Recent ATLAS measurements of correlations in Pb+Pb and Xe+Xe collisions

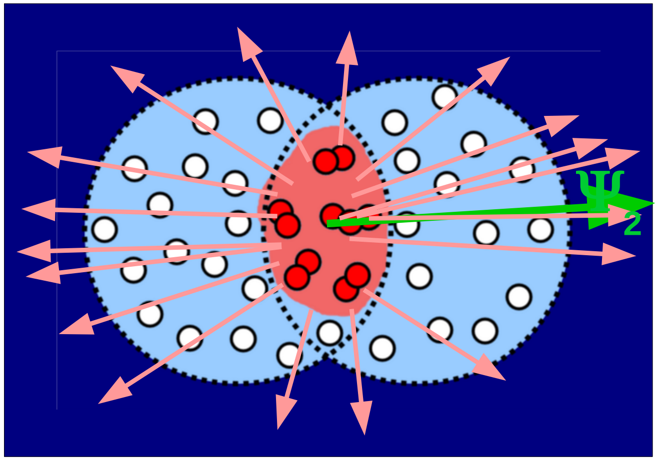
ATLAS EXPERIMENT

Krzysztof Woźniak, IFJ PAN, Kraków, Poland
on behalf of the ATLAS Collaboration

ICHEP 2020 | PRAGUE
40th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS
VIRTUAL CONFERENCE
28 JULY - 6 AUGUST 2020
PRAGUE, CZECH REPUBLIC

Collisions of nuclei - creation of Quark-Gluon Plasma

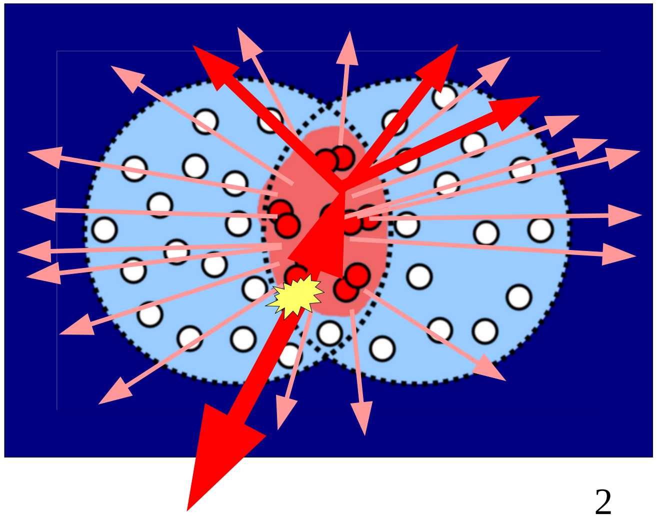
Large energy released in collisions of nuclei leads to creation of strongly interacting dense matter - Quark-Gluon Plasma



Collective phenomena - particle flow

- **Area of the overlap of nuclei has an elongated shape**
- **In this region Quark-Gluon Plasma is created**
- **QGP expands and its components, quark and gluons, behave collectively**
- **More particles are produced in the event plane Ψ**

this talk and the talk by Adam Trzupek



Strong interactions of partons in QGP

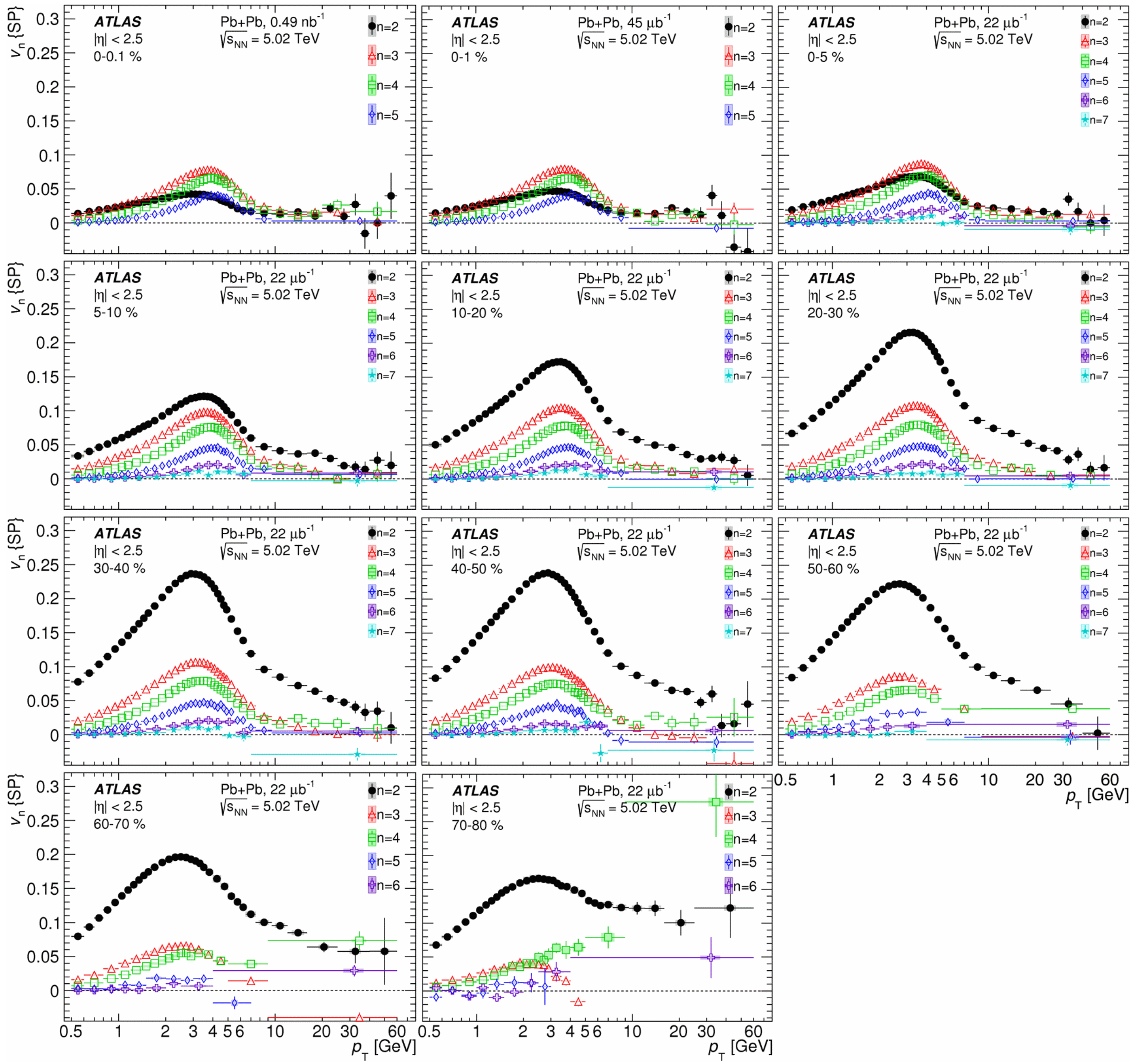
- **Partons created in a hard scattering travel through QGP**
- **Interactions with the dense matter causes that even the most energetic partons loose energy and may be stopped inside QGP area**

see the talk by Helena Santos

Flow harmonics in Pb+Pb collisions at 5.02 TeV

Detailed measurements of harmonics v_2-v_7:

- **p_T dependence**
  - **an increase up to ~3 GeV**
  - **a decrease above ~3 GeV**
- **centrality dependence - harmonics are the larges in mid-central (20-50%) events**
- **harmonics up to v_7 are non-zero**
- **various methods of calculations of flow harmonics**

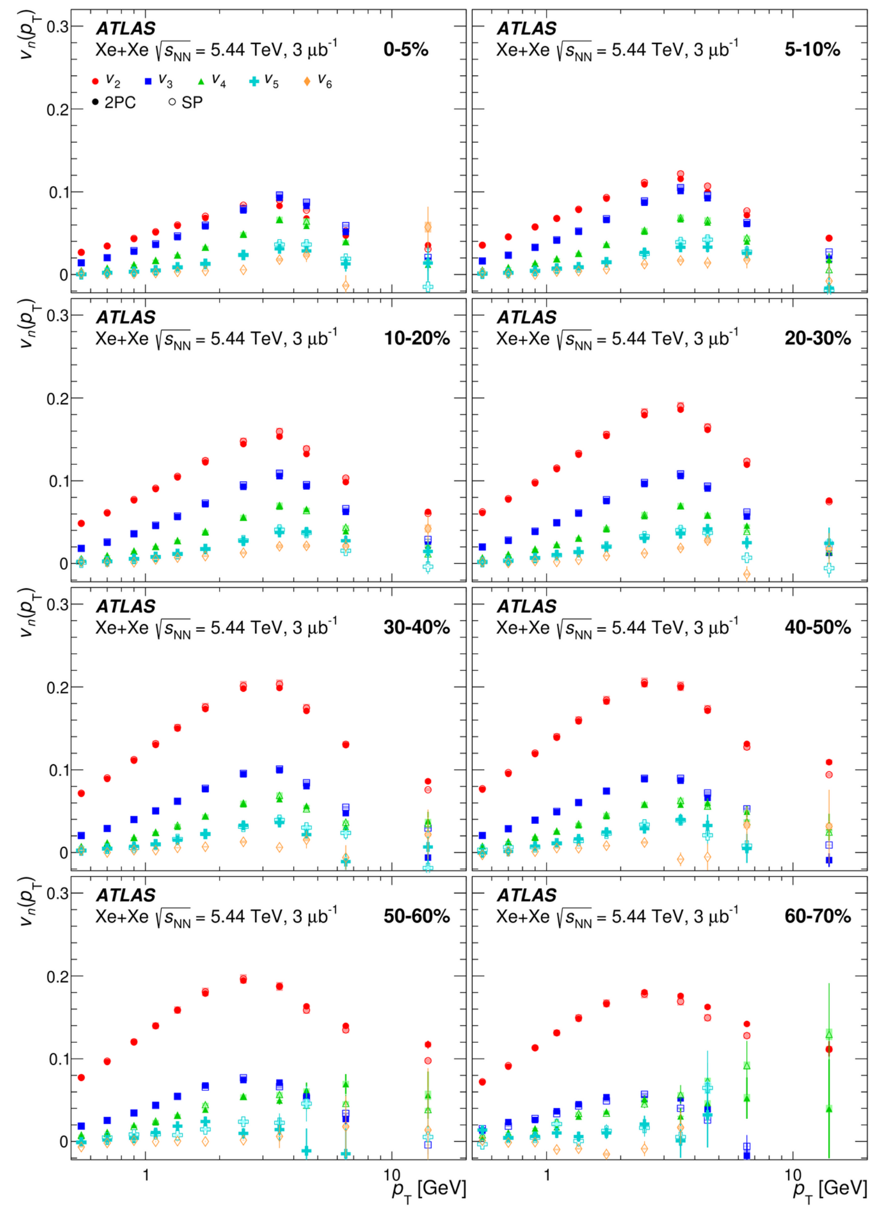


ATLAS, Eur. Phys. J. C 78 (2018) 997.

