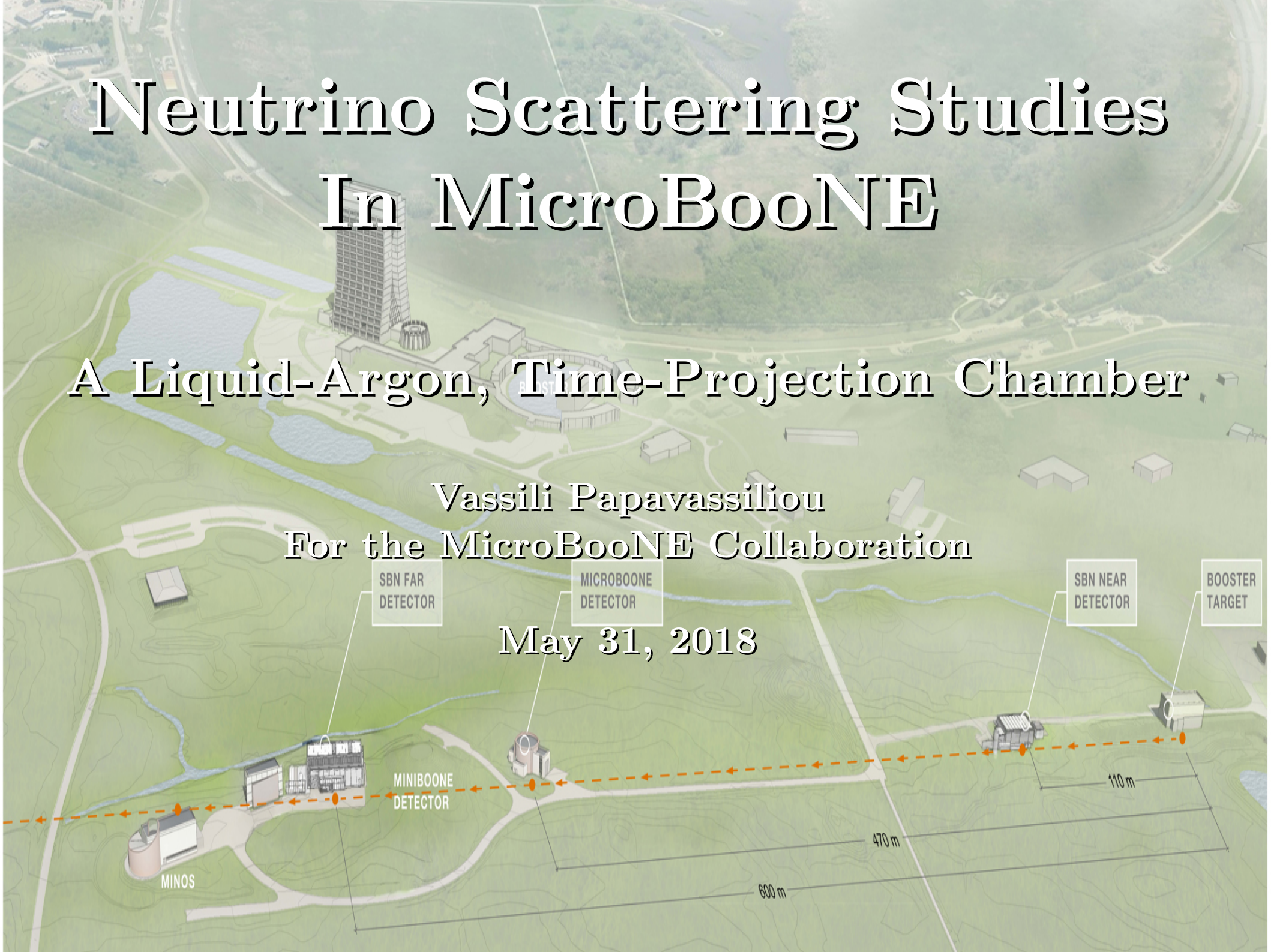
Neutrino Scattering Studies In MicroBooNE

A Liquid-Argon, Time-Projection Chamber

Vassili Papavassiliou
For the MicroBooNE Collaboration

May 31, 2018



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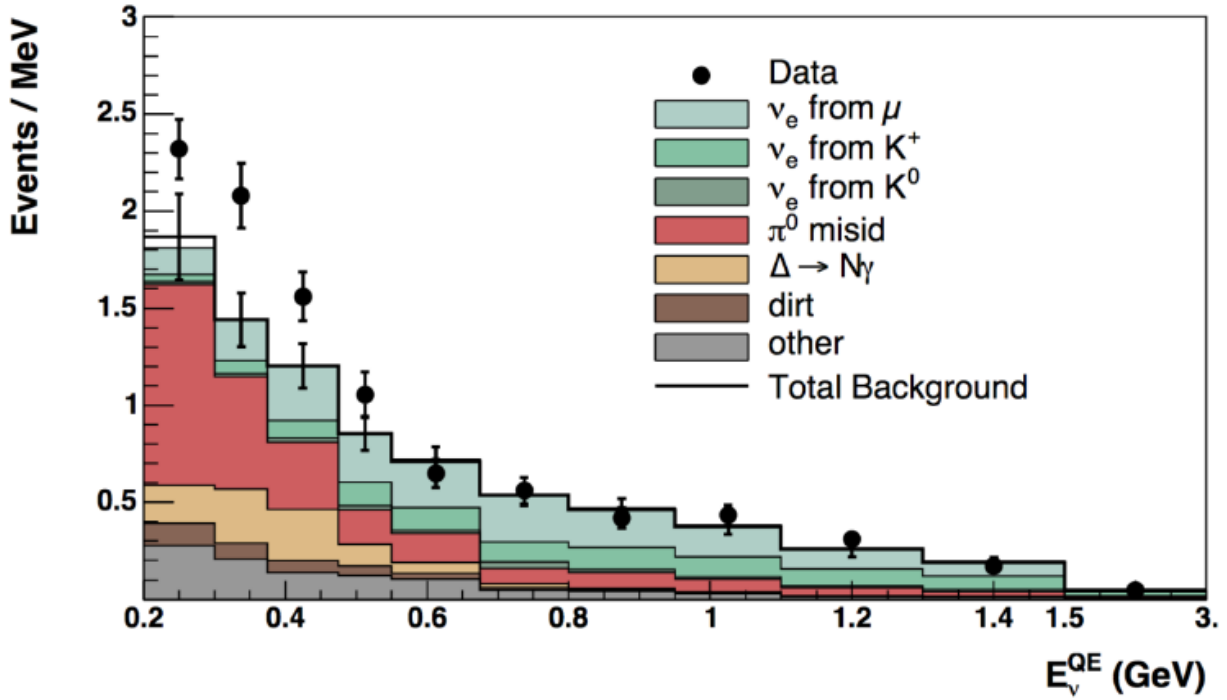
175 collaborators
31 institutions (7 non-U.S.)
43 postdocs
53 graduate students

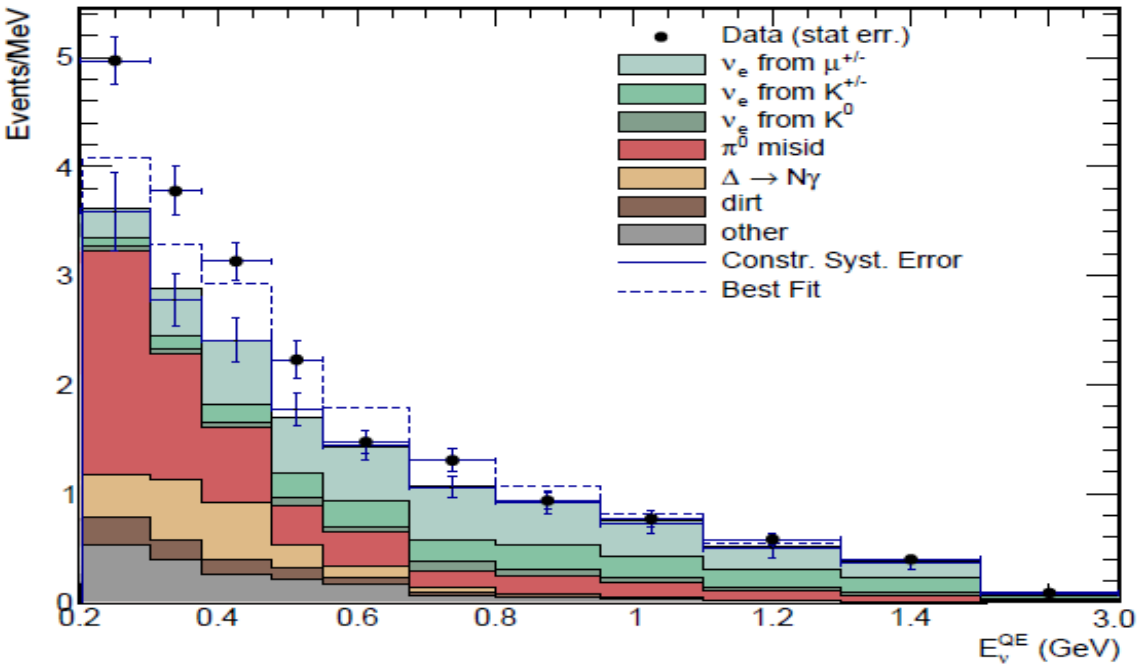
Motivation



A.A. Aguilar-Arevalo *et al.*, *Phys. Rev. Lett.*, **102**:101802, 2009

- MiniBooNE: "Unexplained excess of electron-like events" at low energies
  - Oscillations would require at least a fourth, "sterile" neutrino species
  - Energy dependence not fully consistent with oscillation
  - Electron signals could be unresolved photon-to-e^+e^- conversions
- New experiment/technology needed to resolve the issue → LArTPC
- Require good knowledge of cross sections at these energies

Motivation



A.A. Aguilar-Arevalo *et al.*, arXiv:1805.12028 (5/30/2018)

- MiniBooNE: "Observation of a significant excess of electron-like events[...]"
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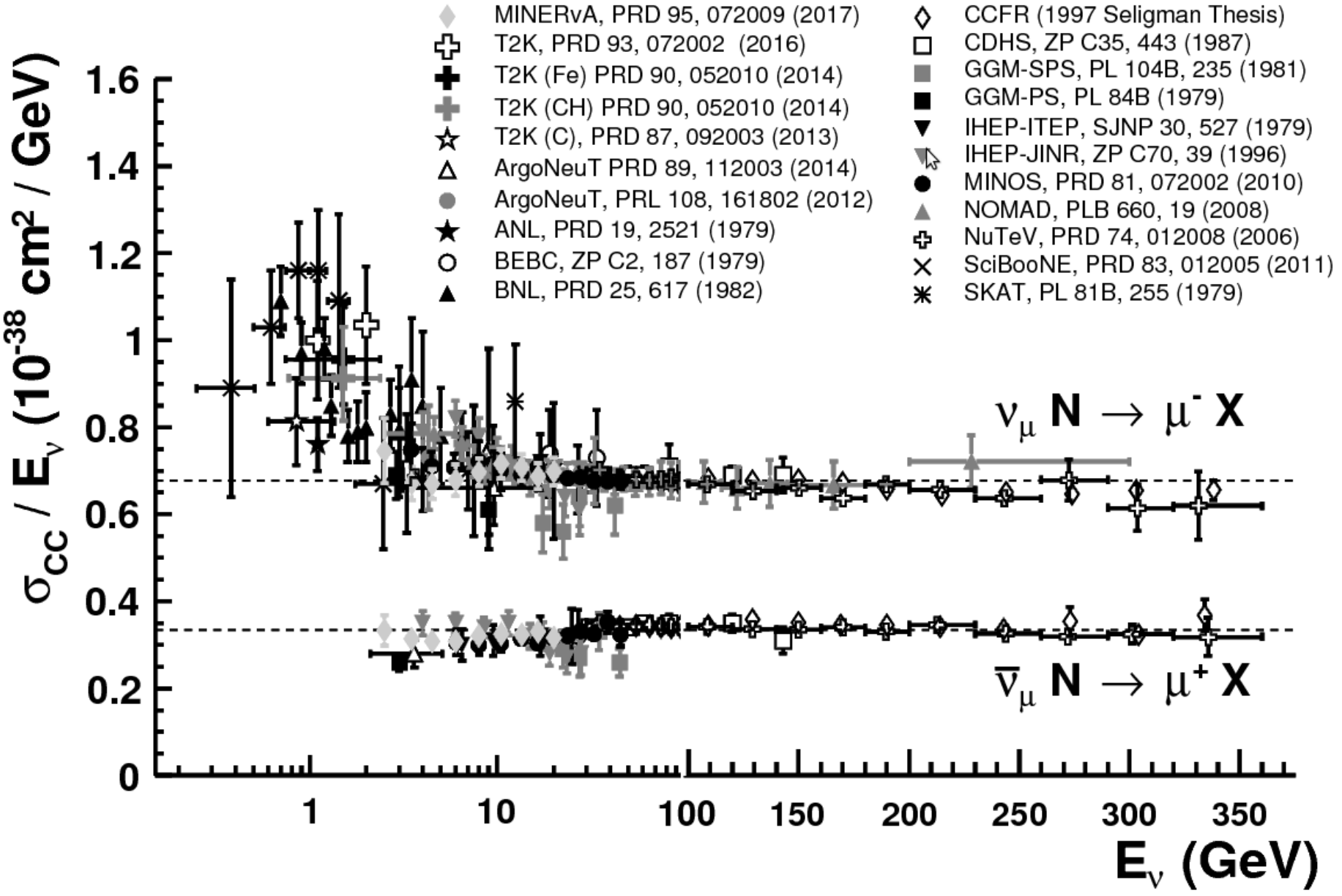
Total Charged-Current Cross Sections



