The Fermilab Short-Baseline Neutrino Program: A Search for Sterile Neutrinos and A Study of ν-Argon Interactions

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Neutrino Interactions

CETUP

July 22-31, 2014

Plan of Talk

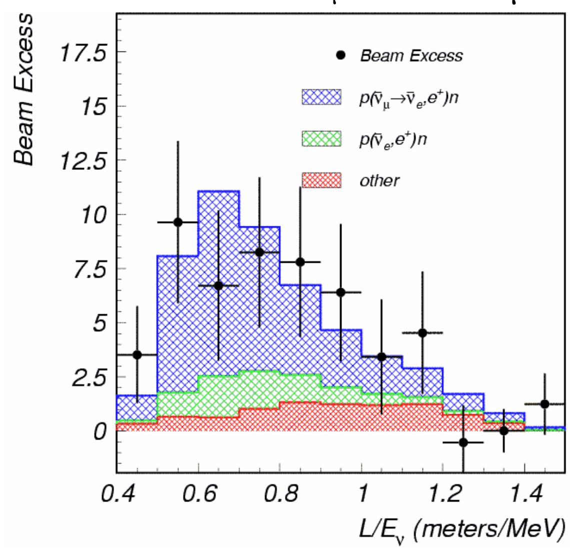
- The Oscillation program and its motivation.
- How do we address it.
- The R&D program
- Detector descriptions.
- Sensitivities to Sterile Neutrinos.
- Measurements of ν-Argon cross-sections
- Status and Conclusions

Many techniques I will describe are currently being developed and used by ArgoNeut.
My thanks to ArgoNeut for allowing me to use some of their data as examples.

Why look for Sterile Neutrinos?

- The LSND, MiniBooNE accelerator anomalies

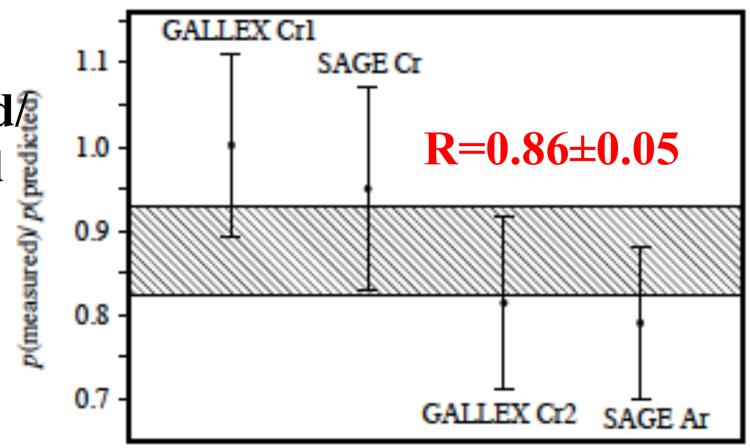
Excess $\bar{\nu}_e$ signal in $\bar{\nu}_\mu$ beam. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?



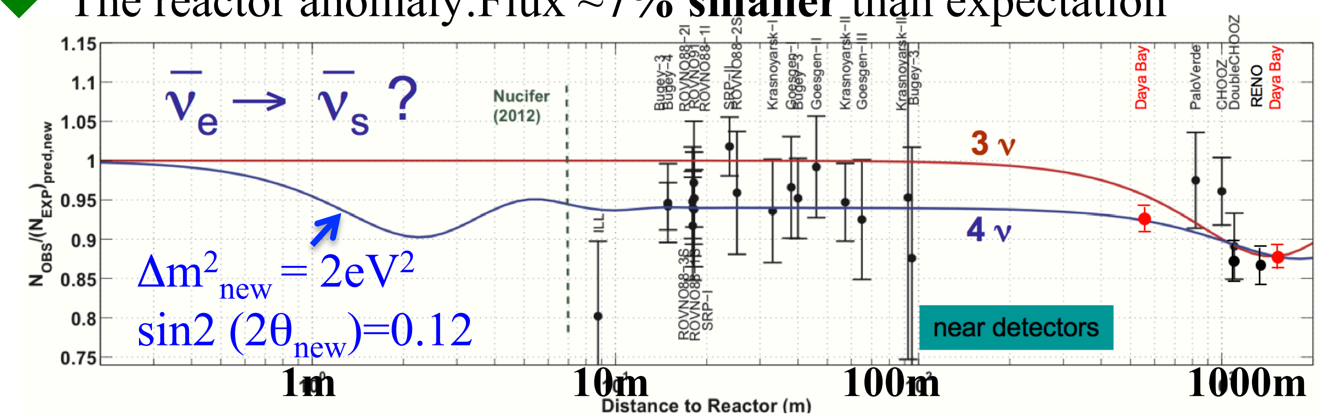
- The radioactive source anomaly:

Rate **smaller by ~ 14%**

R= Measured/ predicted



- The reactor anomaly:Flux ~**7% smaller** than expectation



All ~ 3 σ effects

Could be explained by additional neutrino with a mass of ~ 1 eV/c^2: Sterile (no Z^0 coupling)

Motivation or, the Genealogy of the BNB program

LSND

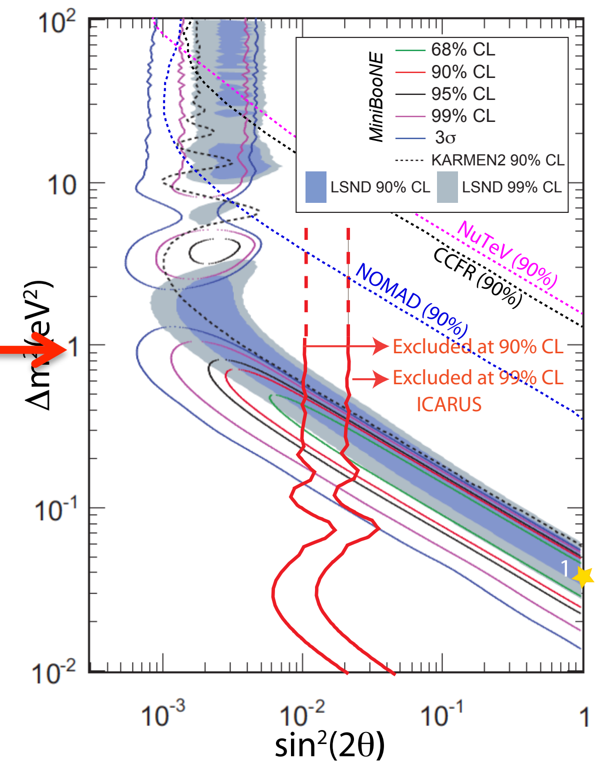
Interesting effect!

LSND observed a (~3.8σ) excess of $\bar{\nu}_e$ events in a pure $\bar{\nu}_\mu$ beam

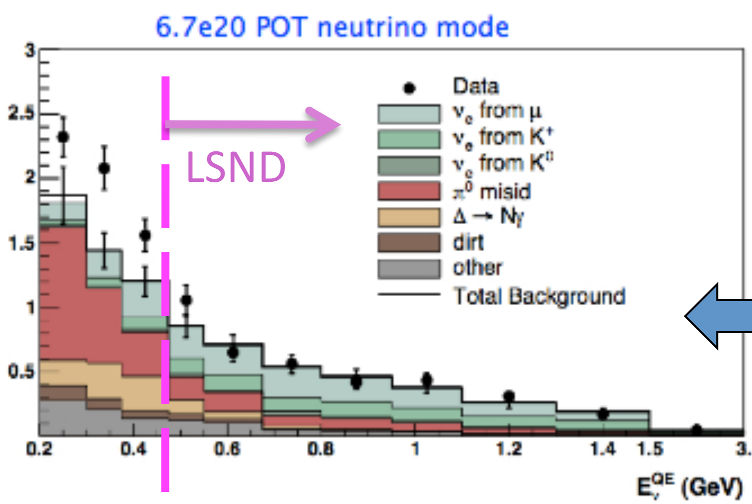
If due to oscillations:

L/E → High $\Delta m^2 \sim 1\ eV^2$

Can only be accomodated by a NEW and STERILE neutrino



MiniBooNE Booster Neutrino Beam at Fermilab



MiniBooNE

Excess mostly at **Low energy in ν and $\bar{\nu}$.**

Liquid Argon:
MicroBooNE
ICARUS +LAr1-ND

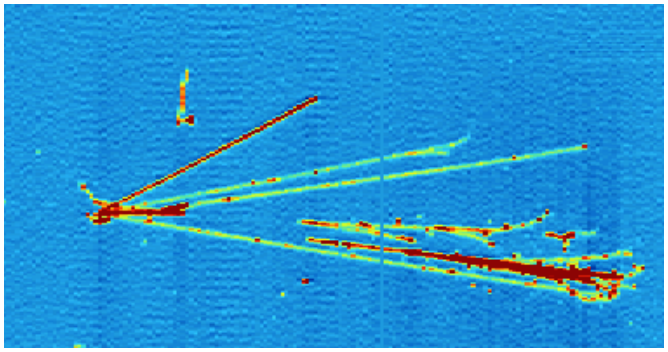
Bands at the Beach Club

Argon and the Noble Gases

Saturday, July 19th approx. 5:30pm

Why is Liquid Argon different from MiniBooNE?

- MiniBooNE searched for $\nu_\mu \rightarrow \nu_e$ oscillations
- Looked for excesses of ν_e in a ν_μ beam and of $\overline{\nu_e}$ in a $\overline{\nu_\mu}$ beam.
- ν_e identified by their Charged Current Interactions → e shower in final state
  → Fuzzy Cerenkov Ring
- But MiniBooNE could not distinguish between a photon and an electron shower.
- Is the excess due to
  - Electrons (→ oscillations to sterile)?
  - Or Photons ?
- **Liquid Argon is good at**
  - Distinguishing between electrons and photons.
  - Reducing photon background
  - Neutrino energy reconstruction.



Nature of MiniBooNE excess → Main MicroBooNE task

What should we be looking for?

- To reproduce the same conditions as in MiniBooNE

  Locate MicroBooNE in same beam and at ~ same distance as MiniBooNE.

MicroBooNE(170 tons) at 470m (just upstream of MiniBooNE)

- If the LSND and/or MiniBooNE $\nu_\mu \rightarrow \nu_e$ signals are due to a sterile ν
- Then: $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$
- Implies ν_e appearance AND ν_μ disappearance
- Must look for BOTH.

What is needed?

- Determine the INTRINSIC ν_e flux in the ν beam for the ν_e appearance search
- Constrain the ν_μ flux for ν_μ disappearance search
- Constrain the ν_e from μ decay using the ν_μ flux.
- Is the MiniBooNE excess **intrinsic** to the beam or distance dependent?

NEAR Detector: LAr1-ND(150tons) at 110m

What should we be looking for?

- To maximize a potential oscillation effect, increase the detector mass and its baseline :

ICARUS (760 tons) at 600m (downstream of MiniBooNE)

- The full capabilities of a 3-detector configuration are currently being evaluated.

- Presentation at the Fermilab PAC this week.

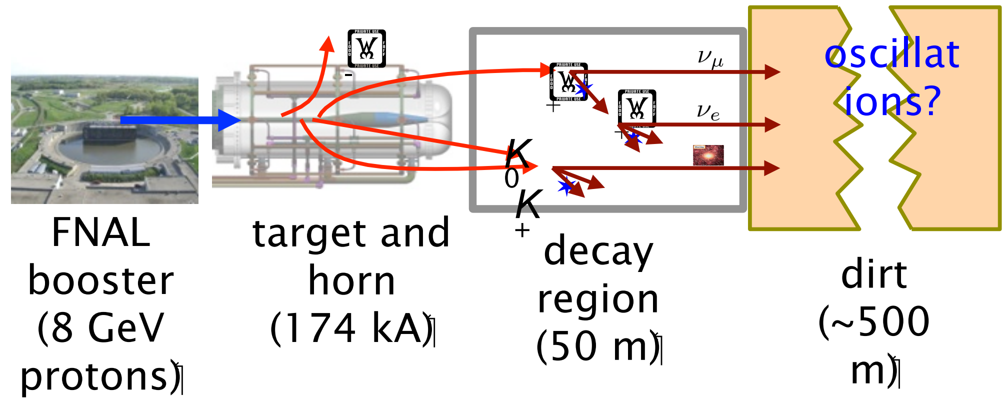
- **For most of the rest of this talk: Concentrate on MicroBooNE and LAr1-ND.**
- And present what could be achieved with:
- a 3-year run of MicroBooNE (6.6 x 10^{20} POTs)

  combined with
- LAr1-ND taking data during the 3rd year (2.2 x 10^{20} POTs)

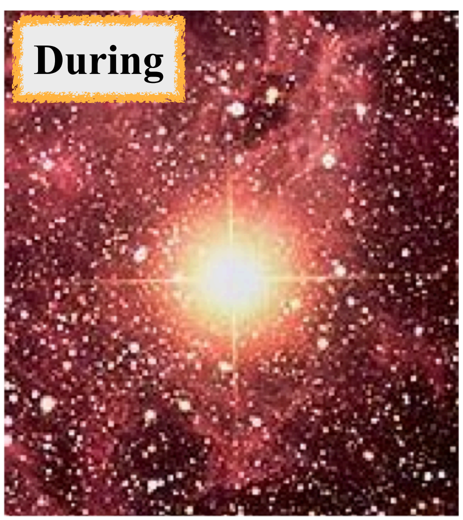
The Short Baseline Physics Program

- Resolve the cause and origin of the MiniBooNE low energy excess.
- Search for Oscillations at a high Δm^2.
  - $\nu_\mu - \nu_e$ appearance.
  - ν_μ disappearance.
- **Measure Neutrino-Argon interactions with high statistics in a region relevant to LBNE**

Using
The Fermilab Booster Neutrino Beam



- SuperNova sensitivity.



And, hopefully, another beam.....

The R&D Program

- MicroBooNE
  - Cold electronics: preamps in cryostat.

    Shorter wire-preamp cables and lower temperature→Decrease noise.
  - Filling without evacuation.
  - Longer (2.5m) drift length. (ICARUS: 1.5m)
  - TPC field calibration using a Laser.
  - Reconstruction.
  - Continuous readout for SuperNova purposes
  - Background to proton decay studies.

- LAr1-ND: Closely aligned to the Long Baseline technology
  - More electronics in the cold: including digitization.
  - Membrane Cryostat
  - TPC according to Long Baseline design.

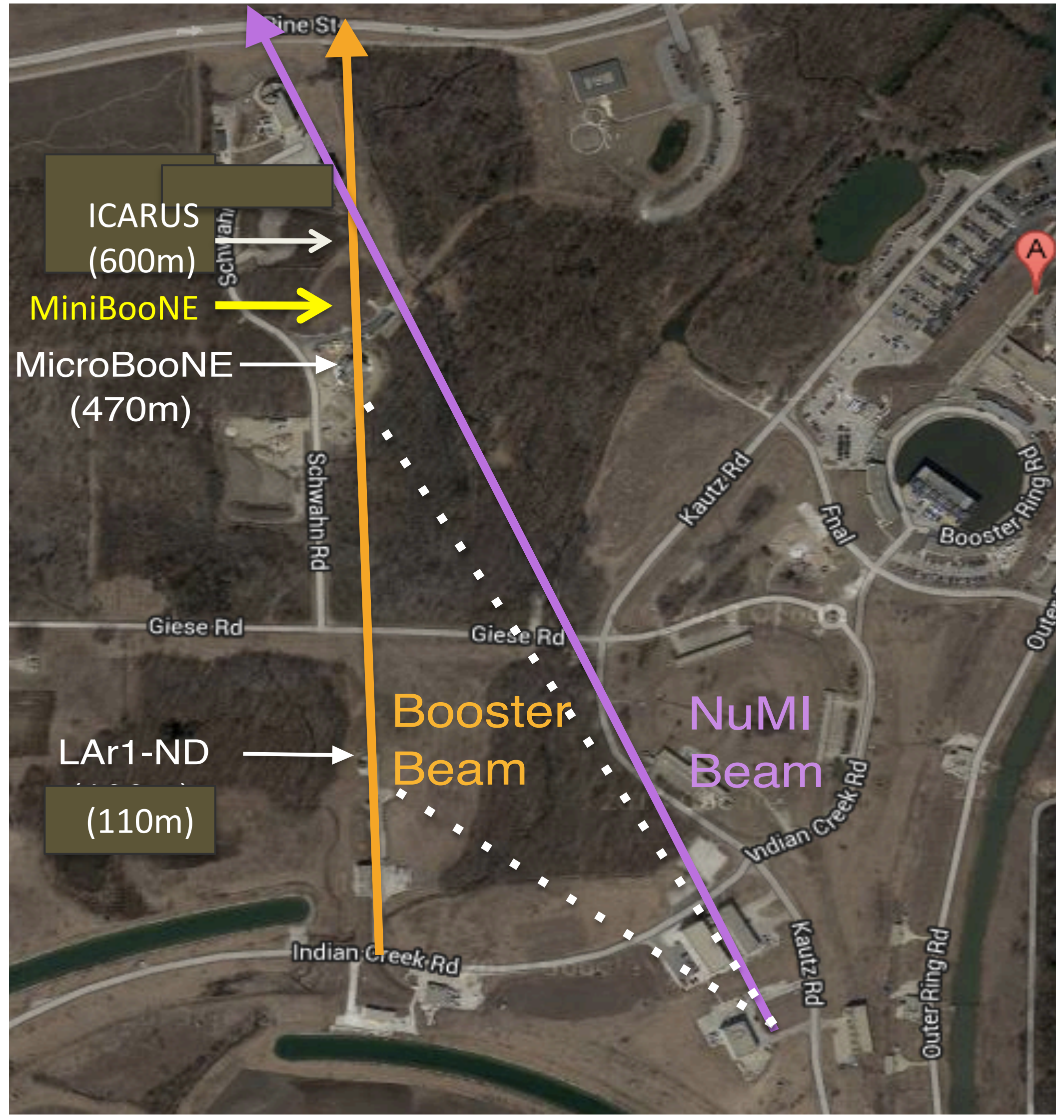
Where are we located?

The Fermilab Booster Neutrino Beam (BNB) (and NUMI beam in off-axis configuration).

