

# Production of charm-strange mesons at $\sqrt{s}=5.02$ TeV in heavy ion collisions

The 2025 International Conference on the  
Structure of Baryons, Baryons 2025

November 14<sup>th</sup>, 2025

International Convention Center Jeju, Jeju



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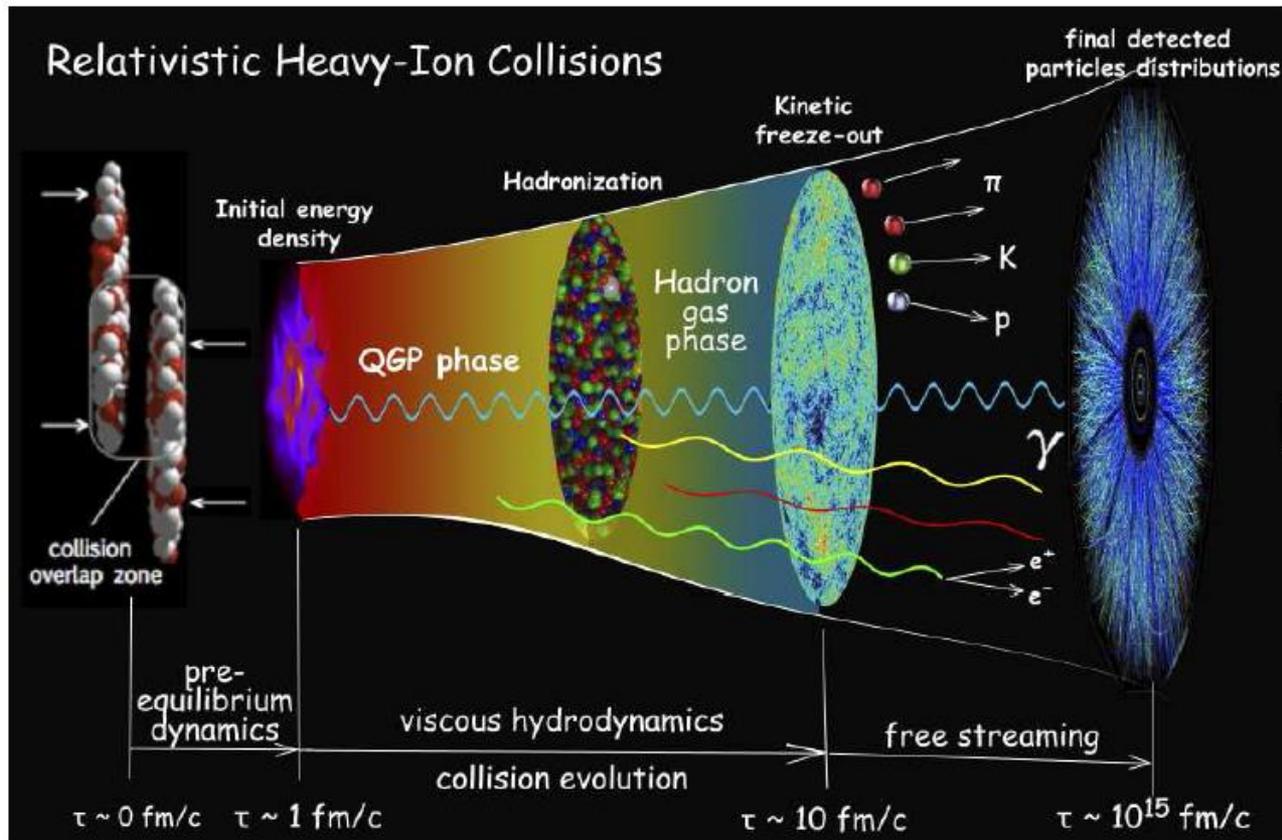
In collaboration with Su Houg Lee, [arXiv:2510.18673](https://arxiv.org/abs/2510.18673)

# Outline

- Introduction
- Charm-strange mesons in heavy ion collisions
- Charm-strange meson production by coalescence
- Conclusions

# Introduction

## – Relativistic heavy ion collisions



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

# Charm-strange mesons in heavy ion collisions

## – Strangeness enhancement

T.P. Koch, B. Muller and J. Rafelski, Phys. Rept. **142** 167 (1986)

: The strangeness enhancement in heavy ion collisions than in elementary collisions