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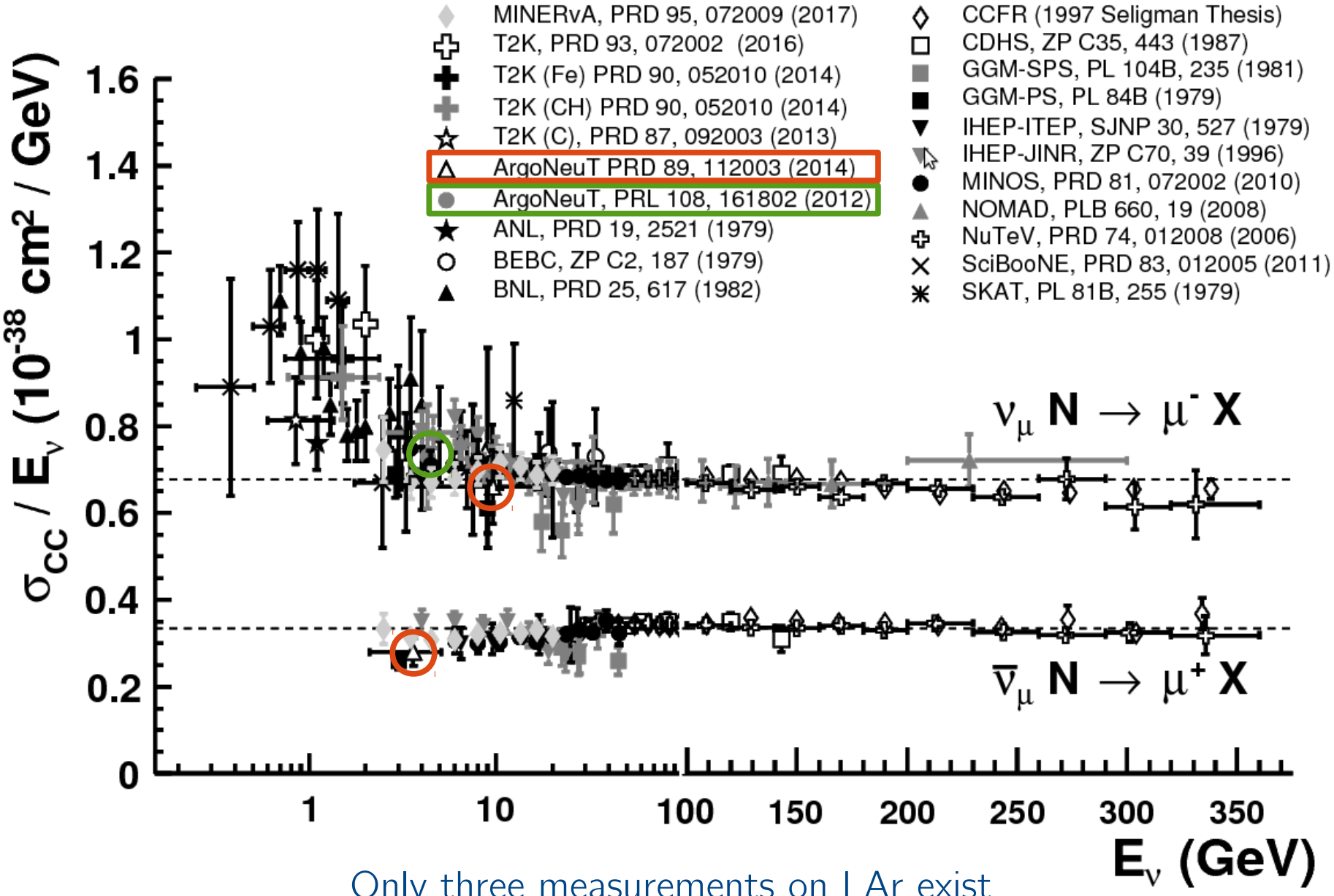
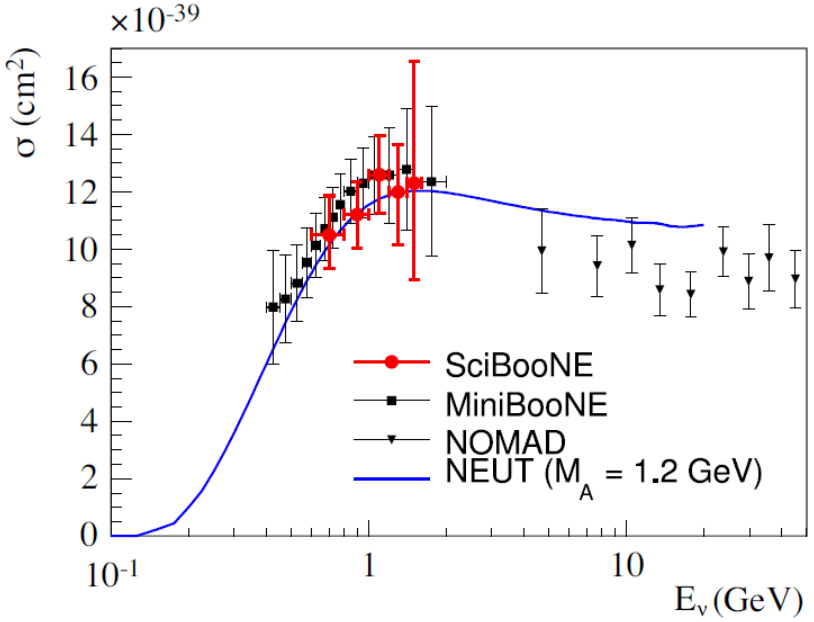


Only three measurements on LAr exist

Disagreements Among Experiments



G.T. Garvey *et al.*, Physics Reports **580** (2015) 1–45

- Usually assume dipole form factors:

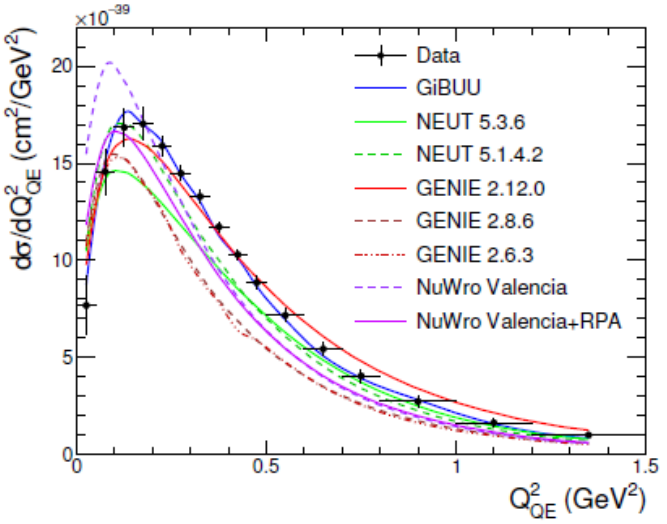
$$G_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

  - From neutron decay:

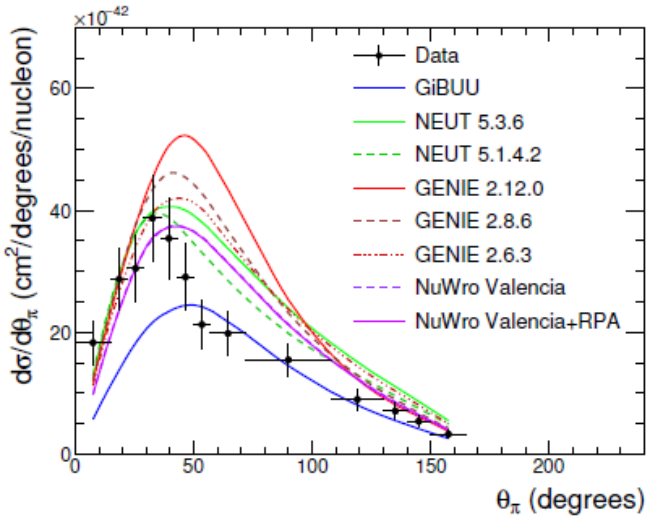
$$g_A \simeq 1.27$$

- MiniBooNE CCQE cross section best described with $M_A \simeq 1.2\,\mathrm{GeV}$
- More typical values, though on H and D targets, are $M_A \simeq 1.0\,\mathrm{GeV}$
- Possible explanation: MiniBooNE measurement includes $1\mu 2p$ final states
  - Protons mostly below Cherenkov threshold at MiniBooNE energies
- Development of 2p2h (two-particle, two-hole) models
  - Meson exchange currents, short- and long-range correlations...

Monte Carlo Event Generators



(a) MiniBooNE ν-CH_2 CCQE.

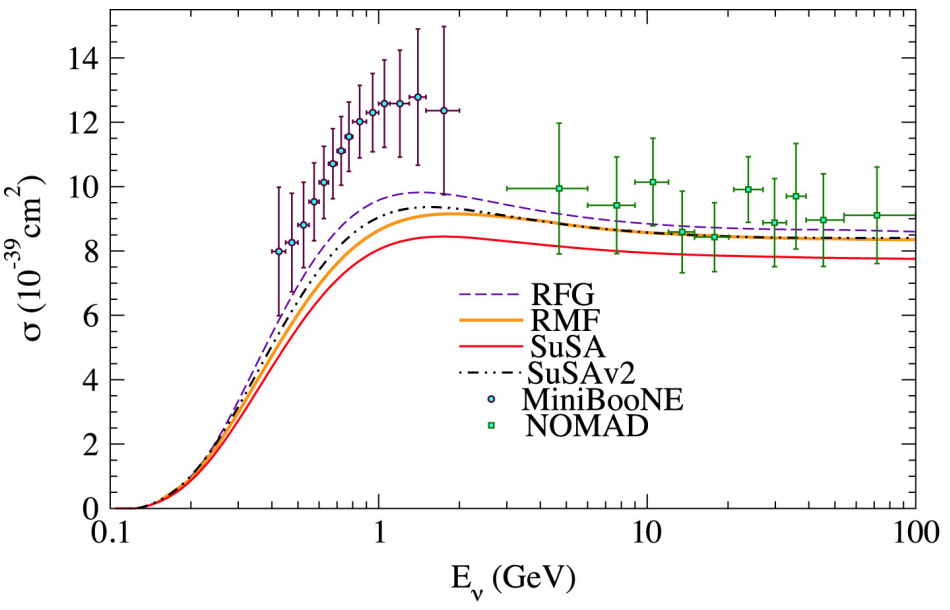


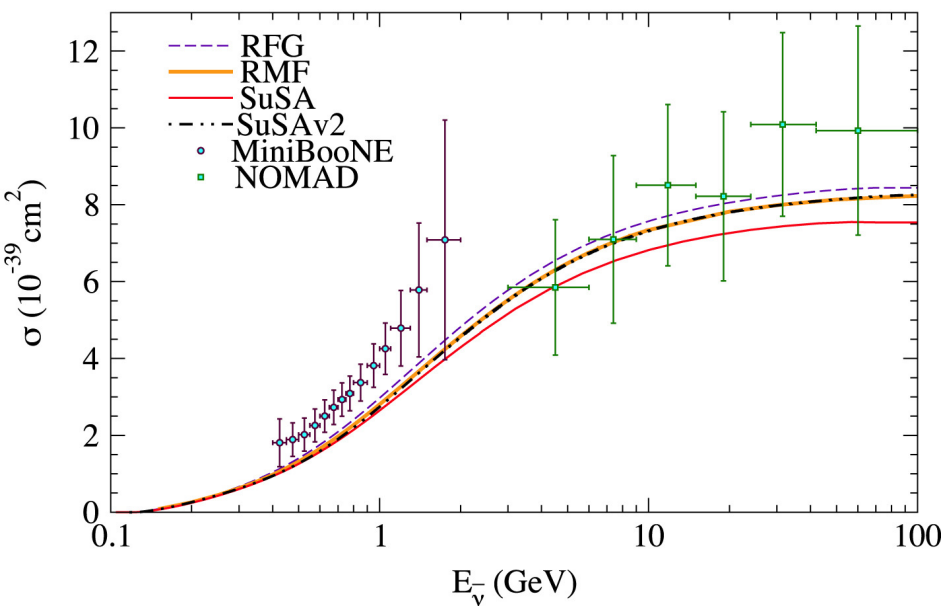
(b) MINERvA ν-CH CC1$\pi^{\pm}$.

