Coalescence production of charmonium states in heavy ion collisions

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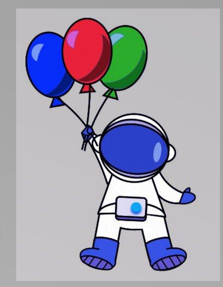
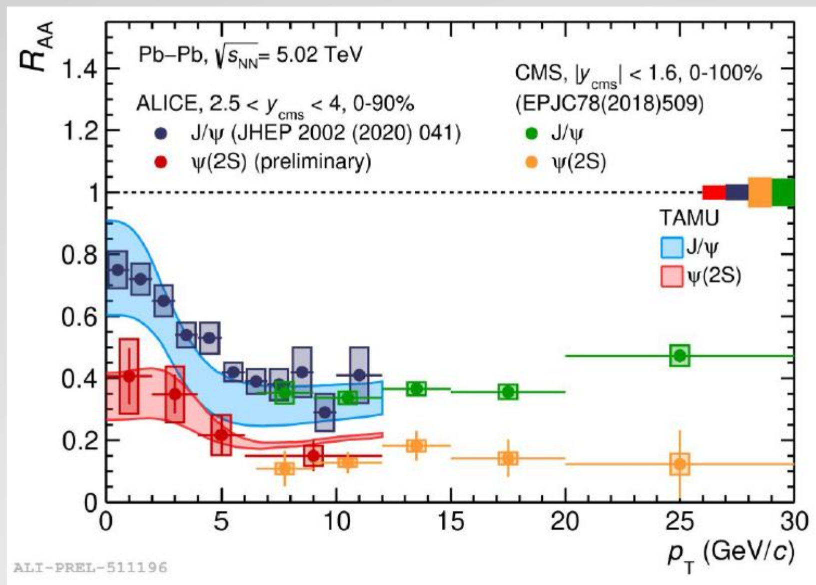


Abstract

We study charmonium states, J/ψ, $\psi(2S)$, and $\chi_{c1}(1P)$ mesons in heavy ion collisions by focusing on their production from charm and anti-charm quarks in a quark-gluon plasma by coalescence. Starting from the investigation on the difference in their internal structures, or different wave functions of charmonium states we calculate the yield and transverse momentum distributions of charmonium states produced in heavy ion collisions. We show that the wave function distribution plays a significant role, especially, in the production of charmonium states, leading to the transverse momentum distribution of the $\psi(2S)$ meson as large as that of the J/ψ meson. We also discuss the anisotropic flow, or elliptic and triangular flow of charmonium states using the transverse momentum distribution of charmonium states. We find that the internal structure differences as well as feed-down contributions of charmonium states are averaged out for elliptic and triangular flow, resulting in similar elliptic and triangular flow for all charmonium states. Based on our evaluation of elliptic and triangular flow of charmonium states we also discuss *the quark number scaling of elliptic and triangular flow* for charmonium states in heavy ion collisions.

Introduction

- The larger charm quark density at LHC is expected to result in enhanced chances for the formation of J/ψ from QGP [1,2].
- Measurements of centrality independent J/ψ R_{AA} at forward rapidity, and also those of J/ψ elliptic flows at LHC support possibilities of J/ψ production from charm quarks in the QGP by recombination [3,4].
- Recent measurements by ALICE showing that R_{AA} of both J/ψ and ψ(2S) mesons at low transverse momentum regions supports the production of charmonium states by recombination [5].

