HYDJET++ MODEL FOR RELATIVISTIC HEAVY ION COLLISIONS AT RHIC AND LHC

L. Bravina, H. Brusheim Johansson, J. Crkovska,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. Influence of resonance decays

IV. NCQ-scaling for v2 at RHIC and LHC

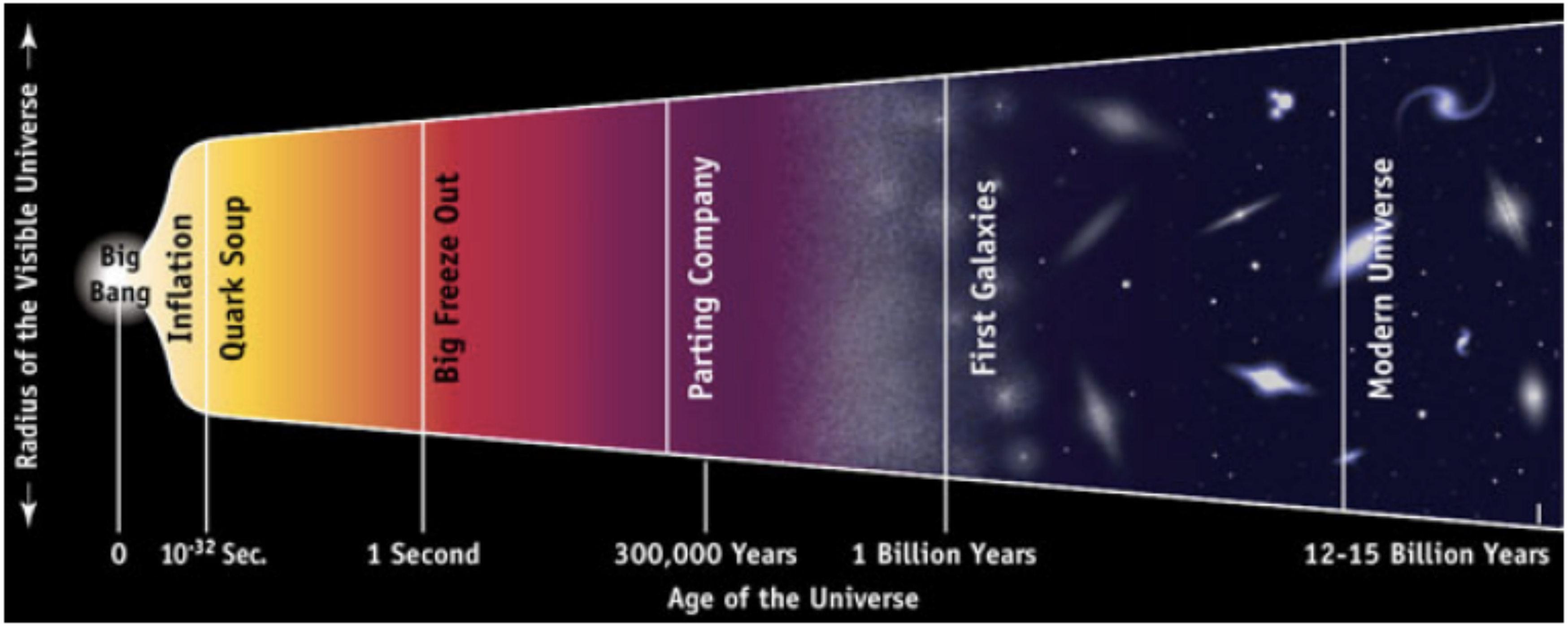
V. Model results for the ratio $v4/(v2)^2$ at RHIC and LHC

VI. High harmonics and ridge

VII. Conclusions

Heavy-Ion Collisions

- aim to recreate conditions as in Universe shortly after Big Bang
- high energy densities and temperatures $\Rightarrow$ new state of matter
- LHC (CERN), RHIC (BNL)



Collective flow

- flow is a collective motion of particles
- pressure gradient inside fireball creates an outward motion of matter
- bulk properties of created medium
- can be described by thermodynamics
- the most thoroughly studied both in experiment and theory

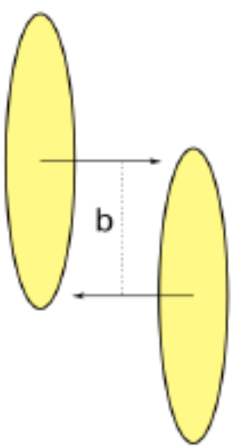
Flow in HIC

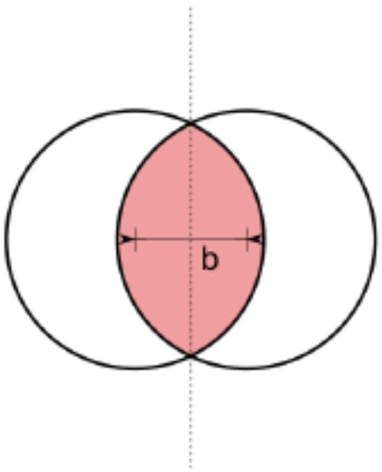
Isotropic flow

- additional momentum boost due to medium expansion

Anisotropic flow

- initial asymmetry of overlap region function of *b*
- restoration of spatial isotropy $\Rightarrow$ momentum anisotropy
- information about early stages of collision





Azimuthal distribution

Fourier decomposition

- angular anisotropy can be developed into a Fourier series

$$\frac{dN}{d\varphi} = \frac{N}{2\pi}\left[1 + 2\sum v_n \cos\left(n(\varphi - \Psi_R)\right)\right] \quad (1)$$

$$v_n = \langle \cos\left(n(\varphi - \Psi_R)\right)\rangle$$

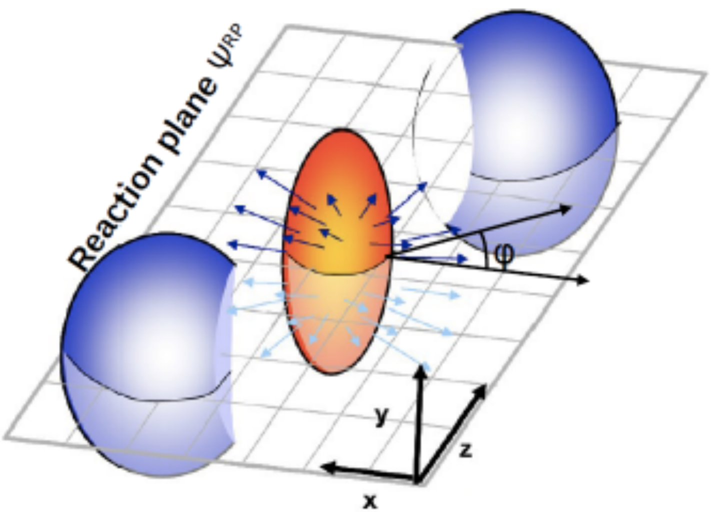
$$\varepsilon_n = \sqrt{\langle r^2 \cos\left(n\varphi\right)\rangle^2 + \langle r^2 \sin\left(n\varphi\right)\rangle^2} / \langle r^2 \rangle$$

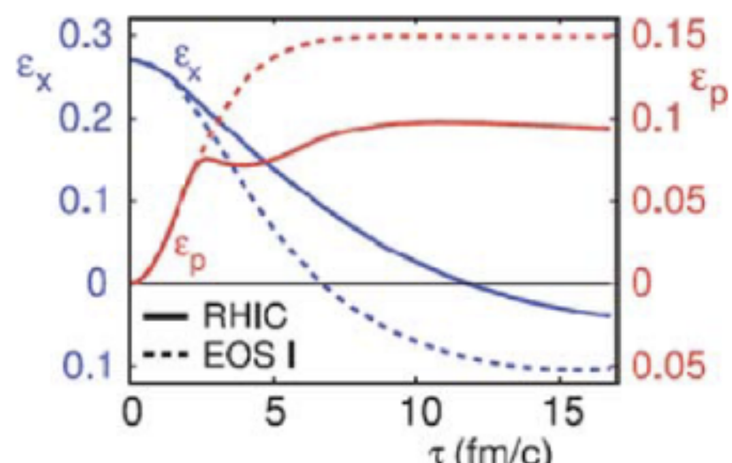
- φ is azimuthal angle in momentum
- Ψ_R is reaction plane angle
- the first term represents isotropic flow
- v_1 directed flow, v_2 elliptic flow, v_3 triangular flow

Elliptic flow

$$v_2 = \langle \cos(2(\varphi - \Psi_R)) \rangle$$

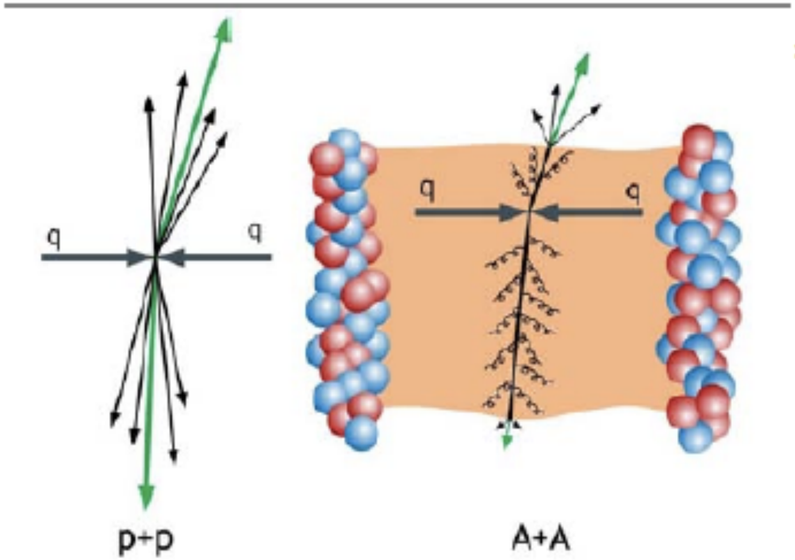
- dominant contribution to the anisotropic flow
- originates from the almond shape of overlap region
- evolution reduces spatial anisotropy ⇒ momentum anisotropy ⇒ self-quenching phenomenom

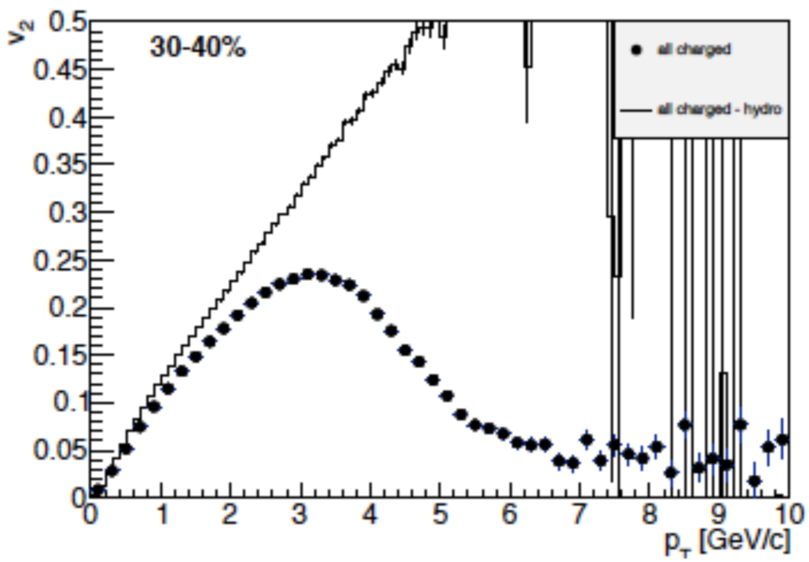




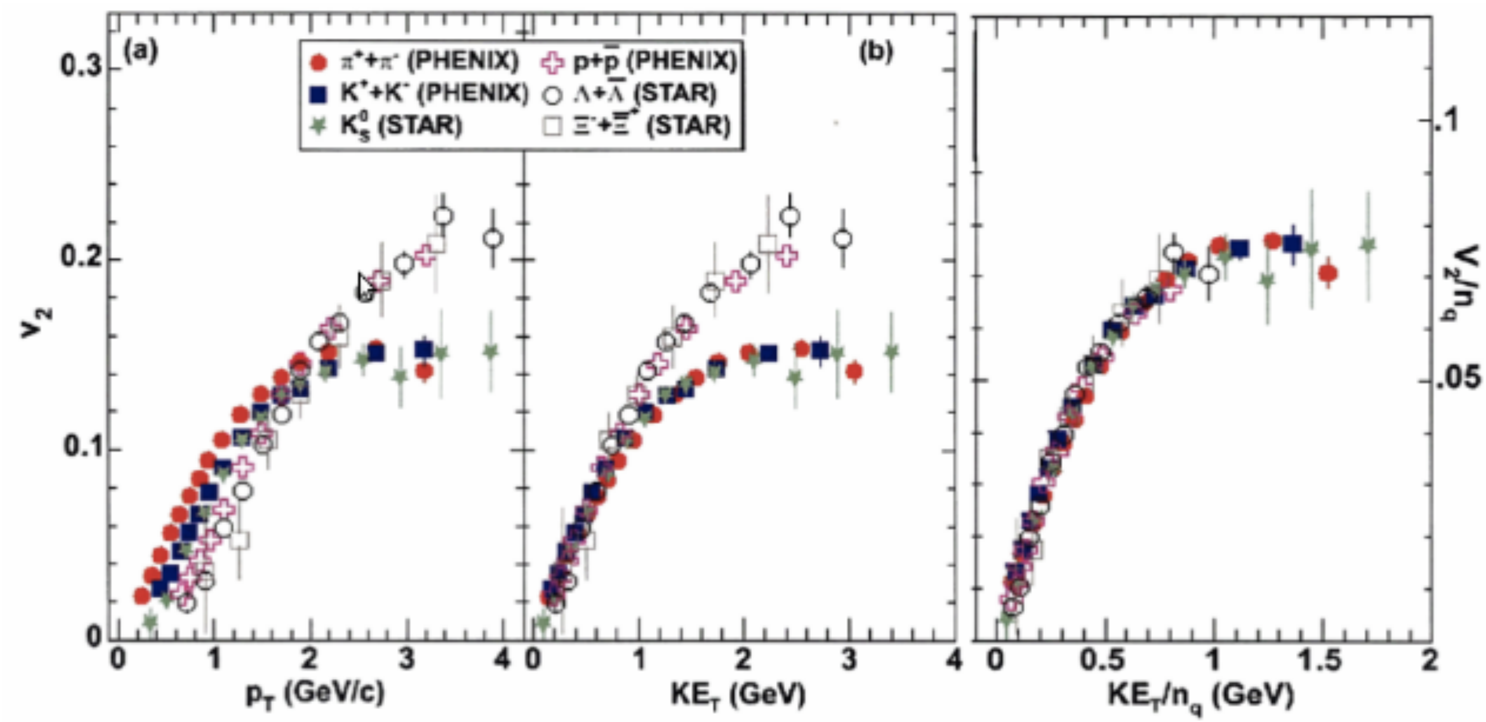
Jet quenching

- high-p_T $q\bar{q}$ pair moving in opposite direction $\Rightarrow$ 2 cones at $\Delta\phi \approx \pi$
- pair created at the edge of the fireball $\rightarrow$ one jet exits the region immediately, the other travels through the medium





Number-of-constituent-quark scalling



Phys. Rev. Lett **98** (2007) 162301

- favours v_2 formation on partonic level
- favours coalescence-production scenario

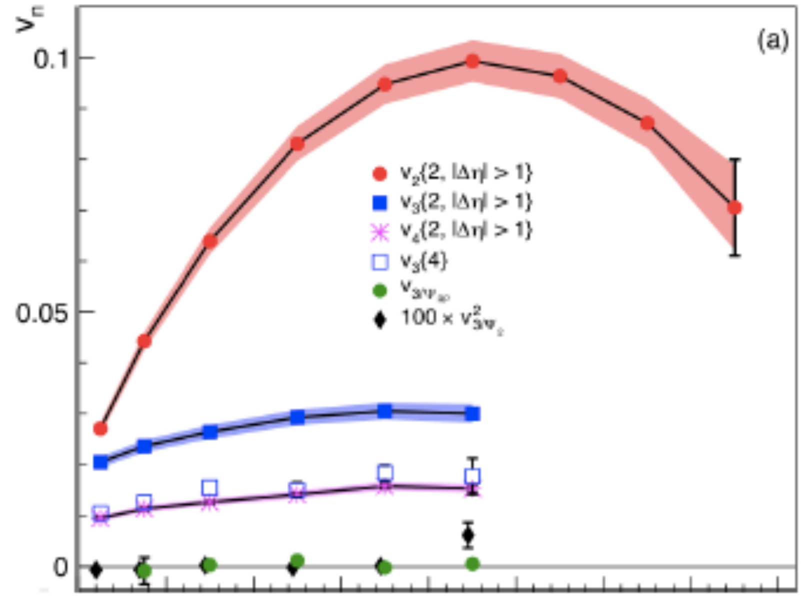
Event-by-event fluctuations

- largest pressure gradient along minor axis Ψ_n

$$v_n(\Psi_n) = \langle \cos\left(n(\varphi - \Psi_n)\right)\rangle$$

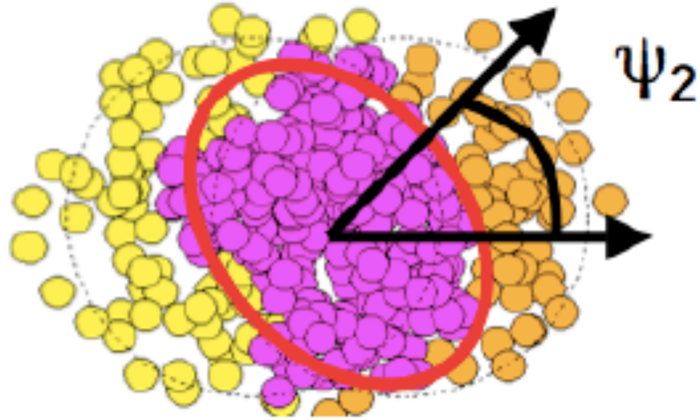
- Ψ_2 and Ψ_3 uncorrelated
- v_2 and v_3 $\Rightarrow$ higher coefficients

$\Rightarrow$ need at least Ψ_2 and Ψ_3 to describe the system

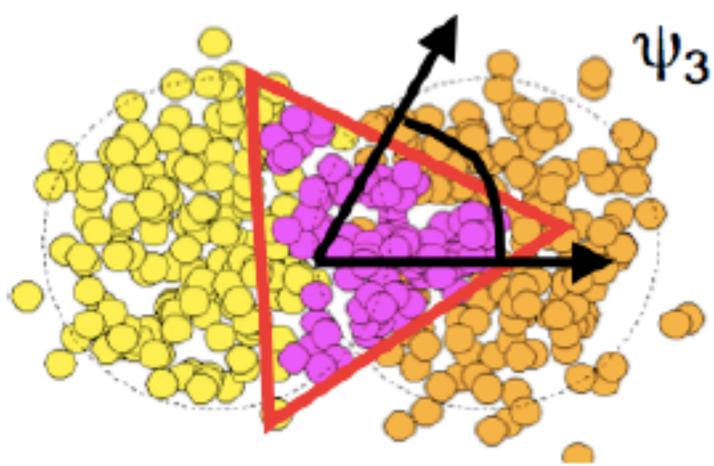


Phys. Rev. Lett **107** (2011) 032301

B. Alver et al., arXiv:0805.441



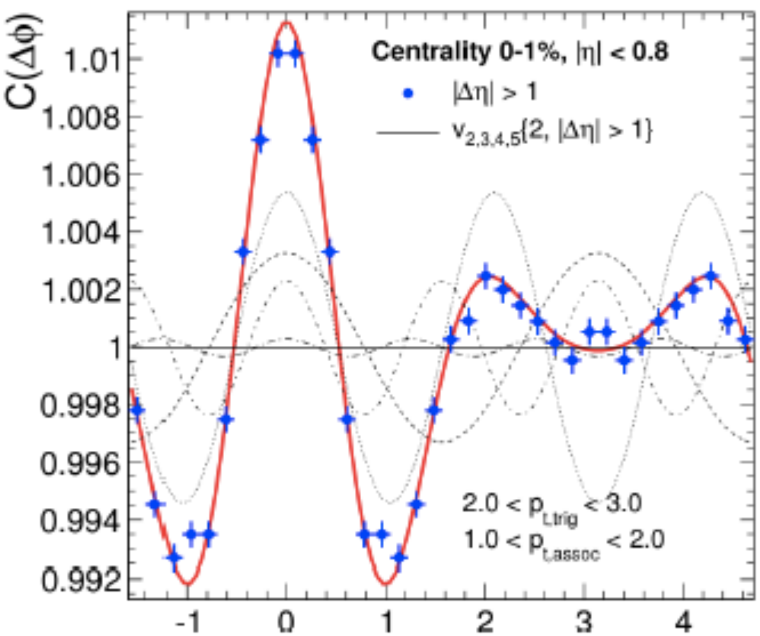
$$\varepsilon = \frac{\sqrt{\left\langle r^2 \cos(2\phi)\right\rangle^2 + \left\langle r^2 \sin(2\phi)\right\rangle^2}}{\left\langle r^2 \right\rangle}$$



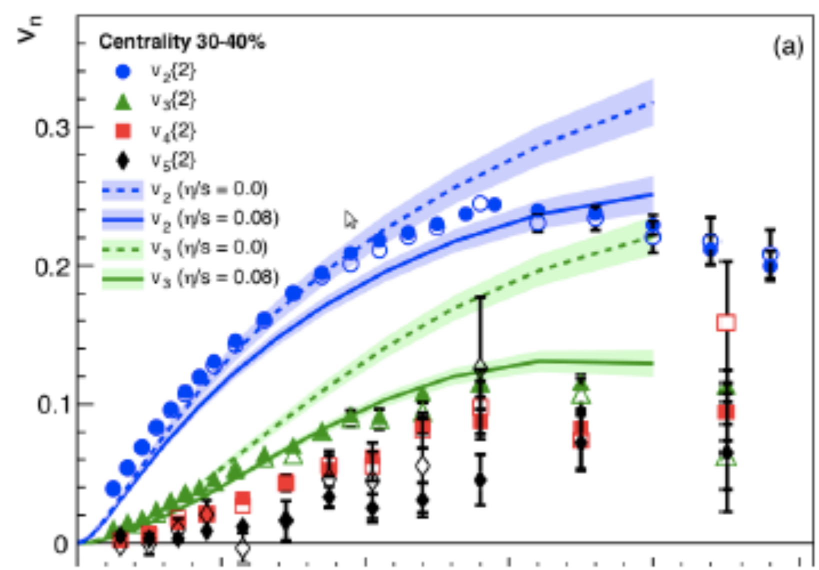
$$\varepsilon_3 = \frac{\sqrt{\left\langle r^2 \cos(3\phi)\right\rangle^2 + \left\langle r^2 \sin(3\phi)\right\rangle^2}}{\left\langle r^2 \right\rangle}$$

