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MicroBooNE to DUNE:
Pushing the envelope of high-precision neutrino physics

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DUNE

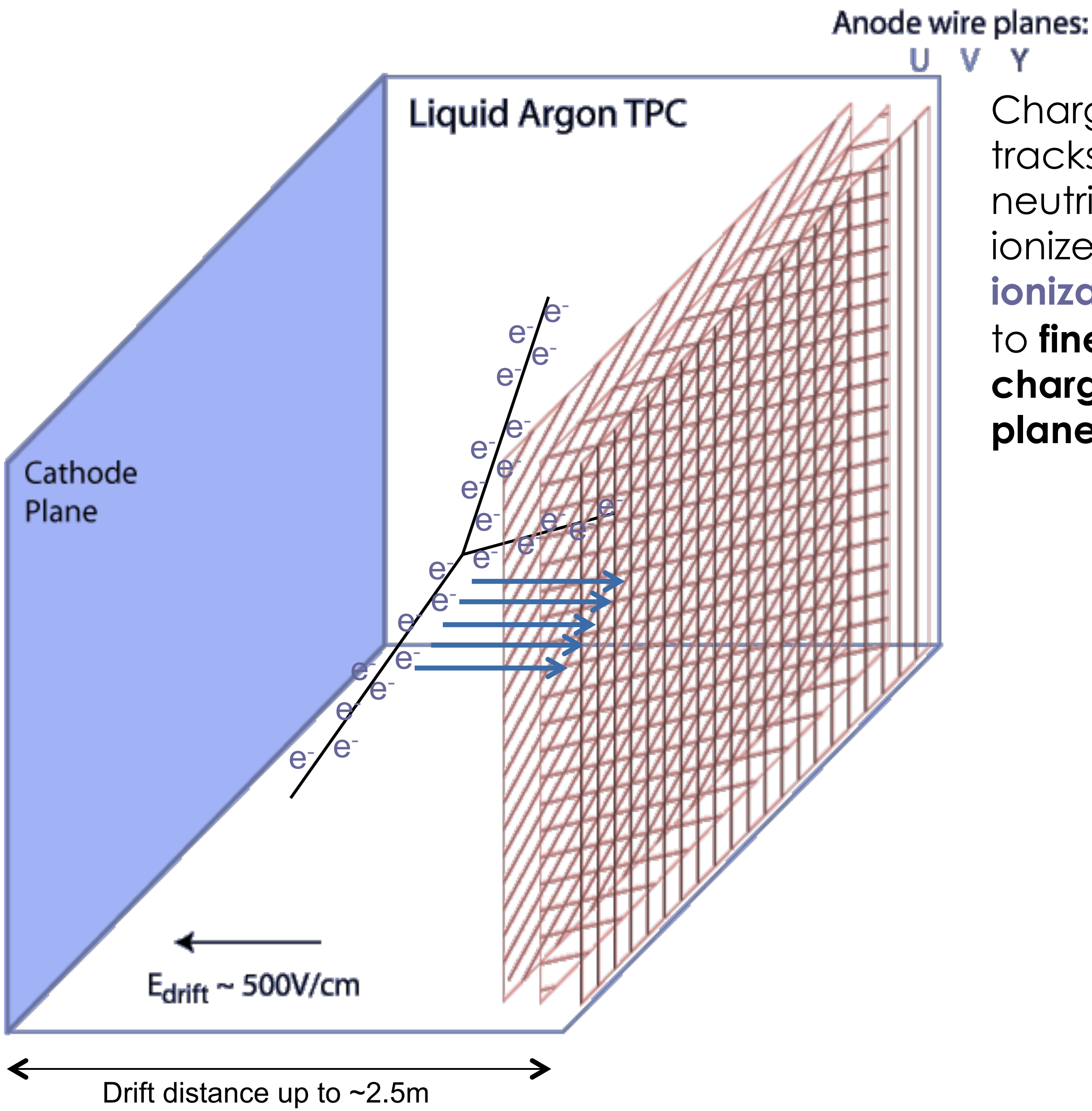
experimental Setup
oscillation physics potential
other physics opportunities
plans and timeline

MicroBooNE

experimental setup
physics goals and opportunities
current status

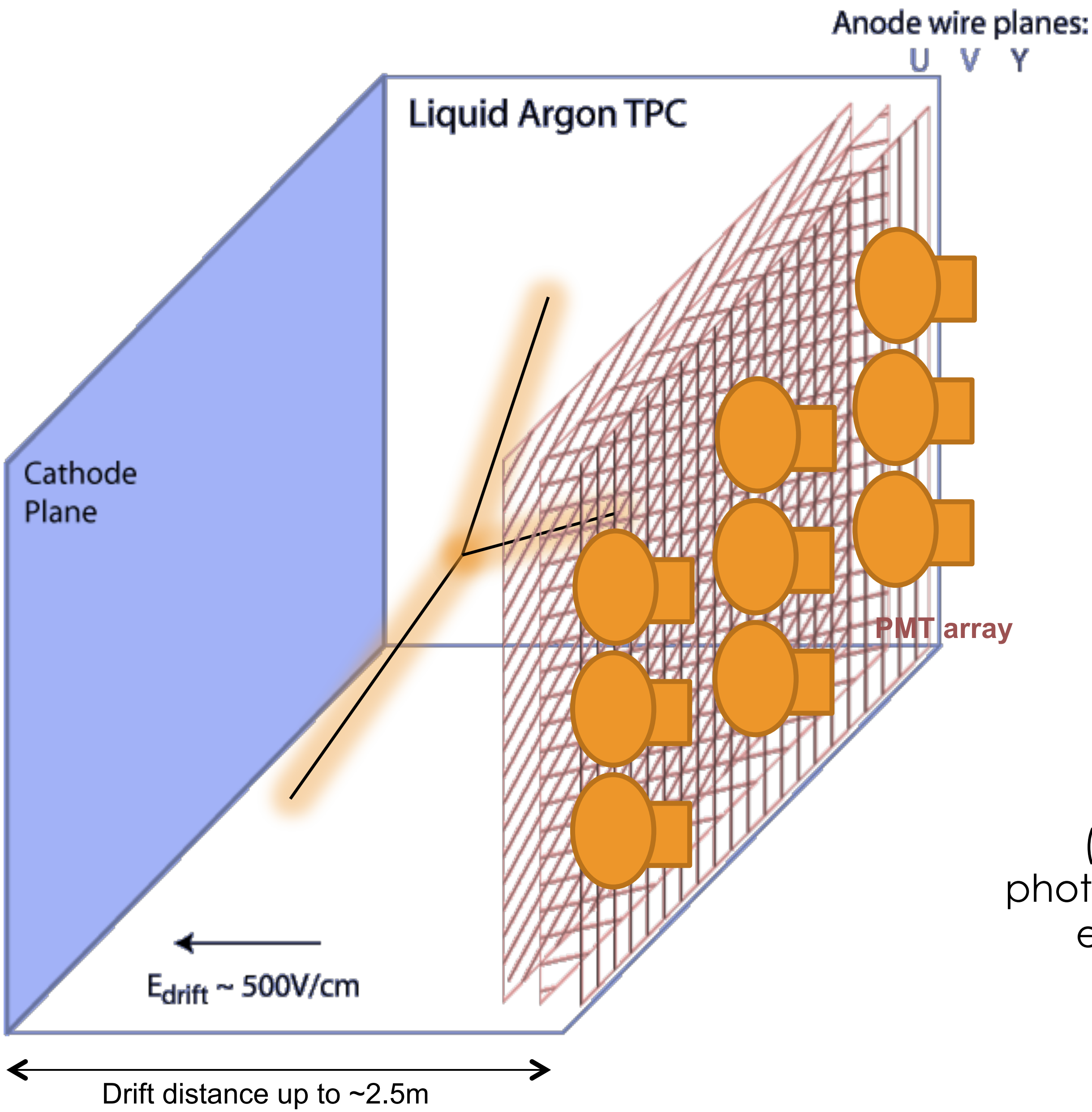
First, (brief) intro to LArTPC's…

LArTPC working principle



Charged particle tracks produced in neutrino interactions ionize argon atoms; **ionization charge** drifts to **finely segmented charge collection planes** over ~1-few ms.

LArTPC working principle

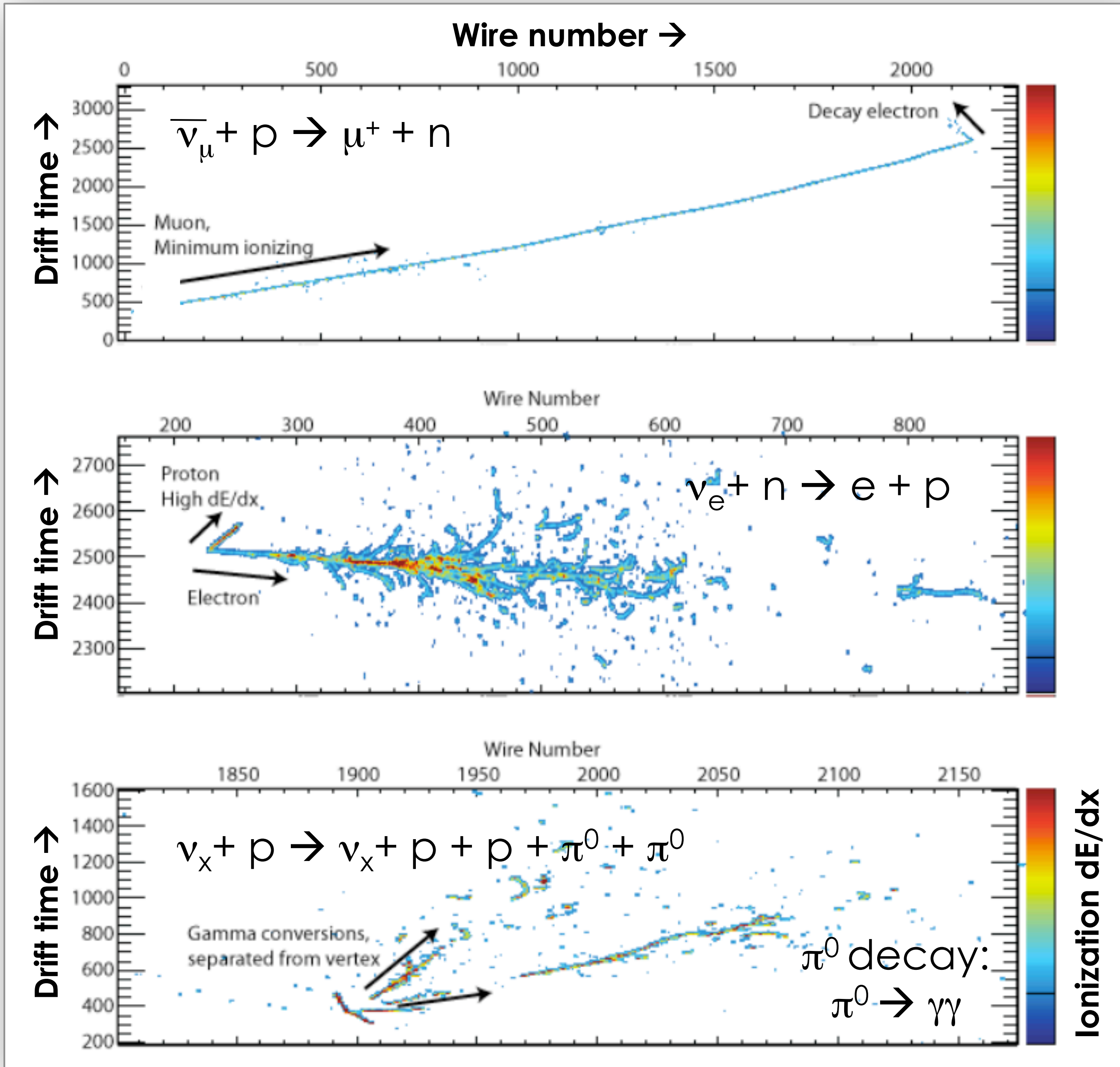


Prompt **scintillation light** (~few ns) is detected by photo-sensitive detectors for event t_0, drift coordinate determination, and triggering

LArTPC exquisite event topology

Bubble chamber-quality data, with calorimetric information (ionization dE/dx)

High event selection efficiency and excellent background rejection!

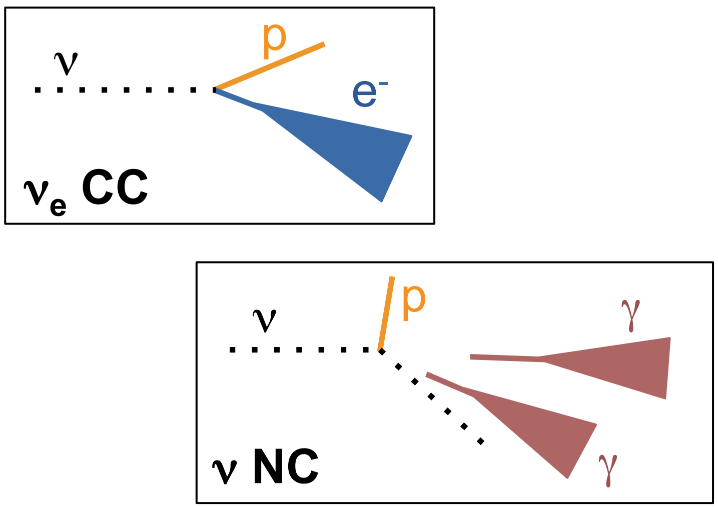


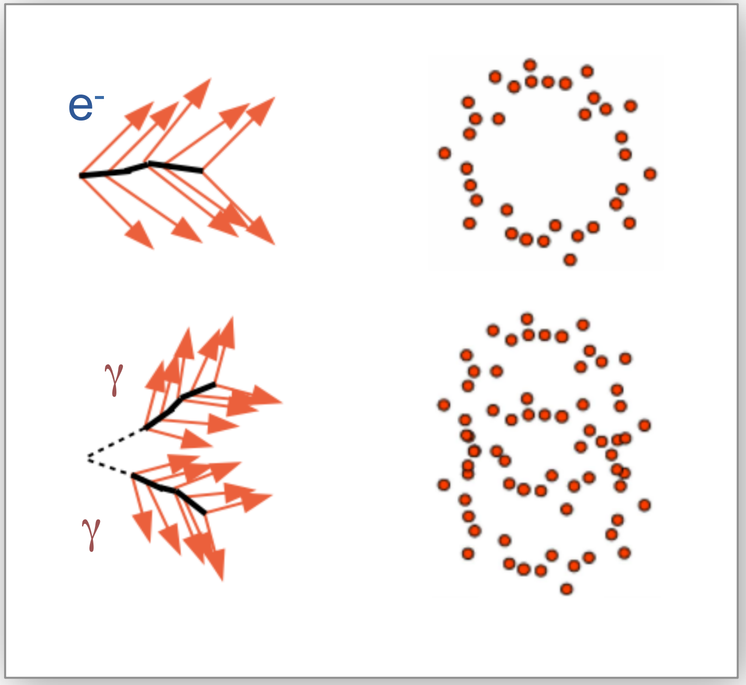
Example simulated neutrino events (E_ν ~ 0.5-1 GeV)

LArTPC e/γ separation capability

A **single e** and a **single** γ are indistinguishable in a Cherenkov detector; ν_e CC measurements are plagued by NC π^0 or photon backgrounds…

but not in a LArTPC!



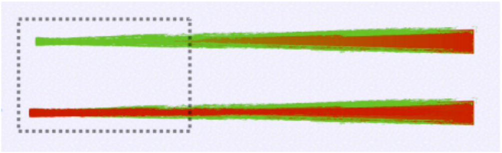


Typical e/γ separation: ~90% → Ideal technology for ν_e measurements

LArTPC e/γ separation capability

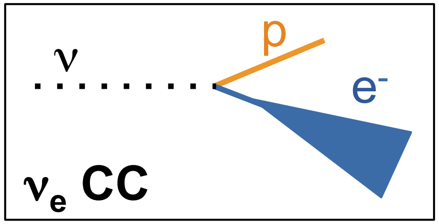
Electron

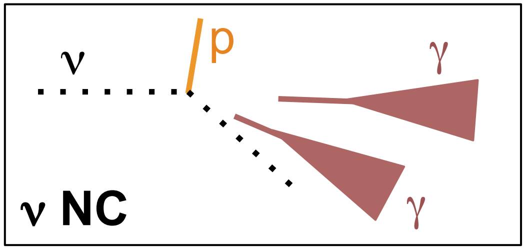
$$\gamma \rightarrow e^{+} + e^{-}$$



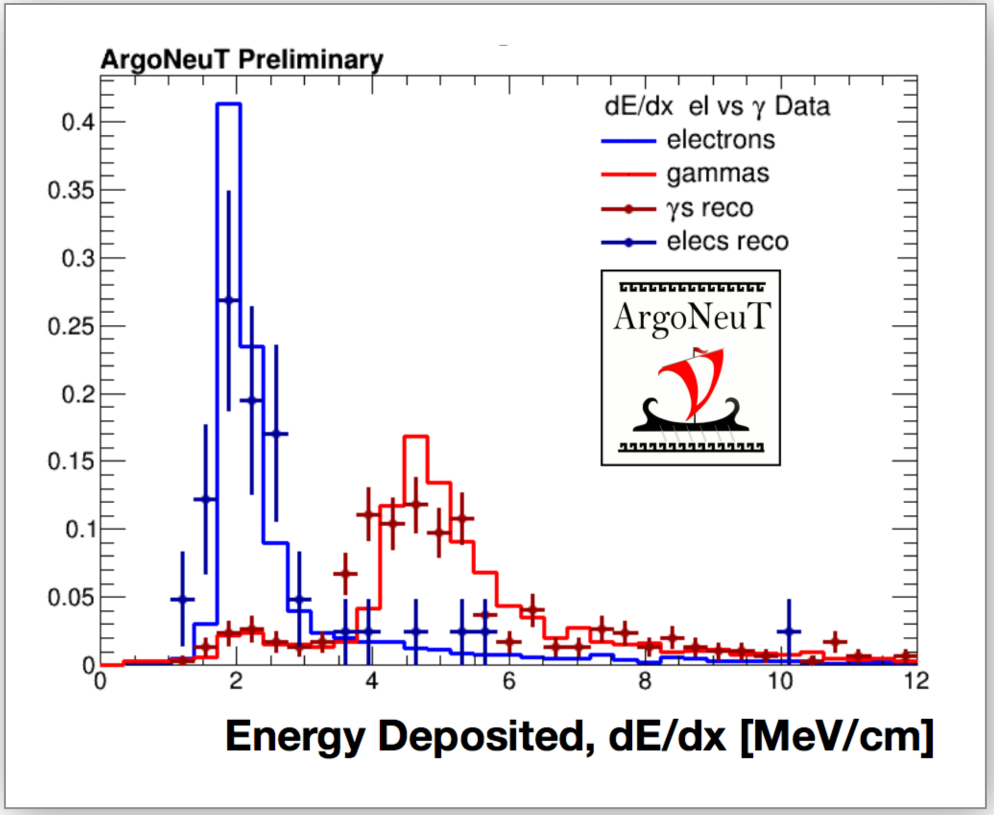
γ's rejected on the basis of:

1. detached shower vertex





2. larger dE/dx deposited at the beginning of shower (2 MIP vs. 1 MIP)



Typical e/γ separation: ~90% → Ideal technology for ν_e measurements

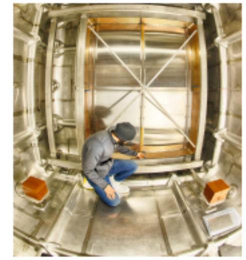
LArTPC development in the US: now +/-10 years

