Anisotropic flow measurements in high energy hadron collisions

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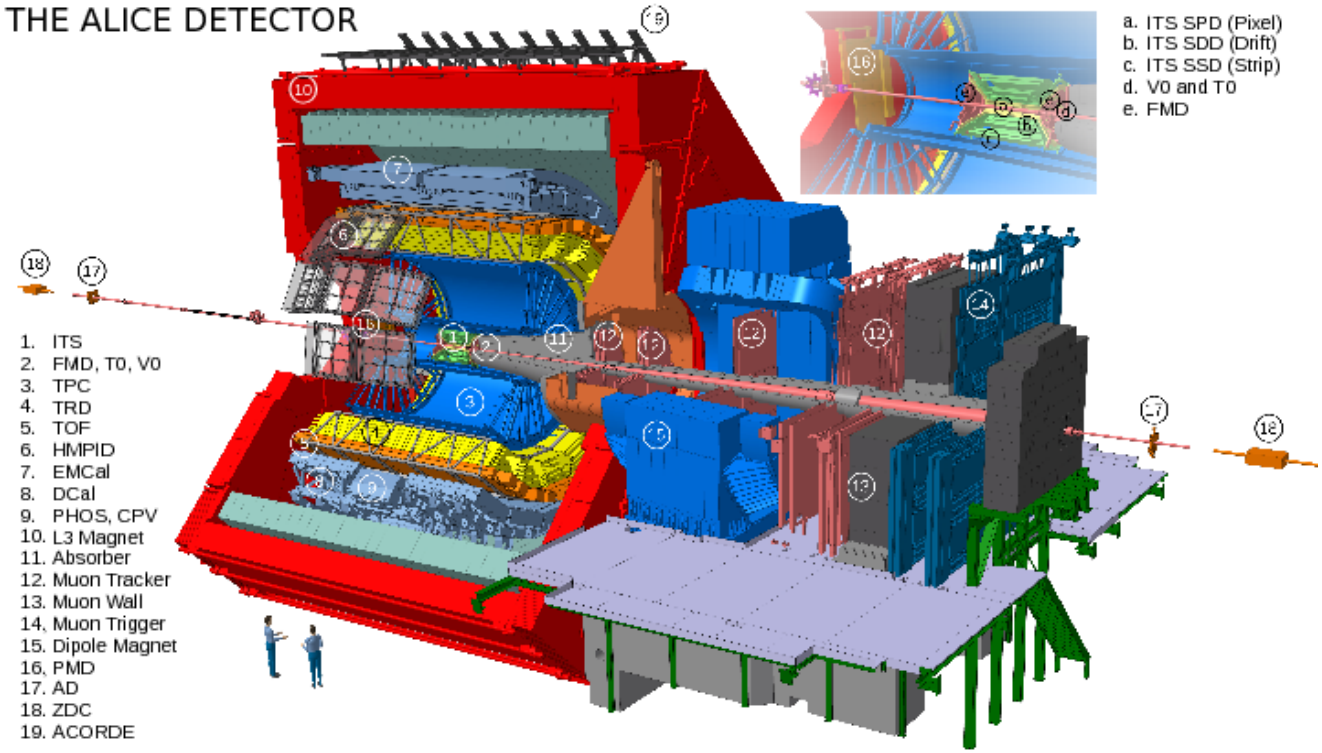
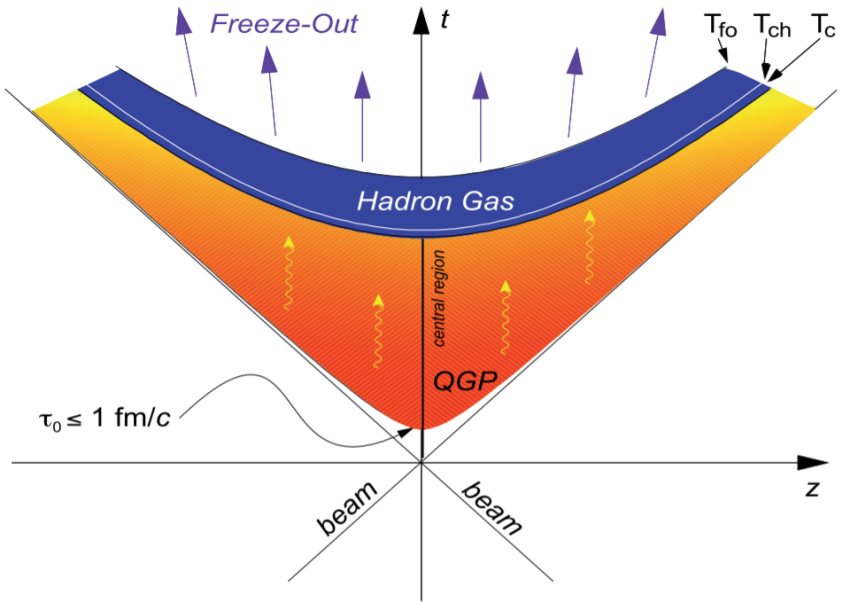
Heavy-ion collisions and QGP

- ultrarelativistic heavy-ion collisions $\rightarrow$ production of quark-gluon plasma (QGP) $\rightarrow$ anisotropic flow measurements
- ALICE = 18 detectors (most important: ITS, TPC, TOF)



A. Tauro, ALICE Schematics (2017)

Collision evolution and phase diagram of the nuclear matter



R. Stock, arXiv:0807.1610 (2008)

- phase transition $T_c = 151$ MeV [1]
- chemical freeze-out $T_{ch} = 155$ MeV, kinetic freeze-out $T_{fo} = 95 \pm 10$ MeV [2]

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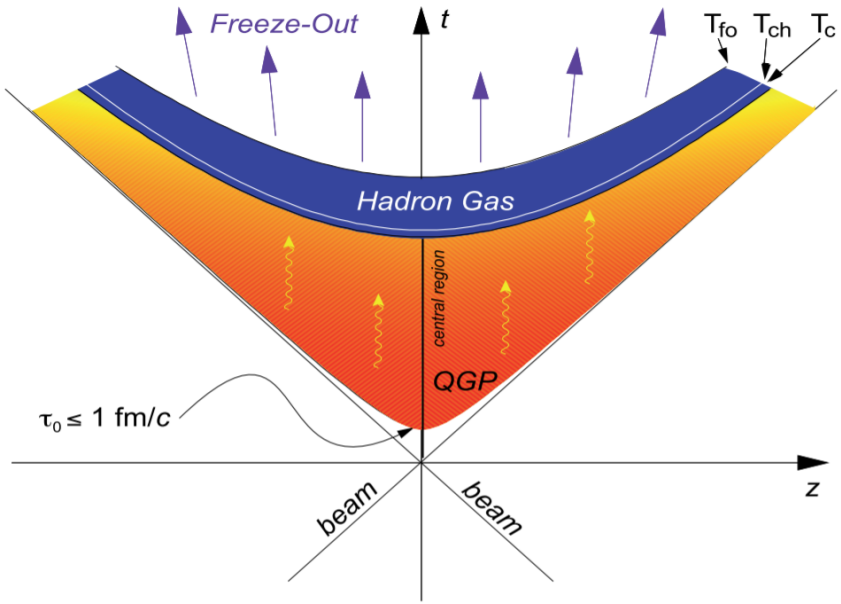

