HEXAGONAL FLOW AS INTERPLAY OF ELLIPTIC AND TRIANGULAR FLOWS

E. Zabrodin

in collaboration with

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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)

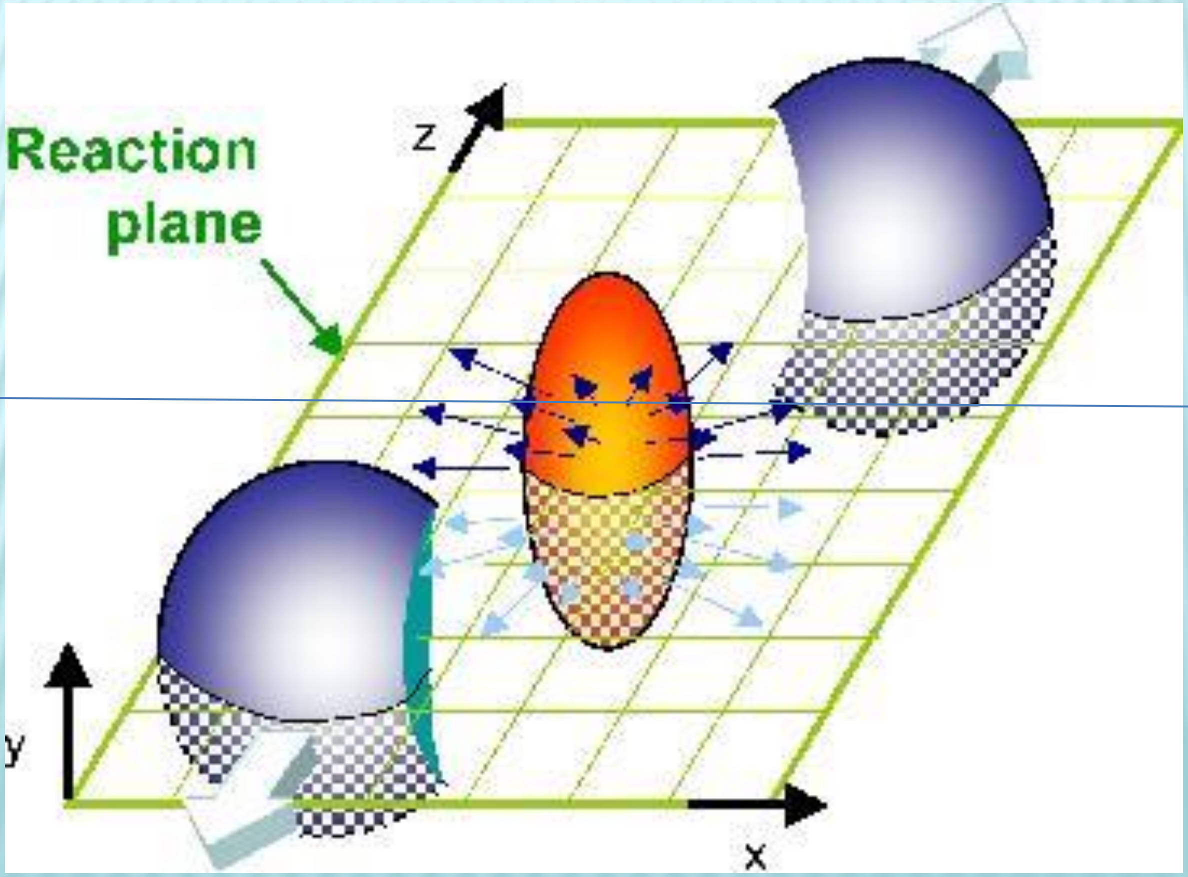
III. Jets influence on NCQ-scaling and $v4/(v2)^2$ ratio at RHIC and LHC

IV. Hexagonal flow v6

ANISOTROPIC FLOW

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

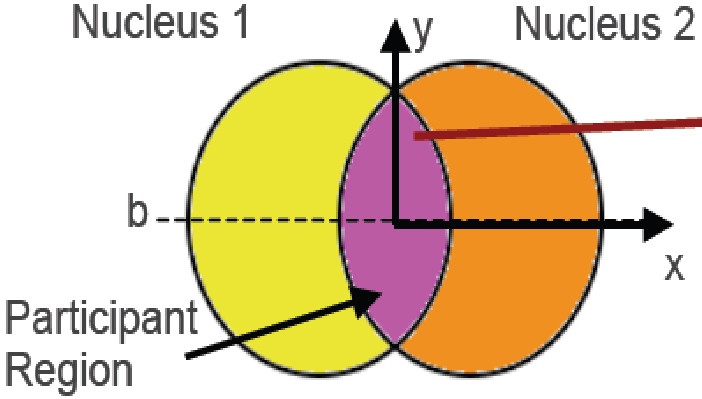
$$\frac{dN}{d\varphi}=\frac{1}{2\pi}(1+\sum_{n=1}^{\infty}2v_n(p_t)\cos[n(\varphi-\psi_r)])$$



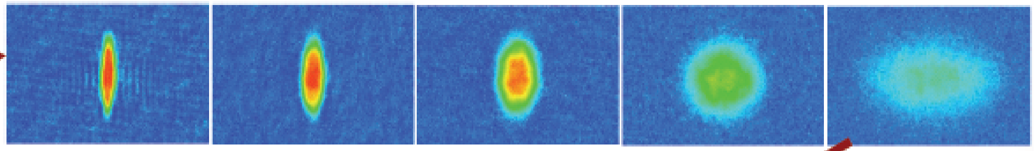
ELLIPTIC FLOW

B. Alver, talk at Rencontres Ions Lourds (2010)

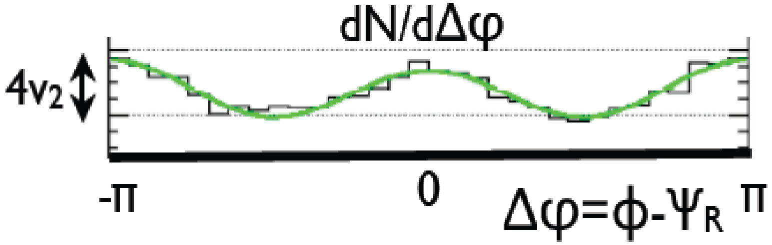
Initial anisotropy



Pressure driven expansion



Final anisotropy

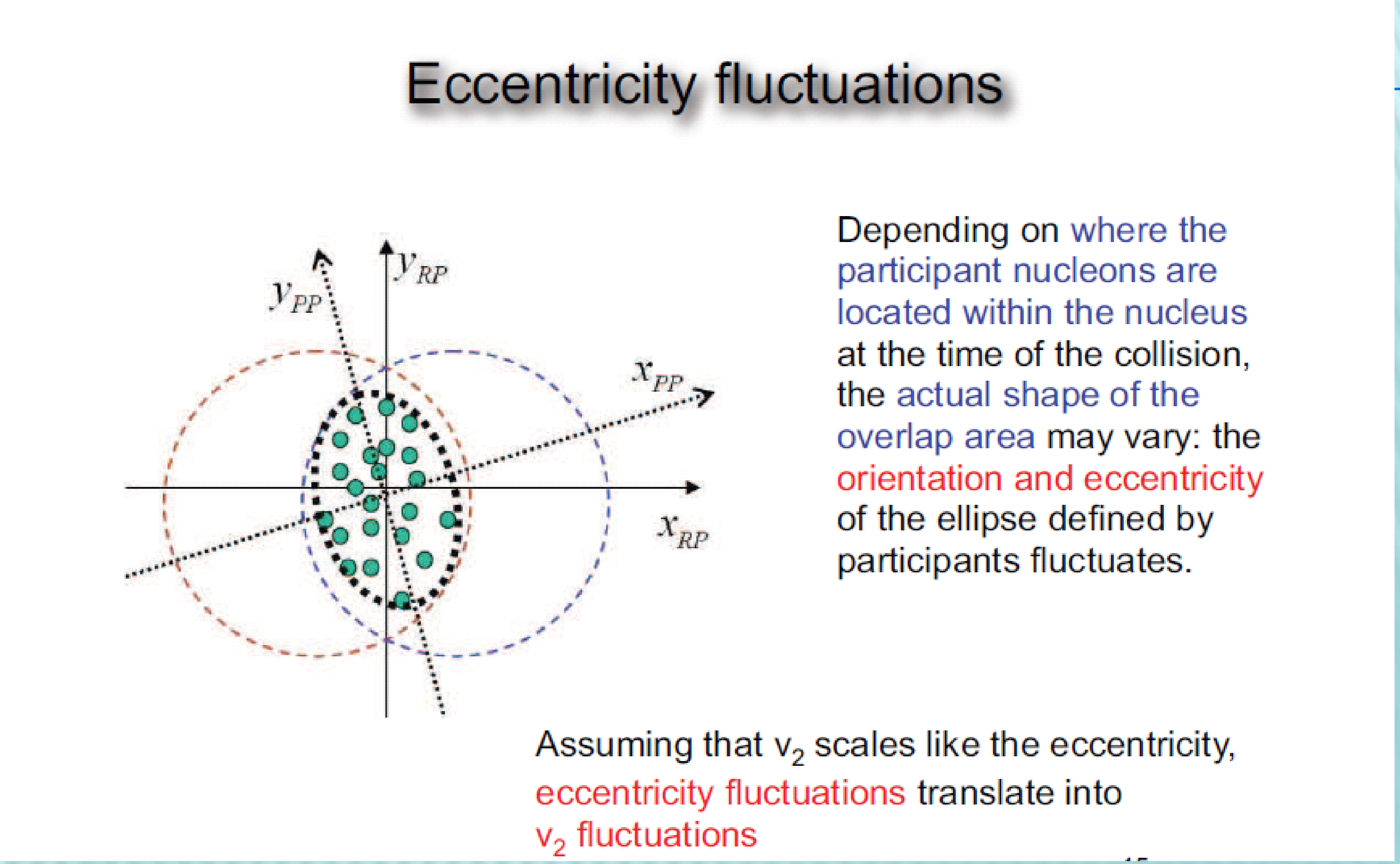


$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_R)\right)\right)$$

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

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

J.-Y. Ollitrault



Eccentricity fluctuations

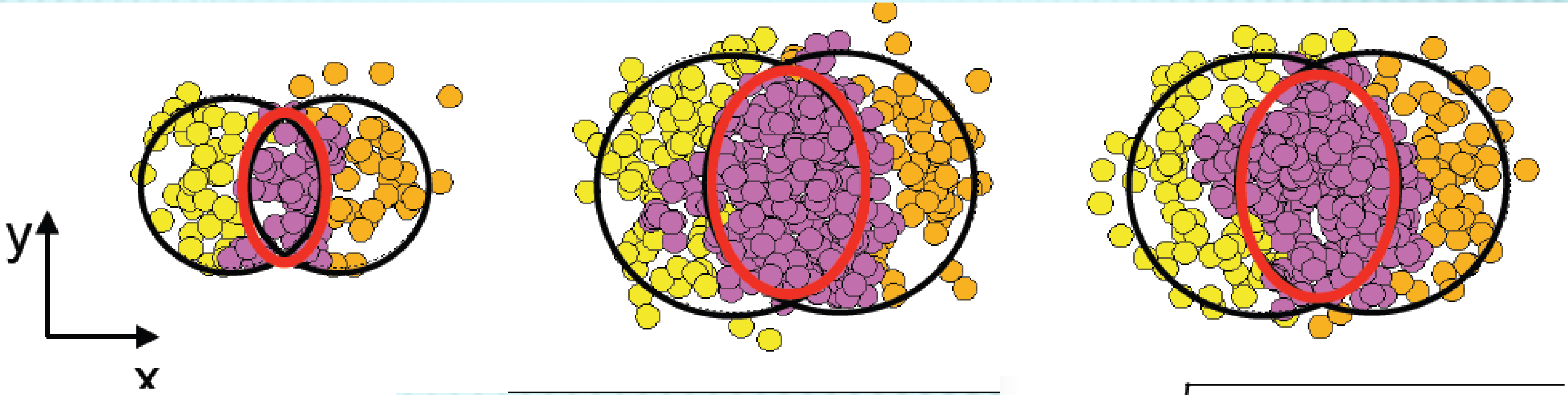
Depending on where the participant nucleons are located within the nucleus at the time of the collision, the actual shape of the overlap area may vary: the orientation and eccentricity of the ellipse defined by participants fluctuates.

