Multi-particle azimuthal correlations and flow in *pp* and *p*+Pb collisions with the ATLAS detector at the LHC

Krzysztof Woźniak, IFJ PAN, Krakow

Datasets and publications on flow harmonics

Data

p+Pb	5.02 TeV	28 nb^{-1}
pp	5.02 TeV	0.17 pb^{-1}
pp	13 TeV	0.9 pb^{-1}
p+Pb	5.02 TeV	28 nb^{-1}
pp	13 TeV	0.9 pb^{-1}
Pb+Pb	2.76 TeV	7 μb^{-1}
pp	8 TeV	19.5 fb^{-1}

ATLAS publications:

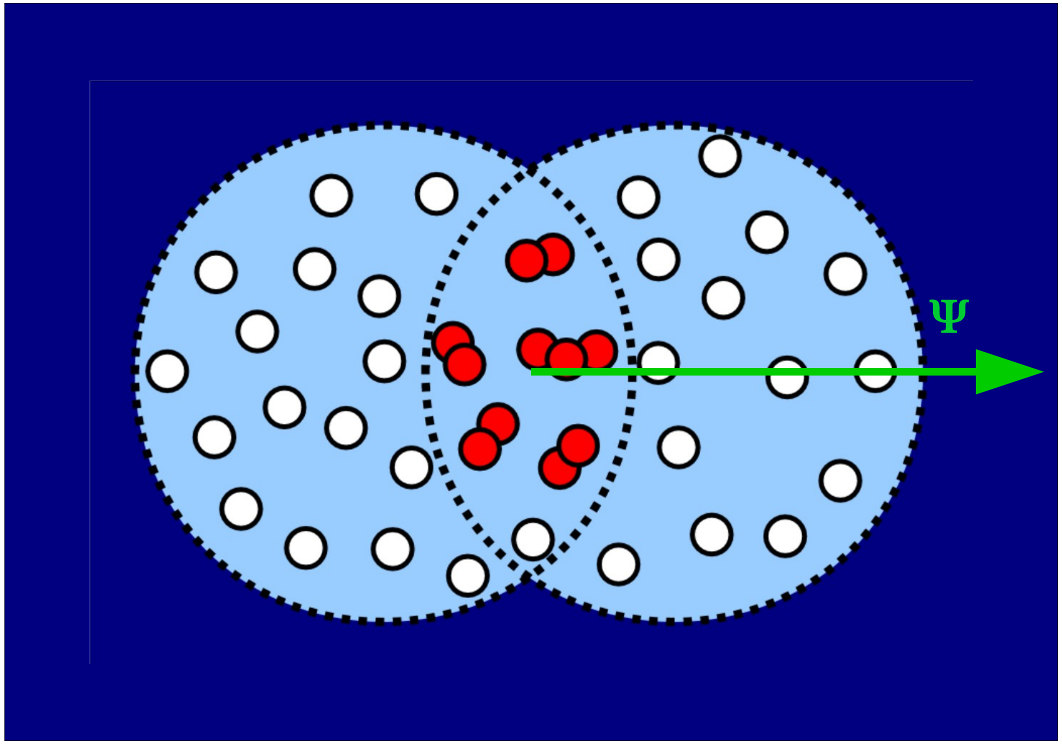
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

- **subevent cumulants**
  Phys. Rev. C 97 (2018) 024904
- **mixed flow harmonics**
  Phys. Lett. B 789 (2019) 444
- **elliptic flow in Z boson tagged events**
  ATLAS-CONF-2017-068

Multi-particle correlation and origin of flow

Collisions of nuclei

- Area of the overlap of nuclei has an elongated shape



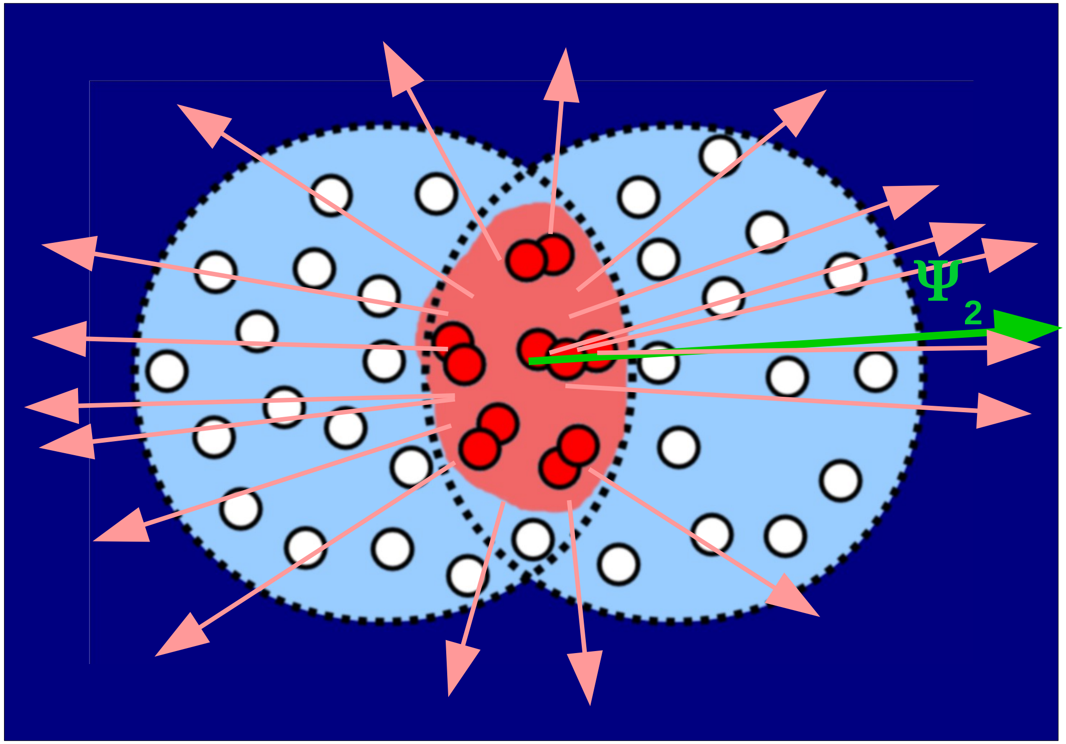
Event plane

Azimuthal angle Ψ - defined by the line joining centers of nuclei

Multi-particle correlation and origin of flow

Collisions of nuclei

- Area of the overlap of nuclei has an elongated shape
- In this region Quark-Gluon Plasma is created
- More particles are produced in the event plane Ψ



Event plane

Azimuthal angle Ψ - defined by the line joining nuclei centers

Experimentally estimated azimuthal angle Ψ_2

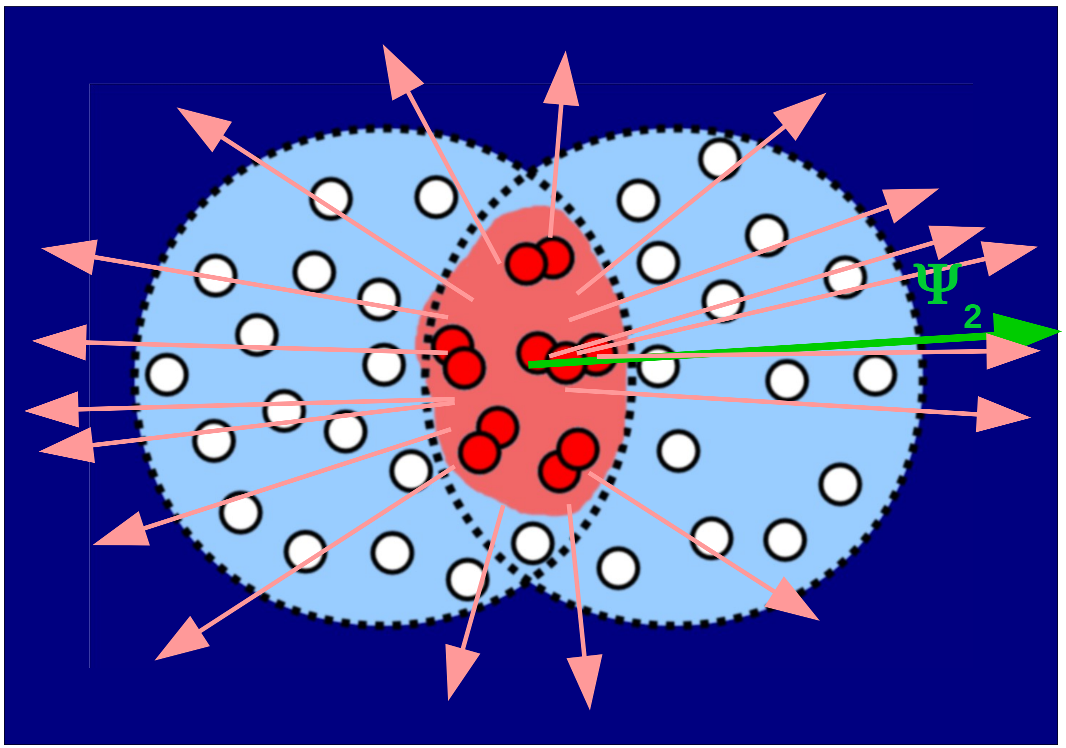
Multi-particle correlation and origin of flow

