Overview of *(a subset)* neutrino experiments: Nu experiments and a new landscape

Bonnie Fleming

Yale University

First results and future prospects with high precision, large LArTPC detectors

From European Strategy Workshop: Big questions

What is the origin of the neutrino masses ?

What is the optimal strategy towards a complete set of measurements of neutrino oscillation parameters and towards a precision global fit of the PMNS matrix ?

Is the existing experimental program (reactor, SBL) sufficient to confirm or exclude the existence of sterile neutrino states with masses in the eV/cÇ range ?

How to search for heavy neutral leptons with present and future facilities ?

Is gravity described by the Einstein theory of general relativity?

How do gravitational waves help to understand Dark Sector of the universe?

What is the proton-proton cross section at ultra-high energies?

How can cosmic neutrino's help to pin-down their properties oscillations and mass hierarchy?

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How to … ities ?

Is … ?

How do … iverse?

V

For both of these, understanding neutrino interactions and measuring cross sections in particular in the 0.5-2 GeV energy range is critical…

How can cosmic neutrino’s help to pin-down their properties oscillations and mass hierarchy?

Answered one question (neutrino mass)

→ Created many more….

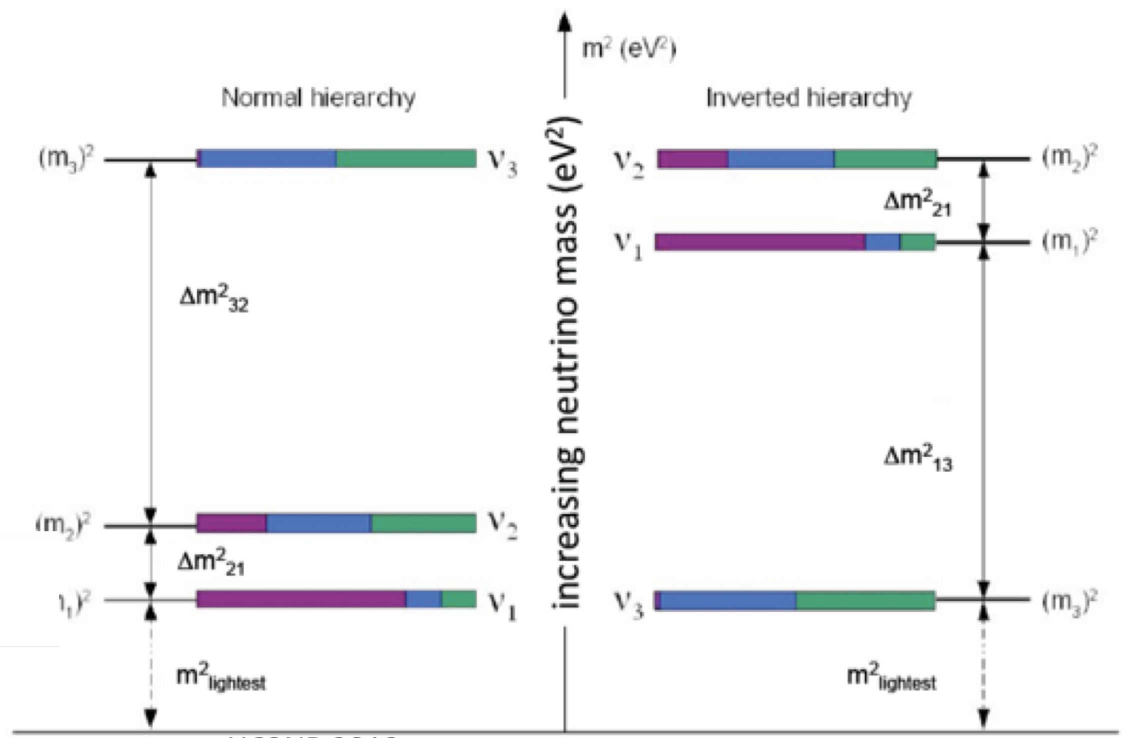
Leptonic Mixing Matrix

flavor states participating in standard weak interactions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrino mass states

Now know all the mass differences and mixing angles (their flavor content)
For the weakly interacting neutrinos



$$\theta_{12} \approx 34^\circ$$

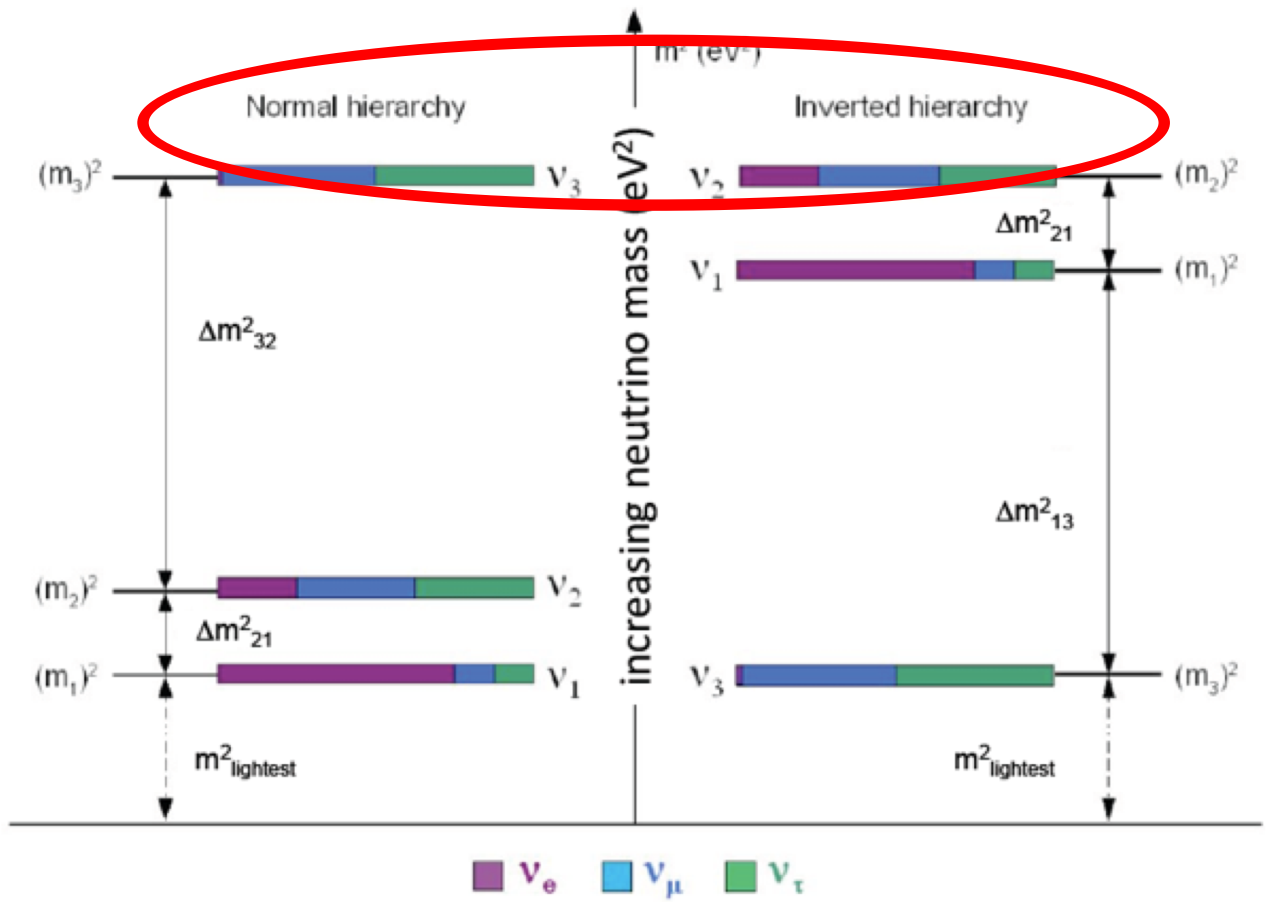
$$\theta_{23} \approx 45^\circ$$

$$\theta_{13} \approx 9^\circ$$

$$\Delta m^2_{21} \approx 7.5 \times 10^{-5} eV^2$$

$$|\Delta m^2_{31}| \approx 2.4 \times 10^{-3} eV^2$$

$$\delta_{CP} = \ ?$$



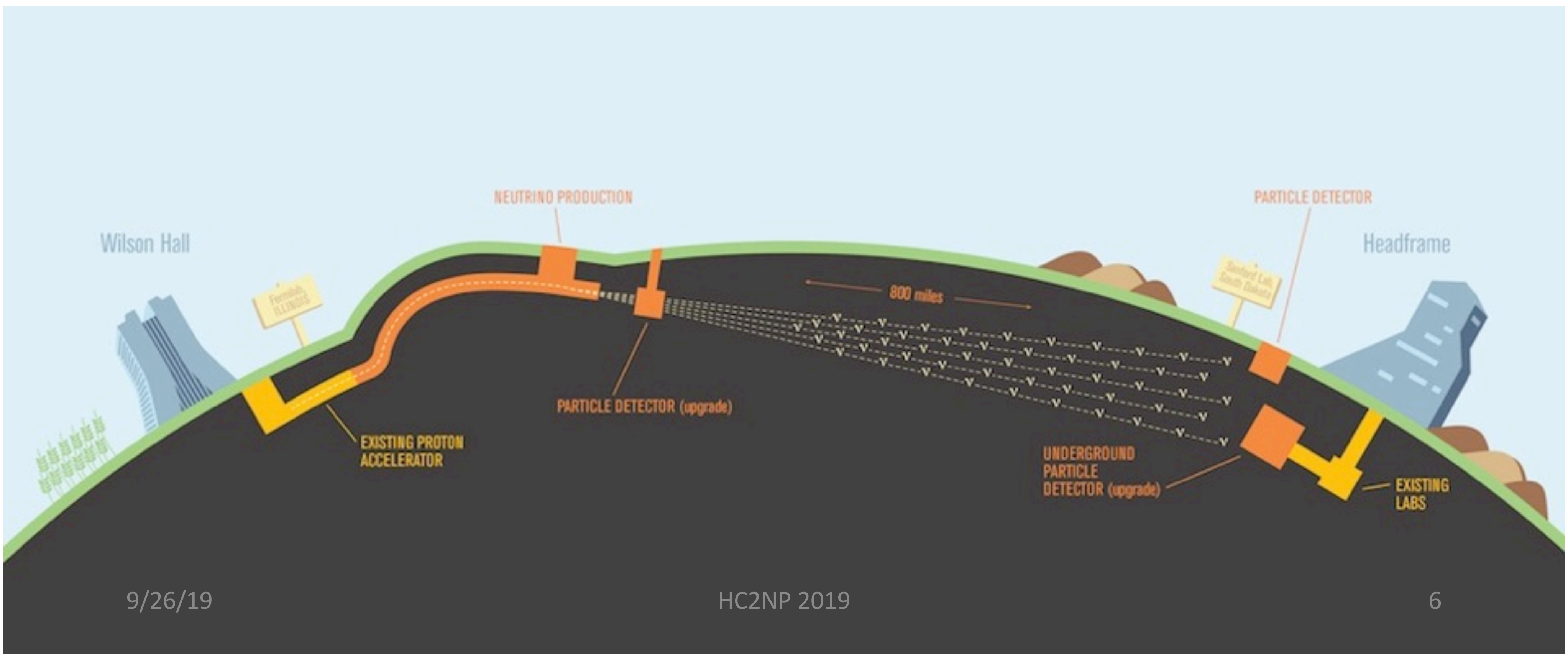
*- is **CP** violated in the neutrino sector?*

(do neutrinos oscillate at the same rate as anti-neutrinos?)

*- to what extent does the 3 ν paradigm **describe nature**?*

Deep Underground Neutrino Experiment (DUNE)

- Look for electron neutrino (anti-neutrino) appearance and muon neutrino disappearance
- Wide band beam – 0.5-10 GeV new neutrino beam at Fermilab
- Baseline of 1300km from Fermilab to Homestake – lots of matter to observe mass hierarchy effects
- Measure CP Violation



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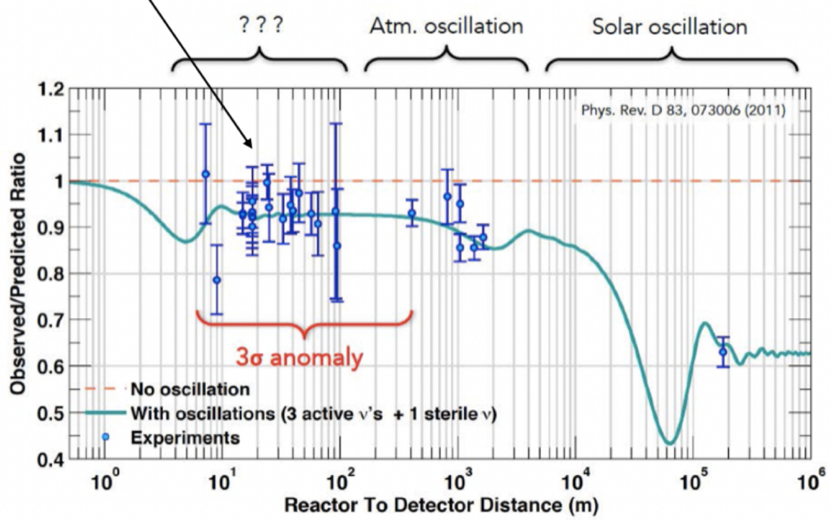
The Reactor Anomaly

At short baselines experiments see fewer neutrinos than expected (red line)

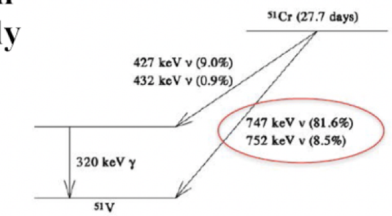


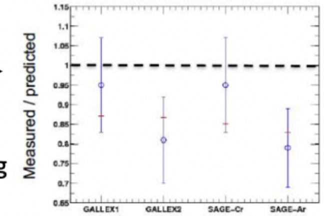
G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller, D.Lhuillier, M. Cribier, and A. Letourneau, Phys. Rev D 83, 073006 (2011)

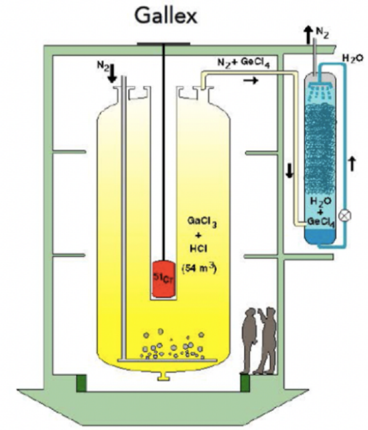
The Gallium Anomaly

Source measurements.....

