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ν_μ CC0π interactions with one or more protons in MicroBooNE

arXiv:2403.19574

Steven Gardiner (gardiner@fnal.gov)

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μBooNE

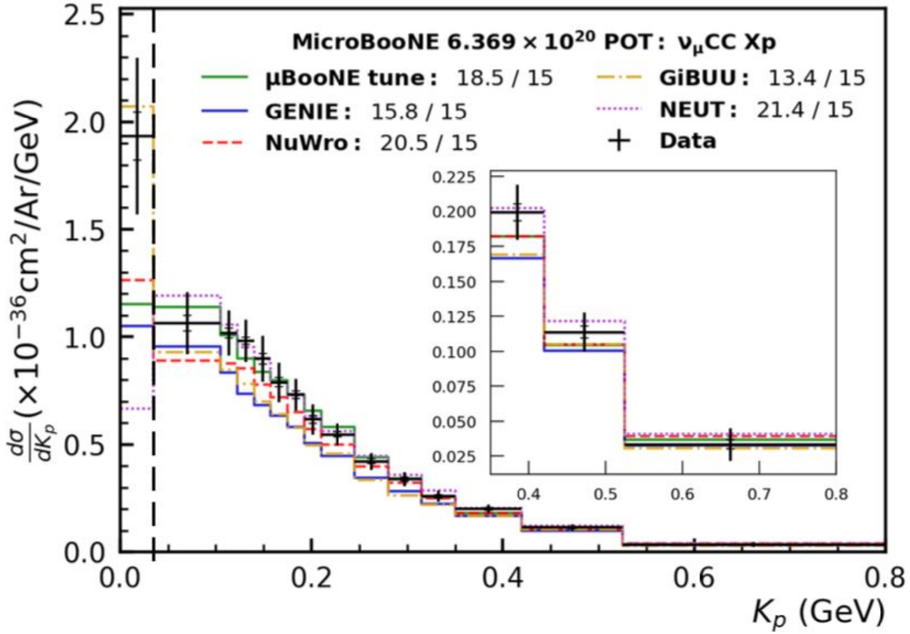
Relationship to other recent MicroBooNE results

- ν_μ CC**0πNp** (for N ≥ 1)

- **More inclusive** than 1p analysis
  - Previous talk by Andy Furmanski
  - Poster by Afro Papadopoulou
  - arXiv:2310.06082

- **More exclusive** than simultaneous 0pNp measurements
  - Poster by Ben Bogart
  - arXiv:2402.19281 and arXiv:2402.19216

arXiv:2402.19281



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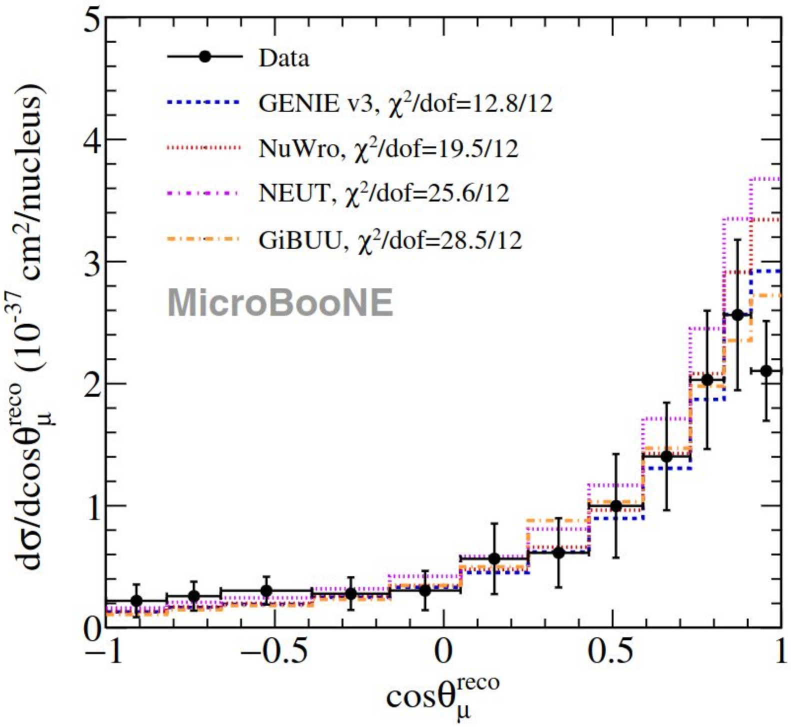
Previous ν_μ CC0πNp cross sections from MicroBooNE

- First ν-Ar single-differential results
  - 5 observables, 5 distributions, 43 bins
  - 0.3 GeV/c proton threshold
  - 1.6×10^{20} protons-on-target (POT)
- Many improvements since then
  - Over 4x more data (6.79×10^{20} POT)
  - Log-likelihood particle ID: JHEP 2021, 153
  - Improved understanding of detector response: Eur. Phys. J C 82, 454 (2022)
  - Tuned neutrino interaction model: Phys. Rev. D 105, 072001 (2022)

Phys. Rev. D 102, 112013 (2020)



