Heavy Quark Coalescence

Exotics and Exotic Phenomena in heavy ion collisions

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APCTP, Pohang

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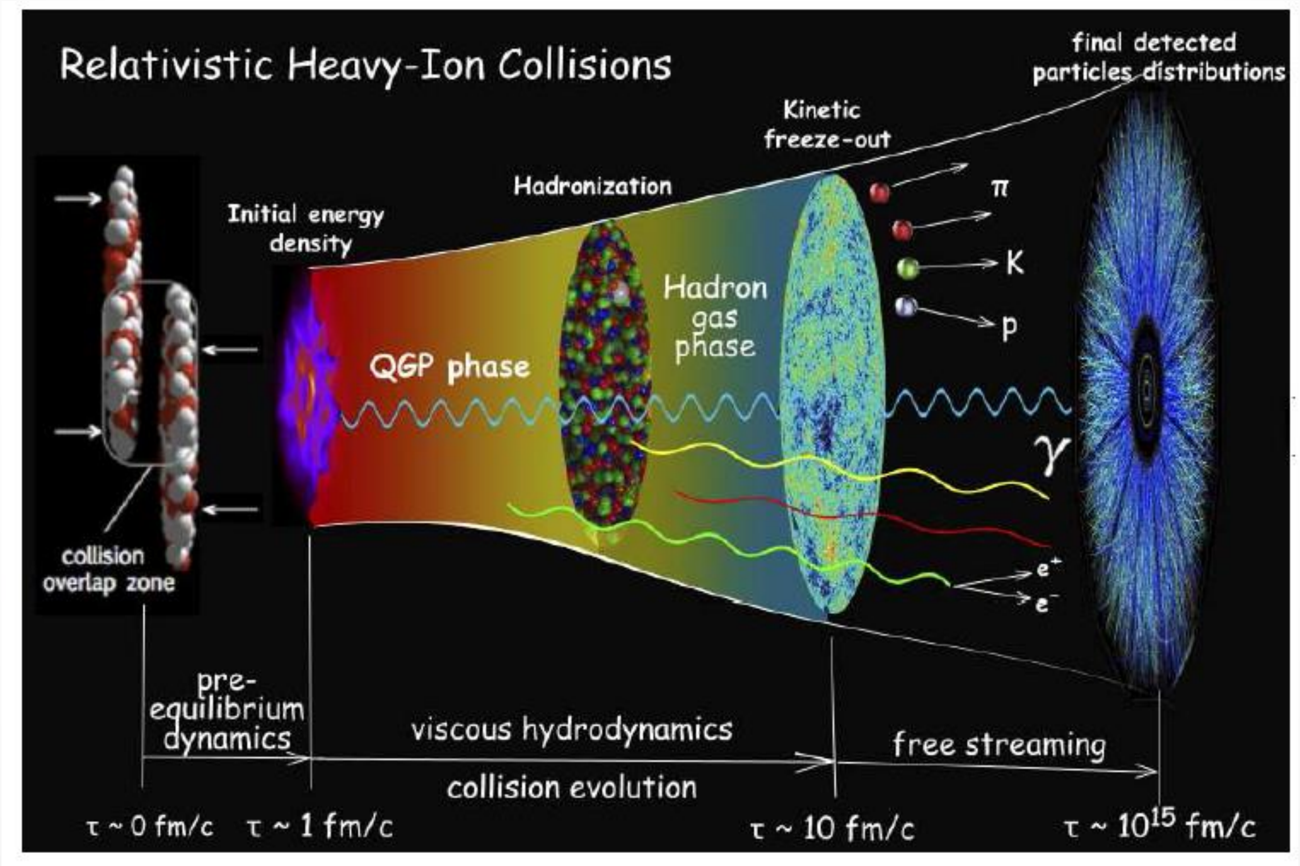
Outline

- Introduction
- Charmed hadrons in heavy ion collisions
- Hadron production in heavy ion collisions
- Multicharmed and exotic hadron production
- Conclusion

