Production of multi-charmed hadrons in heavy ion collisions

HaPhy-CENuM joint workshop:
The Future of Lattice-QCD studies in Korea

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Pukyong National University
Busan

Sungtae Cho
Kangwon National University

based on works in arXiv:1907.12786
in collaboration with Su Houng Lee at Yonsei

Outline

- Introduction
- Charmed hadrons in heavy ion collisions
- Hadron production by quark coalescence
- Transverse momentum distribution of charmed hadrons
- Conclusion

Physics Potential – some examples

- Heavy-flavor and quarkonia
  - Multiply Heavy Flavoured hadrons. e.g.: Ξ_{cc}, Ω_{cc}, Ω_{ccc}
  - $\chi_{c1,2}$ states
  - Ultimate precision on B mesons at low p_T
  - X, Y, Z charmonium-like states (e.g. X(3872))
- Low-mass dielectrons
  - Precision measurement of the thermal dilepton continuum, $0 < m < 3$GeV
- Real soft photons
  - down to 50MeV/c
- Real ultra-soft photons
  - Very low p_T photons: $1\text{MeV/c} < p_T^{\gamma} < 100\text{MeV/c}$
  - dedicated small forward spectrometer at $3.5 < |\eta| < 5$)

→ Hadron formation from deconfined QGP

→ Chiral symmetry restoration ρ-a1 sector

→ QGP Radiation unchartered phase space region

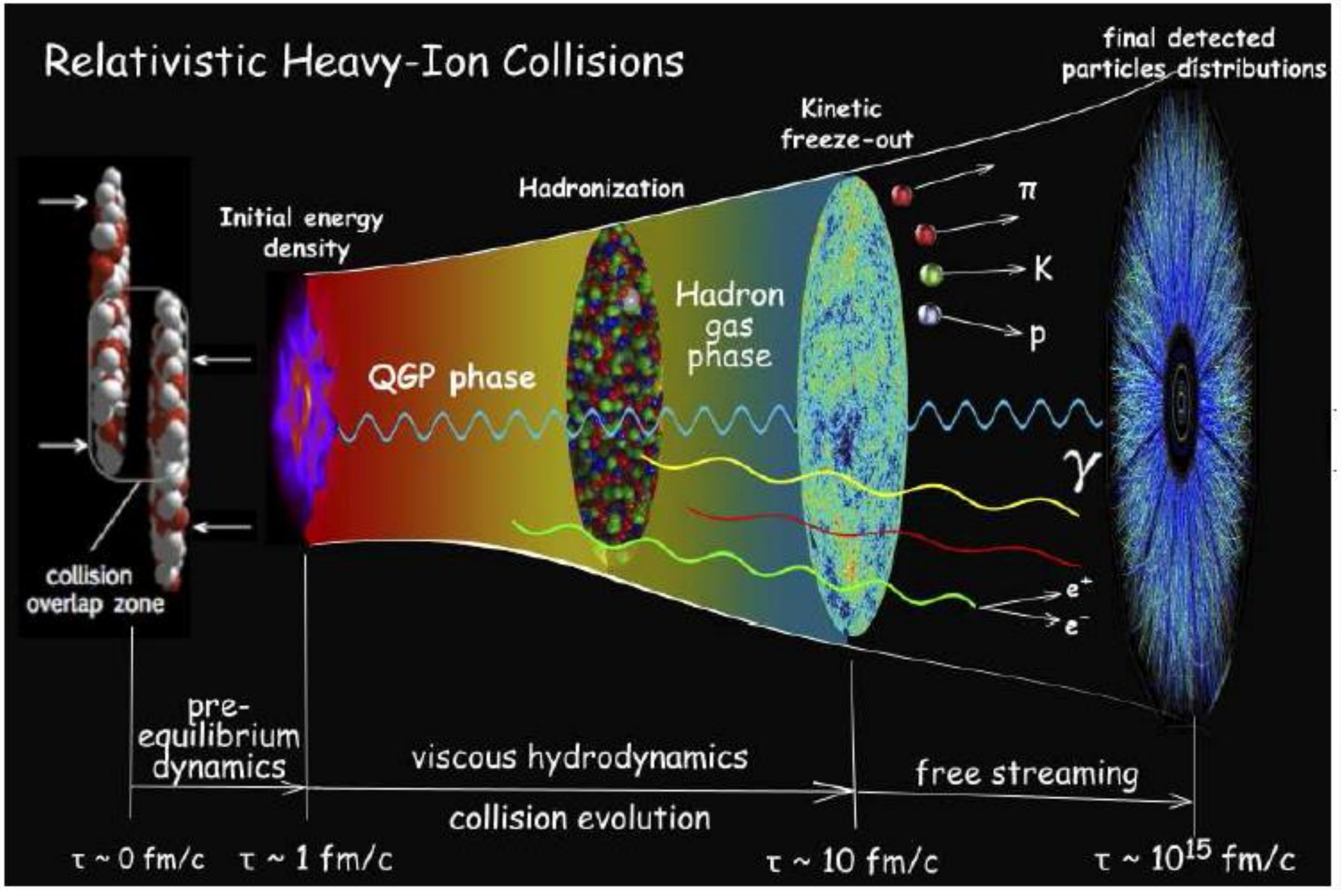
→ Test of soft theorems

L. Musa (CERN) – SQM, Bari, 10-15 June 2019 11

L. Musa (CERN), Strangeness in Quark Matter 2019, Bari, June 10-15

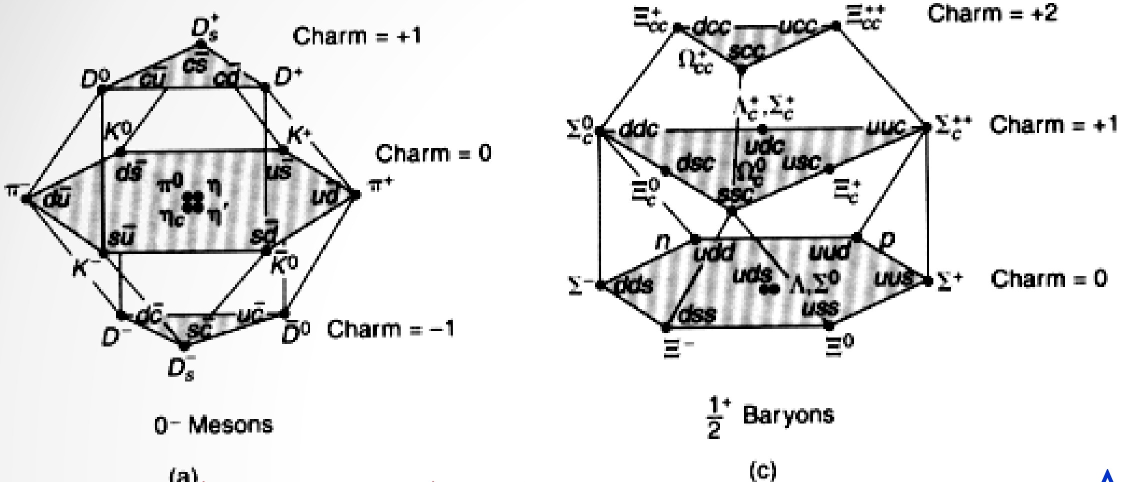
Introduction

– Relativistic heavy ion collisions

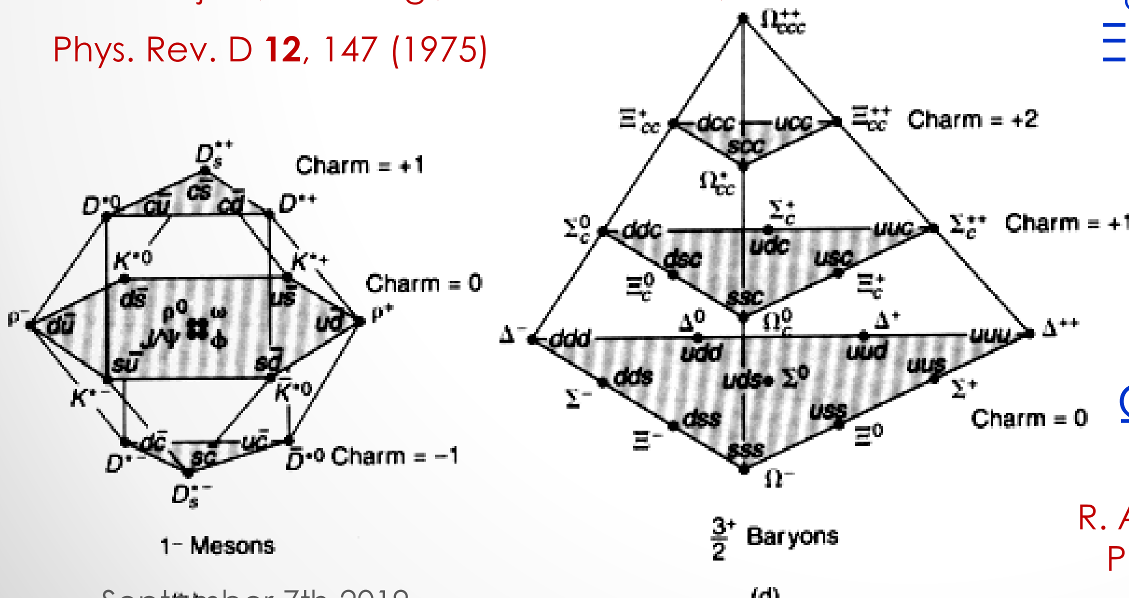


U. W. Heinz, J. Phys. Conf. Ser. **455**, 012044 (2013)

– Charmed hadrons, SU(4)



