Multi-charmed hadron production in heavy ion collisions

2nd CENuM Workshop

July 4th, 2020
Virtual Workshop via Zoom

Sungtae Cho
Kangwon National University

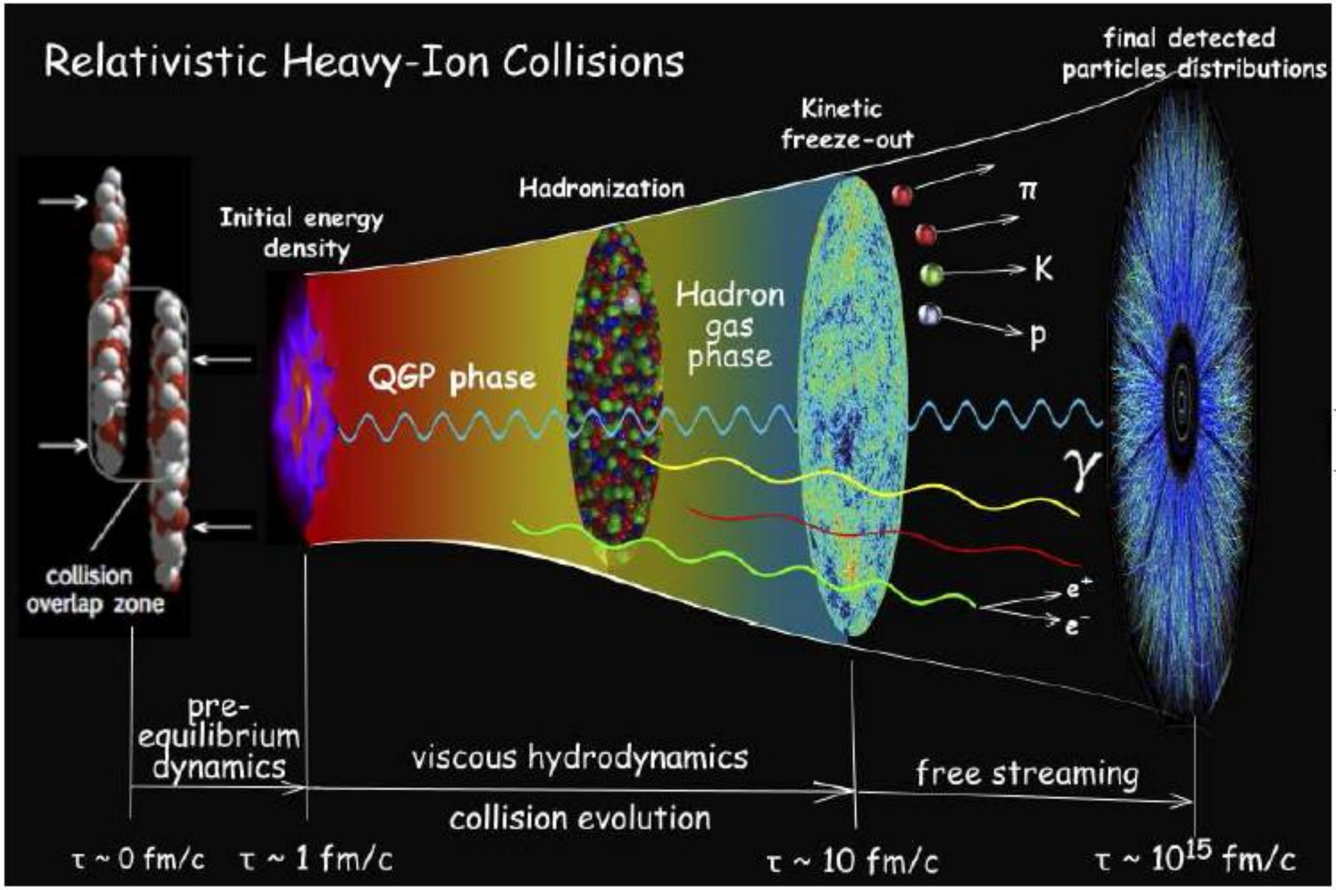
based on works in
Phys. Rev. C. **91**, 054914 (2015),
Phys. Rev. C. **101**, 024902 (2020),
Phys. Rev. C. **101**, 024909 (2020)

Outline

- Introduction
- Charmed hadrons in heavy ion collisions
- Multi-charmed Hadron production in heavy ion collisions
- Transverse momentum distribution of multi-charmed hadrons
- Conclusion

