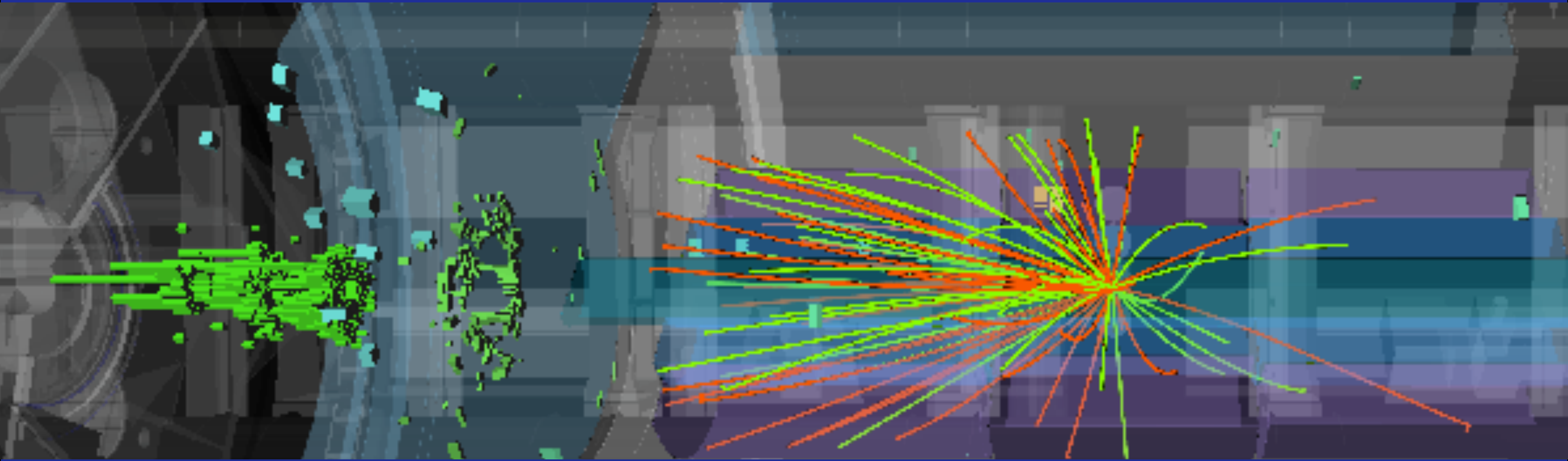
Recent ATLAS measurements of correlations in *pp* and *p* + Pb collisions



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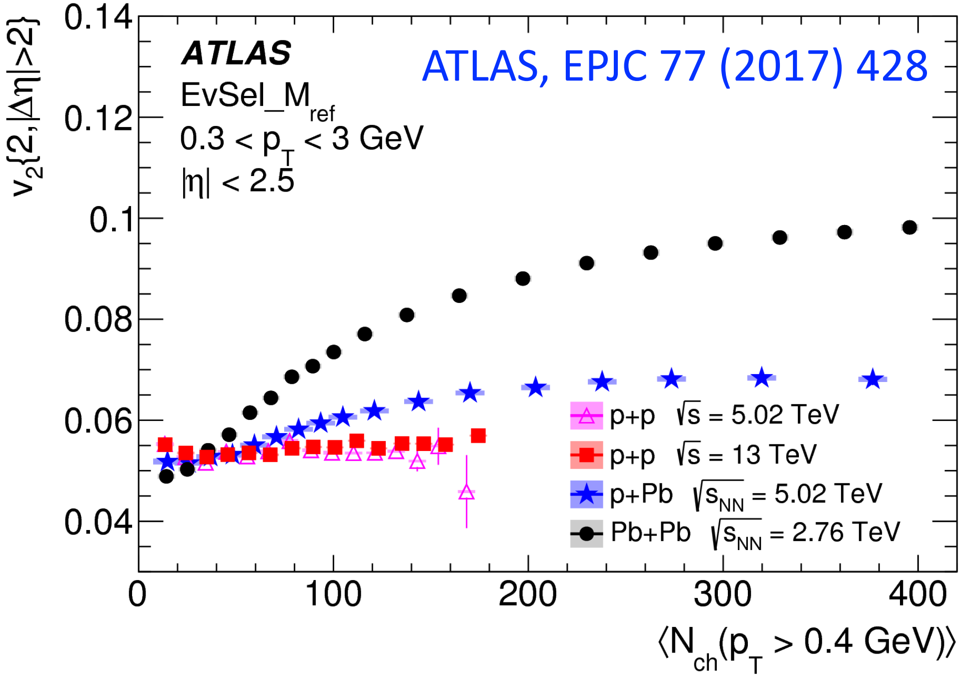
ICHEP 2020 | PRAGUE

40th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

28 JULY - 6 AUGUST PRAGUE, CZECH REPUBLIC

Collectivity in small systems

In *pp* and *p*+Pb collisions, measurements of multi-particle correlations show evidence of significant collective effects



In *pp* and *p*+Pb collisions similar flow harmonics as in heavy ion collisions are observed.

Small system flow results are supported by hydrodynamical models, (e.g. Phys.Rev.C 85(2012) 014911)

However, more studies are needed to address questions

- What is the impact of hard processes?
- Is energy loss contributing to the azimuthal anisotropy?
- What is the role of the initial conditions?

Outline

- Charged particle flow in 13 TeV pp collisions with jet particle rejection, ATLAS-CONF-2020-018
- Azimuthal anisotropy of heavy-flavor muons in 13 TeV pp collisions, Phys. ReV. Lett. 124 (2020) 082301
- Azimuthal anisotropy of charged particles in 8.16 TeV p+Pb collisions for $p_T < 50$ GeV, Eur. Phys. J. C 80 (2020) 73
- The mean transverse momentum and flow harmonics correlation in 5.02 TeV p+Pb and Pb+Pb, Eur. Phys. J. C 79 (2019) 985
- Measurements of charged particle correlations in photo-nuclear ultra-peripheral 5.02 TeV Pb+Pb collisions, ATLAS-CONF-2019-022

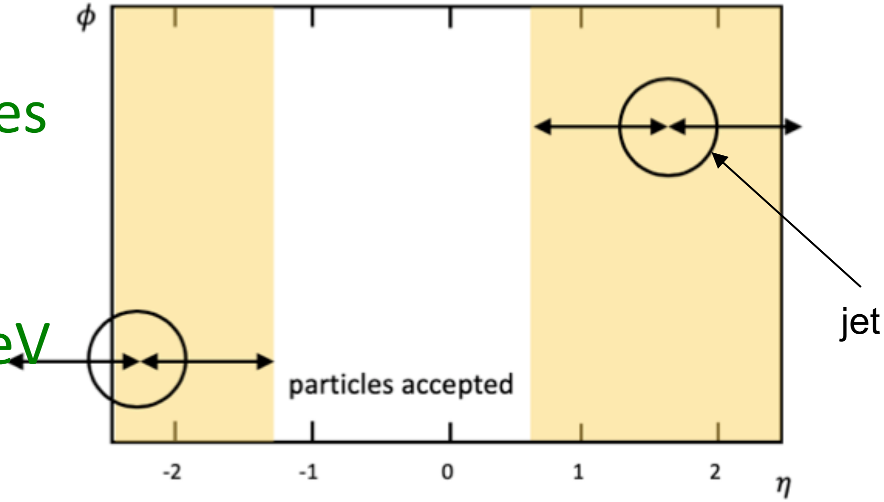
2PC with jet particle rejection in 13 TeV *pp* collisions

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 method with templated fitting procedure is used for minimum bias (MB) 13 TeV *pp* data, ATLAS-CONF-2020-018

