ANISOTROPIC FLOW IN RELATIVISTIC HEAVY ION COLLISIONS AS INTERPLAY OF SOFT PHYSICS AND JETS

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

University of Oslo and Moscow State University

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OUTLINE

I. HYDJET++ model (hydro + jets)

II. Description of elliptic flow in relativistic heavy ion collisions

III. NCQ-scaling at RHIC and LHC

IV. Model results for the ratio $v4/(v2)^2$ at RHIC and LHC

V. High harmonics

VI. Conclusions

I. HYDJET++ =
FASTMS + HYDJET

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 (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}** , **{μ_B, μ_S, μ_Q}**
2. If thermal freeze-out is considered: **T_{th}** , **μ_π**-normalisation constant
3. Volume parameters: **τ, $\Delta\tau$, 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 **[- η_{max}, η_{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 **δ**(b), **ε**(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

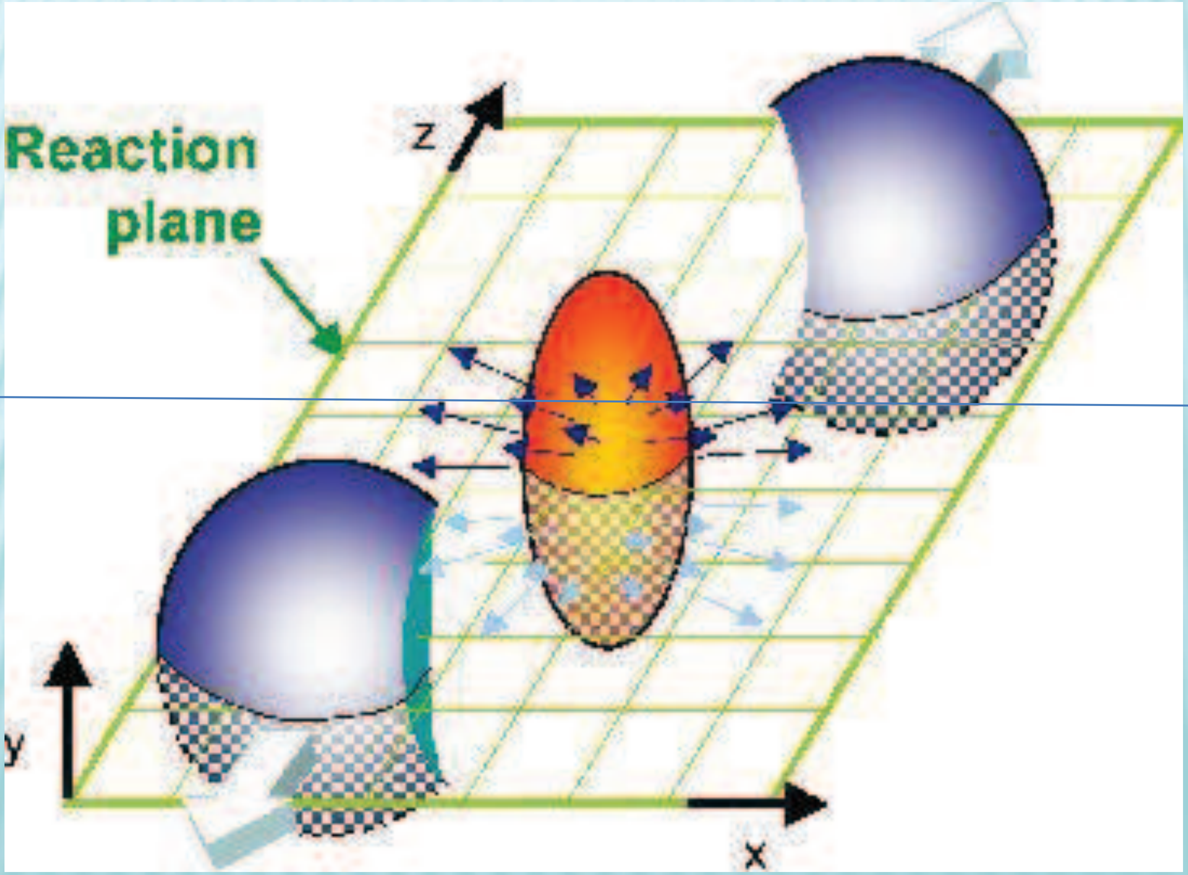
4. ienglu - flag to fix type of medium-induced partonic energy loss (ienglu=0 - radiative and collisional loss, ienglu=1 - radiative loss only, ienglu=2 - collisional loss only, default value is ienglu=0);
   ianglu - flag to fix type of angular distribution of emitted gluons (ianglu=0 - small-angular,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

II. Description of elliptic flow in relativistic heavy ion collisions

Anisotropic flow

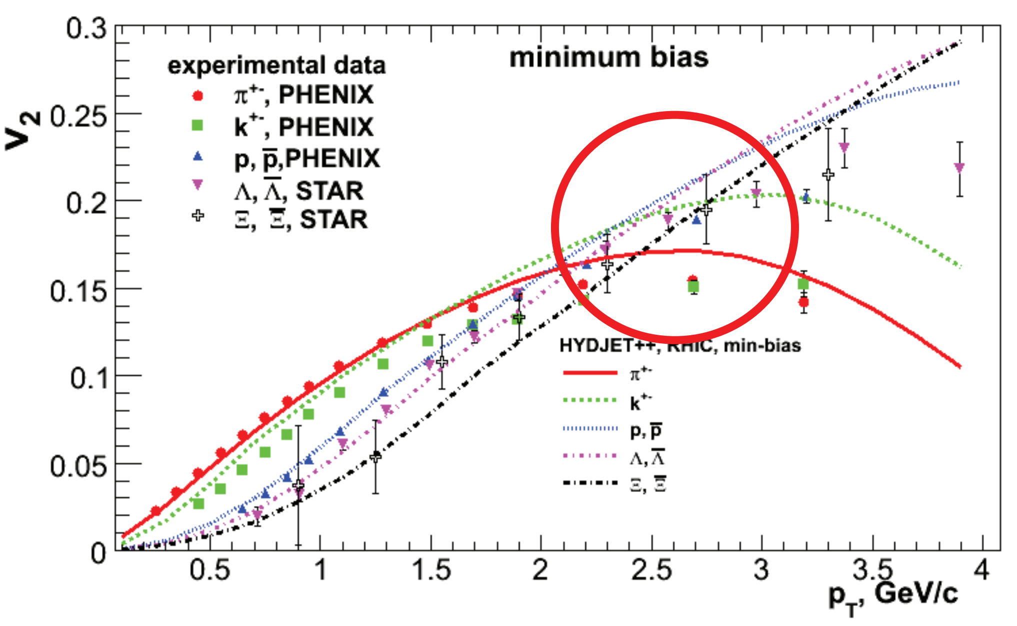
S.Voloshin and Y.Zhang, Z.Phys.C70 (1996) 665

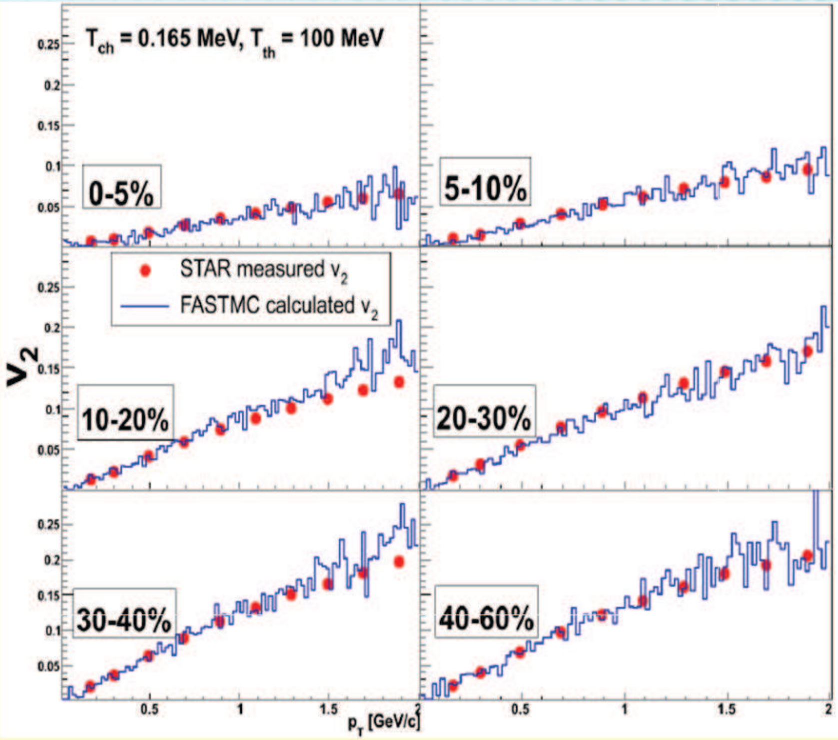
$$\frac{dN}{d\varphi} = \frac{1}{2\pi}\left(1 + \sum_{n=1}^{\infty} 2v_n(p_t)\cos[n(\varphi - \psi_r)]\right)$$