Flow in Xe+Xe collisions

Flow measurement in Xe+Xe collisions

- harmonics v_2 to v_6
- at the first look p_T dependence similar to that for other collision systems

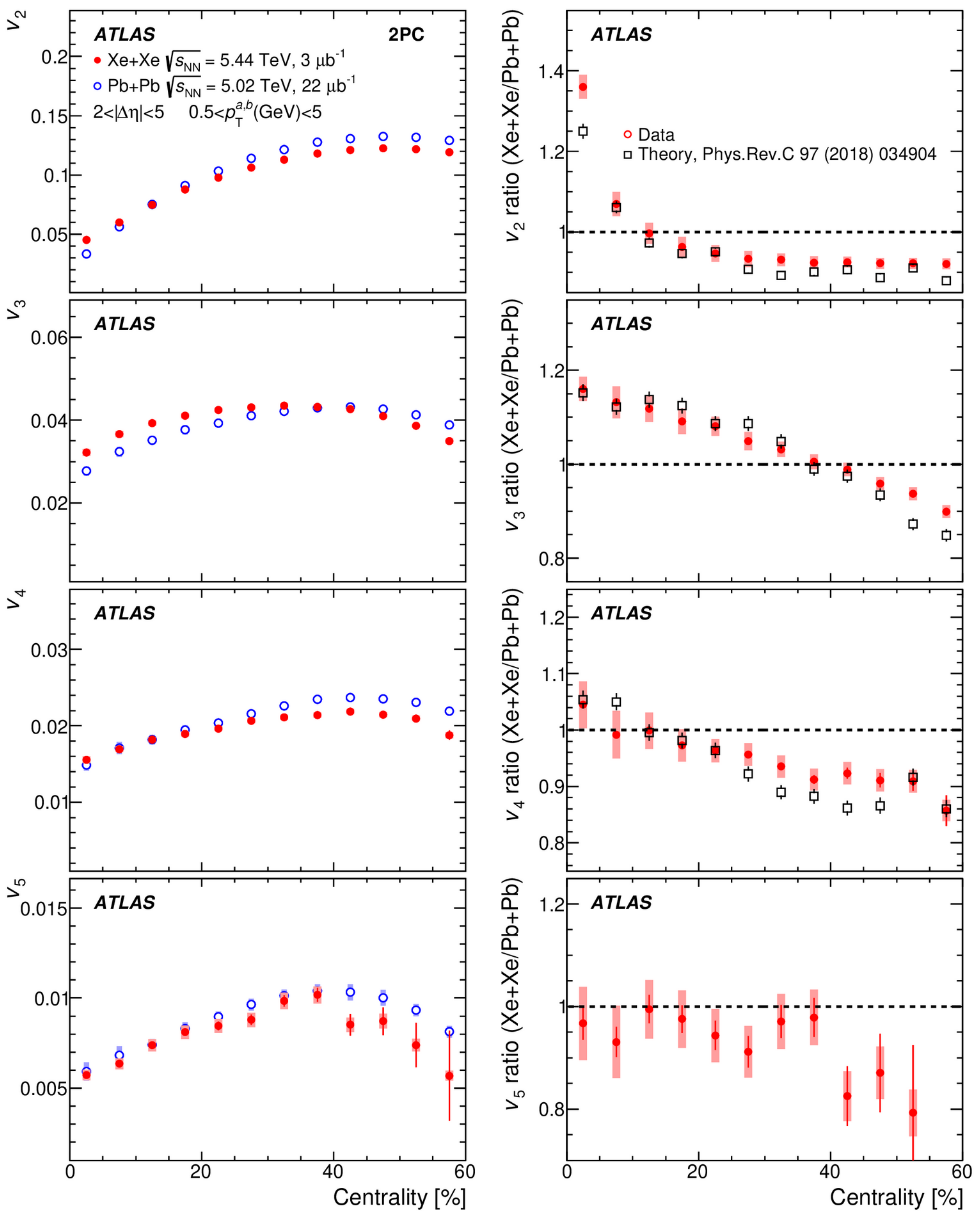


ATLAS, Phys. Rev. C 101 (2020) 024906

Flow in Xe+Xe collisions

Comparison of flow measurement in Xe+Xe and Pb+Pb collisions

- elliptic flow larger in Xe+Xe in most central collisions and smaller in peripheral collisions
- similar, but less strong trend with centrality for v_3 and v_4
- slightly lower v_5 in Xe+Xe than in Pb+Pb collisions in all centralities

