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# D-meson and charmed-baryon measurement in pp and p-Pb collisions with ALICE at the LHC

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*A Large Ion Collider Experiment* (ALICE) at CERN was designed to study the strongly interacting medium created in heavy-ion collisions at the LHC, the *Quark-Gluon Plasma* (QGP). Heavy quarks (charm and beauty), produced in the early stages of the collision, are among the most powerful probes to investigate QGP properties. On this regard, results from pp and p-Pb collisions constitute the needed reference in order to disentangle initial-state from QGP related effects.
Charmed mesons ($D^0$, $D^+$, $D^{*+}$ and $D_s^+$) were reconstructed via their hadronic decays at mid-rapidity in pp collisions at $\sqrt{s} = 5.02$, 7, 8 and 13 TeV and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The first measurement of the charmed baryon, $\Lambda_c^+$ , at mid-rapidity was performed in pp collisions at $\sqrt{s} = 7$ TeV and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV through the full reconstruction of two of its hadronic decay channels and the partial reconstruction of one of its semileptonic decay channels. Moreover, the first measurement at the LHC of the $\Xi_c^0 \rightarrow e^+\Xi^- \nu_e$ production cross section was performed in pp collisions at $\sqrt{s} = 7$ TeV.
In this contribution recent results on charmed meson and baryon production, measured with the ALICE detector in pp and p-Pb collisions, will be presented.

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## 1. Introduction

Charm and beauty quarks are powerful probes to study the properties of the *Quark-Gluon Plasma* (QGP), the hot and dense state of strongly-interacting matter produced in high-energy heavy-ion collisions. Produced in hard parton scattering processes occurring in the early stages of the collision, they traverse the hot medium, interact with its constituents and experience the whole evolution of the medium. The presence of a medium with a high density of deconfined quarks can affect the heavy-quark hadronisation mechanism. Charm and beauty quarks could hadronise via recombination (coalescence) with other quarks from the medium. Measuring the $\Lambda_c^+/D^0$ ratio in Pb-Pb collisions could evidence a modification of charm fragmentation with respect to the vacuum case and would allow to constrain thermal and coalescence models, which offer different predictions.
The interpretation of particle production measurements in Pb-Pb collisions requires detailed studies also in pp and p-Pb collisions: pp collisions provide the essential reference for measurements in Pb-Pb collisions and a sensitive test of perturbative Quantum ChromoDynamics (*p*QCD) predictions at the LHC energies. The measurement of heavy flavour hadron production in p-Pb collisions is crucial to access *Cold Nuclear Matter* (CNM) effects in the initial and final states, such as modification of the Parton Distribution Functions in nuclei (nPDF) [1], gluon saturation at low Bjorken-$x$ [2], $k_T$ broadening. Some insight into the role of Multi-Parton Interactions (MPI) and the interplay between hard and soft mechanism for particle production can be obtained by studying heavy-flavour production as a function of the multiplicity of charged particles produced in pp and p-Pb collisions [3] [4].

## 2. Charm measurements with ALICE

The ALICE detector, described in detail in [5] [6], consists of a central barrel at mid-rapidity ($|\eta| < 0.9$), a muon spectrometer at forward rapidity ($-4.0 < \eta < -2.5$) and a set of detectors (at forward and backward rapidity) for global collision characterization and triggering purposes.
In this paper, open heavy flavour measurements via hadronic and semileptonic decay reconstruction in the ALICE central barrel will be discussed.

### 2.1 Charmed-meson measurements down to $p_T = 0$ in pp and p-Pb collisions

D mesons and their charge conjugates are reconstructed in ALICE via their hadronic decays at central rapidity ($|y| < 0.5$): $D^0 \to K^-\pi^+$, $c\tau = 123\ \mu$m, branching ratio (BR) = $(3.93 \pm 0.04)\%$; $D^+ \to K^-\pi^+\pi^+$, $c\tau = 312\ \mu$m, BR = $(9.46 \pm 0.24)\%$; $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, strong decay, BR = $(67.7 \pm 0.5)\%$; $D_s^+ \to \phi\ (\to K^-K^+)\pi^+$, $c\tau = 150\ \mu$m, BR = $(2.27 \pm 0.08)\%$. The analyses are based on the reconstruction of the decay vertices displaced by a few hundred $\mu$m from the interaction vertex, exploiting the high track-position resolution close to the interaction vertex provided by the Inner Tracking System (ITS). The large combinatorial background is reduced by selections applied on the decay topology and by the identification of charged kaons and pions via their specific energy loss in the Time Projection Chamber (TPC) and their time-of-flight measured with the Time Of Flight (TOF) detector. Raw D-meson yields are obtained from an invariant mass analysis of