- In events with jets, charged particles close (|Δη|<1) to jet are rejected
- Using anti-kt track jets of R = 0.4, jet p_T >10 GeV and track p_T > 0.5 GeV



To study jet effects, v_n are obtained in *pp* samples:

- All inclusive events without jet particle rejection - **Inclusive v_n**
- All inclusive events with jet particle rejection - **AllEvents v_n**
- Events without jets - **NoJets v_n**
- Events with jets only - **WithJet v_n**

v_2 with jet particle rejection in 13 TeV *pp*

- 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 from the underlying event

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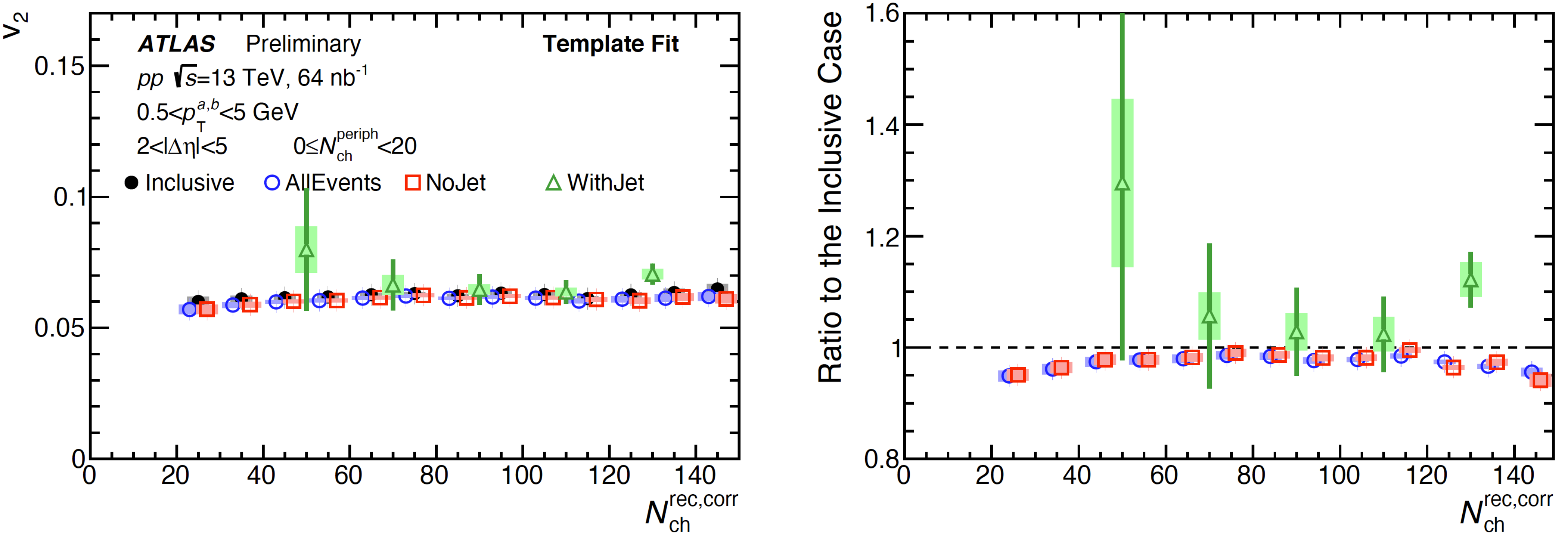

- v_2 very weakly changes with multiplicity
- In AllEvents and NoJet v_2 decrease by 2-5% wrt Inclusive v_2
  - Softening of p_T-spectra when applying jet particle rejection

v_3 with jet particle rejection in 13 TeV *pp*

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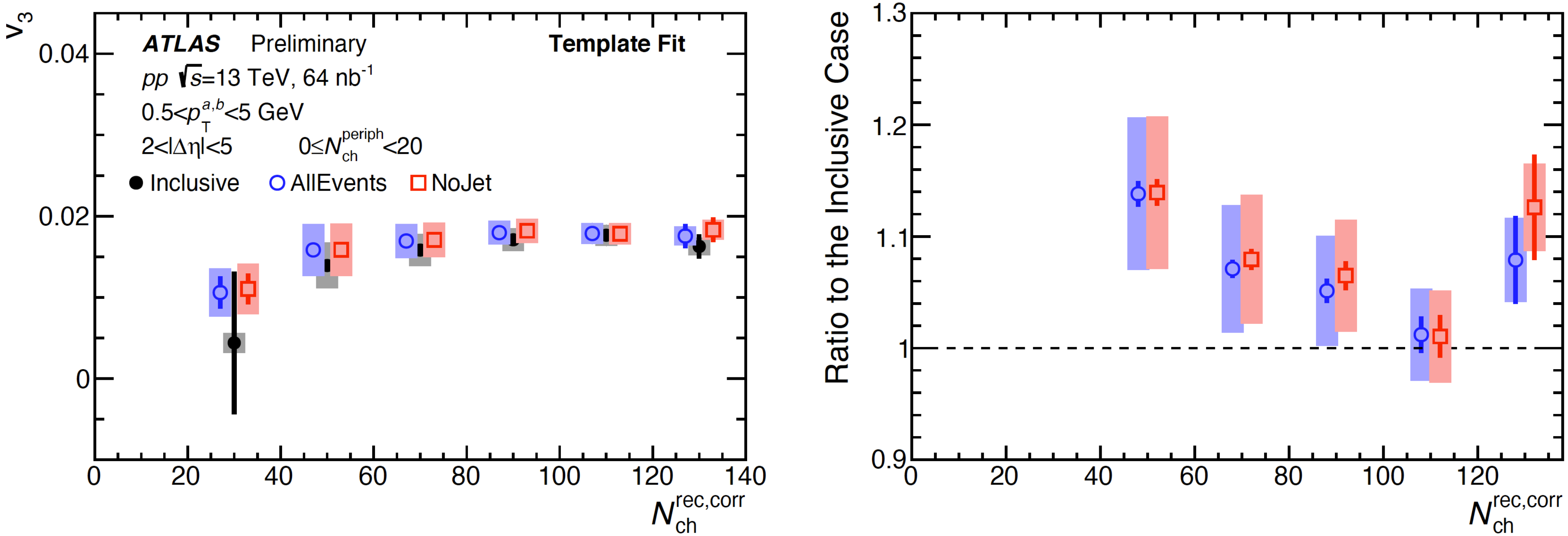


v_3 in AllEvents and NoJet samples increase up to 15% wrt inclusive v_3

- The trend is opposite to that for v_2

Long-range correlations in *pp* collisions arise mostly from underlying event

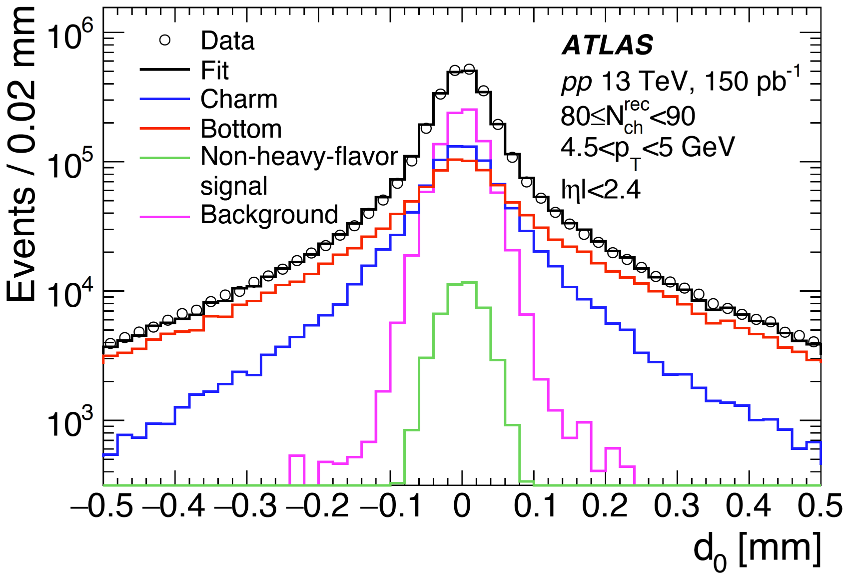
Heavy flavour flow in 13 TeV *pp* collisions

