A Long-Baseline Neutrino, Proton Decay and Supernova Facility Hosted in the US

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CPPM
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Outline

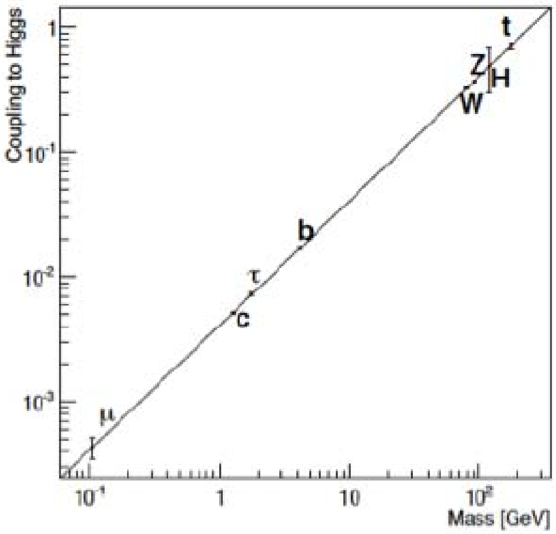
- Neutrinos
- Current Neutrino Program in the US
- Long-Baseline Neutrino Experiment Collaboration
- Science Motivation
  - Long-Baseline Science
  - Underground Science
- LBNE Project
- Science Strategy and Capabilities
- DOE Prioritization Panel (P5) Report
- Summary and Conclusions

Neutrinos are “unusual” particles

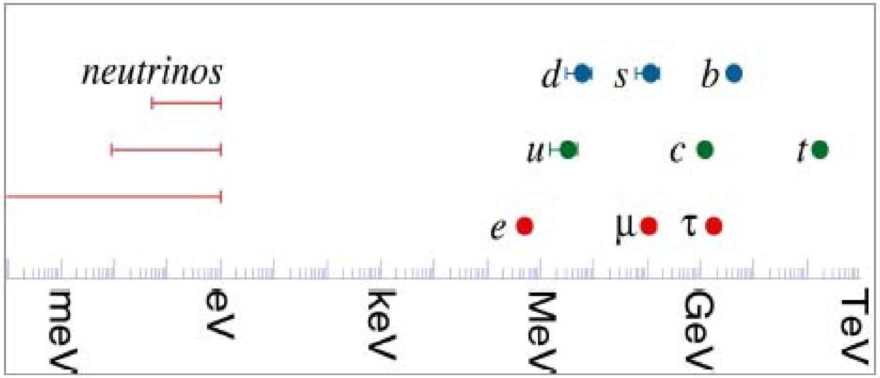
- Only neutral fundamental fermions
  => distinguish particle from anti-particle only by helicity, not charge
- Dramatically lighter than other fermions
  => Is there a different mechanism for generating their mass?
- ν are all left-handed and $\bar{\nu}$ all right-handed
  => Given their non-zero mass, where are the ν of the other helicity?
- Could neutrinos be Majorana particles?
  => neutrinos as their own anti-particle
- Mass and flavor eigenstates very strongly mixed
  => Why do different from the quarks?
- Do neutrinos violate CP?
  => Could they be the key to the baryon asymmetry of the universe?

Towards a bigger picture...

1. Test Higgs sector



2. Find ν masses



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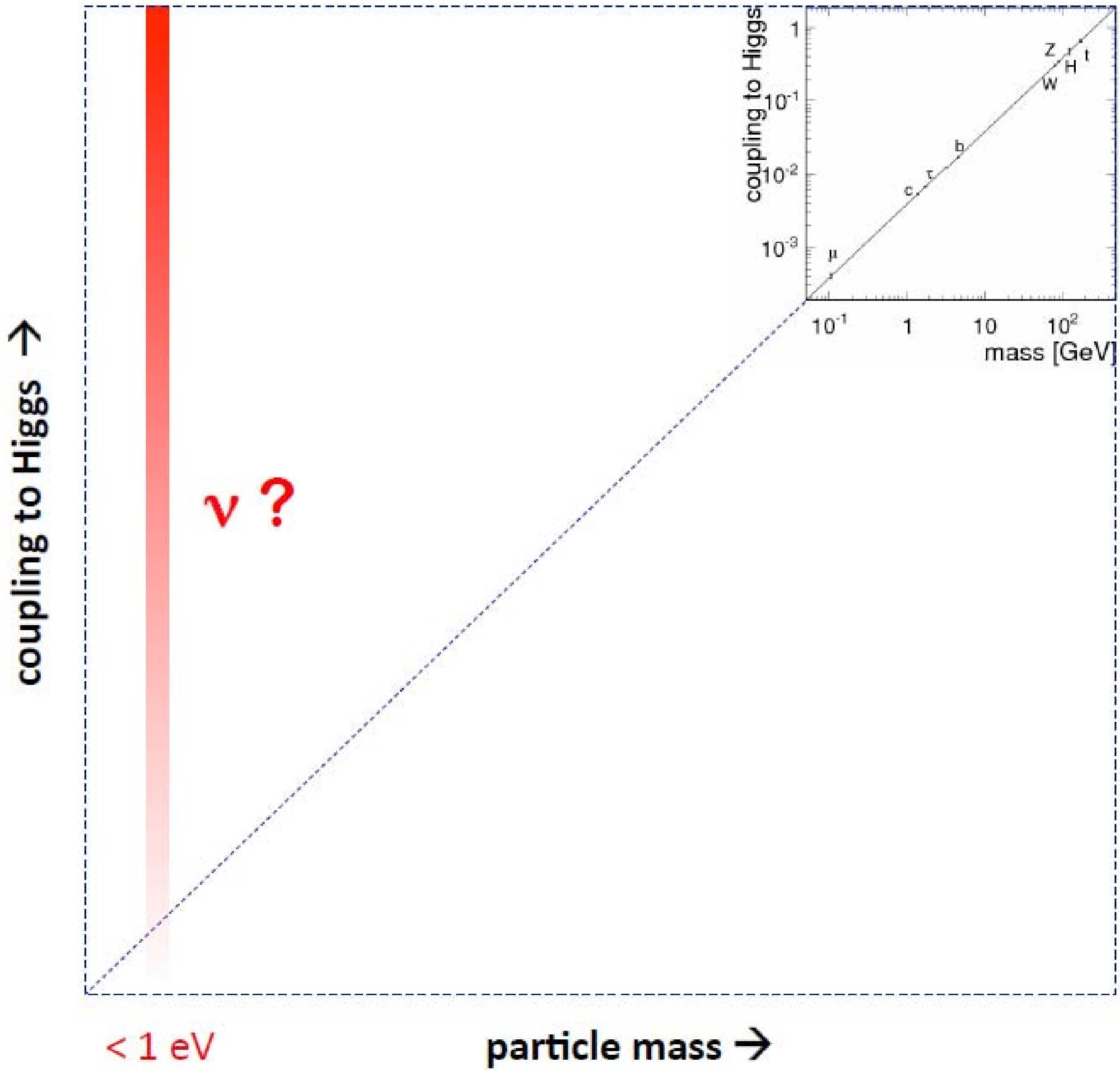
Where are the ν's on this plot? Why are they so light?

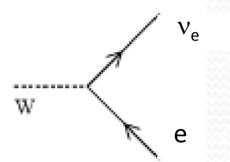


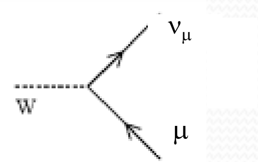
Neutrinos need to be fully understood

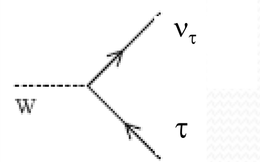
- Many experiments of many types are needed:
  - Accelerator- and reactor-based experiments probe flavor mixing and relative masses of the neutrinos
  - Neutrinoless double-beta decay tests the Majorana vs. Dirac nature of neutrinos
  - Cosmology and direct measurements determine the absolute neutrino mass scale
- This talk will concentrate on the physics that can be learned from accelerator-based experiments.
  => physics of neutrino oscillations

Neutrino Flavor Oscillations

- Neutrino production and detection determined by flavor eigenstates ν_e, ν_μ, ν_τ of the weak interaction







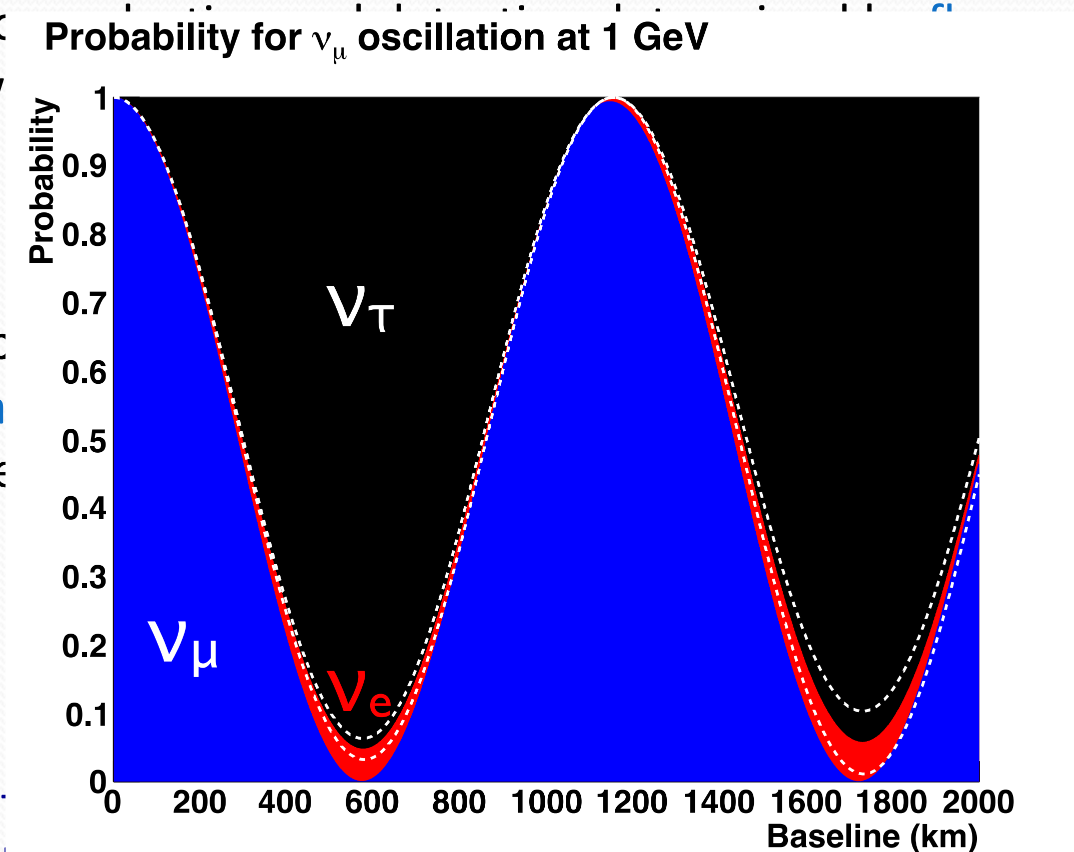
but propagation through space (and matter) is determined by mass eigenstates ν_1, ν_2, ν_3 of the Hamiltonian (with masses m_1, m_2, m_3), these can be related by

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Different masses will lead to interference between the propagating waves that affects the flavor probability at detection as a function of distance - “flavor mixing” or “neutrino oscillations”

Neutrino Flavor Oscillations

- Neutrinc ... igenstates ν_e, ν_μ, ν_τ of the w



ν_τ

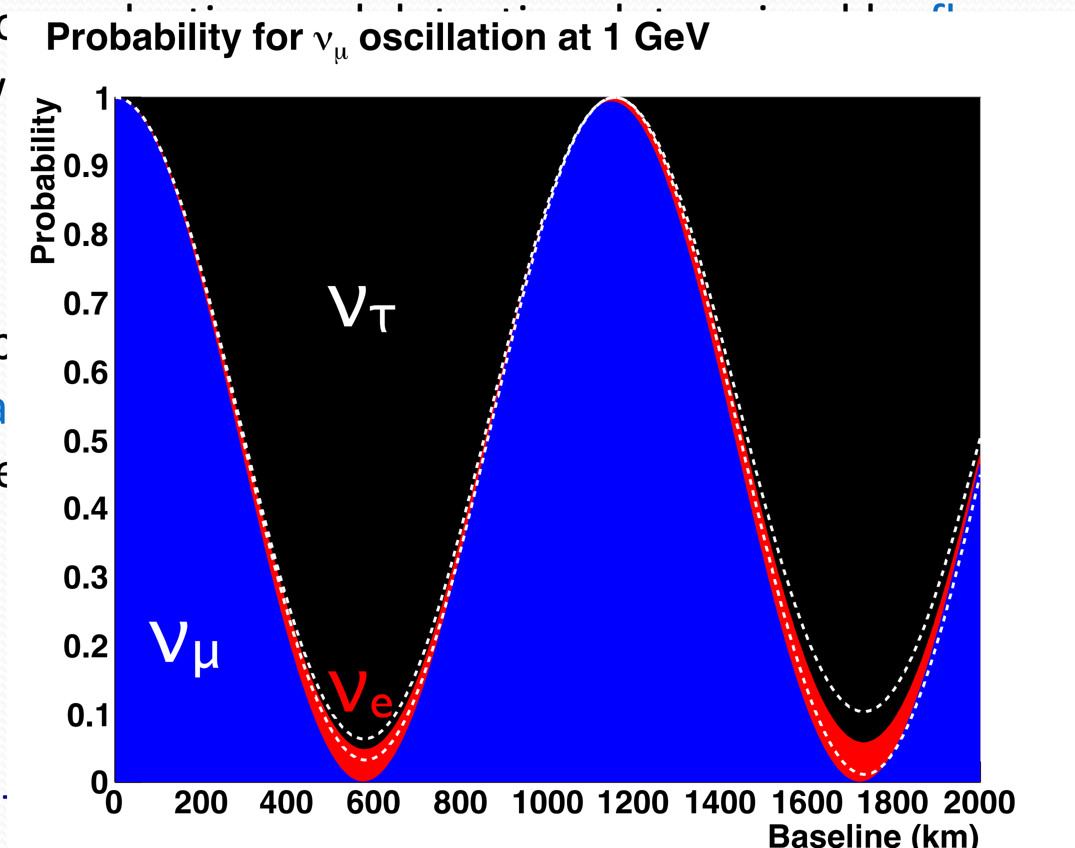
τ

but prop ... l by mass eigensta ... m_2, m_3), these can be relate

- Differen ... pagating waves that affects the flavor probability at detection as a function of distance - "flavor mixing" or "neutrino oscillations"

Neutrino Flavor Oscillations

- Neutrinc ... igenstates ν_e, ν_μ, ν_τ of the w...



but prop... l by mass eigensta... m$_2$, m$_3$), these can be relate...

- Differen... pagating waves that affects the flavor probability at detection as a function of distance - "flavor mixing" or "neutrino oscillations"
- **Quantum interferometry on a continental scale sensitive to minute effects**

PMNS Matrix

Pontecorvo-Maki-Nakagawa-Sakata

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

– U: 3 angles, 1 CP-phase + (2 Majorana phases)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$s_{ij} = \sin\theta_{ij}$
$c_{ij} = \cos\theta_{ij}$

atmospheric and accelerator

reactor and accelerator

solar and reactor

Mixing	Quarks	Leptons
1-2 θ_{12}	13°	34°
2-3 θ_{23}	2.3°	~43°
1-3 θ_{13}	~ 0.5°	~9°

18 months ago our biggest worry was that this was 0!

Phase δ for neutrinos is unknown – related to CP-violation

Neutrino Mixing

Neutrinos

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Quarks

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

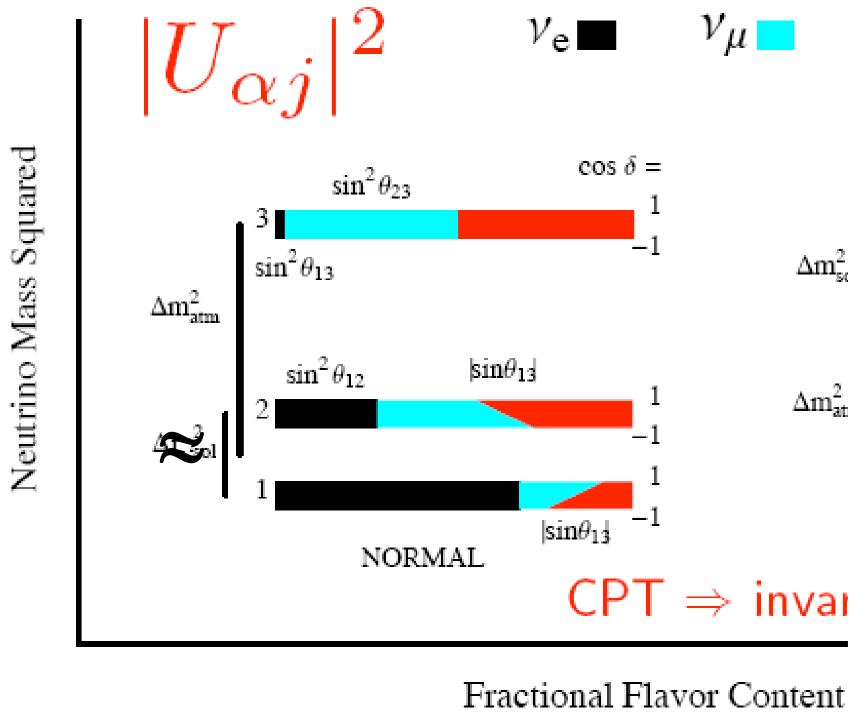
- Strikingly different!
- Is this telling us something fundamental?
  - A different mechanism for mass generation?