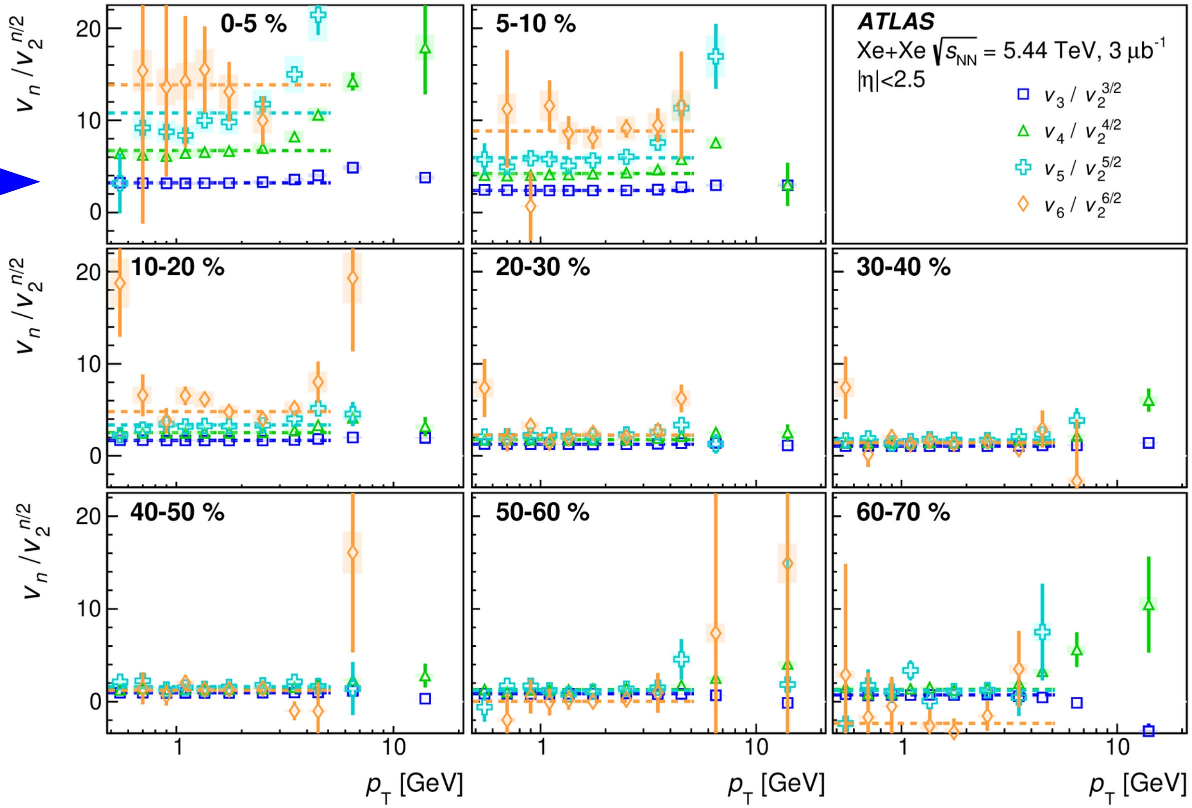


ATLAS, Phys. Rev. C 101 (2020) 024906

Flow in Xe+Xe collisions

Scaling of flow harmonics

- scaling by v_2: $v_n/(v_2)^{n/2}$



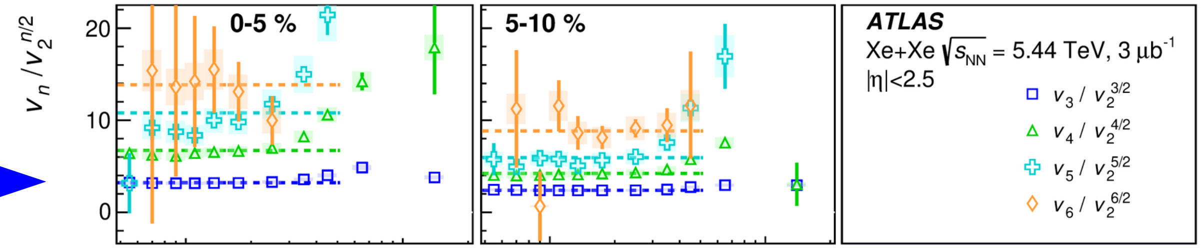
- constant as a function of p_T

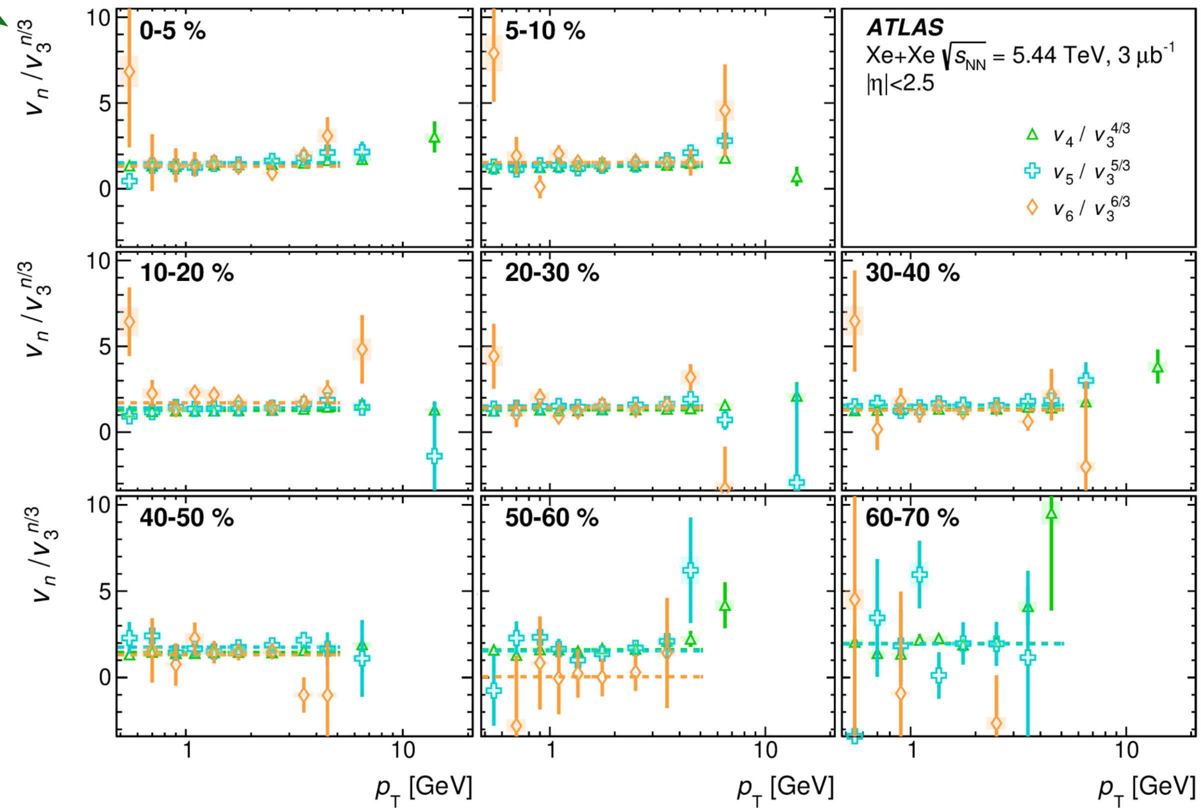
ATLAS, Phys. Rev. C 101 (2020) 024906

Flow in Xe+Xe collisions

Scaling of flow harmonics

- scaling by v_2 $\quad v_n/(v_2)^{n/2}$
- scaling by v_3 $\quad v_n/(v_3)^{n/3}$
- constant as a function of p_T
- similar values of $v_n/(v_3)^{n/3}$ for different v_n





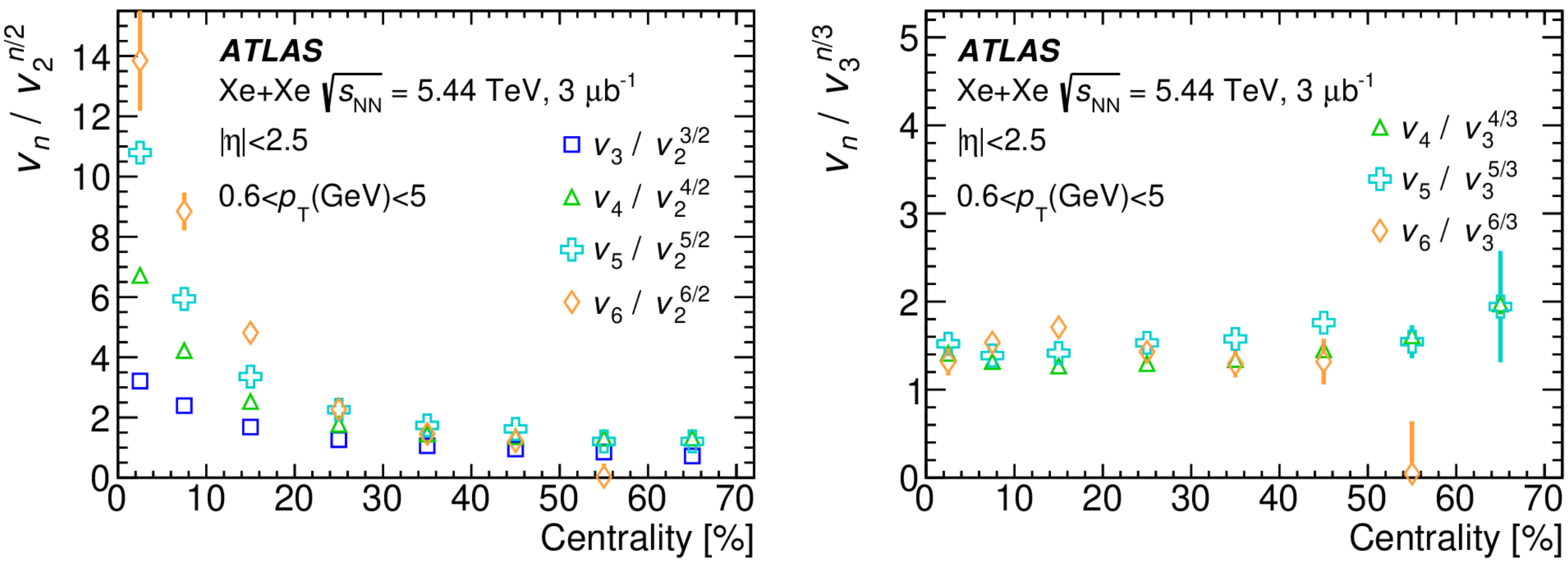
ATLAS, Phys. Rev. C 101 (2020) 024906

Flow in Xe+Xe collisions

Scaling of flow harmonics

- **scaling by v_2** $$v_n/(v_2)^{n/2}$$
- **scaling by v_3** $$v_n/(v_3)^{n/3}$$

- **constant as a function of p_T**
- **scaling by v_3 gives almost the same value for all higher harmonics**

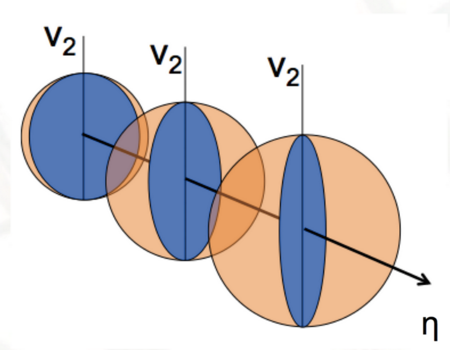


ATLAS, Phys. Rev. C 101 (2020) 024906

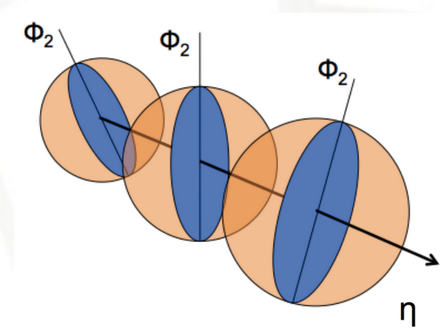
Longitudinal flow decorrelations

Measurement of flow harmonics fluctuations as a function of pseduprapidity

Change of flow magnitude



Change of event plane (twist)



Correlators using flow vectors calculated in different η intervals

$$r_{n|n;k} = \frac{\langle \boldsymbol{q}_n(-\eta)^k \boldsymbol{q}_n^{*k}(\eta_{\mathrm{ref}})\rangle}{\langle \boldsymbol{q}_n(\eta)^k \boldsymbol{q}_n^{*k}(\eta_{\mathrm{ref}})\rangle}; \qquad \boldsymbol{q}_n = \Sigma_i w_i e^{in\phi_i} / \Sigma_i w_i$$

$$r_{n|n;k} = \frac{\langle [v_n(-\eta) v_n(\eta_{\mathrm{ref}})]^k \cos(kn(\Phi_n(-\eta) - \Phi_n(\eta_{\mathrm{ref}})))\rangle}{\langle [v_n(\eta) v_n(\eta_{\mathrm{ref}})]^k \cos(kn(\Phi_n(\eta) - \Phi_n(\eta_{\mathrm{ref}})))\rangle}$$

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

Note:
in the absence of any systematic modifications of flow harmonics
$r = 1$ and $R = 1$

