EFFECT OF JETS ON V_4/V_2^2 RATIO AND CONSTITUENT QUARK SCALING IN RELATIVISTIC HEAVY-ION COLLISIONS

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OUTLINE

I. Motivation

II. HYDJET++ model (hydro + jets)

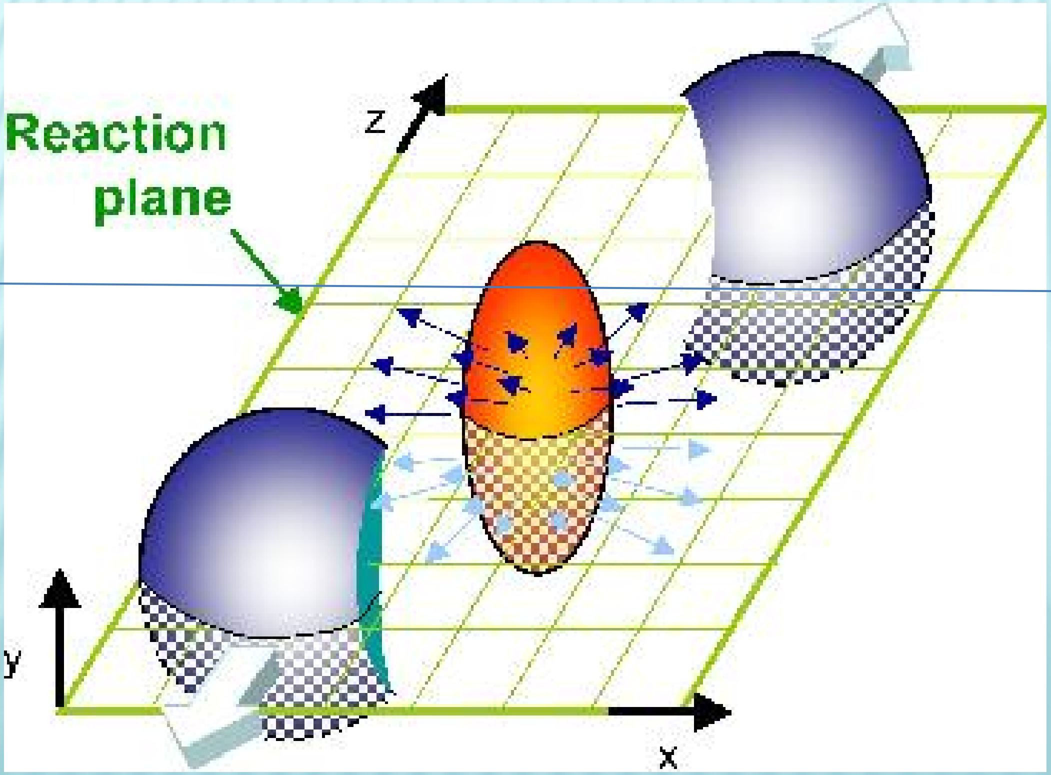
III. Model results for the ratio $v4/(v2)^2$ at RHIC and LHC

IV. NCQ-scaling at RHIC and LHC

I. $v4/(v2)^2$ ratio

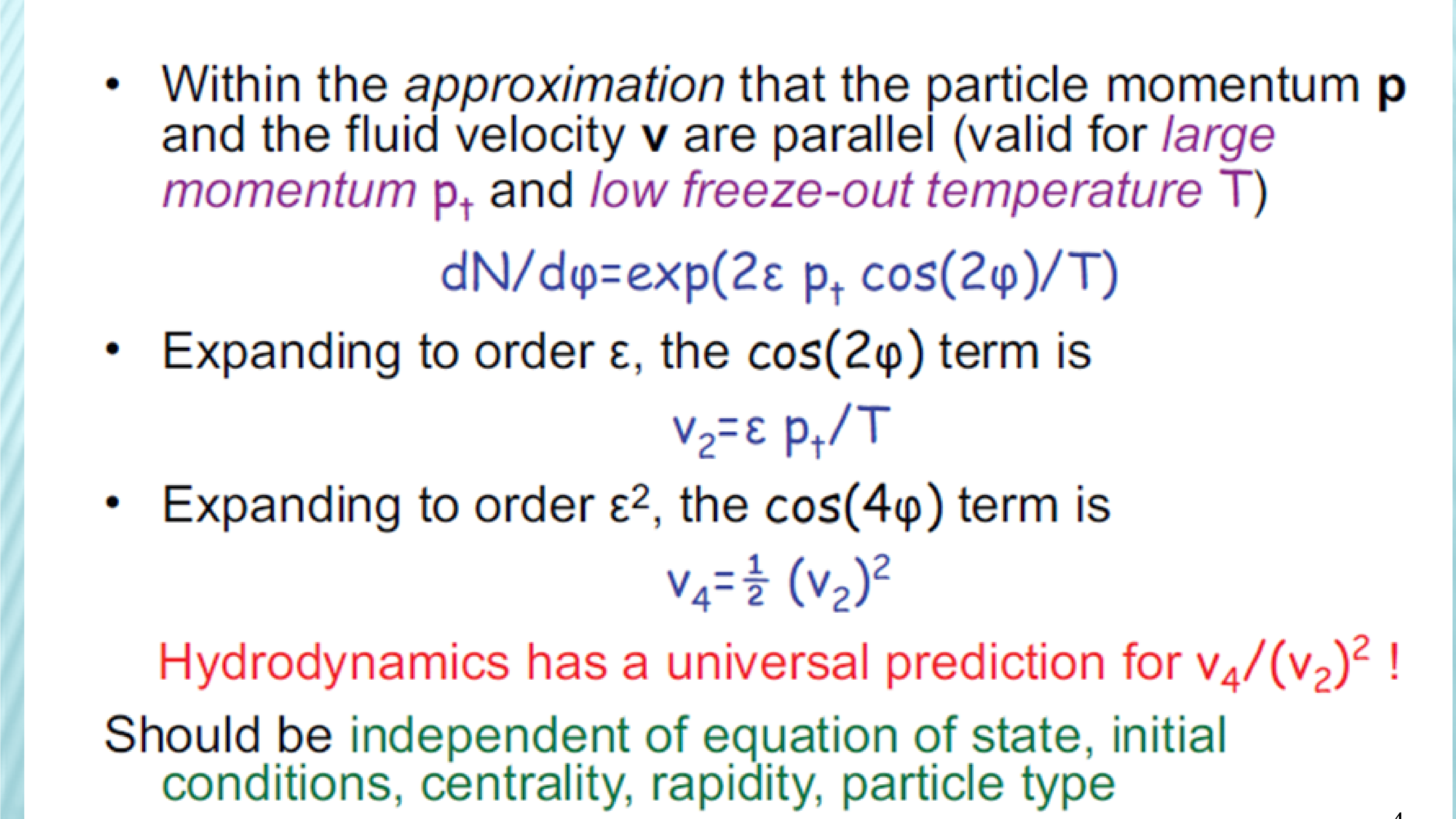
Anisotropic flow

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



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

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

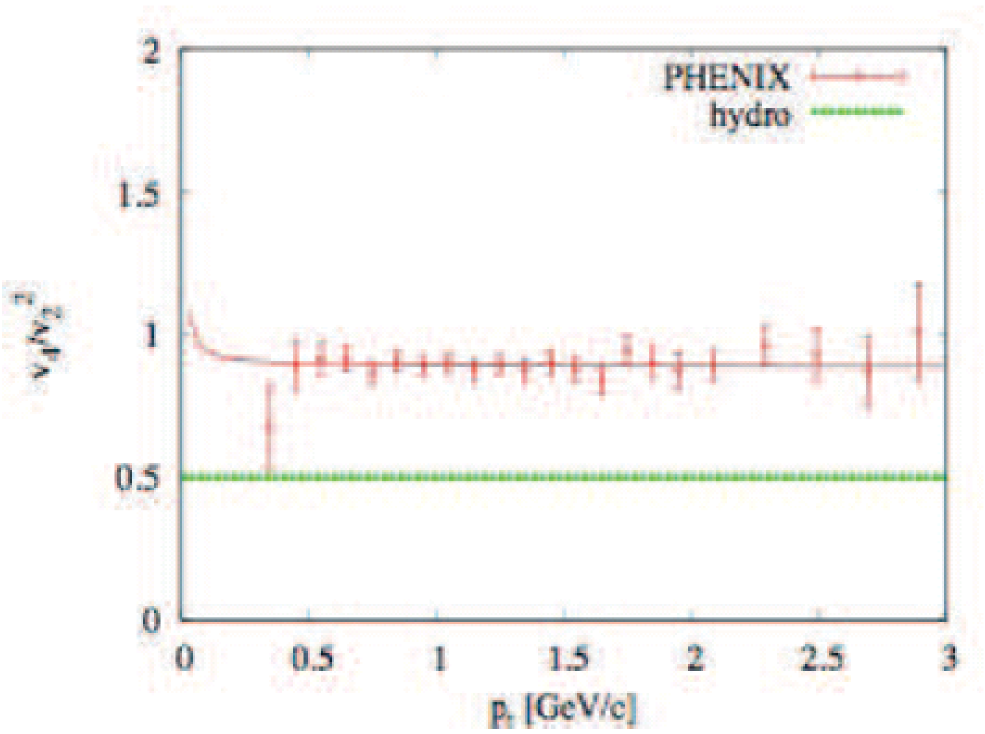
- Expanding to order ε^2, the cos(4φ) term is

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

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

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

Comparison with data



PHENIX data for charged pions

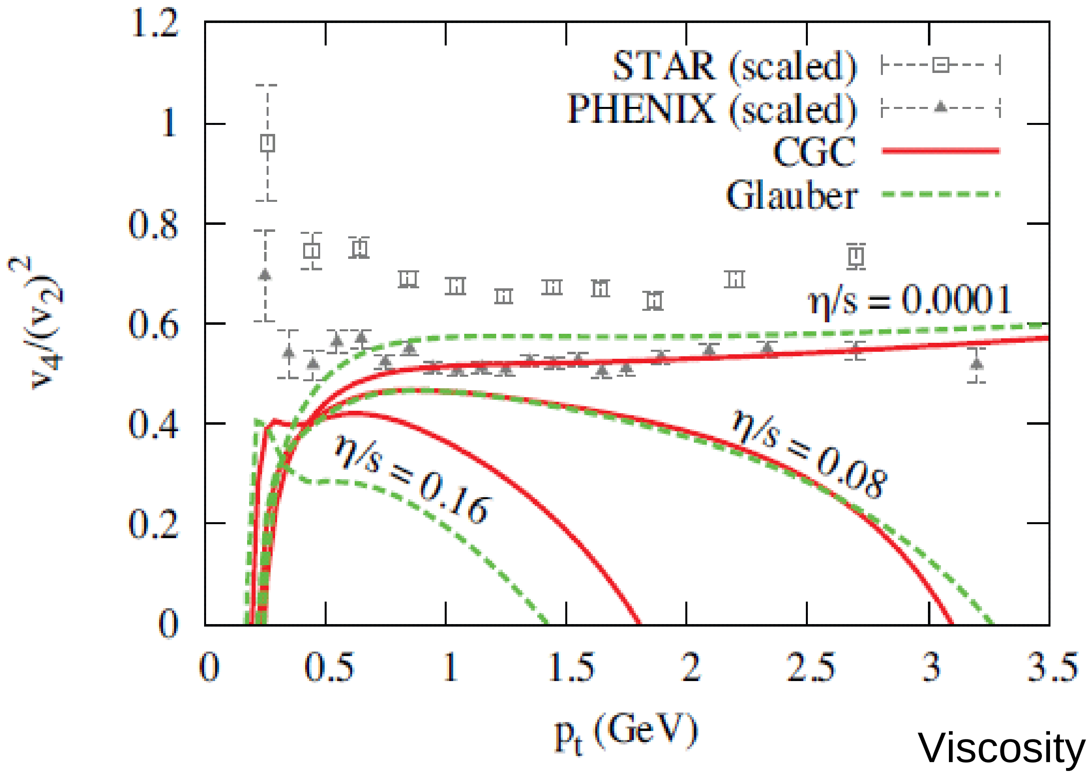
Au-Au collisions at 100+100 GeV

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

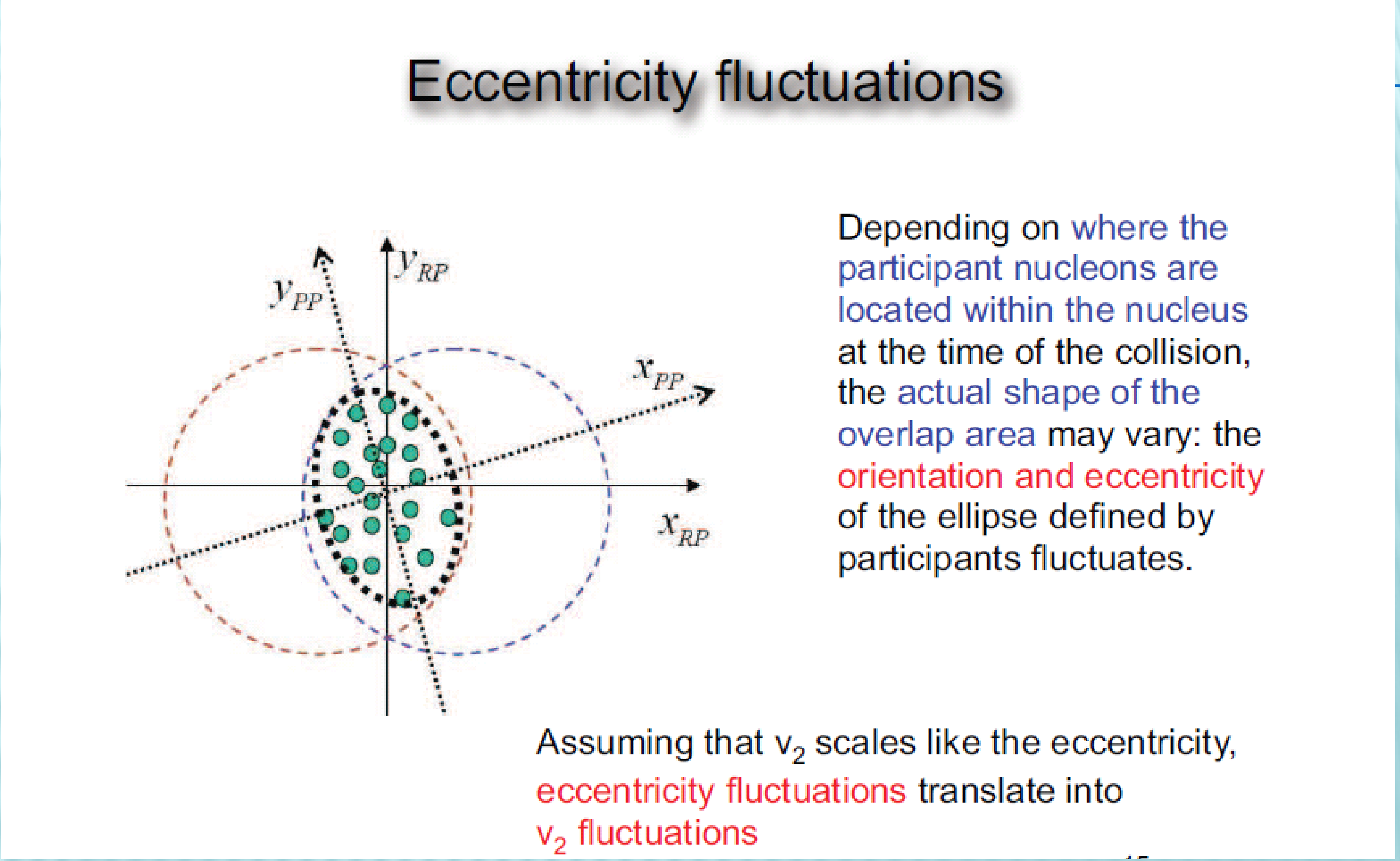


Initial profile has little effect although eccentricities differ.