Introduction

– Relativistic heavy ion collisions



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

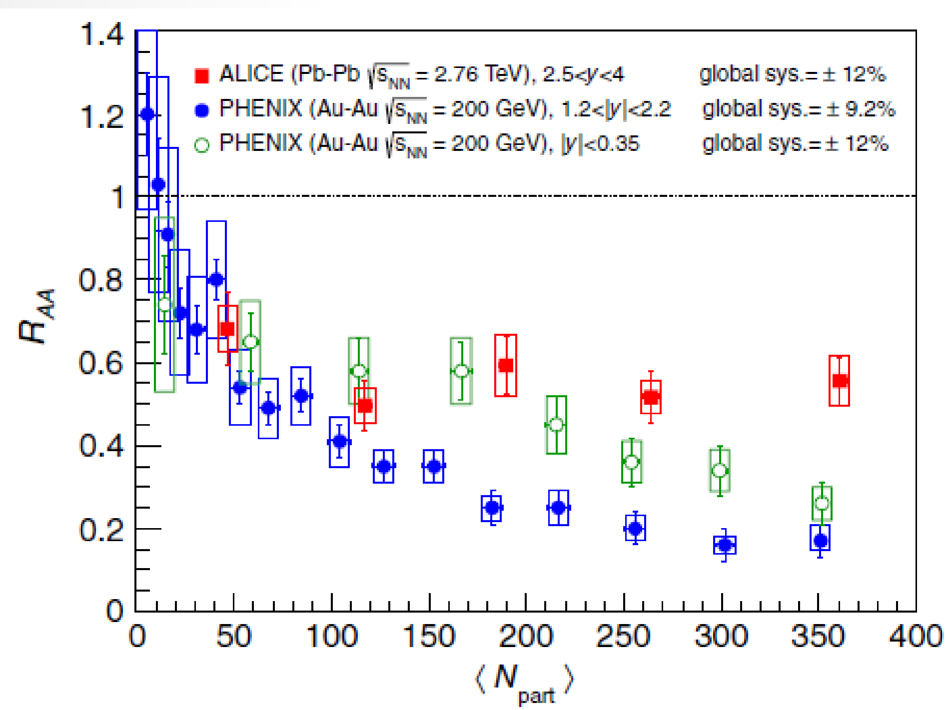
Charmed hadrons in heavy ion collisions

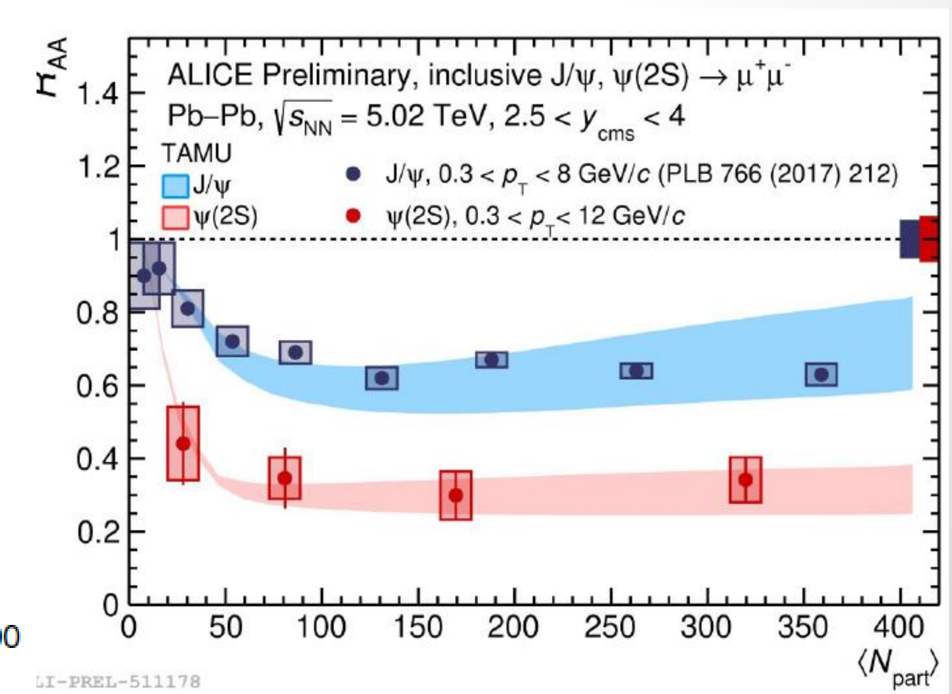
– Regeneration of charmonium states

1) The nuclear modification factor of charmonium states

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

Jon-Are Saetre (Univ. of Bergen), Quark Matter 2022, Krakow, April 4-10

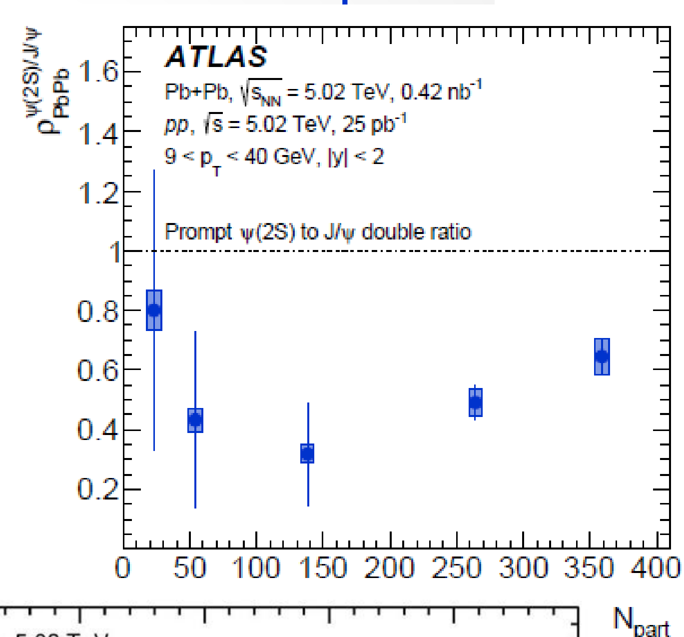


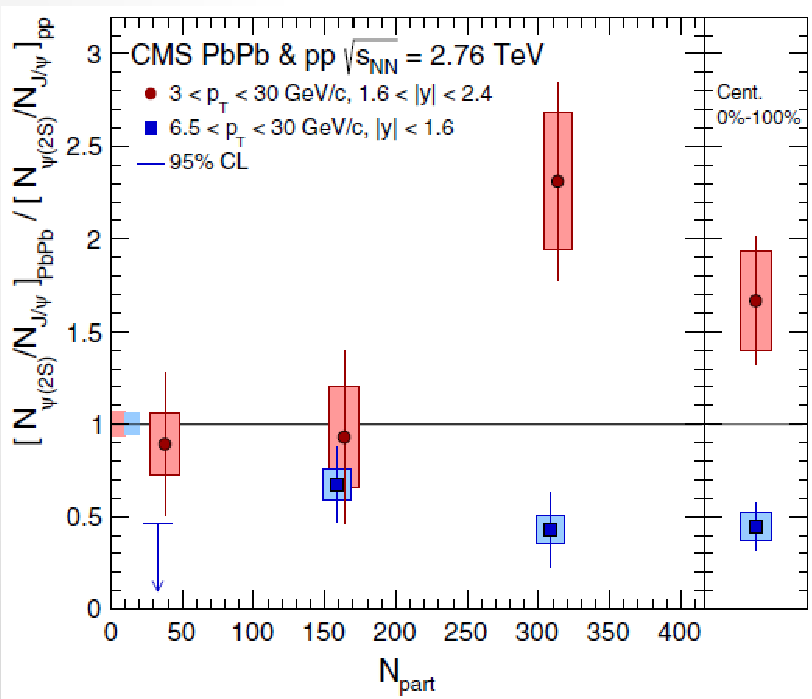


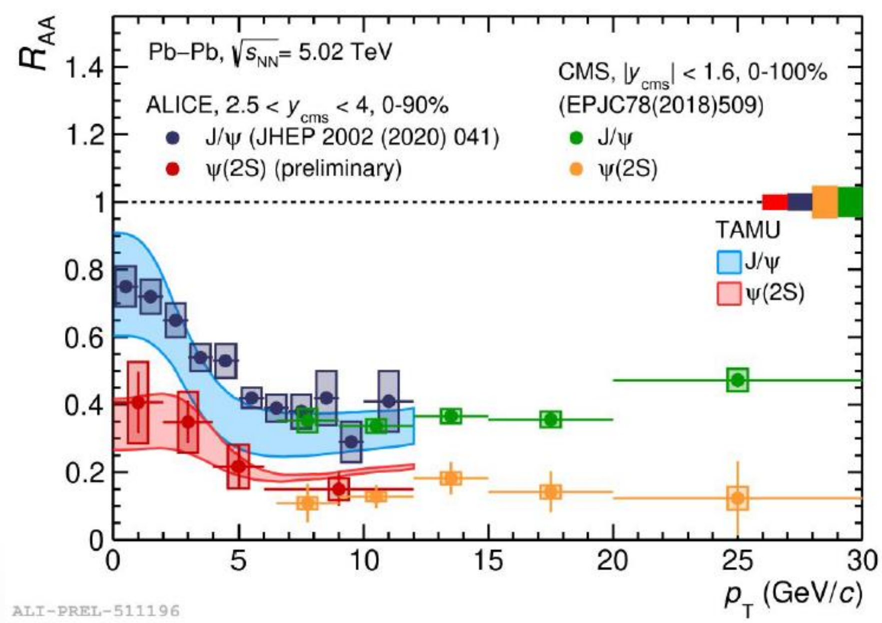
– Nuclear modification factors of the J/ψ and ψ(2S)

1) The nuclear modification factor ratio between the J/ψ and ψ(2S)

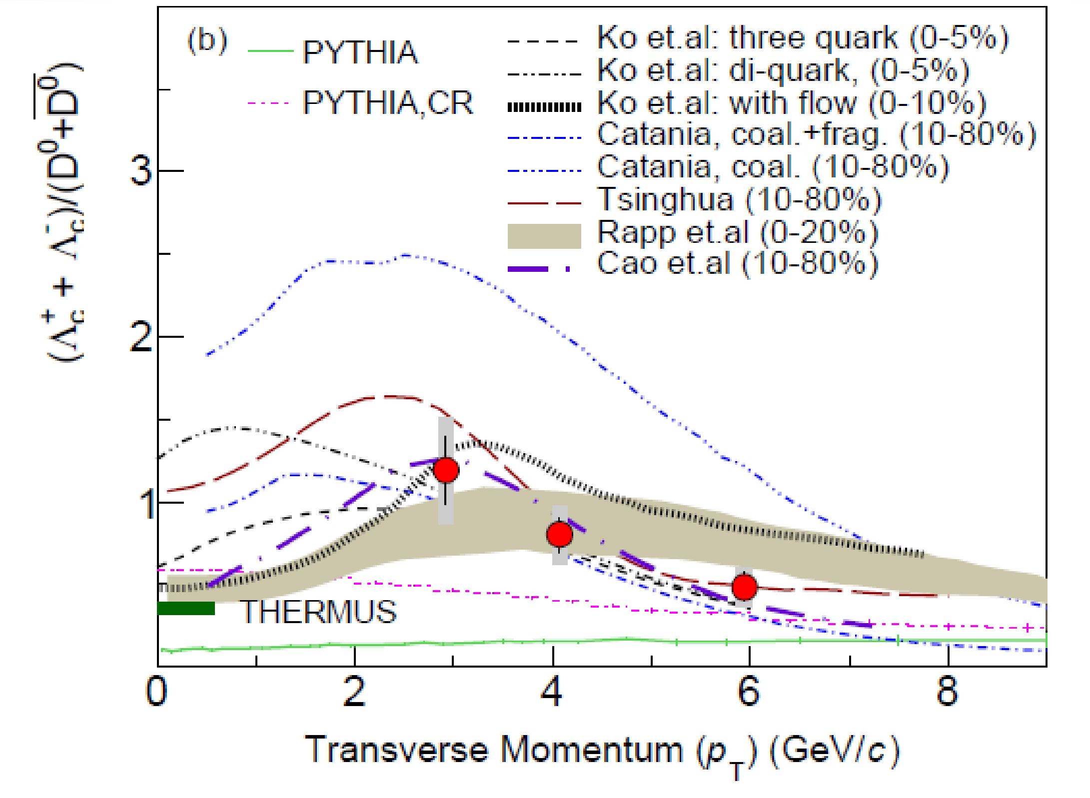
V. Khachatryan et al, Phys. Rev. Lett. **113,** 262301 (2014)
M. Aaboud et al, Eur. Phys. J. C **78,** 762 (2018)





