X Workshop on Particle Correlation and Femtoscopy
25-29 August, 2014

Higher flow harmonics and ridge effect in PbPb collisions with HYDJET++ model

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Outline

- HYDJET++ model (hydro + jet)
- Description of elliptic flow v_2
- Triangular flow v_3 and higher flow harmonics
- Dihadron angular correlations
- Conclusions

HYDJET++ model

I.Lokhtin, L.Malinina, S.Petrushanko, A.Snigirev, I.Arsene, K.Tywoniuk, Comp. Phys. Comm. 180 (2009) 779

The model combines hard and soft physics.

1. Soft part

Hadronization from freez-out surface with distribution function:

$$f_i^{\rm eq}(p^{*0}; T^{\rm ch}, \mu_i, \gamma_s) = \frac{g_i}{\gamma_s^{-n_i^s} \exp\left([p^{*0} - \mu_i]/T^{\rm ch}\right) \pm 1}$$

p^{*0} is the hadron energy in the fluid element rest frame, γ_s is strangeness suppression factor

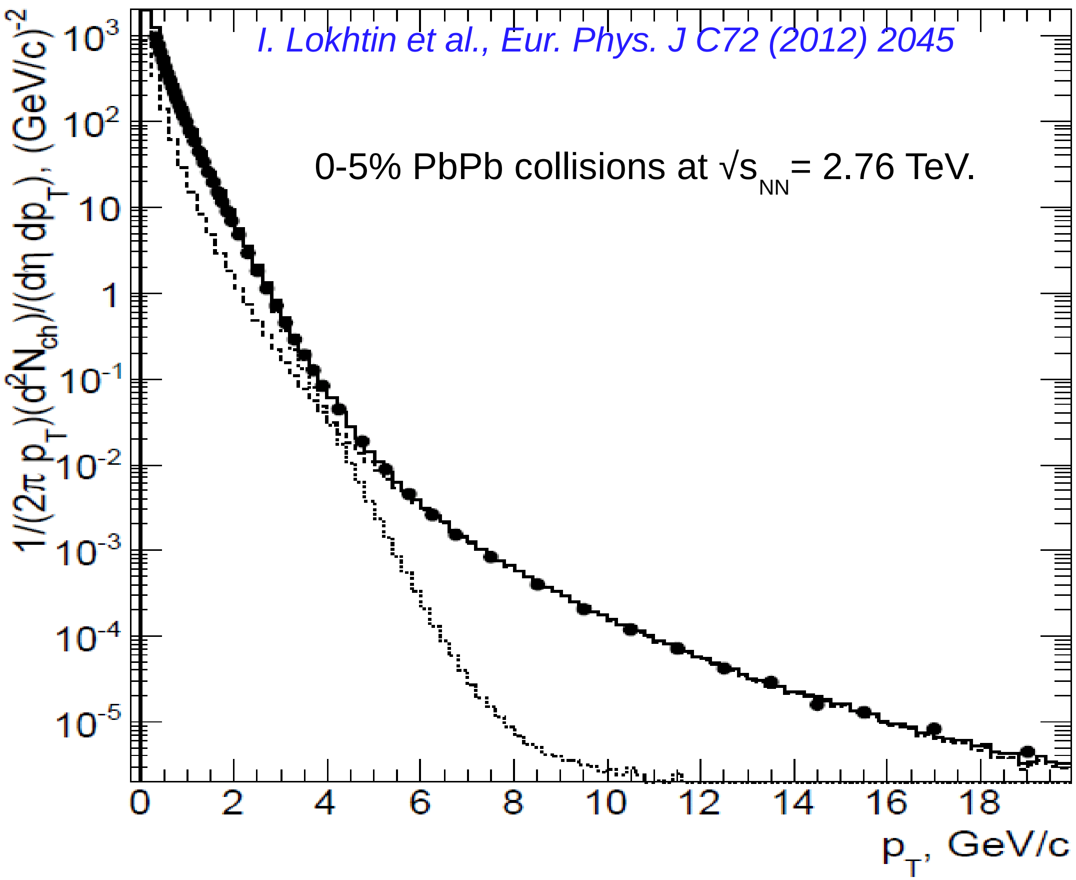
2. Hard part

Initial parton configuration →	parton rescattering & energy loss →	Hadronization
PYTHIA w/o hadronization	PYQUEN *I.P.Lokhtin, A.M.Snigirev, Eur. Phys. J. 45 (2006) 211*	PYTHIA w hadronization

- Parton collisional loss
- Radiative loss

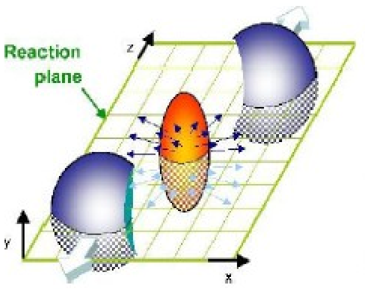
HYDJET++ model

The contribution of soft and hard components into total multiplicity depends on a model parameter: minimal p_T of hard process.



The points are ALICE data, histogram dashed is hard component, dotted is soft component of HYDJET++.

HYDJET++ model:
elliptic flow



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

Soft part:

- Space modulation of freeze-out surface;
- Modulation of liquid velocities on the surface

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

Space asymmetry:

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

R(b) is radius of the freeze-out surface

Momentum asymmetry:

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

φ_u : azimuthal angle of liquid velocity vector

φ : space azimuthal angle

Parameters $\varepsilon(b_0)$, $\delta(b_0)$ are tuned to describe experimental data.

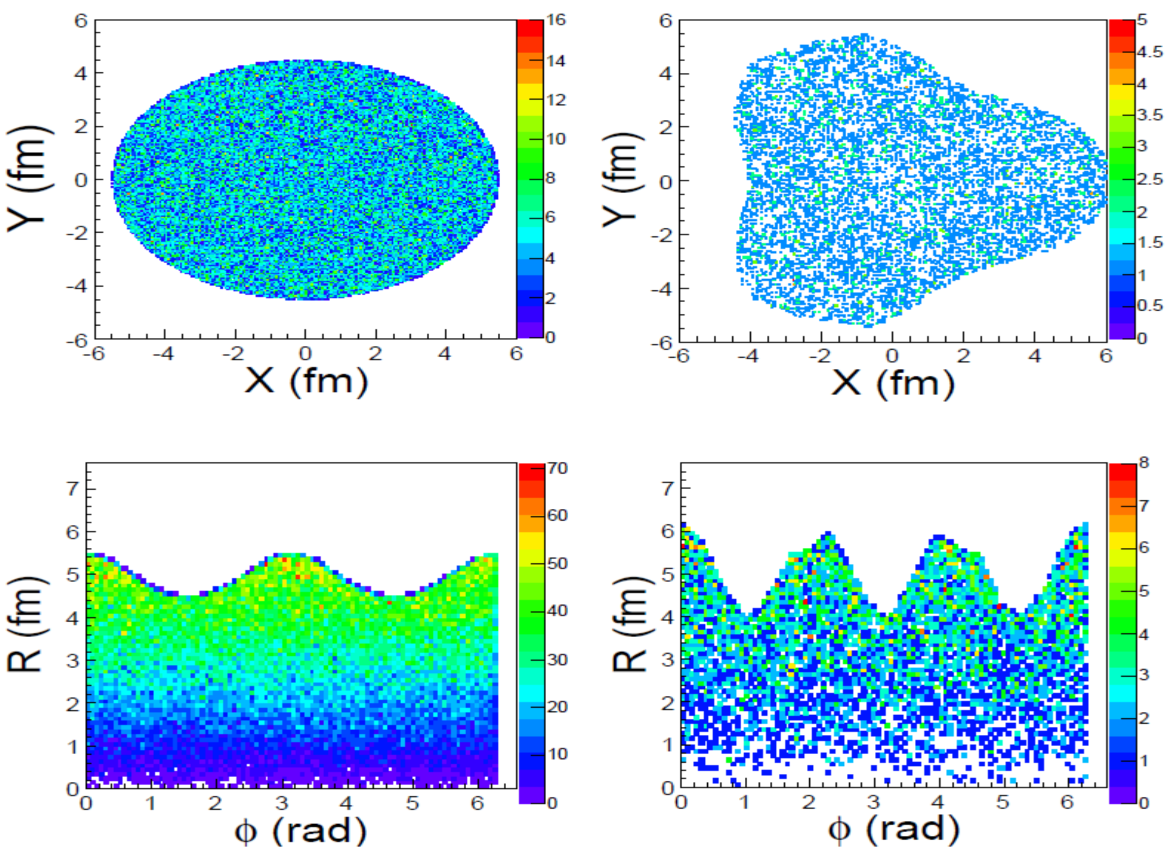
Hard part:

Parton energy loss depends on the path length in the medium: v_2(jet) $\neq 0$

HYDJET++: triangular flow

Space modulation of the freeze-out surface with independent phase Ψ_3 and parameter ε_3 is introduced in the model:

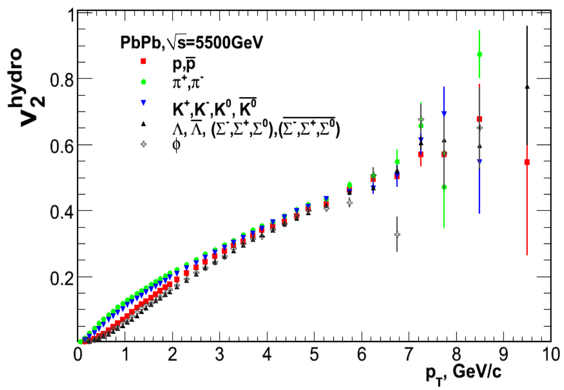
$$R(b,\phi) = R_f(b)\frac{\sqrt{1-\epsilon^2(b)}}{\sqrt{1+\epsilon(b)\cos 2\phi}}[1+\epsilon_3(b)\cos 3(\phi+\Psi_3^{\mathrm{RP}})] \qquad \Psi_3 \neq \Psi_2$$



Particle densities in the transverse plane for v_2 and v_2+ v_3 harmonics.

