Ratio of neutral current single π^0 production cross sections on argon with the MicroBooNE detector

(The MicroBooNE Collaboration)*

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This document expands on the content of the paper titled "Measurement of neutral current single π^0 production on argon with the MicroBooNE detector" [1]. We present here the ratio of the two exclusive cross section measurements first reported in Ref. [1]. Additionally we include projections for the statistical and total uncertainty of all results when the analysis is expanded to the full MicroBooNE data set in the near future.

I. RATIO OF EXCLUSIVE NC $1\pi^0$ CROSS-SECTIONS ON ARGON

Among the primary results presented in Ref. [1] are a pair of exclusive cross section measurements targeting neutral current π^0 production on argon with one proton (1p) or zero protons (0p) in the final state, where the proton kinetic energy threshold is set to be 50 MeV. These measurements, $\sigma_{\mathrm{NC}1\pi^0+1p}$ and $\sigma_{\mathrm{NC}1\pi^0+0p}$, as reported in Ref. [1], are shown in the central and rightmost panels of Figure 1, respectively. The ratio between them, $\frac{\sigma_{\mathrm{NC}1\pi^0+1p}}{\sigma_{\mathrm{NC}1\pi^0+0p}}$, is shown in the leftmost panel of Figure 1. The ratio is calculated simultaneously in all systematic universes utilized in the analysis (described in detail in Sec. II C of Ref. [1]) utilizing functionality provided by the MINERvA Analysis Toolkit [2]. The extracted cross section ratio is $\frac{\sigma_{\mathrm{NC}1\pi^0+1p}}{\sigma_{\mathrm{NC}1\pi^0+0p}} = 0.710 \pm 0.078$ (syst.) $\pm$ 0.114 (stat.). The corresponding breakdowns of systematic and statistical uncertainties on these measurements are shown in Figure 2.

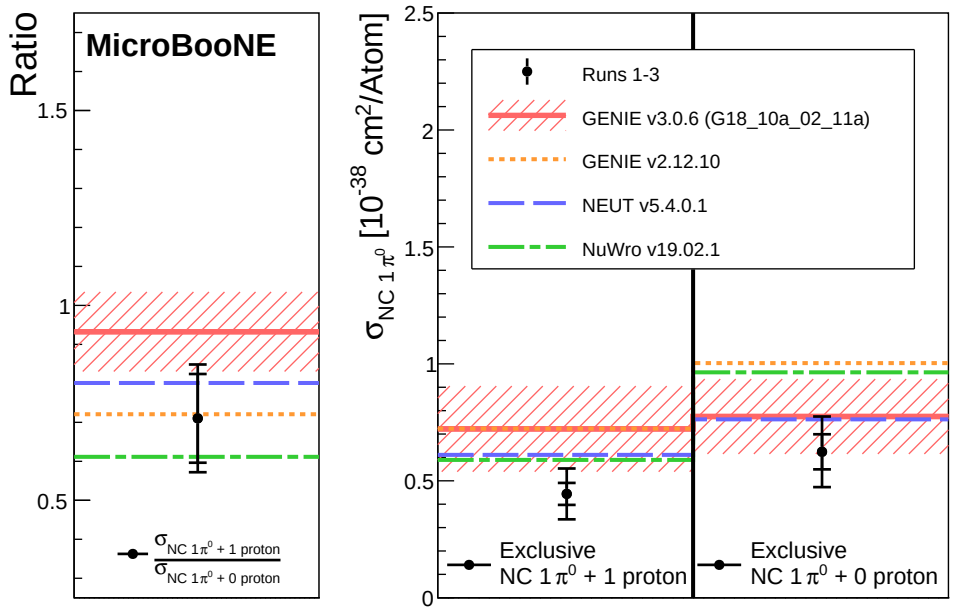

FIG. 1: Measured (left) cross section ratio $\frac{\sigma_{\mathrm{NC}1\pi^0+1p}}{\sigma_{\mathrm{NC}1\pi^0+0p}}$, (center) exclusive cross section $\sigma_{\mathrm{NC}1\pi^0+1p}$, and (right) exclusive cross section $\sigma_{\mathrm{NC}1\pi^0+0p}$, each compared to the corresponding GENIE v3 (G18_10a_02_11a) cross section and its uncertainty (shaded red bands) as well as other contemporary neutrino generators. Inner error bars on data points are statistical only; outer are statistical and systematic, summed in quadrature.