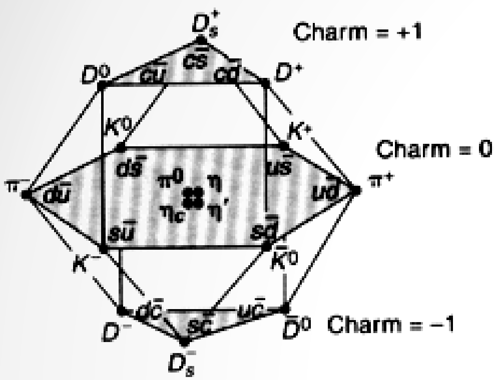


– Regeneration of charmed hadrons : Λ_c/D_0



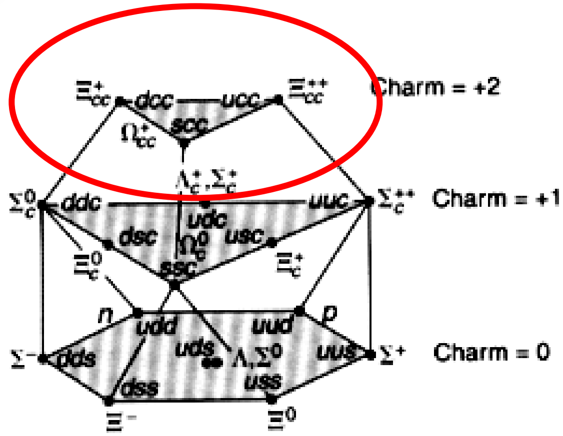
J. Adams et al, (STAR Collaboration), Phys. Rev. Lett. **124**, 172301 (2021)
Y. Oh, C. M. Ko, S. H. Lee, and S. Yasui, Phys. Rev. C **79**, 044905 (2009)
S. Cho, K-J. Sun, C. M. Ko, S. H. Lee, and Y. Oh, Phys. Rev. C **101**, 024909 (2020)

– Charmed hadrons, SU(4)



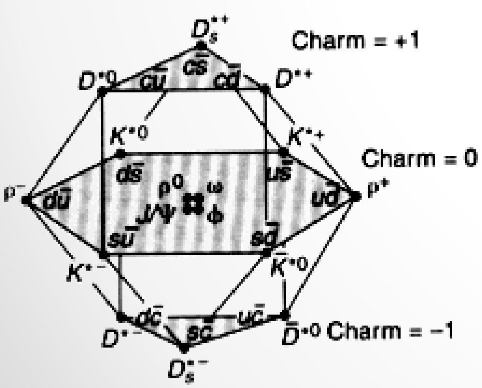
0^- Mesons

(a)



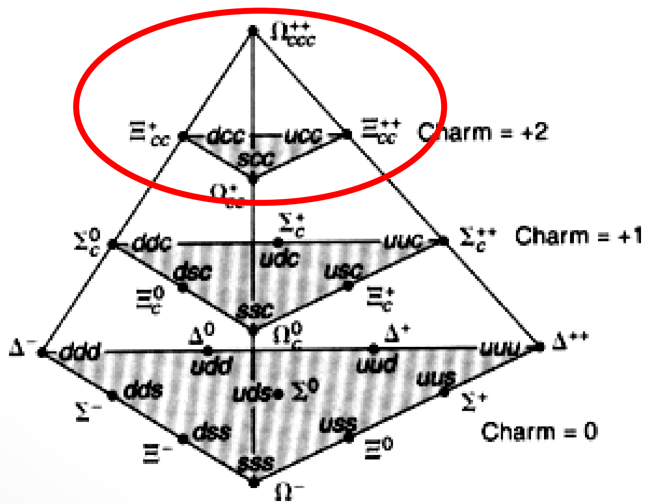
$\frac{1}{2}^+$ Baryons

(c)



1^- Mesons

(b)



$\frac{3}{2}^+$ Baryons

(d)

1) Charmed mesons: D, D*, D_s, D_s*

2) Singly charmed baryons: $\Lambda_c(2286)$, $\Lambda_c(2595)$, $\Lambda_c(2625)$, $\Sigma_c(2455)$, $\Sigma_c(2520)$, $\Xi_c(2470)$, $\Xi_c(2578)$, $\Xi_c(2645)$, $\Omega_c(2695)$, $\Omega_c(2770)$

3) Doubly and triply charmed hadrons, Ξ_{cc}, Ξ^*_{cc}, Ω_{cc}, Ω^*_{cc}, Ω_{ccc}

4) Exotic hadrons: T_{cc}, X(3872)

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

– 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)

$B^\pm \to K^\pm \pi^+ \pi^- J/\psi$

– T_{cc} ($cc\bar{q}\bar{q}$) mesons

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

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

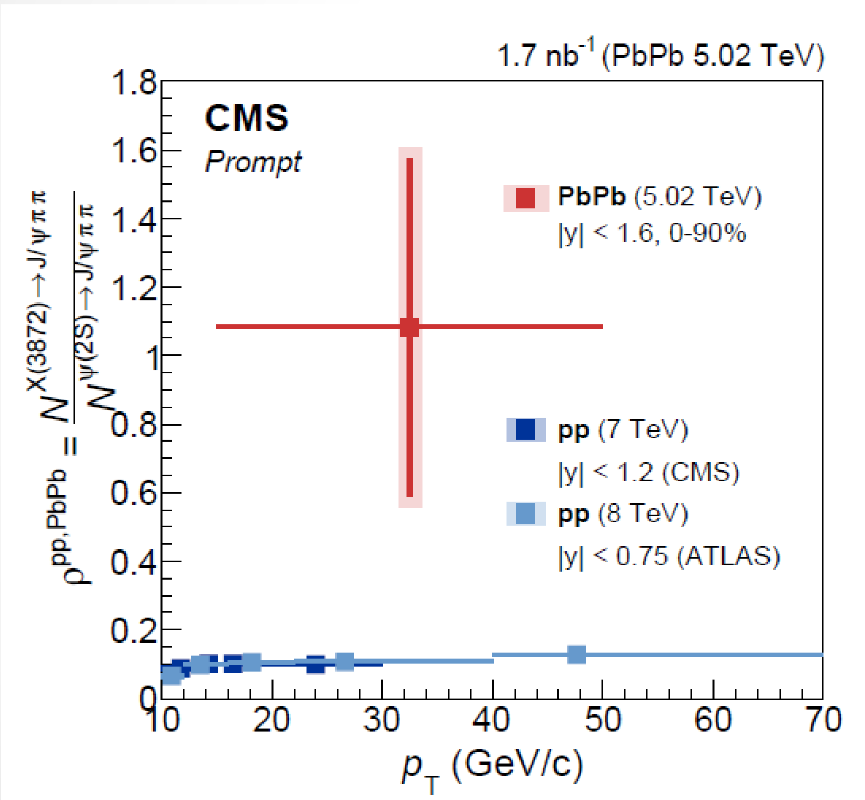
– Estimated yields of X(3872) and T_{cc} mesons

	RHIC				LHC			
	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.
T^1_{cc} [a]	—	4.0×10^{-5}	2.4×10^{-5}	4.3×10^{-4}	—	6.6×10^{-4}	4.1×10^{-4}	7.1×10^{-3}
$X(3872)$	1.0×10^{-4}	4.0×10^{-5}	7.8×10^{-4}	2.9×10^{-4}	1.7×10^{-3}	6.6×10^{-4}	1.3×10^{-2}	4.7×10^{-3}

[a] Particles that are newly predicted by theoretical model.