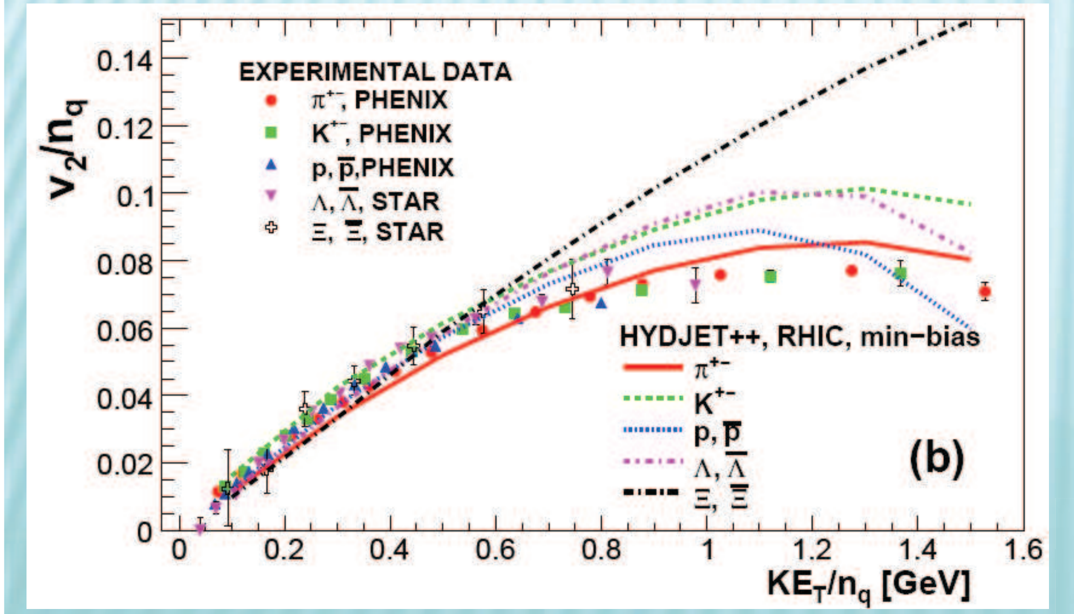


RHIC DATA VS. HYDJET++ MODEL

Au+Au @ 200 AGeV



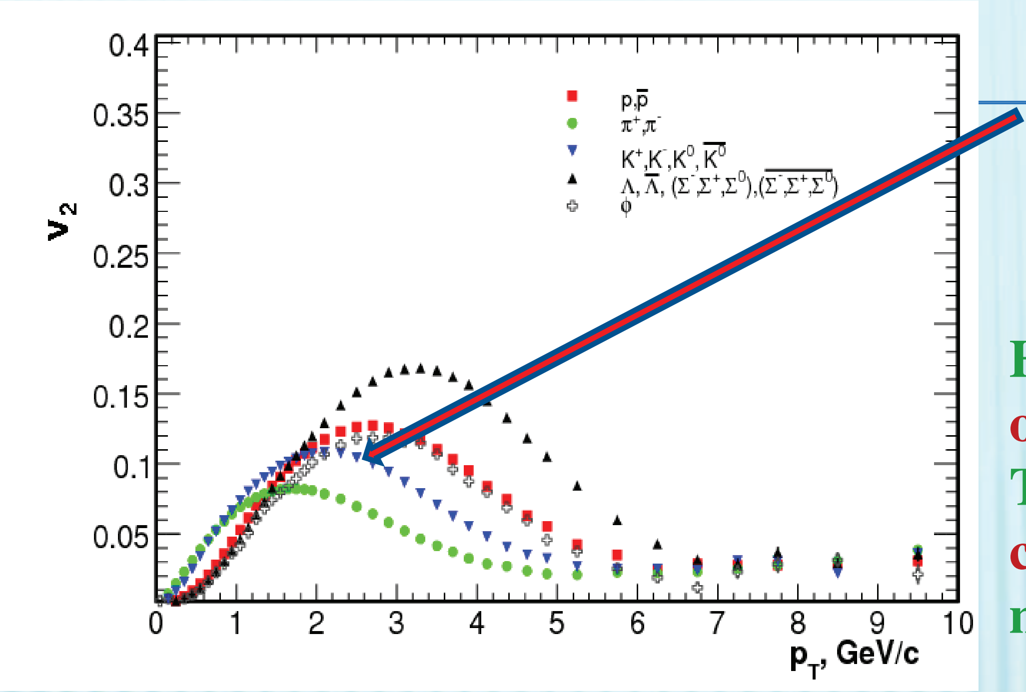




Elliptic flow

G. Eyyubova et al., PRC 80 (2009) 064907;
N.S. Amelin et al., PRC 77 (2008) 014903

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

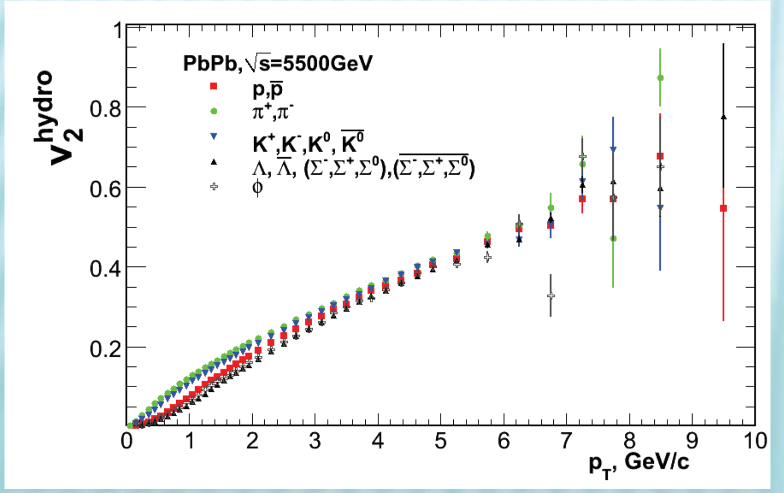


Mass ordering in soft p_T regions then breaks.

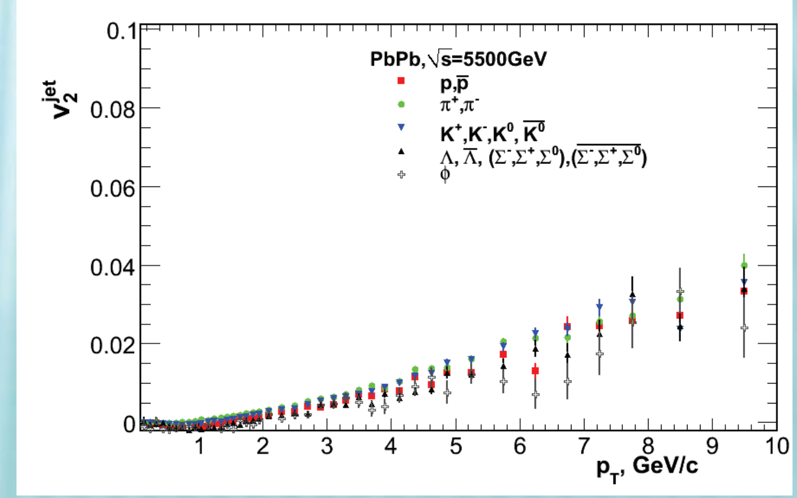
Why?

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

Hydrodynamics



Jet part +quenching



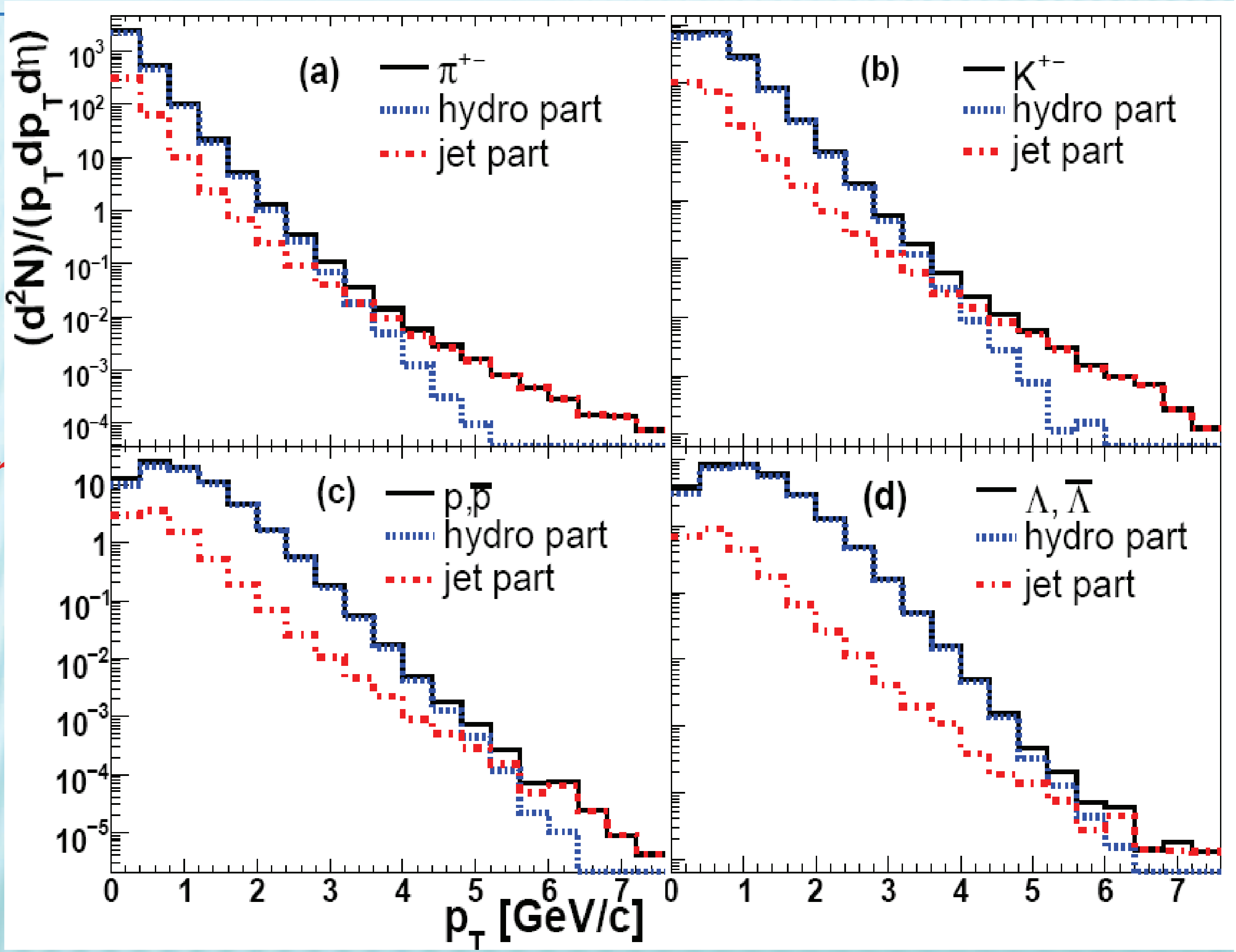
Interplay between hydrodynamics and jets

The p_T specta of π, K, p, Λ with HYDJET++ model, √s=200GeV

The slope for the hydro part depends strongly on mass:

- the heavier the particle -- the harder the spectrum

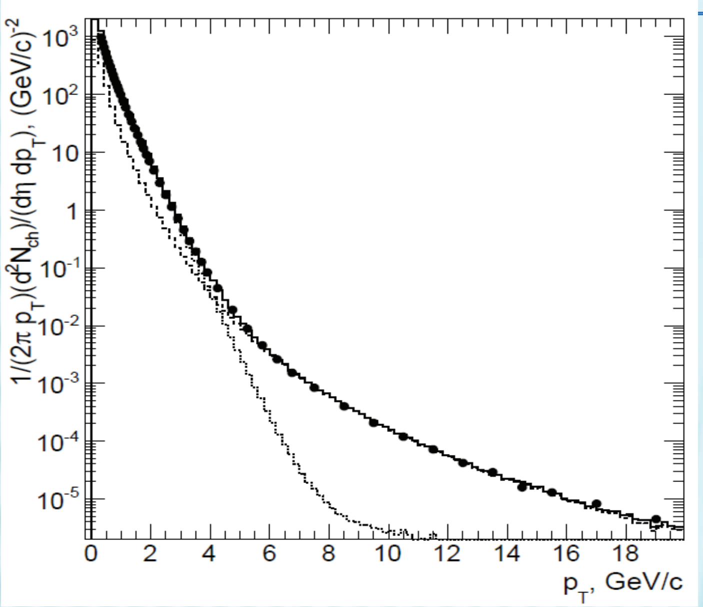
The hydro part dies out earlier for light particles than for heavy ones



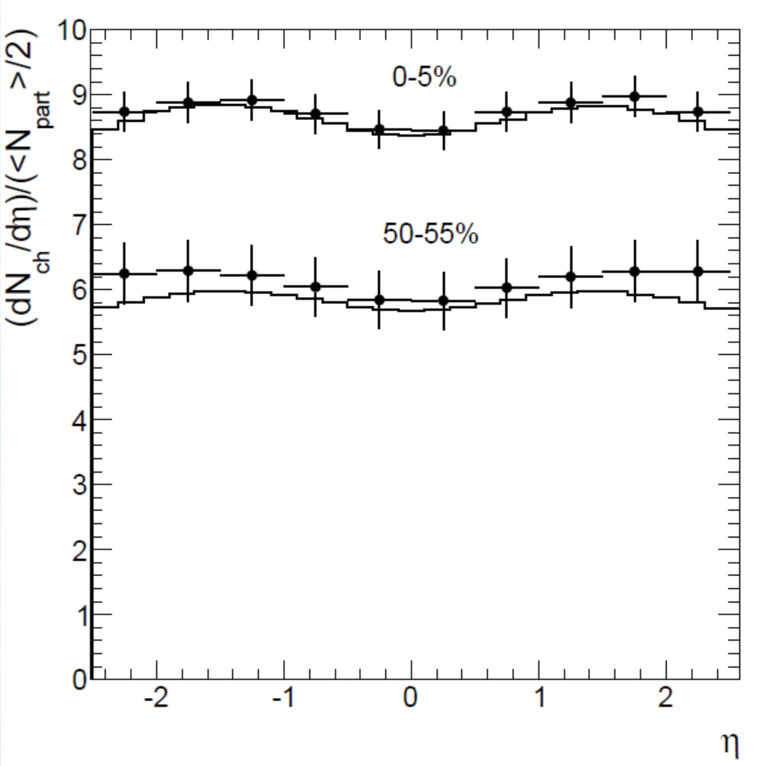
LHC DATA VS. HYDJET++ MODEL

Transverse momentum

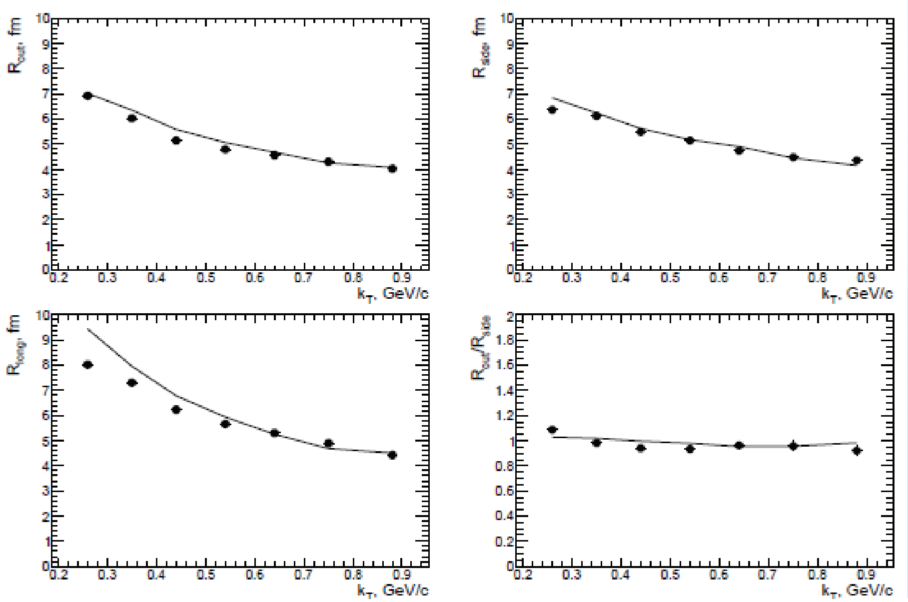
Pb+Pb @ 2.76 ATeV



Rapidity



Correlation radii (femtoscopy)

