Measurement of angular correlations in pp and p+Pb collisions with the ATLAS detector

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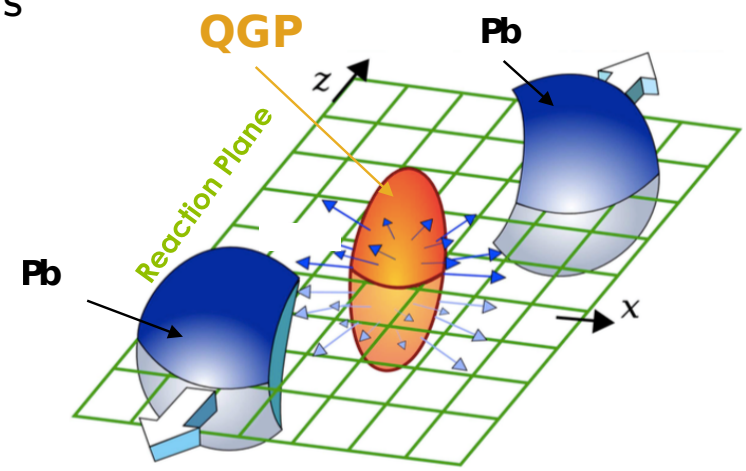
Motivation

- In heavy ion collisions Quark Qluon Plasma (QGP) is produced which features are reflected in collective expansion, jet quenching etc.
- The transport properties of the hot, dense matter can be studied with the particle azimuthal distribution (where v_2 is the elliptic flow):

$$\frac{dN}{d\phi} = \left\langle \frac{dN}{d\phi} \right\rangle \left(1 + \sum_n 2 v_n \cos[n(\phi - \Psi_n)] \right)$$



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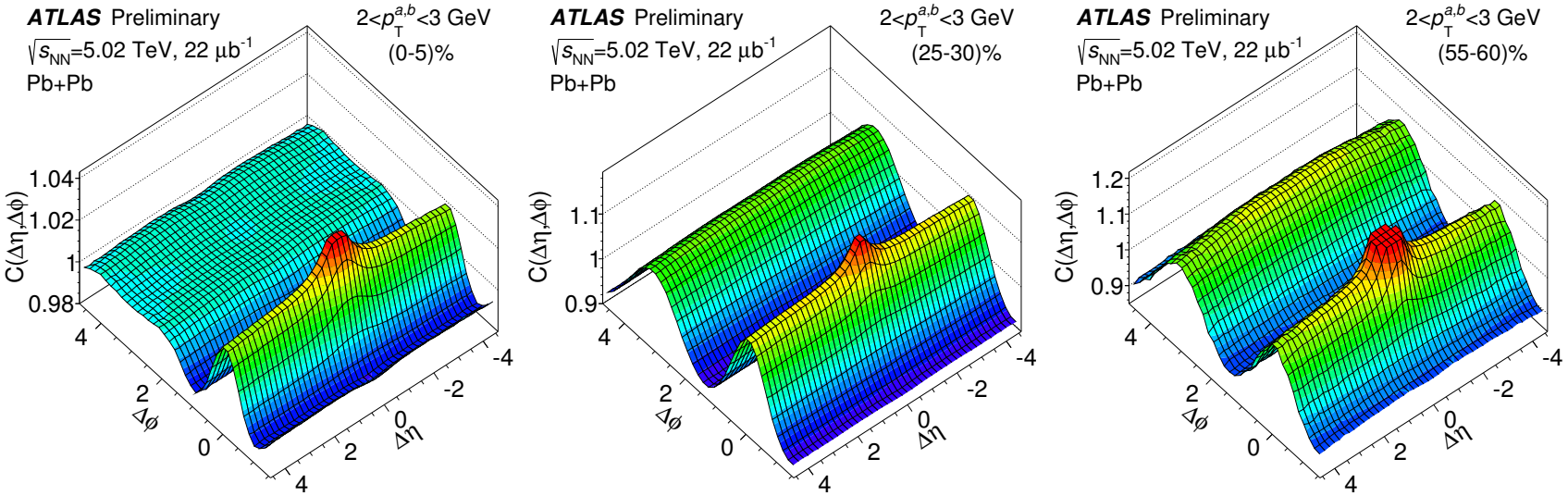
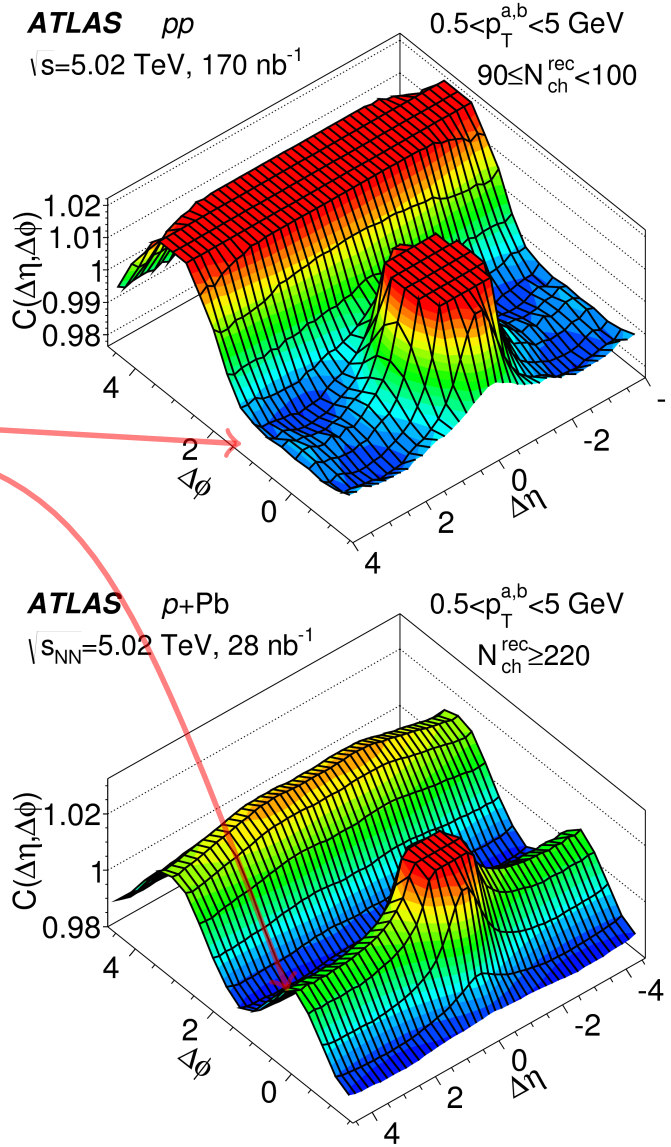