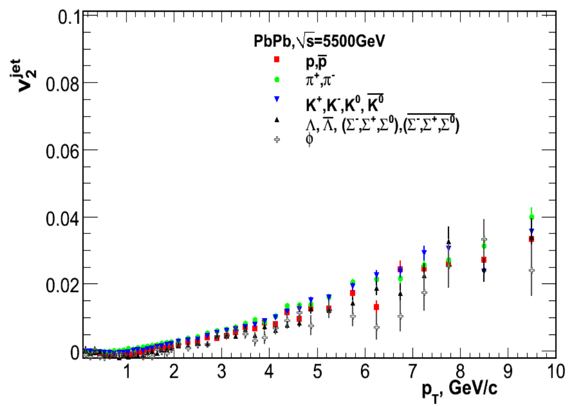
HYDJET++ model: flow

Hydrodynamics

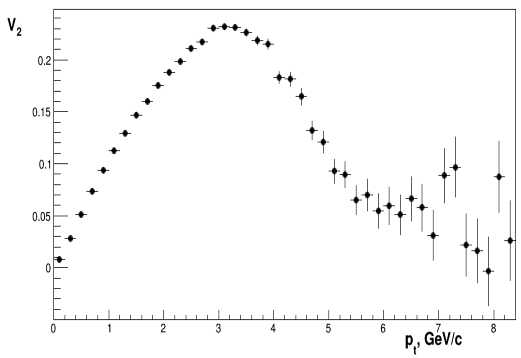


+

Jet part +quenching



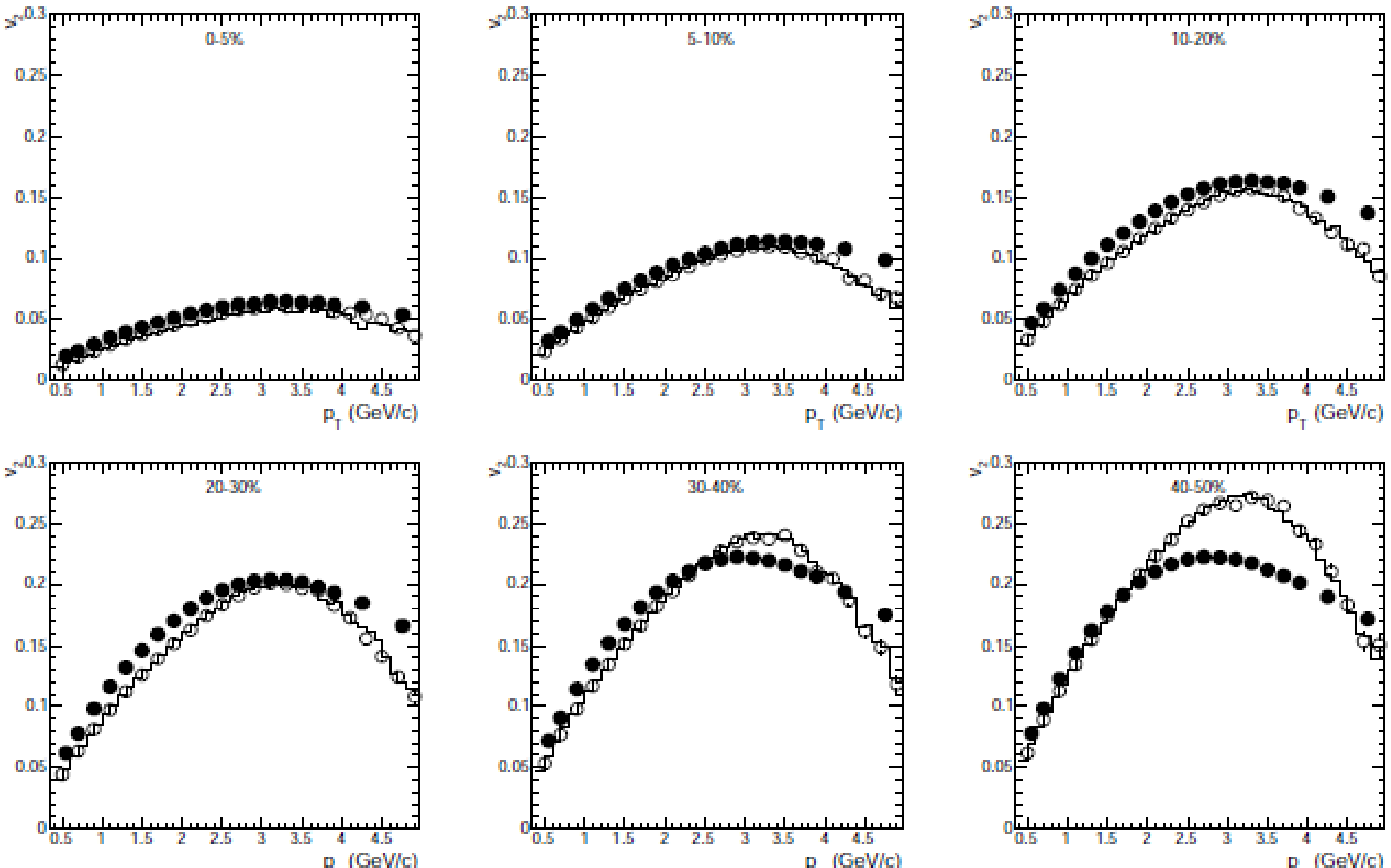
Typical flow pattern



- Even v_n appear in the model because of v_2
- Odd v_n appear in the model because of v_3

HYDJET++ : elliptic flow

v_2

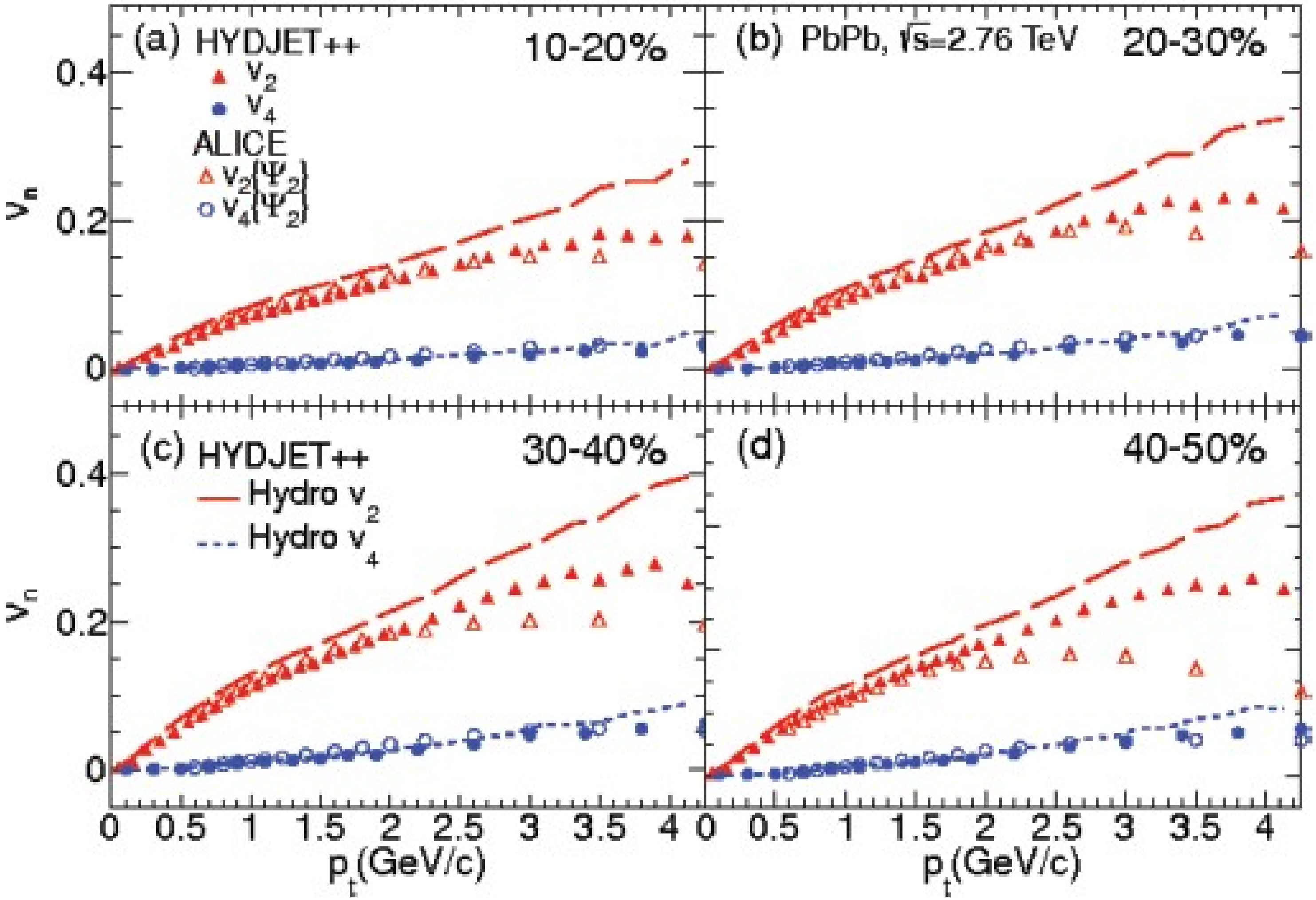


L. Bravina et al., Eur. Phys. J C74 (2014) 2807

The closed circles: ATLAS data (Phys.Rev. C 86, (2012) 014907), $v_n\{EP\}$, PbPb collisions, 2.76 TeV, open circles: $v_n\{EP\}$ for HYDJET++ , histograms: $v_n(\Psi_{RP})$ for HYDJET++

Discrepancy in an intermediate p_t region.

HYDJET++ :
elliptic and quadrangular flow



L. Bravina et al., Pgys.Rev.C78 (2013) 034901

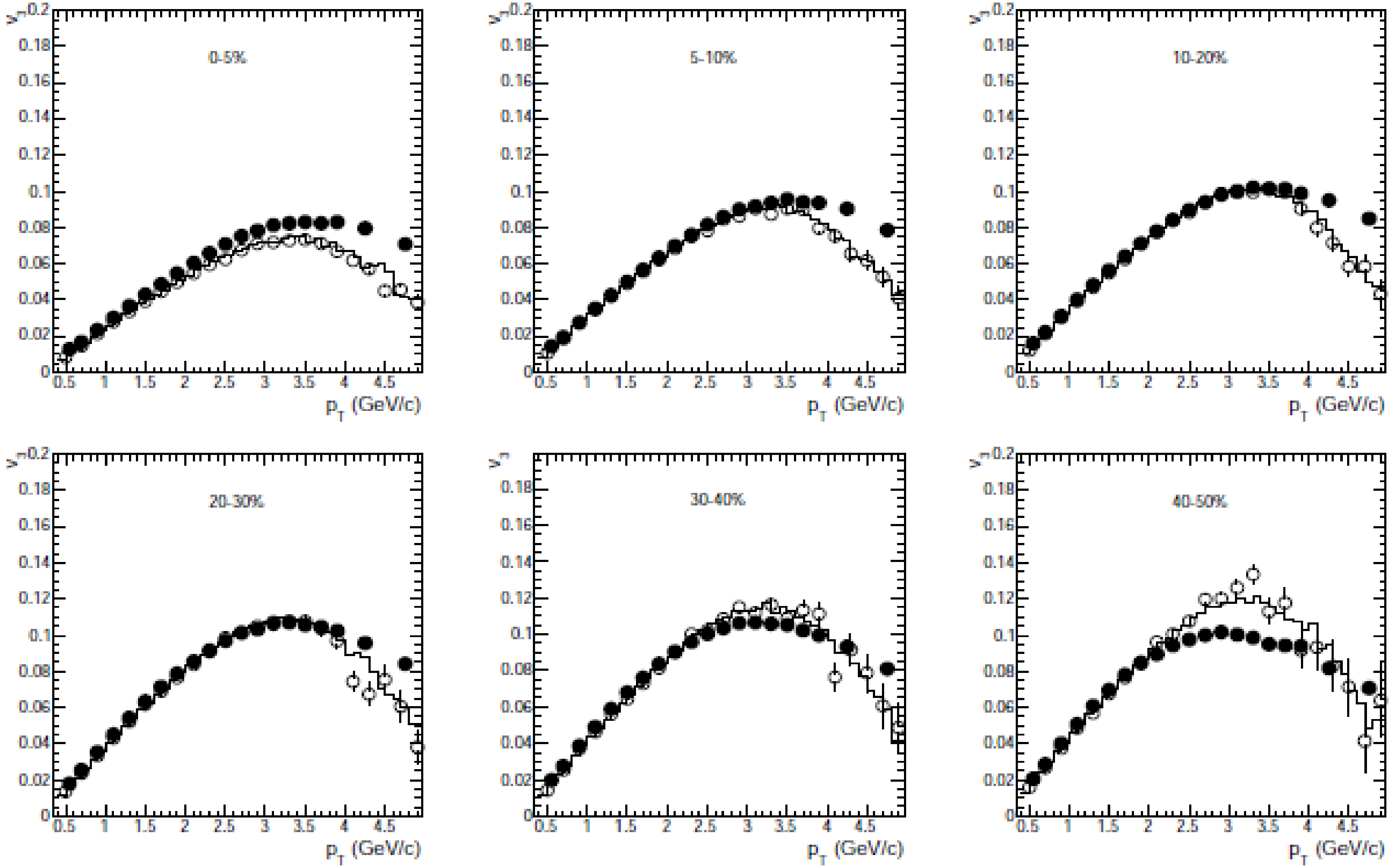
v_4 arising from v_2 (w.r.t Ψ_2) is described well.

In order to describe $v_4\{\Psi_4\}$ additional modulation of flow velocity is introduced currently, no independent Ψ_4.

