Charmed hadrons from heavy ion collisions

Hadron Interactions and Polarizations from Lattice QCD, Quark Model, and heavy ion collisions

March 26th 2019

Yukawa Institute for Theoretical Physics, Kyoto University

Sungtae Cho
Kangwon National University

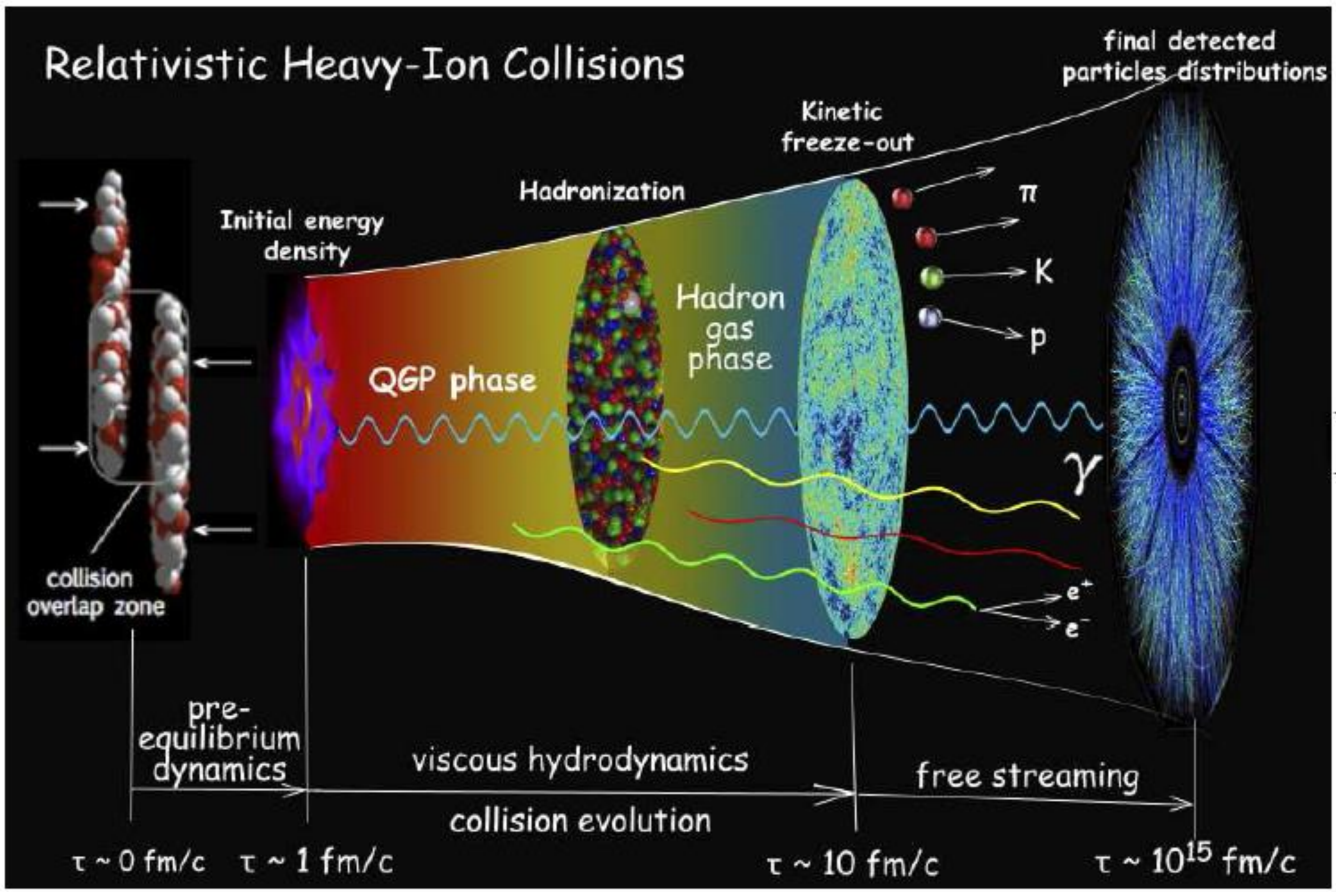
Based on works done in collaboration with Prof. Su Houng Lee at Yonsei University

Outline

- Introduction
- Charmed hadrons in heavy ion collisions
- Hadron production by quark coalescence
- Charmed hadron production by recombination
- Conclusion

Introduction

– Relativistic heavy ion collisions



U. W. Heinz, J. Phys. Conf. Ser. **455**, 012044 (2013)

– Charmed hadrons

1) Charmonium states :

Bound states made up of a charm and an anti-charm quarks

- the 1S scalar η_c and vector J/ψ, three 1P states χ_c (scalar, vector, and tensor), and the 2S vector state ψ'

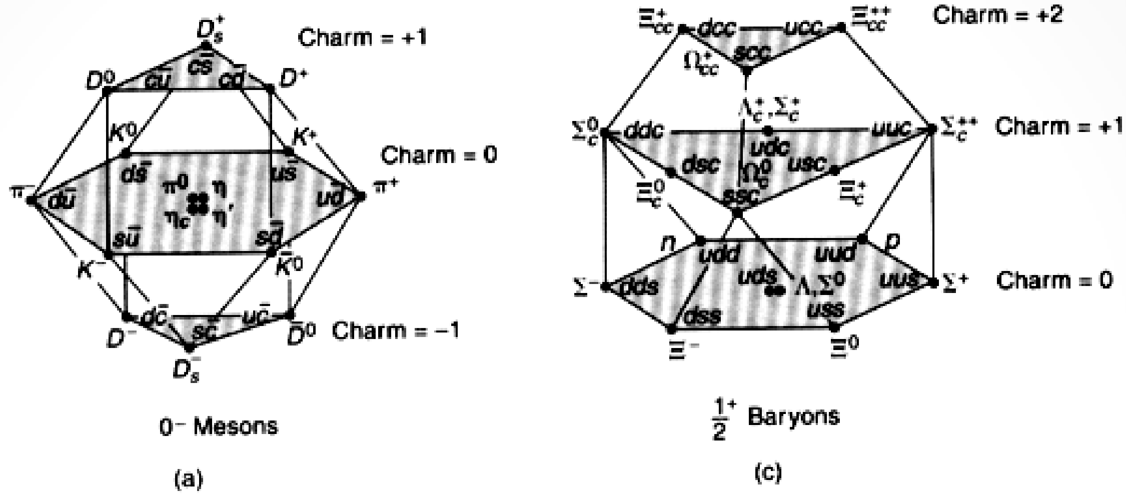
2) Charmed baryons and mesons :

D, D*, D_s, D_s*, $\Lambda_c(2286)$, $\Lambda_c(2595)$, $\Lambda_c(2625)$, $\Sigma_c(2455)$, $\Sigma_c(2520)$, $\Xi_c(2470)$. $\Xi_c(2578)$, $\Xi_c(2645)$, $\Omega_c(2695)$, $\Omega_c(2770)$.

