

Open Charm Production in High Energy Collisions: New Insights from Statistical Thermal Approaches



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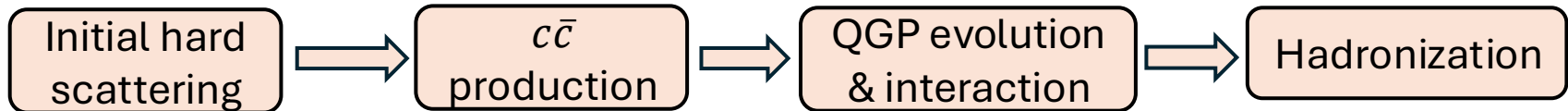
Motivation

- Charm-quark mass ($m_c \sim 1.3 \text{ GeV}/c^2$) provides a hard scale well above QCD scale (Λ_{QCD})

$$m_c \gg \Lambda_{QCD}$$

→ Charm production can be described using perturbative QCD.

- Charm quarks are predominantly produced in initial hard scatterings, before the QGP is formed.
 - Experience the entire evolution of the QGP.
 - Act as heavy probes that retain information about their interaction history with the medium.



- Charm quarks hadronized with other light flavour hadrons at the common chemical freeze-out
→ Statistical Hadronization Model for charm (SHMc) can be used.

SHM for charm (SHMc)

Charm balance equation: No. of initially produced $c\bar{c}$ pairs is related to produced charm hadrons by the relation:

$$N_{c\bar{c}} = \frac{1}{2} g_c V \sum_{h_{oc,1}^i} n_i^{th} + \frac{1}{2} g_c^2 V \sum_{h_{oc,2}^k} n_k^{th} + g_c^2 V \sum_{h_{hc}^j} n_j^{th}$$

Here,

- $n_{i,j,k}^{th}$ -- thermal densities of open and hidden charm hadrons
- $h_{oc,1(2)}^i$ -- open charm hadron with one (two) valence charm quark(s)
- h_{hc}^j -- the hidden charm states
- g_c -- fugacity factor guarantees conservation of no. of $c\bar{c}$ pairs
- V -- hadronization volume per unit rapidity of the fireball.

A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nucl. Phys. A 789 (2007) 334.

SHM for charm (SHMc)

Rapidity density of charm hadrons:

- For small $N_{c\bar{c}}$, the canonical corrections has to be included
- Rapidity density of $c\bar{c}$ pairs :

$$\frac{dN_{c\bar{c}}}{dy} = \frac{1}{2} \sum_{\alpha=1,2} \frac{I_{\alpha}(N_{oc,1})}{I_0(N_{oc,1})} \frac{dN_{oc,\alpha}}{dy} + \frac{dN_{hc}}{dy}$$

- Rapidity density of open charm hadron with $|c| = 1$ is :

$$\frac{dN_{oc,1}^i}{dy} \approx 2 \frac{n_{th}^i}{n_{oc,1}^{tot}} \frac{dN_{c\bar{c}}}{dy}$$

→ Rapidity density of all open charm hadron scales with no. of $c\bar{c}$ produced in the initial hard scatterings.