P. Stowell *et al* 2017 *JINST* **12** P01016

- Event generators still being tuned to data as they are published
  - No single set exists that reliably describes all processes
  - Nuclear structure and final-state interactions among biggest issues
  - But nucleon form factors could also use improvements
    - Especially for neutral-current scattering

Nuclear Models in Event Generators

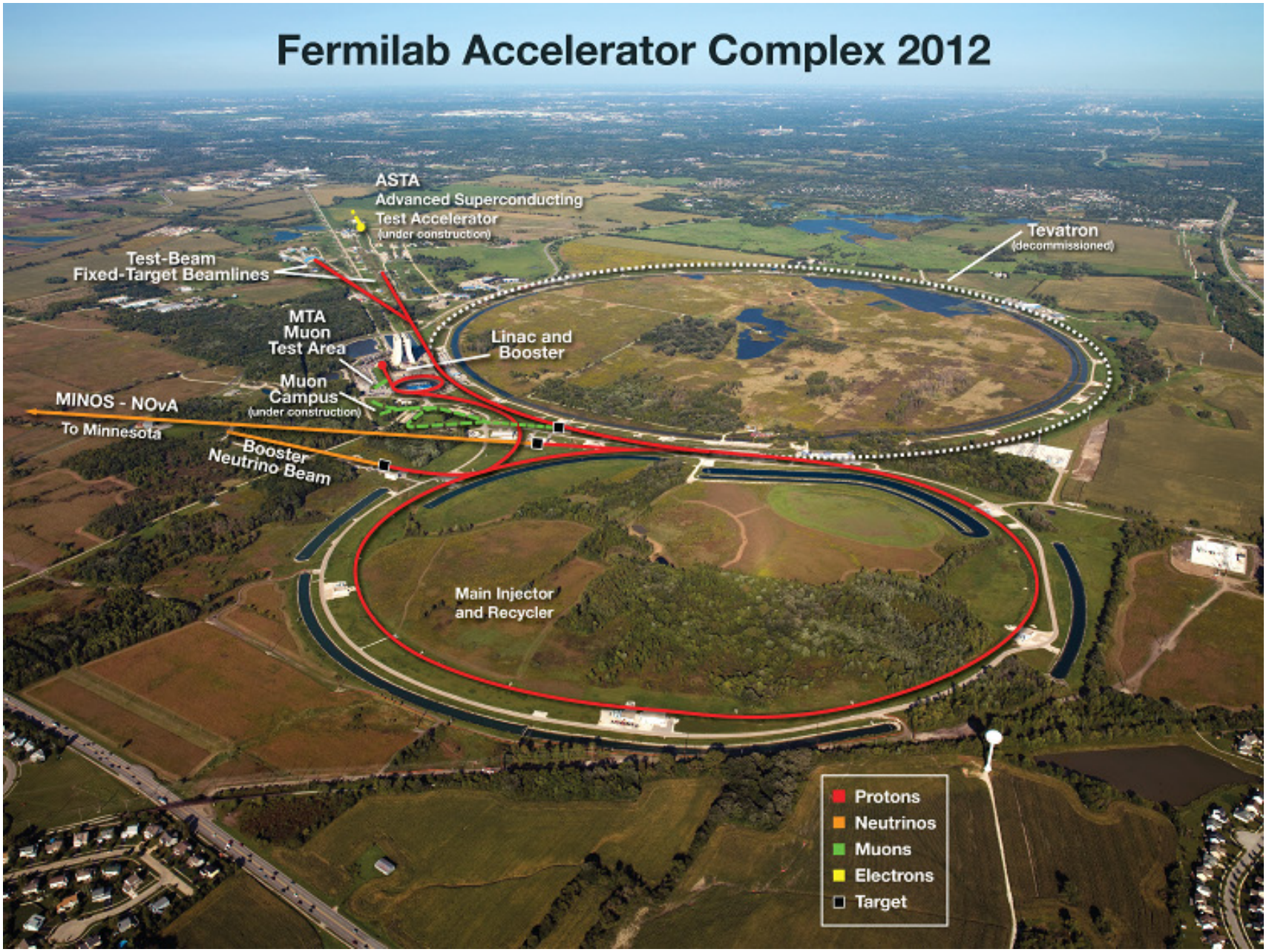




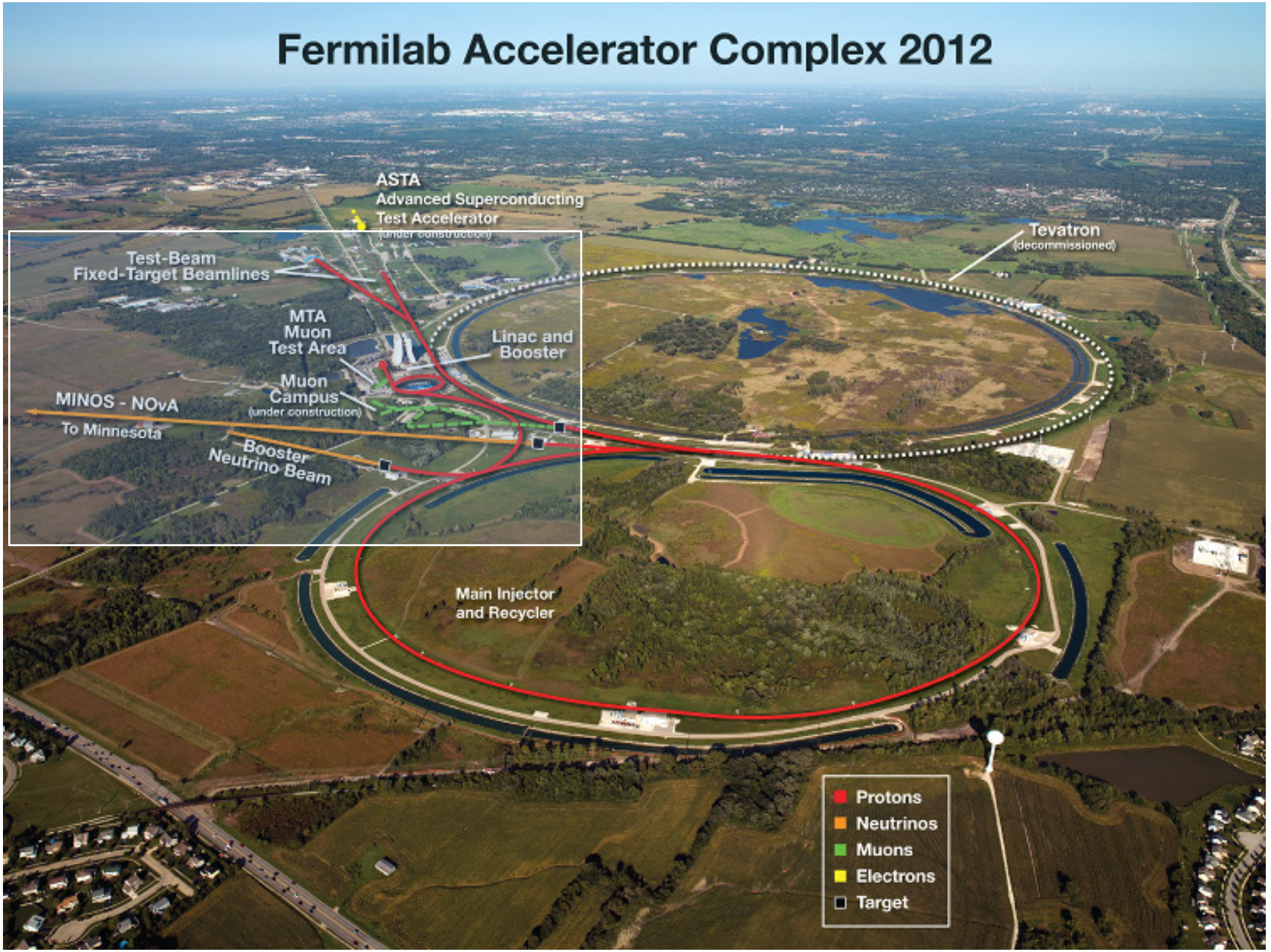
G.T. Garvey *et al.*, Physics Reports **580** (2015) 1–45

- Nuclear structure cannot explain the MiniBooNE/NOMAD discrepancy
  - RFG: Relativistic Fermi Gas
  - RMF: Relativistic Mean Field
  - SuSA: SuperScaling Approach

Booster and Main Injector Neutrino Beams



Booster and Main Injector Neutrino Beams



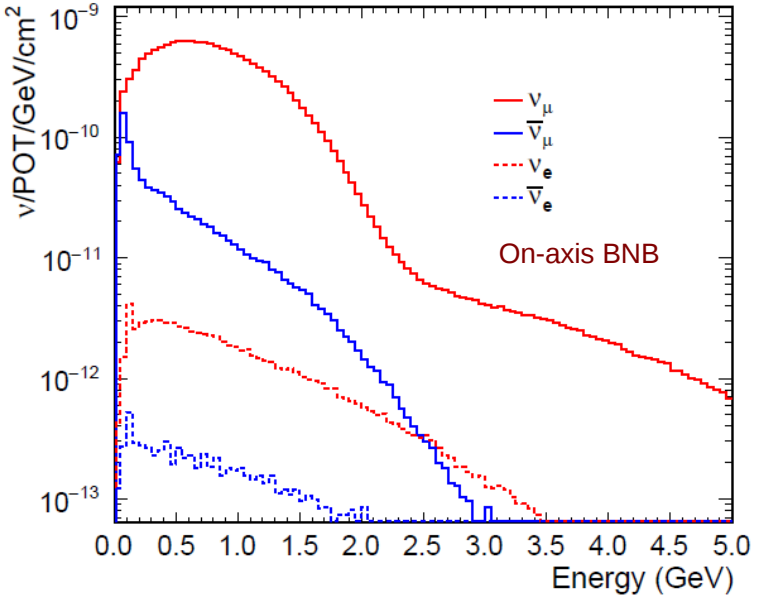
Booster and Main Injector Neutrino Beams

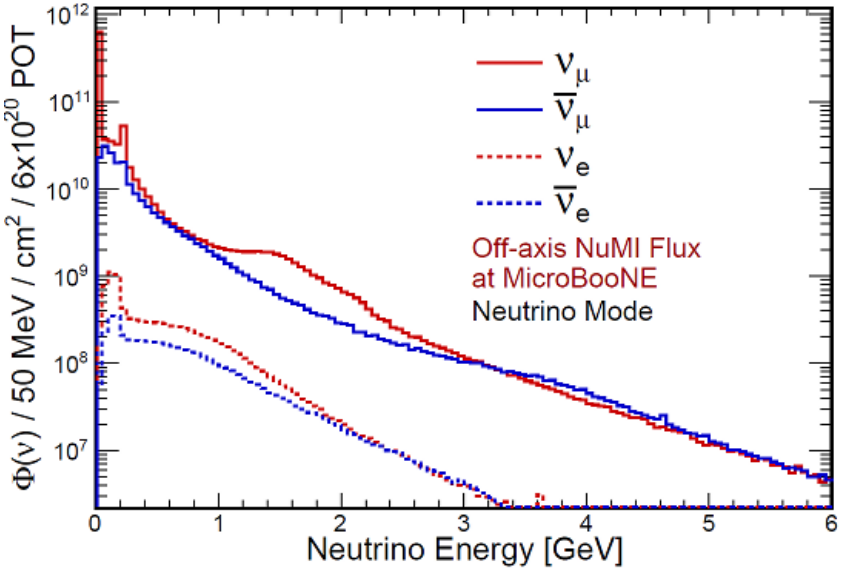
Booster and Main Injector Neutrino Beams

Fermilab Liquid Argon Test Facility

A couple of years later…

Beam Composition





- MicroBooNE Public Note 1031
- Averaged over TPC active volume
- Following method by MiniBooNE

