Sergey PETRUSHANKO
(M.V. Lomonosov Moscow State University)

in collaboration with

Andrey Belyaev, Larisa Bravina, Alexey Chenyshov,
Gyulnara Eyyubova,Vladimir Korotkikh, Igor Lokhtin,
Ludmila Malinina, Alexandre Snigirev, Evgeny Zabrodin

12 years of HYDJET++ generator: history and the latest results

5th International Conference on
Particle Physics and Astrophysics
VIRTUAL in MOSCOW
5 - 9 October 2020

HYDJET and HYDJET++ relativistic heavy ion event generators

HYDJET

(HYDrodynamics + JETs)

event generator to simulate heavy ion event as merging of two independent components (**soft** hydro-type part + **hard** multi-partonic state)

http://cern.ch/lokhtin/hydro/hydjet.html

(latest version 1.9)

I.Lokhtin, A.Snigirev, Eur. Phys. J. C 46 (2006) 2011

HYDJET++

continuation of HYDJET
(improved **soft** component including full set of thermal resonance production + identical to HYDJET **hard** component)

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

(latest version 2.4)

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

HYDJET++ soft component

Soft (hydro) part of HYDJET++ is 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

- ✔ Fast HYDJET-inspired MC procedure for soft hadron generation;
- ✔ 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;
- ✔ written within ROOT framework (C++);
- ✔ contains 16 free parameters (can be reduced to 9).

HYDJET++ hard component

PYQUEN (PYthia QUENched)

http://lokhtin.web.cern.ch/lokhtin/pyquen/

(latest version 1.5.1)

I.P.Lokhtin, A.M.Snigirev, Eur. Phys. J. 45 (2006) 211

Initial parton configuration
PYTHIA6.4 w/o hadronization: mstp(111)=0

↓

Parton rescattering & energy loss (collisional, radiative) + emitted gluons
PYQUEN rearranges partons to update number of strings

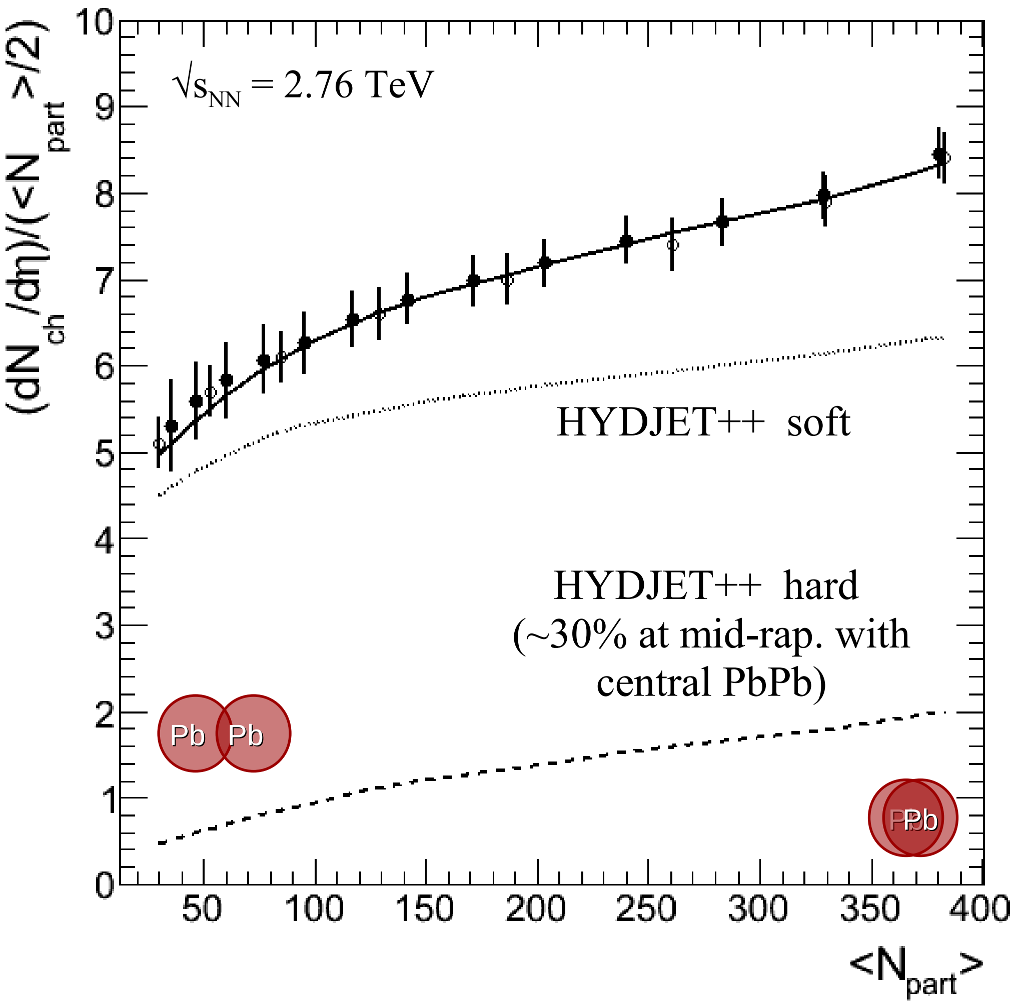
↓

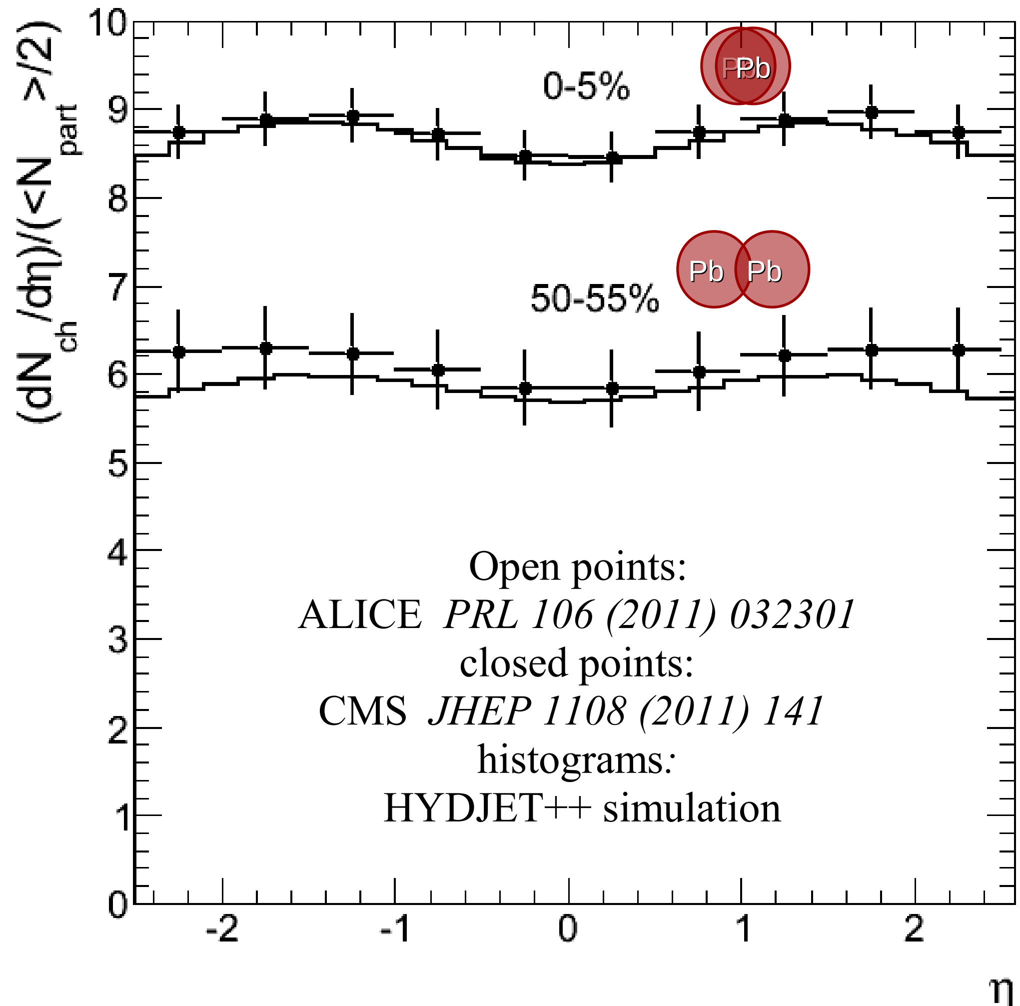
Parton hadronization and final particle formation
PYTHIA6.4 with hadronization: call PYEXEC

Three model parameters: initial maximal 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 to specify the number of hard NN collisions)

Charged multiplicity vs. centrality and pseudorapidity with HYDJET++ at LHC

I.P. Lokhtin, A.V. Belyaev, L.V. Malinina, S.V. Petrushanko, E.P. Rogochaya, A.M. Snigirev, Eur.Phys.J. C (2012) 72:2045

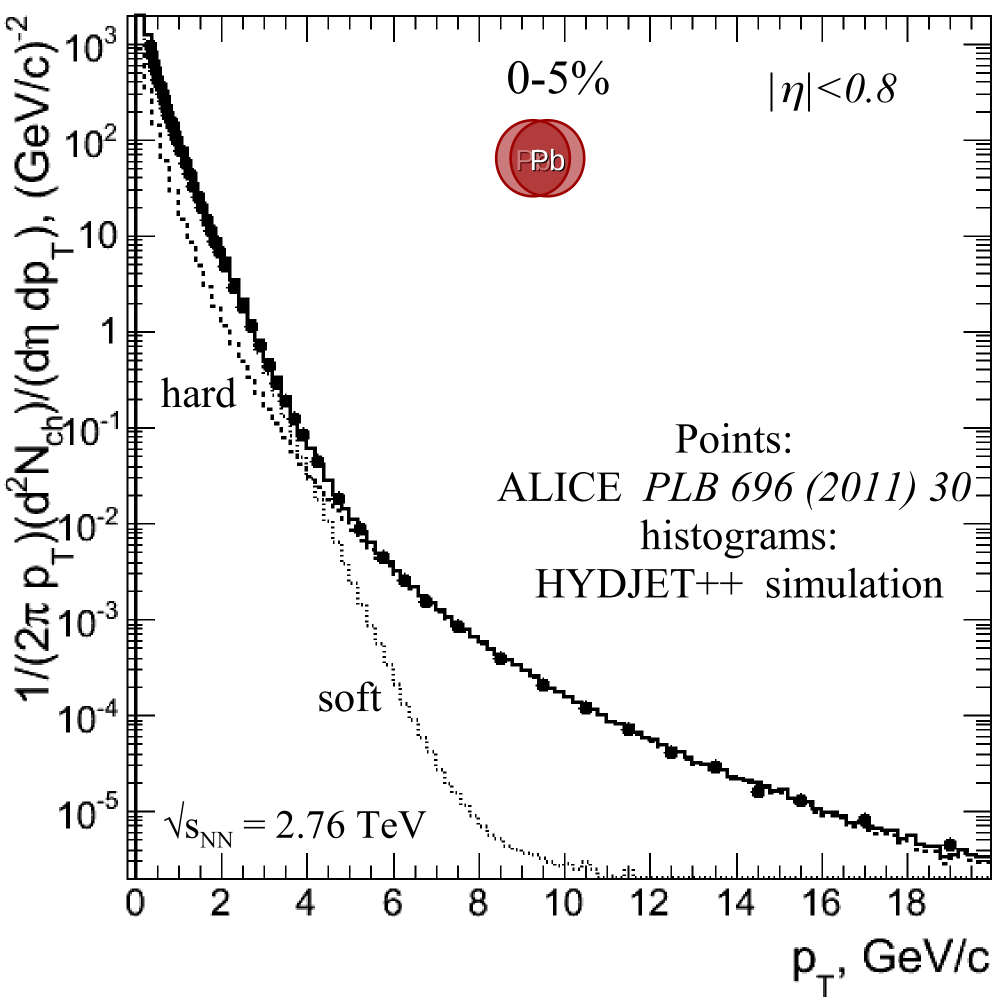


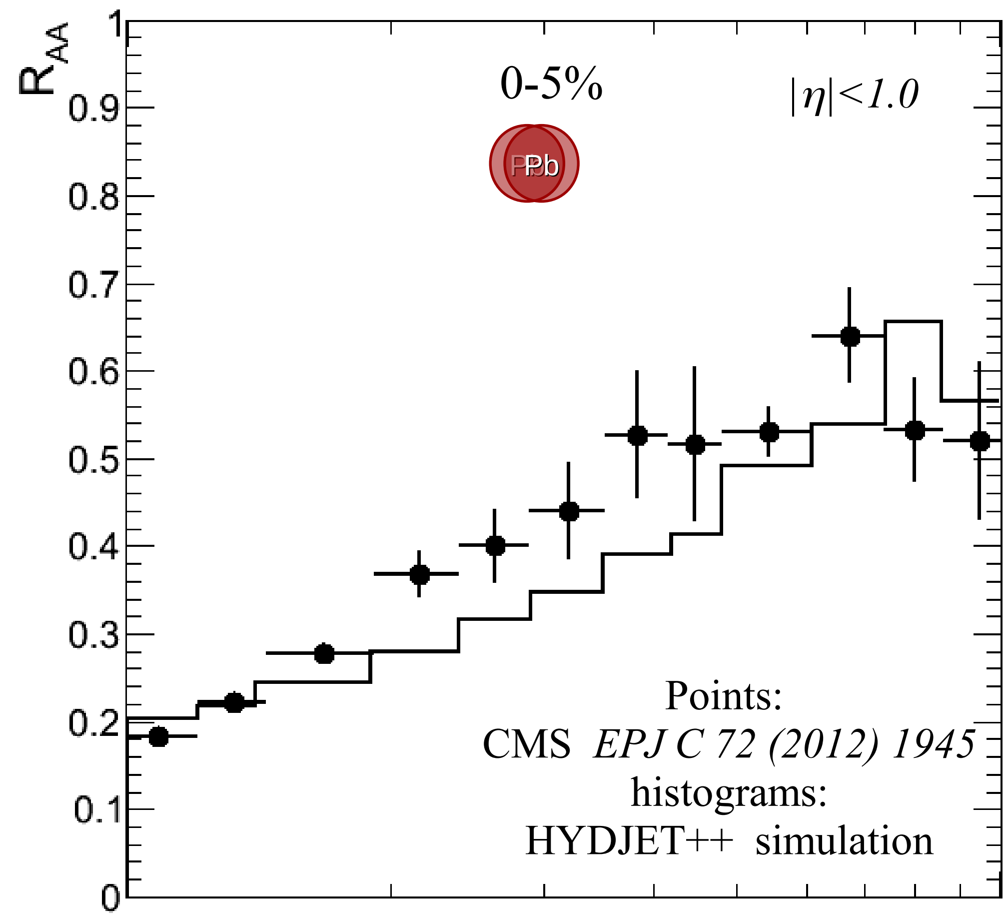


Tuned HYDJET++ reproduces multiplicity vs. event centrality down to very peripheral events, as well as approximately flat pseudorapidity distribution.

p_T-spectrum and nuclear modification factor R_{AA} for inclusive charged hadrons

I.P. Lokhtin, A.V. Belyaev, L.V. Malinina, S.V. Petrushanko, E.P. Rogochaya, A.M. Snigirev, Eur.Phys.J. C (2012) 72:2045



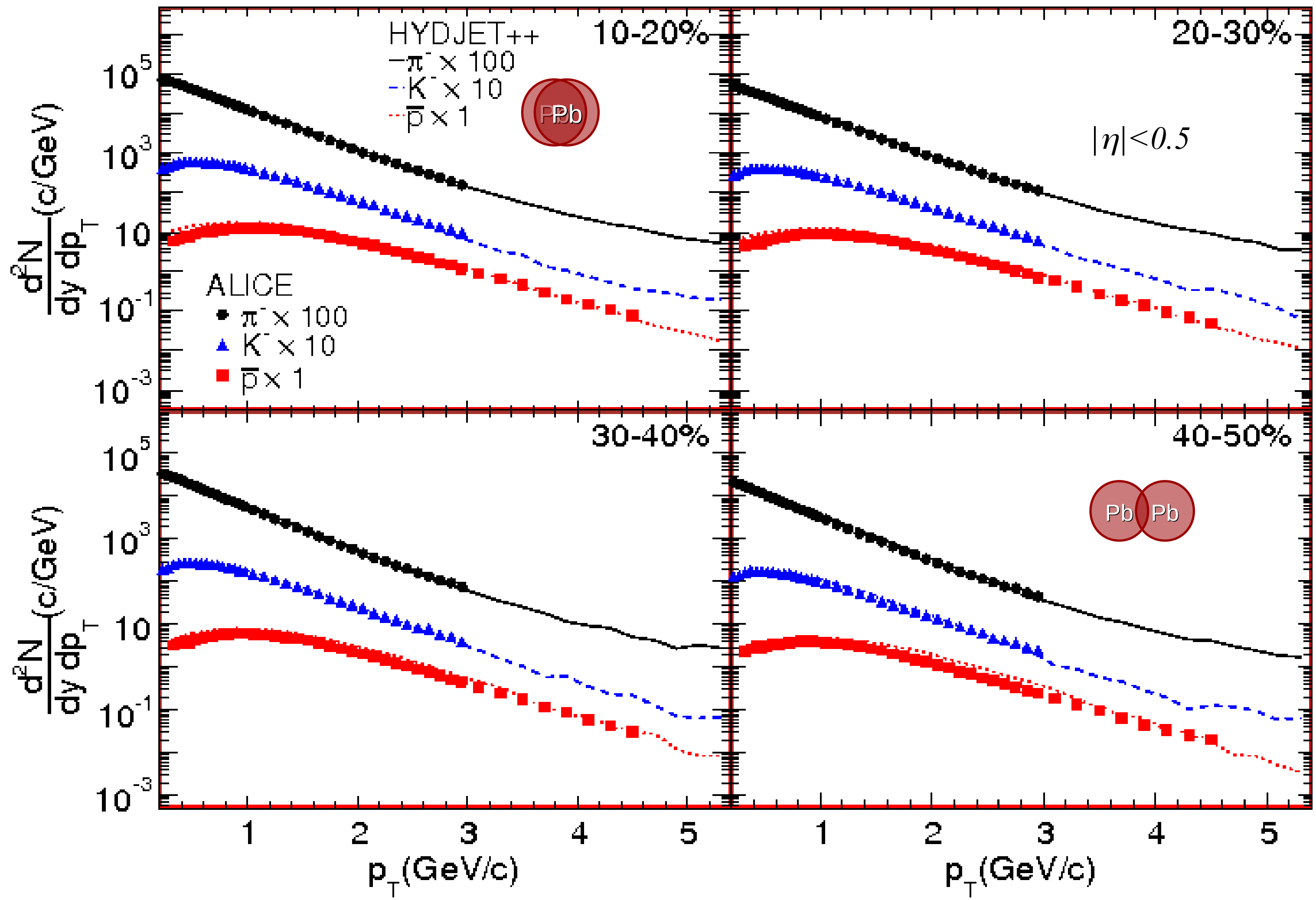


$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / dp_T d\eta}{d^2 \sigma_{pp} / dp_T d\eta}$$

HYDJET++ reproduces p_T-spectrum and R_{AA} of inclusive charged hadrons for central PbPb collisions in mid-rapidity up to $p_T \sim 100$ GeV/*c*.

p_T-spectra of identified hadrons

I.P. Lokhtin, A.V. Belyaev, L.V. Malinina, S.V. Petrushanko, E.P. Rogochaya, A.M. Snigirev, Eur.Phys.J. C (2012) 72:2045



Points: ALICE *APP B 43 (2012) 555*, histograms: HYDJET++ simulation

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

Anisotropic flow generation in HYDJET++ (soft component)

Elliptic flow v_2

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

- Spatial modulation of freeze-out surface;
- Fluid velocity modulation.

