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Azimuthal anisotropy in Xe–Xe and Pb–Pb collisions with the Monte-Carlo model HYDJET++ and the CMS detector at the energies of the LHC

TWENTY-FIRST
LOMONOSOV CONFERENCE
ON ELEMENTARY
PARTICLE PHYSICS
Moscow, Russia
24-30 August 2023

HYDJET and HYDJET++ relativistic Monte-Carlo event generators for heavy ion collisions

HYDJET

(HYDrodynamics + JETs)

Monte-Carlo event generator to simulate heavy ion event as merging of two independent components (**soft** hydro-type part + **hard** multi-partonic state)

http://cern.ch/lokhtin/hydro/hydjet.html

(latest version 1.9)

I.Lokhtin, A.Snigirev, Eur. Phys. J. C 46 (2006) 2011

HYDJET++

continuation of HYDJET

(improved **soft** component including full set of thermal resonance production

+ identical to HYDJET **hard** component)

http://cern.ch/lokhtin/hydjet++

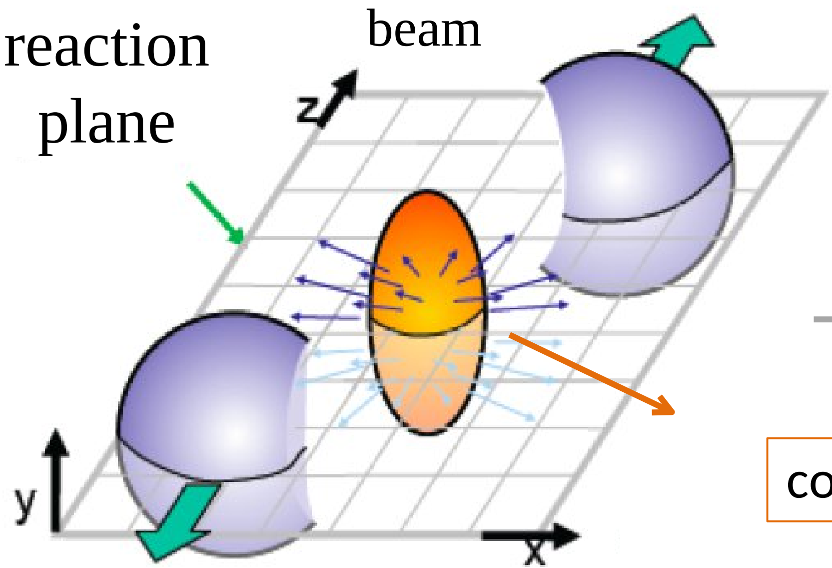
(latest version 2.4.3)

I.Lokhtin, L.Malinina, S.Petrushanko, A.Snigirev, I.Arsene, K.Tywoniuk,

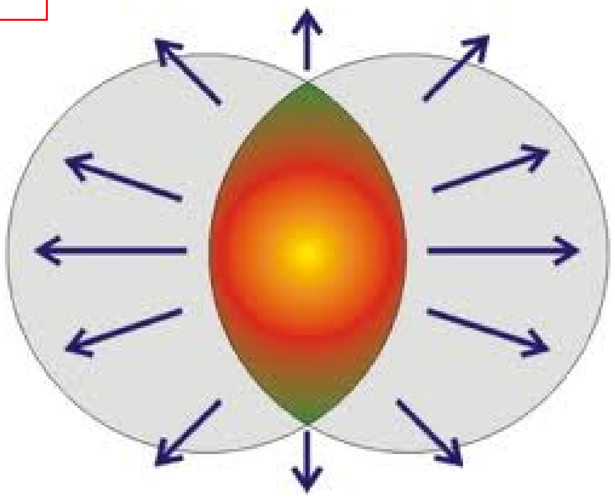
Comp.Phys.Comm. 180 (2009) 779

Azimuthal Correlations and Flow

collision plane



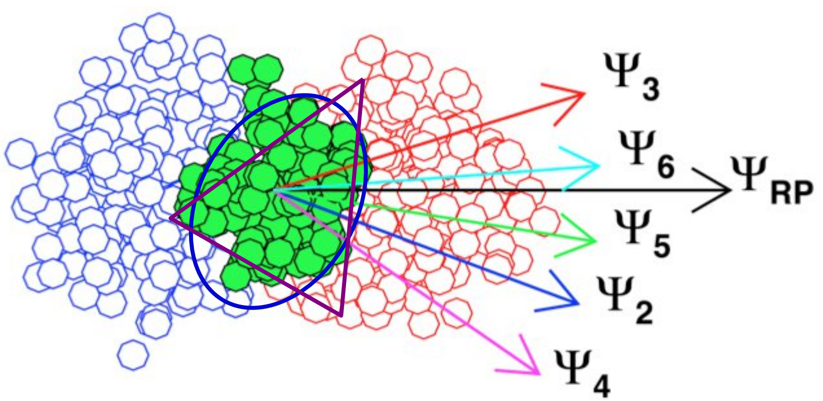
colliding ions



initial evolution stage

Fourier expansion of the azimuthal distribution of particles

$$E\frac{d^3N}{d^3p} = \frac{1}{\pi}\frac{d^2N}{dp_t^2dy}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Psi_n)\right]$$



Elliptical flow v_2

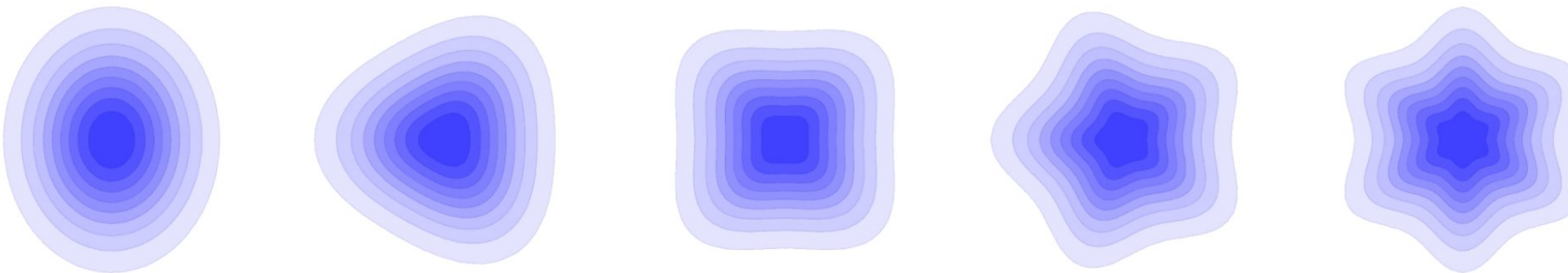
Triangular flow v_3

...

Fluctuations at the initial stage of evolution

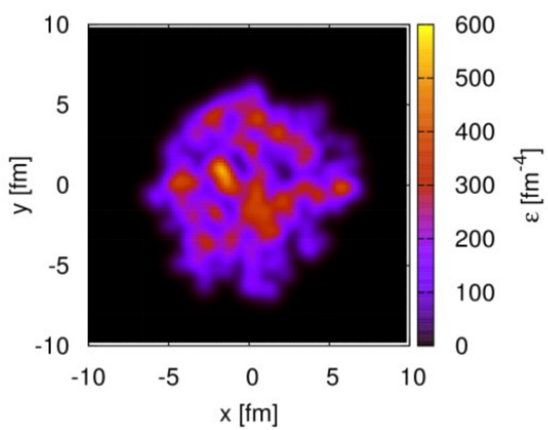
Harmonic flows v_2, v_3 ...

Nonzero harmonic v_2, v_3 etc carry information about the conditions of space-time evolution of nuclear matter and fluctuations of its initial state.

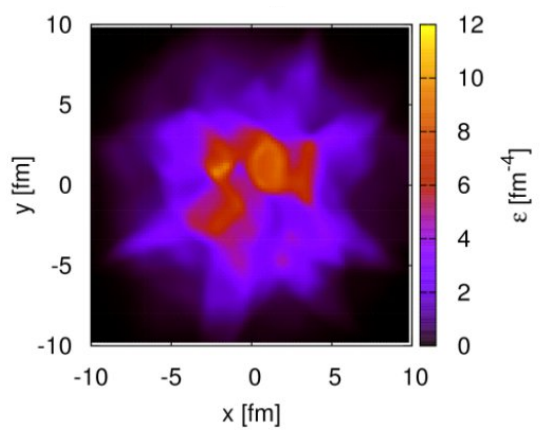


n = 2 n = 3 n = 4 n = 5 n = 6

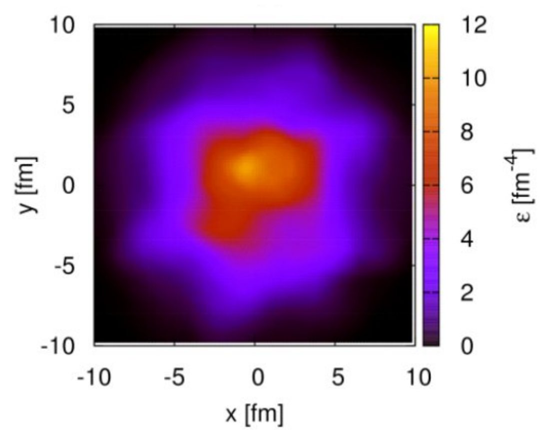
Initial stage



Ideal hydrodynamics



Hydrodynamics with viscosity



Methods for measuring azimuthal anisotropy

True reaction plane method. Model HYDJET++

In the generator, the reaction plane is known in advance — it is set by the internal code of the generator.