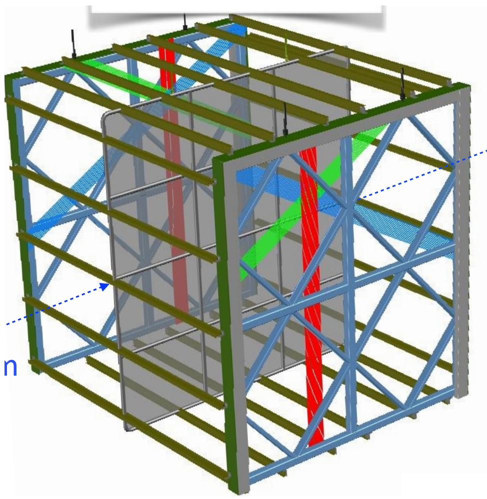
ICARUS: L=600m
476t Active volume TPC

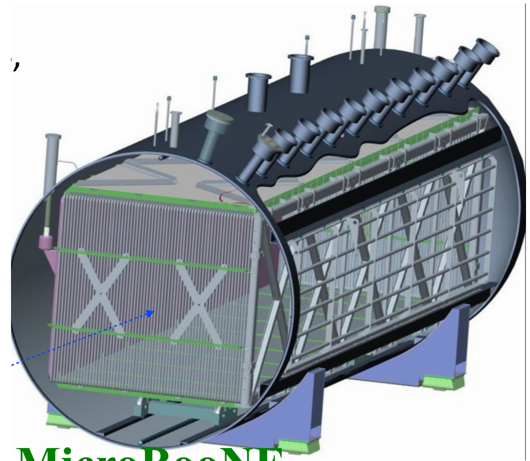
MicroBooNE: L=470m
89t Active volume TPC

LAr1-ND: L=110m
82t Active volume TPC

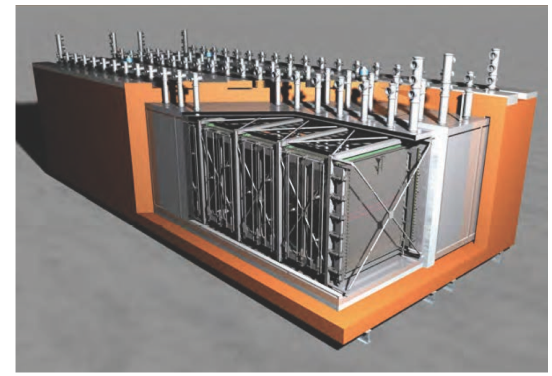


Where are we located relative to an oscillation pattern?





MicroBooNE

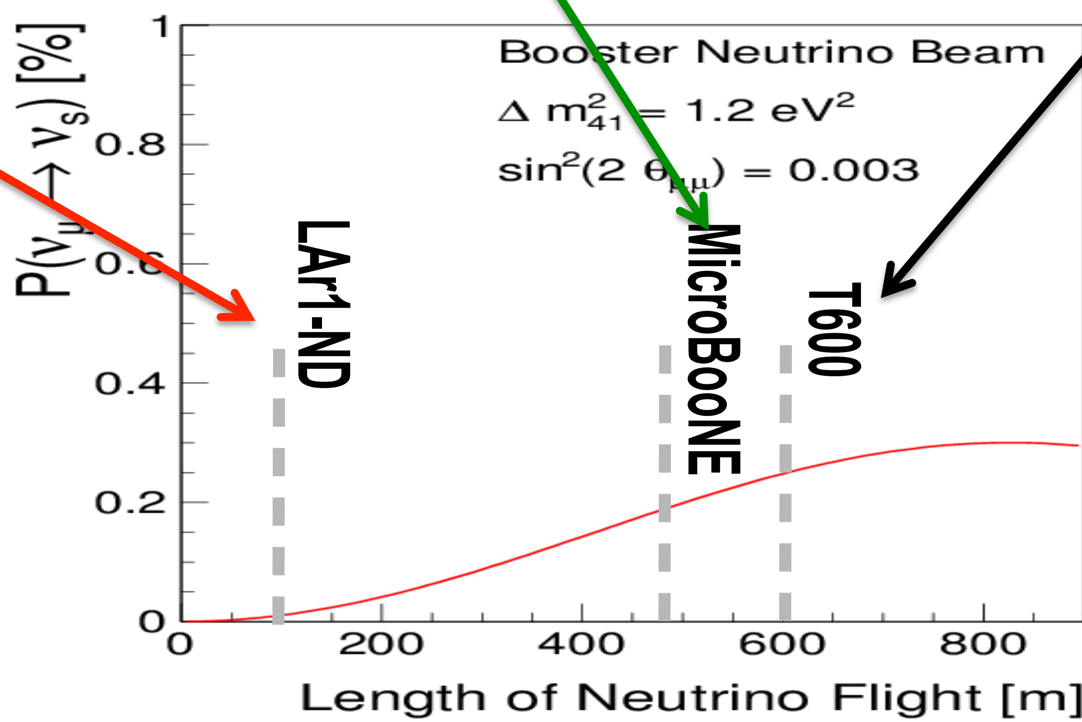


ICARUS

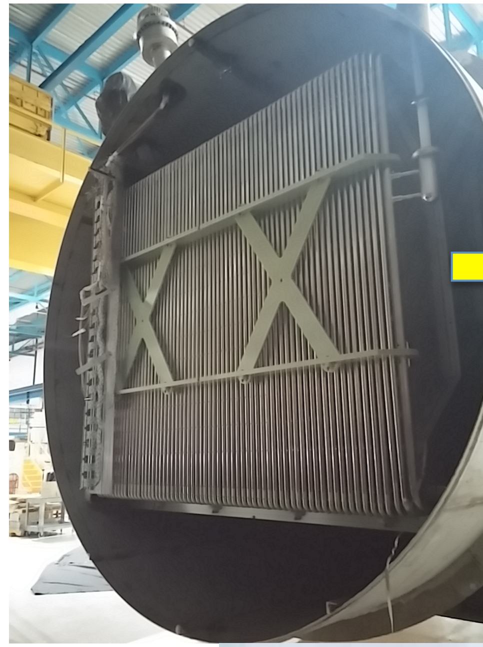
LAr1-ND

Sample the beam BEFORE Oscillations

High statistics event samples



The MicroBooNE Detector



The MicroBooNE Liquid Argon Time Projection Chamber

Neutrinos interact in 89 tons (active volume) Liquid Argon → charged particles.

Ionization e's drift
(**2.5m maximum**)
(1.6mm/μsec)->1.6msec.

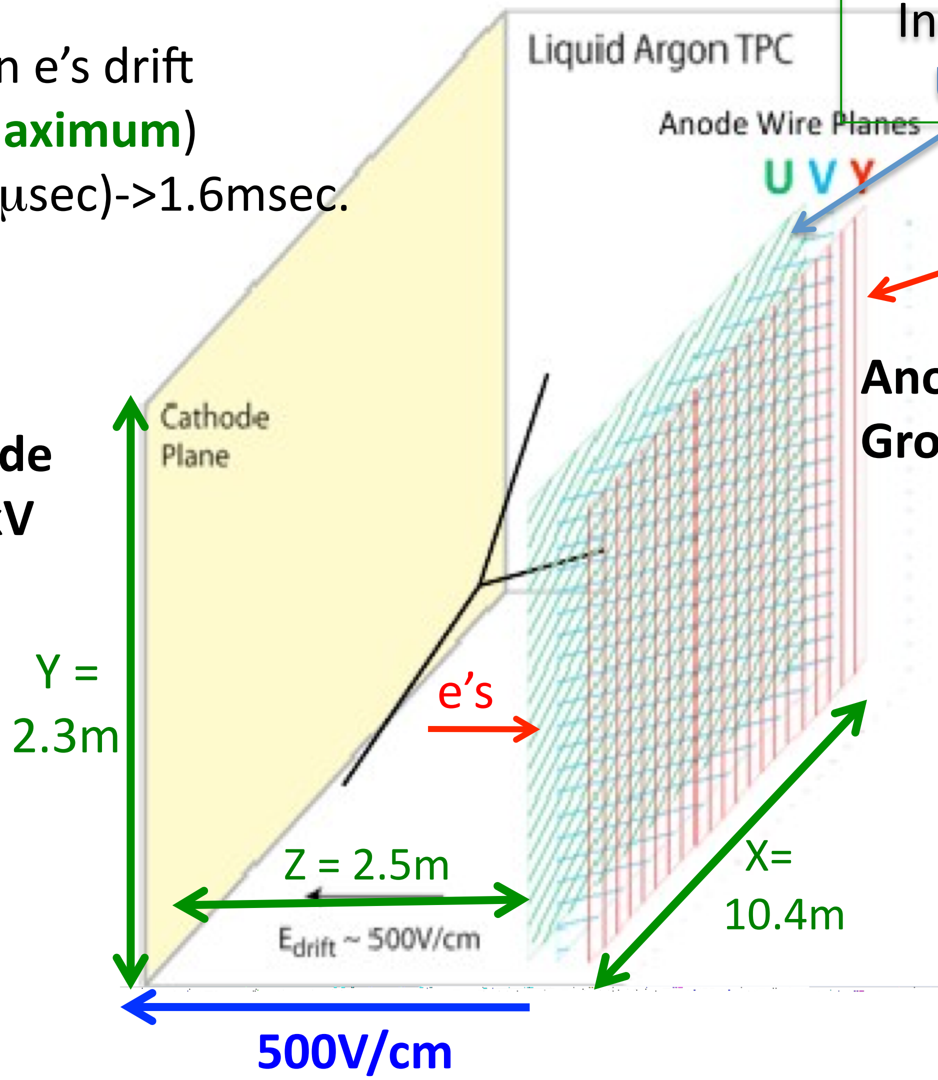
Cathode
-125 kV

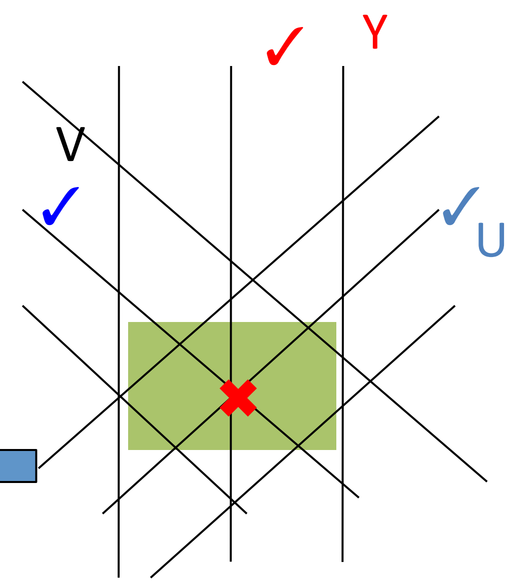
Induction planes
U V ± 60º

Collection plane.
Vertical wires

8256 wires

Anode at
Ground

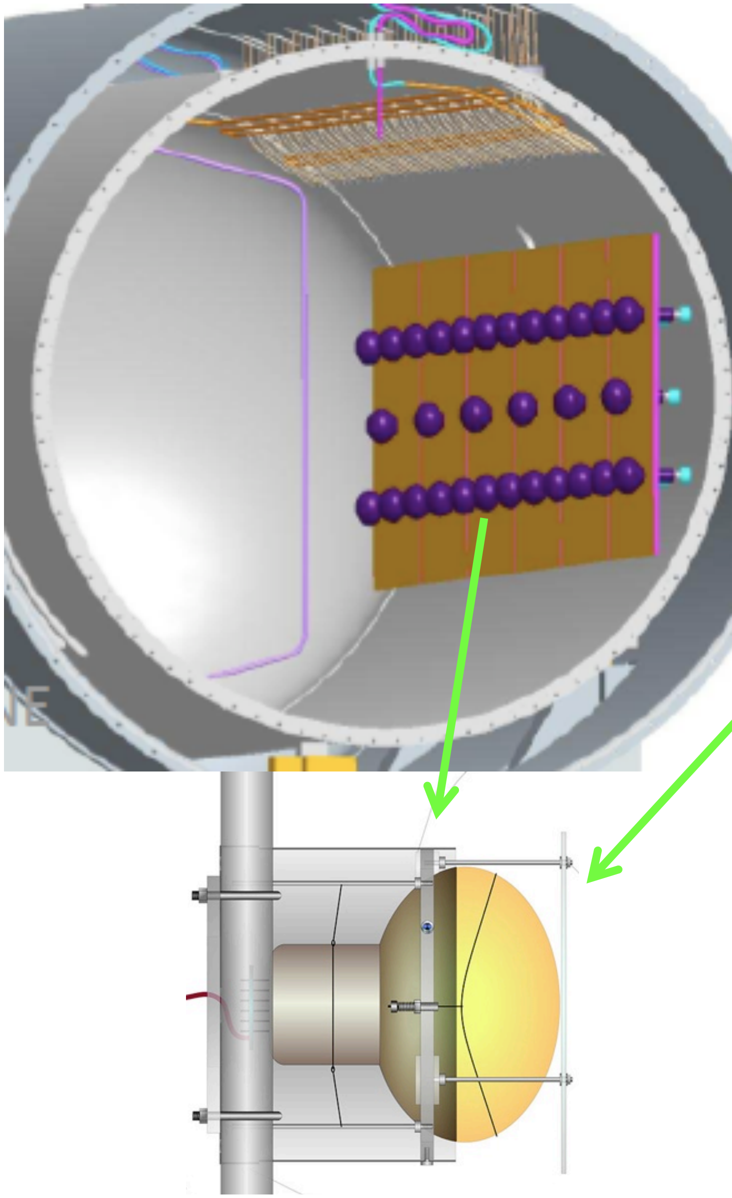




X,Y
Coord.

Drift time from t^0 gives Z
t^0 given by PMT's

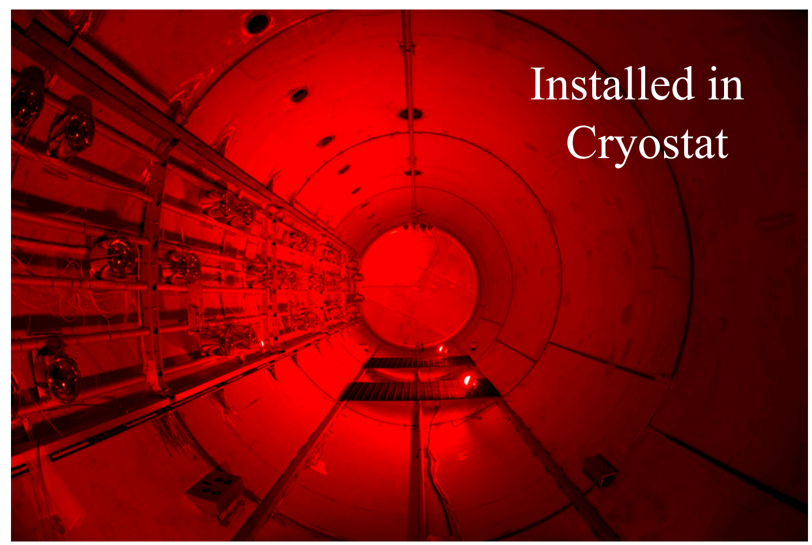
The MicroBooNE Photodetectors



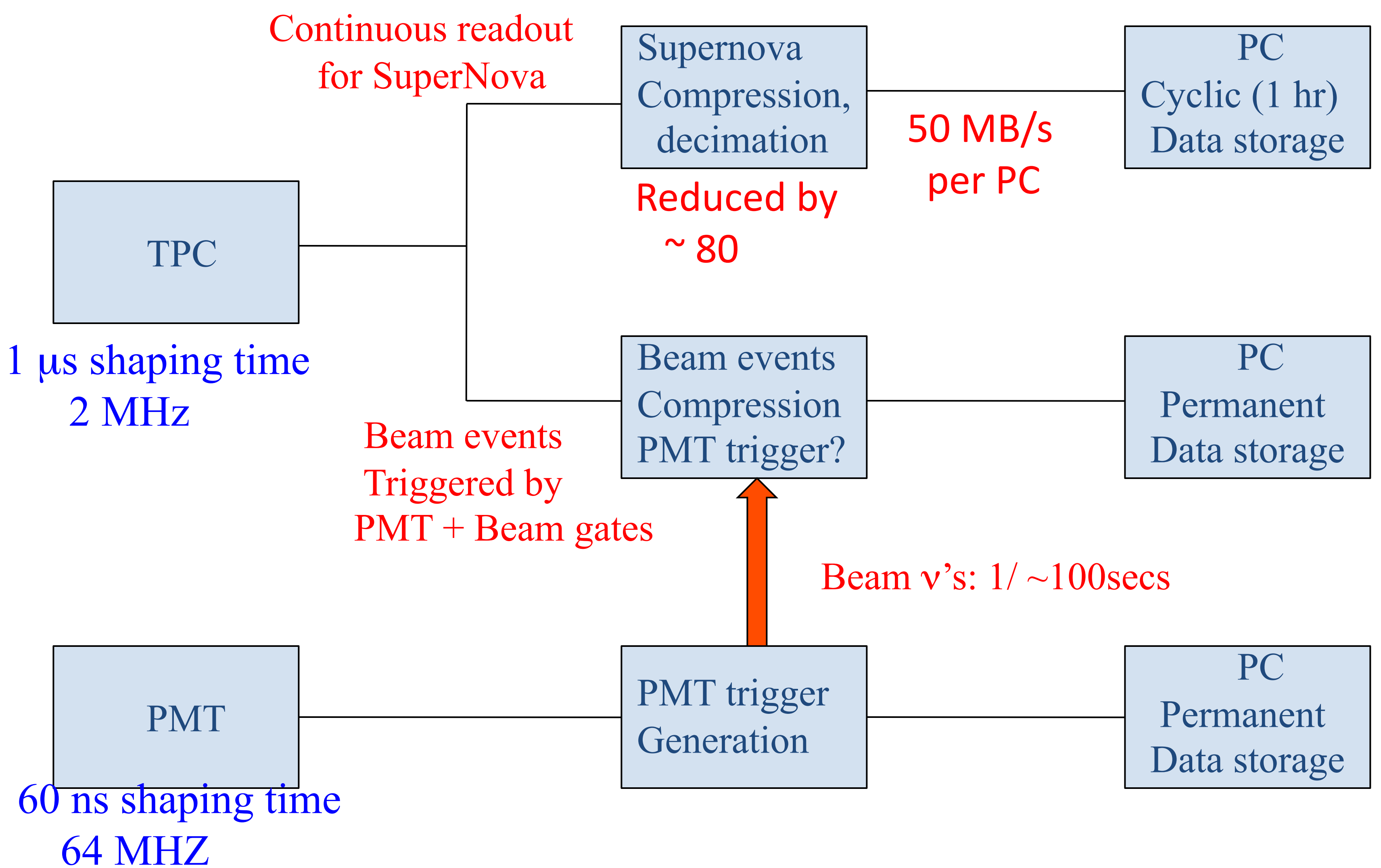
LAr scintillates in the UV at 128nm:
Use it
- To trigger on events in time with beam gate.
- To time and reject cosmic rays within drift time.

