Short-baseline sterile neutrino search

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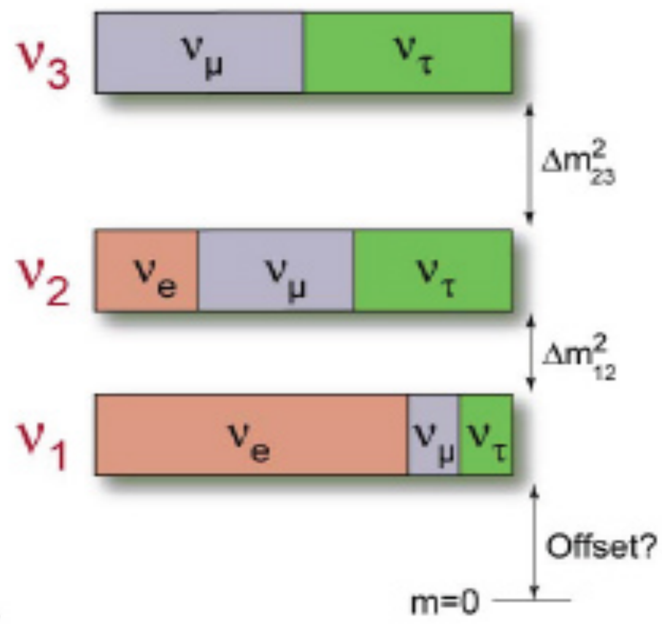
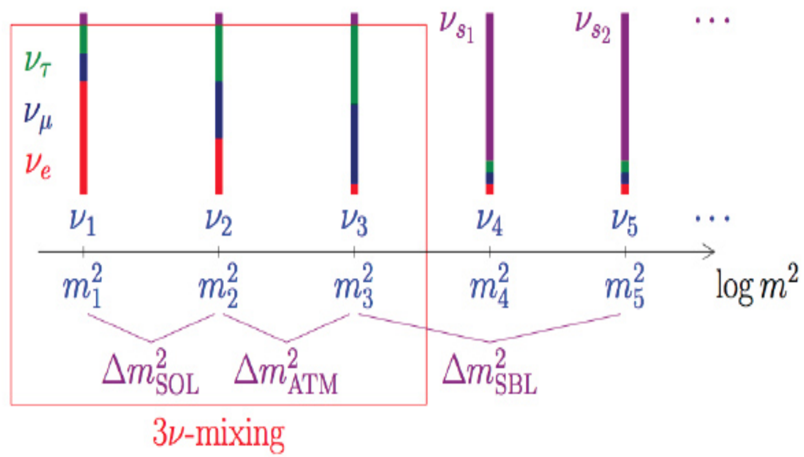
How many neutrino species in nature ?

- Neutrino oscillations have established a picture consistent with the mixing of three physical neutrino ν_e, ν_μ and ν_e with mass eigenstates ν_1, ν_2 and ν_3.
- In particular the mass differences turn out to be relatively small $\Delta m^2_{31} \approx 2.4 \times 10^{-3}$ eV^2 and $\Delta m^2_{21} \approx 8 \times 10^{-5}$ eV^2 and mixing angles are relatively large.
- There are however a number of *"anomalies"* which, if confirmed experimentally, could hint at the presence of an additional, larger squared mass differences in the framework of more than 3 neutrinos with additional "sterile" neutrinos or other effects.



✓ *Three angles (θ_{12}, θ_{13}, θ_{23})*
✓ *Two mass differences (Δm^2_{12}, Δm^2_{23})*

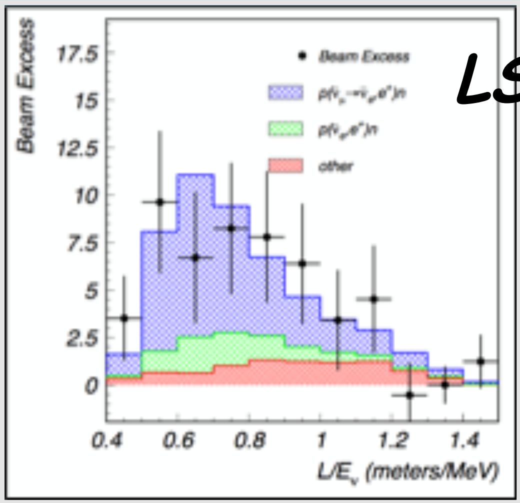


Some persisting anomalies in the neutrino sector

- Distinct classes of anomalies have been reported, namely
  - the apparent *disappearance signal* in the anti-ν_e events (1) detected from near-by nuclear reactors and (2) from intense k-capture calibration sources in the experiments to detect solar ν_e.
  - (3) observation of presumed *excess signals* of ν_e electrons from muon neutrinos from particle accelerators.
- These three independent signals may all point out to the possible existence of at least a fourth non standard and heavier neutrino state driving oscillations at a small distances, with Δm^2_{new} of the order of $\approx 1\ eV^2$ and relatively small $\sin^2(2\theta_{new})$ mixing angles.
- The most popular direction is the one of of "sterile neutrinos" although also other alternatives are possible
- The existence of additional neutrino may be also hinted at — or at least not excluded — by data from big Bang cosmology.

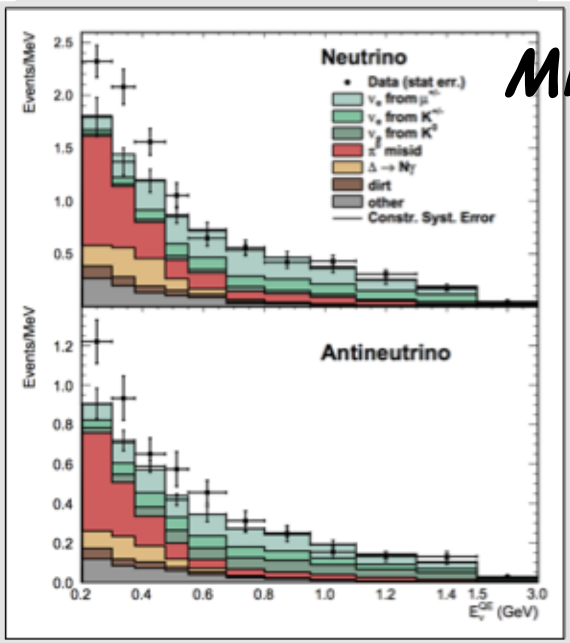
Accelerator-Based Anomalies

- The long standing LSND anomaly still survives.
- MiniBoone at the FNAL ~ 0.7 GeV Booster neutrino beam has not fully confirmed LSND
- But in addition it has observed a new anomaly at small energies for both ν and anti-ν events.



LSND

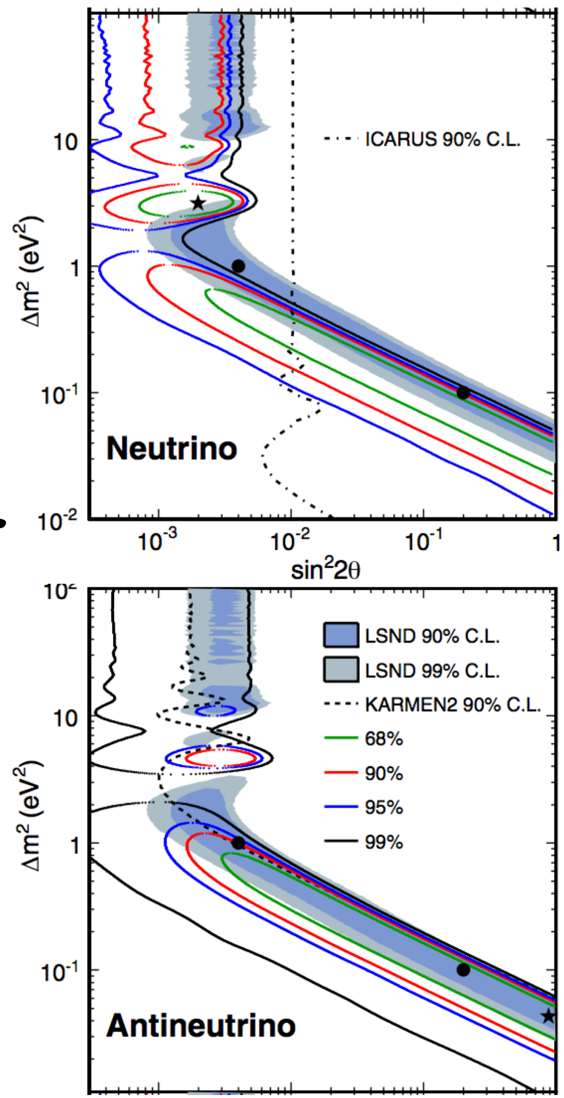
$\bar{\nu}_\mu \to \bar{\nu}_e$?



MiniBooNE

$\nu_\mu \to \nu_e$?

$\bar{\nu}_\mu \to \bar{\nu}_e$?



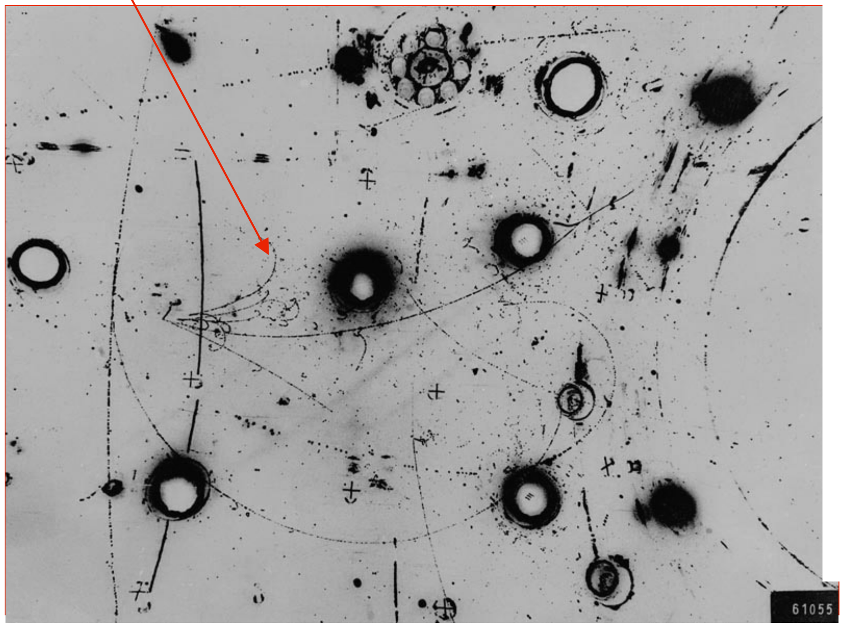
- All these anomalies can be clarified with a new multi detector experiment at a SBL ν beam with the now mature LAr technology.

A new powerful visual detector: the LAr-TPC.....