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



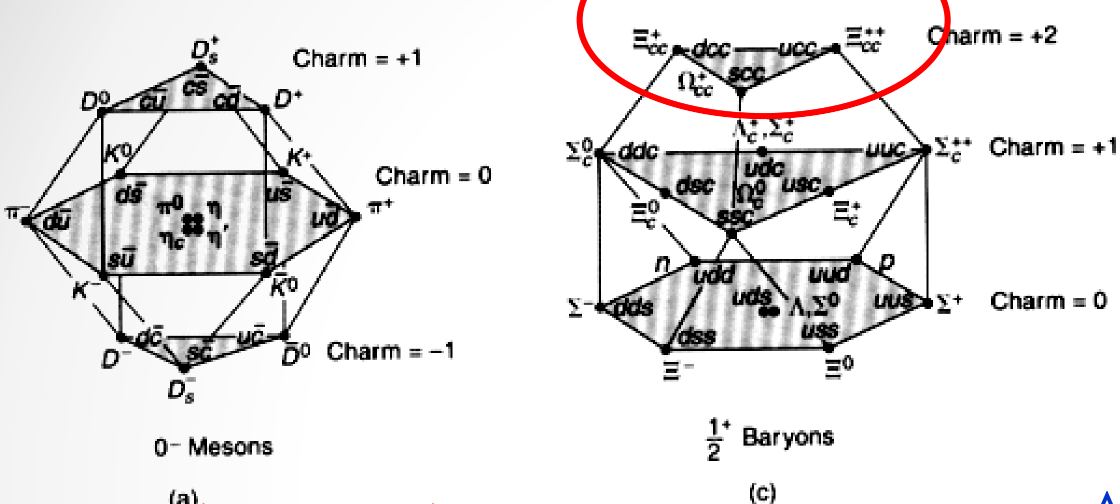
1) Charmonium states : ηc, J/ψ, χc, ψ'

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 and triply charmed hadrons, exotic hadrons : Ξ_{cc}, Ξ^*_{cc}, Ω_{cc}, Ω^*_{cc}, Ω_{ccc}, T_{cc}, X(3872)

R. A. Briceno, H.-W. Lin, and D. R. Bolton, Phys. Rev. D **86** 094504 (2012)

– Charmed hadrons, SU(4)



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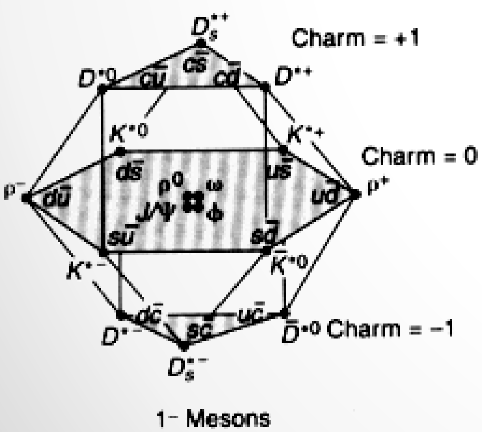
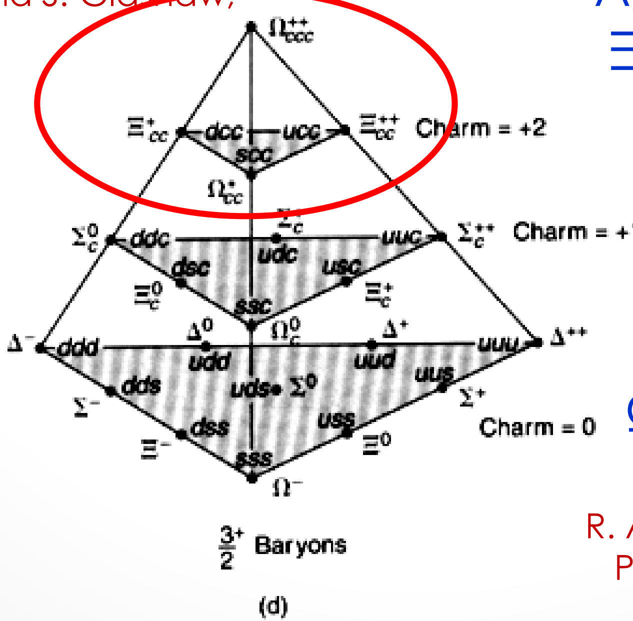
Phys. Rev. D **12**, 147 (1975)





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R. A. Briceno, H.-W. Lin, and D. R. Bolton,
Phys. Rev. D **86** 094504 (2012)

– 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} ($cc\bar{q}\bar{q}$) 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%

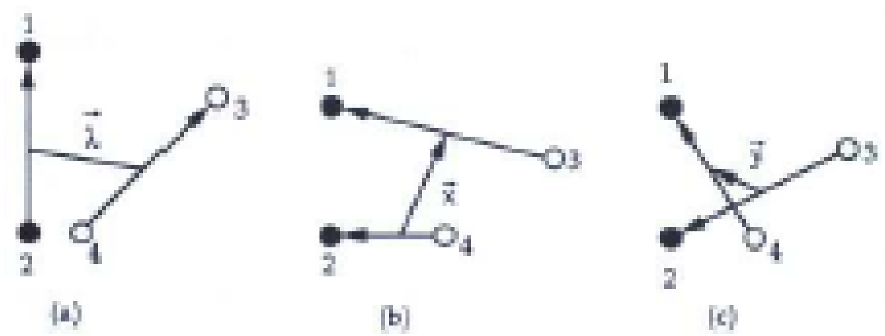
J. Beringer *et al.* (PDG), Phys. Rev. D**86**, 010001 (2012)

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

– Internal structure of X(3872) mesons

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

D. M. Brink and Fl. Stancu, Phys. Rev. D 49, 4665 (1994)



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

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

$$\vec{r}'_1 = \vec{r}_1 - \vec{r}_2$$

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

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

$$\vec{k} = \vec{p}_{lT} + \vec{p}_{\bar{l}T} + \vec{p}_{cT} + \vec{p}_{\bar{c}T},$$

$$\vec{k}_1 = \frac{m_{\bar{l}}\vec{p}_{lT} - m_l\vec{p}_{\bar{l}T}}{m_l + m_{\bar{l}}},$$

$$\vec{k}_2 = \frac{m_c(\vec{p}_{lT} + \vec{p}_{\bar{l}T}) - (m_l + m_{\bar{l}})\vec{p}_{cT}}{m_l + m_{\bar{l}} + m_c},$$

$$\vec{k}_3 = \frac{m_{\bar{c}}(\vec{p}_{lT} + \vec{p}_{\bar{l}T} + \vec{p}_{cT}) - (m_l + m_{\bar{l}} + m_c)\vec{p}_{\bar{c}T}}{m_l + m_{\bar{l}} + m_c + m_{\bar{c}}} \quad \text{(A2)}$$

$$\vec{k} = \vec{p}_{lT} + \vec{p}_{\bar{l}T} + \vec{p}_{cT} + \vec{p}_{\bar{c}T},$$

$$\vec{k}_1 = \frac{m_{\bar{l}}\vec{p}_{lT} - m_l\vec{p}_{\bar{l}T}}{m_l + m_{\bar{l}}},$$

$$\vec{k}_2 = \frac{m_{\bar{c}}\vec{p}_{cT} - m_c\vec{p}_{\bar{c}T}}{m_c + m_{\bar{c}}},$$

$$\vec{k}_3 = \frac{(m_c + m_{\bar{c}})(\vec{p}_{lT} + \vec{p}_{\bar{l}T}) - (m_l + m_{\bar{l}})(\vec{p}_{cT} + \vec{p}_{\bar{c}T})}{m_l + m_{\bar{l}} + m_c + m_{\bar{c}}},$$

