GENERATION OF HIGHER FLOW HARMONICS IN HYDRODYNAMICS WITH JETS IN RELATIVISTIC HIC'S

E. Zabrodin

in collaboration with

L. Bravina, H. Brusheim Johansson, J. Crkovska, G. Eyyubova,V. Korotkikh, I. Lokhtin, L. Malinina, S. Petrushanko, and A. Snigirev

University of Oslo and Moscow State University

NeD/TURIC-2014

Hersonissos, Crete, Greece (9.06-14.06.2014)

OUTLINE

I. Description of anisotropic flow in relativistic heavy ion collisions:

(a) elliptic and triangular flows

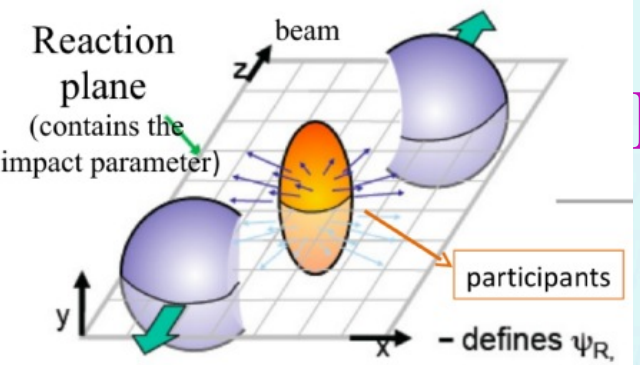
(b) initial fluctuations and higher harmonics

II. HYDJET++ model (hydro + jets)

III. Quadrangular flow and pentagonal flow

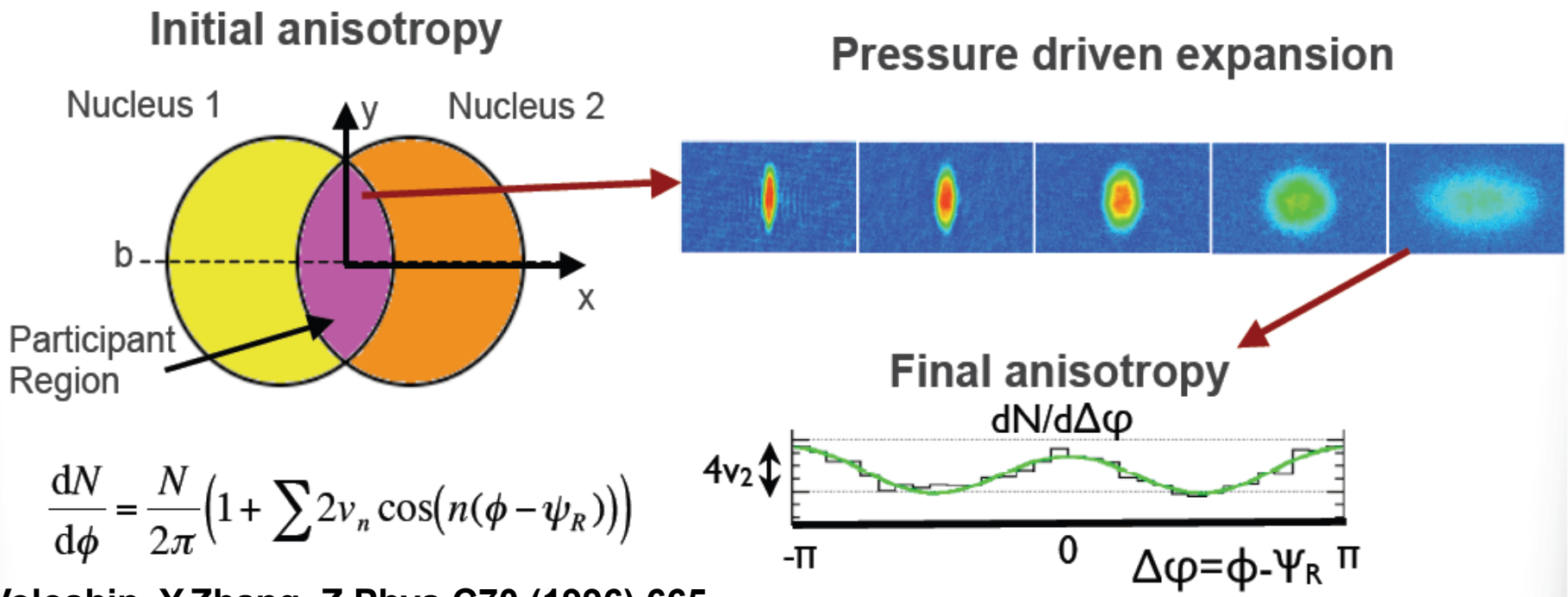
IV. Hexagonal flow

I. DESCRIPTION OF ANISOTROPIC FLOW IN RELATIVISTIC HEAVY ION COLLISIONS



ELLIPTIC FLOW

Initial spatial anisotropy is converted to anisotropy in momentum space



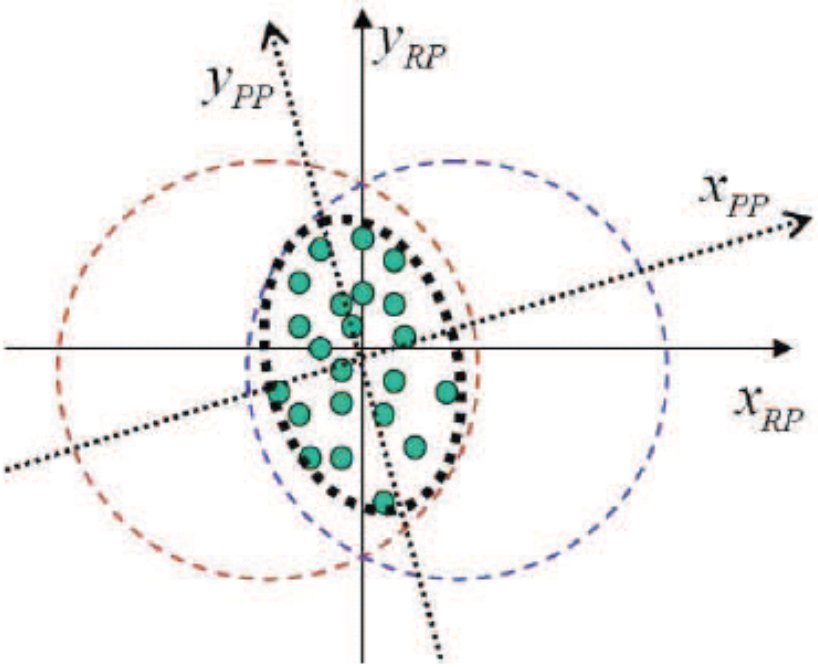
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_R)\right)\right)$$

S.Voloshin, Y.Zhang, Z.Phys.C70 (1996) 665

$$v_2 = \left\langle \cos\left(2(\phi - \underline{\psi_R})\right)\right\rangle \propto \varepsilon$$

Elliptic flow is quantified by the second Fourier coefficient (v_2) of the observed particle distribution

Eccentricity fluctuations



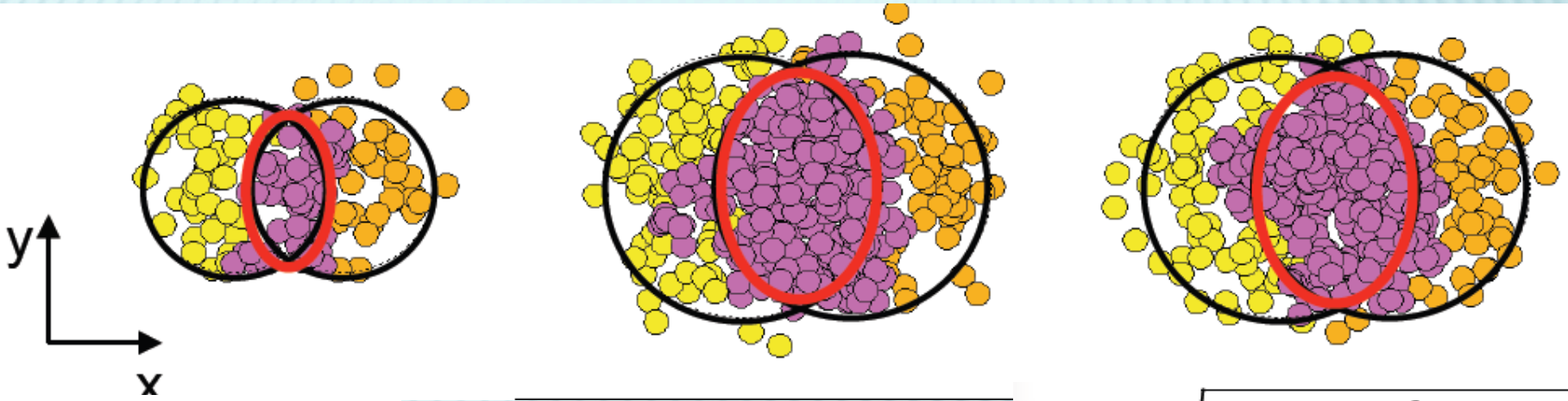
Depending on where the participant nucleons are located within the nucleus at the time of the collision, the actual shape of the overlap area may vary: the orientation and eccentricity of the ellipse defined by participants fluctuates.

Assuming that v_2 scales like the eccentricity, eccentricity fluctuations translate into v_2 fluctuations

Eccentricity fluctuations can be computed in MC Glauber model or derived from experiment by comparing different methods for flow calculation.

ECCENTRICITY

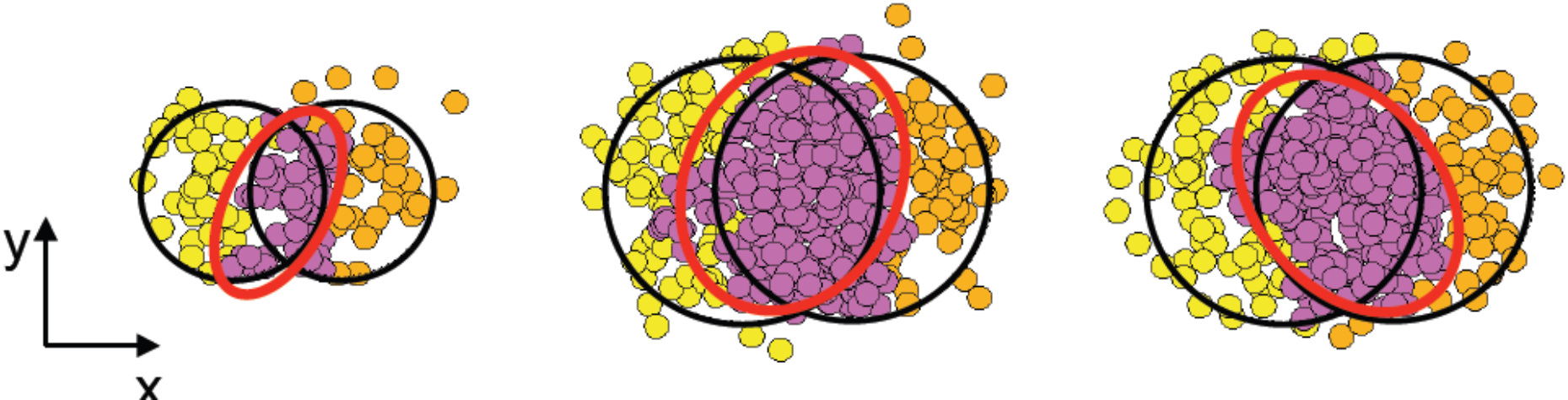
STANDARD



$$\varepsilon_{\mathrm{RP}} = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

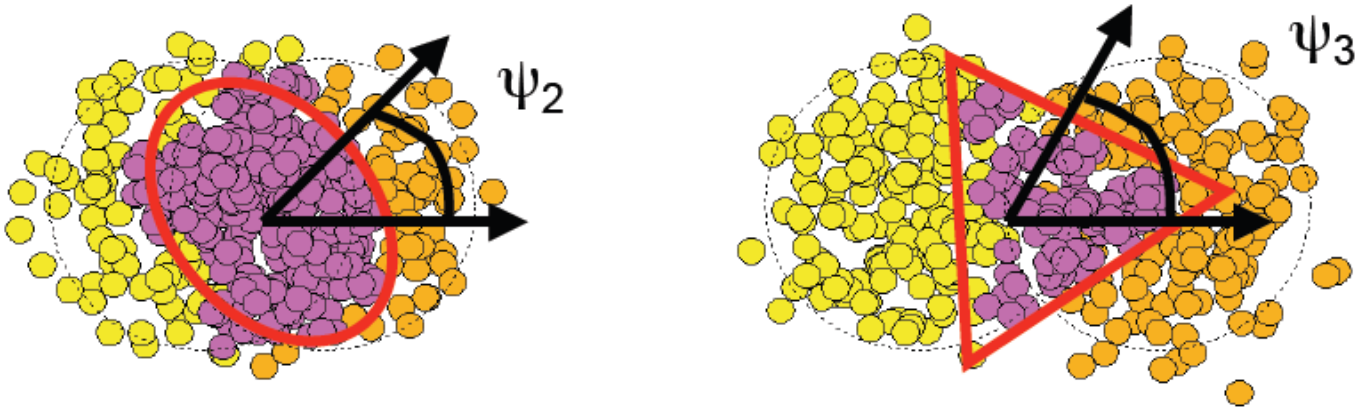
PARTICIPANT

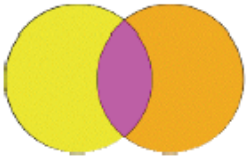
$$\varepsilon_{\mathrm{part}} = \frac{\sqrt{\left(\sigma_y^2 - \sigma_x^2\right)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$