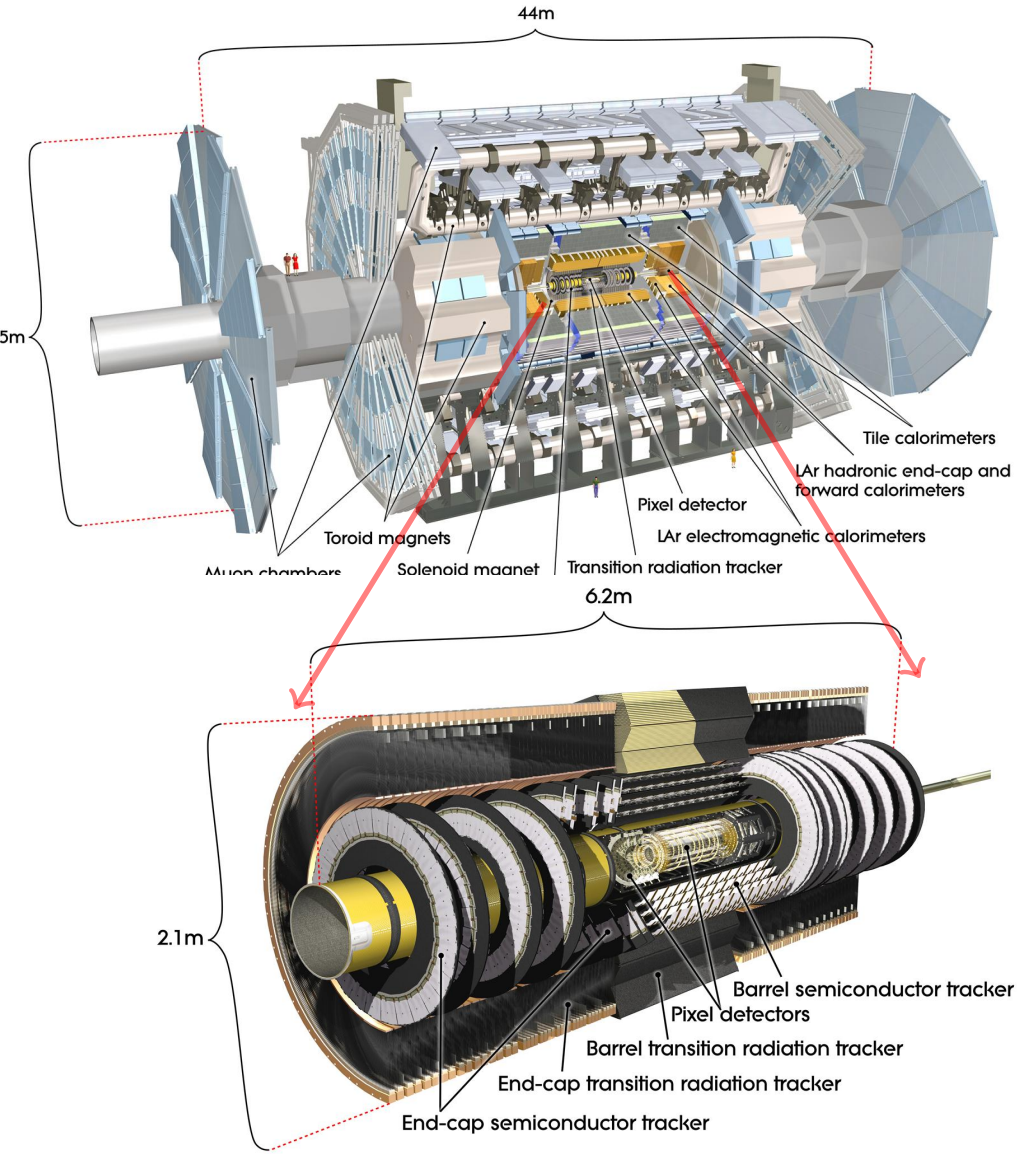
Ridge in pp and p+Pb - is collectivity observed?

- In heavy ion collisions pressure gradients in the formed QGP leads to azimuthal anisotropy (collective flow).
- Long range correlation structure along $\Delta\eta$ and $\Delta\phi \approx 0$ is also observed in pp and p+Pb collisions (**ridge**).
- What is the origin of these correlations in small systems?
  - Initial stage interactions (CGC, ...)? PRD 87 (2013) 094034
  - Initial stage fluctuations + final stage interactions? PRC 88 (2013) 014903
- Below we discuss ridge effect in details:
  - p_T, η, N_{ch}, energy dependence, single-particle v_n

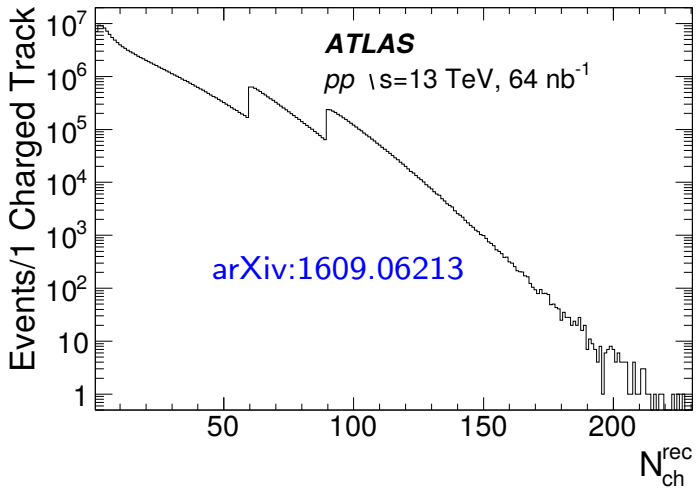
arXiv:1609.06213



ATLAS detector & data



- Dedicated triggers to collect high multiplicity events:
  - Level 1 (L1): cut on the total energy in the calorimeters
  - High Level Trigger (HLT): requirement on the multiplicity of HLT-reconstructed tracks ($p_T > 0.4$ GeV)



- Charged particle correlations measured with Inner Detector (ID): $|\eta| < 2.5$, $p_T > 100$ MeV
- pp at $\sqrt{s} = 5.02$, 13 TeV
- p+Pb at $\sqrt{s_{NN}} = 5.02$, 8.16 TeV

Two-particle correlations (2PC)

- ATLAS data:
  pp: 13 TeV (64 nb^{-1}), 5 TeV (170 nb^{-1})
  p+Pb: 5 TeV (28 nb^{-1})
- Two particle correlation function:

$$C(\Delta\eta, \Delta\phi) = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$

$\Delta\phi = \phi^a - \phi^b$, $\Delta\eta = \eta^a - \eta^b$

- By convention a and b are called *trigger* and *associated* particles.
- S and B are constructed from the same event and from "mixed events".
- B contains only acceptance and detector effects.
- Both S and B are corrected for tracking inefficiencies.
- Per-trigger particle yield:

$$Y(\Delta\phi) = \frac{\int_{-\pi/2}^{3\pi/2} B(\Delta\phi) d\Delta\phi}{N^a \int_{-\pi/2}^{3\pi/2} d\Delta\phi} C(\Delta\phi)$$

