Spectra and Elliptic Flow of Charmed Hadrons in HYDJET++ Model

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Charmed Mesons in Heavy-Ion Collisions

- Production via hard parton-parton scattering
- Thermal production

Number of questions arise on heavy quarks in heavy-ion collisions:

- Are heavy quarks thermalized in quark-gluon plasma?
- What is the interplay between thermal and non–thermal mechanisms of J/ψ meson production?
- What is the mass dependence of medium-induced quark energy loss?

Charmed Mesons in HYDJET++ Model

HYDJET++ (HYDrodynamics + JETs), the event generator to simulate heavy-ion event as merging of two independed components (soft hydro type part + hard multi-partonic state).

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

- Non-thermal production: charm quarks are generated within PYTHIA/PYQUEN with medium induced rescattering and radiative energy loss + PYTHIA hadronization
- Thermal production: the yield of charm hadrons is calculated within statistical hadronization model with charm production being controlled by charm enhancement factor γ_c

Non-thermal Production - Jet Quenching

Energy loss:

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

The scattering probability density:

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

Parton collisional loss (high momentum transfer approximation):

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

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

Parton radiative loss (coherent gluon radiation in BDMS-formalism):

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

with $\bar{k} = \frac{\mu_D^2 \lambda_g}{\omega(1-y)}, \;\; \tau_1 = L/(2\lambda_g), \;\; y = \omega/E$

For heavy quark (dead cone approximation): $\left.\frac{dE}{dl d\omega}\right|_{m_q \neq 0} = \frac{1}{(1+(\beta\omega)^{3/2})^2} \left.\frac{dE}{dl d\omega}\right|_{m_q=0}, \;\; \beta = \left(\frac{\lambda}{\mu_D^2}\right)^{1/3} \frac{m_q}{E}^{4/3}$

Non-thermal Production - Jet Quenching

Three model parameters:

- Initial QGP temperature T_0
- QGP formation time τ_0
- Number of active quark flavors in QGP N_f

Minimal p_T of hard process p_T^{min} controls the contribution of hard and soft part into the total multiplicity.

Thermal Production

Mean multiplicity N_i and Event-by-Event distribution of hadron species i:

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

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

where p^{*0} is the hadron energy in the fluid element rest frame

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

where γ_s is strangeness suppression factor, also quantum statistics is accounted for chemical freeze-out of fireball with the distribution functions in the fluid element rest frame

Thermal Production of Charmed Particles

$$J/\psi, D^0, \overline{D^0}, D^+, D^-, D^{*+}, D^{*-}, D_s^+, D_s^-, \Lambda_c^+, \Lambda_c^-$$

Thermal charmed hadrons are generated within statistical hadronization model

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

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

Where charm enhancement factor γ_c may be set manually or calculated from:

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

where $N_{c\bar{c}}$ is a number of $c\bar{c}$-quark pairs obtained from PYTHIA scaled by $\langle N_{coll} \rangle$ (the factor $K \sim 2$ is applied to take into account NLO pQCD corrections)

Elliptic Flow v_2 in HYDJET++ Model

$$v_2 = \langle \cos[2(\varphi - \Psi_{RP})] \rangle$$

- Hard component: generated via jet quenching dependence on in-medium path length
- Soft component: generated via momentum and spatial anisotropy of the emitting source

The spatial anisotropy:

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

The momentum anisotropy:

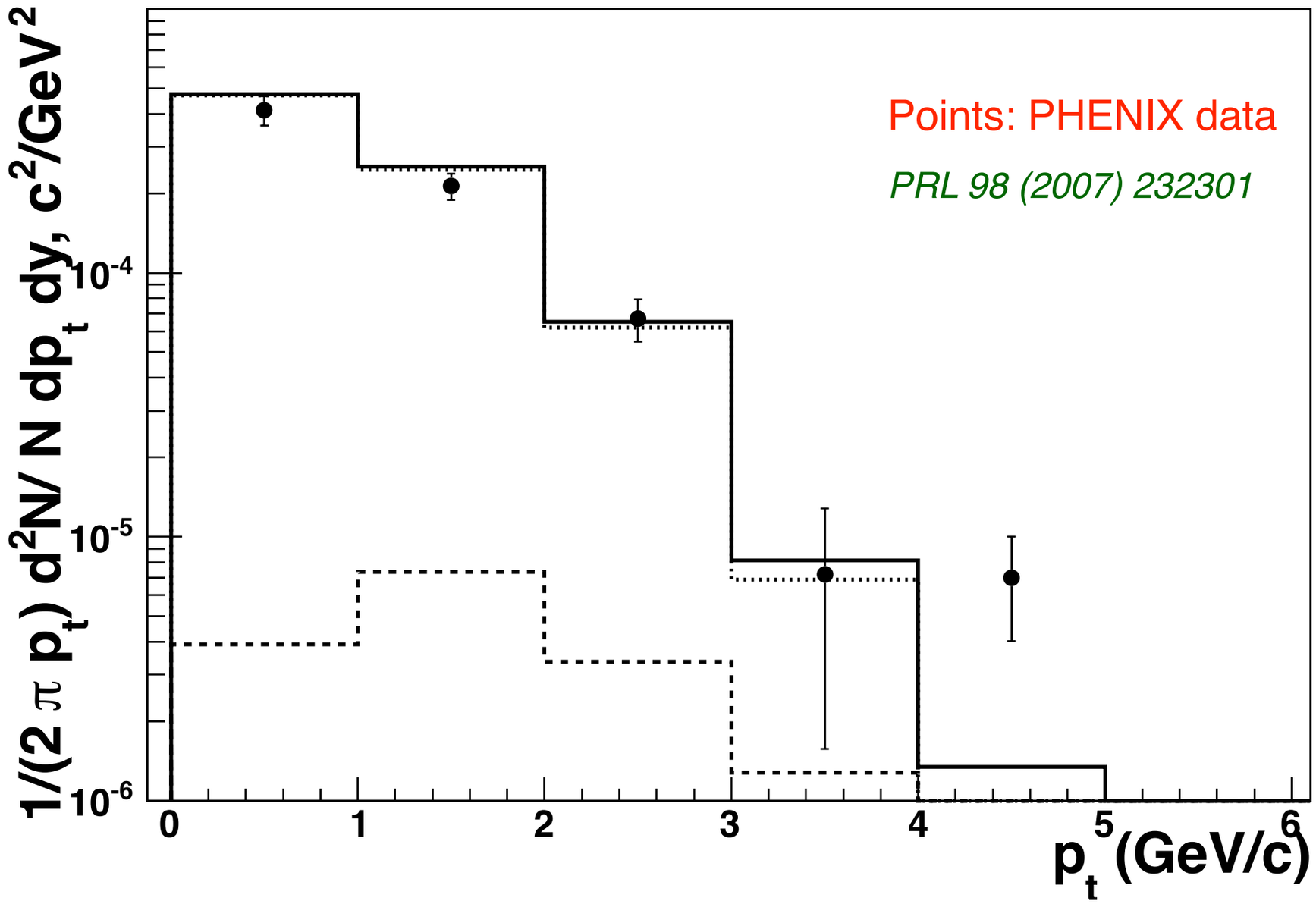
$$\tan \varphi_u = \sqrt{\frac{1 - \delta(b)}{1 + \delta(b)}} \tan \varphi$$

There are two free parameters, obtained by fitting the model prediction to experimental data.