- 32 Hamamatsu R5912-02 14 stage 8 inch pmt’s.
- Located behind collection plane
- Plate coated with Tetraphenyl-butadiene (TPB)

in front of each pmt: to shift UV light to visible



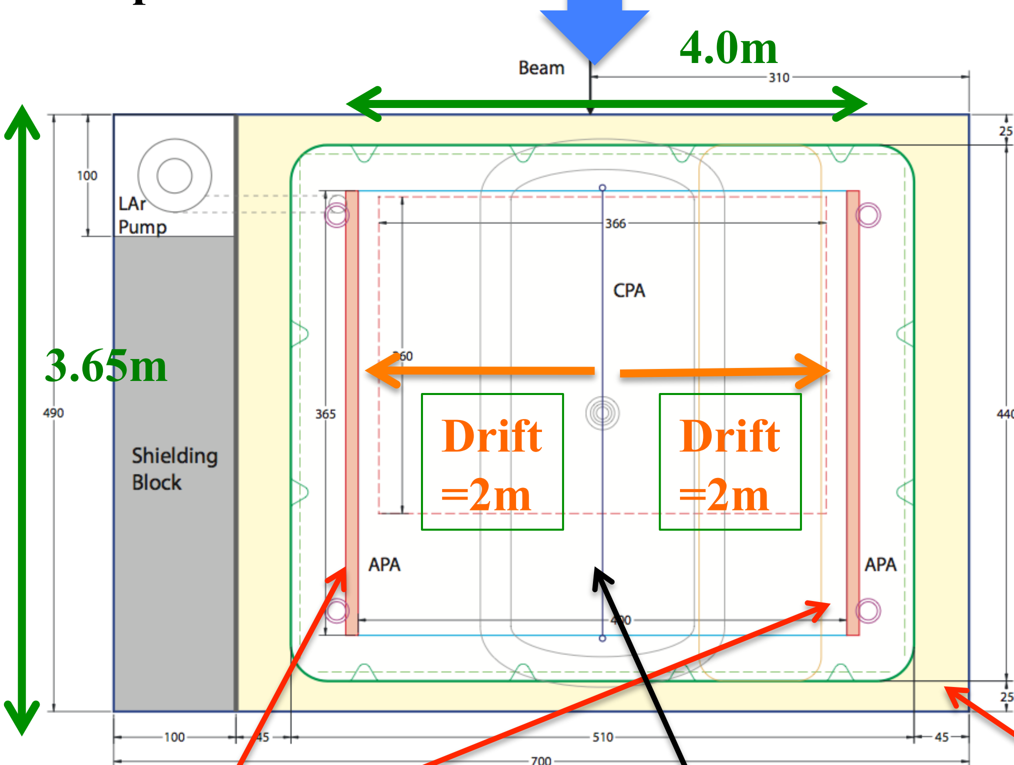
Triggered and SuperNova Continuous readout

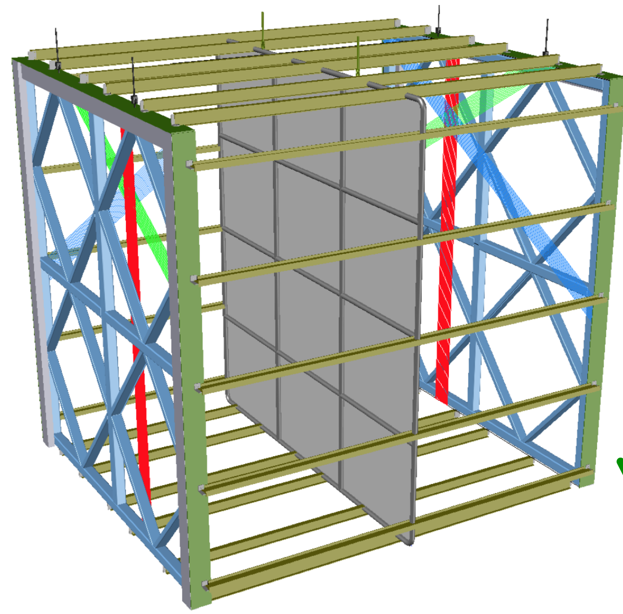


LAr1-ND

Top view

Beam





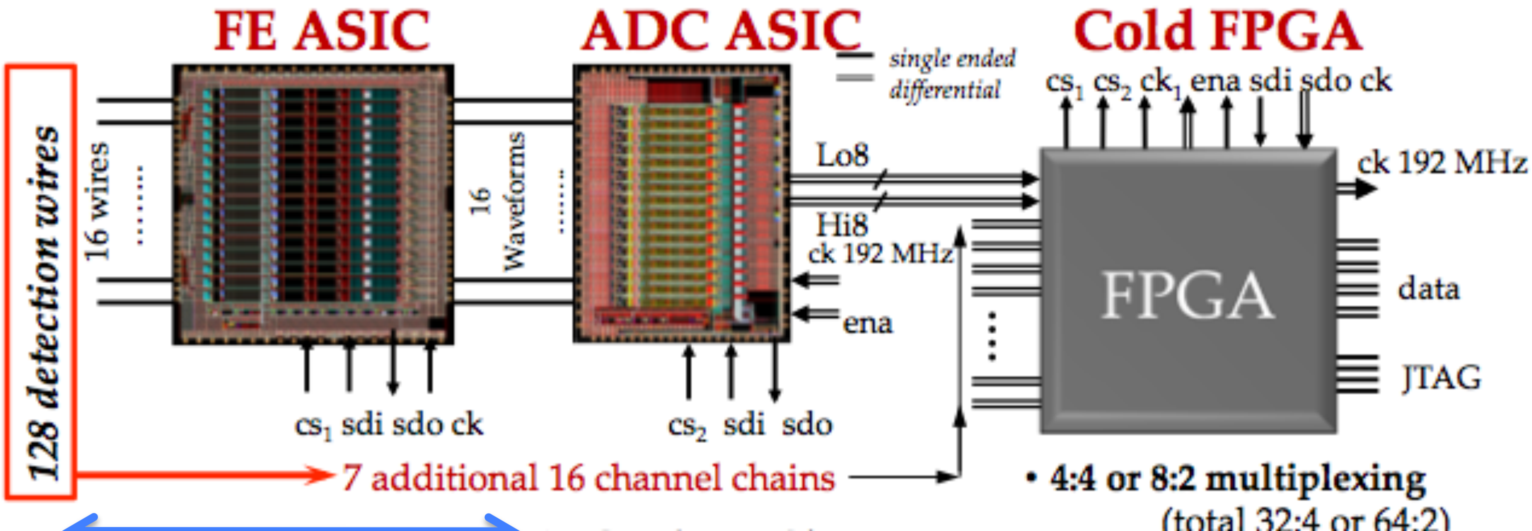
Height
4.0m

2 APA's
Anode Plane Assembly
(wires)

1 CPA
Cathode Plane Assembly

Membrane cryostat
as in LBNE

LAr1-ND Cold Electronics



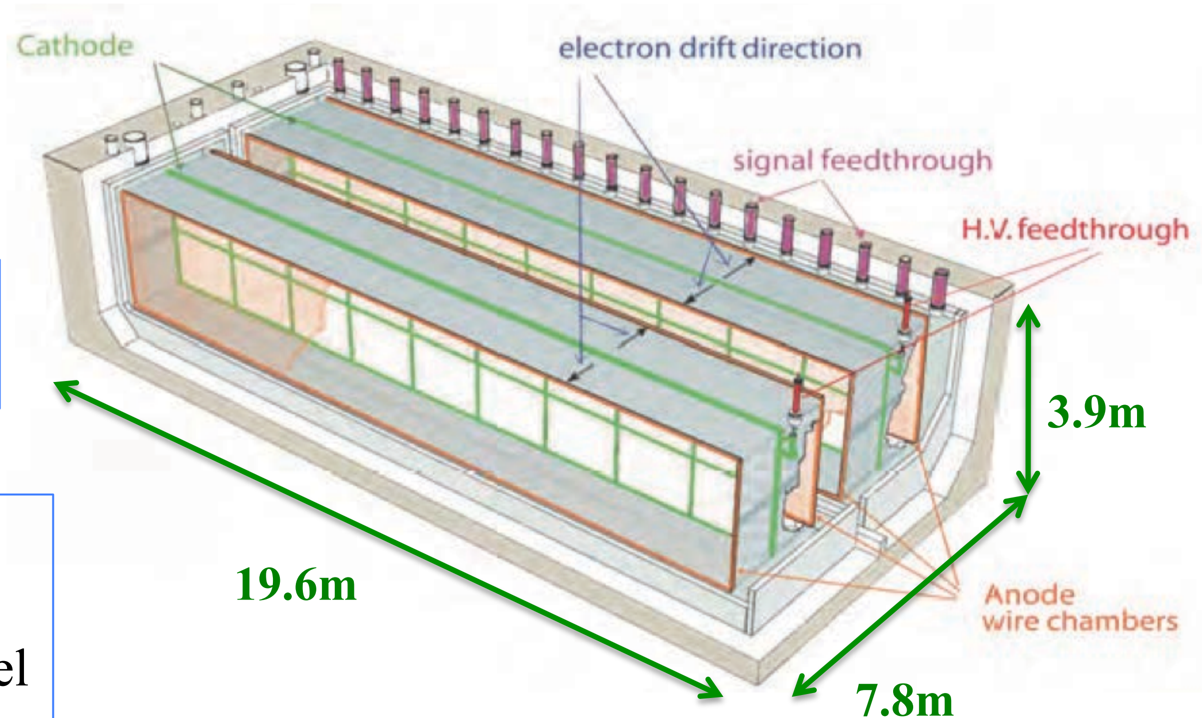
Already COLD in MicroBooNE

COLD in LAr1-ND

LAr1-ND Light Collection

Compact light-guide collection system to detect LAr scintillation light.

ICARUS

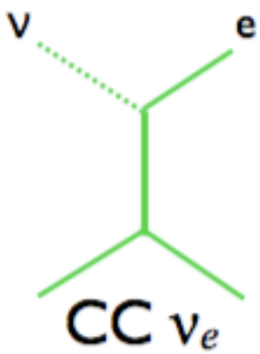


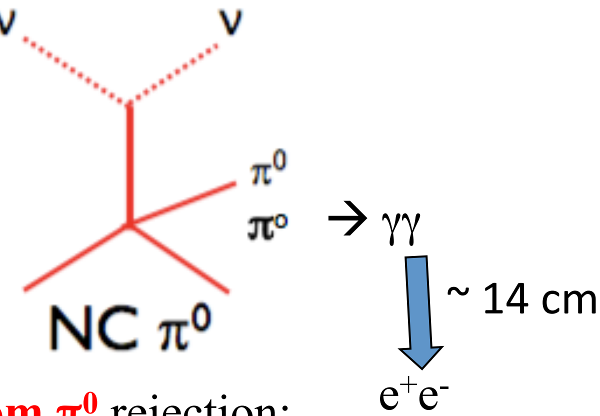
- Gran Sasso:
  Dismantling and move to
- CERN: Refurbishing
  - New electronics
  - New containment vessel
  - New insulation
  - New light collection.
- Fermilab:
  - New Building
  - New cryogenics

- 4 anode wire planes
- Same 3mm wire spacing as MicroBooNE and LAr1-ND
- 2 cathodes

What is the MiniBooNE excess due to? Electrons or Photons?

Electron : Connected to primary vertex
And singly ionizing track in first ~ 2.4cm
before shower develops.



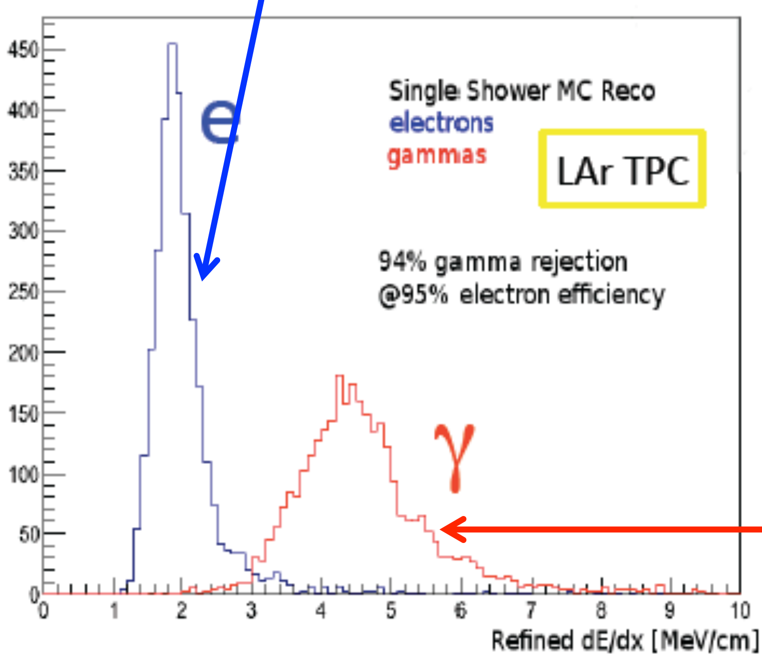


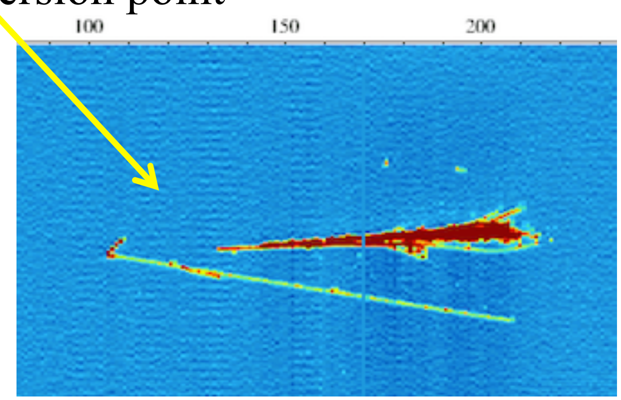
Photons from π^0 rejection:

- Recognize 2 photons → π^0 mass

Single Photon rejection:

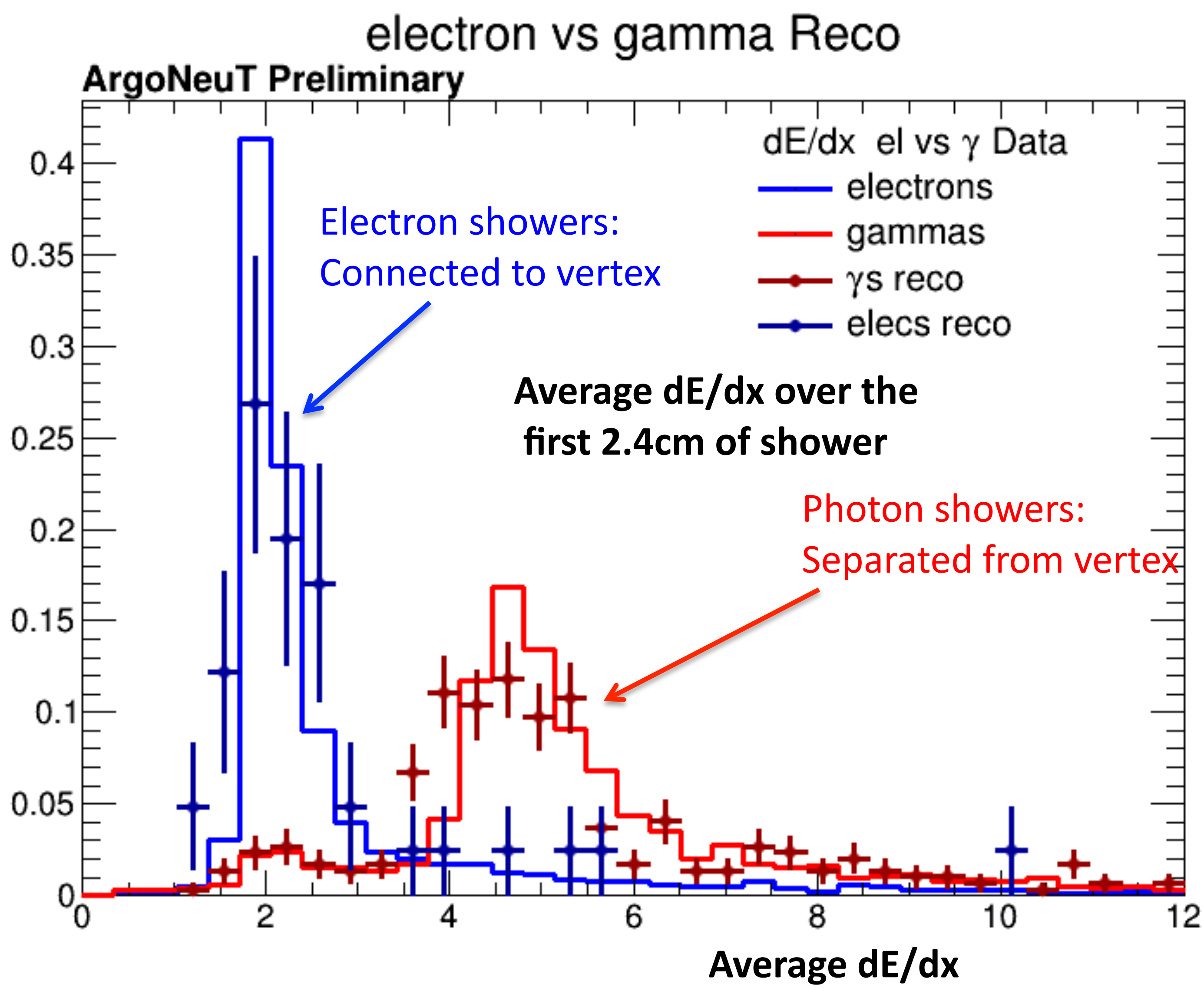
- Gap between primary vertex and conversion point



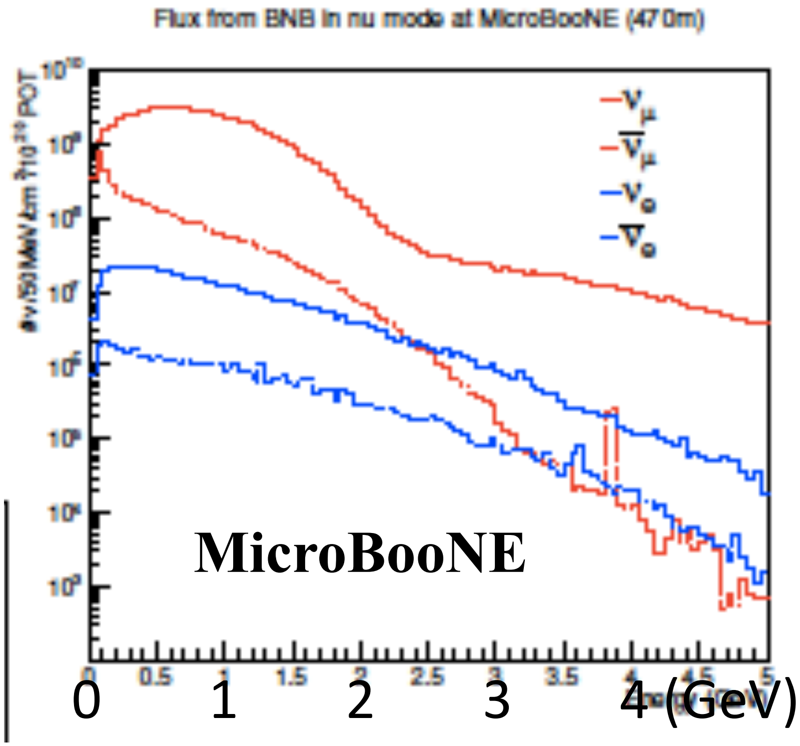


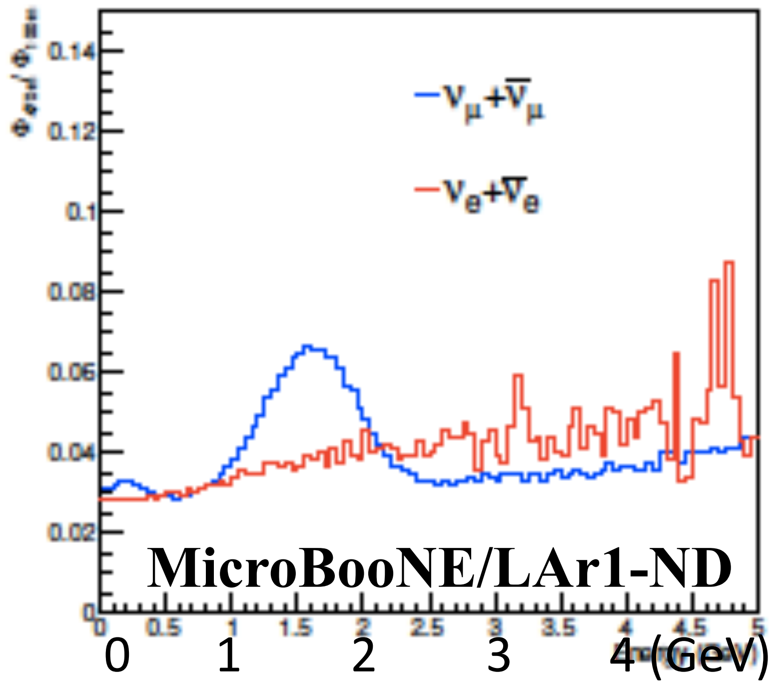
- and doubly ionizing track in first ~ 2.4cm
- → 94% rejection of "single γ".