R&D

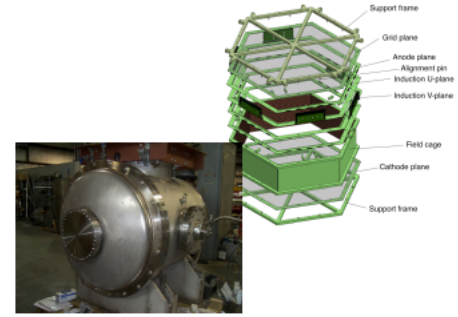
Yale TPC and Bo
(2008 and 2009)
Proof of Concept

LUKE
(2008)
Material Teststand

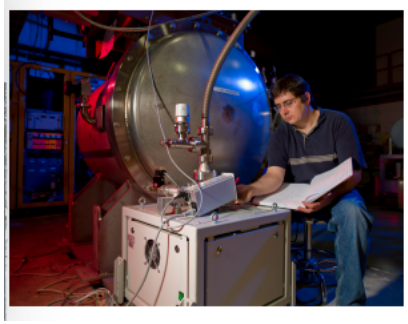
LAPD
(2011)
LAr Purity



35Ton
(2013)
Cryostat Purity

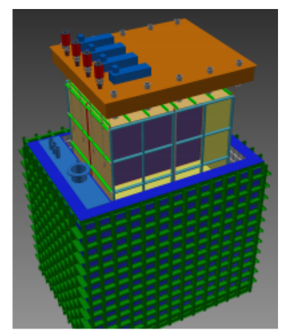


LArIAT and CAPTAIN
(2015)
LArTPC Calibration

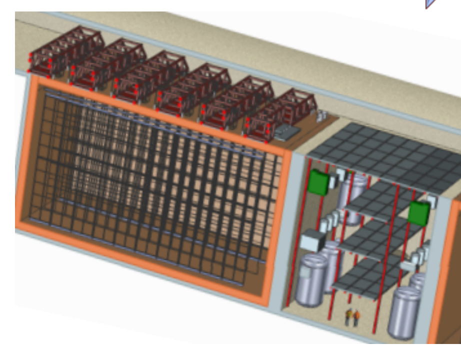


ArgoNeuT
(2009 - 2010)
ν-Ar Cross Sections

MicroBooNE
(2015 - 2018)
MiniBooNE
Low Energy Excess



SBND
(2018 - 2021)
Searches for
Sterile Neutrino Oscillations



DUNE
(2025+)
CP Violation

Physics

Seeking definitive answers to "Big Questions" in neutrino physics

Fundamental questions

	Directly addressed by LArTPC oscillation experiments	MicroBooNE 2015+	DUNE 2025+
What is the value of δ_{CP}?	✓		✓
Is the neutrino mass spectrum normal, or inverted?	✓		✓
What are the absolute neutrino masses?			
Are neutrinos dirac or majorana fields?			
Are there additional, "sterile" neutrino states?	✓	✓	✓
Do we understand exclusive and inclusive neutrino cross sections on nuclear targets?	✓	✓	✓

Pressing experimental questions

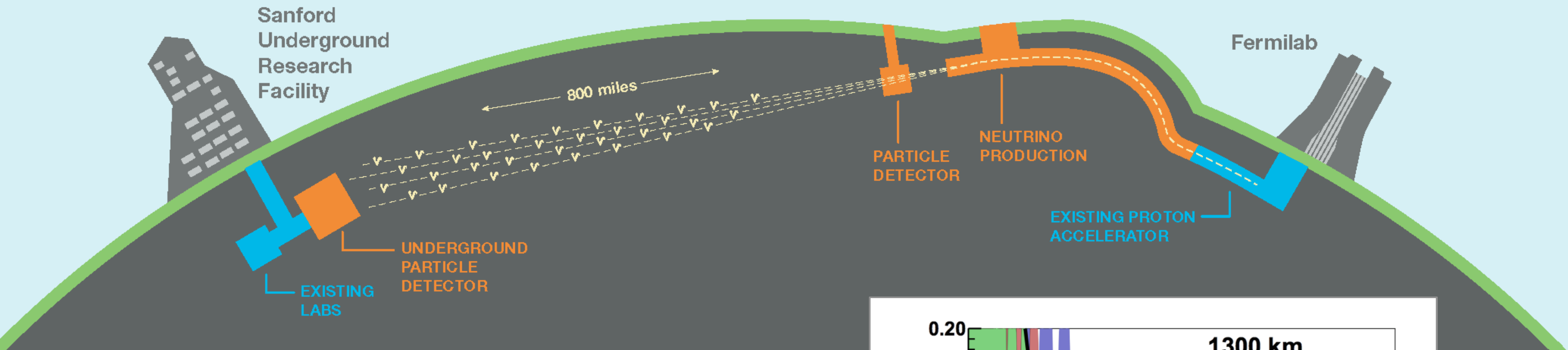
DEEP UNDERGROUND NEUTRINO EXPERIMENT

New **international science collaboration** formed in late 2014 with the submission of an LOI

- February 2015 Collaboration Meeting at FNAL
- 775 collaborators (members from LBNE, LBNO, …)
- 144 institutions
- 26 countries

DUNE experimental setup

DUNE is designed to provide a broad science program of ν oscillation physics, ν interaction physics, underground science, and physics beyond the standard model



Oscillation Physics:

– A baseline of 1300 km

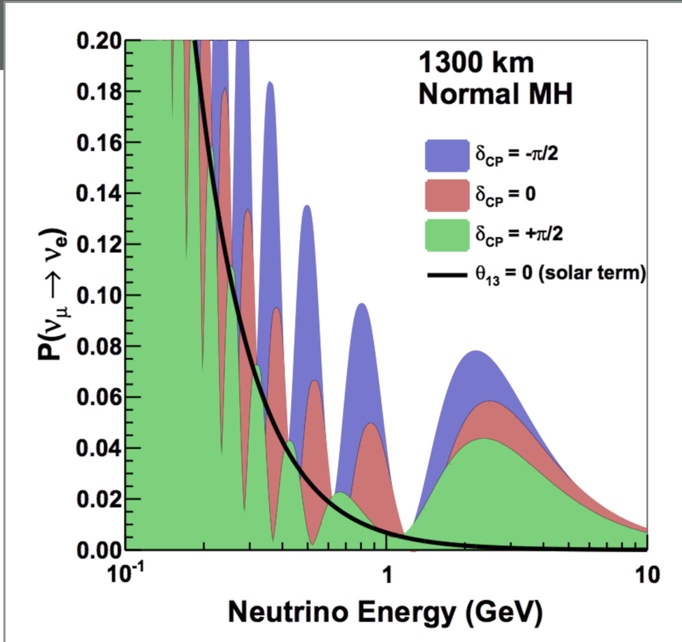
– A megawatt class beam covering the 1st and 2nd oscillation maxima

– A highly capable ND to constrain the FD event rate prediction

– A large (40 kt), high-resolution FD deployed deep underground

– Exposure of 6-10 yr with ~50%/50% $\nu/\bar{\nu}$ running

– Sensitivity to δ_{cp} and the MH in the same experiment

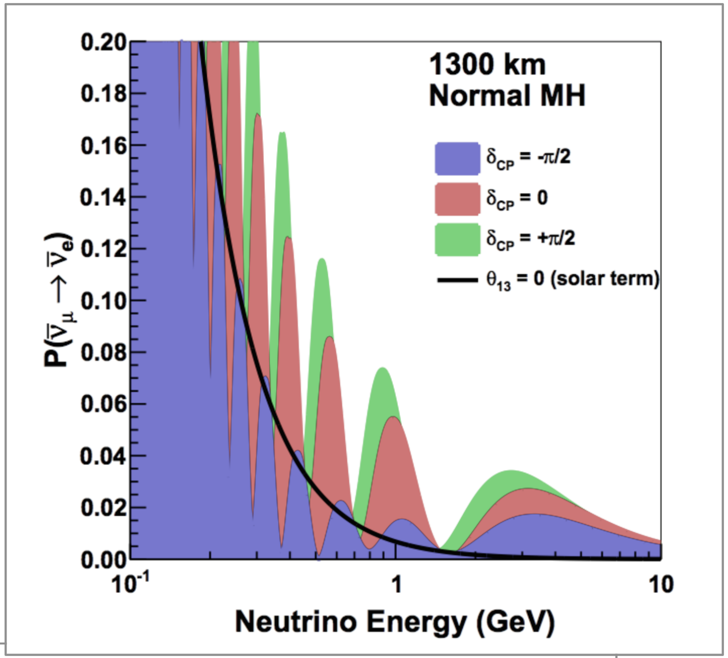


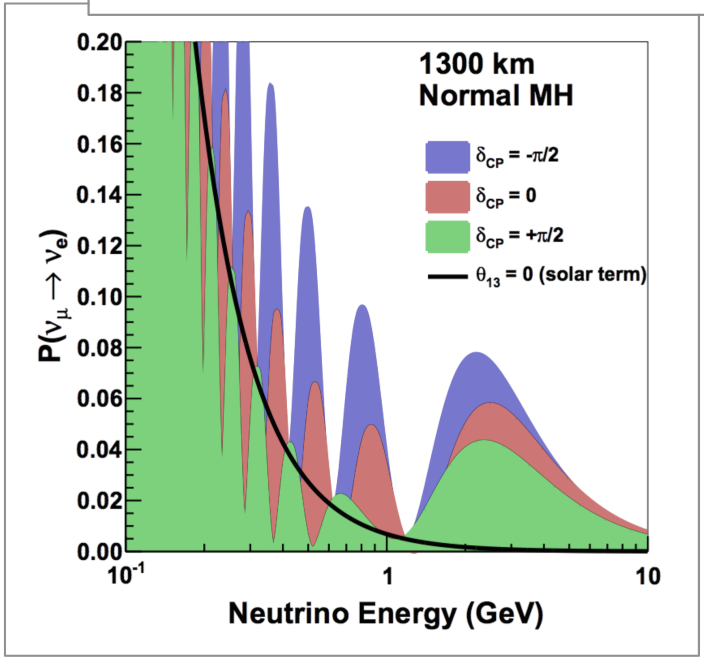
DUNE primary science goals: I. MH and dCP

Focus of DUNE's scientific program:

- determination of the neutrino mass hierarchy (MH): normal or inverted
- explicit demonstration of leptonic CP violation, if it exists ($\delta_{CP} \neq 0$)

Possible by precisely measuring differences between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities





DUNE vs. LBNF scope

Detectors and science collaboration will be managed separately from the neutrino facility and infrastructure

Long-Baseline Neutrino Facility (LBNF)
– Neutrino beamline
– Near detector complex (but not the ND)
– Far site (Sanford Lab) conventional facilities; detector hall, cryogenic systems
– Operating costs for all of the above

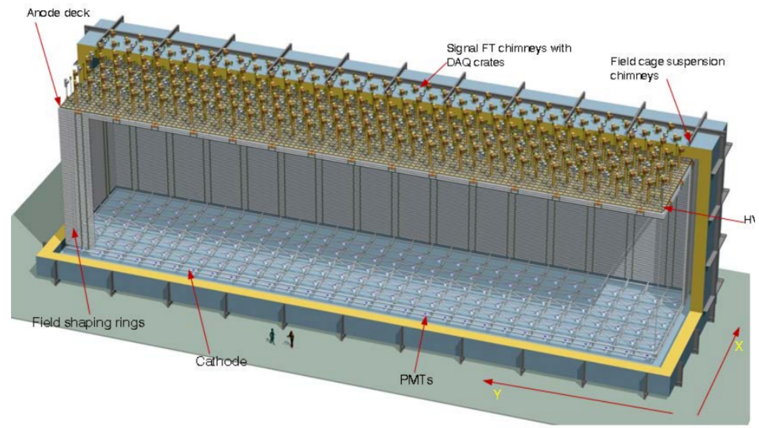
Deep-Underground Neutrino Experiment (DUNE)
– Definition of scientific goals and design requirements for all facilities
– The Near and Far Detectors
– The scientific research program

DUNE far detector

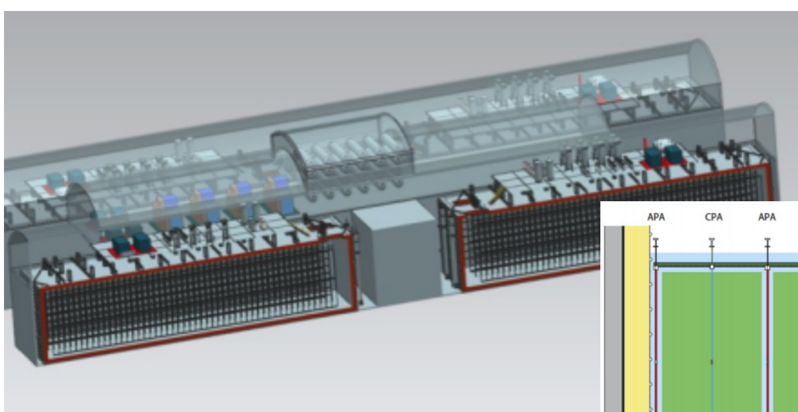
- Heart of a deep underground neutrino and nucleon decay observatory
- **Liquid Argon (LAr) Time Projection Chamber (TPC) with a 40 kt fiducial mass**
- Staged construction with the goal of the first 10 kt by 2021/22

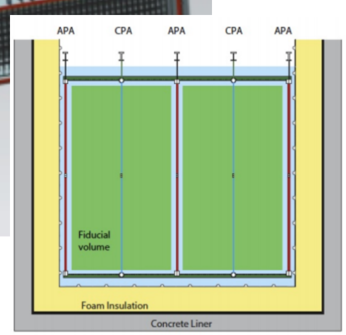
Two potential designs:

Single phase (current reference design)
– Based on ICARUS T600 design
– Horizontal drift ~3.6 m
– Wire pitch of 5 mm
– Detection and electronics in liquid
– Modular approach
– Well known cost and schedule



Dual phase (alternate design)
– New technique; signal amplification
– Vertical drift ~10 - 20 m
– Detection and electronics in gas
– Adaptable to cryostat shape
– Low thresholds, high S/N ratio
– Pitch of 3 mm or less

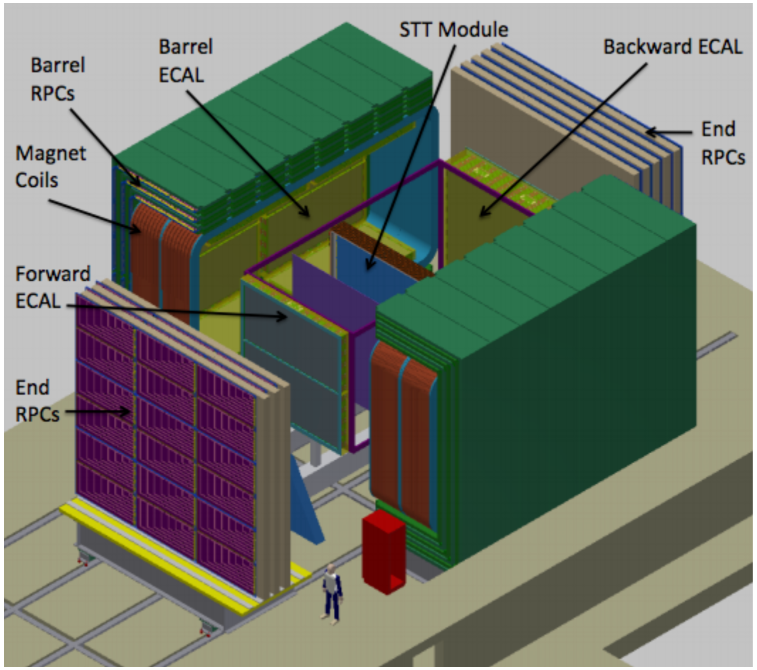




DUNE near detector

Detector requirements
– Constrain flux rate and shape to the few % level
– Charge ($\nu/\bar{\nu}$) separation
– Constrain relevant cross sections
– Provide a wealth of physics measurements

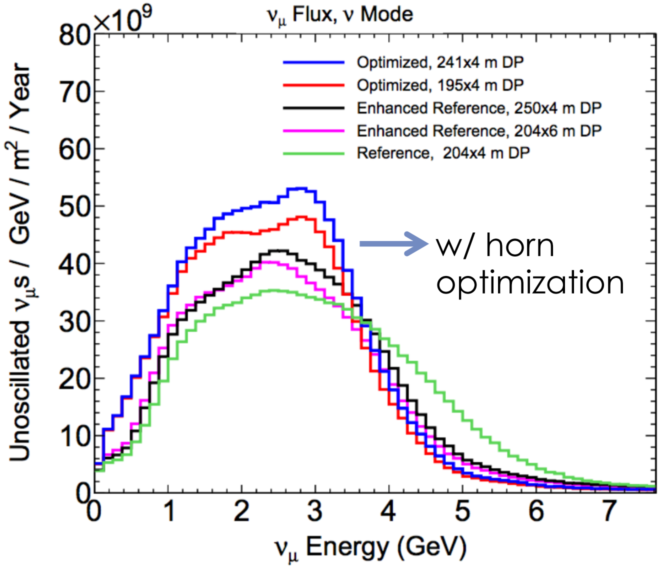
Detector Options
– Fine Grained Tracker (reference)
– LArTPC
– High pressure GArTPC
– Hybrid detector (ArTPC + FGT)



Neutrino beam

Beam requirements

- 1.2 MW, upgradeable to 2.3 MW (120 GeV protons):
  - POT/pulse: 7.5×10^{13} p
  - Cycle time: 1.2 sec
  - Uptime: 56%
- Direction 5.8° downward
- Wide-band spectrum covering the 1st and 2nd oscillation maxima

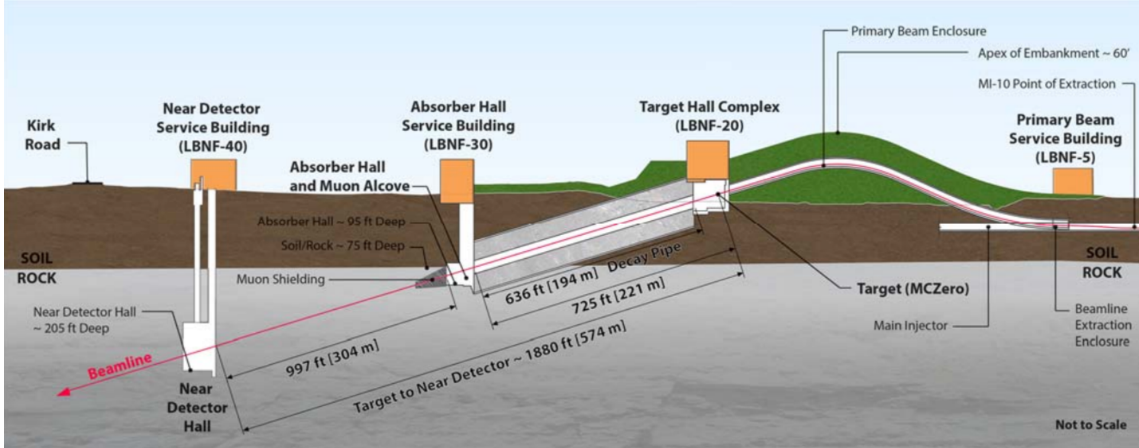


Can use 60 - 80 GeV protons

- Increase flux at 2nd max
- Reduces high energy tail
- Need more POT to maintain power

