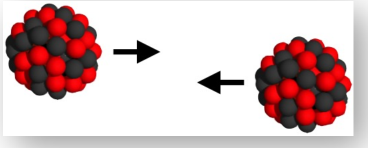
Characterizing the collective behavior in small and large systems with ATLAS

Pengqi (Bill) Yin, Columbia University, For the ATLAS Collaboration

May 21, 2021

New results since SQM2019

- Flow in large systems
  - HF muon+hadron correlations in Pb+Pb, Phys. Lett. B 807 (2020) 135595
  - Charged particle flow in Xe+Xe, Phys. Rev. C 101 (2020) 024906
  - Flow decorrelation in Xe+Xe and Pb+Pb, Phys. Rev. Lett. 126 (2021) 12230
  - v_n – [p_T] correlation in Xe+Xe and Pb+Pb, ATLAS-CONF-2021-001



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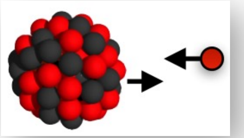
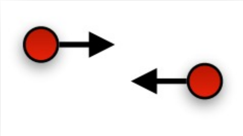
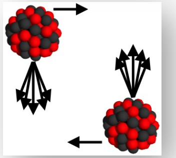
  - High-p_T correlations in *p*+Pb, Eur. Phys. J. C 80 (2020) 73
  - HF muon+hadron correlations in *pp*, Phys. Rev. Lett. 124 (2020) 082301
  - Sensitivity of flow to jets in *pp*, ATLAS-CONF-2020-018
  - Z-tagged ridge in *pp*, Eur. Phys. J. C 80 (2020) 64
  - Photo-nuclear 2PC in Pb+Pb, CERN-EP-2020-246







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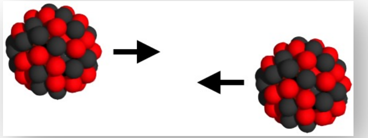
  - v_n – [p

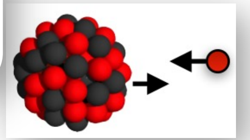


- Flow in

Heavy flavor production and modification in ATLAS

James Nagle, Tue 5/18 10:30

  - High-p



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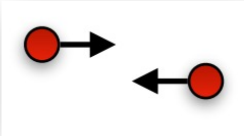

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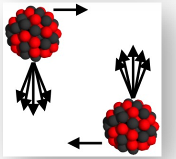
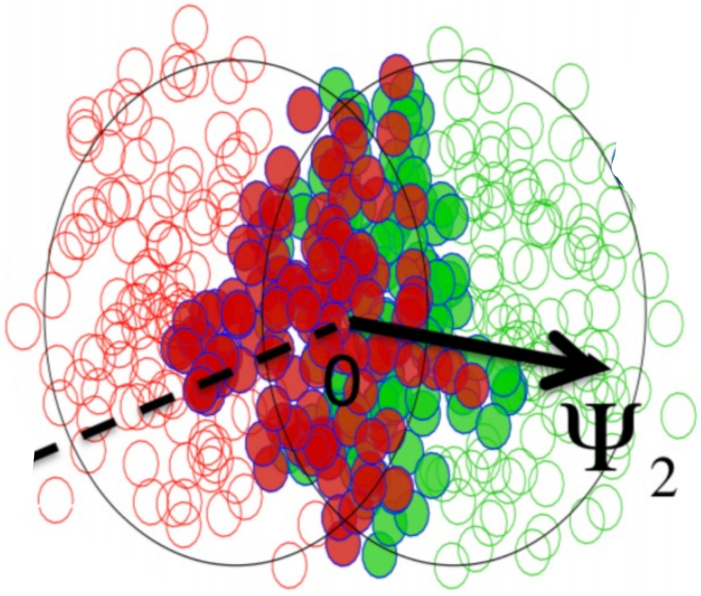


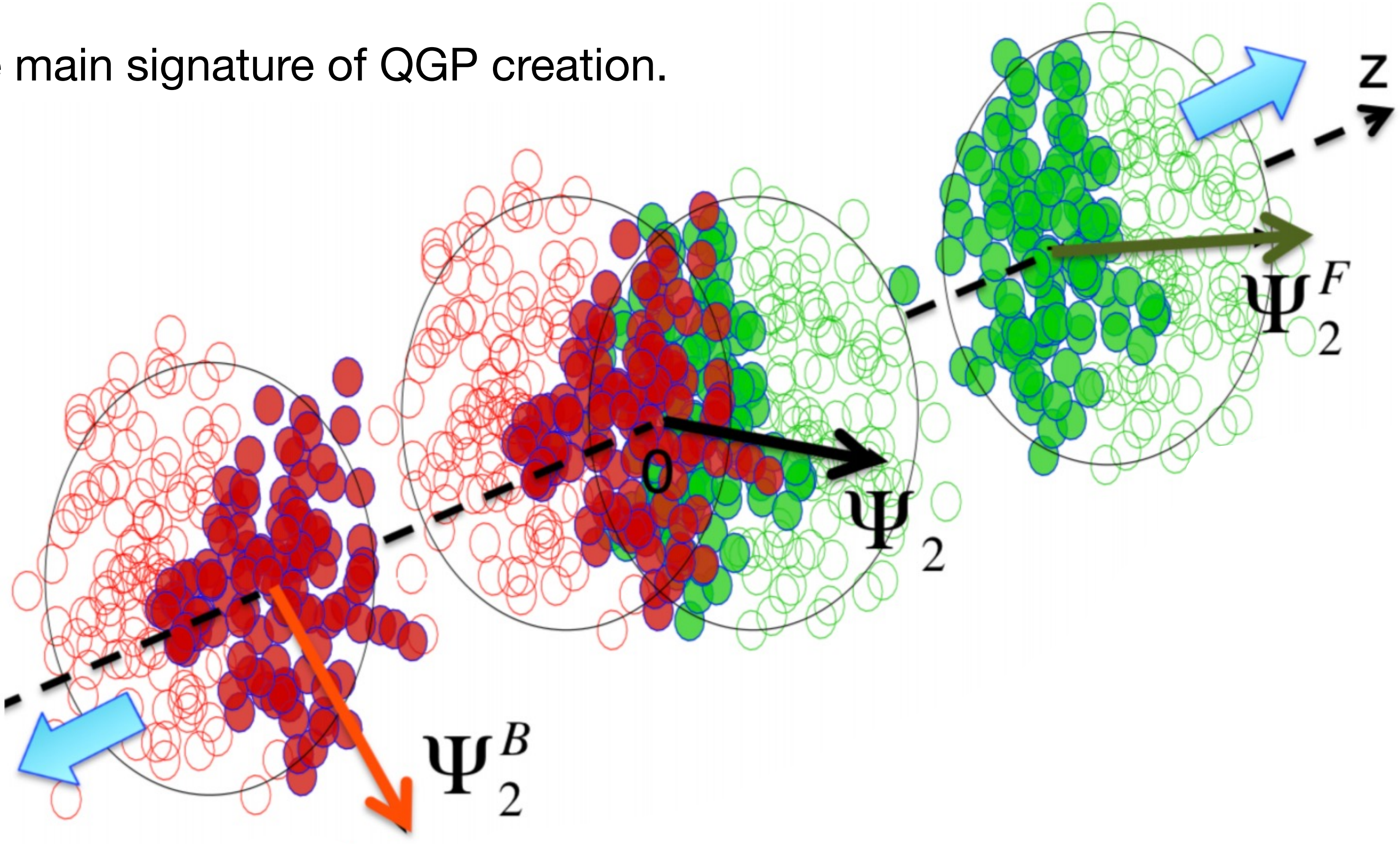
Flow phenomenon

- One of the main signature of QGP creation.



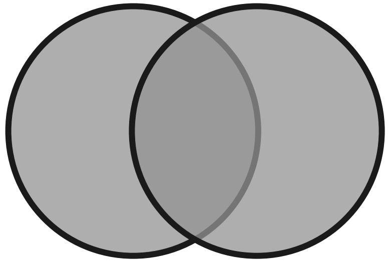
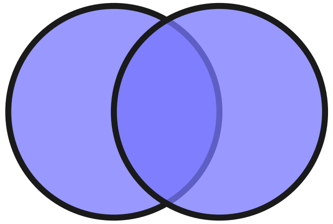
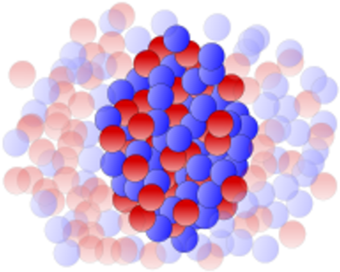
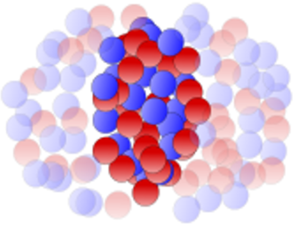
Flow and longitudinal flow decorrelation

- One of the main signature of QGP creation.



- The asymmetry from forward and backward going nucleons gives longitudinal flow fluctuation.
- Help understanding the hydrodynamic expansion, the initial state geometry and fluctuations.

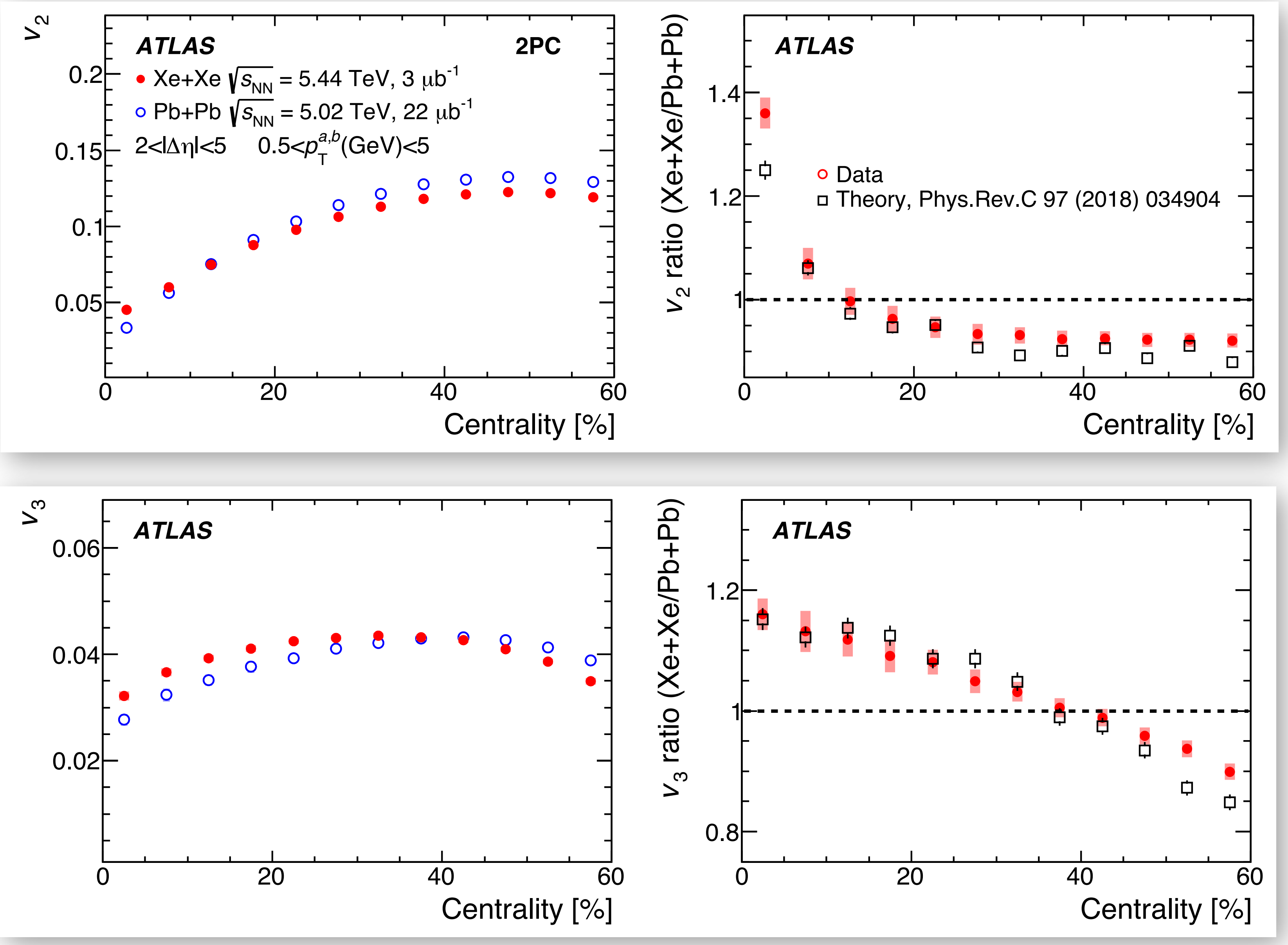
System-size Dependence

Pb+Pb A=208, R=7.5 fm	Xe+Xe A=129, R=6.4 fm		
		Smooth geometry + Ideal hydrodynamics	“Identical v_n”
		Fluctuating geometry + Ideal hydrodynamics	Larger v_n in Xe+Xe
		Fluctuating geometry + Viscous hydrodynamics	

Phys. Rev. C **97**, 034904 (2018)

Charged particle flow in Xe+Xe

Phys. Rev. C 101 (2020) 024906



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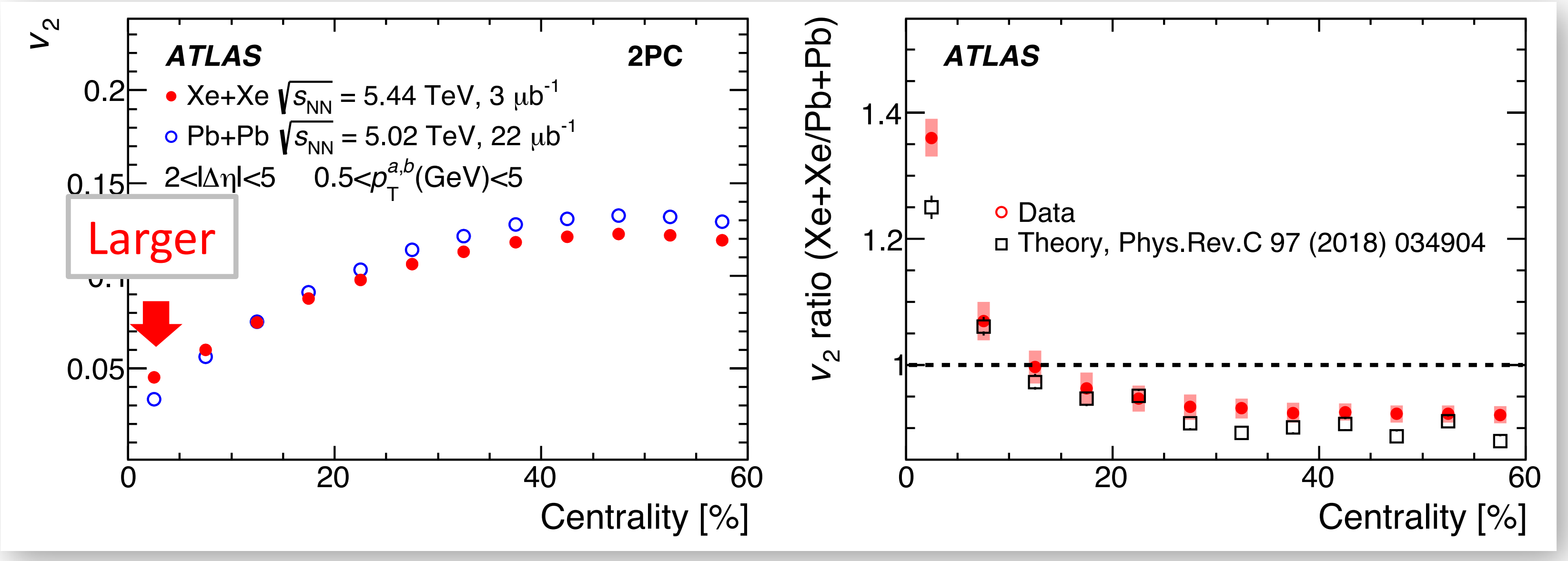
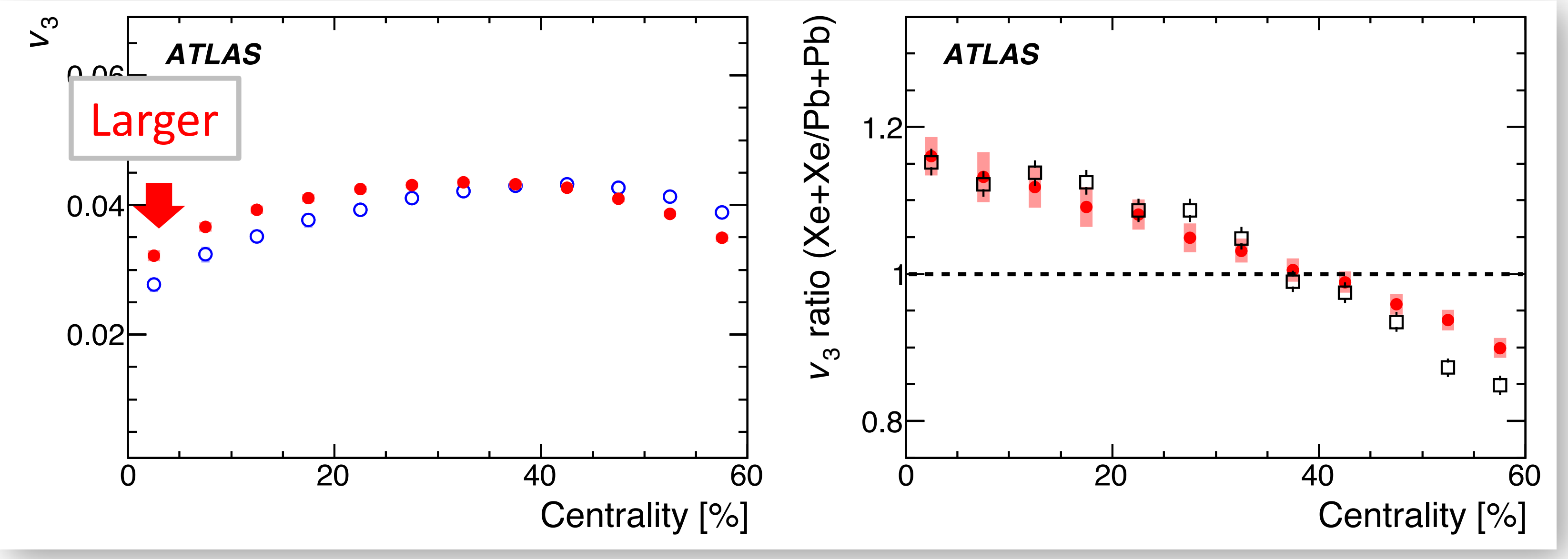
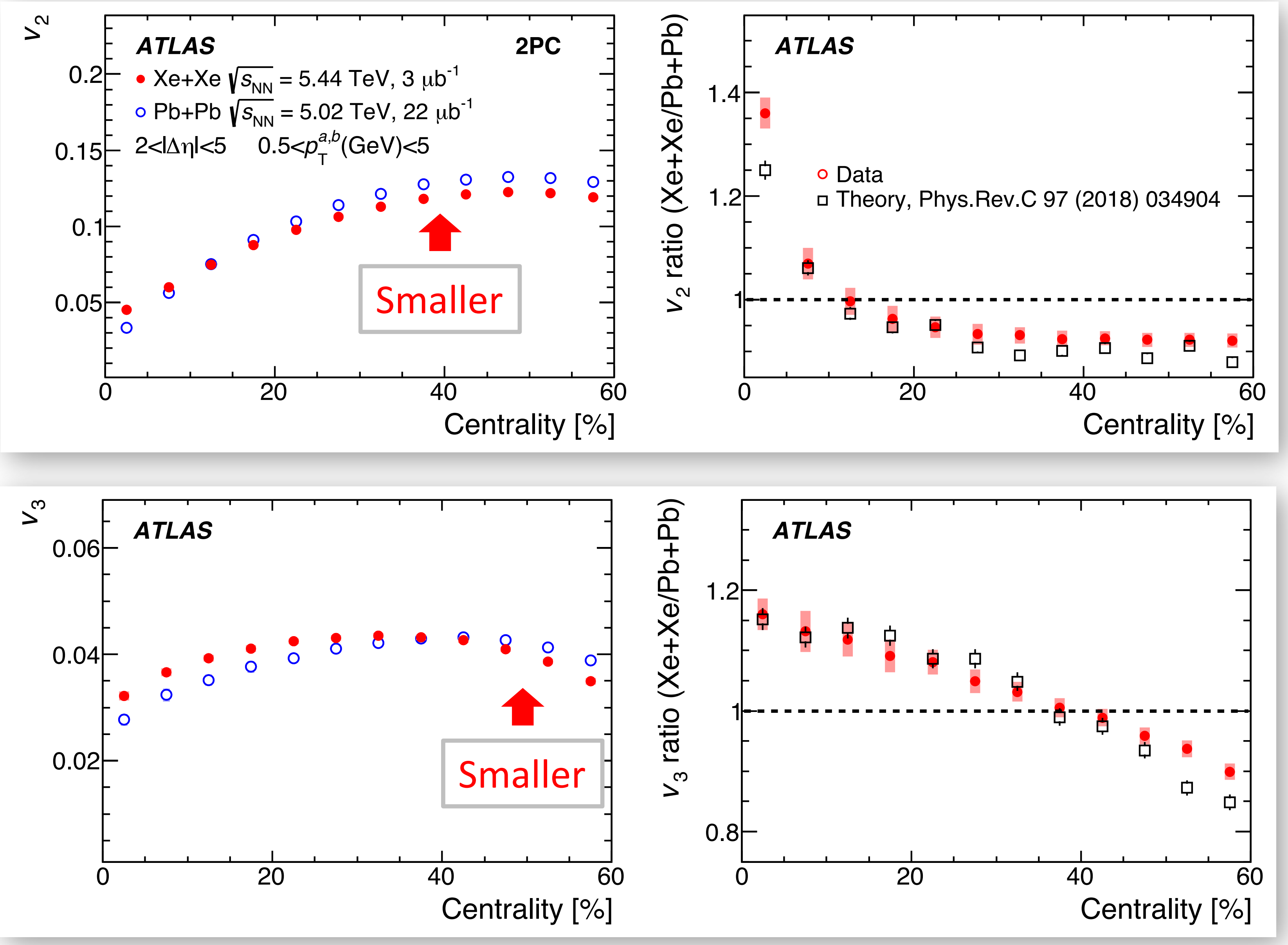




Most central events are dominated by fluctuation effects.

Charged particle flow in Xe+Xe

Phys. Rev. C 101 (2020) 024906



Most central events are dominated by fluctuation effects.

Larger viscous effects when going to more peripheral events.

