

Open charm production and asymmetry in pNe collisions at $\sqrt{s_{NN}} = 68.5 \text{ GeV}$

LHCb Collaboration; Bifani, Simone; Cooke, Naomi; Sahoo, Niladrihari; Swallow, Paul

DOI:

[10.1140/epjc/s10052-023-11641-5](https://doi.org/10.1140/epjc/s10052-023-11641-5)

License:

Creative Commons: Attribution (CC BY)

Document Version

Publisher's PDF, also known as Version of record

Citation for published version (Harvard):

LHCb Collaboration, Bifani, S, Cooke, N, Sahoo, N & Swallow, P 2023, 'Open charm production and asymmetry in pNe collisions at $\sqrt{s_{NN}} = 68.5 \text{ GeV}$ ', *European Physical Journal C*, vol. 83, no. 6, 541. <https://doi.org/10.1140/epjc/s10052-023-11641-5>

[Link to publication on Research at Birmingham portal](#)

General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.



Open charm production and asymmetry in p Ne collisions at $\sqrt{s_{NN}} = 68.5$ GeV

LHCb Collaboration*

CERN, 1211 Geneva 23, Switzerland

Received: 23 November 2022 / Accepted: 30 April 2023
© CERN for the benefit of the LHCb collaboration 2023

Abstract A measurement of D^0 meson production by the LHCb experiment in its fixed-target configuration is presented. The production of D^0 mesons is studied with a beam of 2.5 TeV protons colliding on a gaseous neon target at rest, corresponding to a nucleon–nucleon centre-of-mass energy of $\sqrt{s_{NN}} = 68.5$ GeV. The sum of the D^0 and \bar{D}^0 production cross-section in p Ne collisions in the centre-of-mass rapidity range $y^* \in [-2.29, 0]$ is found to be $\sigma_{D^0}^{y^* \in [-2.29, 0]} = 48.2 \pm 0.3 \pm 4.5 \mu\text{b/nucleon}$ where the first uncertainty is statistical and the second is systematic. The $D^0 - \bar{D}^0$ production asymmetry is also evaluated and suggests a trend towards negative values at large negative y^* . The considered models do not account precisely for all the features observed in the LHCb data, but theoretical predictions including 1% intrinsic charm and 10% recombination contributions better describe the data than the other models considered.

The production of D^0 charm mesons is sensitive to non-perturbative aspects of Quantum Chromodynamics (QCD). As it reflects a large fraction of the overall charm quark production, D^0 meson production can serve as a reference for the study of the modification of hidden charm ($c\bar{c}$ bound states) production in proton-nucleus and nucleus-nucleus collisions, due to the so-called cold nuclear matter (CNM) and hot and dense matter (HDM) effects [1]. Additionally, the study of D^0 and \bar{D}^0 mesons, $c\bar{u}$ and $\bar{c}u$ bound states, may bring new insight on the intrinsic charm content of the nucleon [2], as already performed with the proton-helium (p He) data collected with LHCb at $\sqrt{s_{NN}} = 86.6$ GeV [3], complementing the results obtained in proton–proton (pp) collisions at $\sqrt{s_{NN}} = 13$ TeV via the measurement of $Z + c$ jets [4,5]. Moreover, in collisions involving a high Bjorken- x parton the charm quarks may recombine with valence quarks from the initial hadrons and lead to an asymmetry between the D^0 and \bar{D}^0 production cross-sections [6–8].

In this paper, a measurement of D^0 production in fixed-target proton-neon (p Ne) collisions at the LHC is presented.

The sum of the D^0 and \bar{D}^0 production, and the $D^0 - \bar{D}^0$ production asymmetry, are studied in collisions of protons with energy of 2.5 TeV incident on neon nuclei at rest, corresponding to a nucleon–nucleon centre-of-mass energy of $\sqrt{s_{NN}} = 68.5$ GeV. These measurements are performed in the negative rapidity hemisphere in the centre-of-mass frame where the proton beam and neon target have positive and negative rapidity y^* , respectively.

The LHCb detector [9,10] is a single-arm forward spectrometer designed for the study of particles containing c or b quarks, covering the pseudorapidity range $2 < \eta < 5$ in the laboratory frame. The detector elements that are particularly relevant to this analysis are: the silicon-strip vertex locator (VELO) surrounding the interaction region that allows c and b hadrons to be identified from their characteristic flight distance; a tracking system that provides a measurement of the momentum of charged particles; two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons; a calorimeter system consisting of scintillating-pad and preshower detectors, electromagnetic and hadronic calorimeters; and a muon detector composed of alternating layers of iron and multi-wire proportional chambers. The system for measuring the overlap with gas (SMOG) [11] enables the injection of gases with a pressure of $O(10^{-7})$ mbar in the beam pipe section inside the VELO, allowing LHCb to operate as a fixed-target experiment. SMOG allows the injection of noble gases and therefore gives the unique opportunity to study nucleus-nucleus and proton-nucleus collisions for various gaseous targets. Due to the boost induced by the high-energy proton beam, which travels along the positive- z direction, the LHCb acceptance covers the negative rapidity hemisphere in the centre-of-mass system of the reaction $y^* \in [-2.29, 0]$.

The data samples correspond to a collider configuration in which proton bunches moving towards the detector do not cross any bunch moving in the opposite direction at the nominal pp interaction point. Standard pp collision events were also collected concurrently with the p Ne collision data.

* e-mail: emilie.maurice@lhc.in2p3.fr

Events are selected by the two-stage trigger system [12]. The first level is implemented in hardware, while the second is a software trigger. The hardware trigger requires a minimum deposited energy of 7.8 GeV in the calorimeter for the $D^0 \rightarrow K^-\pi^+$ selection.¹ The software trigger requires a well-reconstructed D^0 decay vertex formed by clearly identified kaon and pion tracks, both of which are required to have a transverse momentum greater than 250 MeV/c and a combined invariant mass in the range [1784, 1944] MeV/c².

Special care is taken to suppress residual pp collisions induced by debunched protons. The PV must lie in the fiducial region $z_{PV} \in [-200, -100] \cup [100, 150]$ mm, where high reconstruction efficiencies are achieved and calibration samples are available. Here z_{PV} is the reconstructed position along the beam axis. The region $-100 < z_{PV} < 100$ mm, where most of the residual pp collisions occur, is excluded. A veto is imposed on events with activity in the backward region, with respect to the proton beam direction, based on the number of hits in the VELO stations upstream of the interaction point.

The offline selection of D^0 candidates is similar to that used in Ref. [13]. Events must contain a primary vertex with at least four tracks reconstructed in the VELO detector. The kaon and pion originating from the D^0 decay are required to be of good quality and to come from a common displaced vertex relatively to the associated PV position to which the D^0 candidate has the smallest impact parameter. Tight requirements are set on the kaon and pion particle identification information. The D^0 candidates are required to have a proper decay time greater than 0.5 ps. The measurements are performed in the range of D^0 transverse momentum $p_T < 8$ GeV/c and $2.0 < y < 4.29$, where y is the rapidity in the laboratory frame.

The detection efficiencies are determined using samples of simulated p Ne collisions. In the simulation, D^0 mesons are generated in simulated proton–proton collisions using PYTHIA 8 [14], which has implemented the Lund string fragmentation model [15], with a specific LHCb configuration [16] and with colliding-proton beam momenta equal to the momenta per nucleon of the beam and target in the centre-of-mass frame. The decays are generated by EVTGEN [17], in which final-state radiation is handled by PHOTOS [18]. The four-momenta of the D^0 decay products are embedded into p Ne minimum bias events that are produced with the EPOS event generator [19] using beam parameters obtained from the data. The event obtained after embedding is then boosted to the laboratory frame to get the fixed-target configuration. Decays of hadronic particles generated with EPOS are also implemented with EVTGEN. The interaction of the generated particles with the detector and its response, are

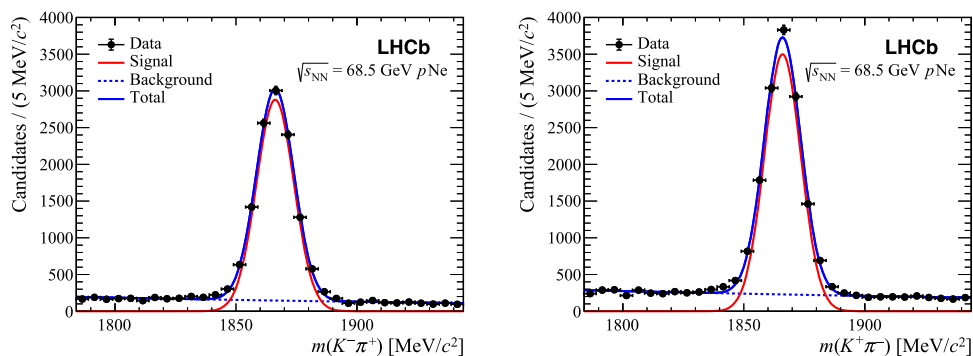
handled with the GEANT4 toolkit [20,21] as described in Ref. [22]. After reconstruction, the simulated events are assigned weights to ensure that the VELO cluster multiplicity distribution matches the distribution in the data.