Thus, one can immediately calculate elliptical, triangular and other flows using the formula:

$v_n = \left\langle \cos\left[n\left(\phi - \psi_{r.p.}\right)\right]\right\rangle$, где $\varphi_{r.p.}$ — azimuth angle of the true reaction plane.

We used this method in our analysis with the HYDJET++ Monte Carlo generator.

The cumulant method. CMS experiment

2- and 4-part correlations in the cumulant method can be described as

$$\langle\langle 2\rangle\rangle = \left\langle\left\langle e^{in(\varphi_1-\varphi_2)}\right\rangle\right\rangle \qquad \langle\langle 4\rangle\rangle = \left\langle\left\langle e^{in(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\right\rangle\right\rangle$$

Here, double brackets mean averaging over particles and events

Cumulants of the 2nd and 4th orders:

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

$$d_n\{4\} = \left\langle\left\langle 4'\right\rangle\right\rangle - 2 * \left\langle\left\langle 2'\right\rangle\right\rangle * \langle\langle 2\rangle\rangle$$

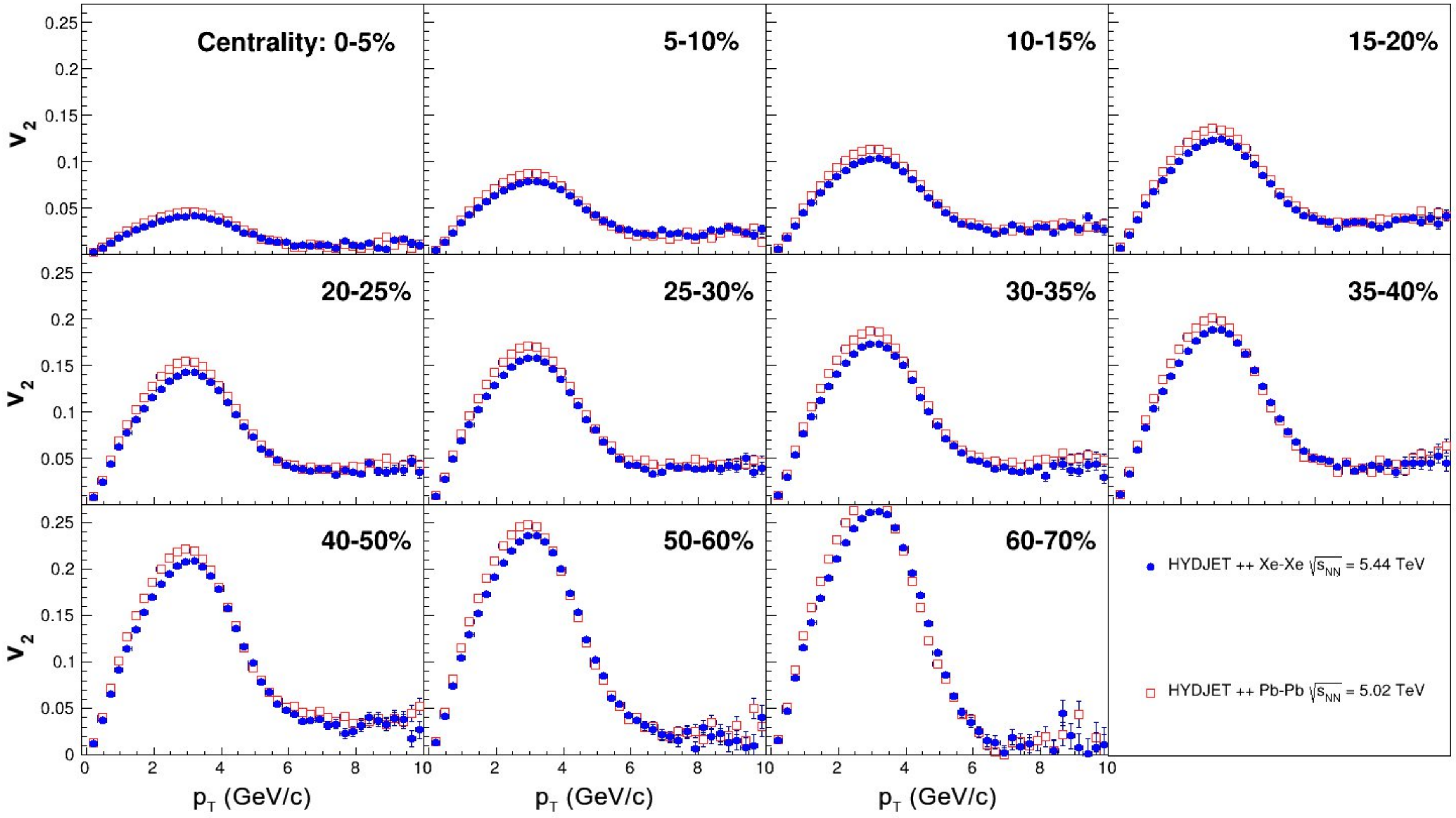
Here, the dash denotes differential correlations, such that one of the particles is in the given p_T bin

Then the elliptic flow through the 4th order cumulants is:

$$v_n\{4\}(p_T) = -d_n\{4\} * (-c_n\{4\})^{-3/4}$$

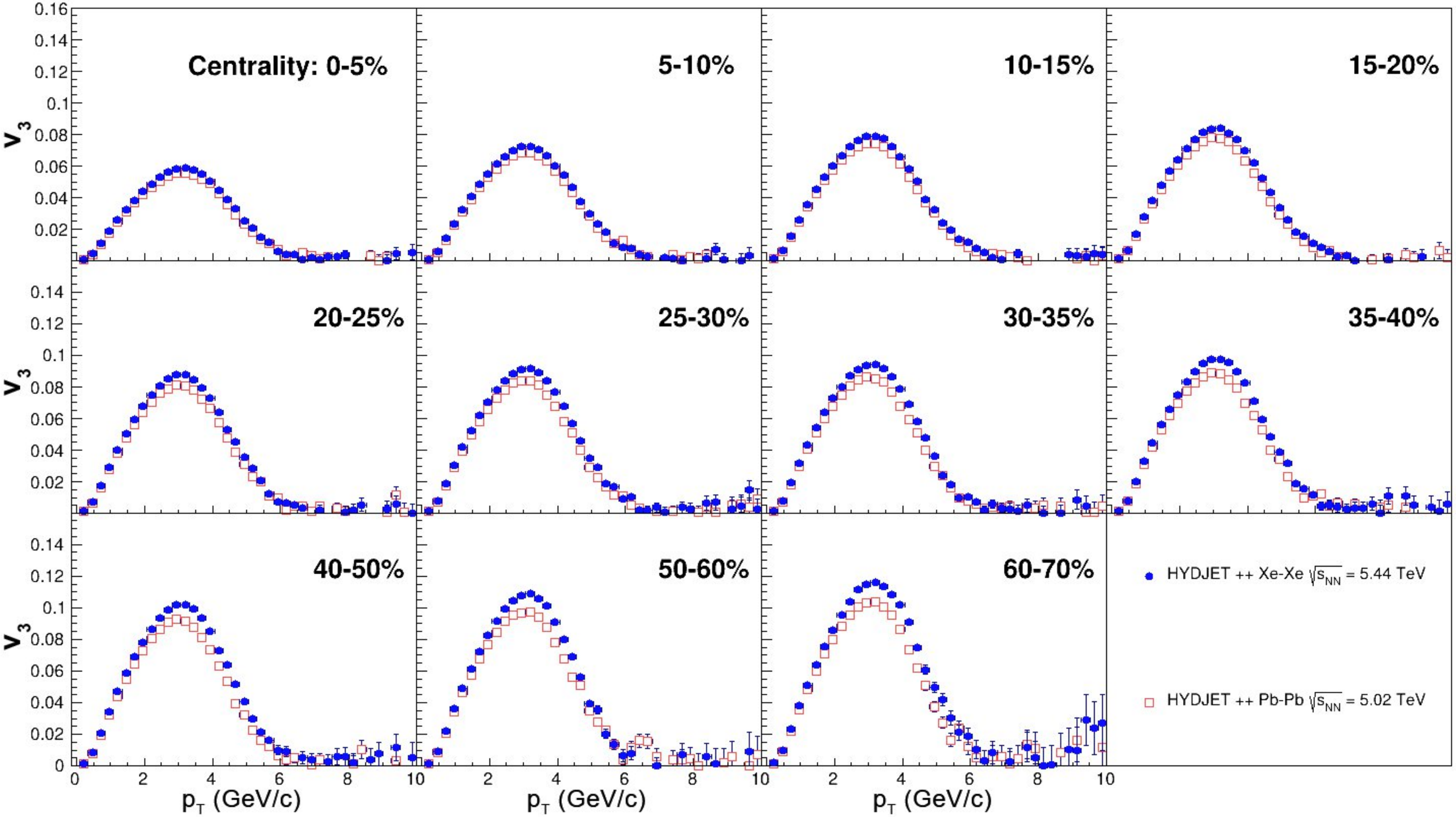
Experimental data was published in
Phys. Rev. C 100 (2019) 044902