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

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

ECCENTRICITY

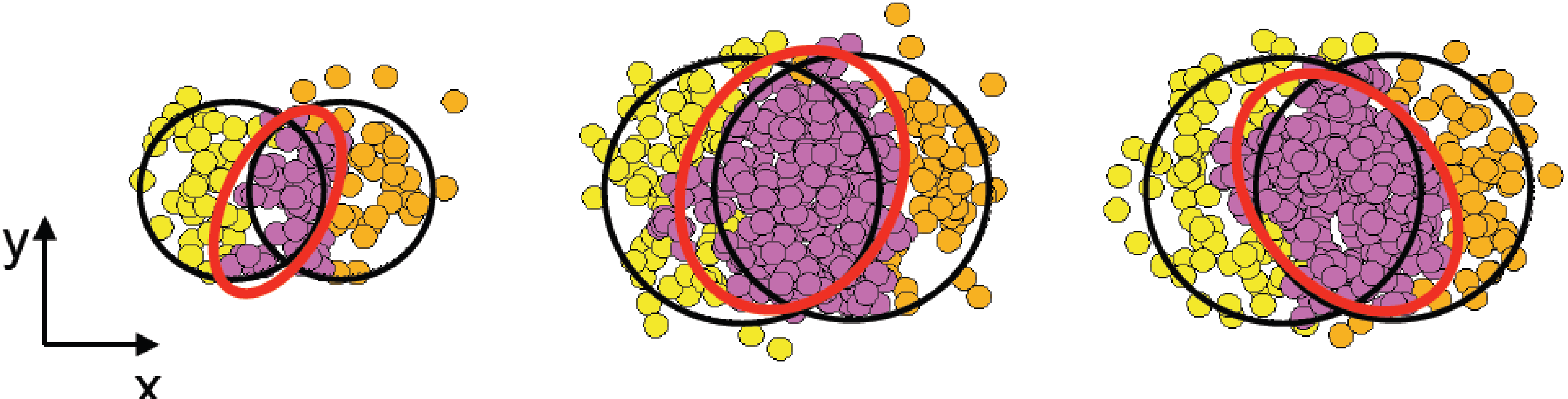
STANDARD



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

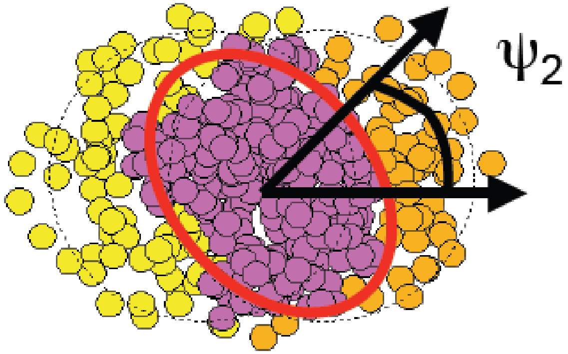
PARTICIPANT

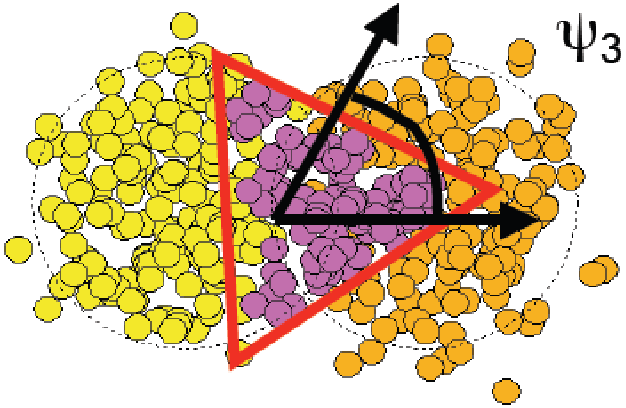
$$\varepsilon_{\mathrm{part}} = \frac{\sqrt{\left(\sigma_y^2 - \sigma_x^2\right)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$

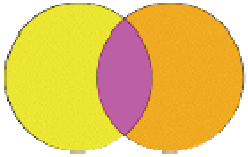


TRIANGULAR FLOW

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



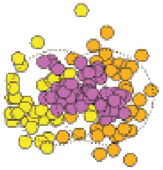




→ $$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1+\sum 2v_n \cos\left(n(\phi-\psi_R)\right)\right)$$

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

$$v_3 = 0$$



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

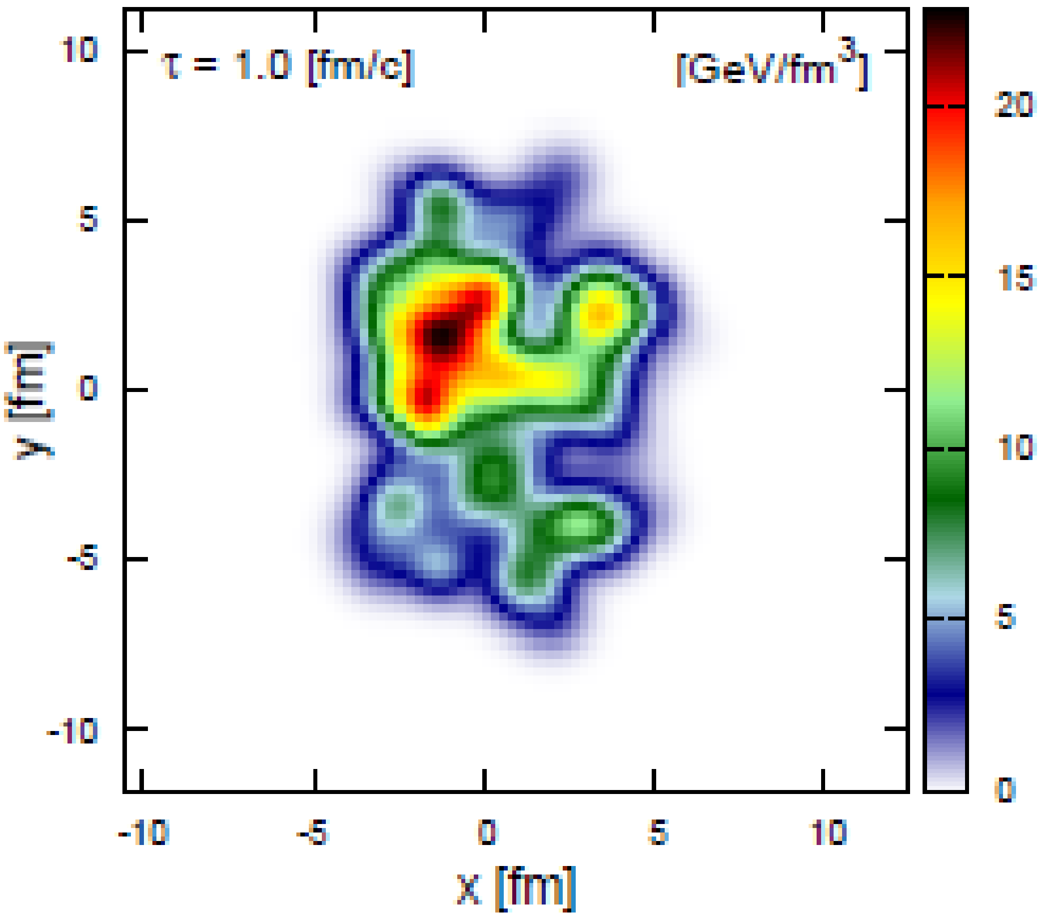
$$v_2 = \left\langle \cos\left(2(\phi-\psi_2)\right)\right\rangle$$

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

The triangular initial shape leads to triangular hydrodynamic flow

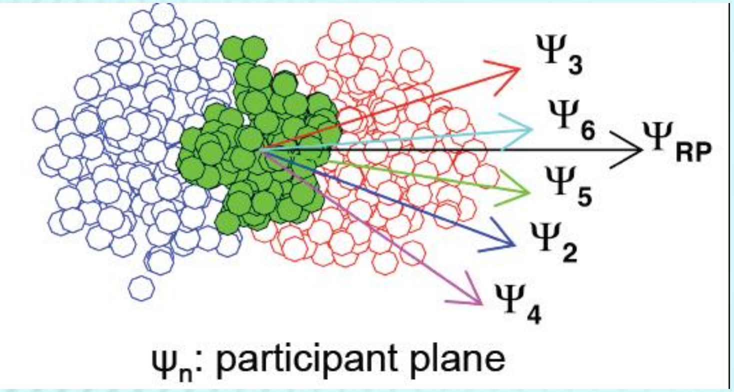
INITAL-STATE FLUCTUATIONS (example)

W.-L. Qian et al., arXiv: 1305.4673 [hep-ph]

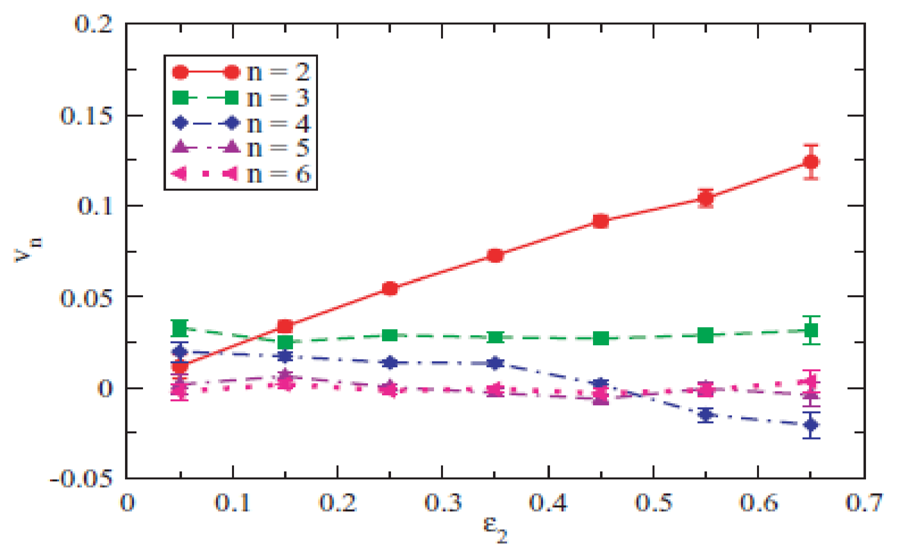


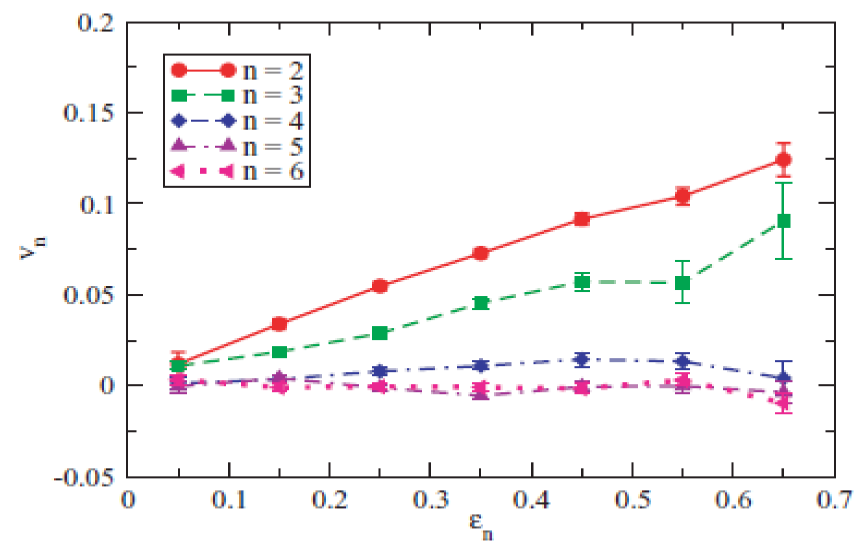
Energy distribution of a random NeXuS event

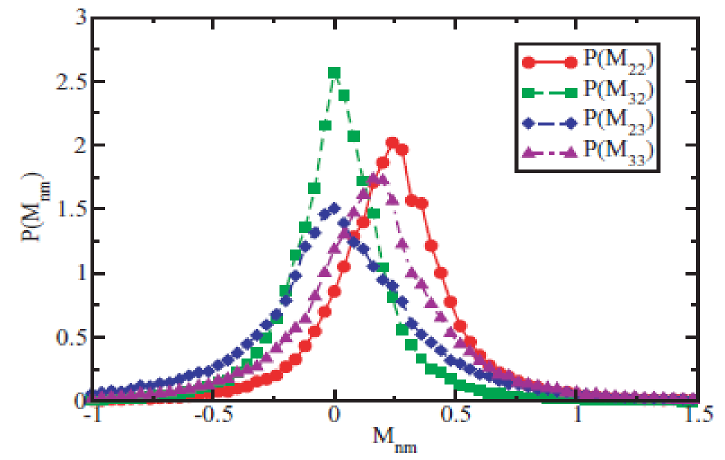
CROSS-TALK BETWEEN FLOW HARMONICS



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







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

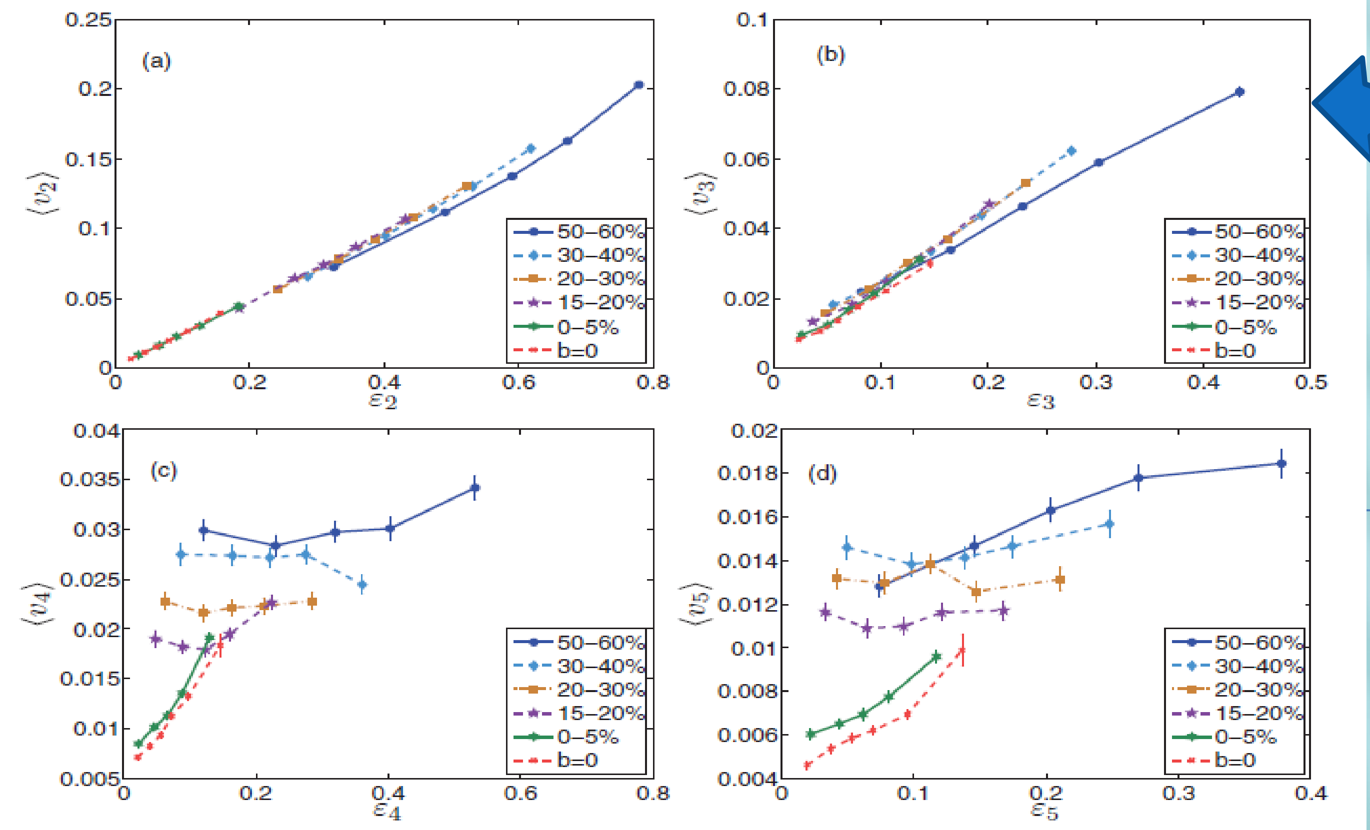
Only the first few flow harmonics of final-state hadrons survive after hydrodynamic evolution

