

Hydro-inspired freeze-out model with jets for relativistic heavy ion collisions (HYDJET++)

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Contributions to the results presented:

A. Belyaev, L.V. Bravina, J. Crkovska, E. Fotina, B.H. Brusheim Johansson, V. L. Korotkikh,
I.P. Lokhtin, L.V. Malinina, E. Nazarova, S.V. Petrusanko, G. Ponimatkin, E. Pronina,
A.M. Snigirev, E.E. Zabrodin

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Outline

- HYDJET++ model for heavy ion collisions
- Description of experimental observables with HYDJET++:
 - Spectra and multiplicities
 - Azimuthal anisotropy
 - Di-hadron angular correlation
 - Jet quenching
 - Charm production

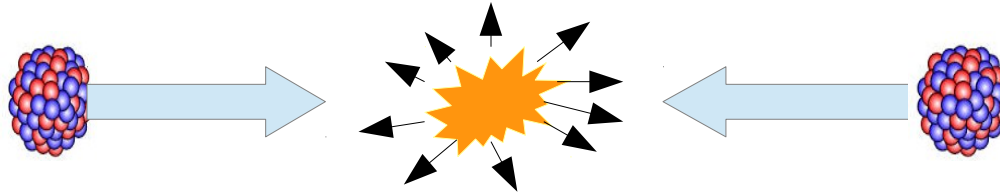
HYDJET++ Original paper: I.Lokhtin, L.Malinina, S.Petrushanko, A.Snigirev, I.Arsene, K.Tywoniuk, Comp. Phys. Comm. 180 (2009) 779

<http://cern.ch/lokhtin/hydjet++>

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HYDJET++ model for heavy ion collisions

Simplifies the pictures of heavy ion collisions as merging of 2 components:



- **soft hydro-type part**
(represented by hadron emission
assuming thermal equilibrium)

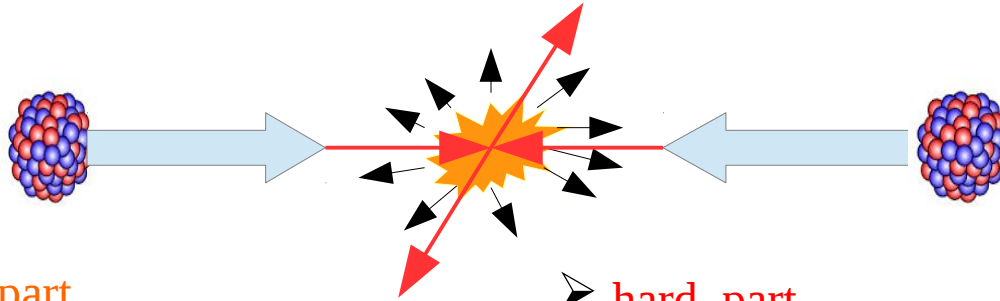
Based on the adapted FAST MC model:

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

HYDJET++ model for heavy ion collisions

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➤ **soft hydro-type part**
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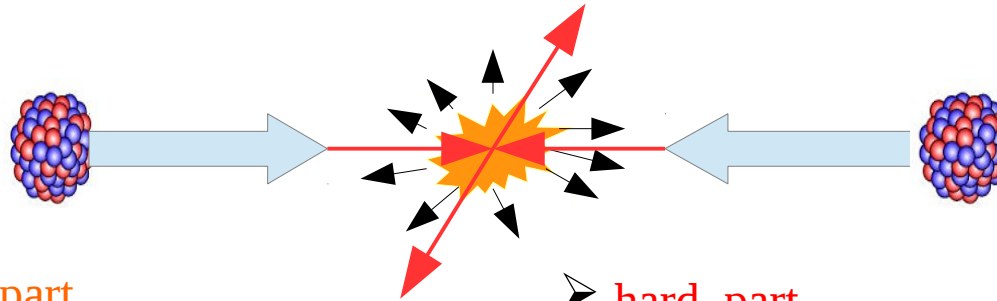
➤ **hard part**
(represented by hard parton scattering and
later hadronization)

Based on PYTHIA with quenching:
PYQUEN: [I.P.Lokhtin, A.M.Snigirev,](#)
[Eur. Phys. J. 45 \(2006\) 211](#)

Nuclear shadowing is accounted for:
[K.Tywniuk et al., Phys. Lett. B 657 \(2007\) 170](#)

HYDJET++ model for heavy ion collisions

Simplifies the pictures of heavy ion collisions as merging of 2 components:

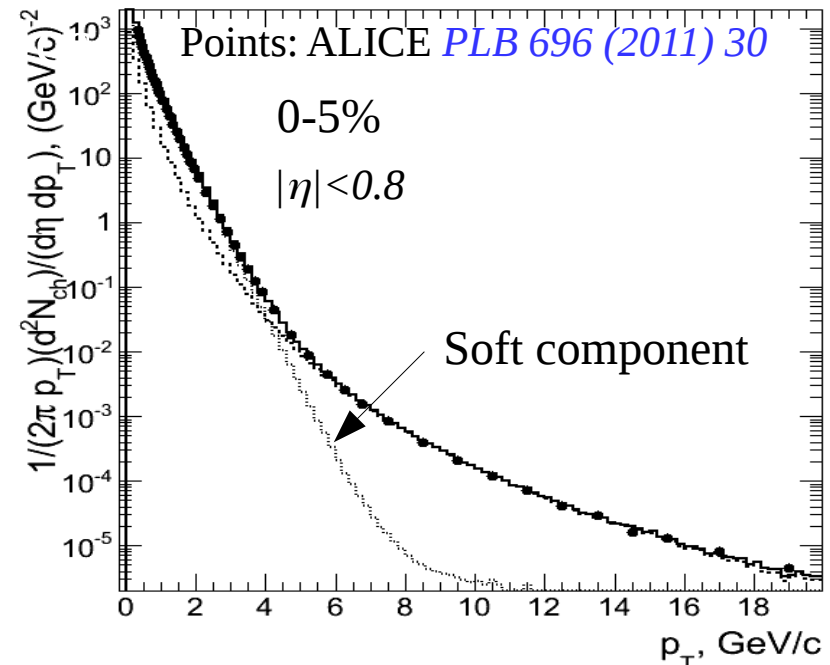


➤ **soft hydro-type part**
(represented by hadron emission assuming thermal equilibrium)

➤ **hard part**
(represented by hard parton scattering and later hadronization based on PYTHIA)

Soft and hard components:

- The contribution of the hard part to the total multiplicity is control by p_{Tmin} parameter (parton hard scattering in PYTHIA)
- Modification of the hard part due to interactions with the medium is simulated
- No modification of soft part



Thermal production

- Hadrons are produced on the freeze-out hypersurface with particle density ρ and effective volume V_{eff} . Multiplicities are defined with T^{ch} for stable hadrons and resonances:

$$\overline{N}_i = \rho_i(T, \mu_i) V_{\text{eff}} \quad P(N_i) = \exp(-\overline{N}_i) \frac{(\overline{N}_i)^{N_i}}{N_i!}$$

Mean multiplicity EbE distribution

- Momentum distribution is defined with T^{th} .

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

Momentum distribution function in the fluid element rest frame

- Decay kinematics is taken into account.
- The final hadron spectrum are given by the superposition of thermal distribution and collective flow of fireball liquid assuming Bjorken's scaling.

Hard component

Initial parton configuration

PYTHIA w/o hadronization



parton rescattering & energy loss



Hadronization

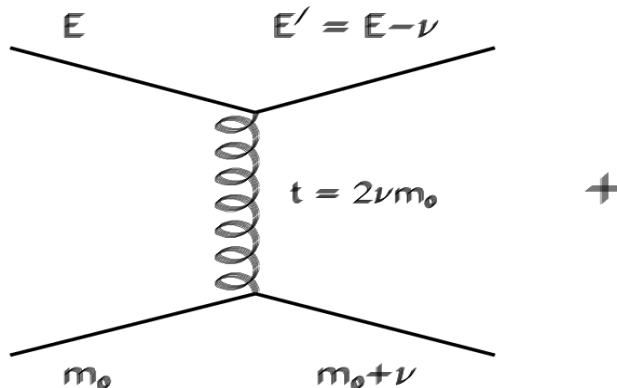
PYTHIA w hadronization

Energy loss, general kinetic integral equation with scattering probability density:

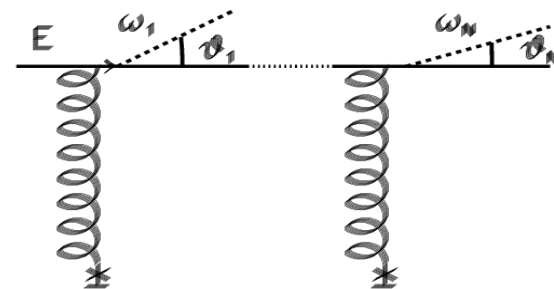
$$\Delta E(L, E) = \int_0^L dl \frac{dP(l)}{dl} \lambda(l) \frac{dE(l, E)}{dl}$$

$$\frac{dP(l)}{dl} = \frac{1}{\lambda(l)} \exp(-l/\lambda(l))$$

- Collisional loss
(high momentum transfer approximation)



