Production of charm-strange mesons in heavy ion collisions

The Reimei Workshop : Hadron interactions with strangeness and charm

June 28th, 2024
Uni Hotel, Jeju, Korea

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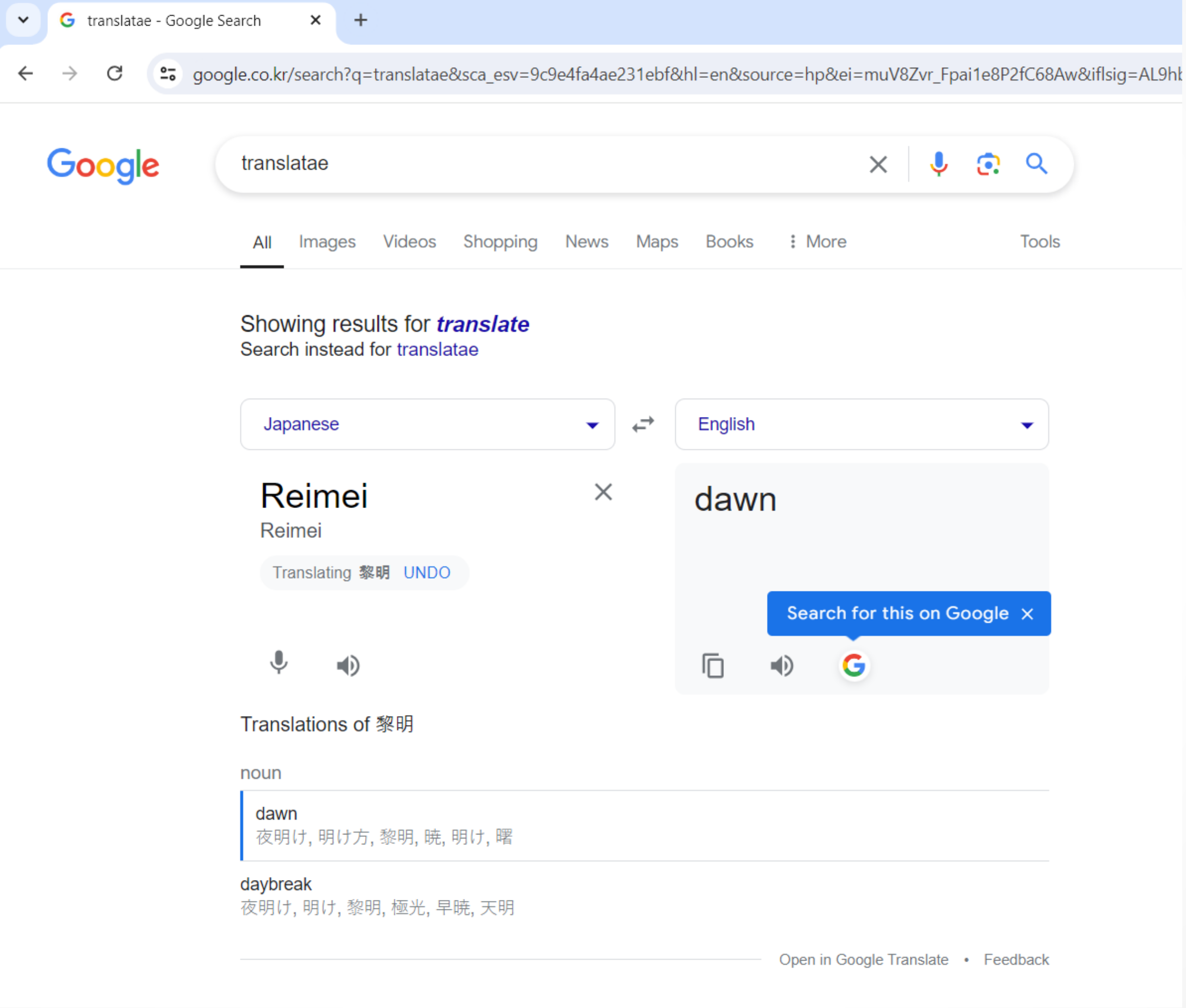
Kangwon National University

– Reimei workshop



– Production of charm-strange mesons

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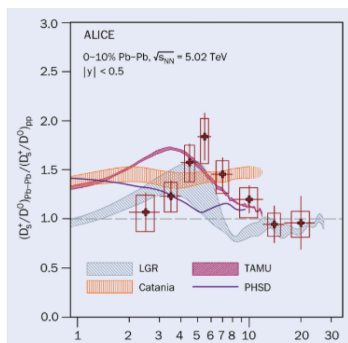
Charm-strange mesons probe hadronisation

21 December 2021

A report from the ALICE experiment.



The ALICE collaboration has reported a new measurement of the production of D_s^+ mesons, which contain a charm and an anti-strange quark, in Pb–Pb collisions collected in 2018 at a centre- of-mass energy per nucleon pair of 5.02 TeV. The large data sample and the use of machine-learning techniques for the selection of particle candidates led to increased precision on this important quantity.

https://cerncourier.com

S. Acharya et al, (ALICE Collaboration), Phys. Lett. **B** 827, 136986 (2022)

– Production of $D_{s0}(2317)$ mesons

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

Table 2.4
Summary of exotic hadrons with heavy flavors. The notations are the same as those in Table 2.3.

Particle	m [MeV]	(I, J^P)	$q\bar{q}/qqq(L)$	Multiquark	Mol. (L)	ω_{Mol} [MeV]
$D_s(2317)$	2317	$(0, 0^+)$	$c\bar{s}\,(P)$	$c\bar{s}q\bar{q}$	$DK\,(S)$	273(B)
$X(3872)$	3872	$(0, 1^+)$	$c\bar{c}\,(P)$	$c\bar{c}q\bar{q}$	$D\bar{D}^*\,(S)$	3.6(B)
$Z_c(3900)$	3900	$(1, 1^+)$	–	$c\bar{c}u\bar{d}$	–	–
$Z_c(4430)$	4430	$(1, 1^+)$	–	$c\bar{c}u\bar{d}$	$D_1\bar{D}^*\,(S)$	13.5(B)
$Z_b(10610)$	10610	$(1, 1^+)$	–	$b\bar{b}u\bar{d}$	–	–
$Z_b(10650)$	10650	$(1, 1^+)$	–	$b\bar{b}u\bar{d}$	–	–
$X(5568)$	5568	$(1, 0^+)$	–	$s\bar{b}u\bar{d}$	–	–
$P_c(4380)$	4380	$(1/2, 3/2^-)^b$	–	$c\bar{c}uud\,(S)$	$\bar{D}\Sigma_c^*\,(S)$	60(B)
$P_c(4450)$	4450	$(1/2, 5/2^+)^b$	–	$c\bar{c}uud\,(P)$	–	–

Table 3.4
Summary of particle yields for heavy hadrons (cf. Table 2.4).