## – $J/\psi$ 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

# – Production of charm-strange mesons

The screenshot shows a web browser displaying a CERN Courier article. At the top, there is an advertisement for INFICON with the text 'Vacuum Measurement with Plug-and-Play Solutions' and 'Upgrade now'. Below the ad is the CERN Courier logo and the tagline 'Reporting on international high-energy physics'. A navigation menu includes 'Physics', 'Technology', 'Community', 'In focus', and 'Magazine'. The article title is 'Charm-strange mesons probe hadronisation', dated 21 December 2021, with a sub-headline 'A report from the ALICE experiment.' To the left of the article are social media sharing icons for Facebook, Twitter, LinkedIn, Email, and Print. The main content features a plot of the ratio  $(D_s^+ / D^0)_{Pb-Pb} / (D_s^+ / D^0)_{pp}$  versus  $\sqrt{s_{NN}}$  (GeV) for ALICE. The plot shows data points with error bars and theoretical curves from LGR, Catania, TAMU, and PHSD. The text to the right of the plot states: '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.'

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

# – Quark coalescence

V. Greco, C. M. Ko, and P. Levai, Phys. Rev. C **68**, 034904 (2003)

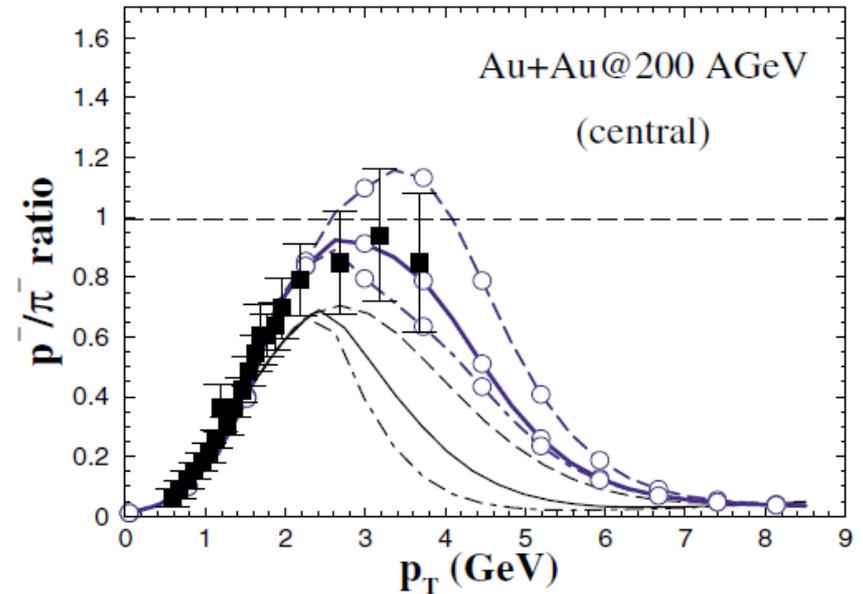
R. J. Freis, B. Muller, C. Nonaka, and S. Bass, Phys. Rev. C **68**, 044902 (2003)

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

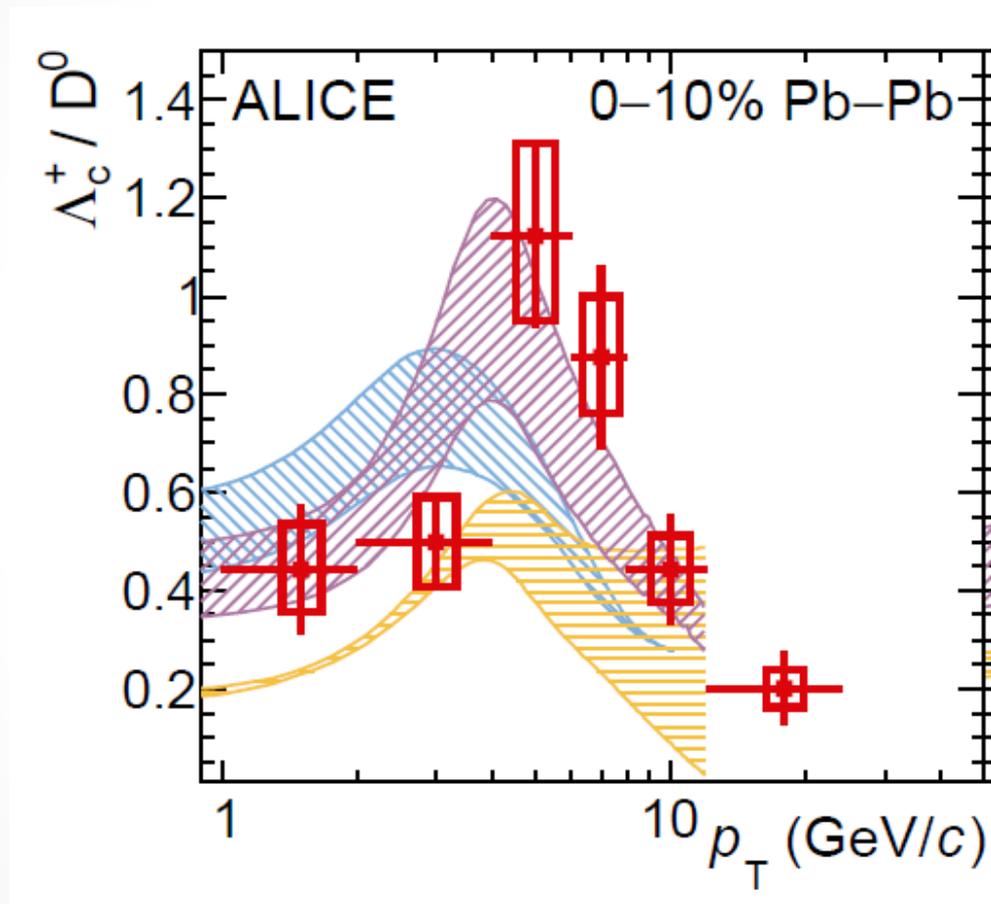
1) The coalescence probability function, the Wigner function