TRIANGULAR FLOW

B. Alver and G.Roland, PRC 81 (2010) 054905

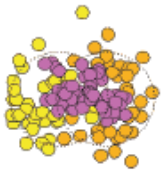




$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_R)\right)\right)$$

$$v_2 = \left\langle \cos\left(2(\phi - \psi_R)\right)\right\rangle$$

$$v_3 = 0$$



$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_n)\right)\right)$$

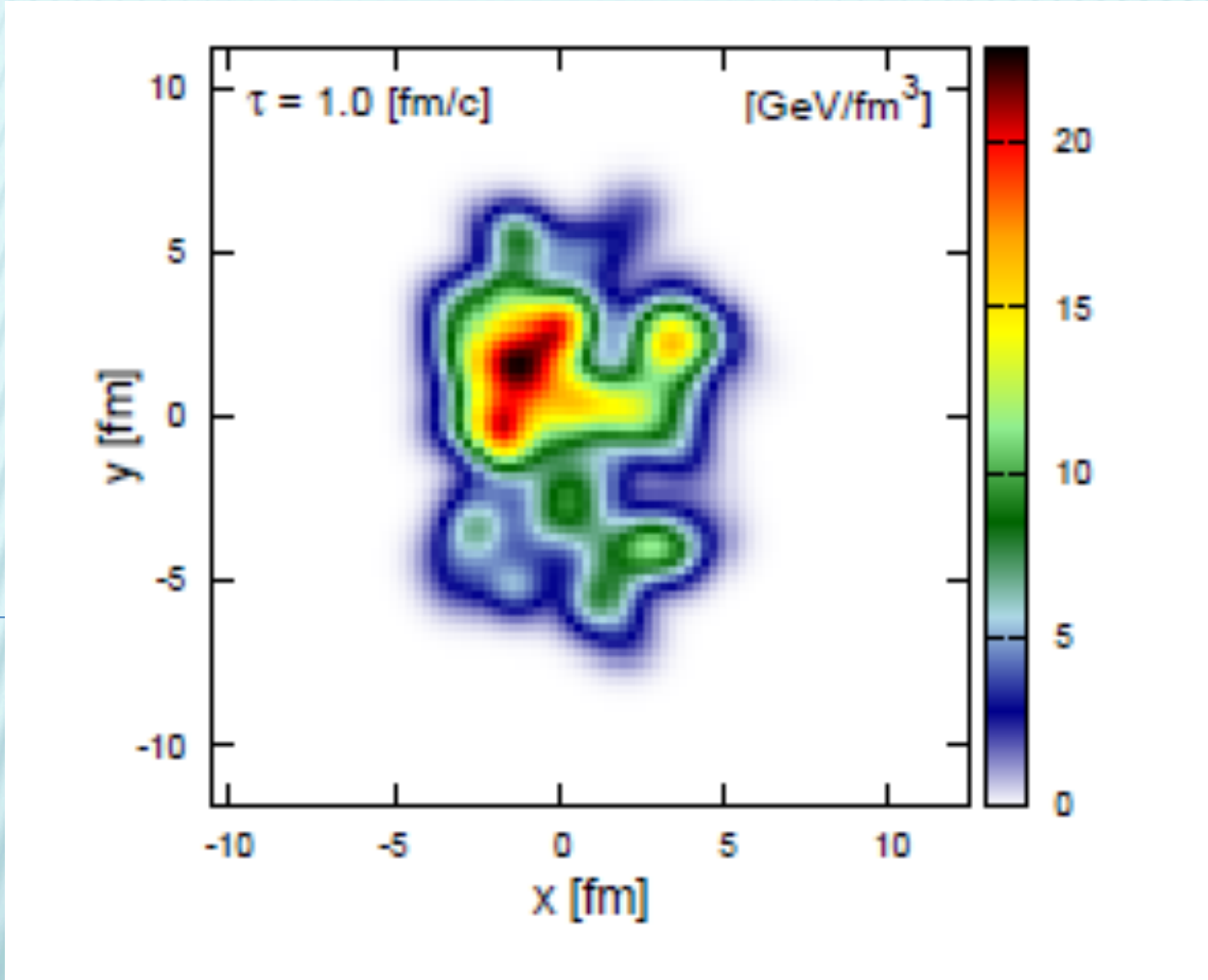
$$v_2 = \left\langle \cos\left(2(\phi - \psi_2)\right)\right\rangle$$

$$v_3 = \left\langle \cos\left(3(\phi - \psi_3)\right)\right\rangle$$

The triangular initial shape leads to triangular hydrodynamic flow

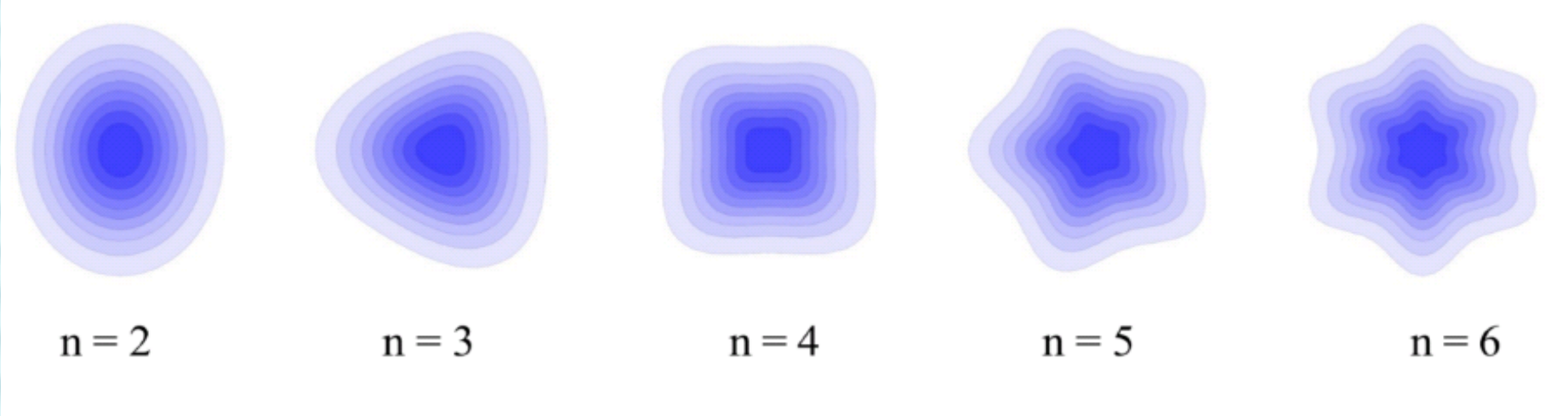
INITAL-STATE FLUCTUATIONS (example)

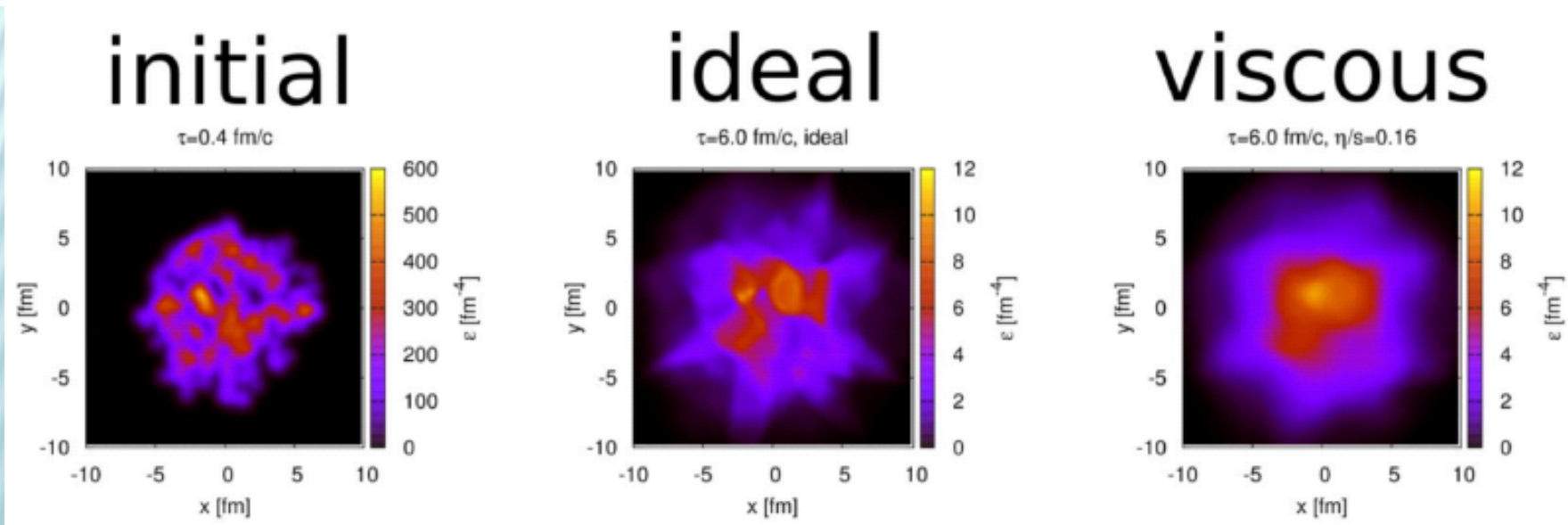
W.-L. Qian et al., JPG 41 (2013) 015103



Energy distribution of a random NeXuS event

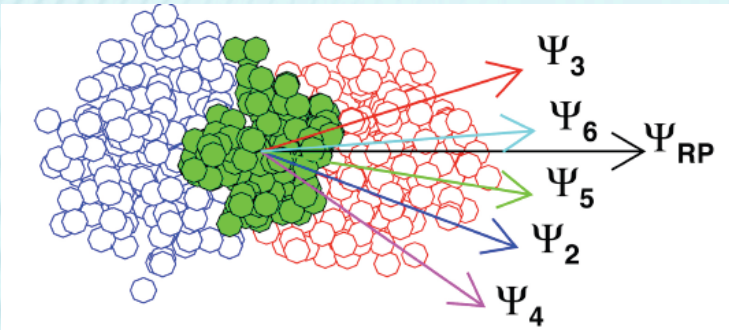
HIGHER FLOW HARMONICS





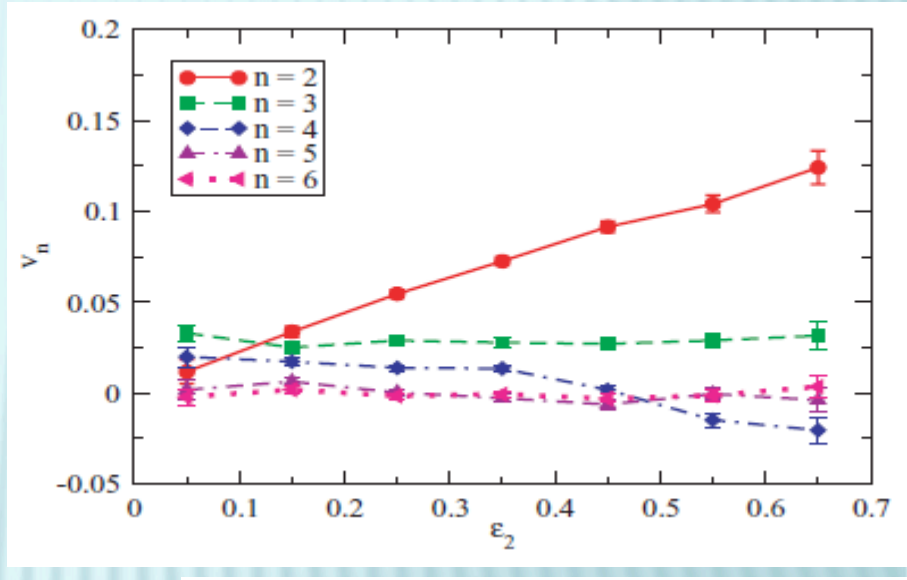
Non-zero higher Fourier coefficients can carry important information about the space-time evolution of the QCD-matter and initial fluctuations