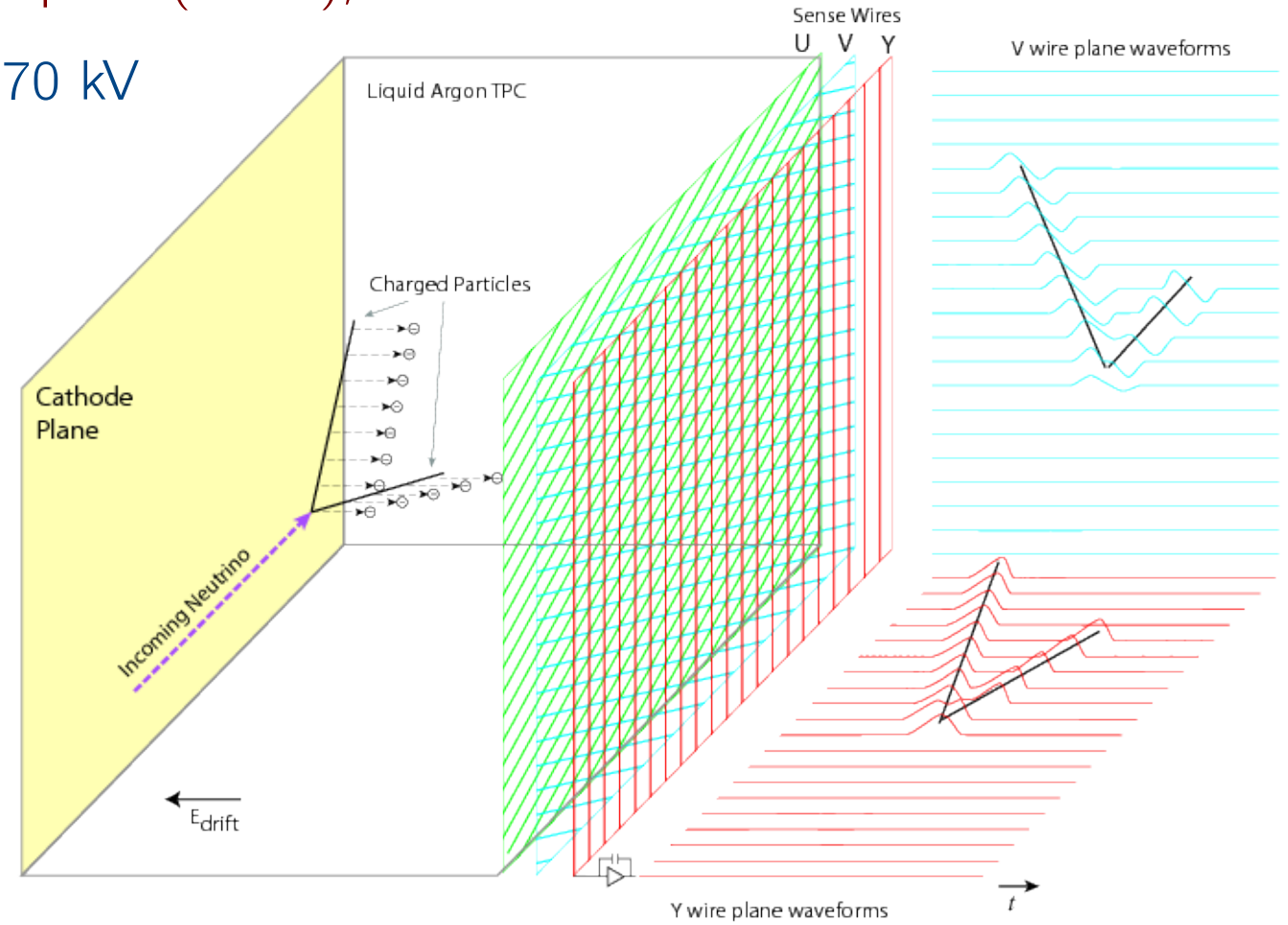
A.A. Aguilar Arevalo *et al.*, Phys. Rev. **D79** (2009) 072002

  - Updated K^+ production in p-Be
  - Affects the high-energy tail

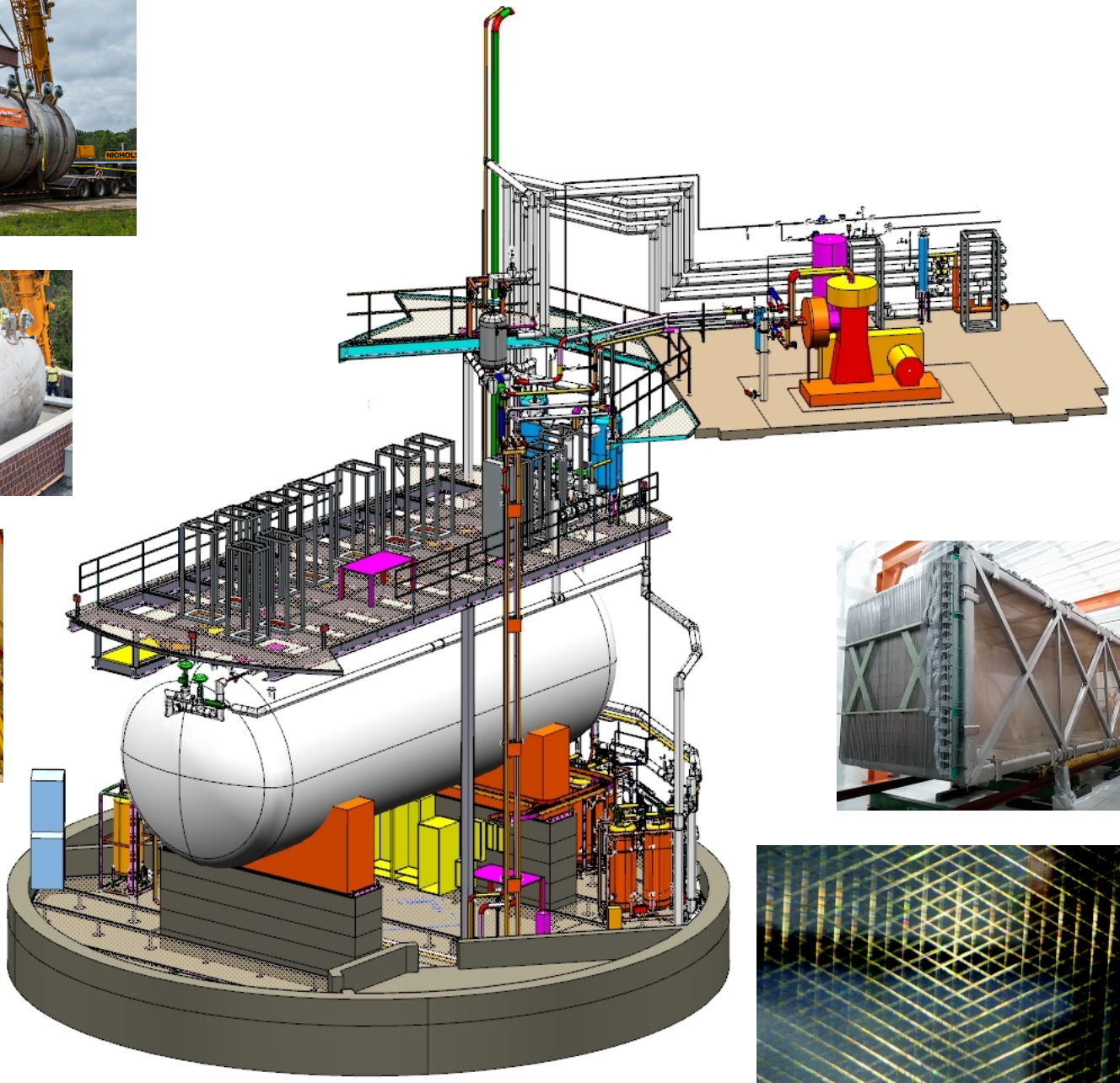
- Generated with code made available on github (M. Del Tutto)
  `https://github.com/marcodeltutto/NuMIFlux`

Liquid Argon Time Projection Chamber

- Active volume contains 84 tons of LAr
- Three wire planes, 3 mm wire spacing
  - Induction planes, wires at ±60°
  - Collection plane (anode), wires vertical
- Drift HV = 70 kV

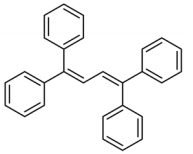


MicroBooNE LArTPC

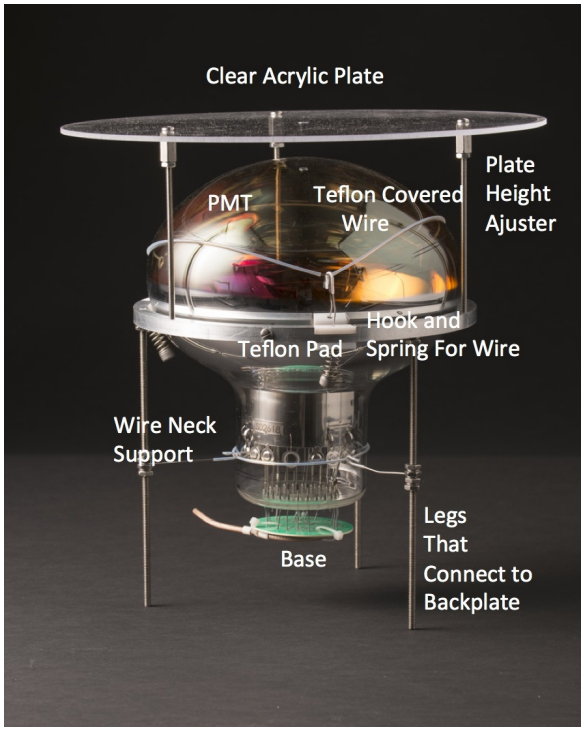


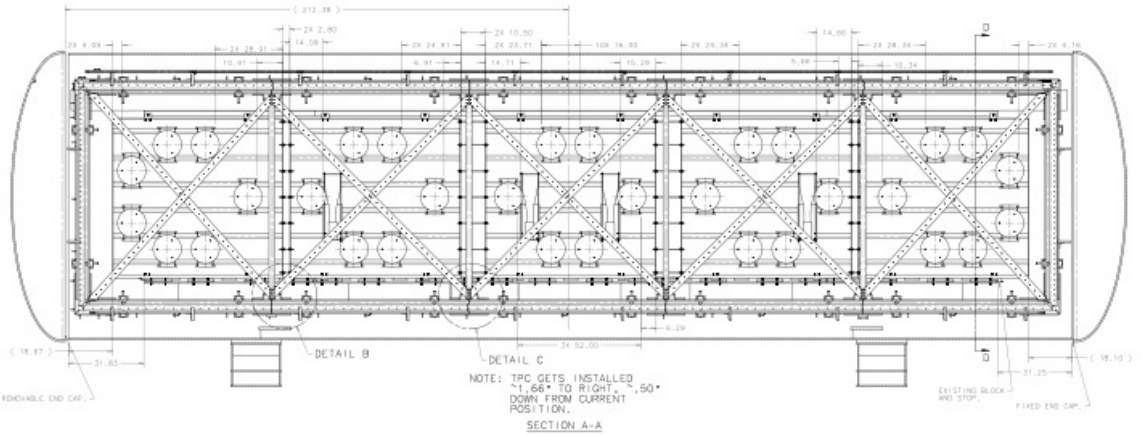
Light Detection System

- Argon is a very efficient scintillator
  - Emission at VUV (128 nm)
  - Must be wavelength-shifted to visible
    - Use plates covered in tetraphenyl butadiene (TPB)