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Due to correlations between the individual exclusive cross section measurements, the systematic uncertainties corresponding to the flux and GENIE are significantly reduced by calculating the ratio between the measurements. Conversely, because the two individual measurements are statistically independent, by construction, the statistical uncertainty is amplified by calculating the ratio between the measurements. The systematic uncertainty corresponding to the detector model is similarly increased slightly by calculating the ratio, because of the limited Monte Carlo statistics used to evaluate those uncertainties. The systematic uncertainties corresponding to POT counting and modeling of the number of targets used in the analysis drop to identically zero by calculating the ratio between the measurements.

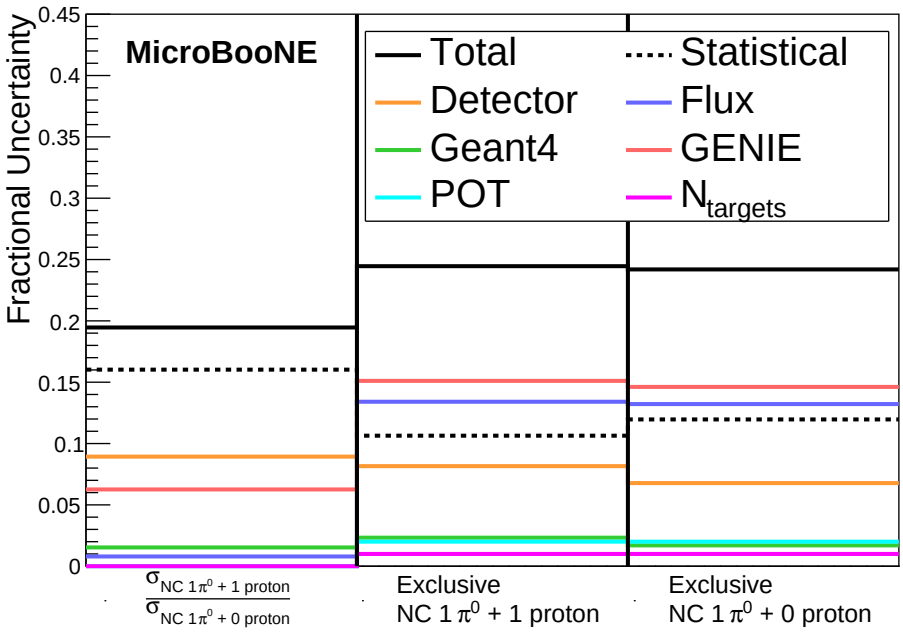

FIG. 2: Error budget for the (left) cross section ratio $\frac{\sigma_{\mathrm{NC1}\pi^0+1p}}{\sigma_{\mathrm{NC1}\pi^0+0p}}$, (center) exclusive cross section $\sigma_{\mathrm{NC1}\pi^0+1p}$, and (right) exclusive cross section $\sigma_{\mathrm{NC1}\pi^0+0p}$ measurements.

II. PROJECTIONS OF UNCERTAINTIES FOR COMPLETE MICROBOONE DATASET

The cross section measurements presented in Ref. [1] are calculated using data collected during the period 2016–2018 and referred to as "Runs 1–3". The processing of the remainder of the MicroBooNE data, referred to as "Runs 4-5" (collected during the period 2018-2020), is expected to increase the total available statistics for analysis by approximately 78%. The plots below show projected statistical and total uncertainties on the cross section measurements presented in Ref. [1] and in Sec. I of this note, assuming that the statistics utilized in the analysis are increased by 78% and that no other changes to the analysis are made (*i.e.* the systematic uncertainties are not changed). To calculate the projected impact of using the full data set, the statistical uncertainty for each of the exclusive cross section measurements and for the semi-inclusive cross section measurement is multiplied by $\frac{1}{\sqrt{1.78}}$, and the total uncertainty is recalculated by summing-in-quadrature this revised statistical uncertainty and the unaltered systematic uncertainty. Note that for the ratio of cross sections, the statistical and total uncertainties for the ratio are not directly modified using the described scheme, but rather the ratio is recalculated using as inputs the exclusive cross sections that have each been recalculated using the described scheme.

