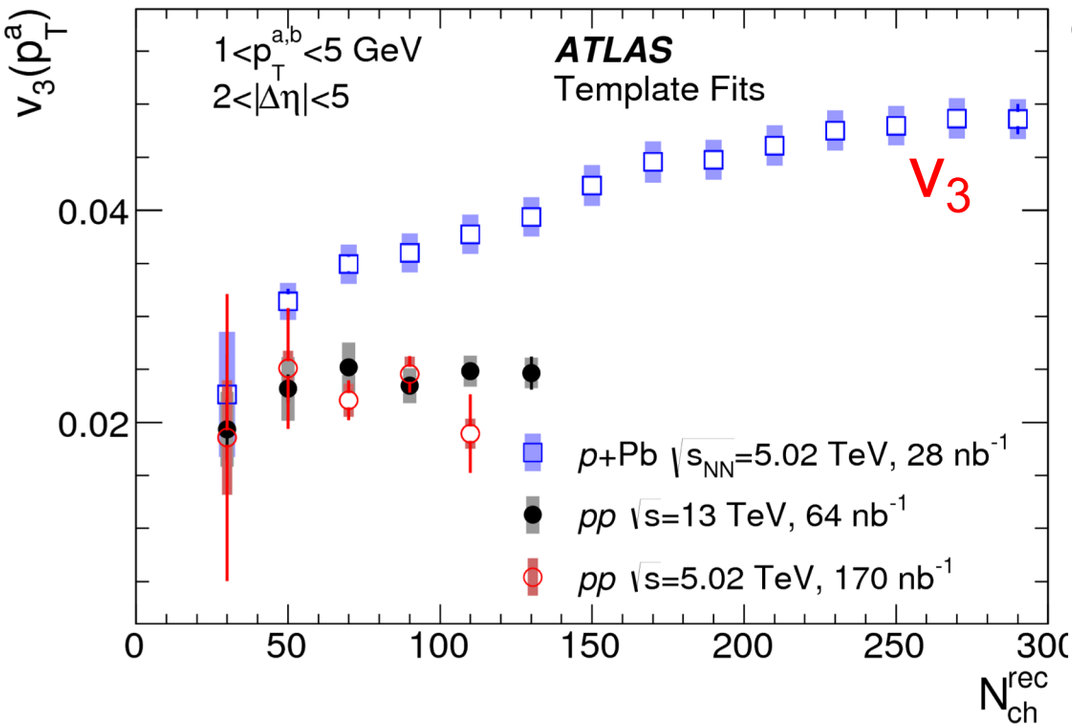
- Consistent values for v_2 between 5.02 TeV and 13 TeV *pp* collisions.
  - No dependence of v_2 on collision energy

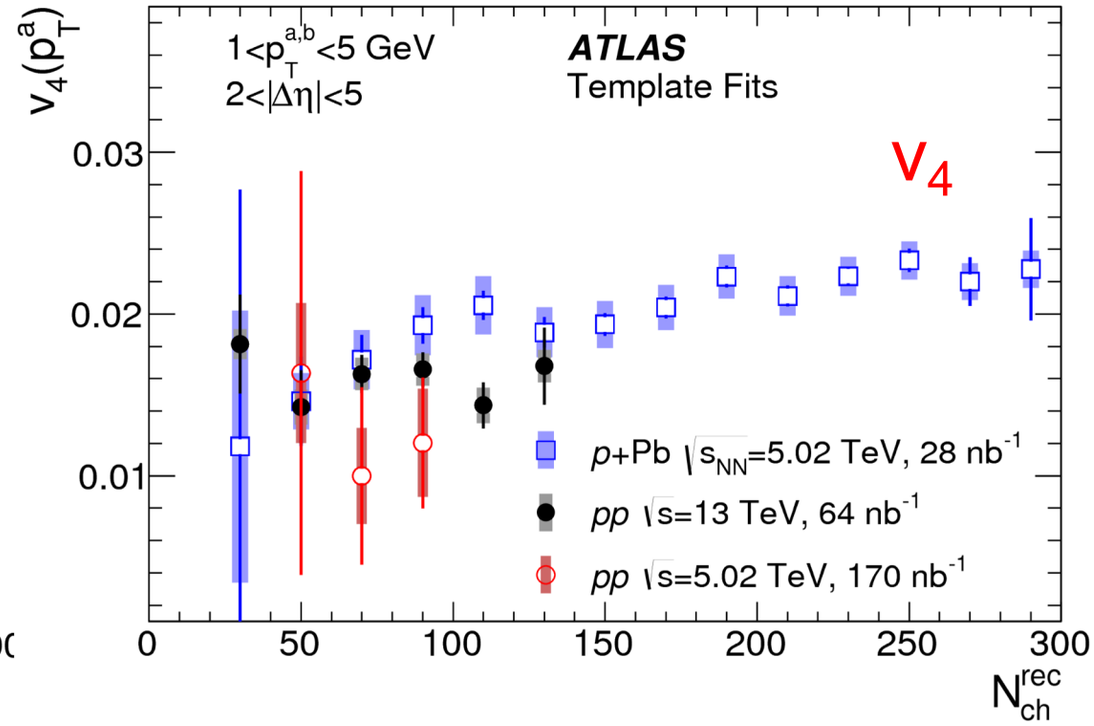
Shape of $v_2(p_T)$ in *pp* and *p*+Pb



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

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

The trivial multiplicity dependence is non-trivial

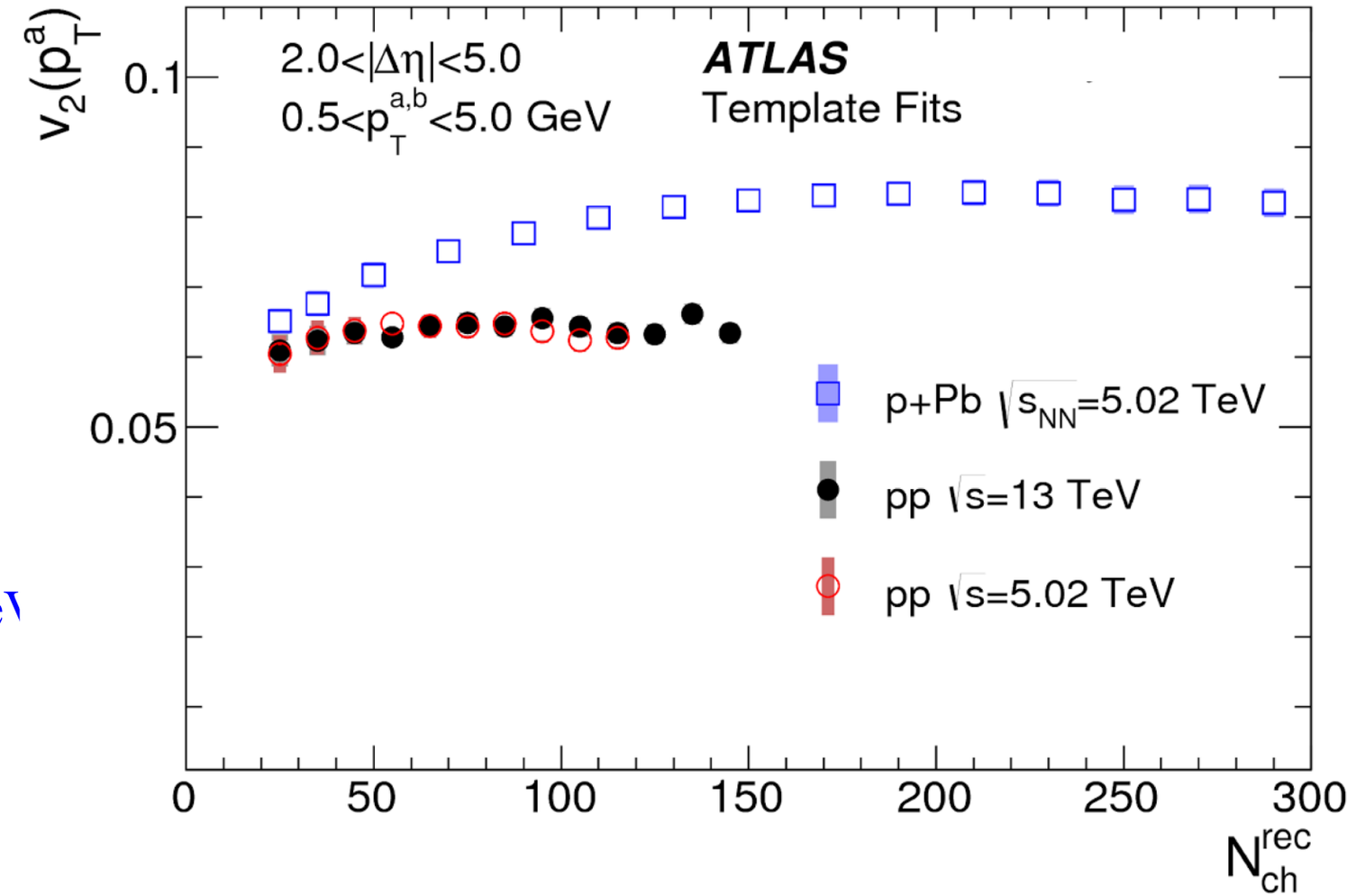
Only a weak dependence on multiplicity seen for pp v_2.

For p+Pb clear multiplicity dependence is seen for v_2.

p+Pb v_2 is larger than pp v_2.