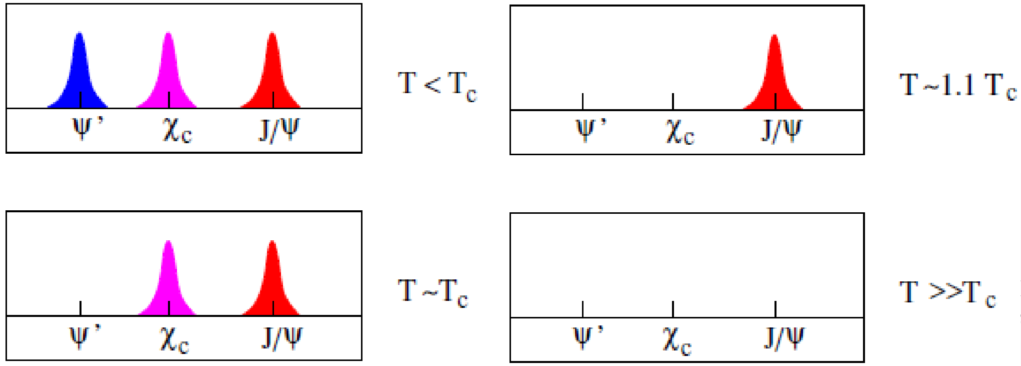
Charmed hadrons in heavy ion collisions

– 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

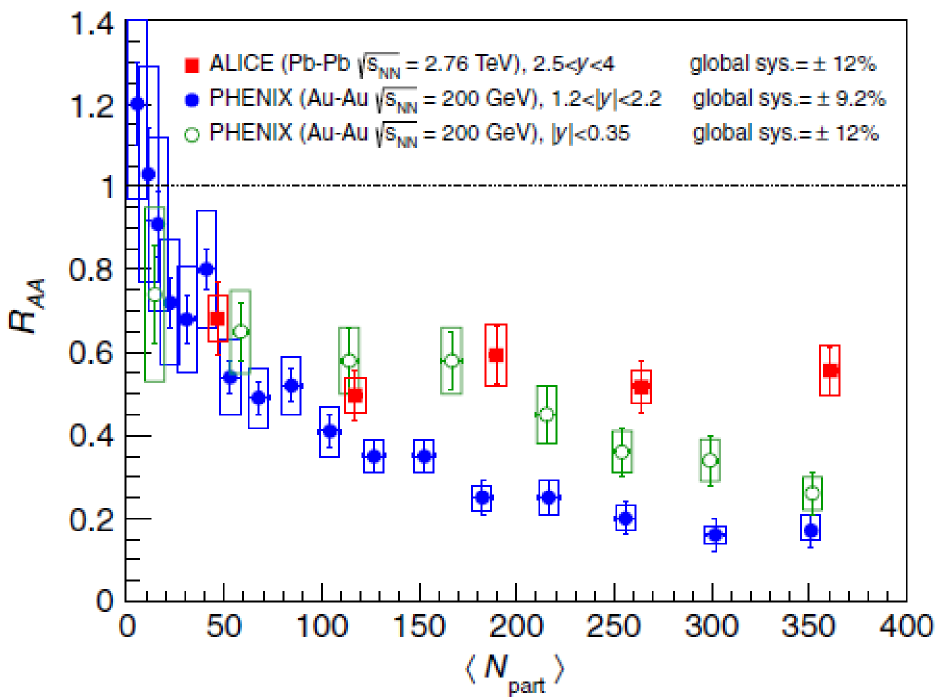


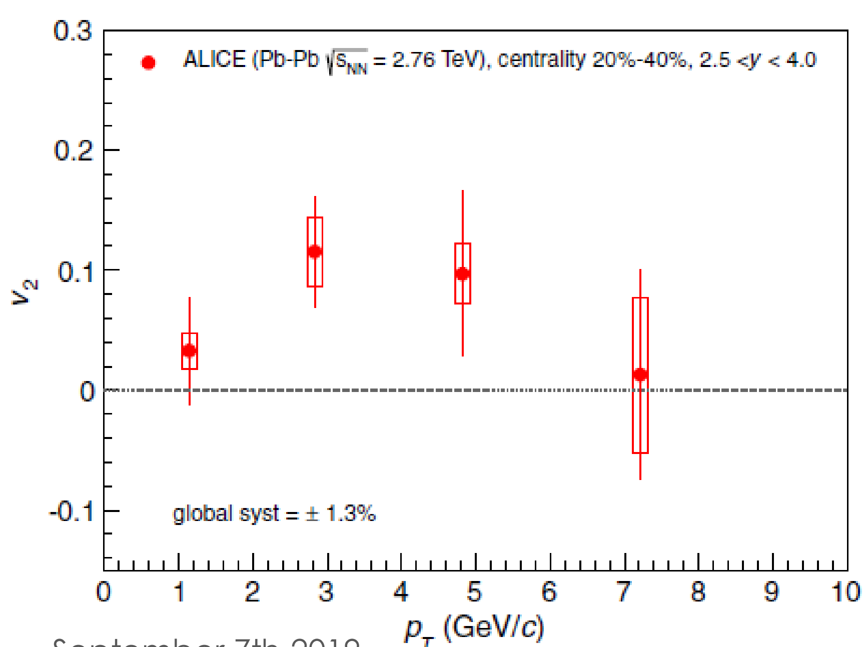
H. Satz, J. Phys. G. **32**, R25 (2006)

– 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





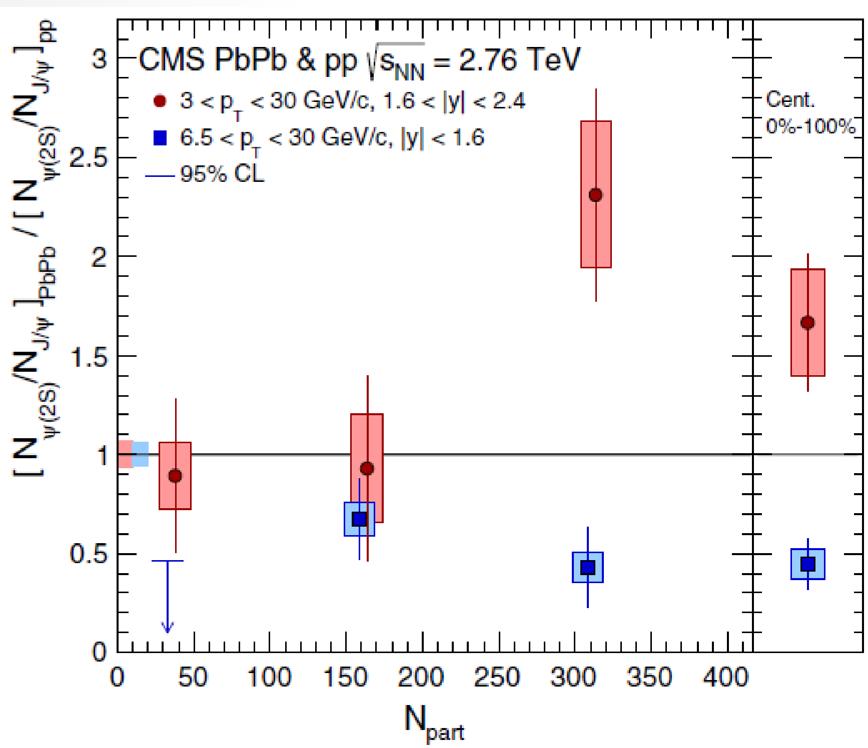
2) Elliptic flow of the J/ψ

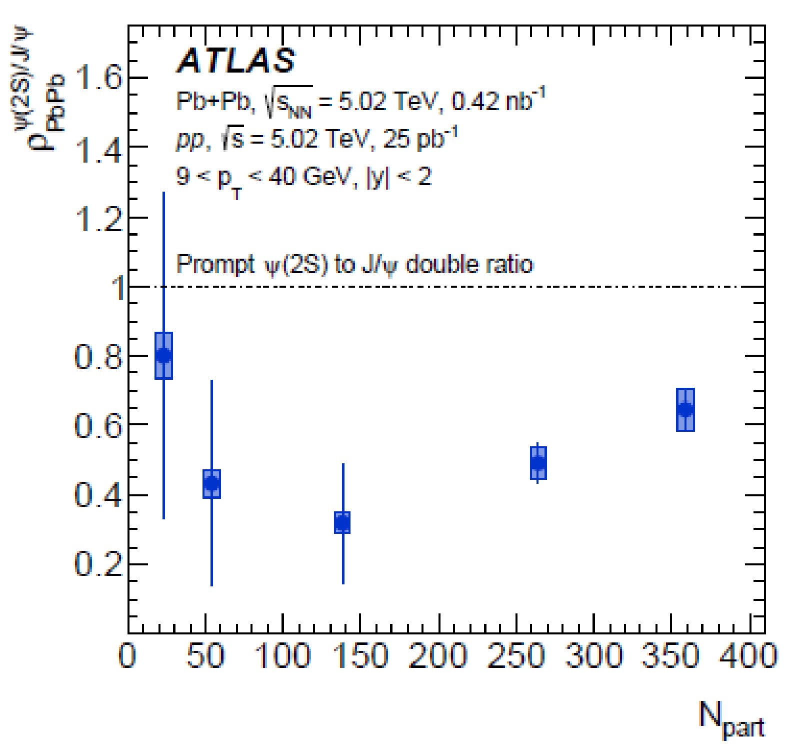
E. Abbas et al, Phys. Rev. Lett. **111**, 162301 (2013)

– Charmonium states in heavy ion collisions

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

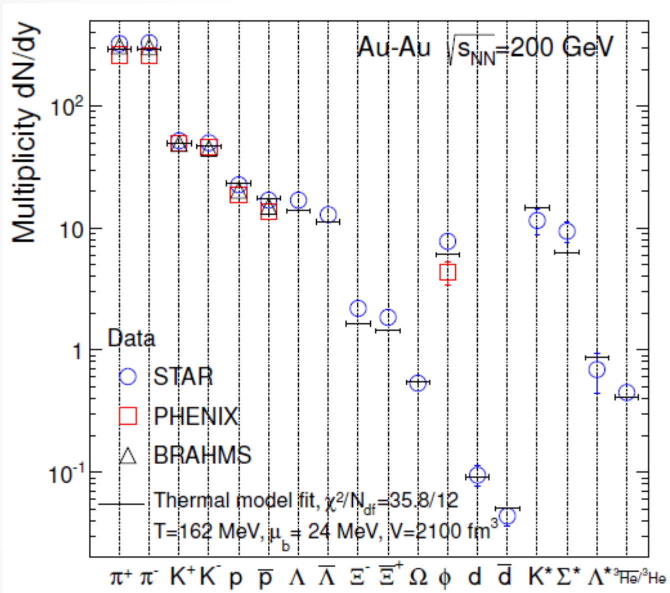
V. Khachatryan et al, Phys. Rev. Lett. **113**, 262301 (2014)
M. Aaboud et al, Eur. Phys. J. C **78**, 762 (2018)

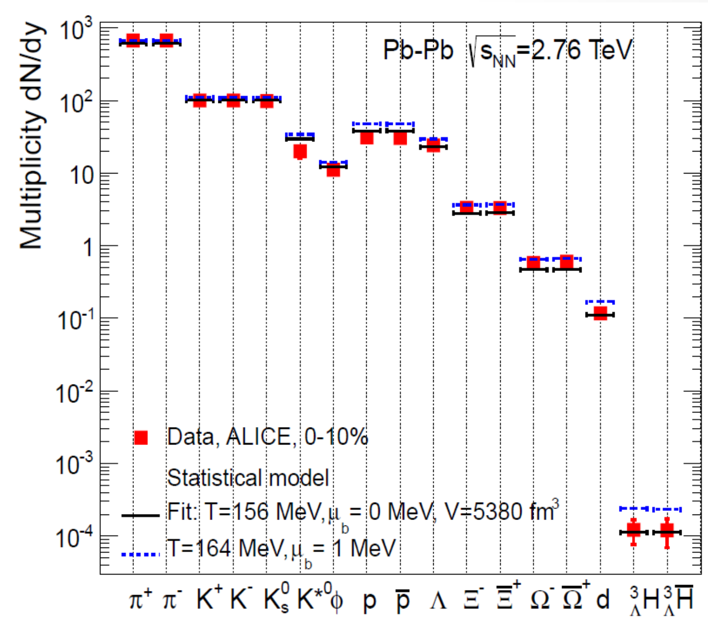




– Multi-charm hadron production

1) Yields in statistical hadronization 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}	1.0×10^{-2}	1.3×10^{-3}	2.8×10^{-2}	4.9×10^{-3}
Ξ^*_{cc}	6.4×10^{-3}	9.0×10^{-4}	1.8×10^{-2}	3.3×10^{-3}
Ω_{scc}	2.8×10^{-3}	2.5×10^{-4}	8.0×10^{-3}	9.0×10^{-4}
Ω^*_{scc}	1.5×10^{-3}	1.6×10^{-4}	4.3×10^{-3}	6.0×10^{-4}