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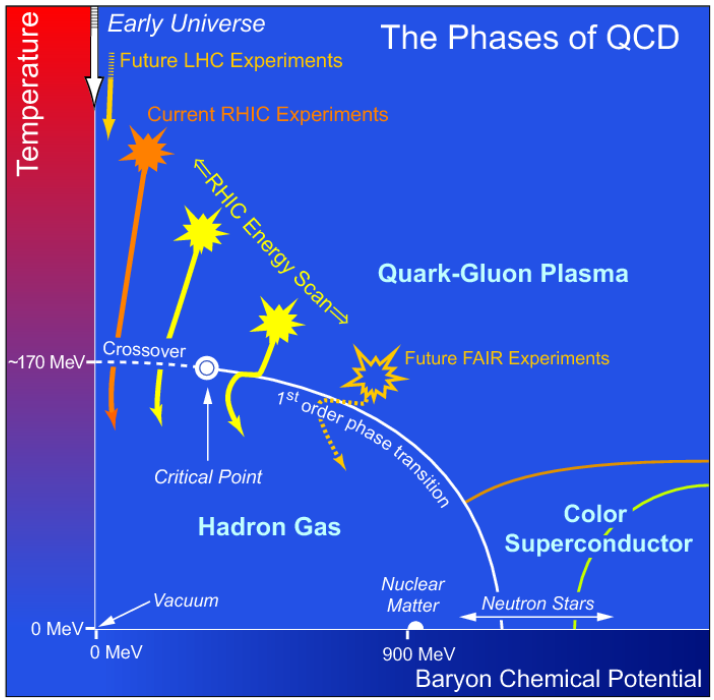


L. Kumar, Mod. Phys. Lett. A 28:1330033 (2013)

Anisotropic flow

- anisotropy in the initial geometry of the collision $\rightarrow$ collective expansion of the medium $\rightarrow$ anisotropy in the particle distribution
- azimuthal distribution of particles (Fourier)

$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n(\varphi - \Psi_n)\right] \tag{1}$$

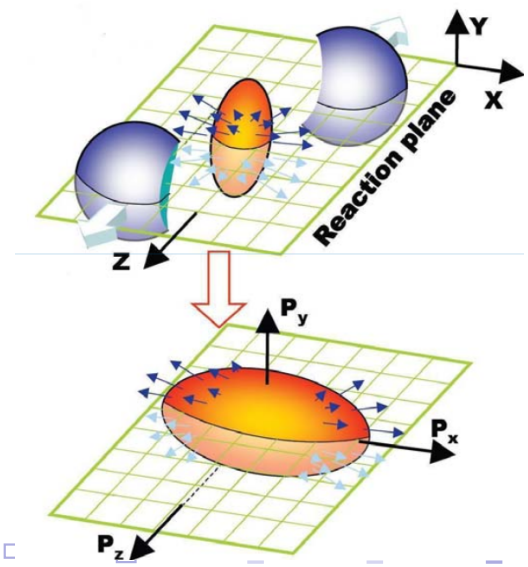
- flow coefficients

$$v_n = \langle \cos\left[n(\varphi - \Psi_n)\right] \rangle \tag{2}$$

- azimuthal correlations, e.g. two-particle correlation

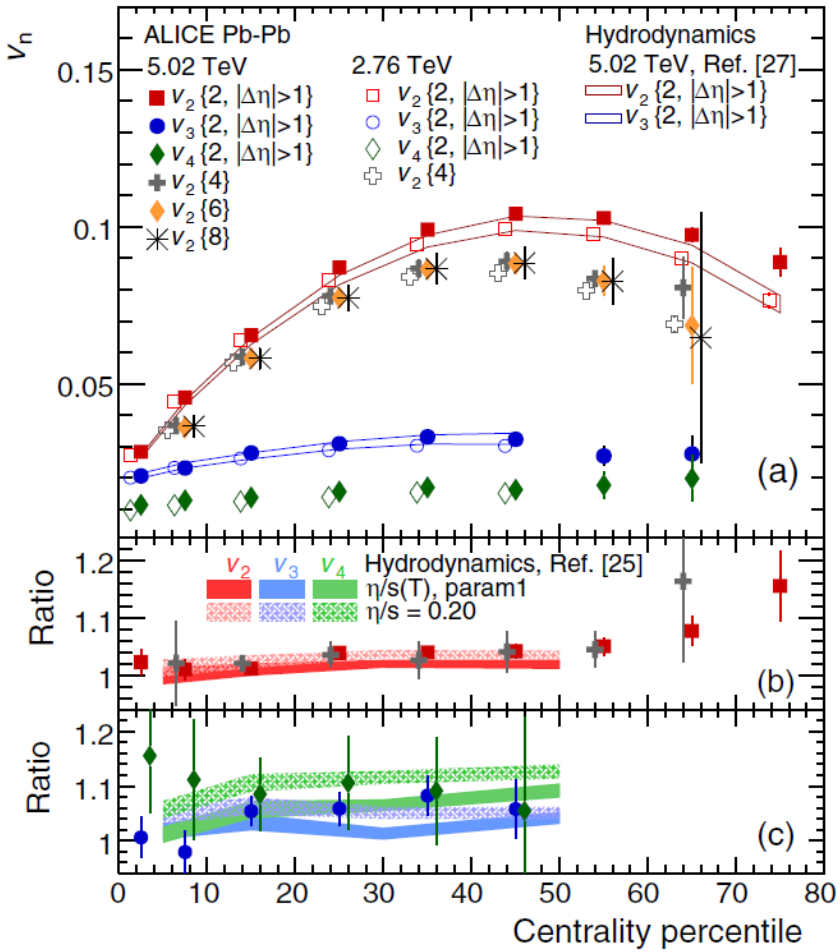
$$\langle v_n^2 \rangle = \langle \langle \cos\left[n(\varphi_1 - \varphi_2)\right] \rangle \rangle \tag{3}$$

