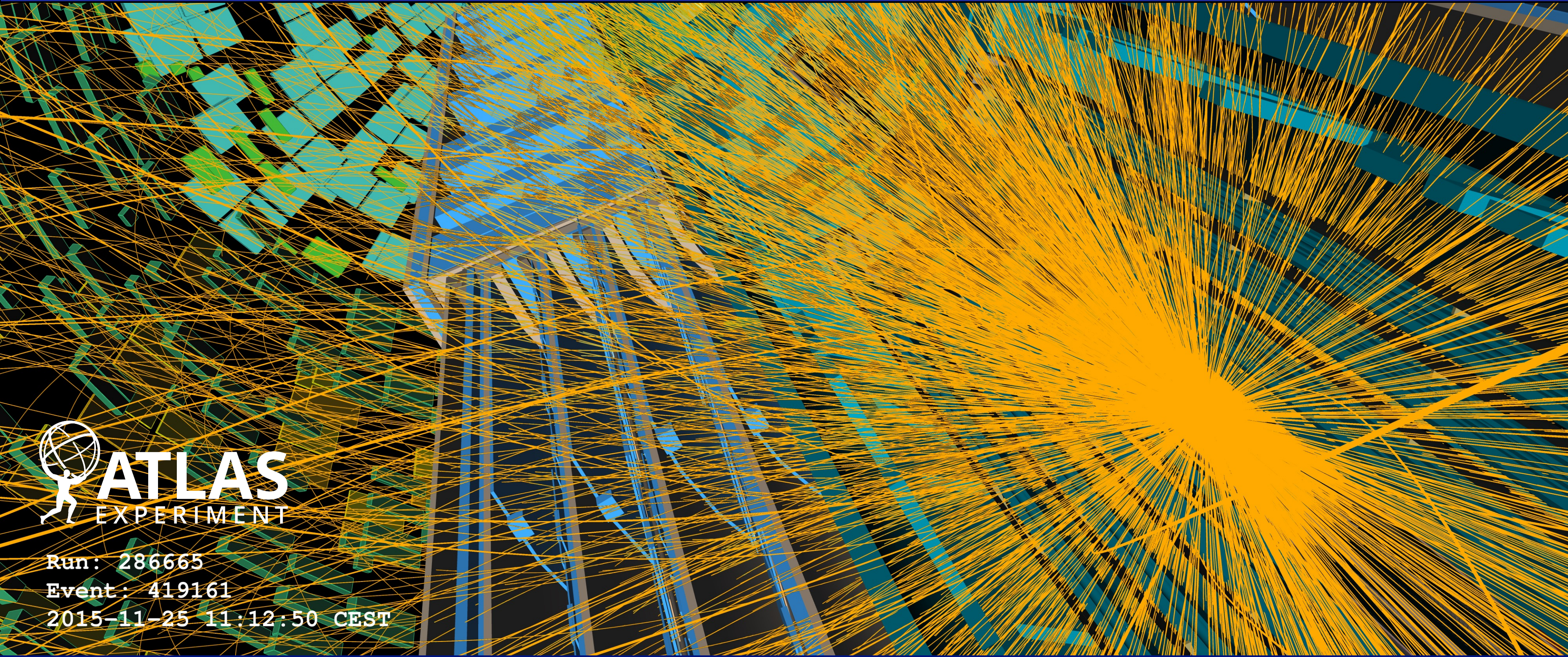
Collective dynamics of heavy ion collisions in ATLAS



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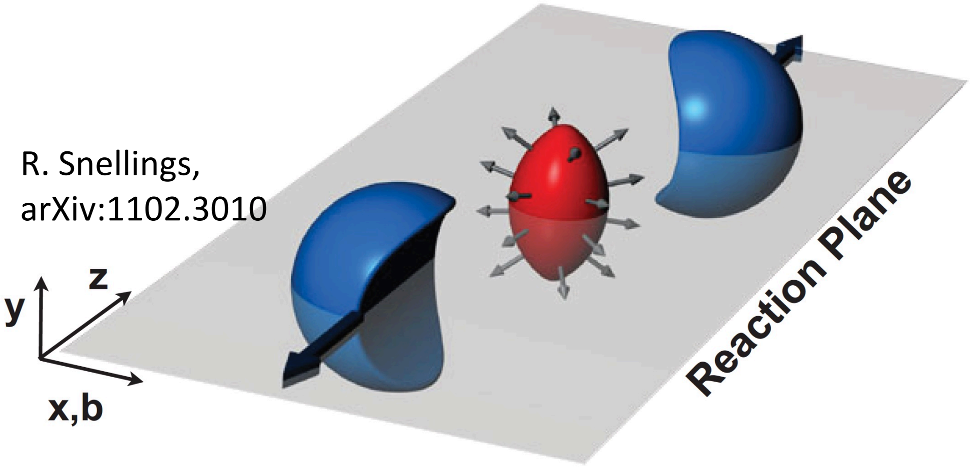
Institute of Nuclear Physics PAN, Kraków

LXXI International conference "NUCLEUS -2021. Nuclear physics and elementary particle physics. Nuclear physics technologies"
September 20-25, 2021

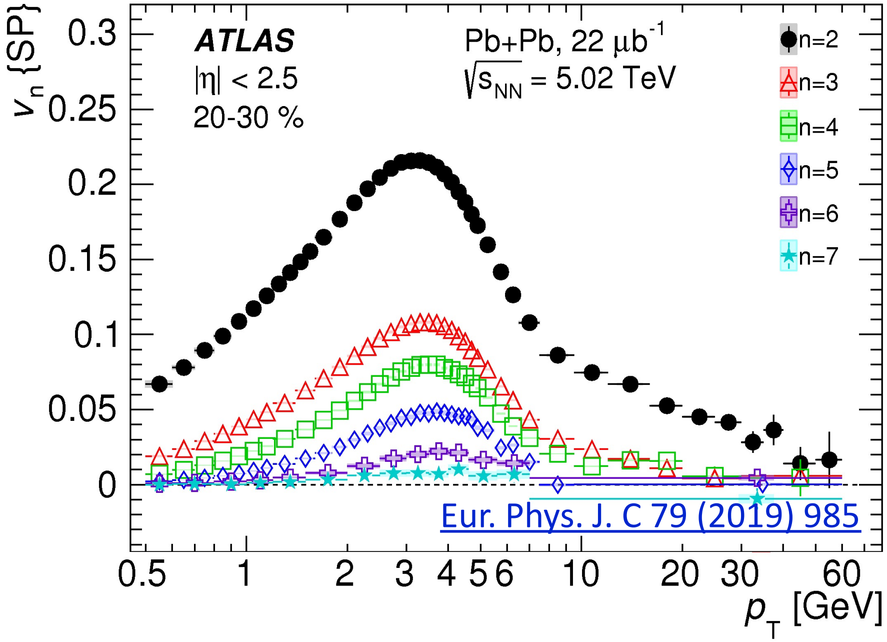
Motivation

- Large azimuthal anisotropy observed in heavy-ion collisions at RHIC and the LHC is one of main signatures of quark-gluon plasma (QGP)