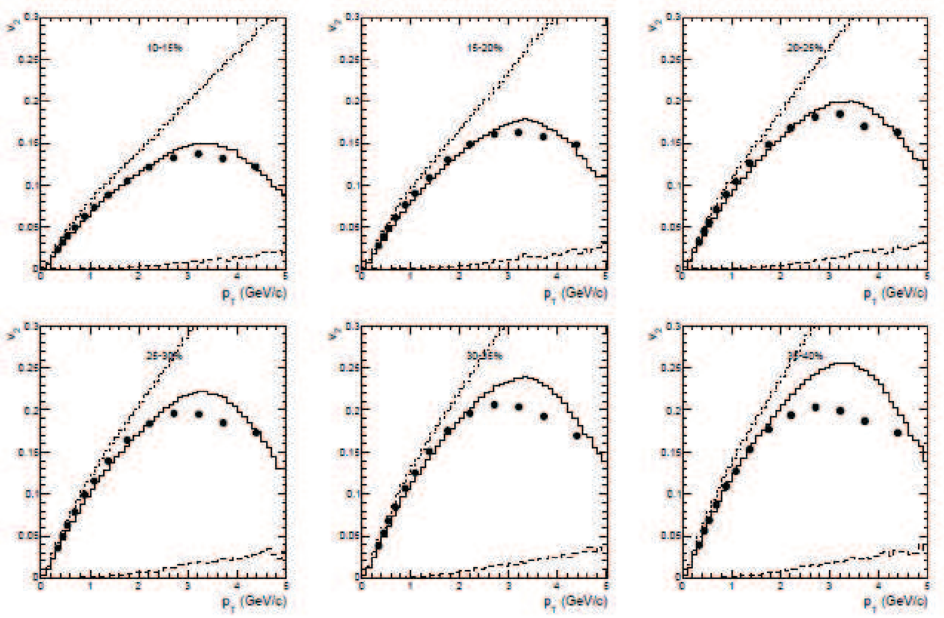


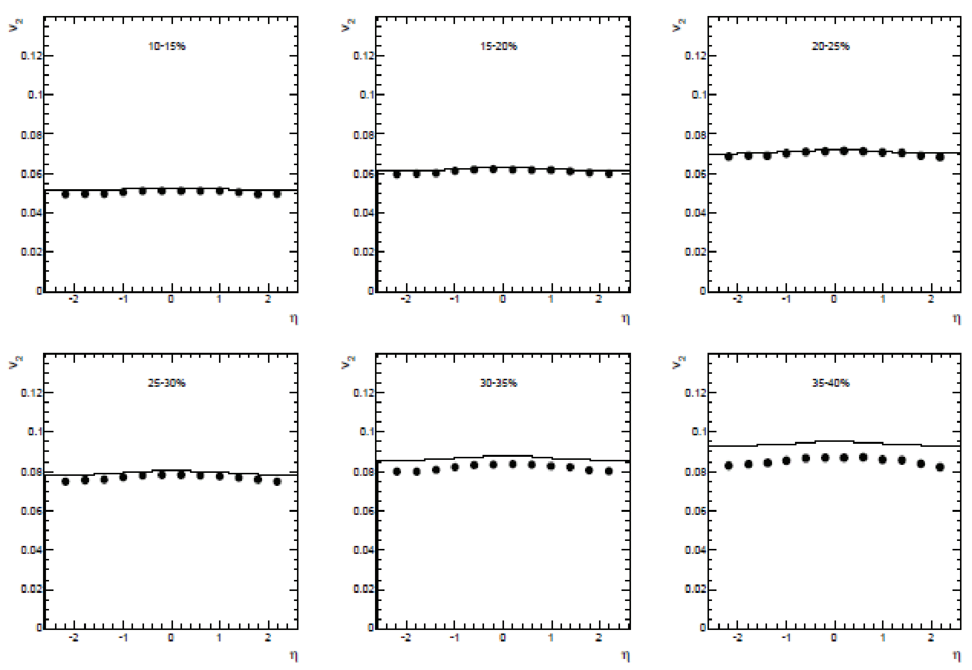
I. Lokhtin et al., Eur. Phys. J C72 (2012) 2045