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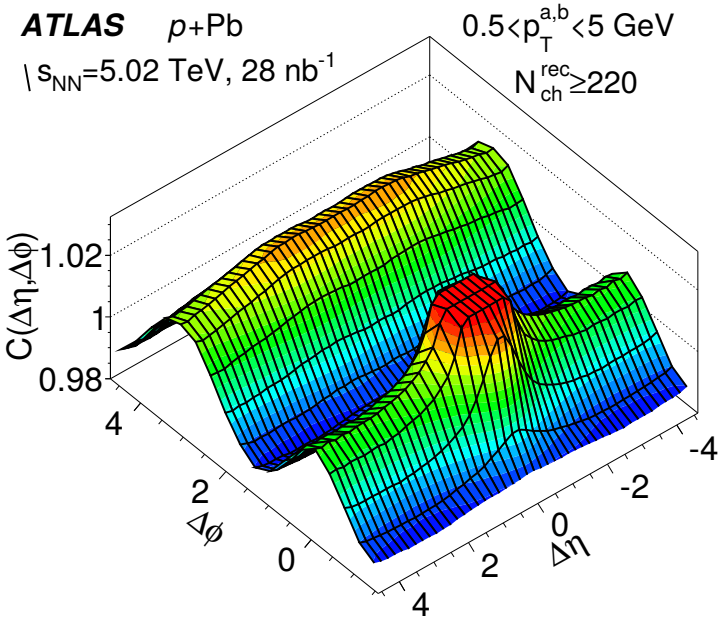
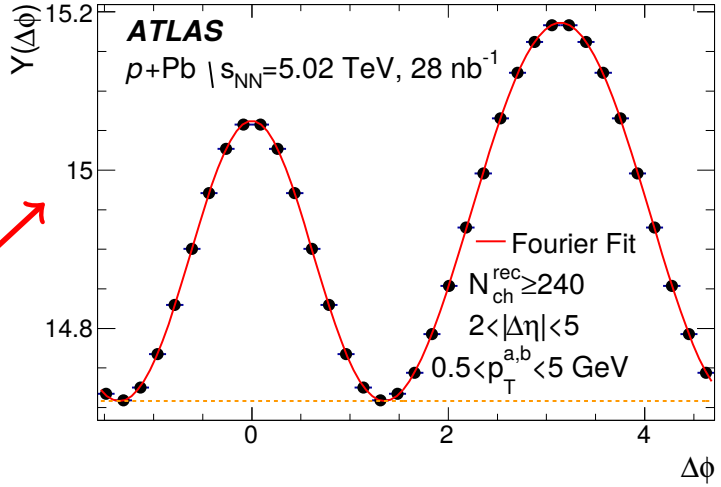




Template fitting

- To separate the ridge from other correlations (e.g. dijets), ATLAS developed a template fitting procedure (PRL 116, 172301 (2016))

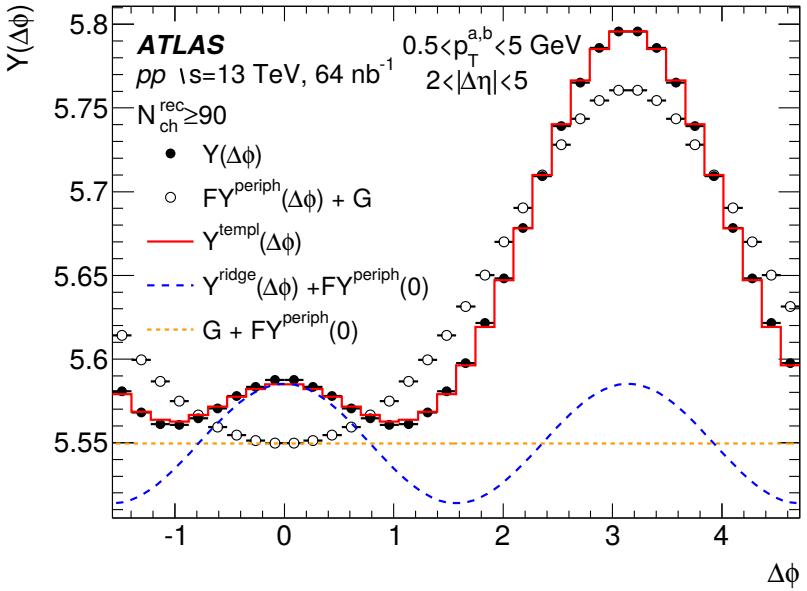
$$Y^{templ}(\Delta\phi) = Y^{ridge}(\Delta\phi) + FY^{periph}(\Delta\phi)$$

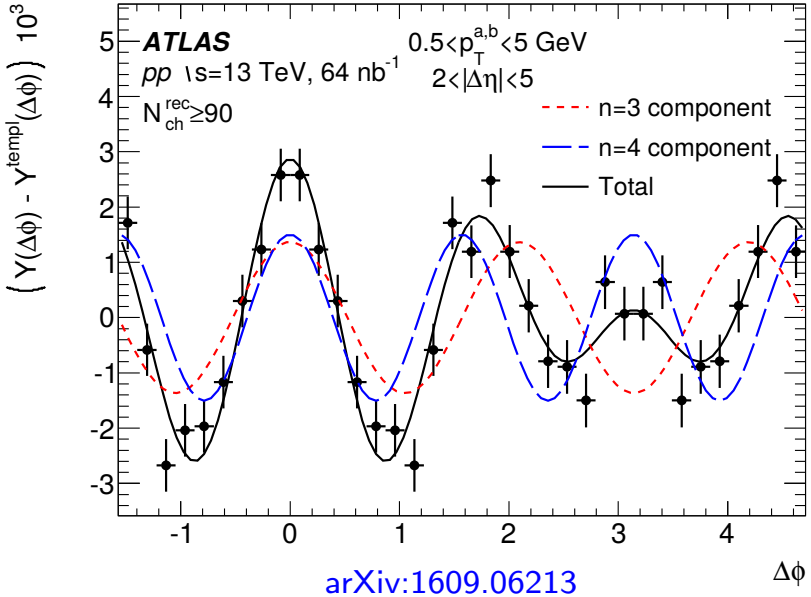
where

$$Y^{ridge}(\Delta\phi) = G\left(1 + \sum_{n=2}^{\infty} 2v_{n,n}\cos(n\Delta\phi)\right)$$

$Y^{periph}(\Delta\phi)$ – per trigger particle yield in low-multiplicity events

- $Y(\Delta\phi)$ is assumed to result from a superposition of peripheral ($0 < N_{ch}^{rec} < 20$) events, scaled by multiplicative factor, F, and Y^{ridge}.
- Fit include harmonics 2-4.





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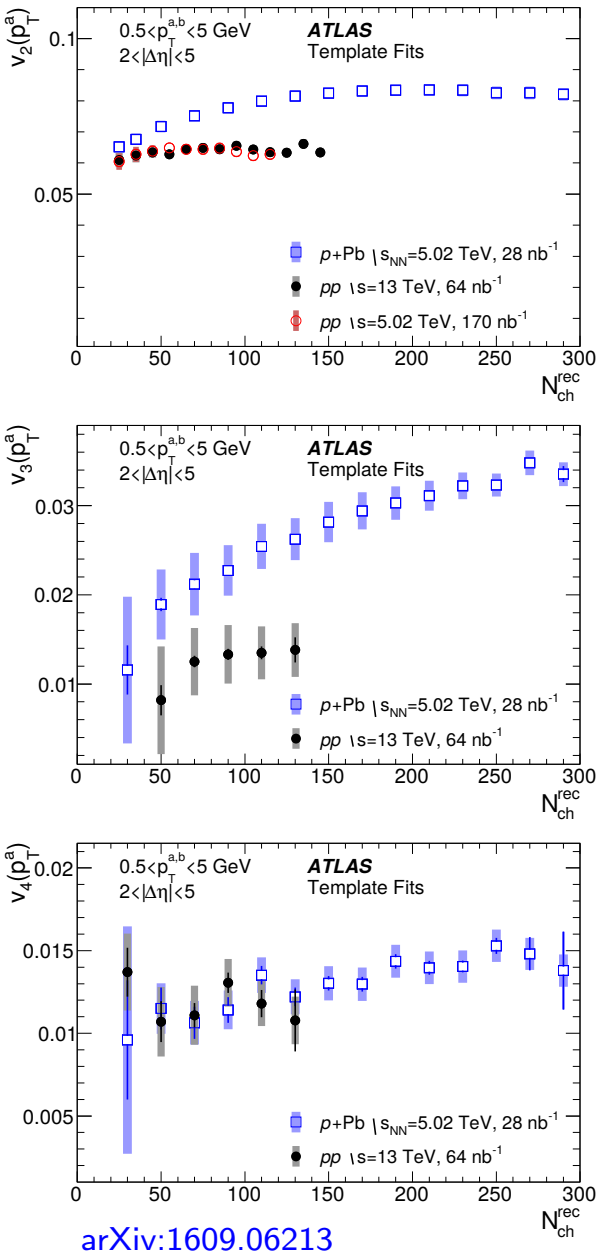
v_n dependence on N_{ch}^{rec}

