Recent Results from MiniBooNE and the Future Project LBNE

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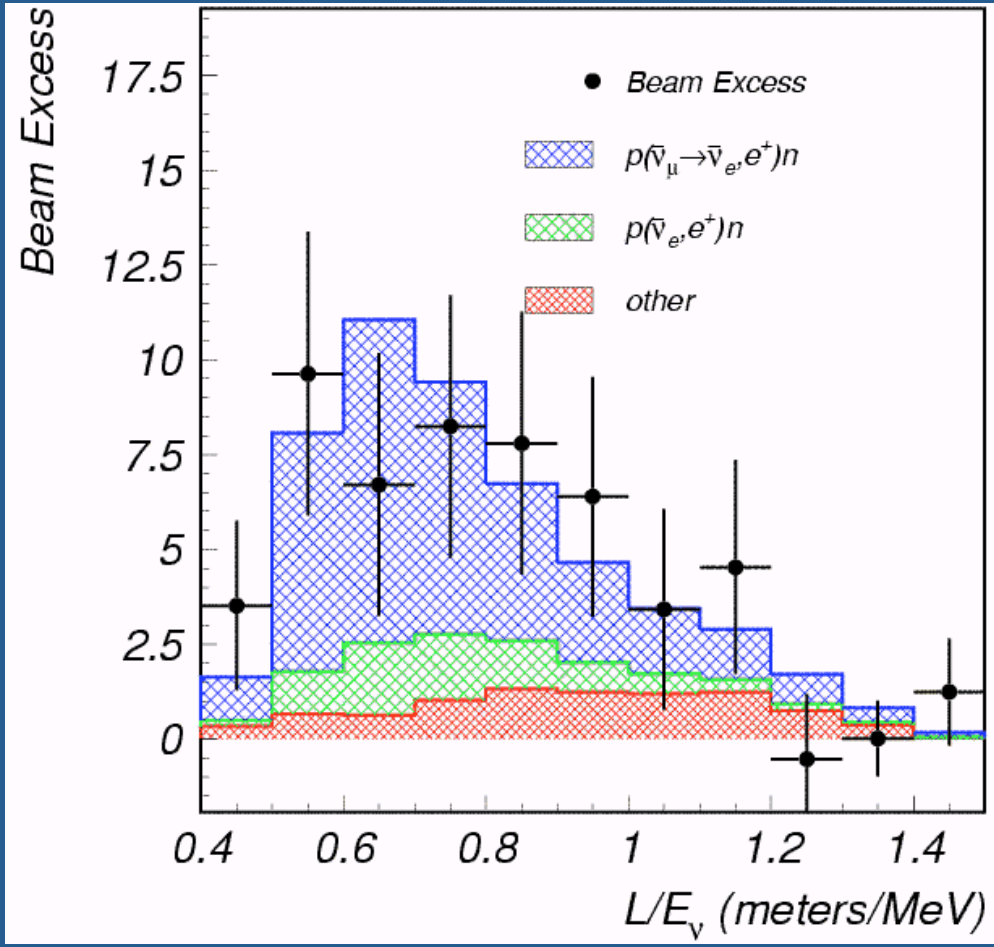
Outline

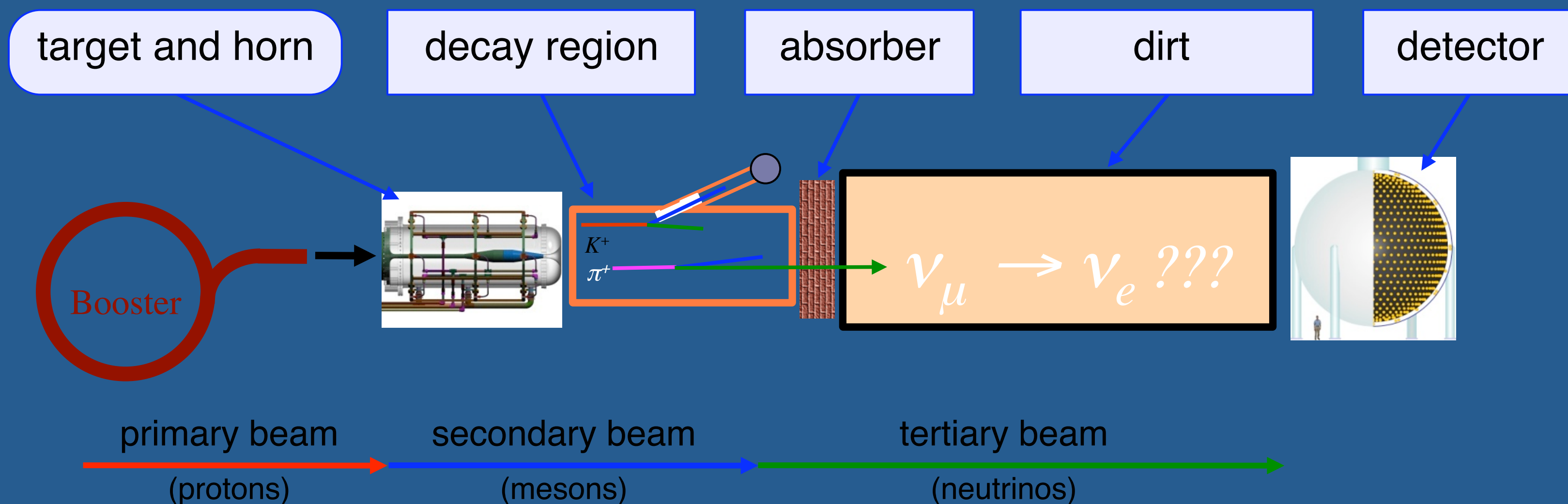
- Overview of MiniBooNE
- Recent Oscillation Results
- Introduction to the Next Generation of Long-Baseline Experiment
- Sensitivity Potential of LBNE
- Conclusions

MiniBooNE motivated by LSND Result

- MiniBooNE designed to test LSND result: 3.8σ appearance of electron antineutrino in muon antineutrino beam
- Use the same L/E but in different energy regime – different systematics:
  - LSND L=30m E~30MeV
  - MiniBooNE L=500m E~500MeV

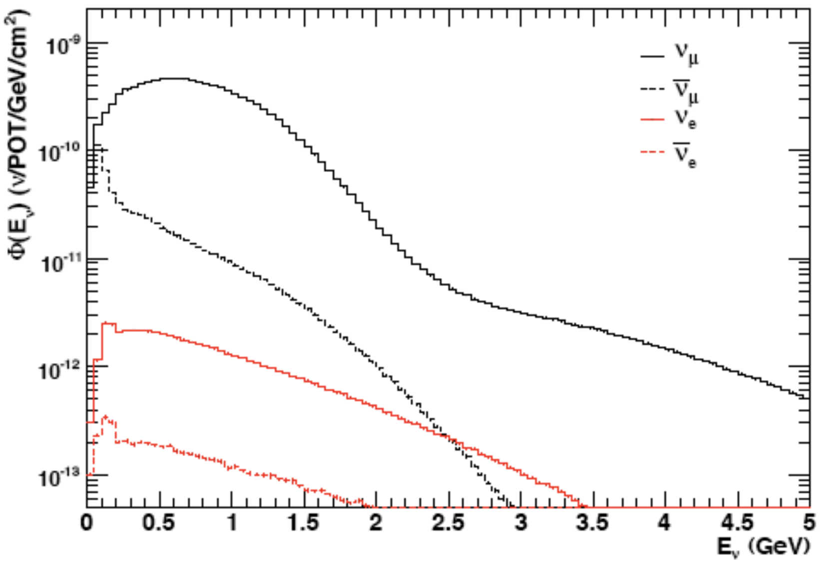


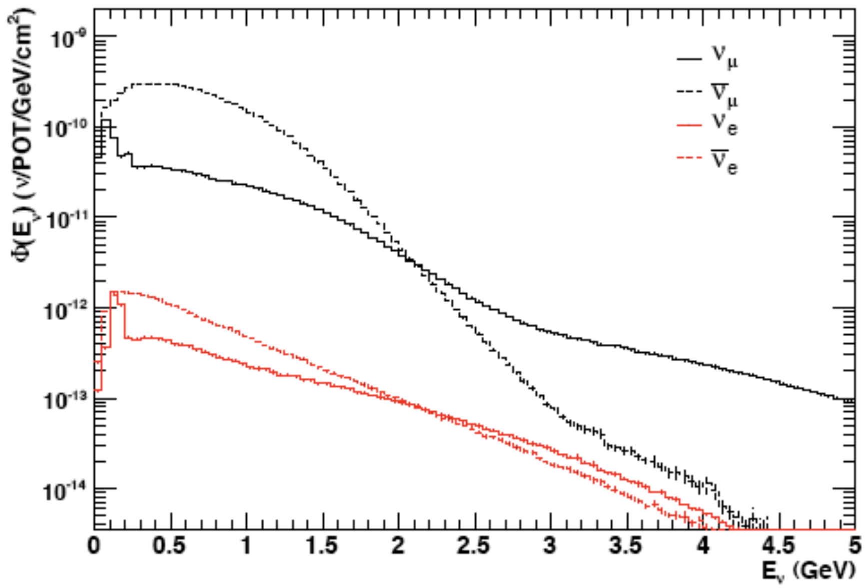
MiniBooNE Experiment



- Standard neutrino beam generation
- Since August 2002
  - 6.46×10^{20} POT neutrino mode
  - 4.86×10^{20} POT antineutrino mode
- Began antineutrino running for additional 5.0×10^{20} POT in September

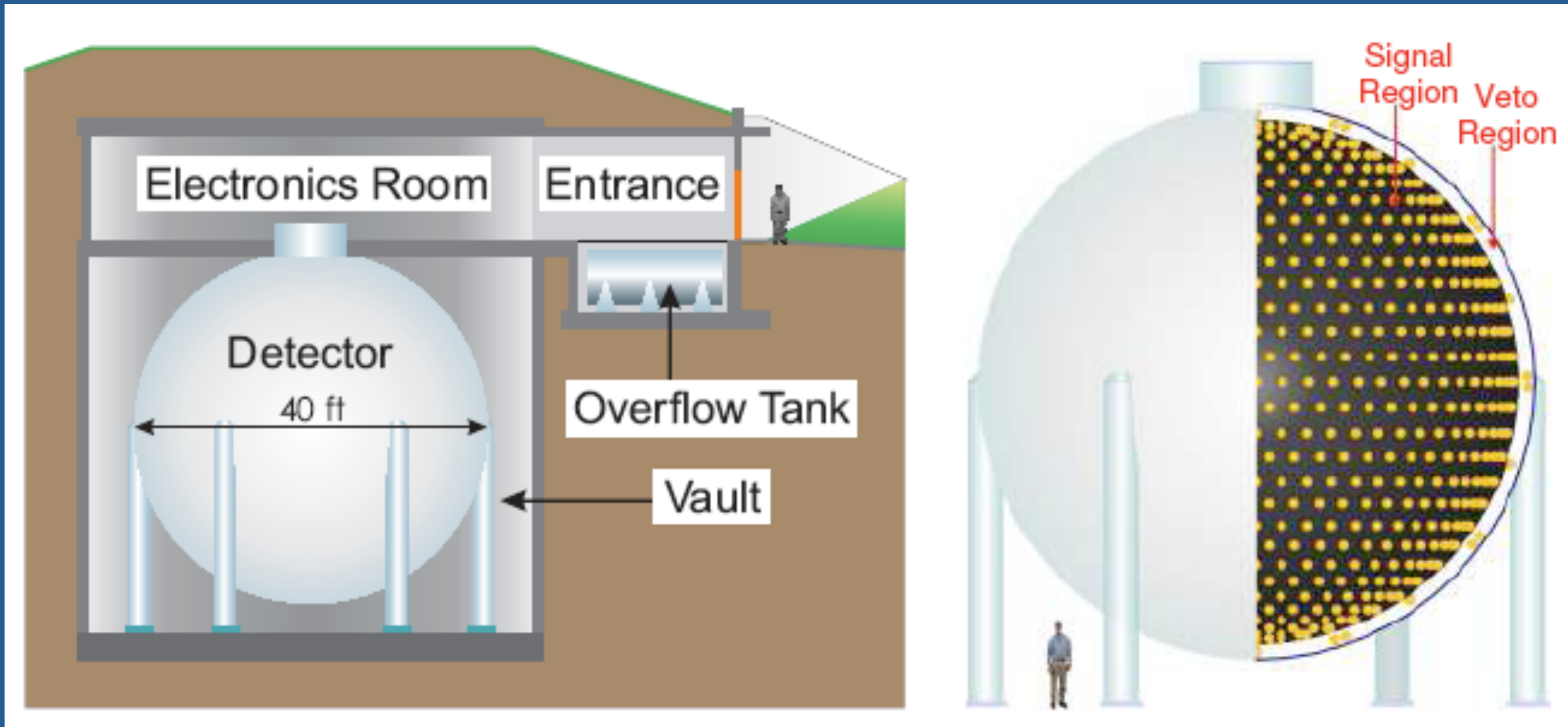
MiniBooNE Neutrino and Antineutrino Fluxes