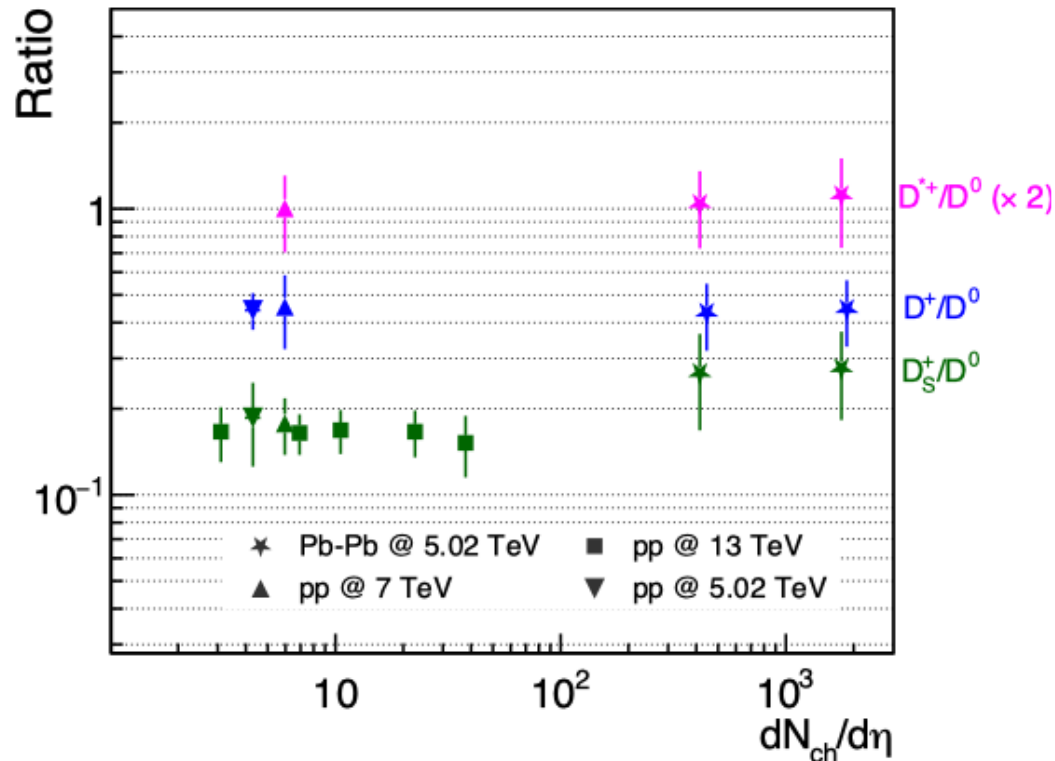
→ For a given $N_{c\bar{c}}$ and knowing T, V from thermal analysis of light hadron yields, we can predict densities of open charm hadrons using SHMc.

SHM for charm (SHMc)

- Statistical Hadronization model THERMUS is used.
- Implemented additional known charmed baryon resonances from 2022 PDG.
- Fixed parameters:
 - $T_{\text{ch}} = 156.5 \text{ MeV}$,
 - $\mu_B = \mu_Q = \mu_S = 0$ and
 - $\gamma_S = 1$
- Particle densities is given as: $n_i^{th} = n_i^p + \sum_j BR(j \rightarrow i)n_j^r$

D-mesons to D^0 ratios

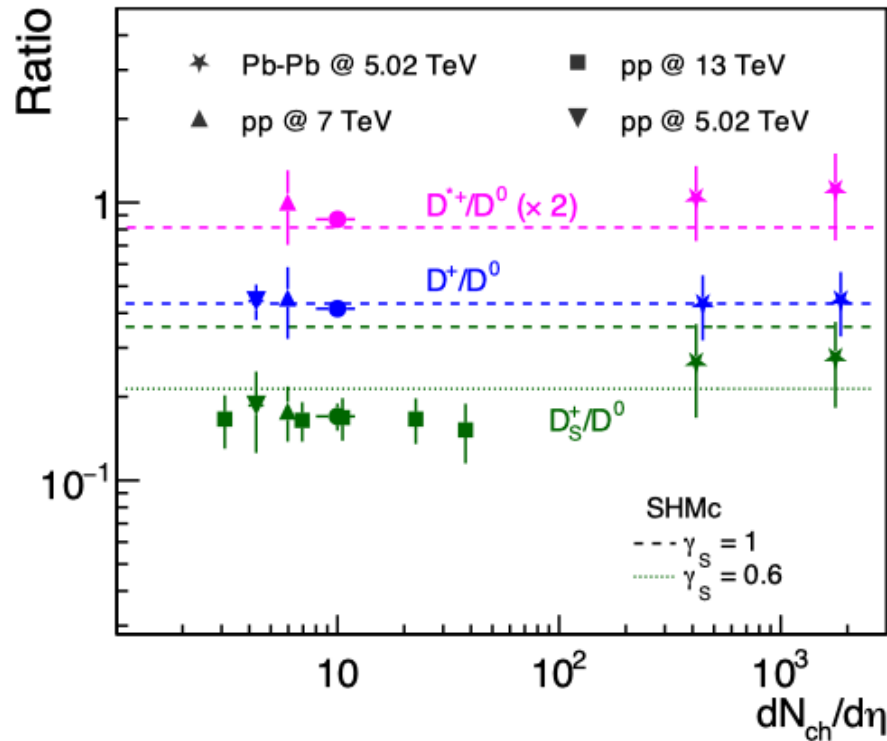
	D^0	D^+	D^{*+}	D_s^+
Quark content	$c\bar{u}$	$c\bar{d}$	$c\bar{d}$	$c\bar{s}$
Rest mass (GeV/c ²)	1.864	1.869	2.010	1.968
Spin (J)	0(scalar)	0(scalar)	1(vector)	0(scalar)
Decay channel	$D^0 \rightarrow K^-\pi^+$	$D^+ \rightarrow K^-\pi^+\pi^+$	$D^{*+} \rightarrow D^0\pi^+$	$D_s^+ \rightarrow K^+K^-\pi^+$