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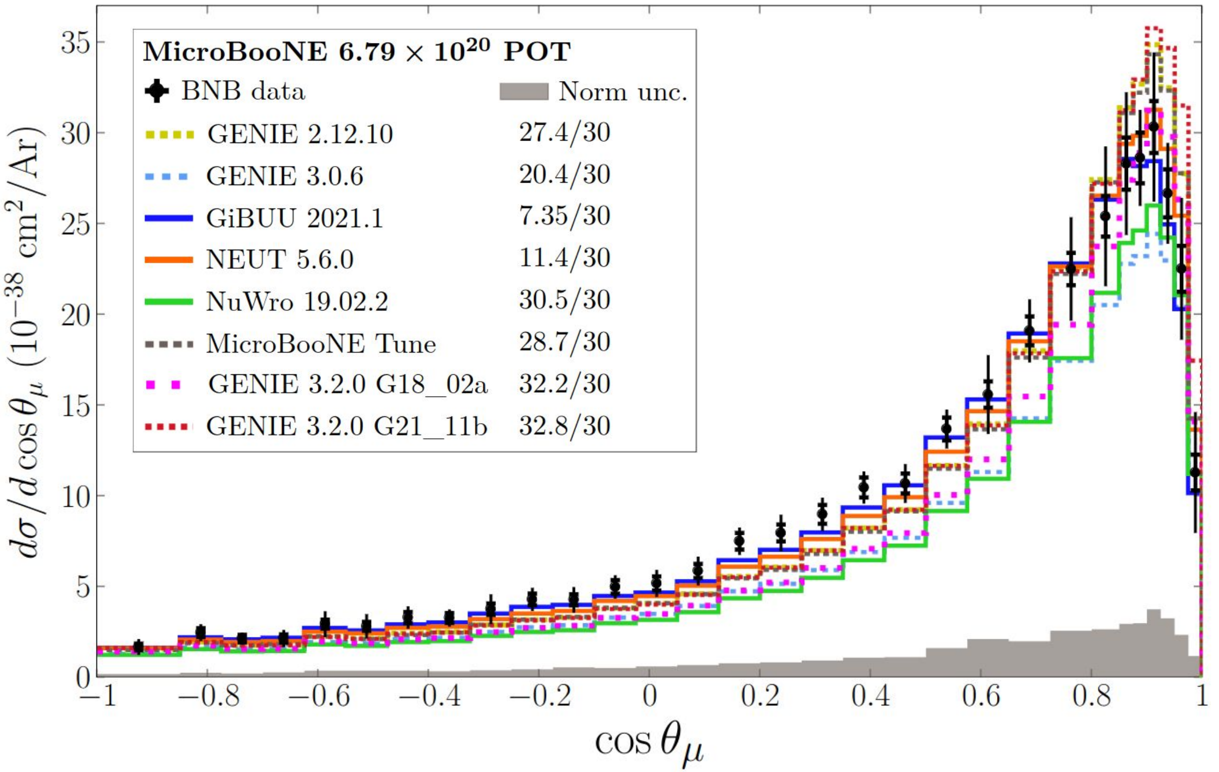
Current ν_μ CC0πNp measurements

arXiv:2403.19574

- We can now report much more detail
- 10 observables, 14 distributions, 359 bins
- 2D and 1D results
- **0.25 GeV/c** proton threshold
- Statistical and systematic **correlations** between all data points



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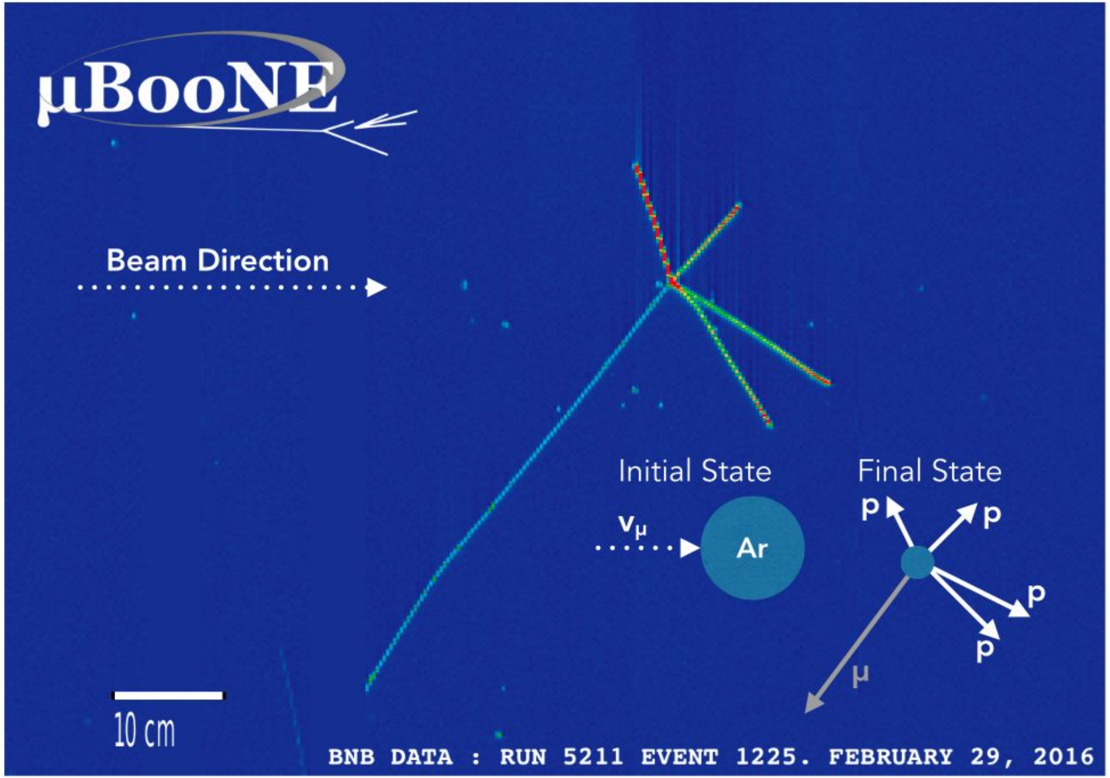
Signal definition

- ν_μ CC on Ar, at least one final-state proton
- Zero (anti)mesons
- $p_\mu \in [0.1, 1.2]$ GeV/c
- $p_p \in [\mathbf{0.25}, 1.0]$ GeV/c
- Restricted phase space motivation similar to 1p analysis
- The p_p limit only applies to the **leading proton**