<u>*Spatial anisotropy*</u>

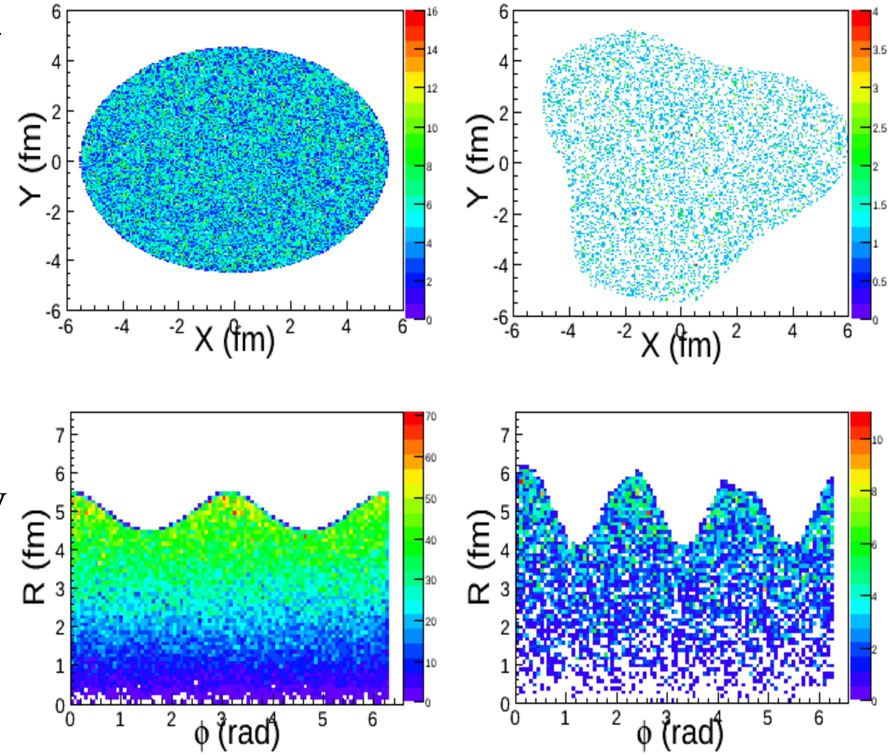
$$\varepsilon(b) = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2}$$

R(b) – surface radius

<u>*Momentum anisotropy*</u>

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

φ_u - azimuthal angle of fluid velocity
φ - spatial azimuthal angle



Triangular flow v_3

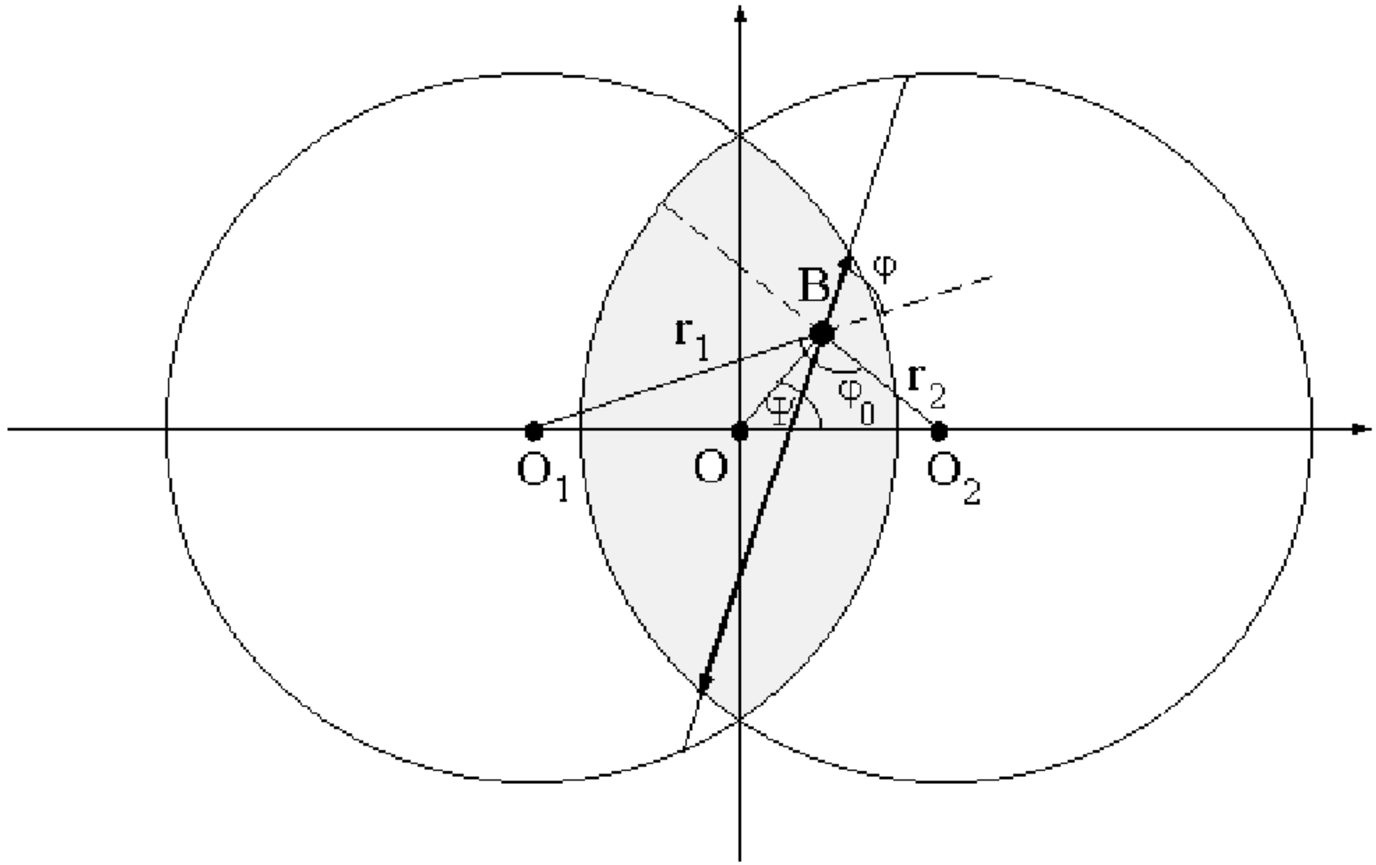
Spatial modulation of freeze-out surface as cos(3φ) with independent phase Ψ_3 and parameter ε_3

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

Three parameters $\varepsilon(b_0)$, $\varepsilon_3(b_0)$ и $\delta(b_0)$ are tuned to fit the data.

The simple modification of the HYDJET++ via introducing the distribution over spatial anisotropy parameters permits model to reproduce both elliptic and triangular flow fluctuations in heavy ion collisions at the LHC energy.

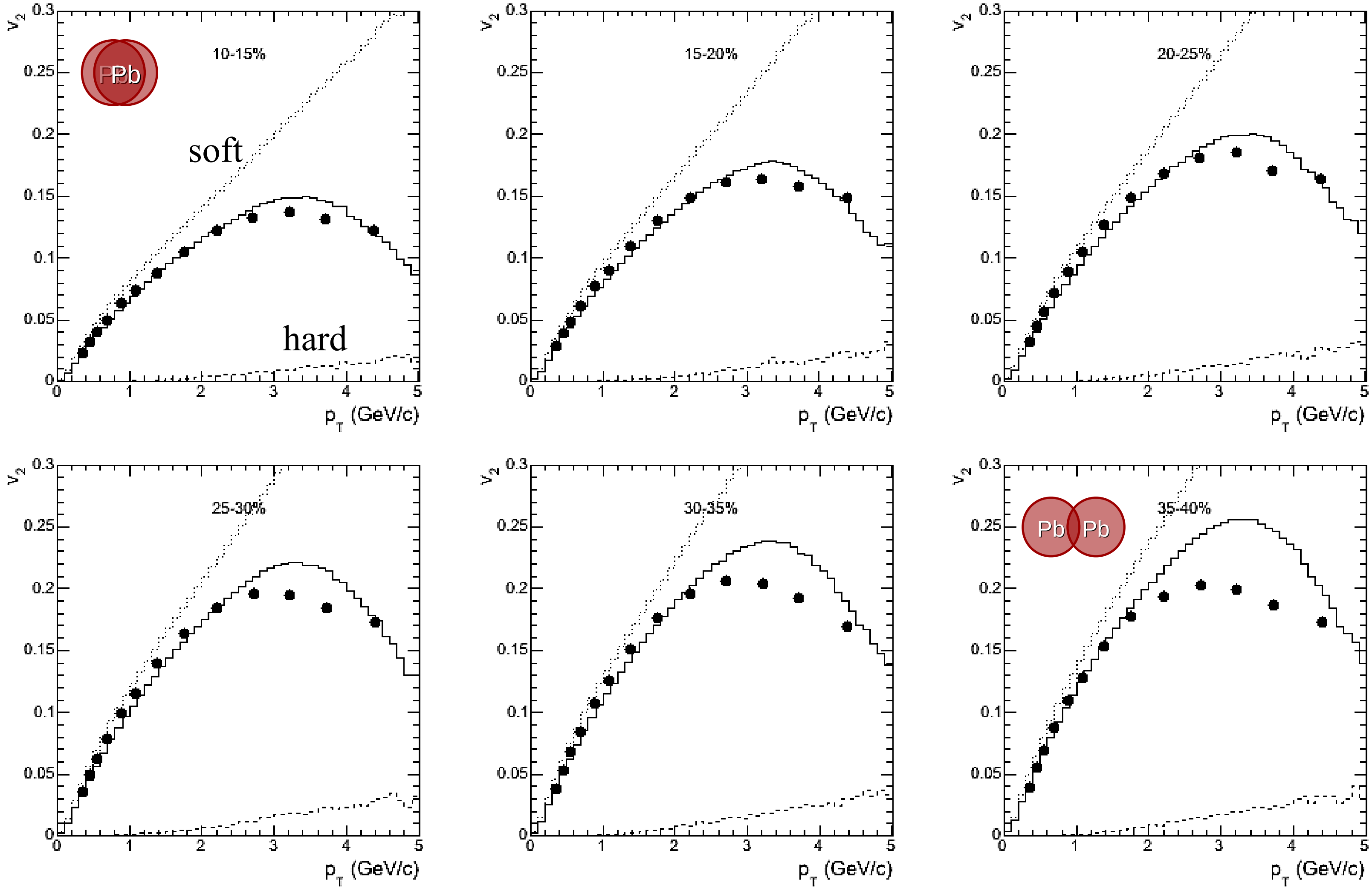
Anisotropic flow generation in HYDJET++ (hard component)



Some anisotropic flow for hard component (elliptic flow and higher even harmonics at high transverse momenta) is generated due to partonic rescattering and energy loss in azimuthally asymmetric volume of the medium.

Elliptic flow in HYDJET++ vs. LHC data

I.P. Lokhtin, A.V. Belyaev, L.V. Malinina, S.V. Petrushanko, E.P. Rogochaya, A.M. Snigirev, Eur.Phys.J. C (2012) 72:2045

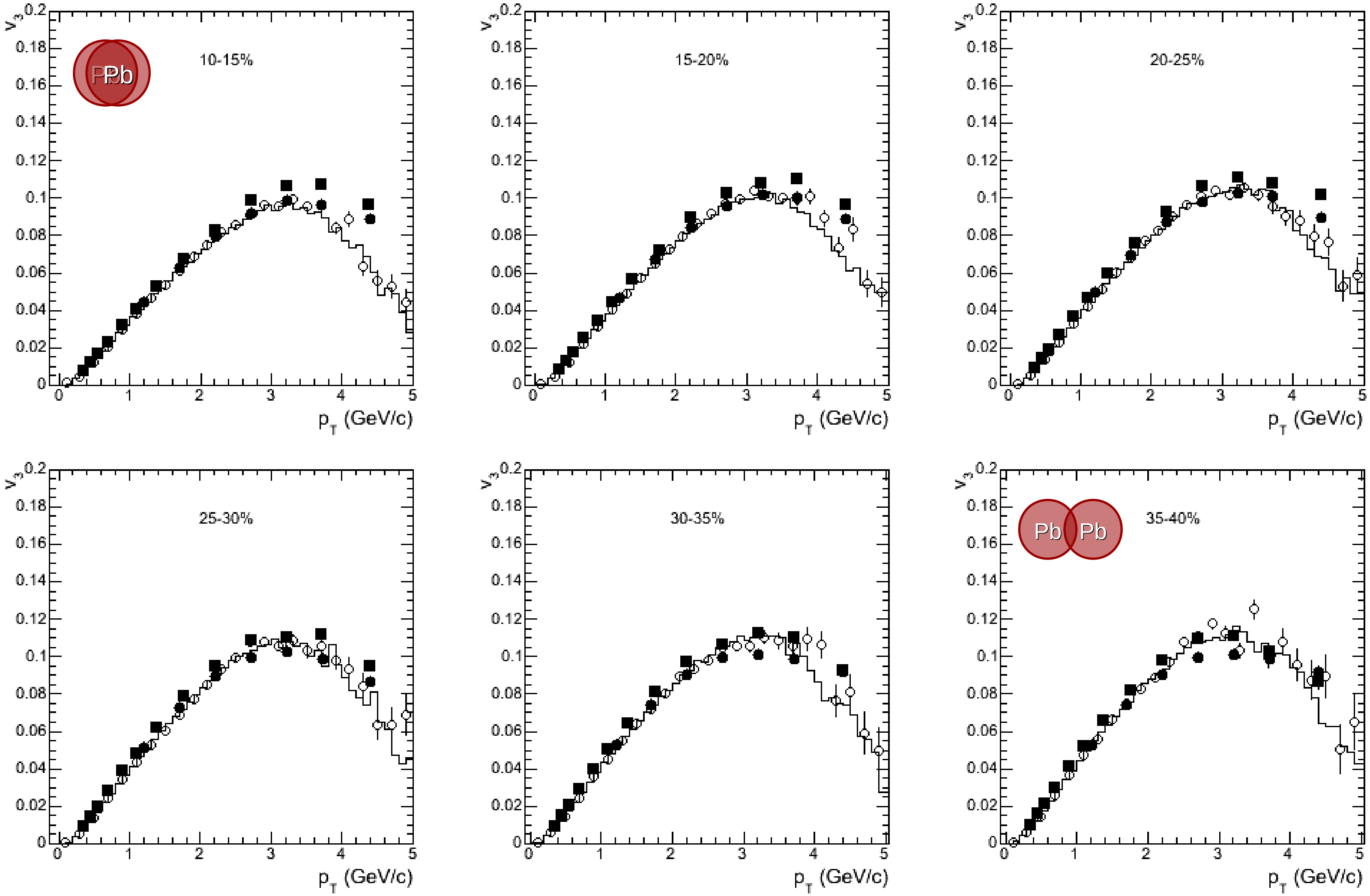


Points: CMS data v2{4} *PRC 87 (2013) 014902*

histograms: HYDJET++ "true" $v_2(\psi_2)$, dashed line (soft), dotted line (hard)

Triangular flow in HYDJET++ vs. LHC data

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, Eur.Phys.J. C (2014) 74:2807

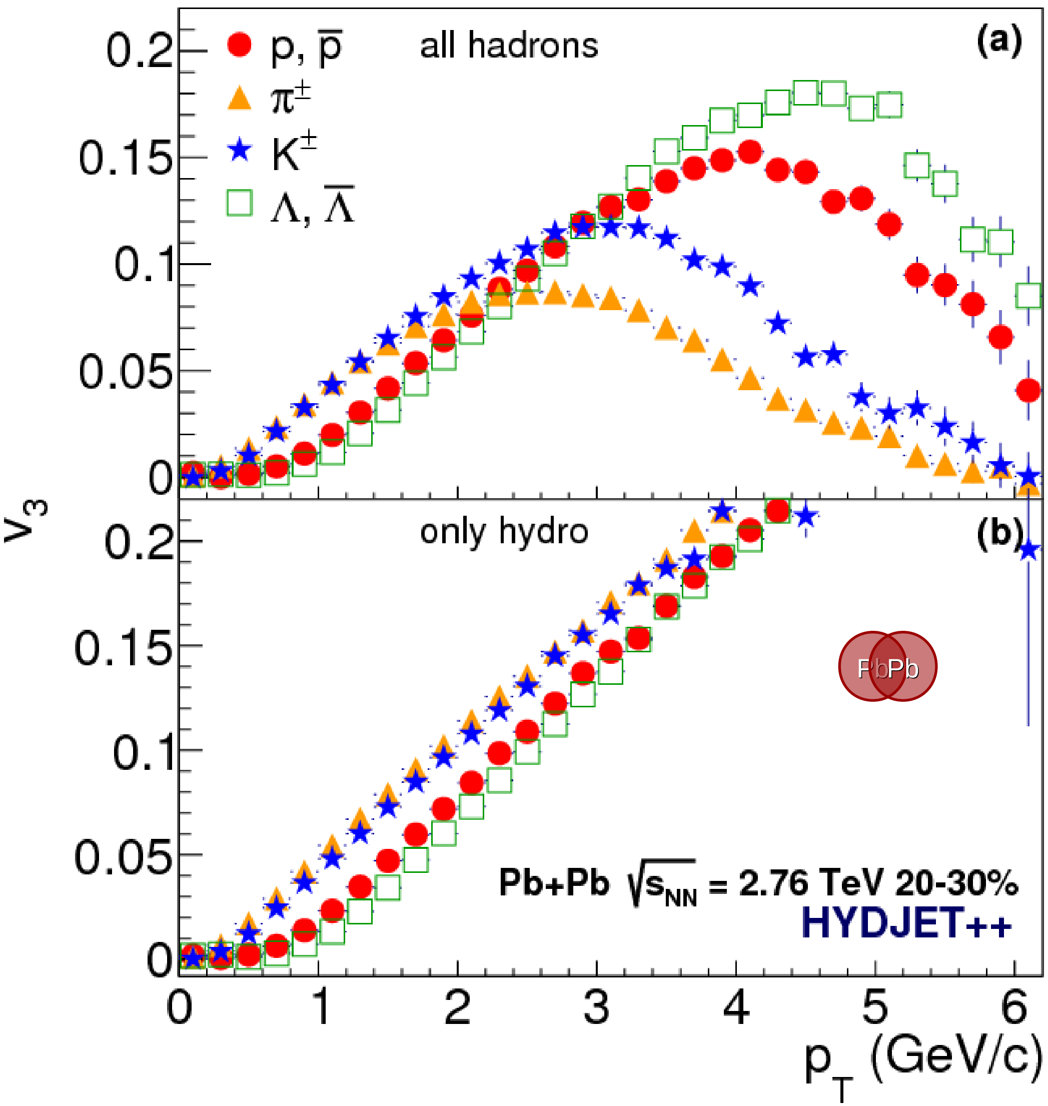


Closed circles and squares: CMS data $v_3\{2\}$ & $v_3\{EP\}$ *PRC 89 (2014) 044906*

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

Interplay of hydrodynamics and jets

J. Crkovska, J. Bielcik, L. Bravina, B.H. Brusheim Johansson, E. Zabrodin, G. Eyyubova, V.L. Korotkikh, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, Phys. Rev. C 95 (2017) 014910



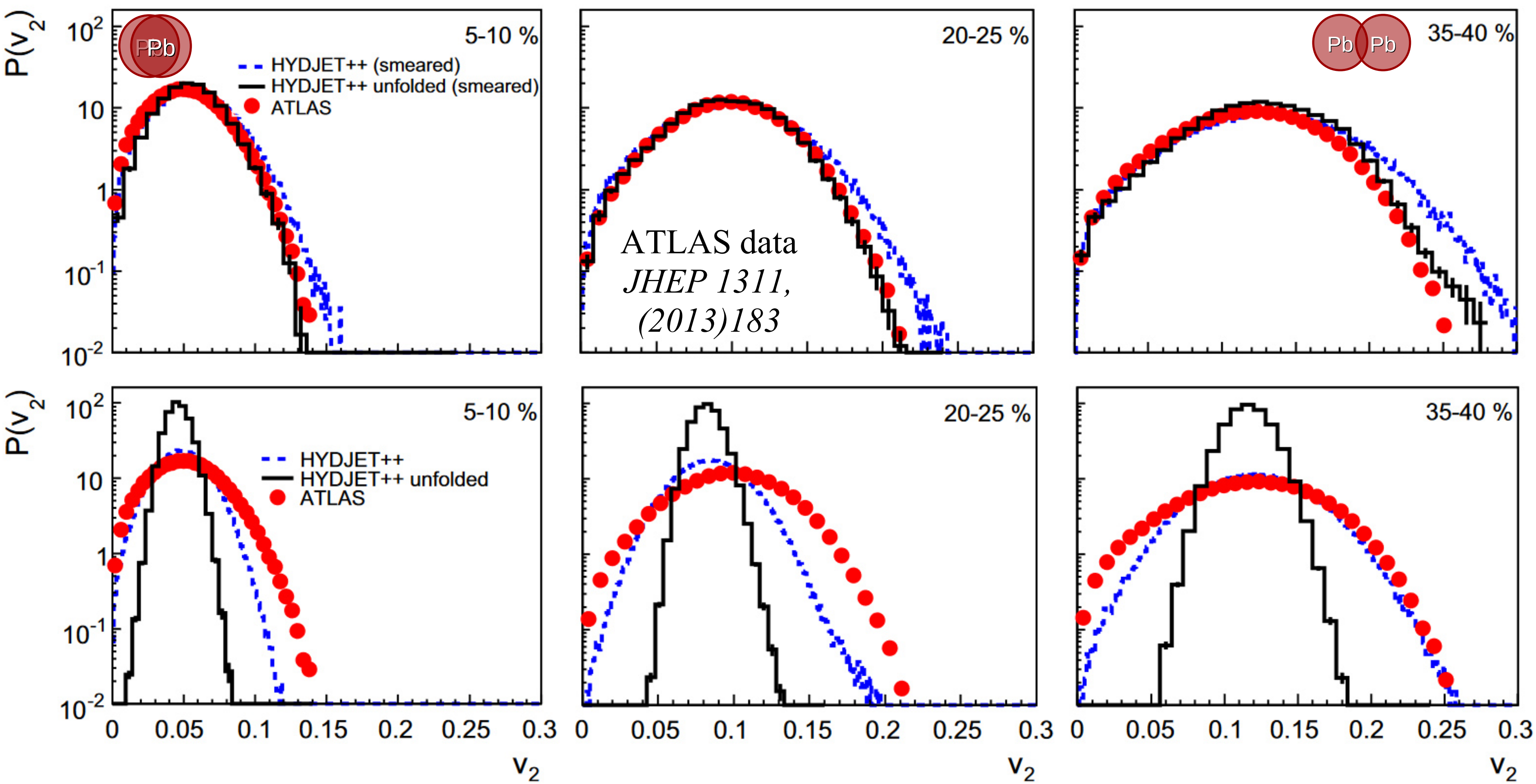
Hydrodynamics gives mass ordering of v_3.

The model possesses crossing of baryon and meson branches.

The reason for the mass ordering break at 2 GeV/*c* is traced to hard processes (jets).