The D^0 signal yields are obtained from extended unbinned maximum likelihood fits to their mass distributions. The signals are described by Gaussian functions while the background contributions are described by exponential functions. Figure 1 shows the $K^-\pi^+$ and $K^+\pi^-$ invariant mass distributions obtained after all selection criteria are applied to the entire p Ne data set, with the fit functions superimposed. Additionally, the signal yields are determined in intervals of p_T with edges (0, 0.5, 1, 1.5, 2, 3, 8 GeV/c) and y^* with edges (−2.29, −1.5, −1.0, −0.5, 0). These yields are corrected for the total efficiencies, which account for the geometrical acceptance of the detector, and the efficiencies of the trigger, event selection including the D^0 selection, PV and track reconstruction, and particle identification. Particle identification [23] and tracking [24] efficiencies are obtained from control samples of pp collision data. All other efficiencies are determined using samples of simulated data.

Several sources of systematic uncertainties are considered, affecting either the determination of the signal yields or the total efficiencies. They are summarised in Table 1 separately for contributions that are correlated and uncorrelated between the kinematic intervals. Systematic uncertainties on the signal determination include the contribution from b -hadron decays and the maximum contamination from residual pp collisions. More precisely, the fraction of signal from b -hadrons, included in the extracted yield and determined through the study of the impact parameter distribution of the D^0 candidates with respect to the primary vertex, is 1.1%. Contributions from residual pp collisions are estimated using samples of pure p Ne collisions and pure pp collisions, both samples being collected using dedicated LHC beam configurations. These contributions result in a total 2.3% uncertainty assigned to the signal determination. Since the tracking and particle identification efficiencies are determined using pp control samples, the differences between the track multiplicity in p Ne and pp collisions are considered as systematic uncertainties. Overall, systematic uncertainties of 3.0% and 3.6% are assigned due to tracking and particle identification efficiencies, respectively. The PV reconstruction systematic uncertainty is determined by considering the variation of the efficiency over the whole z_{PV} range and the difference between the simulation and a data-driven approach to evaluate the PV efficiency. Possible contamination from collisions between the beam and atoms different from neon is quantified using data samples recorded with no neon injection, resulting in an upper limit of 1.2%, identified as the neon purity uncertainty. Two uncorrelated systematic uncertainties are also considered. First, the uncertainty related to the mass fit is evaluated using alternative models for signal and back-

¹ Inclusion of charge-conjugate processes is implied throughout, unless otherwise said.

Fig. 1 Invariant mass distributions of (left) $K^- \pi^+$ and (right) $K^+ \pi^-$ candidates. The data are overlaid with the result of the fit



ground shapes that reproduce the mass shapes equally well. Another source of uncertainty is associated with the accuracy of the simulation used to compute the acceptances and efficiencies. This uncertainty accounts for the finite size of the simulation sample and observed discrepancies between the data and the simulation, in the rapidity and p_T distributions.

The integrated luminosity is determined to be $\mathcal{L}_{pNe} = 21.7 \pm 1.4 \text{ nb}^{-1}$ from the yield of electrons elastically scattering off the target atoms as presented in Ref. [25]. The measured D^0 and \bar{D}^0 cross-section per target nucleon within $y^* \in [-2.29, 0]$, after taking into account the known branching fraction of $D^0 \rightarrow K^- \pi^+$ [26], is

$$\begin{aligned} \sigma_{D^0}^{y^* \in [-2.29, 0]} &= \frac{Y_{D^0 \rightarrow K^- \pi^+}}{\mathcal{B}_{D^0 \rightarrow K^- \pi^+} \times \varepsilon_{D^0} \times \mathcal{L}_{pNe}} \\ &= 48.2 \pm 0.3 \text{ (stat.)} \pm 4.5 \text{ (syst.)} \mu\text{b/nucleon,} \end{aligned}$$

where $Y_{D^0 \rightarrow K^- \pi^+}$, $\mathcal{B}_{D^0 \rightarrow K^- \pi^+}$ and ε_{D^0} are D^0 yield, branching fraction and total efficiency respectively. No correction is applied to account for the small fraction (1.1%) of signal from b -hadron decay. The cross-section per target nucleon, extrapolated to the full phase-space using PYTHIA 8 with a specific LHCb tuning and with the CT09MCS parton distribution functions [27], assuming forward-backward symmetry in the rapidity distribution, thus neglecting a possible small asymmetry induced by nuclear Parton Distribution Functions, is

$$\sigma_{D^0}^{4\pi} = 97.6 \pm 0.7 \text{ (stat.)} \pm 9.1 \text{ (syst.)} \mu\text{b/nucleon.}$$

The D^0 differential cross-sections per target nucleon, as functions of y^* and p_T , are shown in Fig. 2. These results are compared with the fixed-order plus next-to-leading-logarithms resummation model calculations (FONLL) [28, 29], and a parton-hadron-string dynamics (PHSD) transport calculation [30]. Both predictions fail to reproduce either the low (PHSD) or high (FONLL) p_T region, while the rapidity shapes are in better agreement with the data. Most features of the LHCb measurements are well described by alternative predictions with (Vogt 1% IC) or without (Vogt no IC) intrinsic charm contributions, both taking into account the shadowing effect [31], and by predictions (MS) including 1% intrinsic charm and 10% recombination contributions

Table 1 Systematic and statistical uncertainties on the signal yields. Systematic uncertainties correlated between y^* or p_T bins affect all measurements by the same relative amount. Ranges denote the minimum and the maximum values among the y^* or p_T bins

Systematic uncertainties	
Correlated between bins	
Signal determination	2.3%
Tracking efficiency	3.0%
Particle identification efficiency	3.6%
PV reconstruction efficiency	4.1%
Neon purity	1.2%
Luminosity	6.5%
Uncorrelated between bins	
Signal and background model	[0.3, 5.6]%
Simulation sample	[0.7, 8.0]%
Total correlated uncertainty	9.3%
Total uncorrelated uncertainty	[1.1, 9.2]%
Total statistical uncertainty	[2.3, 7.7]%

[6]. Note that only the FONLL predictions include the factorization scale and parton distribution function uncertainties, while the bands in Vogt’s predictions represent the variation due to the shadowing, and PHSD or MS models have no uncertainty. Note also that D^0 and D^* measurements have been performed by the STAR experiment in $\sqrt{s} = 200 \text{ GeV}$ pp collisions at midrapidity [32], showing a better agreement with FONLL predictions at moderate and large p_T .

Finally, the $D^0 - \bar{D}^0$ production asymmetry is presented. It is quantified as

$$A_{\text{prod}} = \frac{Y_{\text{corr}}(D^0) - Y_{\text{corr}}(\bar{D}^0)}{Y_{\text{corr}}(D^0) + Y_{\text{corr}}(\bar{D}^0)}, \tag{1}$$

where $Y_{\text{corr}}(D^0)$ and $Y_{\text{corr}}(\bar{D}^0)$ correspond to the $D^0 \rightarrow K^- \pi^+$ and $\bar{D}^0 \rightarrow K^+ \pi^-$ efficiency corrected yields respectively. The uncertainties associated with the luminosity determination, neon purity and particle identification efficiency cancel in the asymmetry. Furthermore, uncertainties related to the tracking efficiency and simulation samples partially cancel. A conservative systematic uncertainty of 2.8% is

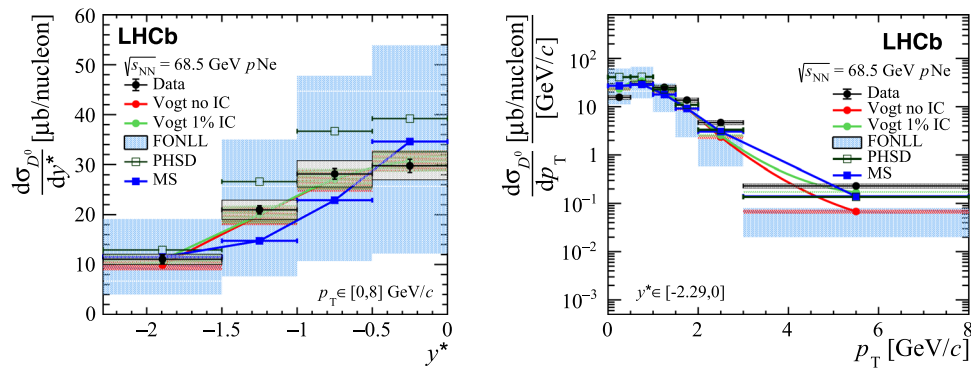


Fig. 2 Measured D^0 cross-section in $\sqrt{s_{NN}} = 68.5$ GeV p Ne collisions as function of (left) y^* and (right) p_T . The quadratic sums of statistical and uncorrelated systematic uncertainties are given by the

bars, while the grey boxes represent the correlated systematic uncertainties. The data are overlaid with theoretical predictions as described in the text

