2x2 Demonstrator Physics with NuMI

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2x2 Analysis Selection & Systematics Meeting

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

Context

- The paraphrased request: illustrate 2x2 Demonstrator physics capabilities with N POT NuMI exposure to motivate continued operation, possibly up to FNAL beam (upgrade) shutdown
  - Beam delivery scenarios:
    - 0 POT
    - 4.7E20 POT (minimum request)
    - 7.1E20 POT
    - 11.8E20 POT

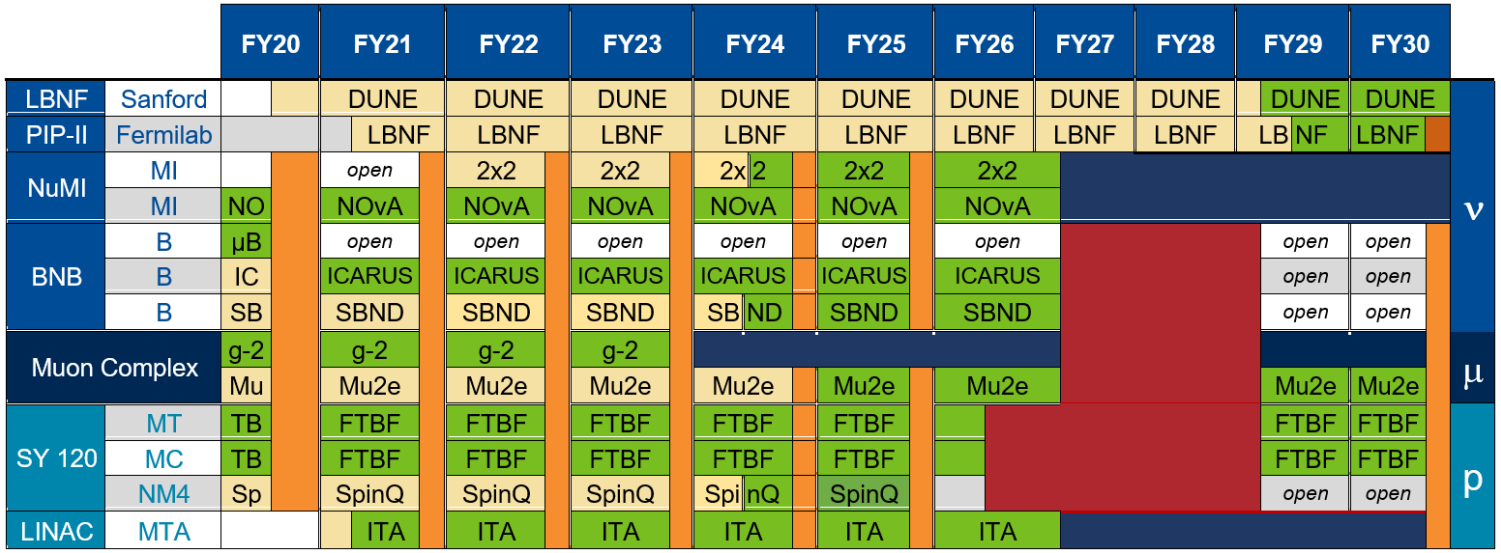
- *Here, physics case for extended 2x2 operation in NuMI*
  - Largely drawn from studies performed by others:
    - Callum Wilkinson: 2x2 cross sections
    - Stephen Greenberg: charged-currrent muon neutrino on Ar interactions
    - Elise Hinkle: mesonless charged-current muon neutrino differential cross section measurements
    - Yifan Chen: charged-current electron neutrino on Ar interactions
    - Andrew Cudd: Kaon production
    - Zach Hulcher: Kaon and lambda production

"Accelerator Complex Status & Plans", A. Valishev & M. Clay (January 2024 FNAL PAC)

