이학박사학위 논문

ALICE에서 수행한 양성자-양성자 충돌에서의 매력쿼크를 포함한 중입자의 생성량과 매력쿼크 붕괴 비율 측정

Charm baryon production and fragmentation fractions in pp collisions with ALICE

2023년 2월

인하대학교 대학원

물리학과

서 진 주

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지도교수 권 민 정

이 논문을 박사학위 논문으로 제출함

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CHARM BARYON PRODUCTION

Charm baryon production and fragmentation fractions in pp collisions with ALICE

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Abstract

The measurements of Λ_c^+, $\Xi_c^{0,+}$, $\Sigma_c^{0,++}$, and the first measurement of Ω_c^0 baryons performed with the ALICE detector at midrapidity in pp collisions at $\sqrt{s} = 5.02$ and $13\,\mathrm{TeV}$ were measured. Also, the first measurements of the total charm cross section at midrapidity and the fragmentation fractions at midrapidity in pp collisions at the LHC including the charm baryons were measured. The charm fragmentation fractions in pp collisions at $\sqrt{s}$ = 5.02 TeV were measured for the first time, showing that charm fragmentation was not universal across collision systems.

Keywords: Heavy-Ion Collisions, Quark-gluon plasma,

Heavy quark, Charm quark, Charmed baryon

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Chapter 1

Introduction

1.1 Scientific motivation

1.1.1 Quark Gluon Plasma

The Standard Model of particle physics describes the fundamental constituents of matter and the laws governing their interactions. It also accounts for how collective phenomena and equilibrium properties of matter arise from elementary interactions. Theory makes quantitative statements about the equation of state of Standard Model matter, about the nature of the electroweak and strong phase transitions, and about the fundamental properties such as transport coefficients and relaxation times. In addition, there has been considerable theoretical progress in describing how out-of-equilibrium evolution drives non-abelian matter towards equilibrium. Collisions of nuclei at ultra-relativistic energies offer a unique possibility for testing some key facets of the rich high-temperature thermodynamics of the Standard Model in laboratory-based experiments. They test the strong interaction sector of the Standard Model at energy densities at which partonic degrees of freedom dominate equilibration processes. They thus give access to the partonic dynamics that drives fundamental non-abelian matter towards equilibrium and that determines the properties of the QCD high temperature phase, the Quark Gluon Plasma [1, 2].

The field of ultra-relativistic nuclear collisions has seen enormous progress since the mid-eighties, from the first signals of colour deconfinement at the SPS to the evidence, at RHIC, for a strongly-coupled QCD medium that quenches the momenta of hard partons [3]. Nuclear collisions at the LHC offer an almost ideal environment for a broad programme of characterization of the properties of this unique state of matter [4]. Besides providing access to the highest-temperature, longest-lived experimentally accessible QCD medium, they also provide an abundant supply of self-calibrating heavy-flavour probes. In addition, the very low net baryon density eases the connection between experimental measurements and lattice QCD calculations significantly [5].