LHC DATA VS. HYDJET++ MODEL

Pb+Pb @ 2.76 ATeV

Elliptic flow



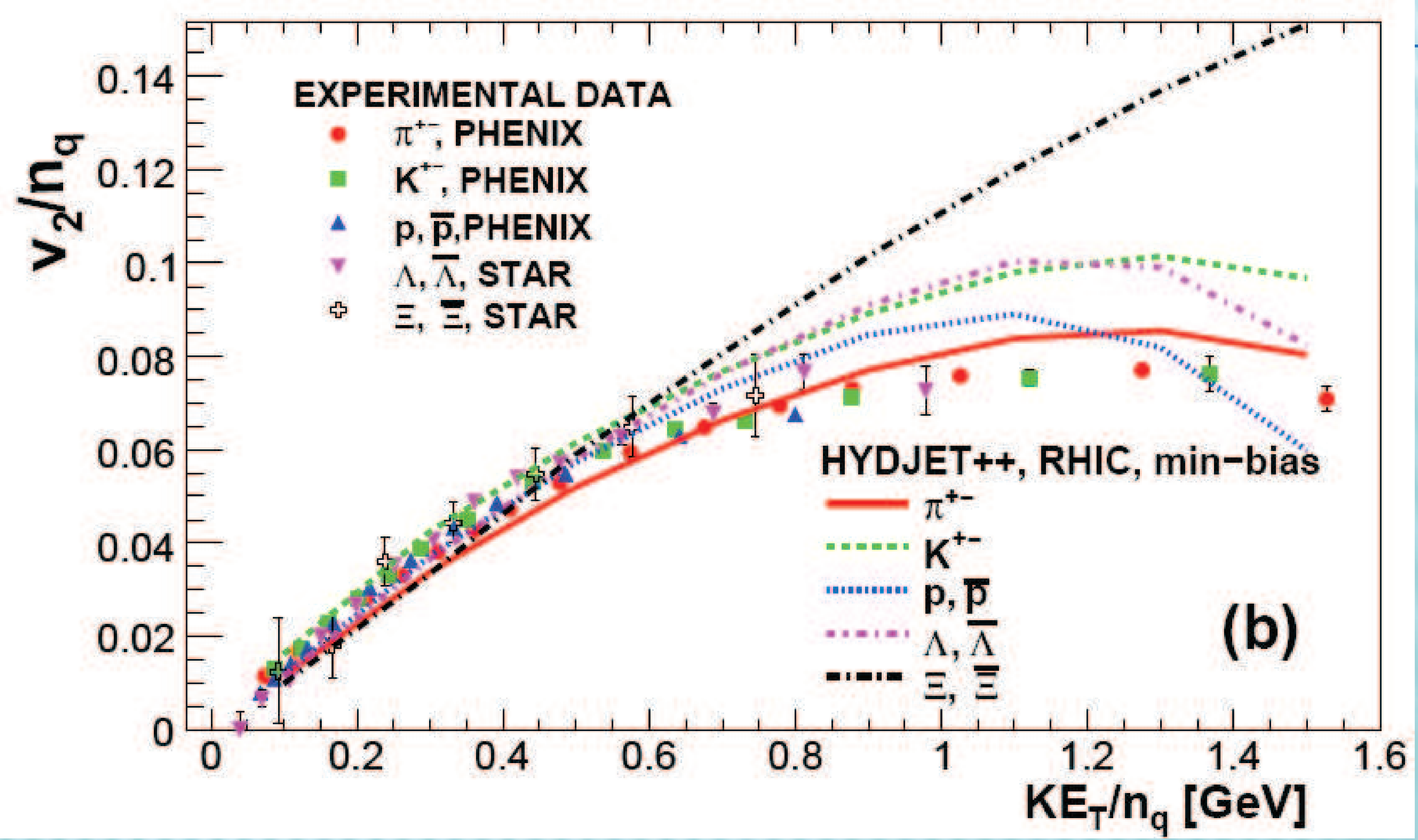


I. Lokhtin et al., Eur. Phys. J C72 (2012) 2045

Model gives a fair description of various observables at both RHIC and LHC

III. Number-of-constituent- quark (NCQ) scaling

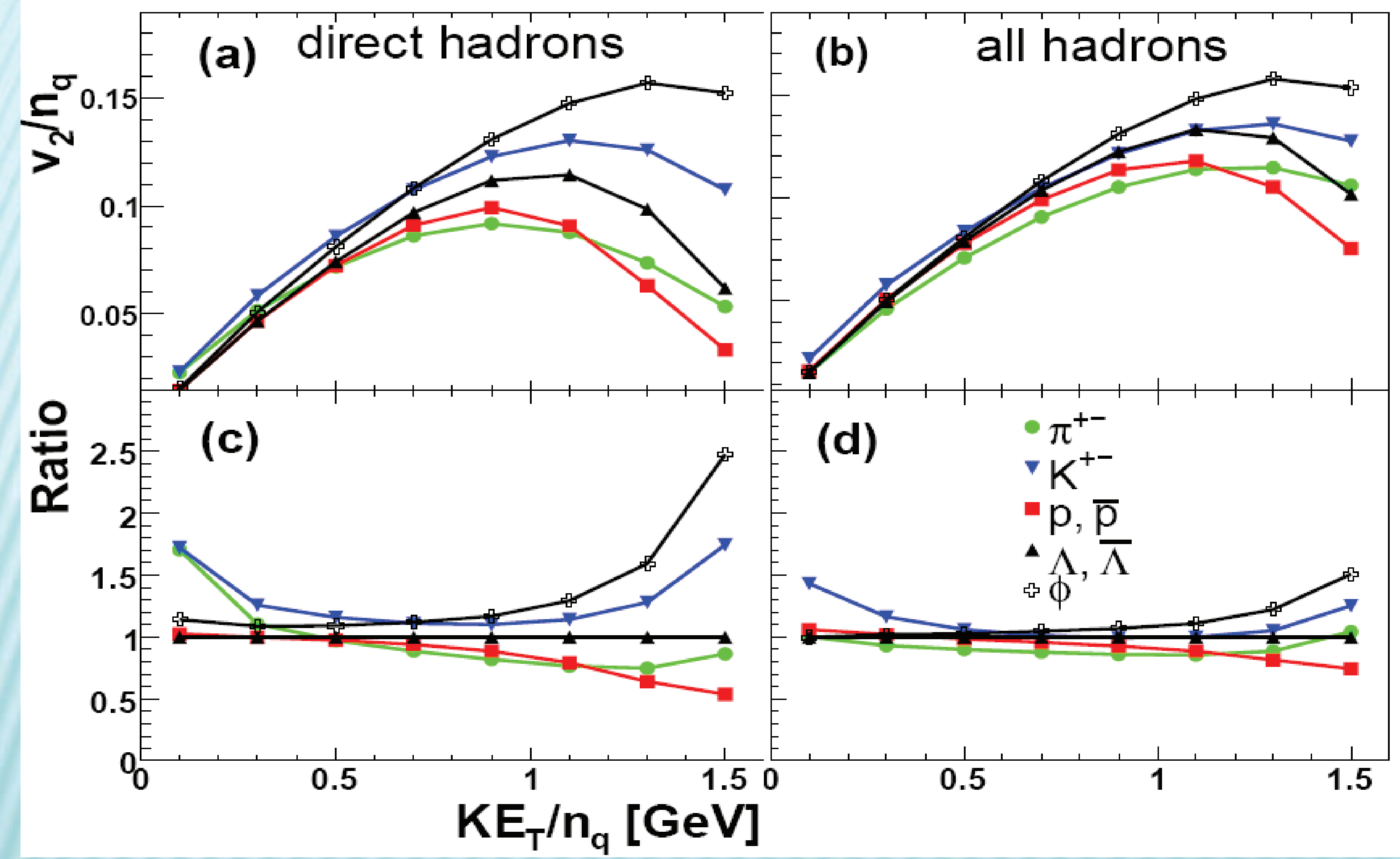
COMPARISON WITH RHIC DATA



The agreement seems to be good at **$KE_T/n_q < 0.7$ GeV**

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

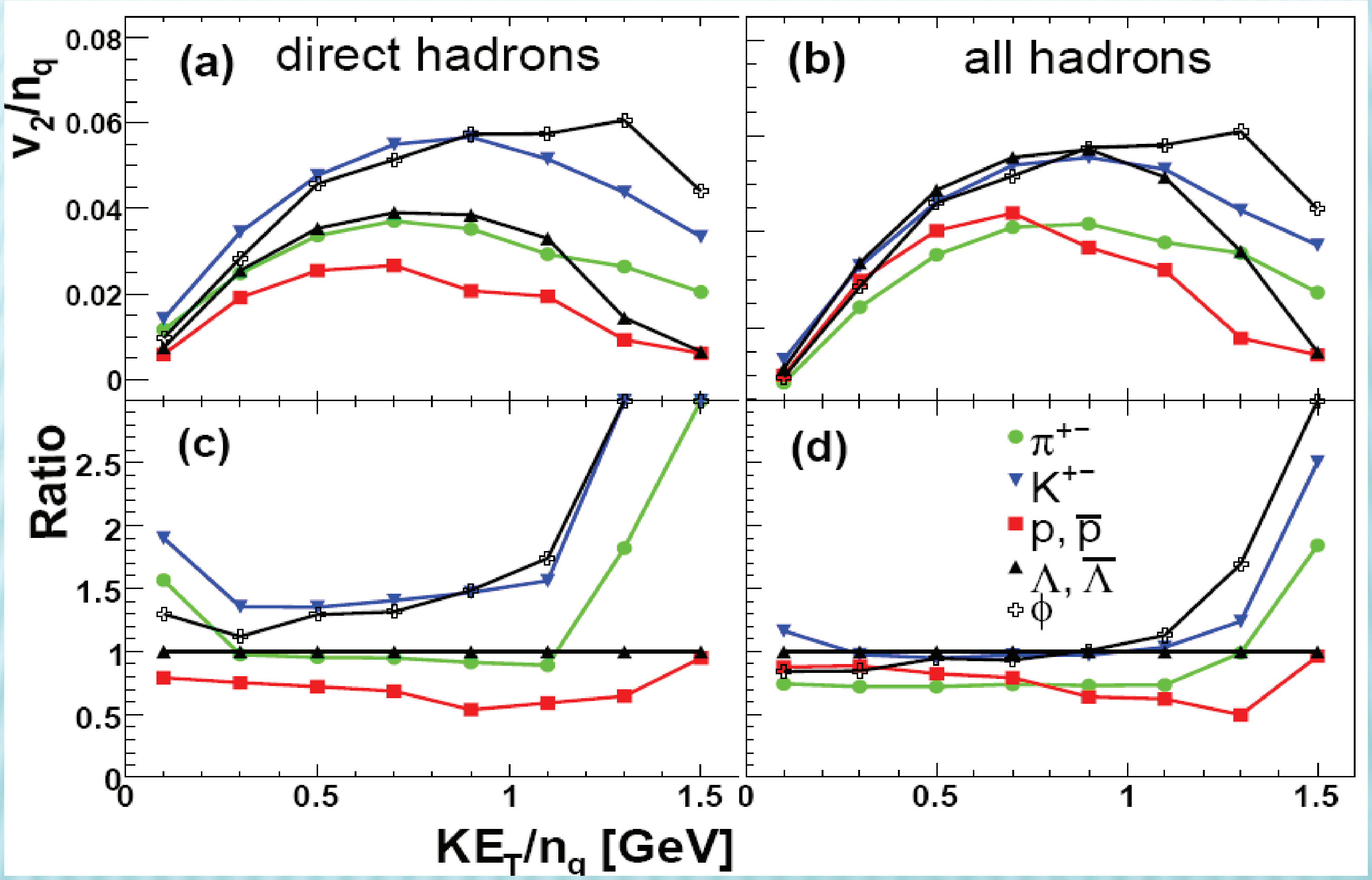
One of the explanations of KE_T/n_q scaling is partonic origin of the elliptic flow.

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

NCQ scaling at LHC

No scaling for
direct particles

Appearance of the approximate
scaling for all particles



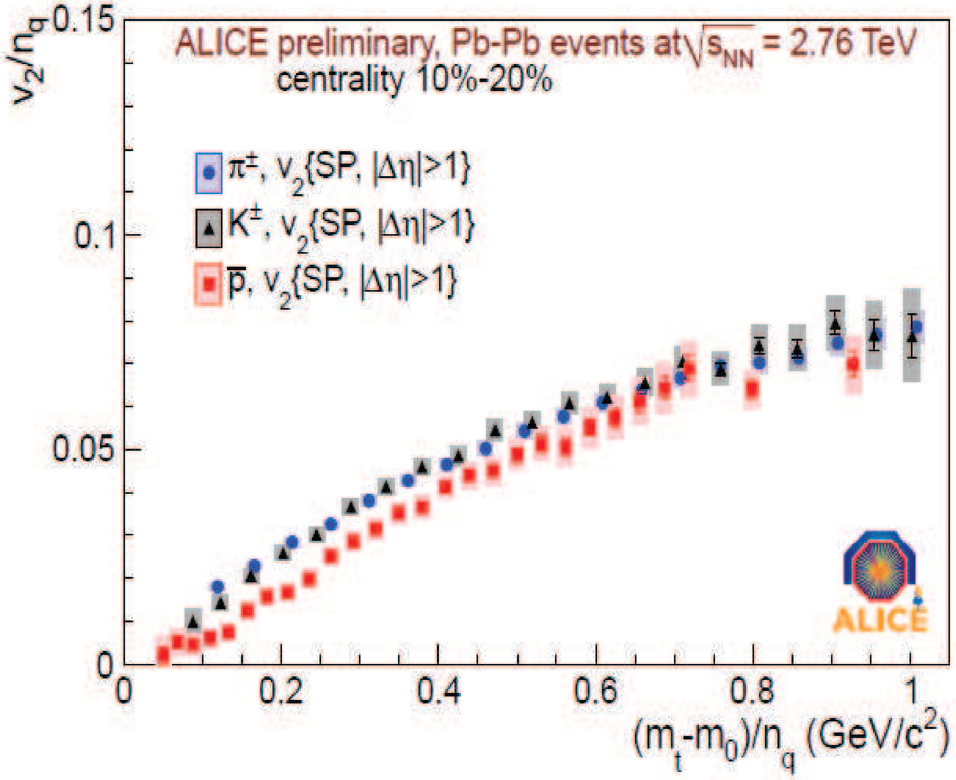
G.Eyyubova et al., PRC 80 (2009) 064907

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

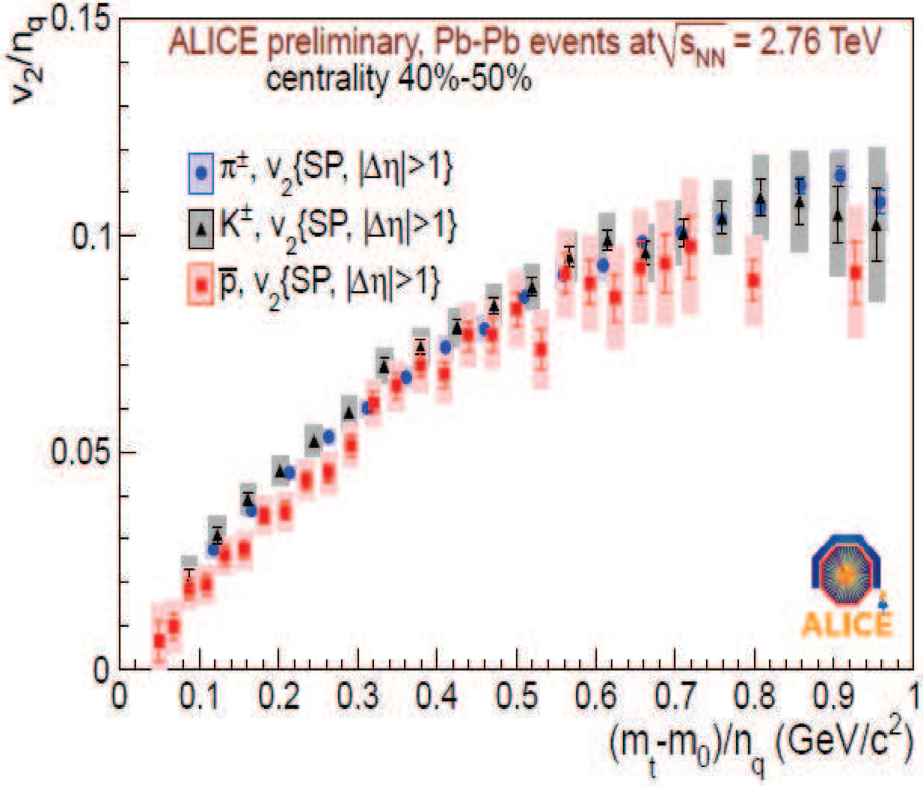
Experimental results (LHC)