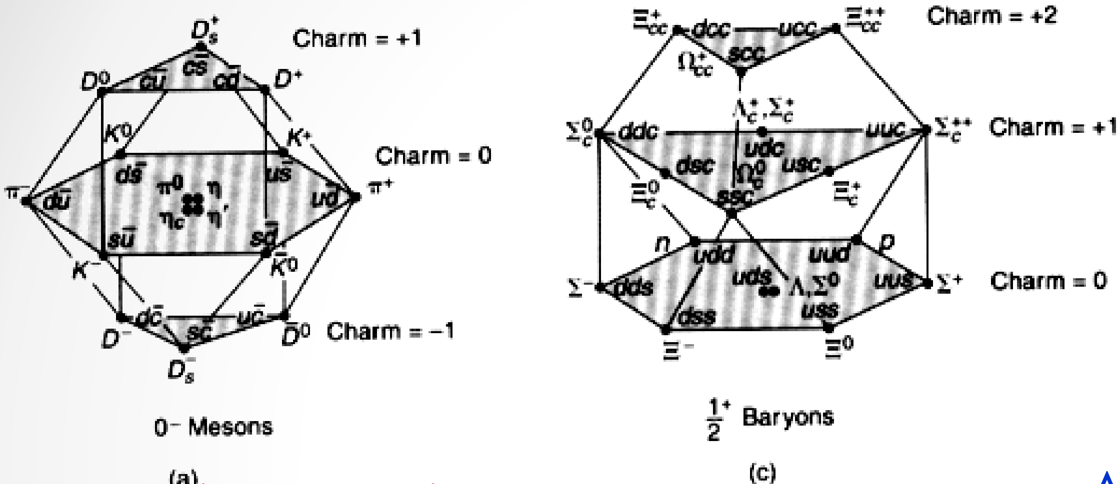
Introduction

– Relativistic heavy ion collisions



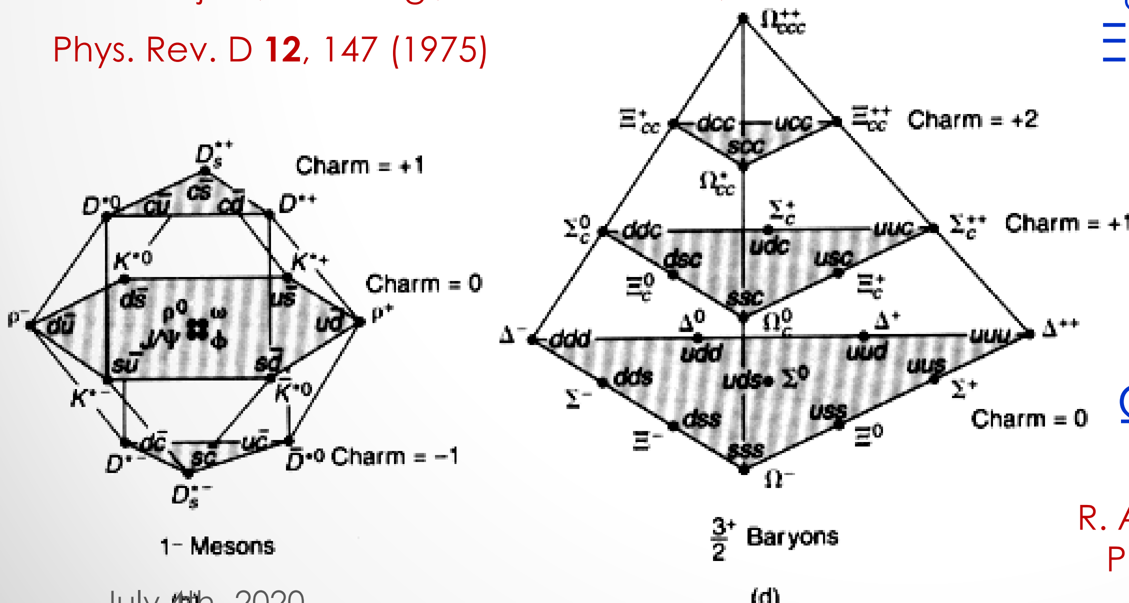
U. W. Heinz, J. Phys. Conf. Ser. **455**, 012044 (2013)

– Charmed hadrons, SU(4)



A. De Rújula, H. Georgi, And S. Glashaw,

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



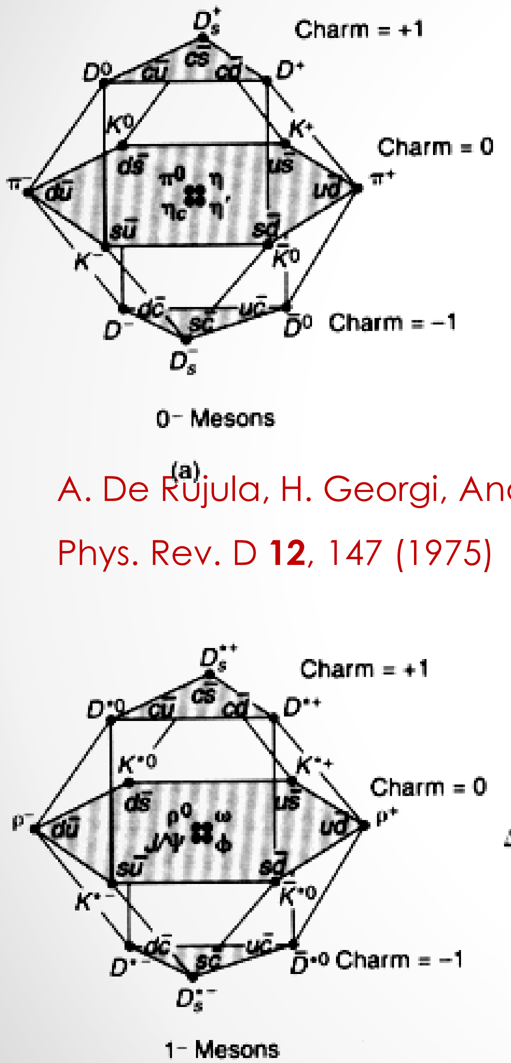
1) Charmonium states : ηc, J/ψ, χc, ψ'

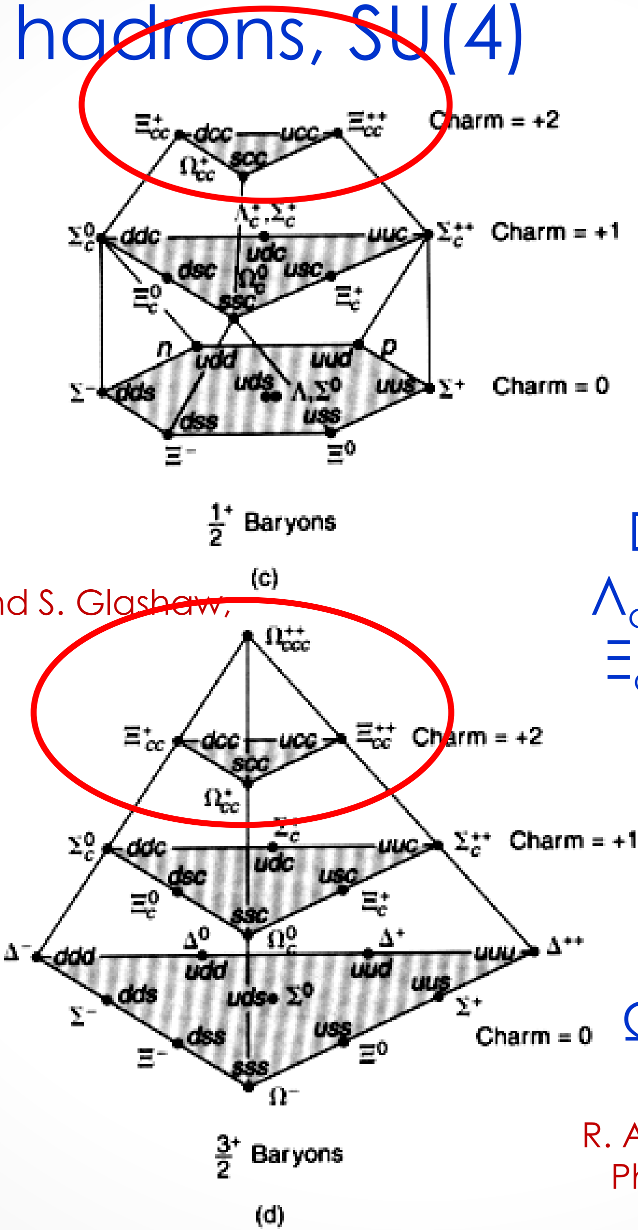
2) Charmed baryons and mesons : D, D*, D_s, D_s*, $\Lambda_c(2286)$, $\Lambda_c(2595)$, $\Lambda_c(2625)$, $\Sigma_c(2455)$, $\Sigma_c(2520)$, $\Xi_c(2470)$, $\Xi_c(2578)$, $\Xi_c(2645)$, $\Omega_c(2695)$, $\Omega_c(2770)$

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)





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

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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)

– 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%

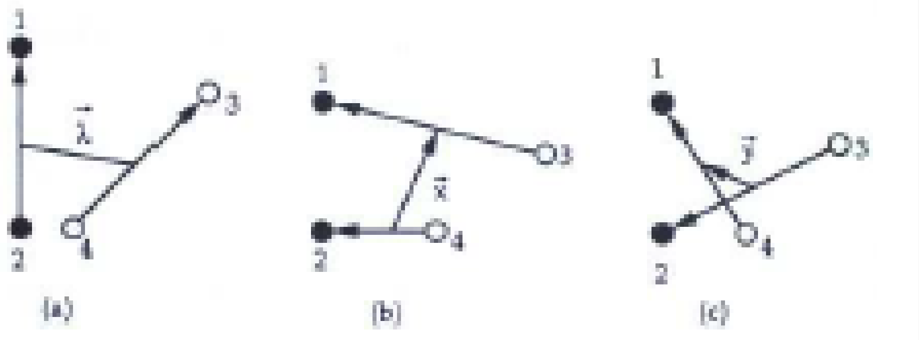
J. Beringer *et al*. (PDG), Phys. Rev. D**86**, 010001 (2012)