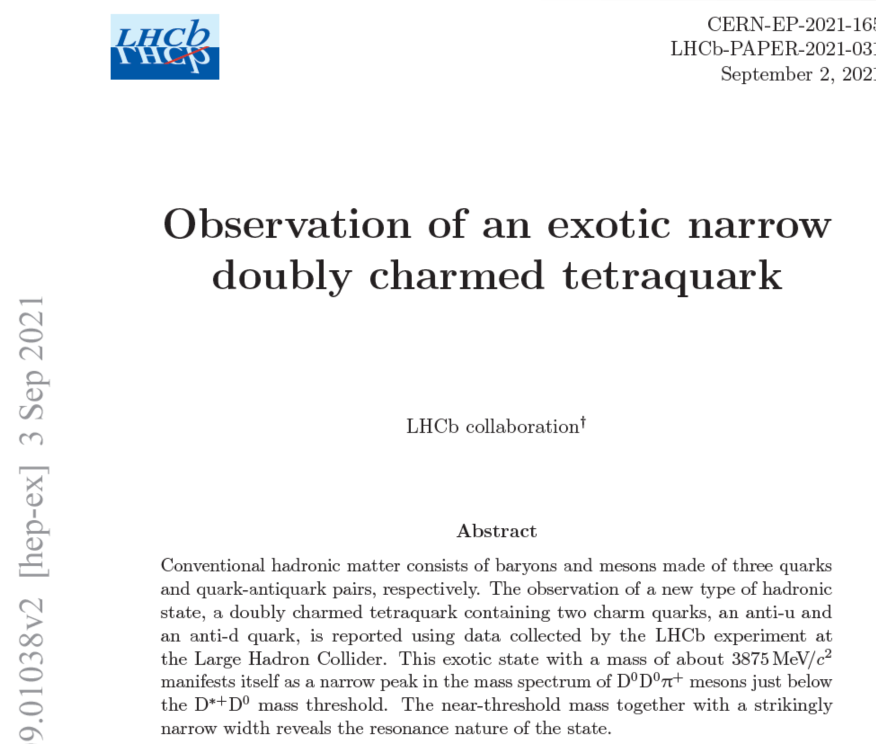
S. Cho *et al.* (EXHIC Collaboration), Phys. Rev. C **84**, 064910 (2011)

– Recent measurements of X(3872) in Pb+Pb collisions and an exotic doubly charmed tetraquark, T_{cc} in p+p collisions



$$\rho^{pp} = 0.106 \pm 0.008\,(\text{stat}) \pm 0.004\,(\text{syst})$$
$$\rho^{PbPb} = 1.08 \pm 0.49\,(\text{stat}) \pm 0.52\,(\text{syst}).$$

Albert M. Sirunyan et al. [CMS Collaboration], arXiv: 2102.13048



arXiv:2109.01038v2 [hep-ex] 3 Sep 2021

LHCb

CERN-EP-2021-165
LHCb-PAPER-2021-031
September 2, 2021

Observation of an exotic narrow doubly charmed tetraquark

LHCb collaboration†

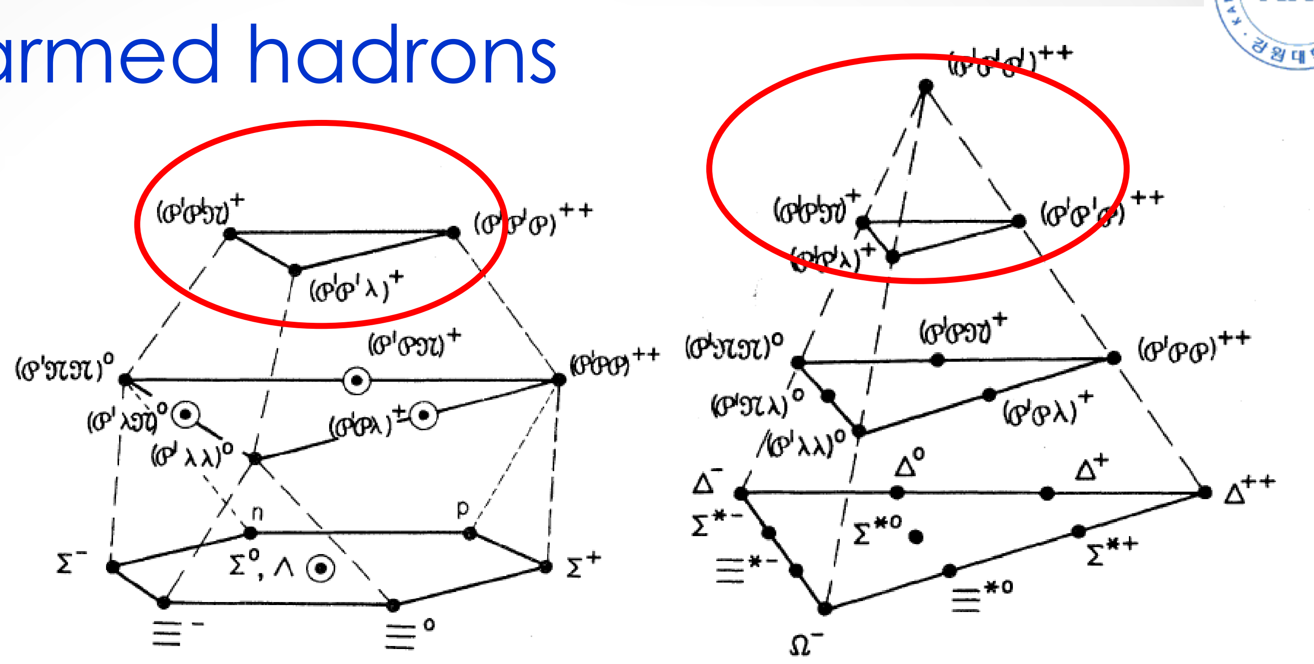
Abstract

Conventional hadronic matter consists of baryons and mesons made of three quarks and quark-antiquark pairs, respectively. The observation of a new type of hadronic state, a doubly charmed tetraquark containing two charm quarks, an anti-u and an anti-d quark, is reported using data collected by the LHCb experiment at the Large Hadron Collider. This exotic state with a mass of about 3875 MeV/c^2 manifests itself as a narrow peak in the mass spectrum of $D^0D^0\pi^+$ mesons just below the $D^{*+}D^0$ mass threshold. The near-threshold mass together with a strikingly narrow width reveals the resonance nature of the state.