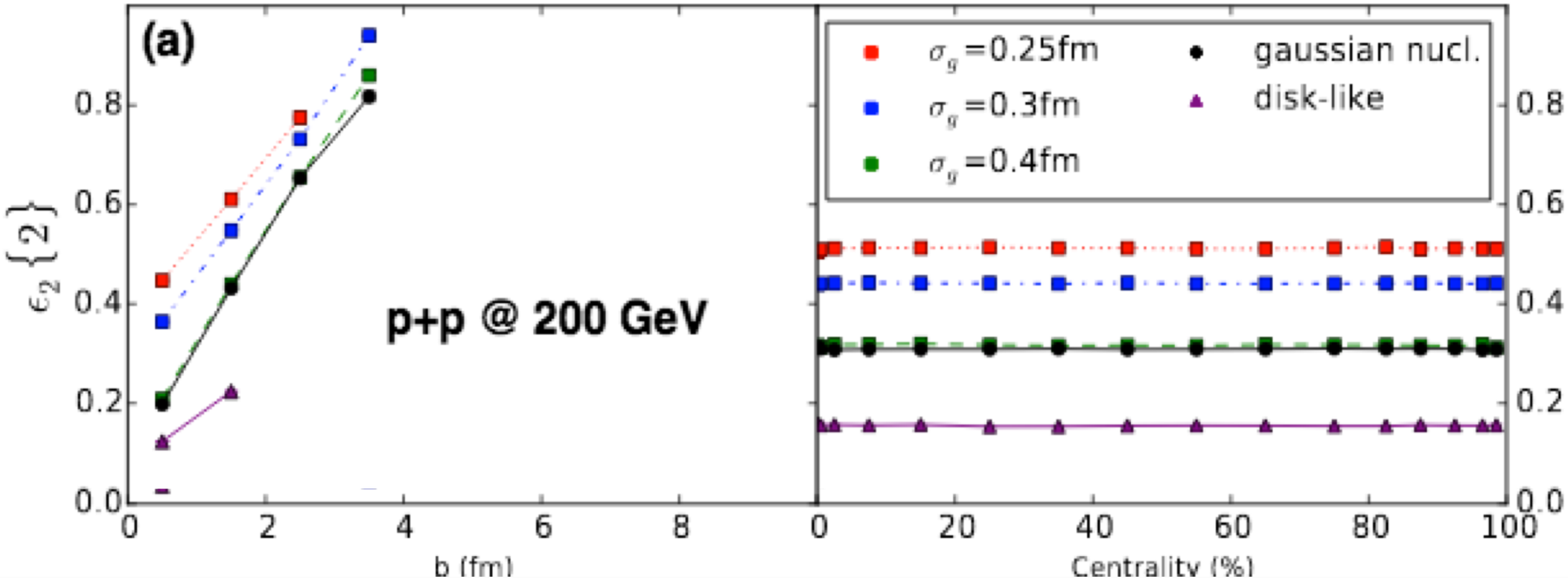
Consistent values for v_2 between 5.02 TeV and 13 TeV pp collisions.

No dependence of v_2 on collision energy.



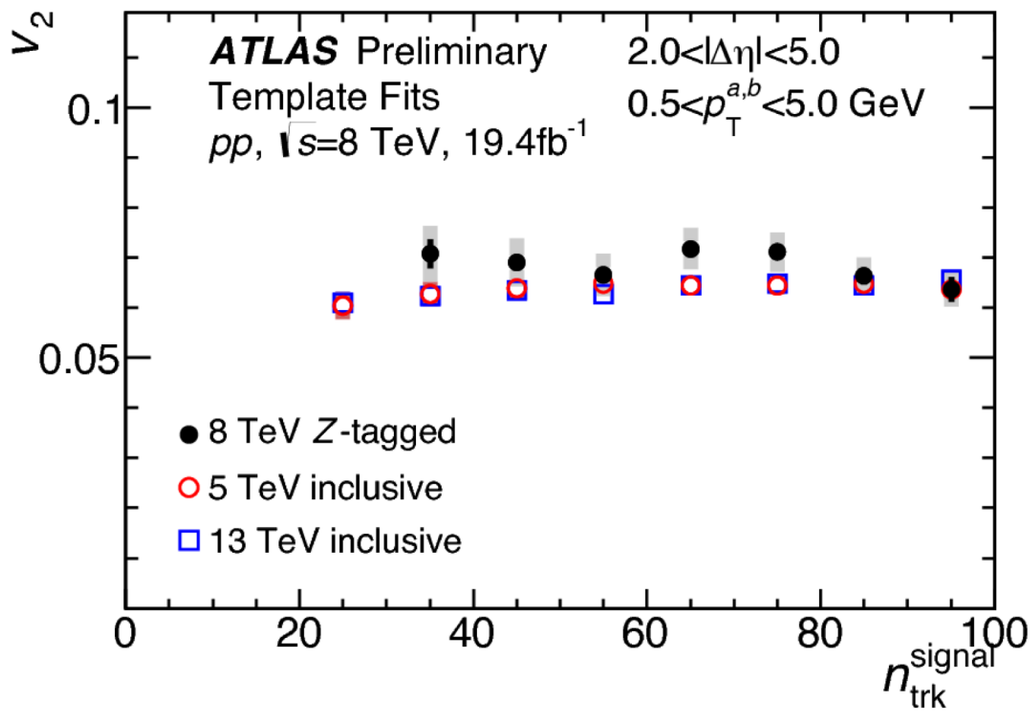
Phys. Rev. C 96 (2017) 024908

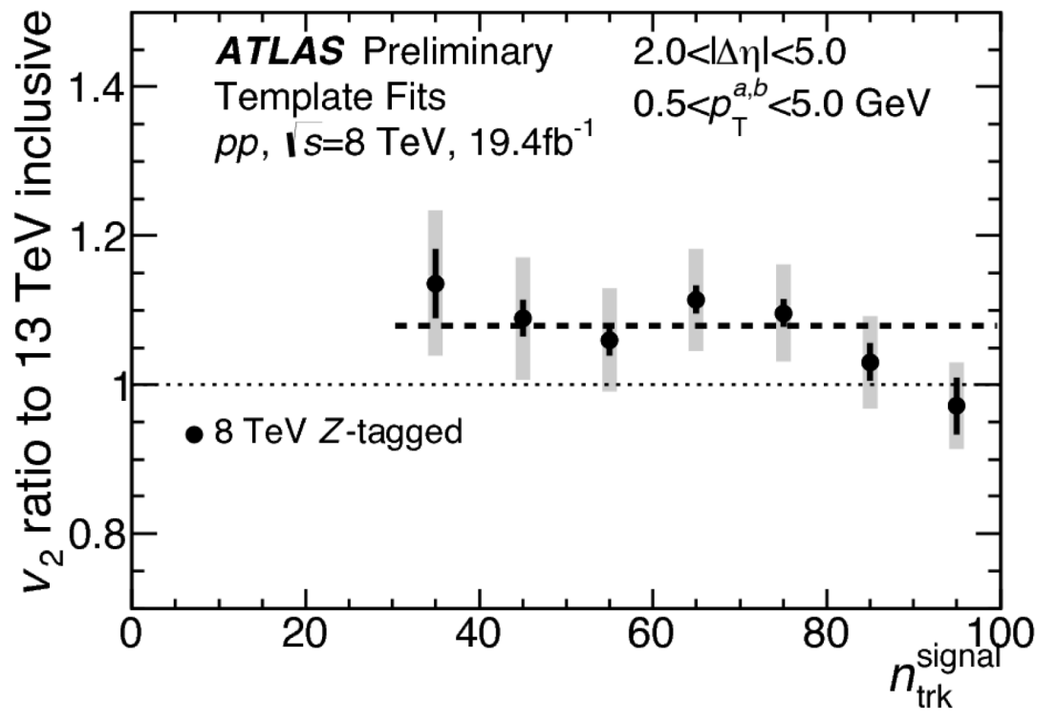
Why is there no multiplicity dependence in *pp* v_n



- One answer comes from U. Heinz and collaborators : Phys. Rev. C. 94.024919
- No correlation between multiplicity and eccentricity in *pp* collisions
- But correlation present between eccentricity and impact parameter
- Need to bin *pp* events not by multiplicity but by impact parameter!

v_2 in Z-boson tagged pp events





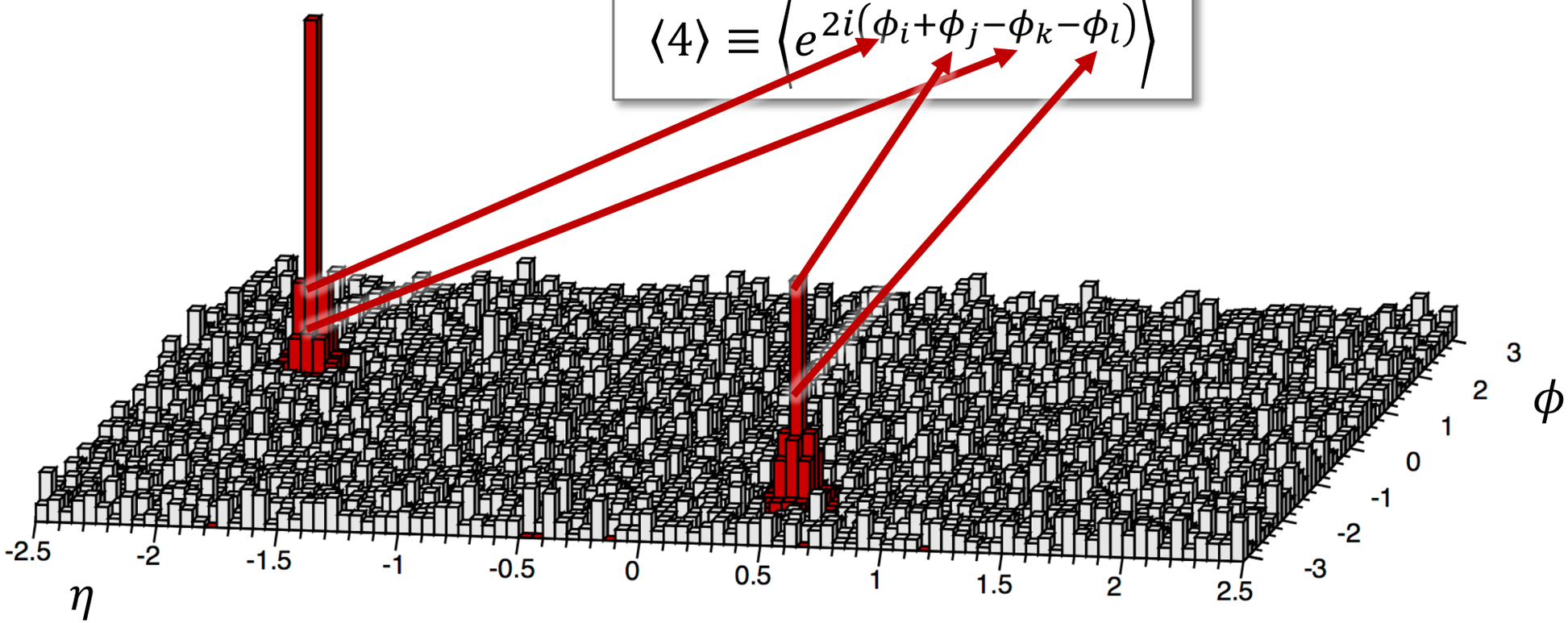
- Can constrain smaller impact parameter indirectly: by requiring the presence of a hard scattering, for example presence of a Z-boson.
- Recently done by ATLAS using high-luminosity *pp* data at 8 TeV
- The *pp*-v_2 in Z-boson tagged events shows slight increase rather than a decrease!