The probability density distributions of elliptic flow

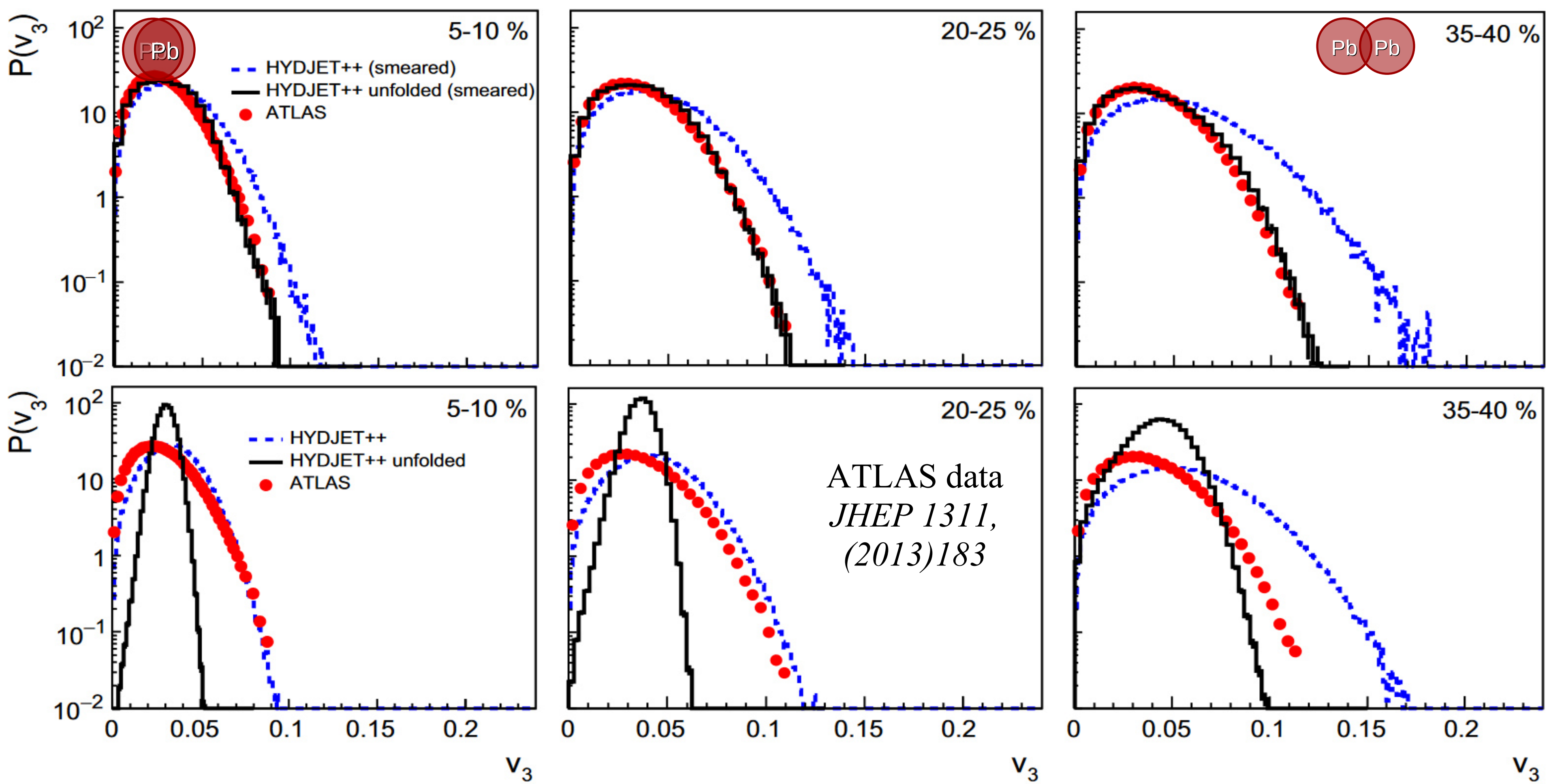
L. V. Bravina, E. S. Fotina, V. L. Korotkikh, I. P. Lokhtin, L. V. Malinina, E. N. Nazarova, S. V. Petrushanko, A. M. Snigirev, E. E. Zabrodin, Eur.Phys.J. C 75 (2015) 588



The top/bottom row: the model results with/without the additional smearing of spatial anisotropy parameters. Dashed and solid histograms: HYDJET++ before and after the unfolding procedure.

The probability density distributions of triangular flow

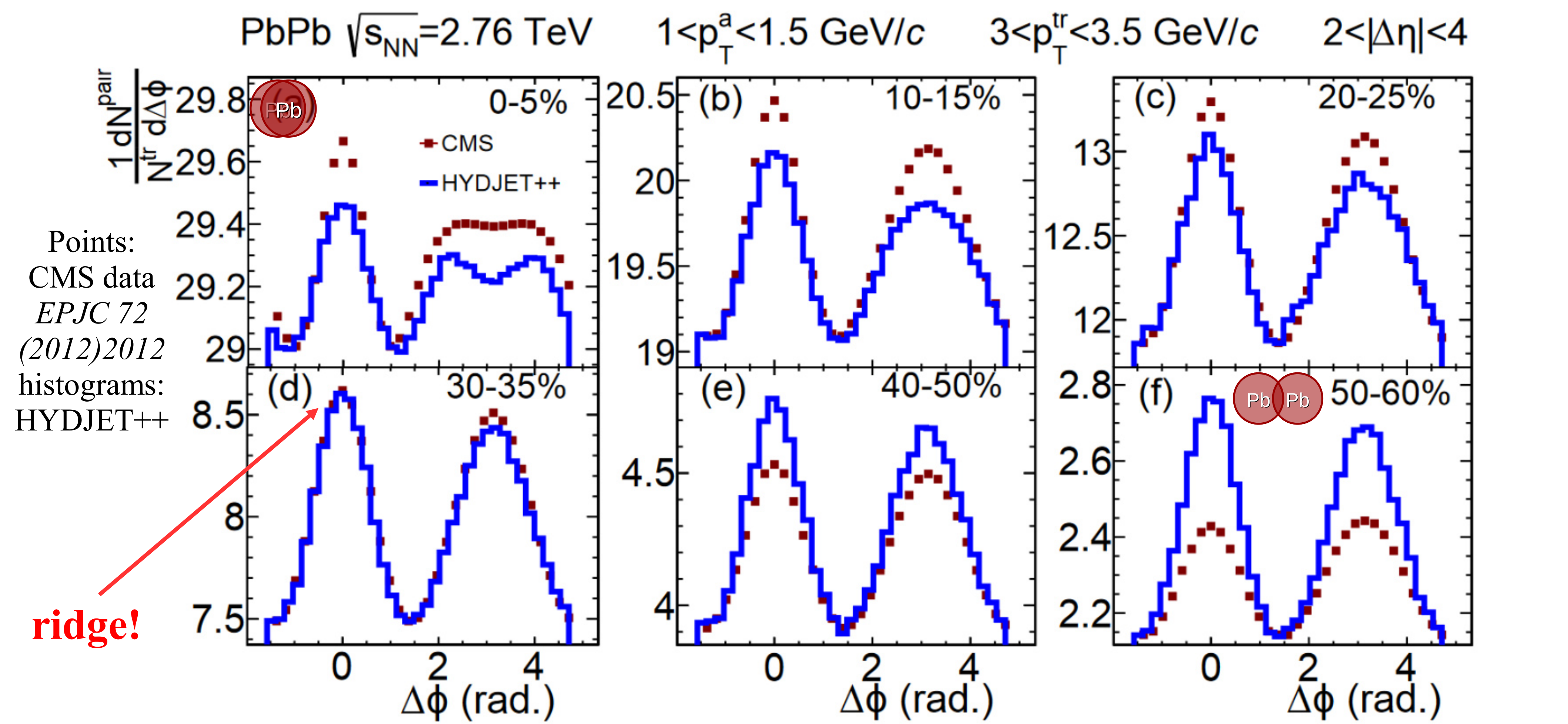
L. V. Bravina, E. S. Fotina, V. L. Korotkikh, I. P. Lokhtin, L. V. Malinina, E. N. Nazarova, S. V. Petrushanko, A. M. Snigirev, E. E. Zabrodin, Eur.Phys.J. C 75 (2015) 588



The top/bottom row: the model results with/without the additional smearing of spatial anisotropy parameters. Dashed and solid histograms: HYDJET++ before and after the unfolding procedure.

Dihadron angular correlations ("ridge") in HYDJET++

G. Eyyubova, V. L. Korotkikh, I. P. Lokhtin, S. V. Petrushanko, A. M. Snigirev, L. Bravina, E. E. Zabrodin, Phys. Rev. C 91 (2015), 064907



Interplay of elliptic and triangular flows in HYDJET++ yields long-range two-particle azimuthal correlations (*ridge effect*), but centrality dependence of the correlation strength seems to be a bit stronger.

Charm production in HYDJET++

1) Thermal charm production in HYDJET++ (soft component)

Thermal charmed hadrons J/ψ, D^0, 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, Phys.Lett. B 571 (2003) 36; Nucl. Phys. A 789 (2007) 334*

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

γ_c - charm enhancement factor, which may be treated as a free model parameter, or (as an option) may be obtained from the equation:

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

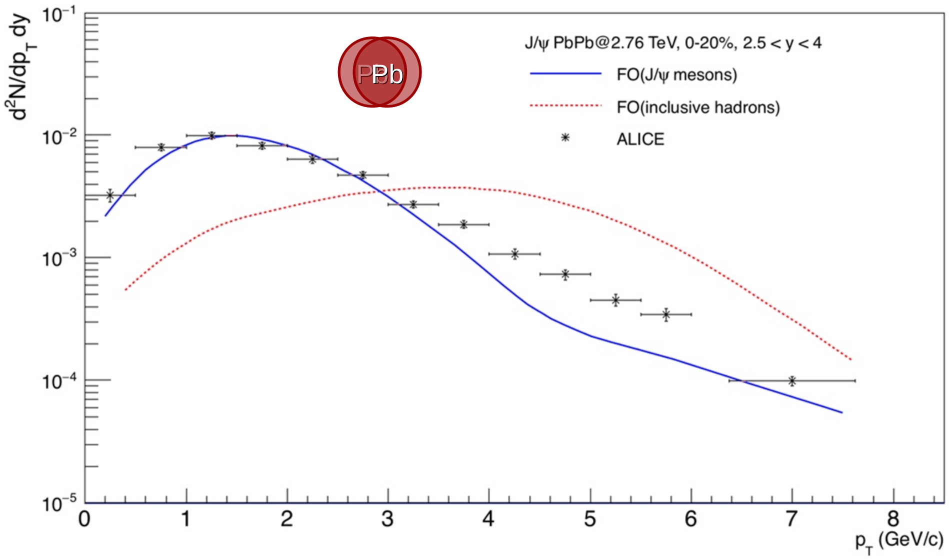
where number of c-quark pairs N_{cc} is calculated with PYTHIA (the factor K~2 is applied to take into account NLO pQCD corrections) and multiplied by the number of NN sub-collisions for given centrality.

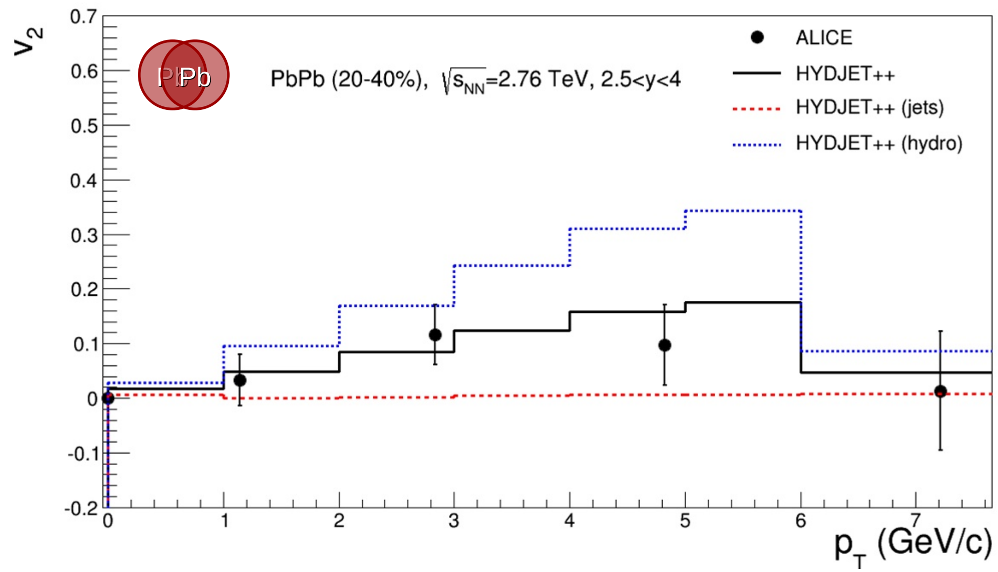
2) Non-thermal charm production in HYDJET++ (hard component)

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

J/ψ meson p_T-spectrum and elliptic flow

I.P. Lokhtin, A.V. Belyaev, G.Kh. Eyyubova, G. Ponimatkin, E. Pronina, J.Phys. G 43 (2016) 125104



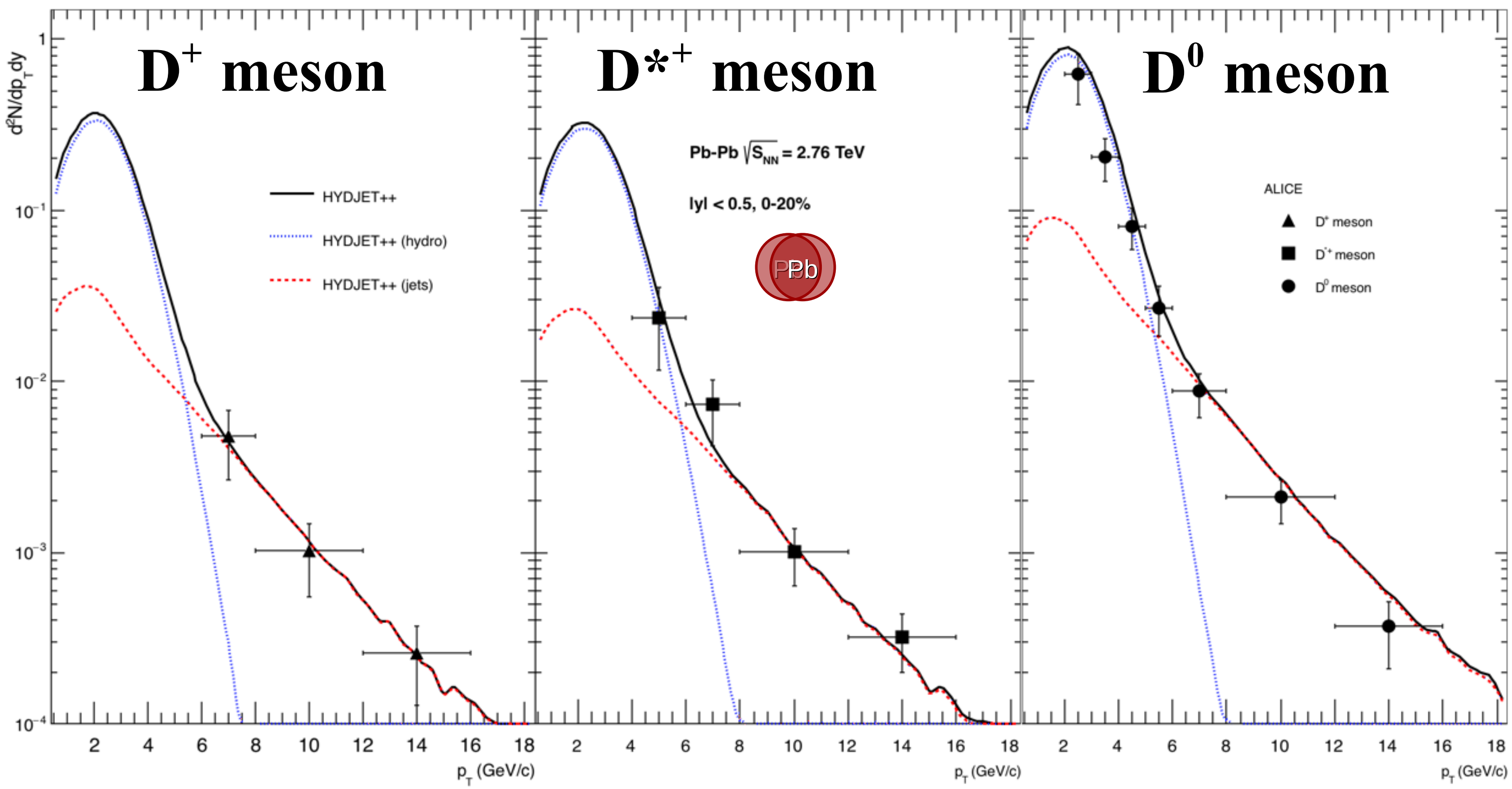


Points: ALICE data *JHEP 05 (2016) 179, PRL 111 (2013) 162301*
histograms: HYDJET++

HYDJET++ reproduces p_T-spectrum & $v_2(p_T)$ of J/ψ with another freeze-out parameters then for inclusive hadrons ⇒ thermal freeze-out of J/ψ-mesons happens before thermal freeze-out of light hadrons.

D-meson p_T-spectra

I.P. Lokhtin, A.V. Belyaev, G.Kh. Eyyubova, G. Ponimatkin, E. Pronina, J.Phys. G 43 (2016) 125104

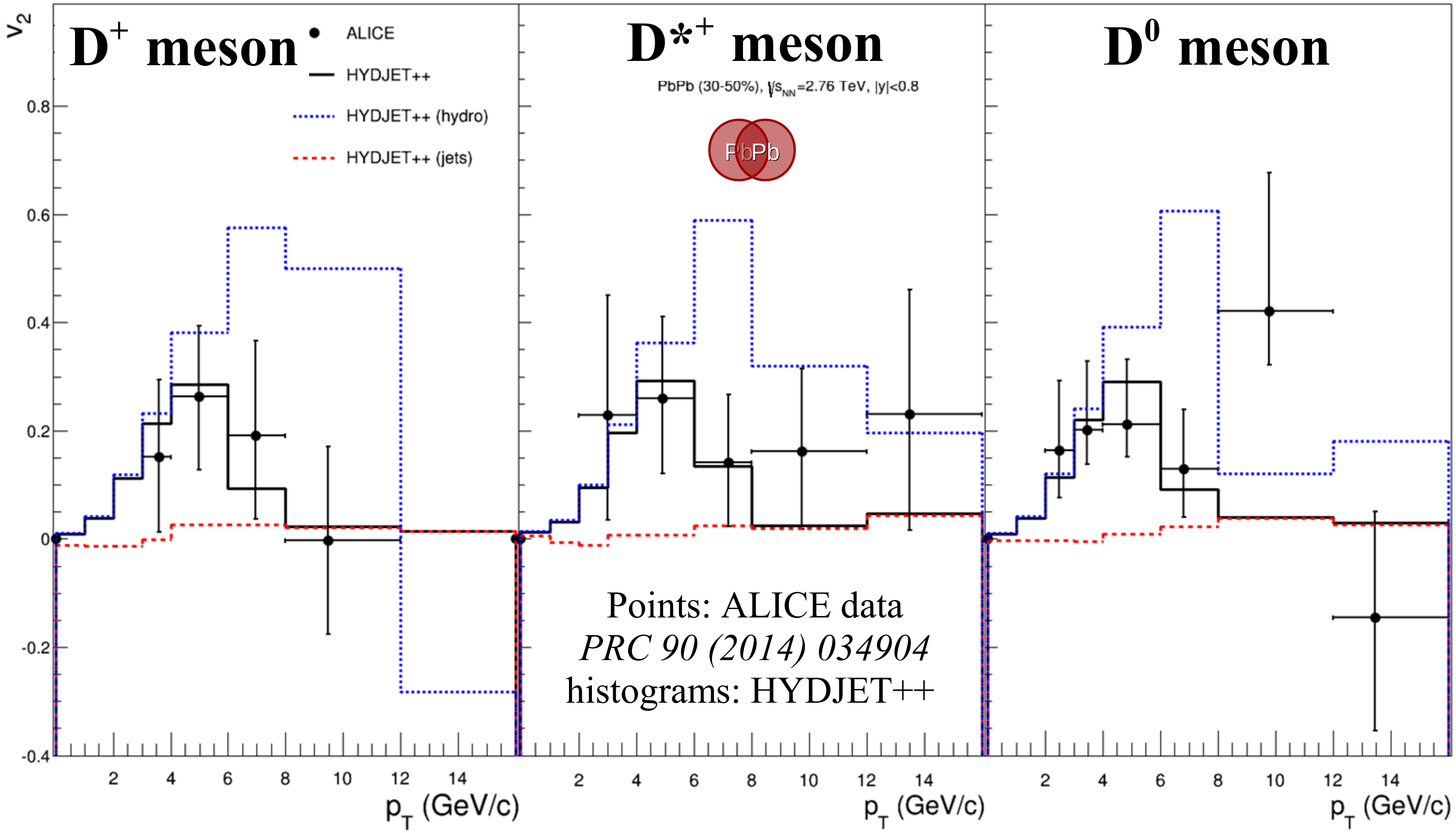


Points: ALICE data, *JHEP 1209 (2012) 112* histograms: HYDJET++

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

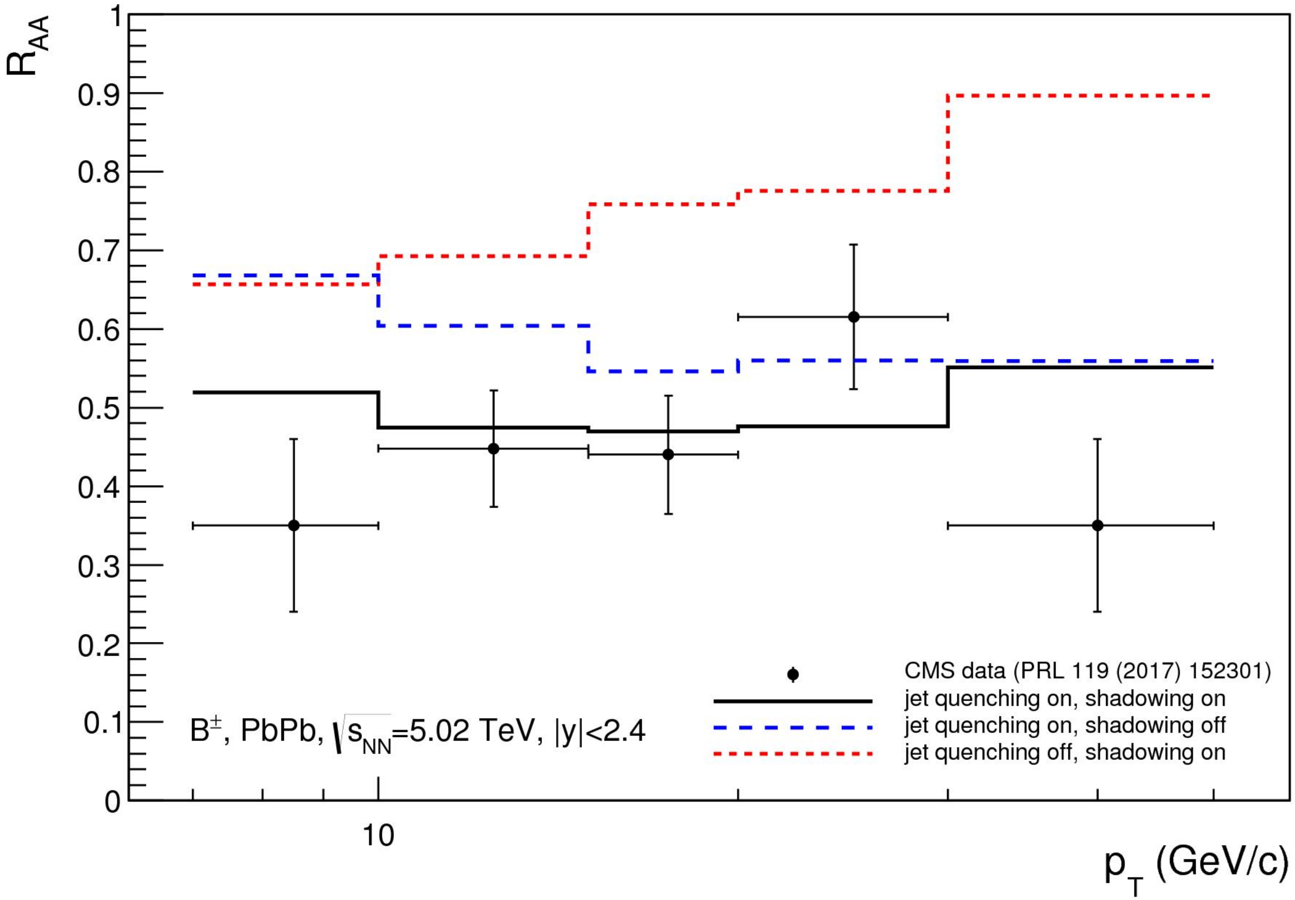
Elliptic flow of D-mesons

I.P. Lokhtin, A.V. Belyaev, G.Kh. Eyyubova, G. Ponimatkin, E. Pronina, J.Phys. G 43 (2016) 125104