R. Snellings, arXiv:1102.3010

Azimuthal anisotropy is “driven” by asymmetry in initial geometry



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$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$$

Flow harmonics

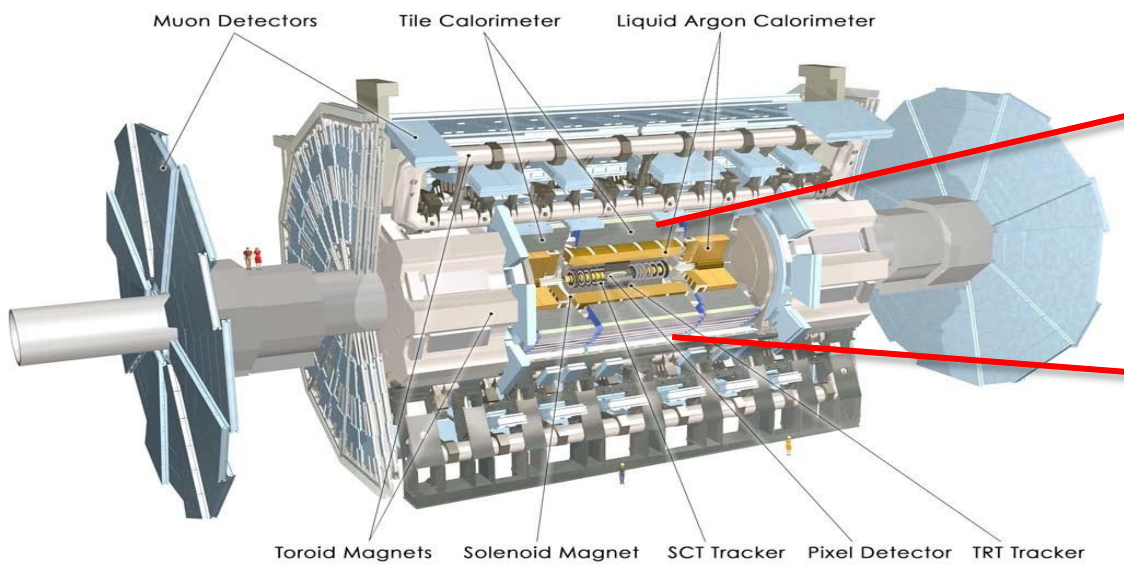
- Space–time evolution of QGP is described by hydrodynamic models
  - Transport parameters (viscosity, η/s ,..), equation of state (EOS), …
- QGP models are constrained by flow harmonics and their correlations

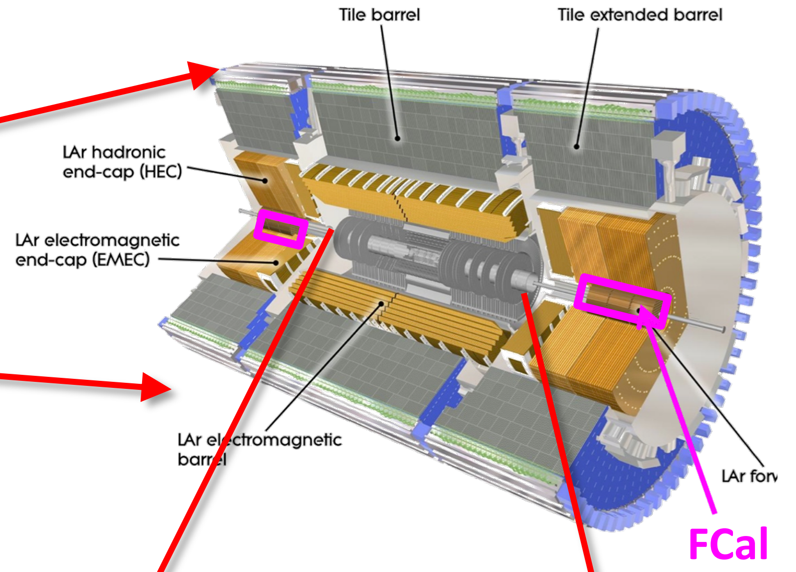
Outline

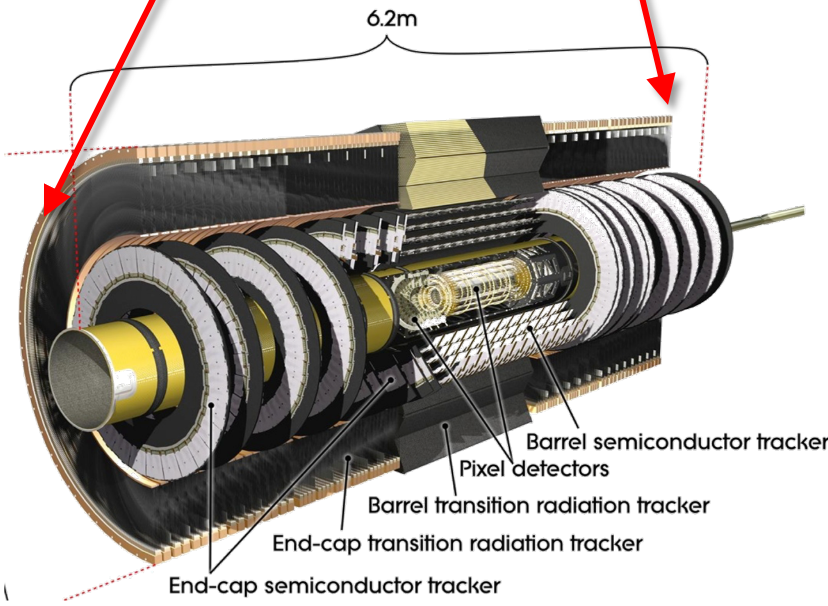
- Longitudinal flow decorrelations in 5.44 TeV Xe+Xe and ATLAS-CONF-2021-001 5.02 TeV Pb+Pb collisions, Phys. Rev. Lett. 126, 122301 (2021)
- The mean transverse momentum and flow harmonics correlation in 5.02 TeV *p*+Pb and Pb+Pb and 5.44 TeV Xe+Xe collisions, Eur. Phys. J. C 79 (2019) 985, ATLAS-CONF-2021-001
- Azimuthal anisotropy of heavy-flavor muons in 5.02 TeV Pb+Pb and 13 TeV pp collisions, arXiv:2109.00411 [nucl-ex], Phys. Lett. B 807 (2020) 135595, Phys. ReV. Lett. 124 (2020) 082301
- Charged particle flow in 13 TeV pp collisions with jet particle rejection, ATLAS-CONF-2020-018

See also AGTLAS presentations
- H. Hamdaoui, Sat 13:00
- M. Krivos, Sec.4, Tue 14:05

ATLAS Detector







Three main subsystems:

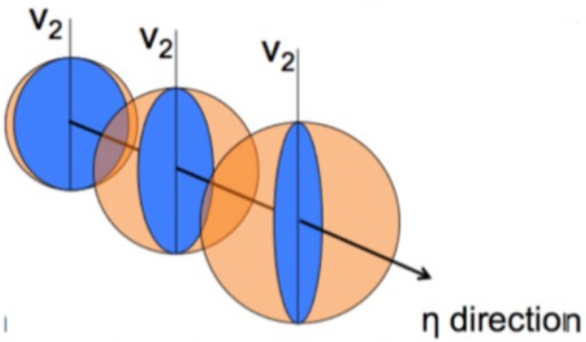
- Inner Detector (ID)–tracking $|\eta|<2.5$
- Calorimetry – $|\eta|<4.9$
    - FCal $3.1<|\eta|<4.9$
- Muon Spectrometer - $|\eta|<2.7$

Fast trigger systems:

- Level 1 (L1)
- High Level Trigger (HLT)

Flow decorrelation in 5.44 TeV Xe+Xe collisions

Flow decorrelations provide significant insight into longitudinal fluctuations of the initial conditions (eccentricity)



$$v_n(\eta_1) \neq v_n(\eta_2)$$

- Correlation between flow vectors at –*η* and *η* with respect to *η*$_{\mathrm{ref}}$ measured with correlator

ID FCall

$$r_{n|n}(\eta) = \frac{\langle \boldsymbol{q}_n(-\eta)\boldsymbol{q}_n^*(\eta_{\mathrm{ref}})\rangle}{\langle \boldsymbol{q}_n(\eta)\boldsymbol{q}_n^*(\eta_{\mathrm{ref}})\rangle}$$

Flow vectors measured with charged particle tracks over |*η*|<2.5

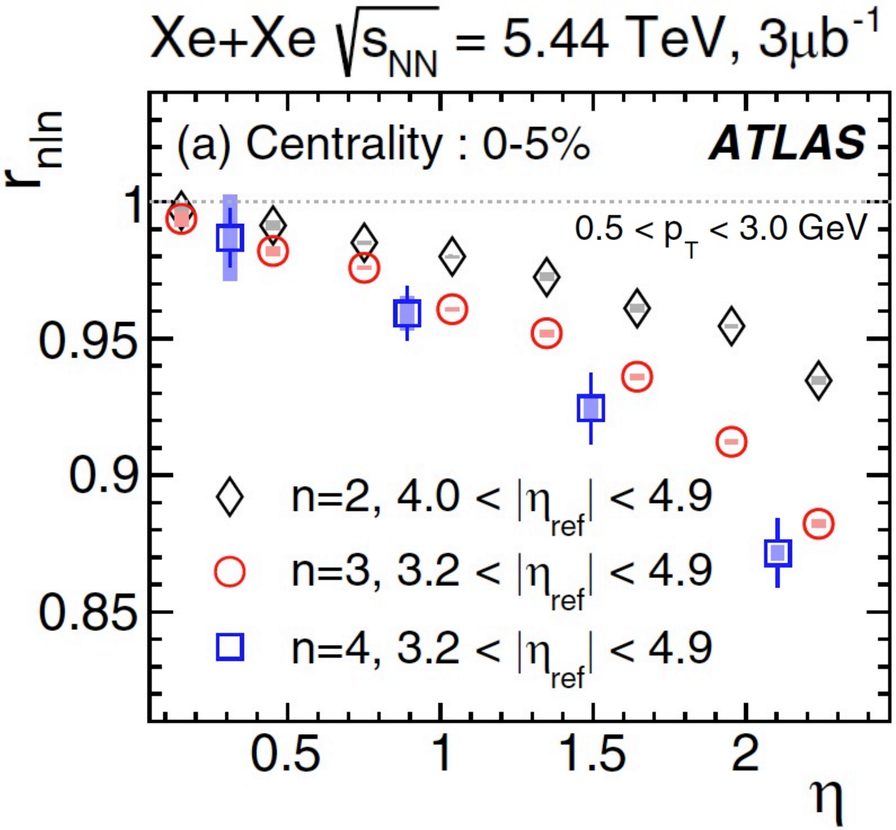
$$\boldsymbol{q}_n \equiv \frac{\sum_i w_i e^{in\phi_i}}{\sum_i w_i}$$

$$\sim v_n e^{-in\Phi_n}, \quad \sim \varepsilon_n e^{-in\Psi_n}$$

Reference flow vector measured in FCal calorimeter, |*η*$_{\mathrm{ref}}$|> 4

- *r* is sensitive to breakdown of the factorization of product of two-particle flow harmonics into product of single-particle flow harmonic
  - r < 1: decorrelation signal

Flow decorrelations in 5.44TeV Xe+Xe collisions



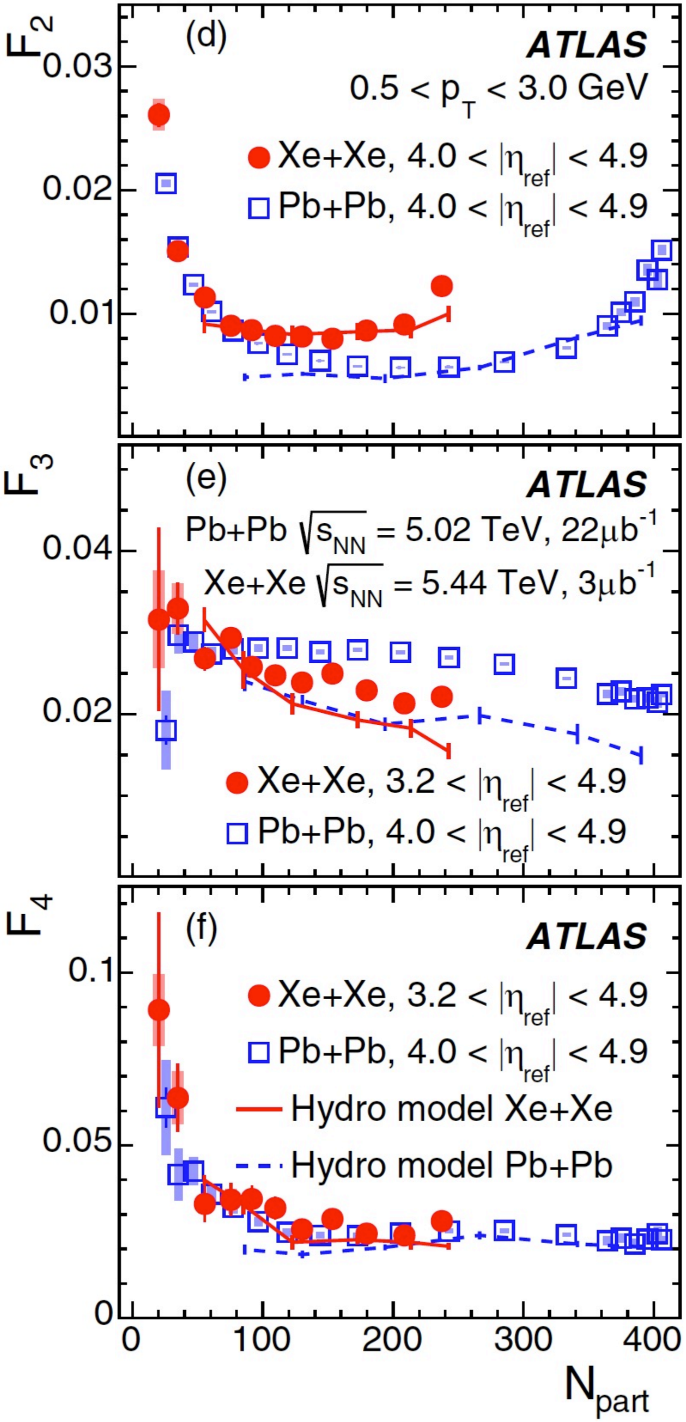
Phys. Rev. Lett. 126, 122301 (2021)