ATLAS-CONF-2017-068

Standard cumulants

- In standard cumulant, non-flow sources contribute to four-particle correlation ⟨4⟩;

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



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

Subevent cumulants

- In standard cumulant, non-flow sources contribute to four-particle correlation ⟨4⟩;
- In the subevent method, particles are correlated across all subevents (long-range).
  - 3 subevent cumulant can further suppress away-side jet contribution;

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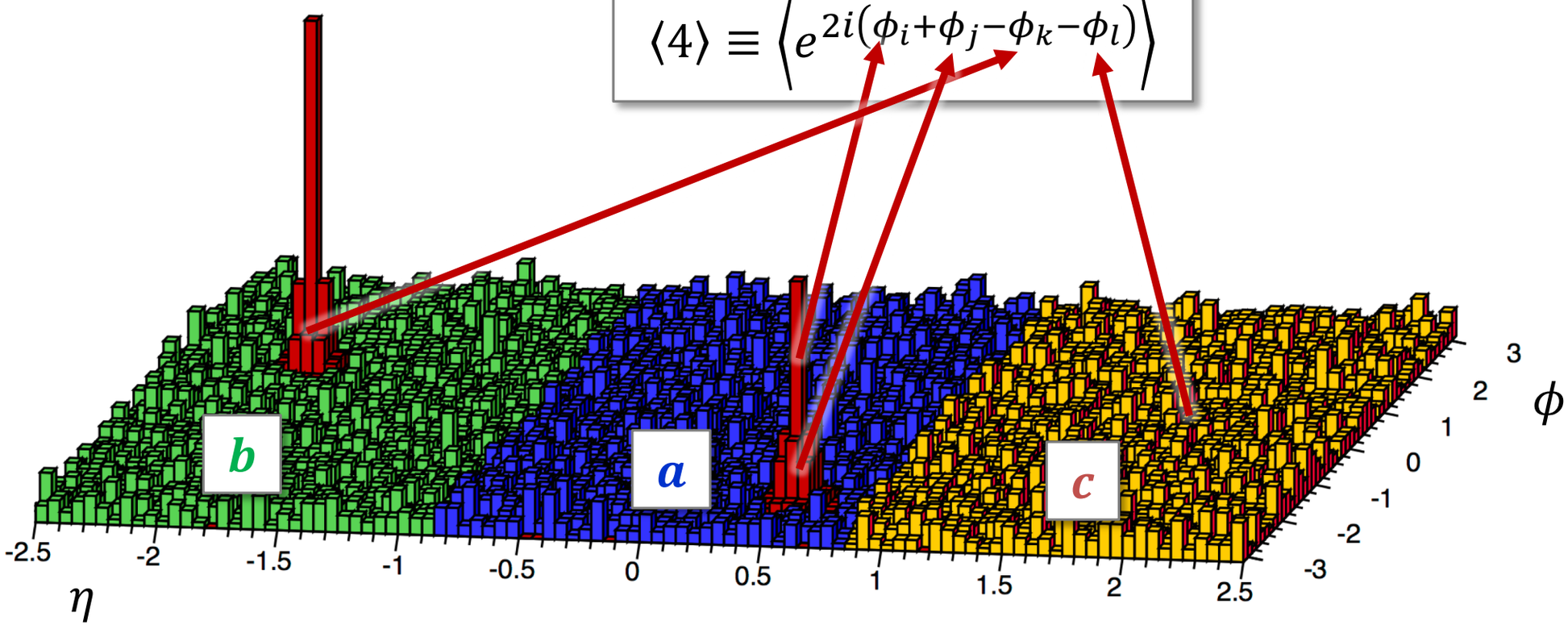

$$C_2^{2a|b,c}\{4\} \equiv \langle 4 \rangle_{2a|b,c} - 2\langle 2 \rangle_{a|b}\langle 2 \rangle_{a|c}$$

Phys. Rev. C 96, 034906 (2017)

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- 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
- Also check data-driven way.

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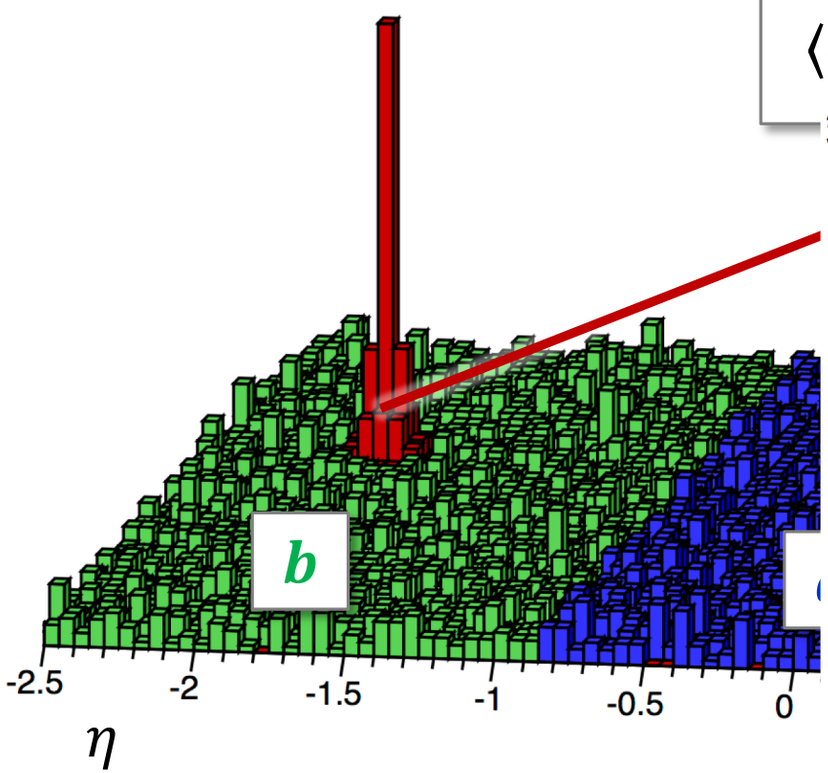

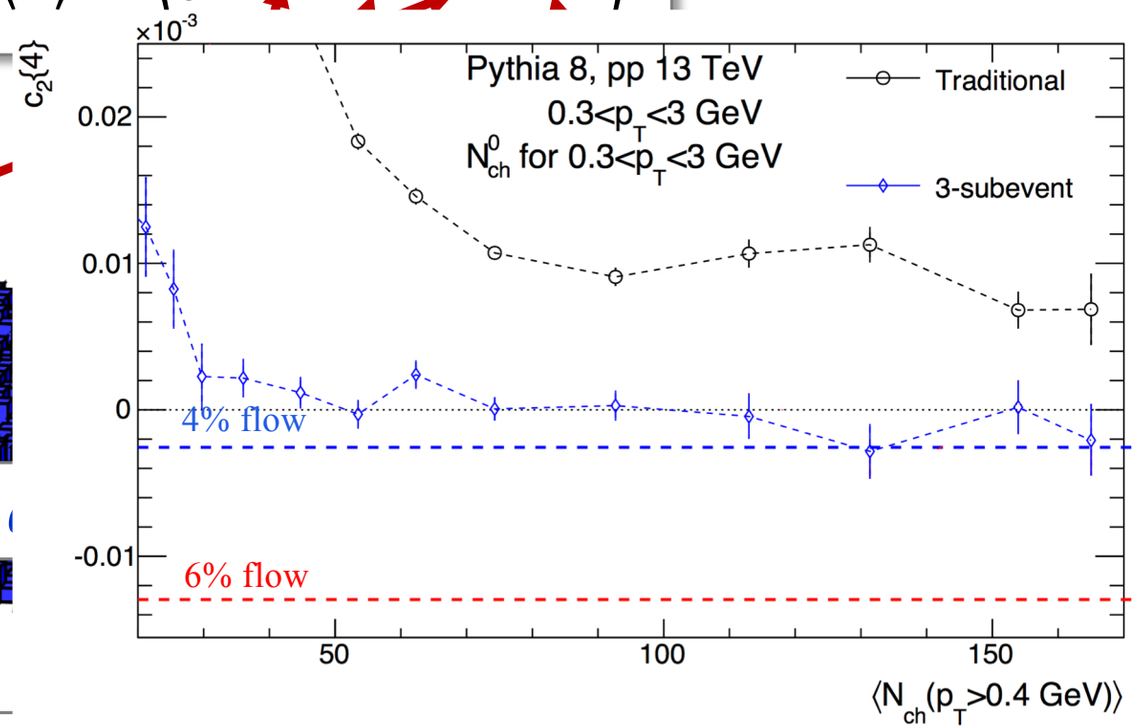

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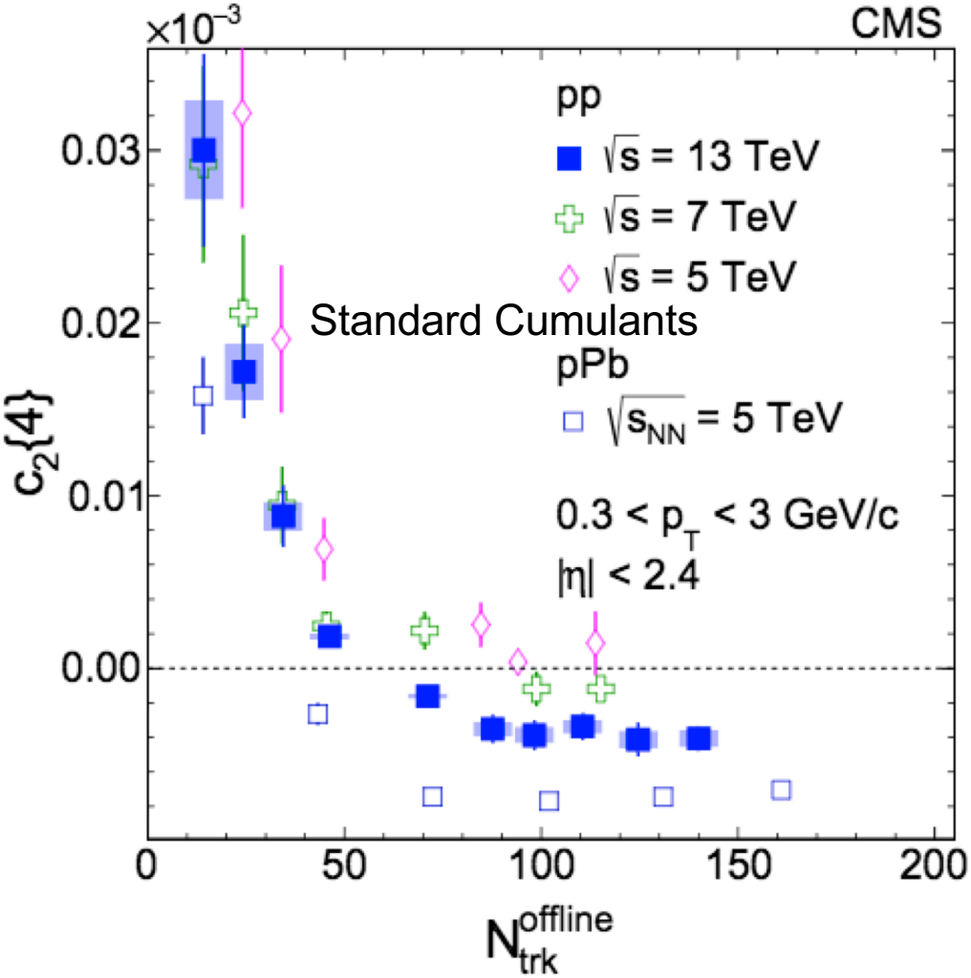
Cumulants: Energy dependence