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

B-meson suppression factor vs. p_T



I.P. Lokhtin, A.A. Sidorova, J. Exp. Theor. Phys. 128 (2019) 586

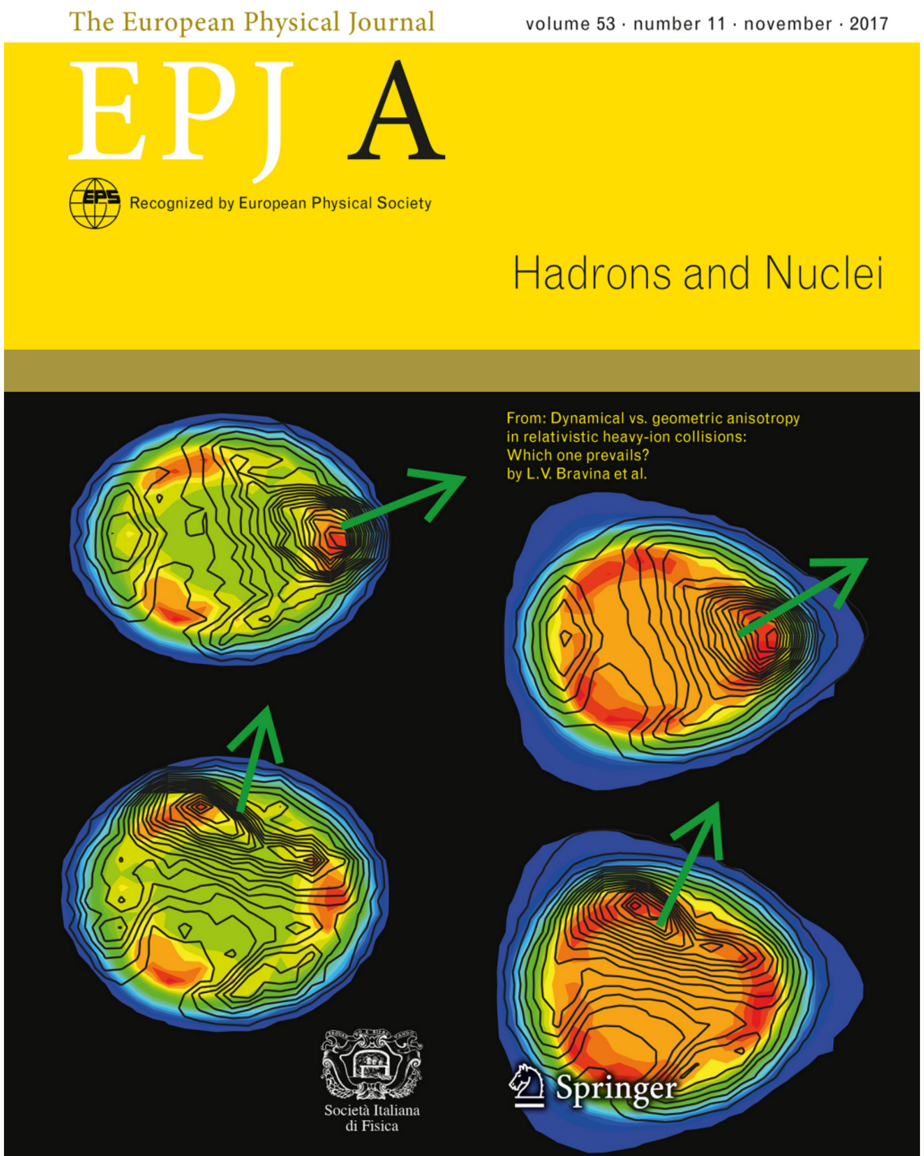
Points: CMS data *PRC 119 (2017) 152301* histograms: HYDJET++

The contributions of nuclear shadowing and jet quenching into B-meson suppression are comparable at p_T~ 10 GeV/c; the relative contribution of jet quenching gets stronger with increasing p_T, and totally dominates at p_T> 30 GeV/c.

B-meson R_{AA} due to jet quenching (nuclear shadowing) decreases (increases) with p_T; the interplay between two effects results in a weak (roughly constant) p_T dependence of R_{AA}.

Thus HYDJET++ reproduces the trend seen in the data if both mechanisms (jet quenching & nuclear shadowing) are taken into account.

Dynamical vs. geometric anisotropy



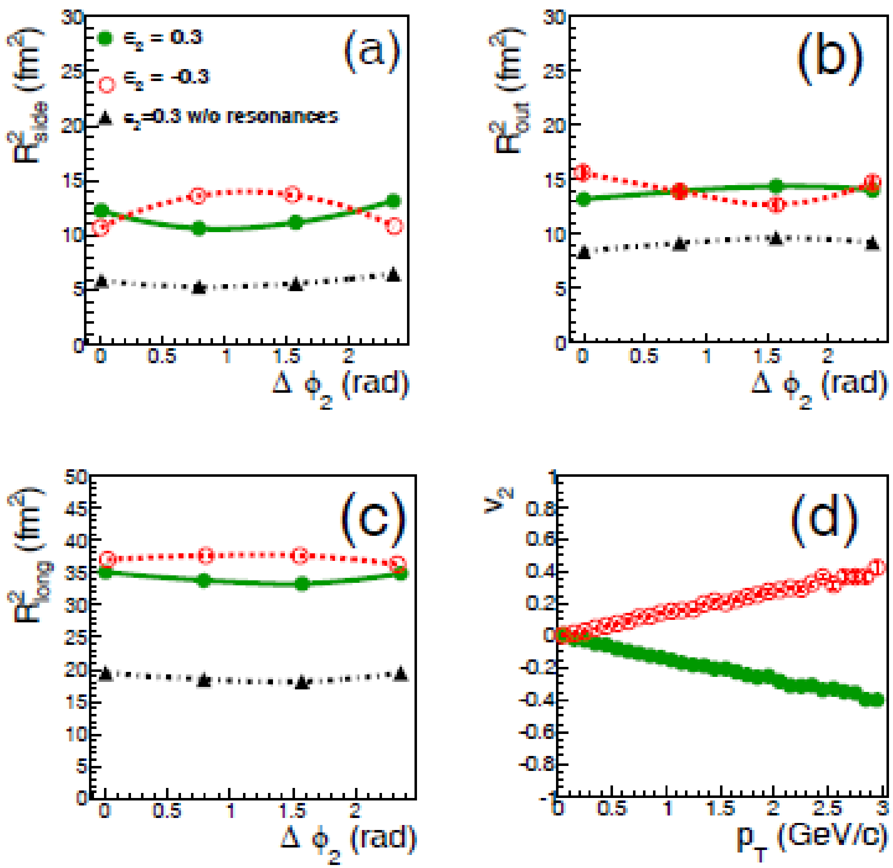
L.V. Bravina, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, E.E. Zabrodin

"Dynamical vs. geometric anisotropy in relativistic heavy-ion collisions: Which one prevails?"

Eur. Phys. J. A 53 (2017) 219.

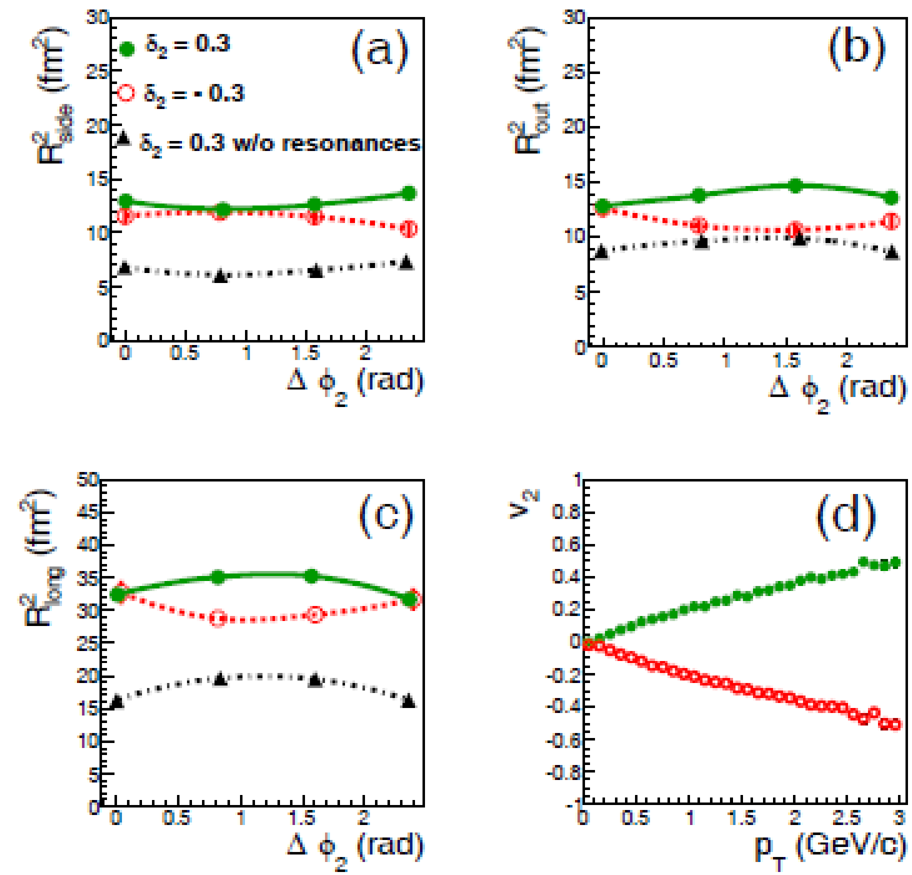
Elliptic flow and femtoscopic radii oscillations w.r.t. Ψ_2

Only SPATIAL anisotropy



Either flow or radii oscillations are reproduced

Only DYNAMICAL anisotropy

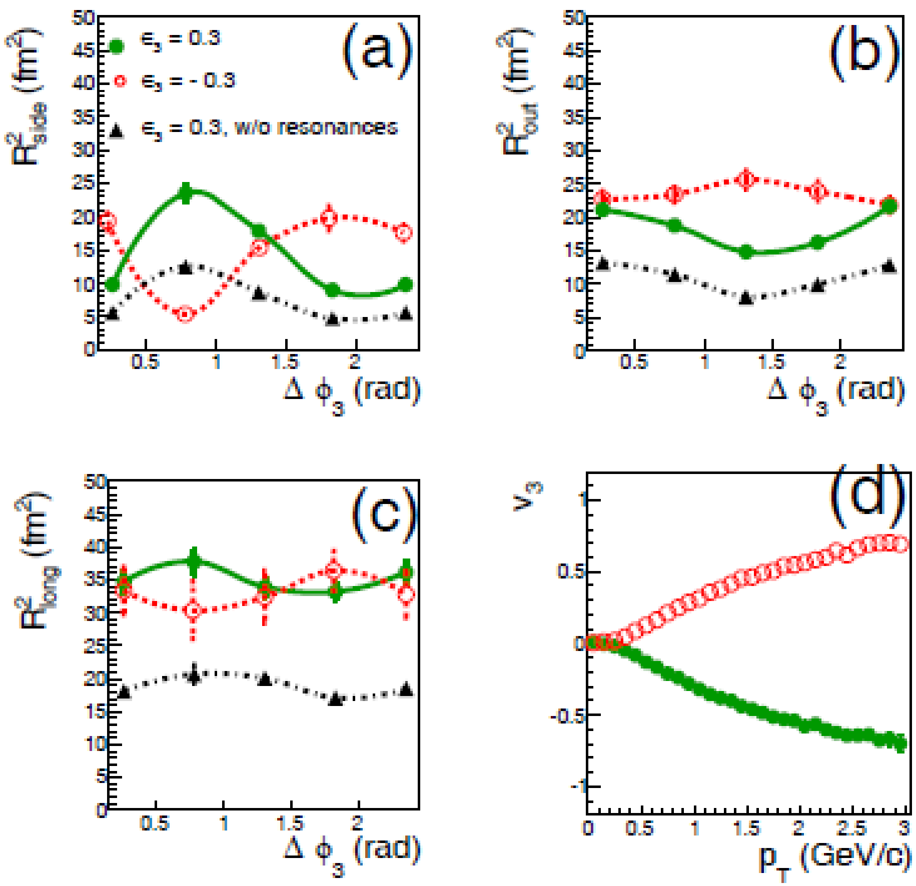


Correct v_2 and oscillation phases

L.V. Bravina, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, E.E. Zabrodin, Eur. Phys. J. A 53 (2017) 219.

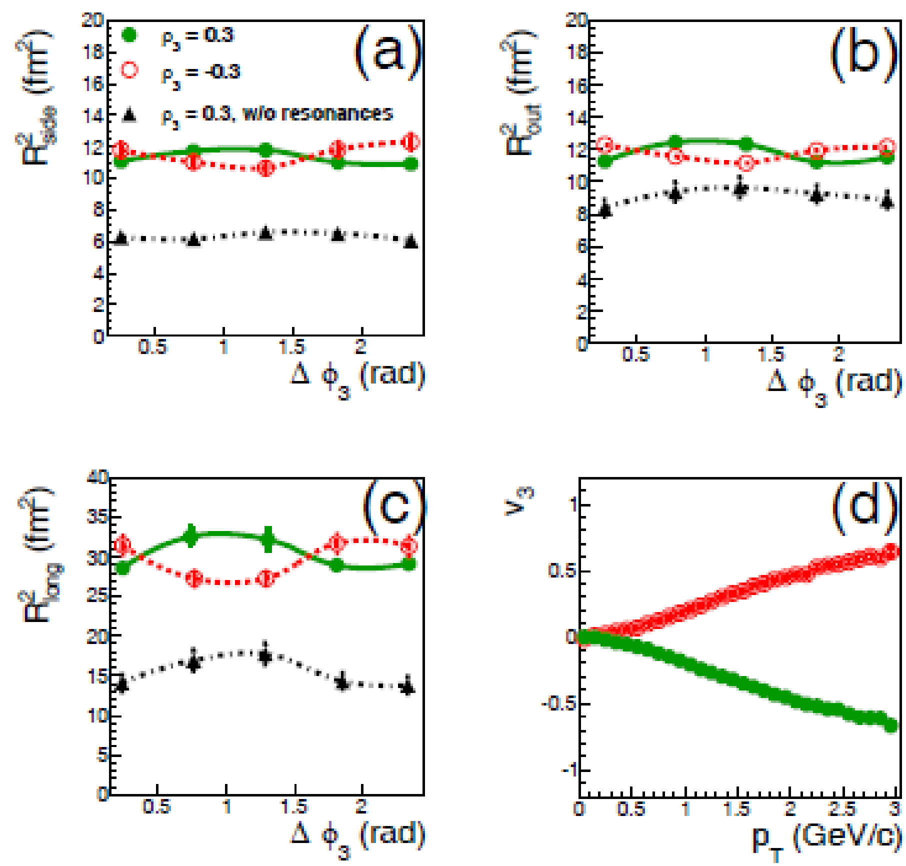
Triangular flow and femtoscopic radii oscillations w.r.t. Ψ_3

Only SPATIAL anisotropy



Again, either flow or radii oscillations are reproduced

Only DYNAMICAL anisotropy



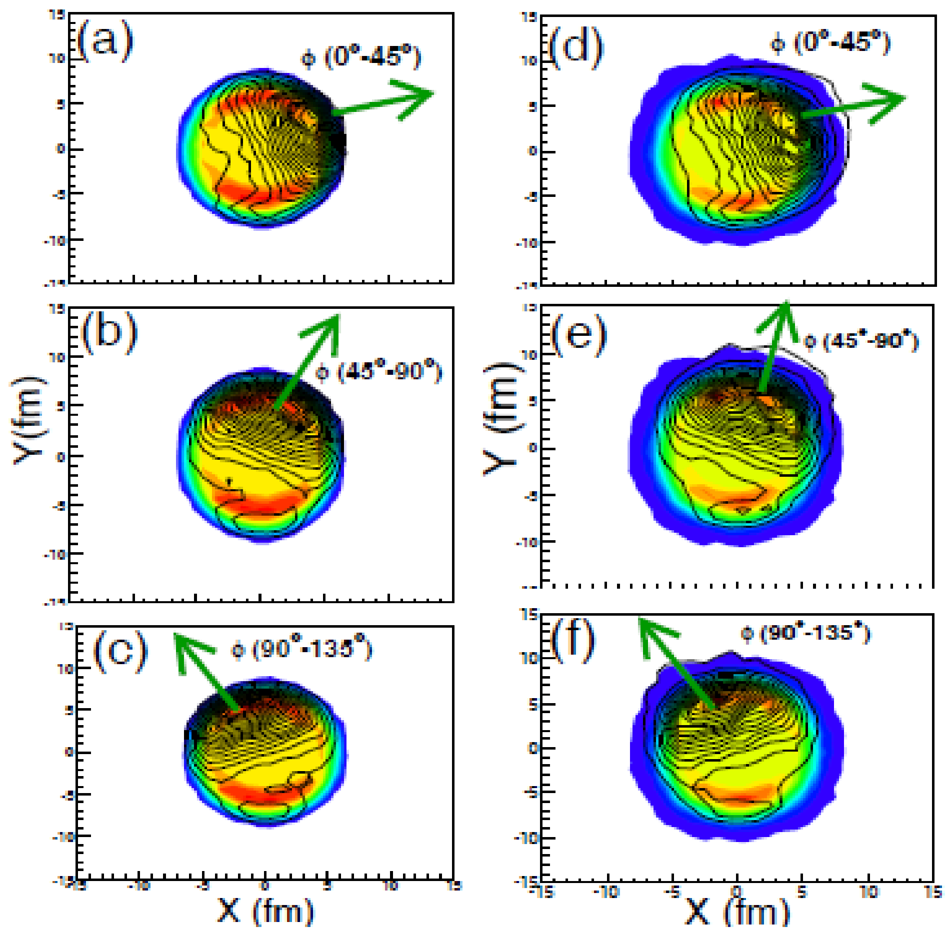
Correct v_3 and oscillation phases

L.V. Bravina, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, E.E. Zabrodin, Eur. Phys. J. A 53 (2017) 219.

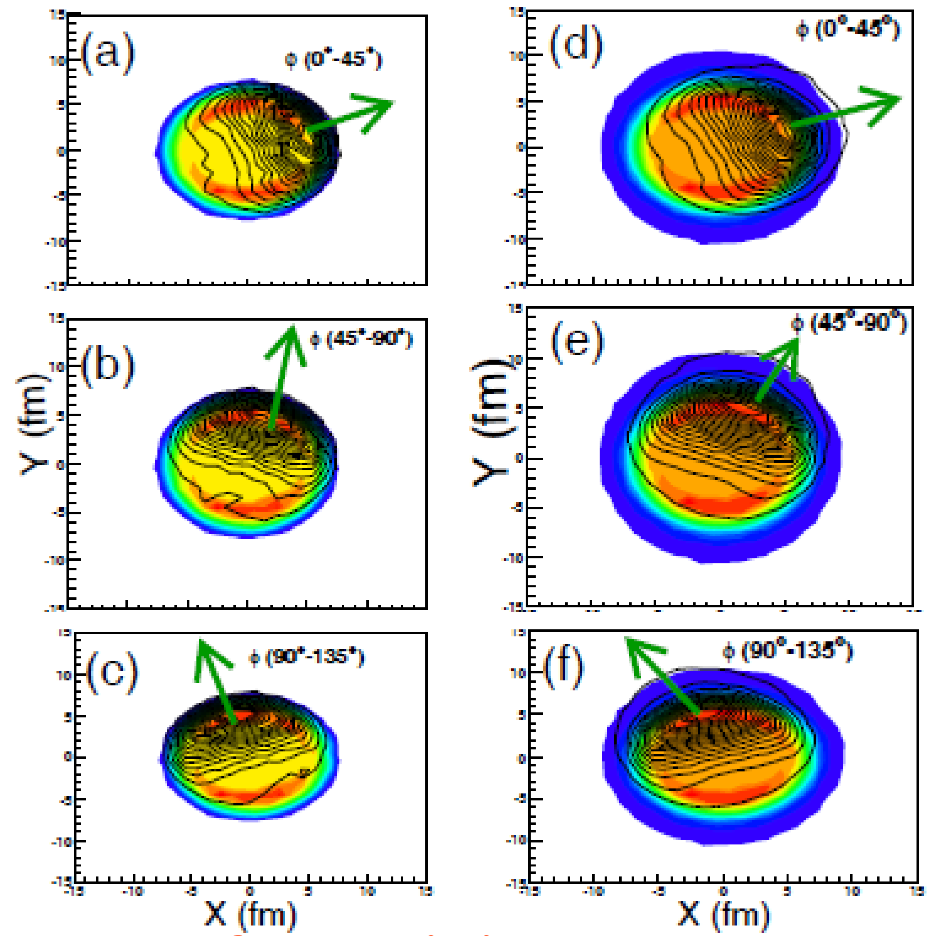
Pion emission function
Influence of resonance decays

ELLIPTIC anisotropy

Only SPATIAL anisotropy



Only DYNAMICAL anisotropy



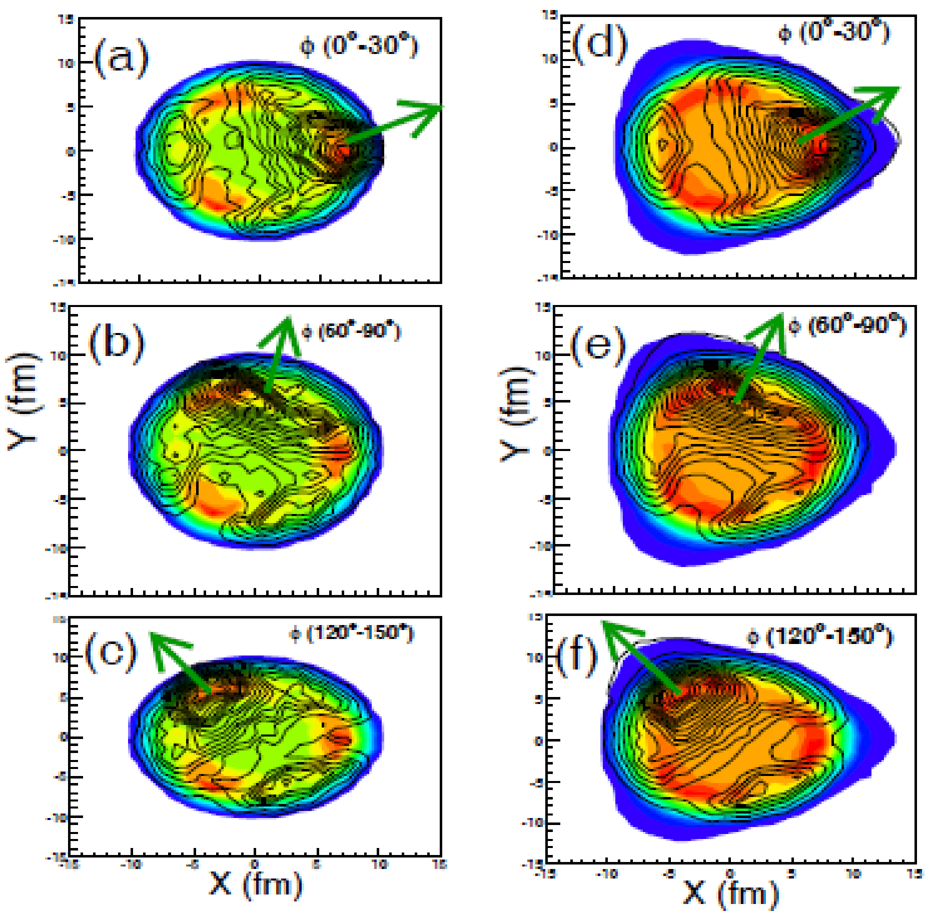
Decays of resonances provide significant increase of the emitting areas and make the radii oscillations but do not change the phases.