Mass Hierarchy

$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$$



S. Parke

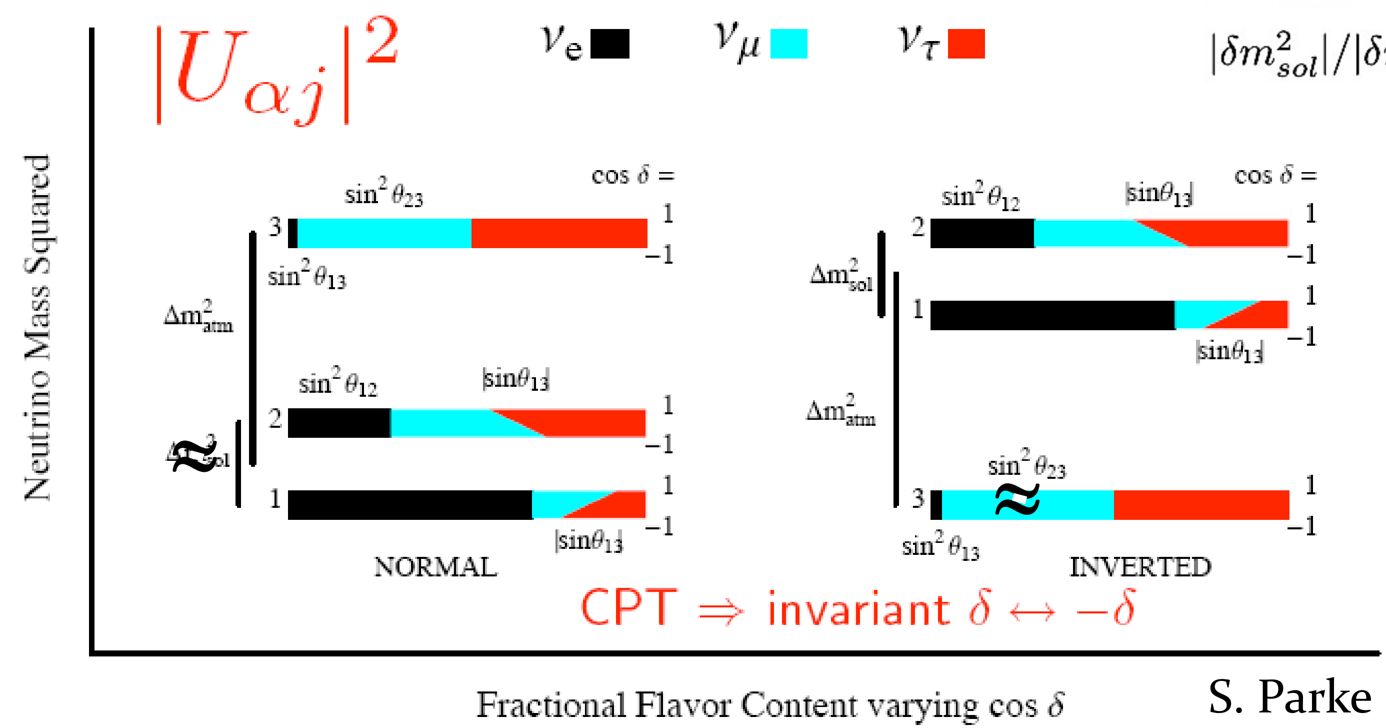
Mass Hierarchy

Discriminate between many GUTs

$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$

$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$

$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$



- Mass hierarchy related to Dirac vs. Majorana nature of neutrinos
- If inverted ordering, m_1 and m_2 are quasi-degenerate … does this imply some new symmetry?

ν_e Appearance in a ν_μ Beam

Approximation to 3-flavor vacuum mixing with $\Delta m_{21}^2 << \Delta m_{31}^2$

$$P(\nu_\mu \rightarrow \nu_e) \simeq s_{23}^2 \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

L – distance from source to detection
E – neutrino energy

- Effectively 2-flavor mixing
- L/E choice chosen for oscillation maxima
- Amplitude proportional to $\sin^2 2\theta_{13}$
- No δ dependence evident

ν_e Appearance in a ν_μ Beam

Vacuum Oscillation (3-flavor mixing)

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \quad = \quad & s_{23}^2 \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} + c_{13}^2 c_{23}^2 \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
& + 8 c_{13}^2 s_{13} c_{12} s_{12} s_{23} c_{23} \sin \frac{\Delta m_{21}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \cos \left(\frac{\Delta m_{32}^2 L}{4E} + \delta \right) \\
& - 2 s_{12}^2 s_{23}^2 \sin^2 2\theta_{13} \sin \frac{\Delta m_{21}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \cos \frac{\Delta m_{32}^2 L}{4E} \\
& + 4 c_{13}^2 s_{12}^3 s_{13} s_{23} \left(s_{23} s_{13} s_{12} - 2 c_{12} c_{23} \cos \delta \right) \sin^2 \frac{\Delta m_{21}^2 L}{4E}
\end{aligned}
$$

J. Boehm, thesis 2009

- δ dependence manifest in interference terms
- Effect of CP process is $\delta \to -\delta$ hence the nomenclature δ_{CP}

CP Violation and Neutrino Mass

- Leptogenesis – role of leptons in birth of the universe
  - Observationally the universe is matter-antimatter asymmetric
  - Sakharov (1967) showed that CP violation is needed to produce such an asymmetry
  - CP violation occurs in the Standard Model but it isn't enough to explain the observed asymmetry
  - If neutrinos oscillate then another source of CP violation is possible
- Grand Unified Theories attempt to unify electromagnetic, weak, and strong interactions – usually relate leptons to quarks
  - Related to light ν masses and unseen massive right-handed neutrinos
  - Intricately related to nucleon decay

Matter Effect

$$
\begin{aligned}
P_{\mu e} = {} & s_{23}^2 \frac{\sin^2 2\theta_{13}}{C_{13}^2} \sin^2 C_{13}\Delta - 2\alpha s_{12}^2 s_{23}^2 \frac{\sin^2 2\theta_{13}}{C_{13}^2} \sin C_{13}\Delta \\
& \times \Big[\Delta \frac{\cos C_{13}\Delta}{C_{13}} (1 - A\cos 2\theta_{13}) - A \frac{\sin C_{13}\Delta}{C_{13}} \frac{\cos 2\theta_{13} - A}{C_{13}} \Big] \\
& + \alpha s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin C_{13}\Delta}{A C_{13}^2} \Big\{ \cos\delta \big[C_{13} \sin(1+A)\Delta \\
& - (1 - A\cos 2\theta_{13}) \sin C_{13}\Delta \big] - C_{13} \sin\delta \big[\cos C_{13}\Delta - \cos(1+A)\Delta \big] \Big\} \\
& + c_{23}^2 \frac{\sin^2 2\theta_{12}}{C_{12}^2} \sin^2 \alpha C_{12}\Delta \\
& - s_{13} \frac{\sin 2\theta_{12}}{C_{12}} \sin 2\theta_{23} \frac{(1-\alpha)\sin\alpha C_{12}\Delta}{1 + A - \alpha + A\alpha c_{12}^2} \Big\{ \sin\delta \big[\cos\alpha C_{12}\Delta - \cos(A+\alpha-2)\Delta \big] \\
& + \cos\delta \Big[\sin(A+\alpha-2)\Delta - \sin\alpha C_{12}\Delta \Big(\frac{\cos 2\theta_{12} - \frac{A}{\alpha}}{C_{12}} - \frac{\alpha A C_{12}}{2(1-\alpha)} \frac{\sin^2 2\theta_{12}}{C_{12}^2} \Big) \Big] \Big\} \\
& - 2\alpha s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta) \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \qquad (2.6
\end{aligned}
$$

J. Boehm

- Additional ν_e interaction → mixing angles and mass differences modified by terms proportional to electron density
- Sign of effect depends on mass ordering
- **Next generation experiments need to confirm/refute the three-flavor model – sensitivity to new interactions**

Is the three-neutrino model complete?

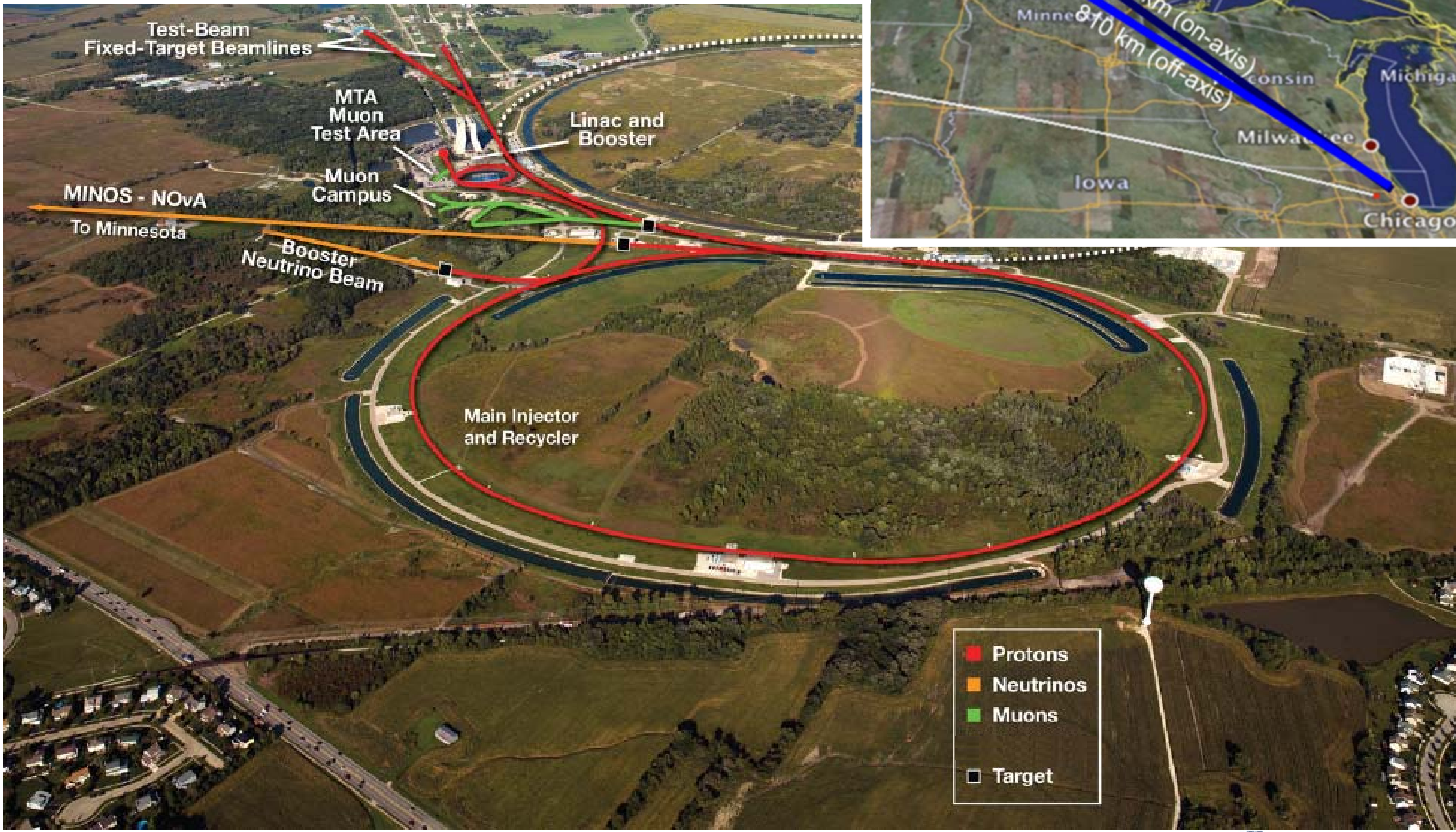
- Hints of deviations implying a fourth "sterile" neutrino
  - Reactor anomaly => ~7% deficit at short distances
  - Short-baseline anomaly, a.k.a. "LSND anomaly" => small ν_μ -> ν_e appearance rate at small L/E
- These effects can be tested by
  - Direct searches for sterile neutrino signatures
  - Over-constraining to PMNS matrix to test it unitarity

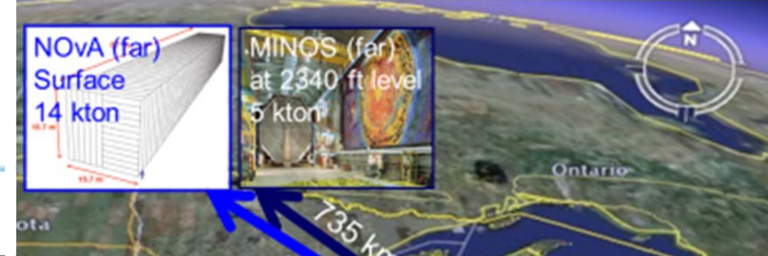
Accelerator-Based Neutrino Program in the U.S.

Fermilab hosts an active and diverse accelerator-based neutrino program.

- Two neutrino beams in operation and a third under design
- Four experiments currently taking data
- Three completed experiments analyzing data
- One experiment under construction
- One experiment under design
- Two proposals reviewed by the PAC and under consideration by Fermilab management
- Several experimental proposals submitted or in development.
- Supporting test beam program for detector development and calibration.

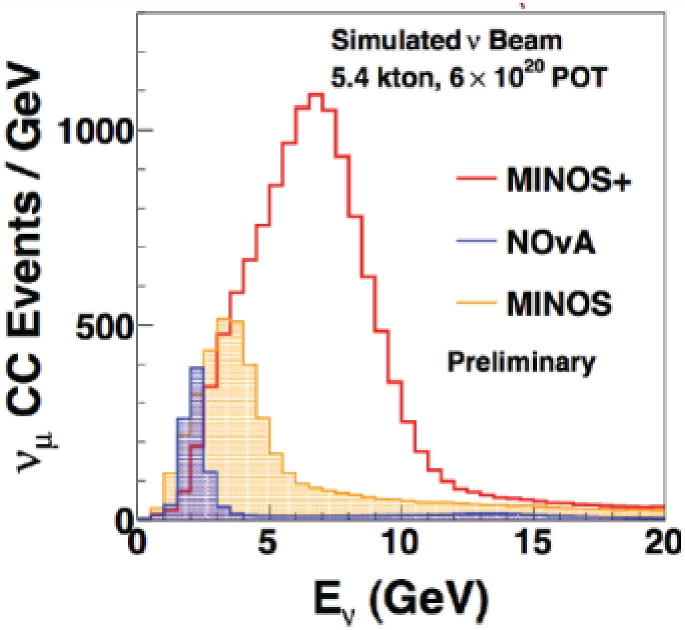
Fermilab Accelerator Complex



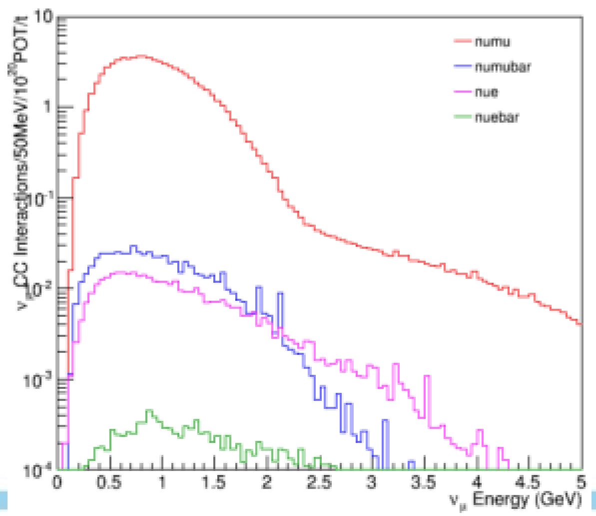


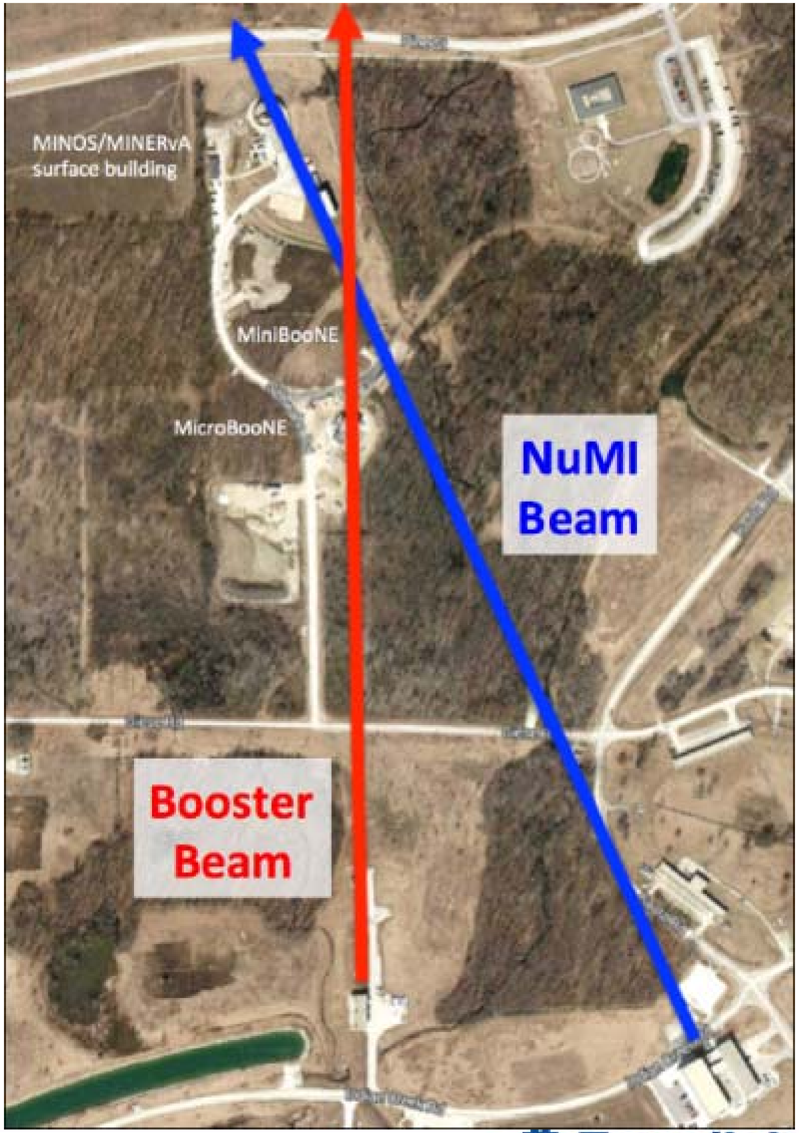
NuMI and Booster Beams

NuMI:
- tunable 1 GeV to >10 GeV
- Near hall at 1 km
- Far detectors 735 – 810 km