Charged particle flow in Xe+Xe

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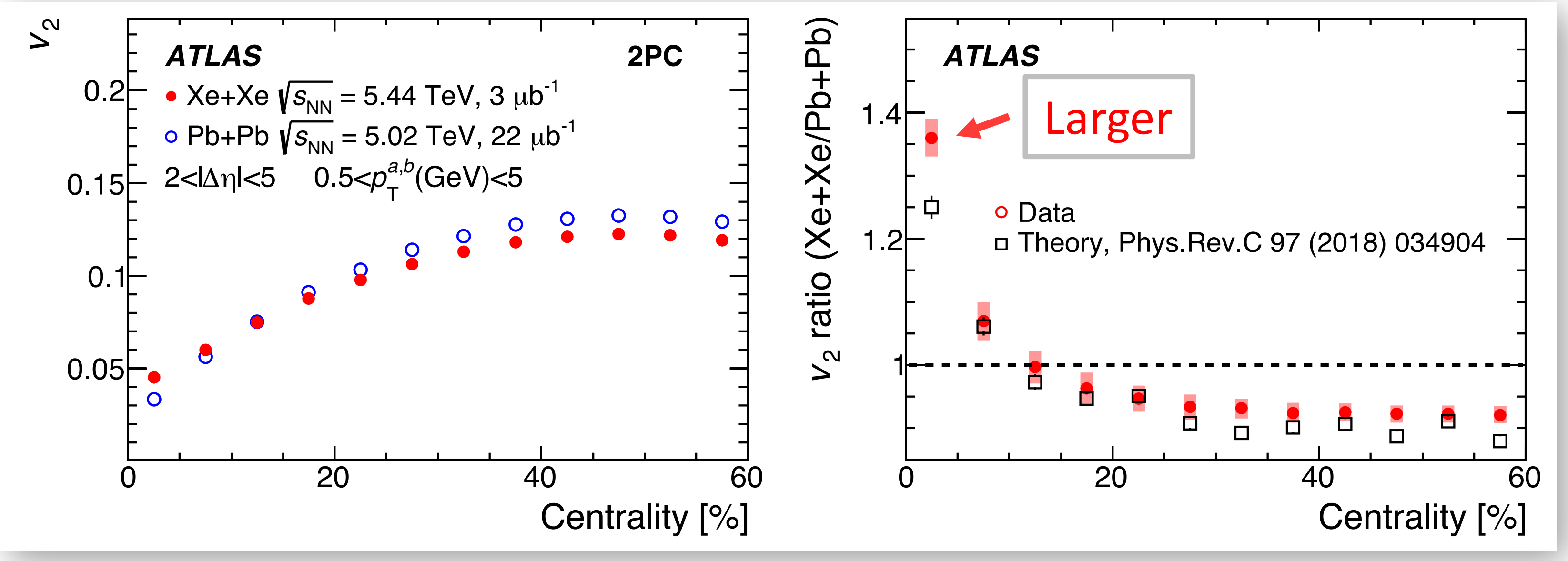

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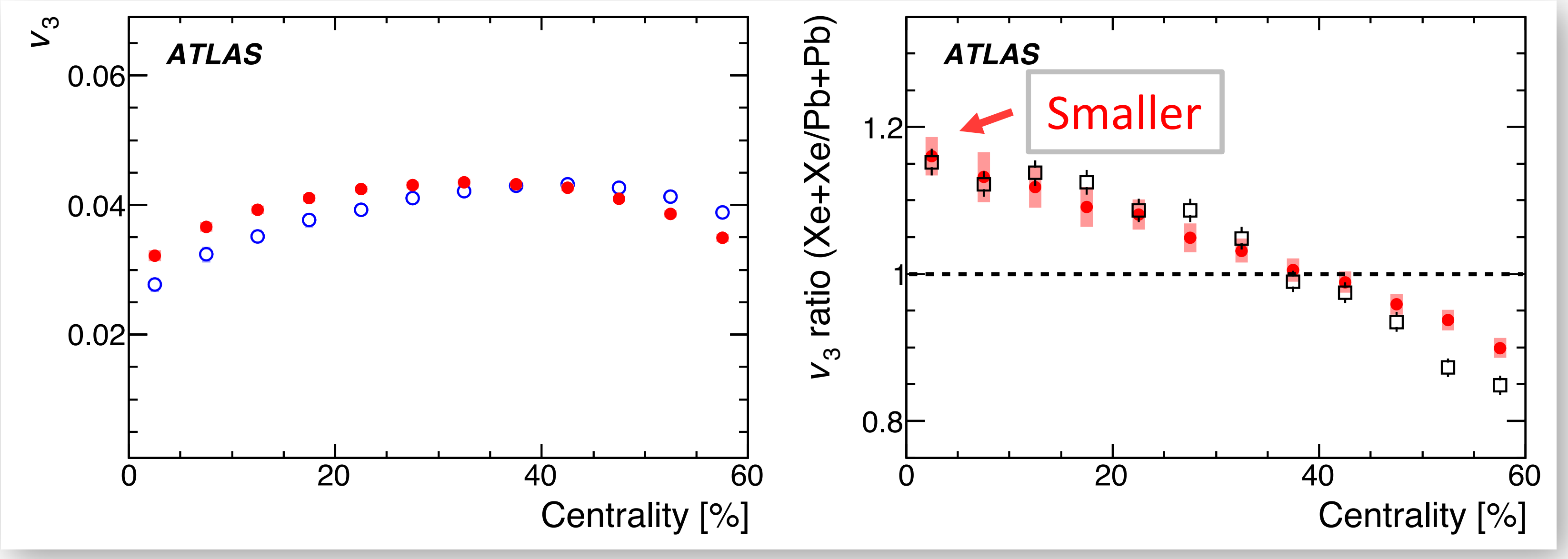
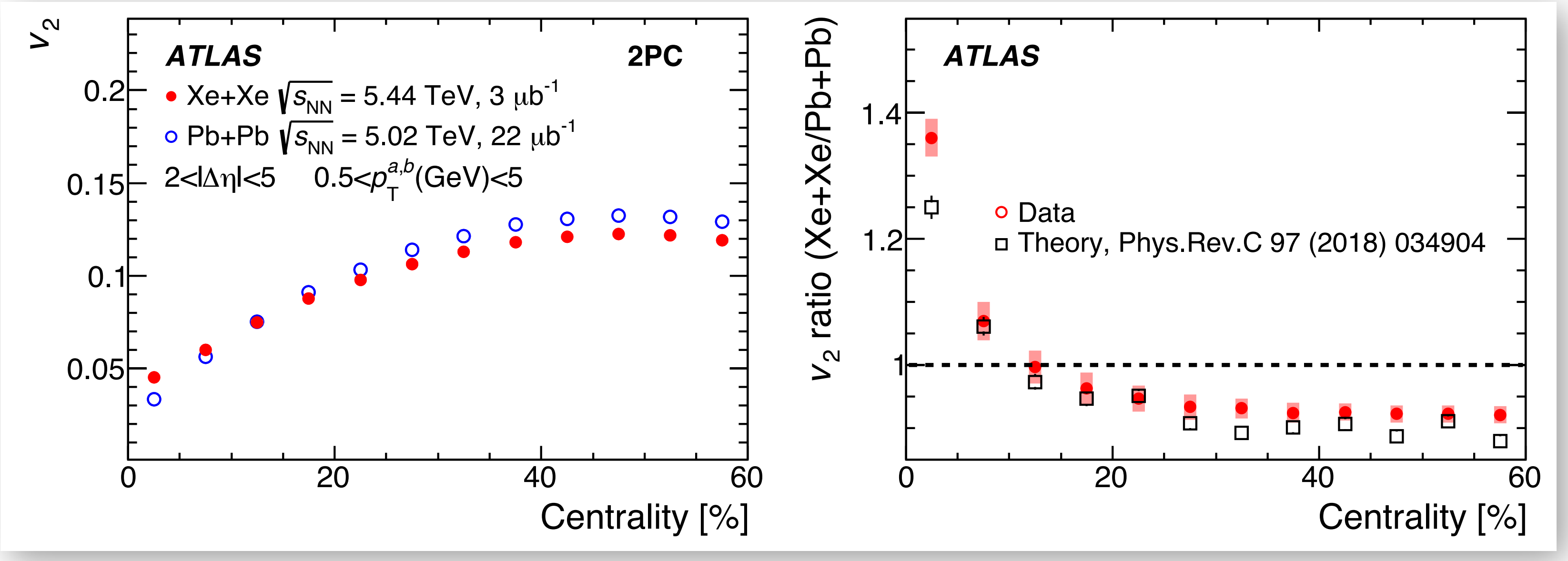
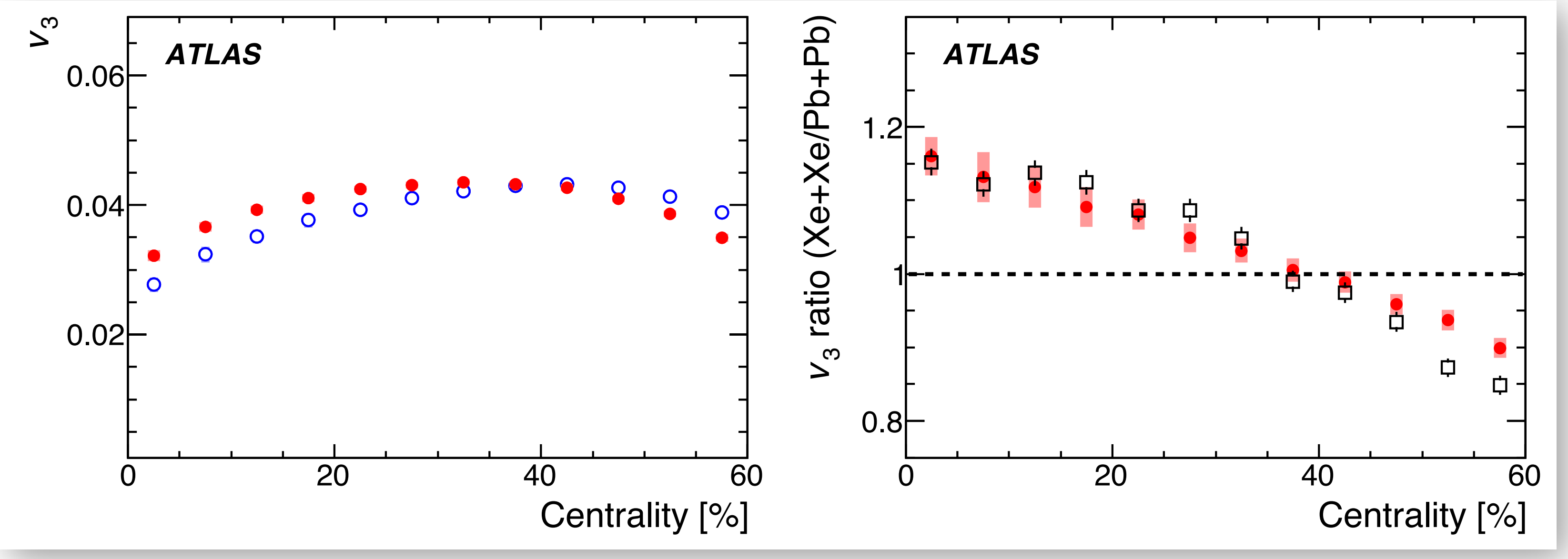


With increasing harmonic, viscous effects lower the v_n in Xe+Xe.

Charged particle flow in Xe+Xe

Phys. Rev. C 101 (2020) 024906





Most central events are dominated by fluctuation effects.

Larger viscous effects when going to more peripheral events.

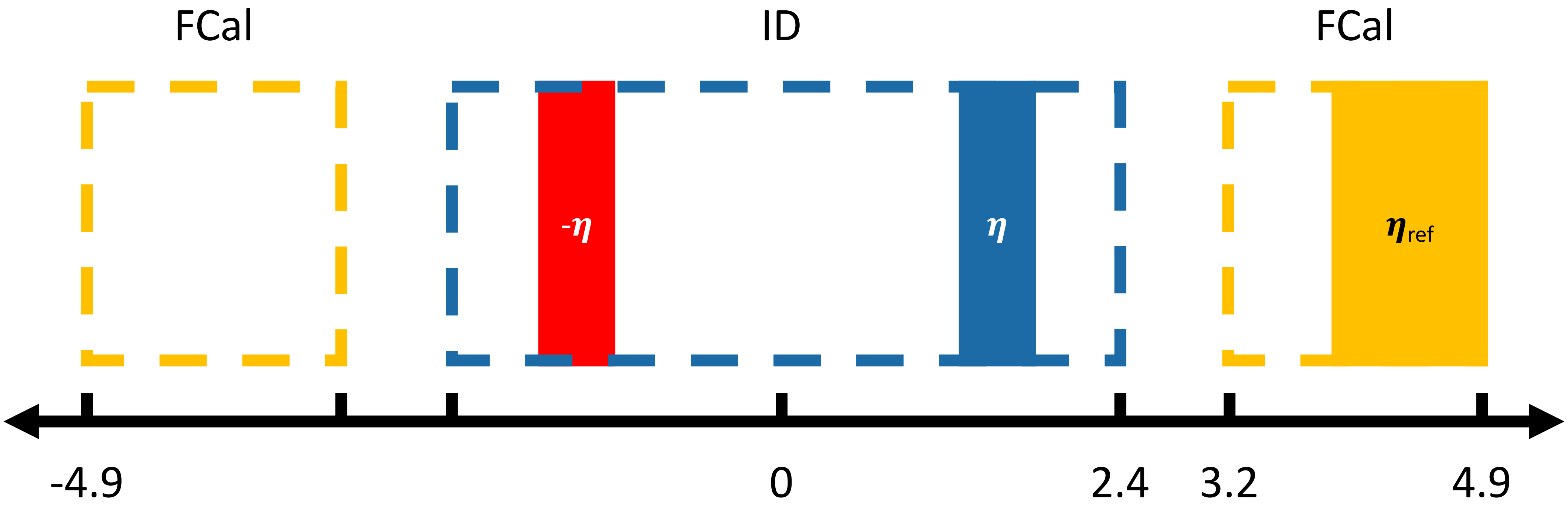
With increasing harmonic, viscous effects lower the v_n in Xe+Xe.

Interplay of fluctuations in the collision geometry and viscous effects.

Flow decorrelation

Phys. Rev. Lett. 126 (2021) 12230

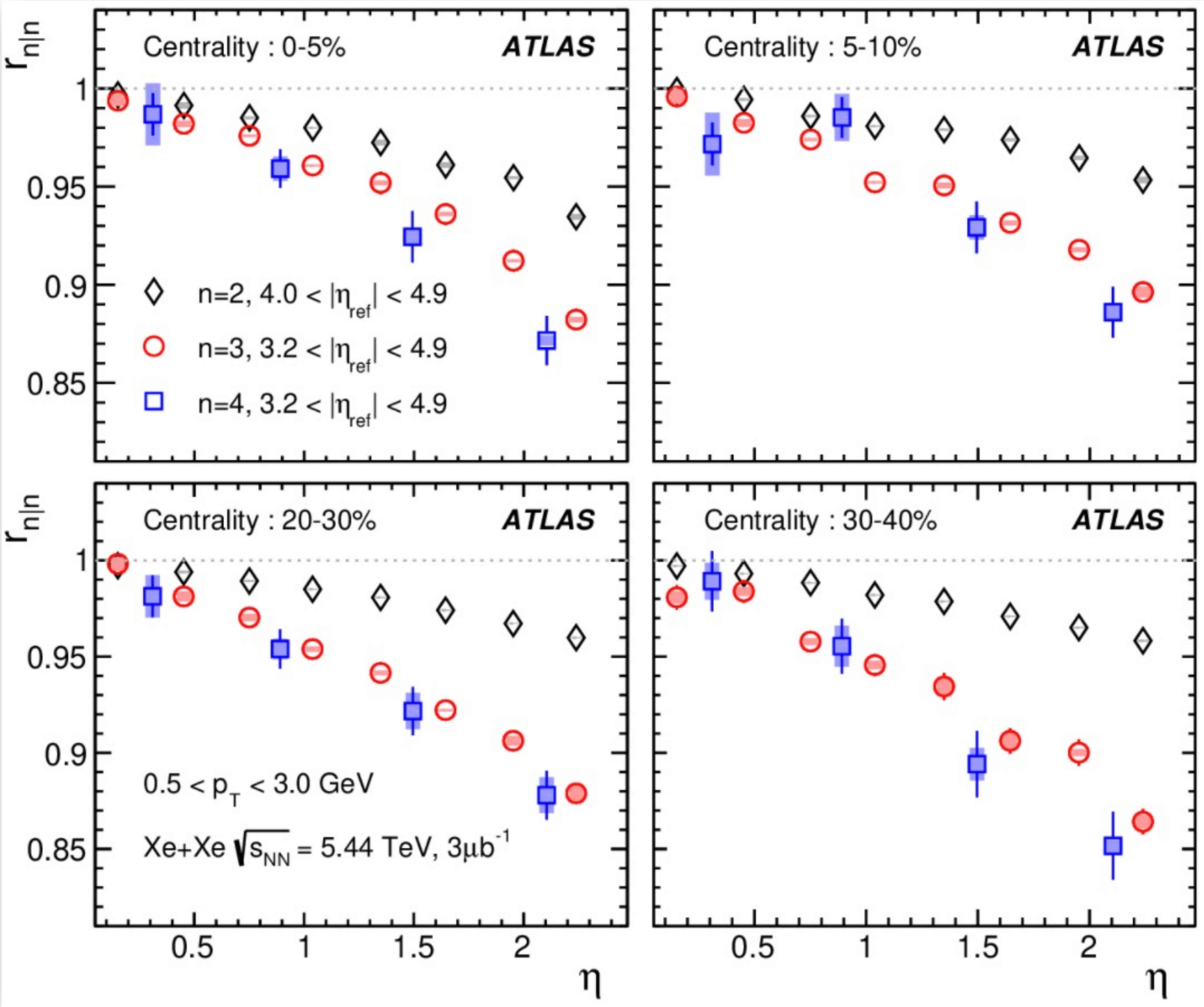
Flow vector: $\mathbf{q}_n \equiv \Sigma_j w_j e^{in\phi_j} / (\Sigma_j w_j)$



Decorrelation between $-\eta$ and η: $r_{\mathrm{n|n}}(\eta) = \frac{\langle q_{\mathrm{n}}(-\eta) q^*_{\mathrm{n}}(\eta_{\mathrm{ref}}) \rangle}{\langle q_{\mathrm{n}}(\eta) q^*_{\mathrm{n}}(\eta_{\mathrm{ref}}) \rangle} \leq 1$

Flow Decorrelation

Phys. Rev. Lett. 126 (2021) 12230



Flow Decorrelation

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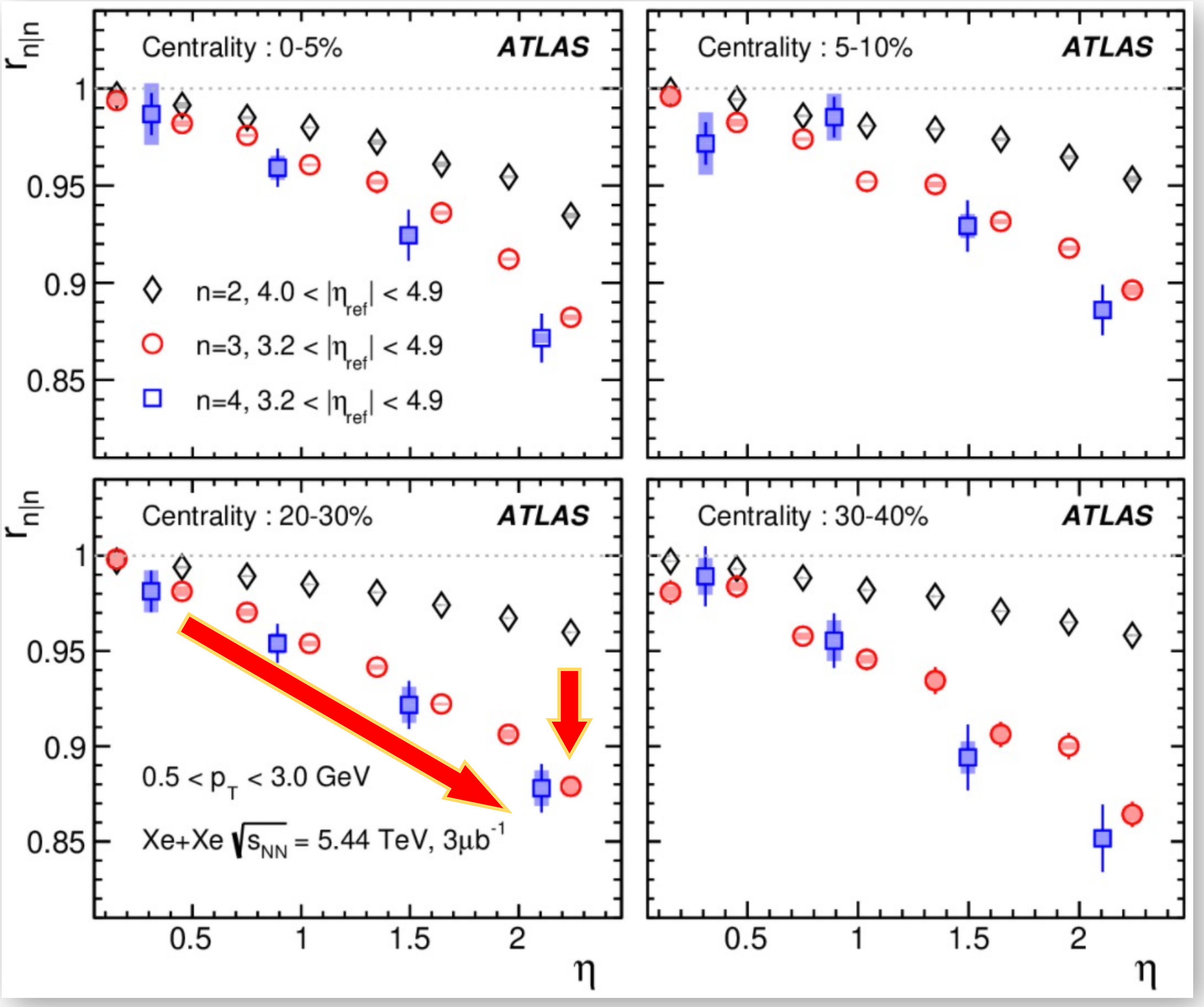

- Increase linearly with η.
- $r_{2|2}$ - strong centrality dependence.
- $r_{3|3}$ $r_{4|4}$ - weak centrality dependence.
- Increase significantly from n=2 to n=3.
- Smaller change from n=3 to n=4

Flow Decorrelation

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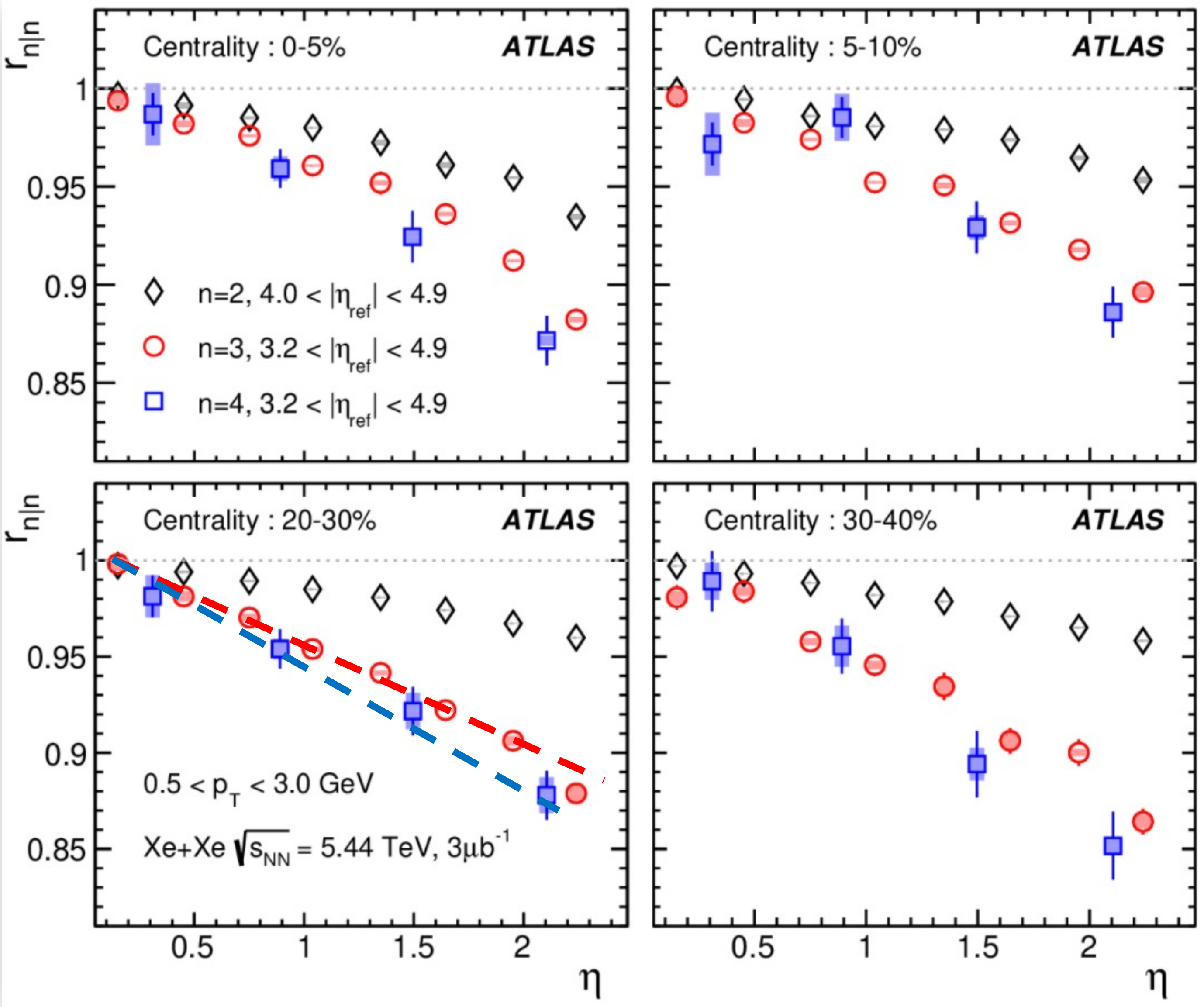

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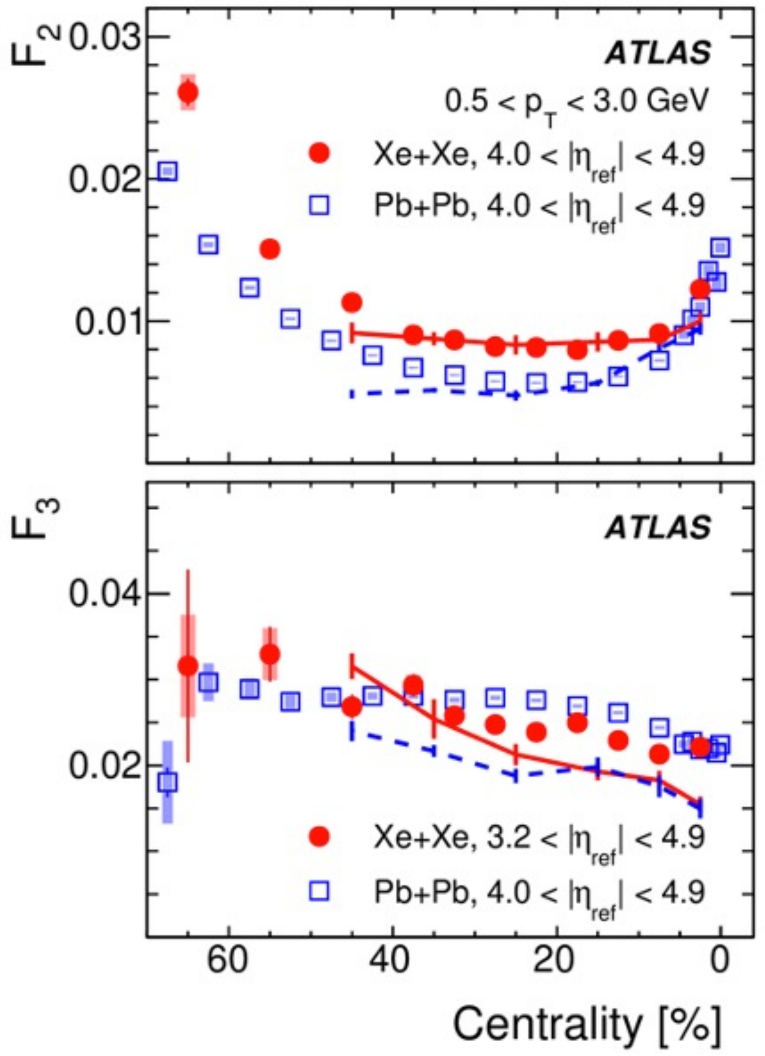
- $r_{3|3}$ $r_{4|4}$ - weak centrality dependence.
- Increase significantly from n=2 to n=3.
- Smaller change from n=3 to n=4
- Quantify by slope:

$$r_{n|n}(\eta) = 1 - 2F_n\eta$$

Decorrelation strength

Flow Decorrelation

Phys. Rev. Lett. 126 (2021) 12230



F2 strong centrality dependence.