	RHIC		LHC	
	Stat.	Coal.	Stat.	Coal.
Ω_{ccc}	1.1×10^{-4}	1.1×10^{-6}	4.0×10^{-4}	5.3×10^{-6}
T_{cc}	8.9×10^{-4}	5.3×10^{-5}	2.7×10^{-3}	1.3×10^{-4}
X_2	5.7×10^{-4}	5.6×10^{-4}	1.7×10^{-3}	1.7×10^{-3}
X_4	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

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

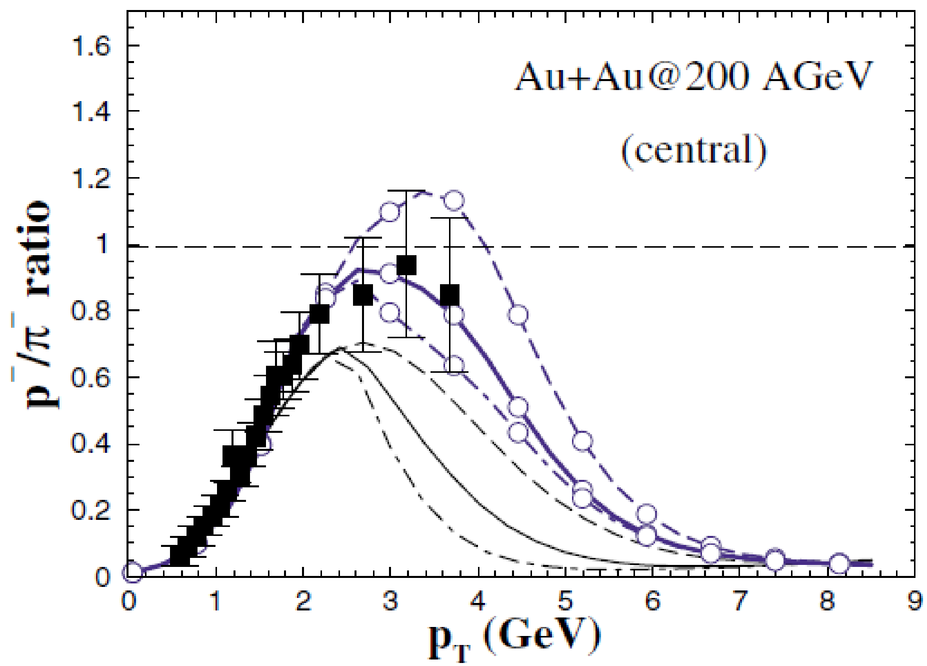
– Hadron production by recombination

: 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



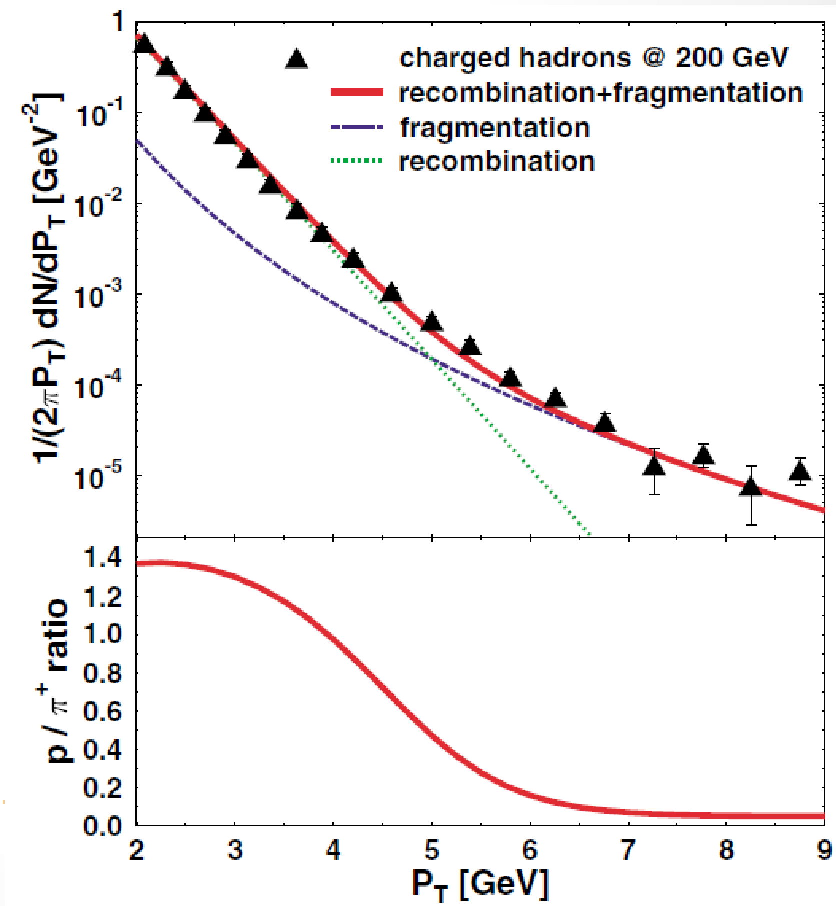
2) The transverse momentum spectra

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

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

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

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



and

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

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

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

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

Transverse momentum distributions of charmed hadrons

– 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

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

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

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

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

2) Integration of the Wigner function over the spatial coordinates

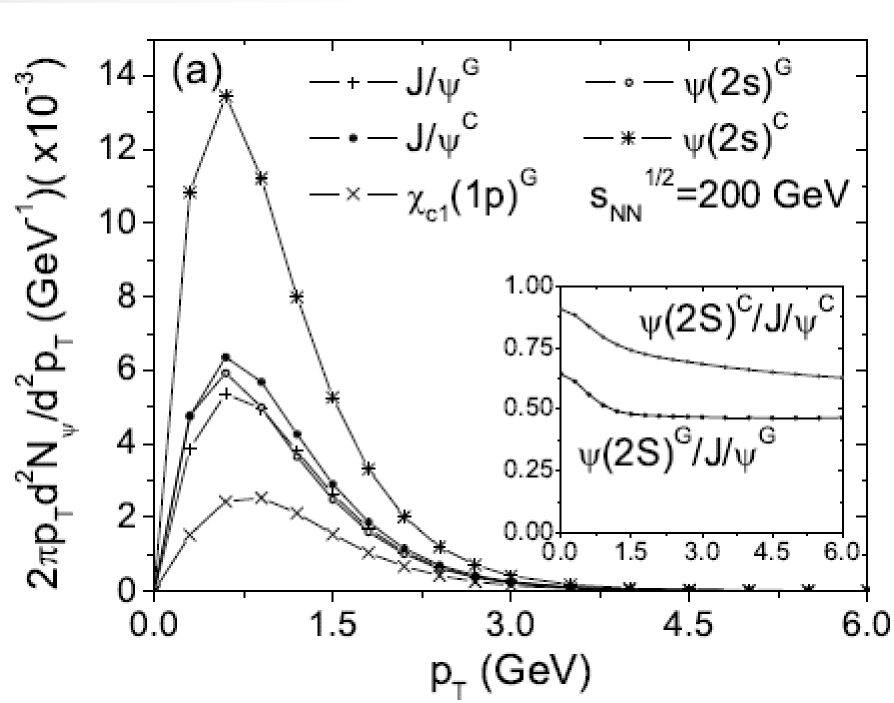
$$\int d^3\vec{r} W_\psi(\vec{r},\vec{k}) = \begin{cases} (2\sqrt{\pi}\sigma)^3 e^{-k^2\sigma^2} & \psi_s^G; J/\psi \\ \frac{2}{3}(2\sqrt{\pi}\sigma)^3 e^{-k^2\sigma^2}\sigma^2 k^2 & \psi_p^G; \chi_c \\ \frac{2}{3}(2\sqrt{\pi}\sigma)^3 e^{-k^2\sigma^2}\left(\sigma^2 k^2 - \frac{3}{2}\right)^2 & \psi_{10}^G;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

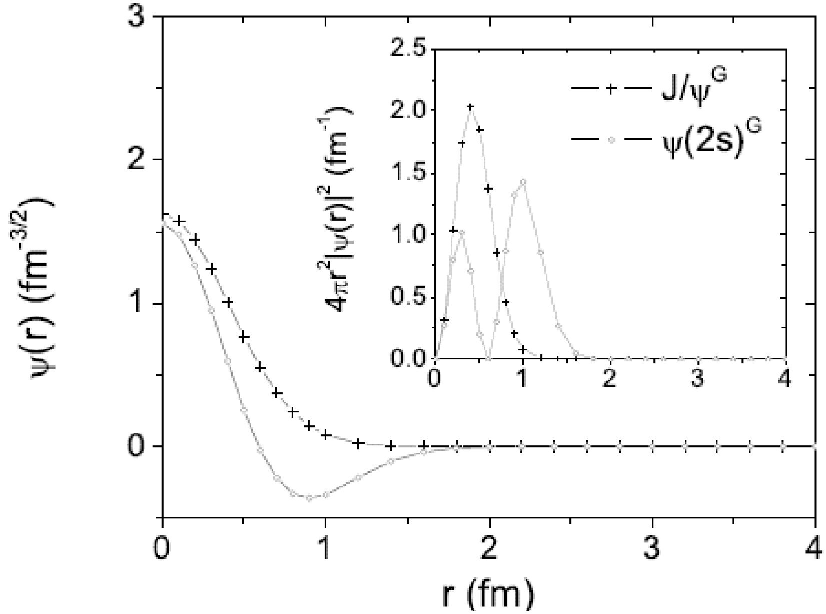
$$\int d^3\vec{r} W(\vec{r},\vec{k}) = \left|\tilde{\psi}(\vec{k})\right|^2$$