HYDJET++ : triangular flow

The simple parametrization: $\varepsilon_3(b) \propto \varepsilon_0^{1/3}(b)$

v_3

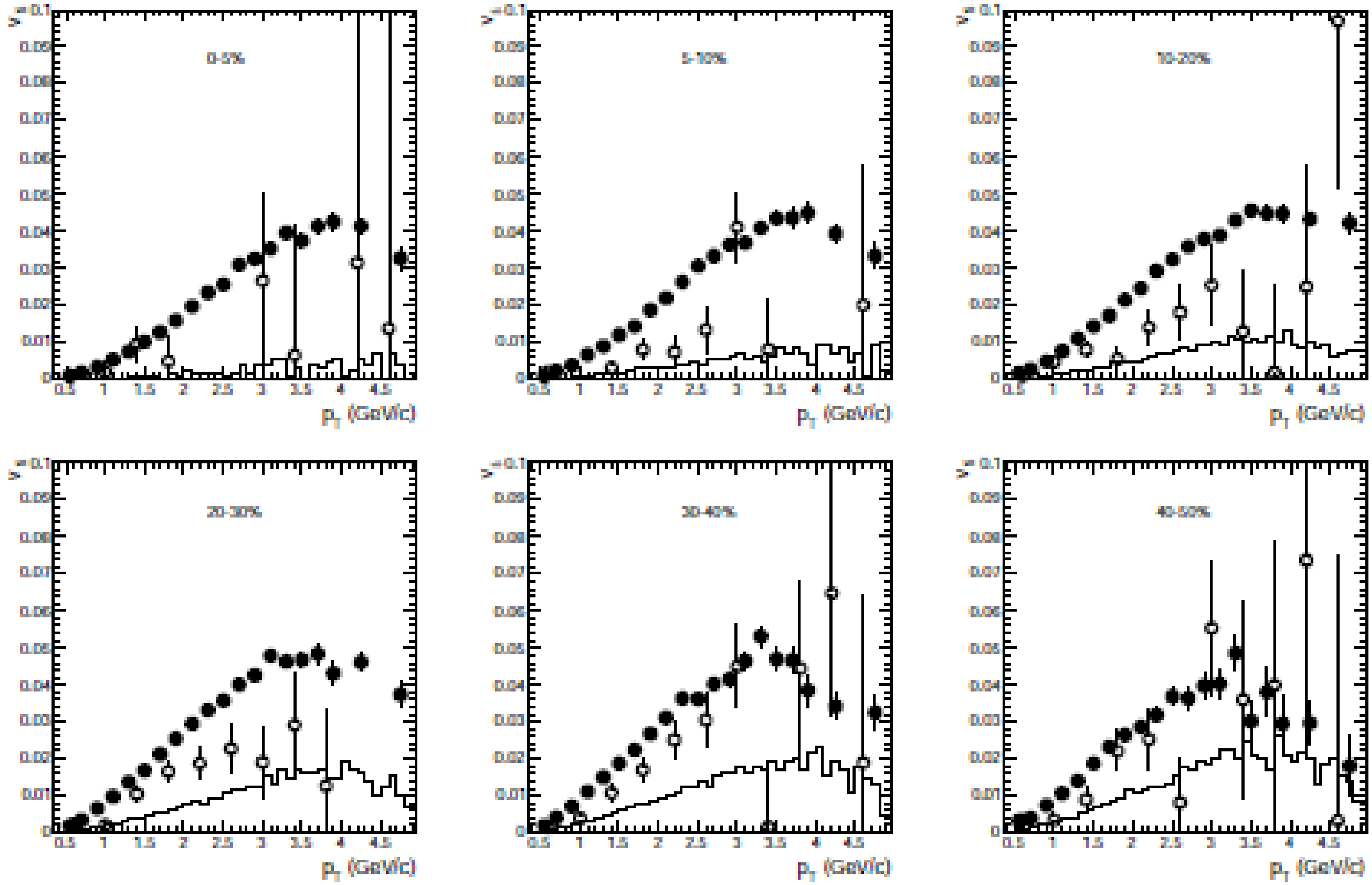


L. Bravina et al., Eur. Phys. J C74 (2014) 2807

The closed circles: ATLAS data (Phys.Rev. C 86, (2012) 014907), $v_n\{EP\}$, PbPb collisions, 2.76 TeV, open circles: $v_n\{EP\}$ for HYDJET++, histograms: $v_n(\Psi_{RP})$ for HYDJET++

HYDJET++ :
higher order harmonics

V_5



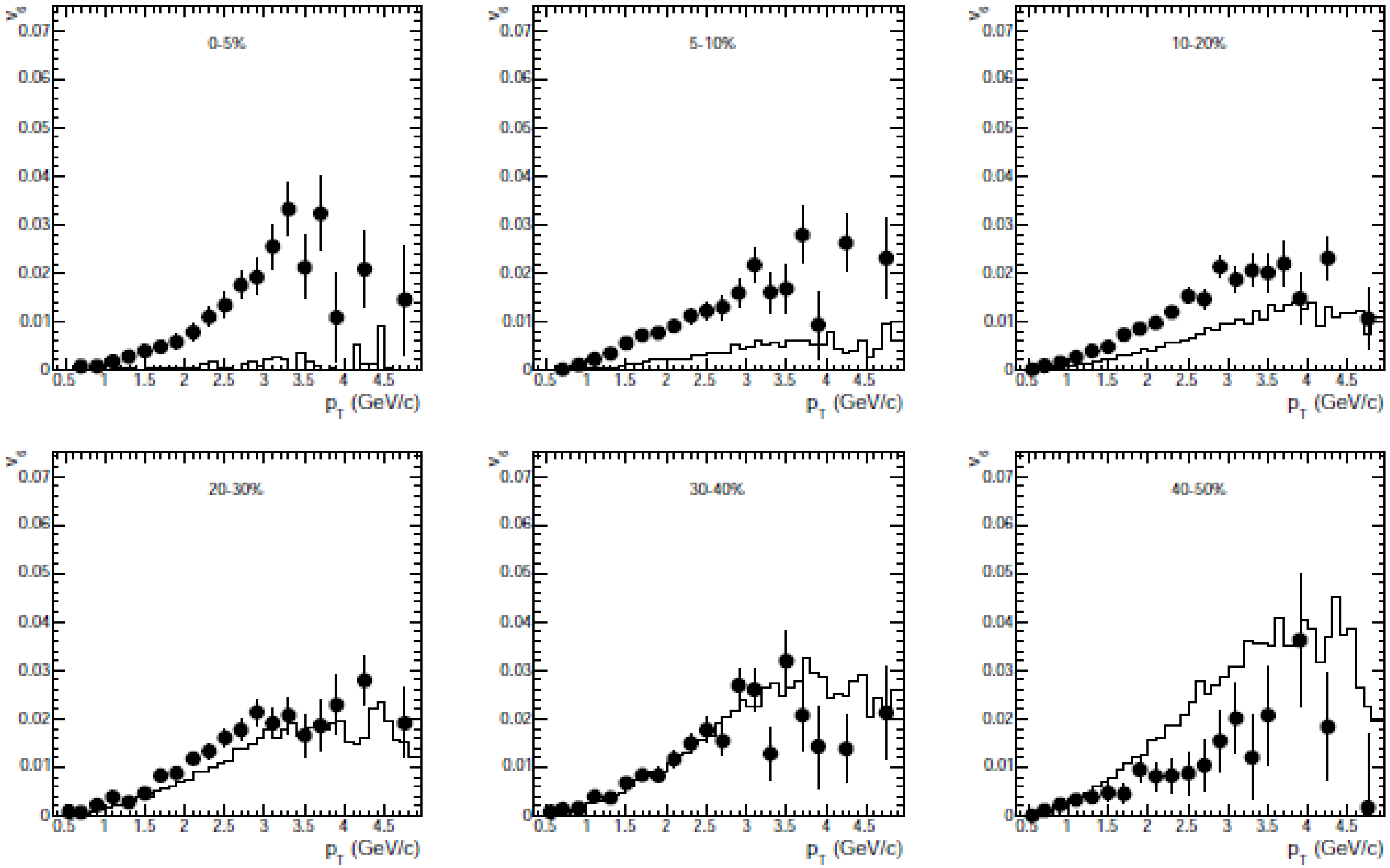
L. Bravina et al., Eur. Phys. J C74 (2014) 2807

The closed circles: CMS data $v_n\{EP\}$, PbPb collisions, 2.76 TeV,
open circles: $v_n\{EP\}$ for HYDJET++ ; histograms: $v_n(\Psi_{RP})$ for HYDJET++

central collisions → the possible presence of the additional pentagonal flow parameter

HYDJET++ :
higher order harmonics

V_6



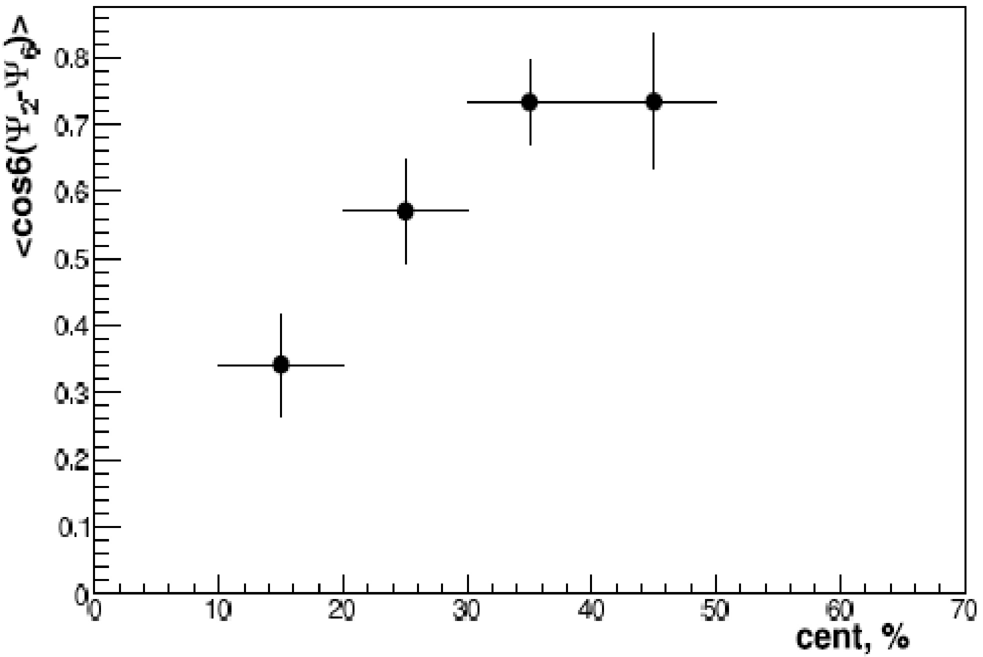
L. Bravina et al., Eur. Phys. J C74 (2014) 2807

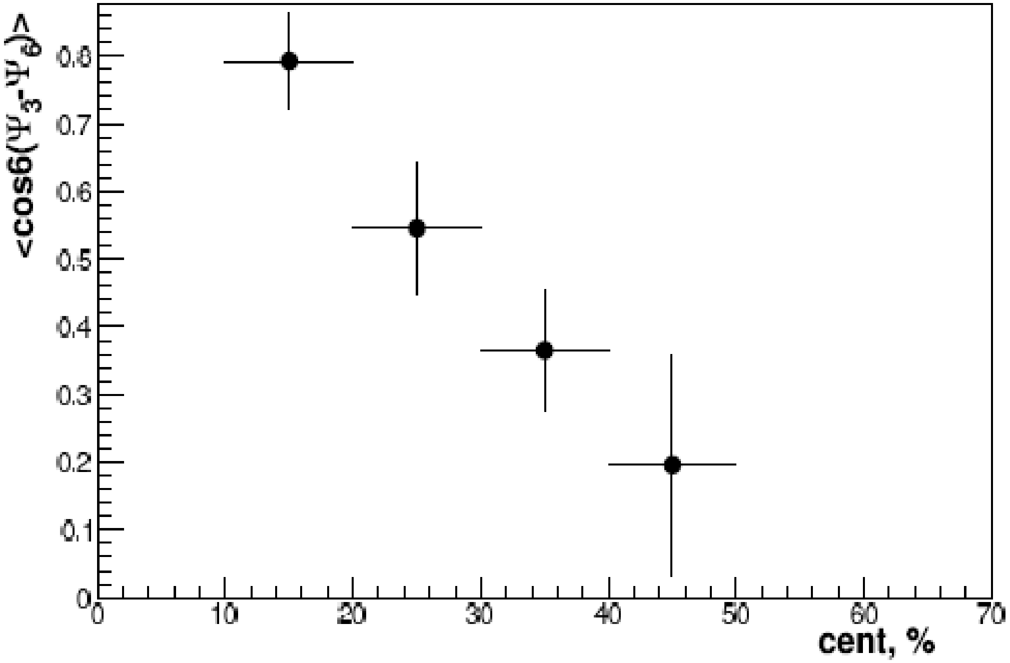
The closed circles: CMS data $v_6\{EP\}$, PbPb collisions, 2.76 TeV,
histograms: $v_6(\Psi_2)$ for HYDJET++ ; $v_6(\Psi_6)$ in progress

V_6 also has a contribution from v_3 (only contribution from v_2 is shown).

Two-plane correlators

Ψ_2 , Ψ_3 are known in the model, Ψ_6 is reconstructed with EP method.





Contribution from v_3 increases for more central collisions.

Behavior of the plane correlators is in line with the experimental observations.