CROSS-TALK BETWEEN FLOW HARMONICS

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

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

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



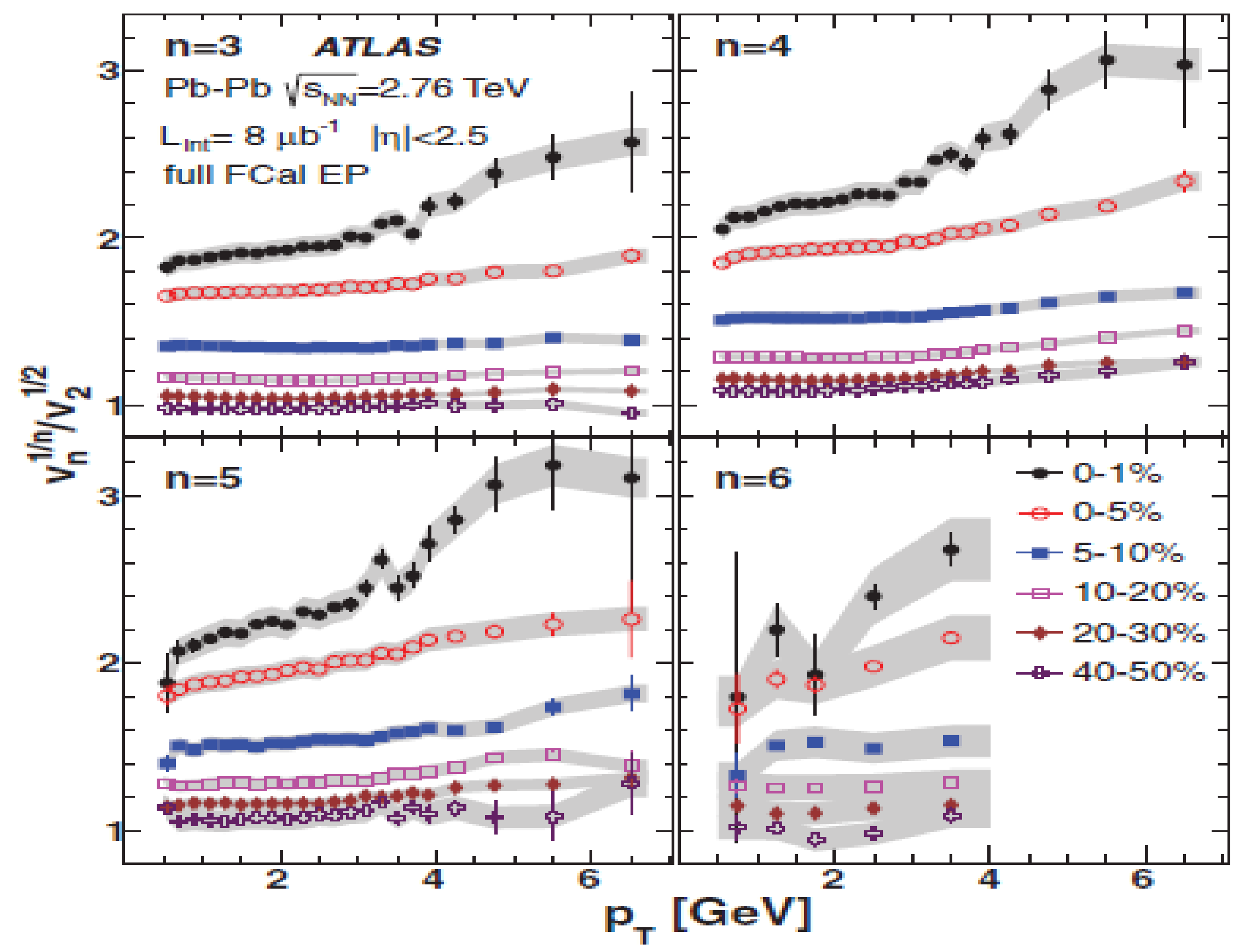
(1) The basic response of v2 and v3 to eccentricities is approx. linear

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

SCALING OF HIGHER ORDER FLOW HARMONICS

J.-Y. Ollitrault :

$$V_n^{1/n} \square V_2^{1/2}$$



ATLAS, PRC 86 (2012) 014907

HYDJET++ event generator

I.Lokhtin, L.Malinina, S.Petrushanko, A.Snigirev, I.Arsene, K.Tywoniuk,
Comp. Phys. Commun.180 (2009) 779-799 (arXiv:0809.2708[hep-ph])

● **The soft part** of HYDJET++ event represents the "thermal" hadronic state.
✓ multiplicities are determined assuming thermal equilibrium
✓ hadrons are produced on the hypersurface represented by a parameterization of relativistic hydrodynamics with given freeze-out conditions
✓ chemical and kinetic freeze-outs are separated
✓ decays of hadronic resonances are taken into account (360 particles from **SHARE** data table) with "home-made" decayer
the model reproduces soft hadroproduction features at RHIC and LHC (particle spectra, elliptic flow, HBT)

● **The hard**, multi-partonic part of HYDJET++ event is identical to the hard part of Fortran written HYDJET (PYTHIA6.4xx + PYQUEN1.5) => now PYTHIA Pro-Q20 tune !!
PYQUEN event generator is used for simulation of rescattering, radiative and collisional energy loss of hard partons in expanding quark-gluon plasma created in ultrarelativistic heavy ion AA collisions. HYDJET++ includes nuclear shadowing correction for parton distributions (important at LHC!)
Impact-parameter dependent parameterization of *nuclear shadowing (K.Tywoniuk, I.Arsene, L.Bravina, A.Kaidalov and E.Zabrodin, Phys. Lett. B 657 (2007) 170)*

Model parameters.

1. Thermodynamic parameters at chemical freeze-out: T_{ch} , $\{\mu_B, \mu_S, \mu_Q\}$

2. If thermal freeze-out is considered: T_{th} , μ_π-normalisation constant

3. Volume parameters: $\tau, \Delta\tau$, **R**

1. ρ_u^{max} -maximal transverse flow rapidity for Bjorken-like parametrization

5. η_{max} -maximal space-time longitudinal rapidity which determines the rapidity interval $[-\eta_{max}, \eta_{max}]$ in the collision center-of-mass system.

6. Impact parameter range: minimal b_{min} and maximal b_{max} impact parameters

7. Flow anisotropy parameters $\delta(b)$, $\epsilon(b)$

PYTHYA+PYQUEN obligatory parameters

9. Beam and target nuclear atomic weight **A**

10. $\sqrt{s_{NN}}$ –c.m.s. energy per nucleon pair (PYTHIA initialization at given energy)

11. **ptmin** – minimal pt of parton-parton scattering in PYTHIA event (ckin(3) in /pysubs/)

12. **nhsel** flag to include jet production in hydro-type event:

0 - jet production off (pure FASTMC event),
1 - jet production on, jet quenching off (FASTMC+njet*PYTHIA events),
2 - jet production & jet quenching on (FASTMC+njet*PYQUEN events),
3 - jet production on, jet quenching off, FASTMC off (njet*PYTHIA events),
4 - jet production & jet quenching on, FASTMC off (njet*PYQUEN events);

13. **ishad** flag to switch on/off nuclear shadowing

Parameters of energy loss model in PYQUEN

(default, but can be changed from the default values by the user)

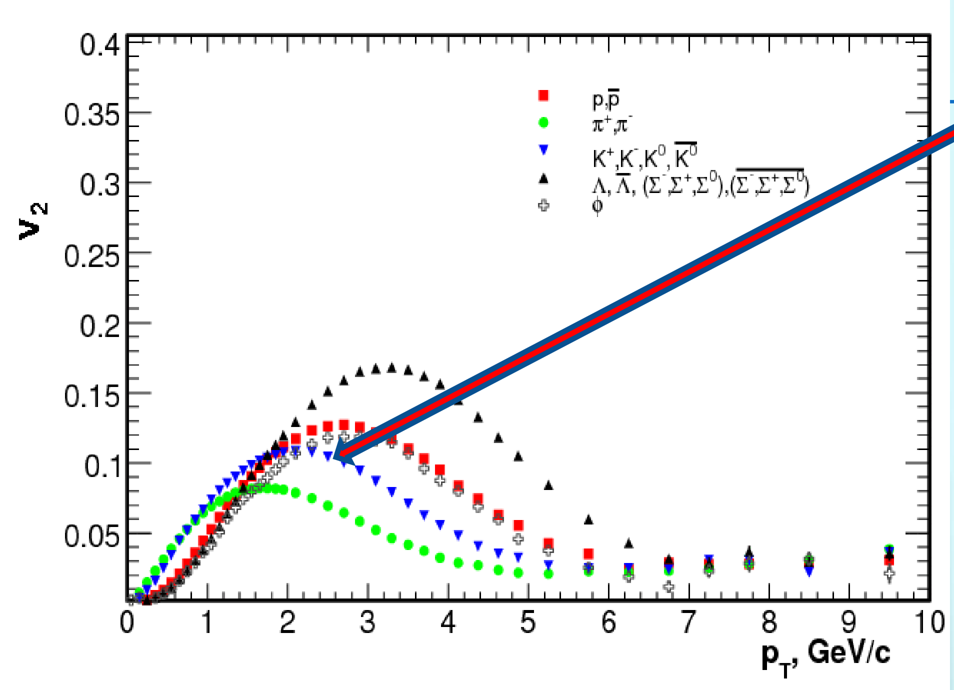
1. T0 - initial temparature of quark-gluon plasma for central
 Pb+Pb collisions at mid-rapidity (initial temperature
for other centralities and atomic numbers will be calculated automatically)
 at LHC: T0=1 GeV, at RHIC(200 AGeV) T0=0.300 GeV

2. tau0 - proper time of quark-gluon plasma formation
at LHC: tau0=0.1 fm/c, at RHIC(200 AGeV) tau0=0.4 fm/c

3. nf - number of active quark flavours in quark-gluon plasma
(nf=0, 1, 2 or 3) at LHC: nf=0, at RHIC(200 AGeV) nf=2

4. ienglu - flag to fix type of medium-induced partonic energy loss
   (ienglu=0 - radiative and collisional loss, ienglu=1 - radiative loss only,
   ienglu=2 - collisional loss only, default value is ienglu=0);
   ianglu - flag to fix type of angular distribution of emitted gluons
   (ianglu=0 - small-angular, ianglu=1 - wide-angular,
   ianglu=2 - collinear, default value is ianglu-0).
   ienglu=0

V_2 in HYDJET++ for different particles (centrality 30%)



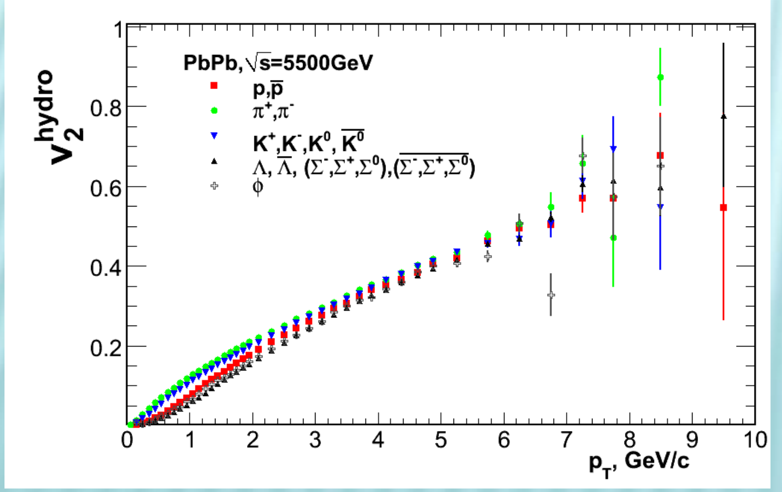
Mass ordering in soft p_T regions then breaks.

Why?

