Heavy-ion results from CMS

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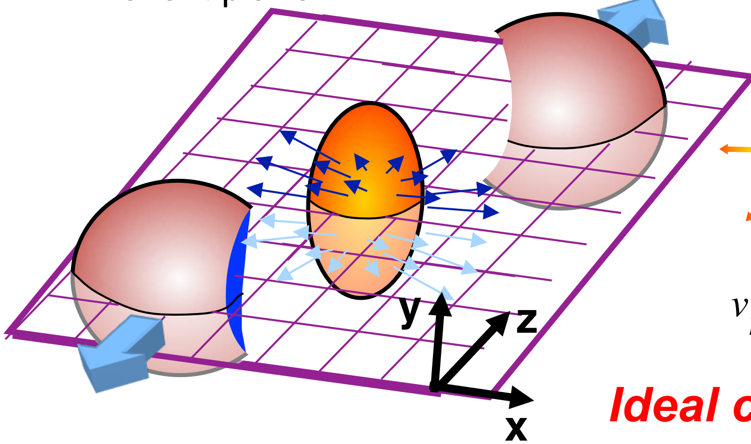
Outline

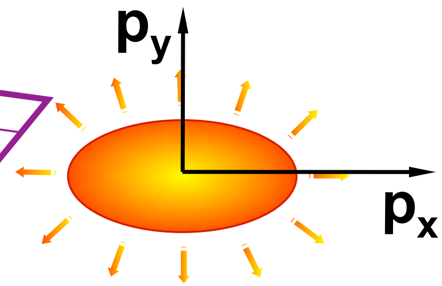
- Azimuthal anisotropy
  - conventional methods
  - Initial-state fluctuations (ISF) and higher order Fourier harmonics
- Collectivity over a wide p_T range in PbPb collisions
- Collectivity in smallest pp collision systems
- ISF on sub-nucleonic level and factorization breaking
- Principal Component Analysis (PCA) method – a simple case
- PCA method in flow physics – leading and sub-leading flow modes
- The PCA analysis in pPb and PbPb collisions at the LHC energy
- Conclusions

Anisotropy harmonics v_n – conventional methods

Event Plane (EP) method

event plane x-z



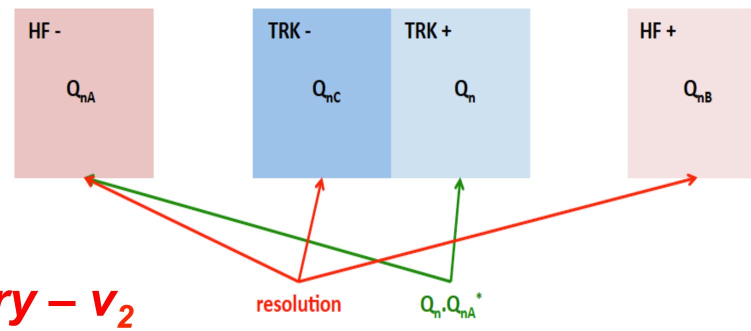


$$v_n = \langle \cos n(\phi - \Psi_n) \rangle$$

Scalar Product (SP) method

$|\Delta\eta| > 3$

$$v_n\{SP\} = \frac{\boxed{\langle Q_n \cdot Q_{nA}^* \rangle}}{\boxed{\sqrt{\frac{\langle Q_{nA} \cdot Q_{nB}^* \rangle \langle Q_{nA} \cdot Q_{nC}^* \rangle}{\langle Q_{nB} \cdot Q_{nC}^* \rangle}}}}$$



Ideal circle-like geometry – v_2

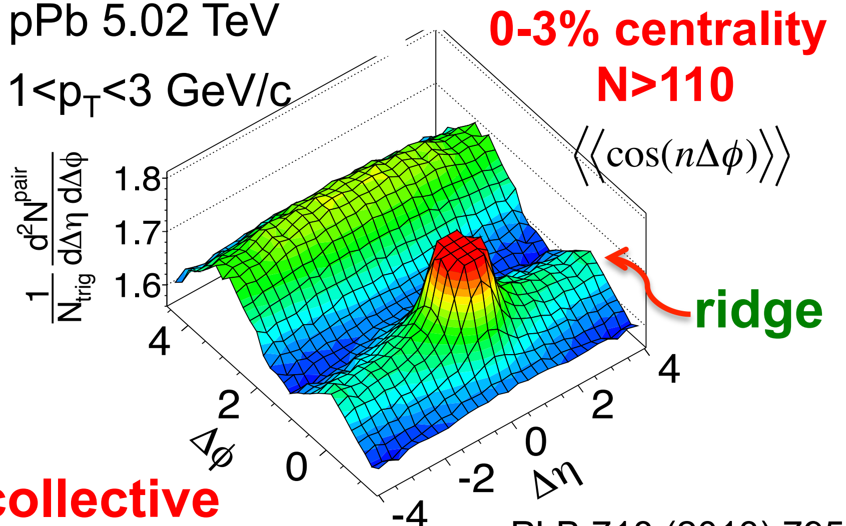
two-particle correlation method

pPb 5.02 TeV

$1<p_T<3$ GeV/c

0-3% centrality
N>110

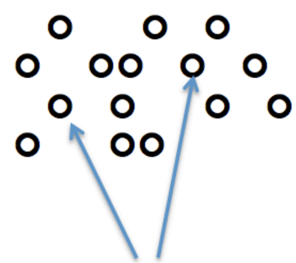
$$\langle\langle \cos(n\Delta\phi) \rangle\rangle$$



PLB 718 (2013) 795

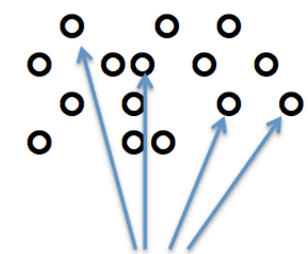
collective behavior

multi-particle correlation method



$$\left\langle e^{in(\varphi_1 - \varphi_2)} \right\rangle$$

Advantage wrt 2-part.corr.: removes two- and three-particle non-flow correlation



$$\left\langle e^{in(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)} \right\rangle$$

- v_n from even higher order cumulants:

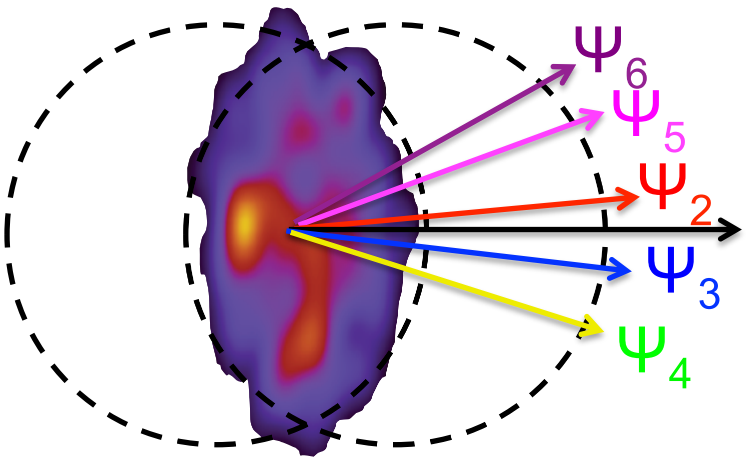
Lee-Yang zero method

correlates all particles of interest

Role of initial state fluctuations on anisotropy

Anisotropy harmonics with order higher than 2

Phys.Rev. C89 (2014) 044906 *(arXiv:1310.8651)*

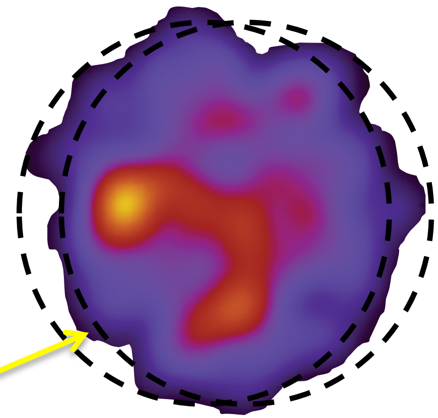


v_2, v_3, v_4, v_5 and v_6 using multiple methods

Simple, circle-like geometry does not describe the formed system precisely enough

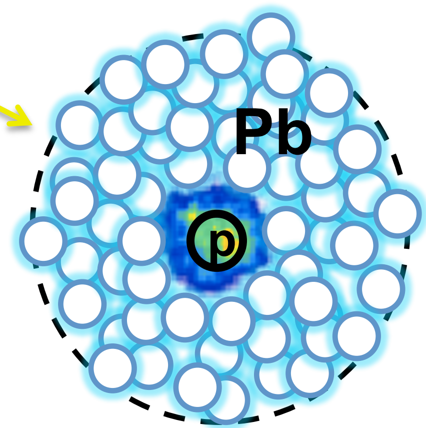
initial-state fluctuations dominates

Ultra-central collisions



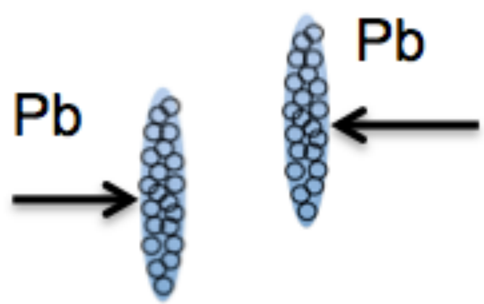
JHEP 1402 (2014) 088 *(arXiv:1312.1845)*

