Charmed hadron production in heavy ion collisions

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Outline

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

Introduction

– 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)

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

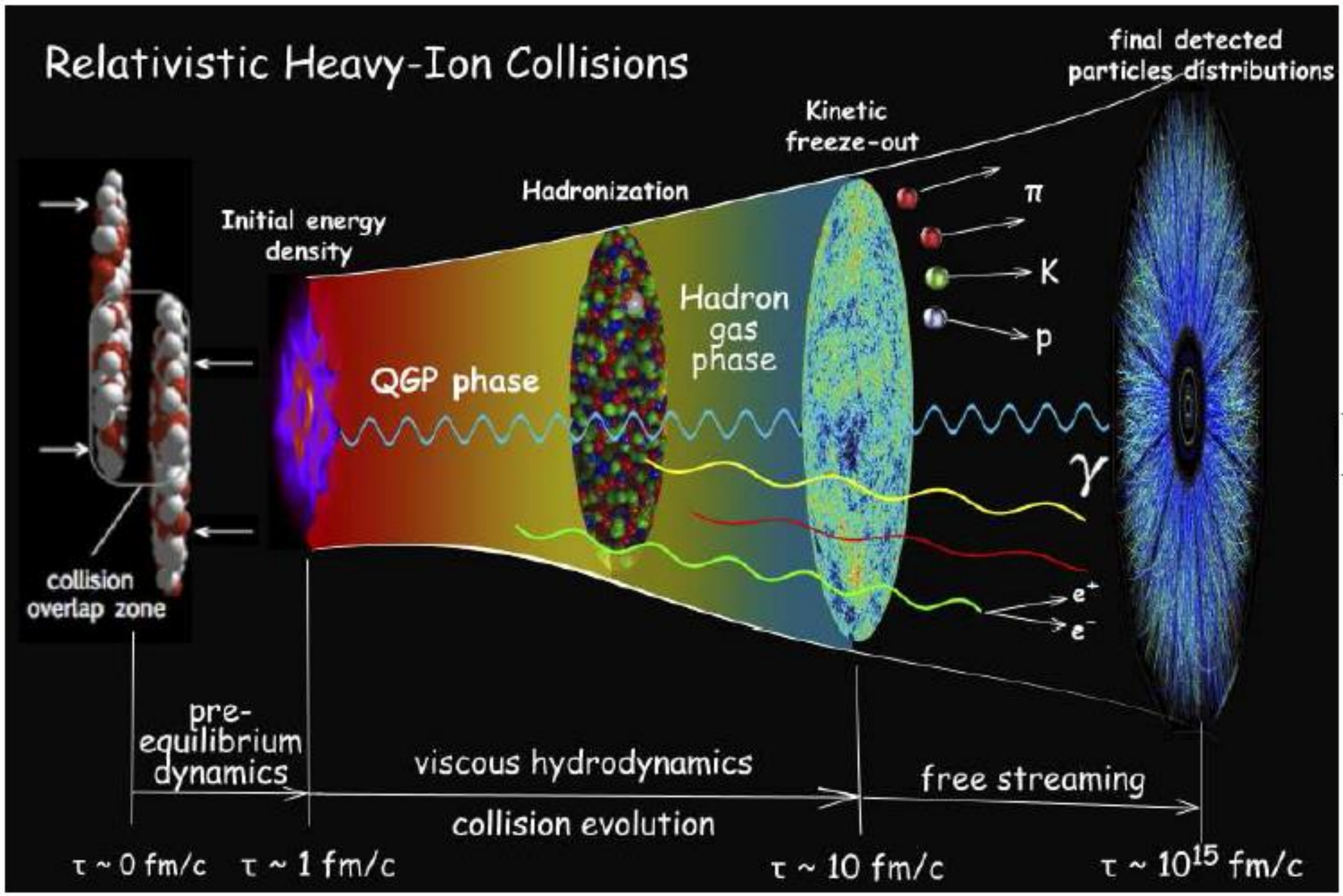
Mass $m = 3871.68 \pm 0.17$ MeV
$m_{X(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
$m_{X(3872)} - m_{\psi(2S)}$
Full width $\Gamma < 1.2$ MeV, CL $= 90\%$