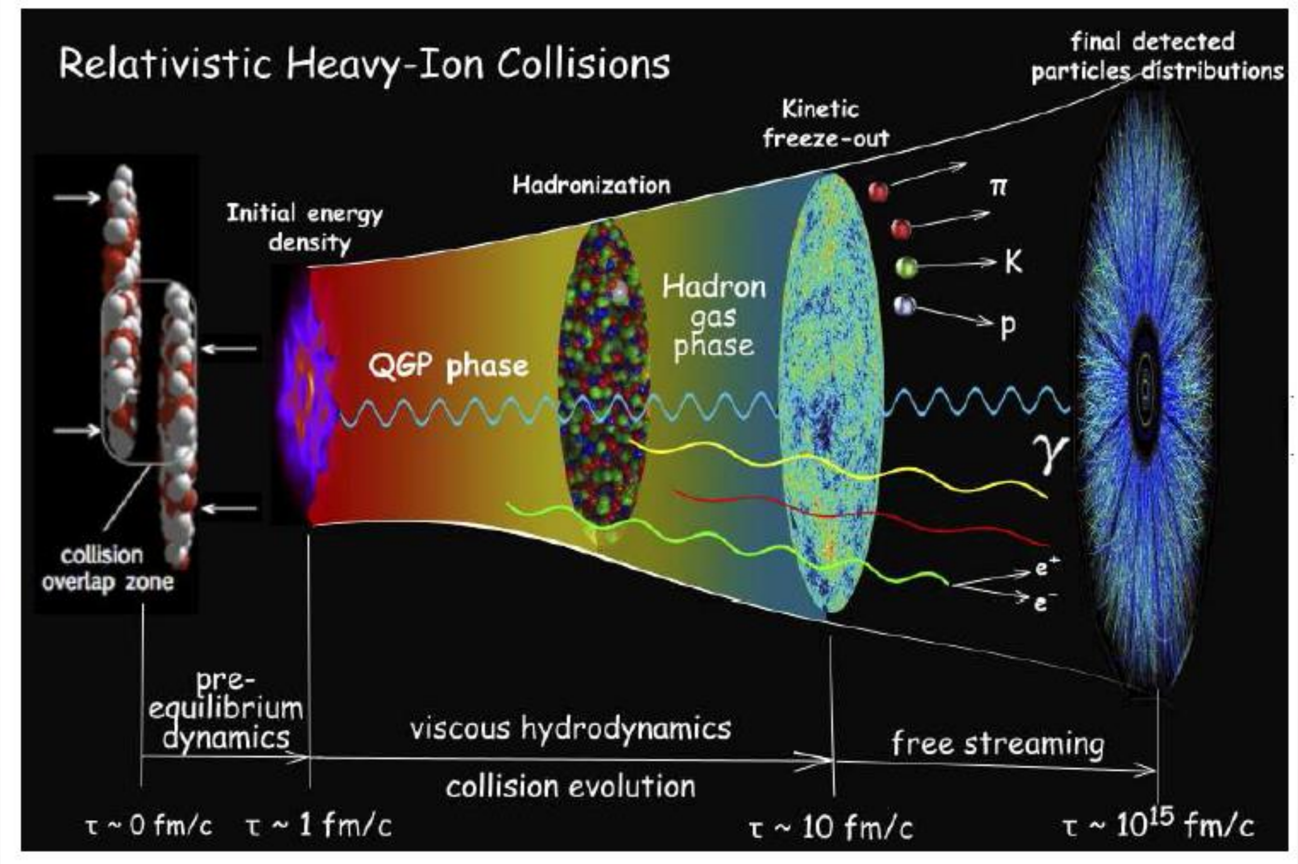
Particle	Scenario 1		Mol.	Stat.
	$q\bar{q}/qqq$	Multiquark		
RHIC				
$D_s(2317)$	2.3×10^{-2}	2.4×10^{-3}	6.5×10^{-3}	6.6×10^{-2}
LHC (2.76 TeV)				
$D_s(2317)$	5.2×10^{-2}	4.3×10^{-3}	1.4×10^{-2}	1.5×10^{-1}
LHC (5.02 TeV)				
$D_s(2317)$	6.5×10^{-2}	5.4×10^{-3}	1.8×10^{-2}	1.9×10^{-1}

Outline

- Introduction
- Charmed hadrons in heavy ion collisions
- Charmed hadron production by coalescence
- Production of charm-strange mesons
- Conclusion

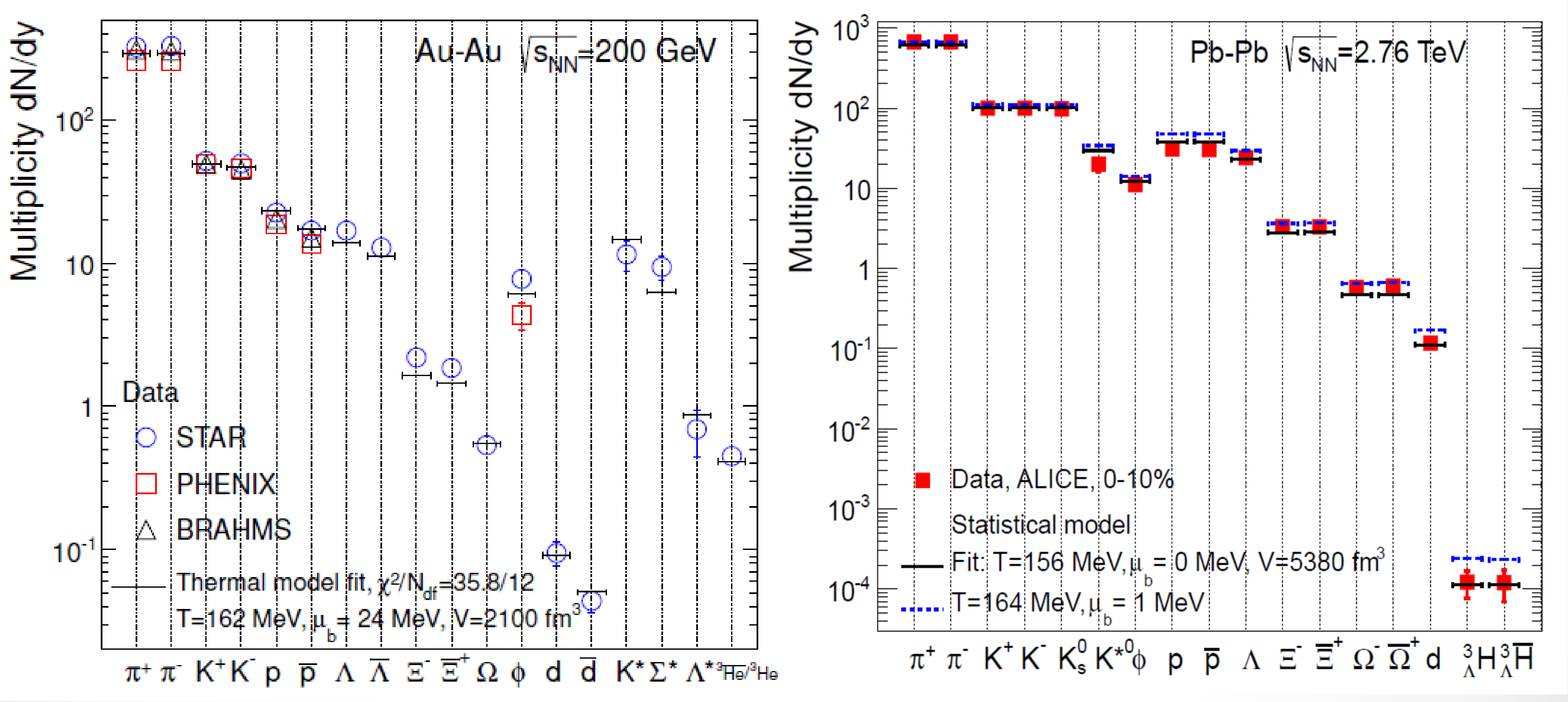
Introduction

– Relativistic heavy ion collisions



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

– 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)