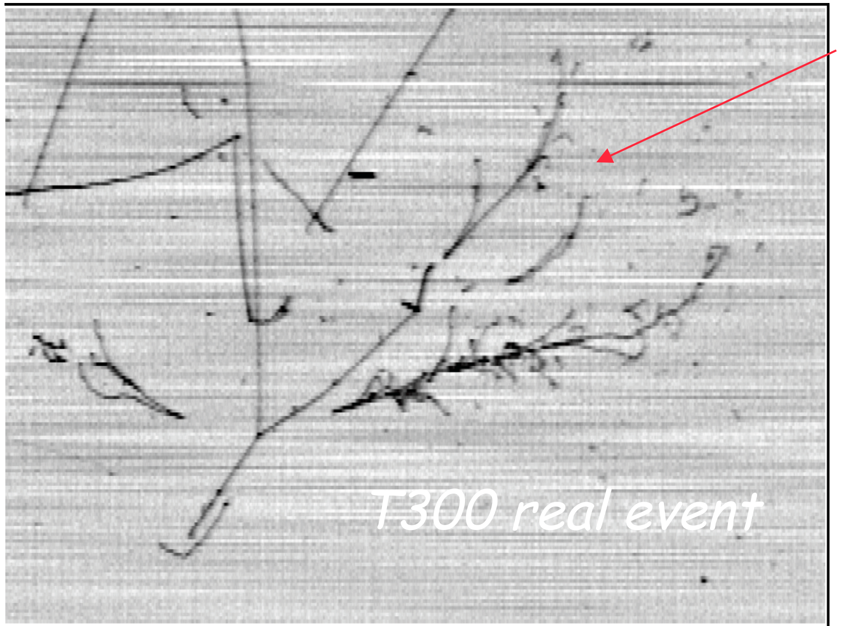
Bubble diameter ≈ 3 mm (diffraction limited)

LAr is a cheap liquid (≈1 Eur/litre), vastly produced by industry

Gargamelle Bubble chamber



ICARUS Electronic chamber



"Bubble" size $3 \times 3 \times 0.3\ mm^3$

Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

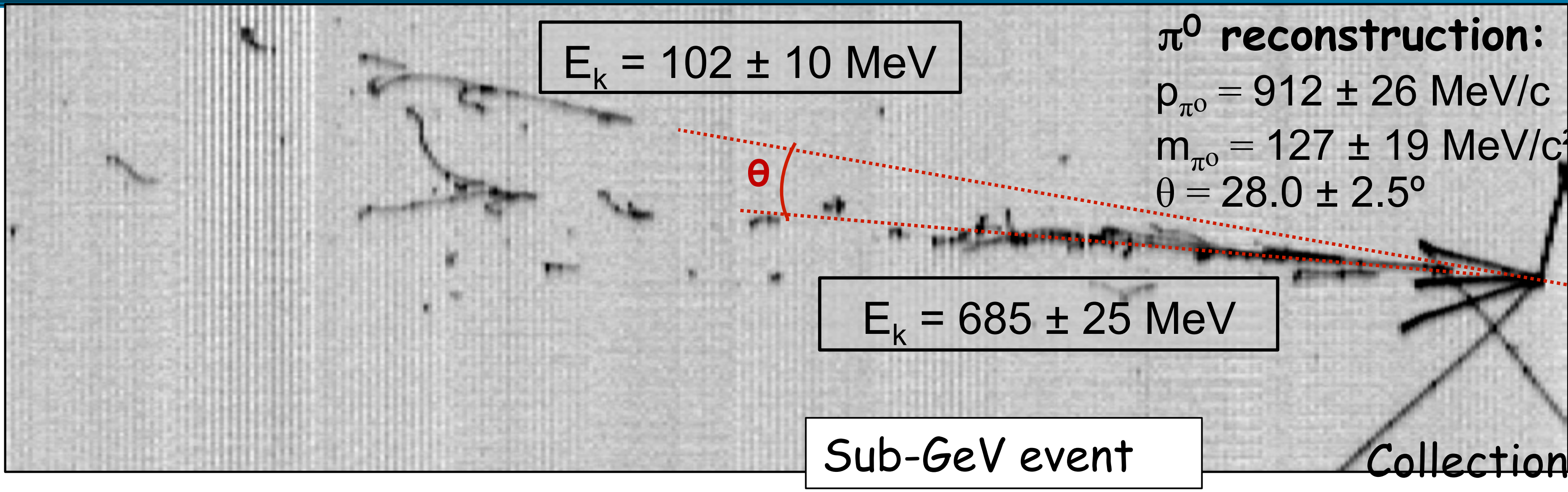
Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

Bringing the LAr -TPC technology to a success

- The ICARUS collab. has originally developed the LAr-TPC technology.
- Located in the underground LNGS laboratory of INFN, at 730 km from CERN, ICARUS T600 detector has successfully completed 3 years physics program.
- Over 3000 ν events have been collected at ≈ 25 GeV CNGS beam from CERN (8.6 10^{19} p.o.t.)
- A dedicated trigger was also setup to collect cosmic rays and atmospheric neutrinos.
- Together with all previous test beam runs, the T600 operation allowed a very positive assessment of the LAr-TPC detection capabilities.

- The T600 will undergo to an extensive overhauling in the next 2 years at CERN for a forthcoming experimental program on sterile ν search

e/γ separation and π^0 reconstruction in ICARUS

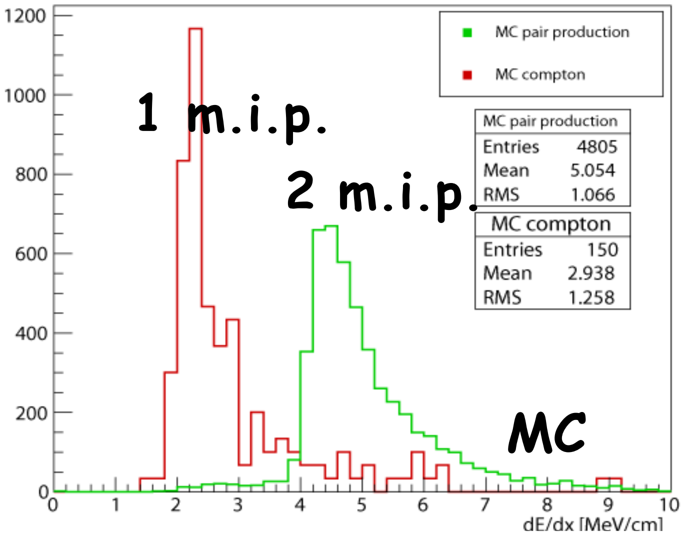


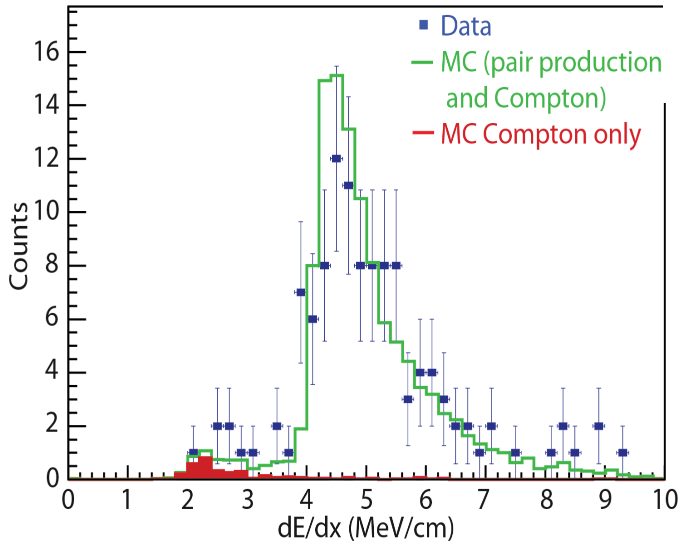
π^0 reconstruction:

p_{π^0} = 912 ± 26 MeV/c

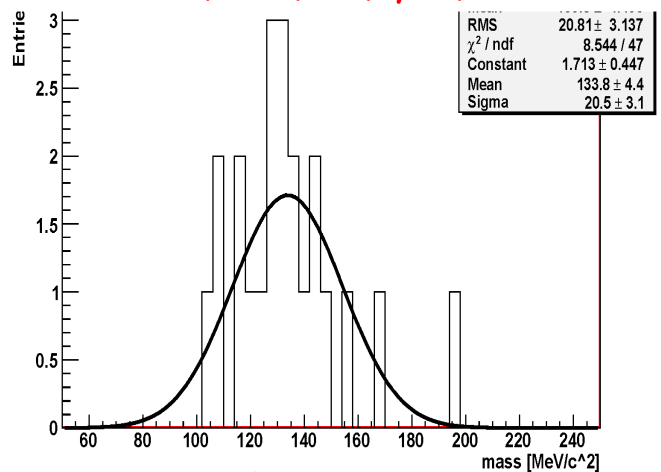
m_{π^0} = 127 ± 19 MeV/c²

θ = 28.0 ± 2.5°





Mγγ: 133.8±4.4(stat)±4(syst) MeV/c²



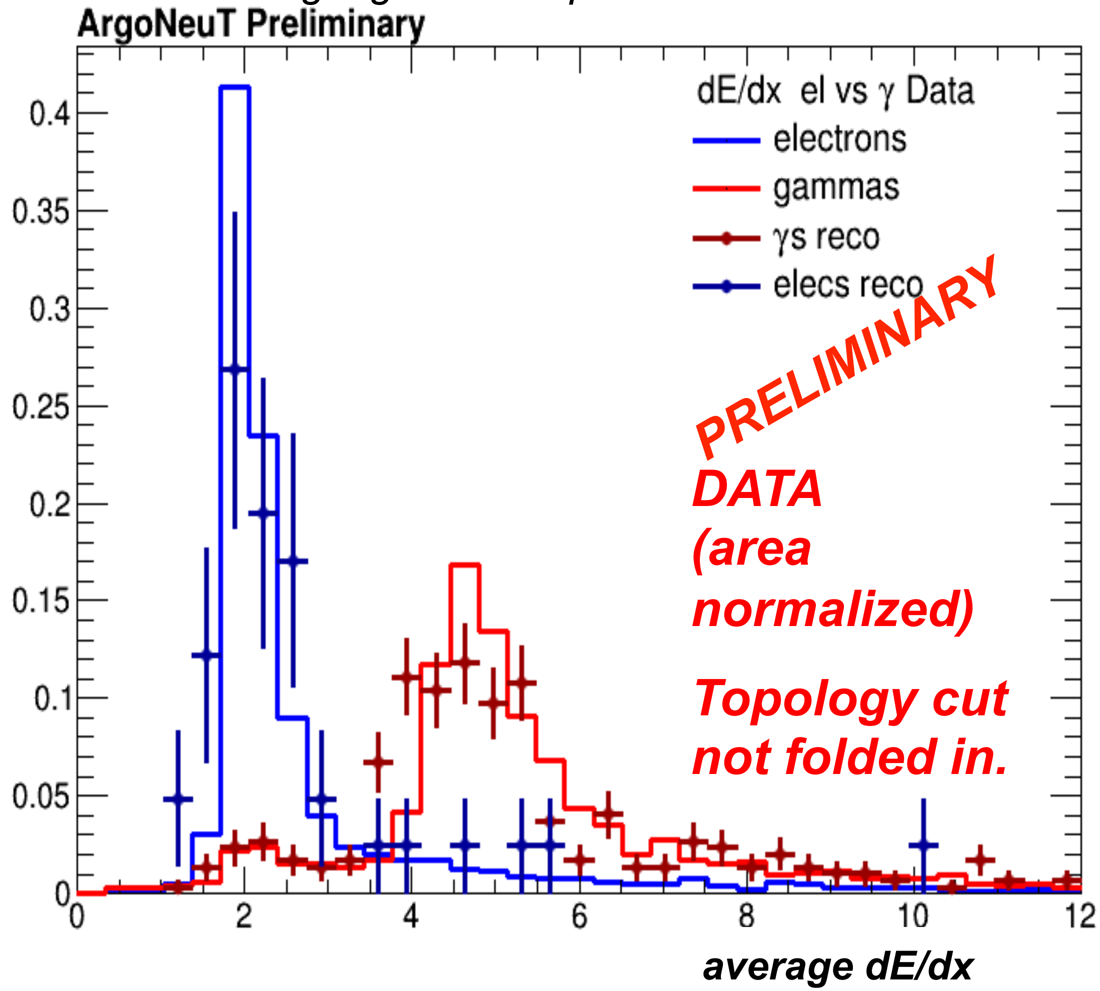
Unique feature of LAr to distinguish e from γ and reconstruct π^0

➔ Estimated bkg. from π^0 in NC and ν_μ CC : negligible (from MC and scanning)

Data-Based dE/dx plot

- Gammas defined as EM showers detached from visible vertex.
- Electrons defined as EM showers with visible vertex activity and no gap.
- Electron events require no track matched to MINOS muon.

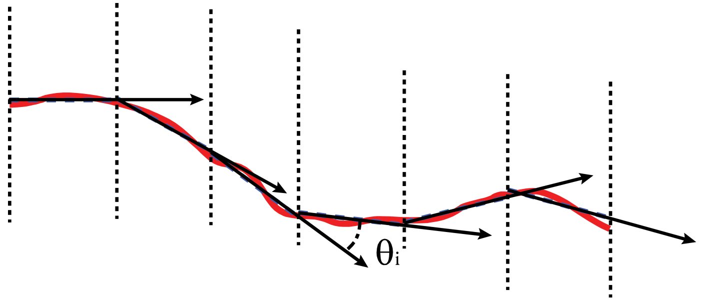
Electron/single gamma separation



Landau-like distribution of electron event single hit charge depositions.