- Significant magnitude of decorrelation is observed, $r_{n|n}<1$
- A linear decrease of $r_{n|n}$ with η is observed for n = 2, 3 & 4
  - The η dependence is parametrized by a linear function

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

Centrality and system dependence of flow decorrelation in Xe+Xe and Pb+Pb collisions

- F_2 shows a strong dependence on N_{part}, in contrast to F_3 and F_4
- For $N_{part} \lesssim 80$, F_n for Xe+Xe and Pb+Pb agree
- For $N_{part} > 80$, F_2 is larger in Xe+Xe while opposite relation is observed for F_3
- Hydro model qualitatively describes F_2 and F_4 but fails for F_3



Phys. Rev. Lett. 126, 122301 (2021)

v_n-$[p_T]$ correlation in *p*+Pb, Pb+Pb and Xe+Xe collisions

Correlation between magnitudes of flow harmonics and mean event transverse momentum, $[p_T]$, is expected to be sensitive to initial conditions

The modified Pearson correlation coefficient(Phys. Rev. C 93 (2016) 044908):

$$R = \frac{cov(v_n^2,[p_T])}{\sqrt{Var(v_n^2)}\sqrt{Var([p_T])}} \quad \longrightarrow \quad \rho = \frac{\mathrm{cov}(v_n\{2\}^2,[p_T])}{\sqrt{\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}}\sqrt{c_k}}$$

To exclude the multiplicity effect in *R* variances of v_n^2 and $[p_T]$ are replaced by:

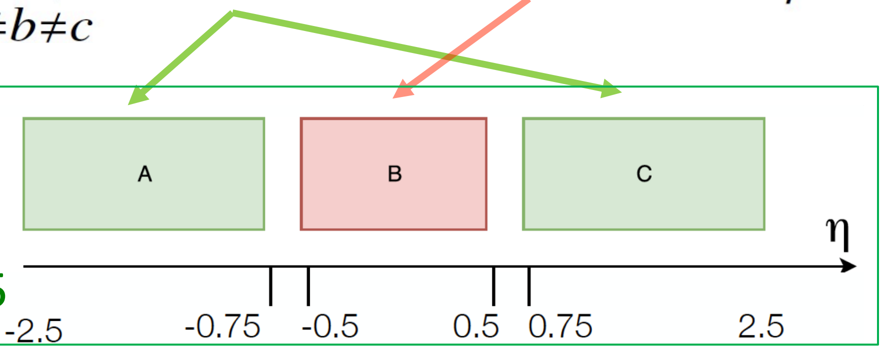
$$\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}} = \langle corr_n\{4\}\rangle - \langle corr_n\{2\}\rangle^2$$

$$c_k = \left\langle \frac{1}{(N_B(N_B-1))} \sum_b \sum_{b \neq b'} (p_{T,b} - \langle [p_T]\rangle)(p_{T,b'} - \langle [p_T]\rangle) \right\rangle$$

$$cov(v_n\{2\}^2,[p_T]) = \left\langle \frac{1}{N_{pairs}N} \sum_{a \neq b \neq c} e^{in\phi_a - in\phi_c}(p_{T,b} - \langle [p_T]\rangle) \right\rangle$$

Covariance is calculated using 3 subevents:

- B - for $[p_T]$ $|\eta| < 0.5$
- A + C - for v_n^2 measurement $|\eta| > 0.75$



$\rho(N_{ch})$ for v_2

$$\rho = \frac{\mathrm{cov}(v_n\{2\}^2, [p_\mathrm{T}])}{\sqrt{\mathrm{Var}(v_n\{2\}^2)_\mathrm{dyn}}\sqrt{c_k}}$$

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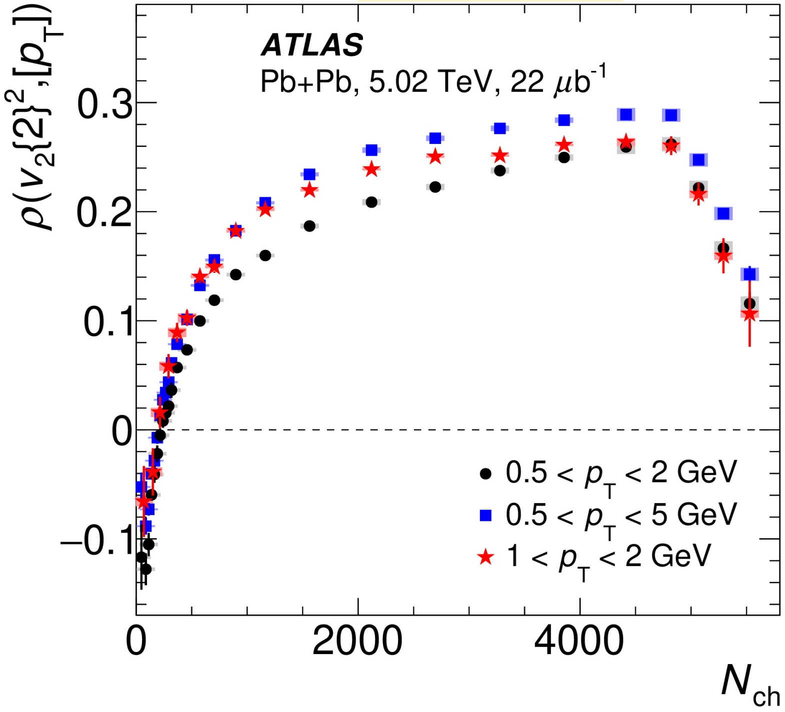
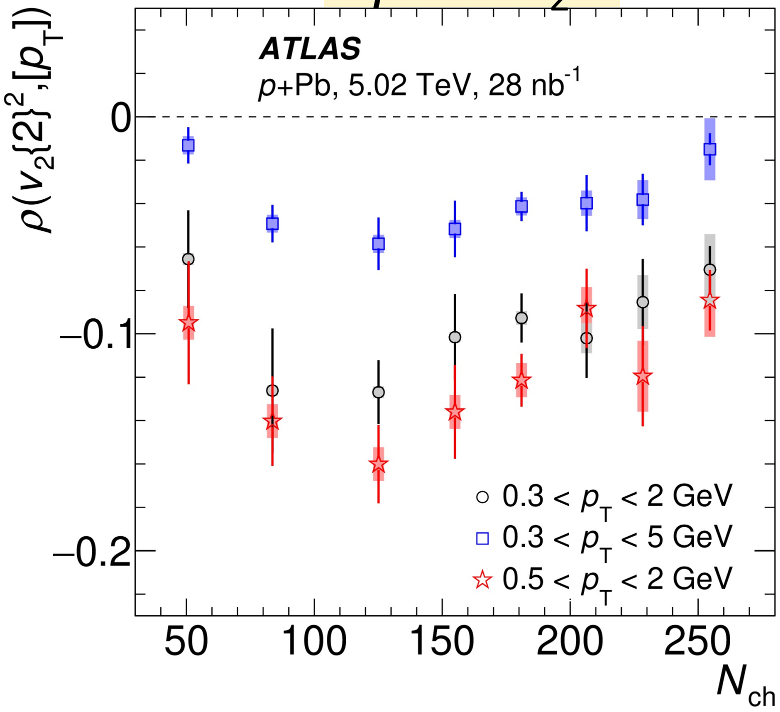
Pb+Pb v_2



p+Pb v_2



- For Pb+Pb collisions ρ for v_2 is negative at low N_{ch} then rises to a value ~0.3, falls in most central collisions
- For *p*+Pb collisions ρ is negative, no apparent dependence on N_{ch} is observed

