Thermal and non-thermal charmed meson production in heavy ion collisions at LHC

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in collaboration with
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Within such paradigma, a number of questions on heavy flavours arise:

- Are heavy quarks thermalized in quark-gluon plasma?
- What is the mass dependence of medium-induced quark energy loss?
- Are charmed hadrons (D, J/ψ) in a kinetic equilibrium with the medium?
- How the specific pattern of quarkonium suppression related to the interplay between thermal and non-thermal mechanisms of J/ψ meson production?

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In this talk, I'll present some results of the phenomenological analysis of LHC data on p_T-spectra and elliptic flow of charmed hadrons (D, J/ψ) in PbPb collisions at $\sqrt{s_{NN}}$=2.76 TeV in the frameworks of two-component HYDJET++ model. The comparision with RHIC results is also discussed.

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, the latter is based on PYQUEN - PYthia QUENched).

http://cern.ch/lokhtin/hydro/hydjet.html *(latest version 1.9)*

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

HYDJET++ (HYDJET v.2.*) – continuation of HYDJET (identical hard component + improved soft component including full set of thermal resonance production).

http://cern.ch/lokhtin/hydjet++ *(latest version 2.2)*

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

HYDJET++ (soft component): physics frames

Soft (hydro) part of HYDJET++ is based on the adapted FAST MC model:
Part I: *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*
Part II: *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 (but this number may be reduced to 9)

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:
$V_{eff}(b)=V_{eff}(0)N_{part}(b)/N_{part}(0)$, $\tau_f(b)=\tau_f(0)[N_{part}(b)/N_{part}(0)]^{1/3}$

HYDJET++ (hard component): PYQUEN (PYthia QUENched)

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

Parton rescattering & energy loss (collisional, radiative) + emitted g
PYQUEN rearranges partons to update ns 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 $P_{T\,min}$ to specify the number of hard NN collisions)

I.P.Lokhtin, A.M.Snigirev, Eur. Phys. J. 45 (2006) 211 (latest version 1.5.1)

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

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,

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 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)

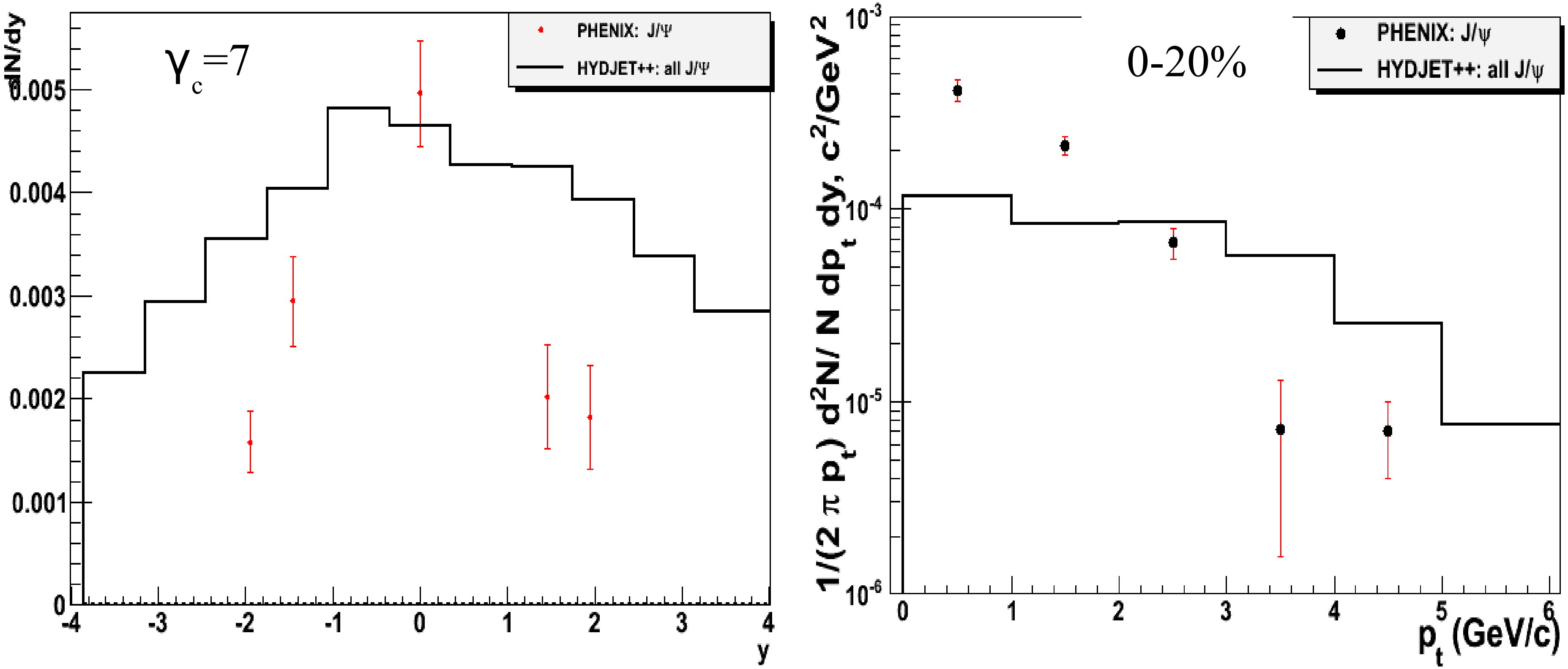
and multiplied by the number of NN sub-collisions for given centrality

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 radiative and collisional energy loss of heavy quarks (b, c)

Charmed mesons at RHIC (J/ψ)

I.P. Lokhtin et al., J.Phys.Conf.Ser. 270 (2011) 012060

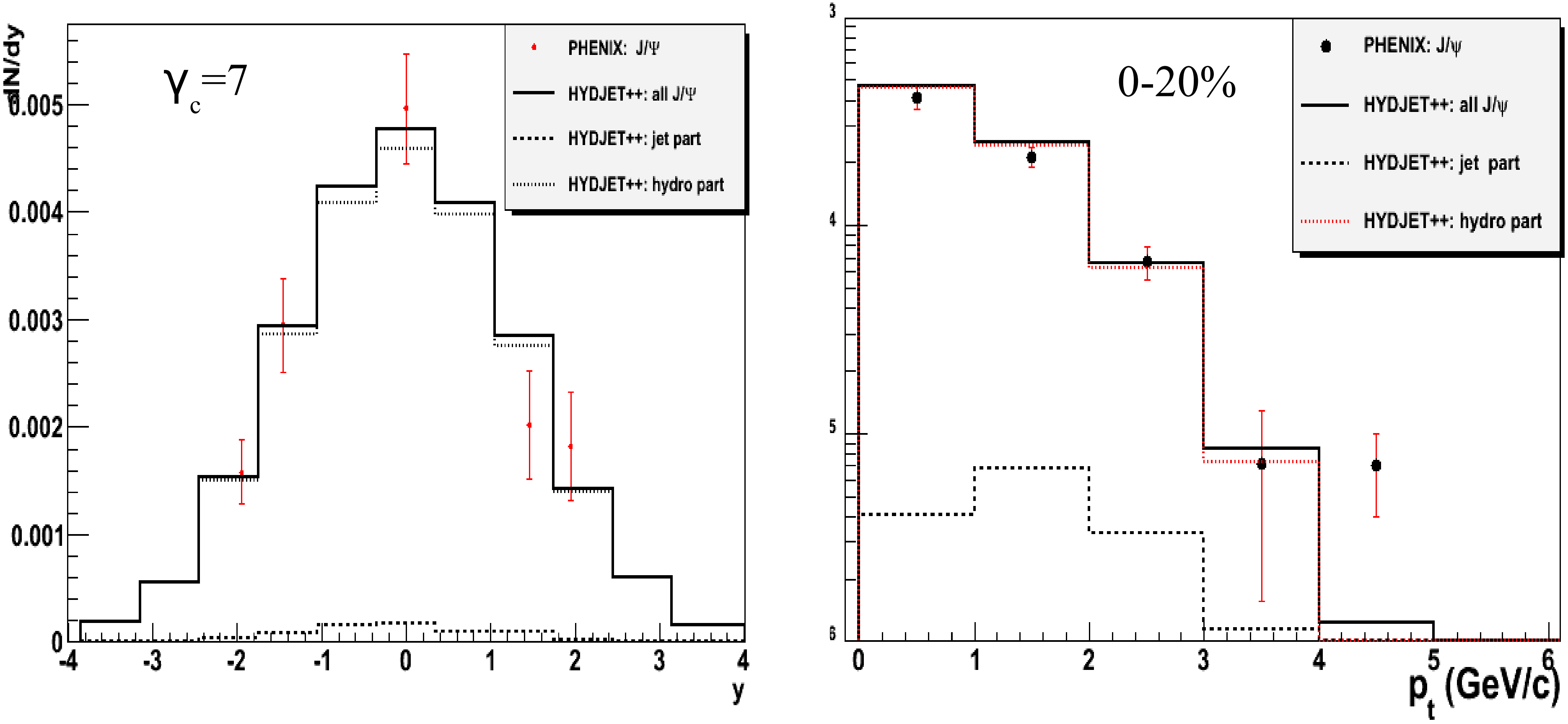


Points: PHENIX data *PRL 98 (2007) 232301);* histograms: HYDJET++

If thermal freeze-out for J/ψ happens at the same temperature as for inclusive hadrons, T_{th}=100 MeV (η^{max}=3.3, ρ_u^{max}=1.1) then simulated spectra are much wider than the data

Charmed mesons at RHIC (J/ψ)

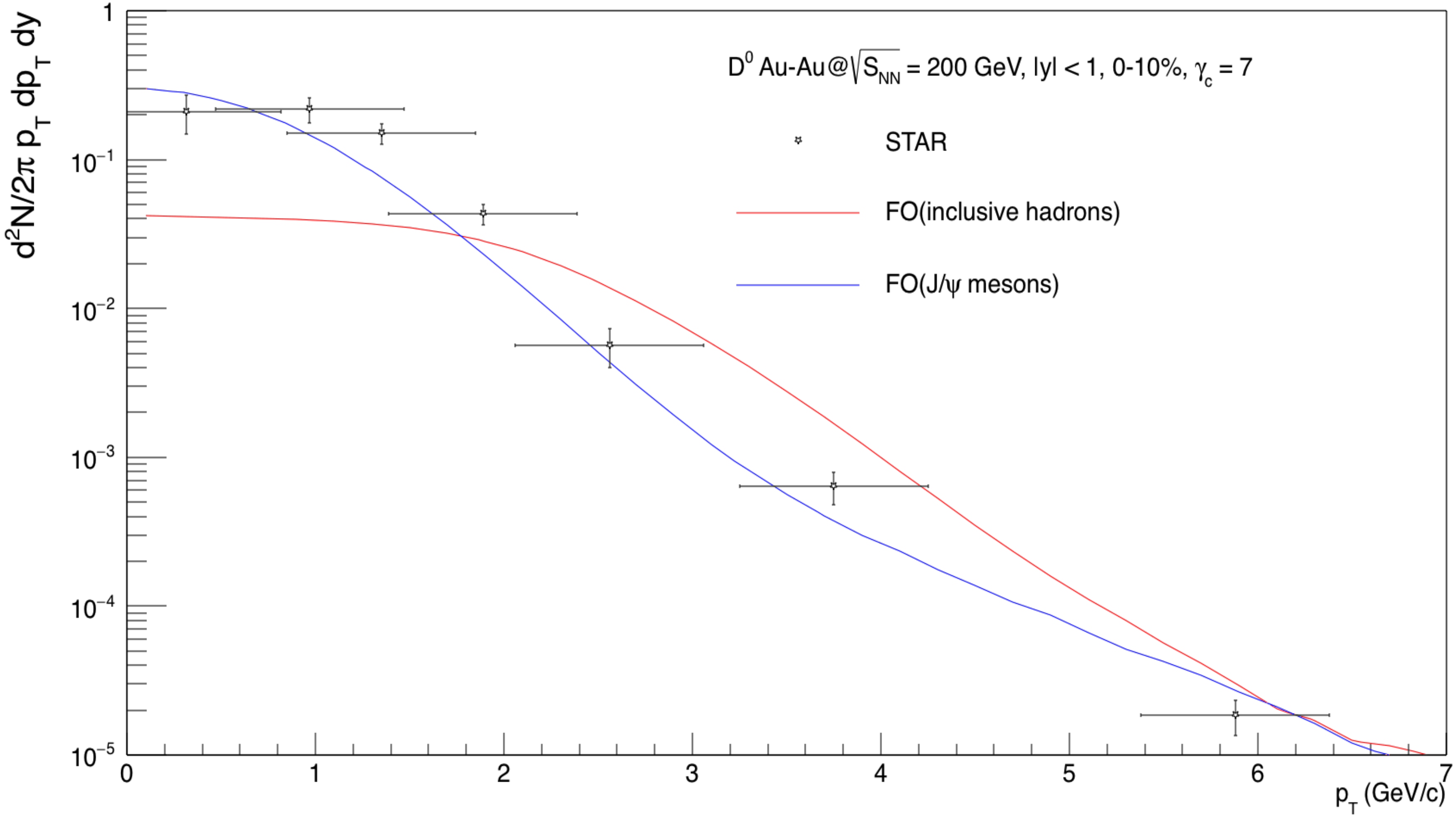
I.P. Lokhtin et al., J.Phys.Conf.Ser. 270 (2011) 012060