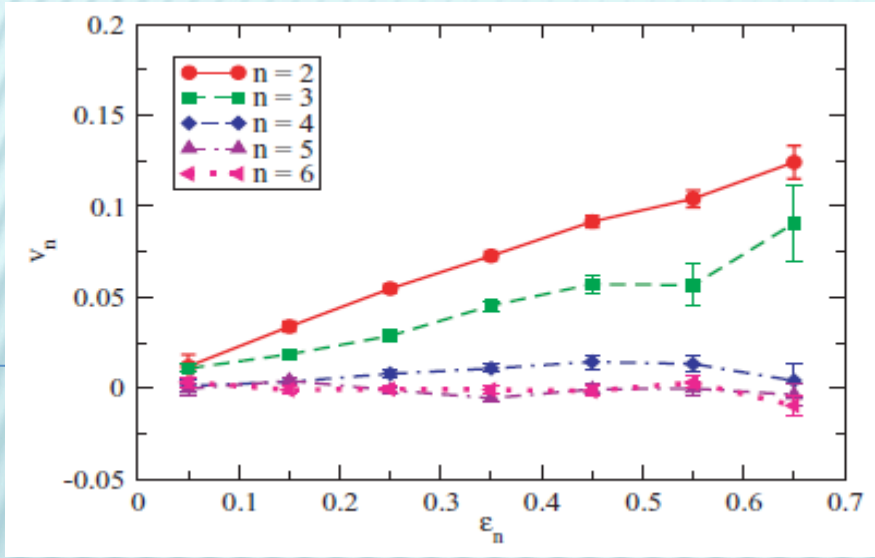
CROSS-TALK BETWEEN FLOW HARMONICS



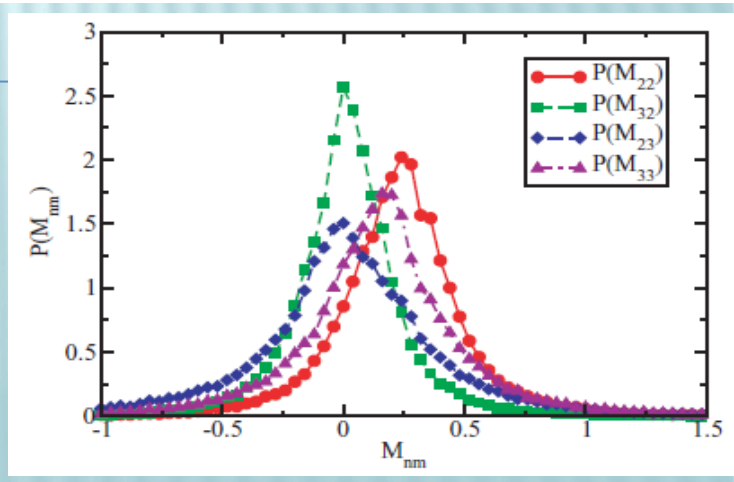
ψ_n: participant plane

G.-Y. Qin et al, PRC 82 (2010) 064903





$$\begin{pmatrix} v_2 \\ v_3 \end{pmatrix} = \begin{pmatrix} M_{22} & M_{23} \\ M_{32} & M_{33} \end{pmatrix} \begin{pmatrix} \epsilon_2 \\ \epsilon_3 \end{pmatrix}$$



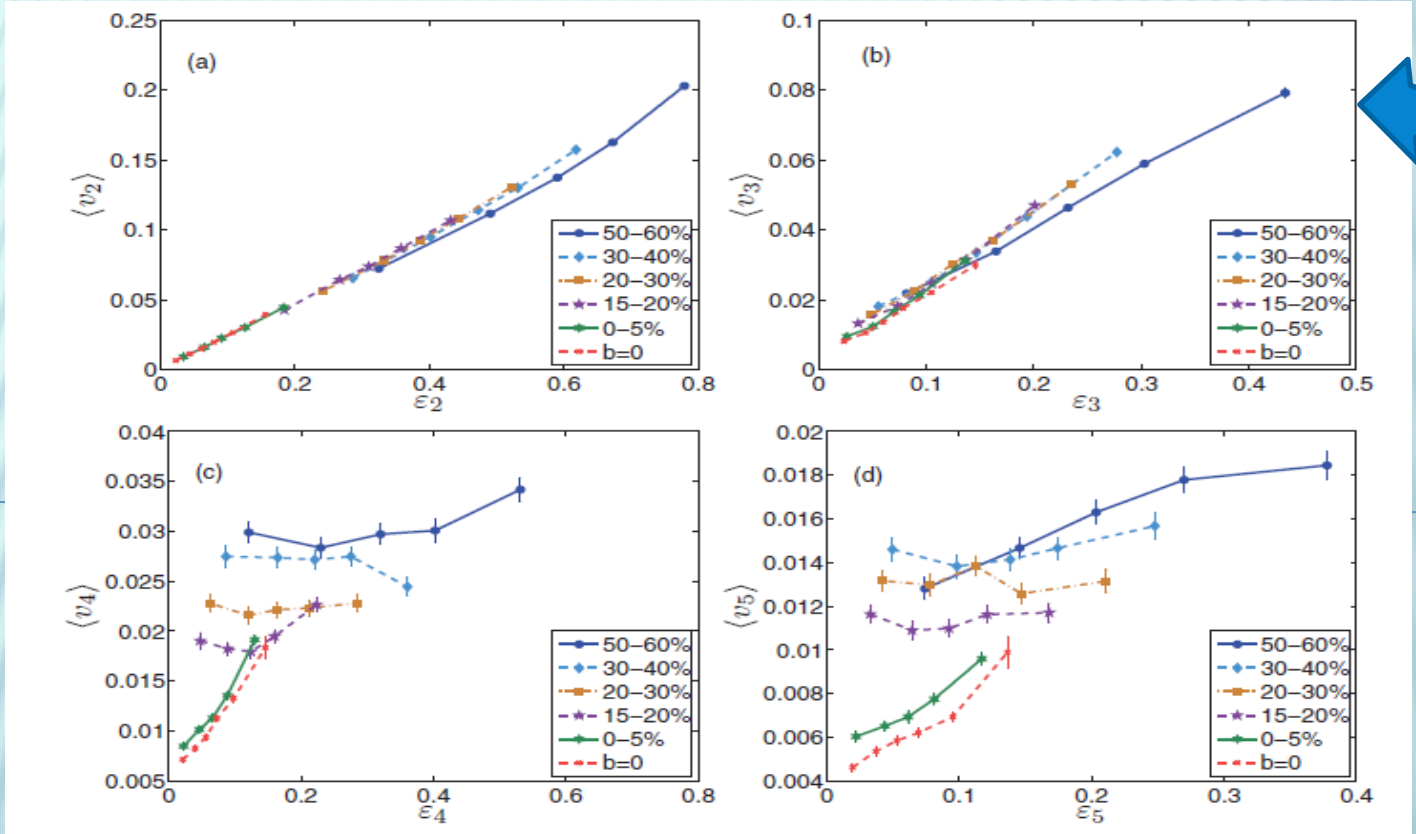
Only the first few flow harmonics of final-state hadrons survive after hydrodynamic evolution

CROSS-TALK BETWEEN FLOW HARMONICS

Z. Qiu and U. Heinz, PRC 84 (2011) 024911

$$\varepsilon_n e^{in\psi_n^{\mathrm{PP}}} = -\frac{\int dx\, dy\, r^2 e^{in\phi}\, e(x,y)}{\int dx\, dy\, r^2\, e(x,y)}$$

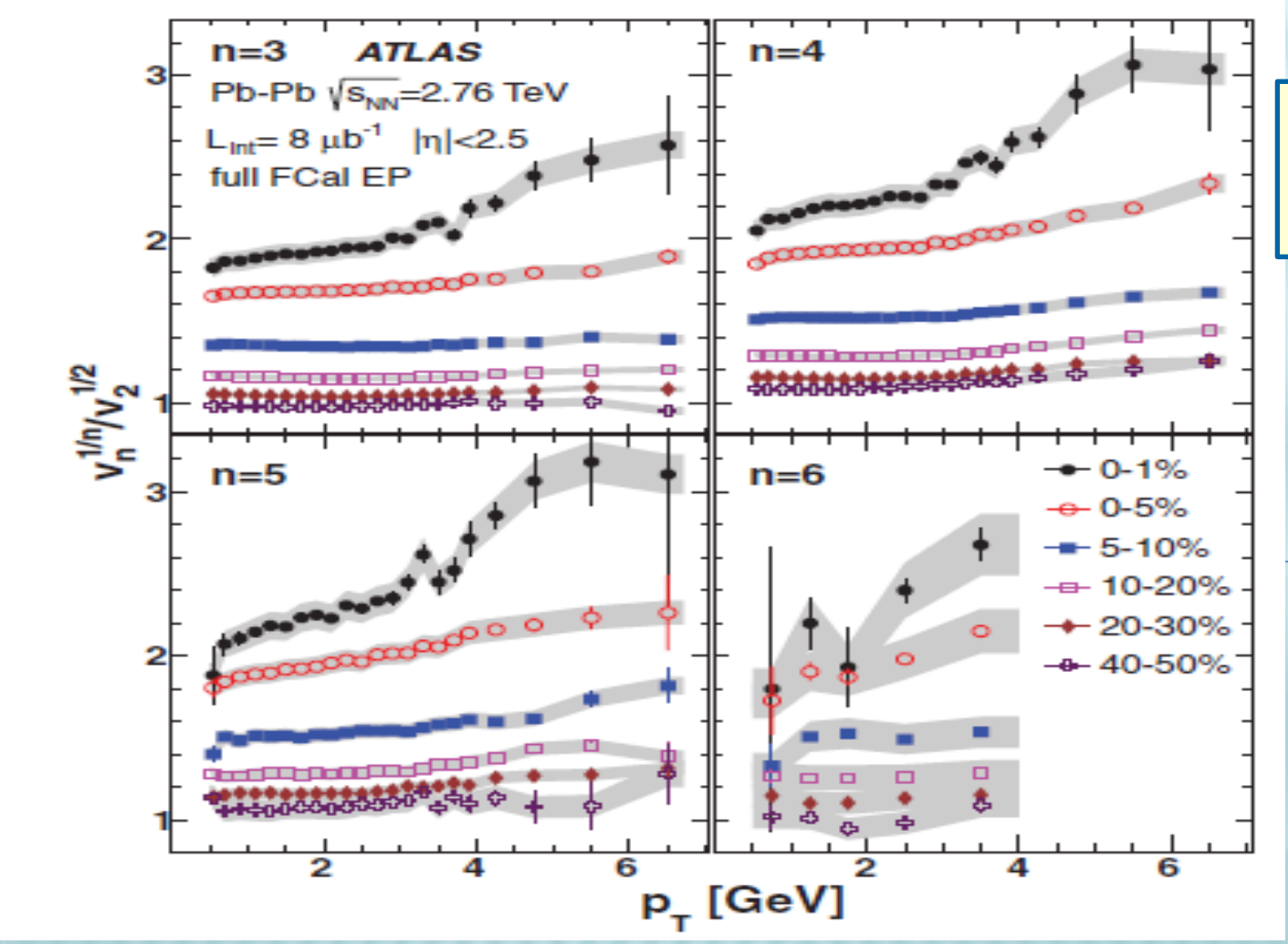
$$v_n(y, p_T)\, e^{in\psi_n^{\mathrm{EP}}(y,p_T)} = \frac{\int d\phi_p\, e^{in\phi_p} \frac{dN}{dy\, p_T dp_T\, d\phi_p}}{\frac{dN}{dy\, p_T dp_T}}$$



(1) The basic response of v2 and v3 to eccentricities is approx. linear

(2) Higher flow coefficients show poor correlation with the eccentricities of the same order

SCALING OF HIGHER ORDER FLOW HARMONICS



J.-Y. Ollitrault :

$V\downarrow n \uparrow 1/n \propto V\downarrow 2 \uparrow 1/2$

Ratios are almost insensitive to P_T from 1GeV/c to 4GeV/c

Results for n=3 are lower than that for higher harmonics

ATLAS, PRC 86 (2012) 014907

II. HYDJET++ = FASTMS + HYDJET

H Y D J E T + +

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/hydjet++

I.Lokhtin, L.Malinina, S.Petrushanko, A.Snigirev, I.Arsene, K.Tywoniuk, Comp.Phys.Comm. 180 (2009) 779

Soft

the "thermal" hadronic state generated on the chemical and thermal freeze-out hypersurfaces obtained from the parametrization of relativistic hydrodynamics with present freeze-out conditions (the adapted event generator FAST MC).

Hard

the multiple scattering of hard partons is based on accumulated energy loss via gluon radiation which is associated with each parton scattering in expanding quark-gluon fluid (PYQUEN jet quenching model).