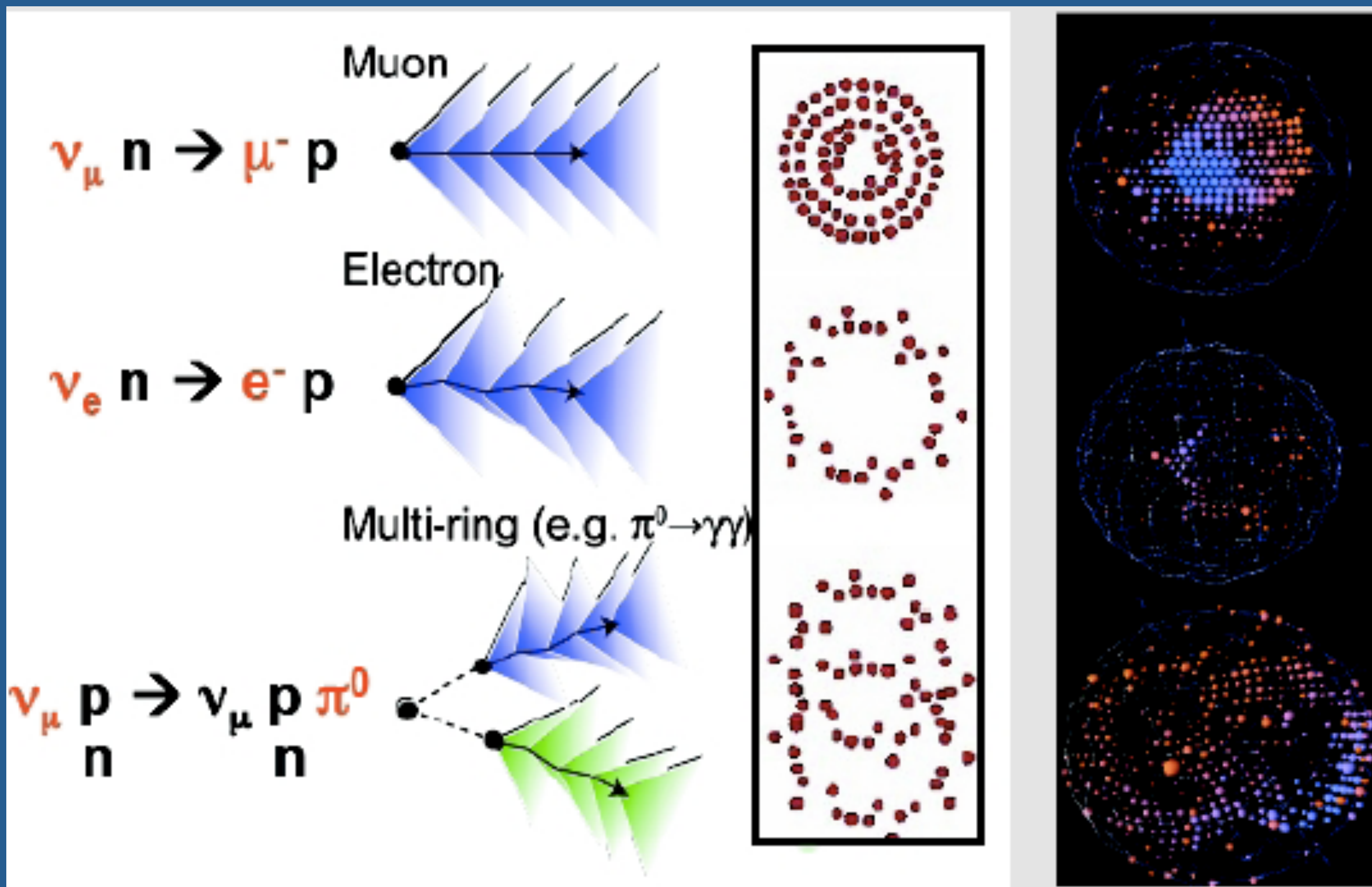
- Well-understood neutrino beam
- Neutrino mode:
  - wrong-sign background ~6%
  - Intrinsic electron neutrino ~0.5%
- Antineutrino mode:
  - Wrong-sign background ~ 18%
  - Intrinsic electron neutrino ~0.6%

MiniBooNE Detector



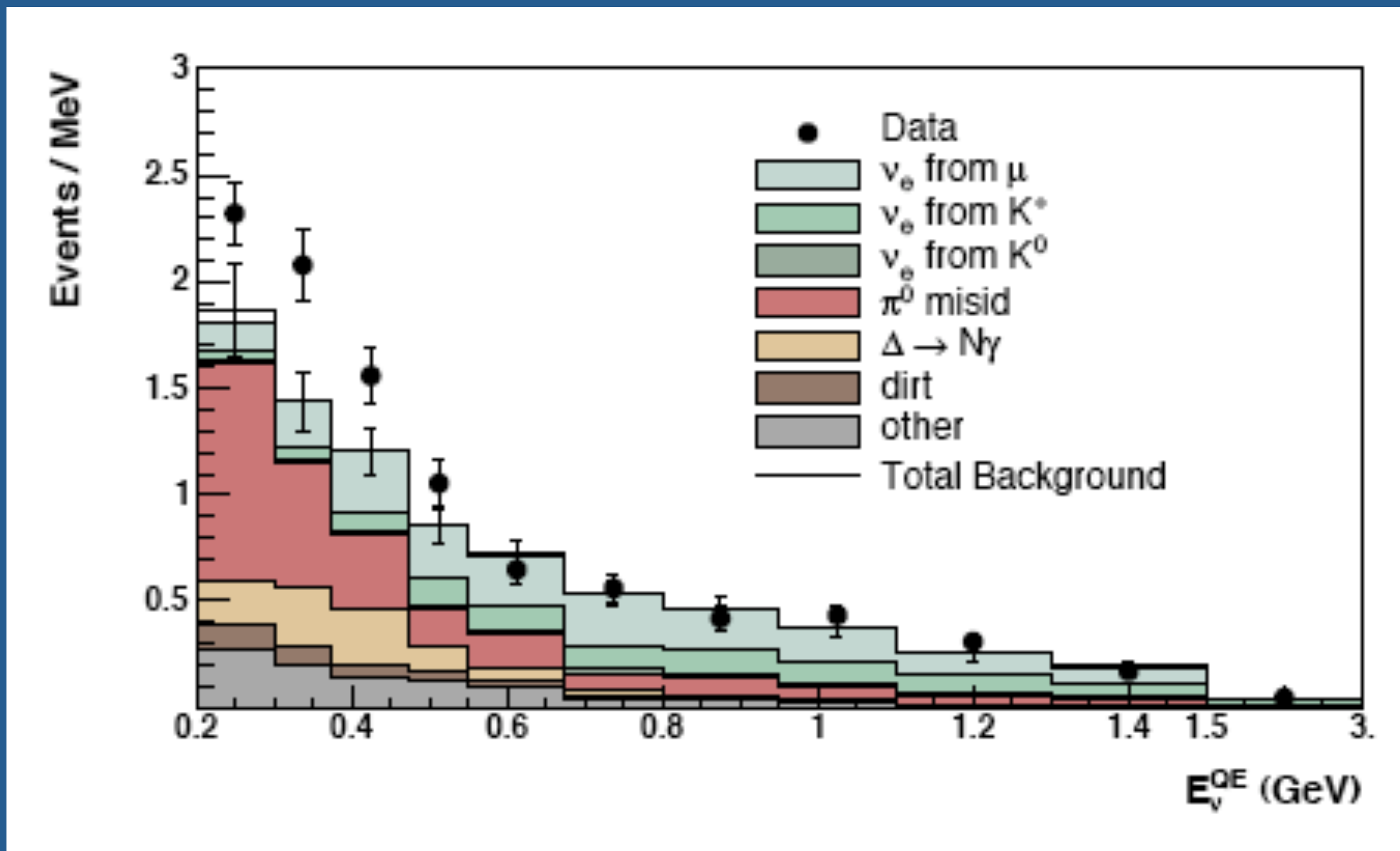
- 12m diameter tank
- 900 tons pure mineral oil
- optically isolated inner region with 1280 PMTs – photocathode coverage ~ 10%

