Charm Hadrons in pp collisions at LHC energy within a Coalescence plus Fragmentation approach

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The recent experimental measurements on pp collisions at $\sqrt{s} = 5.02$ TeV have shown a very large abundance of heavy baryon production corresponding to a ratio of $\Lambda_c/D^0 \sim 0.6$, about one order of magnitude larger than what measured in $e^+e^-$, ep collisions and even in pp collisions at LHC, but at forward rapidity. We apply for the first time to pp collisions a quark coalescence plus fragmentation approach developed for AA collisions, assuming the formation of Hot QCD matter at finite temperature. An approach that has correctly predicted a $\Lambda_c/D^0 \sim O(1)$ in AA collisions at RHIC energy. We calculate the heavy baryon/meson ratio and the pr spectra of charmed hadrons with and without strangeness content: $D^0$, $D_s$, $\Lambda_c^+$, $\Xi_c$ and $\Omega_c$ in pp collisions at top LHC energies, finding a satisfactory result for the measured $\Lambda_c^+/D^0$ and the $\Xi_c/D^0$ without any specific tuning of parameters to pp collisions. At variance with other approaches a coalescence approach predicts also a significant production of $\Omega_c$ such that $\Omega_c/D^0 \sim O(10^{-1})$ .

I. INTRODUCTION

The production of heavy flavored baryons in high energy collisions has become accessible mainly in the last decade in $e^+e^-$\textsuperscript{1}, $e^+p$\textsuperscript{2,3}, and in pp collisions at forward rapidity at LHC energy\textsuperscript{4}. The hadronization and, in particular, the heavy flavour hadronization of HQs in pp collisions is usually described by the traditional fragmentation mechanism. An overall analysis on the charmed hadron production have indicated that the charm fragmentation fraction $f(c \to D^0)$ is about 0.6, while $f(c \to D^+) \simeq 0.25$ with a feed-down from resonances such that $f(c \to D^+) \simeq 0.25$, while the strange charm meson represents only about a $8 - 10\%$ of the production and for the heavy baryon is estimated a fraction of $f(c \to \Lambda_c^+) \simeq 0.06$\textsuperscript{5}. Such an heavy baryon production is similar to the one estimated also by Monte Carlo generators like PYTHIA.

Very recent measurements in pp and pA collisions at top LHC in the mid-rapidity region have shown a surprising large production of the $\Lambda_c$ baryons. Such a production at low $p_T$ corresponds to $\Lambda_c/D^0 \sim 0.5 - 0.6$, at variance with some early observation in pp at large rapidity\textsuperscript{6}. This is nearly an order of magnitude larger than what expected with the traditional fragmentation approach. Furthermore, it has been observed in preliminary results even a significant $\Xi_c$ production with a $\Xi_c/D^0 \sim 0.2 - 0.3$, while the fragmentation approach considers such a production as negligible\textsuperscript{6}.

In AA collisions a large $\Lambda_c$ production, again with $\Lambda_c/D^0 \sim O(1)$, was predicted about ten years ago assuming an hadronization via quark coalescence\textsuperscript{8}, an approach that has been able also to correctly describe several features of the produced hadrons for both light and heavy hadrons\textsuperscript{8,9}. Such a predic-

tion was confirmed by the STAR data in Au + Au at 200 AGeV\textsuperscript{20} and also by the successive measurements by ALICE in Pb + Pb at 5.02 ATeV\textsuperscript{21,22}, with a similar but somewhat reduced $\Lambda_c/D^0$ ratio, as again correctly predicted by a coalescence plus fragmentation approach\textsuperscript{13}.

In ultra-relativistic nucleus-nucleus collisions these results have been justified by the formation of a deconfined matter of quarks and gluons (QGP). The general expectation in elementary pp collision is that a QGP is not created, but above TeV energy have been observed several features similar to those in AA collisions: strangeness enhancement\textsuperscript{23}, the ridge and large collectivity\textsuperscript{24} and enhancement of the baryon to meson ratios\textsuperscript{25,26}. Theoretical studies of these phenomena in small collision systems have observed that hydrodynamics and transport calculations are able to give reasonable description of the $p_T$ spectra and even two-particle correlations\textsuperscript{27-30}, and recently also an approximate quark number scaling of hadron elliptic flows was shown for these collision systems\textsuperscript{31}. This would point to the possible formation of a hot QCD matter at energy density larger than the pseudo-critical one, with a lifetime $\tau \approx 2$ fm/c.