v_2 for collisions of Xe-Xe with an energy of 5.44 TeV and Pb-Pb with an energy of 5.02 TeV per nucleon in the c.m.s. in the Monte Carlo HYDJET++ generator relative to the true reaction plane (statistics of approx. 1 million events for each centrality)



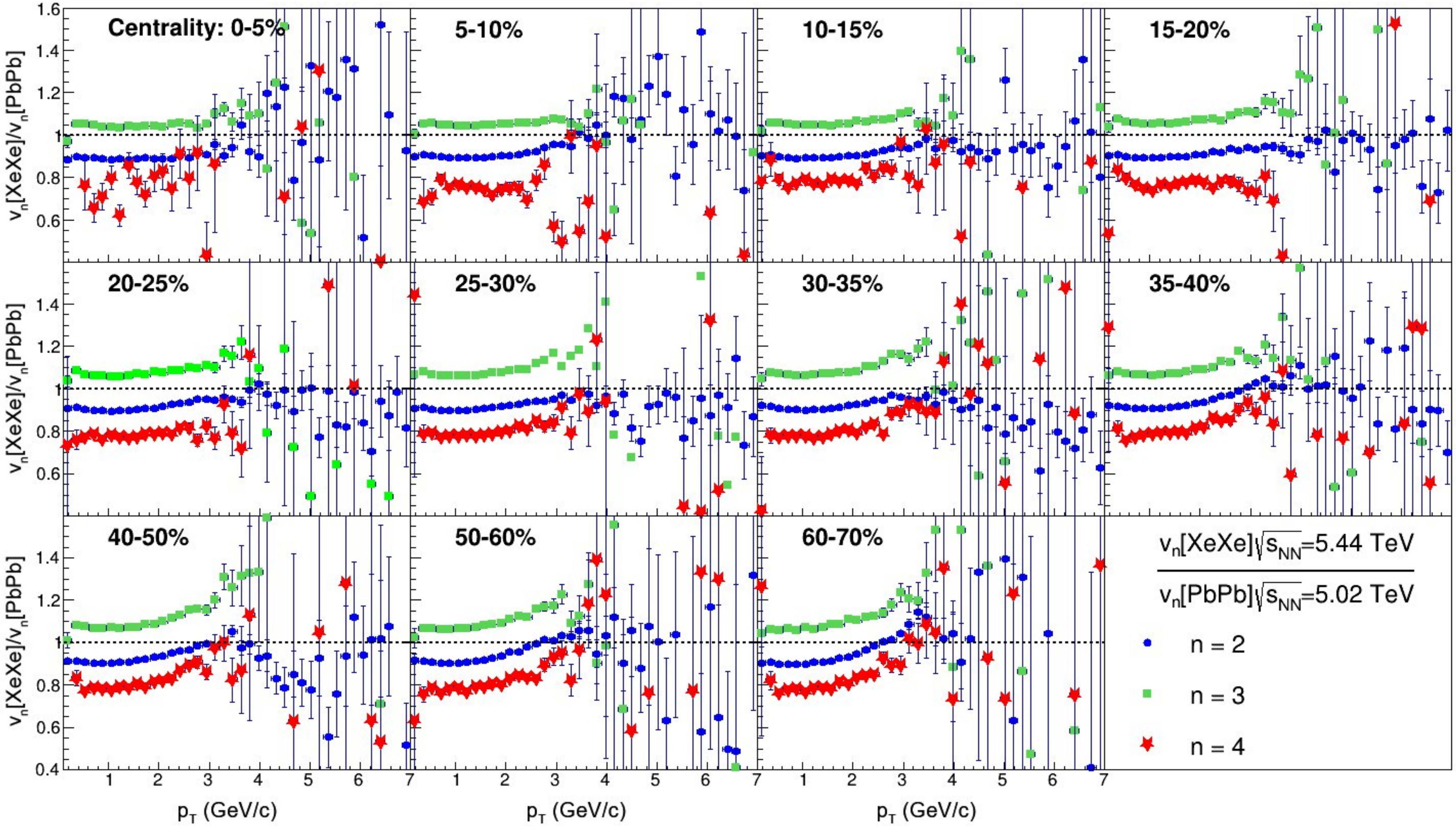
- The form of the dependence is consistent with CMS experimenthal data in Phys. Rev. C 100 (2019) 044902
- For all centralitis: v_2 for Pb-Pb is higher than Xe-Xe ones

v_3 for Xe-Xe collisions with energy 5.44 TeV and Pb-Pb collisions with energy 5.02 TeV per nucleon in the c.m.s. in the Monte Carlo HYDJET++ generator relative to the true reaction plane (statistics of approx. 1 million events for each centrality)



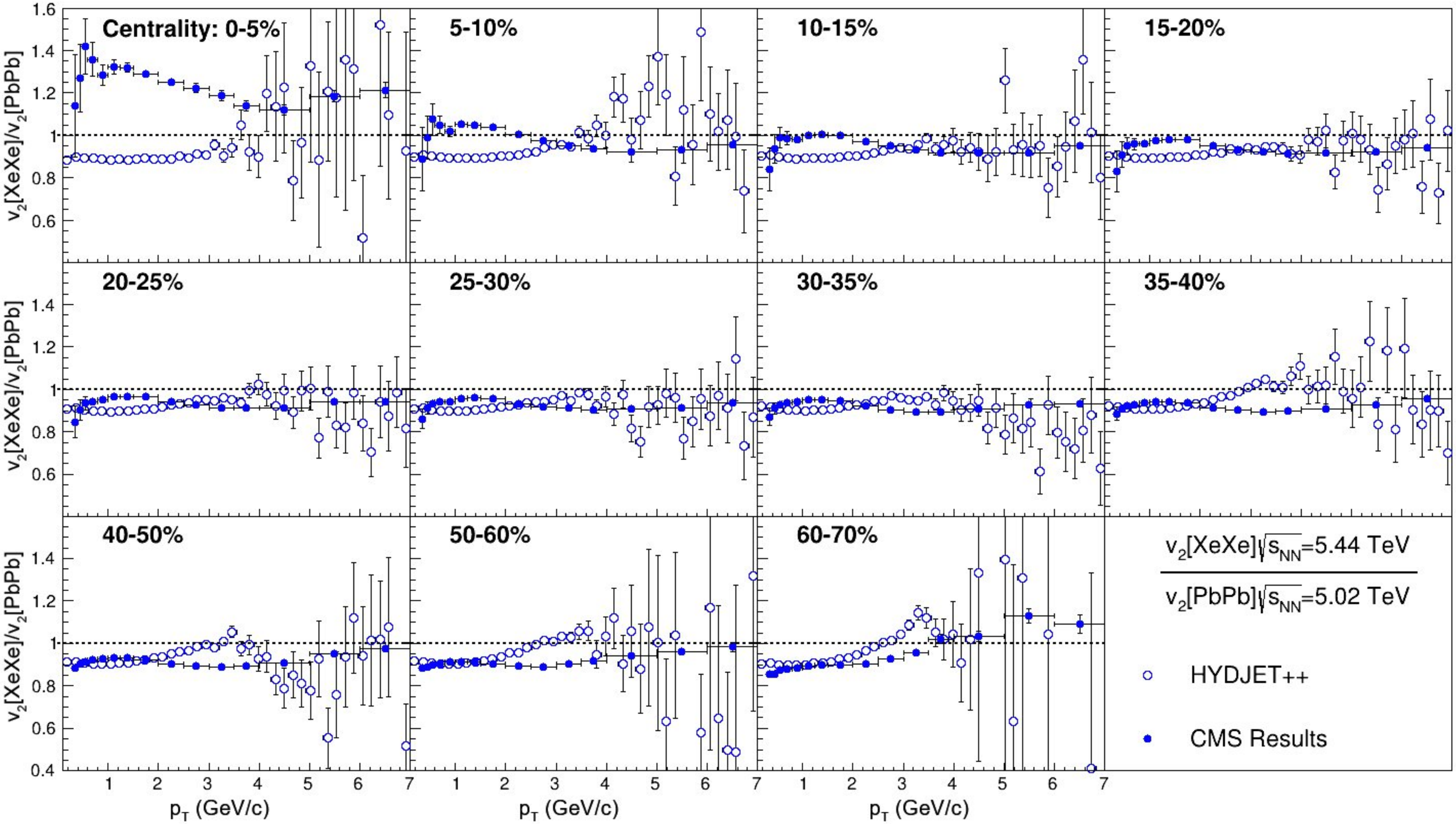
- The form of the dependence is consistent with CMS experimenthal data in Phys. Rev. C 100 (2019) 044902
- For all centralitis: v_3 for Xe-Xe is higher than Pb-Pb ones

Harmonic ratios $v_n\,[XeXe]/v_n\,[PbPb]$ at energies of 5.44 TeV and 5.02 TeV per nucleon in the c.m.s. in the Monte Carlo HYDJET++ generator relative to the true reaction plane (statistics of approx. 1 million events for each centrality).