- v_2^{pp} has almost no dependence on energy and only a weak multiplicity dependence.
- v_n are similar at low multiplicities for pp and p+Pb.
- v_n decreases with increasing n for all systems.
- v_3^{p+Pb} and v_4^{p+Pb} seems to rise continuously for the N_{ch}^{rec} ranges shown.



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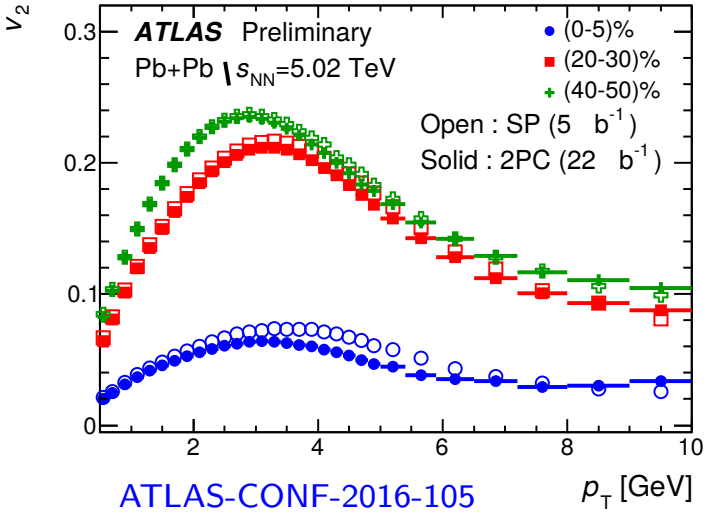
p_T dependence of v_n

- v_2^{pp} and v_2^{p+Pb} show trend characteristic for collective flow observed in Pb+Pb. Increase up to p_T ~3 GeV and then fall for high p_T.



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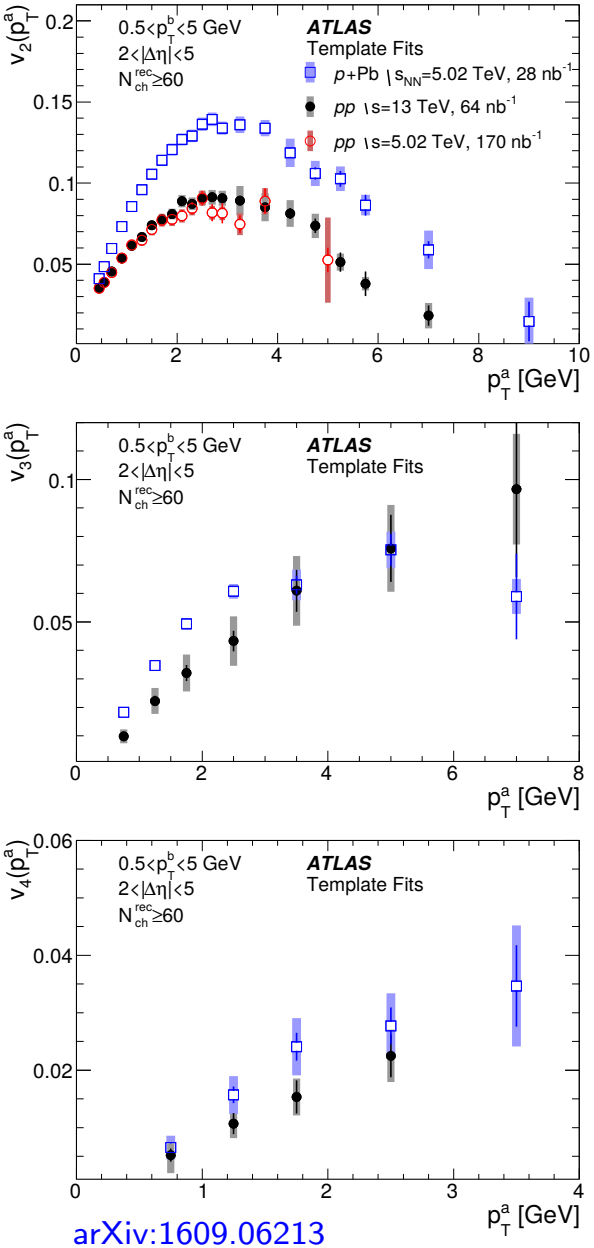
- v_2^{pp} shows no energy dependence.
- v_3 and v_4 rises with p_T for both systems, however p+Pb generally shows a faster increase with p_T.



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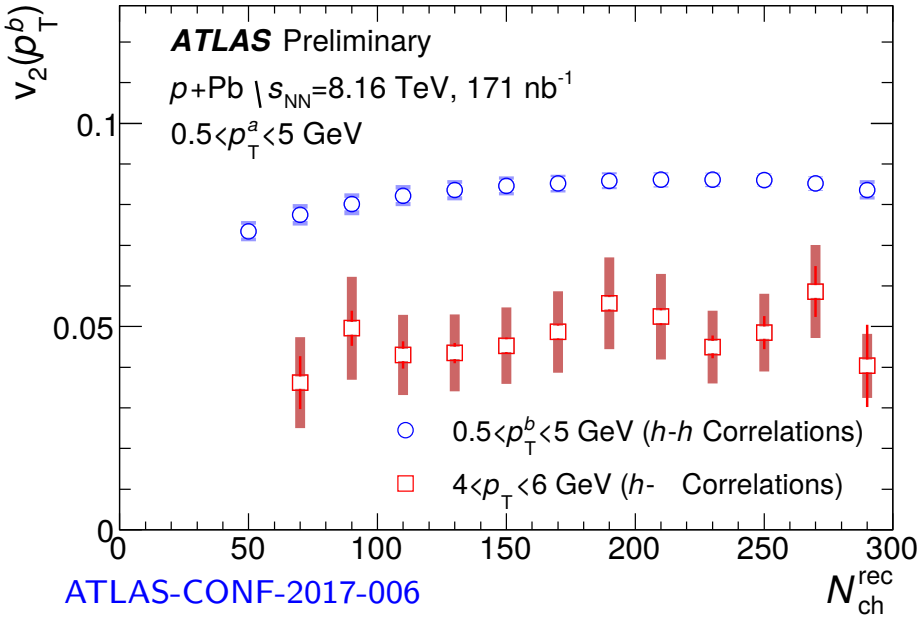
Muon and charged particles correlations

- p+Pb: 8.16 TeV (171 nb^{-1})
- With long range correlation between muons and inclusive charged particles the azimuthal anisotropy of HF quarks in p+Pb collisions can be studied.
- Using the template fitting method v_2 was extracted.
- A significant $v_2^{h-\mu}$ is observed but shows no multiplicity dependence.
- $v_2^{h-\mu}$ decrease with increasing muon-p_T (for shown p_T range).