It has to be considered that signatures of hadronization by recombination/coalescence has been spotted even at FNAL in $\pi^- + A$ by the observation that the $D^-/D^+$ ratio at forward rapidity gets close to unity against the fragmentation approach predicting a vanishing ratio. This is also known as “leading particle effect” and is explained as a recombination of the charm with the valence d quark\textsuperscript{32}. This represents a signature that a highly dense quark medium favor an hadronization by quark recombination, in this case with valence quark.

An attempt to explain the large charmed baryon production with respect to the charmed mesons
has been proposed in [32] assuming a statistical hadronization model (SHM) with the inclusion of a large set of charm-baryon states beyond the current listings of the Particle Data Group [34], and reproducing the $D^0$ and $\Lambda_c$, $p_T$-spectra assuming independent fragmentation of charm quarks with the hadronic ratios fixed by the SHM. In such an approach the enhanced feed-down from excited charm baryons can account for the large $\Lambda_c/D^0$ ratio at low $p_T$ as measured by ALICE collaboration. However, the decay of excited charm baryon states proposed have not been seen in the $e^+e^-$ annihilation (Belle [32]). Another approach able to give an enhancement of the $\Lambda_c$ production in $pp$ collision is given by a color reconnection mechanism [30], as recently implemented in PYTHIA 8. It has been shown that this model is consistent with the CMS result for the $\Lambda_c/D^0$ ratio [37], but still seems to fail to reproduce a significant production for higher charmed baryons like $\Xi_c$.

In this Letter, we present results for charm hadron production in $pp$ collisions at top LHC energy assuming a coalescence plus fragmentation approach occurring in a bulk matter according to viscous hydro simulations that have been applied to study the spectra and collectivity in $pp$ collisions [27]. The approach is essentially the same as the one developed for AA collisions to study the spectra and the enhanced baryon over meson ratio for both light and heavy sector [10, 13].

We provide a comprehensive study for the production as a function of the transverse momentum of $D^0$, $D_s$, $\Lambda_c^+$, $\Xi_c$ and also the $\Omega_c$ that will be likely measured in the near future. We also show the details of the feed-down from resonances. We find a quite satisfying description of the available data, including an abundant production for $\Xi_c$. The production of these baryons is larger than color reconnection in PYTHIA8 [38] and also to other hadronization approaches including charm states according to the quark models [33]. An advantage of such an approach is that it could provide a unified description of charm hadron production at low and intermediate $p_T$ in $pp$, $pA$ and $AA$ collisions above the TeV energy scale.

II. HYBRID HADRONIZATION BY

COALESCEENCE AND FRAGMENTATION

The coalescence model was initially proposed as an hadronization mechanism in heavy ion collisions at RHIC energy to explain the $p_T$ spectra and the splitting of elliptic flow of light mesons and baryons [9, 38, 41]. Subsequent works have been devoted to extended the model to include finite width to take into account for off-shell effects [12, 44]. While recently it has been extended to LHC energies to describe mainly the spectra of light hadrons like $\pi, K, p, \phi, \Lambda$ and the baryon to meson ratios at both RHIC and LHC energies [10]. For the HF hadron chemistry in $AA$ collisions, it has been investigated with the coalescence model predicting a large $\Lambda_c/D^0$ [3, 13, 17, 18].

In this section we recall the basic elements of the coalescence model developed in [8, 39, 40, 45] and based on the Wigner formalism. The momentum spectrum of hadrons formed by coalescence of quarks can be written as:

$$
\frac{dN_H}{dy d^2p_T} = g_H \int \prod_{i=1}^{N_q} \frac{d^3p_i}{(2\pi)^3E_i} \cdot d\sigma_i \cdot f_q(x_i, p_i) \delta^{(2)}(P_T - \sum_{i=1}^{n} p_{T,i})
$$

with $g_H$ we indicate the statistical factor to form a colorless hadron from quarks and antiquarks with spin 1/2. The $d\sigma_i$ denotes an element of a space-like hypersurface, while $f_q$ are the quark (anti-quark) phase-space distribution functions for $i$-th quark (anti-quark). Finally $f_H(x_1...x_{N_q}, p_1...p_{N_q})$ is the Wigner function which describes the spatial and momentum distribution of quarks in a hadron. $N_q$ is the number of quarks that form the hadron and for $N_q = 2$ Eq.11 describes meson formation, while for $N_q = 3$ the baryon one. For $D$ mesons the statistical factors $g_D = 1/36$ gives the probability that two random quarks have the right colour, spin, isospin to match the quantum number of the considered mesons. For $\Lambda_c$ the statistical factors is $g_{\Lambda_c} = 1/108$.