pairs/triplets of tracks with proper charge sign combination.
Production cross section measurements of prompt D mesons were performed in pp collisions at $\sqrt{s}$ = 7 TeV and 2.76 TeV [7, 8, 9, 10] and found to be well described by *p*QCD calculations. The $p_{\mathrm{T}}$-differential cross sections for $\mathrm{D}^0$ at $\sqrt{s}$ = 5 TeV and $\mathrm{D}_{\mathrm{s}}^{+}$ at $\sqrt{s}$ = 7 TeV are shown in Fig. 1, together with FONLL [11] [12] and GM-VFNS [13] *p*QCD calculations. The theoretical predictions tend to reproduce the measured cross sections within the large theoretical uncertainties.

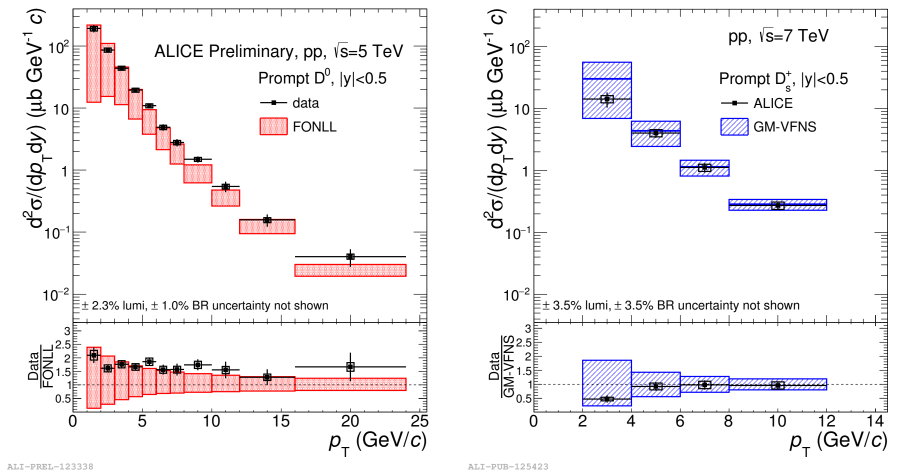


**Figure 1:** Transverse momentum-differential cross sections of prompt $\mathrm{D}^0$ mesons in pp collisions at $\sqrt{s}$ = 5 TeV (left panel) and prompt $\mathrm{D}_{\mathrm{s}}^{+}$mesons in pp collisions at $\sqrt{s}$ = 7 TeV (right panel, from [10]) compared with FONLL [11] [12] and GM-VFNS [13] theoretical calculations.

In order to extend the $\mathrm{D}^0$ measurement down to $p_{\mathrm{T}} = 0$, where the decay-vertex selection becomes very inefficient, a different analysis technique, based on particle identification (PID) and background subtraction was developed [14]. The cross section measurement obtained for prompt $\mathrm{D}^0$ in pp collisions is shown in Fig. 2.

Next, CNM effects on charm meson production are studied. The nuclear modification factor $R_{\mathrm{pPb}}$ is built as the ratio of the D-meson cross section in p-Pb collisions relative to the one in pp collisions scaled by the atomic mass number of the lead nucleus. Figure 3 shows the average of the non-strange D-meson $R_{\mathrm{pPb}}$ in the interval $0 < p_{\mathrm{T}} < 36$ GeV/*c*. The measured $R_{\mathrm{pPb}}$ [16] is compared with theoretical calculations: models including CNM effects [17, 18, 19, 20], shown in Fig. 3 (left), describe quite well the experimental results within uncertainties. The comparison is also done with the transport model calculations Duke and POWLANG [21], shown in Fig. 3 (right), which assume that a Quark-Gluon Plasma is formed also in p-Pb collisions. The current precision of the measurement does not allow to discriminate between the two scenarios even though the data seem to disfavour a suppression larger than 15-20% at high $p_{\mathrm{T}}$.