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

Semi-sentral collisions



Semi-peripheral collisions

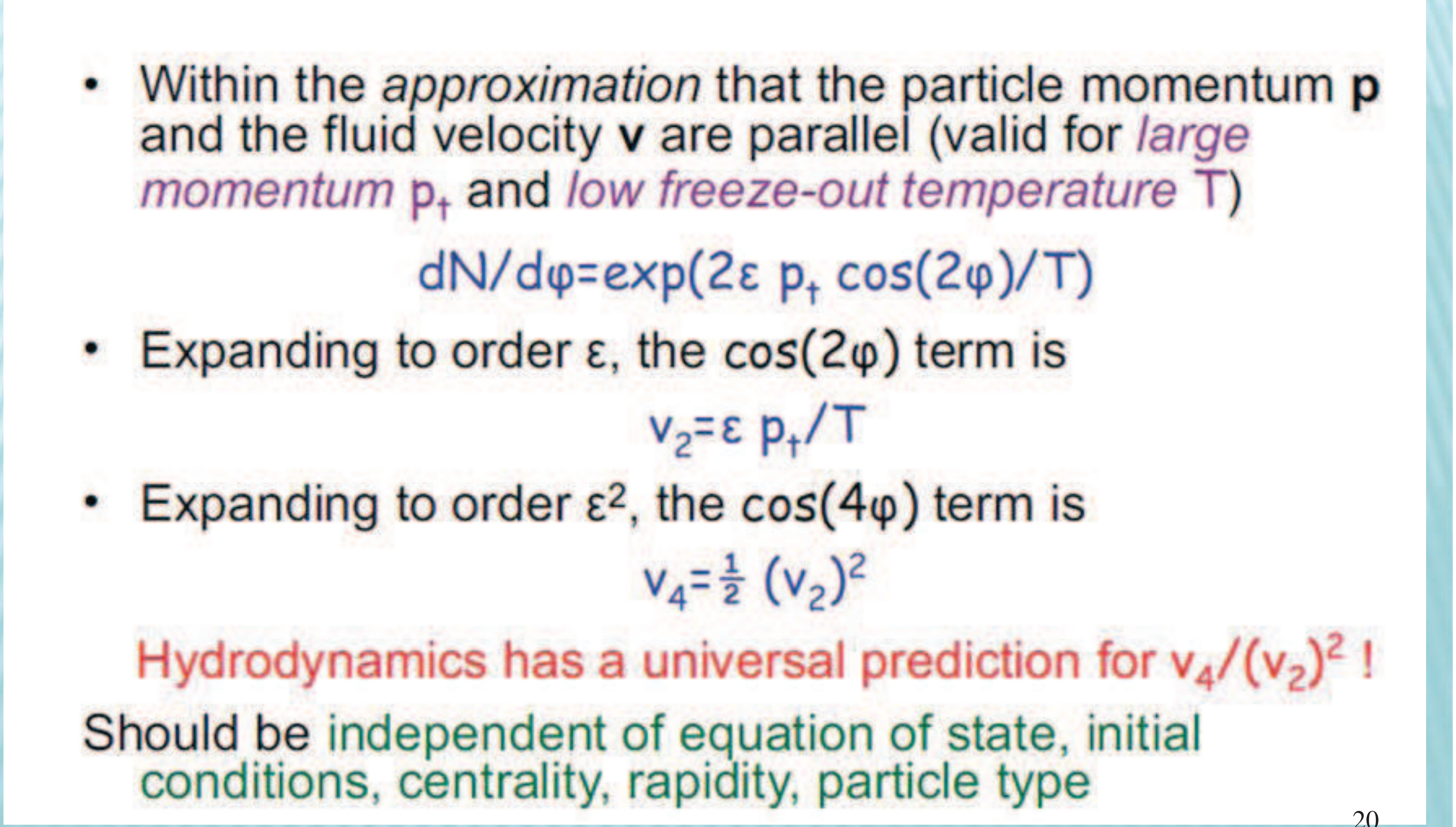


The NCQ scaling is indeed only approximate (2011)

IV. V4/(V2*V2) RATIO

Predictions

N. Borghini, J.-Y. Ollitrault, PLB 642 (2006) 227



- Within the *approximation* that the particle momentum **p** and the fluid velocity **v** are parallel (valid for *large momentum* p_t and *low freeze-out temperature* T)

$$dN/d\varphi=\exp(2\varepsilon\, p_t \cos(2\varphi)/T)$$

- Expanding to order ε, the cos(2φ) term is

$$v_2=\varepsilon\, p_t/T$$

- Expanding to order ε^2, the cos(4φ) term is

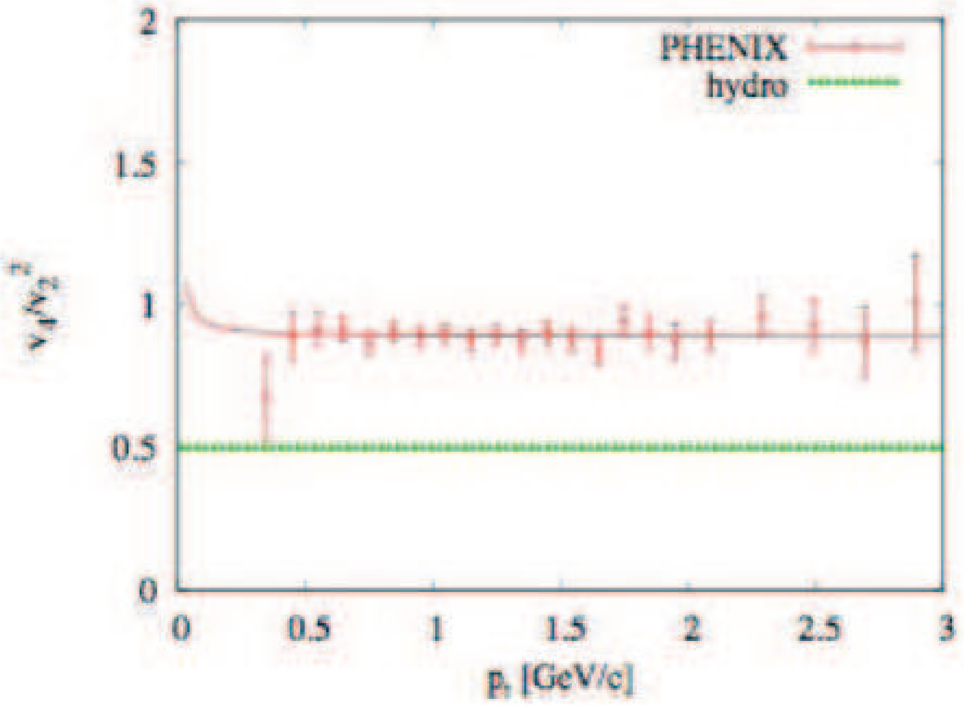
$$v_4=\tfrac{1}{2}\,(v_2)^2$$

Hydrodynamics has a universal prediction for $v_4/(v_2)^2$!

Should be independent of equation of state, initial conditions, centrality, rapidity, particle type

J.-Y. Ollitrault, talk at TORIC'2010

Comparison with data



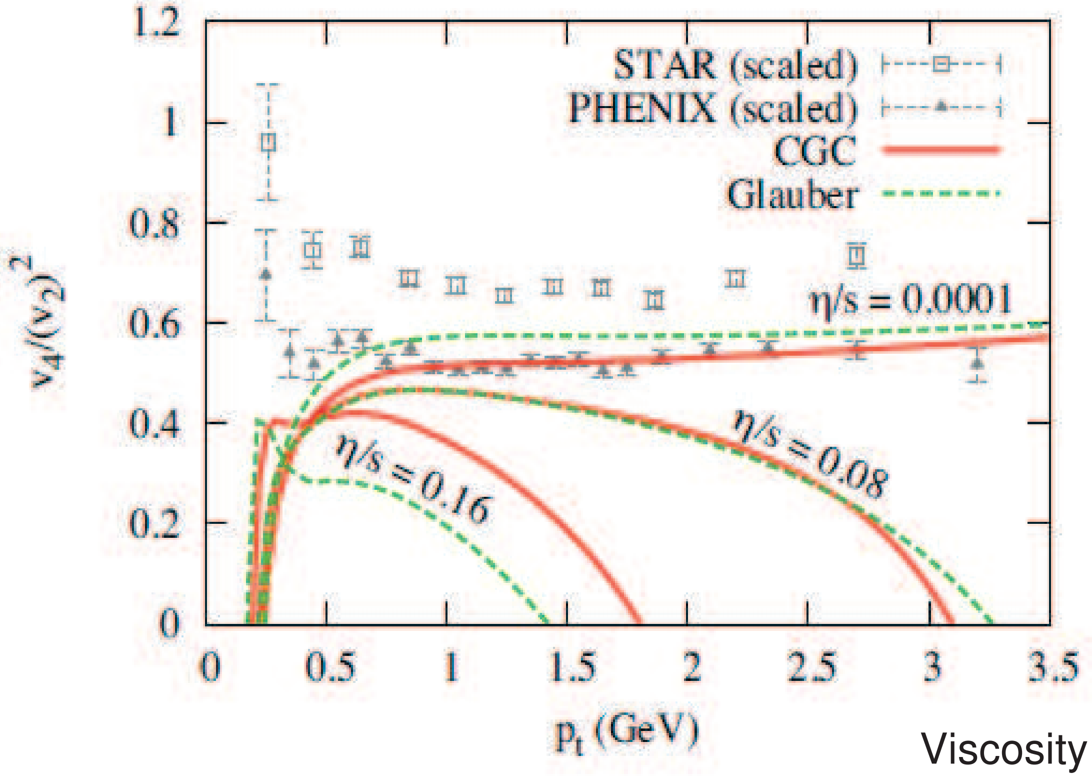
PHENIX data for charged pions

Au-Au collisions at 100+100 GeV

20-60% most central

The ratio is significantly larger than 0.5.
Can this be explained by viscous corrections?

Effects of initial profile and viscosity

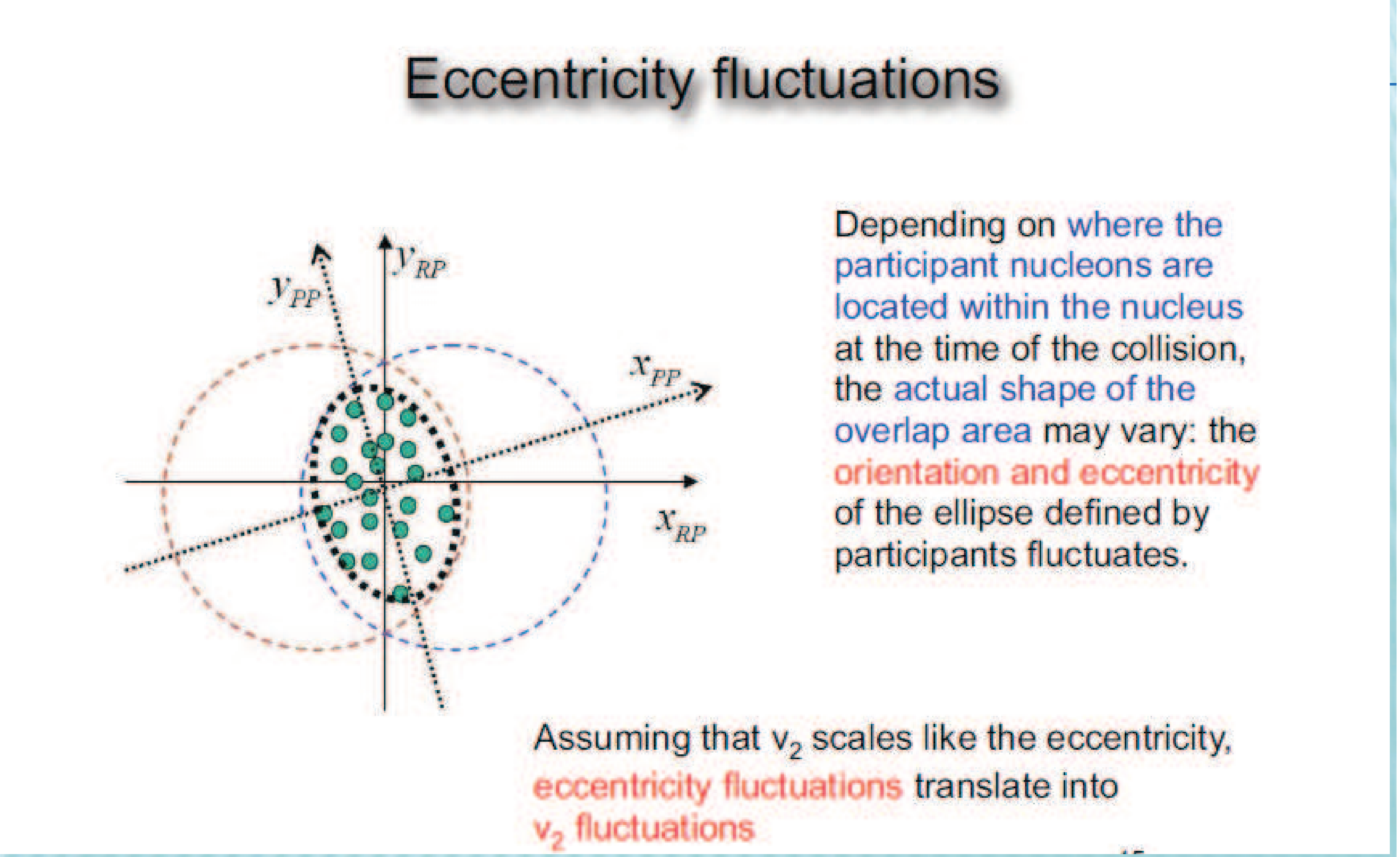


Initial profile has little effect although eccentricities differ.

results strongly depend on viscosity

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

M. Luzum, C. Gombeaud, J.-Y. Ollitrault, PRC81 (2010) 054910



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.