Higher harmonics

- information on initial geometry
- more sensitive to viscosity
- explain shape of 2-particle correlation

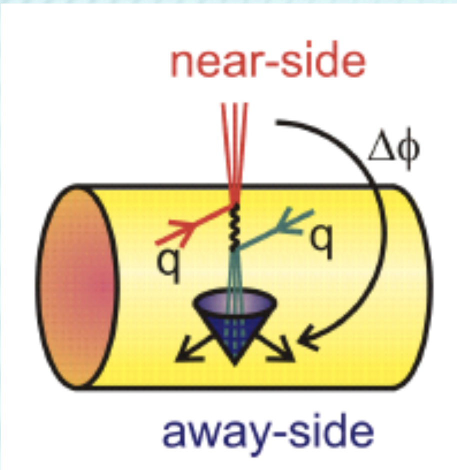


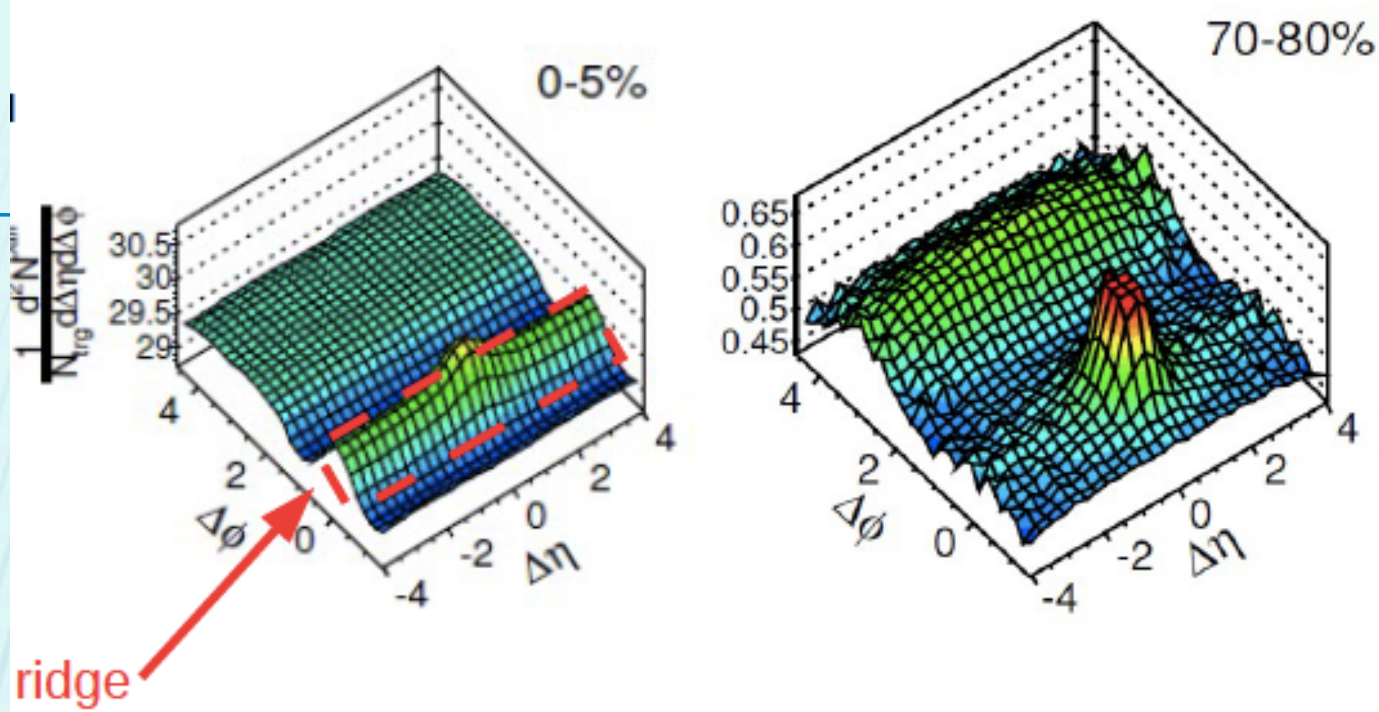
Phys. Rev. Lett **107** (2011) 032301



Phys. Rev. Lett **107** (2011) 032301

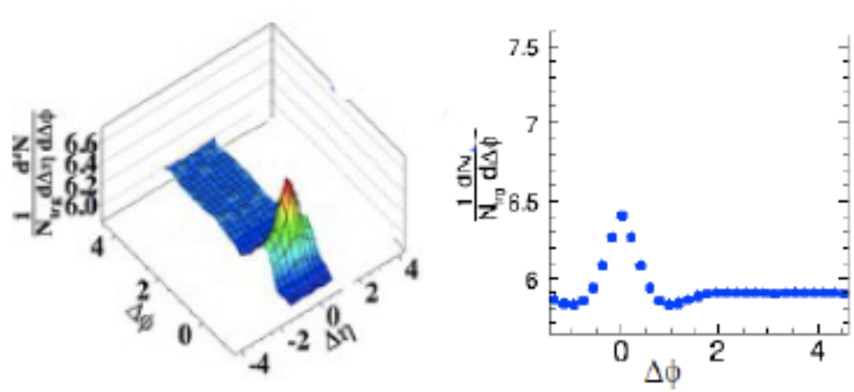
RIDGE



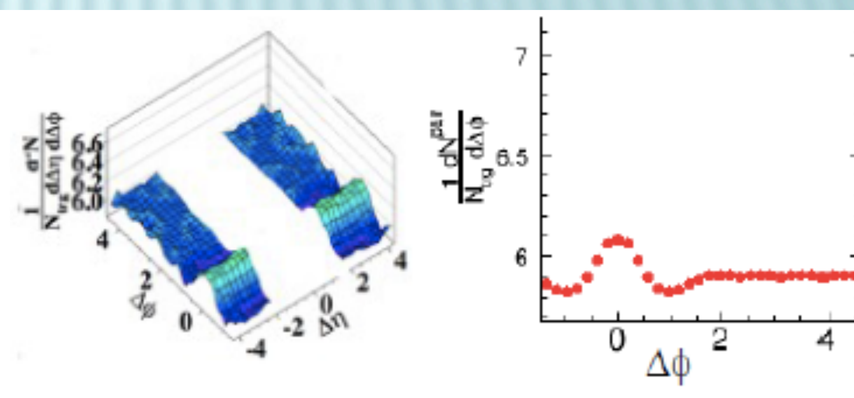


CMS, PbPb 2.76 TeV, Eur. Phys. C 72 (2012) 10052, $3<pt^{trig}<3.5$ Gev/c, $1<pt^{assoc}<1.5$ GeV/c

THE JET REGION



RIDGE REGION



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} , $\{\mu_B, \mu_S, \mu_Q\}$
2. If thermal freeze-out is considered: T_{th} , μ_π-normalisation constant
3. Volume parameters: **τ, Δτ**, **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 $\delta(b)$, $\varepsilon(b)$

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

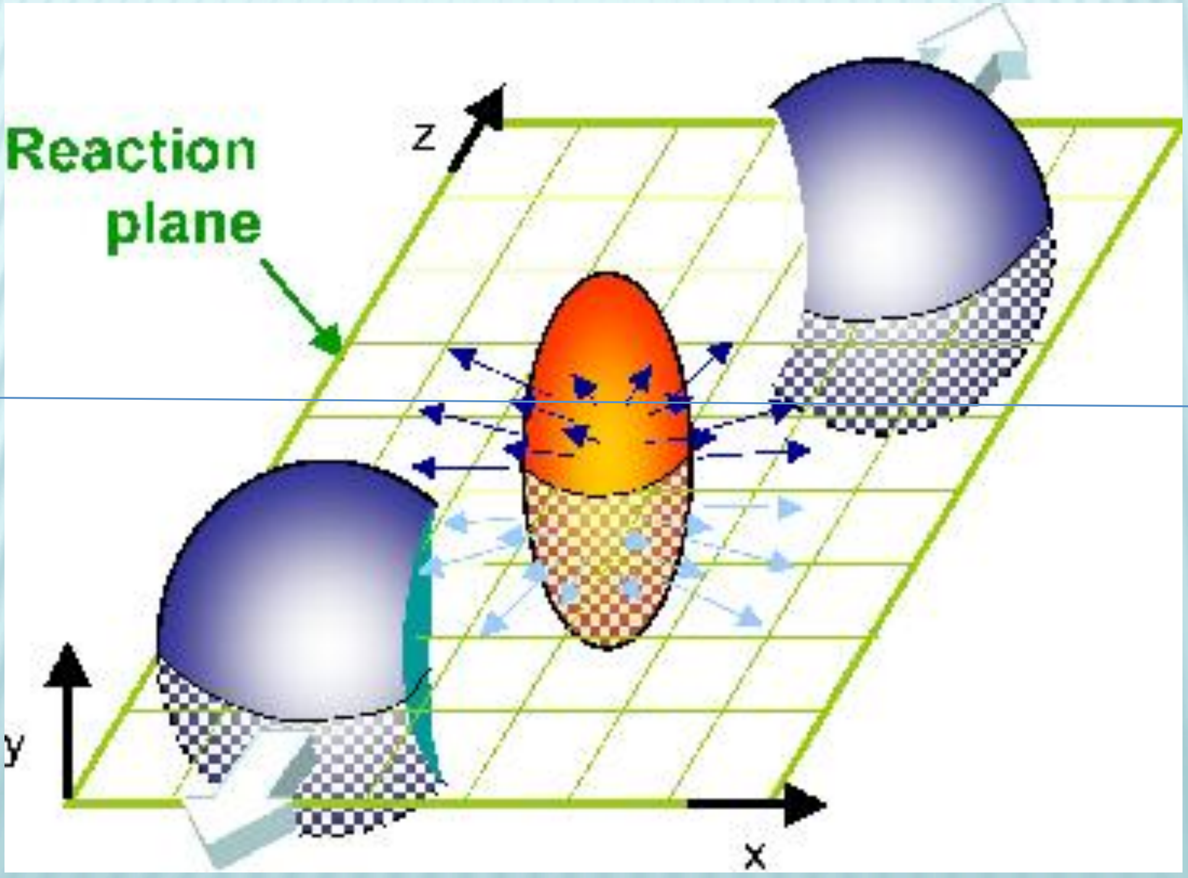
4. ienglu - flag to fix type of medium-induced partonic energy loss
(ienglu=0 - radiative and collisional loss, ienglu=1 - radiative loss only, ienglu=2 - collisional loss only, default value is ienglu=0);
ianglu - flag to fix type of angular distribution of emitted gluons
(ianglu=0 - small-angular,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

II. Elliptic flow in HYDJET++ : interplay of hydrodynamics and jets

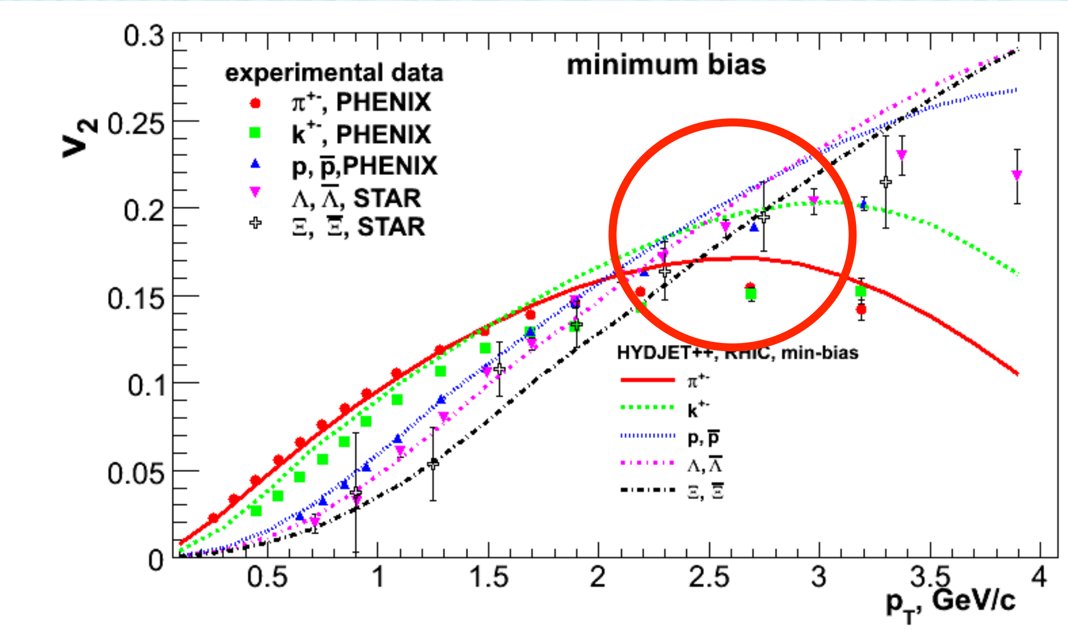
Anisotropic flow

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

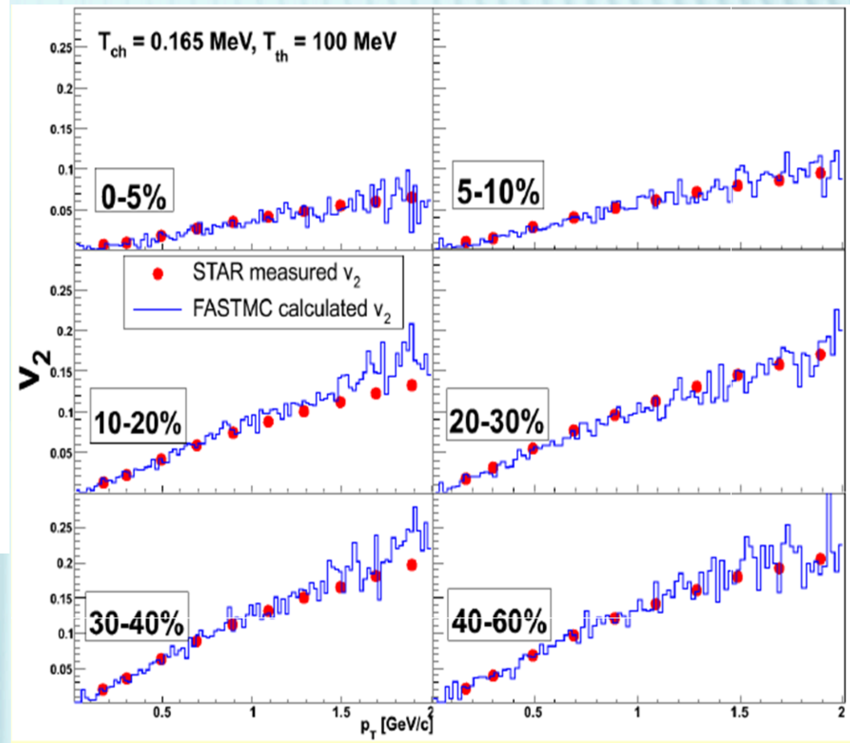
$$\frac{dN}{d\varphi} = \frac{1}{2\pi}\left(1 + \sum_{n=1}^{\infty} 2v_n(p_t)\cos[n(\varphi - \psi_r)]\right)$$

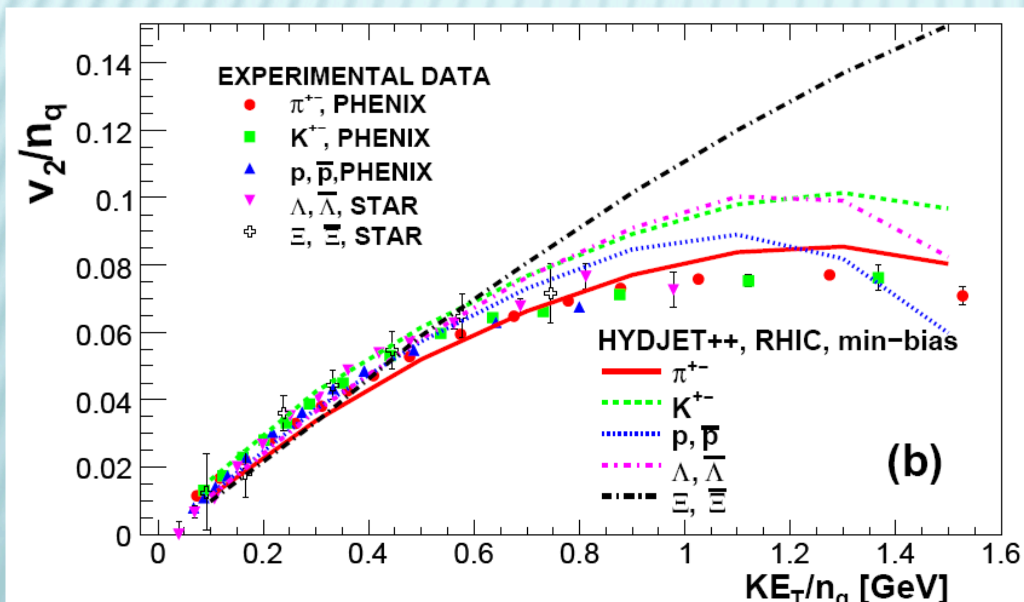


RHIC DATA VS. HYDJET++ MODEL



Au+Au @ 200 AGeV

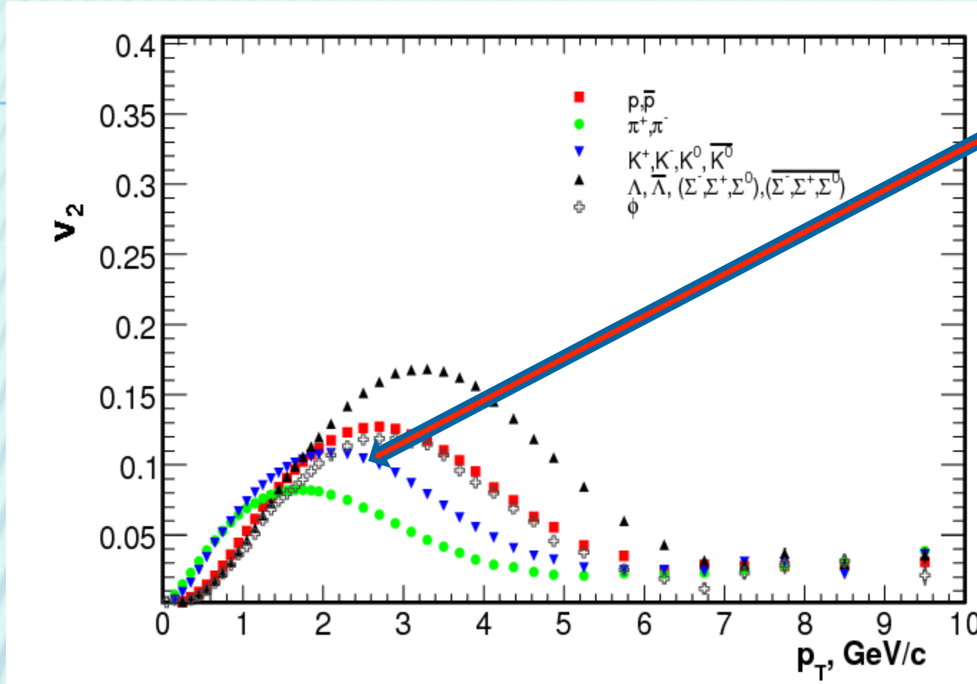




Elliptic flow

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%)

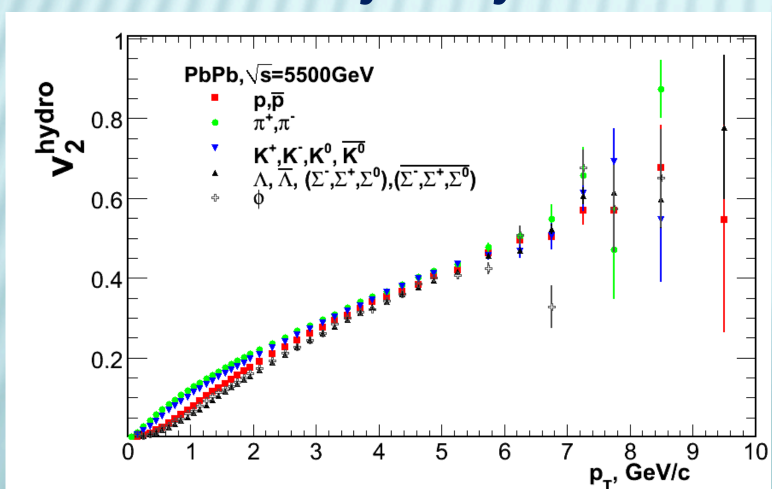


Mass ordering in soft p_T regions then breaks.

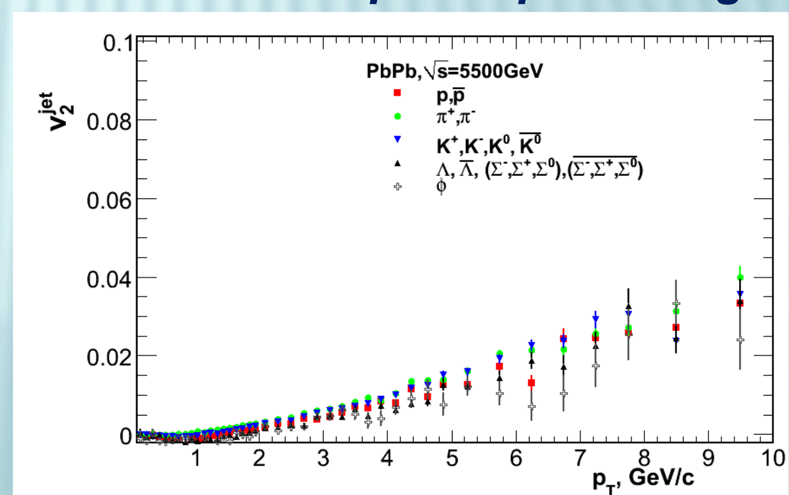
Why?

