Long-Baseline Neutrino Experiment (LBNE)

The future Fermilab to DUSEL flagship particle physics experiment

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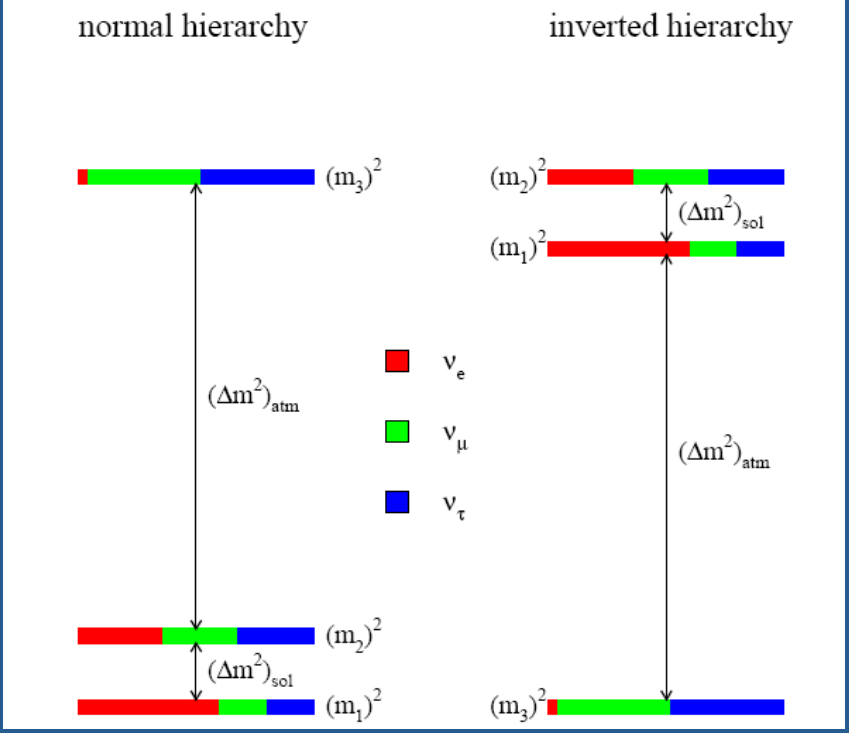
22 January 2010

Long-Baseline Neutrino Physics

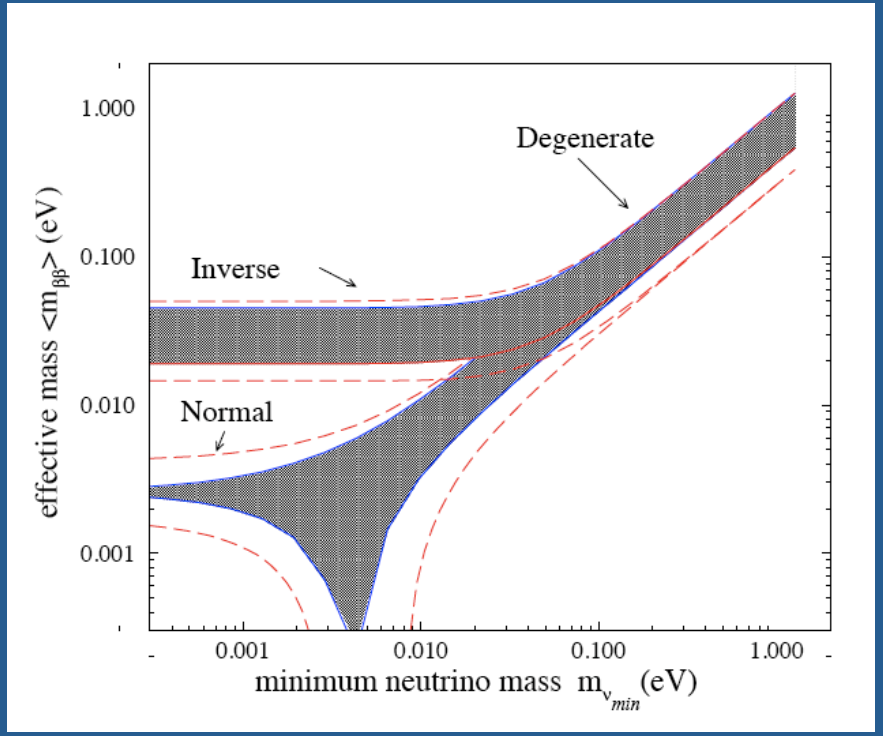
- Motivated by observation of neutrino oscillations
- Atmospheric oscillations (Super-Kamiokande, K2K, MINOS):
  - $\Delta m^2 \sim 2X10^{-3}\ eV^2$
  - $\sin^2 2\theta > 0.9$
- Solar neutrino oscillations (SNO, Super-Kamiokande, SAGE, Homestake, GNO; KamLAND (antineutrinos):
  - $\Delta m^2 \sim 8X10^{-5}\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

Neutrino Mass Hierarchy



Case of only three light neutrino flavors.

From: **hep-ph/0411274**



$0\nu2\beta$ decay effective mass.

From: **hep-ph/0412300**

Mixing Matrix and Oscillation Probabilities

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

- 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

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

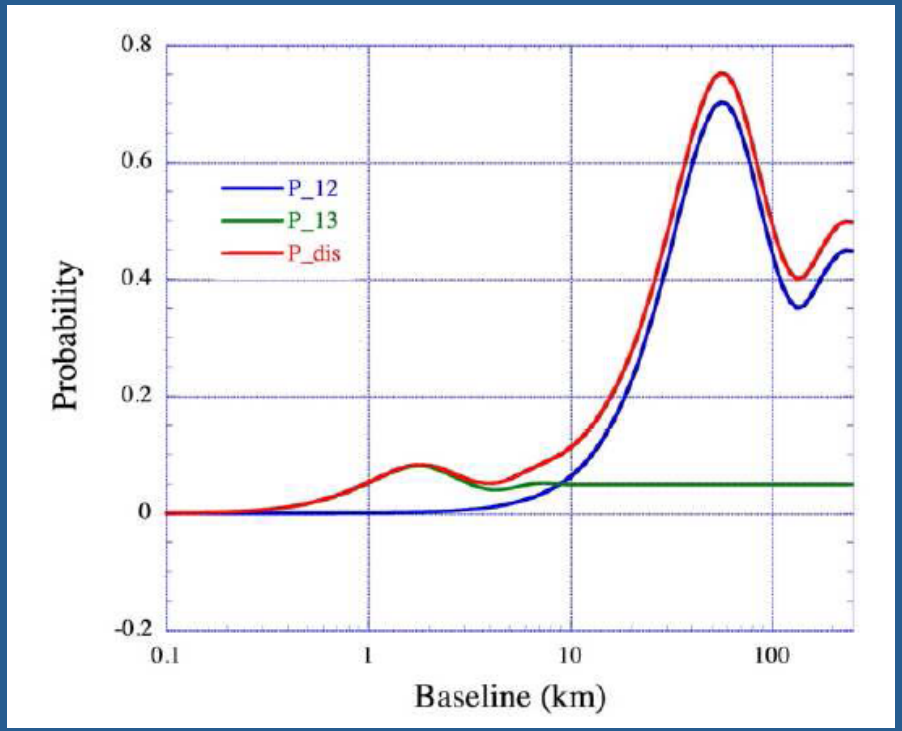
$\Delta_{ij} \equiv \Delta m^2_{ij} L/(4E)$ $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ Phys.Rev. D73 (2006) 073007

- 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!