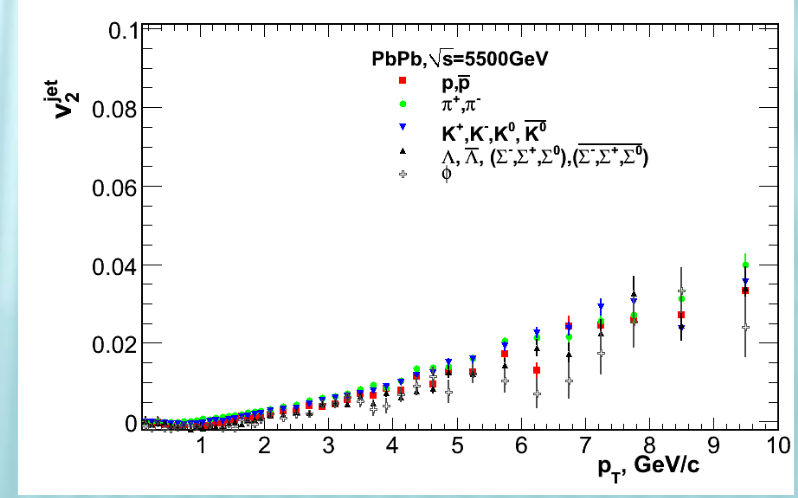
Hydrodynamics gives mass ordering of v2.
The model possesses crossing of baryon and meson branches.

Interplay of hydrodynamics and jets

Hydrodynamics



Jet part +quenching

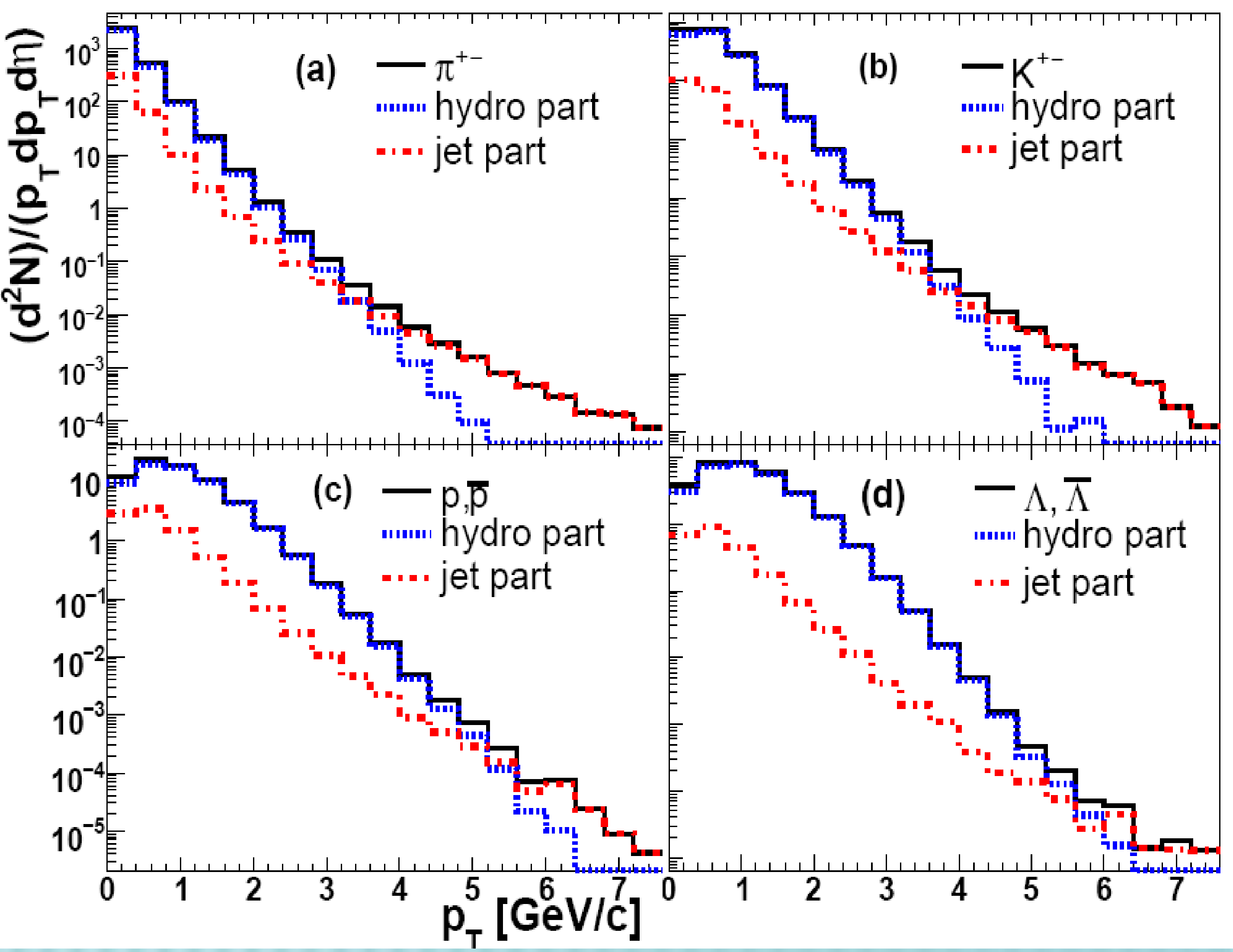


The p_T specta of π, K, p, Λ with HYDJET++ model, $\sqrt{s}$=200GeV

The slope for the hydro part depends strongly on mass:

- the heavier the particle -- the harder the spectrum

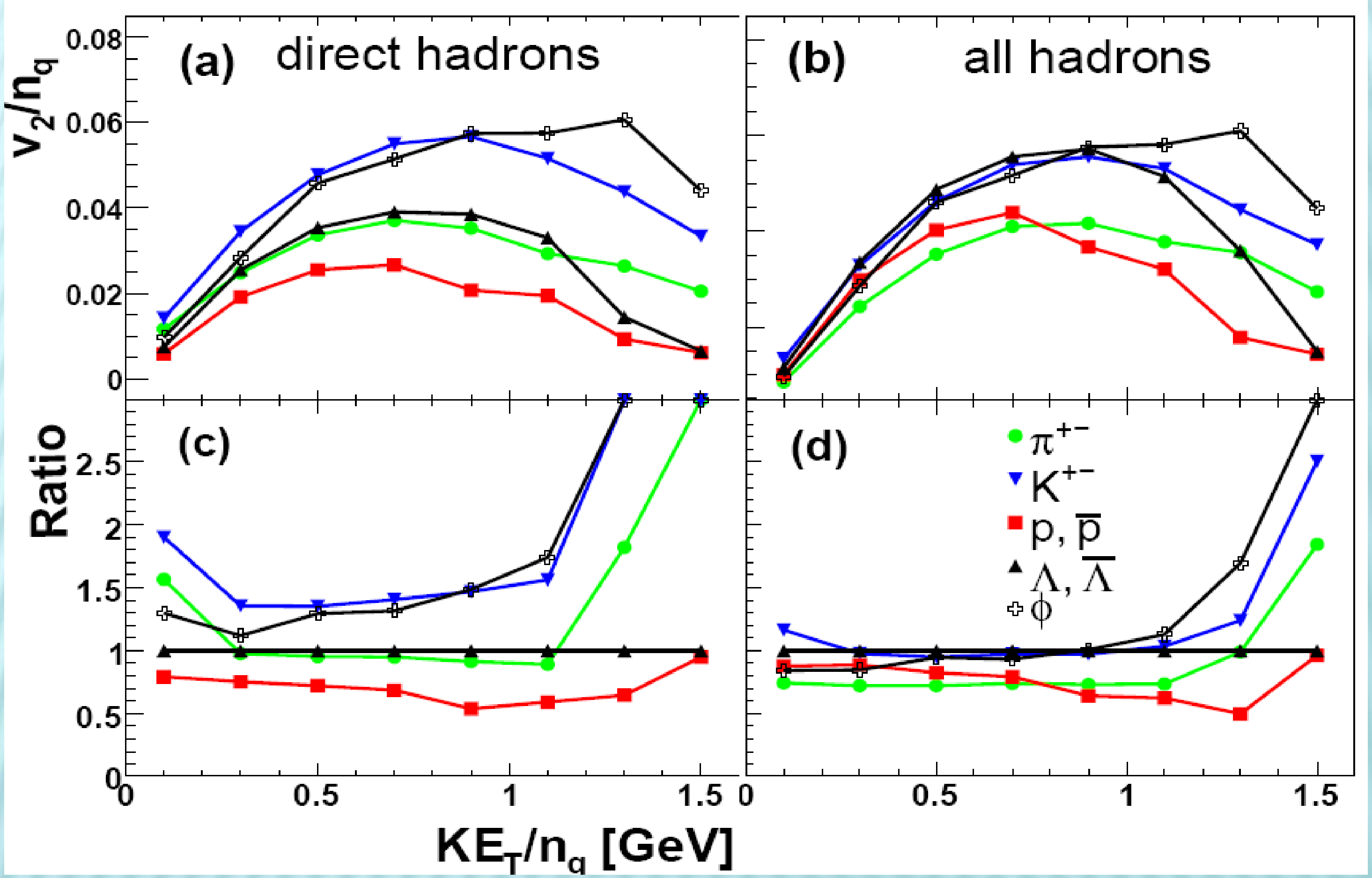
The hydro part dies out earlier for light particles than for heavy ones



NCQ scaling at LHC

No scaling for
direct particles

Appearance of the approximate
scaling for all particles



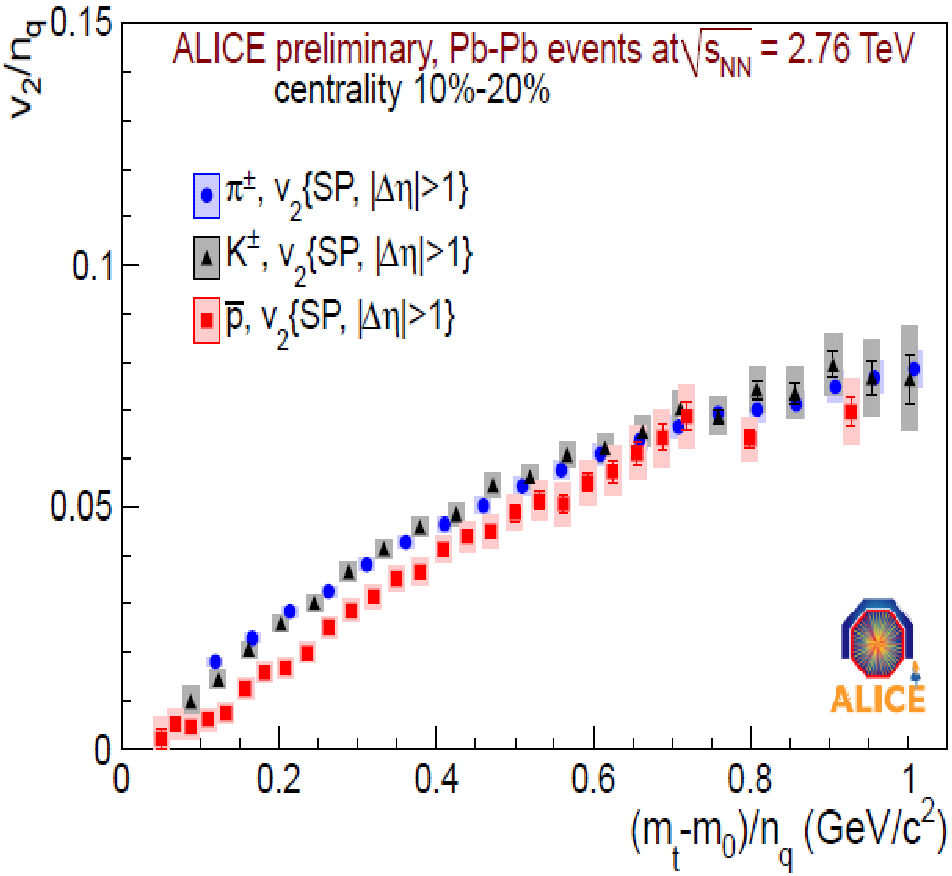
G.Eyyubova et al., PRC 80 (2009) 064907

LHC: NCQ scaling will be only approximate (prediction, 2009)

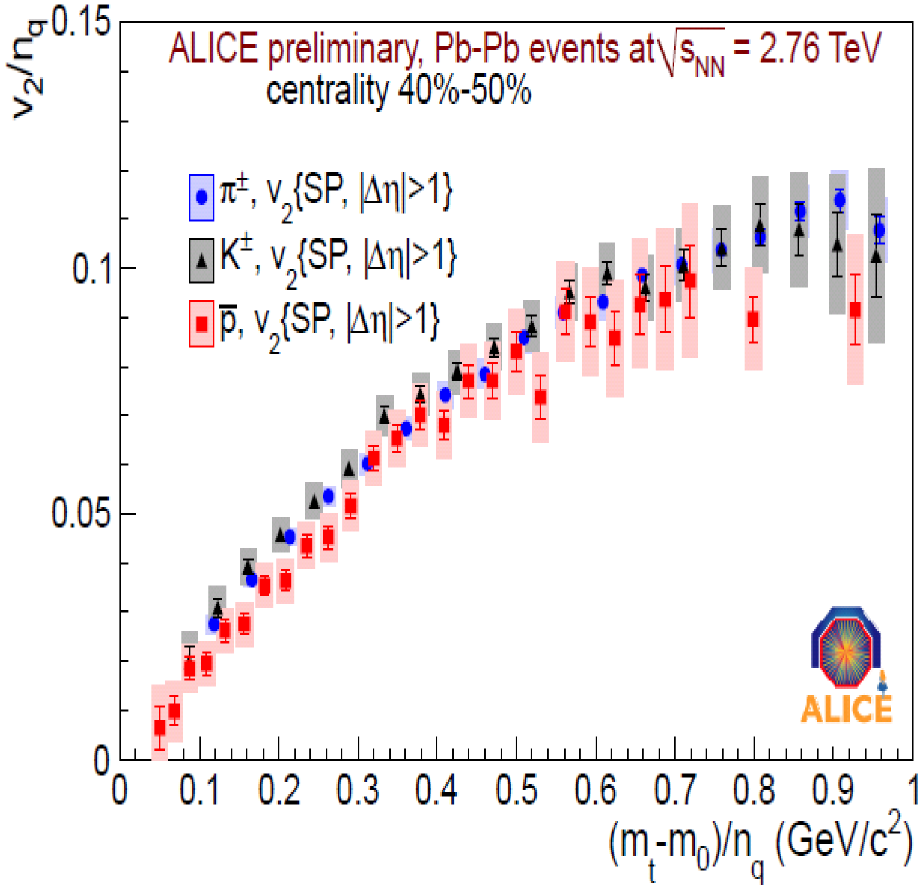
Experimental results (LHC)