Dihadron angular triggered correlations

Signal: correlations of a pair in the same event:

$$S(\Delta\varphi, \Delta\eta) = \frac{1}{N_{trig}} \frac{d^2N^{same}}{d\Delta\varphi d\Delta\eta}$$

Background: correlations of two particles from different events:

$$B(\Delta\varphi, \Delta\eta) = \frac{1}{N_{trig}} \frac{d^2N^{mixed}}{d\Delta\varphi d\Delta\eta}$$

Correlation function, definition 1

$$C(\Delta\phi, \Delta\eta) \equiv \frac{N_{\rm mixed}}{N_{\rm same}} \times \frac{N_{\rm same}(\Delta\phi, \Delta\eta)}{N_{\rm mixed}(\Delta\phi, \Delta\eta)}$$

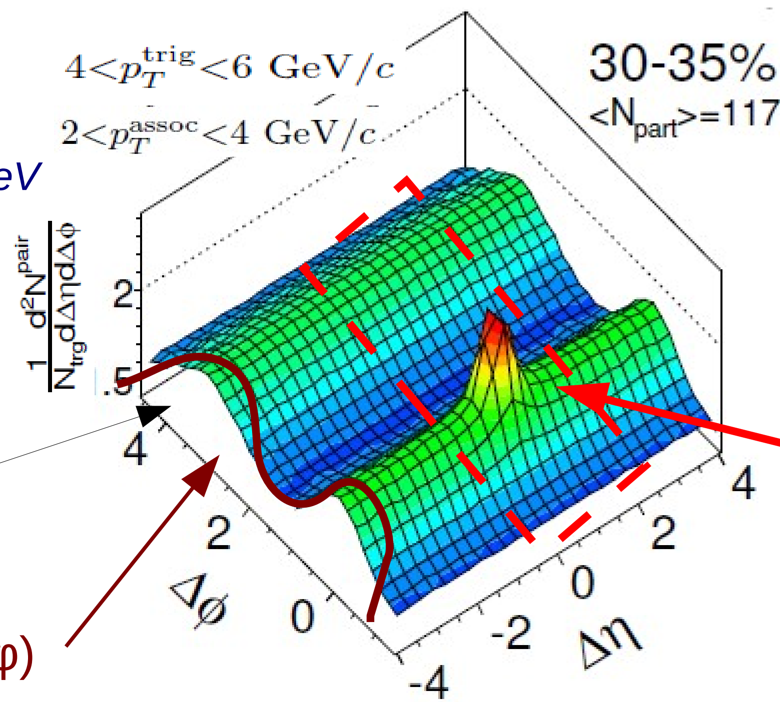
definition 2

$$\frac{1}{N_{trig}} \frac{d^2N}{d\Delta\varphi d\Delta\eta} = B(0,0)\frac{S(\Delta\varphi, \Delta\eta)}{B(\Delta\varphi, \Delta\eta)}$$

$\Delta\varphi = \varphi_1 - \varphi_2$
$\Delta\eta = \eta_1 - \eta_2$

N_{trig} : number of trigger particles.

CMS, PbPb 2.76TeV
arXiv:1107.0032



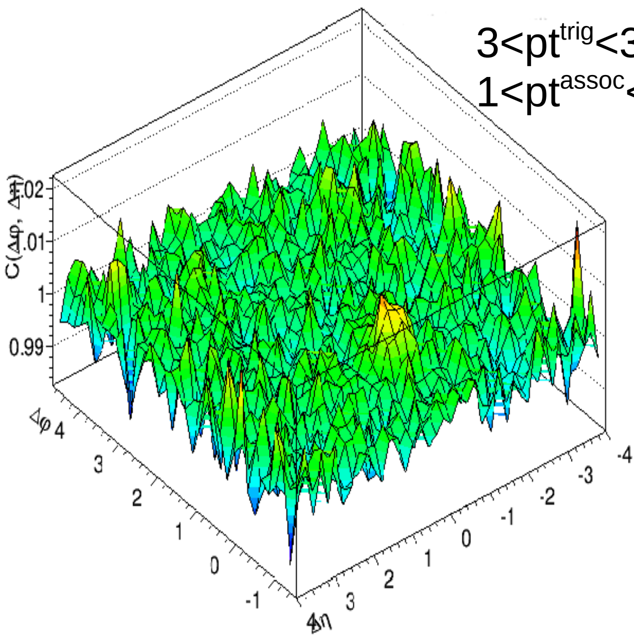
Away-side peak from jet is broad on Δη

Flow, cos(2Δφ)

Short range correlations (small Δη): hadrons inside jets, clusters, resonances

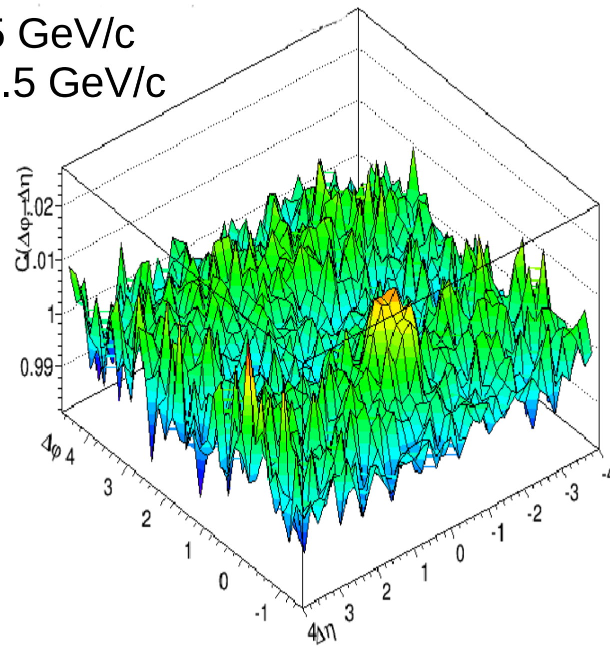
Dihadron angular correlation in HYDJET++, PbPb 2.76 TeV

0% centrality

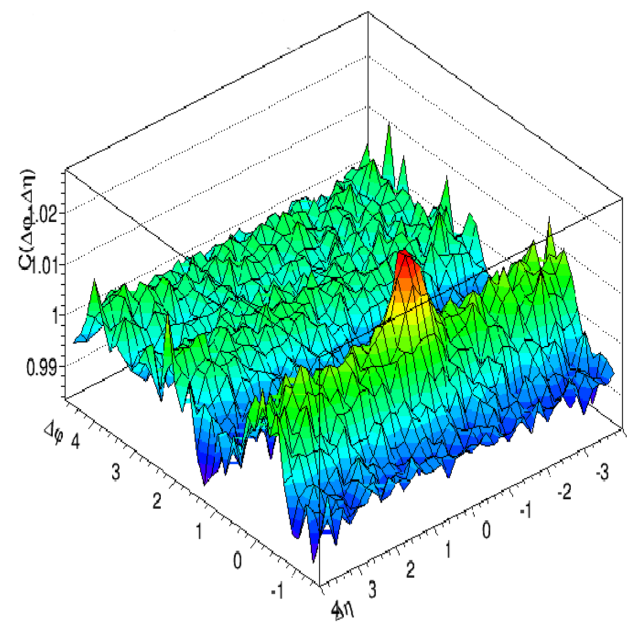


3<pt^{trig}<3.5 GeV/c
1<pt^{assoc}<1.5 GeV/c

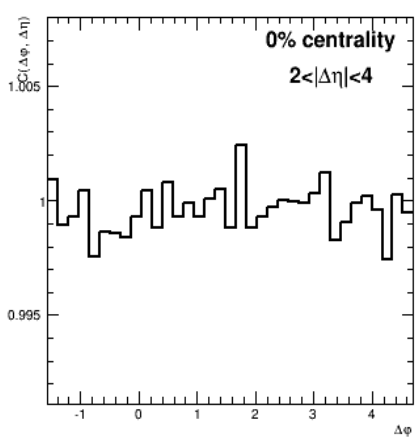
0-5% centrality, v2 only

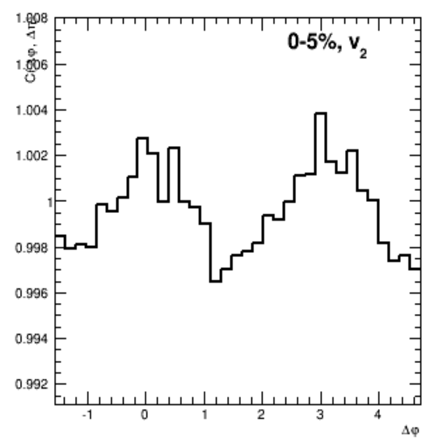


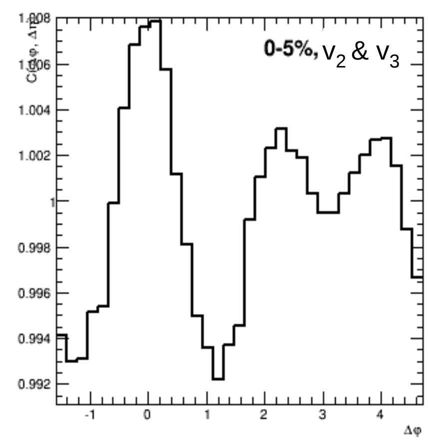
0-5% centrality, v_2 & v_3



Ridge region, 1D



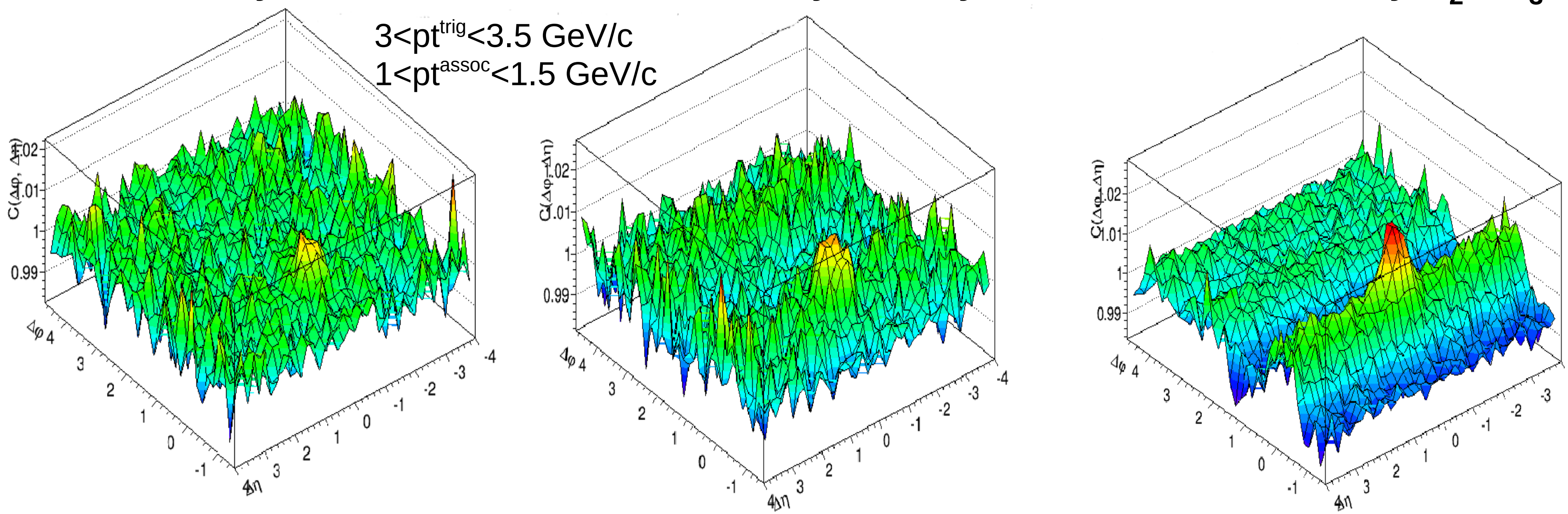




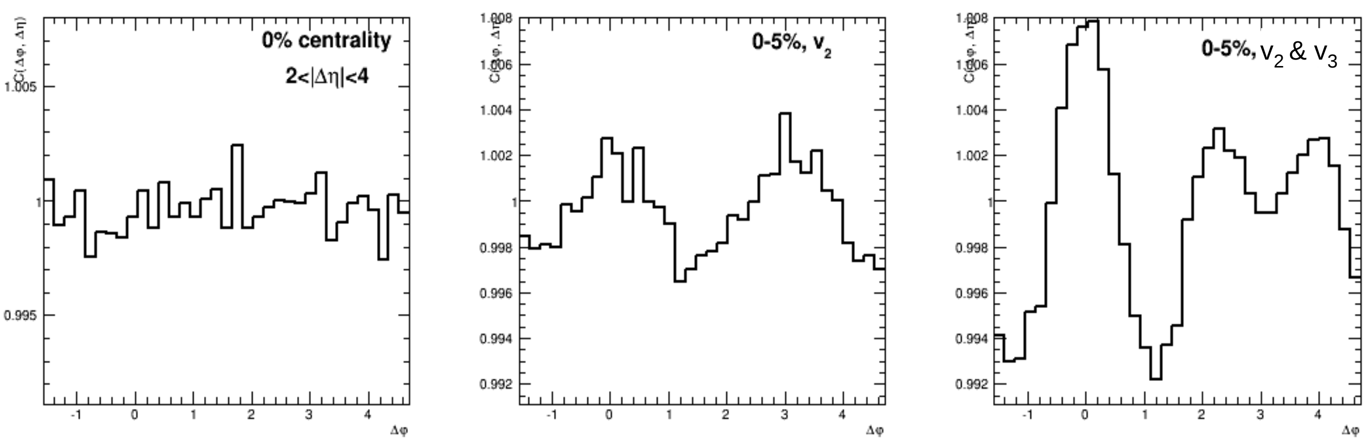
- *The ridge effect appears in the model because of flow v_2 and v_3*
- *v_3 leads to double-peak structure at away-side on Δφ*