Measured in Pb+Pb and Xe+Xe collisions

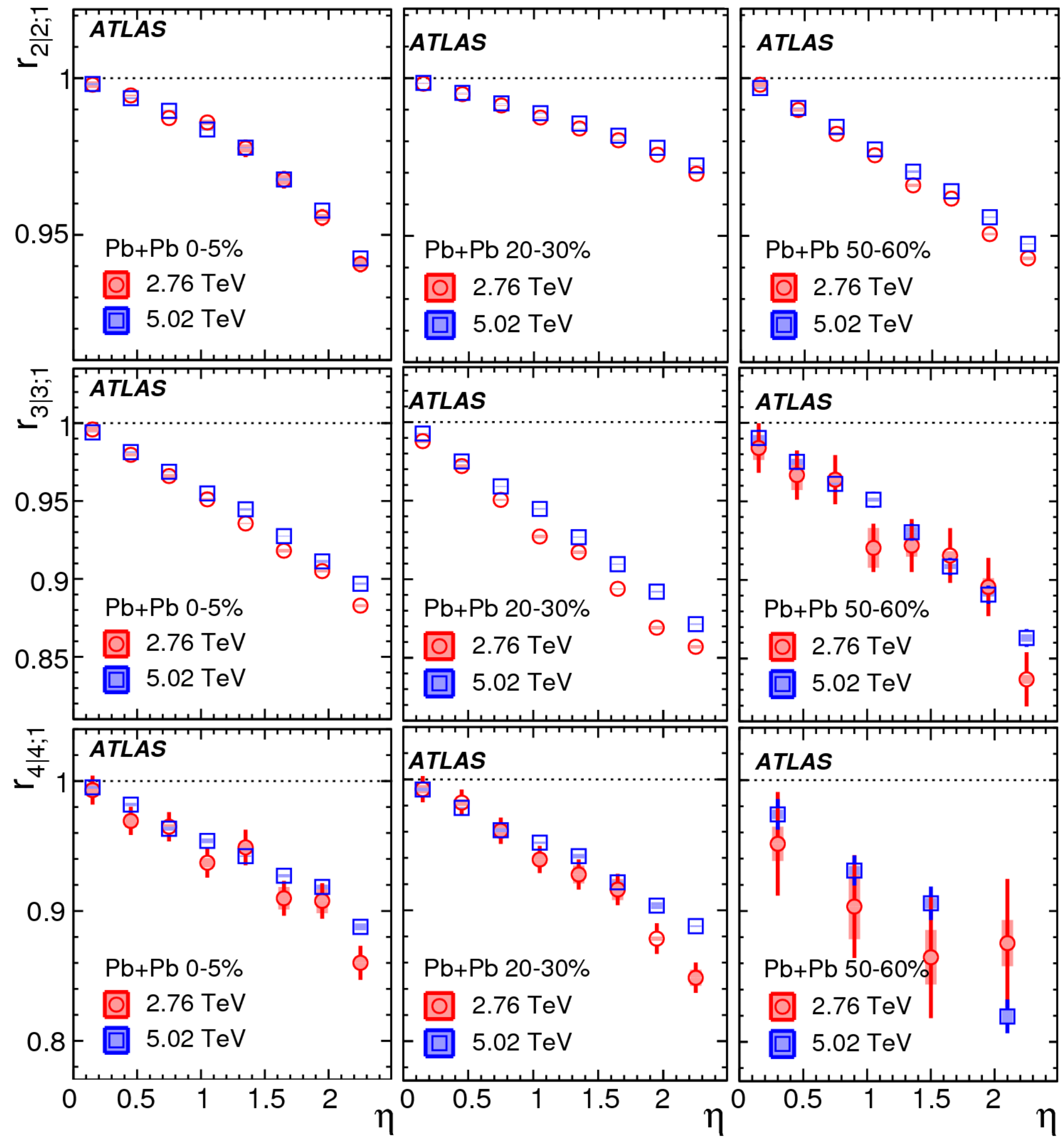
ATLAS, Eur. Phys. J. C 76 (2018) 142 and arxiv:2001.04201

Longitudinal flow decorrelations in Pb+Pb collisions

Pb+Pb

Correlator r

- **flow decorrelations are approximately linear in η**
- **elliptic decorrelation $r_{2|2;1}$ depends on centrality - it deviates from 1 more in central and peripheral collisions than in semi-central collisions**
- **higher order correlators, $r_{3|3;1}$ and $r_{4|4;1}$, departure from 1 is even larger but similar for all centralities**
- **no difference for two Pb+Pb collision energies**

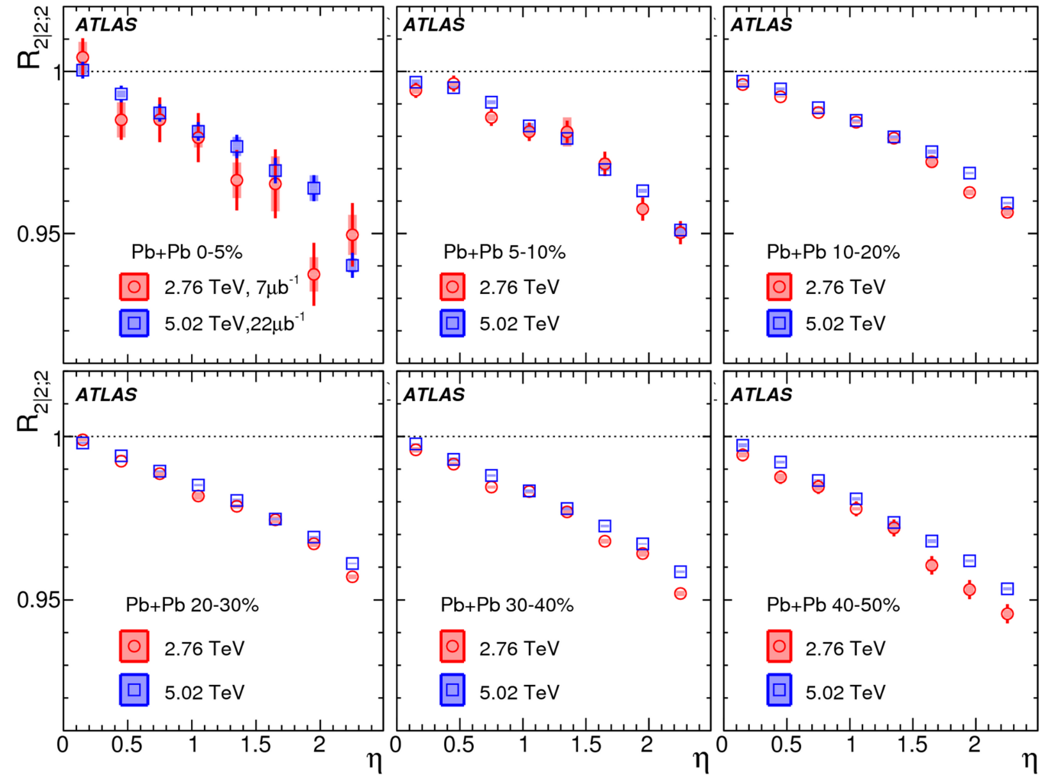


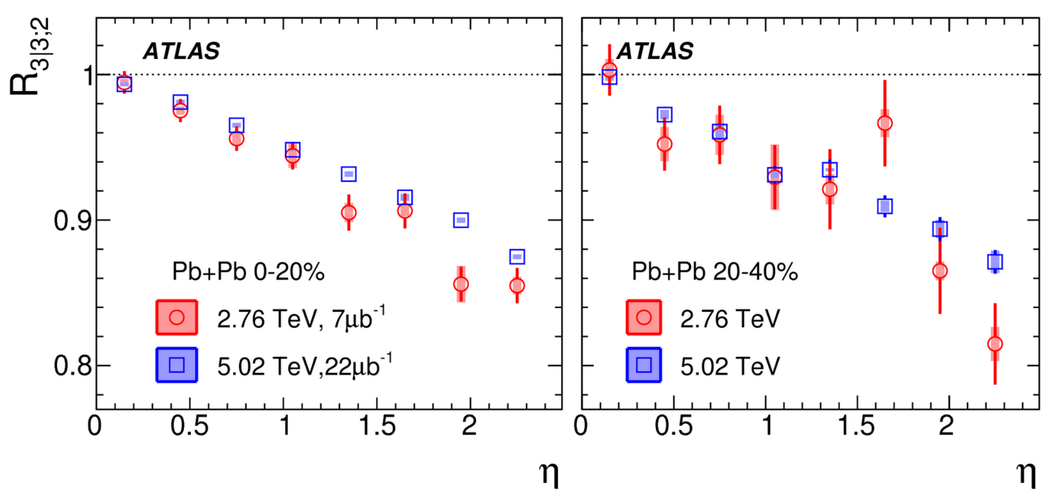
ATLAS, Eur. Phys. J. C 76 (2018) 142

Longitudinal flow decorrelations in Pb+Pb collisions

Correlator R

- **flow decorrelations are approximately linear in η**
- **elliptic decorrelation $R_{2|2;1}$ depends on centrality - it deviates from 1 more in central and peripheral collisions than in semi-central collisions**
- **higher order correlator, $R_{3|3;2}$, deviates from 1 even more but in a similar way for different centralities**
- **no difference for two collision energies**



