Latest QCD Results on Pb-Pb Collisions from CMS

J. Milošević

University of Belgrade, Faculty of Physics and Vinča Institute of Nuclear Sciences,

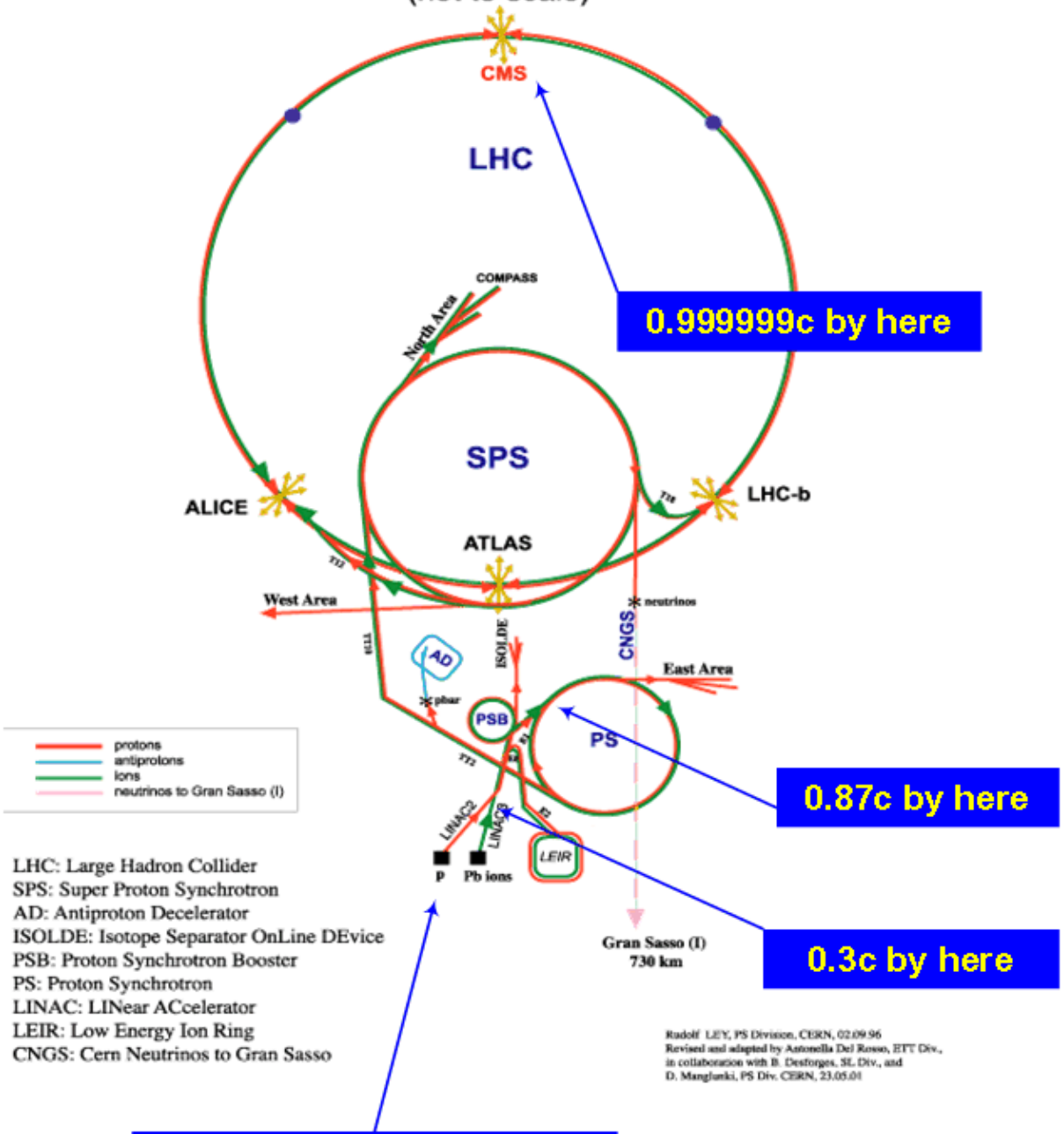
Belgrade, Serbia

on behalf of the CMS Collaboration

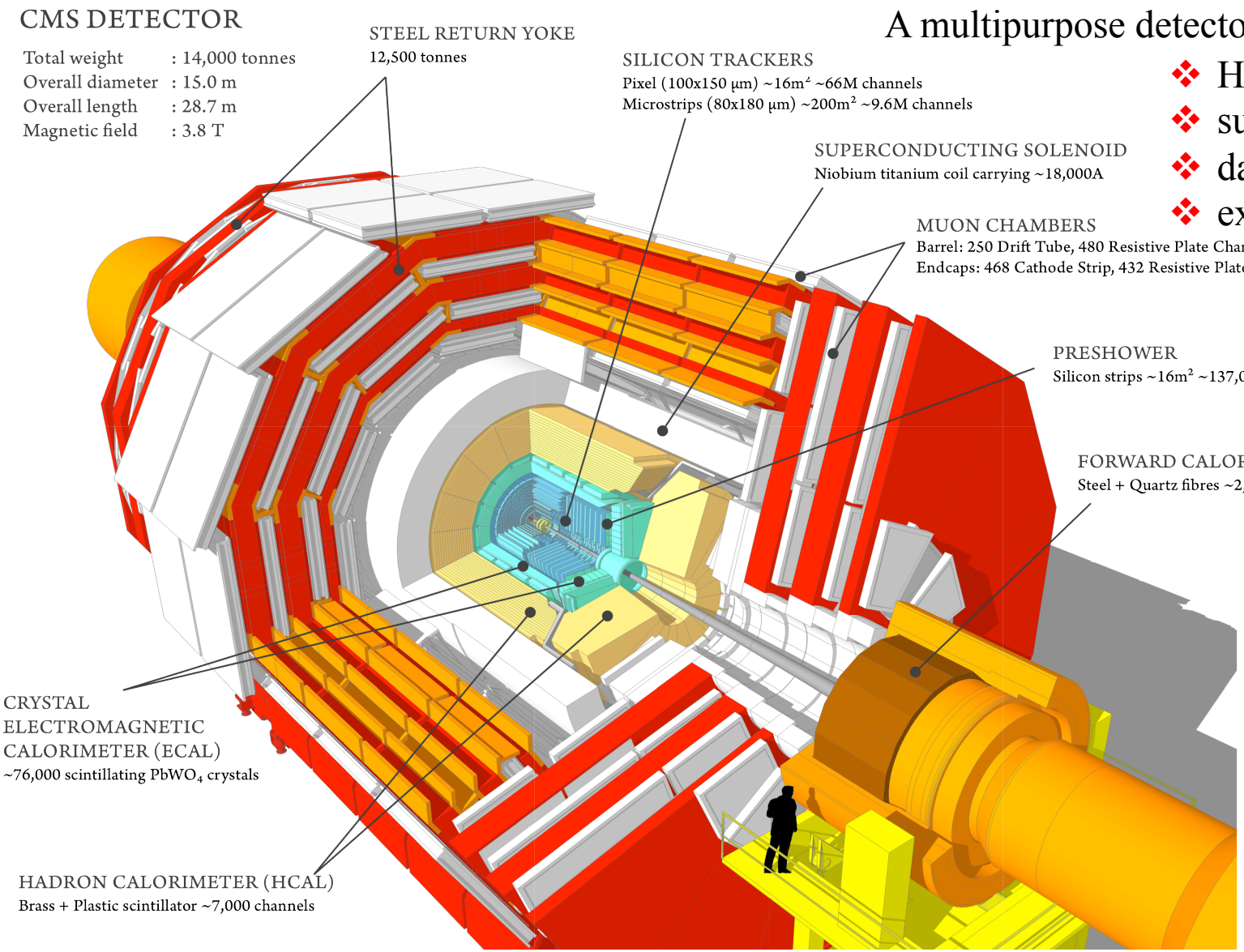
Outline

- CERN and CMS
- Measurements of Fourier coefficients
- Two-particle azimuthal correlations as a tool to study both jets and azimuthal anisotropy
- Comparison of the obtained results
- Conclusions

CERN Accelerators
(not to scale)



Schematic view of the CMS detector



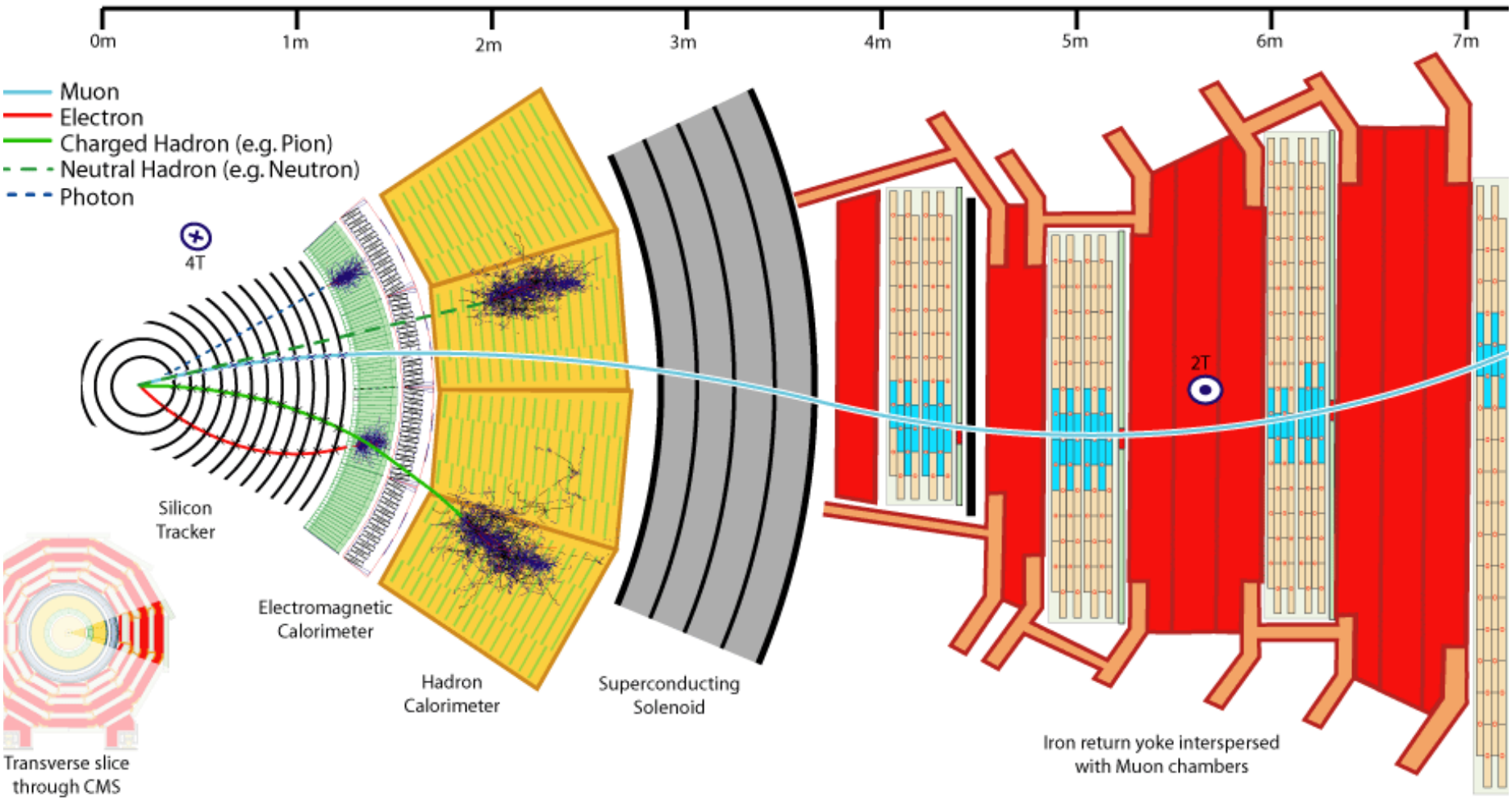
A multipurpose detector to search for:

- Higgs particle
- supersymmetry
- dark matter
- extra dimensions

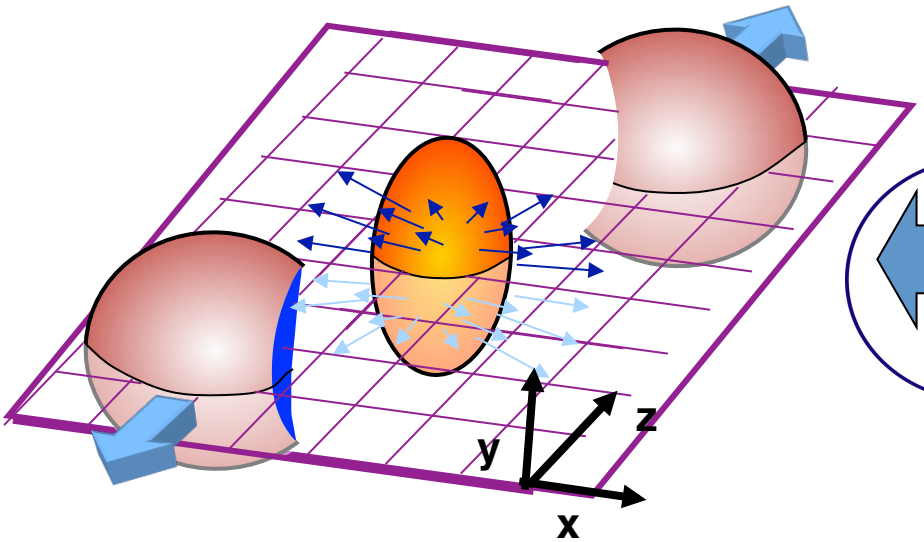
Although designed to study *pp* collisions, CMS is well suited to study heavy ion physics too

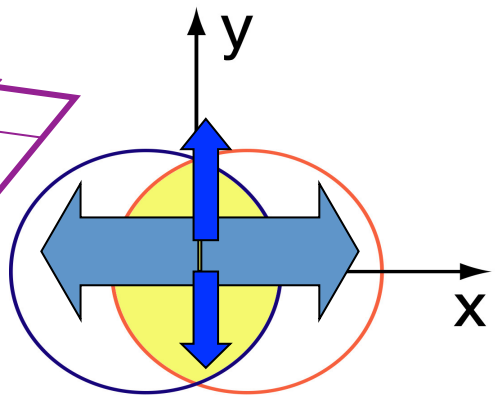
Principles of particle detection within different CMS detector layers

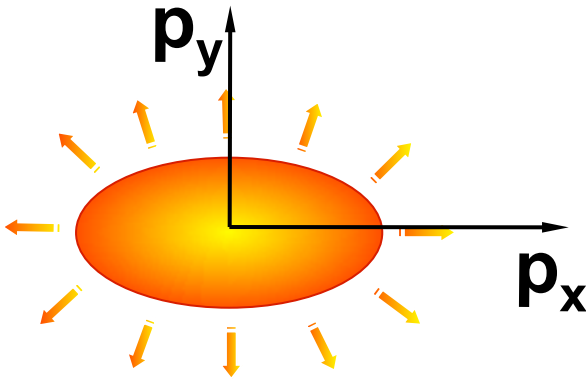
A slice through CMS detector in a plane perpendicular to the beam axis



A drawing about the elliptic flow appearance in a non-central collision

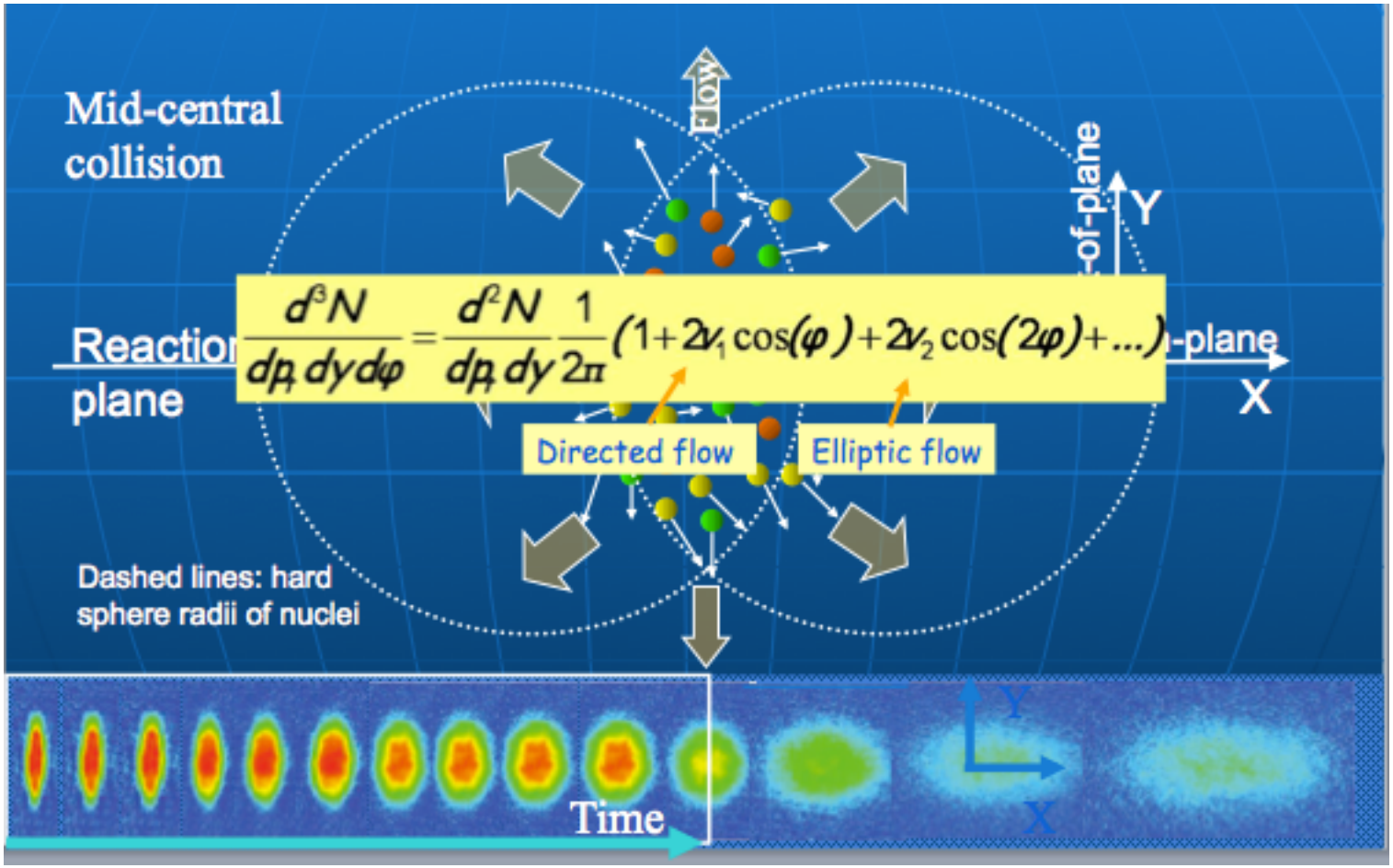






- The elliptic flow is one of, but most famous, forms in which collective movements appear
- Pressure gradient $\nabla p_x > \nabla p_y$ converts
spatial anisotropy $\longrightarrow$ momentum anisotropy $\longrightarrow$ particle yield anisotropy
- Experimentally it is observed as an azimuthally anisotropic distribution of particles measured with respect to the reaction plane (event plane)
- Event plane is constructed in each event from emitted particles themselves