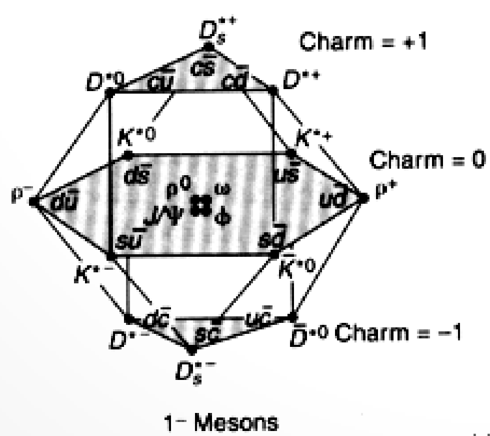
3) Doubly charmed hadrons, exotic hadrons

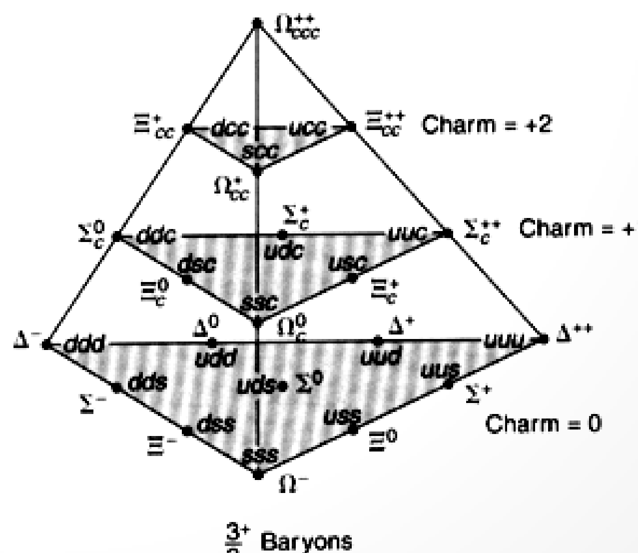
Ξ_{cc}, T_{cc}, X(3872)

– Charmed hadrons, SU(4)



A. De Rujula, H. Georgi, And S. Glashaw,
Phys. Rev. D **12**, 147 (1975)





: Recent measurements of a doubly charmed baryon in 2017

PRL **119**, 112001 (2017) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017

Observation of the Doubly Charmed Baryon Ξ_{cc}^{++}

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 6 July 2017; revised manuscript received 2 August 2017; published 11 September 2017)

– T_{cc} ($cc\underline{qq}$) mesons

Particle	m [MeV]	(I, J^P)
T_{cc}^1	3797	$(0, 1^+)$

S. Cho *et al.* (EXHIC Collaboration), Phys. Rev. C **84**, 064910 (2011)
S. Cho *et al.* (EXHIC Collaboration), Prog. Part. Nucl. Phys. **95**, 279 (2017)
J. Hong, S. Cho, T. Song, and S-H. Lee, Phys. Rev. C **98**, 014913 (2018)

– X(3872) mesons

$X(3872)$ $I^G(J^{PC}) = 0^+(1^{++})$

J. Beringer *et al.* (PDG), Phys. Rev. D**86**, 010001 (2012)

Mass $m = 3871.68 \pm 0.17$ MeV
$m_{X(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
$m_{X(3872)} - m_{\psi(2S)}$
Full width $\Gamma < 1.2$ MeV, CL = 90%

: The first measurement in 2003

S.K. Choi *et al.* [Belle Collaboration], Phys. Rev. Lett. **90**, 242001 (2003)

– Yields of exotic hadrons

Particle	Scenario 1		Scenario 2		Mol.	Stat.
	$q\bar{q}/qqq$	Multiquark	$q\bar{q}/qqq$	Multiquark		
RHIC						
$D_s(2317)$	2.3×10^{-2}	2.4×10^{-3}	2.3×10^{-2}	2.5×10^{-3}	6.5×10^{-3}	6.6×10^{-2}
$X(3872)$	5.4×10^{-4}	5.0×10^{-5}	5.6×10^{-4}	5.3×10^{-5}	9.1×10^{-4}	5.7×10^{-4}
$Z_c(3900)$	–	1.5×10^{-4}	–	1.6×10^{-4}	–	1.5×10^{-3}
$Z_c(4430)$	–	1.5×10^{-4}	–	1.6×10^{-5}	5.0×10^{-5}	6.5×10^{-5}
$Z_b(10610)$	–	2.0×10^{-9}	–	2.1×10^{-9}	–	2.1×10^{-8}
$Z_b(10650)$	–	2.0×10^{-9}	–	2.1×10^{-9}	–	1.6×10^{-8}
$X(5568)$	–	5.1×10^{-5}	–	5.2×10^{-5}	–	2.3×10^{-3}
$P_c(4380)$	–	2.5×10^{-5}	–	2.6×10^{-5}	2.9×10^{-5}	9.2×10^{-5}
$P_c(4450)$	–	1.5×10^{-5}	–	1.5×10^{-5}	–	9.1×10^{-5}
LHC (2.76 TeV)						
$D_s(2317)$	5.2×10^{-2}	4.3×10^{-3}	5.0×10^{-2}	4.5×10^{-3}	1.4×10^{-2}	1.5×10^{-1}
$X(3872)$	1.6×10^{-3}	1.1×10^{-4}	1.7×10^{-3}	1.3×10^{-4}	2.7×10^{-3}	1.7×10^{-3}
$Z_c(3900)$	–	3.4×10^{-4}	–	4.0×10^{-4}	–	4.3×10^{-3}
$Z_c(4430)$	–	3.4×10^{-4}	–	4.0×10^{-4}	1.4×10^{-4}	1.7×10^{-4}
$Z_b(10610)$	–	1.3×10^{-7}	–	1.5×10^{-7}	–	1.9×10^{-6}
$Z_b(10650)$	–	1.3×10^{-7}	–	1.5×10^{-7}	–	1.5×10^{-6}
$X(5568)$	–	5.0×10^{-4}	–	5.2×10^{-4}	–	3.1×10^{-2}
$P_c(4380)$	–	5.0×10^{-5}	–	5.8×10^{-5}	6.4×10^{-5}	2.1×10^{-4}
$P_c(4450)$	–	2.9×10^{-5}	–	3.2×10^{-5}	–	2.0×10^{-4}
LHC (5.02 TeV)						
$D_s(2317)$	6.5×10^{-2}	5.4×10^{-3}	6.4×10^{-2}	5.7×10^{-3}	1.8×10^{-2}	1.9×10^{-1}
$X(3872)$	2.5×10^{-3}	1.8×10^{-4}	2.7×10^{-3}	2.1×10^{-4}	4.5×10^{-3}	2.8×10^{-3}
$Z_c(3900)$	–	5.4×10^{-4}	–	6.4×10^{-4}	–	7.1×10^{-3}
$Z_c(4430)$	–	5.4×10^{-4}	–	6.4×10^{-4}	2.3×10^{-4}	2.8×10^{-4}
$Z_b(10610)$	–	3.4×10^{-7}	–	3.9×10^{-7}	–	5.0×10^{-6}
$Z_b(10650)$	–	3.4×10^{-7}	–	3.9×10^{-7}	–	3.9×10^{-6}
$X(5568)$	–	7.9×10^{-4}	–	8.2×10^{-4}	–	5.0×10^{-2}
$P_c(4380)$	–	7.9×10^{-5}	–	9.3×10^{-5}	1.0×10^{-4}	3.4×10^{-4}
$P_c(4450)$	–	4.7×10^{-5}	–	5.0×10^{-5}	–	3.4×10^{-4}

S. Cho *et al*. (EXHIC Collaboration), Prog. Part. Nucl. Phys. **95**, 279 (2017)

1) Factors for the internal structure of hadrons

s-wave $$\frac{N_i}{g_i}\frac{(4\pi\sigma_i^2)^{3/2}}{V(1+2\mu_i T\sigma_i^2)} \sim 0.168$$

p-wave $$\frac{N_i}{g_i}\frac{(4\pi\sigma_i^2)^{3/2}}{V(1+2\mu_i T\sigma_i^2)}\frac{2}{3}\left[\frac{2\mu_i T\sigma_i^2}{(1+2\mu_i T\sigma_i^2)}\right] \sim 0.040$$

d-wave $$\frac{N_i}{g_i}\frac{(4\pi\sigma_i^2)^{3/2}}{V(1+2\mu_i T\sigma_i^2)}\frac{8}{15}\left[\frac{2\mu_i T\sigma_i^2}{(1+2\mu_i T\sigma_i^2)}\right]^2 \sim 0.011$$