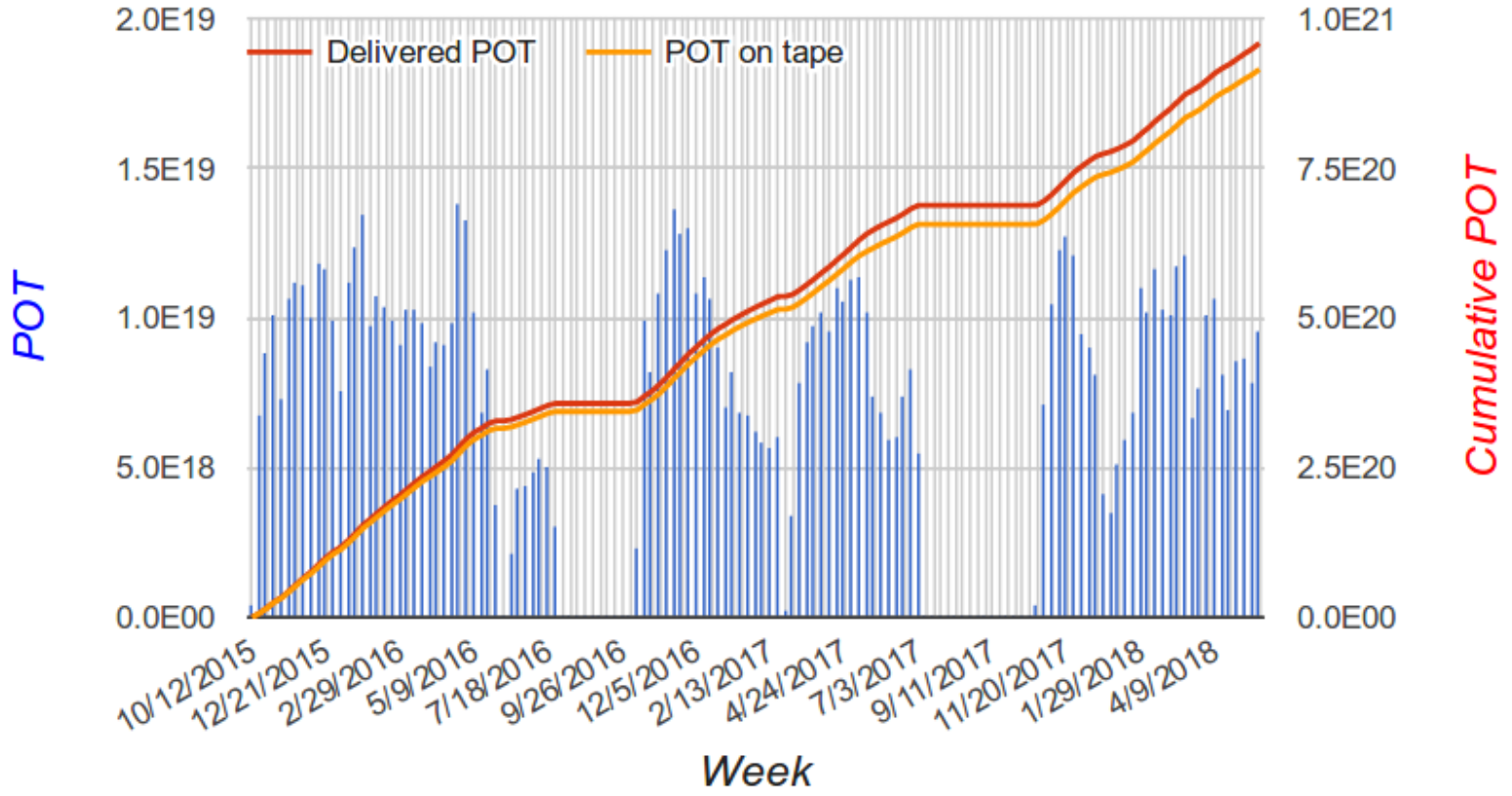
  - Short decay component τ = 6 ns (also: long component, 1.6 μs)
    - Allows precise timing
    - Used for triggering, cosmic rejection





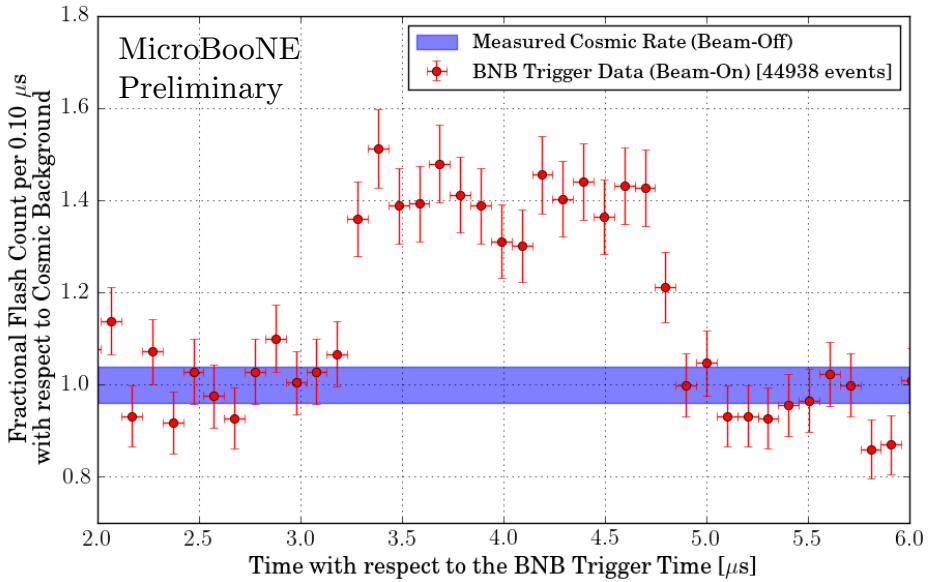
Status

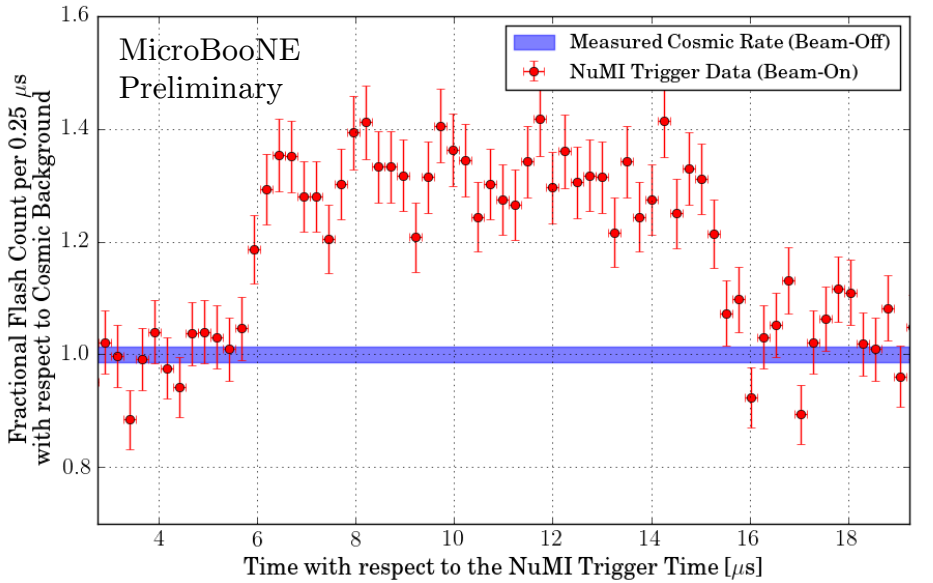
- Started taking cosmic ray data on August, 2015
- First neutrino beam data on October, 2015
- Almost 10^{21} protons on target delivered, > 95% on tape
- Data taking continuing (request: 1.3 x 10^{21})
- Most results presented here are based on 5% of the total sample



https://microboone-exp.fnal.gov/at_work/beam/performance/beam.html

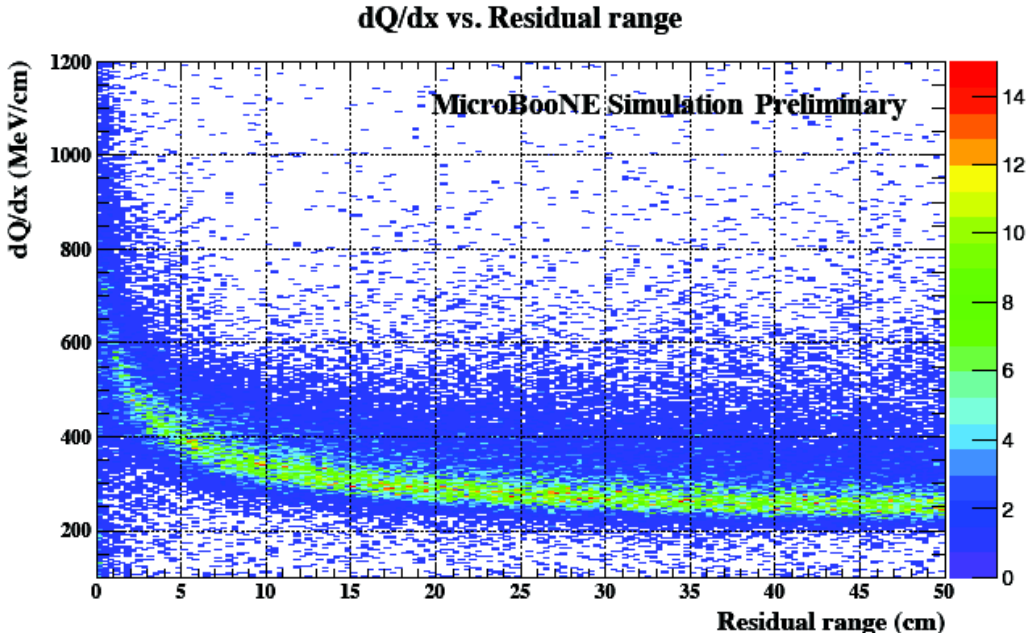
Flash Timing Relative to Beam Spill

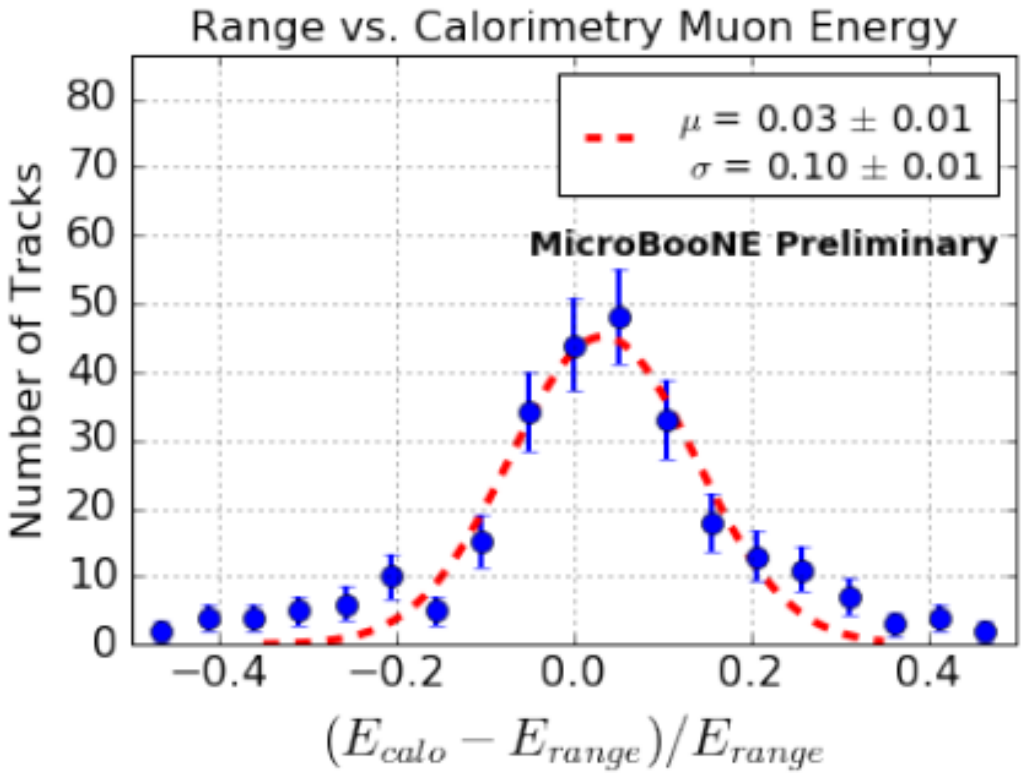




- Beam neutrino events are rare, but there is a clear excess of flashes during the spill
- Major improvements in the beam timing signal distribution between 1st and 2nd run
  - Modified routing of beam signal resulted in significant reduction in jitter
  - Some future analyses could benefit from the improved beam window definition