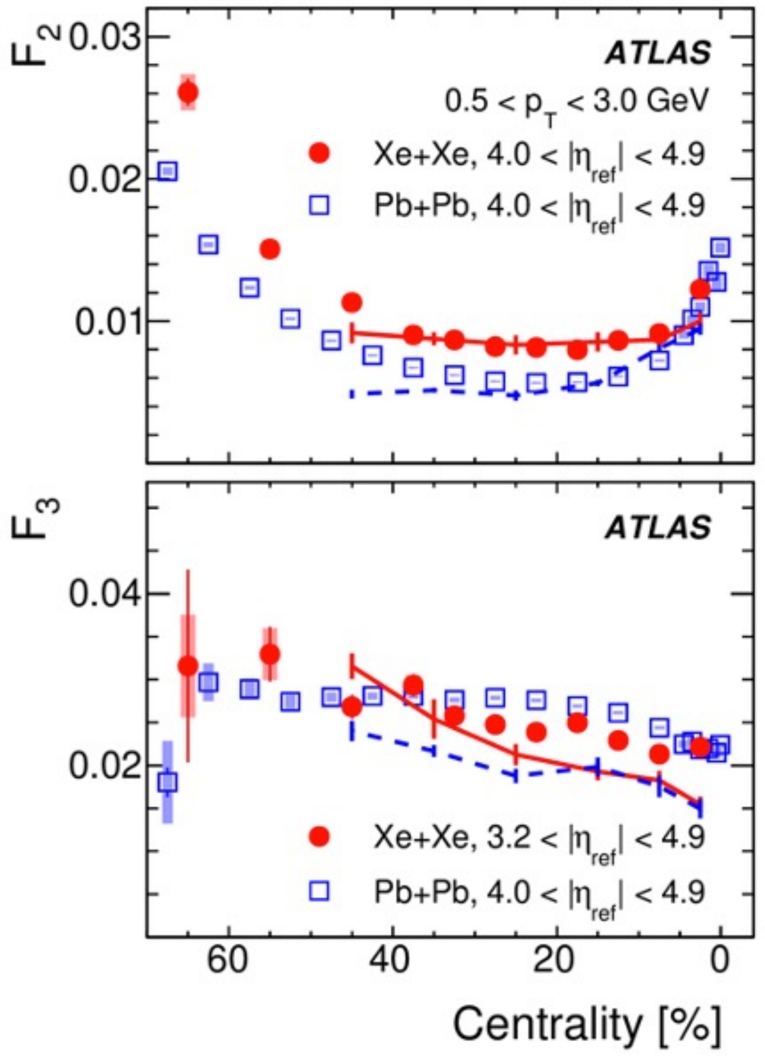
Reverse ordering for n=2 and 3:

$$F_2^{XeXe} > F_2^{PbPb}$$

$$F_3^{XeXe} < F_3^{PbPb}$$

Flow Decorrelation

Phys. Rev. Lett. 126 (2021) 12230



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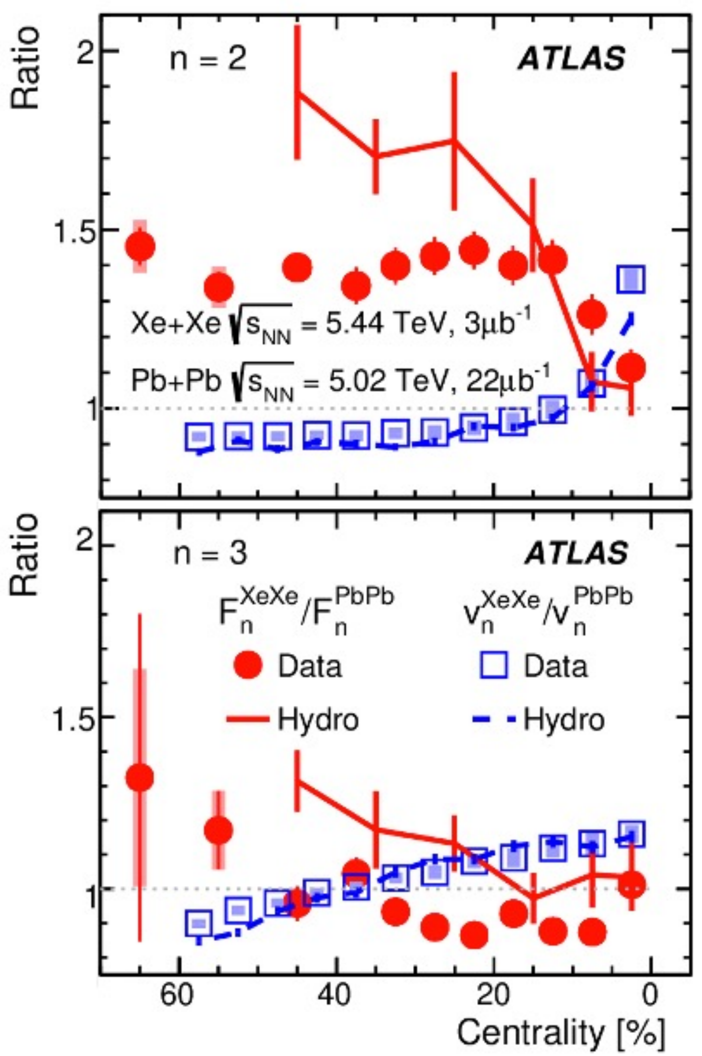
$$F_3^{XeXe} < F_3^{PbPb}$$

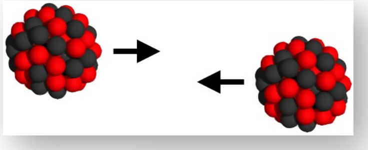
Anti-correlation between v_n and F_n – opposite centrality dependence

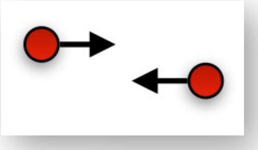
Hydro explains v_n ratio very well but fails to explain F_n ratio.

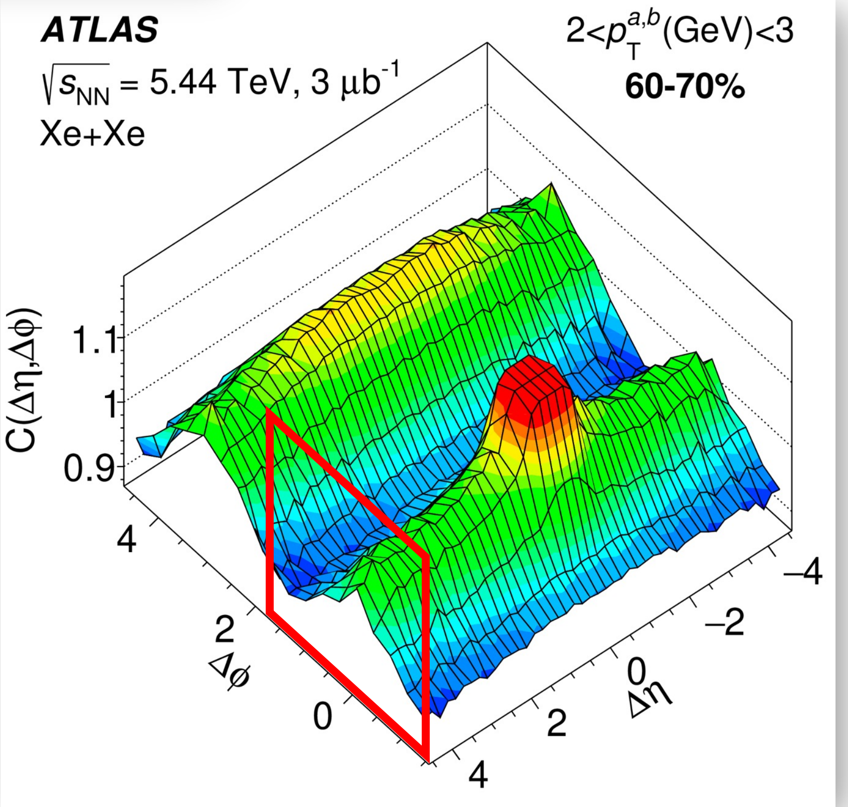
Provide new insights to separate effects of the longitudinal structure of the initial state from other early time and late time effects.

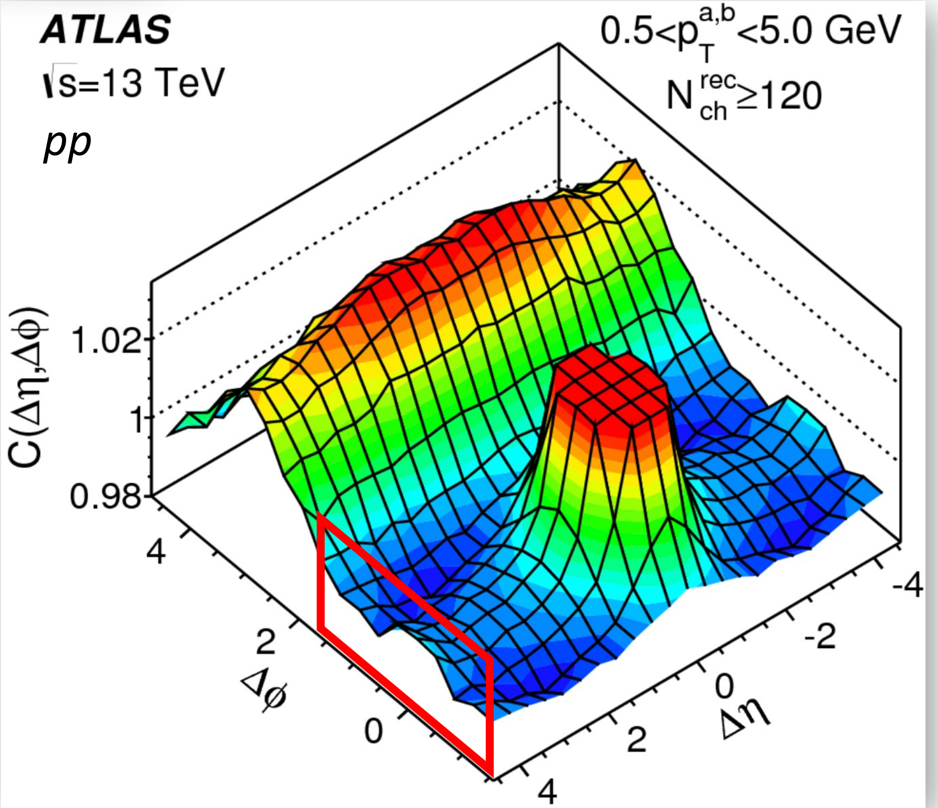


Ridge in small system









Collective flow

Arise from collective behavior?

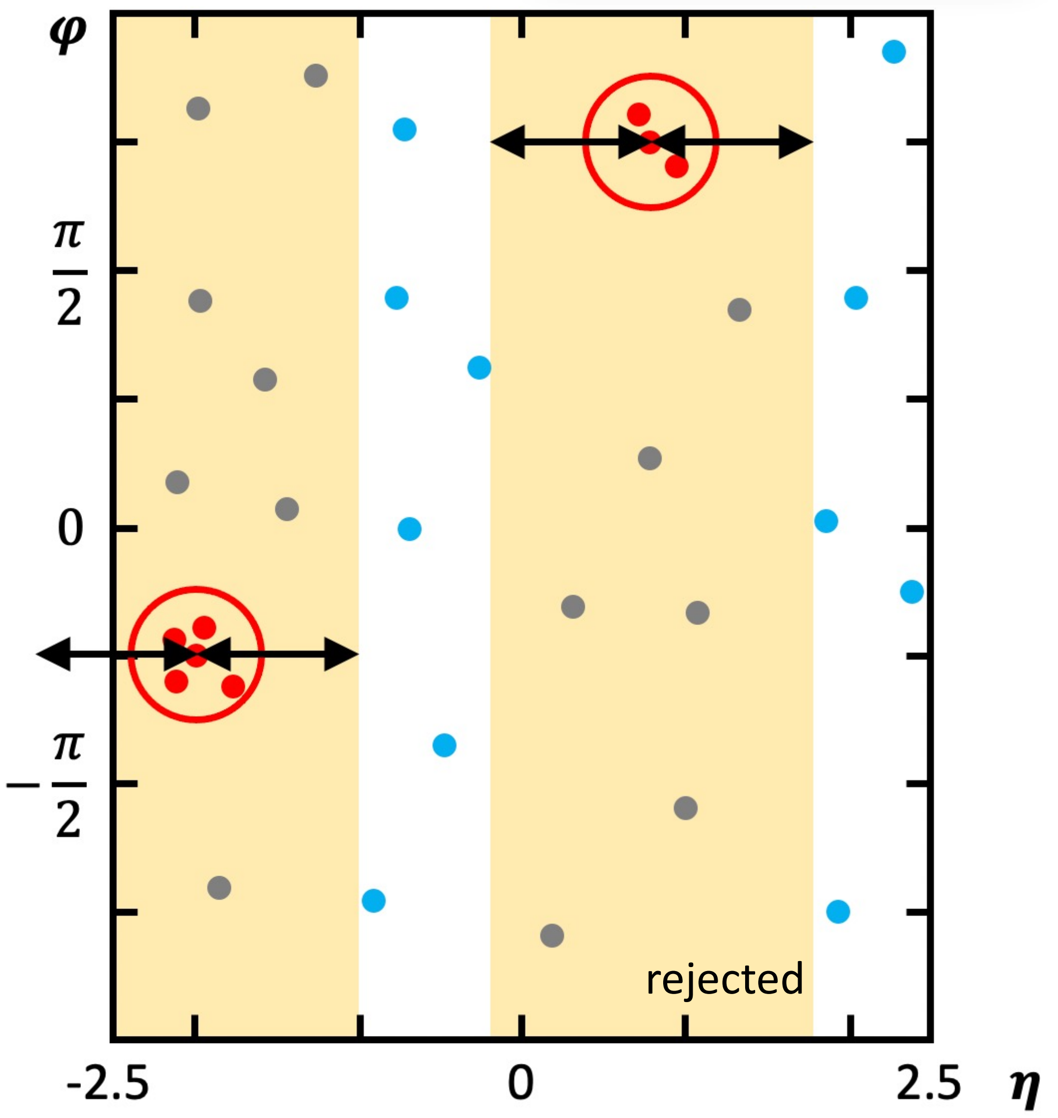
Artifact of semi-hard processes?

Particle rejections around jets

ATLAS-CONF-2020-018

- Tracks separated from jets are used for the two particle correlation study.
- Simply rejecting all tracks within a R = 0.4 cone of the jet axis would introduce artificial structures along the $\Delta\phi$ in two particle correlations (2PC).
- Tracks within $\Delta\eta = \pm1$ from the jet axis of any jets with $p_{\mathrm{T}}^{\mathrm{jet}} > 10$ GeV are dropped.

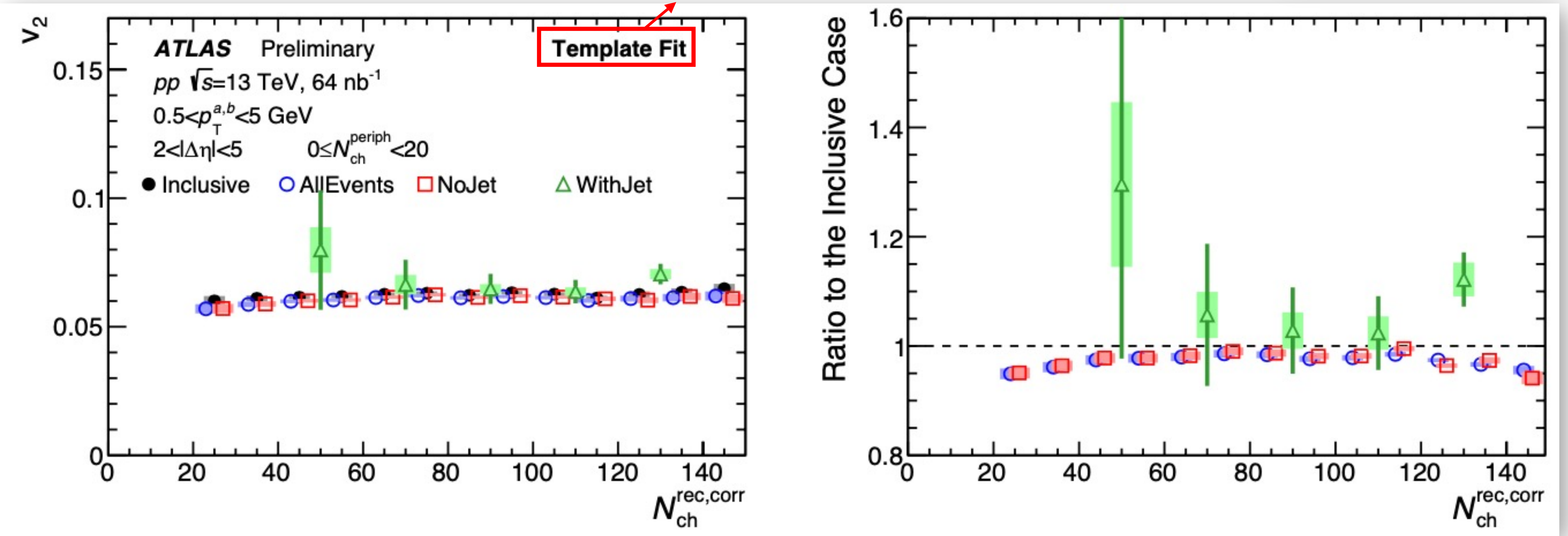
Category	Rejection around jet	Event with jets	Event with no jets
WithJet	✓	✓	✗
NoJet	N/A	✗	✓
AllEvents	✓	✓	✓
Inclusive	✗	✓	✓



Sensitivity of flow to jets in *pp*

ATLAS-CONF-2020-018

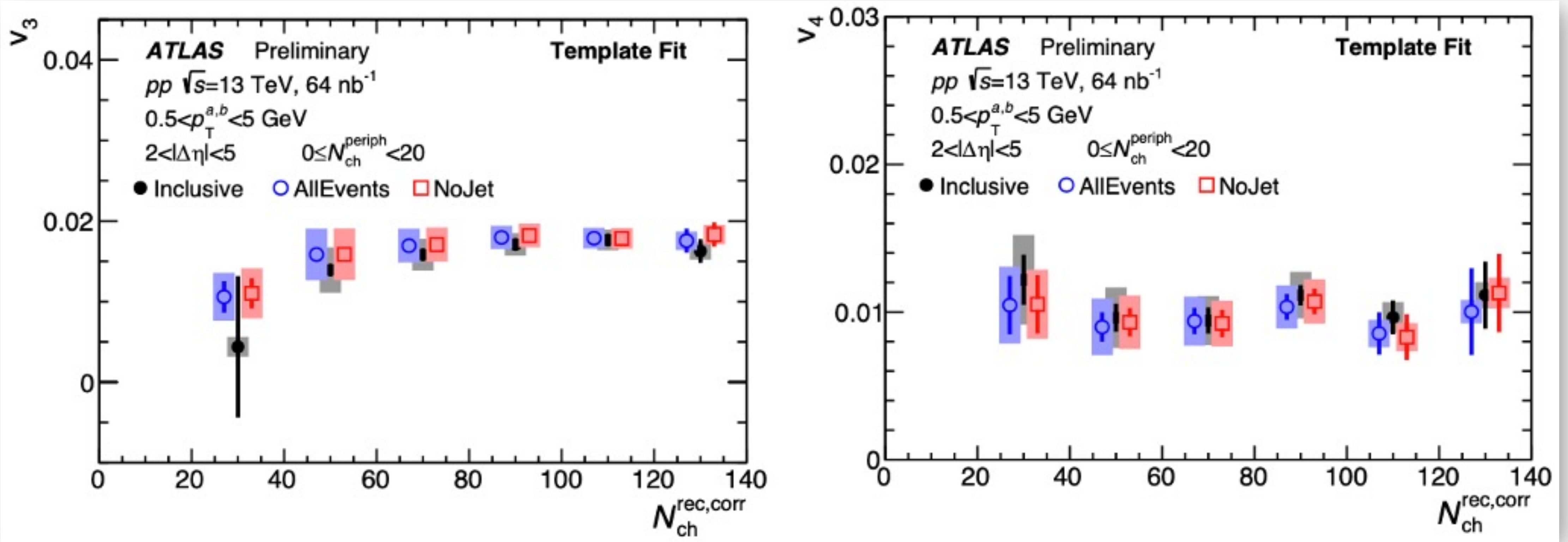
(Phys. Rev. C 96 (2017) 024908)



- The v_2 values are observed to vary weakly with multiplicity.
- The v_2 in *AllEvents* and *NoJet* sets are slightly smaller than the *Inclusive* set.
  - Softening of the p_{T}-spectra during rejection
- The v_2 in the *WithJet* set are consistent with the *Inclusive* set within uncertainties.

Sensitivity of flow to jets in *pp*

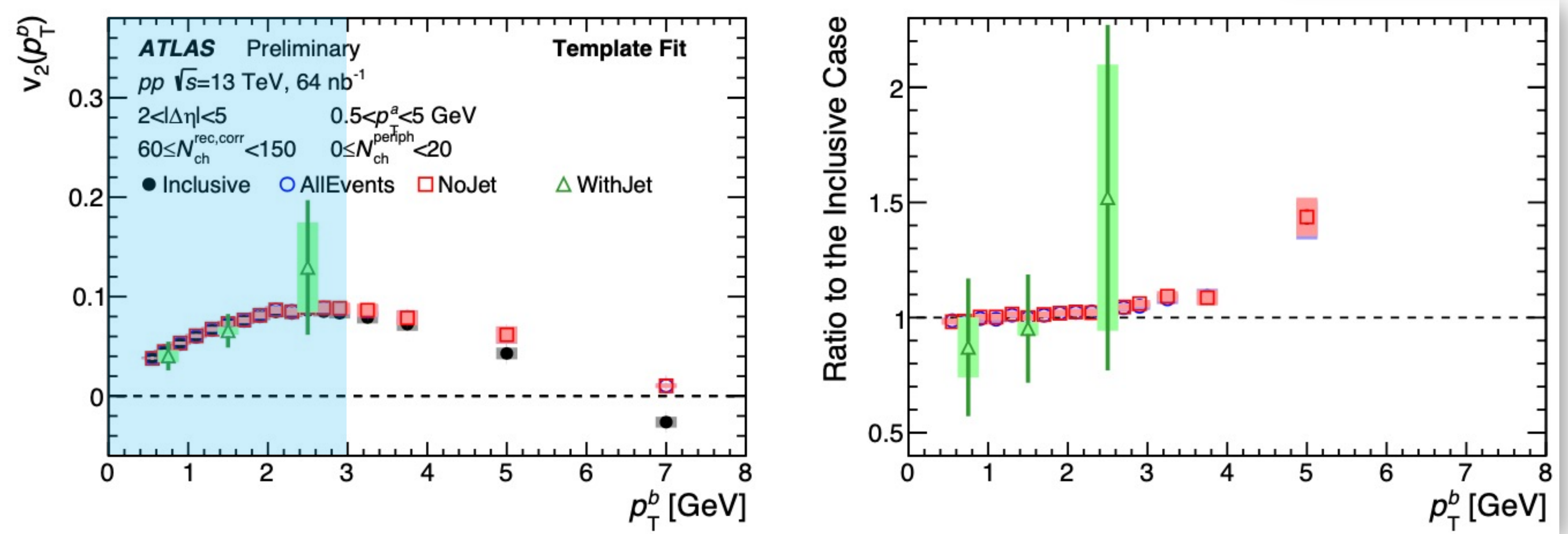
ATLAS-CONF-2020-018



- ➢ The multiplicity dependence of higher order harmonics v_3 and v_4.
- ➢ The values for *AllEvents* and *NoJet* are similar to the *Inclusive*. The difference is about 10%, but with significant uncertainties.
- ➢ The *WithJet* case is not shown here due to large statistical uncertainties.

Sensitivity of flow to jets in *pp*

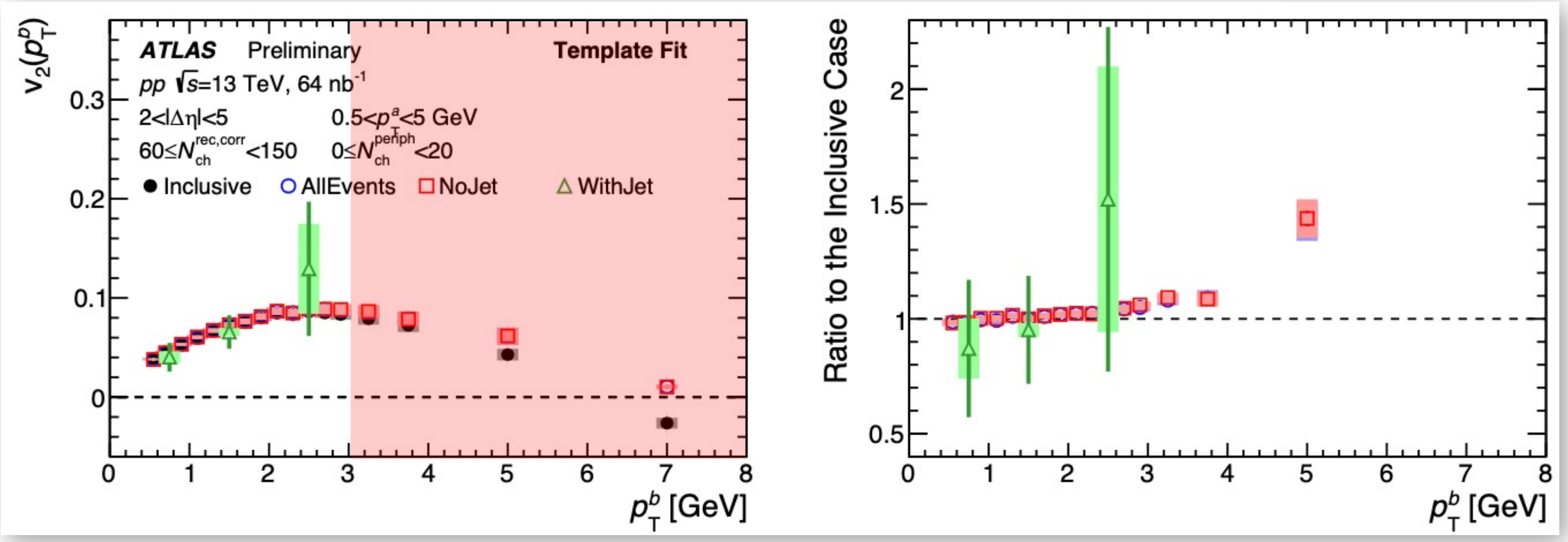
ATLAS-CONF-2020-018



- The v_2 values are observed to be similar up to 3 GeV.
- The *WithJet* is also consistent but with much larger statistical uncertainties.