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

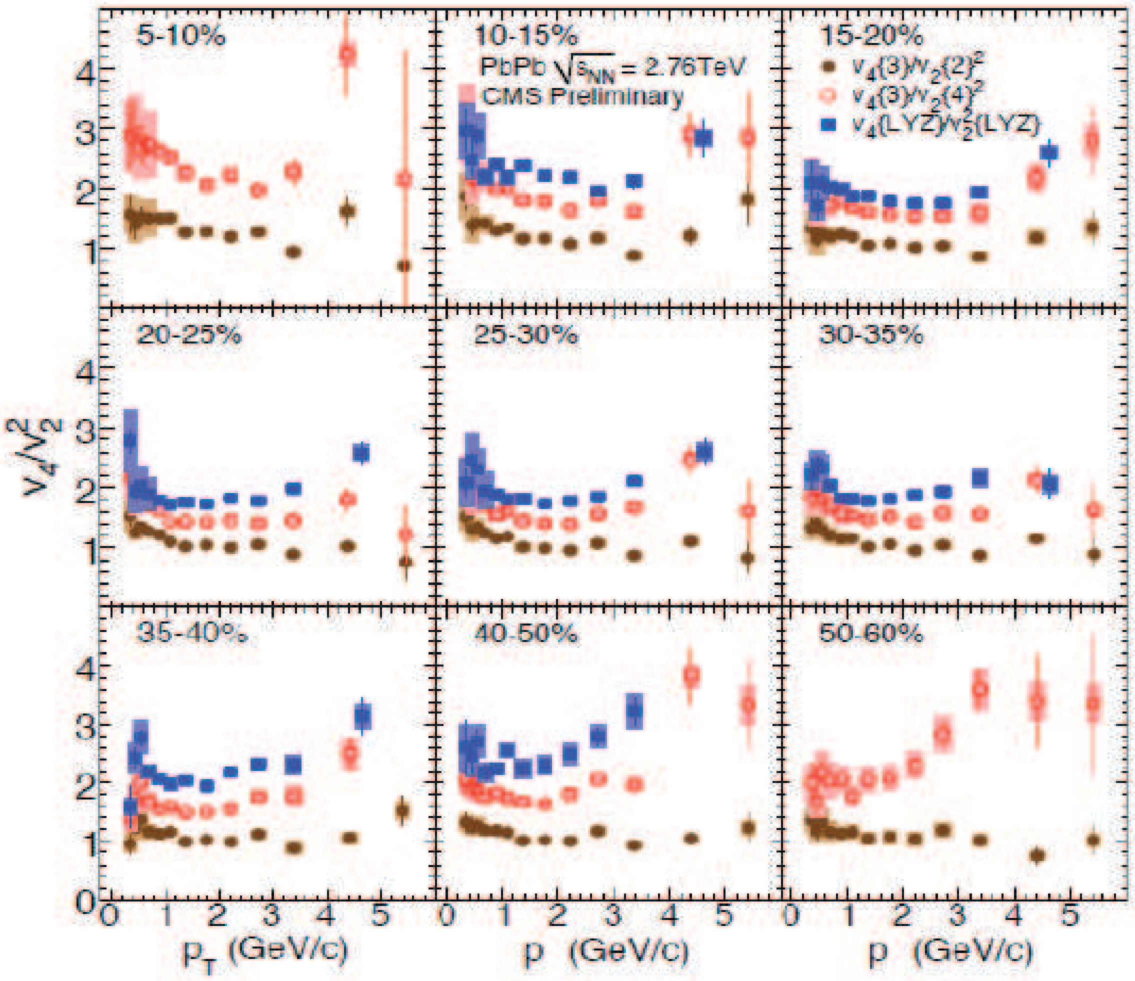
$$\frac{v_4}{v_2^2} = \frac{\langle v_4 (v_2)^2\rangle}{\langle (v_2)^2\rangle^2} = \frac{1}{2}\frac{\langle (v_2)^4\rangle}{\langle (v_2)^2\rangle^2} > \frac{1}{2}$$

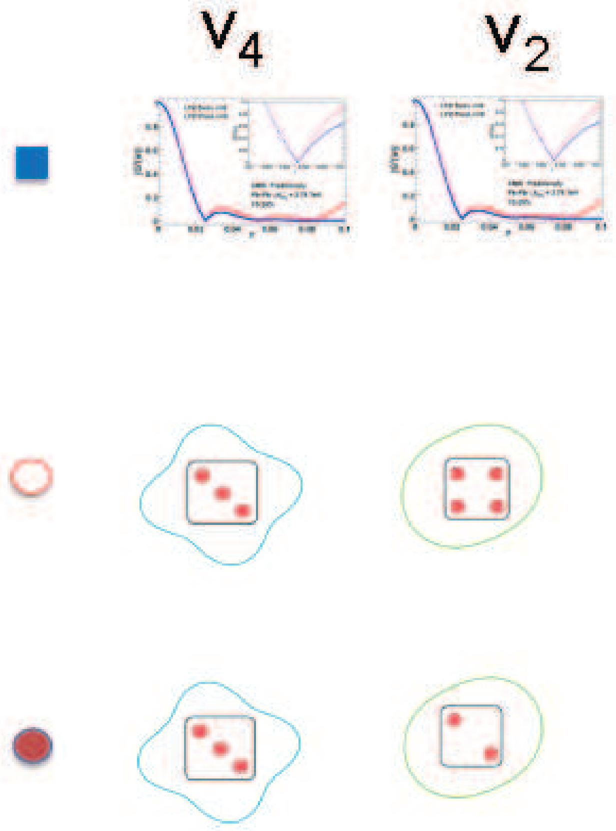
fluctuations

hydro

Similar results obtained using Event Plane method

$v_4 / v_2^2(p_T)$ at mid-rapidity $|\eta| < 0.8$

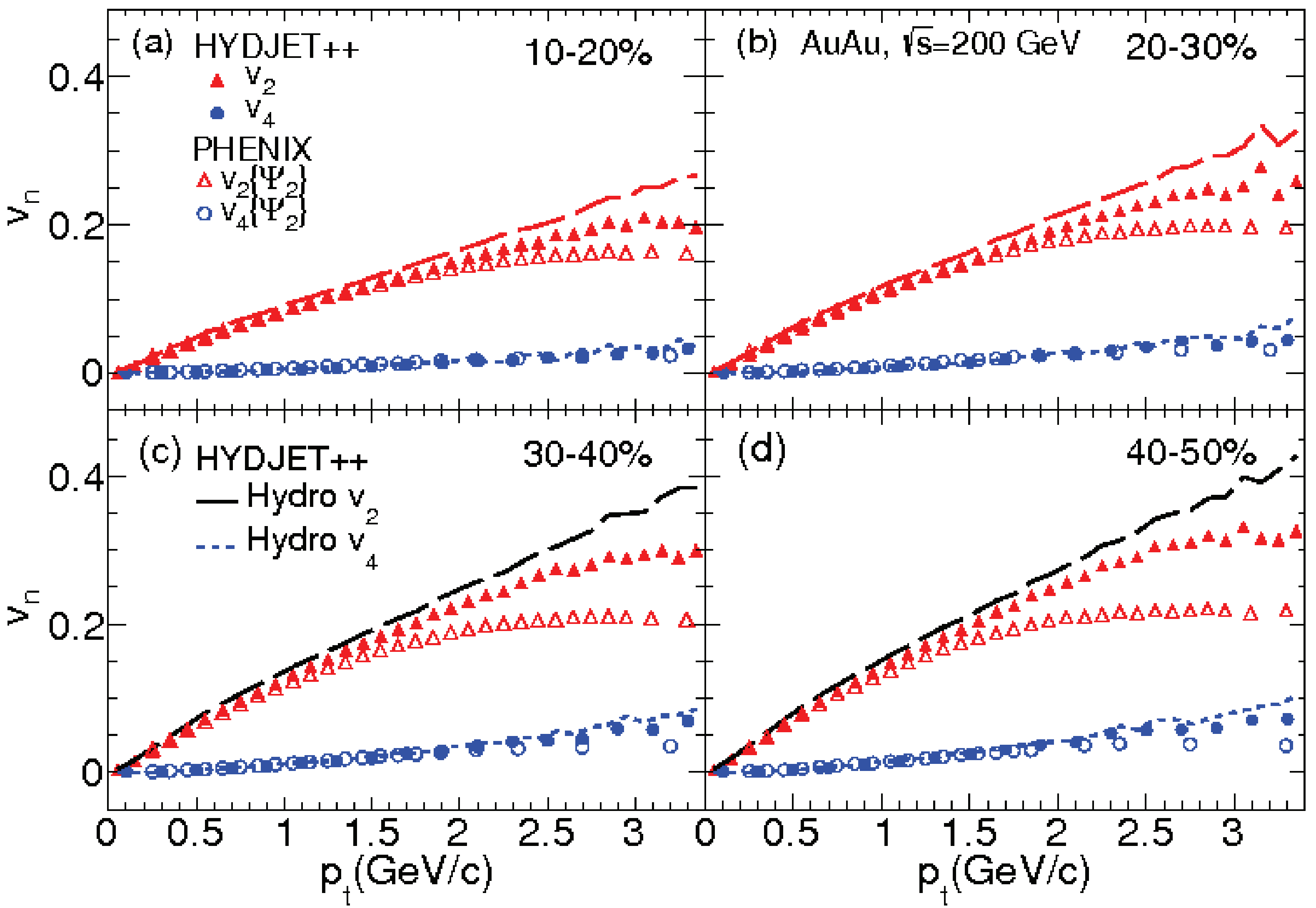




Significantly higher than RHIC: experimental method dependent

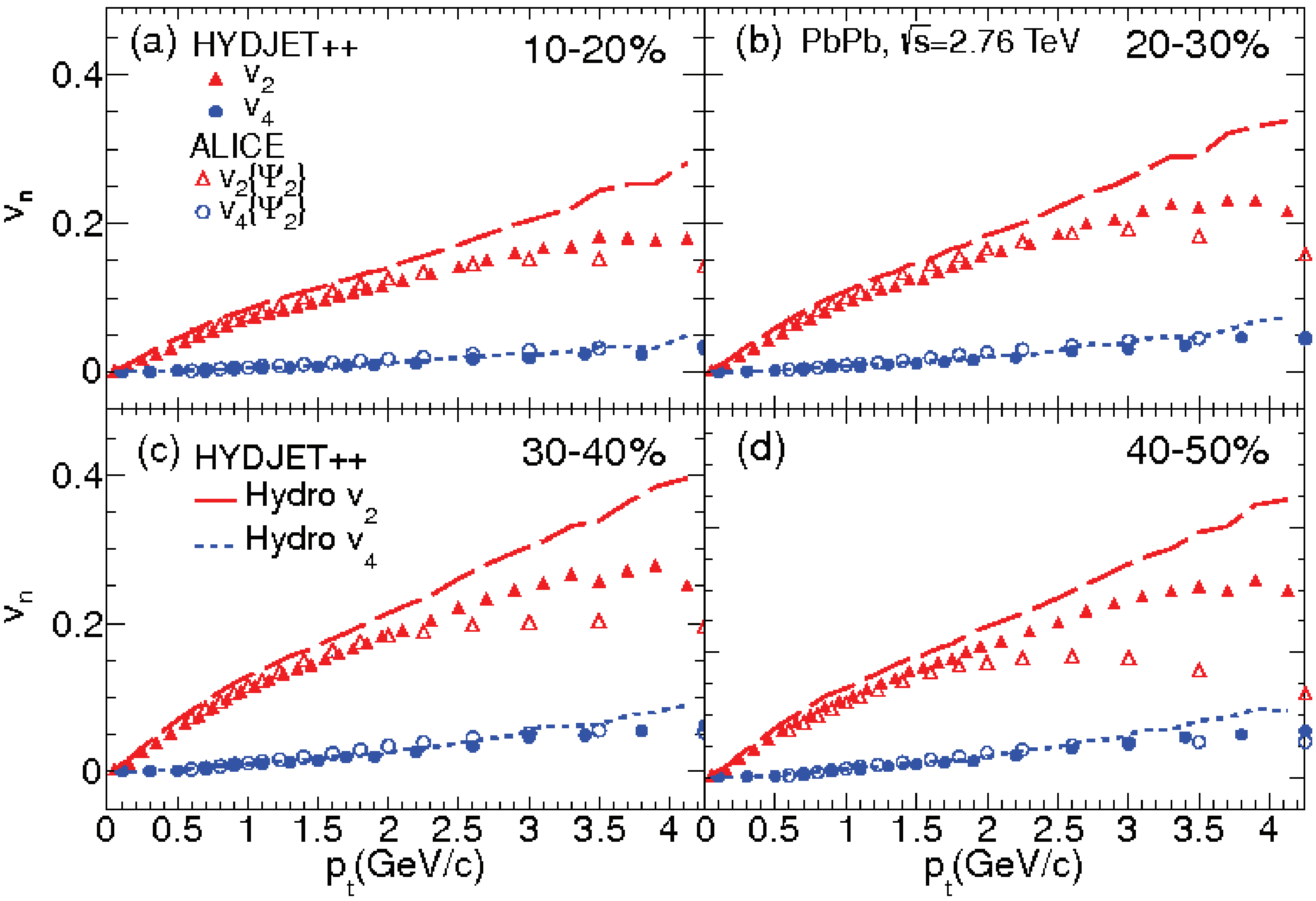
HYDJET++ (RHIC)