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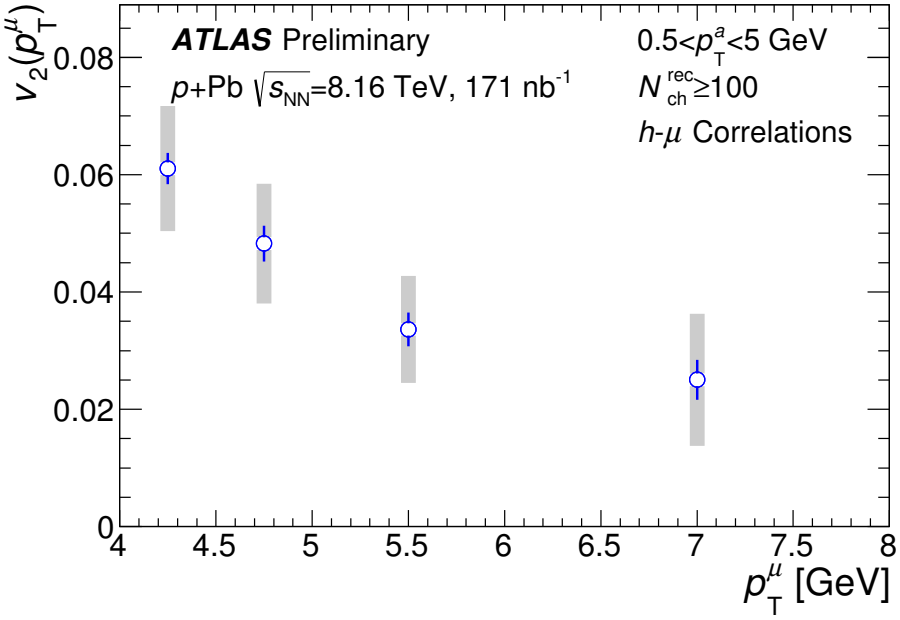


Multi-particle correlations (ATLAS-CONF-2017-007)

- The multi particle cumulant method was proposed to suppress the non-flow correlations which typically involve a low number of particles (resonance decays, jet production, etc.).
- $2k$-particle azimuthal correlations are defined as:

$$\langle\langle corr_n\{2k\}\rangle\rangle = \left\langle\left\langle e^{in[(\phi_1-\Phi_n)+\ldots-(\phi_{k+1}-\Phi_n)+\ldots]}\right\rangle\right\rangle,$$

  where double brackets denote averaging first over tracks and then over events.
- Correlations can be used to construct cumulants (example):

$$c_n\{4\} = \langle\langle corr_n\{4\}\rangle\rangle - 2\langle\langle corr_n\{2\}\rangle\rangle^2$$

- Measured cumulants can be used to estimate v_n:

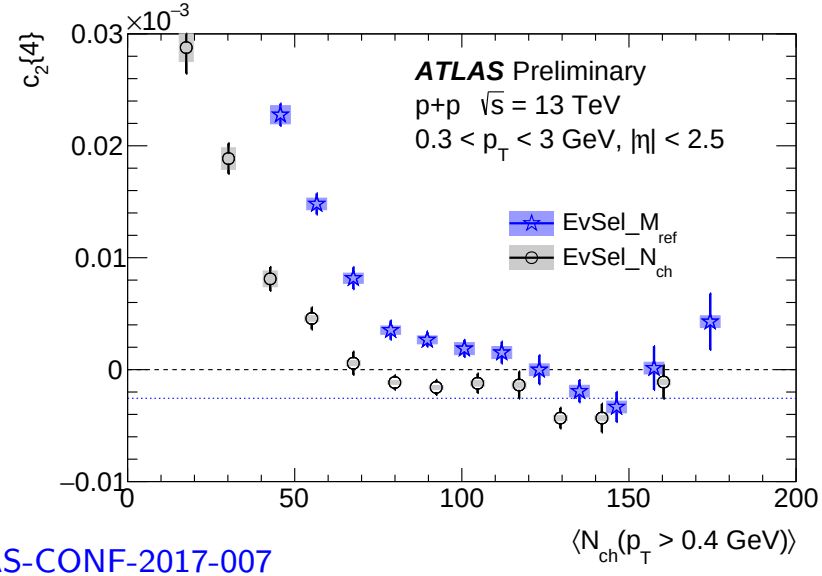
$$v_n\{2\} = \sqrt{c_n\{2\}}$$

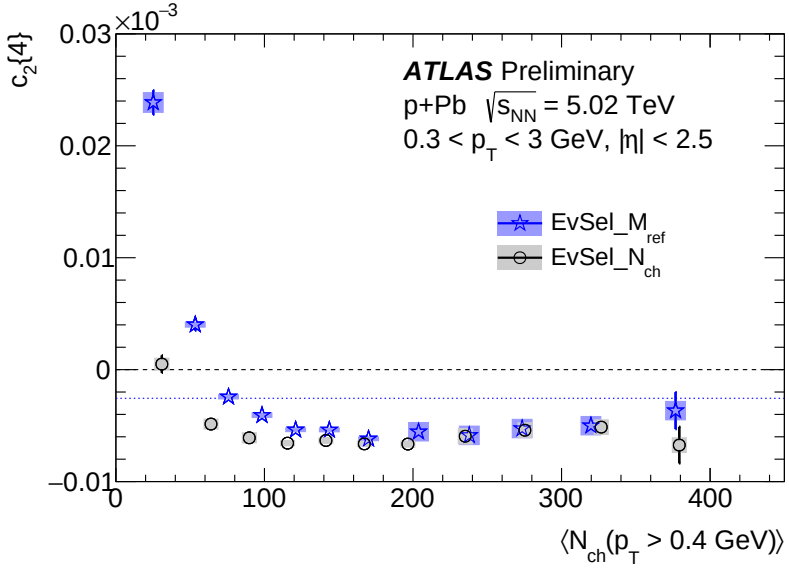
$$v_n\{4\} = \sqrt{-c_n\{4\}}$$

- "Wrong" sign of c_n is typically interpreted as the dominance of non-flow correlations.

Event selection

- Averaging over events is performed in the fixed number of reference particles (charged particles from a given p_T interval) - M_{ref}.
- Results are compared in $N_{ch}(p_T > 0.4\,\mathrm{GeV})$ corrected for tracking efficiency in the events selected using M_{ref}.
- For performance study different event selection was used - number of particles with $p_T > 0.4$ GeV ($\mathrm{EvSel\_N}_{ch}$).
- $c_2\{4\}$ is positive for 13 TeV pp where negative values are expected to come from flow.
- Non-flow correlations associated with multiplicity fluctuations may give negative contributions to measured $c_2\{4\}$ in $\mathrm{EvSel\_N}_{ch}$.