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

Hydrodynamics



Jet part +quenching



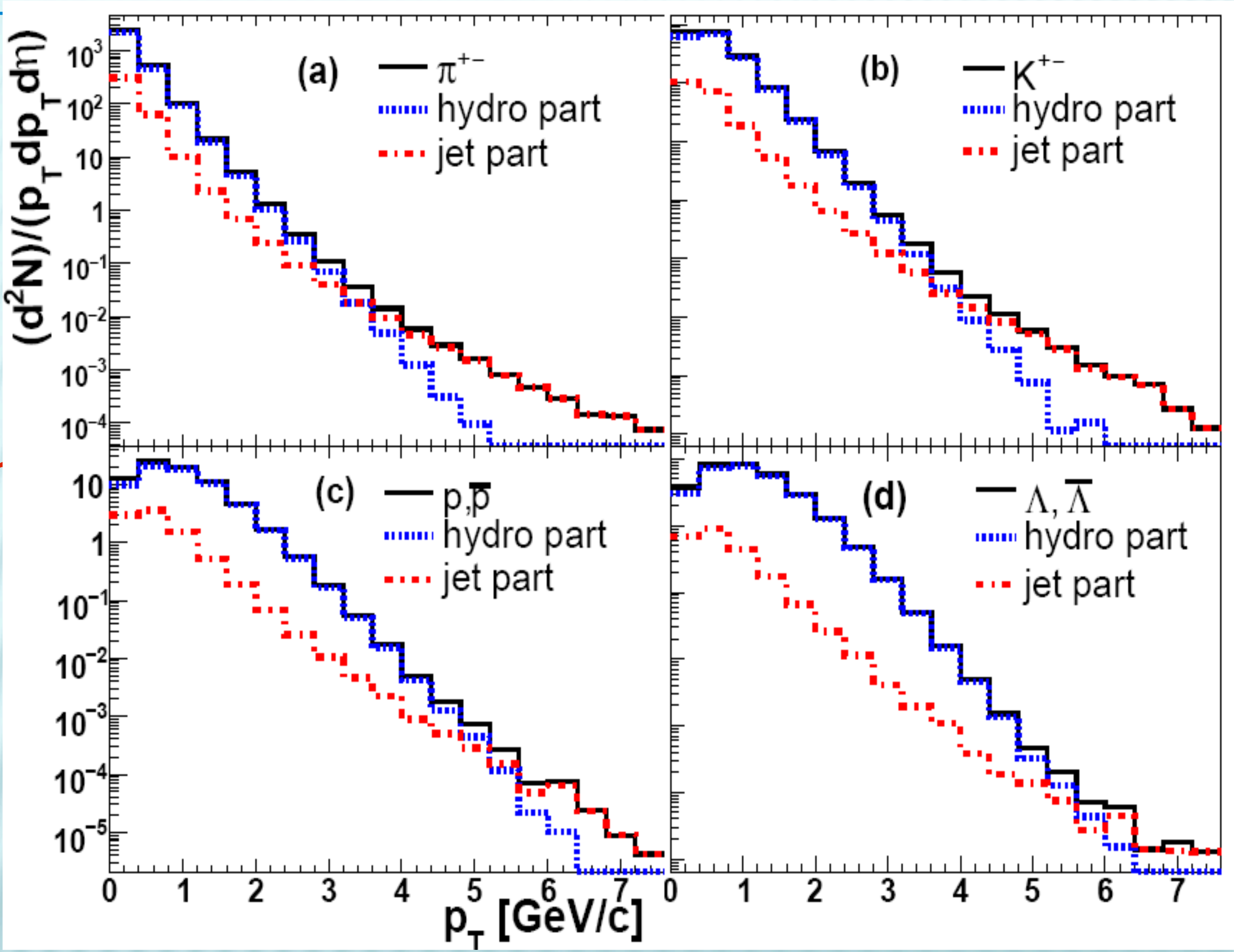
Interplay between hydrodynamics and jets

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

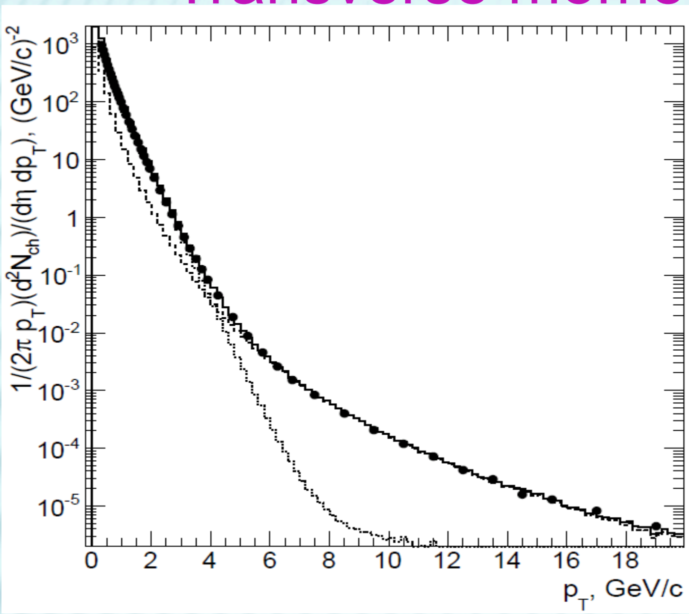
The hydro part dies out earlier for light particles than for heavy ones



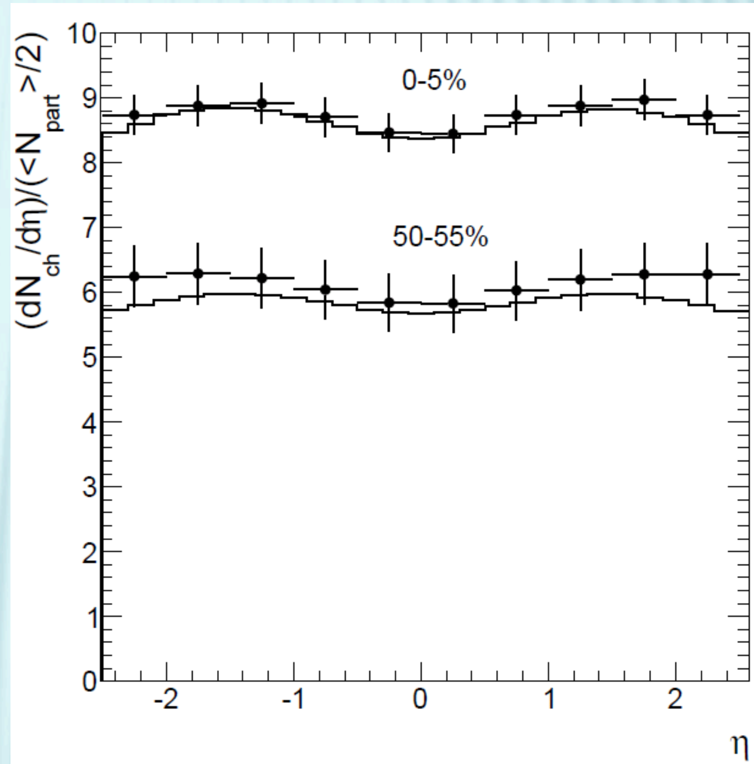
LHC DATA VS. HYDJET++ MODEL

Transverse momentum

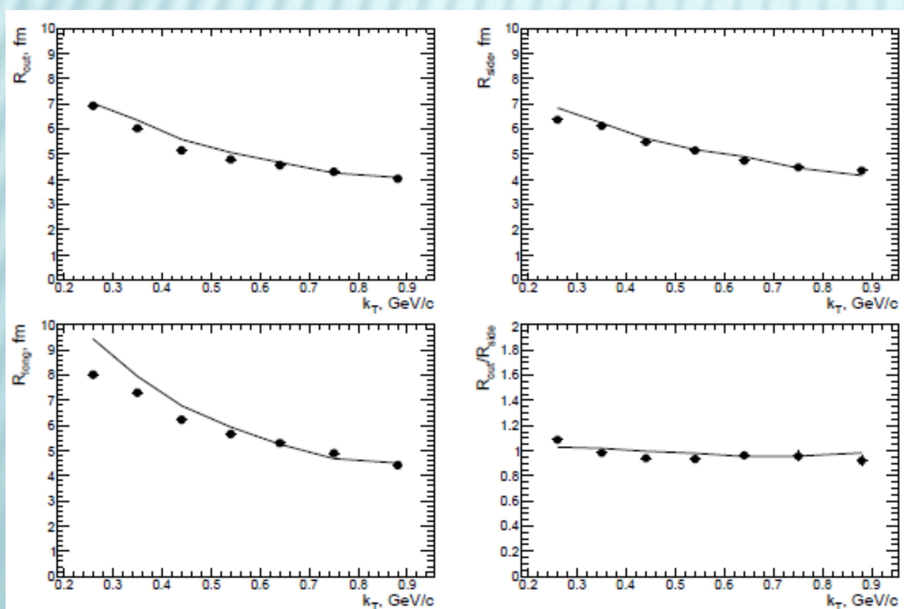
Pb+Pb @ 2.76 ATeV



Rapidity



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

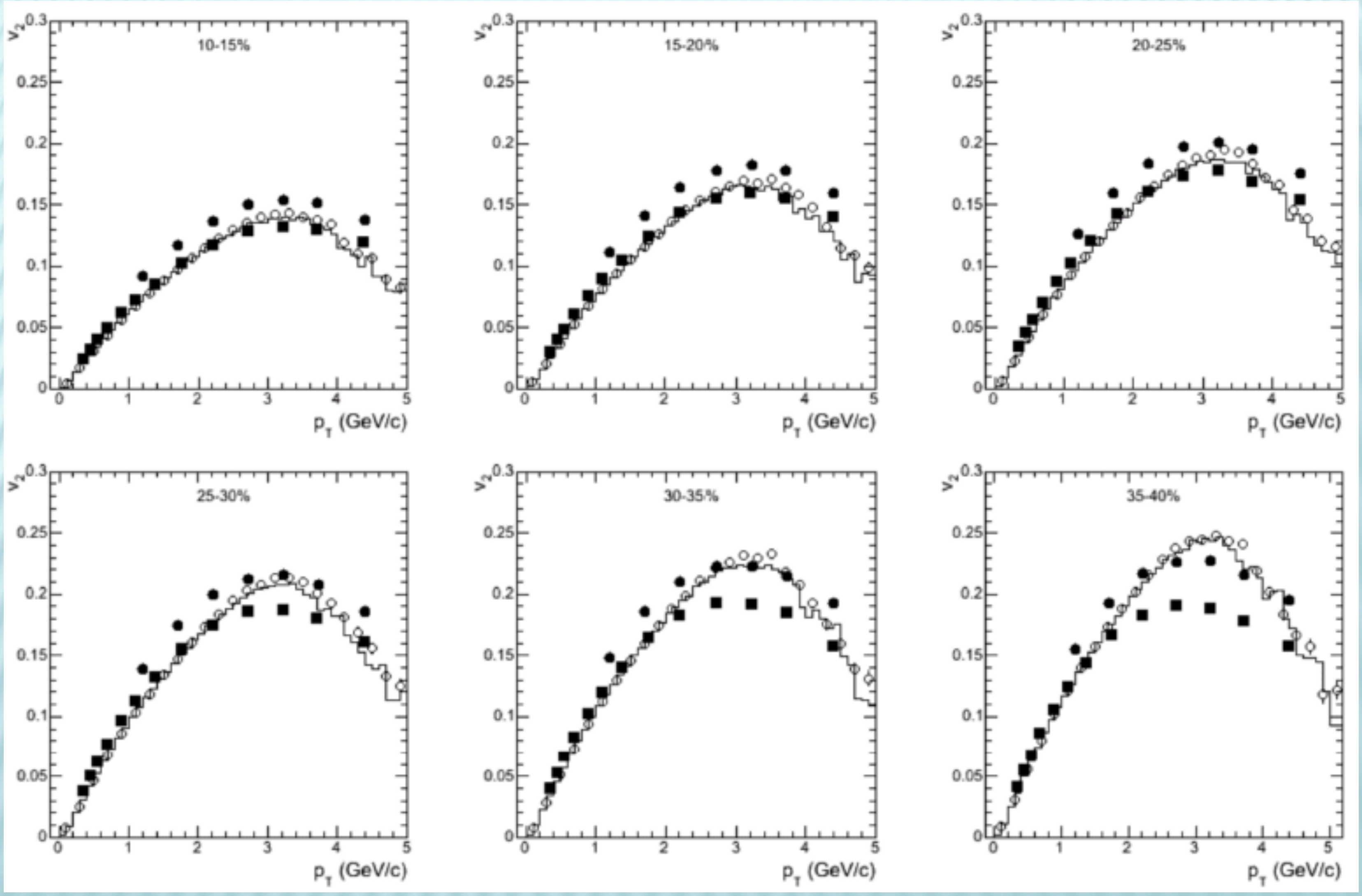


Correlation radii (femtoscopy)

LHC DATA VS. HYDJET++ MODEL

Elliptic flow

Pb+Pb @ 2.76 ATeV



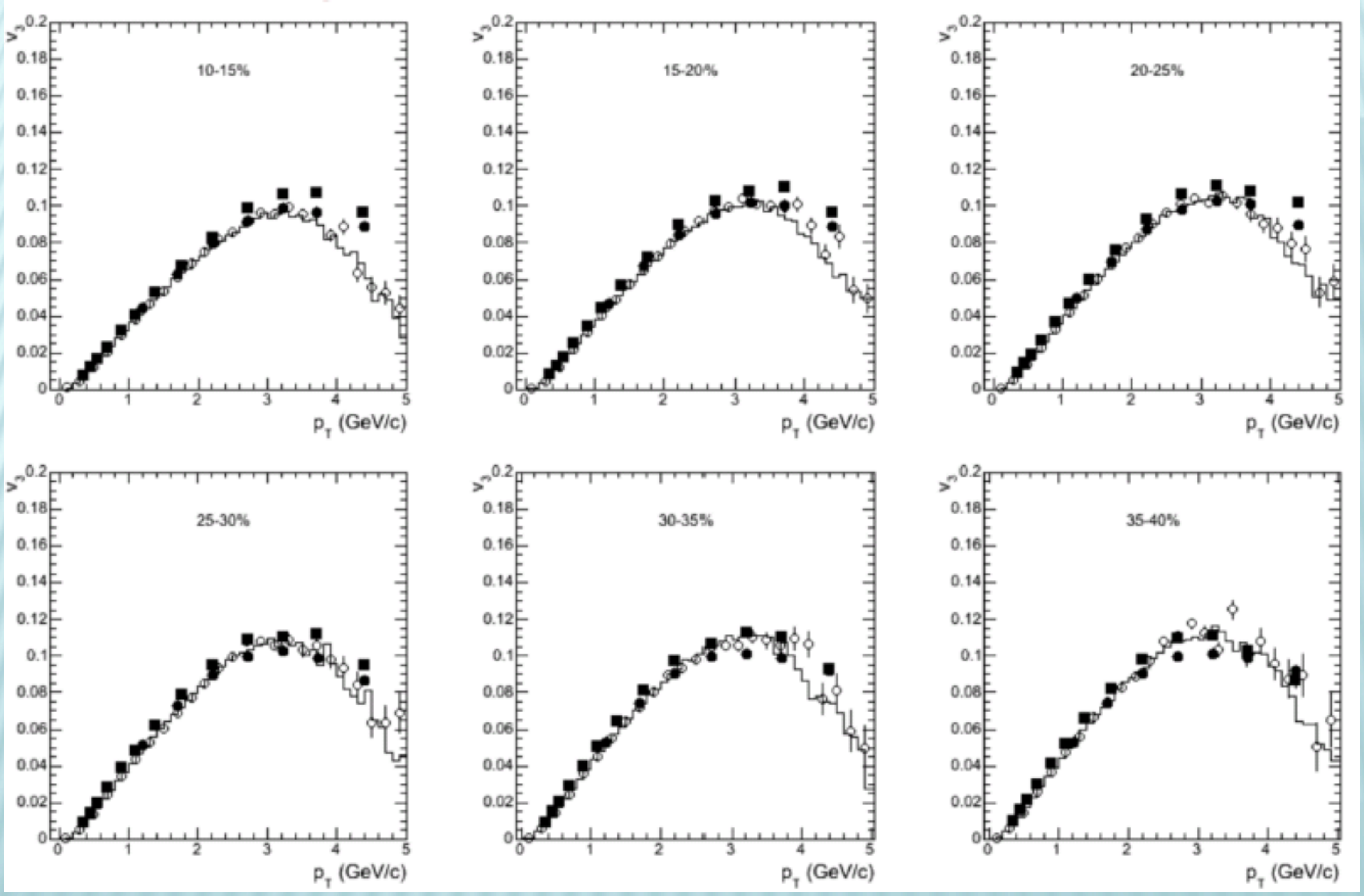
L. B et al., Eur. Phys. J C74 (2014) 2807

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

LHC DATA VS. HYDJET++ MODEL

Triangular flow

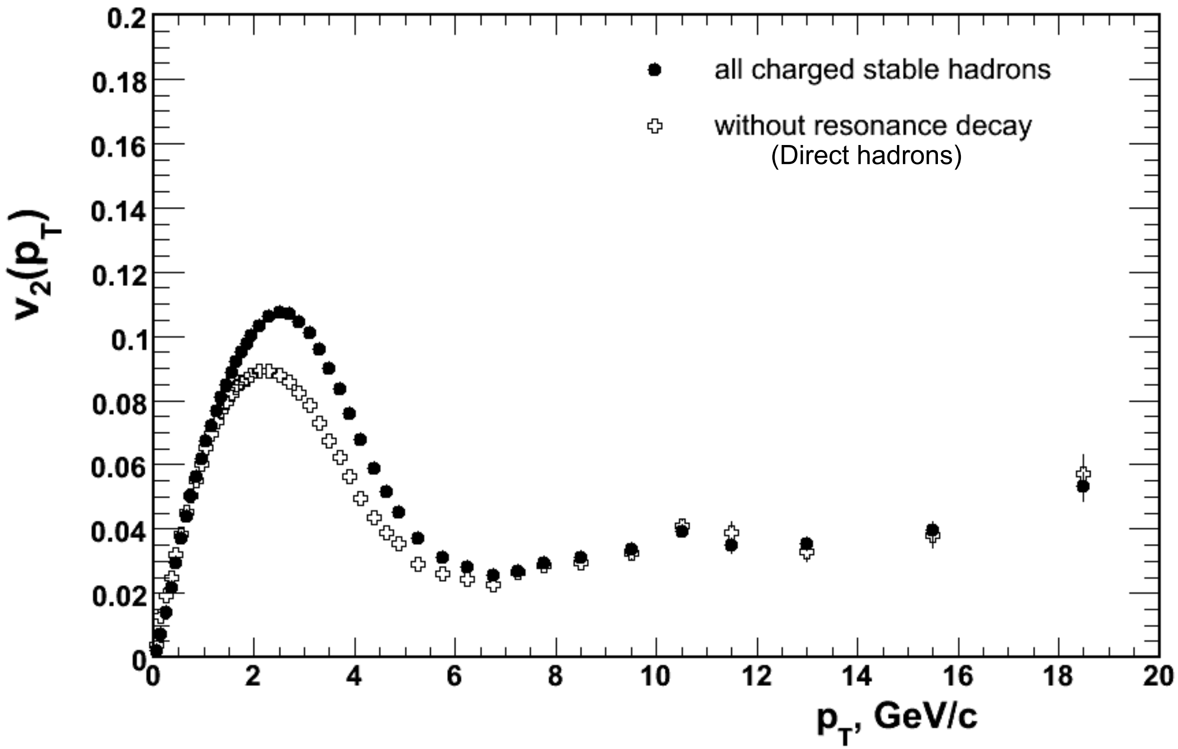
Pb+Pb @ 2.76 ATeV



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

III． Influence of resonance decays

Influence of resonance decay on v2 value



PbPb collisions, c=30%

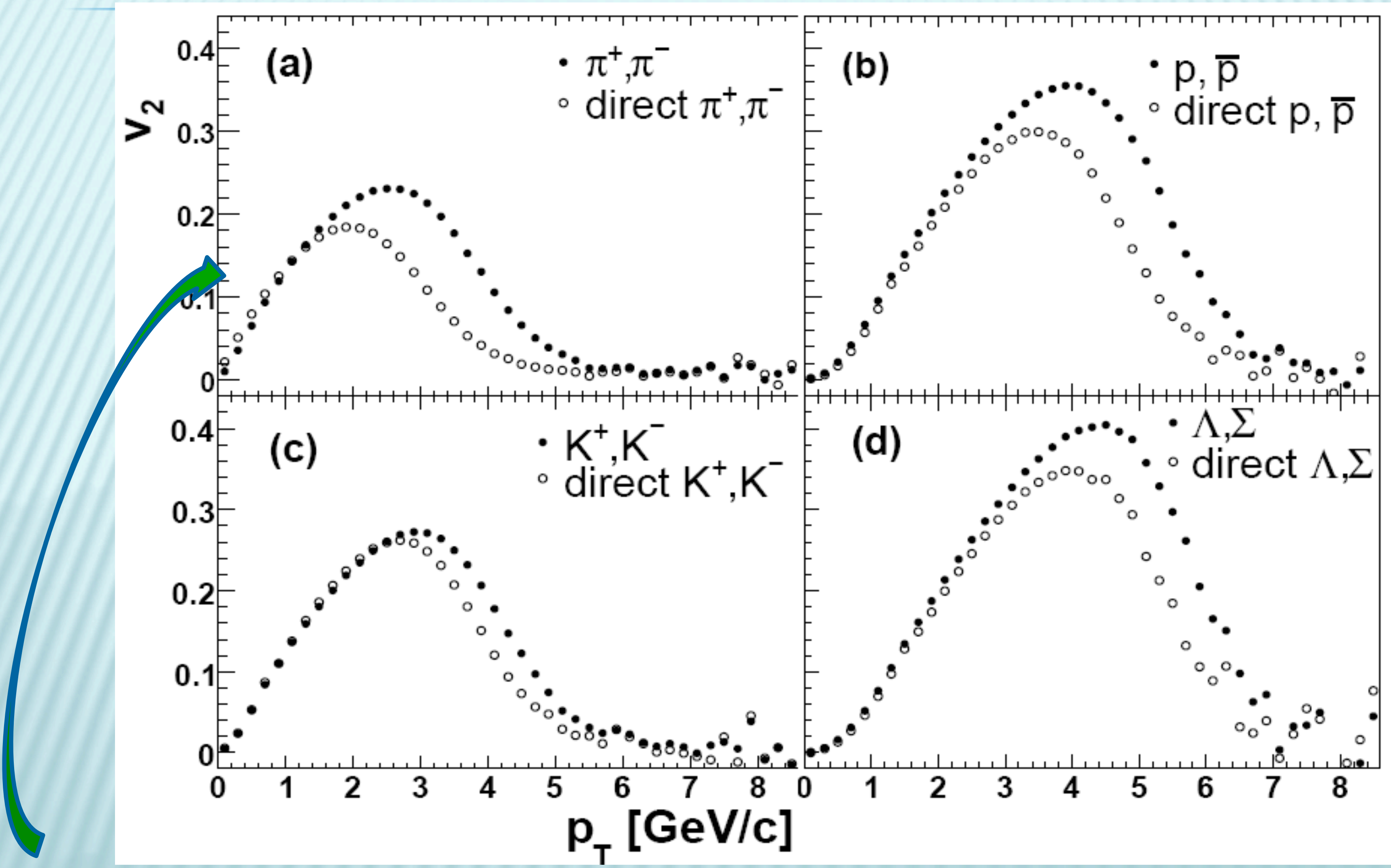
The elliptic flow of directly produced particles is smaller than that for all particles.