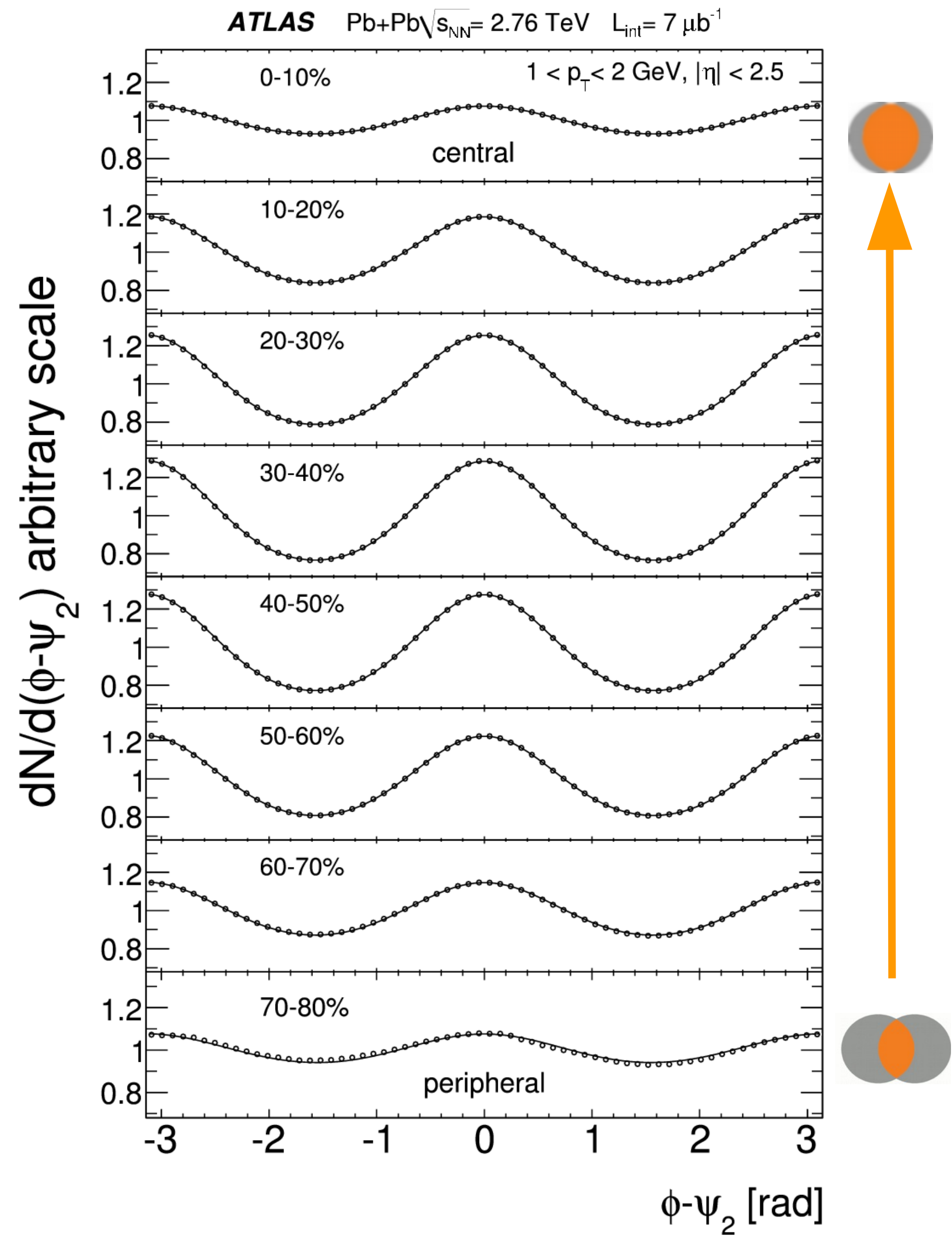
Collisions of nuclei

- **More particles are produced in the event plane Ψ**

$$\frac{dN}{d\phi} \sim 1+2v_2(p_T,\eta)\cos(n(\phi-\Psi_2))$$

$$v_2 = \langle\cos(2(\phi-\Psi_2))\rangle$$

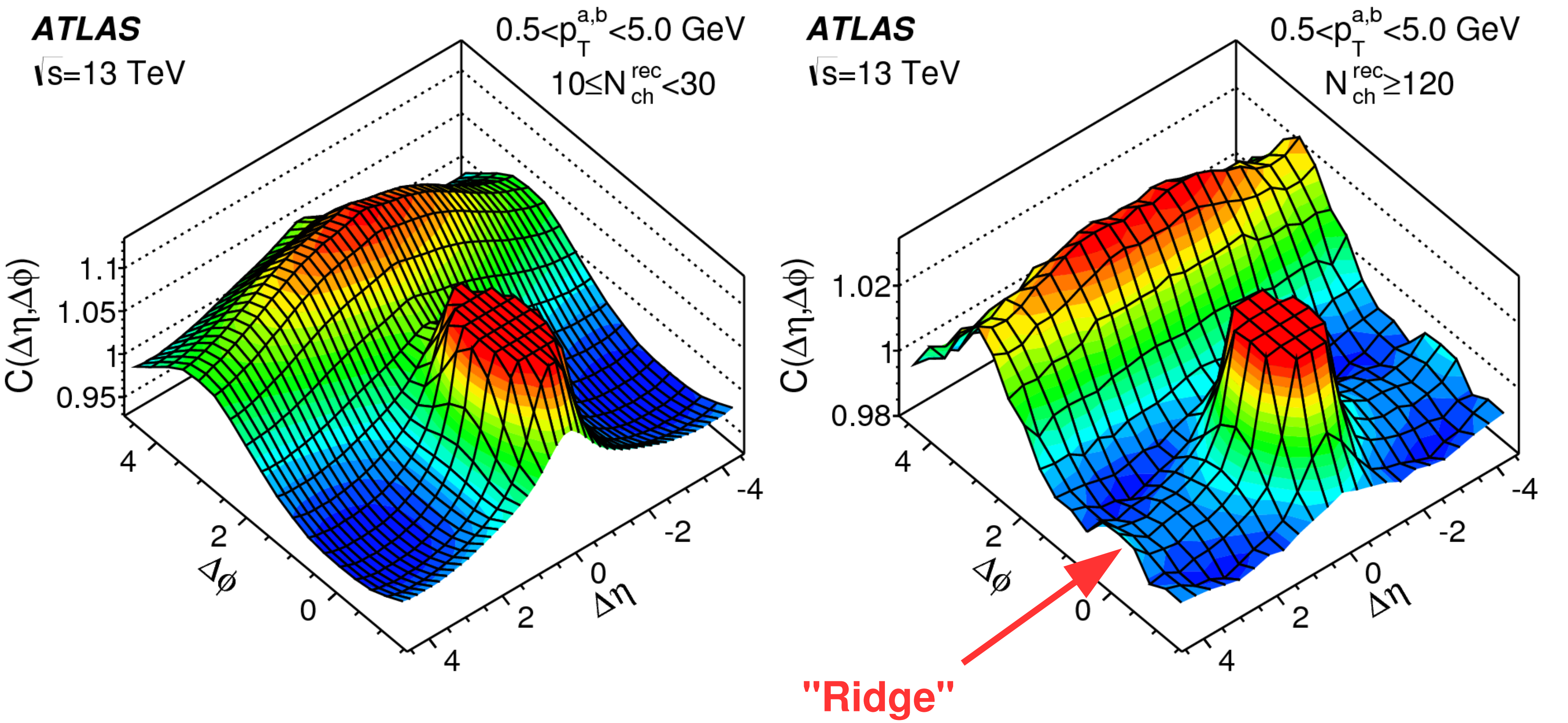




ATLAS, Phys.Lett. B707 (2012) 330

Two-particle correlations

- **Longe range azimuthal correlation in events with high multiplicity**



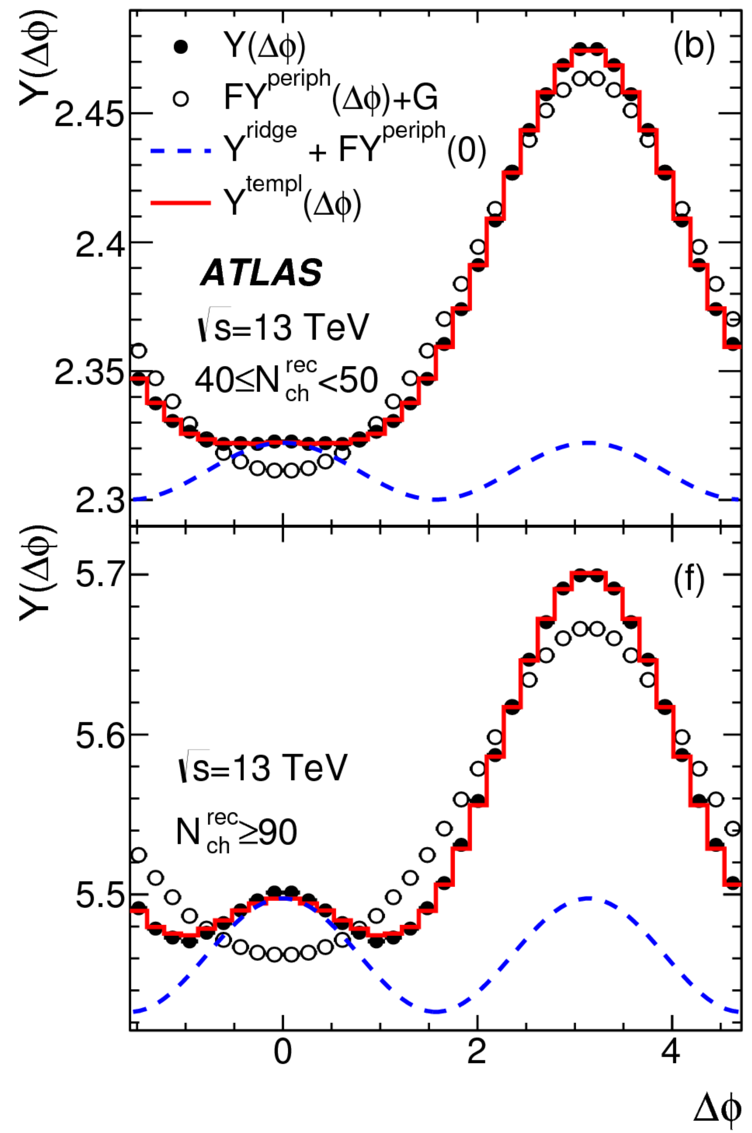
ATLAS, Phys. Rev. Lett. 116 (2016) 172301