Beam-associated stopping long muons (both range and MS)

- Momentum extracted from measurement of deflection angle θ :



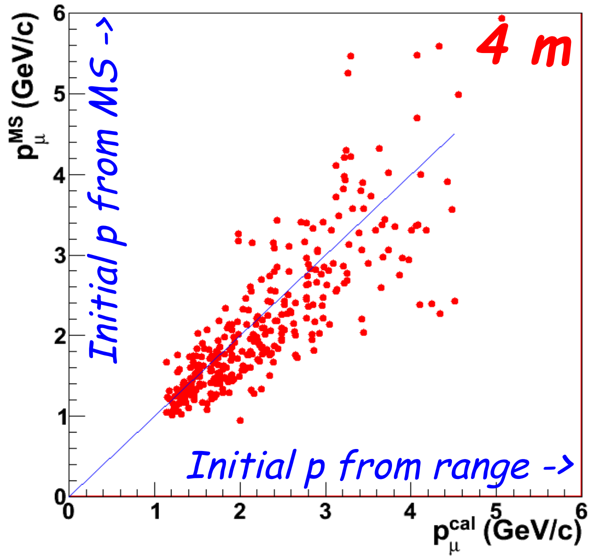
$$\begin{cases} \theta_{MS} \propto \sqrt{L_{seg}}/p \\ \theta_{det} \propto L_{seg}^{-3/2} \end{cases}$$

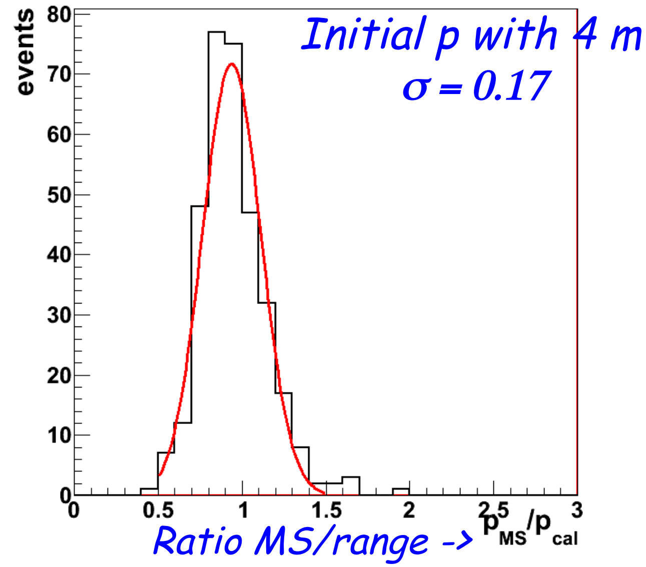
MS angle

detector resolution

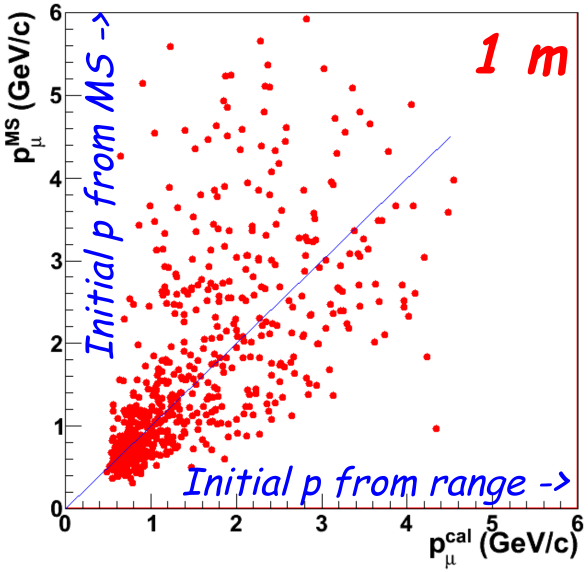
- An optimal segment length is to be chosen, typically 10-20 cm.
- 400 ns time sampling is marginal: 200 ns is a future option.

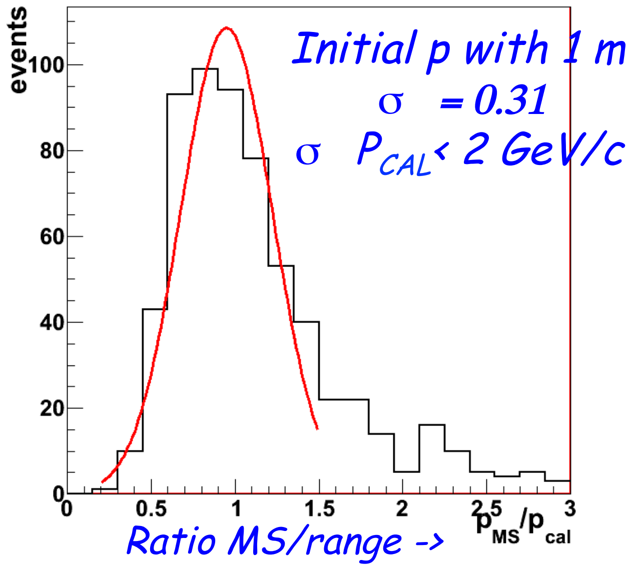
Stopping μ track length: > 5 m   Used length: 4m



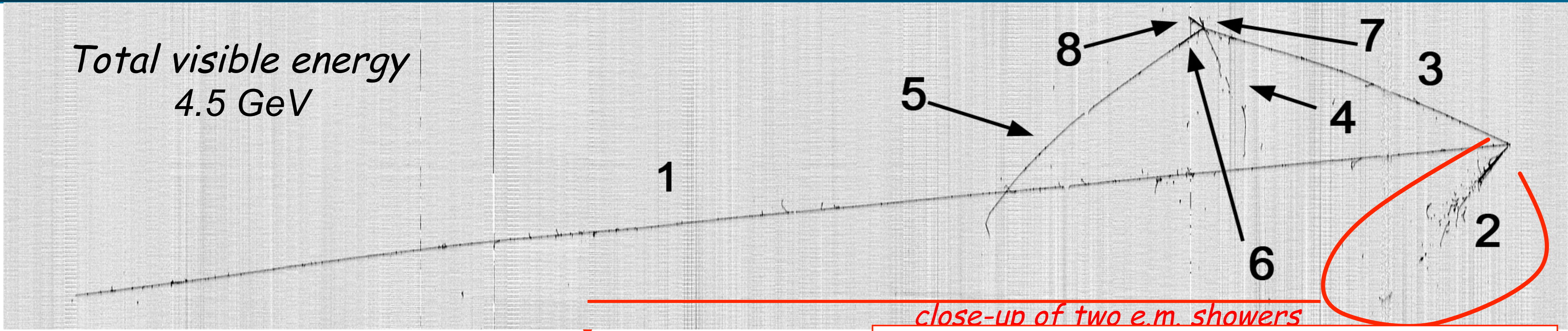


Stopping μ track length: > 2m   Used length: 1m





Run 9927 Event 572

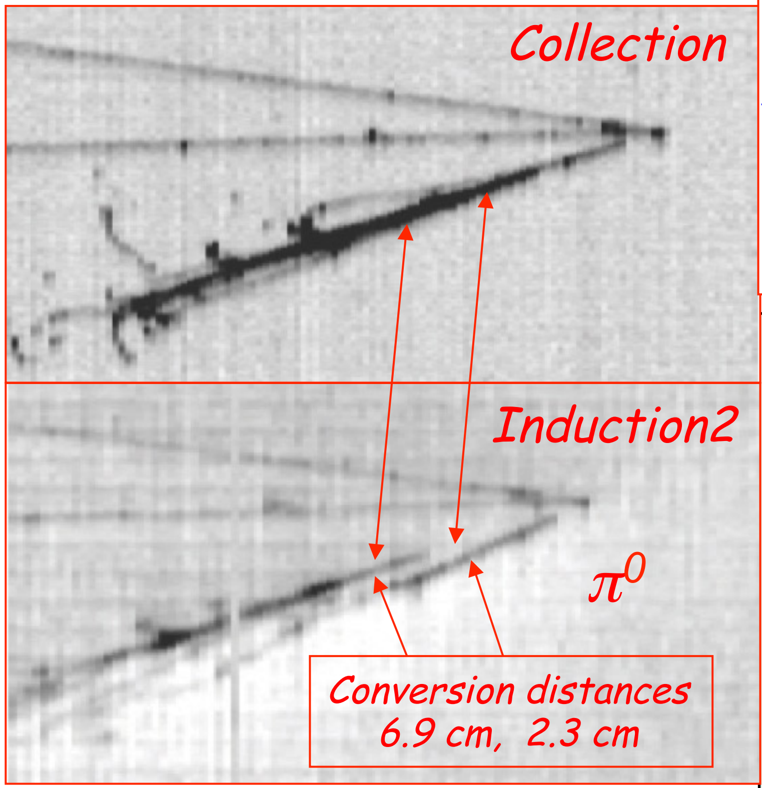


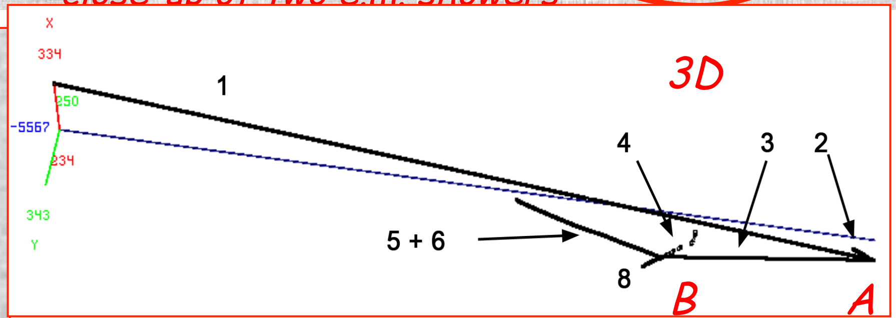
Primary vertex (A):

very long (1), e.m. cascades (2), pion (3)

Secondary vertex (B):

*The longest track (5) is a μ coming from stopping **k** (6). μ decay is observed*





Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2	520.82	0.054	-0.420	-0.906
3 (p)	514.04	-0.001	0.137	-0.991
Sec. vtx.	797			
4	76.99	0.009	-0.649	0.761
5 (μ)	313.9			
6 (K)	86.98	0.000	-0.239	-0.971
7	35.87	0.414	0.793	-0.446
8	283.28	-0.613	0.150	-0.776

Search for anomalous MiniBooNE νe events with ICARUS T600

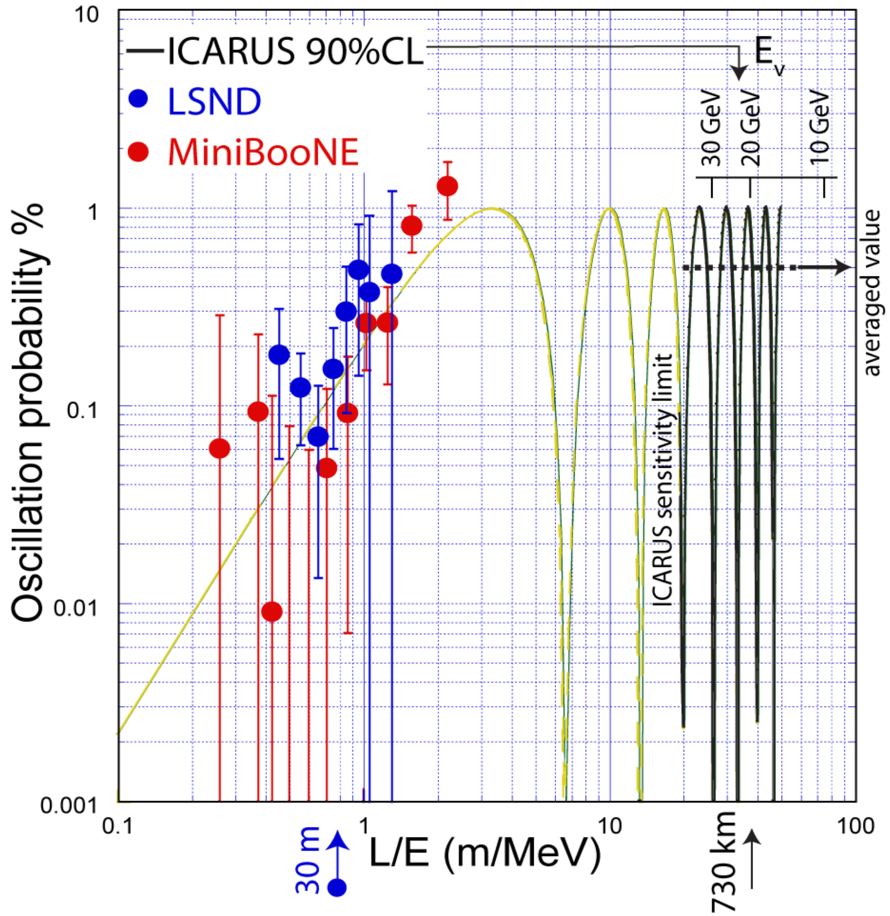
- The CNGS facility has delivered an almost pure ν_μ beam in 10-30 GeV E_ν range (beam associated ν_e ~1%) at a distance L=732 km from target.
- There are important differences with respect to the LSND experiment:

  L/E_ν ~1 m/MeV at LSND

  L/E_ν ≈36.5 m/MeV at CNGS
- At CNGS, the short distance oscillation signal averages to:

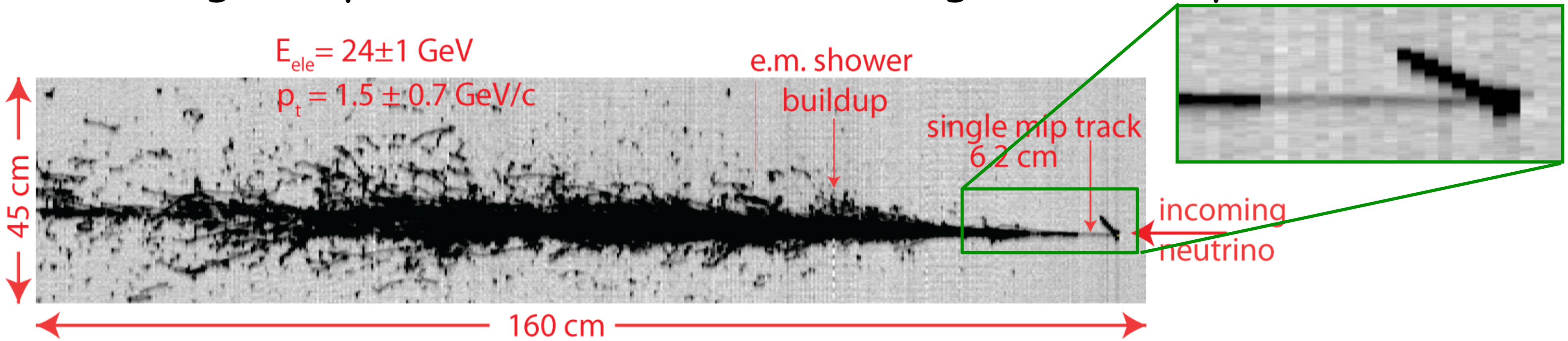
  $\sin^2(1.27\Delta m^2_{new} L/E)$ ~1/2 and

  $\langle P\rangle_{\nu\mu\to\nu e}$ ~ $1/2 \sin^2(2\theta_{new})$
- When compared to other long baseline results (MINOS and T2K) ICARUS operates in a L/E_ν region in which contributions from standard ν oscillations [mostly $\sin(\theta_{13})$] are not yet relevant.



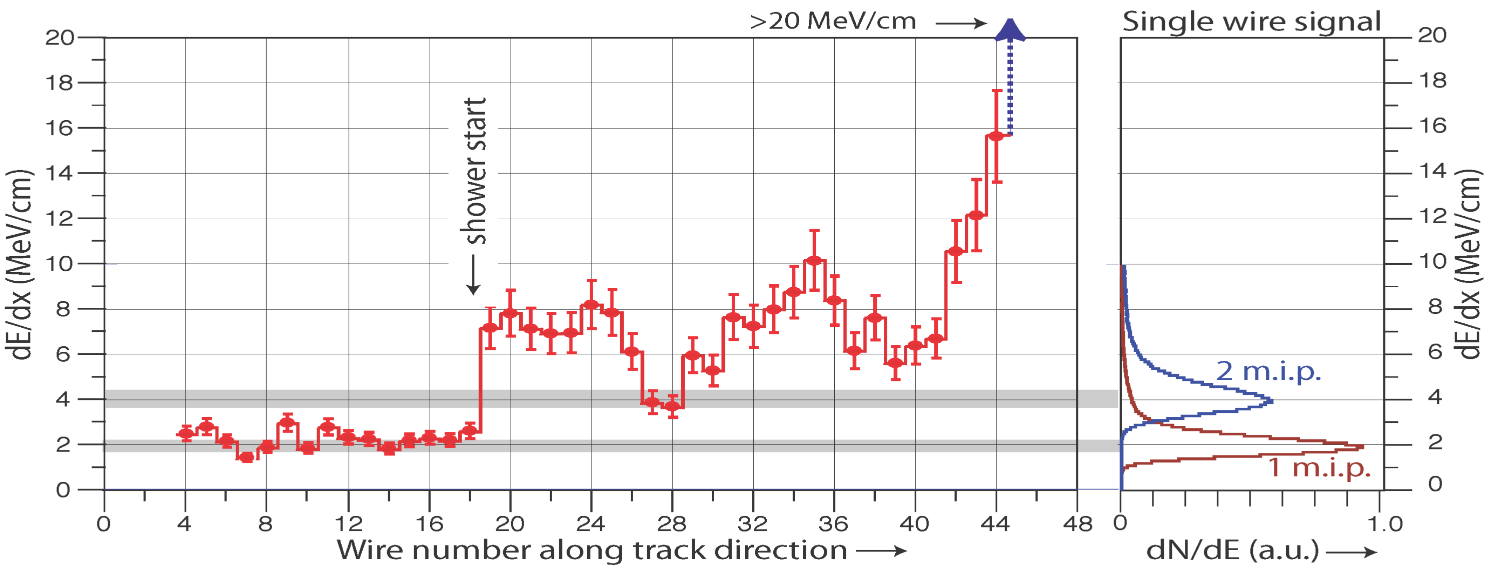
The νe identification in ICARUS Lar-TPC

- The unique detection properties of LAr-TPC technique allow to identify unambiguously individual e-events with high efficiency.



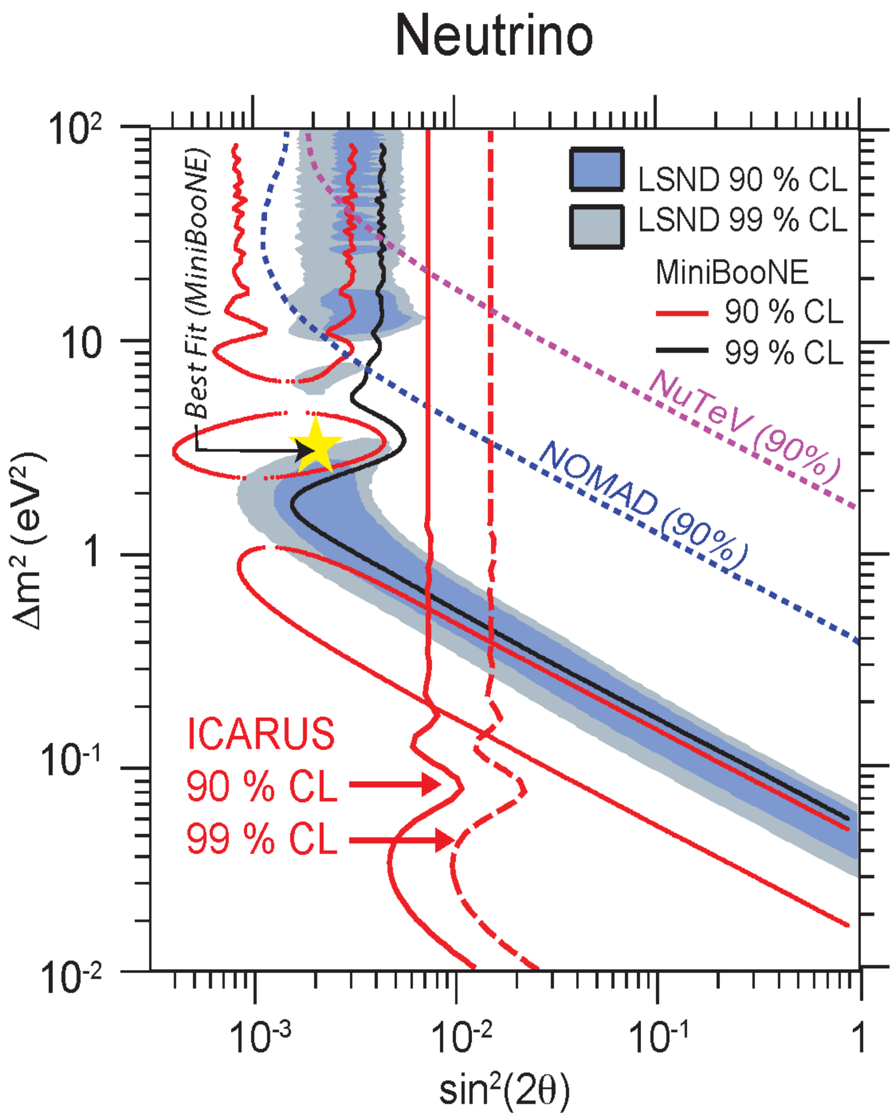
- The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is clearly apparent from individual wires.

Single M.I.P



ICARUS search for the LSND-anomaly

- Events with a clear electron signature have been found in a sample of 2450 ν interactions ($7.23 \; 10^{19}$ pot).
- 6 ν_e events have been observed in agreement with the expectations 7.9 ± 1.0 due to the conventional sources (~33% probability to observe ≤ 6 ν_e events).
- Weighting for the efficiency, ICARUS limits on the number of events due to LSND anomaly are: 5.2 (90 % C.L.) and 10.3 (99 % C.L.).
- These provide the limits on the oscillation probability:
  - $P(\nu_\mu \rightarrow \nu_e) \leq 3.85 \times 10^{-3}$ (90 % C.L.)
  - $P(\nu_\mu \rightarrow \nu_e) \leq 7.60 \times 10^{-3}$ (99 % C.L.)
- The result is confirmed by OPERA