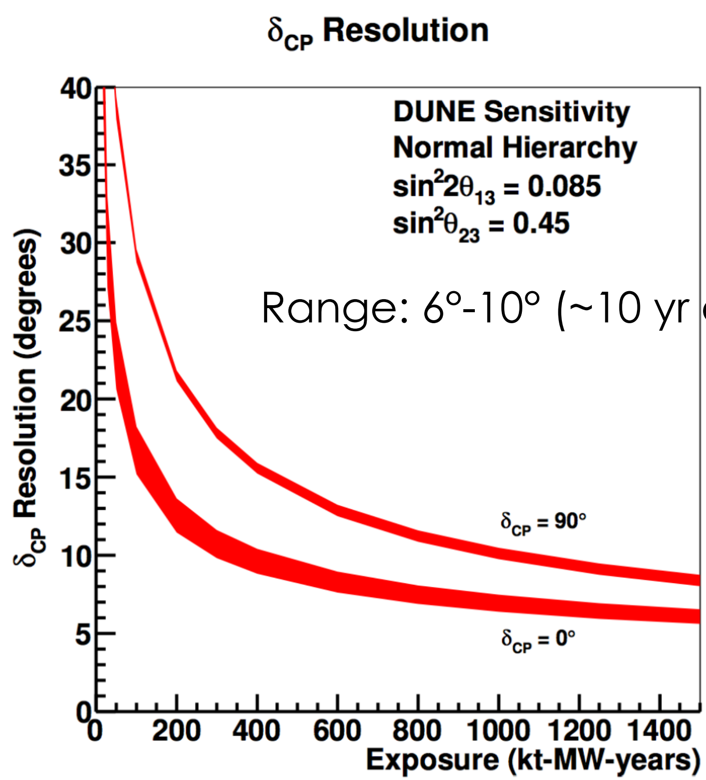
Upgrades from reference design

- PIP-II: increase p throughput
- Horn current: 200 kA → 230 kA
- Target design: C → Be, shape
- Decay Pipe: 204 m → 250 m
- Horn design optimization

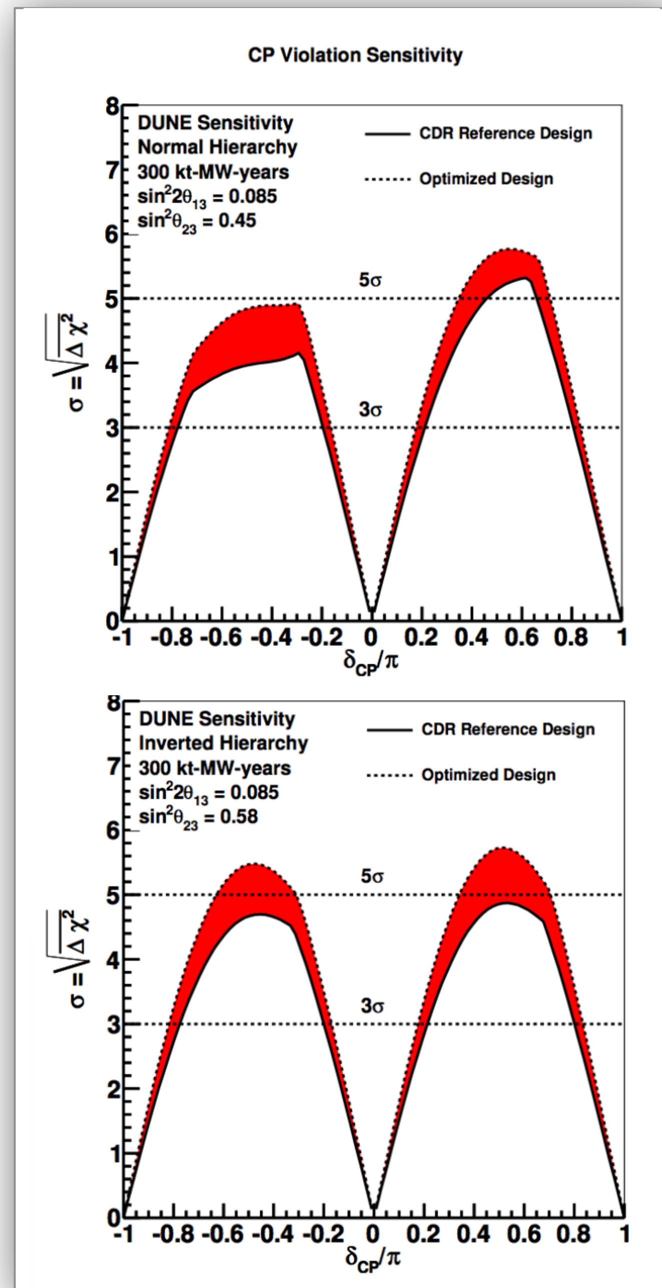


DUNE primary science goals: I. MH and dCP

CPV determination significance vs δ_{CP}
300 kt ·MW ·year exposure
→ 7 years of data (3.5 years ν mode plus 3.5 years in $\bar{\nu}$ mode) with a 40-kt FD and a 1.07-MW 80-GeV beam.



Range: 6°-10° (~10 yr exposure)

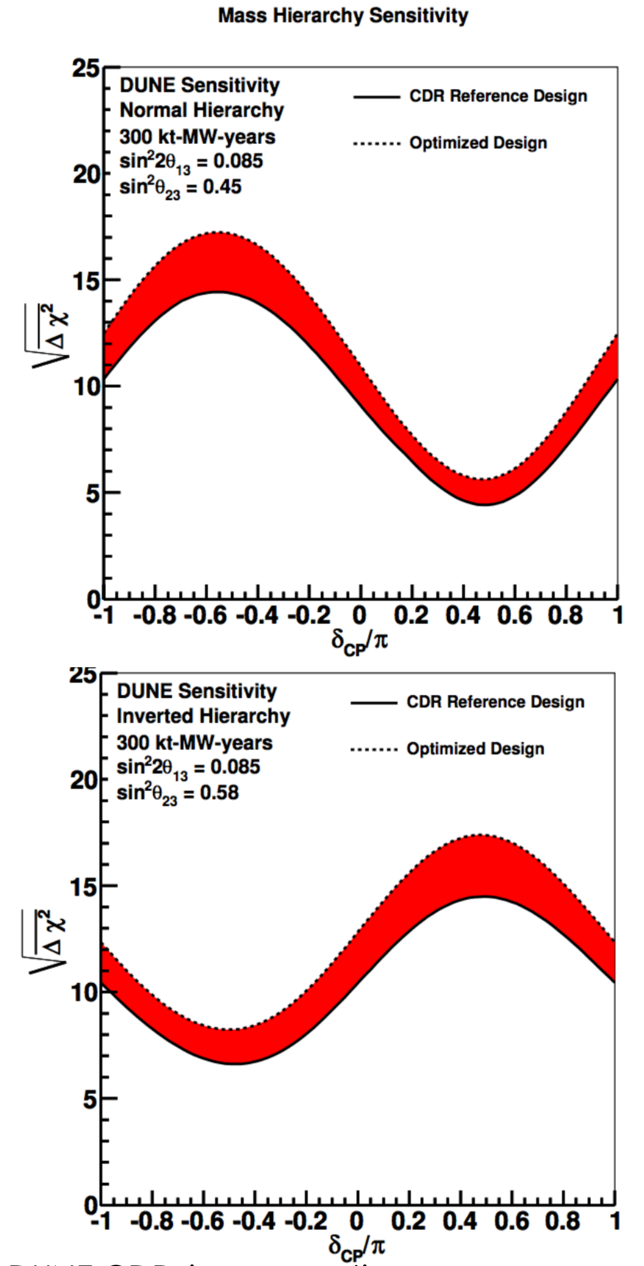


DUNE CDR, in preparation

DUNE primary science goals: I. MH and dCP

MH determination significance vs δ_{CP}
300 kt ·MW ·year exposure
→ 7 years of data (3.5 years ν mode plus 3.5 years in $\bar{\nu}$ mode) with a 40-kt FD and a 1.07-MW 80-GeV beam.

MH is determined at >5σ for 100% of the δ_{CP} values (optimized beam design)
nearly 100% of δ_{CP} values (CDR reference beam design)



DUNE CDR, in preparation

DUNE primary science goals: I. MH and dCP

DUNE will exclude the wrong MH at the 99% C.L. for all values of δ_{CP}

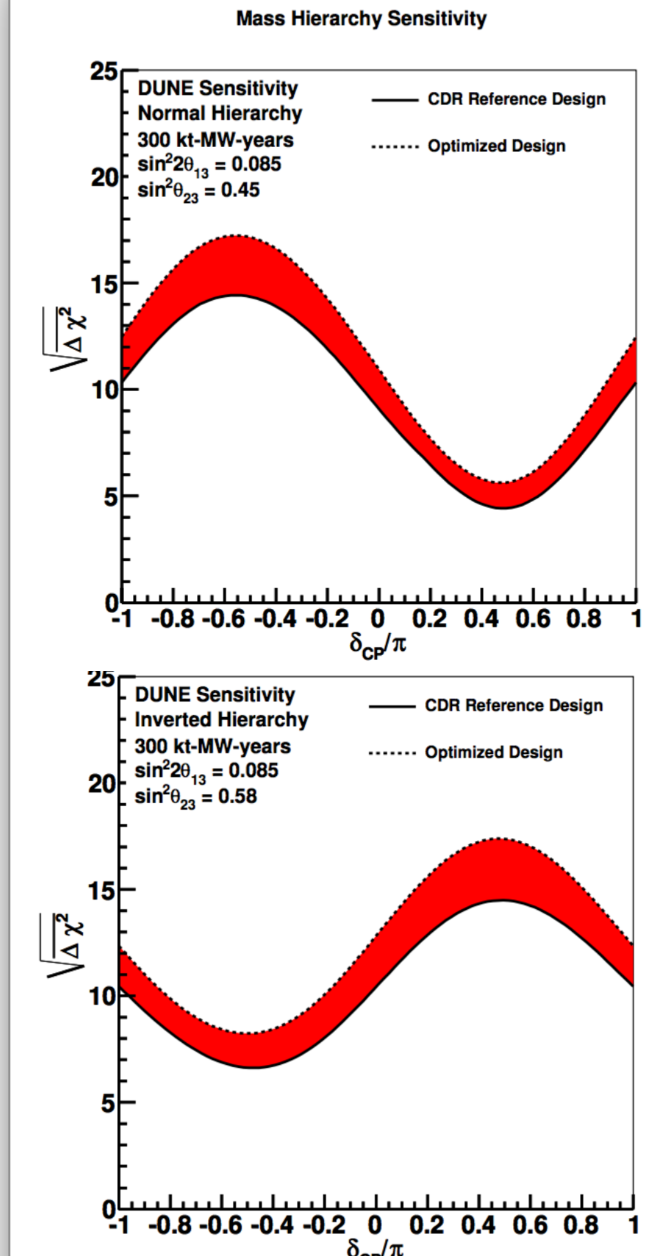
- The 99% C.L. result will come sooner for more favorable δ_{CP} values

DUNE will also constrain $\sin^2(\theta_{13})$, $\sin^2(\theta_{23})$, and ΔM^2_{31}

And has the potential to determine the θ_{23} octant, and measure ν_τ appearance

DUNE long-baseline physics goals also include:

- Over-constrain the PMNS matrix
- Search for exotic physics like NSI, LRI, CPT/Lorentz violation, compact extra dimensions, and sterile neutrinos

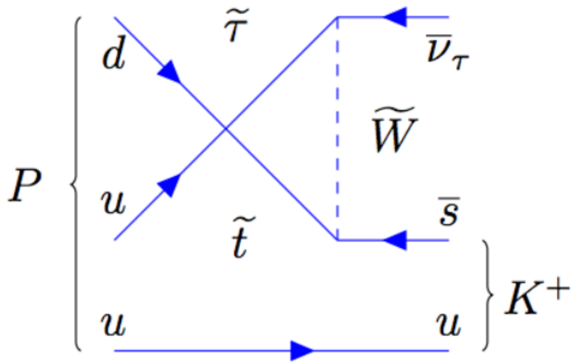


DUNE CDR, in preparation

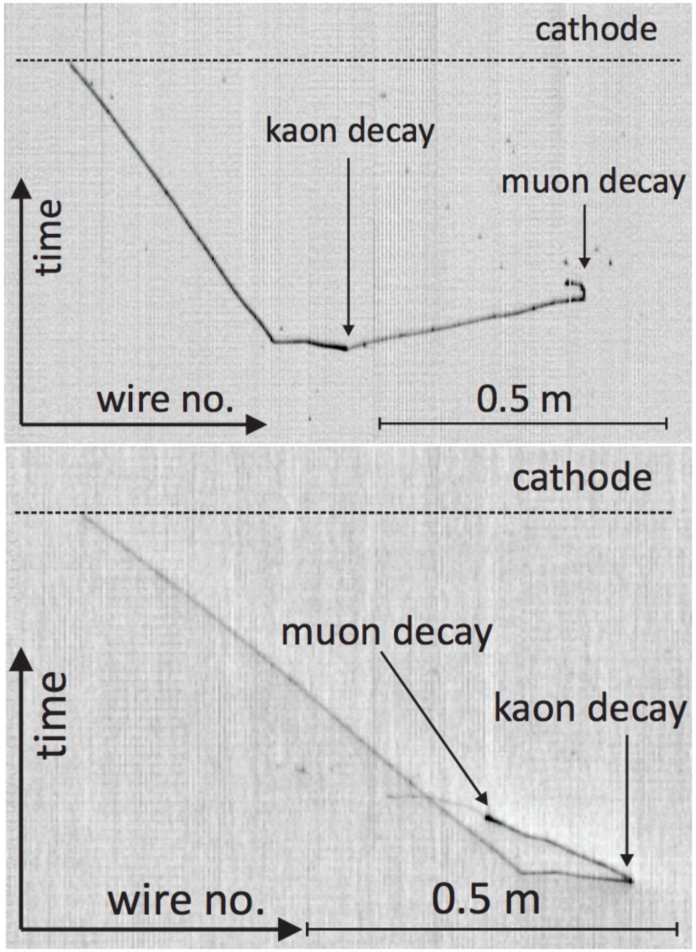
DUNE primary science goals: II. Baryon number violation

Placing the far detector deep underground will provide exciting additional research opportunities in **nucleon decay searches**

E.g. $p \rightarrow K^+\overline{\nu}$



p decay mode from supersymmetric GUT models



ICARUS T600 CNGS Run

DUNE primary science goals: II. Baryon number violation

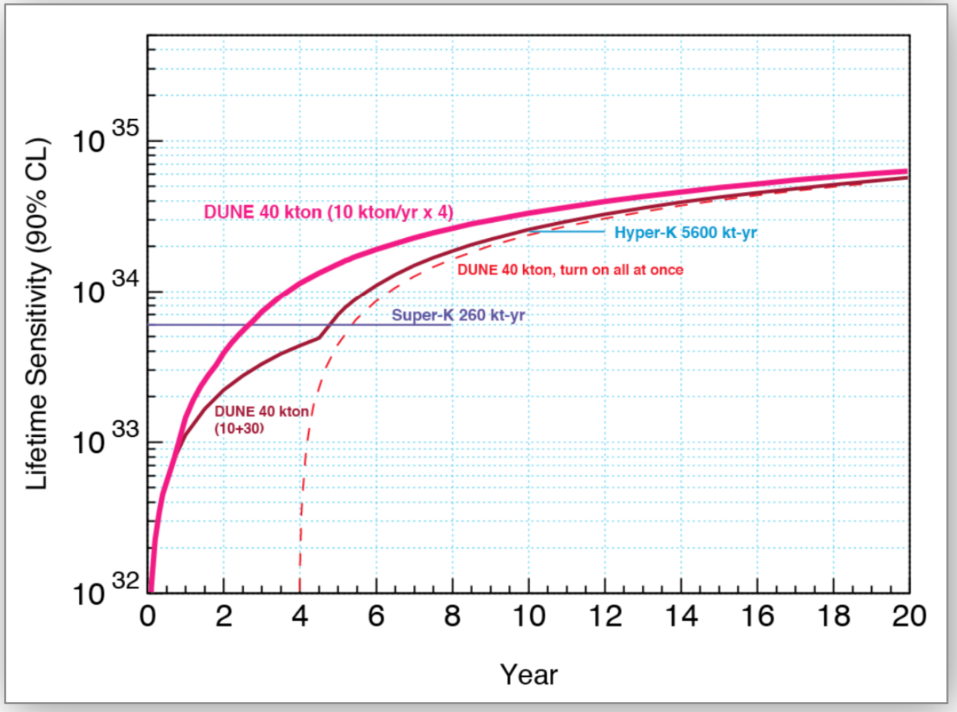
- Superior detection efficiency for K production modes
  - K^+ PID through dE/dx
  - High spatial resolution and low energy thresholds
    → rejection of atmospheric backgrounds
  - High Efficiency (>90%), high purity selections for $p \to \nu K^+$ and $p \to \mu^+ K^0$

Requires suitable triggering systems!