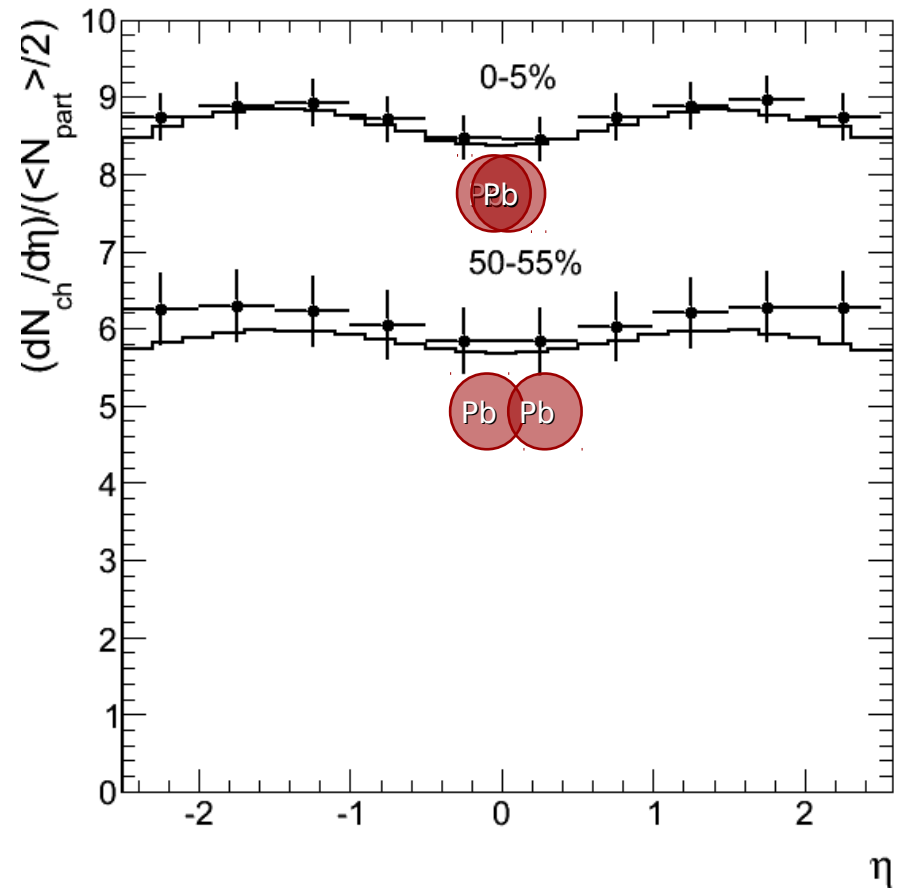
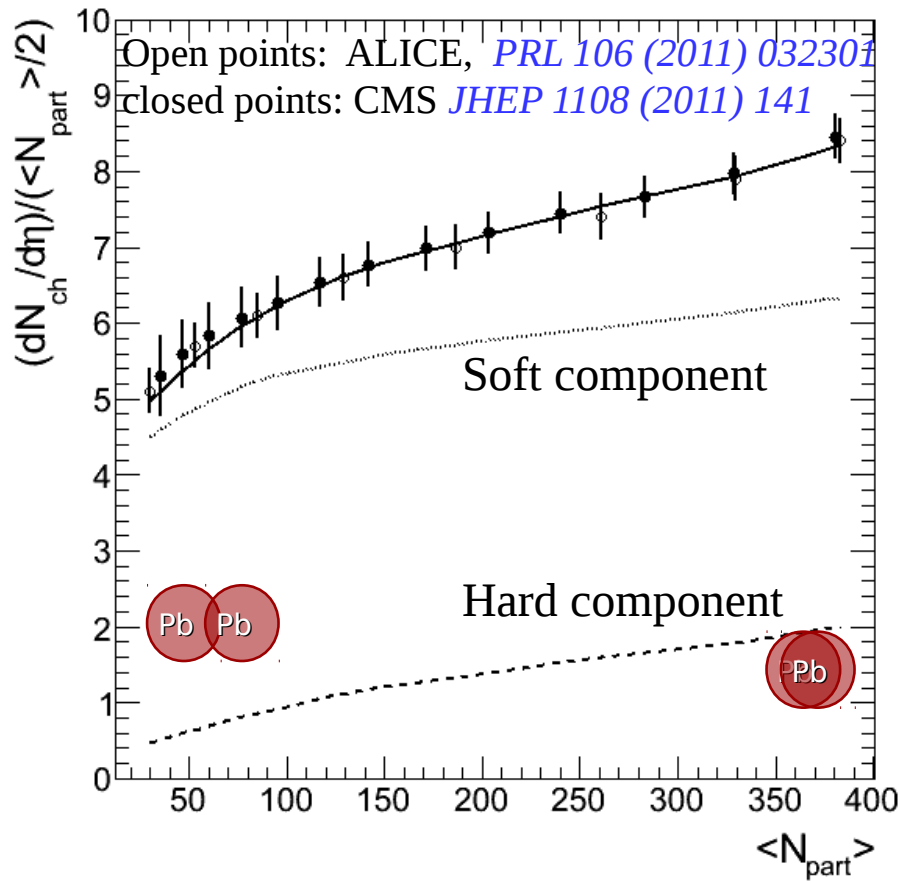
- Radiative loss (coherent gluon radiation in Baier-Dokshitzer-Mueller-Schiff formalism)



- “Dead” cone approximation for massive quarks

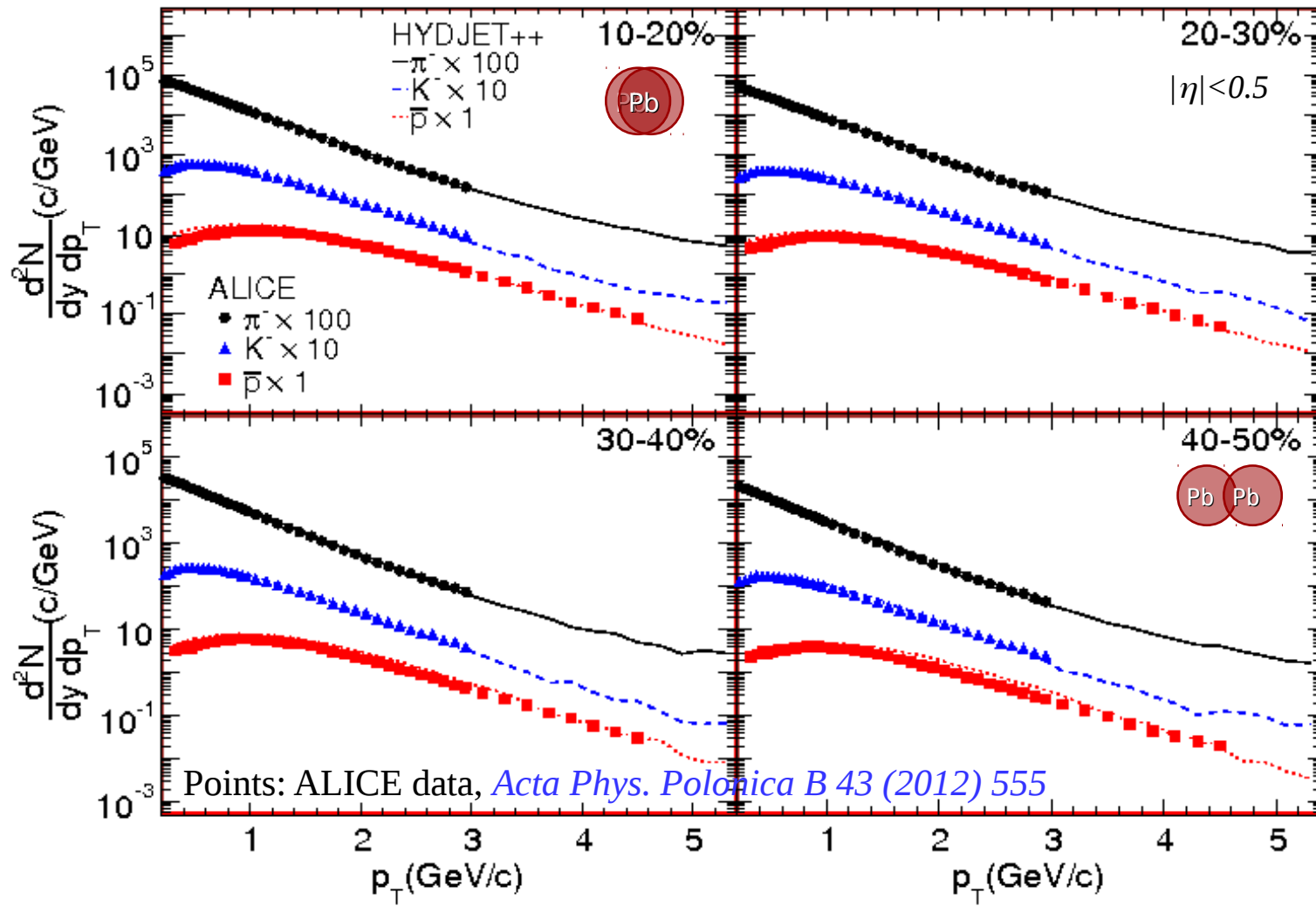
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Charged multiplicity vs. centrality and pseudorapidity



Given set of parameters for central collisions, HYDJET++ reproduces multiplicity vs. event centrality (down to very peripheral events), as well as pseudorapidity distribution.

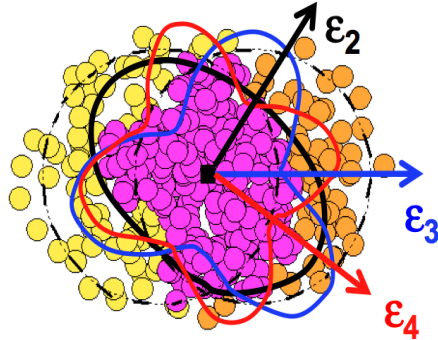
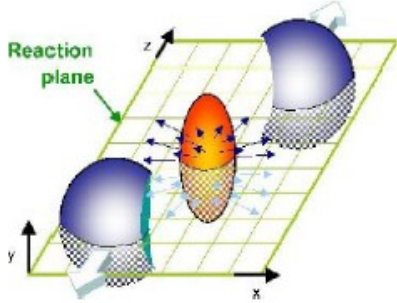
p_T -spectra of identified hadrons



HYDJET++ reproduces p_T -spectrum of pions, kaons and (anti-)protons.

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Anisotropic flow in heavy ion collisions



$$E \frac{d^3 N}{d^3 p} = \frac{1}{\pi} \frac{d^2 N}{dp_t^2 dy} \left[1 + 2 \sum_{n=1}^{\infty} v_n \cos n(\phi - \Psi_n) \right]$$

Global collective flow
w.r.t collision geometry

Eccentricity fluctuations → flow
fluctuation and odd harmonics

v_2 and v_3 in HYDJET++ are due to modification of p_T distribution coming from:

in soft part

in hard part

- Space modulation of freeze-out surface (for v_2 and v_3)
- Velocity modulation of fireball expansion (for v_2 only)

- Energy loss path length dependence (for v_2 only)

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

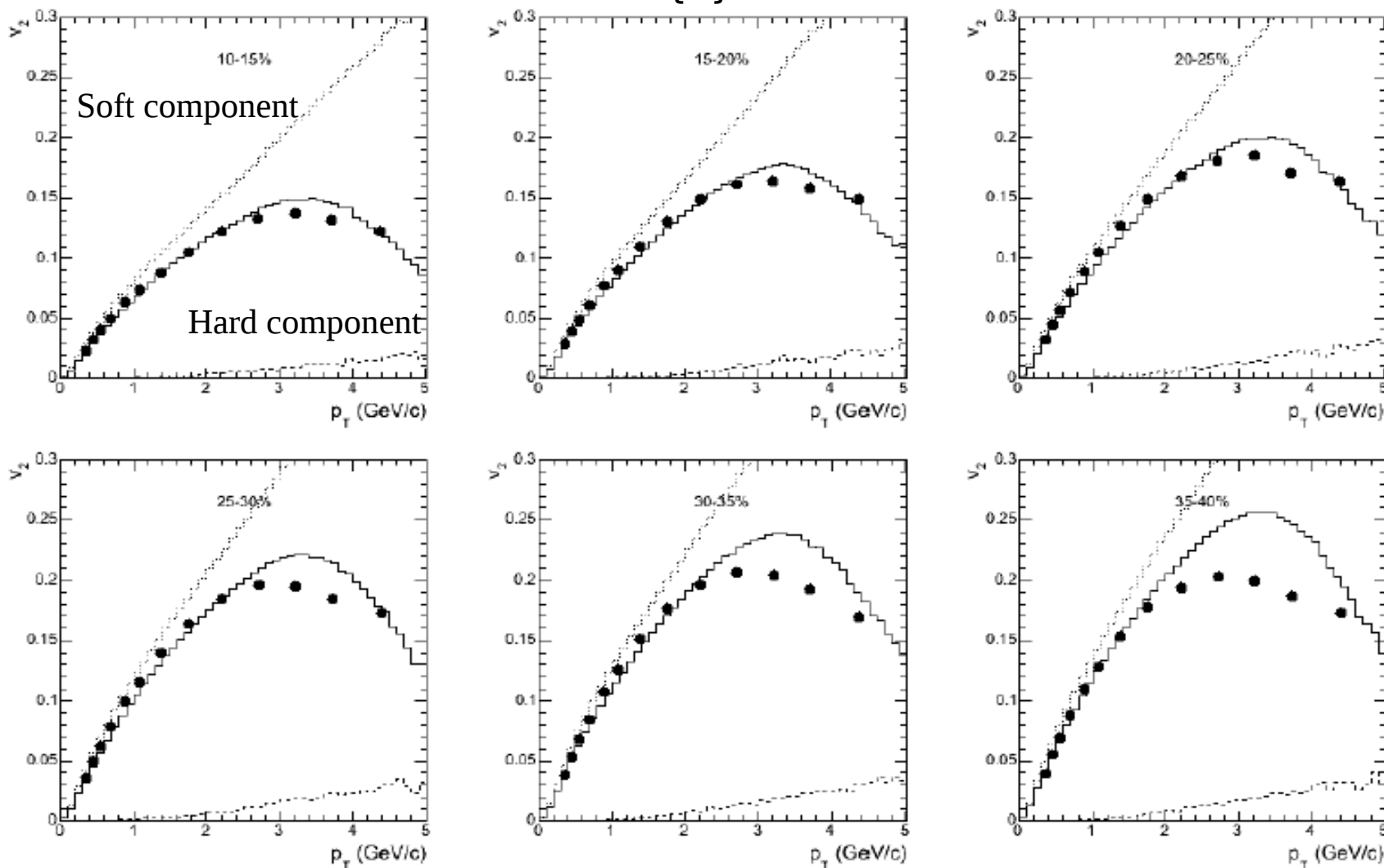
$$\tan \varphi_u = \sqrt{\frac{1 - \delta(b)}{1 + \delta(b)}} \tan \varphi.$$