1.1.2 Heavy quark hadronisation

Measurements of heavy-flavour hadron production in high energy proton–proton (pp) collisions provide important tests of QCD. The cross sections of heavy-flavour hadrons are usually computed using the factorisation approach as a convolution of three factors [6] the parton distribution functions (PDFs) of the incoming protons, ii) the hard-scattering cross section at partonic level, and iii) the fragmentation function of heavy quarks into a given heavy-flavour hadron. The D- and B-meson cross sections in pp collisions at several centre-of-mass energies at the LHC [7, 8, 9] are described within uncertainties by perturbative QCD (pQCD) calculations [10, 11, 12, 13, 14], which use fragmentation functions tuned on $\mathrm{e^+e^-}$ data, over a wide range of transverse momentum (p_T). Measurements of Λ_c^+-baryon production at midrapidity in pp collisions at the centre-of-mass energy $\sqrt{s} = 5.02$ and 7 TeV were reported by the ALICE and CMS collaborations in Refs. [15, 16, 17]. The measured $\Lambda_\mathrm{c}^+/\mathrm{D}^0$ ratio is higher than previous measurements in $\mathrm{e^+e^-}$ [18, 19, 20] and $\mathrm{e^-p}$ [21, 22] collisions, suggesting that charm-hadronisation mechanisms are different in pp collisions at LHC energies. A similar observation was drawn from the measurement of the inclusive Ξ_c^0-baryon production at midrapidity in pp collisions at $\sqrt{s} = 7$ TeV [23]. The charm-baryon cross sections measured in pp collisions are larger than next-to-leading order pQCD-based calculations [14], and larger than expectations from various event generators, namely POWHEG matched to PYTHIA 6 for the parton-shower and the hadronisation stages with Perugia tune [24], PYTHIA 8 with Monash tune [25], and HERWIG 7 [26]. On the other hand, PYTHIA 8 tunes including string formation beyond the leading-colour approximation [27] qualitatively describe the measured $\Sigma_c^{0,+,++}/D^0$ and Λ_c^+/D^0 cross section ratios [28, 17], but underestimate the Ξ_c^0/D^0 ratio [23]. A statistical hadronisation model (SHM) [29] based on the charmed hadron states listed by the Particle Data Group (PDG) [30] underestimates the Λ_c^+/D^0 ratio. However this ratio is qualitatively described by the SHM when the presence of a large set of yet-unobserved higher-mass charm-baryon states is assumed in the calculation as prescribed by the relativistic quark model (RQM) and from lattice QCD [31, 32]. The observed enhancement of the charm-baryon production can also be explained by model calculations considering hadronisation of charm quarks via coalescence in pp collisions [33]. The increased yield of charm baryons makes it mandatory to include their contribution for an accurate measurement of the $c\bar{c}$ production cross section in pp collisions at the LHC [34] and further provide evidence that the assumption of universality (colliding-system independence) of parton-to-hadron fragmentation is not valid.

Chapter 2

Method

2.1 Experimental setup

2.1.1 ALICE Experiment

A description of the ALICE detector2.1 and its performance are reported in Refs. [35, 36]. The data used for these analyses were recorded with a minimum-bias trigger, based on coincident signals in the two scintillator arrays (V0) located on both sides of the interaction vertex. Offline selections, based on the V0 and Silicon Pixel Detector signals [3], were applied to remove background from beam–gas collisions. Pile-up events (less than 1%) containing multiple primary vertices were rejected. Only events with a reconstructed primary vertex position within ± 10 cm in the longitudinal direction from the nominal centre of the detector were used. With these requirements, 1.9×10^9 pp events were selected, corresponding to an integrated luminosity of $\mathcal{L}_{\text{int}} = 32.95 \pm 1.65\ \text{nb}^{-1}$.