C. Ristea et al., EPSHEP 2017



Selected measurements

- v_2 dependence on centrality
- viscosity of the QGP $\eta/s = 0{,}2$



ALICE, Phys. Rev. Lett. 116(13):132302

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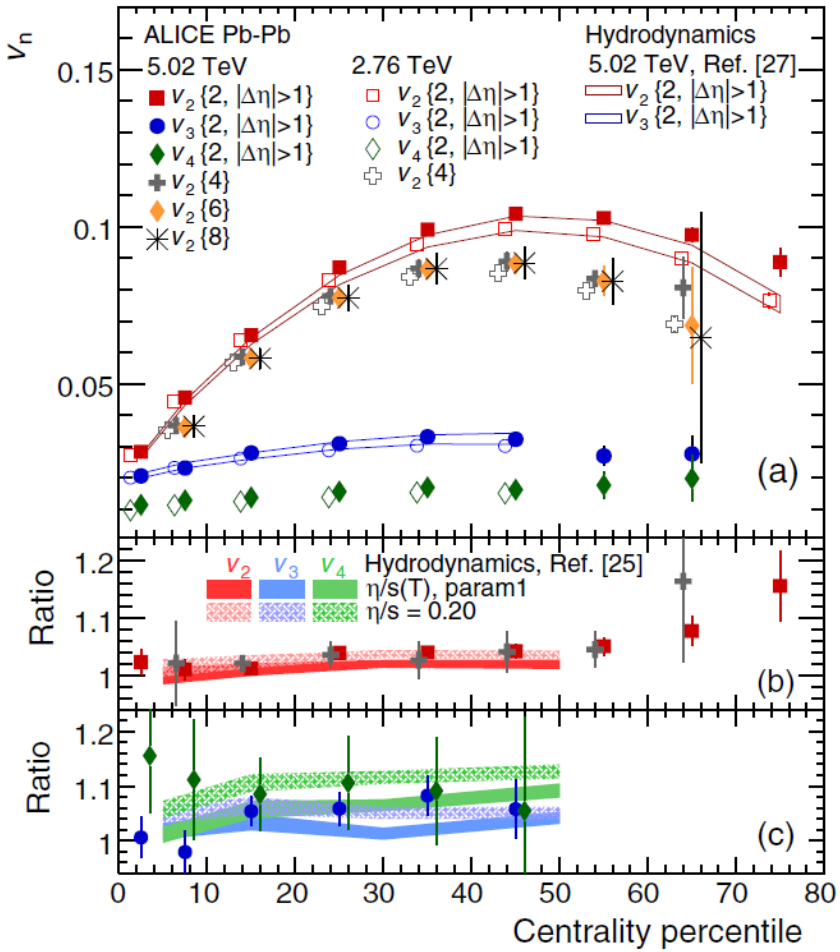

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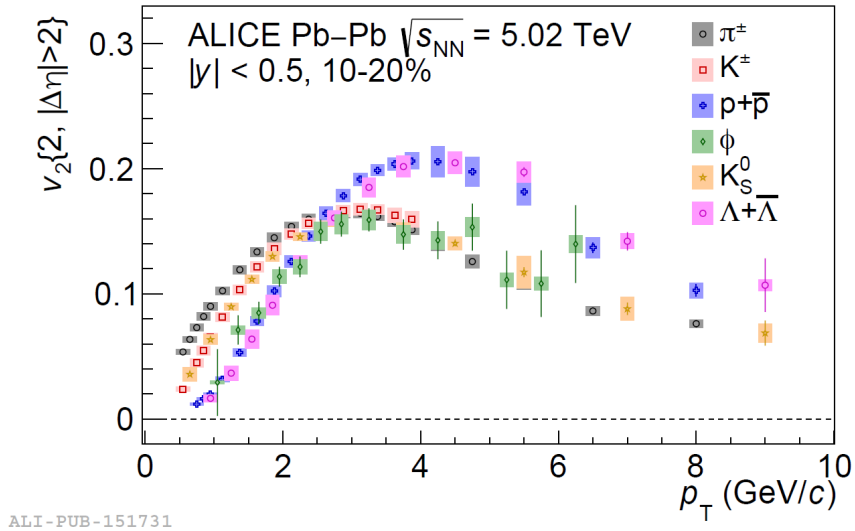
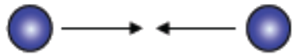


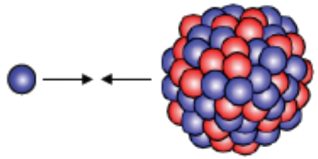
ALICE, JHEP 1809 (2018)

observed phenomena (= consequences of the QGP)

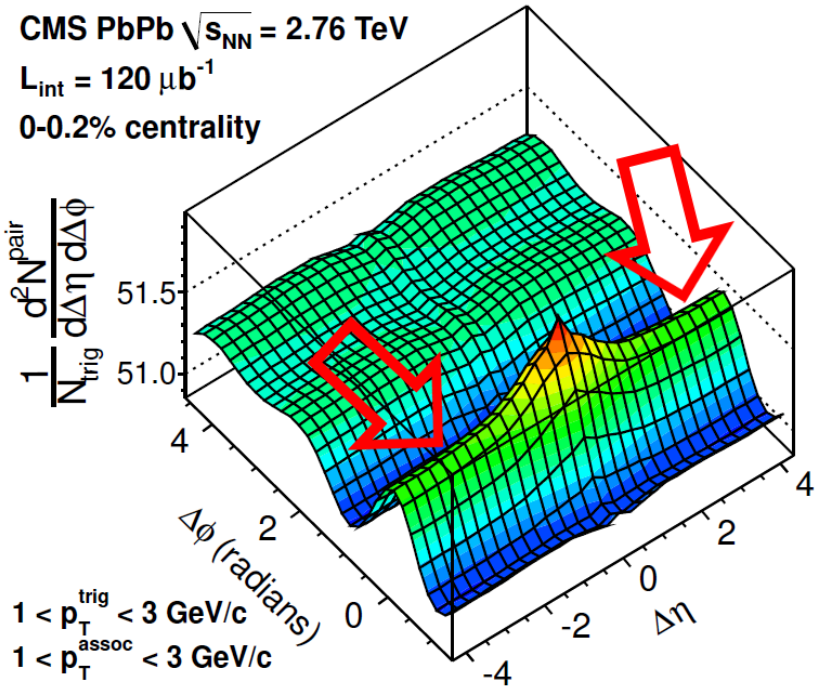
- mass-ordering
- splitting - mesons and baryons