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

II. 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])

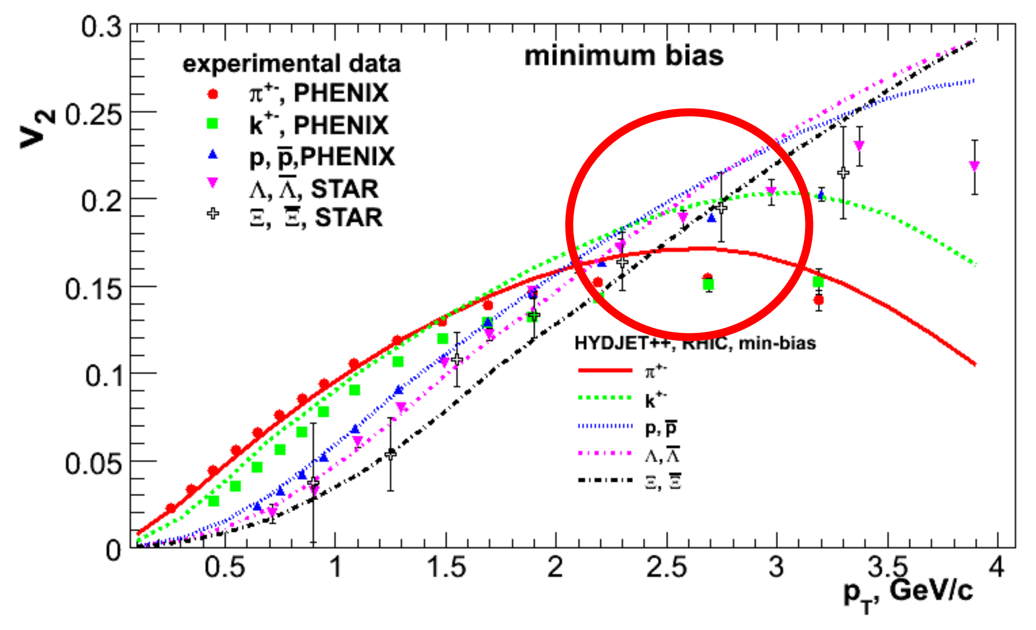
● The soft part of HYDJET++ event represents the "thermal" hadronic state.
✓ multiplicities are determined assuming thermal equilibrium
✓ hadrons are produced on the hypersurface represented by a parameterization of relativistic hydrodynamics with given freeze-out conditions
✓ chemical and kinetic freeze-outs are separated
✓ decays of hadronic resonances are taken into account (360 particles from SHARE data table) with “home-made" decayer

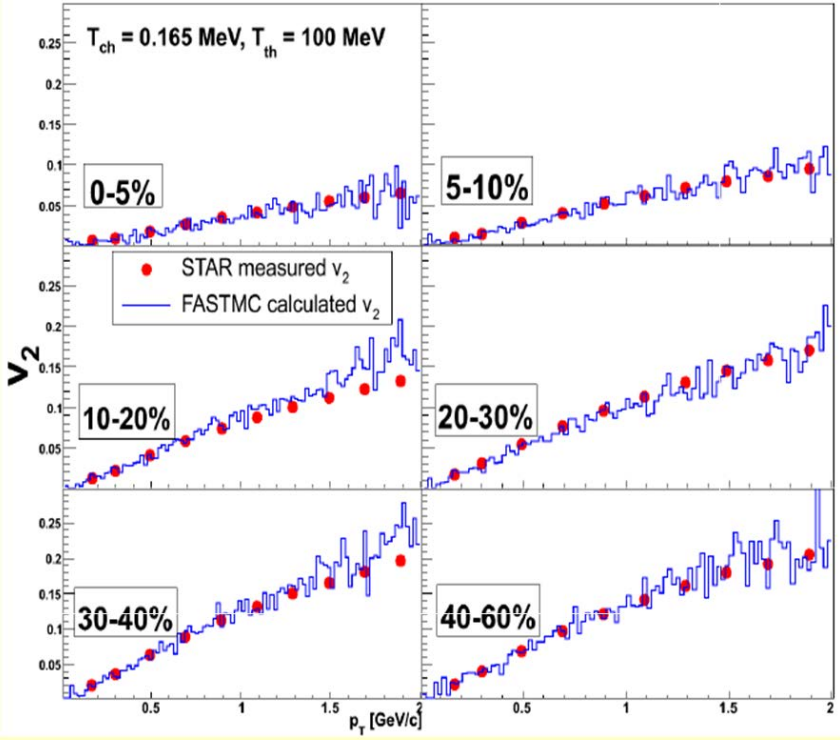
the model reproduces soft hadroproduction features at RHIC (particle spectra, elliptic flow, HBT)

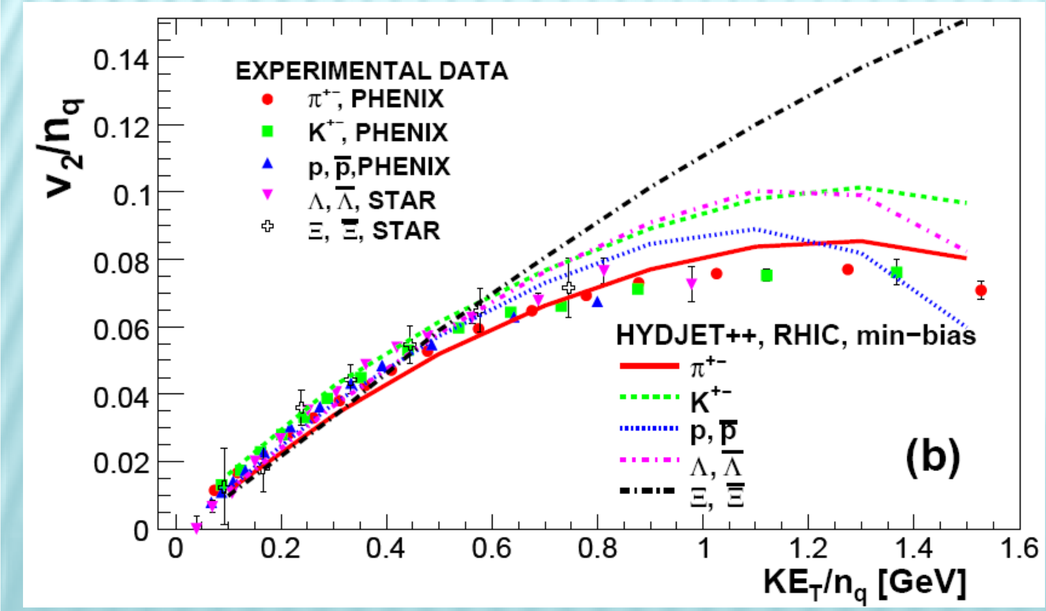
● The hard, multi-partonic part of HYDJET++ event is identical to the hard part of Fortran written HYDJET (PYTHIA6.4xx + PYQUEN1.5).
PYQUEN event generator is used for simulation of rescattering, radiative and collisional energy loss of hard partons in expanding quark-gluon plasma created in ultrarelativistic 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)*

RHIC DATA VS. HYDJET++ MODEL

Au+Au @ 200 AGeV



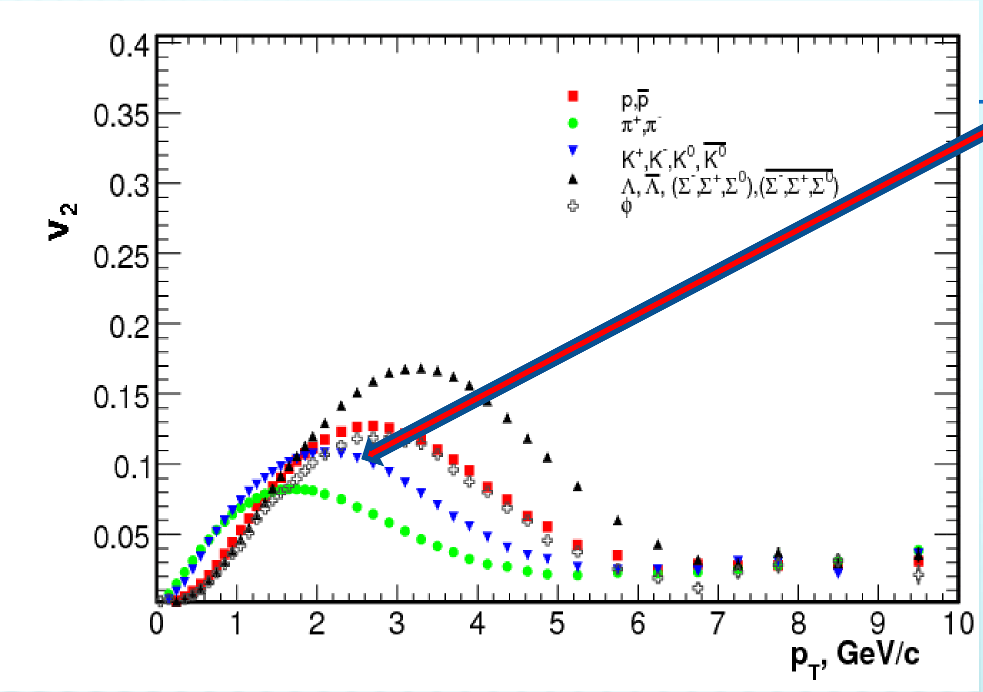




Elliptic flow

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%)

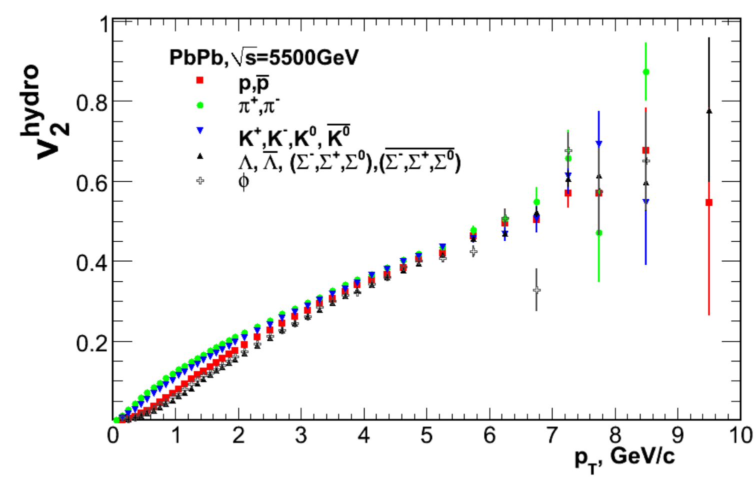


Mass ordering in soft p_T regions then breaks.

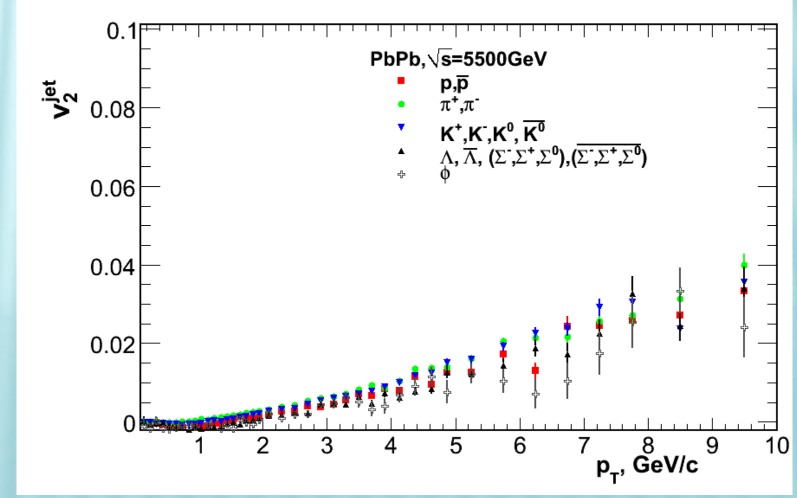
Why?