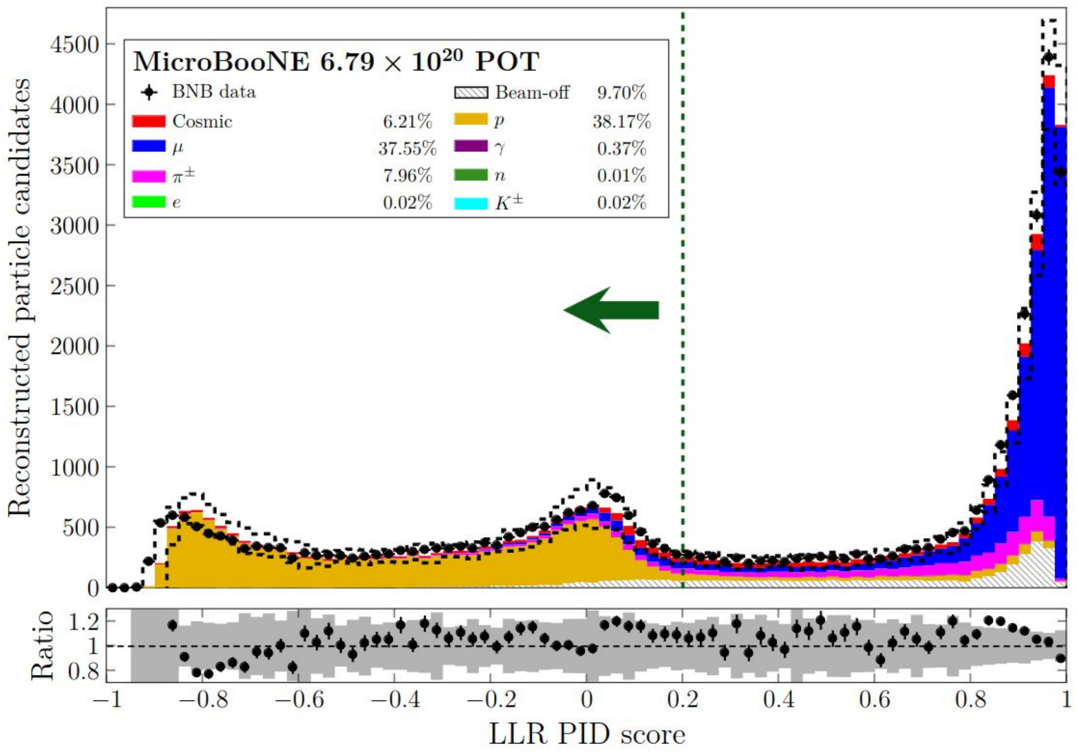
This 4p (!) candidate event is selected



Event selection

- Implemented using automated Pandora reconstruction
- Series of 12 cuts:
    - Find a ν-induced μ
    - that is well-reconstructed
    - and accompanied only by p
- Overall performance
    - 12.3% efficiency
    - 78.5% purity

Proton identification



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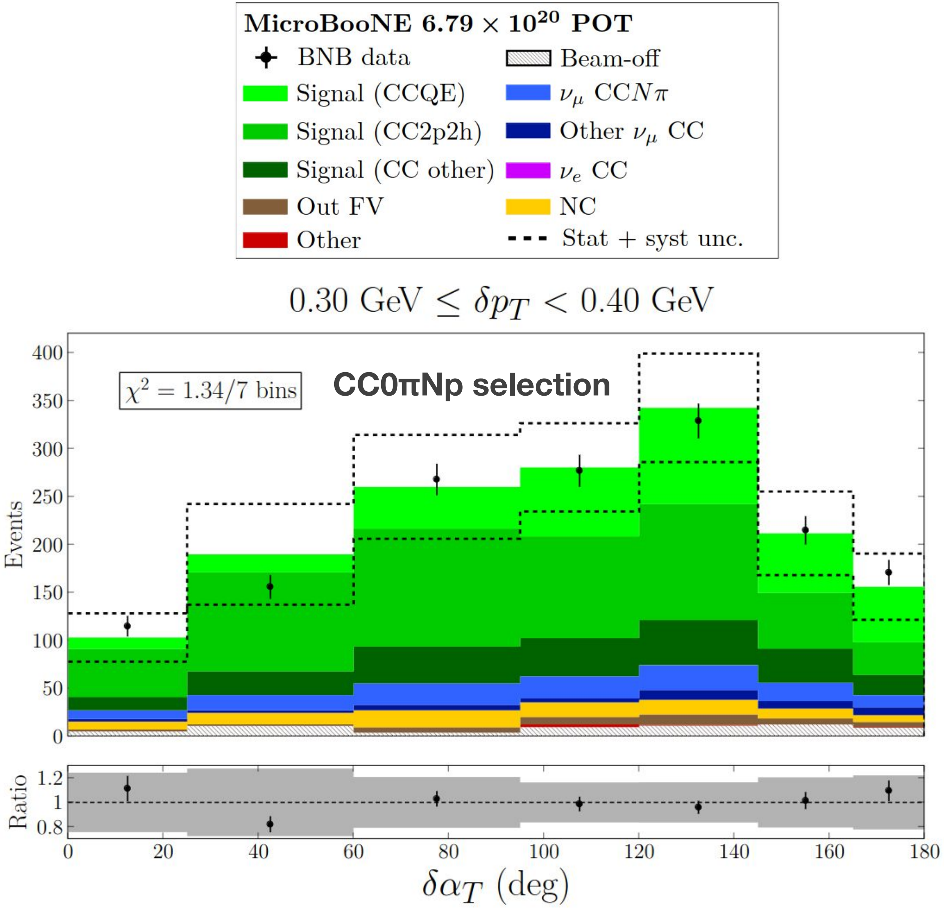
Data/MC comparisons

- Agreement reasonable within uncertainties (χ^2 = 355 / 359 bins)
- 3 dominant backgrounds:
  - **Out of Fiducial Volume** (Out FV)
  - **Neutral-current** (NC)
  - **Pion production** (ν_μ CCNπ)
- Alternate selections made to enhance each, check background prediction