Following the Refs. [8, 13, 45] we adopt for the Wigner distribution function a Gaussian shape in space and momentum,

$$
f_H(...) = \prod_{i=1}^{N_q-1} A_W \exp \left( -\frac{x_i^2}{\sigma_{ri}^2} - \frac{p_{ri}^2}{\sigma_{p\gamma}^2} \right)
$$

where $N_q$ is the number of constituent quarks and $A_W$ is a normalization constant that it has been fixed to guarantee that in the limit $p \to 0$ all the charm hadronize by coalescence in a heavy hadron. This is imposed by requiring that the total coalescence probability gives $\lim_{p \to 0} \rho_{col} = 1$. It has been shown, by other studies, that the inclusion of missing charm-baryon states [13] or the variation of the width of the D meson wave function [16, 17], can permit that all the zero momentum charm quarks can be converted to charmed hadrons. The 4-vectors for the relative coordinates in space and momentum $x_{r1}$ and $p_{r1}$ are related to the quark coordinate in space and momentum by the Jacobian transformations. For mesons the relative coordinates ($x_{r1}, p_{r1}$)
are given only by
\[ x_{r1} = x_1 - x_2, \quad p_{r1} = \frac{m_2 p_1 - m_1 p_2}{m_1 + m_2} \]  

while for baryons we have \( x_{r2} \) and \( p_{r2} \) and the others two relative coordinates \( x_{r2}, p_{r2} \) given by
\[ x_{r2} = \frac{m_1 x_1 + m_2 x_2}{m_1 + m_2} - x_3 \]
\[ p_{r2} = \frac{m_3 (p_1 + p_2) - (m_1 + m_2) p_3}{m_1 + m_2 + m_3}. \]

(4)

The \( \sigma_{ri} \) are the covariant widths, they can be related to the oscillator frequency \( \omega \) by \( \sigma_{ri} = 1/\sqrt{\mu_i \omega} \) where \( \mu_i \) are the reduced masses
\[ \mu_1 = \frac{m_1 m_2}{m_1 + m_2}, \quad \mu_2 = \frac{(m_1 + m_2) m_3}{m_1 + m_2 + m_3}. \]

In our calculations the masses of light and heavy quarks have been fixed to \( m_u, d = 300 \text{ MeV}, \ m_s = 380 \text{ MeV}, \ m_c = 1.5 \text{ GeV}. \) The widths of the Wigner function \( f_\mu \) is related to the size of the hadron and in particular to the root mean square charge radius of the hadron, \( \langle r^2 \rangle_{ch} = \sum_{i=1}^{N} Q_i (\langle x_i - X_{cm} \rangle)^2 \) with \( N = 2, 3 \) for mesons and baryons respectively. For mesons, it is given by
\[ \langle r^2 \rangle_{ch} = \frac{3}{2} Q_1 m_1^2 + Q_2 m_2^2 \sigma_r^2 \]
with \( Q_i \) the charge of the \( i \)-th quark and the center-of-mass coordinate calculated as
\[ X_{cm} = \frac{\sum_{i=1}^{N} m_i x_i}{\sum_{i=1}^{N} m_i}. \]

In a similar way to the mesons, the oscillator frequency and the widths for baryons can be related to the root mean square charge radius of the corresponding baryons by
\[ \langle r^2 \rangle_{ch} = \frac{3}{2} m_1^2 Q_1 + m_2^2 Q_2 \sigma_r^2 \]
\[ + \frac{3}{2} m_3^2 (Q_1 + Q_2) \frac{(m_1 + m_2) Q_3}{(m_1 + m_2 + m_3)} \sigma_r^2 \]

In our approach the Wigner function for the heavy mesons have only one parameter \( \sigma \) that we fix in order to have their mean square charge radius. While the Wigner function for Heavy baryons depends on the two widths \( \sigma_{r1} \) and \( \sigma_{r2} \) as shown in Eq.\( \text{[3]} \). However, for baryons there is only one free parameter, because the two widths are related by the oscillator frequency \( \omega \) through the reduced masses by \( \sigma_{pi} = \frac{1}{\sqrt{\mu_i \omega}} \). The mean square charge radius of mesons and baryons used in this work have been taken from quark model \[46, 47\]. The corresponding widths for heavy hadron are shown in Table 1.