L.V. Bravina, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, E.E. Zabrodin, Eur. Phys. J. A 53 (2017) 219.

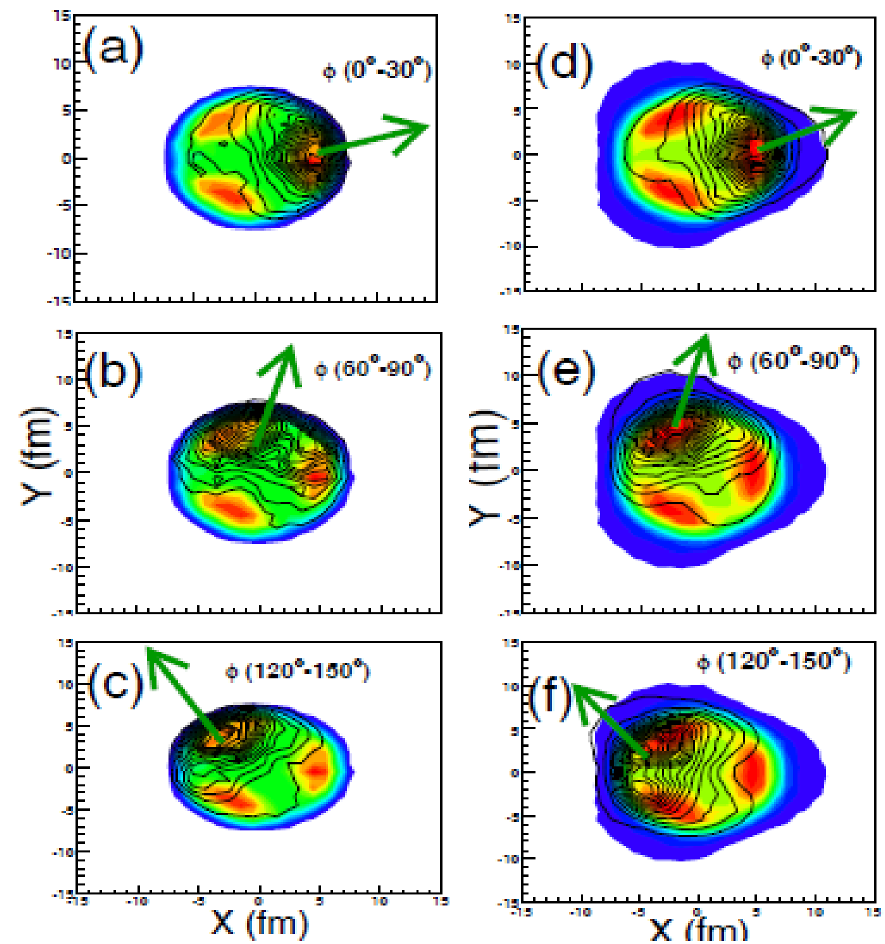
Pion emission function
Influence of resonance decays

TRIANGULAR anisotropy

Only SPATIAL anisotropy



Only DYNAMICAL anisotropy



Decays of resonances provide significant increase of the emitting areas and make the radii oscillations but do not change the phases.

L.V. Bravina, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, E.E. Zabrodin, Eur. Phys. J. A 53 (2017) 219.

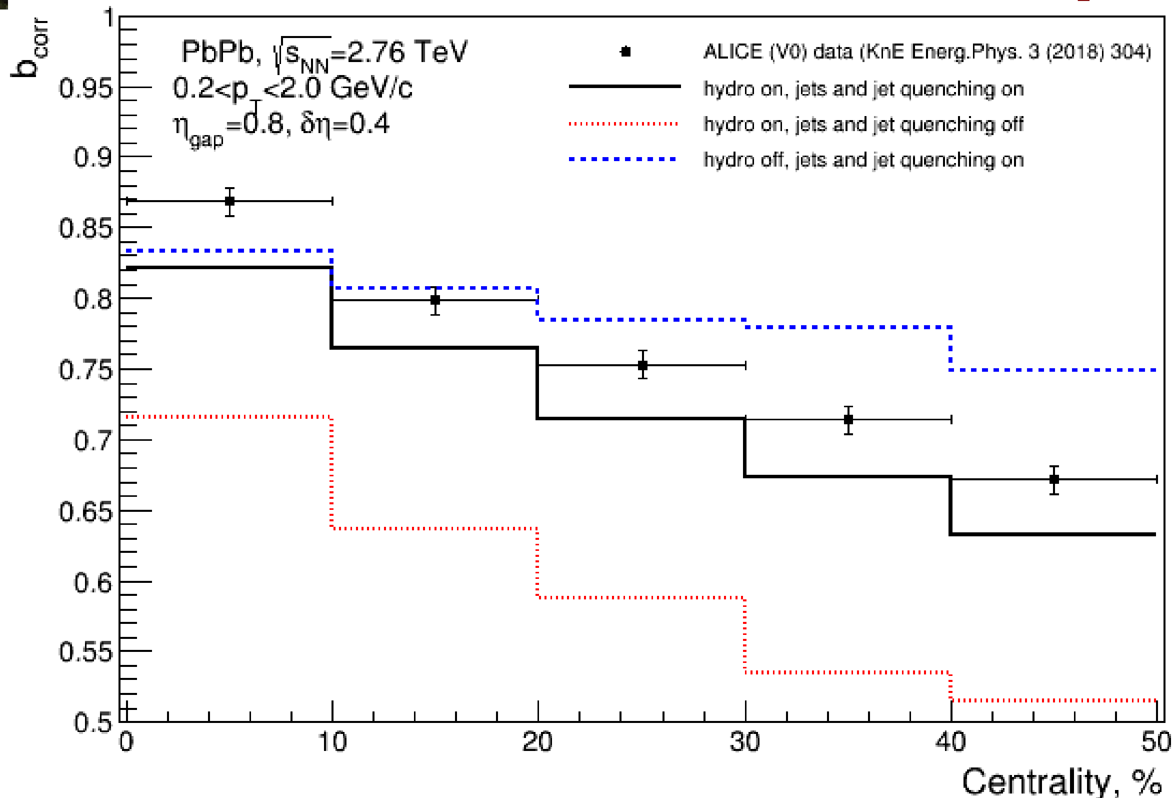
Dynamical vs. geometric anisotropy

- Elliptic or triangular spatial anisotropy alone cannot reproduce simultaneously the correct phase of the radii oscillations and the correct sign of the corresponding flow harmonics.
- Dynamical flow anisotropy provides correct **qualitative** description of both p_T-dependence of v_2 and v_3 and the phases of the femtoscopic radii oscillations.
- Decays of resonances provide significant increase of the emitting areas and make the radii oscillations more pronounced. However, they do not change the phases of the oscillations.

Both spatial and dynamical anisotropies are needed for the quantitative description of both signals.

L.V. Bravina, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, E.E. Zabrodin, Eur. Phys. J. A 53 (2017) 219.

Mechanisms of forward–backward (FB) correlations in the multiplicity of particles



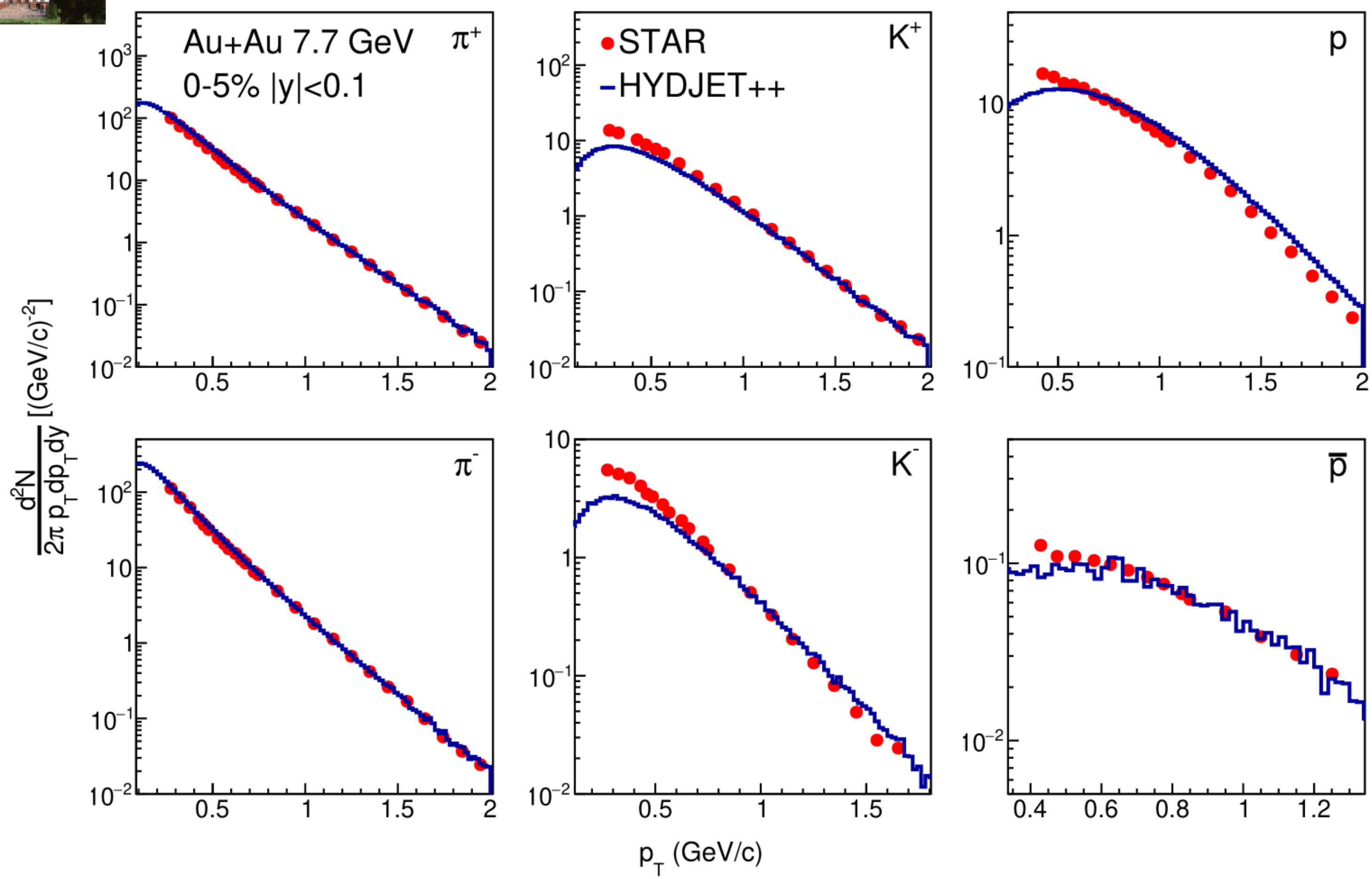
$$b_{corr} = \frac{\langle FB\rangle - \langle F\rangle\langle B\rangle}{\langle F^2\rangle - \langle F\rangle^2}$$

Points: ALICE data
KnE Energ.Phys. 3 (2018) 304
histograms: HYDJET++

HYDJET++ model reproduces quite well the experimentally observed dependence of the strength of FB correlations in the multiplicity of charged particles on the centrality. FB correlations for the hard jet component are stronger than those for the soft hydrodynamic components and, in the most central collisions, they are determined mainly by the hard component. However, both components should be taken into account simultaneously in order to reproduce the correct dependence of the strength of correlations on the centrality of nucleus–nucleus collisions.

E.E. Zabrodin, I.P. Lokhtin, A.A. Sidorova, A.S. Chernyshov.
Journal of Experimental and Theoretical Physics, 130(5) (2020) 660

Tuning of HYDJET++ for NICA energies



I.P. Lokhtin,
A.S. Chernyshov
work in progress

Points: STAR data
Phys. Rev. C 96 (2017) 044904
histograms: HYDJET++

HYDJET++ model reproduces quite well multiplicity and p_T spectrum of identified charged hadrons (pi, K, p) in central Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV (STAR data). We have started to use HYDJET++ for model analysis of some physical observables at NICA energies.

List of the main publications

- [1] G. Eyyubova, L. Bravina, V.L. Korotkih, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, E. Zabrodin, "Jets and decays of resonances: Two mechanisms responsible for reduction of elliptic flow at the CERN Large Hadron Collider (LHC) and restoration of constituent quark scaling", *Phys. Rev. C80 (2009) 064907*
- [2] E.E. Zabrodin, L.V. Bravina, G.Kh. Eyyubova, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, "Influence of jets and resonance decays on the constituent quark scaling of elliptic flow" , *J. Phys. G 37 (2010) 094060*
- [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*
- [7] L. V. Bravina, E.S. Fotina, V.L. Korotkikh, I.P. Lokhtin, L.V. Malinina, E.N. Nazarova, S.V. Petrushanko, A.M. Snigirev, E.E. Zabrodin, "Anisotropic flow fluctuations in hydro-inspired freeze-out model for relativistic heavy ion collisions", *Eur.Phys.J. C 75 (2015) 588*
- [8] I.P. Lokhtin, A.A. Alkin, A.M. Snigirev, "On jet structure in heavy ion collisions", *Eur.Phys. J. C 75 (2015) 452*
- [9] I.P. Lokhtin, A.V. Belyaev, G.Kh. Eyyubova, G. Ponimatkin, E. Pronina, "Charmed meson and charmonium production in PbPb collisions at the LHC", *J.Phys. G 43 (2016) 125104*
- [10] I.P. Lokhtin, A.V. Belyaev, G. Ponimatkin, E. Pronina, G.Kh. Eyyubova, "On the possibility of thermalization of heavy mesons in ultrarelativistic nuclear collisions", *J. Exp. Theor. Phys.* 124 (2017) 285
- [11] J. Crkovska, J. Bielcik, L. Bravina, B.H. Brusheim Johansson, E. Zabrodin, G. Eyyubova, V.L. Korotkikh, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, "Influence of jets and decays of resonances on the triangular flow in ultrarelativistic heavy-ion collisions", *Phys. Rev. C 95 (2017) 014910*
- [12] L.V. Bravina, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, E.E. Zabrodin, "Dynamical vs. geometric anisotropy in relativistic heavy-ion collisions: Which one prevails?, *Eur. Phys. J. A 53 (2017) 219.*
- [13] I.P. Lokhtin, A.A. Sidorova, "Mechanisms of B Meson Suppression in Ultrarelativistic Heavy Ion Collisions" *J. Exp. Theor. Phys. 128 (2019) 586*
- [14] E.E. Zabrodin, I.P. Lokhtin, A.A. Sidorova, A.S. Chernyshov. "Mechanisms of forward–backward correlations in the multiplicity of particles in ultrarelativistic heavy-ion collisions"*J. Exp. Theor. Phys. 130(5) (2020) 660*

SUMMARY

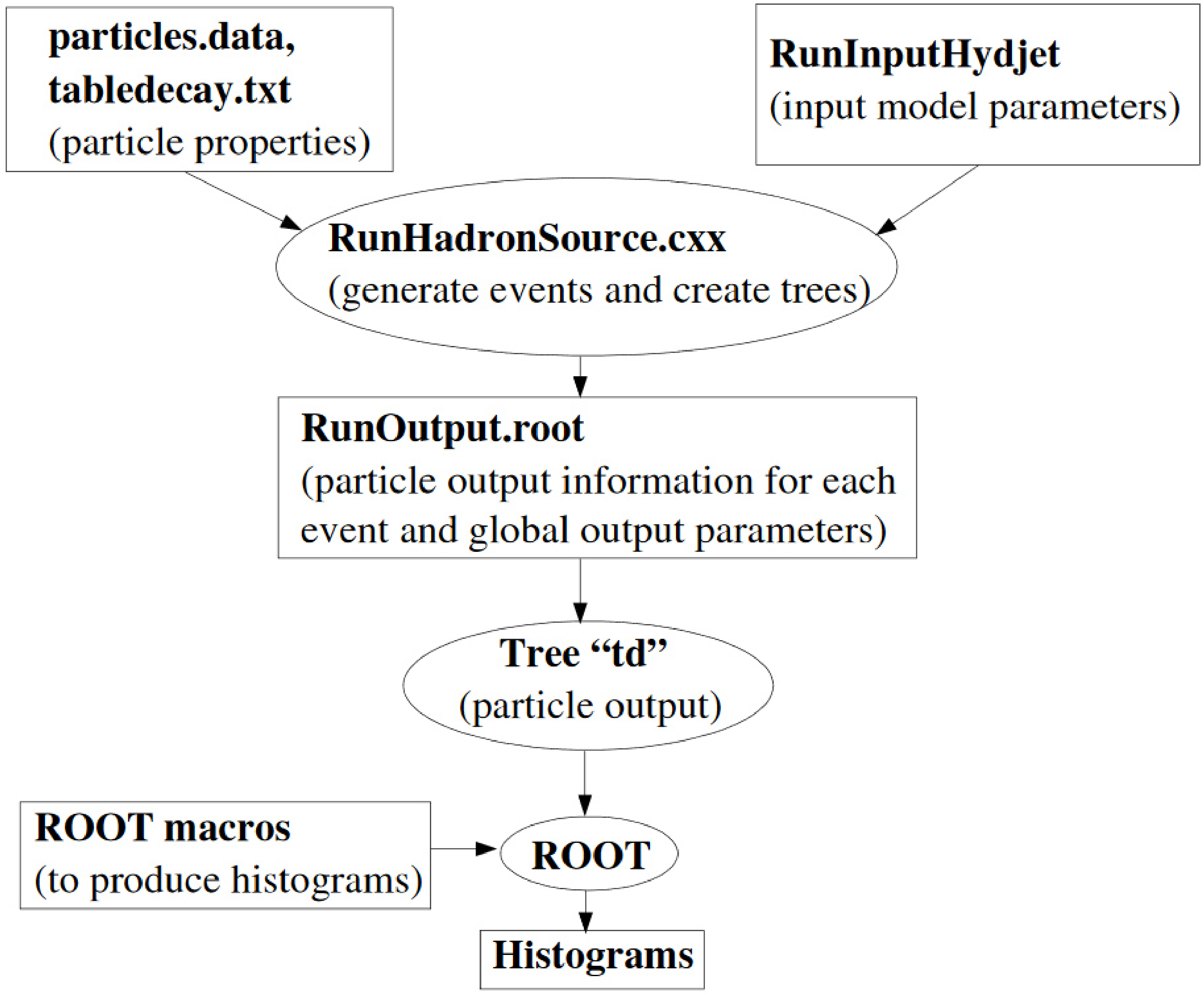
It has been **dozen years** since HYDJET++ Monte-Carlo event generator for the simulation of relativistic heavy ion collisions was developed. Now the generator is widely used for the simulation of nucleus-nucleus interactions from NICA to LHC energies. The model calculations on soft and hard probes of quark-gluon plasma (including collective flow, different kinds of particle correlations, jets, D and B mesons, etc.) agree well with the experimental data.

THANK YOU!

СПАСИБО!