NuMI Operation

NuMI scheduled to cease beam delivery sometime in FY27

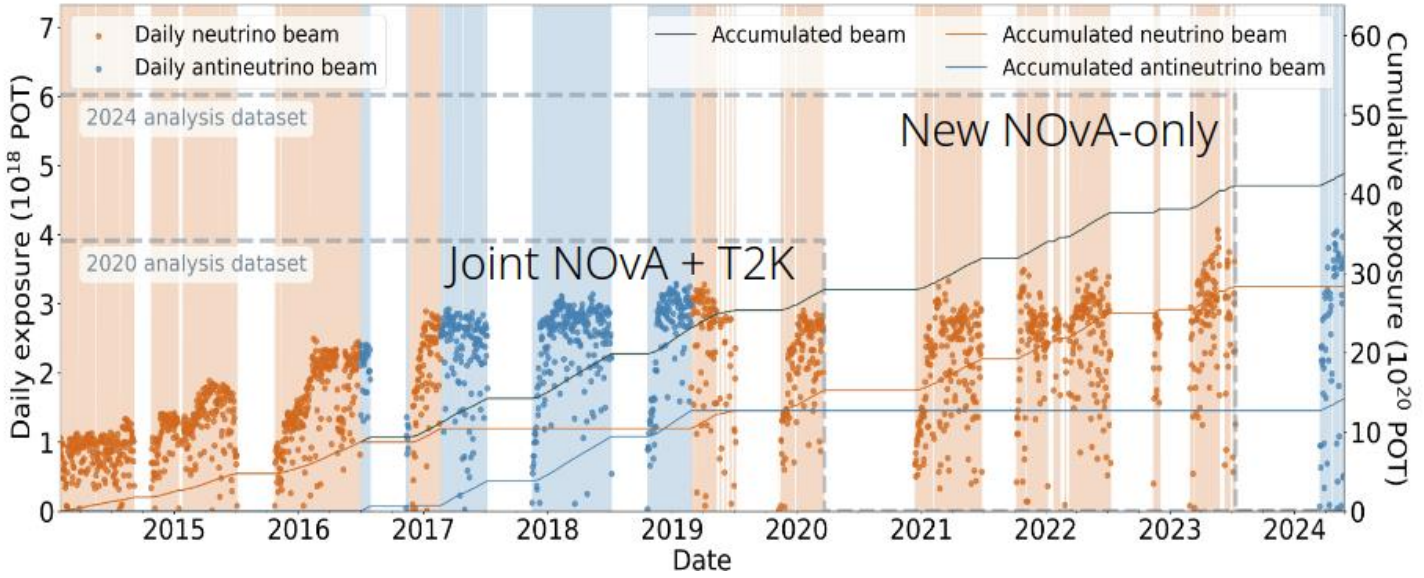
- Operation up to beam shutdown is assumed to be 11.8E20 POT



NOvA dictates NuMI operation mode, likely RHC until beam shutdown

- Highly variable annual exposure

"New NOvA Results with 10 Years of Data", J. Wolcott (Neutrino 2024)



2x2 Demonstrator through the lens of DUNE LBL OA

- ND FDR ~ 2025
  - Does the detector design meet technical specifications?
    - Reconstruct neutrino interactions
    - Match interactions between detectors
    - Cope in a high rate environment

  ==> Technical performance evaluation requiring ~30 days NuMI operations

- DUNE Phase 2 CDR ~ 2026
  - What ND-LAr detector design limitations will MCND need to address?
    - Final state kinematic phase space
      - Proton thresholds?
    - Specific particle topologies
      - Back-to-back charged pions

  ==> Physics performance evaluation requiring *X POT NuMI exposure*: driven by extended operation (potentially with readout upgrades – on par with final design technology) **to understand true technology limitations**