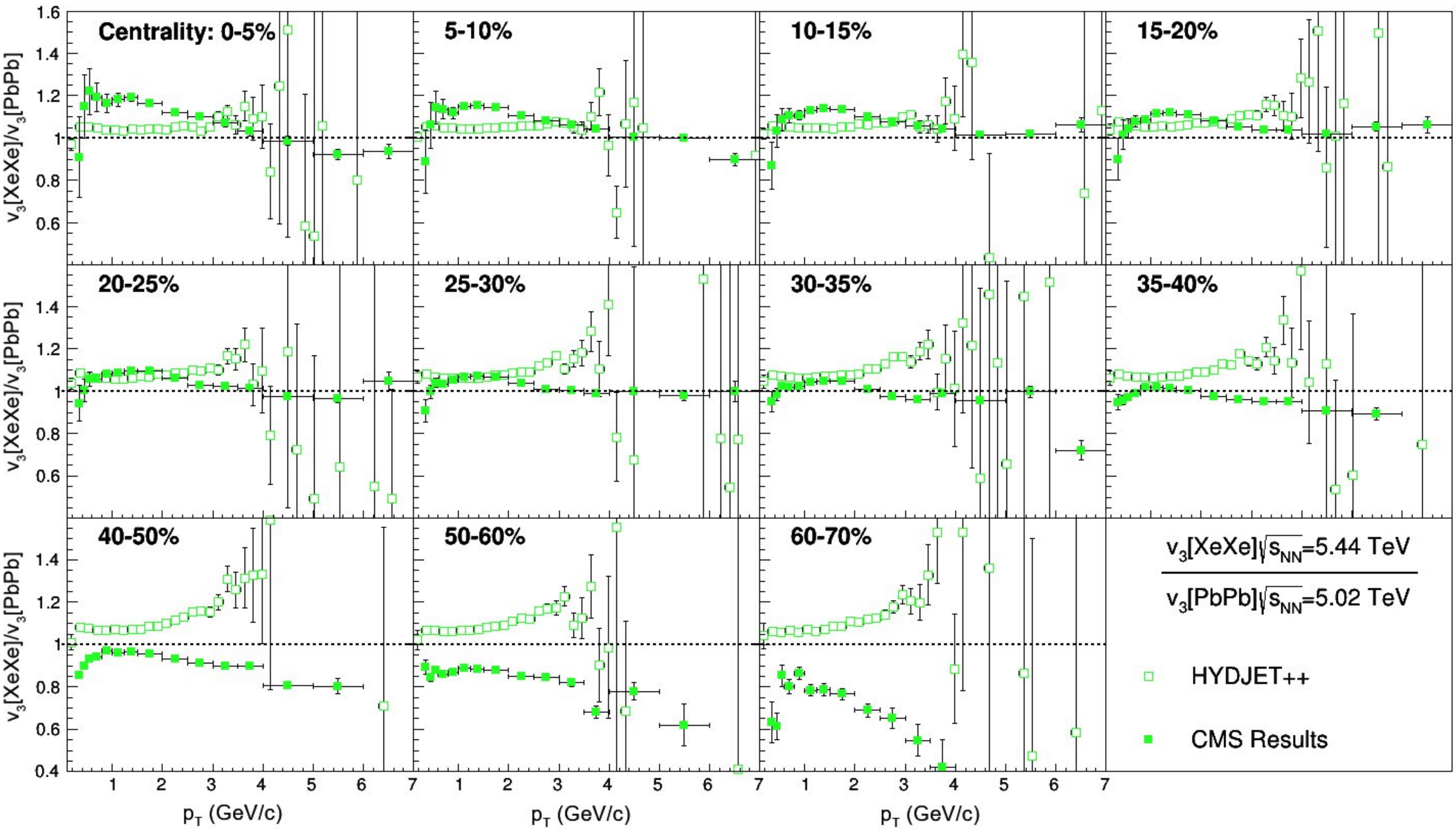
- For all harmonics and all regions of centrality, the form of dependence is the same
- Mutual arrangement of dependencies is preserved
- Ratios of triangular flow above elliptical and above quadrupole ones

Comparison of harmonic ratios v_2 in XeXe and PbPb collisions in the CMS experiment (two-particle correlation method) and the HYDJET++ Monte Carlo generator (true reaction plane method)



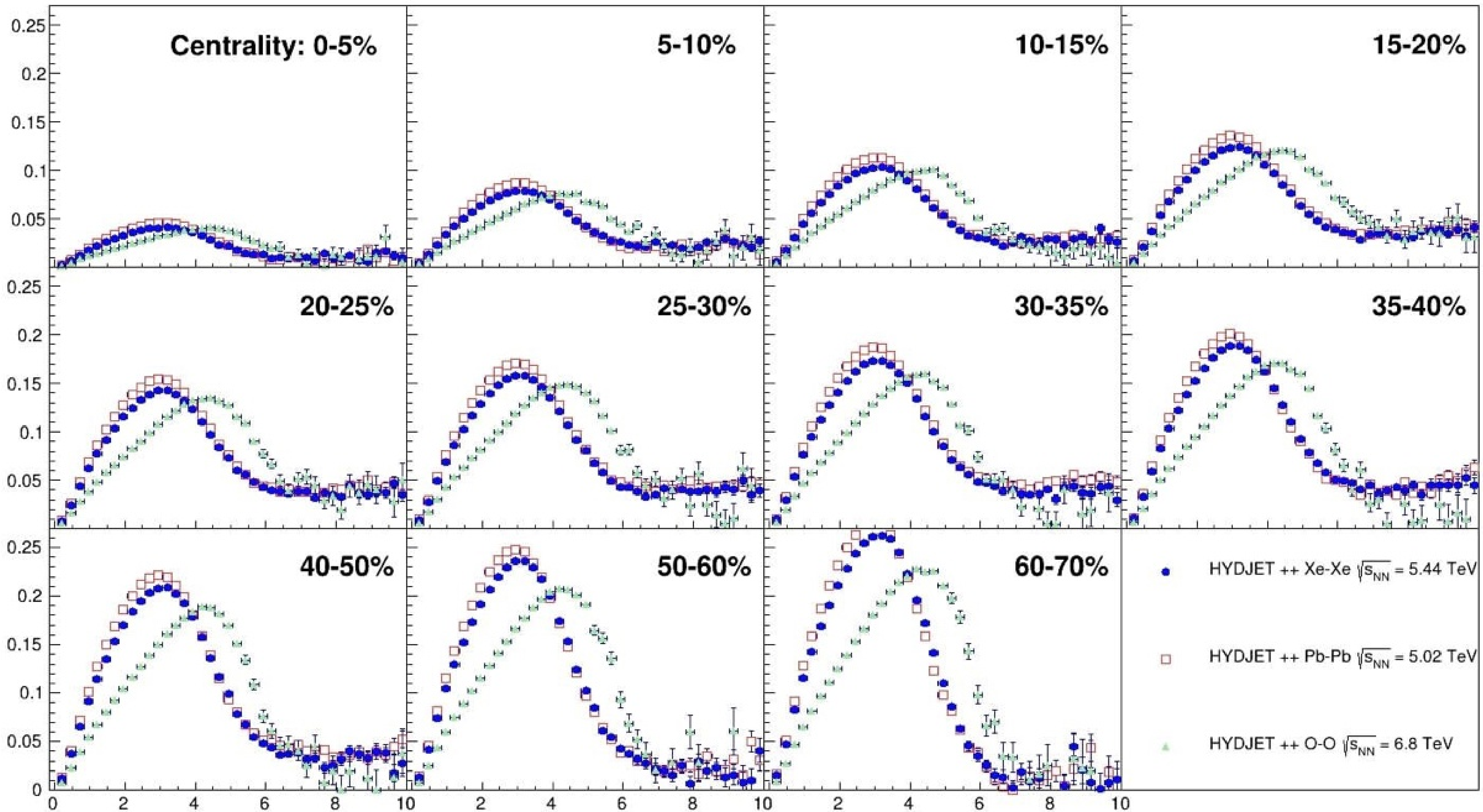
- The HYDJET++ model is in good agreement with the experiment in the region of semi-central interactions
- Serious discrepancies are observed in the region of central interactions