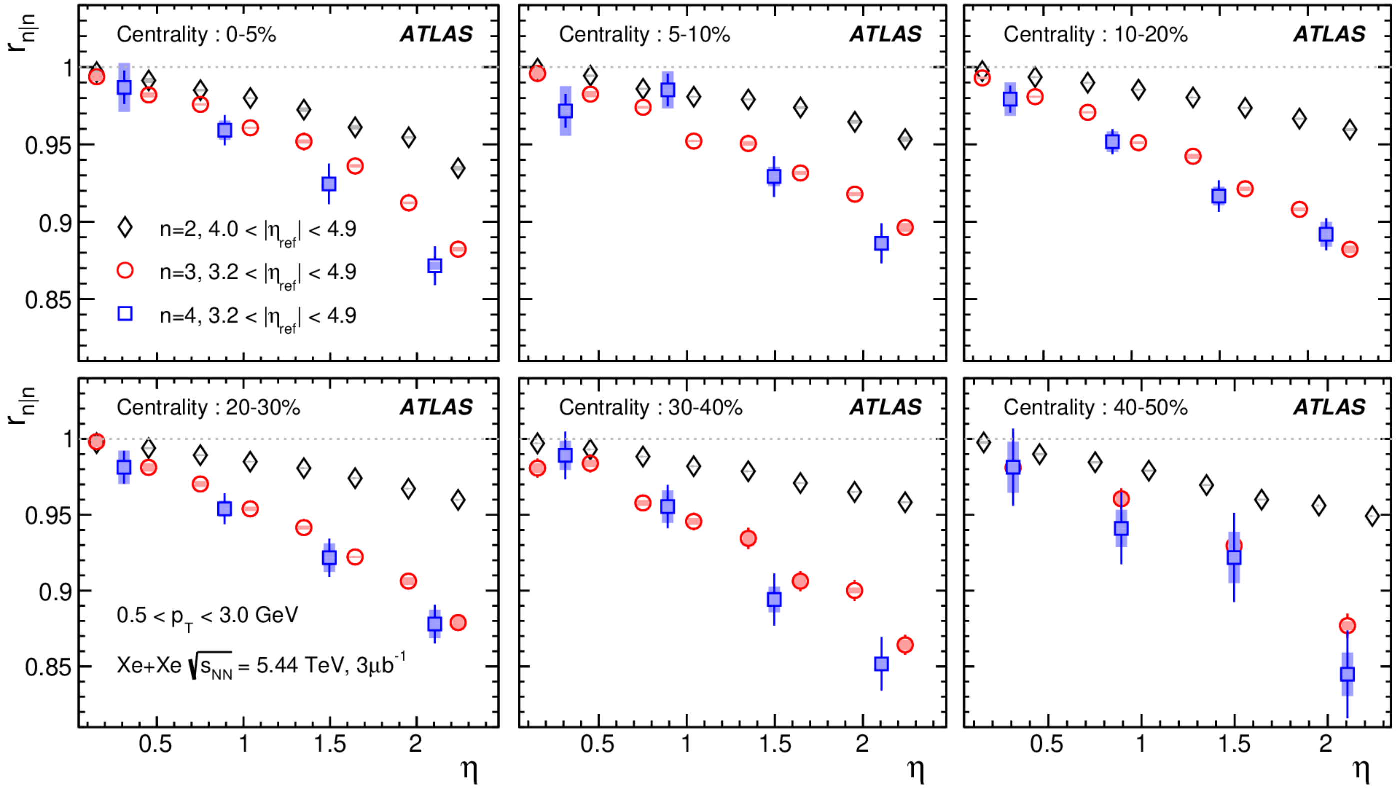


ATLAS, Eur. Phys. J. C 76 (2018) 142

Longitudinal flow decorrelations

Similar trends in Xe+Xe collisions:

- **flow decorrelations are approximately linear in η**
- **$r_{2|2;1}$ depends on centrality - it is larger in central and peripheral collisions than in semi-central collisions**
- **decrease of higher order correlators, $r_{3|3;1}$ and $r_{4|4;1}$, are larger then for $r_{2|2;1}$**



ATLAS, arxiv:2001.04201

Longitudinal flow decorrelations in Pb+Pb collisions

- **flow decorrelations are approximately linear in η**

$$r_{n|n;k} = 1 - 2F^r_{n;k}\,\eta$$

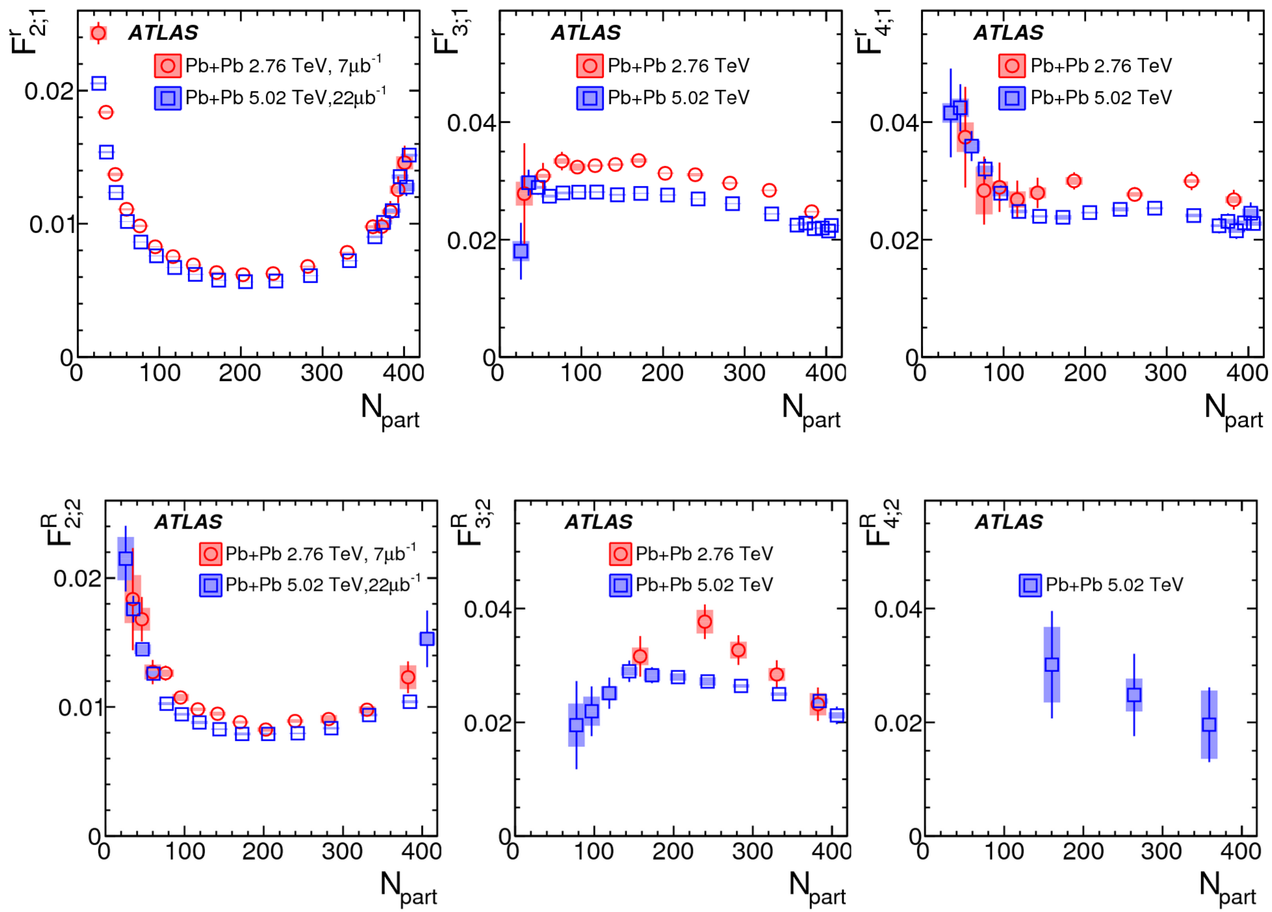
$$R_{n|n;k} = 1 - 2F^R_{n;k}\,\eta$$

- **decorrelation "strength" parameters:**

$$F^r_n = \frac{\sum_i (1 - r_{n|n}(\eta_i))\,\eta_i}{2\sum_i \eta_i^2}$$

$$F^R_n = \frac{\sum_i (1 - R_{n|n}(\eta_i))\,\eta_i}{2\sum_i \eta_i^2}$$

- **F^r_2 and F^R_2 strongly depend on centrality (here N_{part})**



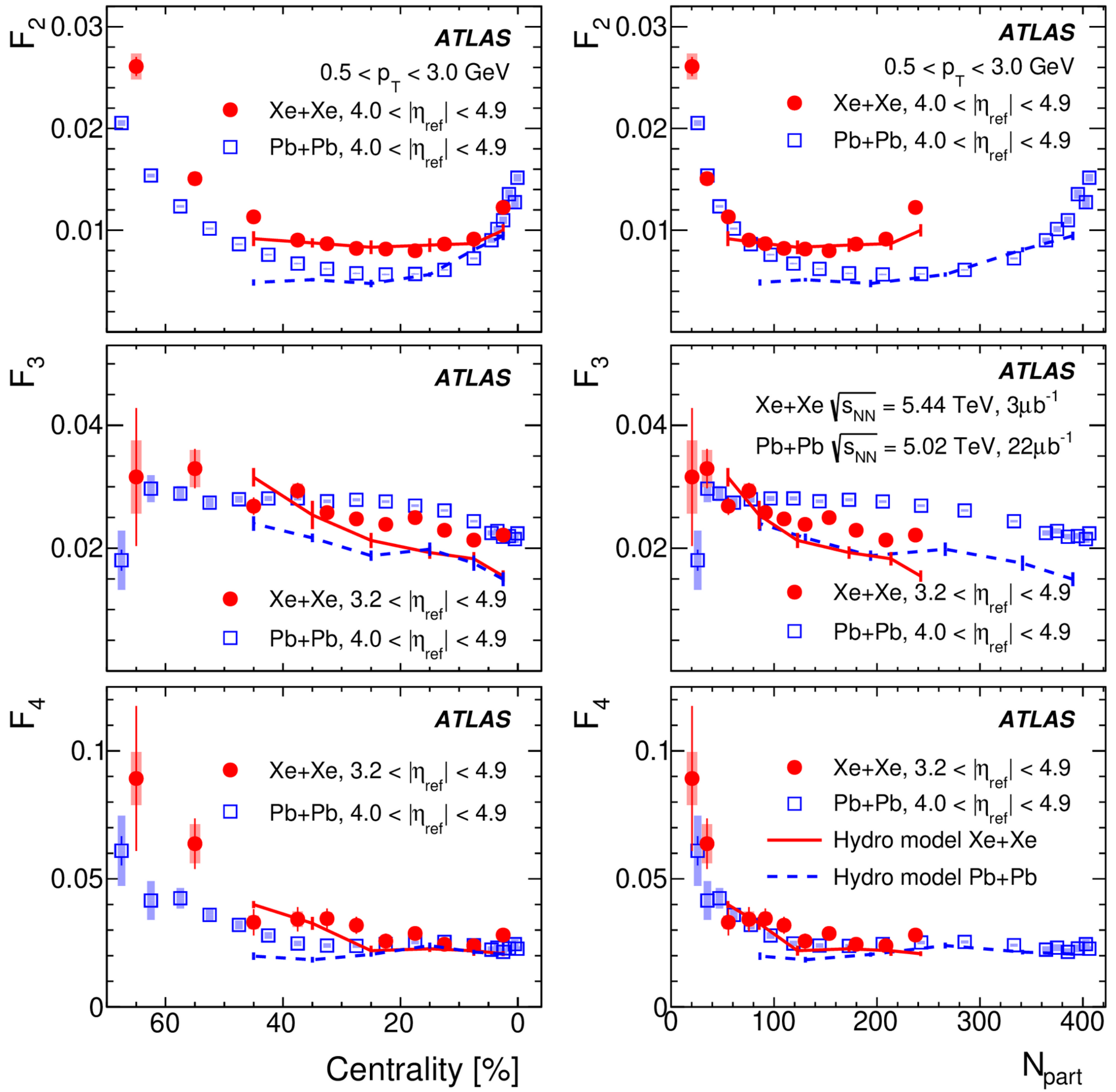
ATLAS, Eur. Phys. J. C 76 (2018) 142

Longitudinal flow decorrelations in Xe+Xe collisions

- decorrelation "strength" parameter:

$$F_n = \frac{\sum_i (1 - r_{n|n}(\eta_i))\eta_i}{2\sum_i \eta_i^2}$$

- F_2 larger in Xe+Xe collisions than in Pb+Pb collisions
- F_3 smaller in Xe+Xe collisions than in Pb+Pb collisions