2) Constraints on constituents in the system

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



# – Measurements of $\Lambda_c^+/D_0$ ratios at LHC



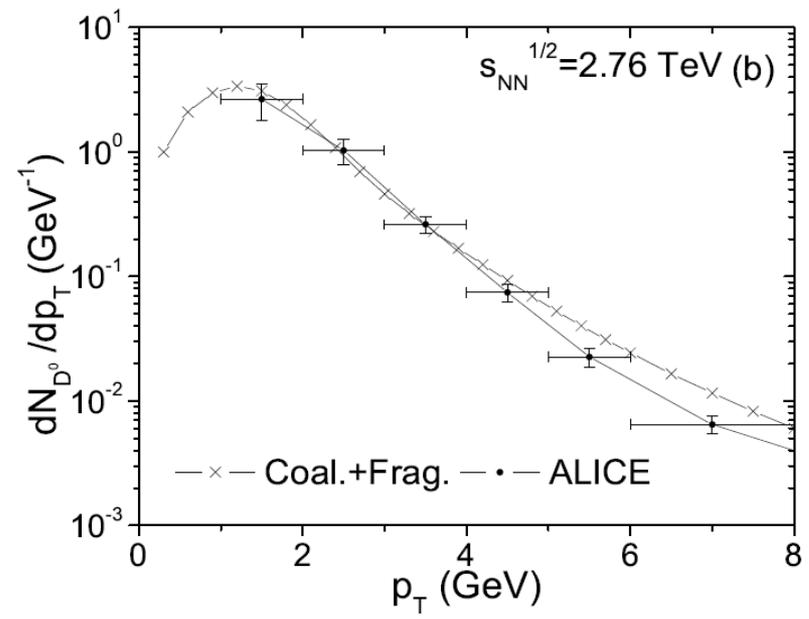
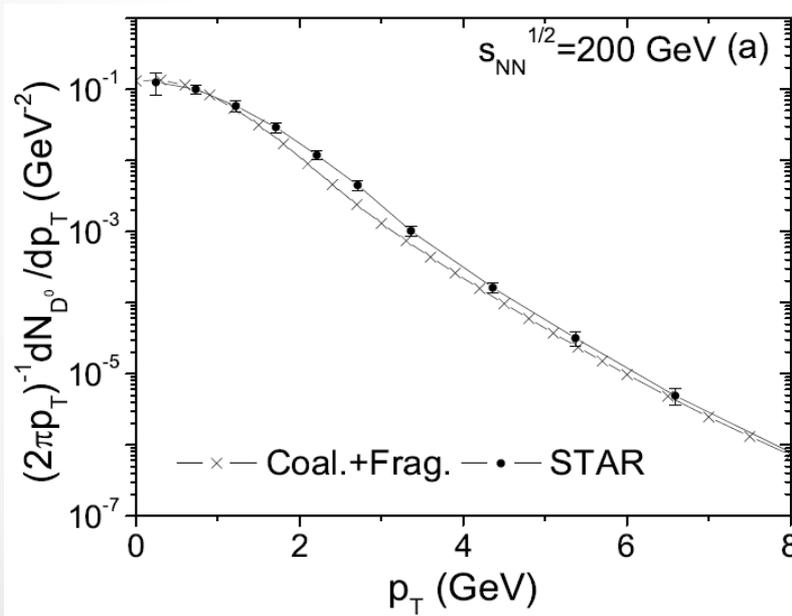
S. Acharya et al, (ALICE Collaboration), Phys. Lett. **B** 839, 137796 (2023)