– Quark coalescence

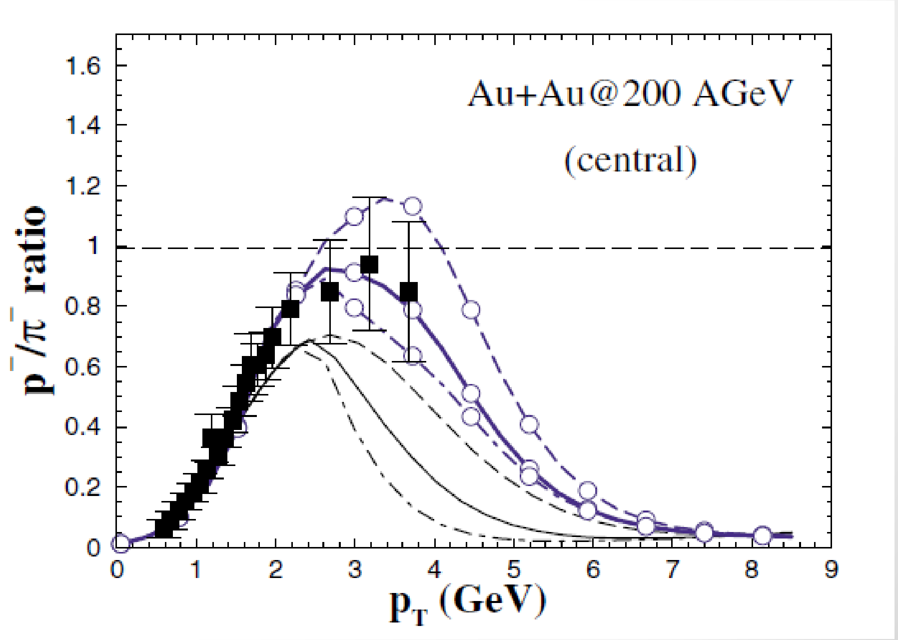
V. Greco, C. M. Ko, and P. Levai, Phys. Rev. C **68**, 034904 (2003)
R. J. Freis. B. Muller, C. Nonaka, and S. Bass, Phys. Rev. C **68**, 044902 (2003)

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

1) The coalescence probability function, the Wigner function

2) Constraints on constituents in the system

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



Charmed hadrons in heavy ion collisions

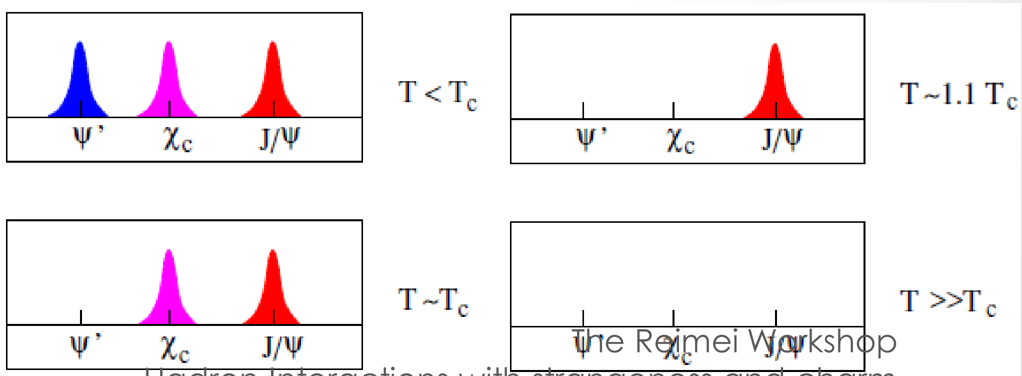
– J/ψ suppression and Debye screening

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

: At $T>T_C$ color charges are Debye screened in QGP, and the Debye screening prevents the formation of the bound states