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

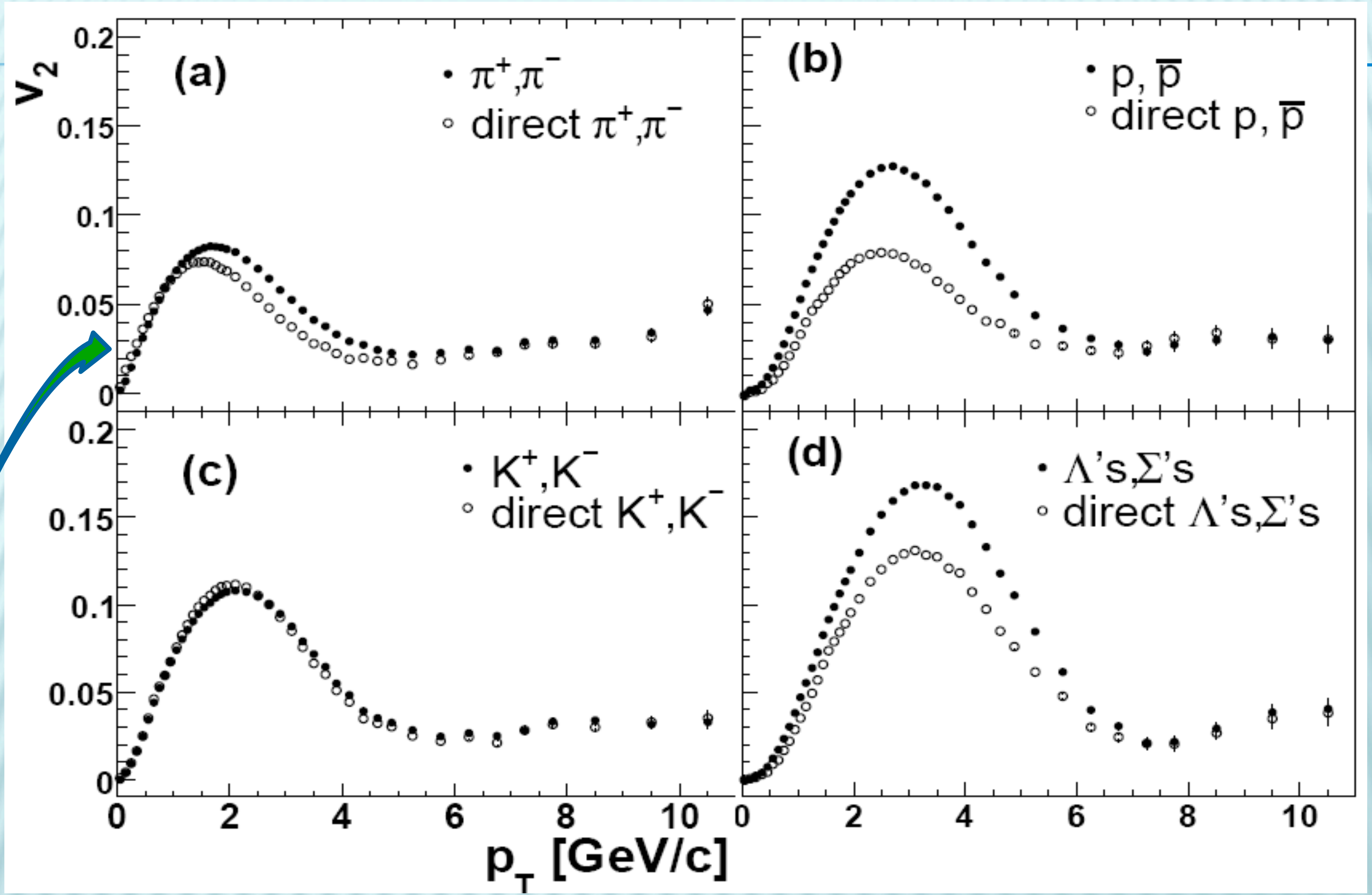
G. Eyyubova et al., PRC 80 (2009) 064907



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

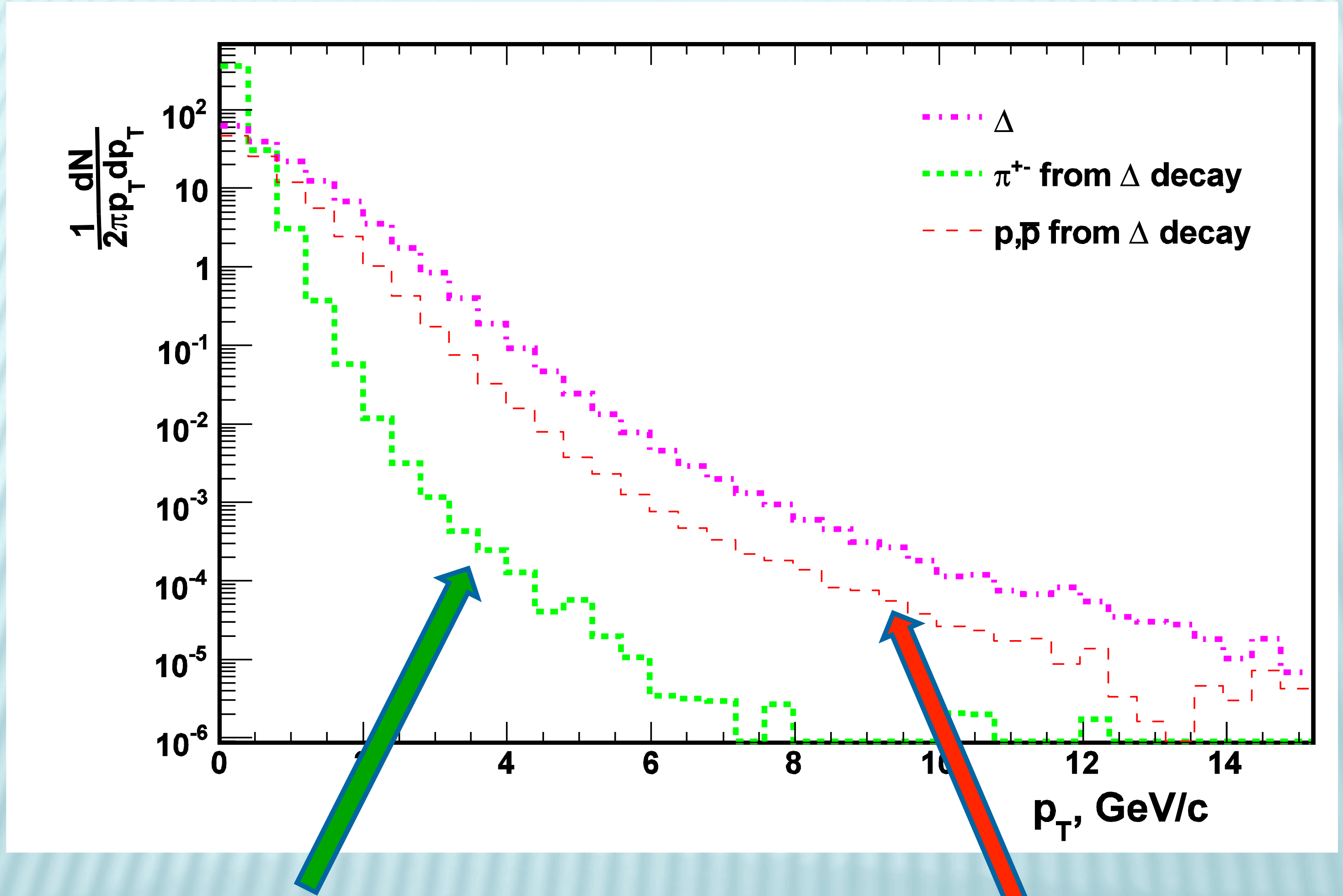


G. Eyyubova et al., PRC 80 (2009) 064907

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

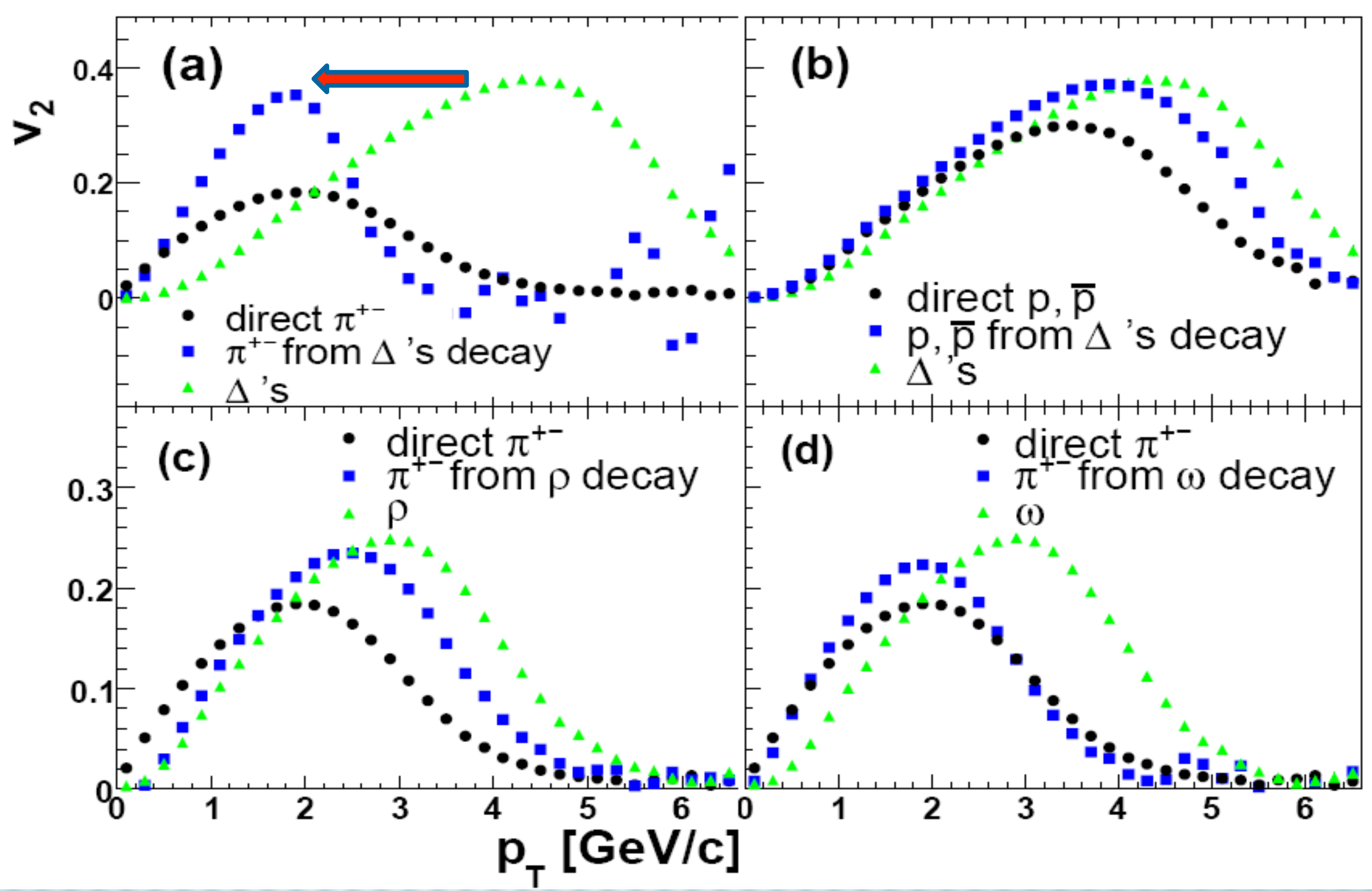
TRANSVERSE MOMENTUM OF SECONDARY PARTICLES