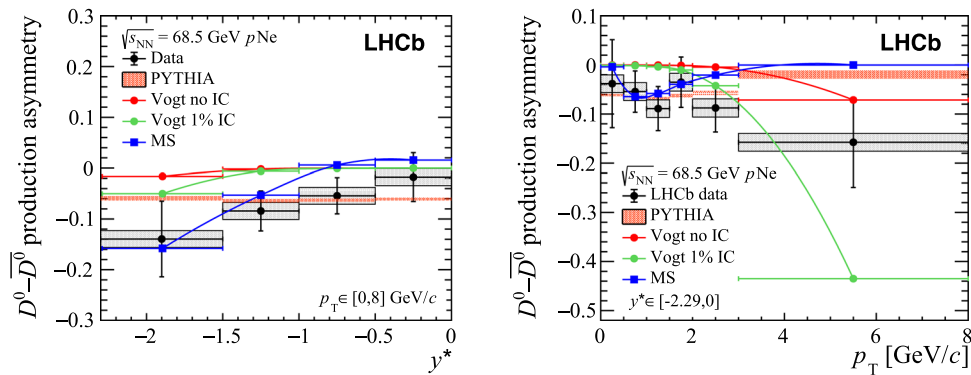


Fig. 3 The $D^0 - \bar{D}^0$ production asymmetry in $\sqrt{s_{NN}} = 68.5$ GeV p Ne collisions as function of (left) centre-of-mass rapidity y^* , and as function of (right) transverse momentum p_T . Quadratic sums of statistical

and uncorrelated uncertainties are given by the error bars, while the grey boxes represent the correlated systematic uncertainties. The data are overlaid with theoretical predictions as described in the text

assigned to account for the uncertainty on the simulated material budget of the detector.

The results are presented in Fig. 3 and indicate a negative asymmetry from ~ 0 down to $\sim -15\%$ from $y^* = 0$ to $y^* = -2.29$. The largest asymmetry is obtained at $y^* = -2.29$, where the valence quark contribution of the neon target is more significant than at $y^* \sim 0$. The data are compared with PYTHIA 8 predictions which show a $D^0 - \bar{D}^0$ asymmetry of about -6% . This asymmetry, which may be caused by the fragmentation models included in PYTHIA [33,34], is compatible with the data, but mostly independent of y^* and p_T . While the Vogt predictions from Ref. [31], which represent an upper limit, do not perfectly reproduce the asymmetry scale, they indicate trends compatible with the data for both the rapidity and transverse momentum ratios. The MS predictions including 1% IC and 10% recombination contributions [6] are also generally consistent with the data.

In summary, a study of D^0 meson production in $\sqrt{s_{NN}} = 68.5$ GeV p Ne collisions with the LHCb experiment is presented. The sum of the D^0 and \bar{D}^0 production cross-section

per target nucleon, measured in the centre-of-mass rapidity range $y^* \in [-2.29, 0]$, is found to be $\sigma_{D^0}^{y^* \in [-2.29, 0]} = 48.2 \pm 0.3$ (stat.) ± 4.5 (syst.) $\mu\text{b/nucleon}$. The $D^0 - \bar{D}^0$ production asymmetry tends towards a negative value of roughly -15% in the $y^* \sim -2$ region, where the valence quark contribution of the neon target is more significant than at $y^* \sim 0$.

Acknowledgements We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MICINN (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), Polish WLCG (Poland) and NERSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from ARC and

ARDC (Australia); Minciencias (Colombia); AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union); A*MIDEX, ANR, IPhU and GLUODYNAMICS/Labex P2IO, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Fundamental Research Funds for the Central Universities, and Sci. and Tech. Program of Guangzhou (China); GVA, XuntaGal, GENCAT and Prog. Atracción Talento, CM (Spain); SRC (Sweden); the Leverhulme Trust, the Royal Society and UKRI (United Kingdom).

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: Data associated to the plots in this publication are made available on the CERN document server at <https://cds.cern.ch/record/2841850>.]

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

Funded by SCOAP³. SCOAP³ supports the goals of the International Year of Basic Sciences for Sustainable Development.

References

- H. Satz, K. Sridhar, Charmonium production versus open charm in nuclear collisions. *Phys. Rev. D* **50**, 3557 (1994). <https://doi.org/10.1103/PhysRevD.50.3557>
- R. Maciula, A. Szczurek, Impact of the LHCb $p+^4\text{He}$ fixed-target D^0/\bar{D}^0 data on the intrinsic $c\bar{c}$ component in the nucleon. *Phys. Rev. D* **105**, 014001 (2022). <https://doi.org/10.1103/PhysRevD.105.014001>
- LHCb Collaboration, R. Aaij et al., First measurement of charm production in fixed-target configuration at the LHC. *Phys. Rev. Lett.* **102**, 132002 (2019). <https://doi.org/10.1103/PhysRevLett.102.132002>
- LHCb Collaboration, R. Aaij et al., Study of Z bosons produced in association with charm in the forward region. *Phys. Rev. Lett.* **128**, 082001 (2022). <https://doi.org/10.1103/PhysRevLett.128.082001>
- The NNPDF Collaboration, R.D. Ball et al., Evidence for intrinsic charm quarks in the proton. *Nature* **608**, 483–487 (2022). <https://doi.org/10.1038/s41586-022-04998-2>
- R. Maciula, A. Szczurek, Recombination mechanism for D^0 -meson production and $D - \bar{D}^0$ production asymmetry in the LHCb $p + ^{20}\text{Ne}$ fixed-target experiment. *Phys. Lett. B* **835**, 137530 (2022). <https://doi.org/10.1016/j.physletb.2022.137530>. [arXiv:2206.02750](https://arxiv.org/abs/2206.02750)
- Fermilab E791 Collaboration, E.M. Aitala et al., Asymmetries between the production of D^+ and D^- mesons from 500 GeV/c π^- -nucleus interactions as a function of x_F and p_T^2 . *Phys. Lett. B* **371**, 157–162 (1996). [https://doi.org/10.1016/0370-2693\(96\)00093-7](https://doi.org/10.1016/0370-2693(96)00093-7)
- E. Braaten, Y. Jia, T. Mehen, Charm–anticharm asymmetries in photoproduction from heavy-quark recombination. *Phys. Rev. D* **66**, 014003 (2002). <https://doi.org/10.1103/PhysRevD.66.014003>
- LHCb Collaboration, A.A. Alves Jr. et al., The LHCb detector at the LHC. *JINST* **3**, S08005 (2008). <https://doi.org/10.1088/1748-0221/3/08/S08005>
- LHCb Collaboration, R. Aaij et al., LHCb detector performance. *Int. J. Mod. Phys. A* **30**, 1530022 (2015). <https://doi.org/10.1142/S0217751X15300227>. [arXiv:1412.6352](https://arxiv.org/abs/1412.6352)
- LHCb Collaboration, R. Aaij et al., Precision luminosity measurements at LHCb. *JINST* **9**, P12005 (2014). <https://doi.org/10.1088/1748-0221/9/12/P12005>. [arXiv:1410.0149](https://arxiv.org/abs/1410.0149)
- LHCb Collaboration, R. Aaij et al., The LHCb trigger and its performance in 2011. *JINST* **8**, P04022 (2013). <https://doi.org/10.1088/1748-0221/8/04/P04022>. [arXiv:1211.3055](https://arxiv.org/abs/1211.3055)
- LHCb Collaboration, R. Aaij et al., First measurement of charm production in fixed-target configuration at the LHC. *Phys. Rev. Lett.* **122**, 132002 (2019). <https://doi.org/10.1103/PhysRevLett.122.132002>. [arXiv:1810.07907](https://arxiv.org/abs/1810.07907)
- T. Sjöstrand, S. Mrenna, P. Skands, A brief introduction to Pythia 8.1. *Comput. Phys. Commun.* **178**, 852 (2008). <https://doi.org/10.1016/j.cpc.2008.01.036>. [arXiv:0710.3820](https://arxiv.org/abs/0710.3820)
- B. Andersson, G. Gutafson, G. Ingelman, T. Sjöstrand, Parton fragmentation and string dynamics. *Phys. Rep.* **97**, 31–45 (1983). [https://doi.org/10.1016/0370-1573\(83\)90080-7](https://doi.org/10.1016/0370-1573(83)90080-7)
- LHCb Collaboration, I. Belyaev et al., Handling of the generation of primary events in Gauss, the LHCb simulation framework. *J. Phys. Conf. Ser.* **331**, 032047 (2011). <https://doi.org/10.1088/1742-6596/331/3/032047>
- D.J. Lange, The EvtGen particle decay simulation package. *Nucl. Instrum. Methods* **A462**, 152 (2001). [https://doi.org/10.1016/S0168-9002\(01\)00089-4](https://doi.org/10.1016/S0168-9002(01)00089-4)
- P. Golonka, Z. Was, PHOTOS Monte Carlo: a precision tool for QED corrections in Z and W decays. *Eur. Phys. J. C* **45**, 97 (2006). <https://doi.org/10.1140/epjc/s2005-02396-4>
- T. Pierog et al., EPOS LHC: test of collective hadronization with data measured at the CERN Large Hadron Collider. *Phys. Rev. C* **C92**, 034906 (2015). <https://doi.org/10.1103/PhysRevC.92.034906>. [arXiv:1306.0121](https://arxiv.org/abs/1306.0121)
- Geant4 Collaboration, J. Allison et al., Geant4 developments and applications. *IEEE Trans. Nucl. Sci.* **53**, 270 (2006). <https://doi.org/10.1109/TNS.2006.869826>
- GEANT4 Collaboration, S. Agostinelli et al., Geant4: a simulation toolkit. *Nucl. Instrum. Methods* **506**, 250 (2003). [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8)
- M. Clemencic et al., The LHCb simulation application, Gauss: design, evolution and experience. *J. Phys. Conf. Ser.* **331**, 032023 (2011). <https://doi.org/10.1088/1742-6596/331/3/032023>
- L. Anderlini et al., The PIDCalib package. LHCb-PUB-2016-021. http://cdsweb.cern.ch/search?p=LHCb-PUB-2016-021&f=reportnumber&action_search=Search&c=LHCb+Notes
- LHCb Collaboration, R. Aaij et al., Measurement of the track reconstruction efficiency at LHCb. *JINST* **10**, P02007 (2015). <https://doi.org/10.1088/1748-0221/10/02/P02007>
- LHCb Collaboration, R. Aaij et al., Measurement of antiproton production in $p\text{He}$ collisions at $\sqrt{s_{\text{NN}}} = 110$ GeV. *Phys. Rev. Lett.* **121**, 222001 (2018). <https://doi.org/10.1103/PhysRevLett.121.222001>
- Particle Data Group, R.L. Workman et al., Review of particle physics. *Prog. Theor. Exp. Phys.* **2022**(8), 083C01 (2022). <https://doi.org/10.1093/ptep/ptac097> <http://pdg.lbl.gov/>
- H.-L. Lai et al., Parton distributions for event generators. *JHEP* **04**, 035 (2010). [https://doi.org/10.1007/JHEP04\(2010\)035](https://doi.org/10.1007/JHEP04(2010)035)
- M. Cacciari, P. Nason, R. Vogt, QCD predictions for charm and bottom quark production at RHIC. *Phys. Rev. Lett.* **95**, 122001 (2005). <https://doi.org/10.1103/PhysRevLett.95.122001>
- M. Cacciari, M. Greco, P. Nason, The p_T spectrum in heavy-flavour hadroproduction. *JHEP* **05**, 007 (1998). <https://doi.org/10.1088/1126-6708/1998/05/007>




