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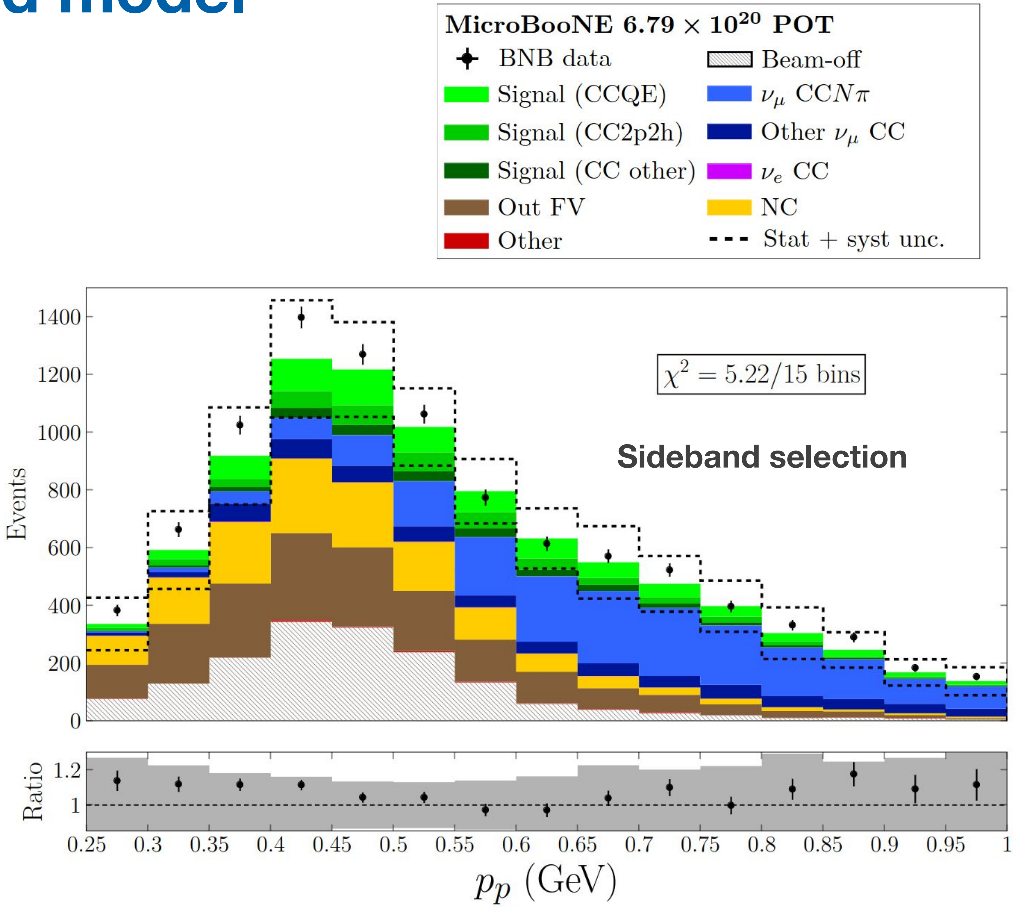
Sideband test of background model

- Logical OR of 3 alternate selections plotted for 359 bins
- **Out FV** and **NC** important at low p_p, **π production** at high p_p
- Satisfactory agreement everywhere in phase space (χ^2 = 178 / 359 bins)
- GENIE-based model used unaltered
- Full sideband results in supplement and data release



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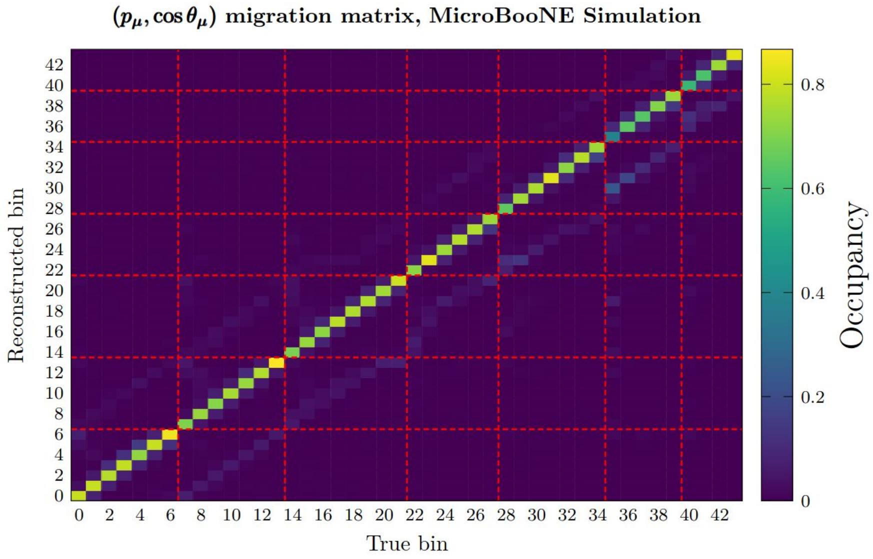
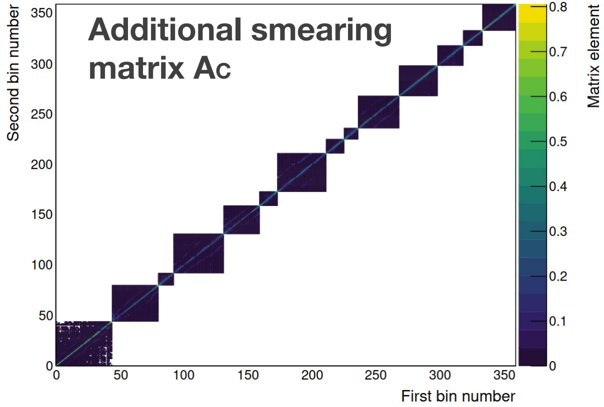
Unfolding

- D'Agostini method used for each of 14 blocks of bins
  - 2-5 iterations depending on specific distribution
  - Validated with mock data
- Additional smearing matrix
  - "Ac" introduced in Wiener-SVD method
  - Supplied here in data release for new model comparisons