Fourier decomposition of azimuthal angle particle distribution

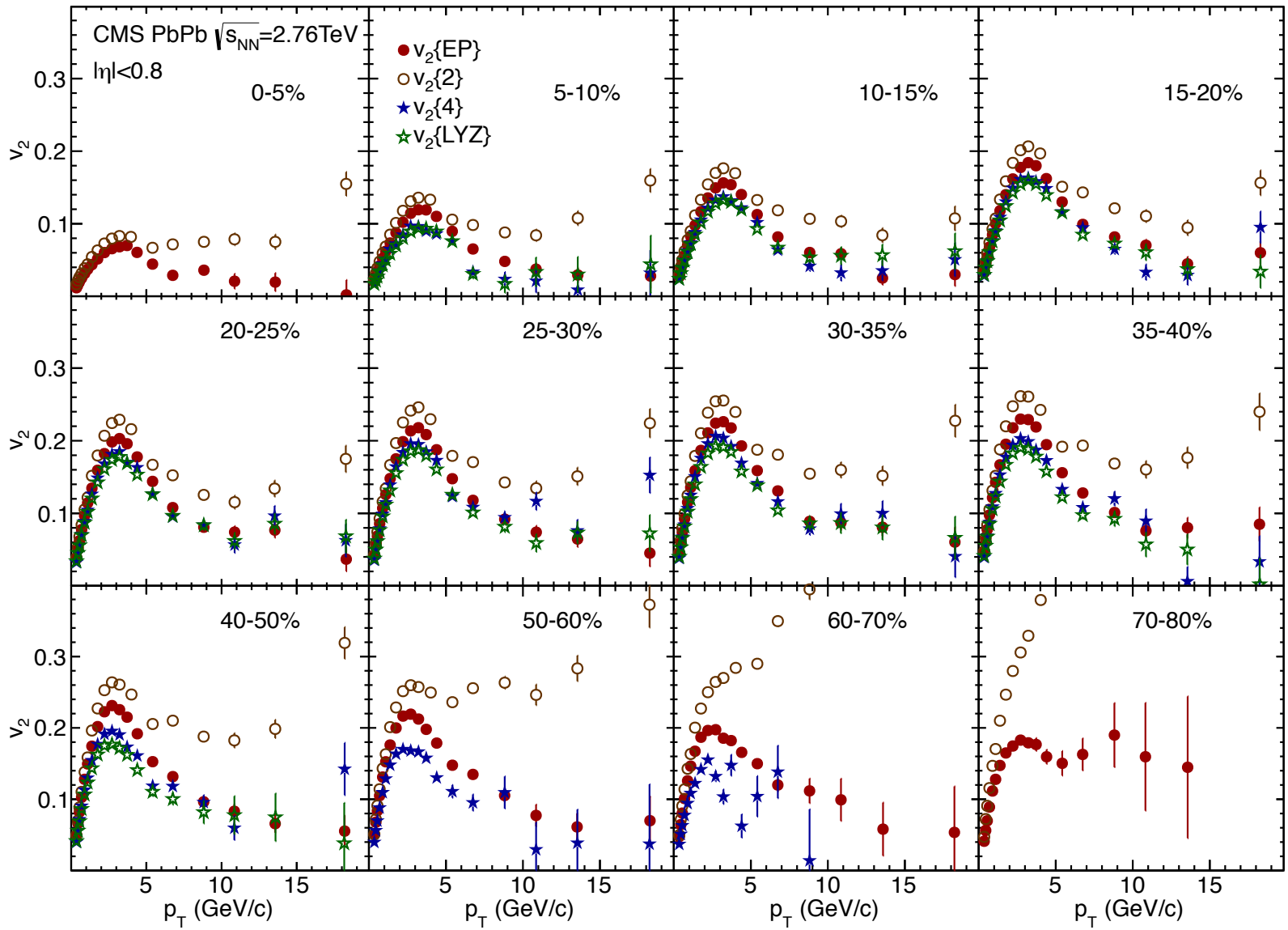


$$\frac{d^3N}{dp_t\,dy\,d\varphi} = \frac{d^2N}{dp_t\,dy}\frac{1}{2\pi}\left(1+2v_1\cos(\varphi)+2v_2\cos(2\varphi)+\ldots\right)$$

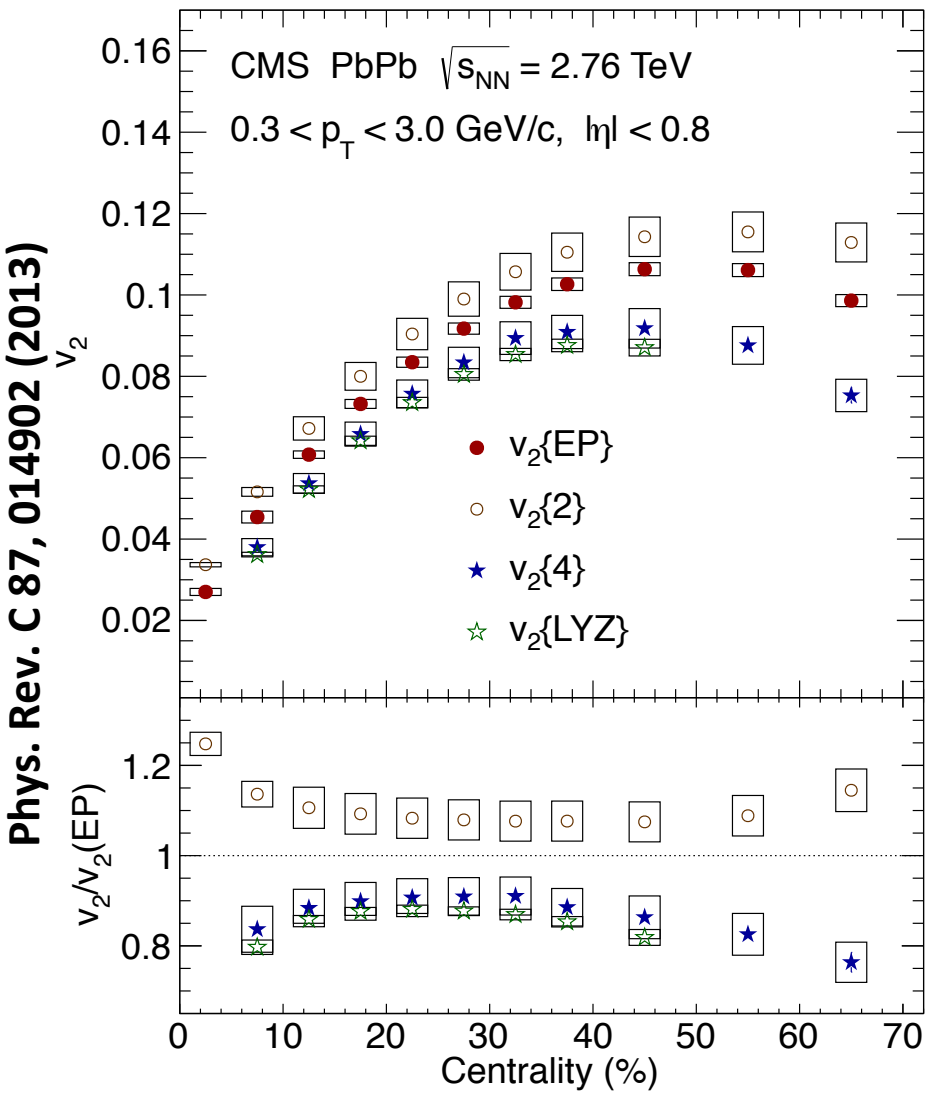
- Beside the event plane, there are cumulant and Lee-Yang Zero method
- The 2-particle azimuthal correlation method is reused in order to get both, azimuthal anisotropy and jet features, simultaneously

The v_2 vs p_T for 12 centralities; 4 methods compared

Phys. Rev. C 87, 014902 (2013)



The v_2 *vs* centrality; 4 methods compared

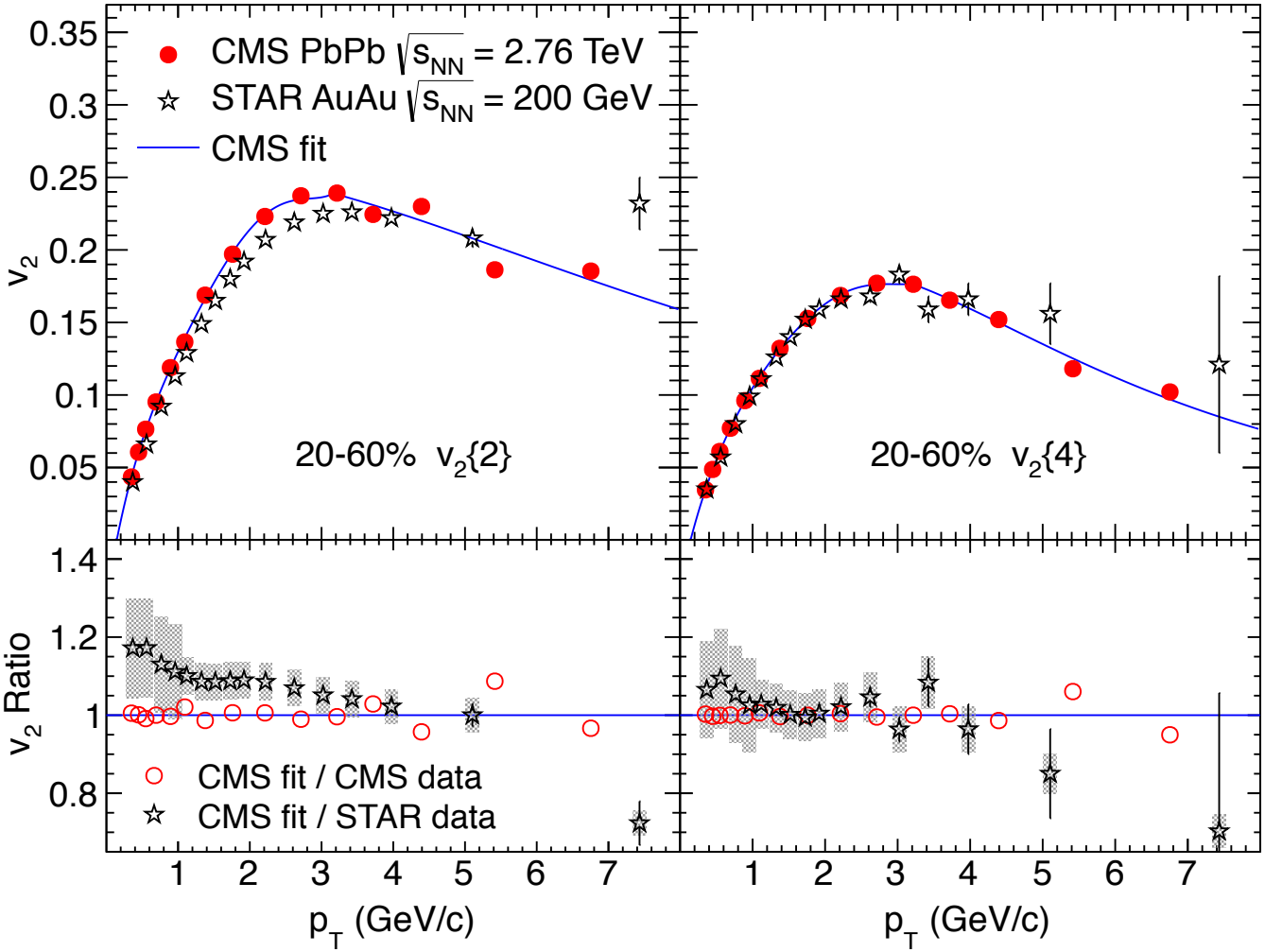


Phys. Rev. C 87, 014902 (2013)

- $v_2\{2\}$ cumulants is equivalent to 2-particle azimuthal correlations. $v_2\{4\}$ cumulant should remove any n-particle correlation where n=2 or 3
- In principle, LYZ method should remove any n-particle correlation, but it works only if number of flow particles dominates
- The v_2 strength is ordered from the highest, obtained with 2-nd order cumulants, up to the lowest obtained with LYZ method
- The differences in the methods (10% up for $v_2\{2\}$ and 10 % down for $v_2\{4\}$) are understood in terms of their sensitivity to initial state eccentricity fluctuations. Larger effect is seen in most central and most peripheral collisions that could be due to nonflow correlations

