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 $J/\psi$ meson production?
- What is the mass dependence of medium-induced quark energy loss?
HYDJET++ (HYDrodynamics + JETs), the event generator to simulate heavy-ion event as merging of two independent components (soft hydro type part + hard multi-partonic state).


- **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 $\gamma_c$
Non-thermal Production - Jet Quenching

Energy loss:
\[ \Delta E(L, E) = \int_0^L dl \frac{dP(l)}{dl} \lambda(l) \frac{dE(l, E)}{dl} \]

The scattering probability density:
\[ \frac{dP(l)}{dl} = \frac{1}{\lambda(l)} \exp\left(-l/\lambda(l)\right) \]

**Parton collisional loss** (high momentum transfer approximation):
\[ \frac{dE^{\text{col}}}{dl} = \frac{1}{4T \lambda \sigma} \int_{\mu_D^2}^{t_{\text{max}}} dt \frac{d\sigma}{dt} t, \quad \frac{d\sigma}{dt} \approx C \frac{2\pi \alpha_s^2(t)}{t^2} \frac{E^2}{E^2 - m_p^2}, \quad \alpha_s = \frac{12\pi}{(33 - 2N_f) \ln(t/\Lambda_{QCD}^2)} \]

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

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

For heavy quark (dead cone approximation):
\[ \left. \frac{dE}{dl d\omega} \right|_{m_q \neq 0} = \frac{1}{(1 + (\beta \omega)^{3/2})^2} \left. \frac{dE}{dl d\omega} \right|_{m_q = 0}, \quad \beta = \left( \frac{\lambda}{\mu_D^2} \right)^{1/3} \frac{m_q^{4/3}}{E} \]
Non-thermal Production - Jet Quenching

**Three model parameters:**

- Initial QGP temperature $T_0$
- QGP formation time $\tau_0$
- 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 $i$:

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

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

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 $\gamma_s$ 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

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

Thermal charmed hadrons are generated within statistical hadronization model


\[ N_D = \gamma_c N_{th}^D \frac{I_1(\gamma_c N_{th}^D)}{I_0(\gamma_c N_{th}^D)}, \quad N_{J/\psi} = \gamma_c^2 N_{th}^{J/\psi} \]

Where charm enhancement factor \( \gamma_c \) may be set manually or calculated from:

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

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.

$$v_2 \propto \frac{2(\delta - \epsilon)}{(1 - \delta^2)(1 - \epsilon^2)}$$
Thermal freeze-out for $J/\psi$ happens at the same temperature as chemical freeze-out

$$T_{J/\psi}^{th} = T_{J/\psi}^{ch} = 0.165 \text{ GeV}, \eta_{max}^{J/\psi} = 1.1, \rho_{max}^{J/\psi} = 0.5$$
Simulated $p_T$ spectrum of $D^0$ matches the data only if freeze-out parameters for $D^0$ are same as for $J/\psi$.
Momentum spectra of $D^0$ and $J/\psi$ 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 $J/\psi$ mesons seem to be not in a kinetic equilibrium with created medium.
Charmed mesons at the LHC - $J/\psi$ meson

Points: ALICE data

$\text{arXiv:1506.08804}$

$\text{HYDJET++}$ reproduces $J/\psi$-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 $J/\psi$ 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

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!)

Points: ALICE data

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$J/\psi$ at the LHC - $v_2$ and $R_{AA}$

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

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

Points: ALICE data

Superposition of thermal and non-thermal components qualitatively reproduces momentum dependence of $J/\psi$ $R_{AA}$ at the LHC.

(but PYTHIA@HYDJET++ tuning is required for adequate $J/\psi$ modelling at high $p_T$).

HYDJET++ reproduces $v_2(p_T)$ with the freeze-out parameters different from ones for inclusive hadrons $\Rightarrow$ kinetic freeze-out of $J/\psi$ thermal component occurs appreciably before freeze-out of light hadrons.
$D$ mesons at the LHC - $v_2$ and $R_{AA}$

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

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

$\langle \cos[2(\phi - \Psi_{RP})]\rangle$

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 $J/\psi$ 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, $J/\psi$- no)

- Thermal freeze-out of $D$ mesons happens simultaneously with thermal freeze-out of light hadrons; thermal freeze-out of $J/\psi$ 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 $p_T \sim 4 \text{ GeV}/c$) seems to be in a kinetic equilibrium with the medium, while $J/\psi$ 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 (?)
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