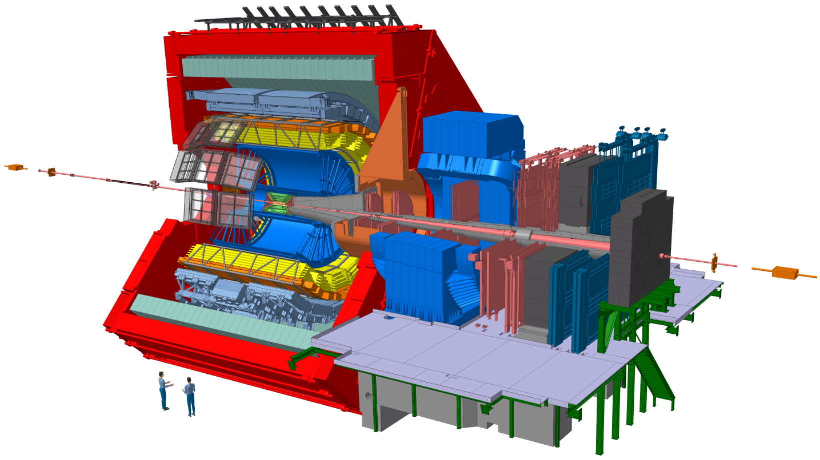

Figure 2.1: *ALICE detector*

Chapter 3

Results

3.1 Charm baryon production

3.1.1 $\Lambda_c^+$and $\Sigma_c^{0,++}$ measurements

ALICE has measured all single-charm hadron ground states in pp collisions, including charm mesons (D^0, D^+, D_s^+) at $\sqrt{s}$ = 5.02 TeV [8] and charm baryons (Λ_c^+, $\Xi_c^{0,+}$ and Ω_c^0) at $\sqrt{s}$ = 5.02 TeV and $\sqrt{s}$ = 13 TeV [17, 37]. In addition, ALICE measured Λ_c^+in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02\,\mathrm{TeV}$ down to $p_{\rm T}$= 0.

The Λ_c^+/D^0 ratios in pp and p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02\,\mathrm{TeV}$ are shown in the Fig.3.1. At low $p_{\rm T}$, the Λ_c^+/D^0 ratio measured in p–Pb collisions was significantly lower than in pp collisions, and at intermediate p_{T}, the $\Lambda_{\mathrm{c}}^{+}/\mathrm{D}^{0}$ ratio measured in p–Pb collisions was higher with respect to the one measured in pp collisions. This modification can be interpreted as due to the radial flow or additional hadronisation process in p–Pb collisions.

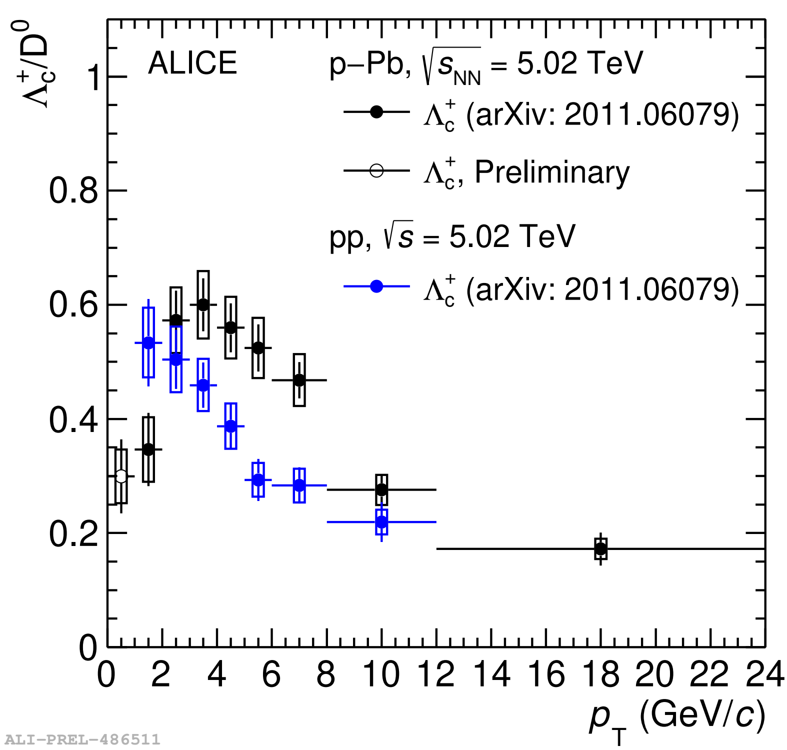

Figure 3.1: $\Lambda_{\mathrm{c}}^{+}/D^{0}$ *as a function of* p_{T}*in pp and p–Pb collisions at* $\sqrt{s}$ = *5.02 TeV* .