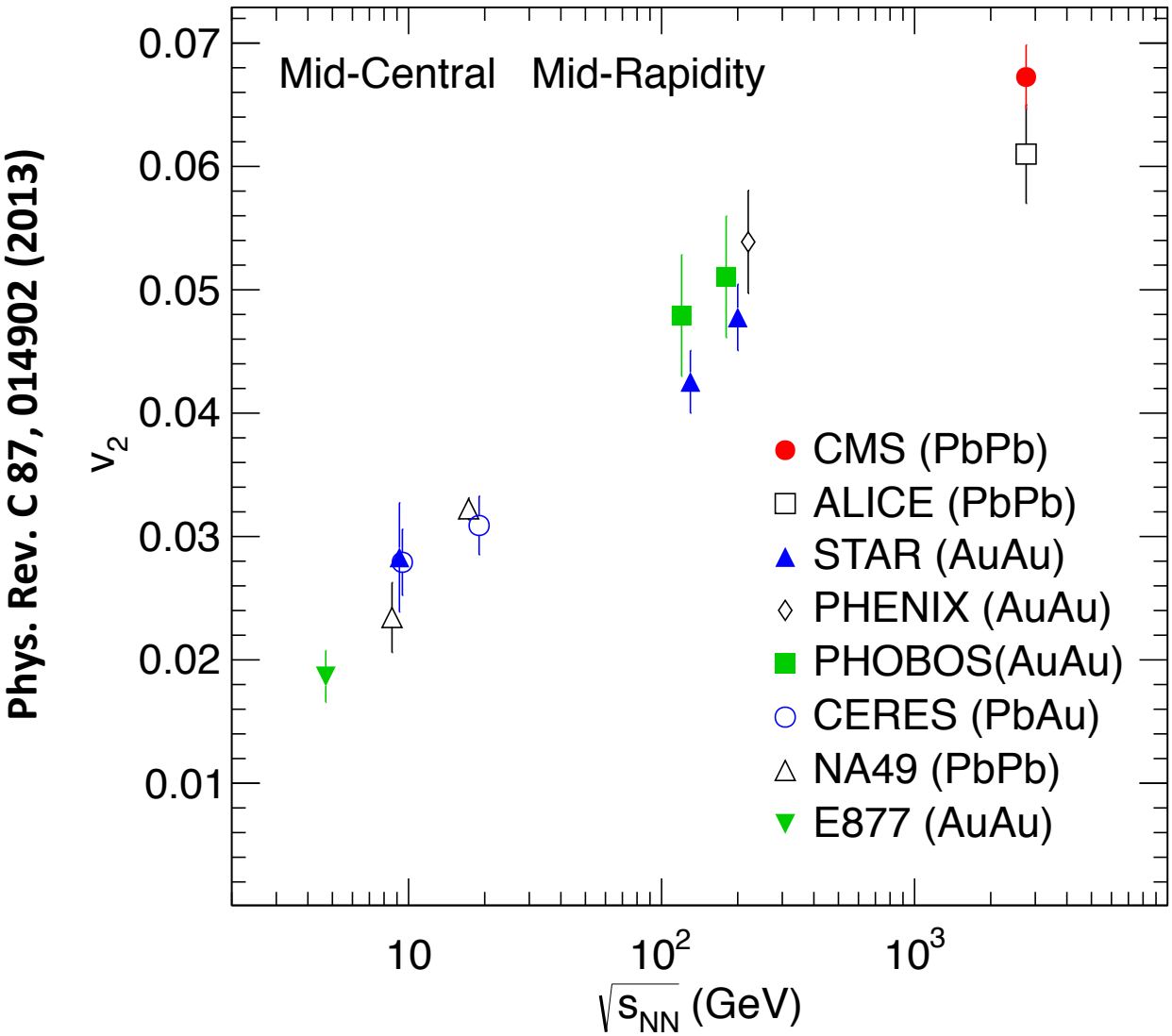
The v_2 compared to the lower RHIC energy

Phys. Rev. C 87, 014902 (2013)



While the relative difference in the $v_2\{2\}$ between the LHC and the RHIC energy is about to 10-15%, for the $v_2\{4\}$ it is smaller than 5% despite the large increase in the center-of-mass energy

The $\sqrt{s_{NN}}$ dependence of the integrated v_2



- The v_2 dependence is spanned over huge range of center-of-mass energy starting from AGS energy, through SPS and RHIC energies up to 2.76TeV LHC energy

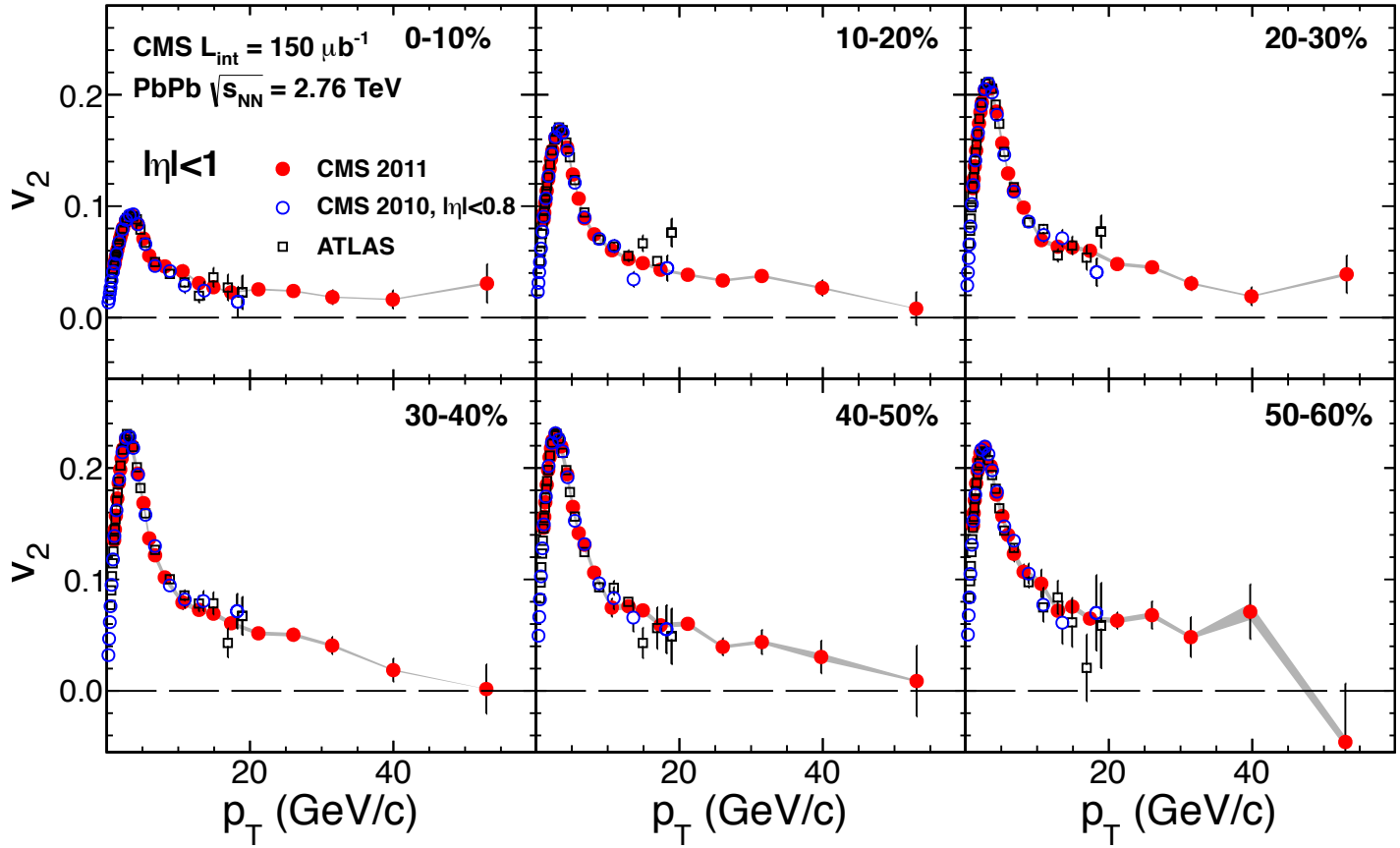
Approximately, the v_2 increase logarithmically with $\sqrt{s_{NN}}$

CMS and ALICE results on v_2 are in a rather good agreement

The comparison is only approximate

CMS elliptic anisotropy vs p_T and centrality in PbPb@2.76TeV

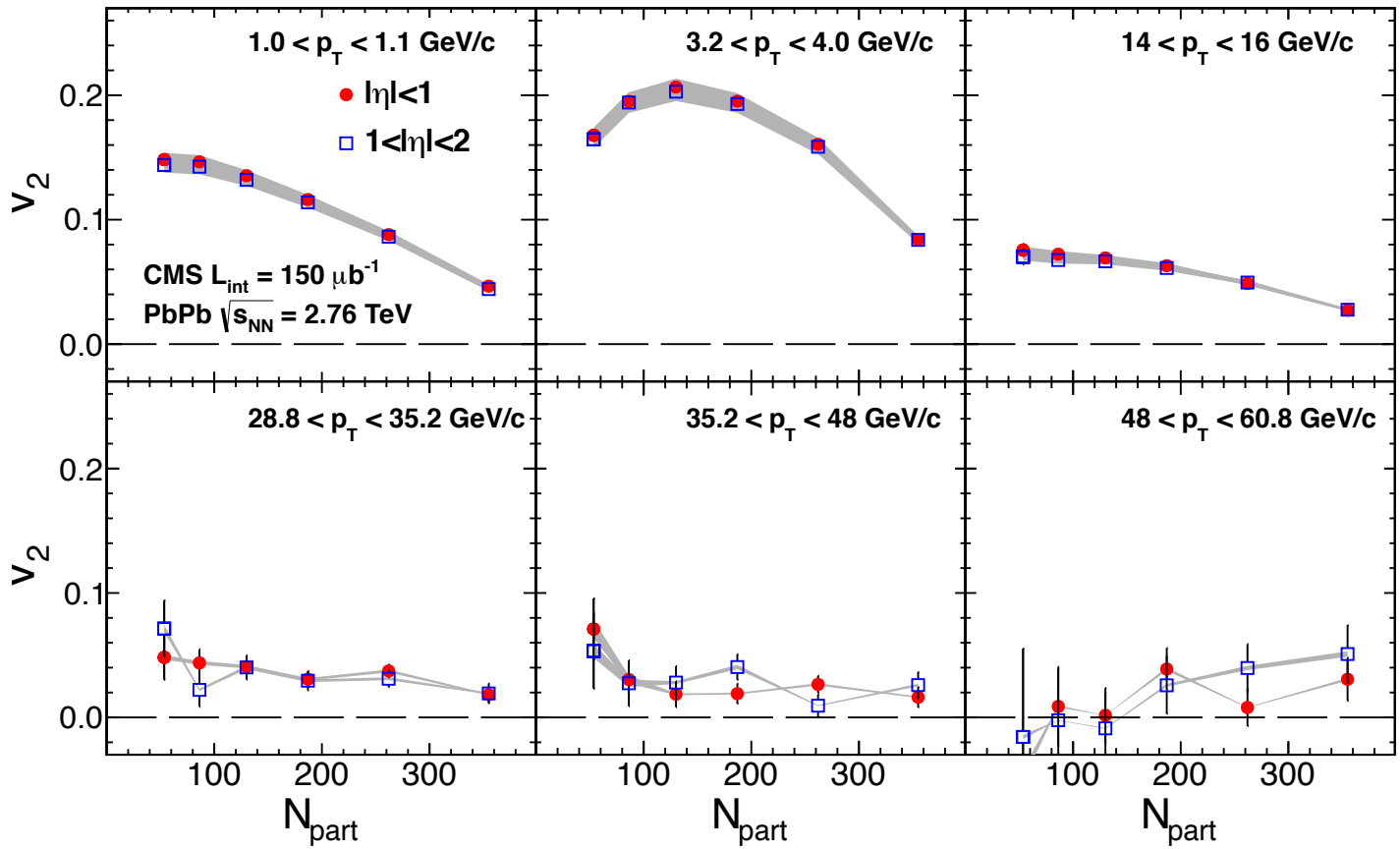
Phys. Rev. Lett. 109, 022301 (2012)