Particle Identification in MiniBooNE



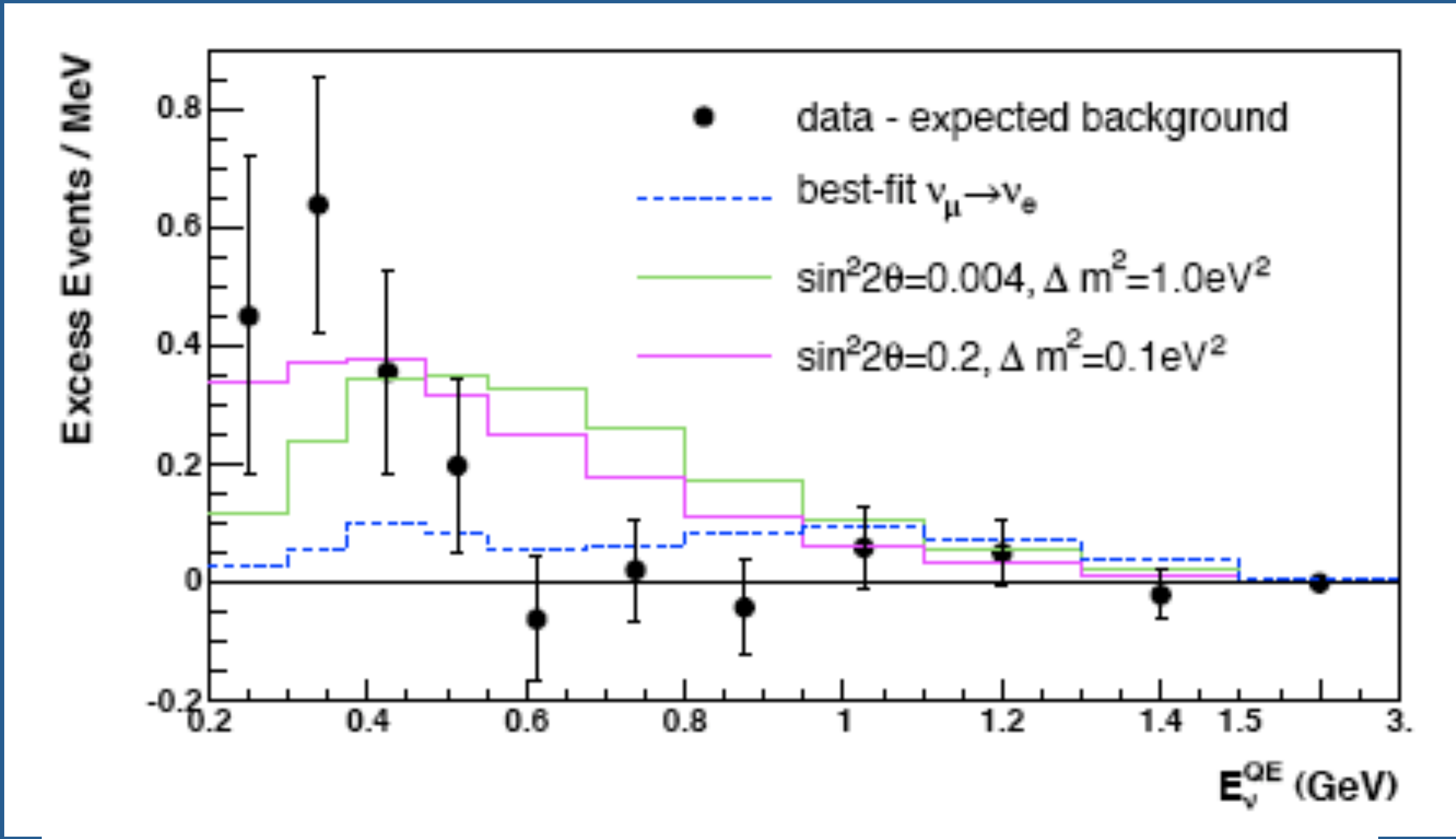
- Predominantly Cherenkov light

Neutrino Results



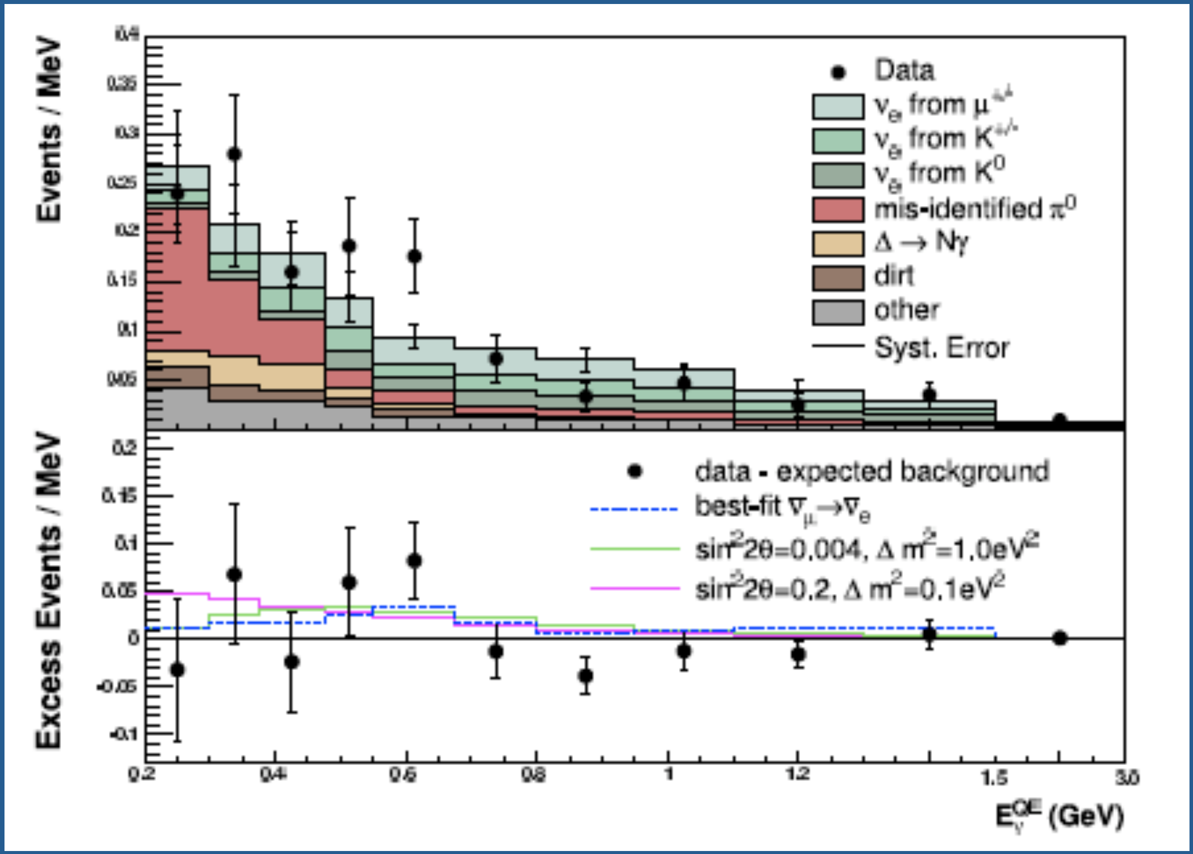
- Consistent with no oscillation above 475 MeV
- Anomalous results below 475 MeV

Low Energy Excess Observed



$$128.8 \pm 20.4 \pm 38.3 \text{ events}$$

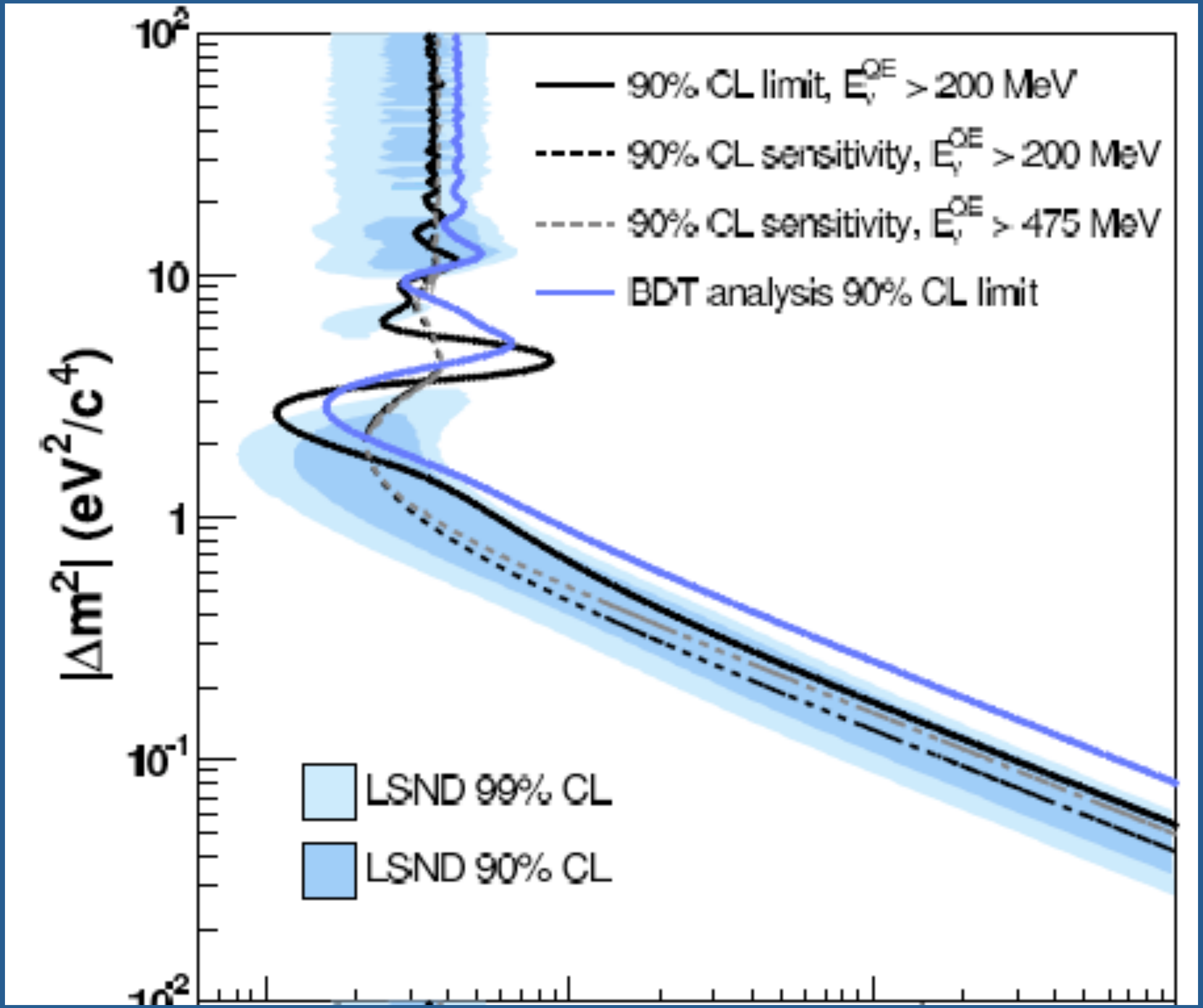
Antineutrino Results



- 3.4×10^{20} POT (low statistics)
- No large excess is observed at low energy (below 475 MeV) unlike for neutrinos −0.5 ± 11.7 events
- 4.86×10^{20} POT currently being analyzed

Antineutrino Oscillation Results

- Results consistent with no oscillation and with LSND
- Need more data!



MiniBooNE Conclusions

- Unexplained low energy excess in neutrinos
- No low-energy excess is observed in antineutrino data
- Standard Model explanations for low-energy excess would require excess for anti-neutrinos
- Need more data in antineutrino mode
- Excess could be evidence for CPT non-conservation
- Need a thorough study for future long-baseline experiments searching for electron neutrino appearance

The MiniBooNE Collaboration

Alabama, Bucknell, Cincinnati, Colorado, Columbia, Embry-Riddle, Fermilab, Florida, Illinois, Indiana, Los Alamos, LSU, MIT, Michigan, Princeton, Saint Mary's, Virginia Tech, Yale