φ_u : azimuthal angle of liquid velocity vector

φ : space azimuthal angle

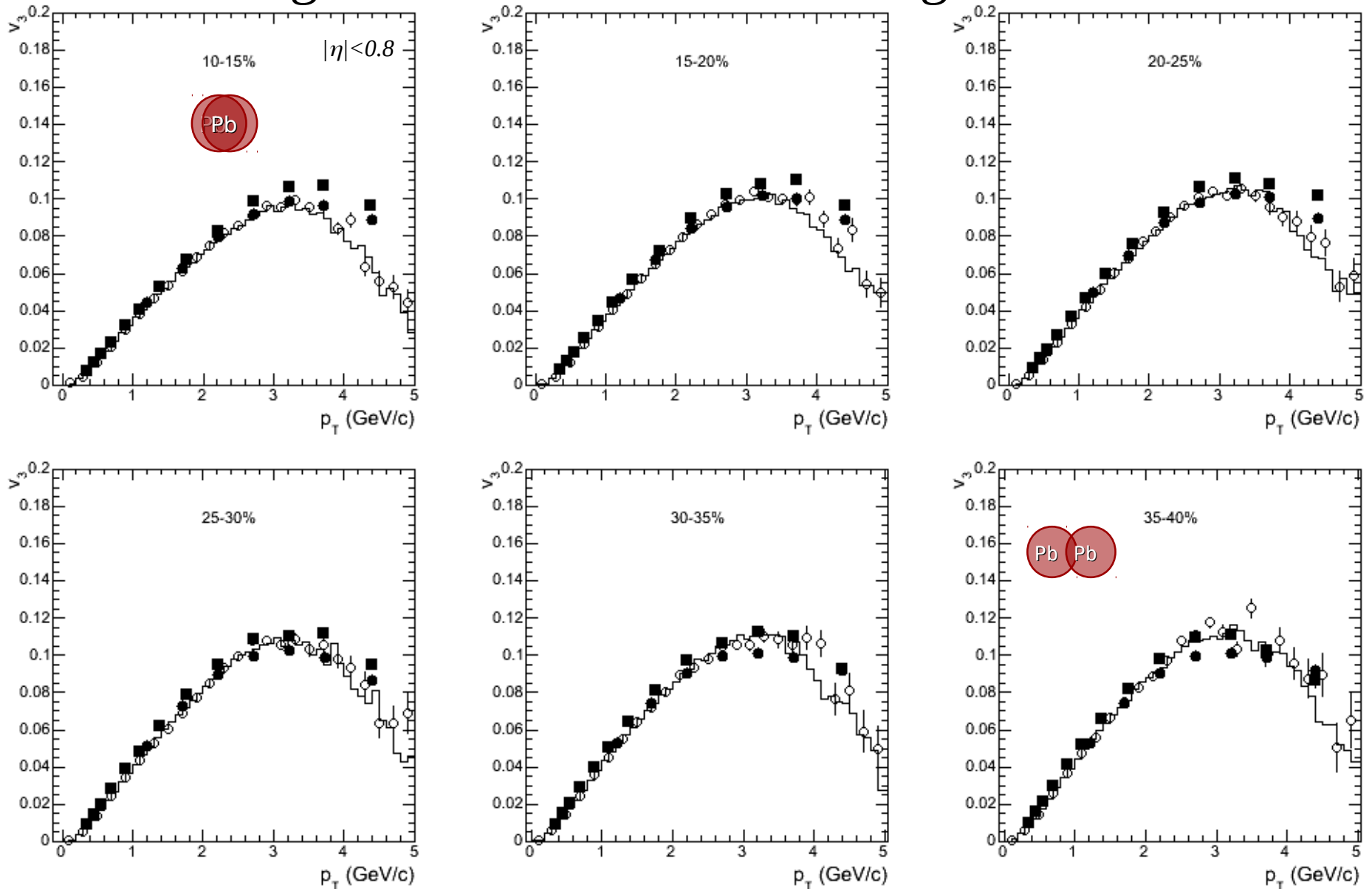
Elliptic flow

Points: CMS data $v_2\{4\}$ [archiv:1204.1409](https://arxiv.org/abs/1204.1409)



- Typical flow shape $v_2(p_T)$ is reproduced by superposition of two components
- Data are described in a wide range of centralities at low and intermediate p_T region

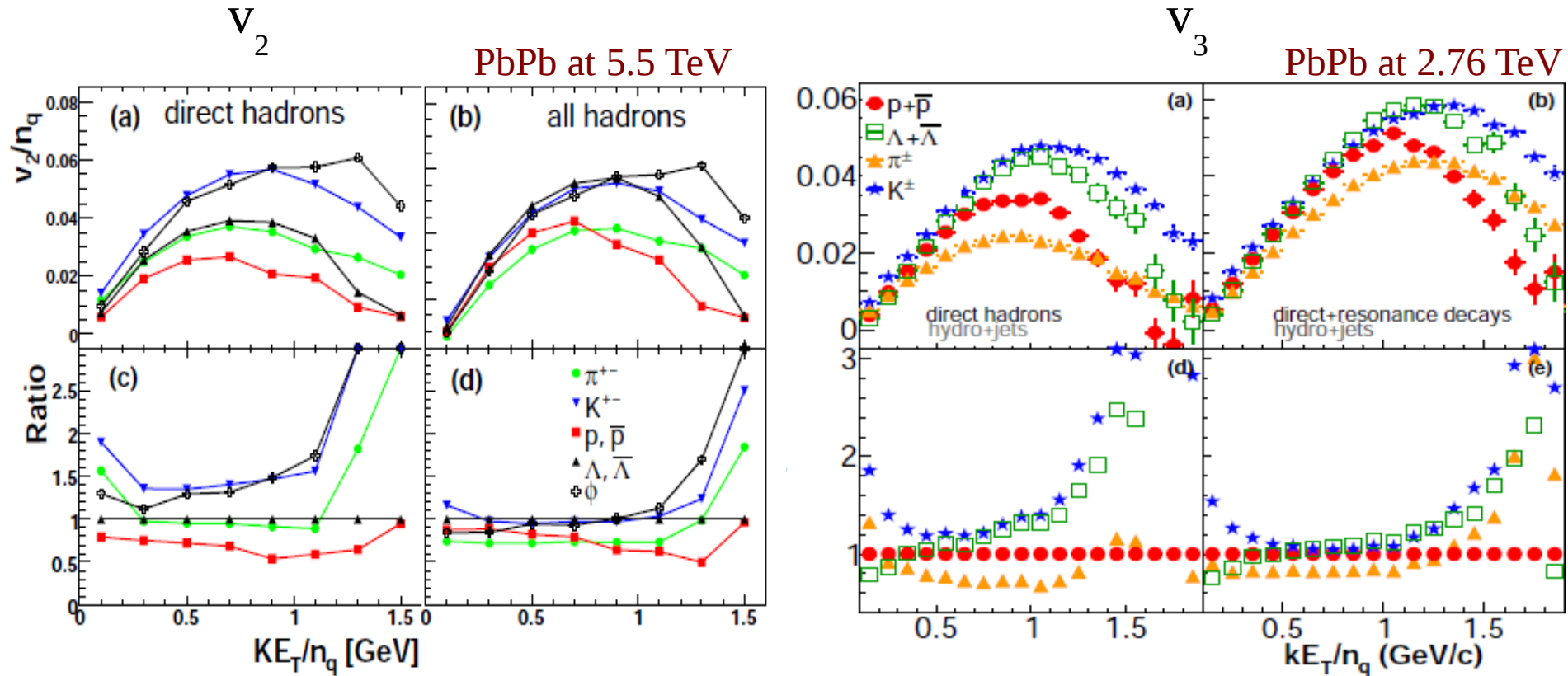
Triangular flow of inclusive charged hadrons



Closed circles and squares: CMS data $v_3\{2\}$ & $v_3\{EP\}$ ([PRC 89 \(2014\) 044906](#));

histograms and open circles: HYDJET++ (“true” $v_3(\psi_3)$ & $v_3\{EP\}$)

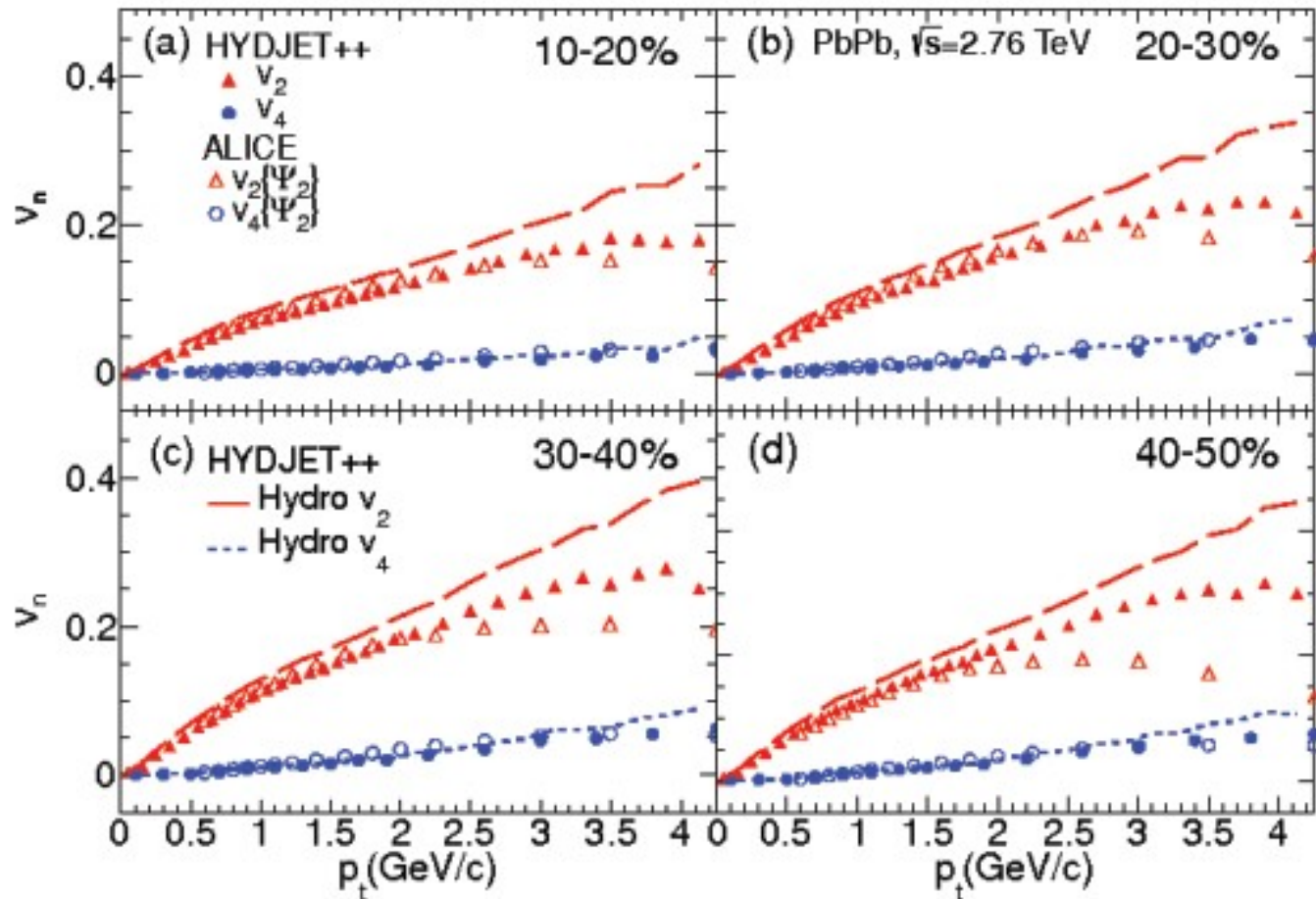
Number of constituent quark scaling



- Resonance decay kinematics works towards the scaling (the violation was predicted for LHC)