### 2.2 Charmed-baryon measurements in pp and p-Pb collisions

The measurement of $\Lambda_{\mathrm{c}}$ production [22] was performed by reconstructing three decay modes: $\Lambda_{\mathrm{c}} \to \mathrm{pK}\pi$ with BR = (6.35 ± 0.33) %; $\Lambda_{\mathrm{c}} \to \mathrm{pK}^0_{\mathrm{S}}$ with BR = (1.58 ± 0.08)% and $K^0_{\mathrm{S}} \to \pi^-\pi^+$ with

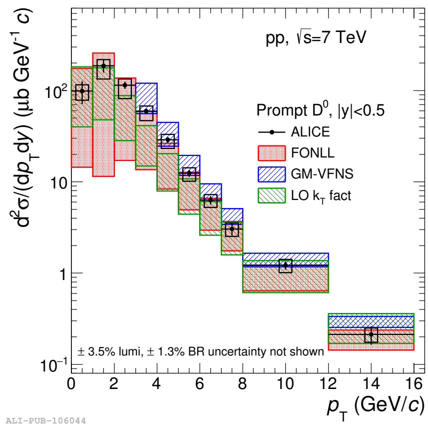


**Figure 2:** Transverse momentum-differential cross section of $D^0$ mesons down to $p_T = 0$, for $|y| < 0.5$ in pp collisions at $\sqrt{s}$ = 7 TeV [14]. FONLL [11] [12], GM-VFNS [13] and $k_T$-factorization [15] theoretical predictions are also shown.

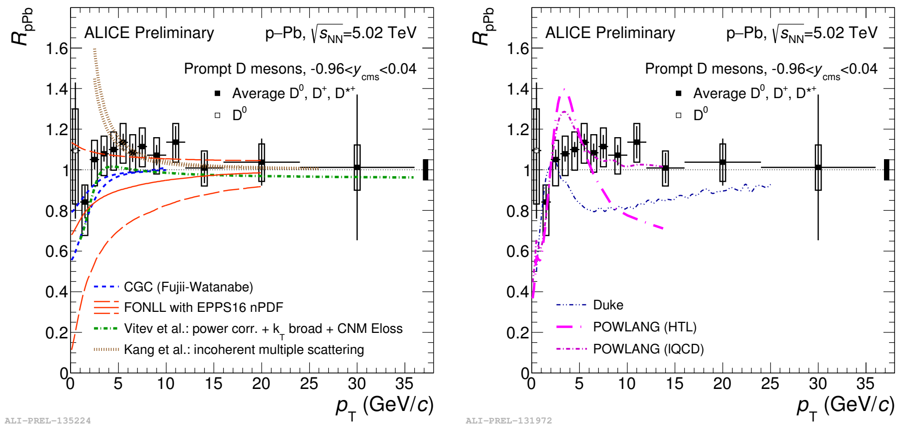


**Figure 3:** Left: Nuclear modification factor $R_{pPb}$ of prompt D mesons in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV: average $R_{pPb}$ of $D^0$, $D^+$and $D^{*+}$mesons in the interval $1 < p_T < 36$ GeV/$c$ [16], shown together with the $D^0$ $R_{pPb}$ in $0 < p_T < 1$ GeV/$c$ [10]. The data are compared with theoretical calculations including only CNM effects (CGC [17], NLO $p$QCD [18] with EPS09 nPDFs [1]), a LO $p$QCD calculation with CNM effects [19] and a calculation based on incoherent multiple scatterings [20]. Right: Same data as on the left. The results are compared to the expectations from the Duke and POWLANG [21] transport models.

