HYDJET++: INTERPLAY BETWEEN SOFT AND HARD PHYSICS

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OUTLINE

I. HYDJET++ model (hydro + jets)

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

III. NCQ-scaling at RHIC and LHC

I. HYDJET++ = FASTMC + 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 Perugia 2011 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: $\mathbf{T_{ch}}$, $\{\mu_B, \mu_S, \mu_Q\}$

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

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

1. $\rho_u^{\max}$ -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 $\delta(b)$, $\varepsilon(b)$

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

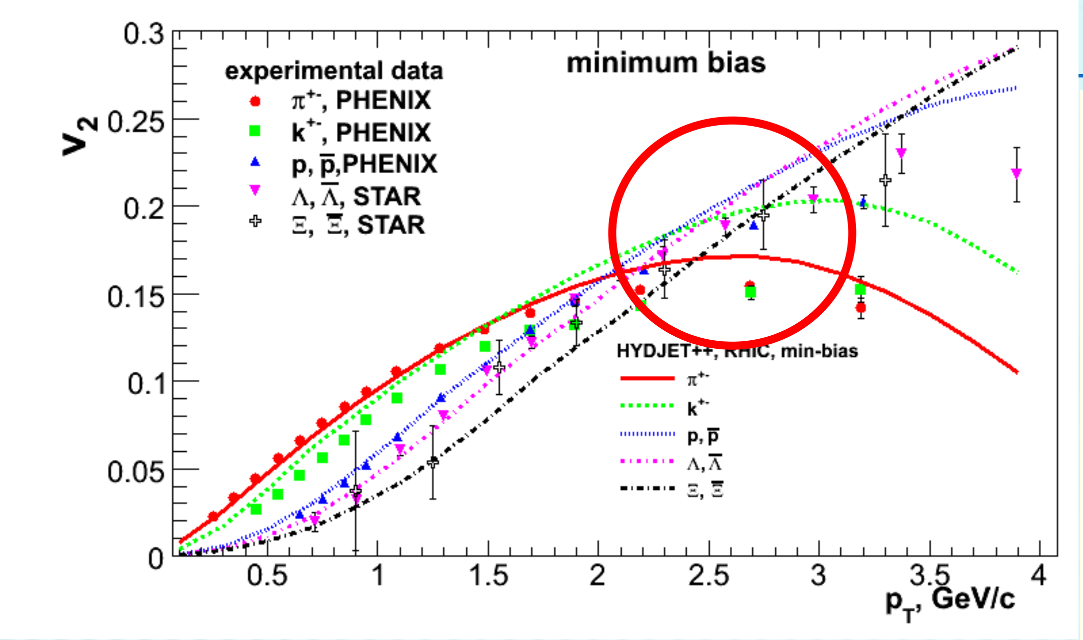
2. tau0 - proper time of quark-gluon plasma formation at LHC: tau0=0.1 fm/c, at RHIC(200 AGeV) tau0=0.4 fm/c

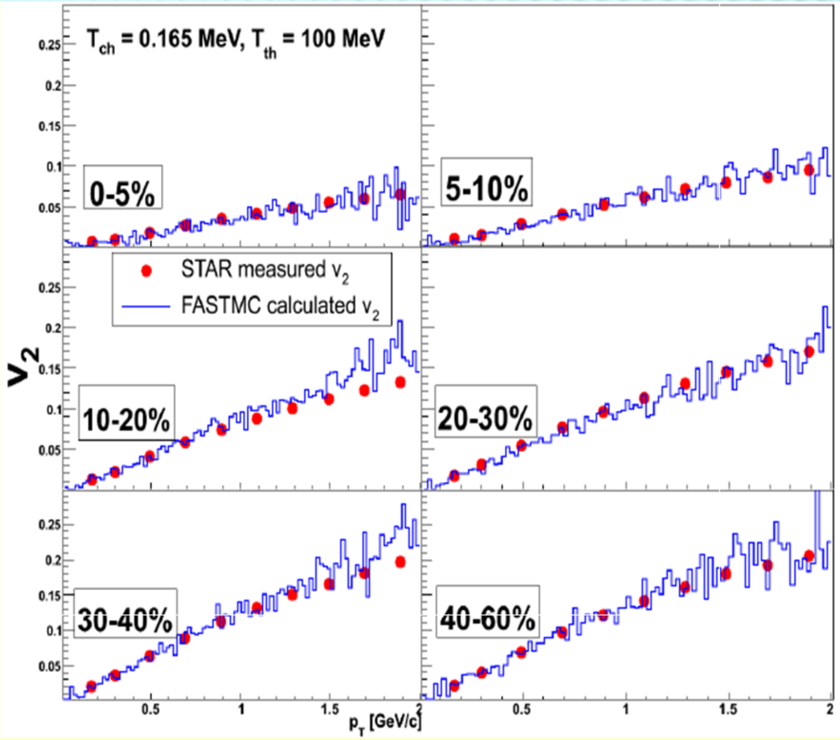
3. nf - number of active quark flavours in quark-gluon plasma (nf=0, 1, 2 or 3) at LHC: nf=0, at RHIC(200 AGeV) nf=2

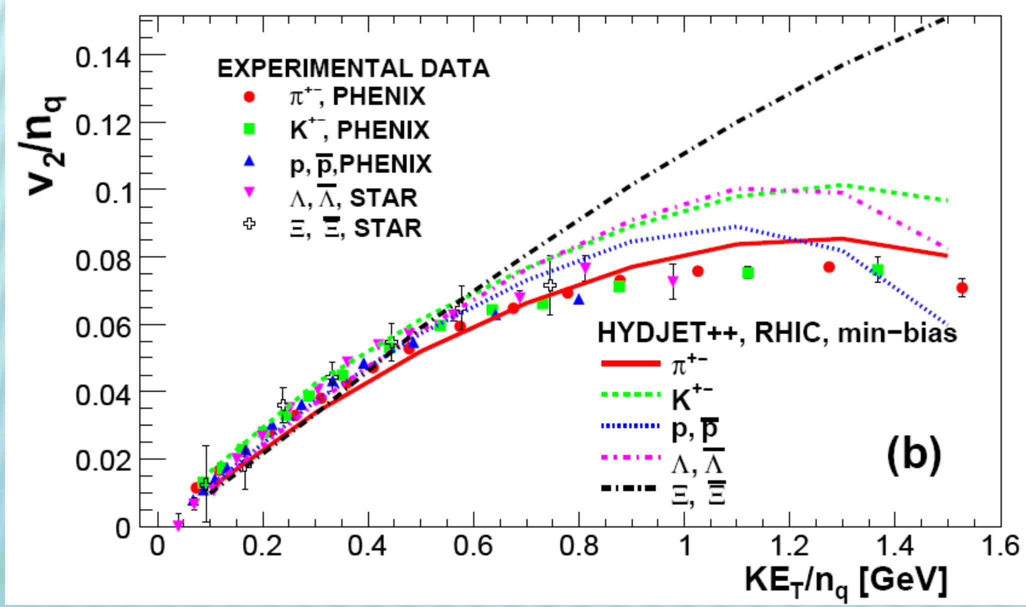
4. ienglu - flag to fix type of medium-induced partonic energy loss
   (ienglu=0 - radiative and collisional loss, ienglu=1 - radiative loss only, ienglu=2 - collisional loss only, default value is ienglu=0);
   ianglu - flag to fix type of angular distribution of emitted gluons
   (ianglu=0 - small-angular,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

RHIC DATA VS. HYDJET++ MODEL

Au+Au @ 200 AGeV



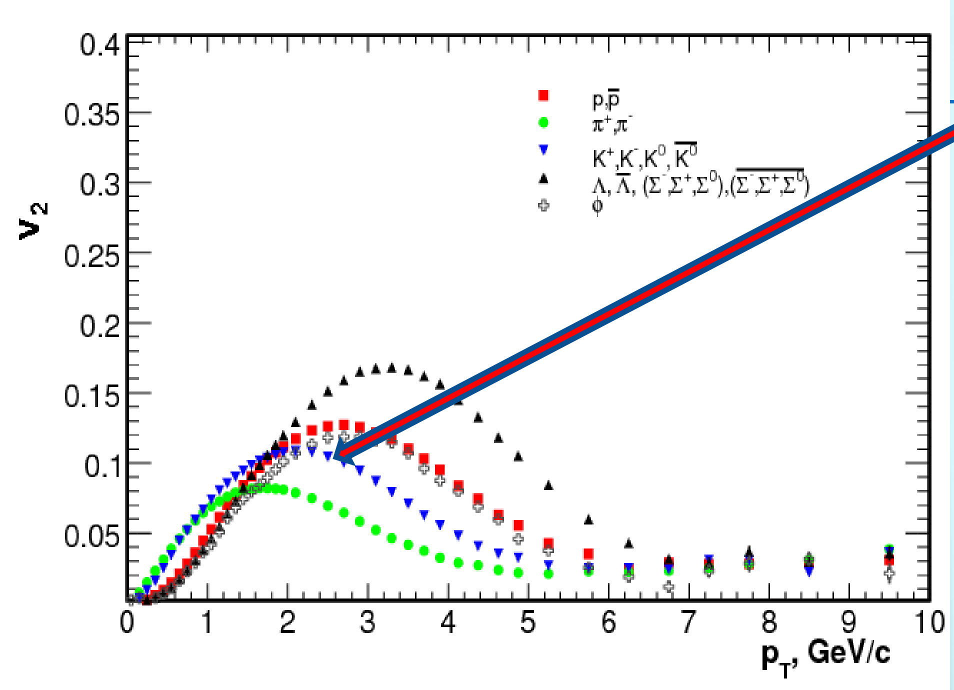




Elliptic flow

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%)



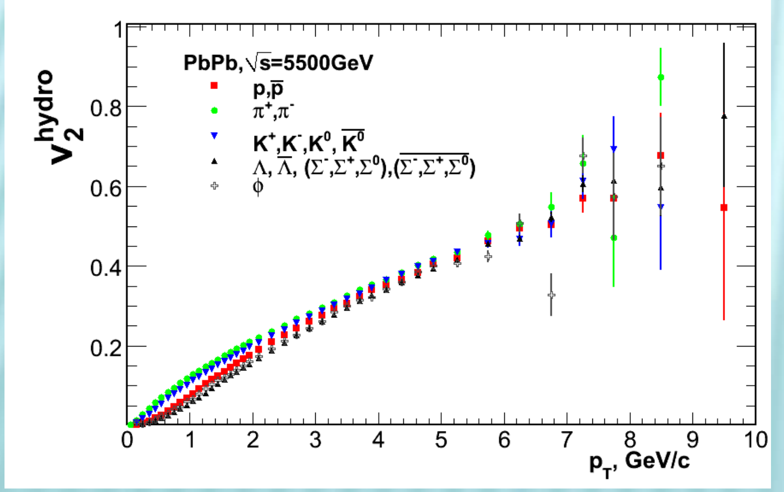
Mass ordering in soft p_T regions then breaks.

Why?

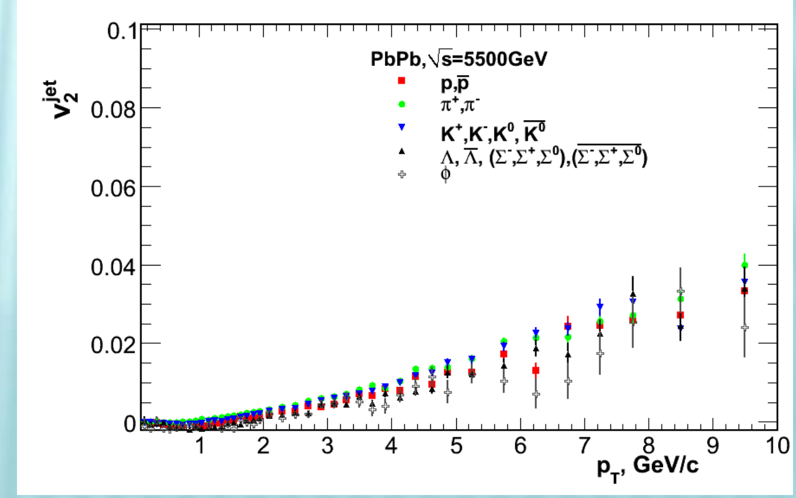
Hydrodynamics gives mass ordering of v2. The model possesses crossing of baryon and meson branches.

Interplay between hydrodynamics and jets

Hydrodynamics



Jet part +quenching

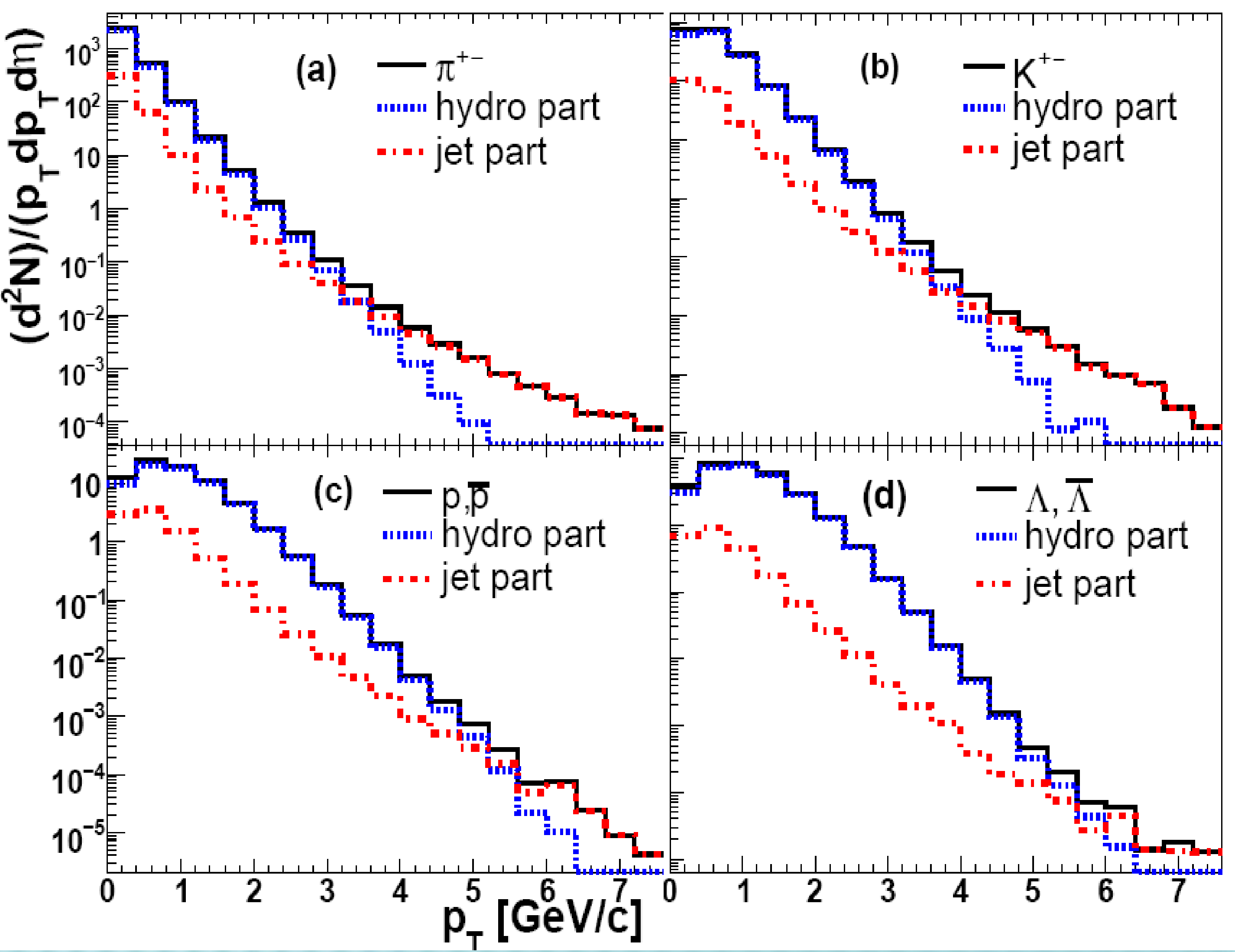


The p_T specta of π, K, p, Λ with HYDJET++ model, √s=200GeV

The slope for the hydro part depends strongly on mass:

- the heavier the particle -- the harder the spectrum

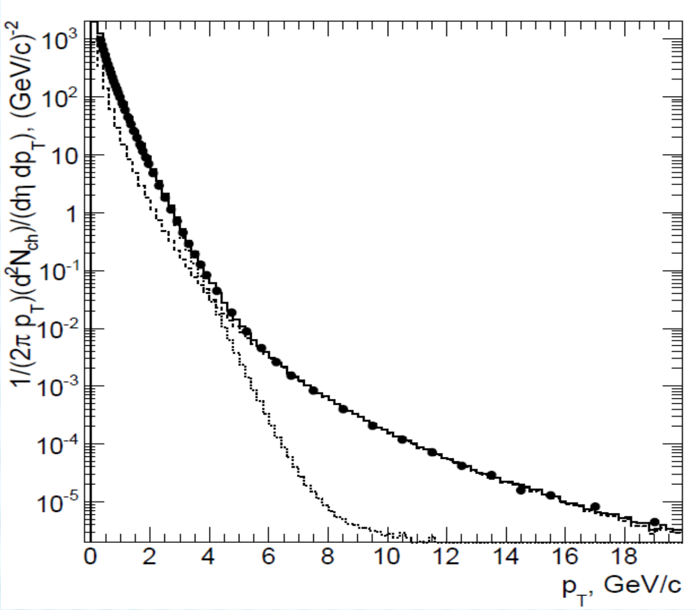
The hydro part dies out earlier for light particles than for heavy ones



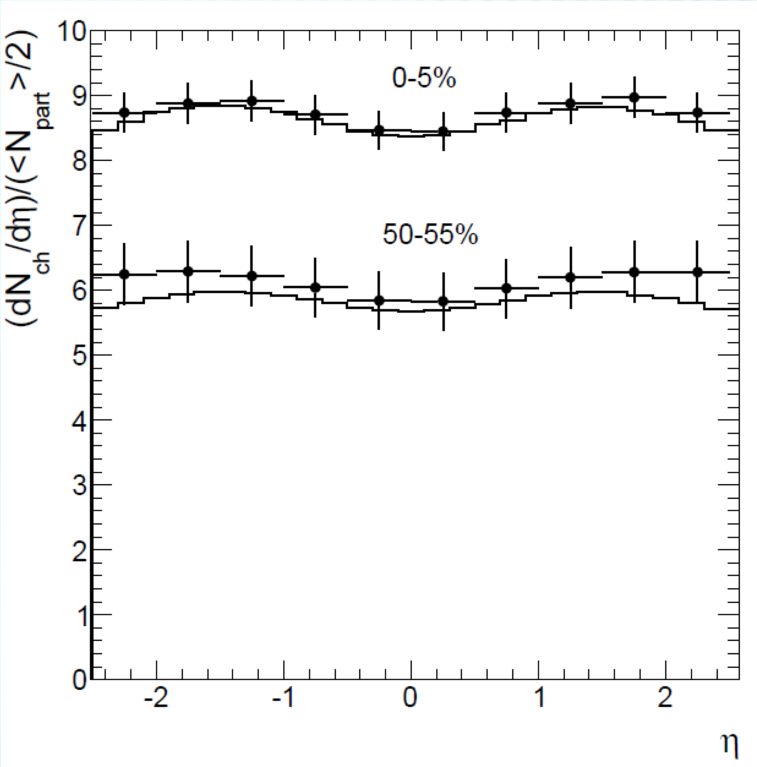
LHC DATA VS. HYDJET++ MODEL

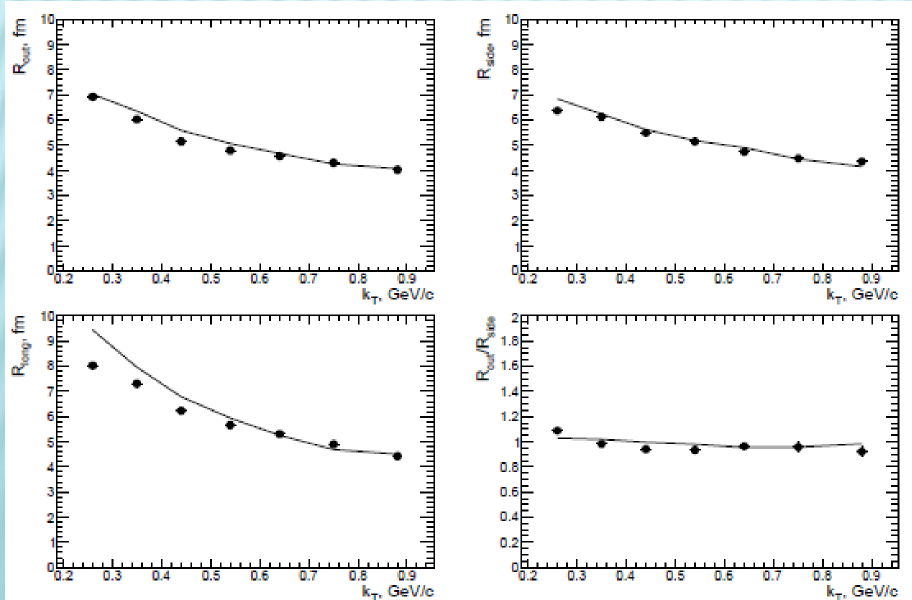
Transverse momentum

Pb+Pb @ 2.76 ATeV



Rapidity





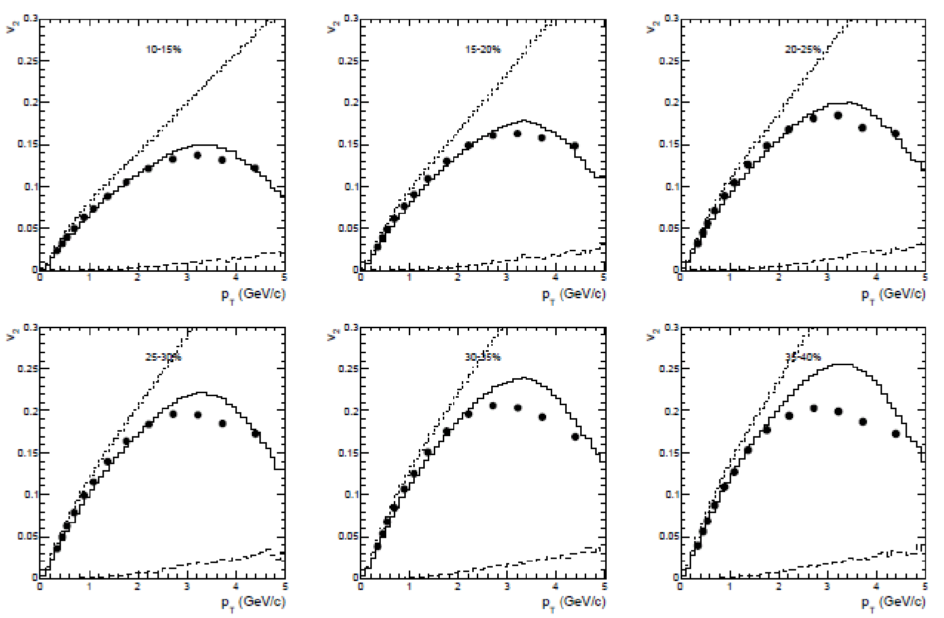
Correlation radii (femtoscopy)

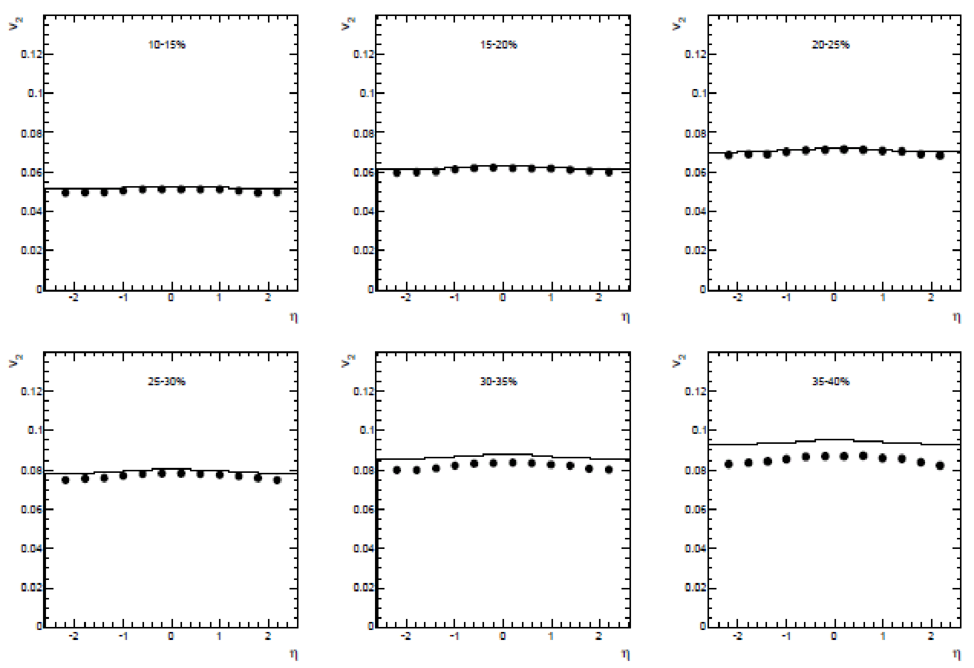
I. Lokhtin et al., arXiv:1204.4820

LHC DATA VS. HYDJET++ MODEL

Pb+Pb @ 2.76 ATeV

Elliptic flow





I. Lokhtin et al., arXiv:1204.4820

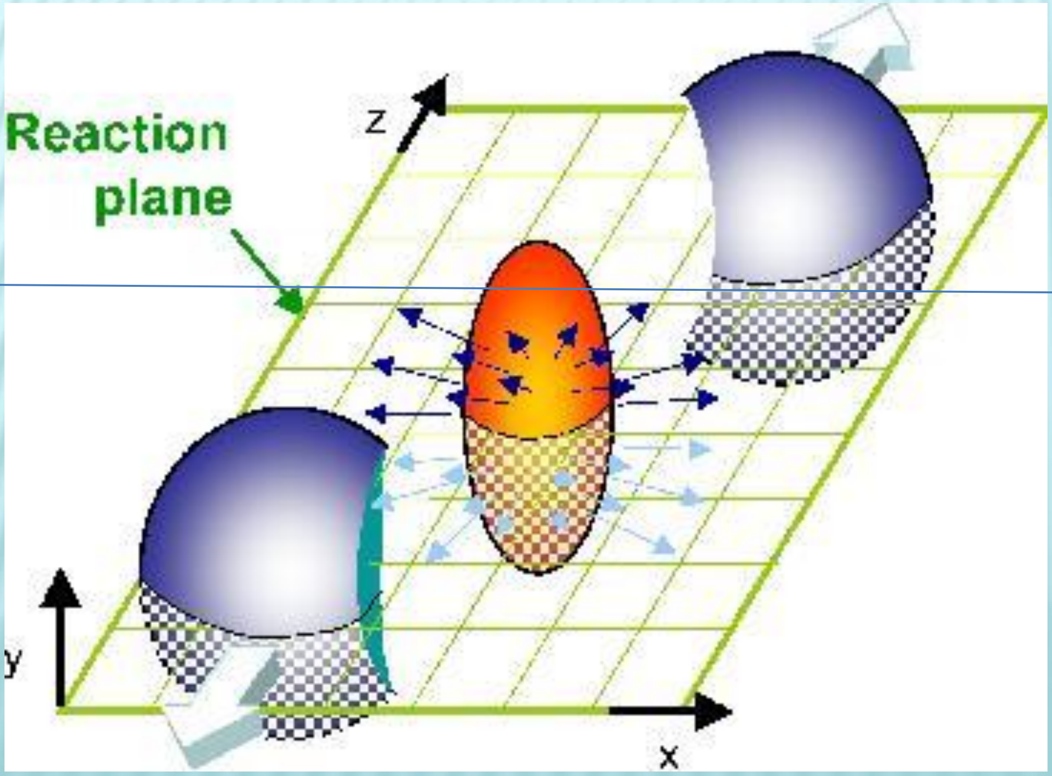
Model gives a fair description of various observables at both RHIC and LHC