Comparison of harmonic ratios v_3 in XeXe and PbPb collisions in the CMS experiment (two-particle correlation method) and the HYDJET++ Monte Carlo generator (true reaction plane method)

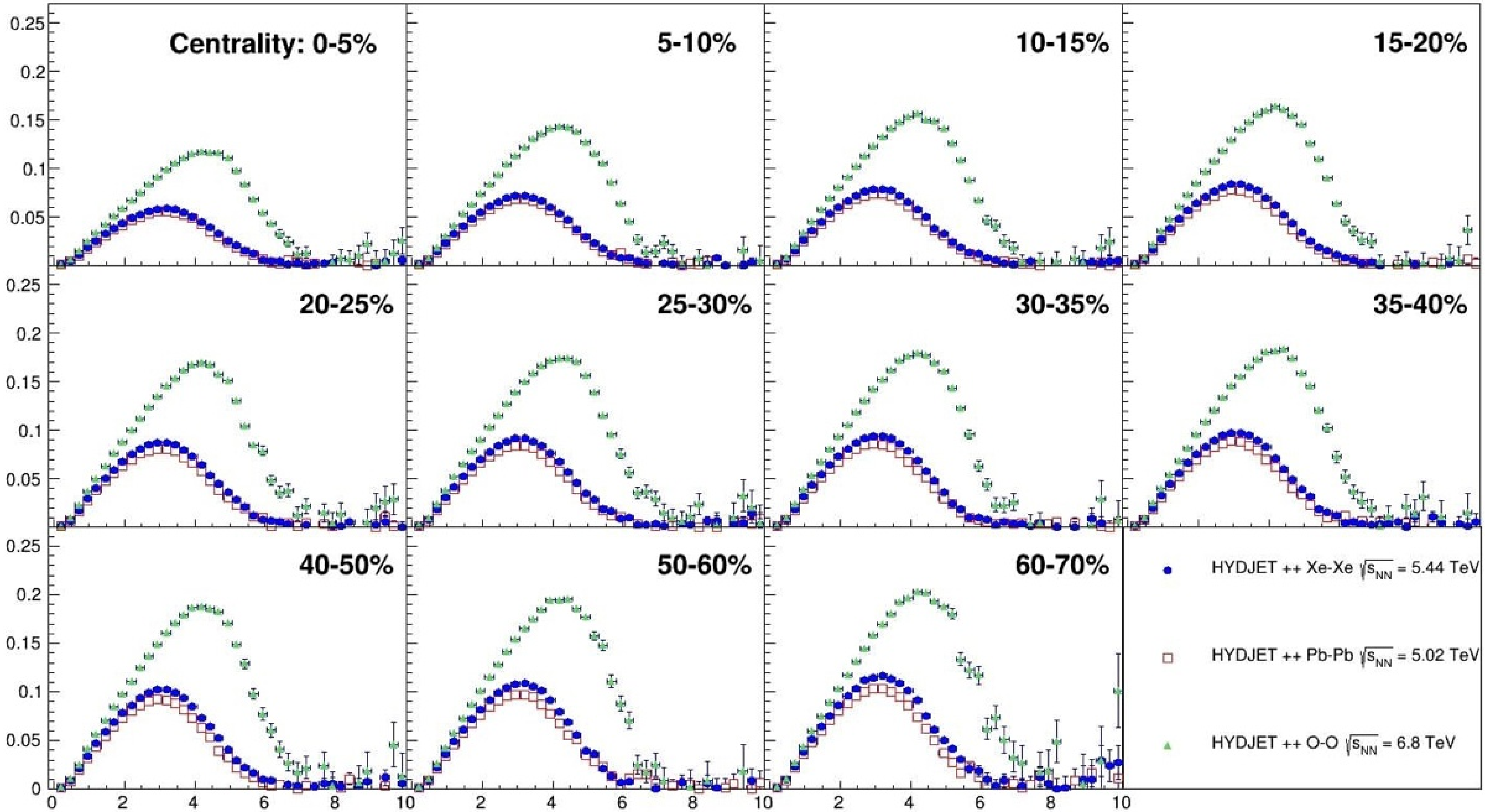


- The HYDJET++ model describes well the region of semi-central collisions
- Central impacts are not described well enough
- There are serious discrepancies with the experiment in the region of peripheral collisions

Predictions v_2 for O-O collisions with an energy of 6.8 TeV per nucleon in the c.m.s. in the Monte Carlo HYDJET++ generator (true reaction plane method) in comparision with Xe-Xe 5.44 TeV and Pb-Pb 5.02 TeV



Predictions v_3 for O-O collisions with an energy of 6.8 TeV per nucleon in the c.m.s. in the Monte Carlo HYDJET++ generator (true reaction plane method) in comparision with Xe-Xe 5.44 TeV and Pb-Pb 5.02 TeV



Conclusions

- Within the framework of the Monte Carlo HYDJET++ model, particle production in Xe-Xe and Pb-Pb collisions was simulated at LHC energies. The results for elliptical, triangular, and quadrupole particle flows based on the experimental data of the CMS setup are compared with the simulation result of the HYDJET++ generator.

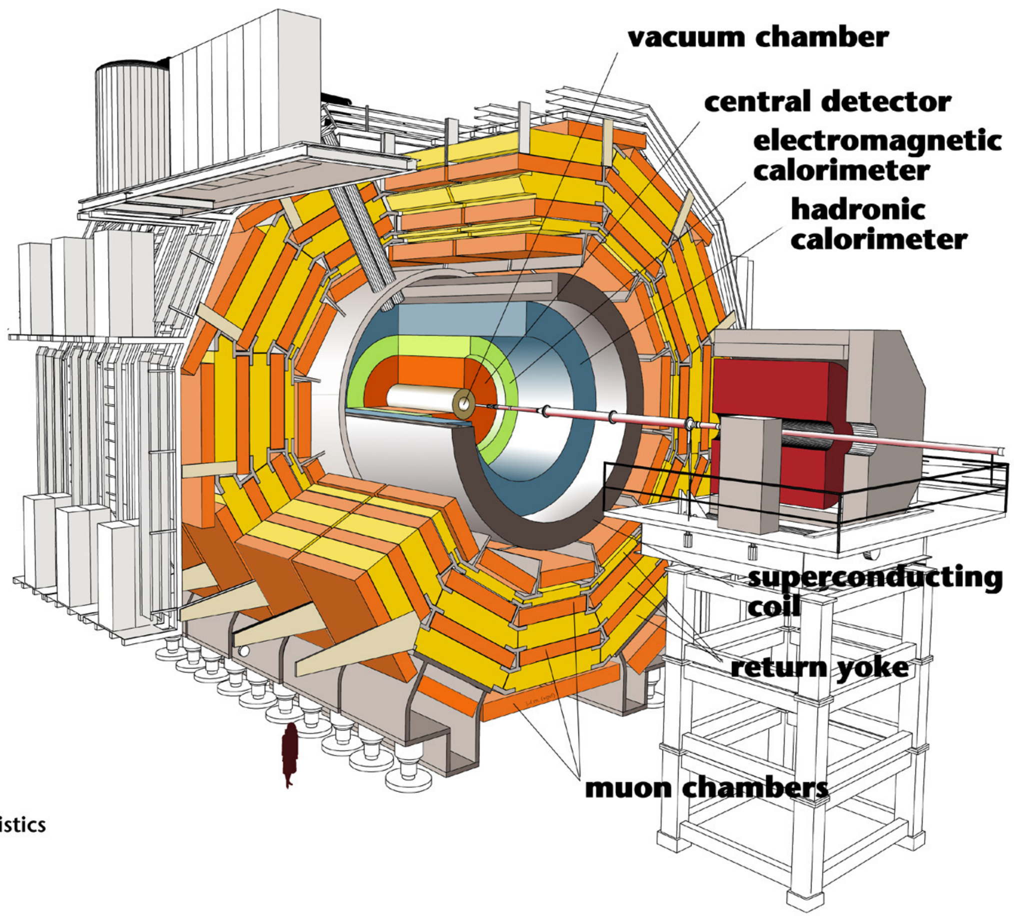
- The HYDJET++ generator describes well the differences in flows in Xe-Xe and Pb-Pb collisions and their ratios in the centrality ranges of 10-50% for v2, 0-30% for v3 and peripheral 50-70% collisions for v4. The deviation of the experimental data for central collisions from the hydrodynamic model is probably caused by the larger fluctuation component of lighter xenon relative to lead collisions. Also, the deformation of the xenon nucleus compared to the almost spherical lead nucleus can also have an influence.