30. T. Song et al., Single electrons from heavy-flavor mesons in relativistic heavy-ion collisions. *Phys. Rev. C* **C96**, 014905 (2017). <https://doi.org/10.1103/PhysRevC.96.014905>
31. R. Vogt, Limits on intrinsic charm production from the SeaQuest experiment. *Phys. Rev. C* **103**, 035204 (2021). <https://doi.org/10.1103/PhysRevC.103.035204>
32. STAR Collaboration, L. Adamczyk et al., Measurements of D^0 and D^{*} production in $p + p$ collisions at $\sqrt{s} = 200$ GeV. *Phys. Rev. D* **86**, 072013 (2012). <https://doi.org/10.1103/PhysRevD.86.072013>
33. E. Norrbin, T. Sjöstrand, Production mechanisms of charm hadrons in the string model. *Phys. Lett. B* **442**, 407–416 (1998). [https://doi.org/10.1016/S0370-2693\(98\)01244-1](https://doi.org/10.1016/S0370-2693(98)01244-1)
34. E. Norrbin, T. Sjöstrand, Production and hadronization of heavy quarks. *Eur. Phys. J. C* **C17**, 137–161 (2000). <https://doi.org/10.1007/s100520000460>

LHCb Collaboration*

R. Aaij³², A. S. W. Abdelmotteleb⁵⁰, C. Abellan Beteta⁴⁴, F. Abudinén⁵⁰, T. Ackernley⁵⁴, B. Adeva⁴⁰, M. Adinolfi⁴⁸, P. Adlarson⁷⁷, H. Afsharnia⁹, C. Agapopoulou¹³, C. A. Aidala⁷⁸, Z. Ajaltouni⁹, S. Akar⁵⁹, K. Akiba³², J. Albrecht¹⁵, F. Alessio⁴², M. Alexander⁵³, A. Alfonso Alberio³⁹, Z. Aliouche⁵⁶, P. Alvarez Cartelle⁴⁹, R. Amalric¹³, S. Amato², J. L. Amey⁴⁸, Y. Amhis^{11,42}, L. An⁴², L. Anderlini²², M. Andersson⁴⁴, A. Andreianov³⁸, M. Andreotti²¹, D. Andreou⁶², D. Ao⁶, F. Archilli¹⁷, A. Artamonov³⁸, M. Artuso⁶², E. Aslanides¹⁰, M. Atzeni⁴⁴, B. Audurier¹², S. Bachmann¹⁷, M. Bachmayer⁴³, J. J. Back⁵⁰, A. Bailly-reyre¹³, P. Baladron Rodriguez⁴⁰, V. Balagura¹², W. Baldini²¹, J. Baptista de Souza Leite¹, M. Barbetti^{22,j}, R. J. Barlow⁵⁶, S. Barsuk¹¹, W. Barter⁵⁵, M. Bartolini⁴⁹, F. Baryshnikov³⁸, J. M. Basels¹⁴, G. Bassi^{29,p}, B. Batsukh⁴, A. Battig¹⁵, A. Bay⁴³, A. Beck⁵⁰, M. Becker¹⁵, F. Bedeschi²⁹, I. B. Bediaga¹, A. Beiter⁶², V. Belavin³⁸, S. Belin⁴⁰, V. Bellee⁴⁴, K. Belous³⁸, I. Belov³⁸, I. Belyaev³⁸, G. Benane¹⁰, G. Bencivenni²³, E. Ben-Haim¹³, A. Berezhnoy³⁸, R. Bernet⁴⁴, S. Bernet Andres⁷⁶, D. Berninghoff¹⁷, H. C. Bernstein⁶², C. Bertella⁵⁶, A. Bertolin²⁸, C. Betancourt⁴⁴, F. Betti⁴², Ia. Bezshyiko⁴⁴, S. Bhasin⁴⁸, J. Bhom³⁵, L. Bian⁶⁸, M. S. Bieker¹⁵, N. V. Biesuz²¹, S. Bifani⁴⁷, P. Billoir¹³, A. Biolchini³², M. Birch⁵⁵, F. C. R. Bishop⁴⁹, A. Bitadze⁵⁶, A. Bizzeti⁴², M. P. Blago⁴⁹, T. Blake⁵⁰, F. Blanc⁴³, J. E. Blank¹⁵, S. Blusk⁶², D. Bobulska⁵³, J. A. Boelhaue¹⁵, O. Boente Garcia¹², T. Boettcher⁵⁹, A. Boldyrev³⁸, C. S. Bolognani⁷⁴, R. Bolzonella^{21,i}, N. Bondar^{38,42}, F. Borgato²⁸, S. Borghi⁵⁶, M. Borsato¹⁷, J. T. Borsuk³⁵, S. A. Bouchiba⁴³, T. J. V. Bowcock⁵⁴, A. Boyer⁴², C. Bozzi²¹, M. J. Bradley⁵⁵, S. Braun⁶⁰, A. Brea Rodriguez⁴⁰, J. Brodzicka³⁵, A. Brossa Gonzalo⁴⁰, J. Brown⁵⁴, D. Brundu²⁷, A. Buonauro⁴⁴, L. Buonincontri²⁸, A. T. Burke⁵⁶, C. Burr⁴², A. Bursche⁶⁶, A. Butkevich³⁸, J. S. Butter³², J. Buytaert⁴², W. Byczynski⁴², S. Cadeddu²⁷, H. Cai⁶⁸, R. Calabrese^{21,i}, L. Calefice¹⁵, S. Cali²³, R. Calladine⁴⁷, M. Calvi^{26,m}, M. Calvo Gomez⁷⁶, P. Campana²³, D. H. Campora Perez⁷⁴, A. F. Campoverde Quezada⁶, S. Capelli^{26,m}, L. Capriotti²⁰, A. Carbone^{20,g}, G. Carboni³¹, R. Cardinale^{24,k}, A. Cardini²⁷, P. Carniti^{26,m}, L. Carus¹⁴, A. Casais Vidal⁴⁰, R. Caspary¹⁷, G. Casse⁵⁴, M. Cattaneo⁴², G. Cavallero⁴², V. Cavallini^{21,i}, S. Celani⁴³, J. Cerasoli¹⁰, D. Cervenkov⁵⁷, A. J. Chadwick⁵⁴, M. G. Chapman⁴⁸, M. Charles¹³, Ph. Charpentier⁴², C. A. Chavez Barajas⁵⁴, M. Chefdeville⁸, C. Chen³, S. Chen⁴, A. Chernov³⁵, S. Chernyshenko⁴⁶, V. Chobanova⁴⁰, S. Cholak⁴³, M. Chruszcz³⁵, A. Chubykin³⁸, V. Chulikov³⁸, P. Ciambone²³, M. F. Cicala⁵⁰, X. Cid Vidal⁴⁰, G. Ciezarek⁴², G. Ciullo^{21,i}, P. E. L. Clarke⁵², M. Clemencic⁴², H. V. Cliff⁴⁹, J. Closier⁴², J. L. Cobbedick⁵⁶, V. Coco⁴², J. A. B. Coelho¹¹, J. Cogan¹⁰, E. Cogneras⁹, L. Cojocariu³⁷, P. Collins⁴², T. Colombo⁴², L. Congedo¹⁹, A. Contu²⁷, N. Cooke⁴⁷, I. Corredoira⁴⁰, G. Corti⁴², B. Couturier⁴², D. C. Craik⁴⁴, M. Cruz Torres^{1,e}, R. Currie⁵², C. L. Da Silva⁶¹, S. Dadabaev³⁸, L. Dai⁶⁵, X. Dai⁵, E. Dall'Occo¹⁵, J. Dalseno⁴⁰, C. D'Ambrosio⁴², J. Daniel⁹, A. Danilina³⁸, P. d'Argent¹⁵, J. E. Davies⁵⁶, A. Davis⁵⁶, O. De Aguiar Francisco⁵⁶, J. de Boer⁴², K. De Bruyn⁷³, S. De Capua⁵⁶, M. De Cian⁴³, U. De Freitas Carneiro Da Graca¹, E. De Lucia²³, J. M. De Miranda¹, L. De Paula², M. De Serio^{19,f}, D. De Simone⁴⁴, P. De Simone²³, F. De Vellis¹⁵, J. A. de Vries⁷⁴, C. T. Dean⁶¹, F. Debernardis^{19,f}, D. Decamp⁸, V. Dedu¹⁰, L. Del Buono¹³, B. Delaney⁵⁸, H.-P. Dembinski¹⁵, V. Denysenko⁴⁴, O. Deschamps⁹, F. Dettori^{27,h}, B. Dey⁷¹, P. Di Nezza²³, I. Diachkov³⁸, S. Didenko³⁸, L. Dieste Maronas⁴⁰, S. Ding⁶², V. Dobishuk⁴⁶, A. Dolmatov³⁸, C. Dong³, A. M. Donohoe¹⁸, F. Dordei²⁷, A. C. dos Reis¹, L. Douglas⁵³, A. G. Downes⁸, P. Duda⁷⁵, M. W. Dudek³⁵, L. Dufour⁴², V. Duk⁷², P. Durante⁴², M. M. Duras⁷⁵, J. M. Durham⁶¹, D. Dutta⁵⁶, A. Dziurda³⁵, A. Dzyuba³⁸, S. Easo⁵¹, U. Egede⁶³, V. Egorychev³⁸, S. Eidelman^{38,*}, C. Eirea Orro⁴⁰, S. Eisenhardt⁵², E. Ejopu⁵⁶, S. Ek-In⁴³, L. Eklund⁷⁷, S. Ely⁶², A. Ene³⁷, E. Eppe⁵⁹, S. Escher¹⁴, J. Eschle⁴⁴, S. Esen⁴⁴, T. Evans⁵⁶