Asymmetric (pPb) high-multiplicity collisions

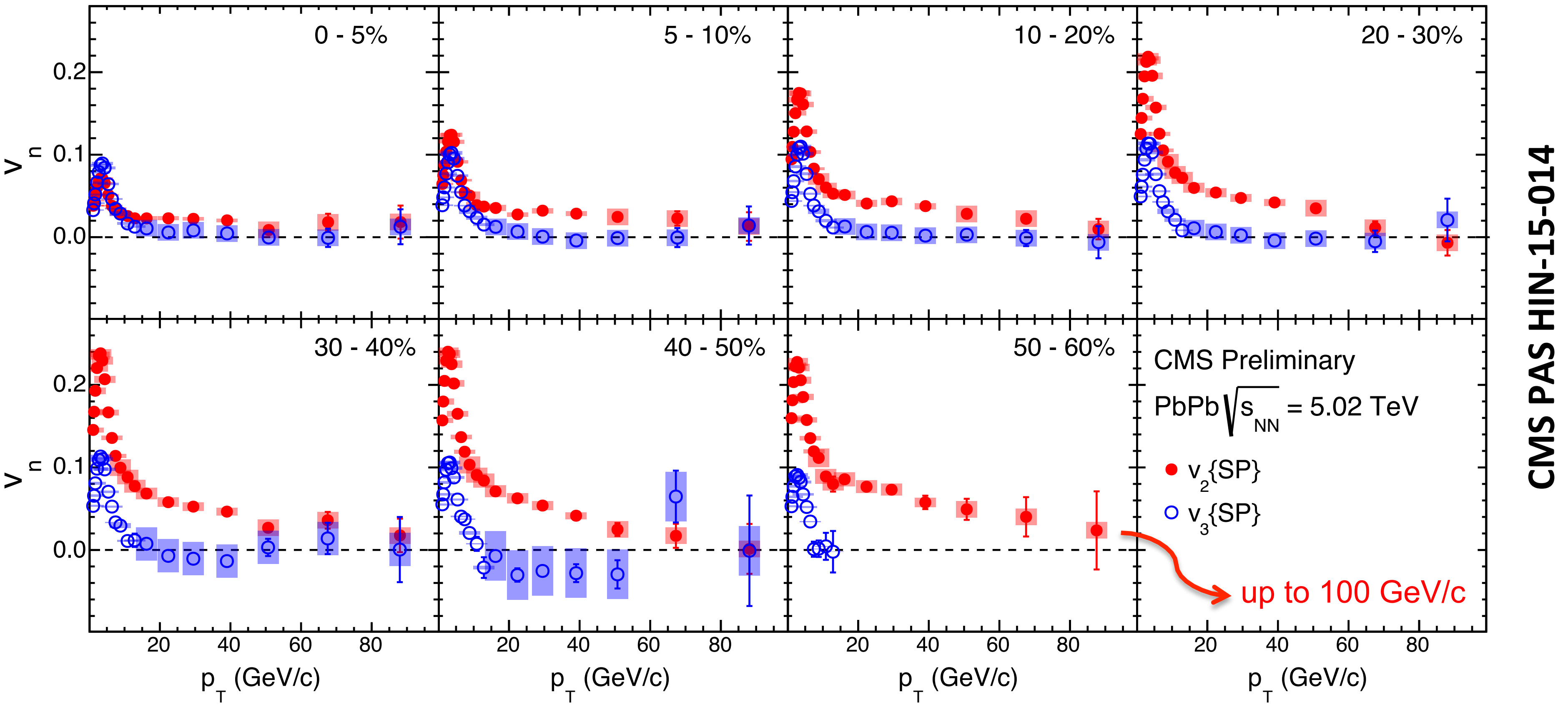


Phys.Lett. B724 (2013) 213 *(arXiv:1305.0609)*

Collectivity over a wide p_T range in PbPb

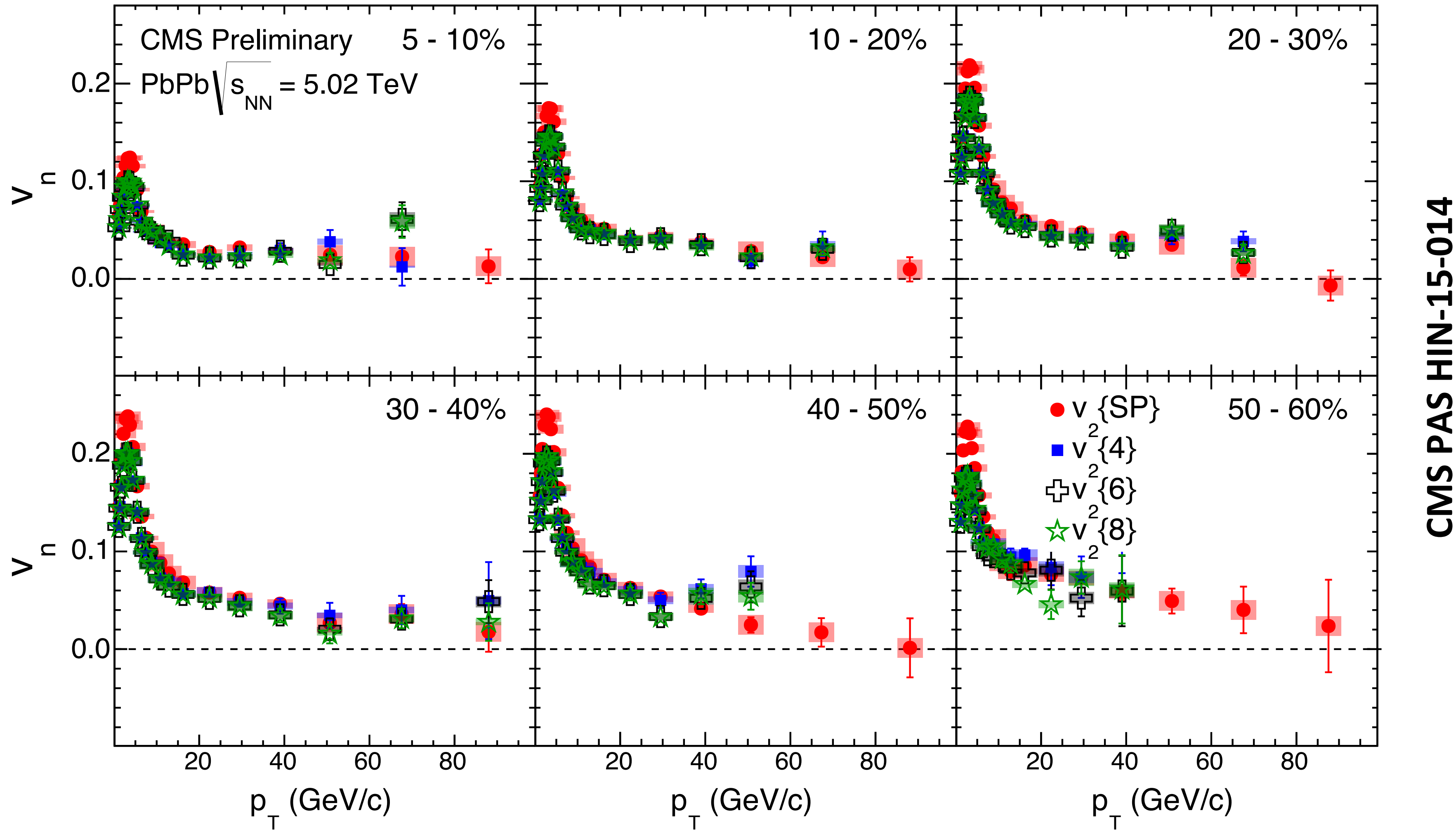


$v_n\{SP\}$ over a wide p_T range



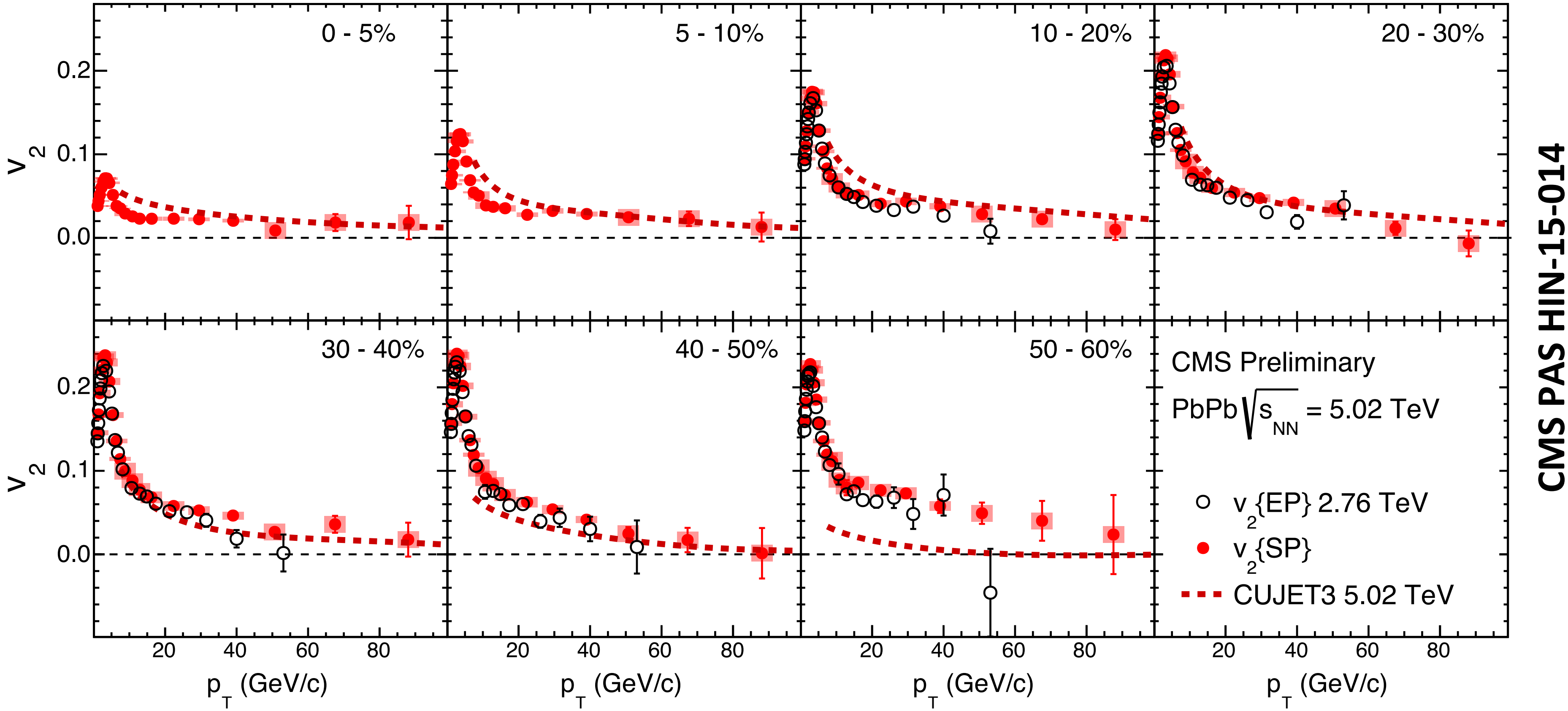
- low-p_T - hydrodynamic flow (v_2 – geometry, v_3 – ISF on nucleonic level)
- v_2 non-zero up to very high p_T
- high-p_T - may reflect the path-length dependence of parton energy loss
- v_2 is complementary to R_{AA} measurements
- v_3 mainly consistent with zero at high-p_T