- Within the framework of the Monte Carlo HYDJET++ model, particle production in O–O collisions was simulated at the assumed energies of the LHC collider in 2024–25. Within the HYDJET++ model, certain differences are observed for O–O collisions compared to the Xe–Xe and Pb–Pb systems.

- Further tuning of the HYDJET++ model is required to describe the behavior of centrality flows of 0–10% for v2 and 30–50% for v3 of various types of nuclei, as well as the development of methods for working with higher-order harmonics.

Thanks for your attention

Compact Muon Solenoid (CMS) on Large Hadron Collider (LHC)



Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

Tracker detector
$|\eta| < 2.4$

Electromagnetic calorimeter
$|\eta| < 3.0$

Hadron calorimeter
$|\eta| < 3.0$

with HF calorimeter up to
$|\eta| < 5.2$

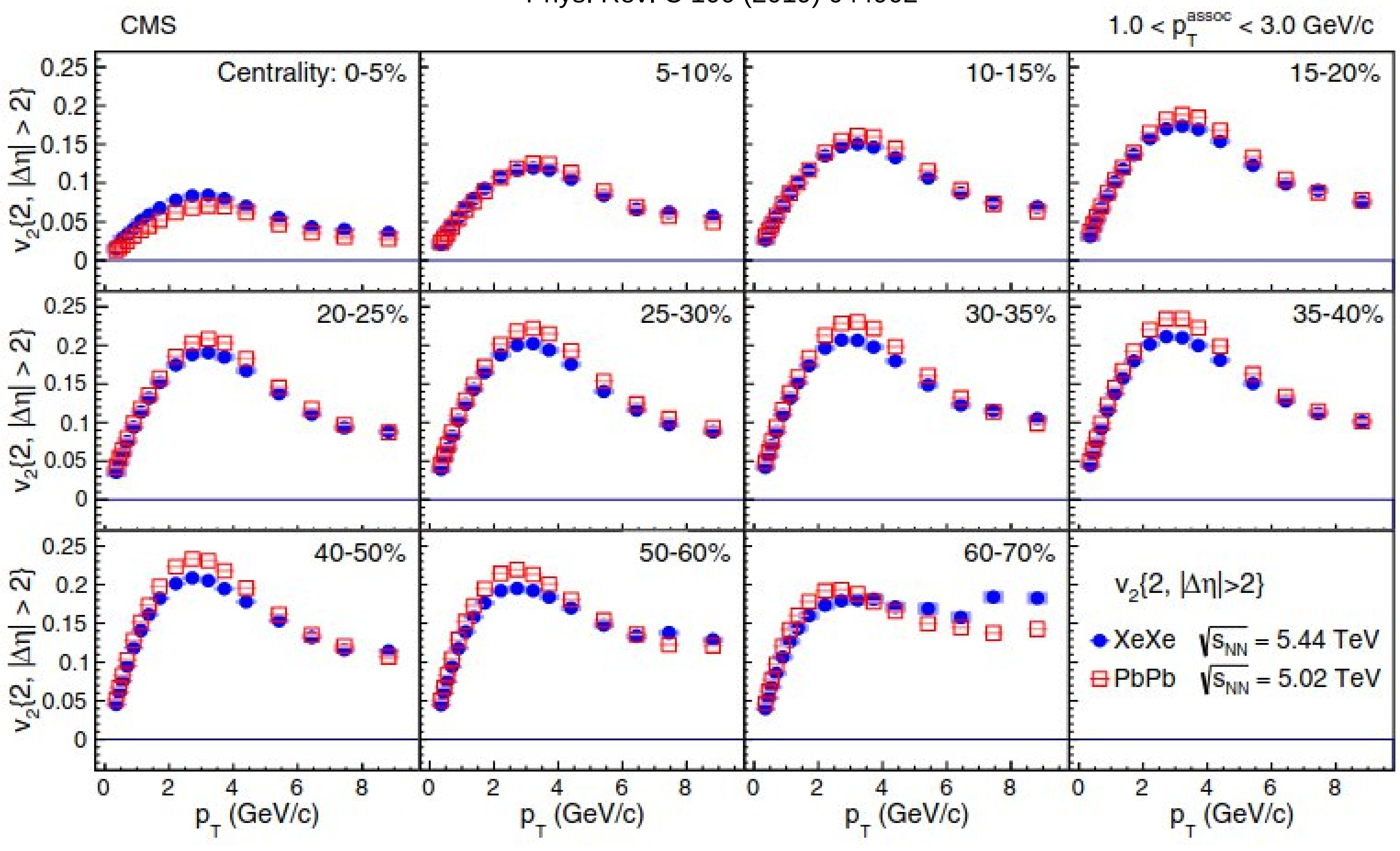
muon chambers
$|\eta| < 2.4$

+ detector CASTOR
$-5.2 < |\eta| < -6.6$

Magnetic field: 3.8 T

v_2 для столкновений Xe-Xe с энергией 5.44 ТэВ и Pb-Pb с энергией 5.02 ТэВ на нуклон в СЦМ в эксперименте CMS

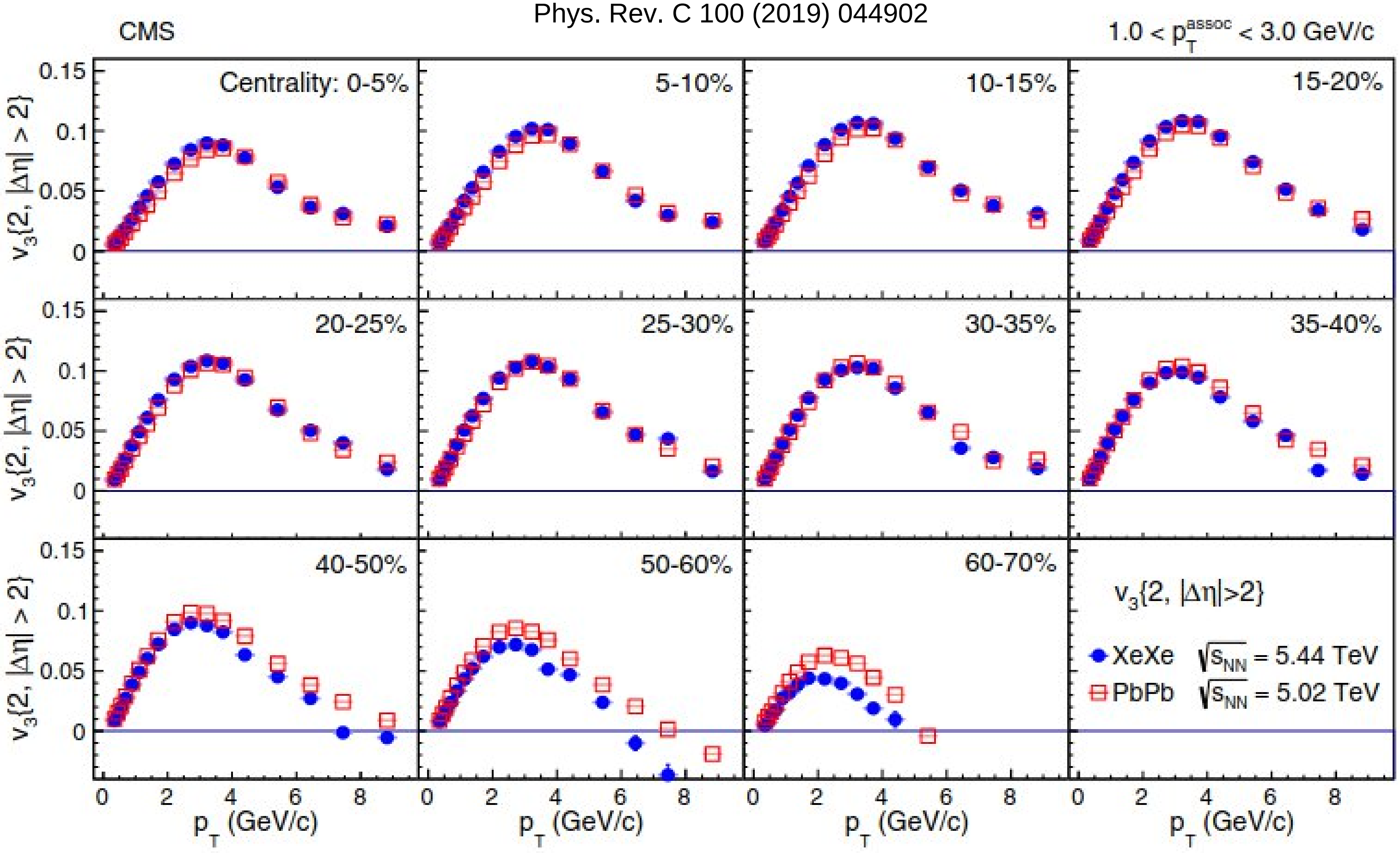
Phys. Rev. C 100 (2019) 044902



Результаты для v_2, полученные в эксперименте CMS методом двухчастичных корреляций.

