First Differential Measurement of the Single π^+ Production Cross Section in Neutrino Neutral-Current Scattering

K. Abe,[61] S. Abe,[61] R. Akutsu,[16] H. Alarakia-Charles,[34] Y. I. Alj Hakim,[55] S. Alonso Monsalve,[9] L. Anthony,[21] S. Aoki,[32] K. A. Apte,[21] T. Arai,[60] T. Arihara,[64] S. Arimoto,[33] Y. Ashida,[70] E. T. Atkin,[21] N. Babu,[38] V. Baranov,[39] G. J. Barker,[71] G. Barr,[47] D. Barrow,[47] P. Bates,[37] L. Bathe-Peters,[47] M. Batkiewicz-Kwasniak,[15] N. Baudis,[47] V. Berardi,[22] L. Berns,[70] S. Bhattacharjee,[38] A. Blanchet,[11] A. Blondel,[58,12] S. Bolognesi,[5] S. Bordoni,[12] S. B. Boyd,[71] C. Bronner,[61] A. Bubak,[56] M. Buizza Avanzini,[36] J. A. Caballero,[54] F. Cadoux,[12] N. F. Calabria,[22] S. Cao,[20] S. Cap,[12] D. Carabadjac,[36,*] S. L. Cartwright,[55] M. P. Casado,[18,†] M. G. Catanesi,[22] J. Chakrani,[35] A. Chalumeau,[58] A. Chvirova,[26] G. Collazuol,[24] F. Cormier,[66] A. A. L. Craplet,[21] A. Cudd,[6] D. D'ago,[24] C. Dalmazzone,[58] T. Daret,[5] P. Dasgupta,[8] C. Davis,[48] Yu. I. Davydov,[39] G. De Rosa,[23] T. Dealtry,[34] C. Densham,[44] A. Dergacheva,[26] R. Dharmapal Banerjee,[72] F. Di Lodovico,[31] G. Diaz Lopez,[58] S. Dolan,[11] D. Douqa,[12] T. A. Doyle,[43] O. Drapier,[36] K. E. Duffy,[47] J. Dumarchez,[58] P. Dunne,[21] K. Dygnarowicz,[69] A. Eguchi,[60] J. Elias,[50] S. Emery-Schrenk,[5] G. Erofeev,[26] A. Ershova,[36] G. Eurin,[5] D. Fedorova,[26] S. Fedotov,[26] M. Feltre,[24] L. Feng,[33] D. Ferlewicz,[60] A. J. Finch,[34] M. D. Fitton,[44] C. Forza,[24] M. Friend,[16,‡] Y. Fujii,[16,‡] Y. Fukuda,[41] Y. Furui,[64] J. García-Marcos,[14] A. C. Germer,[48] L. Giannessi,[12] C. Giganti,[58] V. Glagolev,[39] M. Gonin,[28] R. González Jiménez,[54] J. González Rosa,[54] E. A. G. Goodman,[13] K. Gorshanov,[26] P. Govindaraj,[68] M. Grassi,[24] M. Guigue,[58] F. Y. Guo,[43] D. R. Hadley,[71] S. Han,[33,62] D. A. Harris,[74] R. J. Harris,[34,44] T. Hasegawa,[16,‡] C. M. Hasnip,[11] S. Hassani,[5] N. C. Hastings,[16] Y. Hayato,[61,29] I. Heitkamp,[70] D. Henaff,[5] Y. Hino,[16] J. Holeczek,[56] A. Holin,[44] T. Holvey,[47] N. T. Hong Van,[27] T. Honjo,[46] M. C. F. Hooft,[14] K. Hosokawa,[61] J. Hu,[33] A. K. Ichikawa,[70] K. Ieki,[61] M. Ikeda,[61] T. Ishida,[16,‡] M. Ishitsuka,[65] A. Izmaylov,[26] N. Jachowicz,[14] S. J. Jenkins,[37] C. Jesús-Valls,[29] M. Jia,[43] J. J. Jiang,[43] J. Y. Ji,[43] T. P. Jones,[34] P. Jonsson,[21] S. Joshi,[5] M. Kabirnezhad,[21] A. C. Kaboth,[51,44] H. Kakuno,[64] J. Kameda,[61] S. Karpova,[12] V. S. Kasturi,[12] Y. Kataoka,[61] T. Katori,[31] Y. Kawamura,[46] M. Kawaue,[33] E. Kearns,[2,§] M. Khabibullin,[26] A. Khotjantsev,[26] T. Kikawa,[33] S. King,[31] V. Kiseeva,[39] J. Kisiel,[56] A. Klustová,[21] L. Kneale,[55] H. Kobayashi,[60] L. Koch,[19] S. Kodama,[60] M. Kolupanova,[26] A. Konaka,[66] L. L. Kormos,[34] Y. Koshio,[45,§] K. Kowalik,[42] Y. Kudenko,[26,∥] Y. Kudo,[73] A. Kumar Jha,[14] R. Kurjata,[69] V. Kurochka,[26] T. Kutter,[38] L. Labarga,[1] M. Lachat,[50] K. Lachner,[71] J. Lagoda,[42] S. M. Lakshmi,[56] M. Lamers James,[71] A. Langella,[23] D. H. Langridge,[51] J.