II. V4/(V2*V2) RATIO

II. *v4/(v2)*^{2} ratio

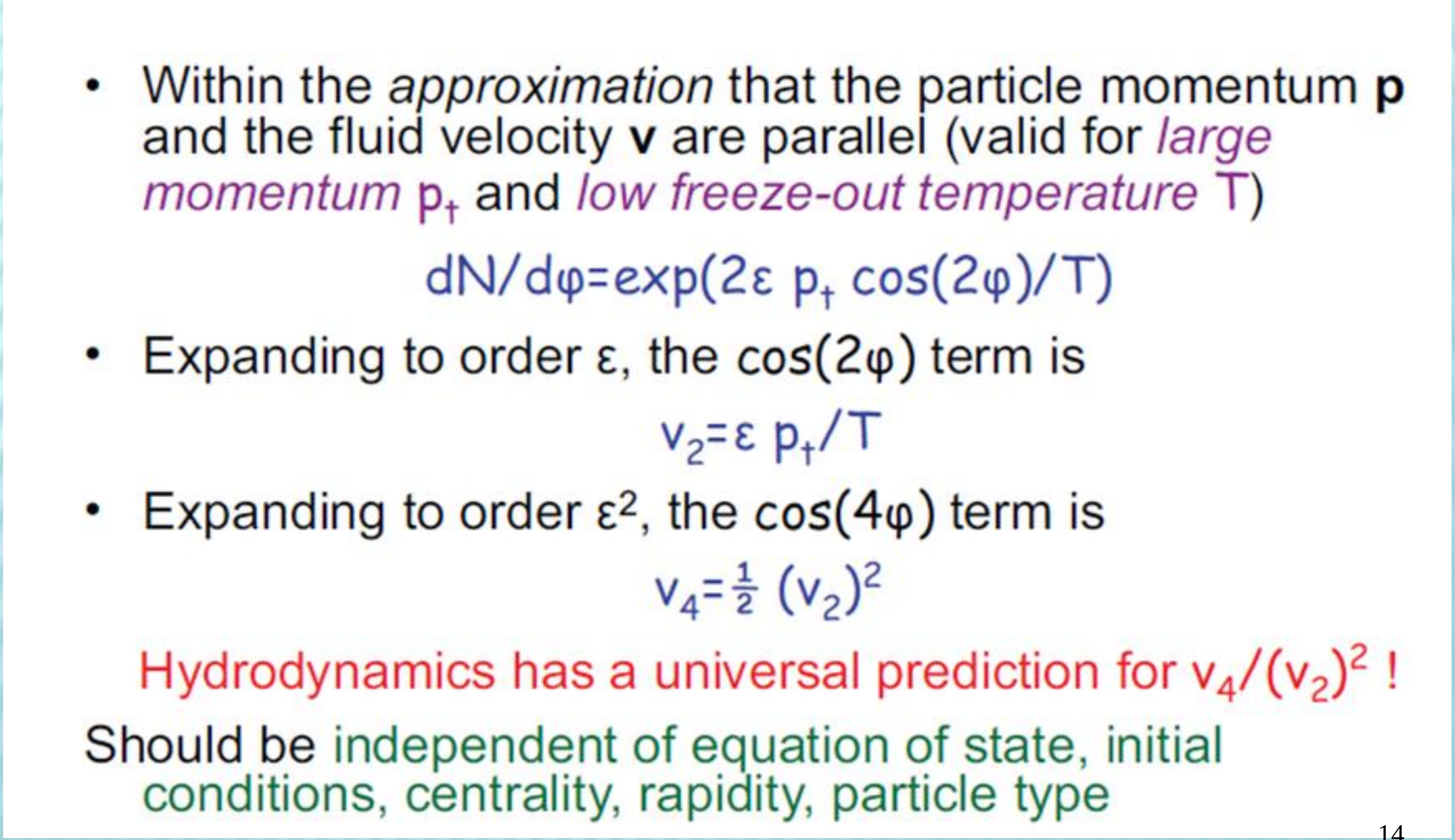
Anisotropic flow

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



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 $\cos(2\varphi)$ term is

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

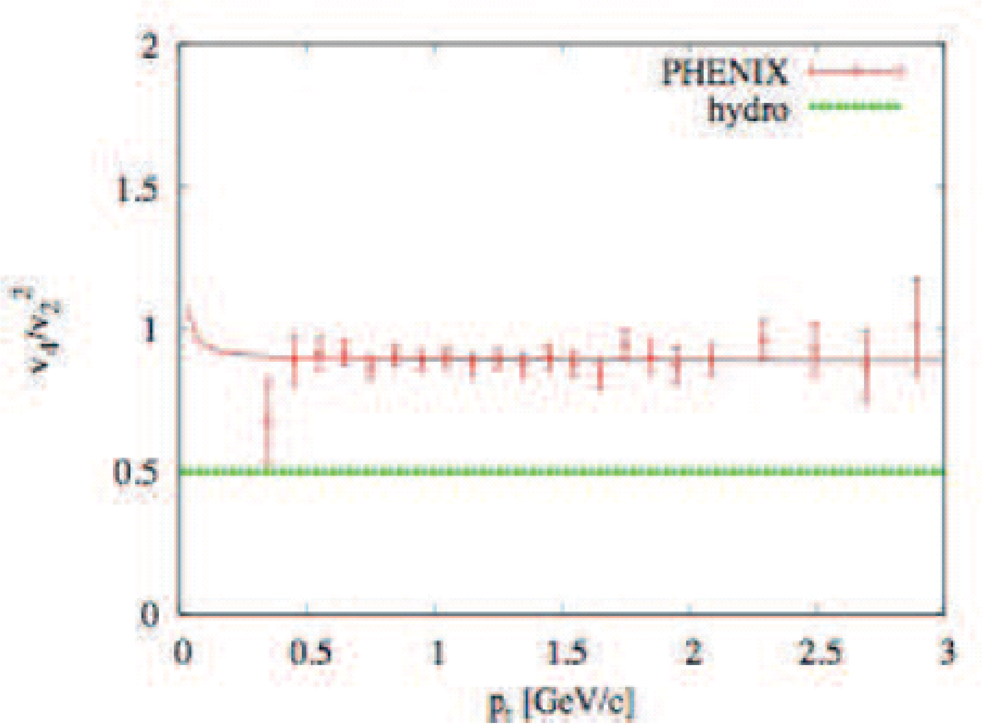
- Expanding to order ε^2, the $\cos(4\varphi)$ term is

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

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

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

Comparison with data



PHENIX data for charged pions

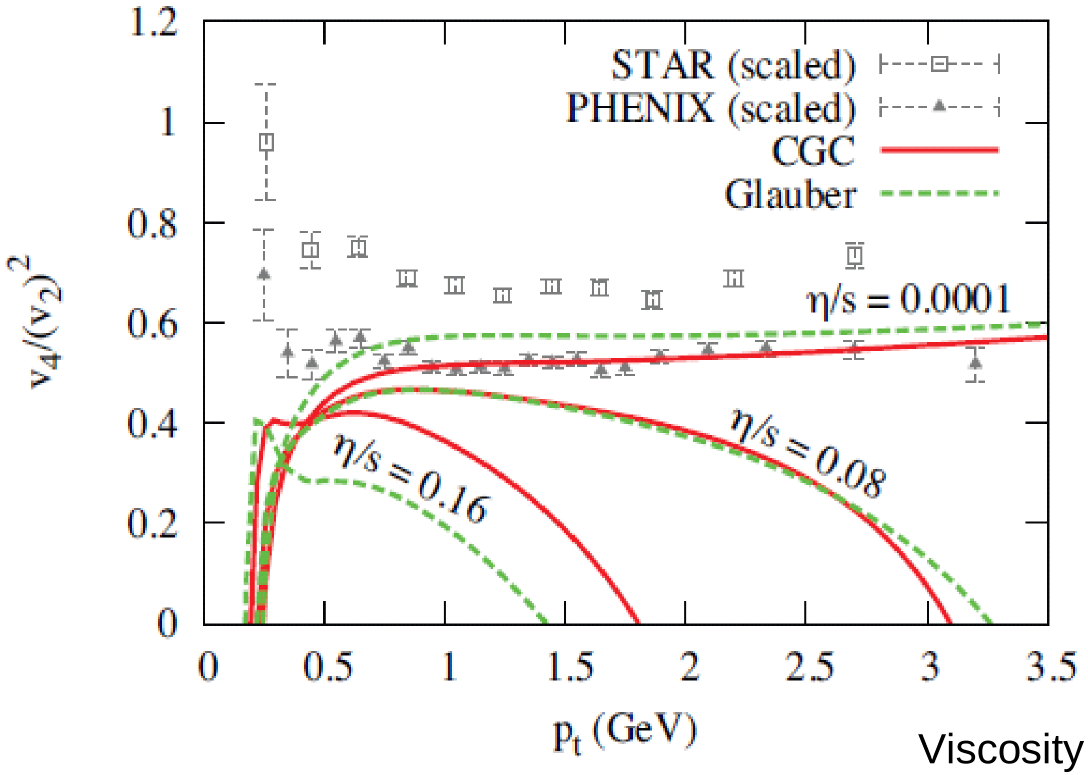
Au-Au collisions at 100+100 GeV

20-60% most central

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

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

Effects of initial profile and viscosity

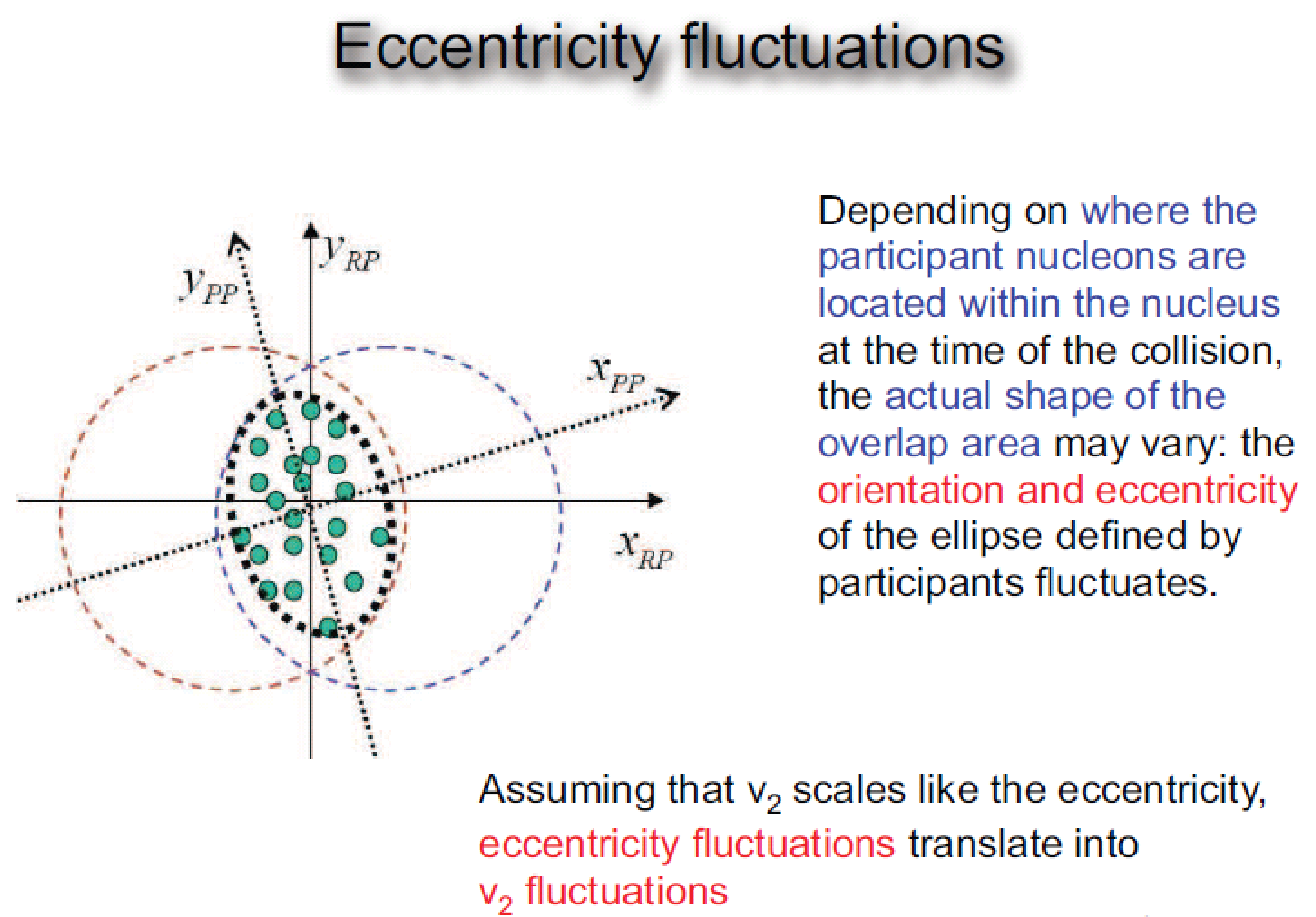


Initial profile has little effect although eccentricities differ.

results strongly depend on viscosity

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

M. Luzum, C. Gombeaud, J.-Y. Ollitrault, Phys.Rev.C81:054910,2010.



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

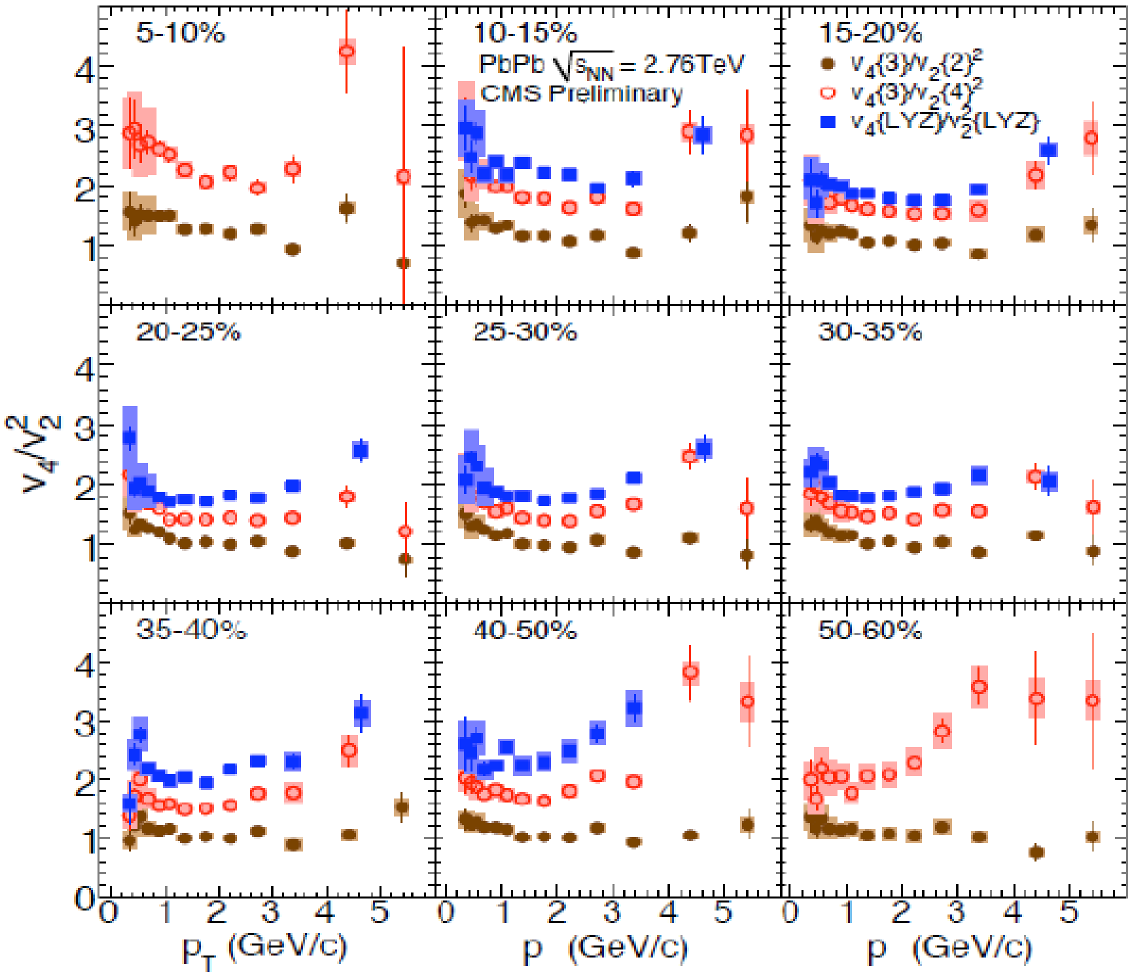
$$\frac{v_4}{v_2^2} = \frac{\langle v_4 (v_2)^2 \rangle}{\langle (v_2)^2 \rangle^2} = \frac{1}{2}\frac{\langle (v_2)^4 \rangle}{\langle (v_2)^2 \rangle^2} > \frac{1}{2}$$