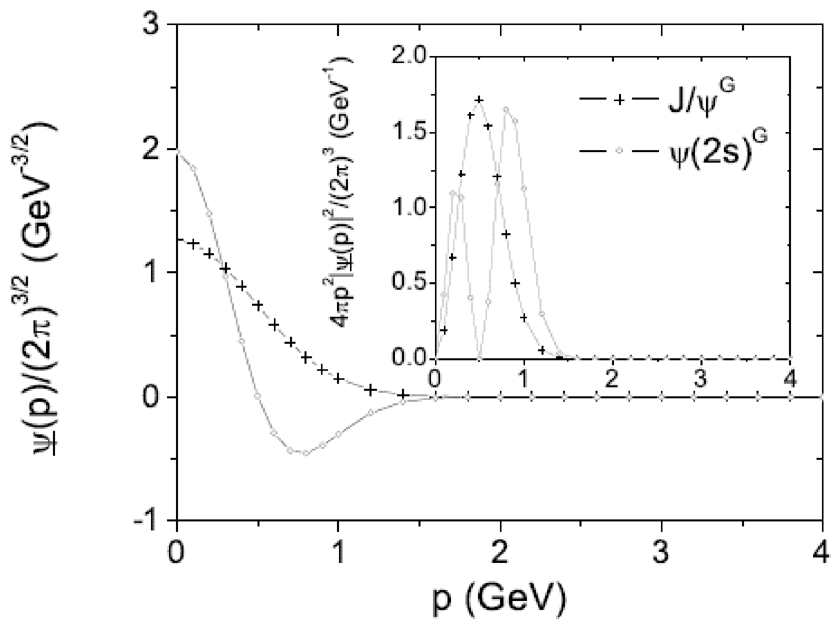
M. Hillery, R. F. O'Connel, M. O. Scully and E. P. Wigner, Phys. Rept. **106**, 121 (1984)

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

3) Transverse momentum distributions of charmonium states







– Production of multi-charm hadrons by recombination

1) Coalescence production of multi-charm 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

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

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

3) Transverse momentum distributions of charm and light quarks

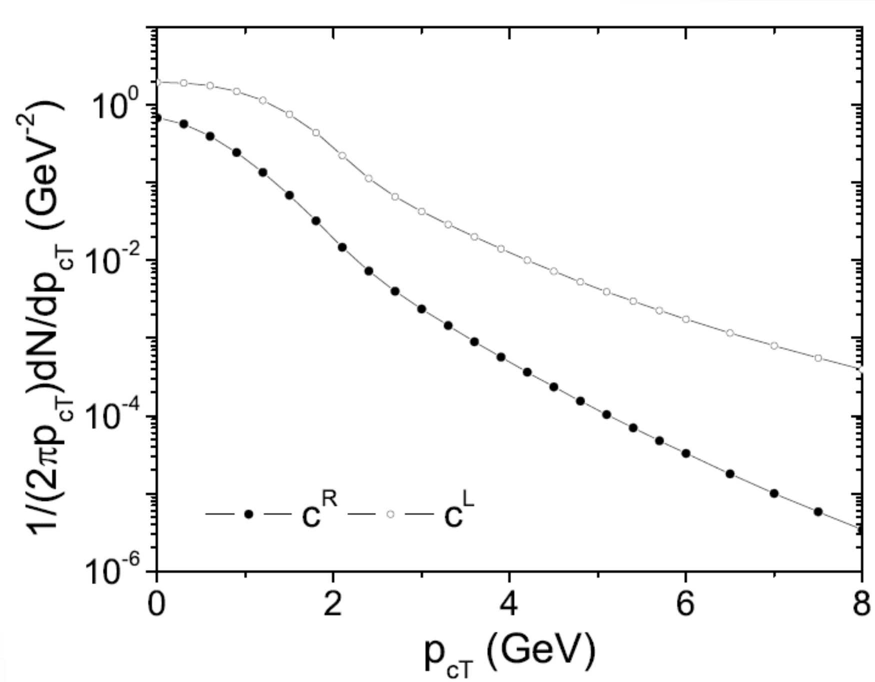
$$\frac{dN_c}{d^2p_T} = \begin{cases} a_0 \exp[-a_1 p_T^{a_2}] & p_T \le p_0 \\ a_0 \exp[-a_1 p_T^{a_2}] + a_3(1+p_T^{a_4})^{-a_5} & p_T \ge p_0 \end{cases}$$

$$\frac{d^2N_l}{d^2p_T} = g_l \frac{V}{(2\pi)^3} m_T e^{-m_T/T_{eff}},$$

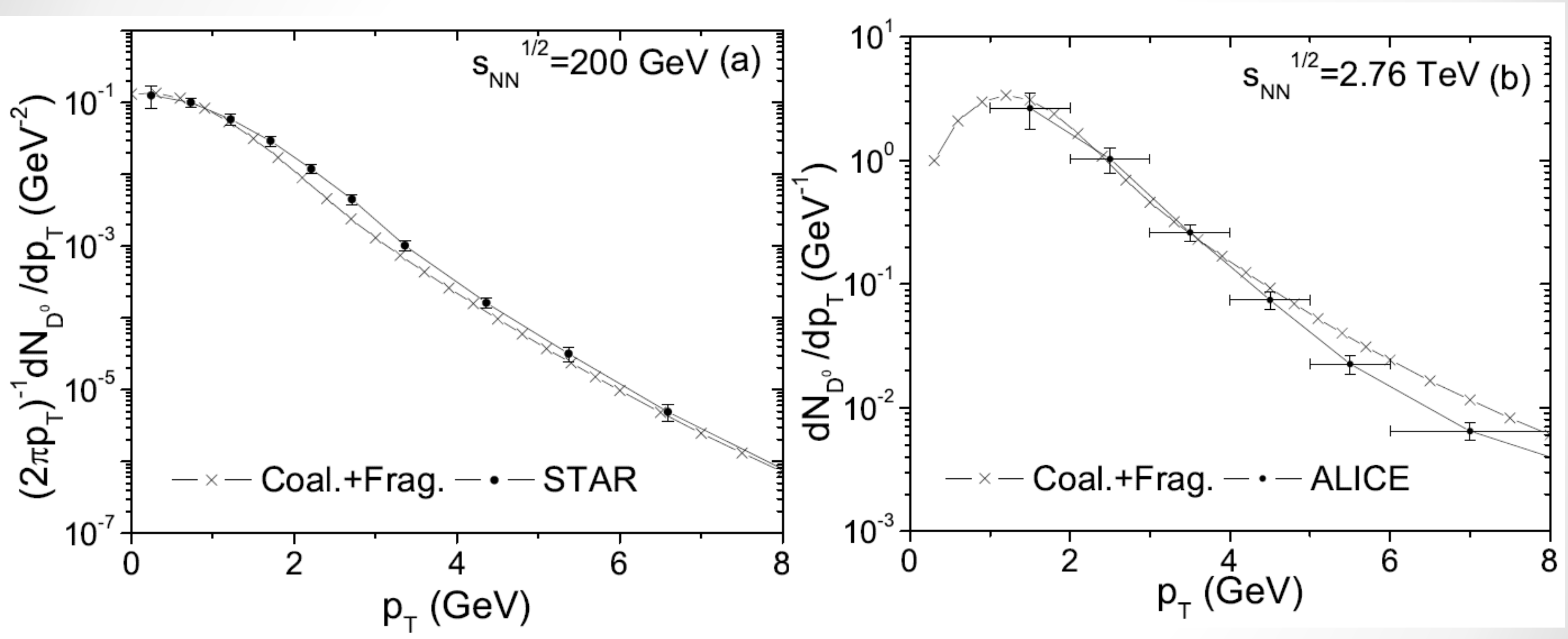
RHIC	a_0	a_1	a_2	a_3	a_4	a_5
$p_T \le p_0$	0.69	1.22	1.57			
$p_T \ge p_0$	1.08	3.04	0.71	3.79	2.02	3.48
LHC	a_0	a_1	a_2	a_3	a_4	a_5
$p_T \le p_0$	1.97	0.35	2.47			
$p_T \ge p_0$	7.95	3.49	3.59	87335	0.5	14.31

S. Plumari, V. Minissale, S. K. Das, G. Coci and V. Greco, Eur. Phys. J. C **78**:348 (2017)
Y. Oh, C. M. Ko, S.-H. Lee, and S. Yasui, Phys. Rev. C **79** 044905 (2009)
S. Cho *et al*. (EXHIC Collaboration), Prog. Part. Nucl. Phys. **95**, 279 (2017)

	RHIC		LHC (2.76 TeV)	
	Sc. 1	Sc. 2	Sc. 1	Sc. 2
T_H (MeV)	162		156	
V_H (fm^3)	2100		5380	
μ_B (MeV)	24		0	
μ_s (MeV)	10		0	
γ_c	22		39	
γ_b	4.0×10^7		8.6×10^8	
T_C (MeV)	162	166	156	166
V_C (fm^3)	2100	1791	5380	3533
$N_u = N_d$	320	302	700	593
$N_s = N_{\bar{s}}$	183	176	386	347
$N_c = N_{\bar{c}}$	4.1		11	
$N_b = N_{\bar{b}}$	0.03		0.44	