Efficiencies and background rates per Mt-yr:

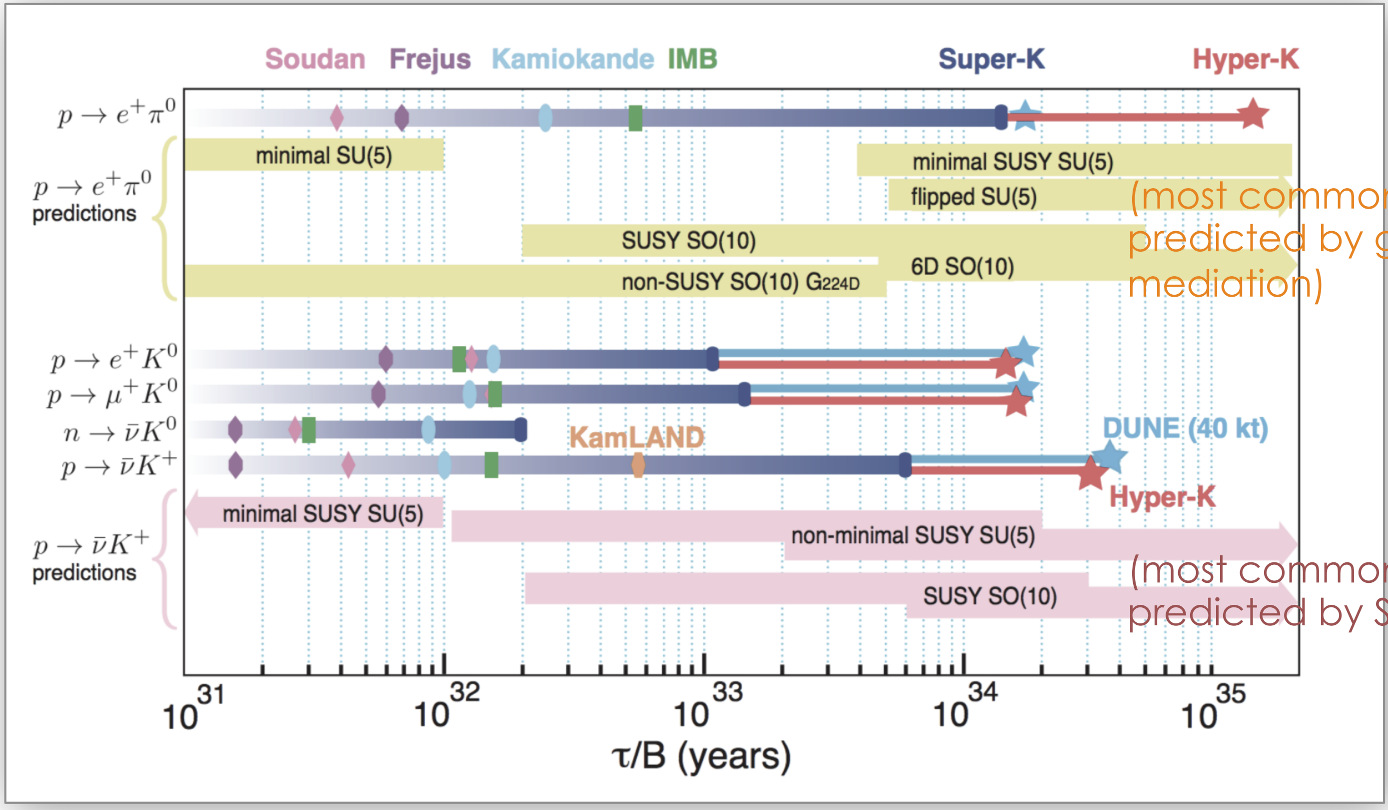
Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \to K^+ \overline{\nu}$	19%	4	97%	1
$p \to K^0 \mu^+$	10%	8	47%	< 2
$p \to K^+ \mu^- \pi^+$			97%	1
$n \to K^+ e^-$	10%	3	96%	< 2
$n \to e^+ \pi^-$	19%	2	44%	0.8

DUNE CDR, in preparation



DUNE primary science goals:
II. Baryon number violation

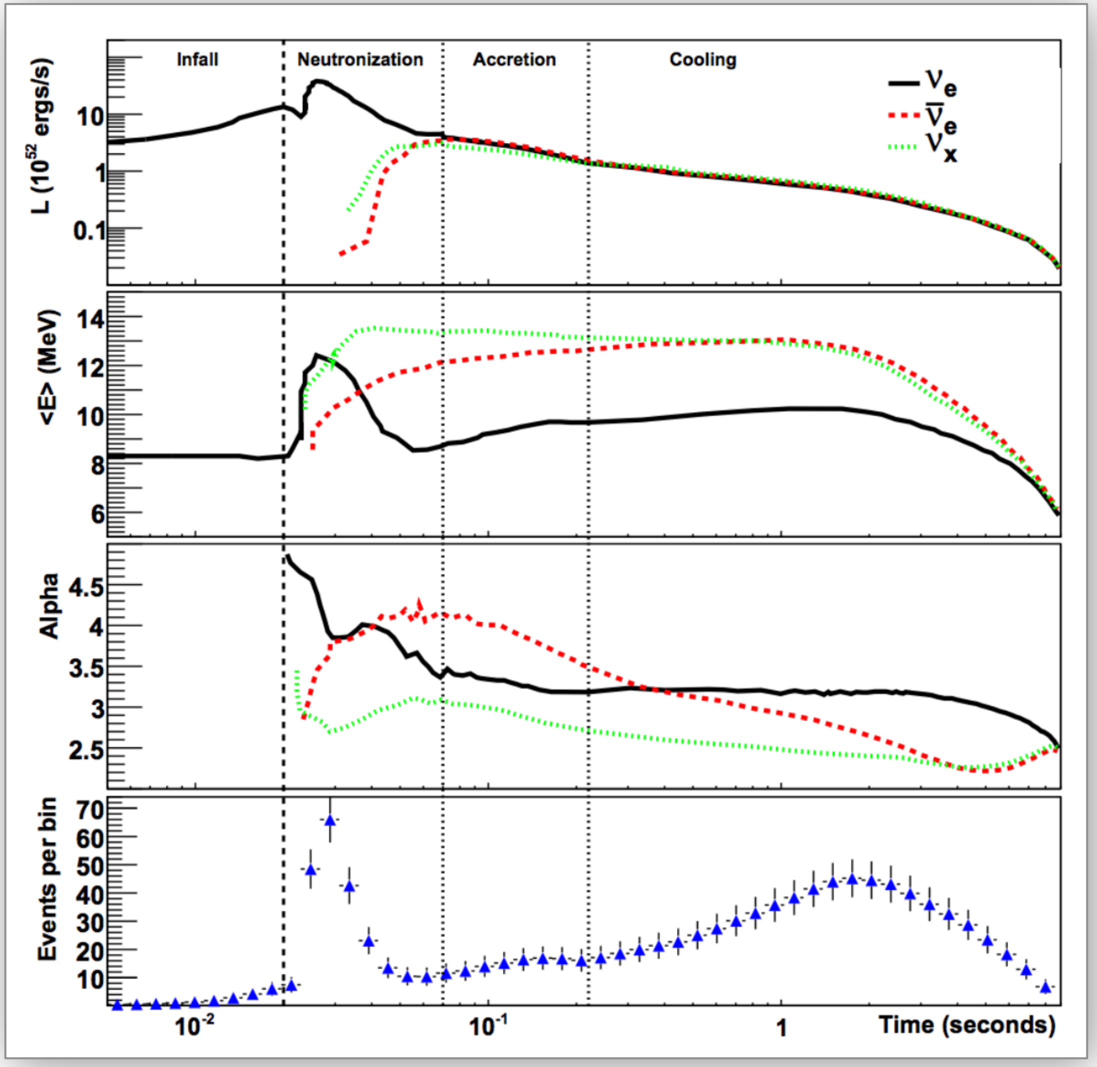
DUNE will search for proton decay in the range of proton lifetimes predicted by a wide range of GUT models.



Published limits: ◆■
Predicted limits: ★ (Poisson statistics and observation=background prediction)

DUNE primary science goals:
III. Supernova neutrinos

Measurements of the **time, flavor, and energy structure of the neutrino burst** will be critical for understanding the dynamics of supernova core collapse, as well as providing information on neutrino properties and other particle physics.

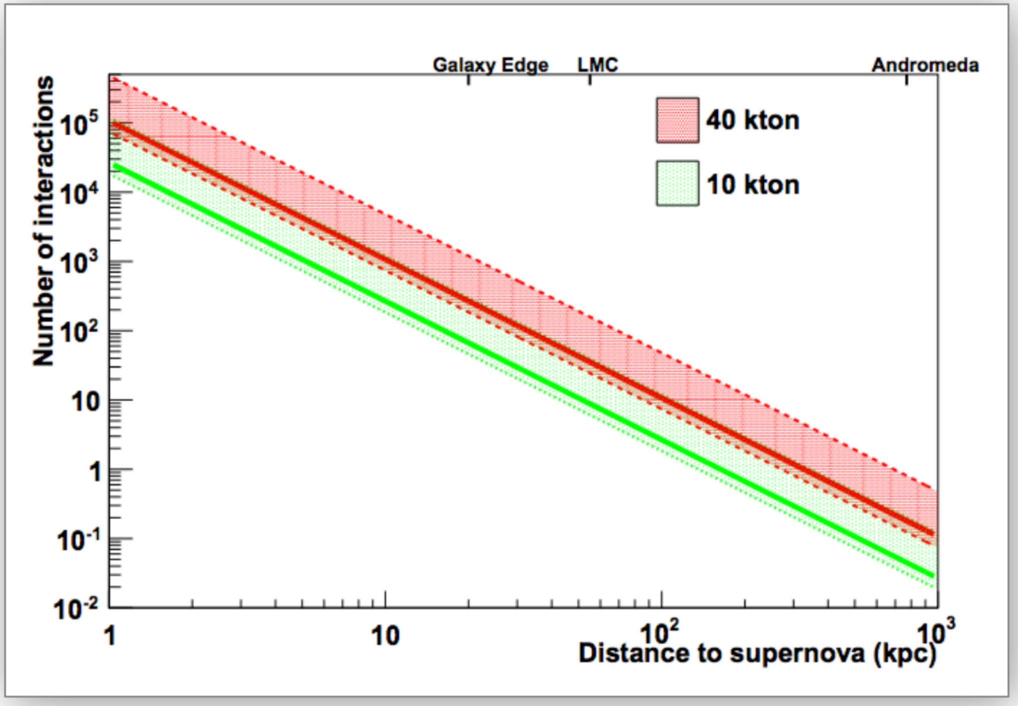


DUNE primary science goals: III. Supernova neutrinos

DUNE will be able to observe the ν_e flux through capture on Ar40.
– Other experiments rely on ν_e capture via inverse β decay through capture on Ar40.
– Unique sensitivity to the electron flavor component of the flux.

– Expect >3,000 events from a supernova at 10 kpc.
– Rates depend on core collapse model, ν oscillation models, and distance.

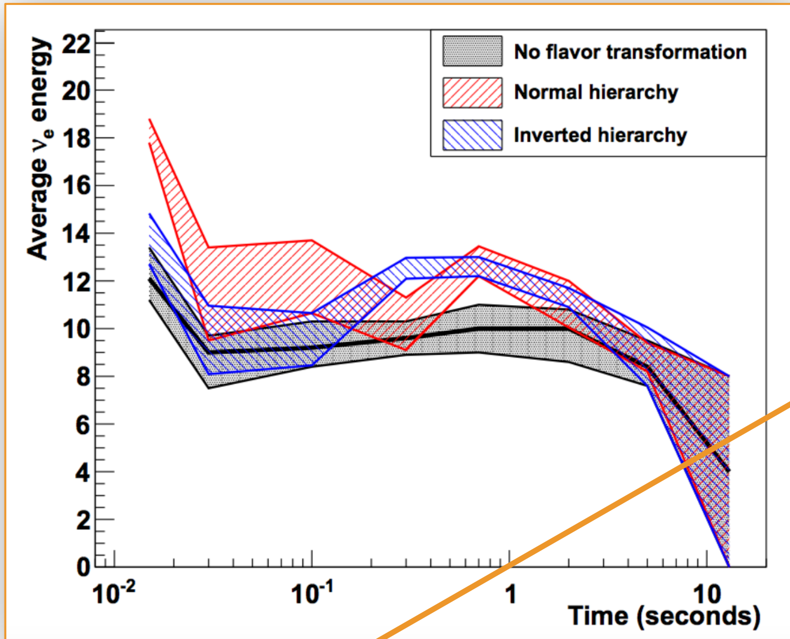
Requires suitable triggering systems.

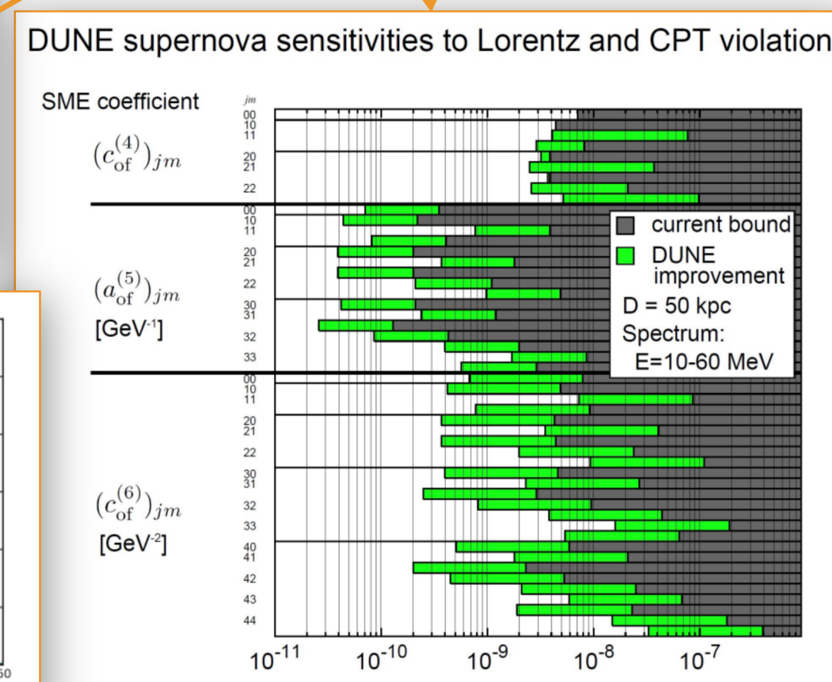


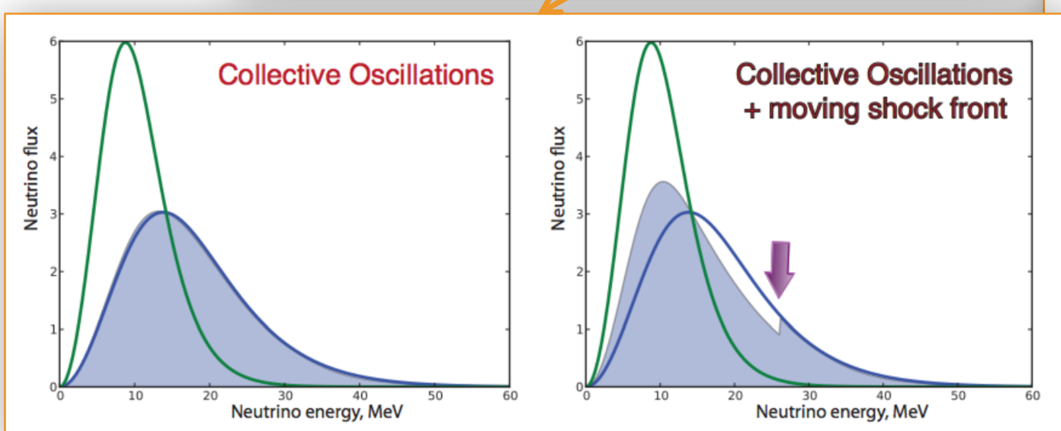
Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*$	2720	3350
$\bar{\nu}_e + {}^{40}\mathrm{Ar} \to e^+ + {}^{40}\mathrm{Cl}^*$	230	160
$\nu_x + e^- \to \nu_x + e^-$	350	260
Total	3300	3770

DUNE primary science goals: III. Supernova neutrinos

Large event sample provides information on time, energy and flavor structure. Allows constraints on SN core collapse dynamics, neutrino oscillation parameters, and other BSM physics models







DUNE ancillary science program

- Atmospheric neutrinos and oscillation measurements
- Neutrino interaction physics utilizing the DUNE near detector, including:
  - a wide-range of measurements of neutrino cross sections
  - studies of nuclear effects, including neutrino final-state interactions
  - measurements of the structure of nucleons
  - measurement of $\sin^2 2\theta_W$
- Search for dark matter signatures
- Accelerator-based neutrino flavor transition measurements with sensitivity to Beyond Standard Model (BSM) physics, such as:
  - non-standard interactions (NSI)
  - sterile neutrinos at both the near and far sites
- Measurements of tau neutrino appearance

Roadmap

Goal: Install the first 10 kt underground on the 2021/22 timescale
- Begin underground physics program, and engage collaboration
- Test all aspects of the the underground installation and detector performance
- Ready for beam physics program when beam turns on

Remaining modules, up to 40 kt, installed in rapid succession
- Initial 10 kt installation provides infrastructure for required conventional facilities
- Opportunity for combination of multiple detector technologies

Construction of a fine-grained near detector

Leverage intermediate neutrino program to inform design, and improve detector performance

Collect beam data by 2024, and run for ~10 exposure-yr

June 2-4, 2015	Successful Fermilab Director's CD-1 "Refresh" Review
July 14-16	DOE CD-1 "Refresh" Review

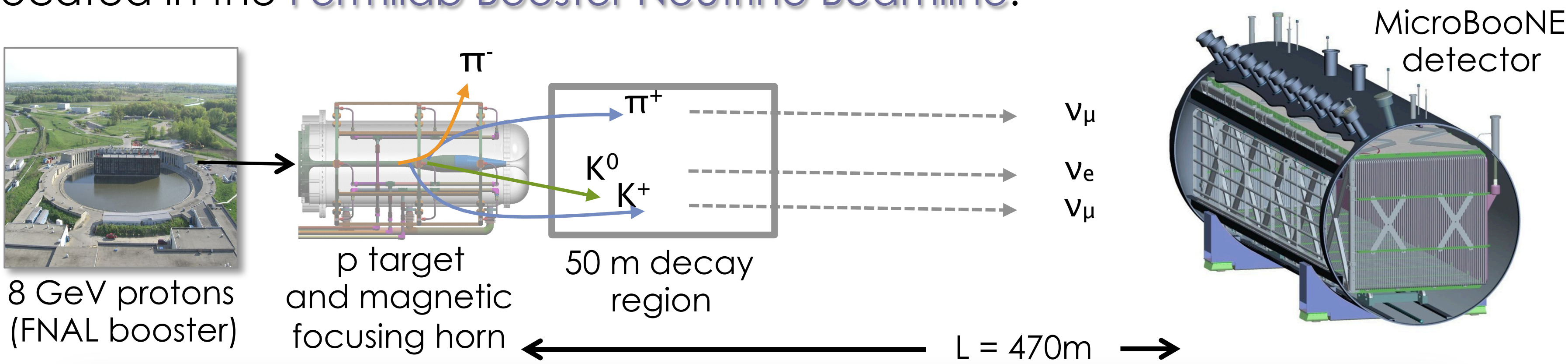
MicroBooNE

- 170 ton LArTPC located in the Fermilab Booster Neutrino Beamline (BNB)
- Currently being commissioned at the Fermilab Liquid Argon Test Facility (LArTF)!

- 121 collaborators strong!
  - 31 postdocs
  - 24 graduate students
  - 24 institutions
  - 3 countries

MicroBooNE

Located in the Fermilab Booster Neutrino Beamline:



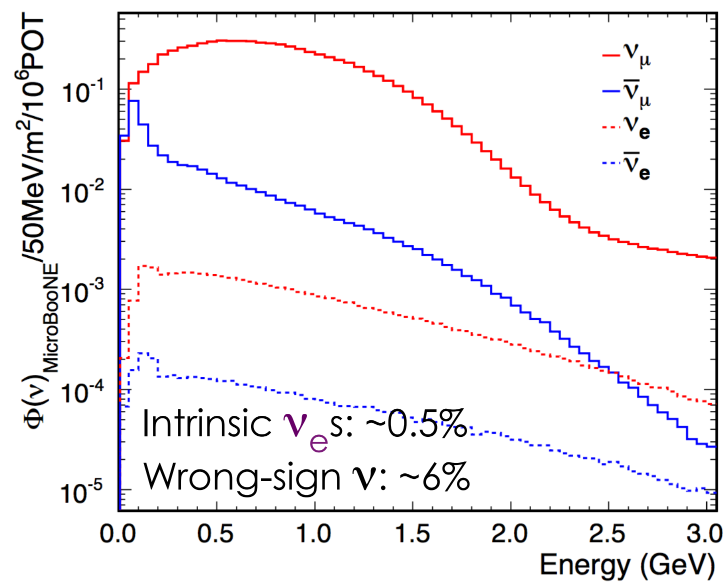
Neutrino flux at MicroBooNE:

>99% muon neutrinos
~6% wrong sign
~0.5% intrinsic electron neutrinos

Beam is pulsed at up to 15 Hz; beam spill is 1.6μs wide

Approved running: neutrino mode, 6.6E20 POT (2-3 years of running)

Data taking with neutrino beam begins this fall!



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First LArTPC with high-statistics event samples in 1 GeV range

During its ~3 years of running, MicroBooNE will collect (up to hundreds of) **thousands** of exclusive and inclusive neutrino interactions.