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

Charmed Mesons at RHIC - J/ψ meson

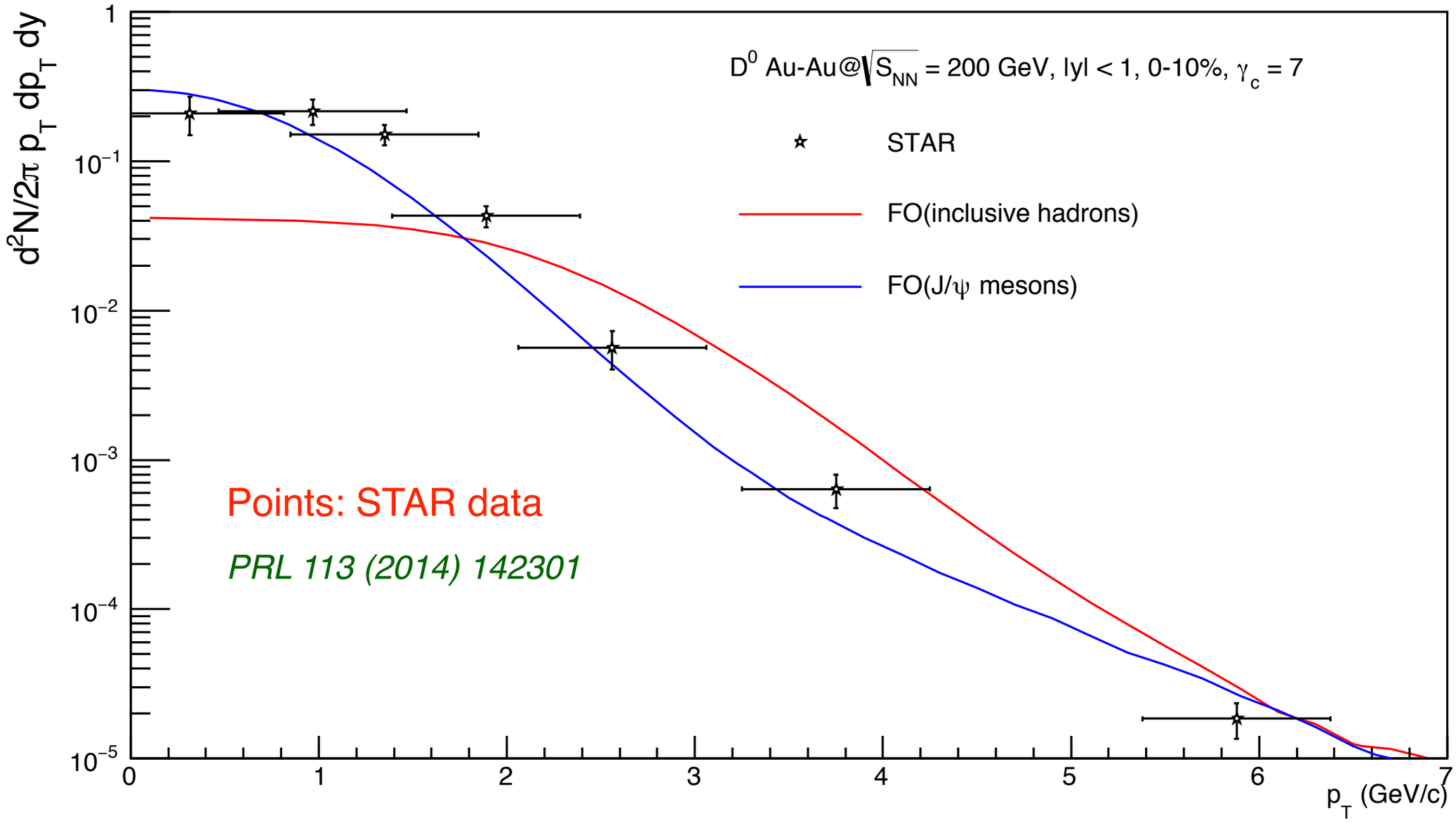
I P Lokhtin *et al* 2011 *J. Phys.: Conf. Ser.* **270** 012060



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

$$T^{th}_{J/\psi} = T^{ch}_{J/\psi} = 0.165\ GeV, \eta^{J/\psi}_{max} = 1.1,\ \ \rho^{J/\psi}_{max} = 0.5$$