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

- In the analysis, HF muon flow harmonics are extracted from single muon - hadron 2PC with template fit procedure
  - Using 13 TeV *pp* data with trigger requiring muon of $p_T > 4$ GeV
  - Background contribution (from light-hadron decays) is removed using imbalance of muon momentum measured in Inner Detector and Muon Spectrometer

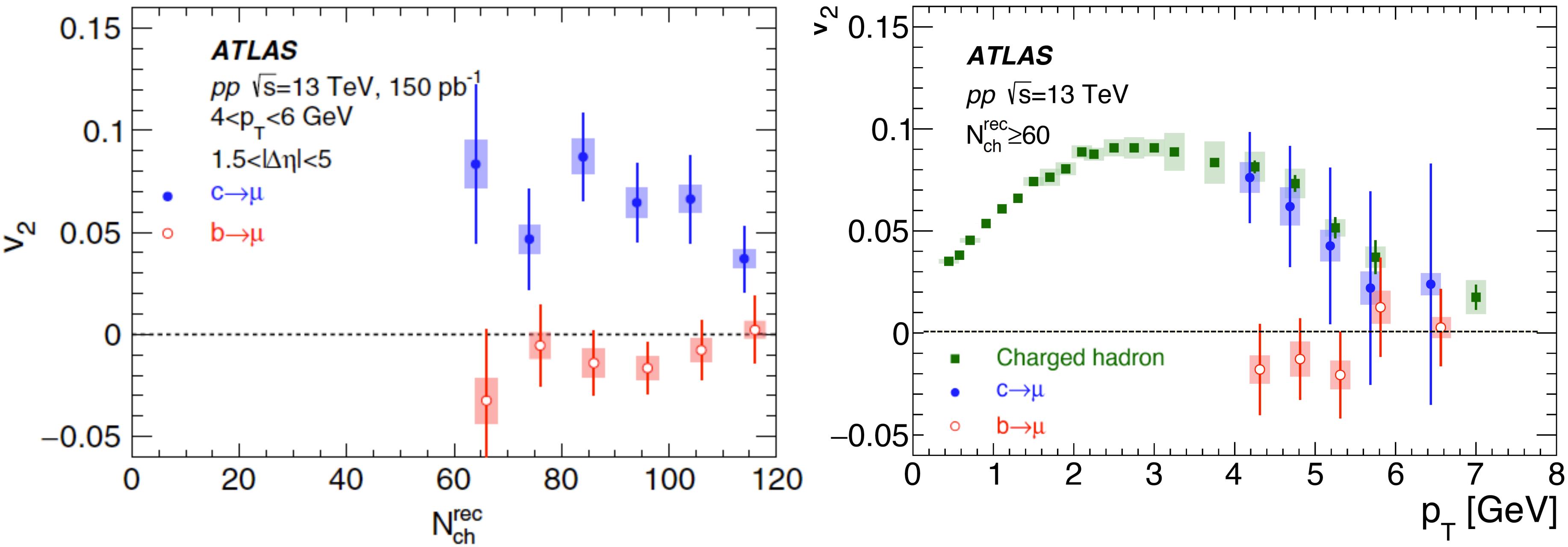
- v_2 of bottom- and charm-decay muons is extracted from HF muon flow using distance-of- closest-approach to collision vertex, d_0
  - Close to vertex charm dominated region
  - Far from vertex bottom dominated region

Phys. Rev. Lett. 124 (2020) 082301



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 flow
- v_2 of beauty decay muons is consistent with 0

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

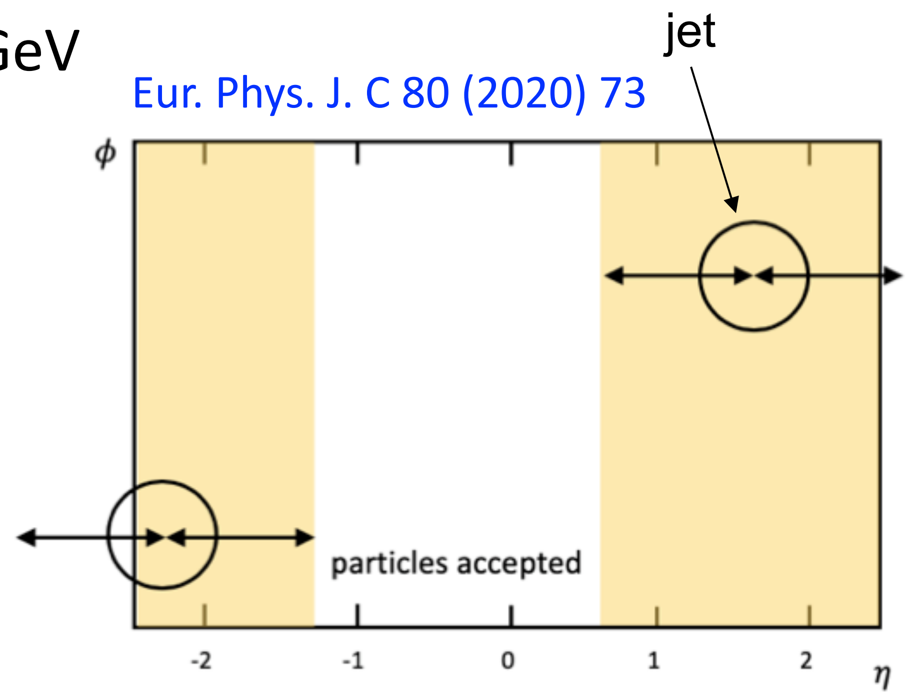
Charged particles v_n at high p_T in 8.16 TeV *p*+Pb

High p_T flow in *p*+Pb collisions has potential to probe alternative mechanisms (e.g. jet energy loss in the QGP)

- Analysis is using 2PC method with the template fitting procedure for
  - Minimum bias
  - Jet-triggered events, $p_T > 75$ GeV
  - jet-triggered events, $p_T > 100$ GeV