$\Delta \rightarrow \pi + p$



The secondary pion spectrum is much softer than proton spectrum

ELLIPTIC FLOW OF DIRECT AND SECONDARY PARTICLES AT RHIC

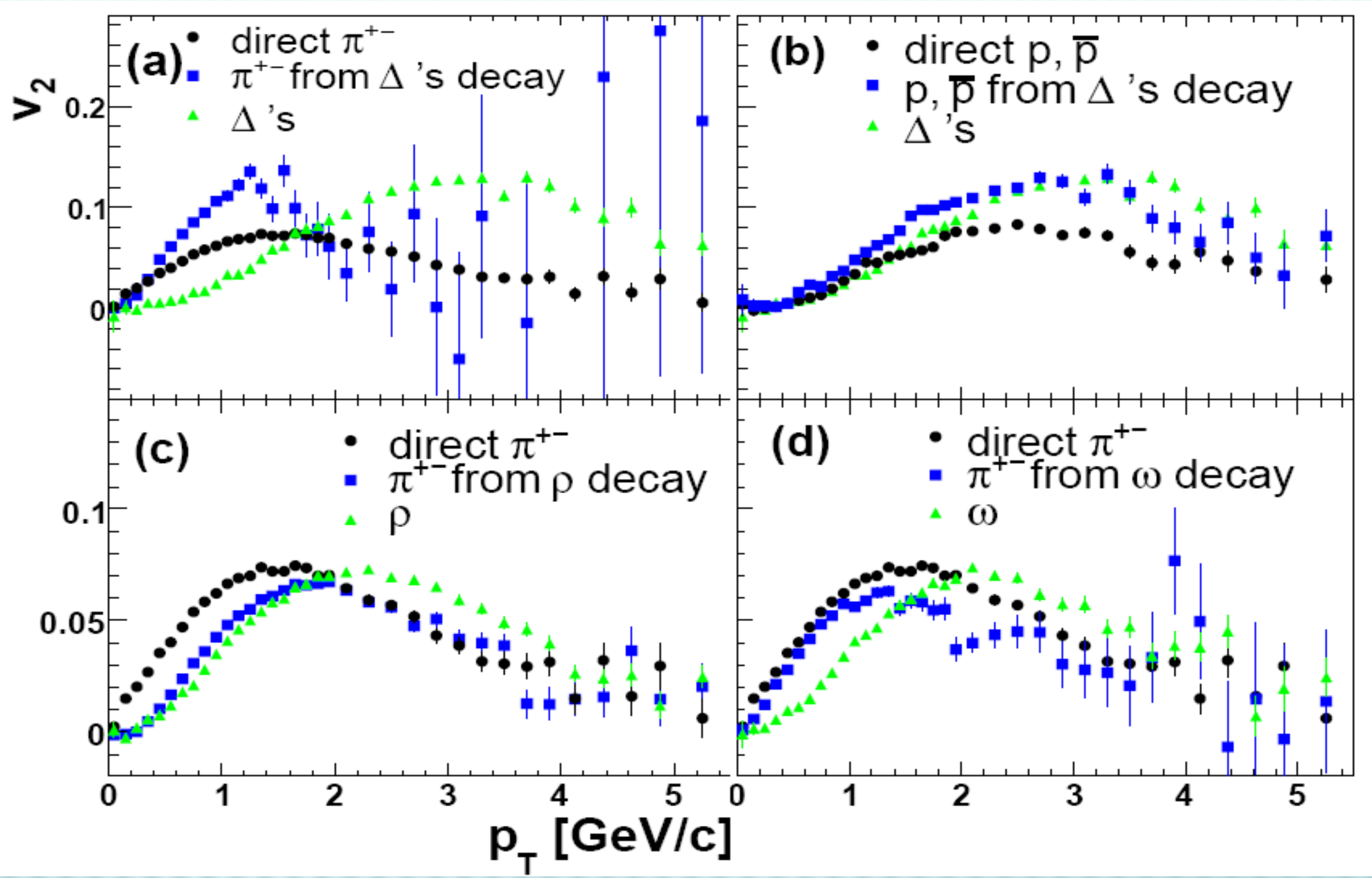


G. Eyyubova et al., PRC 80 (2009) 064907

The heavier resonances have larger v_2 at high transverse momenta

The decay kinematics keeps this high v_2 for products of resonance decays

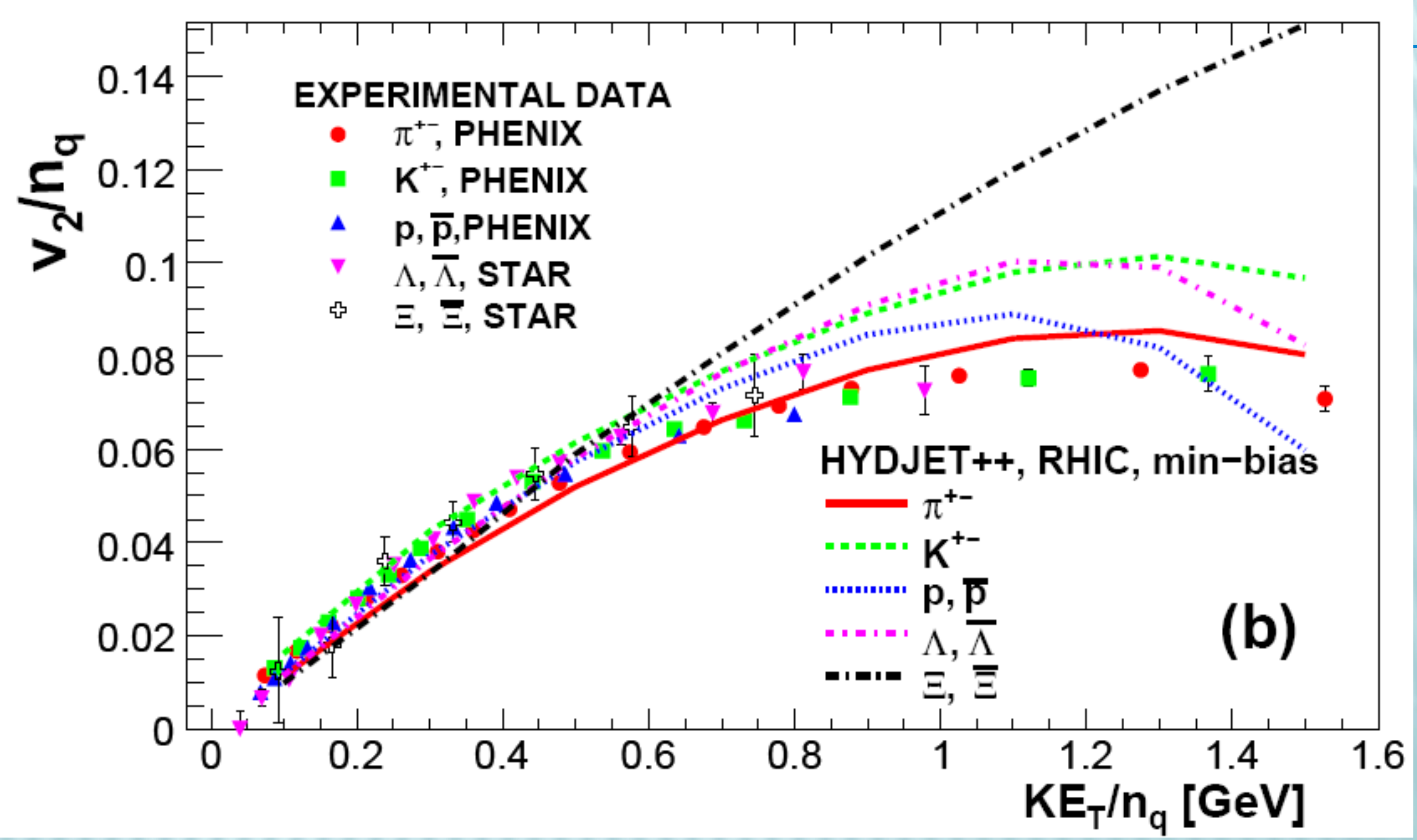
ELLIPTIC FLOW OF DIRECT AND SECONDARY PARTICLES AT LHC



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

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

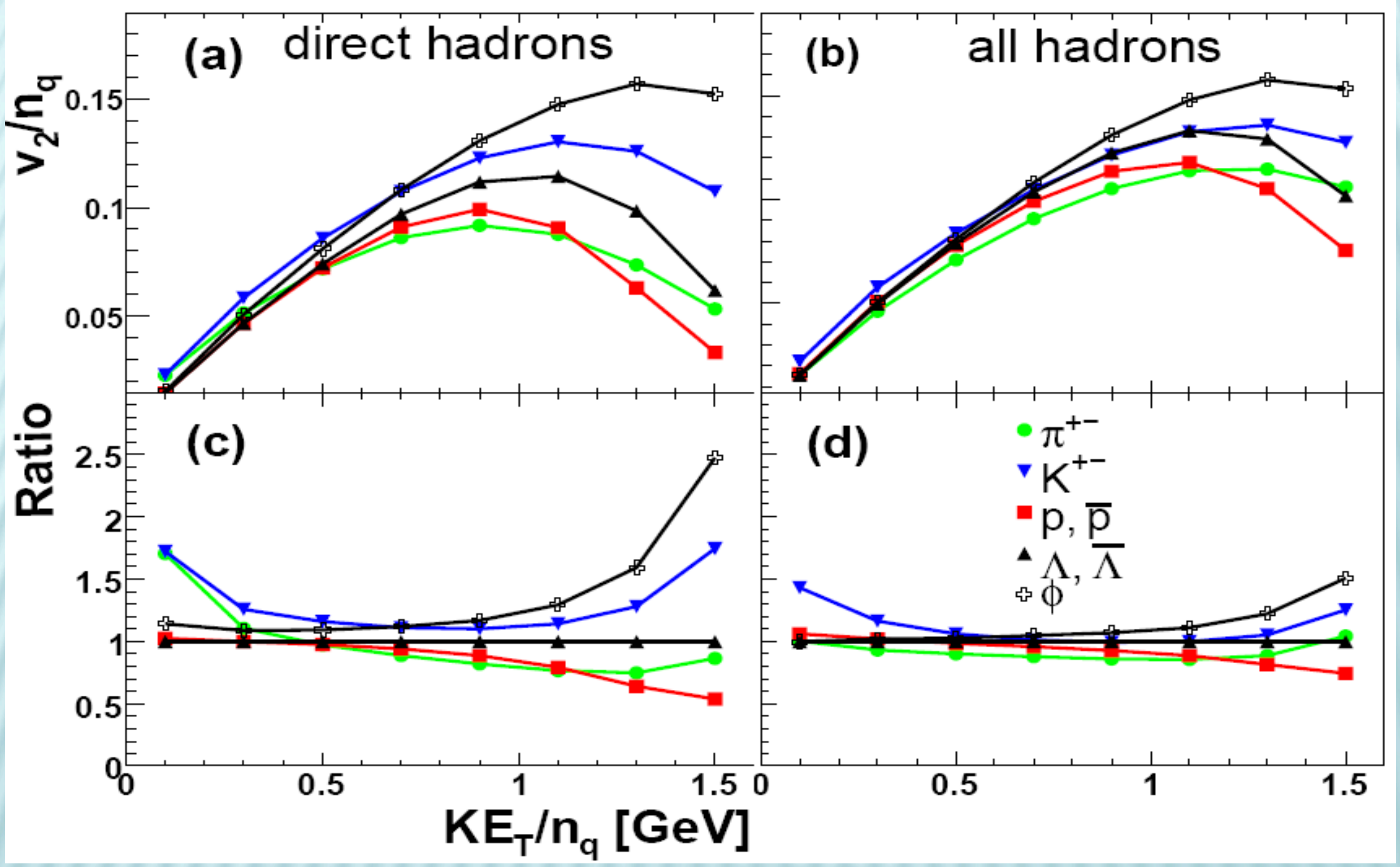
COMPARISON WITH RHIC DATA



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



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

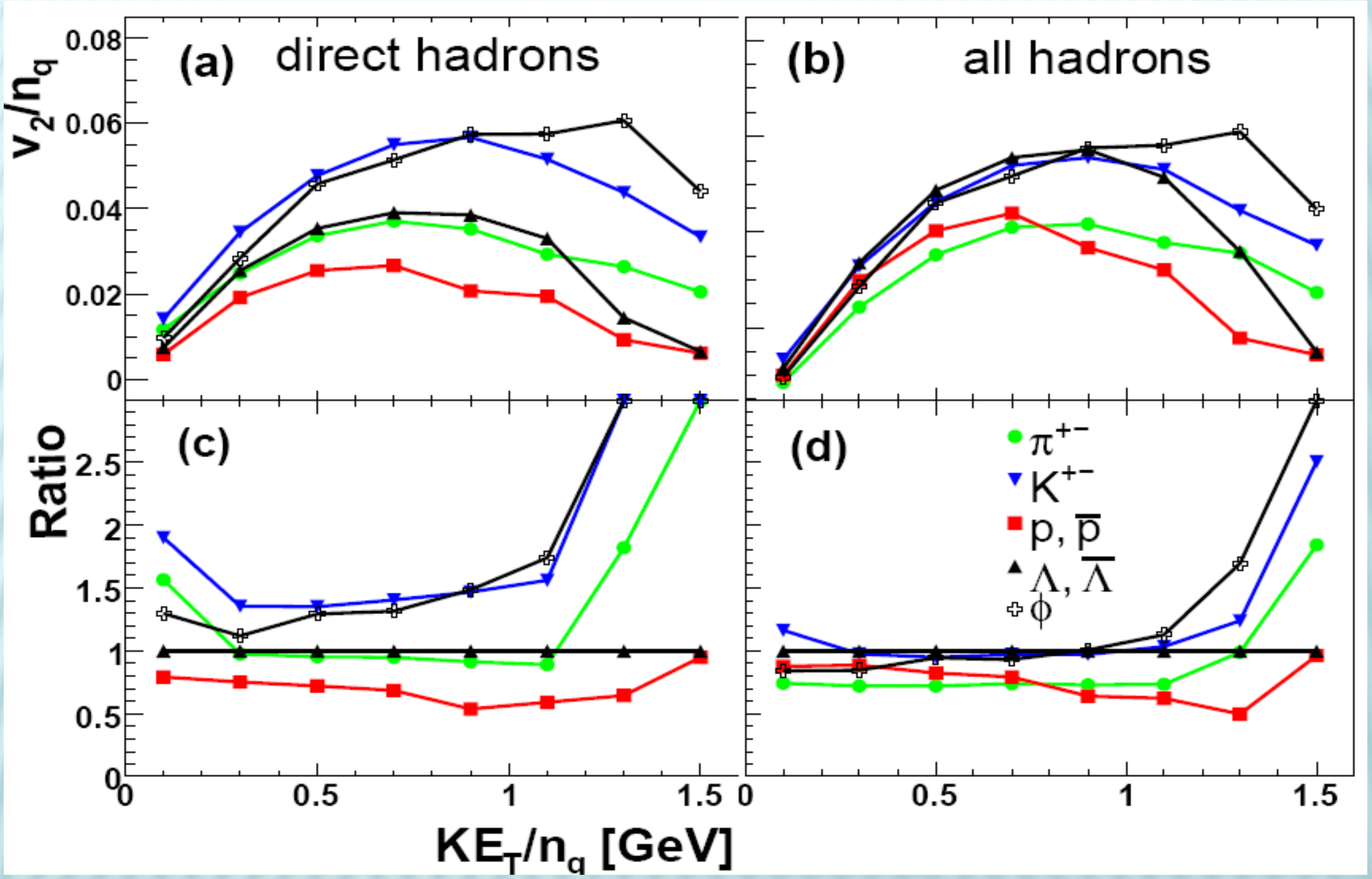
One of the explanations of KE_T/n_q scaling is partonic origin of the elliptic flow.

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



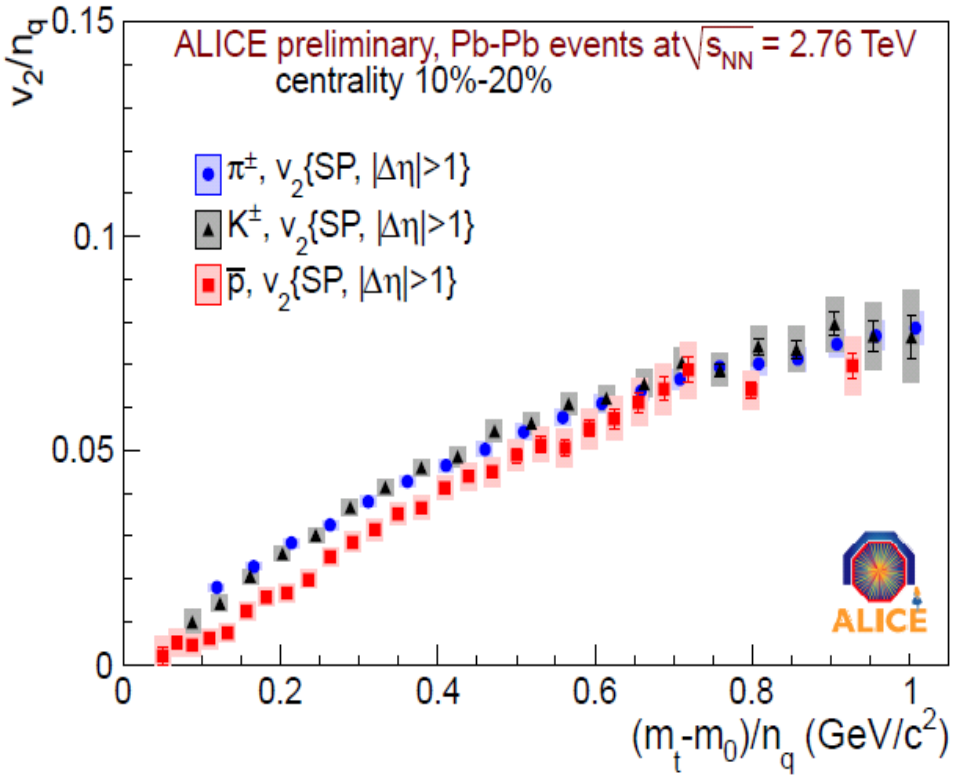
G.Eyyubova et al., PRC 80 (2009) 064907

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

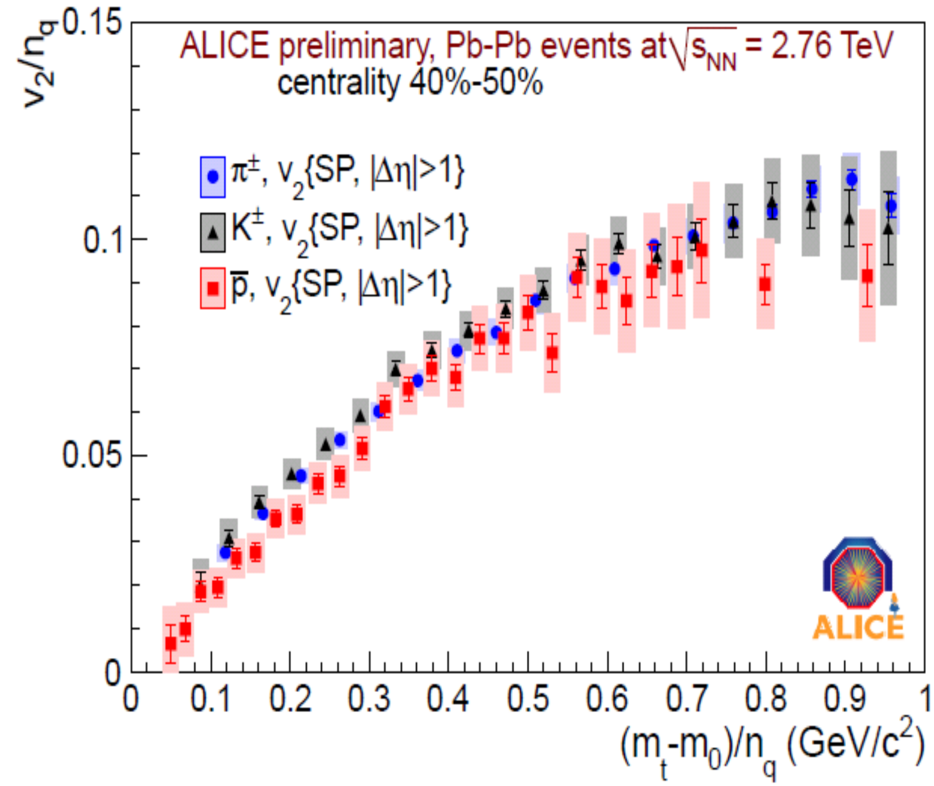
Experimental results (LHC)

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

Semi-sentral collisions



Semi-peripheral collisions



The NCQ scaling is indeed only approximate (2011)

V. 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 $\cos(2\varphi)$ term is

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

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

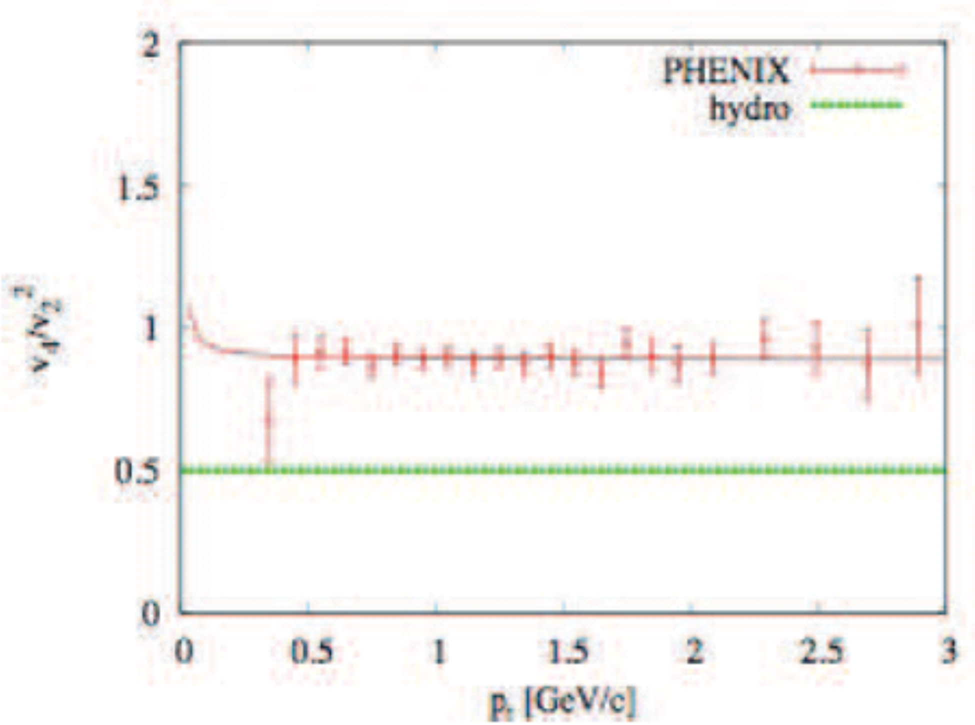
$$v_4 = \tfrac{1}{2}\,(v_2)^2$$

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

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

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

Comparison with data



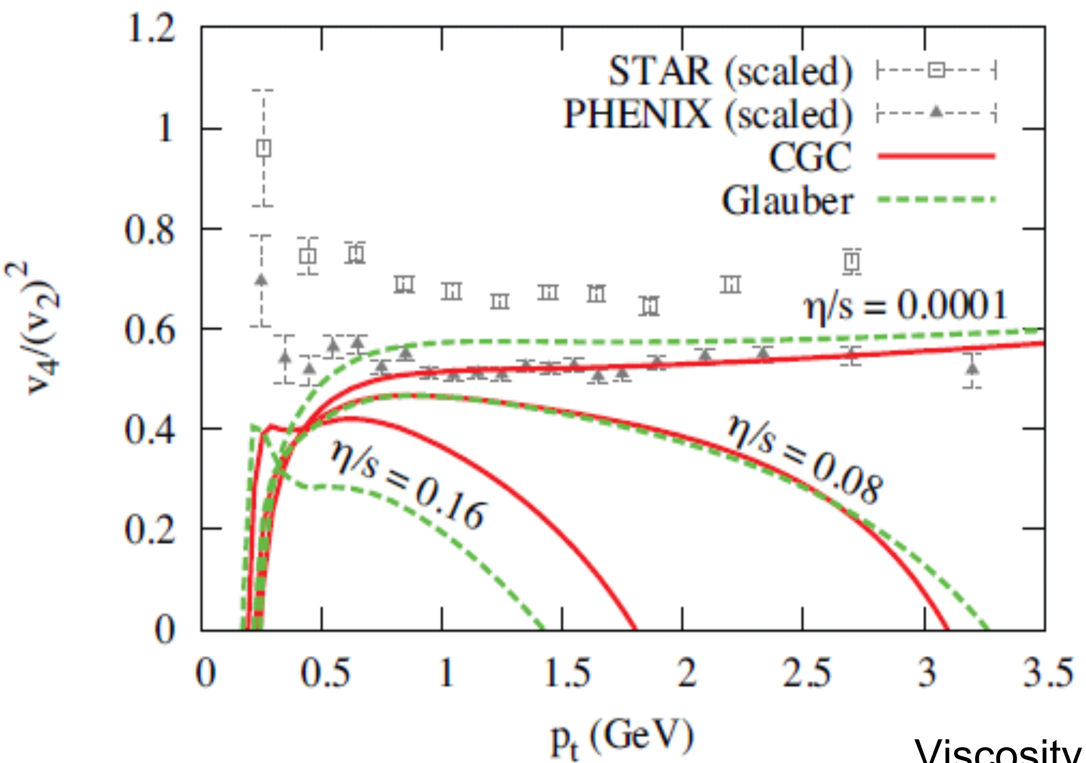
PHENIX data for charged pions

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



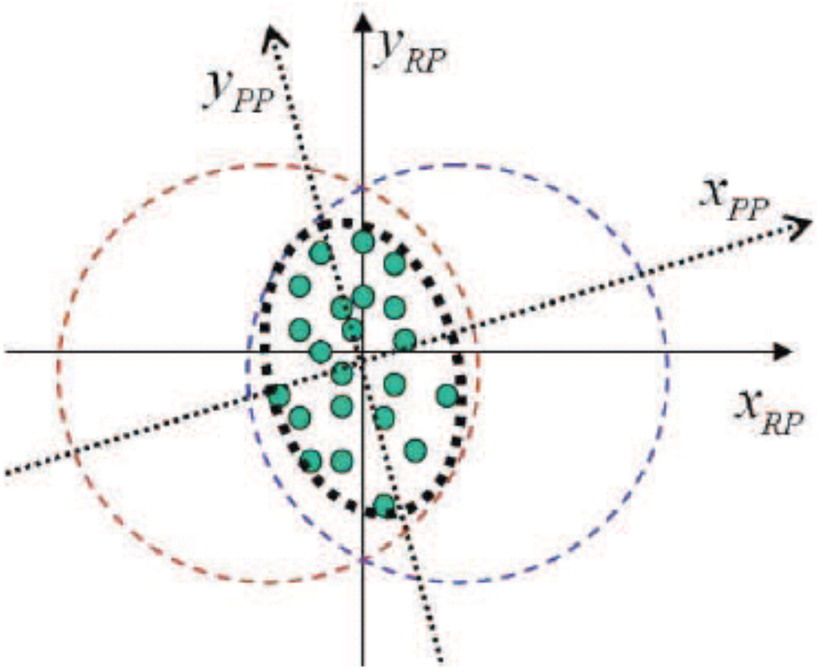
Initial profile has little effect although eccentricities differ.

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

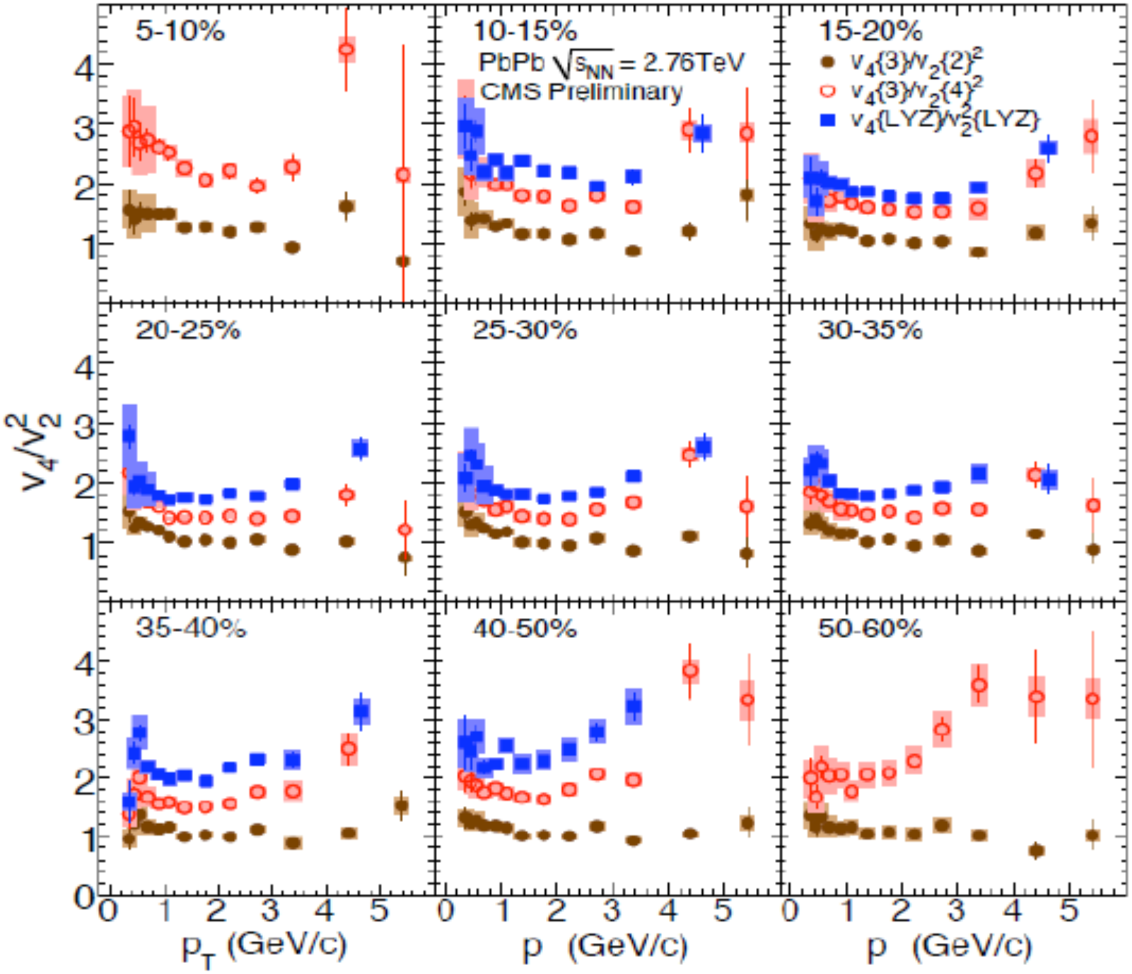
$$\frac{v_4}{v_2^2} = \frac{\langle v_4 (v_2)^2 \rangle}{\langle (v_2)^2 \rangle^2} = \frac{1}{2} \frac{\langle (v_2)^4 \rangle}{\langle (v_2)^2 \rangle^2} > \frac{1}{2}$$