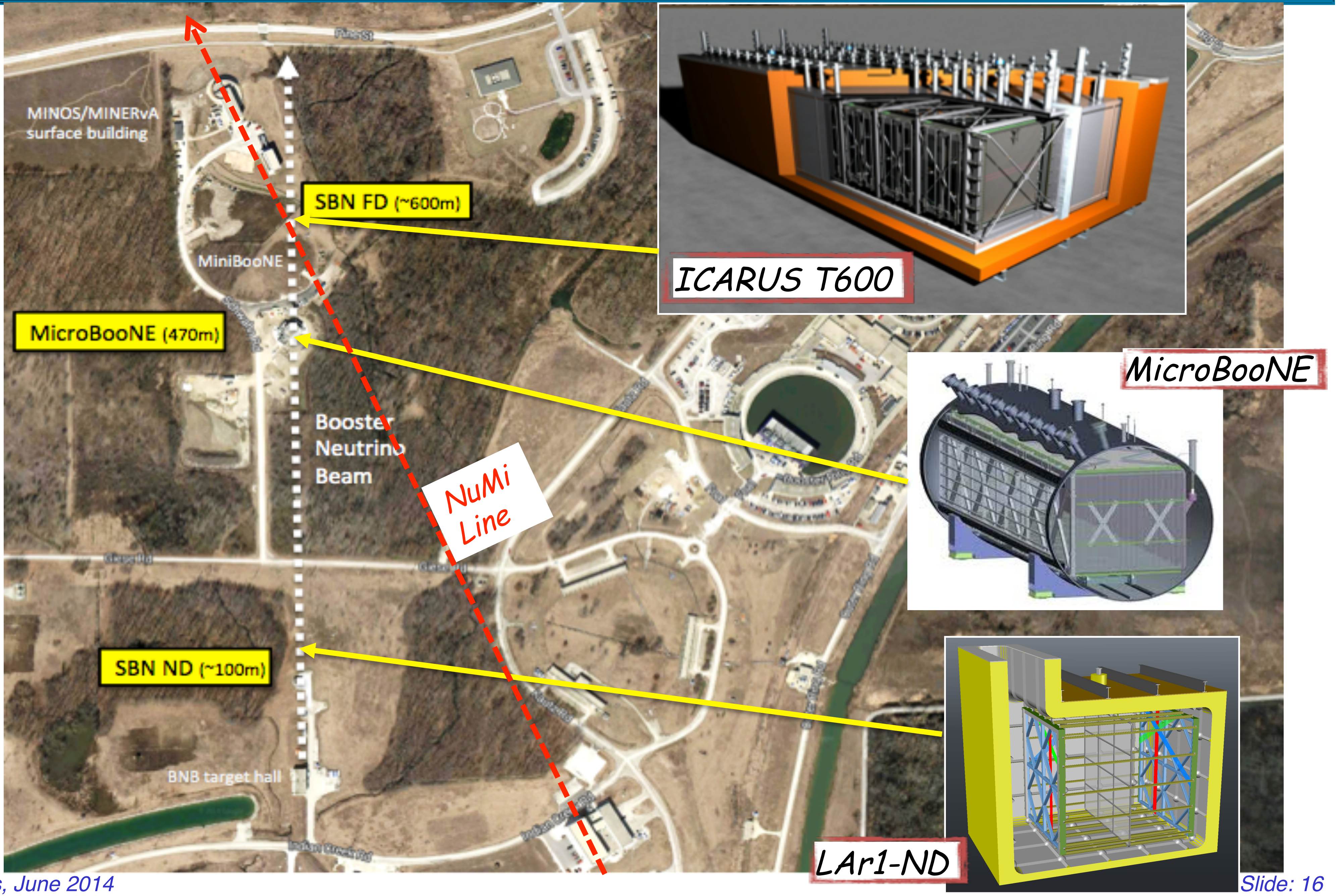
Sterile neutrino search at the FNAL Booster ν beamline

- Two new proposals have been recently submitted (01/2014) to FNAL-PAC for dual detector experiments:
  - P1052: ICARUS, taking advantage of the existing T600 as far detector combined with a new T150 "clone" at a near location;
  - P1053: LAr1-ND, to be used as near detector at the SciBooNE site in combination with the existing MicroBooNE (1st phase).
- At present a joint ICARUS/LAr1-ND/MicroBooNE effort is taking place to develop:
  - a coherent collaborative, international program at FNAL's BNB (and NuMI off-axis) featuring three detectors at different baselines by 2018 (near: Lar1-ND, mid: MicroBooNE, far: ICARUS);
  - a common proposal focusing on cosmic ray induced bgd., beam/detector systematics, logistics.

Basic features of the future LAr-TPC experiment

- The experiment, collecting a large amount of data, may be able to give a likely *definitive* answer to the 3 following queries after a 3 years exposure :
  - the LSND/MiniBooNE appearance of the $\nu\mu \rightarrow \nu e$ oscillation anomalies;
  - The Gallex + Reactor oscillatory disappearance of the initial νe signal;
  - an oscillatory disappearance maybe also be present in the $\nu\mu$ signal, so far unknown.
- In absence of these "anomalies", the signals in each detectors should be a closer copy of each other for all experimental signatures and without strong need of Monte Carlo comparisons.
- A future program may extend the study to antineutrino, but with the addition of the foreseen magnetic field in the LAr-TPC.

SBL at the FNAL ~ 0.8 GeV ν Booster Beam



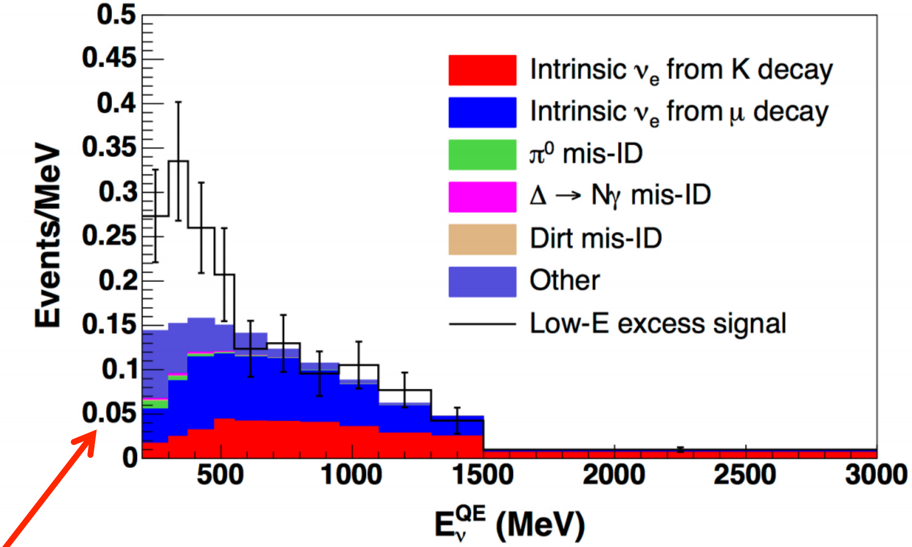
MicroBooNE

- The ~90t MicroBooNE LAr-TPC represents the first step in a phased LAr-based FNAL neutrino program and it will be an excellent R&D play ground in the near future.

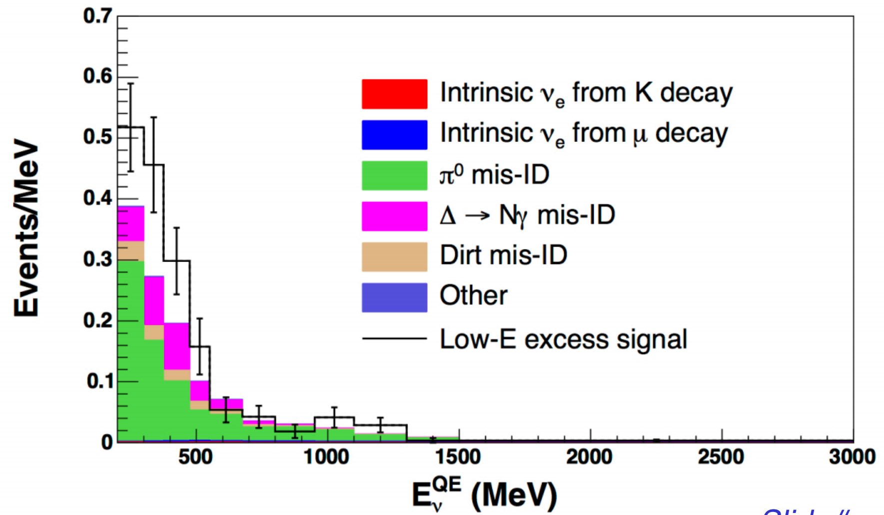
- MicroBooNE will address neutrino cross section measurements and possibly the MiniBooNE low-E excess.
- However, MicroBooNE is not large enough to be able to definitively address the sterile neutrino issue.

LAr-TPC properties (granularity, dE/dx) should allow to distinguish between:

Electrons ?

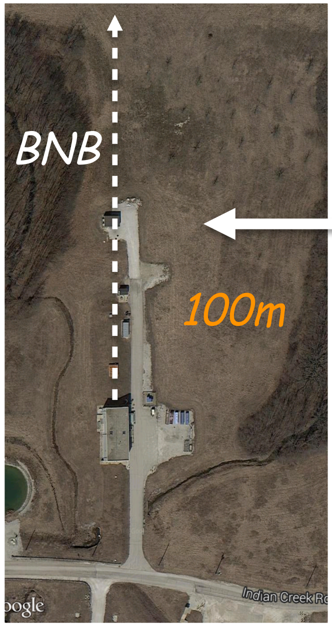


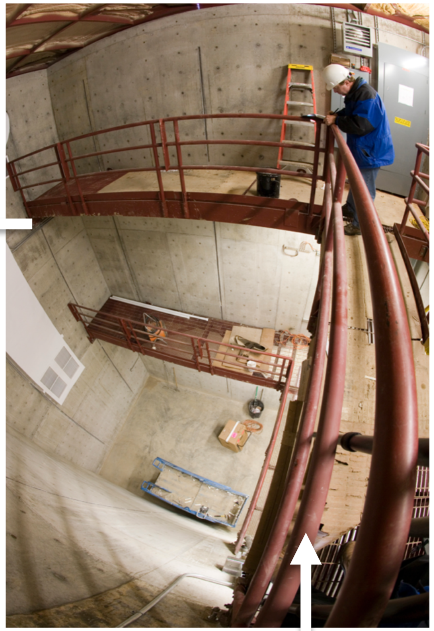
Photons ?



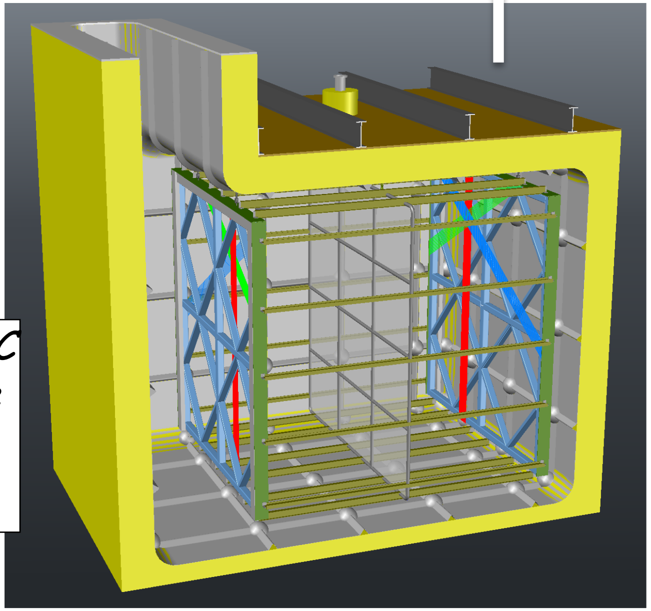
LAr1-ND

- A proposed 82 ton LArTPC near detector at 100 m in FNAL's BNB
  - utilize as many design elements developed for the LBNE Far Detector as feasible
  - implement technology that builds upon experience from the T600, MicroBooNE and the 35-ton membrane cryostat prototype
- LAr-ND would provide high-statistics measurement of the intrinsic BNB content, enabling sensitive oscillation searches in combination with downstream detectors
- Together with MicroBooNE, provide a complete interpretation of the MiniBooNE excess. Photons or electrons? Intrinsic to the beam or appearing?
- Valuable "physics R&D" such as reconstruction development and GeV ν-Ar cross sections. ~1M ν_μ events per year, 6,000 ν_e per year!