Two-particle correlations - subtraction of peripheral

- Y^{periph} - yield in small multiplicity ("peripheral") events treated as containing only non- flow correlations
- at higher multiplicity long range correlation extracted by proper subtraction of Y^{periph}

$$Y^{ridge} = Pedestal * (1 + 2 v_{2,2} \cos(2 \Delta \phi))$$

$$v_{2,2}^{flow} = v_2^2$$

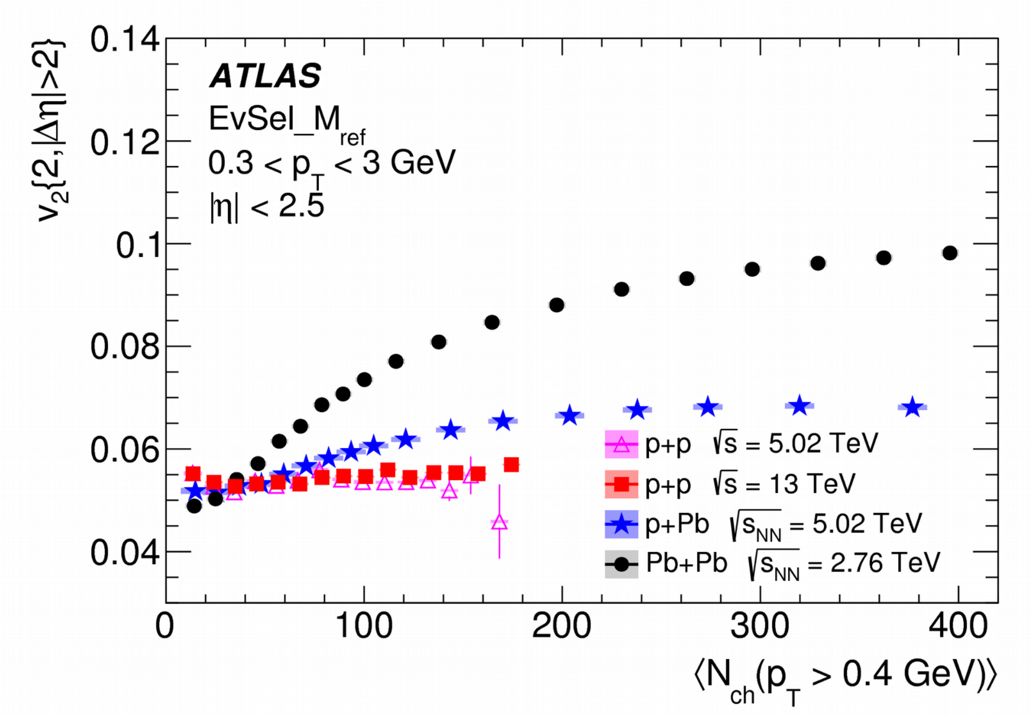


ATLAS, Phys. Rev. Lett. 116 (2016) 172301

Elliptic flow

- **largest for Pb+Pb collisions, smallest for pp collisions**
- **increasing with multiplicity of produced particles in Pb+Pb and p+Pb collisions, approximately constant in pp collisions**
- **independent on collision energy in 5-13 TeV range in pp collisions**

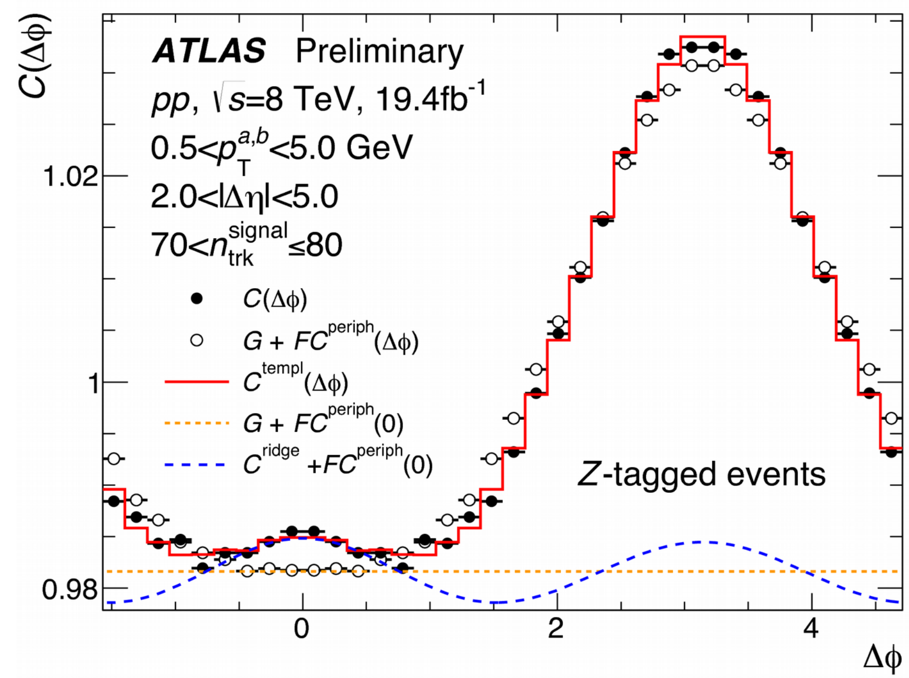
long range correlations present in all collision systems



ATLAS, Eur. Phys. J. C 77 (2017) 428

Elliptic flow in *pp* events with a Z boson

- *pp* collisions at 8 TeV, 19.5 fb^{-1}
- large pileup, $\mu \approx 20$
- 6.2×10^6 events with a Z boson candidate
- template fit method
  (to remove contributions from jets)



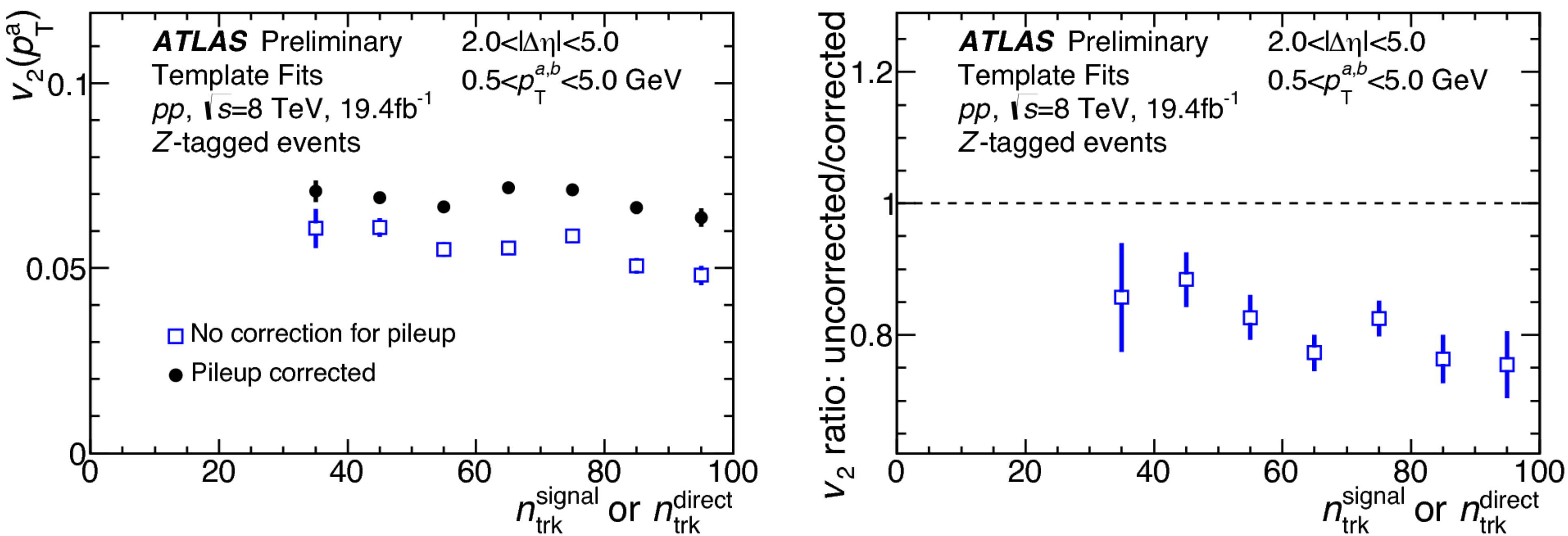
ATLAS, ATLAS-CONF-2017-068

Presence of a Z boson, and thus of a hard scattering:

- increases probability of smaller partonic b
- this may imply lower initial eccentricity than for inclusive events and thus lower v_2

Large pileup - experimental procedures and corrections

- **rejection of tracks incompatible with Z boson vertex**
  $|(z_{0,trk} - z_{vtx}) \sin(\theta)| < 0.75$ mm
- **estimation of the number of remaining background tracks**
- **calculation of correlators for Direct (Signal+Background) and Mixed (Background only) events**
- **calculation of corrected correlator:**
  (Signal$\times$Signal) = (Direct$\times$Direct) - 2(Direct$\times$Mixed) + (Mixed$\times$Mixed)