Small systems

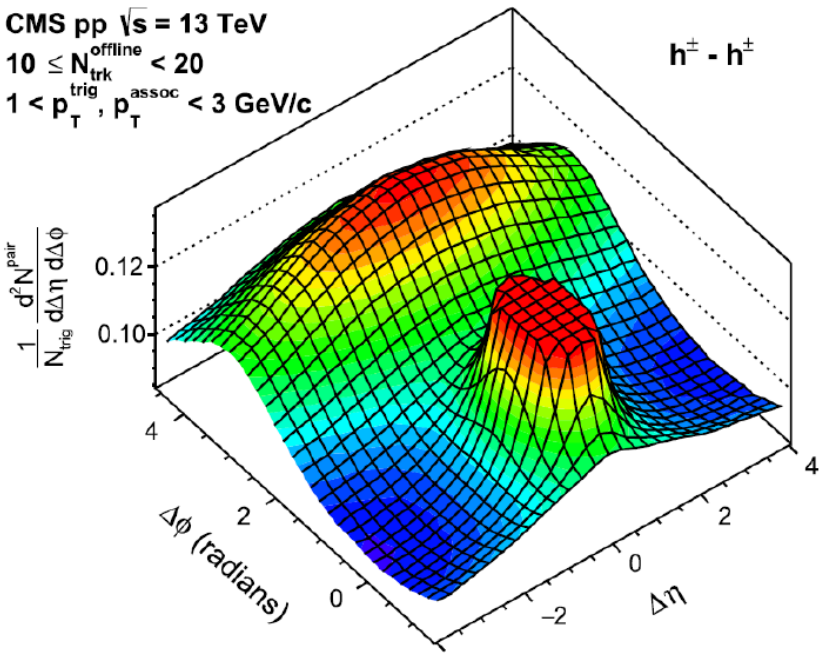




- no collective behavior expected, control measurements



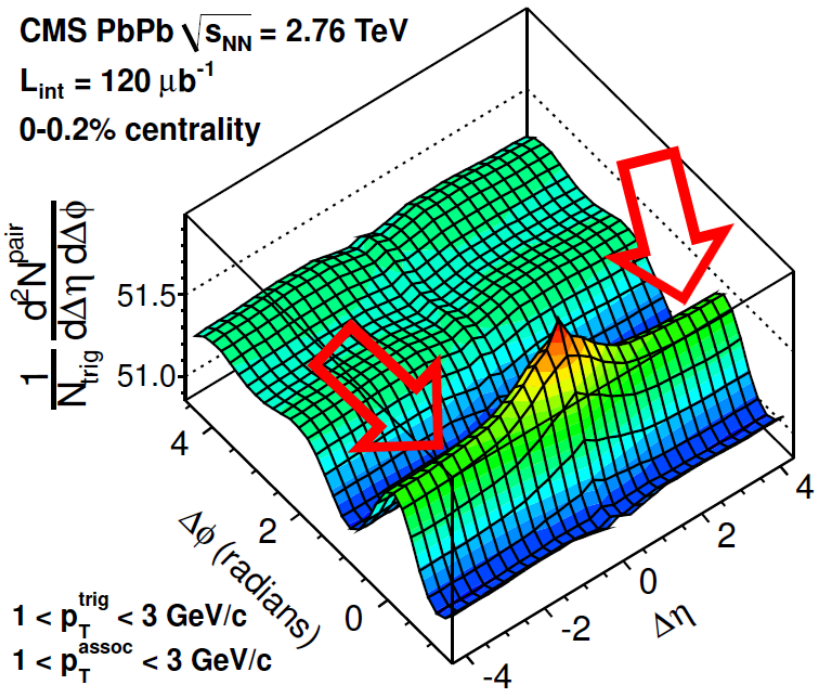
CMS, JHEP 02:088 (2014)



CMS, Phys. Lett. B 765:193–220 (2017)

Small systems

- in 2010 the CMS Collaboration - ridge around $\Delta\phi \approx 0$ in high multiplicity $p + p$ collisions $\rightarrow$ collectivity?



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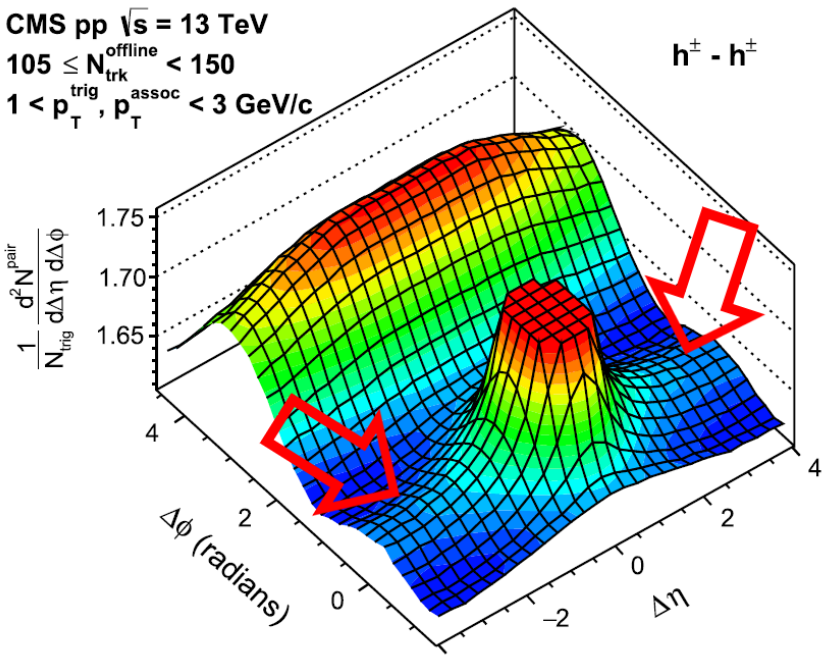
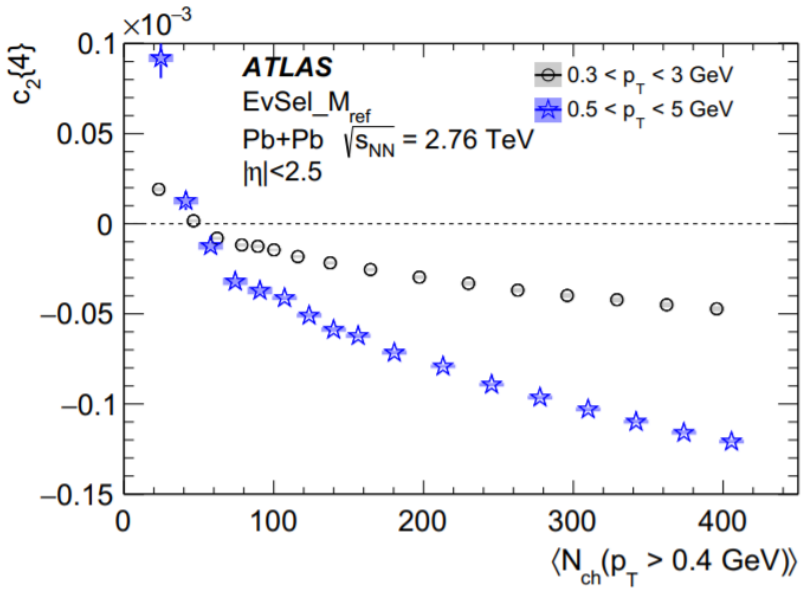