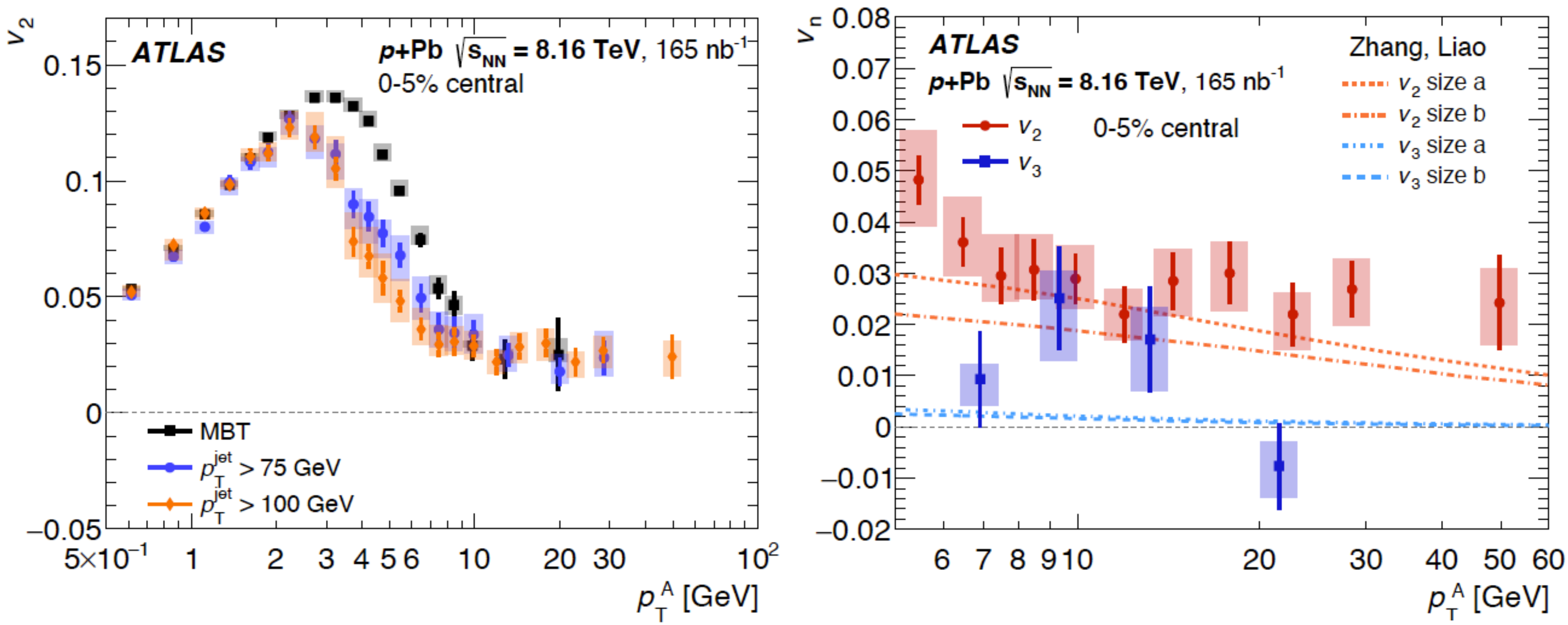
- Associated particles are required $|\Delta\eta^{ab}|>2$, in MB events
- In jet events, additionally charged particles close ($|\Delta\eta|<1$) to any jet of $p_T > 15$ GeV are rejected

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



$v_2(p_T)$ in 8.16 TeV *p*+Pb

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



- v_2 in MB and jet events agree at low $p_T < 2$ GeV and high $p_T > 9$ GeV
  - For $p_T > 9$ GeV, $v_2 \simeq 0.025$
- For $2 < p_T < 9$ GeV, v_2 is larger in MB than in jet events
- Theoretical calculations with jet quenching (arXiv: 1311.5463) slightly underestimate v_2 and v_3
  - Also strong yield suppression predicted, not confirmed experimentally

v_n– $[p_T]$ correlation in 5.02 TeV *p*+Pb and Pb+Pb

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

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

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

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

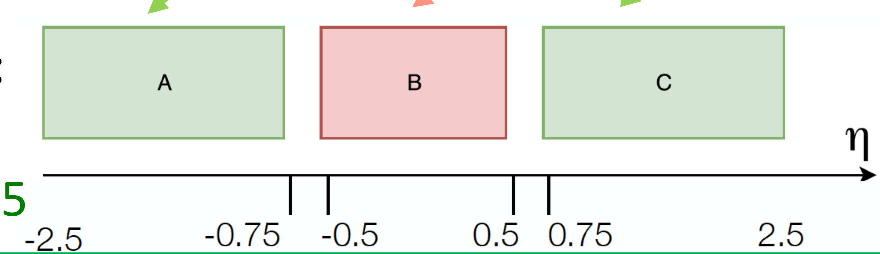
$$\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}} = \langle corr_n\{4\}\rangle - \langle corr_n\{2\}\rangle^2$$

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

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

Covariance is calculated using 3 subevents:

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

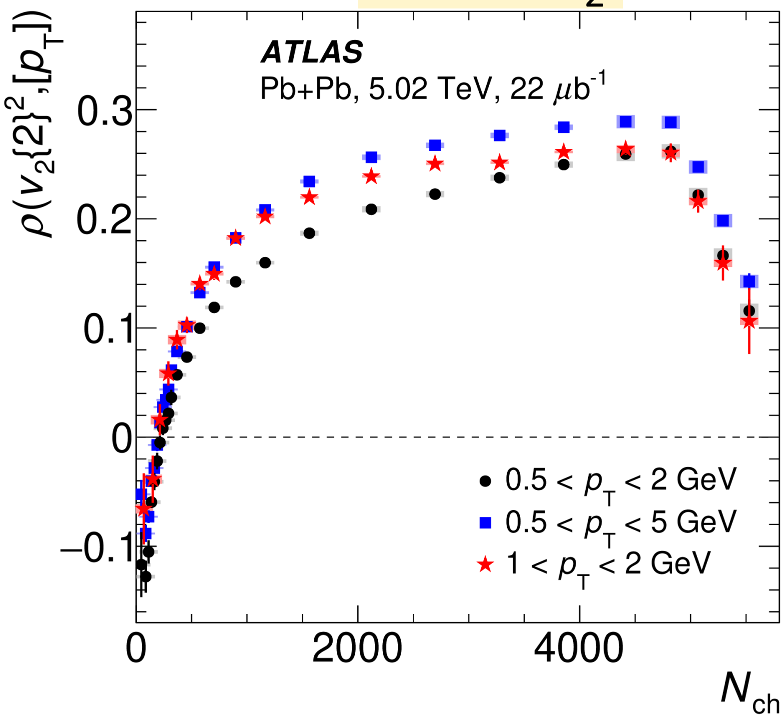


$\rho(N_{ch})$ for v_2

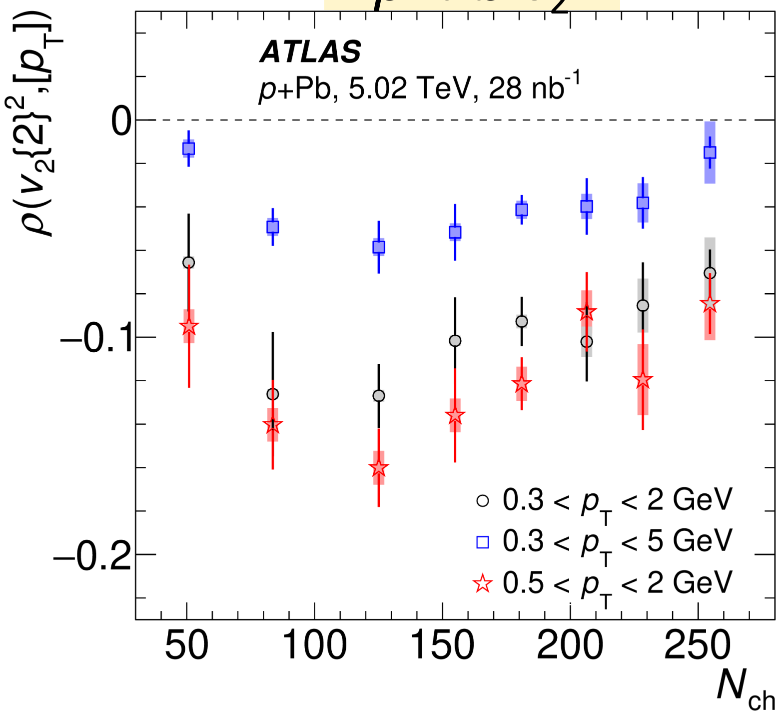
$$\rho = \frac{\mathrm{cov}(v_n\{2\}^2, [p_\mathrm{T}])}{\sqrt{\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}}\sqrt{c_k}}$$