– Sequential melting of charmonium states

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

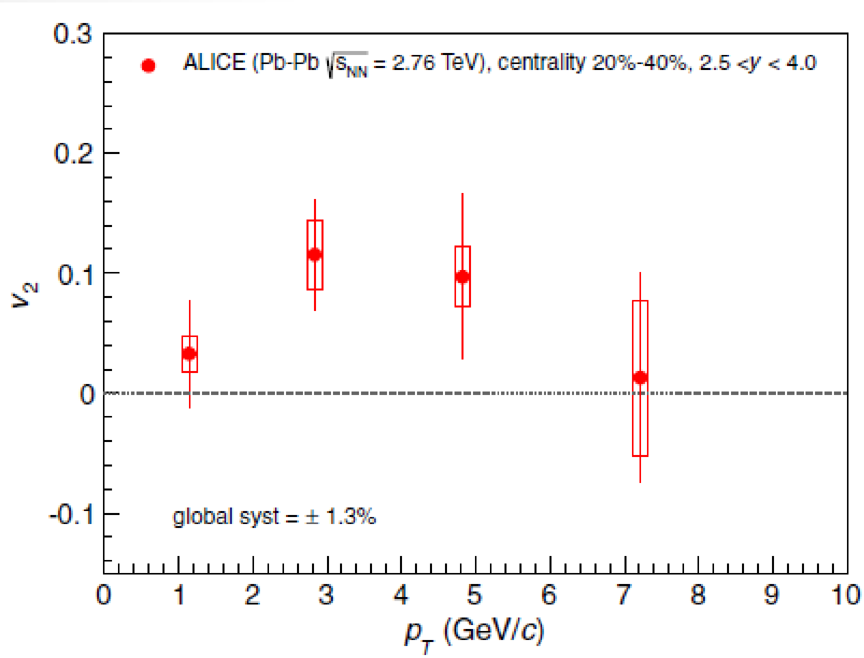


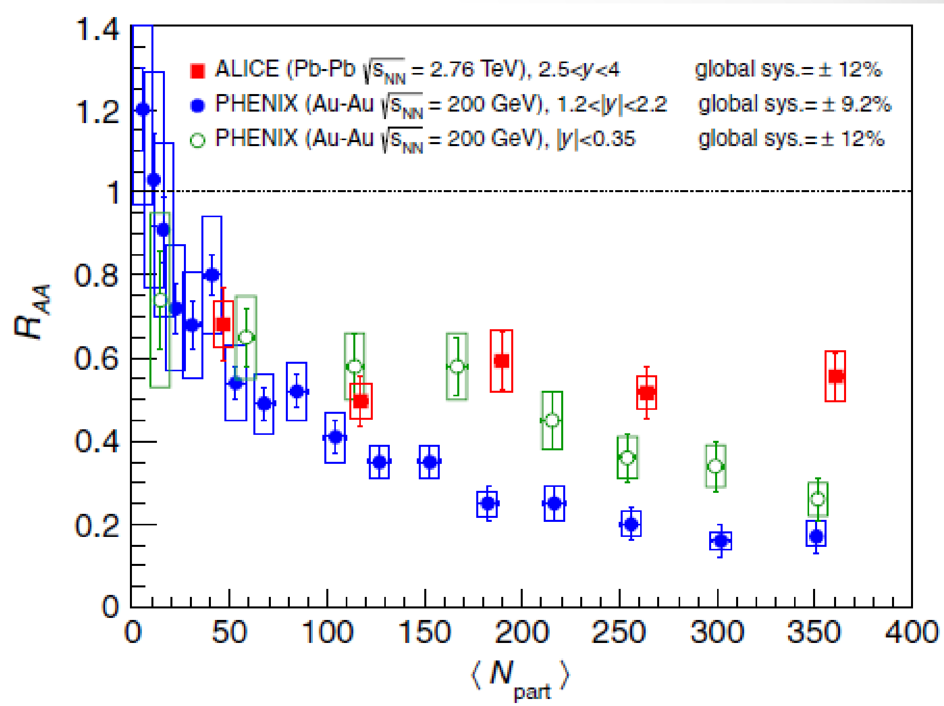
H. Satz, J. Phys. G. **32**, R25 (2006)

– 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

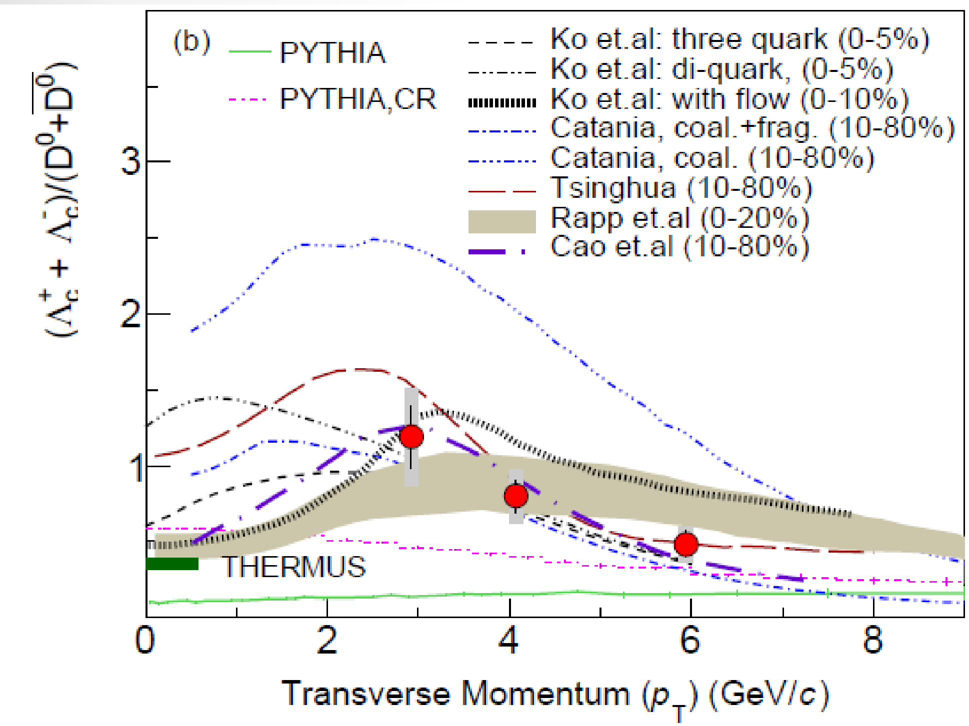


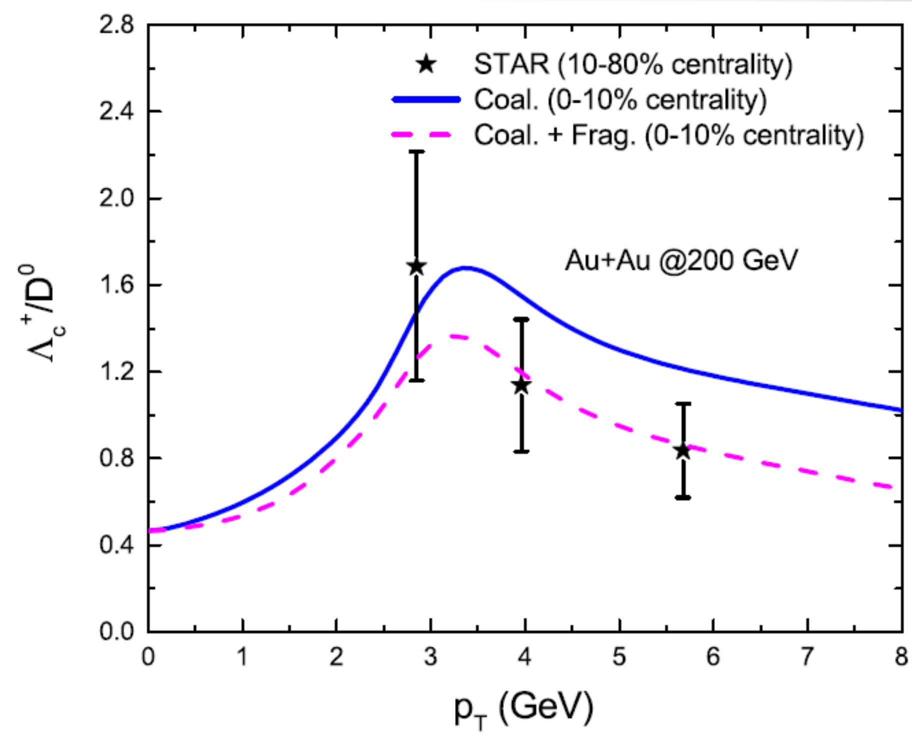


2) Elliptic flow of the J/ψ

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

– Transverse momentum distribution ratios between Λ_c and 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 hadron production by coalescence

– 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)

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

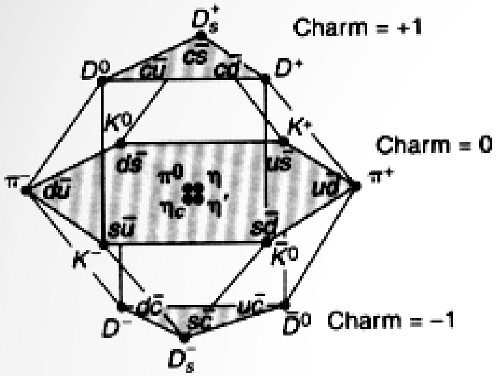
1) The Wigner function, the coalescence probability function

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

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

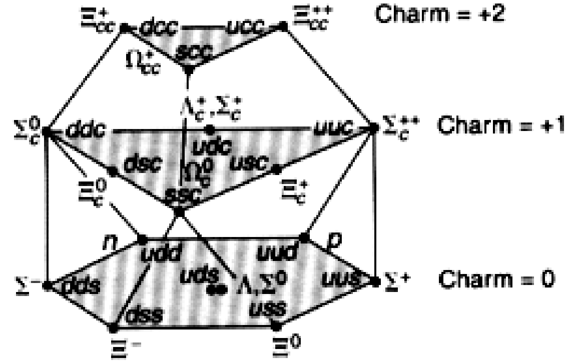
$$\int p_i \cdot d\sigma_i \frac{d^3 p_i}{(2\pi)^3 E_i} f(x_i, p_i) = N_i$$