2) General forms of yields in quark recombination

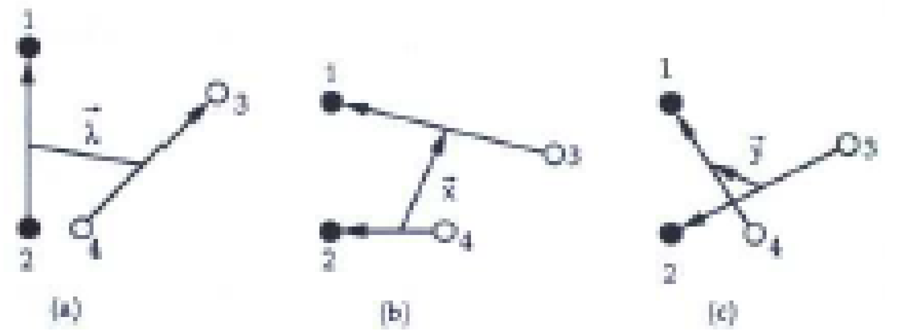
$$N_h^{Coal} \cong g\prod_{j=1}^{n}\frac{N_i}{g_i}\prod_{i=1}^{n-1}\frac{(4\pi\sigma_i^2)^{3/2}}{V(1+2\mu_i T\sigma_i^2)}\frac{(2l_i)!!}{(2l_i+1)!!}\left[\frac{2\mu_i T\sigma_i^2}{(1+2\mu_i T\sigma_i^2)}\right]^{l_i}$$

$$\sigma_i = \frac{1}{\sqrt{\mu_i\omega}} \qquad \frac{1}{\mu_i} = \frac{1}{m_{i+1}} + \frac{1}{\sum^{i} m_j}$$

– Internal structure of X(3872) mesons

1) Possible structures of X(3872) mesons, 3 independent relative coordinates

Fl. Stancu, hep-th/0607077



2) The relative coordinates and momentum of X(3872) mesons

$$\vec{R} = \frac{m_1\vec{r}_1 + m_2\vec{r}_2 + m_3\vec{r}_3 + m_4\vec{r}_4}{m_1 + m_2 + m_3 + m_4}$$
$$\vec{r}_1' = \vec{r}_1 - \vec{r}_2$$
$$\vec{r}_2' = \frac{m_1\vec{r}_1 + m_2\vec{r}_2}{m_1 + m_2} - \vec{r}_3$$
$$\vec{r}_3' = \frac{m_1\vec{r}_1 + m_2\vec{r}_2 + m_3\vec{r}_3}{m_1 + m_2 + m_3} - \vec{r}_4$$

$$\vec{k} = \vec{p}_{lT}' + \vec{p}_{\bar{l}T}' + \vec{p}_{cT}' + \vec{p}_{\bar{c}T}',$$
$$\vec{k}_1 = \frac{m_{\bar{l}}\vec{p}_{lT}' - m_l\vec{p}_{\bar{l}T}'}{m_l + m_{\bar{l}}},$$
$$\vec{k}_2 = \frac{m_c(\vec{p}_{lT}' + \vec{p}_{\bar{l}T}') - (m_l + m_{\bar{l}})\vec{p}_{cT}'}{m_l + m_{\bar{l}} + m_c},$$
$$\vec{k}_3 = \frac{m_{\bar{c}}(\vec{p}_{lT}' + \vec{p}_{\bar{l}T}' + \vec{p}_{cT}') - (m_l + m_{\bar{l}} + m_c)\vec{p}_{\bar{c}T}'}{m_l + m_{\bar{l}} + m_c + m_{\bar{c}}} \quad \text{(A2)}$$

$$\vec{k} = \vec{p}_{lT}' + \vec{p}_{\bar{l}T}' + \vec{p}_{cT}' + \vec{p}_{\bar{c}T}',$$
$$\vec{k}_1 = \frac{m_{\bar{l}}\vec{p}_{lT}' - m_l\vec{p}_{\bar{l}T}'}{m_l + m_{\bar{l}}},$$
$$\vec{k}_2 = \frac{m_{\bar{c}}\vec{p}_{cT}' - m_c\vec{p}_{\bar{c}T}'}{m_c + m_{\bar{c}}},$$
$$\vec{k}_3 = \frac{(m_c + m_{\bar{c}})(\vec{p}_{lT}' + \vec{p}_{\bar{l}T}') - (m_l + m_{\bar{l}})(\vec{p}_{cT}' + \vec{p}_{\bar{c}T}')}{m_l + m_{\bar{l}} + m_c + m_{\bar{c}}},$$

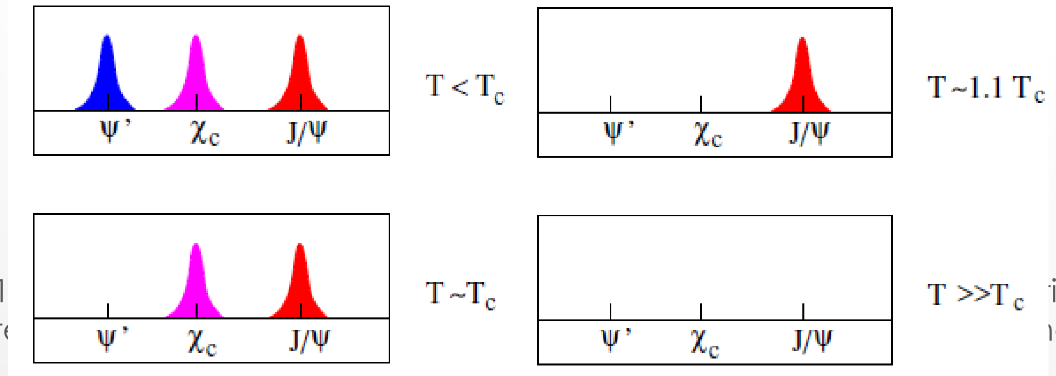
Charmed hadrons in heavy ion collisions

– Charmonium states

T. Matsui and H. Satz, Phys. Lett. B **178** 416 (1986)

1) J/ψ suppression and Debye screening
At $T>T_C$ color charges are Debye screened in QGP, and the Debye screening prevents the formation of the bound states

2) The different charmonium states melt sequentially as a function of their binding strength;
the most loosely bound state disappears first, the ground state last