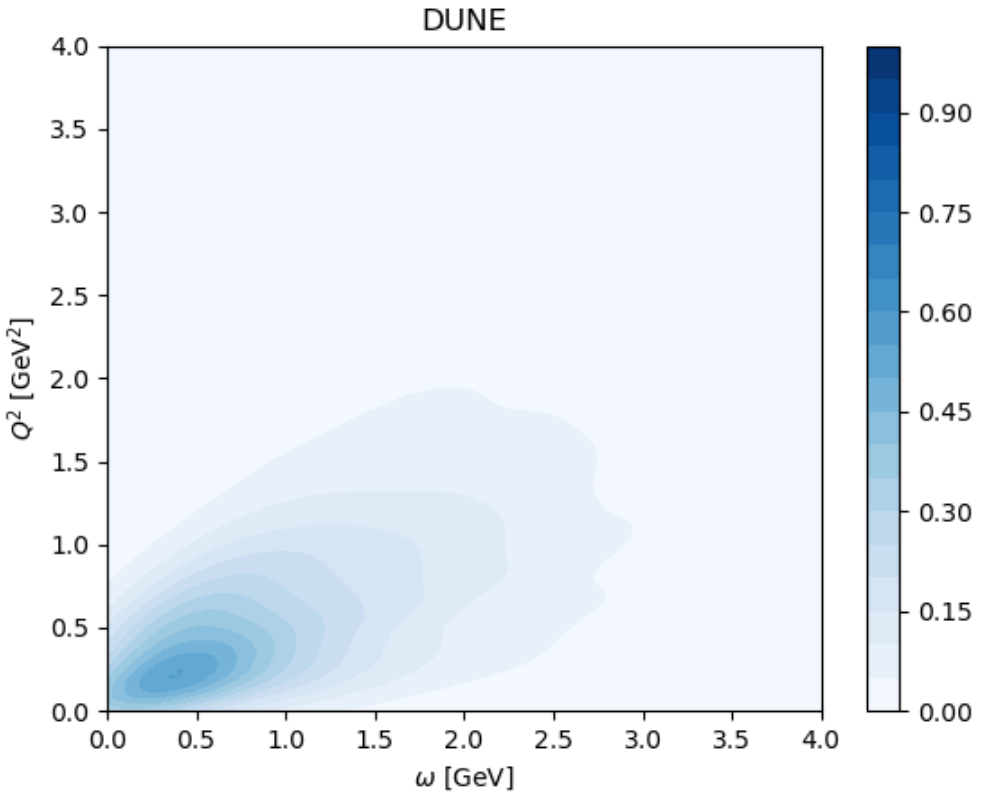
  Fundamentally, these questions cannot be resolved with SBN program

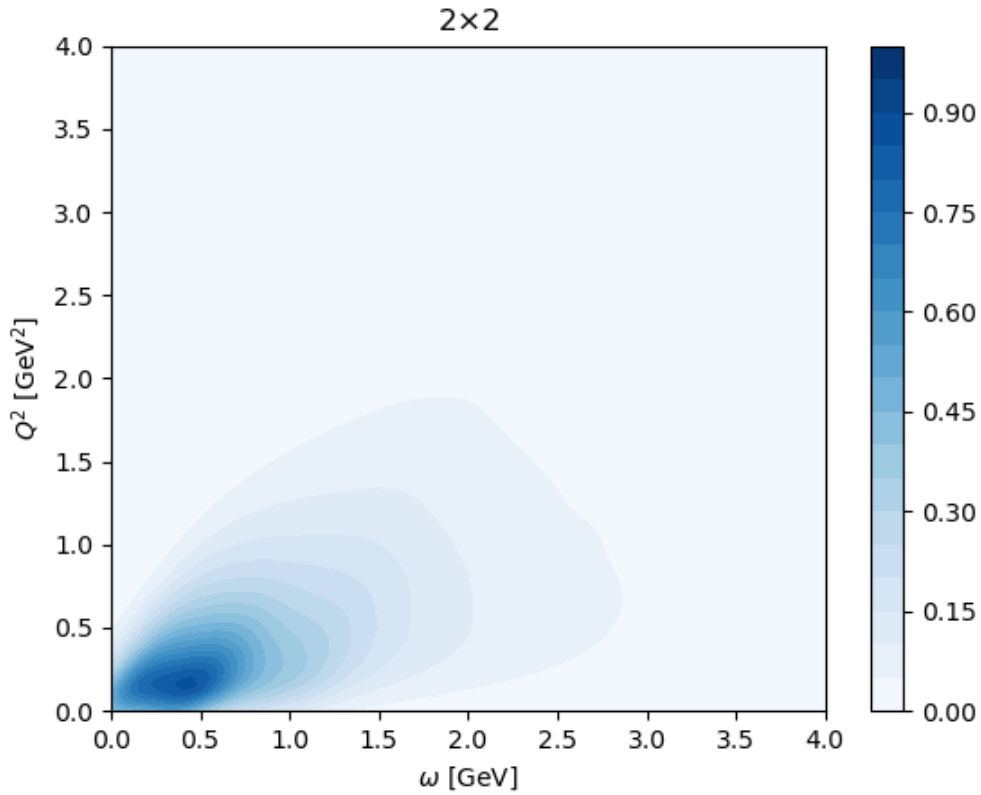
- DUNE OA physics
  - Phase 1 ~ 2031-2035
    - What nu-Ar interaction measurements will inform systematic uncertainties for initial LBL OA?
      - **Given latency between cross section measurements and generator implementation, can we front-load model enhancements for more robust initial LBL OA physics**
  - Phase 2 ~ 2036-204x
    - See "DUNE Phase 2 CDR" above