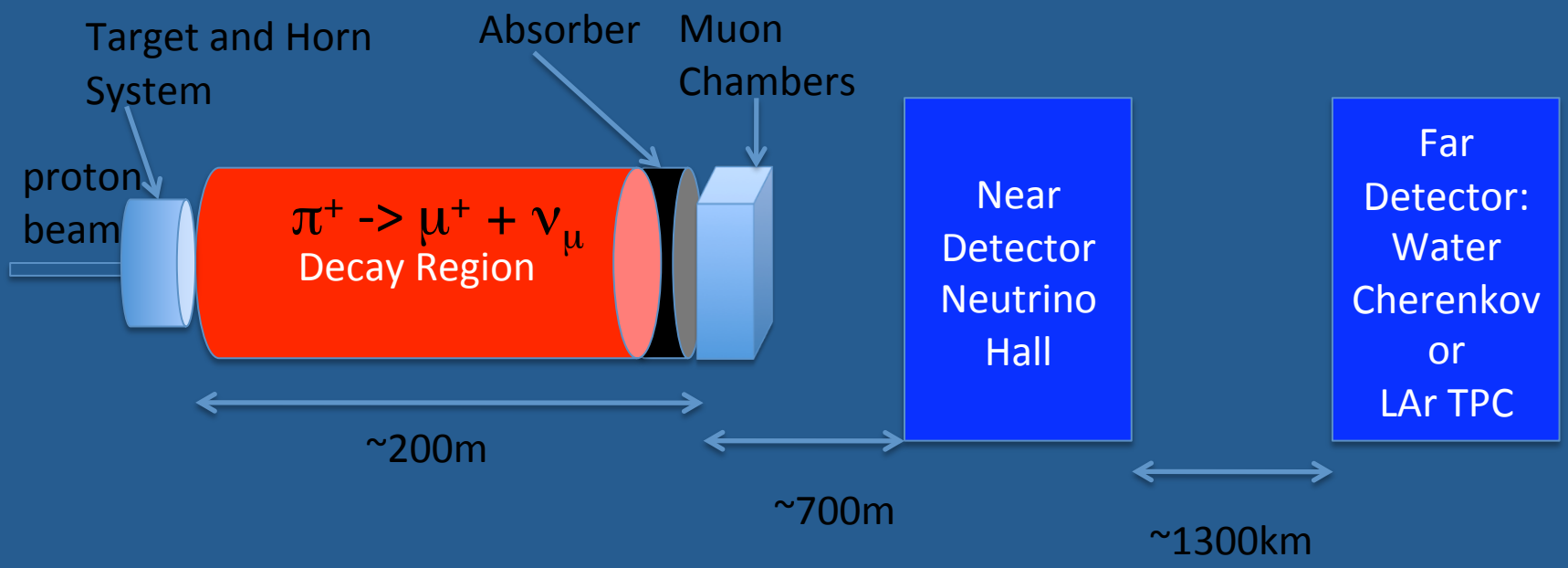
Next Generation Long-Baseline Experiment