# – Transverse momentum distributions of char quarks and D<sup>0</sup> mesons at 2.76 TeV

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

RHIC	$a_0$	$a_1$	$a_2$	$a_3$	$a_4$	$a_5$
$p_T \leq p_0$	0.69	1.22	1.57			
$p_T \geq p_0$	1.08	3.04	0.71	3.79	2.02	3.48
LHC	$a_0$	$a_1$	$a_2$	$a_3$	$a_4$	$a_5$
$p_T \leq p_0$	1.97	0.35	2.47			
$p_T \geq p_0$	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)



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

J. Adam et al. [ALICE Collaboration], JHEP **1603**, 081 (2016)

# Charm-strange meson production by coalescence

- Charm-strange mesons in the coalescence model,  $D_s$ ,  $D_s^*$ ,  $D_{s0}^*(2317)$ ,  $D_{s1}(2460)$

$$\frac{d^2 N_M}{d^2 \vec{p}_T} = \frac{g_M}{V} \int d^3 \vec{r} d^2 \vec{p}_{sT} d^2 \vec{p}_{cT} \delta^{(2)}(\vec{p}_T - \vec{p}_{sT} - \vec{p}_{cT}) \quad W_s(\vec{r}, \vec{k}) = 8e^{-\frac{r^2}{\sigma^2} - k^2 \sigma^2}$$

$$\times \frac{d^2 N_{\bar{s}}}{d^2 \vec{p}_{sT}} \frac{d^2 N_c}{d^2 \vec{p}_{cT}} W_M(\vec{r}, \vec{k}), \quad (2) \quad W_p(\vec{r}, \vec{k}) = \left( \frac{16}{3} \frac{r^2}{\sigma^2} - 8 + \frac{16}{3} \sigma^2 k^2 \right) e^{-\frac{r^2}{\sigma^2} - k^2 \sigma^2}$$

- Transverse momentum distributions

$$\frac{d^2 N_M}{d^2 \vec{p}_T} = \frac{g_M}{V} (2\sqrt{\pi}\sigma)^3 \int d^2 \vec{p}_{sT} d^2 \vec{p}_{cT} e^{-\sigma^2 k^2}$$

$$\times \delta^{(2)}(\vec{p}_T - \vec{p}_{sT} - \vec{p}_{cT}) \frac{d^2 N_s}{d^2 \vec{p}_{sT}} \frac{d^2 N_c}{d^2 \vec{p}_{cT}},$$

$$\frac{d^2 N_M}{d^2 \vec{p}_T} = \frac{g_M}{V} (2\sqrt{\pi}\sigma)^3 \int d^2 \vec{p}_{sT} d^2 \vec{p}_{cT} \frac{2}{3} \sigma^2 k^2 e^{-\sigma^2 k^2}$$

$$\times \delta^{(2)}(\vec{p}_T - \vec{p}_{sT} - \vec{p}_{cT}) \frac{d^2 N_{\bar{s}}}{d^2 \vec{p}_{sT}} \frac{d^2 N_c}{d^2 \vec{p}_{cT}}, \quad ($$

$$\frac{d^2 N_{D_{s0}^*(2317)}}{d^2 \vec{p}_T} = \frac{g_{D_{s0}^*(2317)}}{V^3} (2\sqrt{\pi})^9 (\sigma_1 \sigma_2 \sigma_3)^3$$

$$\times \int d^2 \vec{p}_{qT} d^2 \vec{p}_{\bar{q}T} d^2 \vec{p}_{cT} d^2 \vec{p}_{sT}$$

$$\times \frac{d^2 N_q}{d^2 \vec{p}_{qT}} \frac{d^2 N_{\bar{q}}}{d^2 \vec{p}_{\bar{q}T}} \frac{d^2 N_c}{d^2 \vec{p}_{cT}} \frac{d^2 N_{\bar{s}}}{d^2 \vec{p}_{sT}}$$

$$\times \delta^{(2)}(\vec{p}_T - \vec{p}_{qT} - \vec{p}_{\bar{q}T} - \vec{p}_{cT} - \vec{p}_{sT})$$

$$\times \exp\left(-\sigma_1^2 k_1^2 - \sigma_2^2 k_2^2 - \sigma_3^2 k_3^2\right), \quad (15)$$