Interaction Phase Space

Similar interaction phase space with DUNE

Leverage MINERvA's characterization of NuMI beam
- Wrong-sign neutrino contamination in RHC
- Flux constraints

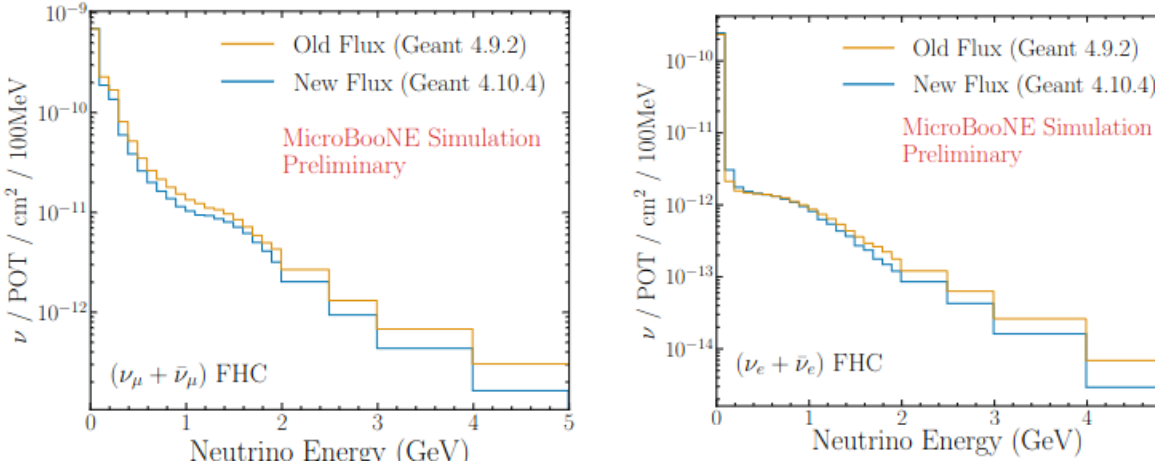




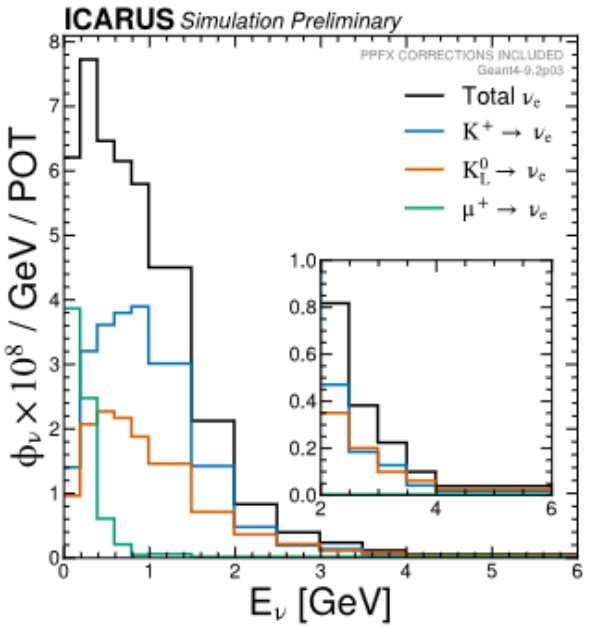
Nu-Ar Cross Section Landscape

- MicroBooNE 2016-2020
  - On-axis BNB FHC
  - ~8 degrees NuMI off-axis
- SBND 2024-present
  - On-axis BNB FHC
- ICARUS @ FNAL 2022-present
  - On-axis BNB FHC
  - ~6 degrees NuMI off axis

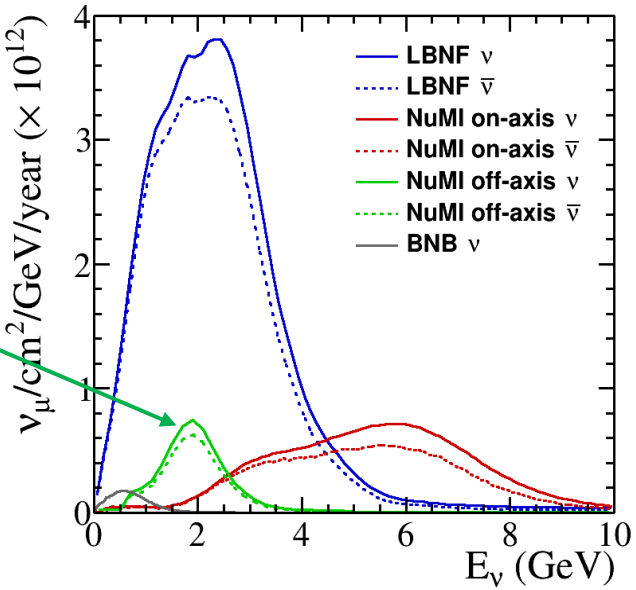
"New physics searches with MicroBooNE", D. Caratelli (Neutrino 2024)



"Status and Plans for Measurements of nu-Ar Interactions at ICARUS", M. Betancourt (NuINT 2024)