Electron neutrinos disappearing





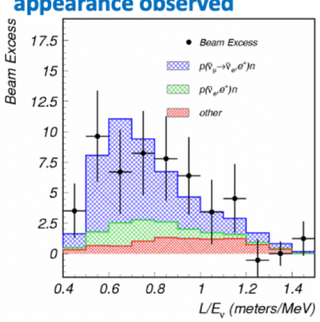


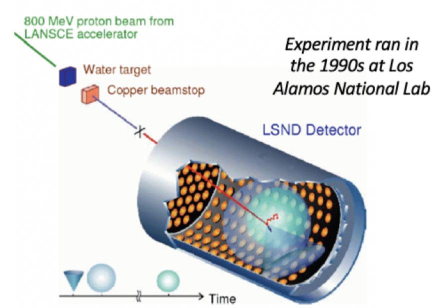
Accelerator Anomaly

LSND

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\bar{\nu}_e$$

Electron neutrino appearance observed



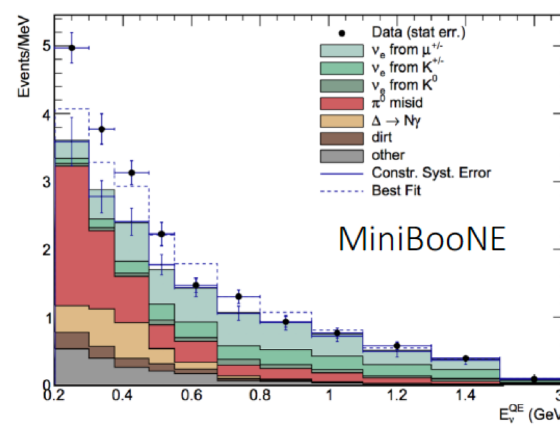


Experiment ran in the 1990s at Los Alamos National Lab

Observed 87.9 ± 22.4 ± 6.0 events above background
Oscillation Probability: 0.26%

Consistent with a Δm^2 on the order of 1 eV^2
(not consistent with 3 flavor picture)

MiniBooNE



New results at 4.5σ

Taken individually, each anomaly is not significant enough to be convincing…. But they are all pointing toward the same thing….

Signals at SBL are at the 2-4σ level
All pointing in the same direction

Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \rightarrow \nu_e$ CC	4.5σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

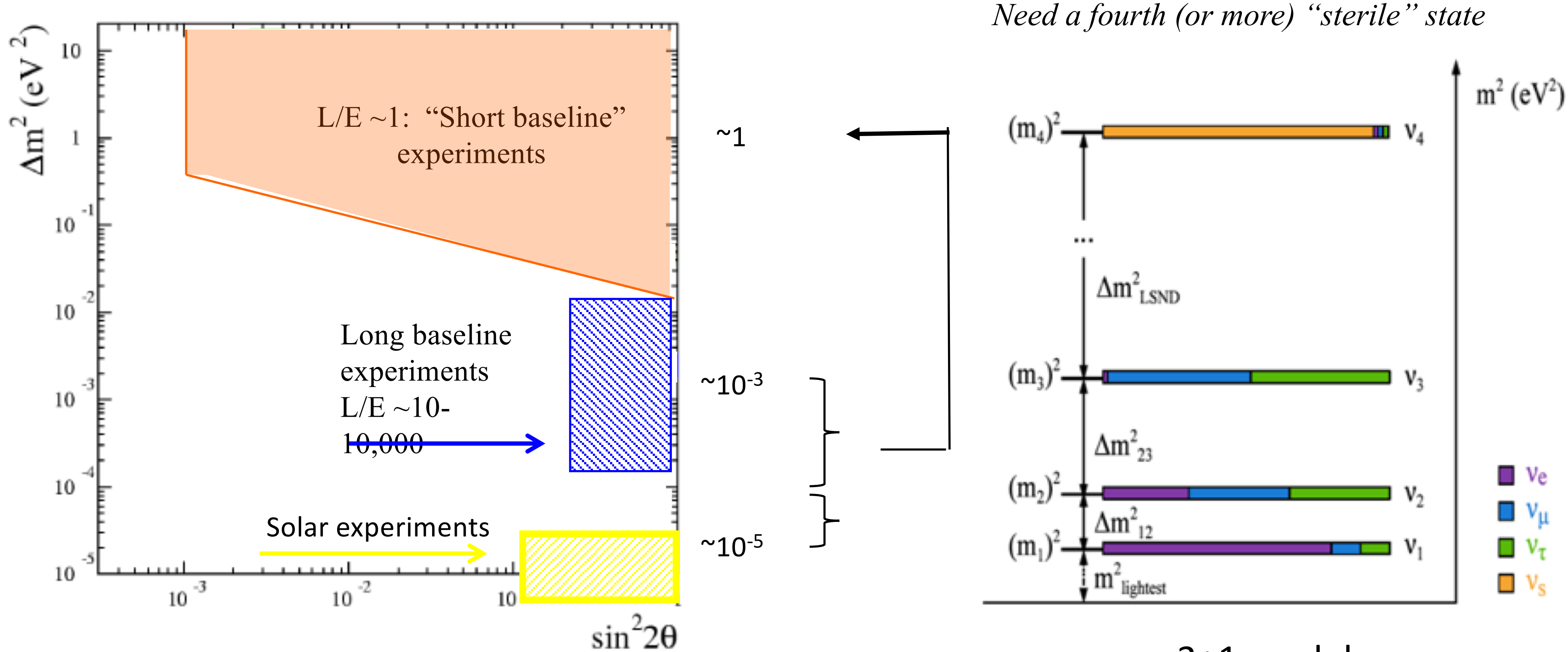
K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv:1204.5379 [hep-ph], (2012)

Most commonly interpreted as hint for one or more new **"sterile"** neutrino (oscillates but does not interact weakly) at large Δm^2_{new} ($\sim$1eV^2) and small mixing.

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m_{ij}^2 \frac{L}{E}\right)$$

Short Baseline Results cannot be explained by three neutrinos responsible for long baseline oscillations

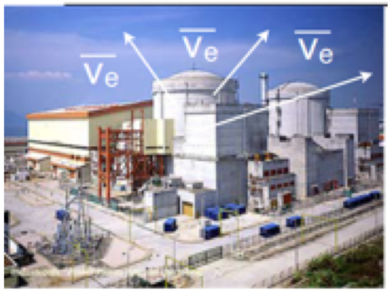
Need a fourth (or more) "sterile" state



3+1 model

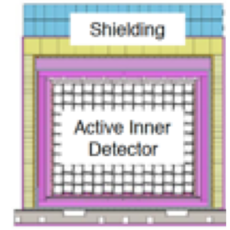
Reactor experiments:

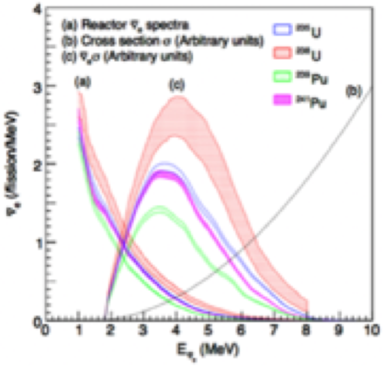
Pure $\overline{\nu}_e$ source produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

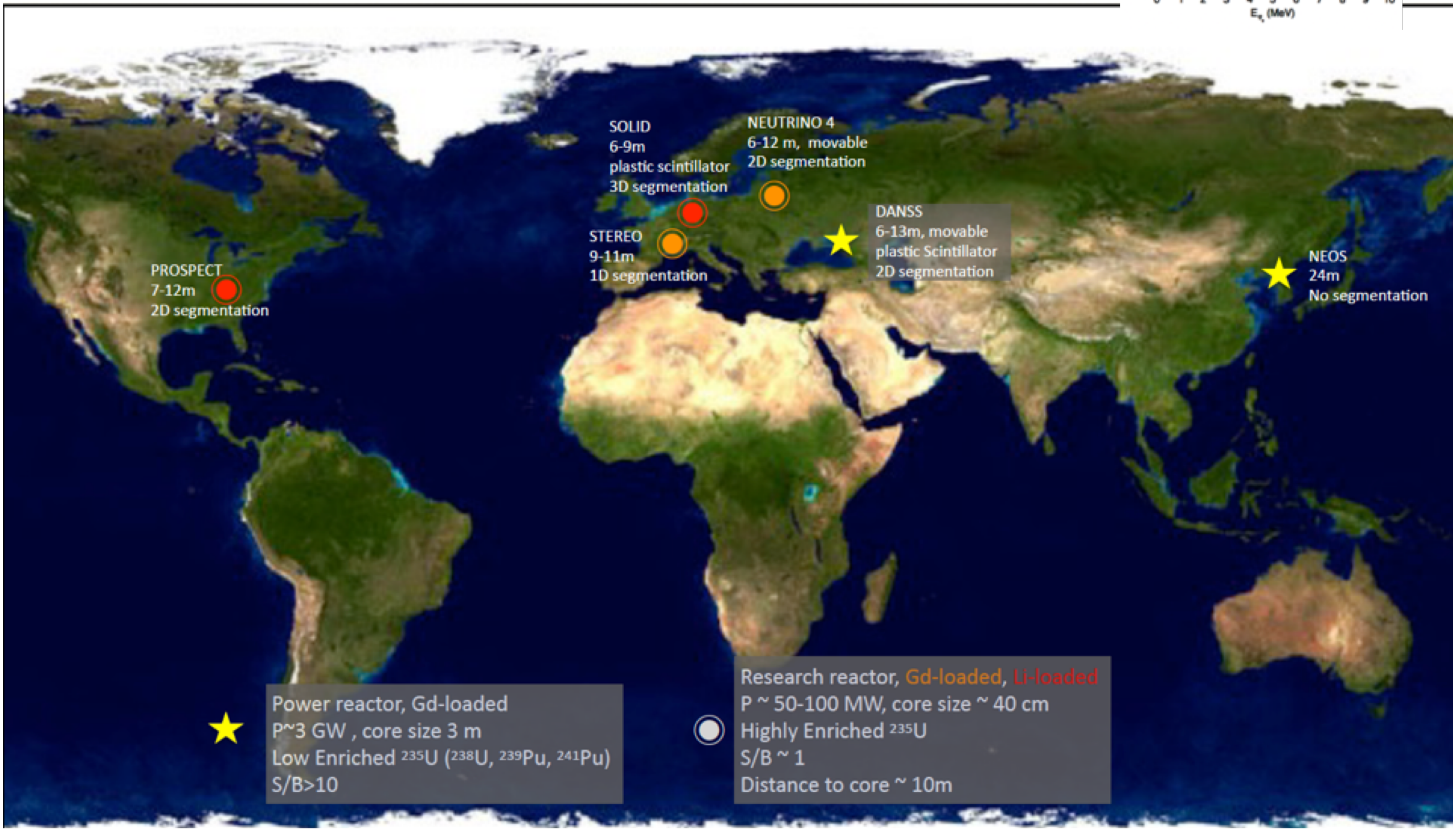


$\overline{\nu}_e$ disappearance

baseline ~m



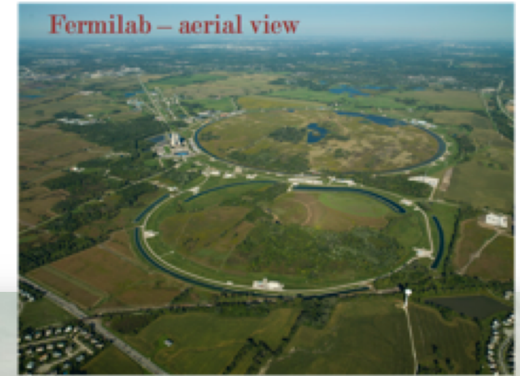


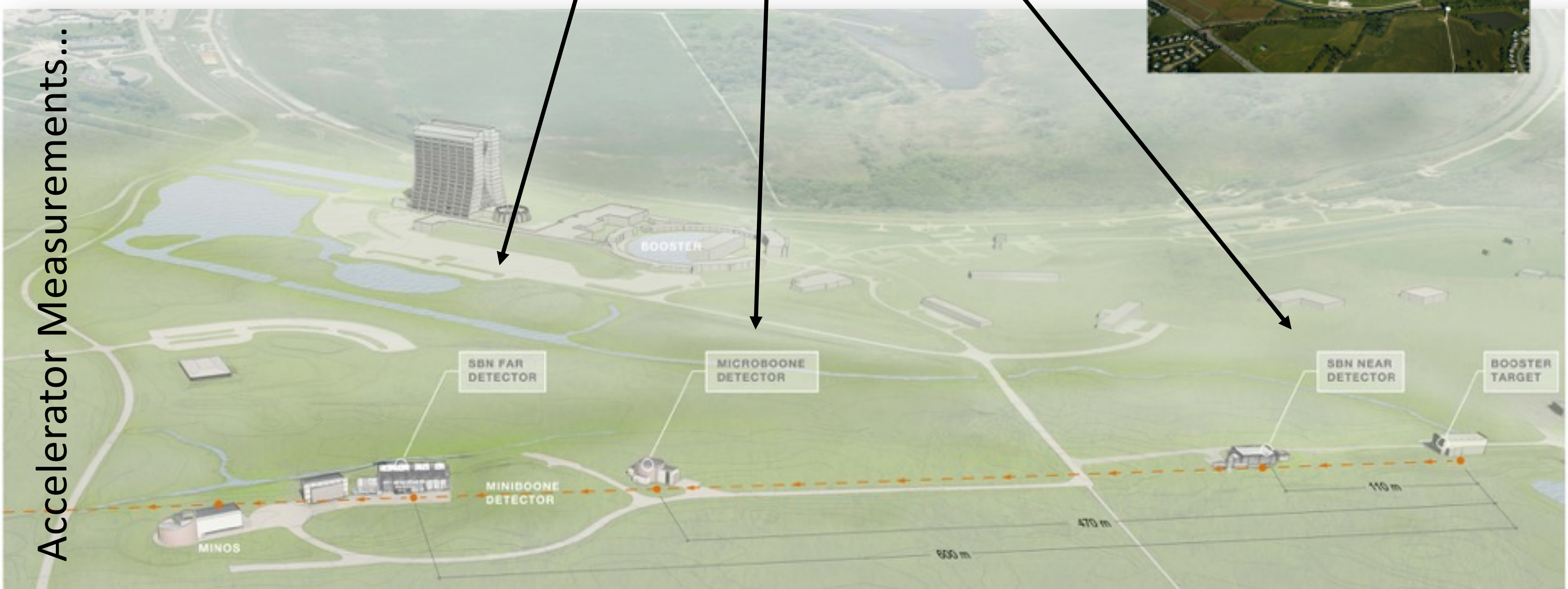


Accelerator Measurements...