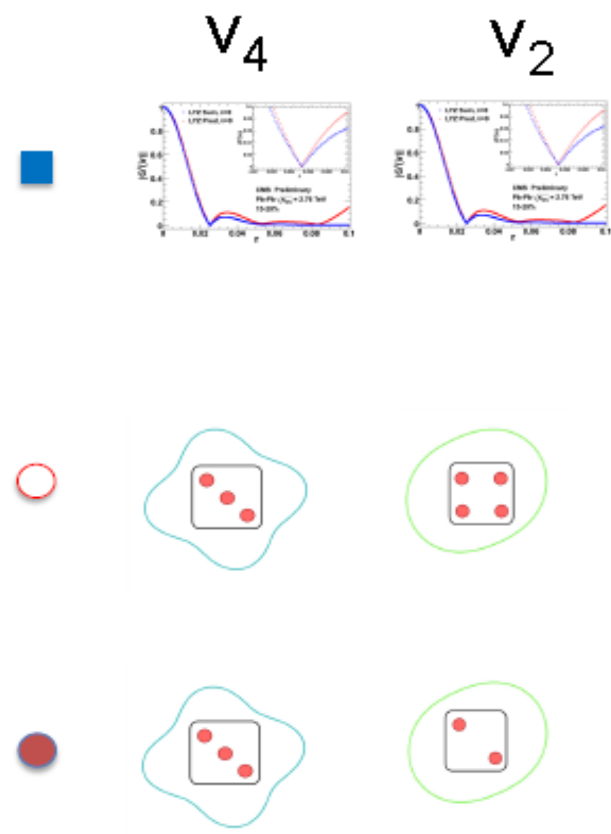
fluctuations

hydro

Similar results obtained using Event Plane method

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

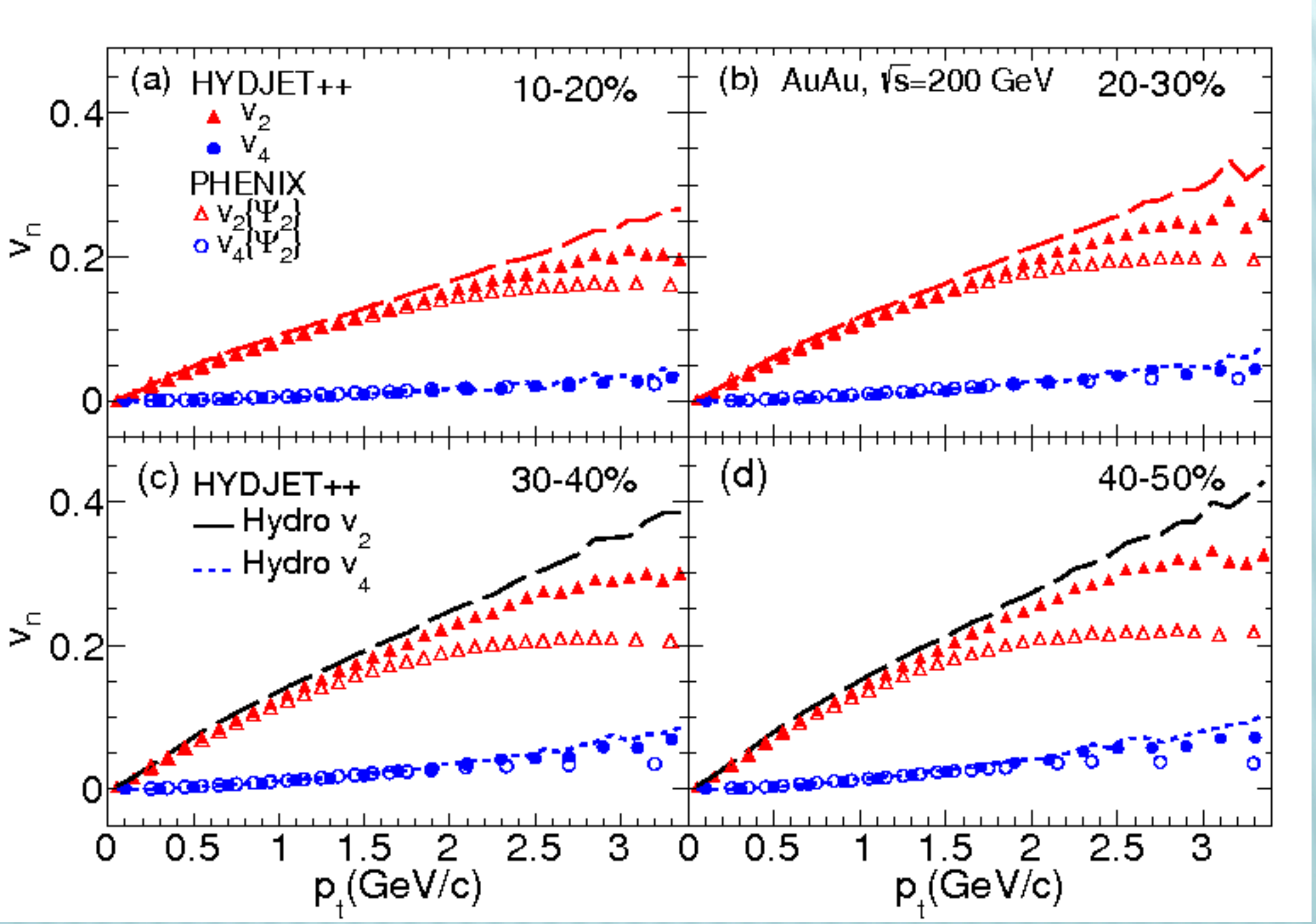




Significantly higher than RHIC: experimental method dependent

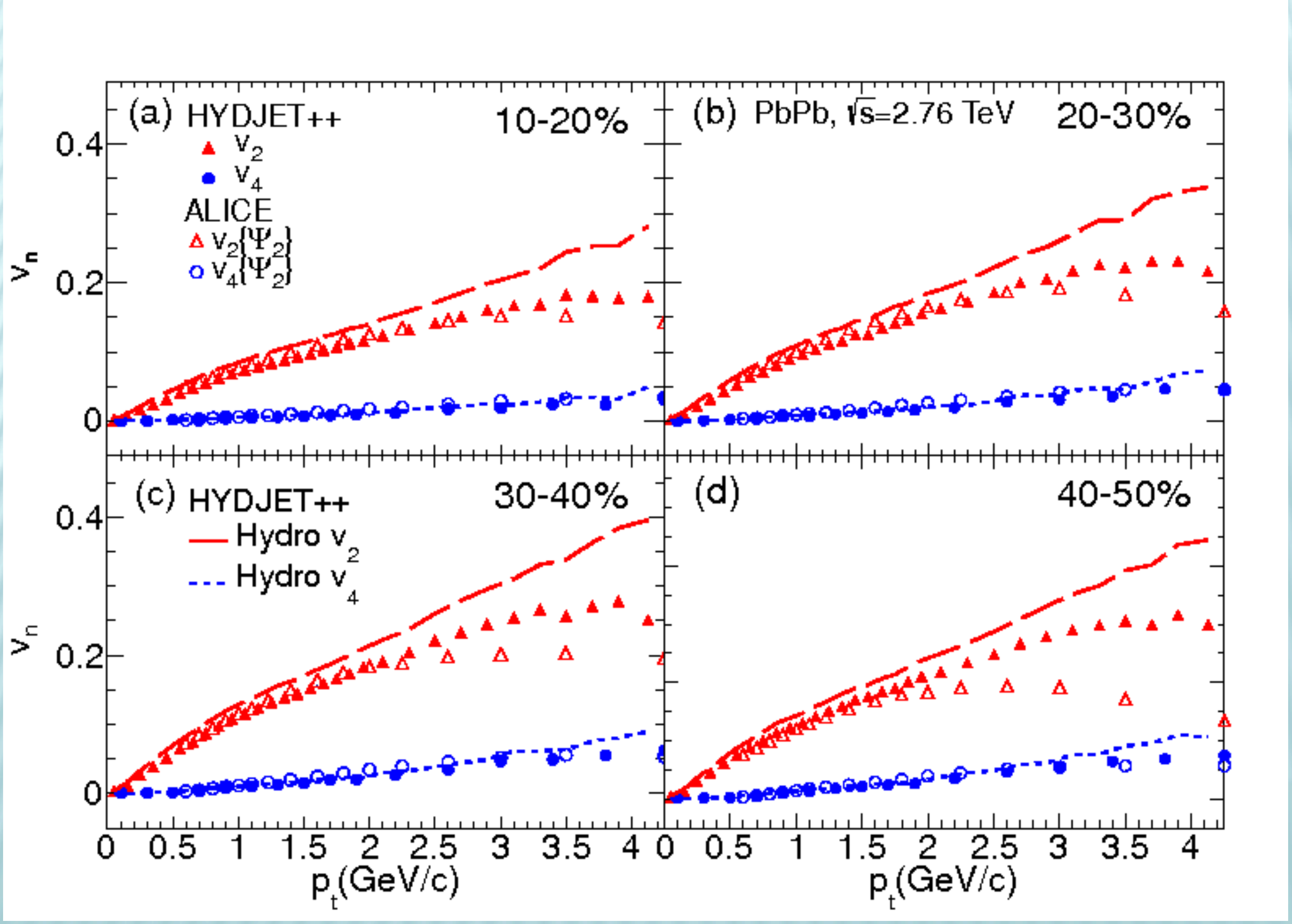
HYDJET++ (RHIC)

Effects to be studied: resonance decay and hard part influence



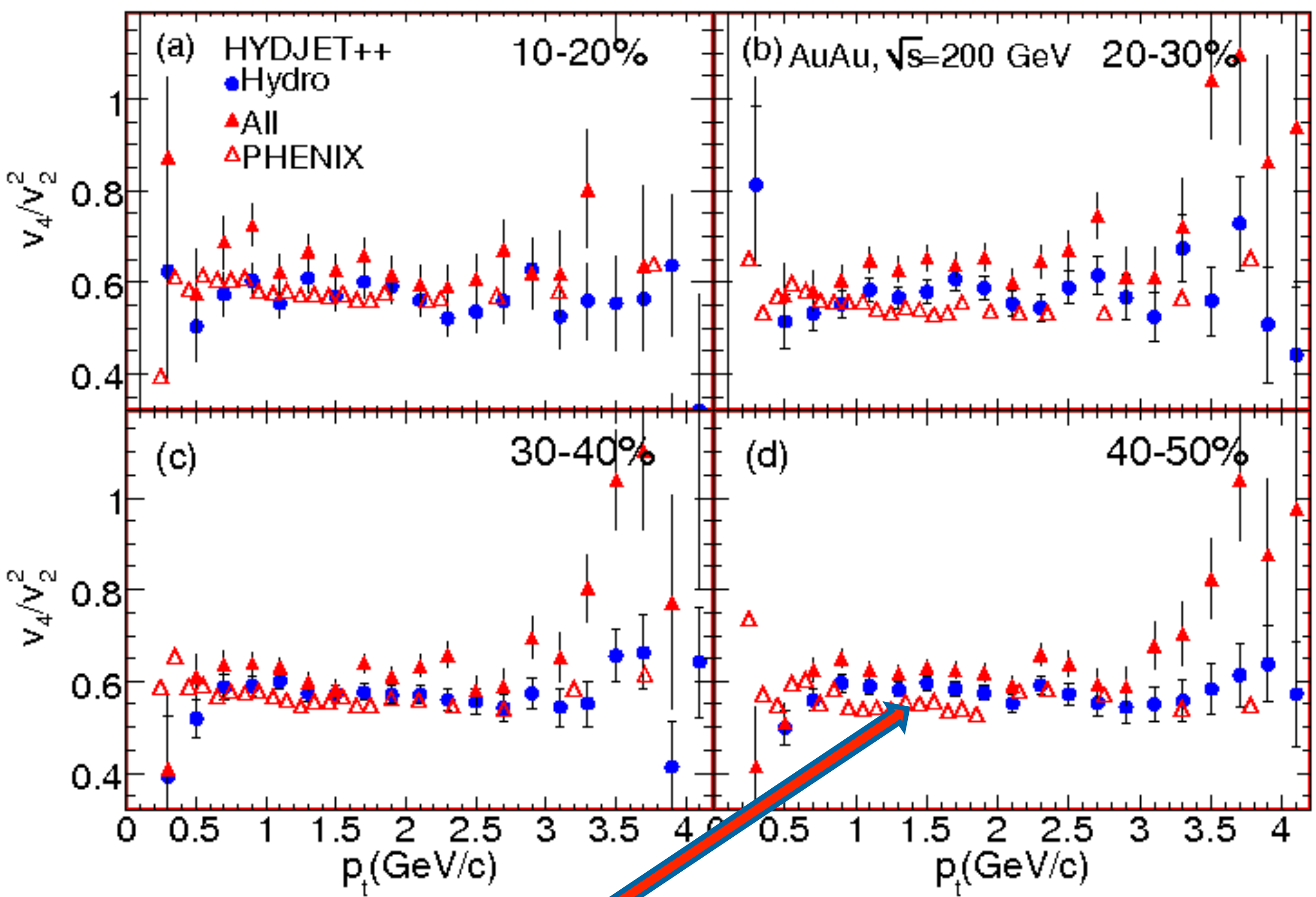
HYDJET++ (LHC)

Pure hydrodynamics vs hydro+jets



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

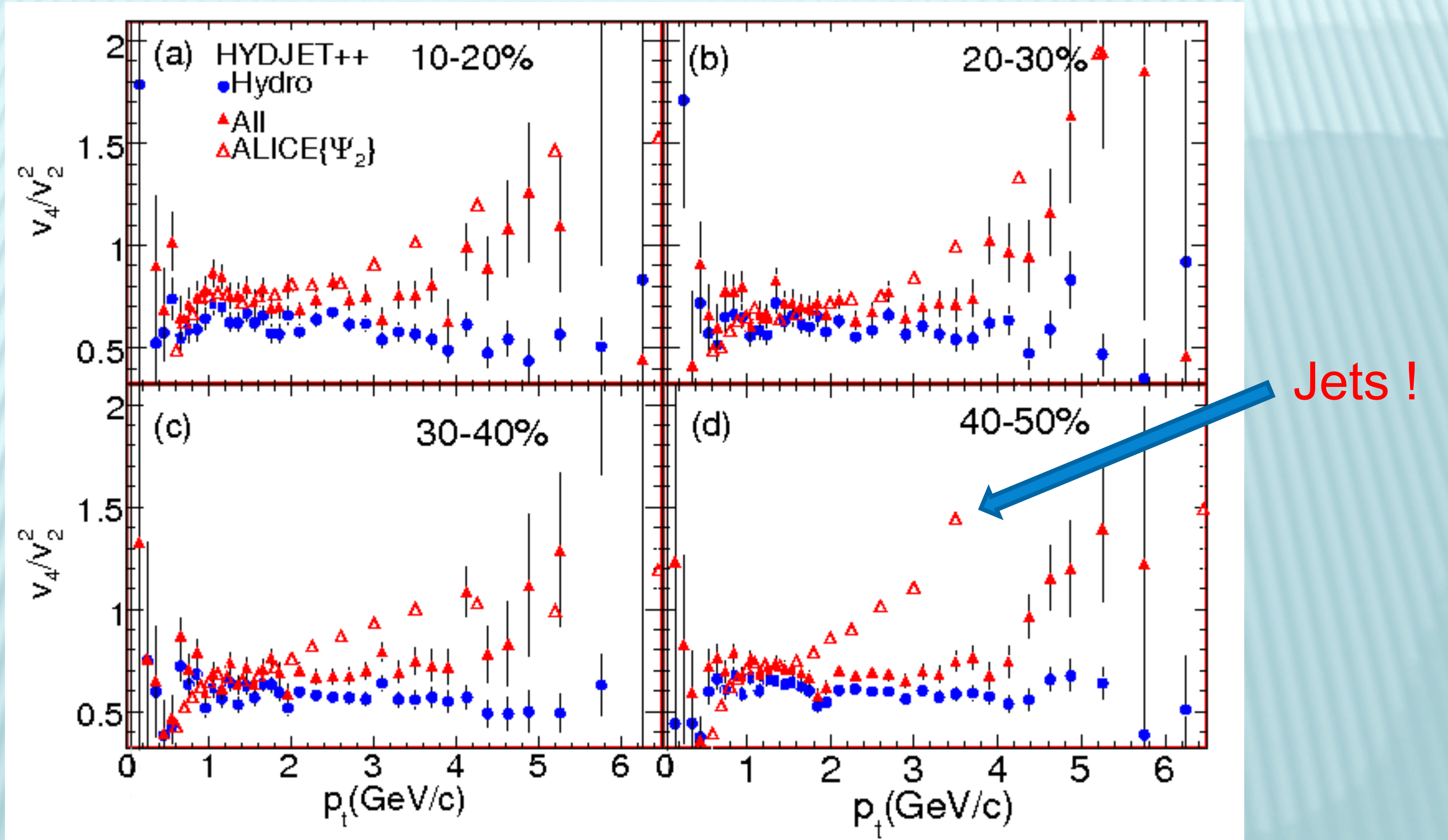
HYDJET++ RESULTS FOR RHIC



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

Jets increase the ratio

HYDJET++ RESULTS FOR LHC



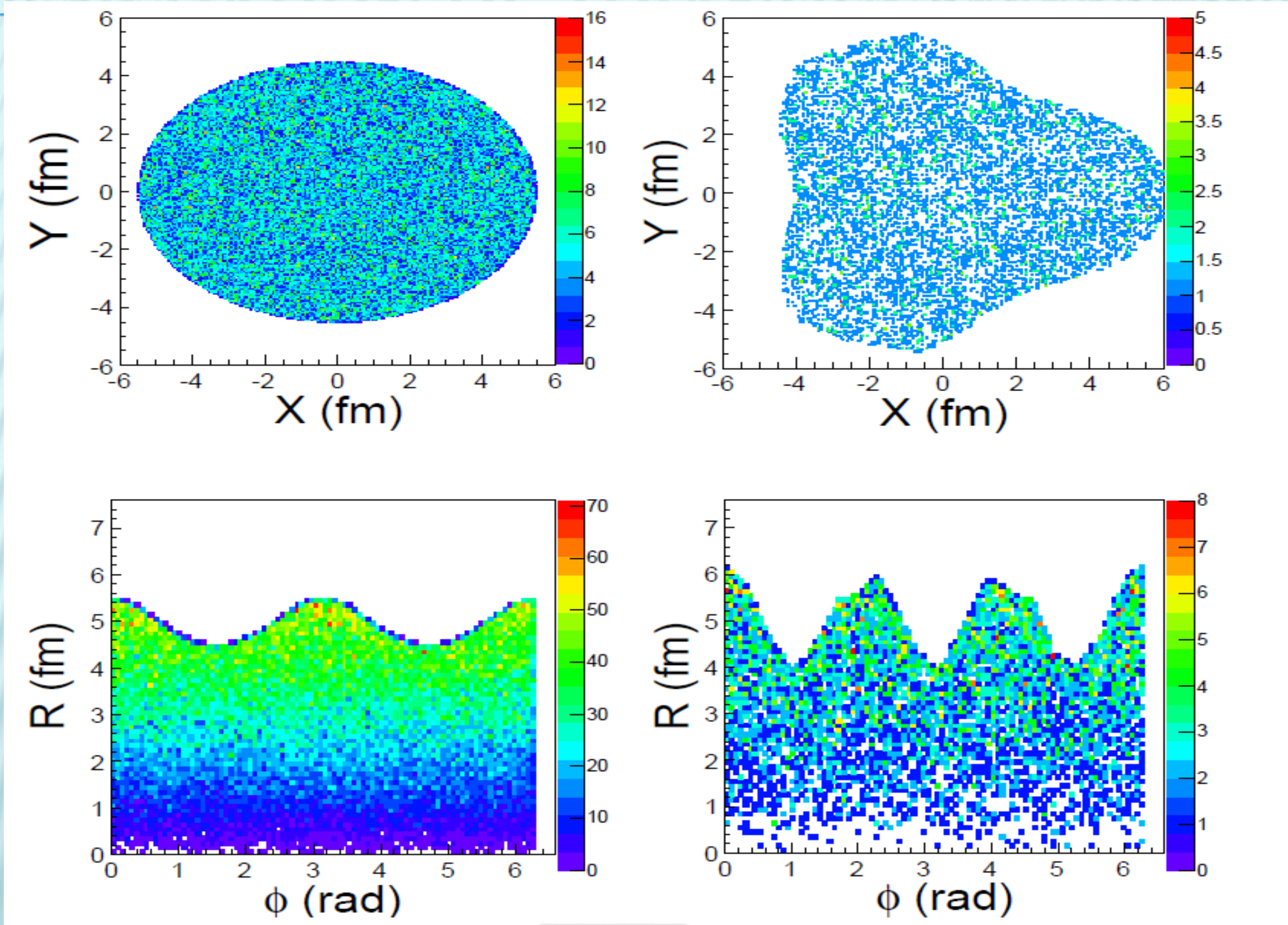
The same tendency is observed in Pb+Pb at LHC

VI. Higher harmonics

GENERATION OF TRIANGULAR FLOW

V2

V3



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

GENERATION OF TRIANGULAR FLOW

Space and Momentum Anisotropy

$$\epsilon(b) = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2},$$

$$v_2 \propto \frac{2(\delta - \epsilon)}{(1-\delta^2)(1-\epsilon^2)}$$

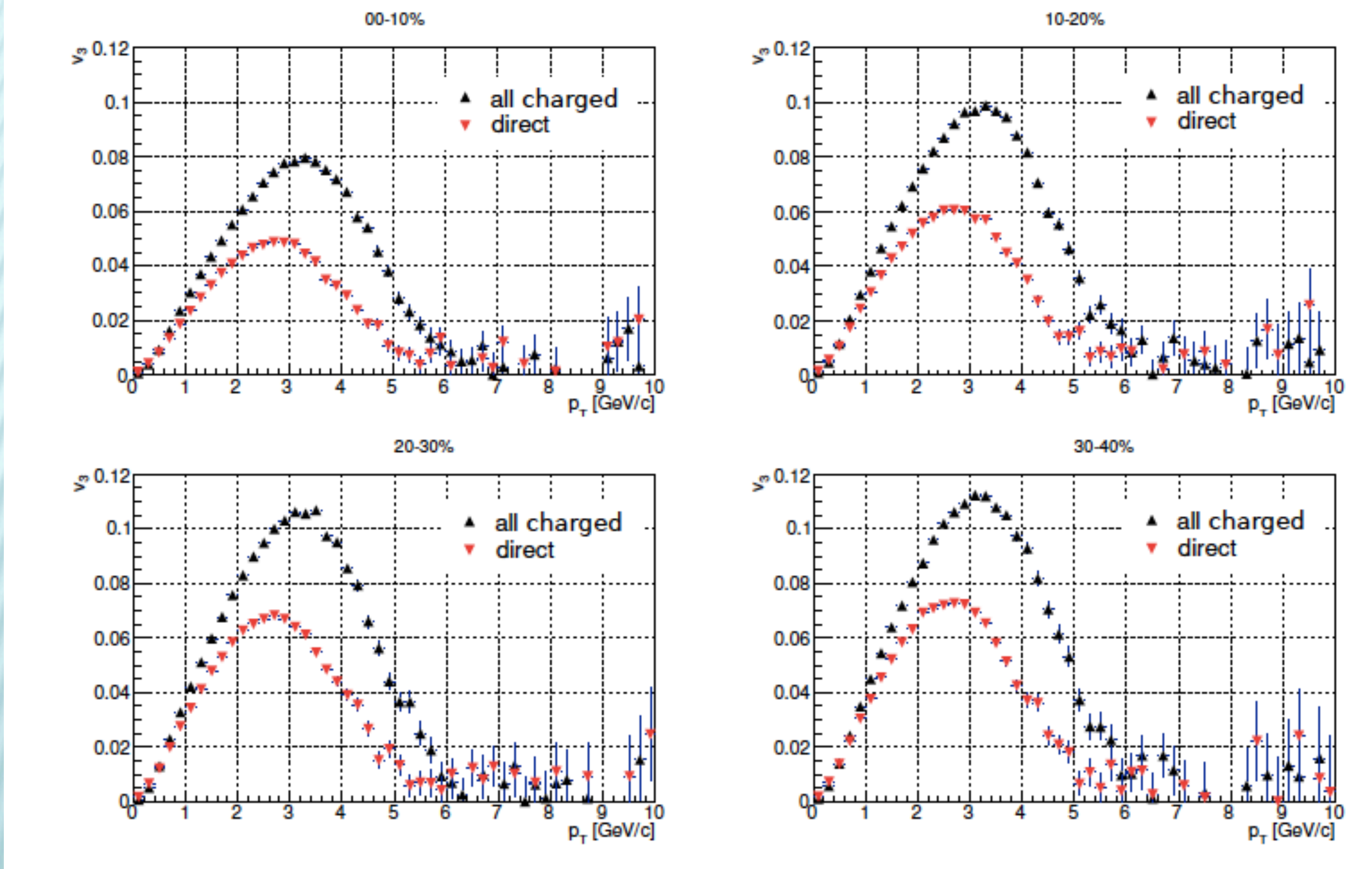
$$\tan \varphi_* = \sqrt{\frac{1-\delta(b)}{1+\delta(b)}} \tan \varphi.$$

Third component is generated as

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

Parameters $\varepsilon(b_0)$,$\varepsilon 3(b_0)$, $\delta(b_0)$ are fitted to the experimental data