$\rho(N_{ch})$ for v_2 in Xe+Xe and Pb+Pb collisions

- Xe+Xe dataset of 3 μb^{-1} is used
- Sensitivity of $\rho(N_{ch})$ to the event class definition
    - using N_{ch}-/ΣE_T-based centrality determination
- Similar trends in centrality for both systems are observed but stronger ρ for v_2 is measured in Pb+Pb collisions
- Theoretical models cannot describe the data quantitatively

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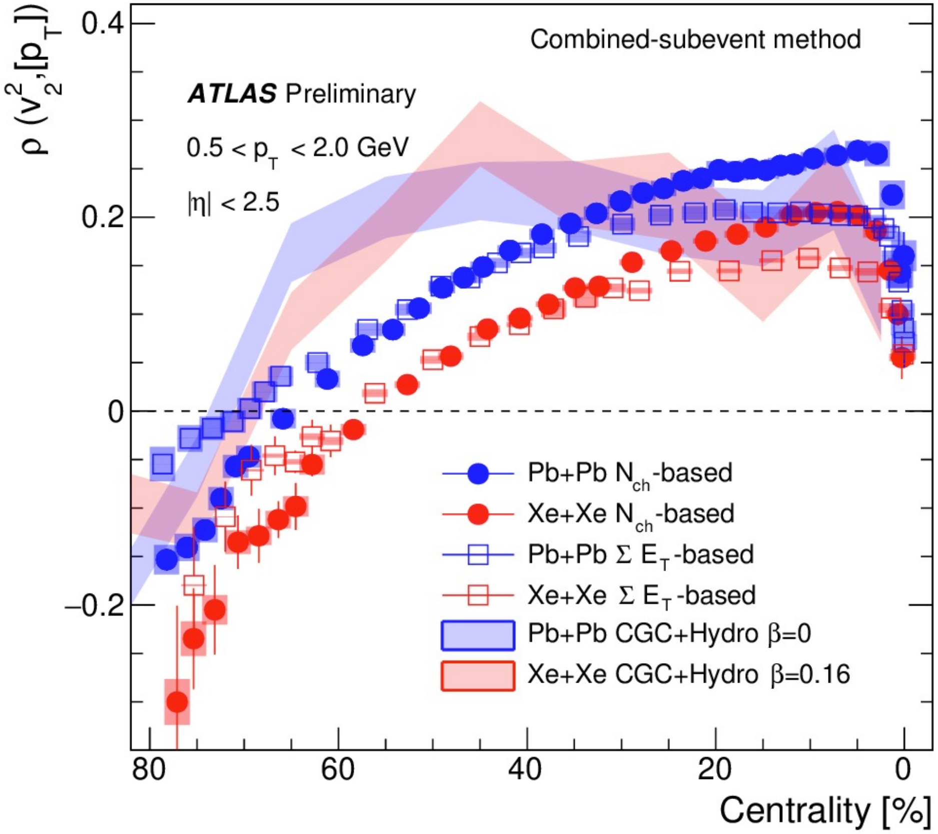
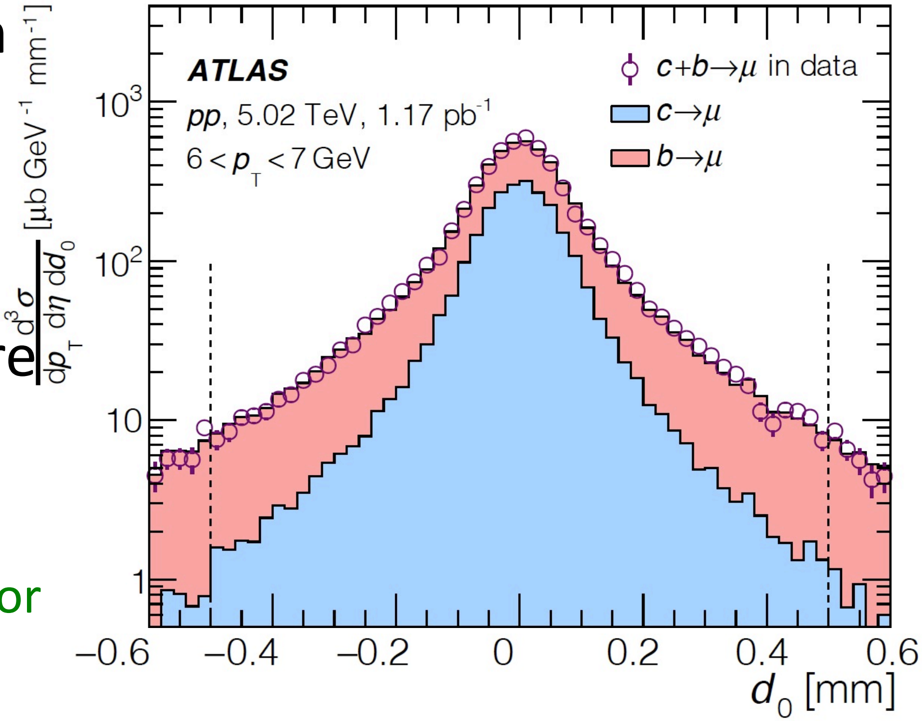


Heavy flavour flow in 5.02 TeV Pb+Pb collisions

Different interplay of radiative and collisional processes for HF quarks than for light quarks is expected