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

1300 km Beam: FNAL to DUSEL

Courtesy of S. Elliott, G. Sinnis, R. Van de Water

Basic Layout



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

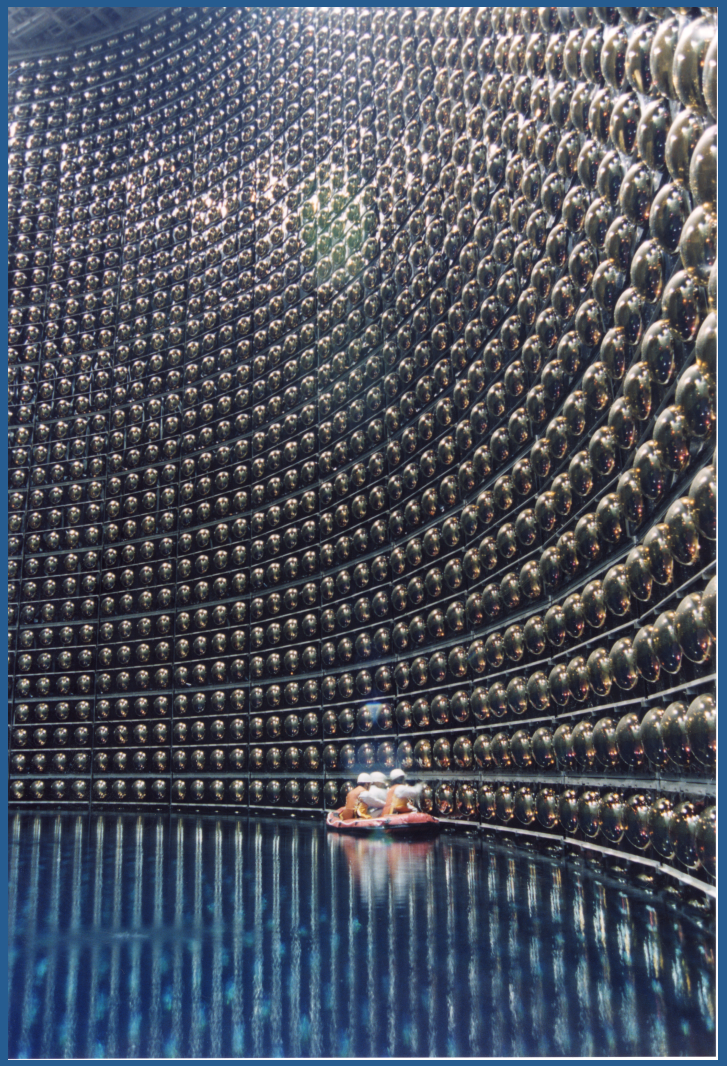
Layout at Fermilab

Project Status

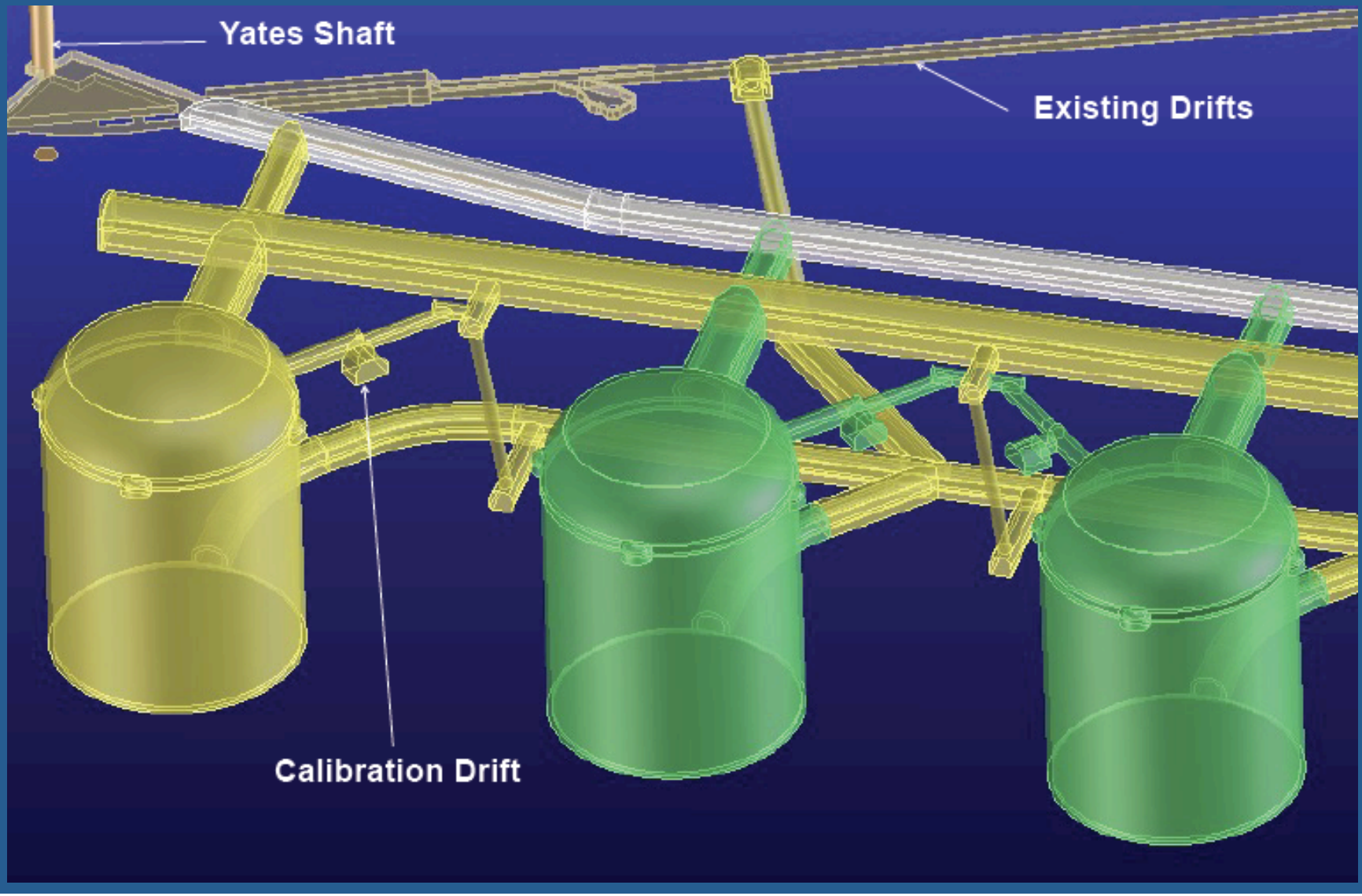
- Strongly recommended in the P5 Report
- Approached from different directions:
  - NSF – DUSEL (South Dakota)
  - DoE – Long-baseline neutrinos
- DoE CD-0 granted
- Collaboration leadership in place
  - Sensitivity plots in this talk are not official collaboration documents
  - Physics study group will become active next week
    - optimize running conditions, consider far detector sizes, define sensitivity requirements according to the scope laid out in CD-0
- DoE-NSF joint meetings next week followed by collaboration meeting
- DUSEL will be reviewed by the National Science Board – February 2011
- Attempt CD-1 approval at a similar time
- Collaboration ~ 35 institutions (and counting)
- Digging begins 2012?