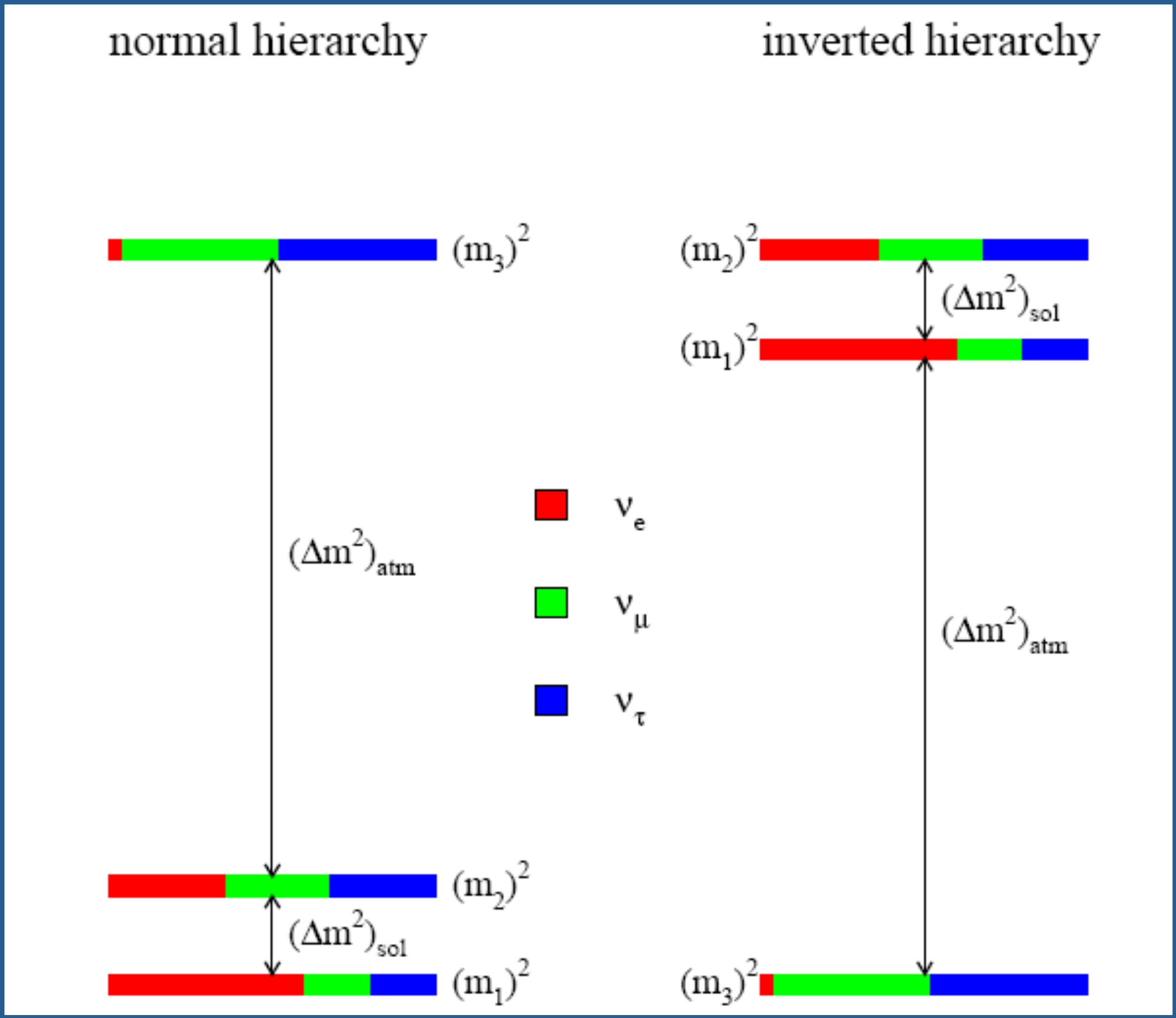
Long-Baseline Neutrino Experiment (LBNE)

The future Fermilab to DUSEL flagship particle physics experiment

Long-Baseline Neutrino Physics

- Motivated by observation of neutrino oscillations
- Atmospheric oscillations (Super-Kamiokande, K2K, MINOS):
  - $\Delta m^2 \sim 2X10^{-3}$ eV^2
  - $\sin^2 2\theta > 0.9$
- Solar neutrino oscillations (SNO, Super-Kamiokande, SAGE, Homestake, GNO; KamLAND (antineutrinos):
  - $\Delta m^2 \sim 8X10^{-5}$ eV^2
  - $\tan^2\theta \sim 0.4$

Neutrino Mass Hierarchy



Case of only three light neutrino flavors. From: **hep-ph/0411274**

Mixing Matrix and Oscillation Probabilities

$$U = \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \begin{array}{c} \nu_1 \qquad\qquad\qquad\qquad \nu_2 \qquad\qquad\qquad\qquad \nu_3 \\ \left[\begin{array}{ccc} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{array}\right] \end{array}$$

- The ``solar'' mixing angle is associated with θ_{12}
- The ``atmospheric'' mixing angle is associated with θ_{23}
- There are now only three remaining unmeasured quantities relevant to neutrino mixing
  - the mass hierarchy, sign of Δm_{31}^2
  - the CP violating phase , δ
  - the mixing angle, θ_{13}
- Our chances of measuring δ depend on the size of θ_{13}

Long-baseline ν_e appearance θ_{13}, δ_{CP}, sign of Δm_{13}^2

$$\begin{aligned} P_{\mu e} &\simeq \left| \sin 2\theta_{13}\ \sin\theta_{23} \sin\Delta_{31} e^{i(\Delta_{32} \pm \delta_{\rm CP})} + \cos\theta_{13}\ \cos\theta_{23} \sin 2\theta_{12} \sin\Delta_{21} \right|^2 \\ &\approx \sin^2 2\theta_{13}\ \sin^2\theta_{23} \sin^2\Delta_{31} \\ &\quad \mp\alpha\ \sin 2\theta_{13}\ \sin\delta_{\rm CP}\ \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}\, \Delta_{31} \sin^2\Delta_{31} \\ &\quad +\alpha\ \sin 2\theta_{13}\ \cos\delta_{\rm CP}\ \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}\, \Delta_{31} \cos\Delta_{31} \sin\Delta_{31} \\ &\quad +\alpha^2\ \cos^2\theta_{23} \sin^2 2\theta_{12}\, \Delta_{31}^2 . \qquad (7) \end{aligned}$$

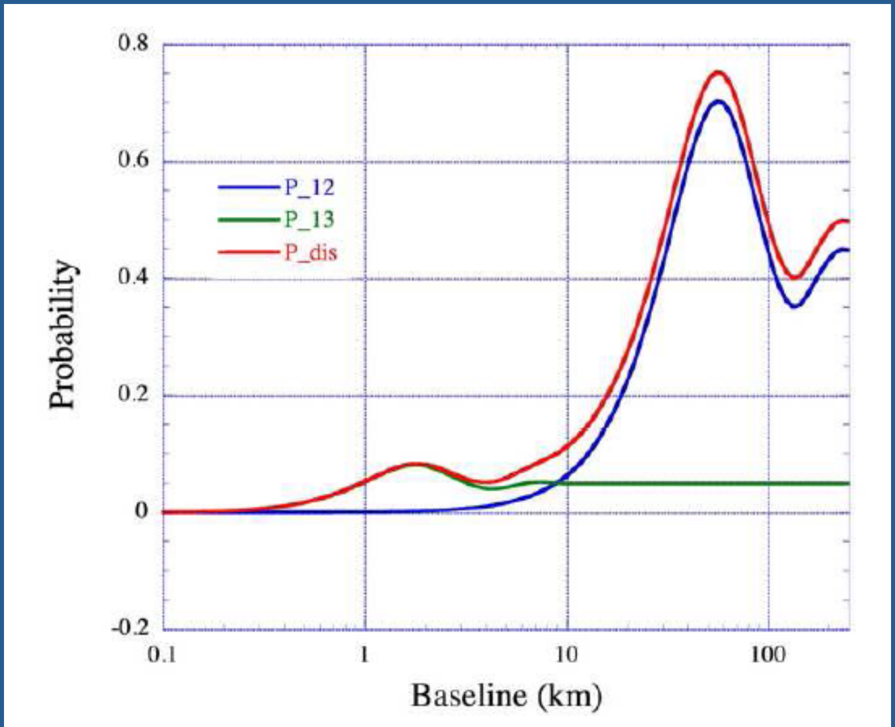
$\Delta_{ij} \equiv \Delta m_{ij}^2 L/(4E)$ $\alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2$ Phys.Rev. D73 (2006) 073007

- Vacuum oscillations, matter effect creates more complicated appearance probability
- Current/Near future accelerator searches for θ_{13} use this method (T2K, NOvA)

Reactor method search for θ_{13}

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{13}^{\;2} L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^{\;2} L}{4E_\nu}\right)$$

- Look for disappearance of ν_e at a short distance from a nuclear reactor
- High flux – systematics limited
- Matter effects negligible
- Two-flavor-like neutrino oscillations

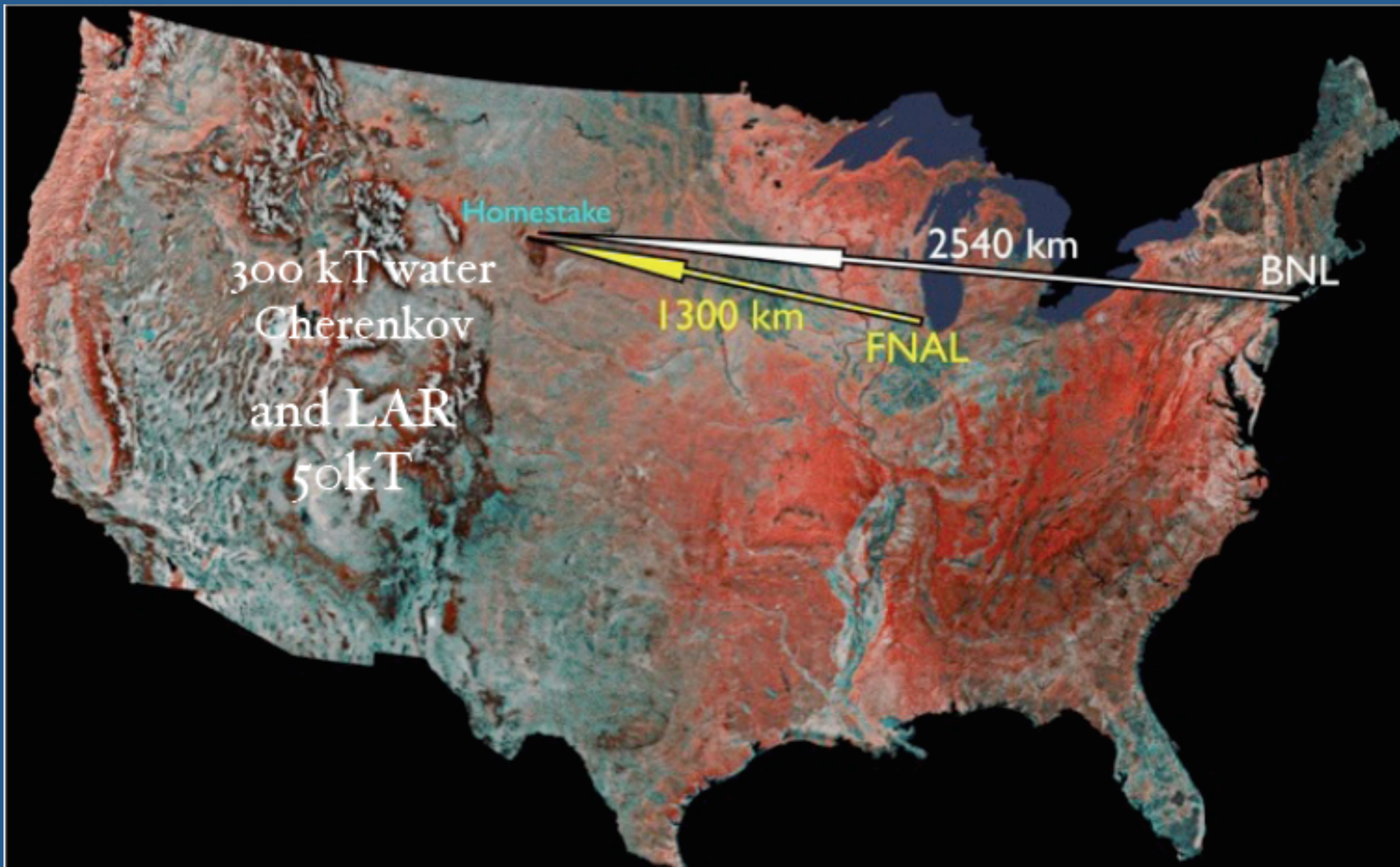


Reactor and accelerator measurements are complementary!