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

Hydrodynamics



Jet part +quenching



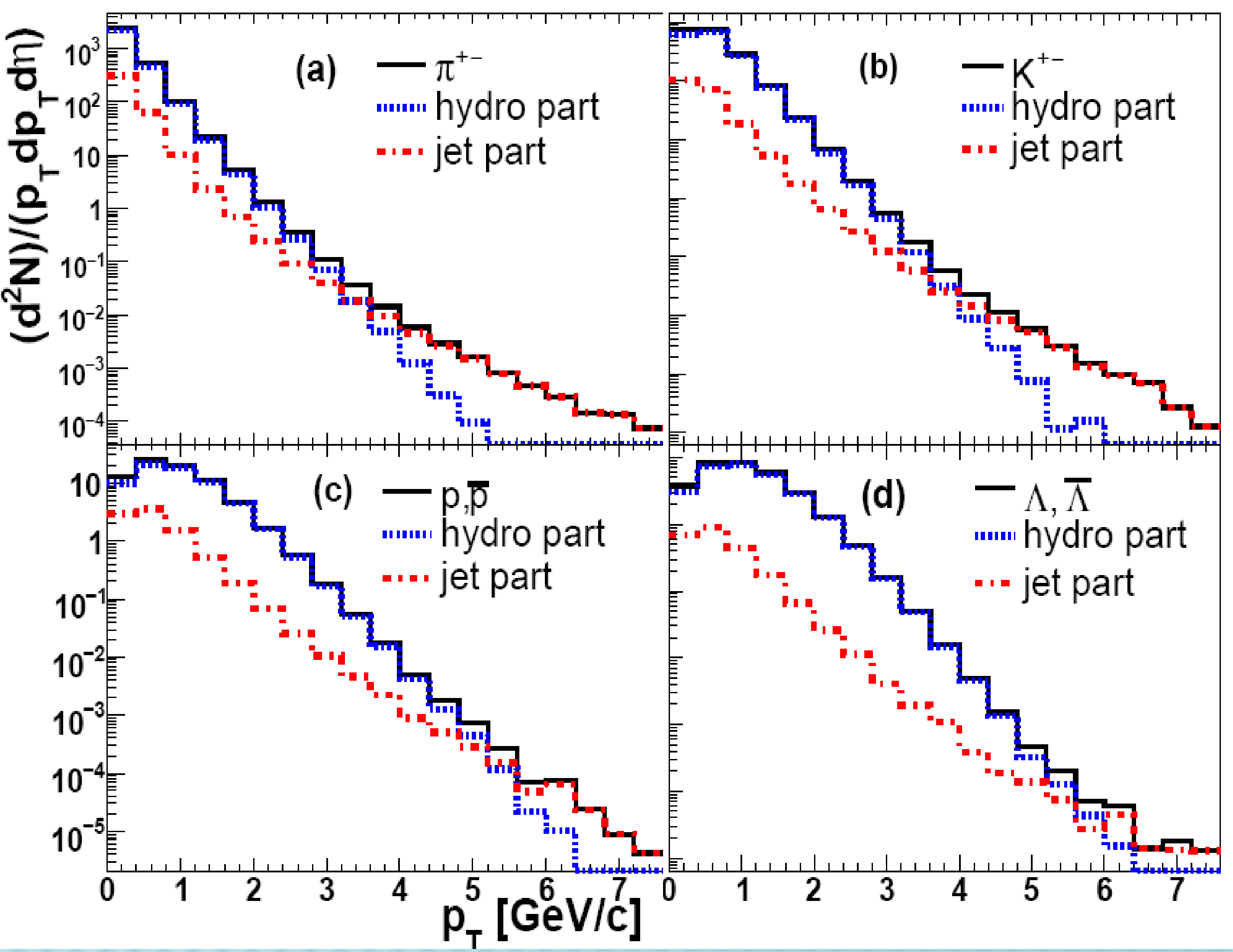
Interplay between hydrodynamics and jets

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

The slope for the hydro part depends strongly on mass:

- the heavier the particle -- the harder the spectrum

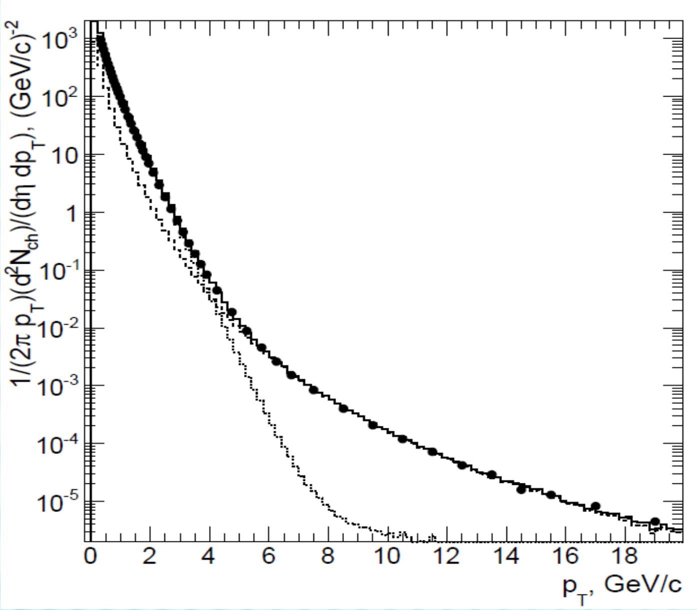
The hydro part dies out earlier for light particles than for heavy ones



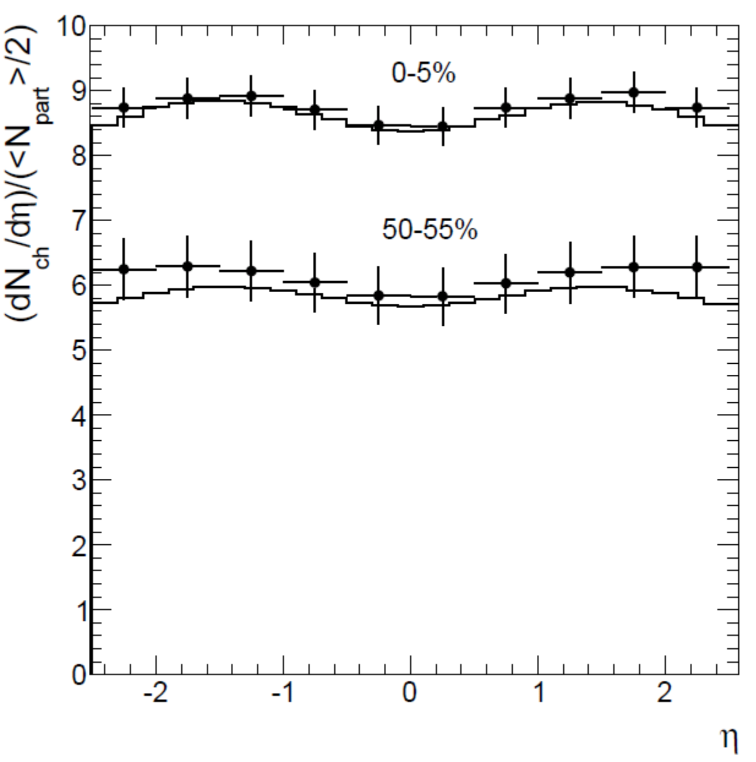
LHC DATA VS. HYDJET++ MODEL

Transverse momentum

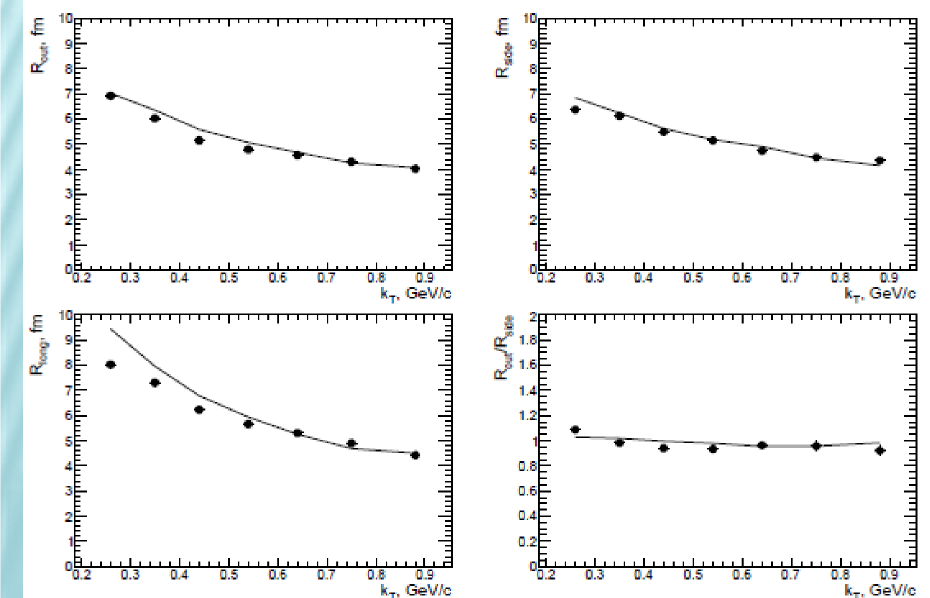
Pb+Pb @ 2.76 ATeV



Rapidity



I. Lokhtin et al., arXiv:1204.4820

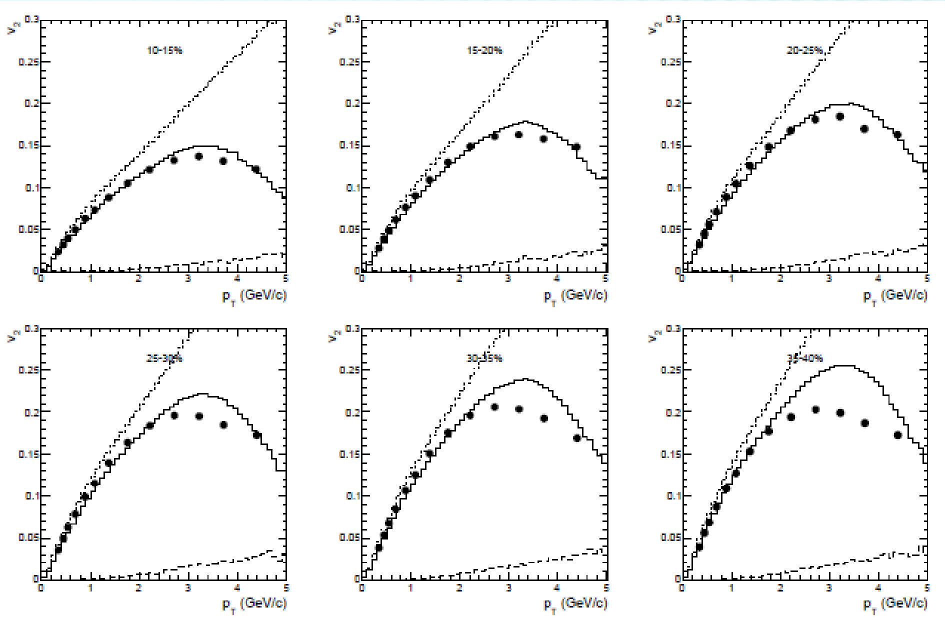


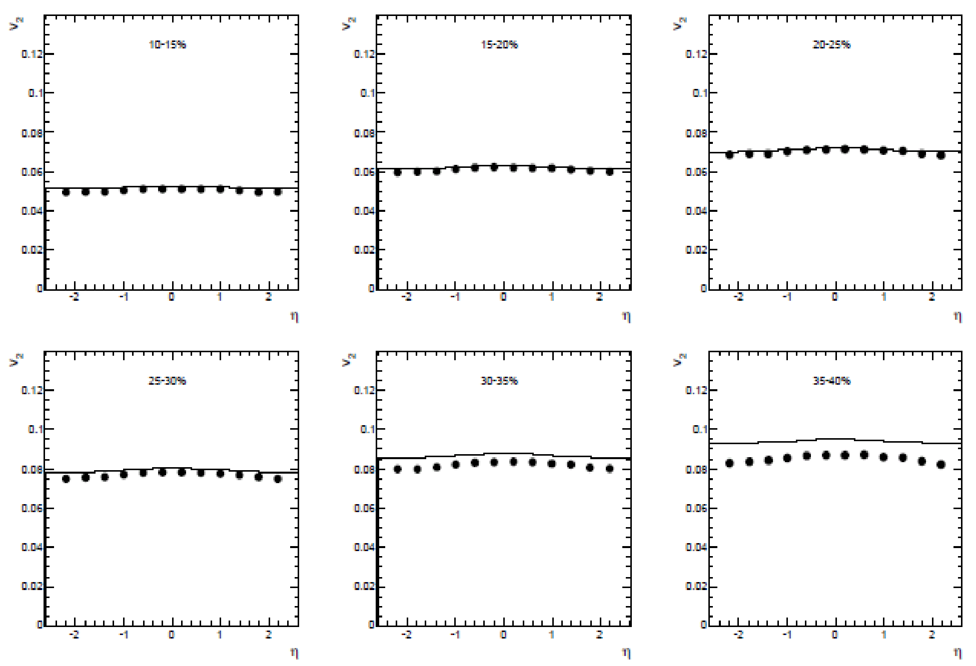
Correlation radii (femtoscopy)