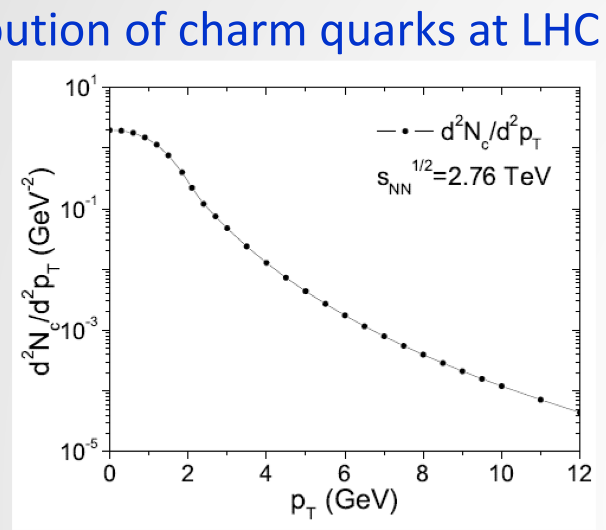


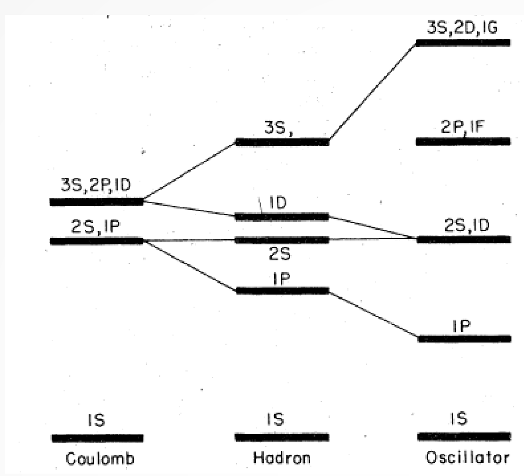
Charm quark v_2 and p_T distributions

- Transverse momentum distribution of charm quarks at LHC [8]

$$\frac{dN_{jet}}{d^2p_T} = A_1\left[1+\left(\frac{p_T}{A_2}\right)^2\right]^{-A_3} + A_4\left[1+\left(\frac{p_T}{A_5}\right)^2\right]^{-A_6}$$

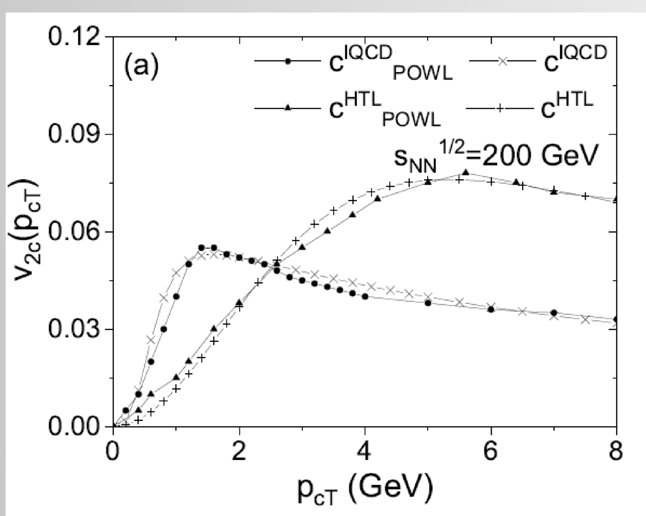
$$\frac{dN_c}{d^2p_T} = \begin{cases} a_0\exp[-a_1p_T^{a_2}] & p_T \le p_0 \\ a_0\exp[-a_1p_T^{a_2}] + a_3(1+p_T^{a_4})^{-a_5} & p_T \ge p_0 \end{cases}$$





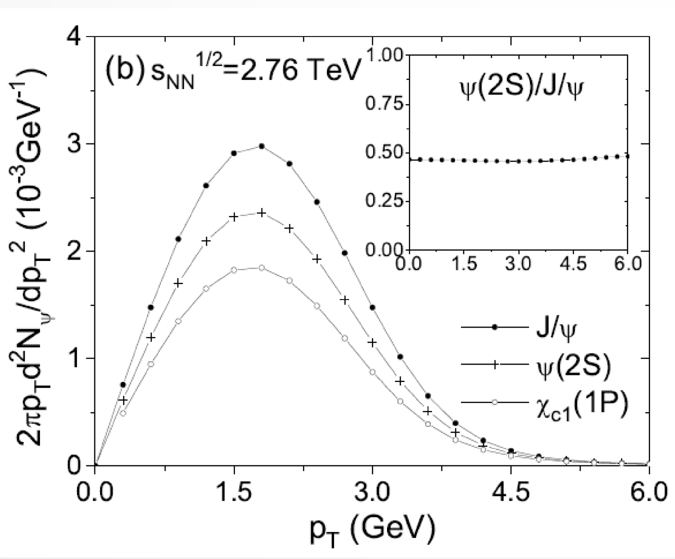
Charmonium state wave functions [10]