Fermilab: Three detector Short Baseline Neutrino (SBN) program on the Booster Neutrino Beamline

Muon neutrino beam (same as MiniBooNE) sampled at SBND near detector (no oscillations), far detectors: MicroBooNE, ICARUS





- MicroBooNE: Address the MiniBooNE Low Energy Excess: Is it electrons or photons?
- SBND: Is there a baseline dependent effect?
- ICARUS: With large detector, span all allowed regions in parameter space at 5σ

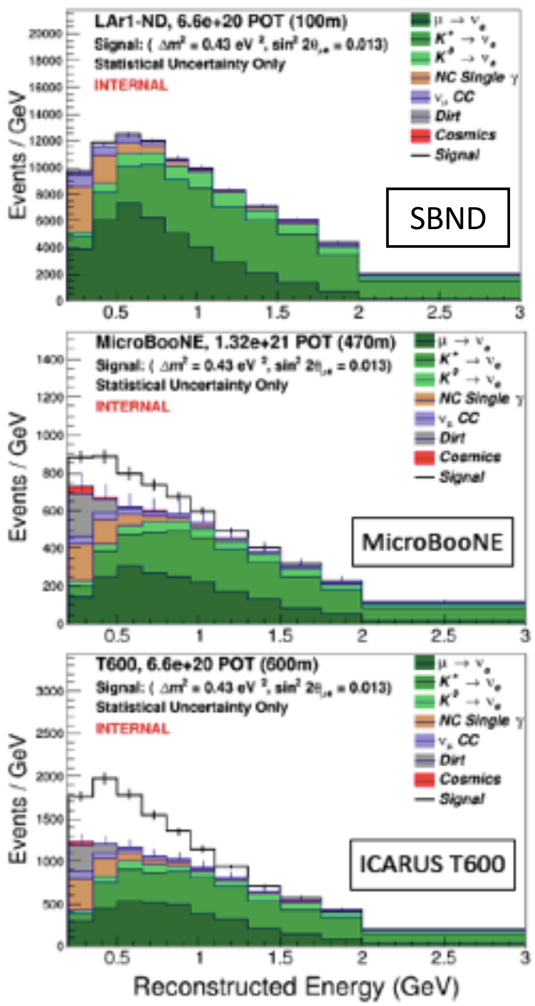
ν_e appearance sensitivity with three detector SBN experiment

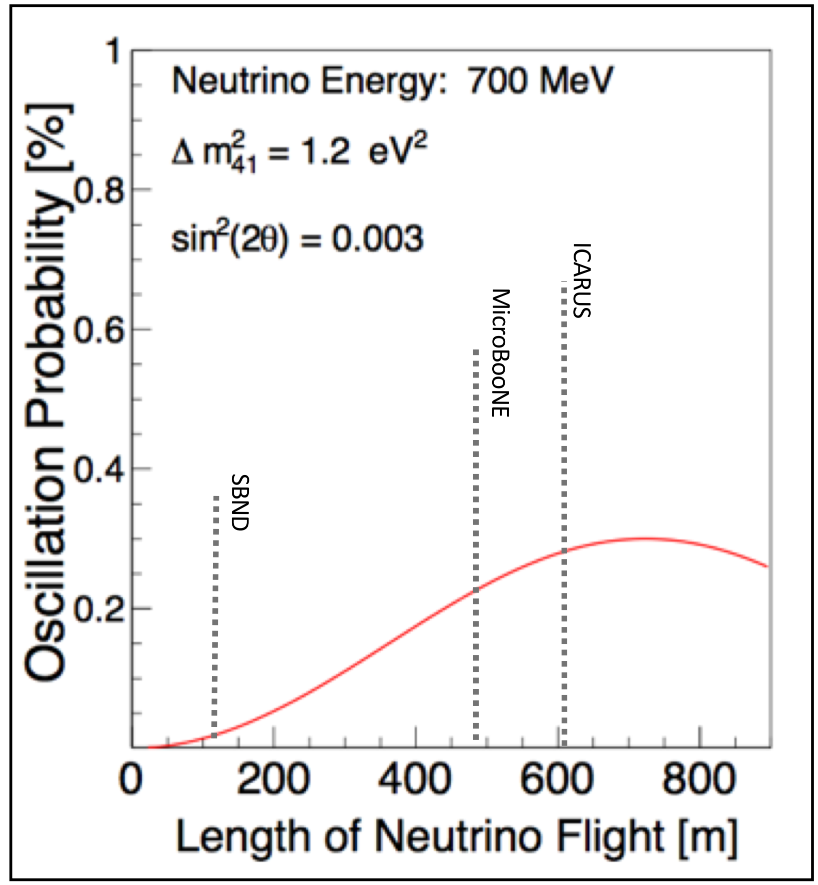
Accelerator Measurements…

SBND

MicroBooNE

ICARUS





Short Baseline

L/E ~1 km/GeV

Hints of new physics

Sterile neutrinos?

Long Baseline

L/E ~ 1000km/GeV

Measuring Mass Hierarchy and Looking for CP Violation

$\nu_\mu \rightarrow \nu_e$ appearance experiments

E_ν 1-10 GeV

Precision detectors:

Liquid Argon TPCs

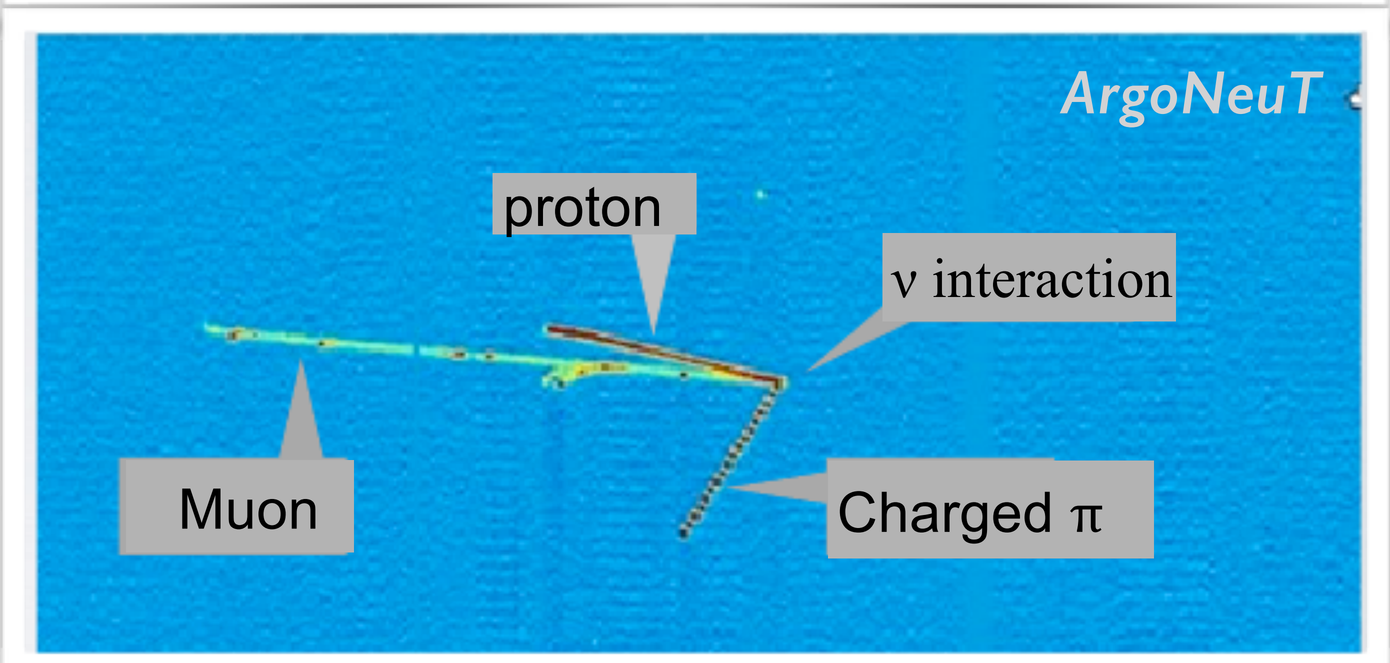
Along the way: wealth of neutrino interaction measurements important for oscillation physics and for neutrino interaction physics

$\nu_\mu \rightarrow \nu_e$ appearance experiments

E_ν 1-10 GeV

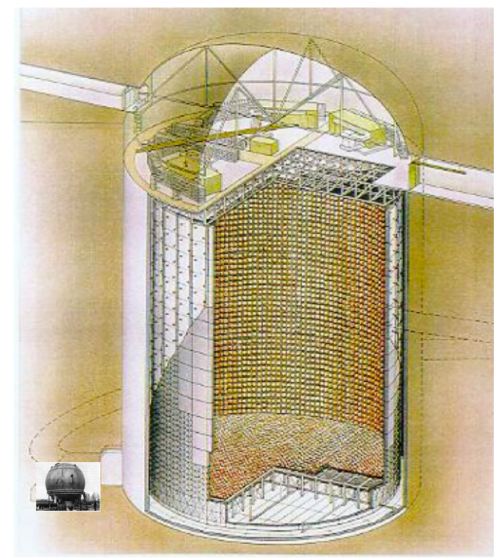
Precision detectors:

Liquid Argon TPCs



Bubble chamber detectors from 1970’s → fine grained

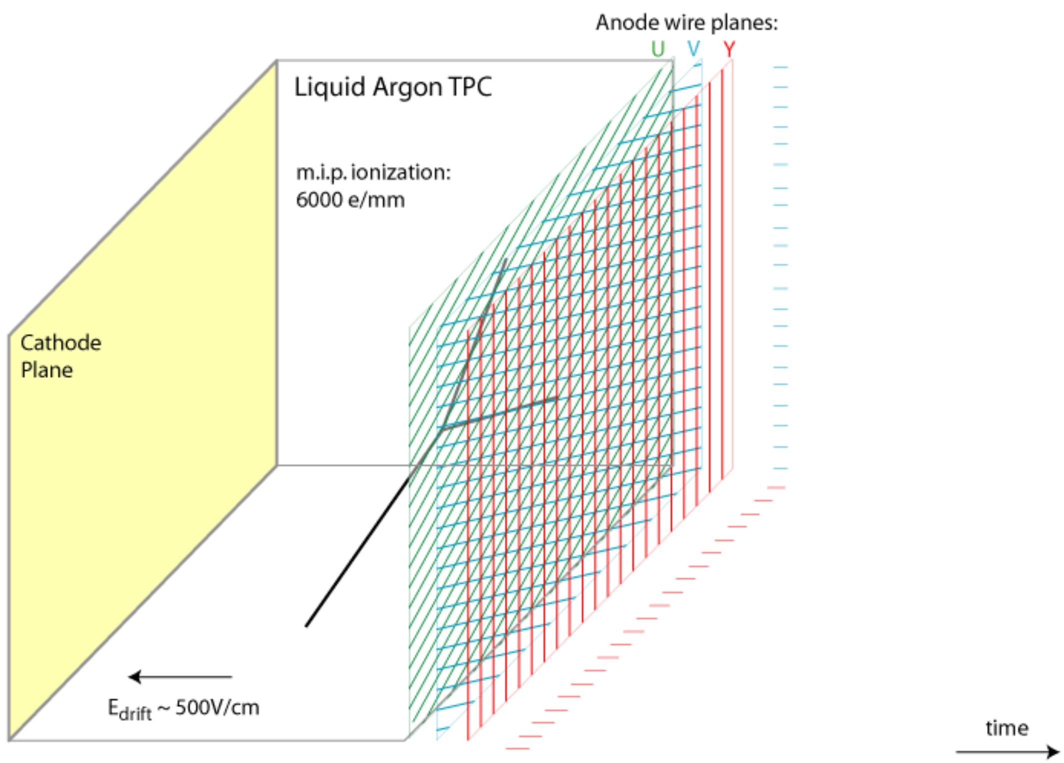
Moved to massive detectors to gain statistics (compromised precision)



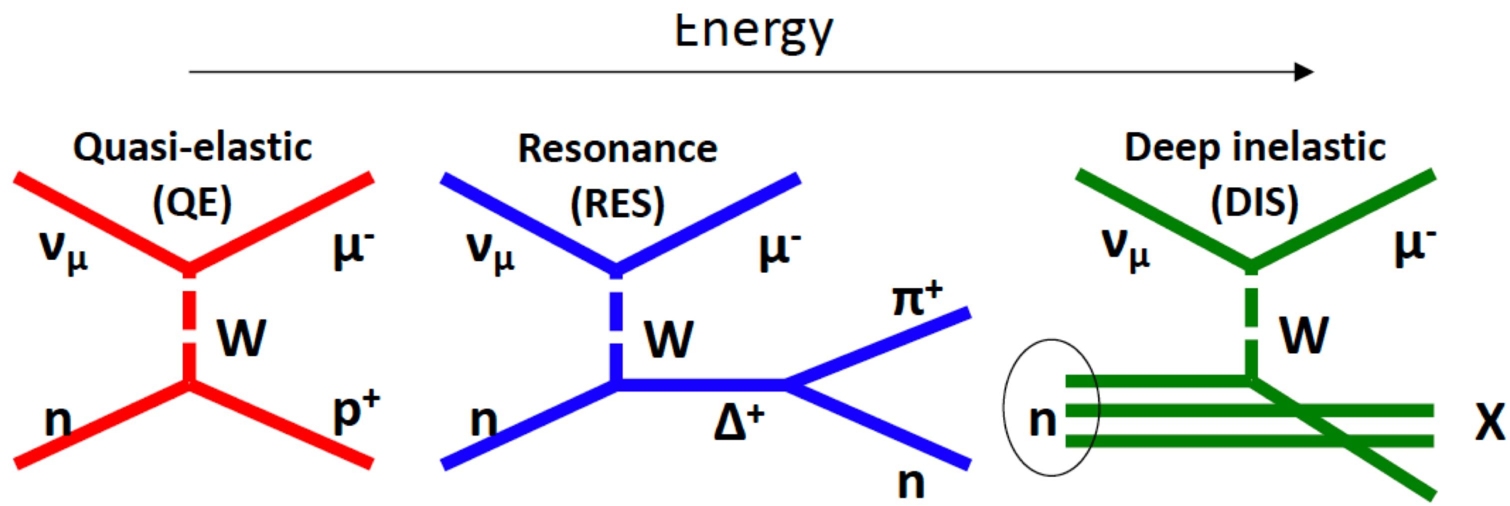
Now moving back to precision detectors but on massive scales → LArTPCS

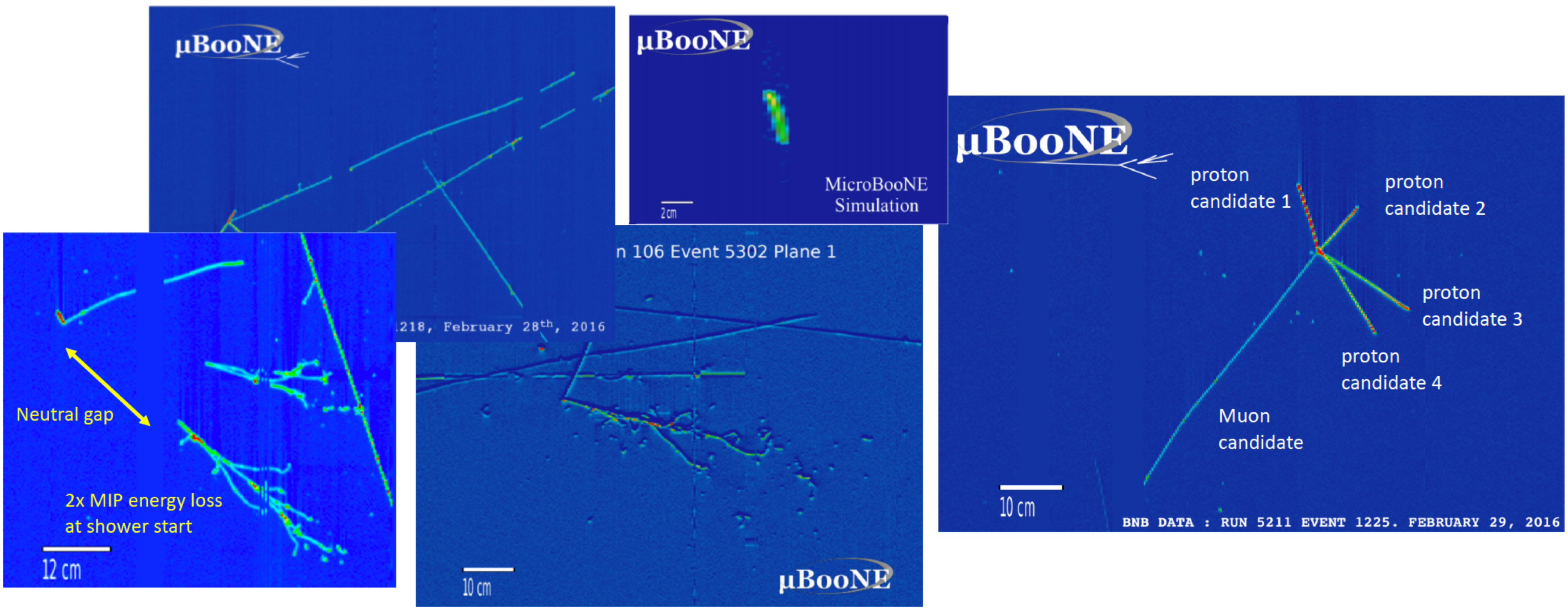
Liquid Argon Time Projection Chambers

- Passing charged particles ionize Argon
- Electric fields drift electrons meters to wire chamber planes
- Induction/Collection planes image charge, record dE/dx