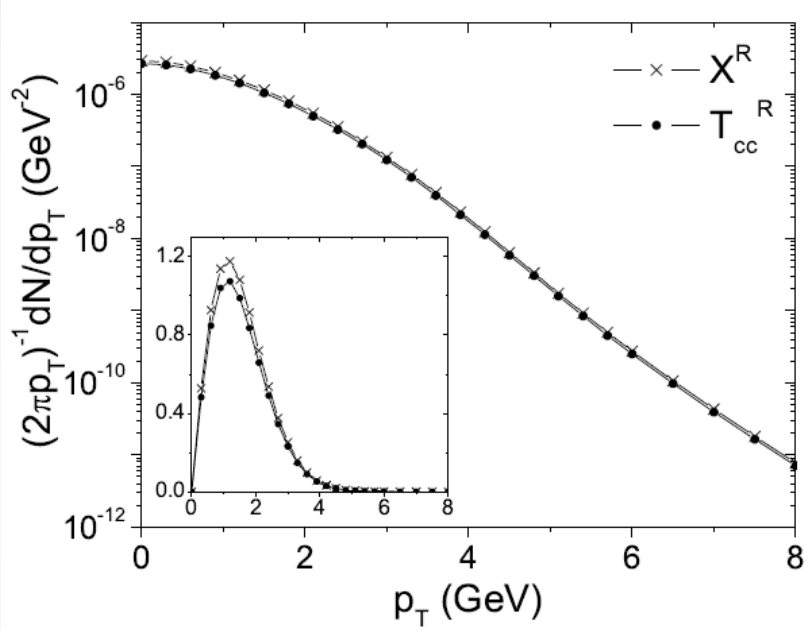


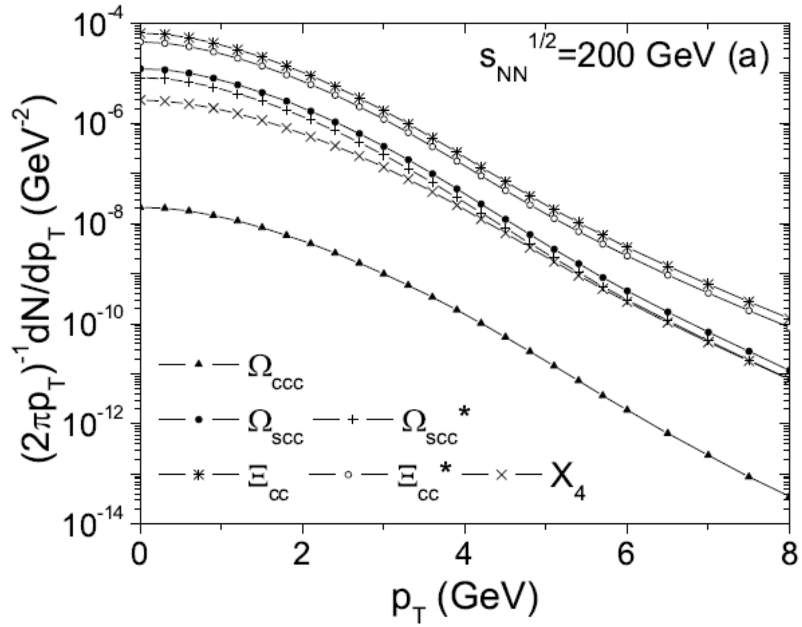
4) Transverse momentum distributions of D^0 mesons

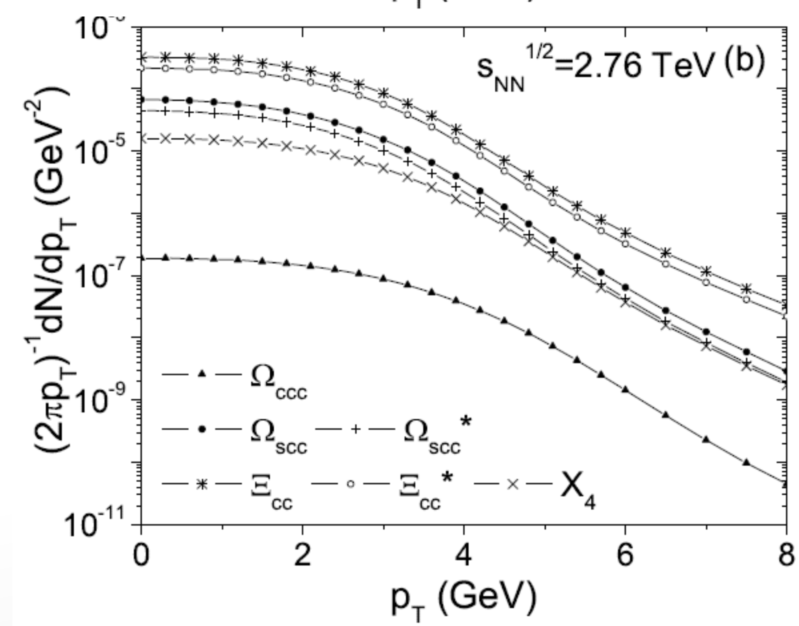


J. Adam et al. [STAR Collaboration], Phys. Rev. C **99**, no. 3, 034908 (2019).
J. Adam et al. [ALICE Collaboration], JHEP **1603**, 081 (2016).

5) Transverse momentum distributions of multi-charm hadrons



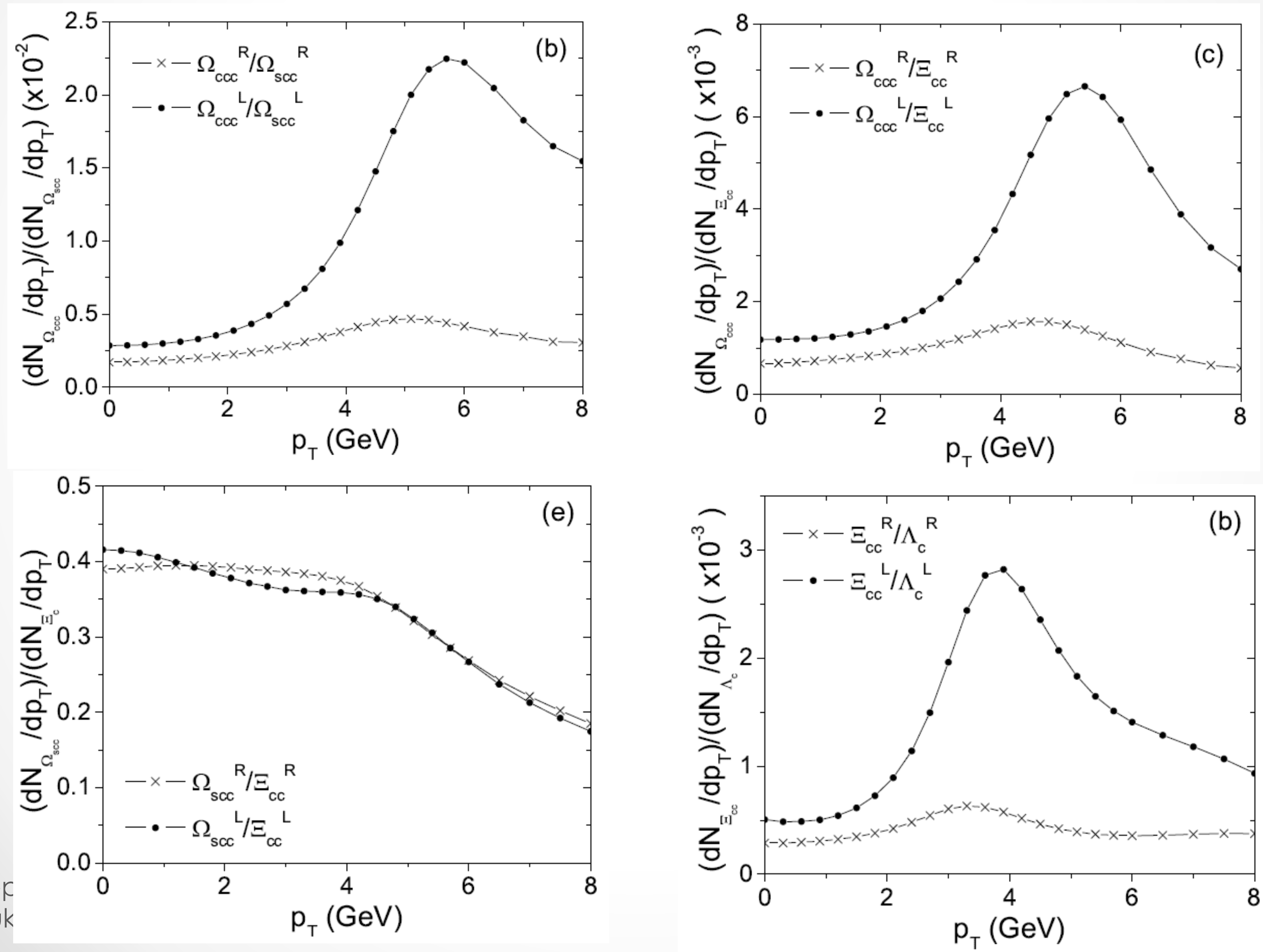




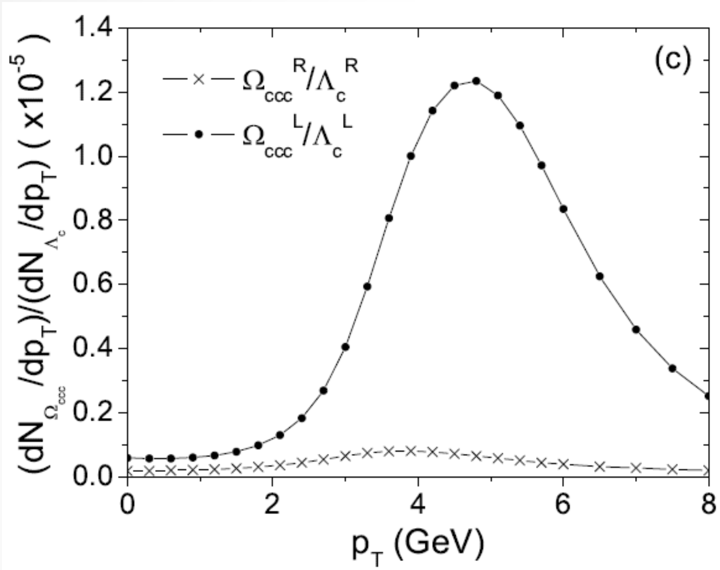
	RHIC	LHC
Ξ_{cc}	4.4×10^{-4}	6.7×10^{-3}
Ξ_{cc}^*	2.9×10^{-4}	4.5×10^{-3}
Ω_{scc}	8.6×10^{-5}	1.3×10^{-3}
Ω_{scc}^*	5.7×10^{-5}	8.5×10^{-4}
Ω_{ccc}	1.7×10^{-7}	5.9×10^{-6}
T_{cc}	2.2×10^{-5}	3.8×10^{-4}
X_4	2.4×10^{-5}	3.8×10^{-4}
X_2	2.6×10^{-4}	4.5×10^{-3}