– Charmed hadrons



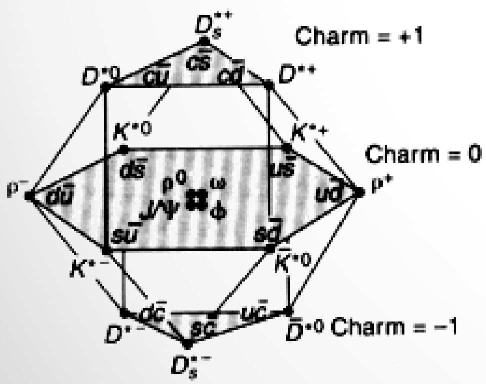
0− Mesons

(a)



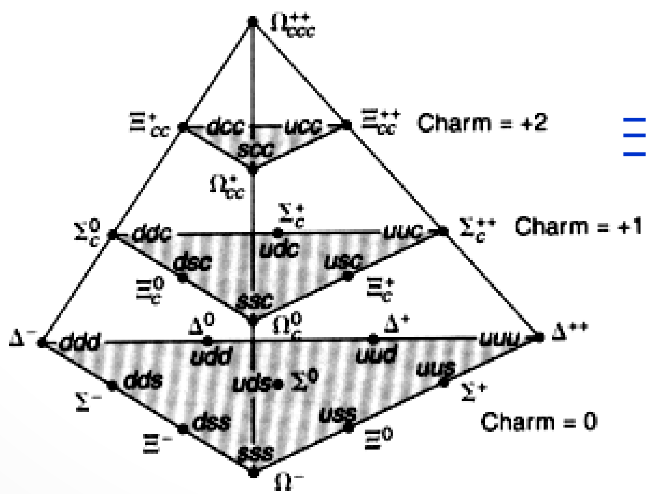
$\frac{1}{2}^+$ Baryons

(c)



1− Mesons

(b)



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

(d)

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

2) Singly charmed baryons: $\Lambda_C(2286)$, $\Lambda_C(2595)$, $\Lambda_C(2625)$, $\Sigma_C(2455)$, $\Sigma_C(2520)$, $\Xi_C(2470)$, $\Xi_C(2578)$, $\Xi_C(2645)$, $\Omega_C(2695)$, $\Omega_C(2770)$

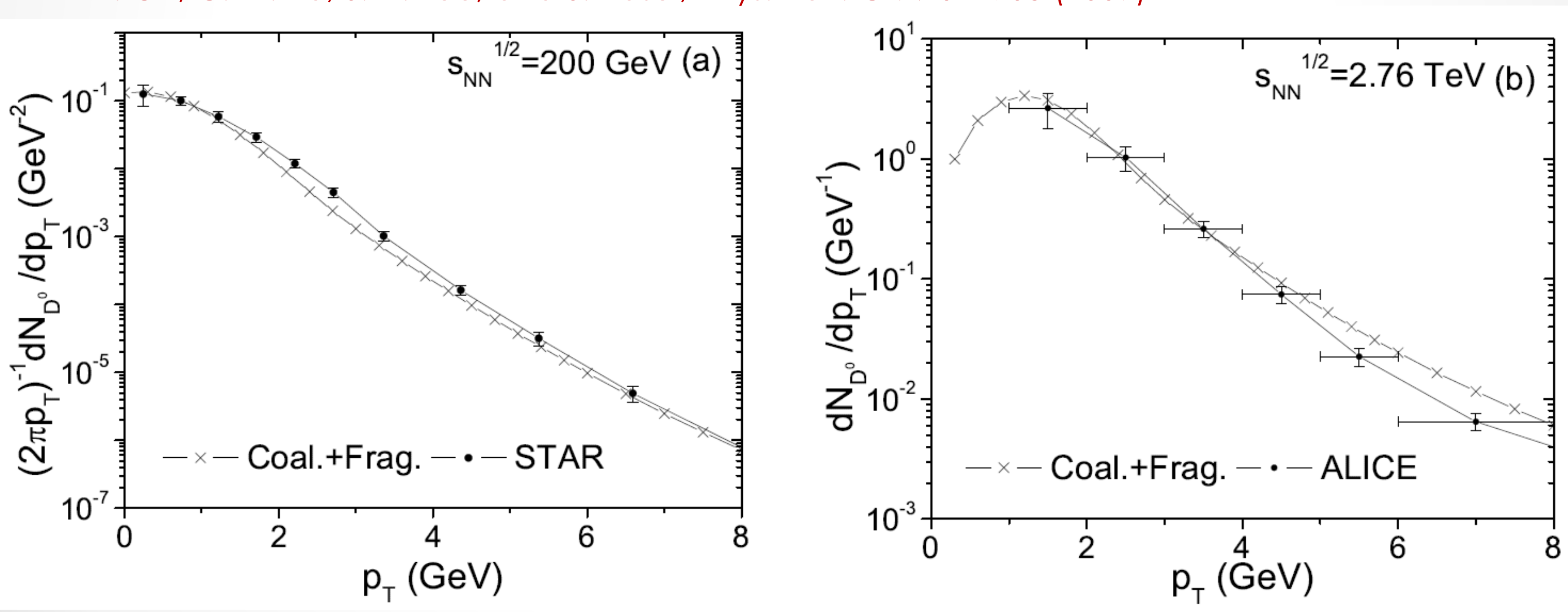
– Transverse momentum distributions of charm, light quarks and D^0 mesons

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

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

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)