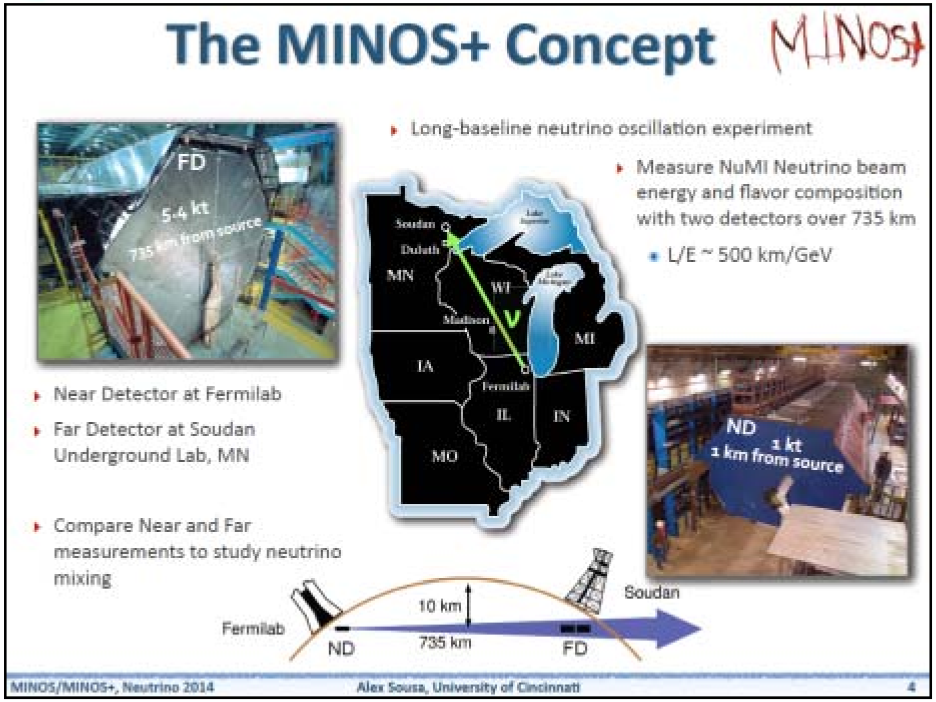


BNB:
- Low energy 0.1 – 1.5 GeV
- Focused on short-baseline oscillations and cross sections





Experiments in the NuMI Beam



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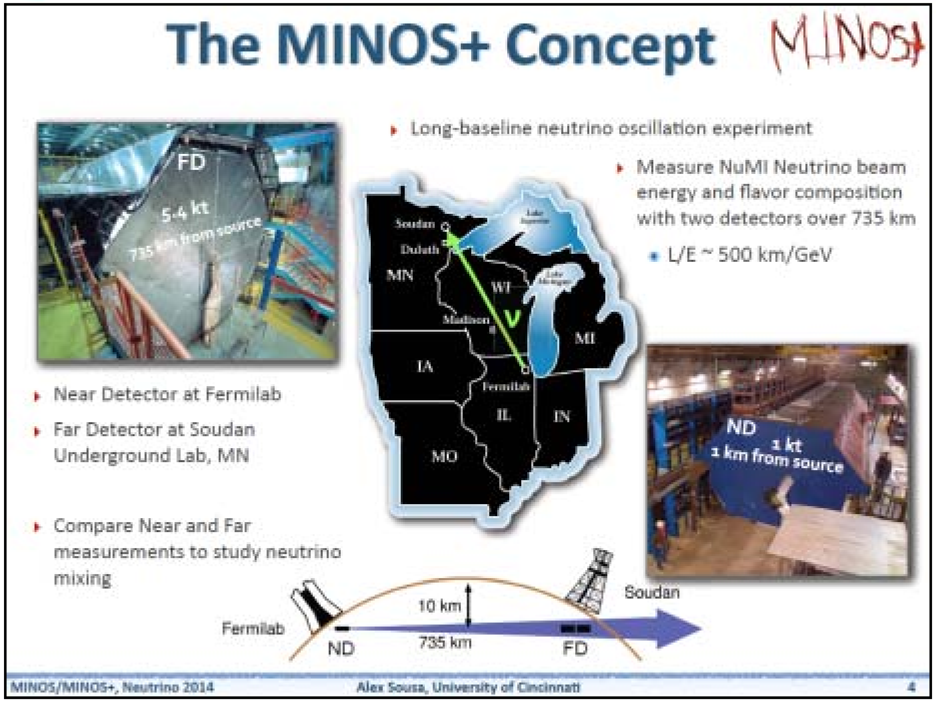
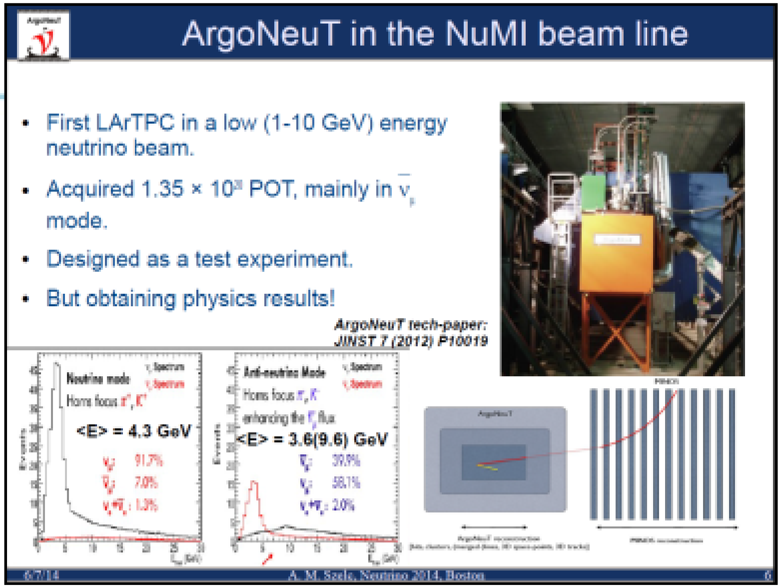
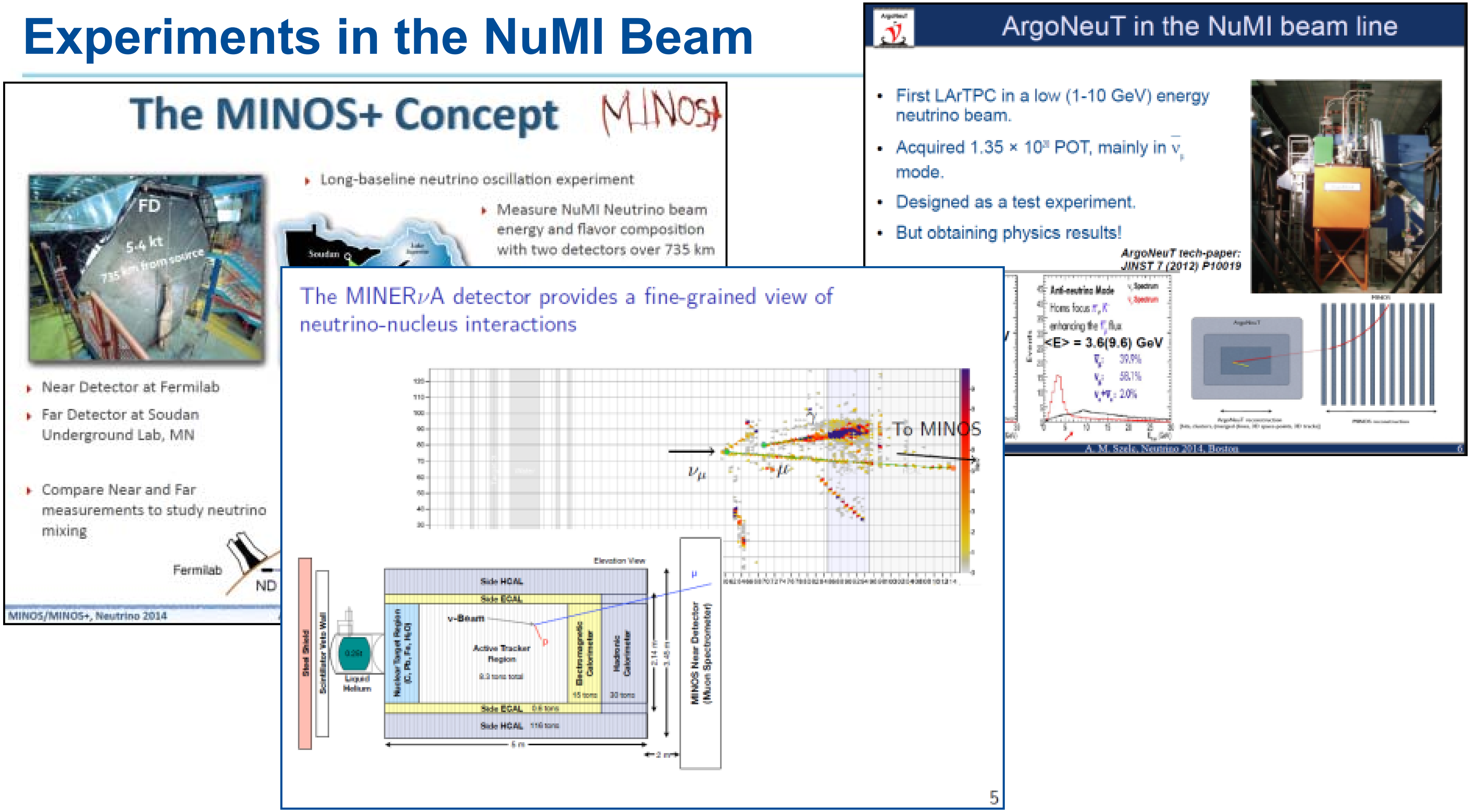
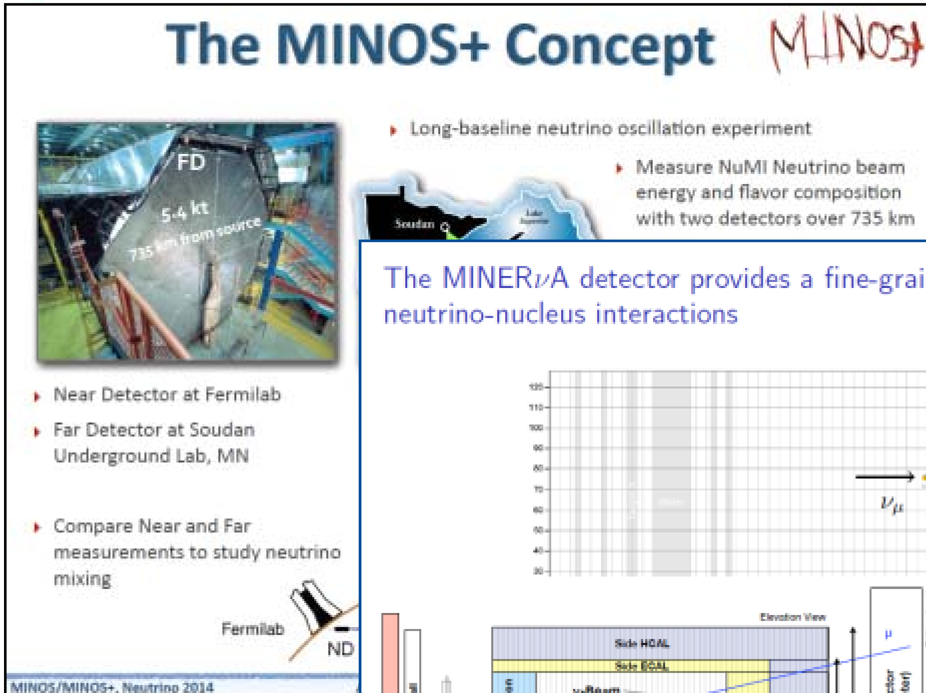


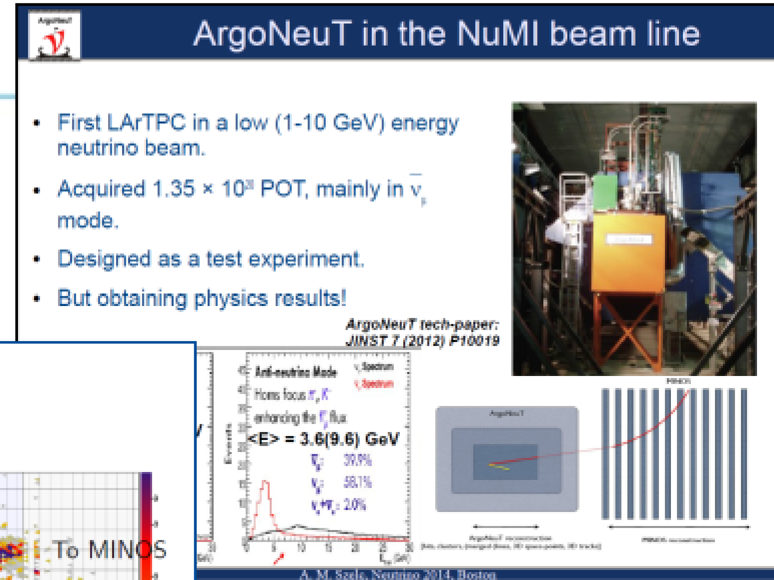


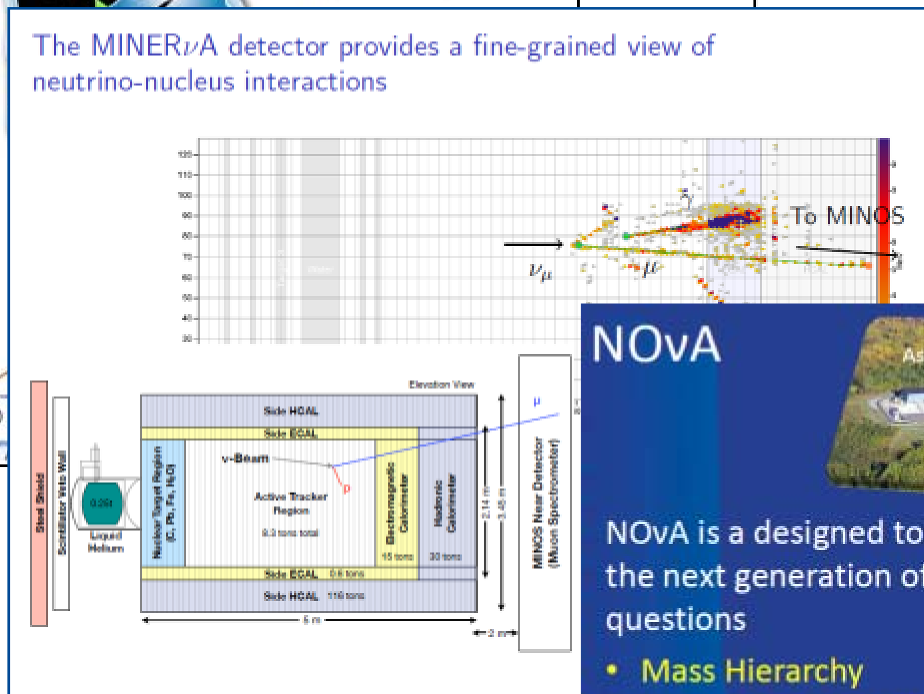
Experiments in the NuMI Beam



Experiments in the NuMI Beam







Experiments in the Booster Neutrino Beam

Experiments in the Booster Neutrino Beam

MicroBooNE

Determine source of MiniBooNE low-energy excess

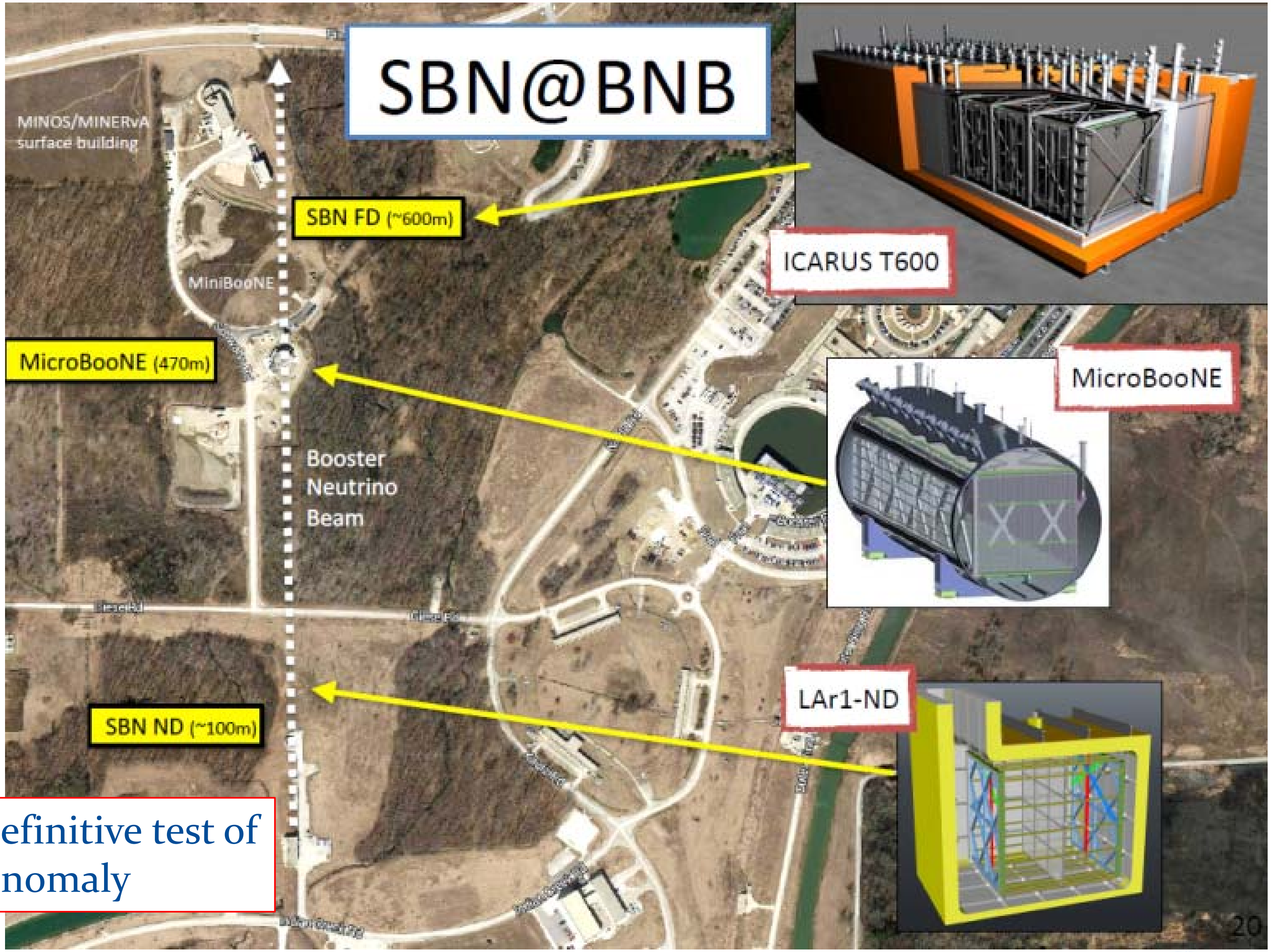
Experiments in the Booster Neutrino Beam