ArgoNeut validates the technique



BNB Flux Spectra in ν mode





Peaks at ~ 600 MeV

~1% ν_e content

MiniBooNE Low Energy Excess

Scaling signal from MiniBooNE: Down for Mass, up for Efficiency
Scaling backgrounds according to better PID and better flux knowledge

Assuming no distance dependence: (**NOT** an oscillation)

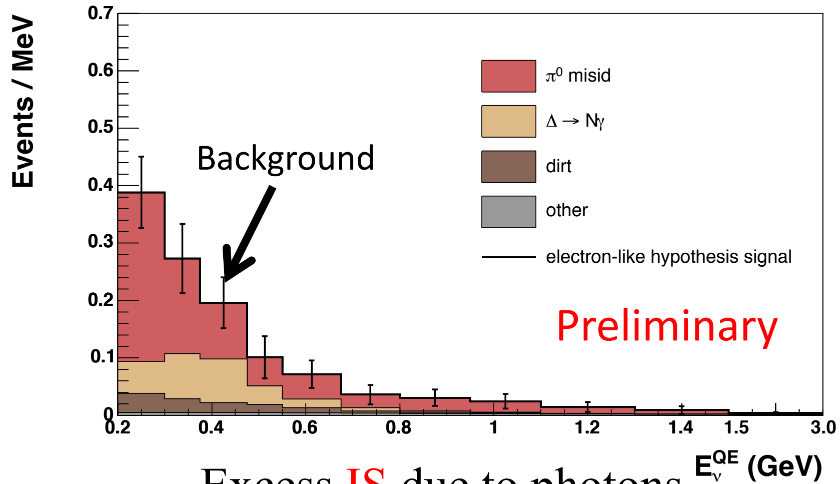
	MicroBooNE	LAr1-ND
Total Events	97	775
"Low-energy Excess"	47.6	380
Background	49.4	394.6
Statistical Error	7.0	19.9
Systematic Error	6.6	52.2
Total Error	9.6	55.9
Statistical Significance of Excess	6.8 σ	19.1 σ
Total Significance of Excess	**5.0** σ	**6.8** σ

6.6×10^{20} POTs | 2.2×10^{20} POTs

If Excess due to Photons.

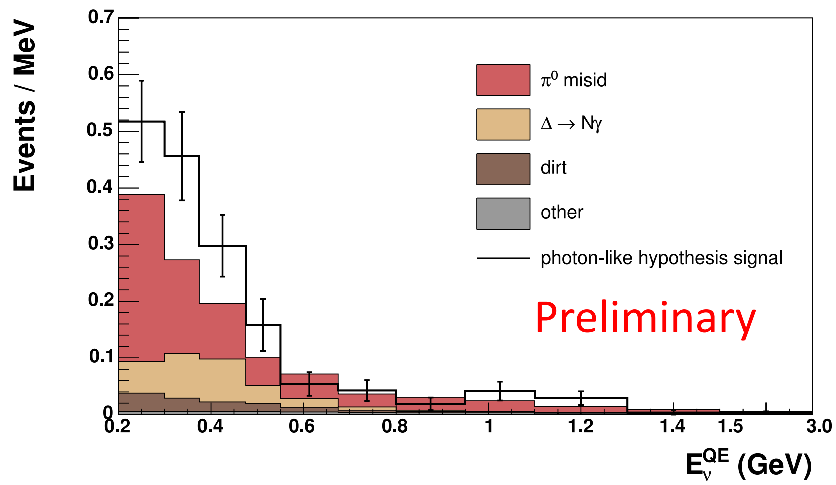
Different Cuts to Select Photons, Reject e's

Excess is NOT due to photons



Excess IS due to photons

→ 4.1σ



(Estimated from MiniBooNE rates)

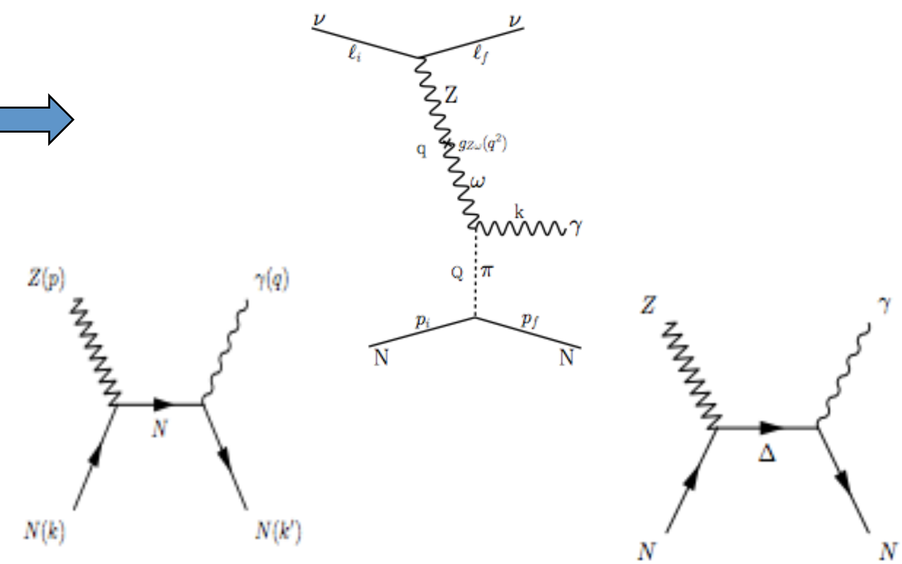
- Background: γ or π^0

OR

- Radiative ν interaction

Examples:

- R. Hill arXiv: 0905.0291
- Jenkins et al arXiv:0906.0984
- Serot et al arXiv: 1011.5913



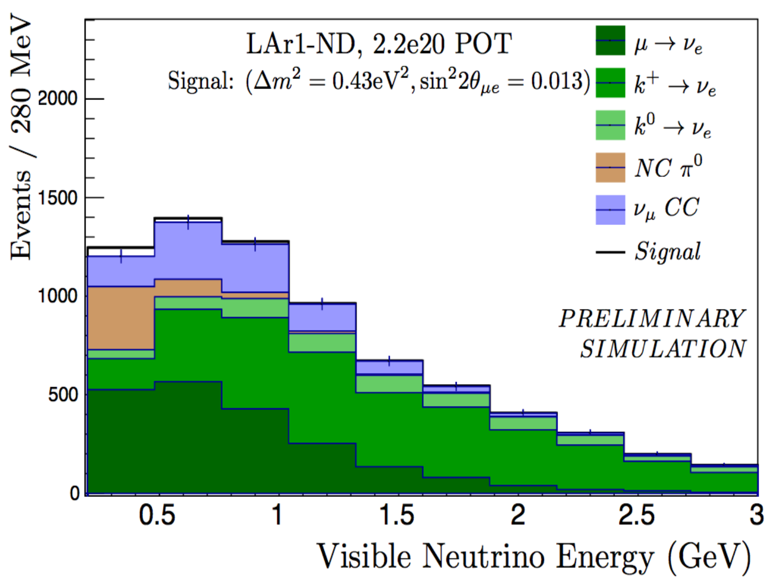
What would we expect for an oscillation at the Global best fit?

- $\nu_\mu \rightarrow \nu_e$ appearance in the context of 3 active + 1 sterile neutrino model (3+1)

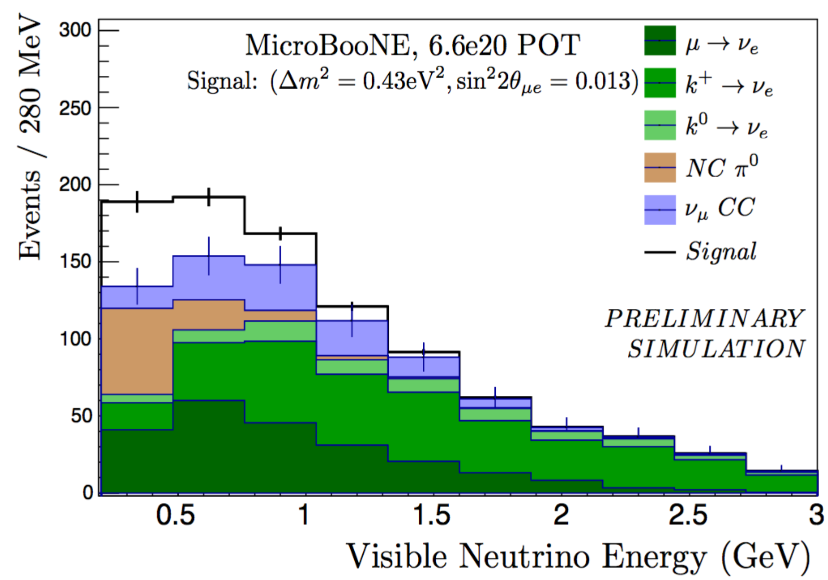
Example Signal: $\Delta m^2 = 0.43\ eV^2$, $\sin^2 2\theta_{\mu e} = 0.013$

Cuts to Select Electrons, Reject γ's

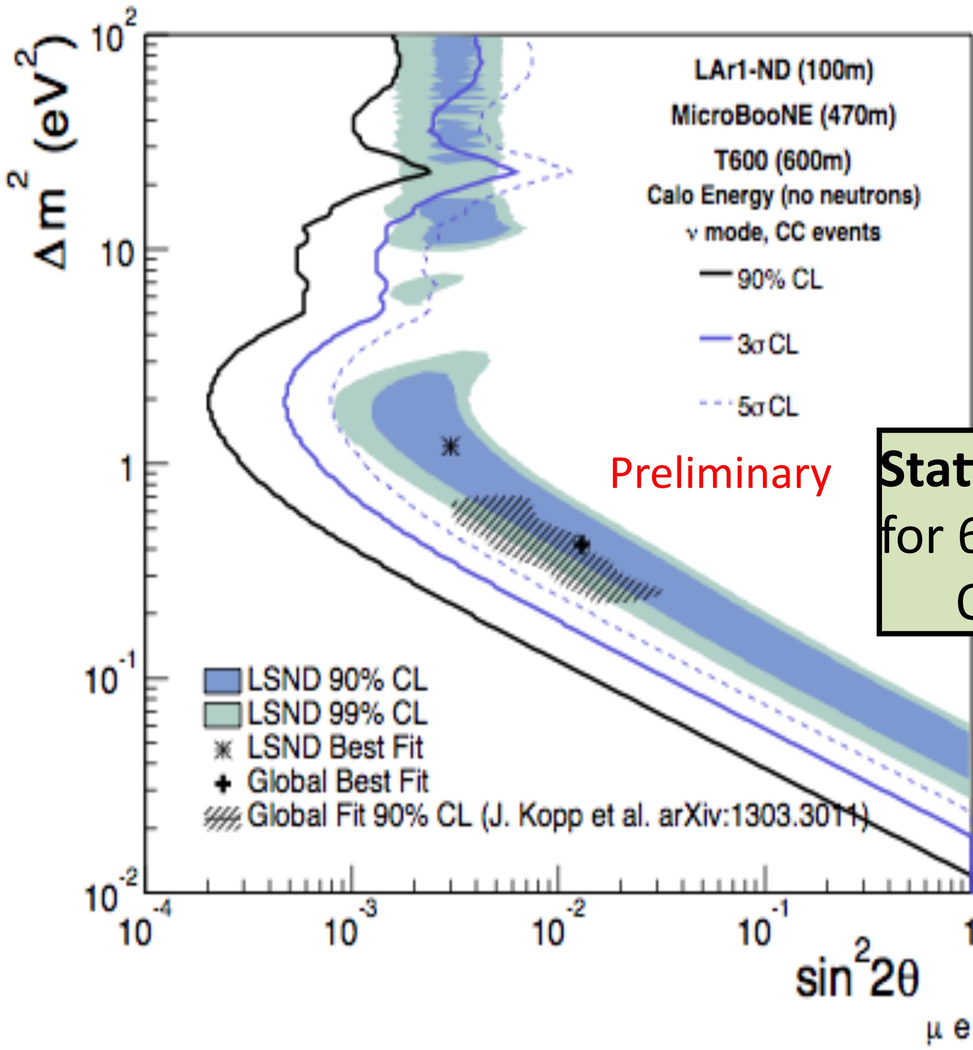
2.2 x 10^{20} POT exposure for LAr1-ND

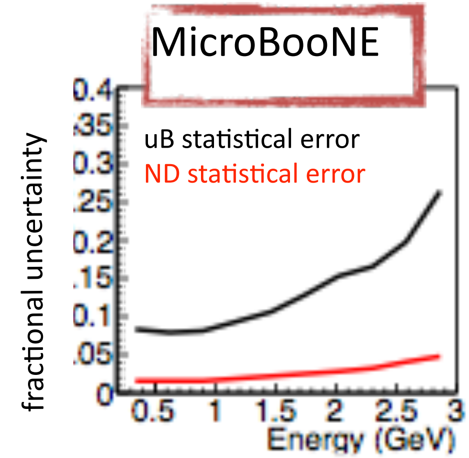


6.6 x 10^{20} POT exposure for MicroBooNE

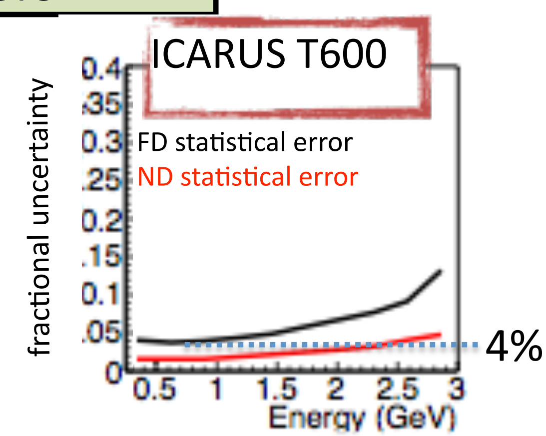


The power of a Three Detector Combination:
$\nu_\mu \rightarrow \nu_e$ sensitivity





Statistical Uncertainty Limit
for 6.6e20 POT exposure
On all 3 detectors

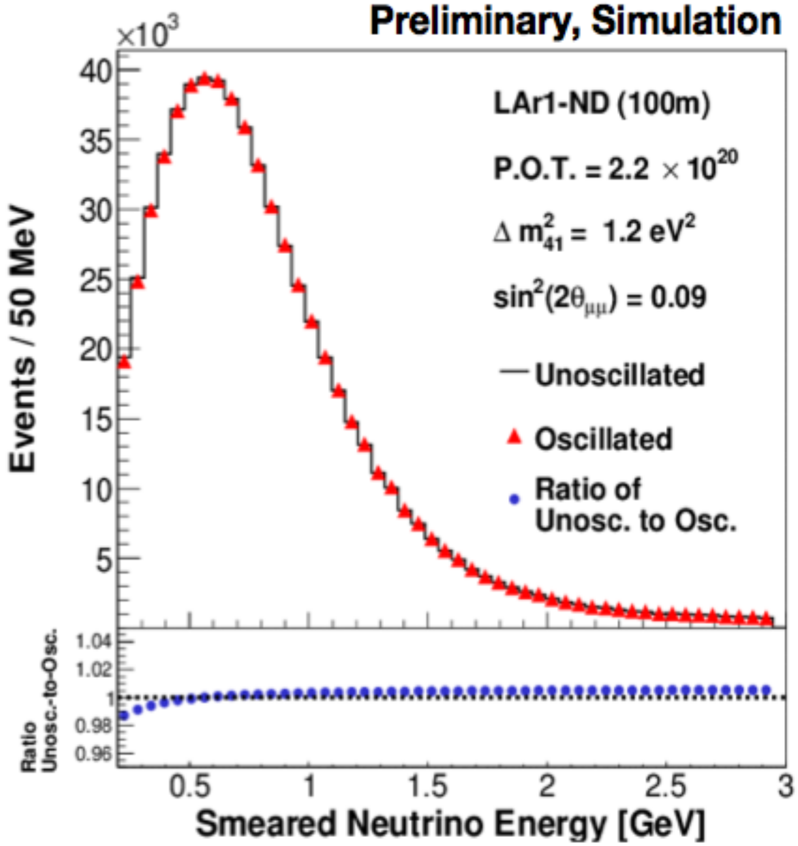


ν_μ Disappearance

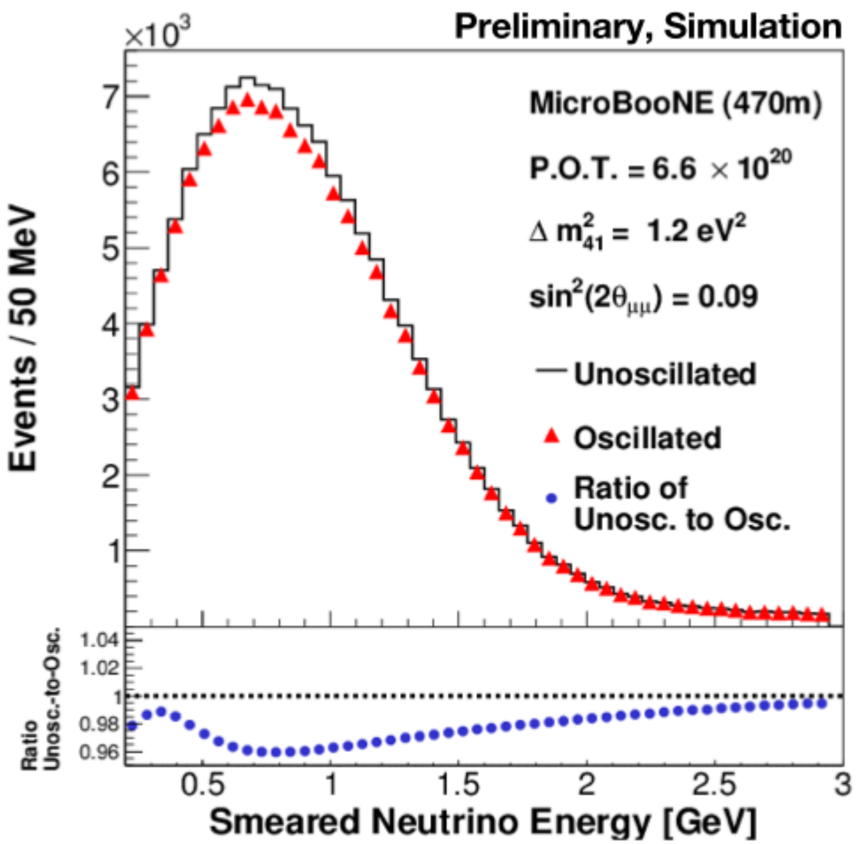
- Testing ν_μ disappearance with a near detector constraint