Charmed Mesons at RHIC - D^0 meson

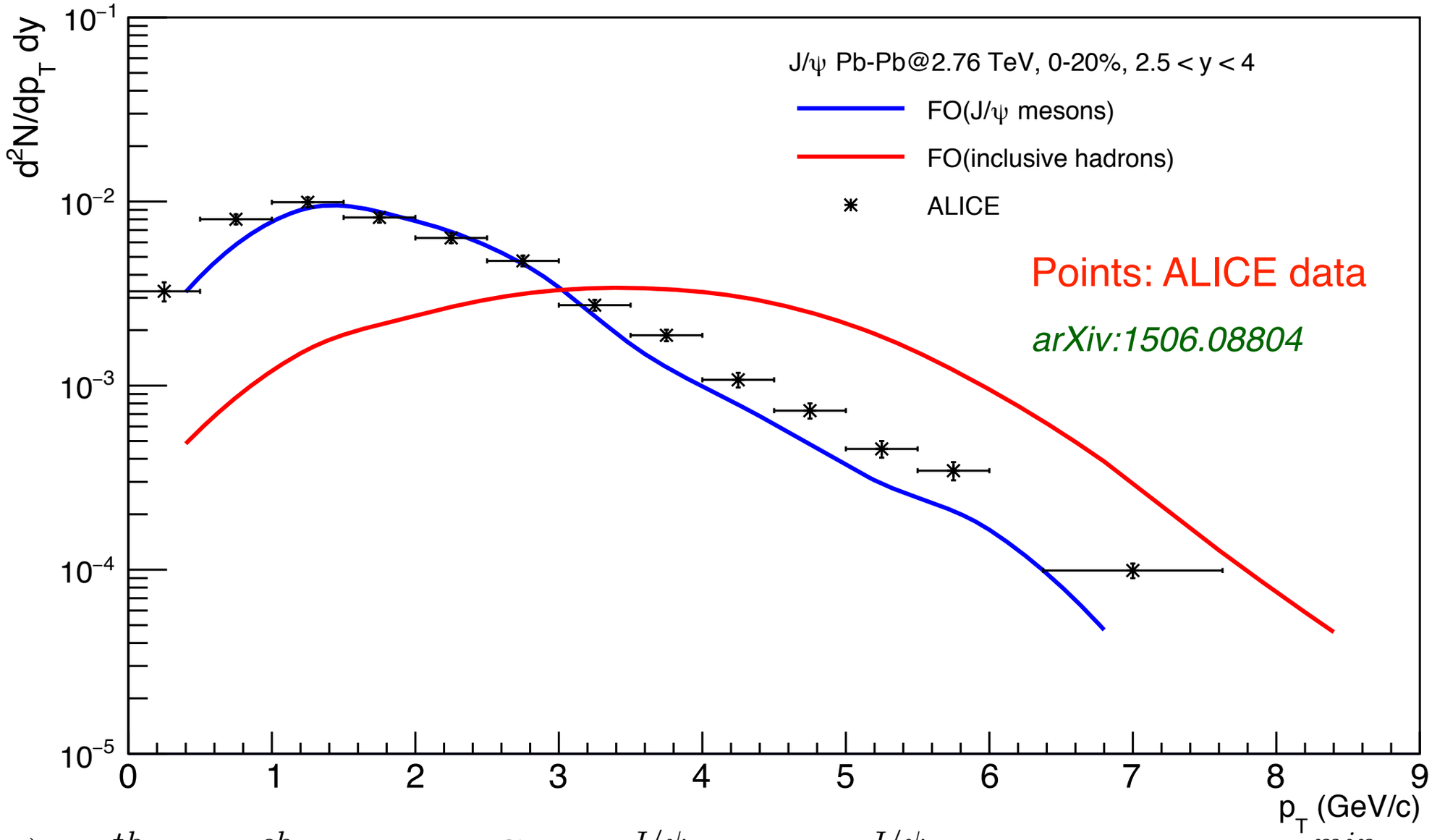


Simulated p_T spectrum of D^0 matches the data only if freeze-out parameters for D^0 are same as for J/ψ

Charmed Mesons at RHIC - Summary

- Momentum spectra of D^0 and J/ψ mesons in most central Au-Au collisions may be reproduced by two-component model including thermal (soft) and non-thermal (hard) components with the same freeze-out parameters
- Thermal freeze-out of charmed mesons happens appreciably before thermal freeze-out of light hadrons, presumably at chemical freeze-out (with reduced radial & longitudinal collective velocities)
- Thus D and J/ψ mesons seem to be not in a kinetic equilibrium with created medium