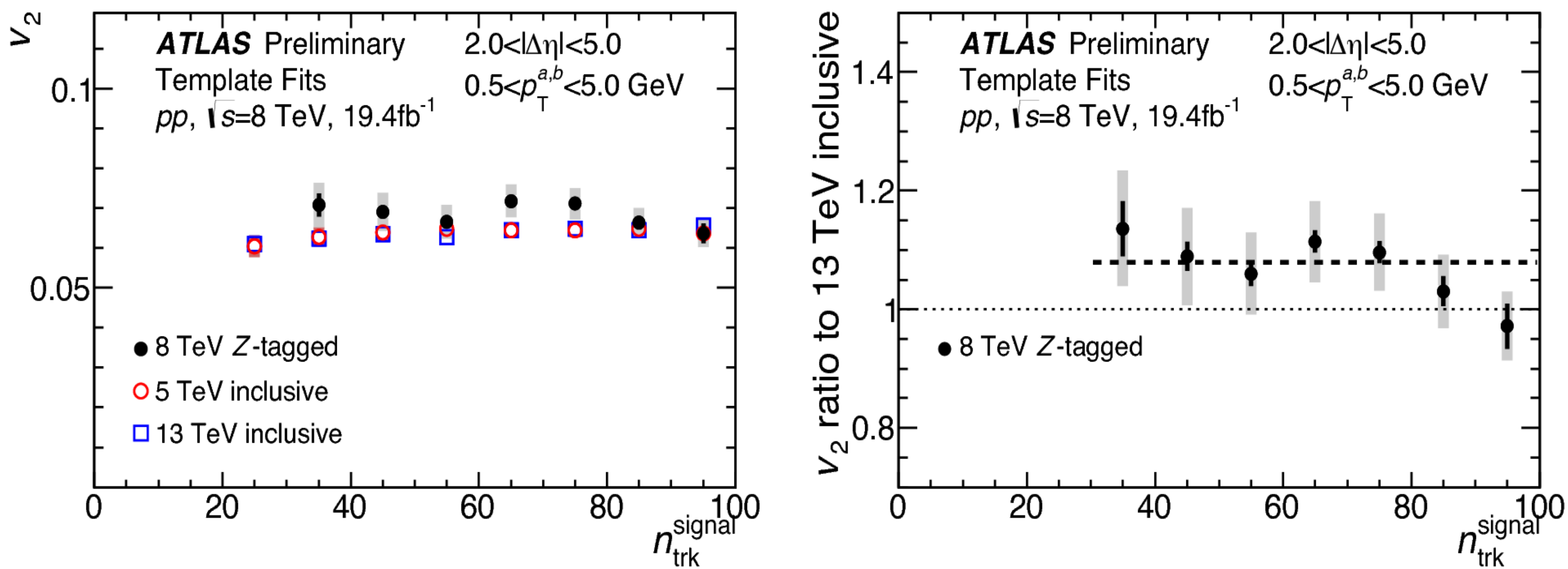


ATLAS, ATLAS-CONF-2017-068

Z boson tagged *pp* collisions

Elliptic flow in Z boson tagged events

- approximately constant as a function of event multiplicity
- **v_2 about 8% larger than in inclusive *pp* events at 5 Tev and 13 TeV**
- difference not due to collision energy - the same values of v_2 in inclusive *pp* collisions at 5 TeV and 13 TeV



ATLAS, ATLAS-CONF-2017-068

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

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

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

- **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

Multi-particle correlations

remove correlations from (low-multiplicity) resonance decays

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

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

Cumulants

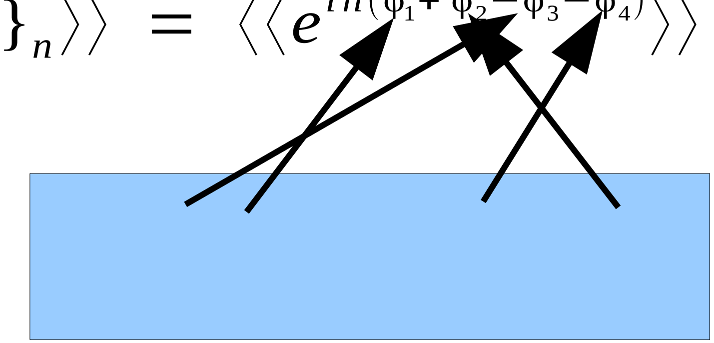
directly remove two-particle correlations

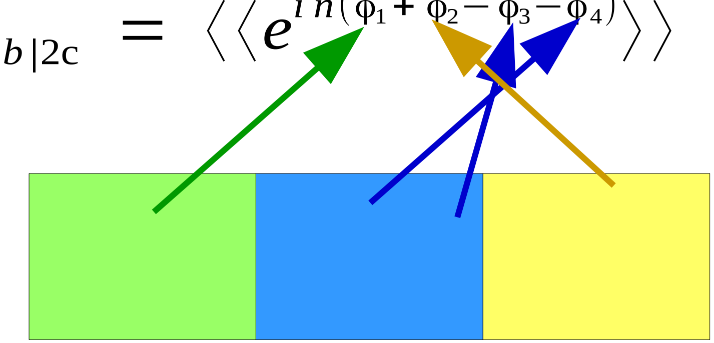
$$c_n\{4\} = \langle\langle\{4\}_n\rangle\rangle - 2\langle\langle\{2\}_n\rangle\rangle^2$$

Subevent methods

particles selected from different regions in pseudorapidity

$$\langle\langle\{4\}_n\rangle\rangle = \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle \qquad \langle\langle\{4\}_n\rangle\rangle_{a,b|2c} = \langle\langle e^{in(\phi_1^a+\phi_2^b-\phi_3^c-\phi_4^c)}\rangle\rangle$$





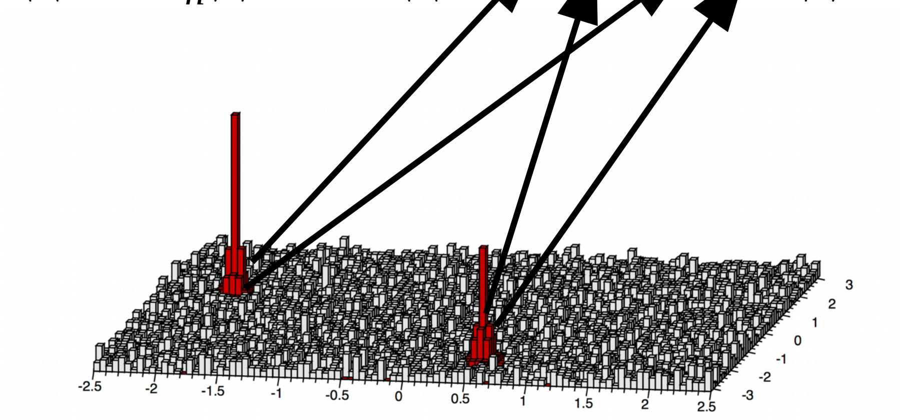
Suppresion of contributions from non-flow effects

Subevent methods

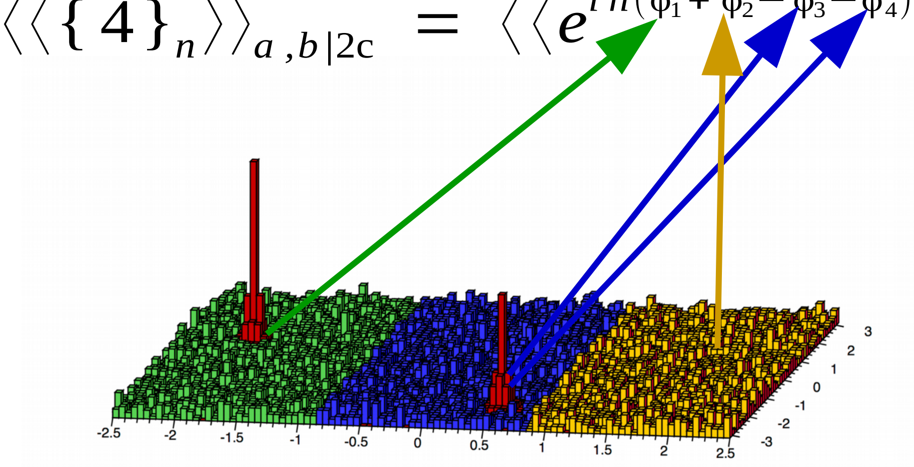
particles selected from different regions in pseudorapidity -

remove contributions from jets

$$\langle\langle \{4\}_n \rangle\rangle = \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle\rangle$$