# – 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. ( $L$ )	$\omega_{\text{Mol}}$ [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				
$D_s(2317)$	$2.3 \times 10^{-2}$	$2.4 \times 10^{-3}$	$6.5 \times 10^{-3}$	$6.6 \times 10^{-2}$
LHC (2.76 TeV)				
$D_s(2317)$	$5.2 \times 10^{-2}$	$4.3 \times 10^{-3}$	$1.4 \times 10^{-2}$	$1.5 \times 10^{-1}$
LHC (5.02 TeV)				
$D_s(2317)$	$6.5 \times 10^{-2}$	$5.4 \times 10^{-3}$	$1.8 \times 10^{-2}$	$1.9 \times 10^{-1}$

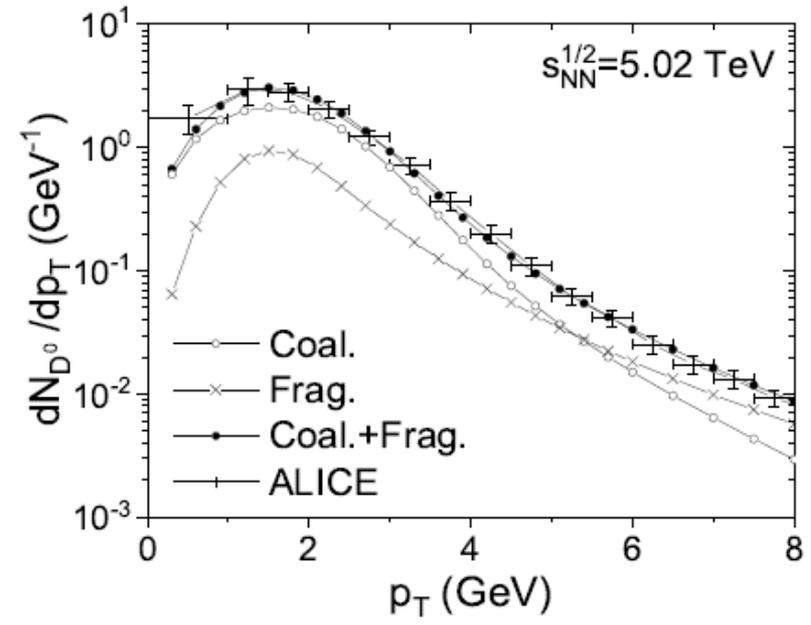
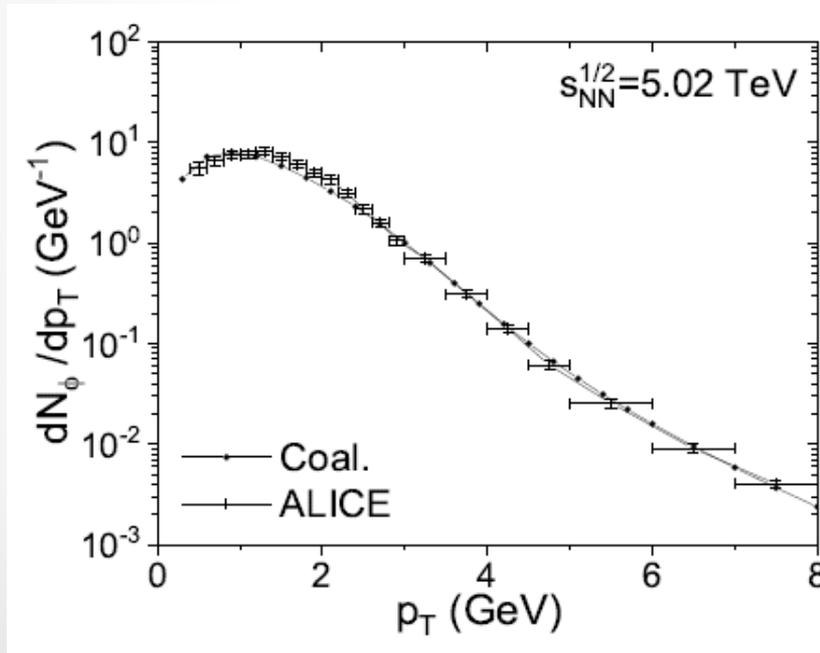