BR = (69.20 ± 0.05) %; $\Lambda_c \rightarrow e\nu\Lambda$ with BR = (3.6 ± 0.4)% $\Lambda \rightarrow p\pi^-$ with BR = (63.9 ± 0.5)%. The hadronic decays were fully reconstructed while the semileptonic decay was partially reconstructed because the neutrino is not detectable with ALICE.
The cross section of prompt $\Lambda_c^+$ baryons in pp collisions at $\sqrt{s}$ = 7 TeV and in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV was extracted in the three different decay channels and using different analysis techniques. To achieve higher precision, these results were averaged together, taking into account the correlation between the statistical and systematic uncertainties. In Fig. 4 on the left, the first measurement of $\Lambda_c^+$-baryon production at LHC energies in pp collisions in the central rapidity region is shown and compared with GM-VFNS $p$QCD calculations [23] and with results from

POWHEG event generator [24]. The GM-VFNS prediction, existing only for $p_T > 3$ GeV/$c$, underestimates the measured cross section by a factor higher than 2.5, while describe well, within uncertainties, the D-meson cross sections at central rapidities [10] and the $\Lambda_c$ cross section at forward rapidity measured by LHCb [25]. POWHEG underestimates the measured cross section by a factor between 4 and 18, while it also describes the cross sections of D mesons in pp collisions.
In Fig. 4 on the right, the $\Lambda_c$ cross section in p-Pb collisions averaged from the measurements in two decay channels is shown and compared with POWHEG calculations, which underestimate the measured cross section by a factor similar to what is observed in pp collisions. Lansberg and Shao Predictions [26], based on a pp data-driven modeling of the scattering at partonic level, underestimate the measurements by a factor two.

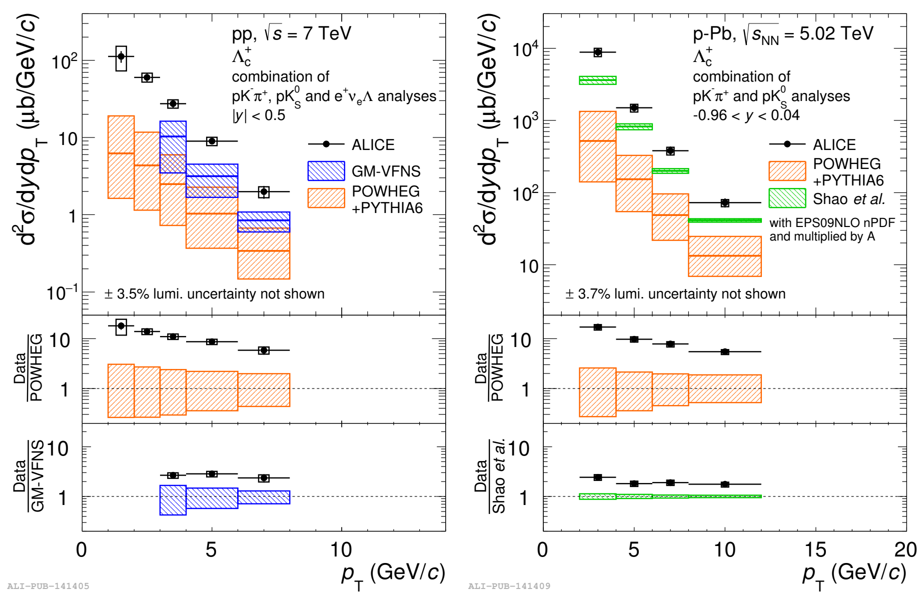


**Figure 4:** Prompt $\Lambda_c^+$ $p_T$-differential production cross section in pp collisions at $\sqrt{s} = 7$ TeV in the transverse momentum interval $1 < p_T < 8$ GeV/$c$ (left) and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the transverse momentum interval $2 < p_T < 12$ GeV/$c$ (right) [22]. Comparisons with GM-VFNS calculation [23], POWHEG event generator [24] and with Lansberg and Shao prediction [26].

The results obtained were used to extract the $\Lambda_c^+ / D^0$ ratio, where for the $D^0$ cross section recent ALICE measurements were taken into account [10] [14]. Results in pp and p-Pb collisions are shown in Fig. 5 and found compatible with each other within uncertainties. Predictions for the pp data sample from PYTHIA8 with two tunes (the Monash 2013 tune [27] and the Mode 0 tune [28]), DIPSY [29] and HERWIG7 are superimposed. The PYTHIA8 tune with enhanced colour reconnection is closer to the data and qualitatively better describes the $p_T$ trend. The p-Pb measurements are compared with calculations from Lansberg and Shao [26], which are, among the available predictions, the closest to the data.