-F. Laporte,[5] D. Last,[50] N. Latham,[31] M. Laveder,[24] M. Lawe,[34] D. Leon Silverio,[59] S. Levorato,[24] S. V. Lewis,[31] B. Li,[9] C. Lin,[21] R. P. Litchfield,[13] S. L. Liu,[43] W. Li,[47] A. Longhin,[24] A. Lopez Moreno,[31] L. Ludovici,[25] X. Lu,[71] T. Lux,[18] L. N. Machado,[13] L. Magaletti,[22] K. Mahn,[40] K. K. Mahtani,[43] M. Mandal,[42] S. Manly,[50] A. D. Marino,[6] D. G. R. Martin,[21] D. A. Martinez Caicedo,[59] L. Martinez,[18] M. Martini,[58,¶] T. Matsubara,[16] R. Matsumoto,[63] V. Matveev,[26] C. Mauger,[48] K. Mavrokoridis,[37] N. McCauley,[37] K. S. McFarland,[50] J. McKean,[21] A. Mefodiev,[26] G. D. Megias,[54] L. Mellet,[40] M. Mezzetto,[24] S. Miki,[61] V. Mikola,[13] E. W. Miller,[18] A. Minamino,[73] O. Mineev,[26] S. Mine,[61,4] J. Mirabito,[2] M. Miura,[61,§] S. Moriyama,[61,§] S. Moriyama,[73] P. Morrison,[13] Th. A. Mueller,[36] D. Munford,[17] A. Muñoz,[36,28] L. Munteanu,[11] Y. Nagai,[8] T. Nakadaira,[16,‡] K. Nakagiri,[60] M. Nakahata,[61,29] Y. Nakajima,[60] K. D. Nakamura,[70] Y. Nakano,[67] S. Nakayama,[61,29] T. Nakaya,[33,29] K. Nakayoshi,[16,‡] C. E. R. Naseby,[21] D. T. Nguyen,[10] V. Q. Nguyen,[36] K. Niewczas,[14] S. Nishimori,[16] Y. Nishimura,[30] Y. Noguchi,[61] T. Nosek,[42] F. Nova,[44] J. C. Nugent,[21] H. M. O'Keeffe,[34] L. O'Sullivan,[19] R. Okazaki,[30] W. Okinaga,[60] K. Okumura,[62,29] T. Okusawa,[46] N. Onda,[33] N. Ospina,[22] L. Osu,[36] Y. Oyama,[16,‡] V. Paolone,[49] J. Pasternak,[21] M. Pfaff,[21] L. Pickering,[44] B. Popov,[58,**] A. J. Portocarrero Yrey,[16] M. Posiadala-Zezula,[68] Y. S. Prabhu,[68] H. Prasad,[72] F. Pupilli,[24] B. Quilain,[28,36] P. T. Quyen,[20,††] E. Radicioni,[22] B. Radics,[74] M. A. Ramirez,[48] R. Ramsden,[31] P. N. Ratoff,[34] M. Reh,[6] G. Reina,[19] C. Riccio,[43] D. W. Riley,[13] E. Rondio,[42] S. Roth,[52] N. Roy,[74] A. Rubbia,[9] L. Russo,[58] A. Rychter,[69] W. Saenz,[58] K. Sakashita,[16,‡] F. Sánchez,[12] E. M. Sandford,[37] Y. Sato,[65] T. Schefke,[38] C. M. Schloesser,[12] K. Scholberg,[7,§] M. Scott,[21] Y. Seiya,[46,‡‡] T. Sekiguchi,[16,‡] H. Sekiya,[61,29,§] T. Sekiya,[64] D. Seppala,[40] D. Sgalaberna,[9] A. Shaikhiev,[26] M. Shiozawa,[61,29] Y. Shiraishi,[45] A. Shvartsman,[26] N. Skrobova,[26] K. Skwarczynski,[51] D. Smyczek,[52] M. Smy,[4] J. T. Sobczyk,[72] H. Sobel,[4,29] F. J. P. Soler,[13] A. J. Speers,[34] R. Spina,[22] A. Srivastava,[19] P. Stowell,[55] Y. Stroke,[26] I. A. Suslov,[39] A. Suzuki,[32] S. Y. Suzuki,[16,‡] M. Tada,[16,‡] S. Tairafune,[70] A. Takeda,[61] Y. Takeuchi,[32,29] H. K. Tanaka,[61,§] H. Tanigawa,[16] V. V. Tereshchenko,[39] N. Thamm,[52] N. Tran,[33] T. Tsukamoto,[16,‡] M. Tzanov,[38] Y. Uchida,[21] M. Vagins,[29,4] M. Varghese,[18] I. Vasilyev,[39] G. Vasseur,[5] E. Villa,[11,12] U. Virginet,[58] T. Vladisavljevic,[44] T. Wachala,[15] D. Wakabayashi,[70] H. T. Wallace,[55] J. G. Walsh,[40] L. Wan,[2] D. Wark,[44,47] M. O. Wascko,[47,44] A. Weber,[19] R. Wendell,[33] M. J. Wilking,[53] C. Wilkinson,[35] J. R. Wilson,[31] K. Wood,[35] C. Wret,[21] J. Xia,[57] K. Yamamoto,[46,‡‡] T. Yamamoto,[46] Y. Yang,[47] T. Yano,[61] N. Yershov,[26]