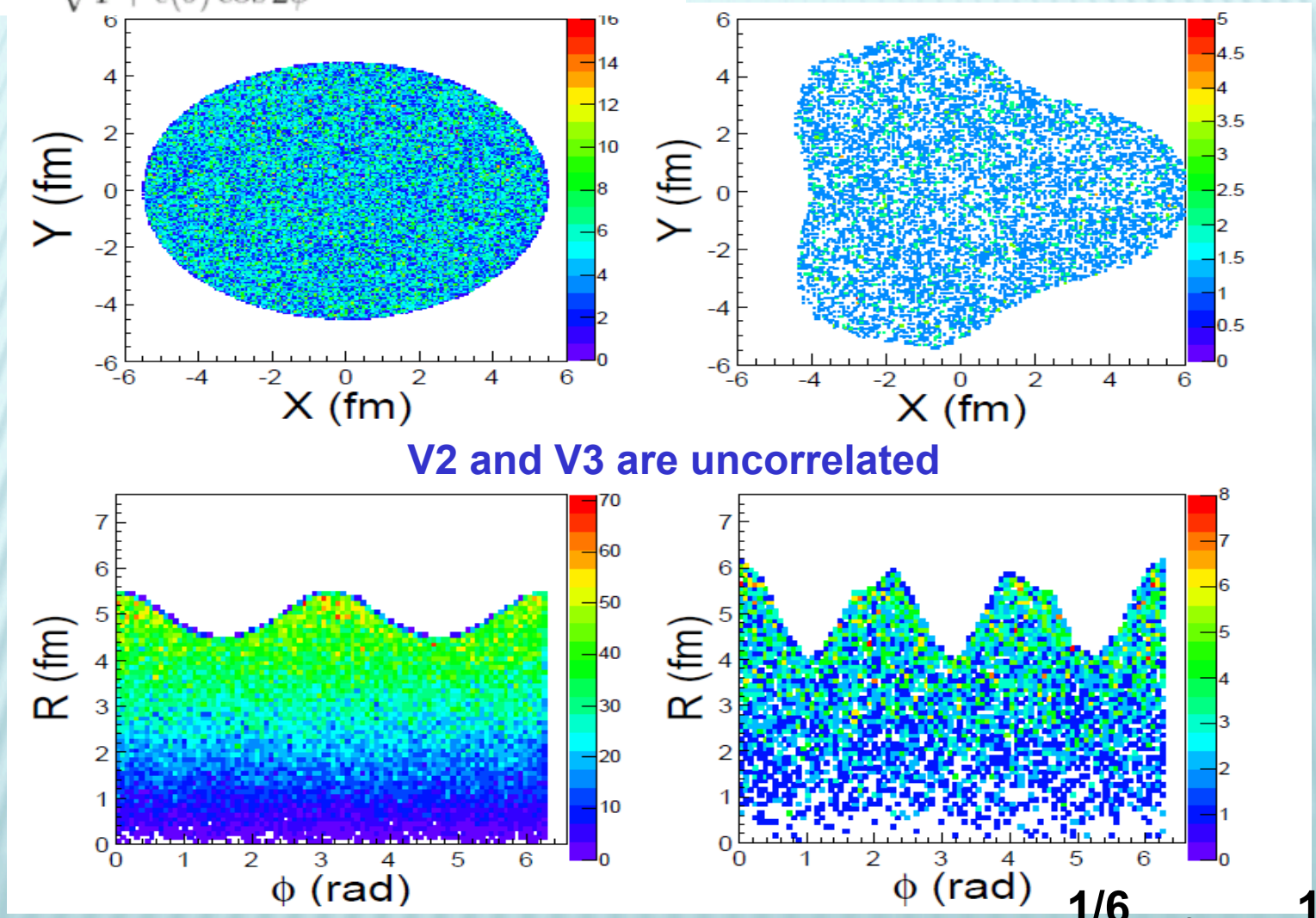
We apply HYDJET++ with tuned input parameters to reproduce the LHC data from PbPb collisions, and to estimate an influence of the hard production mechanism on physics observables.

GENERATION OF TRIANGULAR FLOW

$$R(b,\phi) = R_f(b)\frac{\sqrt{1-\epsilon^2(b)}}{\sqrt{1+\epsilon(b)\cos 2\phi}}[1+\epsilon_3(b)\cos 3(\phi+\Psi_3^{\mathrm{RP}})]$$

Bravina et al., EPJC 74:2807 (2014)

V2



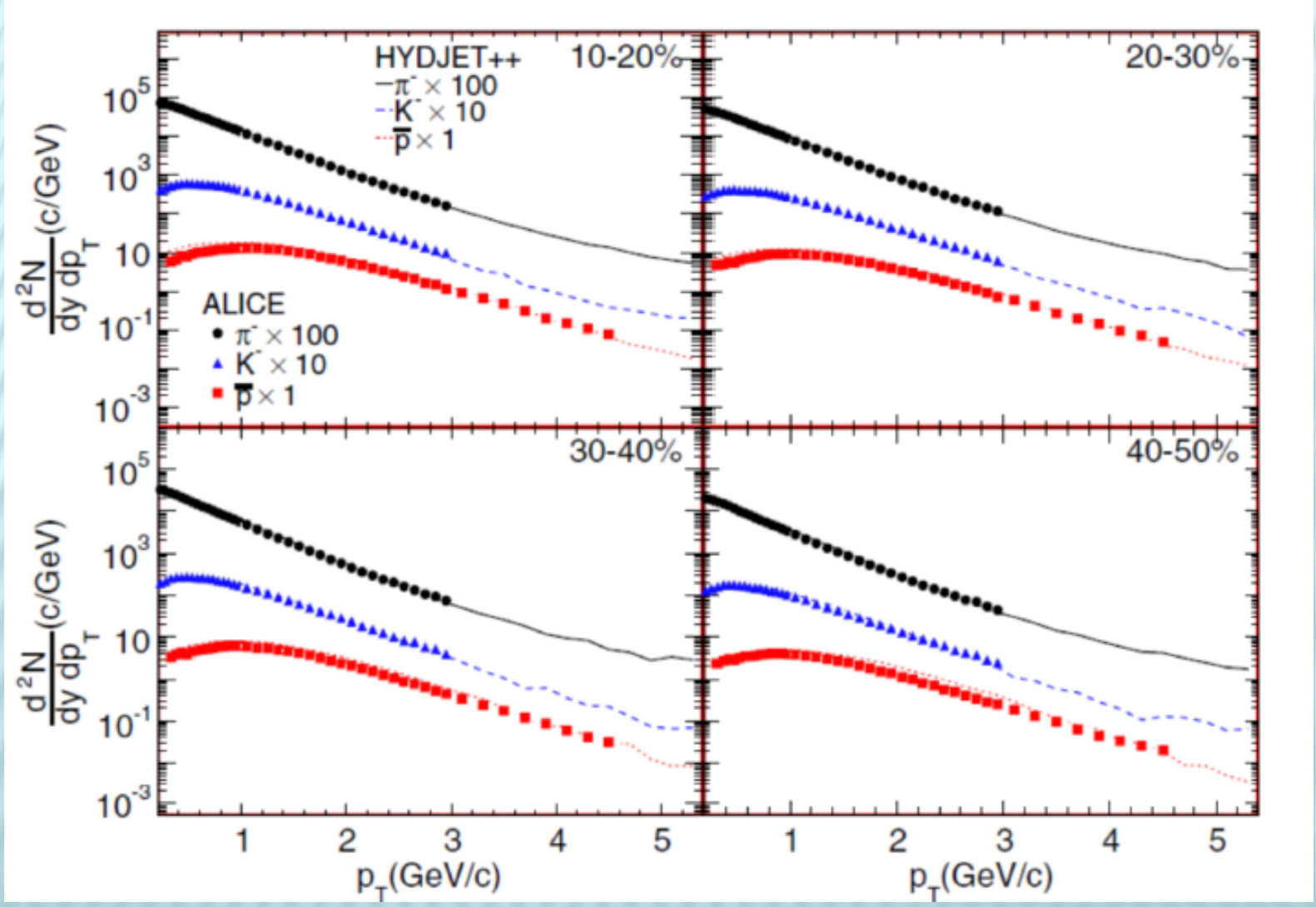
V3

Hint (Teaney, Ollitrault, …): $V_5 \propto V_2 V_3 \quad V_6 \propto \alpha V_2^3 + \beta V_3^2$ (1/6, 1/2)

LHC DATA VS. HYDJET++ MODEL

Particle spectra

Pb+Pb @ 2.76 ATeV



L. Bravina et al., Eur. Phys. J C74 (2014) 2807

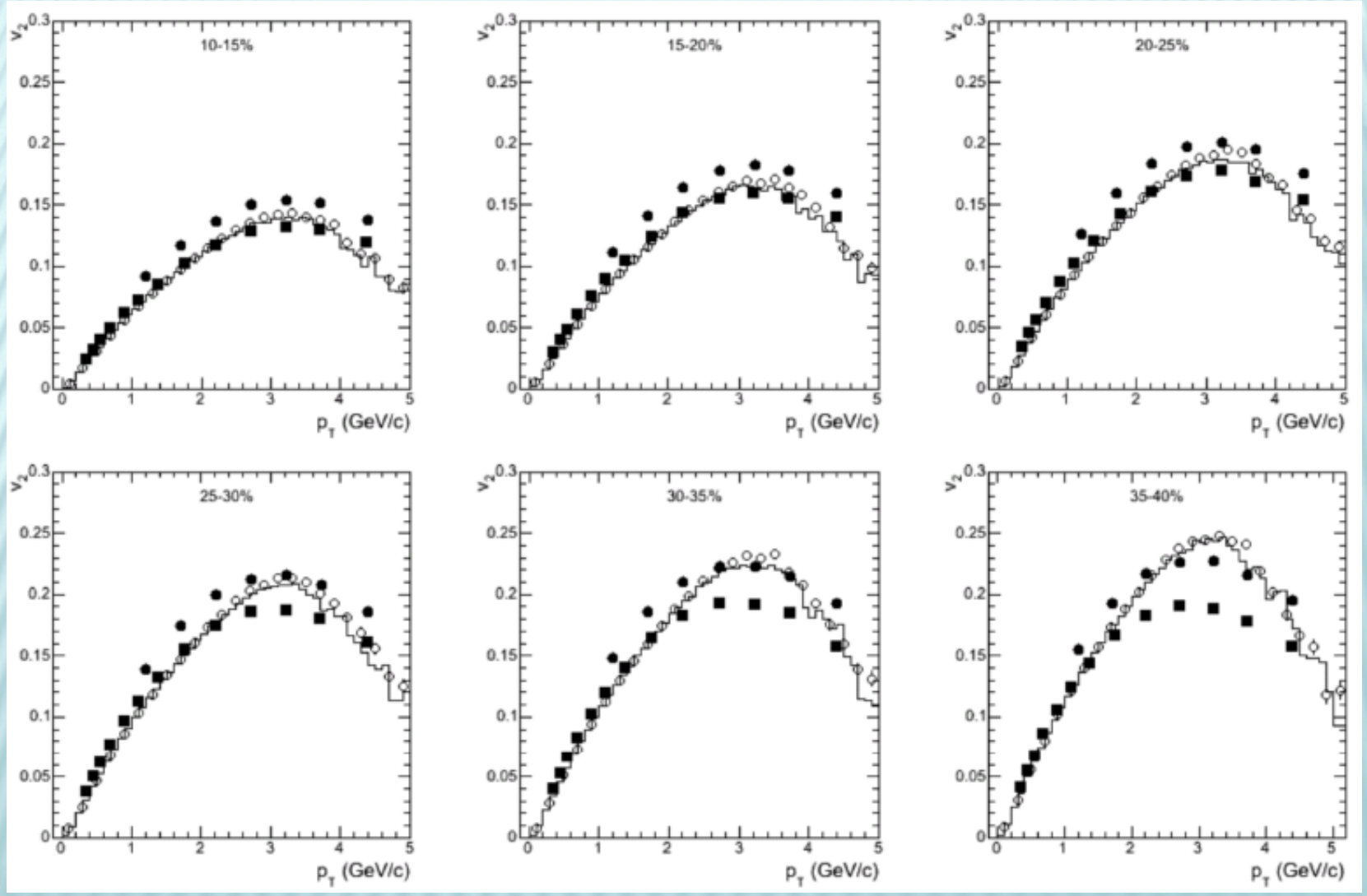
Closed symbols: ALICE data ; Lines: HYDJET++