Points: PHENIX data *PRL 98 (2007) 232301);* histograms: HYDJET++

But if thermal freeze-out for J/ψ happens at the same temperature as chemical freeze-out, $T_{th}(J/\psi)=T_{ch}$=165 MeV (η^{max}=1.1, ρ_u^{max}=0.5), then simulated spectra match the data

Charmed mesons at RHIC (D)



Points: STAR data *PRL 113 (2014) 142301);* histograms: HYDJET++

Simulated p_T-spectrum match the data if freeze-out parameters for D are the same as for J/ψ: $T_{th} = T_{ch}$=165 MeV (η^{max}=1.1, ρ_u^{max}=0.5)

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- Momentum spectra of D and J/ψ mesons in most central AuAu collisions may be reproduced by two-component model including thermal (soft) and non-thermal (hard) components with the same freeze-out parameters

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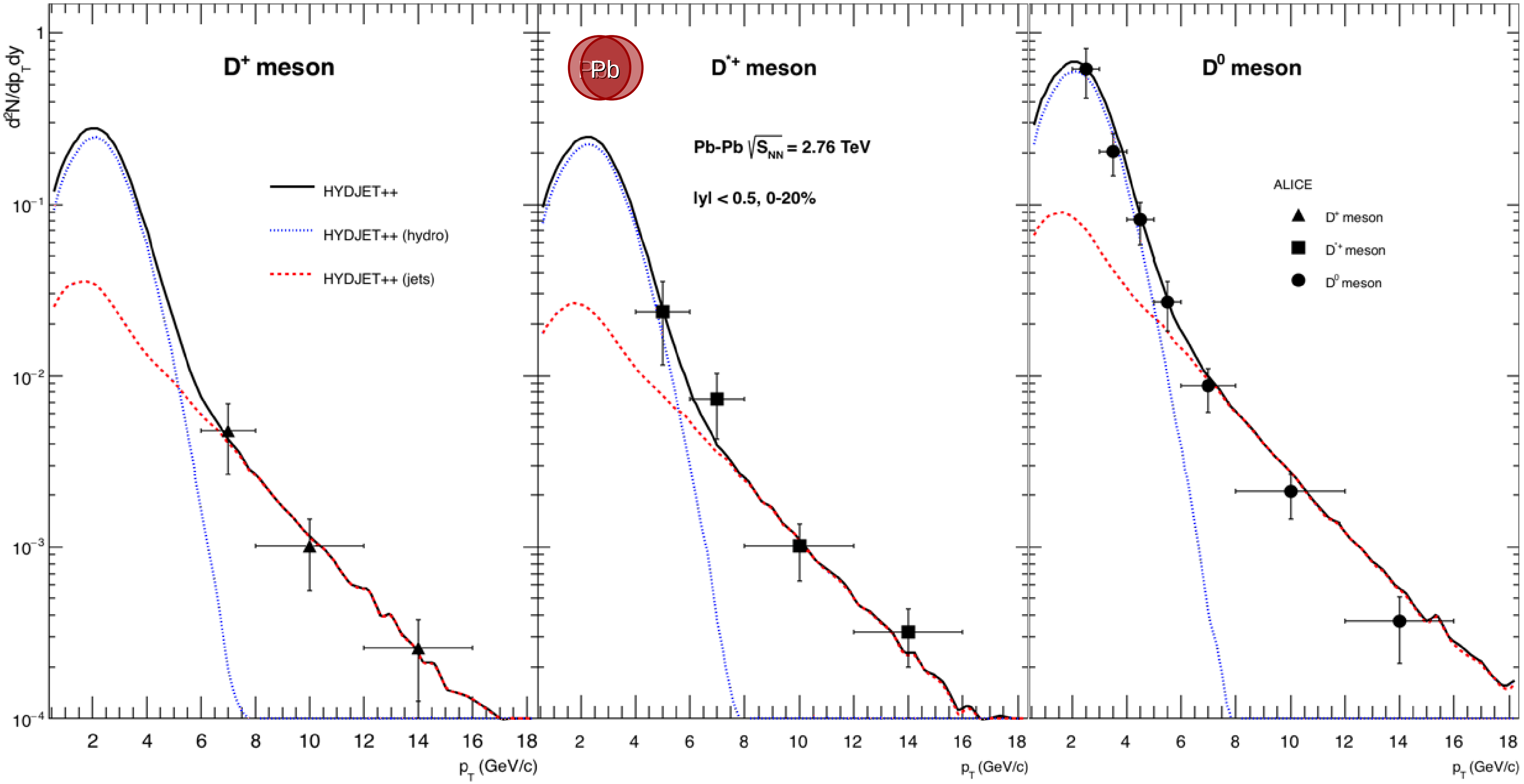
What about charmed mesons at the LHC?

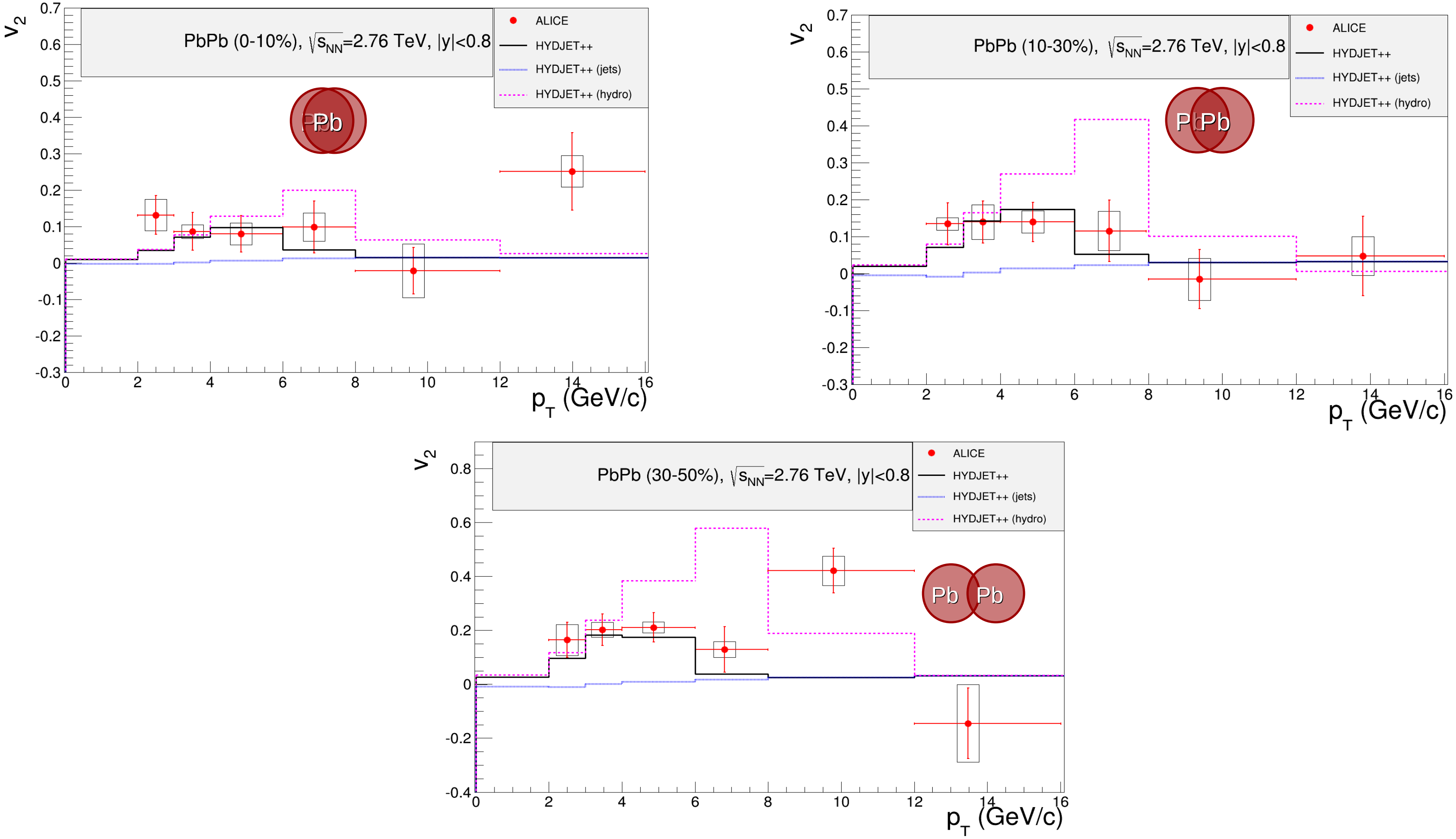
D mesons at LHC (p_T-spectrum)



Points: ALICE data *(JHEP 1209 (2012) 112);* histograms: HYDJET++ (T_{th} = 105 MeV, T_{ch} = 165 MeV, η^{max} = 4.5, ρ_u^{max} = 1.265, γ_c = 11.5, $P_{T\,min}$ = 8.2 GeV/c)

HYDJET++ reproduces p_T-spectrum 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 at LHC (elliptic flow $v_2 = \langle\cos(2\varphi-\psi_R)\rangle$)



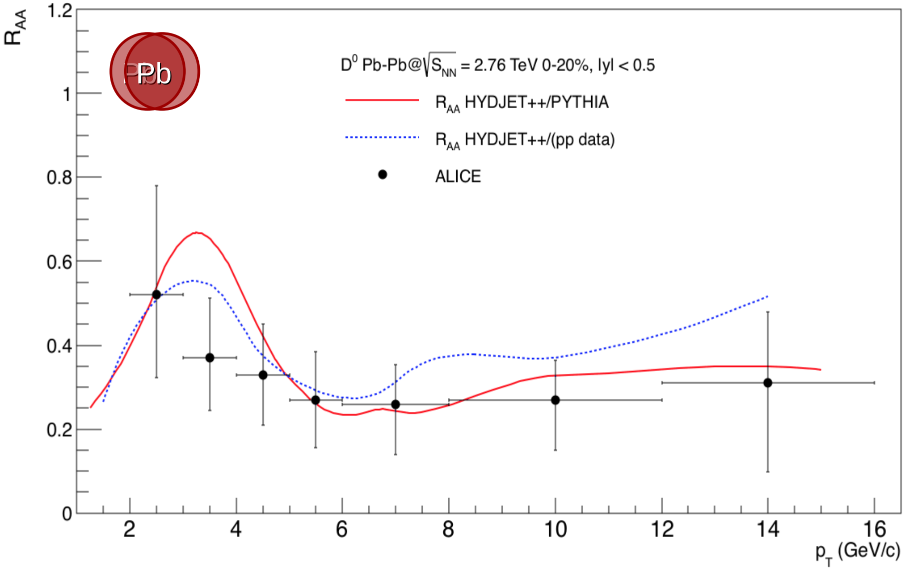
Points: ALICE data *(PRC 90 (2014) 034904));* histograms: HYDJET++

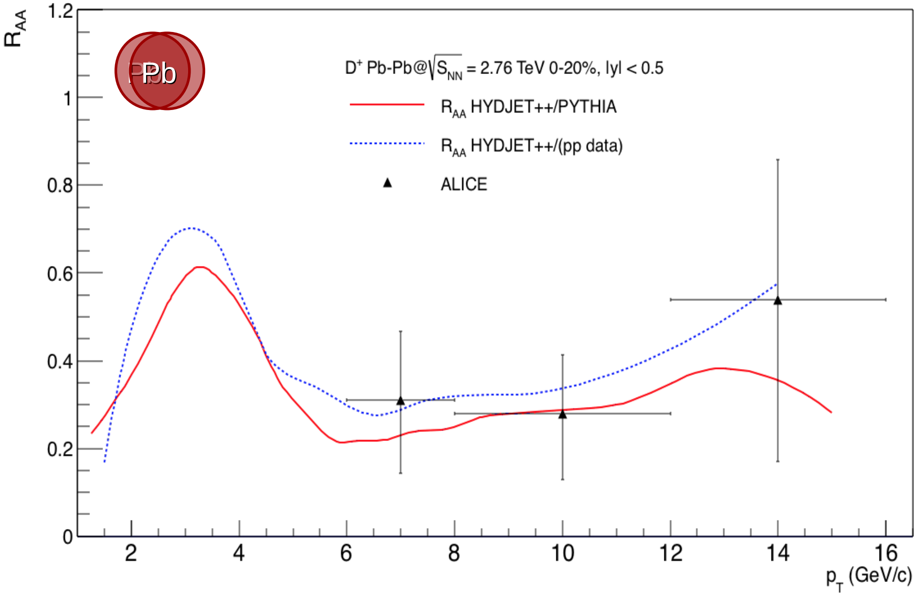
HYDJET++ reproduces $v_2(p_T)$ of D-mesons with the *same freeze-out parameters* as for inclusive hadrons ⇒ significant part of D-mesons (*thermal component*) is in the kinetic equilibrium with the medium; *non-thermal component* is important at high p_T