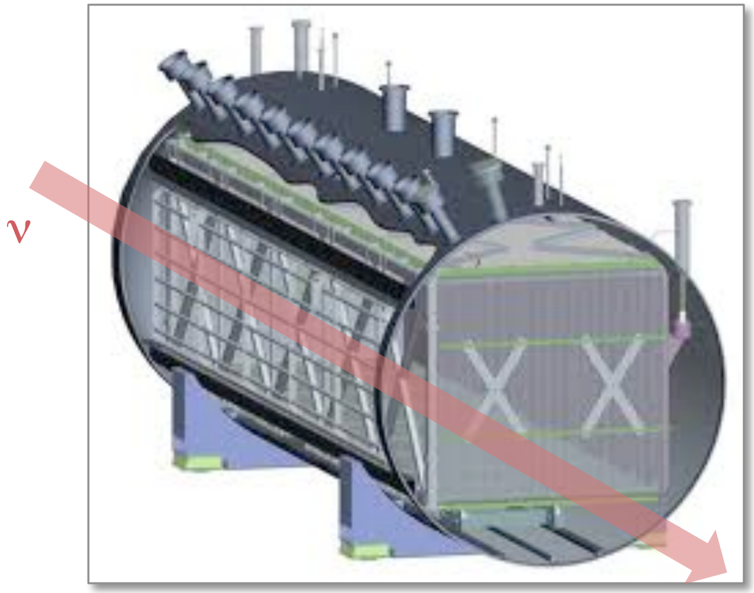
In addition to BNB neutrinos, MicroBooNE will also be able to measure **NuMI off-axis** neutrino interactions.

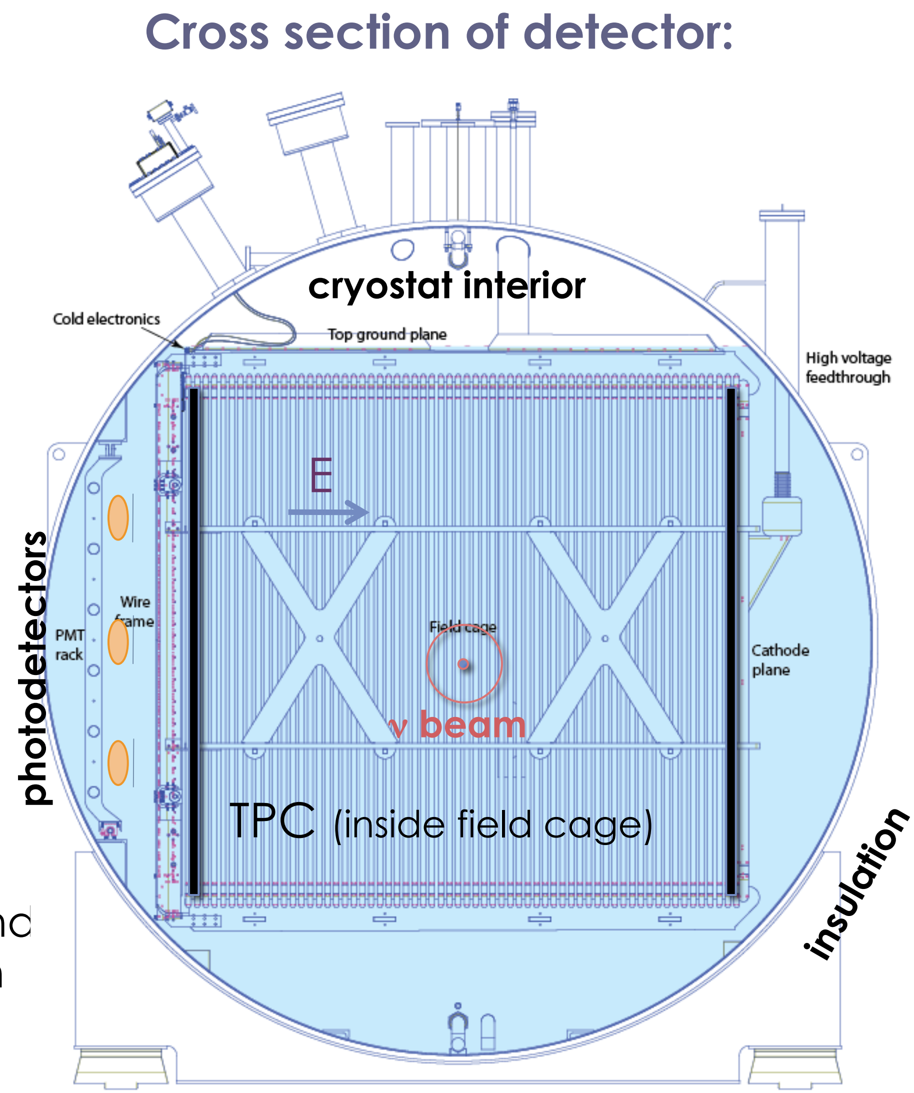
6.6e20 POT (~3 years)

	numu	numubar	nue	nuebar
CC Total	173302	1407	1469	36
CC - QE	95296	773	729	17
CC – RES	75657	604	702	18
CC – DIS	1607	1.3	29	0.5
CC - COH	740	29	8.5	0.7
NC Total	64661	1002	502	17
NC - QE	35951	633	254	7.0
NC - RES	27665	358	236	9.4
NC - DIS	519	1.3	8.8	0.2
NC - COH	525	10	3.2	0.6

GENIE simulated event rates: 87 ton active volume, 6.6e20 POT, **BNB**. 100% selection efficiency. Separation between RES and DIS channels is based on a cut on the hadronic mass W < 2 GeV (RES) and W > 2 GeV (DIS) rather than GENIE interaction mode.

Detector parameters





- 2.5 m x 2.3 m x 10.2 m TPC
- 170 (89) tons total (active) mass
- 2.5 m drift length; -128kV on cathode
- 3 wire planes: 0, ±60° from vertical, 3 mm wire separation
- 8256 wires, digitized at 2MHz
- 32 PMT's digitized at 64MHz for t_0, drift coordinate determination, and triggering for empty beam spill rejection

Detector parameters → Technical goals

Several **technically challenging experimental design requirements** had to be achieved/demonstrated, e.g.:

Ultra high purity

- Requirement to drift a MIP track 2.5 m: <100 ppt O_2 equivalent
- Requirement for scintillation photon detection: <1 ppm N_2
- Had to be achieved without evacuation (for detector scalability)
- Must be maintained: Impurities continuously filtered and monitored

High voltage

- Requirement to achieve 2.5 m drift distance (longest in a neutrino beam!): -128 kV on cathode
- Long drift distance also vital for scaling to larger detectors

Large data volume

- Event size is large: Large number of readout channels with high data volume/channel
- Requires fast readout electronics capable of processing high data rate, and lots of data storage space
- Large number of interactions requires automated reconstruction

Detector parameters → Technical goals

Several **technically challenging experimental design requirements** had to be achieved/demonstrated, e.g.:

Ultra high purity
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- Had to be achieved without evacuation (for detector scalability)
- Must be m

High voltage
- Requireme … am!): -128 kV on
- Long drift c

Large data v
- Event size i … volume/channel
- Requires fast readout electronics capable of processing high data rate, and lots of data storage space
- Large number of interactions requires automated reconstruction

MicroBooNE's technical goals realize a necessary test of the LArTPC technology, at a scope and scale that justifies the design and construction of future, larger LArTPC detectors, including DUNE.

Physics goals

1. Investigate anomalous low energy excess previously observed by MiniBooNE (predecessor experiment in the BNB, downstream from MicroBooNE)

2. Perform high-statistics inclusive and exclusive neutrino cross-section measurements on argon

3. Demonstrate background rejection capabilities and constrain cosmogenic background predictions to future searches for baryon number violation (proton decay, neutron antineutron oscillations)

4. Search for supernova collapse neutrinos, should a nearby supernova core collapse occur during MicroBooNE's lifespan

5. Perform a definitive search for light sterile neutrino oscillations as a part of the Fermilab SBN program

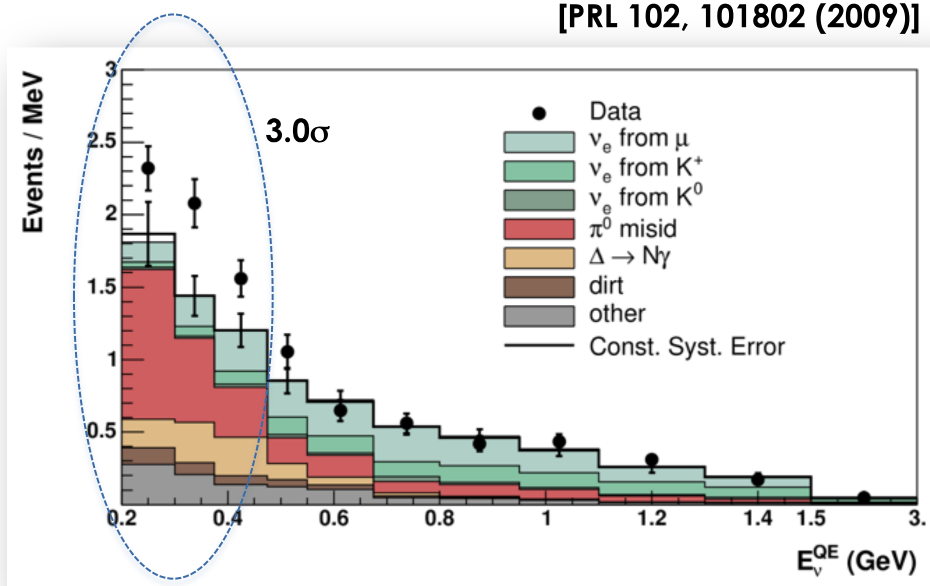
1. MiniBooNE low energy excess

MicroBooNE's primary physics goal (I):

- Investigate the nature of the MiniBooNE low energy excess

- MiniBooNE, a Cherenkov detector, was unable to determine the nature of the excess events as e vs. γ

MiniBooNE unexplained "low energy excess" [PRL 102, 101802 (2009)]

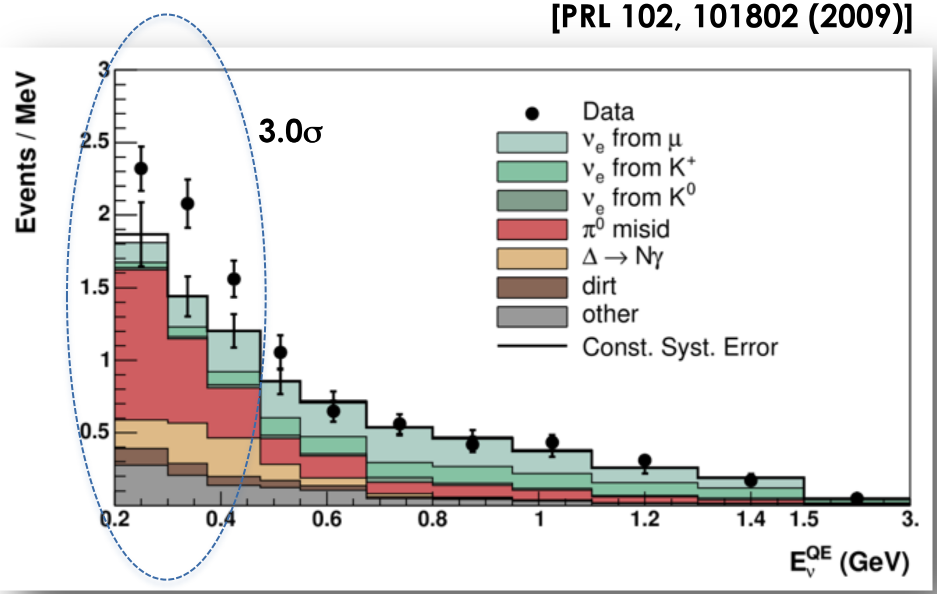


1. MiniBooNE low energy excess

MicroBooNE's primary physics goal (I):

- While the MiniBooNE excess can be interpreted as sterile neutrino oscillations, this interpretation conflicts with constraints from other (null) experiments; the L/E shape of the excess is also somewhat problematic…

MiniBooNE unexplained "low energy excess" [PRL 102, 101802 (2009)]



- A number of other possible interpretations…

Unaccounted ν_e / ν_μ disappearance?

Energy (mis)reconstruction? Cross-section/ nuclear effects?

Misestimated or new electron-like background?

Misestimated or new photon-like background?

1. MiniBooNE low energy excess

MicroBooNE's primary physics goal (I):

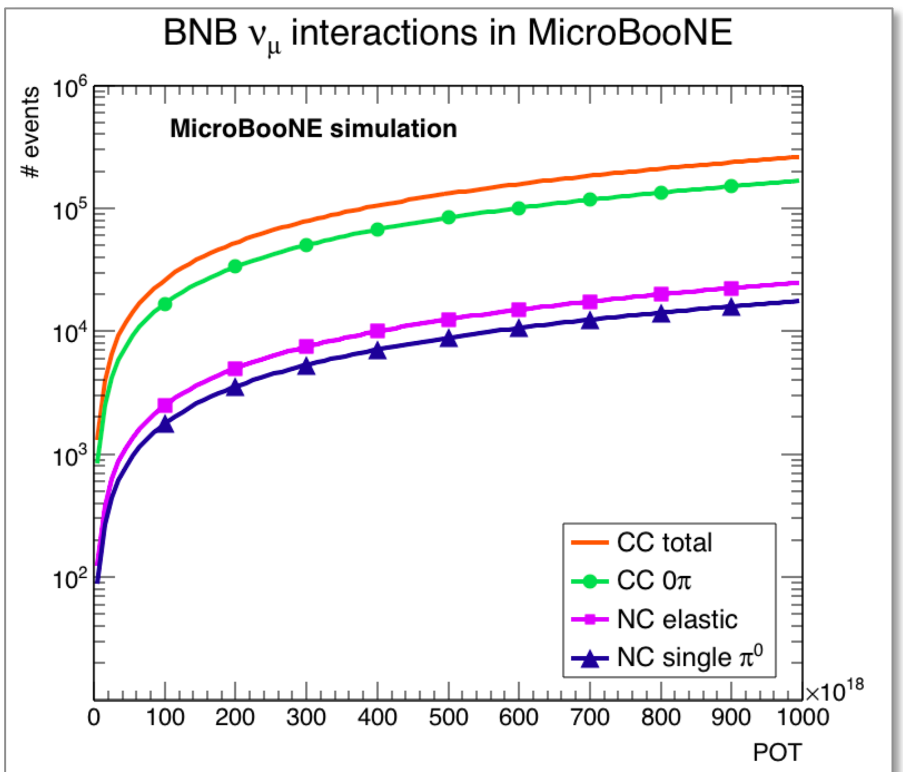
- If an excess is observed and found to be due to **photons**, MicroBooNE could make the first measurement of a novel photon-production mechanism, to be included in neutrino interaction generators, as it could impact future ν_e appearance measurements

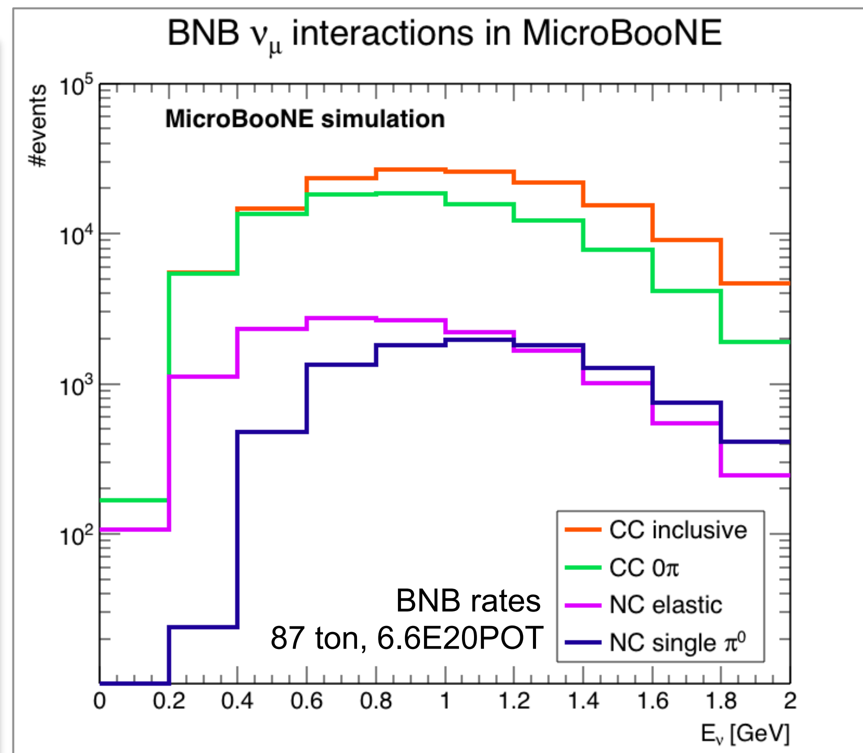
- If the excess is due to **electrons**:
MicroBooNE could be seeing ν_e appearance (sterile neutrino oscillations, NSI, extra dimensions) or be in position to measure some other novel production mechanism (?)