LHC DATA VS. HYDJET++ MODEL

Elliptic flow

Pb+Pb @ 2.76 ATeV

Parameters are tuned



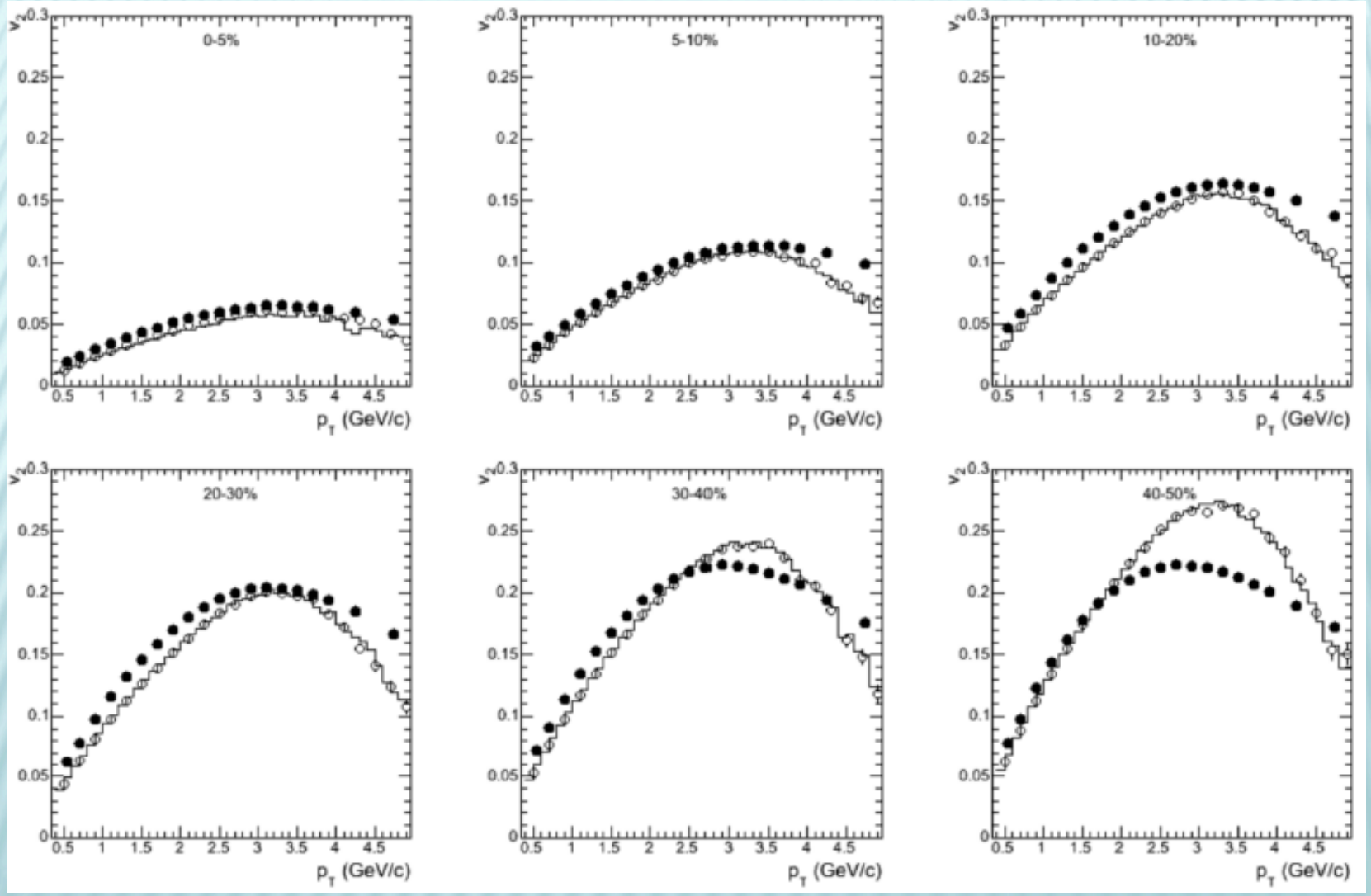
L. Bravina et al., Eur. Phys. J C74 (2014) 2807

Closed symbols: CMS data v2{2Part & LYZ};
Open symbols and histograms: HYDJET++ v2{EP & Psi2}

LHC DATA VS. HYDJET++ MODEL

Elliptic flow

Pb+Pb @ 2.76 ATeV



L. Bravina et al., Eur. Phys. J C74 (2014) 2807

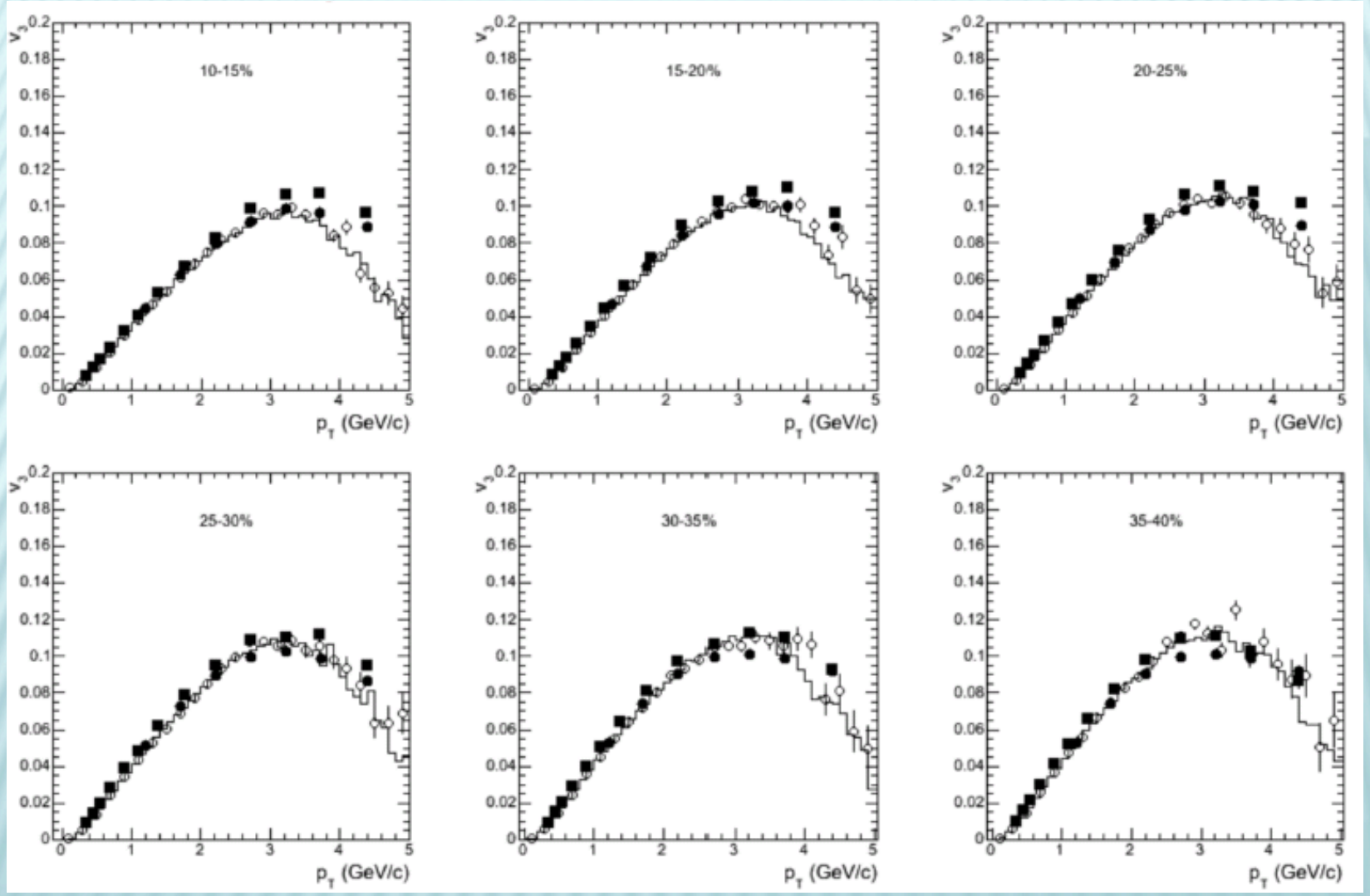
Closed symbols: ATLAS data v2{RP};
Open symbols and histograms: HYDJET++ v2{EP & Psi2}

LHC DATA VS. HYDJET++ MODEL

Triangular flow

Pb+Pb @ 2.76 ATeV

Parameters are tuned



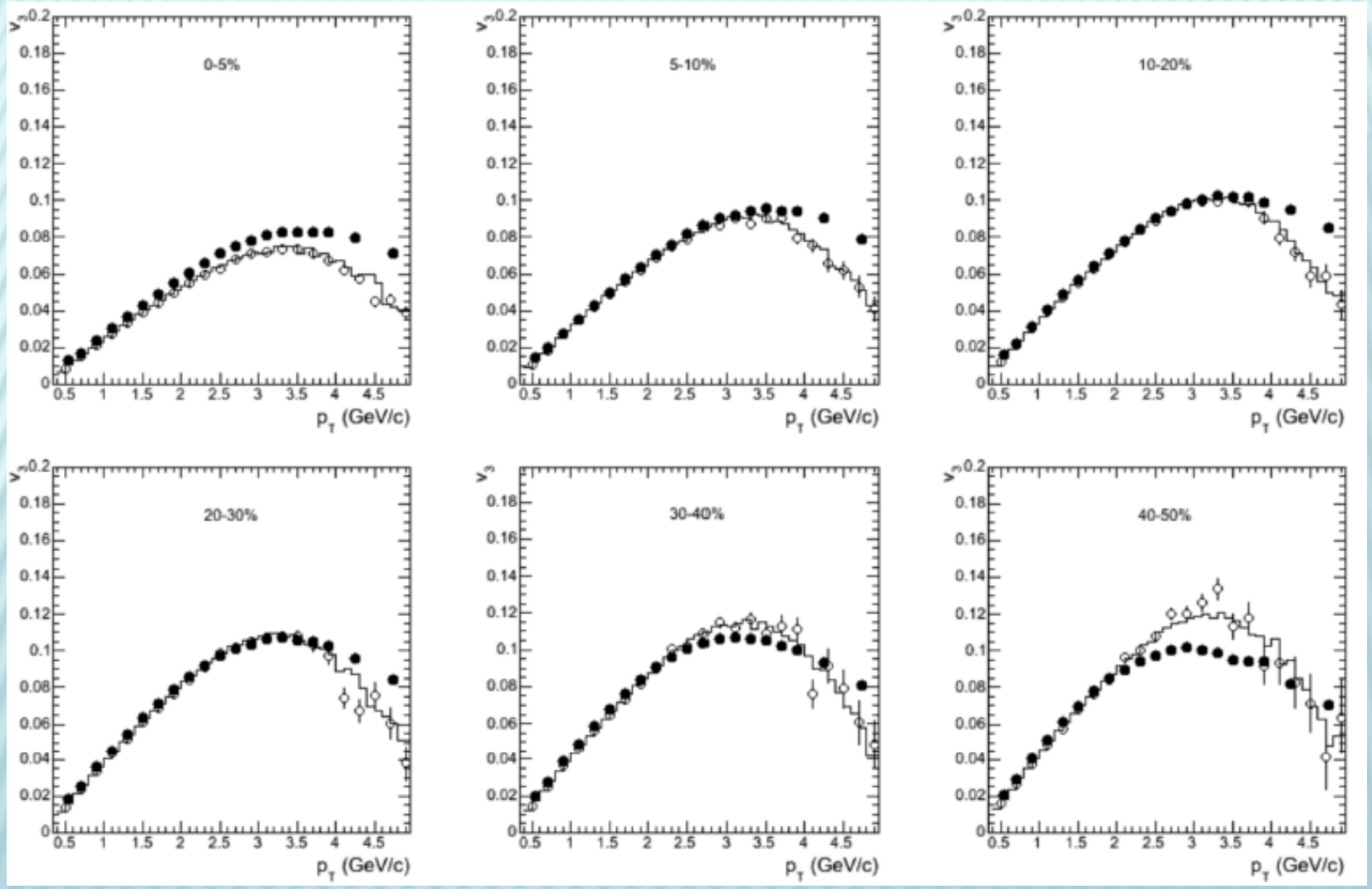
L. Bravina et al., Eur. Phys. J C74 (2014) 2807

Closed symbols: CMS data v3{2Part & LYZ};
Open symbols and histograms: HYDJET++ v3{EP & Psi3}

LHC DATA VS. HYDJET++ MODEL

Triangular flow

Pb+Pb @ 2.76 ATeV



L. Bravina et al., Eur. Phys. J C74 (2014) 2807

Closed symbols: ATLAS data v3{RP};
Open symbols and histograms: HYDJET++ v3{EP & Psi3}