Energy Measurement





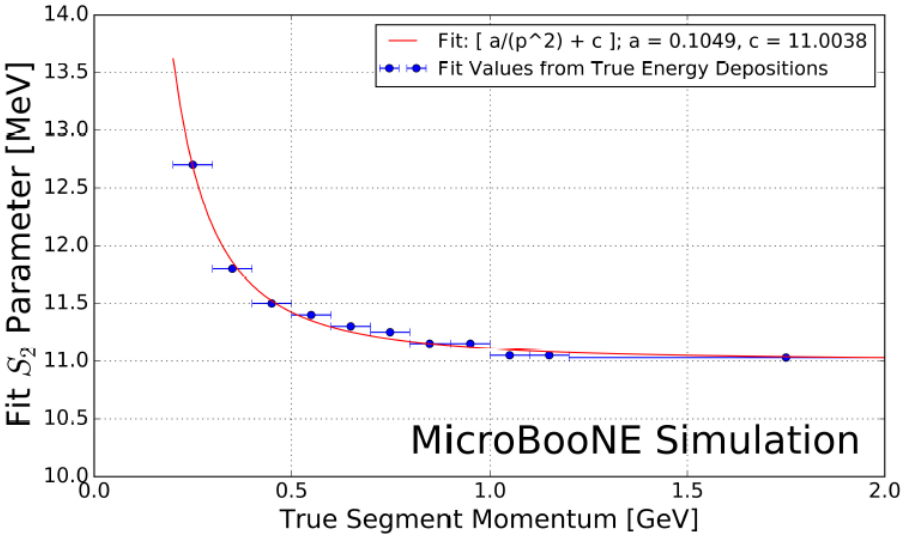
- Energy related to dE/dx through Bethe-Bloch formula
  - First calibrate dQ/dx with crossing muons
    - Field inhomogeneities
    - Recombination
    - Diffusion
    - Direction relative to field
    - Time variations
  - Plot dQ/dx vs. residual range (stopping muons)
  - Obtain absolute energy scale
- Can also measure E from total range of stopped muons
- The two methods compare well

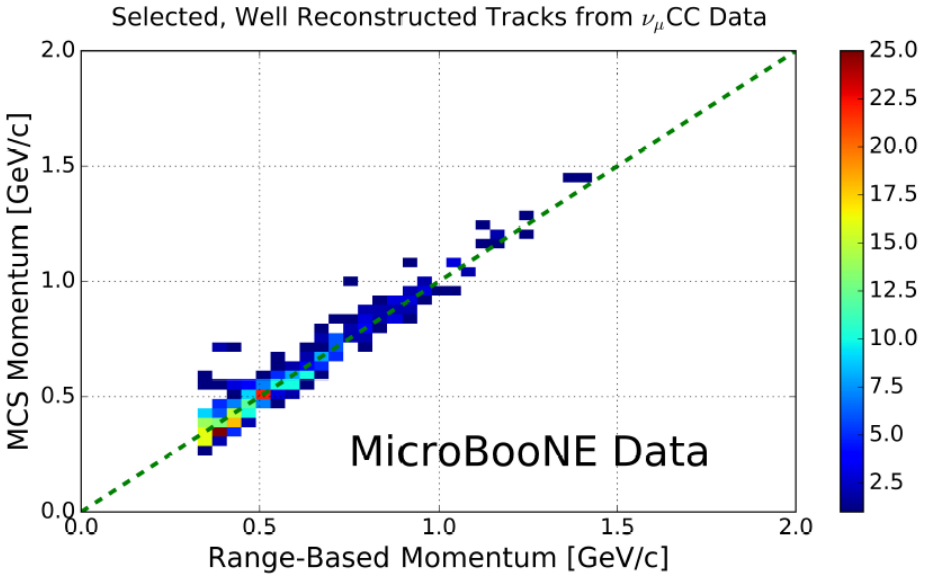
Energy of Exiting Muons

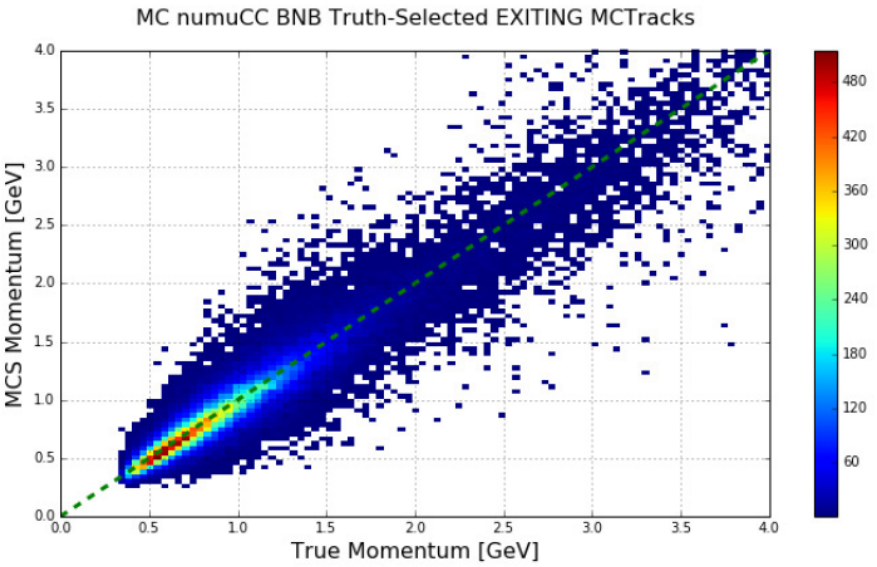
- Can be measured using MCS
  - Highland formula

$$\sigma_o^{\mathrm{HL}} = \frac{S_2}{p\beta c} z \sqrt{\frac{\ell}{X_0}} \left[1 + \epsilon \times \ln\left(\frac{\ell}{X_0}\right) \right]$$

- Checked using partial tracks

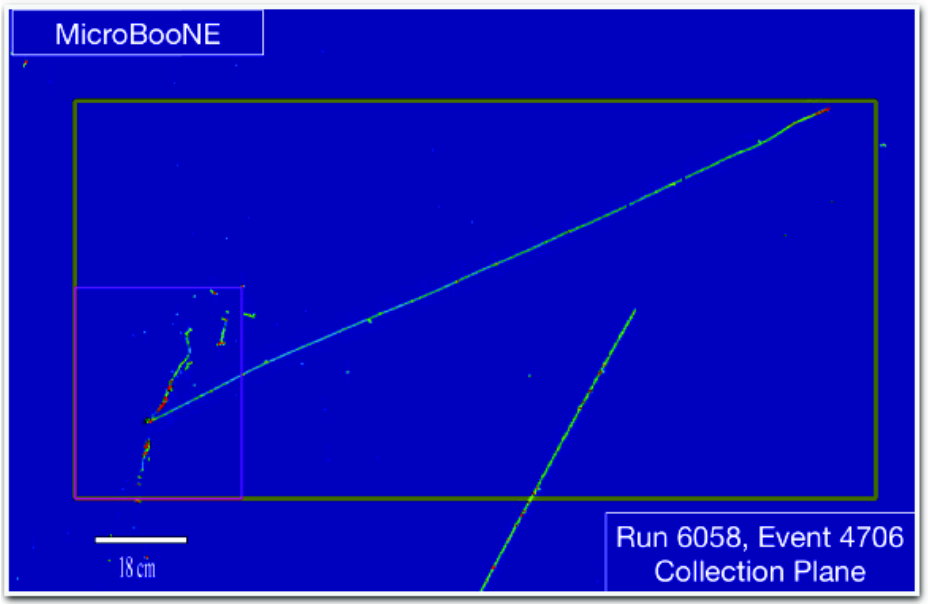


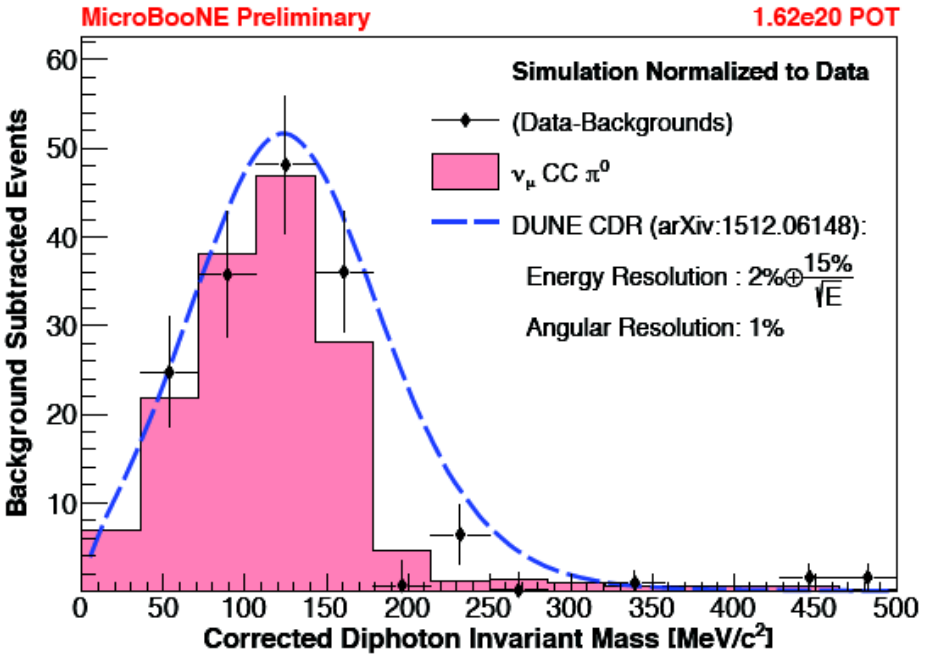




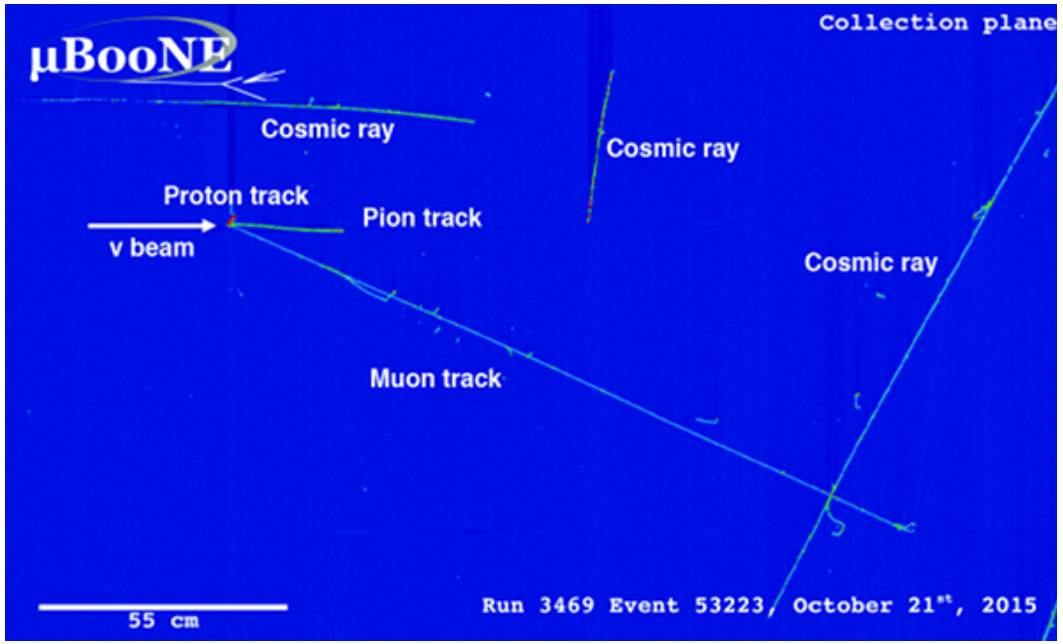
Charged-Current π^0 Production

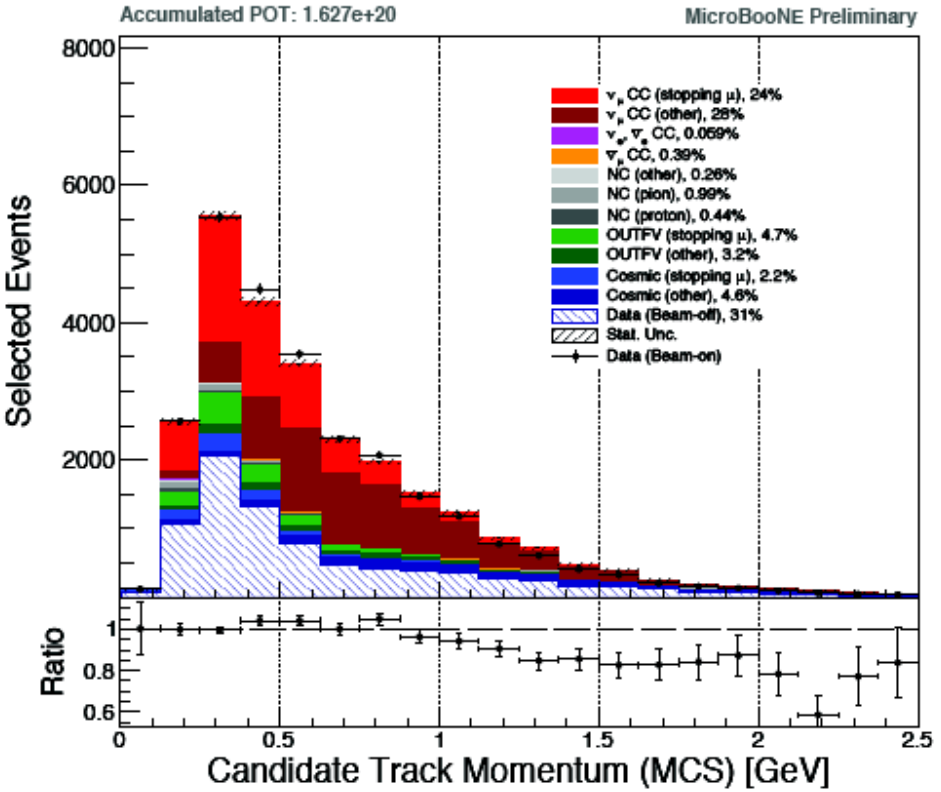
- MicroBooNE Public Note 1032
- Allows study of shower reconstruction performance
- Can be used for shower energy calibration
- NC π^0 production is a source of background for oscillation signal
  - Merged showers or missed shower — can look like single electron
  - Can be studied using CC π^0 production
- Cross section will be presented in a Fermilab W&C seminar on Friday and at Neutrino 2018 next week
  - First measurement on Ar