- The event plane (EP) is constructed from energy deposited in HF calorimeters
- Fourier flattening is used to correct for non-uniformities of the EP distribution
- The strong CMS magnet allowed to measure accurately v_2 up to 60 GeV/c
- The p_T and centrality dependence show an expected behavior

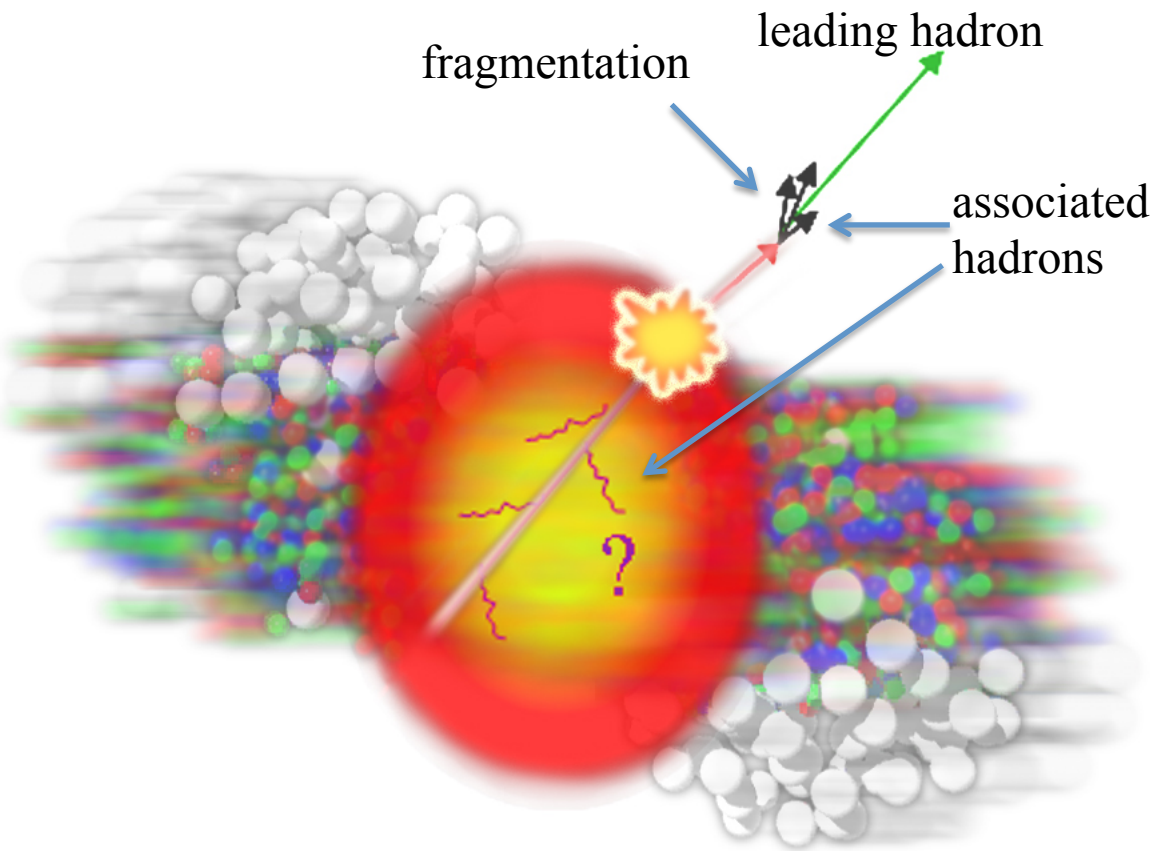
CMS elliptic anisotropy vs p_T and centrality in PbPb@2.76TeV another view

Phys. Rev. Lett. 109, 022301 (2012)



- v_2 integrated over given p_T intervals and ploted *vs* centrality represented via N_{part} calculated using Glauber model
- Again we see expected behavior

Jets in heavy-ion collisions

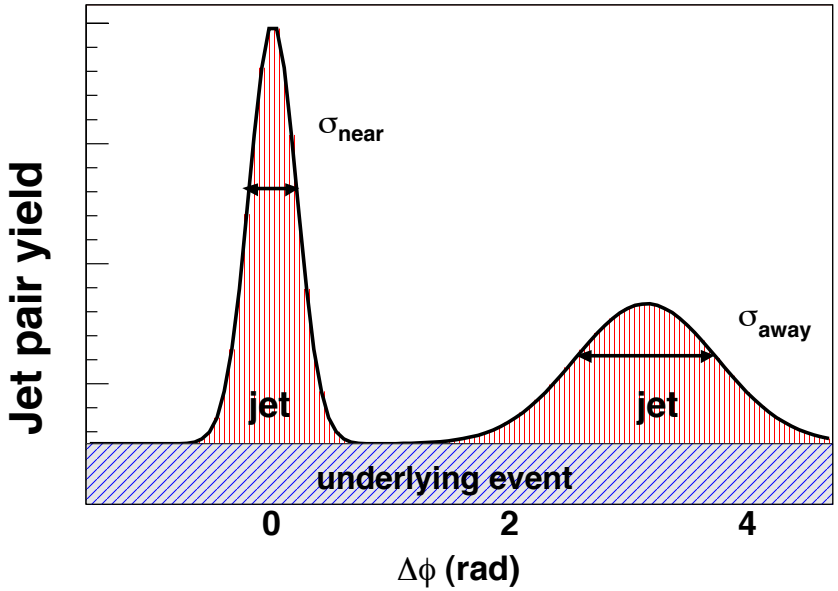


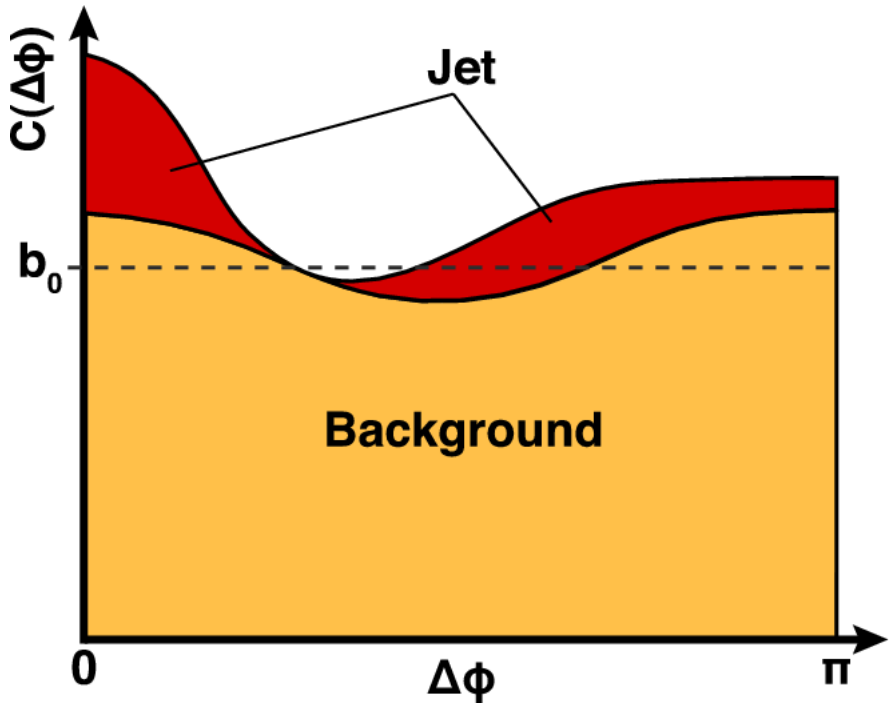
- In heavy-ion collisions, jets could emerge in fragmentation of colliding partons
- Correlating in $\Delta\phi$ the leading (trigger) hadron within certain p_T range with associated hadrons with lower p_T one can get jet signal in a form of di-hadron correlation function
- Within the same signal, azimuthal anisotropy is also present as a cosine-like contribution

Jet features (number of particles associated to a jet and its width) could be obtained statistically by analyzing the distribution of the azimuthal angle difference between the trigger and associated particles.

Methodology

$$C(\Delta\phi) = \frac{N^{same}(\Delta\phi)}{N^{mixed}(\Delta\phi)} \cdot Norm.Fact.$$





$$C(\Delta\phi) = P_0 + J_1(\Delta\phi) + J_2(\Delta\phi)$$

$$C(\Delta\phi) = P_0(1 + 2v_2^a v_2^t \cos(2\Delta\phi)) + J_1(\Delta\phi) + J_2(\Delta\phi)$$

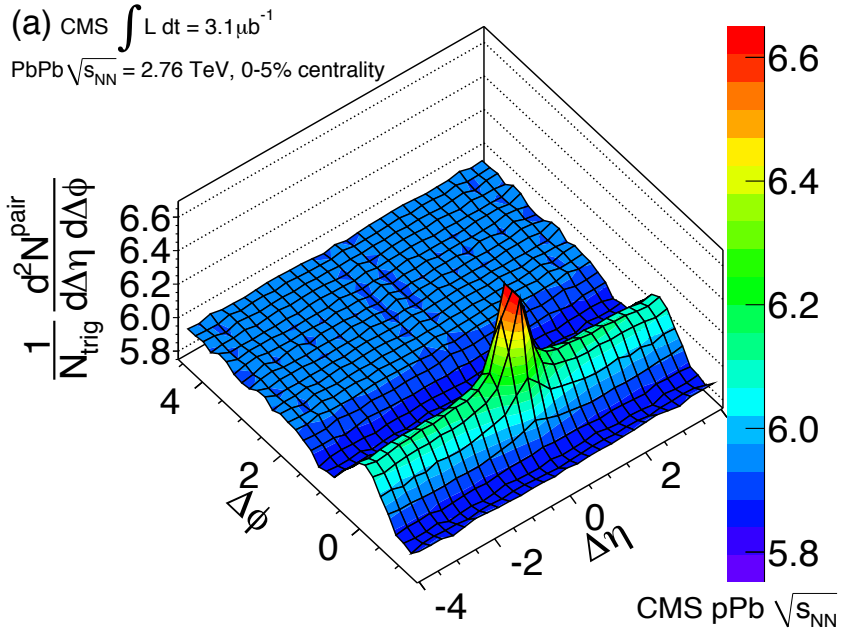
where $J_1(\Delta\phi) = \frac{P_1}{\sqrt{2\pi}\sigma_1}\exp(-\frac{\Delta\phi^2}{2\sigma_1^2})$ and $J_2(\Delta\phi) = \frac{P_2}{\sqrt{2\pi}\sigma_2}\exp(-\frac{(\Delta\phi-\pi)^2}{2\sigma_2^2})$