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

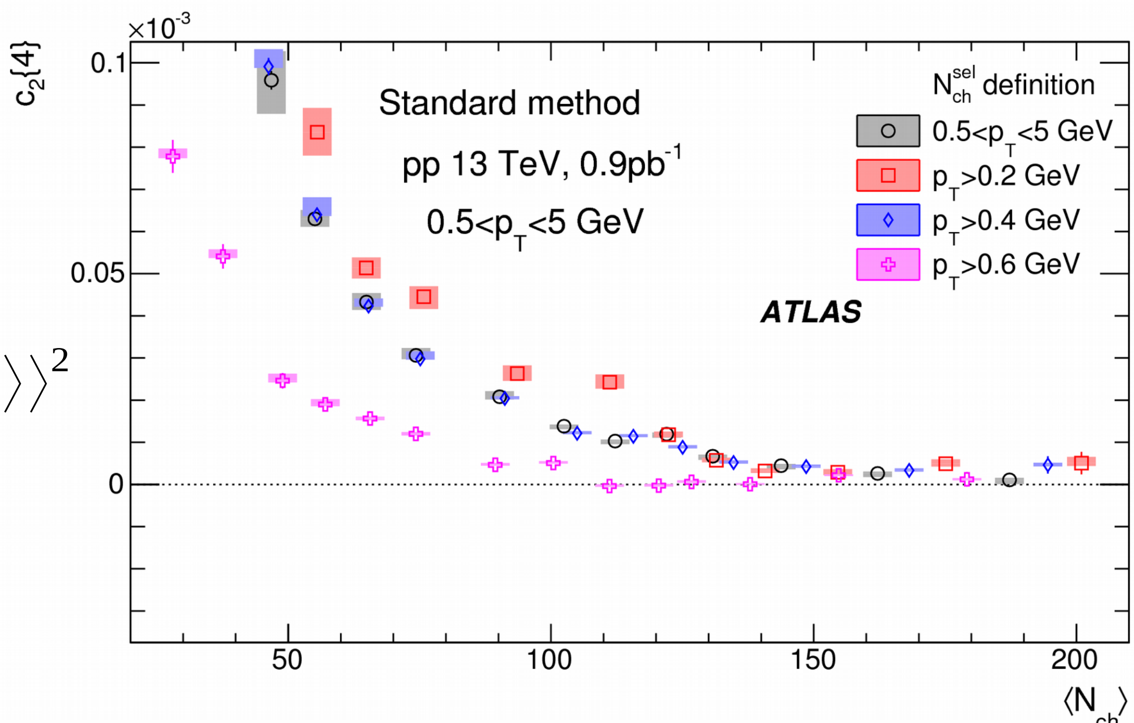


Calculations of standard (and subevent) cumulants:

- values of correlators $\langle\{2k\}_n\rangle$ are calculated for each event
- they are averaged for events with the same multiplicity N_{ch}^{sel} obtained using tracks in one of several tested p_T ranges
- mean values of $c_2\{4\}$ are are combined in wider multiplicity ranges of N_{ch}^{sel}

Change of values of $c_2\{4\}$ for modifications of N_{ch}^{sel} due to different fluctuations

$$c_2\{4\} = \langle\langle\{4\}_2\rangle\rangle - 2\langle\langle\{2\}_2\rangle\rangle^2$$



ATLAS, Phys. Rev. C 97 (2018) 024904

Subevent cumulants

pp

Comparison of standard and subevent cumulants in *pp* collisions at 13 TeV

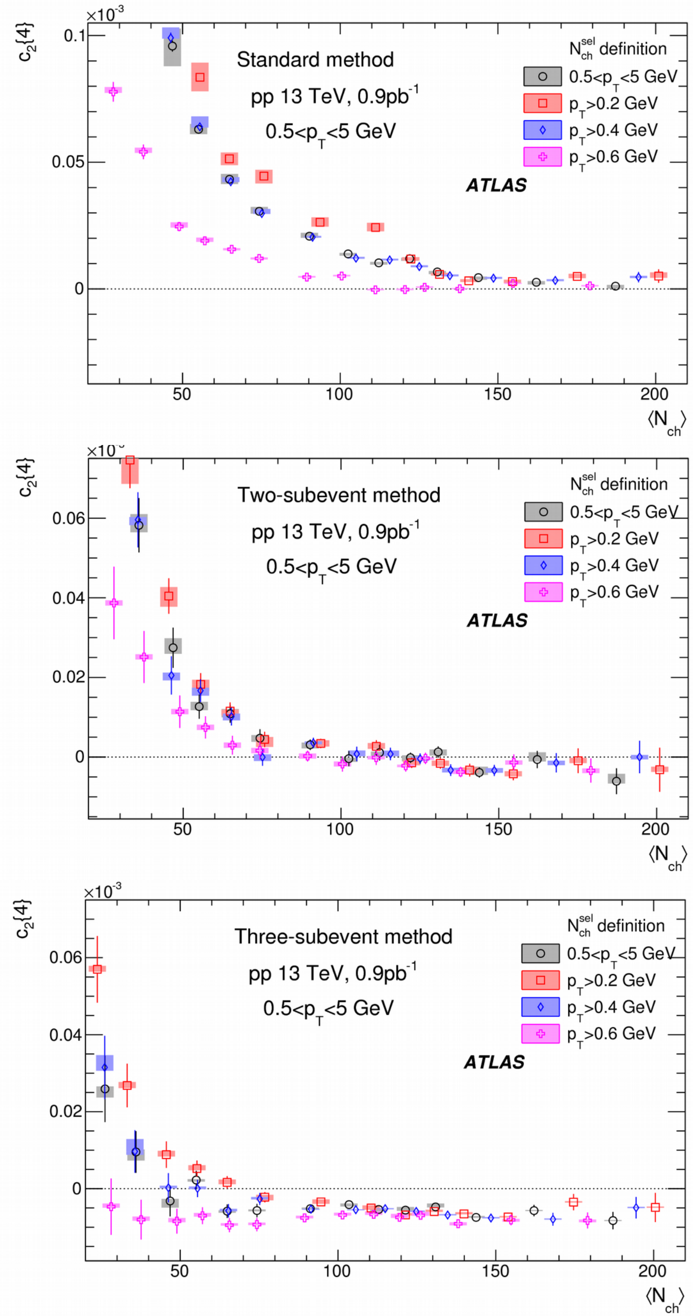
- **values of standard four particle cumulants strongly differ depending on particles selected in the calculations (note also different vertical scales)**
- **for two-subevent and three-subevent cumulants differences are smaller**

only for three-subevent cumulants in a wide multiplicity range values of $c_2\{4\}$ are negative, as it is expected for flow

$$c_n\{4\}_{flow} = -v_n^4$$

positive $c_2\{4\}$ values indicate, that in standard cumulants non-flow effects are present

similar results for *pp* collisions at 5 TeV

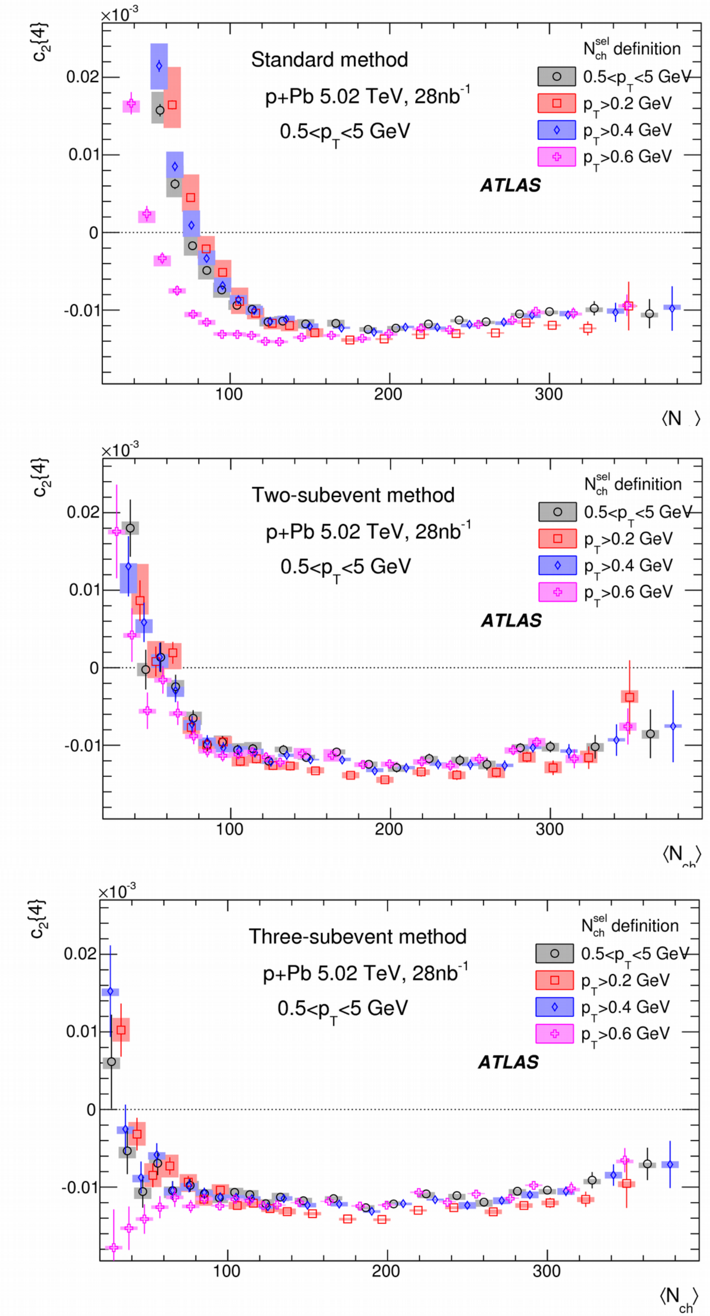


ATLAS, Phys. Rev. C 97 (2018) 024904

Subevent cumulants

Comparison of standard and subevent cumulants in *p*+Pb collisions at 5 TeV

- **values of standard four particle cumulants differ depending on particles selected in the calculations more than in two- and three-subevent cumulants**
- **for three-subevent cumulants the range of negative values of $c_2\{4\}$ is the widest**