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

– 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

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

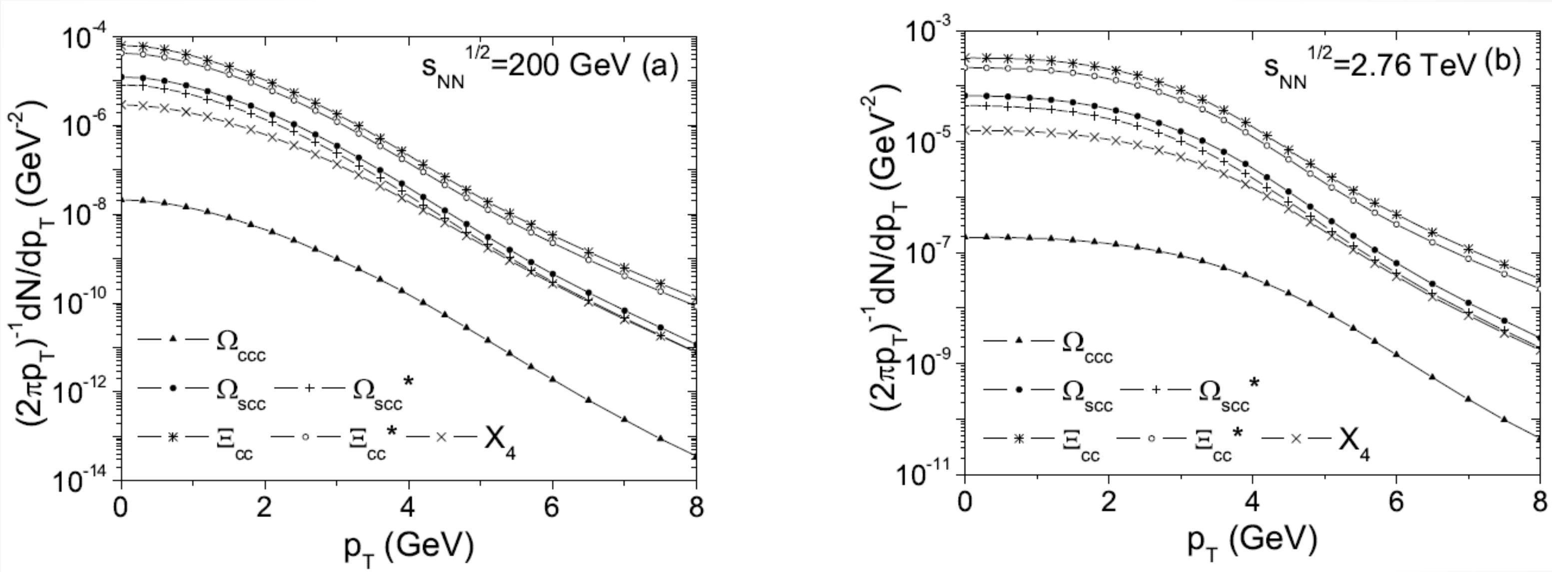
$$N_X = g_X \int p_l \cdot d\sigma_l p_{\bar{l}} \cdot d\sigma_{\bar{l}} p_c \cdot d\sigma_c p_{\bar{c}} \cdot d\sigma_{\bar{c}} \frac{d^3\vec{p}_l}{(2\pi)^3 E_l} \frac{d^3\vec{p}_{\bar{l}}}{(2\pi)^3 E_{\bar{l}}} \frac{d^3\vec{p}_c}{(2\pi)^3 E_c} \frac{d^3\vec{p}_{\bar{c}}}{(2\pi)^3 E_{\bar{c}}}$$
$$\times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

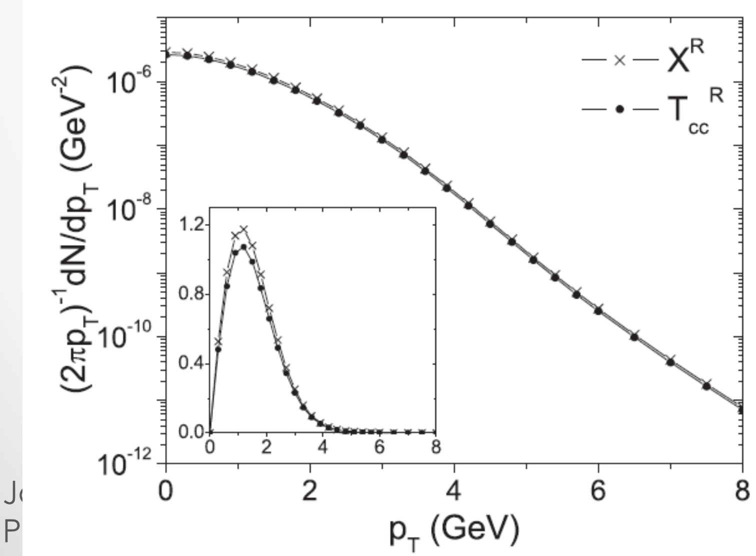
2) Transverse momentum distributions

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

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

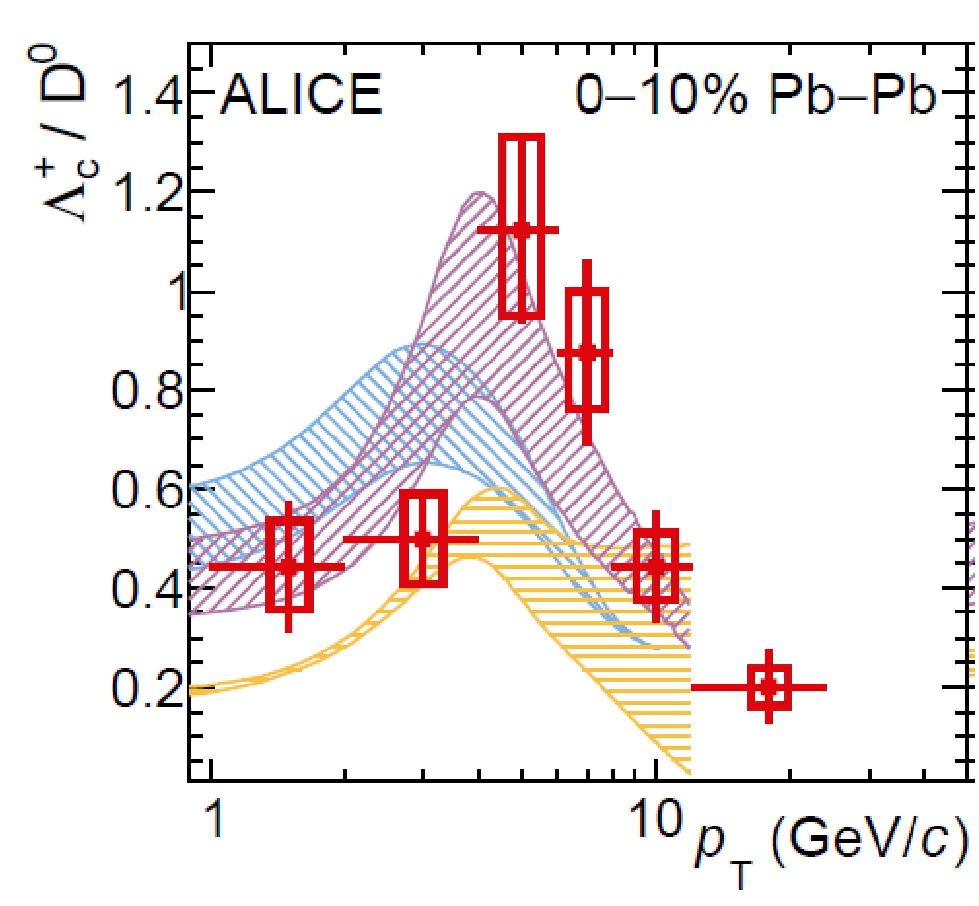
– Transverse momentum distributions of exotic and multi-charmed hadrons