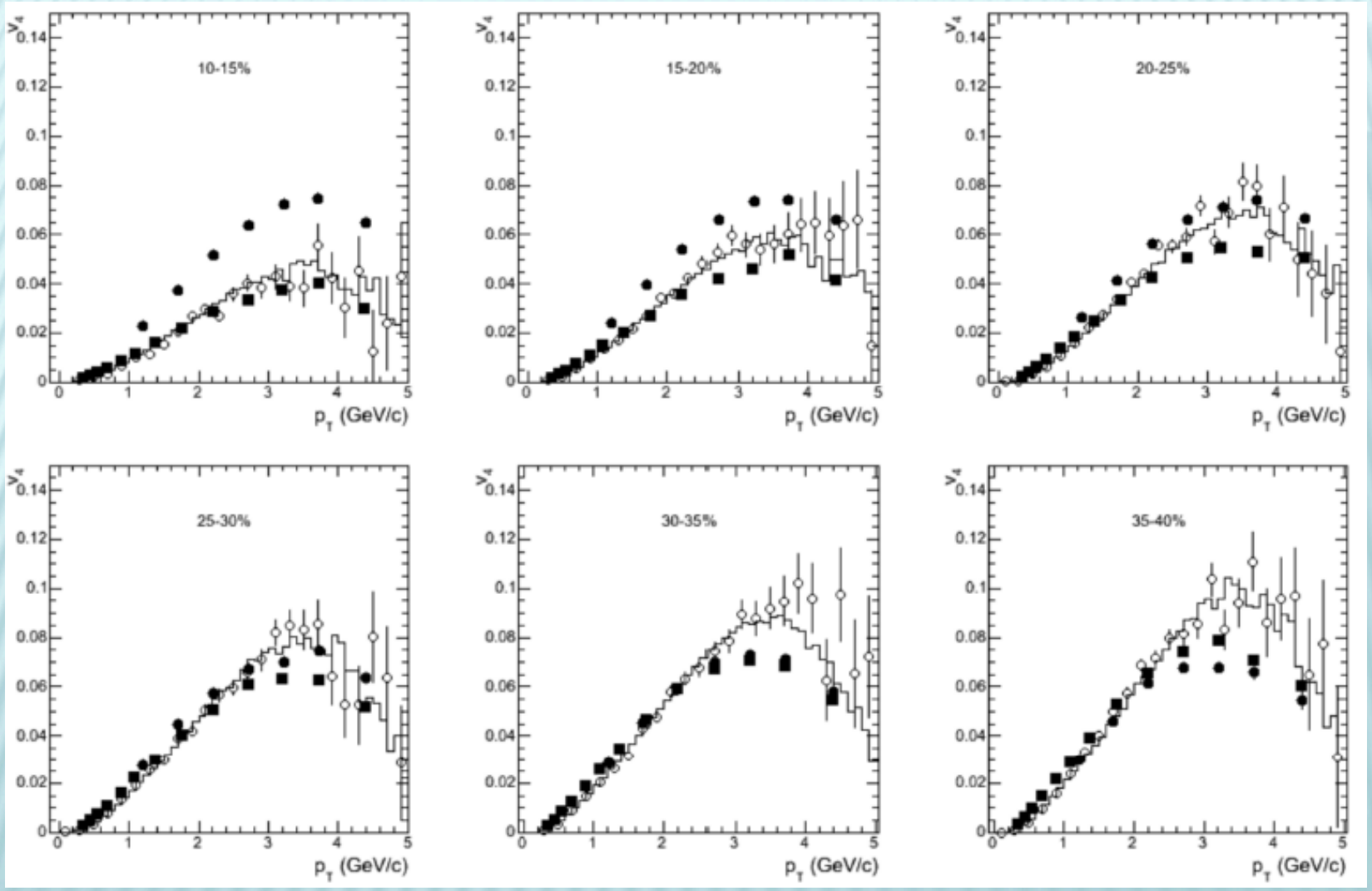
III. HIGHER HARMONICS: V4 and V5

LHC DATA VS. HYDJET++ MODEL

Quadrangular flow

Pb+Pb @ 2.76 ATeV

No extra tuning of parameters



L. Bravina et al., Eur. Phys. J C74 (2014) 2807

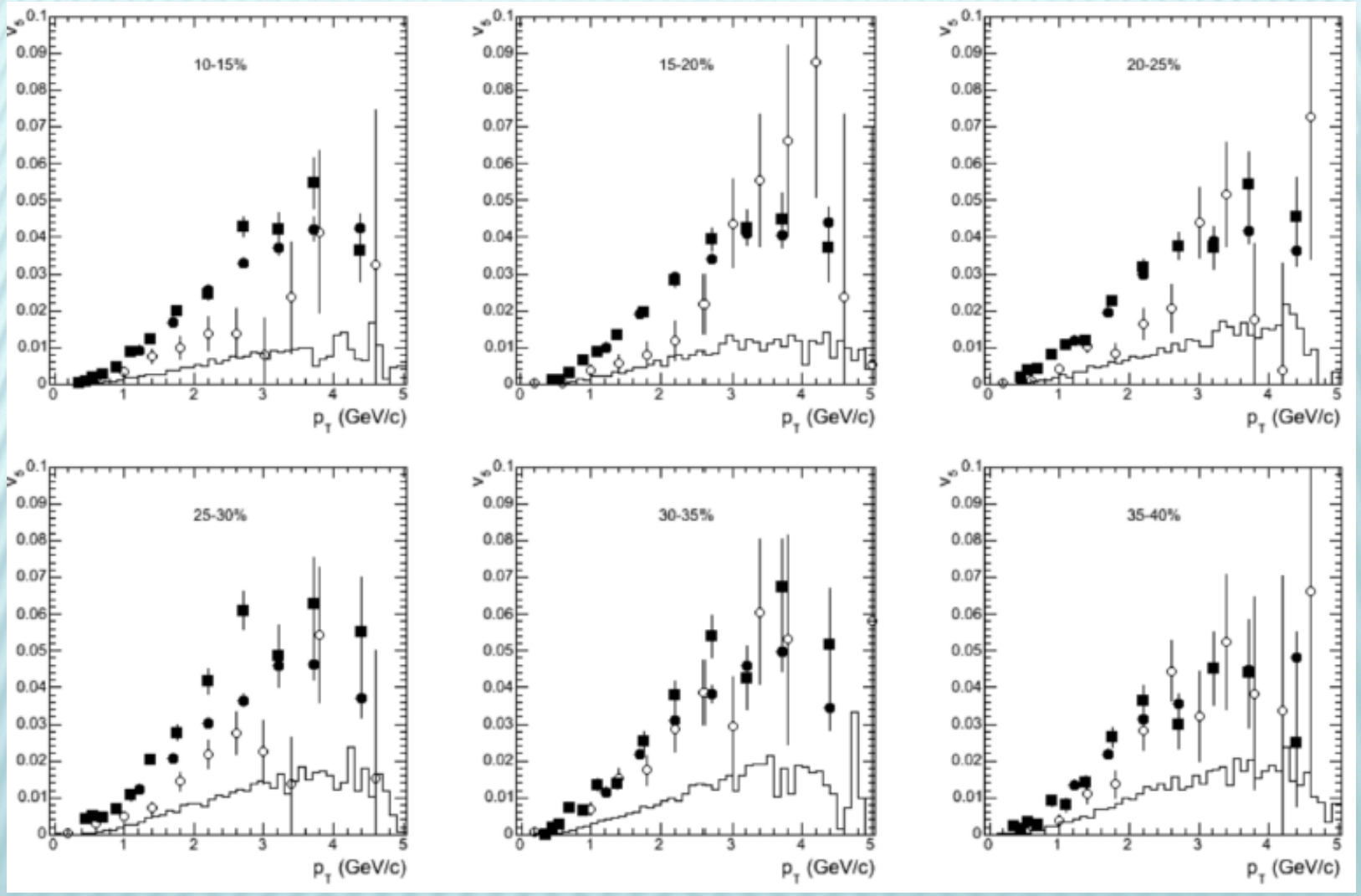
Closed symbols: CMS data v4{2Part & LYZ};
Open symbols and histograms: HYDJET++ v4{EP & Psi2}

v4 is there even if v3 is absent

LHC DATA VS. HYDJET++ MODEL

Pentagonal flow

Pb+Pb @ 2.76 ATeV



L. Bravina et al., Eur. Phys. J C74 (2014) 2807

Closed symbols: CMS data v5{2Part & Psi5};
Open symbols and histograms: HYDJET++ v5{EP & Psi3}

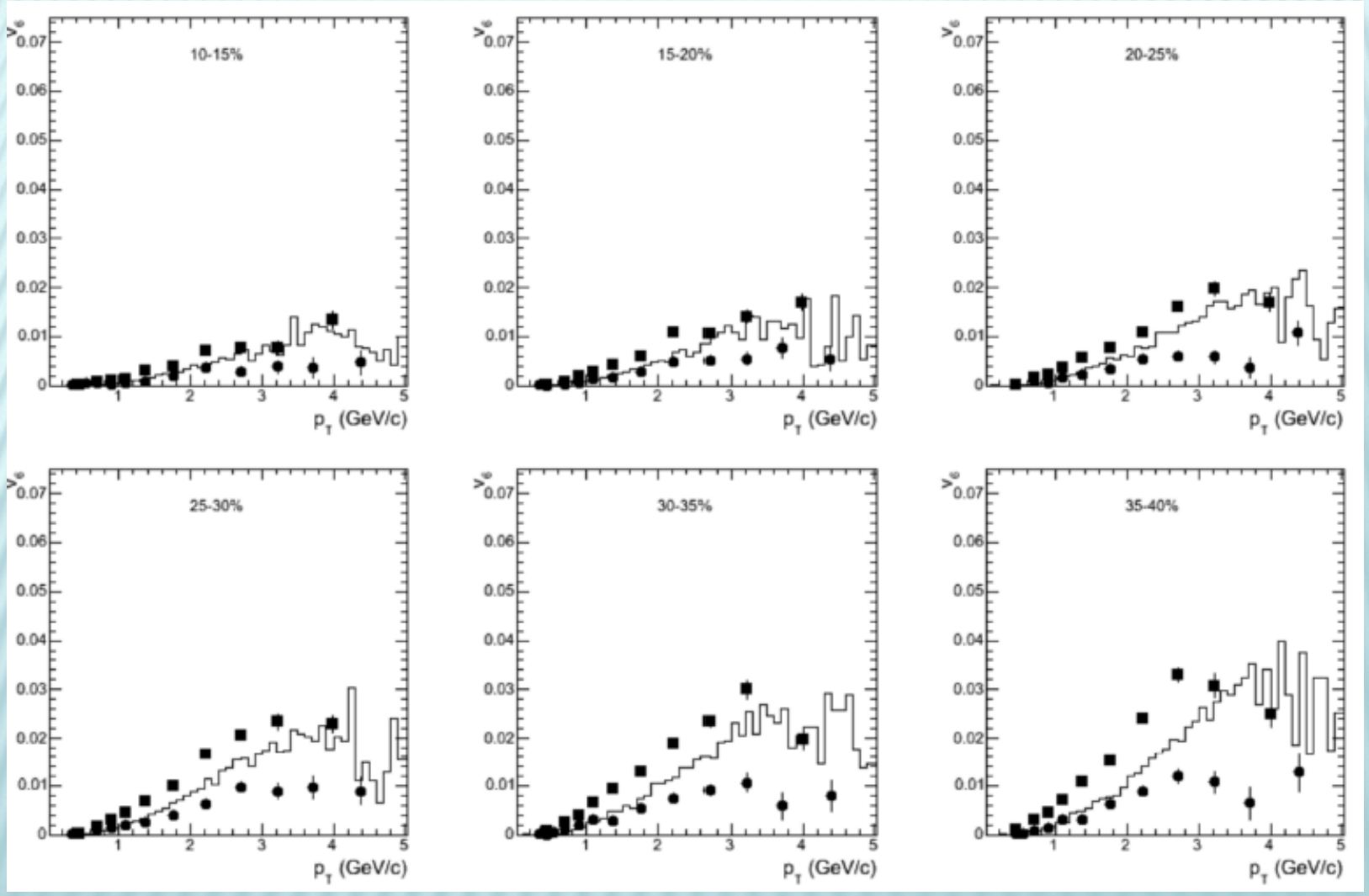
v5 is zero if either v2 or v3 is absent

IV. HIGHER HARMONICS: hexagonal flow v6

LHC DATA VS. HYDJET++ MODEL

Hexagonal flow

Pb+Pb @ 2.76 ATeV



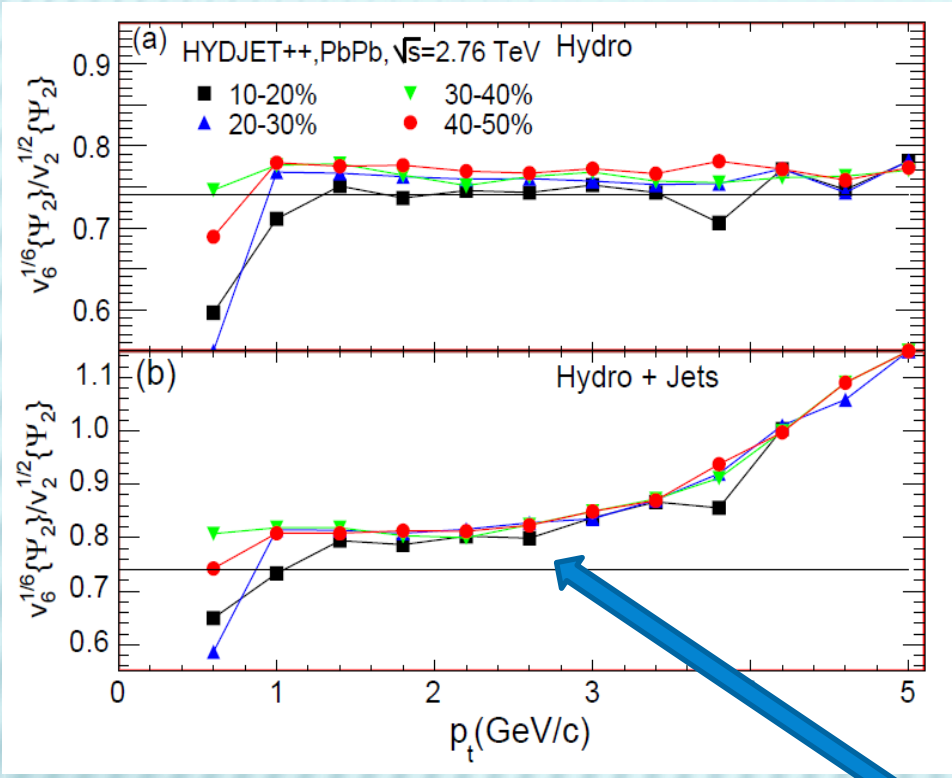
L. Bravina et al., Eur. Phys. J C74 (2014) 2807