U. Yevarouskaya,[43] M. Yokoyama,[60,§] Y. Yoshimoto,[60] N. Yoshimura,[33] R. Zaki,[74] A. Zalewska,[15] J. Zalipska,[42] G. Zarnecki,[15] J. Zhang,[66,3] X. Y. Zhao,[9] H. Zheng,[43] H. Zhong,[32] T. Zhu,[21] M. Ziembicki,[69] E. D. Zimmerman,[6] M. Zito,[58] and S. Zsoldos[31]

(T2K Collaboration)

[1]*Department of Theoretical Physics, University Autonoma Madrid, 28049 Madrid, Spain*
[2]*Department of Physics, Boston University, Boston, Massachusetts, USA*
[3]*Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada*
[4]*Department of Physics and Astronomy, University of California, Irvine, Irvine, California, USA*
[5]*IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*
[6]*Department of Physics, University of Colorado at Boulder, Boulder, Colorado, USA*
[7]*Department of Physics, Duke University, Durham, North Carolina, USA*
[8]*Department of Atomic Physics, Eötvös Loránd University, Budapest, Hungary*
[9]*ETH Zurich, Institute for Particle Physics and Astrophysics, Zurich, Switzerland*
[10]*VNU University of Science, Vietnam National University, Hanoi, Vietnam*
[11]*CERN European Organization for Nuclear Research, CH-1211 Genéve 23, Switzerland*
[12]*Section de Physique, University of Geneva, DPNC, Geneva, Switzerland*
[13]*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[14]*Department of Physics and Astronomy, Ghent University, Proeftuinstraat 86, B-9000 Gent, Belgium*
[15]*H. Niewodniczanski Institute of Nuclear Physics PAN, Cracow, Poland*
[16]*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan*
[17]*Department of Physics, University of Houston, Houston, Texas, USA*
[18]*Institut de Fisica d'Altes Energies (IFAE) - The Barcelona Institute of Science and Technology, Campus UAB, Bellaterra (Barcelona) Spain*
[19]*Institut für Physik, Johannes Gutenberg-Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany*
[20]*Institute For Interdisciplinary Research in Science and Education (IFIRSE), ICISE, Quy Nhon, Vietnam*
[21]*Department of Physics, Imperial College London, London, United Kingdom*
[22]*Dipartimento Interuniversitario di Fisica, INFN Sezione di Bari and Università e Politecnico di Bari, Bari, Italy*
[23]*Dipartimento di Fisica, INFN Sezione di Napoli and Università di Napoli, Napoli, Italy*
[24]*Dipartimento di Fisica, INFN Sezione di Padova and Università di Padova, Padova, Italy*
[25]*INFN Sezione di Roma and Università di Roma "La Sapienza," Roma, Italy*
[26]*Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia*
[27]*International Centre of Physics, Institute of Physics (IOP), Vietnam Academy of Science and Technology (VAST), 10 Dao Tan, Ba Dinh, Hanoi, Vietnam*
[28]*ILANCE, CNRS—University of Tokyo International Research Laboratory, Kashiwa, Chiba 277-8582, Japan*
[29]*Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study, University of Tokyo, Kashiwa, Chiba, Japan*
[30]*Department of Physics, Keio University, Kanagawa, Japan*
[31]*Department of Physics, King's College London, Strand, London WC2R 2LS, United Kingdom*
[32]*Kobe University, Kobe, Japan*
[33]*Department of Physics, Kyoto University, Kyoto, Japan*
[34]*Physics Department, Lancaster University, Lancaster, United Kingdom*
[35]*Lawrence Berkeley National Laboratory, Berkeley, California, USA*
[36]*Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France*
[37]*Department of Physics, University of Liverpool, Liverpool, United Kingdom*
[38]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana, USA*
[39]*Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia*
[40]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
[41]*Department of Physics, Miyagi University of Education, Sendai, Japan*
[42]*National Centre for Nuclear Research, Warsaw, Poland*
[43]*Department of Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, New York, USA*
[44]*STFC, Rutherford Appleton Laboratory, Harwell Oxford, and Daresbury Laboratory, Warrington, United Kingdom*
[45]*Department of Physics, Okayama University, Okayama, Japan*
[46]*Department of Physics, Osaka Metropolitan University, Osaka, Japan*
[47]*Department of Physics, Oxford University, Oxford, United Kingdom*
[48]*Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
[49]*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
[50]*Department of Physics and Astronomy, University of Rochester, Rochester, New York, USA*

[51]*Department of Physics, Royal Holloway University of London, Egham, Surrey, United Kingdom*
[52]*Physikalisches Institut, RWTH Aachen University, III. Aachen, Germany*
[53]*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota, USA*
[54]*Departamento de Física Atómica, Molecular y Nuclear, Universidad de Sevilla, 41080 Sevilla, Spain*
[55]*School of Mathematical and Physical Sciences, University of Sheffield, Sheffield, United Kingdom*
[56]*Institute of Physics, University of Silesia, Katowice, Poland*
[57]*SLAC National Accelerator Laboratory, Stanford University, Menlo Park, California, USA*
[58]*Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), Sorbonne Université, CNRS/IN2P3, Paris, France*
[59]*South Dakota School of Mines and Technology, 501 East Saint Joseph Street, Rapid City, South Dakota, USA*
[60]*Department of Physics, University of Tokyo, Tokyo, Japan*
[61]*Institute for Cosmic Ray Research, Kamioka Observatory, University of Tokyo, Kamioka, Japan*
[62]*Institute for Cosmic Ray Research, Research Center for Cosmic Neutrinos, University of Tokyo, Kashiwa, Japan*
[63]*Department of Physics, Institute of Science Tokyo, Tokyo, Japan*
[64]*Department of Physics, Tokyo Metropolitan University, Tokyo, Japan*
[65]*Faculty of Science and Technology, Department of Physics, Tokyo University of Science, Noda, Chiba, Japan*
[66]*TRIUMF, Vancouver, British Columbia, Canada*
[67]*Department of Physics, University of Toyama, Toyama, Japan*
[68]*Faculty of Physics, University of Warsaw, Warsaw, Poland*
[69]*Institute of Radioelectronics and Multimedia Technology, Warsaw University of Technology, Warsaw, Poland*
[70]*Faculty of Science, Department of Physics, Tohoku University, Miyagi, Japan*
[71]*Department of Physics, University of Warwick, Coventry, United Kingdom*
[72]*Faculty of Physics and Astronomy, Wroclaw University, Wroclaw, Poland*
[73]*Department of Physics, Yokohama National University, Yokohama, Japan*
[74]*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*

(Received 20 March 2025; revised 3 July 2025; accepted 22 August 2025; published 23 October 2025)

Since its first observation in the 1970s, neutrino-induced neutral-current single positive pion production (NC1π^+) has remained an elusive and poorly understood interaction channel. This process is a significant background in neutrino oscillation experiments and studying it further is critical for the physics program of next-generation accelerator-based neutrino oscillation experiments. In this Letter, we present the first double-differential cross-section measurement of NC1π^+ interactions using data from the ND280 detector of the T2K experiment collected in ν-beam mode. The measured flux-averaged integrated cross section is $\sigma = (6.07 \pm 1.22) \times 10^{-41}$ cm^2/nucleon. We compare the results on a hydrocarbon target to the predictions of several neutrino interaction generators and final-state-interaction models. While model predictions agree with the differential results, the data show a weak preference for a cross-section normalization approximately 30% higher than predicted by most models studied in this Letter.