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

: The first measurement in 2003

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

– Relativistic heavy ion collisions



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

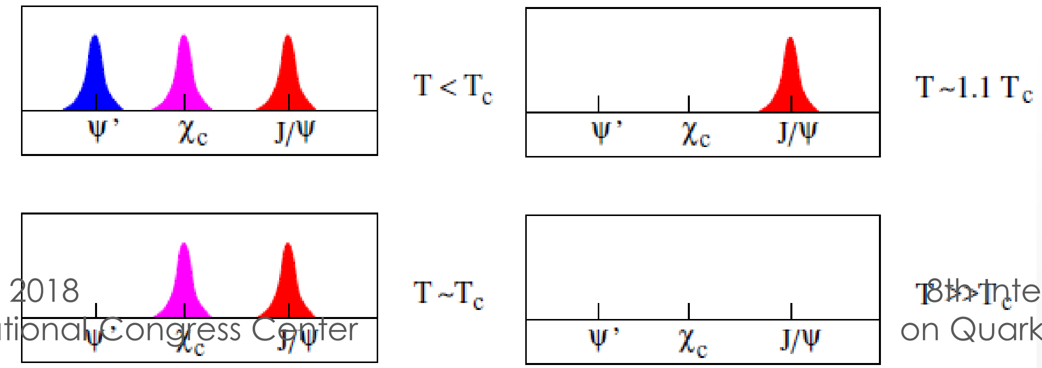
Charmed hadrons in heavy ion collisions

– 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

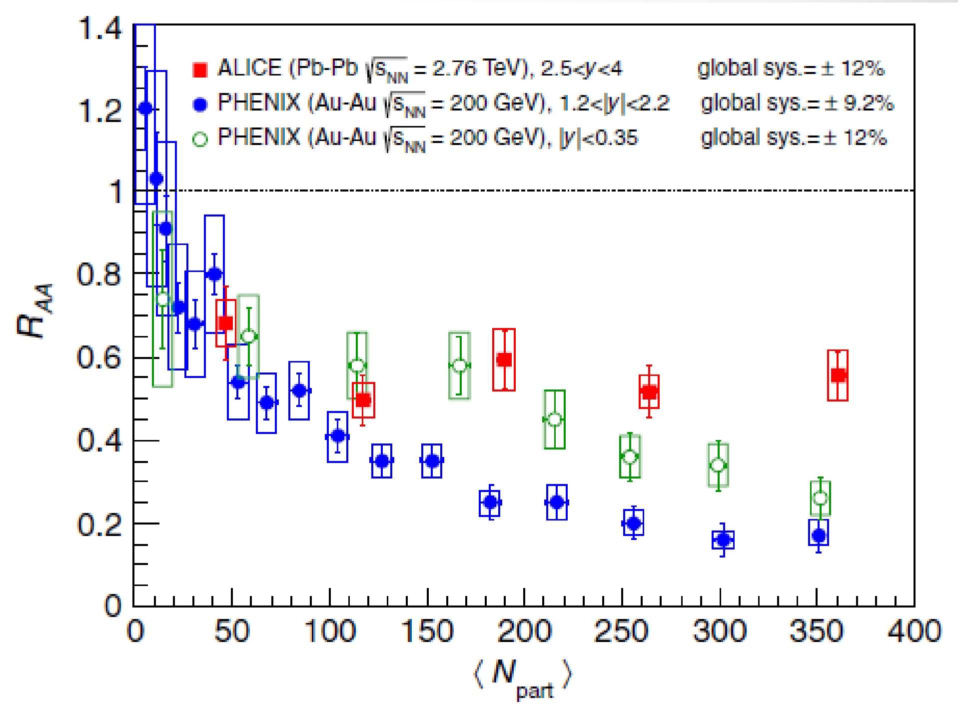


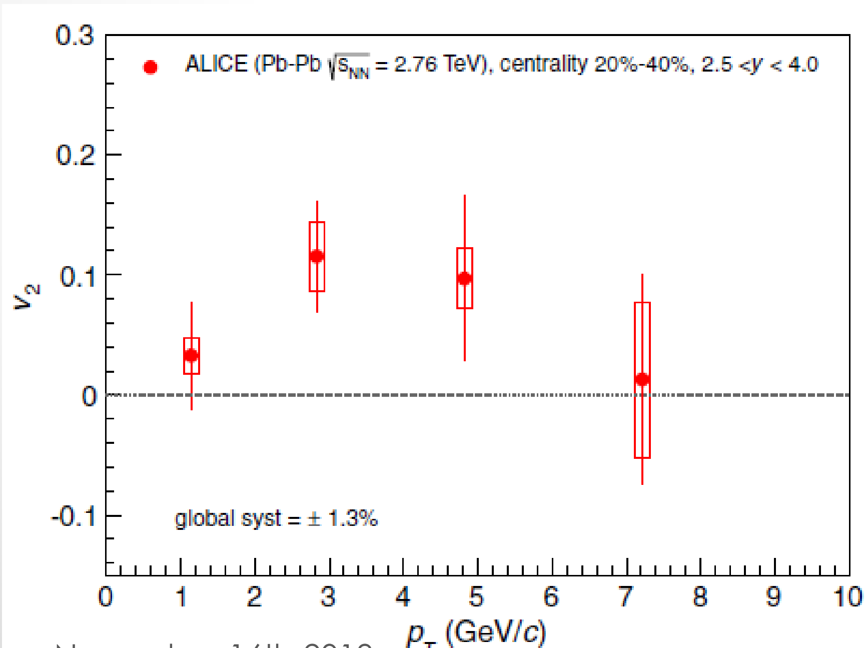
H. Satz, J. Phys. G. **32**, R25 (2006)