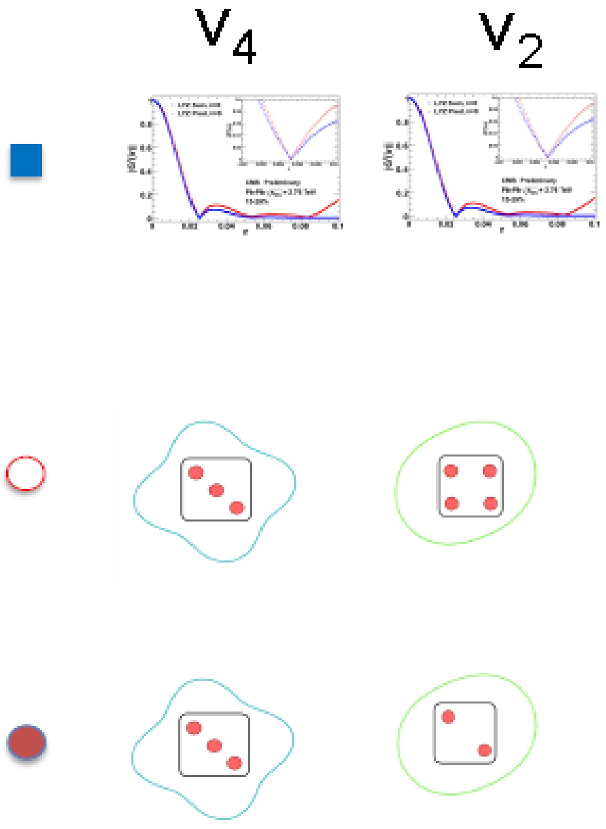
fluctuations

hydro

Similar results obtained using Event Plane method

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

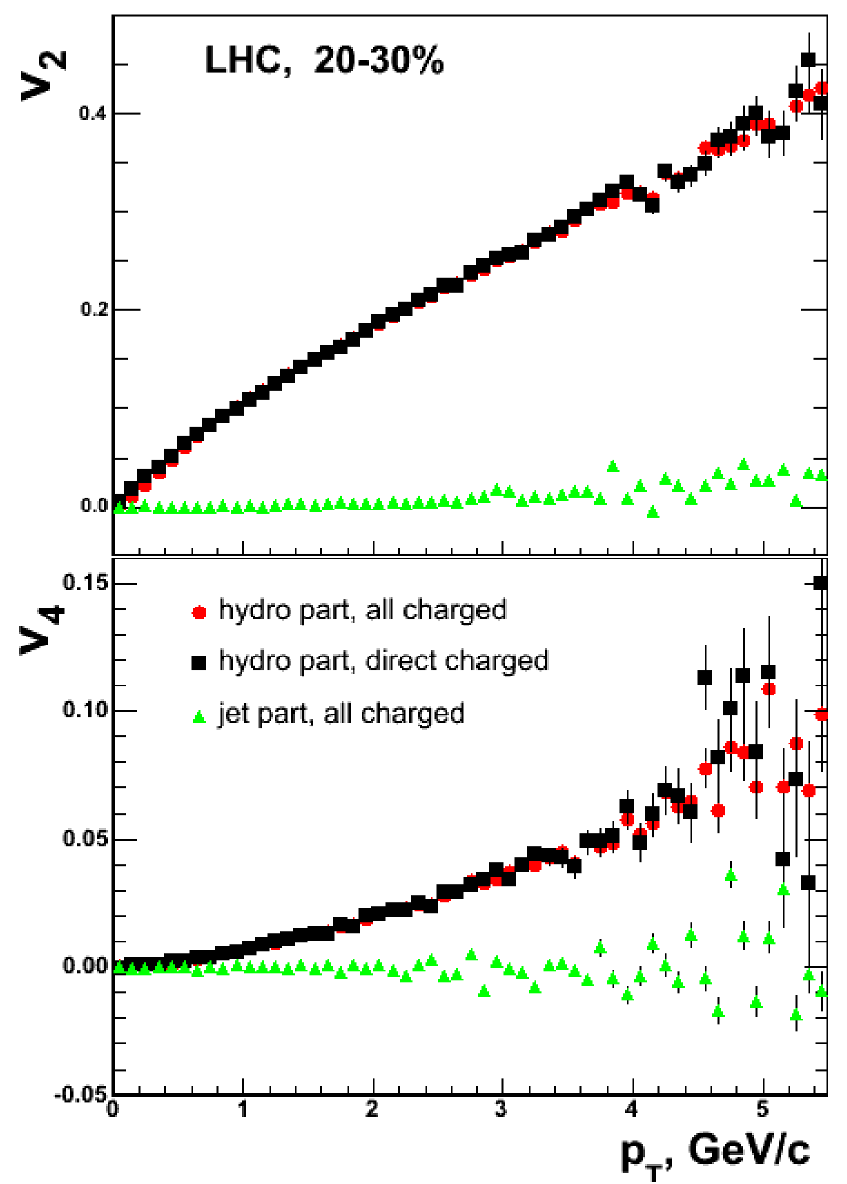


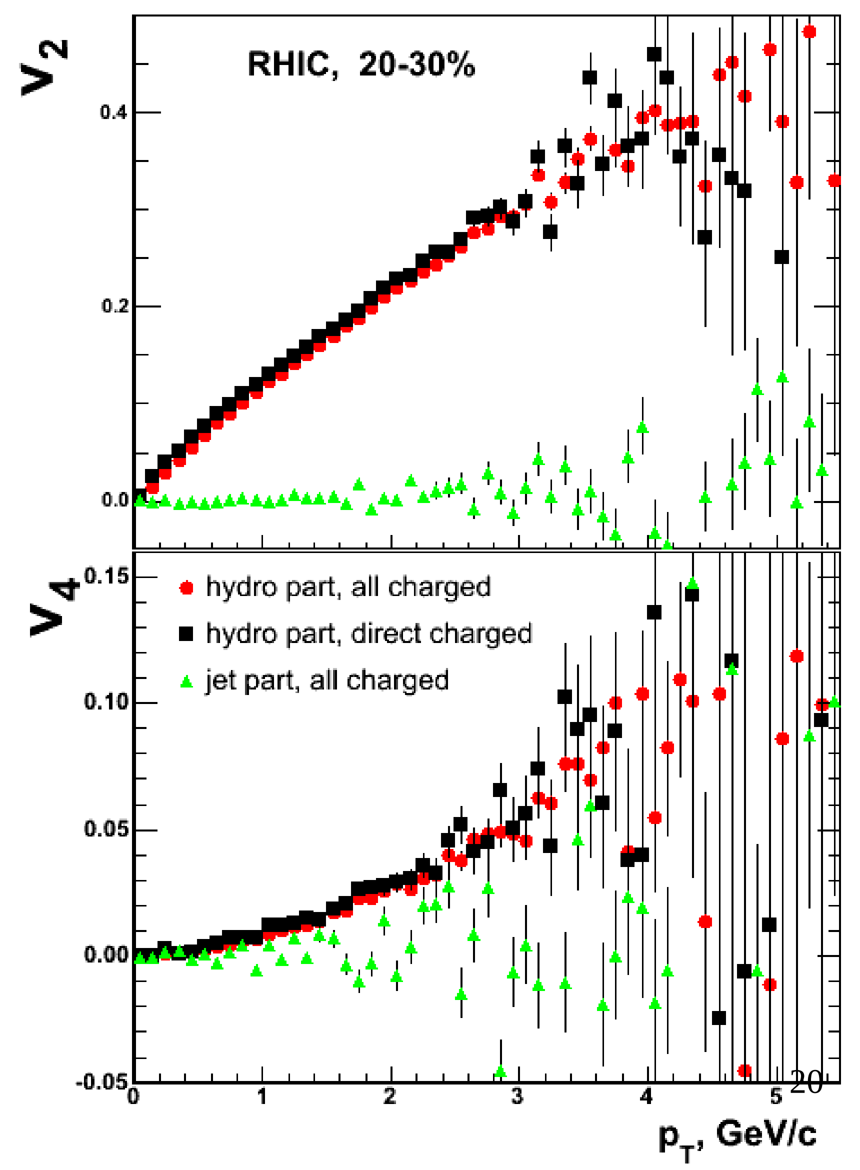


Significantly higher than RHIC: experimental method dependent

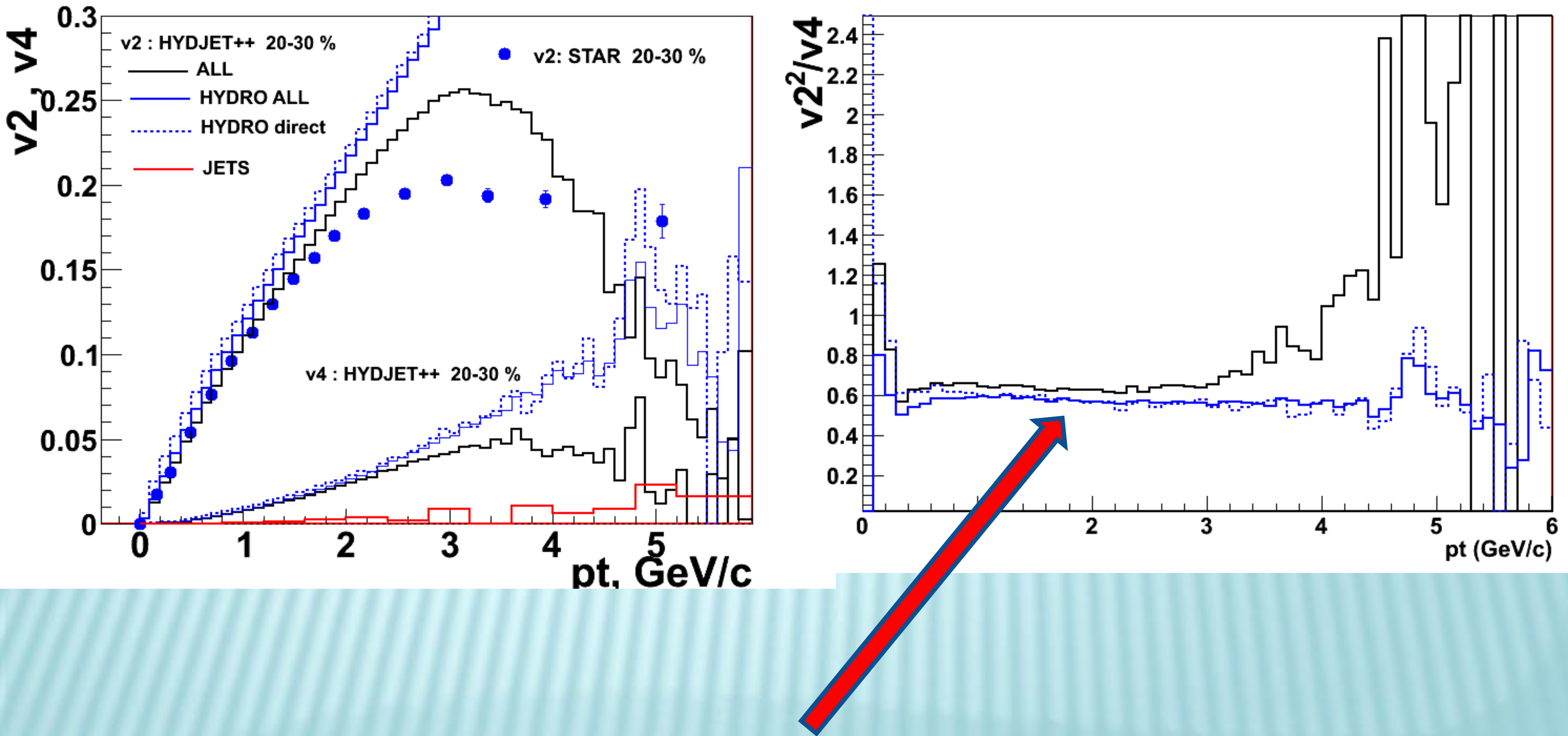
HYDJET++

Effects to be studied: resonance decay and hard part influence



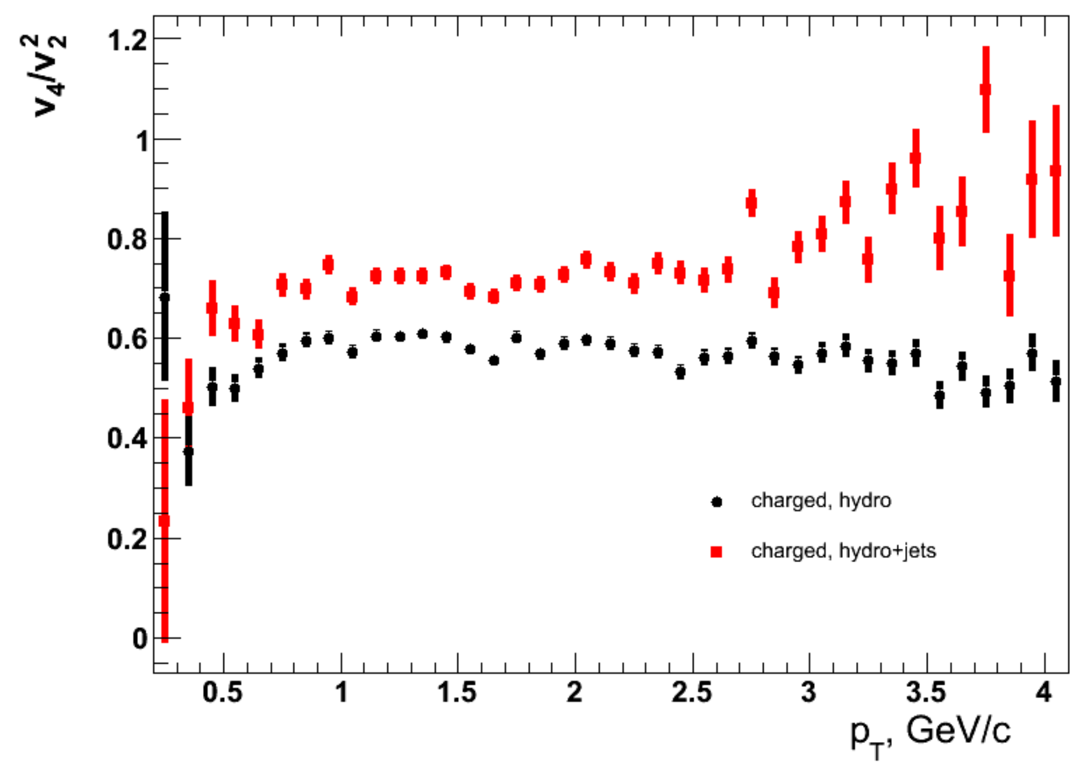


HYDJET++ RESULTS FOR RHIC

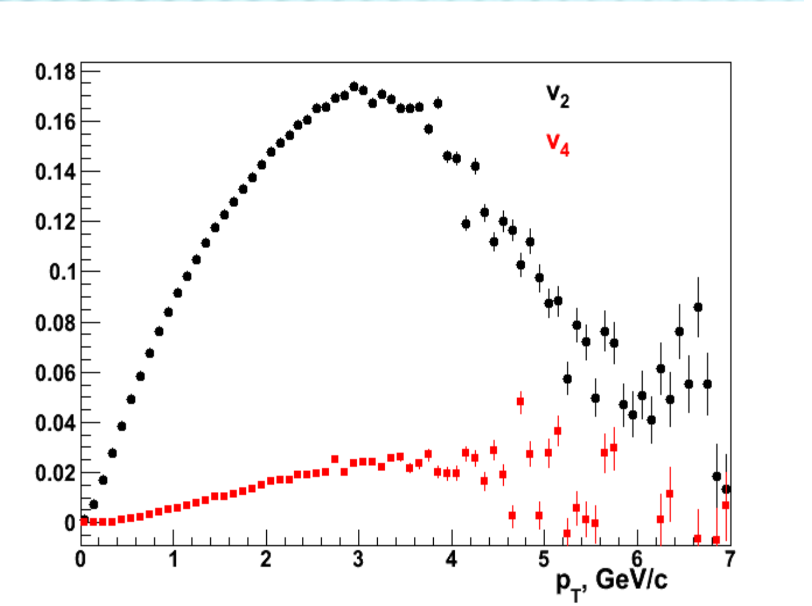


Jets increase the ratio

HYDJET++ RESULTS FOR LHC

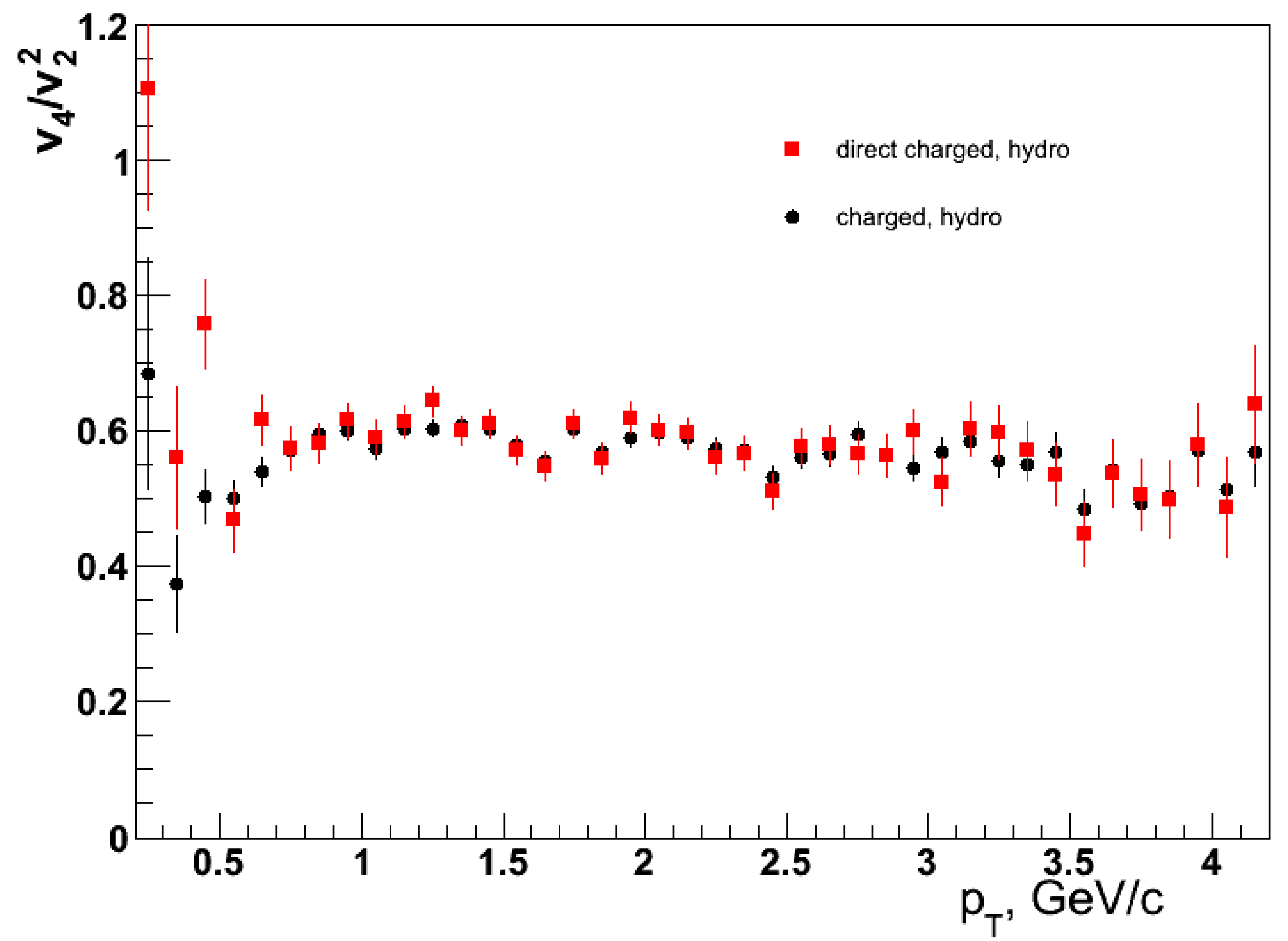


The same tendency is observed in Pb+Pb at LHC



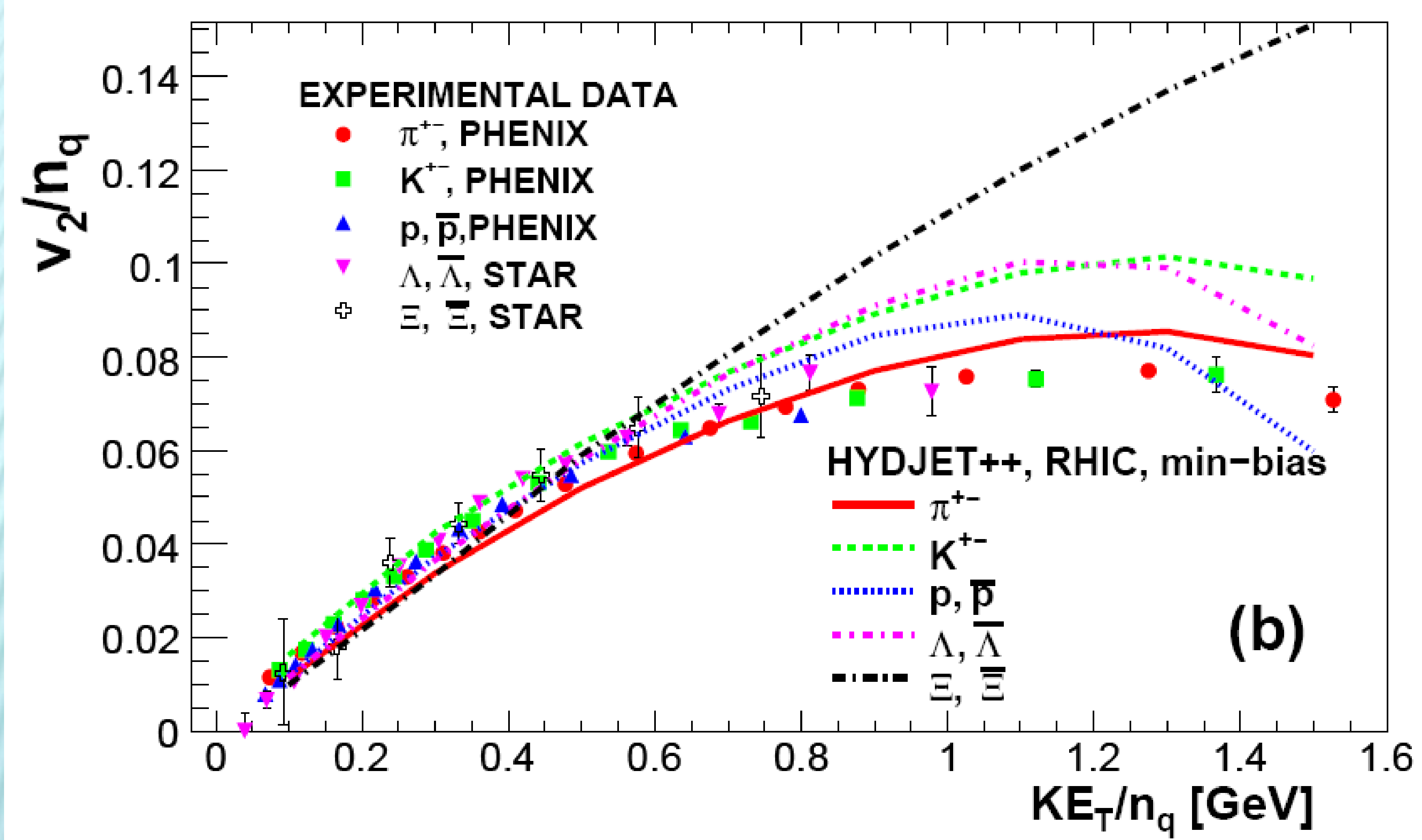
Still, the ratio is below 1

DECAYS OF RESONANCES PLAY MINOR ROLE



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

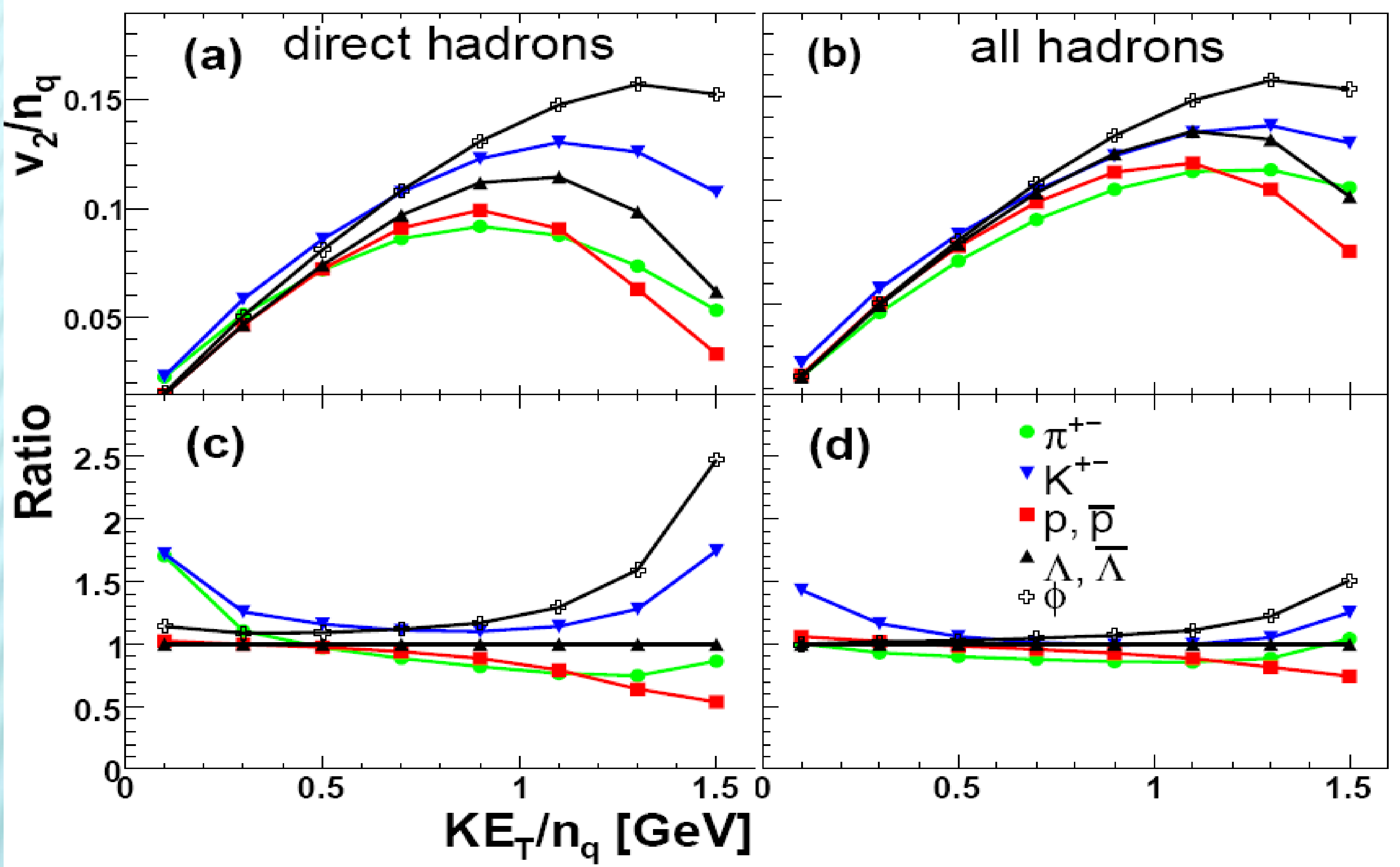
COMPARISON WITH RHIC DATA