DOI: 10.1103/6d32-l452

Introduction—Neutrino physics plays a central role in modern high-energy physics. Following the discovery of neutrino oscillations [1,2], several experiments are ongoing and planned with the aim of precisely characterizing the phenomenology of neutrino oscillations. Neutrino mixing is characterized by three-flavor mixing, depending on two mass

[*]Also at Université Paris-Saclay.
[†]Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
[‡]Also at J-PARC, Tokai, Japan.
[§]Affiliated member at Kavli IPMU (WPI), the University of Tokyo, Japan.
[‖]Also at Moscow Institute of Physics and Technology (MIPT), Moscow region, Russia and National Research Nuclear University "MEPhI," Moscow, Russia.
[¶]Also at IPSA-DRII, France.
[**]Also at JINR, Dubna, Russia.
[††]Also at the Graduate University of Science and Technology, Vietnam Academy of Science and Technology.
[‡‡]Also at Nambu Yoichiro Institute of Theoretical and Experimental Physics (NITEP).

splittings (Δm^2_{23}, Δm^2_{21}) and described by the Pontecorvo-Maki-Nakagawa-Sakata matrix consisting of three mixing angles (θ_{13}, θ_{23}, θ_{12}) and one charge-parity- (CP) violating phase (δ_{CP}). Several parameters are already known with a few percent precision [3], but major unknowns remain: the sign of Δm^2_{23} known as the neutrino mass ordering, whether CP symmetry is violated or not, which is primarily determined by the value of δ_{CP}, and the octant of θ_{23} determining if θ_{23} is smaller than, larger than, or equal to 45°.

For existing and planned neutrino beam experiments, the experimental sensitivity to the unknown neutrino oscillation parameters becomes maximal for neutrino energies ranging from hundreds of MeV to a few GeV. In this energy range, multiple neutrino interaction mechanisms are possible, and poorly understood nuclear effects contribute significant systematic uncertainties [4–7]. Over the past two decades, more than 20 measurements have investigated neutrino single π^0 production. Of these, more than ten have studied neutral-current (NC) interactions [8–20], with the remainder studying charged-current (CC) interactions [21–29]. Similarly, more than 20 analyses have examined single $\pi^\pm$ production, though exclusively through CC interactions [25,30–49]. However, measurements of neutrino NC single $\pi^\pm$ production (NC1$\pi^\pm$) primarily generated by $\nu + p \rightarrow \nu + n + \pi^+$ interactions have been notably absent from the literature.

In this Letter, we address this long-standing absence of results for this channel by presenting the first differential cross-section measurement of NC1π^+ interactions reported as a function of the pion momentum and angle.

Existing measurements—The Gargamelle [50] and ANL [51] bubble chamber experiments measured NC1$\pi^\pm$ interactions over four decades ago. At the time, their focus was demonstrating consistency with the newly proposed standard model of particle physics, confirming the existence of these interactions. One measurement of the NC1$\pi^\pm$ cross section exists in the scientific literature (to the best knowledge of the authors, details on the analysis methodology have been lost), a reanalysis of the Gargamelle reported event rates collected at an average neutrino energy of 2 GeV [52].

NC1$\pi^\pm$ *in long-baseline neutrino experiments*—Figure 1 shows the predicted oscillated muon-neutrino interaction rate as a function of the neutrino energy for two future long-baseline neutrino experiments: Hyper-Kamiokande [53] with an unoscillated neutrino energy peak at ≈0.6 GeV and a water Cherenkov far detector, which focuses on CC0π events, and DUNE [54] with a peak unoscillated neutrino energy of ≈2.5 GeV and a liquid argon far detector using all CC events. The neutrino energy peak is deliberately aligned near the energy where maximum disappearance of the muon flavor is expected for the experiment's baseline, creating a characteristic "dip" in the observed energy distribution. The depth of this dip and its position are used to determine the value of the θ_{23} and Δm^2_{23} parameters. Overlaid is the NC1$\pi^\pm$ predicted event rate, which is a hard to reject background as pions are frequently misidentified as muons in both water Cherenkov detectors and liquid argon detectors. Because of oscillations, the CC event rate associated with muon neutrinos is strongly reduced near the dip; however, all neutrino flavors contribute to the NC rate. As a result, NC1$\pi^\pm$ interactions can add a significant background contribution for muon-disappearance samples. In the Tokai-to-Kamioka (T2K) experiment presented next in this Letter, statistical and systematic uncertainties for this channel are comparable. In the near future, Hyper-Kamiokande and DUNE are expected to select hundreds of NC1$\pi^\pm$ events as part of their oscillation samples. Therefore, better understanding the NC1$\pi^\pm$ cross section and constraining its modeling uncertainty is important for the precision oscillation physics goals of next-generation experiments.

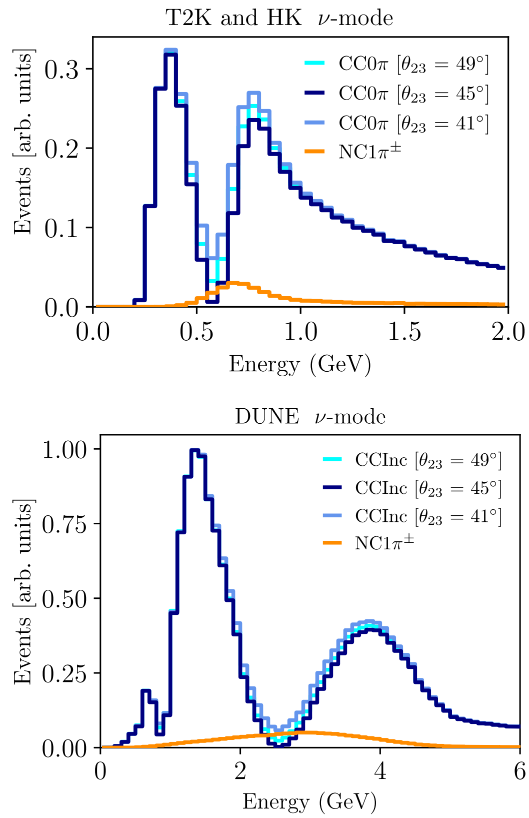

FIG. 1. Expected event rate, in arbitrary units, for CC0π including μ and π Cherenkov thresholds (T2K and Hyper-K) and CC-inclusive (DUNE) muon-neutrino interactions at the Hyper-K (top) and DUNE (bottom) experiments shown as a function of the true neutrino energy. Also overlaid is the expected rate of the NC1$\pi^\pm$ background in each case. The oscillation parameters used are from NuFit5.0 [55] and use GENIEv3 [56,57] truth information to predict the interaction rates using T2K [58] and DUNE [54,59] neutrino fluxes.