LHC DATA VS. HYDJET++ MODEL

Pb+Pb @ 2.76 ATeV

Elliptic flow



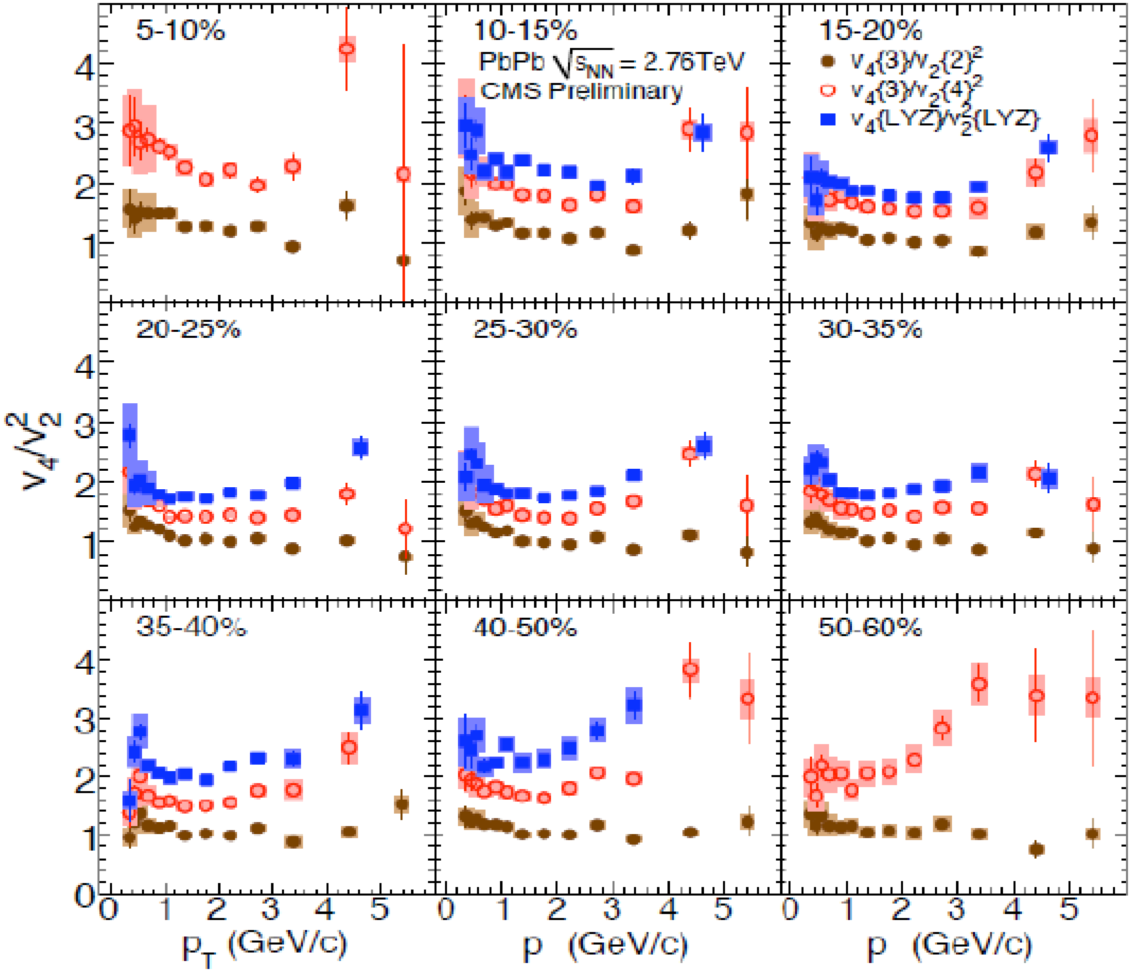


I. Lokhtin et al., arXiv:1204.4820

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

III. V4/(V2*V2) RATIO

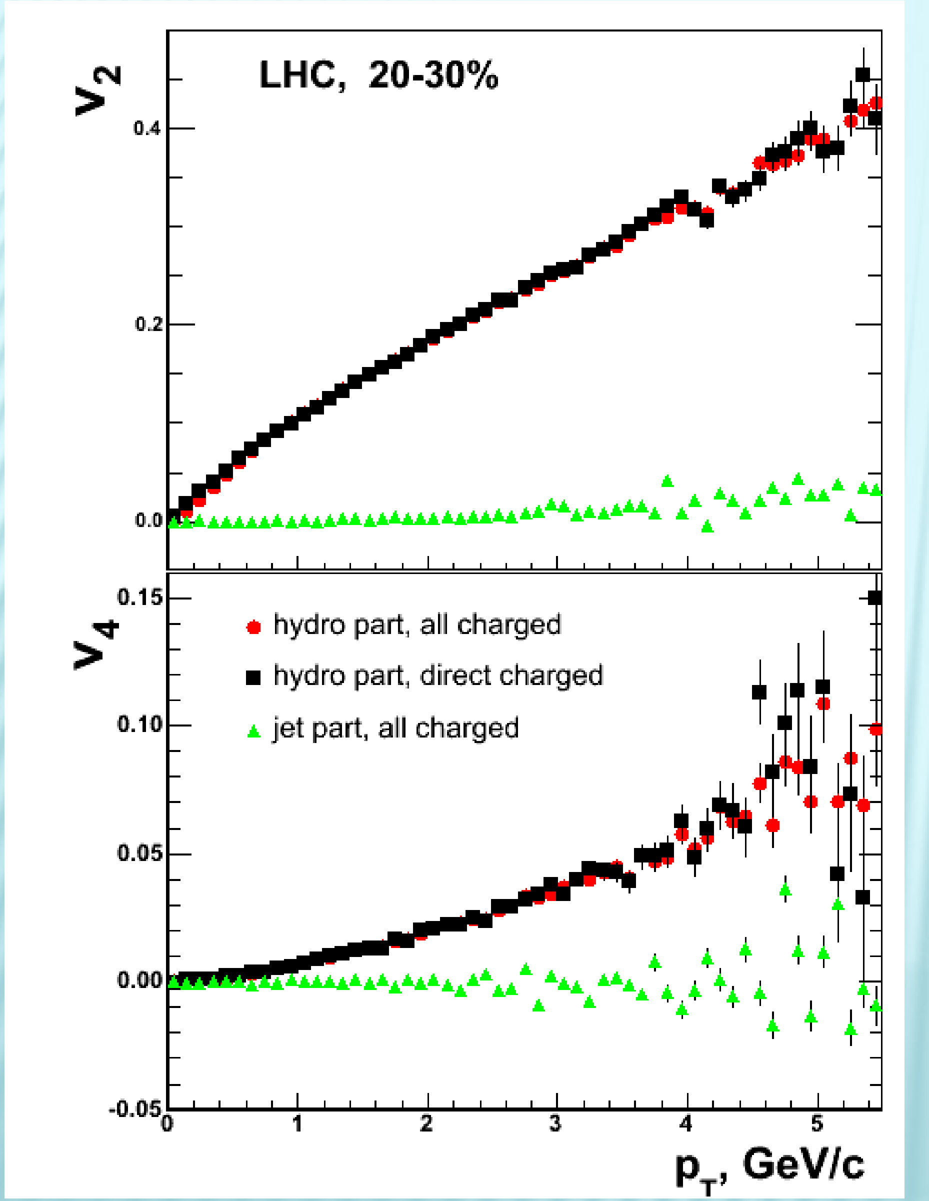
$v_4 / v_2^2(p_T)$ at mid-rapidity $|\eta| < 0.8$

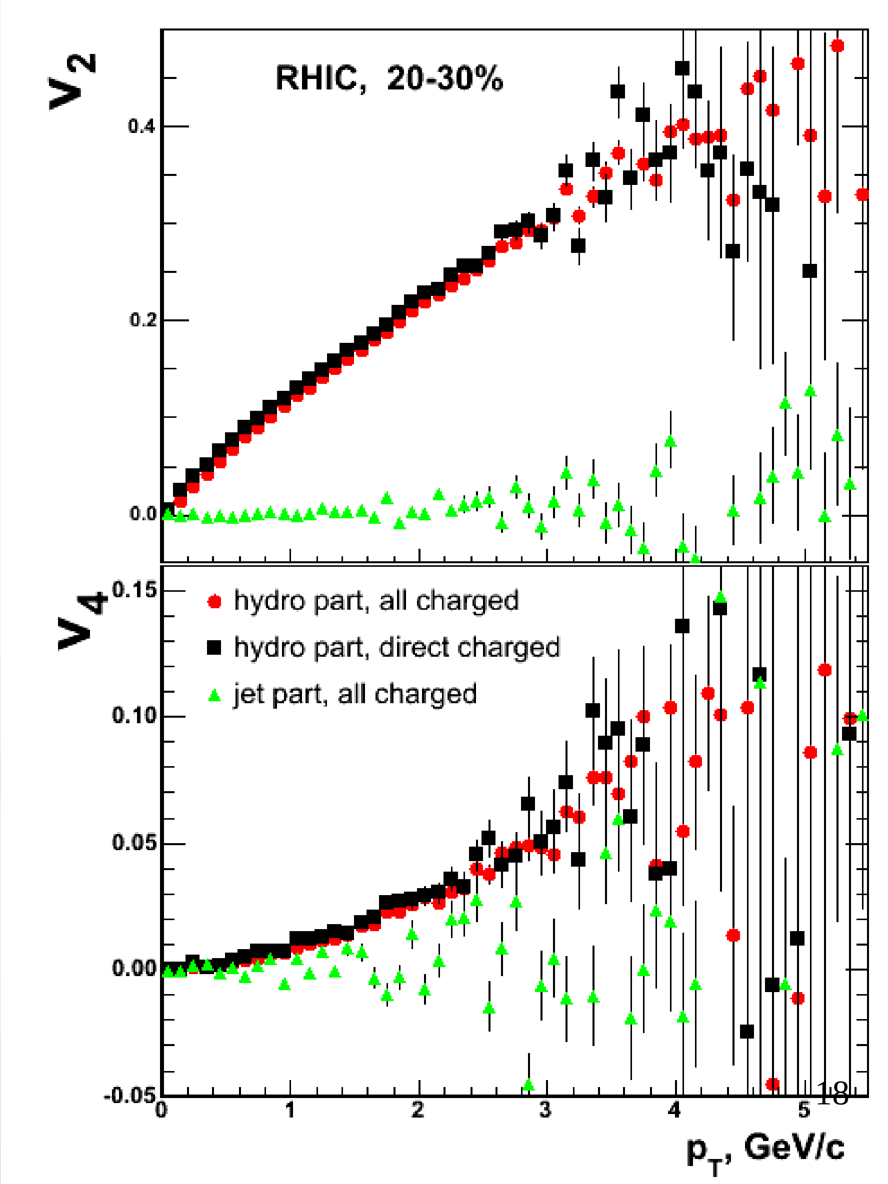


Significantly higher than RHIC: experimental method dependent

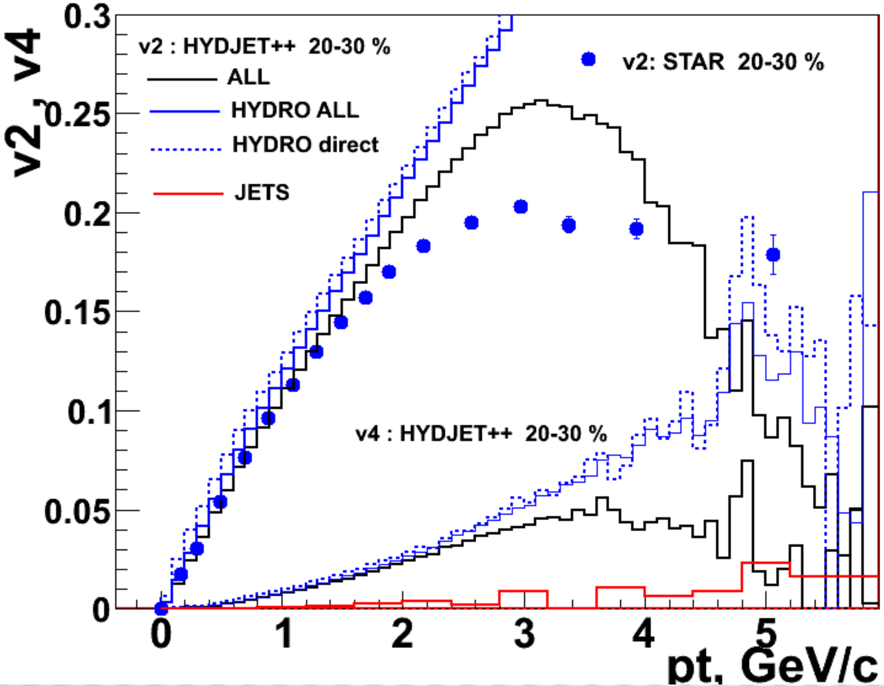
HYDJET++

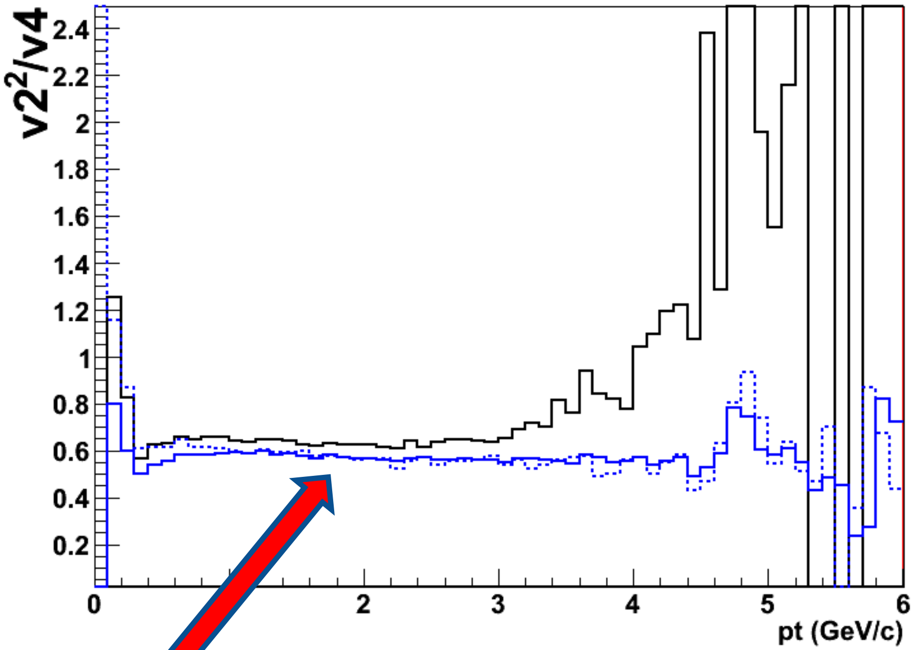
Effects to be studied: resonance decay and hard part influence