F. Fabiano^{27,h}, L. N. Falcao¹, Y. Fan⁶, B. Fang^{11,68}, L. Fantini^{72,o}, M. Faria⁴³, S. Farry⁵⁴, D. Fazzini^{26,m}, L. F. Felkowski⁷⁵, M. Feo⁴², M. Fernandez Gomez⁴⁰, A. D. Fernez⁶⁰, F. Ferrari²⁰, L. Ferreira Lopes⁴³, F. Ferreira Rodrigues², S. Ferreres Sole³², M. Ferrillo⁴⁴, M. Ferro-Luzzi⁴², S. Filippov³⁸, R. A. Fini¹⁹, M. Fiorini^{21,i}, M. Firlej³⁴, K. M. Fischer⁵⁷, D. S. Fitzgerald⁷⁸, C. Fitzpatrick⁵⁶, T. Fiutowski³⁴, F. Fleuret¹², M. Fontana¹³, F. Fontanelli^{24,k}, R. Forty⁴², D. Foulds-Holt⁴⁹, V. Franco Lima⁵⁴, M. Franco Sevilla⁶⁰, M. Frank⁴², E. Franzoso^{21,i}, G. Frau¹⁷, C. Frei⁴², D. A. Friday⁵³, J. Fu⁶, Q. Fuehring¹⁵, T. Fulghesu¹³, E. Gabriel³², G. Galati^{19,f}, M. D. Galati³², A. Gallas Torreira⁴⁰, D. Galli^{20,g}, S. Gambetta^{42,52}, Y. Gan³, M. Gandelman², P. Gandini²⁵, Y. Gao⁷, Y. Gao⁵, M. Garau^{27,h}, L. M. Garcia Martin⁵⁰, P. Garcia Moreno³⁹, J. García Pardiñas^{26,m}, B. Garcia Plana⁴⁰, F. A. Garcia Rosales¹², L. Garrido³⁹, C. Gaspar⁴², R. E. Geertsema³², D. Gerick¹⁷, L. L. Gerken¹⁵, E. Gersabeck⁵⁶, M. Gersabeck⁵⁶, T. Gershon⁵⁰, L. Giambastiani²⁸, V. Gibson⁴⁹, H. K. Gienza³⁶, A. L. Gilman⁵⁷, M. Giovannetti^{23,s}, A. Gioventù⁴⁰, P. Gironella Gironell³⁹, C. Giugliano^{21,i}, M. A. Giza³⁵, K. Gizdov⁵², E. L. Gkougkousis⁴², V. V. Gligorov^{13,42}, C. Göbel⁶⁴, E. Golobardes⁷⁶, D. Golubkov³⁸, A. Golutvin^{38,55}, A. Gomes^{1,a}, S. Gomez Fernandez³⁹, F. Goncalves Abrantes⁵⁷, M. Gonczorz³⁵, G. Gong³, I. V. Gorelov³⁸, C. Gotti²⁶, J. P. Grabowski⁷⁰, T. Grammatico¹³, L. A. Granado Cardoso⁴², E. Graugés³⁹, E. Graverini⁴³, G. Graziani¹, A. T. Grecu³⁷, L. M. Greeven³², N. A. Grieser⁴, L. Grillo⁵³, S. Gromov³⁸, B. R. Gruberg Cazon⁵⁷, C. Gu³, M. Guarise^{21,i}, M. Guittiere¹¹, P. A. Günther¹⁷, E. Gushchin³⁸, A. Guth¹⁴, Y. Guz³⁸, T. Gys⁴², T. Hadavizadeh⁶³, C. Hadjivasiliou⁶⁰, G. Haefeli⁴³, C. Haen⁴², J. Haimberger⁴², S. C. Haines⁴⁹, T. Halewood-leagas⁵⁴, M. M. Halvorsen⁴², P. M. Hamilton⁶⁰, J. Hammerich⁵⁴, Q. Han⁷, X. Han¹⁷, E. B. Hansen⁵⁶, S. Hansmann-Menzemer¹⁷, L. Hao⁶, N. Harnew⁵⁷, T. Harrison⁵⁴, C. Hasse⁴², M. Hatch⁴², J. He^{6,c}, K. Heijhoff³², C. Henderson⁵⁹, R. D. L. Henderson^{50,63}, A. M. Hennequin⁵⁸, K. Hennessy⁵⁴, L. Henry⁴², J. Herd⁵⁵, J. Heuel¹⁴, A. Hicheur², D. Hill⁴³, M. Hilton⁵⁶, S. E. Hollitt¹⁵, J. Horswill⁵⁶, R. Hou⁷, Y. Hou⁸, J. Hu¹⁷, J. Hu⁶⁶, W. Hu⁵, X. Hu³, W. Huang⁶, X. Huang⁶⁸, W. Hulsbergen³², R. J. Hunter⁵⁰, M. Hushchyn³⁸, D. Hutchcroft⁵⁴, P. Ibis¹⁵, M. Idzik³⁴, D. Ilin³⁸, P. Ilten⁵⁹, A. Inglessi³⁸, A. Iniukhin³⁸, A. Ishteev³⁸, K. Ivshin³⁸, R. Jacobsson⁴², H. Jage¹⁴, S. J. Jaimes Elles⁴¹, S. Jakobsen⁴², E. Jans³², B. K. Jashal⁴¹, A. Jawahery⁶⁰, V. Jevtic¹⁵, E. Jiang⁶⁰, X. Jiang^{4,6}, Y. Jiang⁶, M. John⁵⁷, D. Johnson⁵⁸, C. R. Jones⁴⁹, T. P. Jones⁵⁰, B. Jost⁴², N. Jurik⁴², I. Juszczak³⁵, S. Kandybei⁴⁵, Y. Kang³, M. Karacson⁴², D. Karpenkov³⁸, M. Karpov³⁸, J. W. Kautz⁵⁹, F. Keizer⁴², D. M. Keller⁶², M. Kenzie⁵⁰, T. Ketel³², B. Khanji¹⁵, A. Kharisova³⁸, S. Kholodenko³⁸, G. Khreich¹¹, T. Kirn¹⁴, V. S. Kirsebom⁴³, O. Kitouni⁵⁸, S. Klaver³³, N. Kleijne^{29,p}, K. Klimaszewski³⁶, M. R. Kmiec³⁶, S. Koliiev⁴⁶, A. Kondybayeva³⁸, A. Konoplyannikov³⁸, P. Kopciwicz³⁴, R. Kopečna¹⁷, P. Koppenburg³², M. Korolev³⁸, I. Kostiuik^{32,46}, O. Kot⁴⁶, S. Kotriakhova¹, A. Kozachuk³⁸, P. Kravchenko³⁸, L. Kravchuk³⁸, R. D. Krawczyk⁴², M. Kreps⁵⁰, S. Kretschmar¹⁴, P. Krokovny³⁸, W. Krupa³⁴, W. Krzemien³⁶, J. Kubat¹⁷, S. Kubis⁷⁵, W. Kucewicz^{34,35}, M. Kucharczyk³⁵, V. Kudryavtsev³⁸, A. Kupsc⁷⁷, D. Lacarrere⁴², G. Lafferty⁵⁶, A. Lai²⁷, A. Lampis^{27,h}, D. Lancierini⁴⁴, C. Landesa Gomez⁴⁰, J. J. Lane⁵⁶, R. Lane⁴⁸, G. Lanfranchi²³, C. Langenbruch¹⁴, J. Langer¹⁵, O. Lantwin³⁸, T. Latham⁵⁰, F. Lazzari^{29,t}, M. Lazzaroni²⁵, R. Le Gac¹⁰, S. H. Lee⁷⁸, R. Lefèvre⁹, A. Leflat³⁸, S. Legotin³⁸, P. Lenisa^{21,i}, O. Leroy¹⁰, T. Lesiak³⁵, B. Leverington¹⁷, A. Li³, H. Li⁶⁶, K. Li⁷, P. Li¹⁷, P.-R. Li⁶⁷, S. Li⁷, T. Li⁴, T. Li⁶⁶, Y. Li⁴, Z. Li⁶², X. Liang⁶², C. Lin⁶, T. Lin⁵¹, R. Lindner⁴², V. Lisovskyi¹⁵, R. Litvinov^{27,h}, G. Liu⁶⁶, H. Liu⁶, Q. Liu⁶, S. Liu^{4,6}, A. Lobo Salvia³⁹, A. Loi²⁷, R. Lollini⁷², J. Lomba Castro⁴⁰, I. Longstaff⁵³, J. H. Lopes², A. Lopez Huertas³⁹, S. L.ópez Soliño⁴⁰, G. H. Lovell⁴⁹, Y. Lu^{4,b}, C. Lucarelli^{22,j}, D. Lucchesi^{28,n}, S. Luchuk³⁸, M. Lucio Martinez⁷⁴, V. Lukashenko^{32,46}, Y. Luo³, A. Lupato⁵⁶, E. Luppi^{21,i}, A. Lusiani^{29,p}, K. Lynch¹⁸, X.-R. Lyu⁶, L. Ma⁴, R. Ma⁶, S. Maccolini²⁰, F. Machefert¹¹, F. Maciuc³⁷, I. Mackay⁵⁷, V. Macko⁴³, P. Mackowiak¹⁵, L. R. Madhan Mohan⁴⁸, A. Maevskiy³⁸, D. Maisuzenko³⁸, M. W. Majewski³⁴, J. J. Malczewski³⁵, S. Malde⁵⁷, B. Malecki^{35,42}, A. Malinin³⁸, T. Maltsev³⁸, G. Manca^{27,h}, G. Mancinelli¹⁰, C. Mancuso^{11,25,1}, D. Manuzzi²⁰, C. A. Manzari⁴⁴, D. Marangotto^{25,1}, J. M. Maratas^{9,v}, J. F. Marchand⁸, U. Marconi²⁰, S. Mariani^{22,j}, C. Marin Benito³⁹, J. Marks¹⁷, A. M. Marshall⁴⁸, P. J. Marshall⁵⁴, G. Martelli^{72,o}, G. Martellotti³⁰, L. Martinazzoli^{42,m}, M. Martinelli^{26,m}, D. Martinez Santos⁴⁰, F. Martinez Vidal⁴¹, A. Massafferri¹, M. Materok¹⁴, R. Matev⁴², A. Mathad⁴⁴, V. Matiunin³⁸, C. Matteuzzi²⁶, K. R. Mattioli¹², A. Mauri³², E. Maurice¹², J. Mauricio³⁹, M. Mazurek⁴², M. McCann⁵⁵, L. McConnell¹⁸, T. H. McGrath⁵⁶, N. T. McHugh⁵³, A. McNab⁵⁶, R. McNulty¹⁸, J. V. Mead⁵⁴, B. Meadows⁵⁹, G. Meier¹⁵, D. Melnychuk³⁶, S. Meloni^{26,m}, M. Merk^{32,74}, A. Merli^{25,1}, L. Meyer Garcia², D. Miao^{4,6}, M. Mikhasenko^{70,d}, D. A. Milanés⁶⁹, E. Millard⁵⁰,