R. Aaji *et al.* (LHCb Collaboration), arXiv:2109.01038

– Multicharmed hadrons

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



1) Doubly and triply charmed hadrons, Ξ_{cc}, Ξ^*_{cc}, Ω_{cc}, Ω^*_{cc}, Ω_{ccc}

– Observation of the 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)

Hadron production in heavy ion collisions

– Quark coalescence

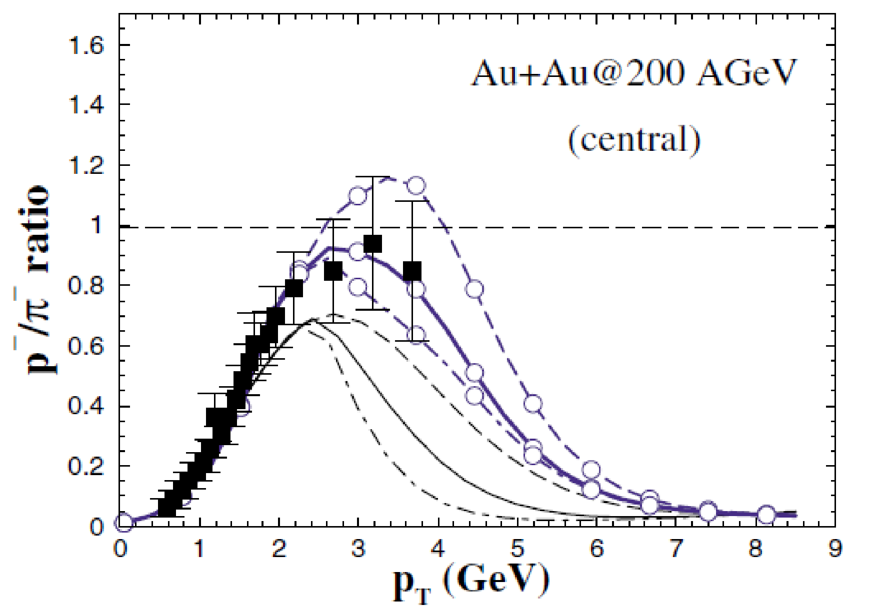
V. Greco, C. M. Ko, and P. Levai, Phys. Rev. C **68**, 034904 (2003)
R. J. Freis. B. Muller, C. Nonaka, and S. Bass, Phys. Rev. C **68**, 044902 (2003)

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

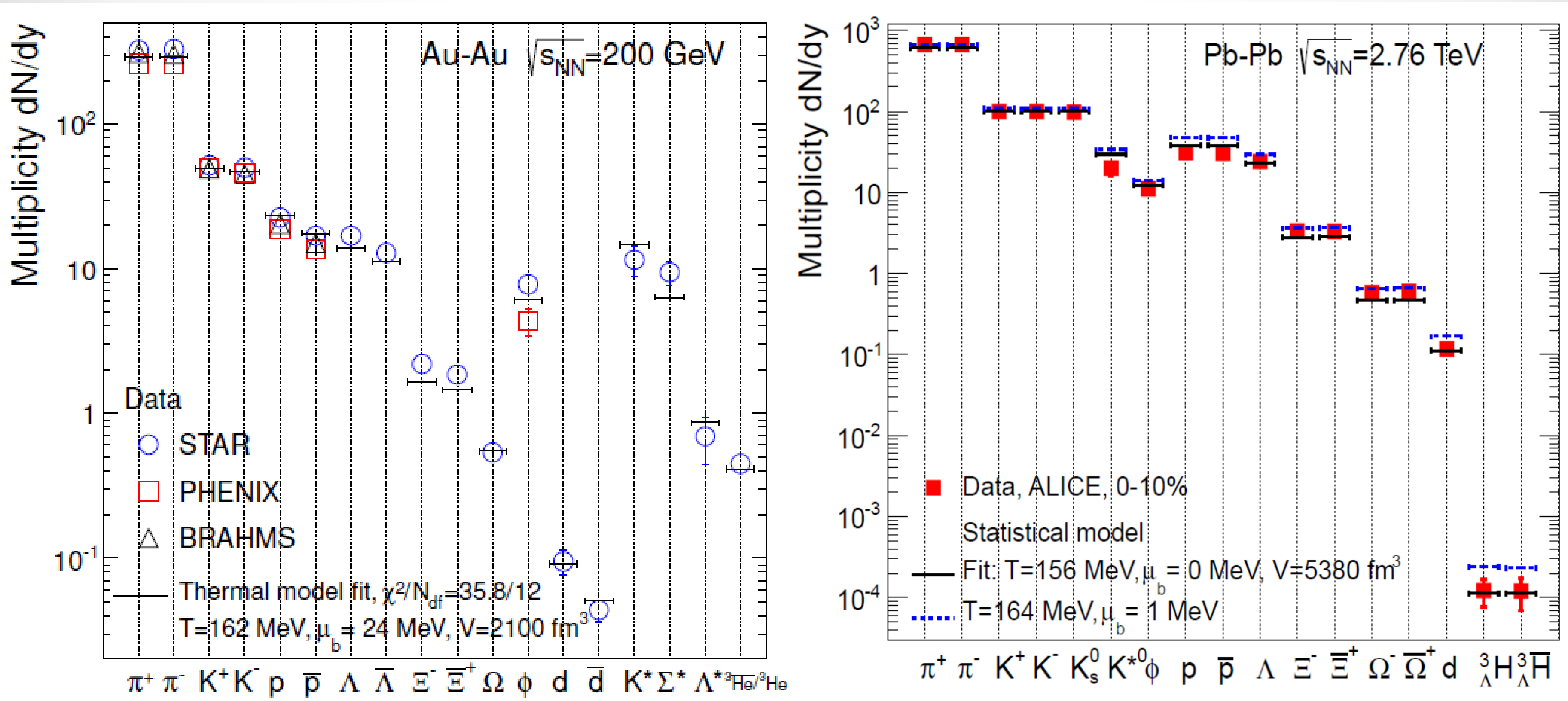
1) The coalescence probability function, the Wigner function

2) Constraints on constituents in the system

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



– Statistical hadronization



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)

Multicharmed and exotic hadron production

– Transverse momentum distribution of multi-charmed hadrons

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

1) 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

$$\frac{d^2N_{\Xi_{cc}}}{d^2\vec{p}_T} = \frac{g_{\Xi_{cc}}}{V^2}(2\sqrt{\pi})^6(\sigma_1\sigma_2)^3 \int d^2\vec{p}_{lT} d^2\vec{p}_{c_1T} d^2\vec{p}_{c_2T} \delta^{(2)}(\vec{p}_T - \vec{p}_{lT} - \vec{p}_{c_1T} - \vec{p}_{c_2T}) \frac{d^2N_l}{d^2\vec{p}_{lT}} \frac{d^2N_{c_1}}{d^2\vec{p}_{c_1T}} \frac{d^2N_{c_2}}{d^2\vec{p}_{c_2T}} \exp(-\sigma_1^2k_1^2 - \sigma_2^2k_2^2).$$

$$\frac{d^2N_X}{d^2\vec{p}_T} = \frac{g_X}{V^3}(2\sqrt{\pi})^9(\sigma_1\sigma_2\sigma_3)^3 \int d^2\vec{p}_{lT} d^2\vec{p}_{\bar{l}T} d^2\vec{p}_{cT} d^2\vec{p}_{\bar{c}T} \delta^{(2)}(\vec{p}_T - \vec{p}_{lT} - \vec{p}_{\bar{l}T} - \vec{p}_{cT} - \vec{p}_{\bar{c}T}) \frac{d^2N_l}{d^2\vec{p}_{lT}} \frac{d^2N_{\bar{l}}}{d^2\vec{p}_{\bar{l}T}} \times \frac{d^2N_c}{d^2\vec{p}_{cT}} \frac{d^2N_{\bar{c}}}{d^2\vec{p}_{\bar{c}T}} \exp(-\sigma_1^2k_1^2 - \sigma_2^2k_2^2 - \sigma_3^2k_3^2).$$