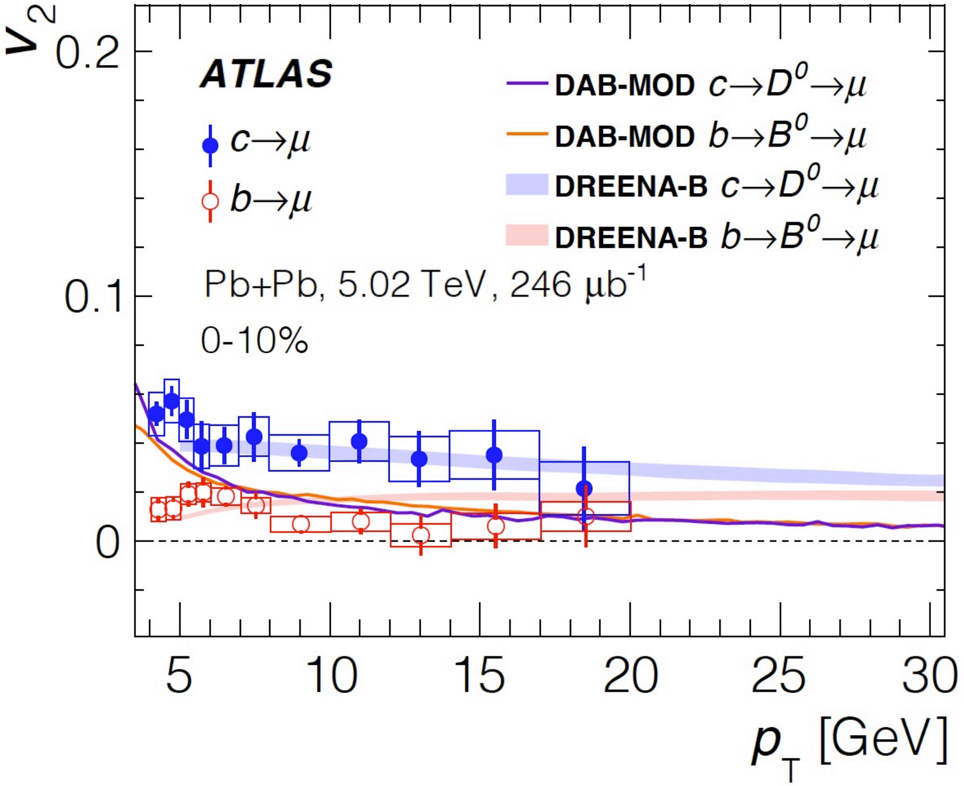
- In the analysis, HF muon v_n harmonics are obtained using muon-hadron two-particle correlations, with template fit method
  - Using data with trigger requiring single muon of $p_T > 4$ GeV
- Muons from heavy-flavour semi-leptonic decays are separated from muons from light-flavour hadron decays using imbalance of muon momentum in ID and MS
- Bottom and charm decay muons are separated by using muon track's transverse impact parameter, d_0
  - Narrower d_0 distribution is observed for charm decay muons than for bottom muons

arXiv:2109.00411 [nucl-ex]

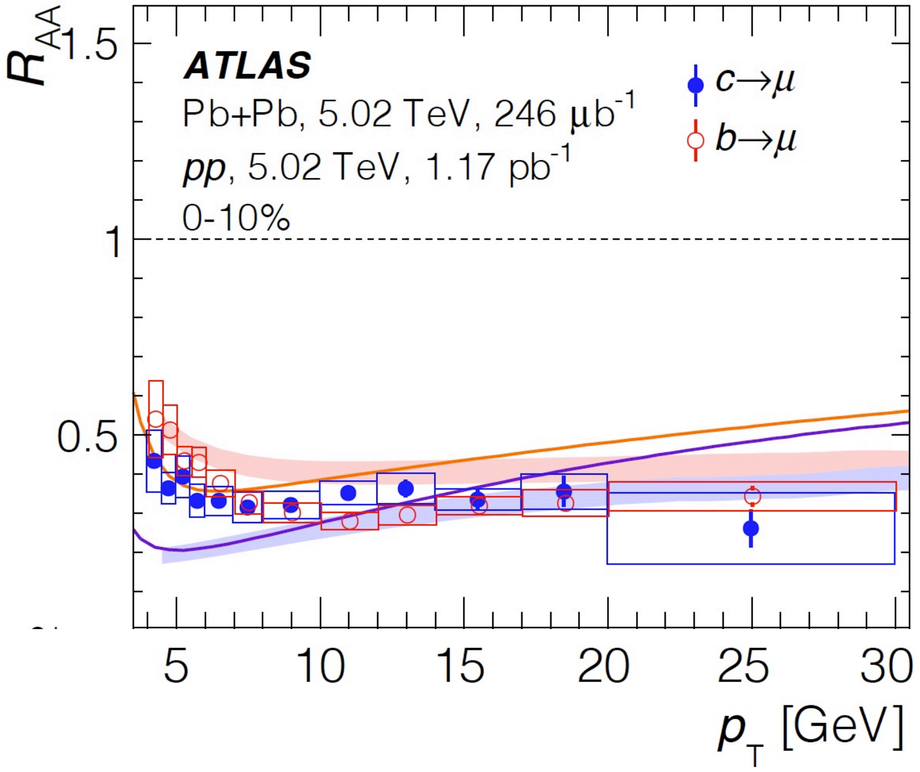


Heavy flavour flow and R_{AA} in Pb+Pb collisions

Phys. Lett. B 807 (2020) 135595



arXiv:2109.00411 [nucl-ex]



Non-zero v_2 is measured for charm and bottom decay muons

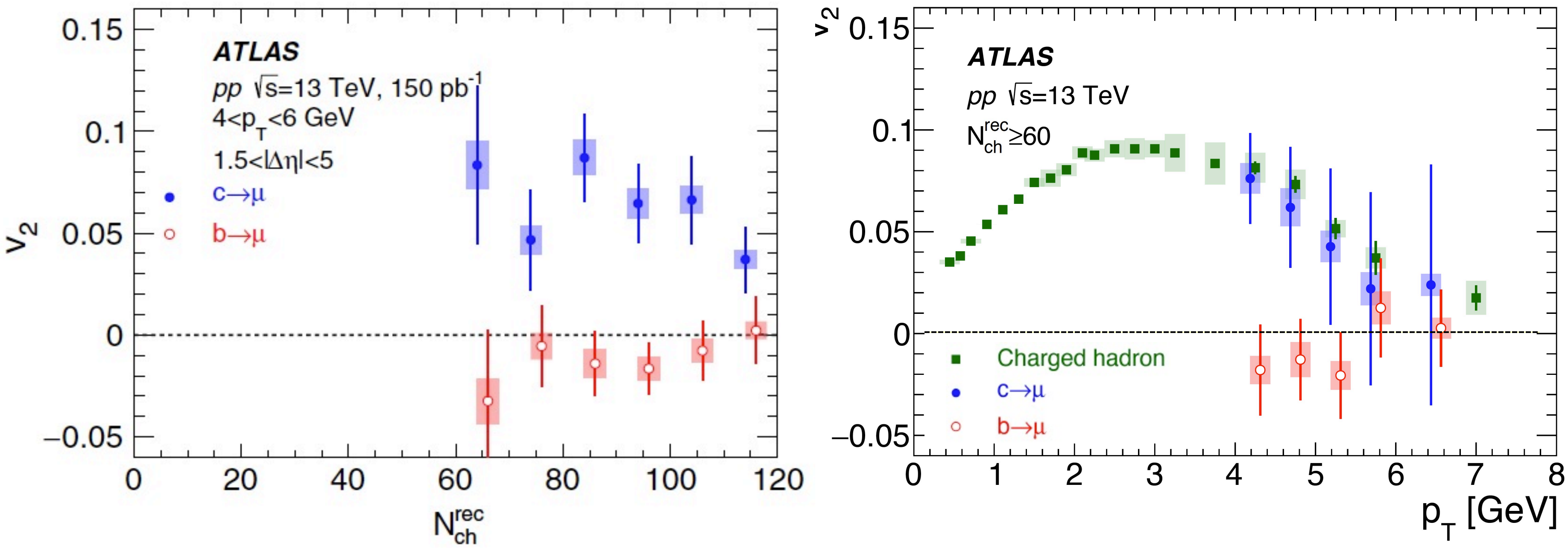
- v_2 for charm decay muons is larger than v_2 for bottom decay muons
- Expected due to larger b quark mass

