

# First Differential Measurement of the Single $\pi^+$ Production Cross Section in Neutrino Neutral-Current Scattering

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Since its first observation in the 1970s, neutrino-induced neutral-current single positive pion production ( $\text{NC}1\pi^+$ ) 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  $\text{NC}1\pi^+$  interactions using data from the ND280 detector of the T2K experiment collected in  $\nu$ -beam mode. The measured flux-averaged integrated cross section is  $\sigma = (6.07 \pm 1.22) \times 10^{-41} \text{ cm}^2/\text{nucleon}$ . 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.

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**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

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

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  $\pi^0$  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 NC1 $\pi^+$  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  $\approx 0.6$  GeV and a water Cherenkov far detector, which focuses on CC0 $\pi$  events, and DUNE [54] with a peak unoscillated neutrino energy of  $\approx 2.5$  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  $\theta_{23}$  and

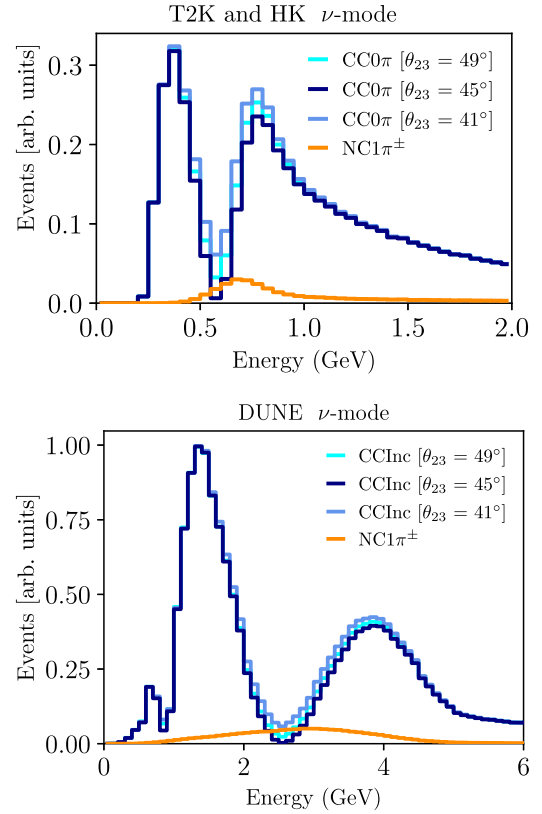


FIG. 1. Expected event rate, in arbitrary units, for CC0 $\pi$  including  $\mu$  and  $\pi$  Cherenkov thresholds (T2K and Hyper-K) and CC-inclusive (DUNE) muon-neutrino interactions at the Hyper-K (top) and DUNE (bottom) experiments shown as a function of the true neutrino energy. Also overlaid is 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.

$\Delta m_{23}^2$  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.

*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  $\nu$ -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  $2.5^\circ$  off axis, resulting in a narrow neutrino energy spectrum peaking at 0.6 GeV [58,62].

The analysis utilizes ND280 data recorded in  $\nu$ -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  $\nu$  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  $\pi^+$ . Full selection details and performance metrics are presented in Ref. [66].

*Analysis strategy*—The  $\text{NC}1\pi^\pm$  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

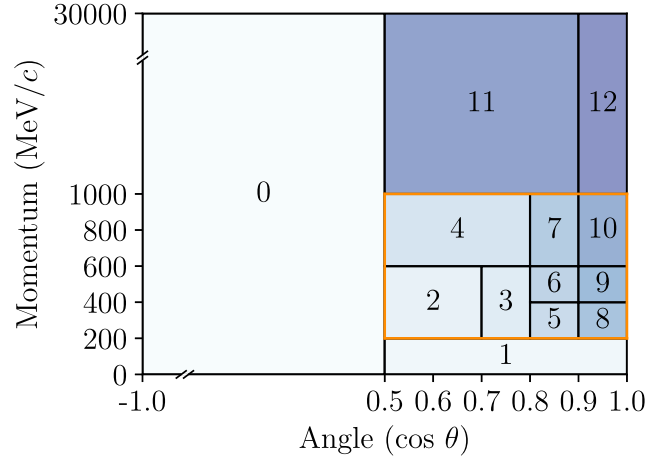


FIG. 2. Scheme of the true pion kinematic bins where the cross section is measured. Bin IDs are shown within their associated kinematic regions. The region of interest, where we report the measurement, is enclosed by an orange solid line and corresponds to bins 2–10. Color shades are used to aid visualization 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