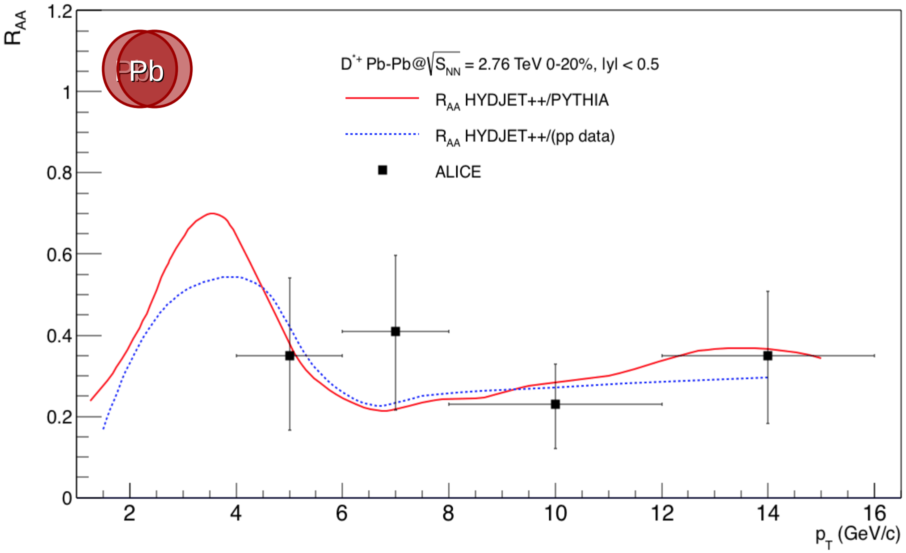
D mesons at LHC (nuclear modification factor R_{AA})

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

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







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

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

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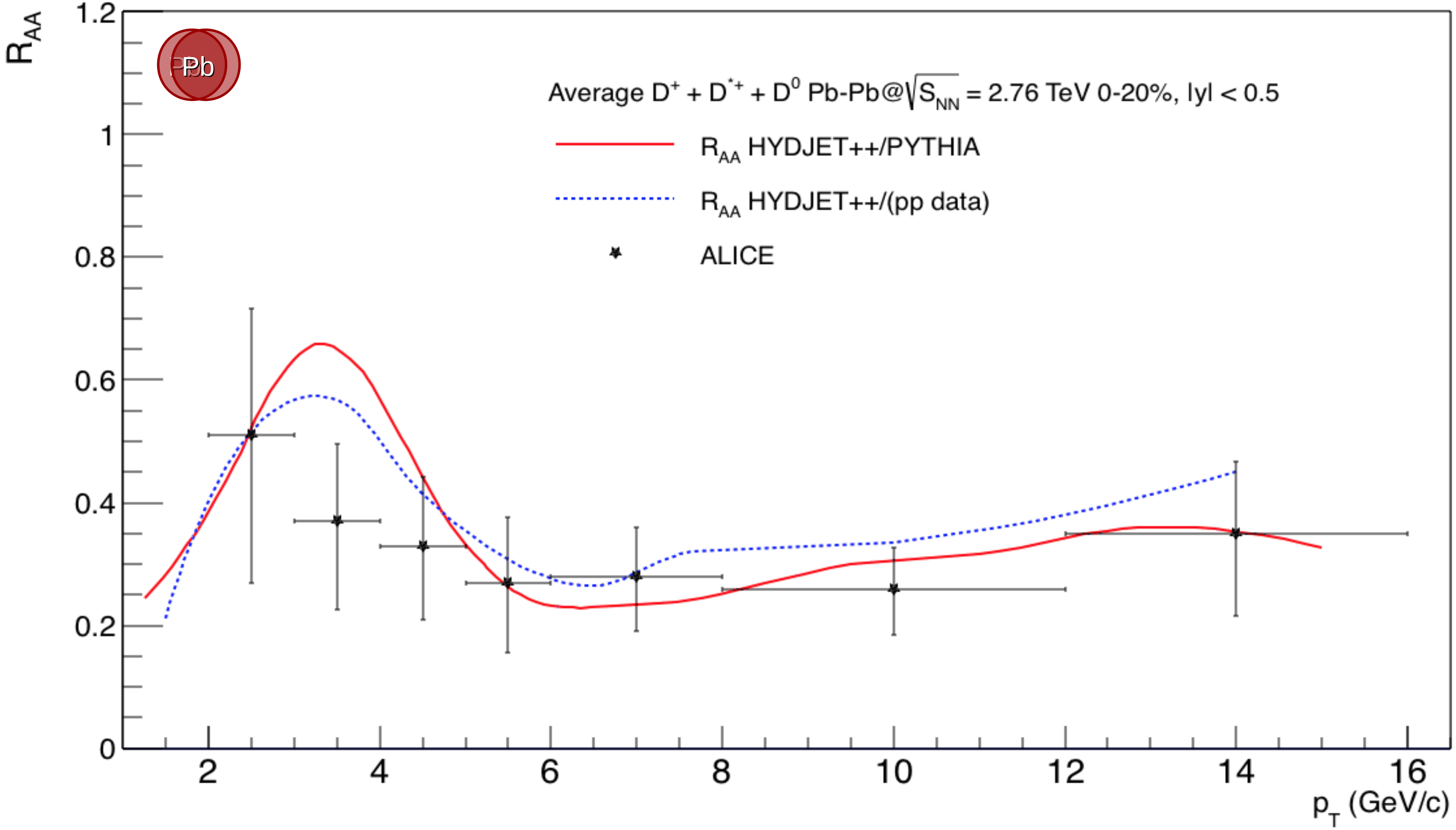

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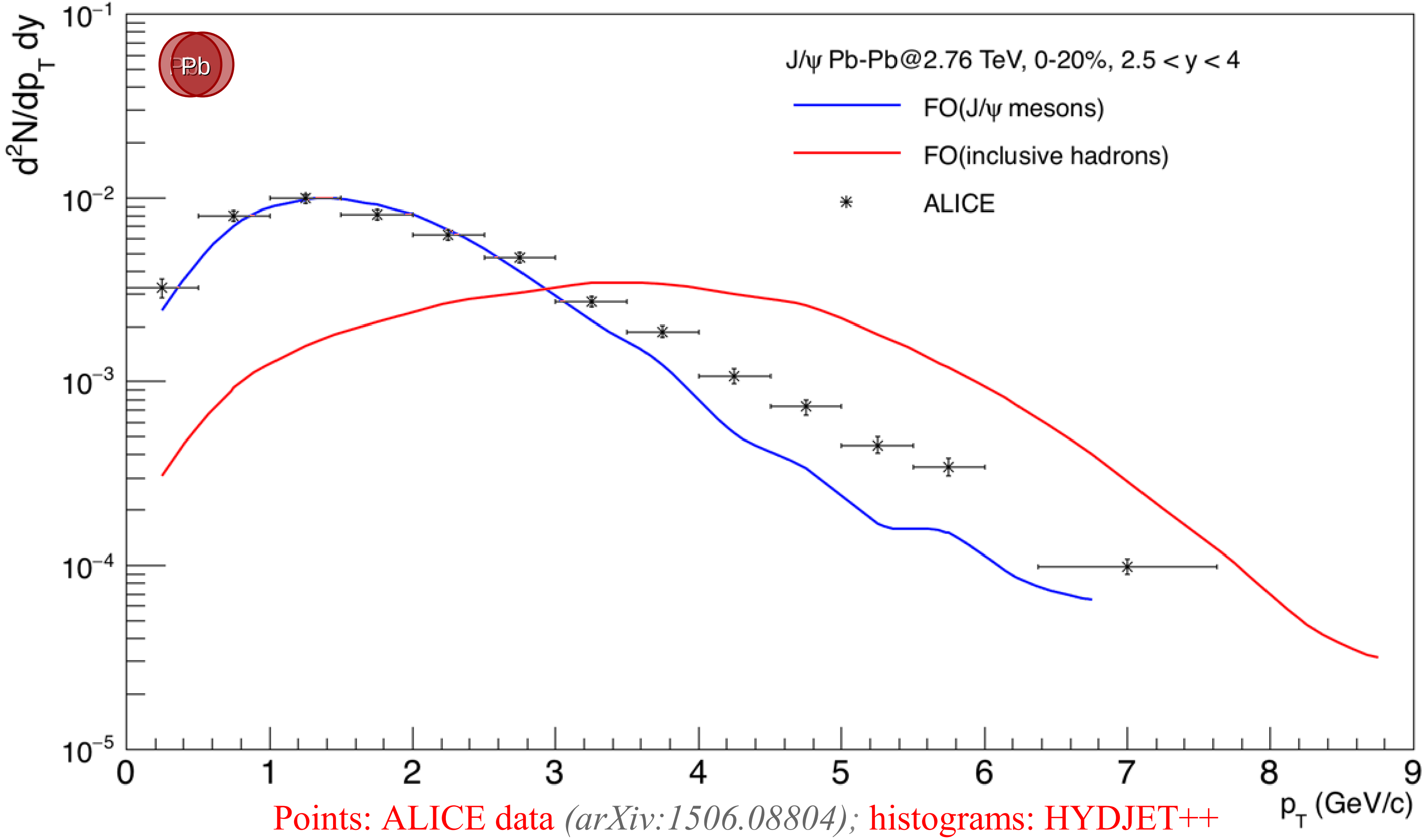
J/ψ mesons at LHC (p_T-spectrum)



Points: ALICE data *(arXiv:1506.08804);* histograms: HYDJET++
($T_{th} = T_{ch} = 165$ MeV, $\eta^{max} = 2.3$, $\rho_u^{max} = 0.6$, $\gamma_c = 11.5$, $P_{T\,min} = 3.0$ GeV/c)

HYDJET++ reproduces J/ψ-meson p_{T}-spectrum (up to ~3 GeV/c) with the *freeze-out parameters different* from ones for inclusive hadrons ⇒ kinetic freeze-out of J/ψ *thermal component* occurs before freeze-out of light hadrons; *non-thermal component* is important at intermediate & high p_T

J/ψ mesons at LHC (nuclear modification factor R_{AA})