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



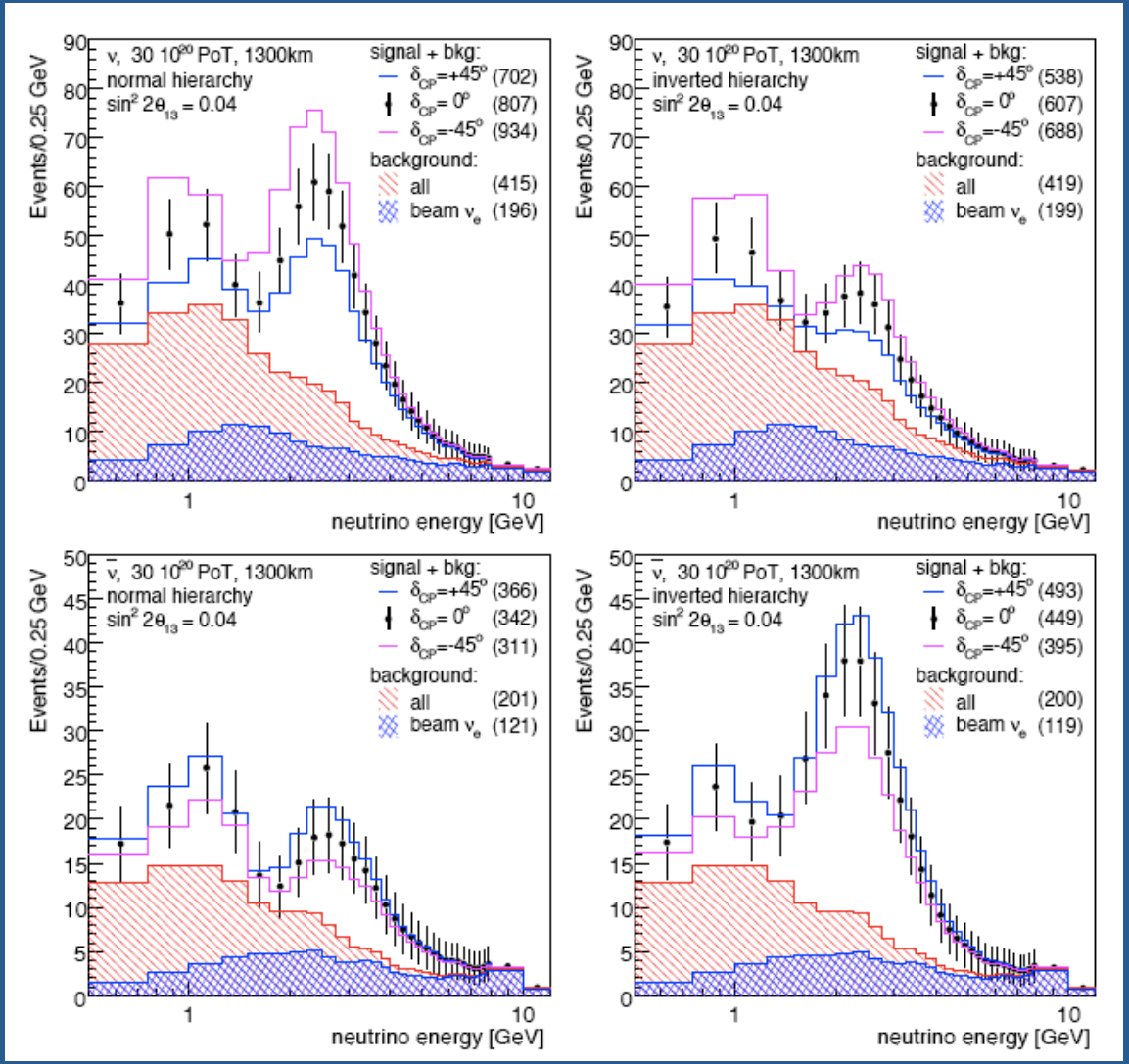
300 kT example



Data in 300 kT of Water Cherenkov

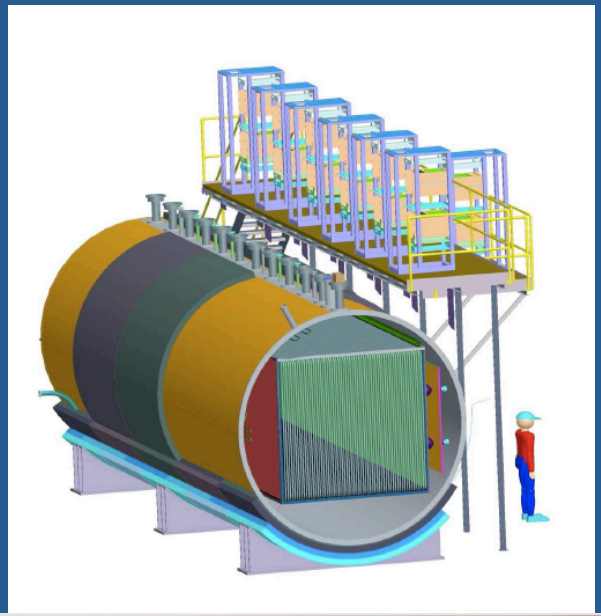
- Intrinsic ν_e – measure in a near detector
- NC background – mostly neutral pion
- Uncertainties on NC backgrounds large – measure in a near detector
- Better resolution of the first maximum
- 90k CC interactions total after oscillations, three years running, 1.2 Mwatts
- 10% uncertainty on background assumed
- Quasi-elastic events only – many charged π's are below Cherenkov threshold

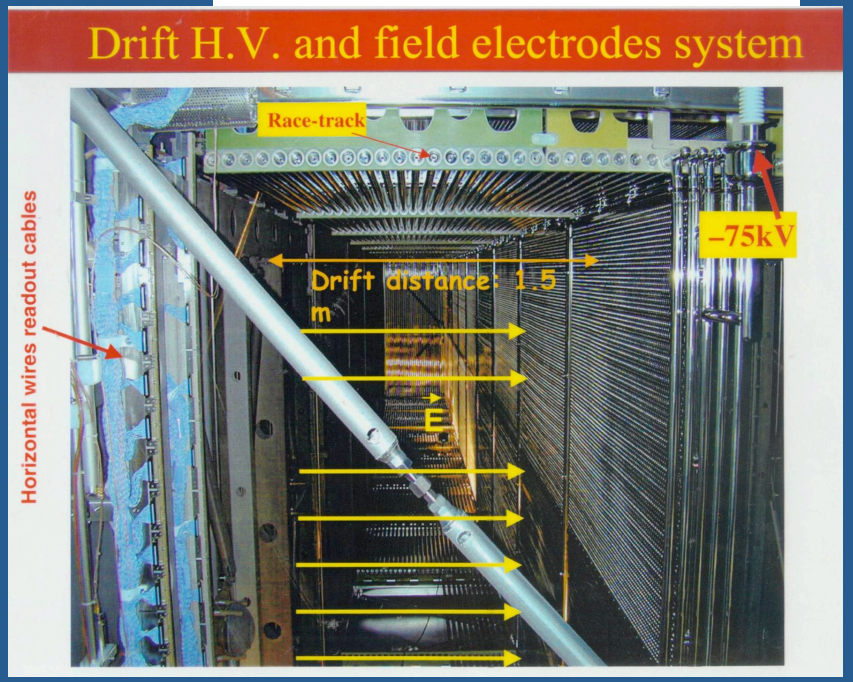
arXiv:0705.4396



LAr TPC

- Much better projected background rejection than water Cherenkov – all charged particles visible
- 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