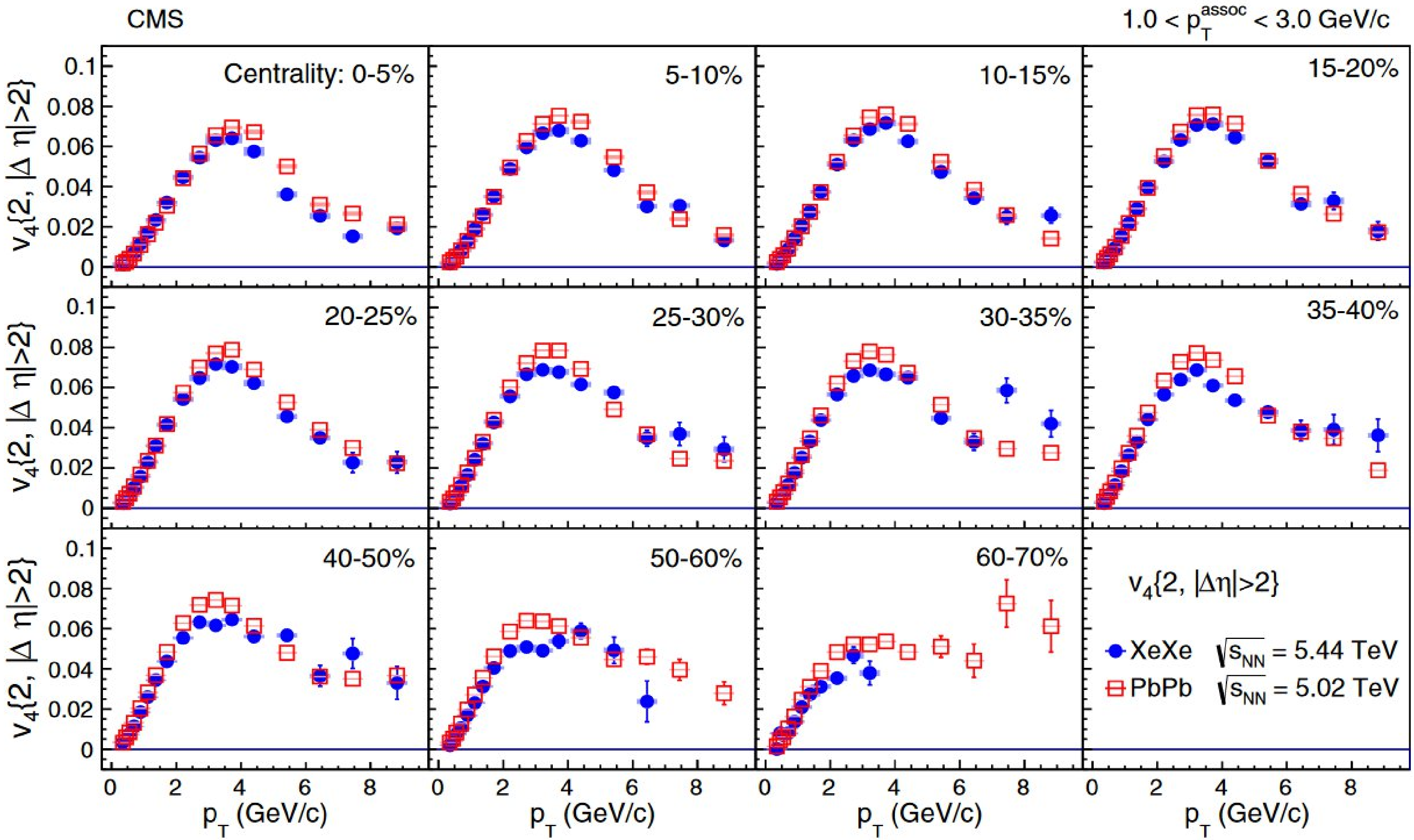
v_3 для столкновений Xe-Xe с энергией 5.44 ТэВ и Pb-Pb с энергией 5.02 ТэВ на нуклон в СЦМ в эксперименте CMS

Phys. Rev. C 100 (2019) 044902



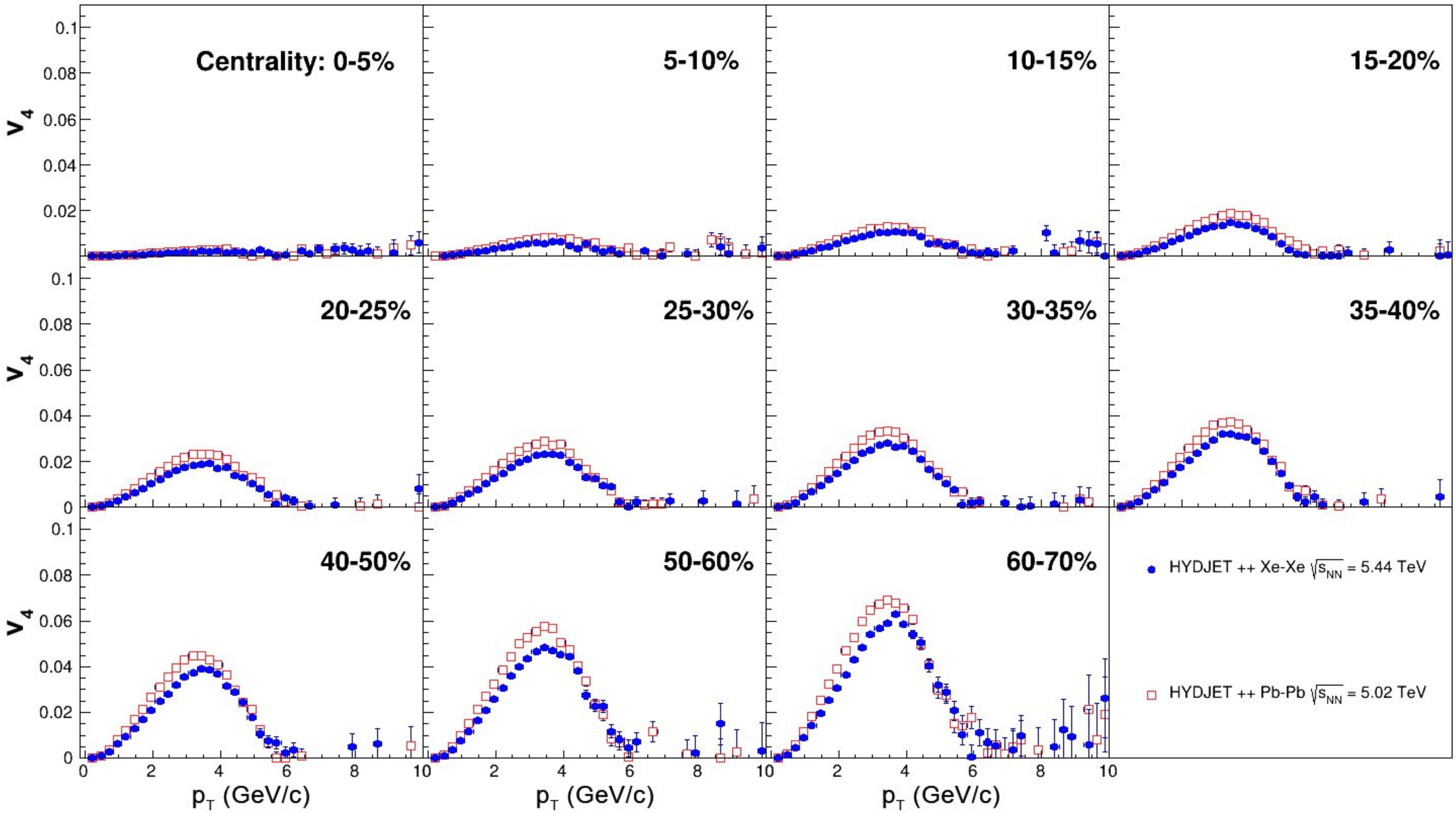
Результаты для v_3, полученные на эксперименте CMS методом двухчастичных корреляций.

v_4 для столкновений Xe-Xe с энергией 5.44 ТэВ и Pb-Pb с энергией 5.02 ТэВ на нуклон в СЦМ в эксперименте CMS