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

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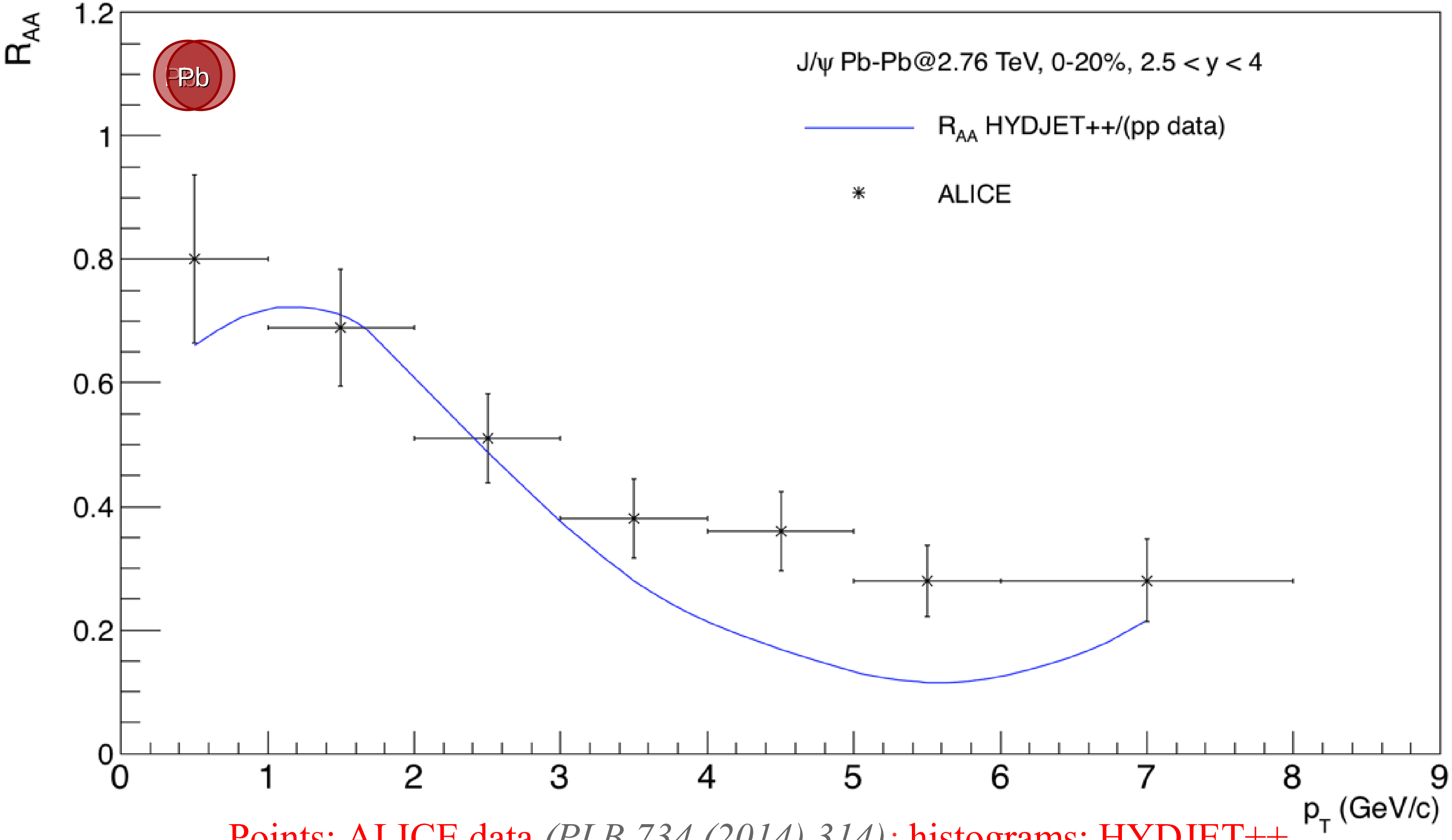
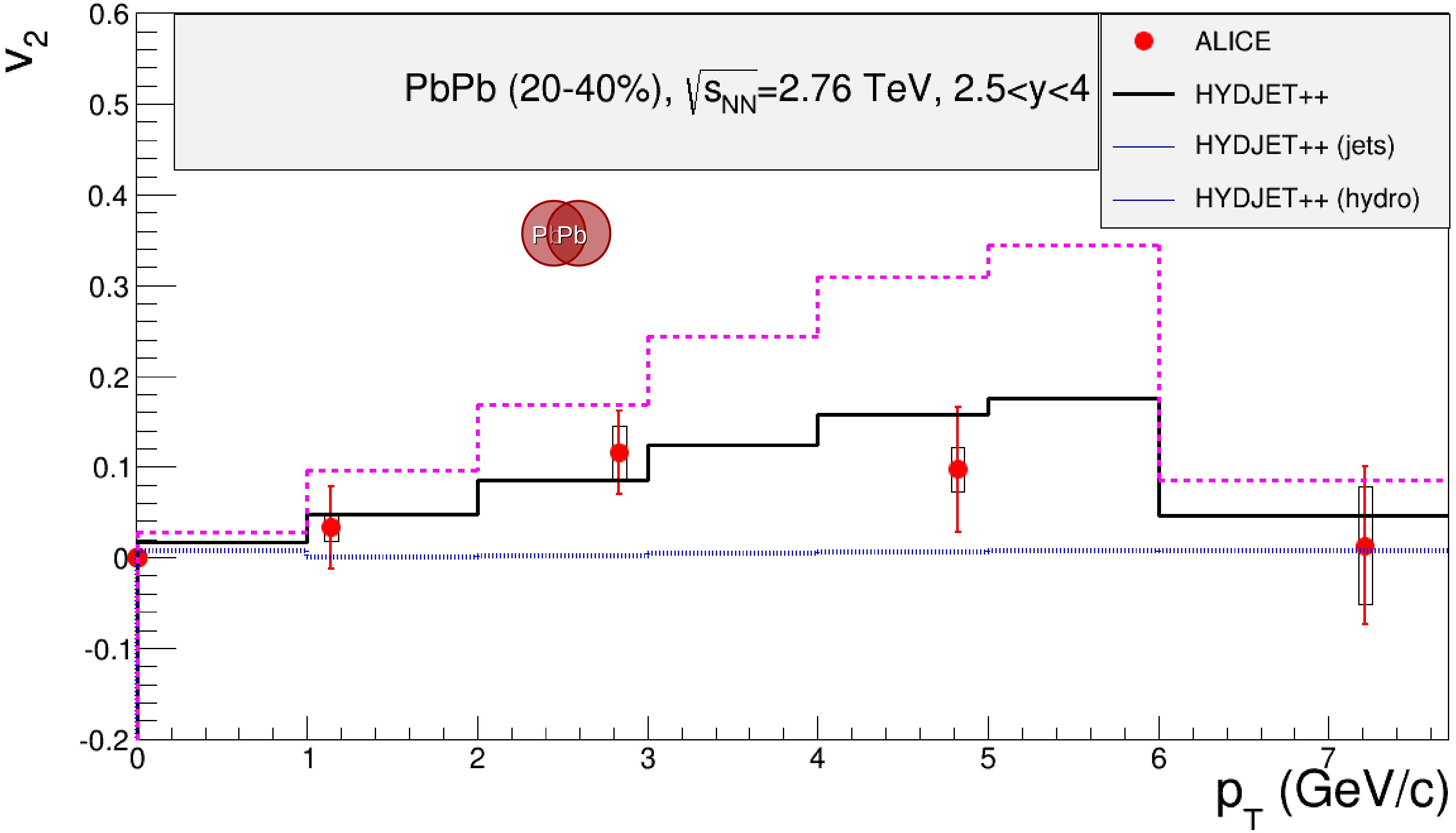


Points: ALICE data *(PLB 734 (2014) 314)*; histograms: HYDJET++

Superposition of *thermal* and *non-thermal components* in HYDJET++ allows us qualitatively to reproduce momentum dependence of J/ψ suppression factor in PbPb collisions at the LHC (but PYTHIA@HYDJET++ tuning is needed for adequate J/ψ modeling at high p_T)

J/ψ mesons at LHC (elliptic flow $v_2 = \langle\cos(2\varphi-\psi_R)\rangle$)



Points: ALICE data *(PRL 111 (2013) 162301);* histograms: HYDJET++

HYDJET++ reproduces $v_2(p_T)$ of J/ψ-mesons with the *freeze-out parameters different* from ones for inclusive hadrons ⇒ kinetic freeze-out of J/ψ *thermal component* occurs appreciably before freeze-out of light hadrons; *non-thermal component* is important at intermediate & high p_T

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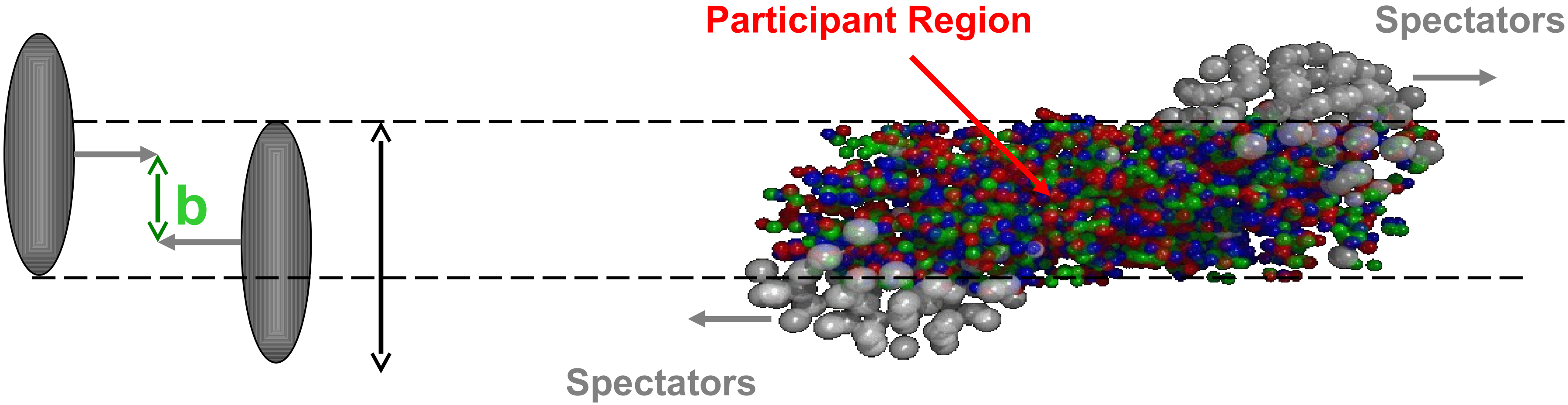
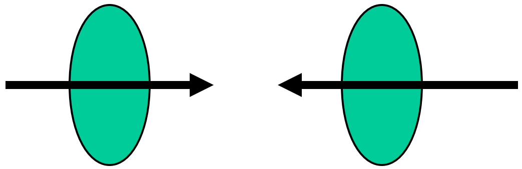
High degree of c-quark thermalization in quark-gluon plasma is achieved in PbPb collisions at the LHC (?)

BACKUP SLIDES

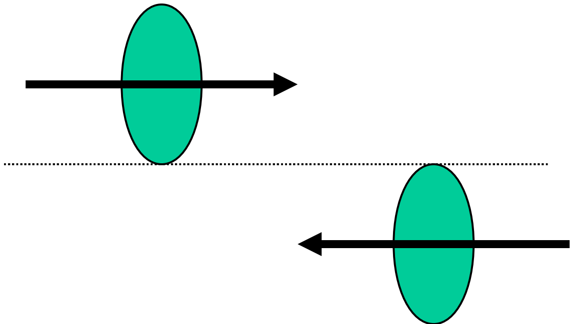
Centrality of nucleus-nucleus interactions



central collision

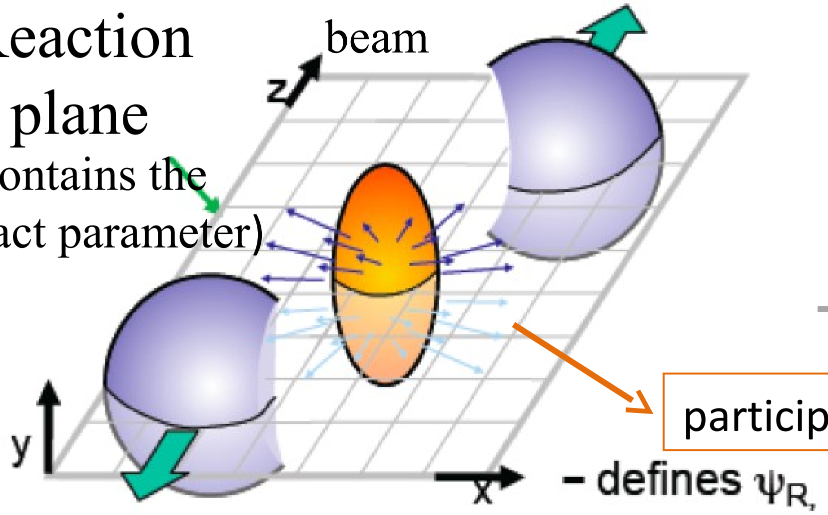


peripheral collision



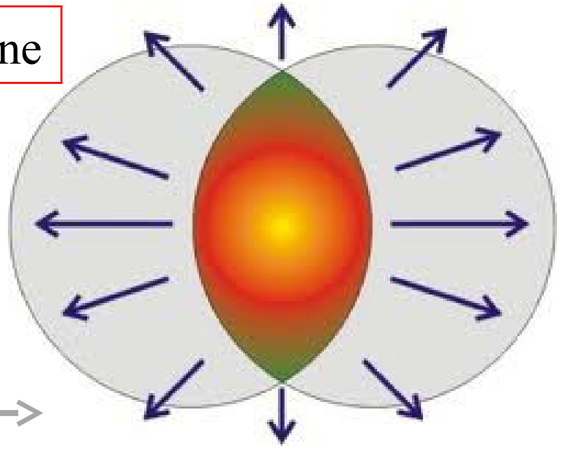
Azimuthal correlations and flow

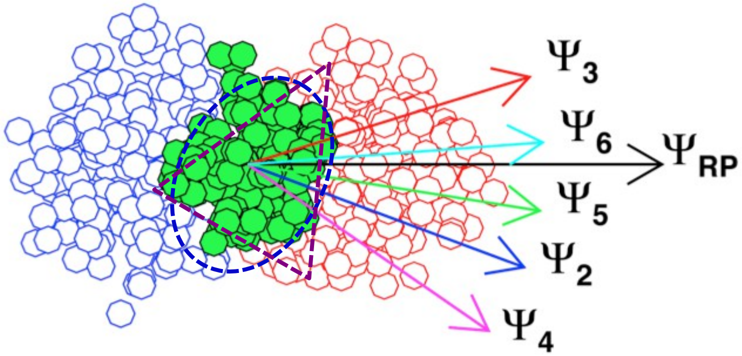
Reaction plane
(contains the impact parameter)



participants

Event plane





Elliptic flow Triangular flow

$$\boxed{\frac{dN}{d\phi} \sim 1 + 2v_2 \cos 2(\phi - \psi_2) + 2v_3 \cos 3(\phi - \psi_3) + \ldots}$$