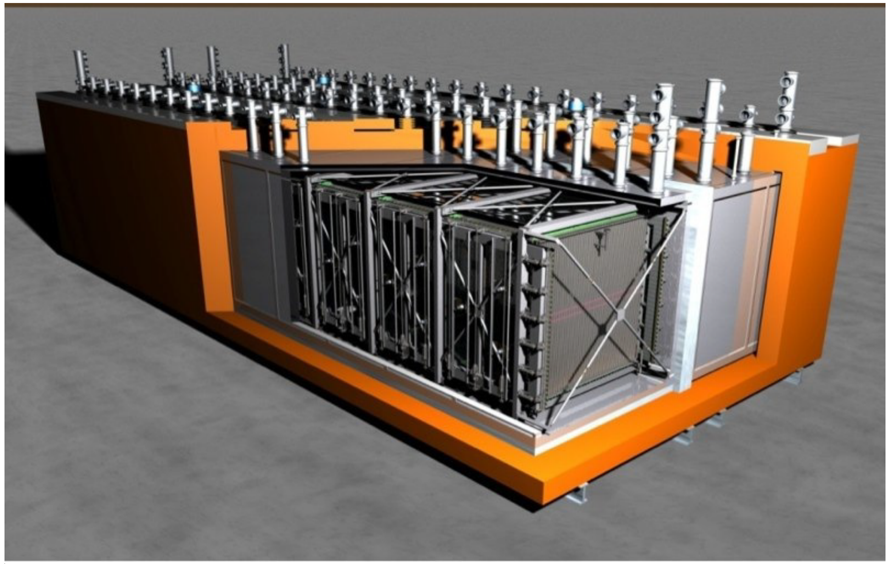


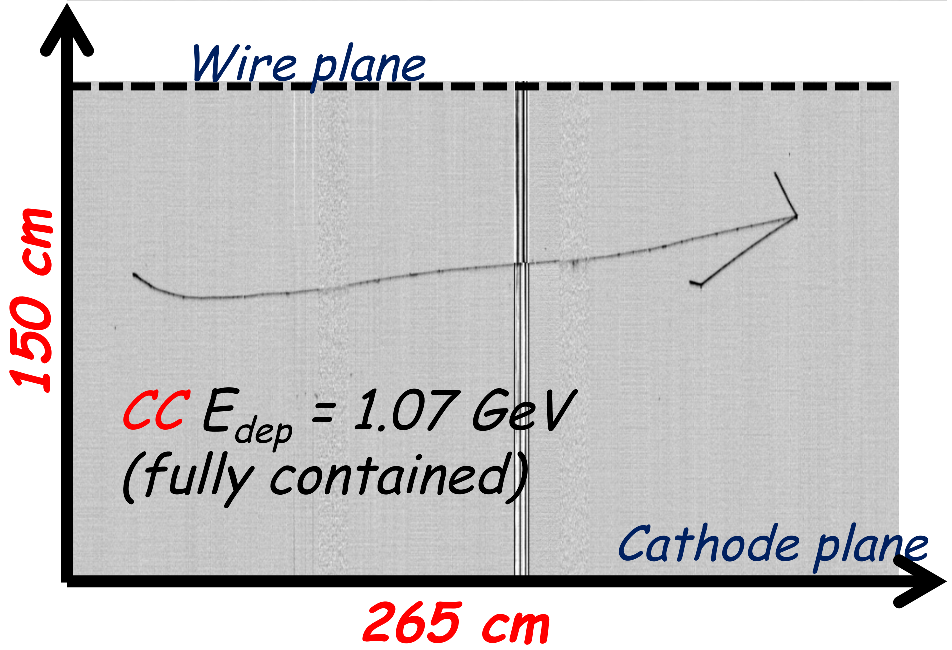
82 ton TPC membrane cryostat design



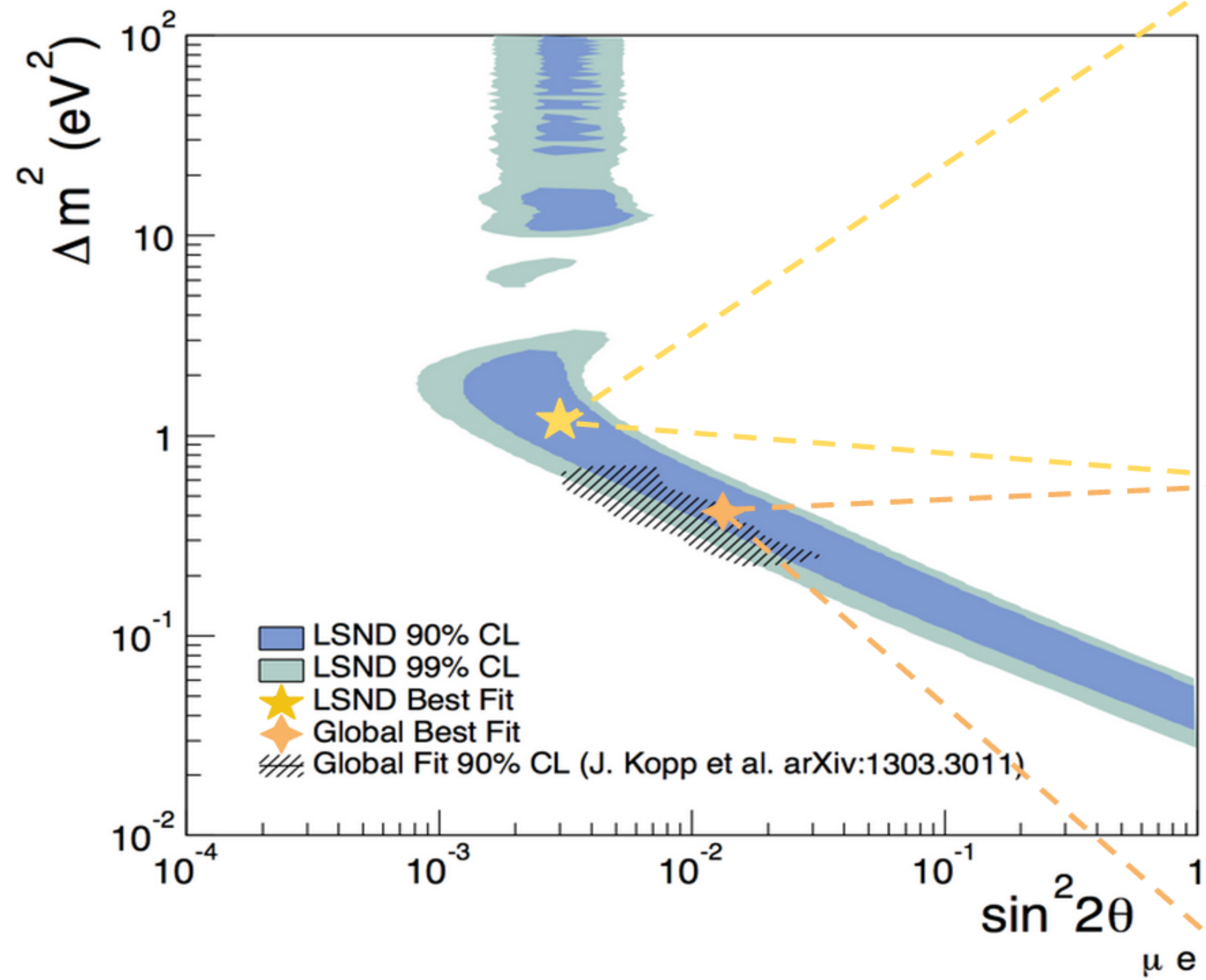
ICARUS

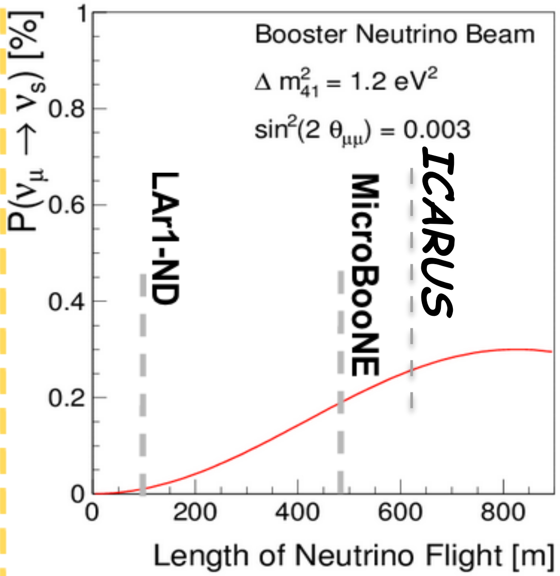
- The T600 (770 ton Lar-TPC) is on its way from LNGS to CERN for a complete overhauling in the next two years.
- Multiple possible technological upgrades (and LAr R&D) are envisaged: new electronics (warm/cold) and DAQ, new cryogenics and LAr vessels, SiPM light collection.
- Additional developments also foressen: doping, B-field …
- An increase of the drift distance is also under consideration, thanks to the excellent Lar purity reached at LNGS (>12 ms) with the possibility to nearly double the active volume.

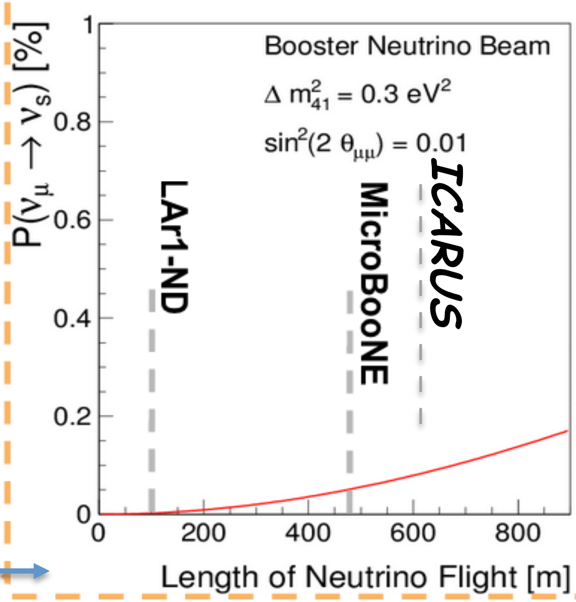




Sterile Neutrino Oscillations on the BNB



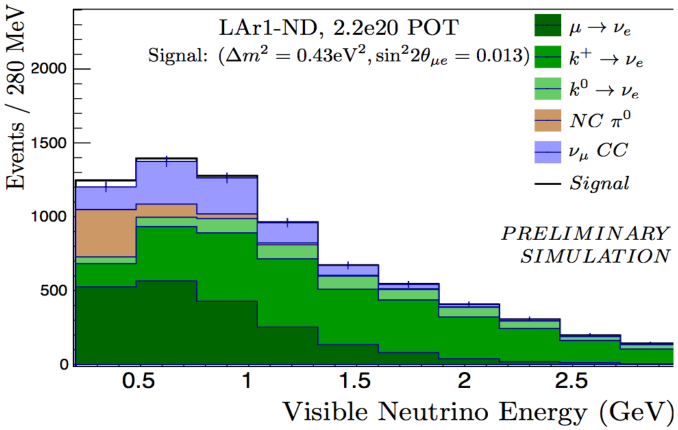




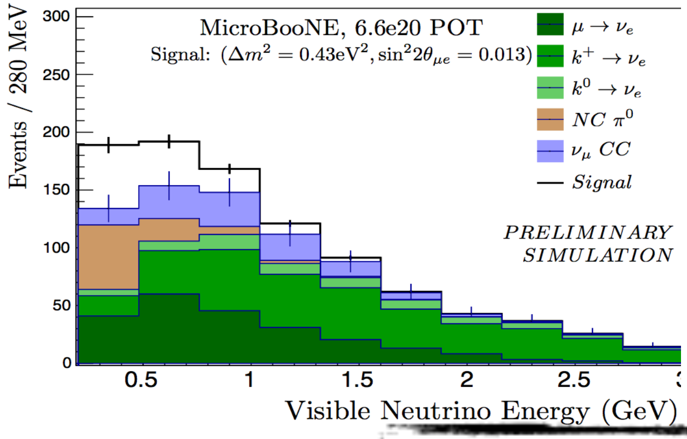
At peak BNB neutrino energy, E = 700 MeV