$\Delta m_{41}^2 = 1.2\ eV^2 \quad \sin^2 2\theta_{\mu\mu} = 0.09$

- LAr1-ND: 2.2×10^{20} POTs



MicroBooNE: 6.6×10^{20} POTs

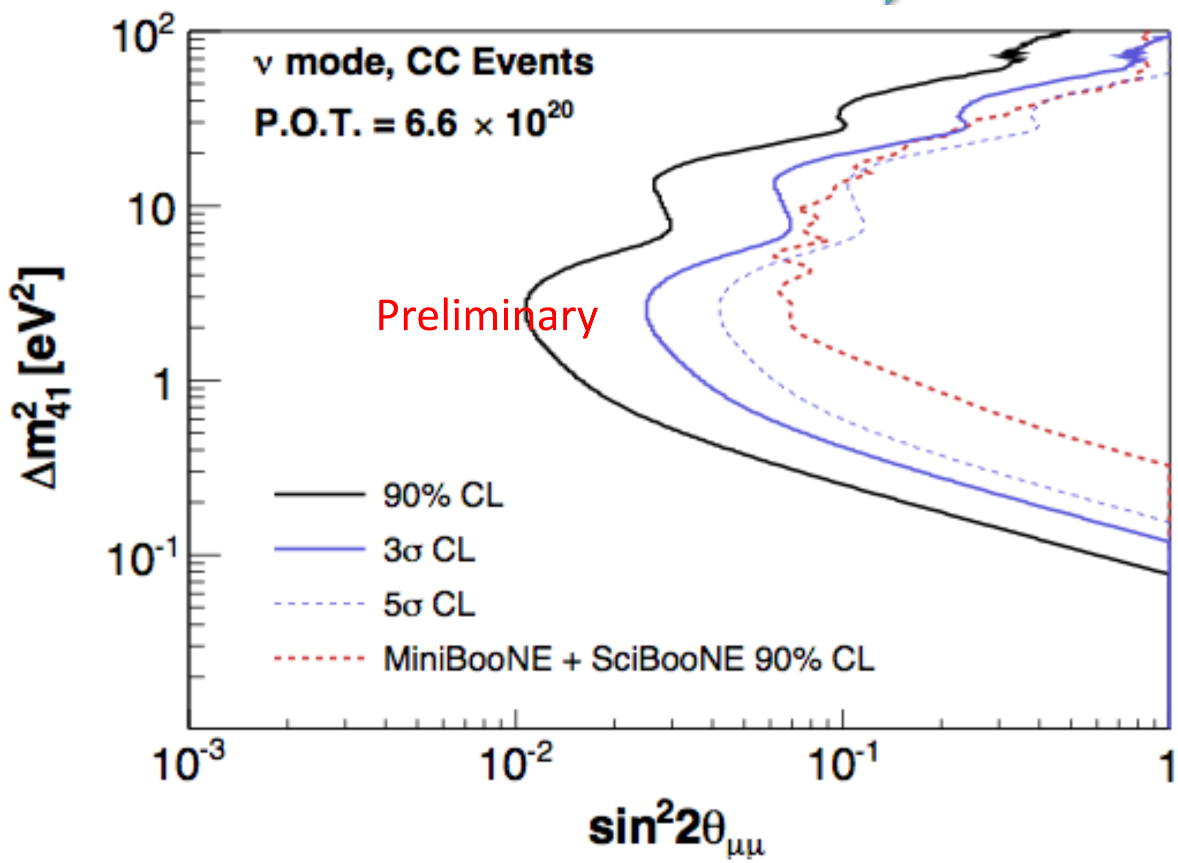


ν_μ Disappearance

6.6x10[20] POT exposure for MicroBooNE

+ND

2.2x10[20] POT exposure for LAr1-ND



ν_μ disappearance not a statistics limited search. Here shown with a 4% systematic uncertainty on the near to far extrapolation.

Previous limit at high Δm^2 limited by near and far detectors being different technologies

Exploiting the full correlations

- The observed electron candidate event rate in LAr1-ND at 110m is used to constrain the expected rate in MicroBooNE and ICARUS.

- The ν_μ are also used as a constraint as they have the same parent as the μ's that generate

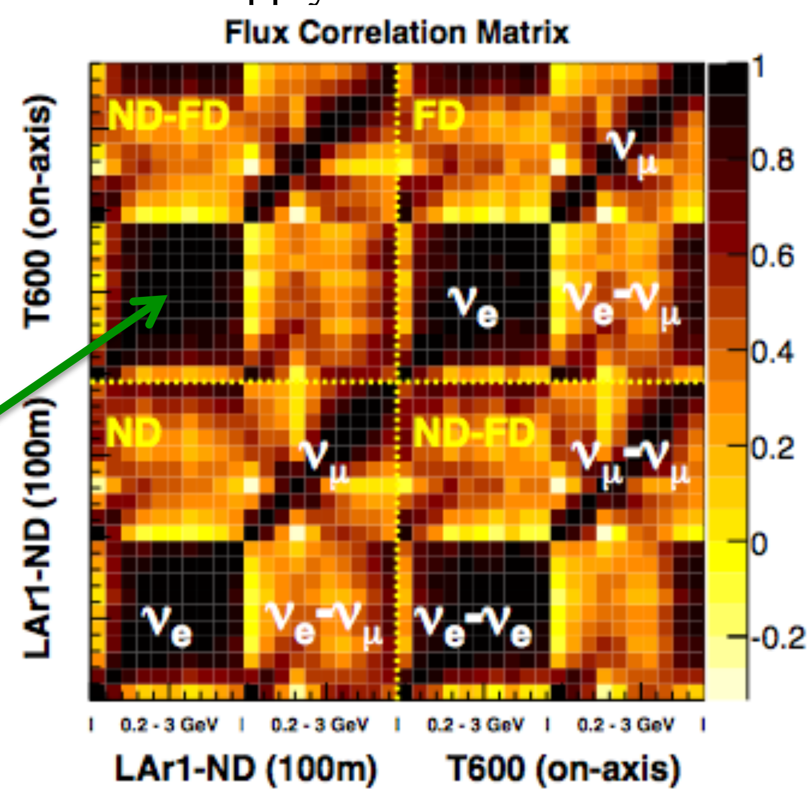
- part (75%) of the intrinsic ν_e background.

- Simultaneous fit to Near, Far, ν_μ and ν_e data sets is used to apply the constraints.

Using a Flux Correlation Matrix between Far (600m) and Near(110m) detectors and between ν_μ and ν_e.

Obtained using ReweightingTechnique
Vary flux: reweight simulated events of **BOTH** ND and FD detectors.
with each variation

Strong Correlation between
Far (600m) and Near(110m) detectors
ν_e fluxes.



Neutrino –Argon Interactions

Neutrino-Argon Interactions at low energy (~ 1 GeV).

- Why are they important?
  - Only measurements on Argon: ArgoNeut.
  - Few measurements in this energy range.
  - Not very consistent.
- **Important**
  - **In their own right.**
  - **For LBNE 2nd max.**
  - **HyperK**

Expected Data Sample

MicroBooNE: 6.6 x 10^{20} protons on target: ~ **120k CC + NC**
LAr1-ND: 2.2 x 10^{20} protons on target (ONE year of data taking): **~1.1M CC + NC**

Process	Reaction	MicroBooNE 6.6 x 10^{20}POT	LAr1-ND 2.2 x 10^{20} POT
CC QE	$\nu_\mu\, n \rightarrow \mu^- p$	48,276	470,497
CC RES	$\nu_\mu\, N \rightarrow \mu^- N$	26,852	220,177
CC DIS	$\nu_\mu\, N \rightarrow \mu^- X$	10,527	82,326
CC Coherent	$\nu_\mu\, Ar \rightarrow \mu^- Ar+\pi$	376	3004

Data presentation.

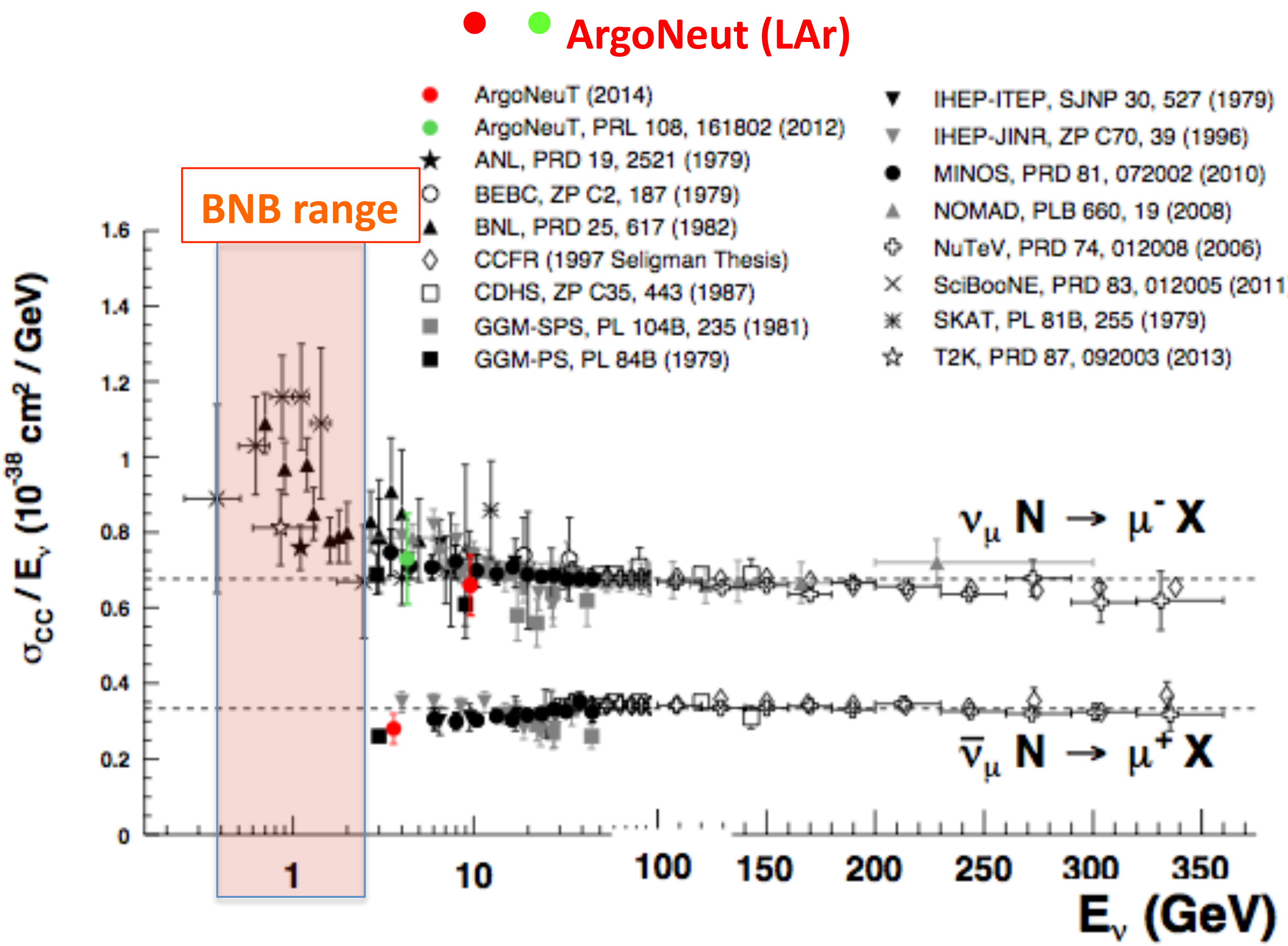
Instead of unravelling specific "true at production" final states
taking into account reinteractions

Present topological final states based on number of protons, number of pions

Process	Reaction	MicroBooNE 6.6×10^{20}POT	LAr1-ND 2.2×10^{20}POT
CC Inclusive		88,098	787,847
CC 0π	$\nu_\mu N \rightarrow \mu^- + Np$	56,580	535,673
	$.\nu_\mu N \rightarrow \mu^- + 0p$	12,680	119,290
	$.\nu_\mu N \rightarrow \mu^- + 1p$	31,670	305,563
	$.\nu_\mu N \rightarrow \mu^- + 2p$	5,803	54,287
	$.\nu_\mu N \rightarrow \mu^- + \geq 3p$	6,427	56,533
CC $1\ \pi^\pm$	$\nu_\mu N \rightarrow \mu$ + nucleons + $1\ \pi^\pm$	21,887	176,361
CC $\geq 2\pi^\pm$	$\nu_\mu N \rightarrow \mu$ + nucleons + $\geq 2\pi^\pm$	1,953	14,659
CC $\geq 1\pi^0$	$\nu_\mu N \rightarrow \mu$ + nucleons + $\geq 1\pi^0$	9,678	76,129

Similarly for Neutral Current Interactions

Inclusive cross section



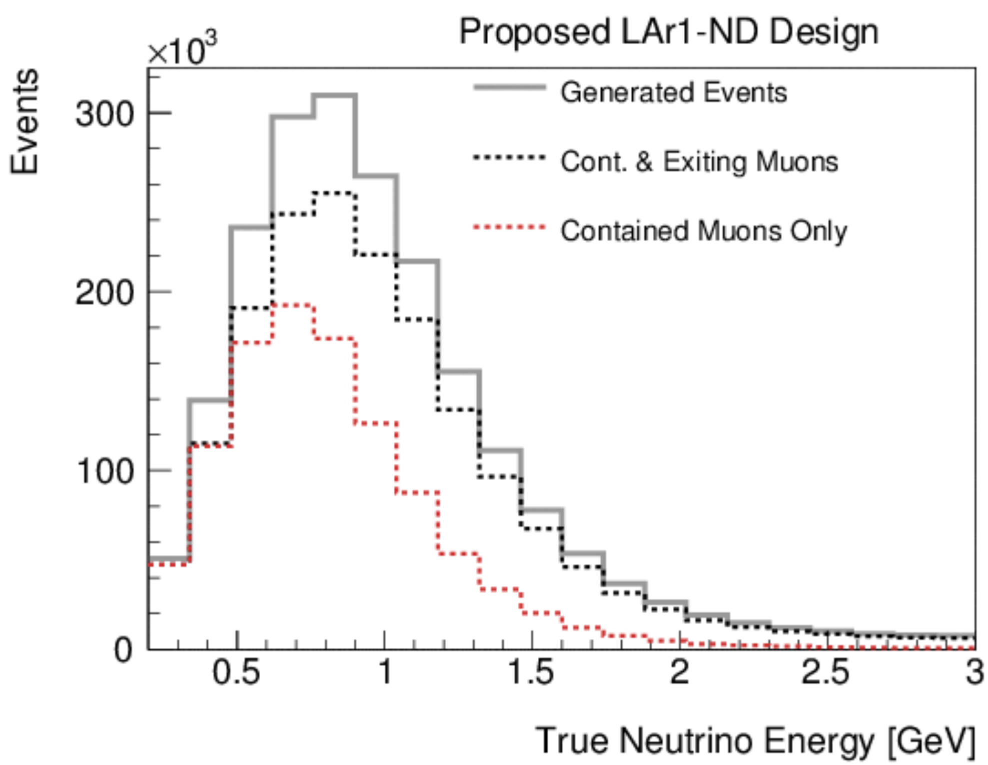
Will measure in a region where

- there are no Argon points and
- some inconsistent results
- 2nd oscillation maximum at LBNE

Charged Current Inclusive in LAr1-ND: Muon measurement.

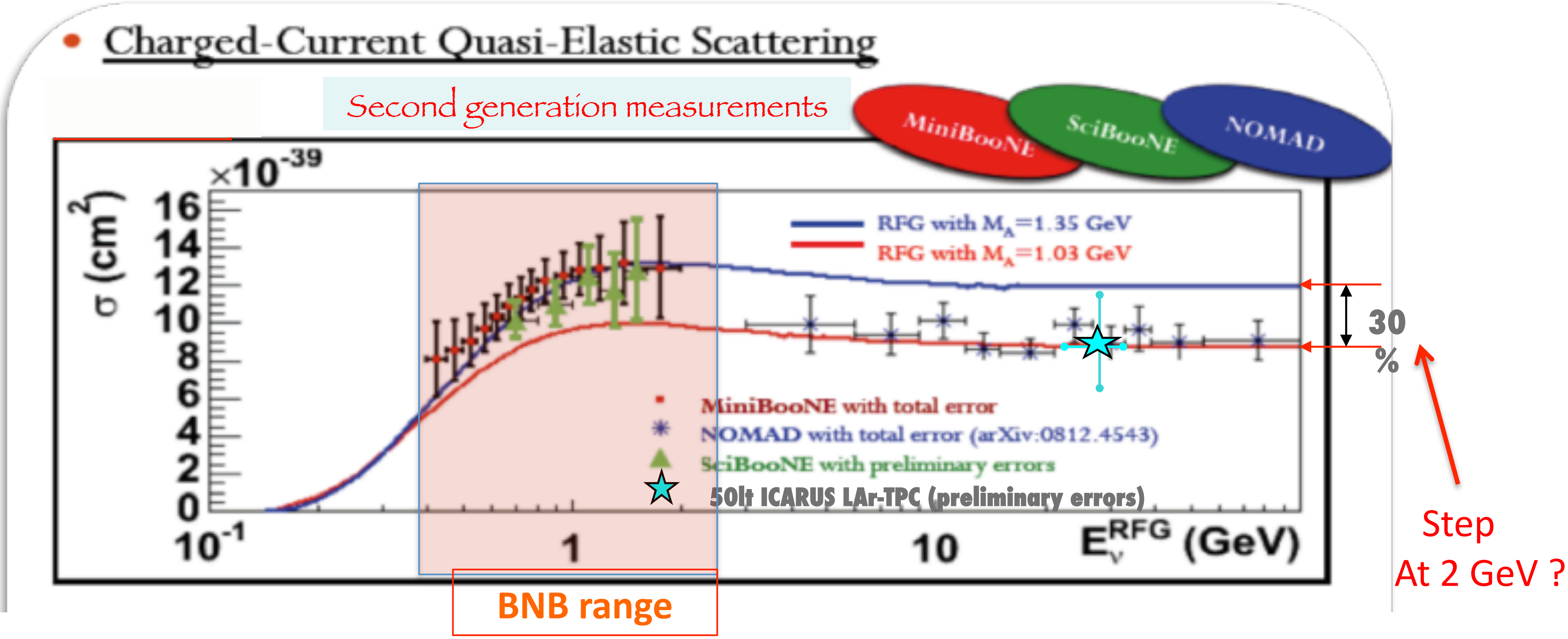
- **Contained muons:** Momentum measured through range and dE/dx with **5%** Resolution
- Can we also use **non-contained muons**?
  - Identification through dE/dx as a function of distance from exit point.
  - Momentum measurement: through multiple scattering.