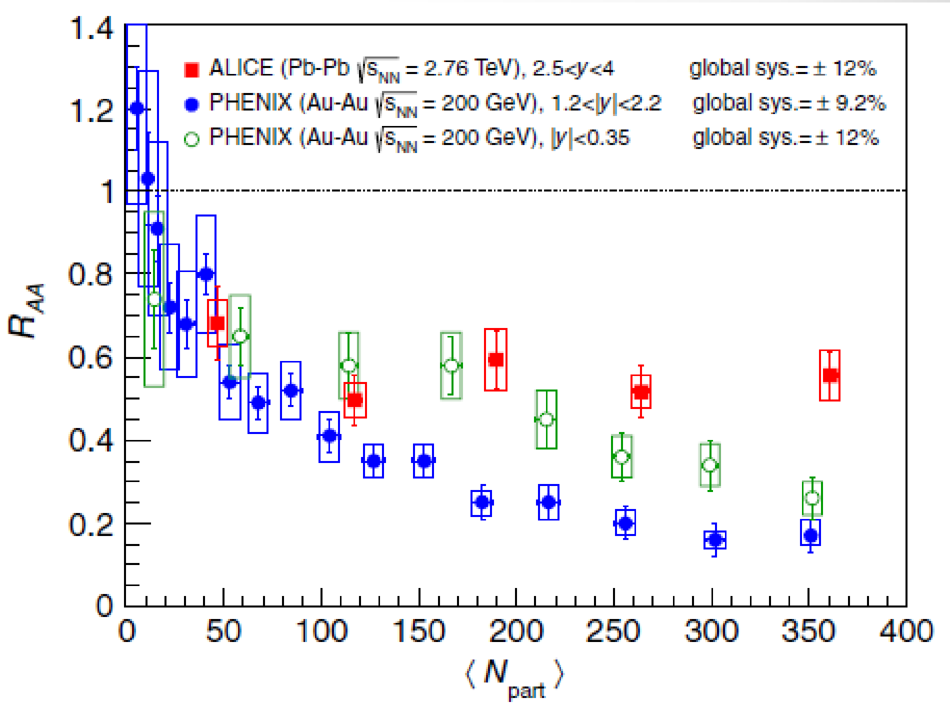


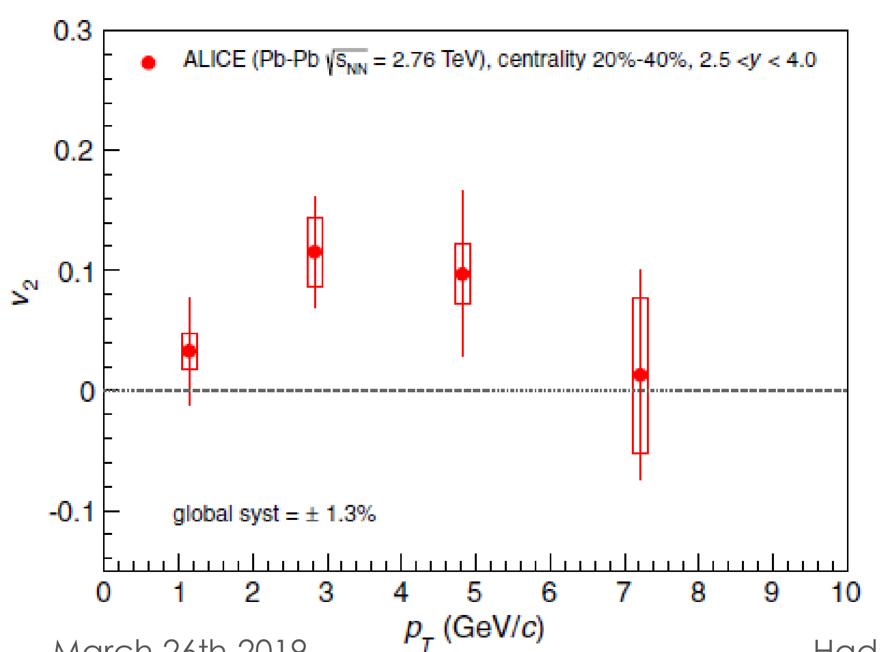
H. Satz, J. Phys. G. **32**, R25 (2006)

– Regeneration of J/ψ mesons

1) The nuclear modification factor of J/ψ mesons

B. Abelev et al, (ALICE Collaboration), Phys. Rev. Lett. **109**, 072301





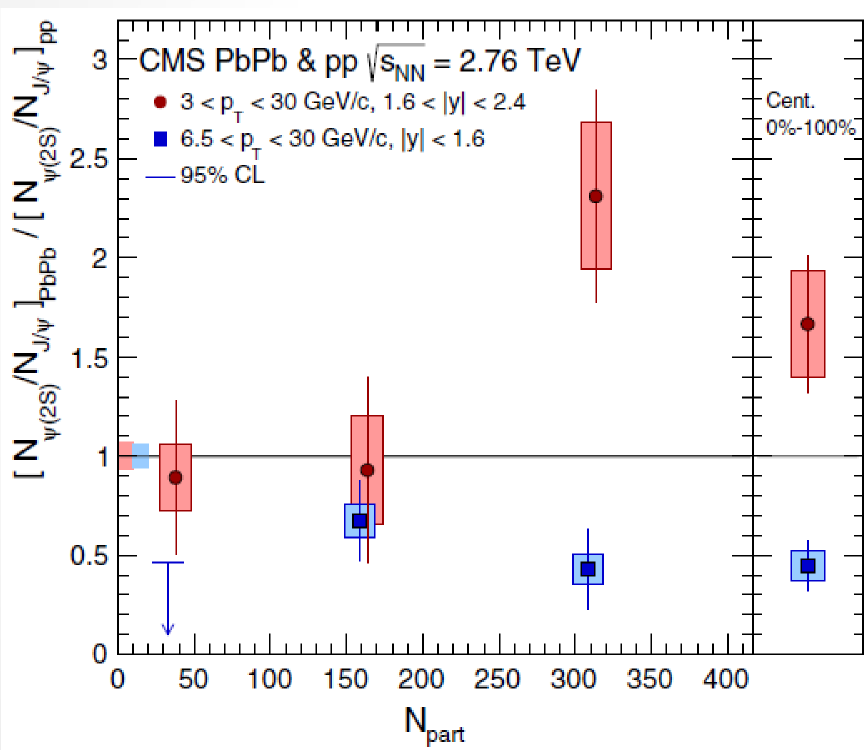
2) Elliptic flow of the J/ψ

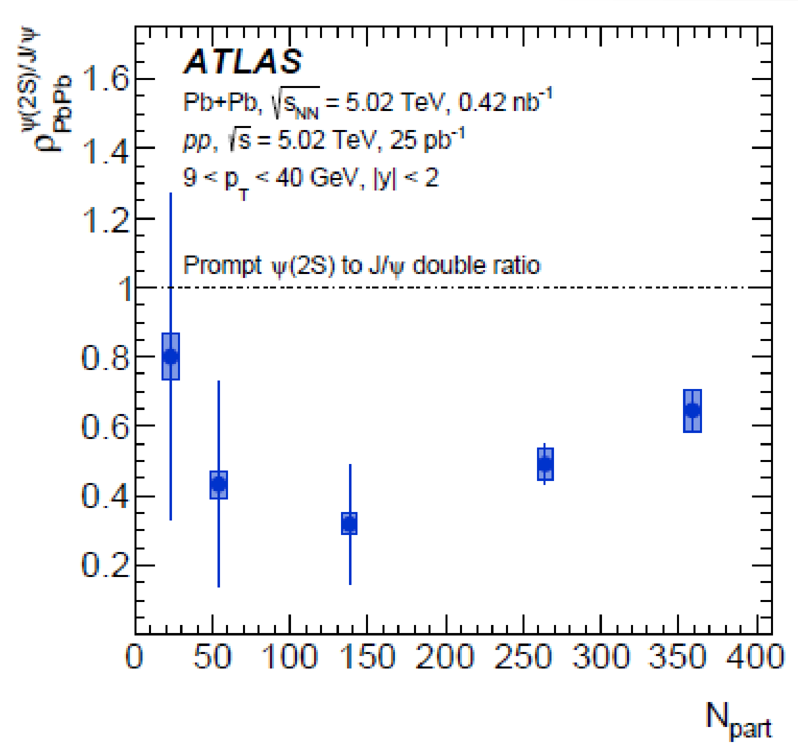
E. Abbas et al, Phys. Rev. Lett. **111**, 162301 (2013)

– Charmonium states in heavy ion collisions

1) The nuclear modification factor ratio between the J/ψ and the ψ'

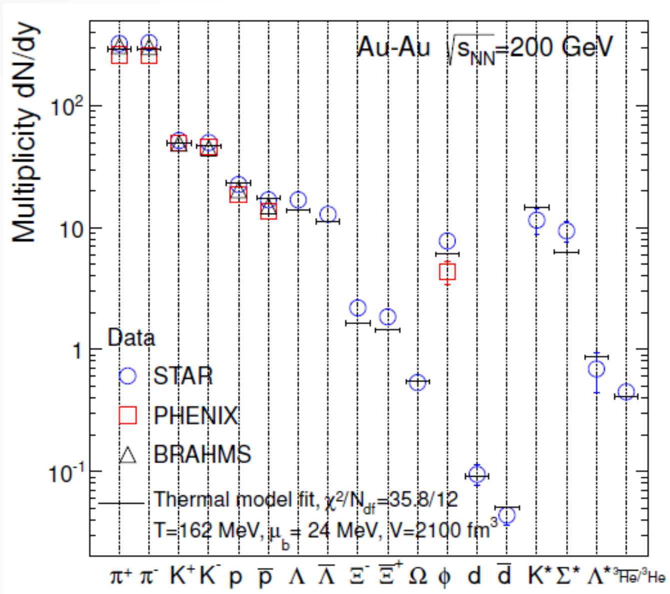
V. Khachatryan et al, Phys. Rev. Lett. **113**, 262301 (2014)
M. Aaboud et al, Eur. Phys. J. C **78**, 762 (2018)