Experimental setup—The T2K long-baseline neutrino experiment [60] studies neutrino oscillations using a highly pure muon (anti)neutrino beam produced by the neutrino facility at the J-PARC proton accelerator. Data collection is divided in ν-beam or $\bar{\nu}$-beam runs. The experiment combines measurements at two detector sites: the near detector facility located 280 m from the proton beam target, including the main near detector ND280, which was used to collect the data for this Letter, and the far detector facility, located 295 km downstream, is the Super-Kamiokande (SK) detector [61]. Both ND280 and SK are placed 2.5° off axis, resulting in a narrow neutrino energy spectrum peaking at 0.6 GeV [58,62].

The analysis utilizes ND280 data recorded in ν-beam mode. ND280 [60] is a magnetized particle detector made of several subdetector modules including two fine-grained detectors (FGD1 and FGD2) [63], three gaseous time-projection chambers [64], and an electromagnetic calorimeter [65]. Together, they provide rich information used to reconstruct the particle type, its trajectory, and its momentum.

Analysis samples—Events with a vertex reconstructed in the fully active hydrocarbon target FGD1 are classified in four different regions: a signal-enriched sample and three background-enriched samples. The signal definition includes all ν and $\bar{\nu}$ interactions without charged leptons in the final state, a single positive pion, any number of protons with momentum below the detection threshold of 200 MeV/c (see details in Ref. [66]), and no other mesons or other charged particles in the final state. Because of ND280's acceptance and particle identification capabilities, the measurement is reported in the kinematic region of interest (RoI) defined by the conditions $\cos\theta_{\pi^+} > 0.5$ and $0.2 < p_{\pi^+} < 1.0$ GeV/c. The neutrino generator NEUT v5.4.0 [67,68] is used with T2K's flux and detector simulation pipeline [60] to predict the rate of these events. Over 200 signal events are expected overall, with approximately 165 in the signal sample at 30.5% efficiency and 51.4% purity, and an integrated detector uncertainty for the predicted event rate below 5%. Three analysis sidebands enriched in background events are used in the analysis. This includes a sample with 81.0% purity in $\bar{\nu}_\mu$ CC events, the most numerous background events in the signal sample corresponding to 28.2% of its selected events. The other sidebands are enriched in events with additional tracks in the neutrino target and events where the main track is identified as a proton instead of a π^+. Full selection details and performance metrics are presented in Ref. [66].

Analysis strategy—The NC1$\pi^\pm$ cross section is measured using an unregularized binned maximum-likelihood fit, the same method described in earlier T2K measurements, e.g., in Refs. [43,69]. The procedure consists of numerically optimizing the parameters of interest, i.e., scaling factors for the number of signal events, together with nuisance parameters describing plausible variations of T2K's flux, detector, and background cross-section models. The agreement with the data is simultaneously maximized

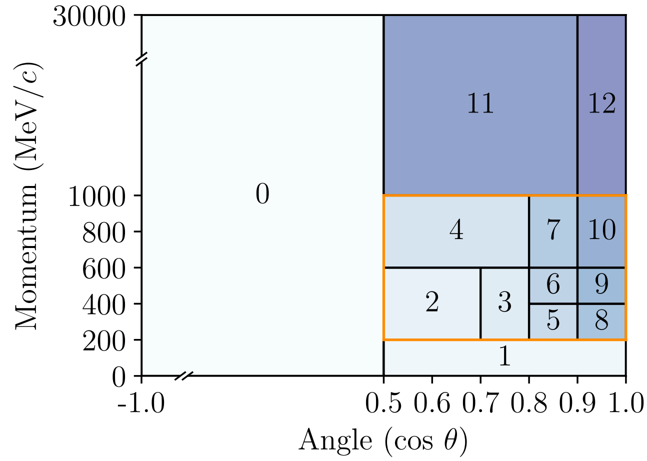

FIG. 2. Scheme of the true pion kinematic bins where the cross section is measured. Bin IDs are shown within their associated kinematic regions. The region of interest, where we report the measurement, is enclosed by an orange solid line and corresponds to bins 2–10. Color shades are used to aid visualization but have no physical meaning.

in the signal- and background-enriched samples. This method provides a data-driven background and flux constraint while unfolding detector effects and providing a postfit prediction of the expected signal events in every analysis bin, which is then used to calculate the signal cross section. In total, the flux-averaged cross section is unfolded in 13 bins in pion angle and momentum, nine of them contained in the RoI. The binning scheme is presented in Fig. 2. The model independence of the cross-section extraction was validated through extensive tests using alternative datasets with controlled variations. In all cases, small or negligible measurement biases were observed, confirming the robustness of the method.

Interaction models—We compare the extracted double-differential and integrated cross section to several

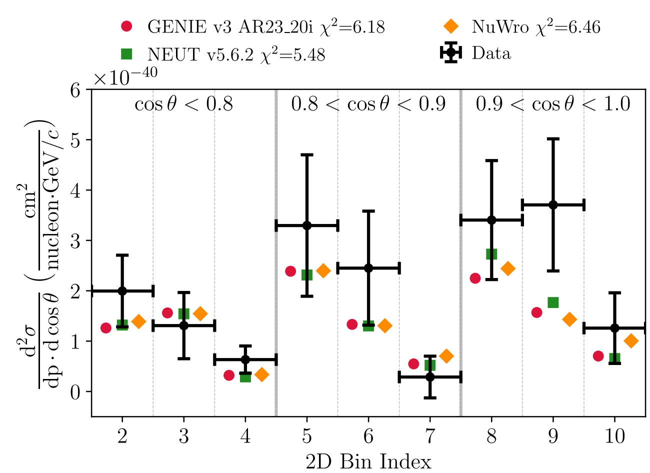

FIG. 3. Measured NC1$\pi^\pm$ double-differential cross section compared to generator predictions.