- Elliptic flow of charm quarks from the transport setup [9]



$$\int d^3\vec{r}W_\psi(\vec{r},\vec{k}) = \begin{cases} (2\sqrt{\pi}\sigma)^3e^{-k^2\sigma^2} & \psi^G_s; J/\psi \\ \frac{2}{3}(2\sqrt{\pi}\sigma)^3e^{-k^2\sigma^2}\sigma^2k^2 & \psi^G_p; \chi_c \\ \frac{2}{3}(2\sqrt{\pi}\sigma)^3e^{-k^2\sigma^2}\left(\sigma^2k^2-\frac{3}{2}\right)^2 & \psi^G_{10}; \psi(2S) \\ 64\pi\frac{a_0^3}{(a_0^2k^2+1)^4} & \psi^C_{1S}; J/\psi \\ 8\pi a_0^3\frac{(a_0^2k^2-1/4)^2}{(a_0^2k^2+1/4)^6} & \psi^C_{2S}; \psi(2S) \end{cases}$$

- Wave function dependence of charmonium states transverse momentum distributions : 1S, 1P, and 2S charmonium states, J/Ψ, χ_{c1}, and Ψ(2S)



Production of charmonium states by recombination

- Hadron productions by recombination in heavy ion collisions [6]

: Great successes in explaining not only the enhanced production of baryons at intermediate transverse momenta but also the quark number scaling of elliptic flows of identified hadrons

- Yields of hadrons in the coalescence model reflect the dynamic process of converting constituents to a bound state in the presence of a partonic matter

$$N^{Coal} = g\int\left[\prod_{i=1}^{n}\frac{1}{g_i}\frac{p_i\cdot d\sigma_i}{(2\pi)^3}\frac{d^3p_i}{E_i}f(x_i,p_i)\right]f^W(x_1,\cdots,x_n:p_1,\cdots,p_n)$$

- Wigner function, the coalescence probability function depends on Lorentz-invariant combinations of the relative coordinates between particles, and parameterizes the overlap integral between particle wave functions

$$f^W(x_1,\cdots,x_n:p_1,\cdots,p_n) = \int\prod_{i=1}^{n}dy_ie^{p_iy_i}\psi^*\left(x_1+\frac{y_1}{2},\cdots,x_n+\frac{y_n}{2}\right)\psi\left(x_1-\frac{y_1}{2},\cdots,x_n-\frac{y_n}{2}\right)$$

- Production of charmonium states by recombination [7]

$$N_\psi = g_\psi\int p_c\cdot d\sigma_cp_{\bar{c}}\cdot d\sigma_{\bar{c}}\frac{d^3\vec{p}_c}{(2\pi)^3E_c}\frac{d^3\vec{p}_{\bar{c}}}{(2\pi)^3E_{\bar{c}}}f_c(r_c,p_c)f_{\bar{c}}(r_{\bar{c}},p_{\bar{c}})W_\psi(r_c,r_{\bar{c}};p_c,p_{\bar{c}}),\quad W_\psi(\vec{r},\vec{k}) = \int\frac{d^3q}{(2\pi)^3}\psi^*(\vec{r}+\vec{q}/2)e^{i\vec{q}\vec{k}}\psi(\vec{r}-\vec{q}/2)$$