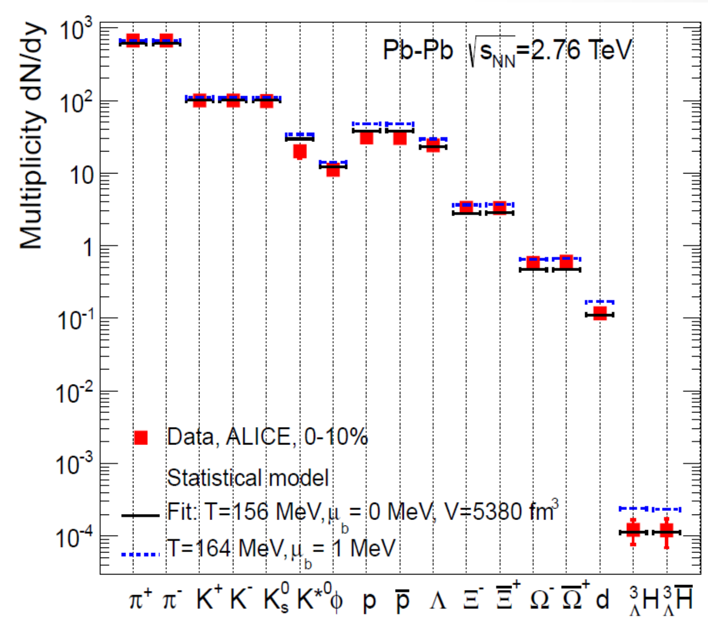




– Doubly charmed hadron production

1) Yields in statistical models





A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nucl. Phys. A **904-905**, 535c (2013)
J. Stachel, A. Andronic, P. Braun-Munzinger, and K. Redlich, J. Phys. Conf. Ser. **509**, 012019 (2014)
S. Cho *et al.* [ExHIC Collaboration], Prog. Part. Nucl. Phys. **95**, 279 (2017)

	RHIC		LHC	
	Stat.	Coal.	Stat.	Coal.
Ξ_{cc}	3.7×10^{-3}	4.4×10^{-4}	1.0×10^{-2}	1.6×10^{-3}
T_{cc}	8.9×10^{-4}	5.3×10^{-5}	2.7×10^{-3}	1.3×10^{-4}
$X(3872)$	5.7×10^{-4}	5.3×10^{-5}	1.7×10^{-3}	1.3×10^{-4}

Hadron production by quark coalescence

– Yields of hadrons in the coalescence model

V. Greco, C. M. Ko, and P. Levai, Phys. Rev. C **68**, 034904 (2003)
R. J. Freis. B. Muller, C. Nonaka, and S. Bass, Phys. Rev. C **68**, 044902 (2003)

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

1) The Wigner function, the coalescence probability function

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

2) A Lorentz-invariant phase space integration of a space-like hyper-surface constraints the number of particles in the system

$$\int p_i \cdot d\sigma_i \frac{d^3 p_i}{(2\pi)^3 E_i} f(x_i, p_i) = N_i$$

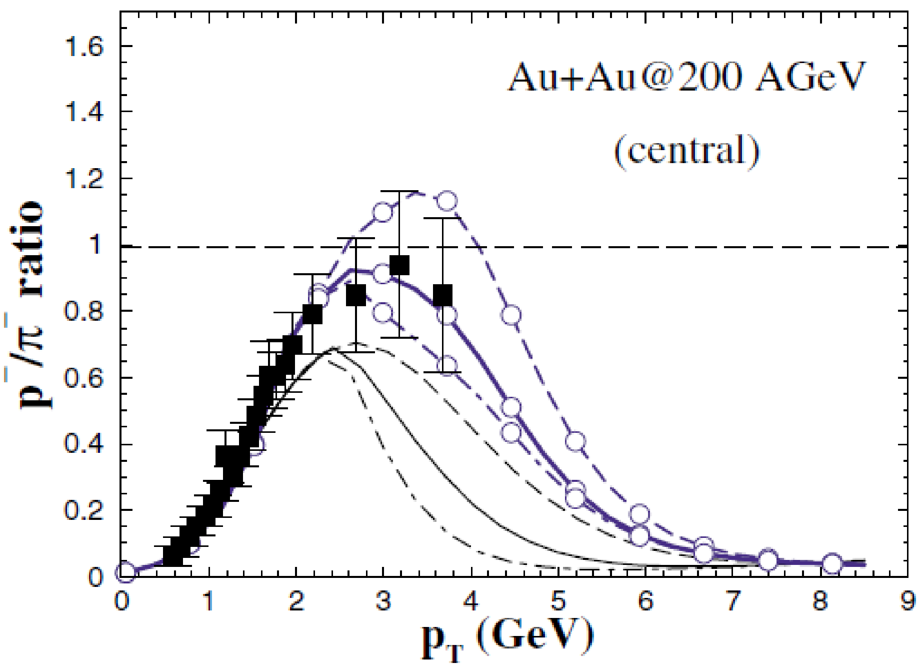
– Hadron production by recombination

: Transverse momentum distributions of hadron yields

1) The puzzle in antiproton/pion ratio

V. Greco, C. M. Ko, and P. Levai, Phys. Rev. Lett. **90**, 202302 (2003)
R. J. Freis. B. Muller, C. Nonaka, and S. Bass, Phys. Rev. Lett. **90**, 202303 (2003)

originated from a competition between two particle production mechanisms
: A fragmentation dominates at large transverse momenta and a coalescence prevails at lower transverse momenta



2) The transverse momentum spectra

$$\frac{dN_M}{d^2\mathbf{p}_T} = g_M \frac{6\pi}{\tau \Delta y R_\perp^2 \Delta_p^3} \int d^2\mathbf{p}_{1T} d^2\mathbf{p}_{2T} \left.\frac{dN_q}{d^2\mathbf{p}_{1T}}\right|_{|y_1| \leqslant \Delta y/2} \left.\frac{dN_{\bar{q}}}{d^2\mathbf{p}_{2T}}\right|_{|y_2| \leqslant \Delta y/2}$$
$$\times \delta^{(2)}(\mathbf{p}_T - \mathbf{p}_{1T} - \mathbf{p}_{2T}) \Theta\left(\Delta_p^2 - \frac{1}{4}(\mathbf{p}_{1T} - \mathbf{p}_{2T}) - \frac{1}{4}[(m_{1T} - m_{2T})^2 - (m_1 - m_2)^2]\right).$$