Light produced at 128nm and shifted to the visible to be collected by PMTs





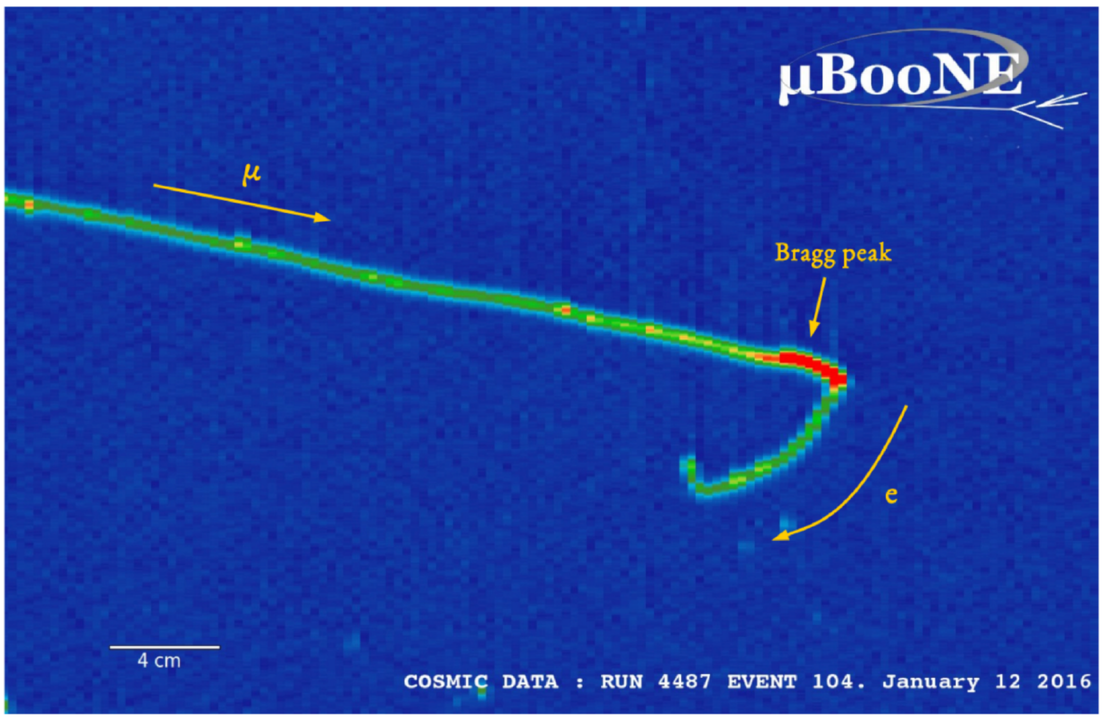
Detectors have spatial resolution on the order of the wire spacing (several mm)

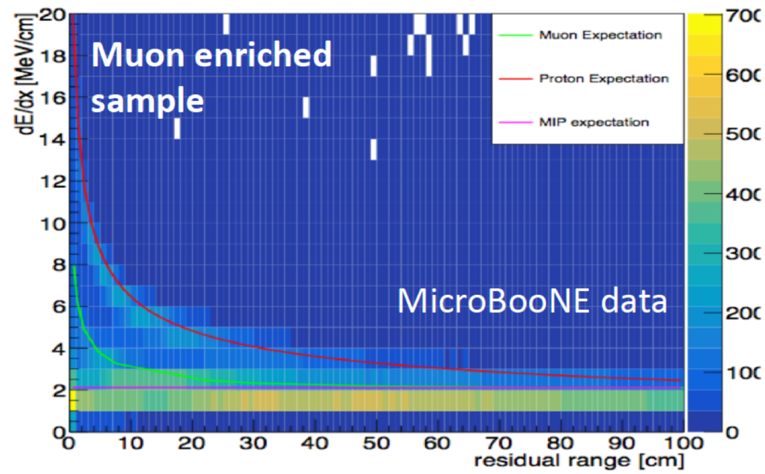
→ topology and calorimetry to identify interaction channels

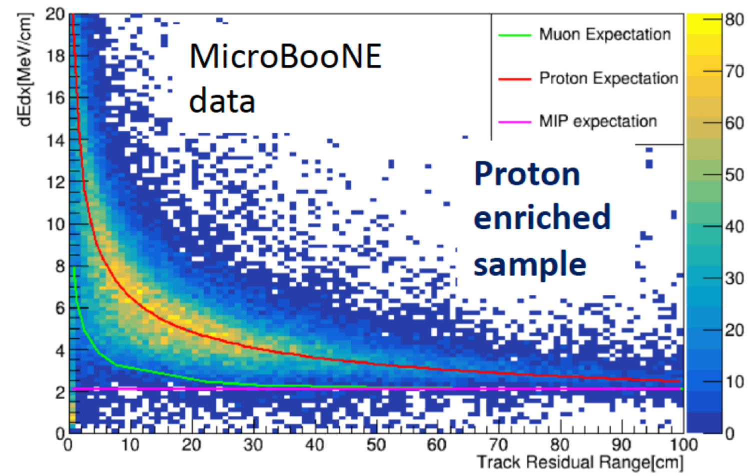
Power of Calorimetry: Identify protons, muons from particle signatures

Color coded: Deposited charge (corresponding to # of ionization electrons)

No charge ⟶ **A lot of charge**







4/16/19 - APS Meeting

JINST 12, P09014 (2017)

A. Schukraft | Fermilab

https://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1056-PUB.pdf

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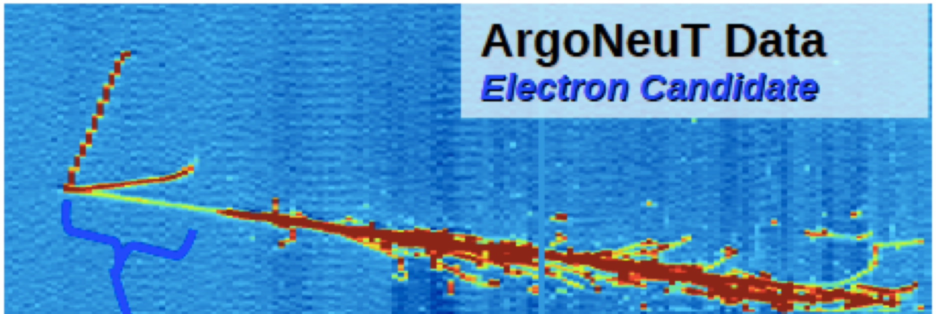
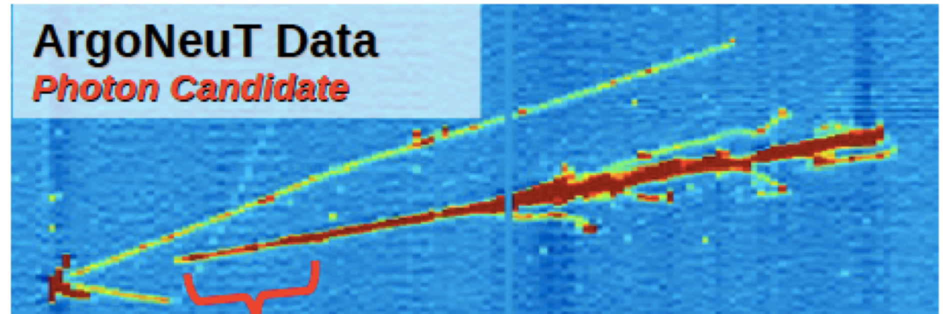
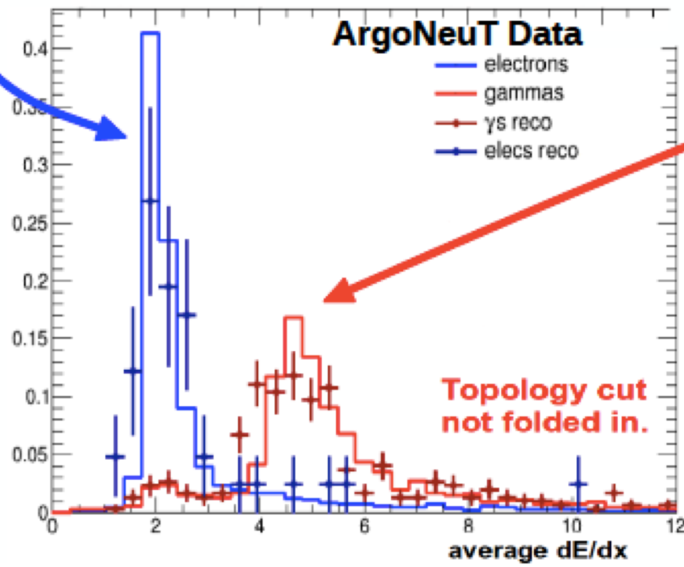
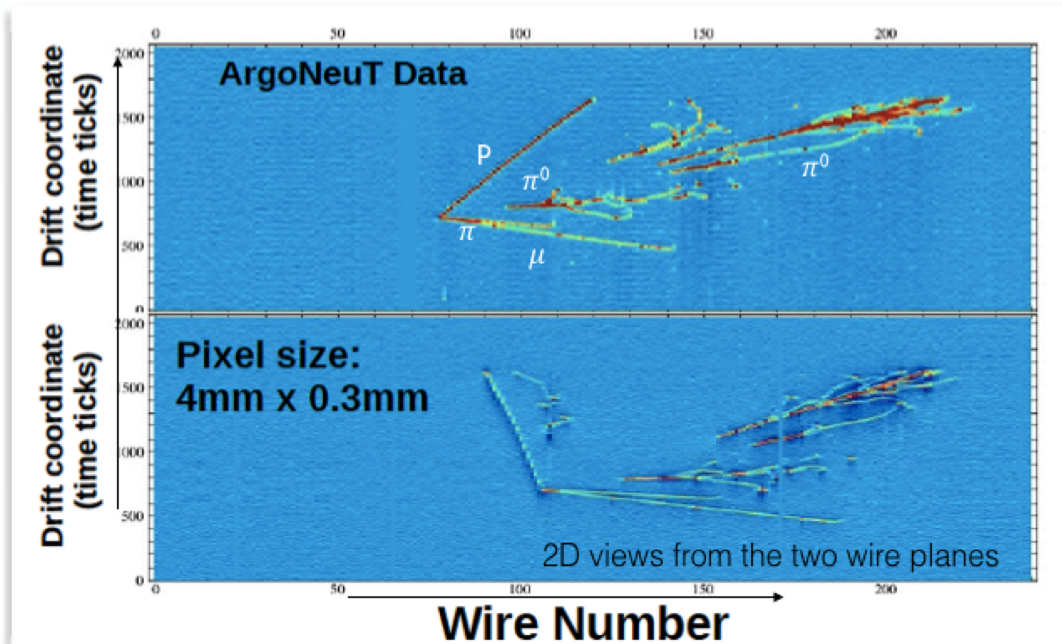
Electron-γ separation in LAr





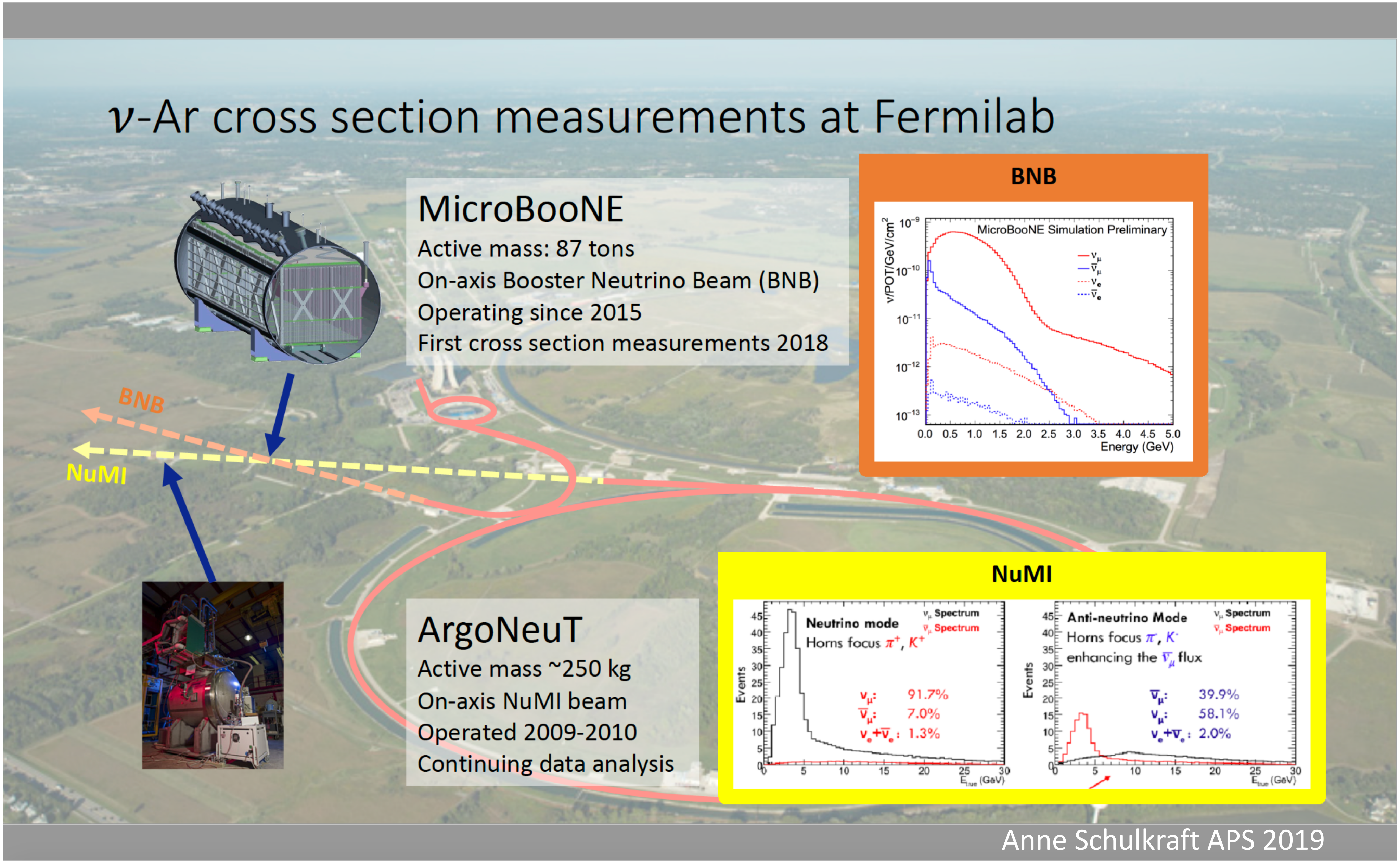


Analyzing topology and dE/dx

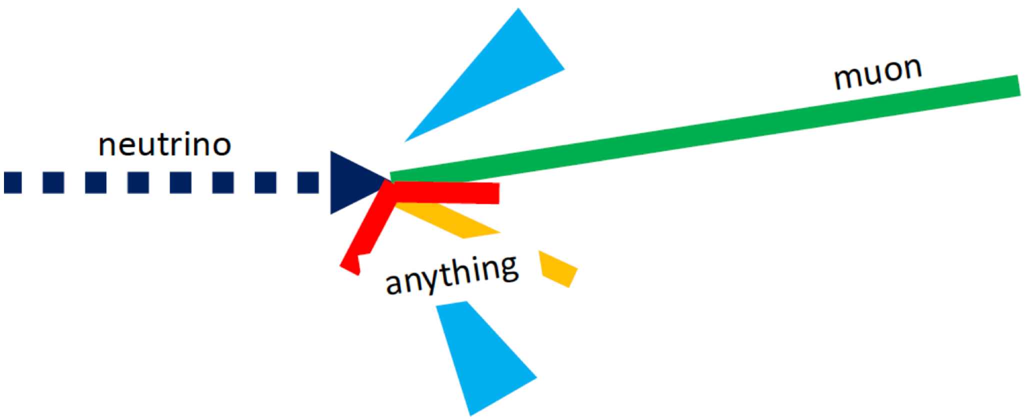


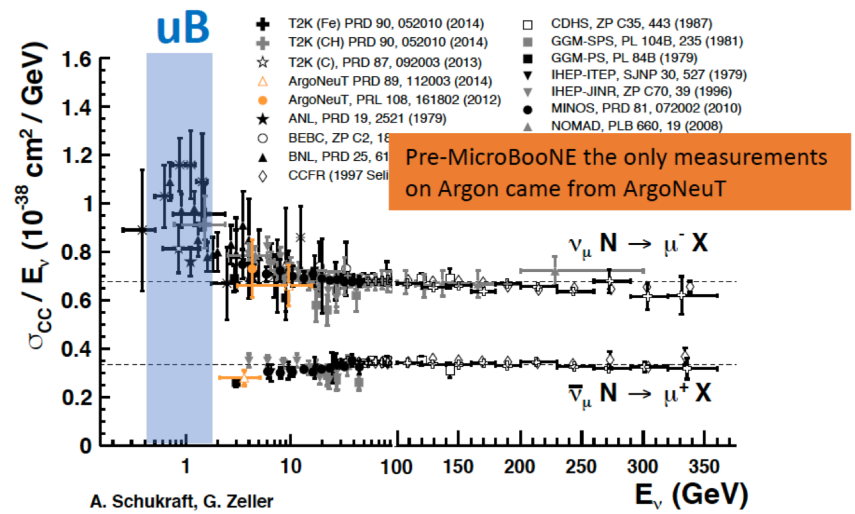
Critical for electron neutrino appearance experiments
Identify the NATURE of the EM signature