Monte-Carlo simulation of hard component (including nuclear shadowing) in 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).*

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 :

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

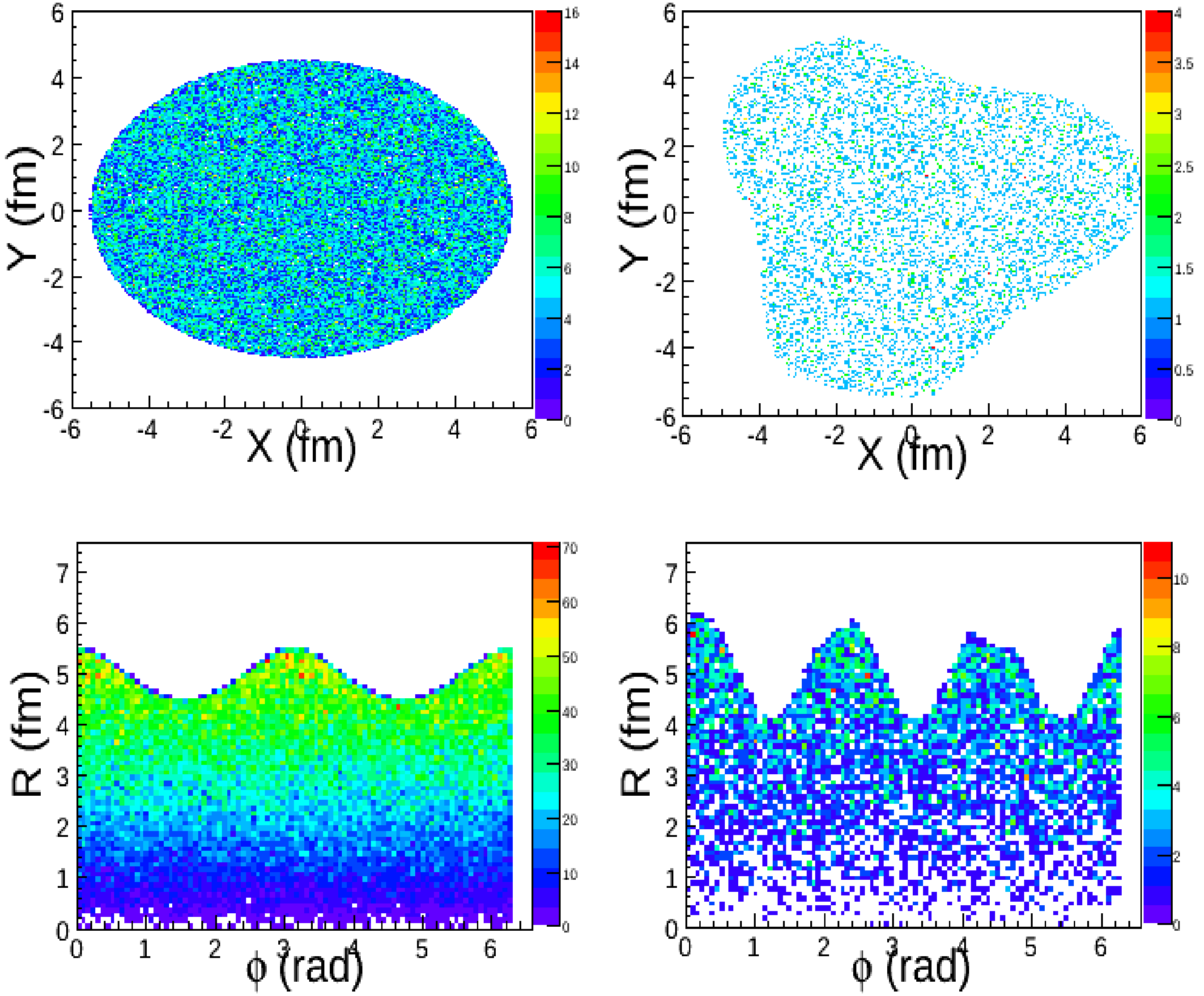
3. The absolute values $\rho_i^{eq}(T^{th},\mu_i^{th})$ are determined by the choice of the free parameter of the model: effective pion chemical potential $\mu_\pi^{eff,th}$ at T^{th}
Assuming for the other particles (heavier then pions) the Botzmann approximation :

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

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

Anisotropic flow generation in HYDJET++ (soft component)

L.V. Bravina et al., *EPJC 74 (2014) 2807*



Anisotropic flow generation in HYDJET++ (soft component)

Elliptic flow v_2

$$\boxed{\frac{dN}{d\phi} \sim 1 + 2v_2 \cos 2(\phi - \psi_2) + 2v_3 \cos 3(\phi - \psi_3) + \ldots}$$

- spatial modulation of freeze-out surface
- fluid velocity modulation

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

Spatial anisotropy

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

R(b) – surface radius

Momentum anisotropy

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

φ_u : azimuthal angle of fluid velocity

φ : spatial azimuthal angle

Triangular flow v_3

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

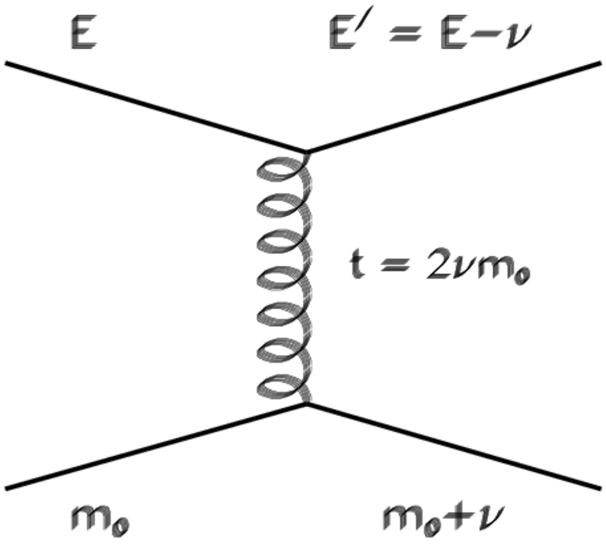
$$R(b,\phi) = R_f(b)\frac{\sqrt{1-\epsilon^2(b)}}{\sqrt{1+\epsilon(b)\cos 2\phi}}[1+\epsilon_3(b)\cos 3(\phi+\Psi_3^{\mathrm{RP}})]$$

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

Medium-induced partonic rescattering and energy loss («jet quenching»)

Collisional loss

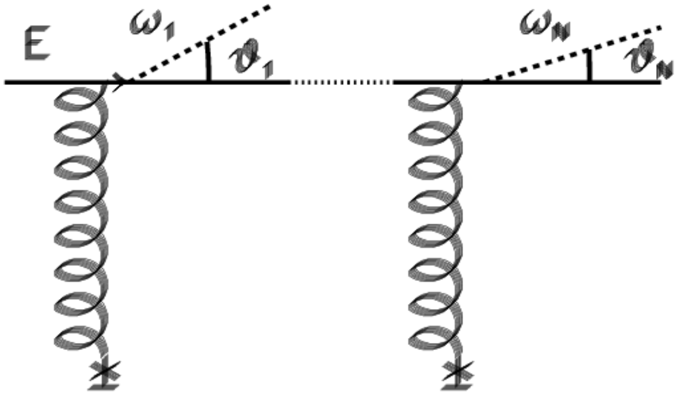
(high momentum transfer approximation)



+

Radiative loss

(BDMPS model, coherent radiation)



PYQUEN: physics frames

General kinetic integral equation:

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

1. Collisional loss and elastic scattering cross section:

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

2. Radiative loss (BDMPS):

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

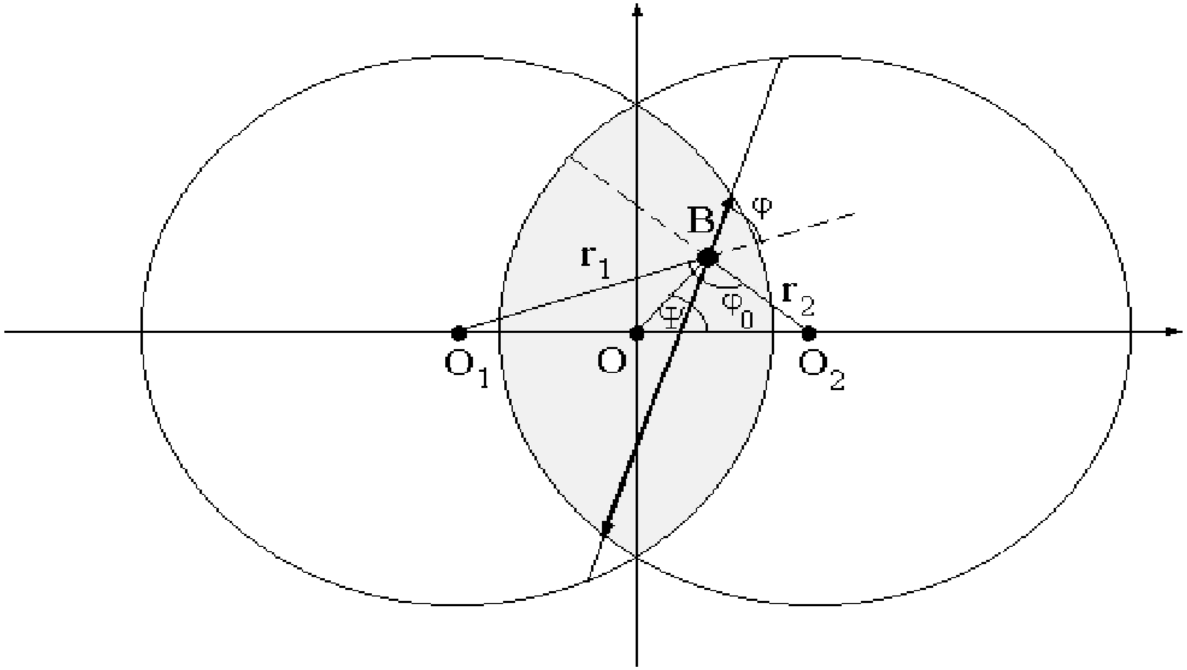
“dead cone” approximation for massive quarks:

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

Nuclear geometry and QGP evolution

impact parameter $b \equiv |O_1O_2|$ - transverse distance between nucleus centers

$\varepsilon(r_1,r_2) \propto T_A(r_1) * T_A(r_2)$ ($T_A(b)$ - nuclear thickness function)



Space-time evolution of QGP, created in region of initial overlaping of colliding nuclei, is descibed by Lorenz-invariant Bjorken's hydrodynamics *J.D. Bjorken, PRD 27 (1983) 140*

Monte-Carlo simulation of parton rescattering and energy loss in PYQUEN

- Distribution over jet production vertex *V(r cosψ, r sinψ)* at im.p. *b*

$$\frac{dN}{d\psi\, dr}(b)=\frac{T_A(r_1)T_A(r_2)}{\int\limits_0^{2\pi} d\psi \int\limits_0^{r_{max}} r dr T_A(r_1)T_A(r_2)}$$

- Transverse distance between parton scatterings $l_i=(\tau_{i+1}-\tau_i)\,E/p_T$

$$\frac{dP}{dl_i}=\lambda^{-1}(\tau_{i+1})\exp\left(-\int\limits_0^{l_i}\lambda^{-1}(\tau_i+s)ds\right), \quad \lambda^{-1}=\sigma\rho$$