2) Transverse momentum distributions of charm and light quarks

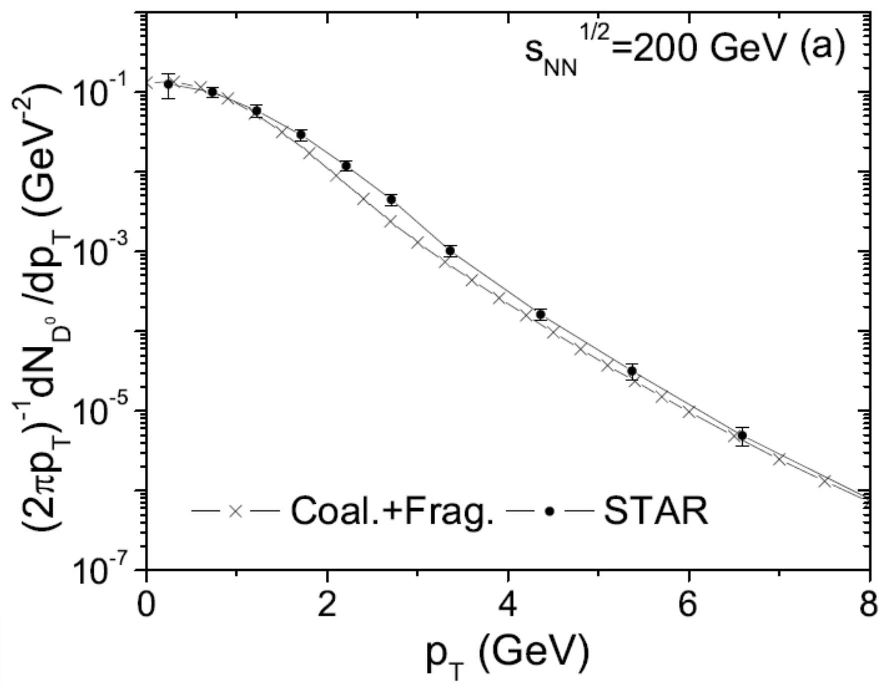
$$\frac{dN_c}{d^2p_T} = \begin{cases} a_0 \exp\left[-a_1 p_T^{a_2}\right] & p_T \le p_0 \\ a_0 \exp\left[-a_1 p_T^{a_2}\right] + a_3\left(1 + p_T^{a_4}\right)^{-a_5} & p_T \ge p_0 \end{cases}$$

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

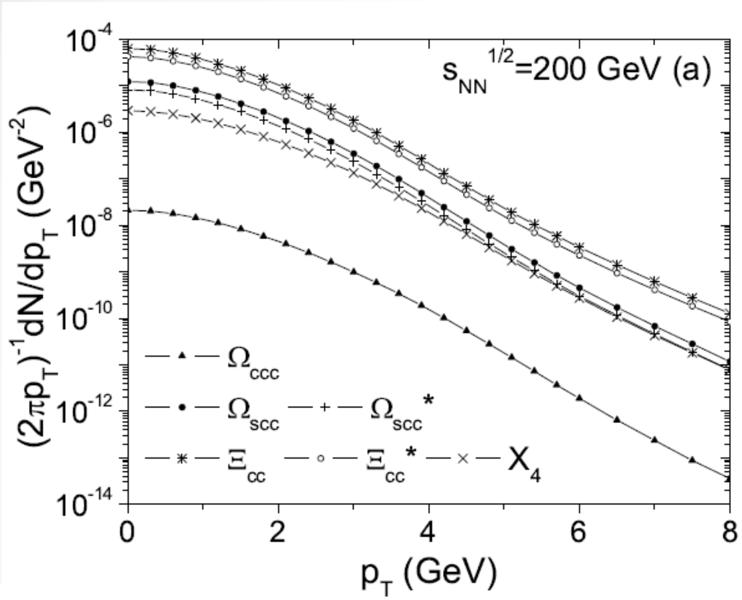
RHIC	a_0	a_1	a_2	a_3	a_4	a_5
$p_T \le p_0$	0.69	1.22	1.57			
$p_T \ge p_0$	1.08	3.04	0.71	3.79	2.02	3.48
LHC	a_0	a_1	a_2	a_3	a_4	a_5
$p_T \le p_0$	1.97	0.35	2.47			
$p_T \ge p_0$	7.95	3.49	3.59	87335	0.5	14.31

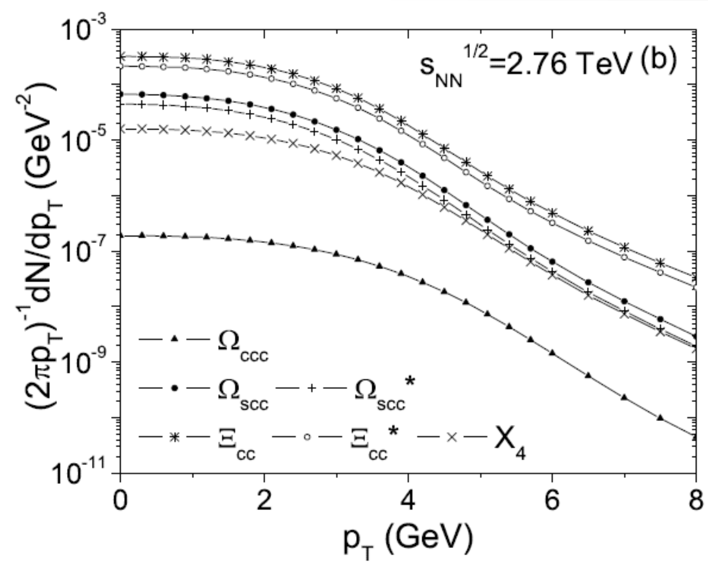
S. Plumari, V. Minissale, S. K. Das, G. Coci and V. Greco, Eur. Phys. J. C **78**:348 (2017)
Y. Oh, C. M. Ko, S.-H. Lee, and S. Yasui, Phys. Rev. C **79** 044905 (2009)
S. Cho *et al*. (EXHIC Collaboration), Prog. Part. Nucl. Phys. **95**, 279 (2017)
J. Adam et al. [STAR Collaboration], Phys. Rev. C **99**, no. 3, 034908 (2019)

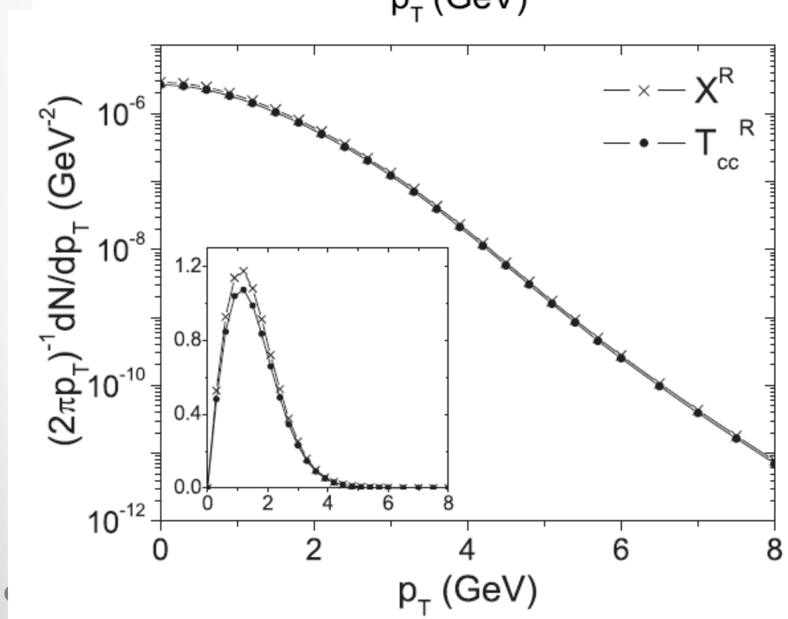
	RHIC		LHC (2.76 TeV)	
	Sc. 1	Sc. 2	Sc. 1	Sc. 2
T_H (MeV)	162		156	
V_H (fm^3)	2100		5380	
μ_B (MeV)	24		0	
μ_s (MeV)	10		0	
γ_c	22		39	
γ_b	4.0×10^7		8.6×10^8	
T_C (MeV)	162	166	156	166
V_C (fm^3)	2100	1791	5380	3533
$N_u = N_d$	320	302	700	593
$N_s = N_{\bar{s}}$	183	176	386	347
$N_c = N_{\bar{c}}$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