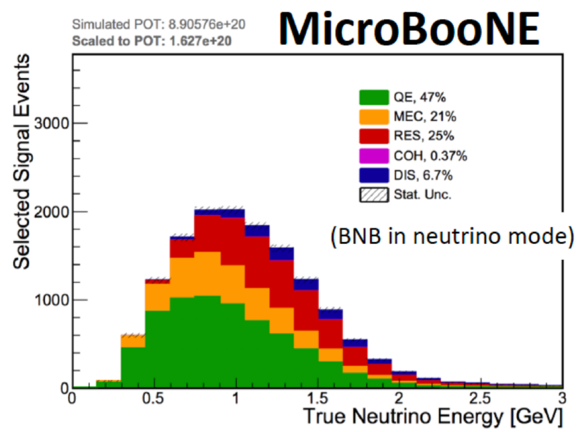
Where are we now?

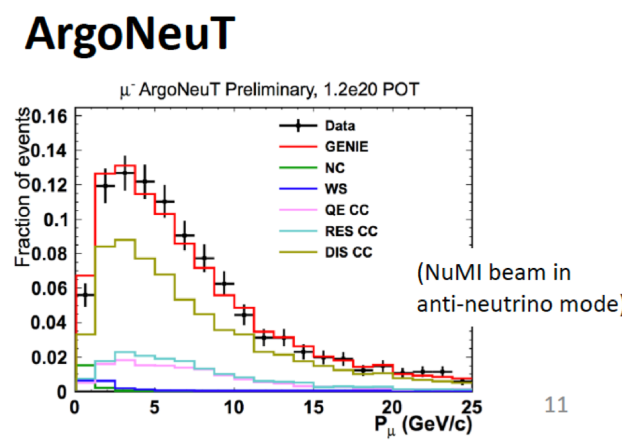


ν_μ Charged-current inclusive channel









The MicroBooNE neutrino energy range is lower than ArgoNeuTs.

Different interaction processes dominate the CC inclusive channel!

https://arxiv.org/abs/1311.2096

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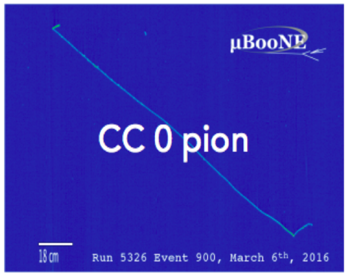
MicroBooNE CC Inclusive ($\nu_\mu + Ar \rightarrow \mu + X$)



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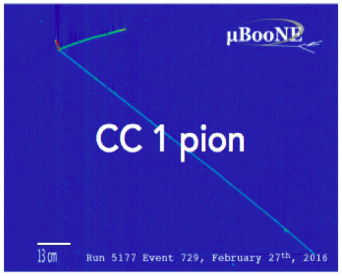

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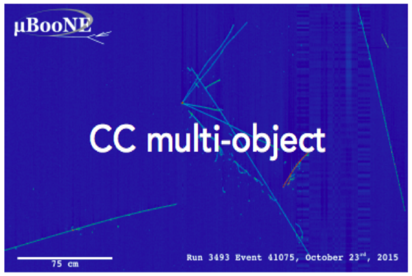
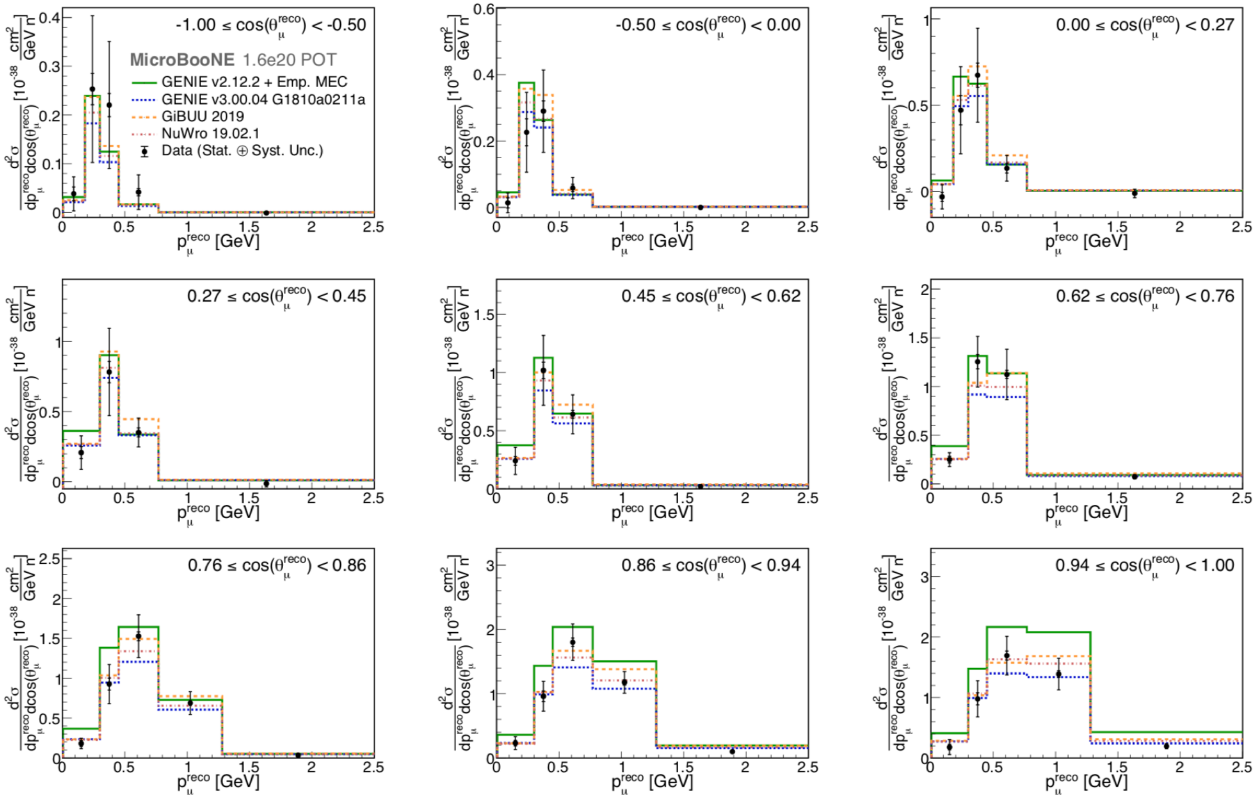


+ …

backwards going muons

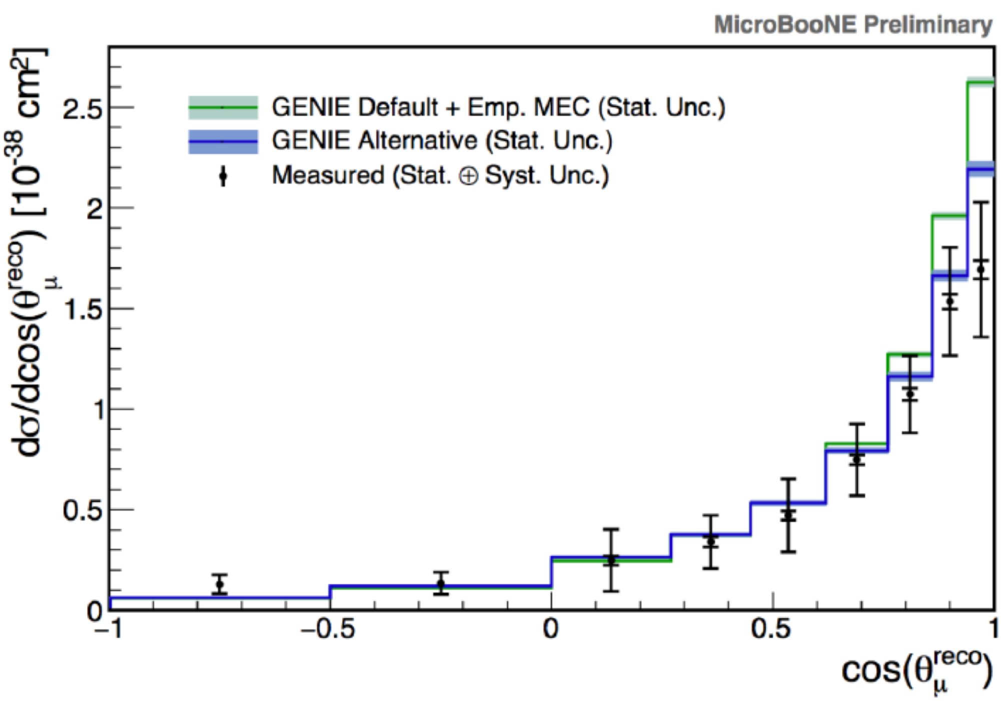


forward going muons

- 26k events (1.6×10^{20} POT)
- pioneering use of MCS to include exiting tracks → full kinematic coverage
- first neutrino double differential cross section measurement on argon

arXiv:1905.09694
Published in PRL

MicroBooNE CC Inclusive (ν_μ + Ar → μ + X)



- first comparison of event generators to high statistics, 2D neutrino data on argon
- Systematic uncertainties are dominant → detector uncertainties → expect improvement in future analyses

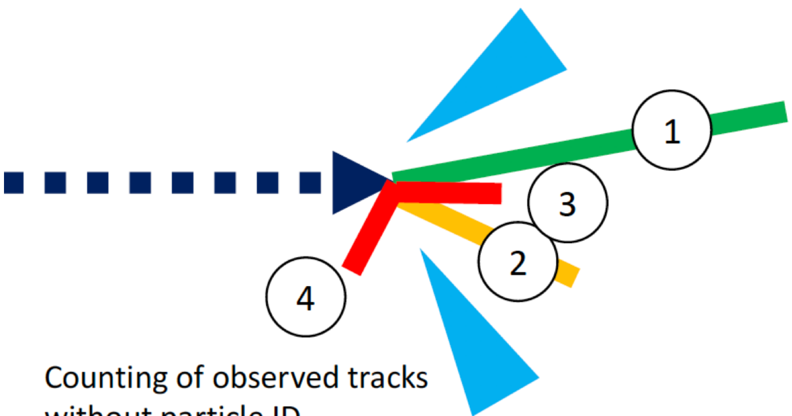
GENIE Default
(v2_12_2)

Nuclear Model: Bodek-Ritchie Fermi Gas
Quasi-elastic: Llewellyn-Smith
Meson-exchange Currents: Empirical
Resonant: Rein-Seghal
Coherent: Rein-Seghal
FSI: hA

GENIE Alternative
(v2_12_2)

Nuclear Model: Local Fermi Gas
Quasi-elastic: Nieves
Meson-exchange Currents: Nieves
Resonant: Berger-Seghal
Coherent: Berger-Seghal
FSI: hA2014

Charged particle multiplicity in the CC inclusive sample

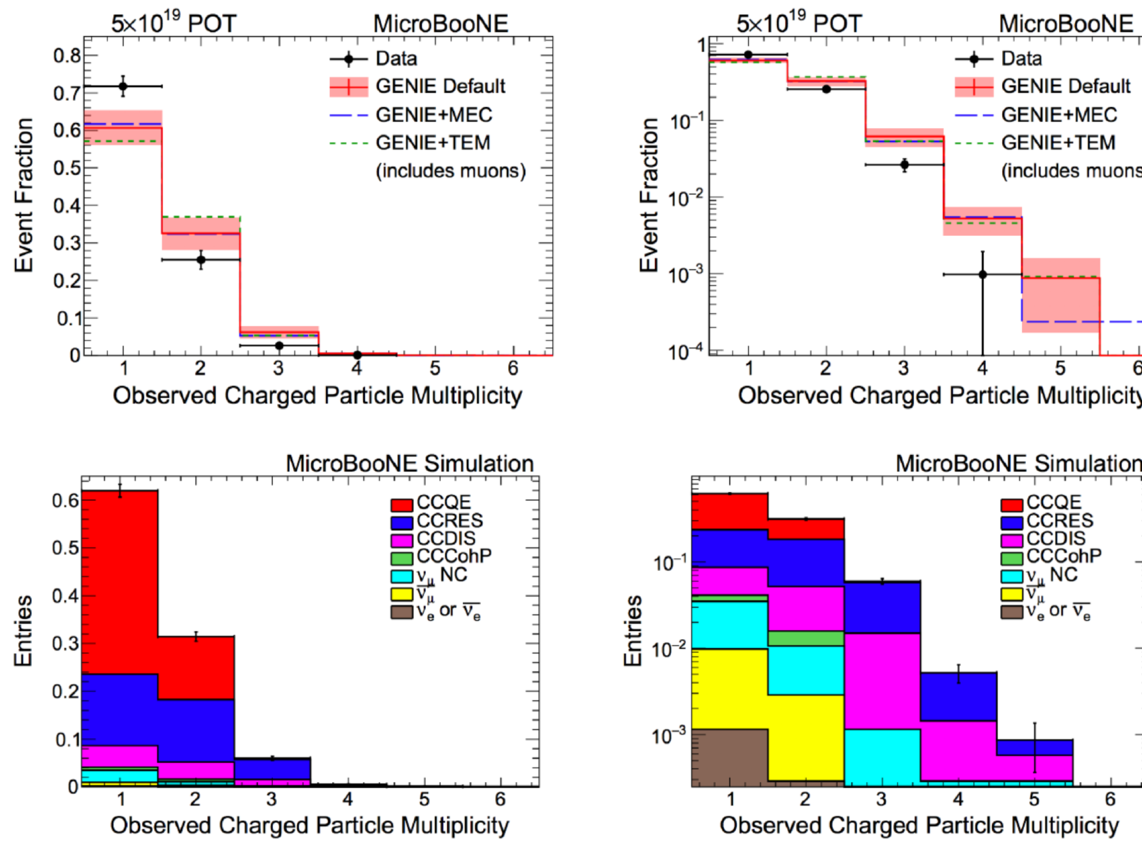


Counting of observed tracks without particle ID

No efficiency or migration correction

Higher multiplicity bins are dominated by RES and DIS processes.