ATLAS, Phys. Rev. C 97 (2018) 024904

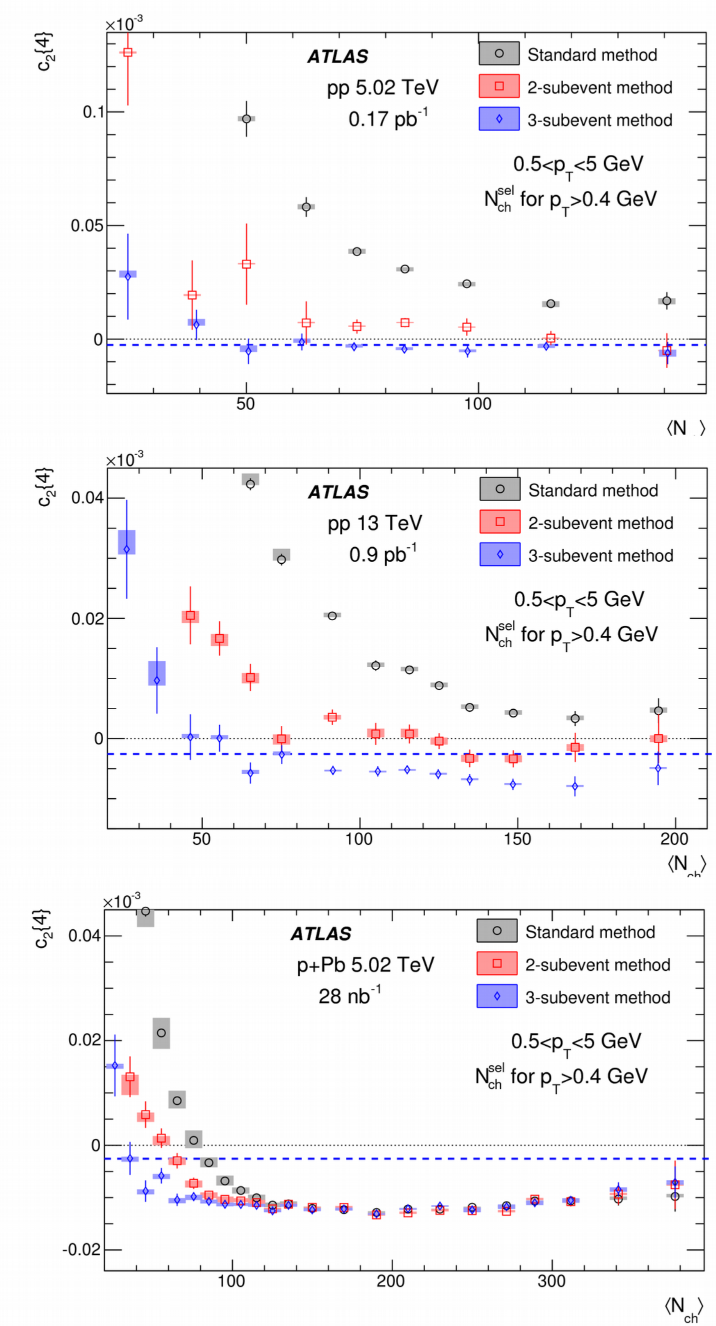
Subevent cumulants

pp

Comparison of standard and subevent cumulants in *pp* and *p*+Pb collisions:

- **in all cases three-subevent cumulants methods gives negative values of $c_2\{4\}$ in the widest multiplicity range**

Note: dashed blue line indicates expected $c_2\{4\}$ value for elliptic flow $v_2 = 4\%$
both vertical and horizontal scales are different



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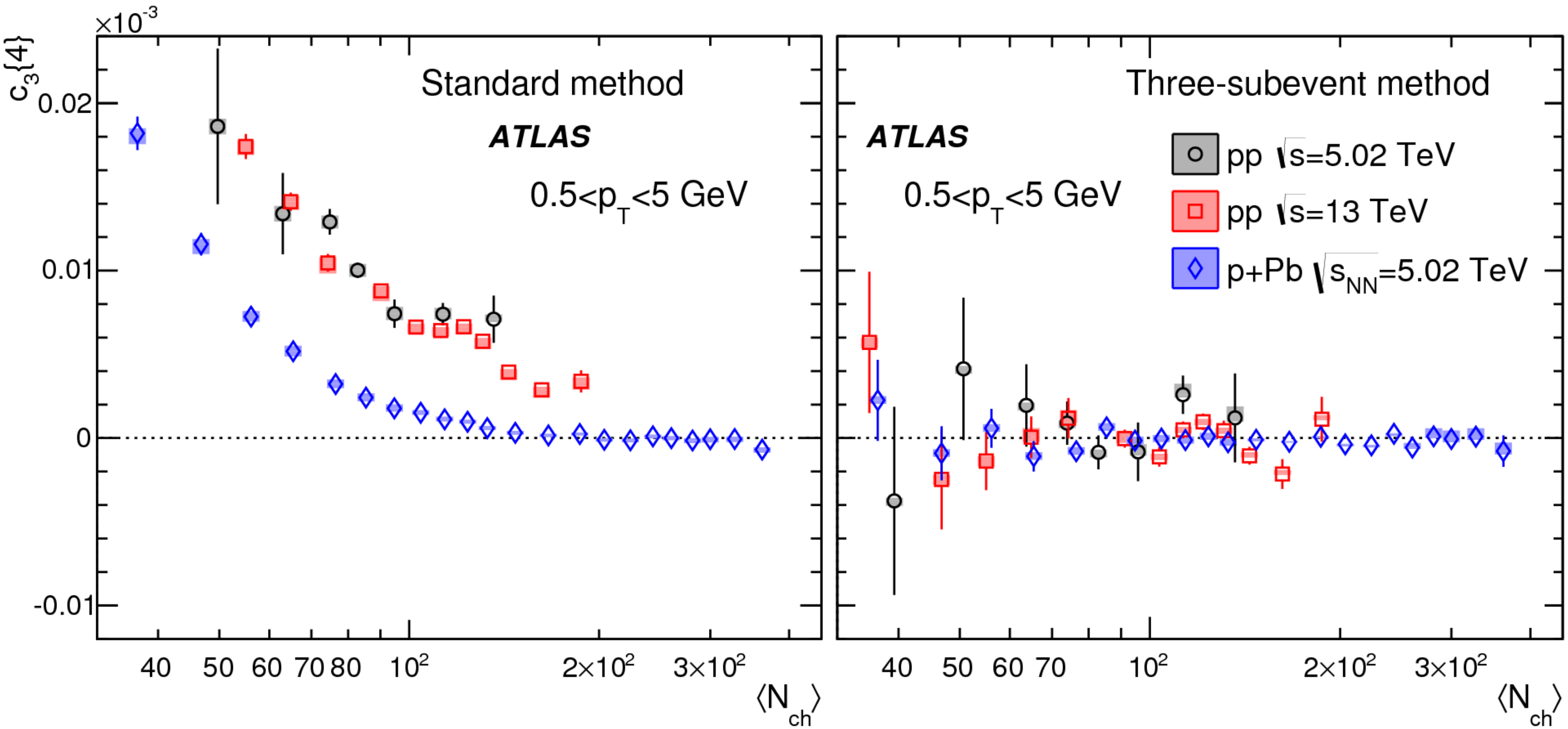
Subevent cumulants

Comparison of $c_3\{4\}$ from calculations using standard and three subevent cumulants in *pp* and *p*+Pb collisions:

- in p+Pb collisions values of $c_2\{4\}$ from three-subevent method are systematically negative (within statistical errors) and correspond to v_3 = 2%



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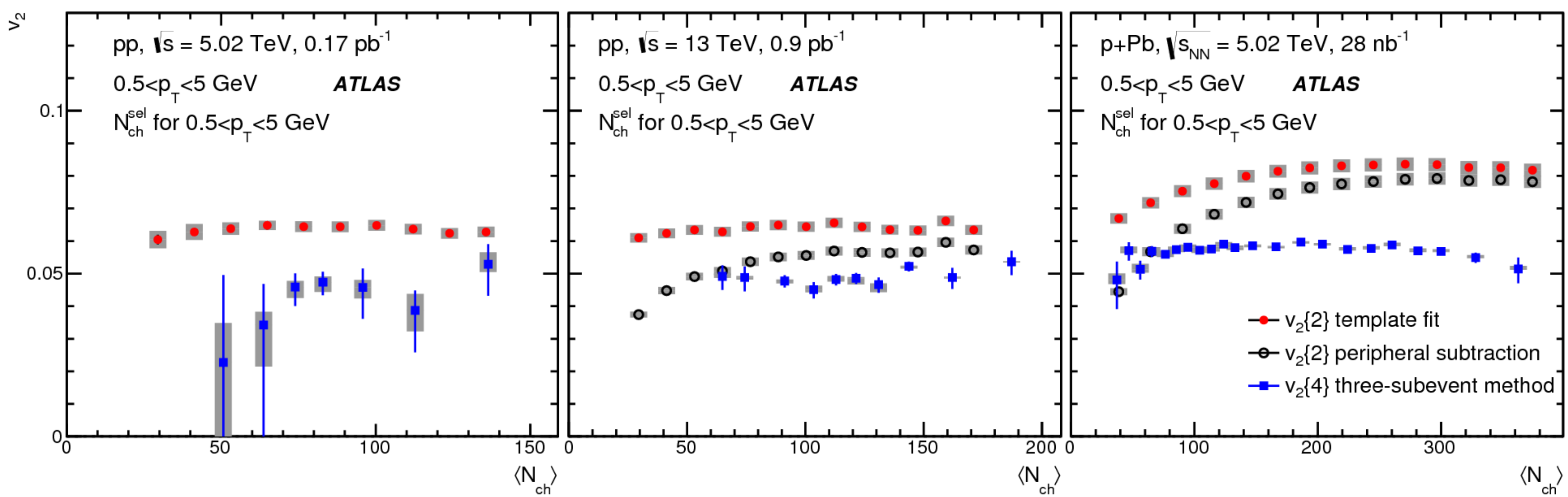
Comparison of different methods of v_2 calculations in *pp* and *p*+Pb collisions:

- values of $v_2\{4\}$ from three-subevent method are always the smallest
- the errors in the three-subevent method are the largest