Dihadron angular correlation in HYDJET++, PbPb 2.76 TeV

0% centrality | **0-5% centrality, v2 only** | **0-5% centrality, v_2 & v_3**



Ridge region, 1D

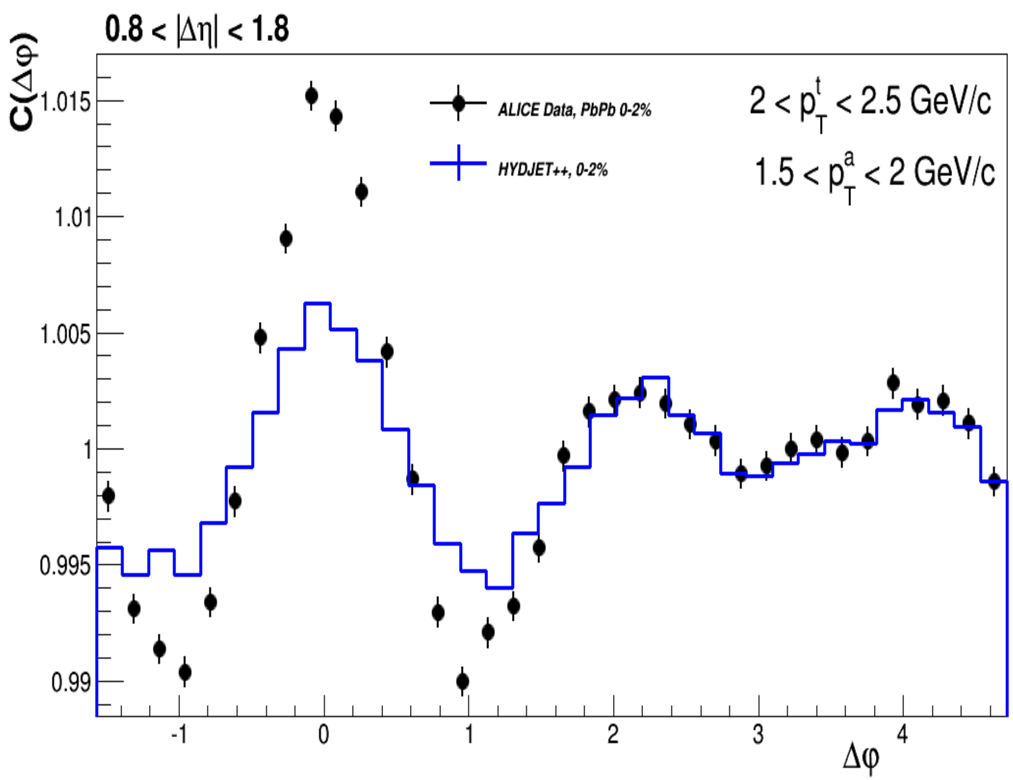


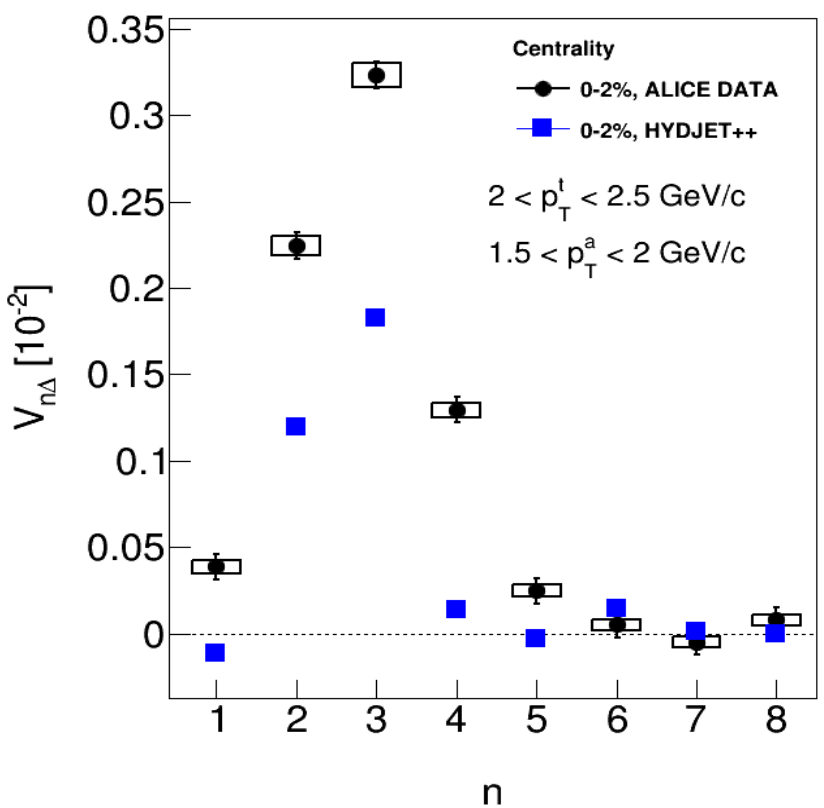
- *The ridge effect appears in the model because of flow v_2 and v_3*
- *v_3 leads to double-peak structure at away-side on Δφ*

HYDJET++ data comparison

Ultra-central collisions, 0-2%

$$\frac{dN^{\text{pairs}}}{d\Delta\phi} \propto 1 + \sum_{n=1}^{\infty} 2V_{n\Delta}(p_T^t, p_T^a)\cos(n\Delta\phi)$$





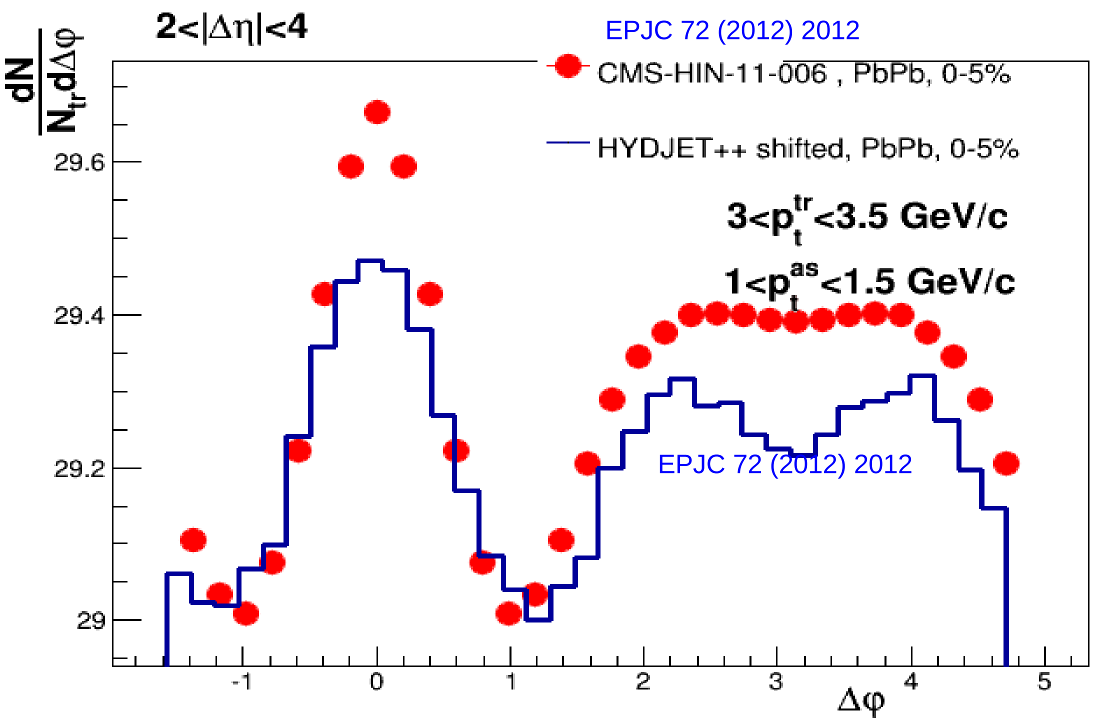
DATA: PLB 708, 249 (2012) ALICE

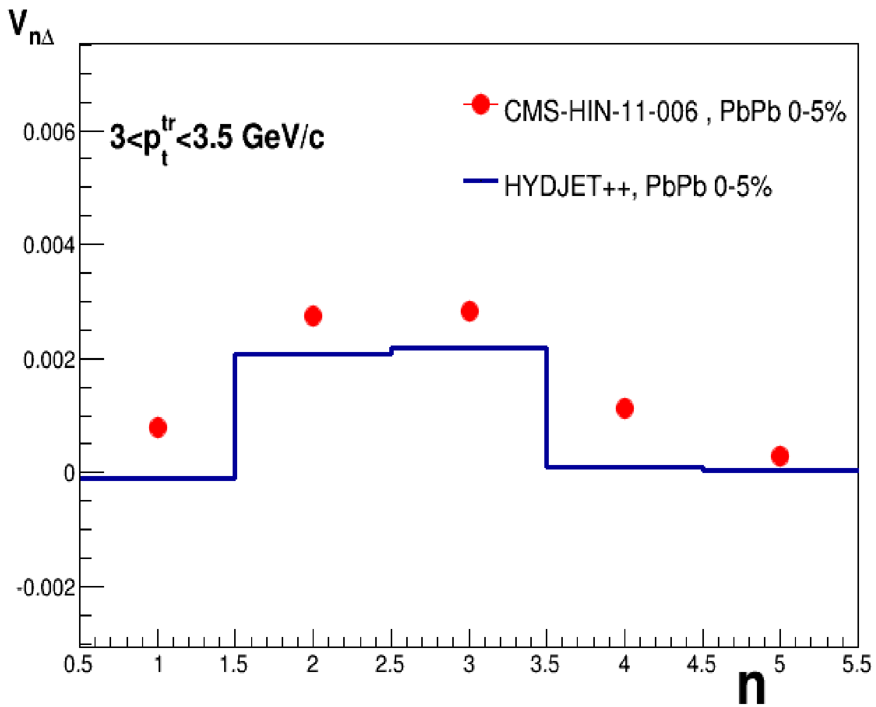
- The ridge is smaller than in data
- Away-side structure is discribed well

- Coefficients $V_{\Delta 2}$, $V_{\Delta 3}$ are smaller and $V_{\Delta 4}$, $V_{\Delta 5}$ are negligible compared to data