MicroBooNE observes less high-multiplicity final states relative to low multiplicity states than GENIE



Eur. Phys. J. C79, 248 (2019)

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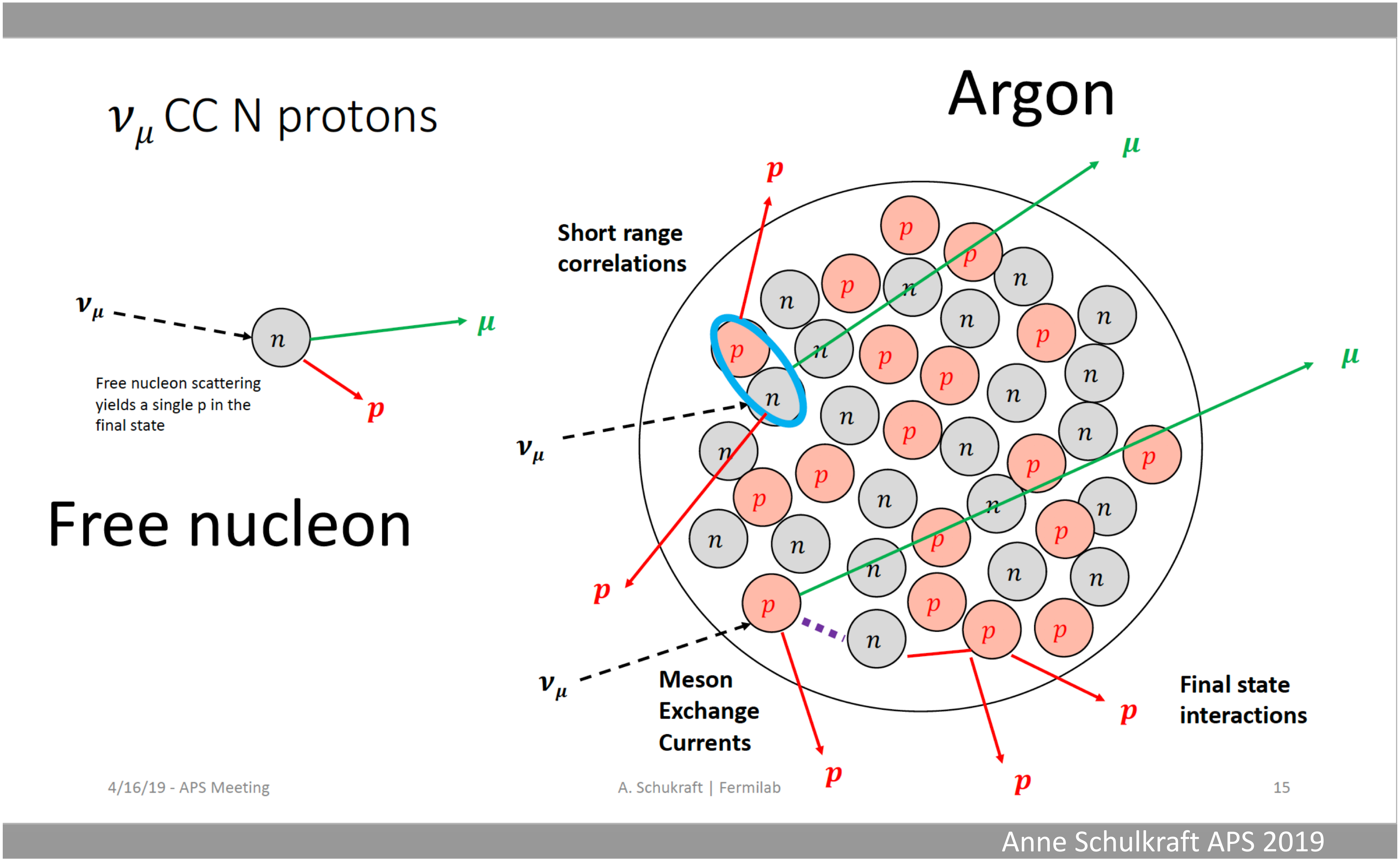
ν_μ CC N protons
Argon
Free nucleon
ν_μ
n
μ
p
Free nucleon scattering yields a single p in the final state
Short range correlations
Meson Exchange Currents
Final state interactions
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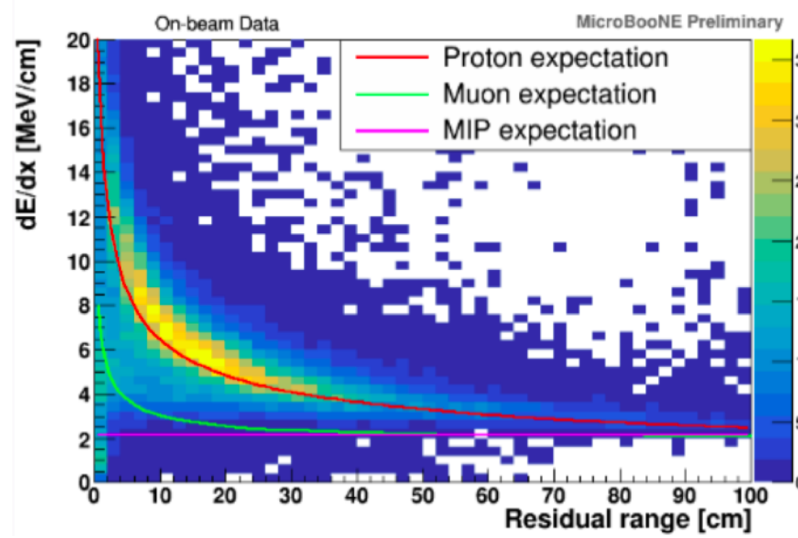
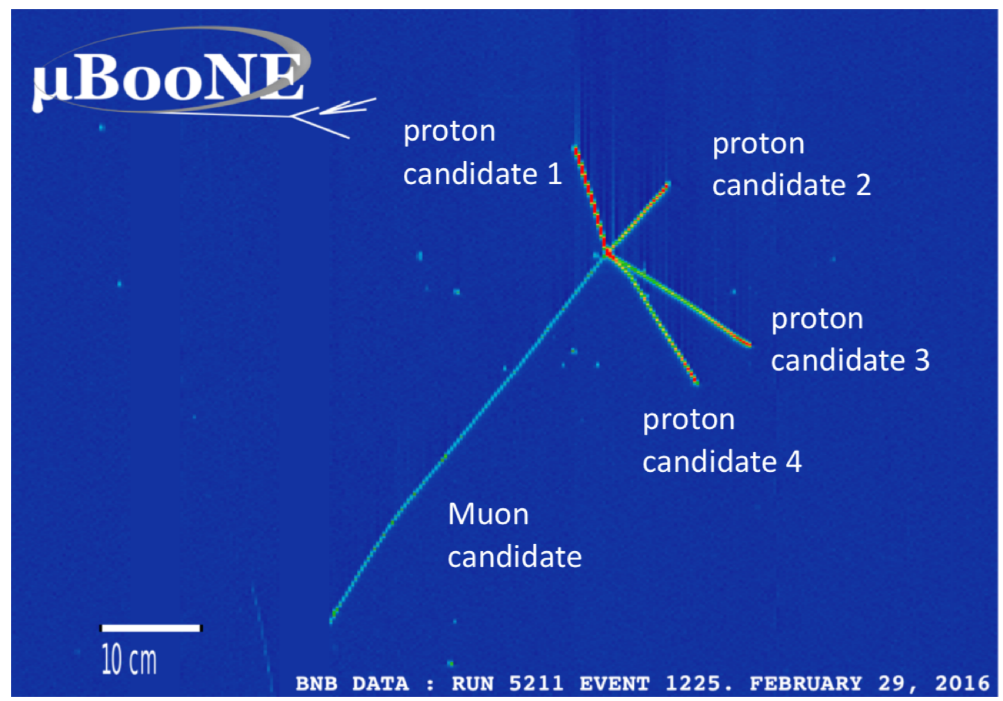
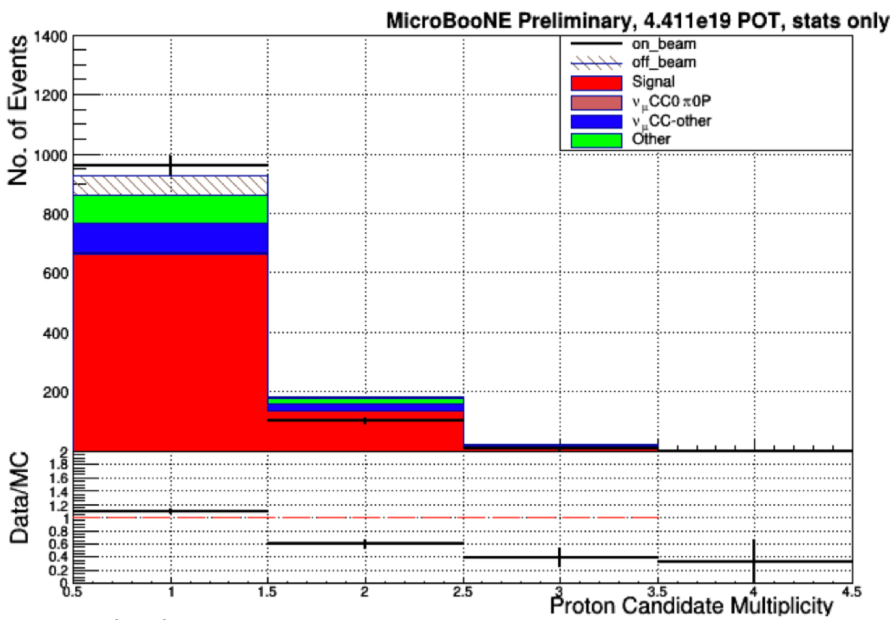
[MicroBooNE public note #1056](#)

Proton Multiplicity

- Successfully identify protons
- multiplicity distribution provides important check of nuclear effects, FSI modeling → of direct relevance to LEE analyses that preferentially select nucleon final states (1p, Np)
- Migration to lower bins due to current high reconstruction threshold

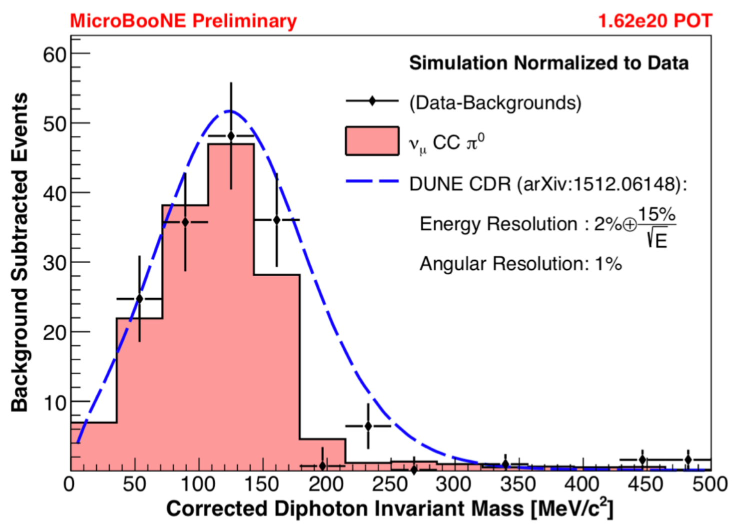


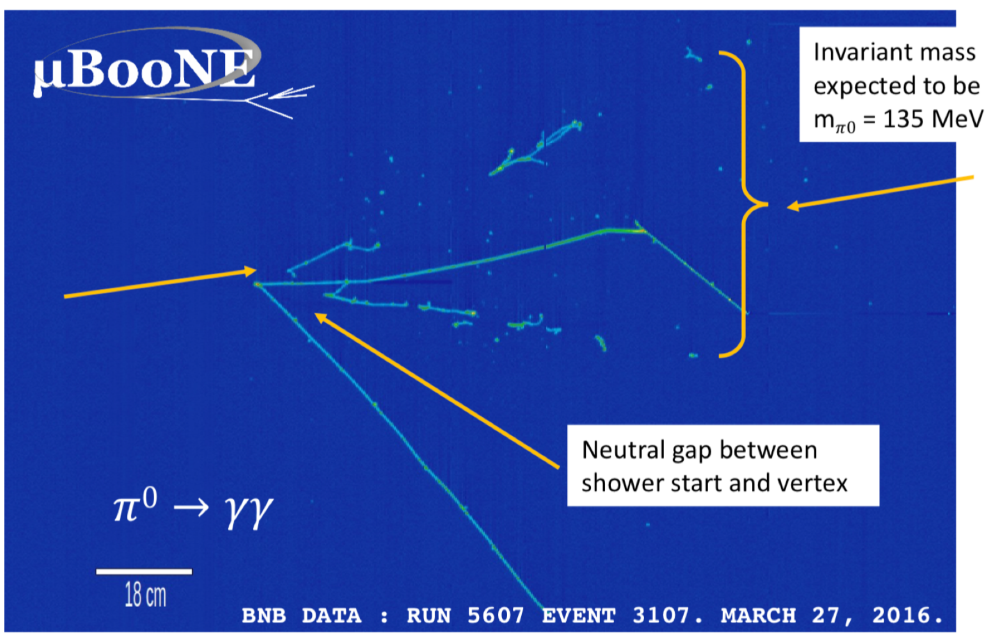




CC π^0 (ν_μ + Ar → μ + π^0)

PRD 99, 091102(R), 2019





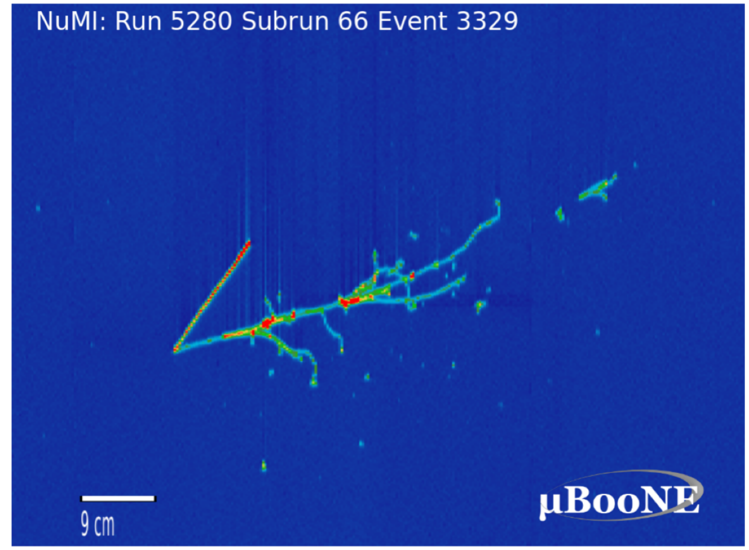
- electron and photon reconstruction is key to neutrino oscillation measurements
- MicroBooNE has developed the first fully automated reconstruction tools for EM reconstruction in LAr TPCs
- observe 20% energy resolution with good data/MC agreement
- first measurement of ν_μ CC π^0 cross section on argon
- validates π^0 production in argon (x2 higher predicted absorption rate than in hydrocarbon)