Figure 3 shows the $\sigma_{\mathrm{NC1}\pi^0+1p}$ and $\sigma_{\mathrm{NC1}\pi^0+0p}$ exclusive cross section measurements and the $\sigma_{\mathrm{NC1}\pi^0}$ semi-inclusive cross section measurement, as presented in Fig. 12 of Ref. [1] with the addition of the projected uncertainties for the full data set. Figure 4 shows the $\sigma_{\mathrm{NC1}\pi^0+1p}$ and $\sigma_{\mathrm{NC1}\pi^0+0p}$ exclusive cross section measurements and their ratio, as presented in Fig. 1 of this note with the addition of the projected uncertainties for the full data set. In all cases, black data points represent the measurement made using MicroBooNE Runs 1-3 and blue data points represent the projection of these measurements to the full MicroBooNE data set, corresponding to Runs 1-5. Table I shows the

breakdown of systematic, statistical, and total uncertainties for all of the measured cross sections for both Runs 1-3 and the Runs 1-5 projection.

For each of the exclusive cross section measurements and for the semi-inclusive cross section measurement, the projected increased statistics minimally impacts the precision of the calculated cross section, because the measurement is already systematically limited. The measurement of the cross section ratio, on the other hand, is currently statistically limited, and correspondingly we see that its precision is projected to be more significantly improved by incorporating the increased statistics.

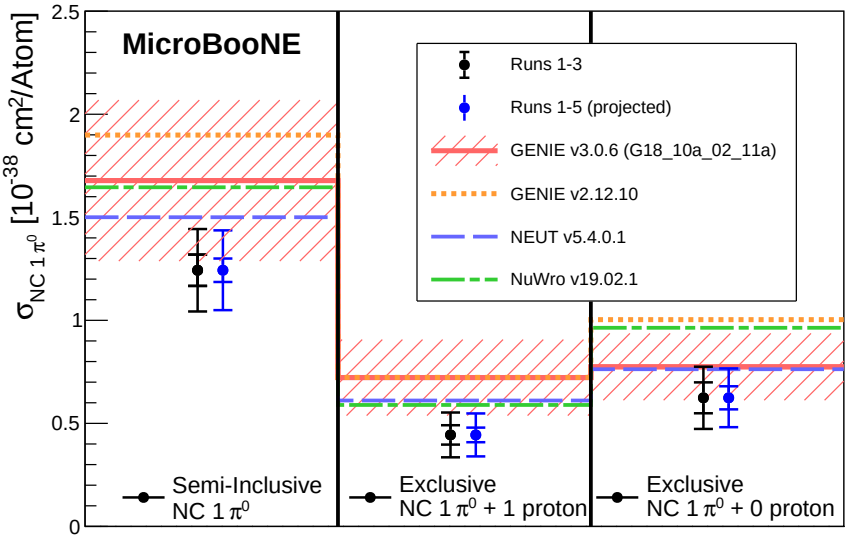

FIG. 3: Measured (left) semi-inclusive cross section $\sigma_{\mathrm{NC1}\pi^0}$, (center) exclusive cross section $\sigma_{\mathrm{NC1}\pi^0+1p}$, and (right) exclusive cross section $\sigma_{\mathrm{NC1}\pi^0+0p}$, each compared to the corresponding GENIE v3 (G18_10a_02_11a) cross section and its uncertainty (shaded red bands) as well as other contemporary neutrino generators. Inner error bars on data points are statistical only; outer are statistical and systematic, summed in quadrature. Black data points represent the measurement made using MicroBooNE Runs 1-3; blue data points represent the projection of the measurement to the full MicroBooNE data set (Runs 1-5), with statistics increased by 78%.

TABLE I: Summary table of the projected uncertainties when expanding from Runs 1-3 to Runs 1-5 of MicroBooNE data, assuming a 78% increase in statistics used in the analysis.