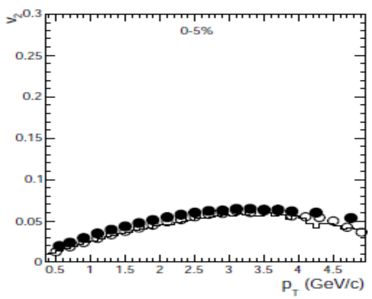
HYDJET++ data comparison

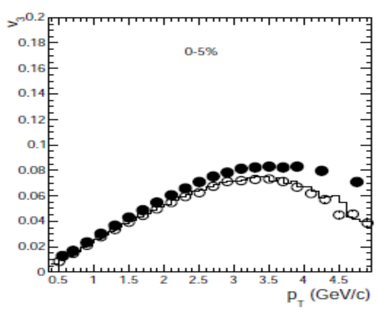
Central collisions, 0-5%

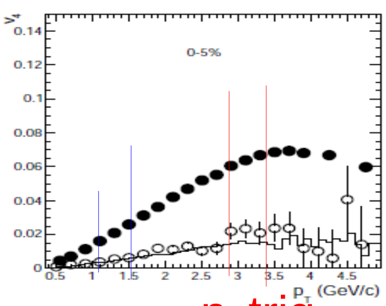




Singular particle flow: v_2 v_3 v_4



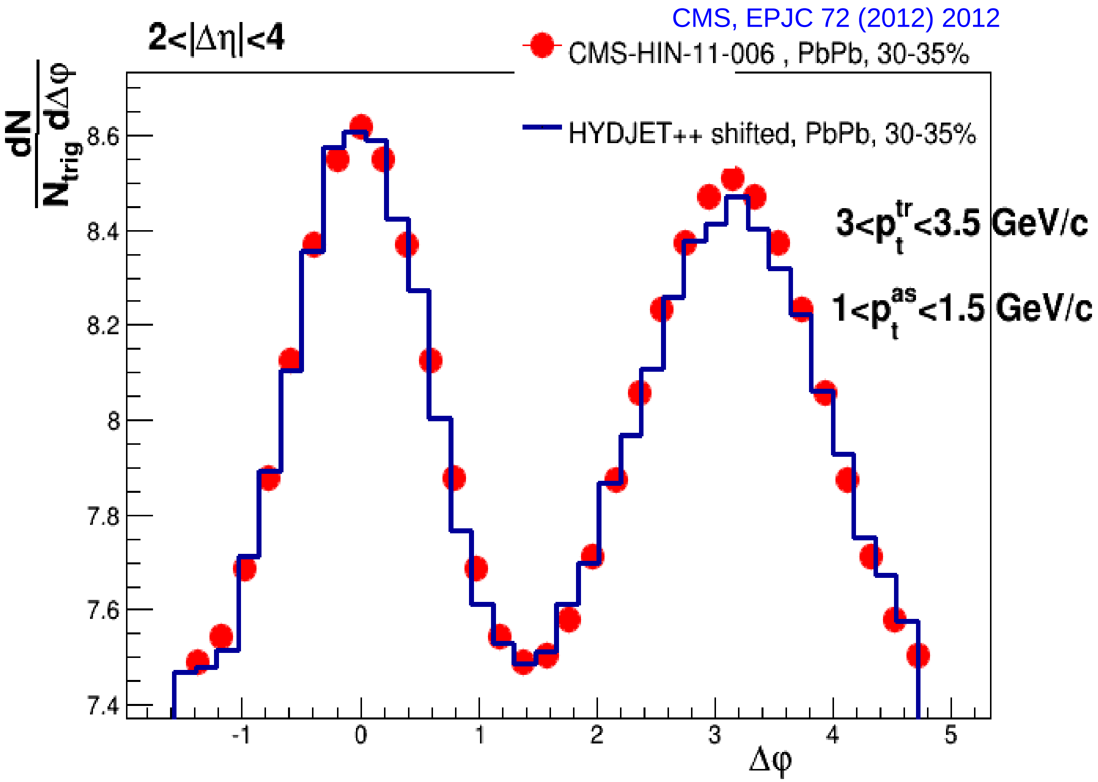


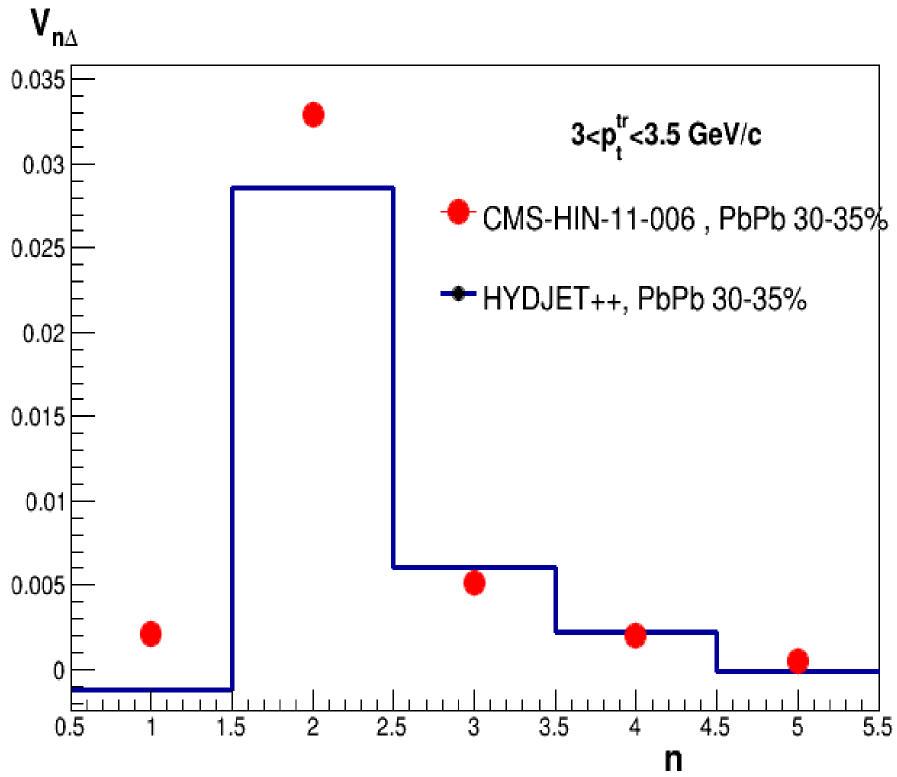


p_t assoc p_t trig

HYDJET++
data comparison

Mid-central collisions, 30-35%

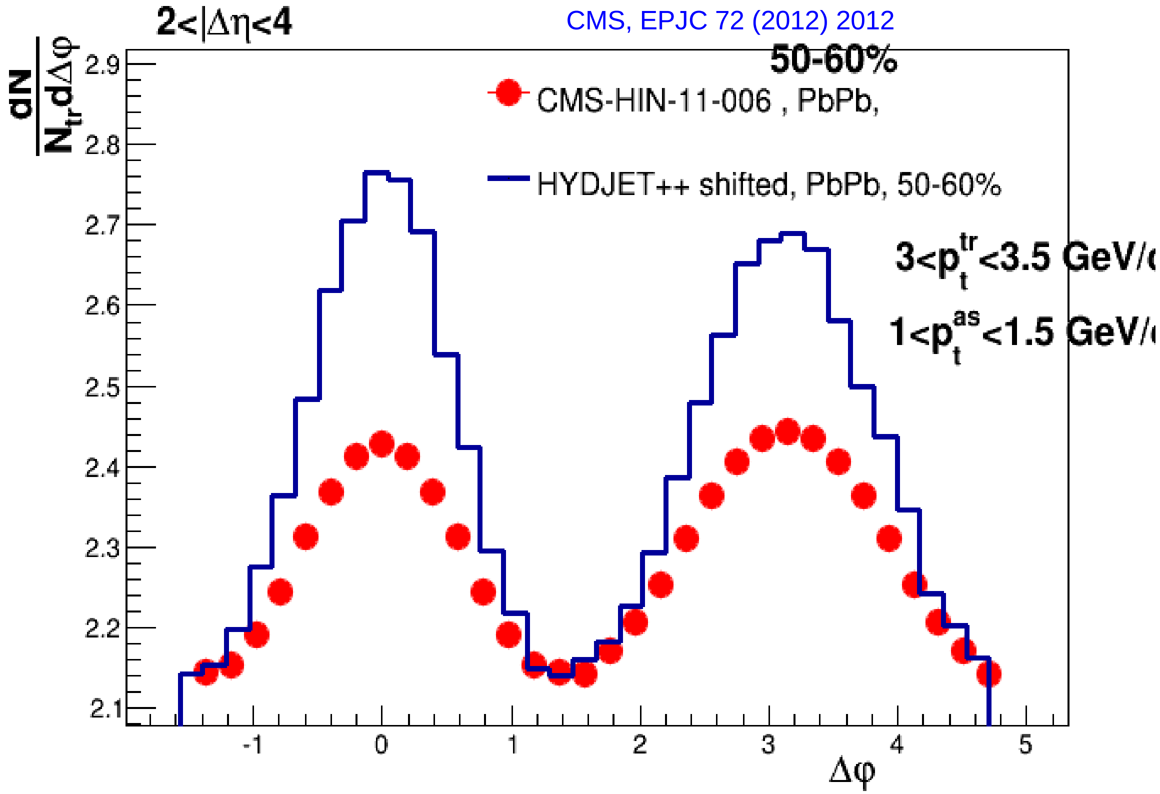


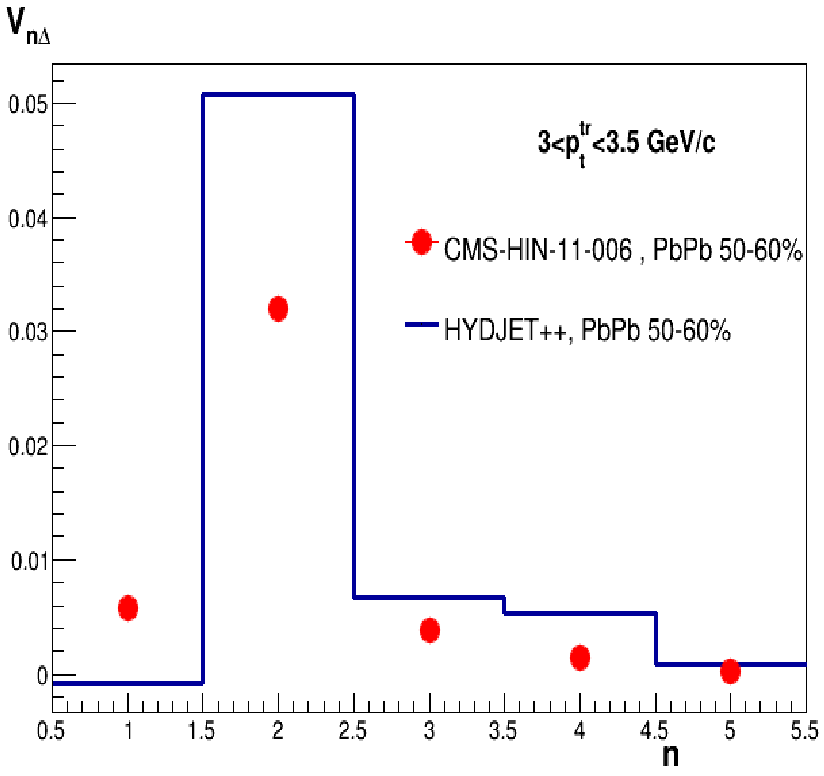


Singular particle flows are described well in this region.

HYDJET++
data comparison

More peripheral collisions, 50-60%





Coefficients $V_{\Delta 2}$ is much smaller compared to data.

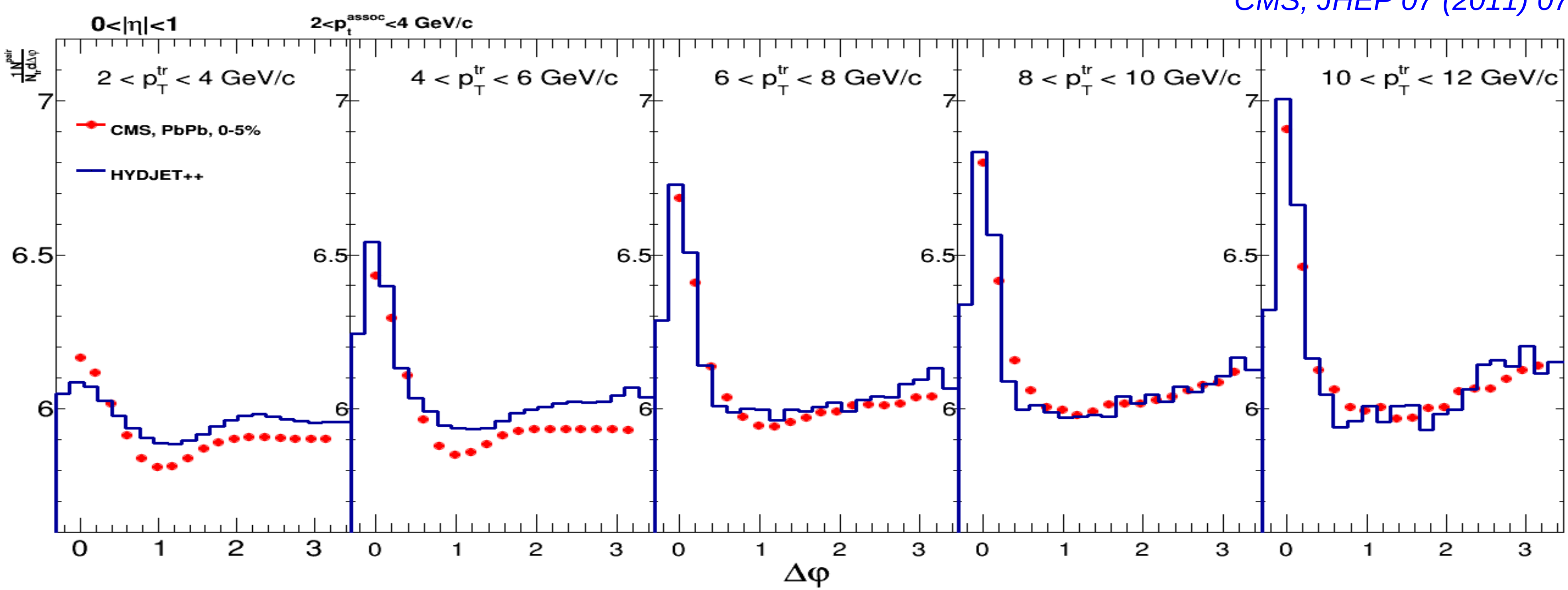
HYDJET++
data comparison, momentum dependence