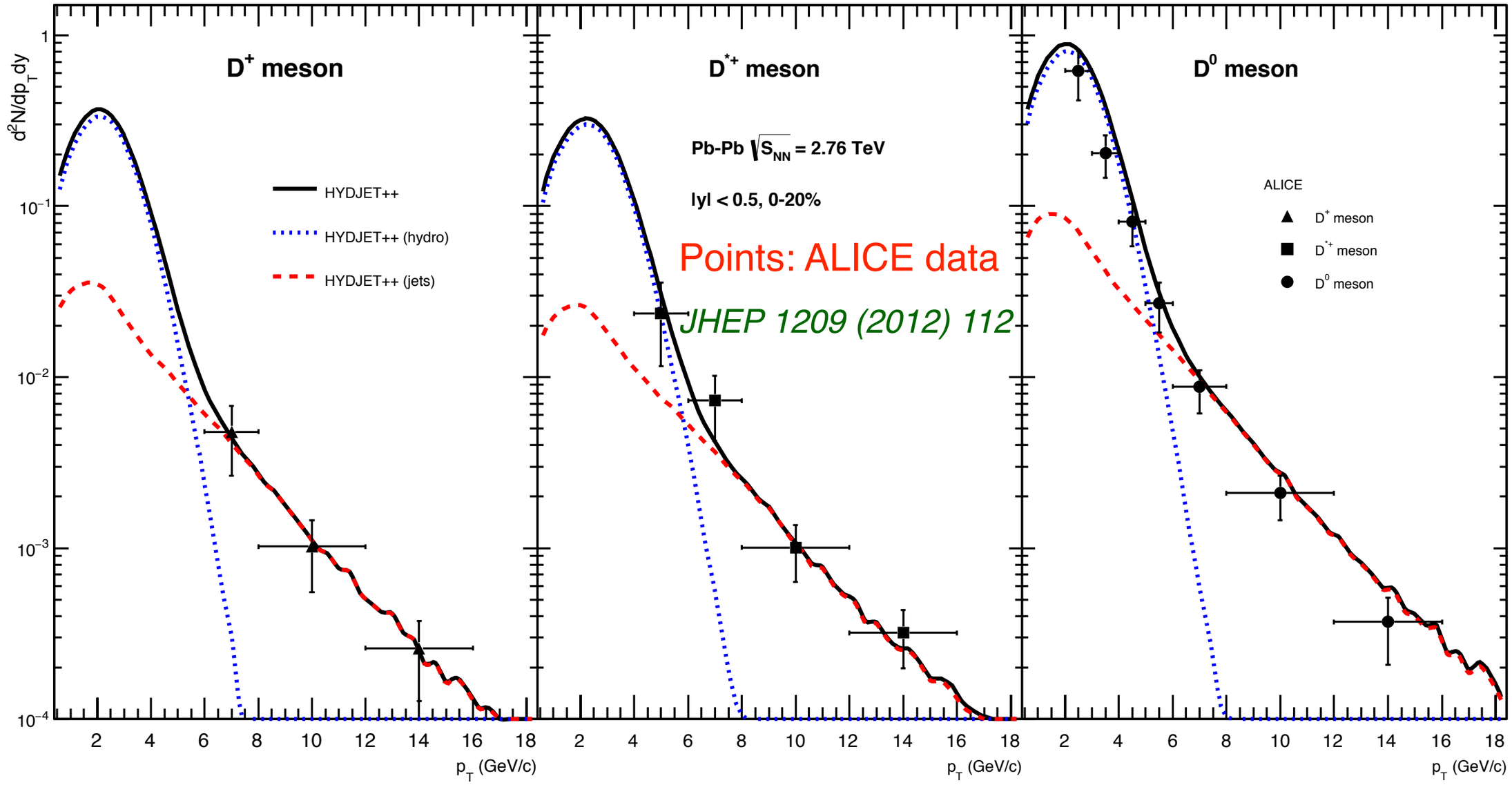
Charmed mesons at the LHC - J/ψ meson



$$\mathrm{FO}(J/\psi) : T^{th}_{J/\psi} = T^{ch}_{J/\psi} = 0.165\ GeV,\ \eta^{J/\psi}_{max} = 2.3,\ \rho^{J/\psi}_{max} = 0.6,\ \gamma_c = 11.5,\ p_T^{min} = 3.0\ GeV/c$$

HYDJET++ reproduces J/ψ-meson p_T spectrum (up to $\sim 3\ GeV/c$) with the freeze-out parameters different from ones for inclusive hadrons $\Rightarrow$ 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 (like at RHIC!)