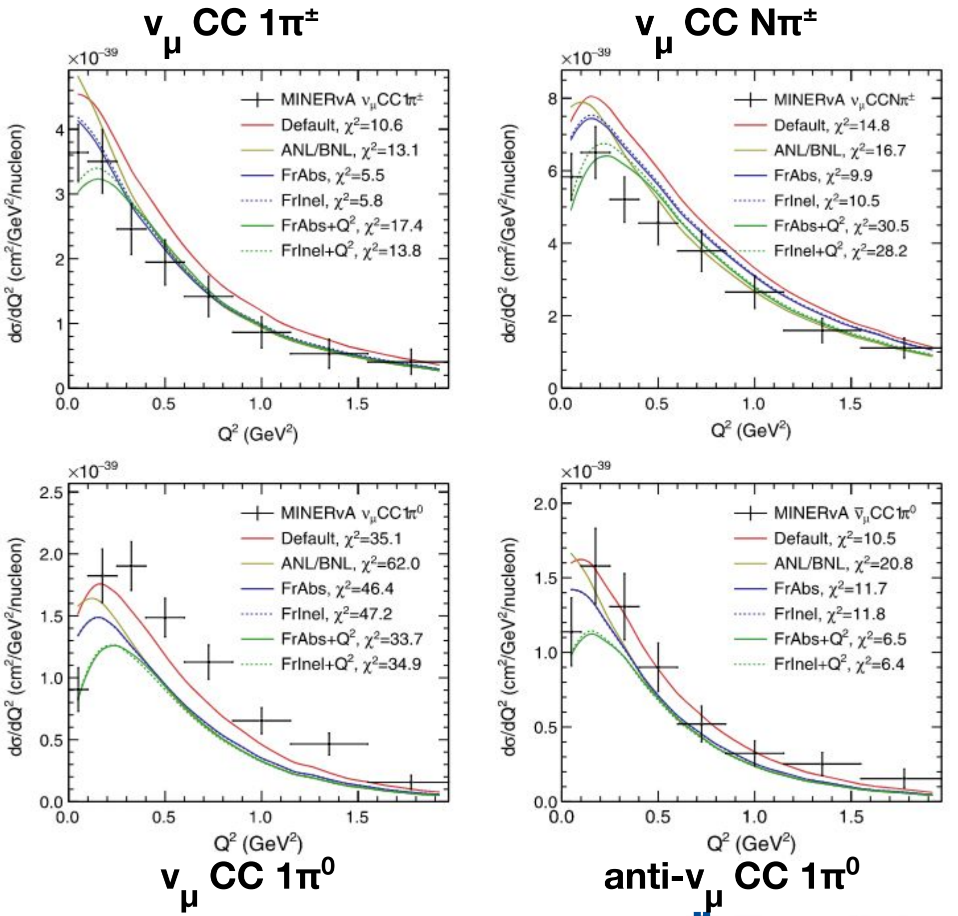
Red dashed lines denote pμ bin boundaries

White regions correspond to matrix elements that are identically zero

Inter-distribution correlations

MINERvA, [Phys. Rev D. 100, 072005 (2019)]

- "Covariance matrix per histogram" is standard practice in data releases
- Experiments can calculate correlations *between* histograms, hard to guess / retrieve later
  - Both systematic and statistical
- When omitted, limits validity of goodness-of-fit
  - **See fitting study by MINERvA**



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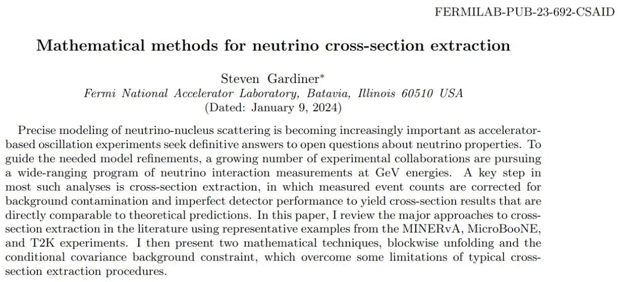
Inter-distribution correlations

- "Blockwise unfolding" technique for reporting this information
- Premiere in this analysis, see also Ben Bogart's poster and talk
- Allows valid χ^2 comparisons to entire data set, boosting model discrimination power
- See supplemental materials and data release

"Cookbook" for reporting these correlations in other experiments: [arXiv:2401.04065]



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Mathematical methods for neutrino cross-section extraction

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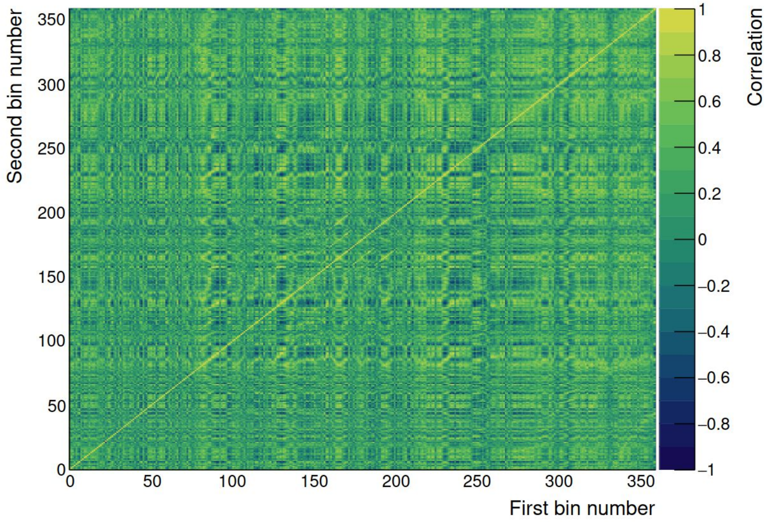
(Dated: January 9, 2024)