– 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





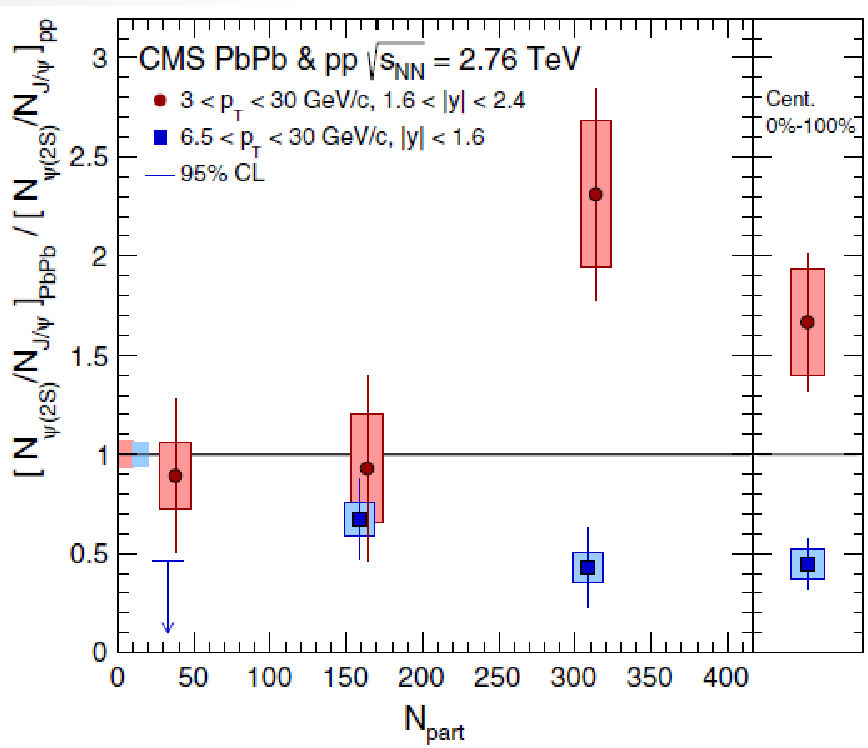
2) Elliptic flow of the J/ψ

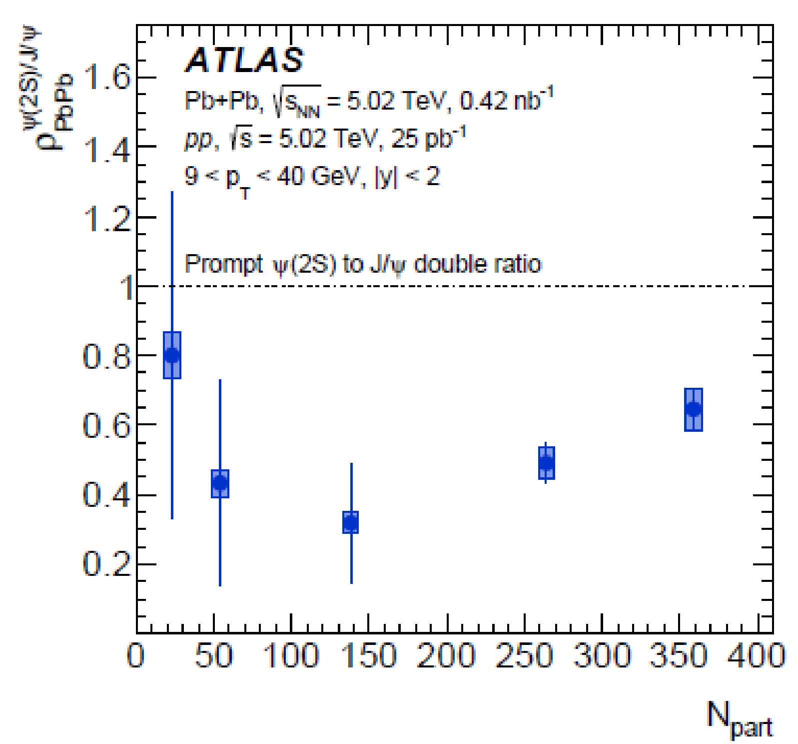
E. Abbas et al, Phys. Rev. Lett. **111**, 162301 (2013)

– Charmonium states in heavy ion collisions

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

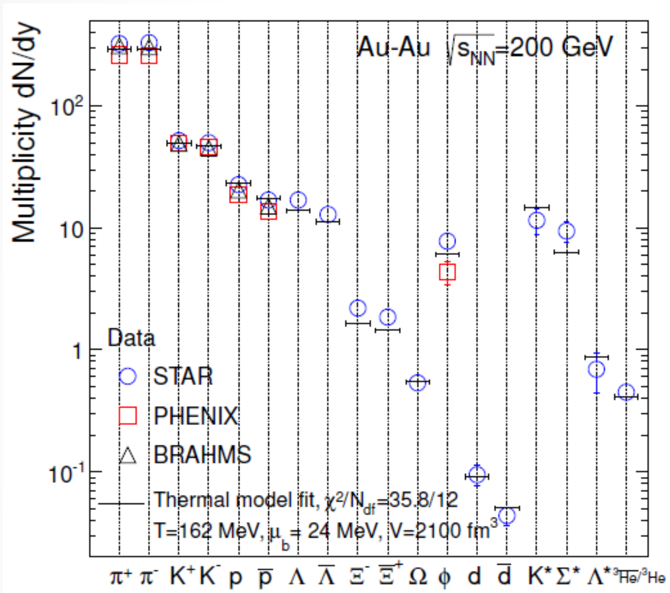
V. Khachatryan et al, Phys. Rev. Lett. **113**, 262301 (2014)
M. Aaboud et al, Eur. Phys. J. C **78**, 762 (2018)