The multi-dimensional integrals in the coalescence formula are evaluated by using a Monte-Carlo method, see \[13\] for more details. In these calculations the partons are distributed uniformly in the transverse plane and rapidity \( y_p \).

The hadron momentum spectra from the charm parton fragmentation is given by:
\[ \frac{dN_{had}}{d^2p_T dy} = \sum_z \int d^2z \frac{dN_{fragm}}{d^2p_T dy} \frac{D_{had/c}(z, \langle r^2 \rangle_{ch})}{z^2} \]

\( D_{had/c}(z, \langle r^2 \rangle_{ch}) \) is the fragmentation function and \( z = p_{had}/p_c \) is the momentum fraction of heavy quarks transfered to the final heavy hadron while \( Q^2 = \langle p_{had}/2z \rangle^2 \) is the momentum scale for the fragmentation process.

In our calculations we have applied a commonly used fragmentation function for heavy quarks, that is the Peterson fragmentation function \[18\]
\[ D_{had}(z) \propto 1/[z(1 - z)^{-1} - \epsilon_c(1 - z)^{-1} \Gamma] \]
where \( \epsilon_c \) is a free parameter that is determined assuring that the shape of the fragmentation function agrees with the experimental data on \( p_T \) distributions. The \( \epsilon_c \) parameter has been fixed to \( \epsilon_c = 0.1 \) for both \( D^0 \) and \( \Lambda_c \) that coupled to FONLL \( p_T \) distribution correctly describe the high \( p_T \) tail dominated by fragmentation, see Fig. 2. In a similar way done in Ref.\[13\] for \( \Lambda \) to \( \Lambda \) annihilations we assume that charm quarks that do not hadronize via coalescence are converted to hadrons by fragmentation. Therefore we can introduce a fragmentation probability given by
\[ P_{frag}(p_T) = 1 - P_{coal}(p_T), \]
where \( P_{coal} \) is the total coalescence probability. The fragmentation fraction that gives the probability that a charm quark fragment in a specific heavy hadron is evaluated according to PYTHIA8 ratios at high \( p_T > 10 \text{ GeV} \) that are similar to the \( e^+ + e^- \) apart from an increase of the fraction for \( \Lambda_c \) and moderate decrease of the fraction going to \( D^0 \), as already done in \[13\].

| Meson | \( \langle r^2 \rangle_{ch} \) | \( \sigma_{r1} \) | \( \sigma_{r2} \) |
|-------|----------------|-------------|-------------|
| \( D^+ \) | 0.184 | 0.282 | — |
| \( D^0 \) | 0.083 | 0.404 | — |
| Baryon | \( \langle r^2 \rangle \) | \( \sigma_{r1} \) | \( \sigma_{r2} \) |
| \( \Lambda^+_c \) | [u,d,c] | 0.15 | 0.251 | 0.424 |
| \( \Xi^+_c \) | [u,s,c] | 0.2 | 0.242 | 0.406 |
| \( \Omega^0_c \) | [s,c] | -0.12 | 0.337 | 0.53 |

**TABLE I**: Mean square charge radius \( \langle r^2 \rangle_{ch} \) in \( fm^2 \) and the widths parameters \( \sigma_{pi} \) in GeV. The mean square charge radius are taken quark model \[46, 47\].
III. FIREBALL AND PARTON DISTRIBUTION

The charm pair production is described by hard process and it is described by perturbative QCD (pQCD) at NNLO. Therefore, the starting point to compute the initial heavy quarks spectra in $pp$ collisions at LHC energy of $\sqrt{s} = 5.02\,\text{TeV}$ is by pQCD calculation. In our calculation the charm quark spectrum have been taken in accordance with the charm distribution in $p + p$ collisions within the Fixed Order + Next-to-Leading Log (FONLL), as given in Refs. [49, 50]. In the recent years, we are observing that hydrodynamics models can also be extended even to extreme situations, for example in observing that hydrodynamics models can also be applied even in quenching mechanism could be negligible, and indeed even in $pA$ collisions show an $R_{pA} \approx 1$.