Suppression of yields of charm and bottom decay muons is observed

- $R_{AA} < 1$ in 4-30 GeV p_T range

Heavy flavour flow in 13 TeV *pp* collisions

Phys. Rev. Lett. 124 (2020) 082301



- Significant v_2 coefficient is observed for charm decay muons
  - v_2 of charm decay muons is consistent with light hadrons v_2
- v_2 of bottom decay muons is consistent with 0

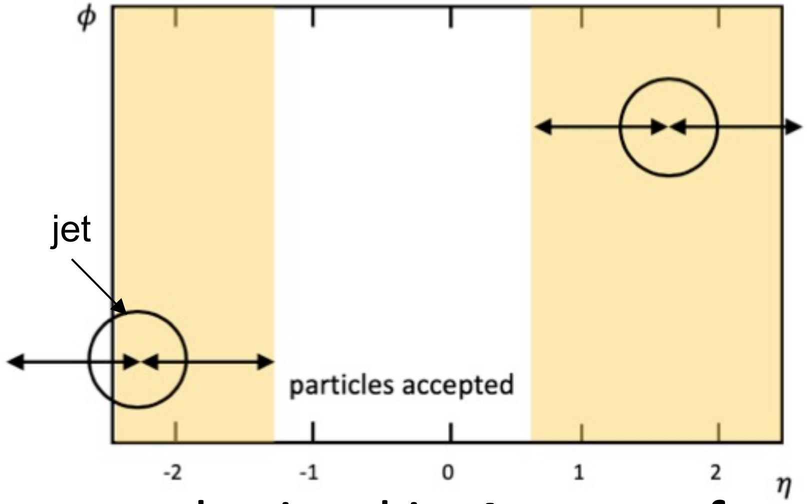
Bottom quarks do not participate in the collective behaviour in high-multiplicity *pp* collisions

2PC with jet particle rejection in 13 TeV *pp* collisions

Additional insight on flow origin in *pp* collisions may be provided by studying correlations in events containing “semi-hard” jets

  - Low scale already probed in *Z*-tagged events (EPJ. C80 (2020) 64)

- 2PC with templated fitting method is used for 13 TeV *pp* collisions
- Using minimum bias (MB) and high-multiplicity triggers (HMTs)
- Studying the jet particle effects (ATLAS-CONF-2020-018):



In events with jets, charged particles close to jet are rejected

  - $|\Delta\eta|<1$ wrt jet axis
  - Using Anti-kt track jets of.
    R = 0.4, jet p_T >10 GeV
    track p_T > 0.5 GeV

- v_n are obtained in 4 types of *pp* samples:
  - All inclusive events - **Inclusive** with jet particles
  - All inclusive events - **AllEvents**
  - Subsample containing only no-jet events - **NoJets**
  - Subsample containing only jets events - **WithJet**

without jet particles

v_2 without jet particles in 13 TeV *pp* collisions

- Integrated v_2 over the 0.5-5 GeV p_T range vs $N_{ch}^{rec,corr}$
    - $N_{ch}^{rec,corr}$ - multiplicity corrected to the number of primary particles

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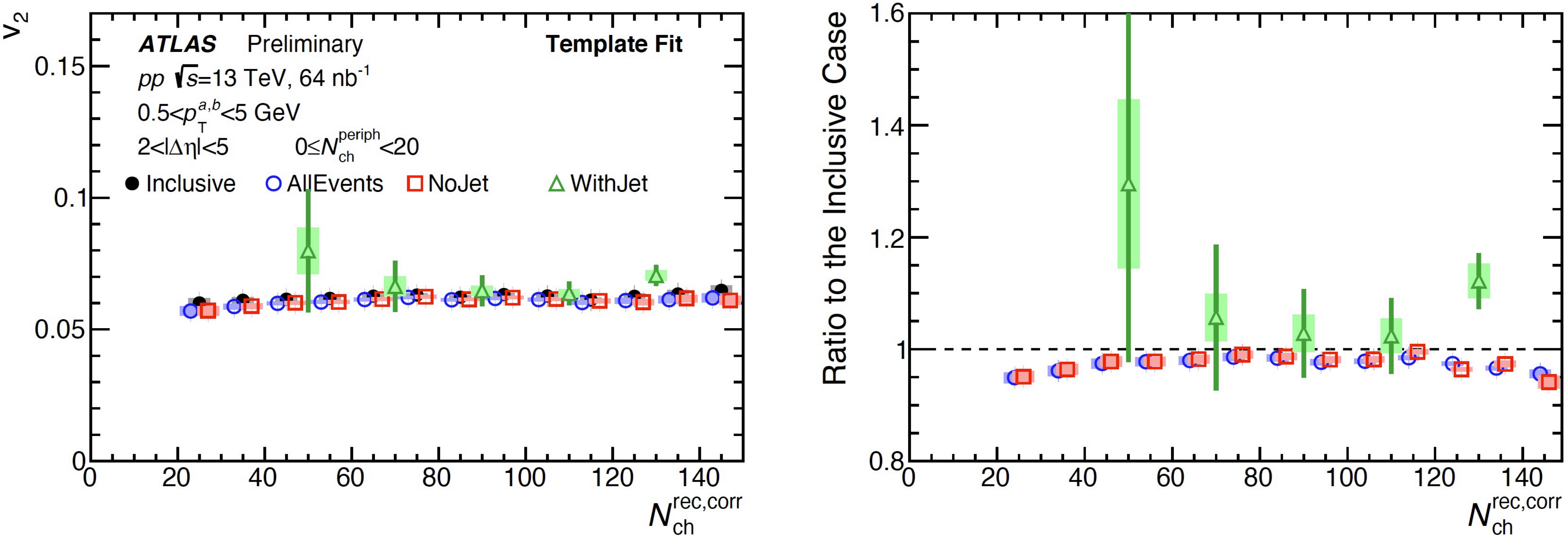