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

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

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

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

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

$$\vec{k} = \vec{p}'_{lT} + \vec{p}'_{\bar{l}T} + \vec{p}'_{cT} + \vec{p}'_{\bar{c}T},$$

$$\vec{k}_1 = \frac{m_{\bar{l}}\vec{p}'_{lT} - m_l\vec{p}'_{\bar{l}T}}{m_l + m_{\bar{l}}},$$

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

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

$$\vec{k} = \vec{p}'_{lT} + \vec{p}'_{\bar{l}T} + \vec{p}'_{cT} + \vec{p}'_{\bar{c}T},$$

$$\vec{k}_1 = \frac{m_{\bar{l}}\vec{p}'_{lT} - m_l\vec{p}'_{\bar{l}T}}{m_l + m_{\bar{l}}},$$

$$\vec{k}_2 = \frac{m_{\bar{c}}\vec{p}'_{cT} - m_c\vec{p}'_{\bar{c}T}}{m_c + m_{\bar{c}}},$$

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

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

Parallel Session - Heavy flavor IV (16:20-18:00)

-Conveners: Tserruya, Itzhak (Weizmann Institute of Science (IL))

time	[id] title	presenter
17:20	[232] LHCb measurements of the exotic tetraquark candidate X(3872) in high multiplicity pp and pPb collisions	DURHAM FOR THE LHCB COLLABORATION, John Matthew (Los Alamos National Laboratory)
17:40	[517] Observation of X(3872) in PbPb collisions with the CMS detector	LEE FOR THE CMS COLLABORATION, Yen-Jie (Massachusetts Inst. of Technology (US))

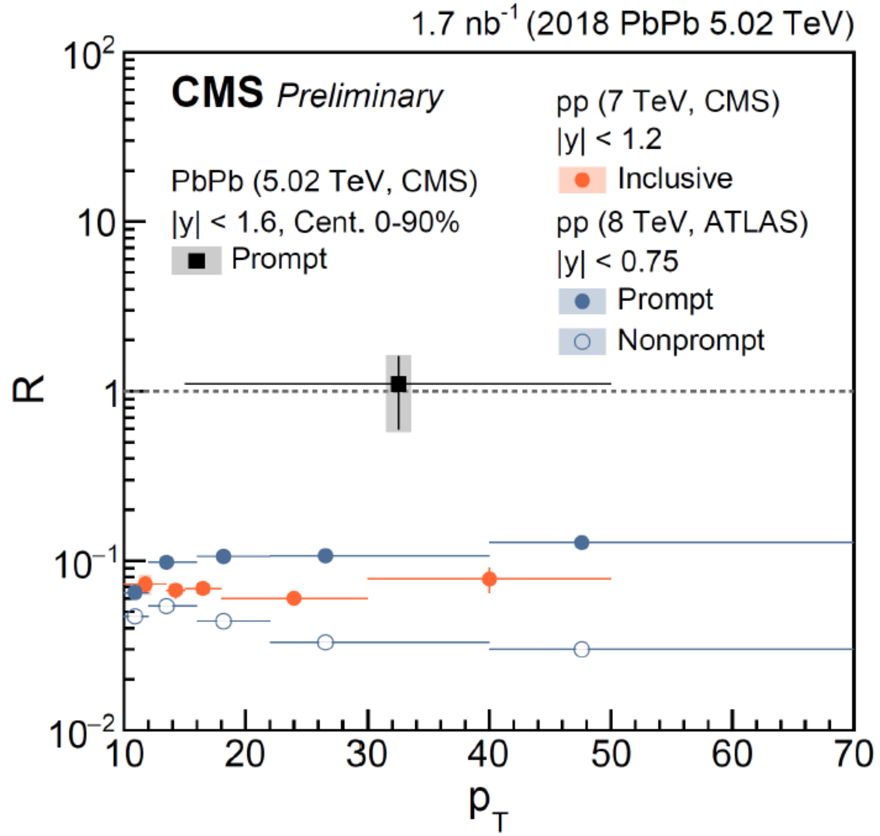
Ratio of X(3872) to ψ(2S) Yields in pp and PbPb

$$R = N^{(\mathrm{Corr})}_{X(3872)} / N^{(\mathrm{Corr})}_{\psi(2S)}$$

In PbPb collisions:

$$R = 1.10 \pm 0.51\ (\mathrm{stat.})\ \pm 0.53\ (\mathrm{syst.})$$

Indication of R enhancement in PbPb collisions with respect to pp at 7 and 8 TeV



CMS-PAS-HIN-19-005

Yen-jie Lee (MIT), Quark Matter 2019, Wuhan, November 4-9

– Recent publications on X(3872) mesons

Deciphering the nature of X(3872) in heavy ion collisions

Hui Zhang,[1,*] Jinfeng Liao,[2,†] Enke Wang,[1,‡] Qian Wang,[1,3,§] and Hongxi Xing[1,¶]

[1] *Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China*
[2] *Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA*
[3] *Theoretical Physics Center for Science Facilities, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*

X(3872) Transport in Heavy-Ion Collisions

Biaogang Wu,[1] Xiaojian Du,[2] Matthew Sibila,[3] and Ralf Rapp[1]

[1] *Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843-3366, USA*
[2] *Fakultät fur Physik, Universität Bielefeld, D-33615 Bielefeld, Germany*
[3] *Department of Physics & Astronomy, Ohio Northern University, Ada, OH 45810, USA*

(Dated: June 18, 2020)

The nature of $X(3872)$ from high-multiplicity pp collisions

Angelo Esposito,[1] Elena G. Ferreiro,[2] Alessandro Pilloni,[3,4] Antonio D. Polosa,[5] and Carlos A. Salgado[2]

[1] *Theoretical Particle Physics Laboratory (LPTP), Institute of Physics, EPFL, 1015 Lausanne, Switzerland*
[2] *Instituto Galego de Física de Altas Enerxías – IGFAE, Universidade de Santiago de Compostela, E-15782 Santiago de Compostela, Galicia-Spain*
[3] *European Centre for Theoretical Studies in Nuclear Physics and related Areas (ECT*) and Fondazione Bruno Kessler, Villazzano (Trento), I-38123, Italy*
[4] *INFN Sezione di Genova, Genova, I-16146, Italy*
[5] *Dipartimento di Fisica and INFN, Sapienza Università di Roma, Piazzale Aldo Moro 2, I-00185 Roma, Italy*