In our calculation the bulk of particles that we assume is a thermalized system of gluons and $u, d, s$ quarks and anti-quarks. The longitudinal momentum distribution is assumed to be boost-invariant in the range $y \in (-0.5, +0.5)$, and is included a radial flow with the following radial profile $\beta_T(r_T) = \beta_{max} \frac{r_T}{R}$, where $R$ is the transverse radius of the fireball. Partons at low transverse momentum, $p_T < 2\,\text{GeV}$, are considered thermally distributed

\[
\frac{dN_{q\bar{q}}}{d^2p_T d^2r_T} = \frac{g_q g_{\bar{q}} T m_T}{(2\pi)^3} \exp\left(-\frac{\gamma_T (m_T - p_T \cdot \beta_T)}{T}\right) \tag{10}
\]

where $m_T = \sqrt{p_T^2 + m_{q\bar{q}}^2}$ is the transverse mass. The factors $g_q = g_{\bar{q}} = 6$ are the spin-color degeneracy. The presence of gluons in the quark-gluon plasma is taken into account by converting them to quarks and anti-quark pairs according to the flavour compositions, as assumed in [8, 51]. For the bulk properties we fix the parameter according to hydro-dynamical simulations [27] with $\tau = 2.5\,\text{fm}/c$, $R = 2\,\text{fm}$ and the temperature of the bulk is $T_C = 165\,\text{MeV}$. For partons at high transverse momentum, $p_T > 2.5\,\text{GeV}$, we consider the minijets distribution that can be obtained from pQCD calculations and parametrized with a power law function, see [13, 52, 53].

IV. HEAVY HADRON TRANSVERSE MOMENTUM SPECTRA AND RATIO

In this section, we discuss the coalescence probability and will be shown the results for the transverse momentum spectra of $D^0$, $D_s$ mesons and for $\Lambda_c$ using the model described in previous sections for $pp$ collisions at $\sqrt{s} = 5\,\text{TeV}$.

The presence of resonance decay has a significant impact because it gives an important contribution to the ground-state spectra. In this study we include ground state hadrons as well as the first excited resonances listed in Table I which includes the resonances of $D$, $\Lambda_c$, $\Xi_c$ and $\Omega_c$ baryons as given by the Particle Data Group [34]. When we consider the resonance states we take into account a suppression factor given by the Boltzmann probability to populate an excited state of energy $E + \Delta E$, at a temperature $T$. This statistical factor is of the form $[m_{H^*}/m_H]^{3/2} \times \exp(-\Delta E/T)$ with $\Delta E = E_{H^*} - E_H$, where $E_{H^*} = \sqrt{p_T^2 + m_{H^*}^2}$ and $m_{H^*}$ is the mass of the resonance, with the same approach already used in [13]. Recent experimental analysis techniques have unveiled information about the $\Sigma_c$ spectra and their contribution to the total $\Lambda_c$ yield, which offer a unique possibility to test the hadronization models in detail [6].

Figure II is shown the coalescence probabilities $P_{\text{coal}}$ for a charm quark to hadronize via coalescence into a specific hadron, as a function of the charm transverse momentum. As shown $P_{\text{coal}}$ is a decreasing function of $p_T$ which means that, at low momentum, charm quarks are more probable to hadronize via coalescence with light partons from the thermalized medium, in particular in our model at $p_T \approx 0$ a charm quark can hadronize only by...
We notice that we show the results for the $\Lambda$ leads to an enhancement of the $\Lambda$ nism. We expect that this particular characteristic is a quite peculiar feature of the coalescence mechanism. In Fig. 2, the coalescence mechanism is the dominant mechanism for the $\Lambda$ production for $p_T \lesssim 5$ GeV. This result emerges from the combination of two conditions: i) the expected fragmentation fraction into $\Lambda_0$ is about 12% of the total produced heavy hadrons, ii) the coalescence contribution in the baryon case is dominant with respect to the mesons case (see Fig. 1) because the coalescence mechanism takes quarks that are already present abundantly in the dense medium created at very high energy even in $pp$ collisions.