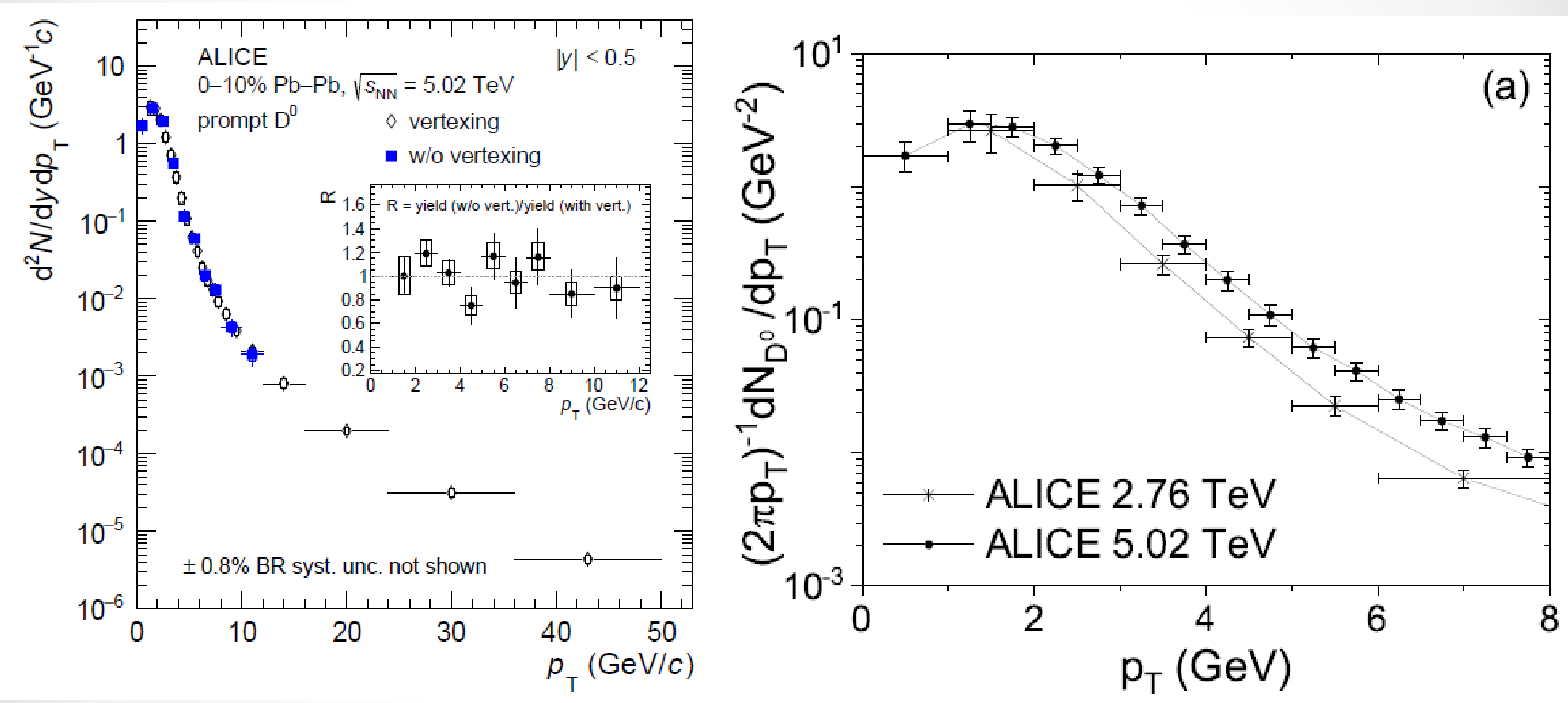
	RHIC	LHC
Ξ_{cc}	4.4×10^{-4}	6.7×10^{-3}
Ξ_{cc}^*	2.9×10^{-4}	4.5×10^{-3}
Ω_{scc}	8.6×10^{-5}	1.3×10^{-3}
Ω_{scc}^*	5.7×10^{-5}	8.5×10^{-4}
Ω_{ccc}	1.7×10^{-7}	5.9×10^{-6}
T_{cc}	2.2×10^{-5}	3.8×10^{-4}
X_4	2.4×10^{-5}	3.8×10^{-4}
X_2	2.6×10^{-4}	4.5×10^{-3}
D^0	0.71	6.0
Λ_c	0.63	4.0

– Measurements of Λ_c/D_0 ratios at LHC



S. Acharya et al, (ALICE Collaboration), Phys. Lett. **B** 839, 137796 (2023)

– Transverse momentum distributions of D^0 mesons at LHC 2.76 and 5.02 TeV



J. Adam et al. [ALICE Collaboration], JHEP **1603**, 081 (2016)
S. Acharya et al, (ALICE Collaboration), JHEP **01**, 174 (2022)

– Production of hadrons both by coalescence and by fragmentation

Coalescence + Fragmentation

$$\frac{\Lambda_{c\ coal} + \Lambda_{c\ frag}}{D^0_{coal} + D^0_{frag}}$$

1) D^0 mesons

67% from by fragmentation including feed-downs

2) Λ_c

7% from by fragmentation including feed-downs

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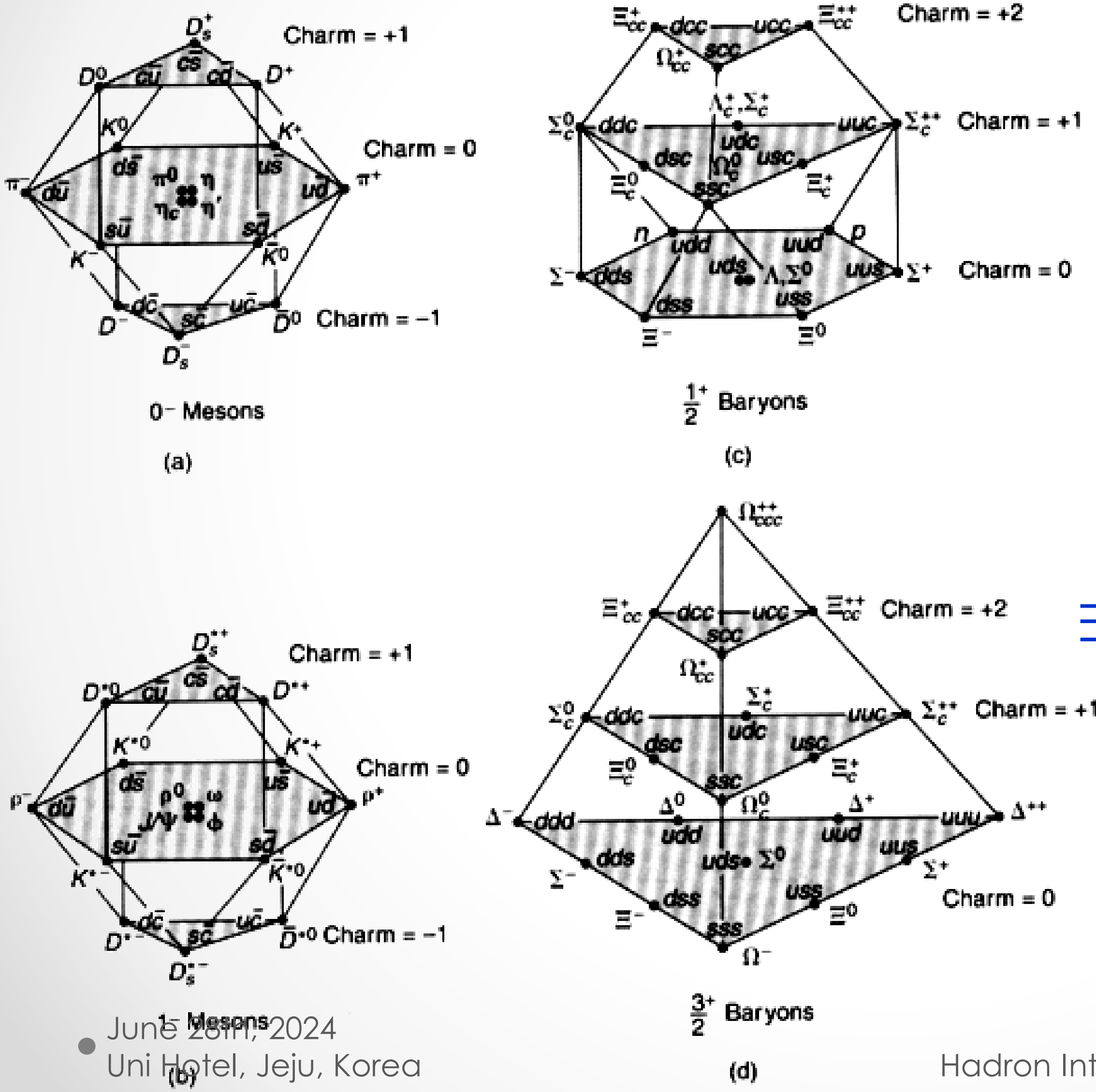
Production of charm-strange mesons