ATLAS, arxiv:2001.04201

Longitudinal flow decorrelations in Pb+Pb collisions

- decorrelation "strength" parameters:

$$F_n^r = \frac{\sum_i (1 - r_{n|n}(\eta_i))\eta_i}{2\sum_i \eta_i^2}$$

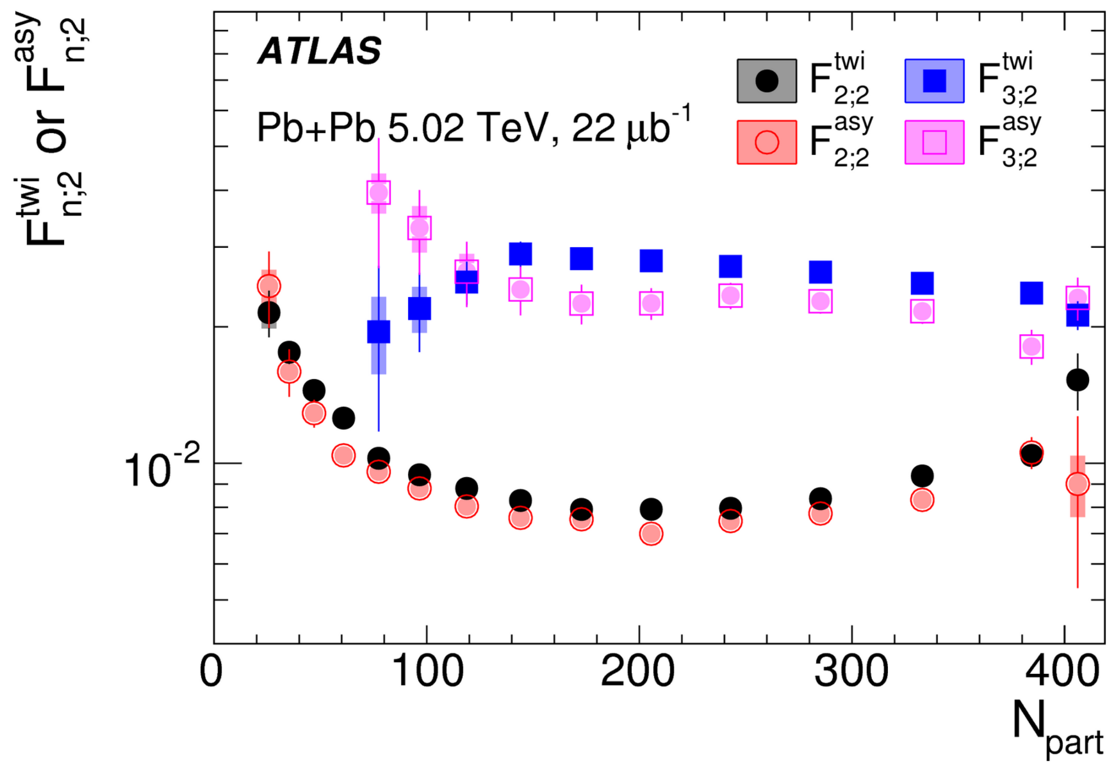
$$F_n^R = \frac{\sum_i (1 - R_{n|n}(\eta_i))\eta_i}{2\sum_i \eta_i^2}$$

- connection with twist and asymmetry fluctuations:

$$F_{n;2}^{twi} = F_{n;2}^{R}$$

$$F_{n;2}^{asy} = F_{n;2}^{r} - F_{n;2}^{R}$$

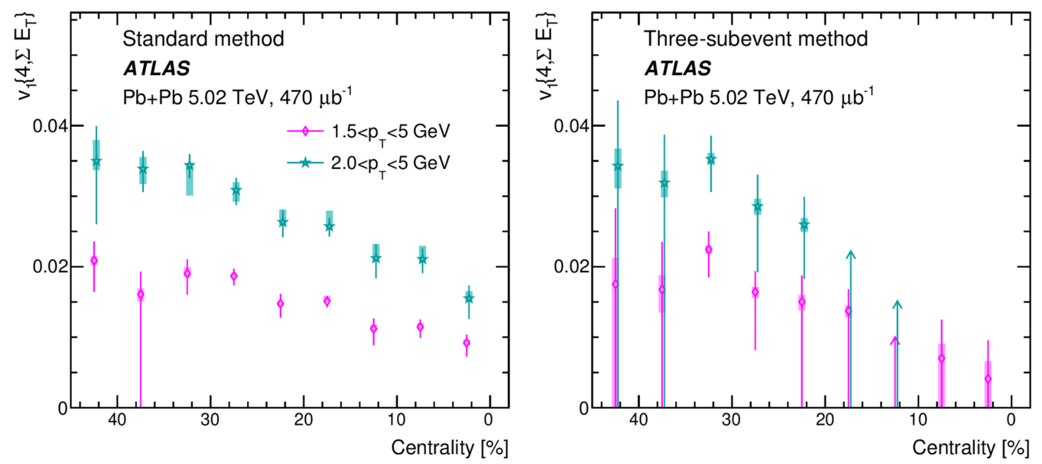
- similar size of these two types of decorrelations

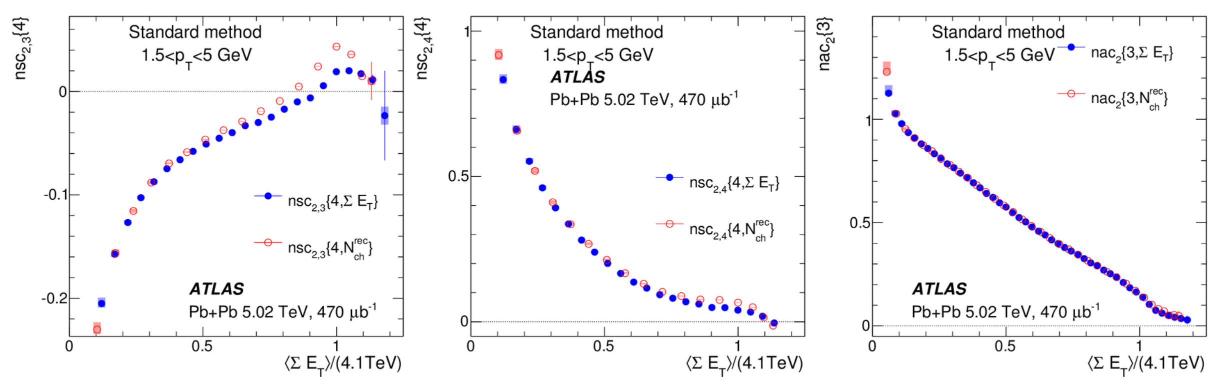


ATLAS, Eur. Phys. J. C 76 (2018) 142

Fluctuations of anizotropic flow in Pb+Pb collisions

- study of event-by-event fluctuations of harmonics, $p(v_n)$ and $p(v_n, v_m)$, using multiparticle cumulants calculated for different centralities and p_T ranges
- negative $c_1\{4\}$ (thus positive $v_1\{4\}$) found
- negative $c_4\{4\}$ implicates a non-linear contribution to v_4 proportional to v_2^2
- negative asymmetric cumulant $nsc_{23}\{4\}$ reflects anticorrelation between v_2 and v_3, while positive $nsc_{24}\{4\}$ is consistent with non-linear contributions to v_4
- centrality fluctuations lead to additional v_n fluctuations





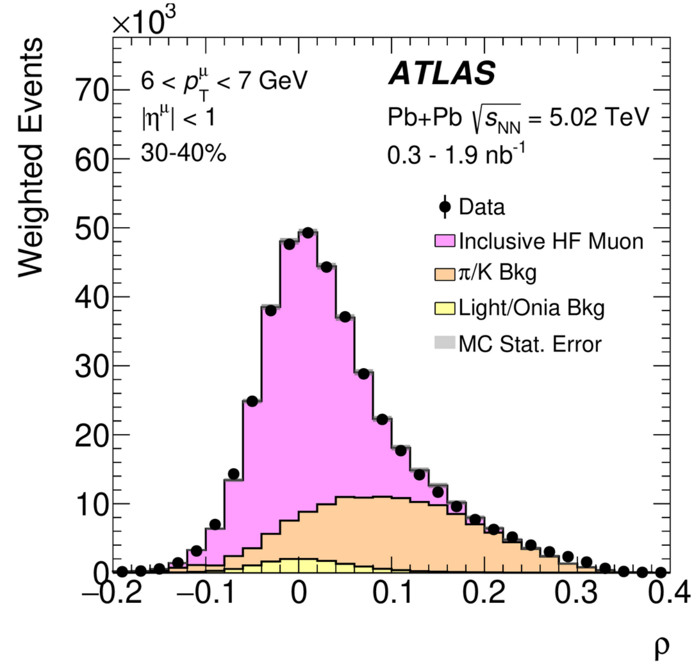
ATLAS, JHEP 01 (2020) 51.