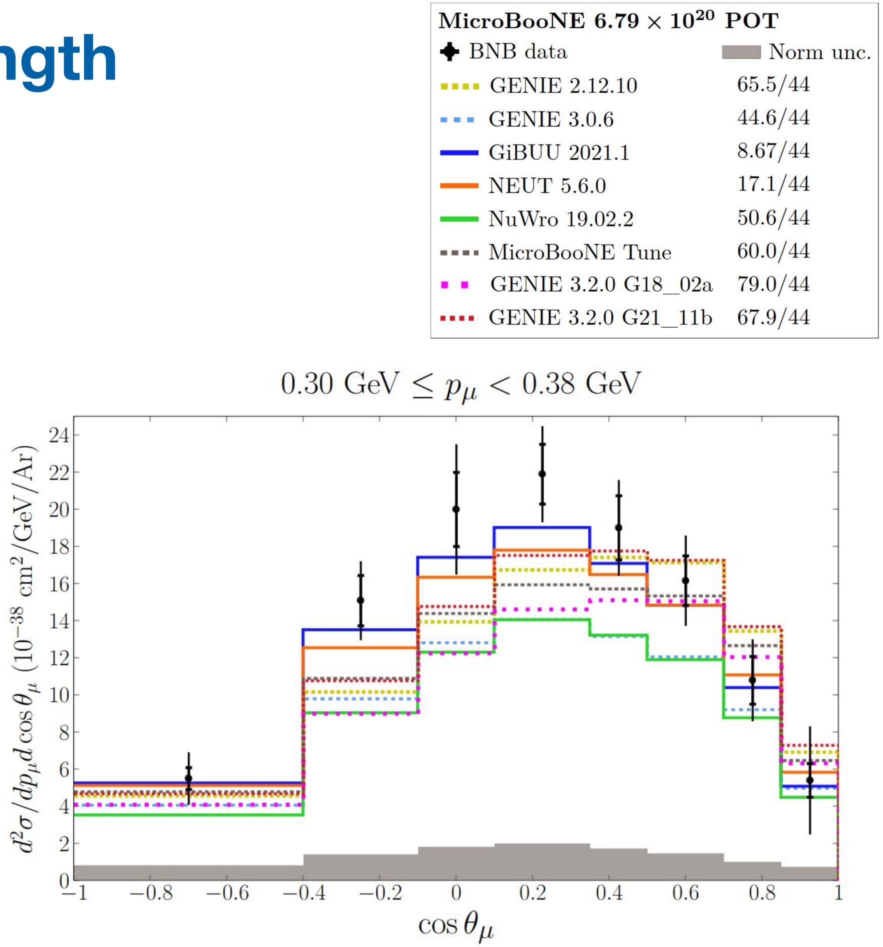
Precise modeling of neutrino-nucleus scattering is becoming increasingly important as accelerator-based oscillation experiments seek definitive answers to open questions about neutrino properties. To guide the needed model refinements, a growing number of experimental collaborations are pursuing a wide-ranging program of neutrino interaction measurements at GeV energies. A key step in most such analyses is cross-section extraction, in which measured event counts are corrected for background contamination and imperfect detector performance to yield cross-section results that are directly comparable to theoretical predictions. In this paper, I review the major approaches to cross-section extraction in the literature using representative examples from the MINERvA, MicroBooNE, and T2K experiments. I then present two mathematical techniques, blockwise unfolding and the conditional covariance background constraint, which overcome some limitations of typical cross-section extraction procedures.

Total correlation matrix for final CC0πNp cross sections



Physics highlights: missing strength

- Data prefer higher cross section in certain phase-space regions
- **Example:** moderate to backward θμ, moderate pμ
- Similar trends seen in other recent MicroBooNE measurements



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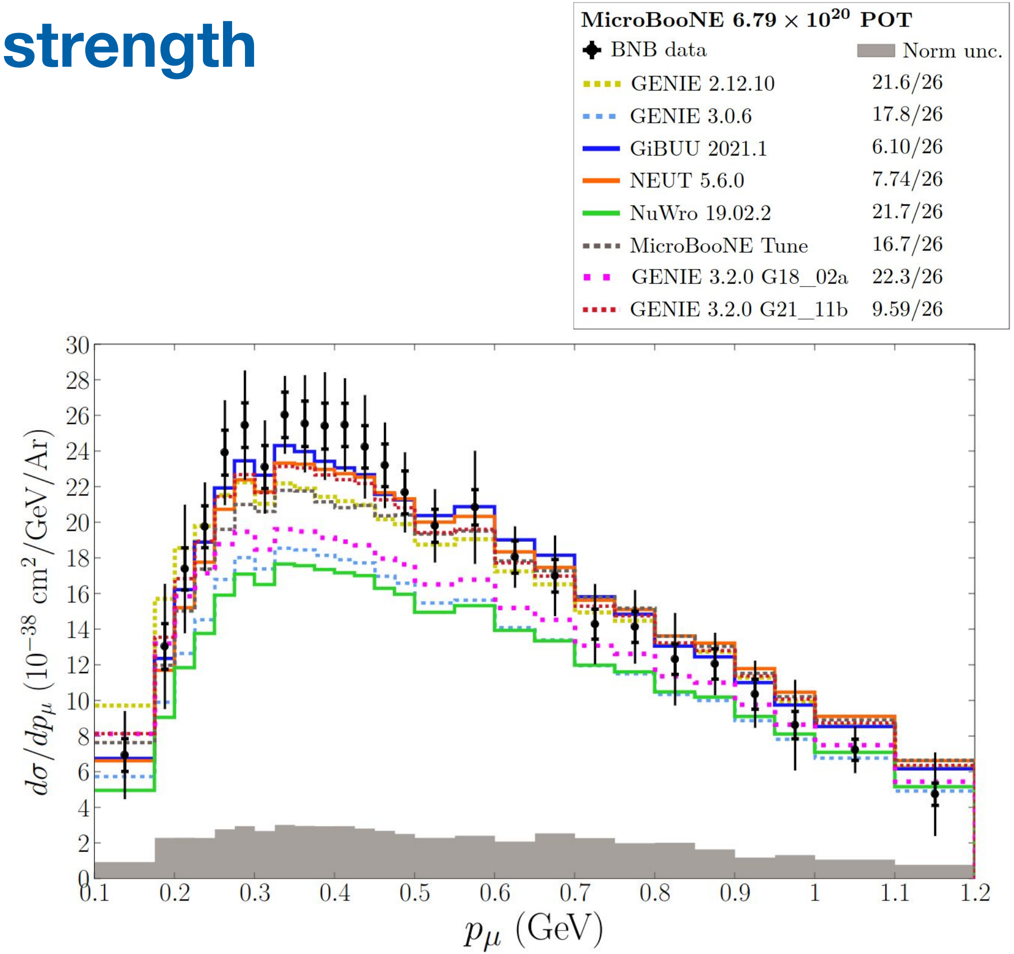