Massive MicroBooNE particle detector moved into place; will see neutrinos this year

The 30-ton MicroBooNE neutrino detector is gently lowered into the Liquid-Argon Test Facility at Fermilab on Monday, June 23. The detector will become the centerpiece of the MicroBooNE experiment, which will study ghostly particles called neutrinos. *Photo: Fermilab*

Determine source of MiniBooNE low-energy excess

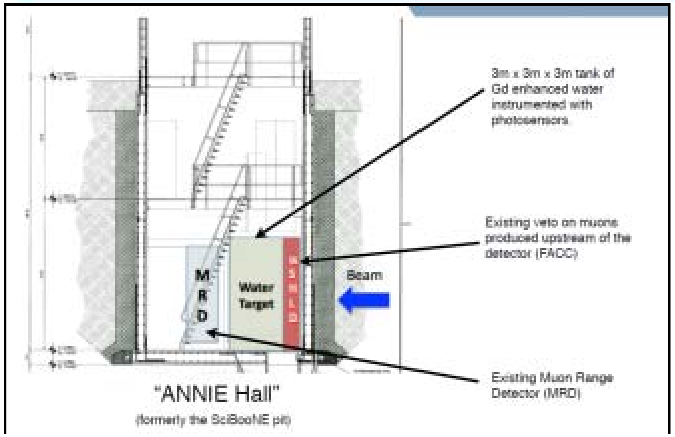
Proposed Short-Baseline Neutrino Program



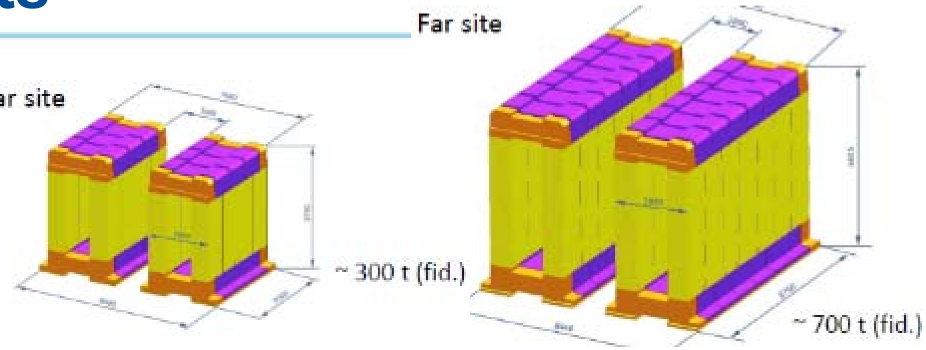
Goal: Definitive test of LSND anomaly

Fermilab

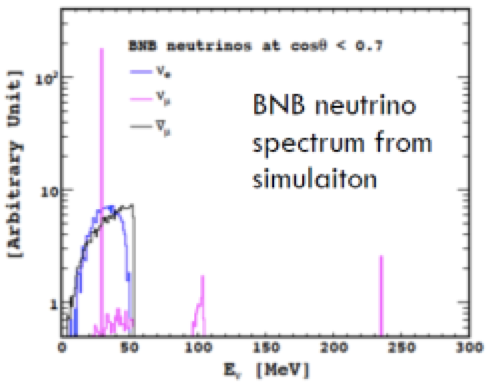
Additional Possible Experiments



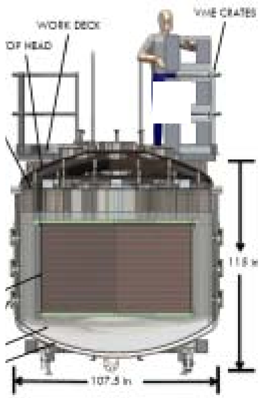
Measure ν-induced backgrounds relevant for large water detectors using an Optical Time Projection Chamber in BNB



Short-baseline ν_μ-disappearance measurement in BNB (NESSiE)



space is available in and out of building at points A, B and C



Calibrate LAr TPC response to low-energy neutrinos with stopped pion beam

Neutrino beam delivery over the last 15 years:

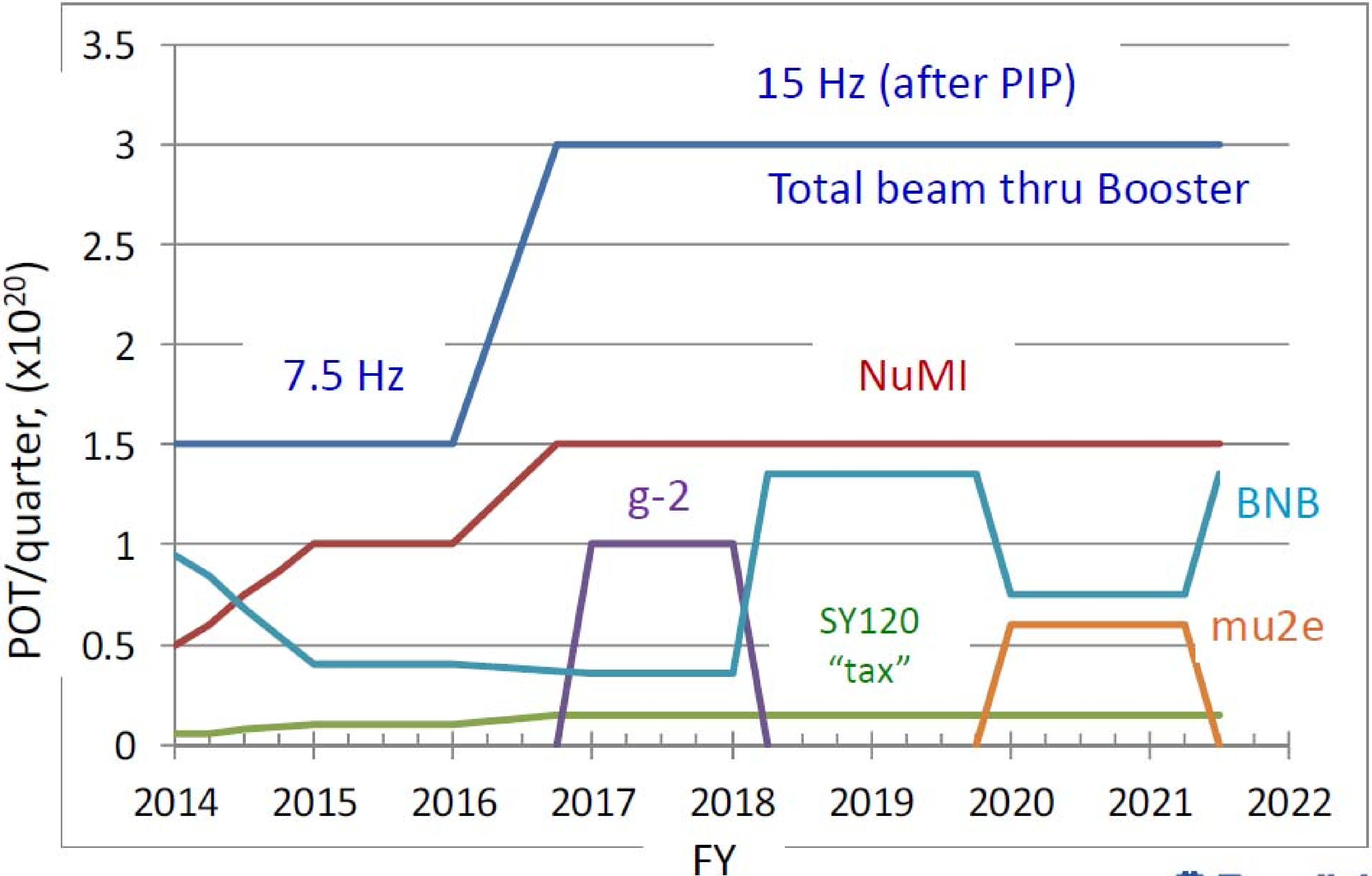
- *Delivering protons to neutrino experiments is a top priority for the Fermilab accelerator complex.*

	protons on target ($x10^{20}$)
K2K	0.92
T2K	6.70
OPERA/ICARUS	1.81
	9.43 = total Asia + Europe
NuMI	18.00
BNB	17.50
	35.50 = total Fermilab

Increasing beam intensity

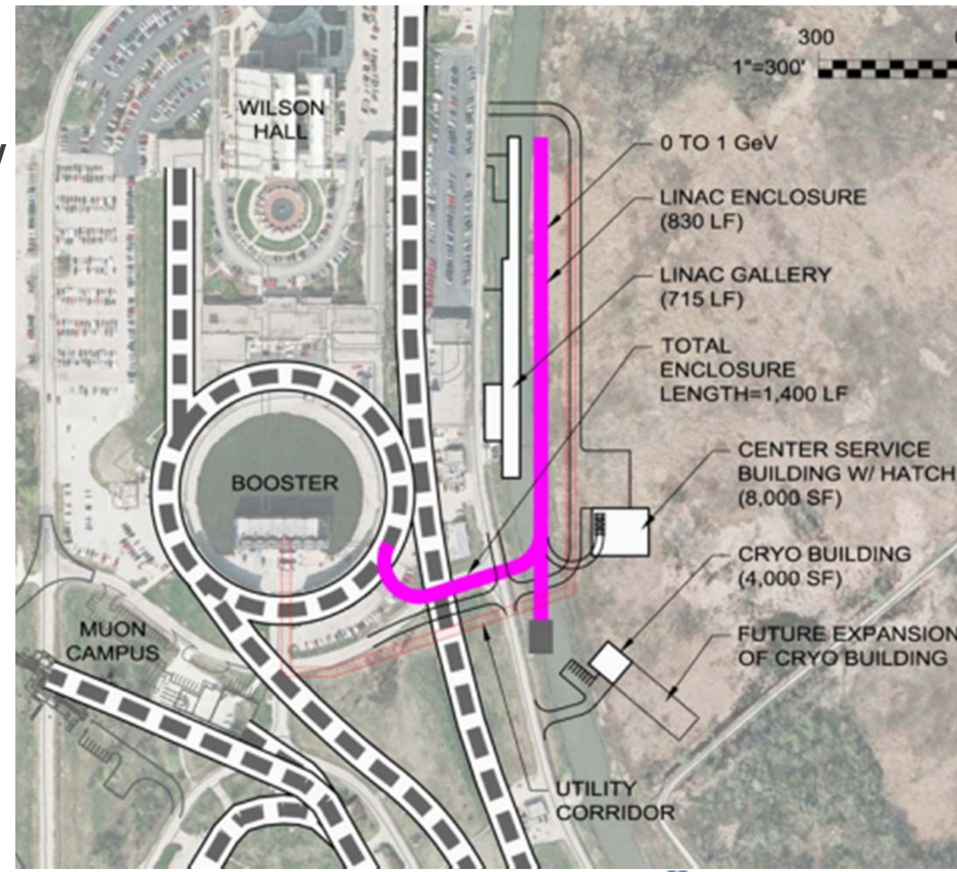
- Upgrades to the Main Injector and Recycler done as part of the NOvA construction will enable doubling the NuMI beam power to 700 kW
  - Convert Recycler to proton-stacking ring
  - Increase Main Injector ramp rate
  - ~10% increase in intensity per pulse
- Proton Improvement Plan (PIP) to increase proton flux from Booster to the Main Injector
  - Refurbish Booster RF system: 7.5 → 15 Hz beam operation
  - Upgrades to Linac and Booster for higher reliability
- Combined upgrades will deliver 700 kW to NOvA and increase the intensity of the Booster Neutrino Beam.

Proton delivery scenario (approximate)



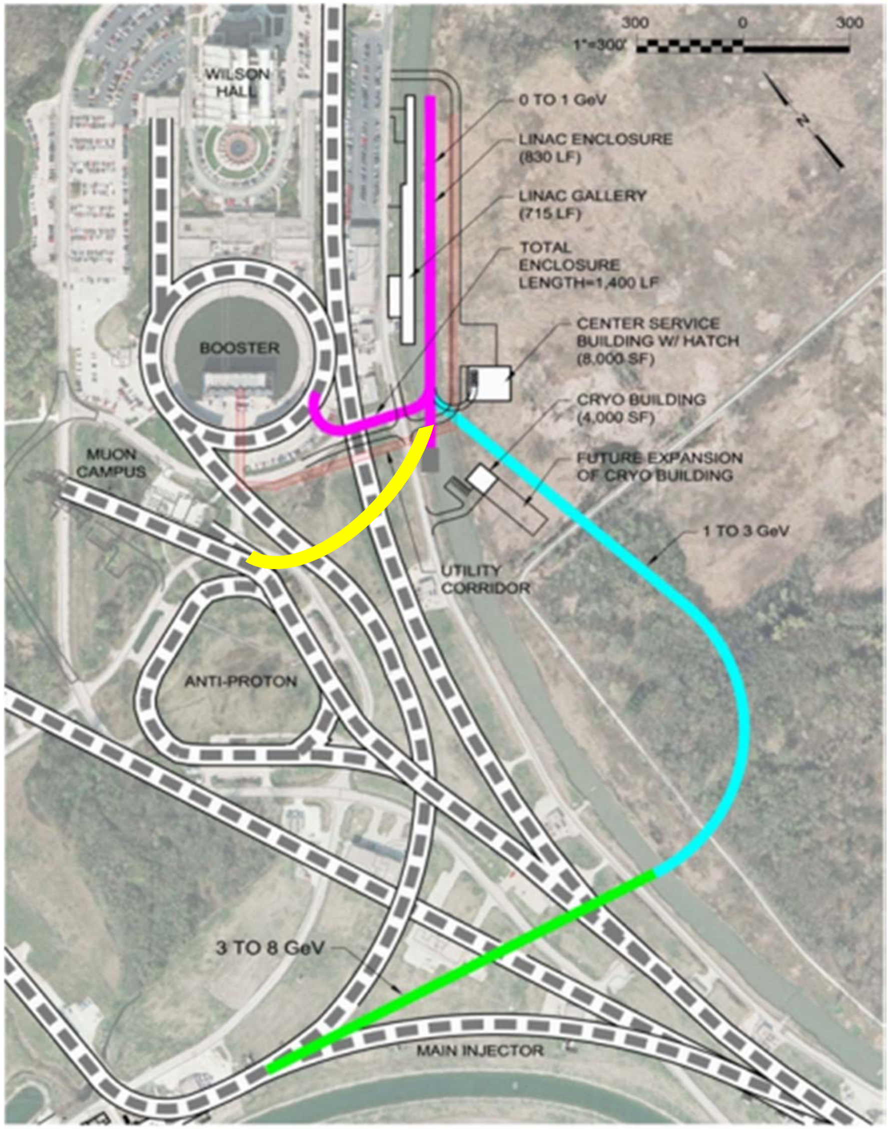
Proton Improvement Plan II (PIP-II)

- Goal is to increase Main Injector beam power to 1.2 MW.
  - Replace the existing 400 MeV linac with a new 800 MeV superconducting linac => 50% increase in Booster intensity.
  - Shorten Main Injector cycle time 1.33 → 1.2 sec.
- Build this concurrently with new long-baseline facility => deliver 1.2 MW to LBNE from t = 0.
- This plan is based on well-developed SRF technology.
- Developing an international partnership for its construction
- Strong support from DOE and P5



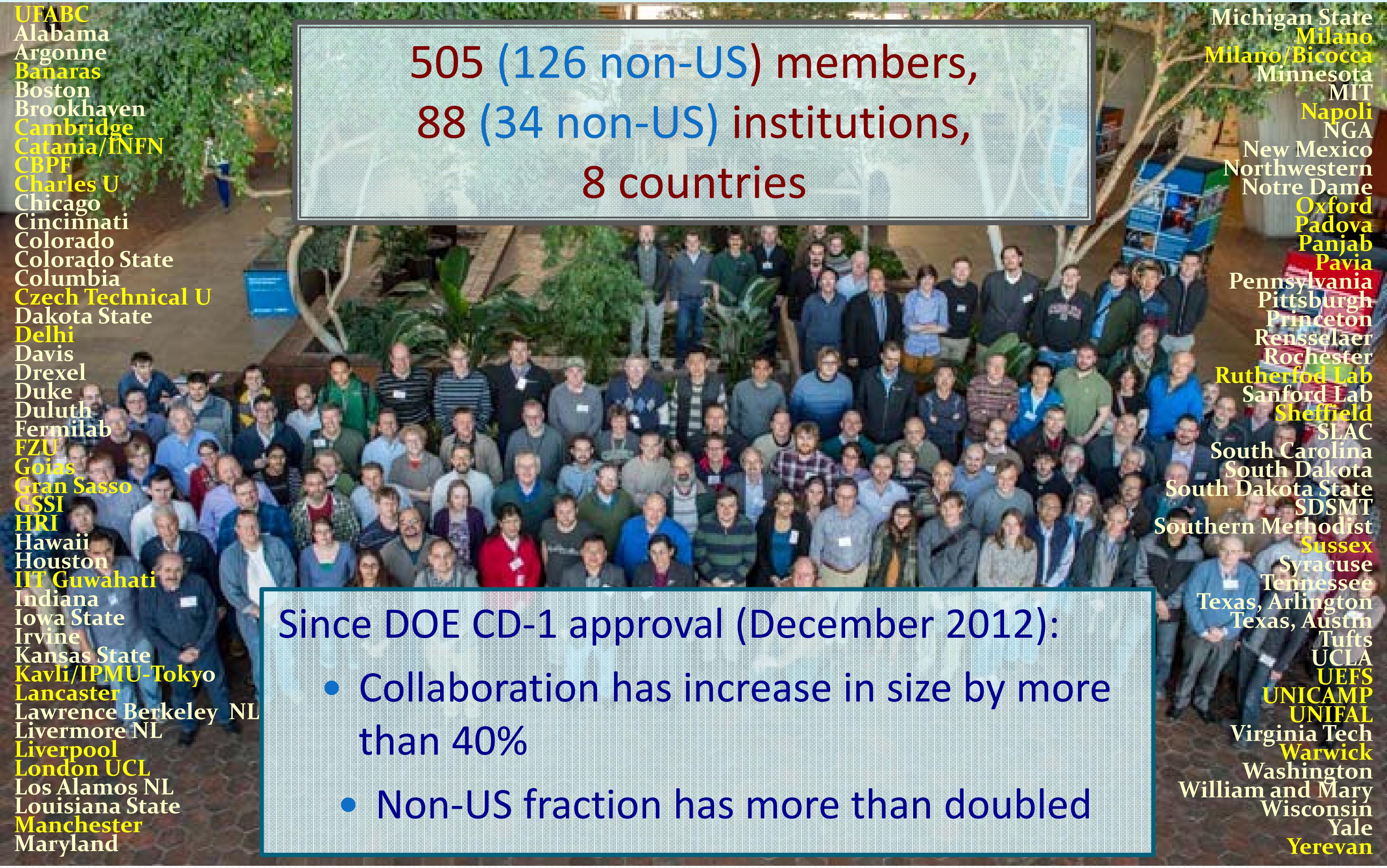
Flexible Platform for the Future

- PIP-II Inherent Capability
  - ~200 kW @ 800 MeV
  - x10 Mu2e sensitivity
- Future upgrade would provide > 2 MW to LBNE
- Flexibility for future experiments
  - Muons, Kaons at 100’s kW