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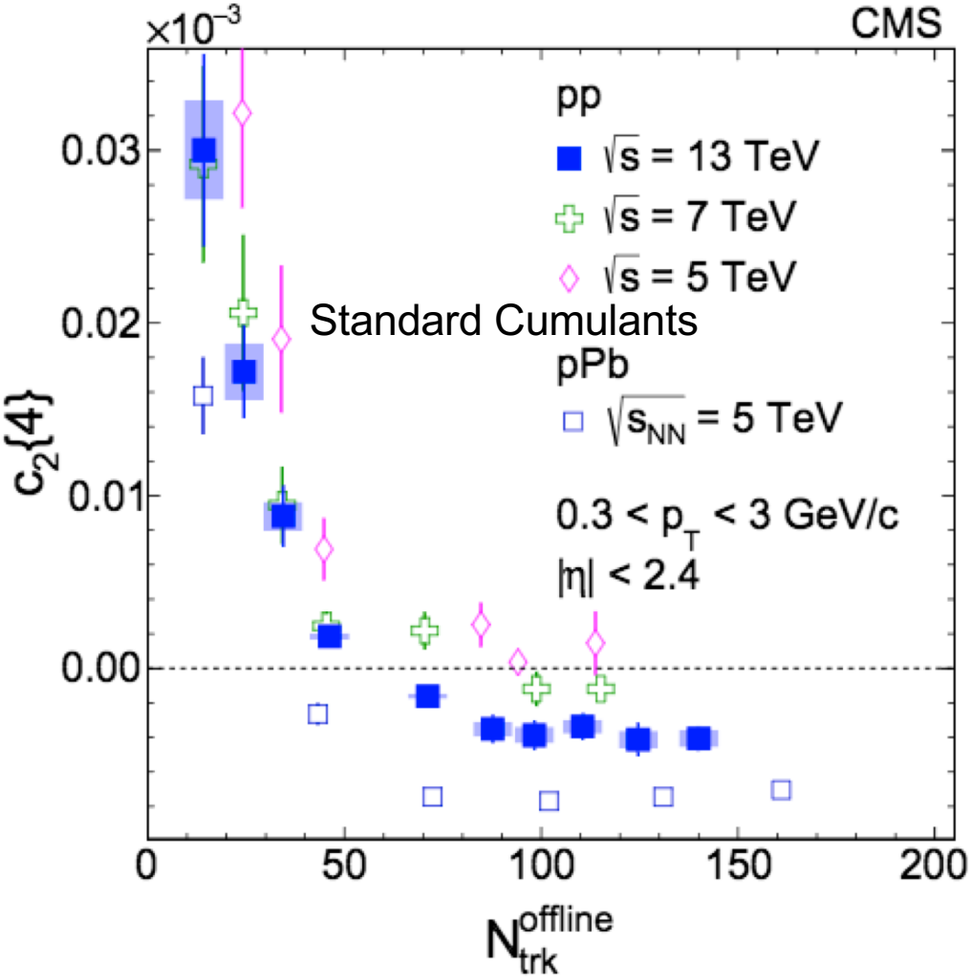
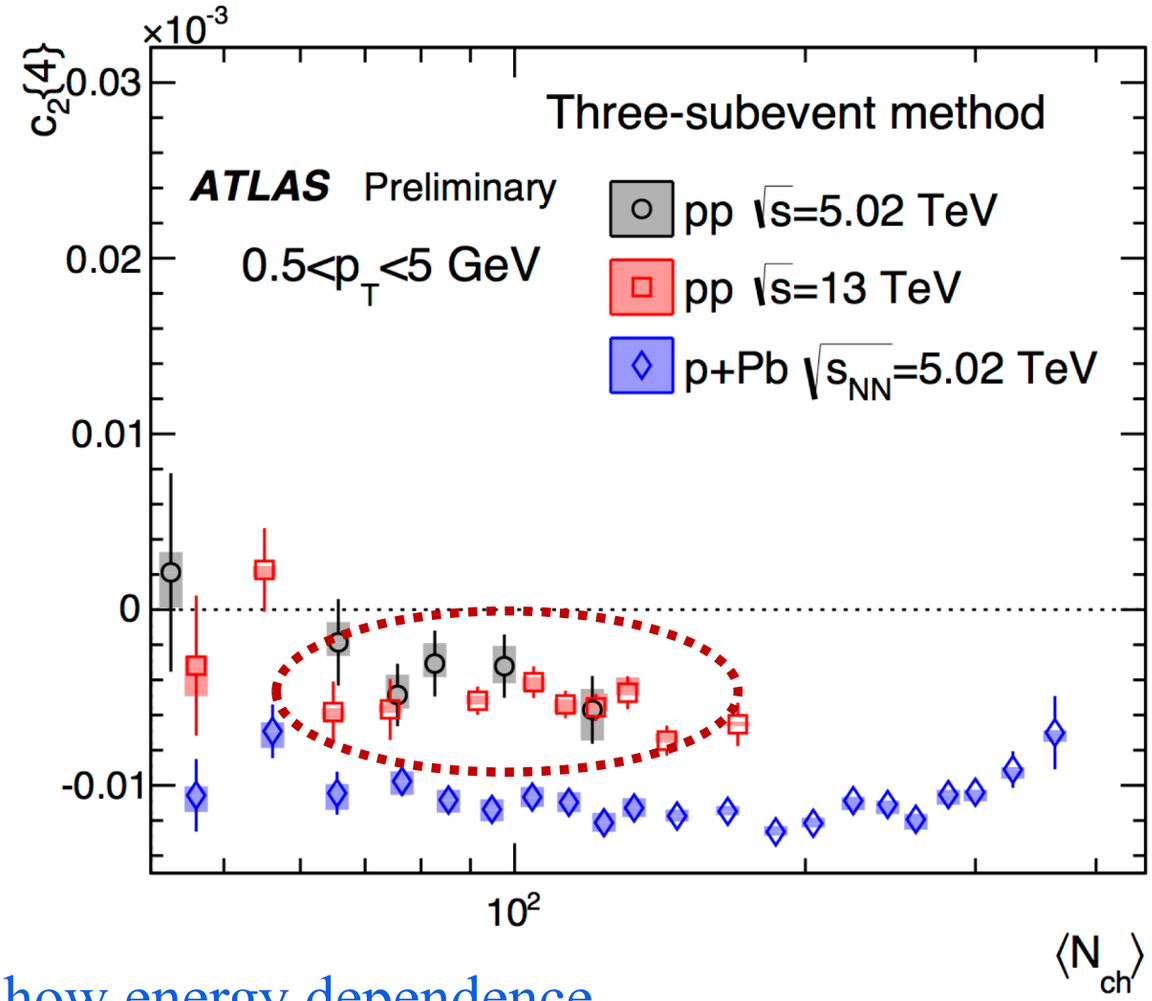
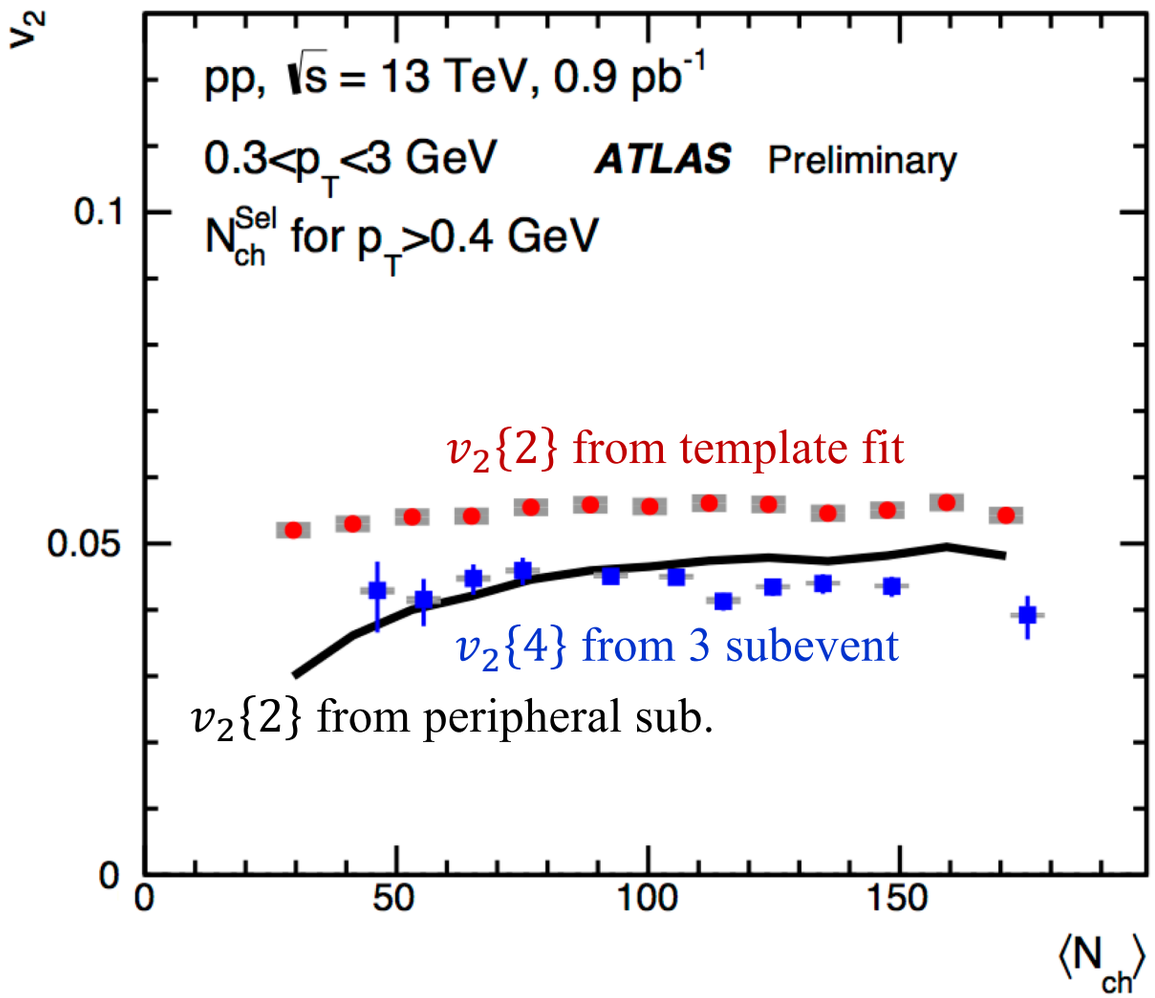