The $\Sigma_{\mathrm{c}}^{0,++}$ /D^{0} ratio measured in pp collisions at $\sqrt{s}$ = 13 TeV is shown in the Fig.3.2. The model calculation from PYTHIA8 Monash [25] largely underestimates the measurement, the statistical hadronisation model

(SHM) with excited charm baryon states predicted by the relativistic quark model (RQM) [38] can describe the measurement within uncertainties. The model calculations of Catania [39] and quark (re-)combination mechanism (QCM) [33] both including the coalescence process, also can describe the measurement. In general, PYTHIA8 implemented colour reconnection beyond the leading-colour approximation (CR-BLC) [27] better describes the Λ_c^+/D^0 ratio and $\Sigma_c^{0,++}$ /D^0 ratio, which do not contain the strange quarks.

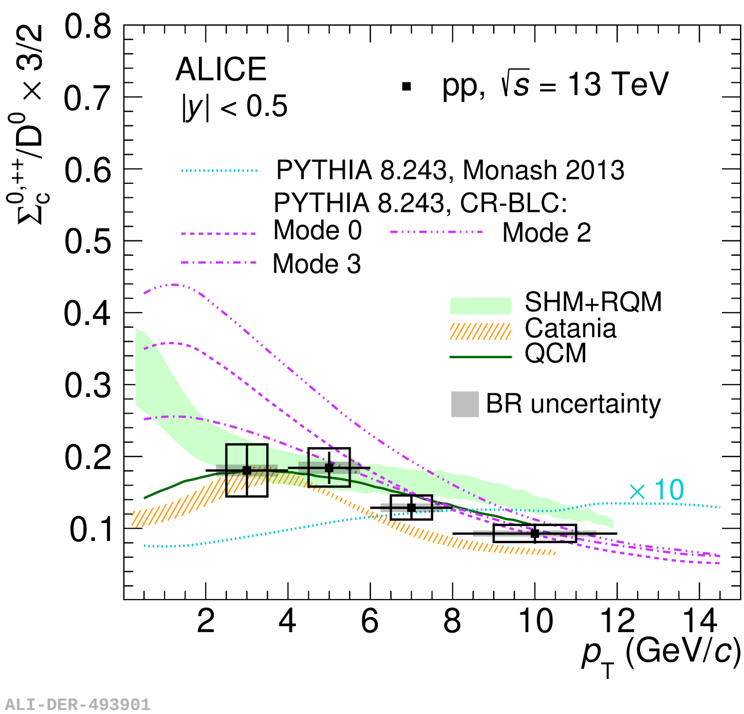

Figure 3.2: $\Sigma_c^{0,++}/D^0$ *ratio as a function of* p_T*at* $\sqrt{s}$ *= 13 TeV .*

3.1.2 $\Xi_c^{0,+}$ and Ω_c^0 measurements

The Ξ_c^0/D^0 and Ξ_c^+/D^0 ratio are shown in the Fig.3.3. Most of the model calculations significantly underestimate the Ξ_c/D^0 ratio. However, the Catania model describes better the ratios in the measured $p_T$interval. It means that both fragmentation and coalescence processes are important in pp collisions for the hadronisation process.