LBNE Collaboration

505 (126 non-US) members,
88 (34 non-US) institutions,
8 countries



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Argonne
Banaras
Boston
Brookhaven
Cambridge
Catania/INFN
CBPF
Charles U
Chicago
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Colorado
Colorado State
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Czech Technical U
Dakota State
Delhi
Davis
Drexel
Duke
Duluth
Fermilab
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Hawaii
Houston
IIT Guwahati
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Iowa State
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South Dakota State
SDSMT
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Sussex
Syracuse
Tennessee
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Texas, Austin
Tufts
UCLA
UEFS
UNICAMP
UNIFAL
Virginia Tech
Warwick
Washington
William and Mary
Wisconsin
Yale
Yerevan

Since DOE CD-1 approval (December 2012):

- Collaboration has increase in size by more than 40%
- Non-US fraction has more than doubled

Scientific Motivation

- Neutrinos are the most abundant known matter particle
- Neutrino (Flavor) Oscillation is a quantum interference phenomenon with potentially unknown implications for fundamental physics
  - ***known neutrino mass and mixing angle values allow quantum interferometry on a continental scale sensitive to minute effects***
- Neutrino mass cannot be understood within the Standard Model – calls for new physics

- Our knowledge of neutrino properties is based on a relative handful of direct measurements

Scientific Motivation

- CP Violation in neutrino sector
  - Violation of a fundamental symmetry of nature; viability of leptogenesis models->matter/antimatter
- Neutrino Mass Hierarchy
  - GUTs, Dirac vs. Majorana nature and feasibility of $0\nu\beta\beta$ decay
- Testing the Three-Flavor Paradigm
  - Precision measurements of known fundamental mixing parameters for neutrinos and anti-neutrinos
  - New physics -> non-standard interactions, sterile neutrinos… (beam + atmospheric ν sources)
  - Precision neutrino interactions studies (near detector)

Scientific Motivation

Fundamental physics enabled by massive detectors underground

- Nucleon Decay
  - Is normal matter stable?
  - Grand Unification Theory
- Astrophysics
  - Supernova ν burst – evolution of a stellar collapse

Importance of LBNE Science

The science of LBNE has been widely recognized to be a top priority.

The Long-Baseline Neutrino Experiment (LBNE) will measure the mass hierarchy and is uniquely positioned to determine whether leptons violate CP. Future multi-megawatt beams aimed at LBNE, such as those from Project X at Fermilab, would enable studies of CP violation in neutrino oscillations with conclusive accuracy. An underground LBNE detector would also permit the study of atmospheric neutrinos, proton decay, and precision measurement of any galactic supernova explosion. This represents a vibrant global program with the U.S. as host.

Report of the 2013 "Snowmass" Summer Study

f. Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. *CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.*

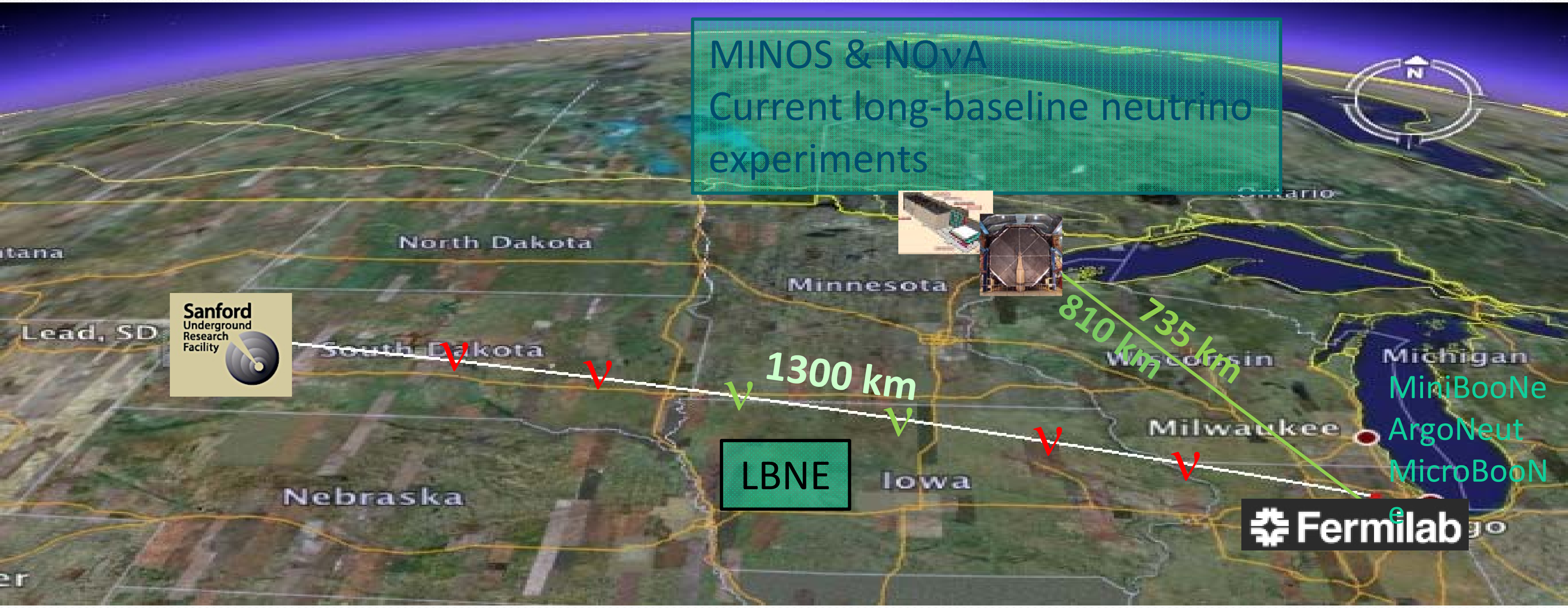
The European Strategy for Particle Physics, Update 2013

The Science Drivers:

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

P5 Report, May 2014

Long-Baseline Measurements



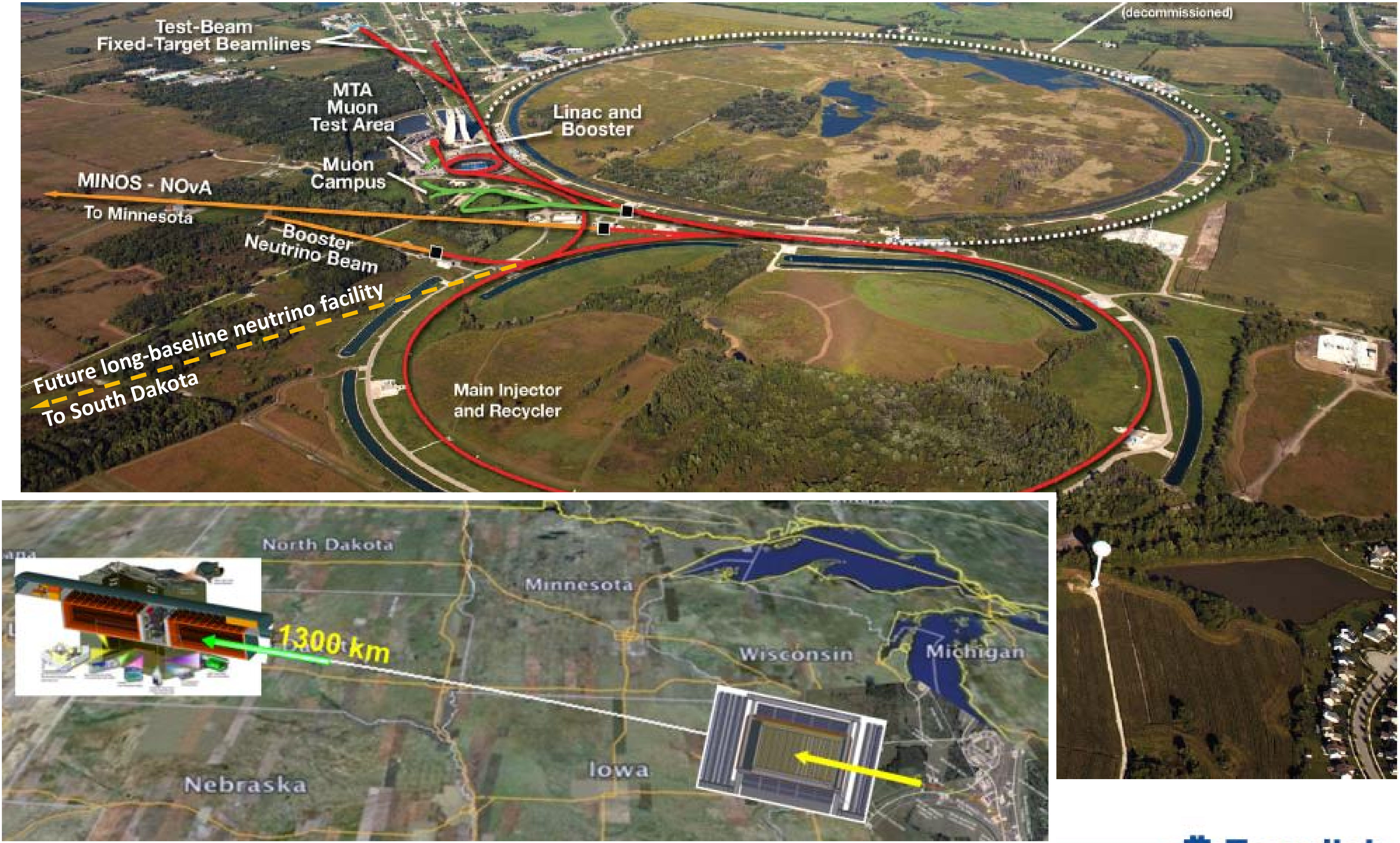
Comprehensive CP Violation, Mass Hierarchy, Non-Standard Interactions
Need Longer Baseline
and High Intensity Broadband Neutrino/Anti-Neutrino Beam

Experimental Parameters

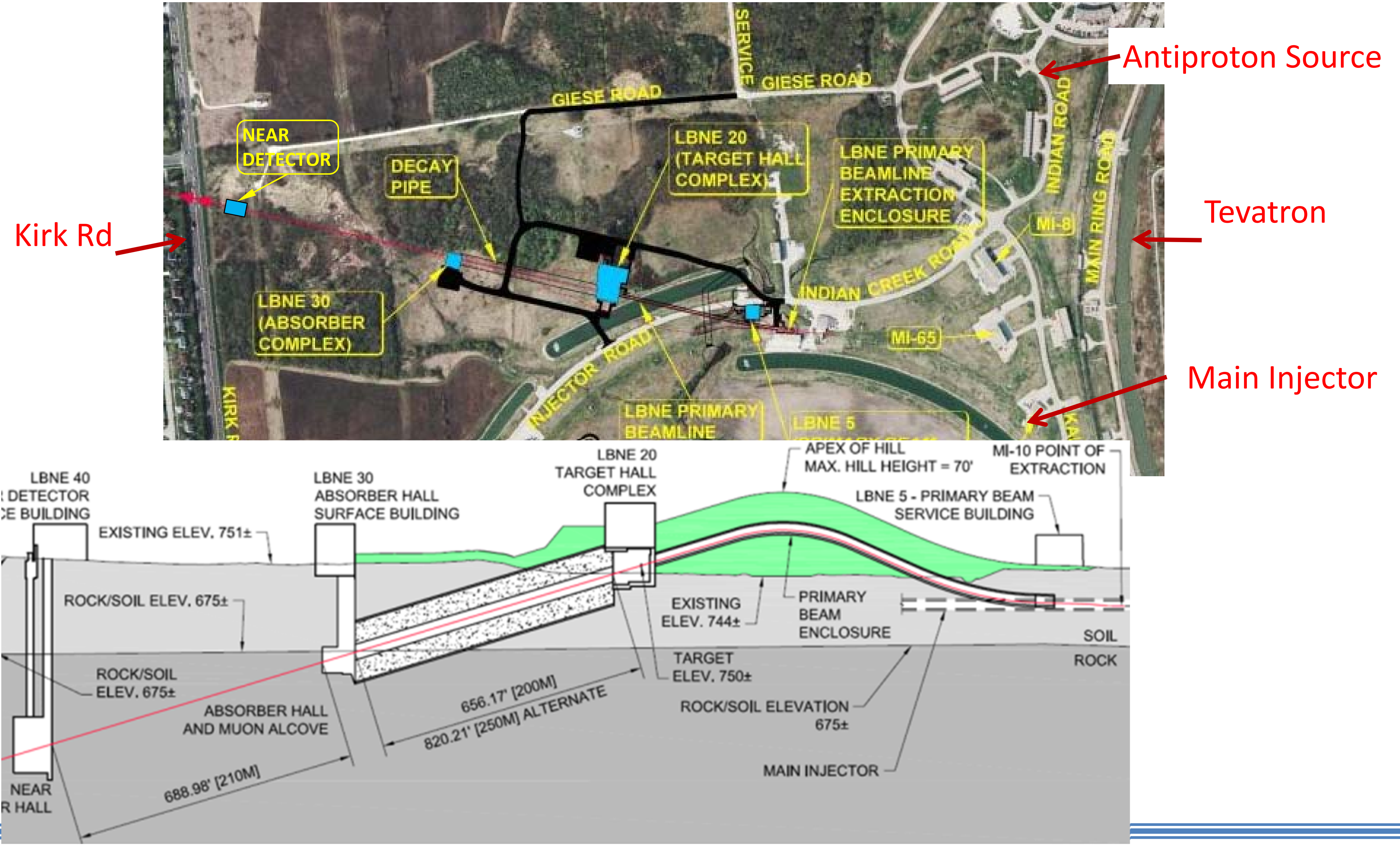
- Wide band neutrino beam from FNAL
  - protons: 60-120 GeV, 1.2 MW; upgradable to 2.3 MW
  - 10 μS pulses every 1.0 to 1.33 sec depending on P energy&power.
  - Neutrinos: sign selected, horn focused, 0.5 - 5 GeV
  - 1300 km thru the Earth to Sanford Underground Research Facility.
- Liquid argon TPC parameters
  - 34 kt fiducial (50kt tot) at 4850 ft level. cosmics ~0.1Hz, beam ~ 9k CC/yr
  - drift ~3.5 m, field: 500 V/cm, 2 mods = (14m(H)X 22m(W)X45m(L))
  - readout: x,u,v, pitch: 5 mm, wrapped wires, 2X108 APAs, 2X(275k ch)
  - Max Yield: ~9000 e/mm/MIP, 10000 ph/mm/MIP
- near detector parameters
  - distance ~450 m, ~3M events/ton/MW/yr
  - Magnetized Fine Grained Tracker (8 ton) with ECAL, and muon id.
  - Supplemented by a small LARTPC (few tons) or gas TPC.

Scale of project is dictated by physics. Beam and ND and FD detectors require high technology. Project can be done in phases with international partners.