- *pp* results from standard cumulants show energy dependence
  - No such dependence was seen in the Template (or 2PC) v_2
  - $c_2\{4\}$ is +ve at 5TeV
- With 3 subevent, negative $C_2\{4\}$ observed in 5.02 TeV *pp*;
- Weak energy dependence in *pp* restored.
- *p*+Pb has larger flow than *pp* in the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

$v_2\{4\}$: Multiplicity dependence



- $v_2\{4\}$ consistent with no. multiplicity dependence (For $N_{ch}>50$)
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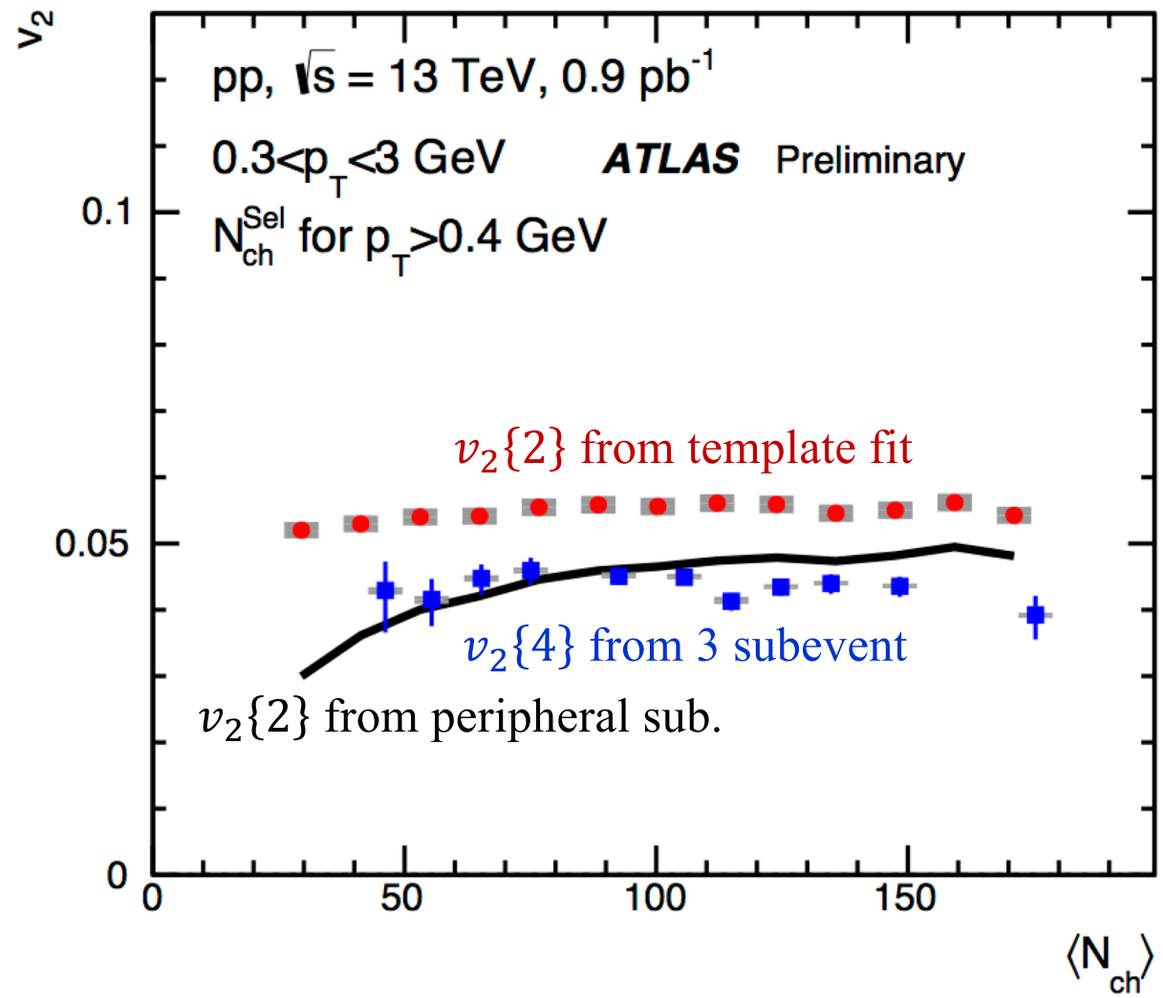
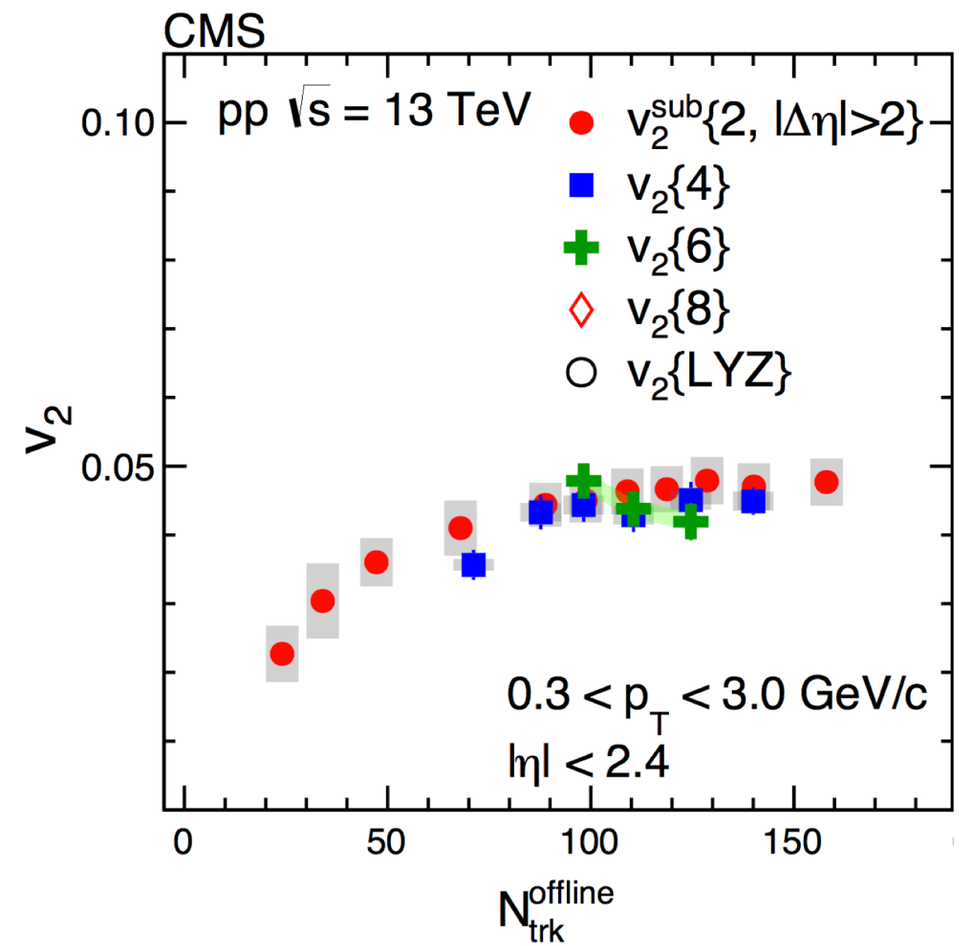
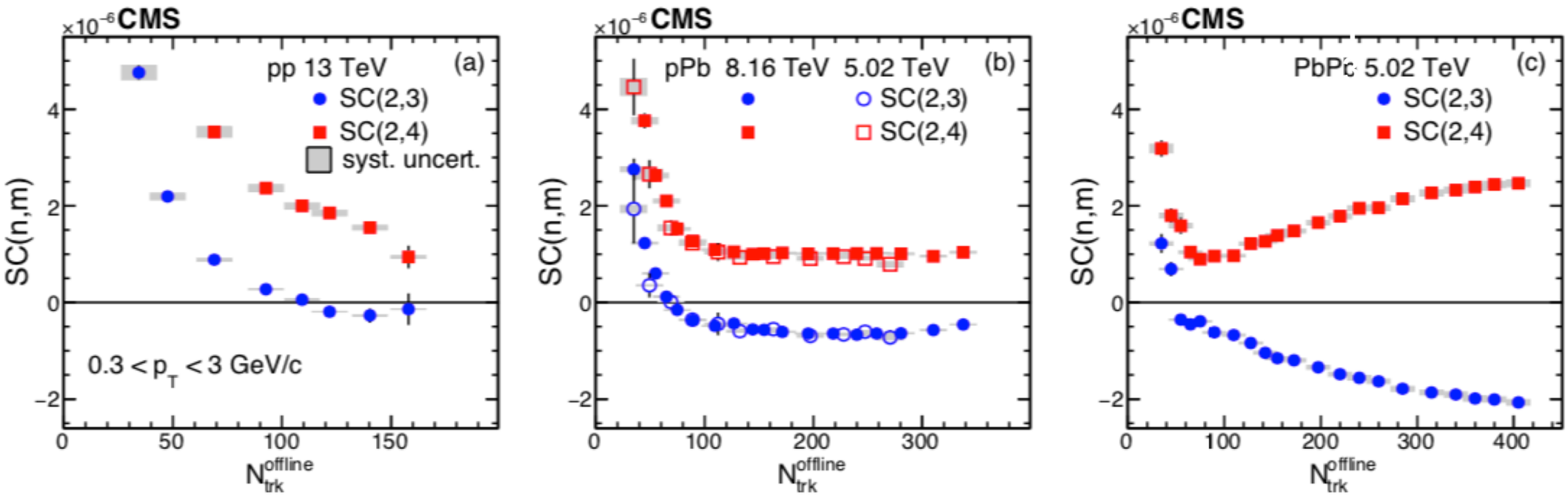