Measurement [units]	$\frac{\sigma_{NC\pi^0+1p}}{\sigma_{NC\pi^0+0p}}$ **(ratio)**	$\sigma_{NC\pi^0}$ **(semi-inclusive)** $[10^{-38}\mathrm{cm}^2/\mathrm{Ar}]$	$\sigma_{NC\pi^0+1p}$ **(exclusive)** $[10^{-38}\mathrm{cm}^2/\mathrm{Ar}]$	$\sigma_{NC\pi^0+0p}$ **(exclusive)** $[10^{-38}\mathrm{cm}^2/\mathrm{Ar}]$
central value	0.710	1.243	0.444	0.624
systematic uncertainty	±0.078 (11.0%)	±0.185 (14.9%)	±0.098 (22.0%)	±0.131 (21.0%)
statistical uncertainty Runs 1-3	±0.114 (16.0%)	±0.076 (6.1%)	±0.047 (10.6%)	±0.075 (12.0%)
statistical uncertainty Runs 1-5 (projected)	±0.085 (12.0%)	±0.057 (4.6%)	±0.035 (8.0%)	±0.056 (9.0%)
total uncertainty Runs 1-3	±0.138 (19.5%)	±0.200 (16.1%)	±0.109 (24.5%)	±0.151 (24.2%)
total uncertainty Runs 1-5 (projected)	±0.116 (16.3%)	±0.194 (15.6%)	±0.104 (23.4%)	±0.143 (22.9%)

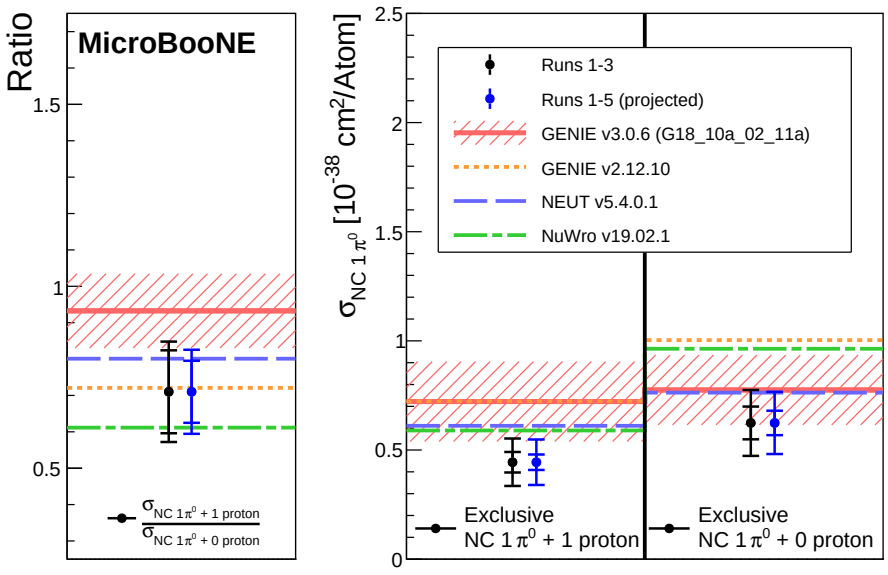

FIG. 4: Measured (left) cross section ratio $\frac{\sigma_{\mathrm{NC1}\pi^0+1p}}{\sigma_{\mathrm{NC1}\pi^0+0p}}$, (center) exclusive cross section $\sigma_{\mathrm{NC1}\pi^0+1p}$, and (right) exclusive cross section $\sigma_{\mathrm{NC1}\pi^0+0p}$, each compared to the corresponding GENIE v3 (G18_10a_02_11a) cross section and its uncertainty (shaded red bands) as well as other contemporary neutrino generators. Inner error bars on data points are statistical only; outer are statistical and systematic, summed in quadrature. Black data points represent the measurement made using MicroBooNE Runs 1-3; blue data points represent the projection of the measurement to the full MicroBooNE data set (Runs 1-5), with statistics increased by 78%.

[1] P. Abratenko *et al.* (MicroBooNE), Phys. Rev. D **107**, 012004 (2023), arXiv:2205.07943 [hep-ex].
[2] B. Messerly *et al.* (MINERvA), EPJ Web Conf. **251**, 03046 (2021), arXiv:2103.08677 [hep-ex].