Eur. Phys. J. C 79 (2019) 985

Pb+Pb v_2



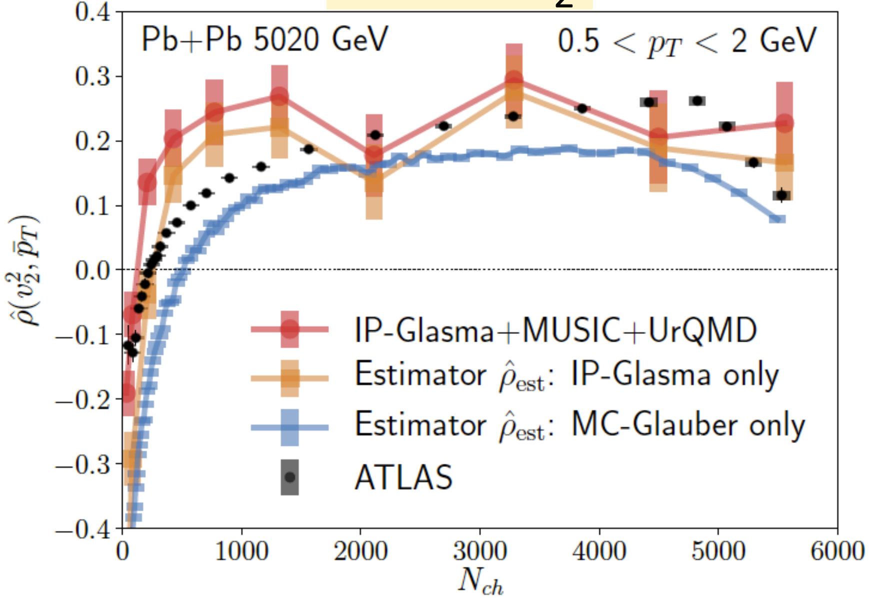
p+Pb v_2



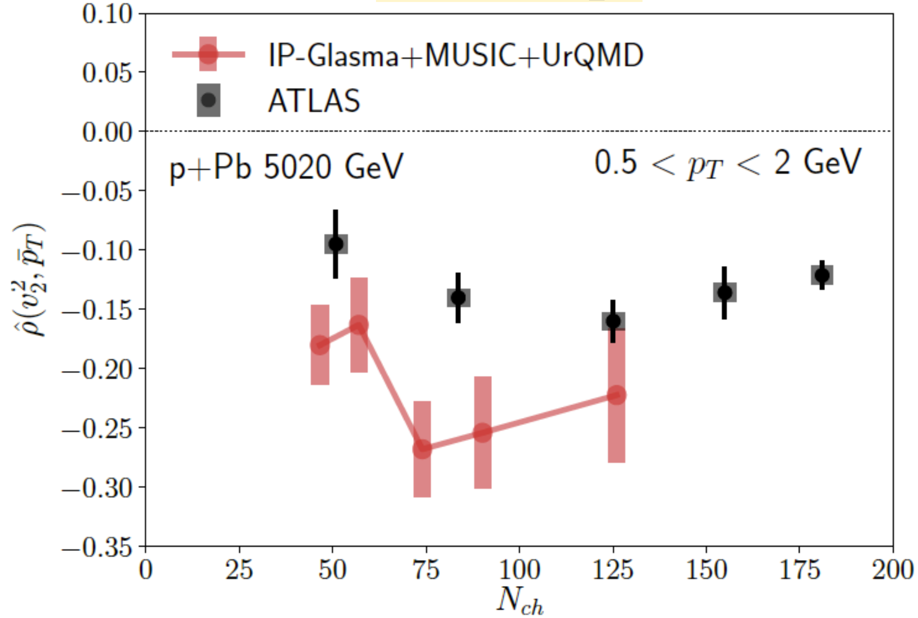
- p+Pb/Pb+Pb dataset of 28 nb^{-1}/22 $\mu\mathrm{b}^{-1}$ is used
- For Pb+Pb collisions ρ for v_2 is negative at low N_{ch} then rise to a value ~0.3, fall in most central
- For p+Pb collisions ρ is negative, no apparent dependence on N_{ch} is observed

Comparison to theoretical models for v_2

Pb+Pb v_2



p+Pb v_2



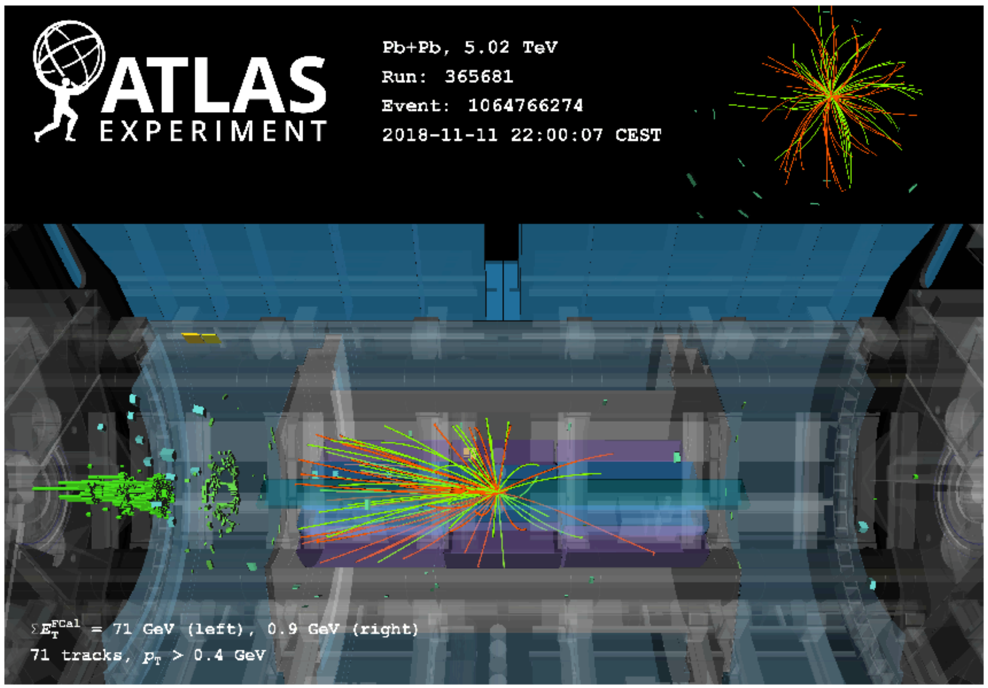
- IP-Glasma+MUSIC+UrQMD model for Pb+Pb collisions qualitatively reproduces *ρ(N_{ch})* arxiv: 2004.00690
  - High statistics MC Glauber estimator decreases in the most central collisions as in the data
- In *p*+Pb collisions, the model correctly predicts the correlator sign but overestimates it magnitude
  - Favours small dimensions of the initial state in small systems

Flow harmonics in γA ultra-peripheral 5.02 TeV Pb+Pb

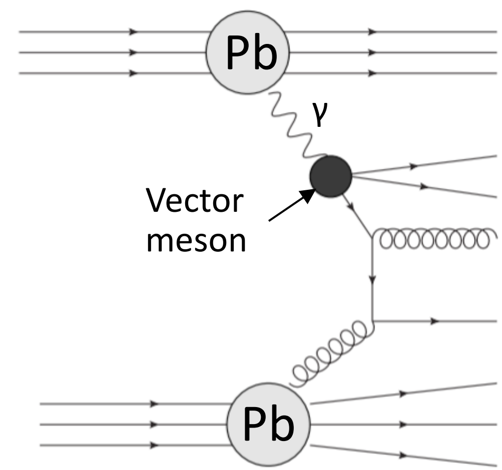
Photo-nuclear collisions in UPC (b>2R) are probing small system dynamics in simple, asymmetric collision involving photons resolved into hadronic state and Pb nucleus (dominant interaction: ρ_0+Pb)