- $v_2\{4\}$ consistent with no. multiplicity dependence (For $N_{ch}>50$)
- $v_2\{4\} < v_2\{2\}$ (template fit): flow fluctuation;
- $v_2\{4\} \approx v_2\{2\}$ (peripheral subtraction): underestimation of $v_2\{2\}$;

Symmetric cumulants: v_n-v_m correlations

Phys. Rev. Lett. 120, 092301 (2018)



pp *p*+Pb Pb+Pb

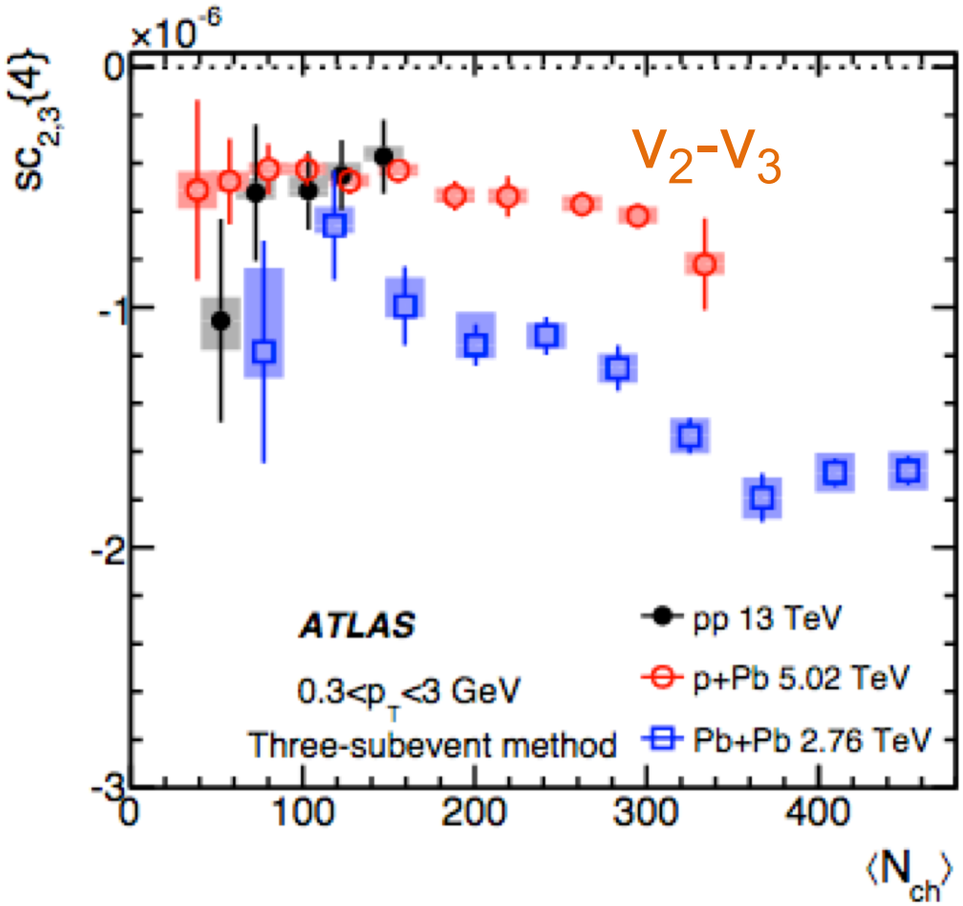
v_2-v_3 correlation

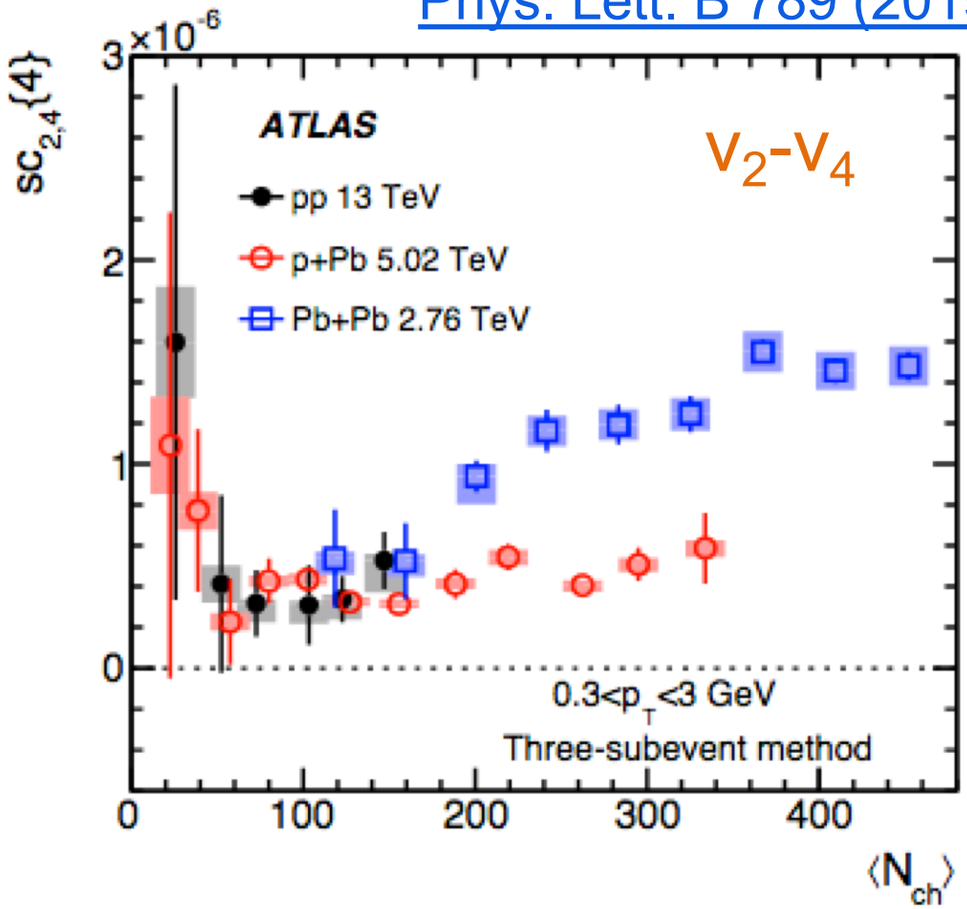
v_2-v_4 correlation

- Correlation between different order harmonic flows using symmetric cumulants in *pp*, *p*+Pb and Pb+Pb collisions
- In Pb+Pb, central *p*+Pb :v_2--v_3 anti-correlated, v_2--v_4 correlated.
- Across most of *pp* and peripheral *p*+Pb: v_2--v_3 correlated

Symmetric cumulants: v_n-v_m correlations

Phys. Lett. B 789 (2019) 444





- Correlation between different order harmonic flows using symmetric cumulants in *pp*, *p*+Pb and Pb+Pb collisions
- Measurements done using sub-event cumulants to suppress non-flow.
- Across all systems and multiplicities: v_2--v_3 anti correlated, v_2--v_4 correlated.
  - Indicates global correlations.

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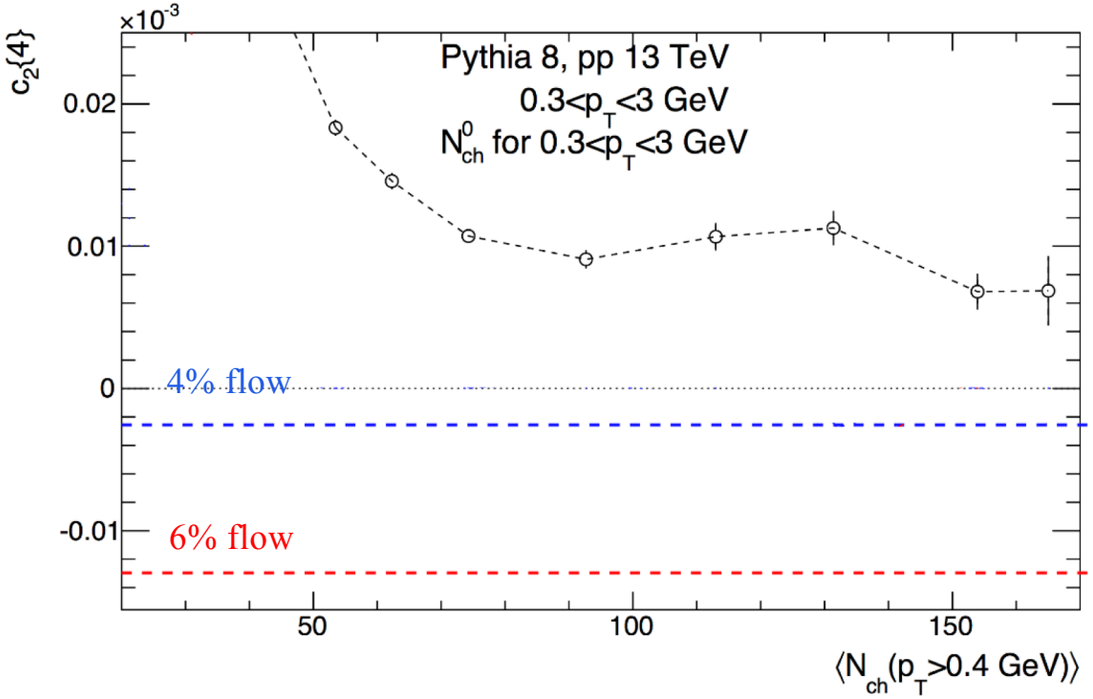
  - Can not be blindly used in *pp* collisions (PYTHIA non-closure)