Collectivity over a wide p_T range



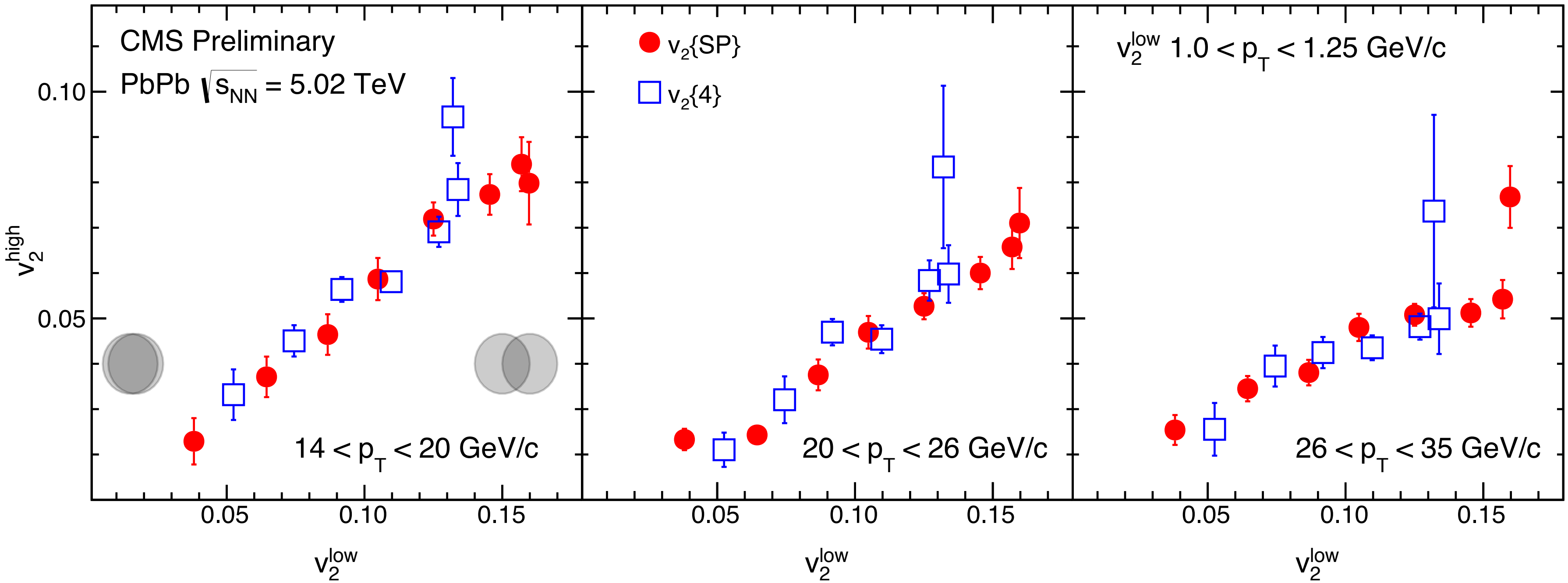
- low-p_T – ratio $v_2\{2k\}/v_2\{SP\} \approx 0.8$ and $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ ← hydrodynamics
- high-p_T – SP and multi-particle correlation tend to converge to the same value
- $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \neq 0$ ← collectivity (likely to be related to jet quenching)

Comparison with lower energy and CUJET3



- A slight increase of v_2 wrt results (EP method) from 2.76 TeV collision energy
- CUJET3 predictions roughly compatible with the data at high-p_T (over 40 GeV/c)
- At lower p_T, CUJET3 overpredicts the experimental v_2

Collectivity over a wide p_T and centrality range

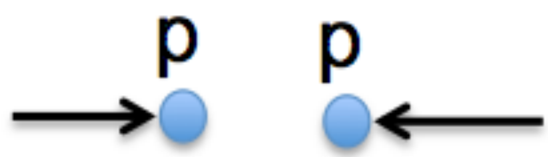


CMS PAS HIN-15-014

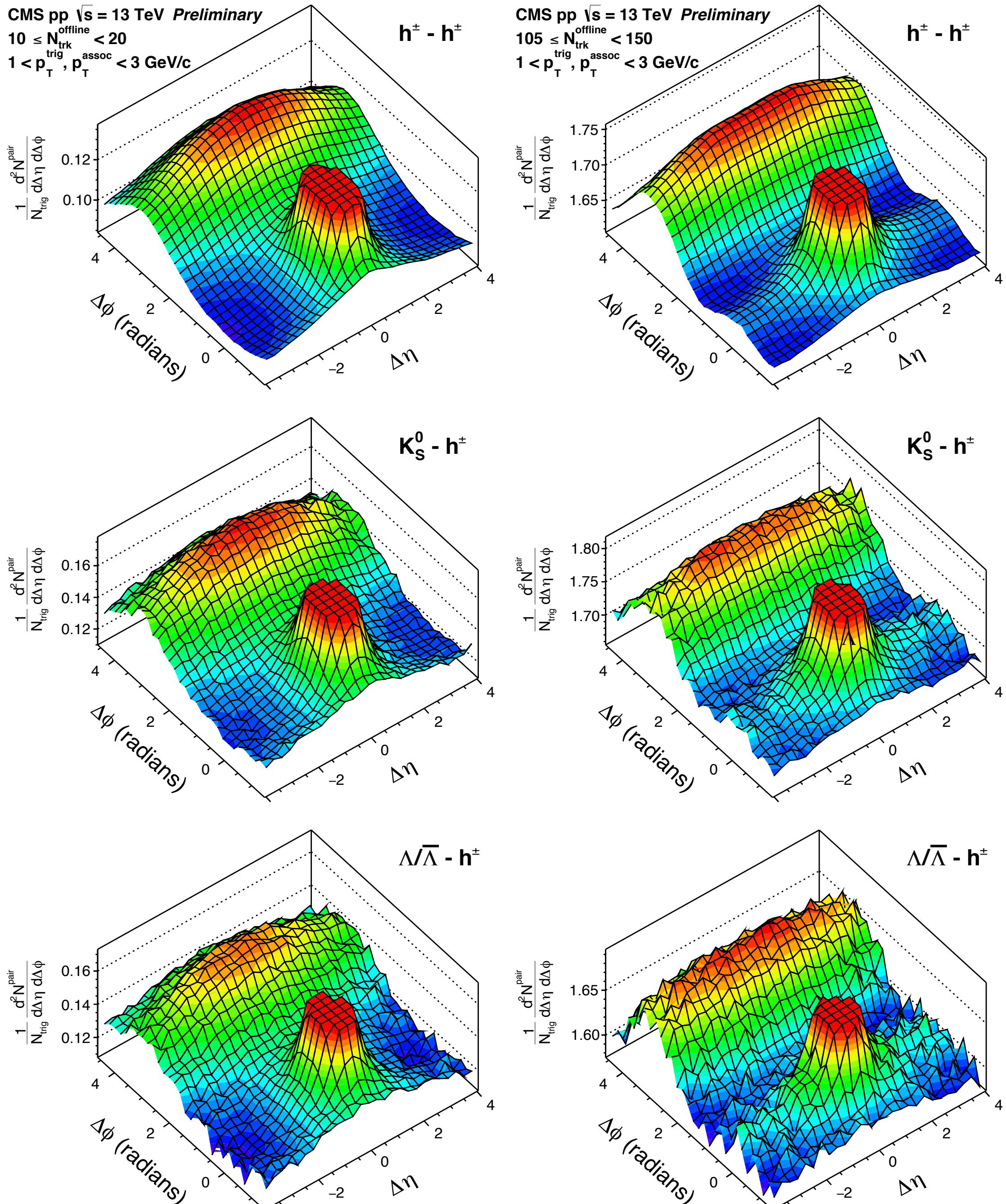
Soft and hard correlation

- Correlation between low-p_T v_2 and high-p_T v_2 over a wide centrality range
- Each point represents one centrality bin
- Strong correlation may indicate that low-p_T v_2 and high-p_T v_2 may have the same origin
- Within uncertainties, slopes between $v_2\{SP\}$ and $v_2\{2k\}$ are compatible
- Extrapolations compatible to 0 within uncertainties