In Fig. 2 we show the results for the $\Lambda_0^+/D^0$ and $D_s^+/D^0$ ratio in comparison with the LHC experimental data for $pp$ collisions at $\sqrt{s} = 5.02$ TeV. The dashed lines show the ratios that comes only from fragmentation. We have also included the LHCb data for the $\Lambda_0^+/D^0$ at high rapidity, $2 < y < 4.5$, where we expect that the contribution of fragmentation is the dominant one and we can observe a good agreement with the fragmentation ratio em-

| Meson | Mass(MeV) | I (J) | Decay modes | B.R. |
|-------|-----------|------|-------------|------|
| $D^+$ | 1869      | $\frac{1}{2}$ (0) | $\Lambda_0^+ \pi^+ \pi^-$ | 100% |
| $D^0$ | 1865      | $\frac{1}{2}$ (0) | $\Lambda_0^+ \pi^+ \pi^-$ | 100% |
| $D_s^+$ | 2007 | $\frac{1}{2}$ (0) | $\Lambda_0^+ \pi^+ \pi^-$ | 100% |

| Resonances |
|------------|
| $\Lambda_0^+$ | 2595 | $0 \left( \frac{1}{2} \right)$ | $\Lambda_0^+ \pi^+ \pi^-$ | 100% |
| $\Xi_s^0$ | 1855 | $0 \left( \frac{1}{2} \right)$ | $\Xi_s^0 \pi^+ \pi^-$ | 100% |
| $\Omega_s^0$ | 2467 | $0 \left( \frac{1}{2} \right)$ | $\Omega_s^0 \pi^+ \pi^-$ | 100% |

TABLE II: Ground states of charmed mesons and baryons as well as their first excited states including their decay modes with their corresponding branching ratios as given in Particle Data Group [34, 54].

coalescence. In our modelling a charm quark that cannot hadronize by coalescence hadronizes by fragmentation with a fragmentation probability given by $P_{\text{fragm}} = 1 - P_{\text{coal}}$. Therefore at high $p_T$ the fragmentation becomes to be the dominant charm hadronization mechanism and a charm will hadronize according to the different fragmentation fraction into specific final charmed hadron channels, as in Ref. [5]. By comparing the different coalescence probabilities in Fig. 1 we notice that at low momenta, the coalescence probability for $\Lambda_c$ and $\Xi_c$ are similar than the one for $D^0$ which is a quite peculiar feature of the coalescence mechanism. We expect that this particular characteristic leads to an enhancement of the $\Lambda_c/D^0$ ratio. In Fig. 2 we show the $p_T$ spectra of $D^0$ (left panel), $D_s$ (mid panel) and $\Lambda_c$ (right panel) at mid-rapidity from $pp$ collisions. The total charm cross sections used in this work is $\sigma_{cc}/dy = 1.0$ mb. The black dot-dashed line and the red dashed line refer to the hadron spectra obtained by the contribution from pure coalescence and pure fragmentation respectively. We observe that the contribution of fragmentation is the dominant mechanism for the production of $D^0$ in all the $p_T$ range explored and coalescence gives only a few percent of contribution to the total spectrum, while in $AA$ the contribution is significantly larger and comparable to the fragmentation one. For the $D_s^+$ spectrum the contribution of both mechanism becomes similar due to the fact that the fragmentation fraction for $D_s^+$ is quite small, about 8% of the total heavy hadrons produced, according to Ref. [5]. The inclusion of both hadronization mechanisms provide a quite good comparison with the experimental data and the coalescence leads to an enhancement of the $D_s^+$ production.