- Radiative and collisional energy loss per scattering

$$\Delta E_{tot,i}=\Delta E_{rad,i}+\Delta E_{col,i}$$

- Transverse momentum kick per scattering

$$\Delta k_{t,i}^2=\left(E-\frac{t_i}{2\mathrm{m}_{0\mathrm{i}}}\right)^2-\left(p-\frac{E}{p}\frac{t_i}{2\mathrm{m}_{0\mathrm{i}}}-\frac{t_i}{2\mathrm{p}}\right)^2-m_q^2$$

Angular structure of energy loss in PYQUEN

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

Collinear radiation $\theta=0$

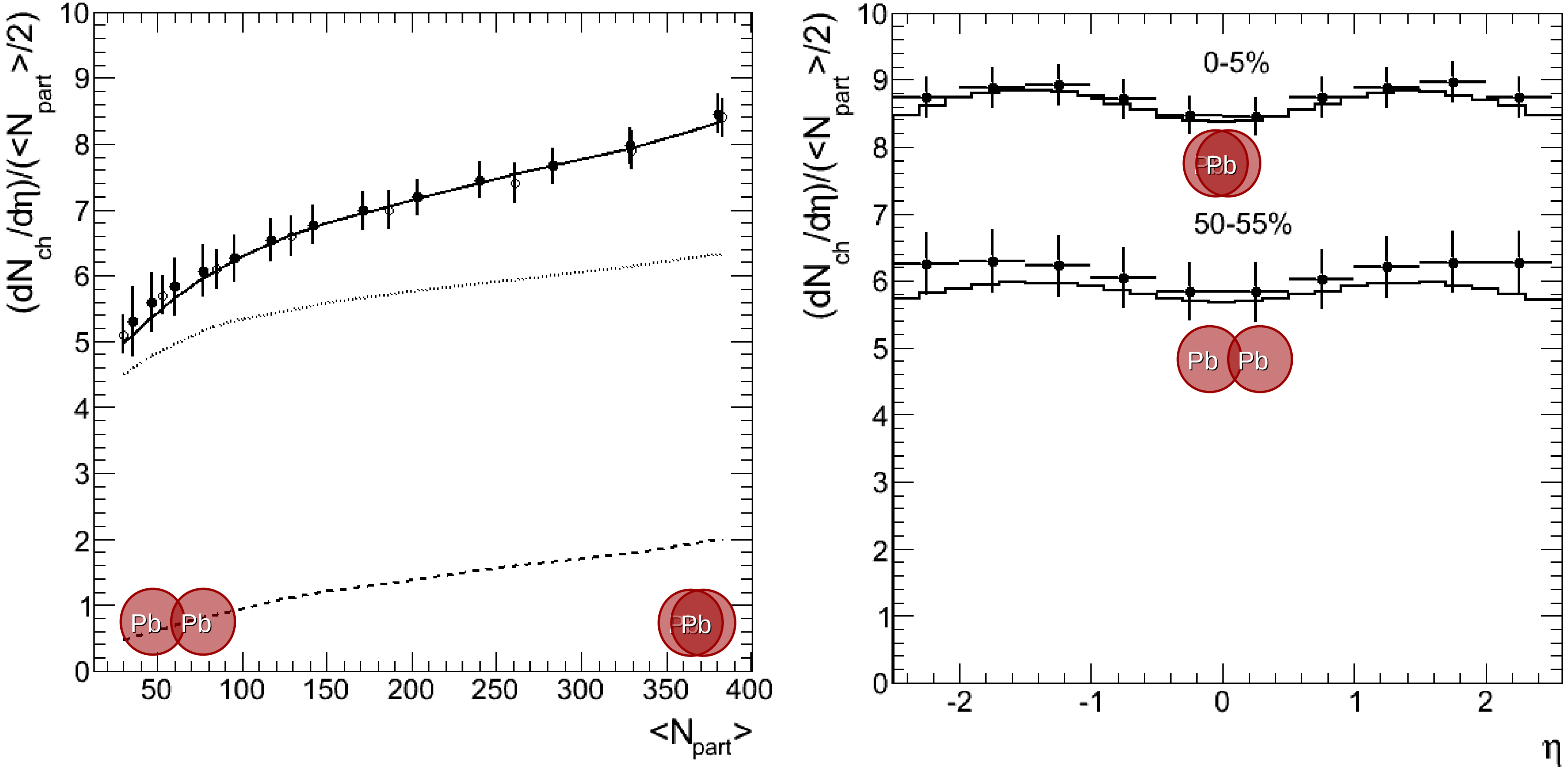
Small-angular radiation $\frac{dN^g}{d\theta} \propto \sin\theta \exp\left(\frac{-(\theta-\theta_0)^2}{2\theta_0^2}\right), \quad \theta_0 \sim 5^o$

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

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

Charged multiplicity vs. centrality and pseudorapidity

I.P. Lokhtin et al., EPJC 72(2012) 2045

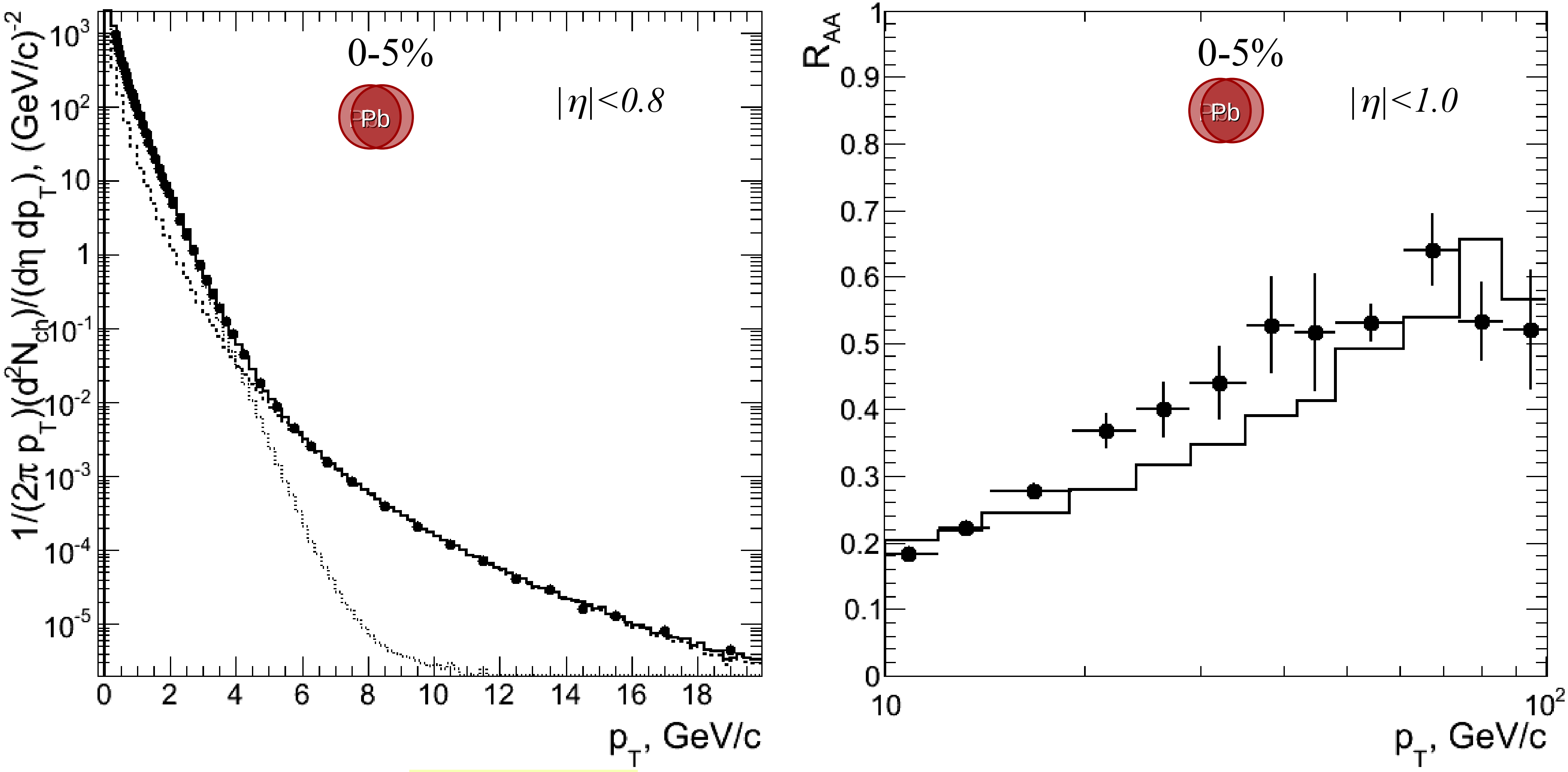


Open points: ALICE data *(PRL 106 (2011) 032301)*, closed points: CMS data *(JHEP 1108 (2011) 141);*
histograms: HYDJET++

Tuned HYDJET++ reproduces multiplicity vs. event centrality (down to very peripheral events) with contribution of hard component to multiplicity in mid-rapidity for central PbPb ~30%, as well as approximately flat pseudorapidity distribution.

P_T-spectrum and R_{AA} for inclusive charged hadrons

I.P. Lokhtin et al., EPJC 72(2012) 2045



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

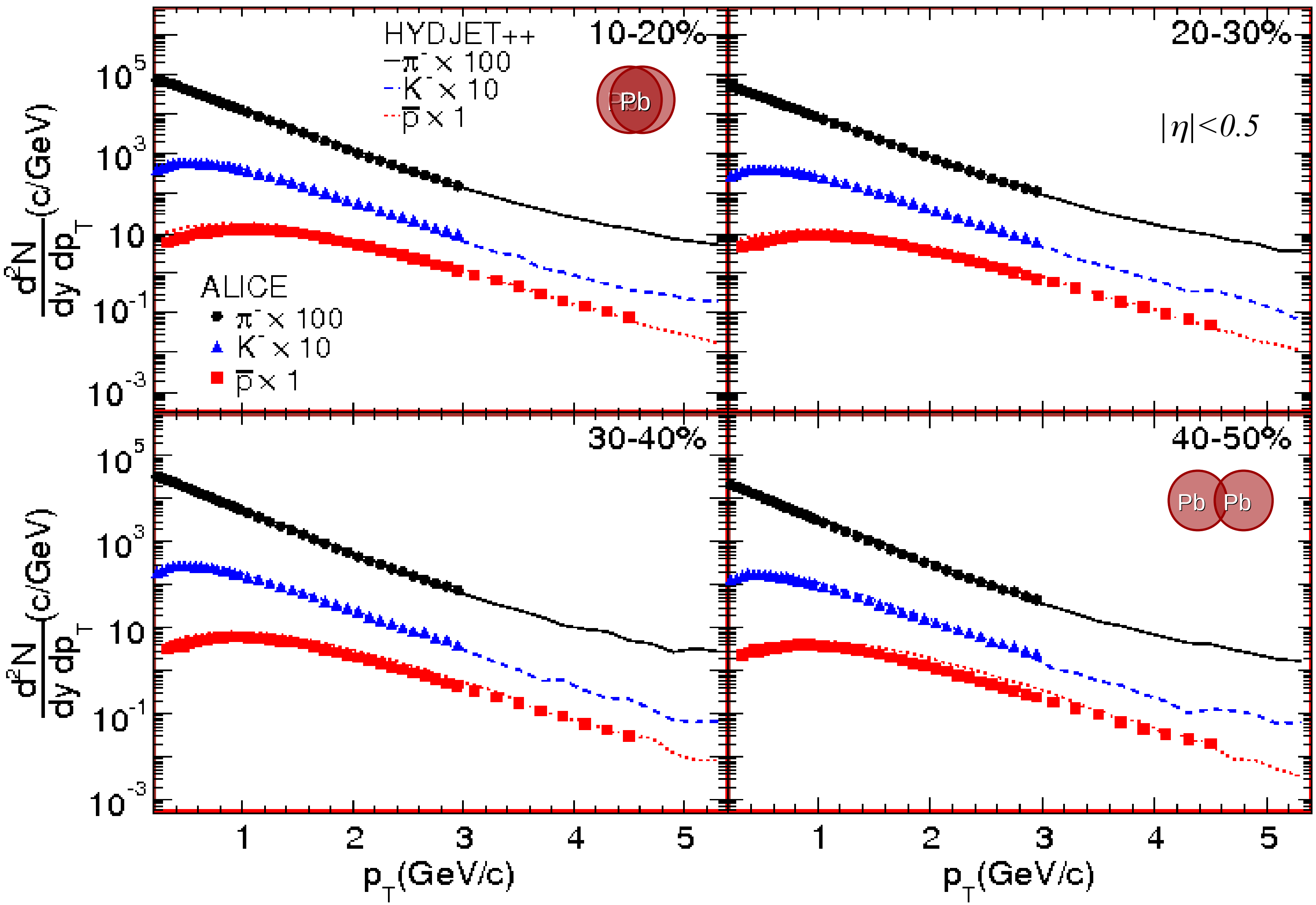
R_{AA}>1: enhancement
R_{AA}=1: no medium effect
R_{AA}<1: suppression