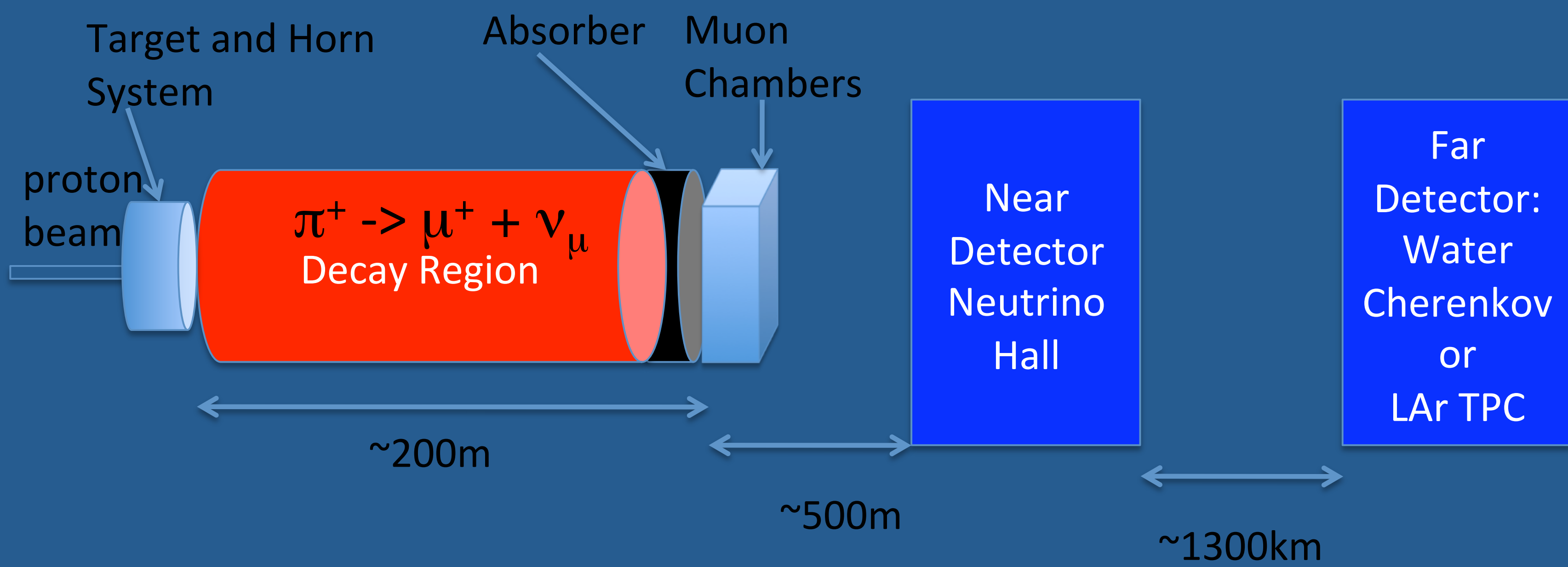
Next Generation Long-Baseline Experiment

- Enhanced study of θ_{13}
- Measurement of the mass hierarchy
- Measurement of δ_{CP}
- Longer-baseline to explore more than one oscillation maximum

LBNE Baseline



Basic Layout

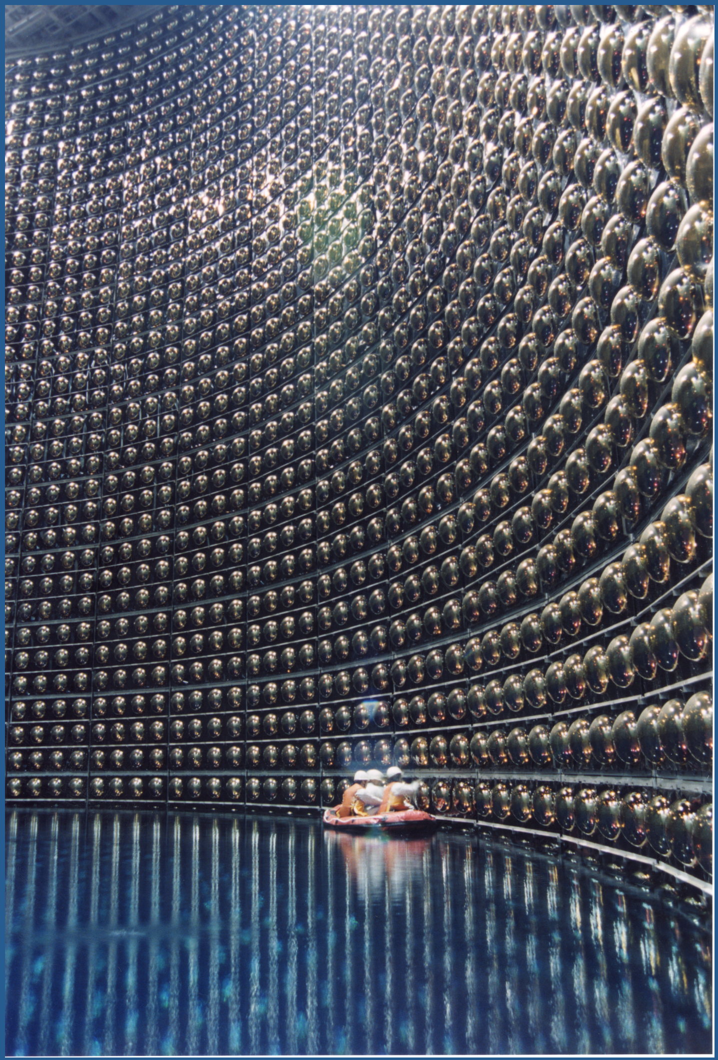


- Start with 700 kWatt beam
- Project X -> 2 Mwatt beam

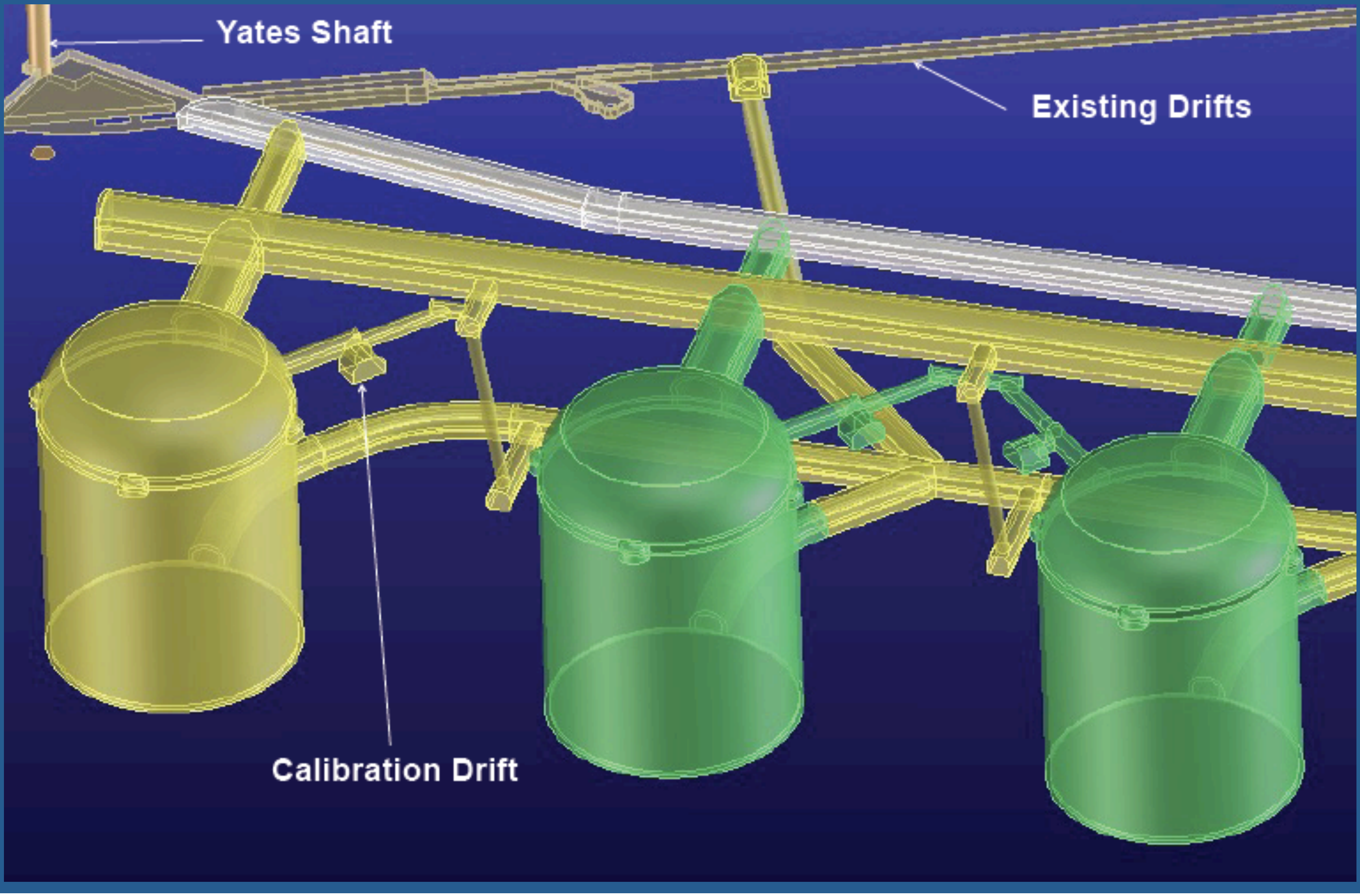
Layout at Fermilab

Water Cherenkov Detector

- Large mass, low cost
- Existence proof – Super-Kamiokande 50 kiloton detector (22.5 kT fiducial)
- Current default plan – modules with 100 kT of fiducial volume
- Excellent showering vs. non-showering separation: ν_μ/ν_e separation
- We could start building tomorrow