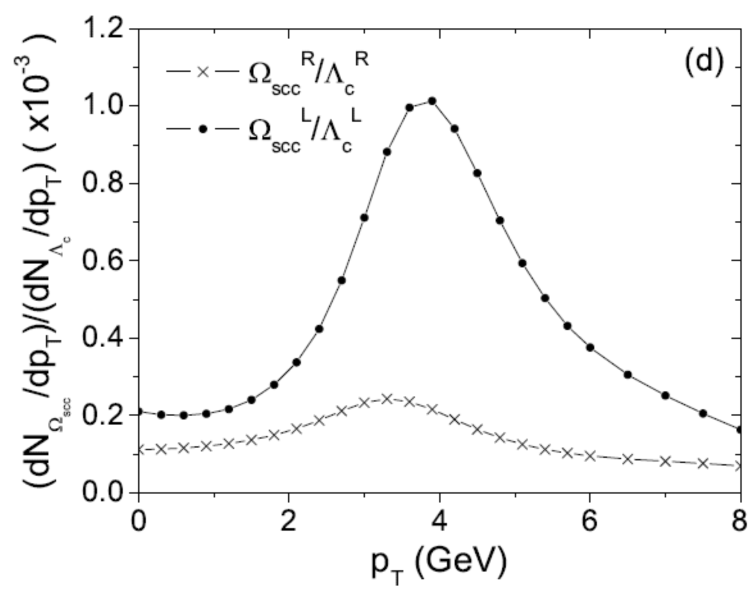
6) Transverse momentum distribution ratios

a) Baryon/baryon (ccc/ccq, ccc/ccs, ccq/ccs, and ccq/cqq)

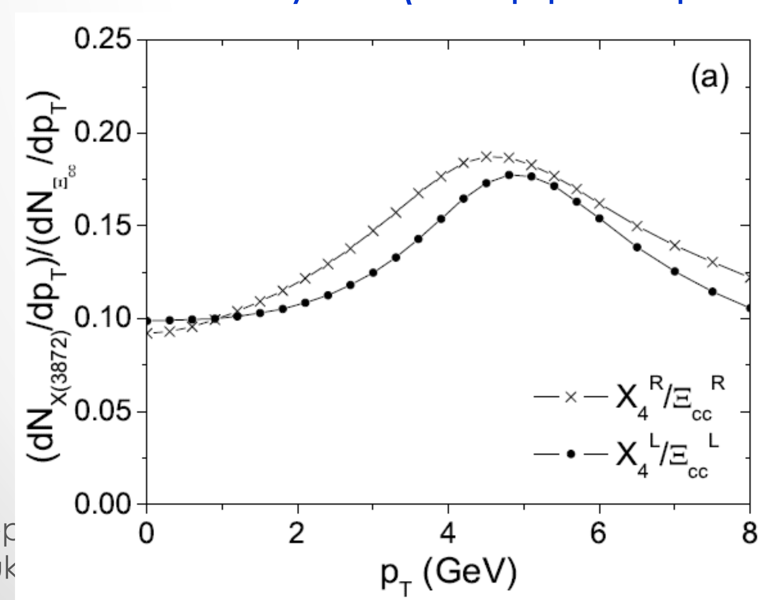


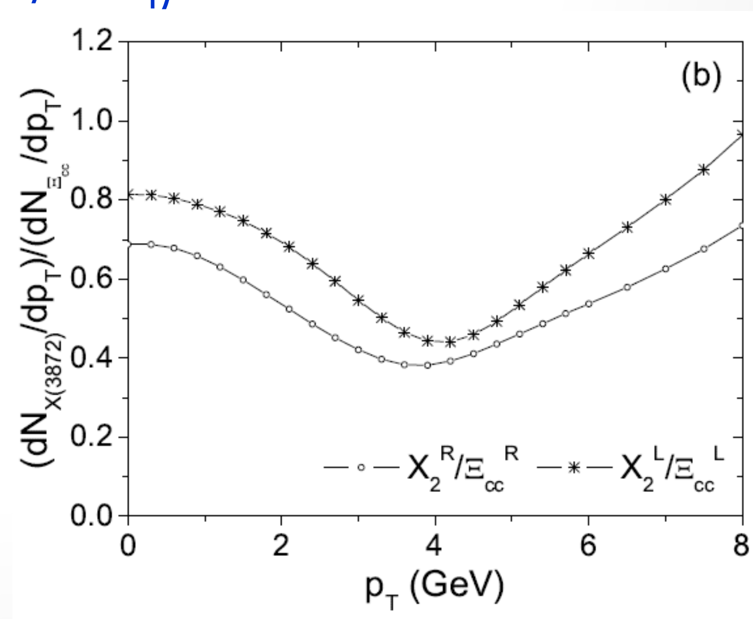
b) Baryon/baryon (ccc/cqq, or ccs/cqq)

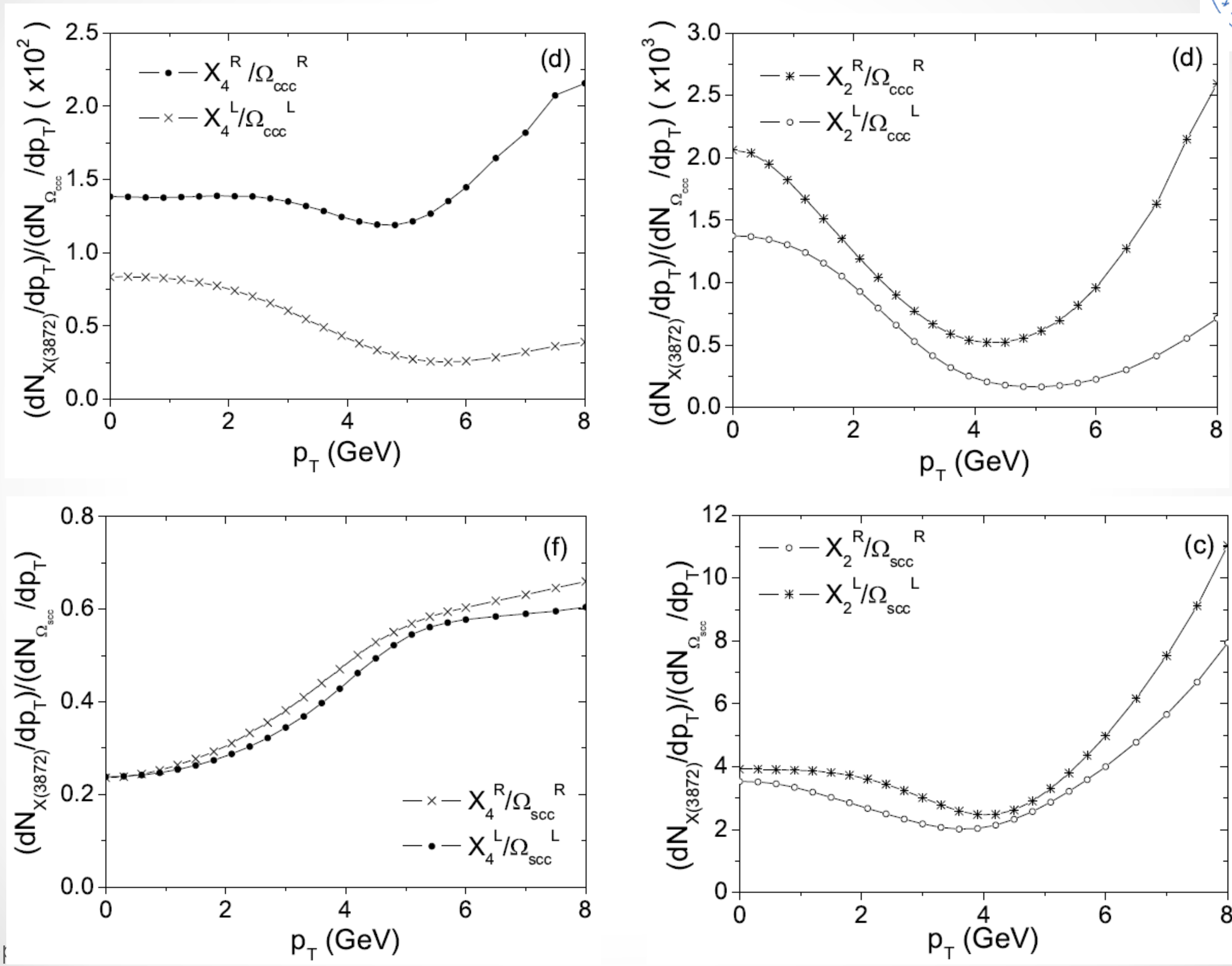




c) Meson/baryon (ccqq/ccq, or cc/ccq)