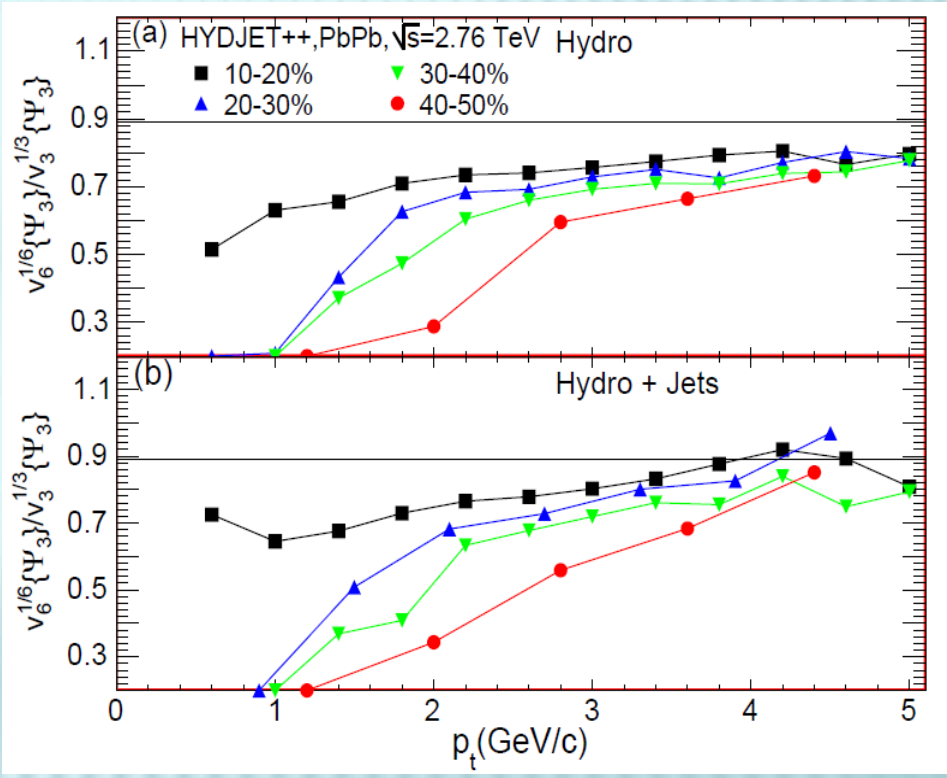
Closed symbols: CMS data v6{Psi2 & LYZ};
Open symbols and histograms: HYDJET++ v6{Psi2}

v6 is non-zero if either v2 or v3 is absent

Hexagonal flow: $V_6 \propto \alpha V_2^3 + \beta V_3^2$

Bravina et al., PRC 89, 024909 (2014)

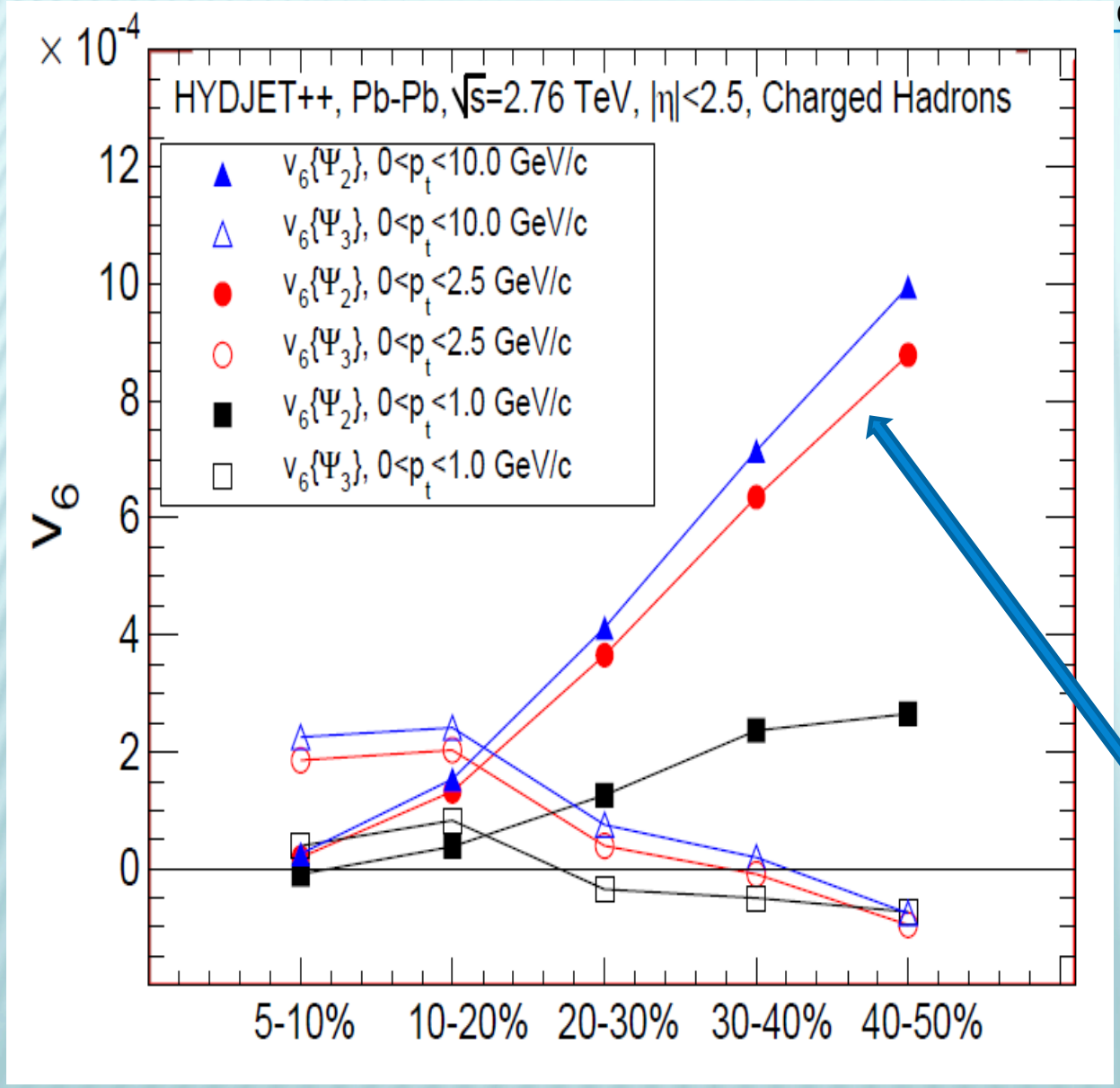




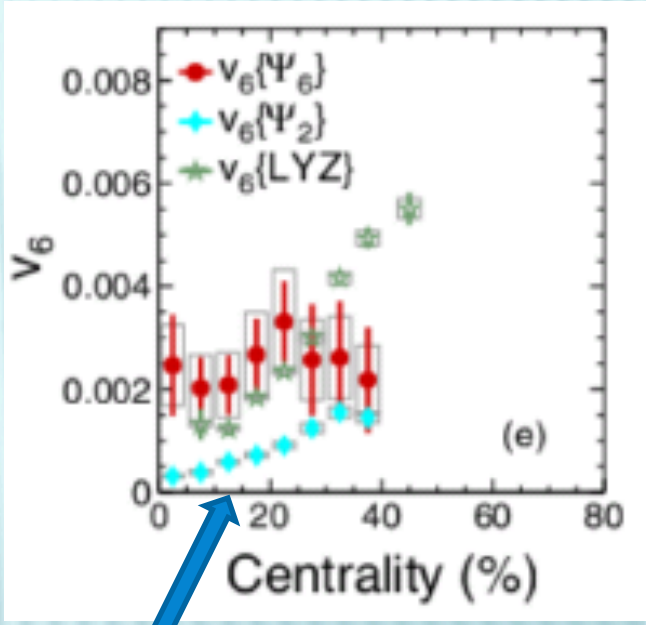
Ψ_2 Scaling? Ψ_3

It would be interesting to study $V_6(\Psi_2)$ and $V_6(\Psi_3)$ in experiment

Hexagonal flow: centrality dependence



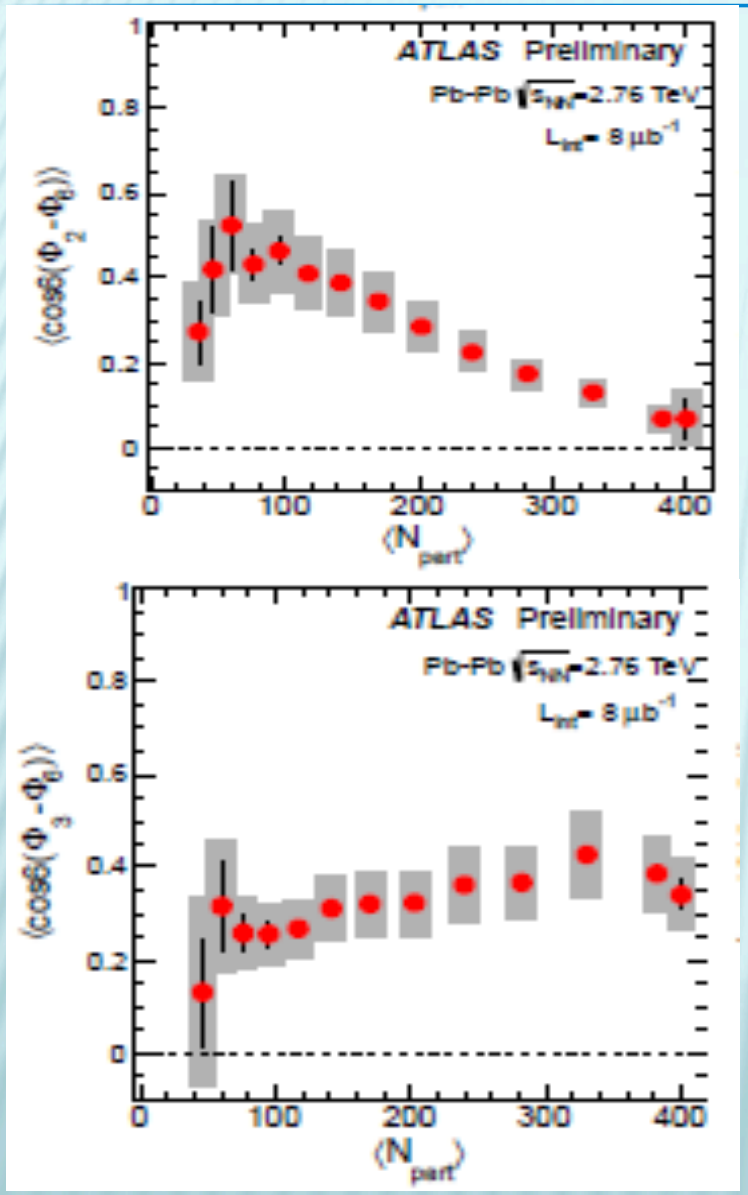
CMS Collab., PRC 89, 024909 (2014)