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Subevent cumulants

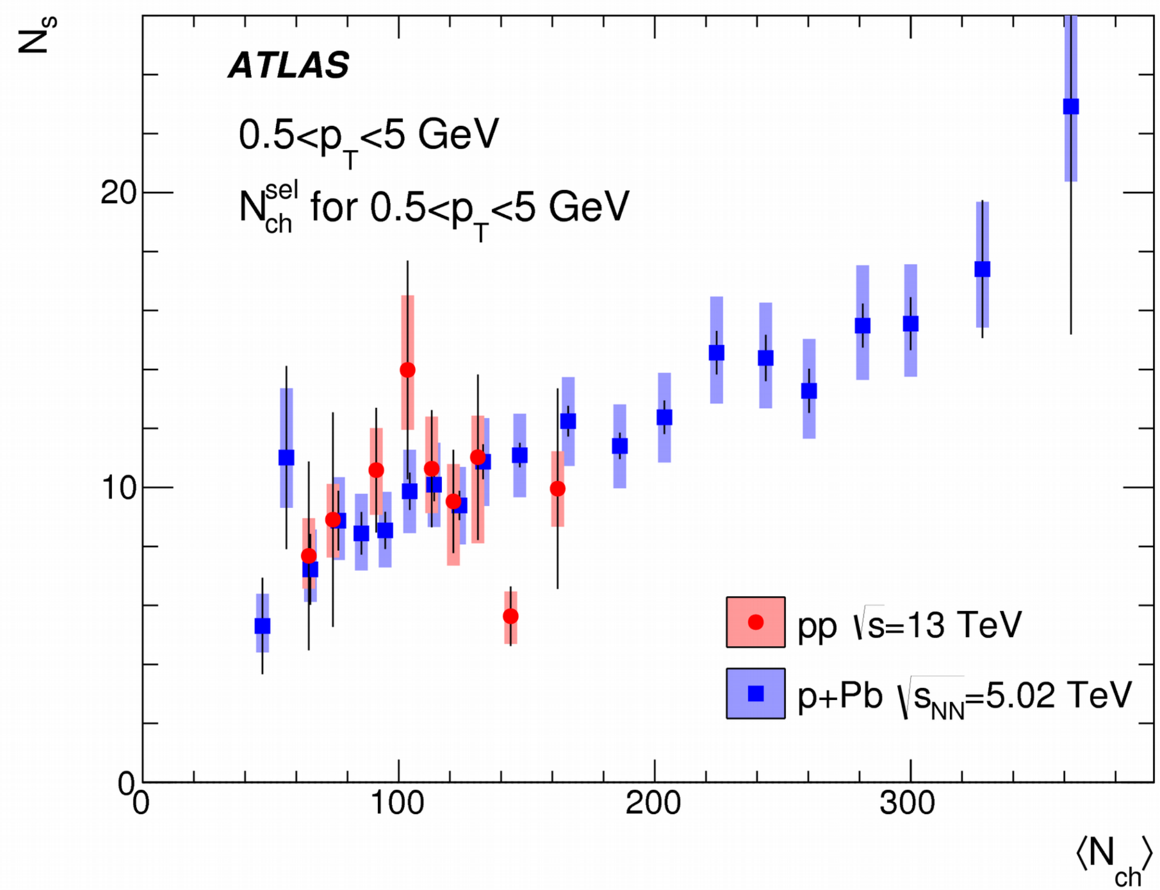
Estimation of the number of emission sources in *pp* and *p*+Pb collisions

- **difference between $v_2\{4\}$ and $v_2\{2\}$ can be interpreted as the influence of event-by-event flow fluctuations and related to the number of sources from which particles are emitted**

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

$$N_s = \frac{4\,v_2\{2\}^4}{v_2\{4\}^4} - 3$$

The number of sources increases approximately linearly with the multiplicity of produced particles



ATLAS, Phys. Rev. C 97 (2018) 024904

Mixed flow harmonics

Symmetric and asymmetric flow harmonics in *pp*, *p*+Pb and low-multiplicity Pb+Pb collisions

- **three-subevent cumulants used to remove non-flow contributions**

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

$$ac_n\{3\}^{a,b|c} = \langle\langle\{3\}_n\rangle\rangle_{a,b|c} = \langle\langle e^{in(\phi_1^a+\phi_2^b-2\phi_3^c)}\rangle\rangle$$

Measured: $sc_{2,3}\{4\}$, $sc_{2,4}\{4\}$ and $ac_2\{3\}$

Symmetric cumulants probe the correlations of flow magnitude

$$sc_{n,m}\{4\} = \langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle$$

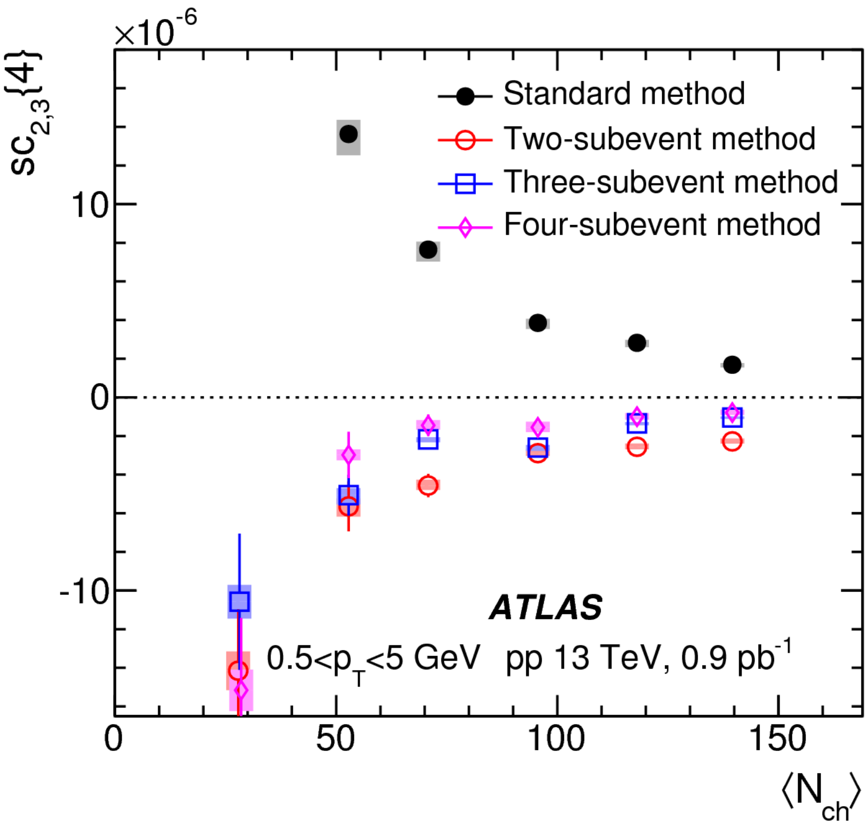
Asymmetric cumulants are sensitive to correlations involving both magnitude and the flow phase Φ_n

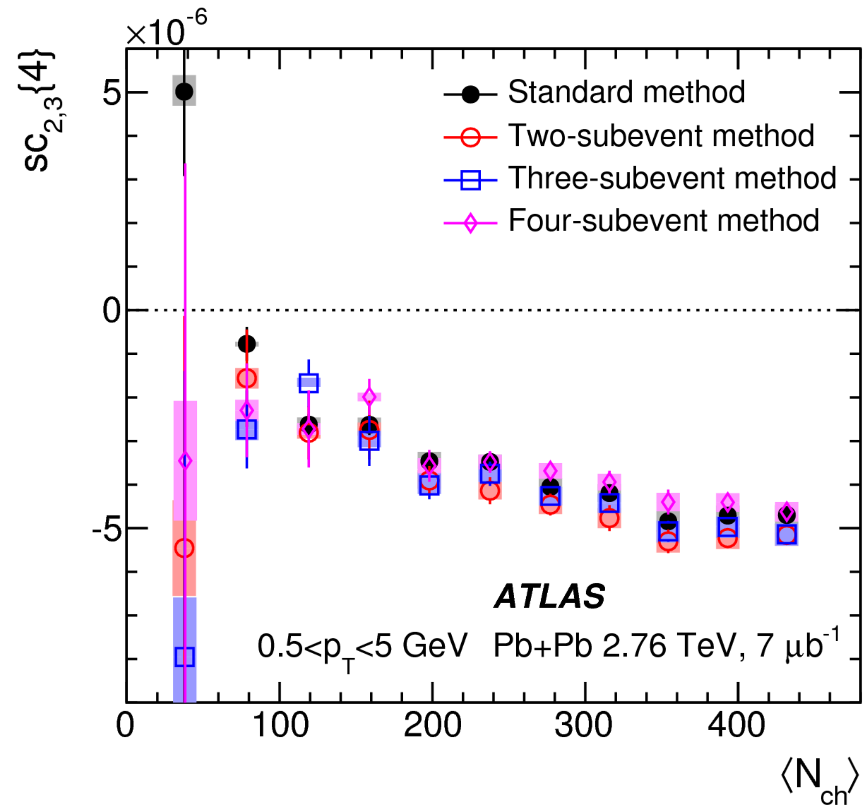
$$ac_2\{3\} = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4)\rangle$$

ATLAS, Phys. Lett. B 789 (2019) 444

Examples of symmetric and asymmetric flow cumulants in *pp* and low-multiplicity Pb+Pb collisions

- **large differences between standard cumulants and two-subevent, three-subevent and four-subevent cumulants**
- **three- and four-subevent methods give similar results**