Points: ALICE (left) *(PLB 696 (2011) 30)* & CMS (right) (*EPJ C 72 (2012) 1945)* data;
histograms: HYDJET++

HYDJET++ reproduces p_T-spectrum and R_{AA} for central PbPb in mid-rapidity up to p_T~100 GeV/c

P_T-spectra of identified hadrons

L.V. Bravina et al., *EPJC 74 (2014) 2807*

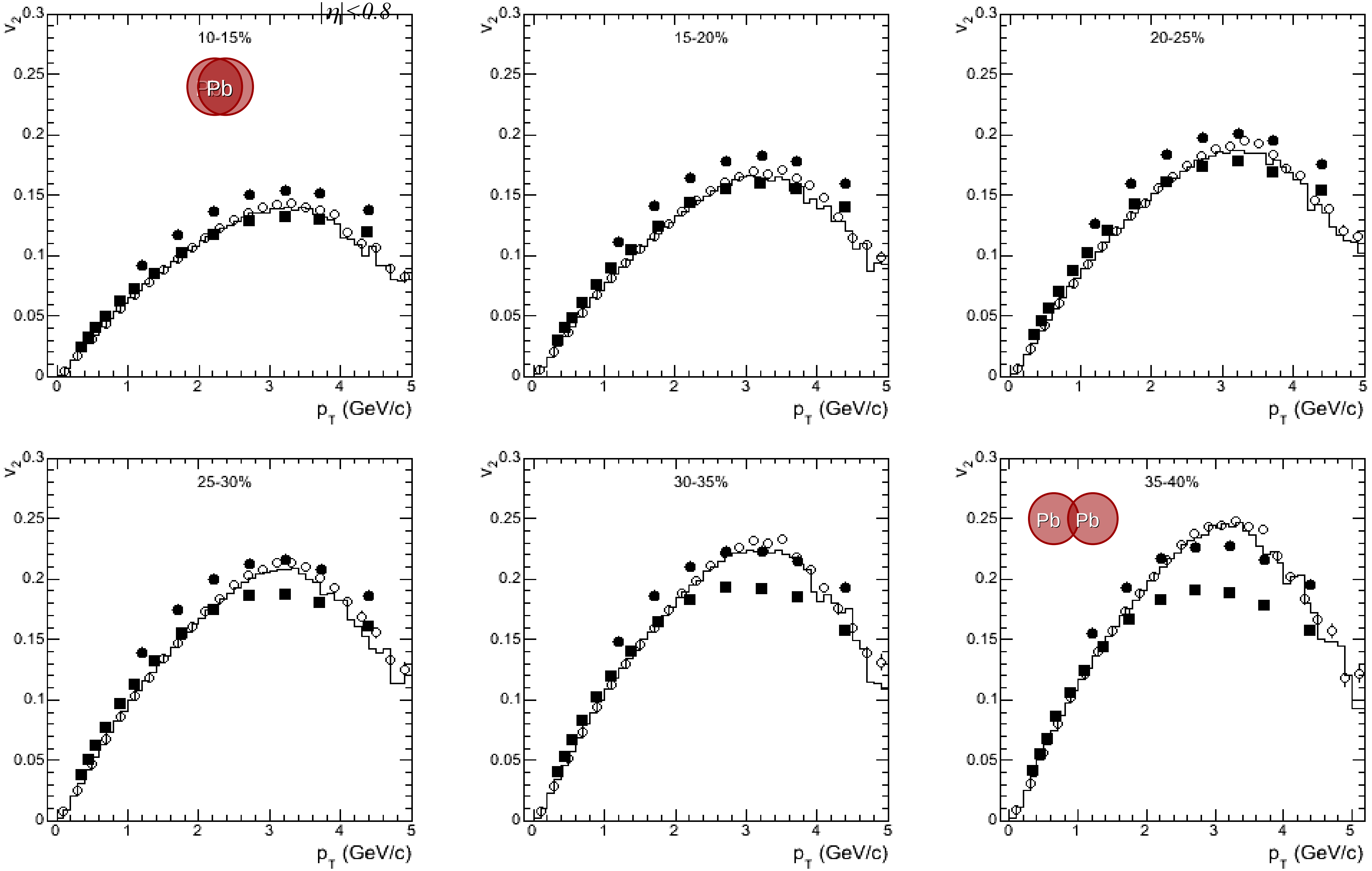


Points: ALICE data *(APP B 43 (2012) 555);* histograms: HYDJET++

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

Elliptic flow of inclusive charged hadrons

L.V. Bravina et al., *EPJC 74 (2014) 2807*

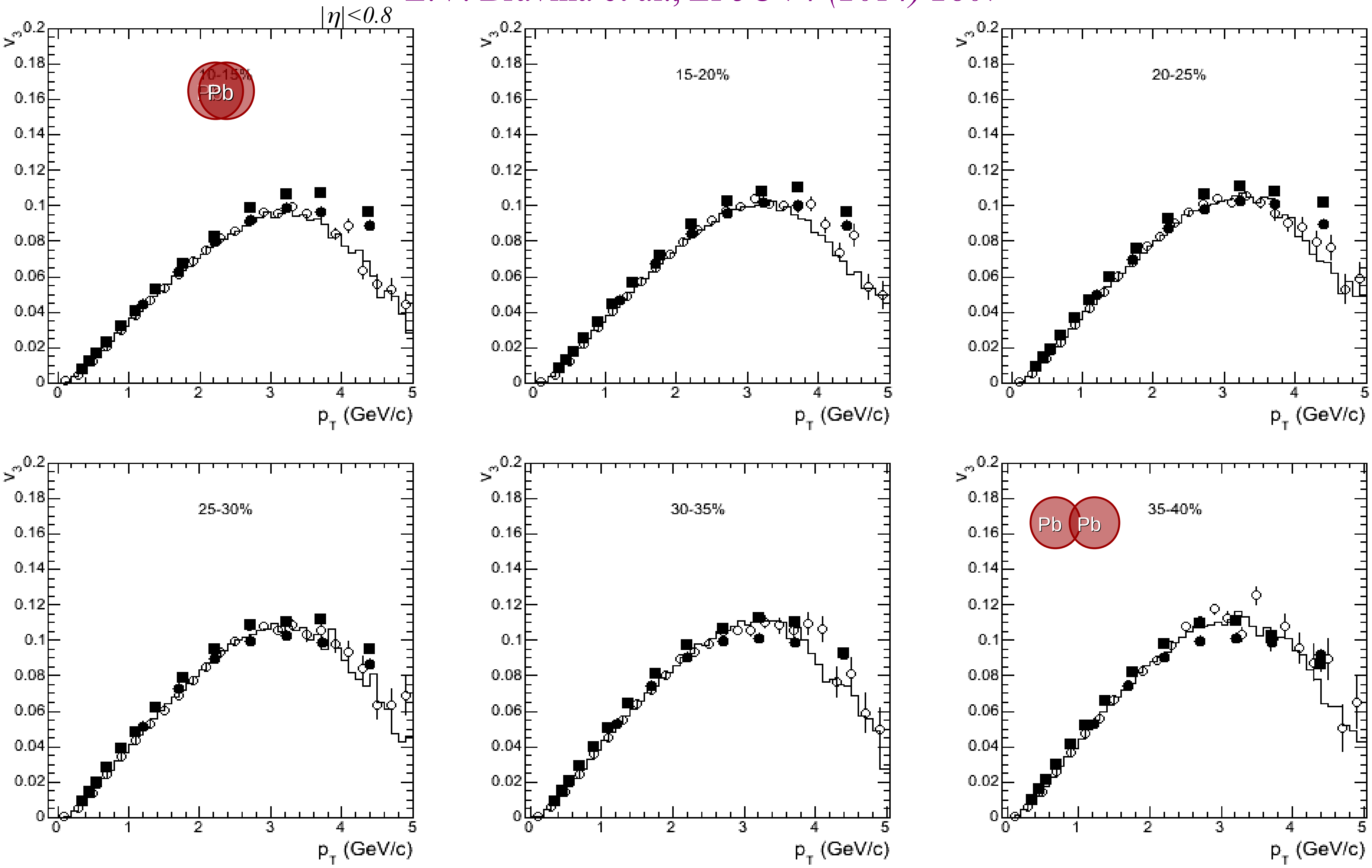


Closed circles and squares: CMS data $v_2\{2\}$ & $v_2\{LYZ\}$ *(PRC 87 (2013) 014902);*

histograms and open circles: HYDJET++ (“true” $v_2(\psi_2)$ & $v_2\{EP\}$)

Triangular flow of inclusive charged hadrons

L.V. Bravina et al., *EPJC 74 (2014) 2807*

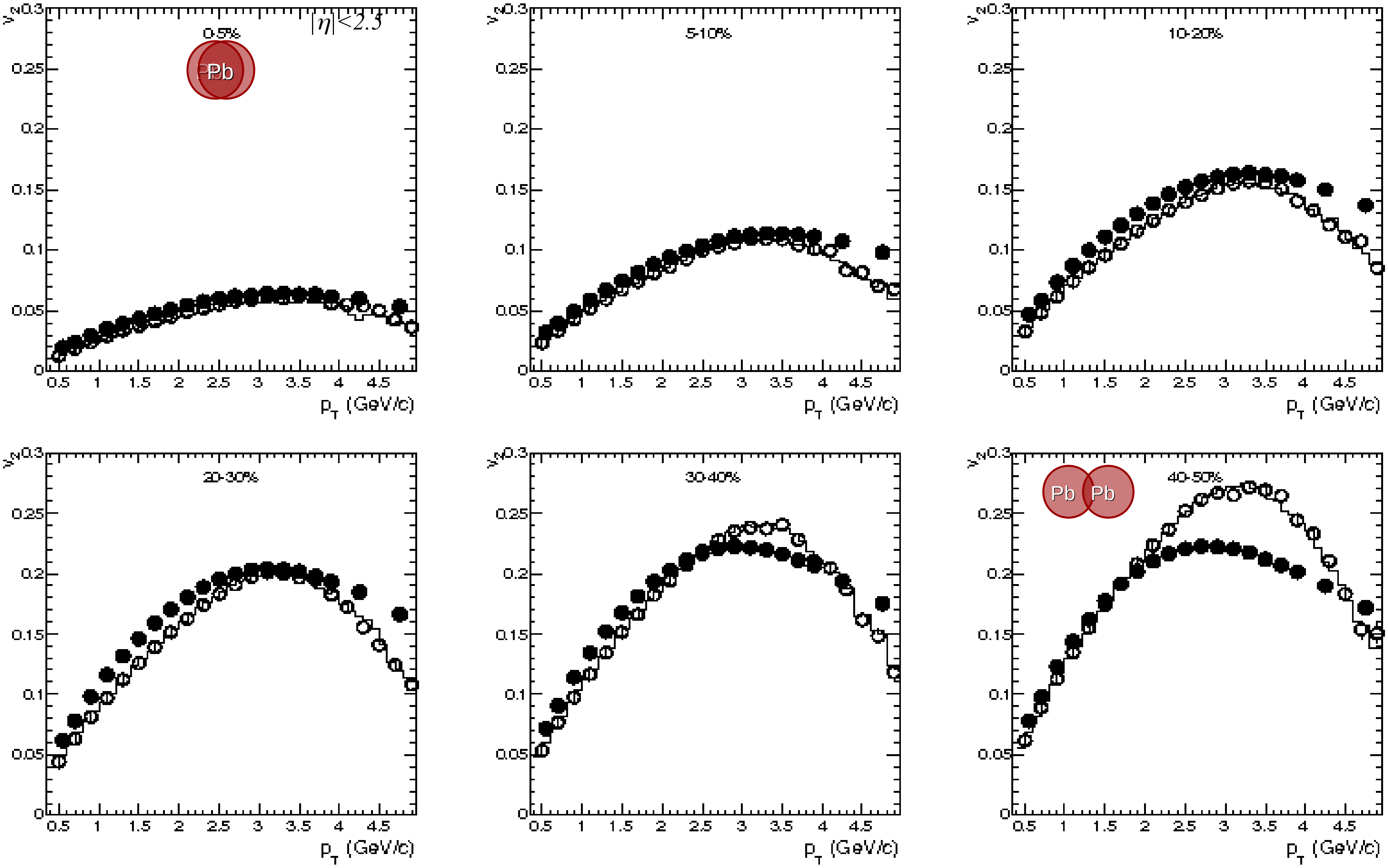


Closed circles and squares: CMS data $v_3\{2\}$ & $v_3\{EP\}$ *(PRC 89 (2014) 044906);*