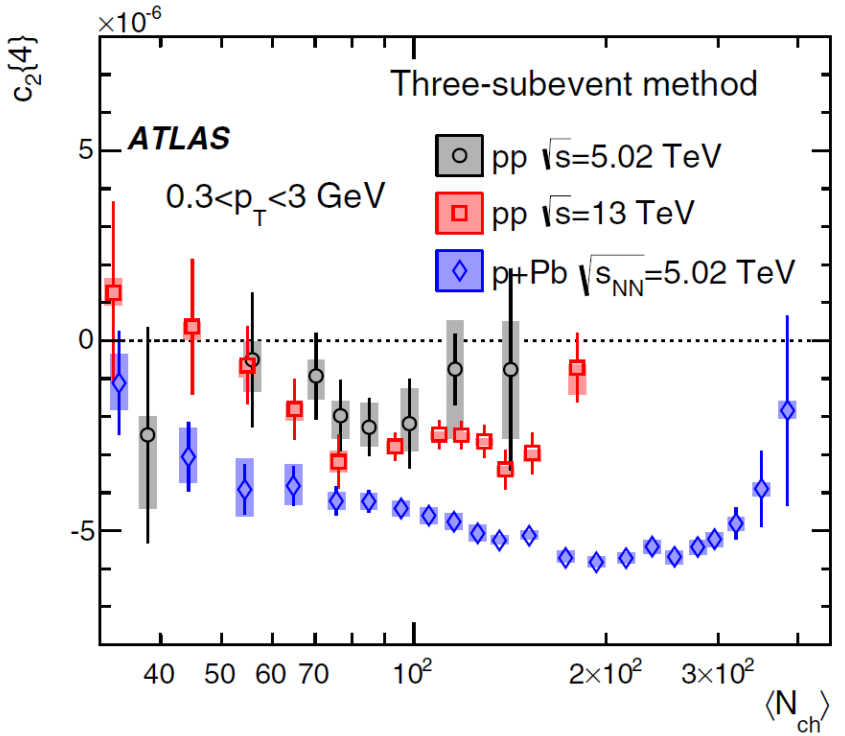
CMS, Phys. Lett. B 765:193–220 (2017)

Cumulant $c_2\{4\}$



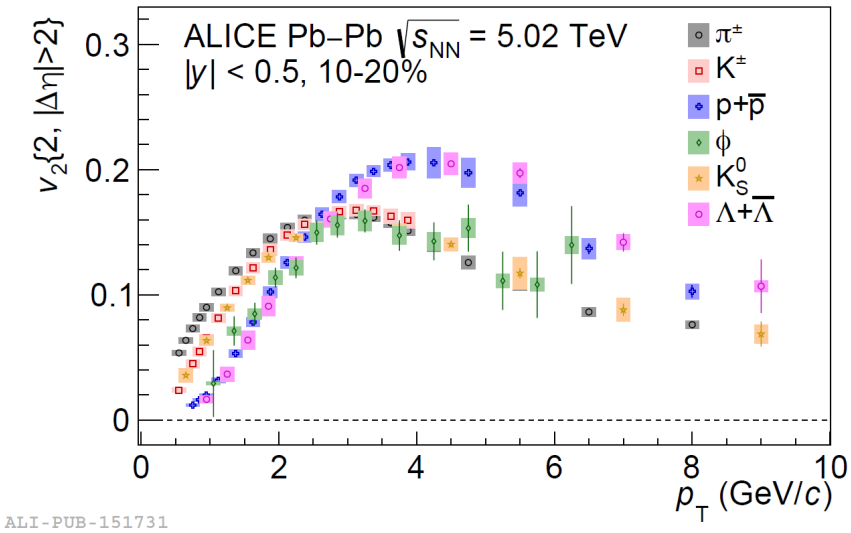
ATLAS, Eur. Phys. J. C 77(6):428 (2017)

- negative value of $c_2\{4\}$ observed in Pb+Pb
- negative value of $c_2\{4\} \rightarrow$ real value of v_2

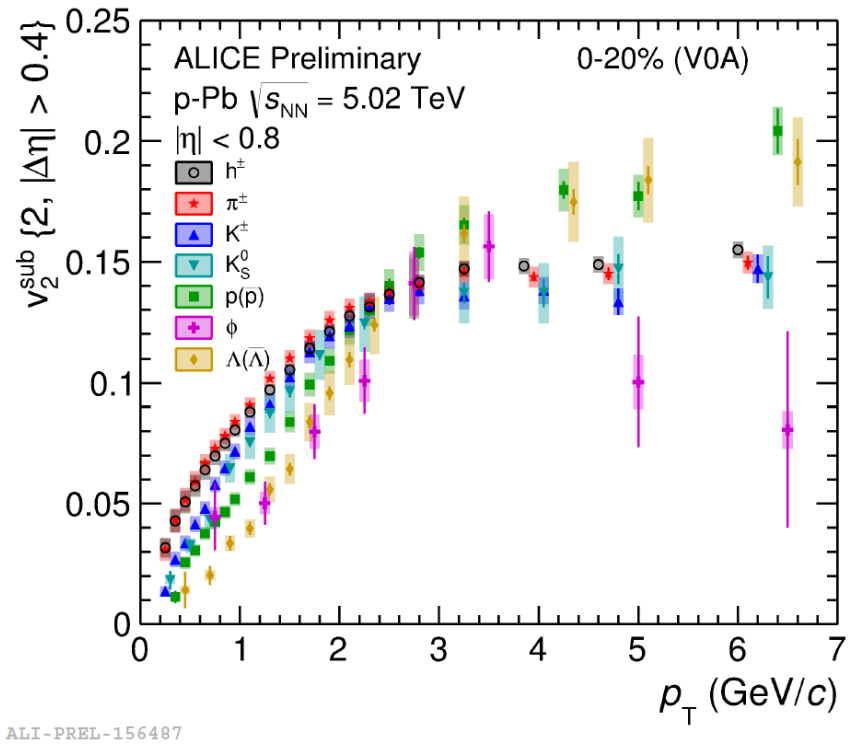


ATLAS, Phys. Rev. C 97(2):024904 (2018)