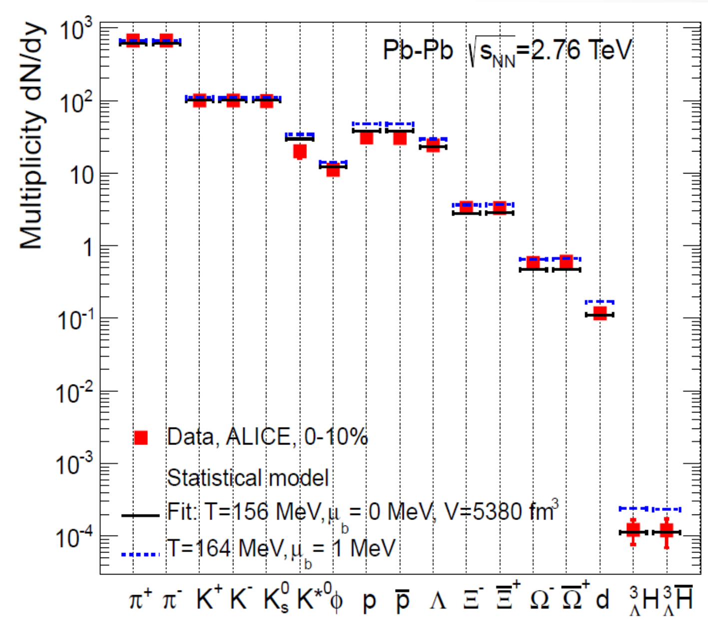




– Doubly charmed hadron production

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)

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

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

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

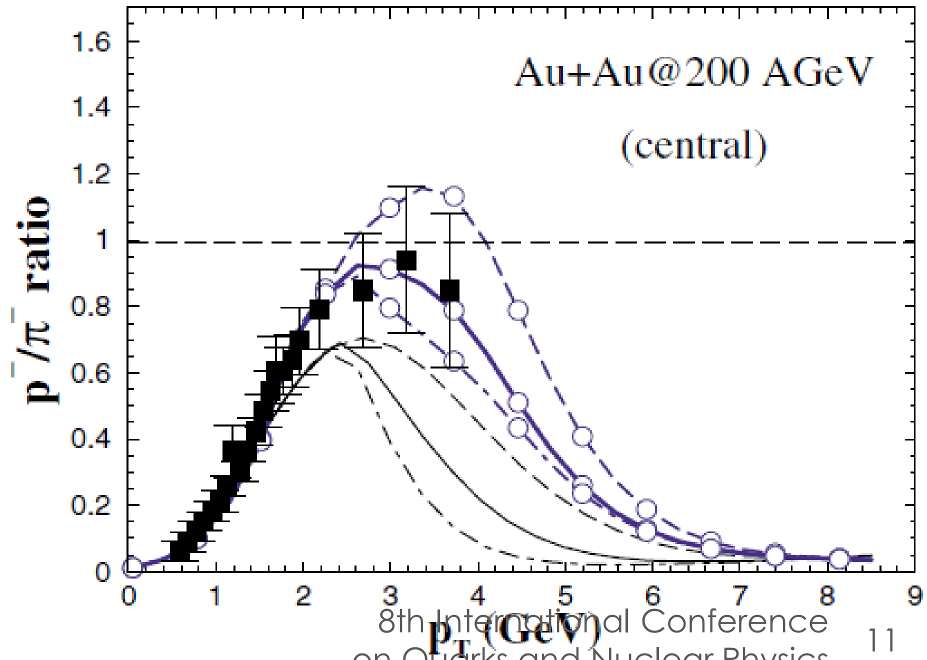
– Hadron production by recombination

: 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

$$\frac{dN_M}{d^2\mathbf{p}_T} = g_M \frac{6\pi}{\tau \Delta y R_\perp^2 \Delta_p^3} \int d^2\mathbf{p}_{1T} d^2\mathbf{p}_{2T} \left.\frac{dN_q}{d^2\mathbf{p}_{1T}}\right|_{|y_1| \leqslant \Delta y/2} \left.\frac{dN_{\bar{q}}}{d^2\mathbf{p}_{2T}}\right|_{|y_2| \leqslant \Delta y/2}$$

$$\times \delta^{(2)}(\mathbf{p}_T - \mathbf{p}_{1T} - \mathbf{p}_{2T}) \Theta\left(\Delta_p^2 - \frac{1}{4}(\mathbf{p}_{1T} - \mathbf{p}_{2T}) - \frac{1}{4}[(m_{1T} - m_{2T})^2 - (m_1 - m_2)^2]\right).$$

$$f_M(x_1, x_2; p_1, p_2) = \frac{9\pi}{2(\Delta_x \Delta_p)^3} \Theta(\Delta_x^2 - (x_1 - x_2)^2)$$

$$\times \Theta\left(\Delta_p^2 - \frac{1}{4}(p_1 - p_2)^2 + \frac{1}{4}(m_1 - m_2)^2\right).$$