ALICE Collaboration, M. Krzewicki et al., JPG 38 (2011) 124047

Semi-sentral collisions



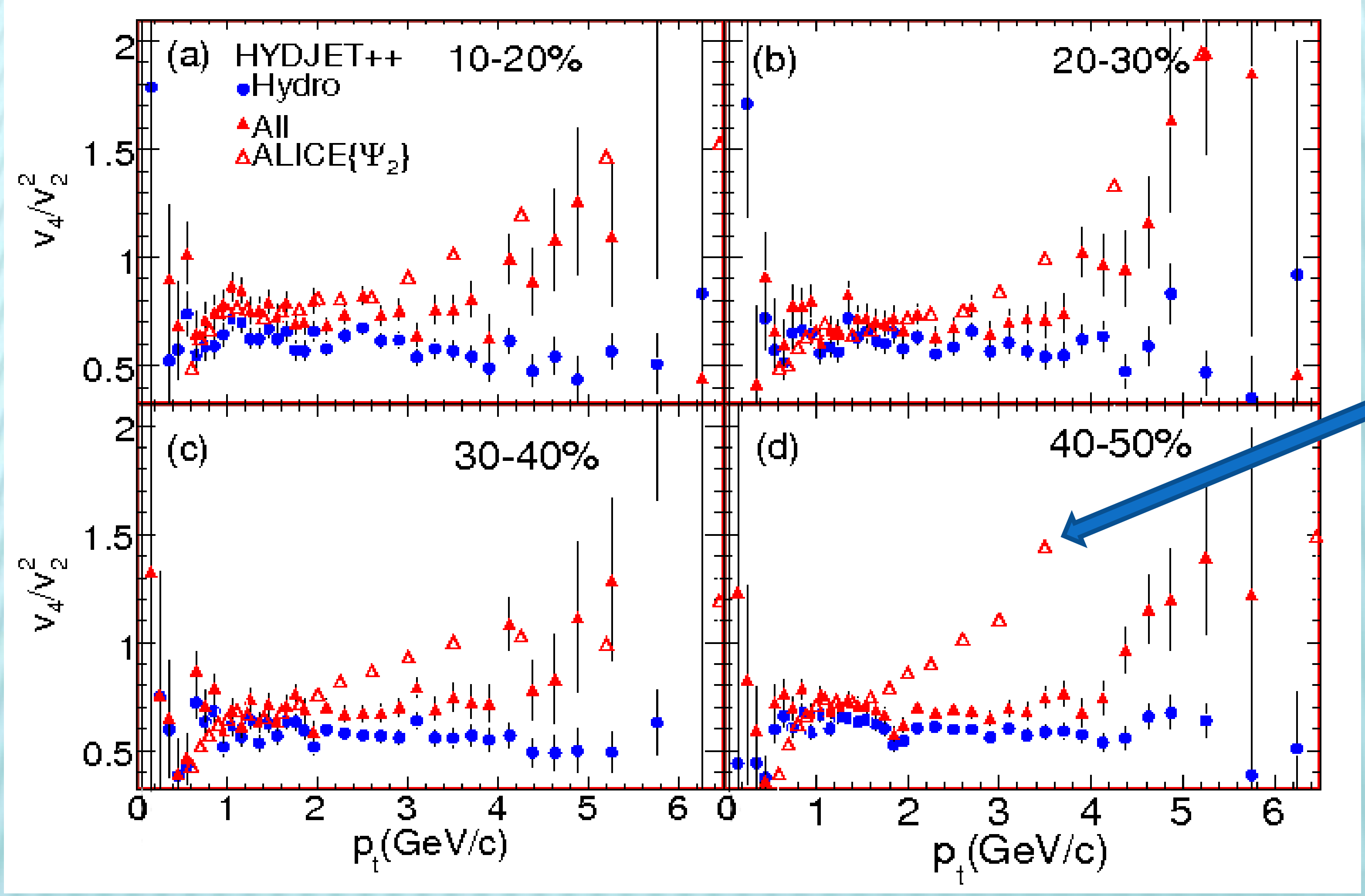
Semi-peripheral collisions



The NCQ scaling is indeed only approximate (2011)

HYDJET++ RESULTS FOR LHC

L.Bravina et al., PRC 87 (2013) 034901

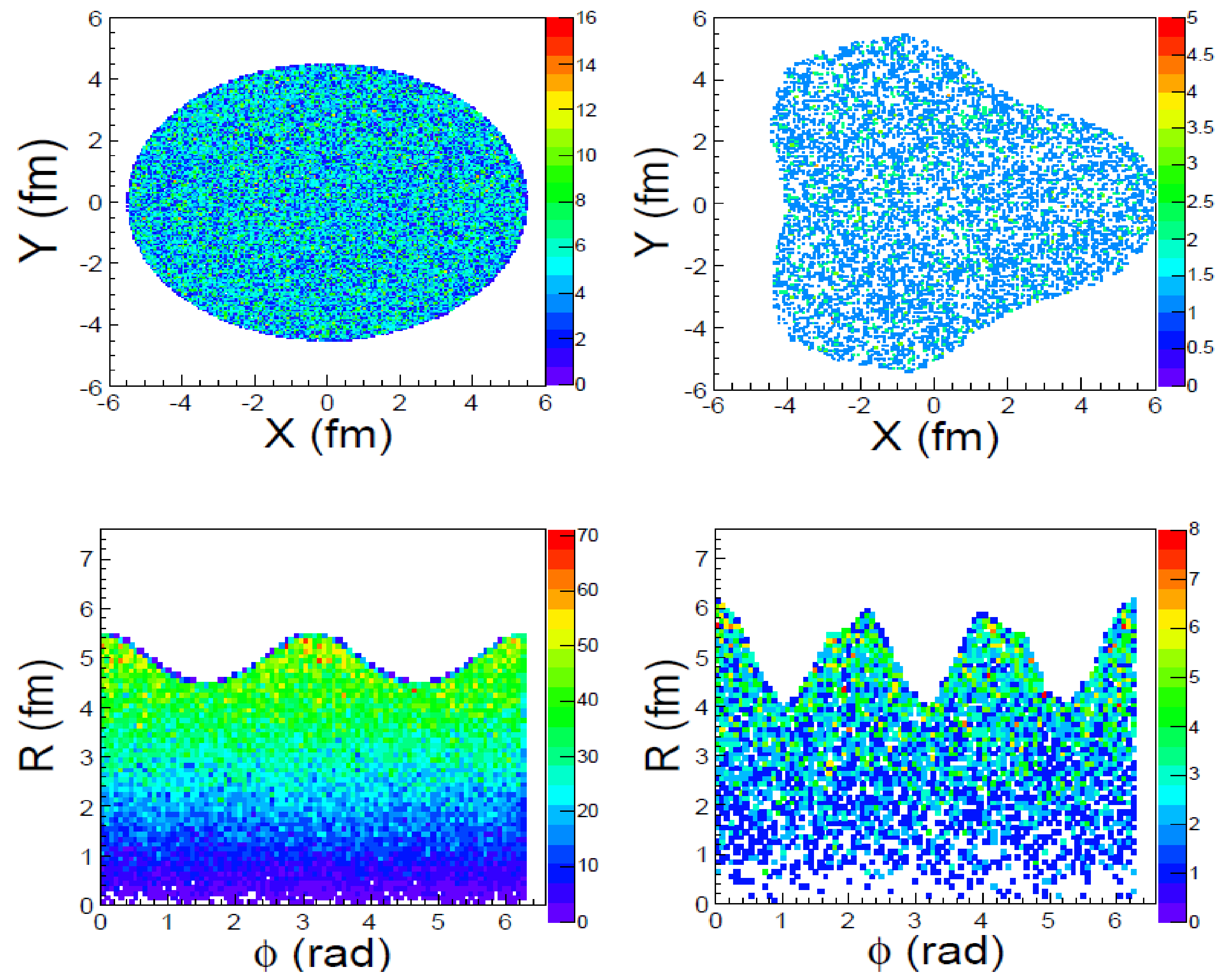


Jets !