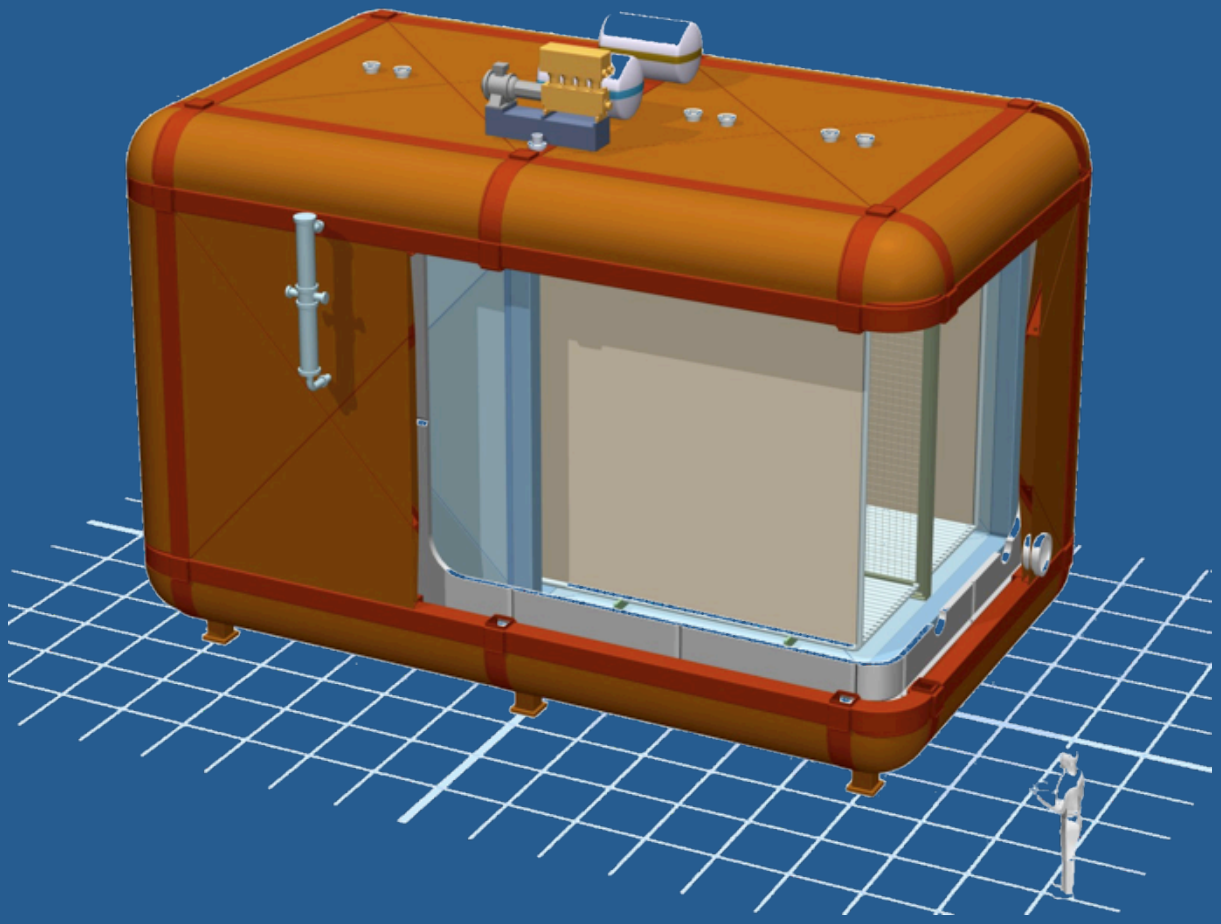




Courtesy of Kevin Lee

LANNDD detector concept

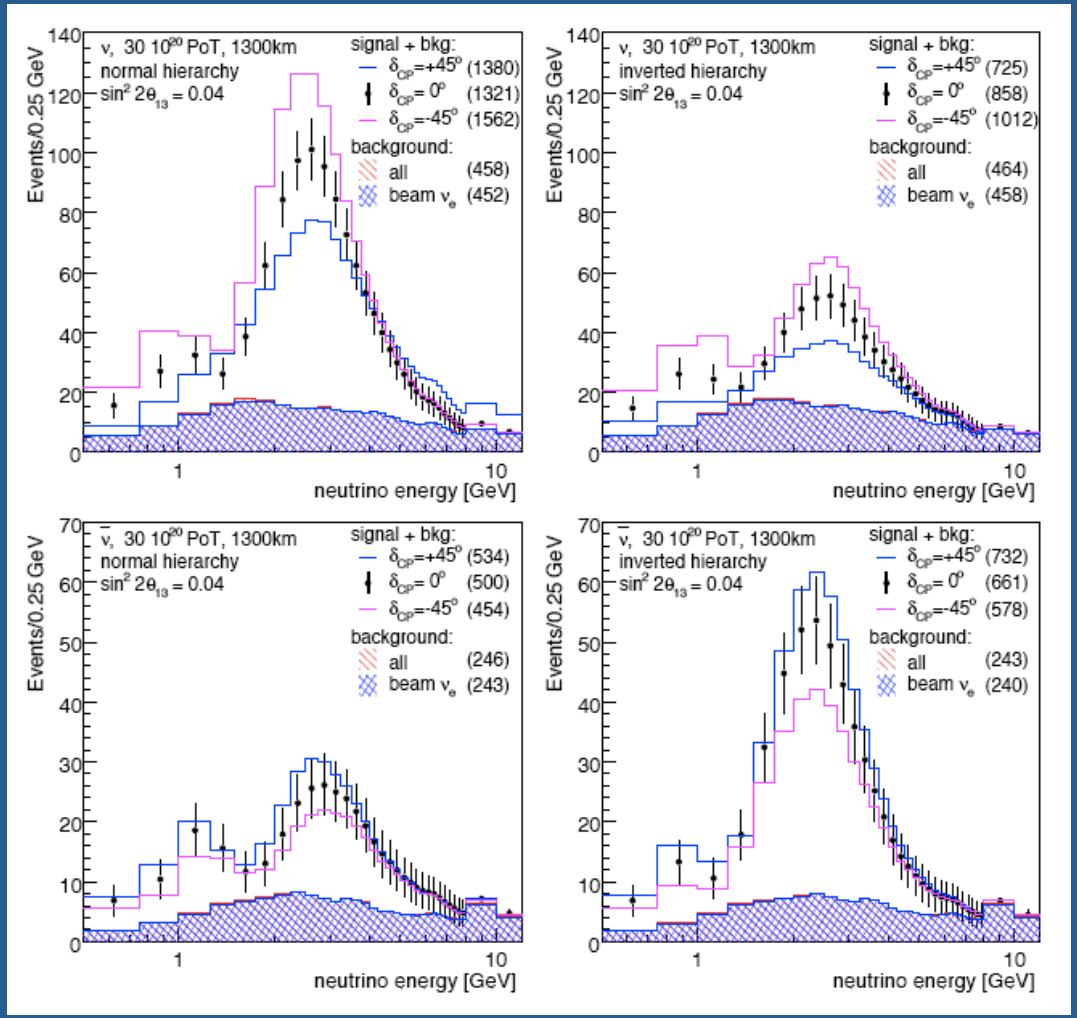
- Evacuable modular structure – better argon purity
- Stackable in a frame
- Can run while still building



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
- 10% uncertainty on background assumed
- All CC events used



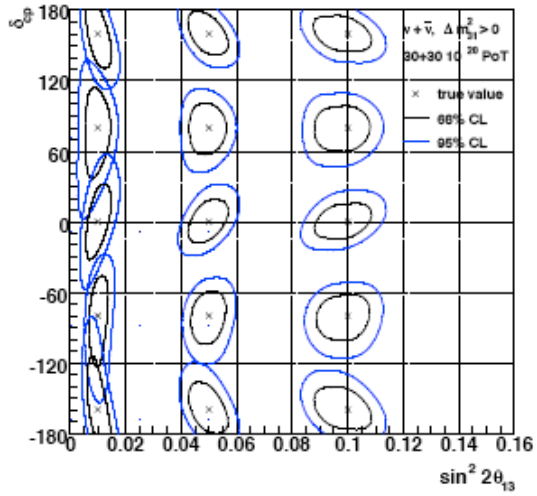
arXiv:0705.4396

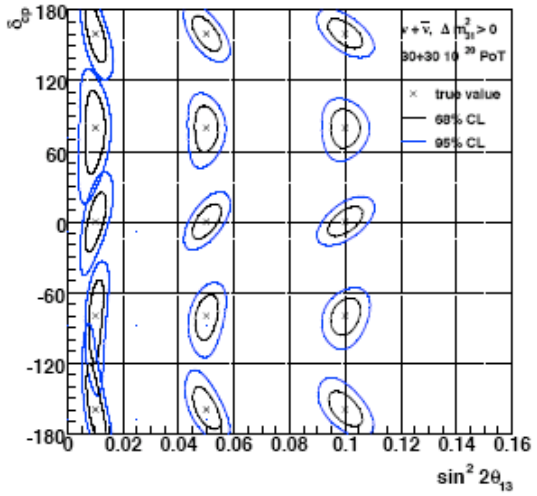
Sensitivities (60 x 10^{20} POT)

Stat and Systematic (10%)