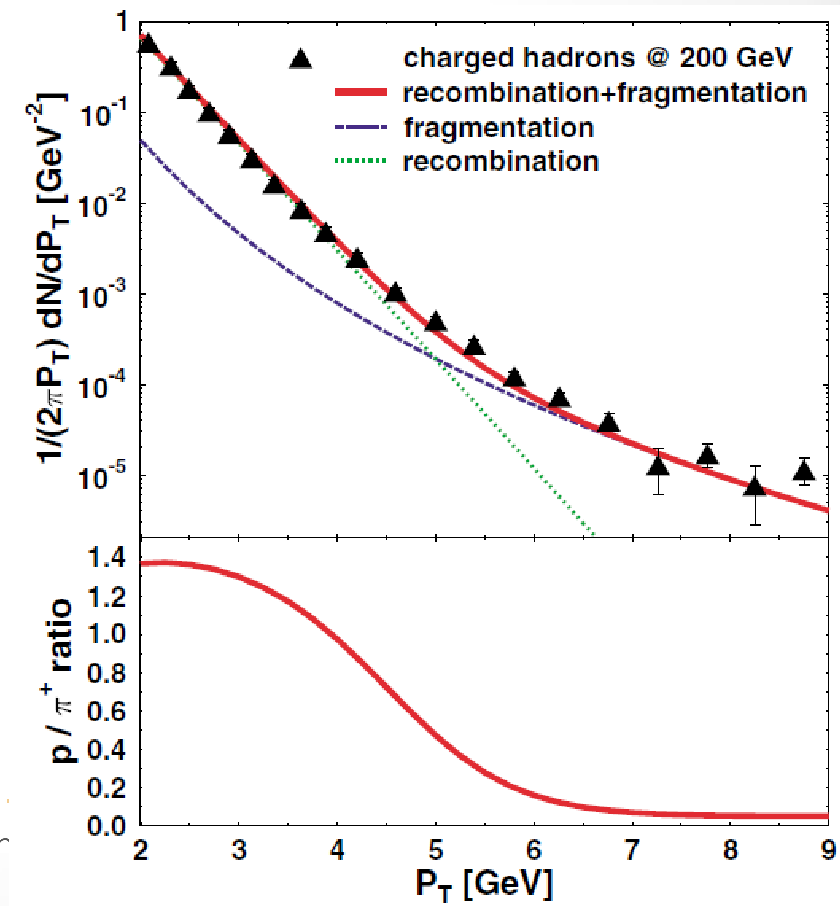
$$f_M(x_1, x_2; p_1, p_2) = \frac{9\pi}{2(\Delta_x \Delta_p)^3} \Theta(\Delta_x^2 - (x_1 - x_2)^2)$$
$$\times \Theta\left(\Delta_p^2 - \frac{1}{4}(p_1 - p_2)^2 + \frac{1}{4}(m_1 - m_2)^2\right).$$

and

$$E\frac{dN_M}{d^3P} = C_M \int_\Sigma \frac{d^3R P \cdot u(R)}{(2\pi)^3} \int \frac{d^3q}{(2\pi)^3}$$
$$\times w_a\left(R; \frac{\mathbf{P}}{2} - \mathbf{q}\right) \Phi_M^W(\mathbf{q}) w_b\left(R; \frac{\mathbf{P}}{2} + \mathbf{q}\right)$$

$$\Phi_M^W(\mathbf{q}) = \int d^3r \Phi_M^W(\mathbf{r}, \mathbf{q})$$

$$\Phi_M^W(\mathbf{r}, \mathbf{q}) = \int d^3r' e^{-i\mathbf{q}\cdot\mathbf{r}'} \varphi_M\left(\mathbf{r} + \frac{\mathbf{r}'}{2}\right) \varphi_M^*\left(\mathbf{r} - \frac{\mathbf{r}'}{2}\right)$$



Charmed hadron production by recombination

– Charmonia production by recombination

S. Cho, Phys. Rev. C **91**, 054914 (2015)

1) Coalescence production of charmonium states

$$N_\psi = g_\psi \int p_c \cdot d\sigma_c p_{\bar{c}} \cdot d\sigma_{\bar{c}} \frac{d^3\vec{p}_c}{(2\pi)^3 E_c} \frac{d^3\vec{p}_{\bar{c}}}{(2\pi)^3 E_{\bar{c}}} f_c(r_c, p_c) f_{\bar{c}}(r_{\bar{c}}, p_{\bar{c}}) W_\psi(r_c, r_{\bar{c}}; p_c, p_{\bar{c}}),$$

The transverse momentum distribution of the charmonium yield

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

$$W_s(\vec{r}, \vec{k}) = 8e^{-\frac{r^2}{\sigma^2} - k^2\sigma^2}$$

$$W_p(\vec{r}, \vec{k}) = \left(\frac{16}{3}\frac{r^2}{\sigma^2} - 8 + \frac{16}{3}\sigma^2 k^2\right) e^{-\frac{r^2}{\sigma^2} - k^2}$$

$$W_{\psi_{10}}(\vec{r}, \vec{k}) = \frac{16}{3}\Big(\frac{r^4}{\sigma^4} - 2\frac{r^2}{\sigma^2} + \frac{3}{2} - 2\sigma^2 k^2 + \sigma^4 k^4 - 2r^2k^2 + 4(\vec{r} \cdot \vec{k})^2\Big) e^{-\frac{r^2}{\sigma^2} - k^2\sigma^2}.$$

2) Integration of the Wigner function over the spatial coordinates

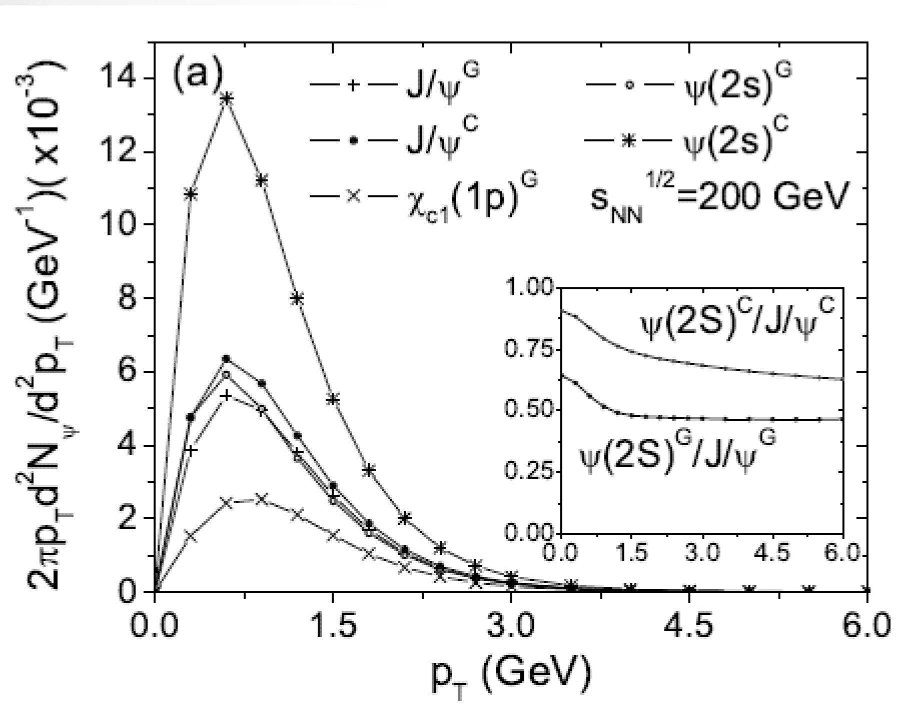
$$\int d^3\vec{r} W_\psi(\vec{r},\vec{k}) = \begin{cases} (2\sqrt{\pi}\sigma)^3 e^{-k^2\sigma^2} & \psi_s^G; J/\psi \\ \frac{2}{3}(2\sqrt{\pi}\sigma)^3 e^{-k^2\sigma^2}\sigma^2 k^2 & \psi_p^G; \chi_c \\ \frac{2}{3}(2\sqrt{\pi}\sigma)^3 e^{-k^2\sigma^2}\left(\sigma^2 k^2 - \frac{3}{2}\right)^2 & \psi_{10}^G;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