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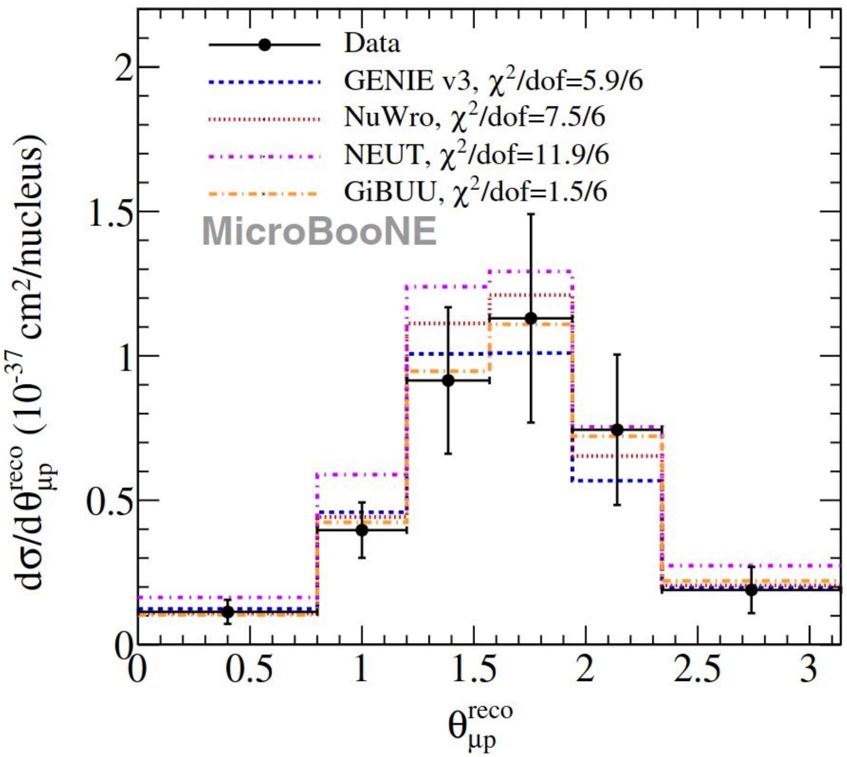
Physics highlights: $\theta_{\mu p}$ shape

- Hint from prior CC0πNp analysis
- Coarse binning, but models seem to be peaking to the left of data
- Distribution sensitive to QE / 2p2h balance

[Phys. Rev. D 102, 112013 (2020)](https://doi.org/10.1103/PhysRevD.102.112013)



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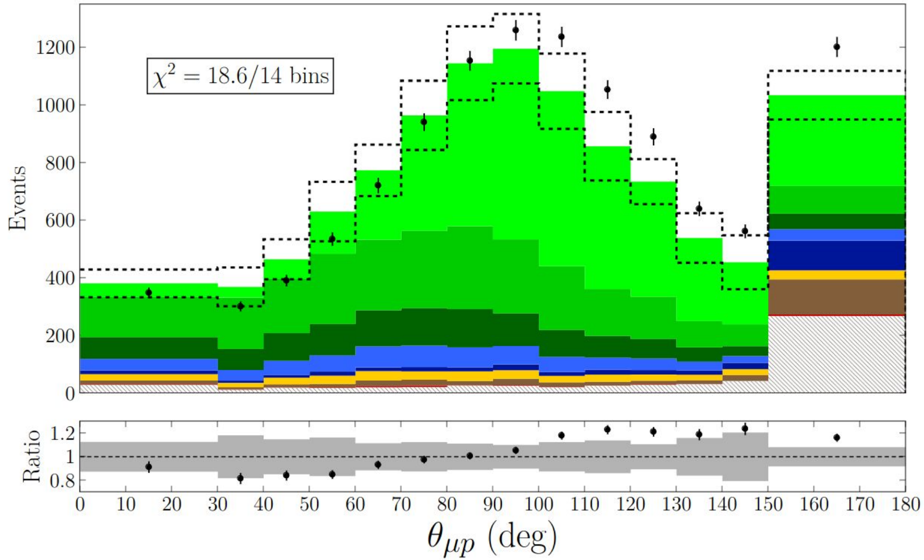
- New analysis achieves much more detailed look



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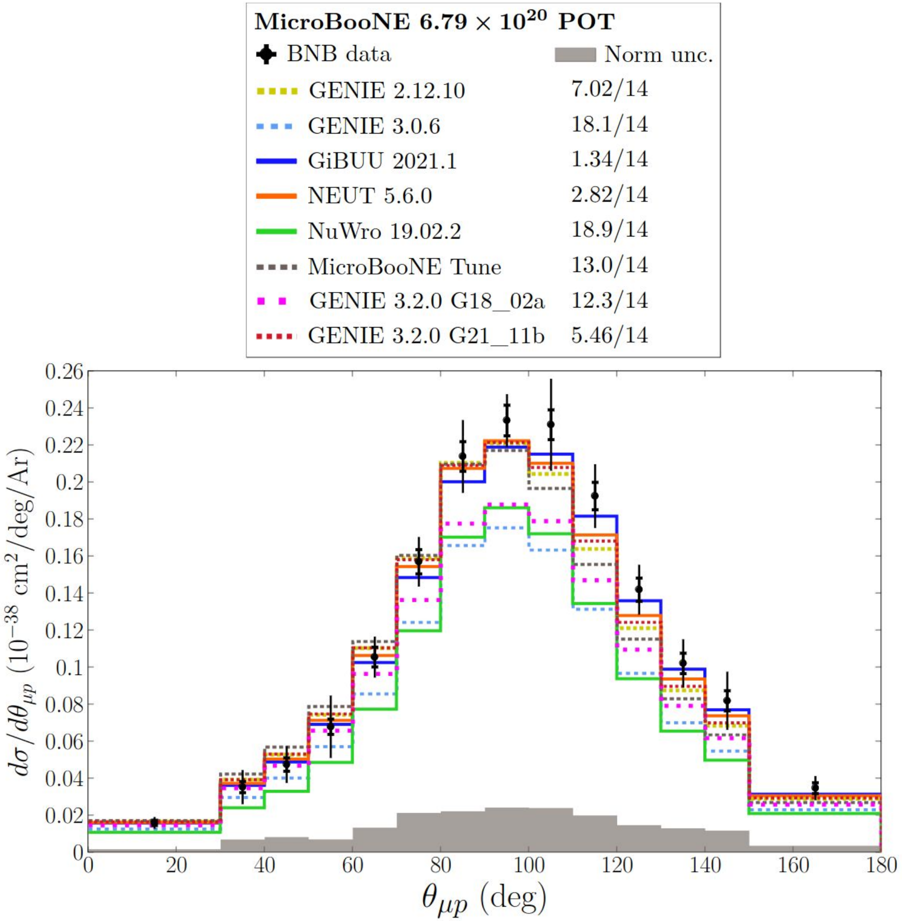