Experimental data:

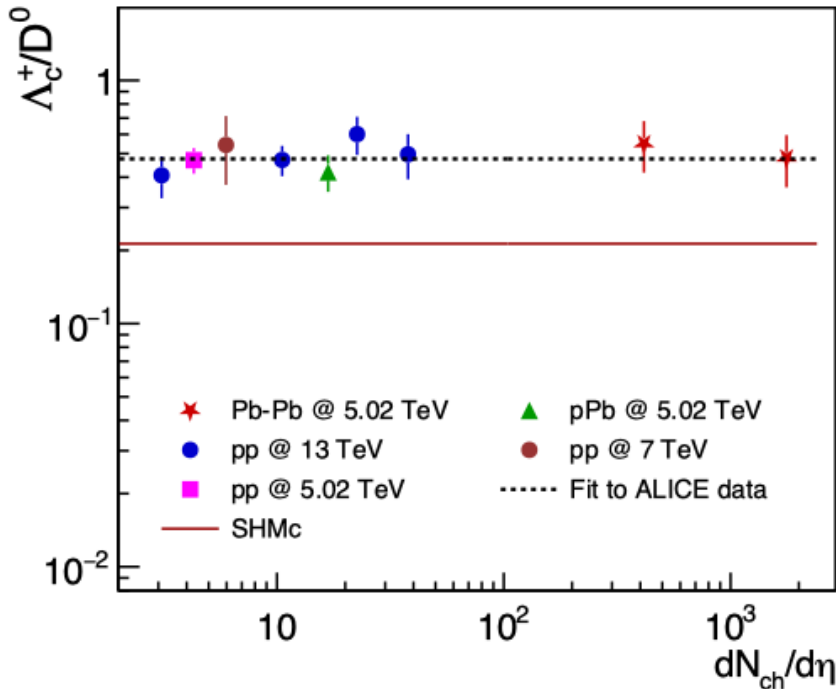
- $\frac{D^+}{D^0}$ and $\frac{D^{*+}}{D^0}$ -- constant as a function of produced charge particle multiplicity
 → Independent of collisions system size and energy
- $\frac{D_s^+}{D^0}$ remains constant for lighter systems; shows increase for heavy-ion colliding system

Comparison with SHMc



- $\frac{D^+}{D^0}$ and $\frac{D^{*+}}{D^0}$: SHMc model is able to explain the ratios for all systems and energies.
- $\frac{D_S^+}{D^0}$: SHMc model is consistently higher for lighter systems and explains HIC
- consistent with strangeness canonical suppression in lighter systems