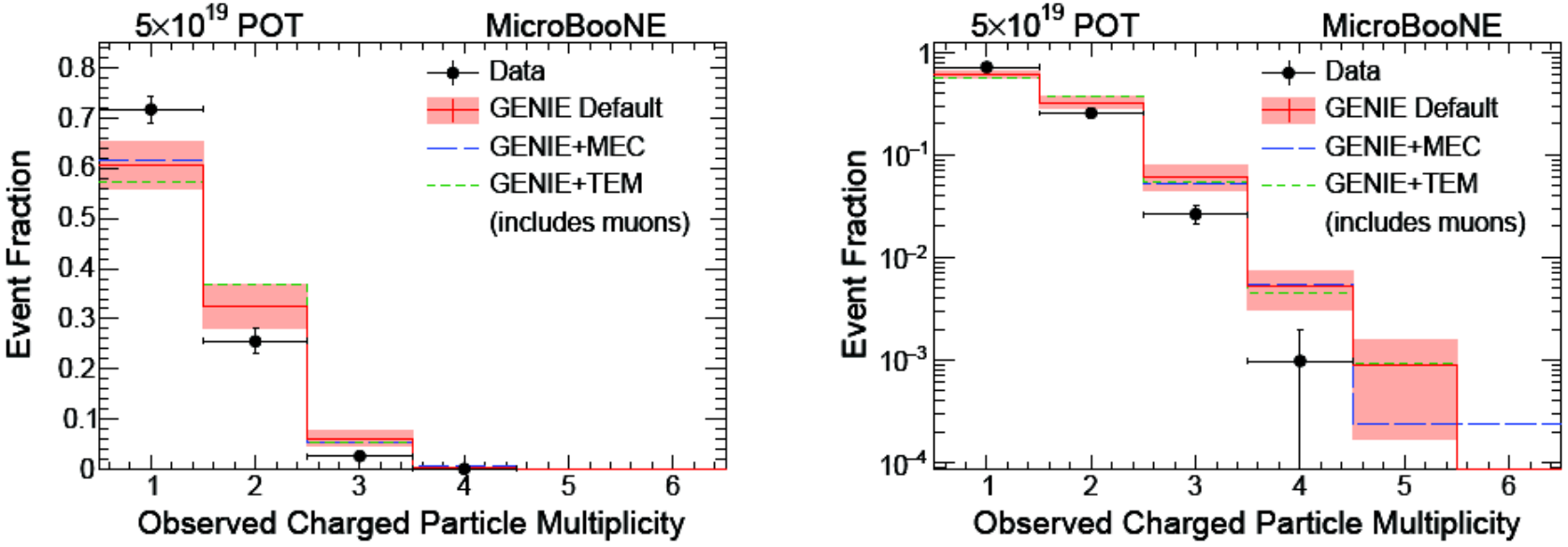
Inclusive Charged-Current Scattering





- MicroBooNE Public Note 1045
- Data somewhat below MC expectation for $p > 1$ GeV/c
  - Systematic uncertainty not yet estimated
- Inclusive total and differential cross sections will be presented at Neutrino 2018 next week
  - Preliminary systematic uncertainty evaluation will also be presented

Charged Particle Multiplicities



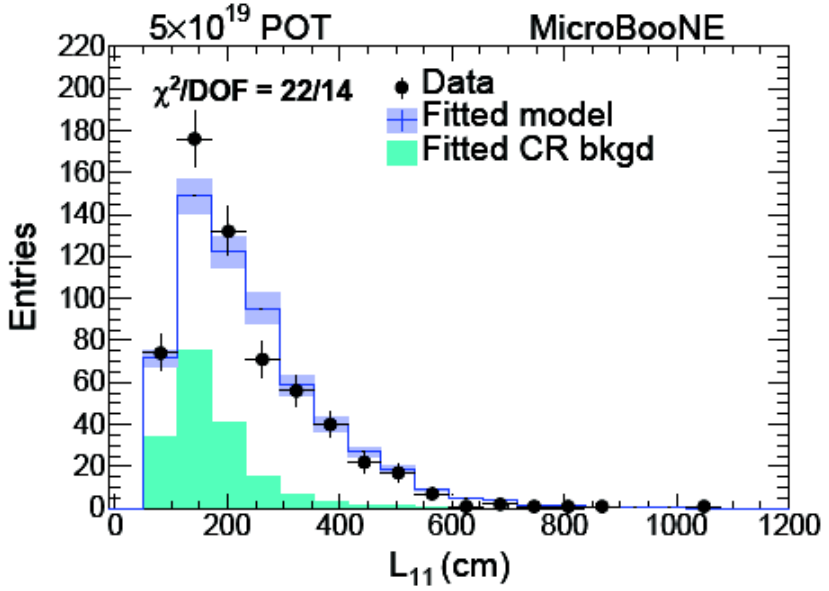
arXiv:1805.06887

- Also at the Fermilab W&C seminar this Friday, submitted to PRD
  - First neutrino-physics paper from MicroBooNE
- Extensive comparisons with GENIE
  - Angular and momentum distributions, correlations
- Good agreement in most variables, but disagreement with multiplicity fractions