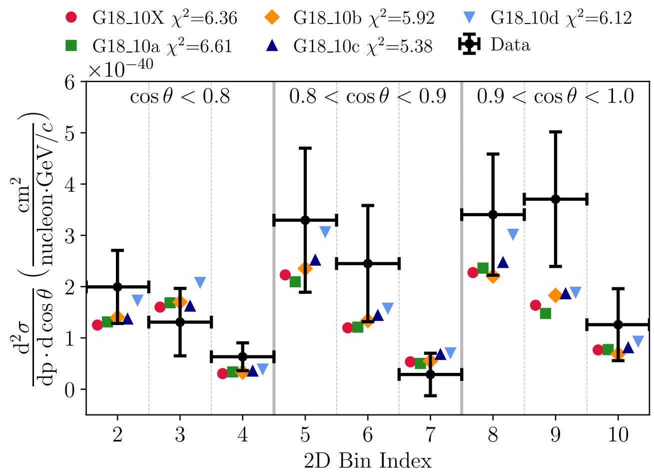

FIG. 4. Measured NC1$\pi^{\pm}$ double-differential cross section compared to various FSI predictions.

interaction generators using NUISANCE [70]: NEUT v5.6.2 [67,68,71], NuWro v19.02.2 [72,73], and GENIEv3 [56,57] using the AR23_20i configuration. These represent a range of commonly used models, which differ in a variety of details including hard scattering processes, nuclear modeling, and reinteractions of interaction products within the nucleus (final-state interactions, FSIs). Additionally, we investigate the role of FSIs using five different GENIE model variations, where the only change is the FSI model used. These represent a broad range of models of varying levels of sophistication ranging from no FSI, and full semiclassical cascade models. They include the INTRANUKE [74] hA single-step empirical model (G18_10a), the INTRANUKE hN full intranuclear cascade (G18_10b), GENIE's implementation of the INCL cascade [75,76] (G18_10c), the Geant4 Bertini cascade [77] (G18_10d), and an unphysical model in which all final-state interactions have been turned off (G18_10X). AR23_20i uses the hA model and is identical to G18_10a for NC pion production, except that the free nucleon pion production tuning from Ref. [78] is applied.

Results—The measured data cross section is compared to different neutrino interaction generator predictions in Fig. 3 and FSI models in Fig. 4. The data agree well with the generator and FSI model predictions, with χ^2 values below 9, the number of differential bins, in all cases. Bins 5, 6, 8, and 9, which cover the kinematic region with highest purity and signal abundance, all prefer a higher signal cross section than that of all models. The data preference for a larger cross section is emphasized when studying the integrated cross section summarized in Table I. Among all the models investigated, GENIEv3 AR23_20i and G18_10X show the largest disagreement, both at a statistical tension with data equivalent to 1.7σ. The best agreement between the data and simulation for the integrated cross section is found with G18_10d.

TABLE I. Integrated cross-section values in the RoI with their associated p values for different generators and FSI models.

Model	σ (cm^2/nucleon)	p value
Data	$(6.07 \pm 1.22) \times 10^{-41}$	$\cdots$
GENIEv3 AR23_20i_00_000	4.02×10^{-41}	0.093
NuWro v19.02.2	4.33×10^{-41}	0.153
NEUT v5.6.2	4.11×10^{-41}	0.108
G18_10X	3.99×10^{-41}	0.089
G18_10a	4.07×10^{-41}	0.100
G18_10b	4.24×10^{-41}	0.133
G18_10c	4.42×10^{-41}	0.176
G18_10d	5.26×10^{-41}	0.507

Conclusions—Using the largest data sample of selected NC1$\pi^{\pm}$ interactions to date, the double-differential cross section for this channel has been presented for the first time. Overall, the differential cross-section results agree with tested model predictions, though we observe a statistically weak preference for a cross section approximately 30% higher than most model expectations. The variations observed across FSI models are greater than those between neutrino interaction generators, and could significantly reduce the observed normalization discrepancy. This highlights the critical need to enhance our understanding of final-state interactions. We anticipate that NC1$\pi^{\pm}$ predictions will benefit from forthcoming high-statistics neutrino interaction measurements from T2K and other experiments. In particular, future measurements that precisely measure final-state hadrons in interactions both with and without final-state pions and utilizing transverse kinematic imbalance observables will be especially valuable to inform existing nuclear ground state and final-state-interaction models, directly benefiting NC1$\pi^{\pm}$ model predictions.

This Letter represents the first study of this interaction primarily with sub-GeV neutrinos enabled by T2K's neutrino beamline, with dedicated emphasis on achieving a model-independent cross-section extraction, as discussed in Ref. [66]. The results can be used to constrain NC1$\pi^{\pm}$ background events for T2K and the future Hyper-Kamiokande experiment planned to start operations in 2027.

DUNE, using an argon target and a higher neutrino energy, will likely benefit from additional studies of this channel. The selection strategy developed for this Letter may guide future NC1$\pi^{\pm}$ measurements at other experiments.

This Letter establishes the foundation for more precise measurements of this channel in T2K and Hyper-Kamiokande using the ND280 detector. With the recent upgrade of the ND280 detector [79] and planned increases in data collection over the coming years, we expect continued improvements in the understanding of this channel, enabling more precise measurements of neutrino oscillation parameters. We anticipate that the upgraded

ND280 geometry, with an enhanced angular acceptance, should allow us to greatly extend the phase space of this measurement in the future to regions where the pion is emitted at large angles with respect to the beam, perhaps even including samples with backward-going pions. An increase in the signal purity is also expected, thanks to the better granularity and timing capabilities of the SuperFGD hydrocarbon target and the addition of time-of-flight panels in the detector. Unlike the target used in this analysis, SuperFGD is also capable of identifying neutrons, opening new avenues to further understand this channel.