- The "ridge" in γA may help to interpret *pp* or *p*+Pb flow results

Pb-going side



Photon-going side



In ATLAS γA events are selected based in the two arm ZDC (|η| ≥ 8.3|)

- One-sided nuclear fragmentation at Pb-going side with pseudorapidity gap at photon-going side ("0nXn" event topology)

2PC in γA ultra-peripheral 5.02 TeV Pb+Pb collisions

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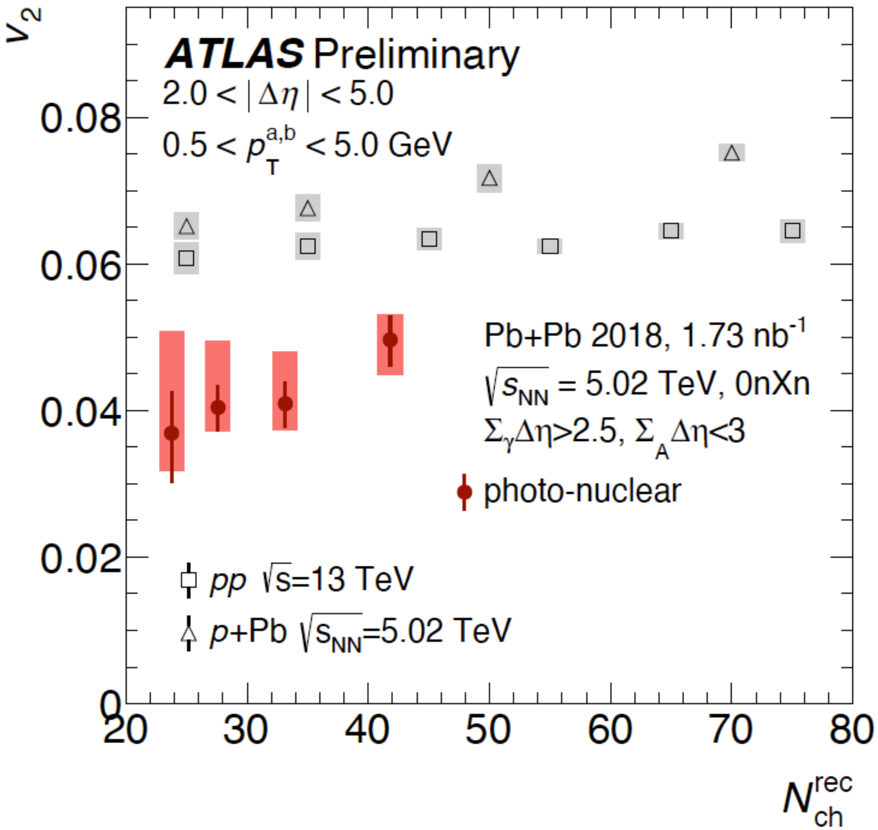
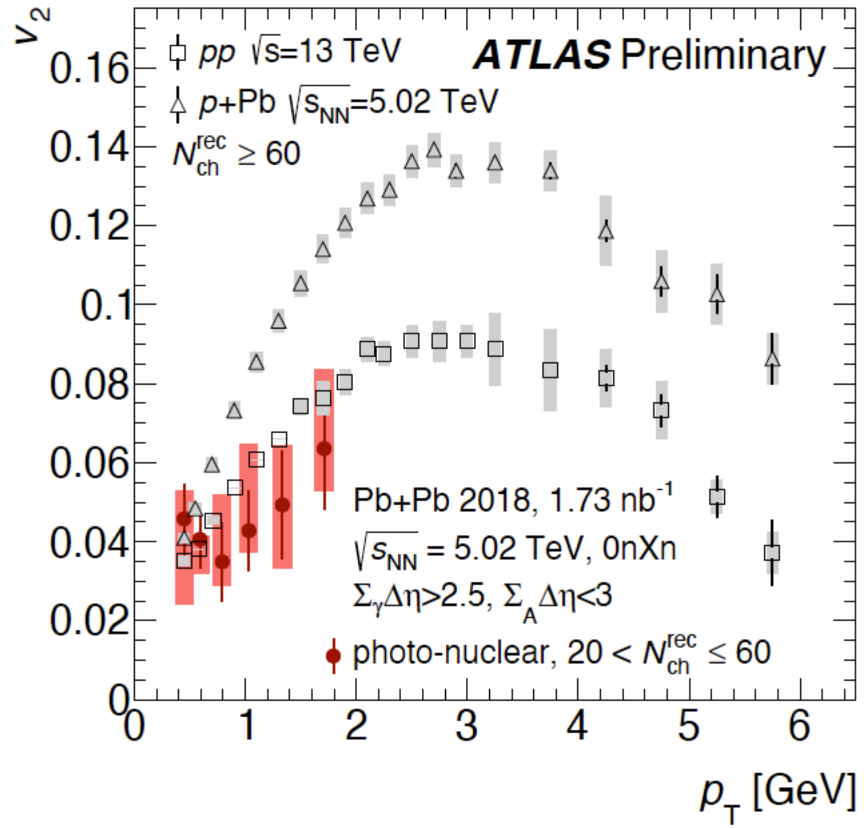




- Significant v_2 in photo-nuclear collisions are measured using 2PC
- In γPb collisions v_2 is smaller than v_2 in pp and p+Pb collisions
- v_2 p_T dependence is similar to hadronic collision systems
- No N_{ch}^{rec} dependence within uncertainties is observed

Summary

- In 13 TeV *pp* collisions, charged particles v_2 only slightly decreases after applying jet particle rejection (by 2-5%)

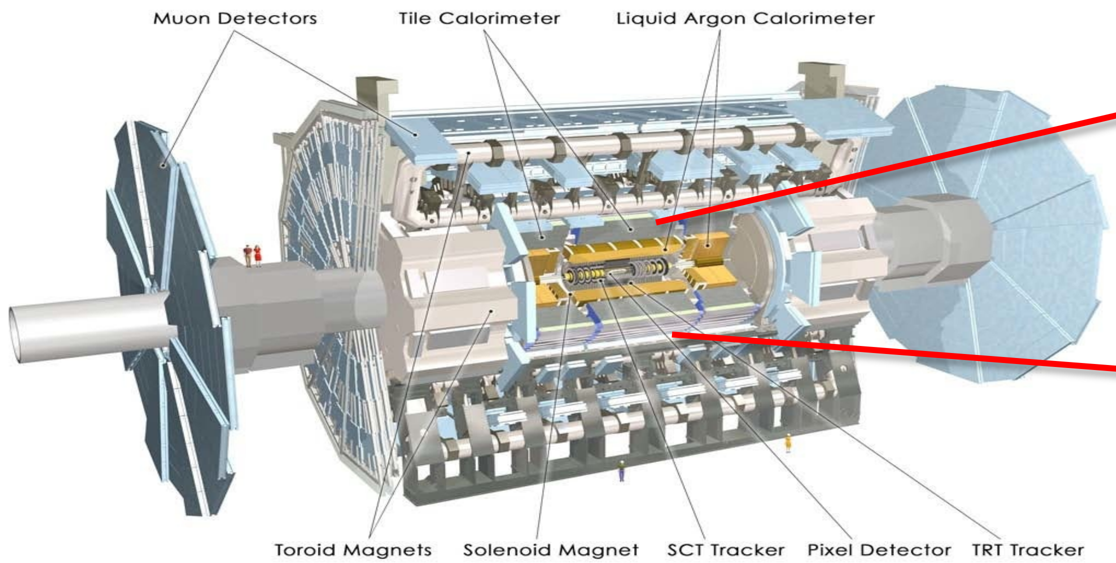
  - Correlations arise from underlying event in *pp* collisions
- In 13 TeV *pp* collisions, v_2 of charm decay muons is consistent with v_2 of light hadrons and v_2 of beauty decay muons is consistent with 0
- In 8.16 TeV *p*+Pb collisions charged particle v_2 remains finite (≈0.025) at high p_T
- Correlations of v_2 with event mean-p_T in 5.02 TeV *p*+Pb are negative and qualitatively compatible with results for peripheral Pb+Pb