Jets increase the ratio and lead to rise of high-pT tail

GENERATION OF TRIANGULAR FLOW

V2

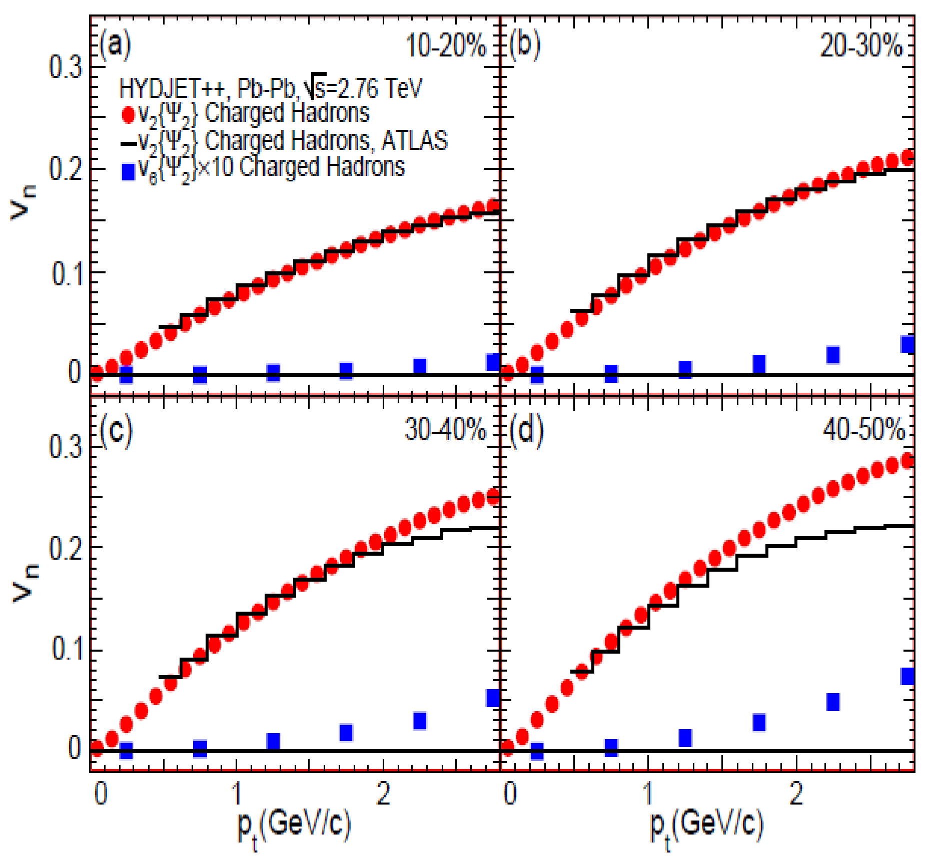


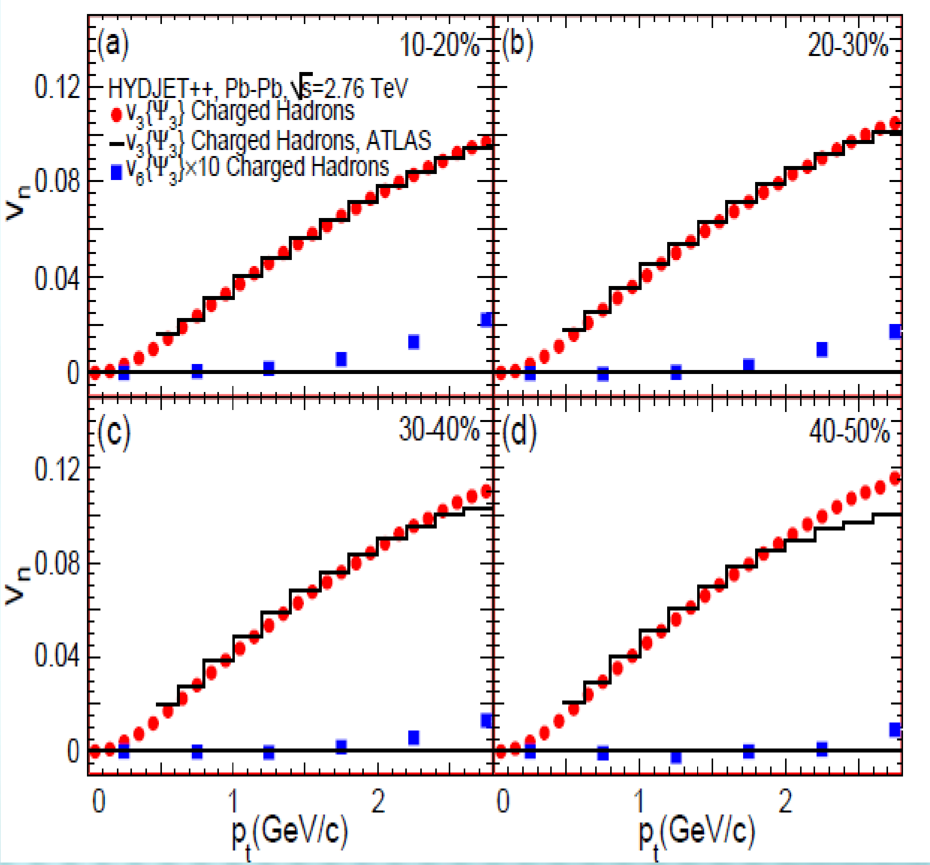
V3

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

HEXAGONAL FLOW IN HYDJET++ AT LHC

L.Bravina et al., to be submitted





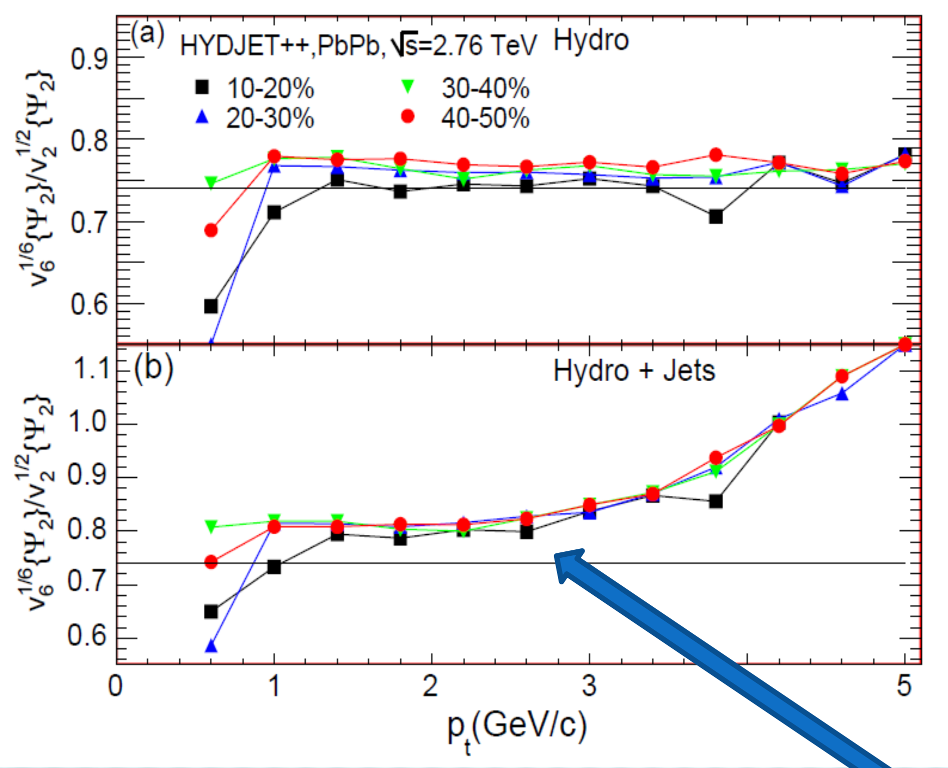
(1) V6 is weak

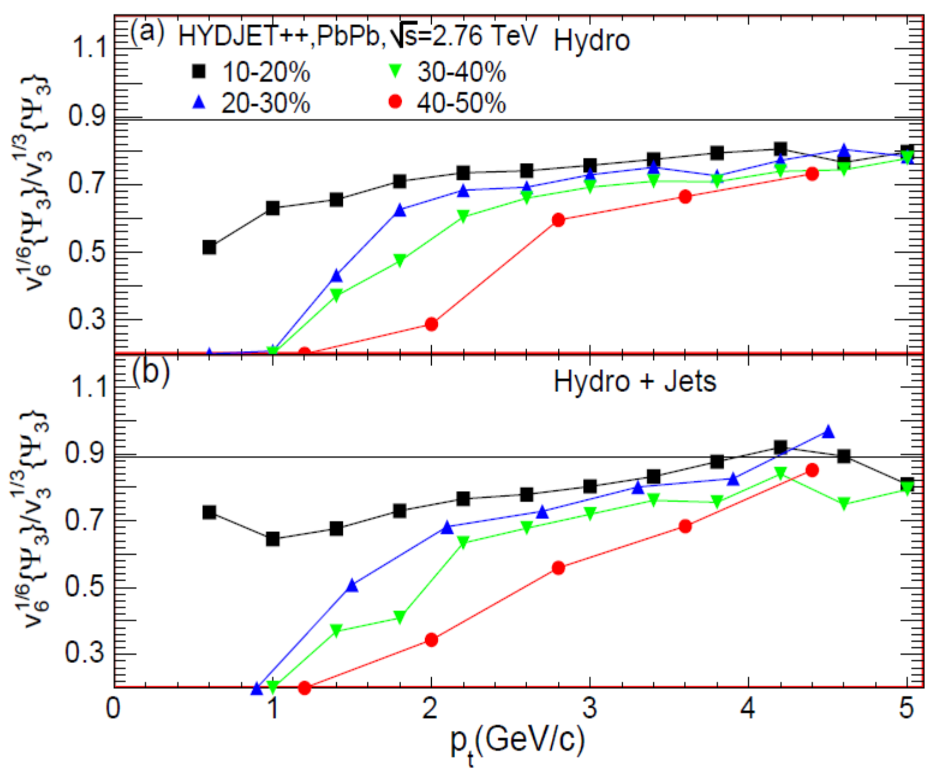
(2) Its high-pt tail increases with rising pT

Hexagonal flow:

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

L.Bravina et al., to be submitted





Ψ_2

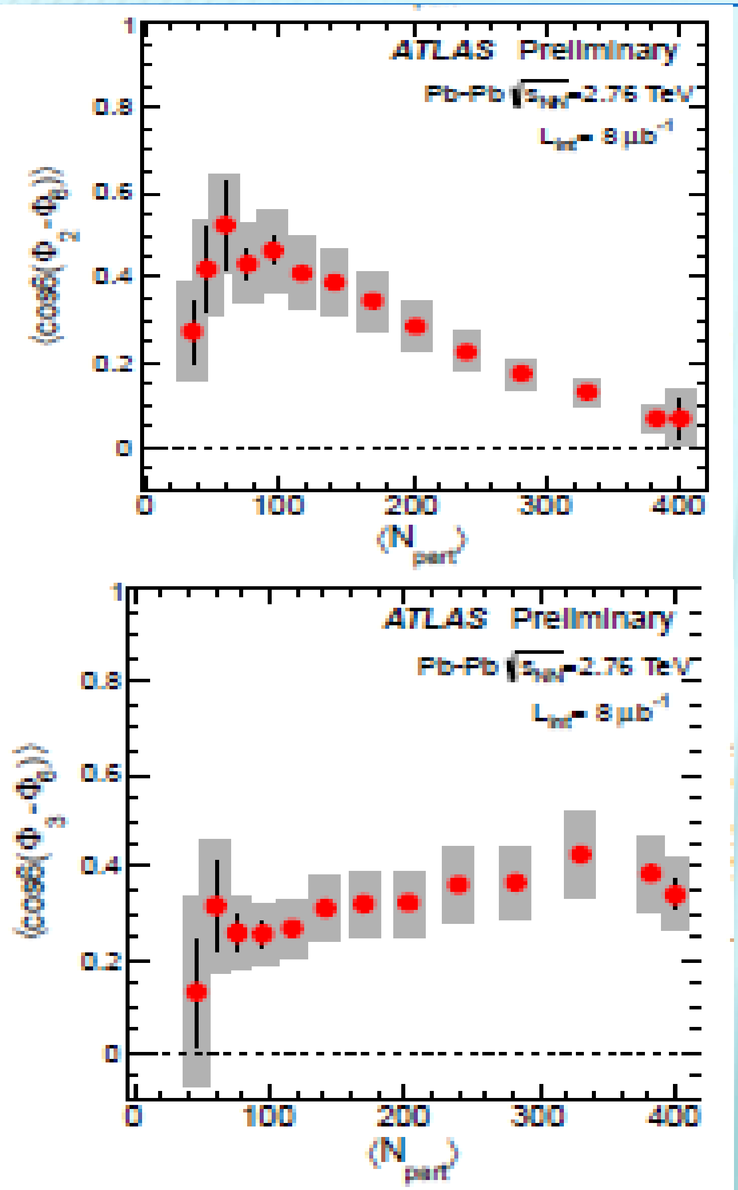
Scaling?

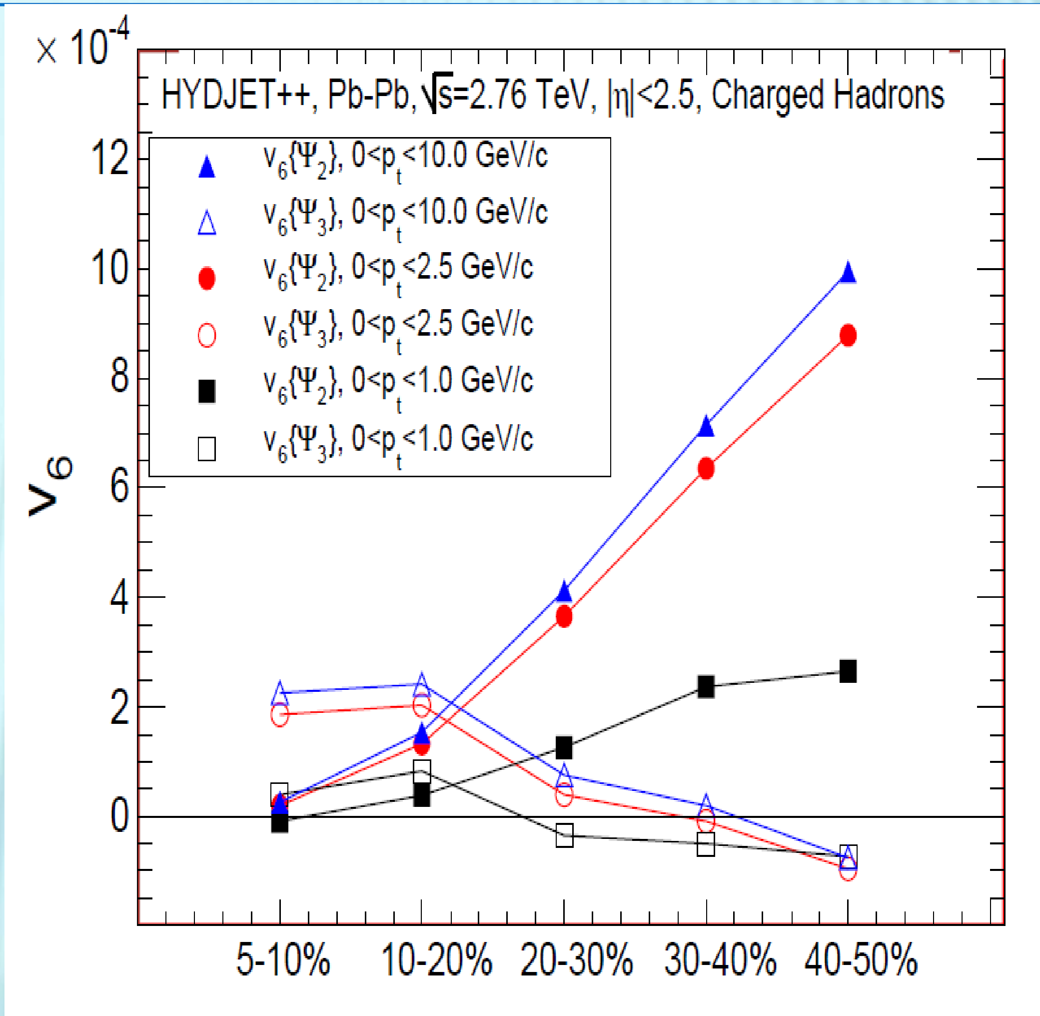
Ψ_3

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

Hexagonal flow: centrality dependence

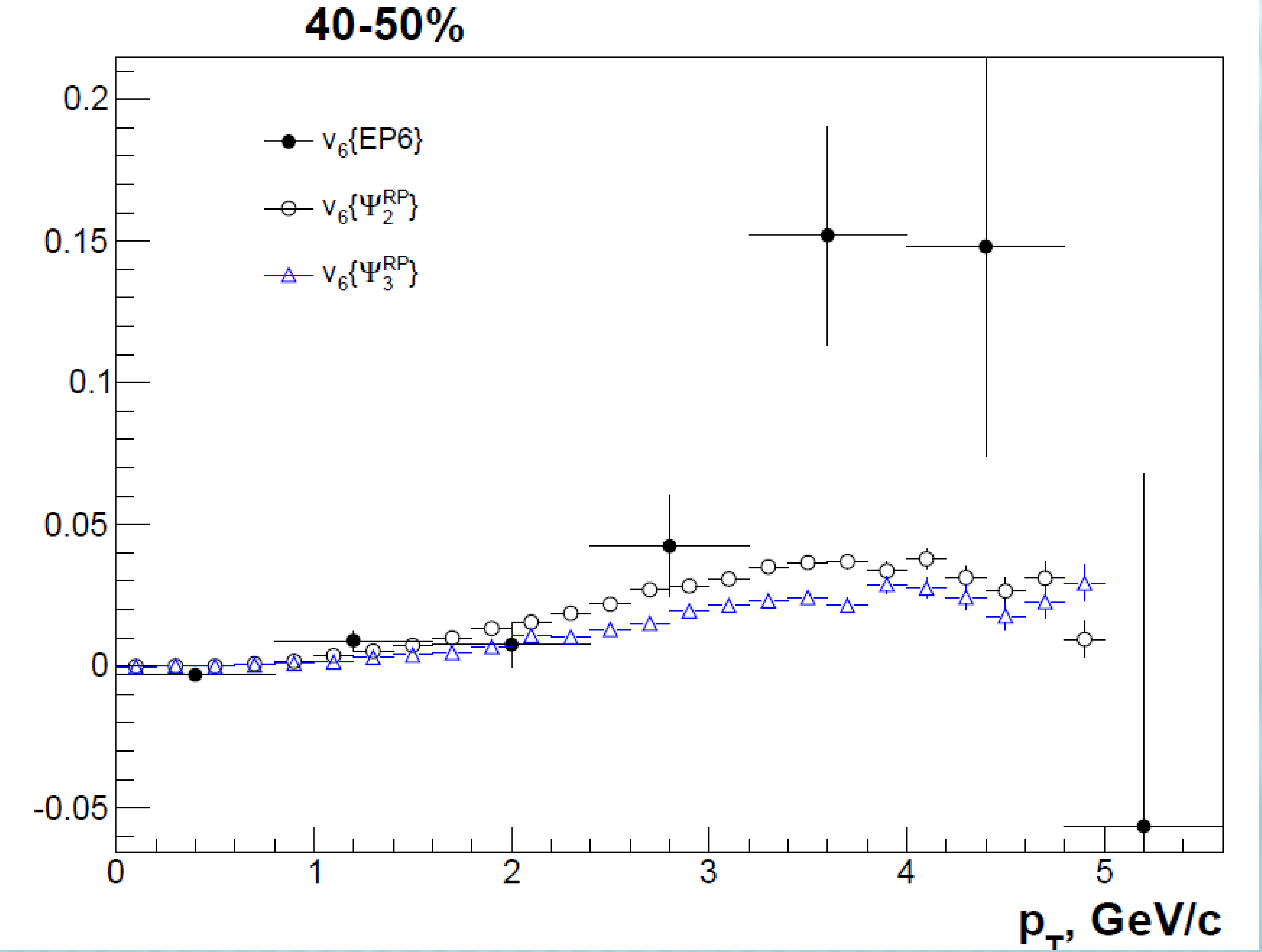
ATLAS-CONF-2012-049





In line with exp. data

Extraction of V6 (Event Plane method)