    For contained tracks > 1m according to ICARUS data: Resolution: 30%.



Contained: **50%**
Non-contained (Long > 1m): **34%**
Total: **84%.**

QuasiElastic



Questions:

QE is an easy topology: 1 muon + 1 proton → **Or is it?**

Nuclear Reinteractions

Nuclear reinteractions → NO proton or MANY Nucleons in Final State
How do we know they are treated correctly in the simulation?

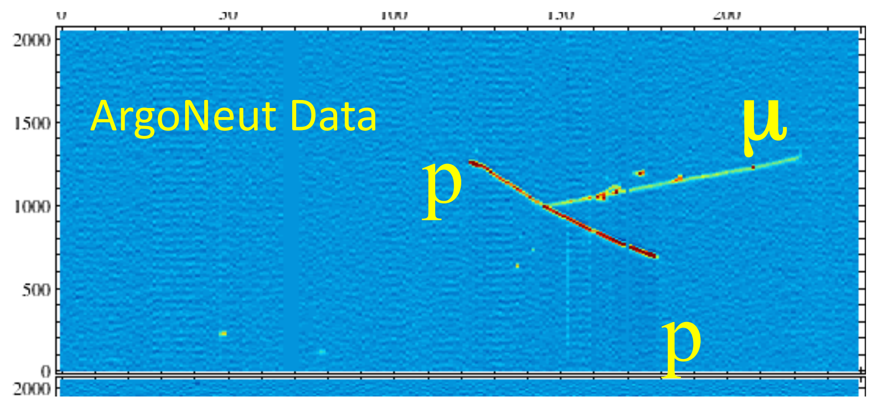
No proton

In NOMAD, the nuclear formation length was tuned such as to

equalize the cross sections calculated from the 2 samples:

- One Muon and No Proton sample
- One Muon and One Proton sample

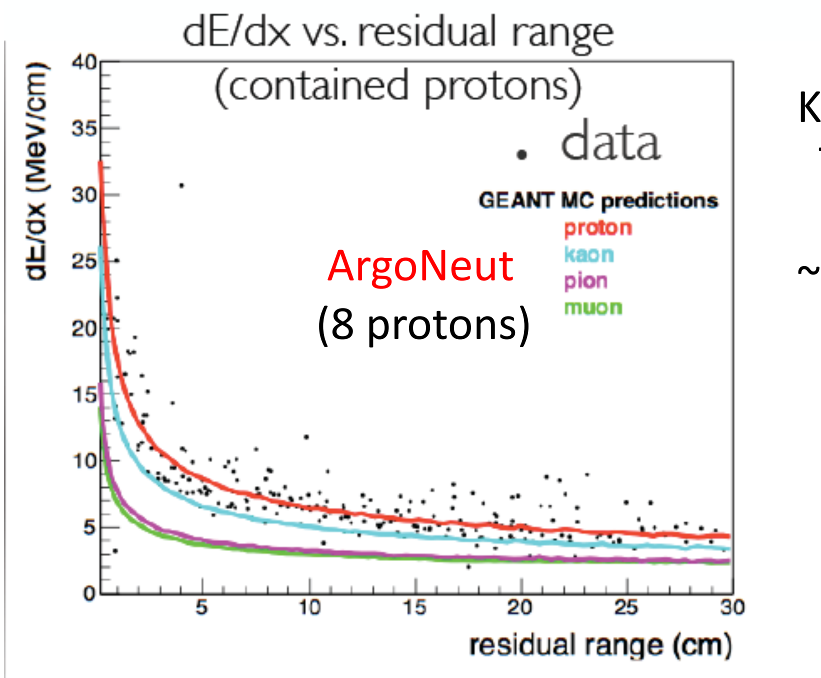
Two-protons



Use dE/dx as a function of residual range (distance from stopping point).

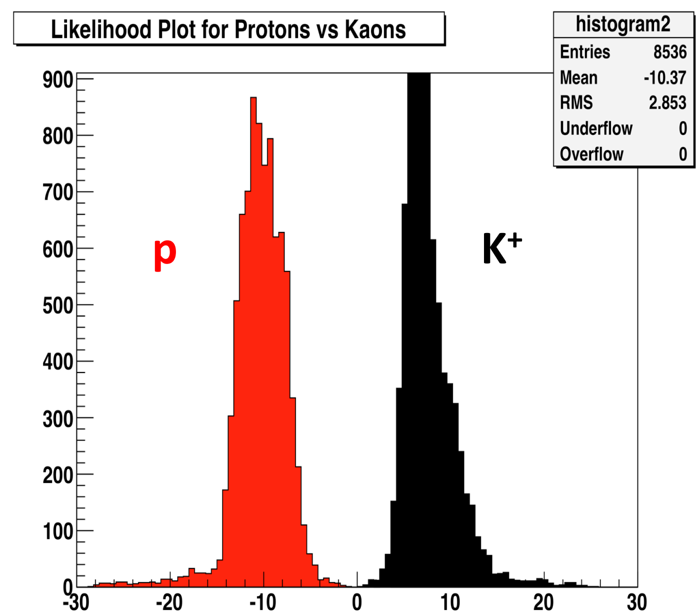
Can we identify them?

Build likelihoods using several measurements along track.
Example: Simulation and Truth

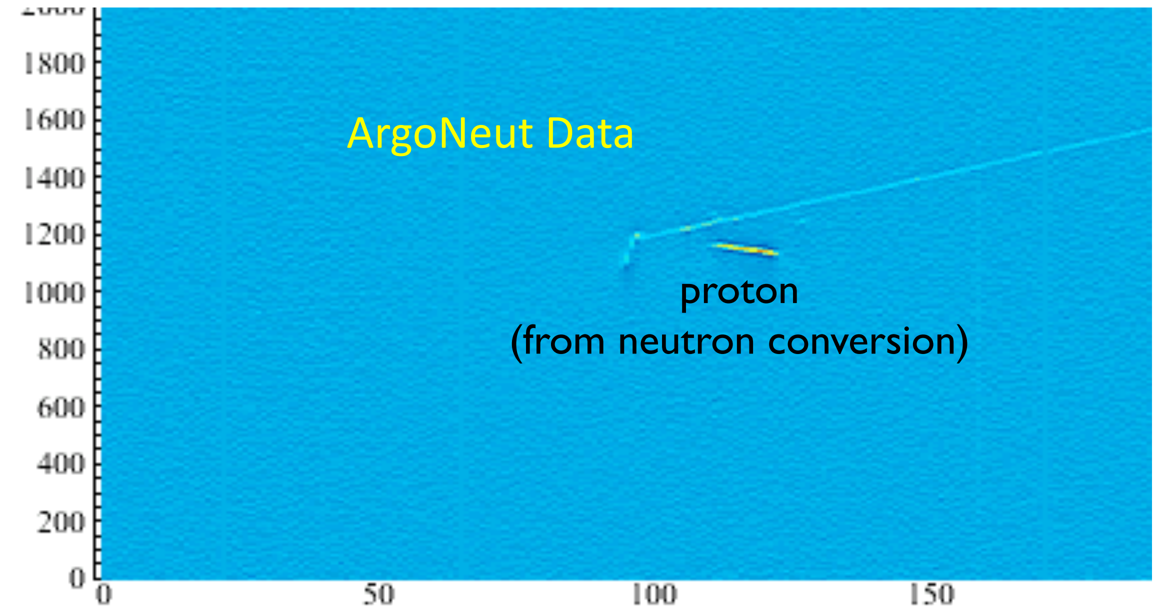


Minimum Kinetic energy: $T_p > 20$ MeV

~ 2 wires = 6mm



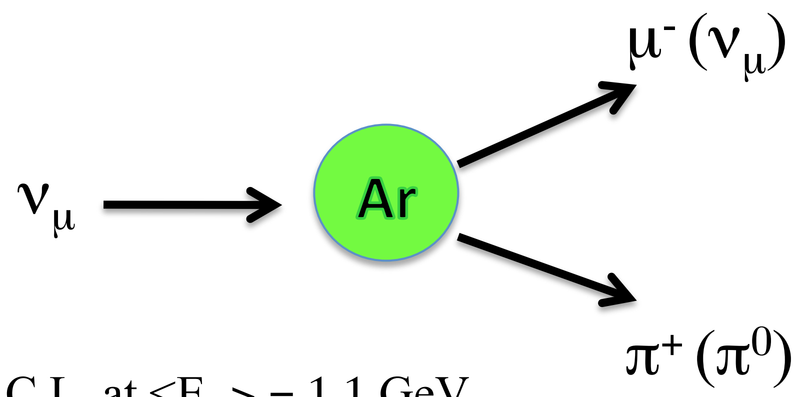
Can we also count neutrons?



Allows:

- Better Nucleon multiplicity measurement in several reactions.
- Better hadronic energy measurement.

Coherent production at $E_\nu < 2$ GeV.



ν_μ interacts with Ar nucleus as a whole.

- **CC π^+ : ν_μ + Ar → Ar + μ^- + π^+**

NO evidence at low energy:

SciBooNE: $\sigma(coh.\pi^+)/\sigma(\nu_\mu CC) < 0.67 \times 10^{-2}$ at 90% C.L. at $<E_\nu> = 1.1$ GeV

K2K: $\sigma(coh.\pi^+)/\sigma(\nu_\mu CC) < 1.36 \times 10^{-2}$ at 90% C.L. at $<E_\nu> = 2.2$ GeV

Above 2 GeV:
Minerva: New data showing signal.
ArgoNeut: First Argon data.
LAr1-ND: ~ 3000 events according to GENIE. Good accuracy measurement.
Excellent for extra activity at vertex.
Pion dE/dx identification and full containment.

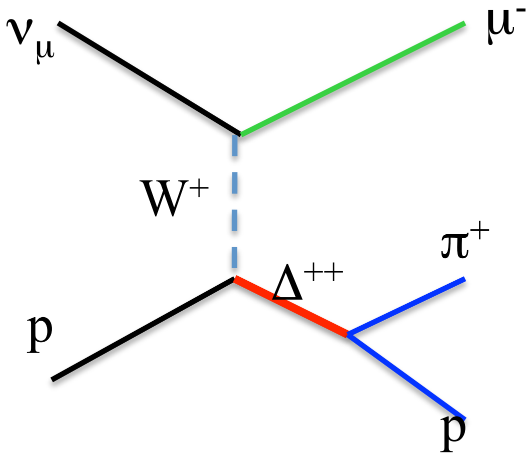
- **NC π^0 : ν_μ + Ar → Ar + ν_μ + π^0**

SciBooNE and MiniBooNE found definite signal at $E_\nu \sim 1$ GeV.

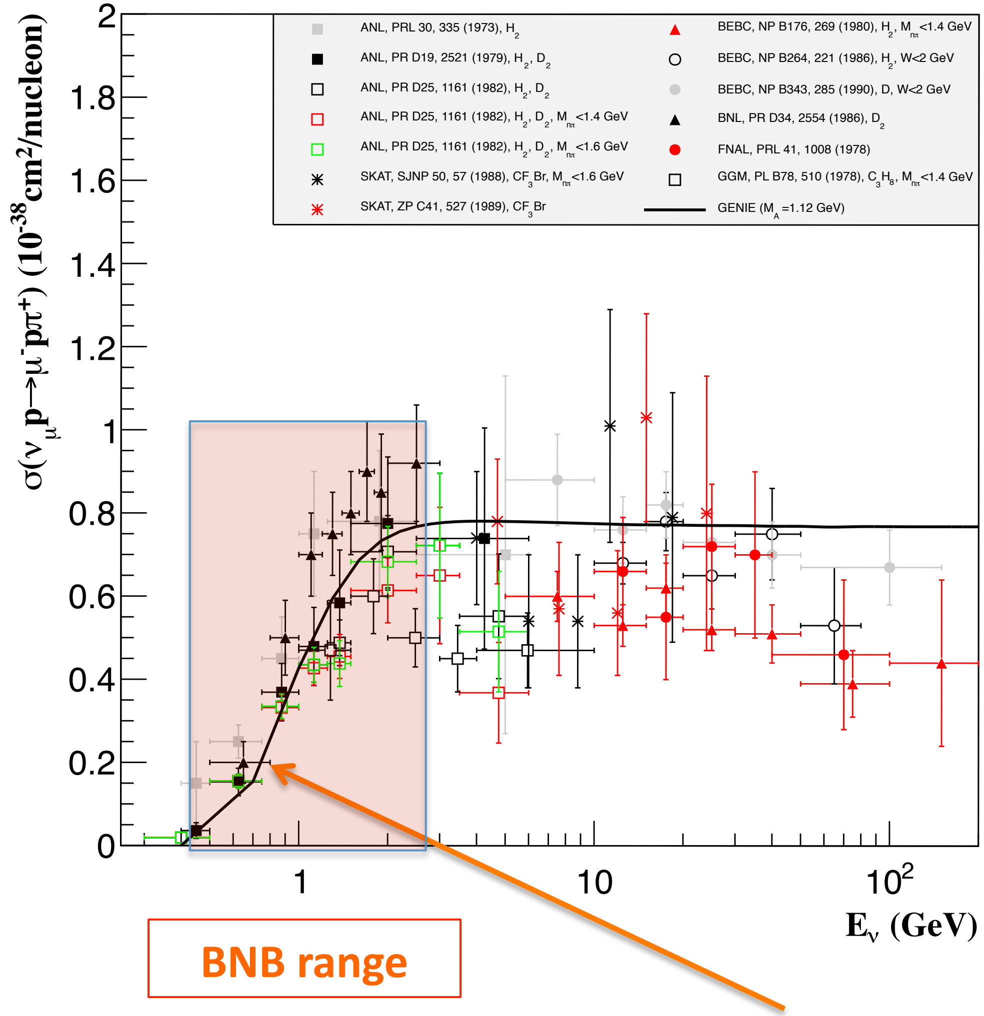
LAr1-ND: π^0 very good signature in LAr. Vertex activity.

Resonance production.

- $\nu_\mu + p \rightarrow \mu^- + \Delta^{++}(\rightarrow p\pi^+)$

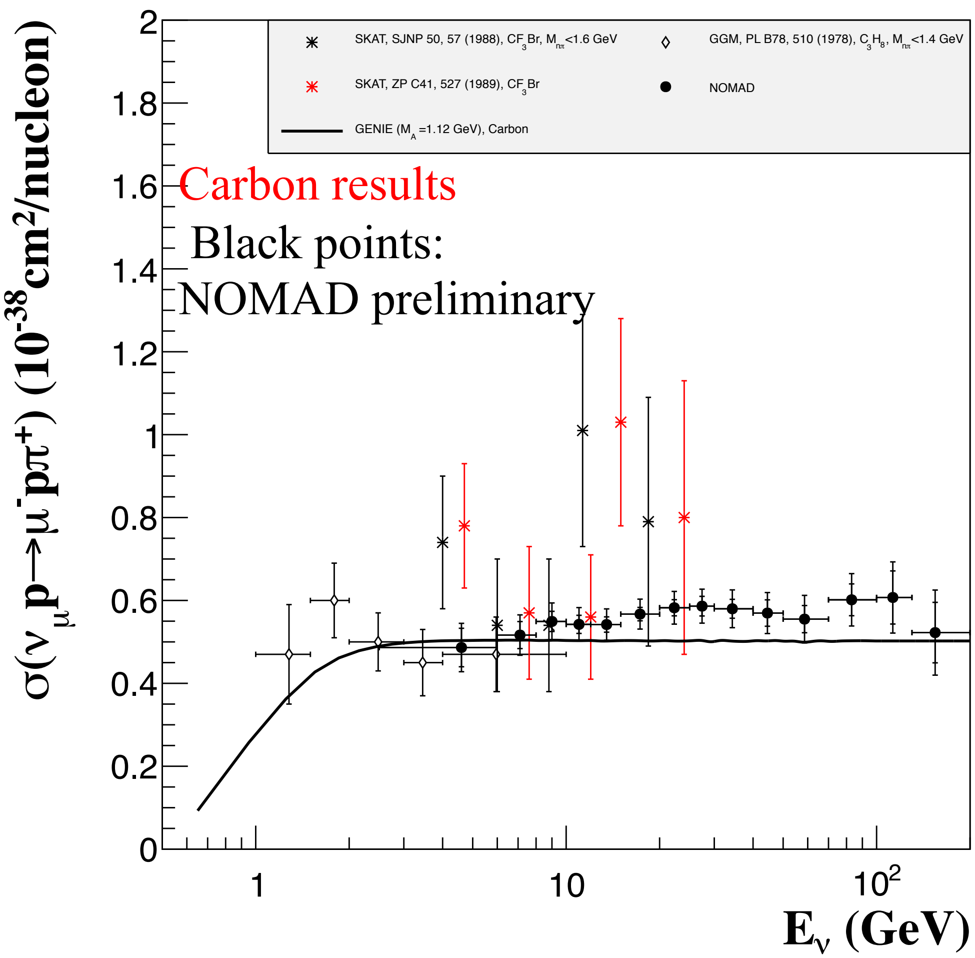


- $\nu_\mu + n \rightarrow \mu^- + \Delta^{+}(\rightarrow p\pi^0)$
  $(\rightarrow n\pi^+)$



LAr1-ND: With good proton and p/π^+ identification should contribute at low energy.

Resonance cross section (NOMAD Preliminary)



Presented at CETUP
Last week

LAr1-ND: Good accuracy on Argon, below the NOMAD points.

SuperNovae neutrino's

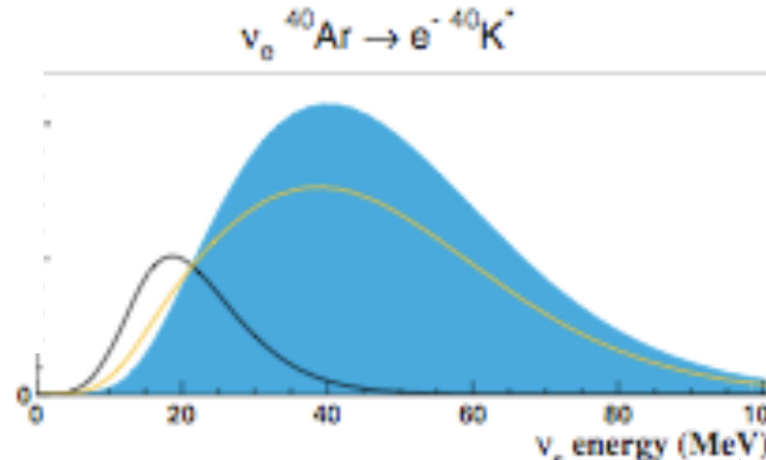
Neutrino events were observed for SN1987a

Between 10 and 20
Absorption events
In each of MicroBooNE and LAr1-ND
About 100 events in ICARUS

$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

expected for a **galactic** supernova

Electron Energy: tens of MeV



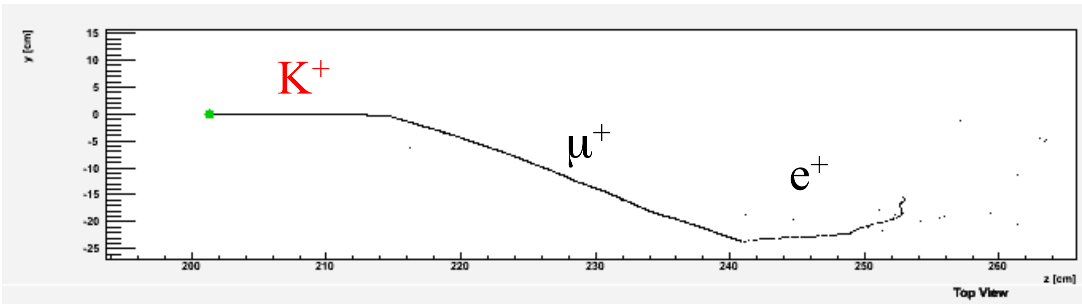
0 20 40 60 80 E_ν (MeV)

0 20 40 60 80 E_e

I. Gil-Botella and A. Rubbia JCAP 10(2003)009

Cannot trigger on these: Data continuously stored in a cyclic buffer
For ~ a few hours, waiting for a SNEWS alert → store data permanently.