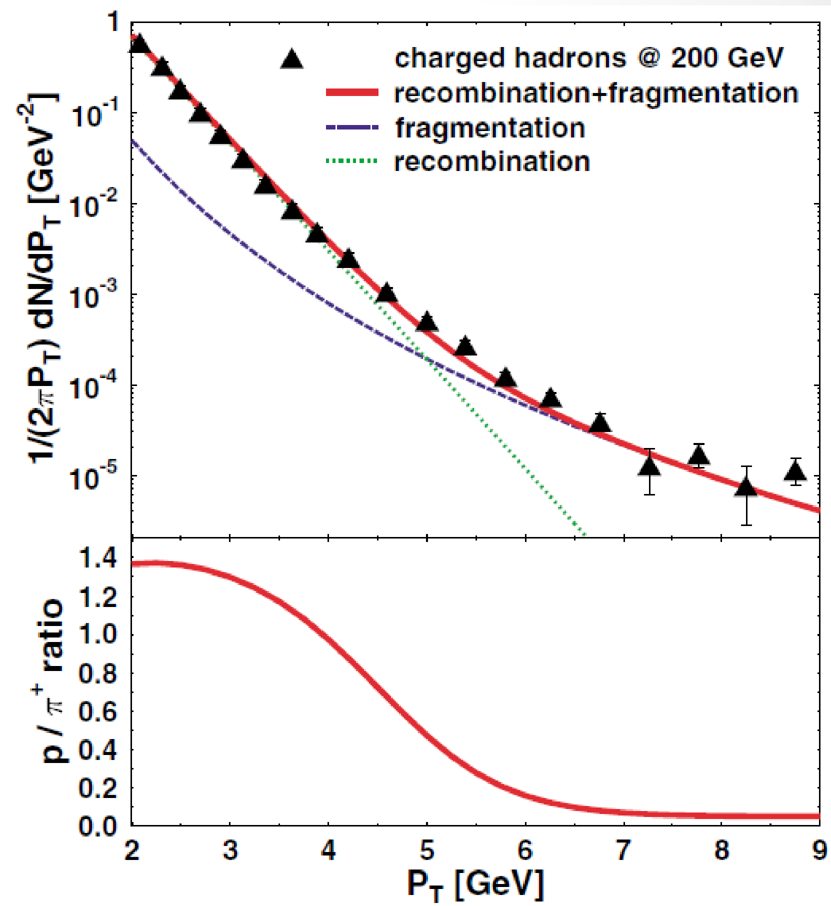
and

$$E\frac{dN_M}{d^3P} = C_M \int_\Sigma \frac{d^3R P \cdot u(R)}{(2\pi)^3} \int \frac{d^3q}{(2\pi)^3}$$

$$\times w_a\left(R; \frac{\mathbf{P}}{2} - \mathbf{q}\right) \Phi_M^W(\mathbf{q}) w_b\left(R; \frac{\mathbf{P}}{2} + \mathbf{q}\right)$$

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

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



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

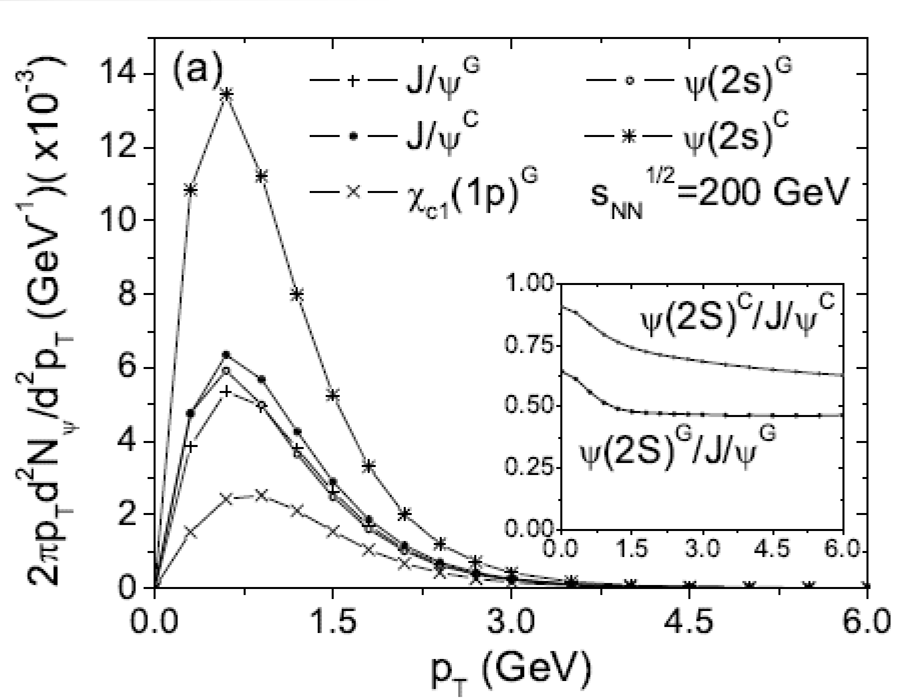
$$\frac{dN_\psi}{d^2\vec{p}_T} = \frac{g_\psi}{V} \int d^3\vec{r} d^2\vec{p}_{cT} d^2\vec{p}_{\bar{c}T} \delta^{(2)}(\vec{p}_T - \vec{p}_{cT} - \vec{p}_{\bar{c}T}) \frac{dN_c}{d^2\vec{p}_{cT}} \frac{dN_{\bar{c}}}{d^2\vec{p}_{\bar{c}T}} W_\psi(\vec{r}, \vec{k})$$