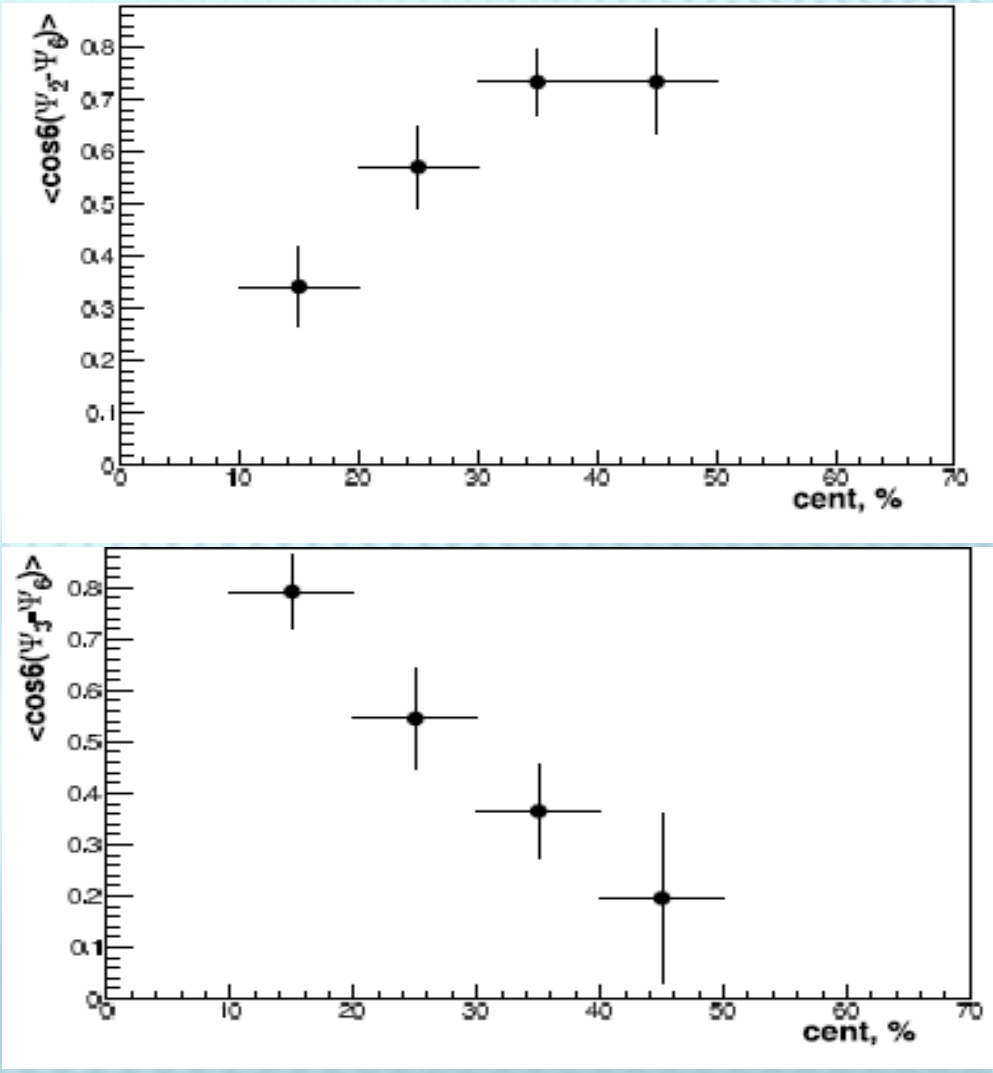


Centrality dependence in HYDJET++ is correct

Hexagonal flow: correlator analysis

ATLAS-CONF-2012-049





In line with experimental data

CONCLUSIONS

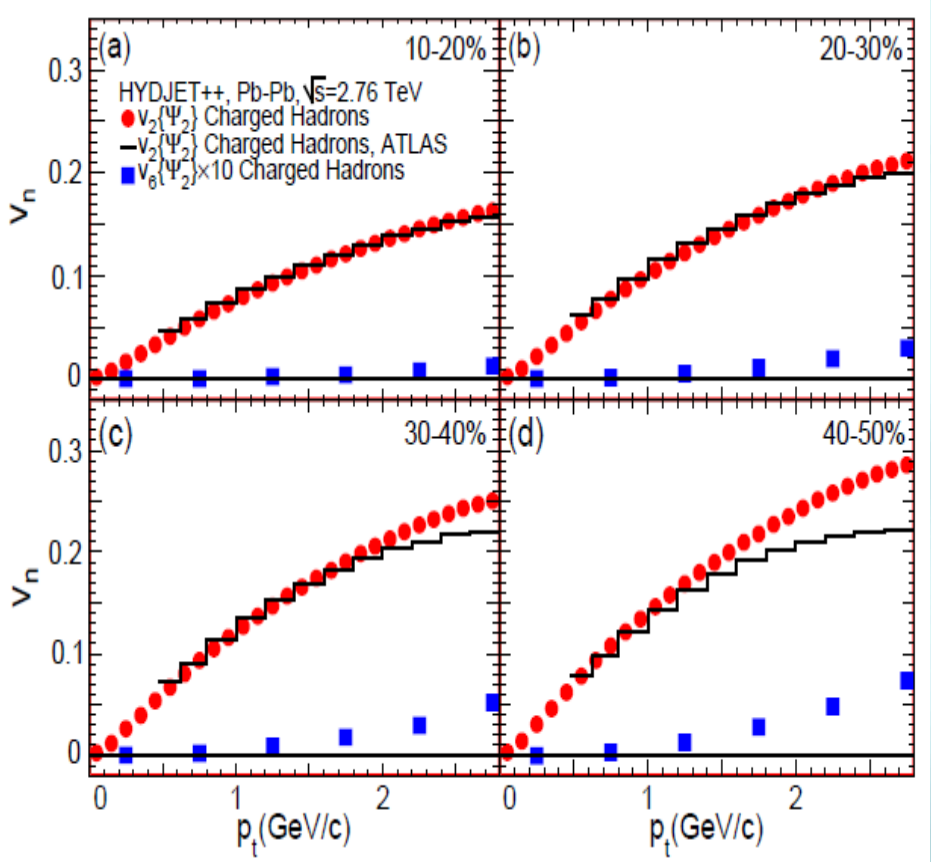
The HYDJET++ model allows us to investigate flow of hydro and jet parts separately, to look at reconstruction of pure hydro flow and its modification due to jet part.

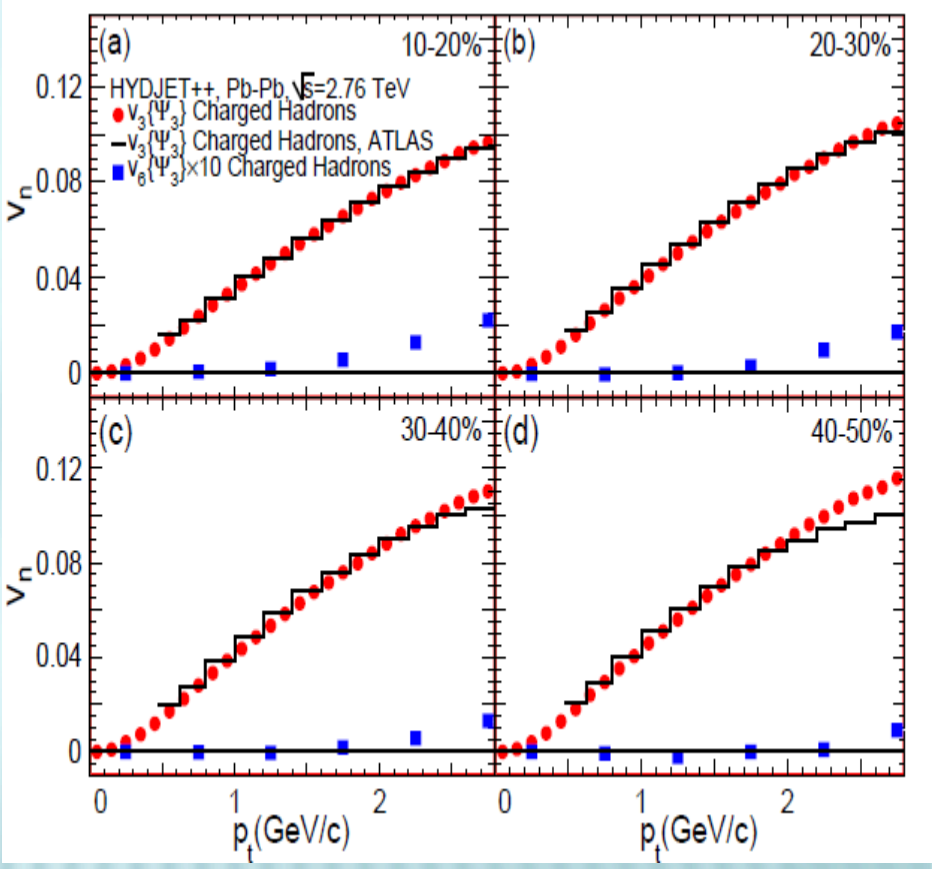
- ***HYDJET++ permits us to study cross-talk of v2 and v3, while other harmonics are absent***
- ***If only v2 is present, only even harmonics appear; odd harmonics arise if v3 is included***
- ***Scaling of $v_6^{1/6}(psi_2)/v_2^{1/2}(psi_2)$ is predicted***
- ***Jets result to increase by 10%-15% of this ratio and lead to rise of its high-pT tail***
- ***Significant part of hexagonal flow and other higher order harmonics comes from elliptic and triangular flows***

Back-up Slides

HEXAGONAL FLOW IN HYDJET++ AT LHC

Bravina et al., PRC 89, 024909 (2014)

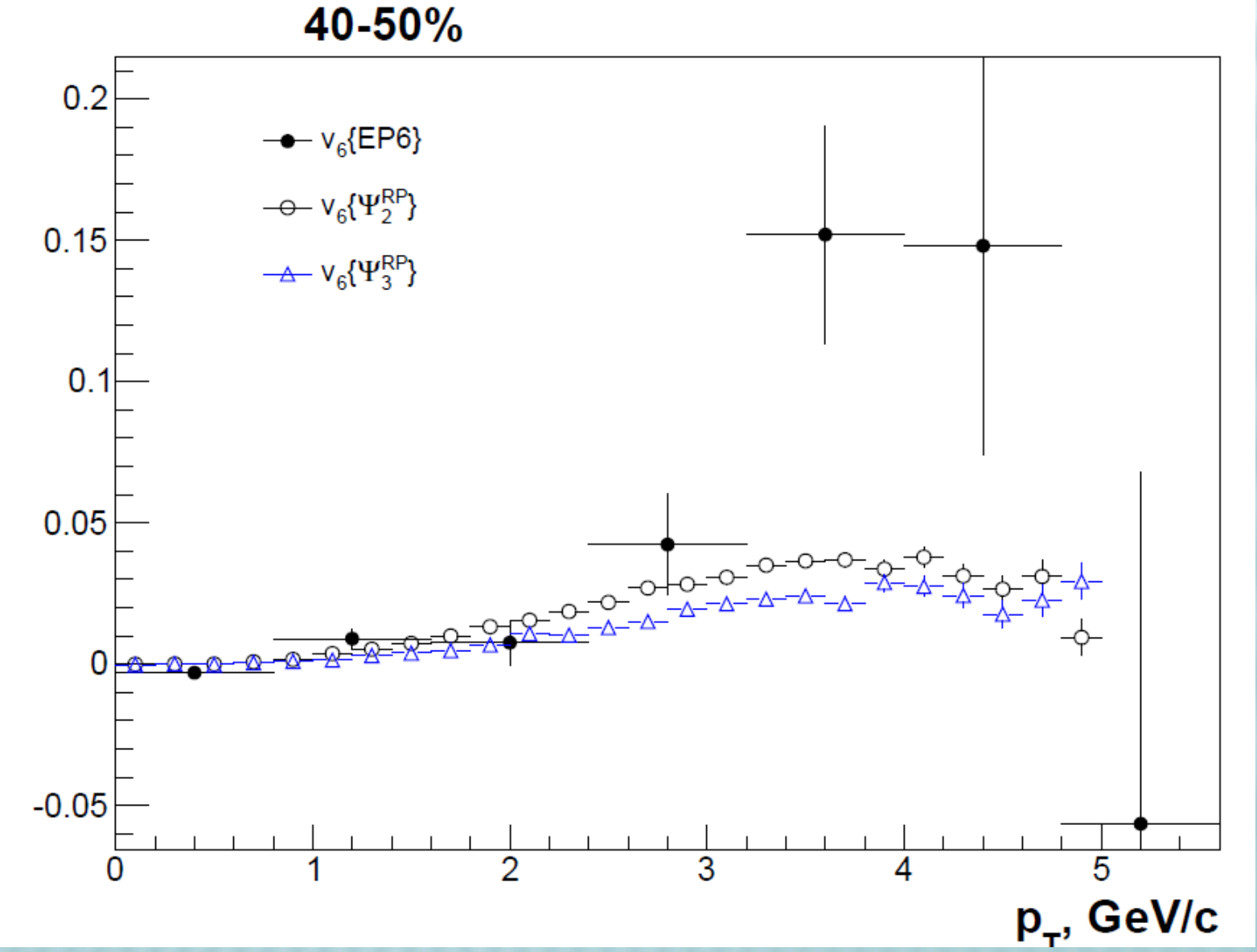




(1) V6 is weak

(2) Its high-pt tail increases with rising pT

Extraction of V6 (Event Plane method)



Methods for v_2 calculation

(1) Event plane method

$$v_2^{obs}\{EP\} = \langle \cos 2(\varphi_i - \Psi_2) \rangle$$

Ψ_2 is the calculated reaction plane angle:

$$\tan n\psi_n = \frac{\sum_i \omega_i \sin n\varphi_i}{\sum_i \omega_i \cos n\varphi_i}, \quad n \geq 1, \quad 0 \leq \psi_n < 2\pi / n$$

$$v_2\{EP\} = \frac{v_2^{obs}\{EP\}}{R} = \frac{v_2^{obs}\{EP\}}{\langle \cos 2(\Psi_2 - \Psi_R) \rangle}$$

(2) Two particle correlation method

$$v_2\{2\} = \sqrt{\langle \cos 2(\varphi_i - \varphi_j) \rangle}$$

(3) Lee-Yang zero method

$$G(ir) = \langle e^{irQ} \rangle, Q = \sum \cos(2\varphi)$$

Integral v_2 is connected with the first minimum r_0 of the module of the G(ir):

$$v_2 = \frac{j_0}{N r_0}$$

Differential flow is calculated by the formula:

$$\frac{v_2(p_T)}{N v_2} = \mathrm{Re}\left(\frac{\langle \cos(2\varphi) e^{ir_0 Q} \rangle}{\langle Q e^{ir_0 Q} \rangle} \right)$$