- v_2 very weakly changes with multiplicity
- v_2 in samples without jet particles decrease by 2-5% wrt Inclusive v_2
    - Softening of p_T-spectra when applying jet particle rejection

v_3 without jet particles in 13 TeV *pp* collisions

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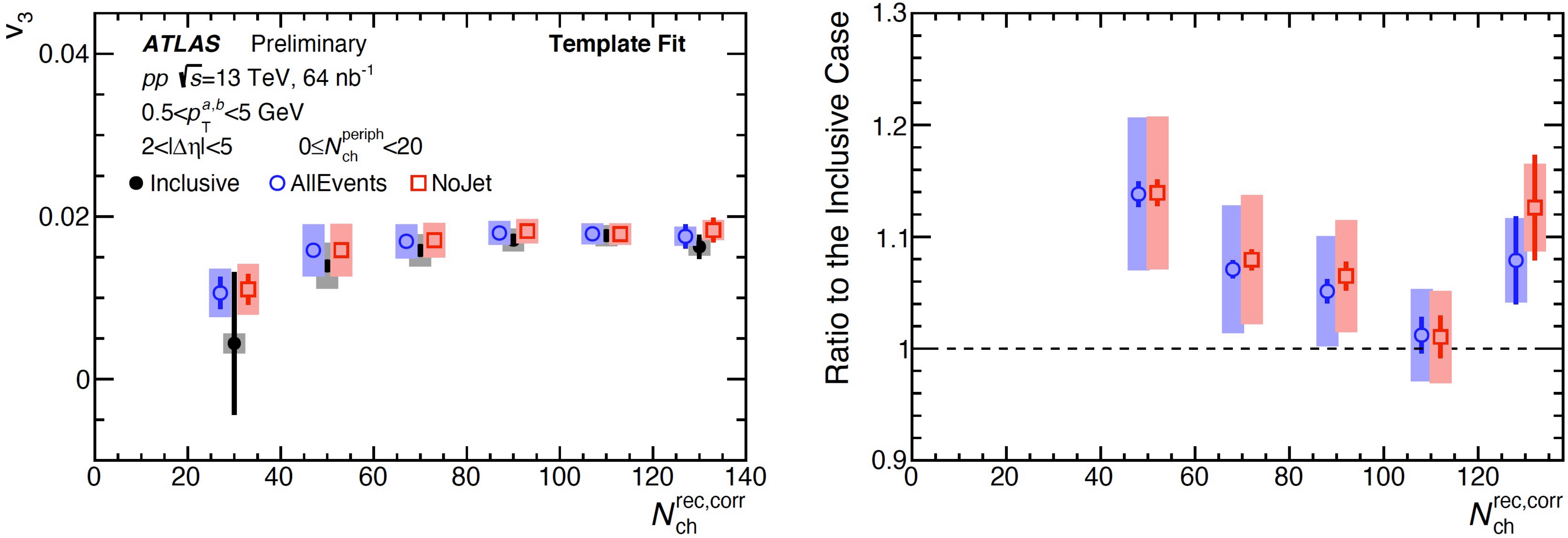


v_3 in samples without jet particles increase up to 15% wrt inclusive v_3

- The trend is opposite to that for v_2
- Softening of p_T -spectra when applying jet particle rejection

The long-range correlations in *pp* collisions are mostly not modified by the presence of jets in the event

Summary

- First measurement of longitudinal decorrelations for flow harmonic in 5.44 TeV Xe+Xe collisions - provide insight into initial state effects
- $v_n\{2\}$ - $[p_T]$ correlations in 5.02 TeV Pb+Pb, 5.44 TeV Xe+Xe and 5.02 TeV p+Pb collisions were measured
    - Strong centrality evolution of ρ in HI, in p+Pb collisions for v_2 is negative
    - A new observable, significant constraint for hydrodynamical models
- Flow harmonics and R_{AA} of charm and bottom decay muons were measured in 5.02 TeV Pb+Pb and 13 TeV pp collisions
    - Heavy quark mass effects seen in the measured R_{AA} and v_n
- In 13 TeV pp collisions, minor changes in charged particles v_n are observed after applying jet particle rejection (by 2-5% for v_2)

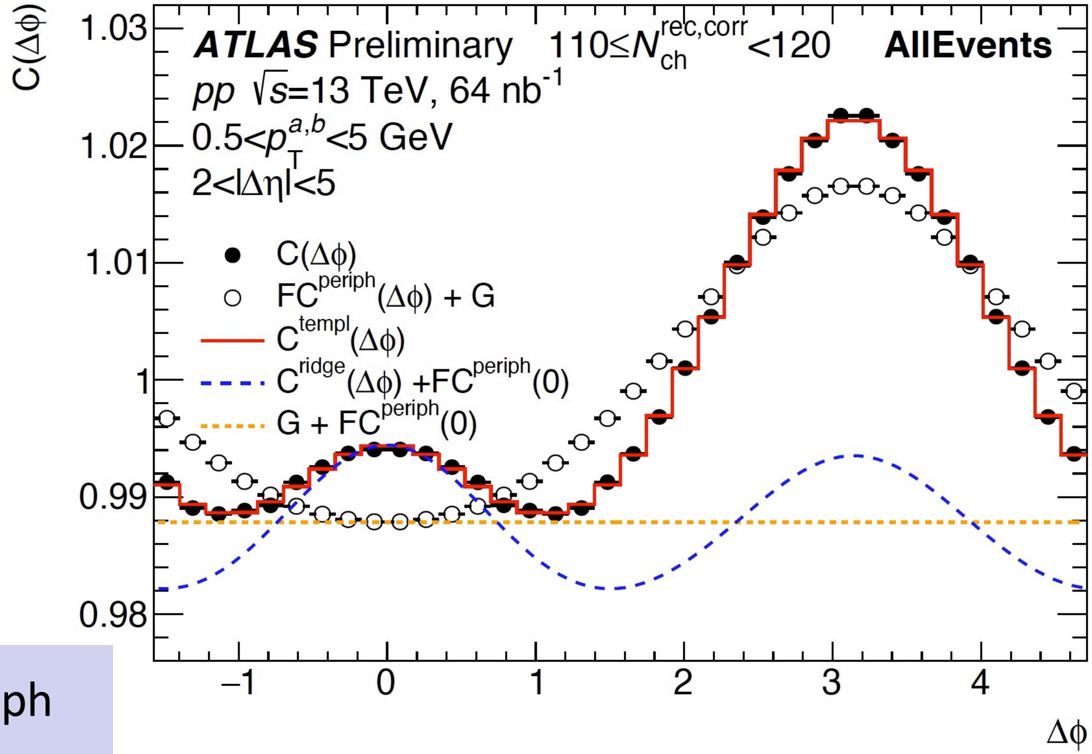
Thank you for your attention!

Template-fitting method

To separate the ridge from background correlations (e.g. due to dijets), template fitting procedure is used (PRL 116 (2016) 172301)

Template fit function (2 free parameters $v_{n,n}$, F):

$$C^{templ}(\Delta\varphi) = C^{ridge} + F\, C^{periph}$$



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- C_{ridge} : Pedestal*(1 +2$v_{n,n}$ cos(nΔϕ))
- F C^{periph} : describes dijets correlations in full N_{ch}^{rec} range
- C^{templ} successfully describes C(Δφ) distributions
- The factorization works well in different $N_{ch}^{rec,corr}$ and p_T - ranges

$$v_{n,n}(p_T^a,p_T^b)=v_n(p_T^a)v_n(p_T^b)$$

v_2 (p_T) with jet particle rejection in 13 TeV *pp*

ATLAS-CONF-2020-018