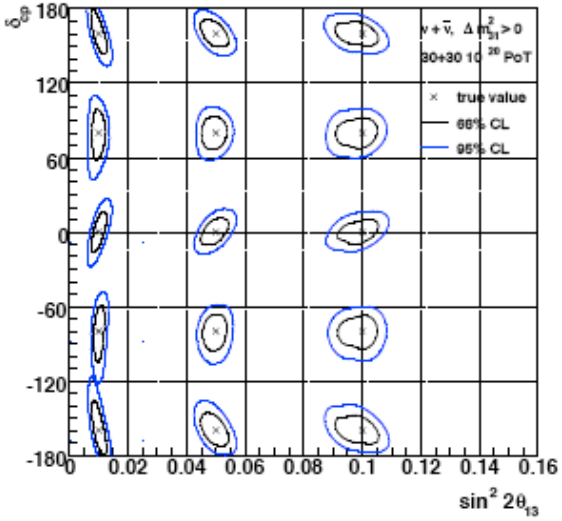
Statistical Only

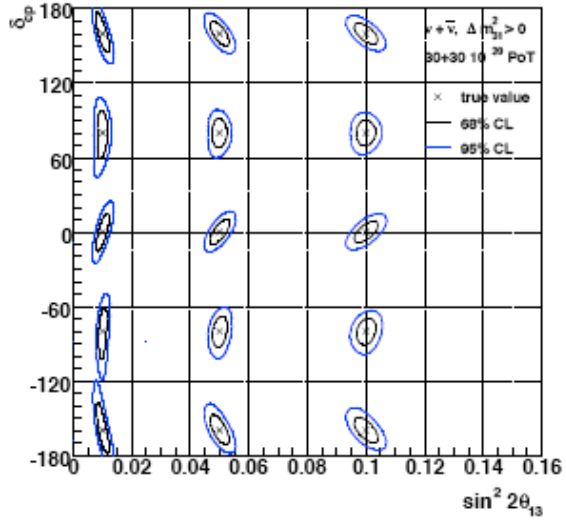
Water Cherenkov (300 kT)





Liquid Argon TPC (100 kT)

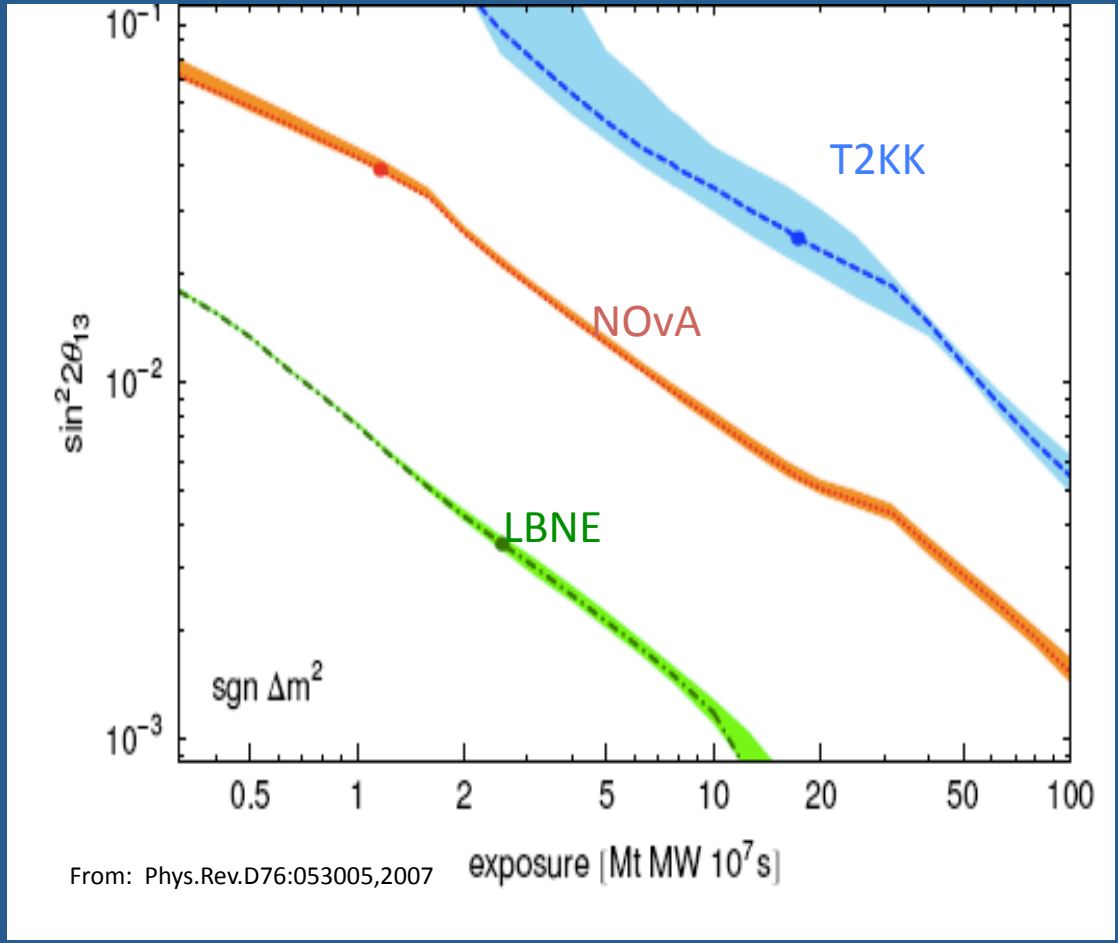




arXiv:0705.4396

LBNE Sensitivity to the mass hierarchy

- Sensitivity to sign of Δm^2 as a function of exposure for true values of $\sin^2 2\theta_{13}$
- Will depend on size of CP non-conservation, true uncertainties (range here 2-10%)
- Depends on final beam and detector configuration



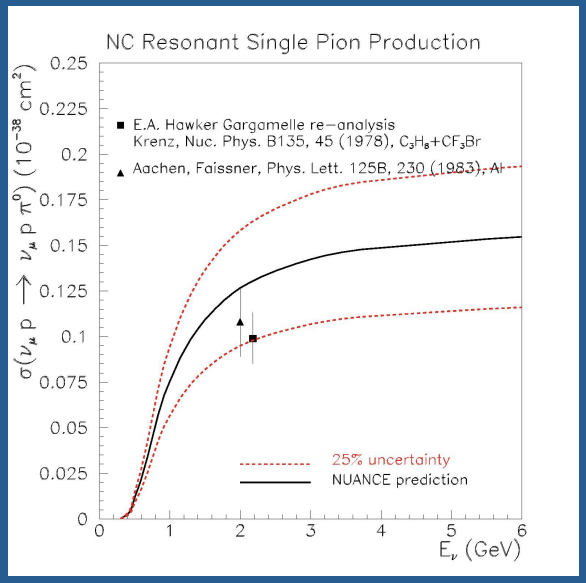
From: Phys.Rev.D76:053005,2007

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 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