HYDJET++ RESULTS FOR RHIC

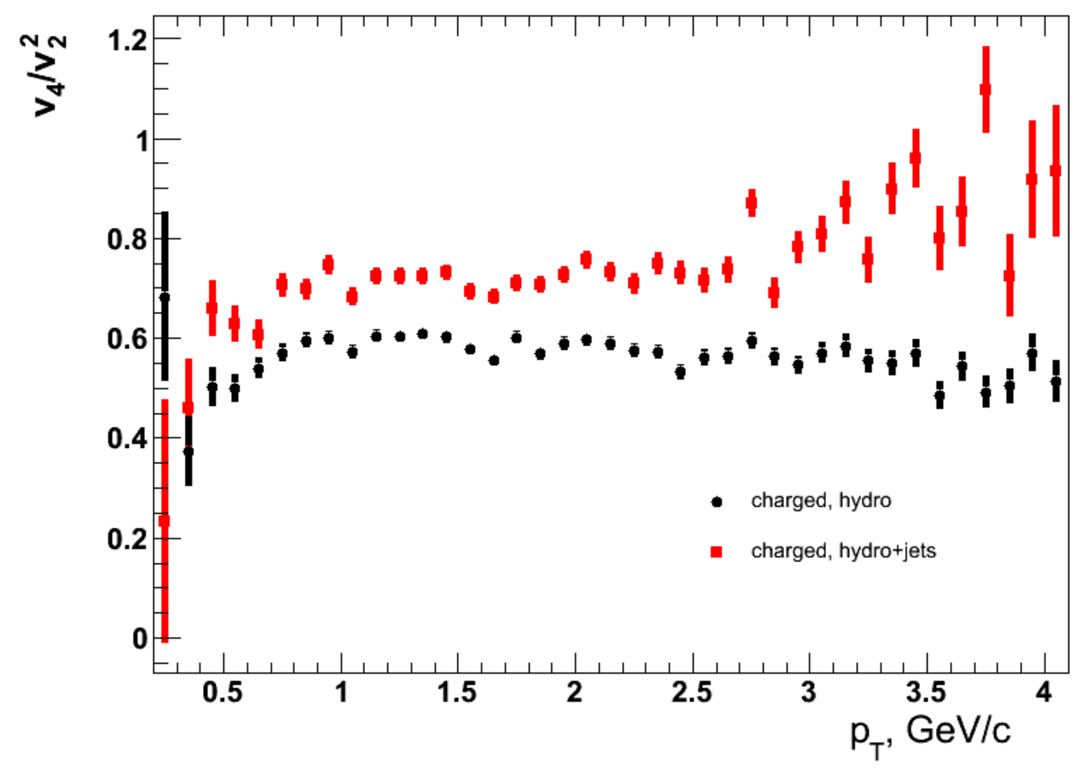


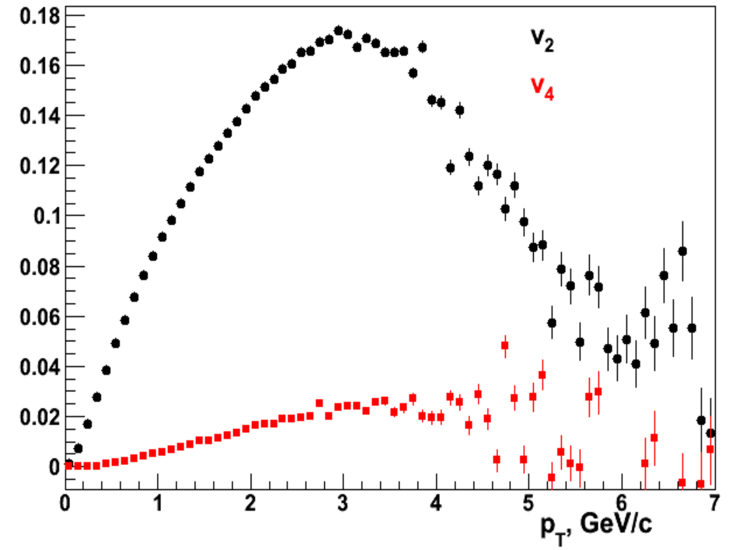


Jets increase the ratio

HYDJET++ RESULTS FOR LHC

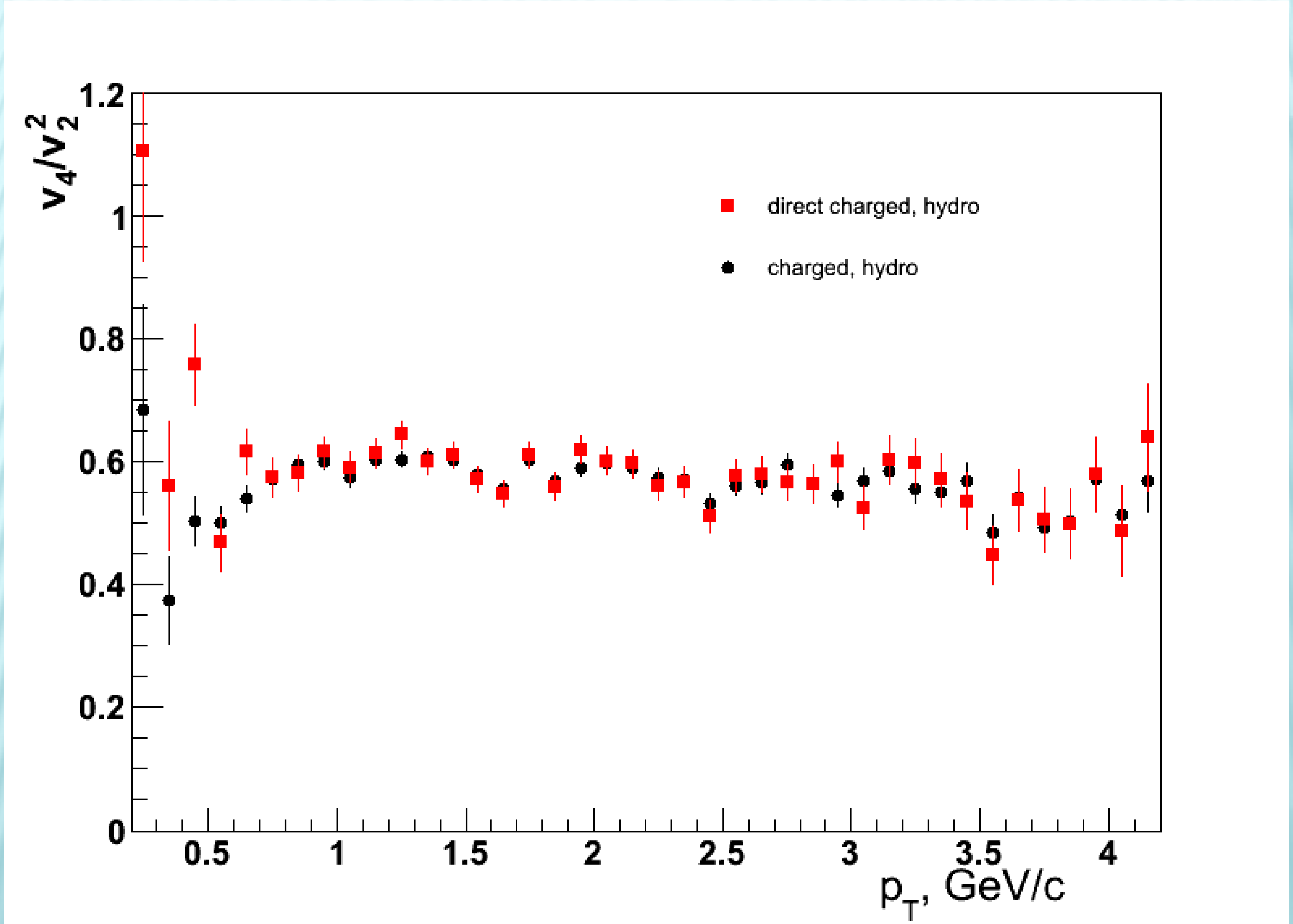
The same tendency is observed in Pb+Pb at LHC