Acknowledgments—The T2K Collaboration would like to thank the J-PARC staff for superb accelerator performance. We thank the CERN NA61/SHINE Collaboration for providing valuable particle production data. We acknowledge the support of MEXT, JSPS KAKENHI, and bilateral programs, Japan; NSERC, the NRC, and CFI, Canada; the CEA and CNRS/IN2P3, France; the Deutsche Forschungsgemeinschaft (DFG Grants No. 397763730 and No. 517206441), Germany; the NKFIH (NKFIH Grants No. 137812 and No. TKP2021-NKTA-64), Hungary; the INFN, Italy; the Ministry of Science and Higher Education (Grant No. 2023/WK/04) and the National Science Centre (Grants No. UMO-2018/30/E/ST2/00441, No. UMO-2022/46/E/ST2/00336, and No. UMO-2021/43/D/ST2/01504), Poland; the RSF (RSF Grant No. 24-12-00271) and the Ministry of Science and Higher Education, Russia; MICINN, ERDF and European Union NextGenerationEU funds, and CERCA program and Generalitat de Catalunya, Spain; the SNSF and SERI, Switzerland; the STFC and UKRI, UK; the DOE, USA, and NAFOSTED (Grants No. 103.99-2023.144 and No. IZVSZ2.203433), Vietnam. We also thank CERN for the UA1/NOMAD magnet, DESY for the HERA-B magnet mover system, the BC DRI Group, Prairie DRI Group, ACENET, SciNet, and CalculQuebec consortia in the Digital Research Alliance of Canada, and GridPP in the United Kingdom, the CNRS/IN2P3 Computing Center in France, and NERSC, USA. In addition, the participation of individual researchers and institutions has been further supported by funds from the ERC (FP7), "la Caixa" Foundation, the European Union's Horizon 2020 Research and Innovation Programme under the Marie Sklodowska-Curie grant; the JSPS, Japan; the Royal Society, UK; French ANR and Sorbonne Université Emergences programs; the VAST-JSPS (Grant No. QTJP01.02/20-22); and the DOE Early Career program, USA.

Data availability—The data that support the findings of this article are openly available [80].

[1] Y. Fukuda *et al.* (Super-Kamiokande Collaboration), Phys. Rev. Lett. **81**, 1562 (1998).

[2] Q. R. Ahmad *et al.* (SNO Collaboration), Phys. Rev. Lett. **89**, 011301 (2002).

[3] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. a. P. Pinheiro, and T. Schwetz, J. High Energy Phys. 12 (2024) 216.

[4] L. Alvarez-Ruso *et al.* (NuSTEC Collaboration), Prog. Part. Nucl. Phys. **100**, 1 (2018).

[5] C. Andreopoulos *et al.* (NuSTEC Collaboration), in *Proceedings of the NuSTEC Workshop on Shallow- and Deep-Inelastic Scattering* (2019), https://inspirehep.net/literature/1747230.

[6] L. Aliaga *et al.* (NuSTEC Collaboration), in *Proceedings of the NuSTEC Workshop on Neutrino-Nucleus Pion Production in the Resonance Region* (2020), https://inspirehep.net/literature/1830405.

[7] K. Abe *et al.* (T2K Collaboration), Eur. Phys. J. C **83**, 782 (2023).

[8] P. Abratenko *et al.* (MicroBooNE Collaboration), Phys. Rev. Lett. **134**, 161802 (2025).

[9] R. Acciarri *et al.* (ArgoNeuT Collaboration), Phys. Rev. D **96**, 012006 (2017).

[10] S. Nakayama *et al.* (K2K Collaboration), Phys. Lett. B **619**, 255 (2005).

[11] P. Abratenko *et al.* (MicroBooNE Collaboration), Phys. Rev. D **107**, 012004 (2023).

[12] J. Wolcott *et al.* (MINERvA Collaboration), Phys. Rev. Lett. **117**, 111801 (2016).

[13] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), Phys. Rev. D **81**, 013005 (2010).

[14] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), Phys. Lett. B **664**, 41 (2008).

[15] P. Adamson *et al.* (MINOS Collaboration), Phys. Rev. D **94**, 072006 (2016).

[16] C. T. Kullenberg *et al.* (NOMAD Collaboration), Phys. Lett. B **682**, 177 (2009).

[17] M. A. Acero *et al.* (NOvA Collaboration), Phys. Rev. D **102**, 012004 (2020).

[18] Y. Kurimoto *et al.* (SciBooNE Collaboration), Phys. Rev. D **81**, 033004 (2010).

[19] Y. Kurimoto *et al.* (SciBooNE Collaboration), Phys. Rev. D **81**, 111102 (2010).

[20] K. Abe *et al.* (T2K Collaboration), Phys. Rev. D **97**, 032002 (2018).

[21] P. Abratenko *et al.* (MicroBooNE Collaboration), Phys. Rev. D **110**, 092014 (2024).

[22] C. Mariani *et al.* (K2K Collaboration), Phys. Rev. D **83**, 054023 (2011).

[23] C. Adams *et al.* (MicroBooNE Collaboration), Phys. Rev. D **99**, 091102 (2019).

[24] D. Coplowe *et al.* (MINERvA Collaboration), Phys. Rev. D **102**, 072007 (2020); **110**, 059903(E) (2024).

[25] C. L. McGivern *et al.* (MINERvA Collaboration), Phys. Rev. D **94**, 052005 (2016).

[26] T. Le *et al.* (MINERvA Collaboration), Phys. Lett. B **749**, 130 (2015).

[27] O. Altinok *et al.* (MINERvA Collaboration), Phys. Rev. D **96**, 072003 (2017).

[28] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), Phys. Rev. D **83**, 052009 (2011).