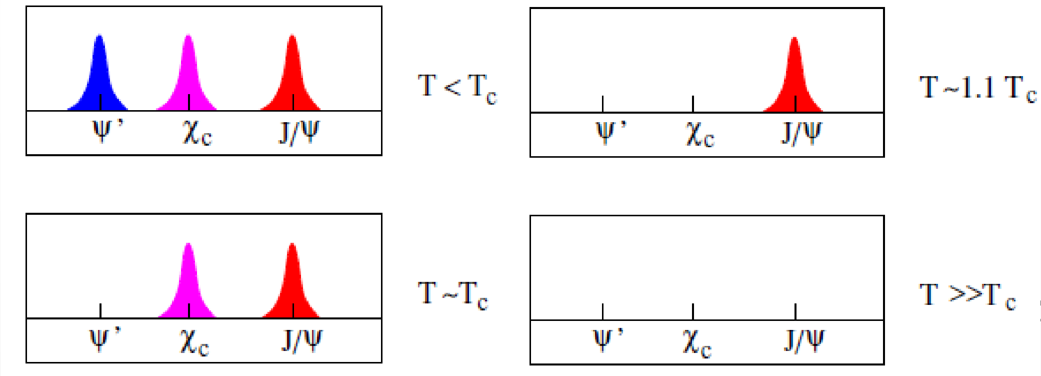
Charmed hadrons in heavy ion collisions

– 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

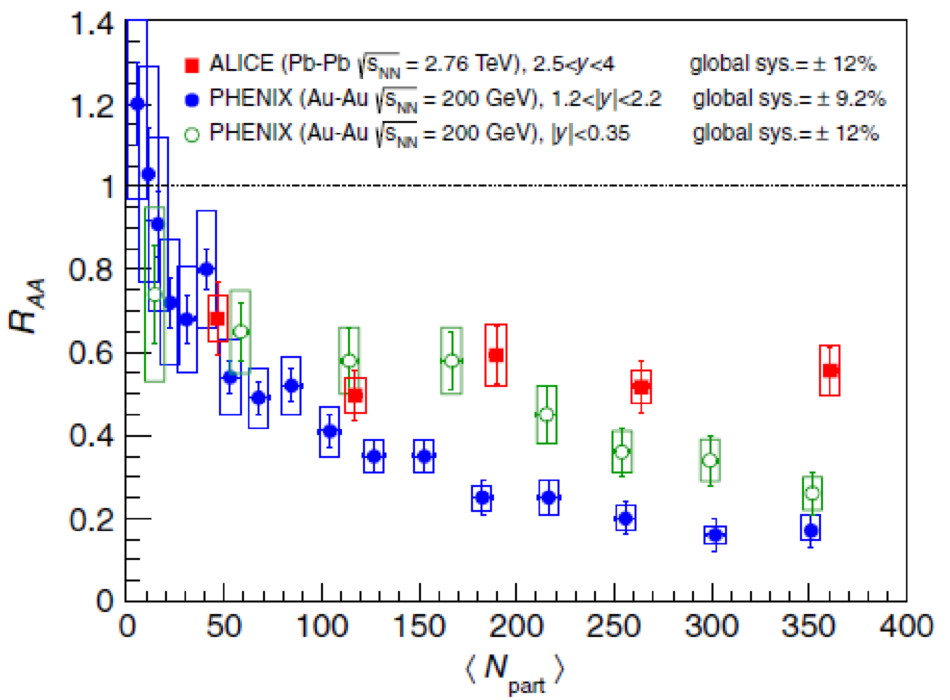


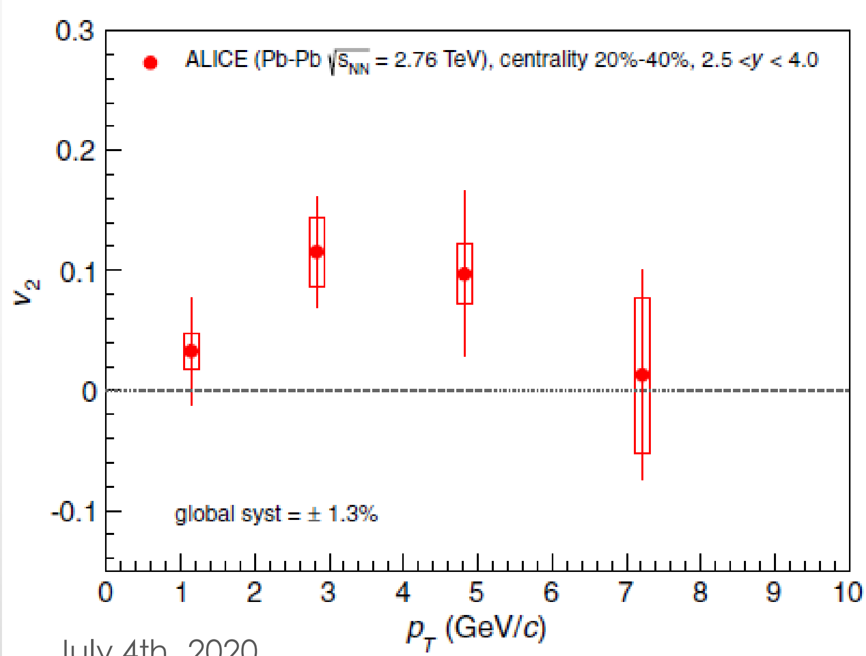
H. Satz, J. Phys. G. **32**, R25 (2006)