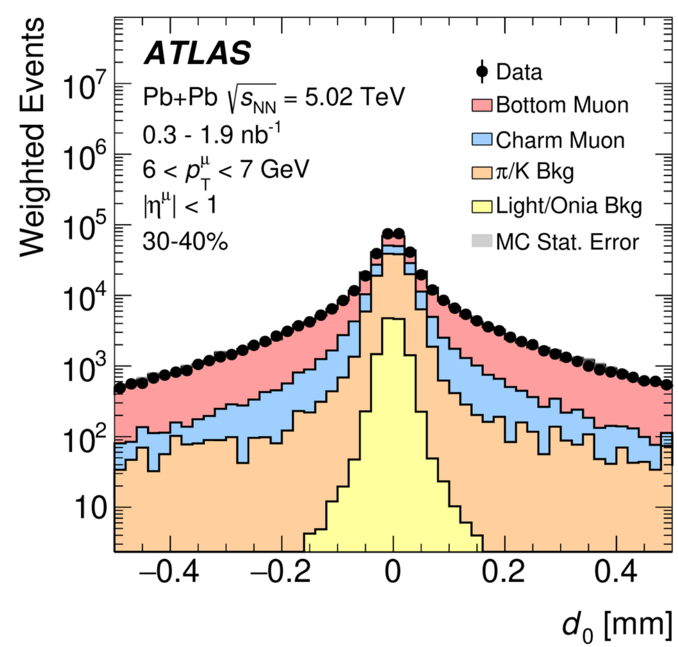
Flow of charm and bottom hadrons

Reconstruction of muons from charm and bottom hadron decays and separation from those from π/K background using:

- **imbalance between momentum measured in the inner detector and in the muon spectrometer**
  $\rho = (p^{ID}-p^{MS})/p^{ID}$
- **transverse impact parameter d_0**

Different distributions of these variables enable separation of muons from different decays





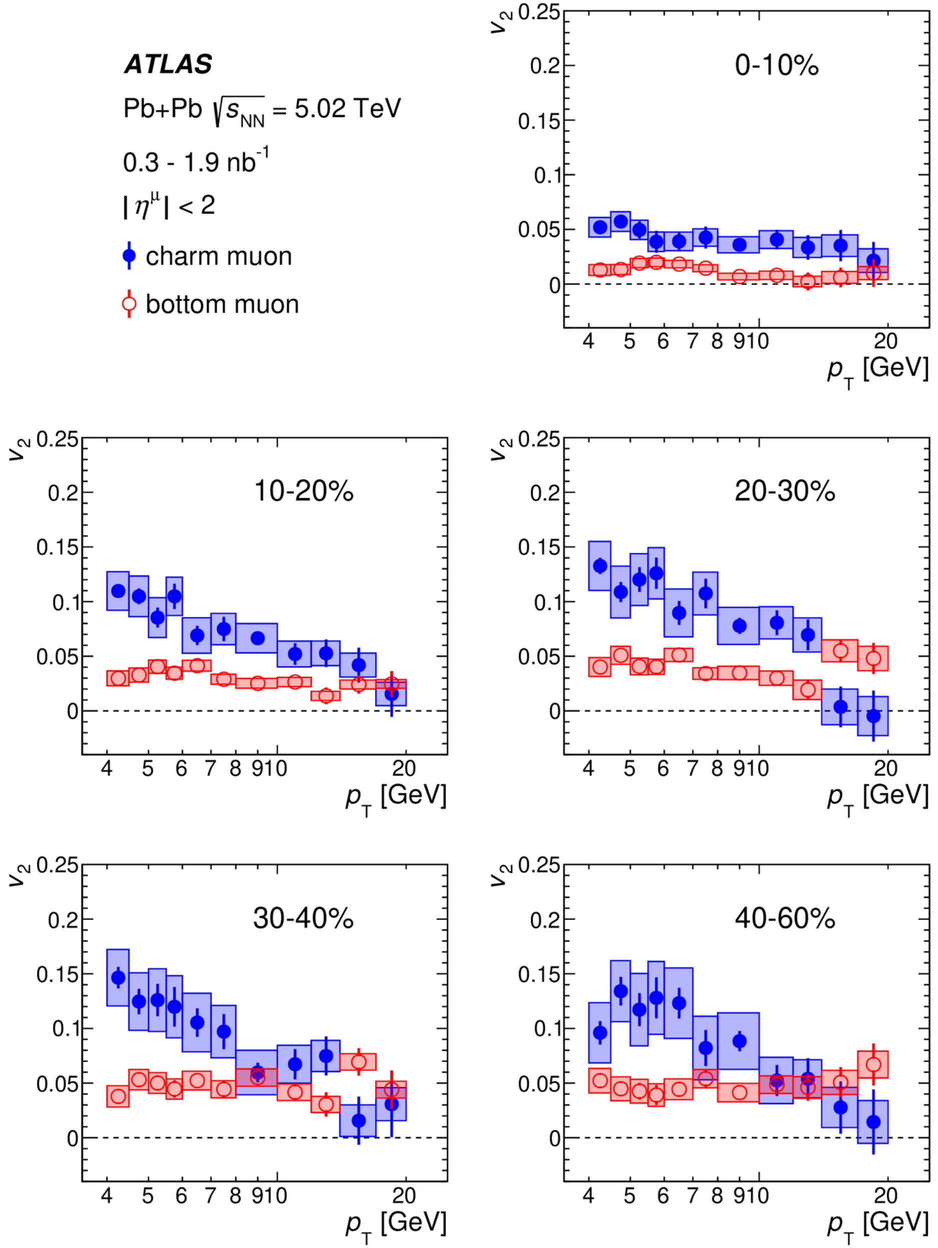
ATLAS, arxiv:2003.03565

Flow of charm and bottom hadrons

Pb+Pb

v_2:

- **elliptic flow of bottom muons is smaller than that of charm muons**
- **v_2 increases in more peripheral collisions**

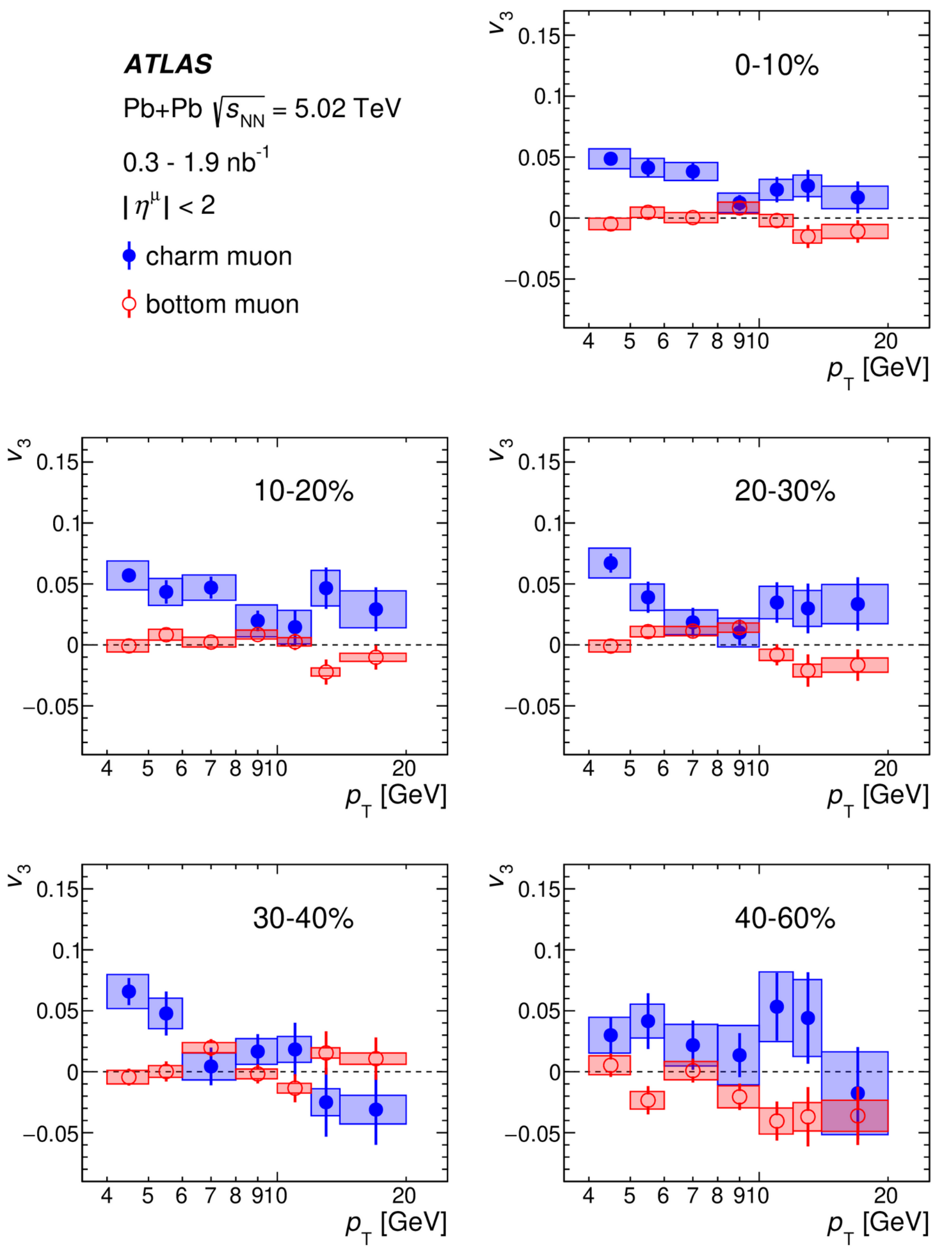


ATLAS, arxiv:2003.03565

Flow of charm and bottom hadrons

v_3:

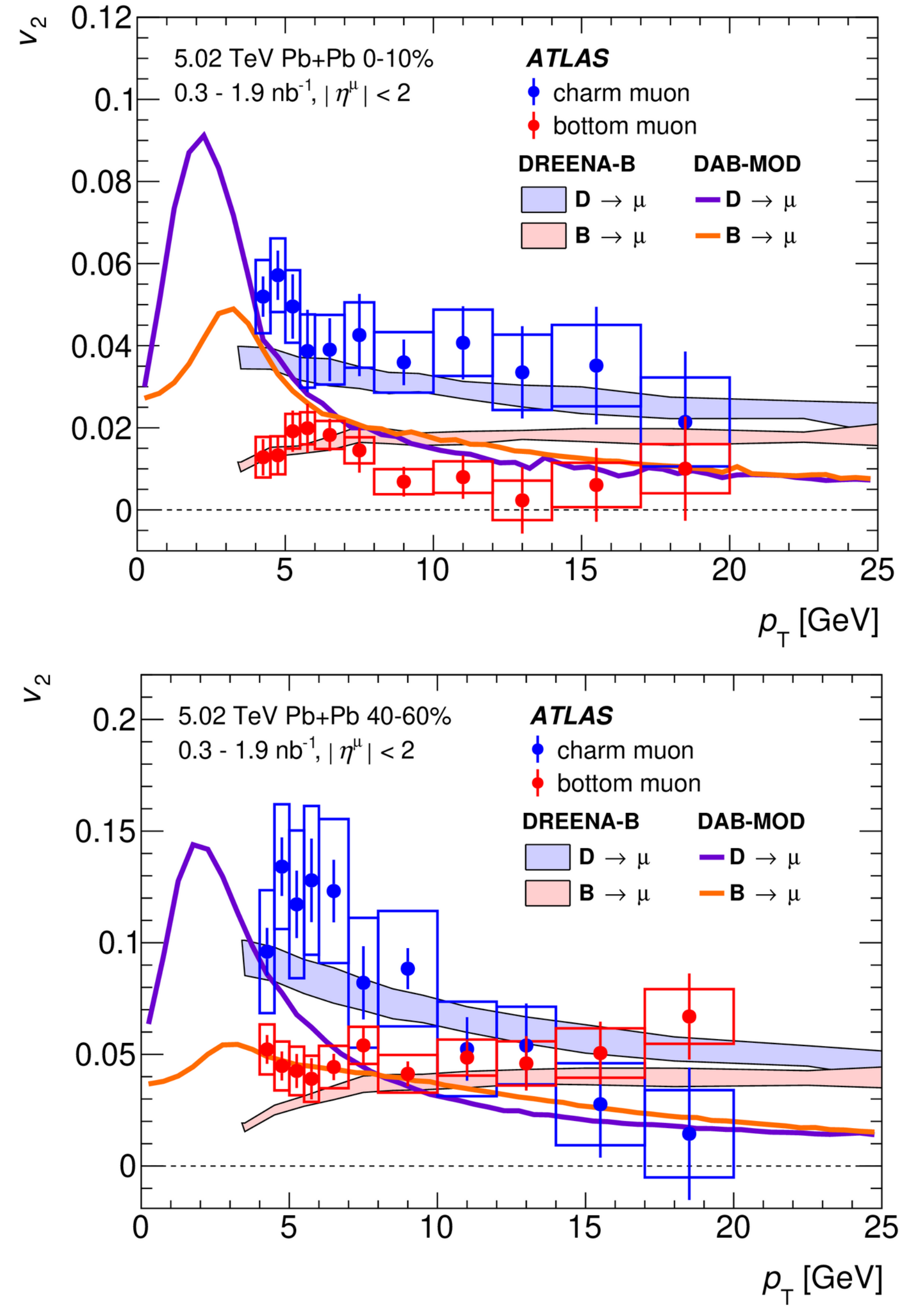
- **also triangular flow of bottom muons is smaller than that of charm muons**



ATLAS, arxiv:2003.03565

Flow of charm and bottom hadrons

Transverse momentum dependence of v_2 has similar trend as predicted by the models, differences may shred the light on details of QGP expansion and the energy-loss mechanism.



ATLAS, arxiv:2003.03565

Summary

Correlation studies in Pb+Pb and Xe+Xe collisions:

- **detailed analysis of azimuthal correlations in Pb+Pb and Xe+Xe collisions,**
- **scaling of v_n / $(v_k)^{n/k}$ ratio,**
- **fluctuations of harmonics as a function of pseudorapididty (longitudinal decorrelations),**
- **analysis of event-by-event fluctuations with multiparticle cumulants,**
- **flow of charm and bottom hadrons.**

Deeper insight into properties and expansion of QGP and the effects of fluctuations of initial conditions in the collisions

Backup

v_n - $[p_T]$ correlations

Pearson correlation coefficient R, substituted by ρ to be not distorted at small multiplicity

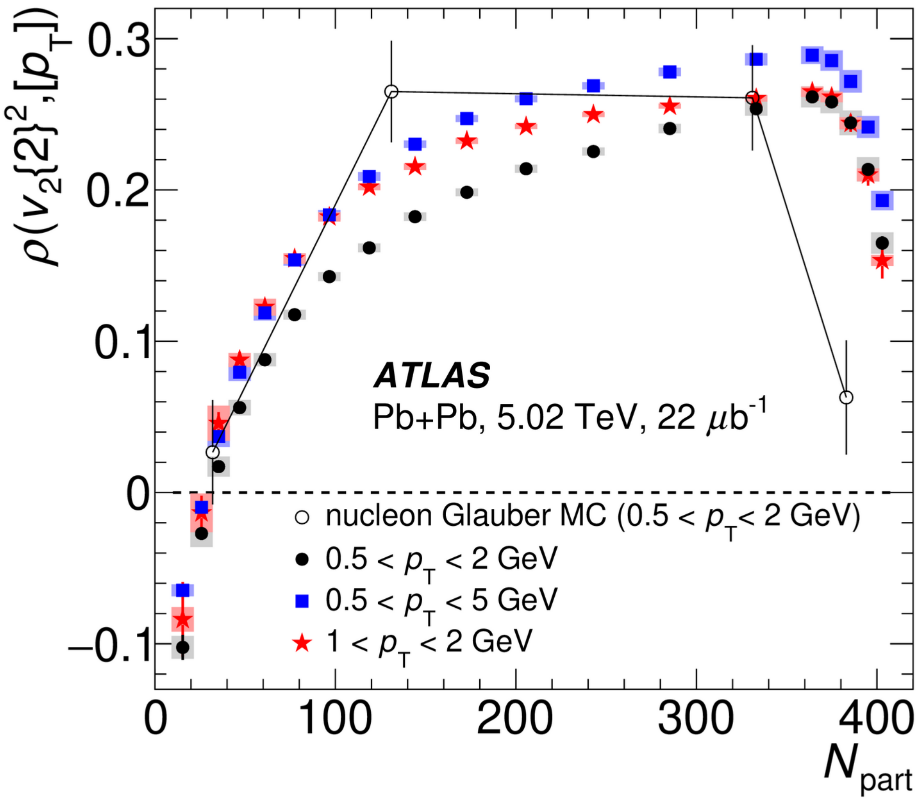
$$R = \frac{cov(v_n\{2\}^2, [p_T])}{\sqrt{Var(v_n\{2\}^2)}\sqrt{Var([p_T])}}$$

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

in which dynamical variances are used

Harmonics are calculated in different psedurapidity intervals (0.75<|η|<2.5) than the mean p_T of the event (|η|<0.5)

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



- **Negative correlation in peripheral collisions**
- **Positive correlation for more central collisions**
- **Qualitatively in agreement with hydrodynamics 1+3D**
  (P. Bożek, Phys. Rev. C93 (2016) 044908)

Suppresion of contributions from non-flow effects

Flow estimation methods

- event plane $v_n = \langle \cos(n(\phi - \Phi_n)) \rangle$
- two-particle correlations $v_{n,n} = \langle \cos(n(\phi_a - \phi_b)) \rangle$
- scalar product $v_n = \mathrm{Re}(\langle q_n^N Q_n^{P*} \rangle / \sqrt{\langle Q_n^N Q_n^{P*} \rangle});\ q_n, Q_n = (1/\Sigma_j w_j) \Sigma_j w_j e^{in\phi_j}$

Multi-particle correlations

$$\langle\langle \{2k\}_n \rangle\rangle = \langle\langle e^{in(\phi_1 + \ldots \phi_k - \phi_{k+1} - \ldots - \phi_{2k})} \rangle\rangle = \langle v_n^{2k} \rangle$$

$$\langle\langle \{4\}_{n,m} \rangle\rangle = \langle\langle e^{in(\phi_1 - \phi_2) + \Im(\phi_3 - \phi_4)} \rangle\rangle = \langle v_n^2 v_m^2 \rangle$$

- standard cumulants $c_n\{4\} = \langle\langle \{4\}_n \rangle\rangle - 2\langle\langle \{2\}_n \rangle\rangle^2$
- symmetric cumulants $sc_{n,m}\{4\} = \langle\langle \{4\}_{n,m} \rangle\rangle - \langle\langle \{2\}_n \rangle\rangle \langle\langle \{2\}_m \rangle\rangle$
- asymmetric $ac_2\{3\} = \langle\langle \{3\}_n \rangle\rangle = \langle\langle e^{i(n\phi_1 + n\phi_2 - 2n\phi_3)} \rangle\rangle^2$

Subevent methods - particles selected from different regions in pseudorapidity

- two-subevents $sc_{n,m}^{2a|2c}\{4\} = \langle\langle \{4\}_{n,m} \rangle\rangle_{2a|2c} - \langle\langle \{2\}_n \rangle\rangle_{a|b} \langle\langle \{2\}_m \rangle\rangle_{a|b}$
- three-subevents $sc_{n,m}^{a,b|2c}\{4\} = \langle\langle \{4\}_{n,m} \rangle\rangle_{a,b|2c} - \langle\langle \{2\}_n \rangle\rangle_{a|c} \langle\langle \{2\}_m \rangle\rangle_{b|c}$
- four-subevents $sc_{n,m}^{a,b|c,d}\{4\} = \langle\langle \{4\}_{n,m} \rangle\rangle_{a,b|c,d} - \langle\langle \{2\}_n \rangle\rangle_{a|c} \langle\langle \{2\}_m \rangle\rangle_{b|d}$

Many different methods tested in order to obtain "real" flow