Identified flow



ALICE, JHEP 1809 (2018)



ALICE, unpublished

Pb+Pb collisions

- mass-ordering
- splitting - mesons and baryons

$p + p$ collisions from Pythia generator

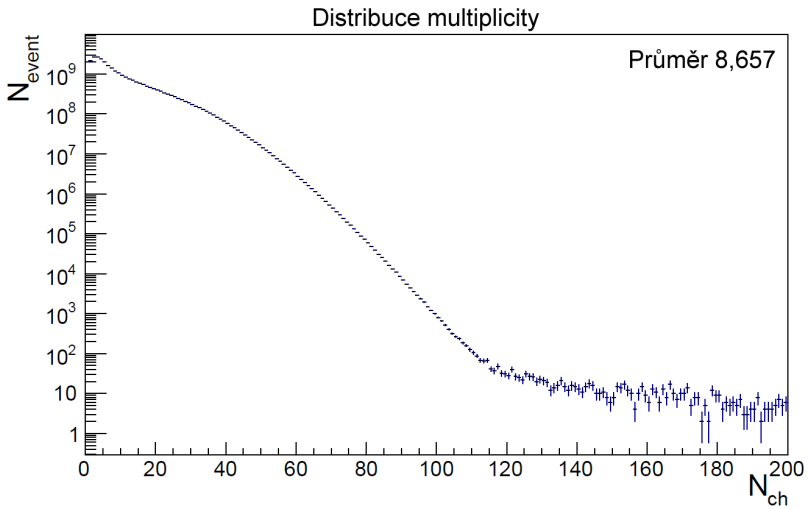
- motivation - to try methods used for analysis of data from small system collisions
- no anisotropic flow in Pythia $\rightarrow$ perfect for tests of non-flow suppression methods

Pythia

- generator of high energy collisions using MC
- output = list of produced particles with properties

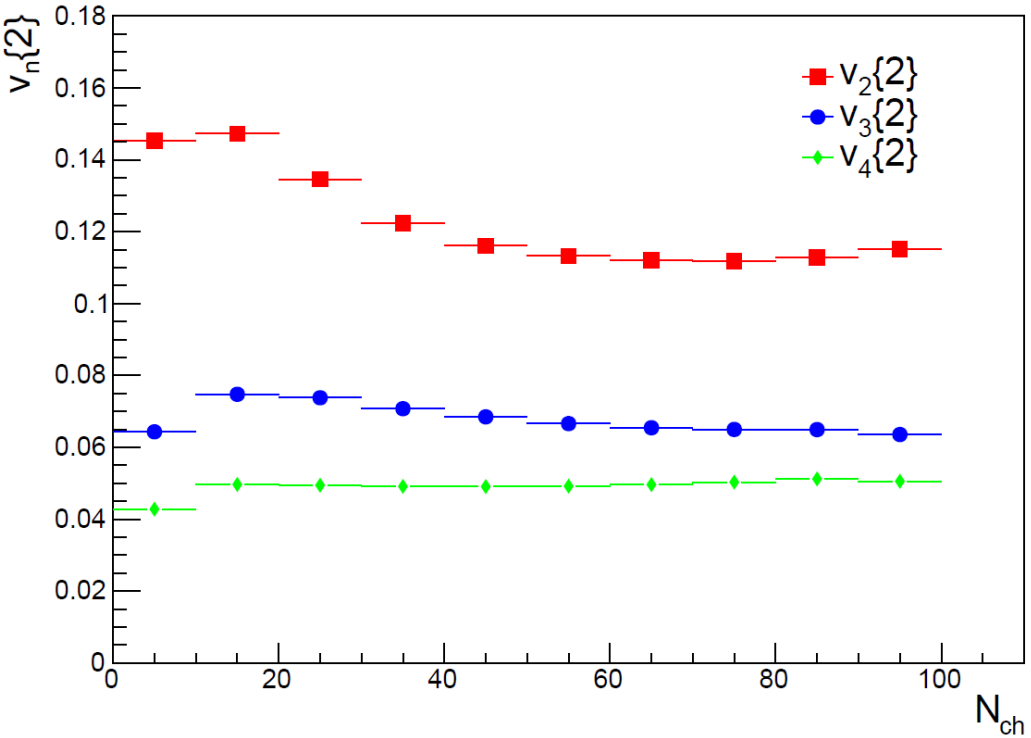
Analysis methods

- azimuthal correlations + subevent method



$3 \cdot 10^{10}$ p+p collisions $\sqrt{s} = 13$ TeV default settings + inelastic soft QCD processes
cut: $0{,}2 < p_T < 3$ GeV, $|\eta| < 0{,}8$

Results - coefficient $v_n\{2\}$



$$Q_n = \sum_{k=1}^{M} e^{in\varphi_k} \tag{4}$$

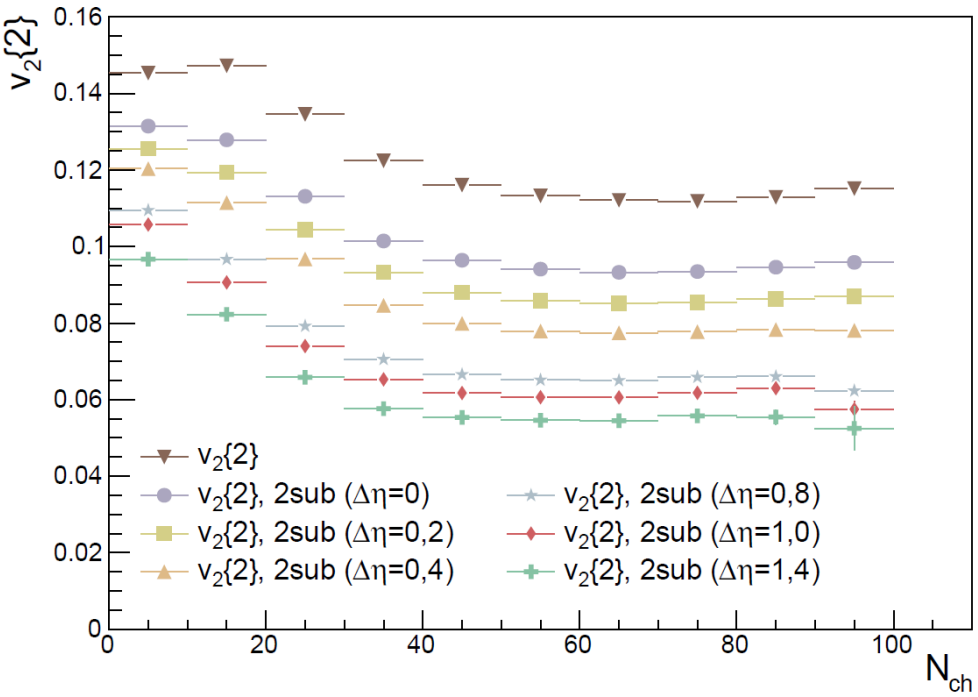
$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)} \tag{5}$$