– 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 flows, v_2 of the J/ψ

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

Multi-charmed hadron production in heavy ion collisions

– 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

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

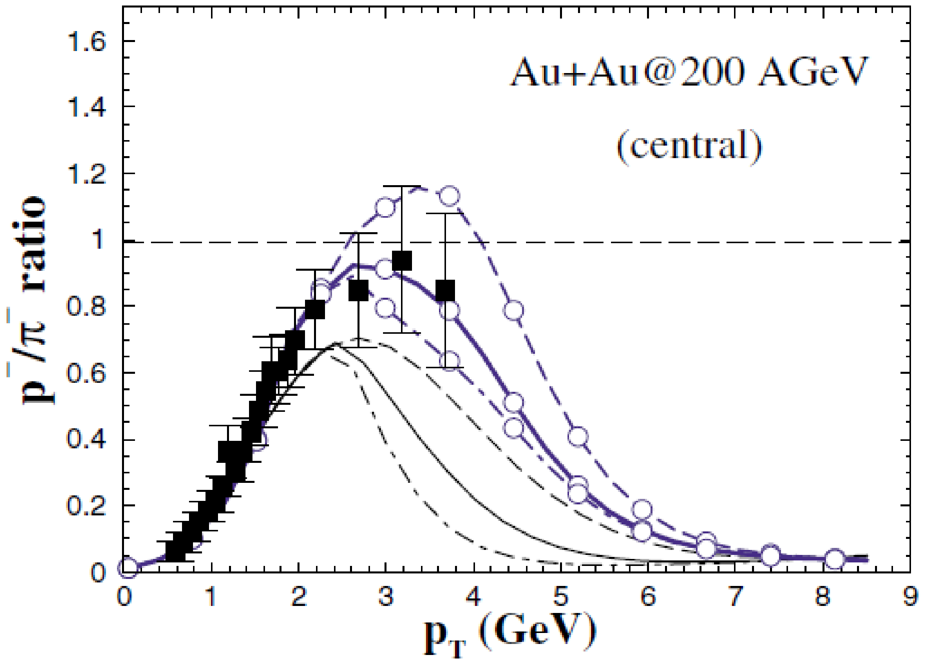
– Hadron production by recombination

: Transverse momentum distributions of hadron yields

1) The puzzle in antiproton/pion ratio

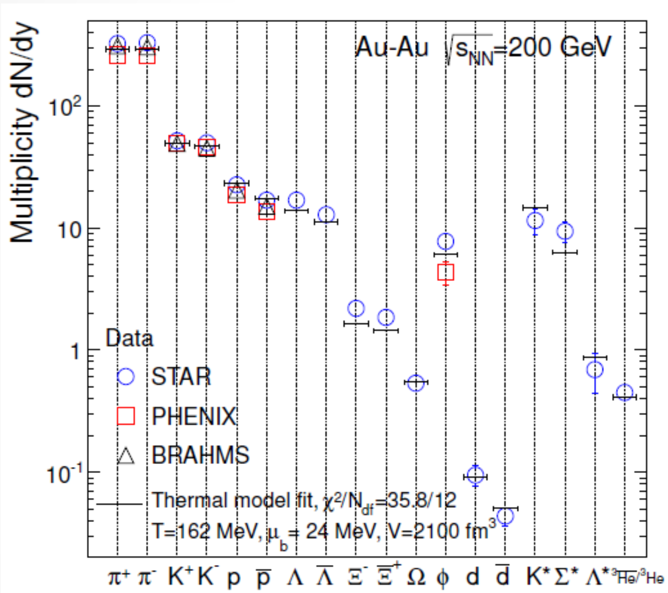
V. Greco, C. M. Ko, and P. Levai, Phys. Rev. Lett. **90**, 202302 (2003)
R. J. Freis. B. Muller, C. Nonaka, and S. Bass, Phys. Rev. Lett. **90**, 202303 (2003)

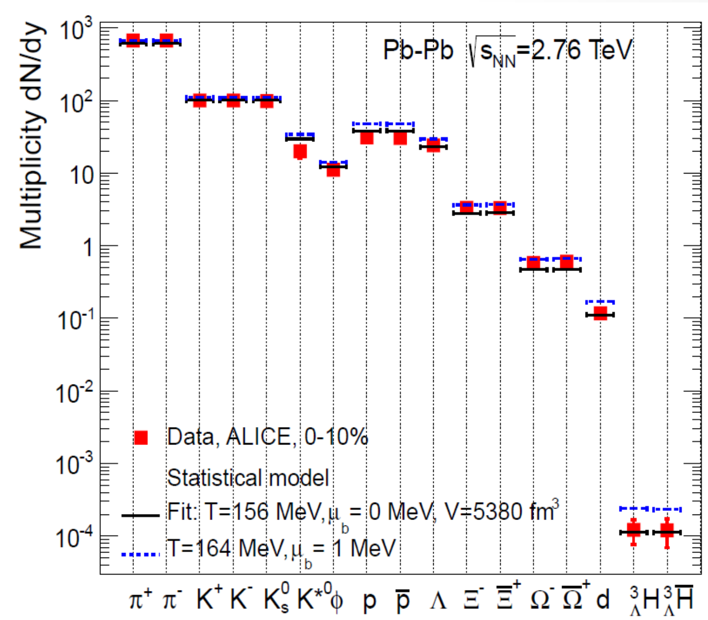
originated from a competition between two particle production mechanisms
: A fragmentation dominates at large transverse momenta and a coalescence prevails at lower transverse momenta



– Multi-charmed hadron production

1) Yields in the statistical hadronization model





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 and S. H. Lee, Phys. Rev. C **101**, 024902 (2020)

	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}

Transverse momentum distributions of multi-charmed hadrons

S. Cho and S. H. Lee, Phys. Rev. C **101**, 024902 (2020)

1) Multi-charmed hadron Yields in the coalescence model

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

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

2) Transverse momentum distributions

$$\frac{d^2 N_{\Xi_{cc}}}{d^2\vec{p}_T} = \frac{g_{\Xi_{cc}}}{V^2} \int d^3\vec{r}_1 d^3\vec{r}_2 d^2\vec{p}_{lT} d^2\vec{p}_{c_1 T} d^2\vec{p}_{c_2 T} \delta^{(2)}(\vec{p}_T - \vec{p}_{lT} - \vec{p}_{c_1 T} - \vec{p}_{c_2 T}) \frac{d^2 N_l}{d^2\vec{p}_{lT}} \times \frac{d^2 N_{c_1}}{d^2\vec{p}_{c_1 T}} \frac{d^2 N_{c_2}}{d^2\vec{p}_{c_2 T}} W_{\Xi_{cc}}(\vec{r}_1', \vec{r}_2', \vec{r}_3', \vec{k}_1, \vec{k}_2, \vec{k}_3),$$

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

3) Transverse momentum distributions of charm and light quarks

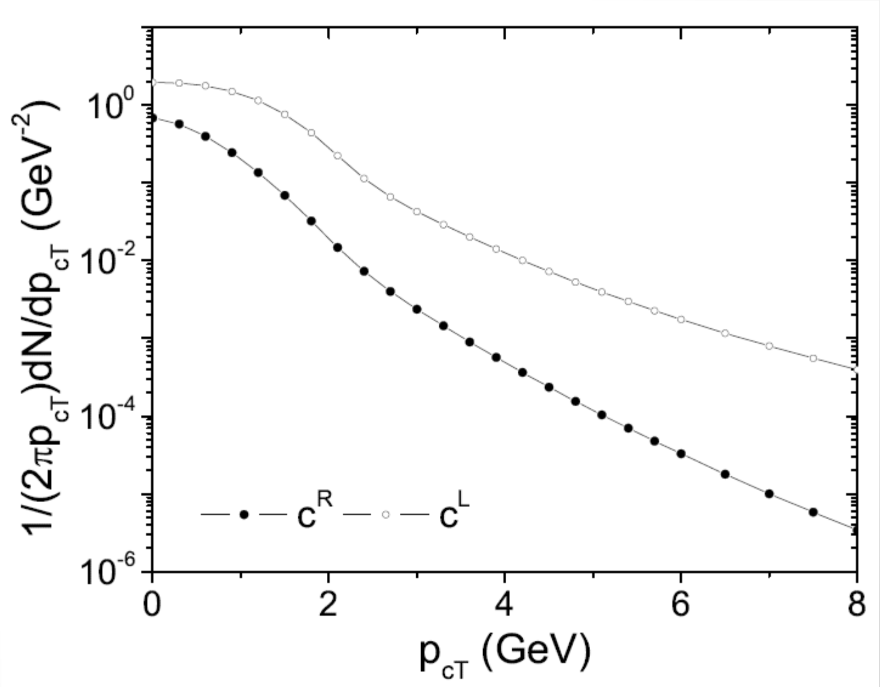
$$\frac{dN_c}{d^2p_T} = \begin{cases} a_0 \exp[-a_1 p_T^{a_2}] & p_T \le p_0 \\ a_0 \exp[-a_1 p_T^{a_2}] + a_3 (1+p_T^{a_4})^{-a_5} & p_T \ge p_0 \end{cases}$$