M. Milovanovic⁴², M.-N. Minard^{8,*}, A. Minotti^{26,m}, T. Miralles⁹, S. E. Mitchell⁵², B. Mitreska⁵⁶, D. S. Mitzel¹⁵, A. Mödden¹⁵, R. A. Mohammed⁵⁷, R. D. Moise¹⁴, S. Mokhnenko³⁸, T. Mombächer⁴⁰, M. Monk^{50,63}, I. A. Monroy⁶⁹, S. Monteil⁹, M. Morandin²⁸, G. Morello²³, M. J. Morello^{29,p}, J. Moron³⁴, A. B. Morris⁷⁰, A. G. Morris⁵⁰, R. Mountain⁶², H. Mu³, E. Muhammad⁵⁰, F. Muheim⁵², M. Mulder⁷³, K. Müller⁴⁴, C. H. Murphy⁵⁷, D. Murray⁵⁶, R. Murta⁵⁵, P. Muzzetto^{27,h}, P. Naik⁴⁸, T. Nakada⁴³, R. Nandakumar⁵¹, T. Nanut⁴², I. Nasteva², M. Needham⁵², N. Neri^{25,1}, S. Neubert⁷⁰, N. Neufeld⁴², P. Neustroev³⁸, R. Newcombe⁵⁵, J. Nicolini^{11,15}, E. M. Niel⁴³, S. Nieswand¹⁴, N. Nikitin³⁸, N. S. Nolte⁵⁸, C. Normand^{8,27,h}, J. Novoa Fernandez⁴⁰, C. Nunez⁷⁸, A. Oblakowska-Mucha³⁴, V. Obraztsov³⁸, T. Oeser¹⁴, D. P. O'Hanlon⁴⁸, S. Okamura^{21,i}, R. Oldeman^{27,h}, F. Oliva⁵², C. J. G. Onderwater⁷³, R. H. O'Neil⁵², J. M. Otalora Goicochea², T. Ovsianikova³⁸, P. Owen⁴⁴, A. Oyanguren⁴¹, O. Ozcelik⁵², K. O. Padeken⁷⁰, B. Pagare⁵⁰, P. R. Pais⁴², T. Pajero⁵⁷, A. Palano¹⁹, M. Palutan²³, Y. Pan⁵⁶, G. Panshin³⁸, L. Paolucci⁵⁰, A. Papanestis⁵¹, M. Pappagallo^{19,f}, L. L. Pappalardo^{21,i}, C. Pappenheimer⁵⁹, W. Parker⁶⁰, C. Parkes⁵⁶, B. Passalacqua^{21,i}, G. Passaleva²², A. Pastore¹⁹, M. Patel⁵⁵, C. Patrignani^{20,g}, C. J. Pawley⁷⁴, A. Pearce⁴², A. Pellegrino³², M. Pepe Altarelli⁴², S. Perazzini²⁰, D. Pereima³⁸, A. Pereiro Castro⁴⁰, P. Perret⁹, M. Petric⁵³, K. Petridis⁴⁸, A. Petrolini^{24,k}, A. Petrov³⁸, S. Petrucci⁵², M. Petruzzo²⁵, H. Pham⁶², A. Philippov³⁸, R. Piandani⁶, L. Pica^{29,p}, M. Piccini⁷², B. Pietrzyk⁸, G. Pietrzyk¹¹, M. Pili⁵⁷, D. Pinci³⁰, F. Pisani⁴², M. Pizzichemi^{26,42,m}, V. Placinta³⁷, J. Plews⁴⁷, M. Plo Casasus⁴⁰, F. Polci^{13,42}, M. Poli Lener²³, M. Poliakov⁶², A. Poluektov¹⁰, N. Polukhina³⁸, I. Polyakov⁴², E. Polycarpo², S. Ponce⁴², D. Popov^{6,42}, S. Popov³⁸, S. Poslavskii³⁸, K. Prasanth³⁵, L. Promberger¹⁷, C. Prouve⁴⁰, V. Pugatch⁴⁶, V. Puill¹¹, G. Punzi^{29,q}, H. R. Qi³, W. Qian⁶, N. Qin³, S. Qu³, R. Quagliani⁴³, N. V. Raab¹⁸, R. I. Rabadan Trejo⁶, B. Rachwal³⁴, J. H. Rademacker⁴⁸, R. Rajagopalan⁶², M. Rama²⁹, M. Ramos Pernas⁵⁰, M. S. Rangel², F. Ratnikov³⁸, G. Raven^{33,42}, M. Rebollo De Miguel⁴¹, F. Redi⁴², J. Reich⁴⁸, F. Reiss⁵⁶, C. Remon Alepuz⁴¹, Z. Ren³, P. K. Resmi¹⁰, R. Ribatti^{29,p}, A. M. Ricci²⁷, S. Ricciardi⁵¹, K. Richardson⁵⁸, M. Richardson-Slipper⁵², K. Rinnert⁵⁴, P. Robbe¹¹, G. Robertson⁵², A. B. Rodrigues⁴³, E. Rodrigues⁵⁴, E. Rodriguez Fernandez⁴⁰, J. A. Rodriguez Lopez⁶⁹, E. Rodriguez Rodriguez⁴⁰, D. L. Rolf⁴², A. Rollings⁵⁷, P. Roloff⁴², V. Romanovskiy³⁸, M. Romero Lamas⁴⁰, A. Romero Vidal⁴⁰, J. D. Roth^{78,*}, M. Rotondo²³, M. S. Rudolph⁶², T. Ruf⁴², R. A. Ruiz Fernandez⁴⁰, J. Ruiz Vidal⁴¹, A. Ryzhikov³⁸, J. Ryzka³⁴, J. J. Saborido Silva⁴⁰, N. Sagidova³⁸, N. Sahoo⁴⁷, B. Saitta^{27,h}, M. Salomoni⁴², C. Sanchez Gras³², I. Sanderswood⁴¹, R. Santacesaria³⁰, C. Santamarina Rios⁴⁰, M. Santimaria²³, E. Santovetti^{31,s}, D. Saranin³⁸, G. Sarpis¹⁴, M. Sarpis⁷⁰, A. Sarti³⁰, C. Satriano^{30,r}, A. Satta³¹, M. Saur¹⁵, D. Savrina³⁸, H. Sazak⁹, L. G. Scantlebury Smead⁵⁷, A. Scarabotto¹³, S. Schael¹⁴, S. Scherl⁵⁴, M. Schiller⁵³, H. Schindler⁴², M. Schmelling¹⁶, B. Schmidt⁴², S. Schmitt¹⁴, O. Schneider⁴³, A. Schopper⁴², M. Schubiger³², S. Schulte⁴³, M. H. Schune¹¹, R. Schwemmer⁴², B. Sciascia^{23,42}, A. Sciuccati⁴², S. Sellam⁴⁰, A. Semennikov³⁸, M. Senghi Soares³³, A. Sergi^{24,k}, N. Serra⁴⁴, L. Sestini²⁸, A. Seuthe¹⁵, Y. Shang⁵, D. M. Shangase⁷⁸, M. Shapkin³⁸, I. Shchemerov³⁸, L. Shchutka⁴³, T. Shears⁵⁴, L. Shekhtman³⁸, Z. Shen⁵, S. Sheng^{4,6}, V. Shevchenko³⁸, B. Shi⁶, E. B. Shields^{26,m}, Y. Shimizu¹¹, E. Shmanin³⁸, R. Shorkin³⁸, J. D. Shupperd⁶², B. G. Siddi^{21,i}, R. Silva Coutinho⁶², G. Simi²⁸, S. Simone^{19,f}, M. Singla⁶³, N. Skidmore⁵⁶, R. Skuza¹⁷, T. Skwarnicki⁶², M. W. Slater⁴⁷, J. C. Smallwood⁵⁷, J. G. Smeaton⁴⁹, E. Smith⁴⁴, K. Smith⁶¹, M. Smith⁵⁵, A. Snoch³², L. Soares Lavra⁹, M. D. Sokoloff⁵⁹, F. J. P. Soler⁵³, A. Solomin^{38,48}, A. Solovov³⁸, I. Solovvey³⁸, R. Song⁶³, F. L. Souza De Almeida², B. Souza De Paula², B. Spaan^{15,*}, E. Spadaro Norella^{25,1}, E. Spedicato²⁰, E. Spiridenkov³⁸, P. Spradlin⁵³, V. Sriskaran⁴², F. Stagni⁴², M. Stahl⁴², S. Stahl⁴², S. Stanislaus⁵⁷, E. N. Stein⁴², O. Steinkamp⁴⁴, O. Stenyakin³⁸, H. Stevens¹⁵, S. Stone^{62,*}, D. Strekalina³⁸, Y. S. Su⁶, F. Suljik⁵⁷, J. Sun²⁷, L. Sun⁶⁸, Y. Sun⁶⁰, P. Svihra⁵⁶, P. N. Swallow⁴⁷, K. Swientek³⁴, A. Szabelski³⁶, T. Szumlak³⁴, M. Szymanski⁴², Y. Tan³, S. Taneja⁵⁶, M. D. Tat⁵⁷, A. Terentev³⁸, F. Teubert⁴², E. Thomas⁴², D. J. D. Thompson⁴⁷, K. A. Thomson⁵⁴, H. Tilquin⁵⁵, V. Tisserand⁹, S. T'Jampens⁸, M. Tobin⁴, L. Tomassetti^{21,i}, G. Tonani^{25,1}, X. Tong⁵, D. Torres Machado¹, D. Y. Tou³, S. M. Trilov⁴⁸, C. Tripp⁴³, G. Tuci⁶, A. Tully⁴³, N. Tuning³², A. Ukleja³⁶, D. J. Unverzagt¹⁷, A. Usachov³², A. Ustyuzhanin³⁸, U. Uwer¹⁷, A. Vagner³⁸, V. Vagnoni²⁰, A. Valassi⁴², G. Valenti²⁰, N. Valls Canudas⁷⁶, M. van Beuzekom³², M. Van Dijk⁴³, H. Van Hecke⁶¹, E. van Herwijnen⁵⁵, C. B. Van Hulse^{40,w}, M. van Veghel⁷³, R. Vazquez Gomez³⁹, P. Vazquez Regueiro⁴⁰, C. Vázquez Sierra⁴², S. Vecchi²¹, J. J. Velthuis⁴⁸, M. Veltri^{22,u}, A. Venkateswaran⁴³, M. Veronesi³², M. Vesterinen⁵⁰, D. Vieira⁵⁹, M. Vieites Diaz⁴³, X. Vilasis-Cardona⁷⁶, E. Vilella Figueras⁵⁴, A. Villa²⁰, P. Vincent¹³, F. C. Volle¹¹, D. vom Bruch¹⁰, A. Vorobyev³⁸, V. Vorobyev³⁸, N. Voropaev³⁸, K. Vos⁷⁴