FIG. 2: (Color online) Transverse momentum spectra for $D^0$, $D_s$ mesons and $\Lambda_c$ baryon at mid-rapidity for $pp$ collisions at $\sqrt{s} = 5$ TeV. Black dot-dashed and red dashed lines refer to the spectra from only coalescence and only fragmentation respectively, the green solid line is the sum of fragmentation and coalescence. Experimental data from [24, 26, 53].
ployed (blue dashed lines). The hybrid approach of coalescence plus fragmentation (solid lines) give a quite good description of the experimental data. The blue band in the $\Lambda_c/D^0$ ratio corresponds to the uncertainty given by a variation of about 10% for the Wigner functions widths related to the uncertainties in the mean square charge radius in the Quark Model estimation [46,47]. The coalescence mechanism plays a dominant role in the enhancement of the $\Lambda^+_c$ giving a $\Lambda^+_c/D^0 \approx 0.6$ at low $p_T$. However, the $\Lambda^+_c/D^0$ ratio in $AA$ collision shows a rise and fall behaviour while in $pp$ collision the same approach results in a decreasing function of $p_T$, similarly to the experimental data. At $p_T \lesssim 1$ GeV the spectra in Fig. 3 slightly underestimate the absolute yield for $D^0$ and to some extent also for $\Lambda_c$, hence the rise up of the ratio at low $p_T$ may not be a solid physical result. The $D^+_s/D^0$ ratio is almost flat in the $p_T$ range explored. Comparing the red solid and dashed lines the different relative contribution of coalescence and fragmentation for $D_s$ and $D^0$ leads to an enhancement of the ratio $D_s/D^0$ of about 20% in all the range of transverse momentum explored.

We have extended this analysis to other single-charmed baryons with content of strangeness, such as $\Xi_c$ and $\Omega_c$. The $\Xi_c$ ratios to $D^0$ and $\Lambda_c$ have been very recently presented by ALICE collaboration showing interesting behaviour in $pp$ collision at top LHC energies, in particular, detecting an abundant $\Xi_c$ production up to 20% of $D^0$, much larger than the expectations in the fragmentation approach even including color reconnection [6]. In Fig. 4 we show the $\Xi_c$ and $\Omega_c$ to $D^0$ ratios at mid-rapidity in $pp$ collisions at $\sqrt{s} = 5.02$ TeV: during the revision process of this manuscript the $\Xi_c$ data have been published by ALICE collaboration [6] and we included them in the figure. In the left panel, we show the $\Xi_c/D^0$ ratio (orange band) including the uncertainties given by the variation of the Wigner function widths. Furthermore, we provide some results for the $\Omega_c/D^0$ ratio. For $D^0$ it has been considered coalescence plus fragmentation. For the $\Omega_c$ are considered cases with only coalescence (green line), coalescence plus fragmentation (purple band), resonances (blue dot-dashed lines). For details see the text.

![Figure 3](image3.png)

**FIG. 3:** (Color online) $\Lambda^+_c/D^0$ (blue band) and $D^+_s/D^0$ (red) ratios as a function of $p_T$ and at mid-rapidity for $pp$ collisions at $\sqrt{s} = 5$ TeV. Experimental data taken from [4,23,24,53]. Solid and dashed lines refer to the cases with both coalescence and fragmentation and to the case with only fragmentation respectively.

![Figure 4](image4.png)