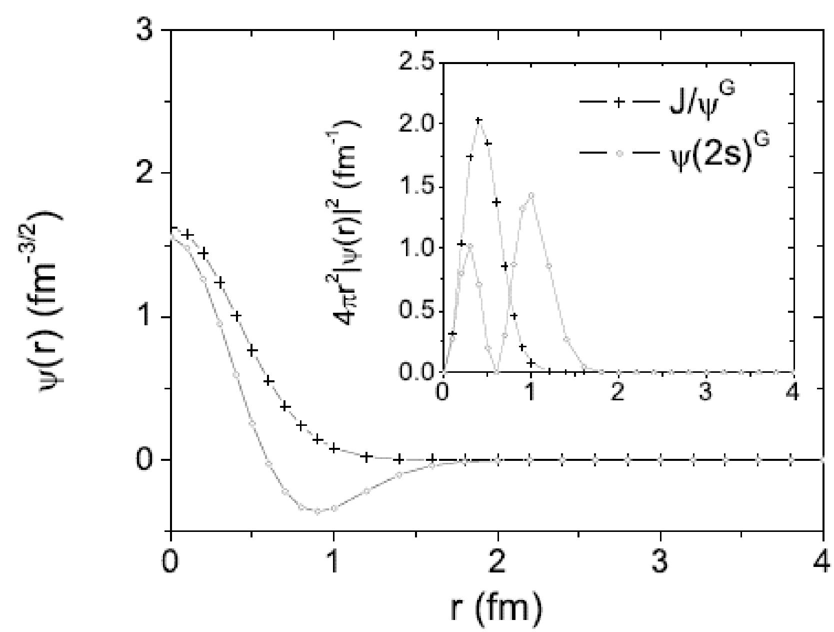
$$\int d^3\vec{r} W(\vec{r},\vec{k}) = \left|\tilde{\psi}(\vec{k})\right|^2$$

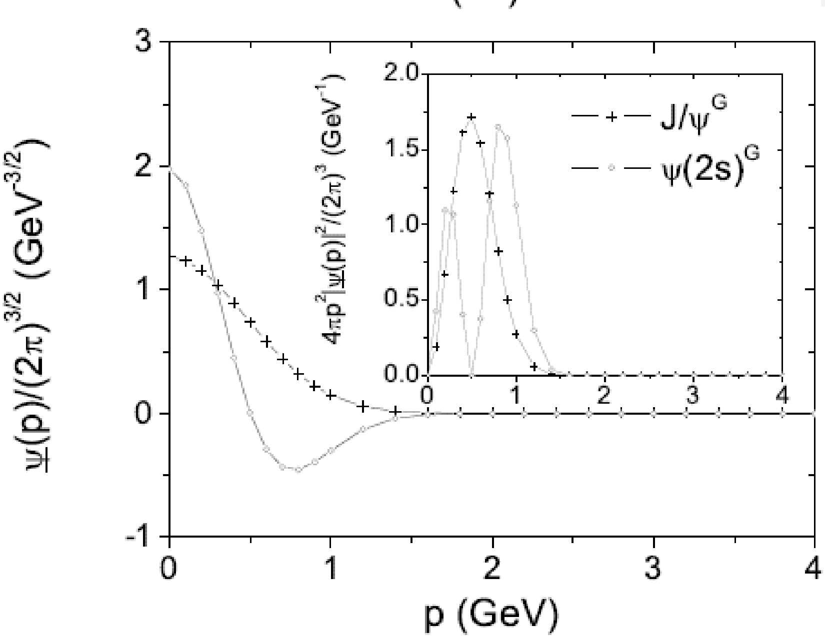
M. Hillery, R. F. O'Connel, M. O. Scully and E. P. Wigner, Phys. Rept. **106**, 121 (1984)

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

3) Transverse momentum distributions







– Production of doubly charmed hadron by recombination

1) Coalescence production of doubly charmed hadrons

$$N_{\Xi_{cc}} = g_{\Xi_{cc}} \int p_l \cdot d\sigma_l p_{c_1} \cdot d\sigma_{c_1} p_{c_2} \cdot d\sigma_{c_2} \frac{d^3\vec{p}_l}{(2\pi)^3 E_l} \frac{d^3\vec{p}_{c_1}}{(2\pi)^3 E_{c_1}} \frac{d^3\vec{p}_{c_2}}{(2\pi)^3 E_{c_2}} f_l(r_l, p_l) f_{c_1}(r_{c_1}, p_{c_1}) \times f_{c_2}(r_{c_2}, p_{c_2}) W_{\Xi_{cc}}(r_l, r_{c_1}, r_{c_2}; p_l, p_{c_1}, p_{c_2})$$

$$N_X = g_X \int p_l \cdot d\sigma_l p_{\bar{l}} \cdot d\sigma_{\bar{l}} p_c \cdot d\sigma_c p_{\bar{c}} \cdot d\sigma_{\bar{c}} \frac{d^3\vec{p}_l}{(2\pi)^3 E_l} \frac{d^3\vec{p}_{\bar{l}}}{(2\pi)^3 E_{\bar{l}}} \frac{d^3\vec{p}_c}{(2\pi)^3 E_c} \frac{d^3\vec{p}_{\bar{c}}}{(2\pi)^3 E_{\bar{c}}} \times f_l(r_l, p_l) f_{\bar{l}}(r_{\bar{l}}, p_{\bar{l}}) f_c(r_c, p_c) f_{\bar{c}}(r_{\bar{c}}, p_{\bar{c}}) W_X(r_l, r_{\bar{l}}, r_c, r_{\bar{c}}; p_l, p_{\bar{l}}, p_c, p_{\bar{c}})$$

2) The transverse momentum distributions

$$\frac{d^2 N_{\Xi_{cc}}}{d^2\vec{p}_T} = \frac{g_{\Xi_{cc}}}{V^2} \int d^3\vec{r}_1 d^3\vec{r}_2 d^2\vec{p}_{lT} d^2\vec{p}_{c_1T} d^2\vec{p}_{c_2T} \delta^{(2)}(\vec{p}_T - \vec{p}_{lT} - \vec{p}_{c_1T} - \vec{p}_{c_2T}) \frac{d^2 N_l}{d^2\vec{p}_{lT}} \times \frac{d^2 N_{c_1}}{d^2\vec{p}_{c_1T}} \frac{d^2 N_{c_2}}{d^2\vec{p}_{c_2T}} W_{\Xi_{cc}}(\vec{r}_1', \vec{r}_2', \vec{r}_3', \vec{k}_1, \vec{k}_2, \vec{k}_3),$$

$$\frac{d^2 N_X}{d^2\vec{p}_T} = \frac{g_X}{V^3} \int d^3\vec{r}_1 d^3\vec{r}_2 d^3\vec{r}_3 d^2\vec{p}_{lT} d^2\vec{p}_{\bar{l}T} d^2\vec{p}_{cT} d^2\vec{p}_{\bar{c}T}\, \delta^{(2)}(\vec{p}_T - \vec{p}_{lT} - \vec{p}_{\bar{l}T} - \vec{p}_{cT} - \vec{p}_{\bar{c}T}) \frac{d^2 N_l}{d^2\vec{p}_{lT}} \frac{d^2 N_{\bar{l}}}{d^2\vec{p}_{\bar{l}T}} \times \frac{d^2 N_c}{d^2\vec{p}_{cT}} \frac{d^2 N_{\bar{c}}}{d^2\vec{p}_{\bar{c}T}} W_X(\vec{r}_1', \vec{r}_2', \vec{r}_3', \vec{k}_1, \vec{k}_2, \vec{k}_3)$$

– Parameters in the coalescence model

Table 3.1
Statistical and coalescence model parameters for Scenario 1 and 2 at RHIC (200 GeV), LHC (2.76 TeV) and LHC (5.02 TeV), and those given in Refs. [14,15]. Quark masses are taken to be $m_q = 350$ MeV, $m_s = 500$ MeV, $m_c = 1500$ MeV and $m_b = 4700$ MeV. In Refs. [14,15], light quark masses were taken to be $m_q = 300$ MeV.