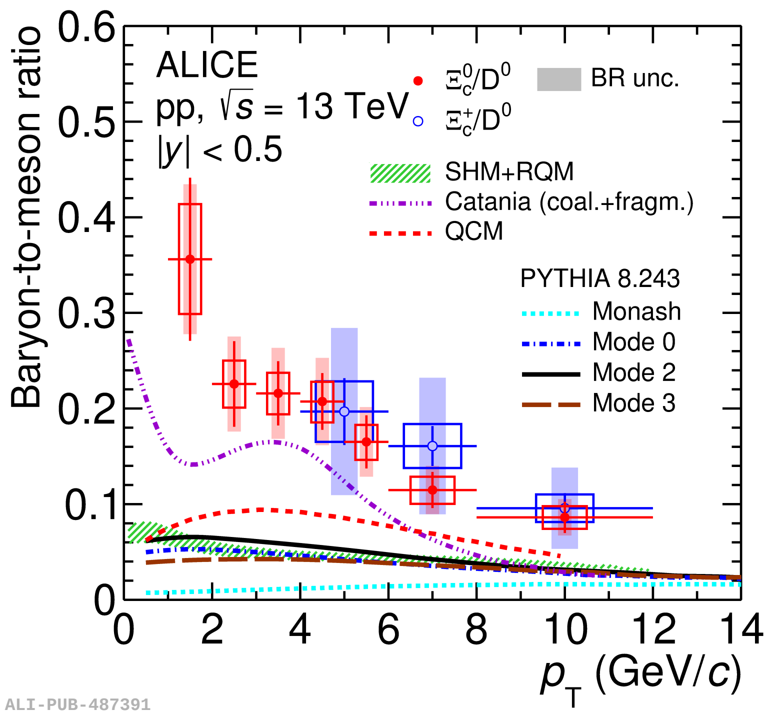

Figure 3.3: Ξ_c^0/D^0 *and* Ξ_c^+/D^0 *ratio as a function of* p_T*at* $\sqrt{s}$ = *13 TeV* .

The $BR(\Omega_c^0 \to \Omega^-\pi^+) \times \sigma(\Omega_c^0)/\sigma(D^0)$ ratio is shown in the Fig.3.4. The branching ratio of $\Omega_c^0 \to \Omega^-\pi^+$ is not measured yet, the theoretical calculation of $BR(\Omega_c^0 \to \Omega^-\pi^+)$ [40] is used to scale the model predictions. Most of the models underestimate the measurements. The Catania model is the calculation that gets closer to the measurements of the Ξ_c^0/D^0 and Ξ_c^+/D^0 ratio and the $BR(\Omega_c^0 \to \Omega^-\pi^+) \times \sigma(\Omega_c^0)/\sigma(D^0)$ ratio.

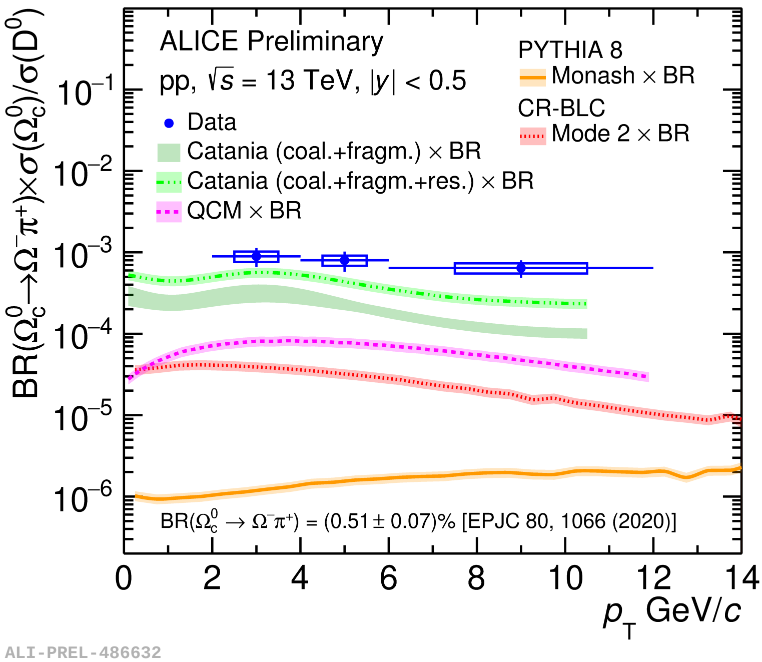

Figure 3.4: *BR*($\Omega_c^0 \to \Omega^-\pi^+$) $\times\Omega_c^0/D^0$ *ratio as a function of* p_T*at* $\sqrt{s}$ = *13 TeV* .