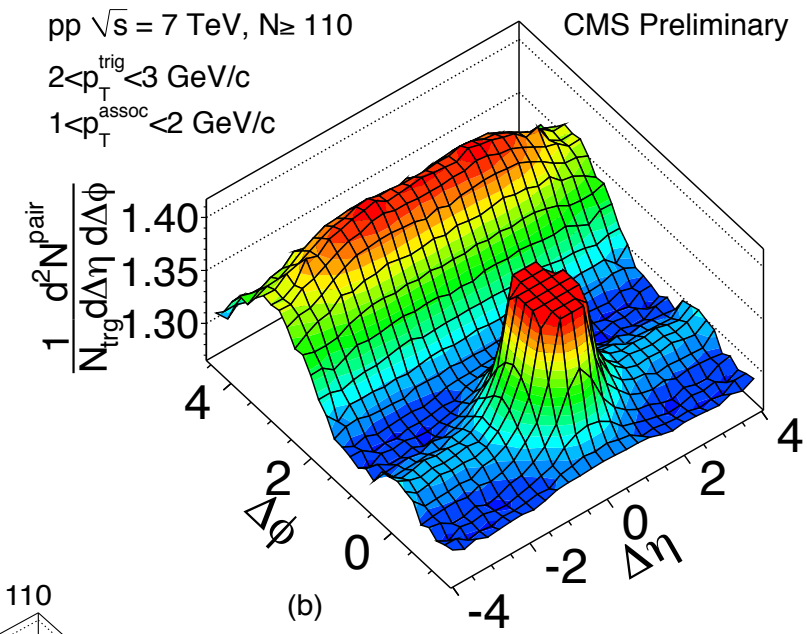
Here, the subscript 1 (2) refers to the near (away) jet

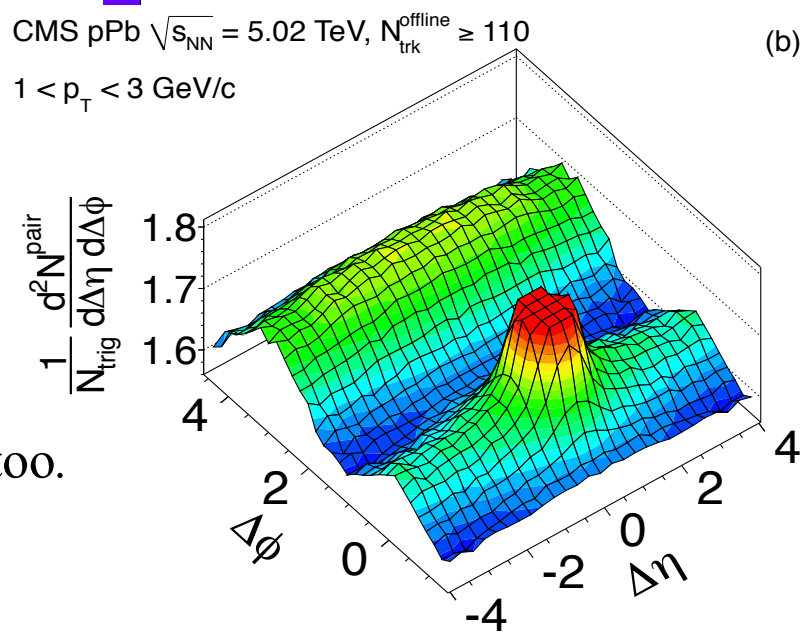
In a more realistic case, Fourier harmonics of higher orders are included

Beside these two, there are other sources of the correlations as femtoscopic correlations, resonances, momentum conservation, photon conversion …

Examples of 2-dimensional dihadron correlations





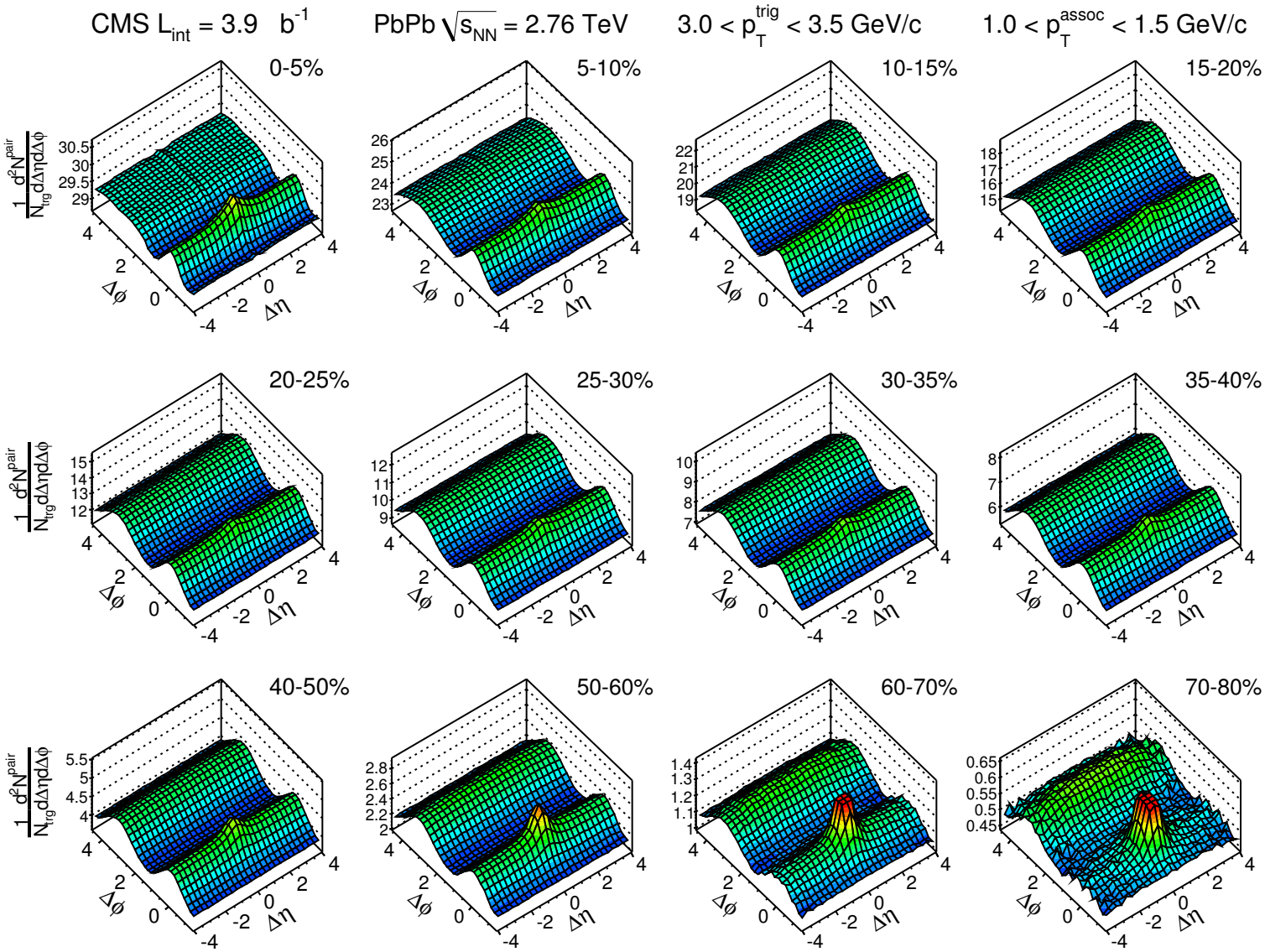


Beside central *PbPb* collisions, the ridge is seen in high-multiplicity *pPb* and even in high-multiplicity *pp* collisions too.

The structure of 2-dim correlation in *pp* is very similar to the one in *pPb* collisions

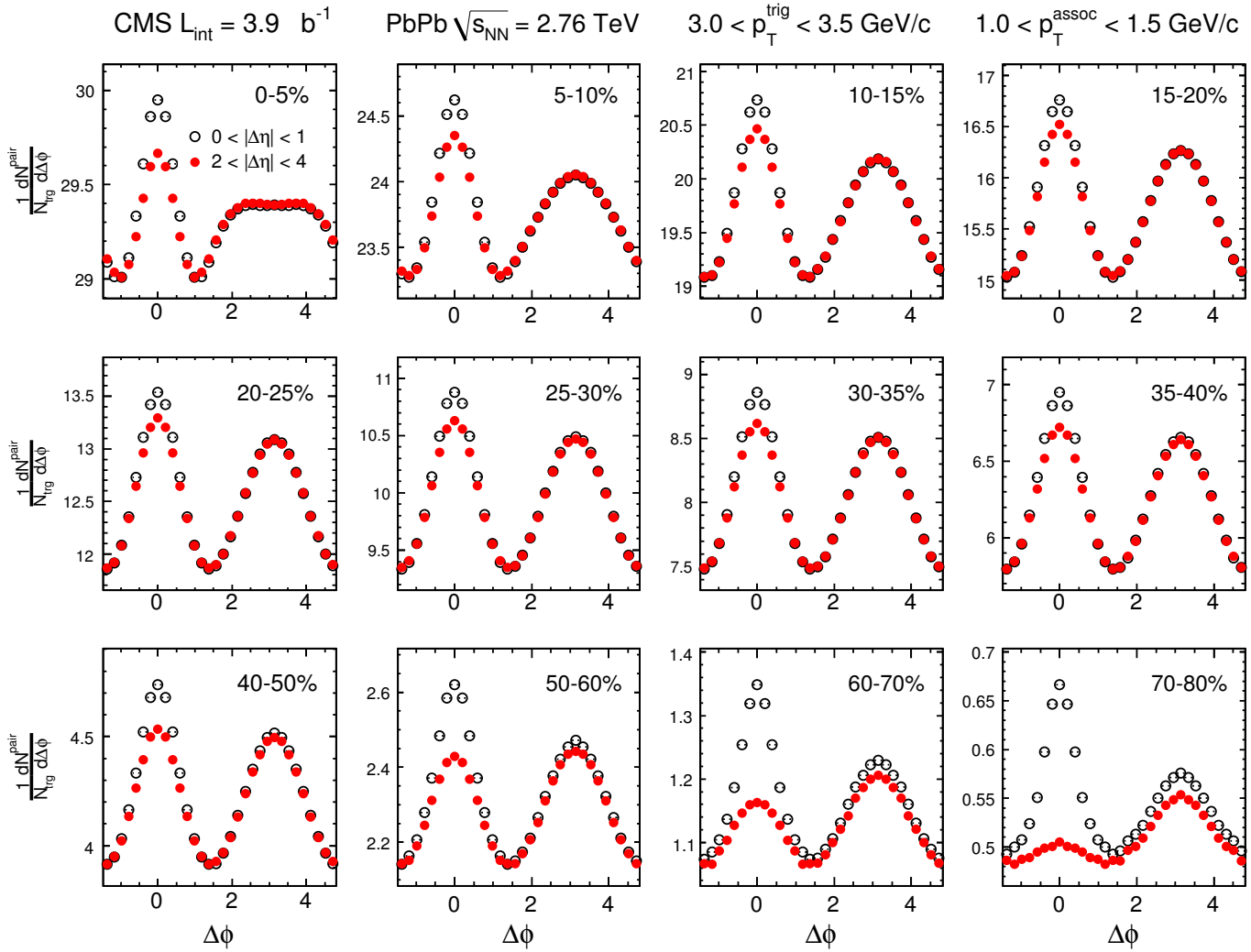
2-dimensional dihadron correlations in 12 centrality bins