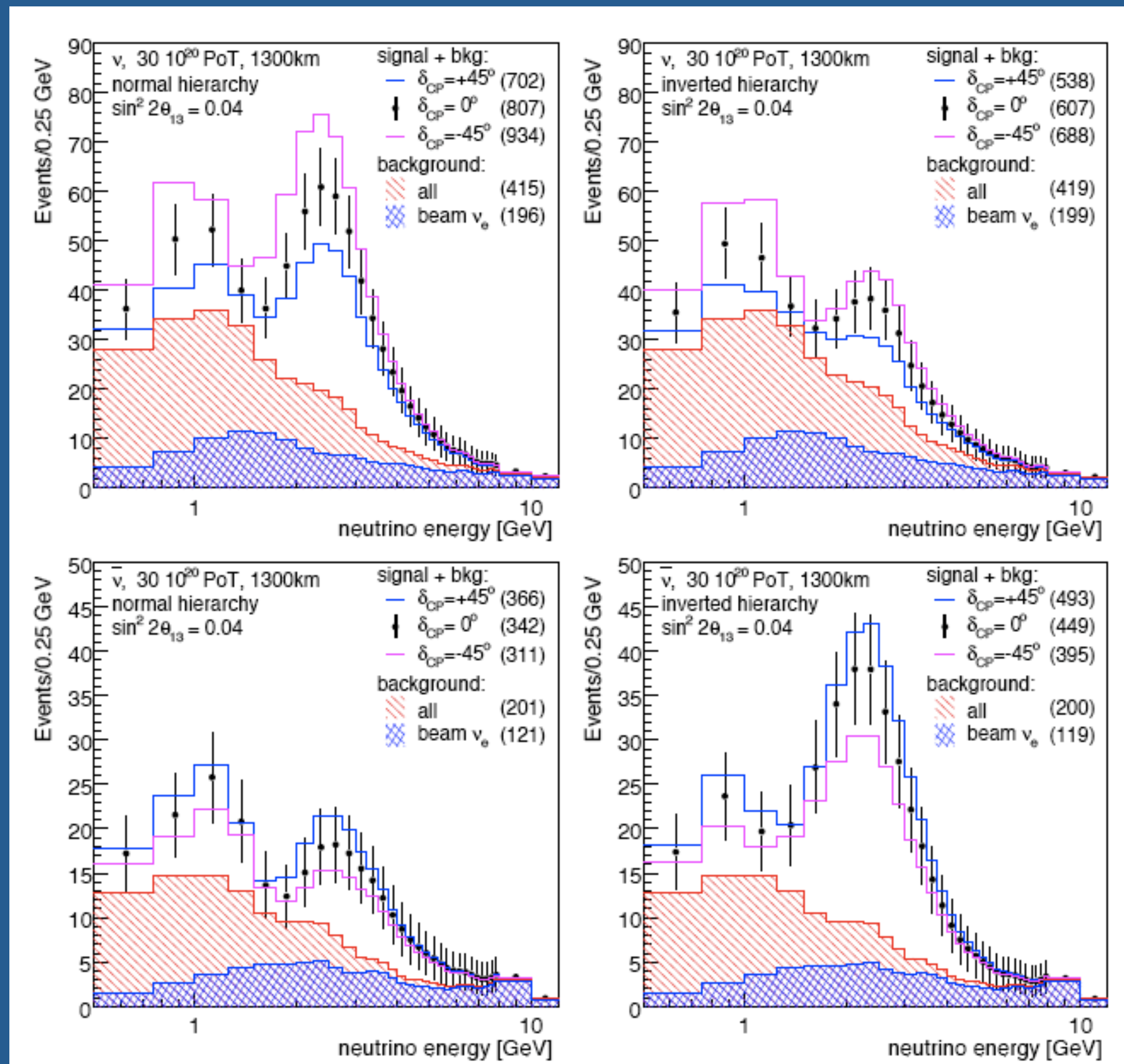


300 kT example



Data in 300 kT of Water Cherenkov

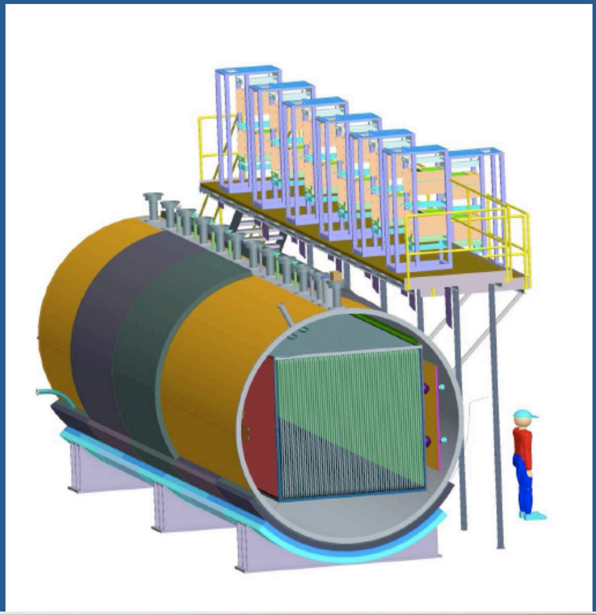
- Intrinsic ν_e – measure in a near detector
- NC background – mostly neutral pion
- Uncertainties on NC backgrounds large – measure in a near detector
- Better resolution of the first maximum
- 90k CC interactions total after oscillations, three years running, 1.2 MWatts

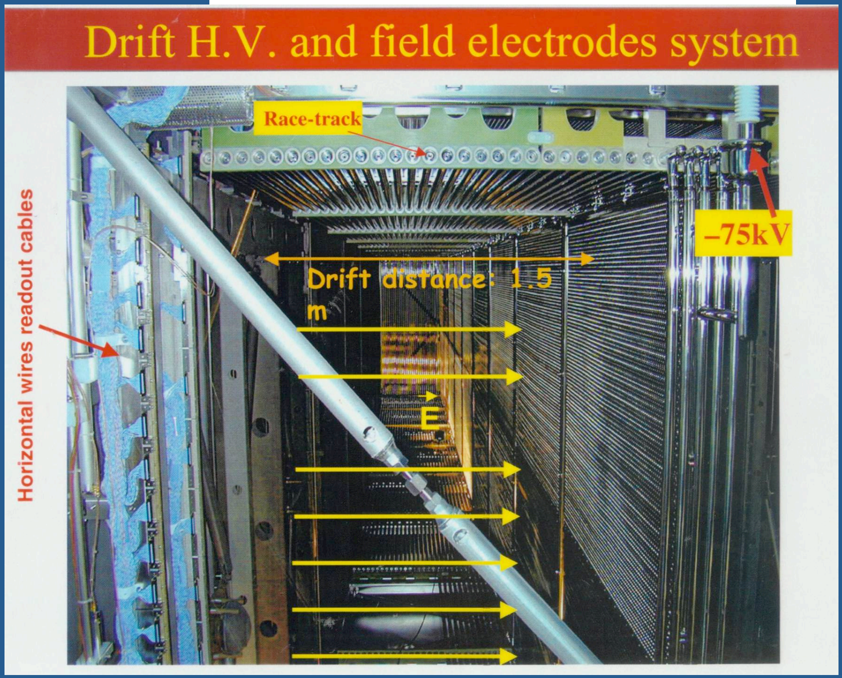


arXiv:0705.4396

LAr TPC

- Much better background rejection than water Cherenkov
- Potentially ``not-so-expensive'' for large masses
- Currently under development
  - ICARUS 600 tons, installed in Gran Sasso, previously run on the surface
  - MicroBooNE 200 tons, planned for Fermilab

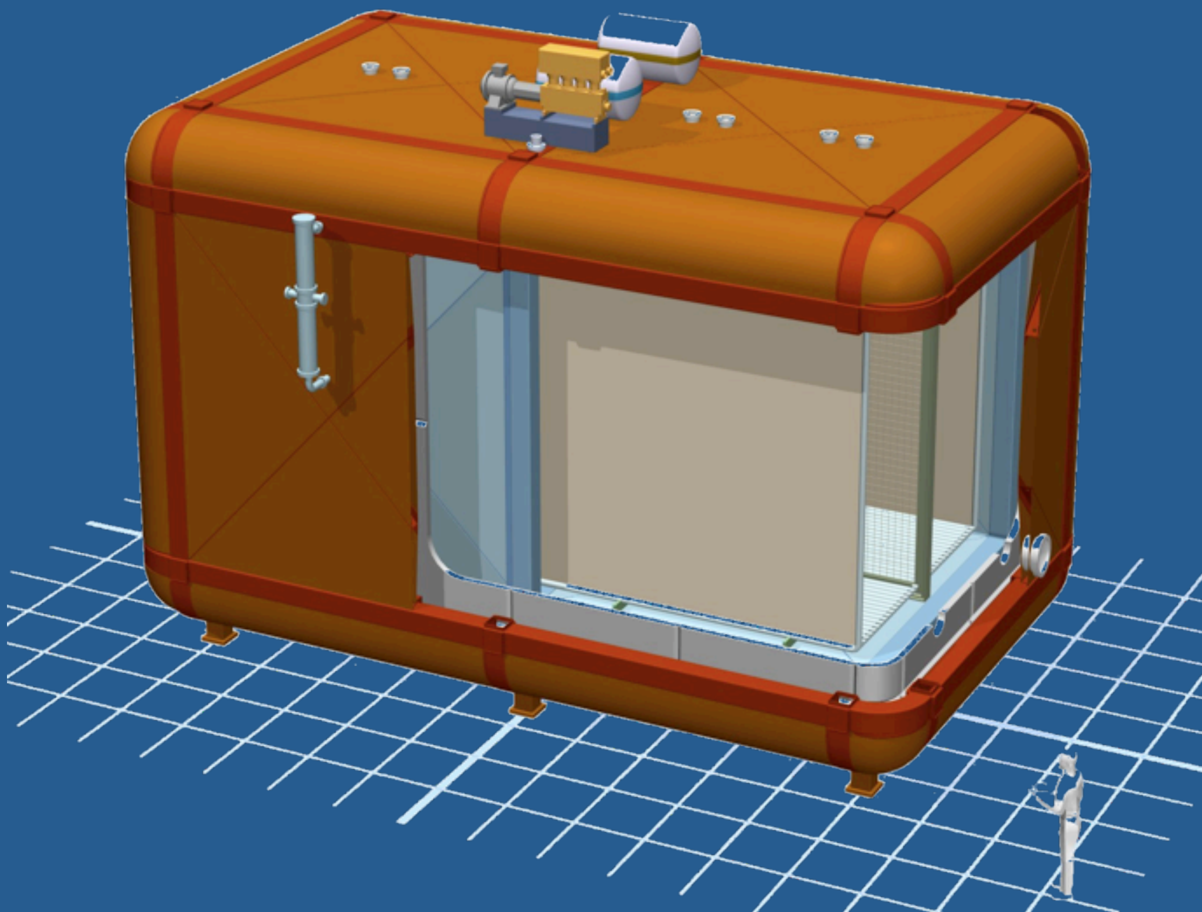




Courtesy of Kevin Lee

LANNDD detector concept

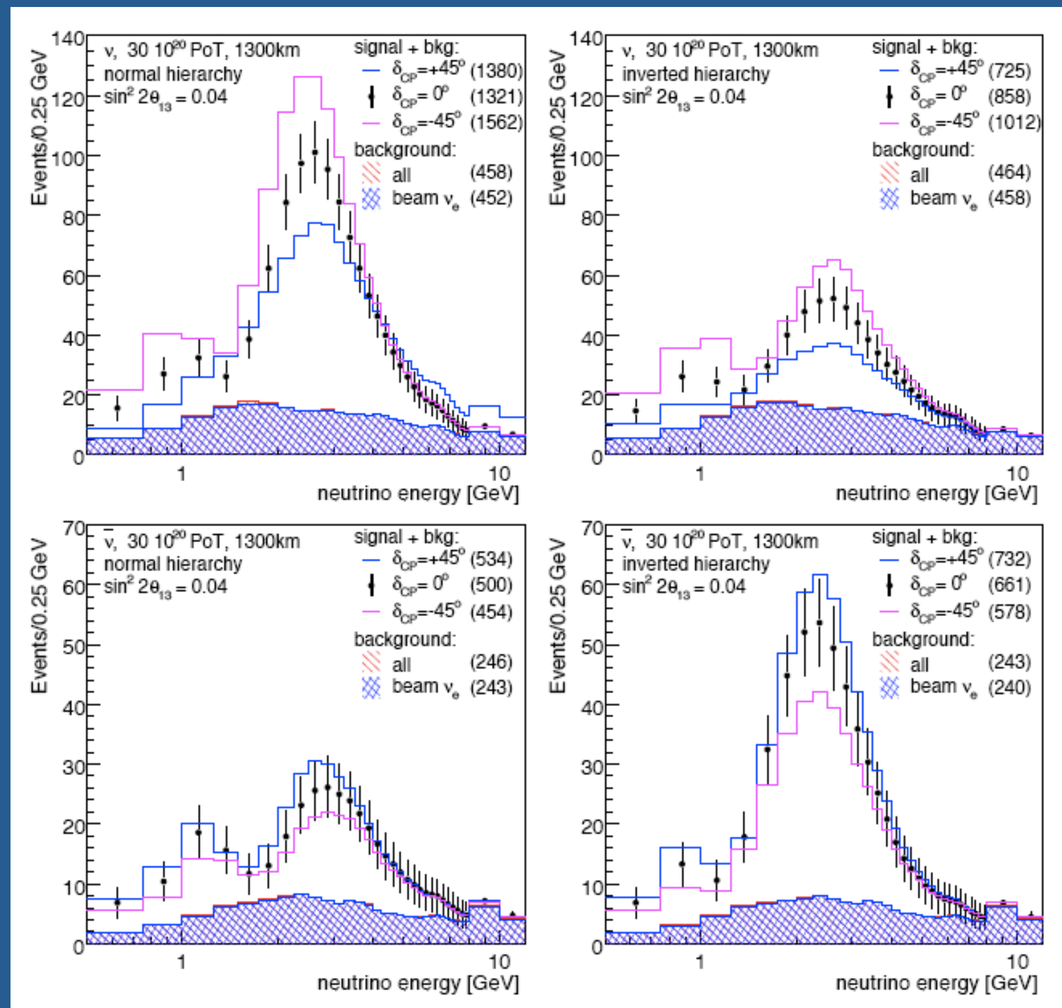
- Evacuable modular structure – better argon purity
- Stackable in a frame
- Can run while still building