**FIG. 4:** (Color online) Left panel: $\Xi^{0,+}/D^0$ ratios as a function of $p_T$ and at mid-rapidity for $pp$ collisions at $\sqrt{s}=5.02$ TeV with both coalescence and fragmentation, data from [6]. Right panel: $\Omega_c/D^0$ ratio. For $D^0$ it has been considered coalescence plus fragmentation. For the $\Omega_c$ we show three cases, the first considering only the coalescence contribution (green line), the second with both coalescence plus fragmentation (purple band) and the third where we include the resonance states present in the PDG in addition to the already considered $\Omega_c^0(2770)$. However, currently there are several $\Omega_c^0$ states that have been seen that could give contribution to the feed-down, but their $J$ values are unknown, i.e. $\Omega_c^0(3000)^0$, $\Omega_c^0(3005)^0$, $\Omega_c^0(3065)^0$, $\Omega_c^0(3090)^0$, $\Omega_c^0(3120)^0$. To supply an idea of how these states may affect the ratio we have included them by assuming for all these resonances $J=3/2$, a kind of average value for their degeneracy (blue dot-dashed line). It is interesting that the contribution from fragmentation is subdominant for $\Xi_c$ and $\Omega_c^0$ in these ratios, therefore in our model the main contribution comes from a pure coalescence mechanism, so this ratio can carry some more relevant information about the hadronization process. There are other interesting particle ratios available lately, thanks to the refinement of particle identification technique. Shown in Fig. 5 are the ratios between the $\Lambda_c$ particles from the decay of the three $\Sigma_c$ states and the total $\Lambda_c$ produced (black band) as
well as the $D^0$ (gold band). The green band is the ratio between the direct $\Sigma_c$ and $\Xi_c$ baryons. The $(\Sigma_c \to \Lambda_c^+)/\Lambda_c$ ratio is different from the fragmentation observed in $e^+e^-$ for $\Sigma_c$ that is only 10% of the $\Lambda_c$ fragmentation [2]. Since these ratios give us information about the contributions from $\Sigma_c$ on the total yield of $\Lambda_c$, they can represent a quite solid test for our approach. The preliminary experimental data for the ratios at $\sqrt{s_{NN}} = 13$ TeV show a behavior that is quite similar to our calculation at least within the current uncertainties. A decreasing behaviour with $p_T$ for the $(\Sigma_c \to \Lambda_c^+)/D^0$ ratio, with a value of about $0.2 \pm 0.05$ at $p_T \sim 3$ GeV and $\sim 0.05$ at $p_T \sim 10$ GeV; while for the $(\Sigma_c \to \Lambda_c^+)/\Lambda_c$ ratio the value is of about $0.4 \pm 0.1$ at $p_T \sim 3$ GeV and $\sim 0.25 \pm 0.05$ at $p_T \sim 10$ GeV. Furthermore as $\Sigma_c/\Xi_c$ ratio exhibits an increase with $p_T$, again similar to our modeling, with a value of about $0.4 \pm 0.15$ at $p_T \sim 3$ GeV and $0.6 \pm 0.15$ at $p_T \sim 10$ GeV. Hence, it is interesting to note how the hybrid approach of hadronization is able to describe the $p_T$ dependence as well as the absolute values for these ratios shown in [2].

\[ \begin{align*}
\text{FIG. 5: (Color online) Ratios of } \Lambda_c \text{ that comes from the decay of } \Sigma_c, \quad (\Sigma_c \to \Lambda_c^+)/D^0 \quad \text{(gold band)} \quad \text{and } \quad (\Sigma_c \to \Lambda_c^+)/\Lambda_c \quad \text{(black band)} \quad \text{as a function of } p_T \quad \text{and at mid-rapidity for } pp \text{ collisions at } \sqrt{s} = 5.02 \text{ TeV. The green band is the } \Sigma_c^+/+\Sigma_c^0/\Xi_c^0 \text{ ratio.}
\end{align*} \]

V. CONCLUSION

In this paper we have studied the formation of charmed hadrons, calculating the baryon and meson spectra and their ratios by extending a model developed in AA collisions to investigate the production of particles observed in $pp$ collisions at top LHC energy.

The large baryon over meson ratios with magnitudes much larger than those from fragmentation fractions ratio measured in $e^+e^-$ collisions, clearly indicate a strong violation of the universality of the fragmentation function. Using our coalescence plus fragmentation model, we have found a good description of the meson and baryon spectra and their ratios. In particular, in the transition from AA collisions to $pp$ collisions our results naturally describe a change of the baryon over meson ratios as a function of the transverse momentum and the enhancement observed in recent experimental data for $\Xi_c/D^0$ [2] ratio along with a prediction for an $\Omega_c/D^0 \approx 0.05 - 0.1$.

It has to be noticed that once the fireball parameters are given by hydro-dynamical studies, the free parameters left in our model are the widths of the wave functions. However these widths are fixed by the charge radii $< r^2 >_{ch}$ of charmed hadrons in the constituent quark model. Hence, there are no free parameters specifically tuned to reproduce the charm hadron production in $pp$ collisions. Nonetheless, it would be interesting to study possible in-medium modification of the wave function by solving the pertinent Schrödinger equation for the bound states. The results obtained seem to suggest that the presence of a hot and dense QCD matter in small collision systems permits the recombination of quarks that significantly modify charm baryon production. In particular, the $\Xi_c/D^0$ [2] and $\Omega_c/D^0$ ratios may shed light on the hadronization mechanism and provide indications on the differences between the approaches that are currently under development, such as the coalescence approach, the color reconnection mechanism in the fragmentation approach [36] and the large feed-down contribution from higher charmed baryon states [33].

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