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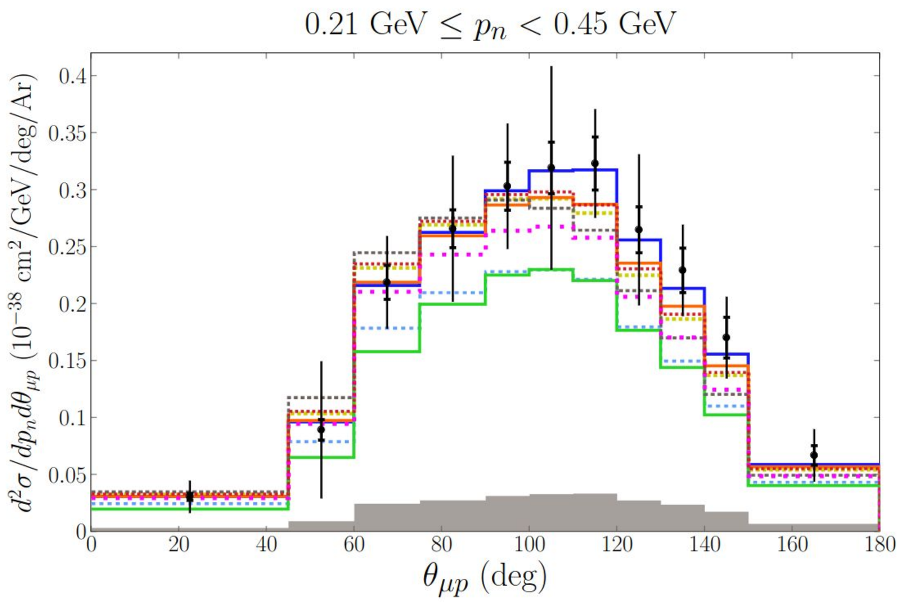
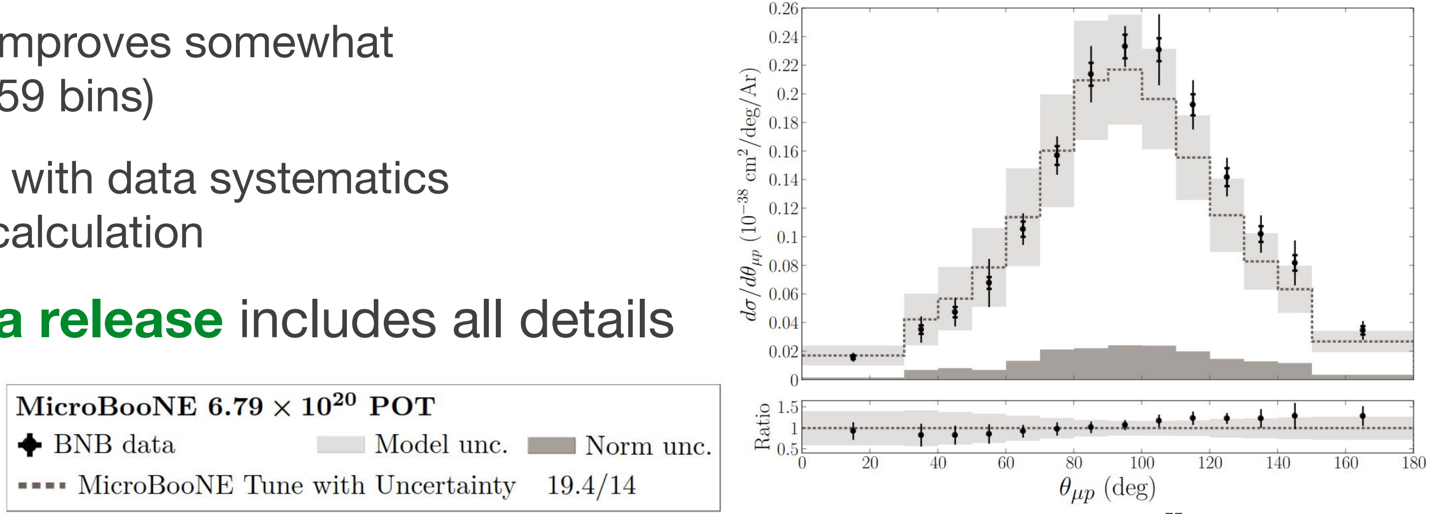


GiBUU does particularly well in the moderate p_n slice (2D)

Physics highlights: overall performance

Model	χ^2 / 359 bins
GENIE 3.0.6	1859
NEUT 5.6.0	2582
MicroBooNE Tune	2673
GENIE 3.2.0 G21_11b	2947
GiBUU 2021.1	4836
NuWro 19.02.1	5315
GENIE 3.2.0 G18_02a	5724
GENIE 2.12.10	7799

- Universal **room for improvement** in comparisons to full data set
- MicroBooNE Tune model uncertainty shown for comparisons in supplement
  - Agreement improves somewhat (χ^2 = 979 / 359 bins)
  - Correlations with data systematics included in calculation
- **Extended data release** includes all details



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"Showing our work" in the supplement

- Basic data release
  - Cross-section results, MicroBooNE flux
  - Overall and partial covariance matrices
  - A_C and example scripts for model comparisons
- Extended data release
  - All information needed to revisit unfolding, uncertainty propagation
  - Stat covariances and systematic universes
  - Script to re-generate covariances between signal bins, sidebands, and the MicroBooNE Tune prediction

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Conclusion

- The **new ν_μ CC0πNp data** from MicroBooNE are highly detailed
  - 10 observables, 14 differential cross sections, 359 bins
- Complementary to our other recent results looking at protons
  - Exclusive 1p (Andy Furmanski's talk), Inclusive 0pNp (Ben Bogart's poster)
- "Blockwise unfolding" provides stringent test of models
  - Work in progress to extend to inter-*analysis* correlated uncertainties
- Coming to NUISANCE soon, basic and extended data releases available in supplemental materials (arXiv:2403.19574)
- This is still only about half our data, **stay tuned for much more** from MicroBooNE!

Thank you!

μBooNE

Backup

Uncertainties

- Systematic variations nearly the same as 1p analysis
- **Out-of-cryostat:** no extra uncertainty, model checked in a sideband study instead
- Recombination model for ionization electrons dominates detector uncertainty (3.3%)