Sensitivity of flow to jets in *pp*

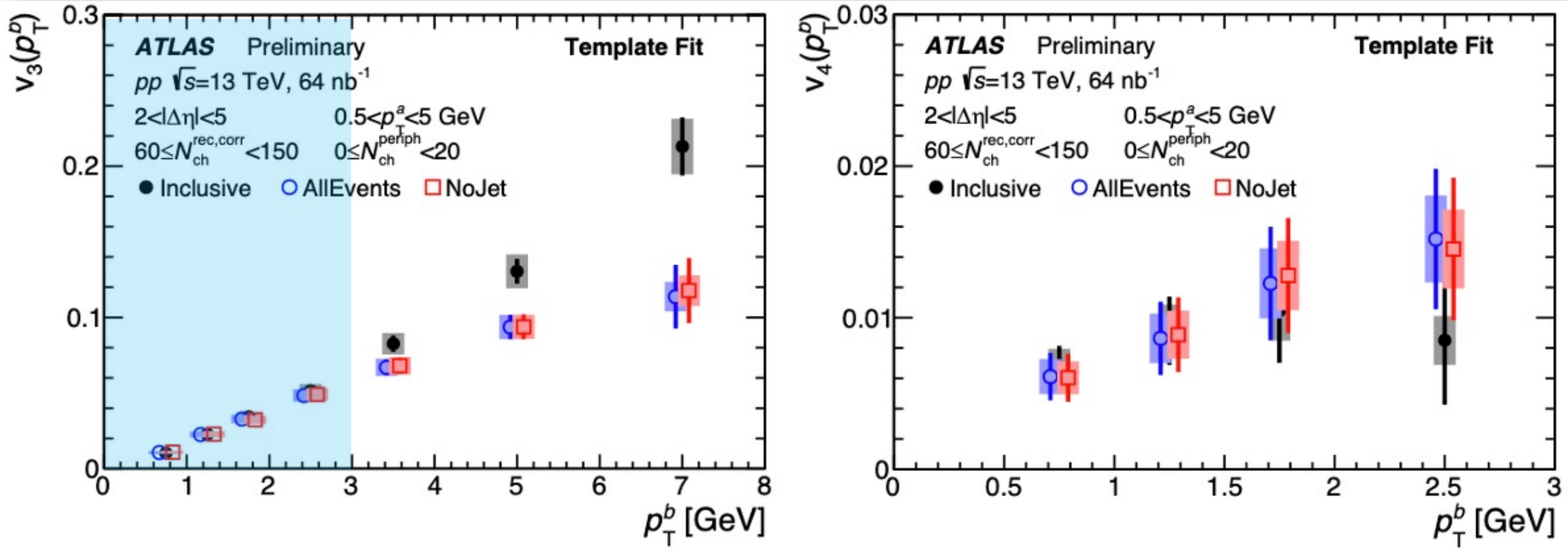
ATLAS-CONF-2020-018



- The v_2 values are observed to be similar up to 3 GeV.
- The *WithJet* is also consistent but with much larger statistical uncertainties.
- At higher p_T, the v_2 in *AllEvents* and *NoJet* sets are larger than the *Inclusive*.
  - *Inclusive* has some bias at higher p_T which is reduced when rejecting tracks near jets.

Sensitivity of flow to jets in *pp*

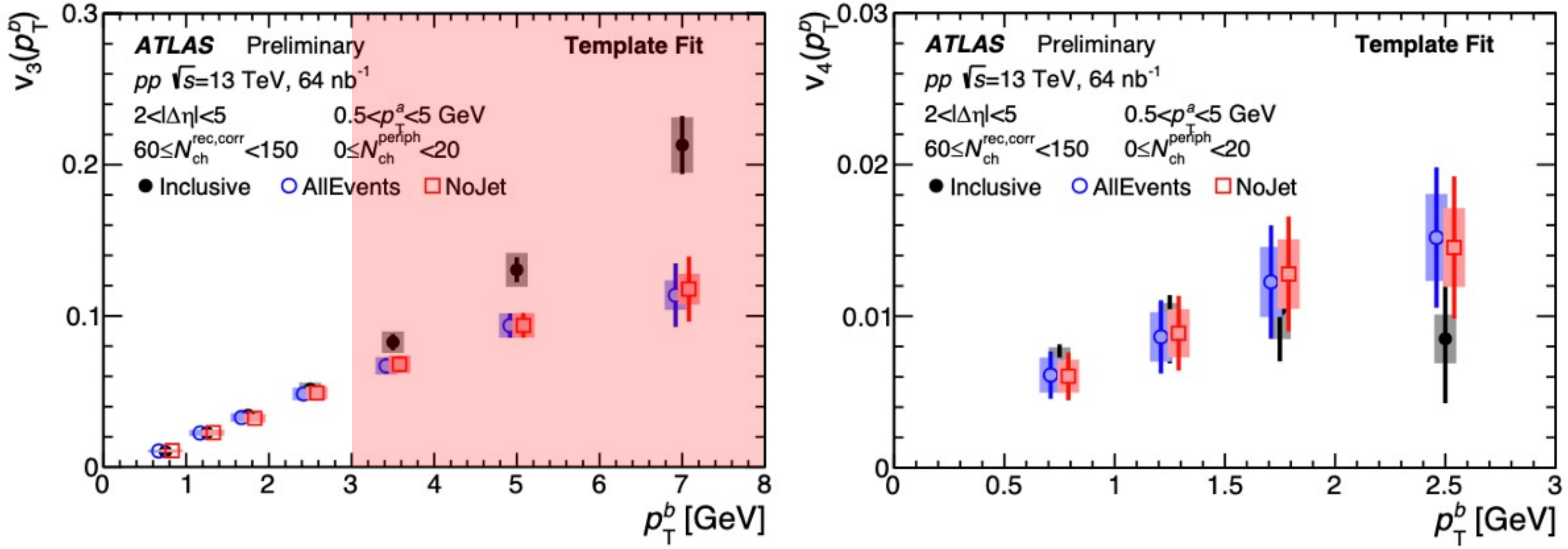
ATLAS-CONF-2020-018



- The v_3 and v_4 values are observed to be similar up to 3 GeV.
- The low- p_{T} v_n are not affected by the presence/absence of jets.

Sensitivity of flow to jets in *pp*

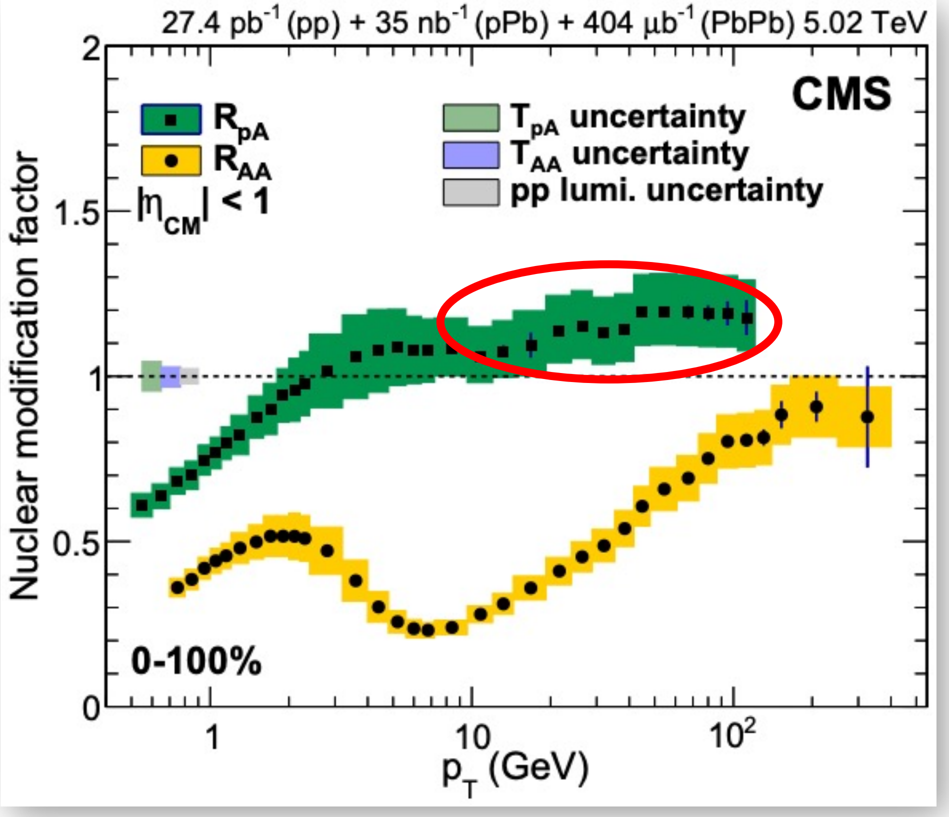
ATLAS-CONF-2020-018



- The v_3 and v_4 values are observed to be similar up to 3 GeV.
- The low- p_T v_n are not affected by the presence/absence of jets.
- The v_3 at higher p_T show large differences. *Inclusive* values are much higher.
  - Indicates high- p_T v_3 in *Inclusive* are biased from jet-bias effects.

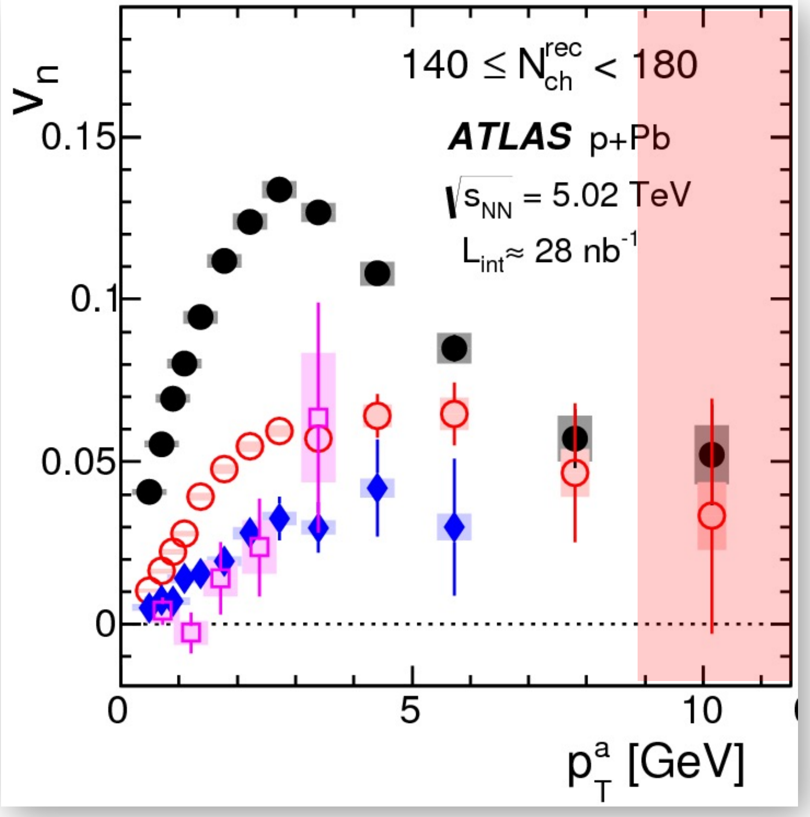
High-p_T correlation in p+Pb

JHEP 04 (2017) 039



No suppression is observed at high p_T.

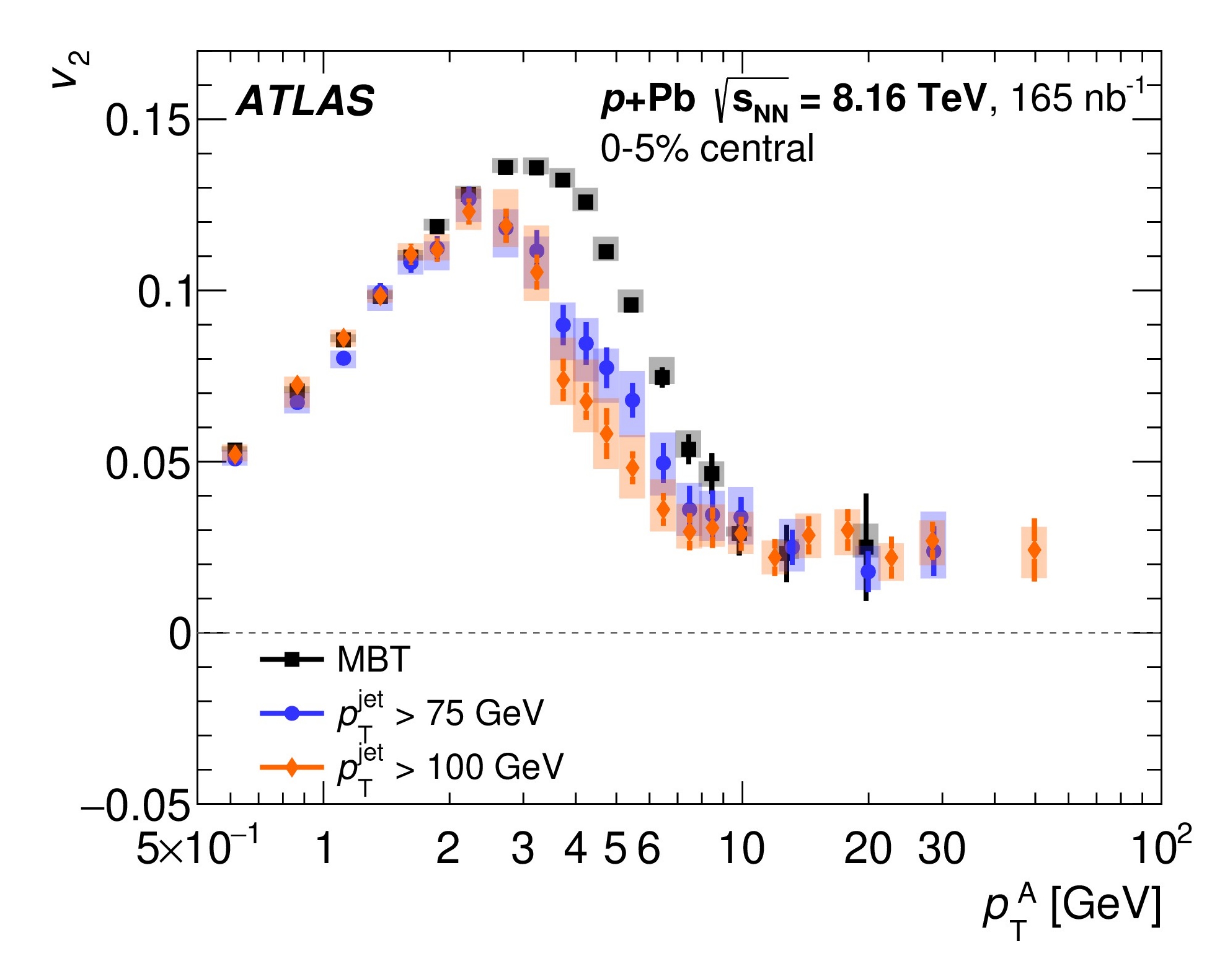
Phys. Rev. C 90, 044906 (2014)



Are low p_T and high p_T particles azimuthally correlated in p+Pb?

High-pT correlation in p+Pb

Eur. Phys. J. C 80 (2020) 73



Three classes:

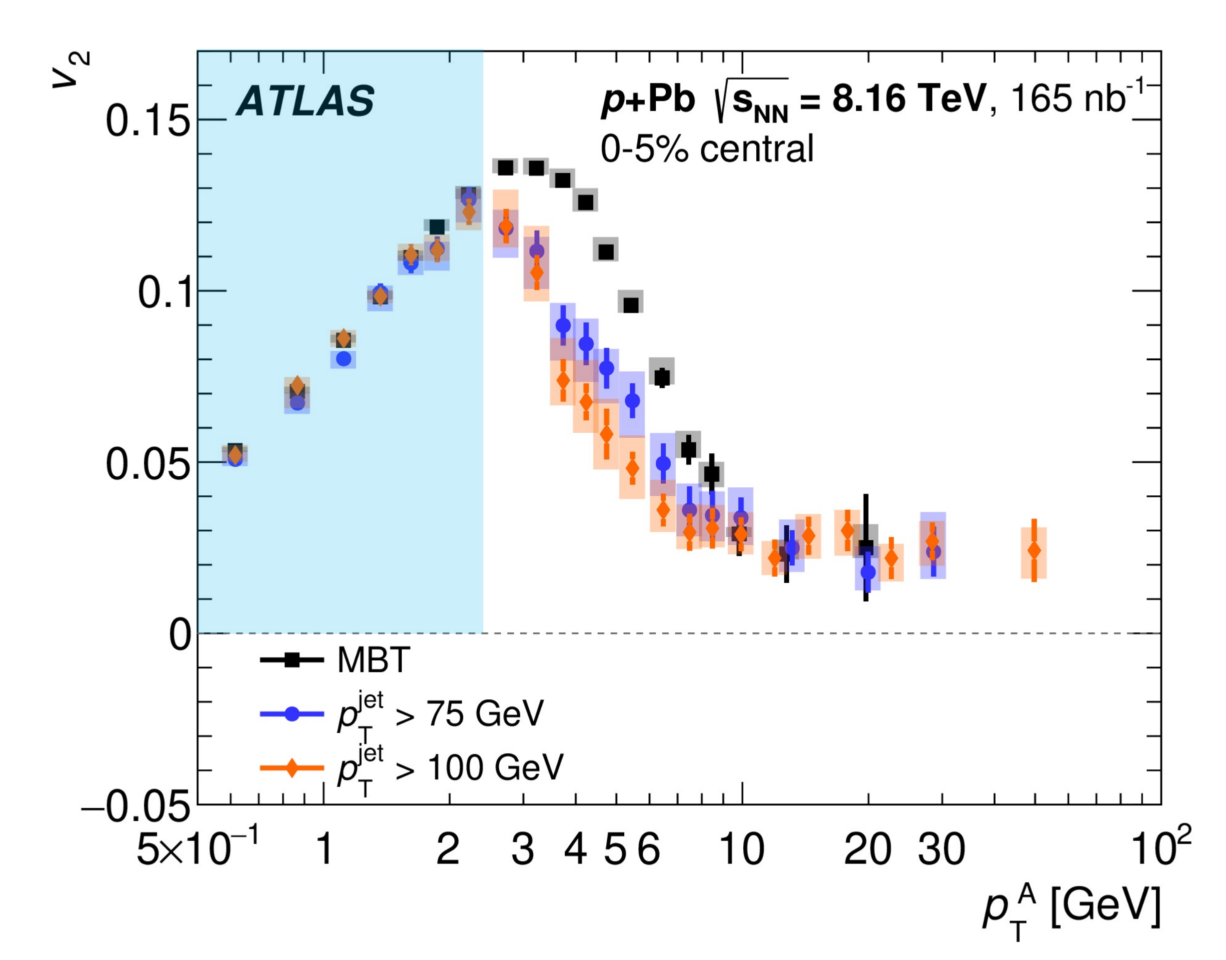
- Minimum-bias
- Events triggered by 75 GeV jets.
- Events triggered by 100 GeV jets.

Only associated particle is |Δη| > 1 relative to all jets p_T > 15 GeV.

- Different from *pp* analysis.
- Jet contribution to reference particles but not to the associated particles in 2PC
- Reduce non-flow bias.

High-pT correlation in *p*+Pb

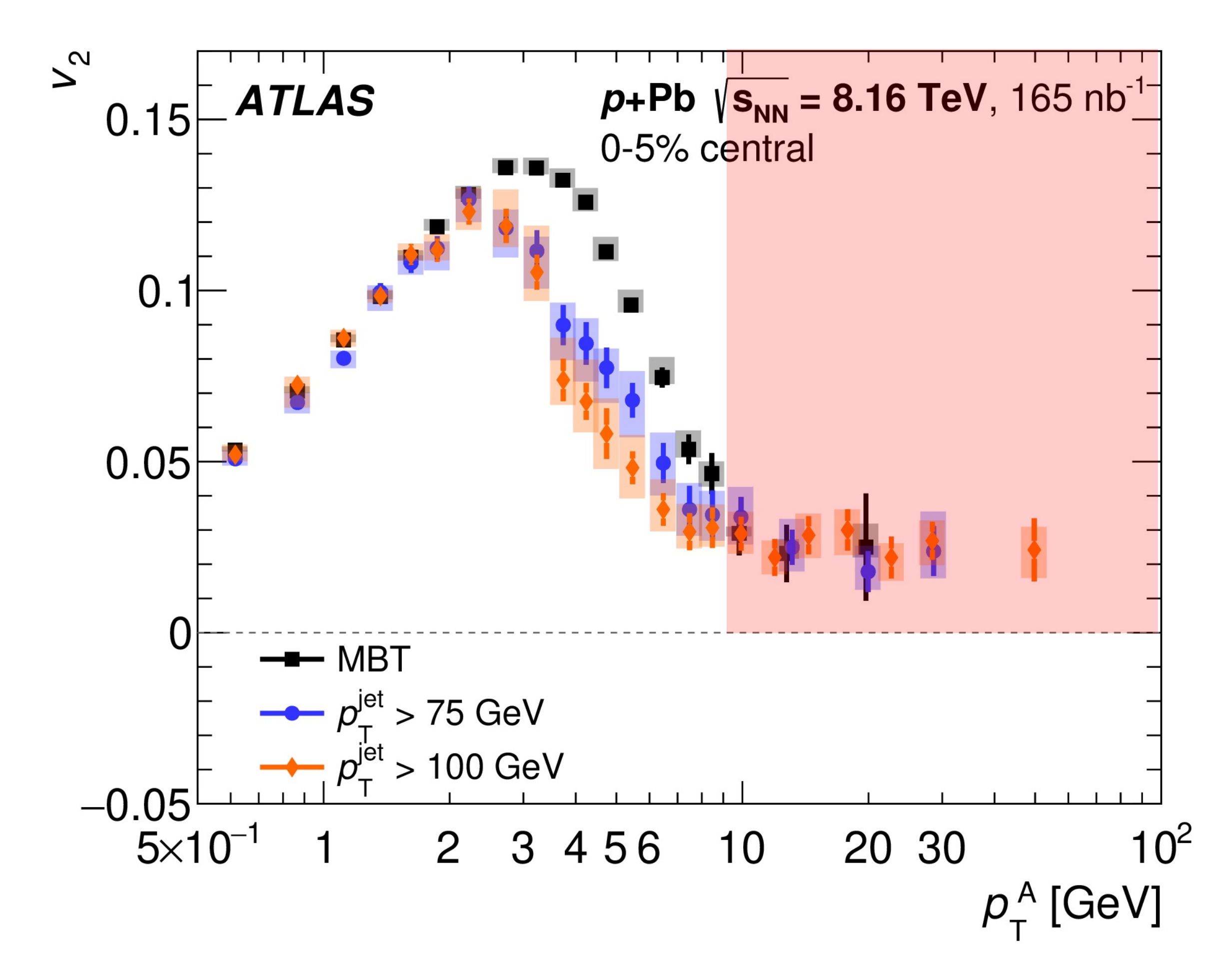
Eur. Phys. J. C 80 (2020) 73



Low p_T bulk flow are consistent.

High-pT correlation in p+Pb

Eur. Phys. J. C 80 (2020) 73

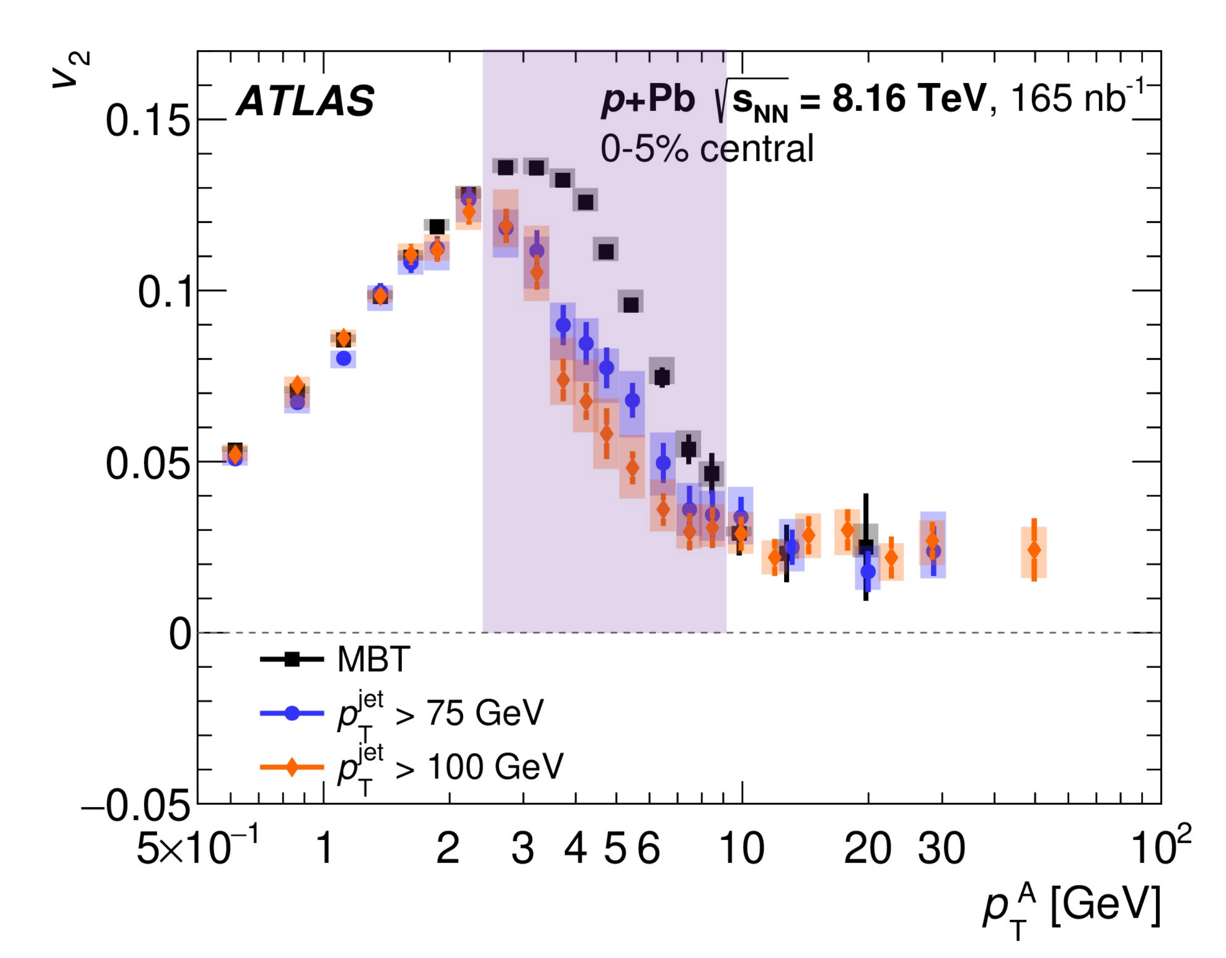


Low p_T bulk flow are consistent.