C. Vrahas⁵² , R. Waldi¹⁷ , J. Walsh²⁹ , G. Wan⁵ , C. Wang¹⁷ , G. Wang⁷ , J. Wang⁵ , J. Wang⁴ , J. Wang³ , J. Wang⁶⁸ , M. Wang⁵ , R. Wang⁴⁸ , X. Wang⁶⁶ , Y. Wang⁷ , Z. Wang⁴⁴ , Z. Wang³ , Z. Wang⁶ , J. A. Ward^{50,63} , N. K. Watson⁴⁷ , D. Websdale⁵⁵ , Y. Wei⁵ , C. Weisser⁵⁸ , B. D. C. Westhenry⁴⁸ , D. J. White⁵⁶ , M. Whitehead⁵³ , A. R. Wiederhold⁵⁰ , D. Wiedner¹⁵ , G. Wilkinson⁵⁷ , M. K. Wilkinson⁵⁹ , I. Williams⁴⁹ , M. Williams⁵⁸ , M. R. J. Williams⁵² , R. Williams⁴⁹ , F. F. Wilson⁵¹ , W. Wislicki³⁶ , M. Witek³⁵ , L. Witola¹⁷ , C. P. Wong⁶¹ , G. Wormser¹¹ , S. A. Wotton⁴⁹ , H. Wu⁶² , J. Wu⁷ , K. Wyllie⁴² , Z. Xiang⁶ , D. Xiao⁷ , Y. Xie⁷ , A. Xu⁵ , J. Xu⁶ , L. Xu³ , L. Xu³ , M. Xu⁵⁰ , Q. Xu⁶ , Z. Xu⁹ , Z. Xu⁶ , D. Yang³ , S. Yang⁶ , X. Yang⁵ , Y. Yang⁶ , Z. Yang⁵ , Z. Yang⁶⁰ , L. E. Yeomans⁵⁴ , V. Yeroshenko¹¹ , H. Yeung⁵⁶ , H. Yin⁷ , J. Yu⁶⁵ , X. Yuan⁶² , E. Zaffaroni⁴³ , M. Zavertyaev¹⁶ , M. Zdybal³⁵ , O. Zenaiev⁴² , M. Zeng³ , C. Zhang⁵ , D. Zhang⁷ , L. Zhang³ , S. Zhang⁶⁵ , S. Zhang⁵ , Y. Zhang⁵ , Y. Zhang⁵⁷ , A. Zharkova³⁸ , A. Zhelezov¹⁷ , Y. Zheng⁶ , T. Zhou⁵ , X. Zhou⁶ , Y. Zhou⁶ , V. Zhovkovska¹¹ , X. Zhu³ , X. Zhu⁷ , Z. Zhu⁶ , V. Zhukov^{14,38} , Q. Zou^{4,6} , S. Zucchelli^{20,g} , D. Zuliani²⁸ , G. Zunica⁵⁶ 