Collectivity in smallest pp systems



2D 2-particle corr. function in low- and high-multiplicity

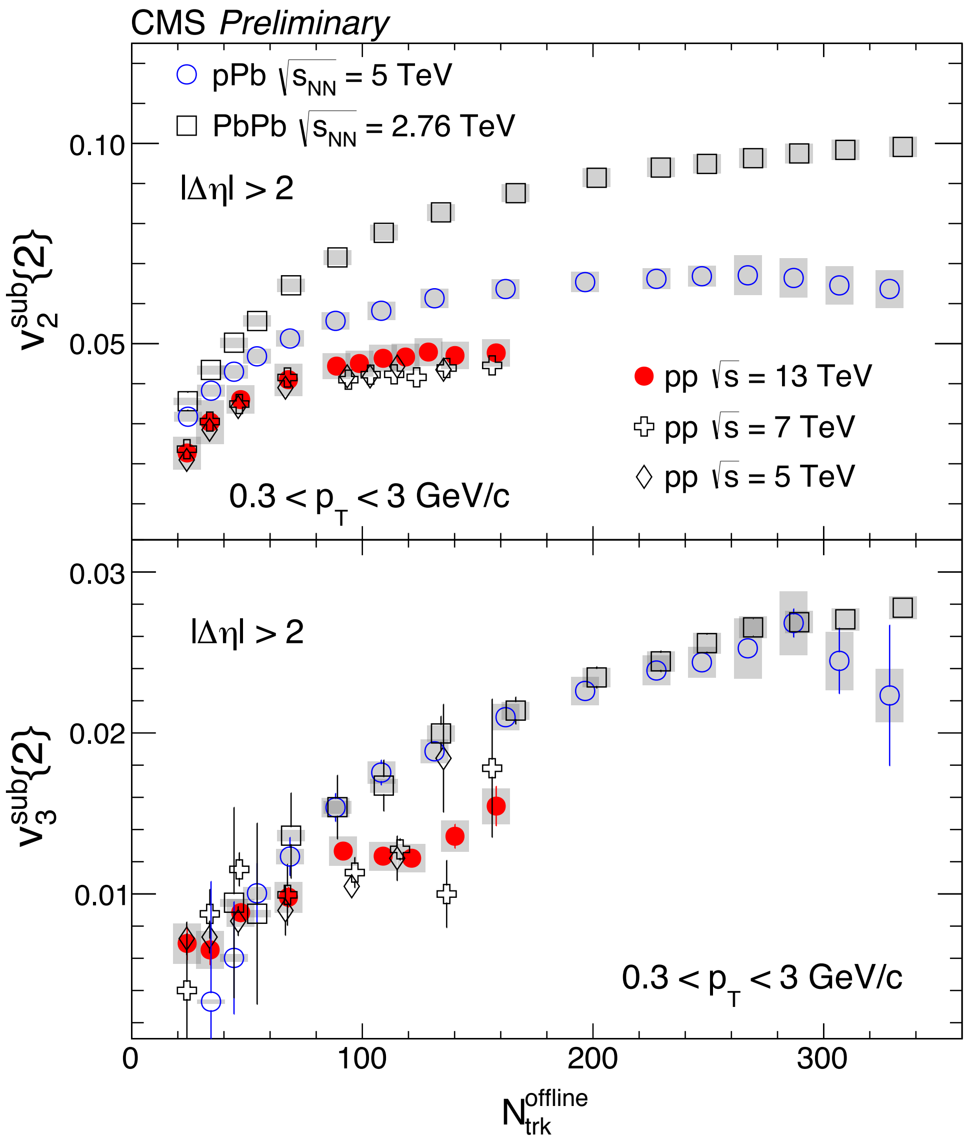


CMS PAS HIN-16-010

- charged-charged or charged-strange ($K_S{}^0$ and $\Lambda/\overline{\Lambda}$) particles
- particles are correlated within given multiplicity bin
- The ridge, at Δϕ ≈ 0 and elongated at Δη, is seen only in high-multiplicity pp events
- The ridge is present not only for charged, but also for strange particles
- What is the origin of the ridge in the smallest pp system?

collective behavior in pp?

$v_2\{2\}$ and $v_3\{2\}$ in pp at different collision energies



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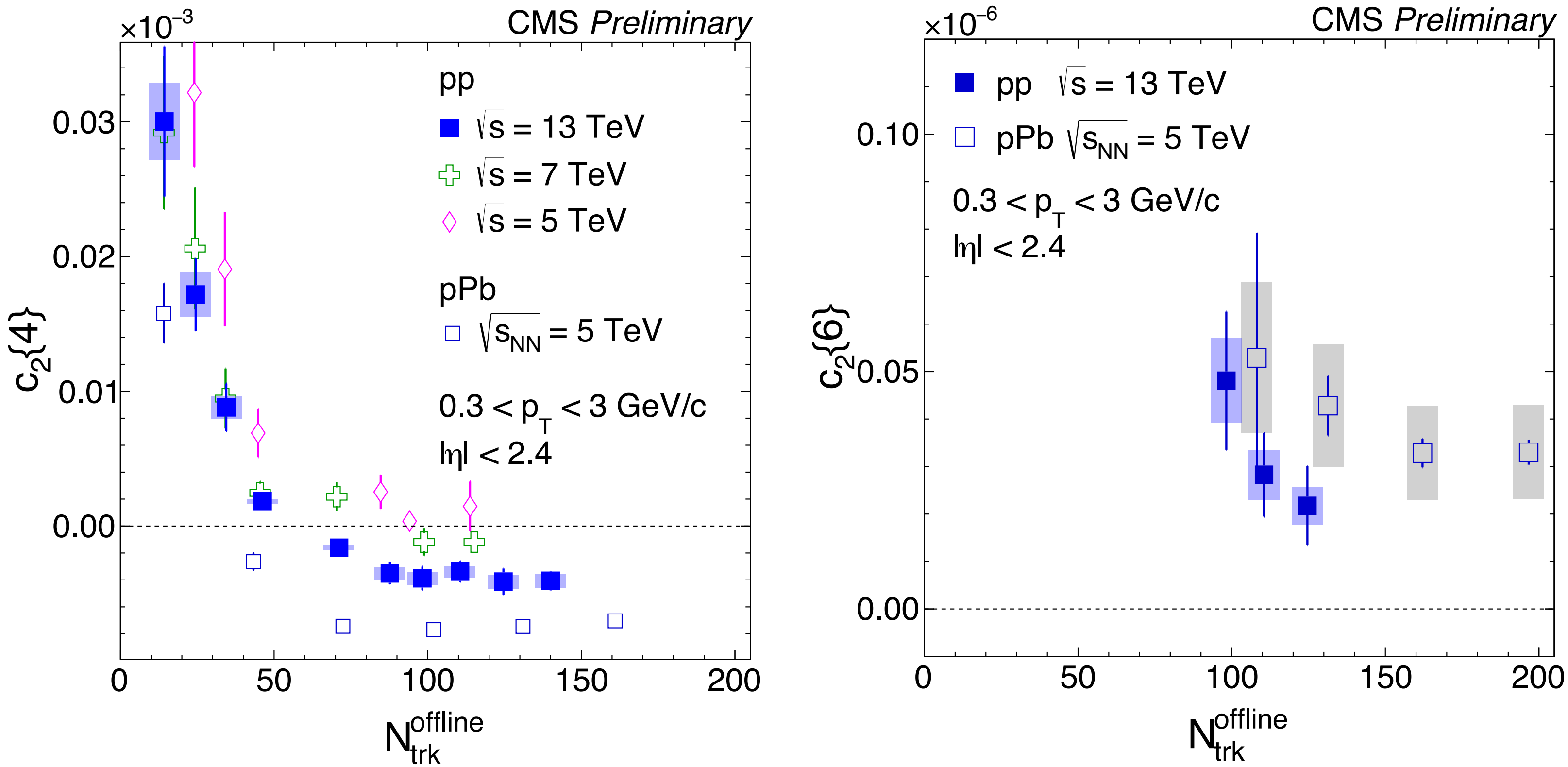
- There is no or a very weak energy dependence of v_2 in pp collisions
- $v_2\{2\}$ in pp collisions shows a similar pattern as the one seen in pPb collisions (gets flat at the highest multiplicities)
- The $v_2\{2\}$ magnitude is ordered: it is highest in PbPb, gets smaller in pPb and become smallest in pp collisions
- In difference of the v_2, the v_3 magnitude is comparable to those in pPb and PbPb collisions
- At low multiplicities, the systematic uncertainties are large for all the three systems
- At high multiplicities, v_3 in pp increases at a slower rate than in pPb and PbPb systems

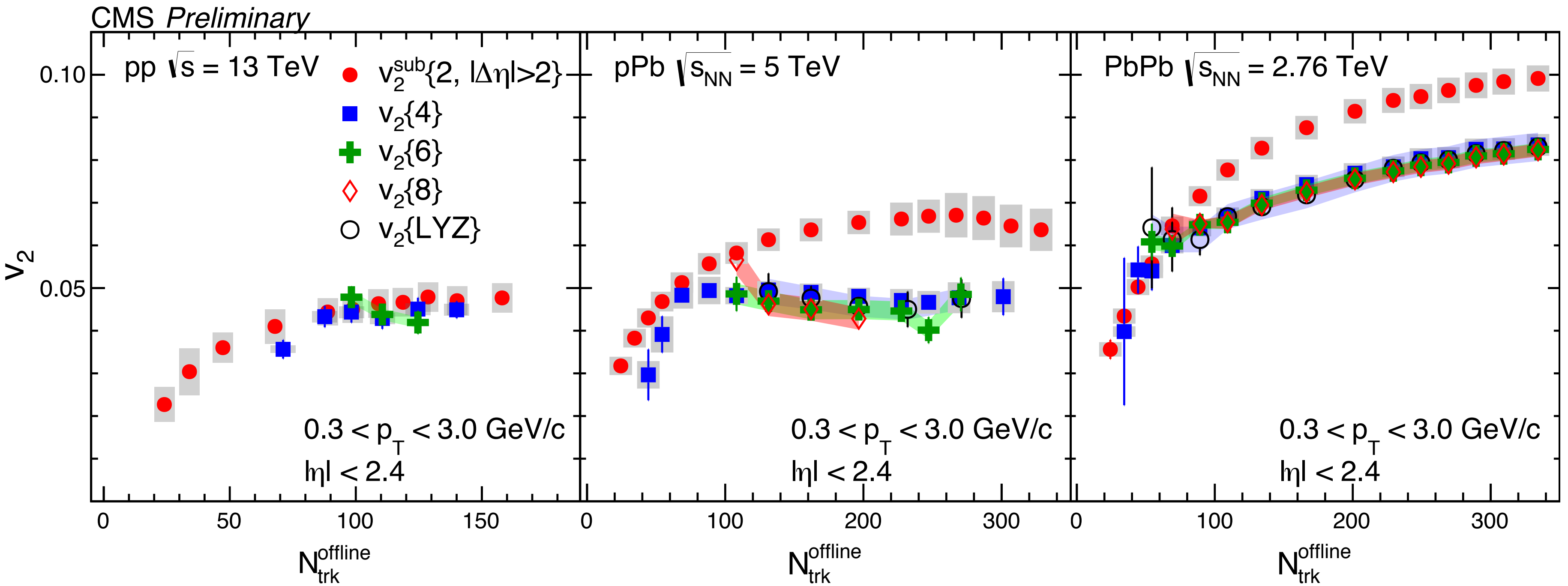
$c_2\{4\}$ and $c_2\{6\}$ in pp at different collision energies



CMS PAS HIN-16-010

- Multi-particle correlations are used to reduce jet correlations from the away side and to explore collective nature of the long-range correlations in pp, $v_2\{4\}$ and $v_2\{6\}$ are extracted
- Clear negative $c_2\{4\}$ at high multiplicities in pp at 13 TeV is seen $v_n\{4\} = \sqrt[4]{-c_n\{4\}}$
- and positive $c_2\{6\}$ $v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}$
- Statistical limitations

v_2 in pp compared to pPb and PbPb results



$v_2\{2\} \geq v_2\{4\} \approx v_2\{6\}$

collectivity!