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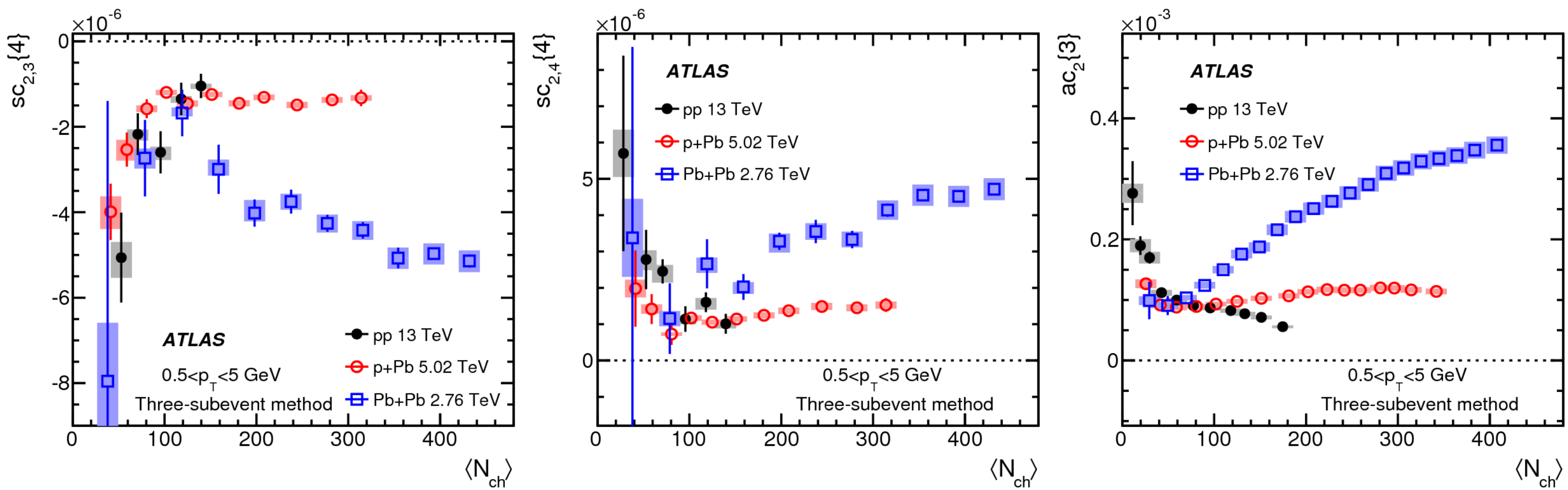
Symmetric and asymmetric flow cumulants from three-subevent method in *pp*, *p*+Pb and low-multiplicity Pb+Pb collisions

- **roughly similar dependence N_{ch} for *pp* and *p*+Pb**
- **distinctly different N_{ch} dependence for *pp*, *p*+Pb and Pb+Pb systems**



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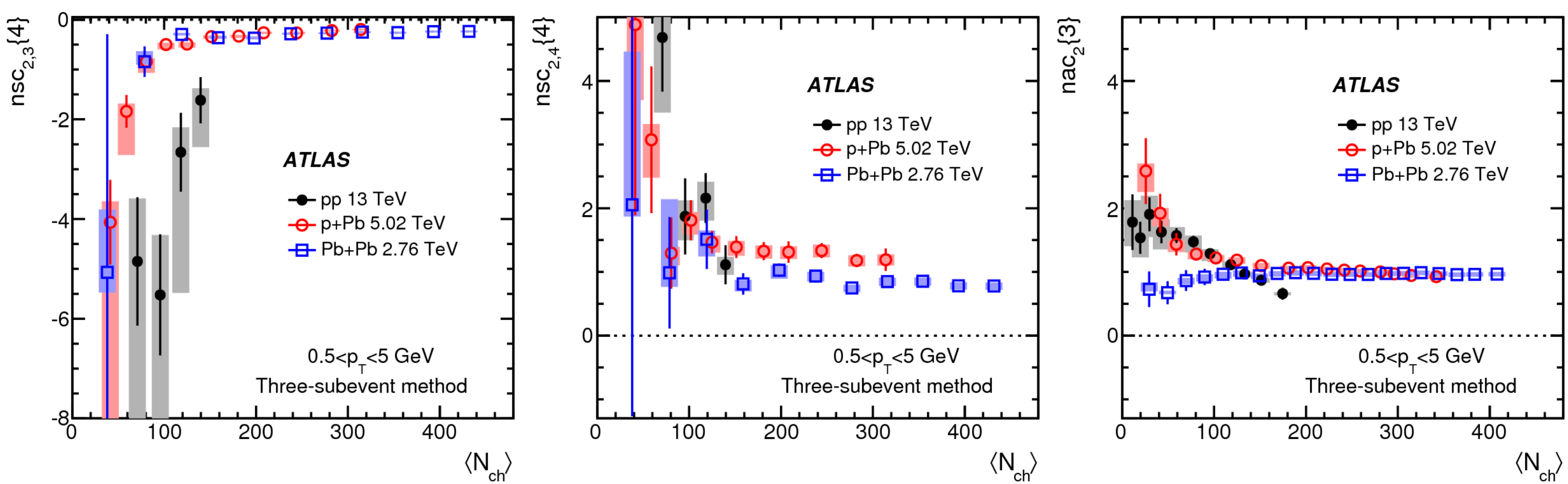
Mixed flow harmonics

Symmetric and asymmetric flow cumulants from three-subevent method in *pp*, *p*+Pb and low-multiplicity Pb+Pb collisions

- **normalization by flow harmonics of appropriate order**

$$nsc_{2,k}\{4\} = \frac{sc_{2,k}\{4\}}{v_2\{4\}^2 v_4\{4\}^2} = \frac{\langle v_2^2 v_k^2 \rangle}{\langle v_2^2 \rangle \langle v_k^2 \rangle} - 1 \qquad nac_2\{3\} = \frac{\langle v_2^2 v_4 \cos(4(\Phi_2 - \Phi_4)) \rangle}{\sqrt{\langle v_2^4 \rangle \langle v_4^2 \rangle}}$$

- **better agreement between *p*+Pb and low-multiplicity Pb+Pb collisions**
- **negative correlation between v_2 and v_3 (from $nsc_{2,3}\{4\}$), positive correlation between v_2 and v_4 (from $nsc_{2,4}\{4\}$)**



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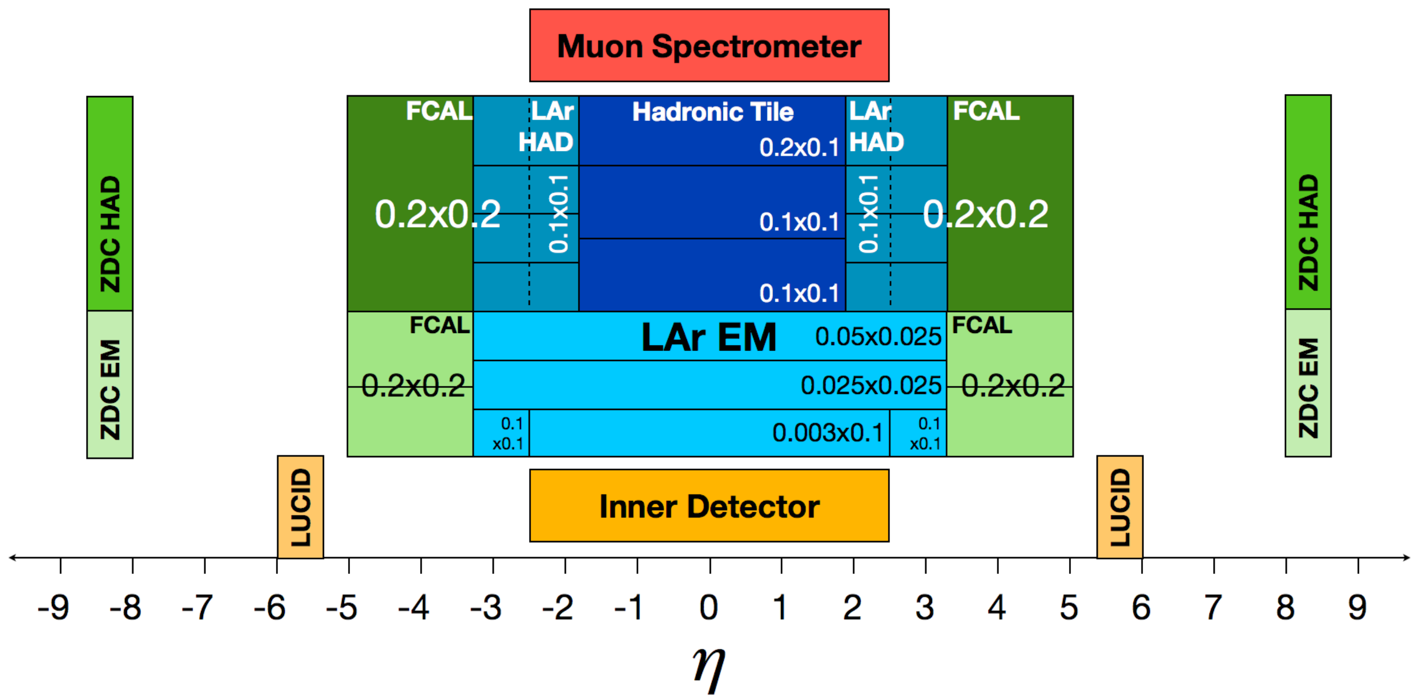
Summary of most recent results on flow harmonics

- Long range azimuthal correlations are present in all collision systems including *pp* interactions
- Elliptic flow in Z boson tagged events is larger than in inclusive event sample - rather contrary to expectation from collision geometry
- Many methods of non-flow removal are used
- Advanced studies of correlations should allow better tests of theoretical models

Backup

The ATLAS detector



Inner detector — $|\eta|<2.5$ — track reconstruction

Calorimeter — $|\eta|<3.2$ — jet reconstruction

Forward Calorimeter — $3.2<|\eta|<4.9$ — centrality determination

Muon spectrometer — $|\eta|<2.7$ — muon reconstruction