	RHIC		LHC (2.76 TeV)		LHC (5.02 TeV)		RHIC	LHC (5 TeV)
	Sc. 1	Sc. 2	Sc. 1	Sc. 2	Sc. 1	Sc. 2	Refs [14,15]	
T_H (MeV)	162		156				175	
V_H (fm^3)	2100		5380				1908	5152
μ_B (MeV)	24		0				20	0
μ_s (MeV)	10		0				10	0
γ_c	22		39		50		6.40	15.8
γ_b	4.0×10^7		8.6×10^8		1.4×10^9		2.2×10^6	3.3×10^7
T_C (MeV)	162	166	156	166	156	166	175	
V_C (fm^3)	2100	1791	5380	3533	5380	3533	1000	2700
ω (MeV)	590	608	564	609	564	609	550	
ω_s (MeV)	431	462	426	502	426	502	519	
ω_c (MeV)	222	244	219	278	220	279	385	
ω_b (MeV)	183	202	181	232	182	234	338	
$N_u = N_d$	320	302	700	593	700	593	245	662
$N_s = N_{\bar{s}}$	183	176	386	347	386	347	150	405
$N_c = N_{\bar{c}}$	4.1		11		14		3	20
$N_b = N_{\bar{b}}$	0.03		0.44		0.71		0.02	0.8

S. Cho *et al.* (EXHIC Collaboration), Prog. Part. Nucl. Phys. **95**, 279 (2017)

1) Transverse momentum distributions of charm quarks

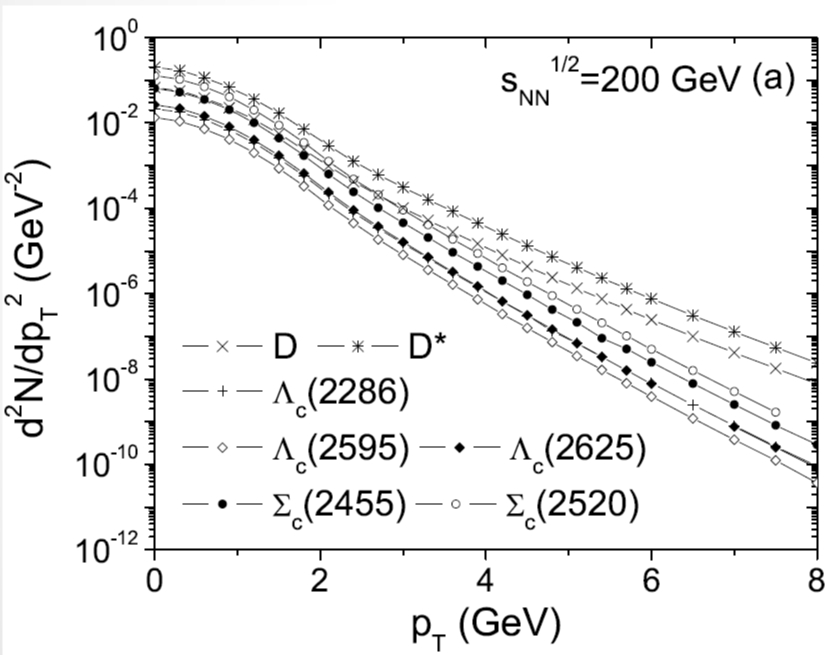
$$\frac{dN_c}{d^2p_T} = \begin{cases} a_0 \exp\left[-a_1 p_T^{a_2}\right] & p_T \le p_0 \\ a_0 \exp\left[-a_1 p_T^{a_2}\right] + a_3\left(1 + p_T^{a_4}\right)^{-a_5} & p_T \ge p_0 \end{cases}$$

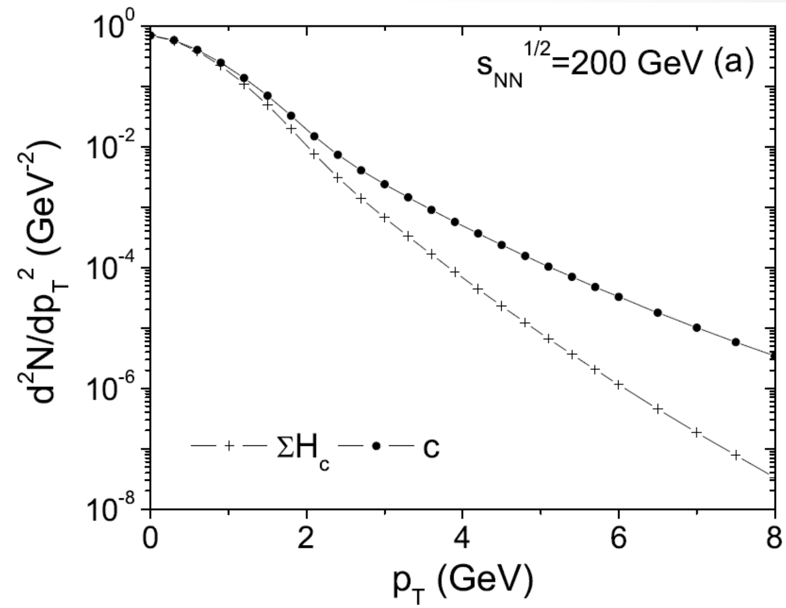
S. Plumari, V. Minissale, S.K. Das, G. Coci, and V. Greco, Eur. Phys. J. C **78**, 348 (2018)

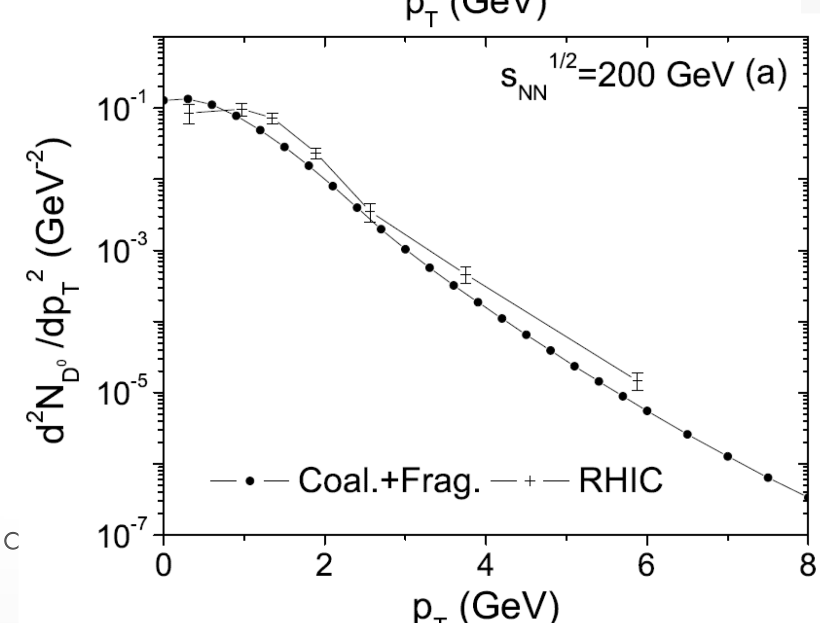
Table 3 Parameters for charm distributions at mid-rapidity for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb+Pb collisions at $\sqrt{s_{NN}} =$ 2.76 ATeV

RHIC	a_0	a_1	a_2	a_3	a_4	a_5
$p_T \le p_0$	0.69	1.22	1.57			
$p_T \ge p_0$	1.08	3.04	0.71	3.79	2.02	3.48
LHC	a_0	a_1	a_2	a_3	a_4	a_5
$p_T \le p_0$	1.97	0.35	2.47			
$p_T \ge p_0$	7.95	3.49	3.59	87335	0.5	14.31

2) Oscillator frequency for charm quark hadrons, w_c







Conclusion

– Charmed hadron from heavy ion collisions

1) Heavy ion collision experiments provide better chances to study production of doubly charmed hadrons as well as exotic hadrons
2) 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
3) The investigation on the transverse momentum distribution ratio between doubly charmed baryons and X(3872) mesons, or other combinations between charmed hadrons helps us understand more the production of charmed hadrons in heavy ion collisions
4) Not only the internal structure but also kinds of constituents can be identified from transverse momentum distributions of charmed hadrons in heavy ion collisions

Thank you for your attention!