Central collisions, 0-5%

Short range correlations, $|\Delta\eta|<1$

flow+non-flow p_t^{tr} non-flow (jets)+jet quenching

CMS, JHEP 07 (2011) 076

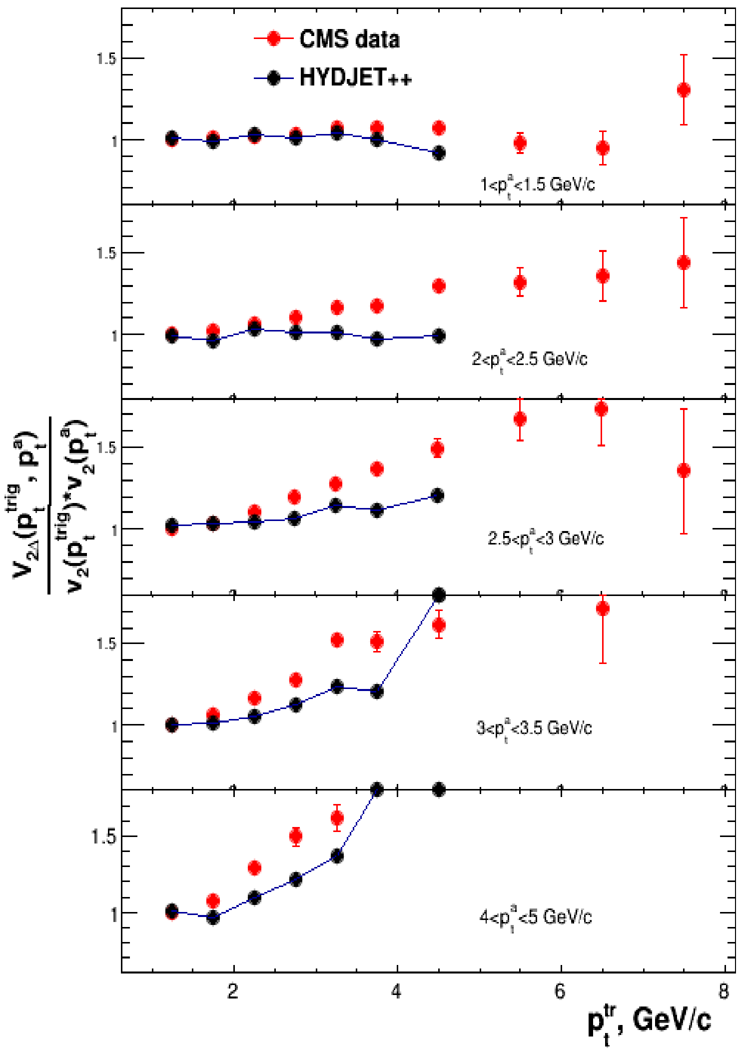


- At 0-5% centrality, HYDJET++ does not reproduce flow harmonics v_n (n>2) very well, neither it reproduces dihadron correlations at low p_t^{tr}.
- At high p_t^{tr} HYDJET++ describes data.

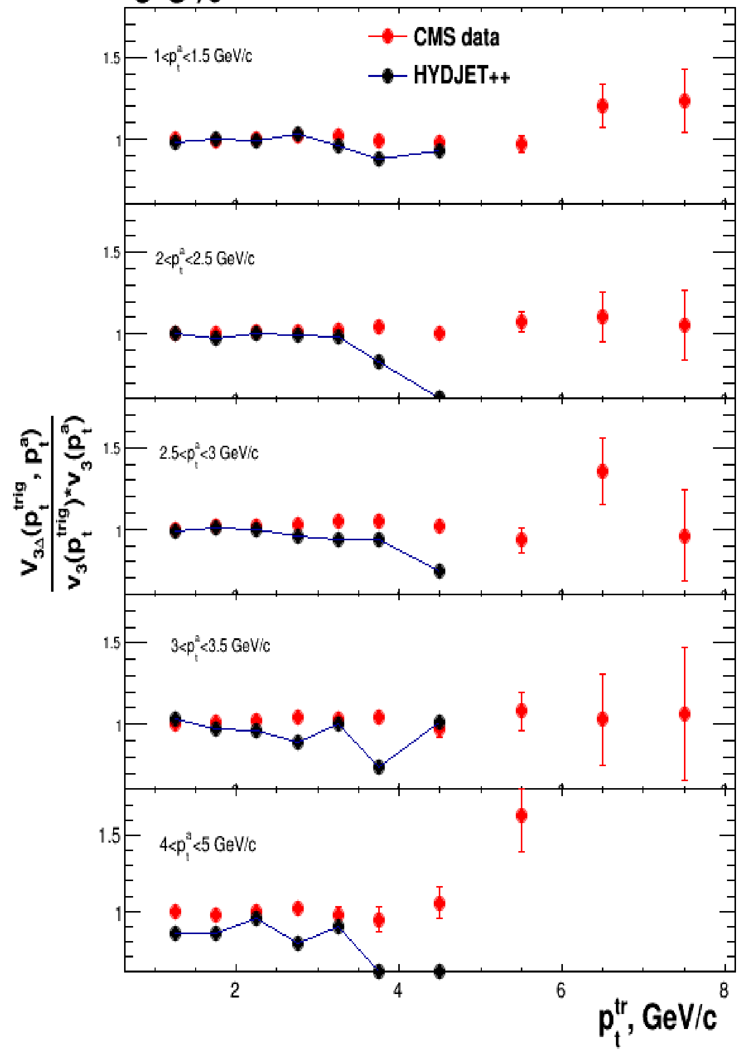
Test of factorization: $V_{\Delta n} \approx v_n\{2\}(p_t^{tr}) * v_n\{2\}(p_t^{a})$

At low p_t one neglects non-flow and estimates: $v_n(p_t^{low}) = \sqrt{V_{\Delta n}(p_t^{low}, p_t^{low})}$; $v_n(p_t) = V_{\Delta n}(p_t, p_t^{low}) / v_n(p_t^{low})$

$V_{\Delta 2}$ factorization



0-5%



$V_{\Delta 3}$ factorization

- Factorization in HYDJET++ breaks due to hard component (non-flow).
- Factorization for $V_{\Delta 2}$ breaks in data at lower p_t compared to HYDJET++.

Conclusion

- Flow in the model:
  - Uncorrelated EbE reaction planes Ψ_2 and Ψ_3 are introduced, independent on η and p_t.
  - Multiplicity fluctuation at the same impact parameter → flow v_2 and v_3 fluctuations (no additional fluctuations due to eccentricity fluctuations)
  - Higher flow harmonics appear from v_2 and v_3 interference in final state (at freeze-out)

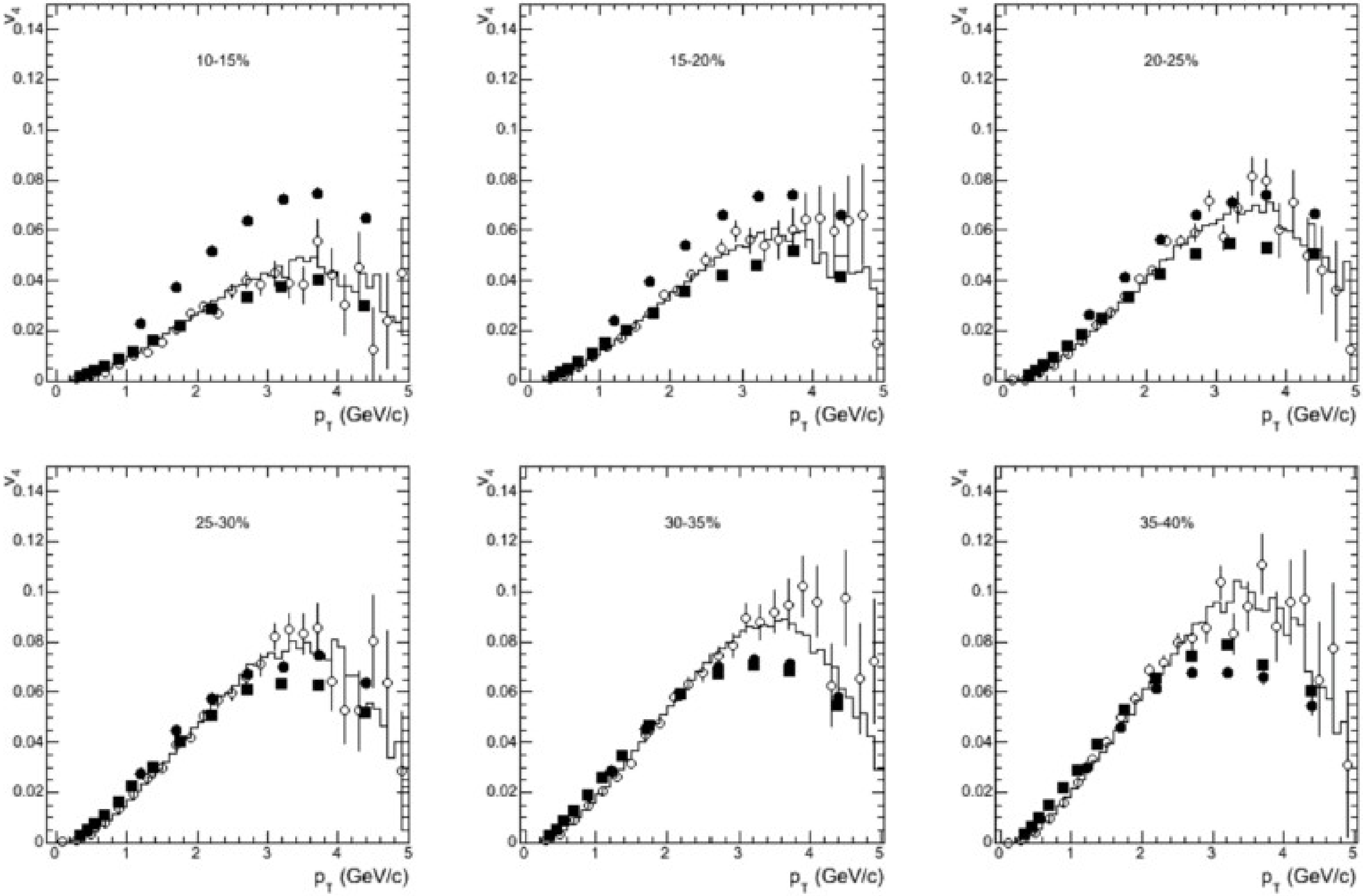
- Data on higher flow harmonics and dihadron angular correlations are described well in mid-central collisions

- The mechanism of interference of v_2 and v_3 is not enough to describe data in central collisions