[29] M. A. Acero *et al.* (NOvA Collaboration), Phys. Rev. D **107**, 112008 (2023).
[30] M. A. Ramírez *et al.* (MINERvA Collaboration), Phys. Rev. Lett. **131**, 051801 (2023).
[31] R. Acciarri *et al.* (ArgoNeuT Collaboration), Phys. Rev. D **98**, 052002 (2018).
[32] R. Acciarri *et al.* (ArgoNeuT Collaboration), Phys. Rev. Lett. **113**, 261801 (2014); **114**, 039901(E) (2015).
[33] A. Rodriguez *et al.* (K2K Collaboration), Phys. Rev. D **78**, 032003 (2008).
[34] M. Hasegawa *et al.* (K2K Collaboration), Phys. Rev. Lett. **95**, 252301 (2005).
[35] A. Bercellie *et al.* (MINERvA Collaboration), Phys. Rev. Lett. **131**, 011801 (2023).
[36] B. Eberly *et al.* (MINERvA Collaboration), Phys. Rev. D **92**, 092008 (2015).
[37] A. Higuera *et al.* (MINERvA Collaboration), Phys. Rev. Lett. **113**, 261802 (2014).
[38] T. Le *et al.* (MINERvA Collaboration), Phys. Rev. D **100**, 052008 (2019).
[39] A. Mislivec *et al.* (MINERvA Collaboration), Phys. Rev. D **97**, 032014 (2018).
[40] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), Phys. Rev. D **83**, 052007 (2011).
[41] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), Phys. Rev. Lett. **103**, 081801 (2009).
[42] K. Hiraide *et al.* (SciBooNE Collaboration), Phys. Rev. D **78**, 112004 (2008).
[43] K. Abe *et al.* (T2K Collaboration), Phys. Rev. D **108**, 092009 (2023).
[44] K. Abe *et al.* (T2K Collaboration), Phys. Rev. D **103**, 112009 (2021).
[45] K. Abe *et al.* (T2K Collaboration), Phys. Rev. D **95**, 012010 (2017).
[46] K. Abe *et al.* (T2K Collaboration), Phys. Rev. Lett. **117**, 192501 (2016).
[47] K. Abe *et al.* (T2K Collaboration), Phys. Rev. D **101**, 012007 (2020).
[48] H. Oshima *et al.* (NINJA Collaboration), Phys. Rev. D **106**, 032016 (2022).
[49] P. Astier *et al.* (NOMAD Collaboration), Nucl. Phys. **B609**, 255 (2001).
[50] W. Krenz *et al.* (Gargamelle Neutrino Propane Collaboration and Aachen-Brussels-CERN-Ecole Poly-Orsay-Padua Collaboration), Nucl. Phys. **B135**, 45 (1978).
[51] M. Derrick *et al.*, Phys. Lett. **92B**, 363 (1980); **95B**, 461(E) (1980).
[52] G. P. Zeller, in *Proceedings of the 2nd International Workshop on Neutrino-Nucleus Interactions in the Few GeV Region* (2003), https://inspirehep.net/literature/636511.
[53] K. Abe *et al.* (Hyper-Kamiokande Collaboration), arXiv:1805.04163.
[54] B. Abi *et al.* (DUNE Collaboration), arXiv:2002.03005.
[55] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, and A. Zhou, J. High Energy Phys. 09 (2020) 178.
[56] C. Andreopoulos *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **614**, 87 (2010).
[57] C. Andreopoulos, C. Barry, S. Dytman, H. Gallagher, T. Golan, R. Hatcher, G. Perdue, and J. Yarba, arXiv:1510.05494.
[58] K. Abe *et al.* (T2K Collaboration), Phys. Rev. D **87**, 012001 (2013); **87**, 019902(A) (2013).
[59] B. Abi *et al.* (DUNE Collaboration), Eur. Phys. J. C **80**, 978 (2020).
[60] K. Abe *et al.* (T2K Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **659**, 106 (2011).
[61] Y. Fukuda *et al.* (Super-Kamiokande Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **501**, 418 (2003).
[62] D. Beavis *et al.* (E899 Collaboration), 10.2172/52878 (1995), https://inspirehep.net/literature/1673806.
[63] P. A. Amaudruz *et al.* (T2K ND280 FGD Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **696**, 1 (2012).
[64] N. Abgrall *et al.* (T2K ND280 TPC Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **637**, 25 (2011).
[65] D. Allan *et al.* (T2K UK Collaboration), J. Instrum. **8**, P10019 (2013).
[66] K. Abe *et al.*, companion paper, Phys. Rev. D **112**, 072008 (2025).
[67] Y. Hayato, Acta Phys. Pol. B **40**, 2477 (2009), https://inspirehep.net/literature/844435.
[68] Y. Hayato and L. Pickering, Eur. Phys. J. Special Topics **230**, 4469 (2021).
[69] K. Abe *et al.* (T2K Collaboration), Phys. Rev. D **108**, 112009 (2023).
[70] P. Stowell *et al.*, J. Instrum. **12**, P01016 (2017).
[71] Y. Hayato, Nucl. Phys. B, Proc. Suppl. **112**, 171 (2002).
[72] T. Golan, C. Juszczak, and J. T. Sobczyk, Phys. Rev. C **86**, 015505 (2012).
[73] T. Golan, J. Sobczyk, and J. Żmuda, Nucl. Phys. B, Proc. Suppl. **229–232**, 499 (2012).
[74] S. Dytman, Acta Phys. Pol. B **40**, 2445 (2009), https://inspirehep.net/literature/844437.
[75] D. Mancusi, A. Boudard, J. Carbonell, J. Cugnon, J.-C. David, and S. Leray, Phys. Rev. C **91**, 034602 (2015).
[76] J. Cugnon, A. Boudard, J. C. David, S. Leray, and D. Mancusi, Eur. Phys. J. Plus **131**, 169 (2016).
[77] D. H. Wright and M. H. Kelsey, Nucl. Instrum. Methods Phys. Res., Sect. A **804**, 175 (2015).
[78] J. Tena-Vidal *et al.* (GENIE Collaboration), Phys. Rev. D **104**, 072009 (2021).
[79] K. Abe *et al.* (T2K Collaboration), arXiv:1901.03750.
[80] T2K Collaboration, First differential measurement of the single positive pion production cross section in neutrino neutral-current scattering, Zenodo, 2025, 10.5281/zenodo.15776045.