Charmed mesons at the LHC - D mesons

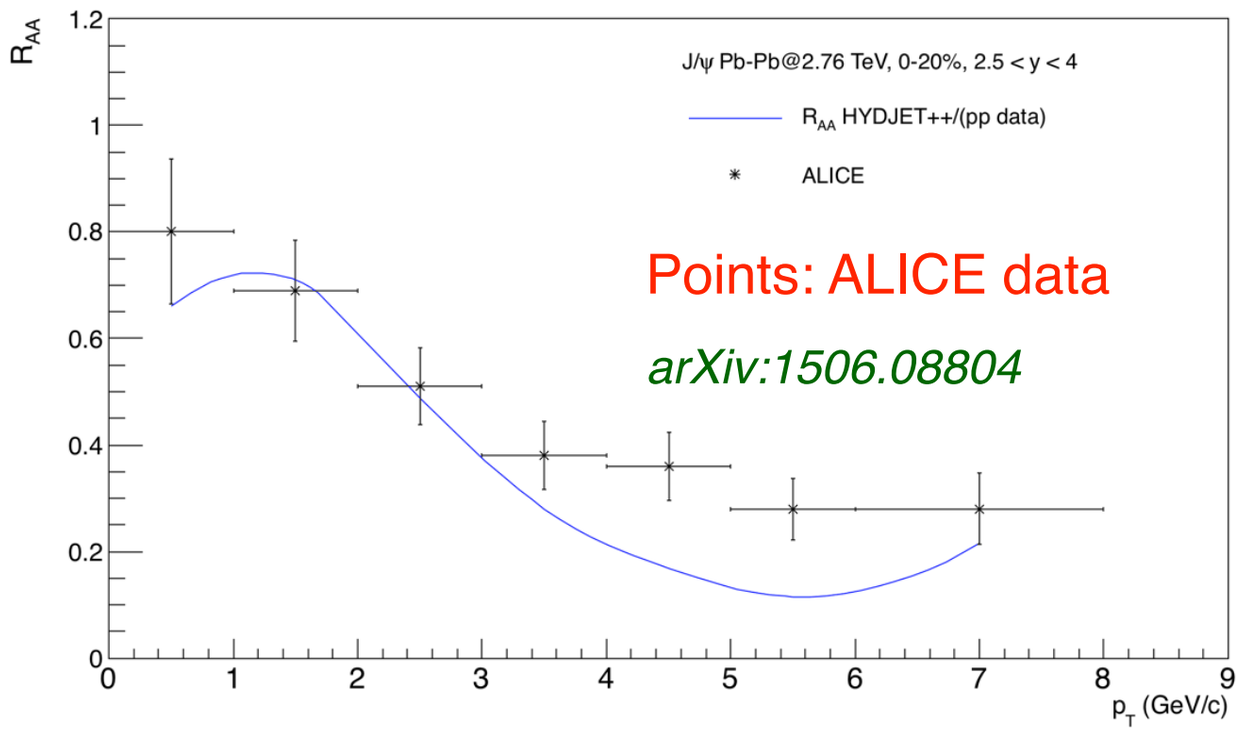


$$\mathrm{FO(inclusive)}: T^{th} = 0.105\ GeV, T^{ch} = 0.165\ GeV, \eta_{max} = 4.5, \rho_{max} = 1.265, \gamma_c = 11.5, p_T^{min} = 8.2\ GeV/c$$