2. Neutrino cross sections

MicroBooNE's primary physics goal (II):

- First LArTPC with high-statistics event samples in 1 GeV range!
- In just 6 months of data taking (1E20 POT), thousands of events in several exclusive and inclusive topologies

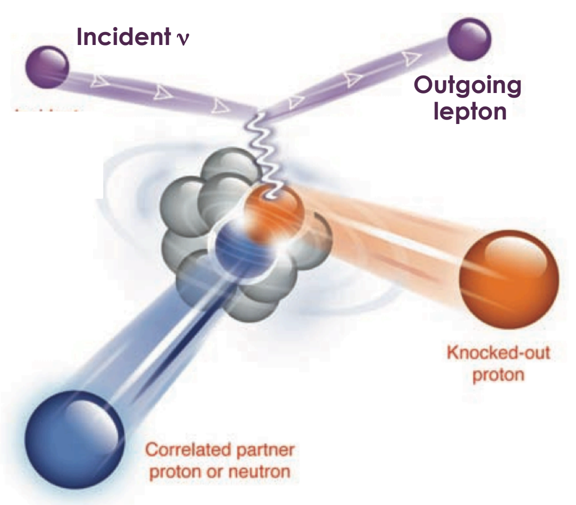


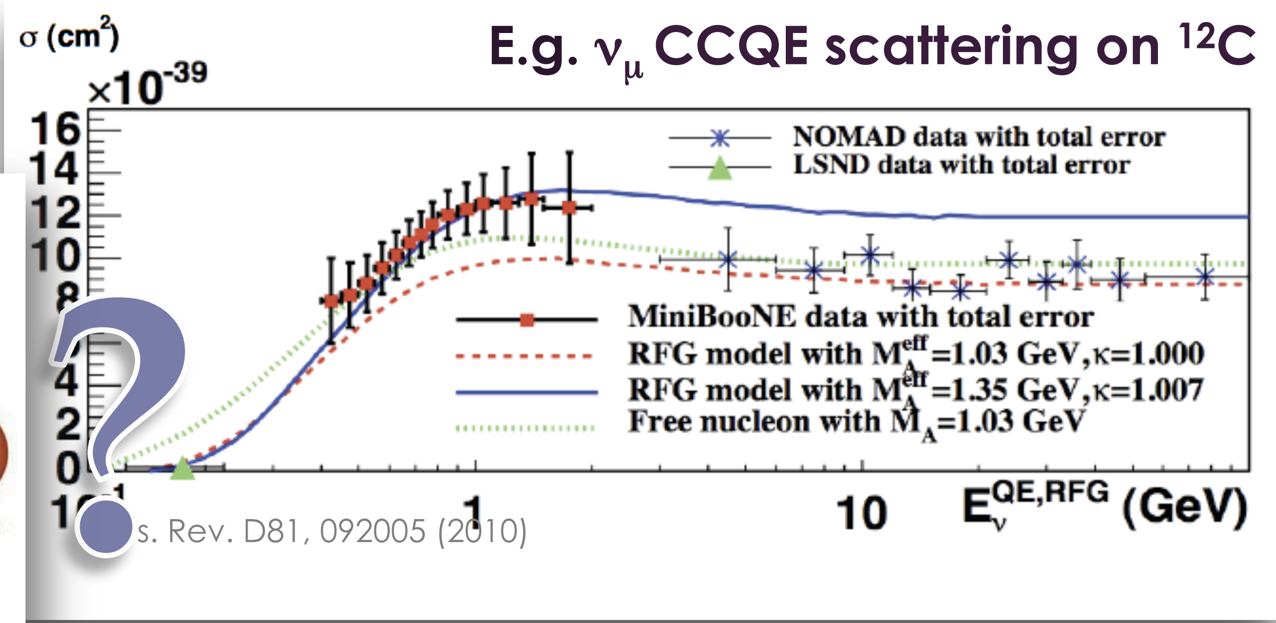


2. Neutrino cross sections

MicroBooNE's primary physics goal (II):

- Measure inclusive and exclusive neutrino cross-sections on argon at ~ 1 GeV
- Classification in terms of final states
- Study nuclear effects, which we now know play a critical role on event rate and event final state information



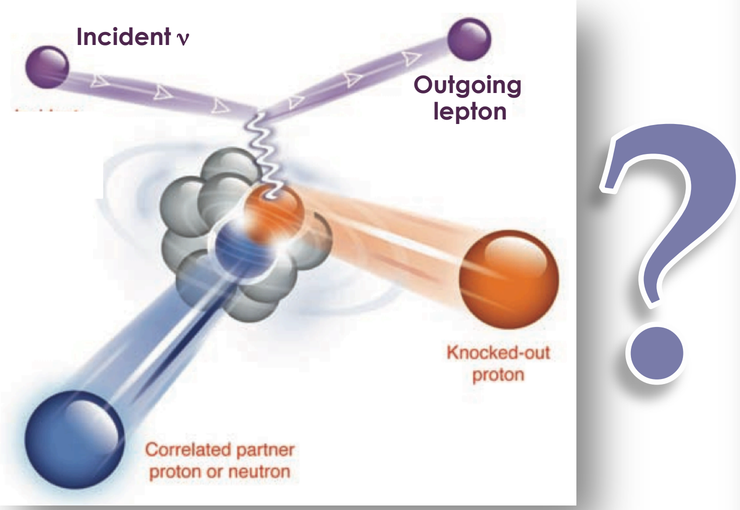


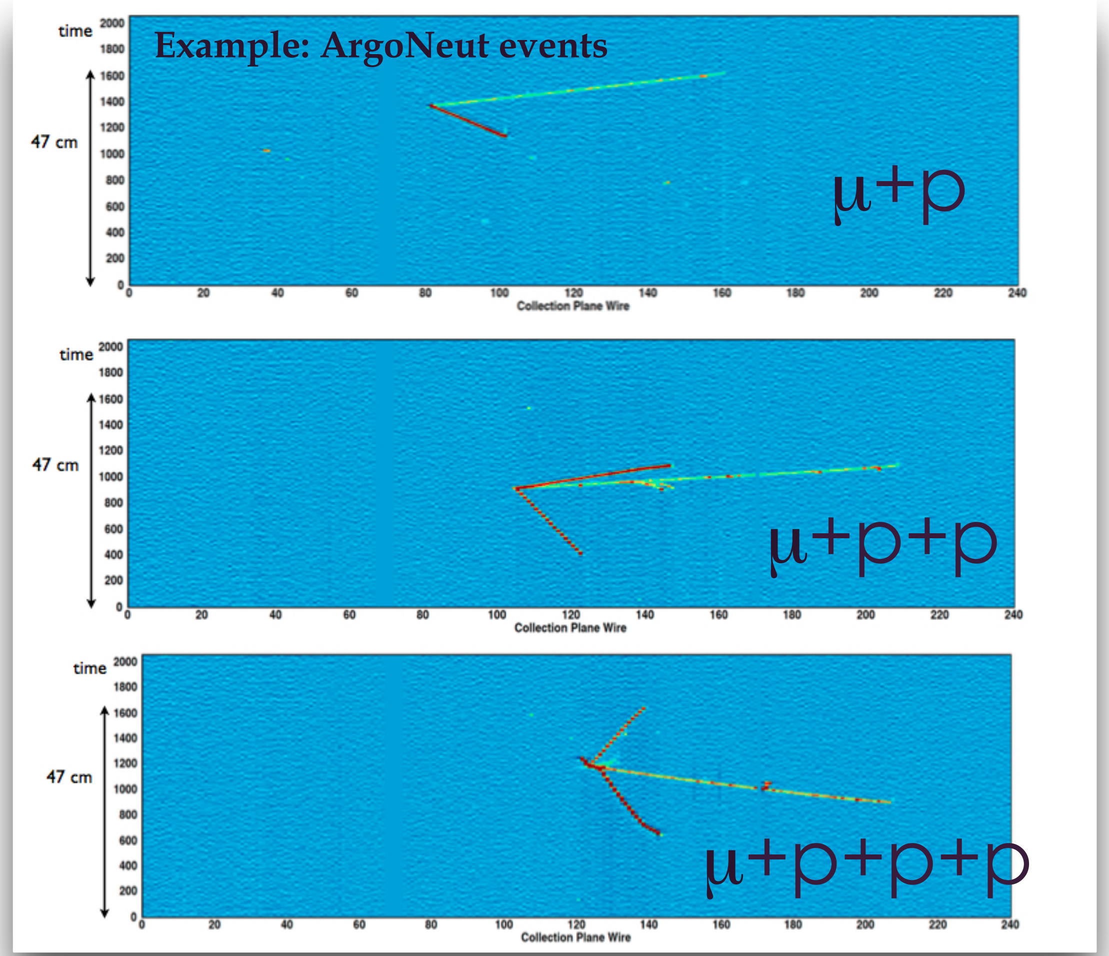
Past cross section measurements (from K2K, MiniBooNE, SciBooNE, MINOS, NOMAD, Minerva) have revealed limitations in our understanding of neutrino interactions

2. Neutrino cross sections

MicroBooNE's primary physics goal (II):

- Event topology and final state information (e.g. proton multiplicity in QE-like interactions, final state kinematics) can be studied with sufficiently low momentum reconstruction thresholds





2. Neutrino cross sections

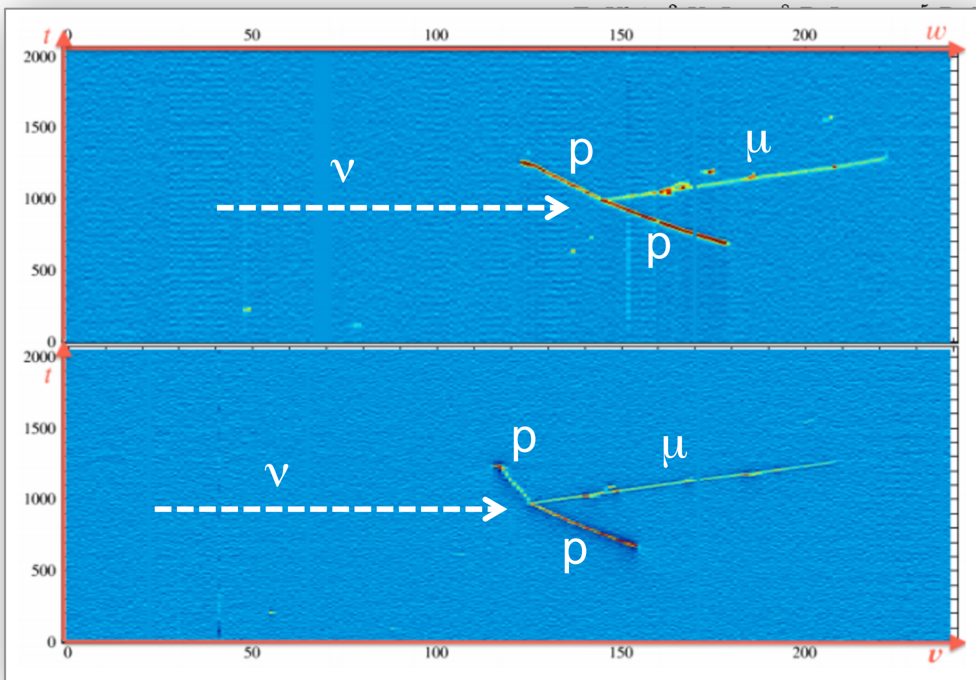
MicroBooNE's primary physics goal (II):

- Event topology and final state information (e.g. proton multiplicity in QE-like interactions, final state kinematics) can be studied with sufficiently low momentum reconstruction thresholds

ArgoNeut Results
Phys. Rev. D 90, 012008 (2014)

The detection of back-to-back proton pairs in Charged-Current neutrino interactions with the ArgoNeuT detector in the NuMI low energy beam line

R. Acciarri,[1] C. Adams,[2] J. Asaadi,[3] B. Baller,[1] T.Bolton,[4] C. Bromberg,[5] F. Cavanna,[2,6] E. Church,[2]
D. Edmunds,[5] A. Ereditato,[7] S. Farooq,[4] B. Fleming,[2] H. Greenlee,[1] G. Horton-Smith,[4] C. James,[1]
...Mehdiyev,[8] B. Page,[5] O. Palamara,[2,9,*] K. Partyka,[2] G. Rameika,[1]
...Spitz,[2] A.M. Szelc,[2] M. Weber,[7] T. Yang,[1] and G.P. Zeller[1]
(ArgoNeuT Collaboration)
...Accelerator Laboratory, Batavia, IL 60510 USA
...iversity, New Haven, CT 06520 USA
...University, Syracuse, NY 13244 USA
...te University, Manhattan, KS 66506 USA
...te University, East Lansing, MI 48824 USA
...ità dell'Aquila e INFN, L'Aquila, Italy
...versity of Bern, Bern, Switzerland
...of Texas at Austin, Austin, TX 78712 USA
...tori Nazionali del Gran Sasso, Assergi, Italy
(Dated: May 19, 2014)



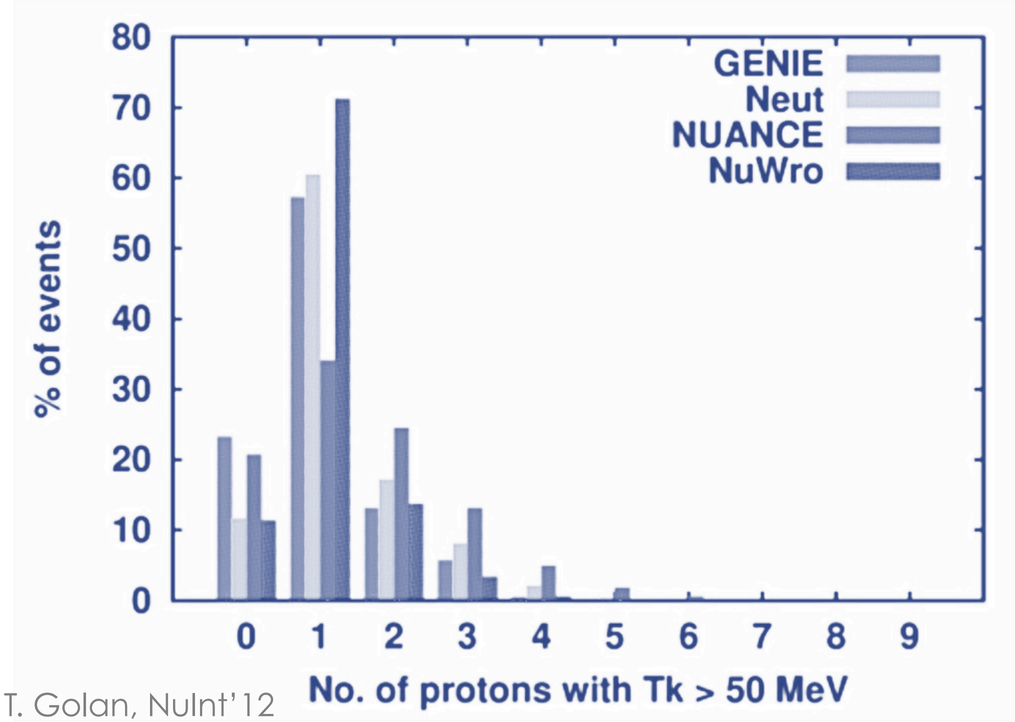
Back-to-back "hammer" events suggest nucleon-nucleon short-range correlations.
Inferred kinematics from recoil nucleons in CM frame (before interaction) support this.

2. Neutrino cross sections

MicroBooNE's primary physics goal (II):

- Event topology and final state information (e.g. proton multiplicity in QE-like interactions, final state kinematics) can be studied with sufficiently low momentum reconstruction thresholds
- Needed as input to neutrino event generators
- Important implications to our ability to reconstruct neutrino energy

Cross-section and nuclear effects modeling: Vastly different predictions from different neutrino event generators



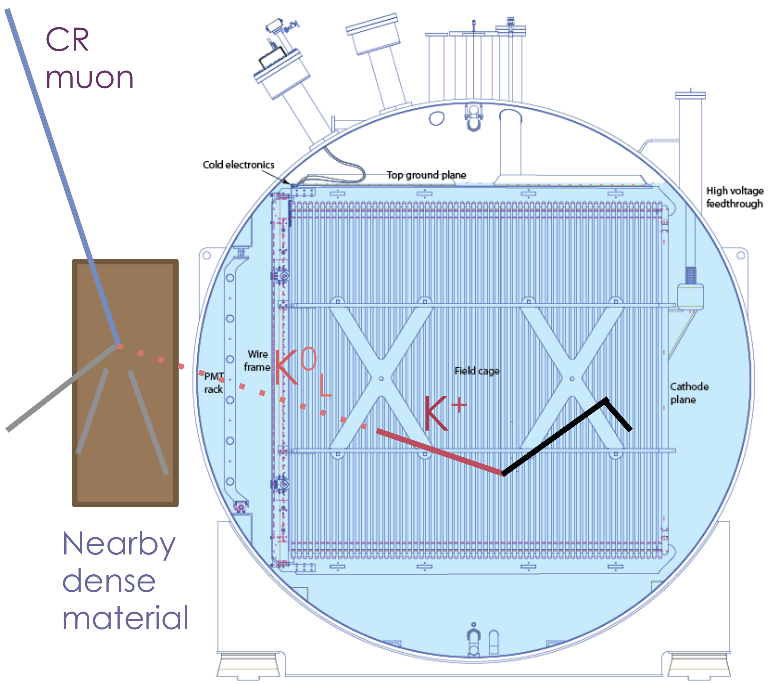
T. Golan, NuInt'12

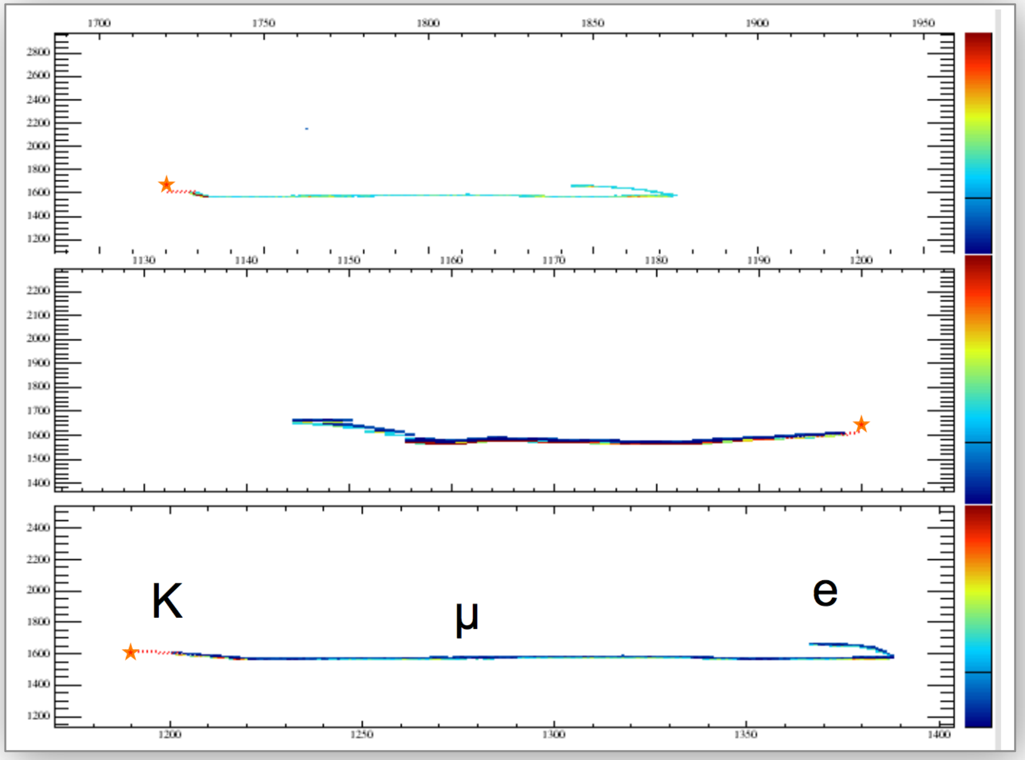
3. Background studies for BNV

Additional physics opportunities (II):

- Investigate backgrounds to baryon number violating processes for larger (underground) detectors
- E.g. **proton decay**

$p \rightarrow K^+ \overline{\nu}$





3. Background studies for BNV

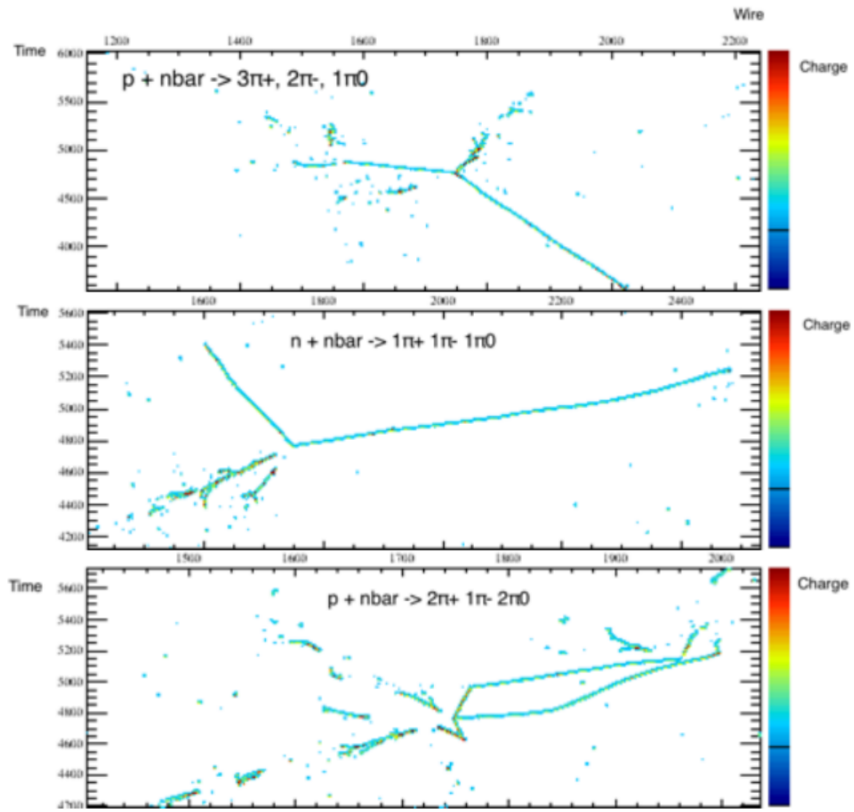
Additional physics opportunities (II):

- Investigate backgrounds to baryon number violating processes for larger (underground) detectors
- E.g. **neutron-antineutron oscillation**

"Star event" topology:
multiple pions from
n̄ annihilation with
nearby p or n (in Ar nucleus)

- Cannot look for this rare process with MicroBooNE; instead,
  - Develop reconstruction, particle ID & event selection.
- Use simulated events, cosmogenic backgrounds, high-energy neutrinos and in-situ data rates to test signal selection and background rejection.