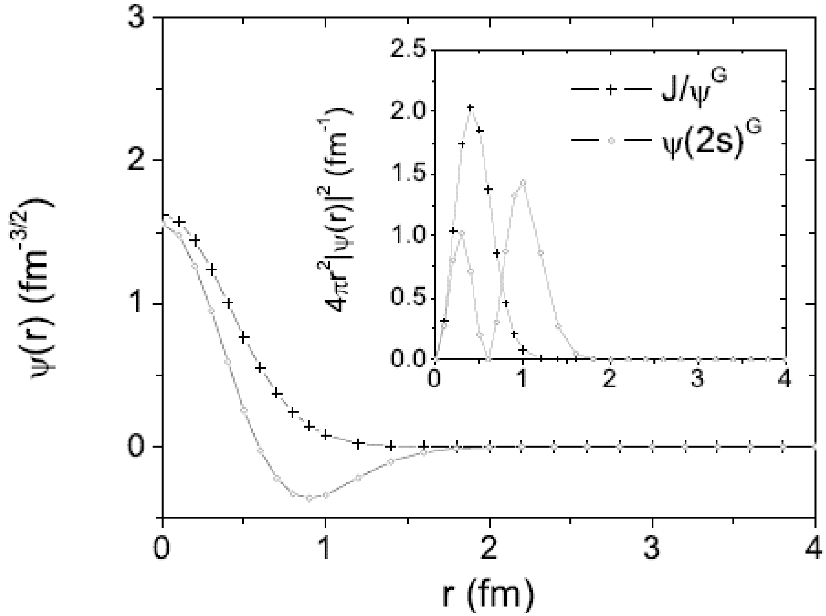
$$W_s(\vec{r}, \vec{k}) = 8 e^{-\frac{r^2}{\sigma^2} - k^2\sigma^2}$$

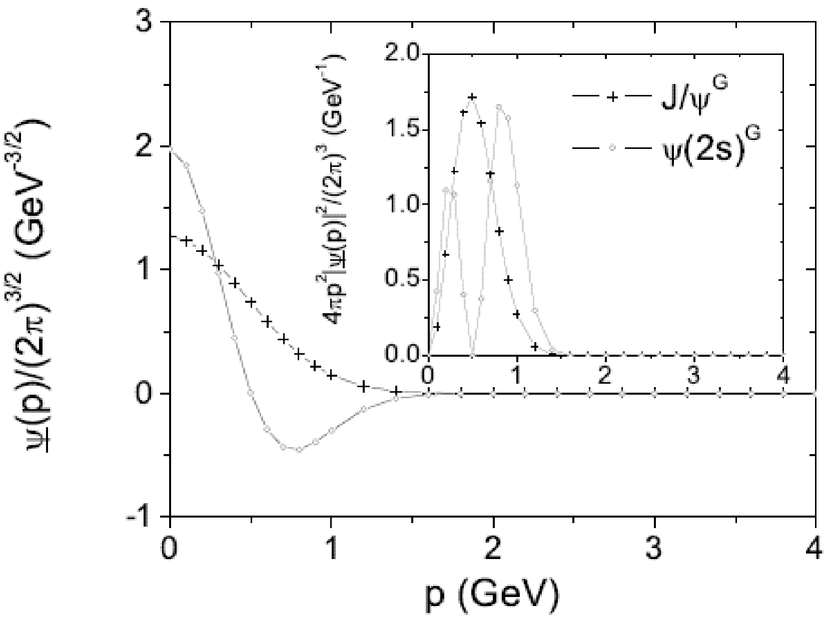
$$W_p(\vec{r}, \vec{k}) = \left(\frac{16}{3}\frac{r^2}{\sigma^2} - 8 + \frac{16}{3}\sigma^2 k^2\right) e^{-\frac{r^2}{\sigma^2} - k^2}$$

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

3) Transverse momentum distributions







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

– Production of doubly charmed hadron by recombination

1) Coalescence production of doubly charmed hadrons

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

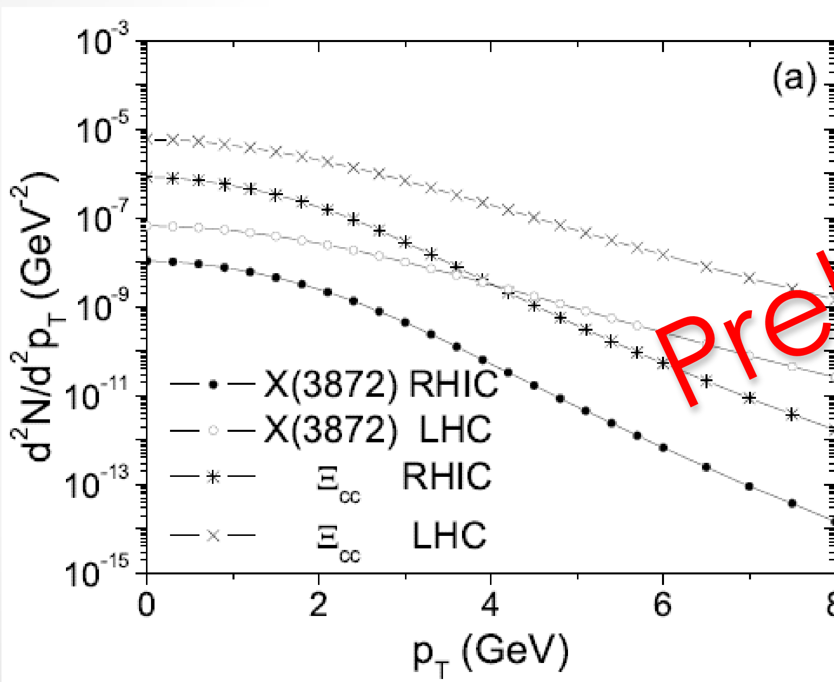
$$N_X = g_X \int p_l \cdot d\sigma_l p_{\bar{l}} \cdot d\sigma_{\bar{l}} p_c \cdot d\sigma_c p_{\bar{c}} \cdot d\sigma_{\bar{c}} \frac{d^3\vec{p}_l}{(2\pi)^3 E_l} \frac{d^3\vec{p}_{\bar{l}}}{(2\pi)^3 E_{\bar{l}}} \frac{d^3\vec{p}_c}{(2\pi)^3 E_c} \frac{d^3\vec{p}_{\bar{c}}}{(2\pi)^3 E_{\bar{c}}} \times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