BACK UP

The Block Structure of HYDJET++



HYDJET++ (soft): input parameters

1-5. Thermodynamic parameters at chemical freeze-out: T^{ch}, $\{\mu_B, \mu_S, \mu_C, \mu_Q\}$ (option to calculate T^{ch}, μ_B and μ_s using phenomenological parameterization $\mu_B(\sqrt{s})$, $T^{ch}(\mu_B)$ is foreseen).
6-7. Strangeness suppression factor $\gamma_S \leq 1$ and charm enchancement factor $\gamma_c \geq 1$ (options to use phenomenological parameterization $\gamma_S(T^{ch}, \mu_B)$ and to calculate γ_c are foreseen).
8-9. Thermodynamical parameters at thermal freeze-out: T^{th}, and μ_π- effective chemical potential of positively charged pions.
10-12. Volume parameters at thermal freeze-out: proper time τ_f, its standard deviation (emission duration) $\Delta\tau_f$, maximal transverse radius R_f.
13. Maximal transverse flow rapidity at thermal freeze-out ρ_u^{max}.
14. Maximal longitudinal flow rapidity at thermal freeze-out η^{max}.
15. Flow anisotropy parameter: $\delta(b) \rightarrow u^\mu = u^\mu(\delta(b),\varphi)$
16. Coordinate anisotropy:
$\varepsilon(b) \rightarrow R_f(b)=R_f(0)[V_{eff}(\varepsilon(0),\delta(0))/V_{eff}(\varepsilon(b),\delta(b))]^{1/2}[N_{part}(b)/N_{part}(0)]^{1/3}$

For impact parameter range bmin-bmax:
$V_{eff}(b)=V_{eff}(0)N_{part}(b)/N_{part}(0)$, $\tau_f(b)=\tau_f(0)[N_{part}(b)/N_{part}(0)]^{1/3}$

Monte-Carlo simulation of hard component (including nuclear shadowing) in HYDJET/HYDJET++

- Calculating the number of hard NN sub-collisions Njet (b, Ptmin, √s) with Pt>Ptmin around its mean value according to the binomial distribution.
- Selecting the type (for each of Njet) of hard NN sub-collisions (pp, np or nn) depending on number of protons (Z) and neutrons (A-Z) in nucleus A according to the formula: $Z=A/(1.98+0.015A^{2/3})$.
- Generating the hard component by calling PYQUEN njet times.
- Correcting the PDF in nucleus by the accepting/rejecting procedure for each of Njet hard NN sub-collisions: comparision of random number generated uniformly in the interval [0,1] with shadowing factor $S(r1,r2,x1,x2,Q2) \le 1$ taken from the adapted impact parameter dependent parameterization based on Glauber-Gribov theory (*K.Tywoniuk et al., Phys. Lett. B 657 (2007) 170)*.

HYDJET++ (soft): main physics assumptions

A hydrodynamic expansion of the fireball is supposed ends by a sudden system breakup at given T and chemical potentials. Momentum distribution of produced hadrons keeps the thermal character of the equilibrium distribution.

Cooper-Frye formula: $$p^0 \frac{d^3 N_i}{d^3 p} = \int_{\sigma(x)} d^3\sigma_\mu(x) p^\mu f_i^{eq}(p^\nu u_\mu(x); T, \mu_i)$$

HYDJET++ avoids straightforward 6-dimensional integration by using the special simulation procedure (like HYDJET): momentum generation in the rest frame of fluid element, then Lorentz transformation in the global frame → uniform weights → effective von-Neumann rejection-acception procedure.

Freeze-out surface parameterizations

1. The Bjorken model with hypersurface $\tau = (t^2 - z^2)^{1/2} = const$
2. Linear transverse flow rapidity profile $\rho_u = \frac{r}{R} \rho_u^{\max}$
3. The total effective volume for particle production at

$$V_{eff} = \int_{\sigma(x)} d^3\sigma_\mu(x) u^\mu(x) = \tau \int_0^R \gamma_r r dr \int_0^{2\pi} d\phi \int_{\eta_{\min}}^{\eta_{\max}} d\eta = 2\pi\tau\Delta\eta \left(\frac{R}{\rho_u^{\max}} \right)^2 (\rho_u^{\max} \sinh \rho_u^{\max} - \cosh \rho_u^{\max} + 1)$$

HYDJET++ (soft): hadron multiplicities

1. The hadronic matter created in heavy-ion collisions is considered as a hydrodynamically expanding fireball with EOS of an ideal hadron gas.

2. "Concept of effective volume" T=const and μ=const: the total yield of particle species is

$$N_i = \rho_i(T,\mu_i)V_{eff}$$

3. Chemical freeze-out : $T, \mu_i = \mu_B B_i + \mu_S S_i + \mu_c C_i + \mu_Q Q_i$; T, μ_B –can be fixed by particle ratios, or by phenomenological formulas

$$T(\mu_B) = a - b\mu_B - c\mu_B^4; \mu_B(\sqrt{s_{NN}}) = \frac{d}{1+e\sqrt{s_{NN}}}$$

4. Chemical freeze-out: all macroscopic characteristics of particle system are determined via a set of equilibrium distribution functions in the fluid element rest frame:

$$f_i^{eq}(p^{0*};T,\mu_i) = \frac{1}{(2\pi)^3}\frac{g_i}{\exp([p^{0*}-\mu_i]/T)\pm 1}$$

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

HYDJET++ (soft): thermal and chemical freeze-outs

1. The particle densities at the chemical freeze-out stage are too high to consider particles as free streaming and to associate this stage with the thermal freeze-out

2. Within the concept of chemically frozen evolution, assumption of the conservation of the particle number ratios from the chemical to thermal freeze-out :

$$\frac{\rho_i^{eq}(T^{ch},\mu_i^{ch})}{\rho_\pi^{eq}(T^{ch},\mu_\pi^{ch})}=\frac{\rho_i^{eq}(T^{th},\mu_i^{th})}{\rho_\pi^{eq}(T^{th},\mu_\pi^{th})}$$

3. The absolute values $\rho_i^{eq}(T^{th},\mu_i^{th})$ are determined by the choice of the free parameter of the model: effective pion chemical potential $\mu_\pi^{eff,th}$ at T^{th}
Assuming for the other particles (heavier then pions) the Botzmann approximation:

$$\mu_i^{th}=T^{th}\ln\left(\frac{\rho_i^{eq}(T^{ch},\mu_i^{ch})}{\rho_i^{eq}(T^{th},\mu_i=0)}\frac{\rho_\pi^{eq}(T^{th},\mu_\pi^{eff,th})}{\rho_\pi^{eq}(T^{ch},\mu_i^{ch})}\right)$$

Particle momentum spectra are generated on the thermal freeze-out hypersurface, the hadronic composition at this stage is defined by the parameters of the system at chemical freeze-out.

PYQUEN: Physics Frames

General kinetic integral equation:

$$\Delta E(L,E)=\int_0^L dx \frac{dP}{dx}(x)\lambda(x)\frac{dE}{dx}(x,E), \quad \frac{dP}{dx}(x)=\frac{1}{\lambda(x)}\exp(-x/\lambda(x))$$

1. Collisional loss and elastic scattering cross section:

$$\frac{dE}{dx}=\frac{1}{4T\lambda\sigma}\int_{\mu_D^2}^{t_{max}} dt\frac{d\sigma}{dt}t, \quad \frac{d\sigma}{dt}\simeq C\frac{2\pi\alpha_s^2(t)}{t^2}, \quad \alpha_S=\frac{12\pi}{(33-2N_f)\ln(t/\Lambda_{QCD}^2)}, \quad C=9/4(gg), 1(gq), 4/9(qq)$$

2. Radiative loss (BDMPS):

$$\frac{dE}{dx}(m_q=0)=\frac{2\alpha_s C_F}{\pi\tau_L}\int_{E_{LPM}\sim\lambda_g\mu_D^2}^{E} d\omega\left[1-y+\frac{y^2}{2}\right]\ln\left|\cos(\omega_1\tau_1)\right|, \quad \omega_1=\sqrt{i\left(1-y+\frac{C_F}{3}y^2\right)\bar{k}\ln\frac{16}{\bar{k}}}, \quad \bar{k}=\frac{\mu_D^2\lambda_g}{\omega(1-y)}, \quad \tau_1=\frac{\tau_L}{2\lambda_g}, \quad y=\frac{\omega}{E}, \quad C_F=\frac{4}{3}$$

“dead cone” approximation for massive quarks:

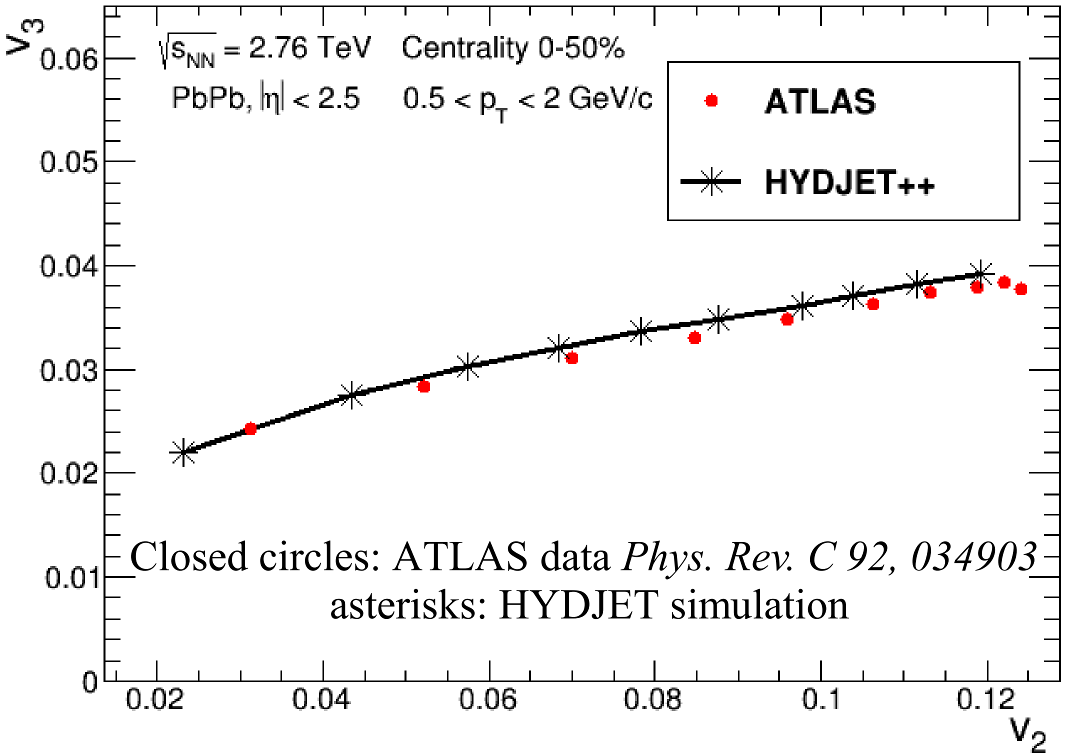
$$\frac{dE}{dx}(m_q\neq 0)=\frac{1}{\left(1+(l\omega)^{3/2}\right)^2}\frac{dE}{dx}(m_q=0), \qquad l=\left(\frac{\lambda}{\mu_D^2}\right)^{1/3}\left(\frac{m_q}{E}\right)^{4/3}$$

Monte-Carlo simulation of hard component (including nuclear shadowing) in HYDJET/HYDJET++

- Calculating the number of hard NN sub-collisions Njet (b, Ptmin, √s) with Pt>Ptmin around its mean value according to the binomial distribution.
- Selecting the type (for each of Njet) of hard NN sub-collisions (pp, np or nn) depending on number of protons (Z) and neutrons (A-Z) in nucleus A according to the formula: $Z=A/(1.98+0.015A^{2/3})$.
- Generating the hard component by calling PYQUEN njet times.
- Correcting the PDF in nucleus by the accepting/rejecting procedure for each of Njet hard NN sub-collisions: comparision of random number generated uniformly in the interval [0,1] with shadowing factor $S(r1,r2,x1,x2,Q2) \leq 1$ taken from the adapted impact parameter dependent parameterization based on Glauber-Gribov theory (*K.Tywoniuk et al.,, Phys. Lett. B 657 (2007) 170*).

Correlation between elliptic and triangular flows and fluctuations

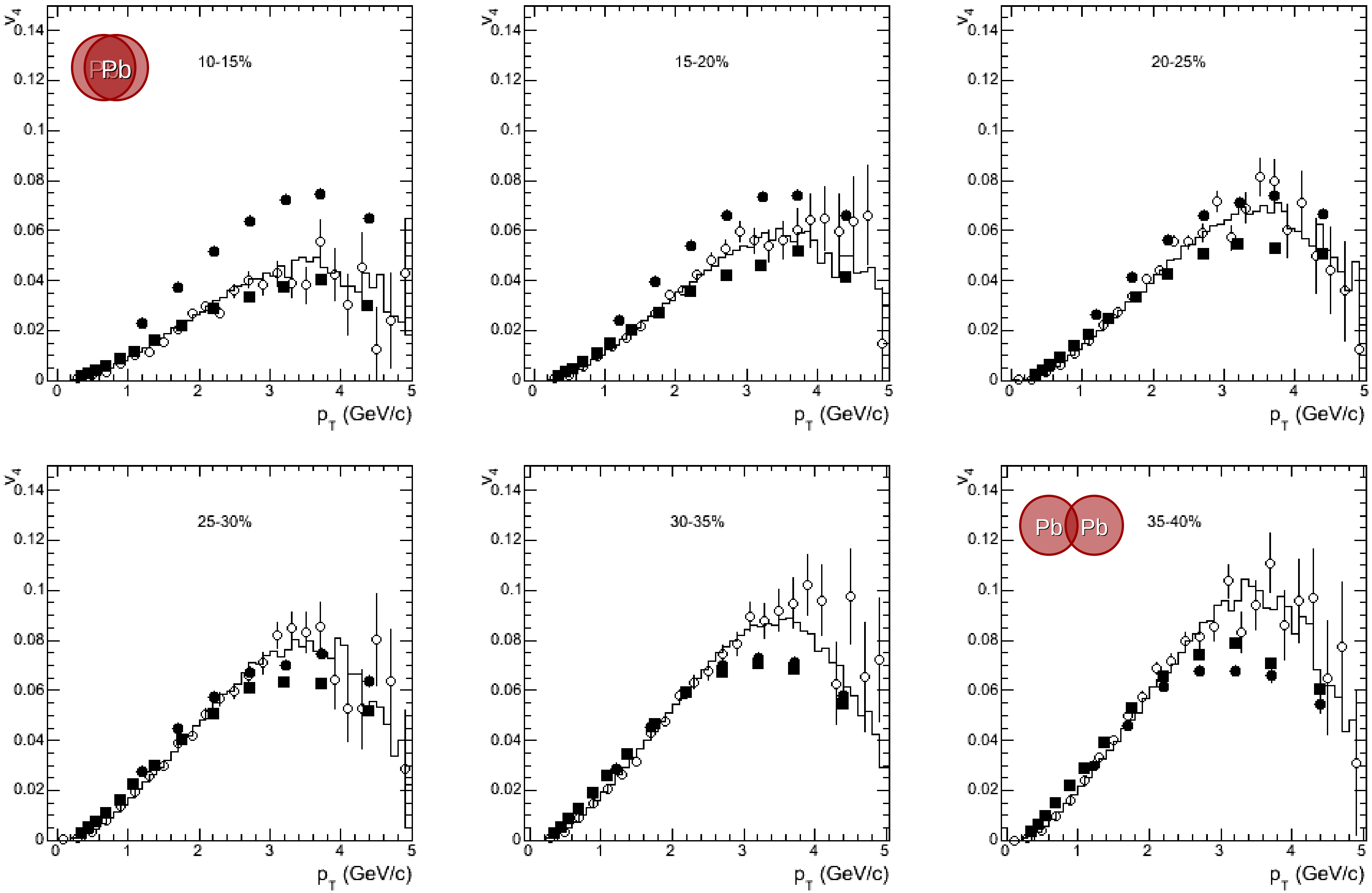
L. V. Bravina, E. S. Fotina, V. L. Korotkikh, I. P. Lokhtin, L. V. Malinina, E. N. Nazarova, S. V. Petrushanko, A. M. Snigirev, E. E. Zabrodin, Eur.Phys.J. C 75 (2015) 588



HYDJET++ reproduces the correlation between elliptic and triangular flows.

Quadrangular flow in HYDJET++ vs. LHC data

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, Eur.Phys.J. C (2014) 74:2807

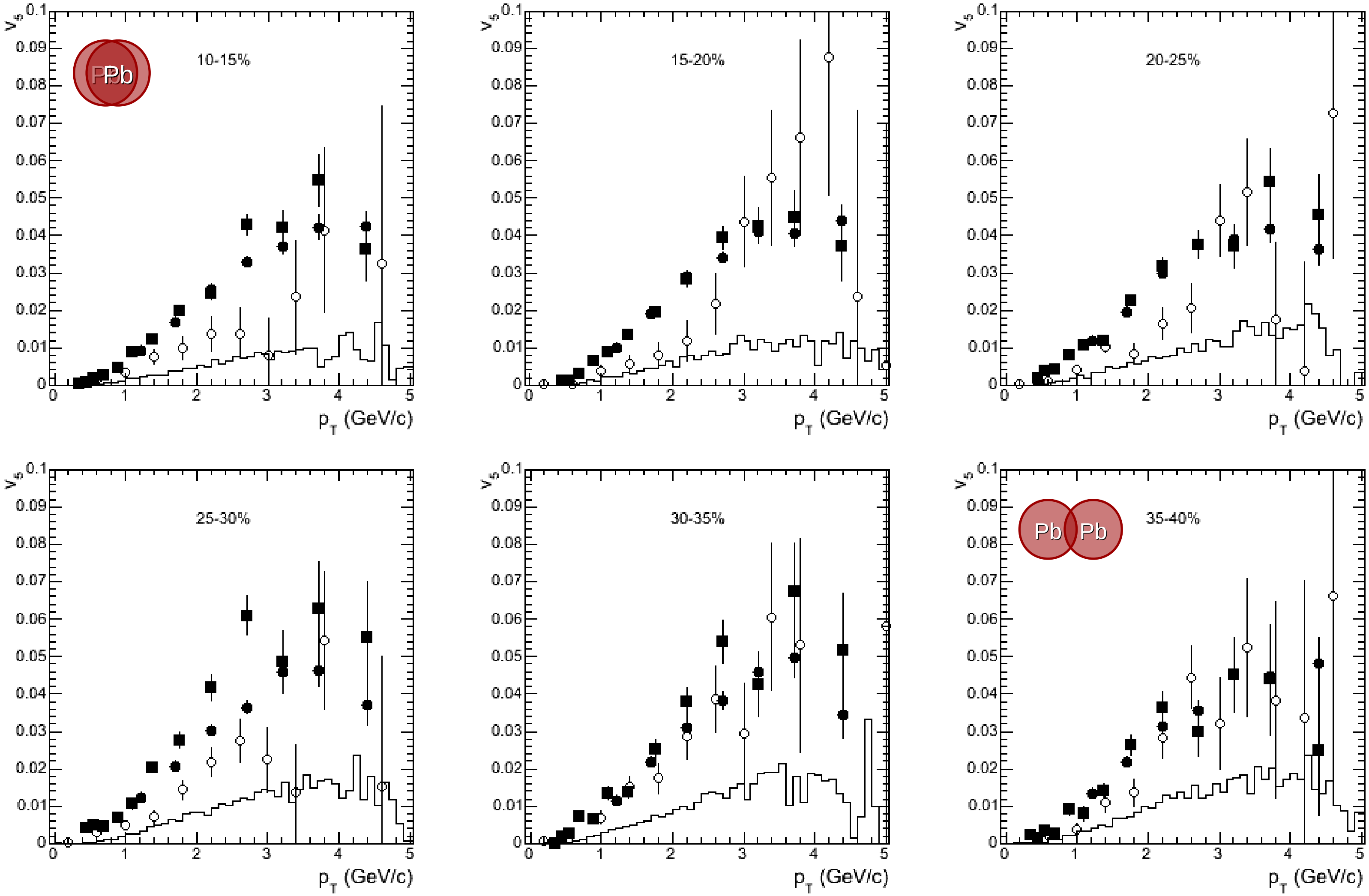


Closed circles and squares: CMS data $v_4\{2\}$ & $v_4\{LYZ\}$ *PRC 89 (2014) 044906*

histograms and open circles: HYDJET++ “true” $v_4(\psi_2)$ and $v_4\{EP\}$

Pentagonal flow in HYDJET++ vs. LHC data

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, Eur.Phys.J. C (2014) 74:2807

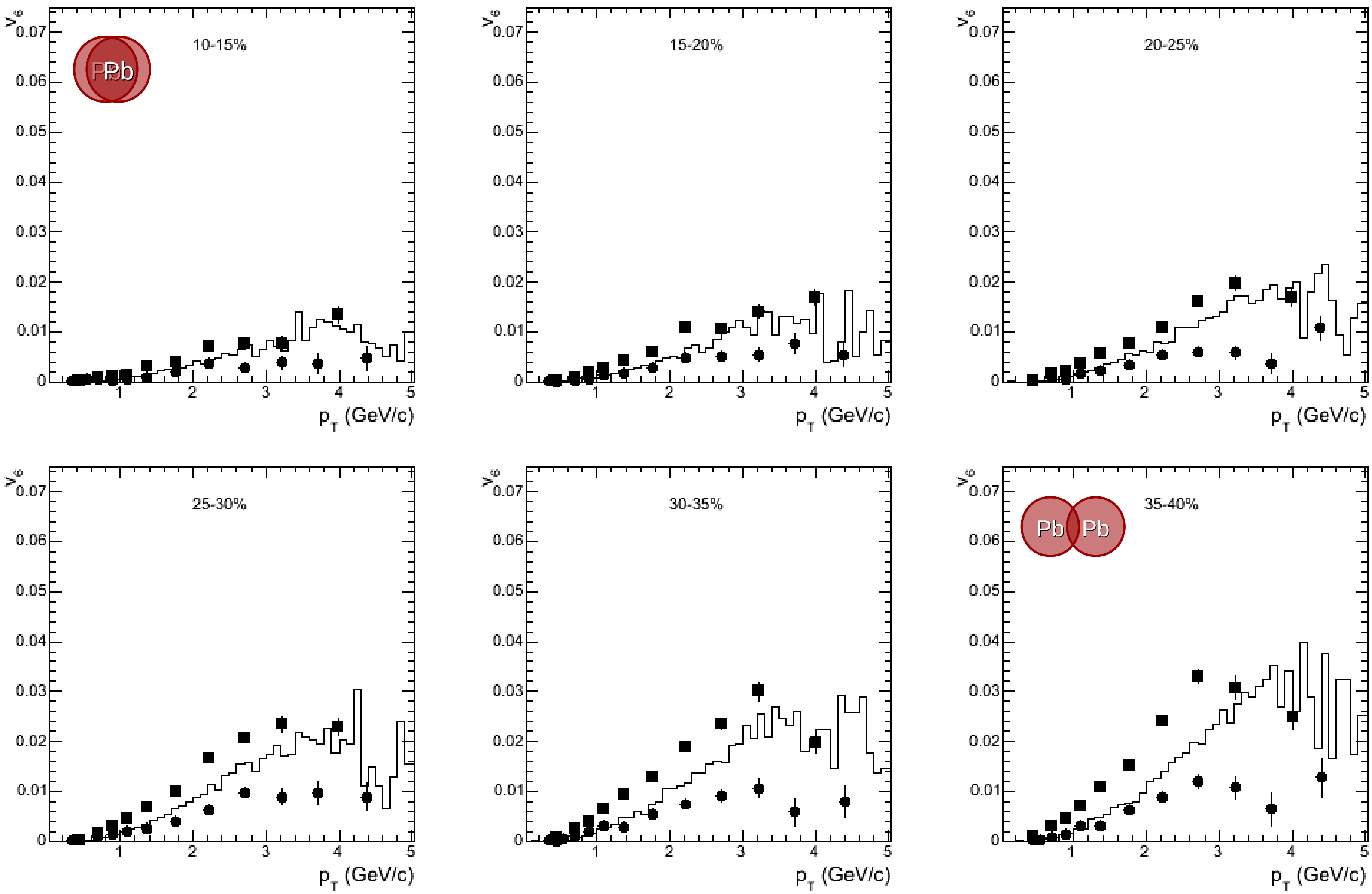


Closed circles and squares: CMS data $v_5\{2\}$ & $v_5\{EP\}$ *PRC 89 (2014) 044906*

histograms and open circles: HYDJET++ “true” $v_5(\psi_3)$ and $v_5\{EP\}$

Hexagonal flow in HYDJET++ vs. LHC data

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, Eur.Phys.J. C (2014) 74:2807