NOvA

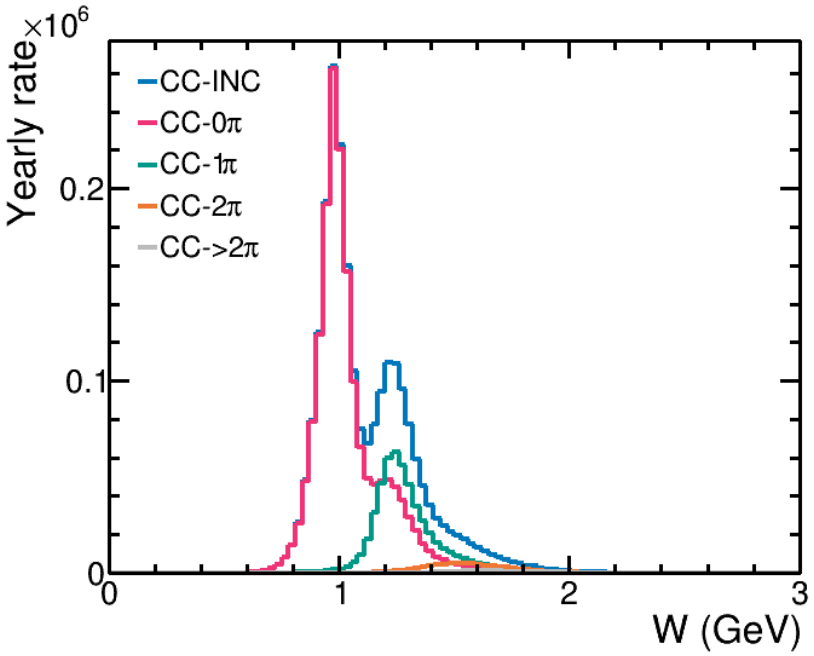


2x2 uniquely positioned to evaluate RES, DIS nu-Ar cross sections

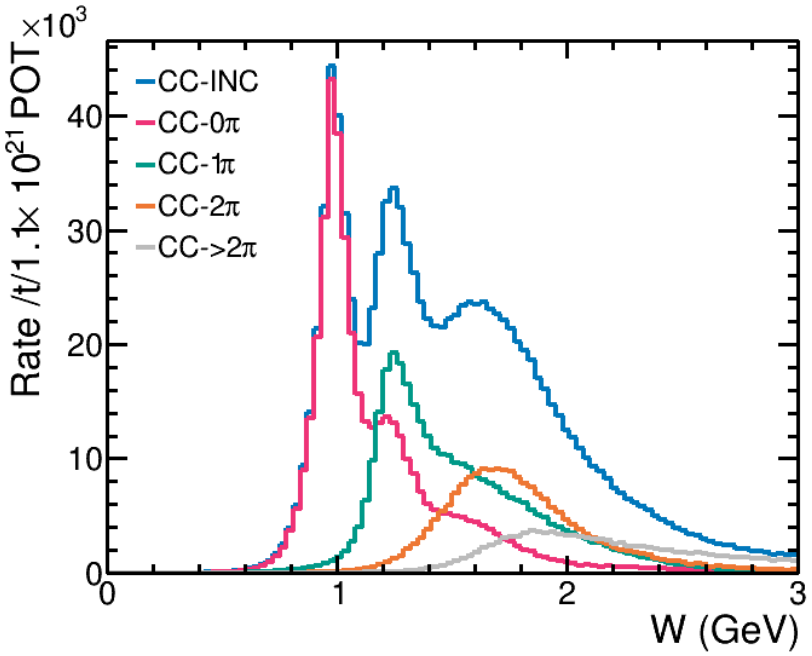
Multi-pion nu-Ar interactions

Plots from C. Wilkinson

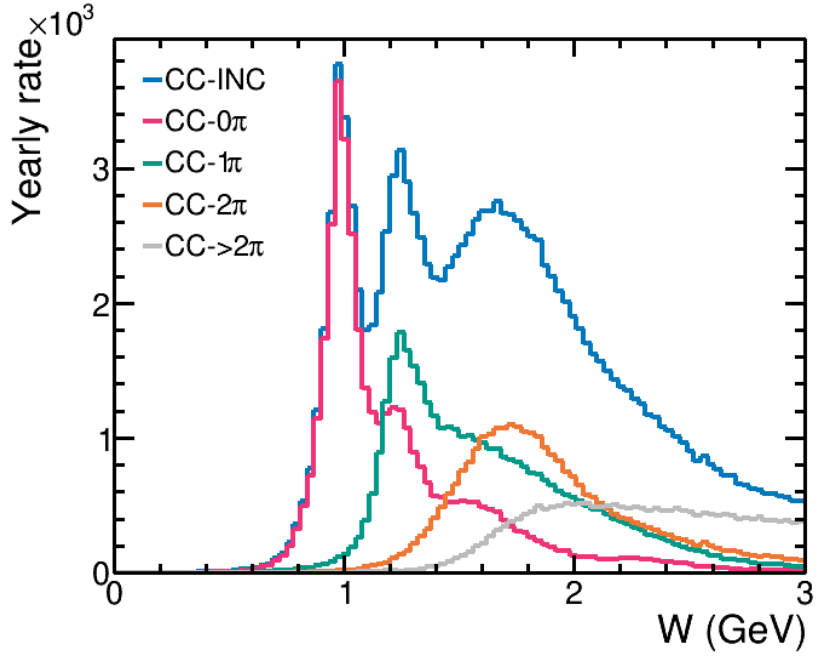
SBND



DUNE



2x2



~10k numuCC charged pion events expected annually (2x2+MINERvA)