Λ_c^+ to D^0 ratio

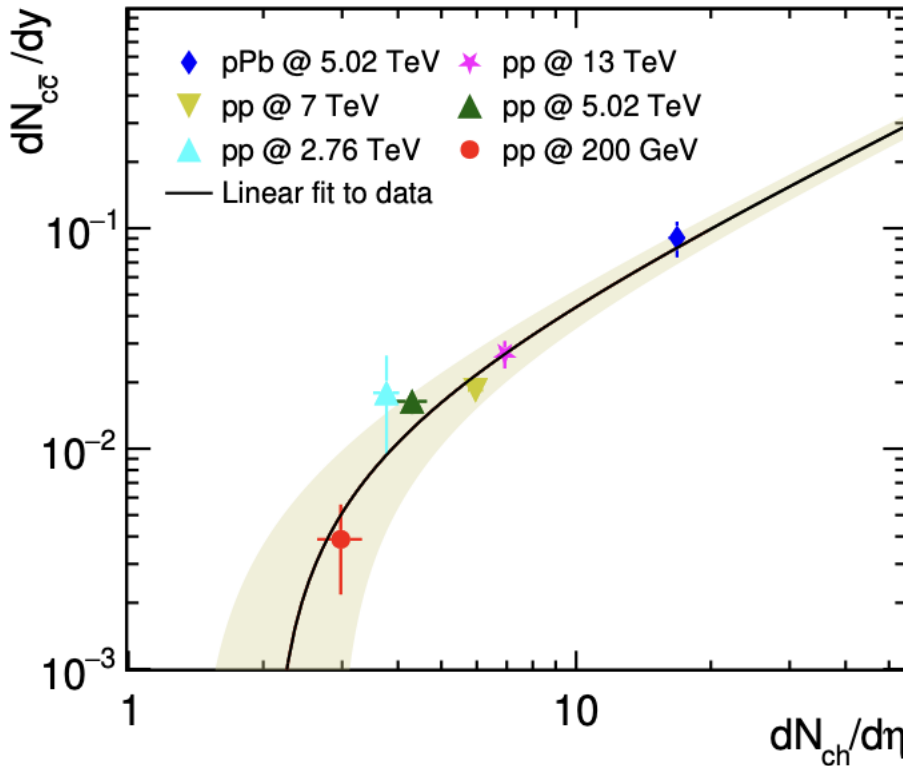


	Λ_c^+
Quark content	udc
Rest mass (GeV/c ²)	2.286
Decay channels	$pK_s^0, pK^-\pi^+ \dots$

- $\frac{\Lambda_c^+}{D^0}$ ratio remains constant -> independence of colliding system size and energies
- SHMc underpredicts ratio – could be due to the missing charmed-baryon resonances contributions to Λ_c^+ in model

- Possible contribution from unknown resonances:
- Rescaled the SHMc predictions for Λ_c^+ to match the data
 - Rescaling factor ~ 2.2 – may be effective contribution of unknown resonances