Backups

HYDJET++ : quadrangular flow

v_4



CMS data, $v_4\{2\}$ — circles, $v_4\{LYZ\}$ — squares

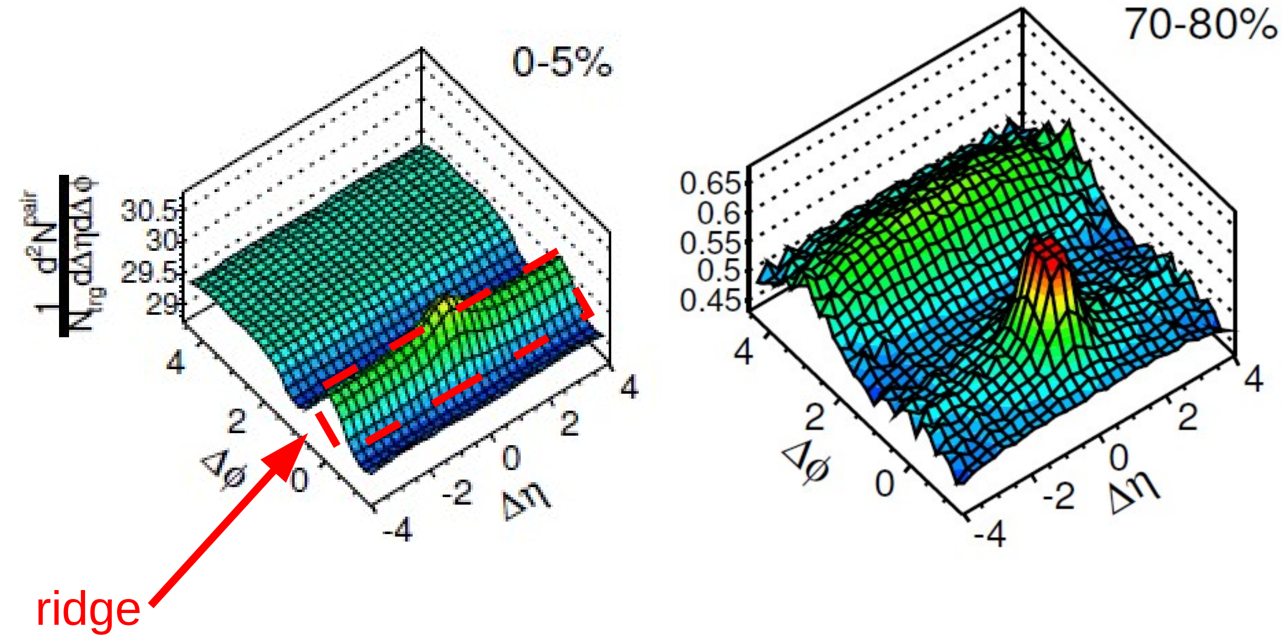
L. Bravina et al., Eur. Phys. J C74 (2014) 2807

Correlation pattern in AA

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

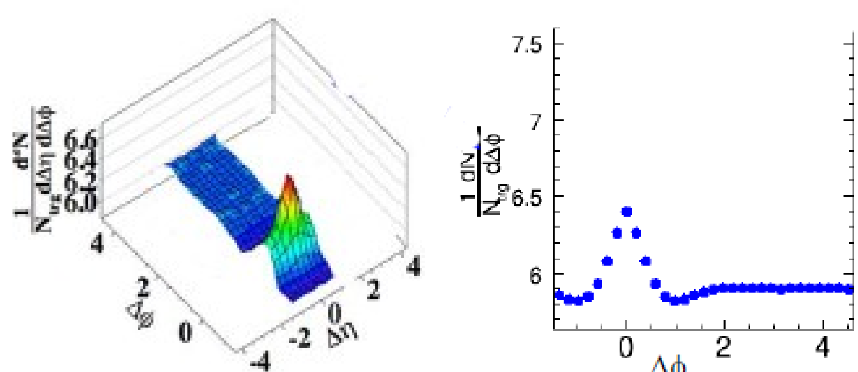
Central collisions:
- The back jet is quenched
- Small flow v_2
- ridge

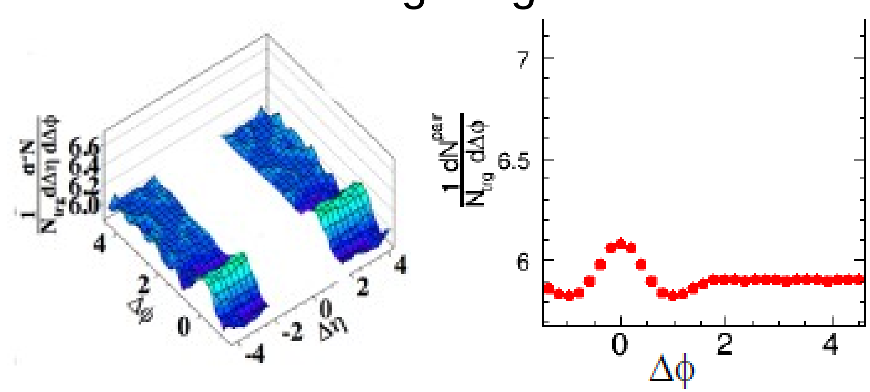
Peripheral collisions:
- Back jet peak
- Small flow v_2
- Small ridge



Jet region, 2D vs 1D

Ridge region





HYDJET++, hard component

Parton collisional loss (high momentum transfer approximation)

$$\frac{dE^{col}}{dl} = \frac{1}{4T\lambda\sigma}\int_{\mu_D^2}^{t_{\max}} dt\frac{d\sigma}{dt}t \qquad \frac{d\sigma}{dt} \cong C\frac{2\pi\alpha_s^2(t)}{t^2}\frac{E^2}{E^2-m_p^2}, \qquad \alpha_s = \frac{12\pi}{(33-2N_f)\ln(t/\Lambda_{QCD}^2)}$$

t is momentum transfer,E and m_p: energy and mass of a hard parton, C is color factor

Radiative loss (coherent gluon radiation in Baier-Dokshitzer-Mueller-Schiff formalism)

– *For massless parton*

$$\frac{dE^{rad}}{dl} = \frac{2\alpha_s(\mu_D^2)C_R}{\pi L}\int_{\omega_{\min}}^{E} d\omega\left[1-y+\frac{y^2}{2}\right]\ln\left|\cos(\omega_1\tau_1)\right| \quad \omega_1 = \sqrt{i\left(1-y+\frac{C_R}{3}y^2\right)\bar{\kappa}\ln\frac{16}{\bar{\kappa}}} \quad \text{with} \quad \bar{\kappa} = \frac{\mu_D^2\lambda_g}{\omega(1-y)}\ \tau_1 = L/(2\lambda_g),\ y=\omega/E$$

w is gluon energy

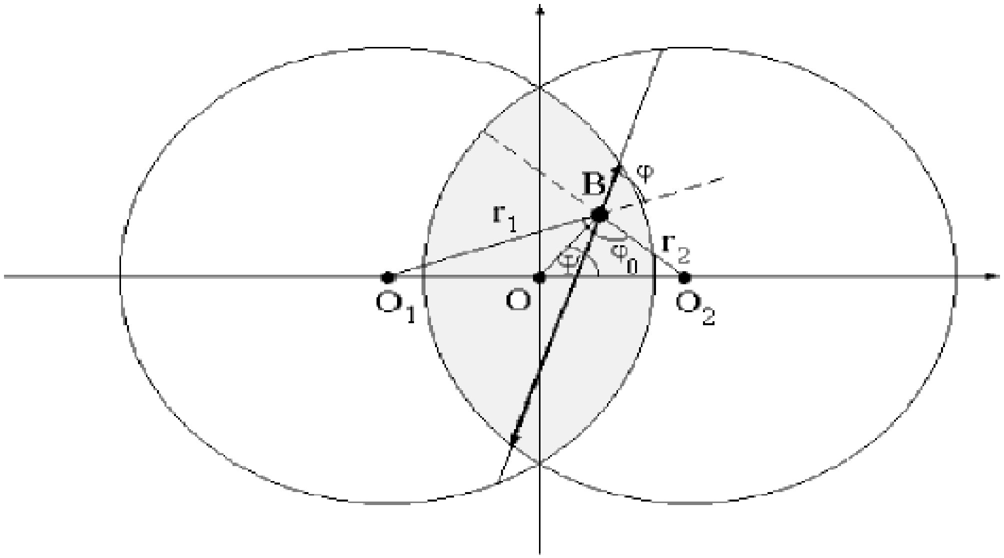
– *For heavy quark (dead cone approximation)*

$$\frac{dE}{dld\omega}\Big|_{m_q\neq 0} = \frac{1}{(1+(\beta\omega)^{3/2})^2}\frac{dE}{dld\omega}\Big|_{m_q=0}, \quad \beta = \left(\frac{\lambda}{\mu_D^2}\right)^{1/3}\left(\frac{m_q}{E}\right)^{4/3}$$

HYDJET++, hard component

Geometry of QGP

Radial profile of energy density $\varepsilon(r_1,r_2) \propto T_A(r_1) * T_A(r_2)$ (T_A(b) - nuclear thickness function)



Jet production vertexes distribution:

$$\frac{dN^{\rm jet}}{d\psi r dr}(b) = \frac{T_A(r_1) \cdot T_A(r_2)}{T_{AA}(b)}$$

HYDJET++, hard component

Halting the rescattering if:
(a) the parton escapes the hot QGP zone, i.e. the temperature in the next point $T(\tau_{i+1}, r_{i+1}, \eta_{i+1})$ becomes lower than T_c

(b) the parton loses so much of energy that its transverse momentum $p_T(\tau_{i+1})$ drops below the average transverse momentum of the "thermal" constituents of the medium.

Three model parameters: initial QGP temperature T_0,
QGP formation time τ_0 and
number of active quark flavors in QGP N_f
(+ minimal p_T of hard process Ptmin)

HYDJET++, soft component

N.S.Amelin, R.Lednisky, T.A.Pocheptsov, I.P.Lokhtin, L.V.Malinina, A.M.Snigirev, Yu.A.Karpenko, Yu.M.Sinyukov, Phys. Rev. C 74 (2006) 064901
N.S.Amelin, R.Lednisky, I.P.Lokhtin, L.V.Malinina, A.M.Snigirev, Yu.A.Karpenko, Yu.M.Sinyukov, I.C.Arsene, L.Bravina, Phys. Rev. C 77 (2008) 014903

Starting point: chemical freeze-out of fireball with the distribution functions in the fluid element rest frame

$$f_i^{\mathrm{eq}}(p^{*0};T^{\mathrm{ch}},\mu_i,\gamma_s)=\frac{g_i}{\gamma_s^{-n_i^s}\exp\left([p^{*0}-\mu_i]/T^{\mathrm{ch}}\right)\pm 1}$$

p^{*0} is the hadron energy in the fluid element rest frame, γ_s is strangeness suppression factor, quantum statistics is accounted for

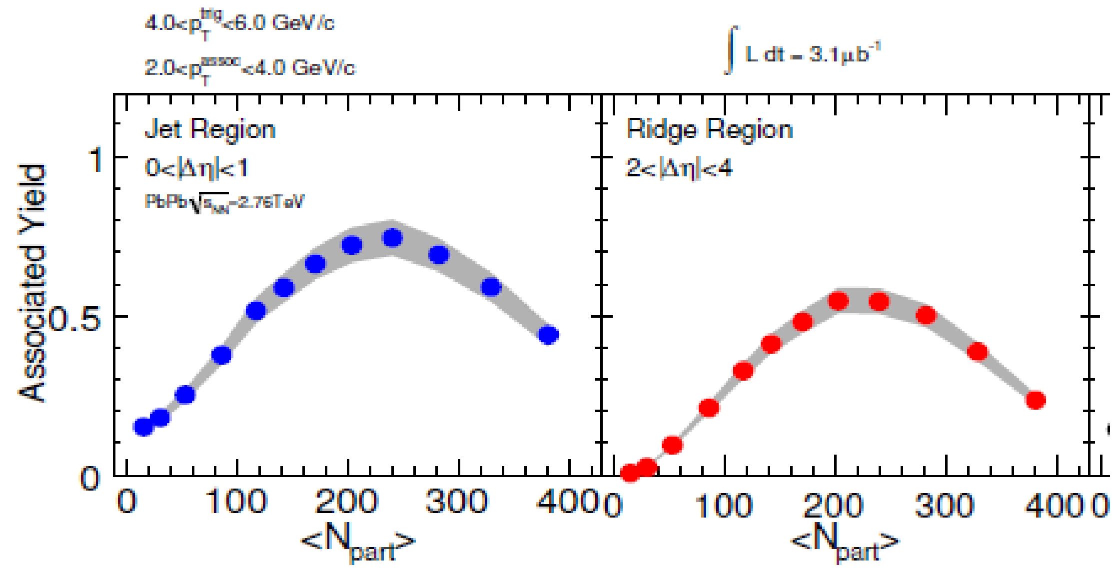
$$\rho_i^{eq}(T,\mu_i)=\int_0^\infty d^3\vec{p}^{\,*} f_i^{eq}(p^{0*};T(x^*),\mu(x^*)_i)=4\pi\int_0^\infty dp^* p^{*2} f_i^{eq}(p^{0*};T,\mu_i)$$

The mean multiplicity N_i of a hadron species *i:*

$$N_i=\rho_i(T,\mu_i)V_{eff} \qquad P(N_i)=\exp\left(-\bar{N}_i\right)\frac{(\bar{N}_i)^{N_i}}{N_i!}$$

HYDJET++ data comparison, Integrated yield

CMS data, PAS HIN 11-006



Integrated associated yields in the near-side jet and ridge regions around, minus constant background (ZYAM method).