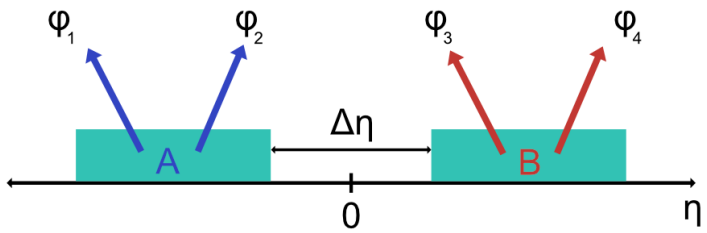
$$\langle\langle 2 \rangle\rangle = \frac{\sum_{event}(W_{\langle 2 \rangle})_i \langle 2 \rangle_i}{\sum_{event}(W_{\langle 2 \rangle})_i} \tag{6}$$

$$c_n\{2\} = \langle\langle 2 \rangle\rangle \tag{7}$$

$$v_n\{2\} = \sqrt{c_n\{2\}} \tag{8}$$

Results - subevent method

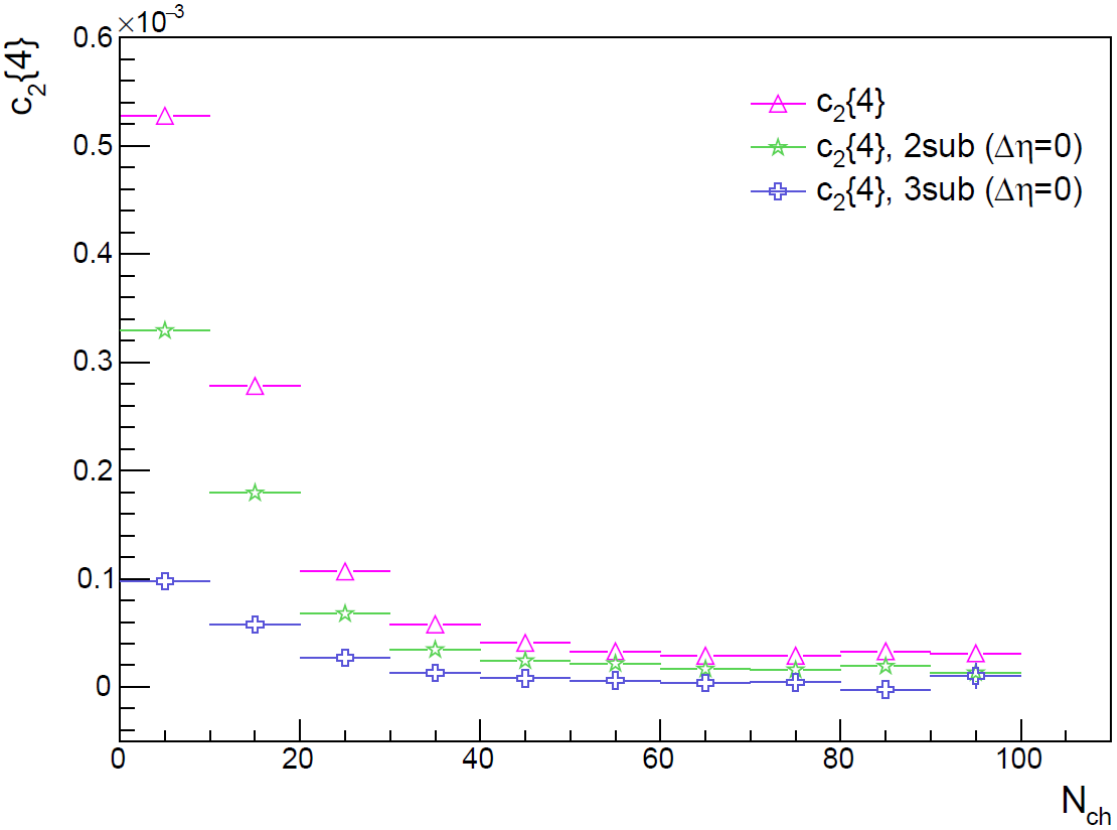




$$\langle\langle 2\rangle\rangle_{AB}^{1,3} \cdot \langle\langle 2\rangle\rangle_{AB}^{2,4} = \langle\langle e^{in(\varphi_1-\varphi_3)}\rangle\rangle\langle\langle e^{in(\varphi_2-\varphi_4)}\rangle\rangle \quad (9)$$

- the method suppresses non-flow effectively

Results - cumulant $c_2\{4\}$



$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2 \tag{10}$$

- Pythia - no anisotropic flow
- subevent method suppresses non-flow

Conclusion

- heavy-ion collision $\rightarrow$ investigation of QGP
- collective behavior is observed in
  - two-particle correlations - near-side ridge
  - identified flow - mass-ordering and splitting
- the value of viscosity of QGP η/s is very low
- collective behavior was observed in small collision systems
- analysis of data from generated p+p collisions using subevent method

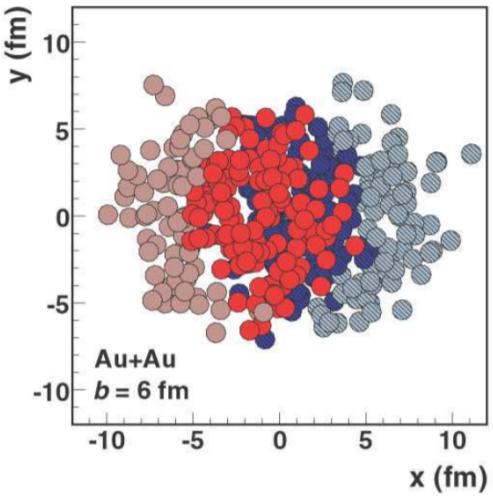
Reference

Y. Aoki, Z. Fodor, S. D. Katz a K. K. Szabó: *The QCD transition temperature: results with physical masses in the continuum limit* [Online]. [cit. 15. 9. 2020]. Phys. Lett. B 643 (2006) 46-54