3.2 Charm fragmentation fractions

3.2.1 Charm fragmentation fractions

The charm fragmentation fractions are measured in pp collisions at $\sqrt{s}$ = 5.02 TeV . The numbers are presented in the Table 3.1 The frag-

$\mathrm{H_c}$	$f(c \to \mathrm{H_c})[\%]$
$\mathrm{D^0}$	$39.1 \pm 1.7(\mathrm{stat})^{+2.5}_{-3.7}(\mathrm{syst})$
$\mathrm{D^+}$	$17.3 \pm 1.8(\mathrm{stat})^{+1.7}_{-2.1}(\mathrm{syst})$
$\mathrm{D_s^+}$	$7.3 \pm 1.0(\mathrm{stat})^{+1.9}_{-1.1}(\mathrm{syst})$
Λ_c^+	$20.4 \pm 1.3(\mathrm{stat})^{+1.6}_{-2.2}(\mathrm{syst})$
Ξ_c^0	$8.0 \pm 1.2(\mathrm{stat})^{+2.5}_{-2.4}(\mathrm{syst})$
$\mathrm{D^{*+}}$	$15.5 \pm 1.2(\mathrm{stat})^{+4.1}_{-2.9}(\mathrm{syst})$

Table 3.1: *Charm quark fragmentation fractions into charm hadrons.*

mentation fraction for the Ξ_c^0 baryon is measured for the first time. The contribution of Ξ_c^+ is considered by doubling the Ξ_c^0 yield since they are isospin partners. The Ω_c^0 is not measured at this energy, so the contribution is included in the systematic uncertainty. The charm fragmentation fractions measured in pp collisions are compared with $\mathrm{e^+e^-}$ and ep measurements in the Fig.3.5. The charm fragmentation fractions measured in pp collisions at the LHC are different from the ones measured in $\mathrm{e^+e^-}$ and ep collisions, showing that the universality of parton-to-hadron fragmentation is not valid.

3.2.2 Charm production cross sections

The charm production cross sections at midrapidity per unit of rapidity are shown in the Fig.3.6. The charm cross section per unit of rapidity in pp collisions at $\sqrt{s} = 5.02\,\mathrm{TeV}$ is measured at the LHC for the first

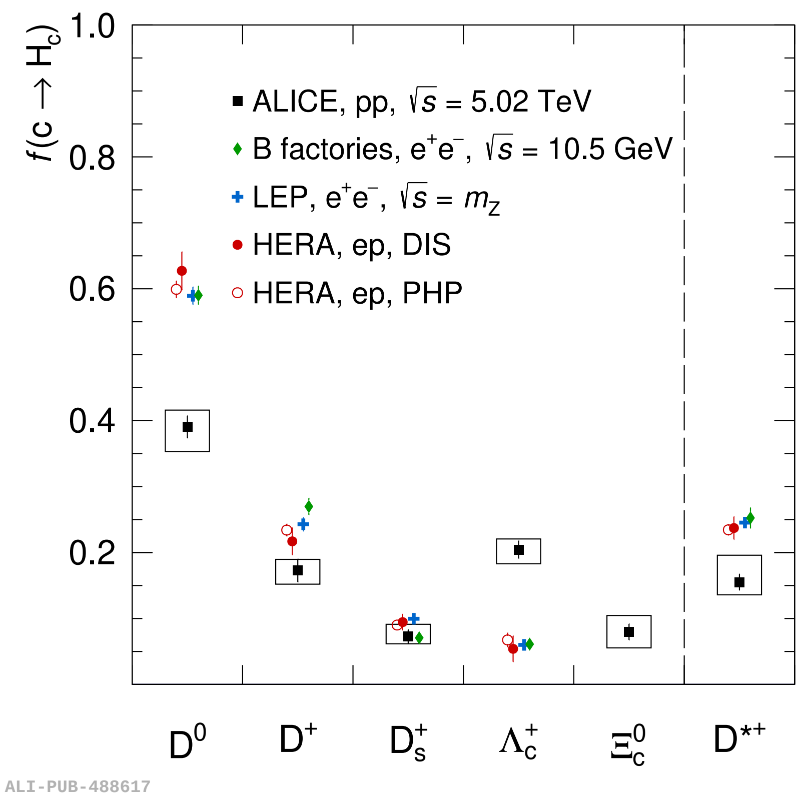

Figure 3.5: *Charm-quark fragmentation fractions into charm hadrons in pp collisions at* $\sqrt{s}$ = *5.02 TeV compared to the measurements in* e^+e^- *and ep collisions.*