The production of the charm-strange baryon $\Xi_c^0$ was measured for the first time at the LHC, through its semileptonic decay into $\Xi_c^0 \rightarrow e^+\Xi^- \ \nu_e$ in pp collisions at $\sqrt{s} = 7$ TeV [30]. Its $p_T$-differential cross section, multiplied by the branching ratio (currently unknown), in the $p_T$ interval $1 < p_T < 8$ GeV/$c$ at mid-rapidity, is shown in the left panel of Fig. 6. The ratio of the

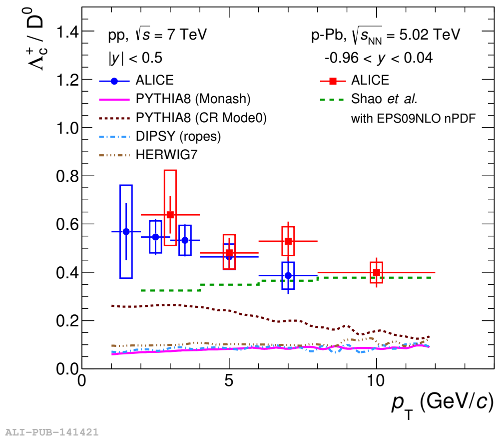


**Figure 5:** The $\Lambda_c^+$ / $D^0$ ratio in pp and p-Pb collisions [22]. The measurements from pp collisions are compared with different event generators [28] [29].

$p_T$-differential cross section of $\Xi_c^0$ multiplied by the branching ratio to that of $D^0$ [10] is shown in Fig. 6 on the right, compared with predictions from PYTHIA 8 event generator with different tunes. Theoretical calculations for the BR varies between 0.8% and 4.2%, defining the uncertainties bands shown in the figure. All the predictions underestimate significantly the measured ratio. As for the $\Lambda_c^+$ case, the Mode 0 tune [28], with a specific tuning on colour reconnection mechanisms, gives a better description of the $\Xi_c^0$ / $D^0$ ratio.

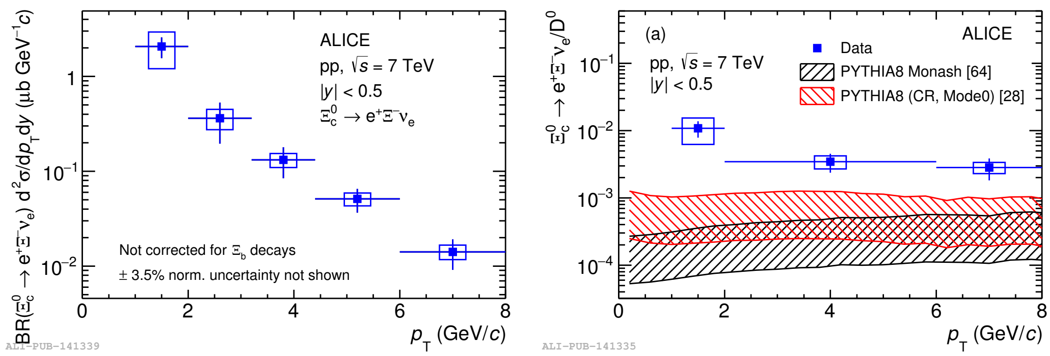


**Figure 6:** The inclusive $\Xi_c^0$ -baryon $p_T$-differential production cross section multiplied by the branching ratio in $\Xi_c^0 \rightarrow e^+\Xi^- \ \nu_e$ (left) as a function of $p_T$ in pp collisions at $\sqrt{s}$ = 7 TeV. Right: $\Xi_c^0$ / $D^0$ ratio as a function of $p_T$ in pp collisions at $\sqrt{s}$ = 7 TeV [30], compared with predictions from PYTHIA 8 with different tunes [27] [28].

## 3. Conclusions

Measurements of open charm production were carried out successfully with the ALICE experiment at the LHC.
The $p_T$ -differential production cross sections for prompt D mesons in pp and p-Pb collisions are reproduced within uncertainties by theoretical predictions based on $p$QCD calculations. The $R_{pPb}$