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

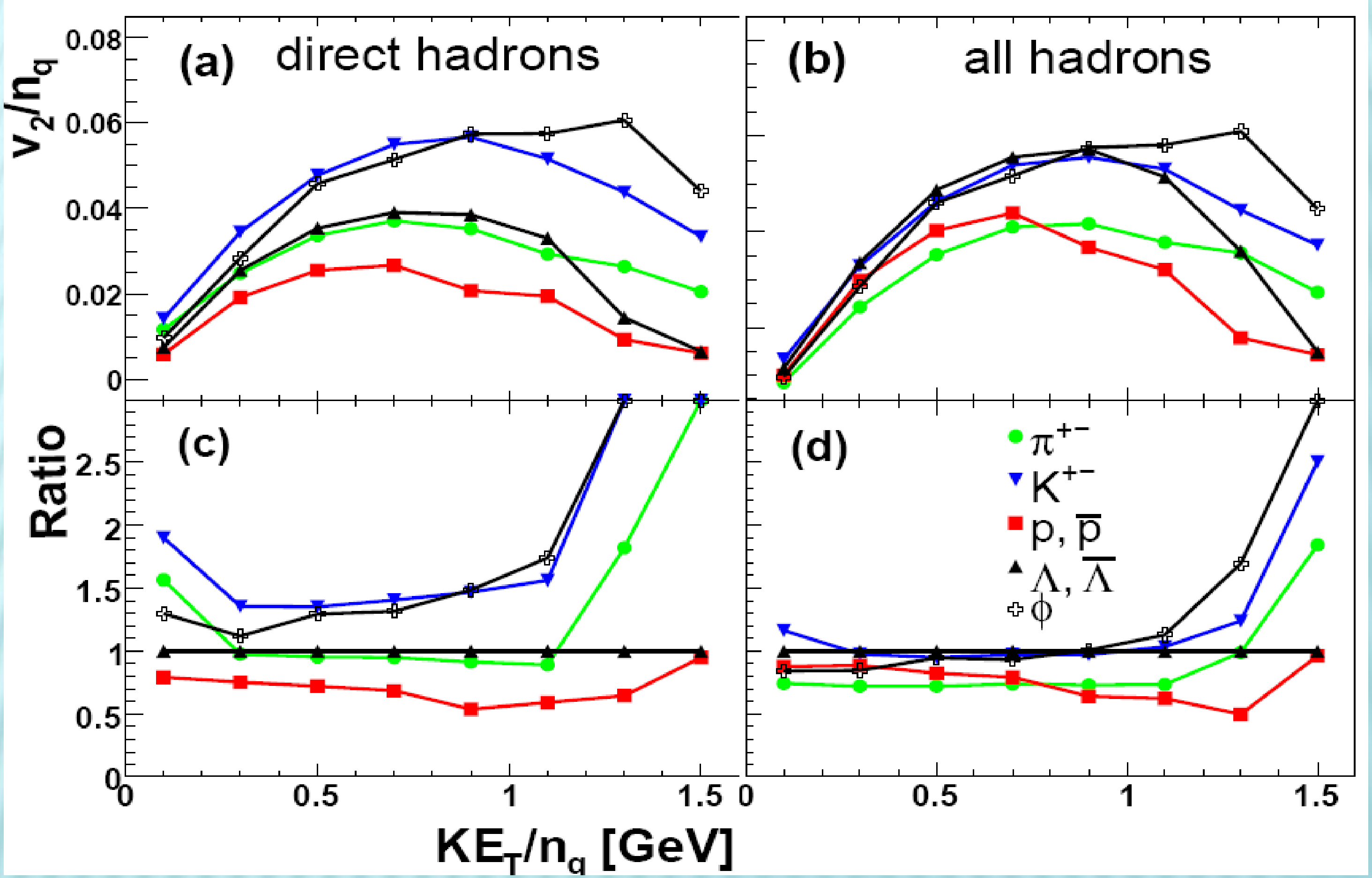


One of the explanations of KE_T/n_q scaling is partonic origin of the elliptic flow. ***However, final state effects (such as resonance decays and jets) may also lead to appearance of the scaling***

NCQ scaling at LHC

No scaling for
direct particles

Appearance of the approximate
scaling for all particles

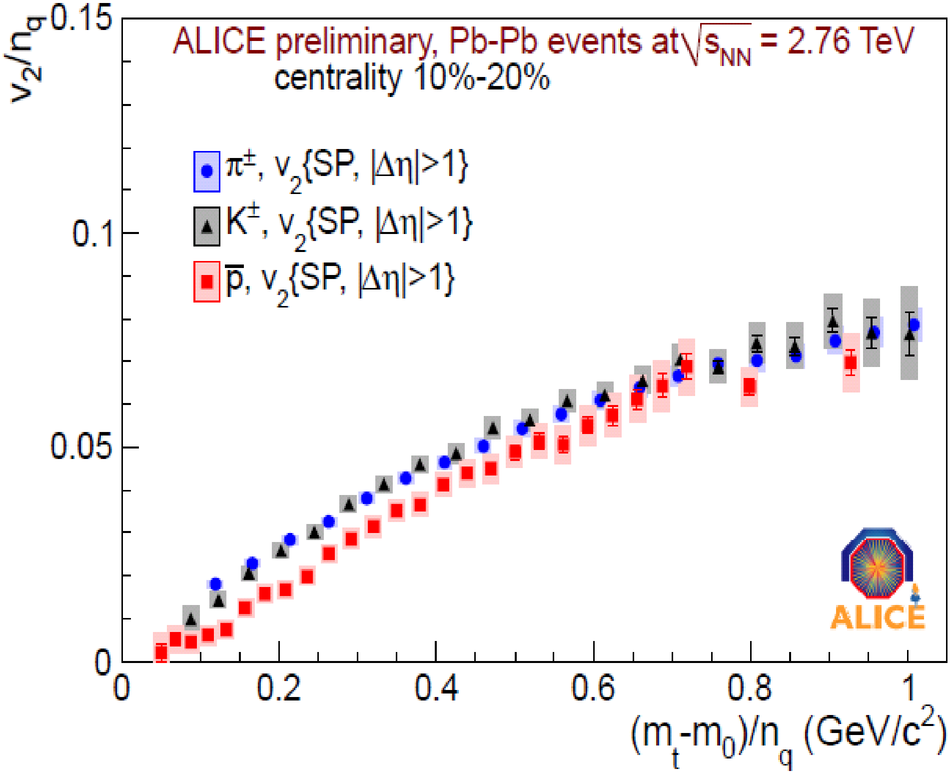


LHC: NCQ scaling will be only approximate (prediction, 2009)

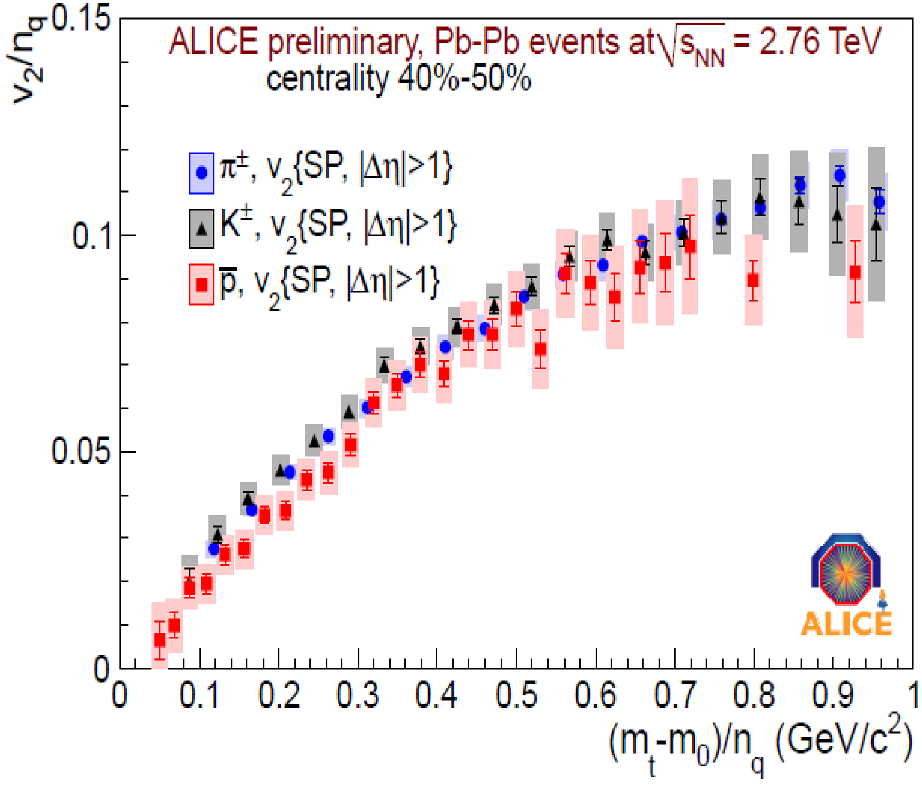
Experimental results (LHC)

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

Semi-sentral collisions



Semi-peripheral collisions



The NCQ scaling is indeed only approximate (2011)

CONCLUSIONS

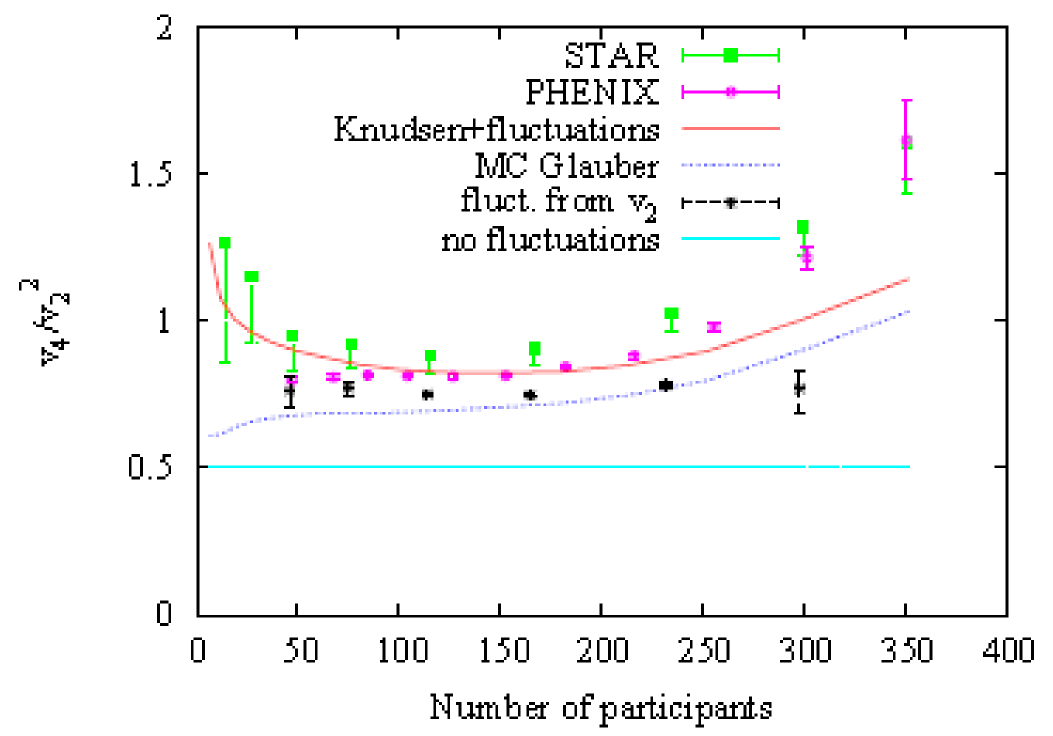
The HYDJET++ model allows to investigate flow of hydro and jet parts separately, to look at reconstruction of pure hydro flow and its modification due to jet part.