# – Transverse momentum distributions of charm and strange quarks at 5.02 TeV

$$\frac{d^2 N_c}{d^2 \vec{p}_{cT}} = \begin{cases} c_1 e^{-c_2 \left(\frac{p_{cT}}{p_{0T}}\right)^{c_3}} & p_{cT} \leq p'_{cT} \\ c_4 e^{-c_5 \left(\frac{p_{cT}}{p_{0T}}\right)^{c_6}} + \frac{c_7}{\left(1.0 + \left(\frac{p_{cT}}{p_{0T}}\right)^{c_8}\right)^{c_9}} & p_{cT} > p'_{cT} \end{cases}$$

$c_1$ (GeV <sup>-2</sup> )	$c_2$	$c_3$	$c_4$ (GeV <sup>-2</sup> )	$c_5$
1.63	0.27	2.03	7.95	3.49
$c_6$	$c_7$ (GeV <sup>-2</sup> )	$c_8$	$c_9$	$p'_{cT}$ (GeV)
3.59	90112	0.50	14.19	1.80

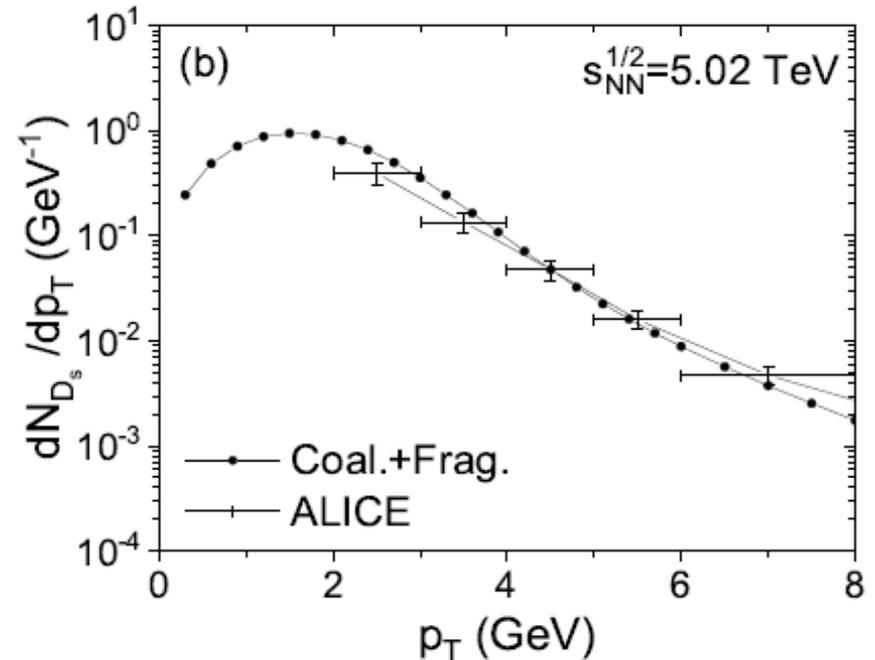
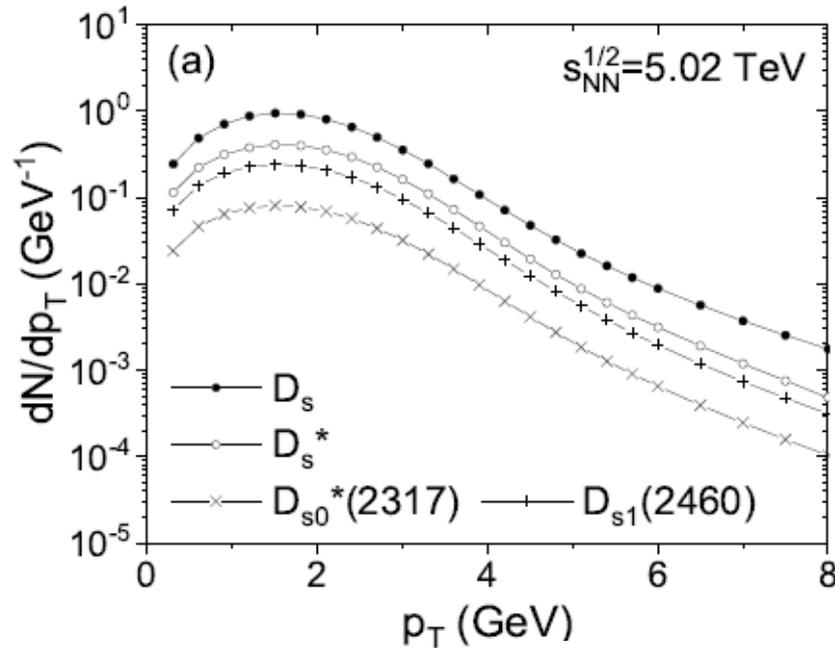
S. Cho and S. H. Lee, arXiv:2510.18673