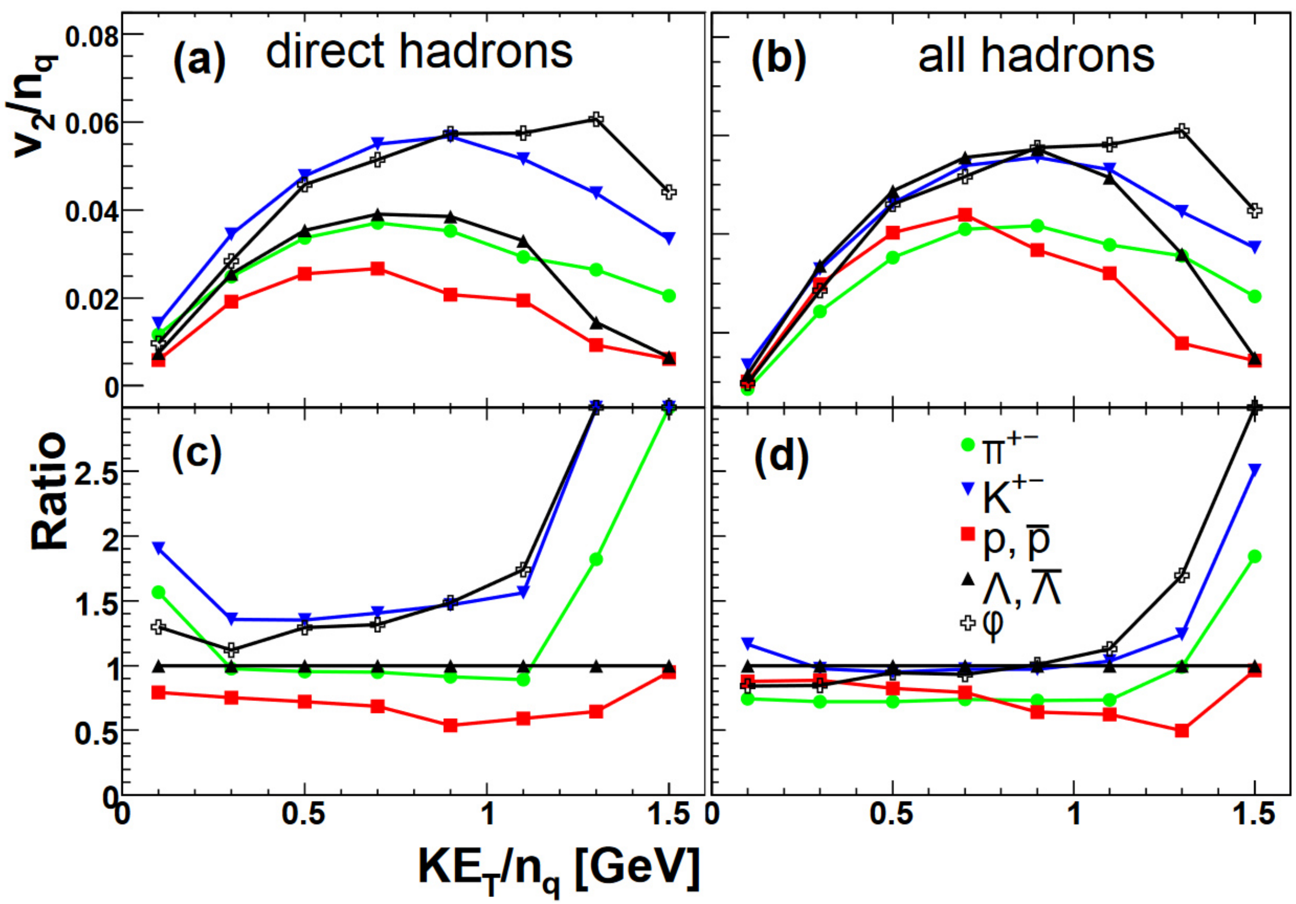


Closed circles and squares: CMS data $v_6\{2\}$ & $v_6\{LYZ\}$ *PRC 89 (2014) 044906*

histograms and open circles: HYDJET++ “true” $v_6(\psi_2)$

Number of constituent quark scaling v_2

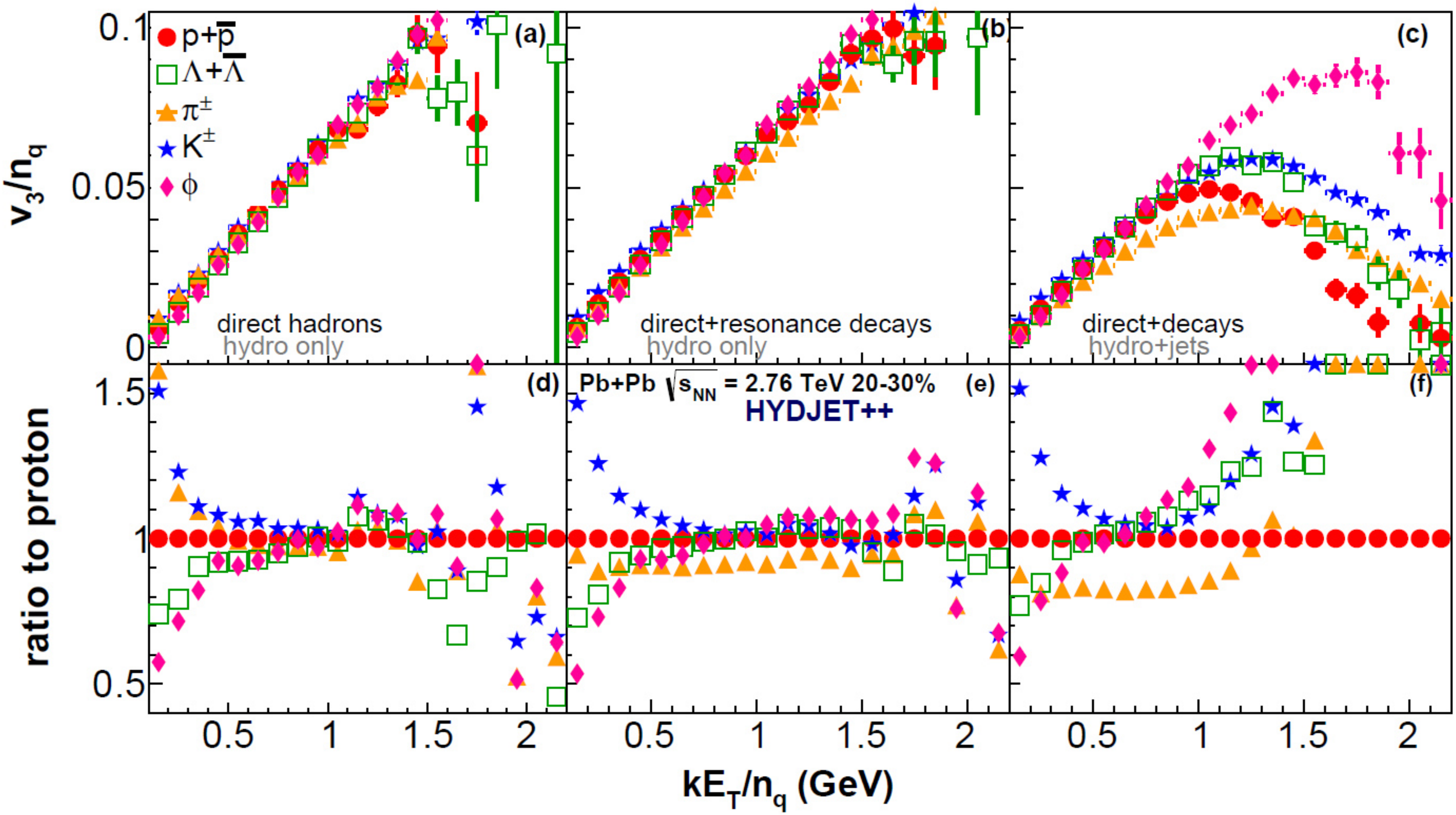
G. Kh. Eyyubova, L. V. Bravina, E. E. Zabrodin,.V. L. Korotkikh, I. P. Lokhtin, L. V. Malinina, S. V. Petrushanko, A. M. Snigirev, Phys. Rev. C 80 (2009) 064907



Resonance decay kinematics works towards the scaling (prediction 2009 for LHC).

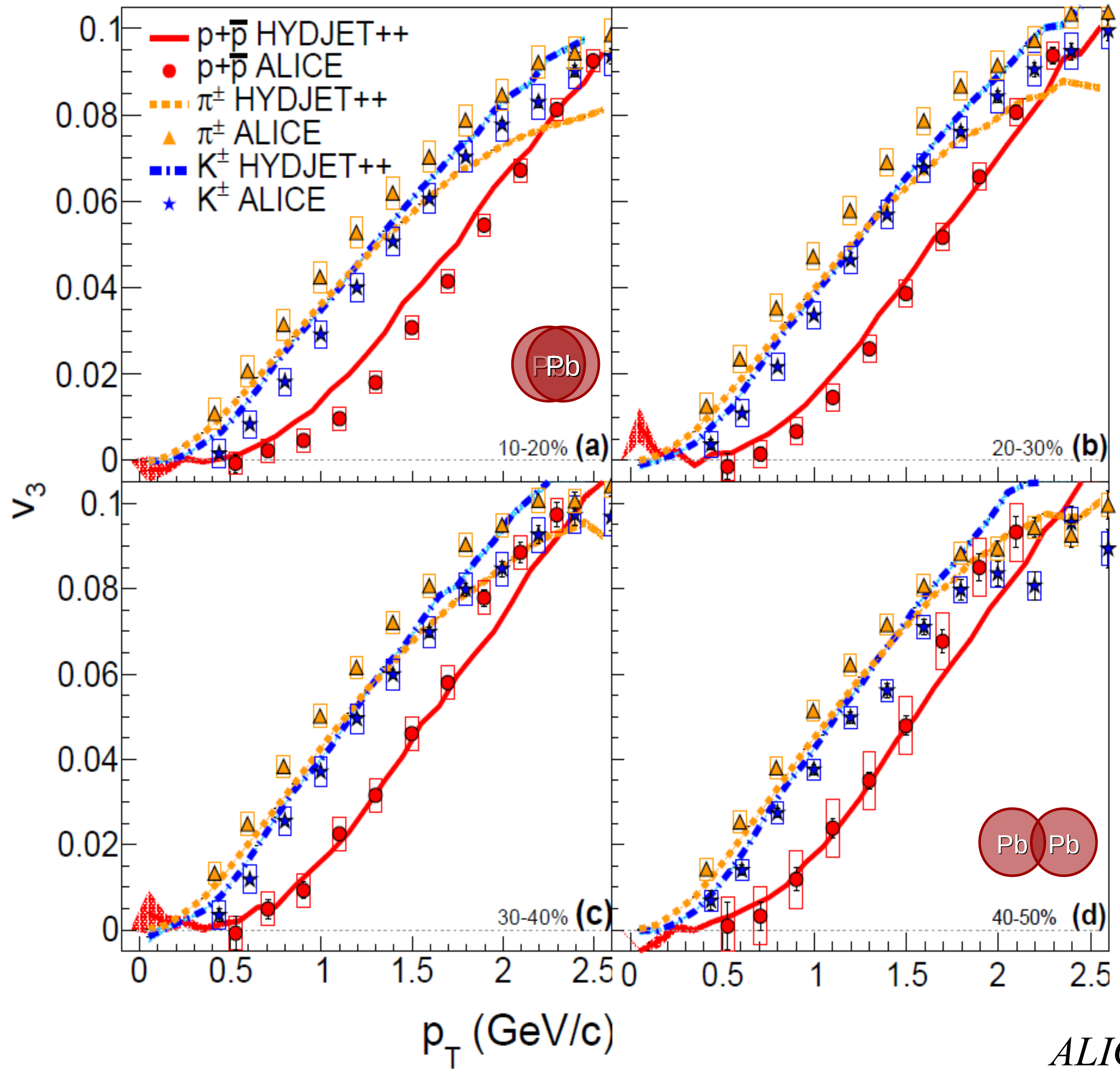
Number of constituent quark scaling v_3

J. Crkovska, J. Bielcik, L. Bravina, B.H. Brusheim Johansson, E. Zabrodin, G. Eyyubova, V.L. Korotkikh, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, arXiv:1603.09621



v_3 in HYDJET++ vs. ALICE

J. Crkovska, J. Bielcik, L. Bravina, B.H. Brusheim Johansson, E. Zabrodin, G. Eyyubova, V.L. Korotkikh, I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, arXiv:1603.09621

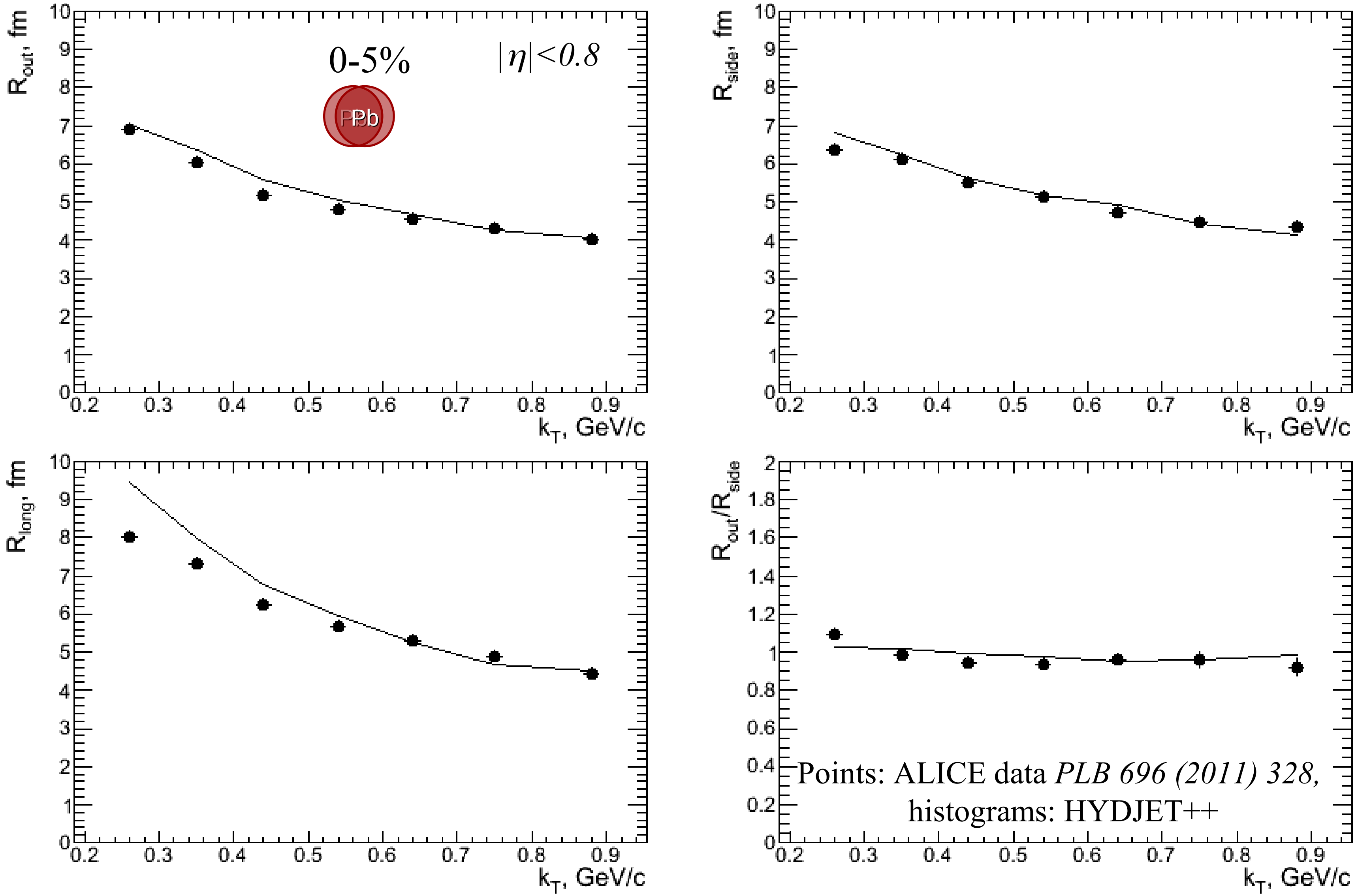


ALICE: arXiv:1606.06057

Femtoscopic momentum correlations (pion pairs)

$$CF=1+\lambda \exp(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2 - 2R_{ol}^2 q_o q_l)$$

I.P. Lokhtin, A.V. Belyaev, L.V. Malinina, S.V. Petrushanko, E.P. Rogochaya, A.M. Snigirev, Eur.Phys.J. C (2012) 72:2045



Charm production in HYDJET++

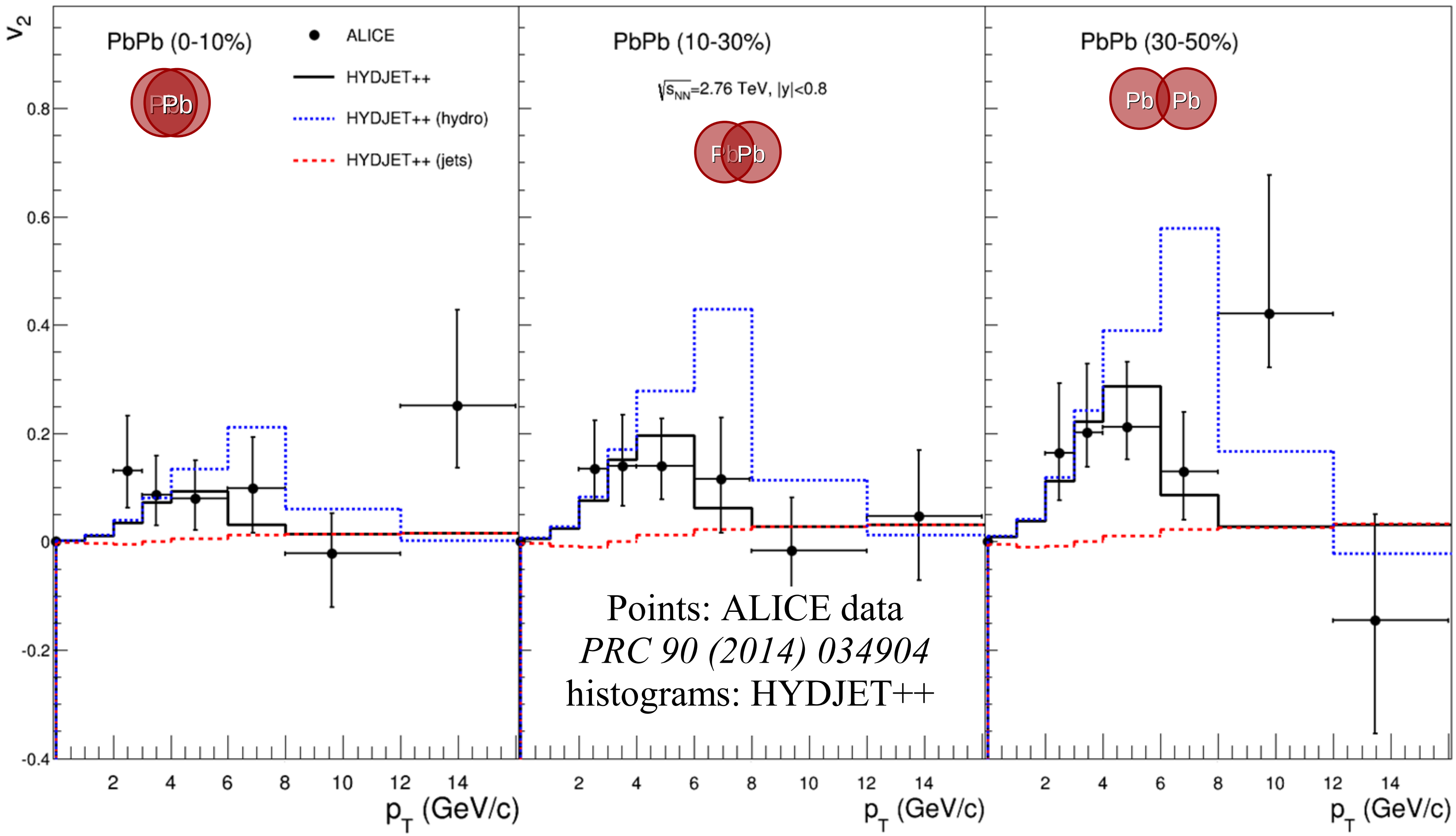
I.P. Lokhtin, A.V. Belyaev, G.Kh. Eyyubova, G. Ponimatkin, E. Pronina, arXiv:1601.00799

The most important parameters for our current consideration are the chemical and thermal freeze-out temperatures, $T_{\rm ch} = 165$ MeV and $T_{\rm th} = 105$ MeV, maximal longitudinal and transverse flow rapidities, $Y_{\rm L}^{\rm max} = 4.5$ and $Y_{\rm T}^{\rm max} = 1.265$, minimal transverse momentum transfer of initial hard scatterings $p_{\rm T}^{\rm min} = 8.2$ GeV/c, and initial maximal temperature of quark-gluon fluid $T_0^{\rm max} = 1$ GeV.

two sets of input parameters: *1)* as for inclusive hadrons (listed above), and *2)* for early thermal freeze-out ($T_{\rm ch} = T_{\rm th} = 165$ MeV, $Y_{\rm L}^{\rm max} = 2.3$, $Y_{\rm T}^{\rm max} = 0.6$, $p_{\rm T}^{\rm min} = 3.0$ GeV/c). The fugacity value $\gamma_{\rm c} = 11.5$ was fixed from absolute J/ψ yields.