Significant v_2 observed at high p_T. Consistent between minimum-bias and jet triggered events.

High-pT correlation in p+Pb

Eur. Phys. J. C 80 (2020) 73



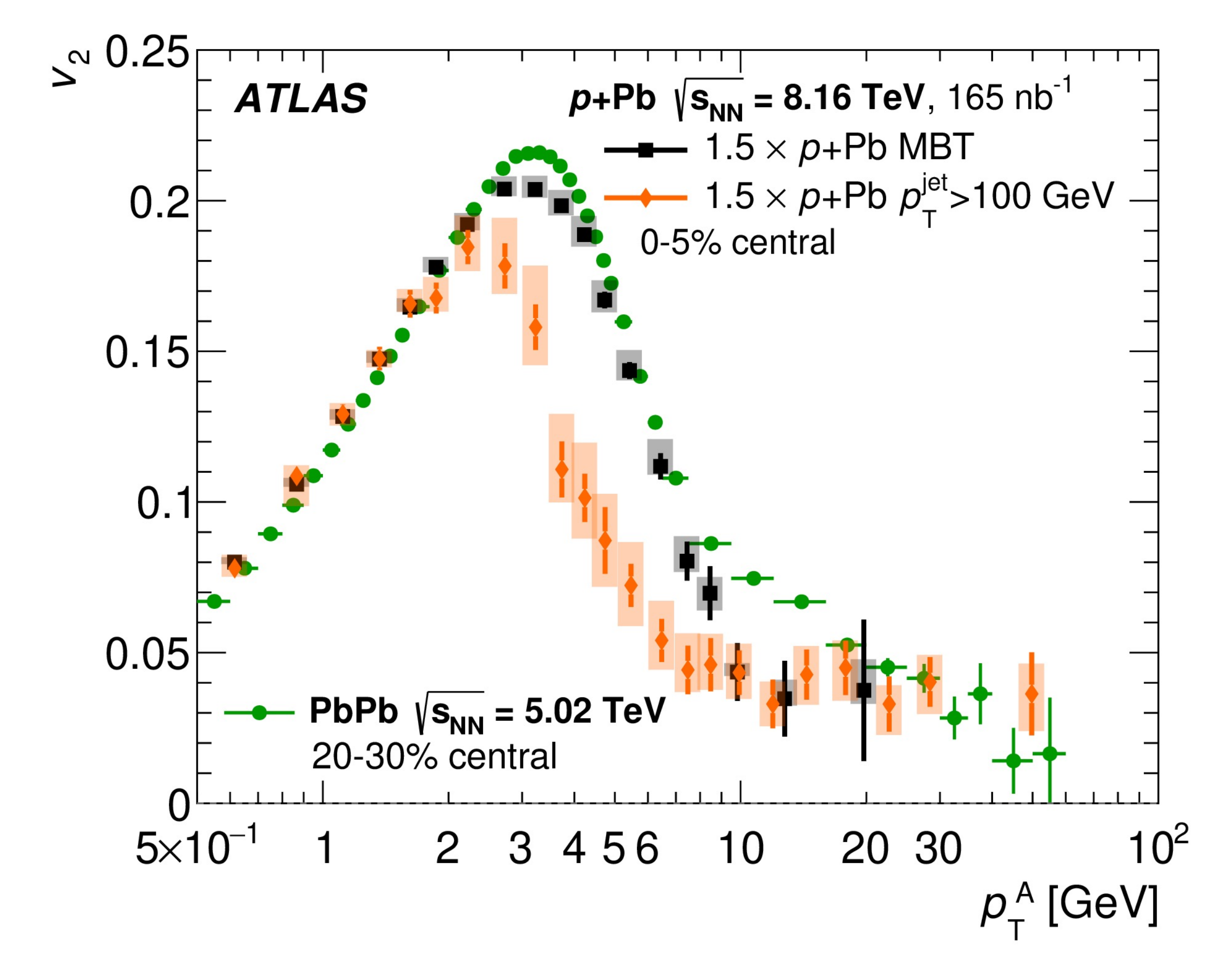
Low p_T bulk flow are consistent.

Significant v_2 observed at high p_T. Consistent between minimum-bias and jet triggered events.

In transition region, jet-triggered events are systematically smaller than the minimum-bias v_2.

High-pT correlation in *p*+Pb

Eur. Phys. J. C 80 (2020) 73



p+Pb (scaled by 1.5) quantitatively agree with Pb+Pb

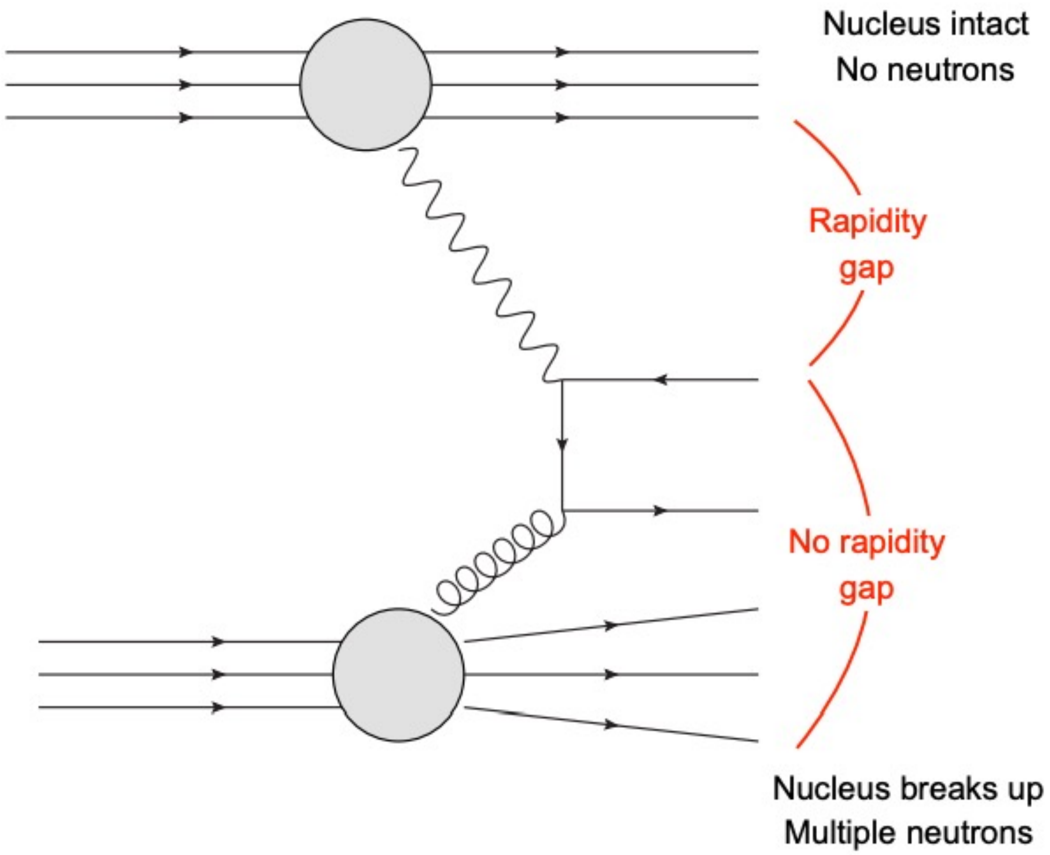
- Slight difference at peak
- A slow decline of v_2 with increasing p_T in Pb+Pb

A common physics interpretation?

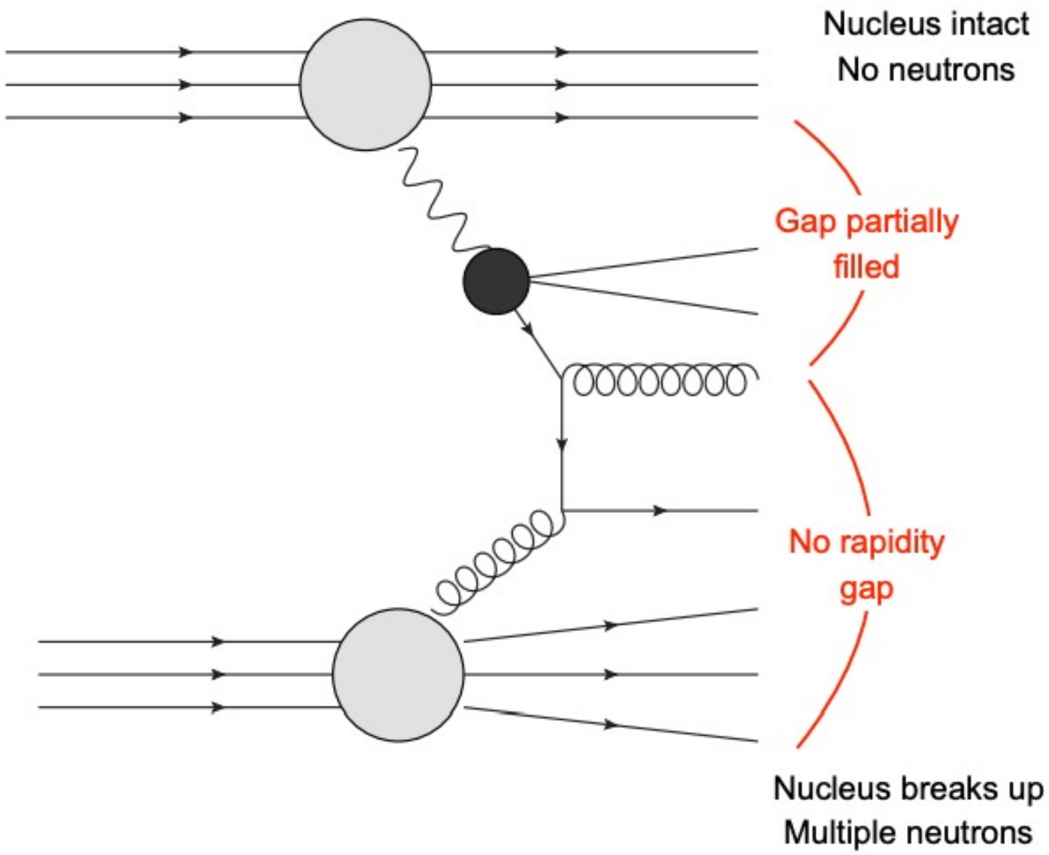
Additional contributions to v_2 at high p_T in Pb+Pb collisions?

Photo-nuclear interactions

Direct γA collisions

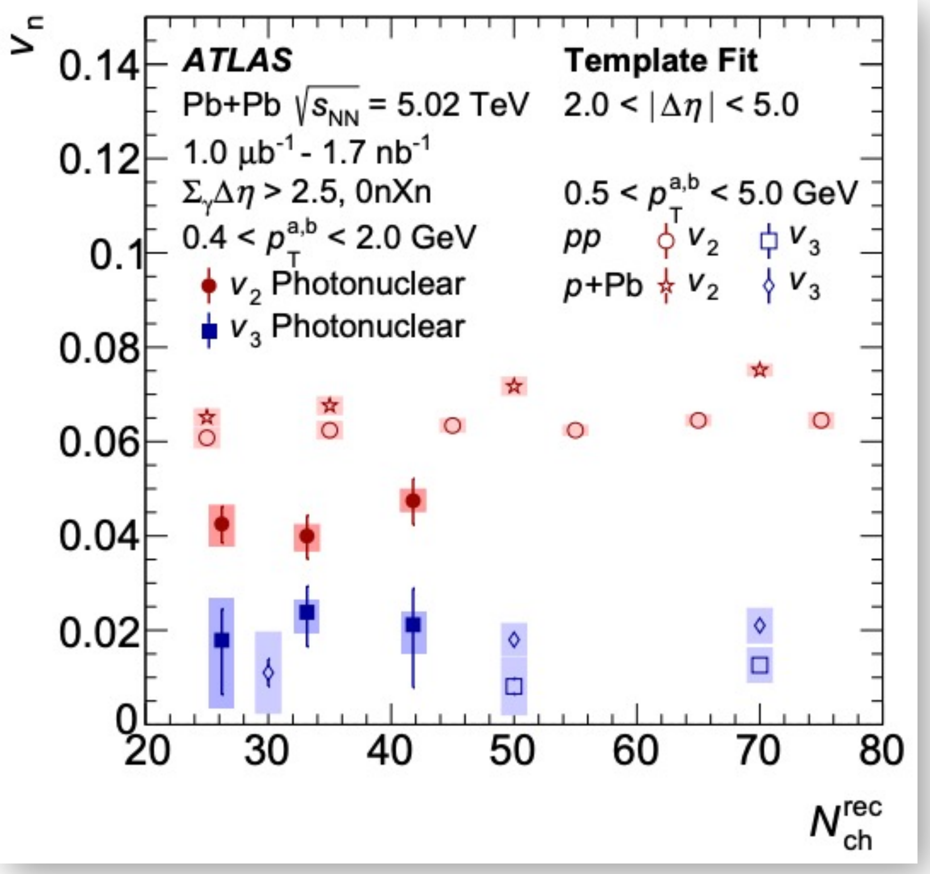


Resolved γA collisions



Flow in photo-nuclear collisions

CERN-EP-2020-246



Observe significant v_2 in photo-nuclear collisions.

v_2 is flat within error

v_2 is systematically smaller than pp and pPb

Consistent v_3 between γA and pp given large uncertainties on both

Summary

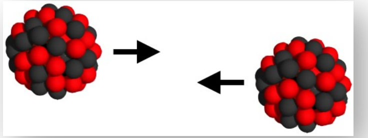
- Flow and longitudinal flow fluctuation in large collision systems
  - Fluctuations in initial geometry increase Xe+Xe v_n and are dominant in central collisions.
  - Viscous effects decrease Xe+Xe v_n and dominant in mid-central & peripheral collisions.
  - Mean v_n and longitudinal v_n decorrelation follow opposite trends.

- Flow measurements in small systems
  - *pp*: Long-range correlations in *pp* collisions are only slightly affected when particles associated with hard or semi-hard processes in the event are removed.
  - *pp*: Low-p_{T} v_n are not affected by presence/absence of jets.
  - *p*Pb: Low p_{T} particle azimuthal anisotropy explained via hydrodynamics and geometry.
  - *p*Pb: v_n from high p_{T} particles cannot be explained in the theoretical context of jet quenching.

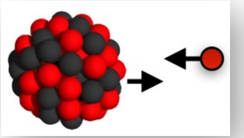
- Flow in photon-induced processes
  - Significant azimuthal anisotropies observed in photo-nuclear collisions.
  - p_{T}-integrated v_2 is systematically smaller than *pp* and *p*+Pb.

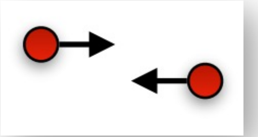
New results since SQM2019

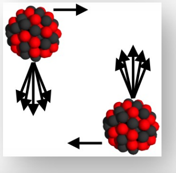
- Flow in large systems
  - HF muon+hadron correlations in Pb+Pb, Phys. Lett. B 807 (2020) 135595
  - Charged particle flow in Xe+Xe, Phys. Rev. C 101 (2020) 024906
  - Flow decorrelation in Xe+Xe and Pb+Pb, Phys. Rev. Lett. 126 (2021) 12230
  - $v_n - [p_T]$ correlation in Xe+Xe and Pb+Pb, ATLAS-CONF-2021-001



- Flow in small systems
  - High-p_T correlations in *p*+Pb, Eur. Phys. J. C 80 (2020) 73
  - HF muon+hadron correlations in *pp*, Phys. Rev. Lett. 124 (2020) 082301
  - Sensitivity of flow to jets in *pp*, ATLAS-CONF-2020-018
  - Z-tagged ridge in pp, Eur. Phys. J. C 80 (2020) 64
  - Photo-nuclear 2PC in Pb+Pb, CERN-EP-2020-246







https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Thank you!

Template-fit method

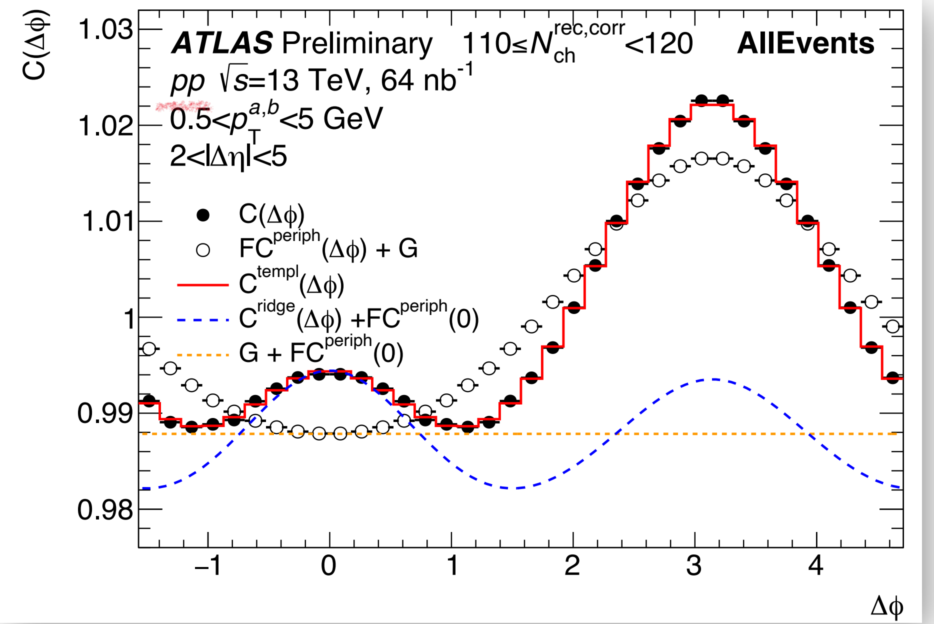
- Plots show 1D 2 particle correlations (2PCs) from *pp* collision.
- The strength of the long-range correlation can be quantified by extracting Fourier moments of the 2PC distribution which are denoted $v_{n,n}$ and defined by:

$$C(\Delta\phi) = C_0\left(1 + 2\Sigma_{n=1}^{\infty} v_{n,n}(p_{\mathrm{T}}^{\mathrm{a}}, p_{\mathrm{T}}^{\mathrm{b}})\cos(n\Delta\phi)\right)$$

- The $v_{n,n}$ are directly related to the single-particle anisotropies v_n. In the case where the $v_{n,n}$ entirely result from the single-particle anisotropy, the $v_{n,n}$ are products of the single-particle v_n:

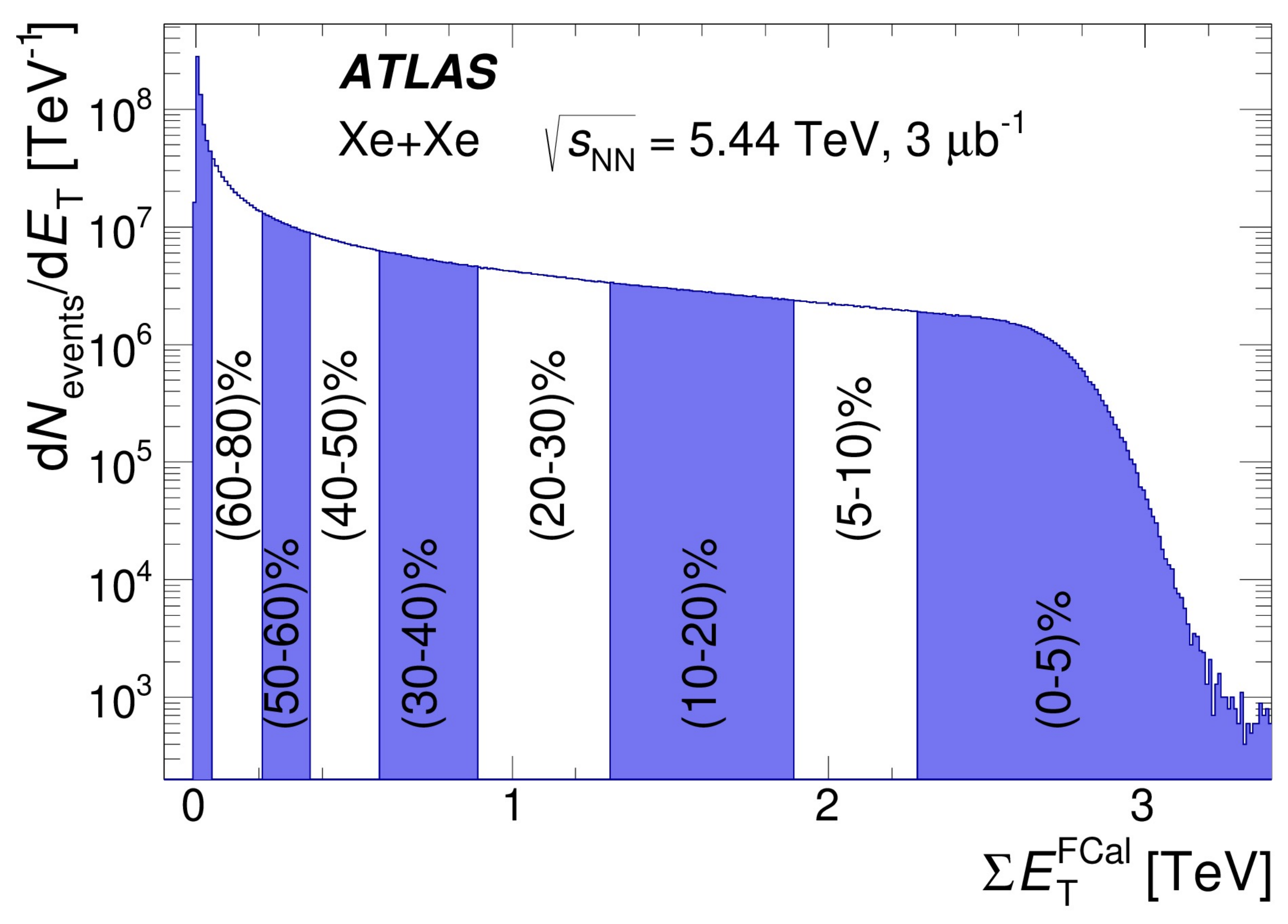
$$v_{n,n}(p_{\mathrm{T}}^{\mathrm{a}}, p_{\mathrm{T}}^{\mathrm{b}}) = v_n(p_{\mathrm{T}}^{\mathrm{a}})v_n(p_{\mathrm{T}}^{\mathrm{b}})$$

- However, in *pp* collisions a significant contribution to the 2PC arises from back-to-back dijets. A template-fit method is used to extract long-range correlation.
- Fit the correlation with template of two components:
  - C^{periph}: Correlation in *pp* peripheral events : Dijet bkgd
  - C^{ridge} : Pedestal*$(1 + 2\sum v_{\mathrm{n,n}}\cos(n\Delta\phi))$: True signal