S. Acharya et al. [ALICE Collaboration], Phys. Lett. B **802**, 135225 (2020)

S. Acharya et al. [ALICE Collaboration], JHEP **01**, 174 (2022)

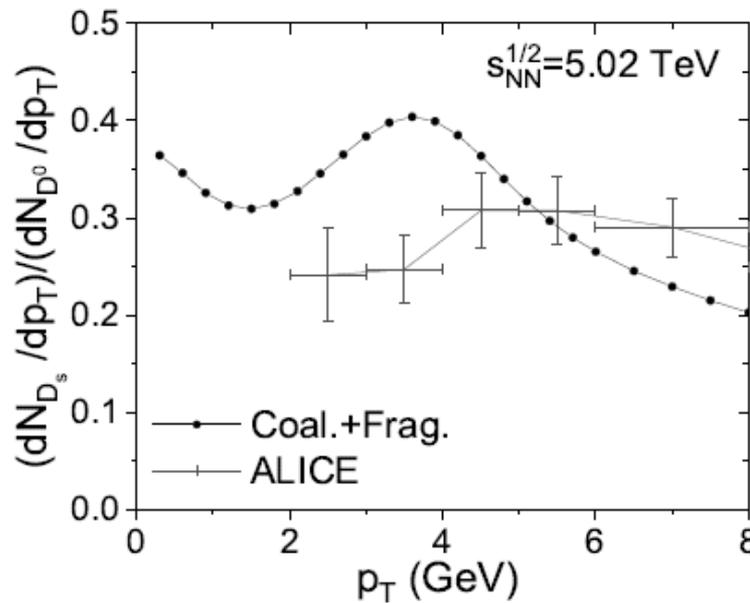
# – Transverse momentum distributions and yields of charm-strange mesons



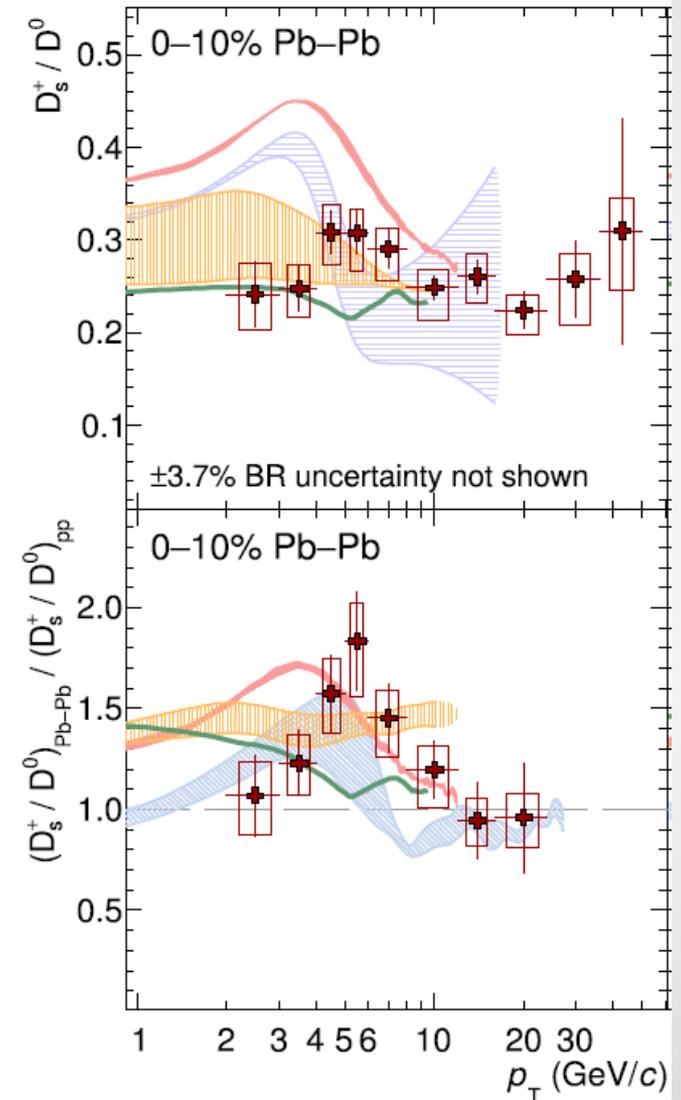
Yields	Coal.	ALICE	SHMc
$\phi^{all}$	14.3	14.937 [31]	
$D^{0all}$	6.54	6.819 [41]	6.42 [36]
$D_s$	0.321		
$D_s^*$	0.963		
$D_{s0}^*(2317)$	0.192		
$D_{s1}(2460)$	0.576		
$D_s^{all}$	2.18	1.89 [42]	2.22 [36]