$c\bar{c}$ production as a function of multiplicity



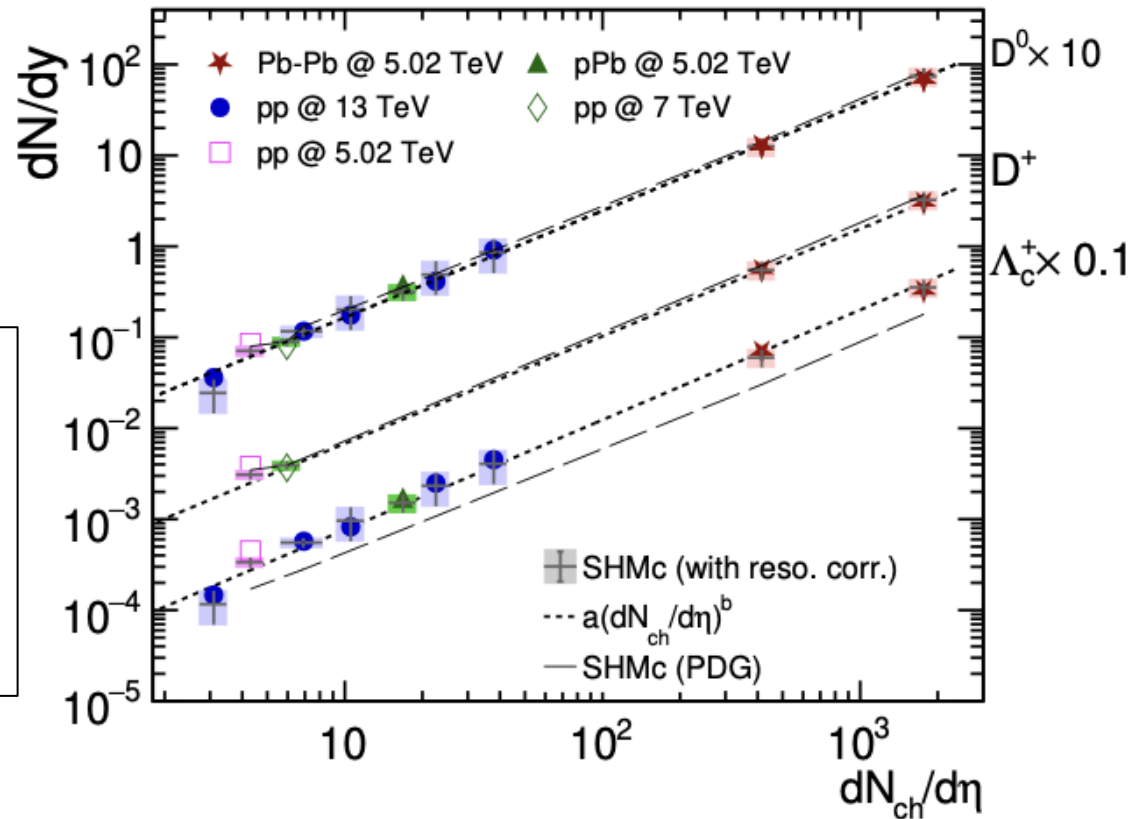
$$N_{c\bar{c}} = \begin{cases} \frac{\sigma_{c\bar{c}}^{pp}}{\sigma_{inel}^{pp}} & \text{in } pp \\ \alpha_A \sigma_{c\bar{c}}^{pp} T_{AA} & \text{in } AA \end{cases}$$

- With increasing energy total charm production cross-section increases strongly.
- Rapidity densities of $c\bar{c}$ pair follow the power-law scaling with $dN_{ch}/d\eta$
- Fit function is used to extract $N_{c\bar{c}}$ value where $\sigma_{c\bar{c}}^{pp}$ are unmeasured
 $\rightarrow N_{c\bar{c}}$ value for different multiplicity in pp collisions at 13 TeV.

Open charm hadrons yield comparison

$$\frac{dN_i}{dy} = 2 \frac{n_i^{th}}{n_{oc,1}^{tot}} \frac{dN_{c\bar{c}}}{dy}$$

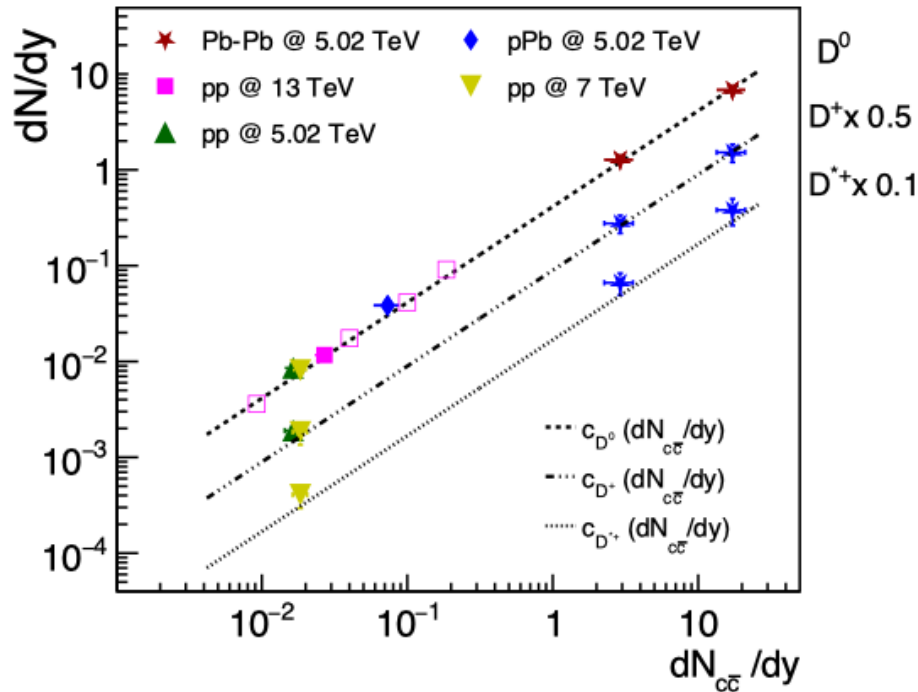
- Yields follow, within uncertainties, the power-law scaling with $dN_{ch}/d\eta$ with a common slope parameter for all particle species ($b \sim 1.2$)



- Data is in agreement with SHMc predictions including resonance correction.