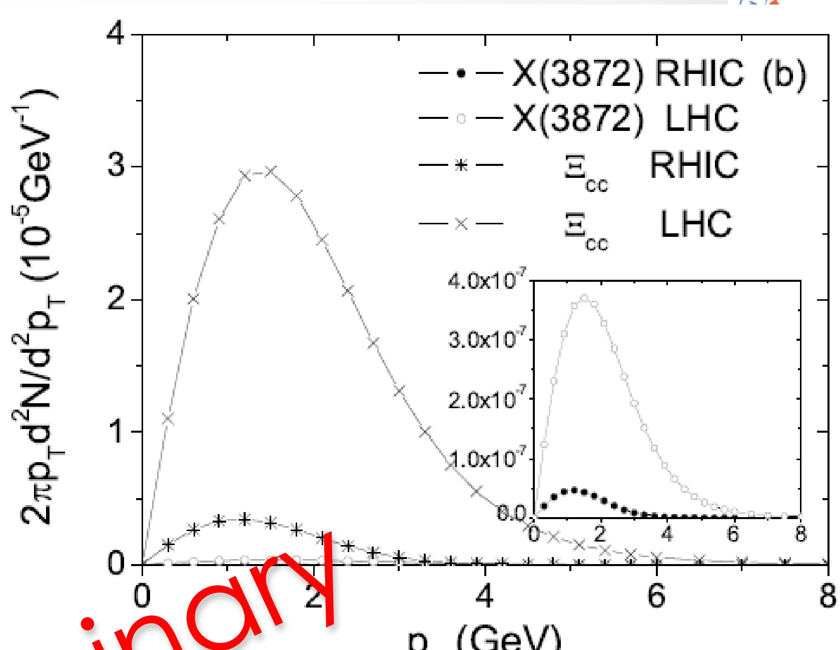
2) The transverse momentum distributions

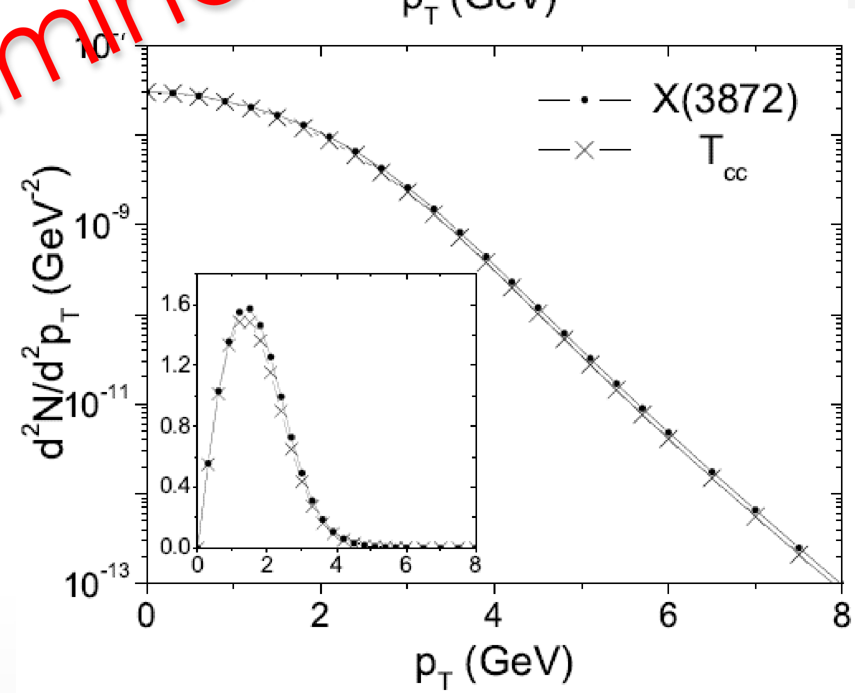
$$\frac{d^2 N_{\Xi_{cc}}}{d^2\vec{p}_T} = \frac{g_{\Xi_{cc}}}{V^2} \int d^3\vec{r}_1 d^3\vec{r}_2 d^2\vec{p}_{lT} d^2\vec{p}_{c_1T} d^2\vec{p}_{c_2T} \delta^{(2)}(\vec{p}_T - \vec{p}_{lT} - \vec{p}_{c_1T} - \vec{p}_{c_2T}) \frac{d^2 N_l}{d^2\vec{p}_{lT}} \times \frac{d^2 N_{c_1}}{d^2\vec{p}_{c_1T}} \frac{d^2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