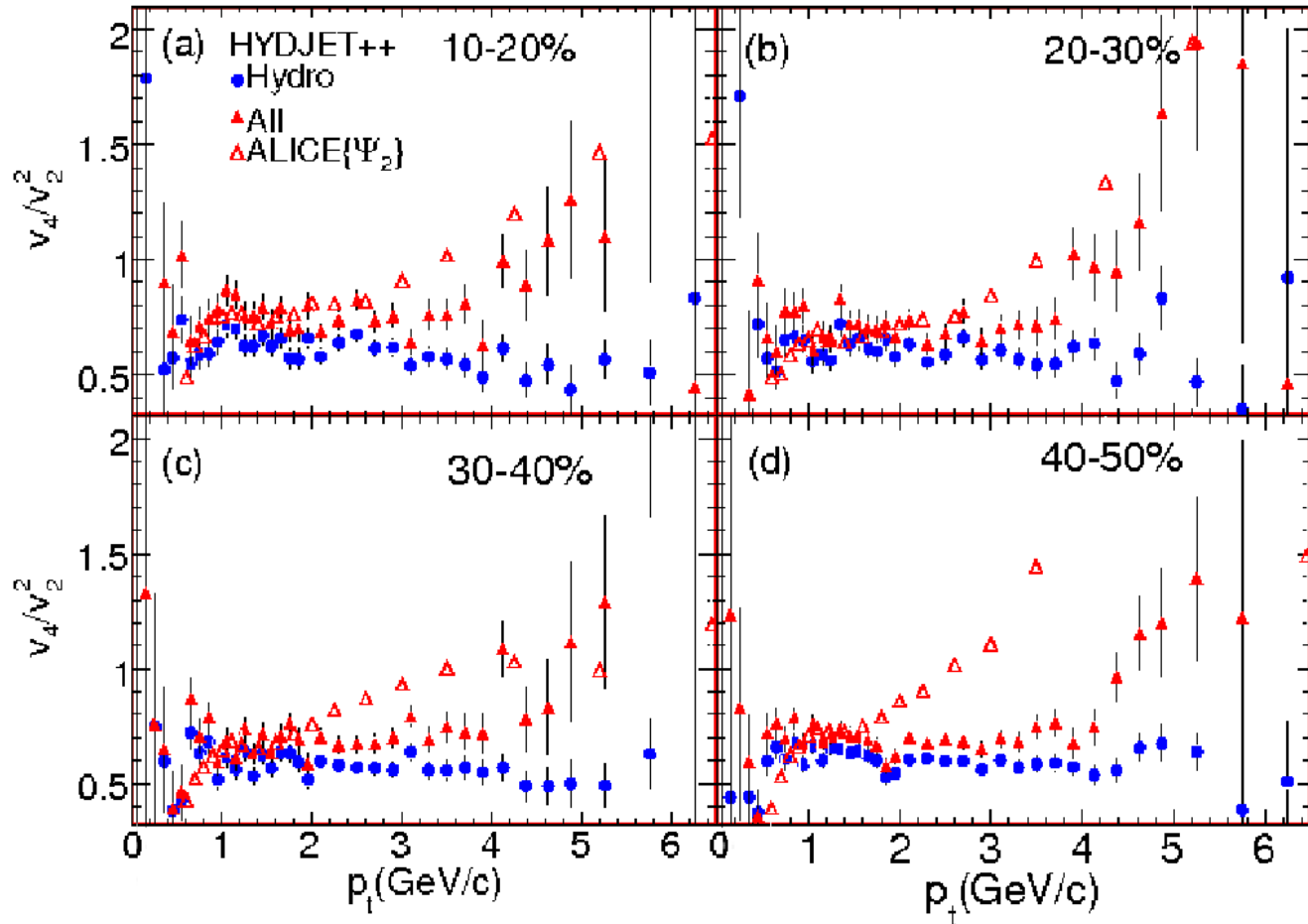
Higher order flow harmonics: elliptic and quadrangular flow

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



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

the ratio $v_4/(v_2)^2$



PbPb at 2.76 TeV

Ratio for the hydro part of HYDJET++ in blue:

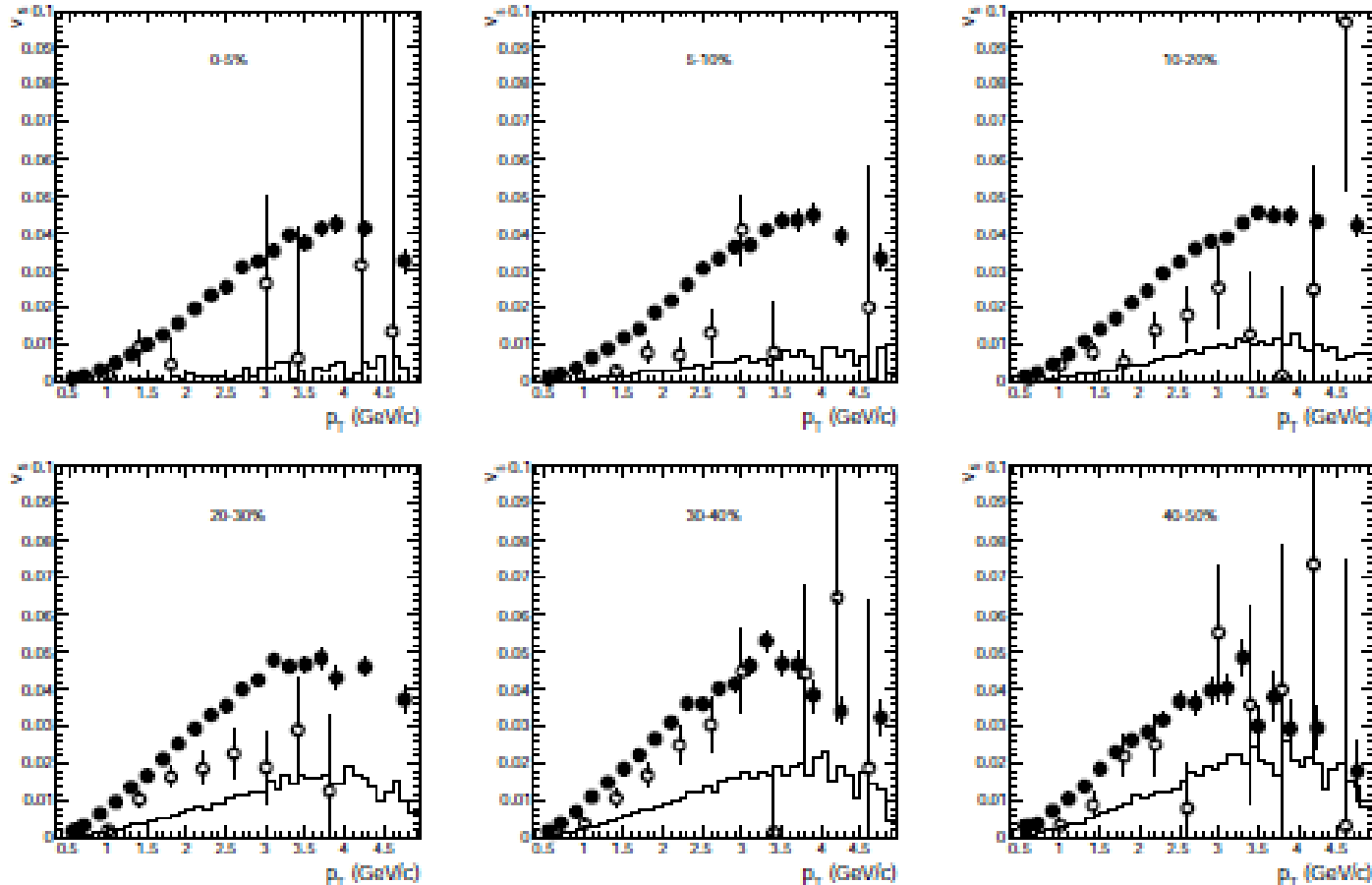
- close to $\frac{1}{2}$,
- \approx constant with p_t

Ratio for hydro+jet part in red triangles:

- rise of high- p_t tail
- Jets increase the ratio by about 15%

Higher order harmonics: pentagonal flow

v_5

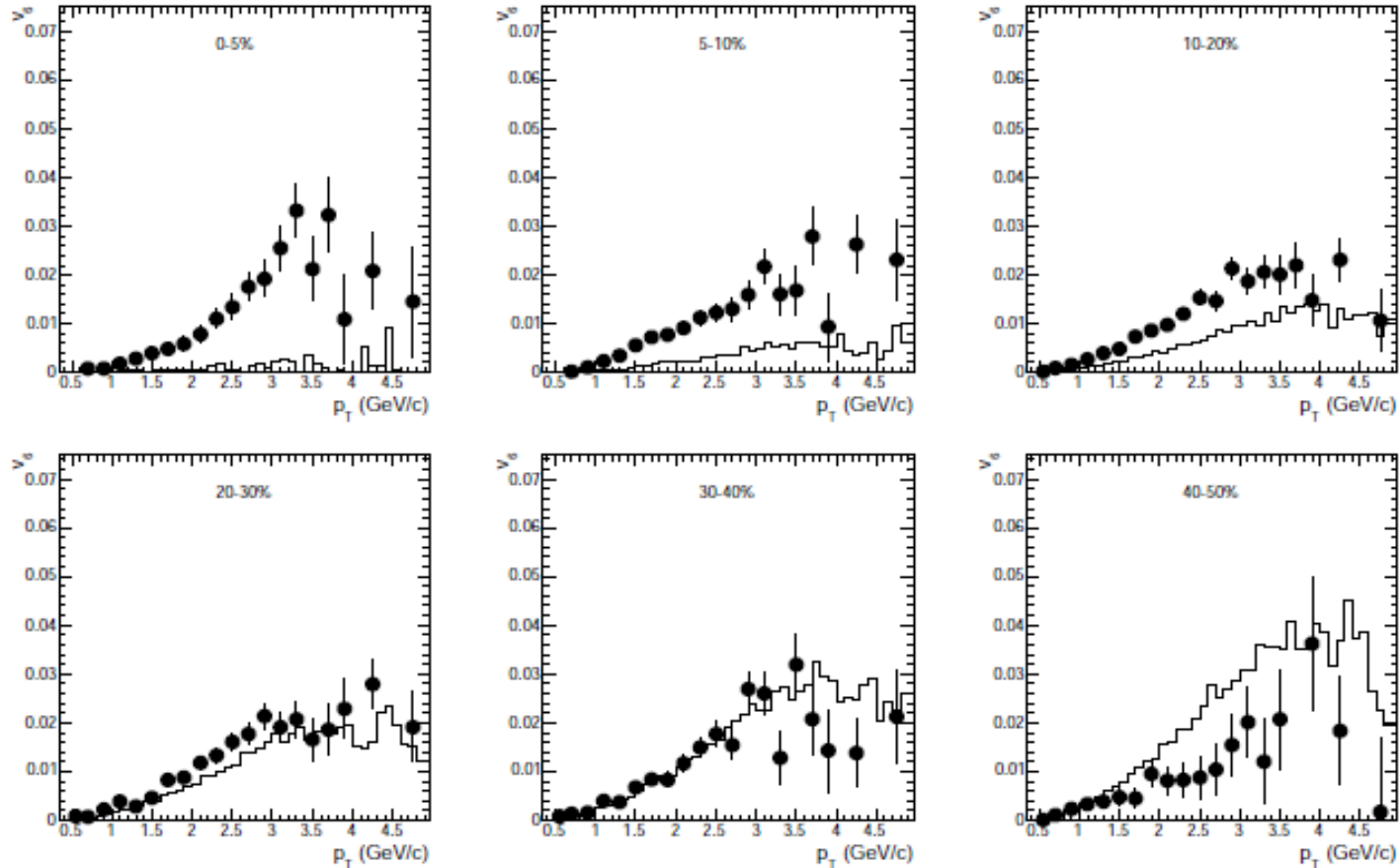


The closed circles: CMS data $v_n\{EP\}$, PbPb collisions, 2.76 TeV,
 open circles: $v_n\{EP\}$ for HYDJET++ ; histograms: $v_n(\Psi_{RP})$ for HYDJET++

central collisions \rightarrow possible presence of additional pentagonal eccentricity fluctuation.

Higher order harmonics: hexagonal flow

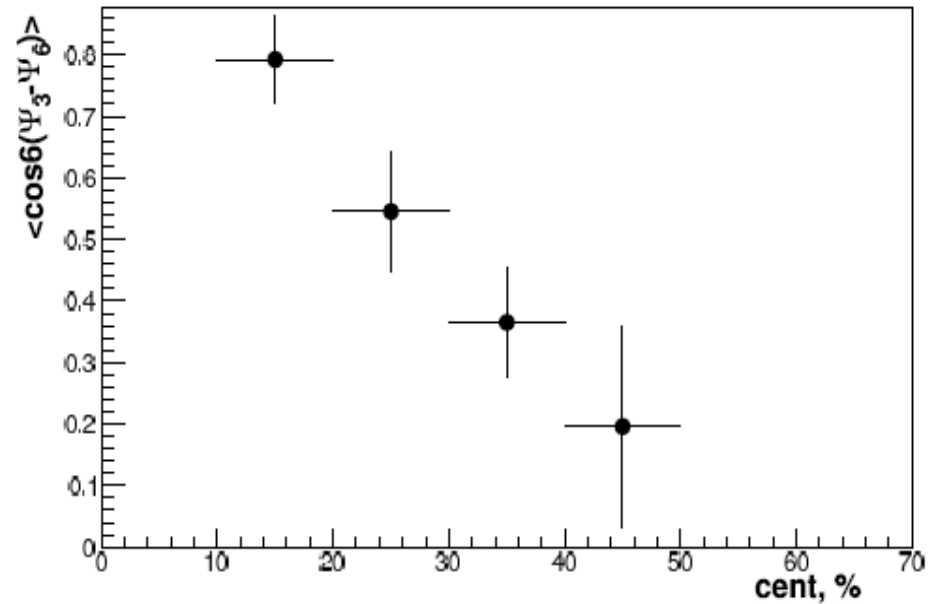
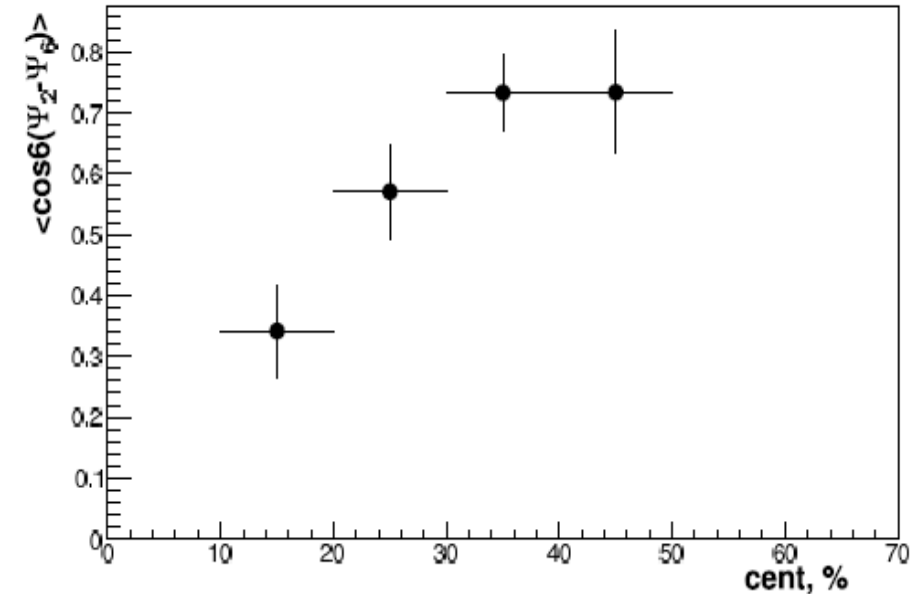
V_6



The closed circles: CMS data $v_6\{EP\}$, PbPb collisions, 2.76 TeV,
histograms: $v_6(\Psi_2)$ for HYDJET++ (contribution from v_2)

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.

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Dihadron angular triggered correlations in HYDJET++, PbPb at 2.76 TeV

Signal: correlations of a pair in the same event:

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

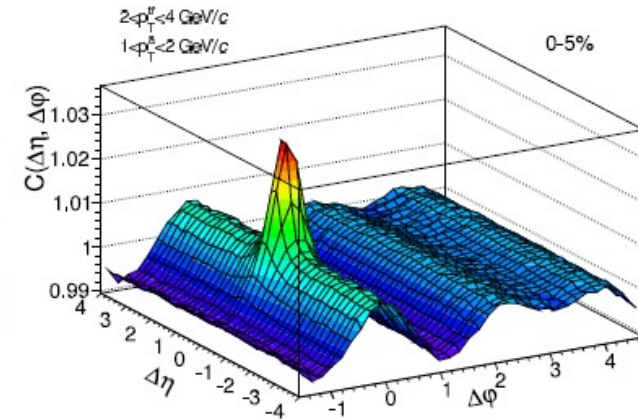
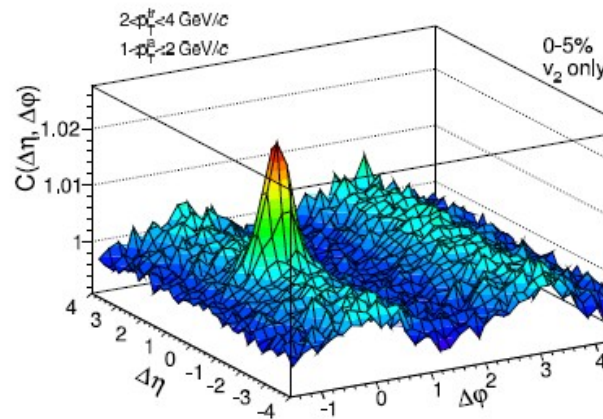
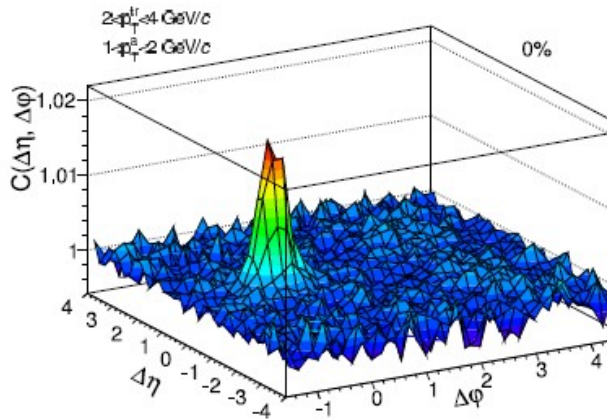
Background: correlations of two particles from different events:

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

0% centrality

0-5% centrality, v_2 only

0-5% centrality, v_2 & v_3



- 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 $\Delta\varphi$

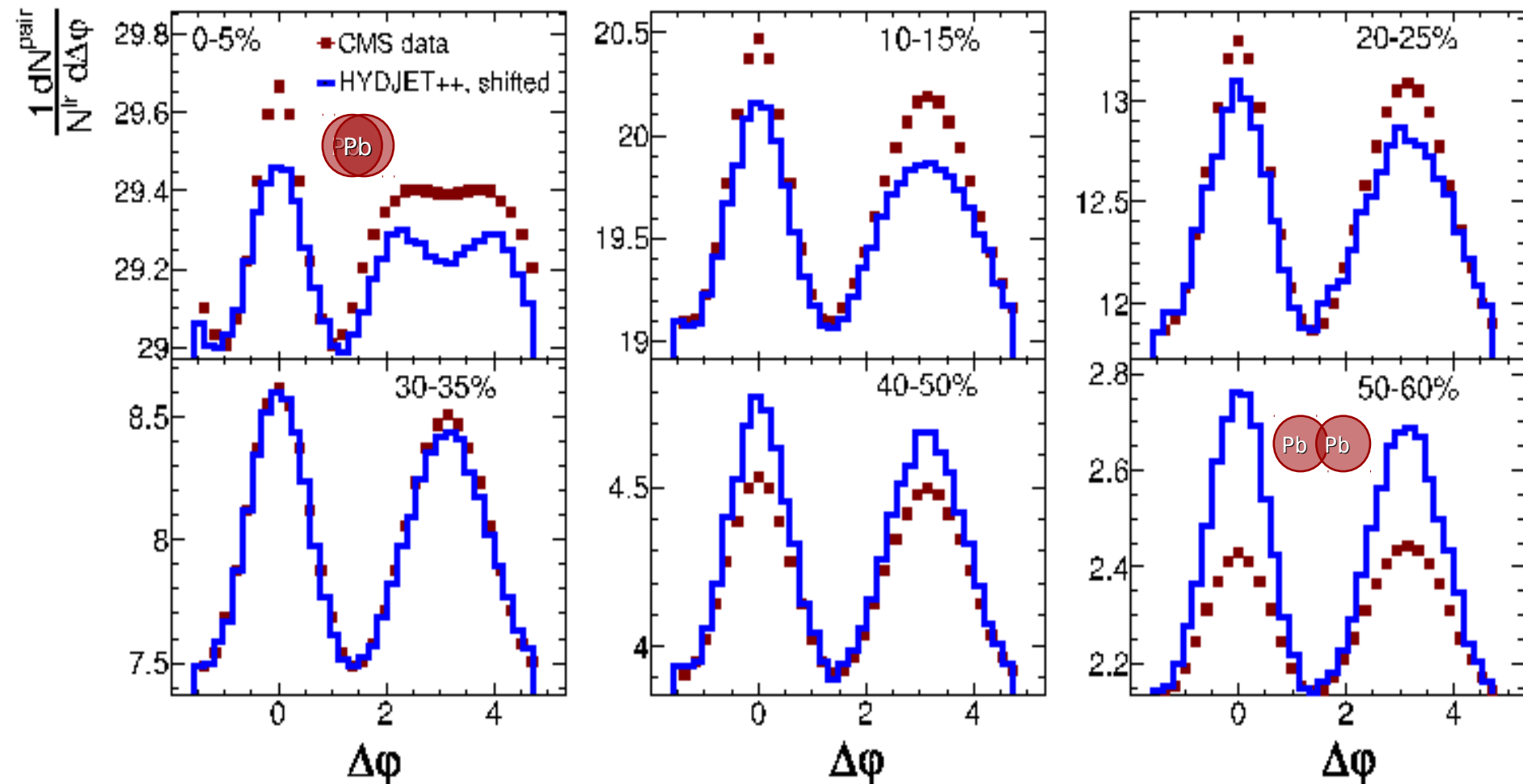
Dihadron angular correlations

PbPb $\sqrt{s_{NN}}=2.76$ TeV

$1 < p_T^a < 1.5$ GeV/c

$3 < p_T^r < 3.5$ GeV/c

$2 < |\Delta\eta| < 4$



Points: CMS data (*EPJC* 72 (2012) 2012)