Appearance/disappearance signals

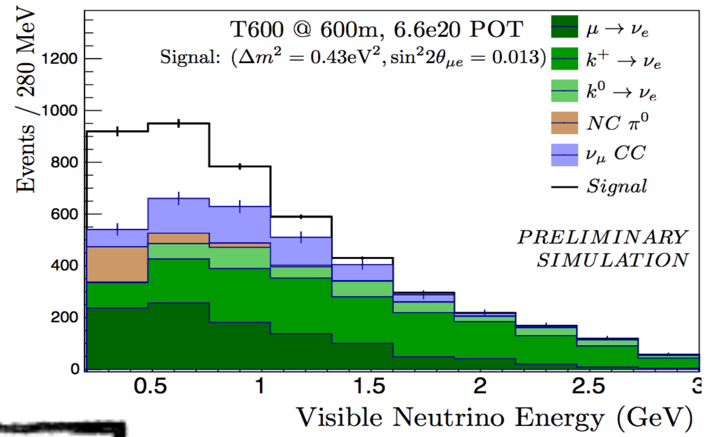
ND @ 100 m

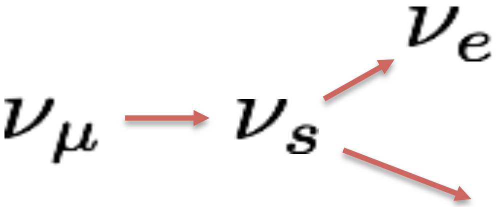


MicroBooNE @ 470 m



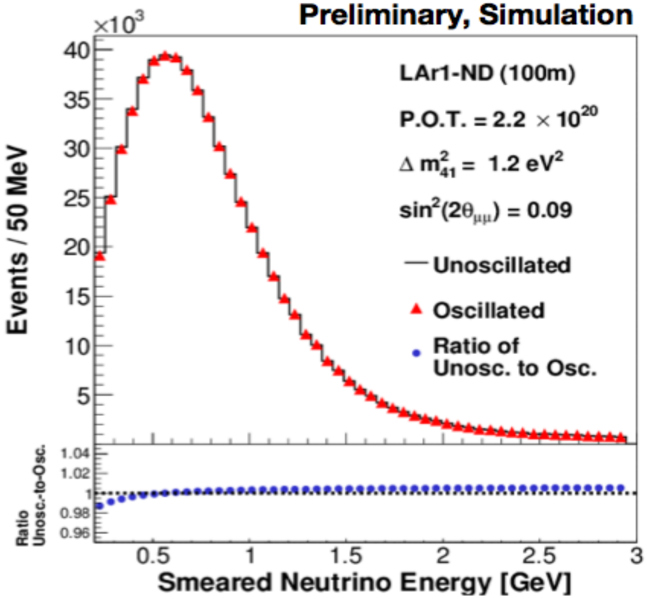
ICARUS T600 @ 600 m

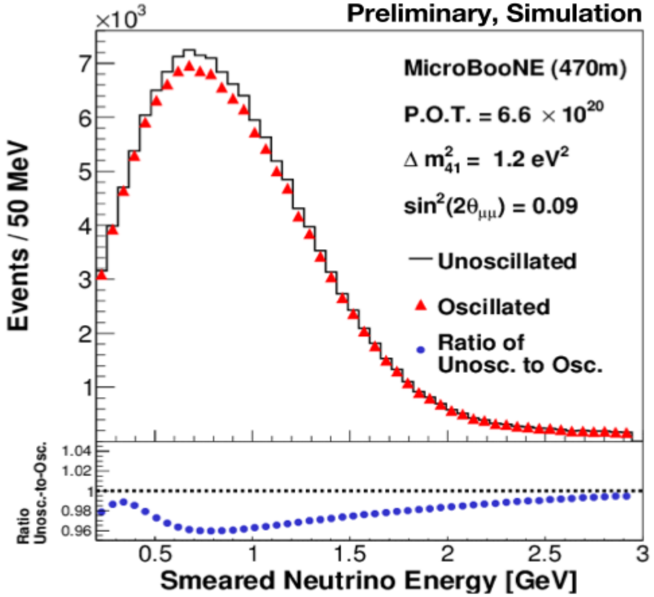


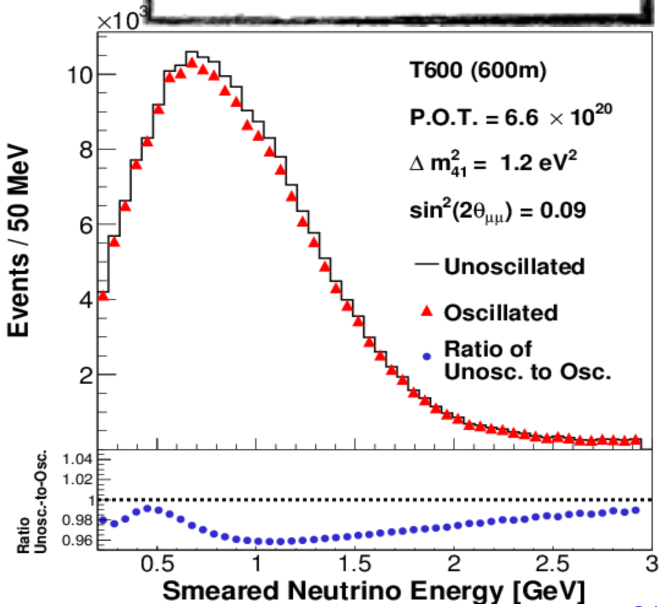


ν_e Appearance

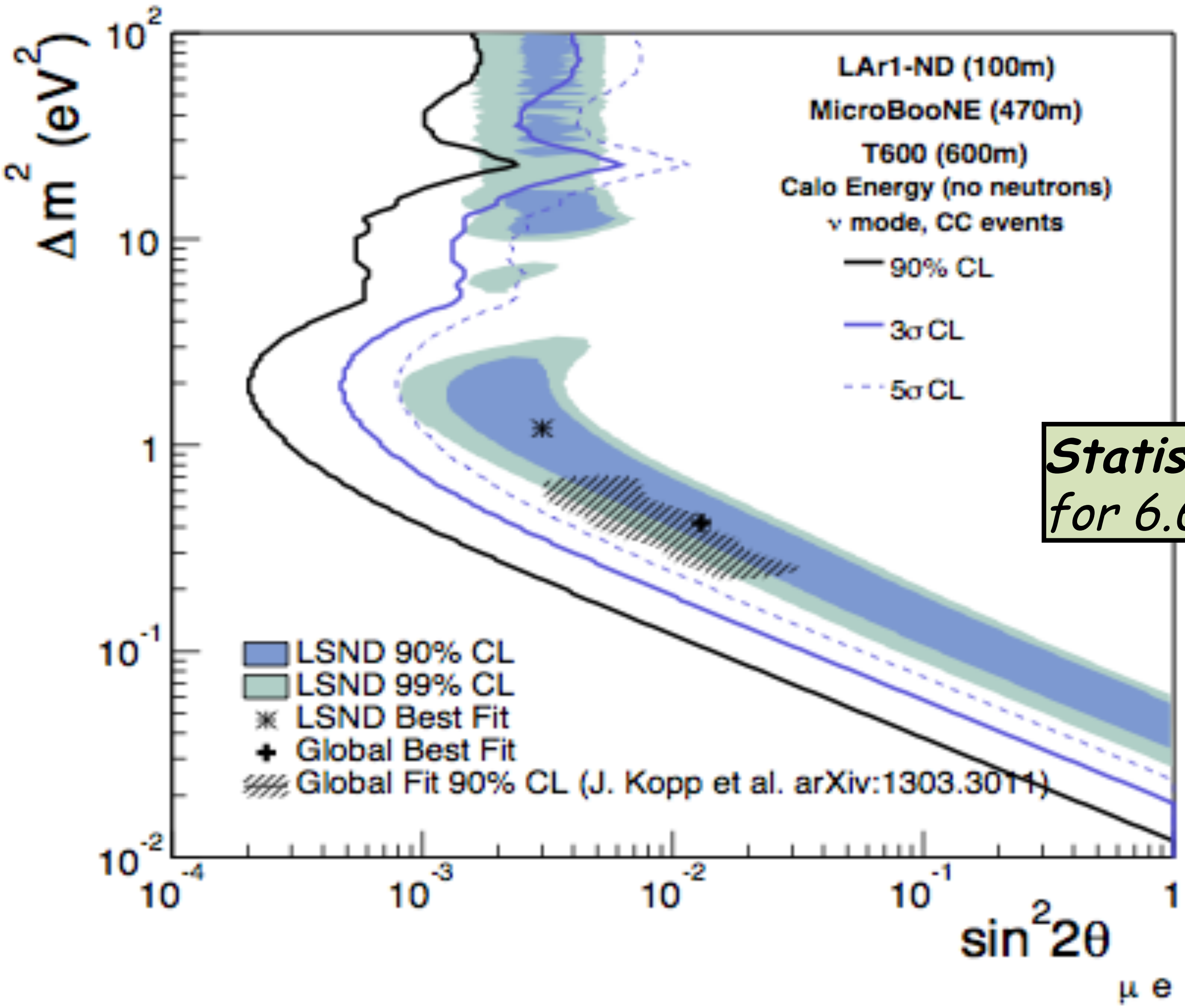
ν_μ Disappearance

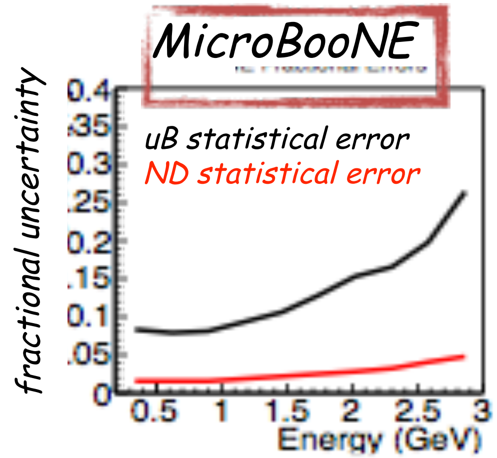




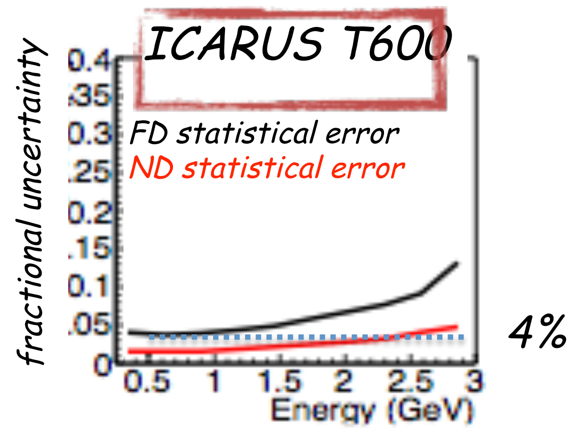


$\nu_\mu \rightarrow \nu_e$ Appearance

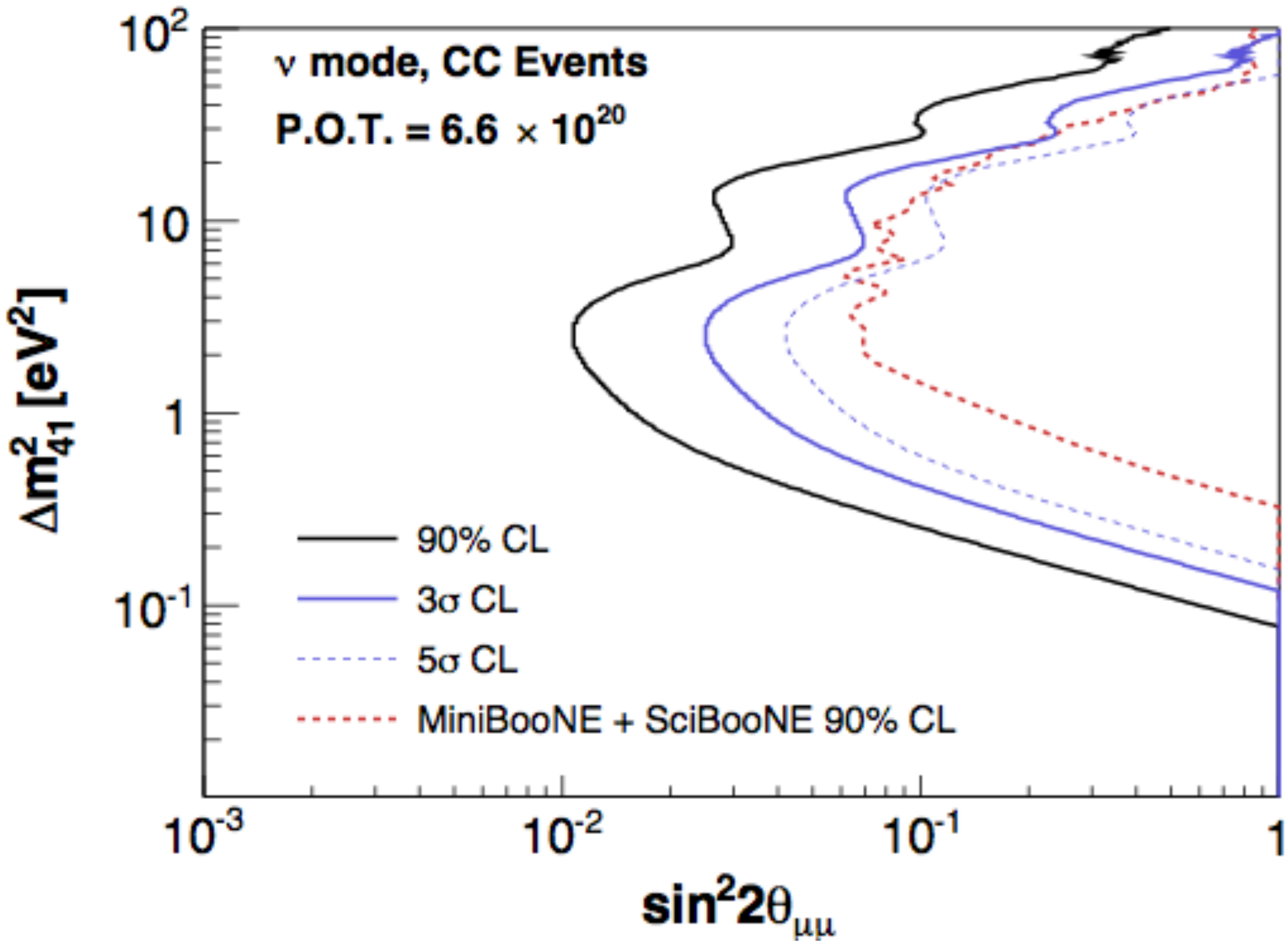




Statistical Uncertainty Limit
for 6.6e20 POT exposure



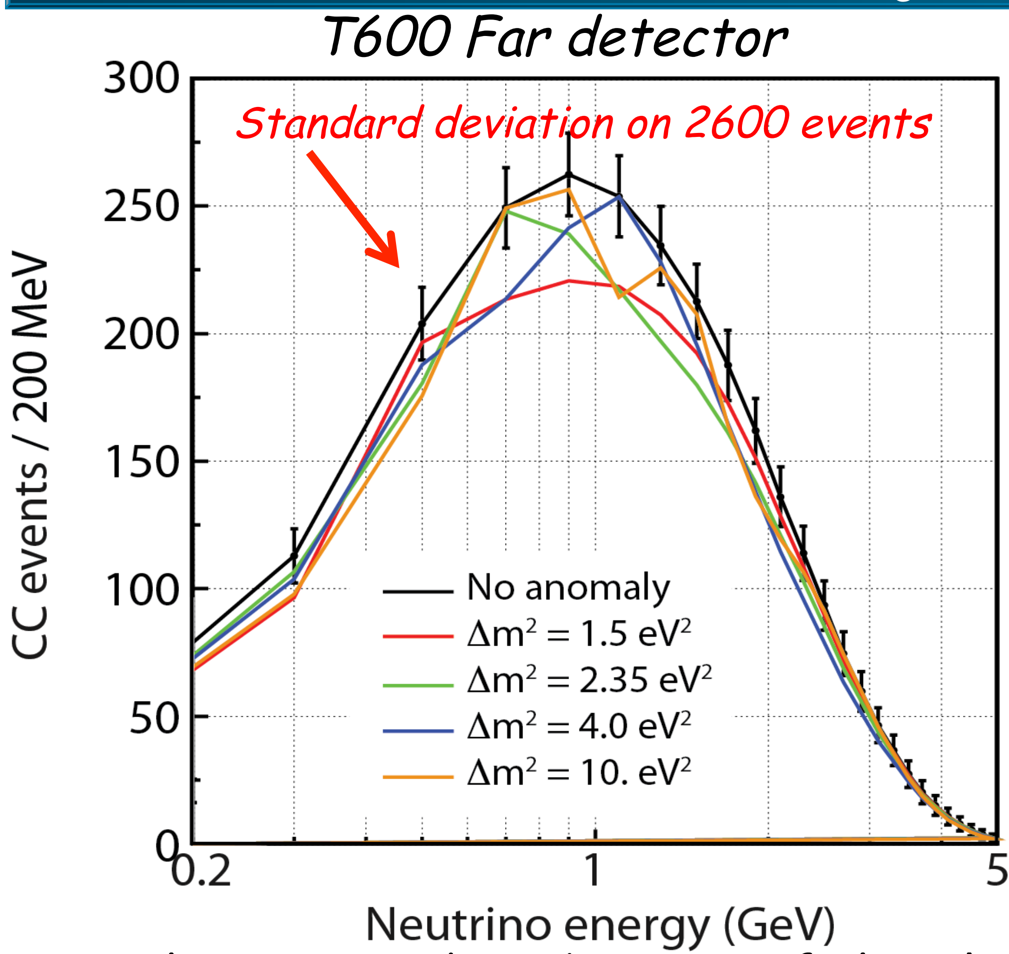
νμ Disappearance

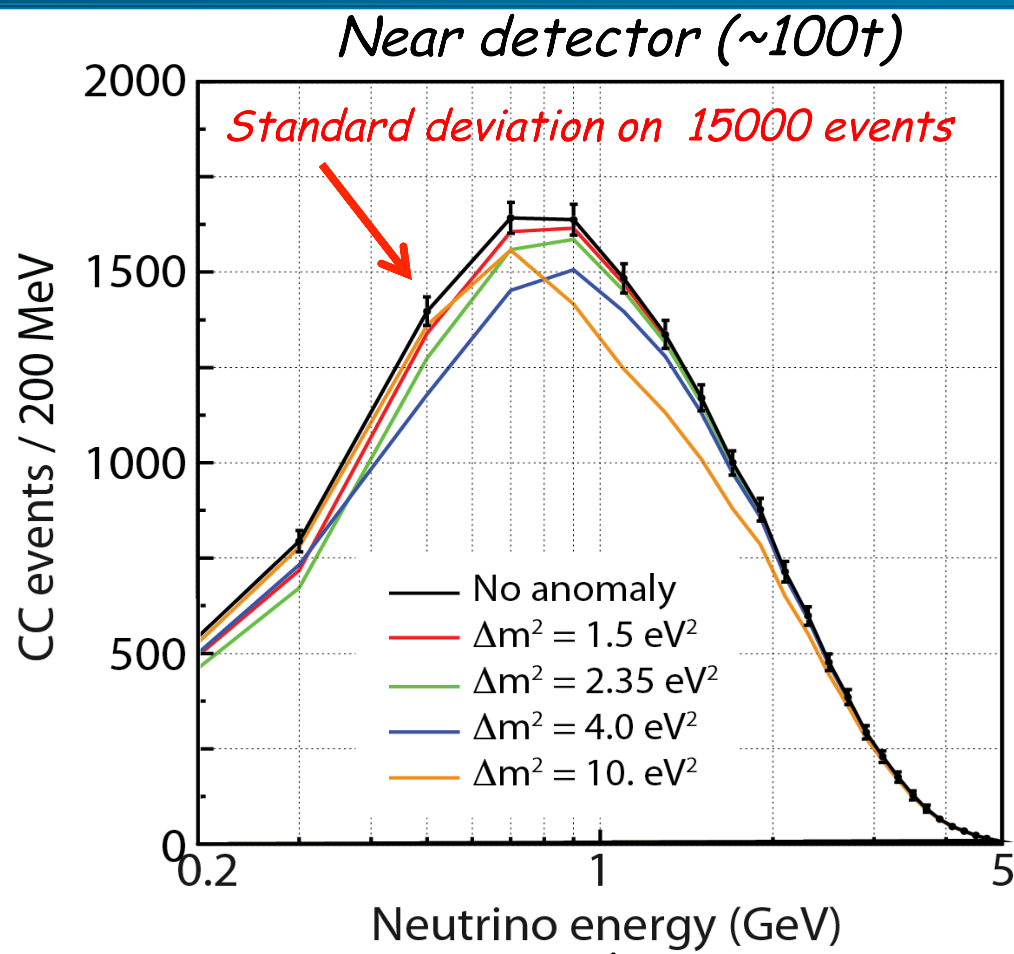


ν_μ disappearance not a statistics limited search. Here shown with a 4% systematic uncertainty on the near to far extrapolation.

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

Sensitivity to ν_e disappearance signals





- The energy distributions of the electron neutrino events is shown respectively for the "Far" and "Near" and a number of possible values in the region of $\Delta m^2 > 1 eV^2$ and $sin^2(2\theta) \approx 0.16$ for 2600 neutrino events.
- The LAr-TPC energy resolution should be adequate to resolve the oscillation pattern in a wide range of Δm^2 values.

Synergy with the Long-Baseline Program

- SBL neutrino program has important synergies with on-going efforts of the future long-baseline neutrino program
  - Continued development of the Liquid Argon TPC technology for neutrino physics.