Effects to be studied: resonance decay and hard part influence



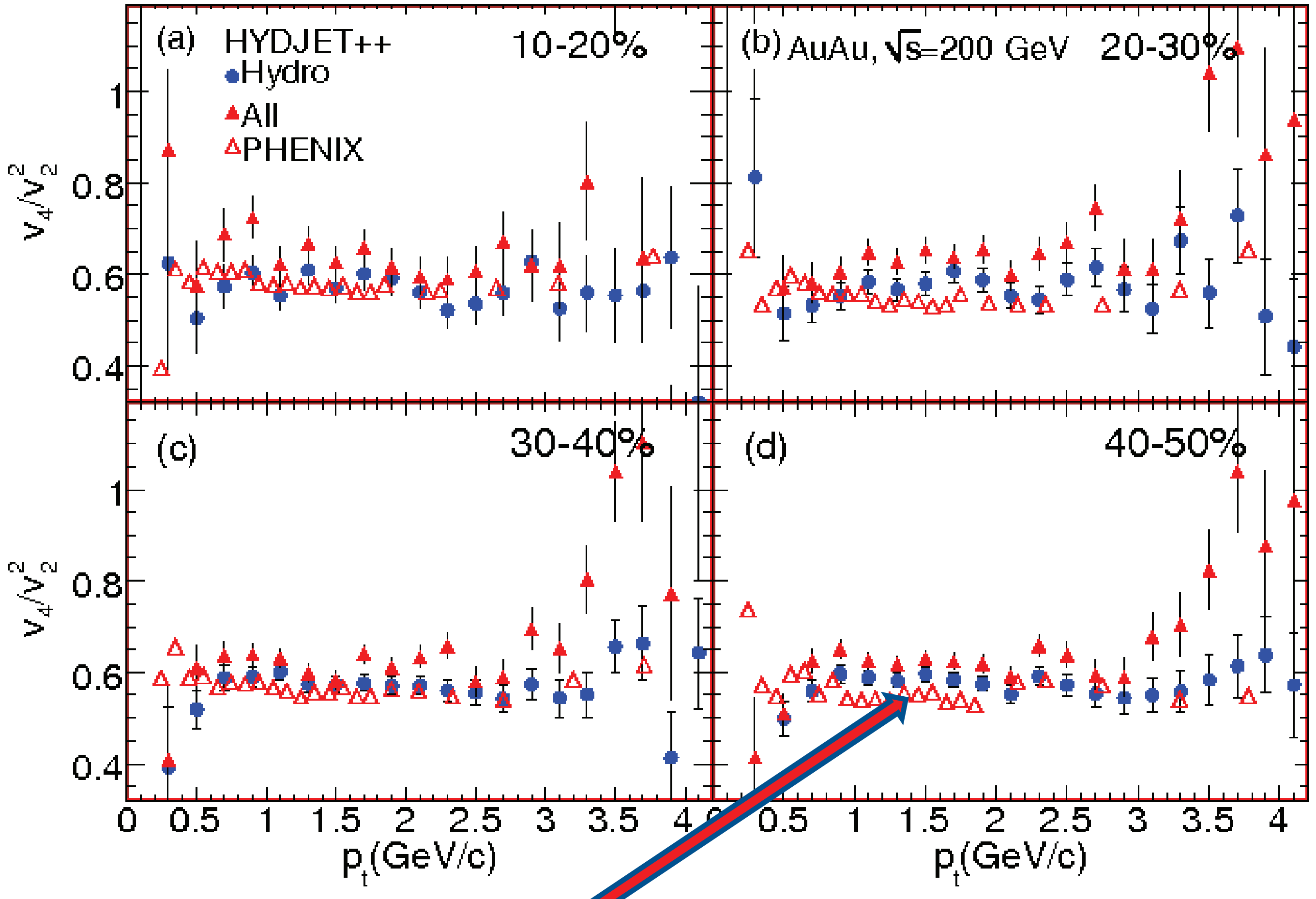
HYDJET++ (LHC)

Pure hydrodynamics vs hydro+jets



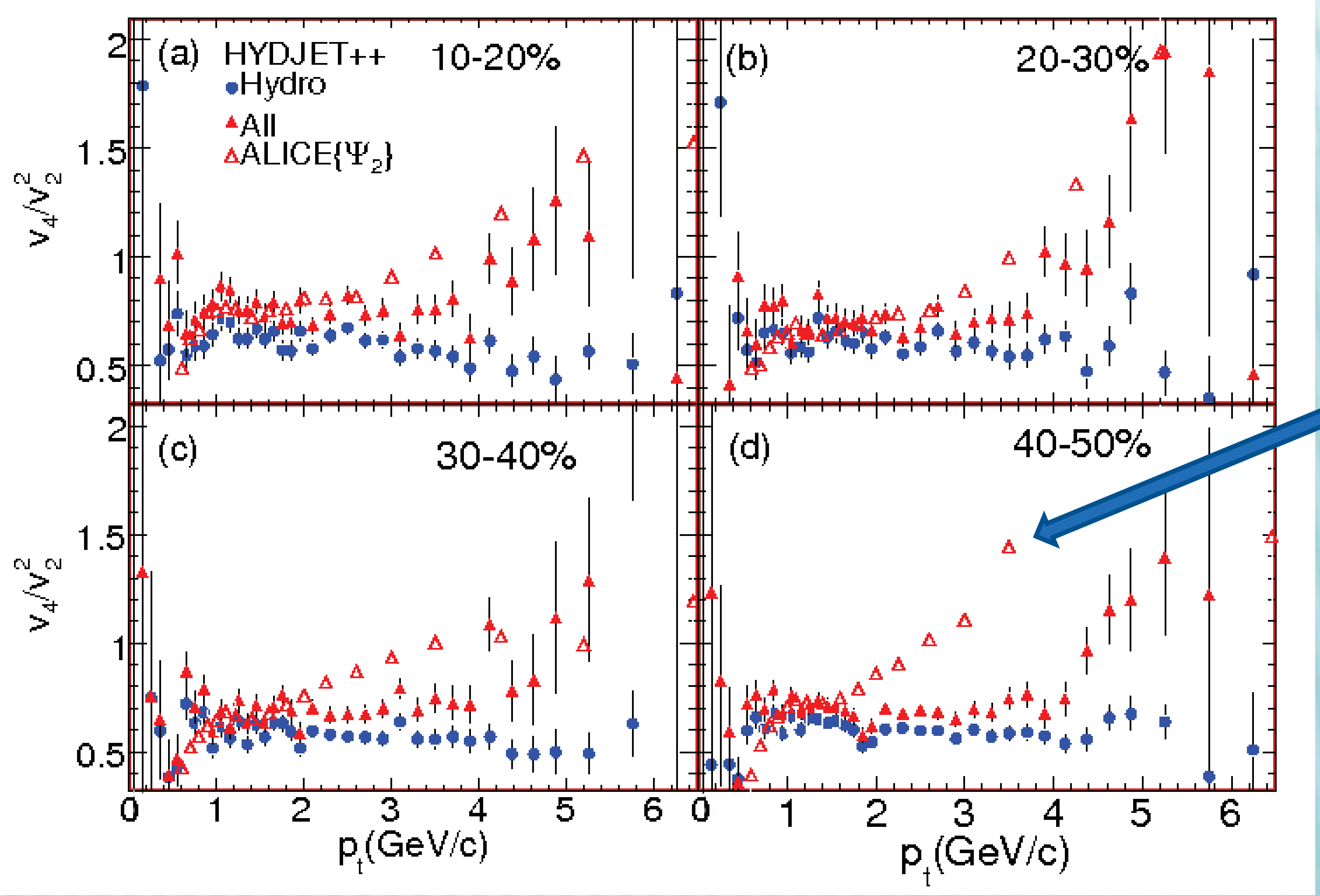
L.B. et al., PRC 80 (2013) 064907

HYDJET++ RESULTS FOR RHIC



Jets increase the ratio

HYDJET++ RESULTS FOR LHC



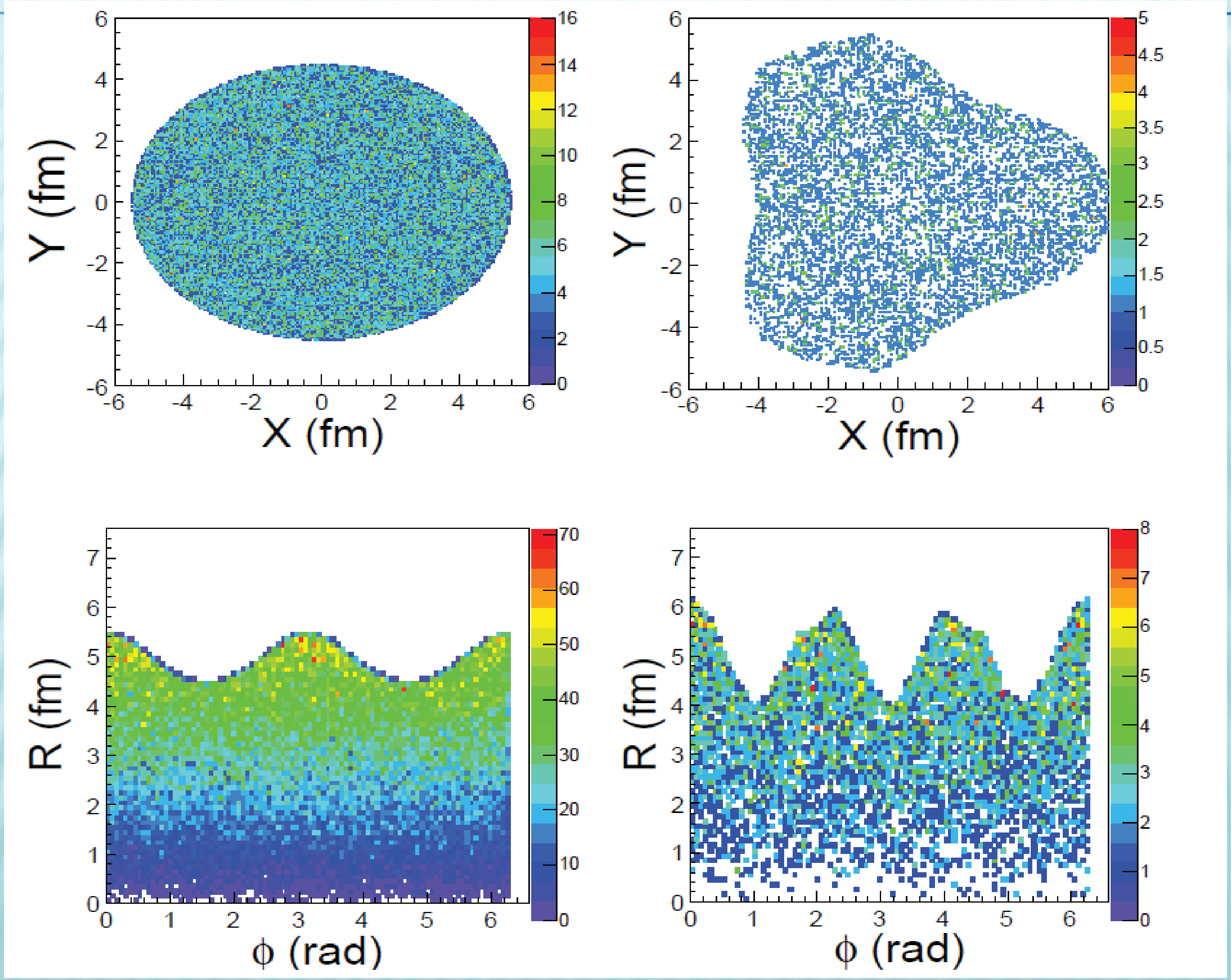
Jets !