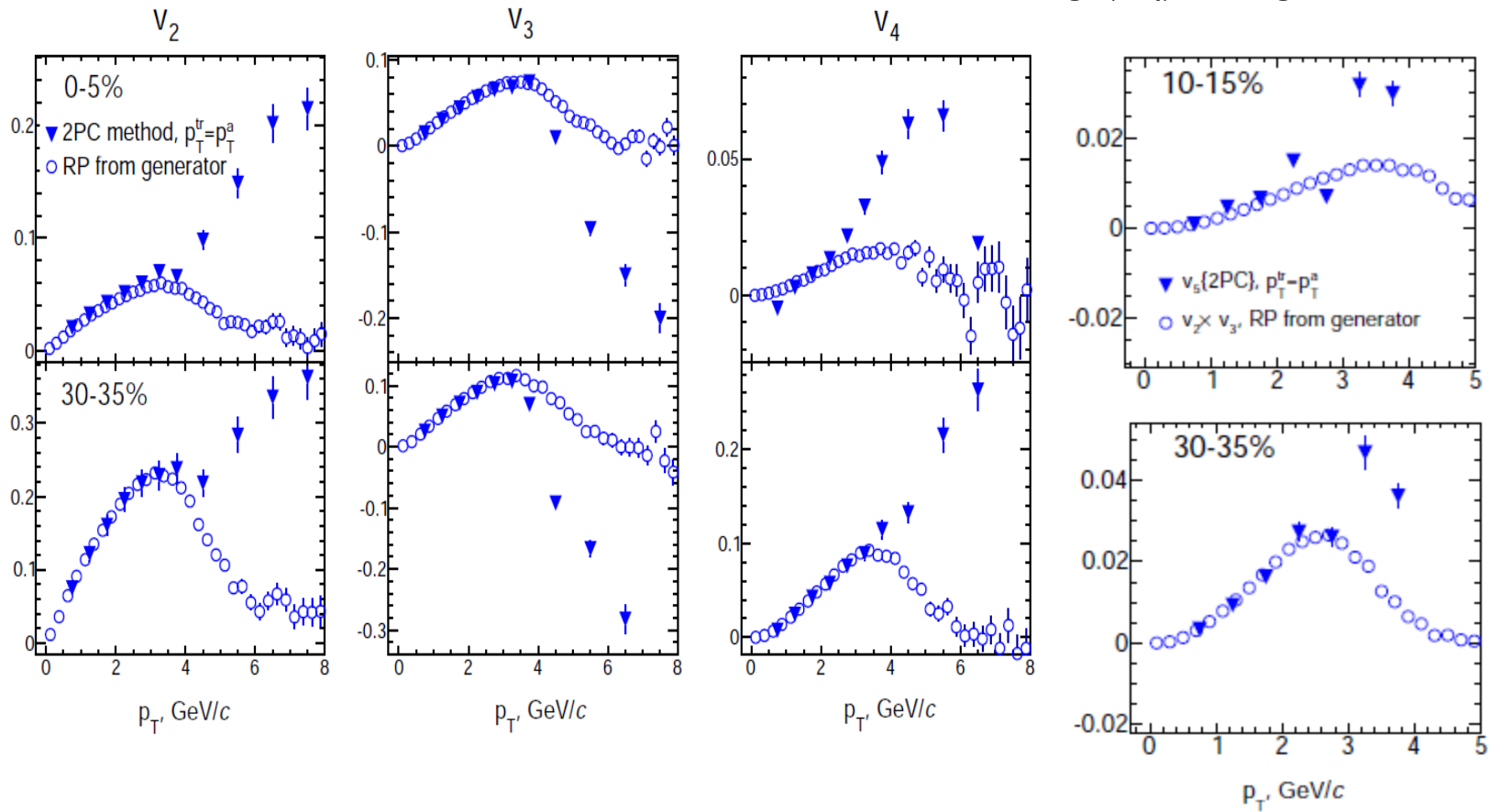
- Interplay of elliptic and triangular flows in HYDJET++ yields long-range 2-particle azimuthal correlations.

Test of factorization: $V_n(p_t^{tr}, p_t^a) \approx v_n(p_t^{tr}) * v_n(p_t^a)$

$$\frac{dN^{pairs}}{d\Delta\varphi} \propto 1 + 2 \sum_{n=1}^{\infty} V_n(p_T^{tr}, p_T^a) \cos n(\Delta\varphi)$$

$$V_n(p_T^{low}, p_T^{low}) = v_n(p_T^{low}) \times v_n(p_T^{low}) + \delta_n$$

At large $|\Delta\eta|$ one neglects non-flow δ



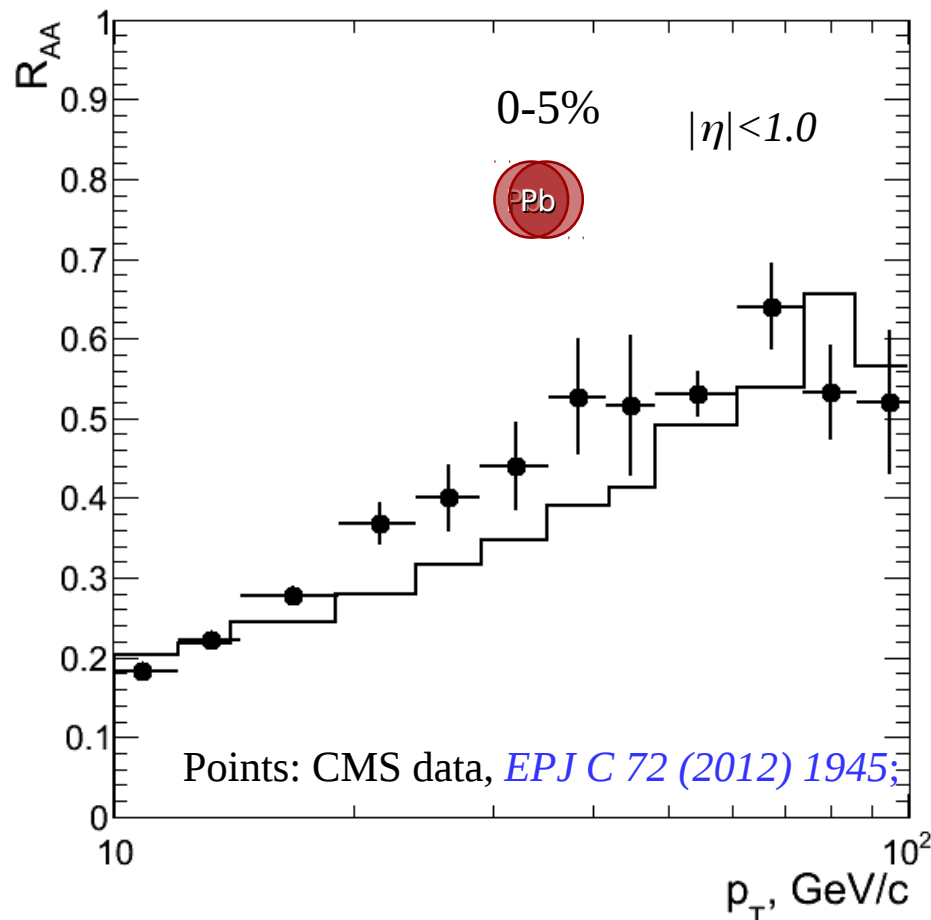
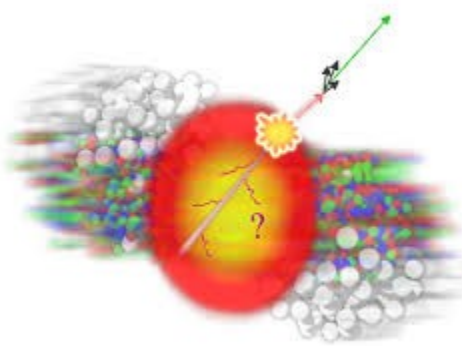
- At low p_T and large $|\Delta\eta|$ V_n factorize into product of single-particle flow v_n
- $\sqrt{V_5}$ factorizes into product of $v_2 * v_3$ at low p_T and large $|\Delta\eta|$

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Nuclear modification factor R_{AA} for inclusive charged hadrons

$$R_{AA} = \frac{\sigma_{pp}^{inel} \frac{d^2 N_{AA}}{dp_T d\eta}}{\langle N_{coll} \rangle \frac{d^2 \sigma_{pp}}{dp_T d\eta}} \sim \frac{\text{"QCD Medium"}}{\text{"QCD Vacuum"}}$$

$R_{AA} > 1$: enhancement
 $R_{AA} = 1$: no medium effect
 $R_{AA} < 1$: suppression



HYDJET++ reproduces R_{AA} for central PbPb in mid-rapidity up to $p_T \sim 100 \text{ GeV}/c$

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- Thermal charm production in HYDJET++

Thermal charmed hadrons J/ψ , D^0 , \bar{D}^0 , D^+ , D^- , D_s^+ , D_s^- , Λ_c^+ , Λ_c^- are generated within the statistical hadronization model

*A.Andronic, P.Braun-Munzinger, K.Redlich, J.Stachel, P.L. B 571 (2003) 36;
Nucl. Phys. A 789 (2007) 334*

$$N_D = \gamma_c N_D^{\text{th}} (I_1(\gamma_c N_D^{\text{th}}) / I_0(\gamma_c N_D^{\text{th}})), \quad N_{J/\psi} = \gamma_c^2 N_{J/\psi}^{\text{th}}$$

γ_c - charm enhancement factor is obtained from the equation:

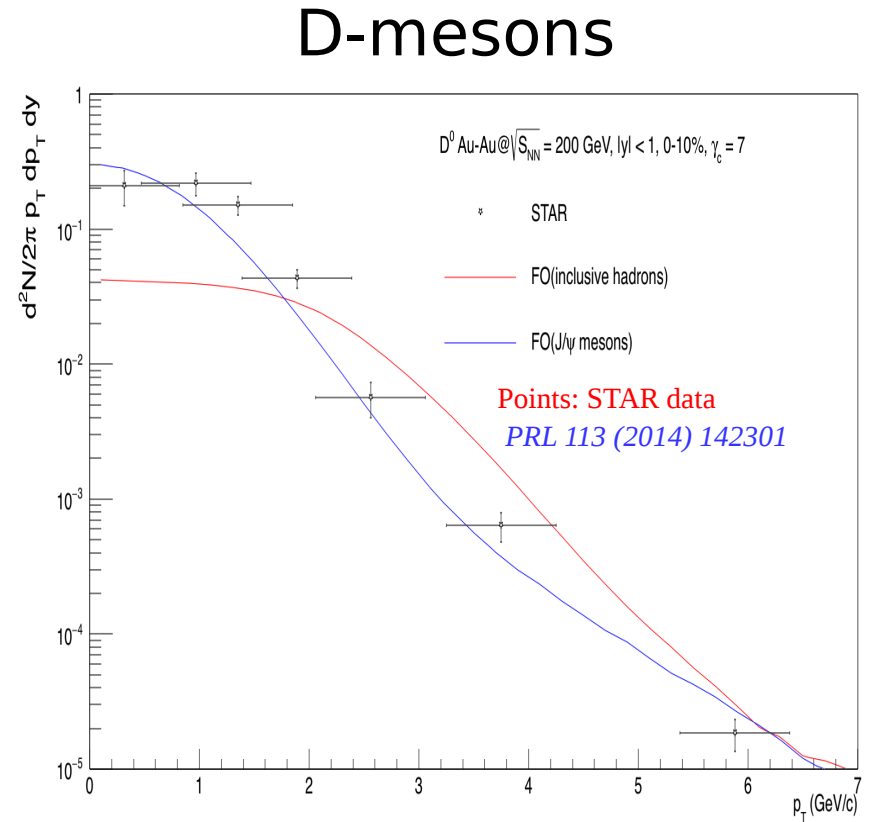
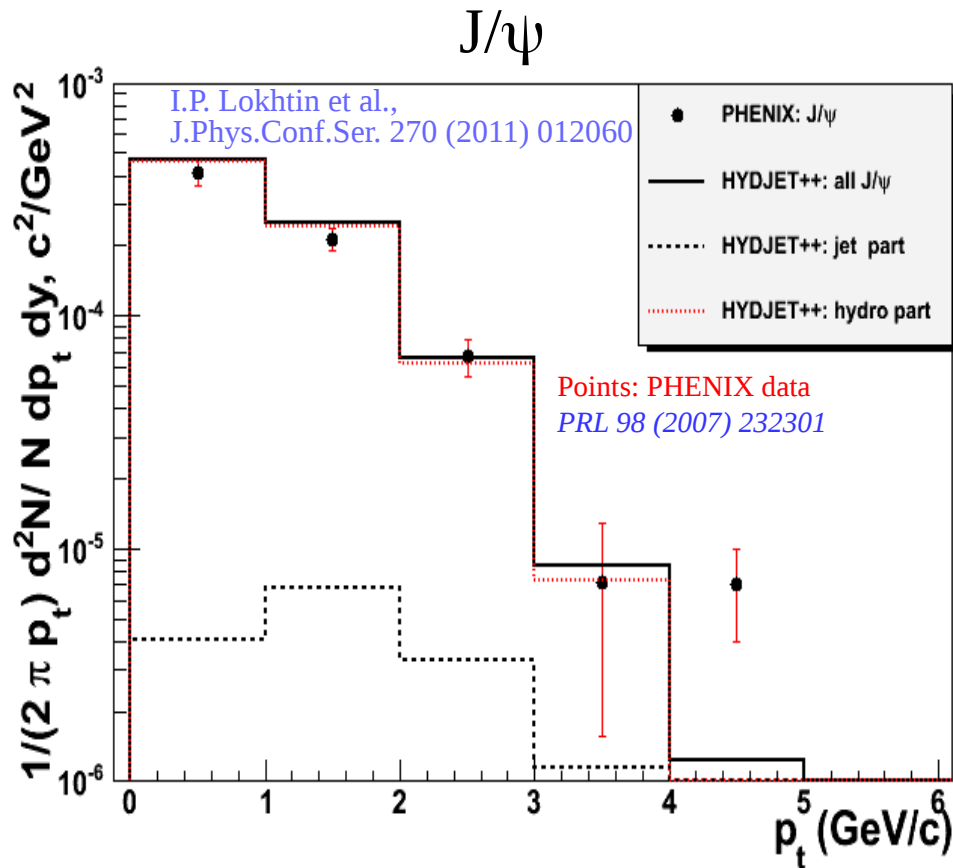
$$N_{cc} = 0.5 \gamma_c N_D^{\text{th}} (I_1(\gamma_c N_D^{\text{th}}) / I_0(\gamma_c N_D^{\text{th}})) + \gamma_c^2 N_{J/\psi}^{\text{th}}$$

Number of c-quark pair N_{cc} is calculated with PYTHIA (the factor $K \sim 2$ is applied to take into account NLO pQCD corrections)

- Non-thermal charm production in HYDJET++

Non-thermal charmed hadrons are generated within PYTHIA taken into account medium-induced rescattering and energy loss of heavy quarks (b,c).

Charm mesons at RHIC (200 MeV)



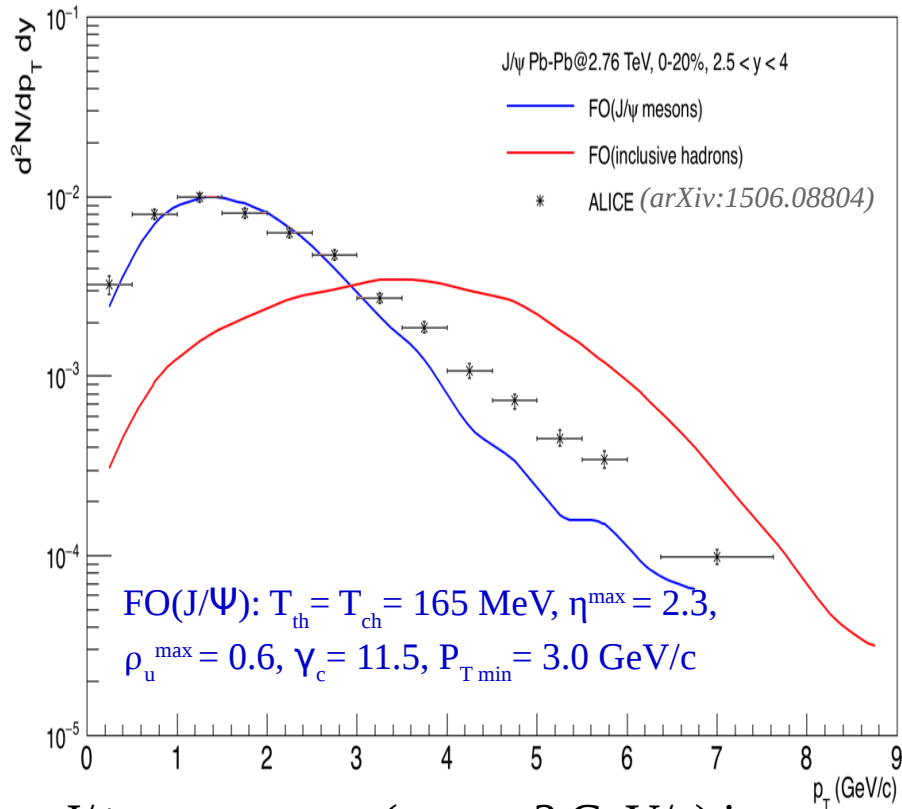
thermal freeze-out for J/ψ happens at the same temperature as chemical freeze-out,

$$T_{th}(J/\psi) = T_{ch} = 165 \text{ MeV} (\eta^{\max} = 1.1, \rho_u^{\max} = 0.5).$$

Simulated p_T -spectrum match the data if freeze-out parameters for D are the same as for J/ψ.

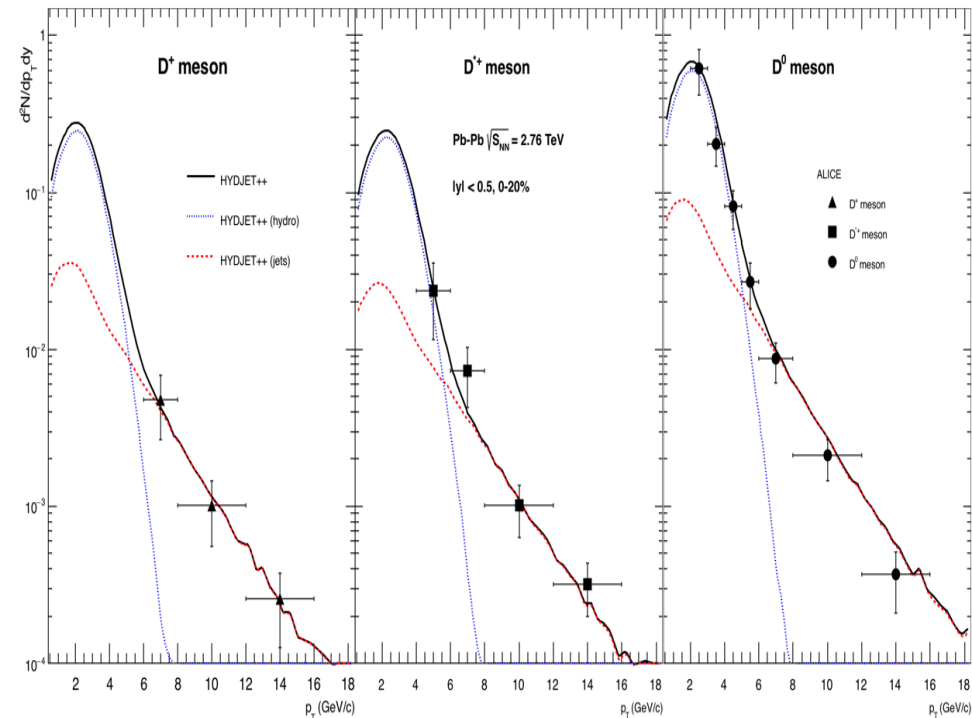
Charm mesons at LHC (2.76 TeV), J/ψ

J/ψ



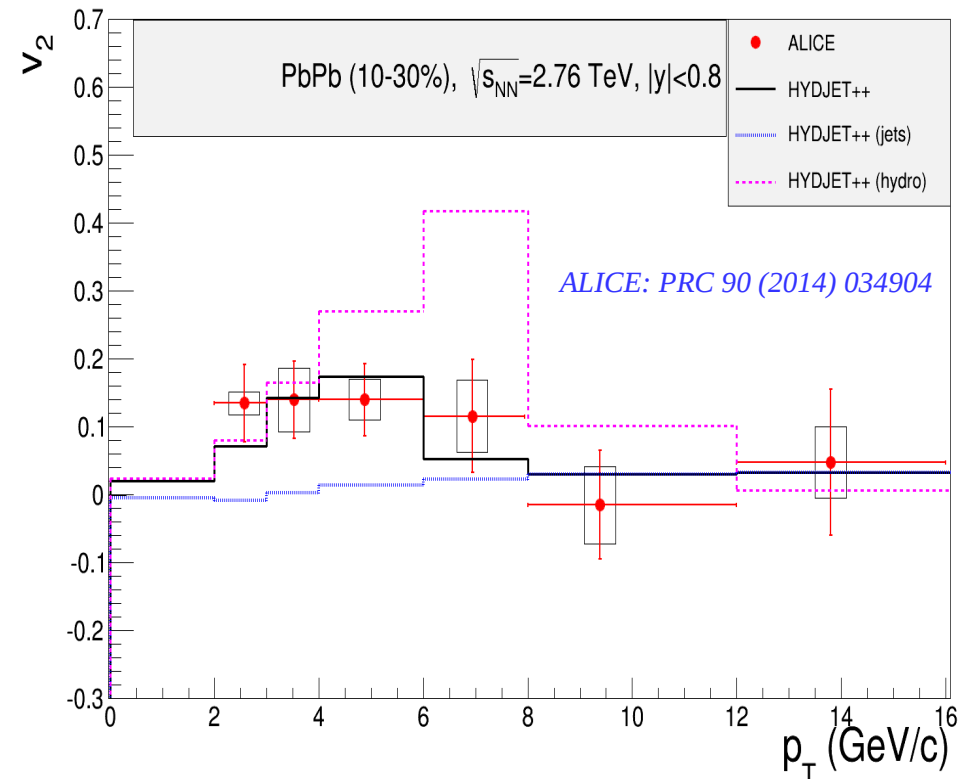
J/ψ p_T -spectrum (up to ~ 3 GeV/c) is reproduced with the freeze-out parameters different from ones for inclusive hadrons \Rightarrow kinetic freeze-out of J/ψ occurs before freeze-out of light hadrons.