Courtesy of Kevin Lee

Data in a large LAr TPC

- 100 kT of liquid argon
- 3e21 POT
- background almost entirely intrinsic ν_e
- 30k CC interactions total after oscillations, 3 years running, 1.2 MWatt



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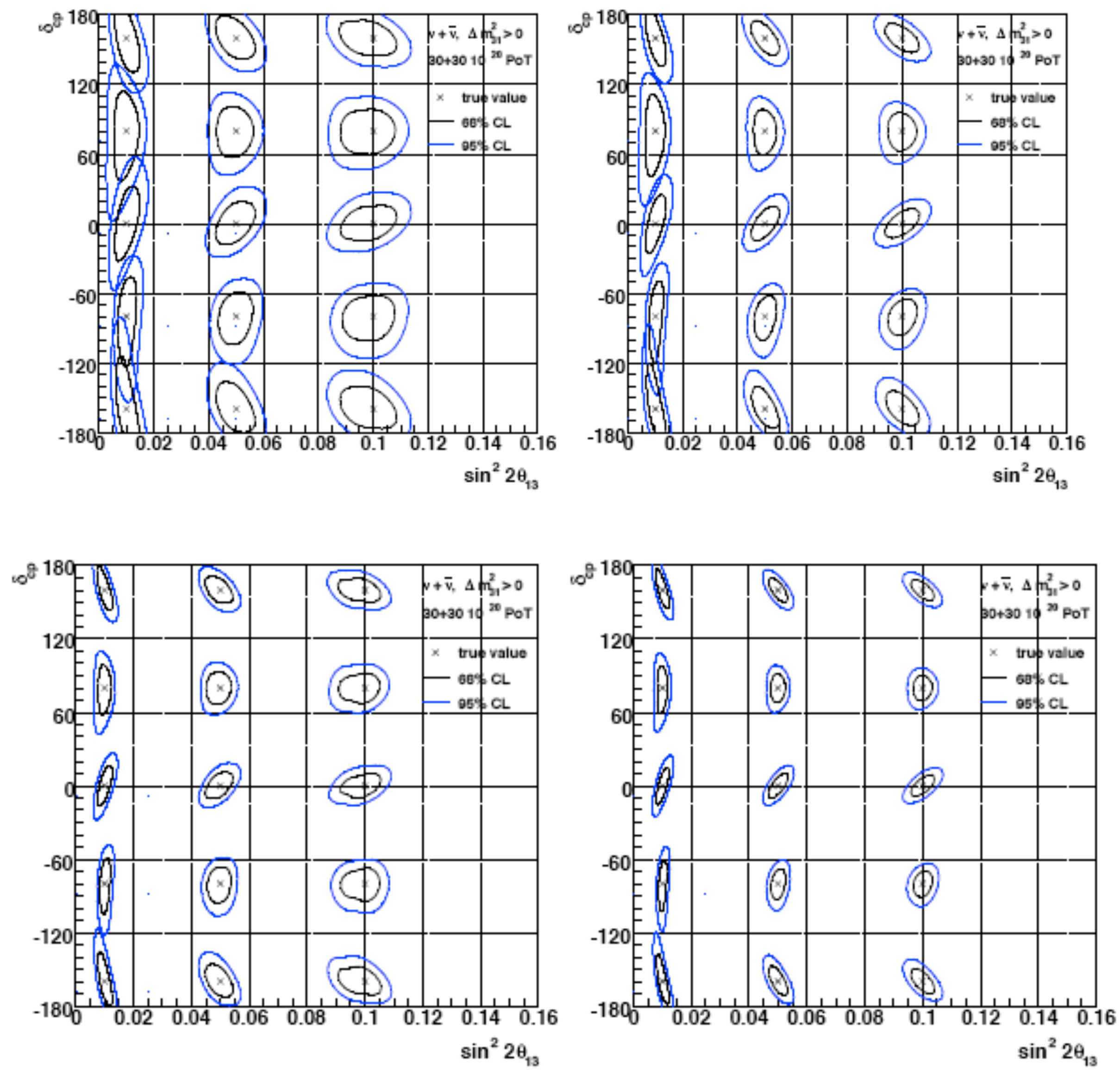
Sensitivities

Water Cherenkov

Liquid Argon TPC



arXiv:0705.4396

LBNE Near Detector Challenge

The near detector complex will measure the neutrino flux, flavor composition and cross-sections required for all oscillation analyses.

This is a particular challenge where the far detector is water Cherenkov.

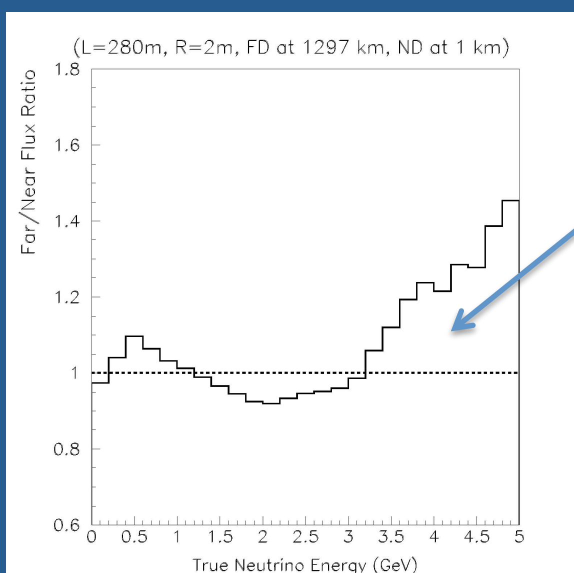
The spectra differ near to far.

The cross-section uncertainties for NC pion backgrounds is large.

Anticipated backgrounds:

- intrinsic ν_e
- NC events which mimic intrinsic ν_e appearance such as single π^0 events

Far/Near Flux Ratio

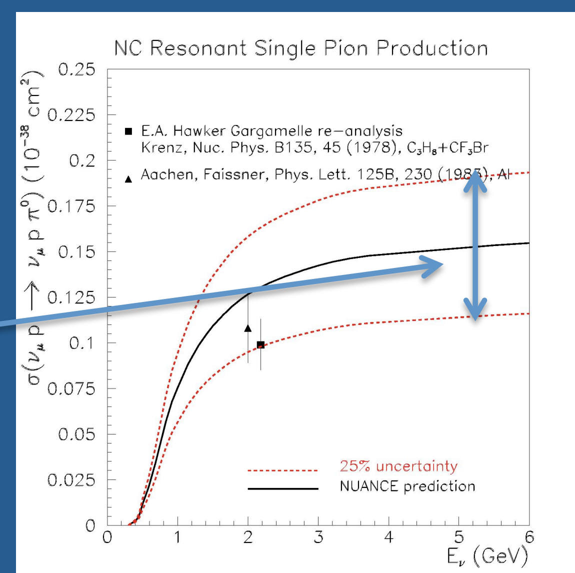


The high energy tail will generate NC interactions in the signal region.

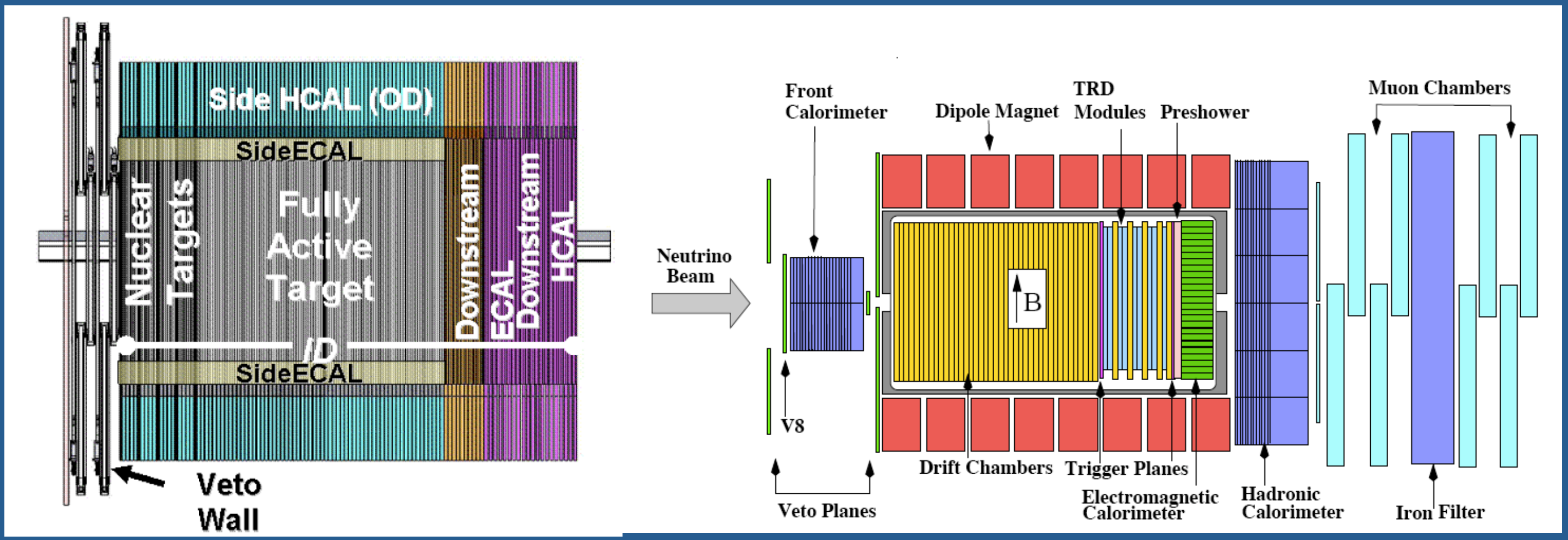
Uncertainties are large.