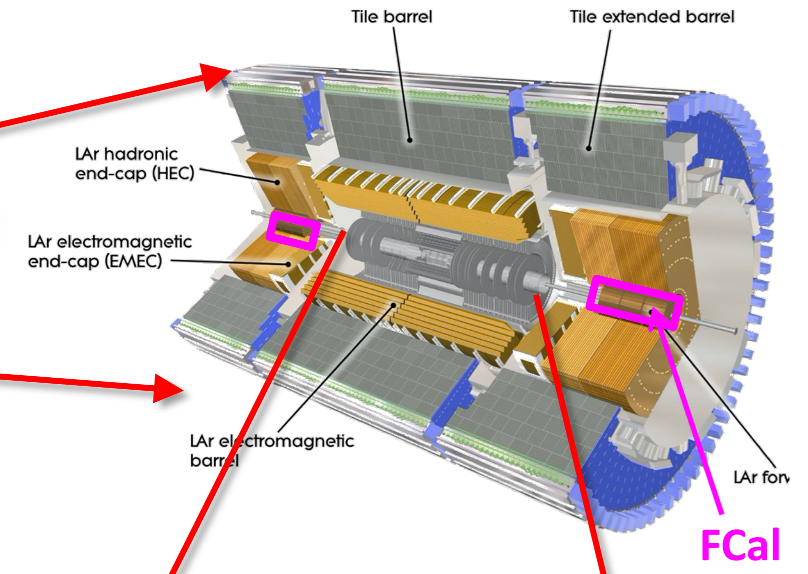
  - Favours small dimensions of the initial state
- Significant charged particle v_2 in γPb ultra-peripheral 5.02 TeV Pb+Pb collisions is measured

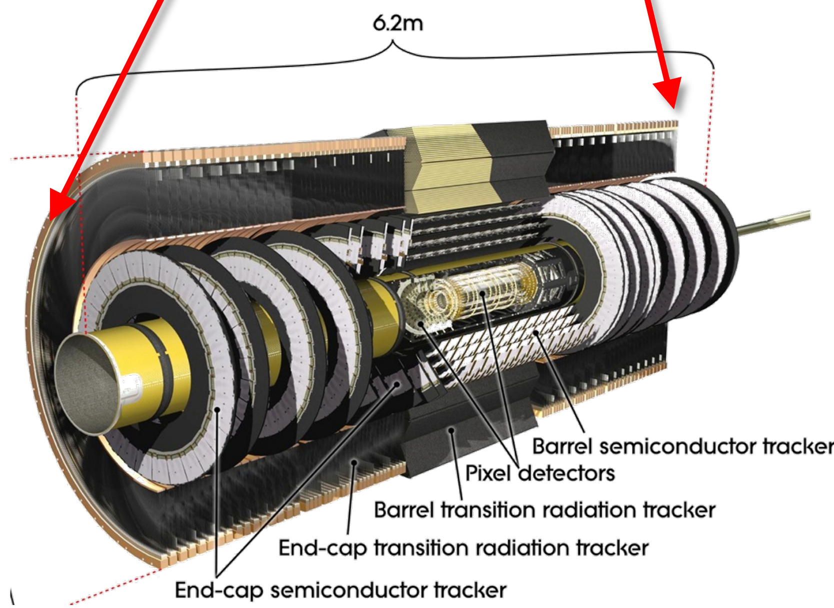
  - Smaller than v_2 in *pp* or *p*+Pb collisions

Thank you for your attention!

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)

v_2, v_3 vs p_T with jet particle rejection

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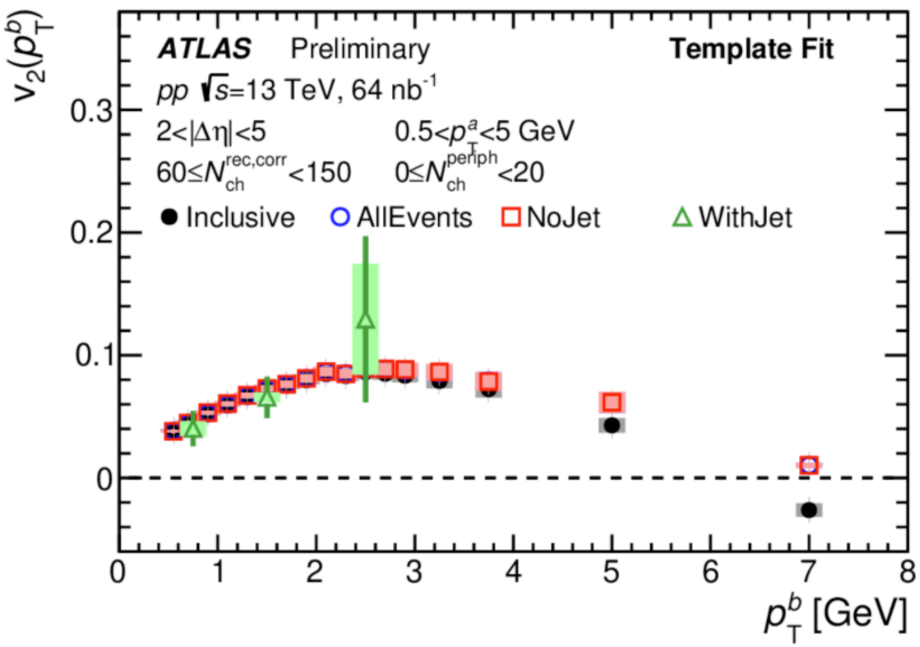

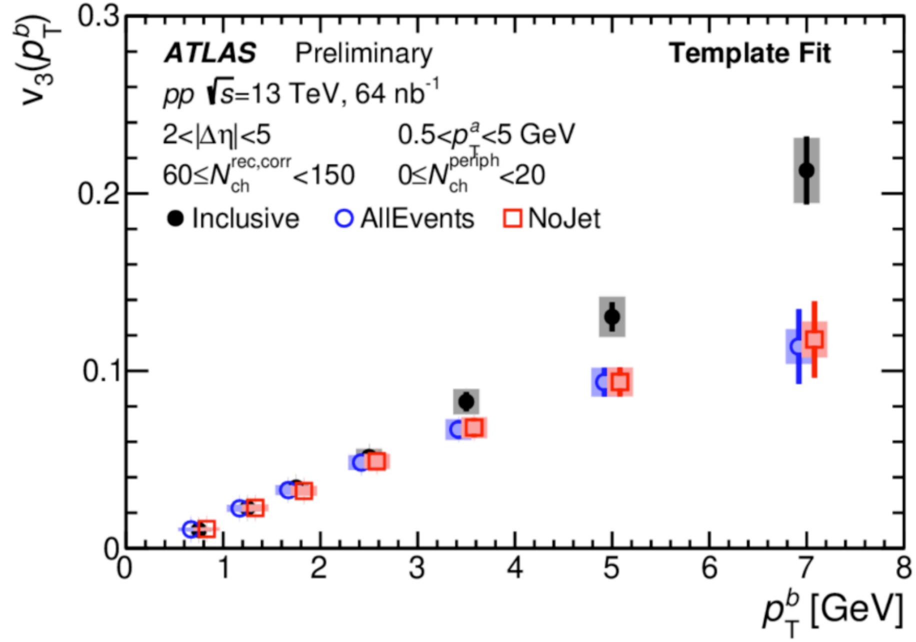

- v_2 in AllEvents and NoJet case is consistent with inclusive v_2 for $p_T < 2.5$ GeV and is larger at higher p_T
- v_3 in AllEvents and NoJet case is consistent with inclusive v_3 for $p_T < 3$ GeV and is lower for higher p_T