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

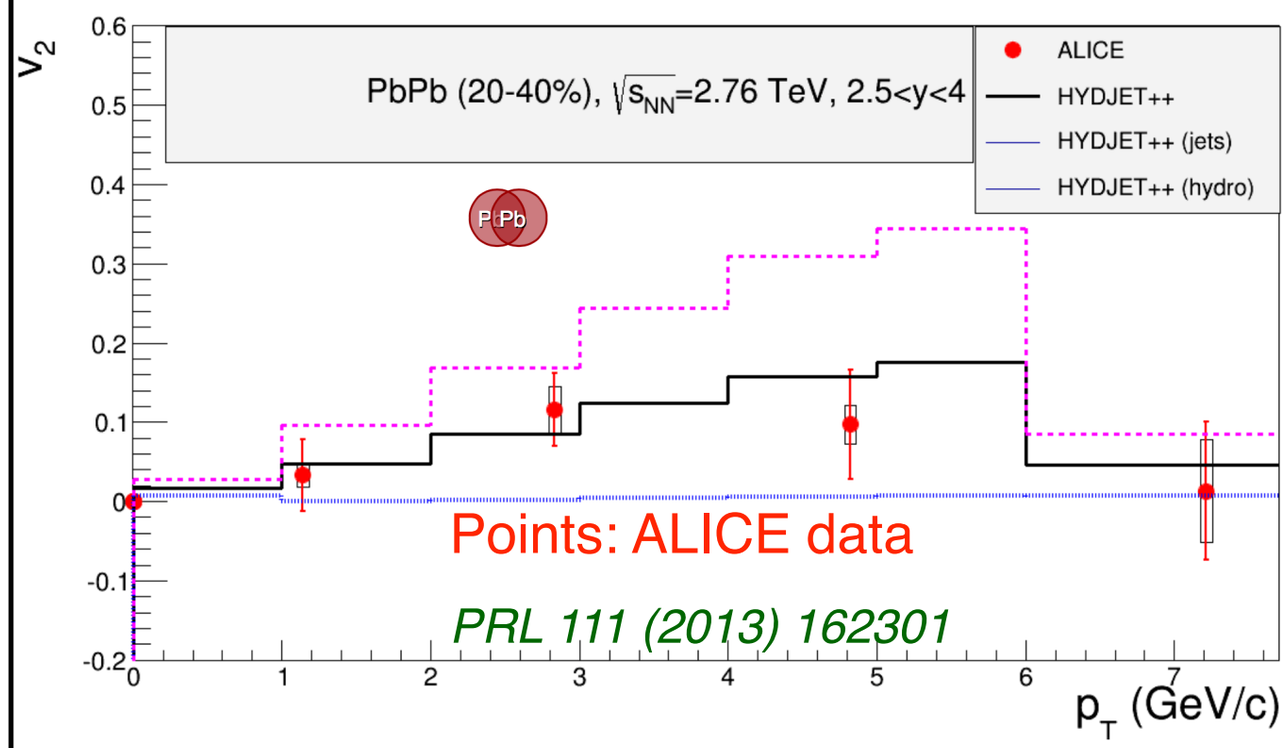
J/ψ at the LHC - v_2 and R_{AA}

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



Superposition of thermal and non-thermal components qualitatively reproduces momentum dependence of J/ψ R_{AA} at the LHC.
(but PYTHIA@HYDJET++ tuning is required for adequate J/ψ modelling at high p_T).

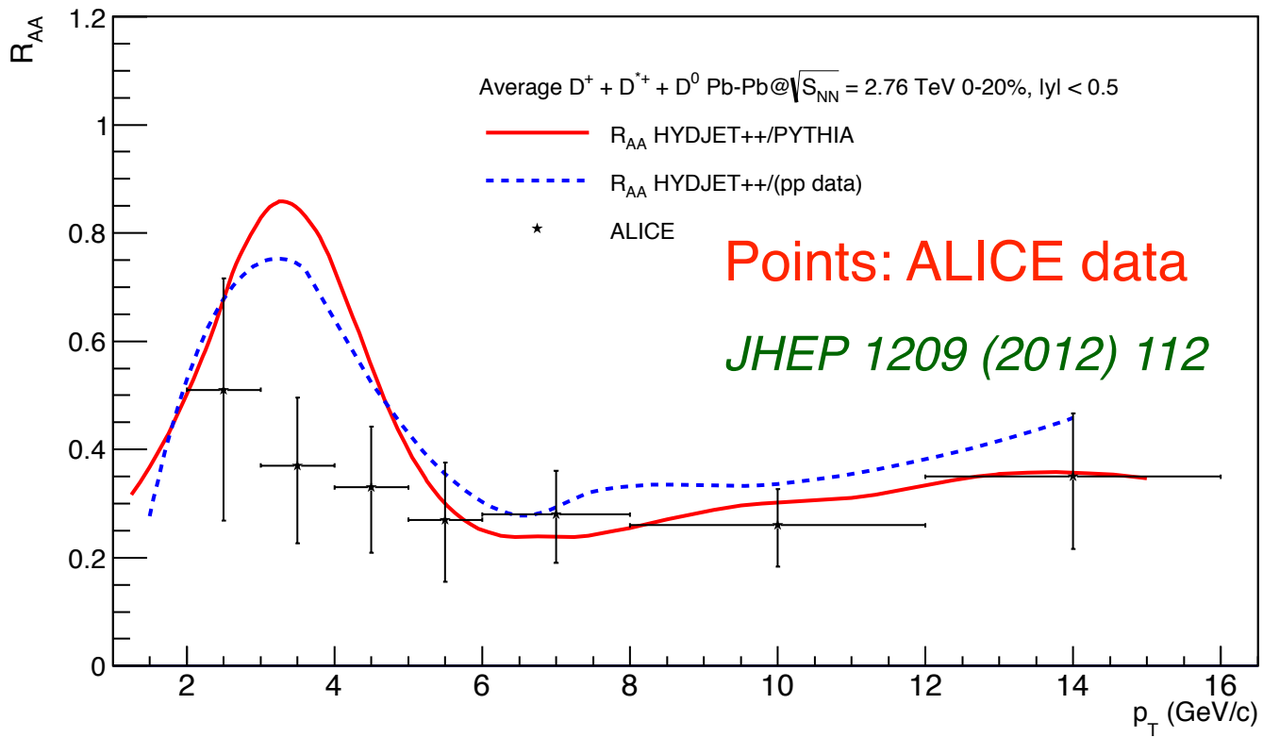
$$v_2 = \langle \cos[2(\varphi - \Psi_{RP})] \rangle$$