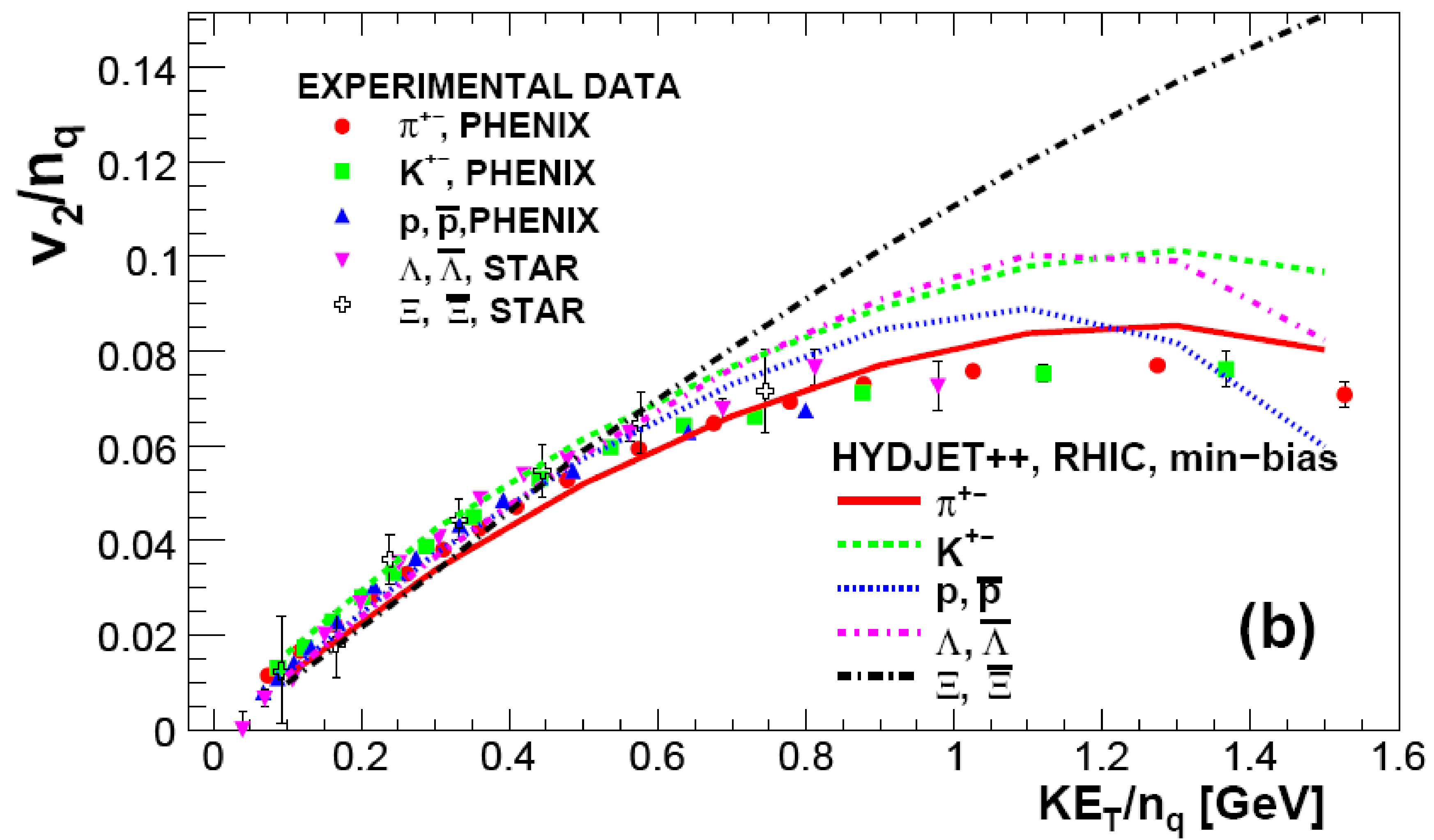
Still, the ratio is below 1

DECAYS OF RESONANCES PLAY MINOR ROLE



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

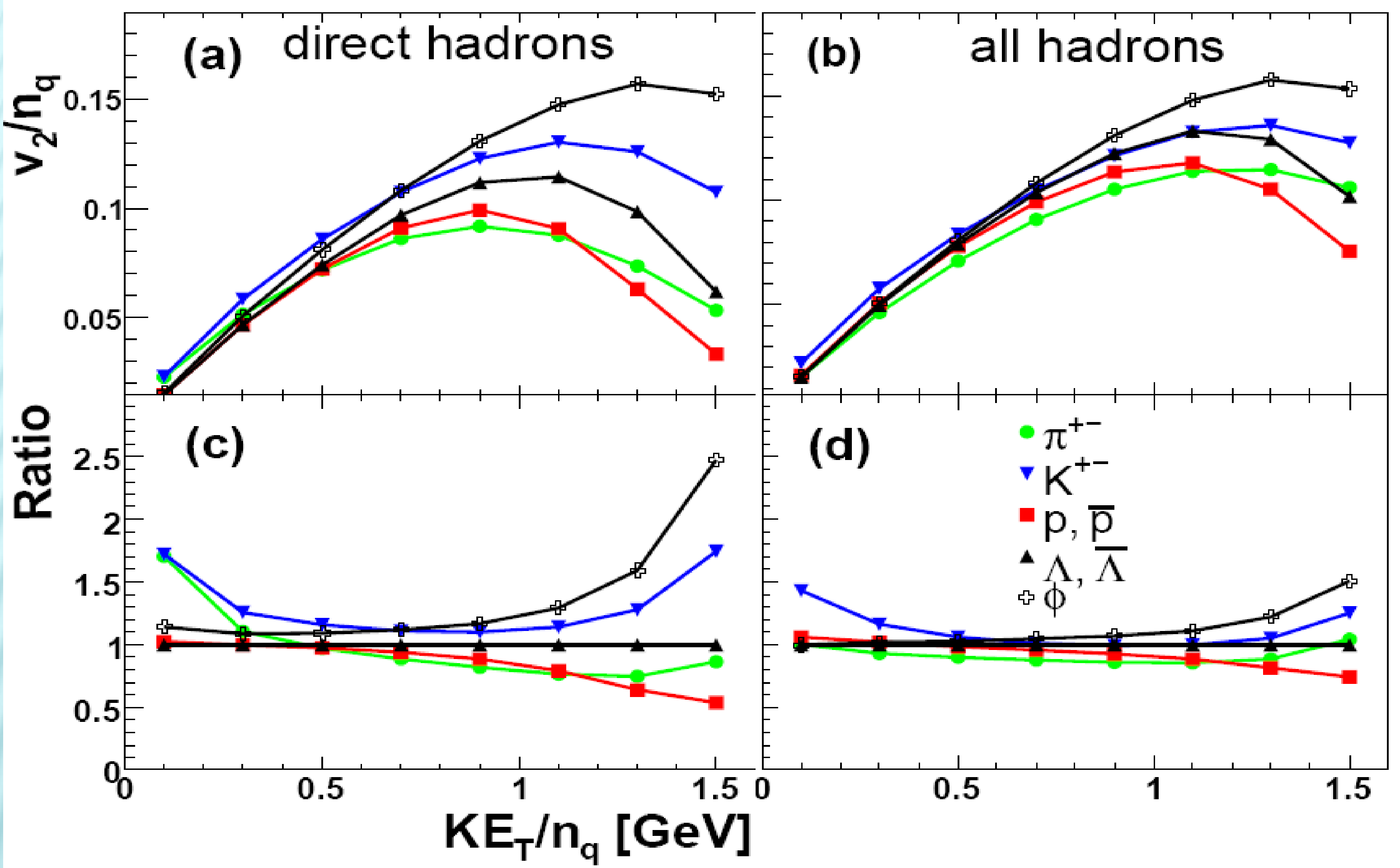
COMPARISON WITH RHIC DATA



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

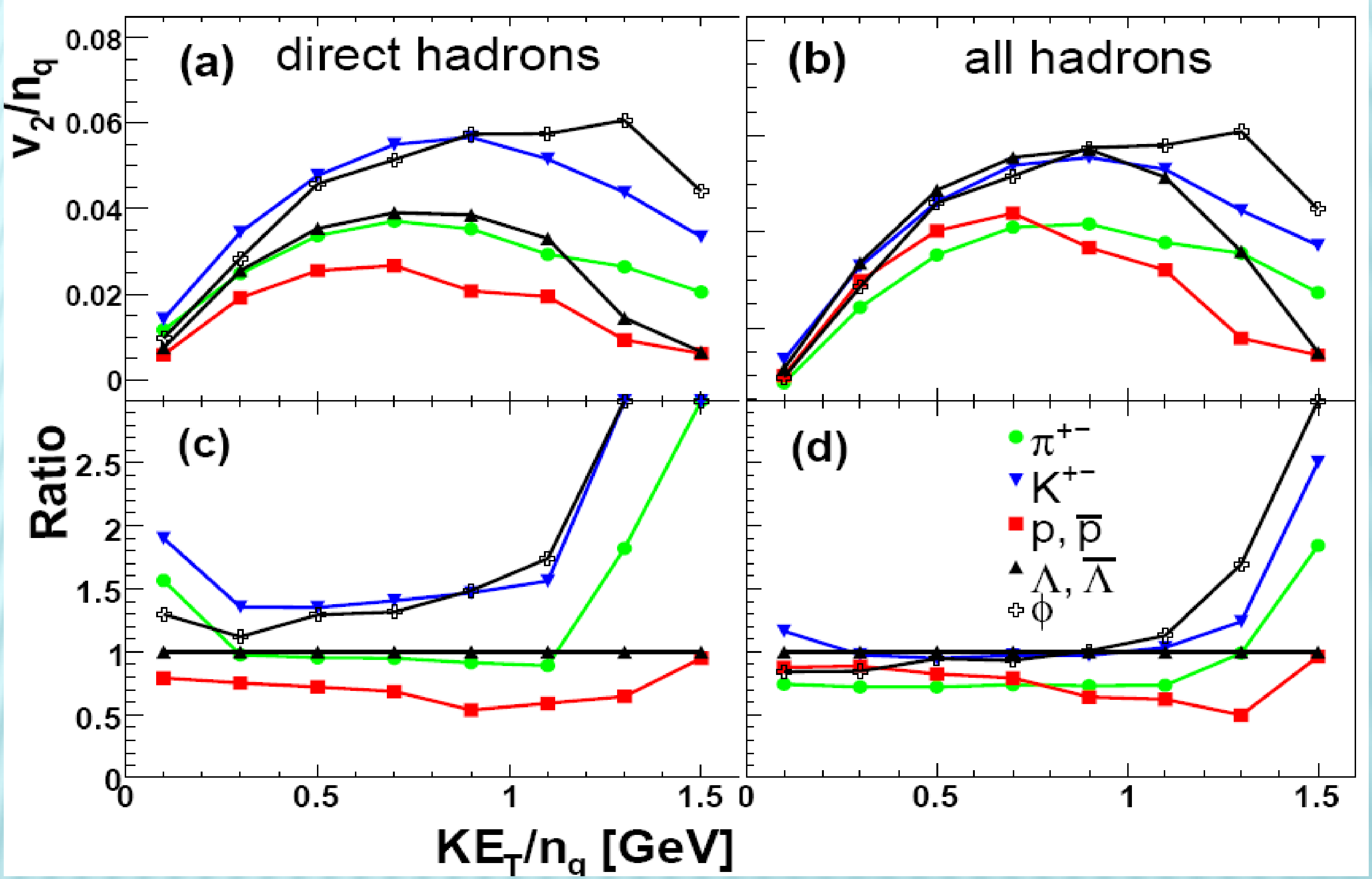


One of the explanations of KE_T/n_q scaling is partonic origin of the elliptic flow.
However, final state effects (such as resonance decays and jets) may also lead to appearance of the scaling

NCQ scaling at LHC

No scaling for
direct particles

Appearance of the approximate
scaling for all particles

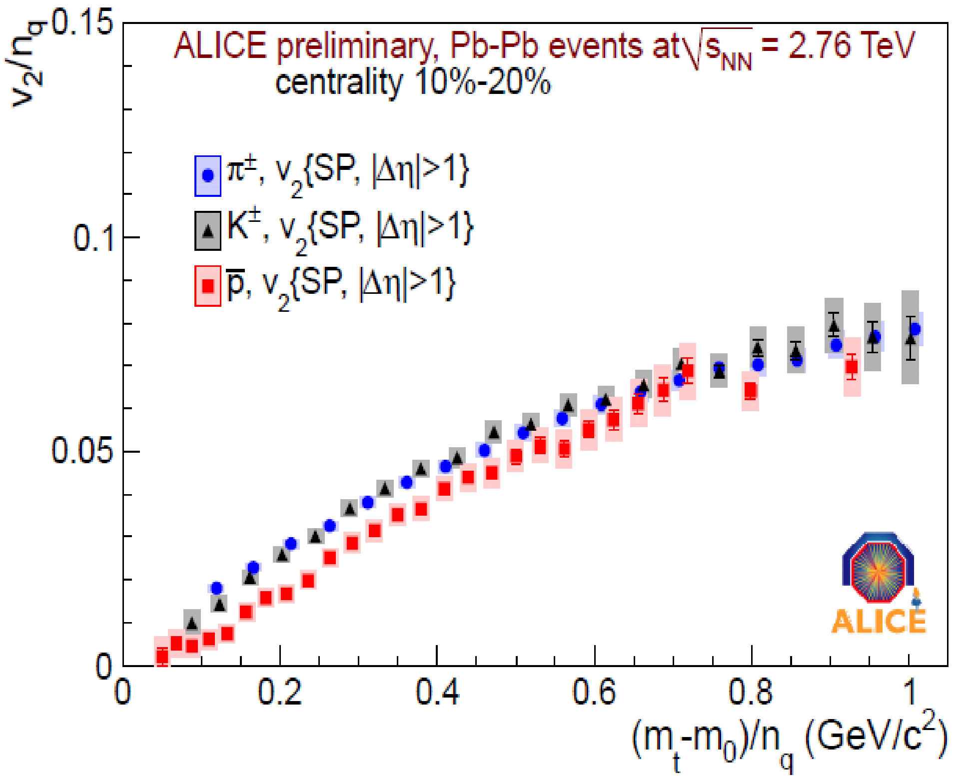


LHC: NCQ scaling will be only approximate (prediction, 2009)

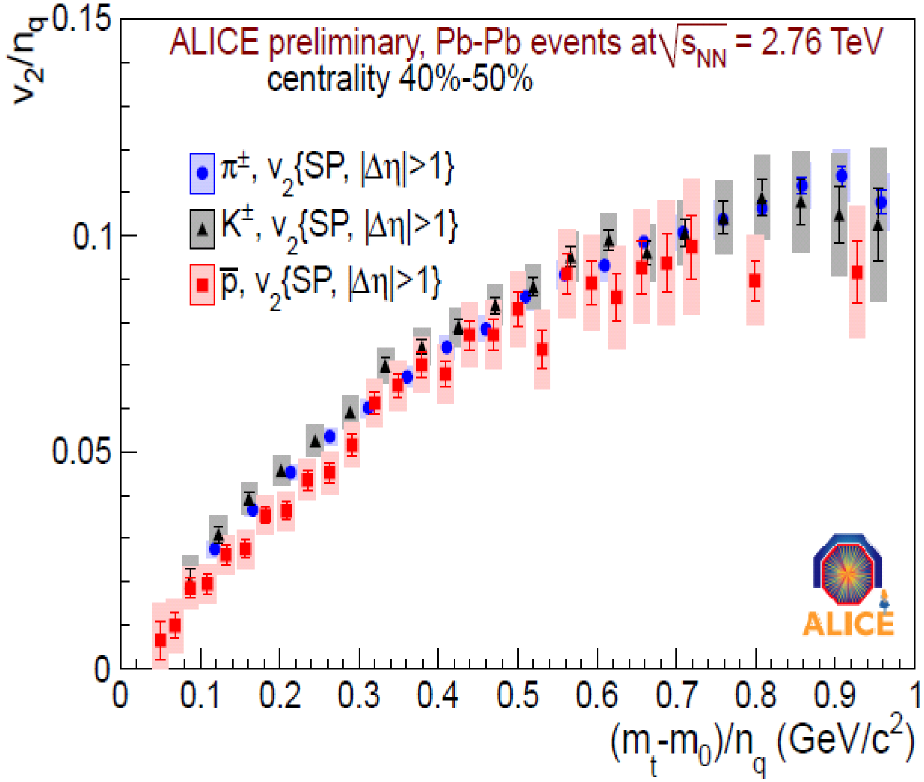
Experimental results (LHC)

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

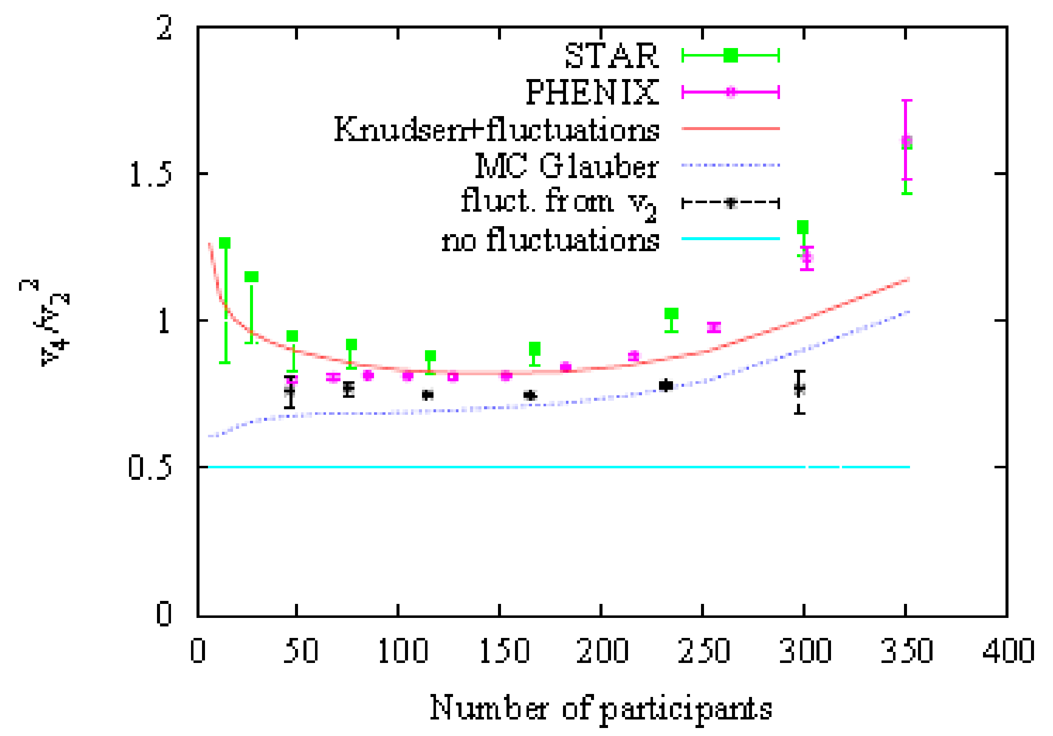
The HYDJET++ model allows to investigate flow of hydro and jet parts separately, to look at reconstruction of pure hydro flow and its modification due to jet part.

- ***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

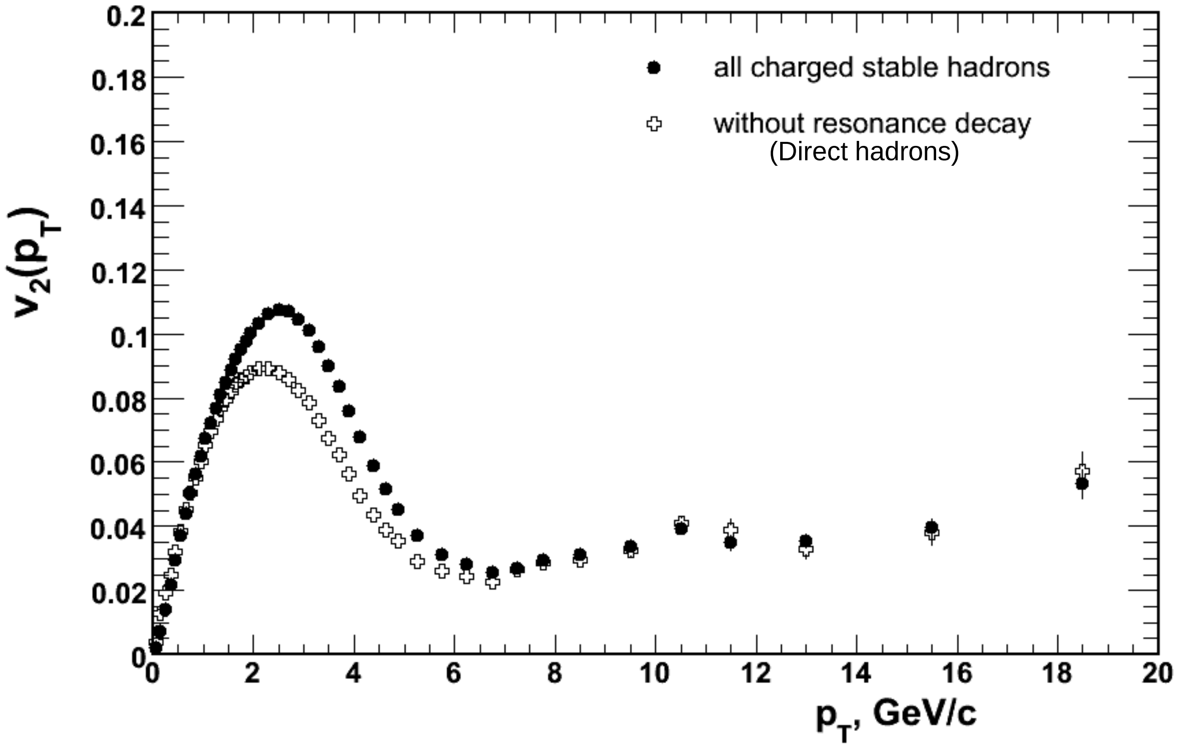
M. Luzum, C. Gombeaud, J.-Y. Ollitrault, Phys.Rev.C81:054910,2010.



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.