  - T600 and MicroBooNE will collect a large ν event statistics in 0-3 GeV range with a νe an enriched component of electron neutrinos (several %) from the dominant three body decay of secondary kaons at ~100 mrad off-axis, ~800 m from NuMI target.

for 1 year exposure at 3 10^{20} pot.

ν_μ CC	anti-ν_μ CC	ν_e CC	anti-ν_e CC
180K	31 K	7.9 K	1.5 K

  - A careful and detailed analysis of these events will be highly beneficial for the future LBNE LAr program, allowing to study very precisely detection efficiencies and kinematical cuts in all neutrino channels and event topologies.

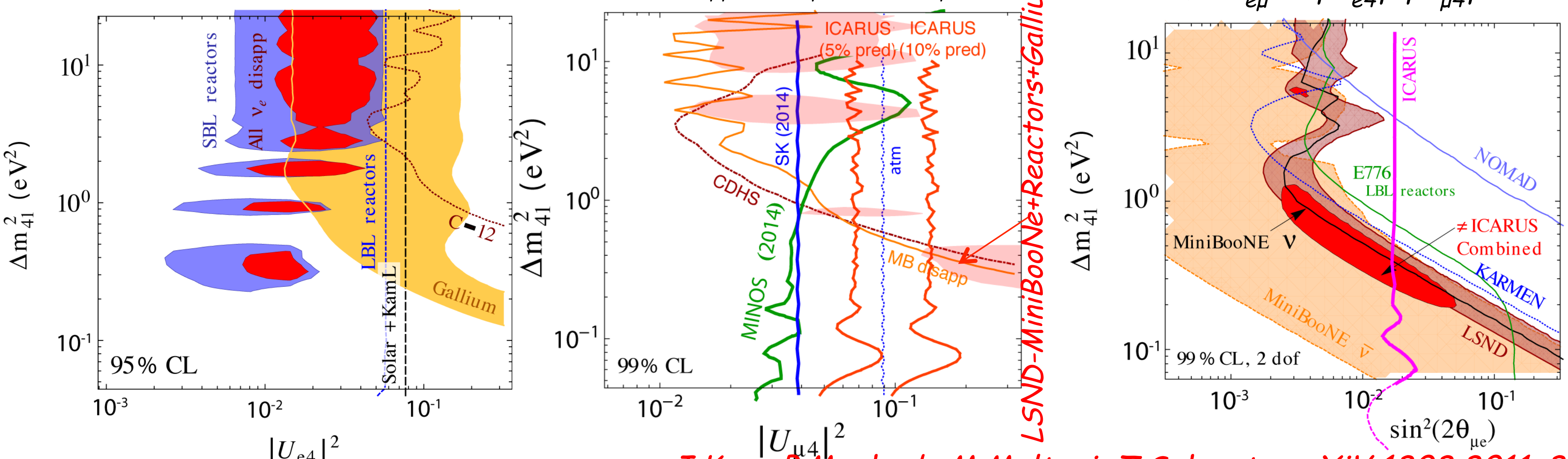
Summary: present and future

- The Big Bang cosmology predicts at most a single sterile neutrino
- Within the 3+1 model the LSND appearance and the νe disappearance require a νμ disappearance in "tension" with present available data.

νe disappearance signal $\sin^2 2\theta_{ee} = 4|U_{e4}|^2 (1-|U_{e4}|^2)$

μ. disappearance signal $\sin^2 2\theta_{\mu\mu} = 4|U_{\mu4}|^2 (1-|U_{\mu4}|^2)$

νμ→νe appearance signal $\sin^2 2\theta_{e\mu} = 4|U_{e4}|^2 |U_{\mu4}|^2$



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- The new reactor and source experiments will give a more accurate (≈ 1 %) answer on the νe disappearance signal
- The νμ disappearance measurements will also be improved.
- The future multiple-detector experiment at FNAL-BNB would permit to address simultaneously all the ν "anomalies" and it could definitely clarify the LSND case at the required 5 σ level.


Thank you !