- ***Jets result to increase by 25% - 30% of the ratio v4/(v2*v2)***
- ***Eccentricity fluctuations can increase the ratio by factor 1.5***
- ***Jets + eccentricity fluctuations are enough to explain RHIC data***
- ***For LHC we can explain 75% of the signal. Other effects are needed***
- ***The predicted violation of the NCQ scaling at LHC is observed***

Back-up Slides

Effects of flow fluctuations and partial thermalization

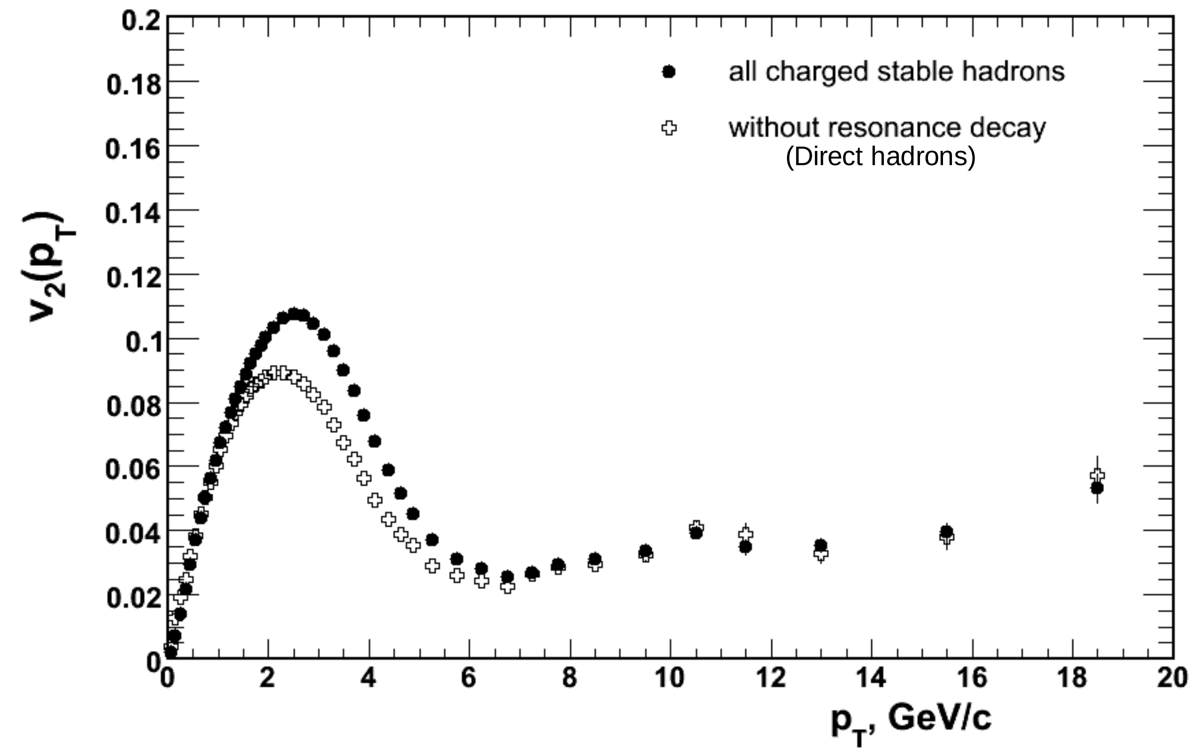
M. Luzum, C. Gombeaud, J.-Y. Ollitrault, Phys.Rev.C81:054910,2010.



Stars: with fluctuations inferred from
the difference between v2{2} and v2{LYZ}.
Dotted line: eccentricity fluctuations from a Monte-Carlo Glauber

Ⅲ． INFLUENCE OF RESONANCE DECAYS

Influence of resonance decay on v2 value



PbPb collisions, c=30%

The elliptic flow of directly produced particles is smaller than that for all particles.