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

Elliptic flow of inclusive charged hadrons

L.V. Bravina et al., *EPJC 74 (2014) 2807*

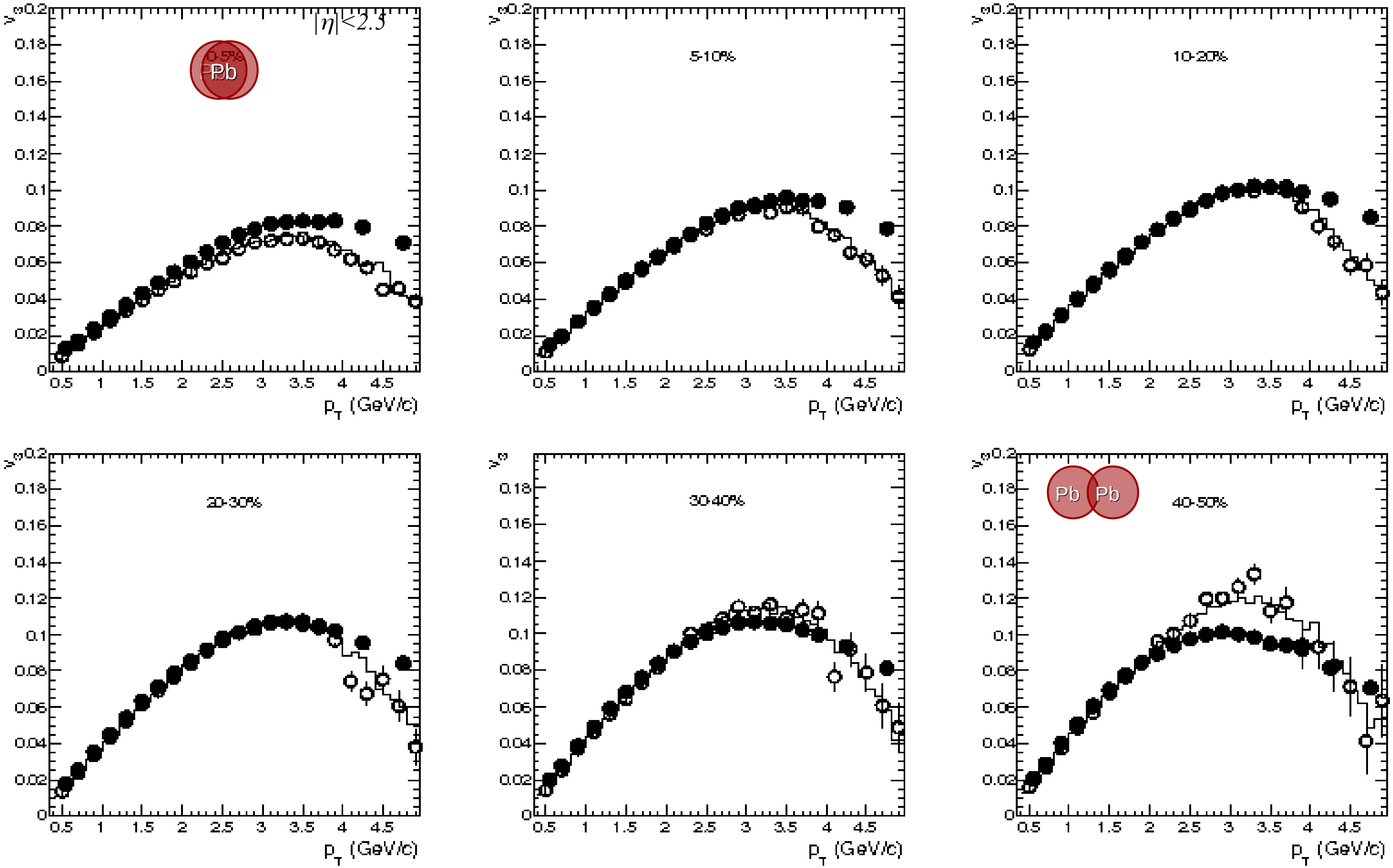


Closed circles: ATLAS data $v_2\{EP\}$ *(PRC 86 (2012) 014907);*

histograms and open circles: HYDJET++ (“true” $v_2(\psi_2)$ & $v_2\{EP\}$)

Triangular flow of inclusive charged hadrons

L.V. Bravina et al., *EPJC 74 (2014) 2807*

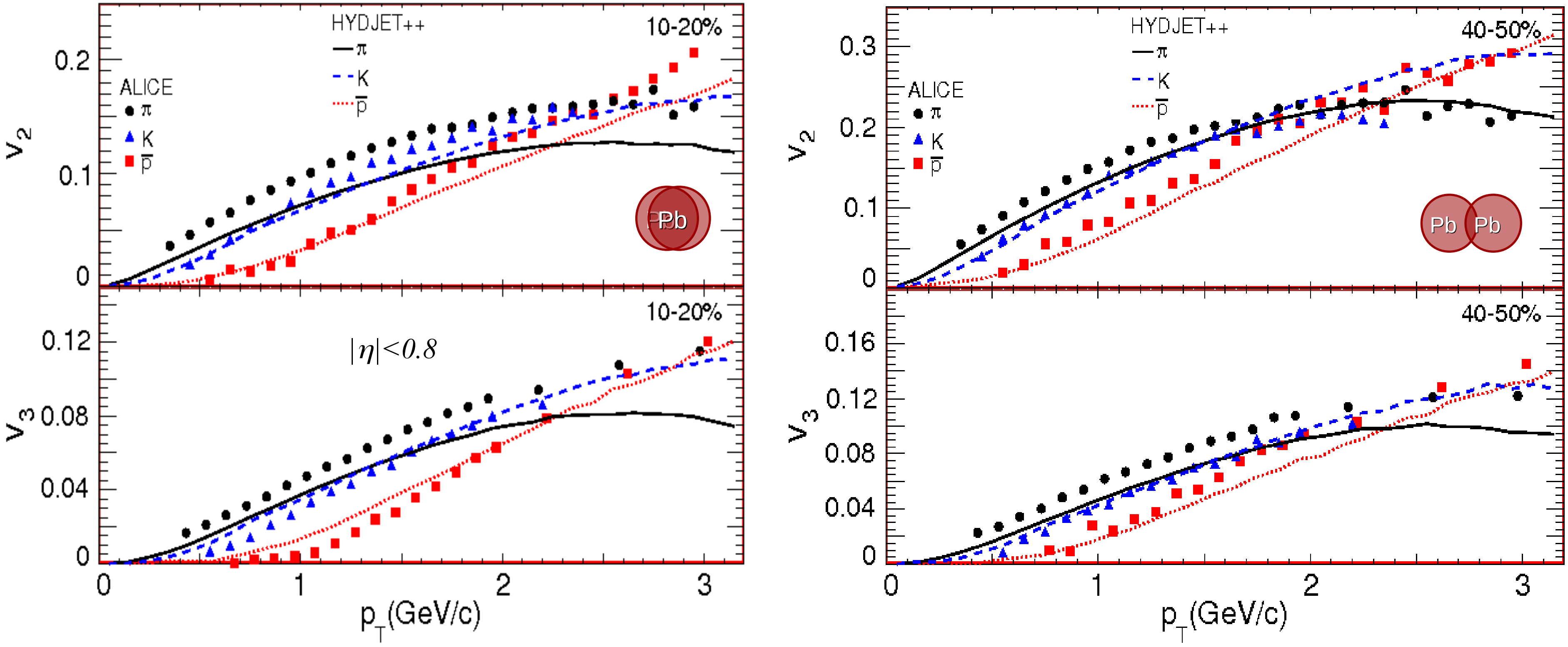


Closed circles: ATLAS data $v_3\{EP\}$ *(PRC 86 (2012) 014907);*

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

Elliptic and triangular flows of identified hadrons

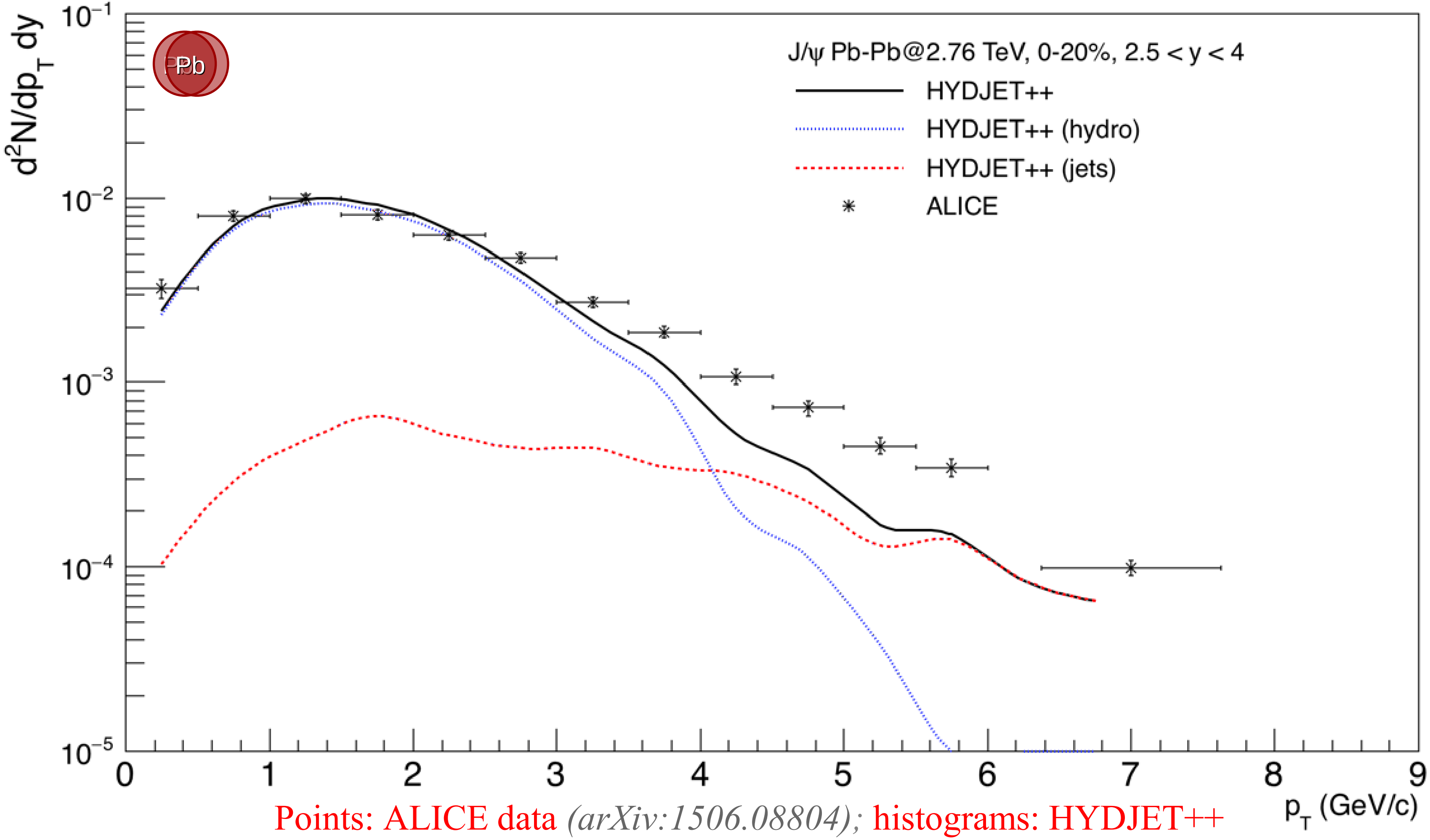
L.V. Bravina et al., *EPJC 74 (2014) 2807*



Points: ALICE data *(JPG 38 (2011) 124047);* histograms: HYDJET++

HYDJET++ reproduces v_2 and v_3 for kaons and (anti-)protons, but rather underestimates the data for pions (stronger non-flow correlations in the data than in the model?)

J/ψ mesons at LHC (p_T-spectrum)



Points: ALICE data *(arXiv:1506.08804);* histograms: HYDJET++
($T_{th} = T_{ch}$ = 165 MeV, η^{max} = 2.3, ρ_u^{max} = 0.6, γ_c = 11.5, $P_{T\,min}$ = 3.0 GeV/c)

HYDJET++ reproduces J/ψ-meson p_{T}-spectrum (up to ~3 GeV/c) with the *freeze-out parameters different* from ones for inclusive hadrons ⇒ kinetic freeze-out of J/ψ *thermal component* occurs before freeze-out of light hadrons; *non-thermal component* is important at intermediate & high p_T