Plots courtesy of Sam Zeller

NC Pion Production



LBNE Near Detector



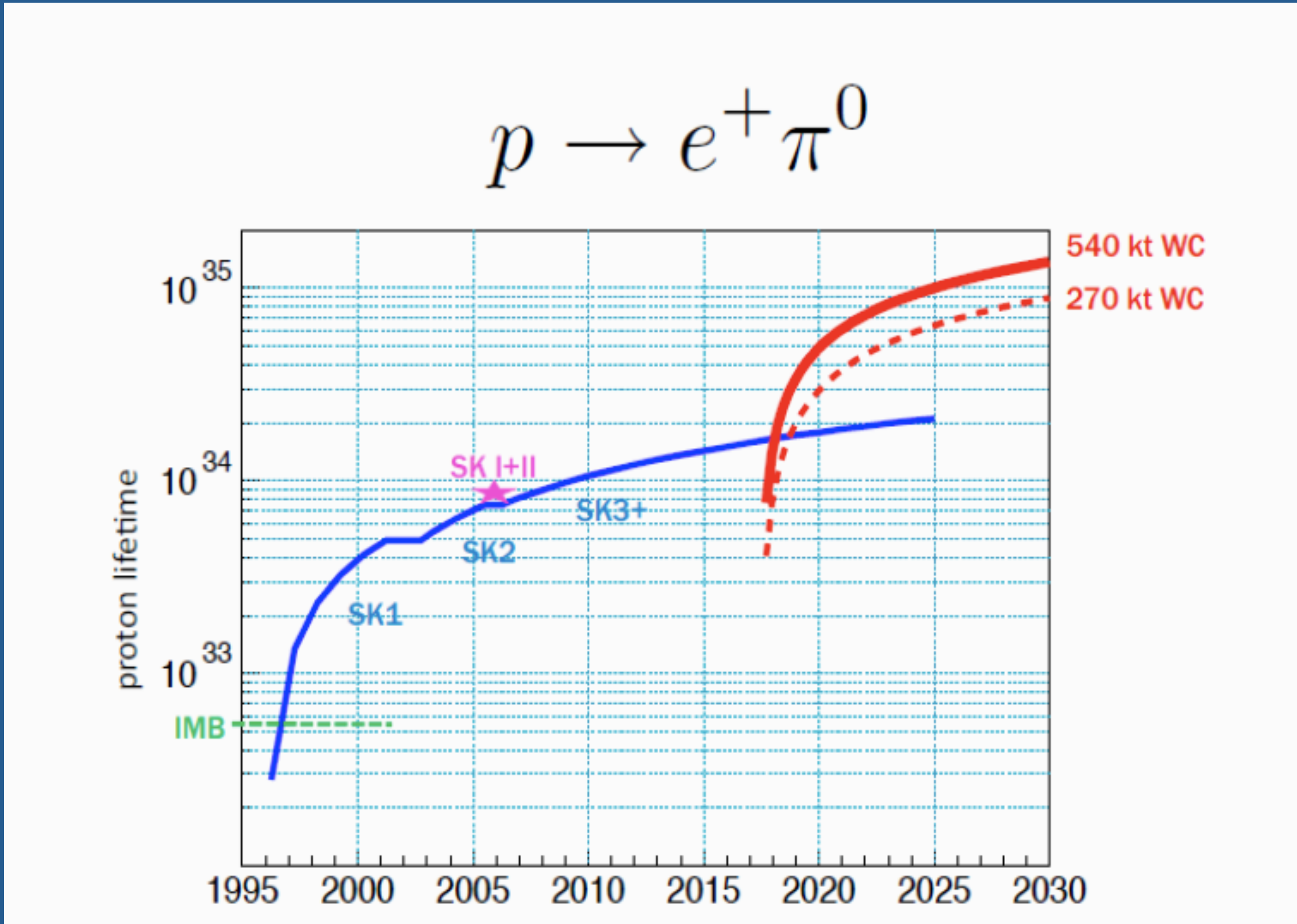
- Need fine-grained ND with a water target to study backgrounds in detail
- For LAr, we are exploring simply moving MicroBooNE or using a module similar to ICARUS

Project Status

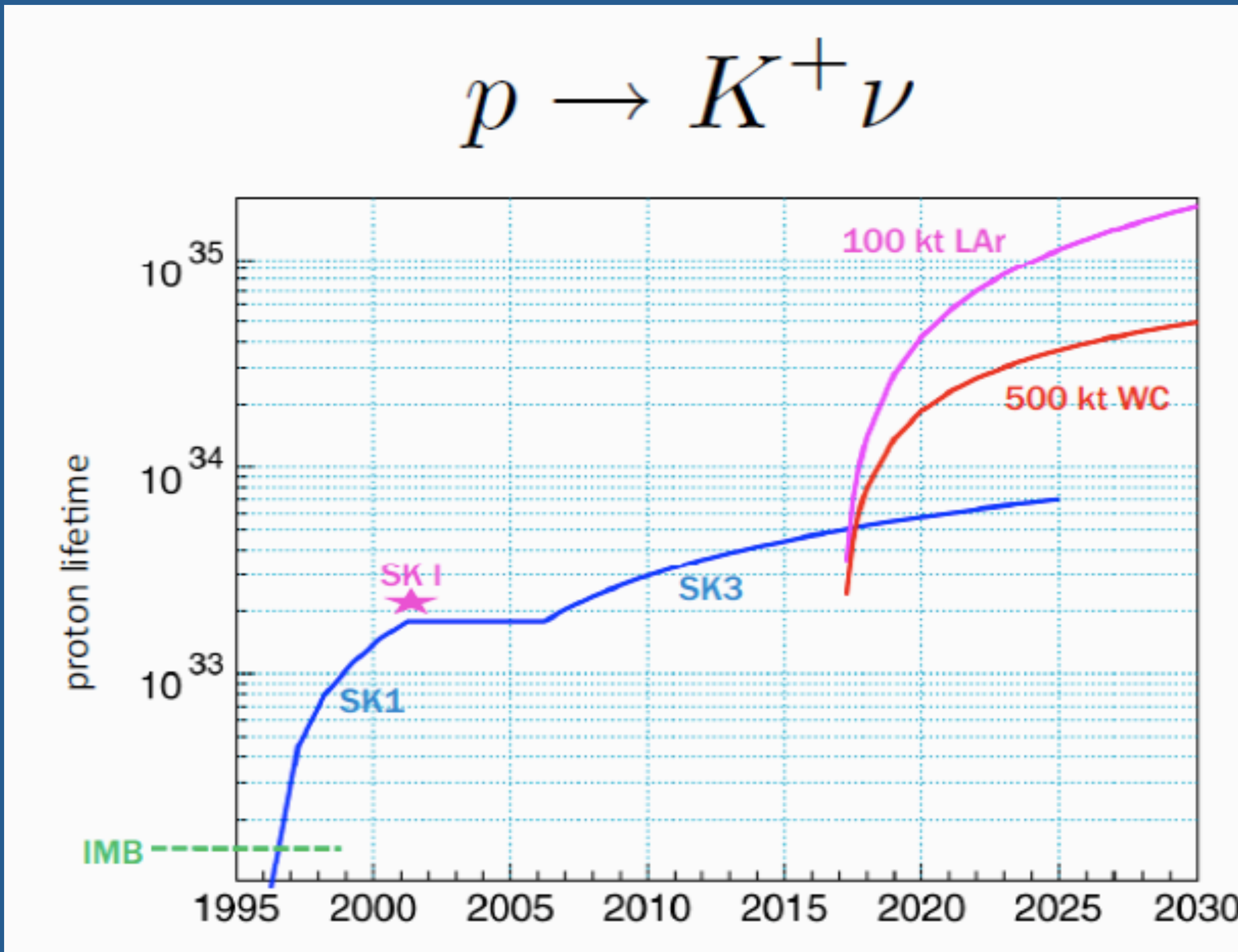
- Strongly recommended in the P5 Report
- Currently awaiting CD-0 approval from DoE
- DUSEL will be reviewed by the National Science Board – February 2011
- Attempt CD-1 approval at a similar time
- Collaboration ~ 35 institutions (and counting)

Other physics

- Proton decay
- Diffuse SN background neutrinos
- Galactic SN detection
- Atmospheric neutrinos
- Solar neutrinos



Courtesy of Bob Svoboda



Plot courtesy of Bob Svoboda

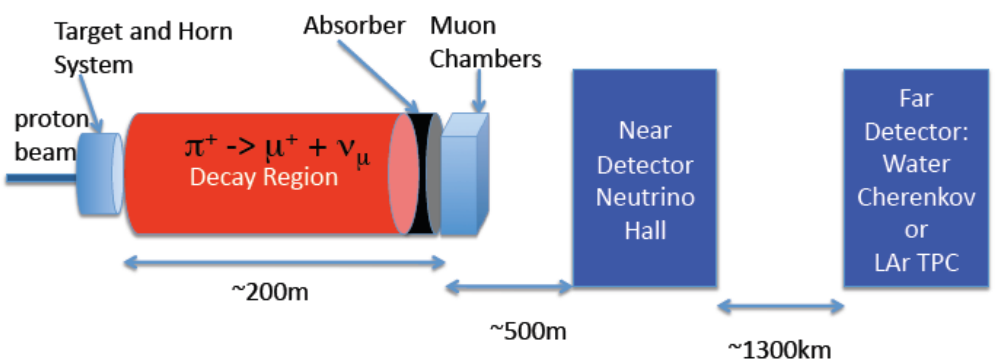
Long-Baseline Neutrino Experiment Conclusions

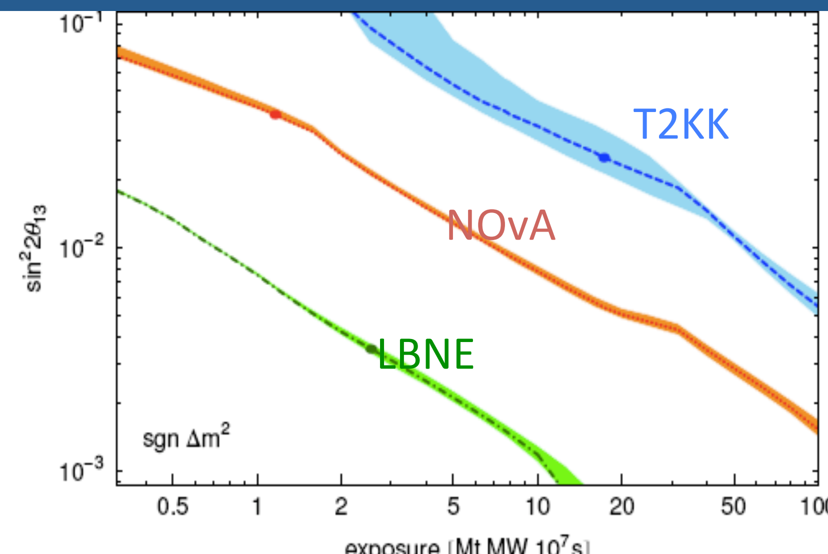
- We have a lot of physics to explore
- LBNE will provide the most extensive study of standard neutrino oscillation physics yet – the only experiment with hierarchy and δ_{CP} reach for $\sin^2 2\theta \sim 0.01$
- A large detector at DUSEL will have a rich physics program and generate exciting results for us to ponder for years to come

LBNE physics

Primary Measurement

- Search for ν_e appearance in a ν_μ beam
- Two oscillation maxima – 2.1 GeV, 700 MeV
- Far detector options –
  - Water Cherenkov
  - Liquid Argon





From: Phys.Rev.D76:053005,2007

Near Detector Mission

- Determine the flavor composition and energy spectrum of the neutrino flux near and far
- Measure backgrounds to ν_e appearance
  - intrinsic ν_e's
  - Processes mimicking ν_e's – NC π^0's, NC γ's
- Accomplish by measuring parent hadron fluxes in the target hall and neutrino fluxes in the ND hall

Measure
NC background
Intrinsic ν_e