CONCLUSIONS

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

Non-linearities between eccentricities and flow harmonics of n-th order (n>3) can be understood in terms of elliptic and triangular flow contributions

Scaling of $v_6^{1/6}\{\Psi_2\}/v_2^{1/2}\{\Psi_2\}$ **is observed for centralities up to 50%**

Jets increase this ratio by 10-15% and lead to rise of the high-pT tail

Centrality dependences v6(v2) and v6(v3) are in line with the behavior of the plane correlators $<\cos\{6(\Psi_2-\Psi_6)\}>$ **and** $<\cos\{6(\Psi_3-\Psi_6)\}>$ **measured experimentally**

Difficult to get genuine information about higher eccentricities !

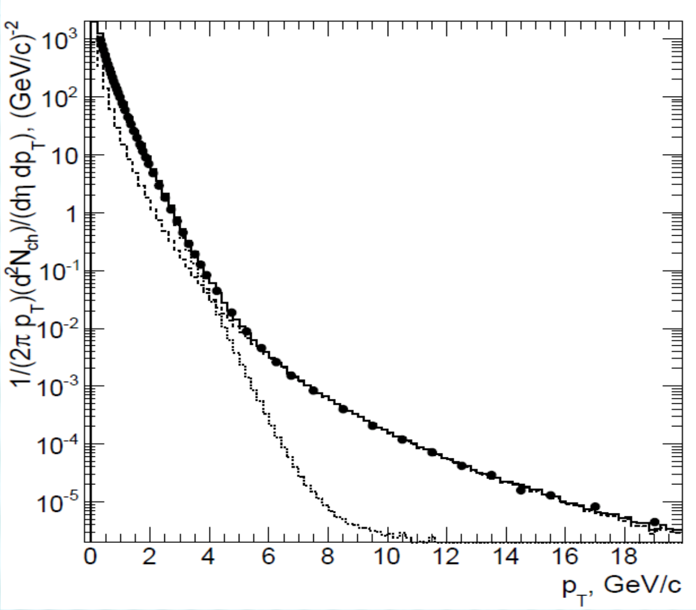
Many thanks to organizers!

Back-up Slides

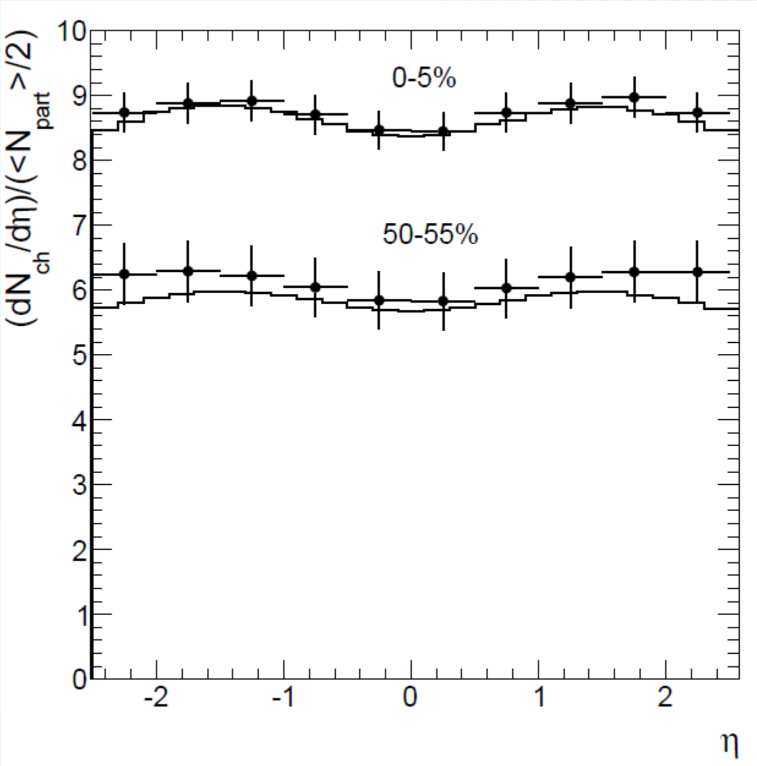
LHC DATA VS. HYDJET++ MODEL

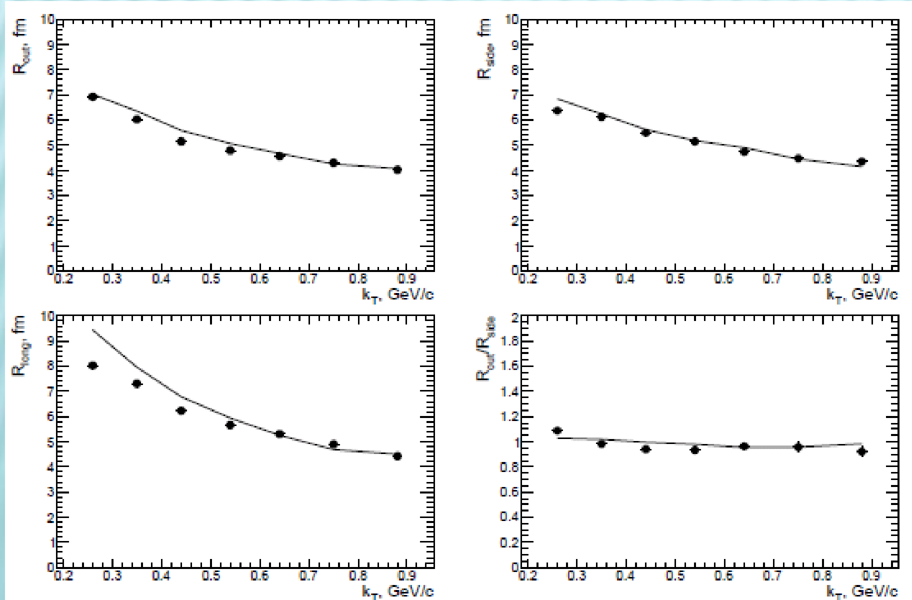
Transverse momentum

Pb+Pb @ 2.76 ATeV



Rapidity



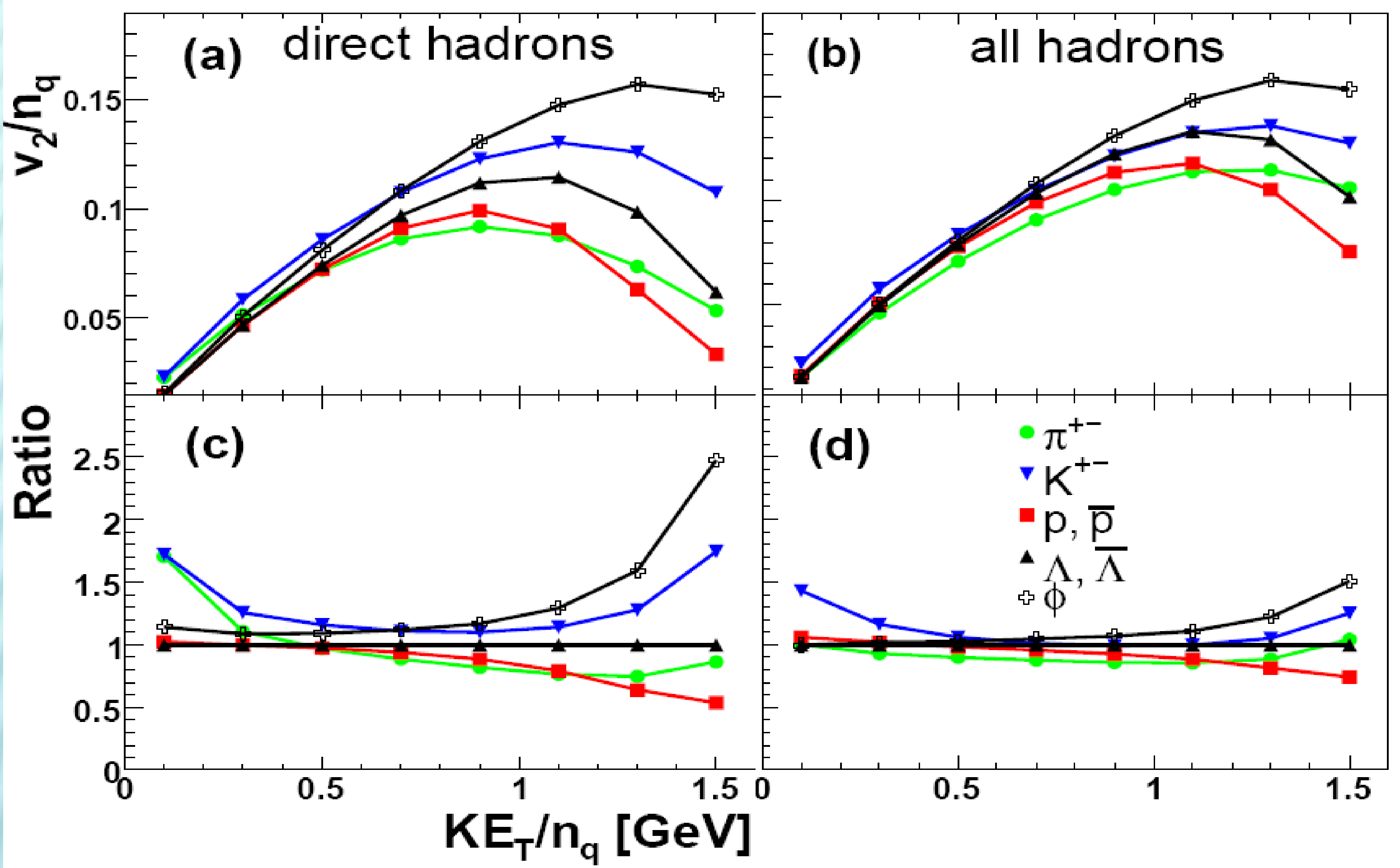


Correlation radii (femtoscopy)

I. Lokhtin et al., Eur. Phys. J C72 (2012) 2045

Number-of-constituent-quark scaling at RHIC

Direct particles: scaling is not good. All particles: KE_T/n_q scaling



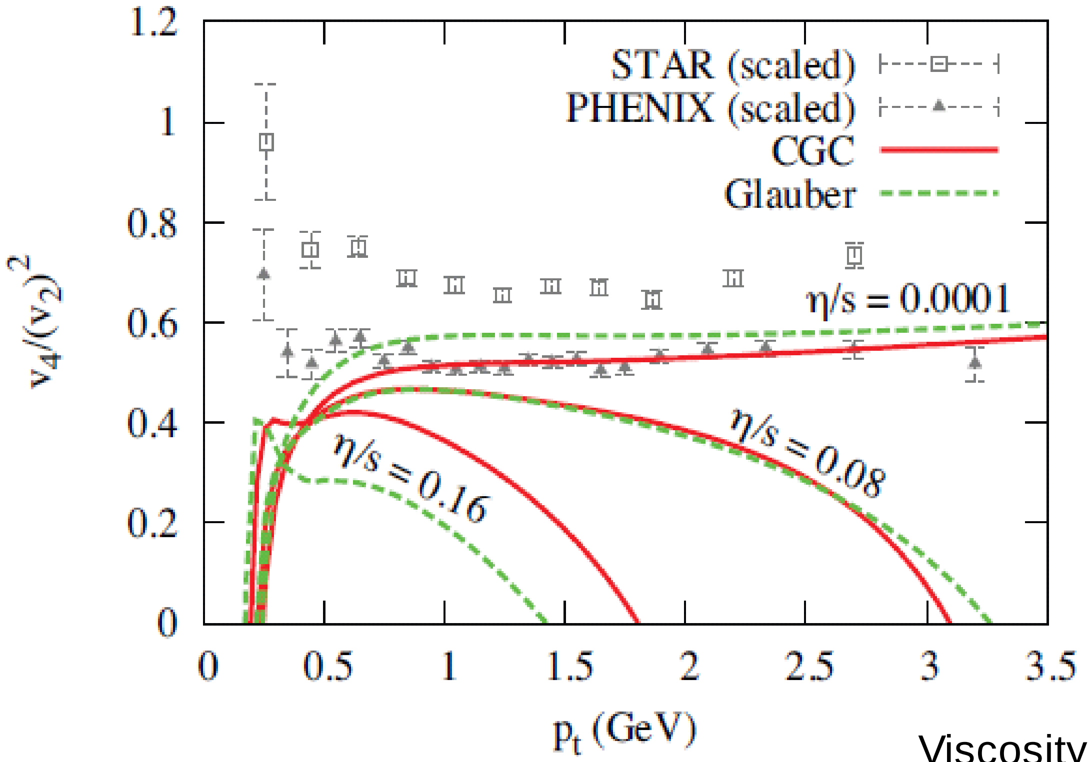
G.Eyyubova et al., PRC 80 (2009) 064907

One of the explanations of KE_T/n_q scaling is partonic origin of the elliptic flow.