==> maximum POT requested

Multi-pion nu-Ar interactions

Tables from S. Greenberg

Updated Containment Numbers – RHC

Total Number of CC Events Expected Per Year

	0 $\pi^{\pm}$	1 $\pi^{\pm}$	2 $\pi^{\pm}$	3+ $\pi^{\pm}$
0 π^0	8.95e+04	6.38e+04	2.52e+04	1.16e+04
1 π^0	2.82e+04	2.66e+04	1.11e+04	6.85e+03
2 π^0	8.06e+03	5.34e+03	3.24e+03	2.82e+03
3+ π^0	2.07e+03	2.01e+03	1.21e+03	1.15e+03

Number of 2x2 Only CC Contained Events Expected Per Year

	0 $\pi^{\pm}$	1 $\pi^{\pm}$	2 $\pi^{\pm}$	3+ $\pi^{\pm}$
0 π^0	7.83e+04	2.80e+04	7.11e+03	1.55e+03
1 π^0	4.57e+03	1.78e+03	4.87e+02	1.06e+02
2 π^0	2.52e+02	7.84e+01	5.04e+01	5.6e+00
3+ π^0	1.12e+01	0.e+00	0.e+00	5.6e+00

Multi-pion nu-Ar interactions

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3+ π^0	2.07e+03	2.01e+03	1.21e+03	1.15e+03

Number of CC Contained Events Expected Per Year

	0 $\pi^{\pm}$	1 $\pi^{\pm}$	2 $\pi^{\pm}$	3+ $\pi^{\pm}$
0 π^0	8.08e+04	3.96e+04	1.24e+04	3.8e+03
1 π^0	1.20e+04	9.28e+03	2.95e+03	1.28e+03
2 π^0	2.16e+03	1.03e+03	4.98e+02	3.19e+02
3+ π^0	3.42e+02	2.46e+02	8.96e+01	6.72e+01

CC nu_e

Limited world measurements!

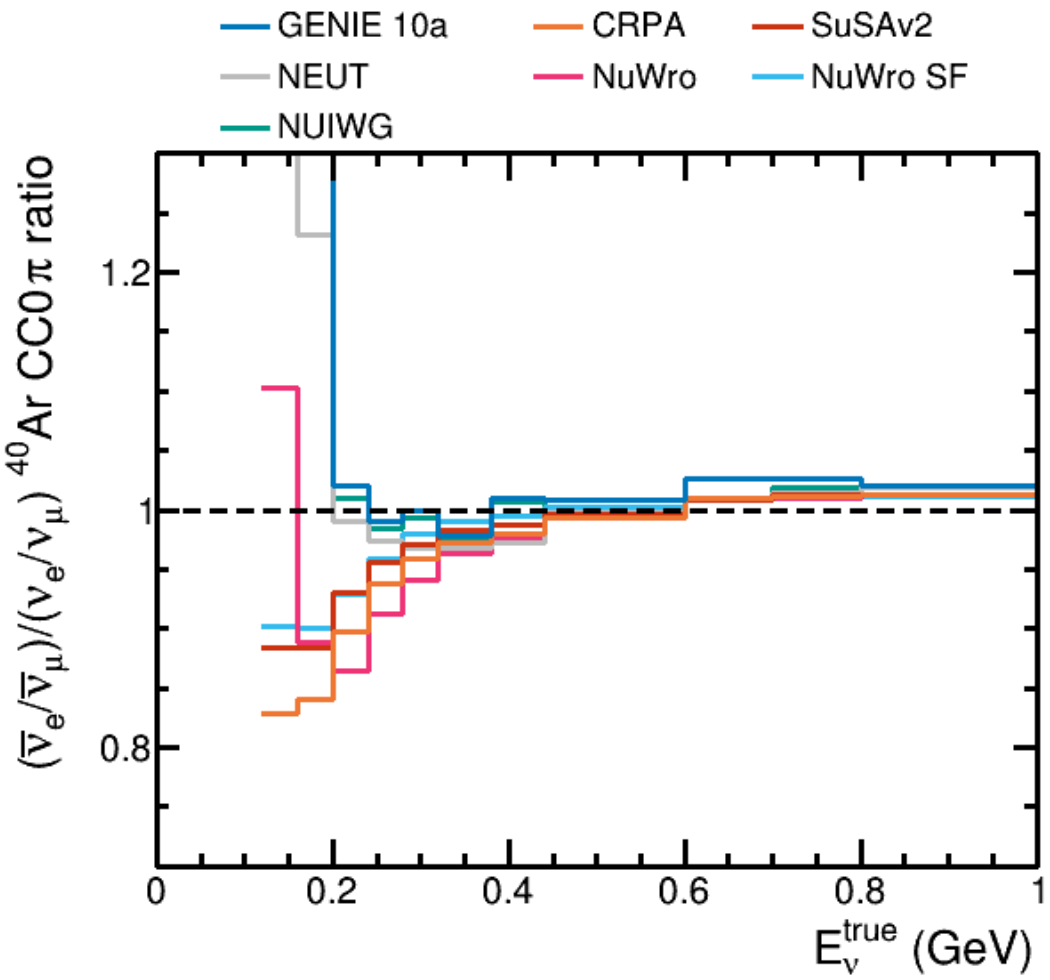
Table 52.5: Published measurements of electron neutrino and antineutrino cross sections from modern accelerator-based neutrino experiments.