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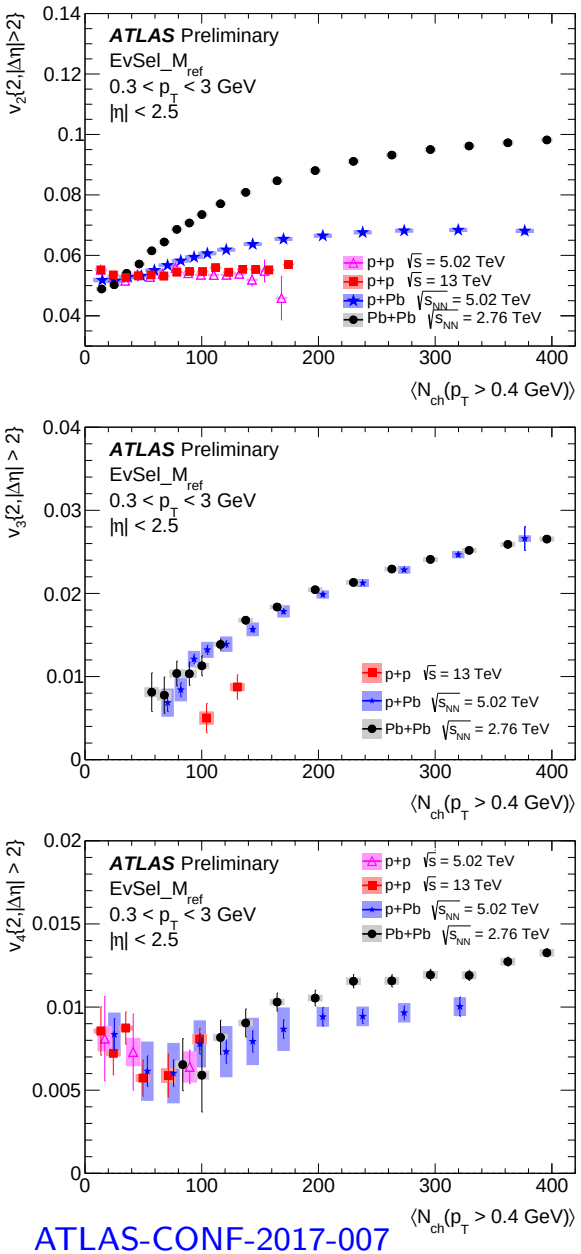
v_2, v_3 and v_4 flow harmonics

- The largest value of $v_2\{2\}$ is observed for Pb+Pb.
- As discussed previously (slide 9), the pp data show a very weak dependence on energy and multiplicity.
- $v_3\{2\}$ is similar for p+Pb and Pb+Pb.
- $v_2\{2\} > v_3\{2\} > v_4\{2\}$ for all systems.



ATLAS-CONF-2017-007

Multi-particle correlations with the subevent method

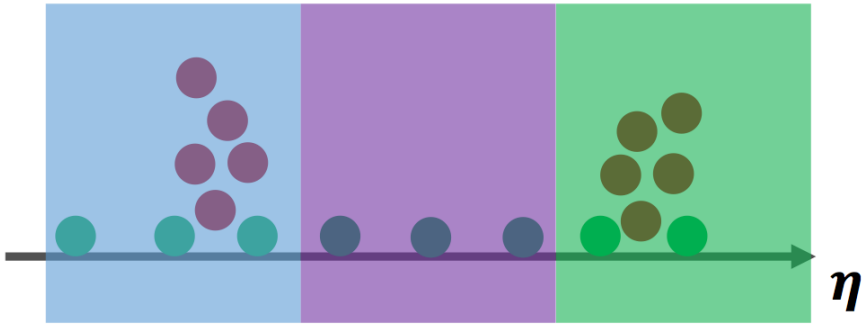
- Standard cumulants usually are affected by non-flow sources (impact from jets may be removed by requiring $\Delta\eta > 2$).
- To suppress these contributions a subevent cumulant method is proposed: (arXiv:1701.03830)
  - particles are divided into several subevents, each covering a distinct η interval,
  - multi-particle correlations are constructed by correlating particles from different subevents.

- 4 particle correlation for two subevents:

$$\langle\{4\}_2\rangle_{2a|2b} = \left\langle e^{2i(\phi_1^a+\phi_2^a-\phi_3^b-\phi_4^b)} \right\rangle$$

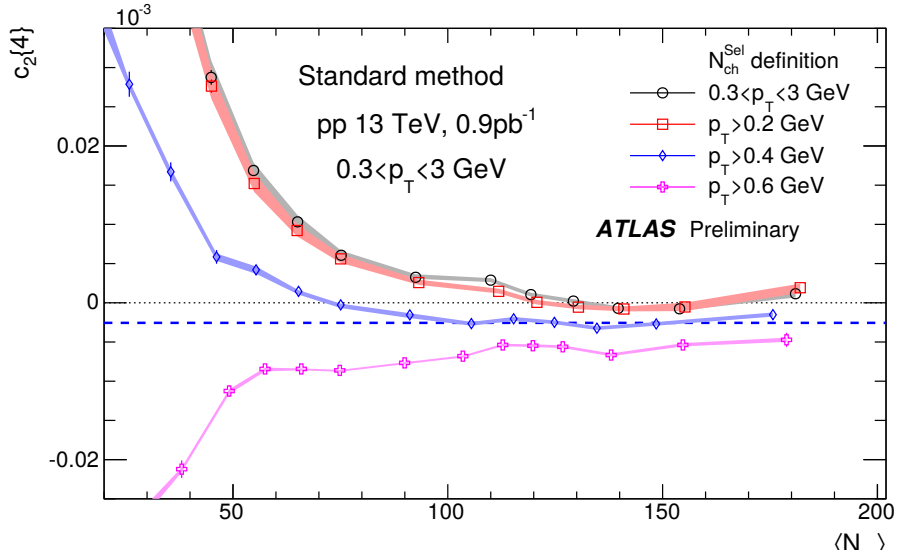
- 4 particle correlation for three subevents:

$$\langle\{4\}_2\rangle_{2a|b,c} = \left\langle e^{2i(\phi_1^a+\phi_2^a-\phi_3^b-\phi_4^c)} \right\rangle$$