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

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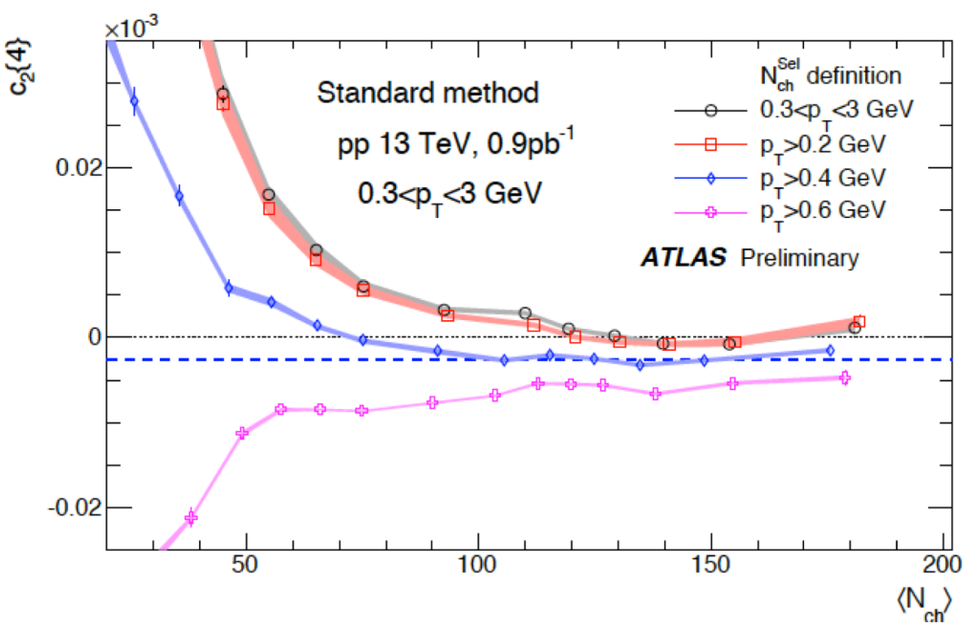
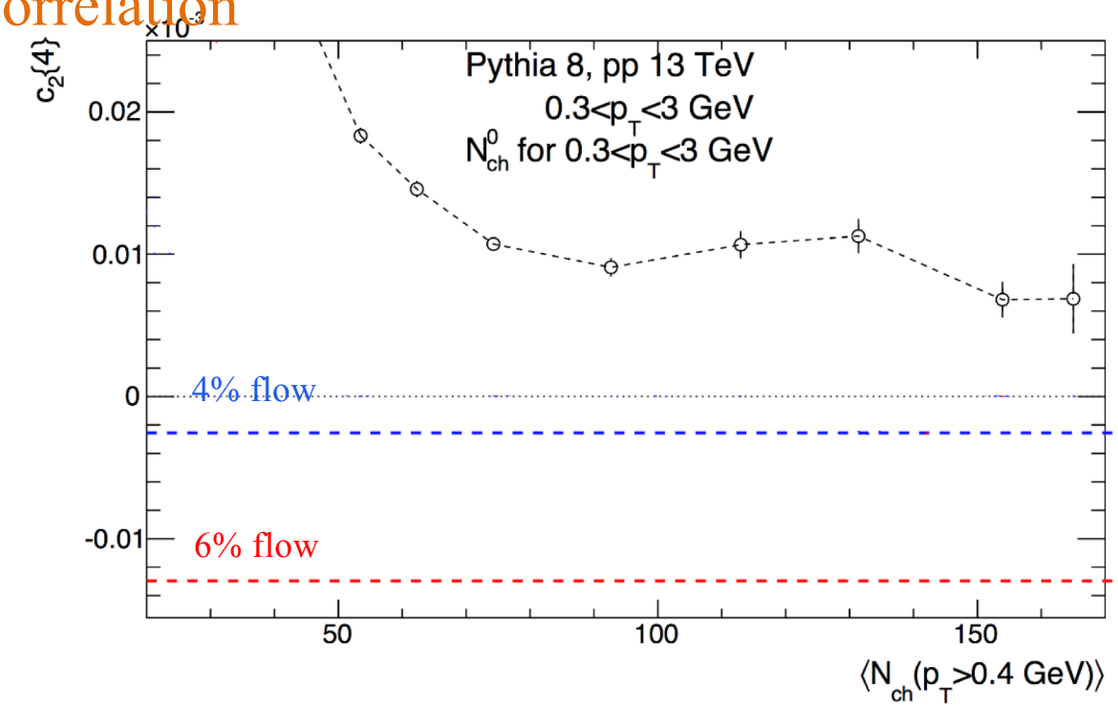
  - Multiplicity fluctuations mimic correlation





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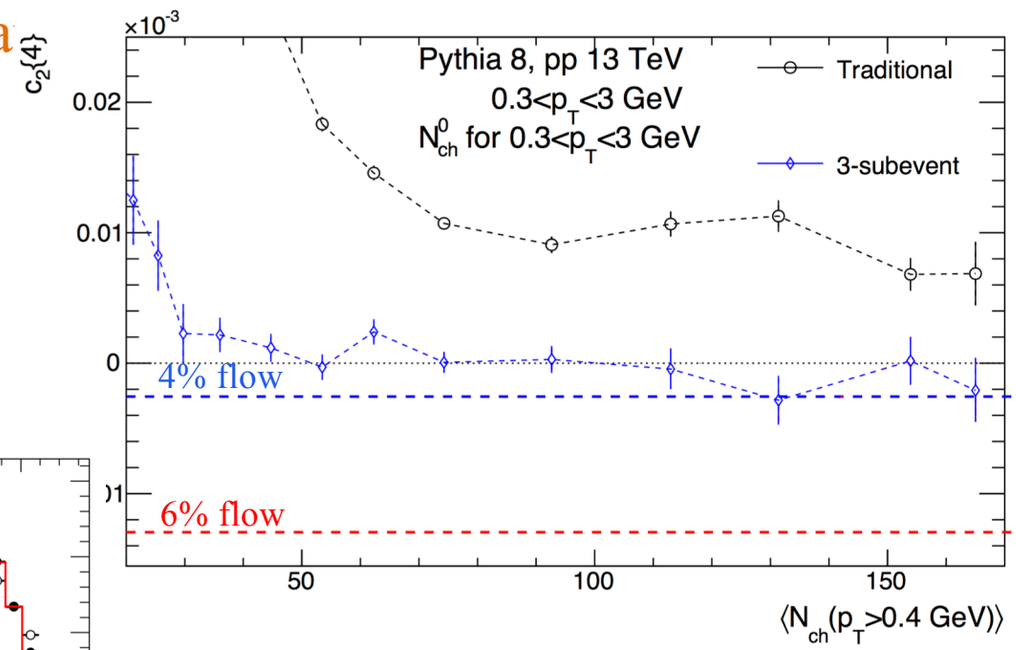
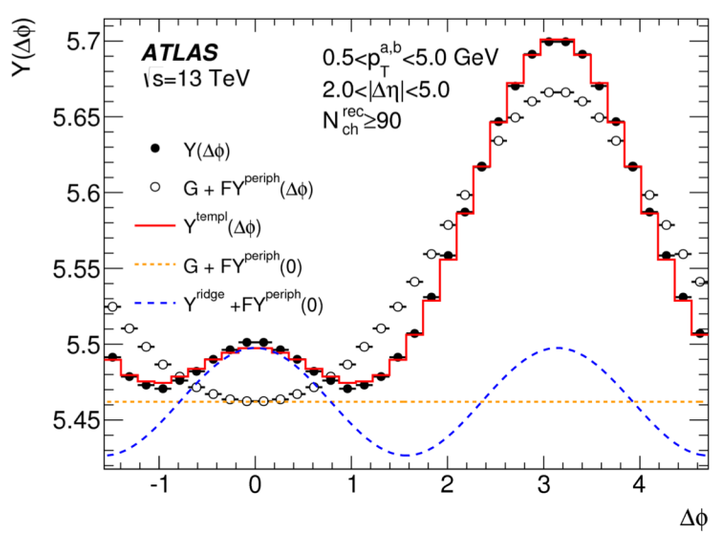


- Non-flow removal
  - Sub-event cumulants
  - Template fitting in 2PC



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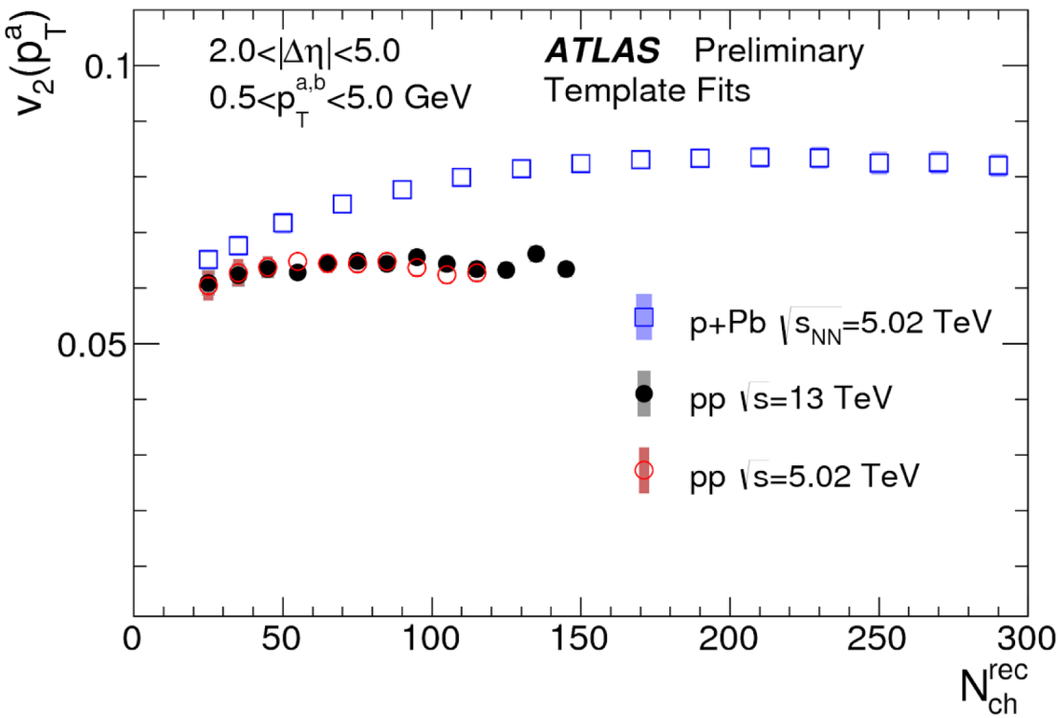