R&D: Background to Proton Decay → $K^+ \bar{\nu}_\mu$

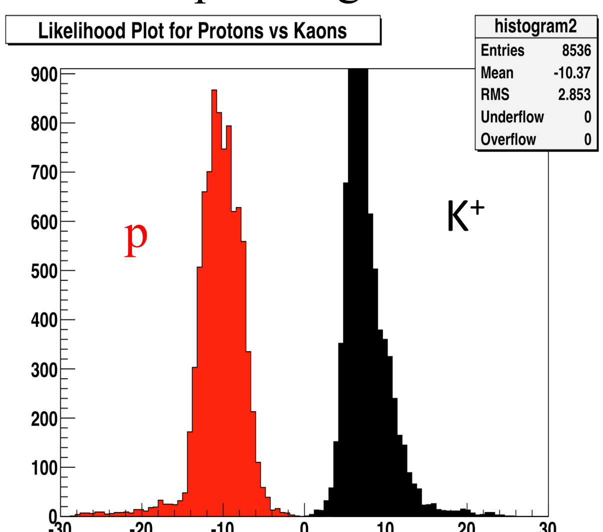


1. Identify K^+

Example: Simulation Studies → Measurements

Separating 339 MeV/c K^+

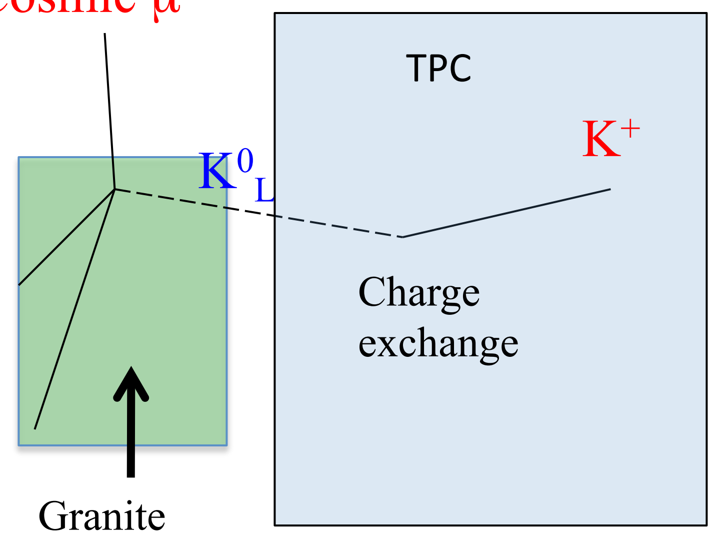
from protons of equal range: 15 cm



Likelihood: 4 dE/dx measurements along track

2. Measure background from cosmic rays

Cosmic μ



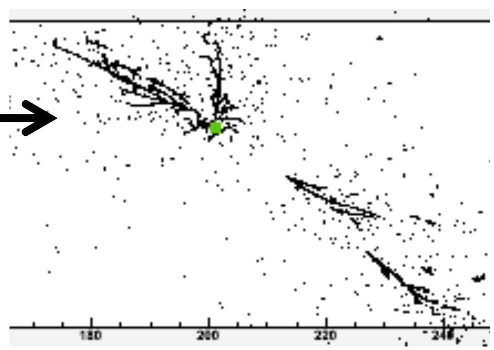
Granite block installed near MicroBooNE

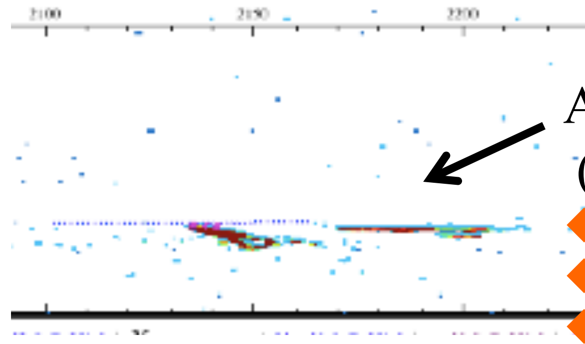
Background to Baryon Non-Conservation: $n\bar{n}$ oscillations → annihilation

Oscillation of neutron to antineutron followed by **annihilation** of antineutron with an Argon nucleus nucleon.

Annihilation

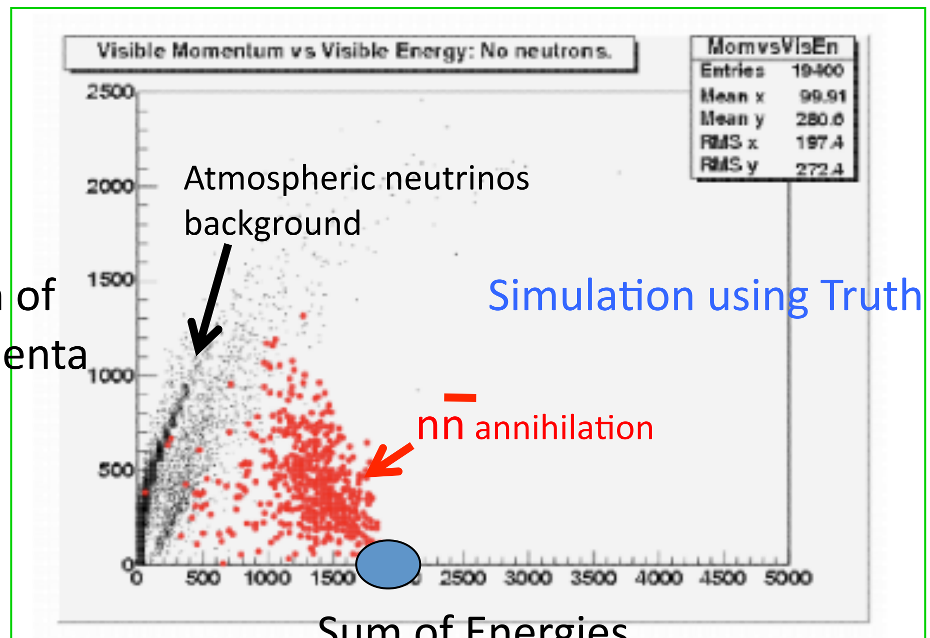
- Spherical
- Zero NET momentum
- Total energy
- = 2 M_n





Atmos. ν (Main background)

- Linear
- Non-zero momentum
- No constraint on energy



Is there additional background from cosmic rays?
Neutral particles entering detector
Depositing 2 GeV?

Measure it in the 3 detectors.

Status and Schedule

- MicroBooNE:
  - Installation in Progress.
  - Cryostat (with TPC+PMT's) moved to final position June 23rd.
  - Insulation, electronics platform and filling next.
  - Data-taking as of End 2014; 3 years for a total of 6.6×10^{20} POT's

- LAr1-ND and ICARUS:
  - Going through approval process
  - Data Spring 2018?

Possible Extensions of the Program

- Anti Neutrino running.

- Magnetizing one or more detectors
  - Reduces “wrong” sign background
    (especially interesting in antineutrino running).
  - Better momentum measurements.
- “Beam OFF-target” running.
  - Searches for exotic particles produced absorber

LAr1-ND Collaboration

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[16] *CERN, Geneva, Switzerland*
[17] *University of Cambridge, Cambridge, UK*

*Spokespersons

10 US institutions
- 3 DOE National Laboratories
- 6 NSF institutions

7 European institutions
- 5 UK institutions
- 1 Swiss institution
- CERN

11 institutions also on MicroBooNE.
Most also LBNE collaborators.

MicroBooNE Collaboration

μBooNE

MicroBooNE Collaboration + Project Team

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University of Cincinnati: R. Grosso, J. St. John, R. Johnson, B. Littlejohn

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Otterbein University: N. Tagg

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Princeton University: K. McDonald, B. Sands

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University of Texas at Austin: S. Cao, J. Huang, K. Lang, R. Mehdiyev

University of Bern, Switzerland: A. Ereditato, D. Goeldi, I. Kreslo, M. Luethi, C. Rudolf von Rohr, T. Strauss, M. Weber

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Virginia Tech: M. Jen, L. Kalousis, C. Mariani

Yale University: C. Adams, E. Church, B. Fleming*, E. Gramellini, A. Hackenburg, B. Russell, A. Szelc

total team (collaboration + project):

- 3 countries
- 23 institutions
- 134 collaborators (includes project team)

* *spokespeople,*
\+ *project manager*

ICARUS Collaboration

M. Antonello[1], B. Baibussinov[2], V. Bellini[4,5], H. Bilokon[6], F. Boffelli[7], M. Bonesini[9], E. Calligarich[8], S. Centro[2,3], K. Cieslik[10], D. B. Cline[11], A. G. Cocco[12], A. Curioni[9], A. Dermenev[13], R. Dolfini[7,8], A. Falcone[7,8], C. Farnese[2], A. Fava[3], A. Ferrari[14], D. Gibin[2,3], S. Gninenko[13], F. Guber[13], A. Guglielmi[2], M. Haranczyk[10], J. Holeczek[15], A. Ivashkin[13], M. Kirsanov[13], J. Kisiel[15], I. Kochanek[15], A. Kurepin[13], J. Łagoda[16], F. Mammoliti[4], S. Mania[15], G. Mannocchi[6], V. Matveev[13], A. Menegolli[7,8], G. Meng[2], G. B. Mills[17], C. Montanari[8], F. Noto[4], S. Otwinowski[11], T. J. Palczewski[16], P. Picchi[6], F. Pietropaolo[2], P. Płoński[18], R. Potenza[4,5], A. Rappoldi[8], G. L. Raselli[8], M. Rossella[8], C. Rubbia[19,14,a], P. Sala[20], A. Scaramelli[20], E. Segreto[1], D. Stefan[1], J. Stepaniak[16], R. Sulej[16], C. M. Sutera[4], D. Tlisov[13], M. Torti[7,8], R. G. Van de Water[17], F. Varanini[3], S. Ventura[2], C. Vignoli[1], H. G. Wang[11], X. Yang[11], A. Zani[7,8], K. Zaremba[18]

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Conclusions

- Looking forward to start data taking within 6 months with MicroBooNE:
  - Minimum low energy excess.
  - First look at LSND excess
  - Cross sections.

- Hoping for approval of extra 2 detectors by PAC soon ,

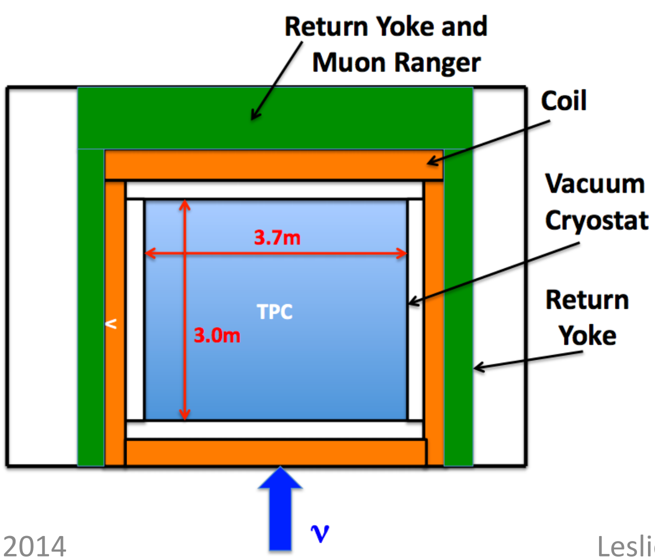
- Next 3 years:
  - Build LAr1-ND
  - Refit ICARUS
  - Analyze MicroBooNE data

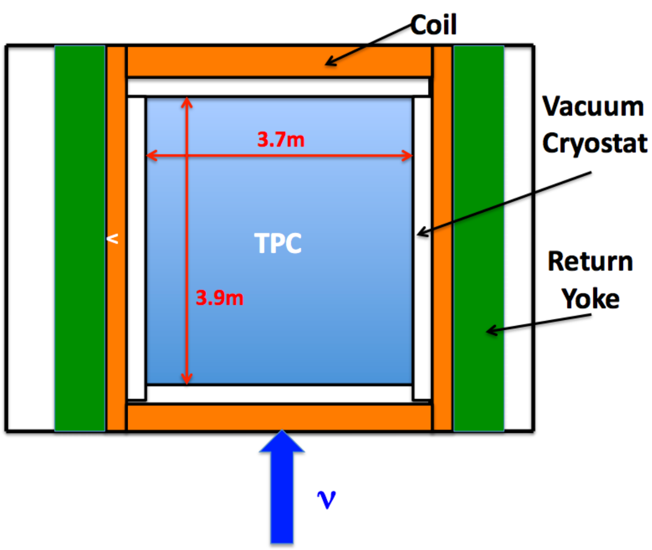
We are on our way !

Back Up

Magnetized LAr1-ND

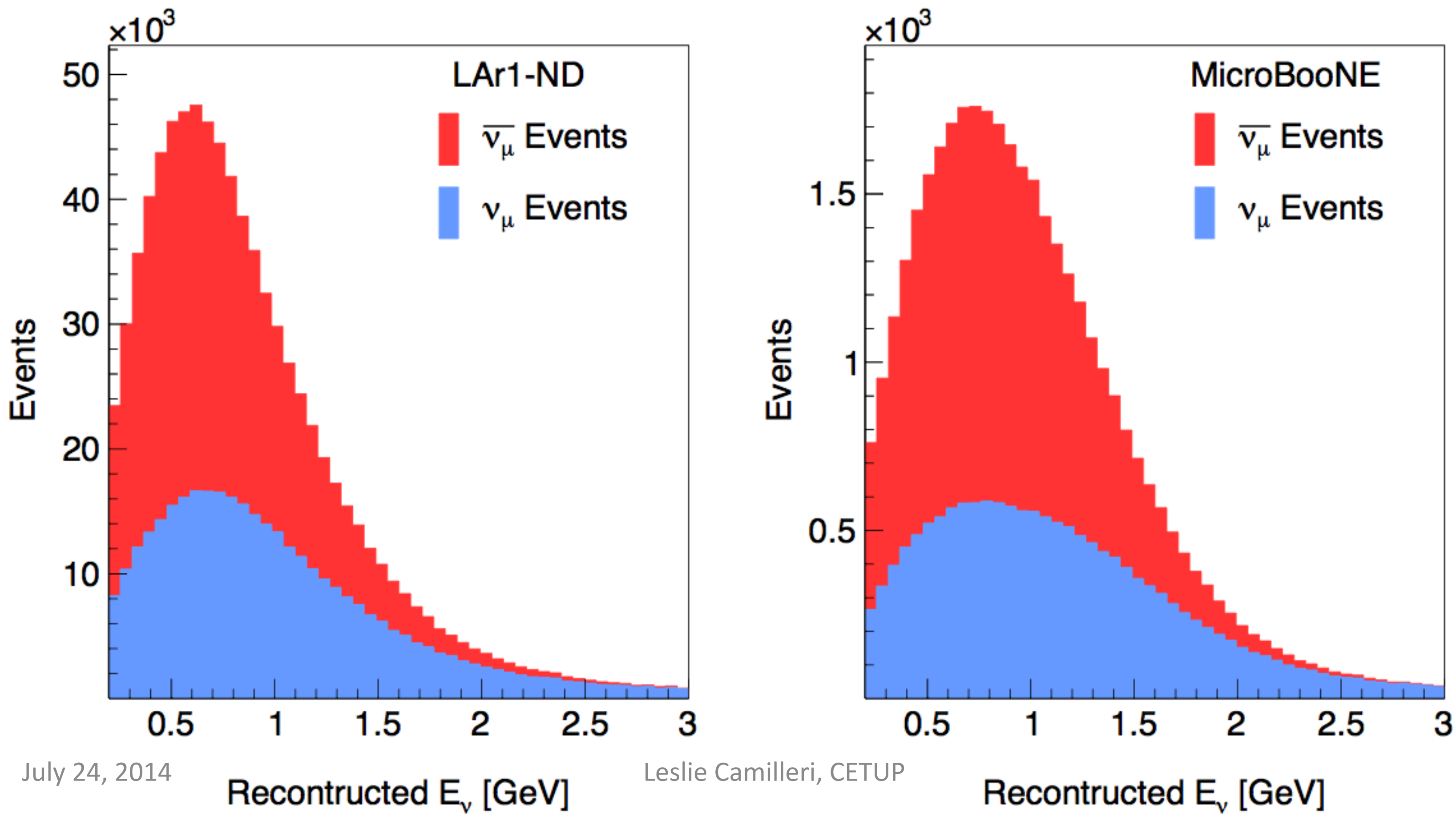
- Two possible detector designs
  - Configuration A: The return yoke downstream of the neutrino beam and be instrumented with scintillator modules to form a muon spectrometer increasing the detector acceptance and allowing for particle ID for escaping charged pions
  - Configuration B: Compared to (A) there is an extended detector volume but contains no downstream spectrometer





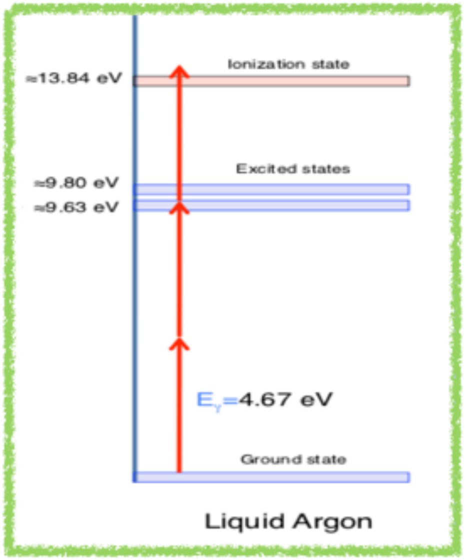
Wrong Sign Contamination

- Charge selection (in antineutrino mode) is one of the main motivating factors for a magnetized detector
  - Neutrino background in the antineutrino beam