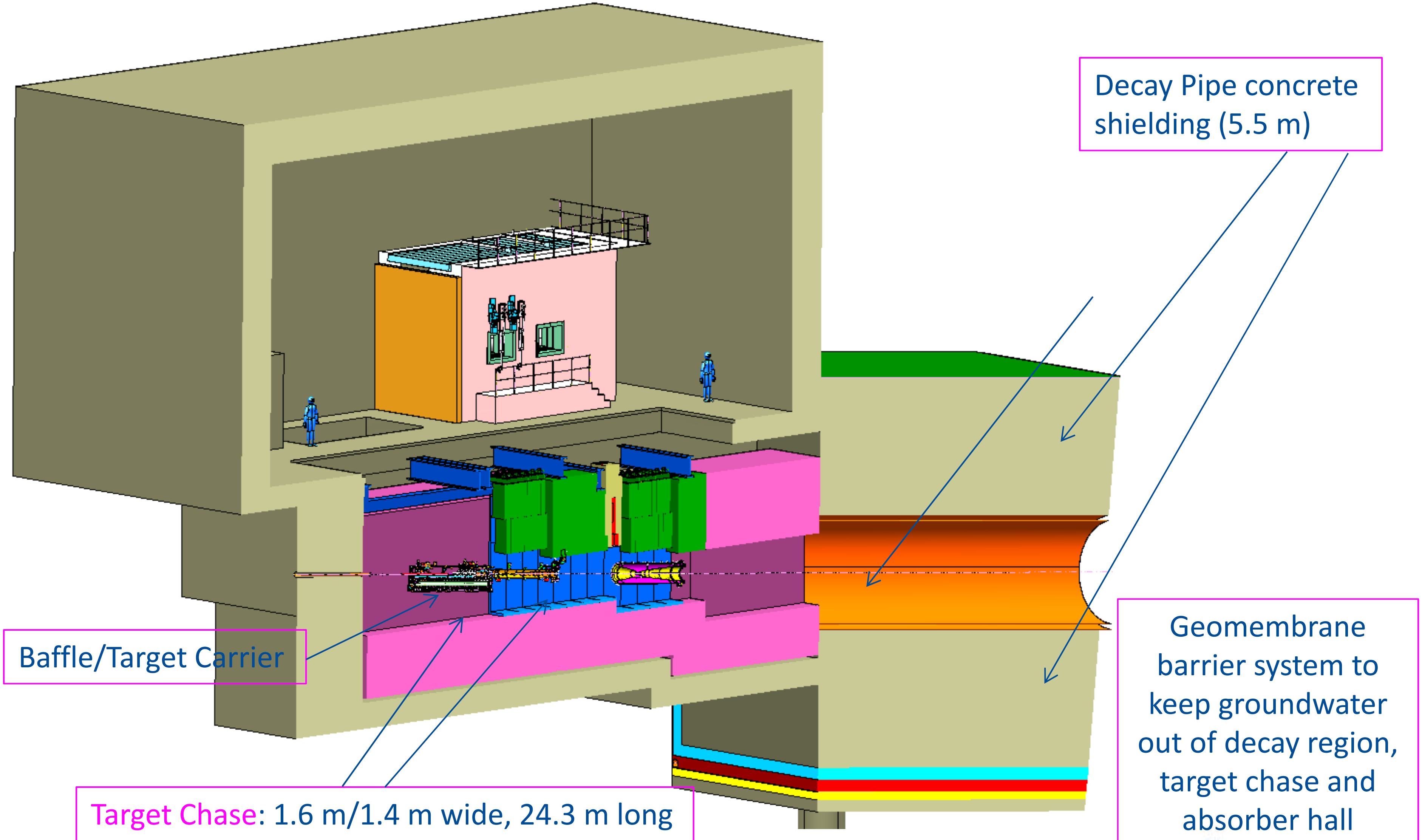
Fermilab Accelerator Complex



LBNE Beamline Design



Target Hall and Decay Pipe Layout

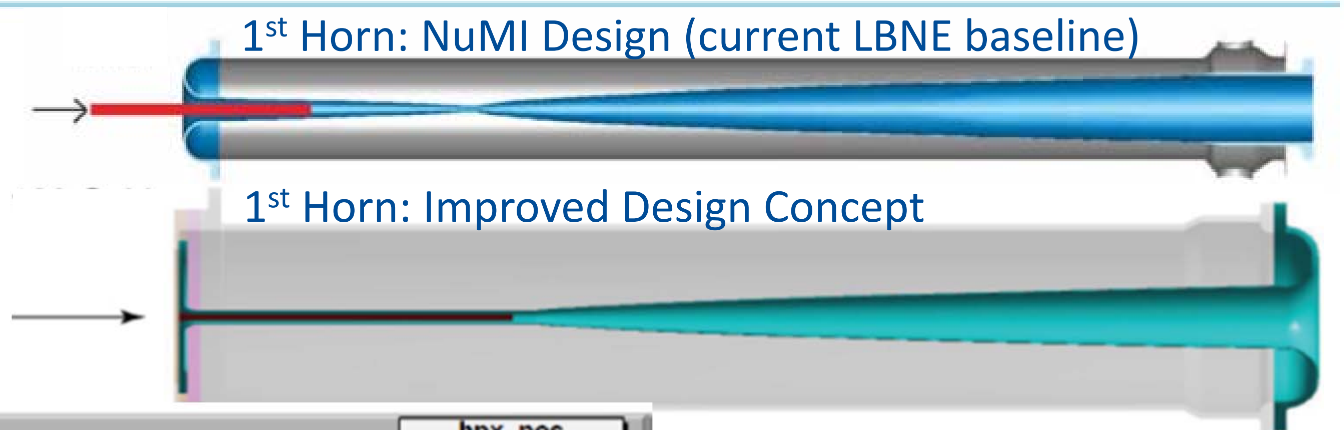


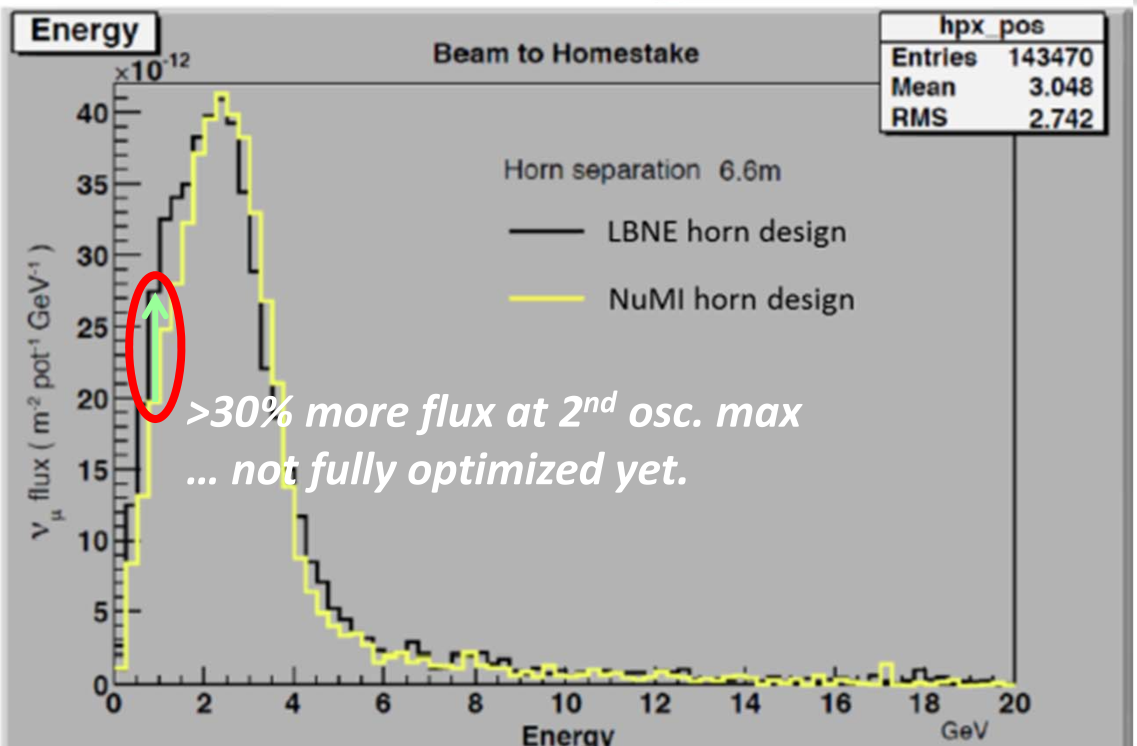
Beam Improvements Under Consideration

Changes	0.5-2 GeV		2-5 GeV		Extra Cost
Horn current 200 kA → 230 kA	1.00		1.12		$0
Proton beam 120 → 80 GeV,700 kW	1.14		1.05		$0
Target graphite → Be	1.10	34%	1.00	31%	< 1 M$
DP Air → He *Recently approved*	1.07		1.11		~ 8 M$
DP diameter 4 m → 6 m	1.06		1.02		~ 17 M$
DP length 200 m → 250 m	1.04		1.12		~ 30 M$
Total	1.48		1.50		

- Target/horn system can be replaced with more advanced designs as they become available.
- Decay pipe design must be fixed at the beginning.
- First four improvements appear technically and financially feasible.
- The last two proposals regarding the decay pipe diameter and length are still under study.

Improved Focusing for Second Oscillation Maximum





This is one example of significant improvements that are possible and needed, which new collaborators could bring into the design of the long-baseline neutrino facility beam design.

Measurements of muons post-absorber

$\pi^+ \longrightarrow \mu^+ + \nu_\mu$

o$E_\nu = (0\text{-}0.43)E_\pi$

o$E_\mu = E_\pi - E_\nu = (0.57\text{-}1.0)E_\pi$

Cherenkov Detectors:

measure all muons above a variable threshold

constrains muon spectrum (correlated with E_ν)

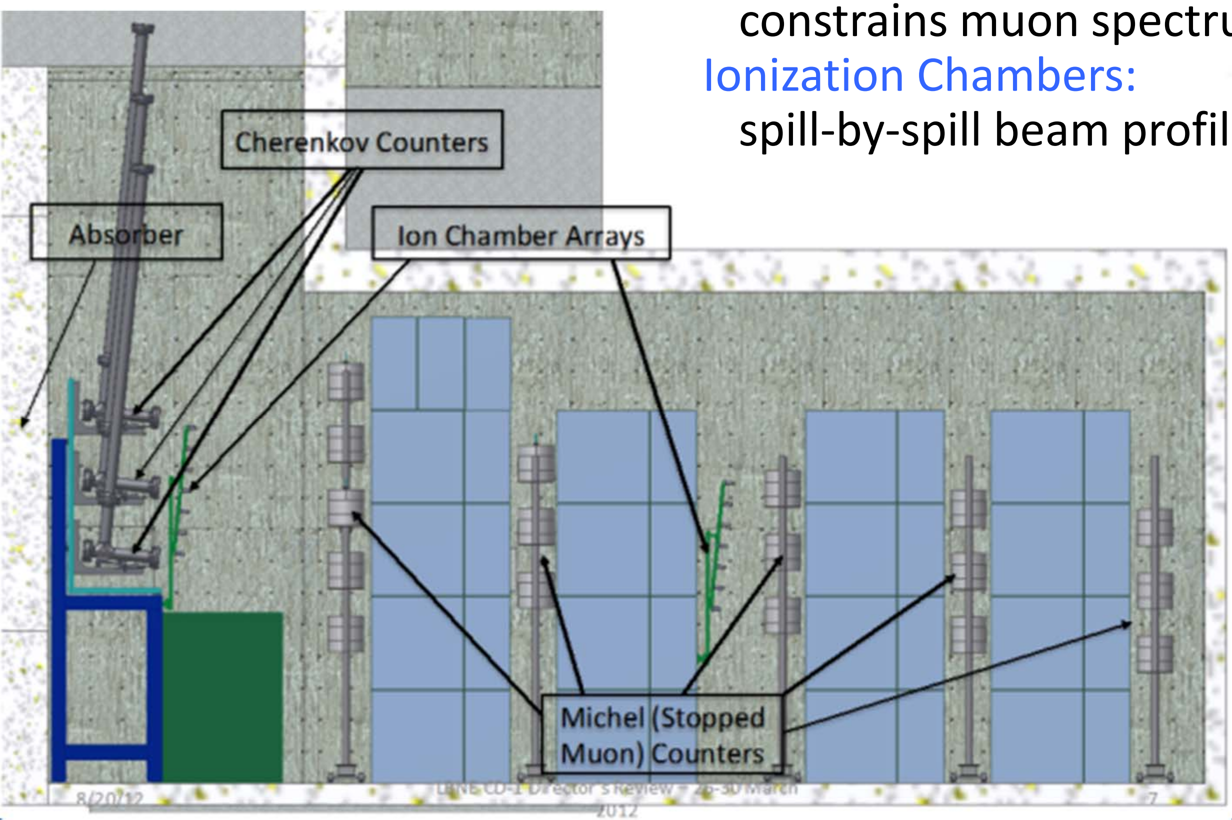
Michel Decay Detectors:

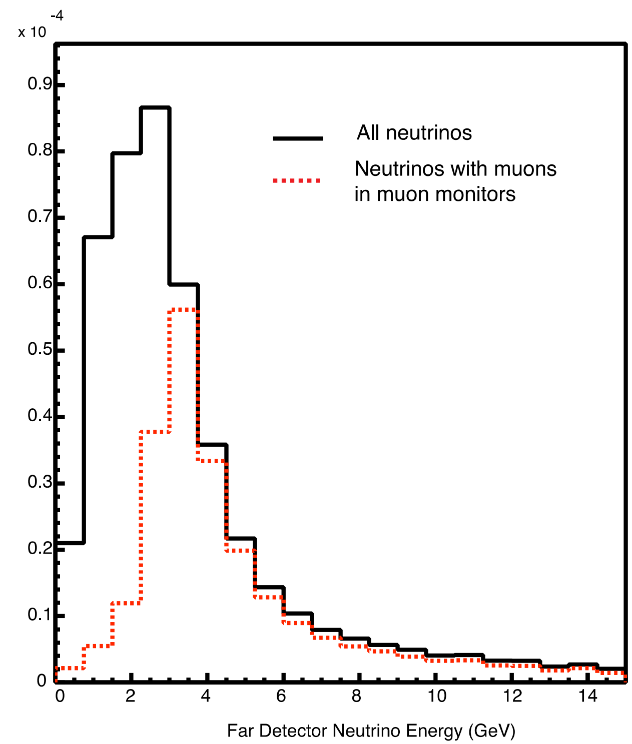
measure muons that stop at a given depth in material

constrains muon spectrum

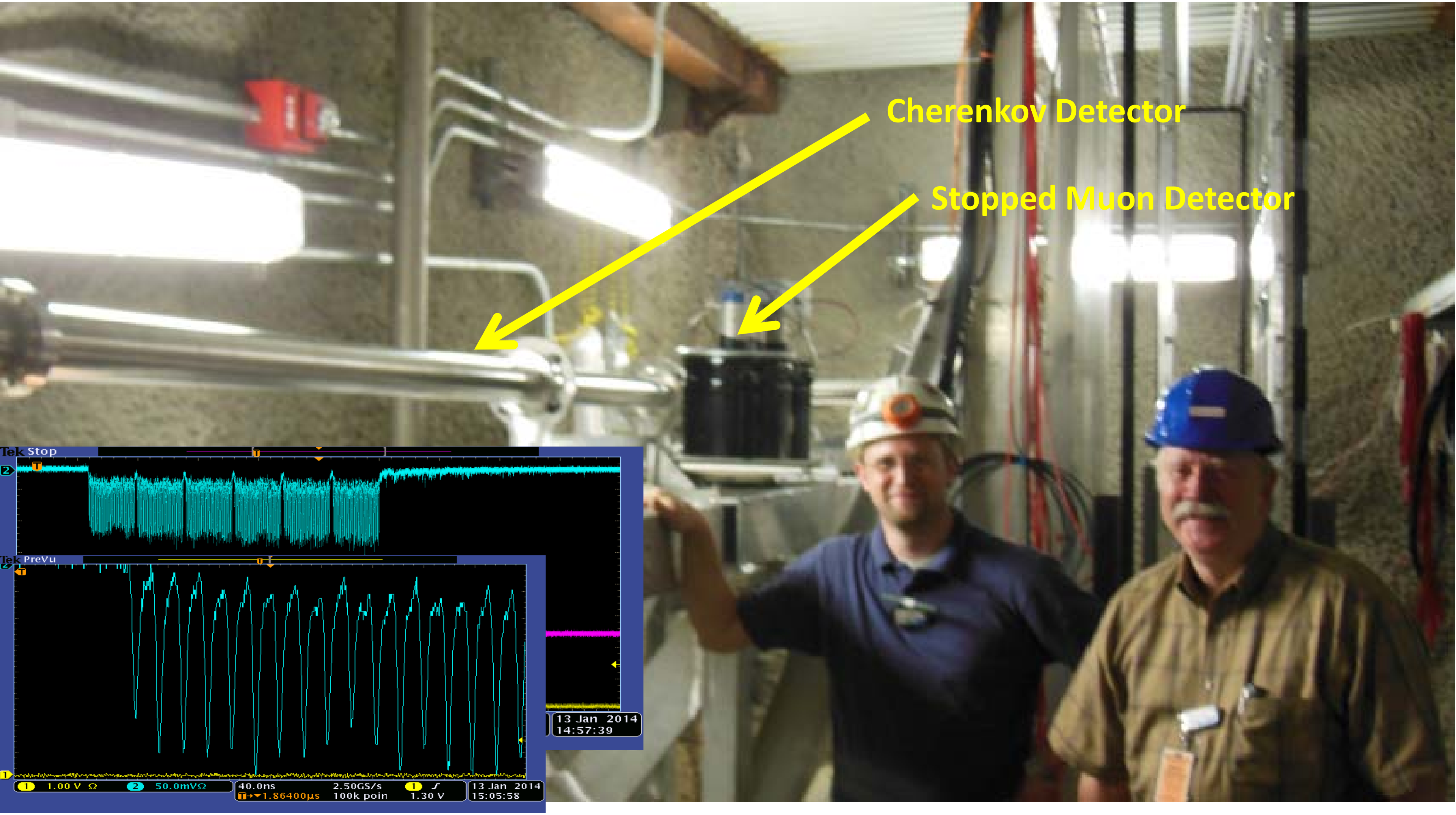
Ionization Chambers:

spill-by-spill beam profile



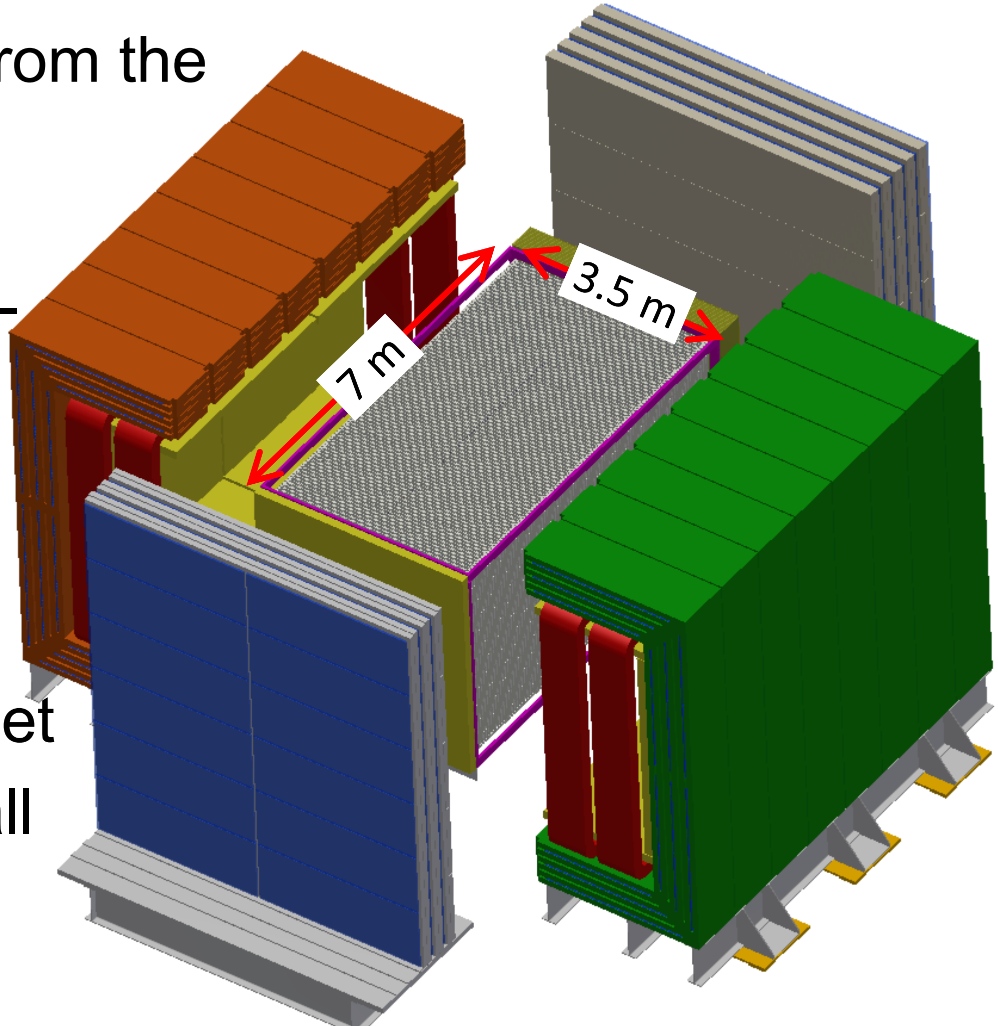


Prototype Muon Detectors in NuMI Beamline



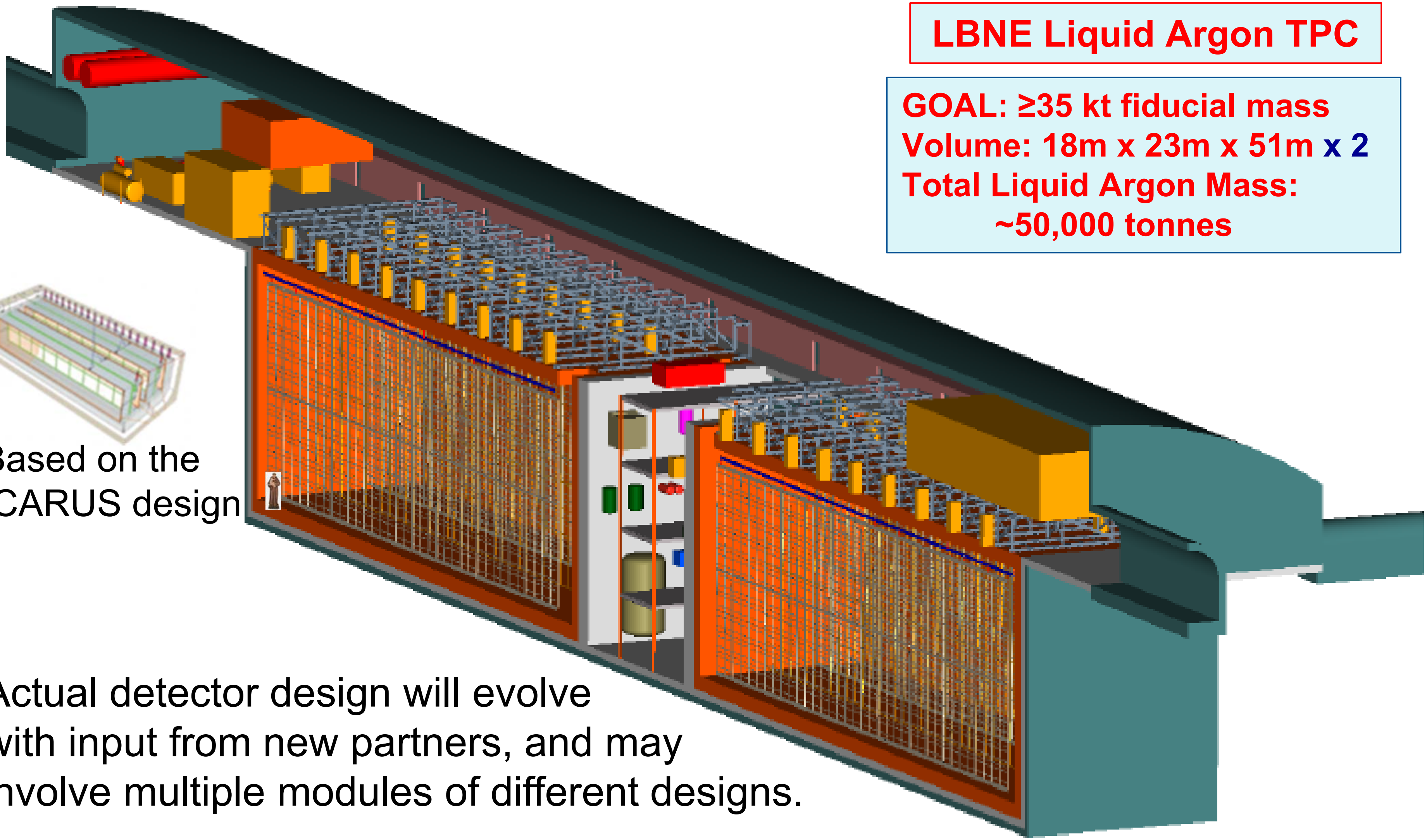
Near Neutrino Detector

- Proposed by collaborators from the Indian institutions
- High precision straw-tube tracker with embedded high-pressure argon gas targets
- 4π electromagnetic calorimeter and muon identification systems
- Large-aperture dipole magnet
- Considering addition of small LAr TPC or GAr TPC "active target"



- Open workshop on 28-29 July – all are invited.

Far Detector



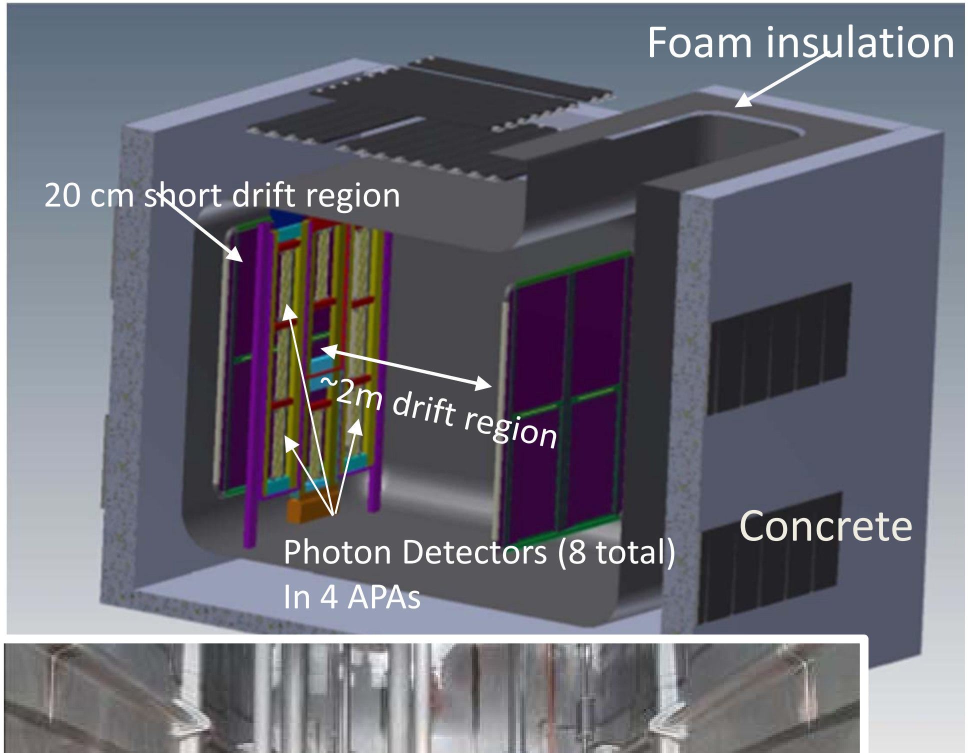
LBNE Liquid Argon TPC

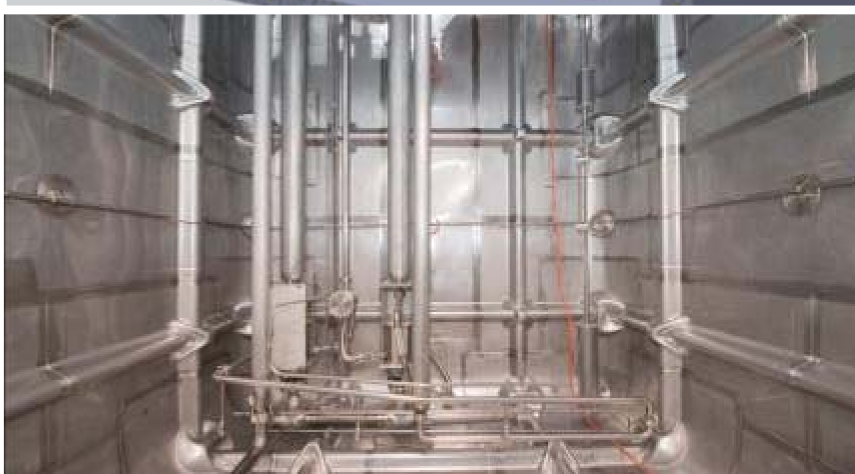
GOAL: ≥35 kt fiducial mass
Volume: 18m x 23m x 51m x 2
Total Liquid Argon Mass:
~50,000 tonnes

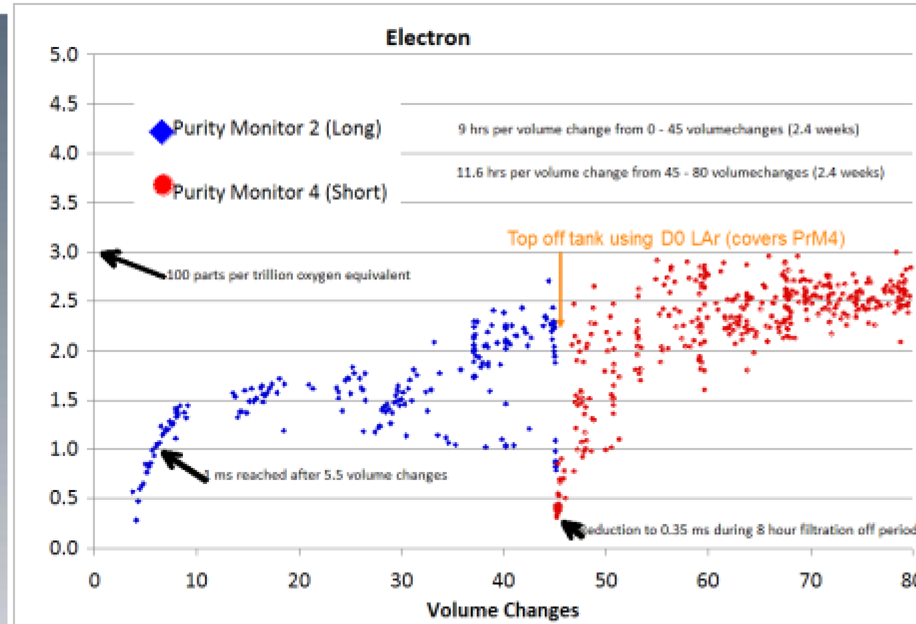
Based on the
ICARUS design

Actual detector design will evolve
with input from new partners, and may
involve multiple modules of different designs.

35 t Prototype Cryostat and Prototype TPC Detector



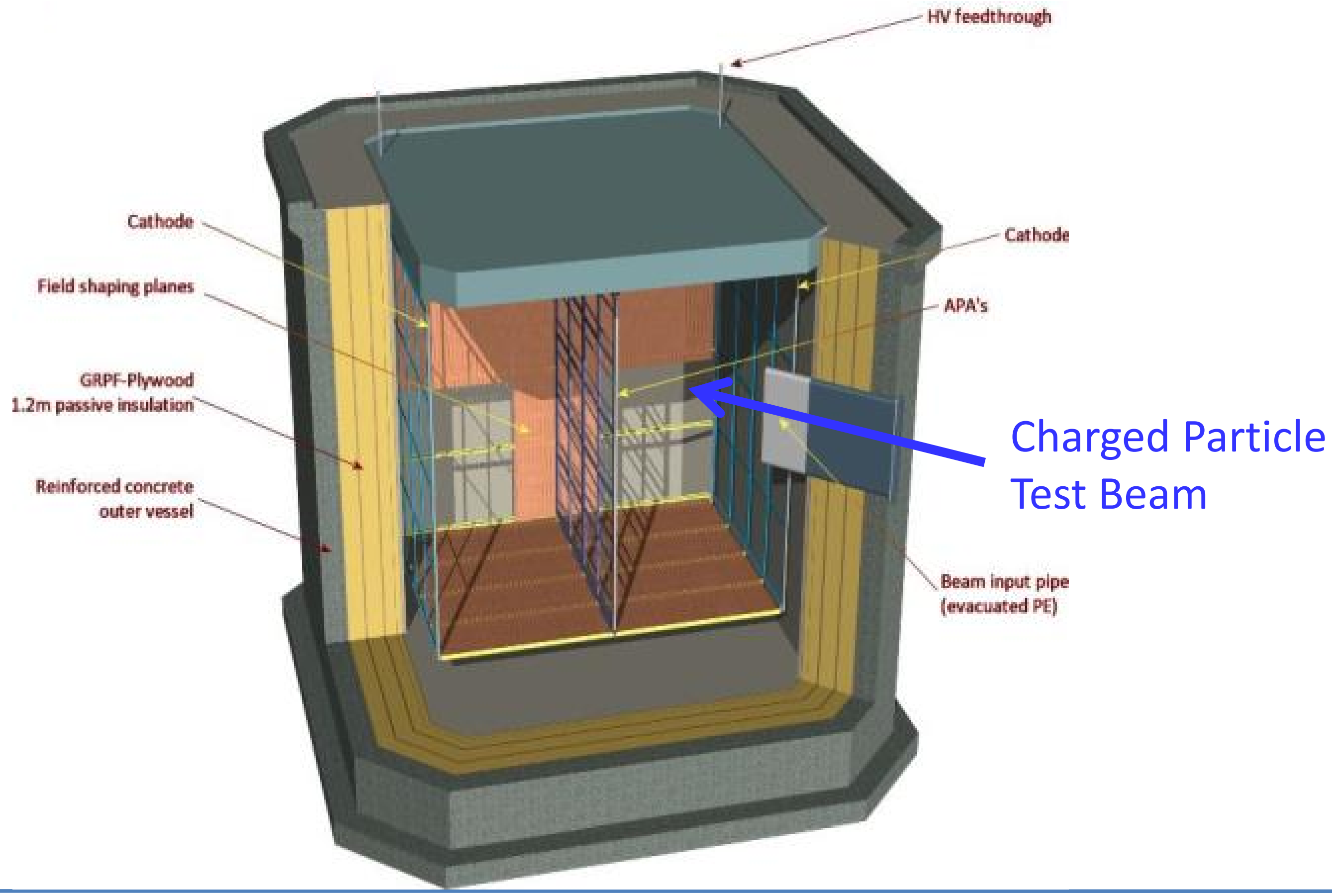




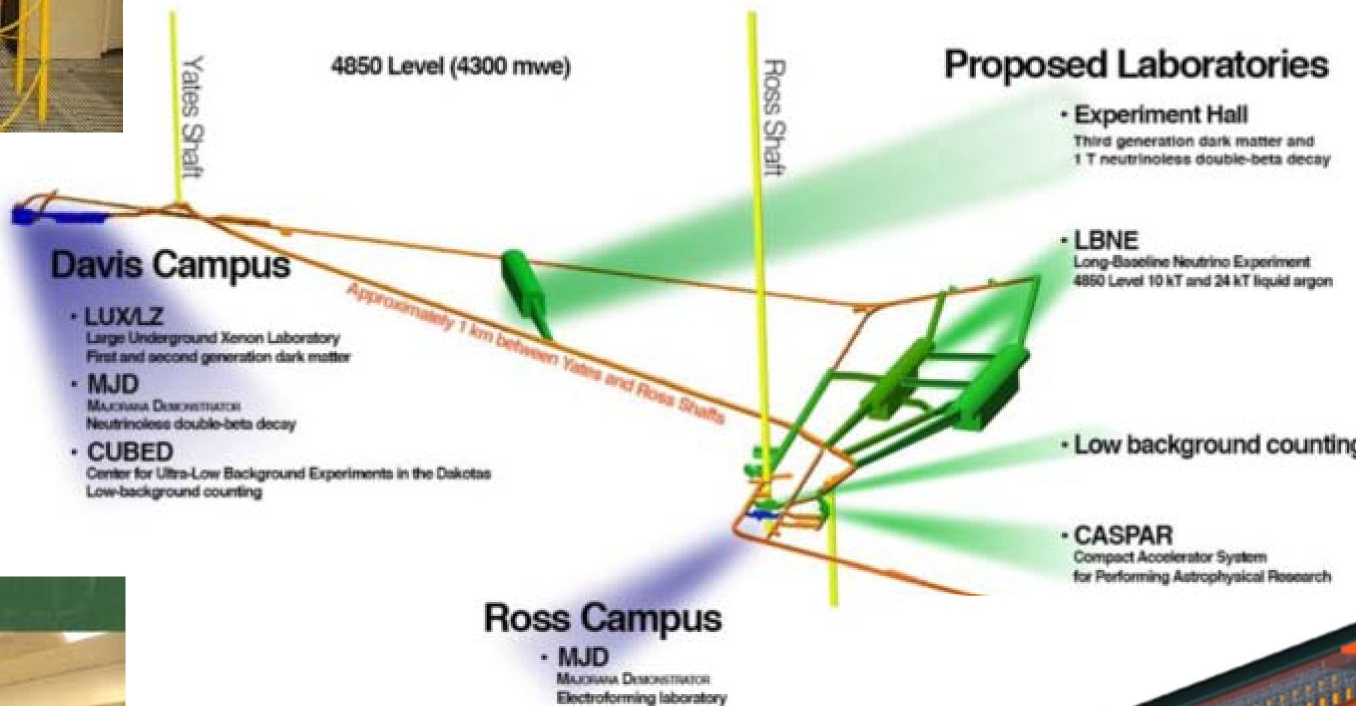
TPC Anode Plane

Full-Scale Prototype in LBNO-DEMO Cryostat

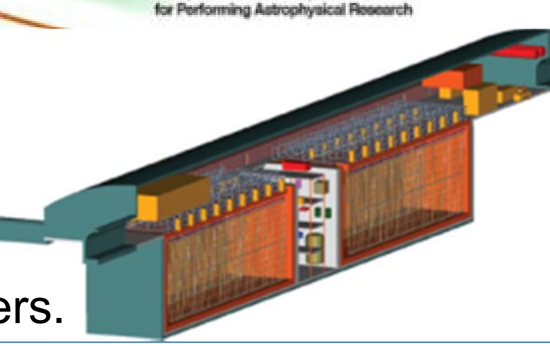
- Together with CERN and the LBNO Collaboration, we are developing a plan to test full-scale LBNE drift cell(s) in the 8x8x8 m^3 cryostat to be built at CERN as part of WA105.