experiment	CC inclusive	QE-like	π production	target
ArgoNeuT	[144]	-	-	Ar
COHERENT	[145]	-	-	I
MicroBooNE	[146, 147]	[148]	-	Ar
MINERνA	-	[149]	-	CH
NOvA	[150]	-	-	CH_2
T2K	[151–153]	-	-	CH, H_2O

Unique opportunity for mesonless nuebar : mesonless numubar cross section ratio measurements -->
critical for deltaCP analysis at DUNE

- Complementary to other experiments
- SBND (neutrino mode)
- ICARUS (neutrino & antineutrino mode)

Plots from C. Wilkinson



Charged-Current electron neutrinos at 2x2 + Mx2

~10k mesonless nue CC (2x2+MINERvA) with maximum allowable POT

Similar approach to current mesonless numubar cross section analysis: lepton PID but limited kinematics reconstruction; differential cross section measurements with final state protons

Counting with topologies breakdown

Table from Y. Chen

ν_e CC total (normalised to 2.5E20 POT)

	0 $\pi^\pm$	1 $\pi^\pm$	2 $\pi^\pm$	3+ $\pi^\pm$
0 π^0	3666.7	2968.7	1677.2	806.3
1 π^0	1504.0	1761.8	1104.6	732.1
2 π^0	551.3	592.2	542.8	391.0
3+ π^0	205.7	295.1	262.4	189.2

ν_e CC $e^\pm$ 2x2 contained (normalised to 2.5E20 POT)

	0 $\pi^\pm$	1 $\pi^\pm$	2 $\pi^\pm$	3+ $\pi^\pm$
0 π^0	33.5	42.8	32.4	17.8
1 π^0	23.1	36.1	24.7	20.2
2 π^0	10.2	14.5	13.7	10.3
3+ π^0	5.0	7.6	7.4	5.1

ν_e CC $e^\pm$ detector contained (normalised to 2.5E20 POT)

	0 $\pi^\pm$	1 $\pi^\pm$	2 $\pi^\pm$	3+ $\pi^\pm$
0 π^0	2699.6	2190.5	1232.2	597.3
1 π^0	1107.8	1302.7	815.2	540.4
2 π^0	407.2	438.4	399.1	281.8
3+ π^0	151.9	215.2	190.7	134.1

Takeaway messages

2x2 Demonstrator provides critical inputs needed for DUNE LBL OA

- ND-LAr technical specifications
  - Neutrino reconstruction
  - Charge-light matching efficacy
- Antineutrino-Ar cross sections
  - Unique access to multipion phase space
  - Cross section ratios to clarify interaction modeling

  ==> leveraging MINERvA's quantitative characterization of NuMI flux
- With redundant measurements between experiments, LArTPC detector systematics comparisons
  - Wire to pixel detector response
  - Fully-active versus segmented volumes
- Inform ND-LAr shortcomings to be rectified in DUNE Phase II (e.g. MCND)

Additional opportunities: neutron production, kaon production, baryon resonances production, BSM, etc.