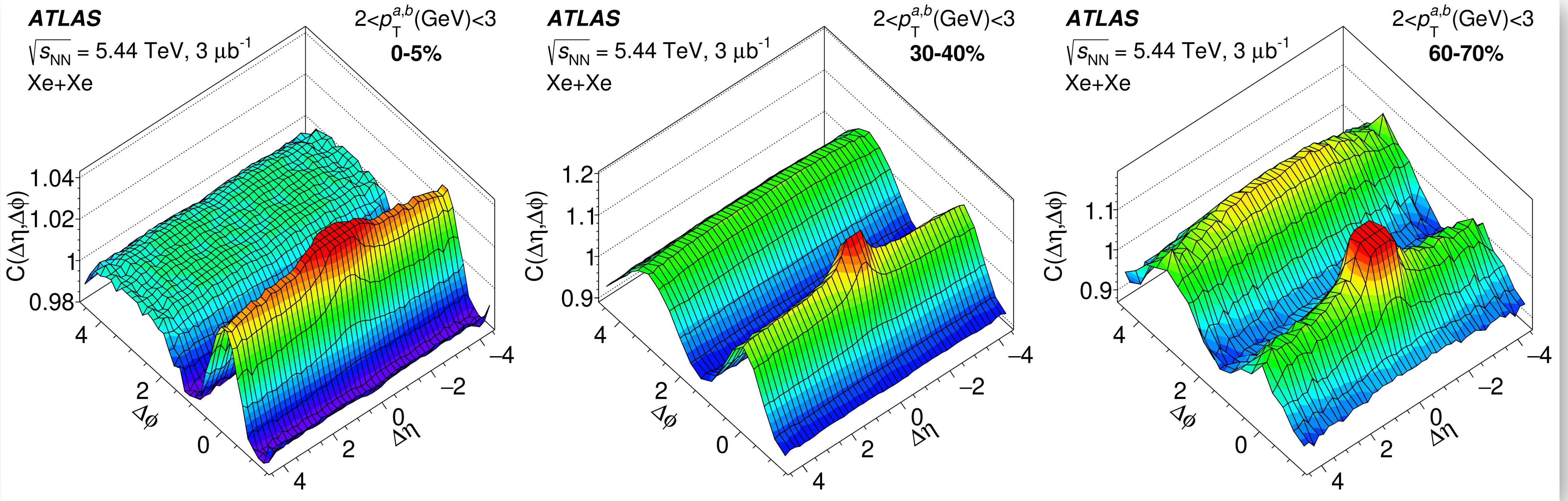
Charged particle flow in Xe+Xe

Phys. Rev. C 101 (2020) 024906



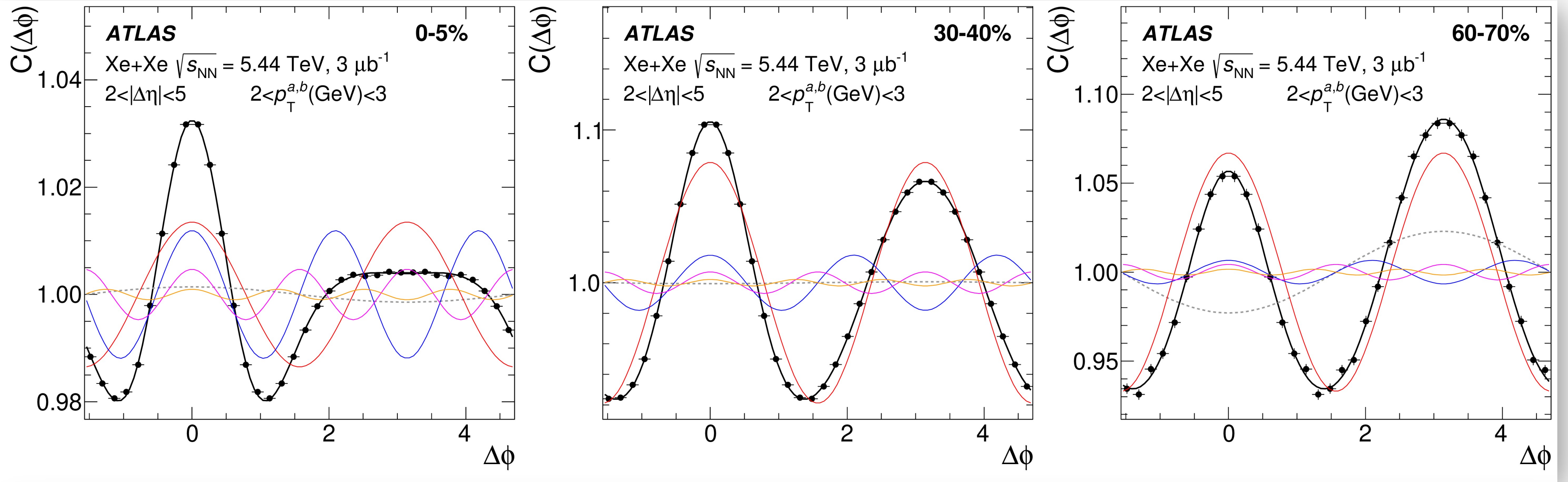
Charged particle flow in Xe+Xe

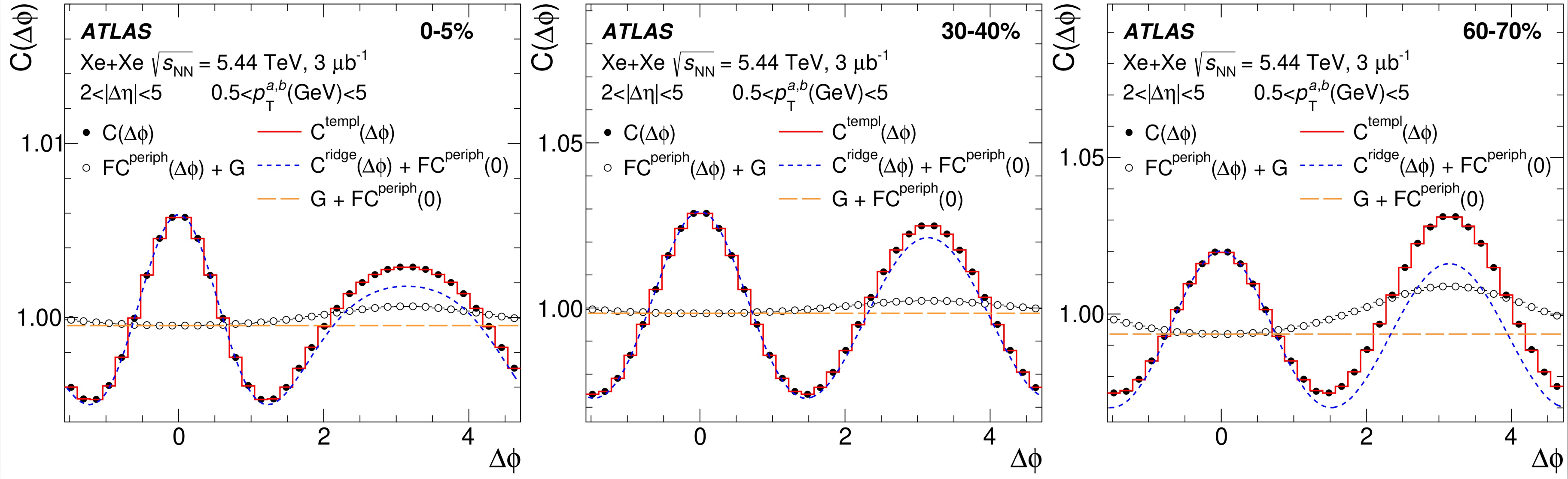
Phys. Rev. C 101 (2020) 024906



Charged particle flow in Xe+Xe

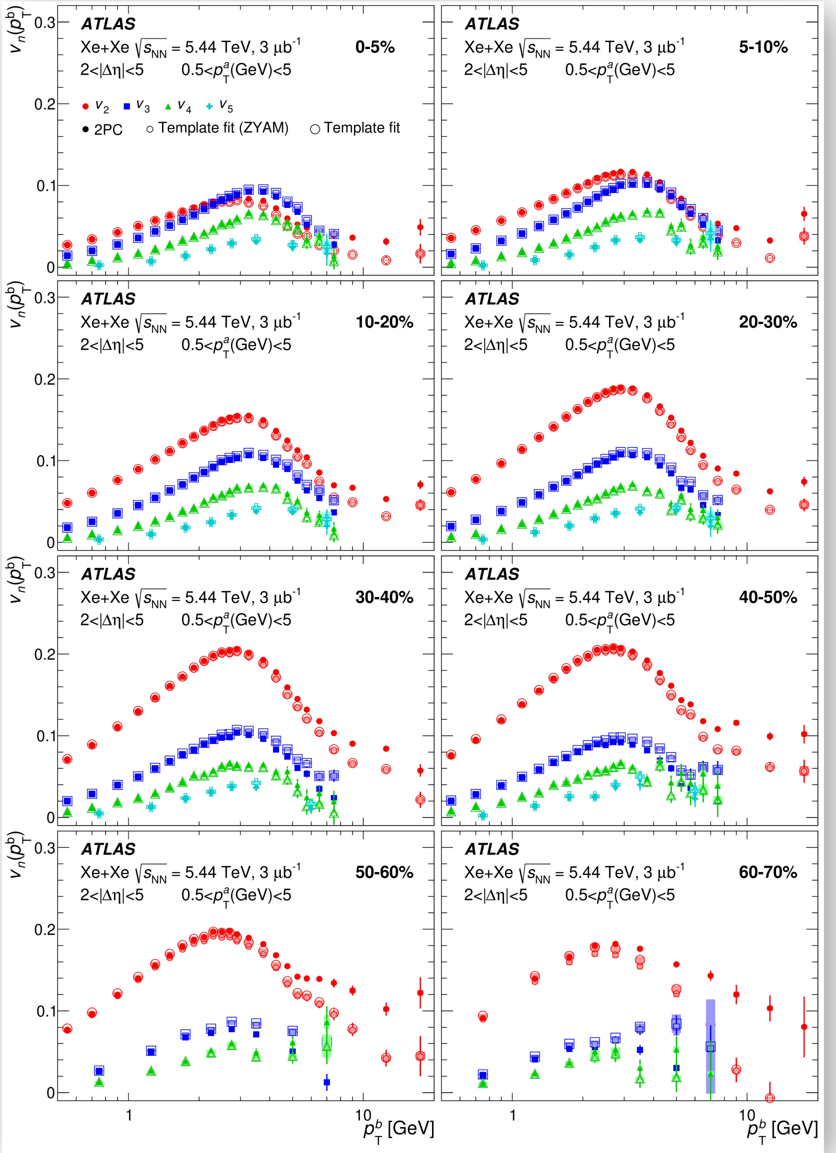
Phys. Rev. C 101 (2020) 024906

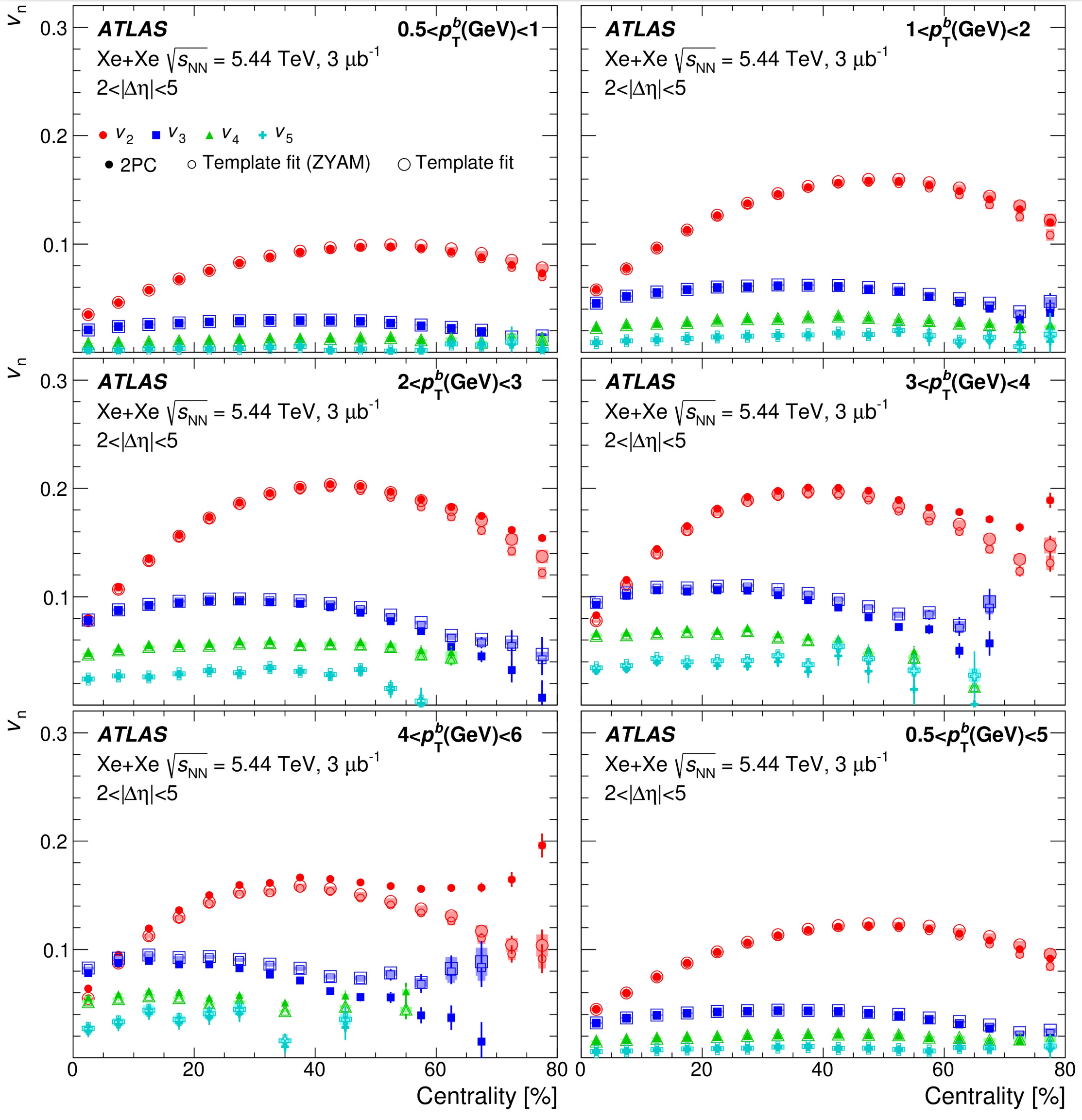




Charged particle flow in Xe+Xe

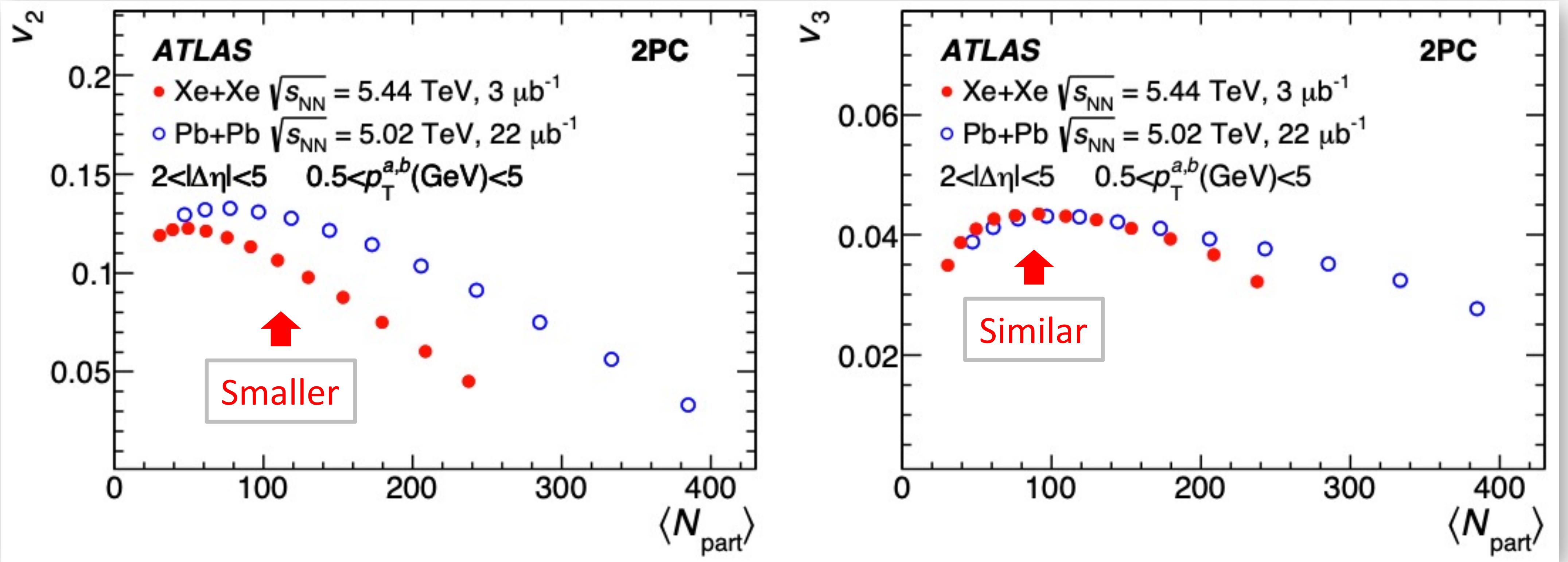
Phys. Rev. C 101 (2020) 024906





Charged particle flow in Xe+Xe

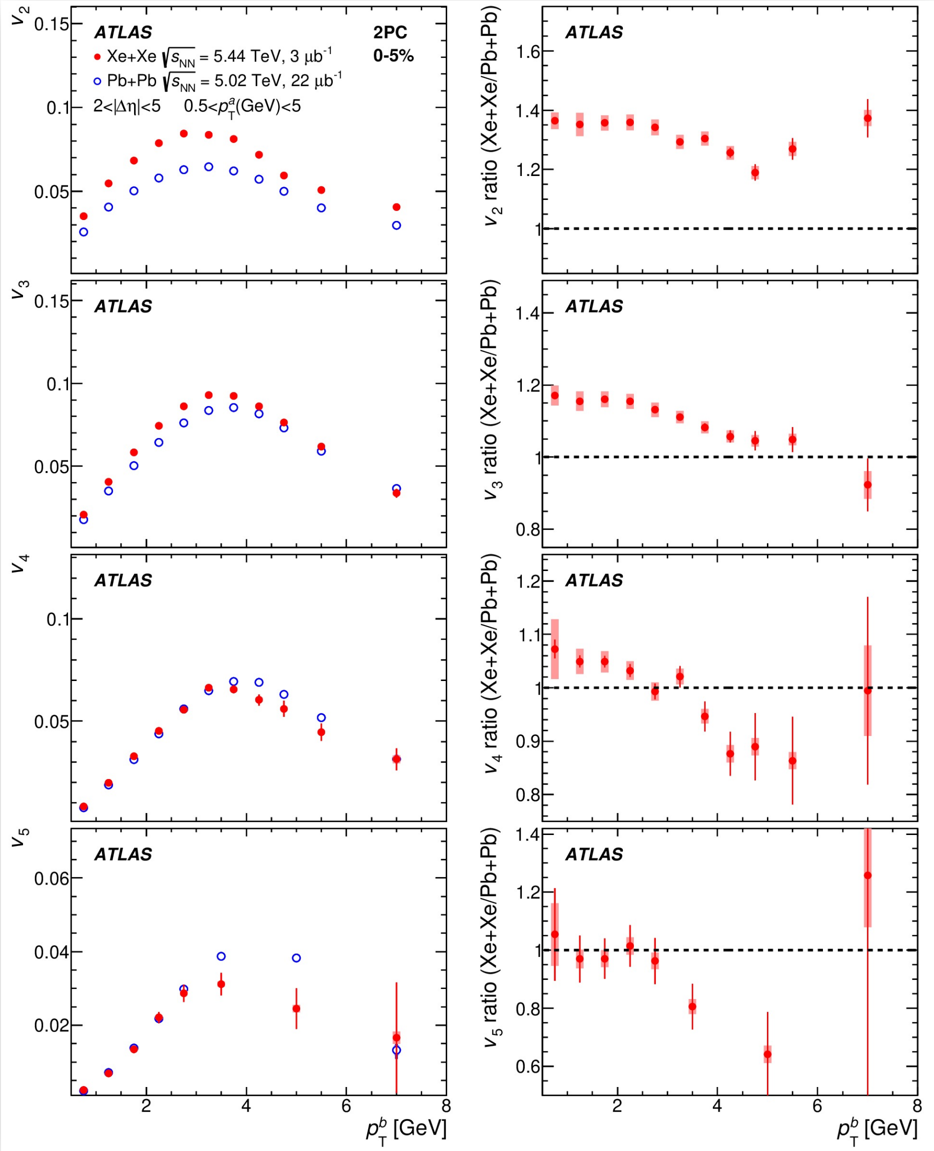
Phys. Rev. C 101 (2020) 024906

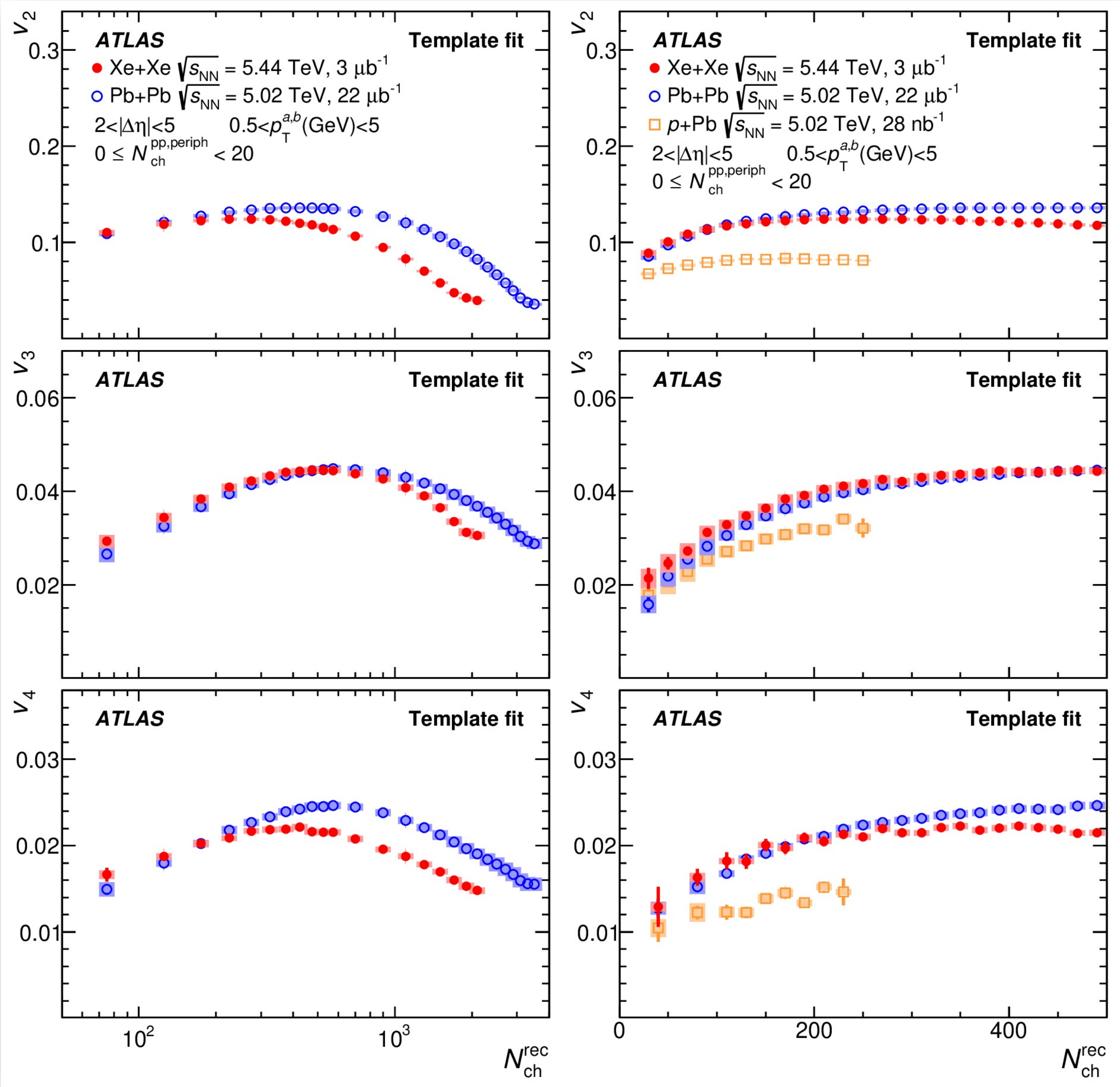


- At same N_{part}, Xe+Xe v_2 is smaller than Pb+Pb.
  - Xe+Xe geometry is less elliptic.
- v_3 is similar except for most central events.
  - Largely driven by fluctuations.

Charged particle flow in Xe+Xe

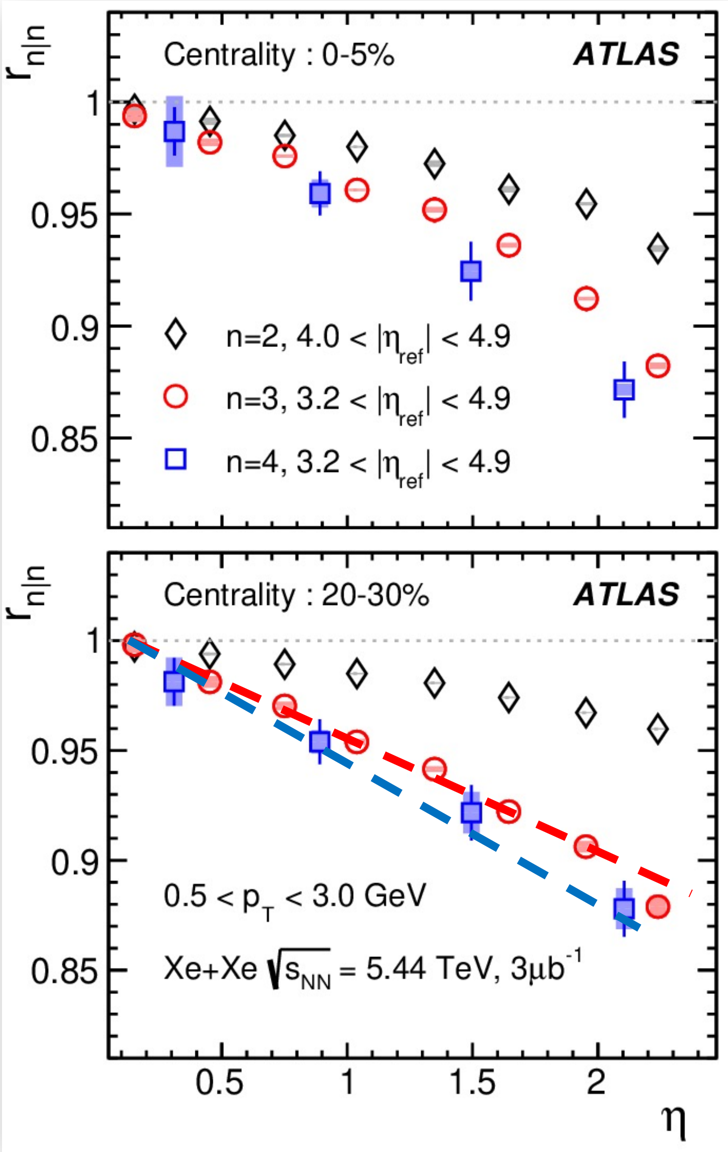
Phys. Rev. C 101 (2020) 024906





Flow Decorrelation

Phys. Rev. Lett. 126 (2021) 12230



Increase "linearly" with $\boldsymbol{\eta}$.