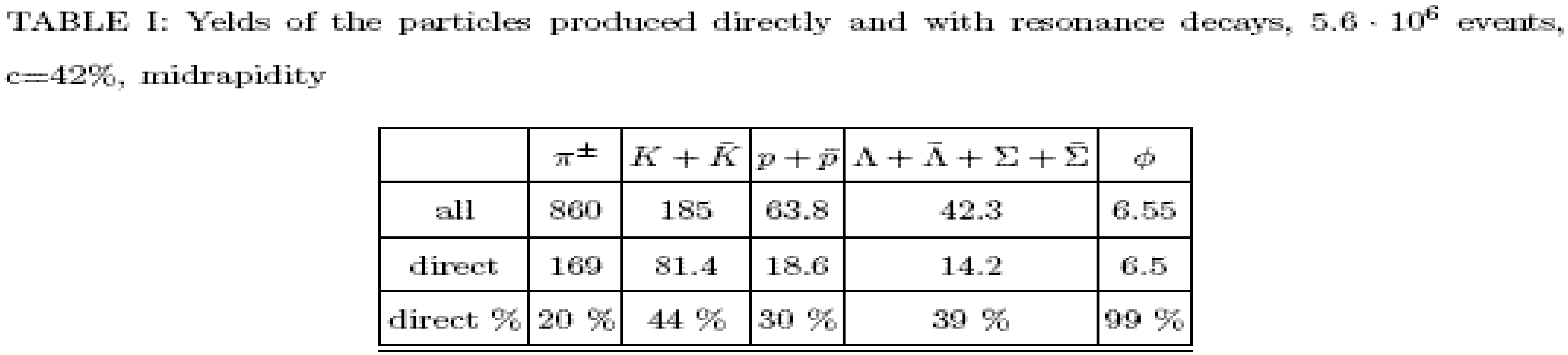
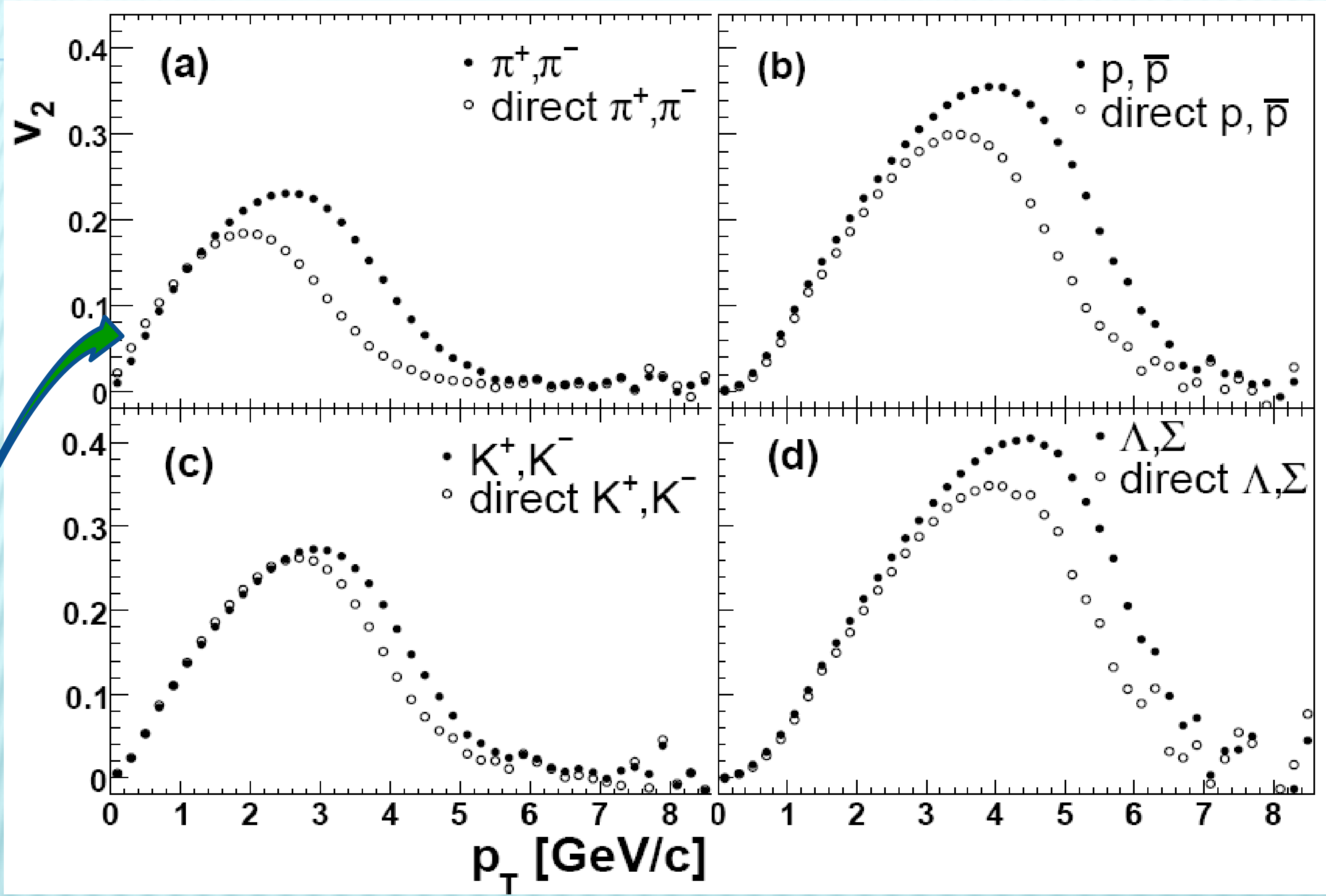


TABLE I: Yelds of the particles produced directly and with resonance decays, $5.6 \cdot 10^6$ events, c=42%, midrapidity

	$\pi^{\pm}$	$K+\bar{K}$	$p+\bar{p}$	$\Lambda+\bar{\Lambda}+\Sigma+\bar{\Sigma}$	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 %

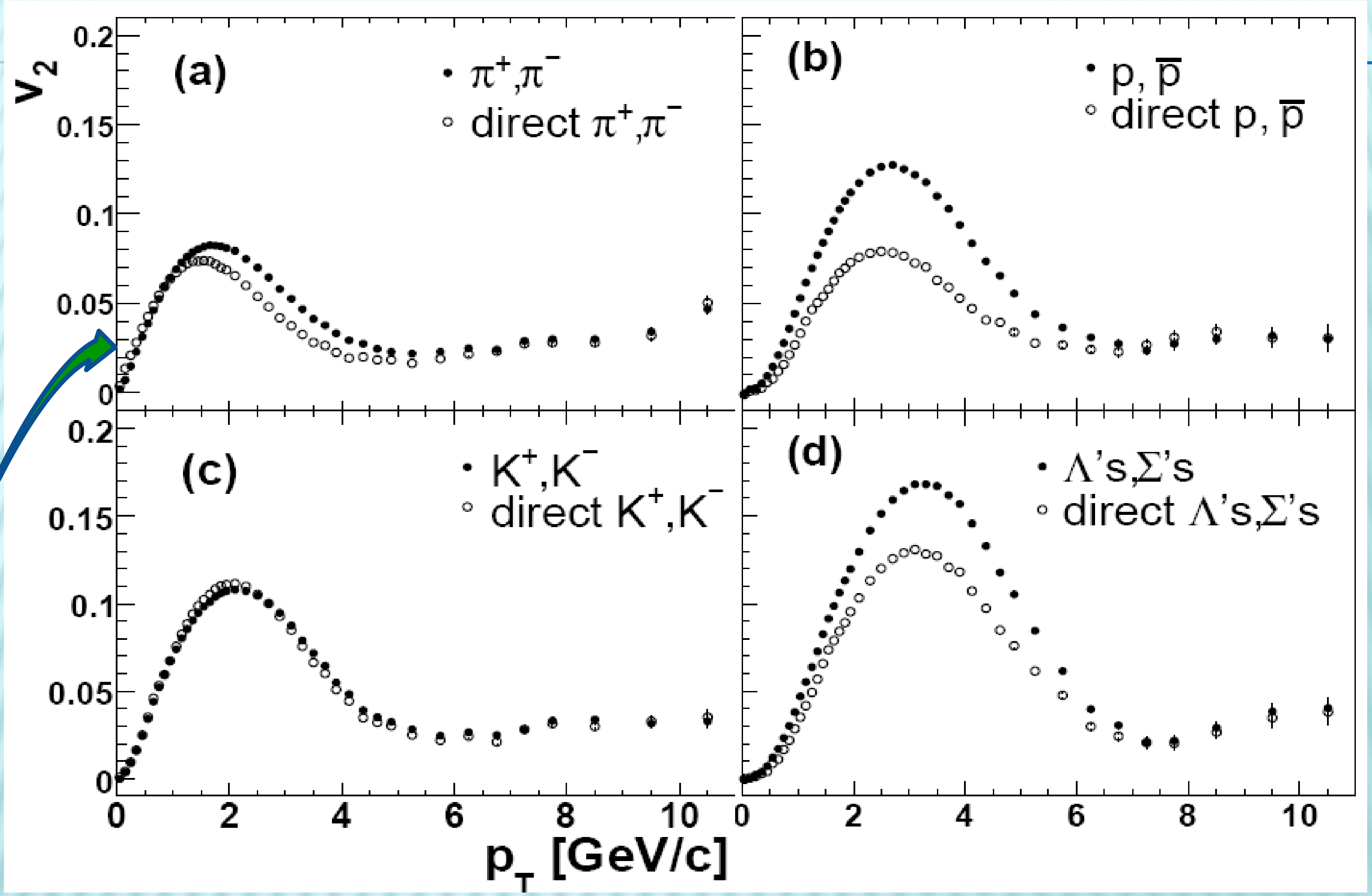
Influence of resonance decays for different type of particles at RHIC



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



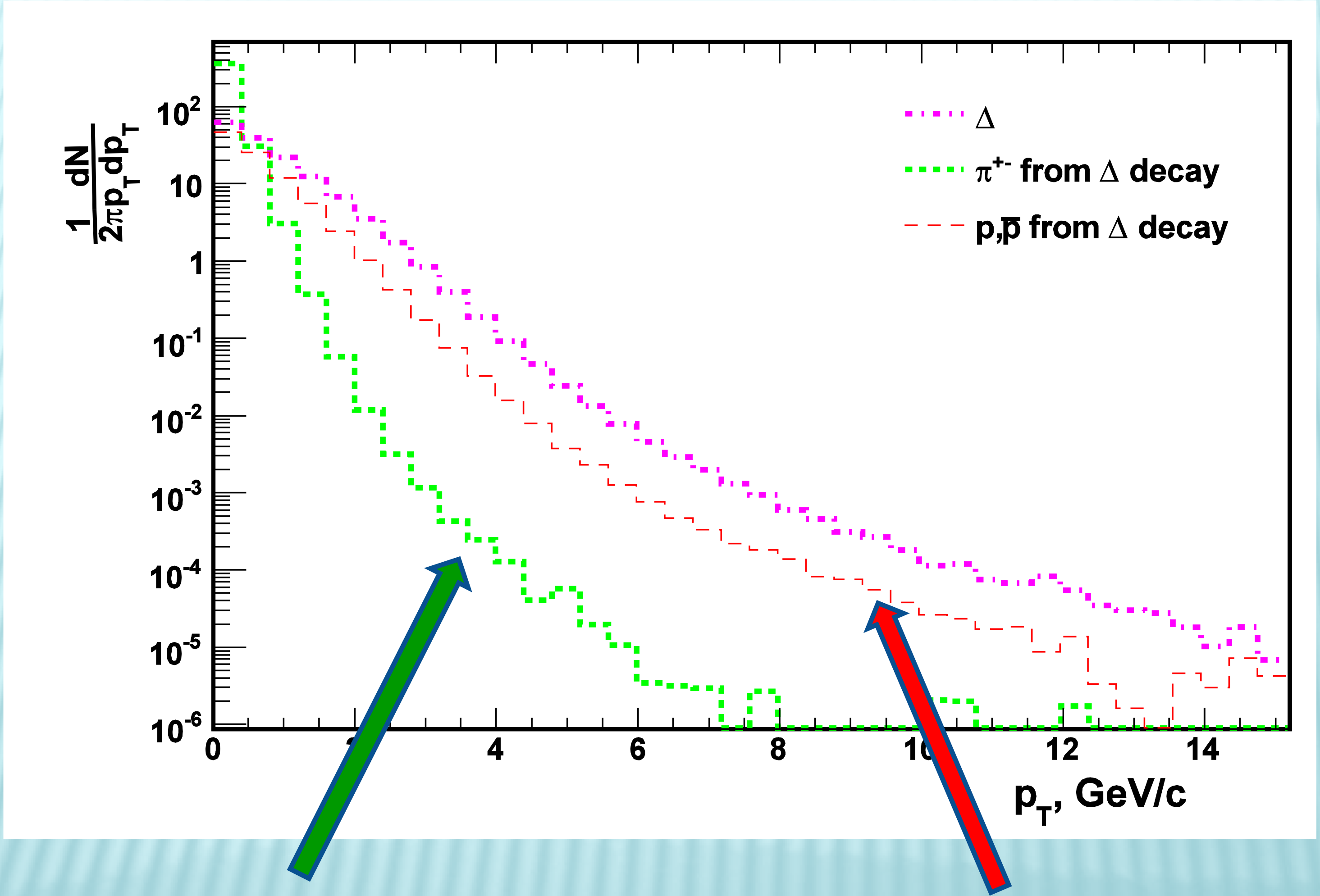
Pions: the resulting flow is weaker at low-pt and larger at high-pt