1) Charmed mesons:
   D, D*, D_S, D_S*
   D_{s0}(2317), D_{s1}(2460)*

2) Singly charmed baryons: Λ_C(2286), Λ_C(2595), Λ_C(2625), Σ_C(2455), Σ_C(2520), Ξ_C(2470), Ξ_C(2578), Ξ_C(2645), Ω_C(2695), Ω_C(2770)

– The ratio of D^+_s/D^0 at LHC

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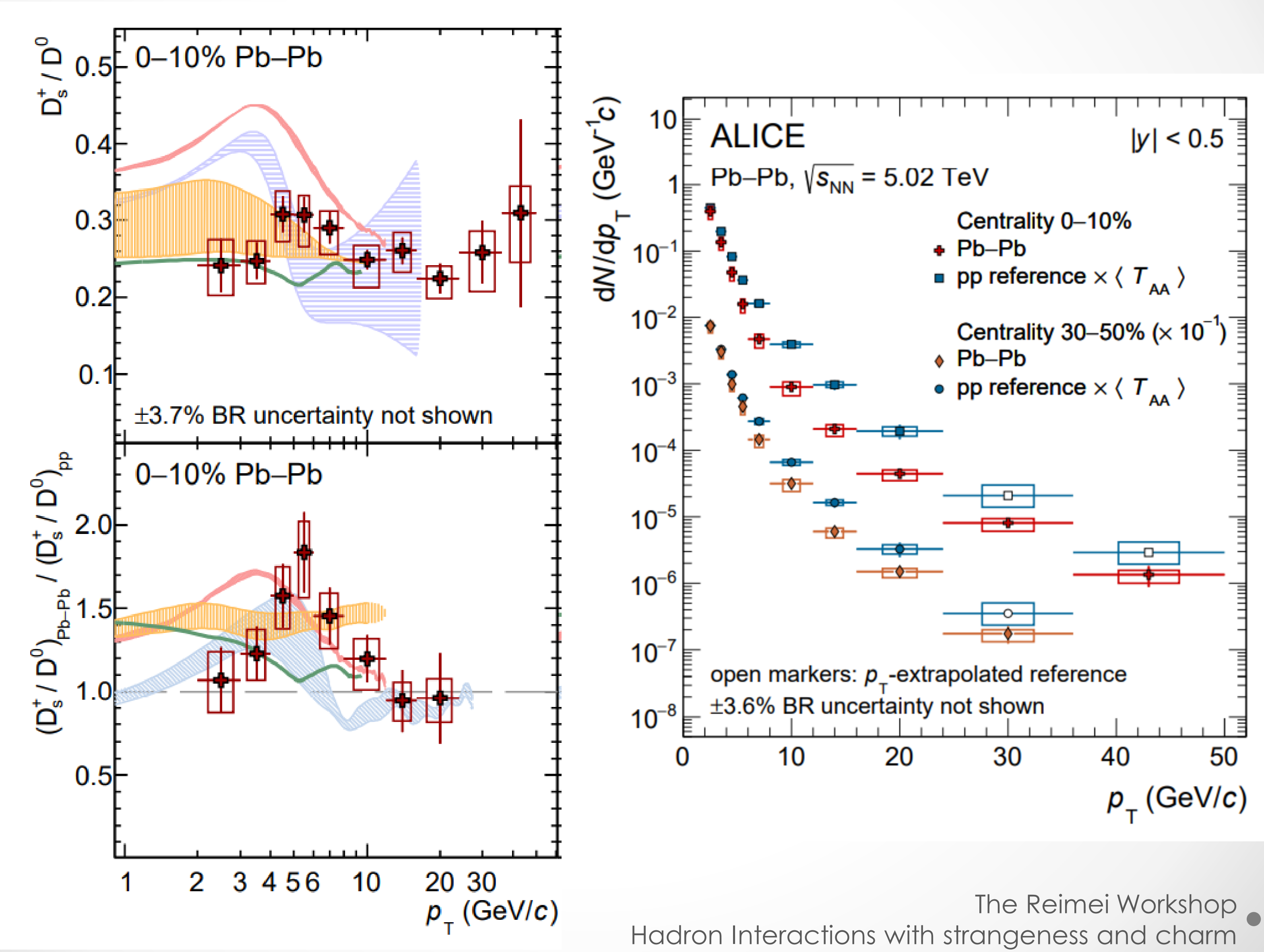

– Transverse momentum distribution of strange quarks

Thermal + Parton

$$\frac{dN_{q,\bar{q}}}{d^2r_T\, d^2p_T} = \frac{g_{q,\bar{q}}\tau m_T}{(2\pi)^3} \exp\left(-\frac{\gamma_T(m_T - p_T \cdot \beta_T \mp \mu_q)}{T}\right), \quad (13)$$

$$\frac{dN_{jet}}{d^2p_T} = A_1\left[1+\left(\frac{p_T}{A_2}\right)^2\right]^{-A_3} + A_4\left[1+\left(\frac{p_T}{A_5}\right)^2\right]^{-A_6}. \quad (15)$$

Table 2 Parameters for minijet parton distributions at mid-rapidity from Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

	A_1	A_2	A_3	A_4	A_5	A_6
g	23.46	4.84	8.08	2.78	2.79	2.31
u, d	24.68	5.11	8.01	0.55	5.65	2.56
$\bar{u}, \bar{d}$	23.12	5.05	8.21	0.57	5.62	2.58
s	24.14	5.11	8.01	0.55	5.65	2.56
$\bar{s}$	23.12	5.00	8.31	0.57	5.62	2.61

S. Plumari, V. Minissale, S. K. Das, G. Coci and V. Greco, Eur. Phys. J. C **78**:348 (2017).

– Strange enhancement

Thermal + Parton

$$\frac{D_{s\ coal} + D_{s\ frag}}{D^0_{coal} + D^0_{frag}}$$

1) D^0 mesons

67% from by fragmentation including feed-downs

2) D_s

8% from by fragmentation including feed-downs

Conclusion

– Production of charm-strange mesons in heavy ion collisions

1) Studying the yield and transverse momentum distribution of hadrons in heavy ion collisions can help us understand hadron production mechanism as well as the properties of the quark-gluon plasma
2) The ratio between heavy quark baryons and mesons contains information on both transverse momentum distribution of not only light quarks but also heavy quarks, reflecting the balance between properties of light and heavy quarks in heavy ion collisions
3) Many more experimental and theoretical studies are expected

Stay tuned for more updates!

Thank you for your attention!