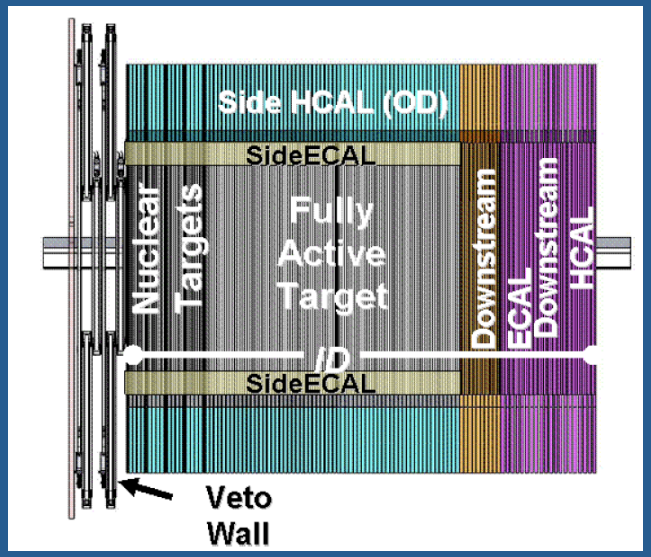
NC Pion Production

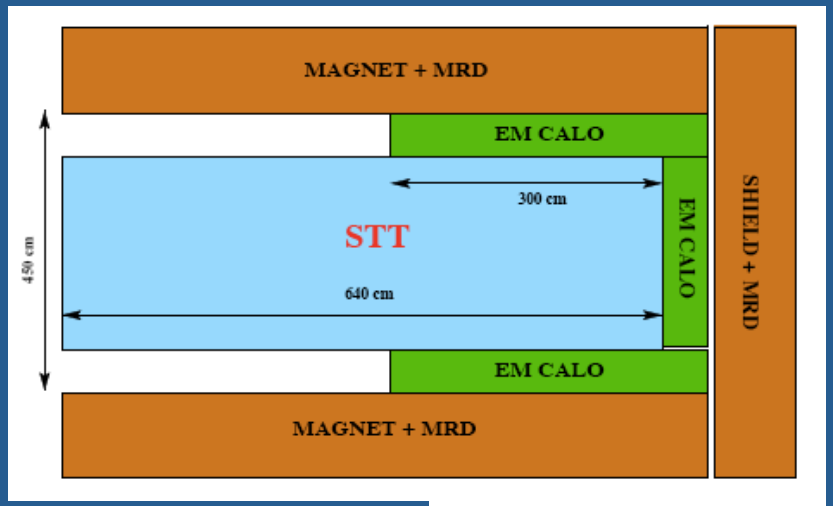


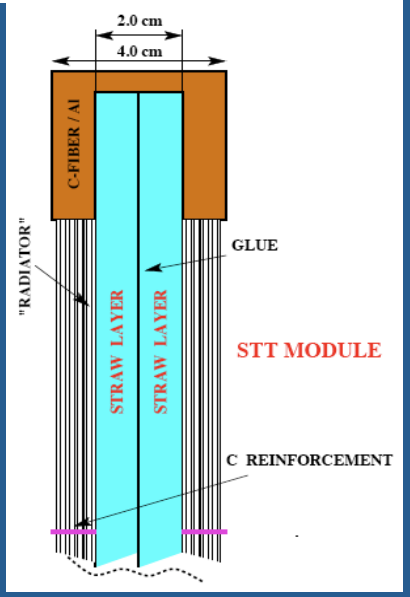
Plot courtesy of Sam Zeller

- Single nucleon cross-section uncertainties large
- Nuclear effects also large
  - absorption
  - inelastic scattering/charge exchange
  - impacts neutrino energy reconstruction
- Resultant kinematic distributions very uncertain with ``uncertain uncertainty''
- Whether or not a pion becomes background depends on its momentum and direction
- We must have thorough near detector measurements on both H_2O and Argon

LBNE Fine-grained Near Detector

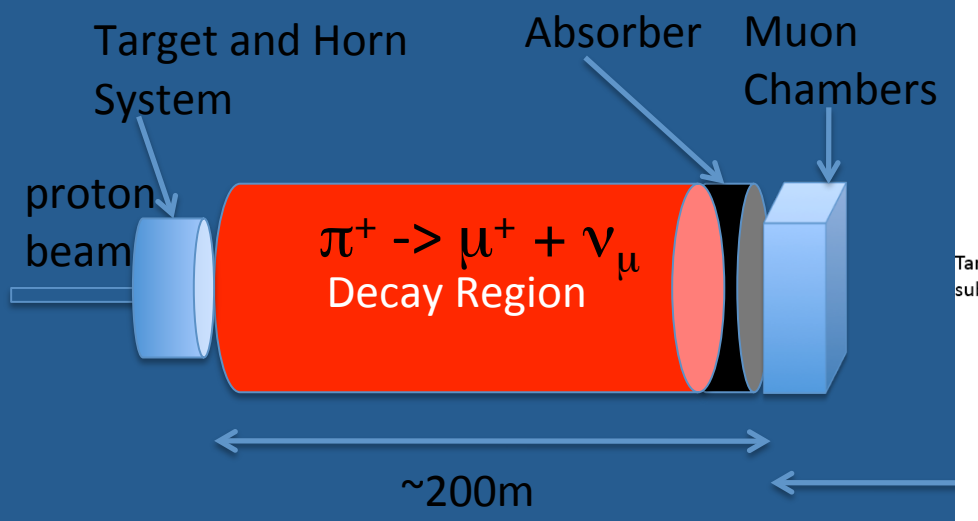


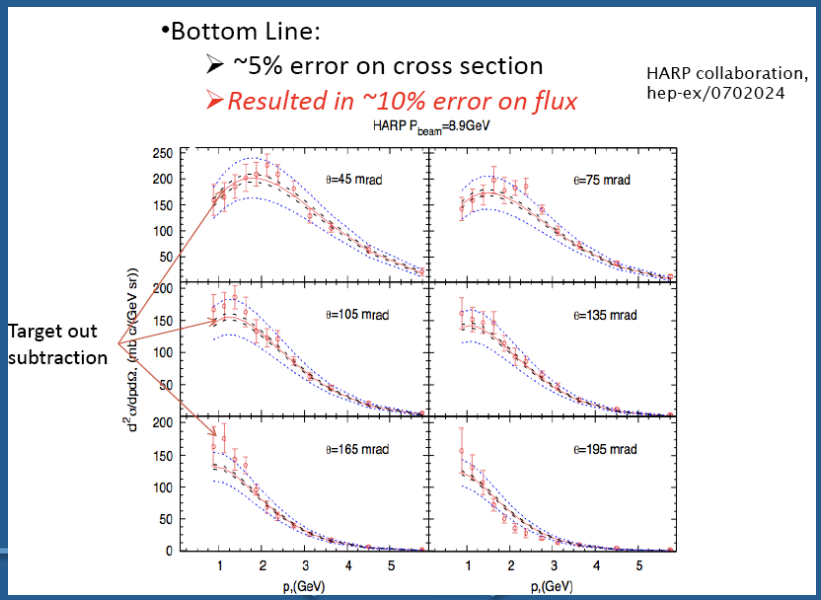




- Need fine-grained ND with a water target embedded in a magnet to study backgrounds in detail
- LAr case, use MicroBooNE or single UCLA module
- Also, add a muon range detector

Flux Studies





- In-situ measurement
- Particle fluxes extreme: > 10^8/ cm^2-spill
- High precision unlikely
- Could use in-situ measurements to validate simulations based on external studies