However, final state effects (such as resonance decays and jets) may also lead to appearance of the scaling

M. Luzum, C. Gombeaud, J.-Y. Ollitrault, PRC 81 (2010) 054910

Effects of initial profile and viscosity



Initial profile has little effect although eccentricities differ.

results strongly depend on viscosity

Viscosity lowers v4 /(v2 $)^2$ for a realistic T_f

Why ε fluctuations change v_4/v_2^2

Experimentally, no direct measure of v_2 and v_4

v_2 and v_4 are measured via azimuthal correlations

v_2 from $\langle cos(2\phi_1 - 2\phi_2)\rangle = \langle (v_2)^2 \rangle$

v_4 from $\langle cos(4\phi_1 - 2\phi_2 - 2\phi_3)\rangle = \langle v_4 (v_2)^2 \rangle$

Experimentally measured

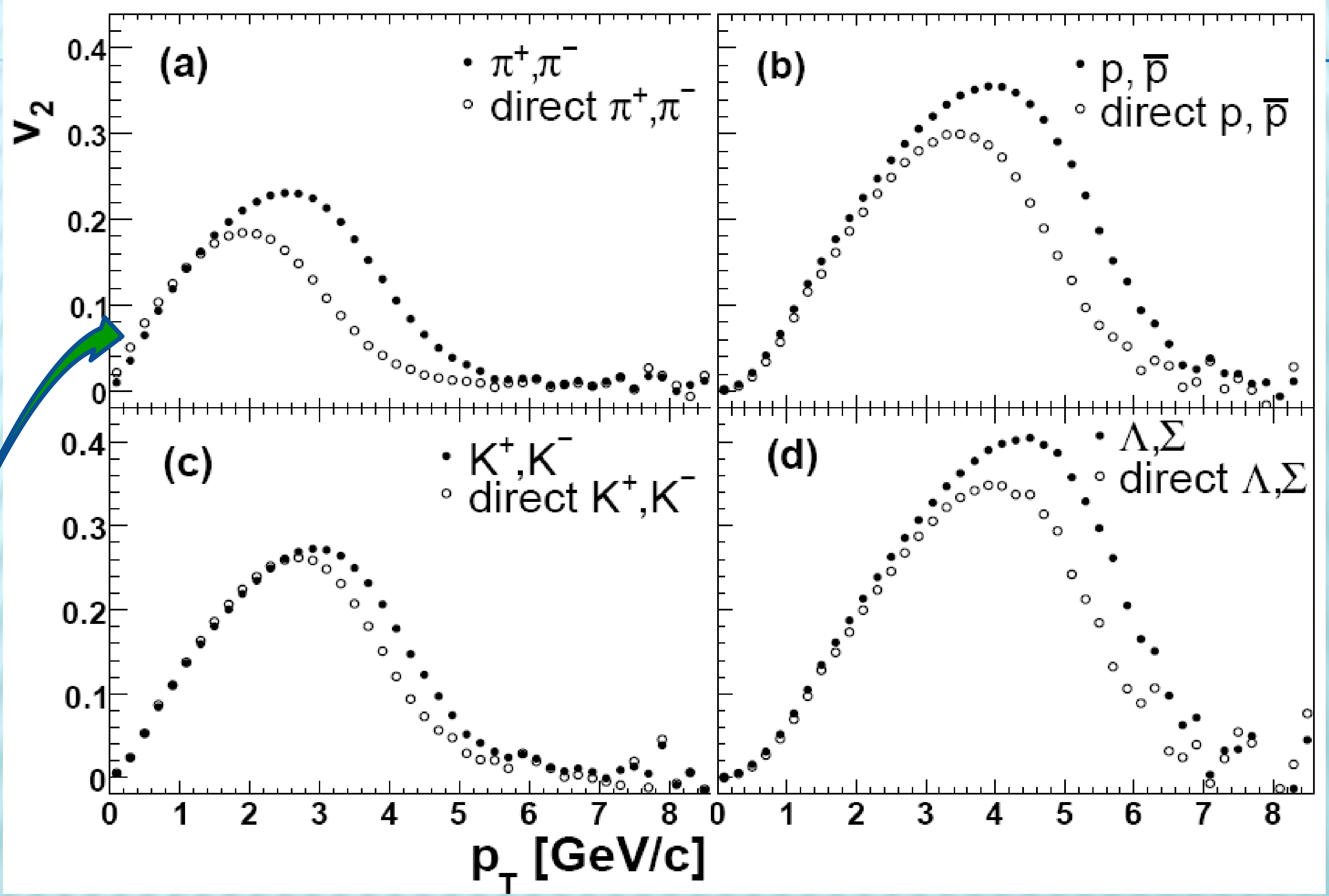
$$\frac{v_4}{v_2^2} = \frac{\langle v_4 (v_2)^2 \rangle}{\langle (v_2)^2 \rangle^2} = \frac{1}{2} \frac{\langle (v_2)^4 \rangle}{\langle (v_2)^2 \rangle^2} > \frac{1}{2}$$

hydro

fluctuations

Similar results obtained using Event Plane method

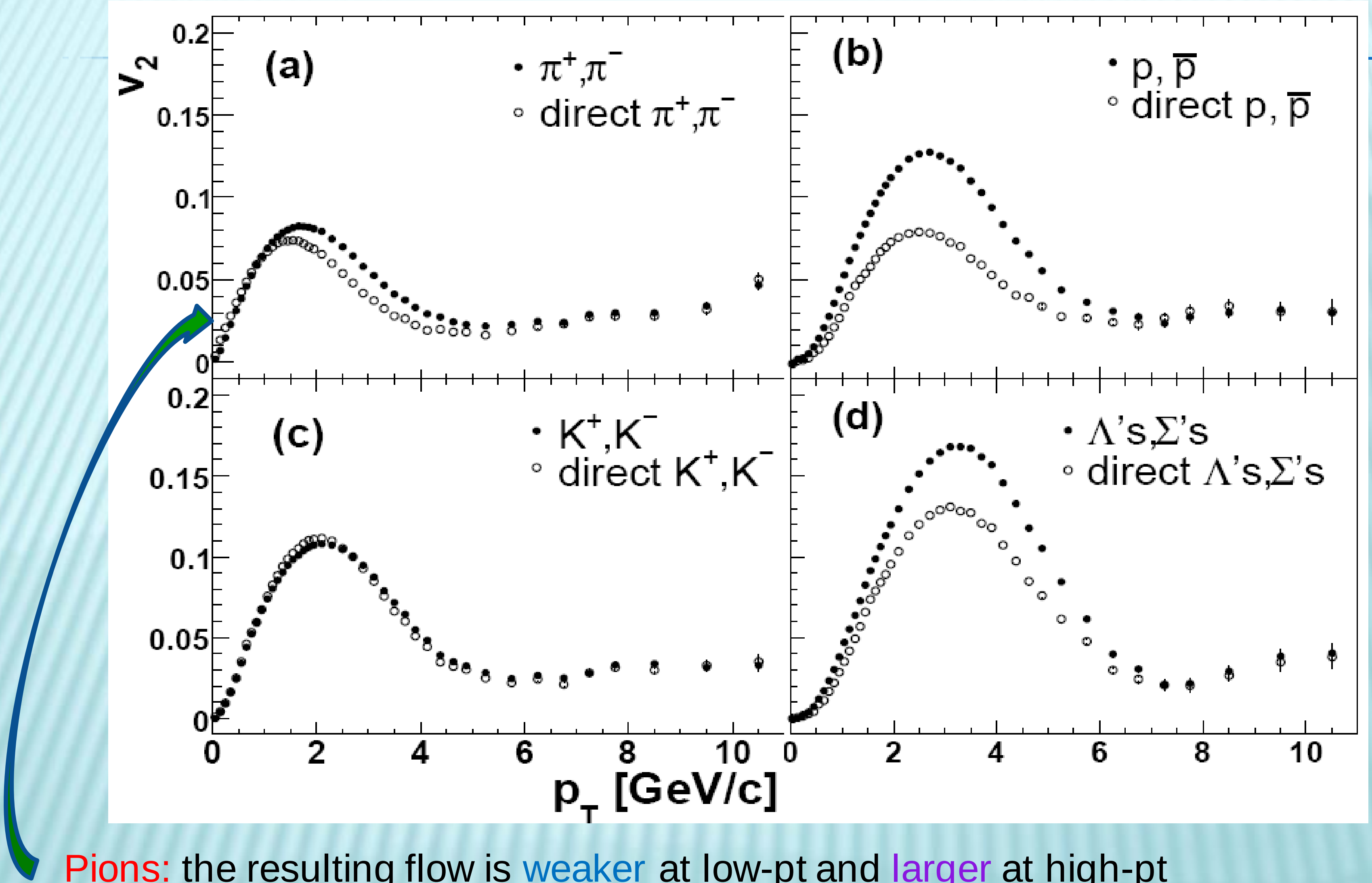
Influence of resonance decays for different type of particles at RHIC



Pions and kaons: the resulting flow is weaker at low-pt and larger at high-pt

Baryons: the resulting flow is stronger than the flow of direct particles

Influence of resonance decays for different type of particles at LHC



Pions: the resulting flow is weaker at low-pt and larger at high-pt

Kaons: both flows almost coincide

Baryons: the resulting flow is stronger than the flow of direct particles

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):

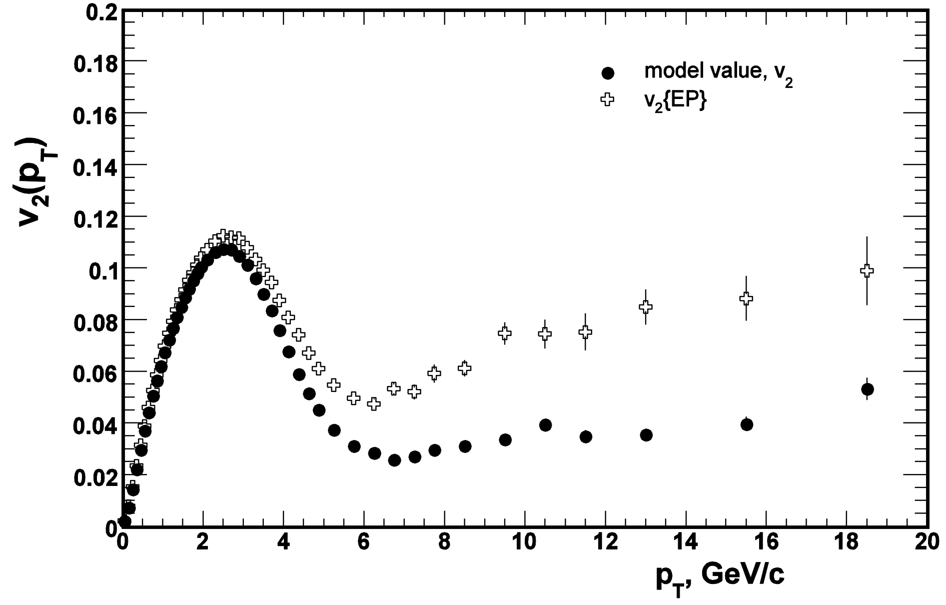
$$v_2 = \frac{j_0}{Nr_0}$$

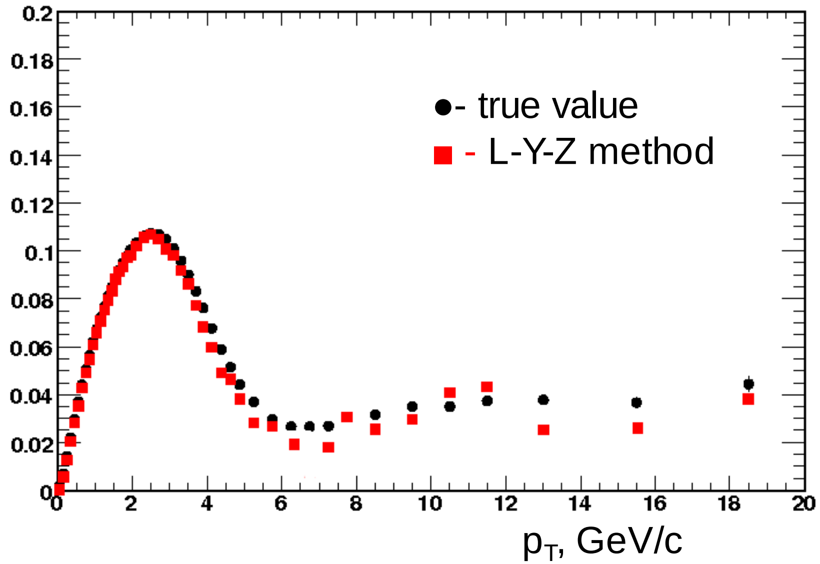
Differential flow is calculated by the formula:

$$\frac{v_2(p_T)}{Nv_2} = \mathrm{Re}\left(\frac{\langle \cos(2\varphi) e^{ir_0 Q} \rangle}{\langle Q e^{ir_0 Q} \rangle} \right)$$

Comparison of Event Plane and Lee-Yang zeroes methods (c=30%)

EventPlane method





Lee-Yang zeroes Method

Event Plane method overestimates v_2 at high p_t due to non-flow correlation (mostly because of jets).