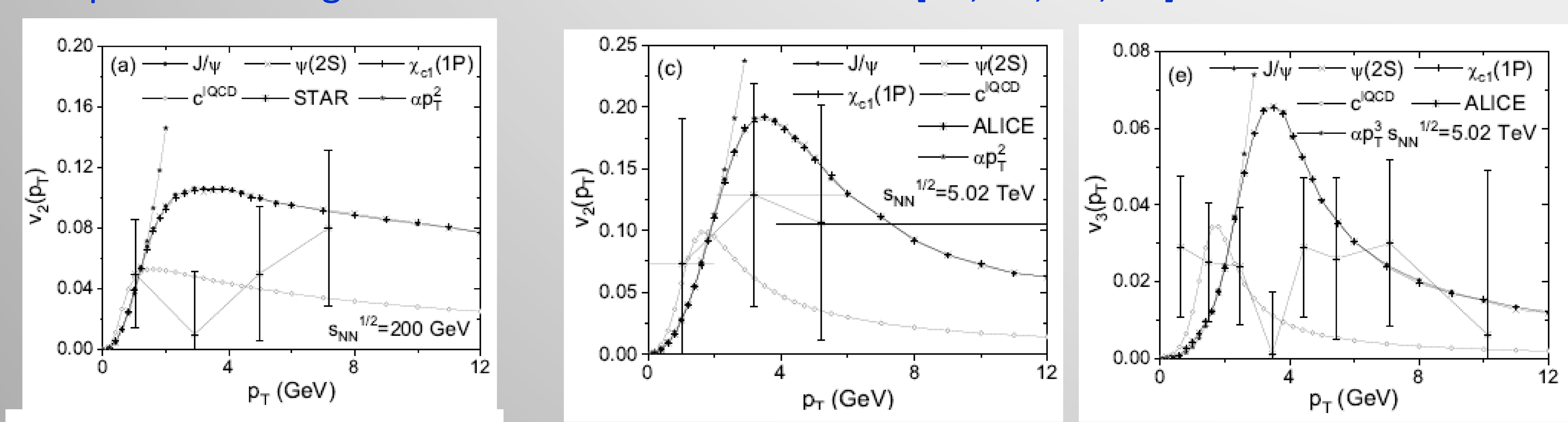
$$\frac{d^2N_\psi}{d^2\vec{p}_T} = \frac{g_\psi}{V}\int d^3\vec{r}d^2\vec{p}_{cT}d^2\vec{p}_{\bar{c}T}\delta^{(2)}(\vec{p}_T-\vec{p}_{cT}-\vec{p}_{\bar{c}T})\frac{d^2N_c}{d^2\vec{p}_{cT}}\frac{d^2N_{\bar{c}}}{d^2\vec{p}_{\bar{c}T}}W_\psi(\vec{r},\vec{k})\quad \frac{dN_\psi}{d\vec{p}_T} = \frac{g_\psi}{V}\int d\vec{p}_{cT}d\vec{p}_{\bar{c}T}\delta(\vec{p}_T-\vec{p}_{cT}-\vec{p}_{cT})\frac{dN_c}{d\vec{p}_{cT}}\frac{dN_{\bar{c}}}{d\vec{p}_{\bar{c}T}}\left|\tilde{\psi}(\vec{k})\right|^2$$

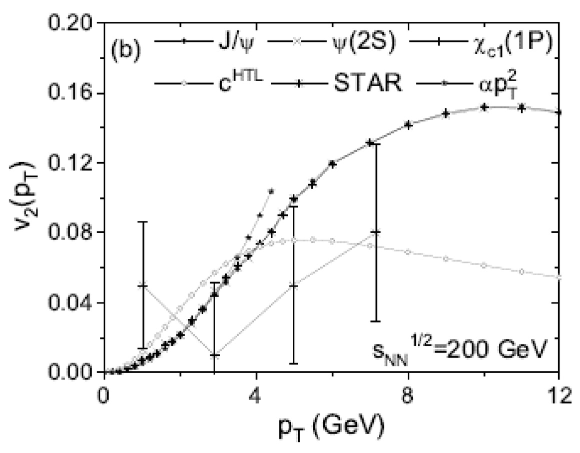
- Elliptic flow, the measure of the final state particle azimuthal distribution with respect to the reaction plane, or the second coefficient of the Fourier expansion v_2

$$v_n(p_T) = \langle\cos(n(\psi-\Psi_n))\rangle = \frac{\int d\psi\cos(n(\psi-\Psi_n))\frac{d^2N}{dp_T^2}}{\int d\psi\frac{d^2N}{dp_T^2}}\quad \frac{d^2N_c}{dp_{cT}^2} = \frac{1}{2\pi p_{cT}}\frac{dN_c}{dp_{cT}}\left(1+\sum_{n=1}^{\infty}2v_{nc}(p_{cT})\cos(n(\phi_c-\Psi_n))\right),$$