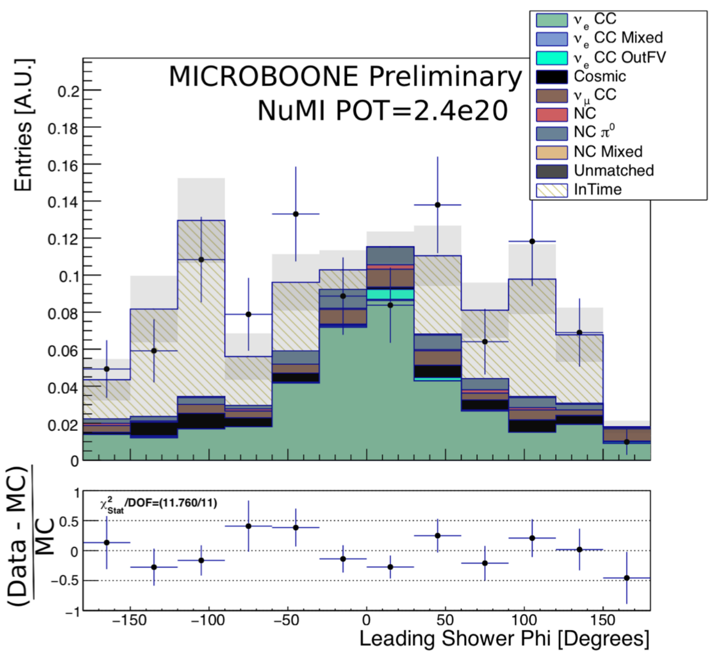
new paper on π^0 reconstruction coming soon

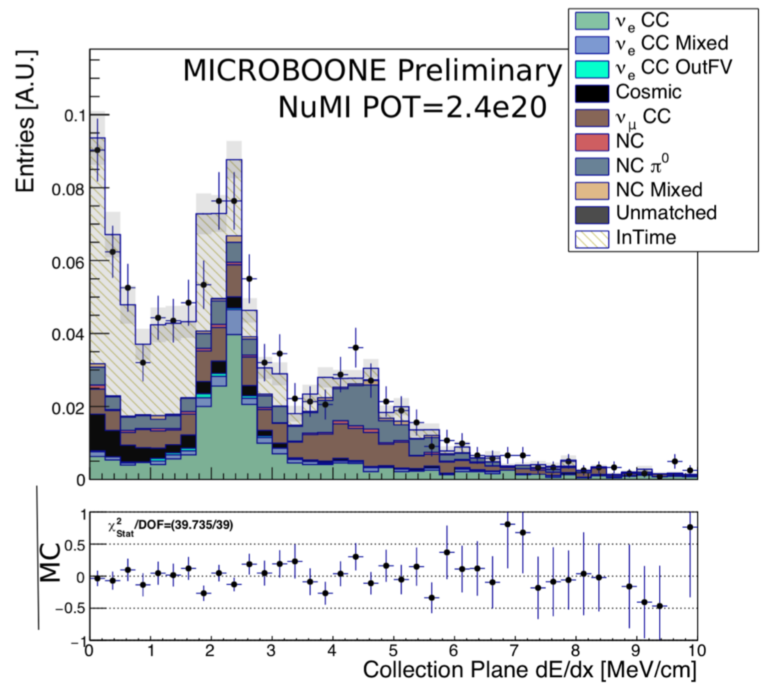
[MicroBooNE public note #1054](#)

ν_e from NuMI Beam

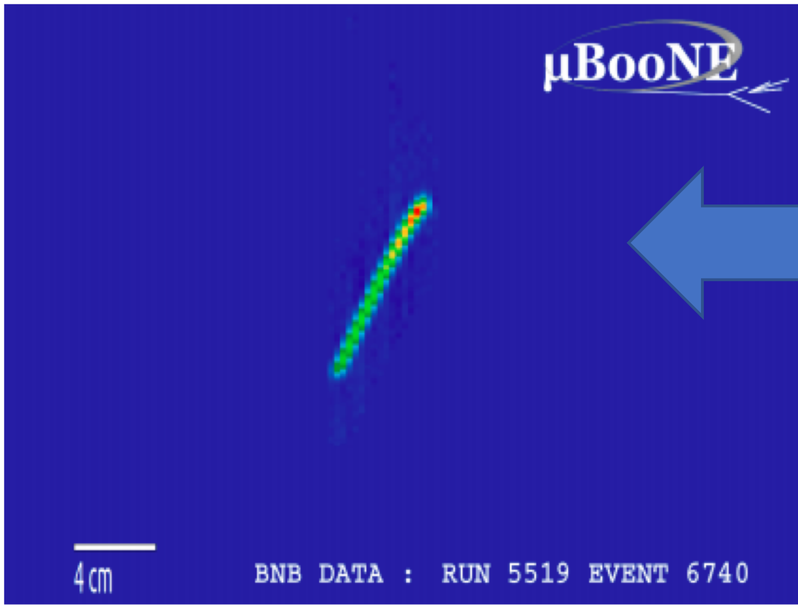
- MicroBooNE sits 8^0 off axis from the NuMI beam
  - NuMI beam is a source of ν_e's in MicroBooNE
  - similar energy as BNB ν_e's
- fully automated ν_e selection and reconstruction
- first e/γ separation in MicroBooNE





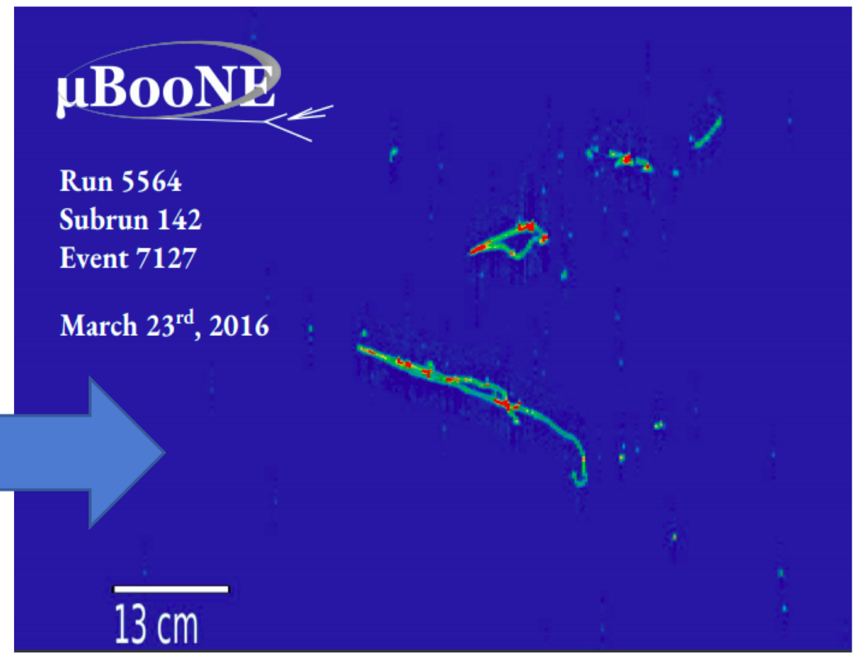


Additional On-Going Neutrino Analyses



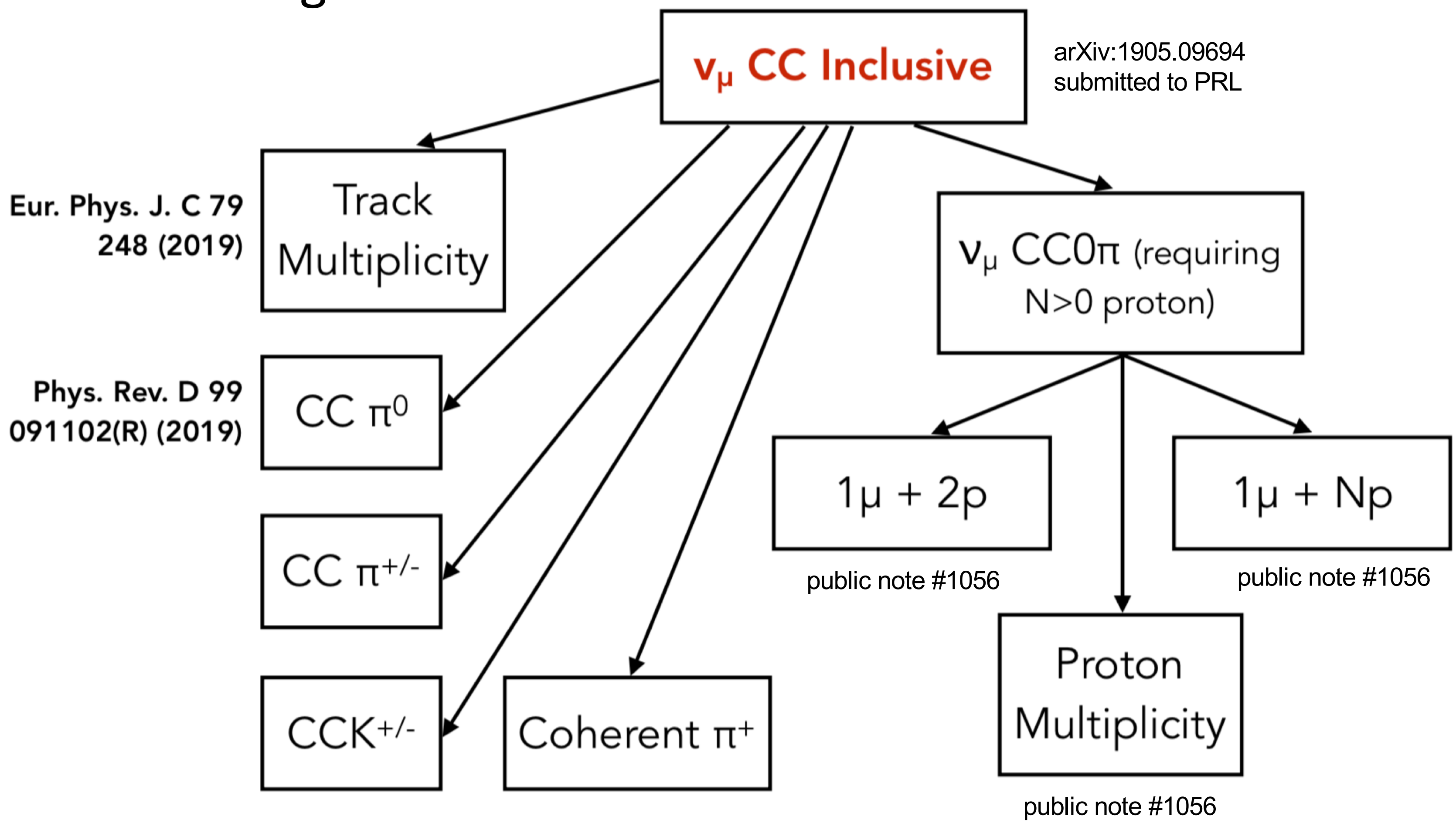
- ν_μ NC elastic scattering
- proton identification and reconstruction
- with low proton detection thresholds, we are at the forefront
- MicroBooNE public note #1053

- ν_μ NC π^0 production
- crucial background constraint for γ LEE
- MicroBooNE public note #1041



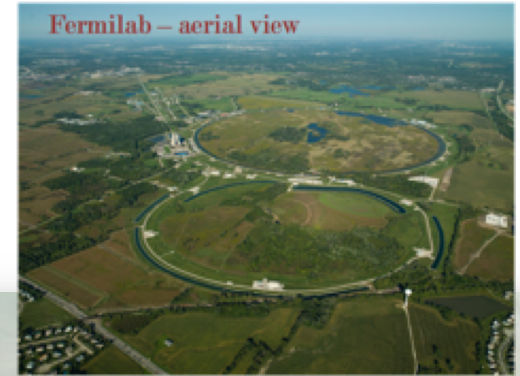
Many New Neutrino Results

- have also studied multiple exclusive modes
- important basis for demonstrating that we understand neutrino interactions on argon for SBN and DUNE

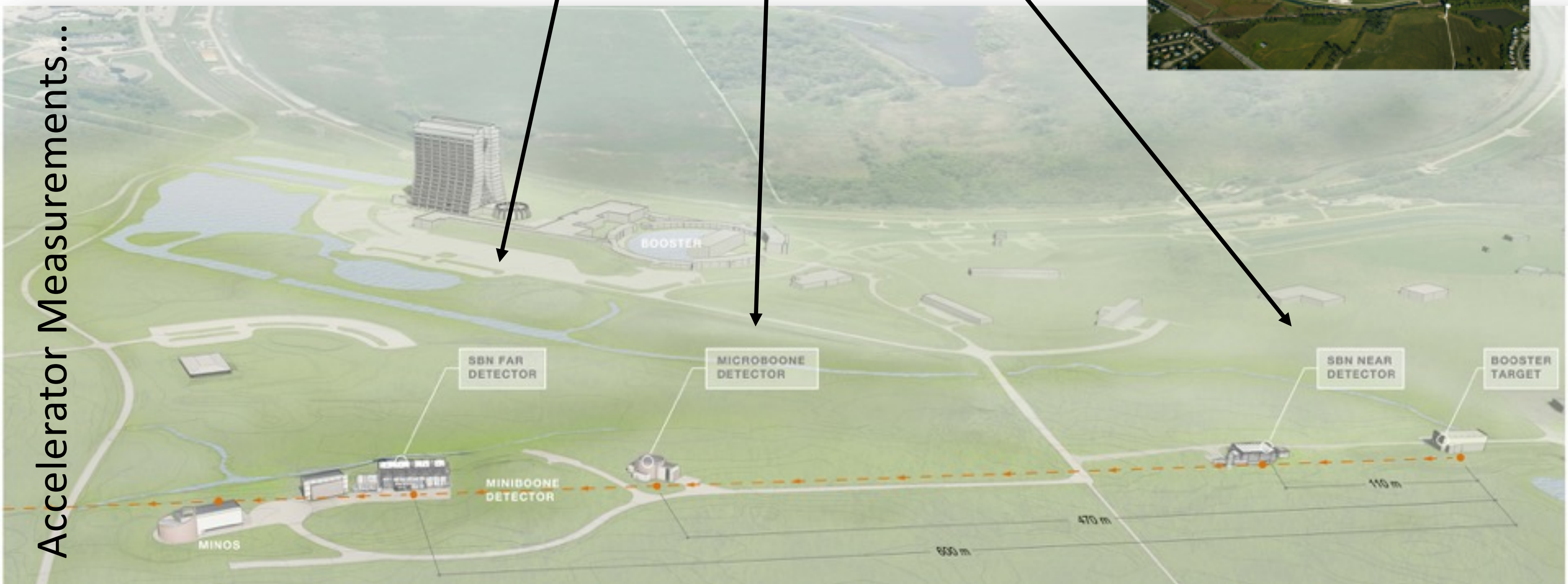


Fermilab: Three detector Short Baseline Neutrino (SBN) program on the Booster Neutrino Beamline

SBND and ICARUS under construction → ICARUS filling now!