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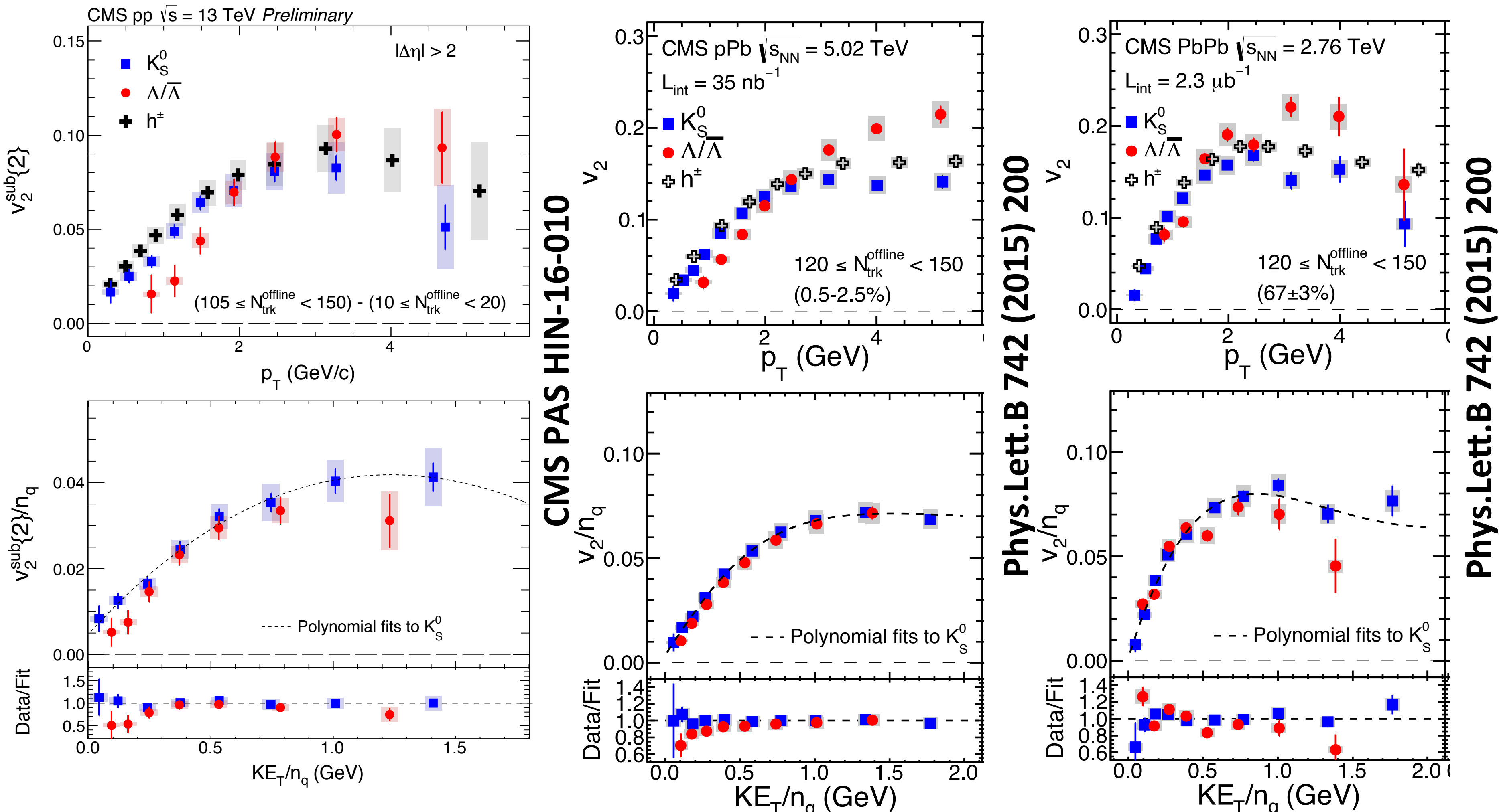
- Elliptic flow in pp measured using 2- and multi-particle correlations – compared to pPb and PbPb results
- $v_2\{2\}/v_2\{4\}(pp) \leq v_2\{2\}/v_2\{4\}(pPb)$ ← related to initial-state (IS) fluctuations
- smaller $v_2\{2\}/v_2\{4\}$ ← less IS fluctuating sources (PRL **112** (2014) 082301)

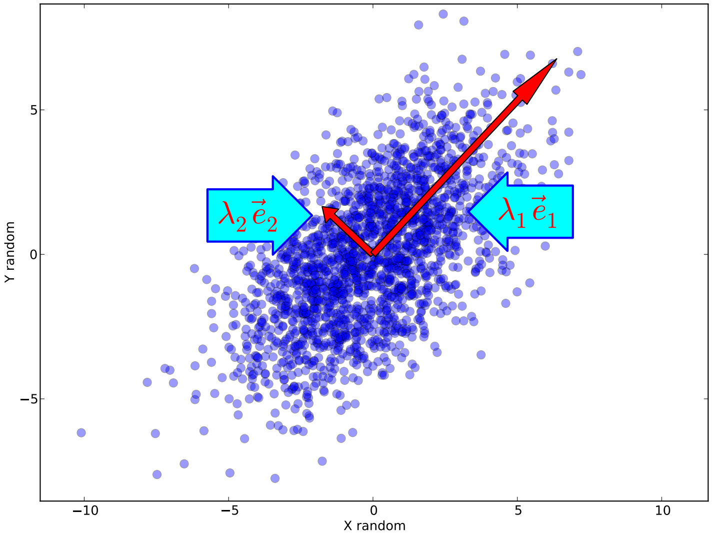
NCQ scaled v_2 in pp collisions compared to pPb and PbPb



collectivity!

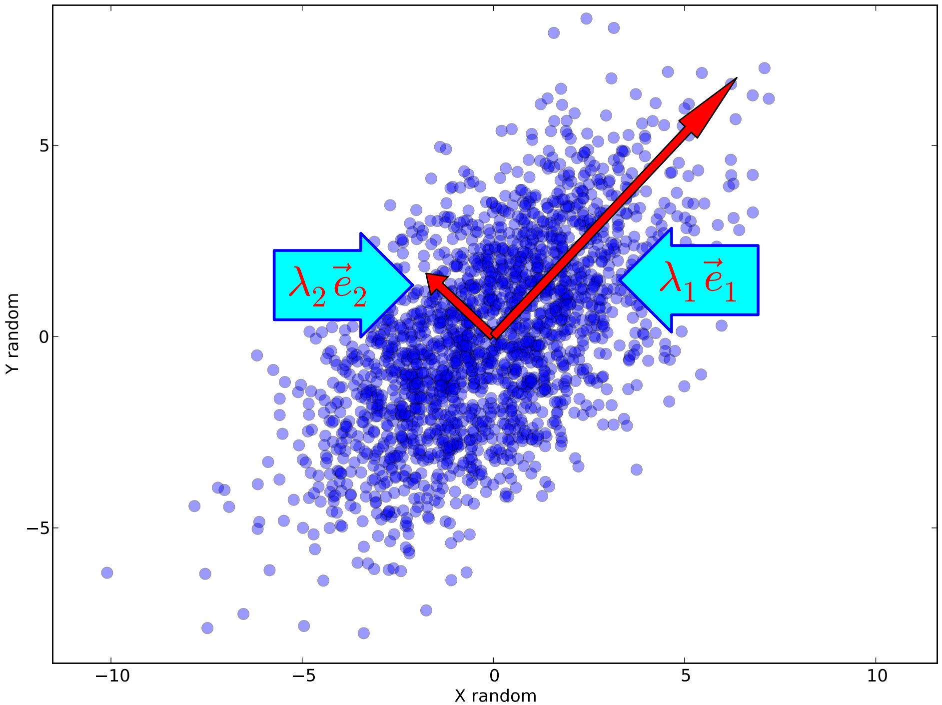
❖ Significant magnitude of the NCQ scaled v_2 in *pp,* comparable to the ones seen in pPb and PbPb collisions

Principal Component Analysis as a new tool to study flow



Principal Component Analysis (PCA) method

A simple 2D example



- Random data generated by 2D multivariate Gauss distribution

$$\vec{X}_n = (x_1, x_2, \ldots, x_n)$$
$$\vec{Y}_n = (y_1, y_2, \ldots, y_n)$$

- a matrix

$$\Sigma = \begin{bmatrix} \mathrm{var}(X) & \mathrm{cov}(X,Y) \\ \mathrm{cov}(X,Y) & \mathrm{var}(Y) \end{bmatrix}$$

- eigenvectors $\boldsymbol{e}_i$ and eigenvalues λ_i by diagonalizing Σ

$$[e]^T \Sigma [e] = diag(\lambda_1, \lambda_2)$$

- First Principal Component: eigenvector $\boldsymbol{e}_1$ points to maximum variance of data cloud. Its magnitude is $\sqrt{\lambda_1} e_1$
- Second Principal Component: eigenvector $\boldsymbol{e}_2$ points to the next maximum variance of data cloud. Its magnitude is $\sqrt{\lambda_2} e_2$