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

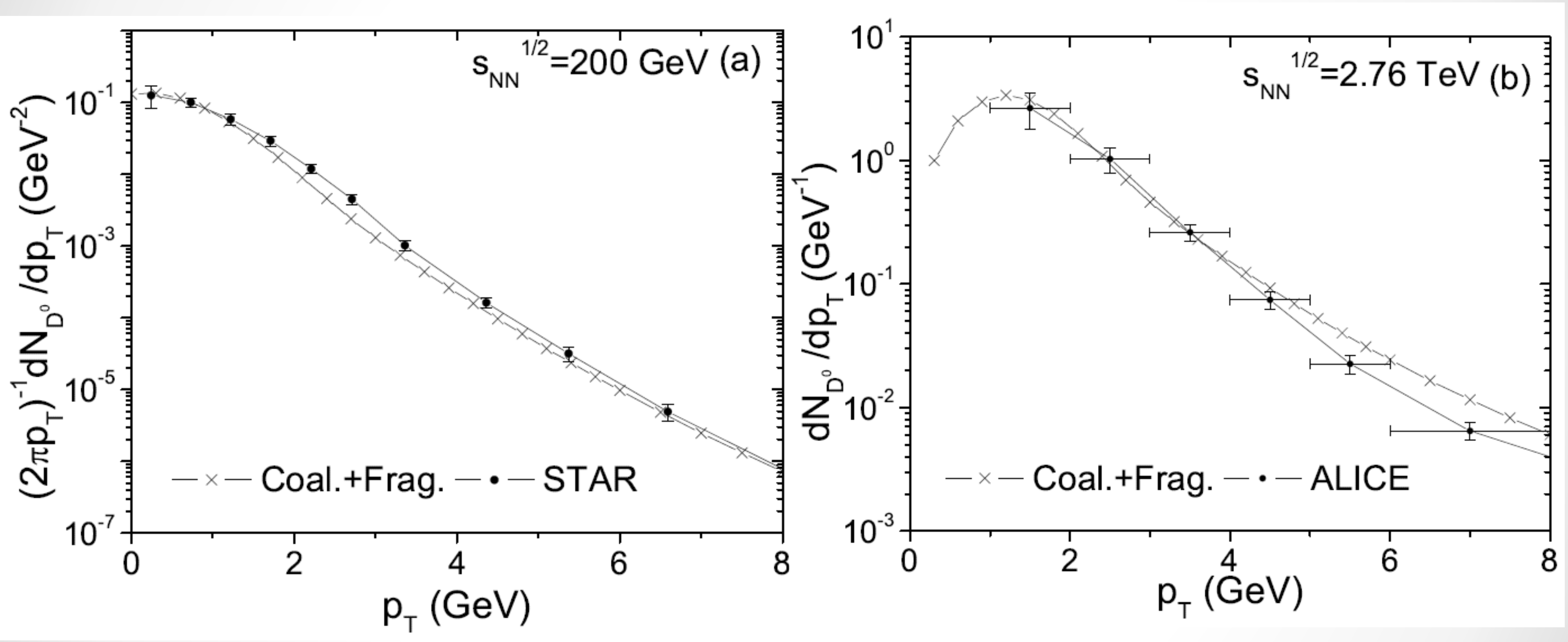
RHIC	a_0	a_1	a_2	a_3	a_4	a_5
$p_T \le p_0$	0.69	1.22	1.57			
$p_T \ge p_0$	1.08	3.04	0.71	3.79	2.02	3.48
LHC	a_0	a_1	a_2	a_3	a_4	a_5
$p_T \le p_0$	1.97	0.35	2.47			
$p_T \ge p_0$	7.95	3.49	3.59	87335	0.5	14.31

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	

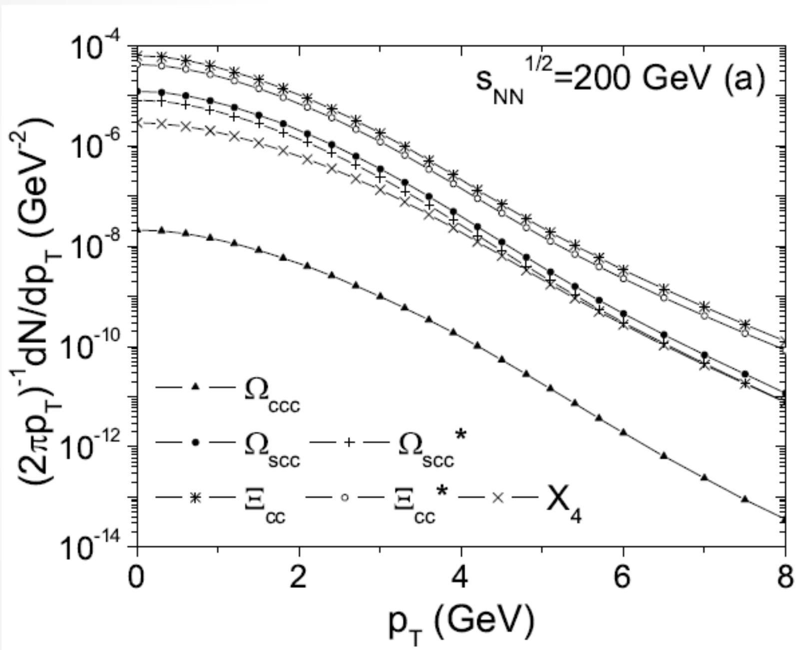


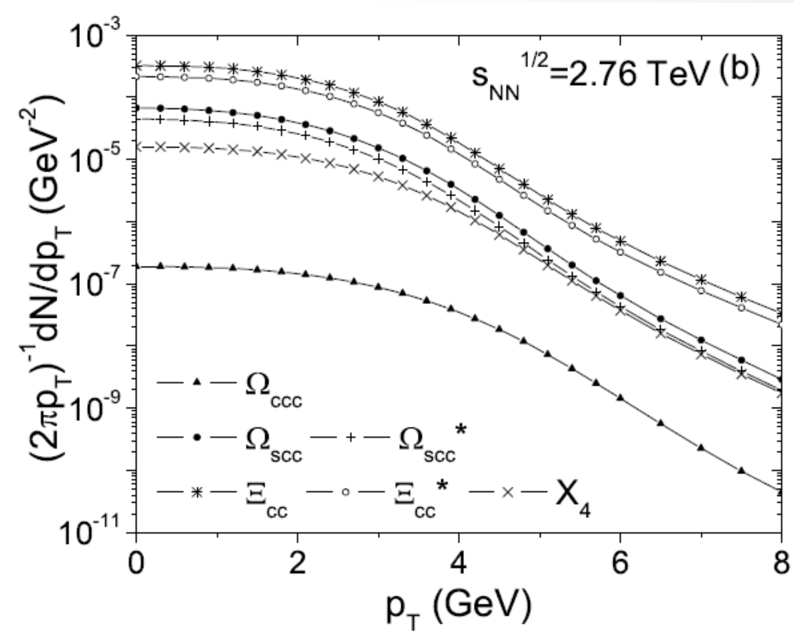
4) Transverse momentum distributions of D^0 mesons