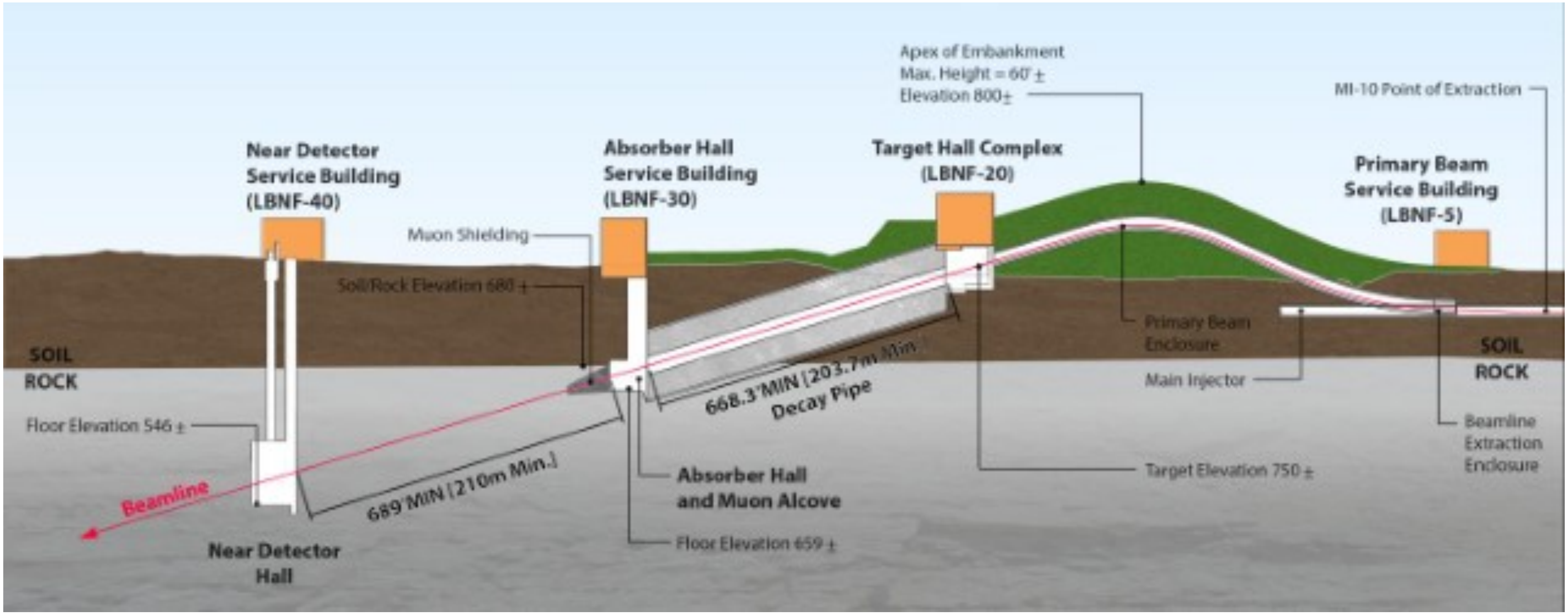


Accelerator Measurements…



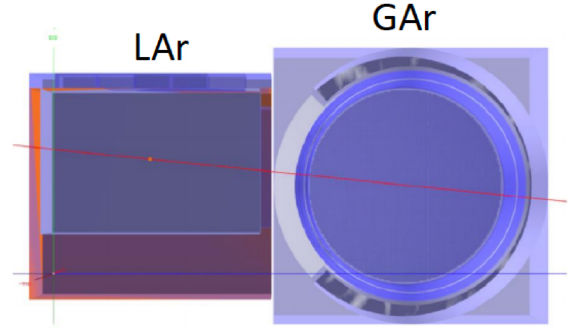
- SBND near detector → huge statistics for neutrino scattering measurements
  - 1M neutrino interactions per year
  - Set to turn on next year – in final construction stage

DUNE near detector neutrino cross section measurements….



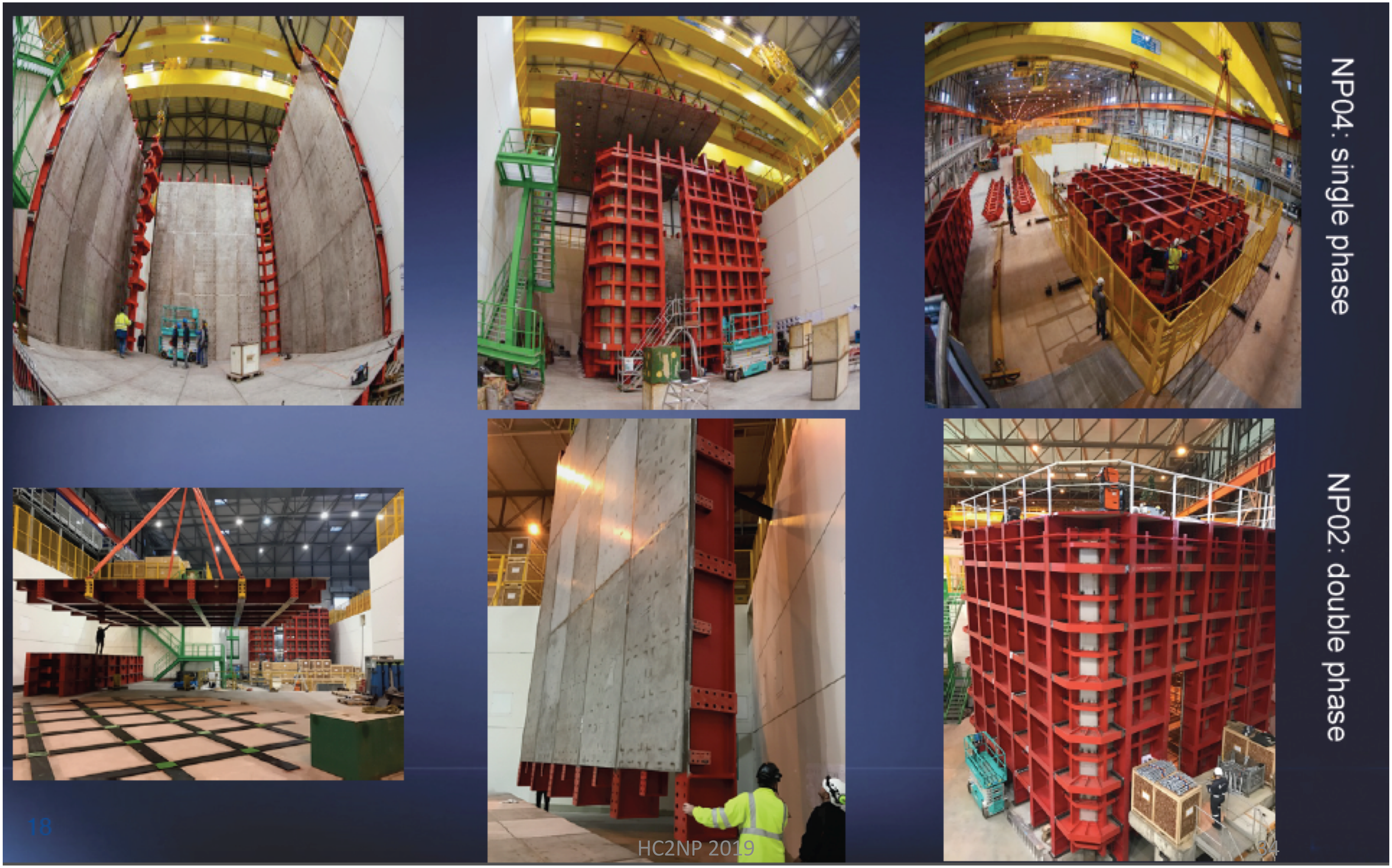
DUNE near detector complex still in design stage:

- 1 x 10^{10} POT at 120 GeV
- 170,000 CC neutrino interactions (60k NC neutrino interactions) per ton
- ~80 ton LArTPC detector
  - → ~10^5 neutrino interactions on argon per year



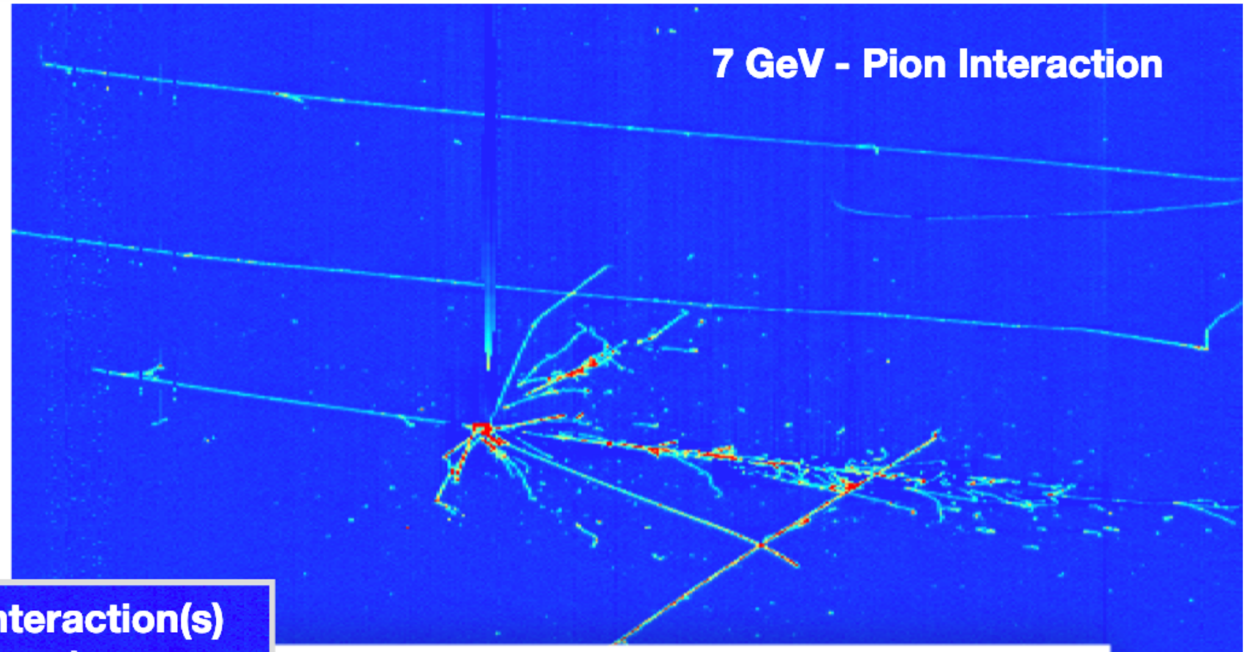
DUNE ND concept

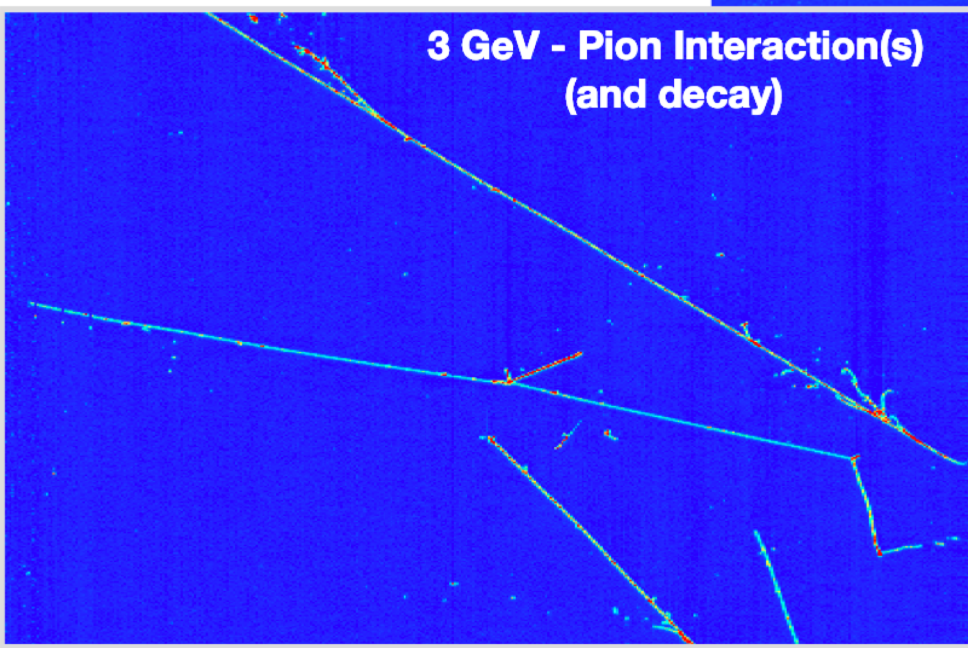
ProtoDUNE single phase commissioned and ran to see test beam before long shutdown!!!

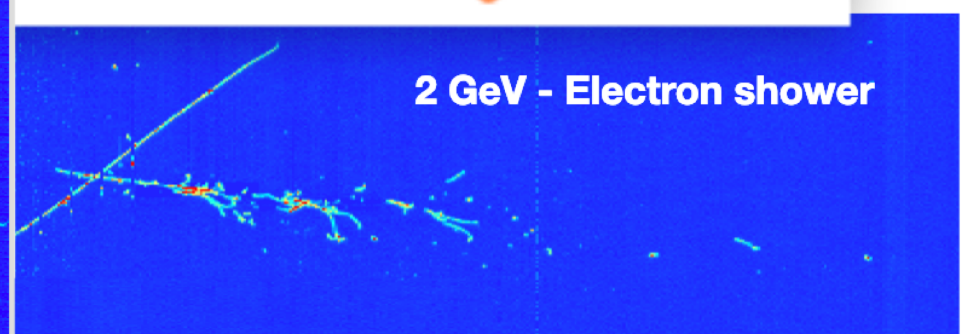


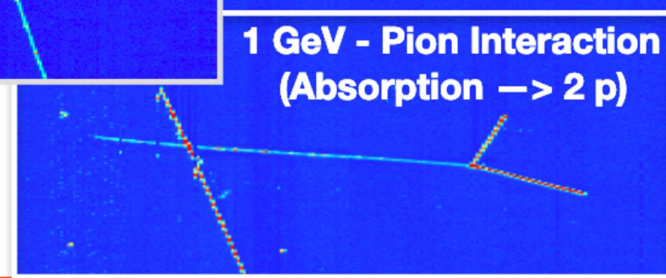
at first glance:

LArTPC data of unprecedented quality



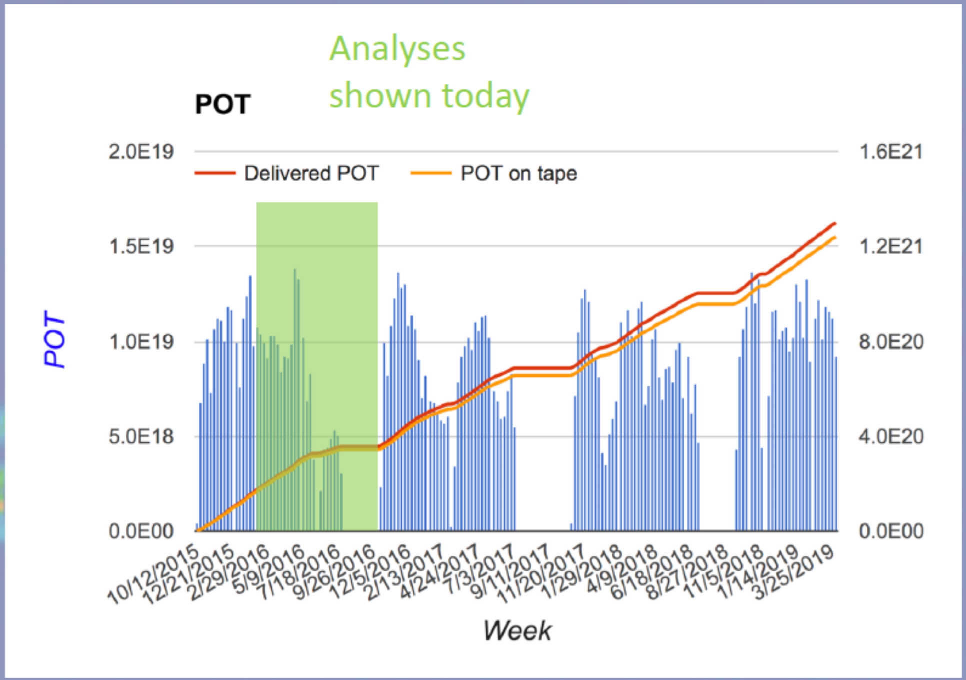






Summary

- First results on “high” statistics precision measurements from MicroBooNE
- More from MicroBooNE on the way



- Higher statistics precision data coming from SBND and DUNE Near detector
- Many nu cross section measurements on the horizon