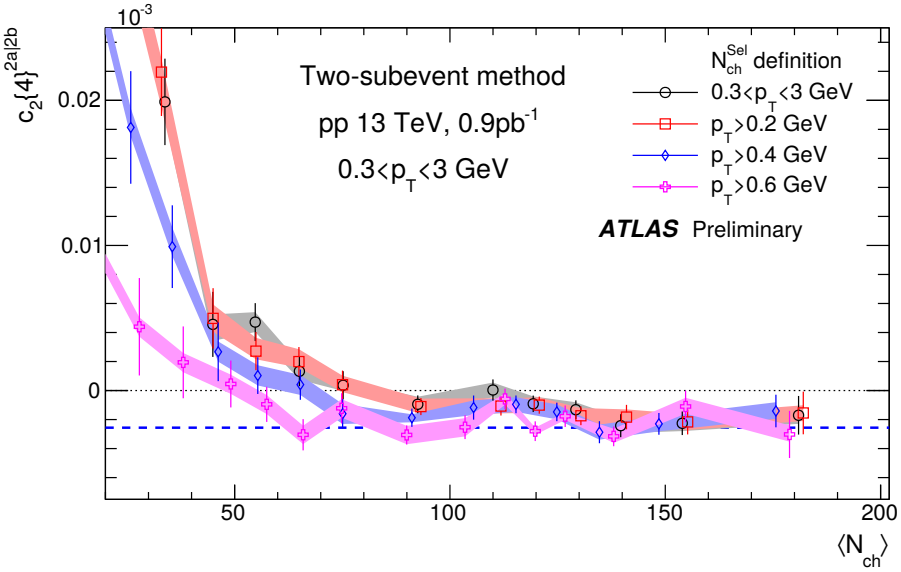


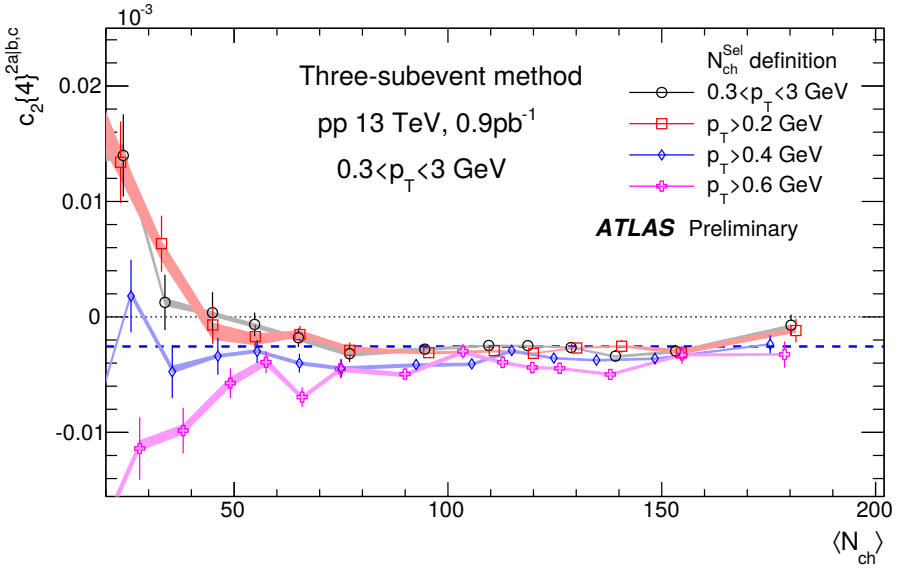
3 sub-event

Standard method, two and three subevent method



- 3 subevent method is the most stable for different N_{ch}^{sel} (various p_T thresholds) against non-flow.
- $c_2\{4\}$ has a negative sign after a more full suppression of non-flow effects.
- Non-flow correlations may still be important at small $\langle N_{ch}^{sel} \rangle$.





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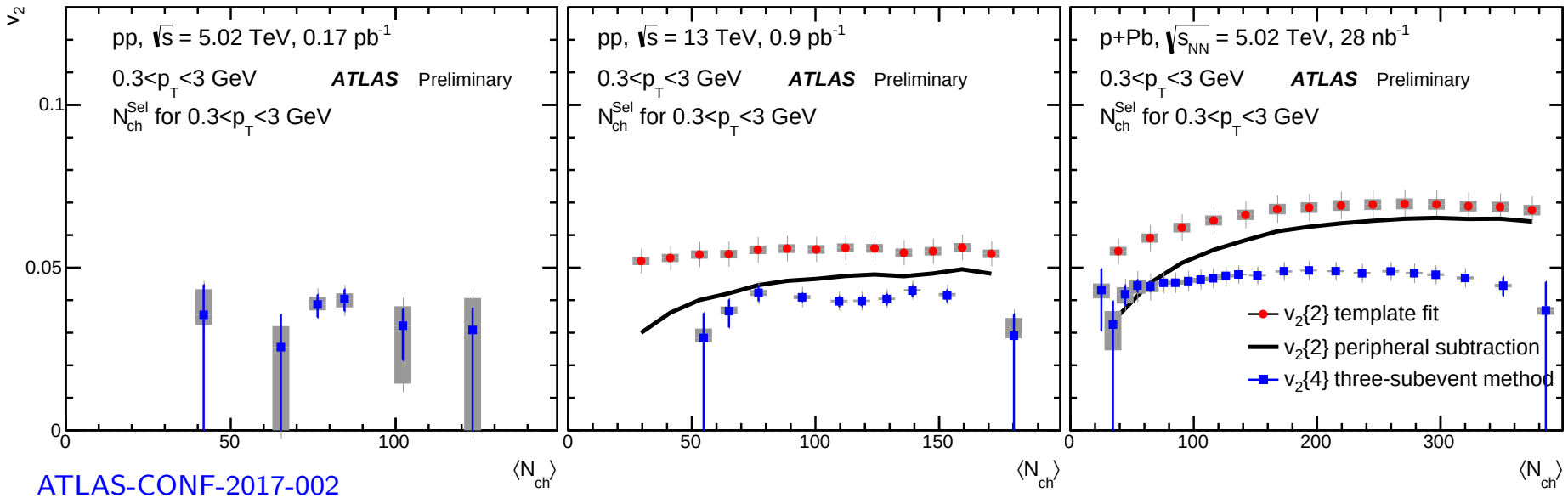
Comparison of v_2 between different methods

- The harmonic flow $v_2\{4\}$ is obtained from the measured $c_2\{4\}$.
- $v_2\{2\} \neq v_2\{4\}$ due to EbyE flow fluctuations associated with fluctuating initial conditions (PRL 112, 082301 (2014)).
- Fluctuations are closely related to the effective number of sources N_s in the initial stage:

$$\frac{v_2\{4\}}{v_2\{2\}} = \left(\frac{4}{3+N_s}\right)^{1/4}$$



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Summary

- Following systems have been studied: pp at $\sqrt{s} = 5.02$, 13 TeV and p+Pb at $\sqrt{s_{NN}} = 5.02$, 8.16 TeV
- v_2, v_3 and v_4 were measured using a template fit method.
  - v_n^{pp} has only a weak multiplicity dependence and almost no dependency on energy.
  - v_n are similar at low multiplicities for pp and p+Pb but v_n^{p+Pb} seems to rise continuously for the N_{ch}^{rec} ranges shown.
- A significant $v_2^{h-\mu}$ is observed but shows no multiplicity dependence.
- $c_2\{4\}$ cummulants measured in pp data at 5.02 and 13 TeV are positive.
- Multiplicity fluctuations give negative contributions to measured $c_2\{4\}$.
- The new subevent cumulant method is more stable for different N_{ch}^{sel}.
- $c_2\{4\}$ has a negative sign after a more full suppression of non-flow correlations.
- Event-by-Event fluctuations may cause $v_2\{2\} \neq v_2\{4\}$.