Example events using $n - \bar{n}$ event generator with MicroBooNE simulation chain:



4. Supernova neutrino detection

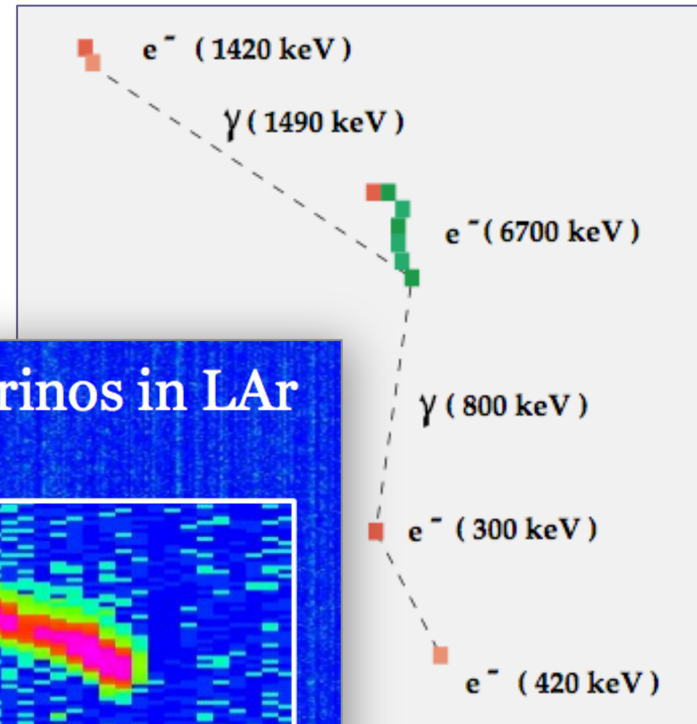
Additional physics opportunities (I):

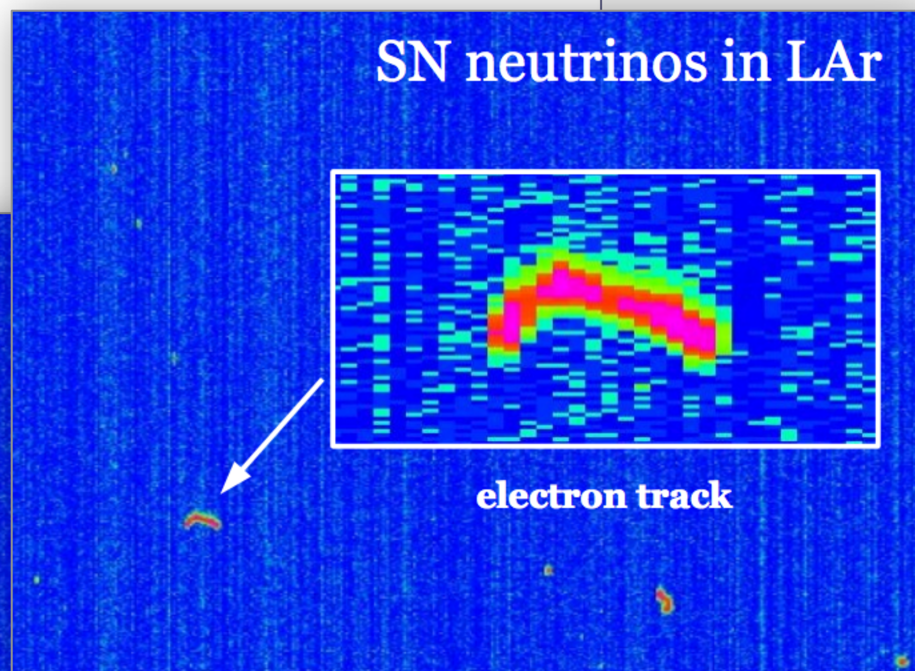
- Detect and study neutrinos from (nearby) supernova collapse

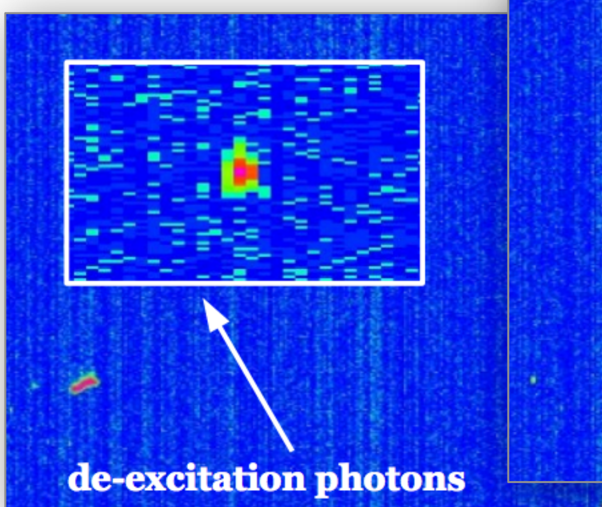
10kpc SN neutrino event rate predictions for MicroBooNE (60 tons):

~a few to a few tens of events!

Signature of low energy ν_e CC absorption on Ar







Off-beam searches are challenging!

A lot of data, which we cannot afford to record continually and without data loss

Each MicroBooNE event: 160 MB

8256 wires
read over 4.8 ms (3x drift size window)
digitized at 2 MHz
12-bit ADC (16-bit packets)

Per event, MicroBooNE will record 10x more data than ATLAS

Event rate of ~0.1-15 Hz
→ need **compression**:
Huffman (lossless) compression for beam/trigger provides sufficient (x ~few) reduction

Being 100% live for SuperNova neutrino search: >30 GB/s !

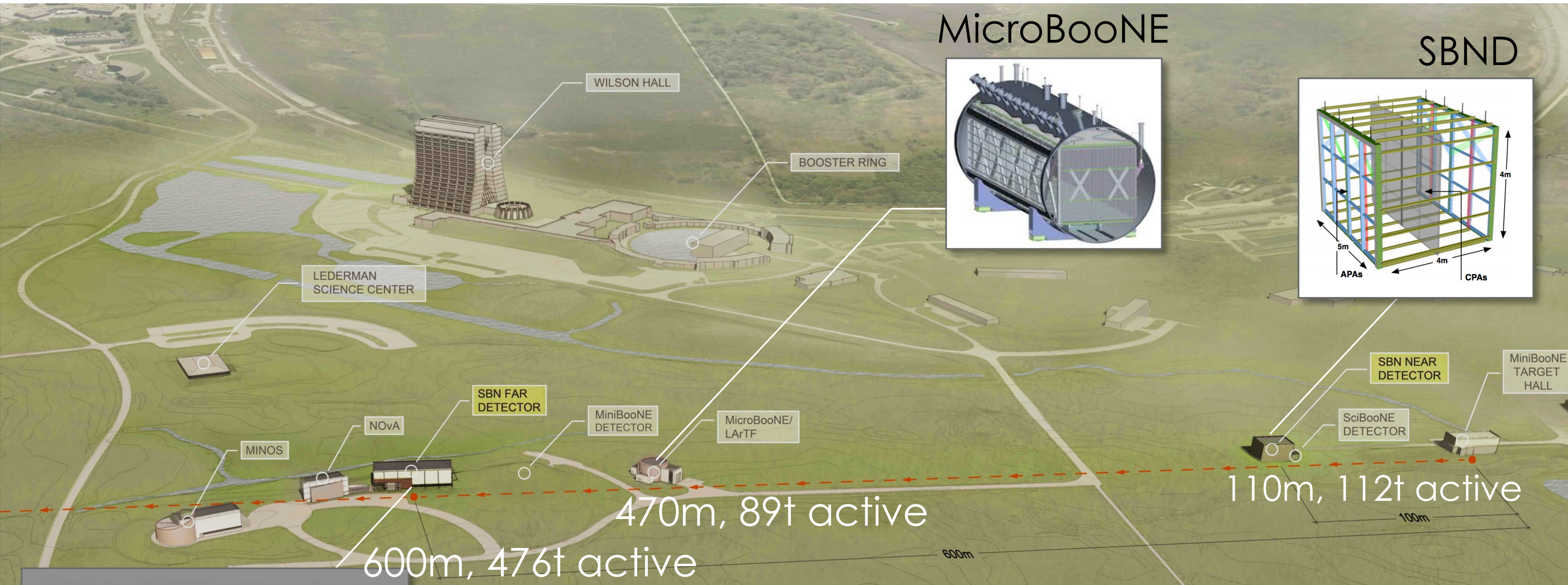
Solution:
Implement additional zero suppression to achieve x 80 reduction and only retain ~few hrs of data on tape at any time

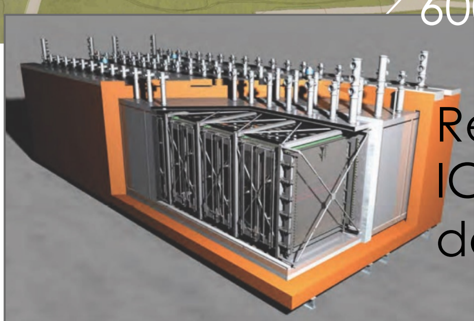
SNEWS

4. Sterile neutrino oscillation search

(Beyond MicroBooNE:) Short Baseline Neutrino program at Fermilab

A **second** & **third** LArTPC placed in the BNB at Fermilab, in line with MicroBooNE





Refurbished ICARUS T600 detector

- Near/mid/far comparison for short-baseline oscillation search
- **Definitive search for sterile neutrino oscillations**

4. Sterile neutrino oscillation search

(Beyond MicroBooNE:) Short Baseline Neutrino program at Fermilab

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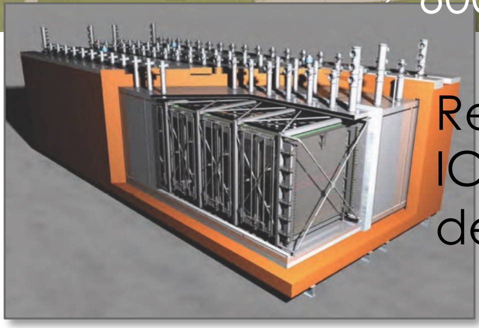


Refurbished ICARUS T600 detector

- Near/mid/far comparison for short-baseline oscillation search
- **Definitive search for sterile neutrino oscillations**

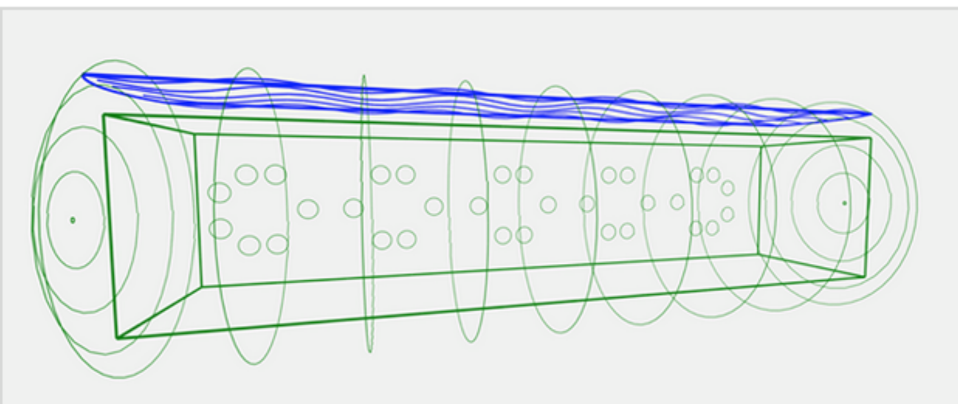
Current status

MicroBooNE installation is complete!
The detector has been filled with LAr,
and critical subsystem commissioning has begun!
The neutrino beam turns on this fall!

MicroBooNE
10 hrs ·

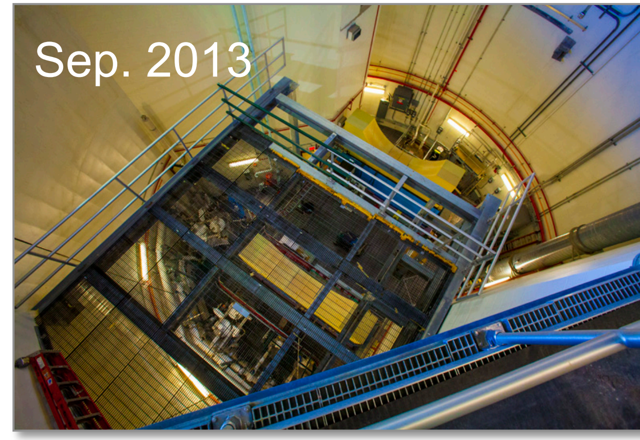
LAr fill complete on July 9, 2015!

Today, we passed a major milestone. The MicroBooNE vessel is officially full!! It took 9 tanker trucks and ~34,000 gallons of high purity liquid argon. Many thanks to our cryogenic experts, Mike Zuckerbrot and Michael Geynisman, for getting us to this point. Next, we start turning on each of our detector sub-systems one-by-one and further purifying the argon. We could not be more excited!



Construction highlights

- LArTF building construction complete as of Sep. 2013, and outfitted for detector for installation
- PMT's and TPC installed in cryostat as of Dec. 2013
- Detector moved to LArTF in June 2014 and foam-insulated in July 2014
- During summer and fall 2014, 6.2 km of cable deployed, all labeled, connecting detector to readout electronics
- Cryogenics installation took place Summer-Fall 2014
- Readout electronics installed in Fall 2014 and commissioned in subsequent months
- UV Laser calibration system installed in Dec. 2014



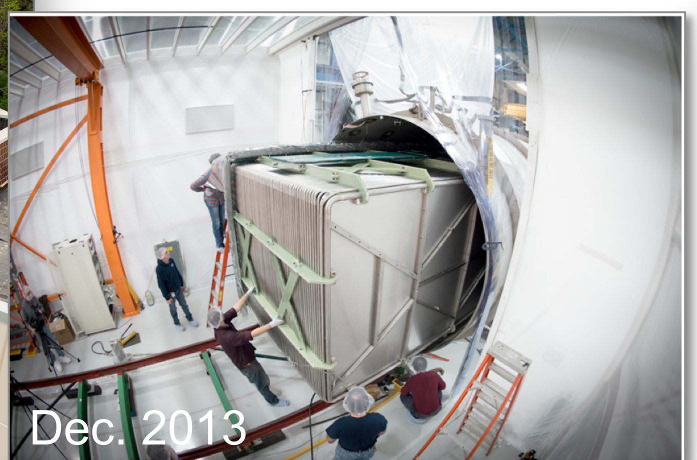
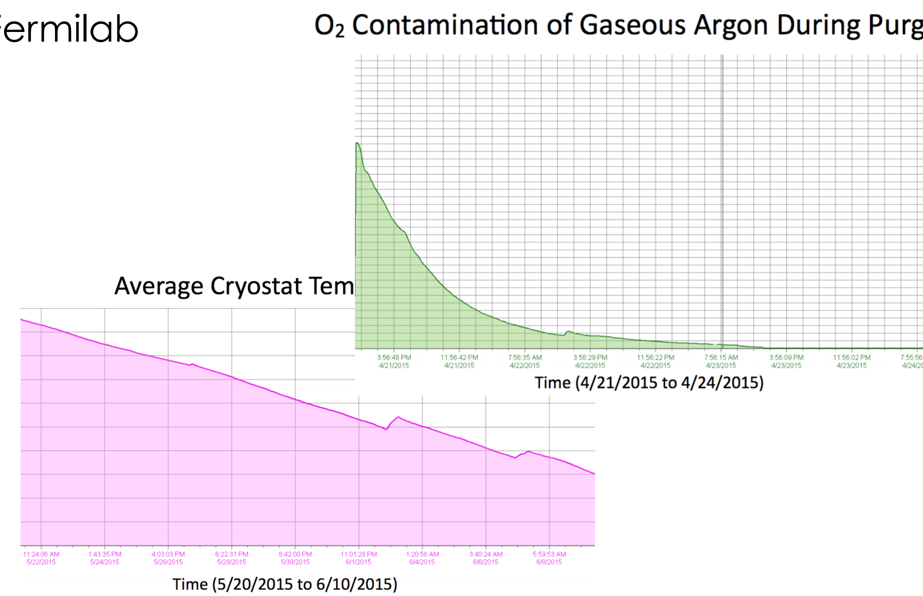


Photo credits: FNAL VMS

Commissioning highlights

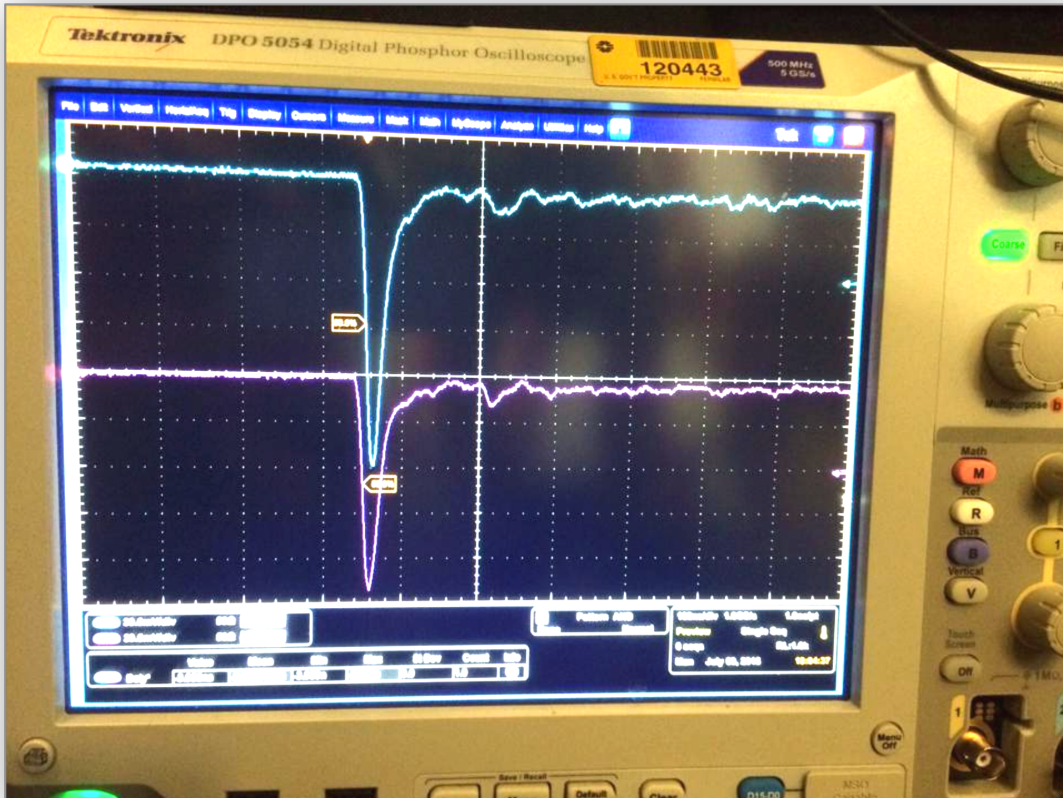
- Have been constantly exercising DAQ over the past months, reading out the full TPC: >20 TB of cold electronics calibration data collected so far!
- Cryostat was purged in April, cooled down in May; filling began on June 17, and was completed on July 9, 2015, reaching LAr purity goals!
- Have been recording and analyzing cold electronics calibration data during cooldown and filling.
- Critical detector subsystems (PMTs, HV, Laser) are being exercised!