Initial-state inhomogeneity

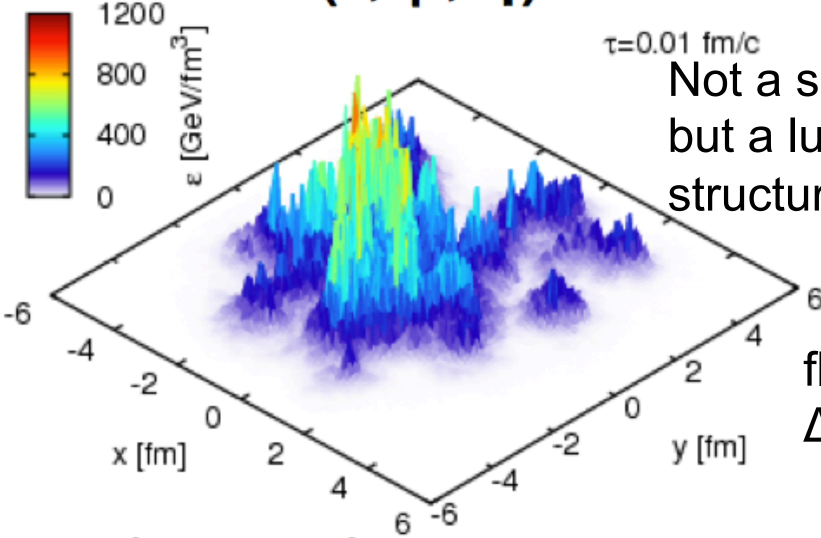
Initial state

$\varepsilon(r,\varphi,\eta)$

EbE hydro. $\longrightarrow$

Final state

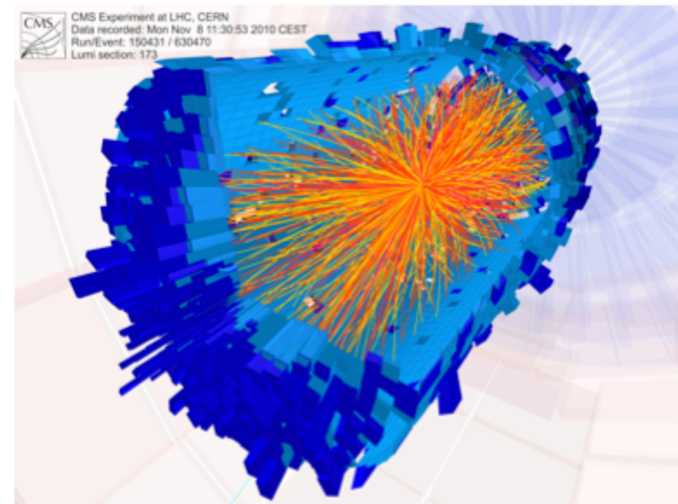
$f(p_T,\varphi,\eta)$



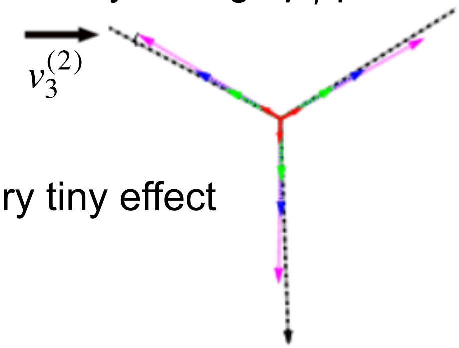
Not a smooth but a lumpy structure

fluctuations $\Delta\varepsilon(r,\phi,\eta)$

overlap zone in x-y



only for high-p_T particles



a very tiny effect

Example: sub-leading triangular flow

- ✧ The goal is to map initial-state and its fluctuations in 3D
- ✧ Local hotspots perturb the EP of a smooth medium, so $\Psi_n(p_T)$ contains information about initial-state fluctuations Phys.Rev.C **92** (2015) 034911
- ✧ Within hydrodynamics, initial-state fluctuations could appear as (sub-leading) flows

PCA method in hydrodynamic flow - prescription

Two very recent theoretical papers: R.S.Bhalerao, J-Y. Ollitrault, S.Pal and D.Teaney, Phys.Rev.Lett. 114 (2015) 152301 and A.Mazeliauskas and D.Teaney, Phys.Rev. C91 (2015) 044902 introduced the PCA as a new method to study hydrodynamics flows

❖ *“The simplest correlations are pairs. The **principal component analysis** is a method which extracts all the information from pair correlations in a way which facilitates comparison between theory and experiment.” J.-Y. Ollitrault*

In this analysis:

10.1103/PhysRevC.92.034911
arXiv:1503.01692
and other CMS analyses

❖ **Input**: two-particle Fourier coefficients measured as

$$V_{n\Delta} = \langle\langle \cos(n\Delta\phi) \rangle\rangle_S - \langle\langle \cos(n\Delta\phi) \rangle\rangle_B$$ where

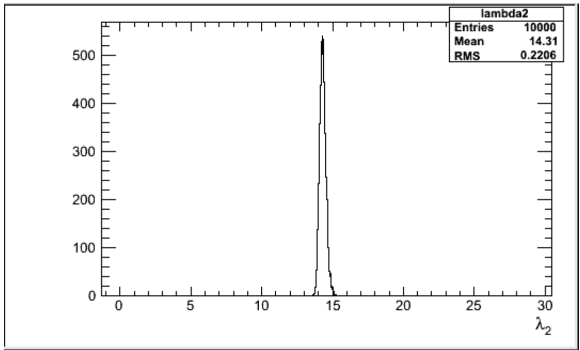
$\langle\langle \cos(n\Delta\phi) \rangle\rangle_S$ and $\langle\langle \cos(n\Delta\phi) \rangle\rangle_B$ are calculated for pairs with $|\Delta\eta|>2$

❖ 7 p_T bins ($0.3<p_T<3.0$ GeV/c); the eigenvalue problem of a matrix $[V_{n\Delta}(p_i,p_j)]$

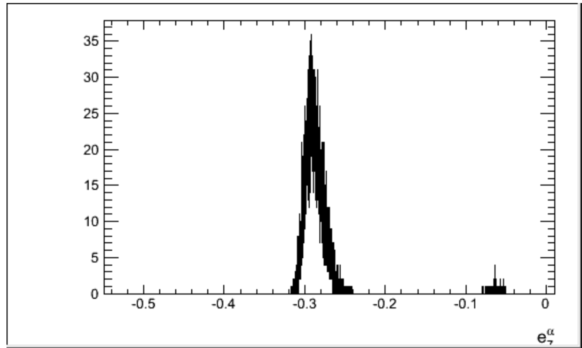
$$\begin{pmatrix} e^{(1)} & e^{(2)} & . & . & . & . & e^{(7)} \end{pmatrix} \begin{bmatrix} V_{n\Delta}(p_1,p_1) & V_{n\Delta}(p_2,p_1) & V_{n\Delta}(p_3,p_1) & . & . & . & . \\ V_{n\Delta}(p_1,p_2) & V_{n\Delta}(p_2,p_2) & V_{n\Delta}(p_3,p_2) & . & . & . & . \\ V_{n\Delta}(p_1,p_3) & V_{n\Delta}(p_2,p_3) & V_{n\Delta}(p_3,p_3) & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & V_{n\Delta}(p_7,p_7) \end{bmatrix} \begin{pmatrix} e^{(1)} \\ e^{(2)} \\ . \\ . \\ . \\ . \\ e^{(7)} \end{pmatrix} = diag\begin{pmatrix} \lambda^{(1)} & \lambda^{(2)} & . & . & . & . & \lambda^{(7)} \end{pmatrix}$$

PCA method in hydrodynamic flow - prescription

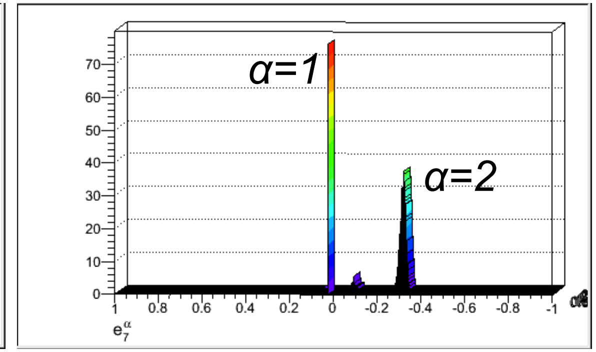
λ distribution, α=2



e distribution, α=2



α=2 signal 200 times smaller wrt α=1



CMS Preliminary

2.5<p_T<3.0 GeV/c

- The new introduced p_T dependent variable, **flow mode**, is defined as

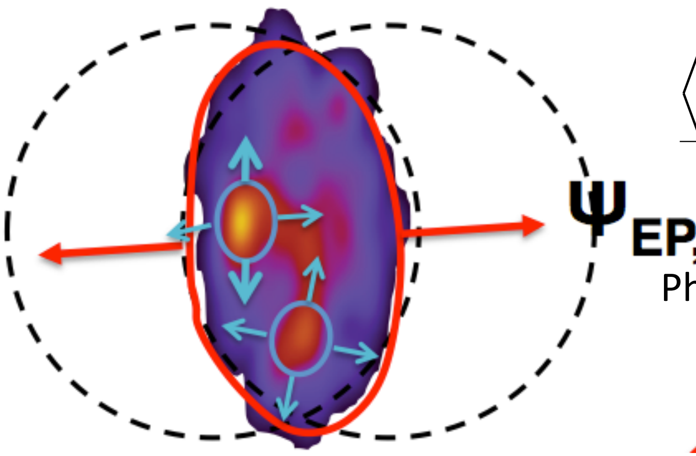
  $V_n^{(\alpha)}(p_i) = \sqrt{\lambda^{(\alpha)}} e^{(\alpha)}(p_i)$ where *α=1,…,7*

- corresponding single-particle flow mode $v_n^{(\alpha)}(p) = \dfrac{V_n^{(\alpha)}(p)}{\langle M(p)\rangle}$
- experimental data ➔ $V_{n\Delta}(p_i,p_j)$ ➔ it has its own statistical error $\Delta V_{n\Delta}(p_i,p_j)$
- The error propagation through $V_n^{(\alpha)}$ up to $v_n^{(\alpha)}$
- $\Delta\lambda^\alpha$ and $\Delta \mathbf{e}^\alpha$ as RMS of the distributions like ones shown above. Matrix elements $V_{n\Delta}$ were perturbed (10k times) within its $\Delta V_{n\Delta}$ → matrix $[V_{n\Delta}]$ **nonlinearly** perturbed

Factorization breaking - connection to the PCA

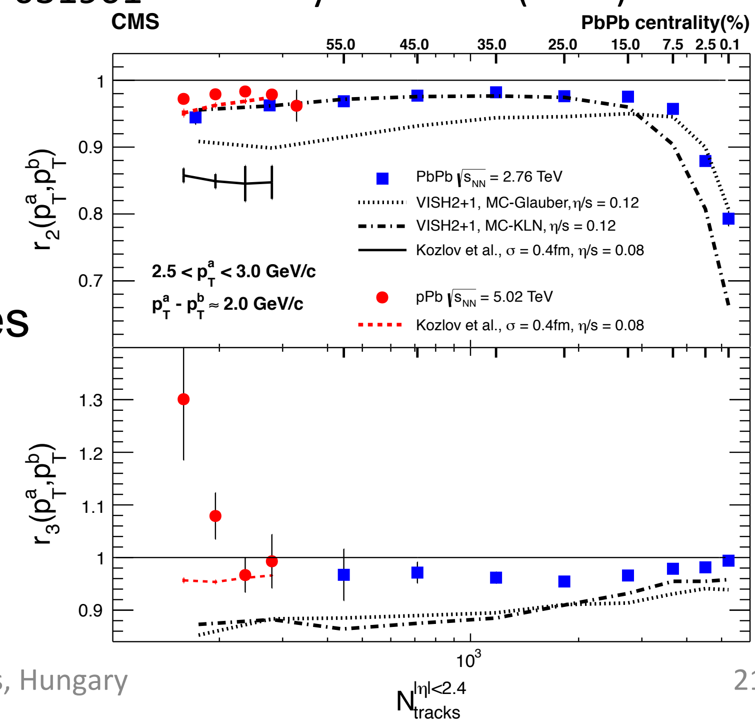
- Initial-state fluctuations → the EP (Ψ_n) depends on p_T *and on* η → factorization is broken. New observable introduced: $r_n = \dfrac{V_{n\Delta}(p_{T1},p_{T2})}{\sqrt{V_{n\Delta}(p_{T1},p_{T1})}\sqrt{V_{n\Delta}(p_{T2},p_{T2})}} =$

$$\frac{\left\langle v_n(p_{T1})v_n(p_{T2})\cos\left[n(\Psi_n(p_{T1})-\Psi_n(p_{T2}))\right]\right\rangle}{\sqrt{v_n^2(p_{T1})v_n^2(p_{T2})}} = \begin{cases} 1 & \text{holds} \\ <1 & \text{brakes} \\ >1 & \text{non-flow} \end{cases}$$