Template-fitting method

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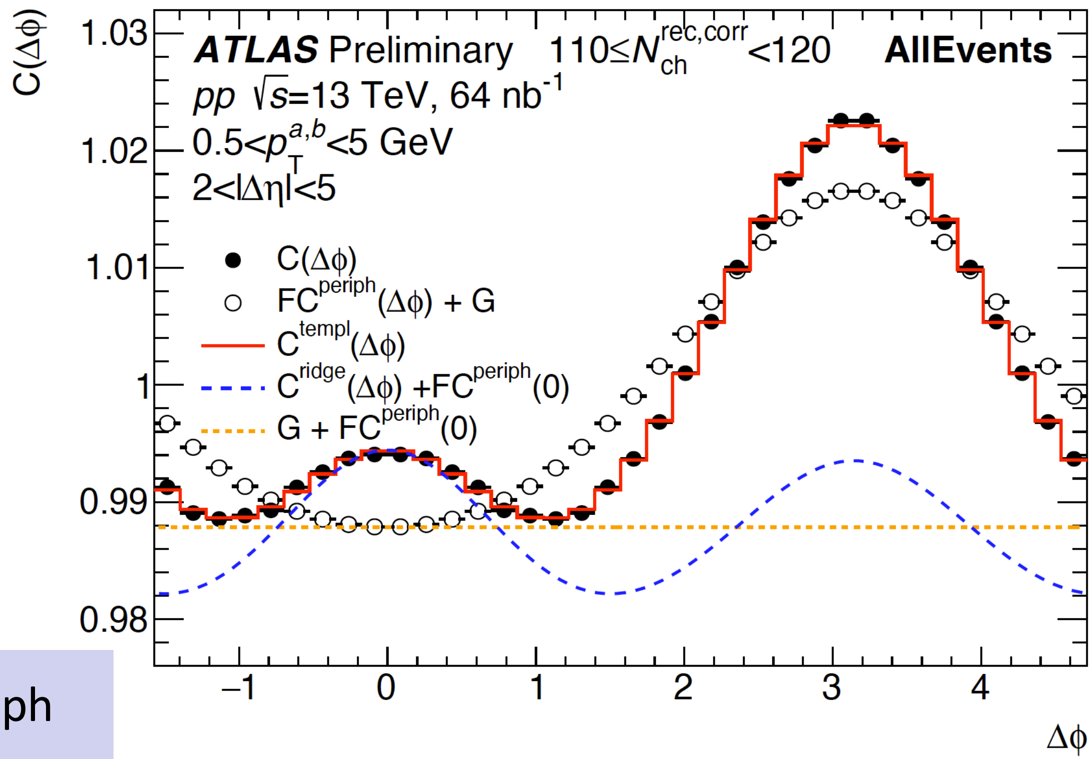
To separate the ridge from background correlations (e.g. due to dijets), template fitting procedure is used (PRL 116 (2016) 172301)



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

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

- 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

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

Selection of γA ultra-peripheral Pb+Pb collisions

Gap quantities constructed from tracks ($|\eta| < 2.5$) and colorimeter clusters ($|\eta| < 4.9$) are used to select γA events:

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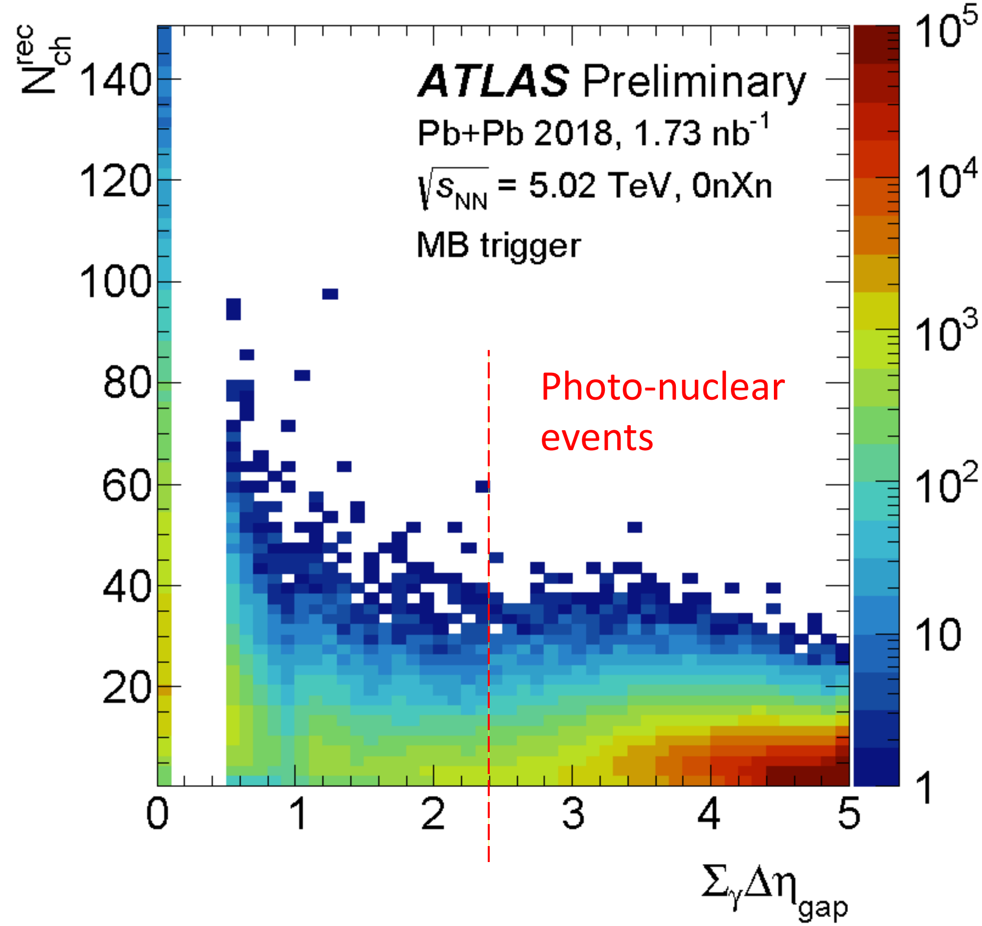
- At photon-going side sum of η differences between adjacent particles ($\Delta\eta_{gap}$, if > 0.5) is required to be $\Sigma_{\gamma}\Delta\eta_{gap} > 2.5$ to ensure a large gap
- At Pb-going side the quantity is required to be $\Sigma_{A}\Delta\eta_{gap} < 3$ to enhance one-sided nuclear fragmentation



- 2PC Template fitting method is used for charged particle ($|\eta|<2.5$) for flow harmonics calculations