3) Transverse momentum distributions of charmed hadrons



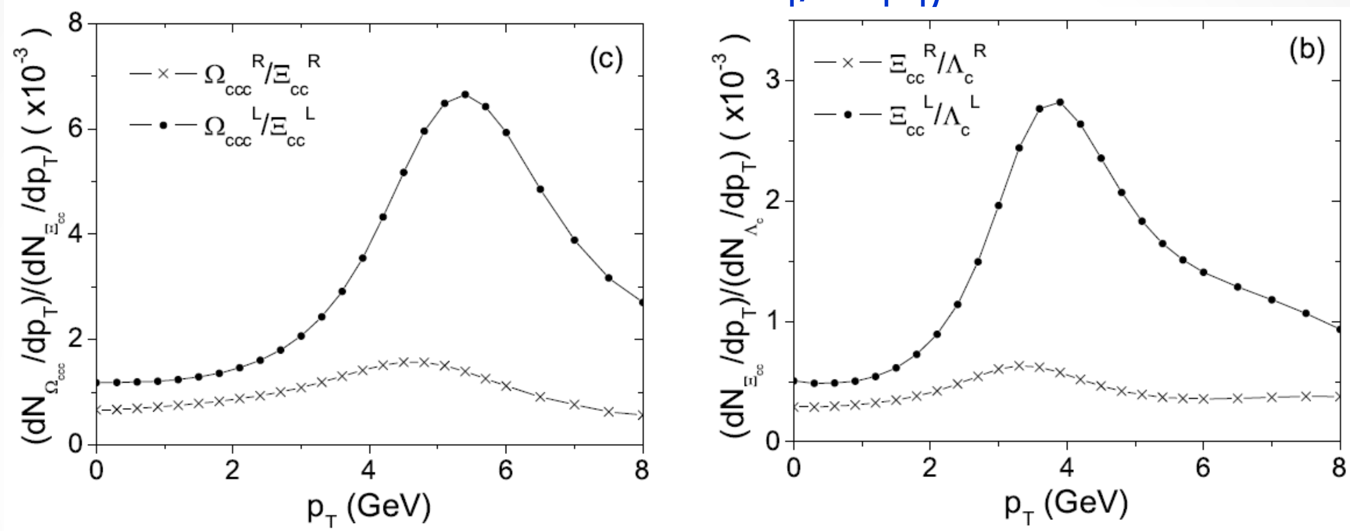




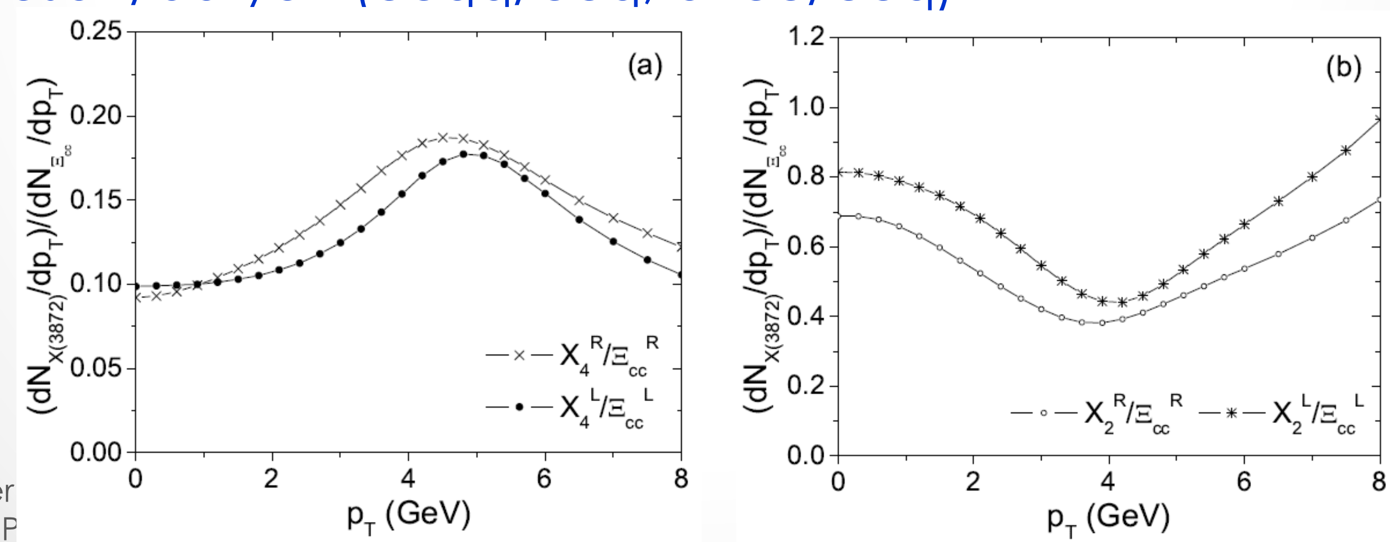
	RHIC	LHC
Ξ_{cc}	4.4×10^{-4}	6.7×10^{-3}
Ξ_{cc}^*	2.9×10^{-4}	4.5×10^{-3}
Ω_{scc}	8.6×10^{-5}	1.3×10^{-3}
Ω_{scc}^*	5.7×10^{-5}	8.5×10^{-4}
Ω_{ccc}	1.7×10^{-7}	5.9×10^{-6}
T_{cc}	2.2×10^{-5}	3.8×10^{-4}
X_4	2.4×10^{-5}	3.8×10^{-4}
X_2	2.6×10^{-4}	4.5×10^{-3}
D^0	0.71	6.0
Λ_c	0.63	4.0