D-mesons

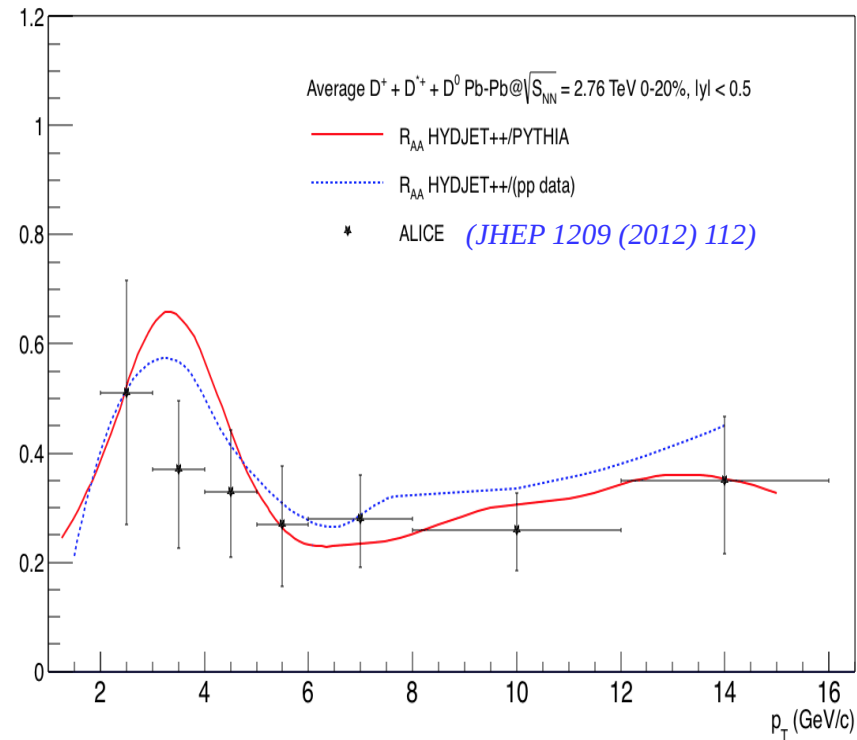


HYDJET++ reproduces p_T -spectrum of D-mesons with the *same freeze-out parameters* as for inclusive hadrons \Rightarrow significant part of D-mesons (*thermal component*) is in the kinetic equilibrium with the medium.

D-mesons: v_2 and R_{AA}

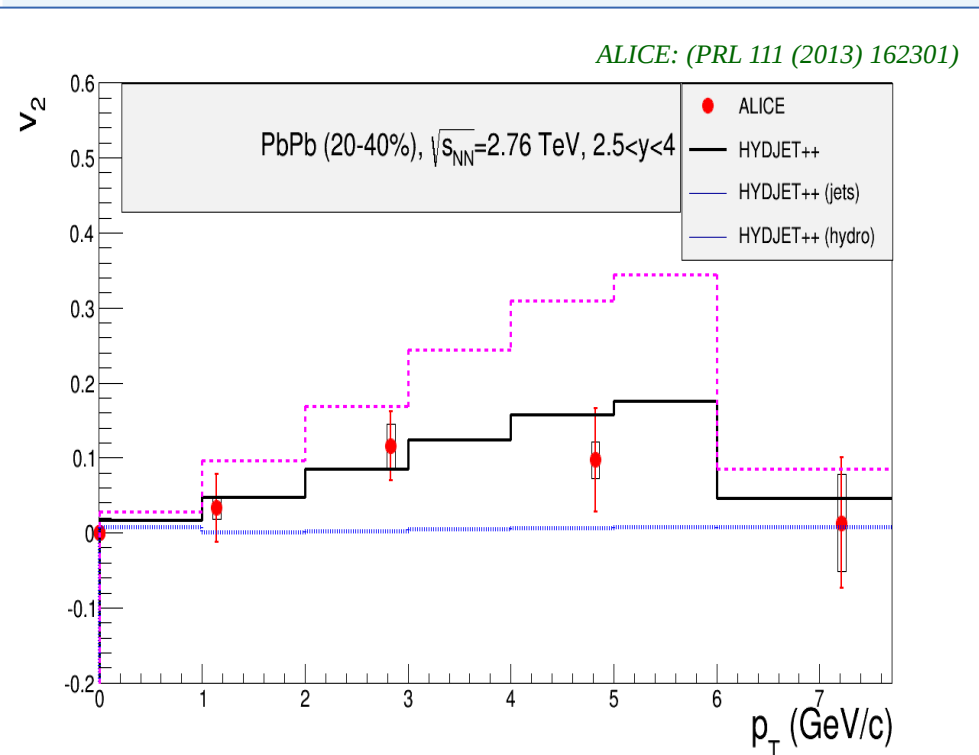


HYDJET++ reproduces $v_2(p_T)$ of D-mesons with the *same freeze-out parameters* as for inclusive hadrons \Rightarrow significant part of D-mesons (*thermal component*) is in the kinetic equilibrium with the medium; *non-thermal component* is important at high p_T

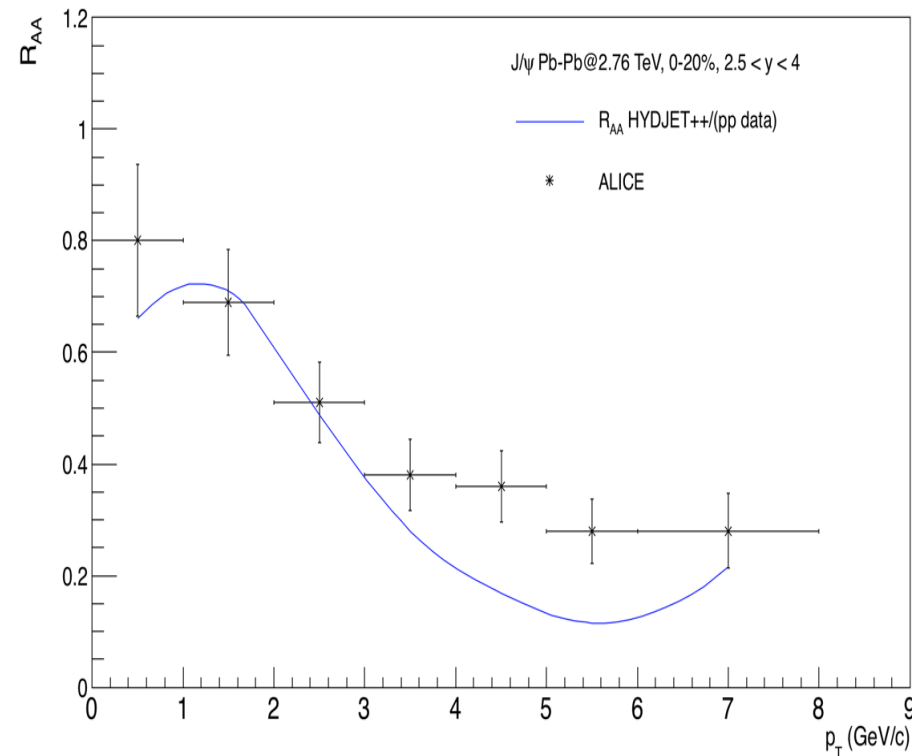


HYDJET++ reproduces $R_{AA}(p_T)$ of D-mesons up to very high $p_T \Rightarrow$ treatment of heavy quark energy loss in hard component of HYDJET++ seems quite successful.

J/ψ: v_2 and R_{AA}



HYDJET++ reproduces $v_2(p_T)$ of J/ψ with the *freeze-out parameters different* from ones for inclusive hadrons \Rightarrow kinetic freeze-out of J/ψ *thermal component* occurs appreciably before freeze-out of light hadrons



Superposition of *thermal* and *non-thermal components* qualitatively reproduces momentum dependence of J/ψ R_{AA} at the LHC

(but PYTHIA@HYDJET++ tuning is needed for adequate J/ψ modeling at high p_T).

Main publications

- [1] G. Eyyubova, L. Bravina, E. Zabrodin, V. L. Korotkikh, I.P Lokhtin, L. Malinina, S. V. Petrushanko, A. M. Snigirev, *Phys. Rev. C* 80 (2009) 064907
- [2] L. Brsvina, B.H. Brusheim Johansson, G. Eyyubova, E. Zabrodin, *Phys. Rev. C* 87 (2013) 034901
- [3] I.P. Lokhtin, A.V. Belyaev, L.V. Malinina, S.V. Petrushanko, E.P. Rogochaya, A.M. Snigirev, “Hadron spectra, flow and correlations in PbPb collisions at the LHC: interplay between soft and hard physics”, *Eur. Phys. J. C* 72 (2012) 2045
- [4] L.V. Bravina, B.H. Brusheim Johansson, G.Kh. Eyyubova, V.L. Korotkikh, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, E.E. Zabrodin. “Hexagonal flow v_6 as a superposition of elliptic v_2 and triangular v_3 flows”, *Phys. Rev. C* 89 (2014) 024909
- [5] L.V. Bravina, B.H. Brusheim Johansson, G.Kh. Eyyubova, V.L. Korotkikh, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, E.E. Zabrodin. “Higher harmonics of azimuthal anisotropy in relativistic heavy ion collisions in HYDJET++ model”, *Eur. Phys. J. C* 74 (2014) 2807
- [6] G. Eyyubova, V.L. Korotkikh, I.P. Lokhtin, S.V. Petrushanko, A.M. Snigirev, L.V. Bravina, E.E. Zabrodin, “Angular dihadron correlations as interplay of elliptic and triangular flows”, *Phys. Rev. C* 91 (2015) 064907

SUMMARY

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Two-component model of relativistic heavy ion collisions HYDJET++ reproduces basic physical observables measured in PbPb collisions at the LHC:

- multiplicity and momentum spectra of inclusive and identified hadrons
- anisotropic flow of inclusive and identified hadrons (including odd and higher harmonics)
- two-particle angular correlations of inclusive hadrons (including “ridge”)
- momentum spectra and elliptic flow of D-mesons
- hadron nuclear modification factor up to very high transverse momentum

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- momentum spectra and elliptic flow of D and J/psi mesons
- hadron nuclear modification factor up to very high transverse momentum

The pattern of multi-hadron and jet production in most central PbPb collisions at the LHC agrees with the formation of hot strongly-interacting matter with hydrodynamical properties (“quark-gluon fluid”), which absorbs energetic quarks and gluons due to their multiple scattering and wide-angle radiative and collisional medium-induced energy loss.

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