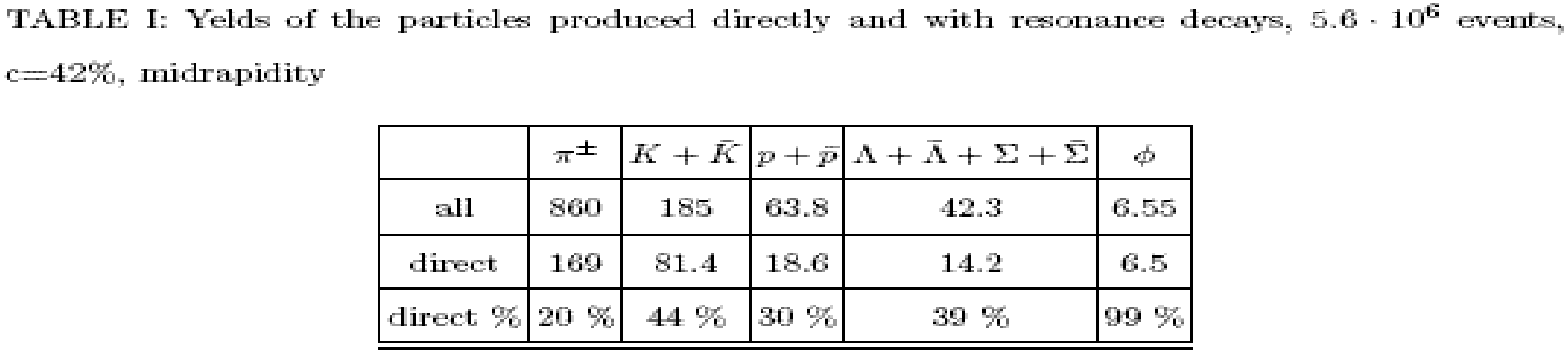
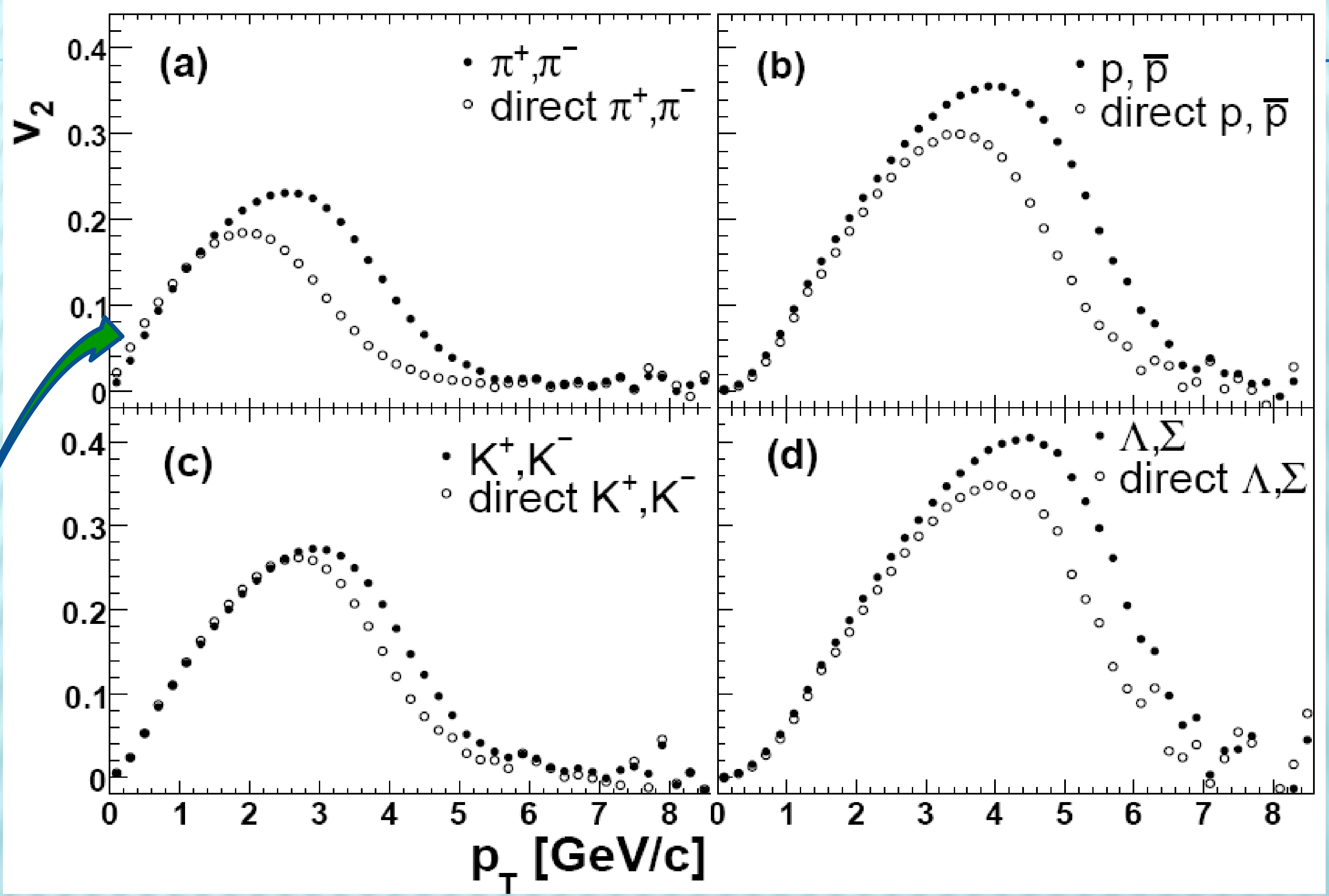


TABLE I: Yelds of the particles produced directly and with resonance decays, $5.6 \cdot 10^6$ events, c=42%, midrapidity

	$\pi^{\pm}$	$K+\bar{K}$	$p+\bar{p}$	$\Lambda+\bar{\Lambda}+\Sigma+\bar{\Sigma}$	ϕ
all	860	185	63.8	42.3	6.55
direct	169	81.4	18.6	14.2	6.5
direct %	20 %	44 %	30 %	39 %	99 %

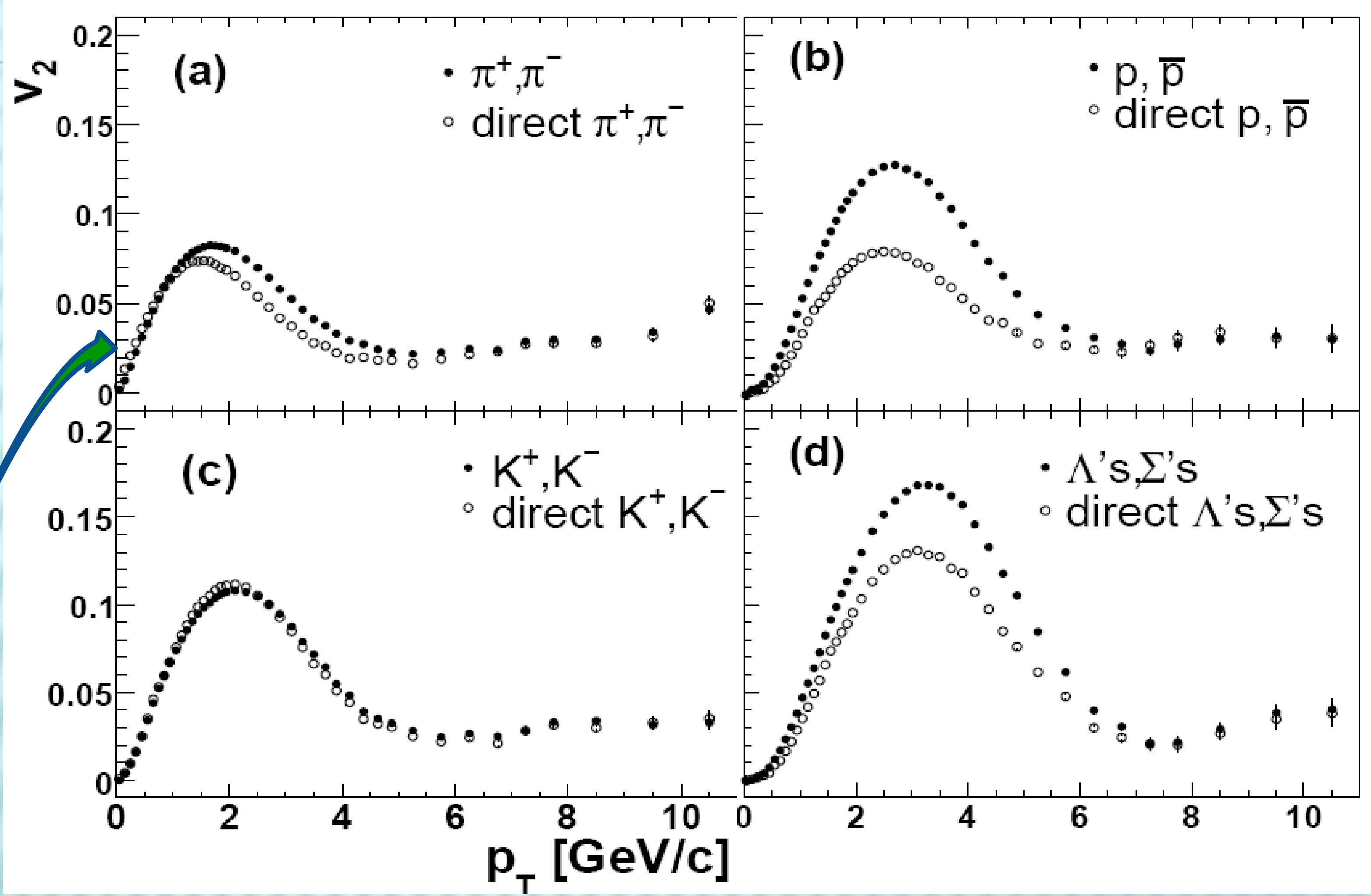
Influence of resonance decays for different type of particles at RHIC



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



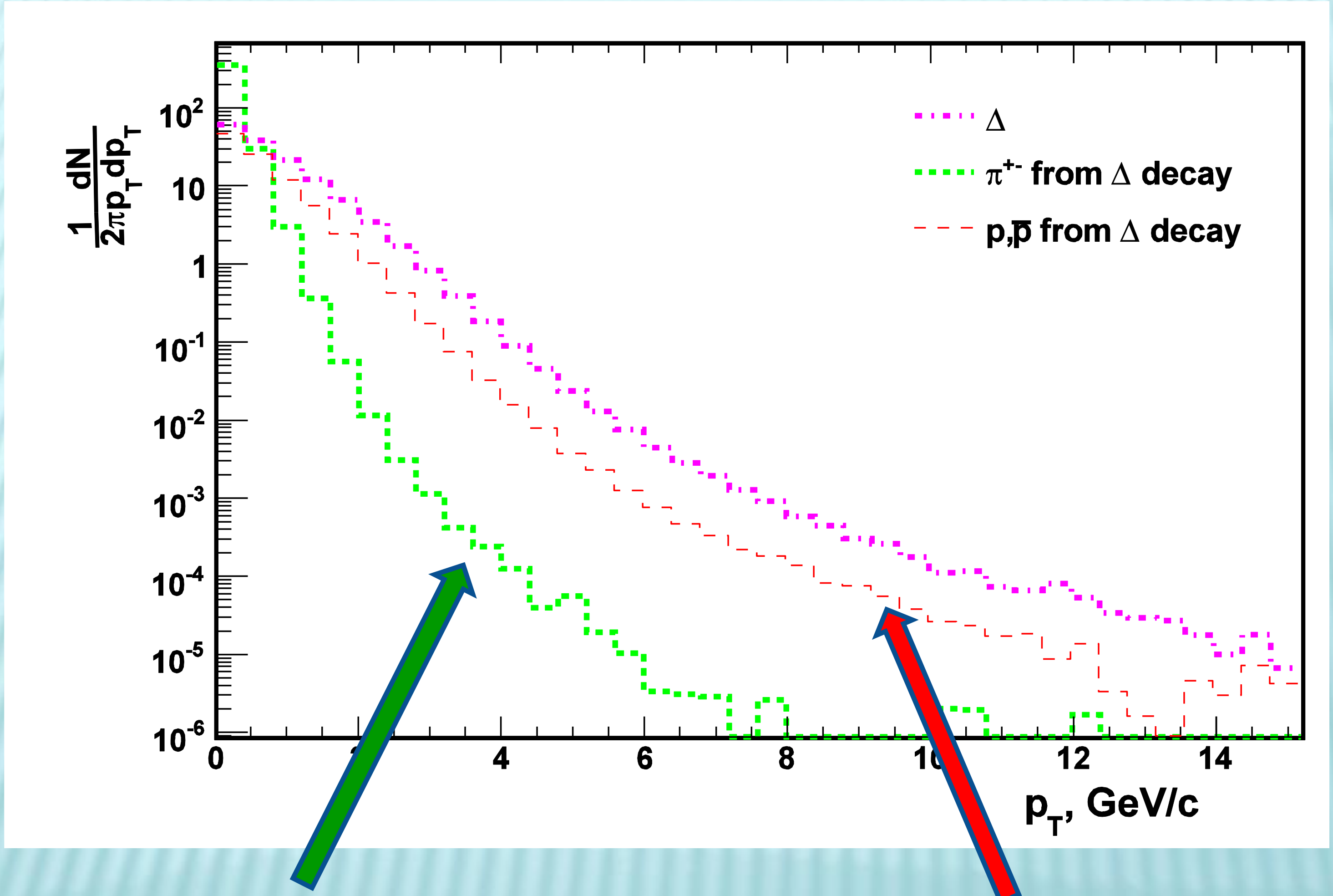
Pions: the resulting flow is weaker at low-pt and larger at high-pt