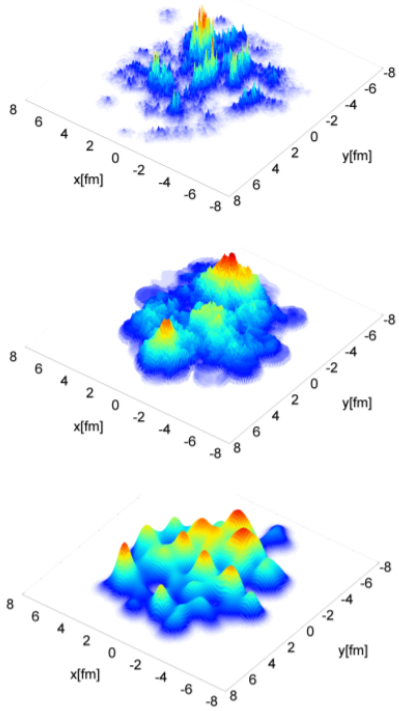
B. Abelev et al.: *Pion, Kaon, and Proton Production in Central Pb–Pb Collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV* [Online]. [cit. 15. 9. 2020]. Phys. Rev. Lett. 109:252301 (2012)

Backup

Flow

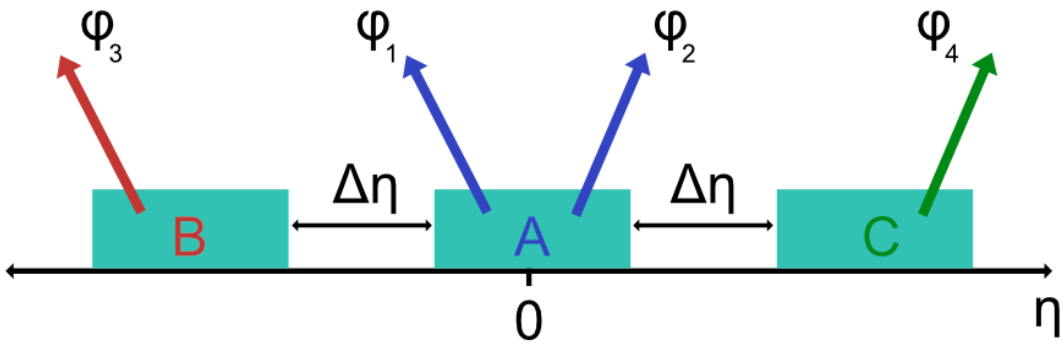


Michael L. Miller et al., Ann. Rev. Nucl. Part. Sci. 57:205-243 (2007)



Bjoern Schenke et al., arXiv:1202.6646 (2012)

3-subevent method



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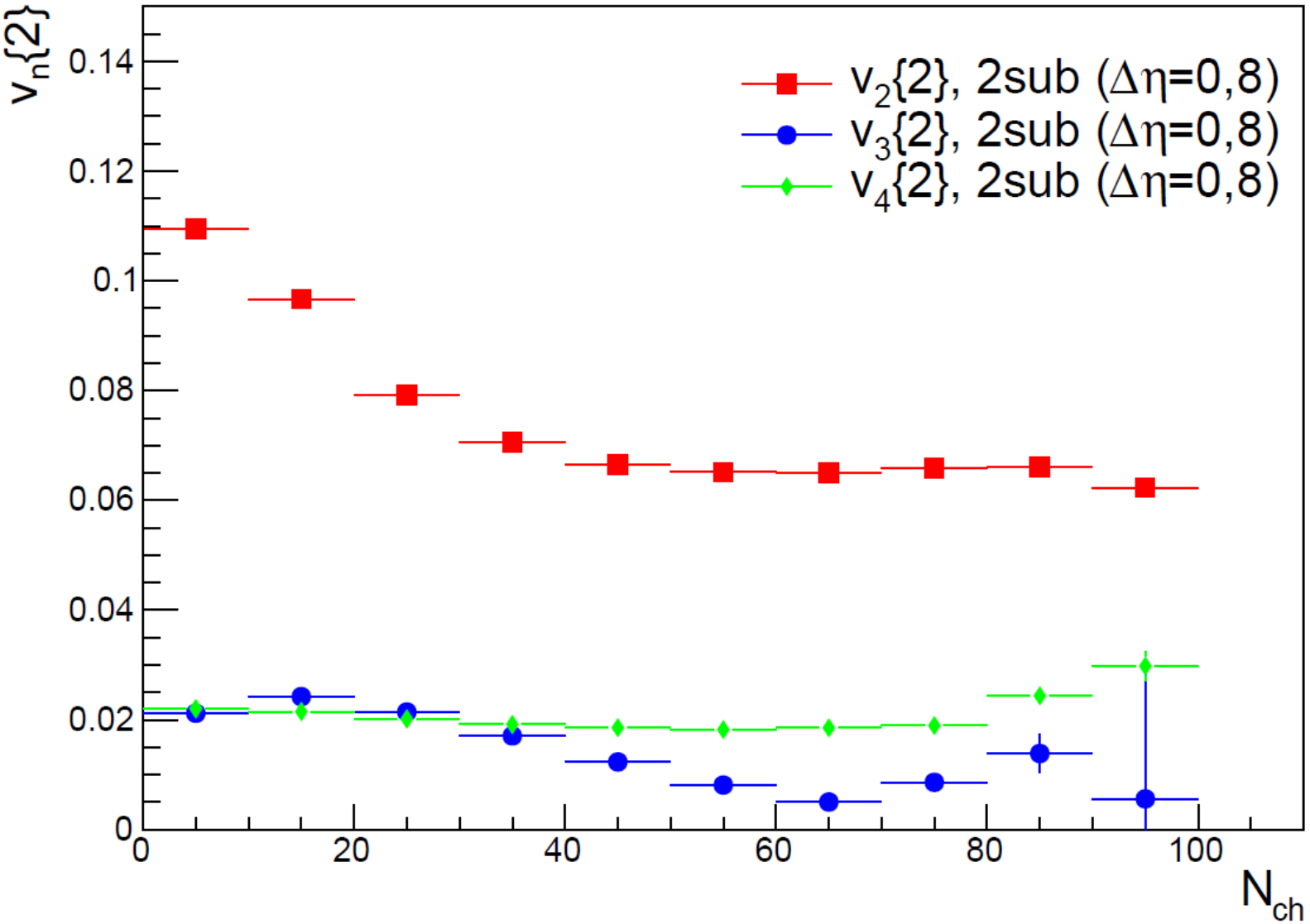
$v_n\{2\}$


v_n{2}
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
100
N_ch
v_2{2}, 2sub (Δη=0,8)
v_3{2}, 2sub (Δη=0,8)
v_4{2}, 2sub (Δη=0,8)