The same tendency is observed in Pb+Pb at LHC

V. High harmonics

GENERATION OF TRIANGULAR FLOW

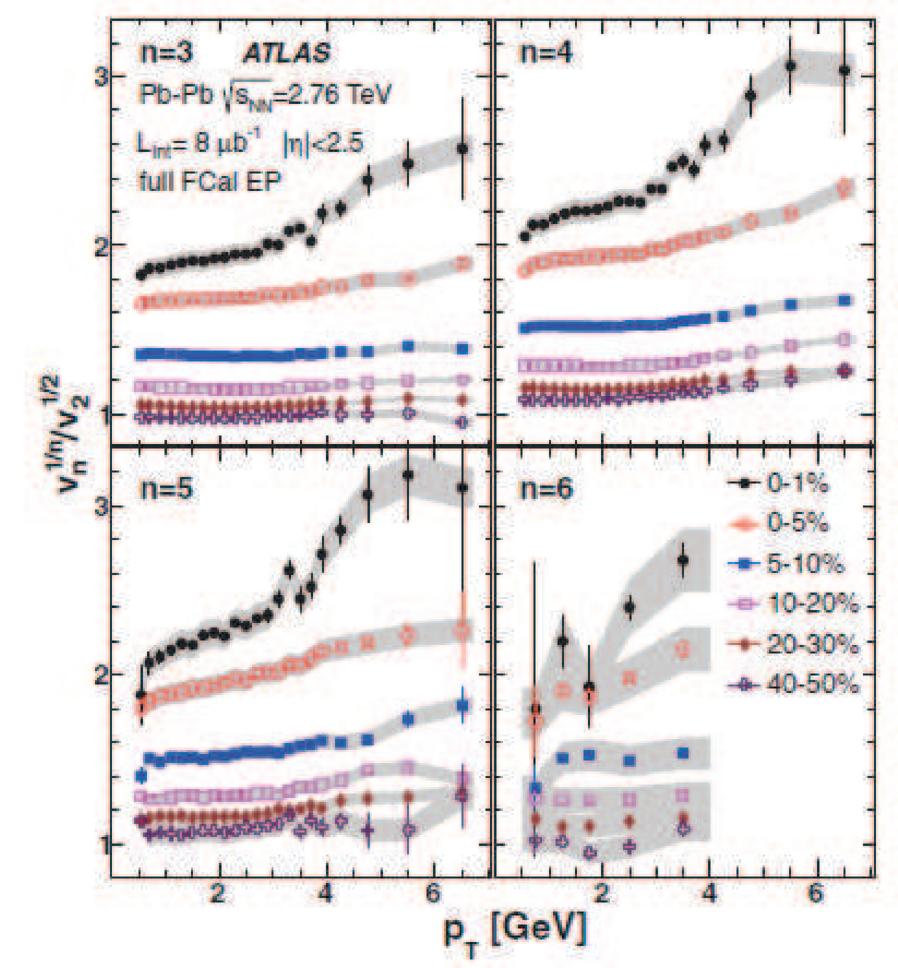
V2

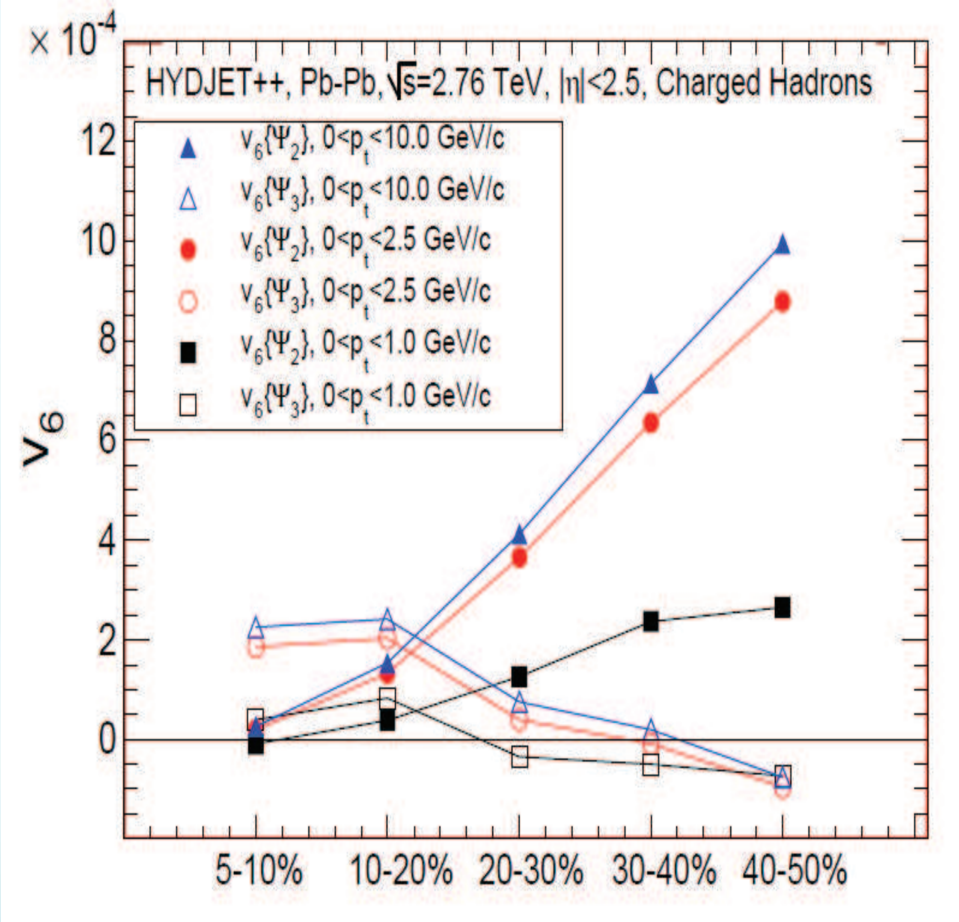


V3

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

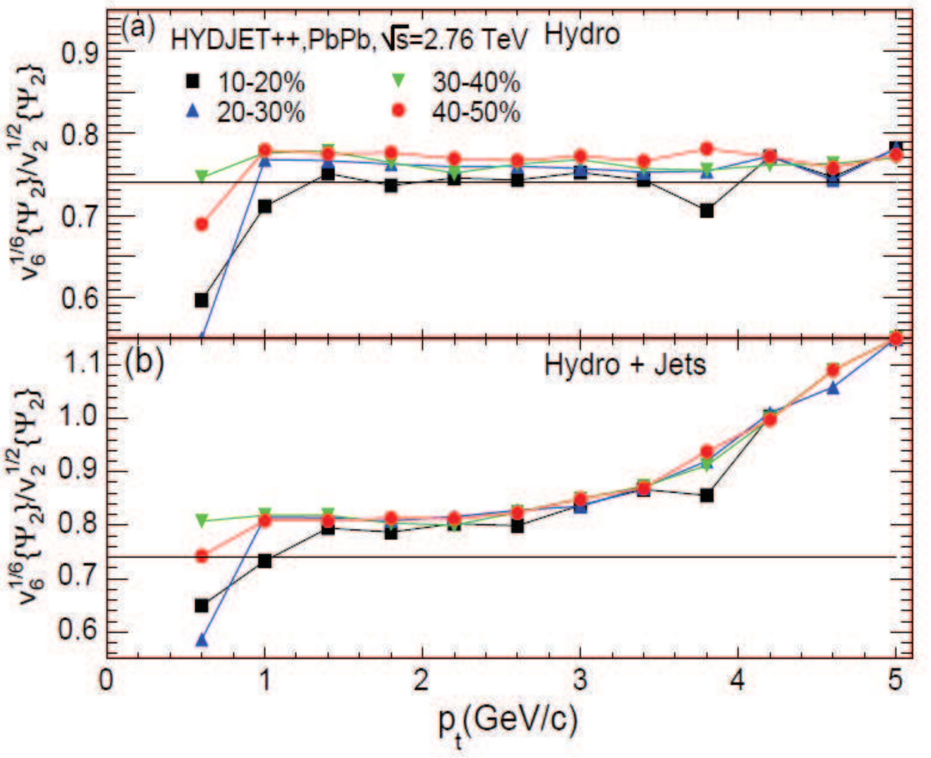
ATLAS, PRC 86 (2012) 014907



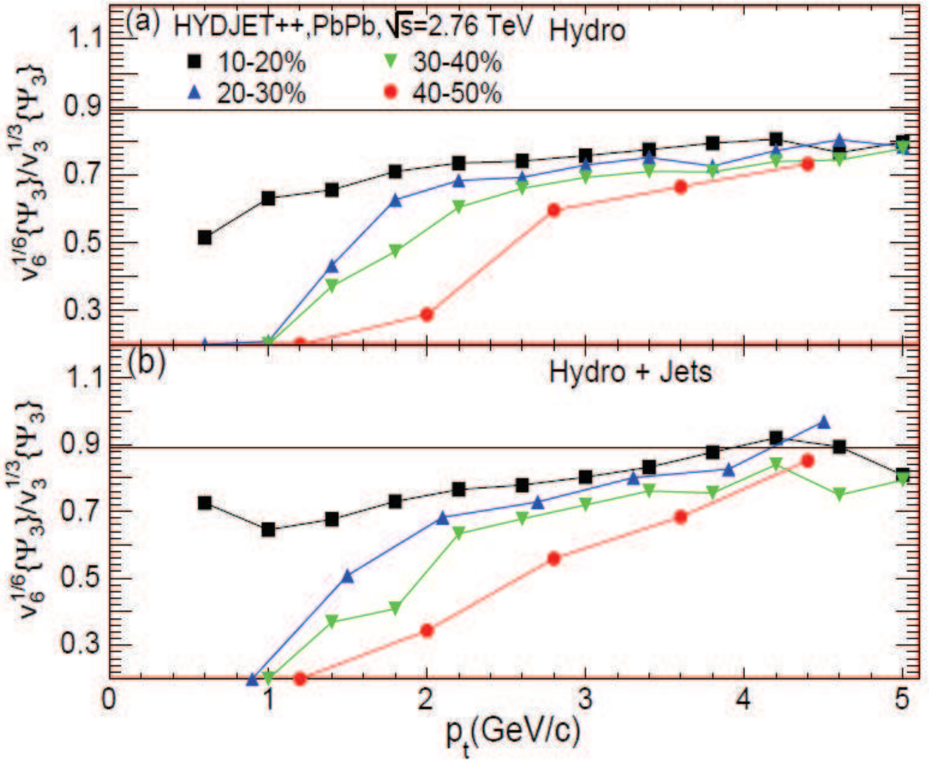


Higher order harmonics scaling

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



Ψ_2



Ψ_3

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

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.

- ***Jets result to increase by 25% - 30% of the ratio v4/(v2*v2)***
- ***Jets + eccentricity fluctuations are enough to explain both RHIC and LHC data***
- ***Jets lead to rise of the high-pT tail of the ratio***
- ***The predicted violation of the NCQ scaling at LHC is observed***
- ***Higher order harmonics – just interplay between hydrodynamics and jets ?***

Back-up Slides