of prompt D mesons in p-Pb collisions is consistent with unity within uncertainties, however the current precision of the measurement does not allow to discriminate between CNM effects and effects related to the possible QGP formation.
The charm baryon $\Lambda_c^+$ production cross section was measured in pp collisions at $\sqrt{s}$ = 7 TeV and p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. Theoretical calculations underestimate the measured cross section. The $\Lambda_c$ / $D^0$ yield ratios measured in pp and p-Pb collisions are compatible within uncertainties. Event generators with different hadronisation schemes underestimate pp results. The first LHC measurement of the $p_T$-differential cross section of the charm-strange baryon $\Xi_c^0$, multiplied by the branching ratio $\Xi_c^0 \rightarrow e^+\Xi^- \nu_e$ was performed in pp collisions at $\sqrt{s}$ = 7 TeV. Several event generators with various models and tunes for the hadronisation mechanism underestimate underestimate significantly the $\Xi_c^0$ / $D^0$ ratio. The $\Lambda_c$ and $\Xi_c^0$ measurements presented can provide important constraints to the models of charm quark hadronisation.

## References

[1] K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP **0904**, 065 (2009)

[2] I. Vitev, Phys. Rev. C **75**, 064906 (2007)

[3] T. Sjostrand and M. van Zijl, Phys. Rev. D **36**, 2019 (1987).

[4] S. Porteboeuf and R. Granier de Cassagnac, Nucl. Phys. Proc. Suppl. **214**, 181 (2011)

[5] B. Abelev *et al.* [ALICE Collaboration], Int. J. Mod. Phys. A **29**, 1430044 (2014)

[6] K. Aamodt *et al.* [ALICE Collaboration], JINST **3**, S08002 (2008).

[7] B. Abelev *et al.* [ALICE Collaboration], JHEP **1201**, 128 (2012)

[8] B. Abelev *et al.* [ALICE Collaboration], Phys. Lett. B **718**, 279 (2012)

[9] B. Abelev *et al.* [ALICE Collaboration], JHEP **1207**, 191 (2012)

[10] S. Acharya *et al.* [ALICE Collaboration], Eur. Phys. J. C **77**, no. 8, 550 (2017)

[11] M. Cacciari, M. Greco and P. Nason, JHEP **9805**, 007 (1998)

[12] M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason and G. Ridolfi, JHEP **1210**, 137 (2012)

[13] B. A. Kniehl, G. Kramer, I. Schienbein and H. Spiesberger, Phys. Rev. D **84**, 094026 (2011)

[14] J. Adam *et al.* [ALICE Collaboration], Phys. Rev. C **94**, no. 5, 054908 (2016)

[15] B. A. Kniehl, G. Kramer, I. Schienbein and H. Spiesberger, Eur. Phys. J. C **72**, 2082 (2012)

[16] B. B. Abelev *et al.* [ALICE Collaboration], Phys. Rev. Lett. **113**, no. 23, 232301 (2014)

[17] H. Fujii and K. Watanabe, Nucl. Phys. A **915**, 1 (2013)

[18] S. Frixione, M. L. Mangano, P. Nason and G. Ridolfi, Phys. Lett. B **308**, 137 (1993)

[19] R. Sharma, I. Vitev and B. W. Zhang, Phys. Rev. C **80**, 054902 (2009)

[20] Z. B. Kang, I. Vitev, E. Wang, H. Xing and C. Zhang, Phys. Lett. B **740**, 23 (2015)

[21] A. Beraudo, A. De Pace, M. Monteno, M. Nardi and F. Prino, JHEP **1603**, 123 (2016)

[22] S. Acharya *et al.* [ALICE Collaboration], arXiv:1712.09581 [nucl-ex].

[23] B. A. Kniehl, G. Kramer, I. Schienbein and H. Spiesberger, Eur. Phys. J. C **41**, 199 (2005)

[24] S. Frixione, P. Nason and G. Ridolfi, JHEP **0709**, 126 (2007)

[25] R. Aaij *et al.* [LHCb Collaboration], Nucl. Phys. B **871**, 1 (2013)

[26] J. P. Lansberg and H. S. Shao, Eur. Phys. J. C **77**, no. 1, 1 (2017)

[27] P. Skands, S. Carrazza and J. Rojo, Eur. Phys. J. C **74**, no. 8, 3024 (2014)

[28] J. R. Christiansen and P. Z. Skands, JHEP **1508** (2015) 003

[29] C. Bierlich and J. R. Christiansen, Phys. Rev. D **92**, no. 9, 094010 (2015)

[30] S. Acharya *et al.* [ALICE Collaboration], arXiv:1712.04242 [hep-ex].

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