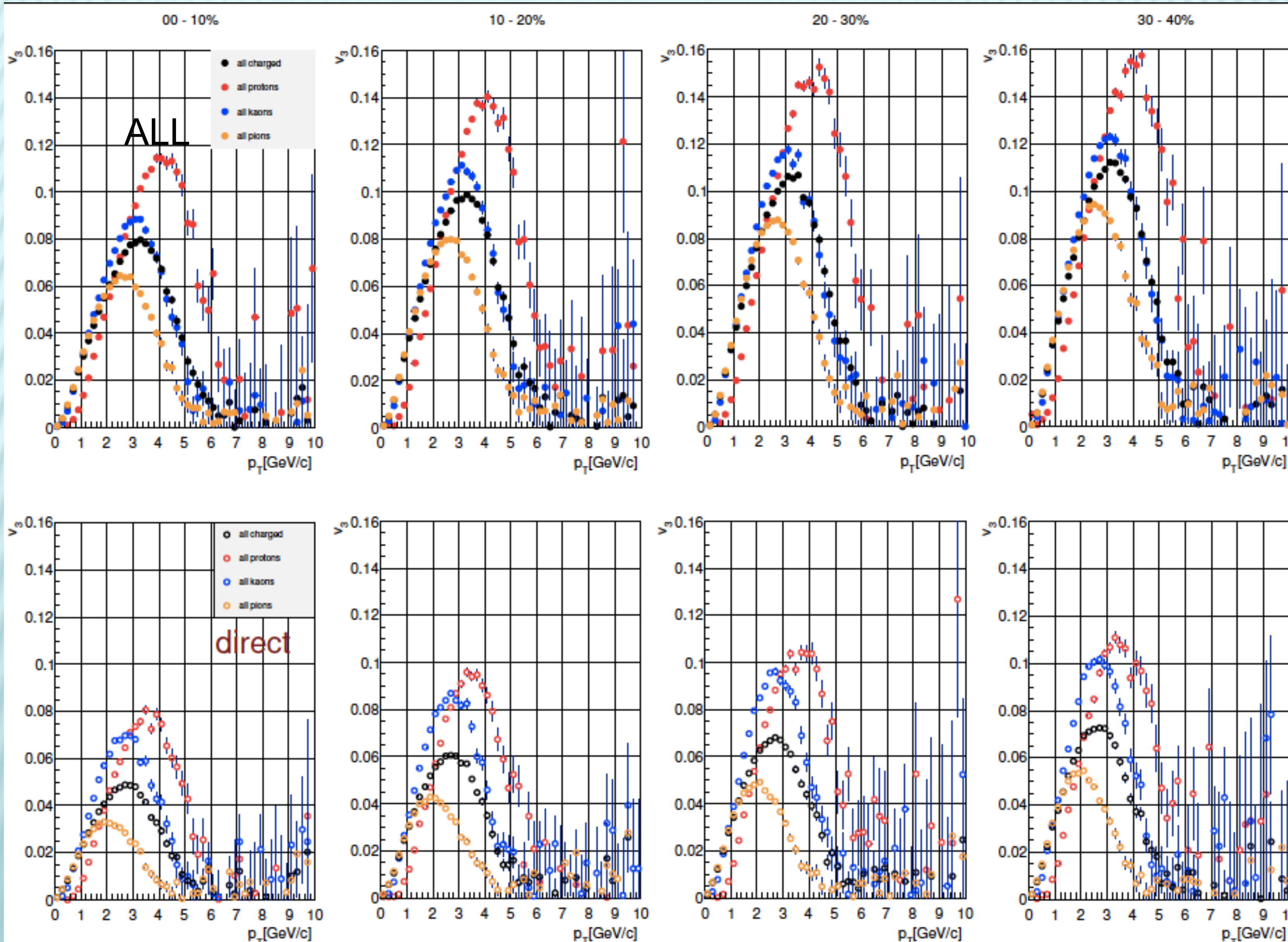
GENERATION OF TRIANGULAR FLOW



V3

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

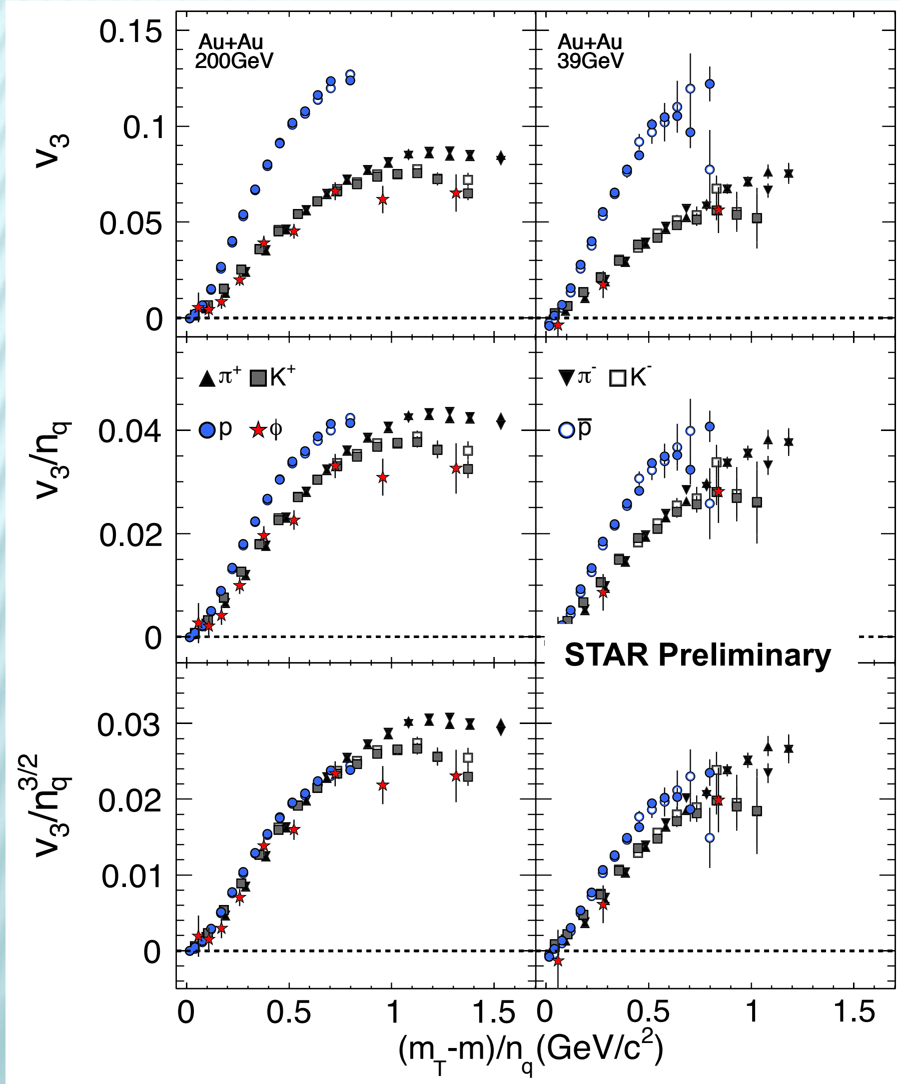
V3 for all and directly produced particles at different centralities at LHC

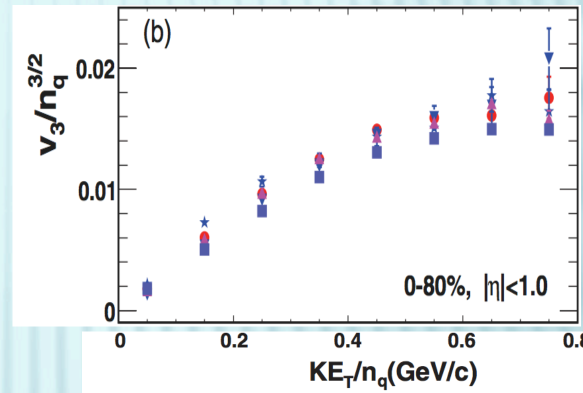


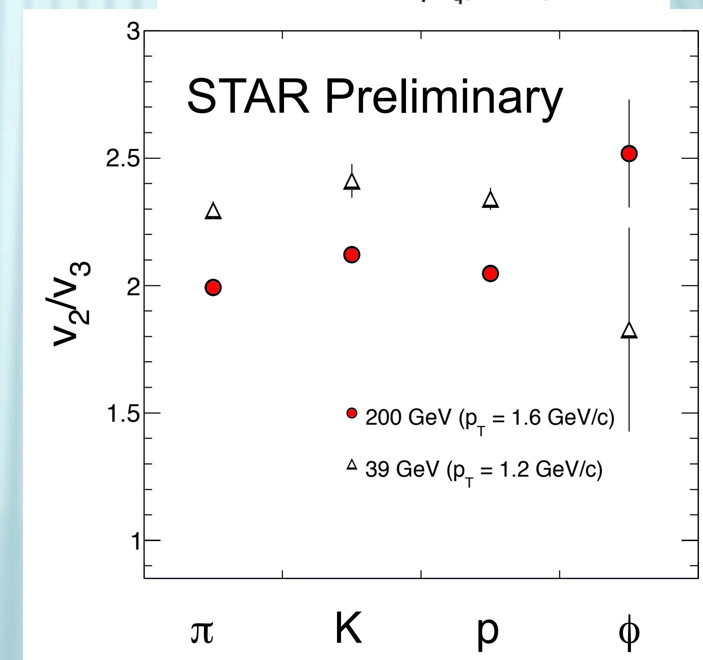
NUMBER-OF-CONSTITUENT QUARK SCALING FROM XU SUN (QM2014)

R. Lacey, J. Phys. G: Nucl. Part. Phys. 38 (2011) 124048
AMPT: PRC 84, 064907 (2011)
Harri Niemi, QM14, Friday

200 GeV **39 GeV**



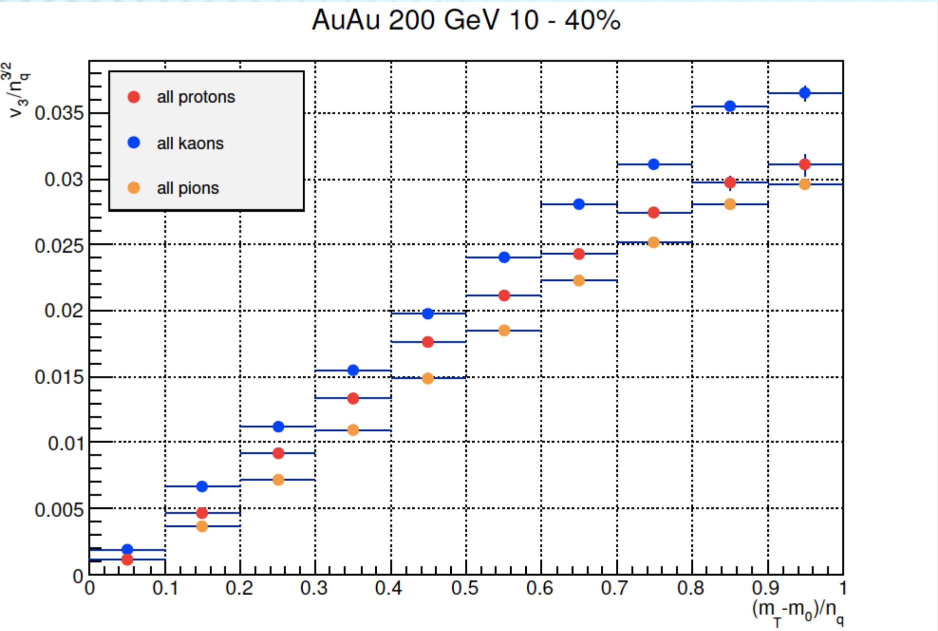


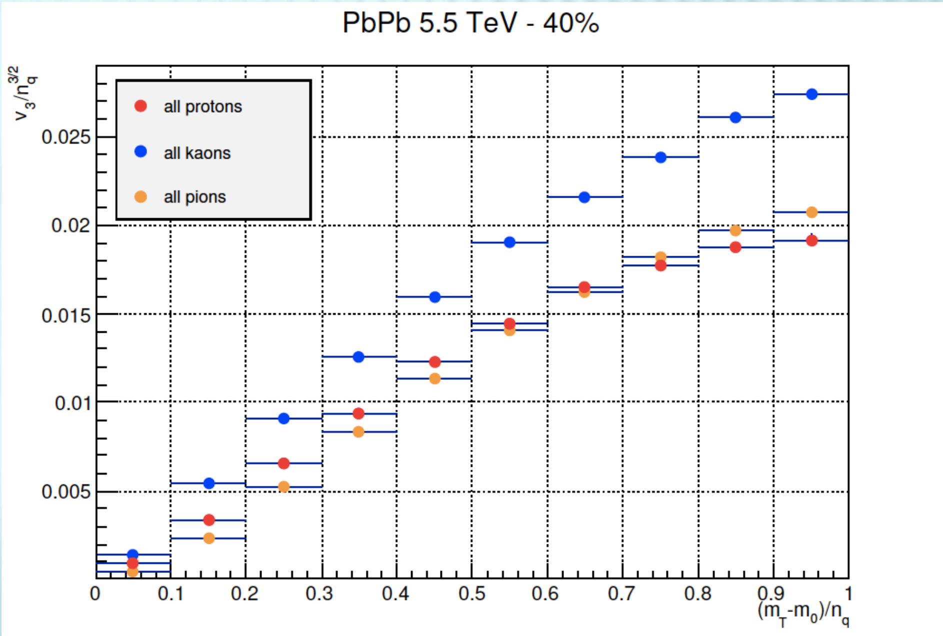


NUMBER-OF-CONSTITUENT QUARK SCALING FROM XU SUN QM TALK FROM STAR COLLABORATION

- Collective behavior for v_3 at 39 and 200 GeV
  - Mass ordering at low p_T, similar to v_2
  - $v_2/v_3 > 1$: v_2 geometry +fluctuation
    v_3 fluctuation
- More energies (19.6, 27,…) and particle species (K^0_s,Λ,…) coming soon

$V_3/NQ^{3/2}$ SCALING AT 200 AND 5500 AGEV IN HYDJET++



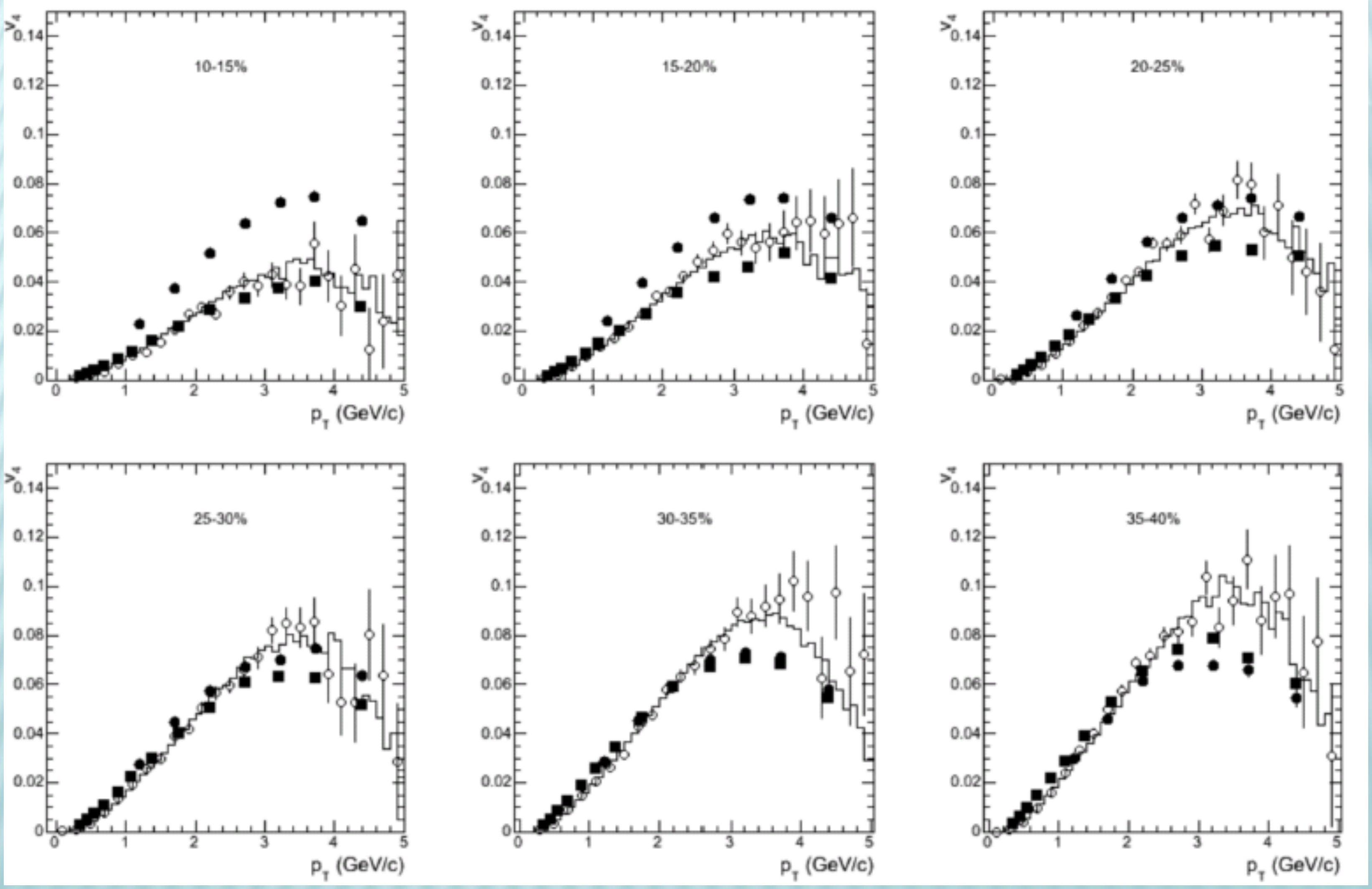


HYDJET++ shows deviation from scaling at higher energies
Is it an accident scaling, found in START at 200 AGeV ?

LHC DATA VS. HYDJET++ MODEL

Quadrangular flow

Pb+Pb @ 2.76 ATeV

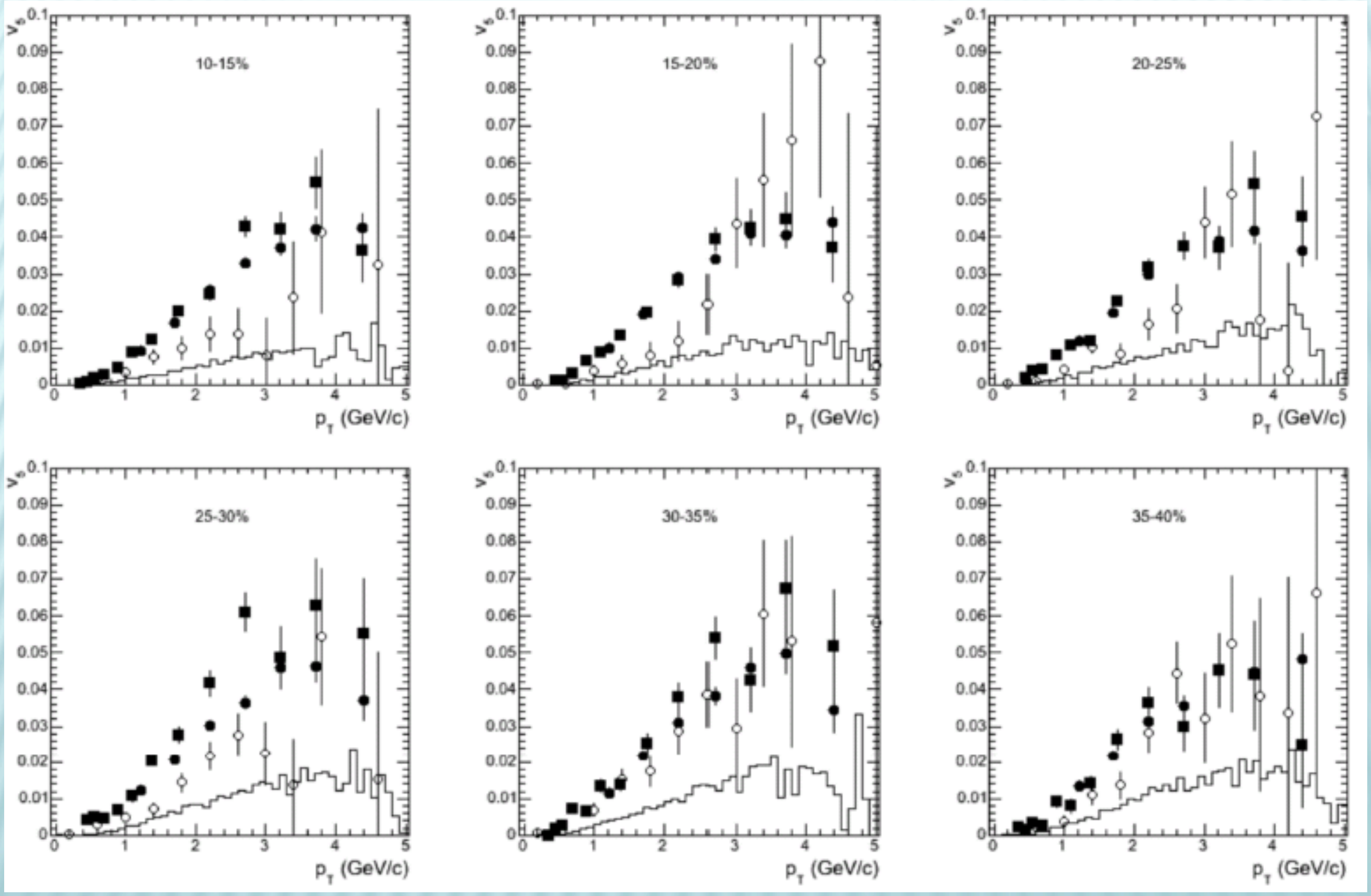


L. B et al., Eur. Phys. J C74 (2014) 2807

LHC DATA VS. HYDJET++ MODEL

Pentagonal flow

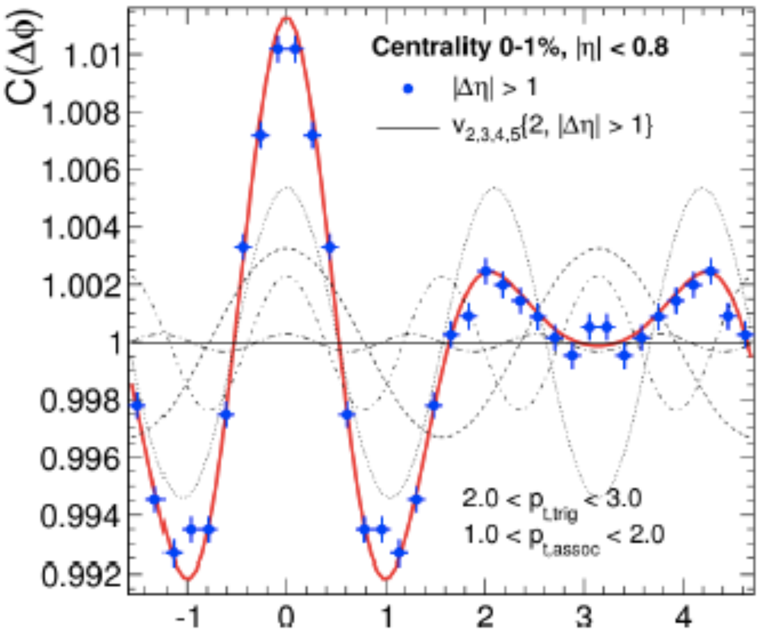
Pb+Pb @ 2.76 ATeV



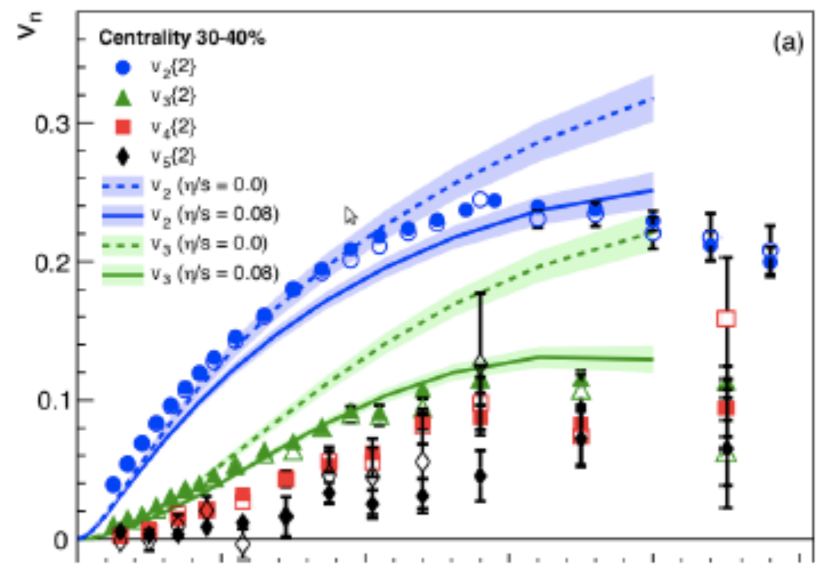
L. B et al., Eur. Phys. J C74 (2014) 2807