Kaons: both flows almost coincide

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

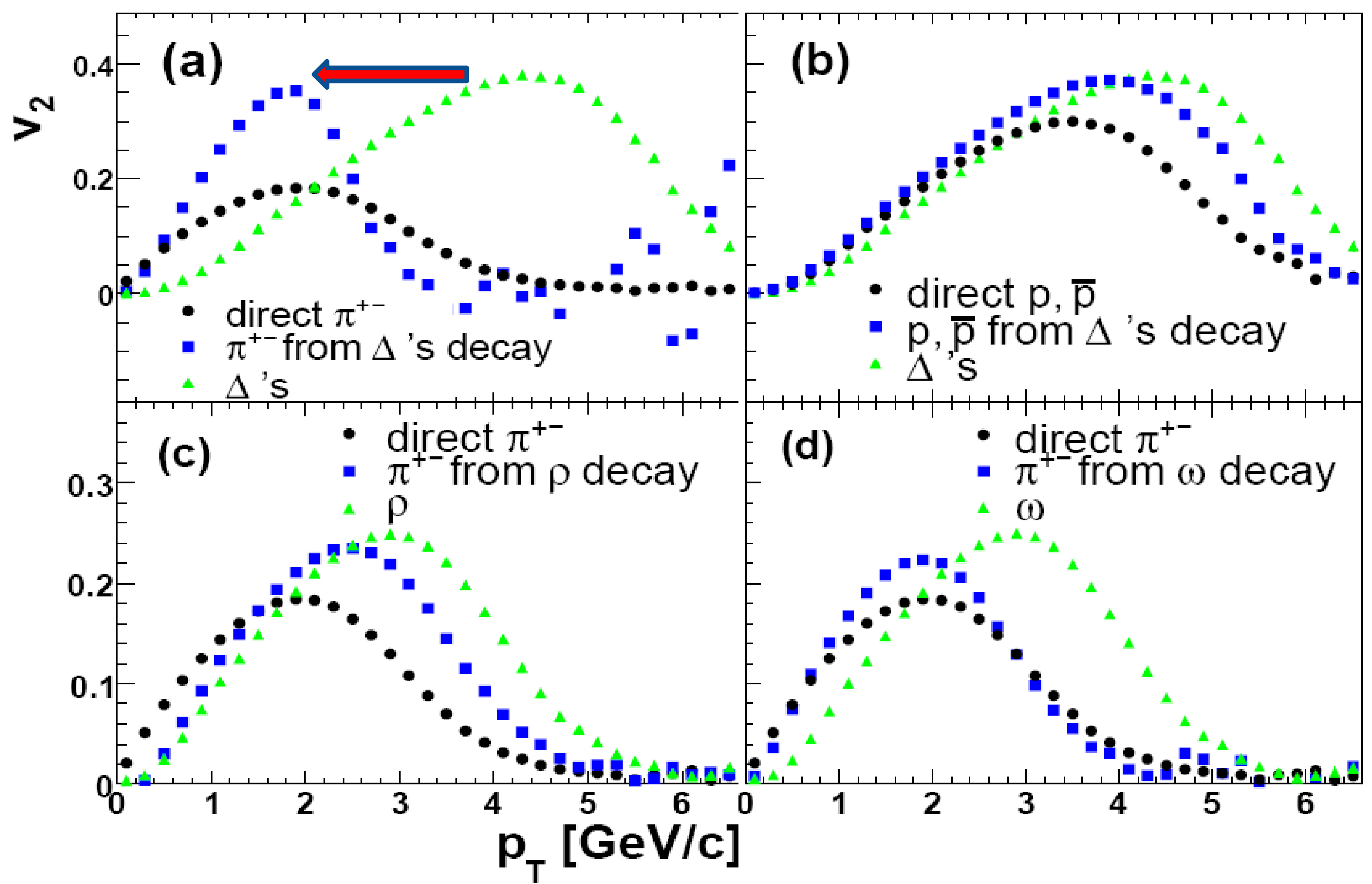
TRANSVERSE MOMENTUM OF SECONDARY PARTICLES

$\Delta \rightarrow \pi + p$



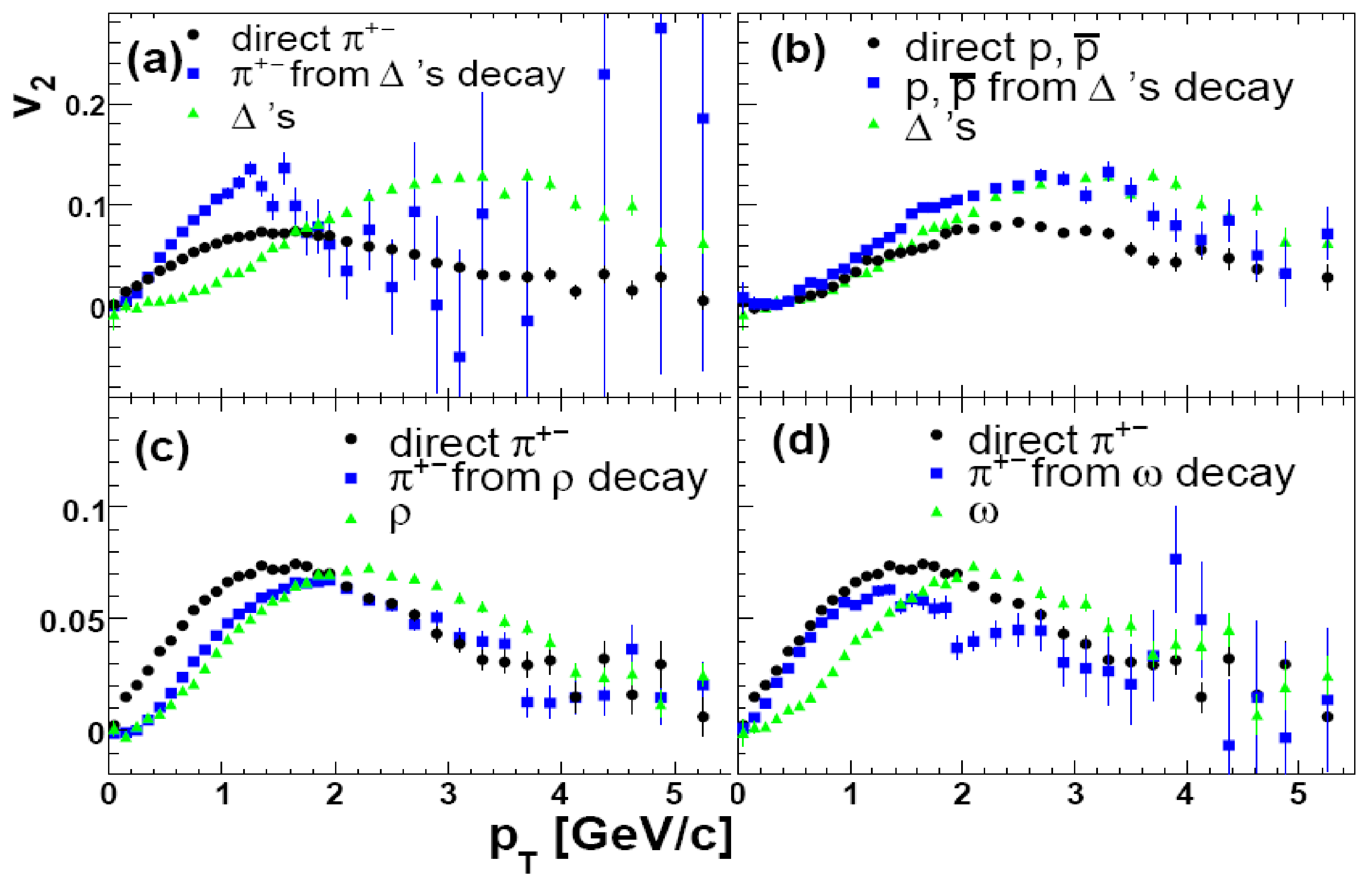
The secondary pion spectrum is much softer than proton spectrum

ELLIPTIC FLOW OF DIRECT AND SECONDARY PARTICLES AT RHIC



The heavier resonances have larger v_2 at high transverse momenta
The decay kinematics keeps this high v_2 for products of resonance decays

ELLIPTIC FLOW OF DIRECT AND SECONDARY PARTICLES AT LHC



At low transverse momenta: pions from baryon resonances enhance the flow; pions from meson resonances reduce it

Ⅴ． PARAMETERS OF THE MODEL

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:

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

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

(2) Two particle correlation method

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

(3) Lee-Yang zero method

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

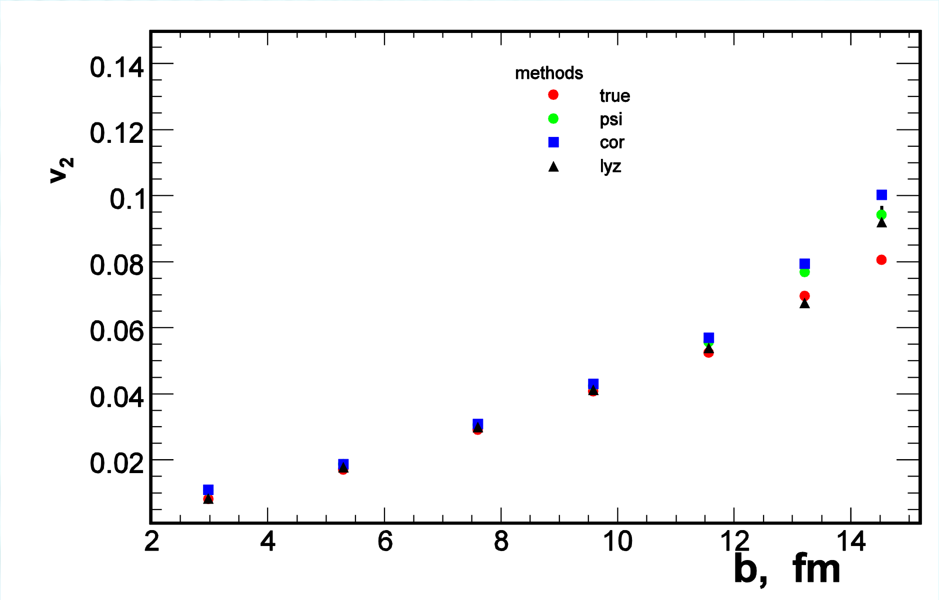
Integral v_2 is connected with the firs minimum r_0 of the module of the G(ir):

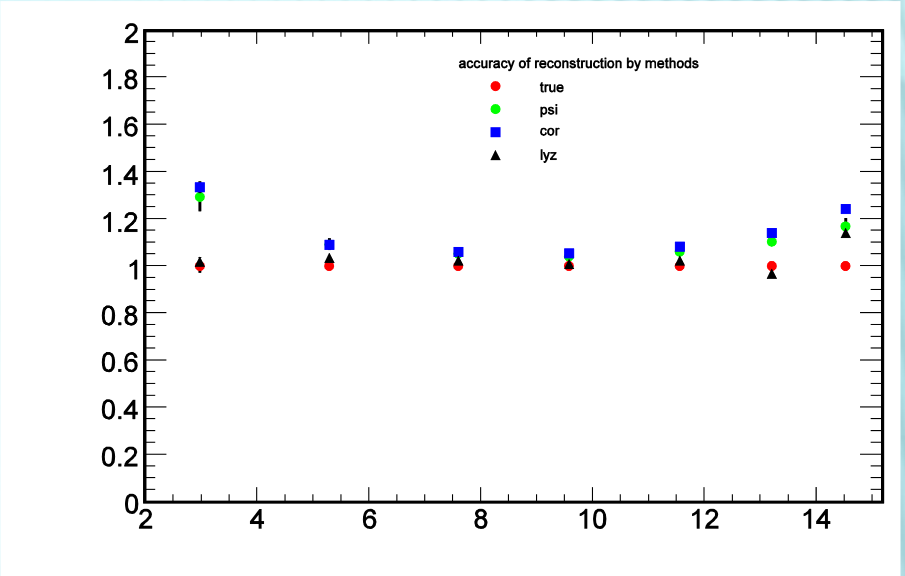
$$v_2 = \frac{j_0}{Nr_0}$$

Differential flow is calculated by the formula:

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

RECONSTRUCTION OF INTEGRAL VALUE OF V2 BY THE METHODS

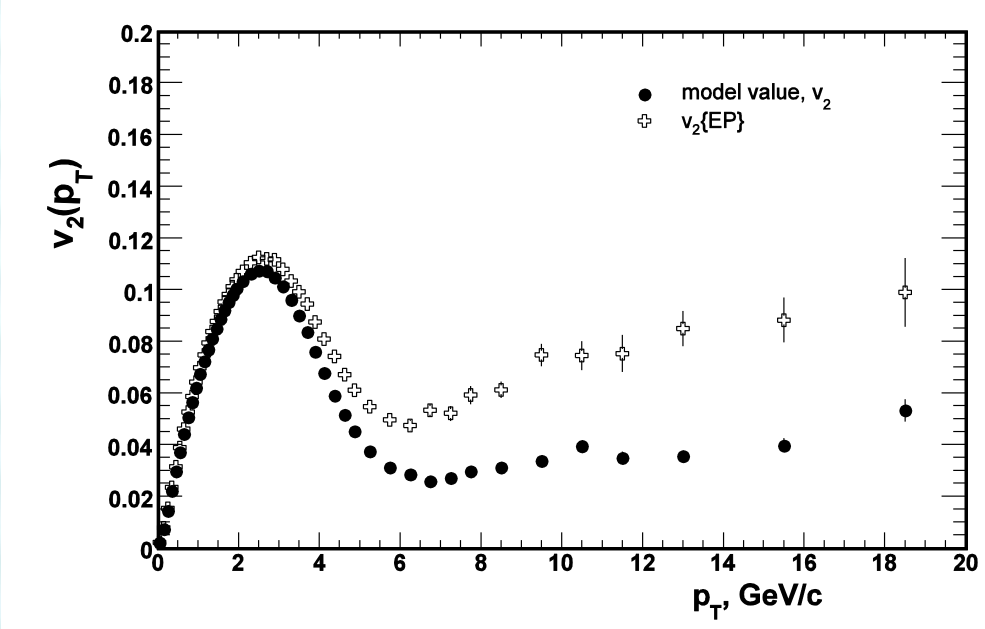


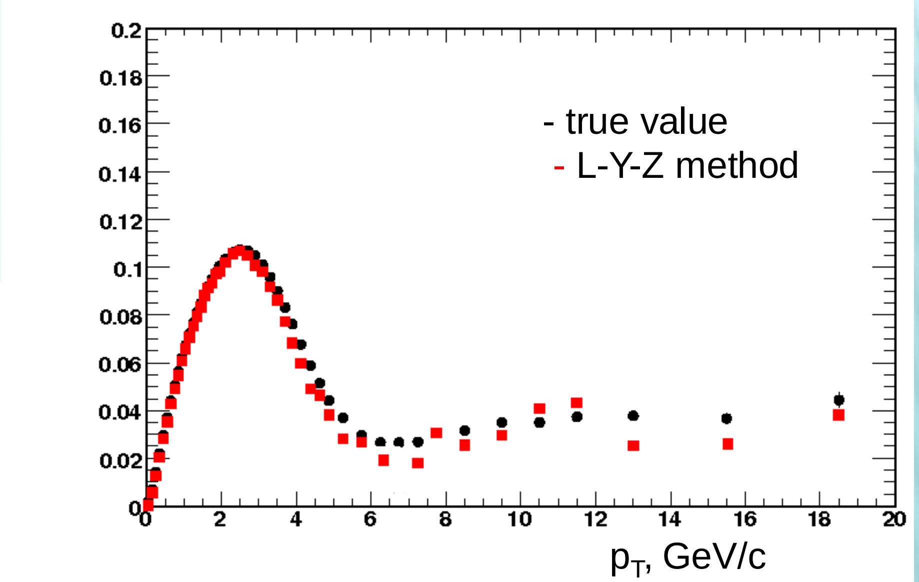


The better reconstruction is achived in midcentral collision for the methods, while Lee-Yang zero method tends to reconstruct true value at more central and more periferal collision.

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).