Some hints on non-linearity in 0-5% central collisions

Increase significantly from n=2 to n=3

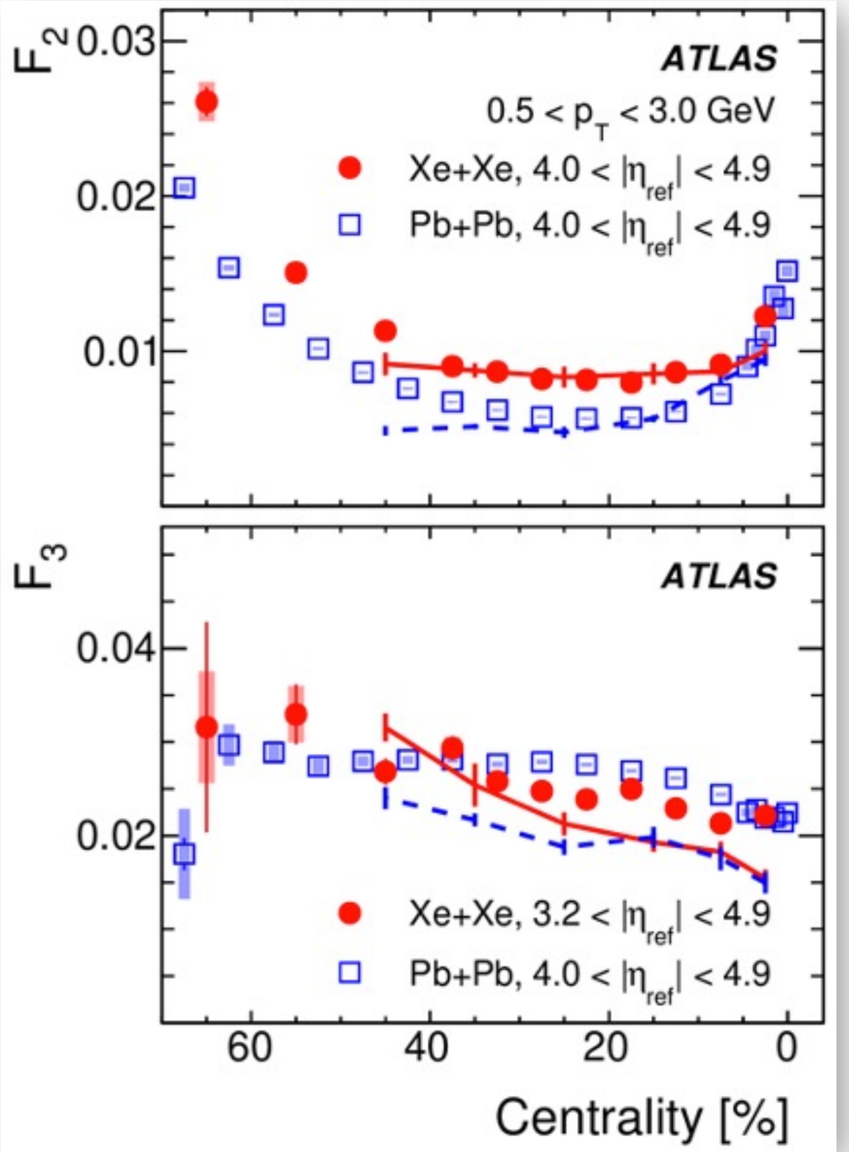
Relatively smaller change from n=3 to n=4

Quantify by slope:

$$r_{n|n}(\eta) = 1 - 2F_n\eta$$

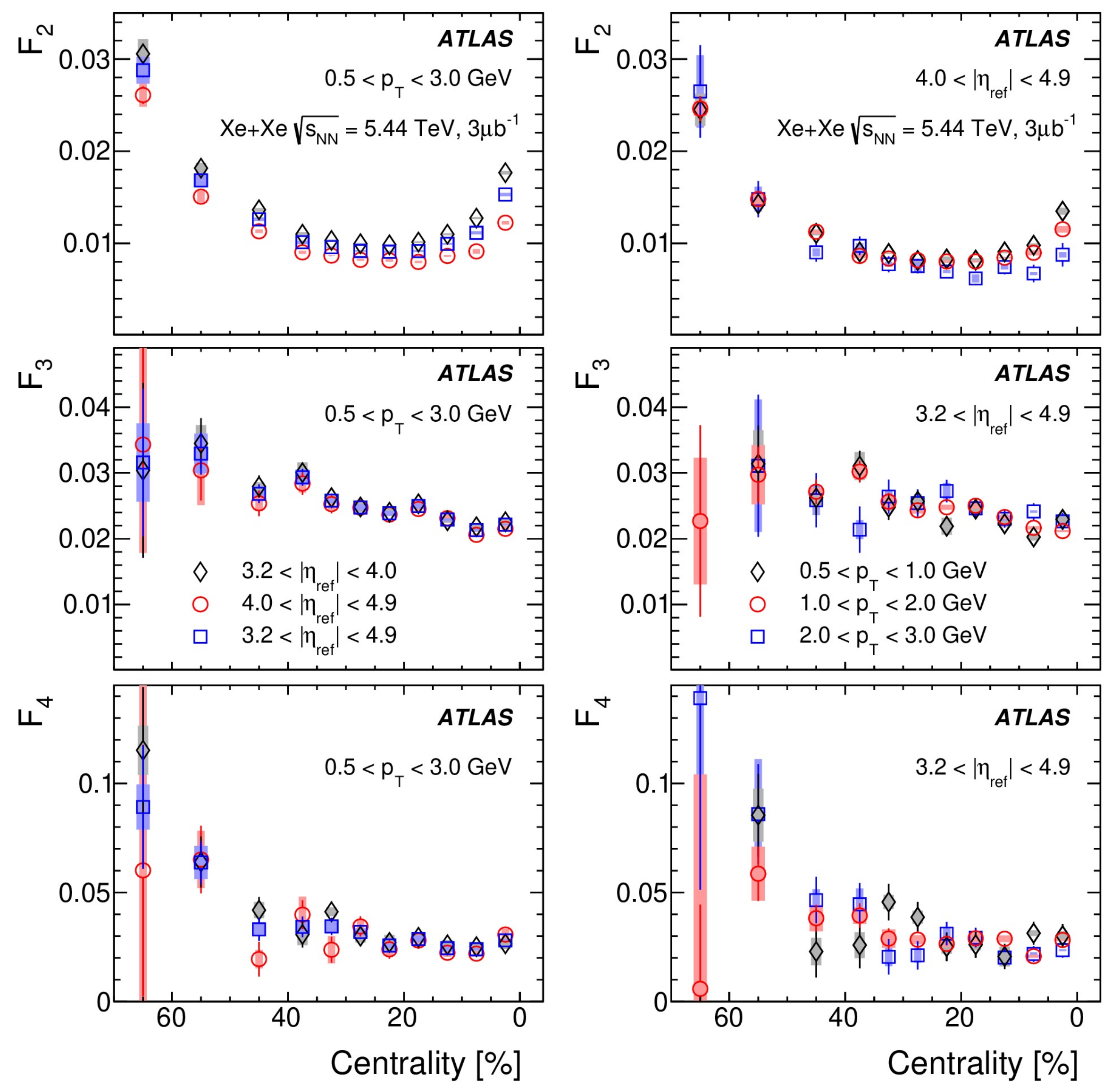
$$F_2^{XeXe} > F_2^{PbPb}$$

$$F_3^{XeXe} < F_3^{PbPb}$$



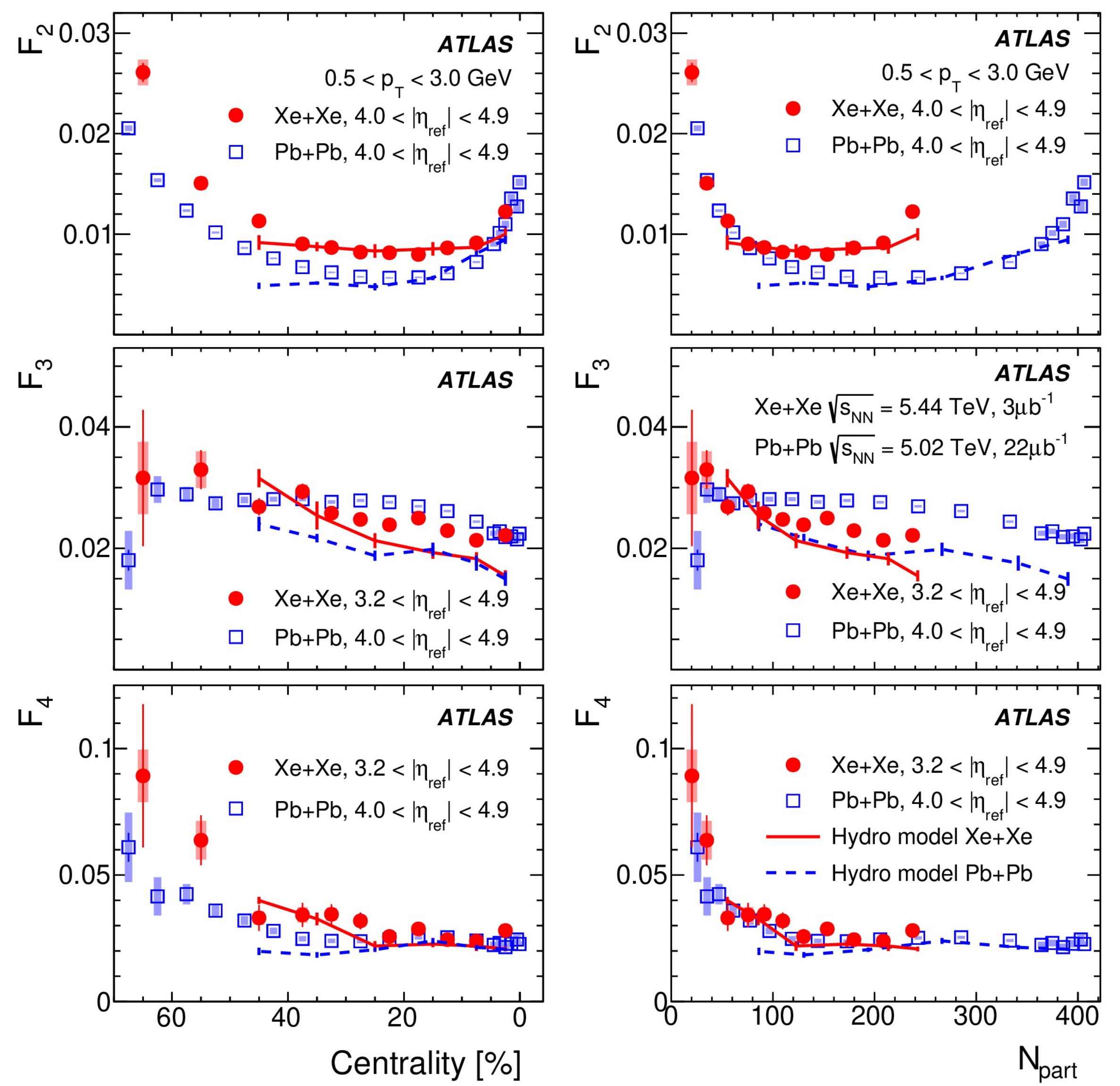
Flow Decorrelation

Phys. Rev. Lett. 126 (2021) 12230



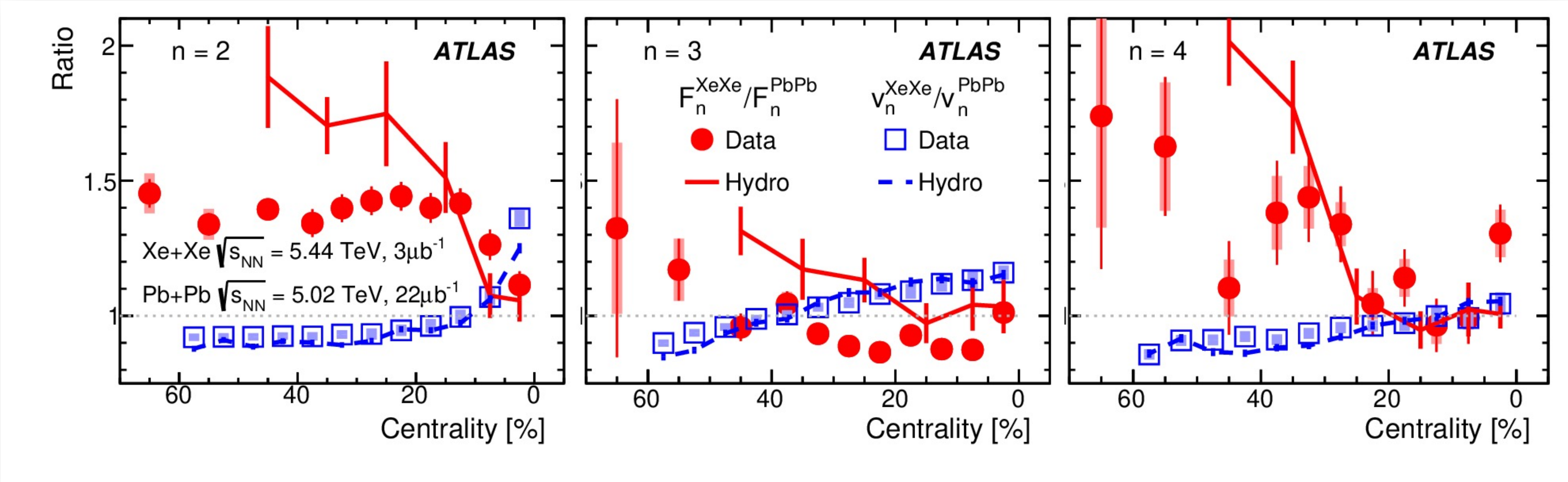
Flow Decorrelation

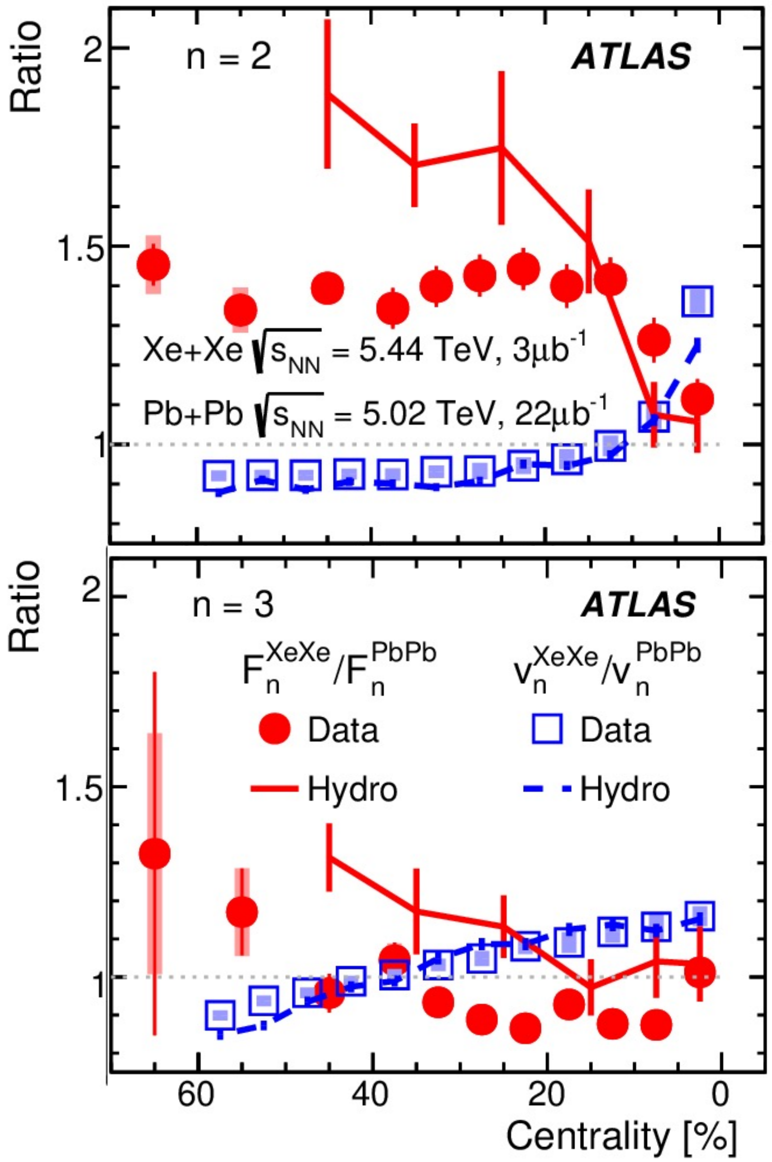
Phys. Rev. Lett. 126 (2021) 12230



Flow Decorrelation

Phys. Rev. Lett. 126 (2021) 12230

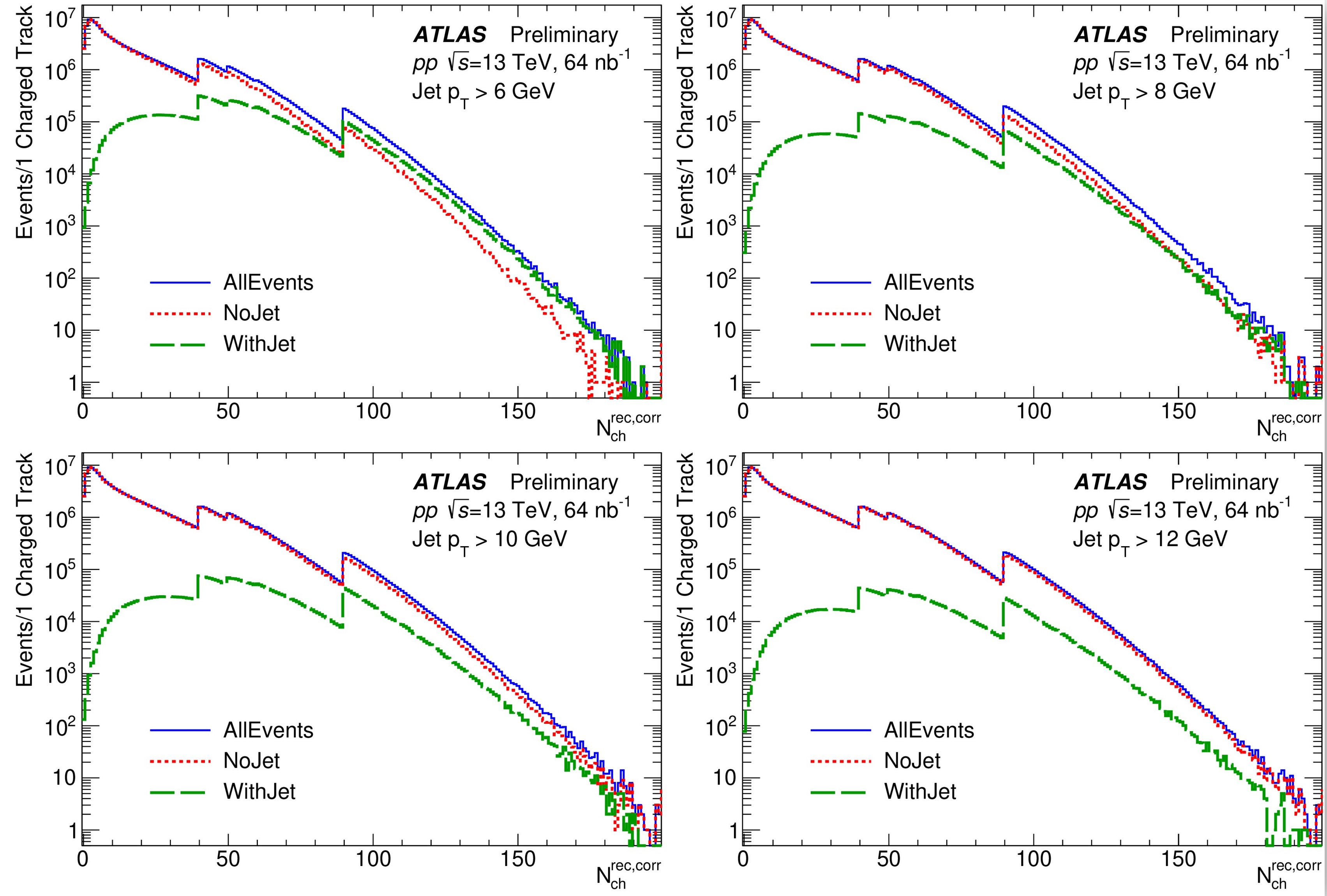




n = 2
ATLAS
Xe+Xe √sNN = 5.44 TeV, 3μb-1
Pb+Pb √sNN = 5.02 TeV, 22μb-1
n = 3
ATLAS
F_n^XeXe/F_n^PbPb
Data
Hydro
v_n^XeXe/v_n^PbPb
Data
Hydro
Ratio
Ratio
Centrality [%]
2
1.5
1
60
40
20
0