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

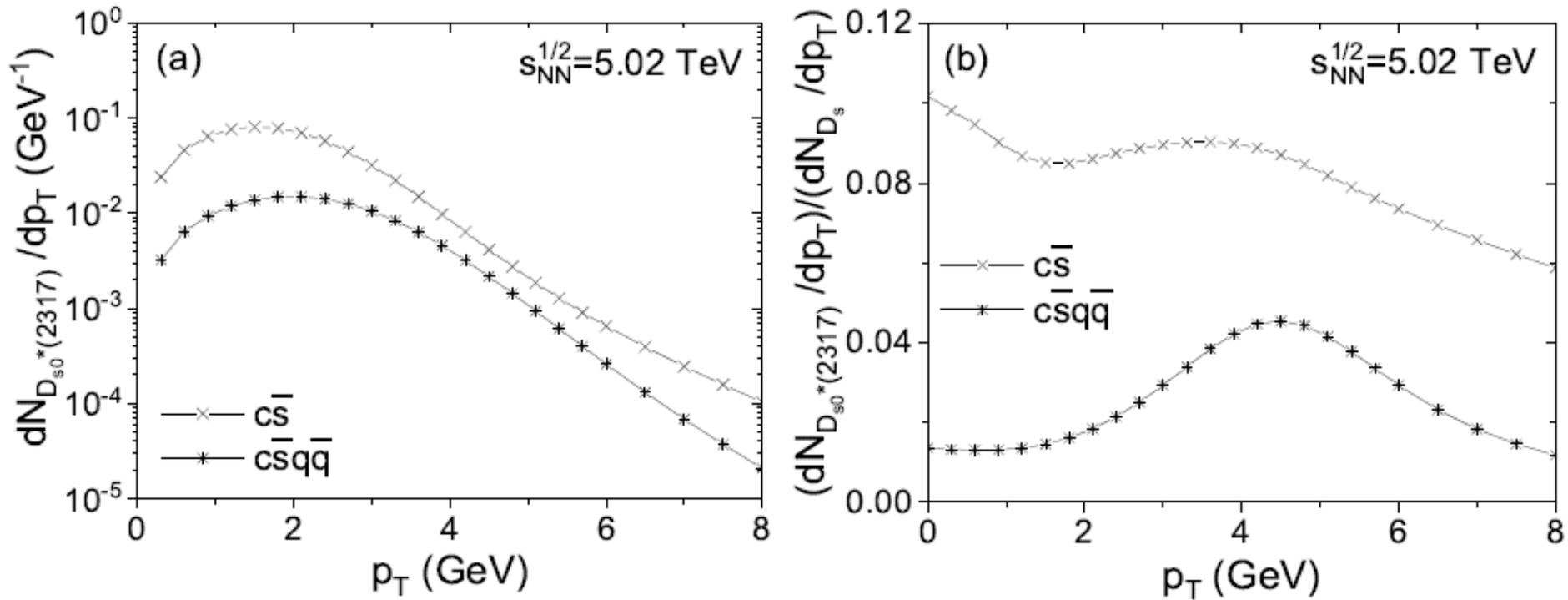
# – Transverse momentum distribution ratio between $D^0$ and $D_s$ mesons



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



# – Transverse momentum distributions of $D_{s_0}^*(2317)$ mesons in two- and four-quark states



Yields	Ther.	$c\bar{s}$	$c\bar{s}q\bar{q}$	Mol.
Coal.	0.180	0.192	0.0419	
ExHIC [8]	0.19	0.064	0.0057	0.018

# Conclusion

- Production of Charm-strange mesons at  $\sqrt{s} = 5.02$  TeV in heavy ion collisions
- 1) Studying the production of charm-strange mesons can help us understand in more detail the hadron production mechanism as well as the strangeness enhancement in heavy ion collisions
- 2) It is essential to consider the production of  $D_s^*$ ,  $D_{s0}^*(2317)$ , and  $D_{s1}(2460)$  mesons in order to understand the yield or transverse momentum distribution  $D_s$  mesons
- 3) Heavy ion collision experiments can provide chances to identify the internal structure of  $D_{s0}^*(2317)$  mesons
- 4) Many more studies are expected; stay tuned for new results soon



Thank you for your attention!