Phys.Rev. C87 (2013) 031901

Phys.Rev. C87 (2013) 034913



Phys. Rev. C **92** (2015) 034911 *(arXiv:1503.01692)*

- If there is only one principal component for each harmonic *n* → $V_{n\Delta}(p_i,p_j)$ factorizes

- r_n i.e. $V_{n\Delta}(p_i,p_j)$ results are partially integrated, while mutually orthogonal eigenmodes contain all information

Factorization breaking - connection to the PCA

❖ The given harmonic order *n* has also higher (α>2) eigenmodes ordered from largest to smallest, while in r_n they are not clearly distinguished

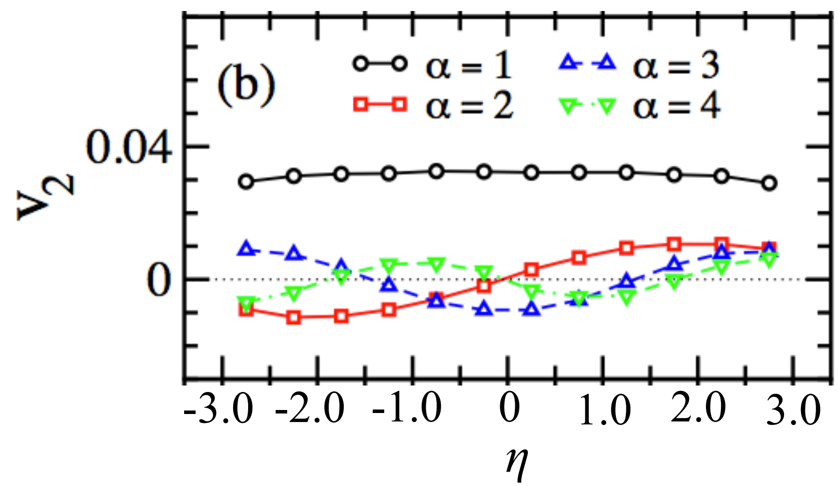
❖ The PCA can approximately reconstruct two-particle $V_{n\Delta}(p_i,p_j)$ coefficients

$$V_{n\Delta}(p_i,p_j) \approx \sum_{\alpha=1}^{k\leq N_b} V_n^{(\alpha)*}(p_i) V_n^{(\alpha)*}(p_j) \qquad \text{where } N_b=7$$

which can be used to calculate the factorization breaking ratio r_n

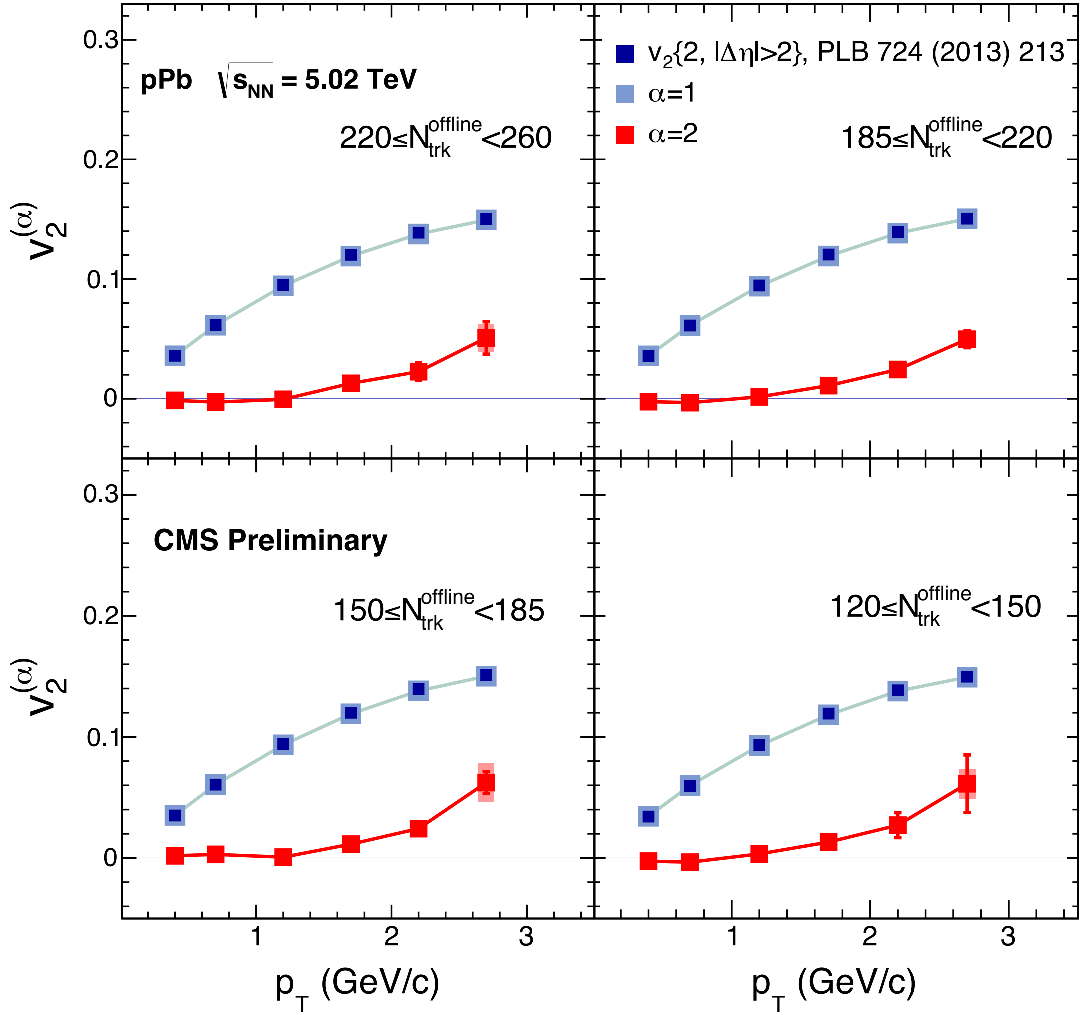
❖ So, the PCA is a good tool for analysis in hydrodynamics with fluctuations in the initial state

❖ Note that the PCA uses the whole p_T range simultaneously to extract the information on both leading and sub-leading flow modes



Phys.Rev.Lett. 114 (2015) 152301

Results – elliptic flows in pPb collisions

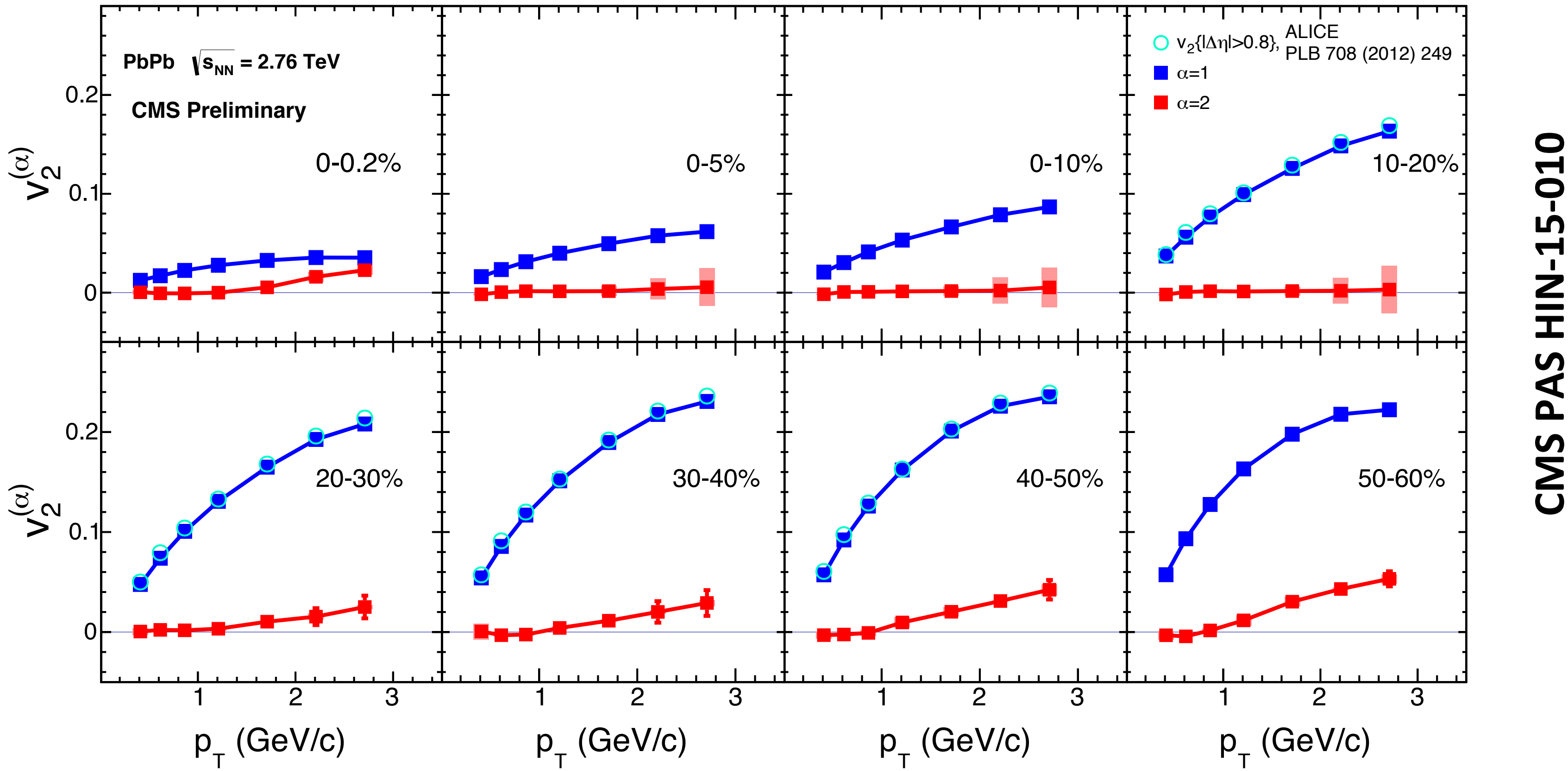


- The leading flow mode, *α=1*, practically identical to the v_2 measured using two-particle correlations
- The sub-leading flow mode, *α=2*, is essentially equal to zero at small p_T and increases up to 4-5% going to the high-p_T