– Transverse momentum distribution ratios

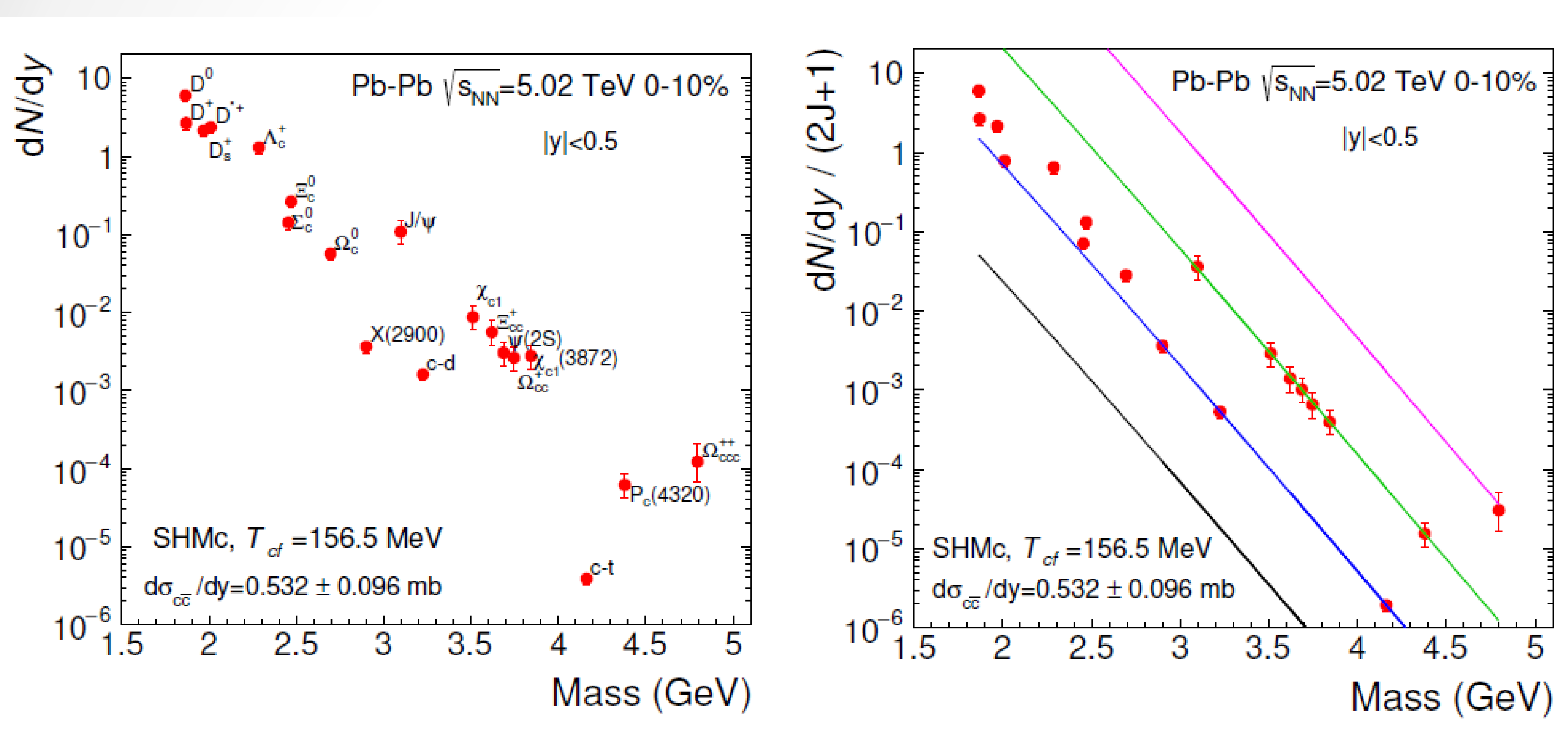
1) Baryon/baryon (ccc/cca, or ccq/cqq)



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

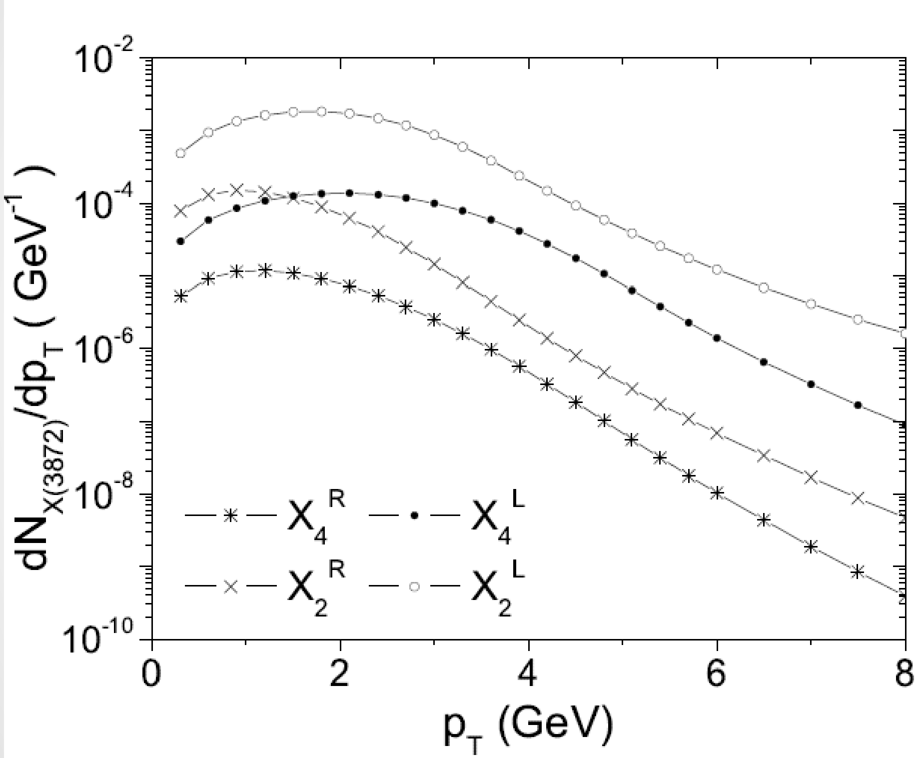


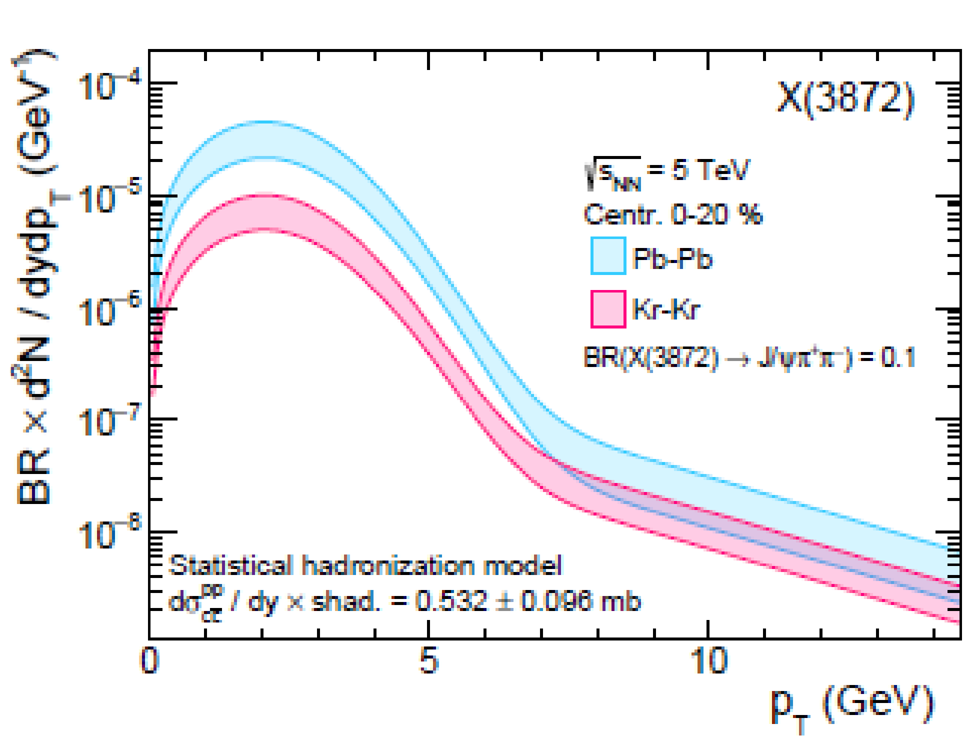
– The 1st comparison with results from the statistical hadronization model



A. Andronic, P. Braun-Munzinger, M. K. Kohler, A. Mazeliauskas, K. Redlich, J. Stachel, and V. Vislavicius, J. High Energy Phys. **2021**, 35 (2021).

– The 2nd 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).

Conclusions

– Heavy Quark Coalescence

1) Studying production of hadrons in heavy ion collisions can help us to understand hadron production mechanism
2) Heavy ion collision experiments provide better chances to study production of multicharm hadrons as well as exotic hadrons
3) Transverse momentum distributions are dependent on the internal structure of the hadron
4) Transverse momentum distribution ratios between multi-charm hadrons and exotic hadrons, or other combinations between charmed hadrons reflect the internal structure of the exotic hadron

Thank you for your attention!