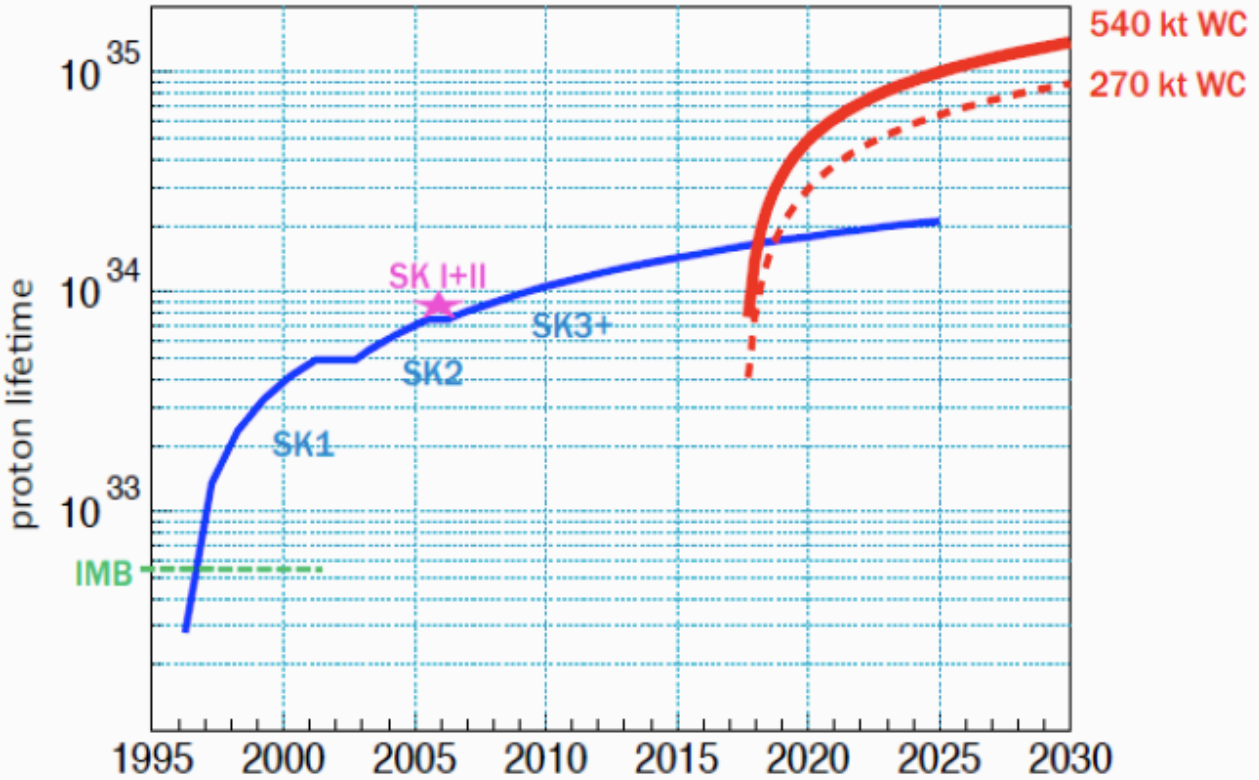
~1300km

- External measurements
- HARP (above π^+ production for MiniBooNE), MIPP, NA-61
- Used by K2K, MiniBooNE, T2K
- Make precise hadron production measurements of of target and horn materials
- Input to simulations

Other physics

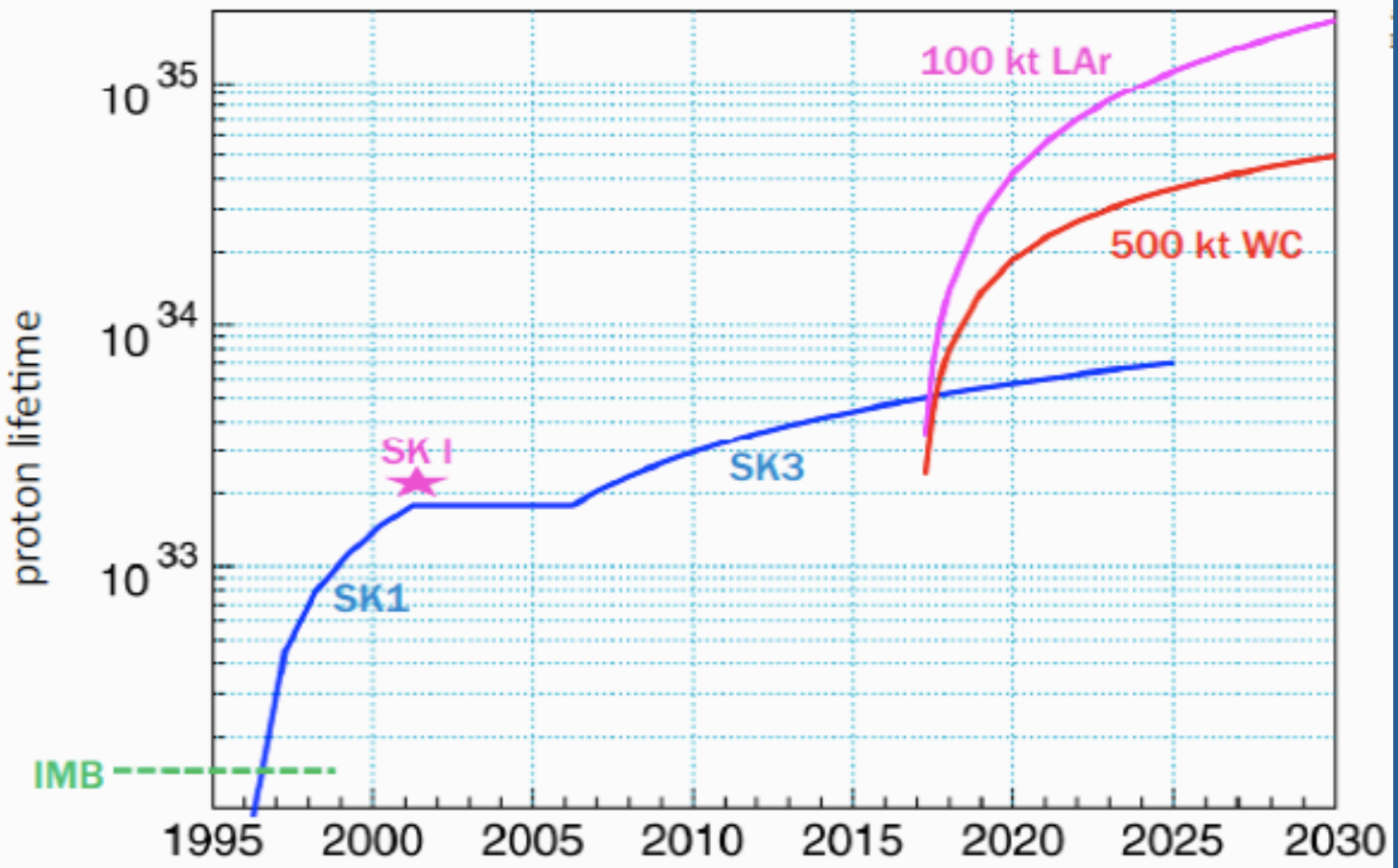
- Proton decay
- Diffuse SN background neutrinos
- Galactic SN detection
- Atmospheric neutrinos
- Solar neutrinos
- Near detector physics

$$p \rightarrow e^{+}\pi^{0}$$



Courtesy of Bob Svoboda

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



Plot courtesy of Bob Svoboda

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
- Thank you to the organizers for this wonderful conference