CMS PAS HIN-15-010

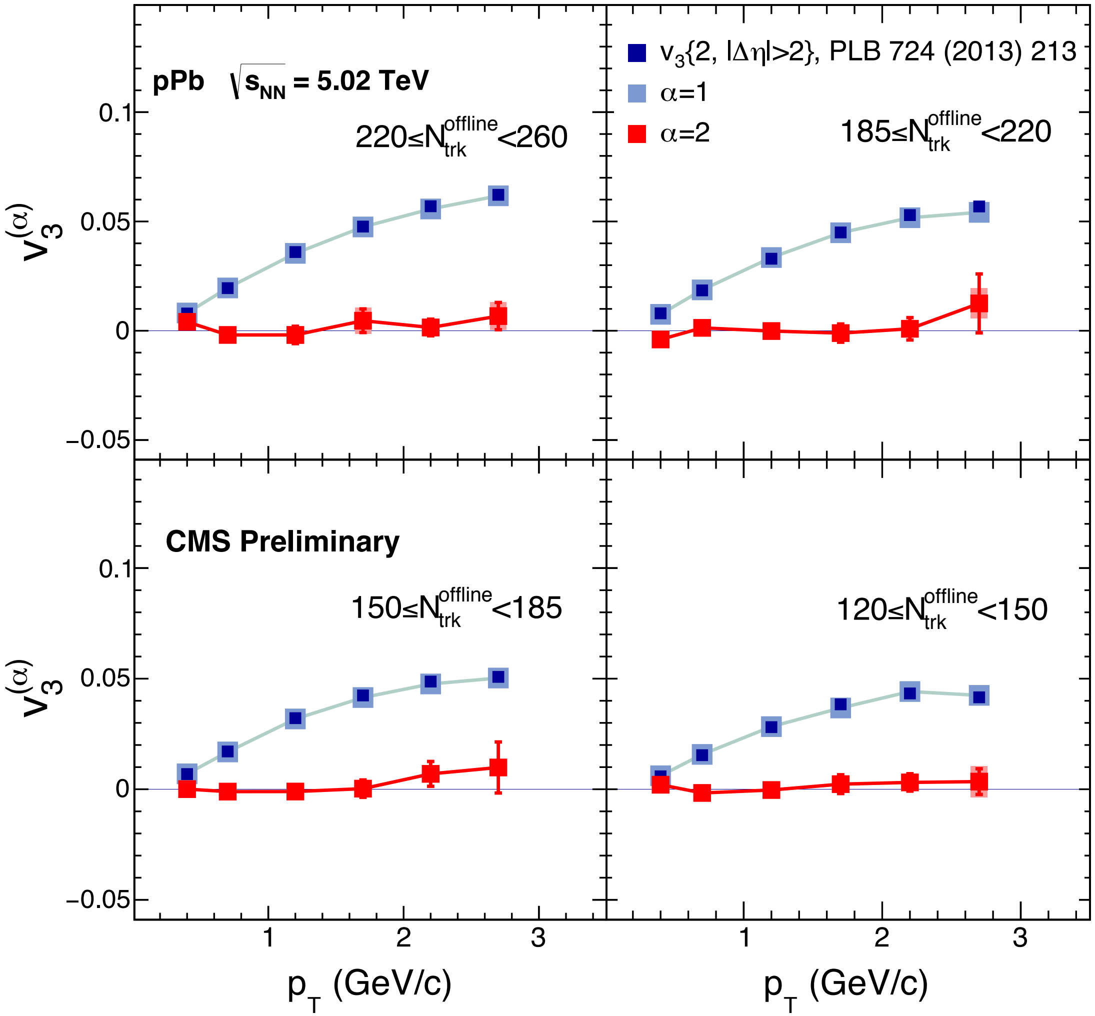
- The first experimental measurement of the elliptic sub-leading flow
- Systematical uncertainties small or comparable to statistical ones only at high-p_T

Results – elliptic flows in PbPb collisions



- The leading flow mode, *α=1,* essentially equal to the v_2 measured by ALICE using two-particle correlations
- The sub-leading flow mode, *α=2,* is positive at UCC and for collisions with centralities above 20%
- In the region 0-20% centrality comparable with zero
- Similar behavior wrt the r_2 results (10.1103/PhysRevC.92.034911, *arXiv: 1503.01692)*

Results – triangular flows in pPb collisions

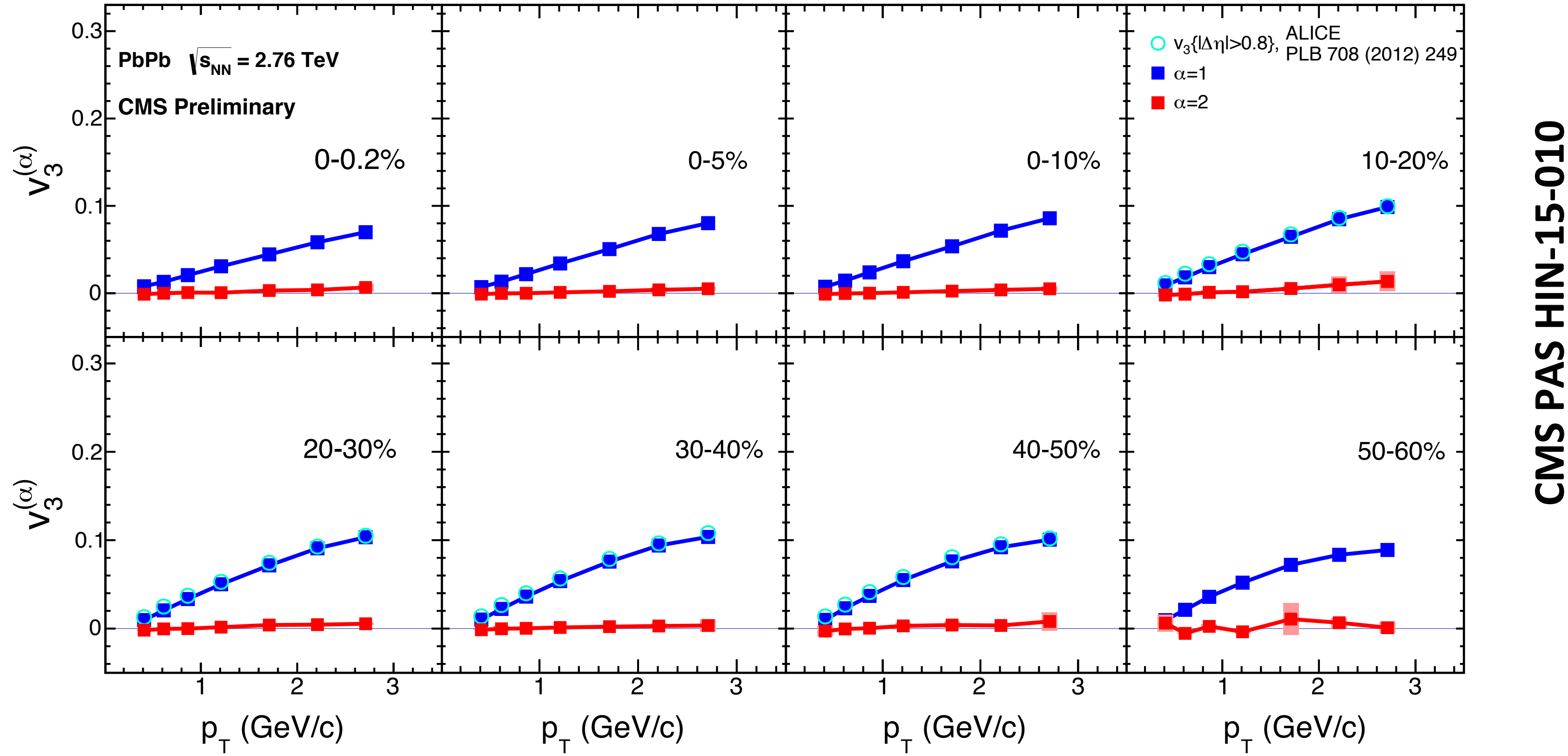


- The leading triangular flow mode, *α=1,* nearly identical to the v_3 measured using two-particle correlations
- The sub-leading flow mode, *α=2,* is comparable with zero within the given uncertainties.

CMS PAS HIN-15-010

- The first experimental measurement of the triangular sub-leading flow

Results – triangular flows in PbPb collisions



- Again, the leading flow mode, *α=1,* essentially equal to the v_3 measured by ALICE using two-particle correlations
- The sub-leading flow mode, *α=2,* is, within the uncertainties, equal to zero
- Results have a similar centrality dependence to that observed for r_3 (Phys. Rev C **92** (2015) 034911, *arXiv: 1503.01692)*

Conclusions

- The v_2 and v_3 measured up to 100 GeV/c in PbPb at 5 TeV
- The elliptic and triangular flow in pp collisions at the LHC energies
- The sub-leading flow modes are for the first time experimentally measured in both pPb and PbPb collisions at the LHC energies
- The behavior of the sub-leading elliptic flow modes is in a qualitative agreement with the r_2 factorization-breaking results
- The sub-leading triangular flow modes in both collision system is small if not zero showing that the triangular flow factorizes much better than the elliptic flow
- These results could help in better understanding of the initial-state fluctuations