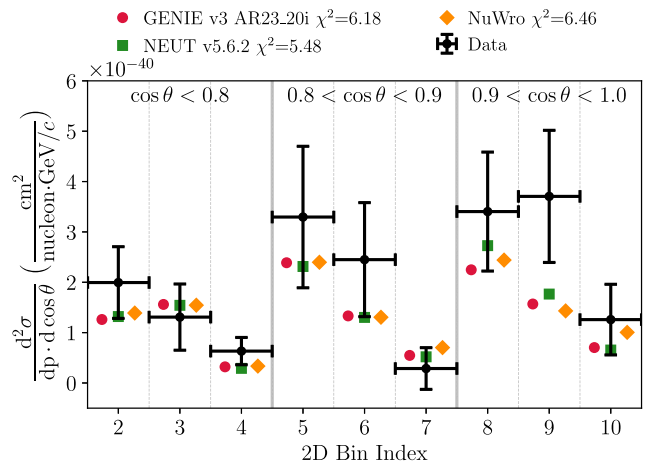


FIG. 3. Measured  $\text{NC}1\pi^\pm$  double-differential cross section compared to generator predictions.

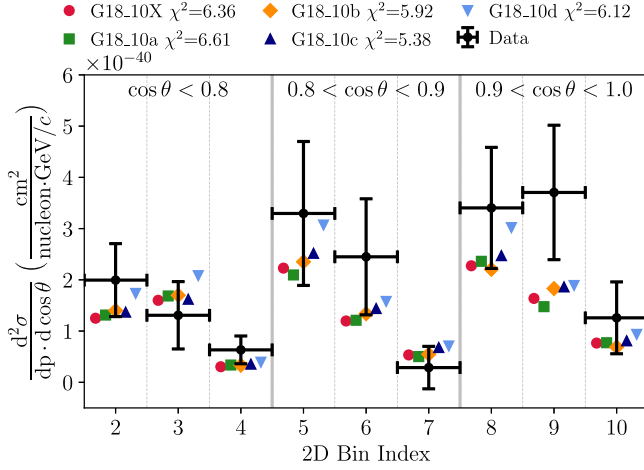


FIG. 4. Measured  $\text{NC}1\pi^\pm$  double-differential cross section compared to various FSI predictions.

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  $\chi^2$  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  $1.7\sigma$ . 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                   | $\sigma$ (cm <sup>2</sup> /nucleon) | $p$ value |
|-------------------------|-------------------------------------|-----------|
| Data                    | $(6.07 \pm 1.22) \times 10^{-41}$   | ...       |
| GENIEv3 AR23_20i_00_000 | $4.02 \times 10^{-41}$              | 0.093     |
| NuWro v19.02.2          | $4.33 \times 10^{-41}$              | 0.153     |
| NEUT v5.6.2             | $4.11 \times 10^{-41}$              | 0.108     |
| G18_10X                 | $3.99 \times 10^{-41}$              | 0.089     |
| G18_10a                 | $4.07 \times 10^{-41}$              | 0.100     |
| G18_10b                 | $4.24 \times 10^{-41}$              | 0.133     |
| G18_10c                 | $4.42 \times 10^{-41}$              | 0.176     |
| G18_10d                 | $5.26 \times 10^{-41}$              | 0.507     |

**Conclusions**—Using the largest data sample of selected  $\text{NC}1\pi^\pm$  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  $\text{NC}1\pi^\pm$  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  $\text{NC}1\pi^\pm$  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  $\text{NC}1\pi^\pm$  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  $\text{NC}1\pi^\pm$  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.

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*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.