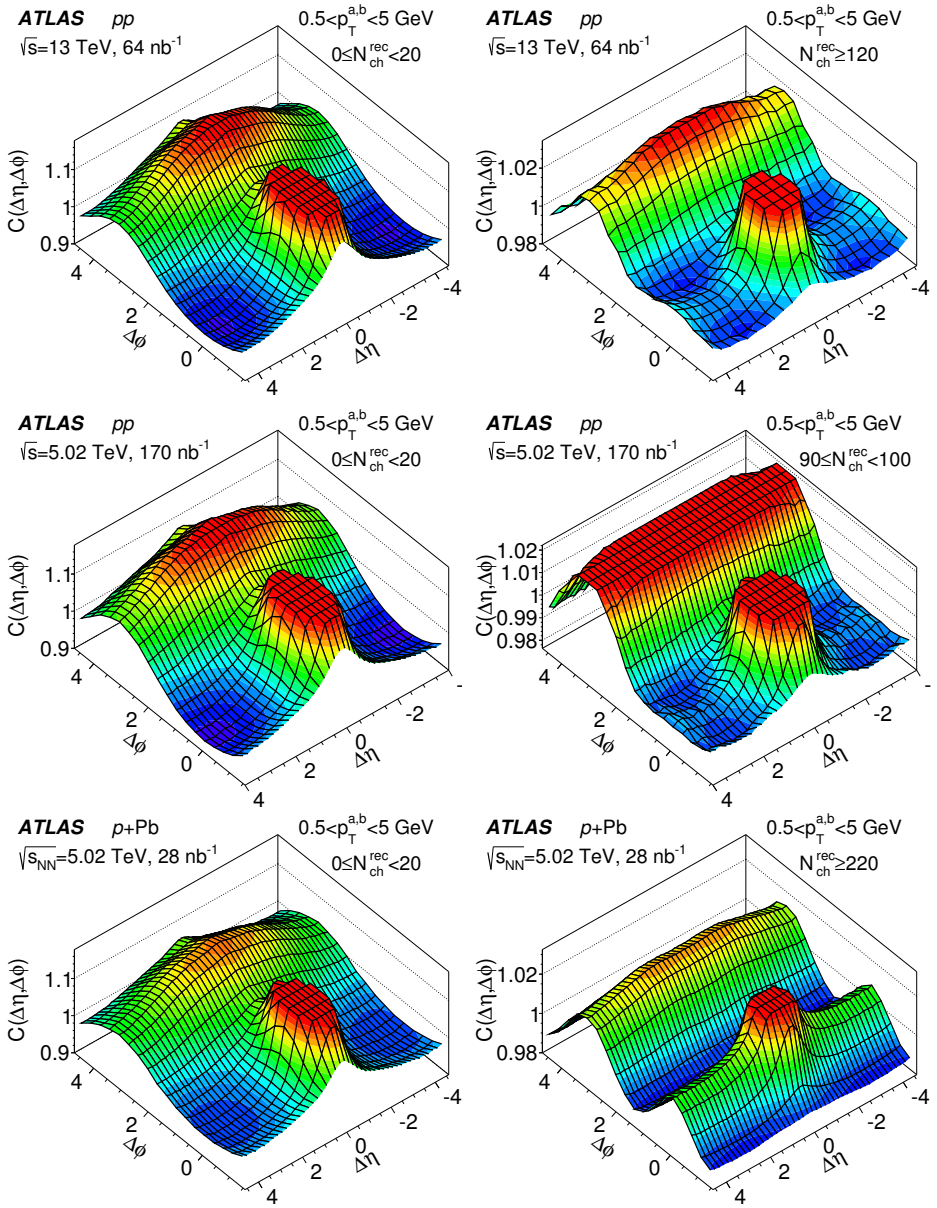
More information can be found in
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Thank you for your attention

Backup slides

Event activity classes

- Left panel – low-multiplicity events ($0 < N_{ch}^{rec} < 20$).
- Right panel – high-multiplicity events.
- Low-multiplicity correlations originate from hard-scattering processes (jets, dijets, ...).
- These features also dominate the high-multiplicity correlations; additionally a ridge extends over the entire measured $\Delta\eta$ range.
- Ridge is also present at $\Delta\phi \sim \pi$ but it is covered by the non flow correlations.



arXiv:1609.06213

Test of factorization in template fits

- If the $v_{n,n}$ obtained from the template fits are the results of single-particle modulation, then the $v_{n,n}$ should factorize:

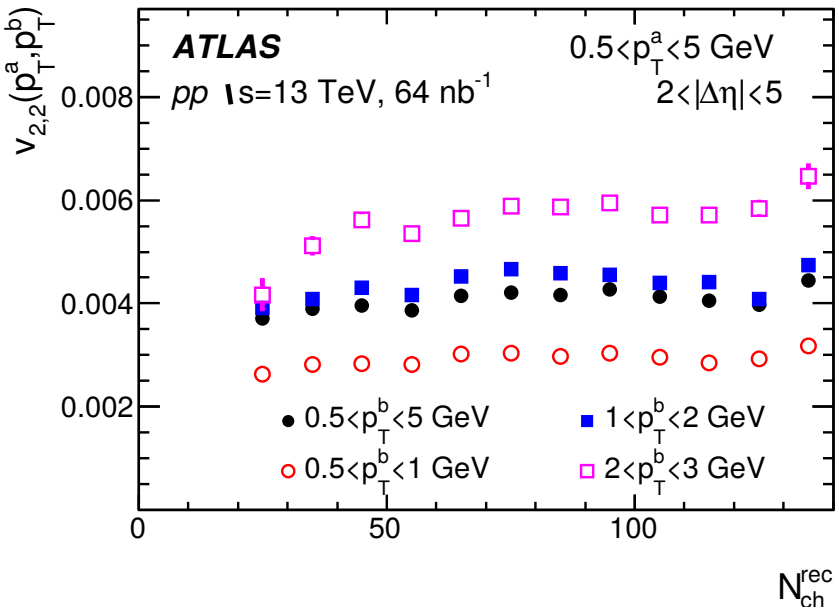
$$v_{2,2}(p_T^a, p_T^b) = v_2(p_T^a) v_2(p_T^b)$$

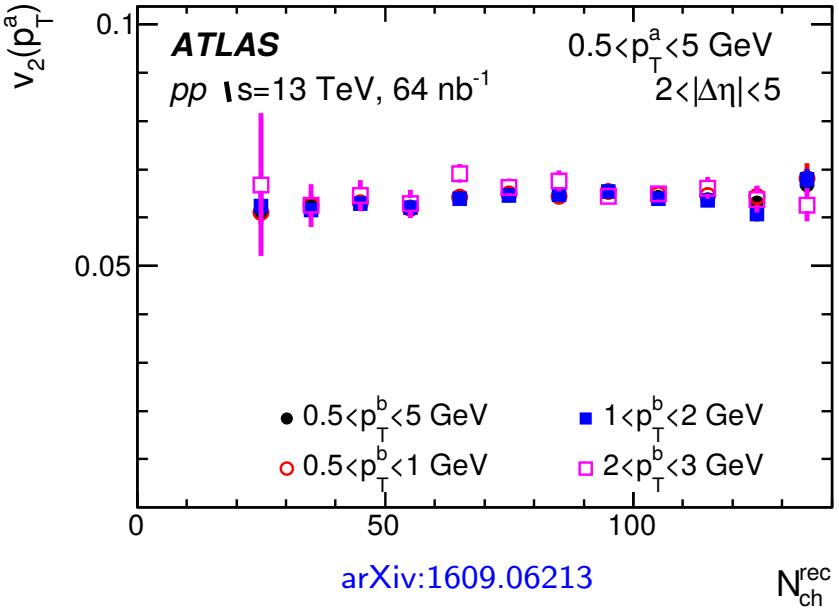
- Factorization can be tested experimentally by measuring $v_2(p_T^a)$ for different ranges of p_T^b:

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

- $v_2(p_T^a)$ shows no dependency on reference p_T^b.
- The factorization works well in different N_{rec}^{ch} and p_T ranges for both, pp and p+Pb.

only statistical uncertainties are presented





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