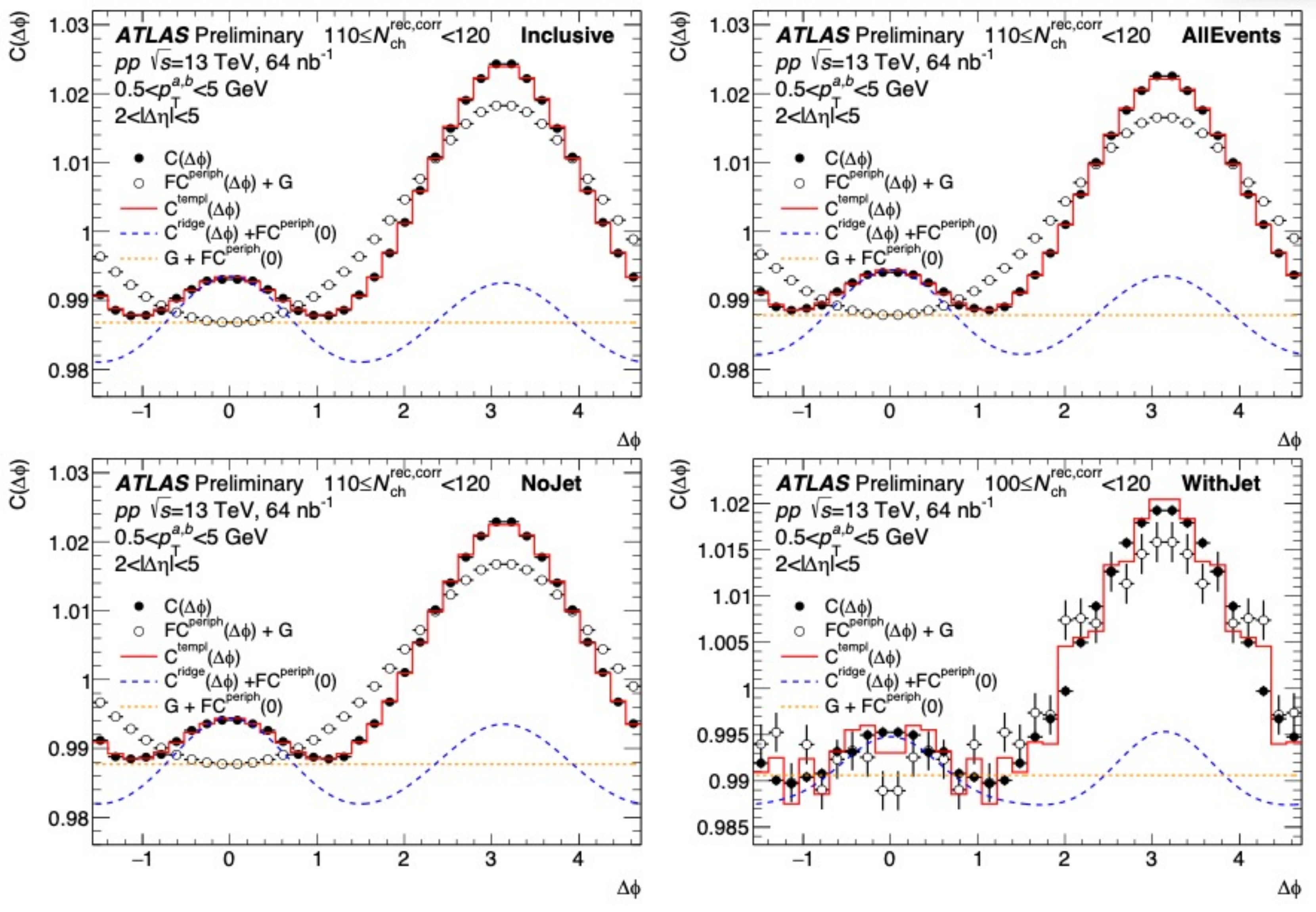
Sensitivity of flow to jets in *pp*

ATLAS-CONF-2020-018



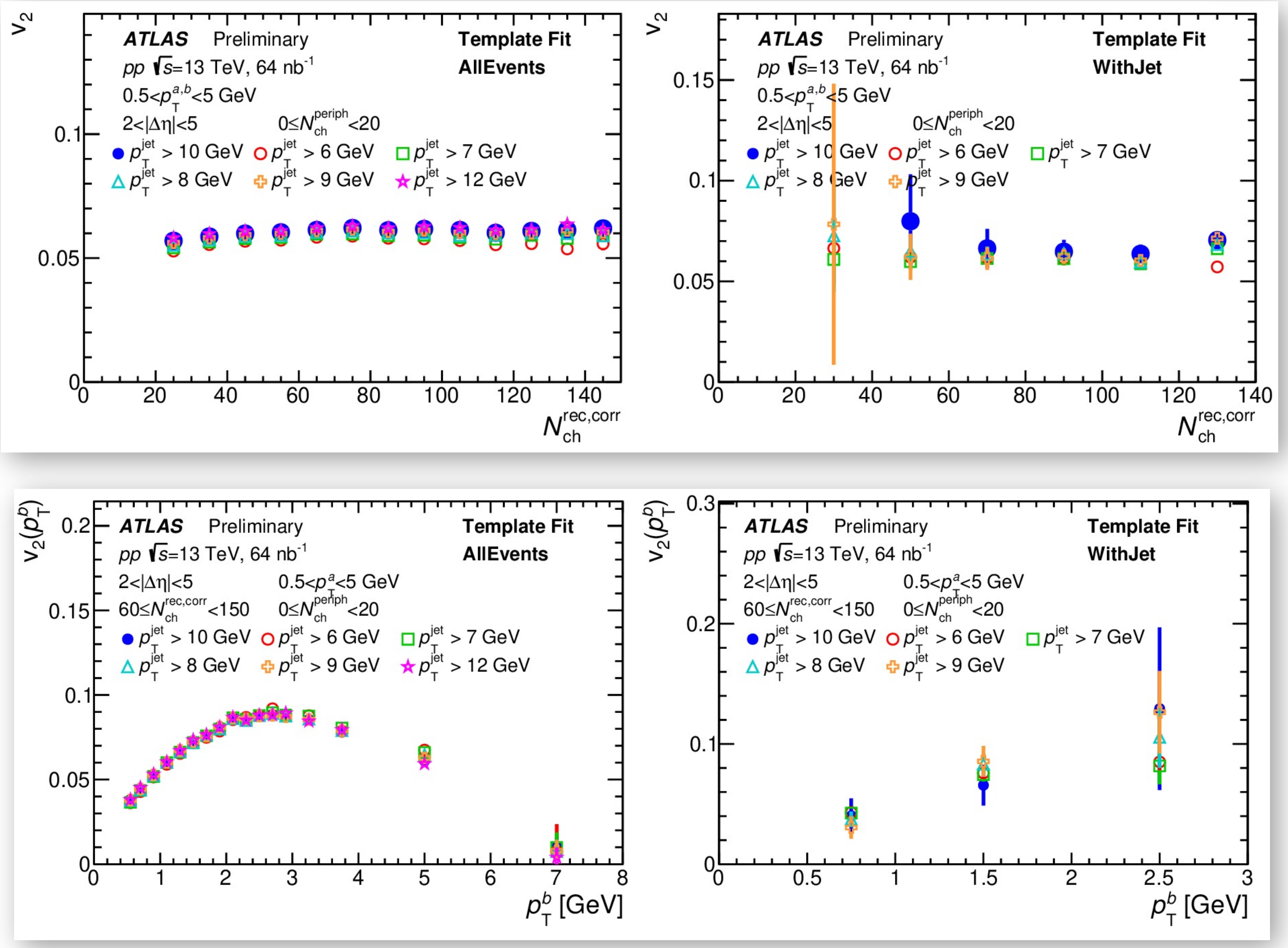
Sensitivity of flow to jets in *pp*

ATLAS-CONF-2020-018



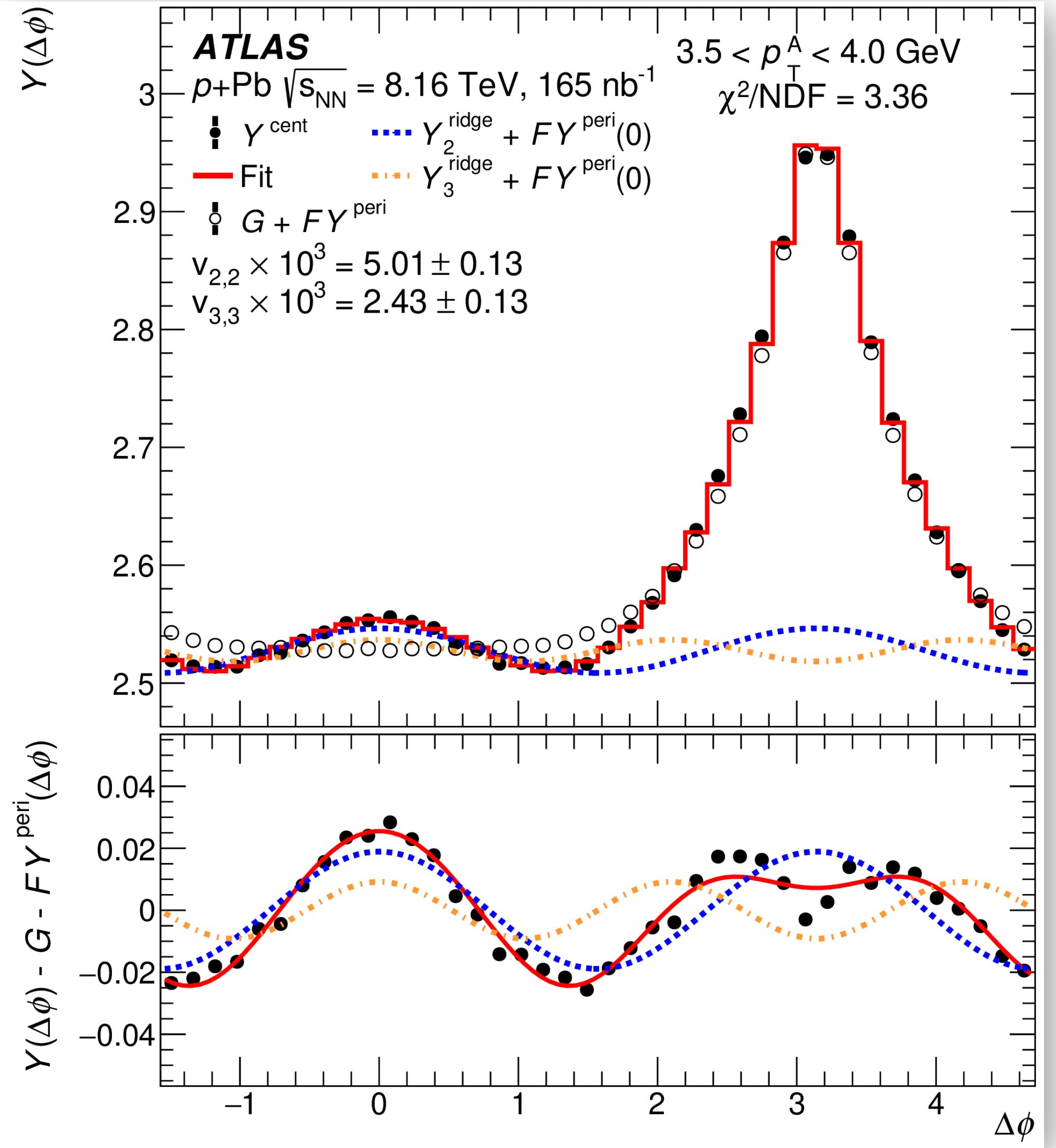
Sensitivity of flow to jets in *pp*

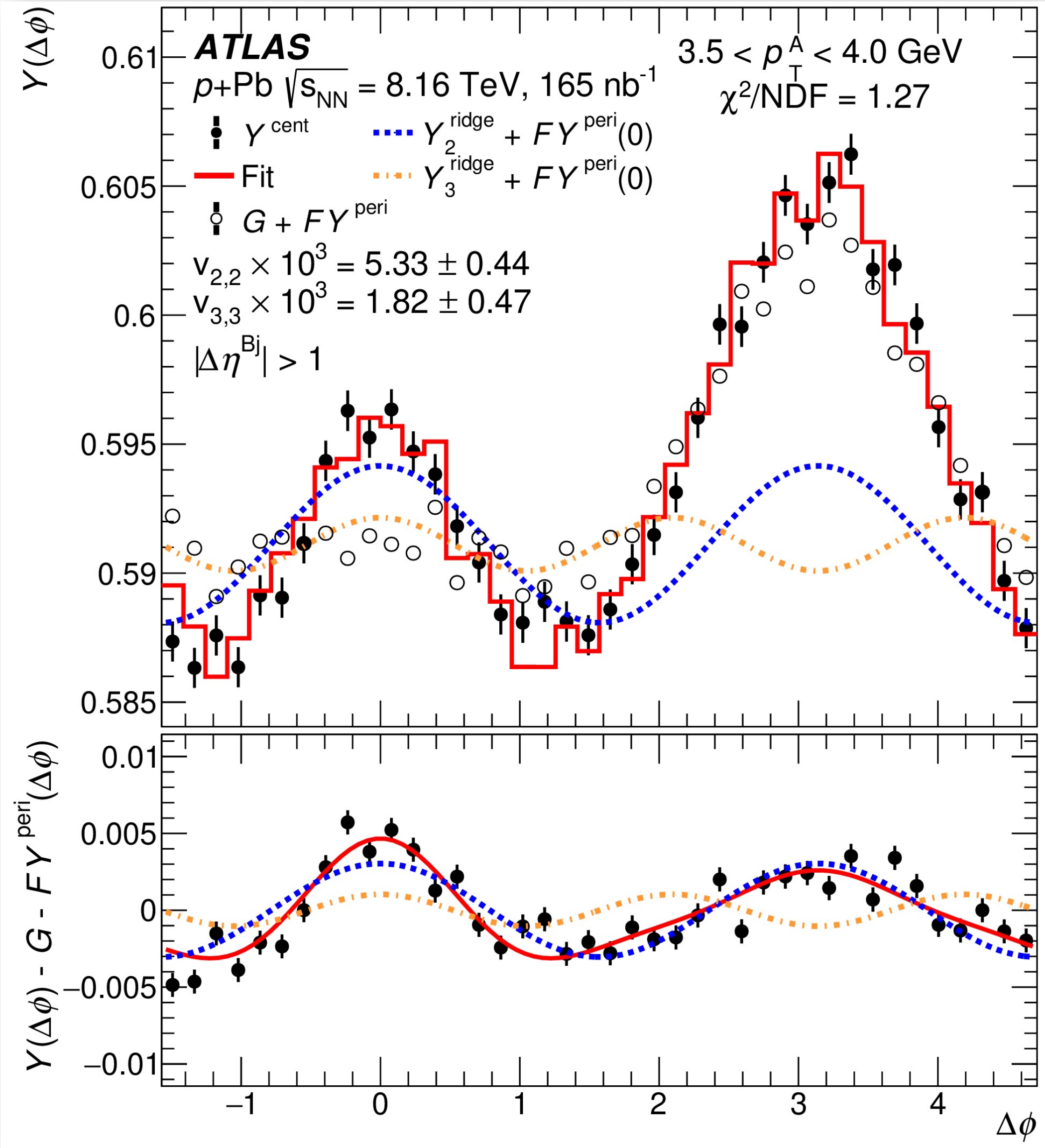
ATLAS-CONF-2020-018



High-pT correlation in p+Pb

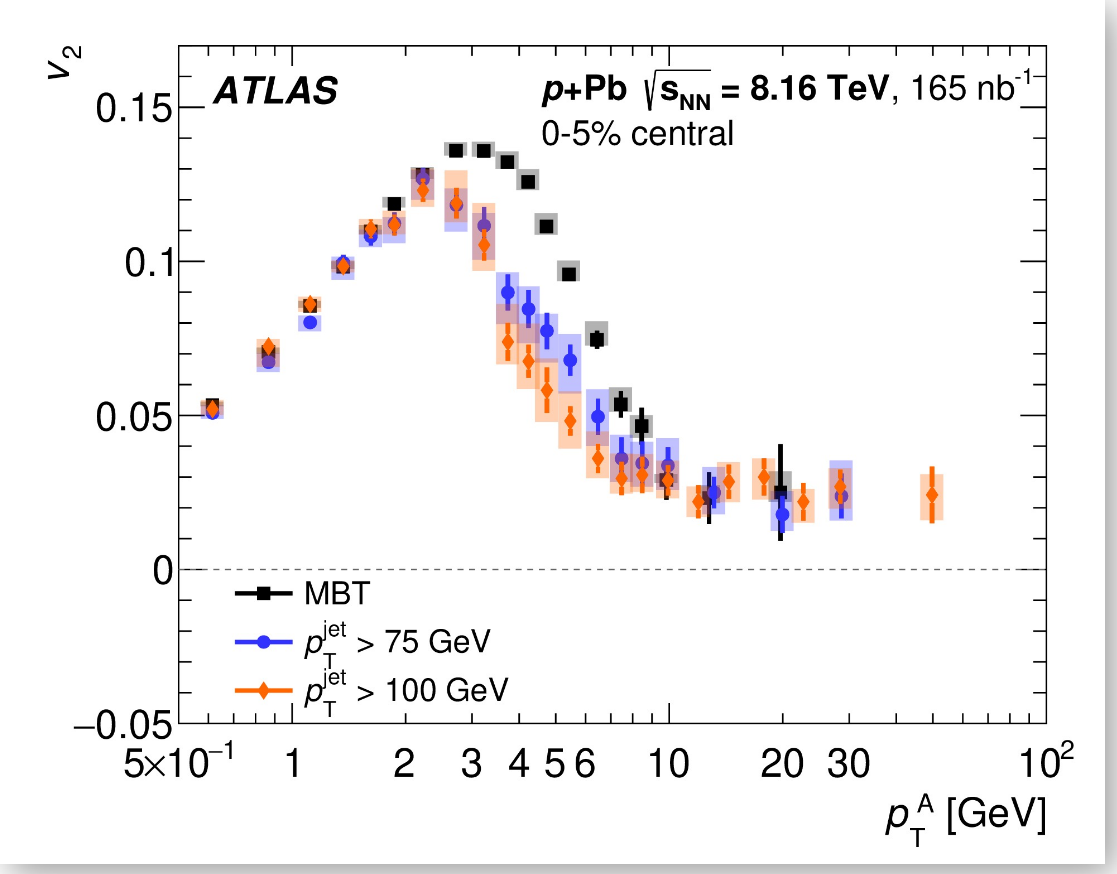
Eur. Phys. J. C 80 (2020) 73

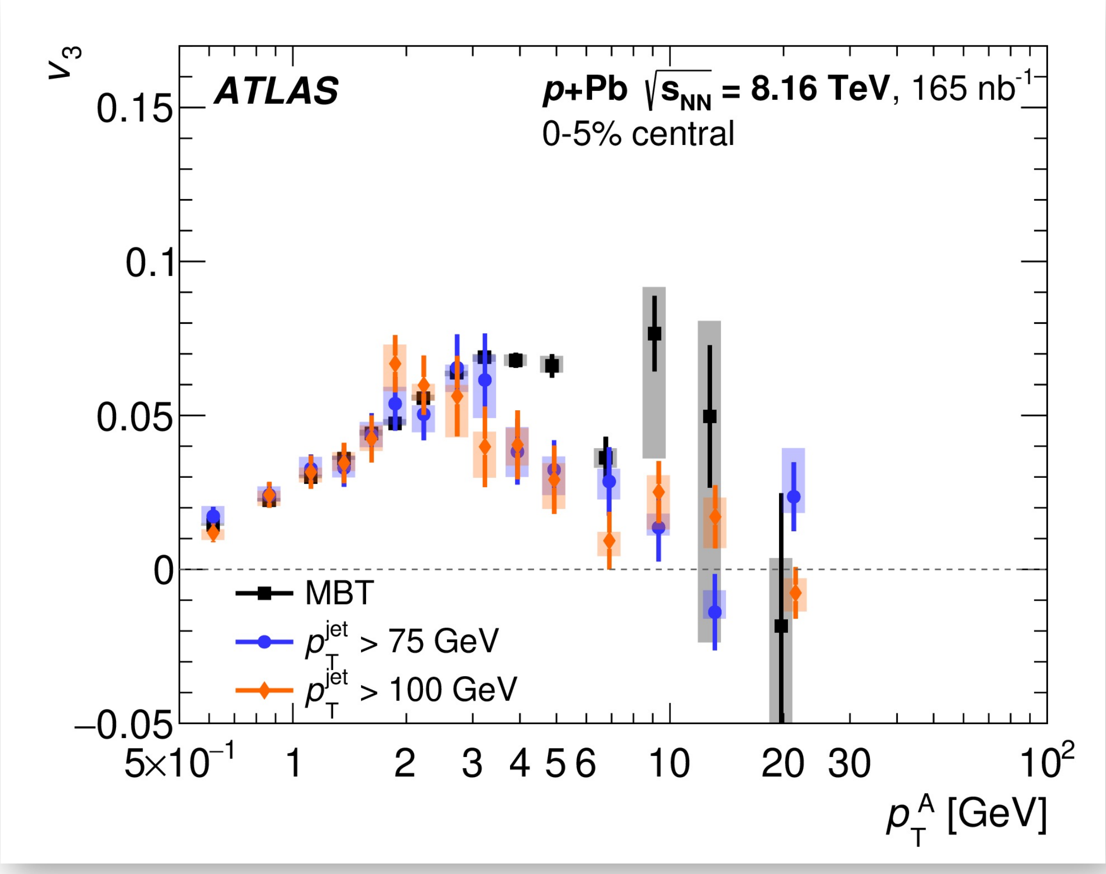




High-pT correlation in p+Pb

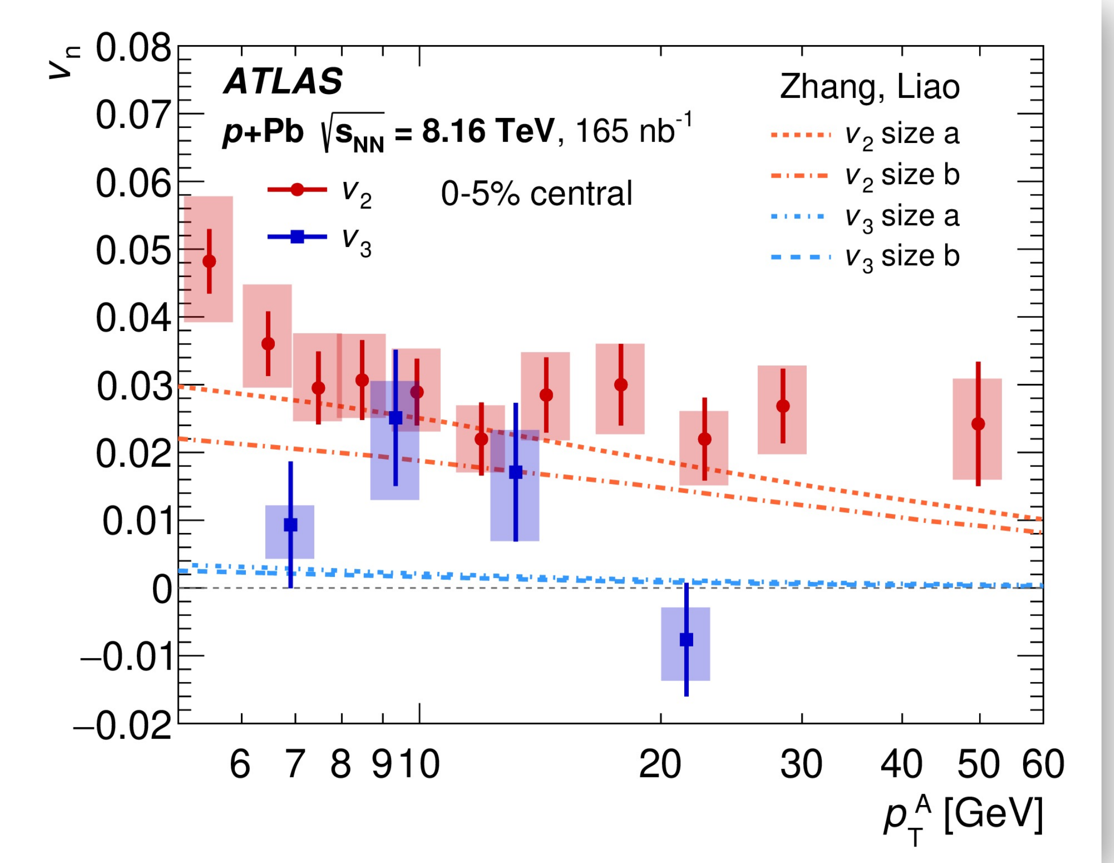
Eur. Phys. J. C 80 (2020) 73

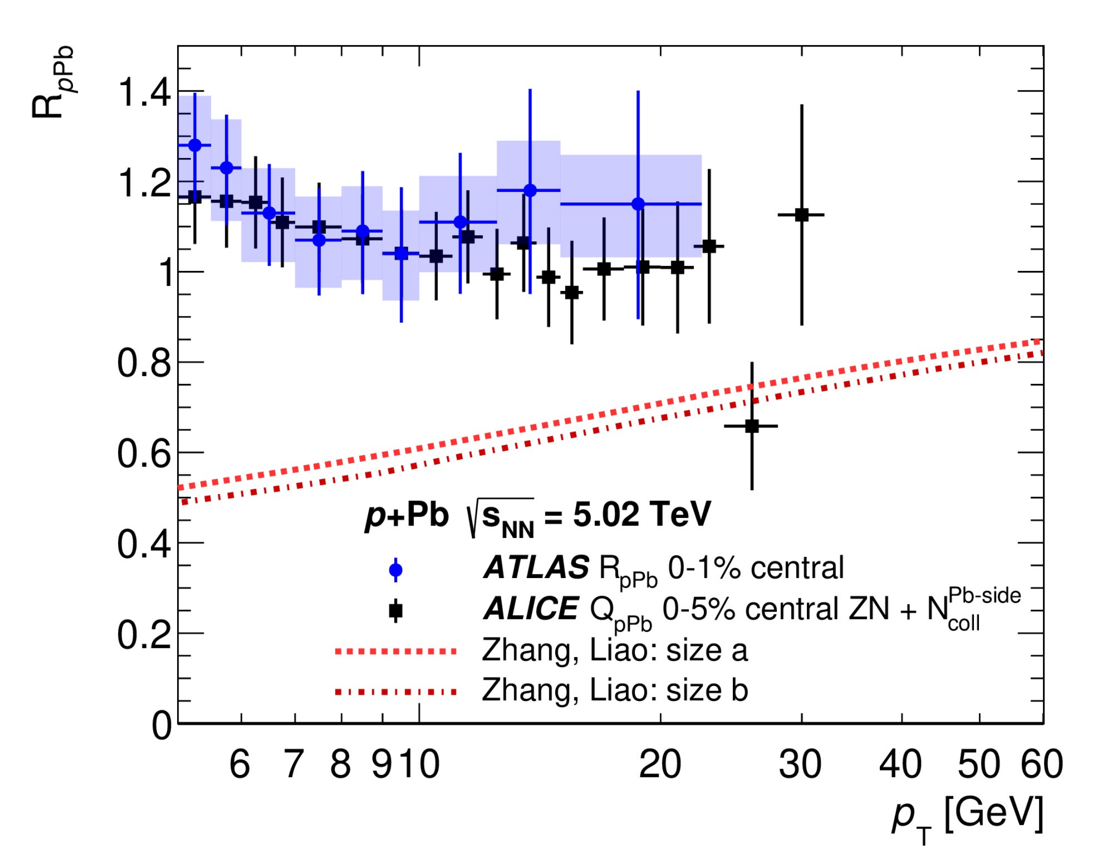




High-pT correlation in p+Pb

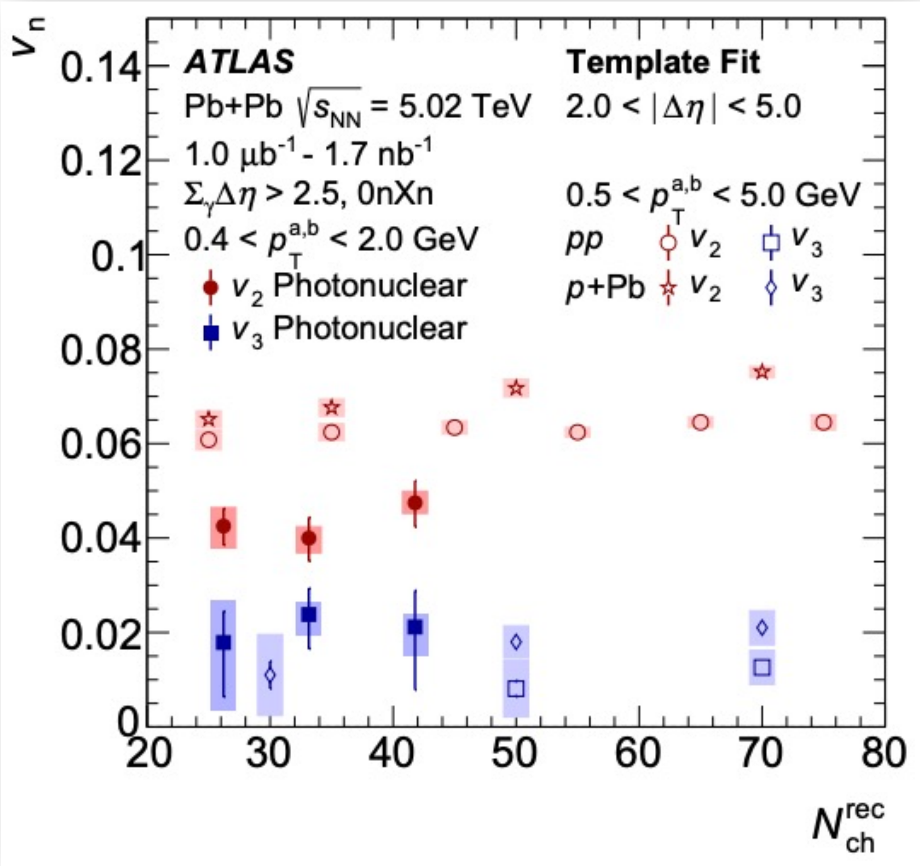
Eur. Phys. J. C 80 (2020) 73

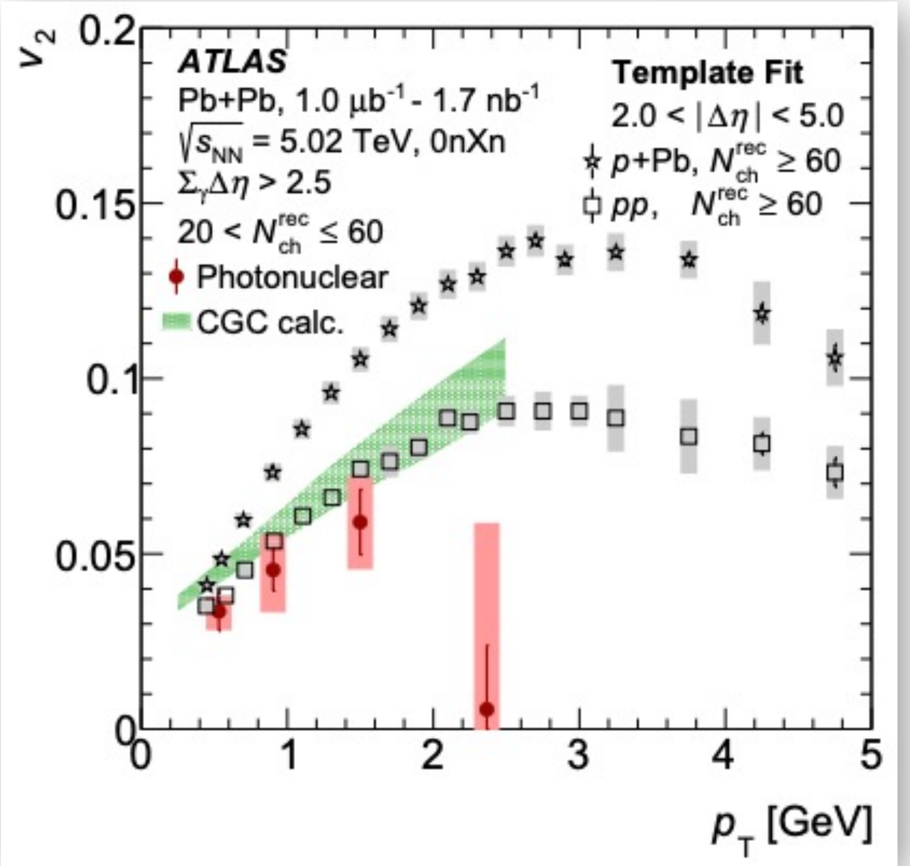




Flow in photo-nuclear collisions

CERN-EP-2020-246





- Observe Significant v_2 in photo-nuclear collisions
  - v_2 is flat within error and systematically smaller than pp and pPb
  - pT dependent results consistent within uncertainties