Open charm production as a function of $N_{c\bar{c}}$

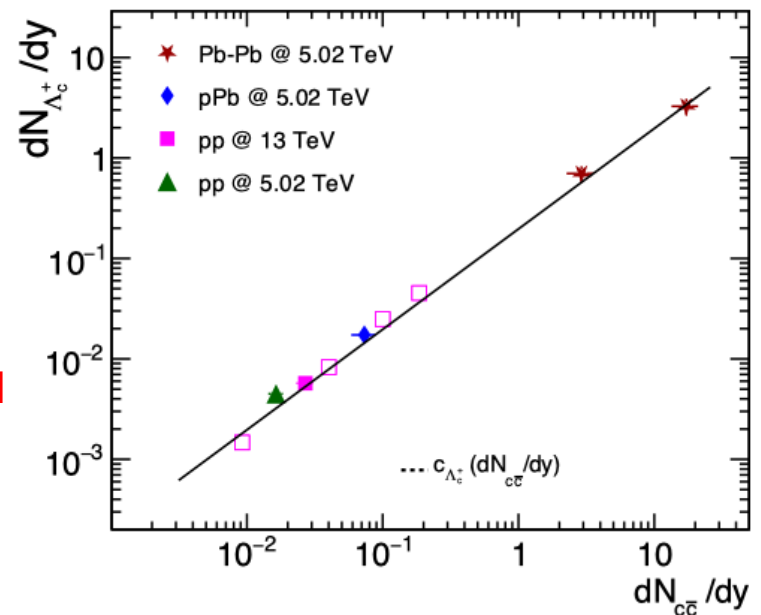
D-Mesons



x-axis open symbols predicted

- Open charm production yield follow within uncertainties the proportional scaling with $N_{c\bar{c}}$

Λ_c^+ baryon



- D-mesons and Λ_c^+ baryon yields scale with initially produced $c\bar{c}$ pairs.
- The proportionality coefficients corresponds to the thermal density ratios calculated using SHMc.

Summary

- SHMc provides a good description of open charm hadrons carrying charm quantum-number $|c| = 1$.
- Open charm production scales in leading order with total charm production cross-section independent of collision energy and colliding systems.
- Rapidity density of charm-anticharm quark pairs exhibits a power-law scaling with the produced charged-particle pseudo-rapidity density.
- Open charm mesons D^0 , D^+ , and D^{*+} -- slope coefficient is quantified by the appropriate thermal density ratio calculated in the SHMc at the chiral crossover temperature, $T_c = 156.5$ MeV.

Acknowledgement

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- **I sincerely thank the ALICE Collaboration** for producing and publishing beautiful, high-quality data that enable us to explore and unravel the hidden mysteries of nature.
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Peter at 80: A Great Physicist, Mentor & Inspiration

My memories and Gratitude:

- ✓ **Peter:** An exceptional **physicist**, a **great leader**, and a **wonderful mentor**.
- ✓ **First interaction in 2008-09:** At GSI, plotted anti-nuclei over nuclei ratio vs p_T → Observed the annihilation effect for the 1st time using the ALICE TPC.
- ✓ **Extremely helpful and supportive:** Grateful for his recommendation that helped me secure my first permanent position.
- ✓ **Privileged to have collaborated with Peter and Johanna:** opportunity to learn from both of them -- not only about physics, but also about being a good mentor and colleague.
- ✓ **Remarkable memory and passion for physics:** I am always amazed. He could recall papers published decades ago – even their publication period and key findings.



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Thank you for
your attention!