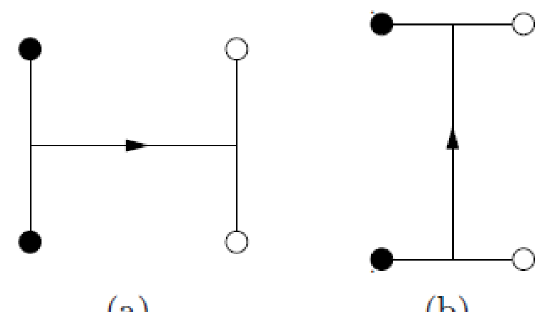



(d)
X_4^R/Ω_{ccc}^R
X_4^L/Ω_{ccc}^L
$(dN_{X(3872)}/dp_T)/(dN_{\Omega_{ccc}}/dp_T)$ ($\times 10^2$)
p_T (GeV)
(d)
X_2^R/Ω_{ccc}^R
X_2^L/Ω_{ccc}^L
$(dN_{X(3872)}/dp_T)/(dN_{\Omega_{ccc}}/dp_T)$ ($\times 10^3$)
p_T (GeV)
(f)
X_4^R/Ω_{scc}^R
X_4^L/Ω_{scc}^L
$(dN_{X(3872)}/dp_T)/(dN_{\Omega_{scc}}/dp_T)$
p_T (GeV)
(c)
X_2^R/Ω_{scc}^R
X_2^L/Ω_{scc}^L
$(dN_{X(3872)}/dp_T)/(dN_{\Omega_{scc}}/dp_T)$
p_T (GeV)

– Dependence of the transverse momentum distribution on internal relative coordinates

1) The Wigner function of the (3872) meson

$$W_X(\vec{r}_1,\vec{r}_2,\vec{r}_3,\vec{k}_1,\vec{k}_2,\vec{k}_3)$$
$$= 8^3 \exp\left(-\frac{r_1^2}{\sigma_1^2} - \sigma_1^2 k_1^2\right) \exp\left(-\frac{r_2^2}{\sigma_2^2} - \sigma_2^2 k_2^2\right) \exp\left(-\frac{r_3^2}{\sigma_3^2} - \sigma_3^2 k_3^2\right)$$



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

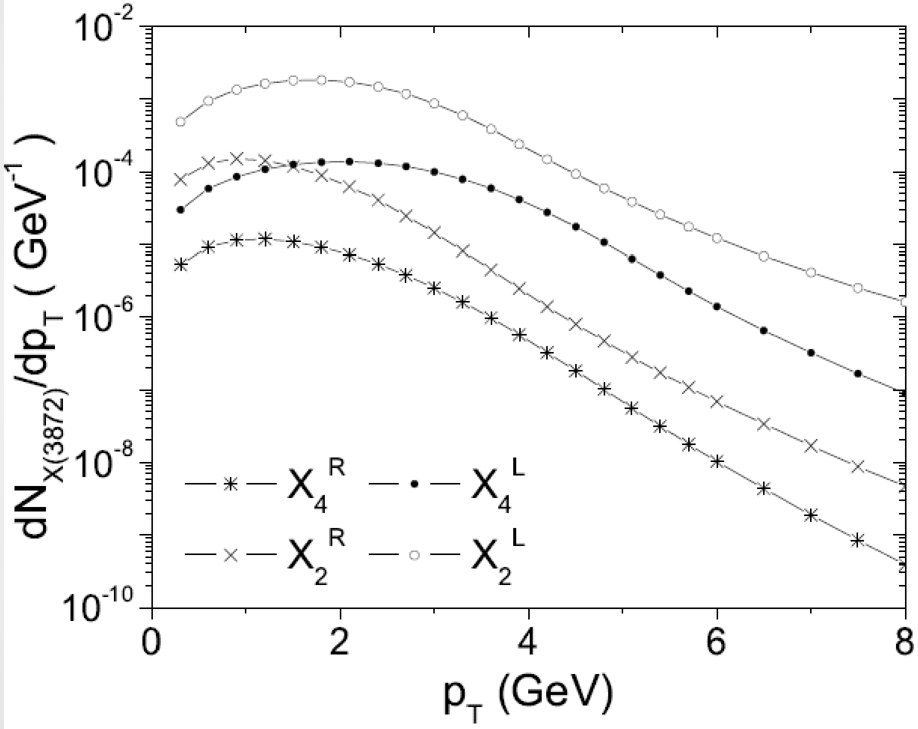
$$\mu_1 = \frac{m_l m_{\bar{l}}}{m_l + m_{\bar{l}}}, \quad \mu_2 = \frac{(m_l + m_{\bar{l}})m_c}{m_l + m_{\bar{l}} + m_c},$$
$$\mu_3 = \frac{(m_l + m_{\bar{l}} + m_c)}{m_l + m_{\bar{l}} + m_c + m_{\bar{c}}},$$

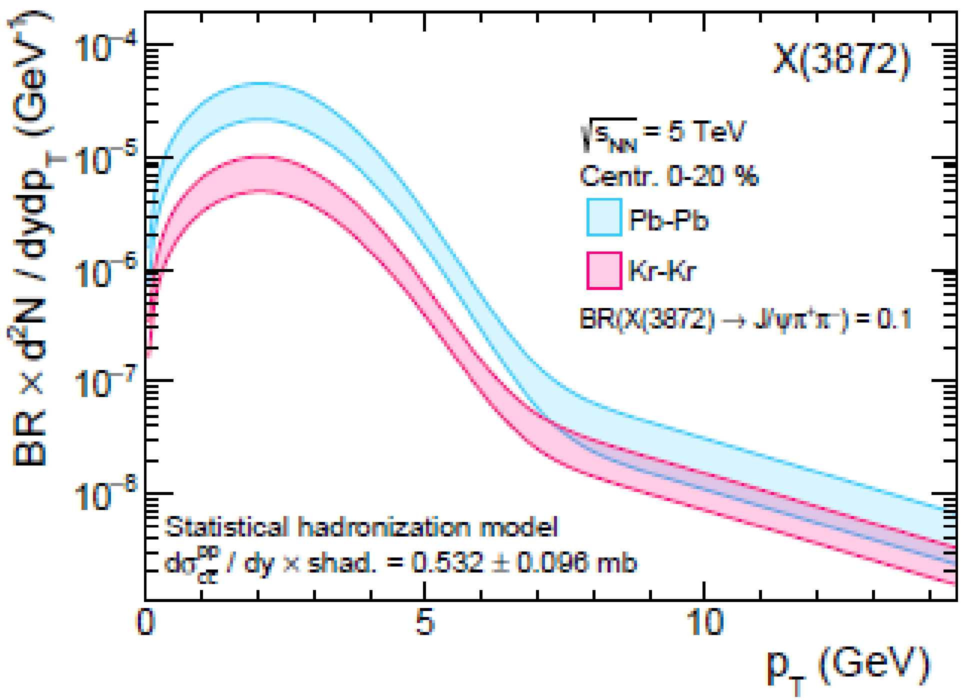
$$\vec{k} = \vec{p}'_{lT} + \vec{p}'_{\bar{l}T} + \vec{p}'_{cT} + \vec{p}'_{\bar{c}T},$$
$$\vec{k}_1 = \frac{m_{\bar{l}}\vec{p}'_{lT} - m_l\vec{p}'_{\bar{l}T}}{m_l + m_{\bar{l}}},$$
$$\vec{k}_2 = \frac{m_{\bar{c}}\vec{p}'_{cT} - m_c\vec{p}'_{\bar{c}T}}{m_c + m_{\bar{c}}},$$
$$\vec{k}_3 = \frac{(m_c +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

$$\mu_1 = \frac{m_l m_{\bar{l}}}{m_l + m_{\bar{l}}}, \quad \mu_2 = \frac{m_c m_{\bar{c}}}{m_c + m_{\bar{c}}},$$
$$\mu_3 = \frac{(m_l + m_{\bar{l}})(m_c + m_{\bar{c}})}{m_l + m_{\bar{l}} + m_c + m_{\bar{c}}}.$$

$$-\sigma_1^2 k_1^2 - \sigma_2^2 k_2^2 - \sigma_3^2 k_3^2 = -\frac{1}{\omega}\frac{1}{m_l + m_{\bar{l}} + m_c + m_{\bar{c}}}\Bigg(\frac{m_{\bar{l}} + m_c + m_{\bar{c}}}{m_l}p_l'^2 + \frac{m_c + m_{\bar{c}} + m_l}{m_{\bar{l}}}p_{\bar{l}}'^2 + \frac{m_{\bar{c}} + m_l + m_{\bar{l}}}{m_c}p_c'^3 + \frac{m_l + m_{\bar{l}} + m_c}{m_{\bar{c}}}p_{\bar{c}}'^2$$
$$-2(\vec{p}'_l\cdot\vec{p}'_{\bar{l}} + \vec{p}'_{\bar{l}}\cdot\vec{p}'_c + \vec{p}'_c\cdot\vec{p}'_{\bar{c}} + \vec{p}'_l\cdot\vec{p}'_c + \vec{p}'_{\bar{l}}\cdot\vec{p}'_c + \vec{p}'_{\bar{l}}\cdot\vec{p}'_{\bar{c}})\Bigg)$$

– Comparison with results from statistical hadronization model





A. Andronic, P. Braun-Munzinger, M. K. Kohler, K. Redlich and J. Stachel, arXiv:1901.09200

Conclusion

– Production of multi-charmed hadrons in heavy ion collisions

1) Heavy ion collision experiments provide better chances to study production of multi-charm hadrons as well as exotic hadrons
2) Transverse momentum distributions of charmonium states are affected by their intrinsic wave function distributions
3) Transverse momentum distribution ratios between multi-charm hadrons and X(3872) mesons, or other combinations between heavy quark hadrons reflect the distribution of momentum among constituent quarks : the momentum of the heavy quark hadron is mostly carried by the heavy quark
4) The transverse momentum distribution is also dependent on the internal structure of the hadron

Thank you for your attention!