Higher harmonics

- information on initial geometry
- more sensitive to viscosity
- explain shape of 2-particle correlation

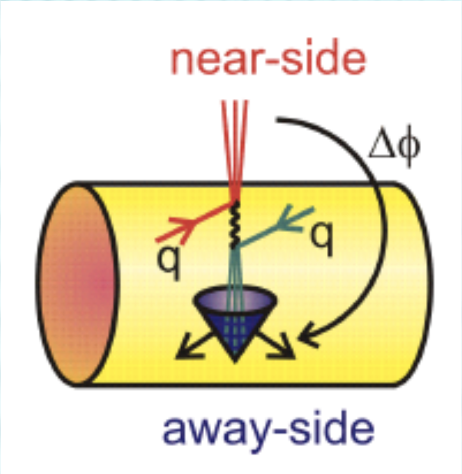


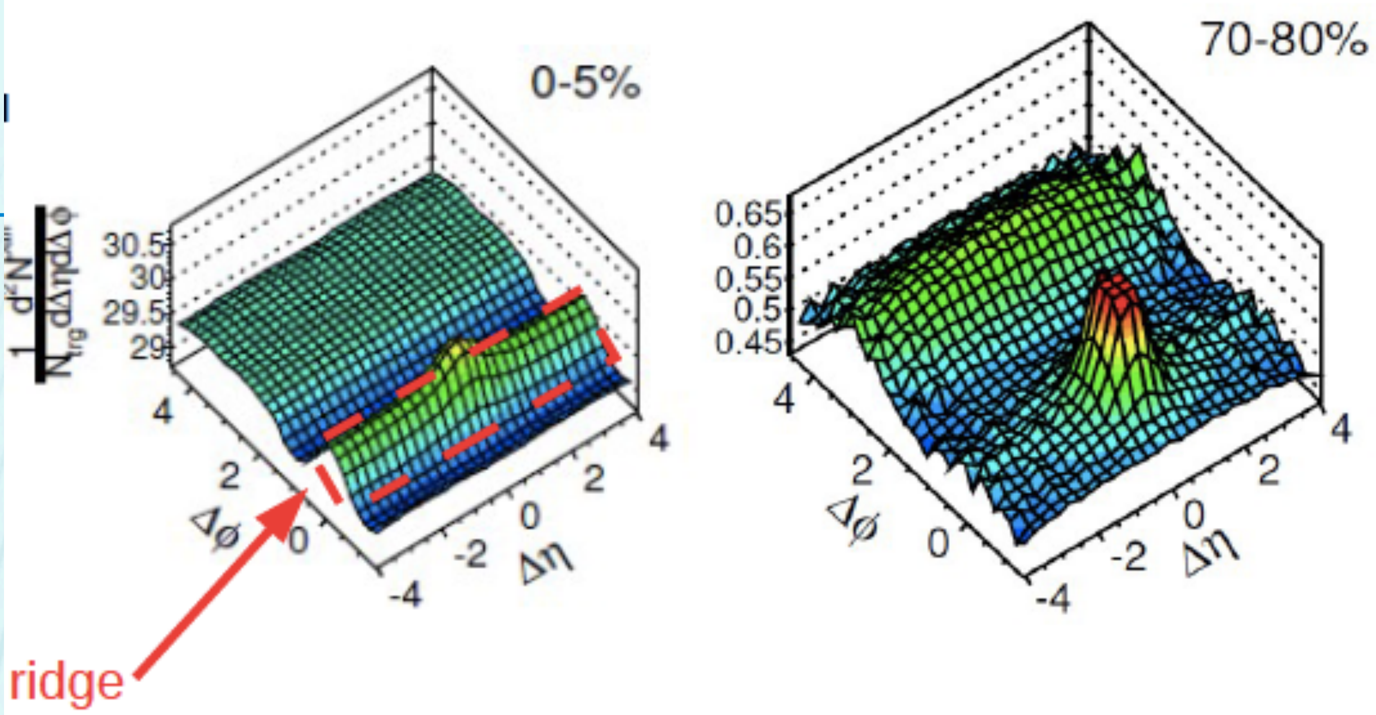
Phys. Rev. Lett **107** (2011) 032301



Phys. Rev. Lett **107** (2011) 032301

RIDGE

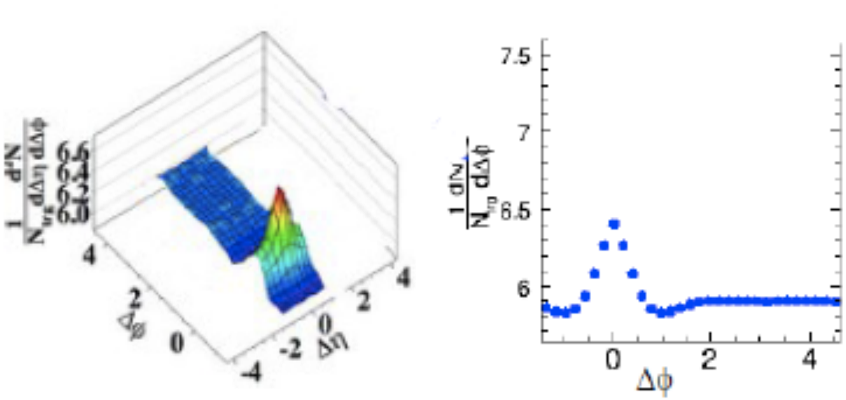


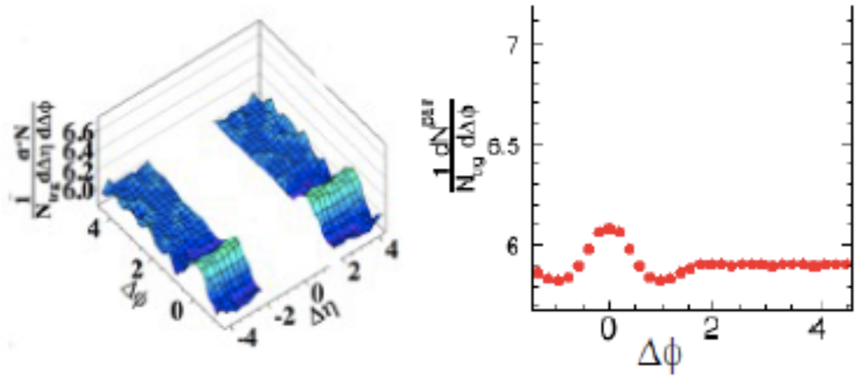


CMS, PbPb 2.76 TeV, Eur. Phys. C 72 (2012) 10052, $3 < pt^{trig} < 3.5$ Gev/c, $1 < pt^{assoc} < 1.5$ GeV/c

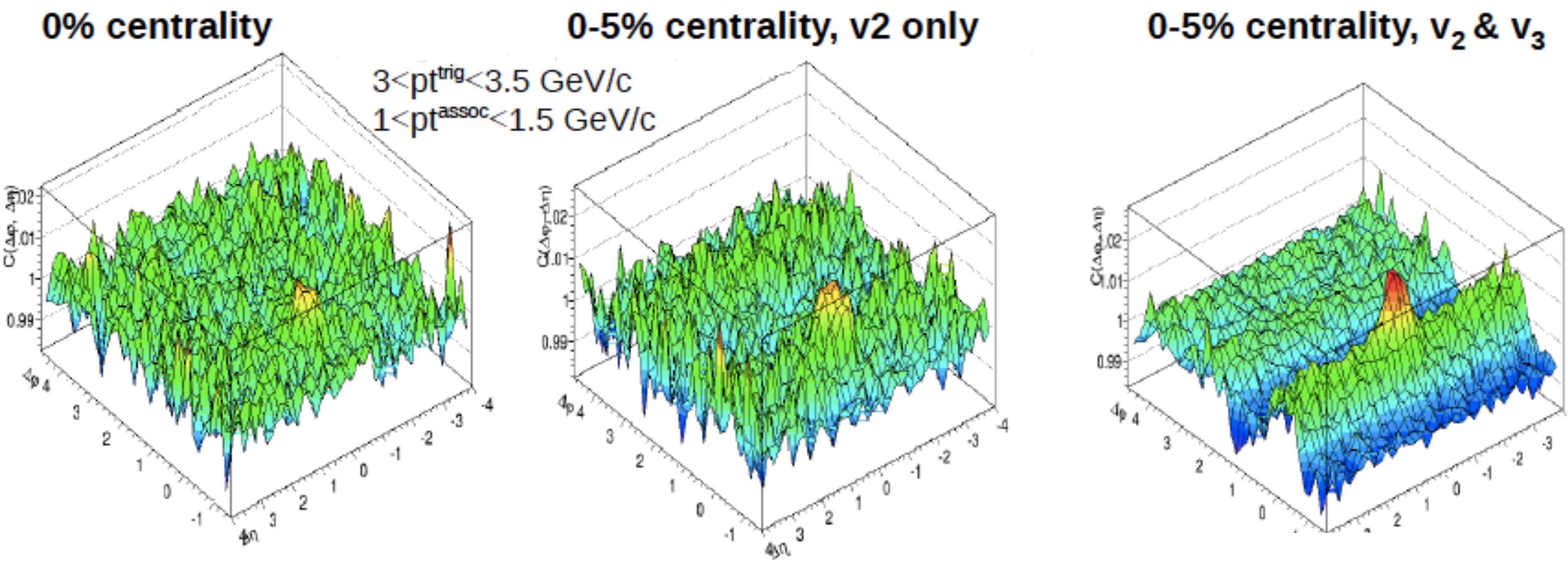
THE JET REGION

RIDGE REGION

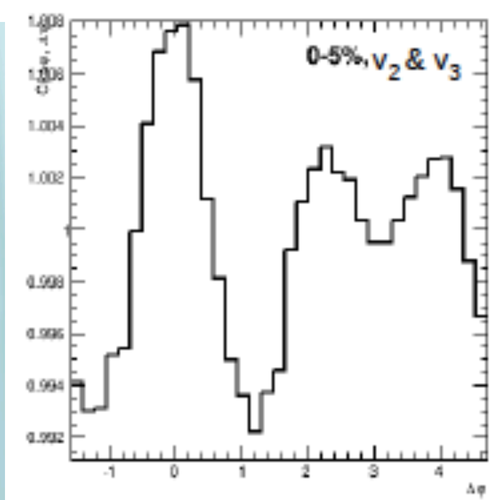




RIDGE AND HIGHER HARMONICS



RIDGE IN HYDJET++ APPEARS DUE TO V2 AND V3



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 and decays of resonances are important components of the anisotropic flow description***

- ***Jets + eccentricity fluctuations are enough to explain both RHIC and LHC data on v4/(v2*v2) ratio, including the high-pT tail***

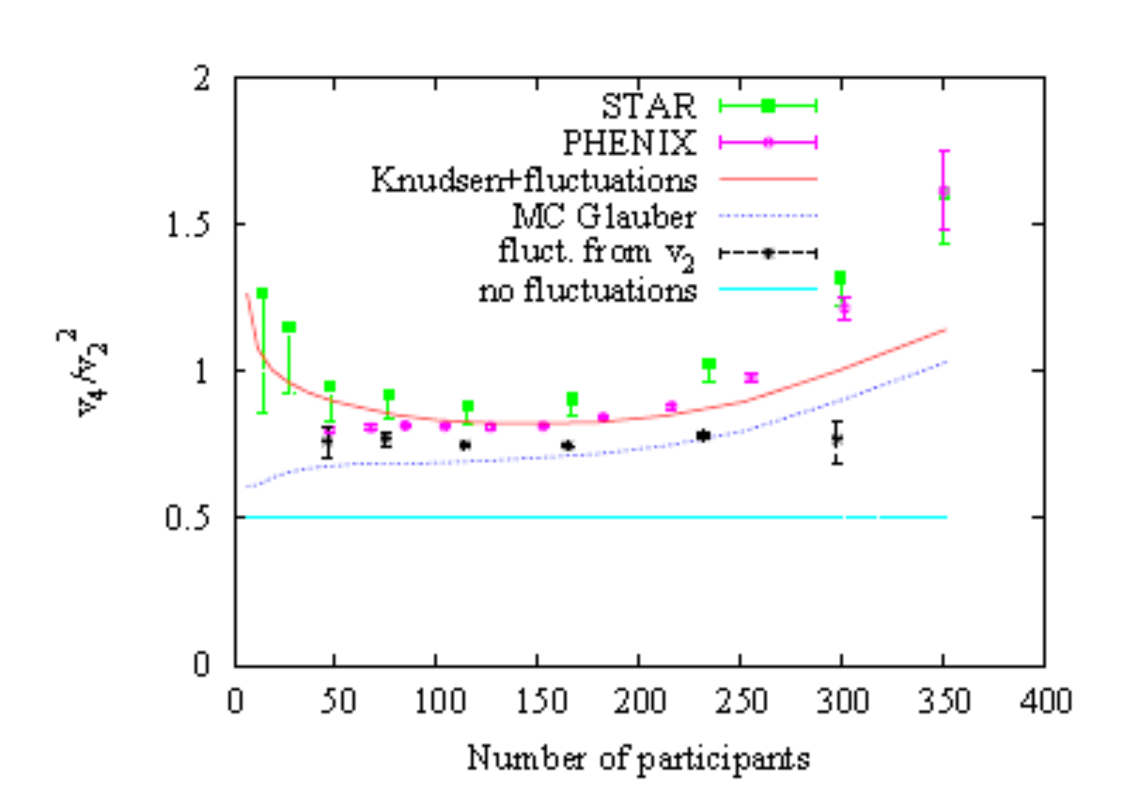
- ***The predicted violation of the NCQ scaling at LHC is observed***

- ***Higher order harmonics and ridge – just an interplay of elliptic and triangular flows ?***

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

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:

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

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

(2) Two particle correlation method

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

(3) Lee-Yang zero method

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

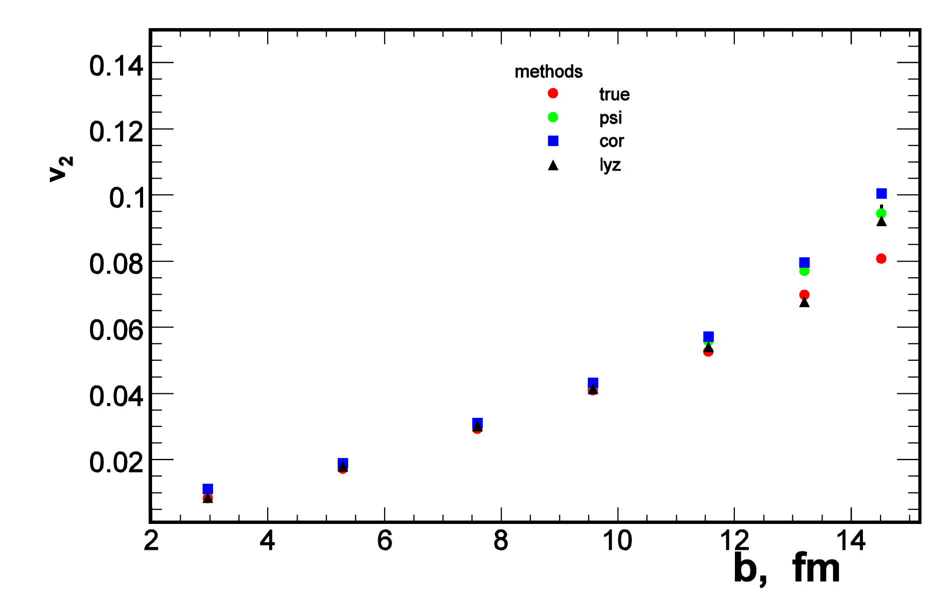
Integral v_2 is connected with the firs minimum r_0 of the module of the G(ir):

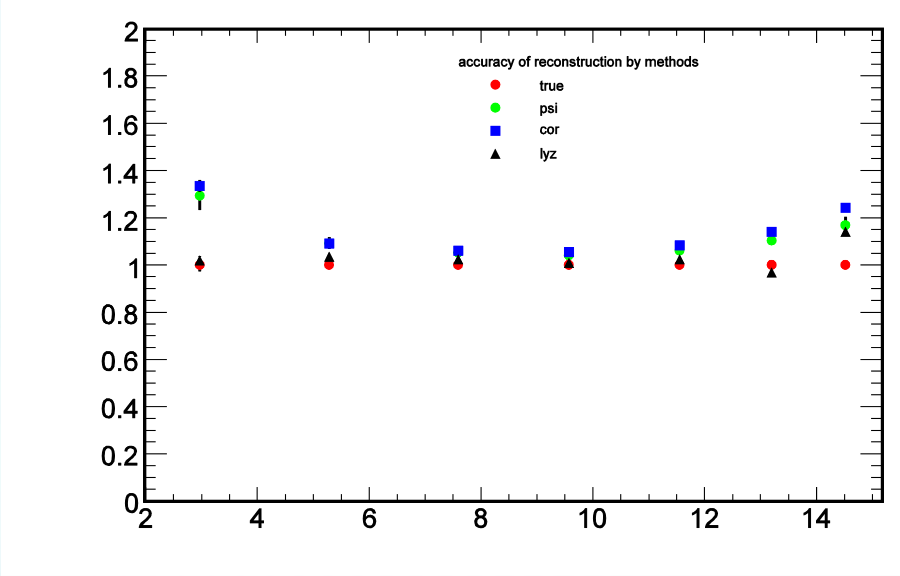
$$v_2 = \frac{j_0}{Nr_0}$$

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

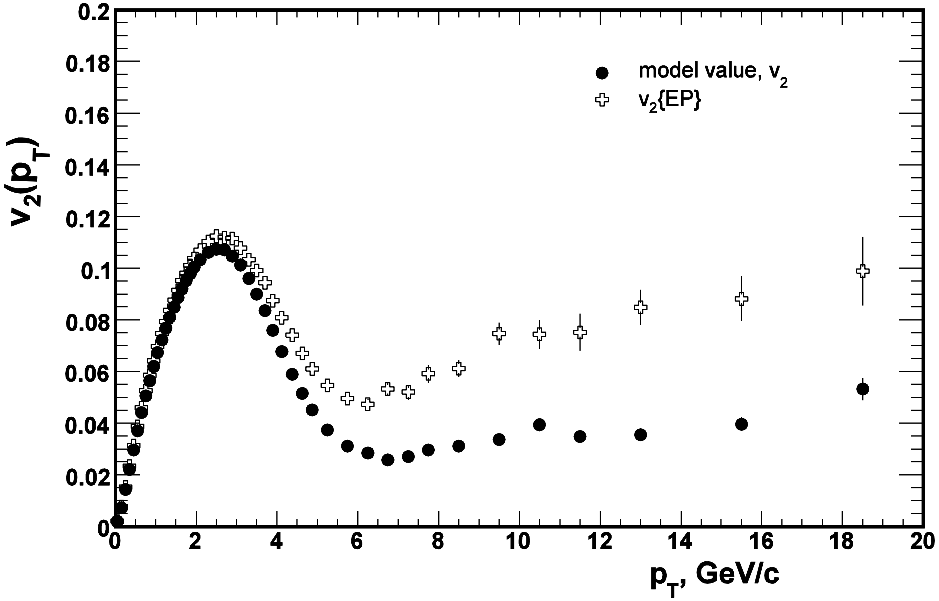


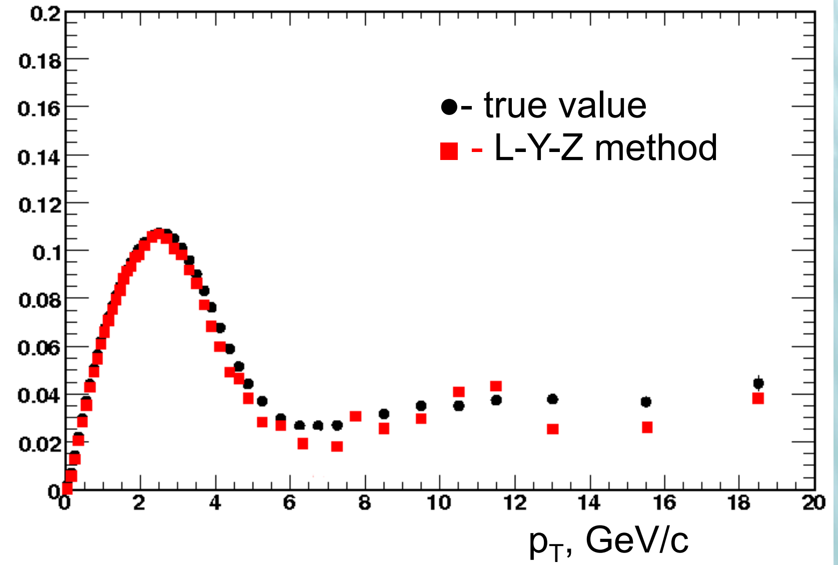


The better reconstruction is achived in midcentral collision for the methods, while Lee-Yang zero method tends to reconstruct true value at more central and more periferal collision.

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).