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-charmed hadrons

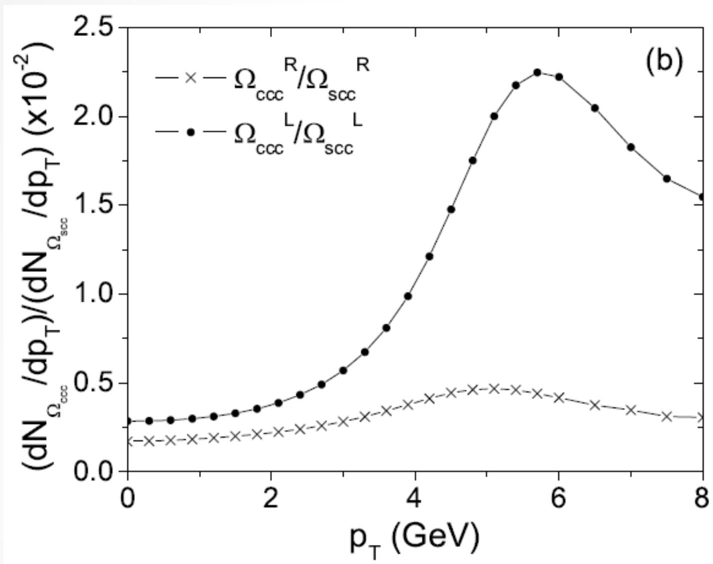


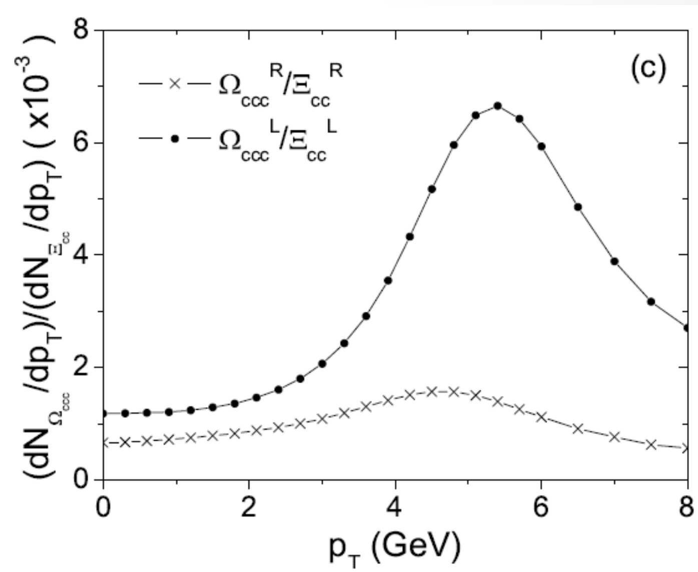


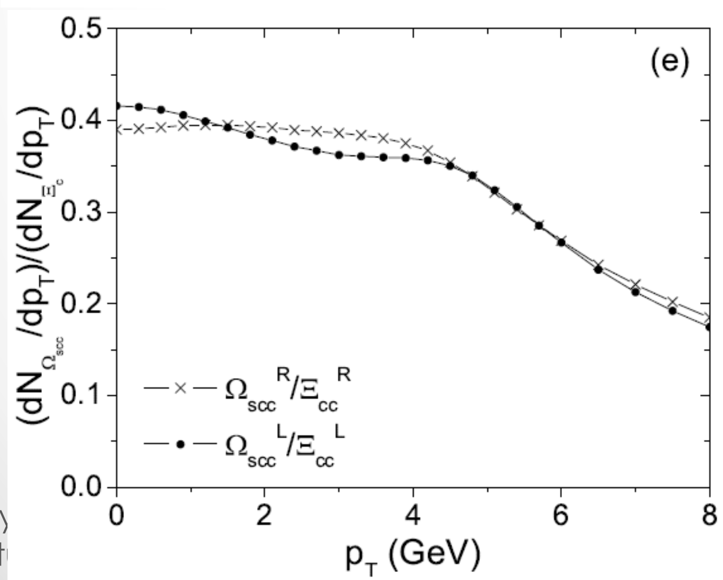
	RHIC	LHC
Ξ_{cc}	4.4×10^{-4}	6.7×10^{-3}
Ξ_{cc}^*	2.9×10^{-4}	4.5×10^{-3}
Ω_{scc}	8.6×10^{-5}	1.3×10^{-3}
Ω_{scc}^*	5.7×10^{-5}	8.5×10^{-4}
Ω_{ccc}	1.7×10^{-7}	5.9×10^{-6}
T_{cc}	2.2×10^{-5}	3.8×10^{-4}
X_4	2.4×10^{-5}	3.8×10^{-4}
X_2	2.6×10^{-4}	4.5×10^{-3}
D^0	0.71	6.0
Λ_c	0.63	4.0

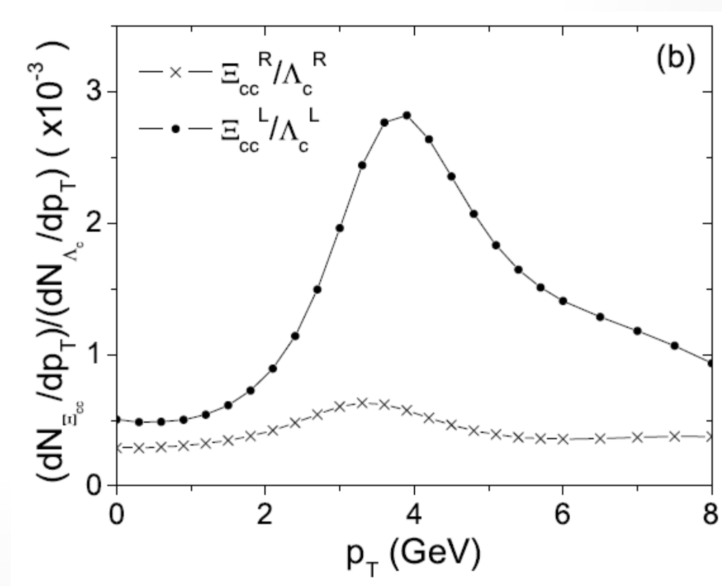
6) Transverse momentum distribution ratios