¹ Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil

² Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

³ Center for High Energy Physics, Tsinghua University, Beijing, China

⁴ Institute of High Energy Physics (IHEP), Beijing, China

⁵ School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

⁶ University of Chinese Academy of Sciences, Beijing, China

⁷ Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China

⁸ Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France

⁹ Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France

¹⁰ Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

¹¹ Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France

¹² Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

¹³ LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France

¹⁴ I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany

¹⁵ Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany

¹⁶ Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany

¹⁷ Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

¹⁸ School of Physics, University College Dublin, Dublin, Ireland

¹⁹ INFN Sezione di Bari, Bari, Italy

²⁰ INFN Sezione di Bologna, Bologna, Italy

²¹ INFN Sezione di Ferrara, Ferrara, Italy

²² INFN Sezione di Firenze, Florence, Italy

²³ INFN Laboratori Nazionali di Frascati, Frascati, Italy

²⁴ INFN Sezione di Genova, Genoa, Italy

²⁵ INFN Sezione di Milano, Milan, Italy

²⁶ INFN Sezione di Milano-Bicocca, Milan, Italy

²⁷ INFN Sezione di Cagliari, Monserrato, Italy

²⁸ Università degli Studi di Padova, Università e INFN, Padova, Padua, Italy

²⁹ INFN Sezione di Pisa, Pisa, Italy

³⁰ INFN Sezione di Roma La Sapienza, Rome, Italy

³¹ INFN Sezione di Roma Tor Vergata, Rome, Italy

³² Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands

³³ Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands

³⁴ Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Kraków, Poland

³⁵ Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland

³⁶ National Center for Nuclear Research (NCBJ), Warsaw, Poland

³⁷ Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania

³⁸ Affiliated with an Institute Covered by a Cooperation Agreement with CERN, ICCUB, Universitat de Barcelona, Barcelona, Spain

- ³⁹ Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain
- ⁴⁰ Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia-CSIC, Valencia, Spain
- ⁴¹ European Organization for Nuclear Research (CERN), Geneva, Switzerland
- ⁴² Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
- ⁴³ Physik-Institut, Universität Zürich, Zurich, Switzerland
- ⁴⁴ NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
- ⁴⁵ Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
- ⁴⁶ University of Birmingham, Birmingham, UK
- ⁴⁷ H.H. Wills Physics Laboratory, University of Bristol, Bristol, UK
- ⁴⁸ Cavendish Laboratory, University of Cambridge, Cambridge, UK
- ⁴⁹ Department of Physics, University of Warwick, Coventry, UK
- ⁵⁰ STFC Rutherford Appleton Laboratory, Didcot, UK
- ⁵¹ School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK
- ⁵² School of Physics and Astronomy, University of Glasgow, Glasgow, UK
- ⁵³ Oliver Lodge Laboratory, University of Liverpool, Liverpool, UK
- ⁵⁴ Imperial College London, London, UK
- ⁵⁵ Department of Physics and Astronomy, University of Manchester, Manchester, UK
- ⁵⁶ Department of Physics, University of Oxford, Oxford, UK
- ⁵⁷ Massachusetts Institute of Technology, Cambridge, MA, USA
- ⁵⁸ University of Cincinnati, Cincinnati, OH, USA
- ⁵⁹ University of Maryland, College Park, MD, USA
- ⁶⁰ Los Alamos National Laboratory (LANL), Los Alamos, NM, USA
- ⁶¹ Syracuse University, Syracuse, NY, USA
- ⁶² School of Physics and Astronomy, Monash University, Melbourne, Australia, associated to⁵⁰
- ⁶³ Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to²
- ⁶⁴ Physics and Micro Electronic College, Hunan University, Changsha City, China, associated to⁷
- ⁶⁵ Guangdong Provincial Key Laboratory of Nuclear Science, Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Institute of Quantum Matter, South China Normal University, Guangzhou, China, associated to³
- ⁶⁶ Lanzhou University, Lanzhou, China, associated to⁴
- ⁶⁷ School of Physics and Technology, Wuhan University, Wuhan, China, associated to³
- ⁶⁸ Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia, associated to¹³
- ⁶⁹ Universität Bonn-Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany, associated to¹⁷
- ⁷⁰ Eotvos Lorand University, Budapest, Hungary, associated to⁴²
- ⁷¹ INFN Sezione di Perugia, Perugia, Italy, associated to²¹
- ⁷² Van Swinderen Institute, University of Groningen, Groningen, The Netherlands, associated to³²
- ⁷³ Universiteit Maastricht, Maastricht, The Netherlands, associated to³²
- ⁷⁴ Faculty of Material Engineering and Physics, Cracow, Poland, associated to³⁵
- ⁷⁵ DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain, associated to³⁹
- ⁷⁶ Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden, associated to⁵³
- ⁷⁷ University of Michigan, Ann Arbor, MI, USA, associated to⁶²
- ^a Also at Universidade de Brasília, Brasília, Brazil
- ^b Also at Central South U., Changsha, China
- ^c Also at Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China
- ^d Also at Excellence Cluster ORIGINS, Munich, Germany
- ^e Also at Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras
- ^f Also at Università di Bari, Bari, Italy
- ^g Also at Università di Bologna, Bologna, Italy
- ^h Also at Università di Cagliari, Cagliari, Italy
- ⁱ Also at Università di Ferrara, Ferrara, Italy
- ^j Also at Università di Firenze, Florence, Italy
- ^k Also at Università di Genova, Genoa, Italy

- ^l Also at Università degli Studi di Milano, Milan, Italy
- ^m Also at Università di Milano Bicocca, Milan, Italy
- ⁿ Also at Università di Padova, Padua, Italy
- ^o Also at Università di Perugia, Perugia, Italy
- ^p Also at Scuola Normale Superiore, Pisa, Italy
- ^q Also at Università di Pisa, Pisa, Italy
- ^r Also at Università della Basilicata, Potenza, Italy
- ^s Also at Università di Roma Tor Vergata, Rome, Italy
- ^t Also at Università di Siena, Siena, Italy
- ^u Also at Università di Urbino, Urbino, Italy
- ^v Also at MSU-Iligan Institute of Technology (MSU-IIT), Iligan, Philippines
- ^w Also at Universidad de Alcalá, Alcalá de Henares, Spain
- *Deceased