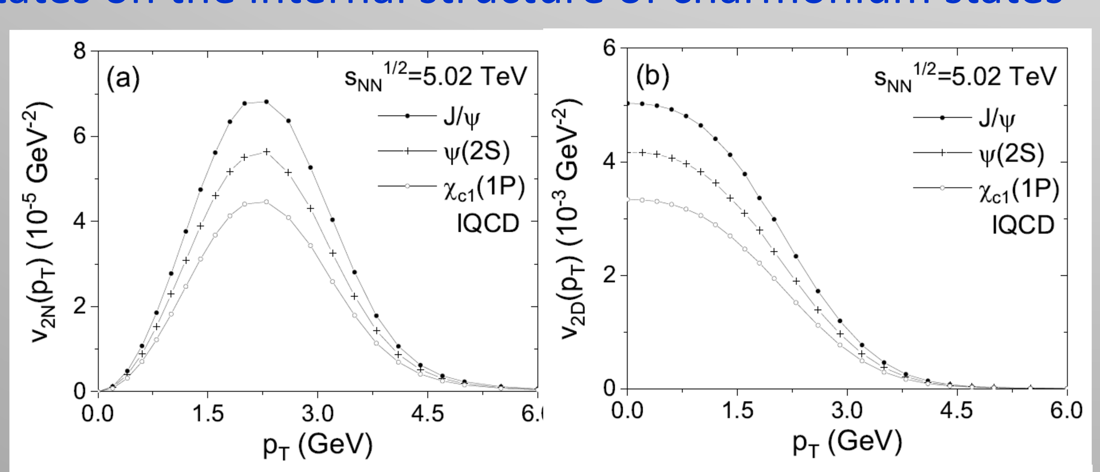
v_2 and v_3 of charmonium states

- Elliptic and triangular flows of charmonium states [11, 12, 13, 14]





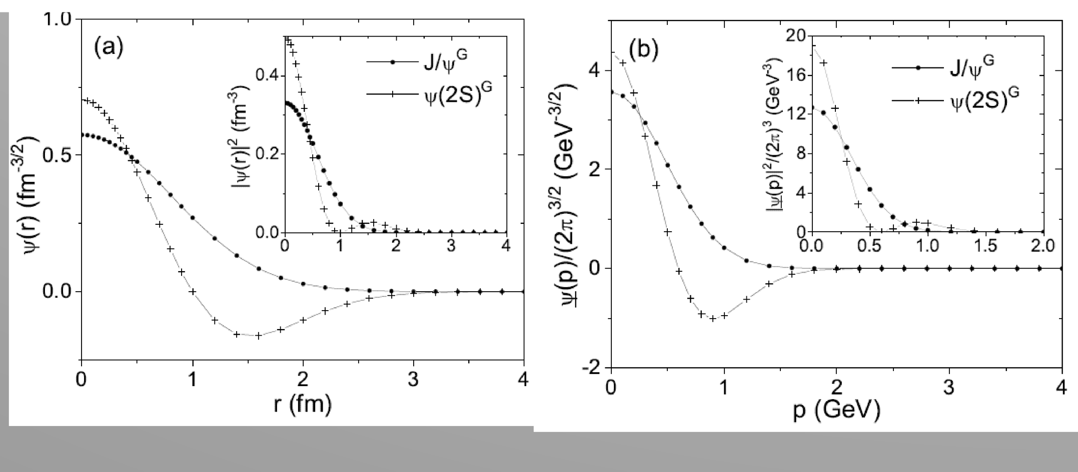
- The dependence of elliptic flow of charmonium states on the internal structure of charmonium states



- The quark number scaling of charmonia v_2 and v_3

$$v_{n,c\bar{c}}(p_T) \approx 2v_{n,c}(p_T/2)$$

- Wave function distributions in momentum space [11]



Conclusions

- Charmonia production by recombination from charm quarks in a quark-gluon plasma in heavy ion collisions, especially at low transverse momentum regions contributes significantly to the transverse momentum distributions, or the nuclear modification factor, R_{AA} of charmonium states

- It is necessary to take into account different internal structures, or different wave function distributions of charmonium states in evaluating not only the yield, transverse momentum distributions, but also anisotropic flow of charmonia

- The enhanced transverse momentum distribution of ψ(2S) mesons, compared to that of J/ψ mesons, is originated from intrinsic wave function distributions between ψ(2S) and J/ψ mesons [7]

- Elliptic and triangular flow of ψ(2S) mesons are almost same as those of J/ψ mesons due to an average over transverse momentum distributions in v_n

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