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

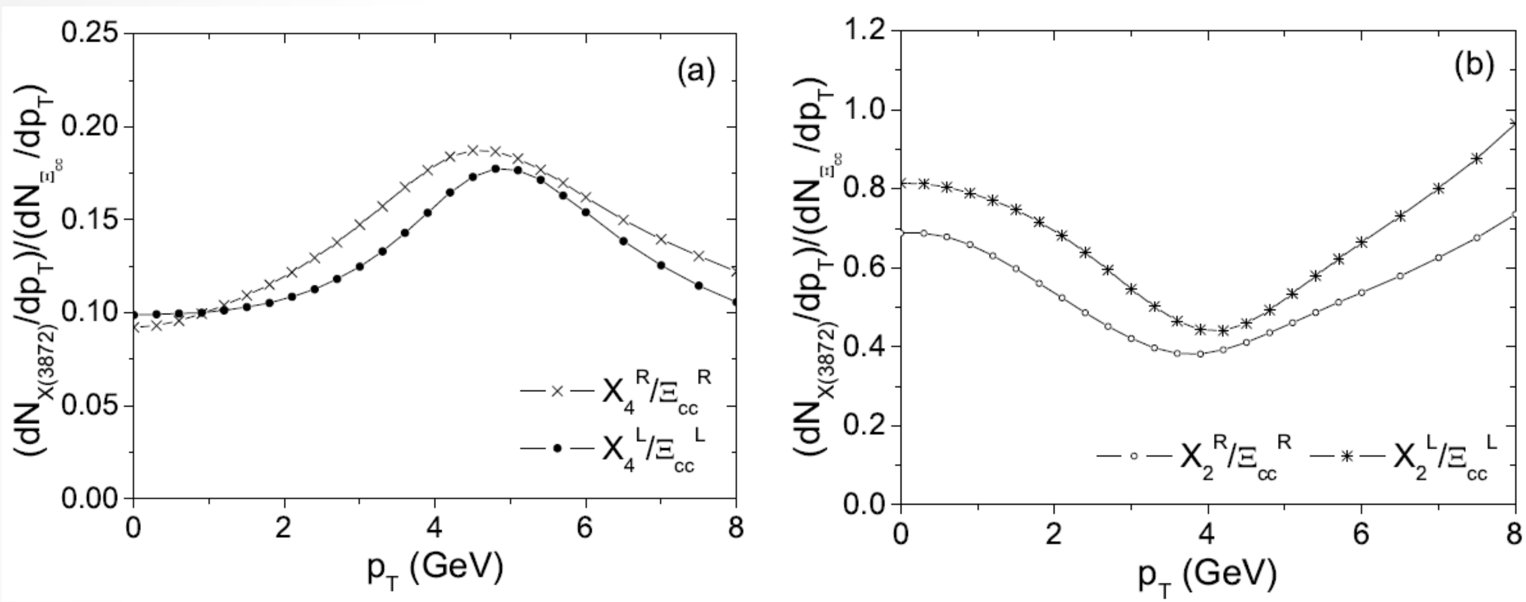




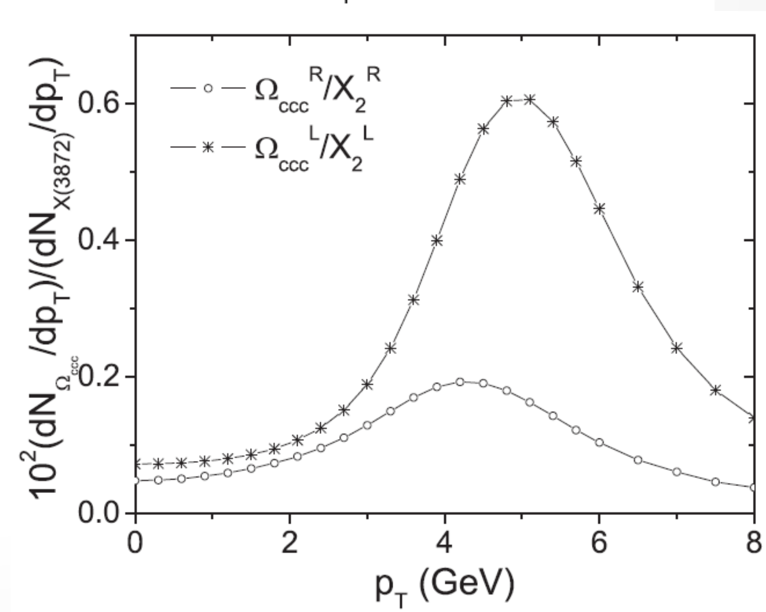




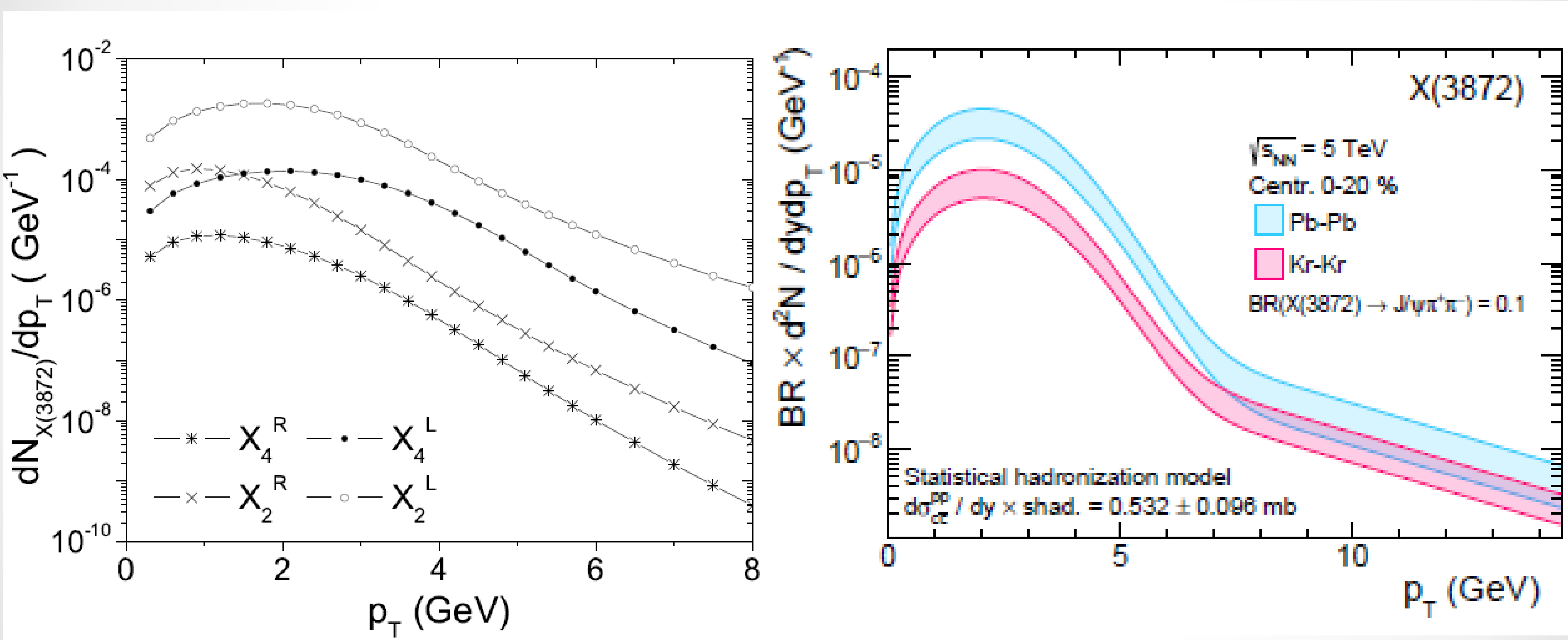
b) Meson/baryon (ccqq/ccq, or cc/ccq)



c) Baryon/meson (ccc/cc)



– Comparison with results from the statistical hadronization model



A. Andronic, P. Braun-Munzinger, M. K. Kohler, K. Redlich and J. Stachel, Phys. Lett. B **797**, 134836 (2019).

Conclusion

– Multi-charmed hadron production in heavy ion collisions

1) Heavy ion collision experiments provide excellent chances to study production of multi-charm hadrons as well as exotic hadrons
2) Transverse momentum distributions of charmed hadrons are directly affected by not only those of charm and light quarks but also numbers of constituent quarks.
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
4) Investigation on transverse momentum distribution of various charmed hadrons as well as those ratios can give us useful information on the properties of quark-gluon plasma

Thank you for your attention!