time, resulting in the 3.1.

$$\mathrm{d}\sigma^{c\bar{c}}/\mathrm{dy}|^{\mathrm{pp,5.02TeV}}_{|\mathrm{y}|<0.5} = 1165 \pm 44(\mathrm{stat})^{+134}_{-101}(\mathrm{syst})\mu\mathrm{b} \tag{3.1}$$

According to the new measured charm fragmentation fractions, the charm cross section measurements in pp collisions at $\sqrt{s} = 2.76\,\mathrm{TeV}$ [41] and $7\,\mathrm{TeV}$ [42] are updated and are about 40% higher than the previously published results. The measurements with new charm fragmentation fractions lie at the upper edge of the pQCD calculations [12, 43].

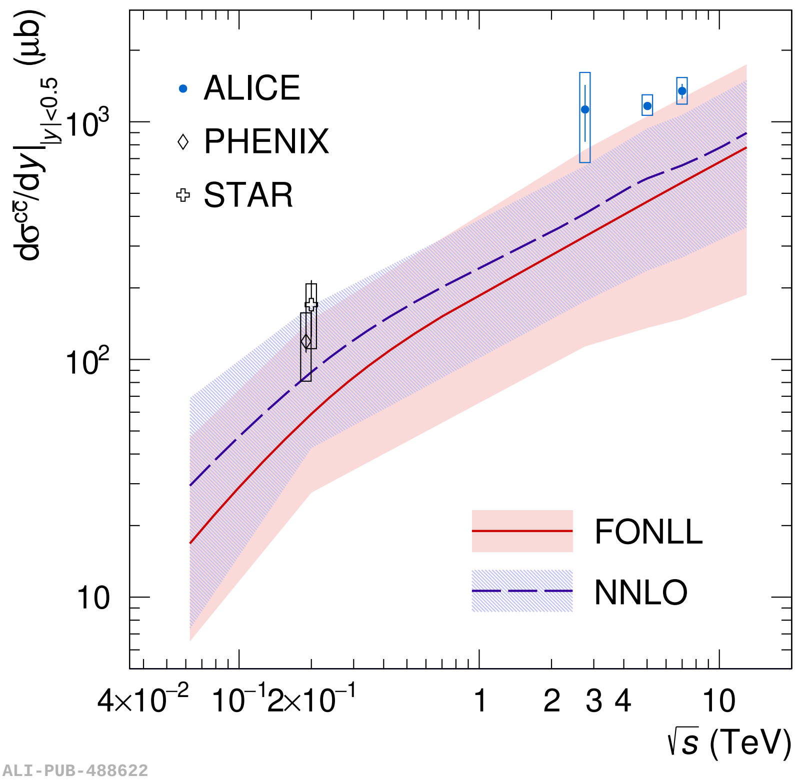

Figure 3.6: *Charm production cross section at midrapidity as function of the collision energy.*

Chapter 4

Summary and Conclusion

ALICE has measured all single-charm hadron ground states in pp collisions at $\sqrt{s}$ = 5.02 TeV and $\sqrt{s}$ = 13 TeV . Large enhancement of all charm baryons was measured in pp collisions with respect to e^+e^- collisions. The charm fragmentation fractions in pp collisions at $\sqrt{s}$ = 5.02 TeV were measured for the first time, showing that charm fragmentation is not universal across collision systems.

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