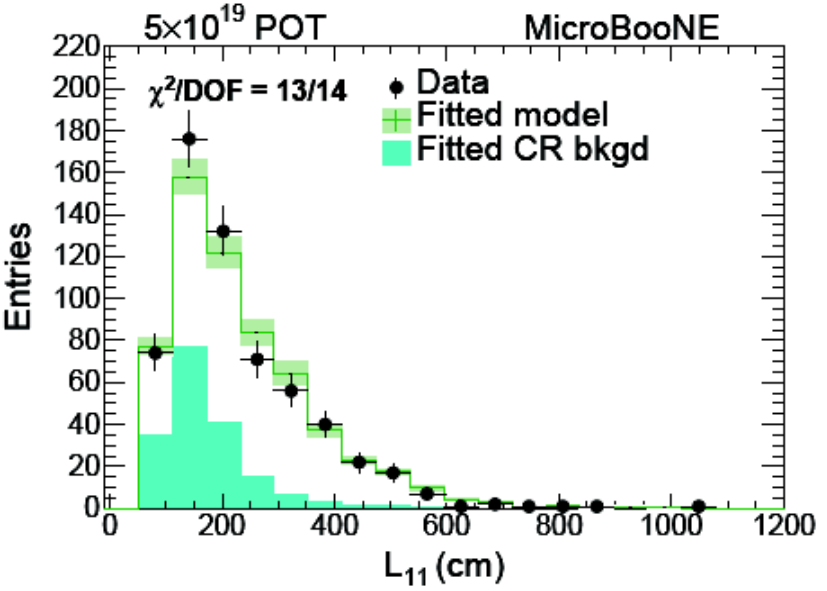
Comparison with two GENIE Models

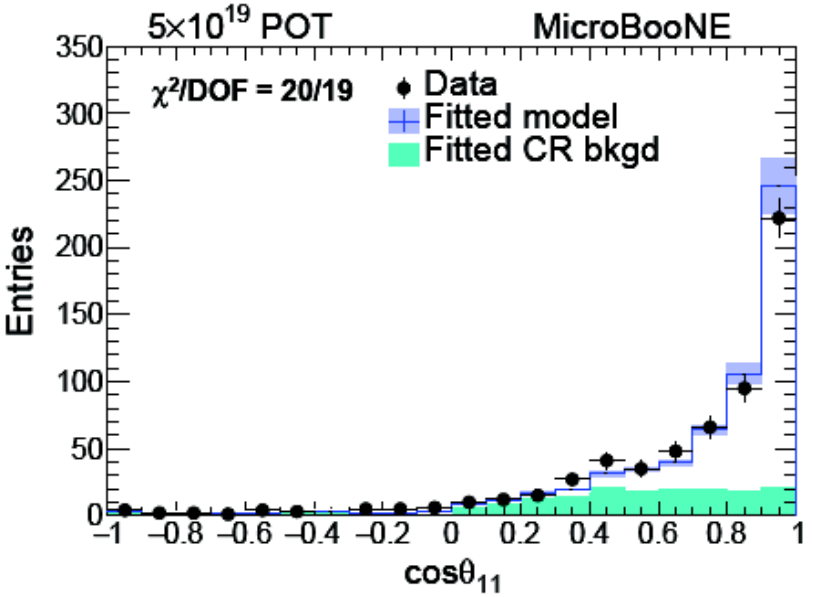
Examples: Events with multiplicity one

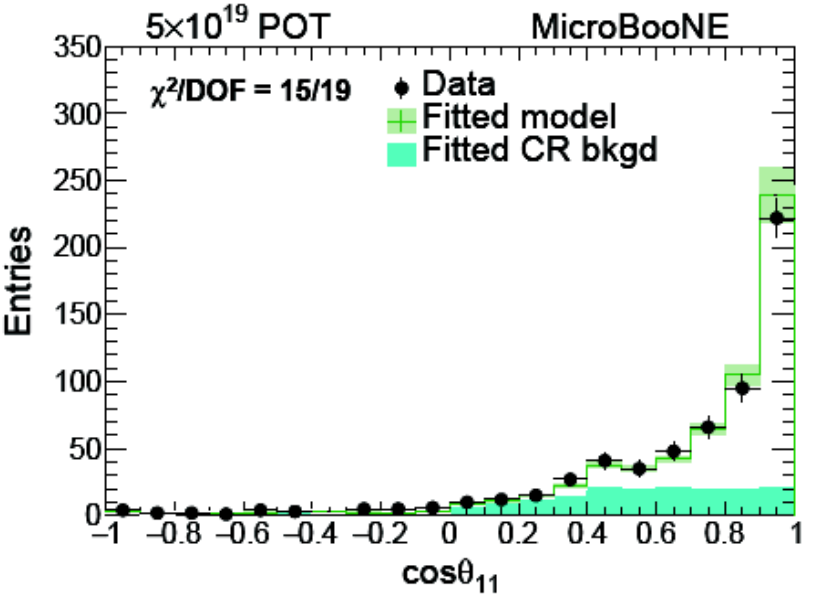
GENIE + MEC



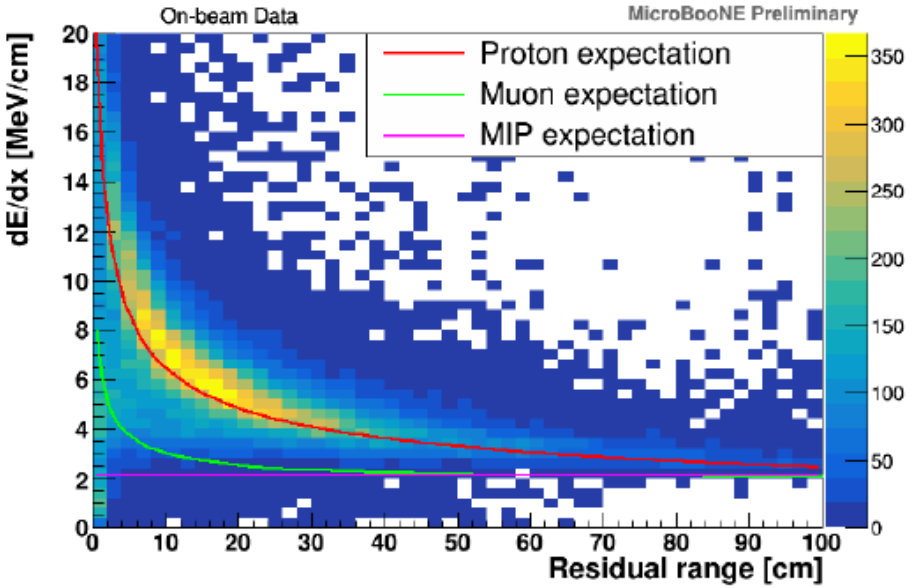
GENIE + TEM

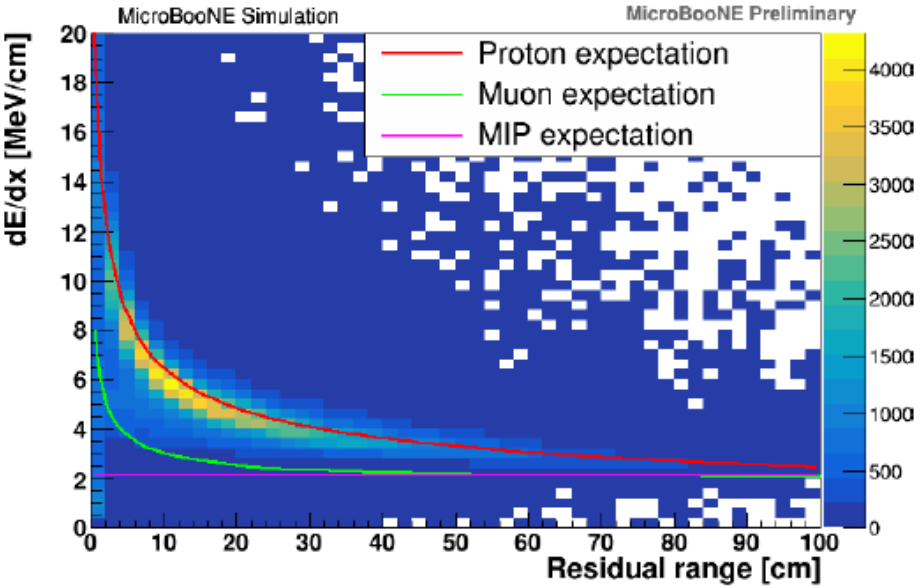




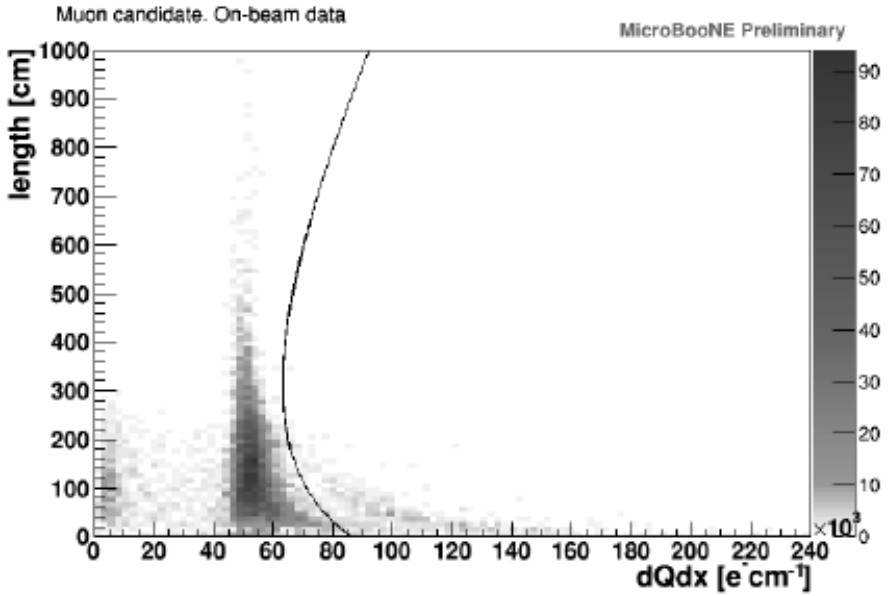


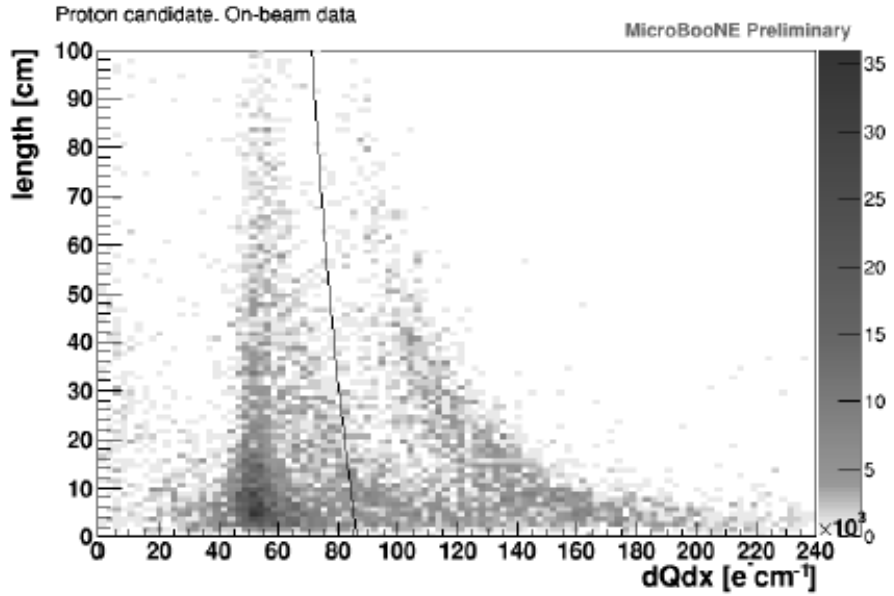
Particle Identification from *dE/dx*





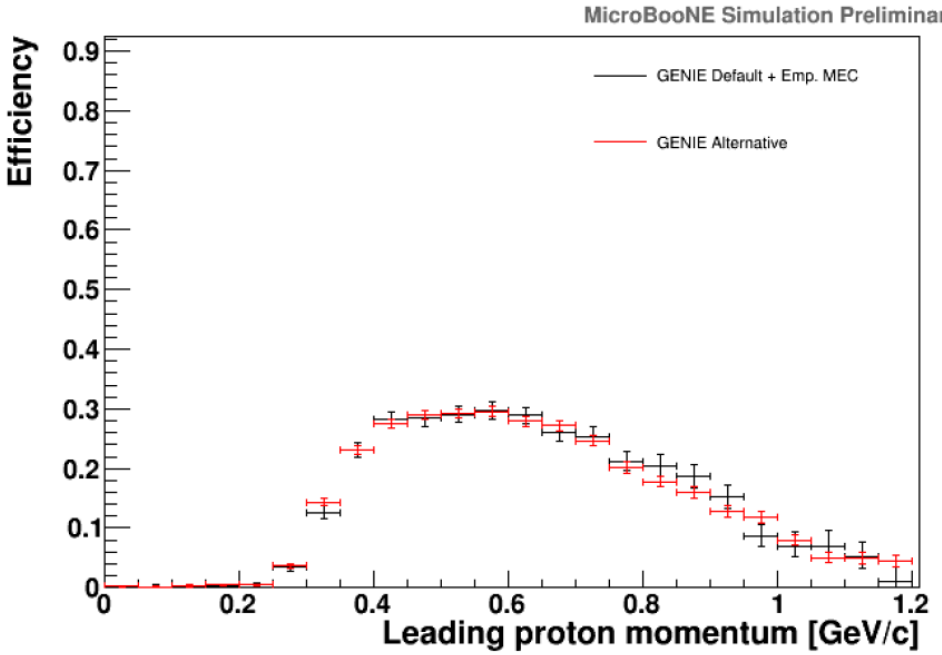
Cut on "truncated mean" *dQ/dx*





CC Np0π — Proton Detection Efficiency

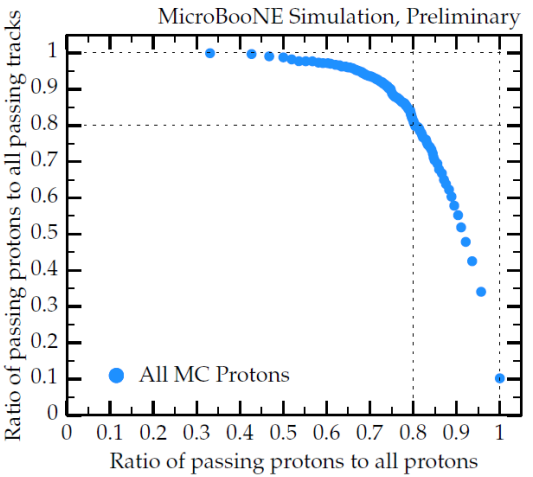
- Useful mode for oscillation searches
- Can reach kinetic energies down to about 40 MeV (momentum 300 MeV/c)
  - Compared to about 450 MeV/c momentum for MINERvA and T2K
- Efficiency does not depend strongly on generator model



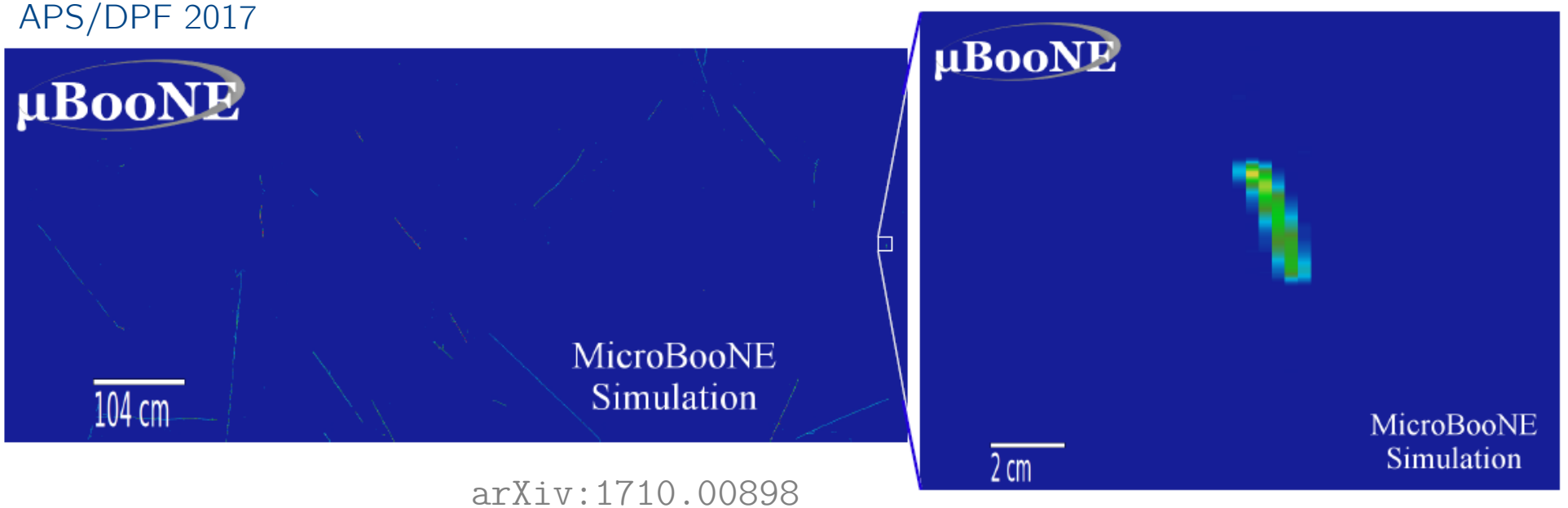
MC	Default + Emp. MEC	Alternative
nuclear momentum	Relativistic Fermi Gas	Local Fermi Gas
QE model	Llewellyn-Smith	Nieves
MEC model	Empirical	Valencia
resonance model	Rein-Sehgal	Berger-Sehgal
final state interactions	hA	hA2014

Neutral-Current, Elastic Cross Section

- Important for searches of sterile neutrinos through flux disappearance
- Sensitive to the strange, axial form factor
  - Value of Δs, the strange quark contribution to the nucleon spin
- Proton ID based on Gradient Boosted Decision Trees
- Finding protons among many cosmic-ray tracks
- Purity vs. efficiency from simulation
- Update at NuFact2018 and Spin2018



APS/DPF 2017



arXiv:1710.00898

Conclusions

- MicroBooNE has been taking for almost three years
  - Live times close to 100%
- Demonstration of LArTPC technology in a surface detector
  - Automated track reconstruction
  - Energy determination
  - Particle identification
  - Cosmic-ray rejection
- Cross section measurements and kinematic distributions starting to provide tests of GENIE models
  - Nuclear structure
  - Final-state interactions
  - Nucleon form factors
- More results to be released in the next few weeks or months
  - Fermilab W&C this week, Mass, Neutrino, PASCOS, NuFact, Spin