Kaons: both flows almost coincide

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

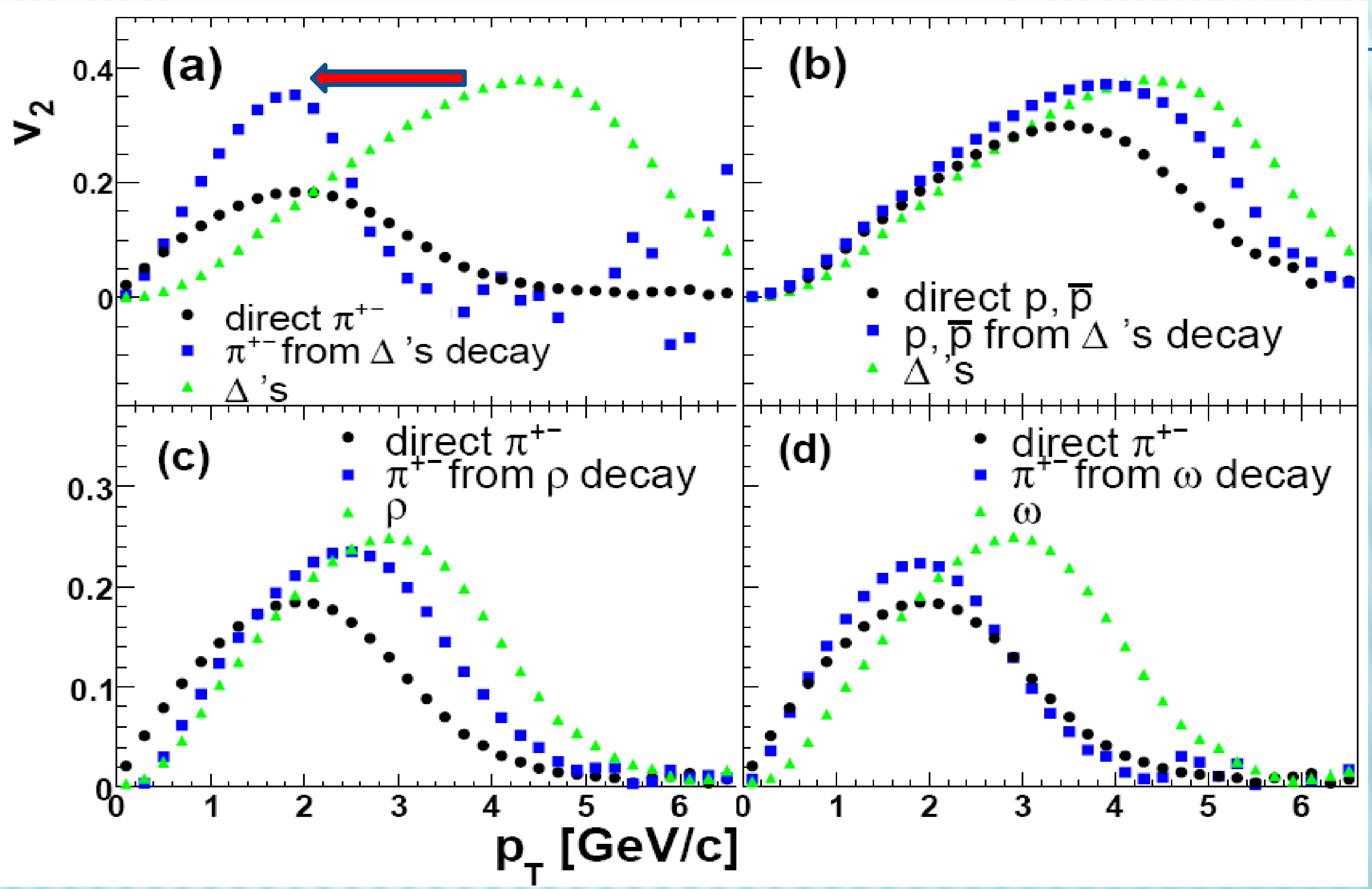
TRANSVERSE MOMENTUM OF SECONDARY PARTICLES

$\Delta \rightarrow \pi + p$



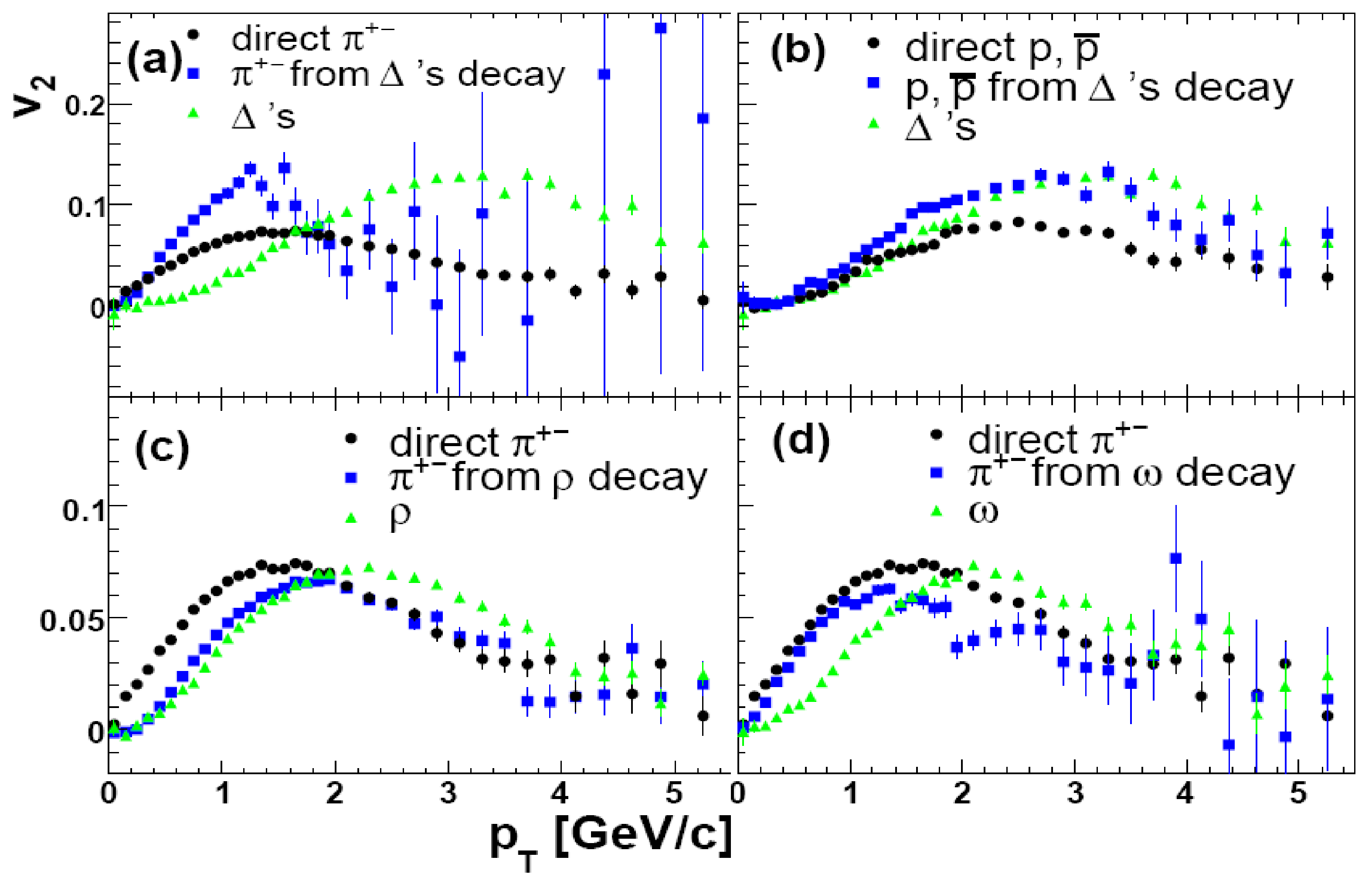
The secondary pion spectrum is much softer than proton spectrum

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

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: 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

Methods for $\mathbf{v_2}$ calculation

(1) Event plane method

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

Ψ_2 is the calculated reaction plane angle:

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

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

(2) Two particle correlation method

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

(3) Lee-Yang zero method

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

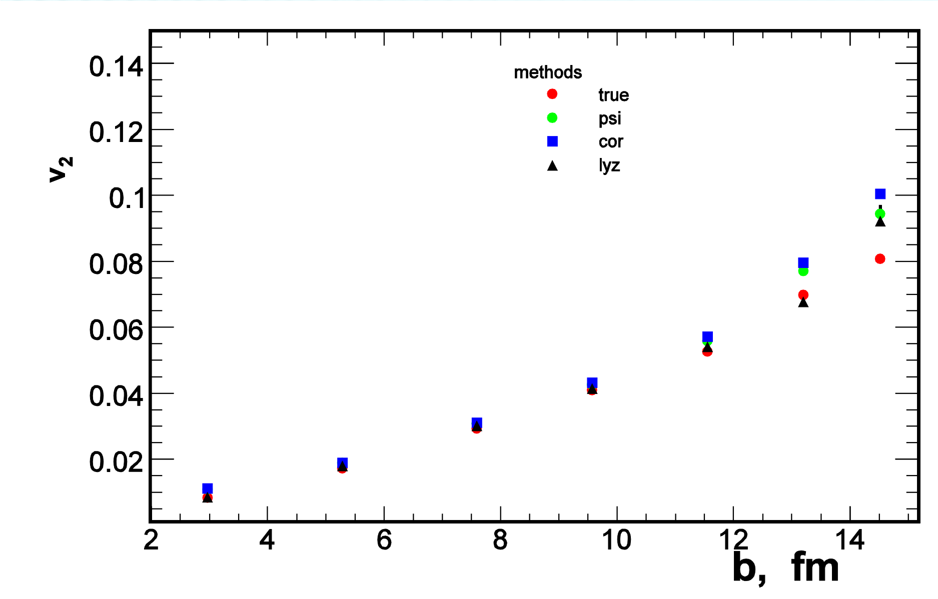
Integral v_2 is connected with the firs minimum r_0 of the module of the G(ir):

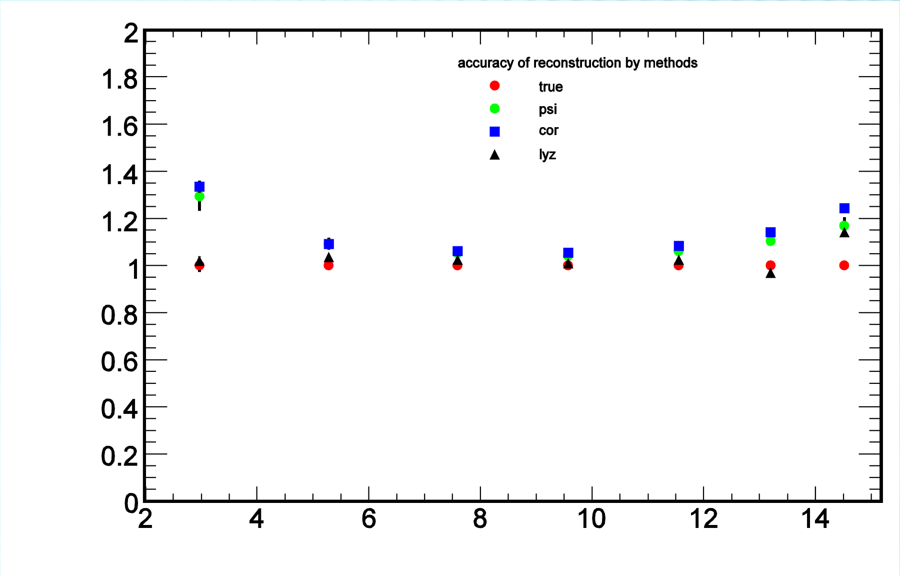
$$v_2 = \frac{j_0}{Nr_0}$$

Differential flow is calculated by the formula:

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

RECONSTRUCTION OF INTEGRAL VALUE OF V2 BY THE METHODS

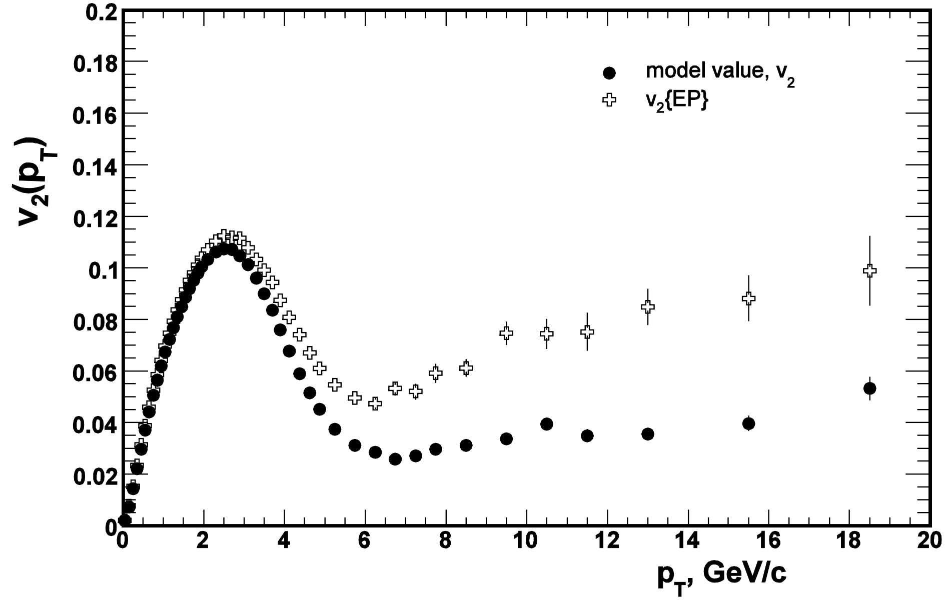


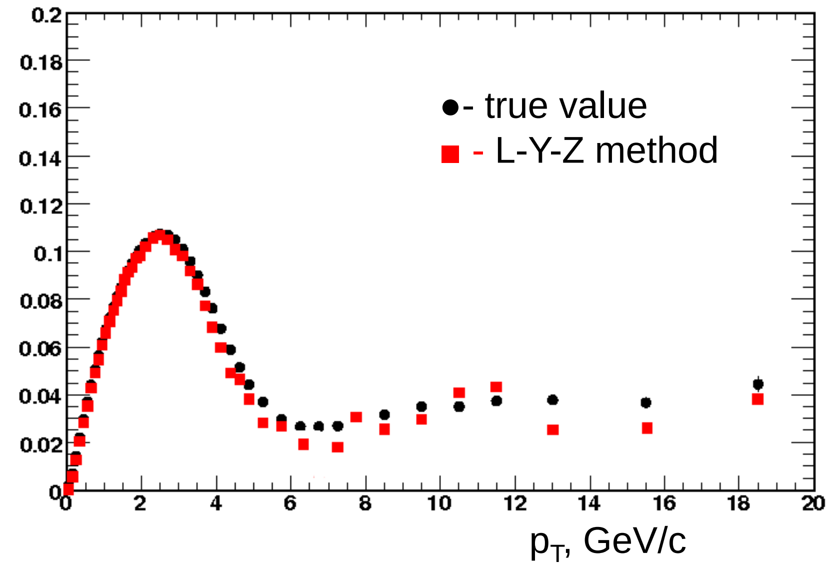


The better reconstruction is achived in midcentral collision for the methods, while Lee-Yang zero method tends to reconstruct true value at more central and more periferal collision.

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).