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

– p_T distributions



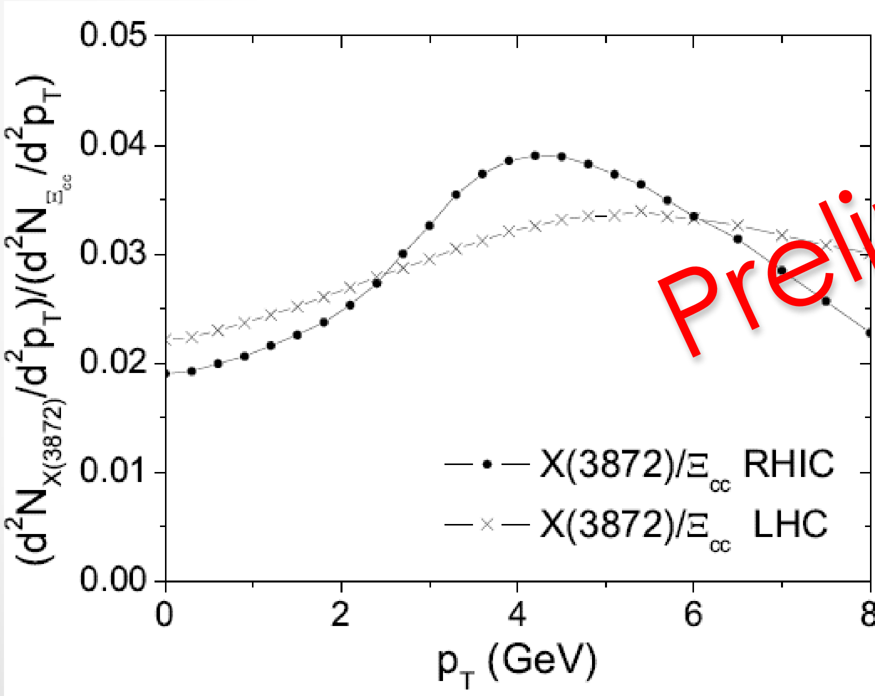


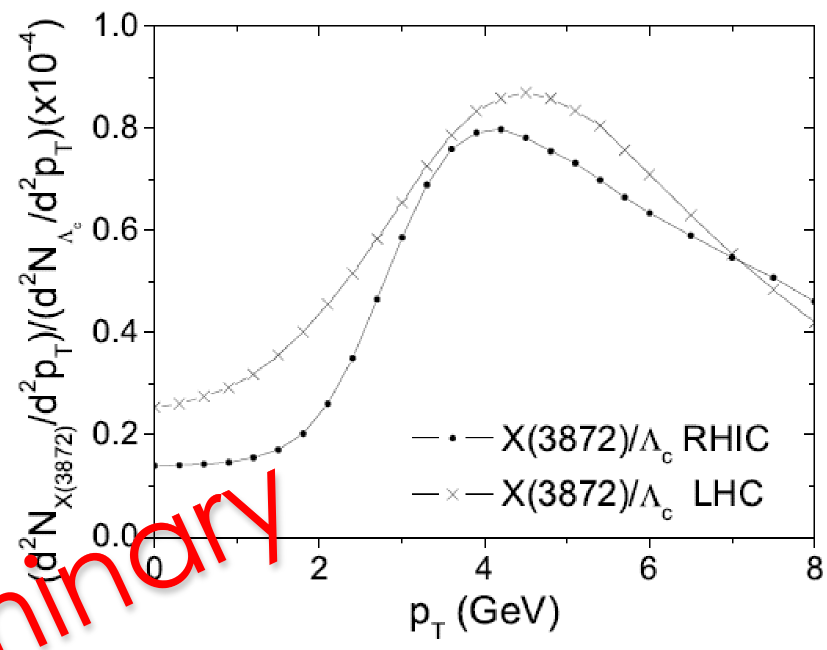


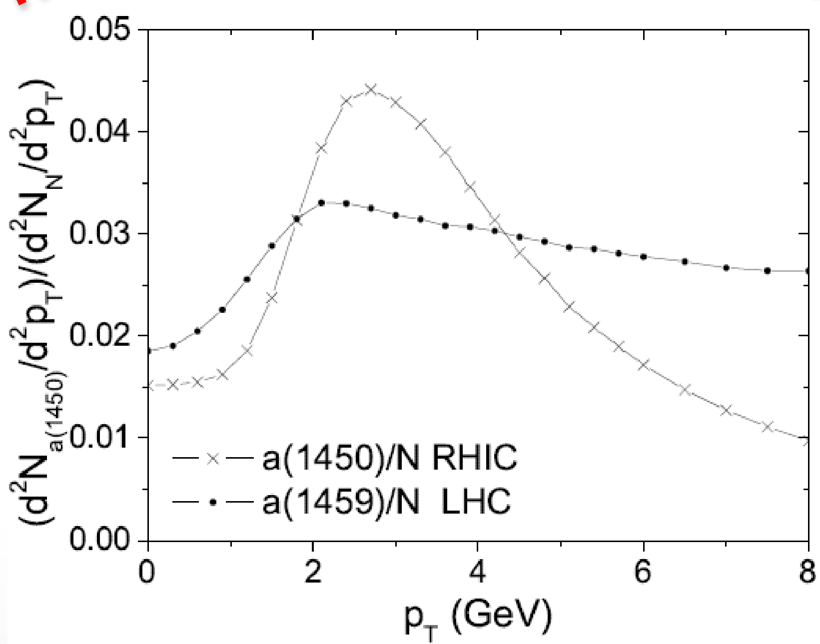
Preliminary

– Transverse momentum distribution ratios

1) Meson/baryon or qqcc/qcc ratio







Preliminary

Conclusion

– Charmed hadron production in relativistic heavy ion collisions

1) Heavy ion collision experiments can 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 distributions ratio between doubly charmed baryons and X(3872) mesons, or other combinations between heavy quark hadrons can lead us to understand in detail the production mechanism of hadrons produced from the quark-gluon plasma in heavy ion collisions
4) We expect to identify further not only the internal structure but also constituents of hadrons by measuring transverse momentum distributions in heavy ion collisions

Thank you for your attention!