- Shifts began on June 1, 2015 in ROC West at Fermilab



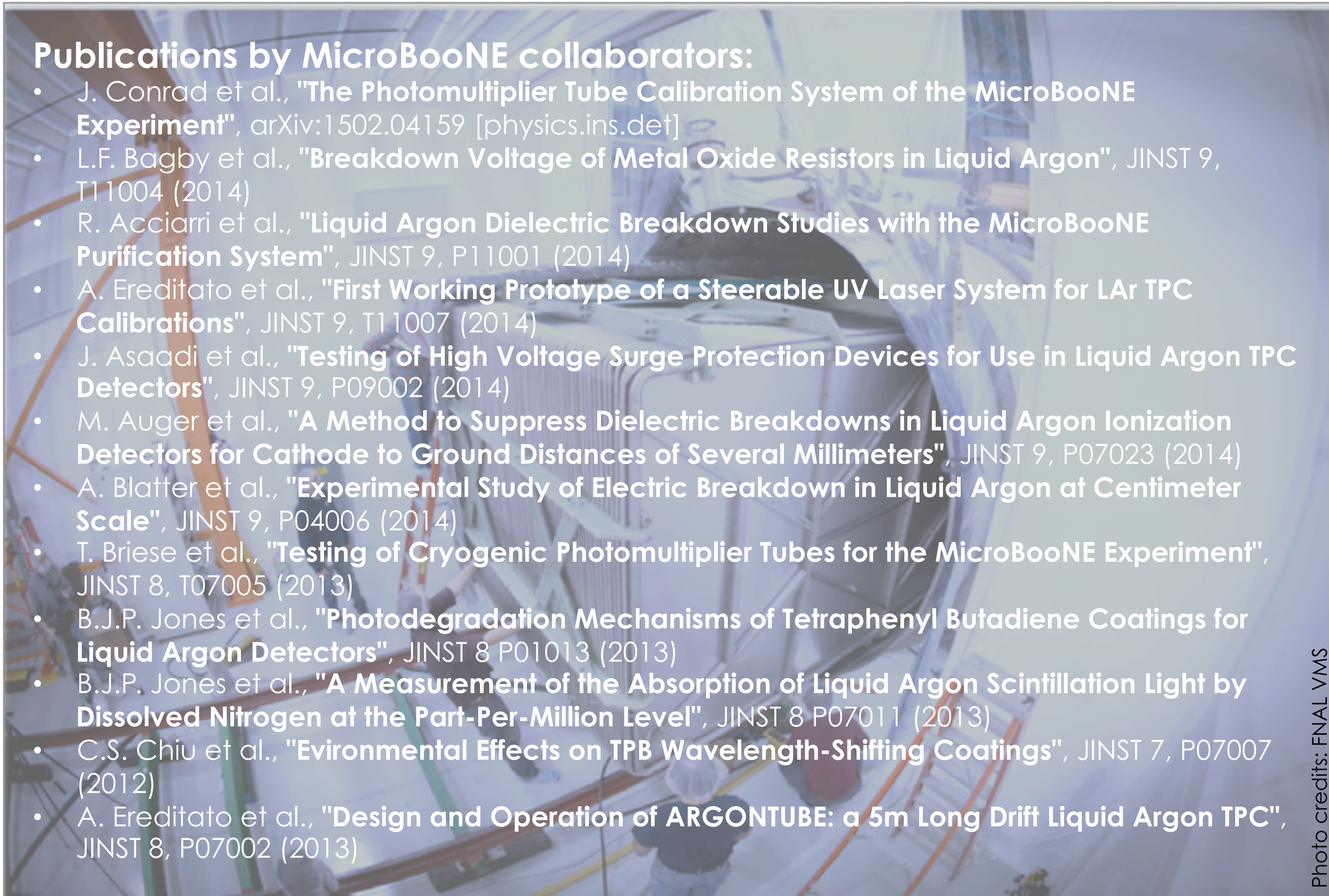
Commissioning highlights

All 32 PMTs are ON (as of yesterday)!
We can now see interactions in argon (cosmics)!



First test PMT calibration run using PMT readout electronics was taken overnight!

MicroBooNE is already a success story!



Publications by MicroBooNE collaborators:

- J. Conrad et al., **"The Photomultiplier Tube Calibration System of the MicroBooNE Experiment"**, arXiv:1502.04159 [physics.ins.det]
- L.F. Bagby et al., **"Breakdown Voltage of Metal Oxide Resistors in Liquid Argon"**, JINST 9, T11004 (2014)
- R. Acciarri et al., **"Liquid Argon Dielectric Breakdown Studies with the MicroBooNE Purification System"**, JINST 9, P11001 (2014)
- A. Ereditato et al., **"First Working Prototype of a Steerable UV Laser System for LAr TPC Calibrations"**, JINST 9, T11007 (2014)
- J. Asaadi et al., **"Testing of High Voltage Surge Protection Devices for Use in Liquid Argon TPC Detectors"**, JINST 9, P09002 (2014)
- M. Auger et al., **"A Method to Suppress Dielectric Breakdowns in Liquid Argon Ionization Detectors for Cathode to Ground Distances of Several Millimeters"**, JINST 9, P07023 (2014)
- A. Blatter et al., **"Experimental Study of Electric Breakdown in Liquid Argon at Centimeter Scale"**, JINST 9, P04006 (2014)
- T. Briese et al., **"Testing of Cryogenic Photomultiplier Tubes for the MicroBooNE Experiment"**, JINST 8, T07005 (2013)
- B.J.P. Jones et al., **"Photodegradation Mechanisms of Tetraphenyl Butadiene Coatings for Liquid Argon Detectors"**, JINST 8 P01013 (2013)
- B.J.P. Jones et al., **"A Measurement of the Absorption of Liquid Argon Scintillation Light by Dissolved Nitrogen at the Part-Per-Million Level"**, JINST 8 P07011 (2013)
- C.S. Chiu et al., **"Evironmental Effects on TPB Wavelength-Shifting Coatings"**, JINST 7, P07007 (2012)
- A. Ereditato et al., **"Design and Operation of ARGONTUBE: a 5m Long Drift Liquid Argon TPC"**, JINST 8, P07002 (2013)

Photo credits: FNAL VMS

Summary

We are entering a new era of high-precision neutrino physics measurements enabled by the LArTPC technology.

MicroBooNE is contributing as an important R&D step for DUNE and the LArTPC technology in general, proving detector scalability.

Extremely rich physics of its own, including:

- MiniBooNE low energy excess
- Neutrino cross sections on Ar
- Sterile neutrino oscillations through the expanded SBN program

MicroBooNE data taking has begun! We expect first neutrino data this Fall!

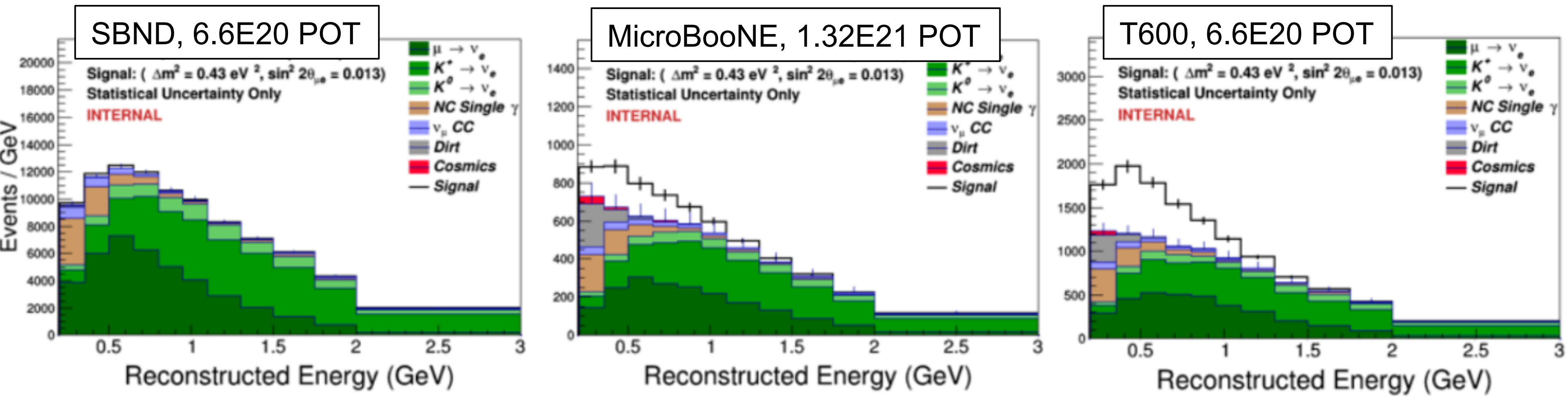
Fermilab's LBNF will provide a MW class neutrino beam and conventional facilities for the DUNE near and far detectors.

In the longer term, DUNE will determine the neutrino MH and measure δ_{CP} with the use of a 40kton LArTPC situated deep underground and a highly capable ND at LBNF.

Plus, a rich physics program including SN neutrinos, nucleon decay, neutrino interaction and nuclear physics, exotic neutrino oscillations, and other physics beyond the standard mode.

SBN appearance search

The high-statistics event sample in SBND constrains the expected ν_e background event rate in MicroBooNE and ICARUS, reducing systematic uncertainties; ICARUS' large mass provides necessary statistical power for an electron neutrino appearance search

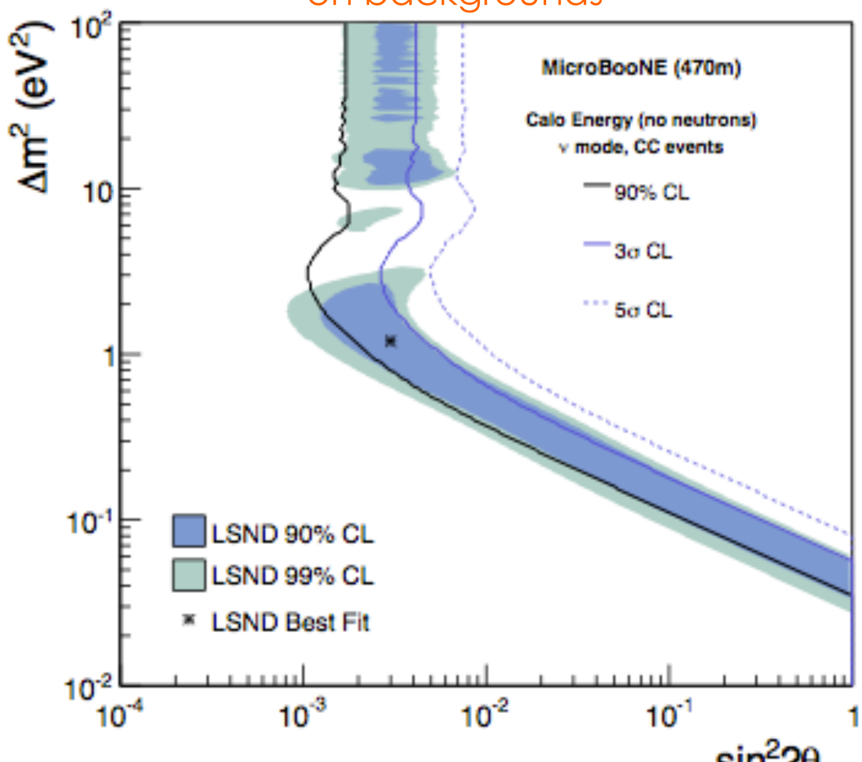


- The dominant background in all three detectors comes from the beam **intrinsic** backgrounds
- The **dirt** and **cosmic** backgrounds depend greatly on the detector geometry and location within the beam
- For comparison the "Kopp Global" best fit signal is shown, demonstrating how well it could observed across the three detectors

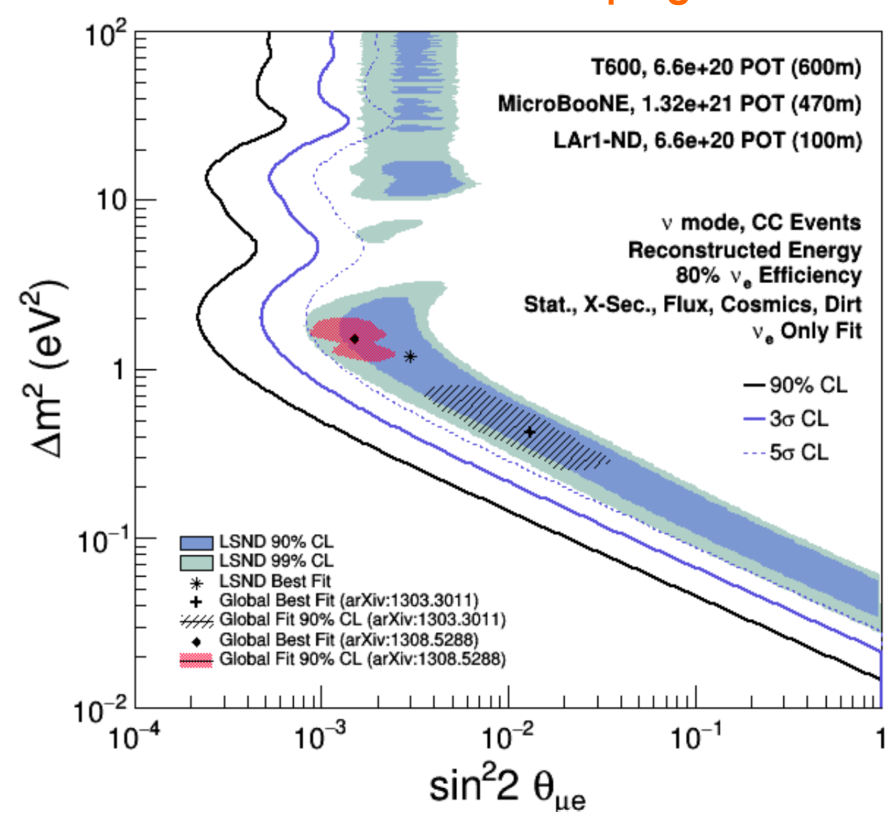
SBN appearance search

The high-statistics event sample in SBND constrains the expected ν_e background event rate in MicroBooNE and ICARUS, reducing systematic uncertainties; ICARUS' large mass provides necessary statistical power for an electron neutrino appearance search

MicroBooNE-only, 6.6e20 POT
20% uncorrel. systematic uncertainty
on backgrounds



Three-detector SBN program

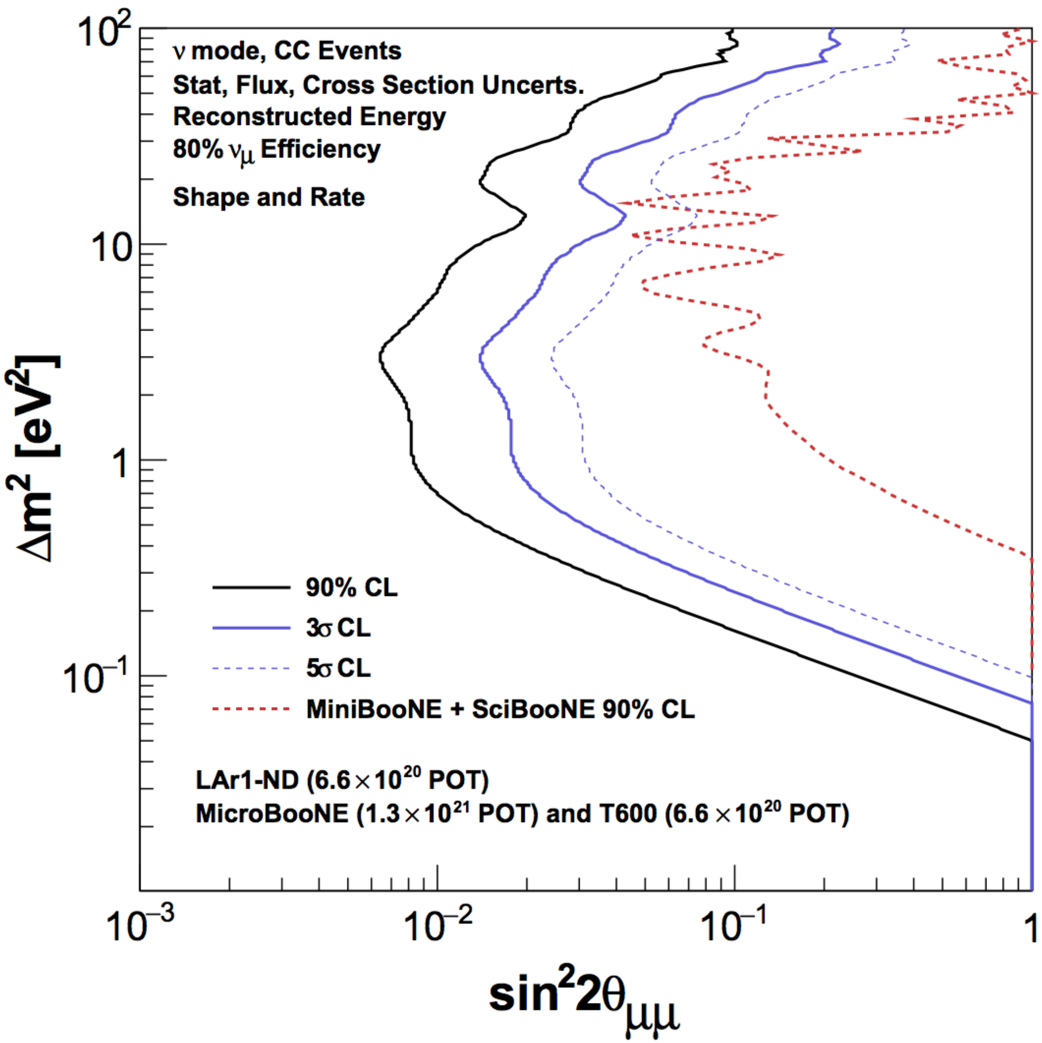


[SBND Proposal 2013, SBN Proposal 2015]

SBN disappearance search

SBN can also perform a competitive search for **muon neutrino disappearance**.

Needed to fully interpret any excess of electron neutrino events as oscillations involving sterile neutrinos:
a corresponding disappearance of muon neutrinos with ~greater than or equal probability is expected



BNB

- The FNAL Accel. Division has successfully replaced the BNB horn and is in the process of commissioning it.
- Horn had been in service since 2004.
- Horn had been pulsed 400M+ times (twice its design, world record!)
- Decision was made to replace horn after several cooling lines became clogged last year.
- The new filtering system is now more robust against introducing debris

When?

- SBND and (refurbished) ICARUS expected to be operational in BNB in 2018
- An extended (+6.6E20 POT) run will commence concurrently with all three detectors (MicroBooNE will have already collected 6.6E20 POT)

- The groundbreaking for the SBN detector buildings will take place this summer!
  - This starts an exciting period for all three collaborations
  - Activities range from design, to construction, to commissioning, and, eventually, data analysis

- MicroBooNE will provide us the first look at what we might be seeing at short-baselines

A well-motivated, forward-driving neutrino program

This program is a platform to develop the technical and analysis techniques necessary for DUNE and other future LArTPC's

It brings together LArTPC expertise from all over the world to collaborate on this program:

on detector design, reconstruction development,
analysis of millions of neutrino events and
sensitive, multi-channel oscillation searches