Eur. Phys. J. C, 72(2012)



Projection of 2-dim correlations onto Δϕ for 0<|Δη|<1 and 2<|Δη|<4

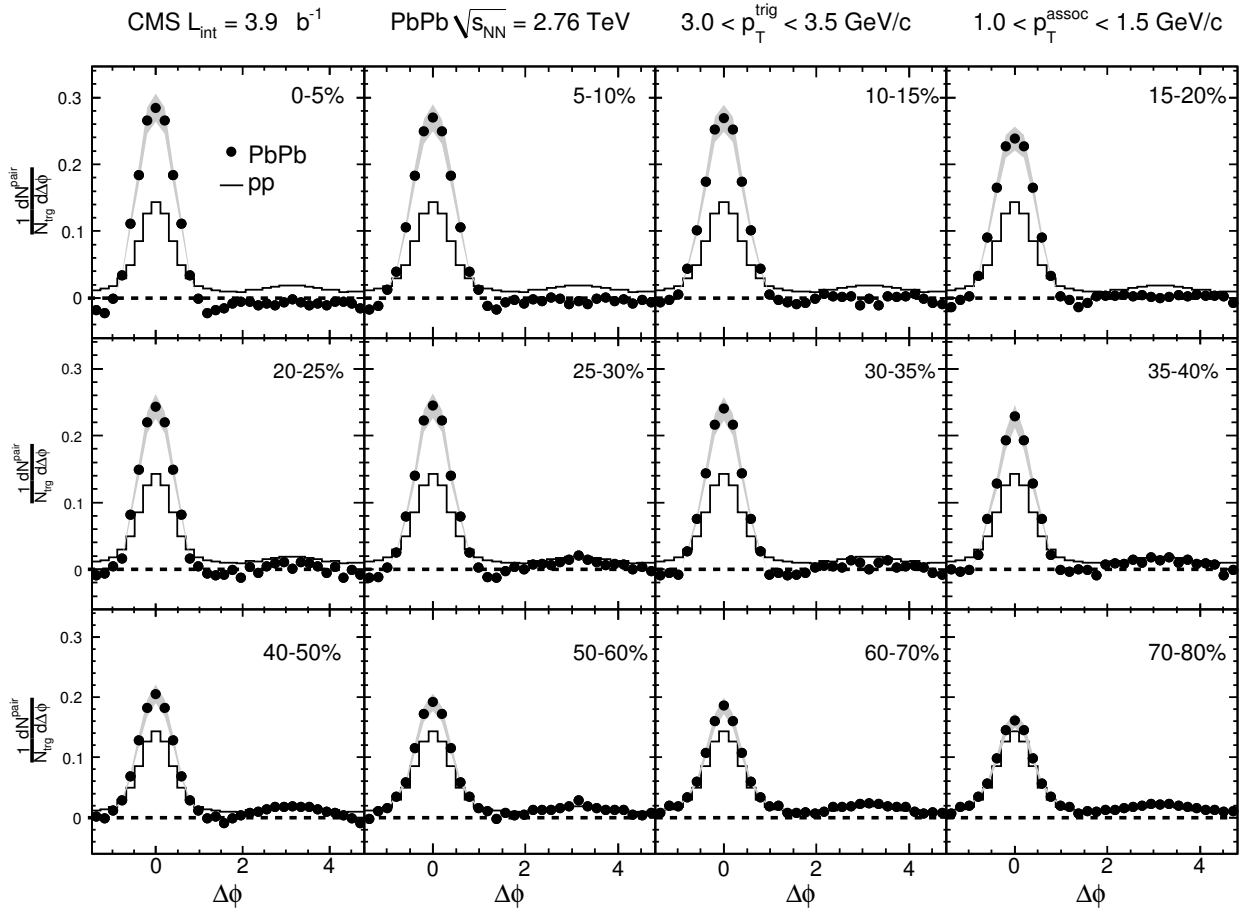
Eur. Phys. J. C, 72(2012)



Cutting on |Δη|, jet contribution could be largely suppressed in the long-range region of 2<|Δη|<4 with respect to the short-range one 0<|Δη|<1

The difference between the short-range and long-range per-trigger-particle associated yields for $0<|\Delta\eta|<1$ and $2<|\Delta\eta|<4$

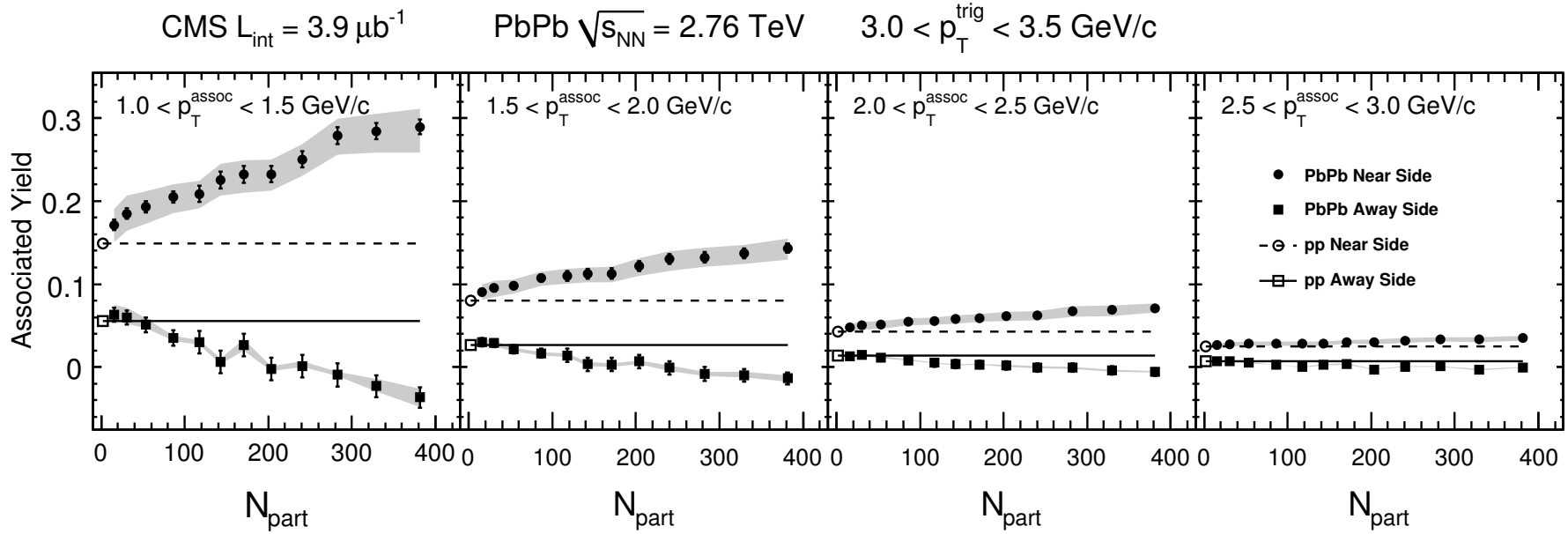
Eur. Phys. J. C, 72(2012)



Away side is rather flat and close to 0. *pp* results are shown as reference and they are similar to very peripheral *PbPb* data.

The integrated associated yields for near and away side in *PbPb* at $\sqrt{s_{NN}} = 2.76 TeV$

Eur. Phys. J. C, 72(2012)



The gray bands represent systematic uncertainties

Near side yield increases going from very peripheral to most central collisions

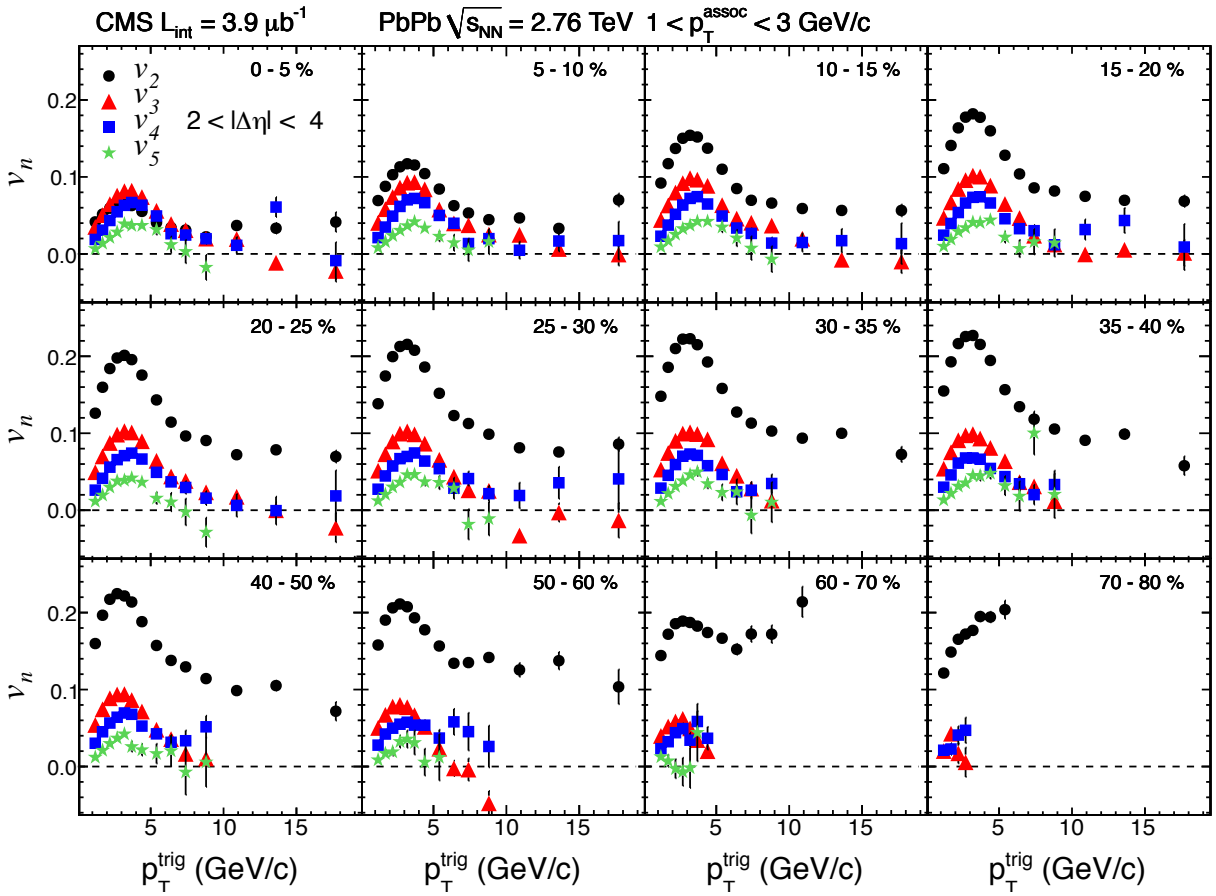
In difference of RHIC, as p_T increases, the centrality dependence becomes less pronounced