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

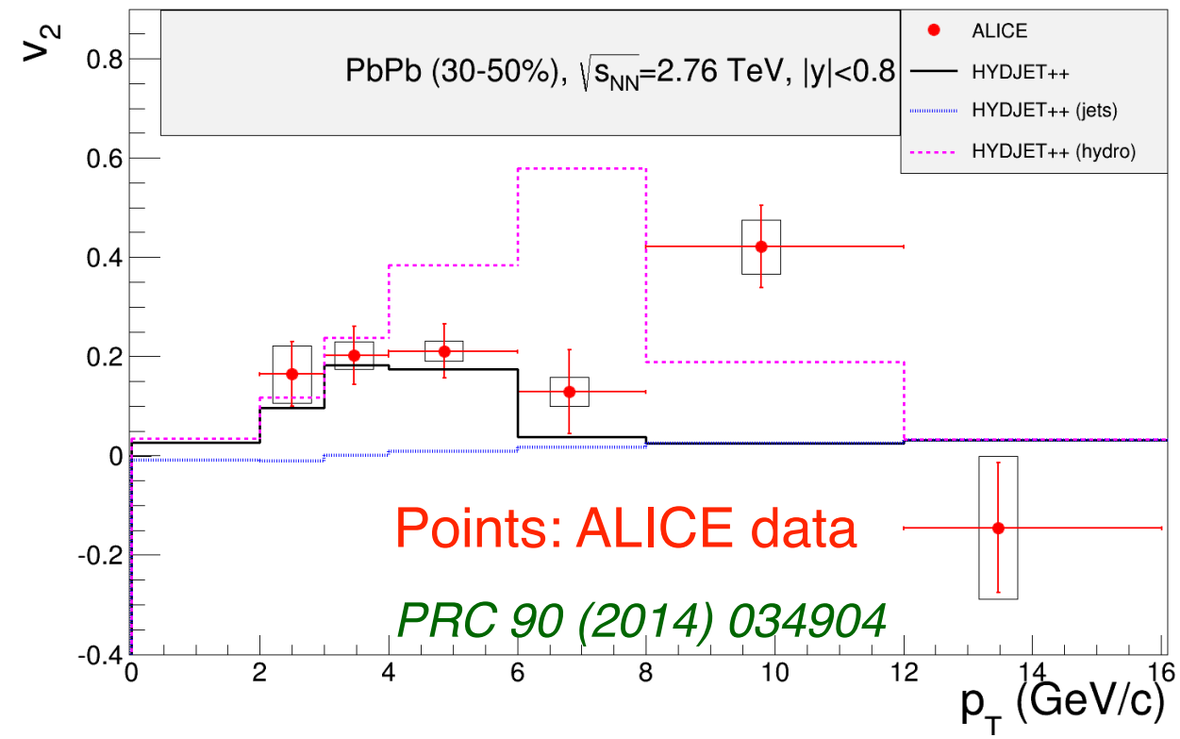
D mesons at the LHC - v_2 and R_{AA}

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



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

$$v_2 = \langle \cos[2(\varphi - \Psi_{RP})] \rangle$$



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

Charm at the LHC - Summary

- Momentum spectra and elliptic flow of D and J/ψ mesons in Pb-Pb collisions may be reproduced by two-component model including thermal (soft) and non-thermal (hard) components (D mesons with same FO-parameters as for inclusive hadrons, J/ψ- no)
- Thermal freeze-out of D mesons happens simultaneously with thermal freeze-out of light hadrons; thermal freeze-out of J/ψ mesons happens appreciably before thermal freeze-out of light hadrons, presumably at chemical freeze-out (with reduced radial & longitudinal collective velocities, and enhanced non-thermal contribution).
- Thus the significant part of D mesons (up to $p_T \sim 4\ GeV/c$) seems to be in a kinetic equilibrium with the medium, while J/ψ mesons – not yet. Taking into account non-thermal production mechanism & in-medium heavy quark energy loss are important at high transverse momenta

Significant degree of c-quark thermalization in QGP is achieved in Pb-Pb collisions at the LHC (?)

Acknowledgments

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european social fund in the czech republic

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