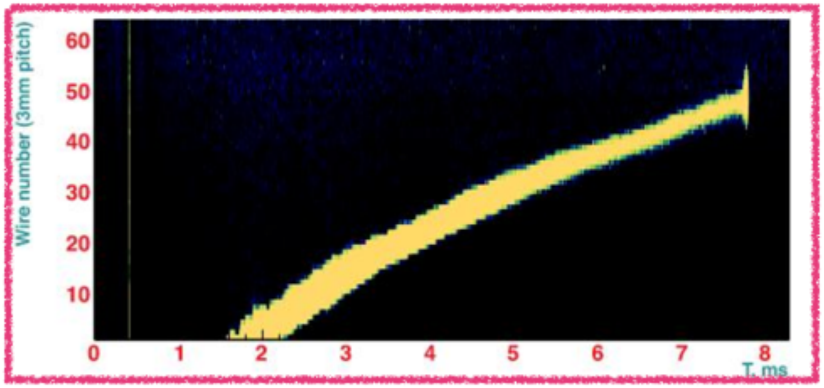


Laser Calibration in MicroBooNE

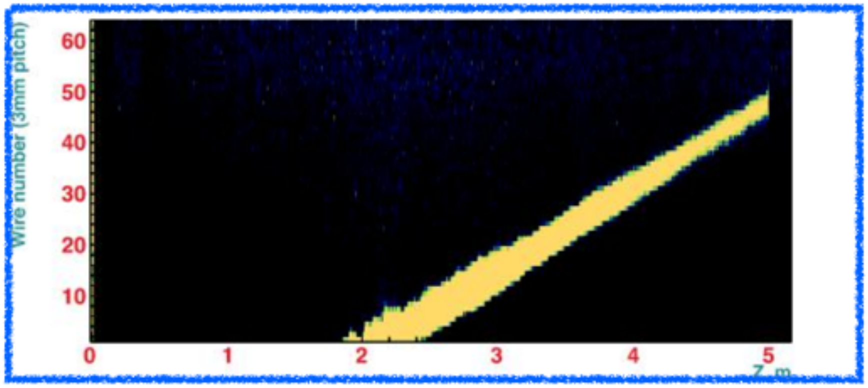
- Field non-uniformity arise
  - Distortion expected by Ar^+ accumulation @ cathode
  - Needs to be calibrated out
- Laser Calibration System (LCS)
- LCS inject laser to ionize Ar along the path
  - $\lambda \cong 266$ nm, need high intensity to ionize
  - Distortion shows up in the reconstructed signal path



Plot & Diagram ... courtesy of C. Rudolf



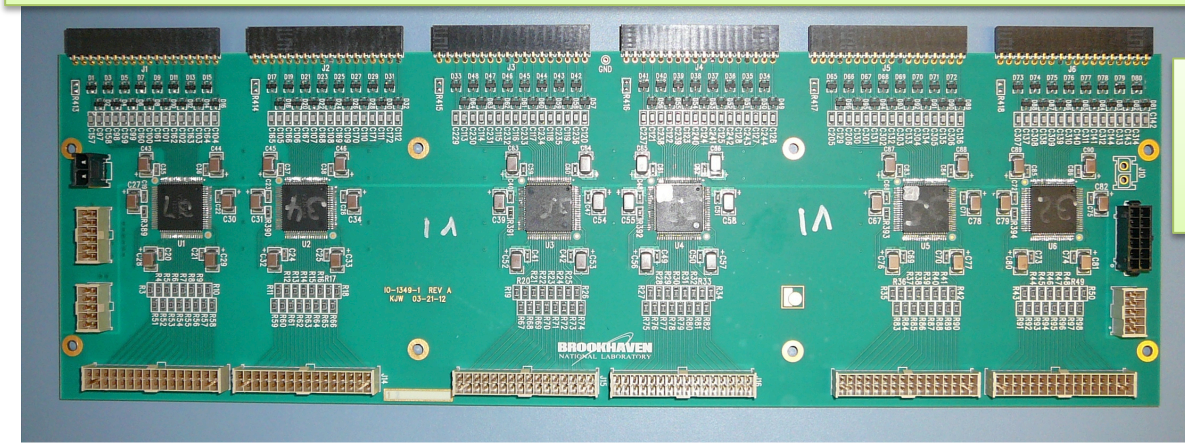
Laser path @ ArgonTube
(**Uncalibrated**)



Laser path @ ArgonTube
(**Calibrated**)

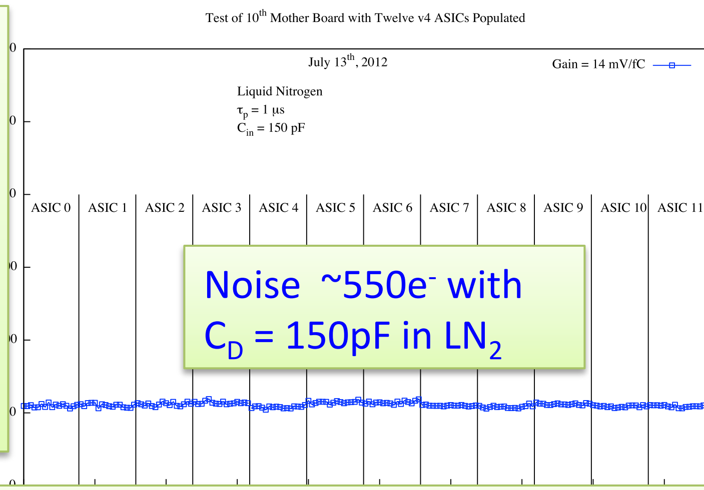
Cold Electronics Performance

16 channel/chip charge amplifier: Adjustable Gain 4.7, 6.8, 14.0, 25.0 mV/fC
Adjustable peaking time 0.5,1,2,3 μs, 5.5 mW/channel



Prototype Vertical
Cold Mother Board
with prototype ASICs

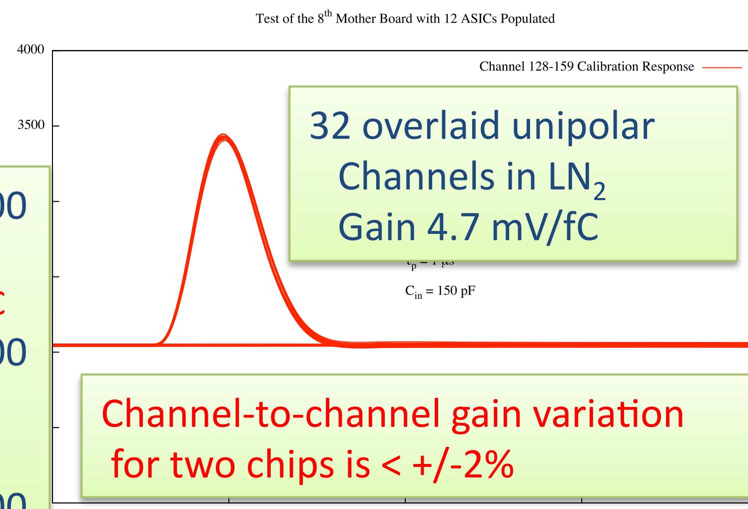
Crosstalk < 0.3%



2500
e^-
1500
500

Noise ~550e^- with
C_D = 150pF in LN_2

0 100 channel



3000
ADC
2000
1000

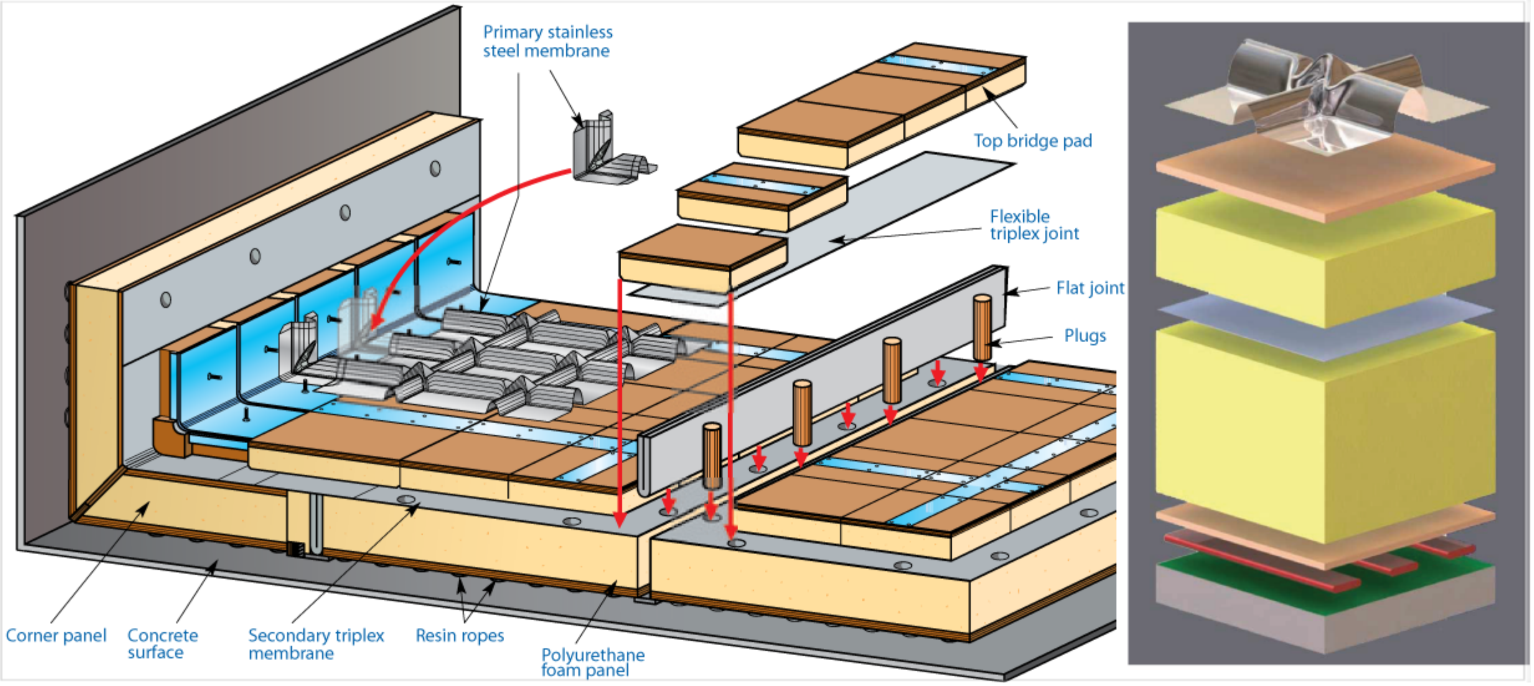
32 overlaid unipolar
Channels in LN_2
Gain 4.7 mV/fC

Channel-to-channel gain variation
for two chips is < +/-2%

0 100 sample (time)

Membrane Cryostat

Original thought:
Locate LAr1-ND in the SciBooNE Hall at 100m



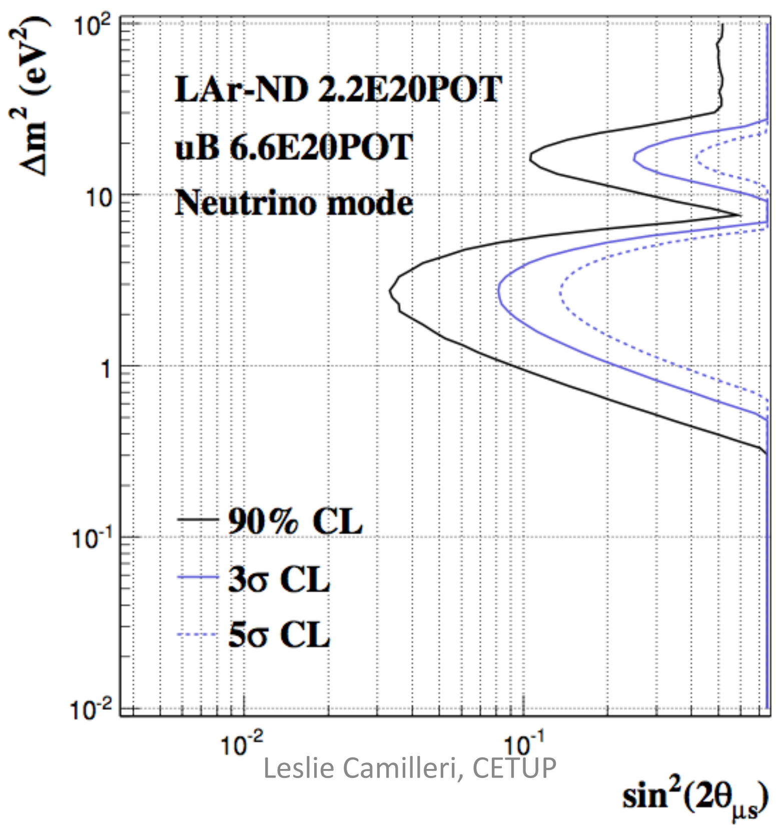
MiniBooNE Low Energy Excess

Process	Events (μB)	Events (LAr1-ND)	MiniBooNE unc.	dE/dx unc.	Total unc.	Error (μB)	Error (LAr1-ND)
$\mu \to \nu_e$	21.5	171.3	0.26	0.1	0.28	6.0	47.7
$K^+ \to \nu_e$	6.4	51.3	0.22	0.1	0.24	1.55	12.4
$K^0 \to \nu_e$	1.8	14.7	0.38	0.1	0.39	0.73	5.79
ν_μ CC	4.9	38.9	0.26	0.0	0.26	1.27	10.1
$\nu_\mu e \to \nu_\mu e$	3.8	30.7	0.25	0.1	0.27	1.03	8.26
NC π^0	6.7	53.4	0.13	0.1	0.16	1.10	8.77
Dirt	0.9	6.9	0.16	0.1	0.19	0.16	1.31
$\Delta \to N\gamma$	2.5	19.8	0.14	0.1	0.17	0.43	3.40
Other	0.9	7.6	0.25	0.1	0.27	0.26	2.04
Total	49.4	322.1				6.55	52.23

	MicroBooNE	LAr1-ND
Total Events	97	775
"Low-energy Excess"	47.6	380
Background	49.4	394.6
Statistical Error	7.0	19.9
Systematic Error	6.6	52.2
Total Error	9.6	55.9
Statistical Significance of Excess	6.8 σ	19.1 σ
Total Significance of Excess	**5.0 σ**	**6.8 σ**

Probing Active to Sterile Oscillations with Neutral-Currents

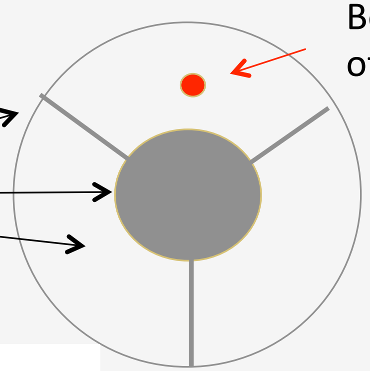
- A unique probe of sterile neutrino oscillations, directly sensitive to any "sterile" flavor content, is available through neutral-current (NC) neutrino interactions. In this type of search, one looks for an overall depletion of the flavor-summed event rate.
- We have considered the NC π^0 channel, due to its characteristic event topology and kinematics. Unlike other NC channels, the presence of the two photons from the π^0 decay pointing back to a common vertex, with an invariant mass corresponding to $m_{\pi 0}$, provides a powerful discriminant against potential backgrounds.



Dark Matter Searches with Booster Beam Off-Target Running

BNB has the capability to steer the protons past the target and onto the 25m or 50m iron dump

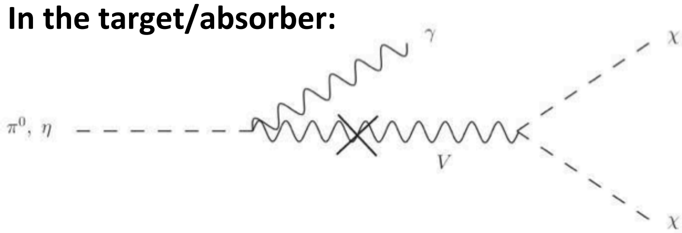
Fins
Be Target
Air gap



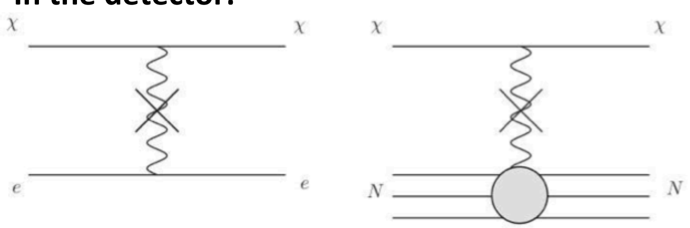
Beam spot position in beam off target mode (~1 mm spread)

-Target is 1 cm diameter
-Air gap between target and horn inner conductor is ~1 cm

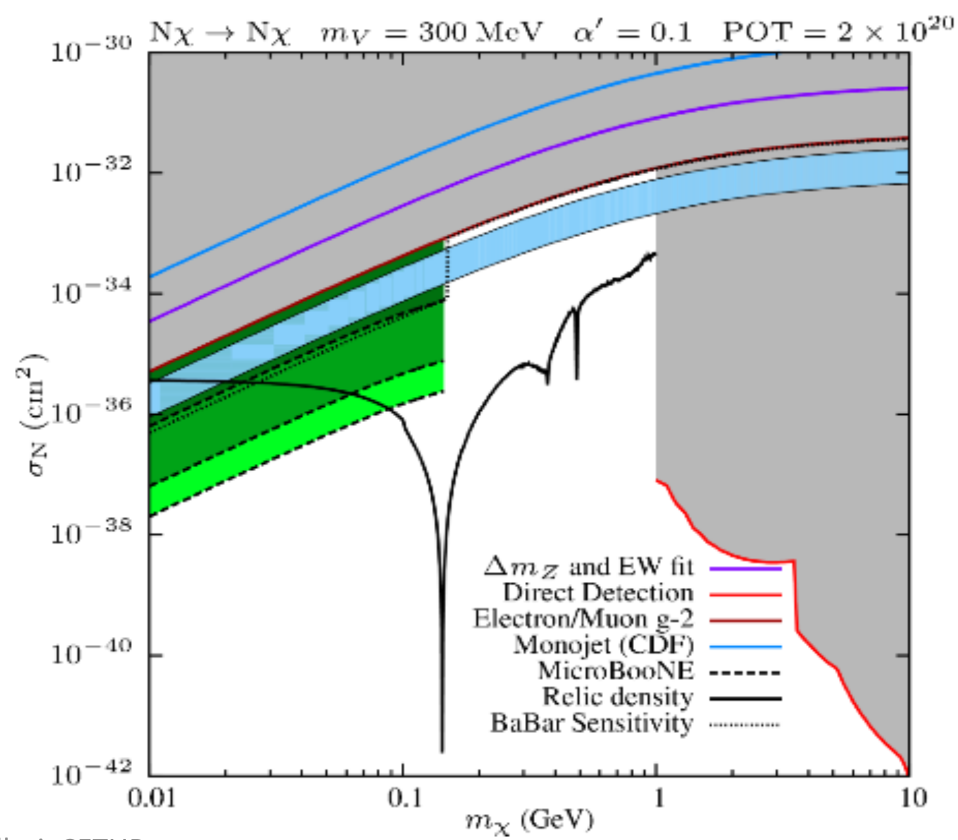
In the target/absorber:



In the detector:



Electron Elastic scattering   Nucleon Elastic scattering



Background events: 1600
Excess:
1-10 light green
10-1000 Green
>1000 dark green

LAr1-ND Schematics