The yield in *PbPb* match the one from *pp* in most peripheral collisions

The away side yield decreases with centrality, becoming negative for rather central collisions!?

Extracted Fourier harmonics from the dihadron correlation *PbPb* data for 2<|Δη|<4

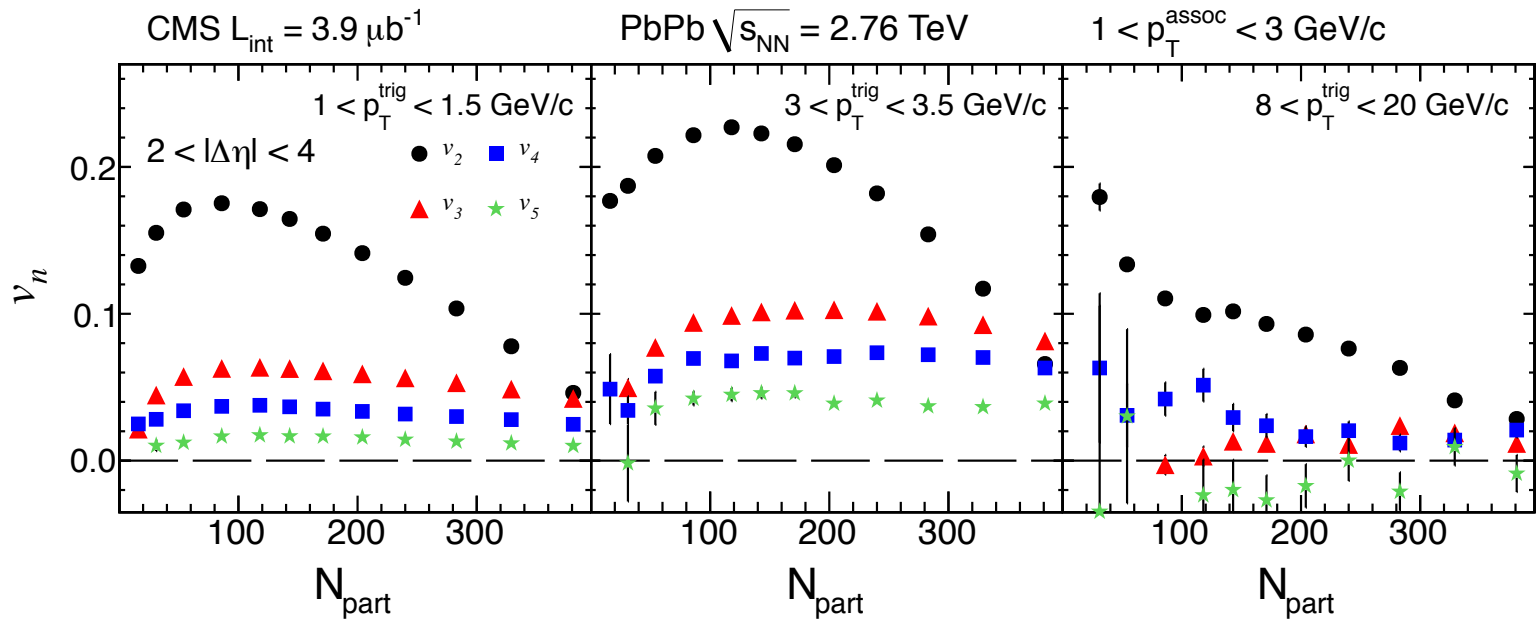
Eur. Phys. J. C, 72(2012)



- Expected ordering of the v_n magnitudes which decreases going from *n=2 to n=5*
- A proper shape of the obtained p_T dependence
- A proper centrality dependence
- Due to the statistical limitations in very peripheral events, the dependences are truncated
- Rather similar values are found using the standard methods

The centrality dependence of the extracted Fourier harmonics

Eur. Phys. J. C, 72(2012)



- The v_n values are integrated over the given p_T^{trig} intervals and presented *vs* centrality expressed via N_{part}
- Again, proper ordering of the v_n, transverse momentum and centrality is present

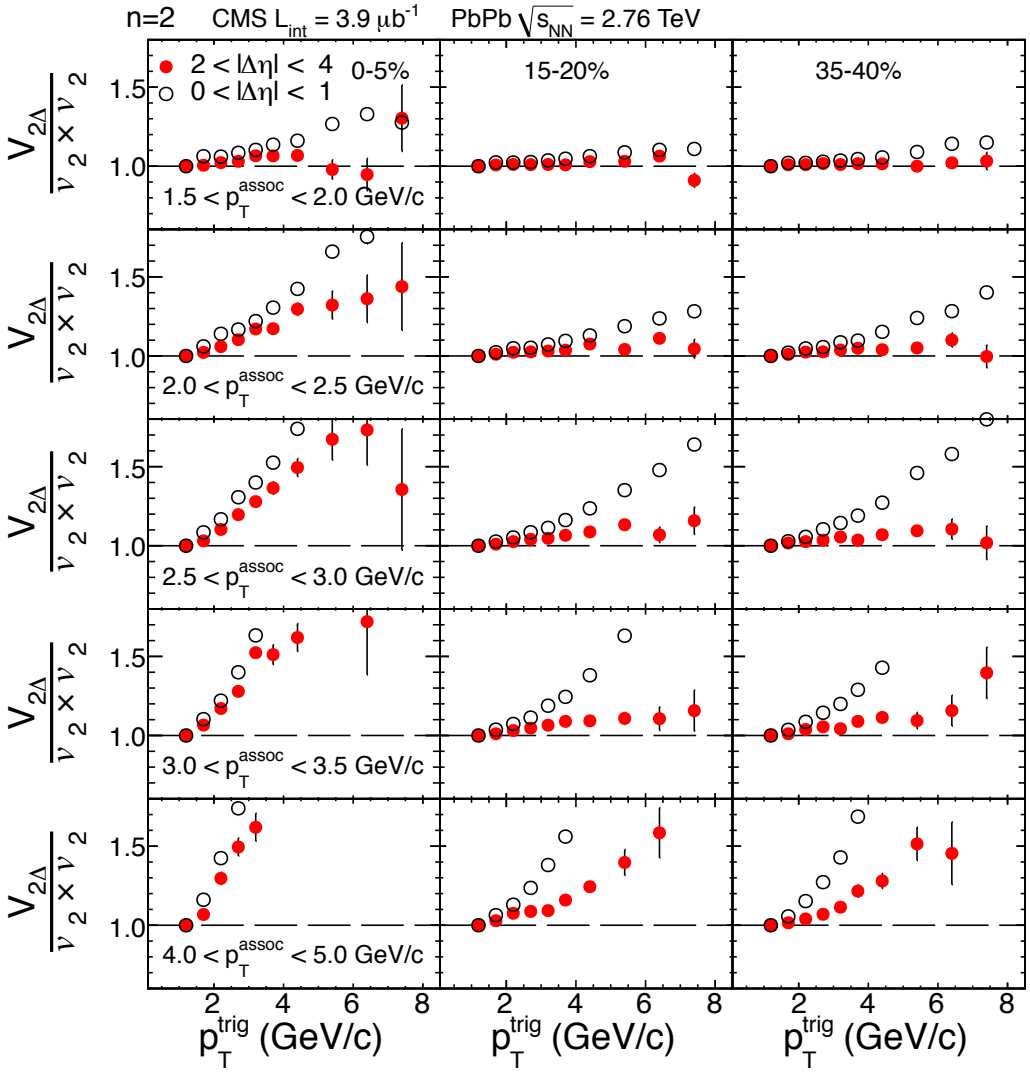
Conclusions

- The measurements of the Fourier coefficients cover a broad p_T, η and centrality range
- Four different methods have been employed to study v_n *vs* centrality and transverse momentum. They have different sensitivity to the non-flow correlations and initial geometrical fluctuations
- The results are compared mutually and to the results from the lower energies
- Two-particle azimuthal correlations are used as a tool to study both jets and azimuthal anisotropy
- The obtained results are shown *vs* centrality and transverse momentum
- Two distinct regions in |Δη| are analyzed in order to suppress jet (anisotropy) contribution
- The near-side yield increases going from peripheral to central *PbPb* collisions, while the away-side yield decreases
- They match the extracted yield in *pp* for most peripheral data
- The corresponding Fourier decomposition was performed as a function of both: centrality and p_T. Obtained harmonics show a typical behavior

Backup

Extraction of Fourier harmonics from the dihadron correlation *PbPb* data

Eur. Phys. J. C, 72(2012)



Fourier decomposition:

$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\phi} = \frac{N^{assoc}}{2\pi}\left\{1+\sum_{n=1}^{N^{max}} 2V_{n\Delta}\cos(n\Delta\phi)\right\}$$

Factorisation:

$$V_{n\Delta}(p_T^{trig}, p_T^{assoc}) = v_n(p_T^{trig})\cdot v_n(p_T^{assoc})$$

Fourier harmonics:

$$v_n(p_T^{trig}) = \frac{V_{n\Delta}(p_T^{trig}, p_T^{low})}{v_n(p_T^{low})}$$

No evidence for factorisation in short-range region due to jet-like correlation.

The factorisation is rather well satisfied for semicentral collisions in the long-range region

The factorisation is similar or even better for higher orders