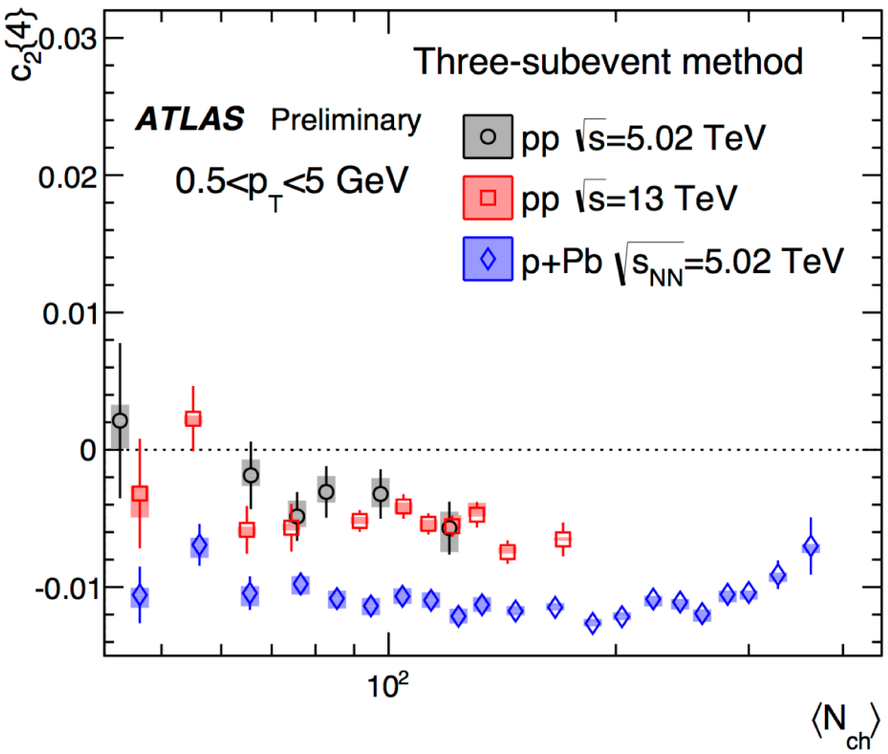

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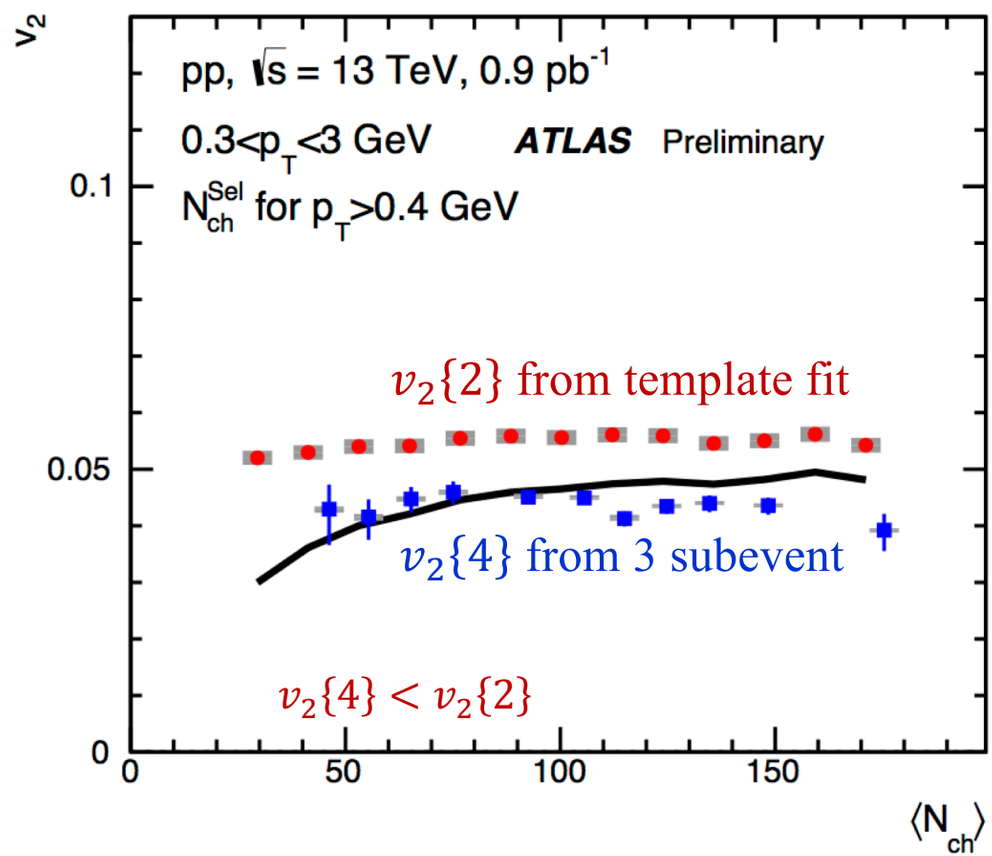
  - $v_2\{4\}<v_2\{2\}$
  - Event by event v_2 fluctuations



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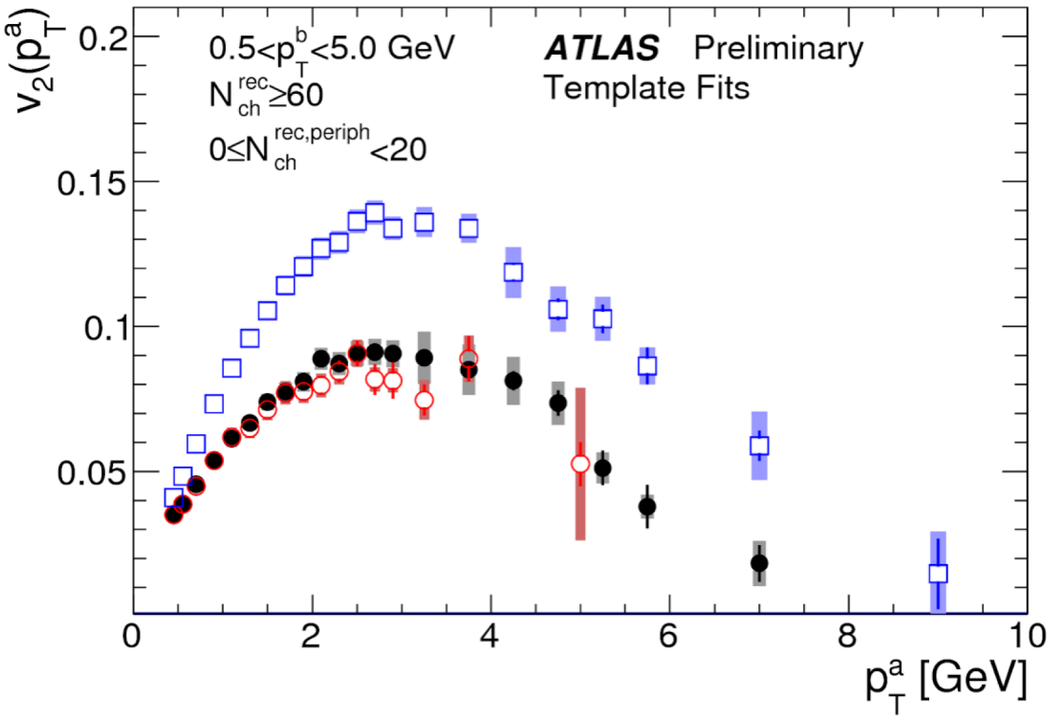

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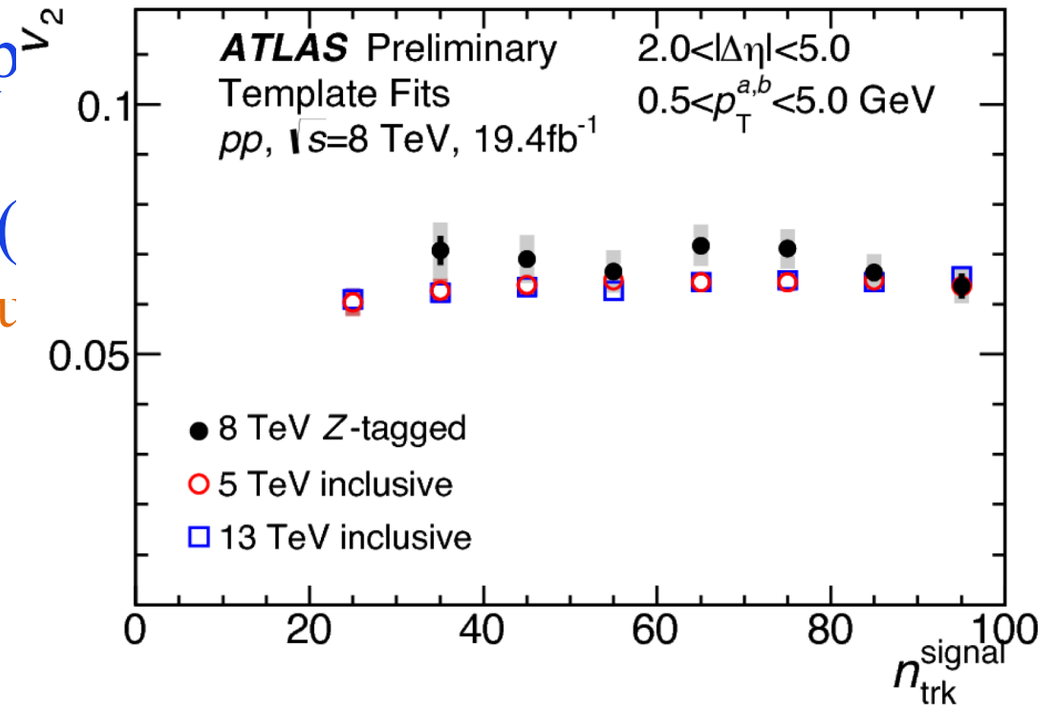

- p_T dependence qualitatively similar to AA and *p*+Pb collisions
- No/weak dependence on impact parameter?

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  - Seen both in 2PC as well as sub-event cumulants
- No dependence on multiplicity!
  - $v_2\{4\}<v_2\{2\}$
  - Event by event v_2 fluctuations
- p_T dependence qualitatively similar to AA and *p*+Pb collisions
- No/weak dependence on impact parameter?
- Global nature of collision does not imply hydrodynamic behavior
  - Relics of measurement technique may still be present!