Elliptic flow of D-mesons

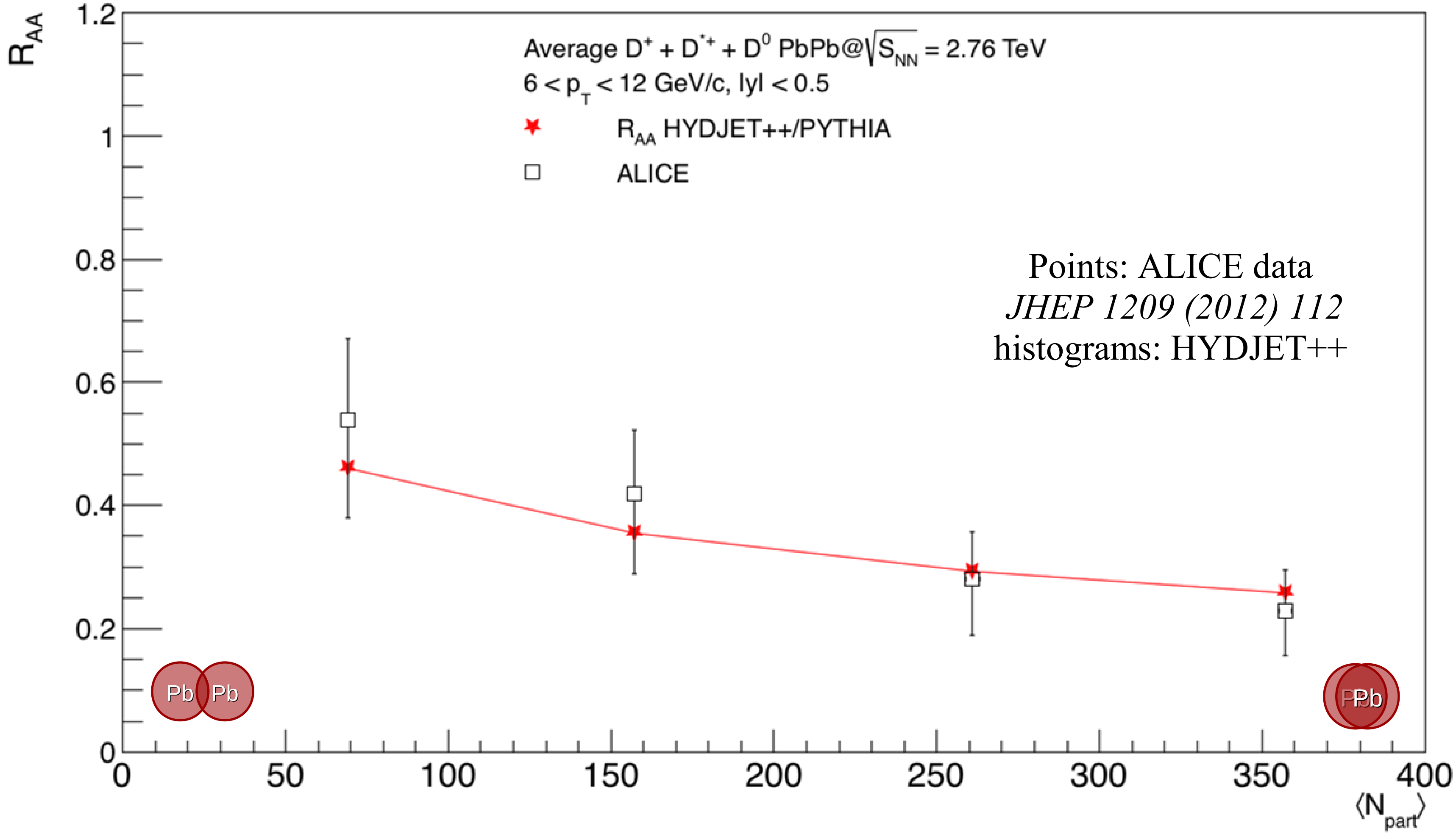
I.P. Lokhtin, A.V. Belyaev, G.Kh. Eyyubova, G. Ponimatkin, E. Pronina, J.Phys. G 43 (2016) 125104



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

D mesons, nuclear modification factor RAA

I.P. Lokhtin, A.V. Belyaev, G.Kh. Eyyubova, G. Ponimatkin, E. Pronina, arXiv:1601.00799



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

Angular structure of energy loss in PYQUEN

Radiative loss, three options (simple parametrizations) for angular distribution of in-medium emitted gluons:

Collinear radiation $\theta = 0$

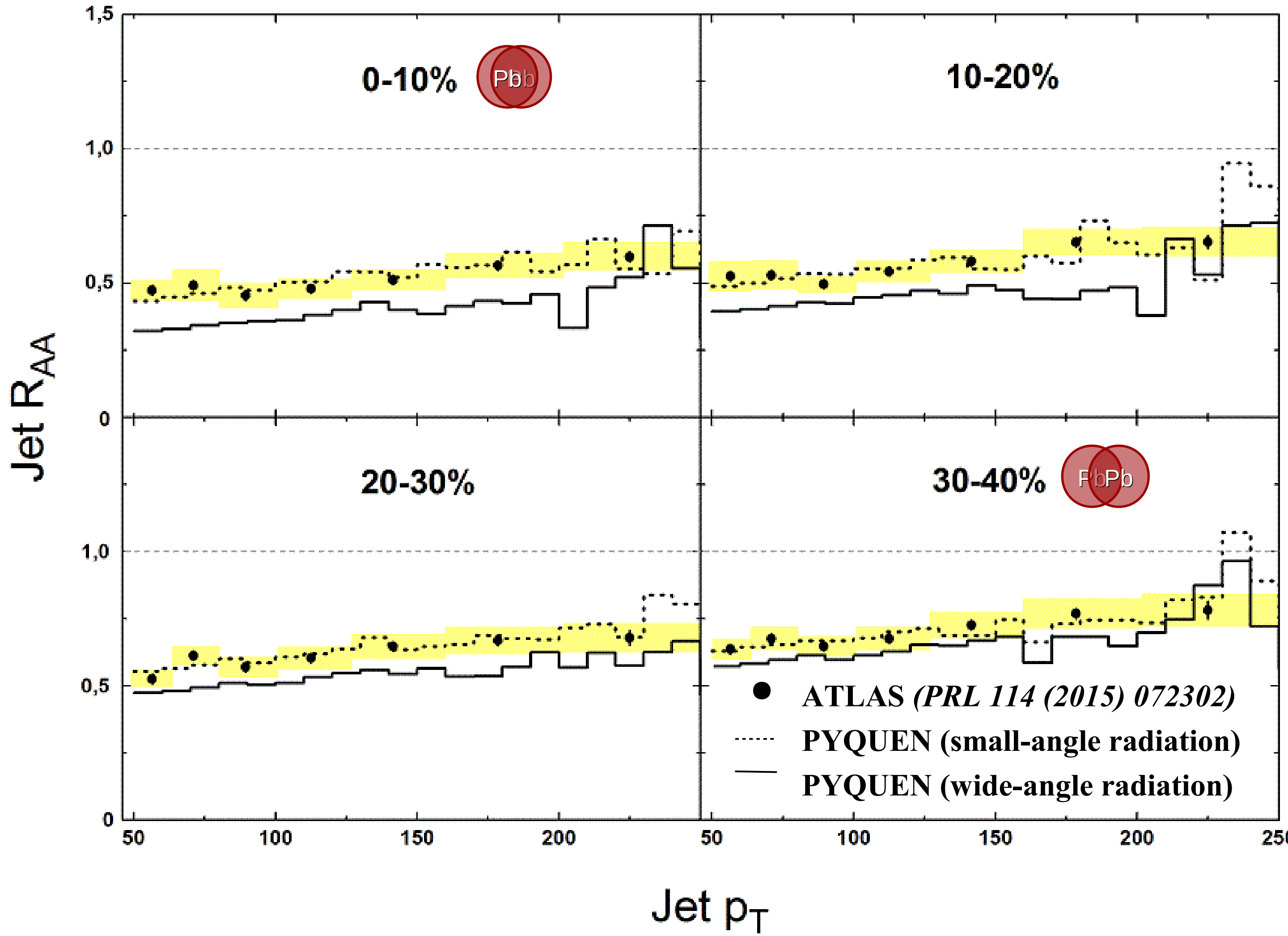
Small-angular radiation $\frac{dN^g}{d\theta} \propto \sin\theta \exp\left(\frac{-(\theta-\theta_0)^2}{2\theta_0^2}\right), \quad \theta_0 \sim 5^o$

Wide-angular radiation $\frac{dN^g}{d\theta} \propto \frac{1}{\theta}$

Collisional loss always "out-of-cone" (energy is absorbed by medium)

Suppression factor of inclusive jets vs. p_T in ATLAS and PYQUEN

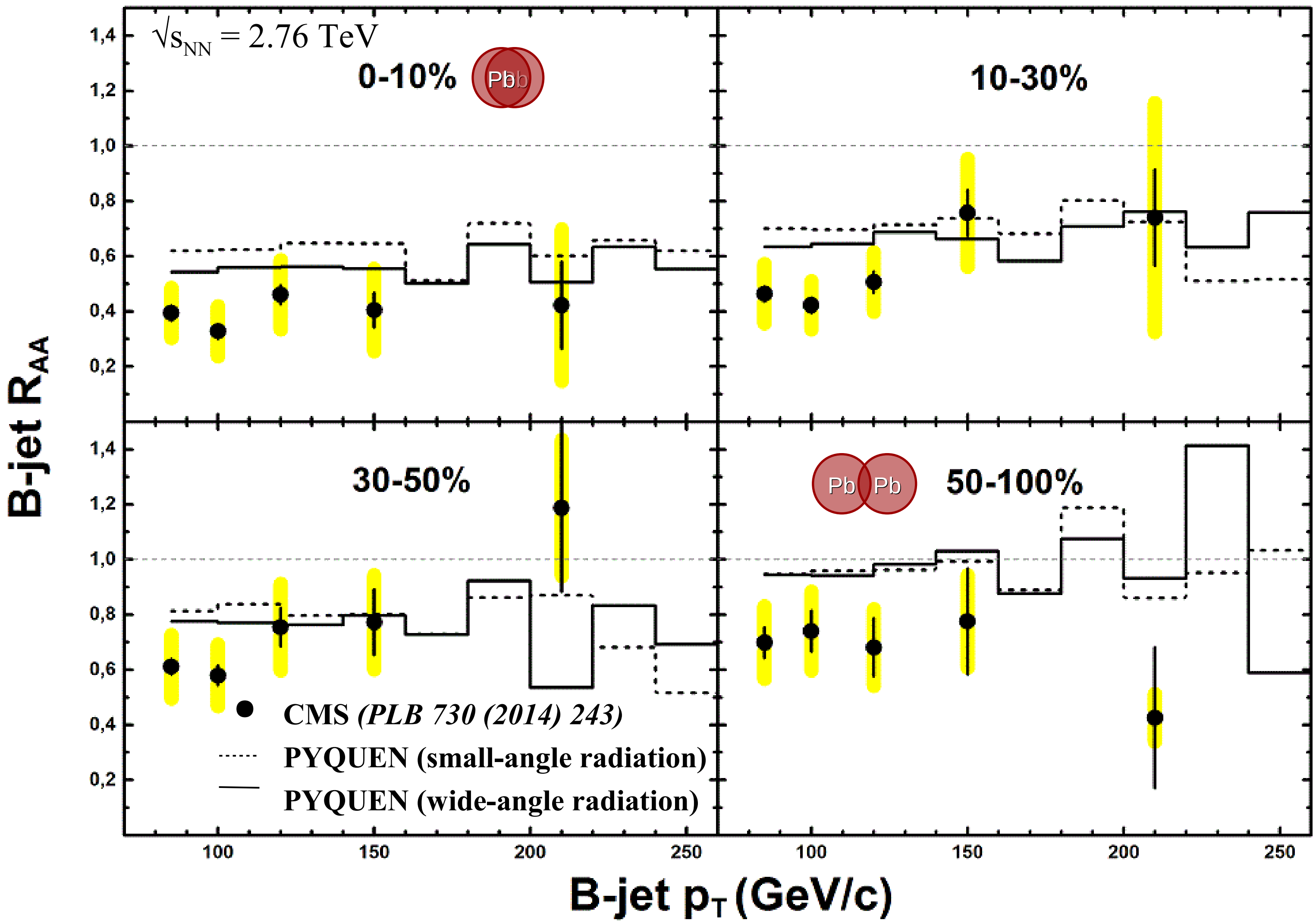
I.P. Lokhtin, A.A. Alkin, A.M. Snigirev, Eur.Phys. J. C (2015) 75



PYQUEN simulation results for R_{AA} are close to the data within statistical and systematic experimental uncertainties.

Suppression factor of b-jets vs. p_T in CMS and PYQUEN

I.P. Lokhtin, A.A. Alkin, A.M. Snigirev, Eur.Phys. J. C (2015) 75

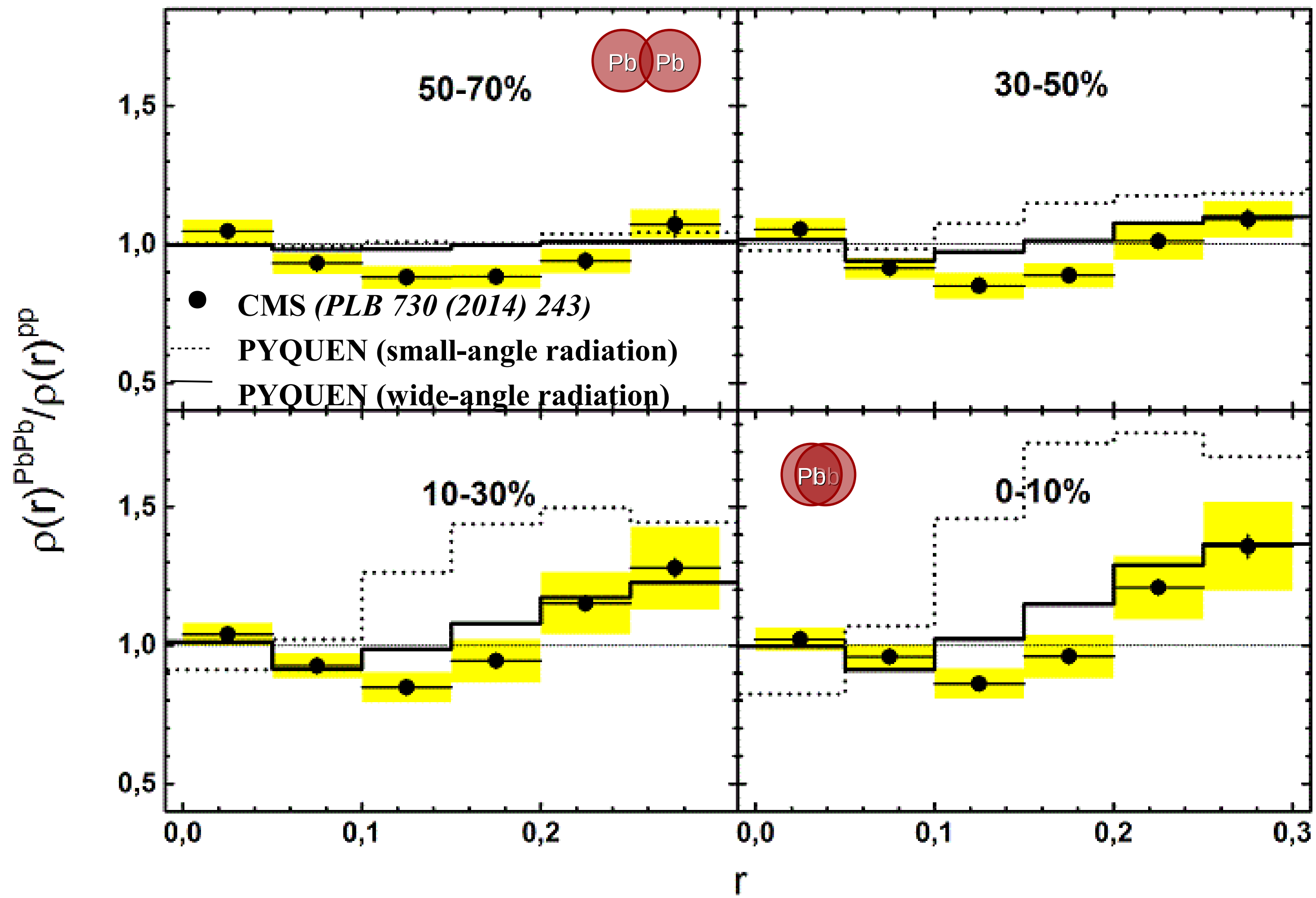


Reproduced well by PYQUEN

Jet shapes
PYQUEN vs. CMS data

$$\rho(r) \sim \frac{1}{\delta r}\frac{1}{N_{\rm jet}}\sum_{\rm jets}\frac{p_{\rm T}(r-\delta r/2, r+\delta r/2)}{p_{\rm T}^{\rm jet}}$$

I.P. Lokhtin, A.A. Alkin, A.M. Snigirev, Eur.Phys. J. C (2015) 75

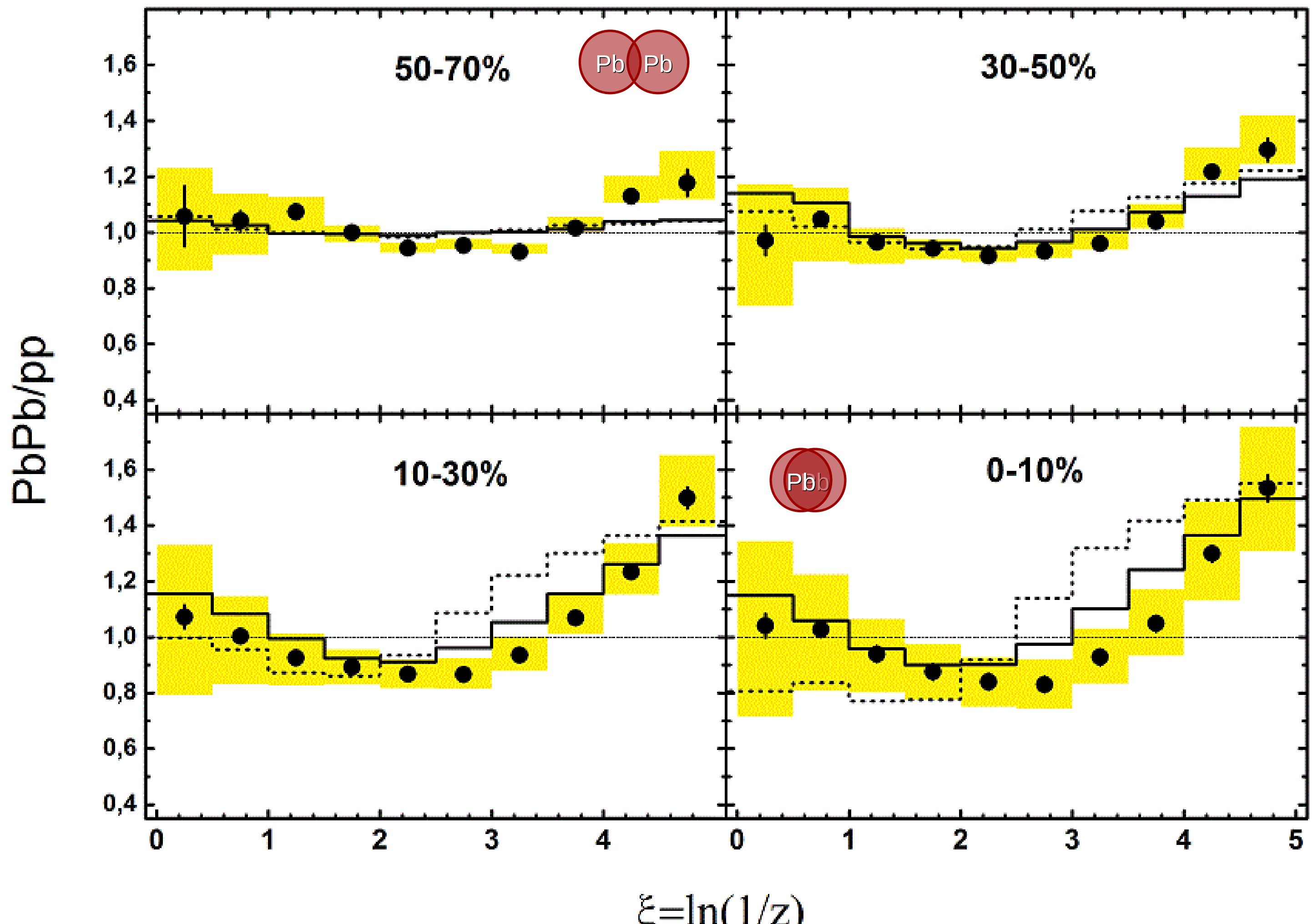


The modification of radial jet profile (E_T^{jet}>100 GeV, R=0.3): excess at large radii; suppression at intermediate radii; core is unchanged. Reproduced well by PYQUEN with wide-angle radiative + collisional partonic energy loss.

Jet fragmentation function PYQUEN vs. CMS data

$$\xi = -\ln z = -\ln \frac{p_T^{track}}{p_T^{jet}}$$

I.P. Lokhtin, A.A. Alkin, A.M. Snigirev, Eur.Phys. J. C (2015) 75



The modification of longitudinal jet profile (E_T^{jet}>100 GeV, R=0.3): excess at low p_T ; suppression at intermediate p_T; high p_T is slightly enhanced. Reproduced well by PYQUEN with wide-angle radiative + collisional partonic energy loss.