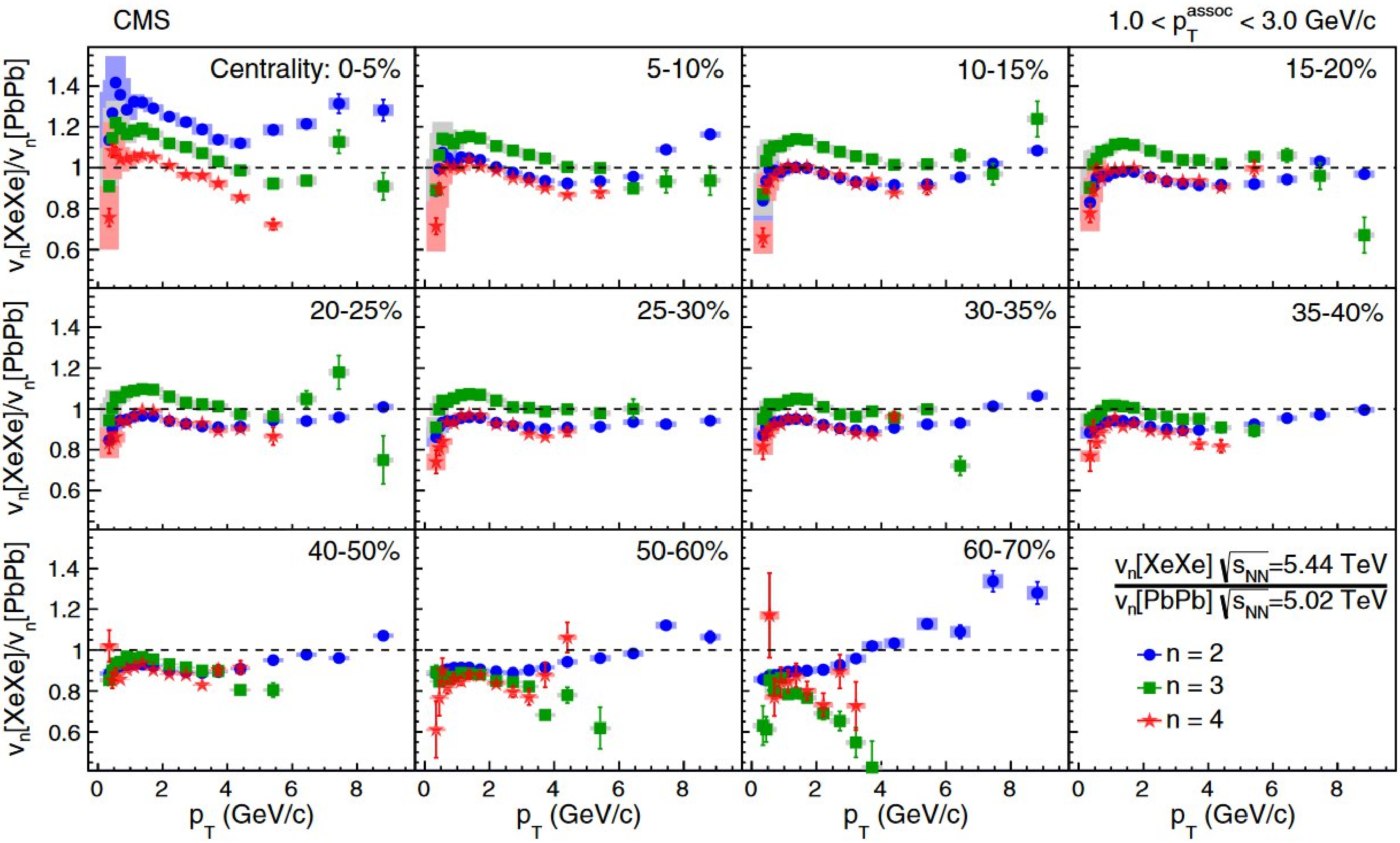
Результаты для v_4, полученные на эксперименте CMS методом двухчастичных корреляций.

v_4 для столкновений Xe-Xe с энергией 5.44 ТэВ и Pb-Pb с энергией 5.02 ТэВ на нуклон в СЦМ в Монте-Карло генераторе HTDJET++

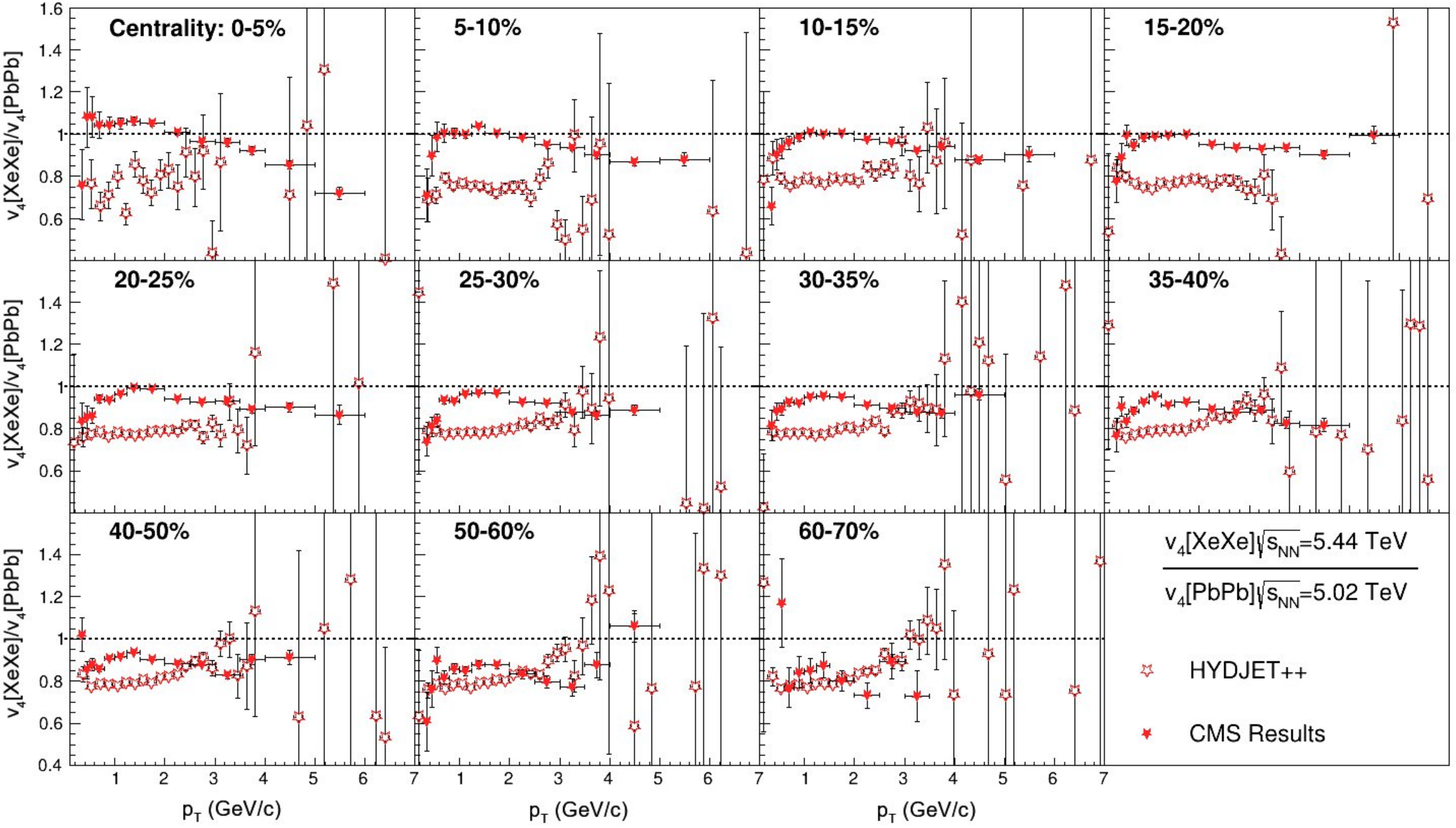


Результаты для v_4, полученные в генераторе HYDJET++ относительно истинной плоскости реакции (статистика ок. 1 млн. событий для каждой центральности).

Отношения гармоник $v_n\,[XeXe]/v_n\,[PbPb]$ при энергиях 5.44 ТэВ и 5.02 ТэВ на нуклон в СЦМ в Монте-Карло генераторе HYDJET++



Comparison of harmonic ratios v_4 in XeXe and PbPb collisions in the CMS experiment (two-particle correlation method) and the HYDJET++ Monte Carlo generator (true reaction plane method)



- The model does not adequately describe the behavior of quadrupole flows ratios
- There is a coincidence of dependences in the region of peripheral collisions