Planned Location of LBNE Cavern(s)



Actual layout will follow from detector design(s) agreed upon with international partners.

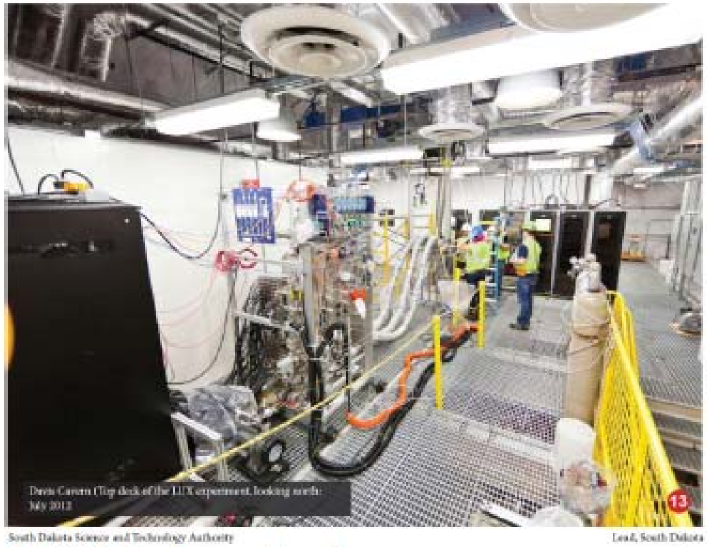


Sanford Underground Research Facility

Majorana (0νββ)

Entrance to Davis Cavern

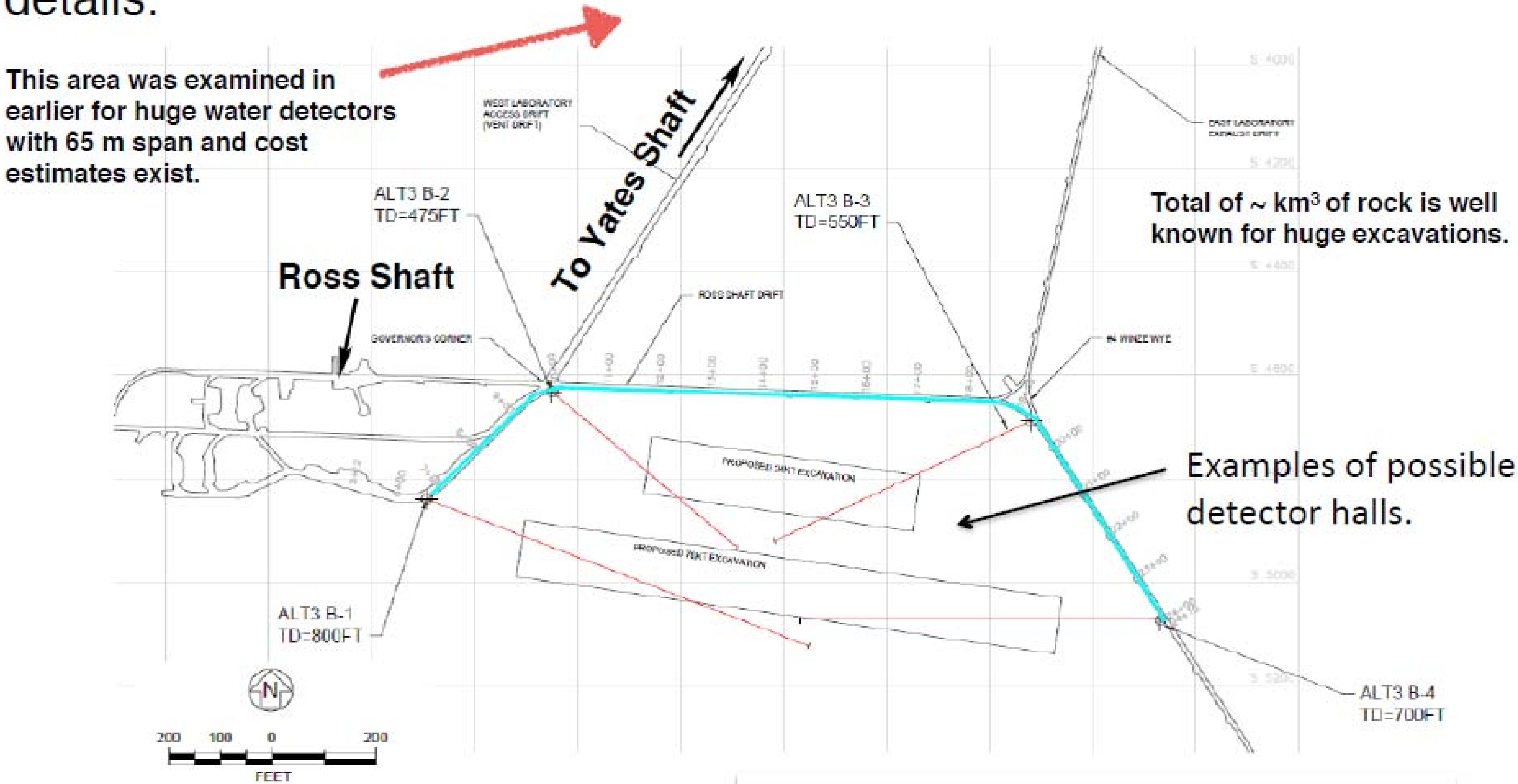
- Experimental Facility at 4300 MWE
- Two vertical access shafts for safety.
- Shaft refurbishment has been on-going and has reached 1700' level
- Total investment in underground infrastructure is >$100M.
- Facility donated to the State for science in perpetuity.



LUX (dark matter)

CF Far Site Geotech Program

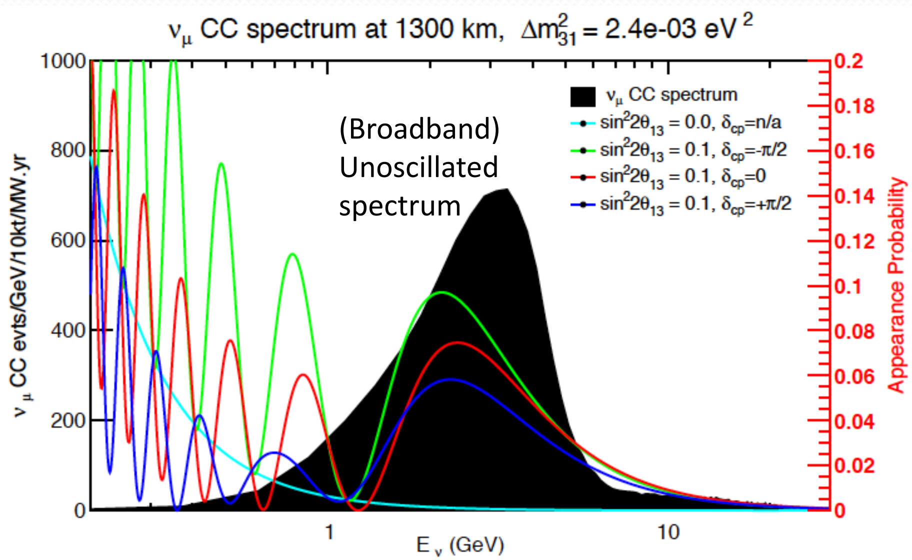
- General area where detector(s) could be placed is being explored.
- This drilling program was recently completed. The rock is known to be quite capable of handling large excavations, but report will contain details.

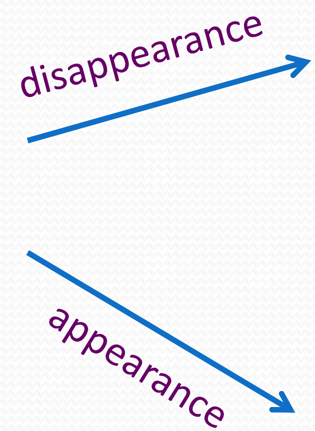


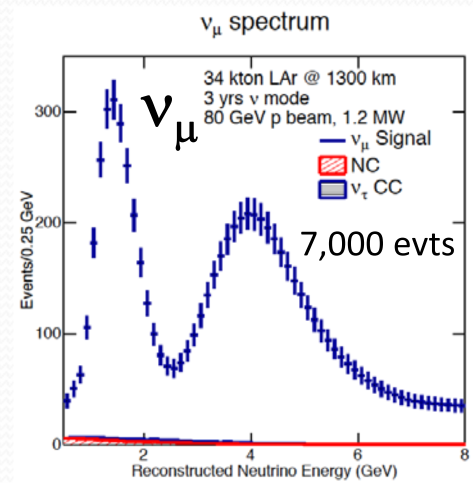
Experimental Strategy

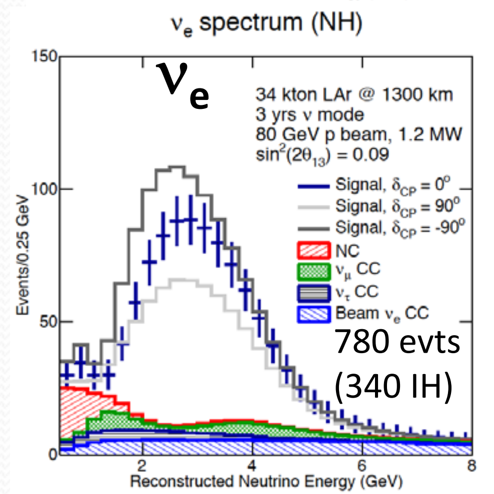
- A comprehensive experiment with sensitivity to CP asymmetry, mass ordering and spectral shape.
- Our experimental focus is on $\nu_\mu \rightarrow \nu_e$ and anti-$\nu_\mu \rightarrow$anti-ν_e with superb particle identification and energy resolution, as this channel is most suitable for current neutrino beam and detector technologies.
- The measured neutrino mixing parameters in the 3-flavor framework suggest that the CP asymmetry will be <30% (first max) and higher at lower energies and therefore >1000 events are needed.
- World-wide studies have concluded that beams with 1-2 MW of power at high energies and unprecedented large far detector fiducial mass is needed regardless of baseline to achieve above statistics.
- A baseline of >1000 km and a broad-band beam are needed to satisfy these conditions.
- Detector must have sufficient overburden to allow sensitivity to nucleon decay and supernova.

Essential Experimental Technique







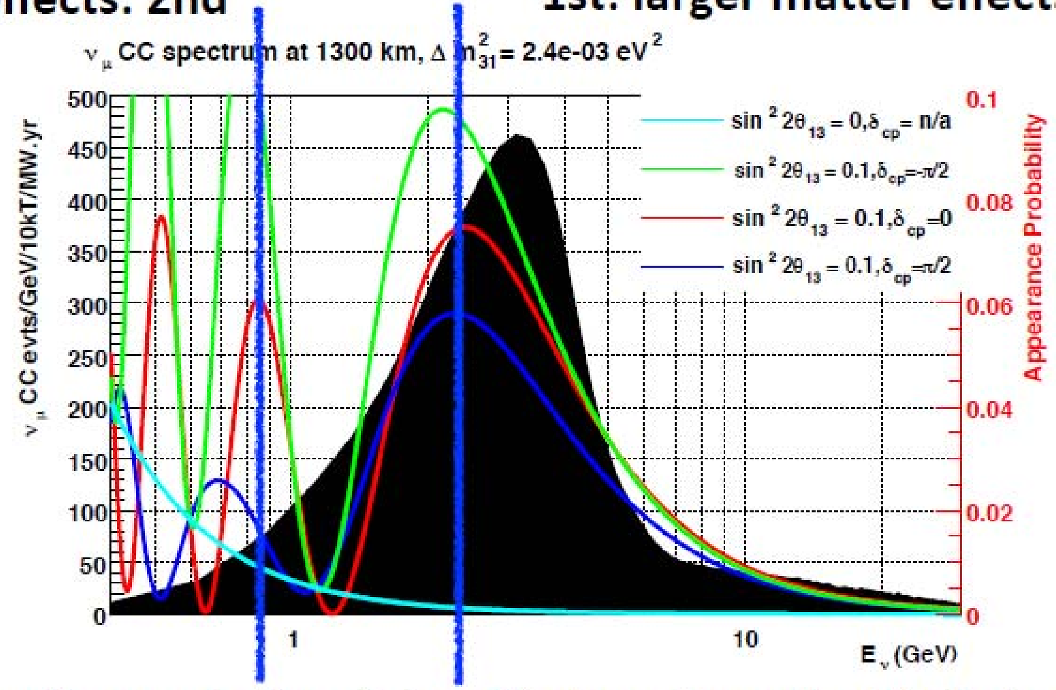


- Produce a pure ν_μ muon-neutrino beam with energy spectrum matched to oscillation pattern at the chosen distance
- Measure spectrum of ν_μ and ν_e at a distant detector
- **LBNE is a near optimal choice of beam and distance for sensitivity to CP violation, CP phase, neutrino mass hierarchy and other oscillation parameters *in same experiment***

Neutrino Asymmetries

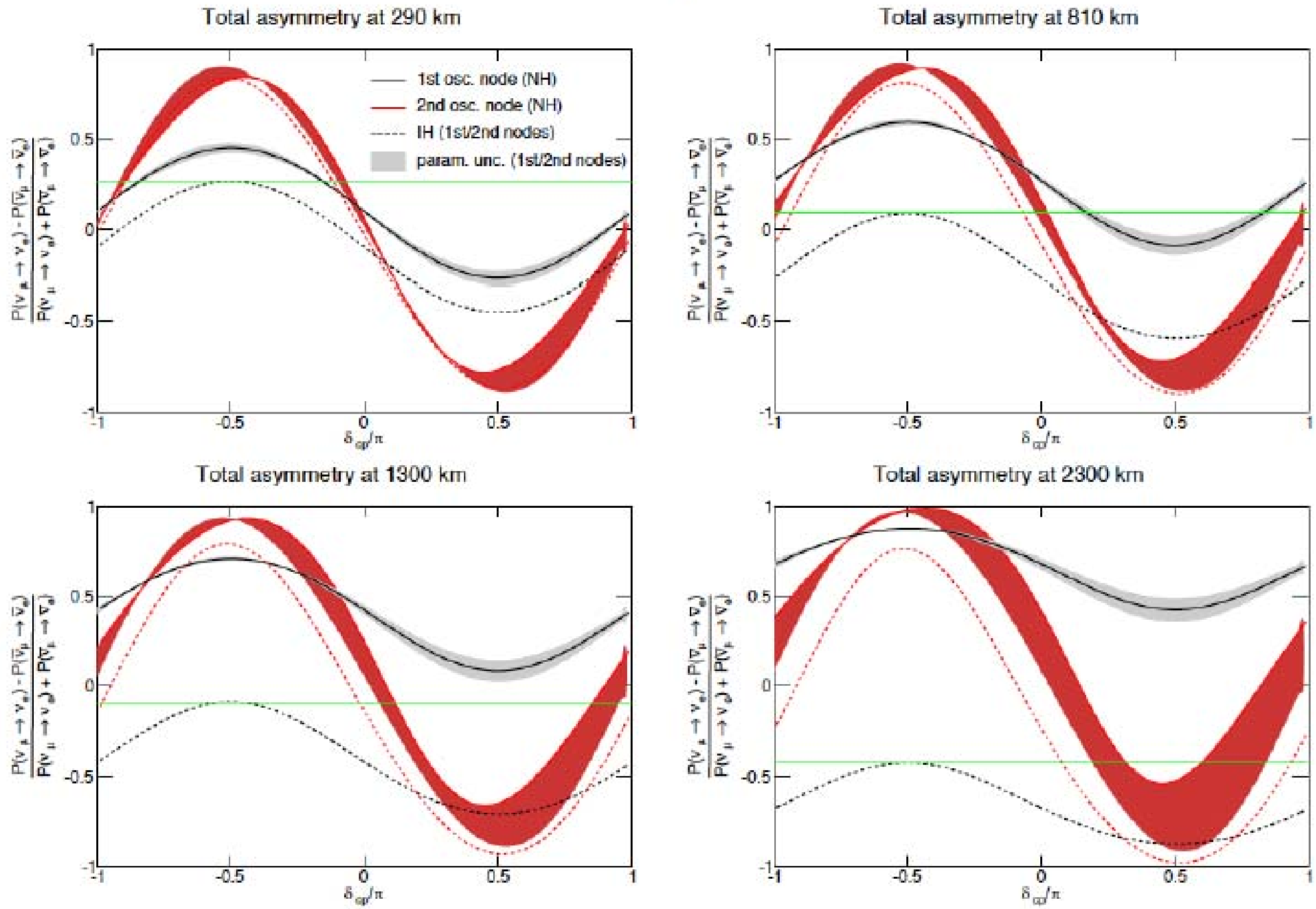
Larger CP effects: 2nd

1st: larger matter effects



- At 1300 km the events from 1st and 2nd maximum (and in-between) measure the asymmetries from both matter effects and CP.
- With sufficient statistics all ambiguities can be resolved. We need ~1000-2000 events with good energy resolution and particle ID.
- The requirement for statistics and low systematics is difficult and is required of any reasonable design.
- Event rate at 2nd is limited by pion decay kinematics and X-section indep. baseline

Baseline optimization

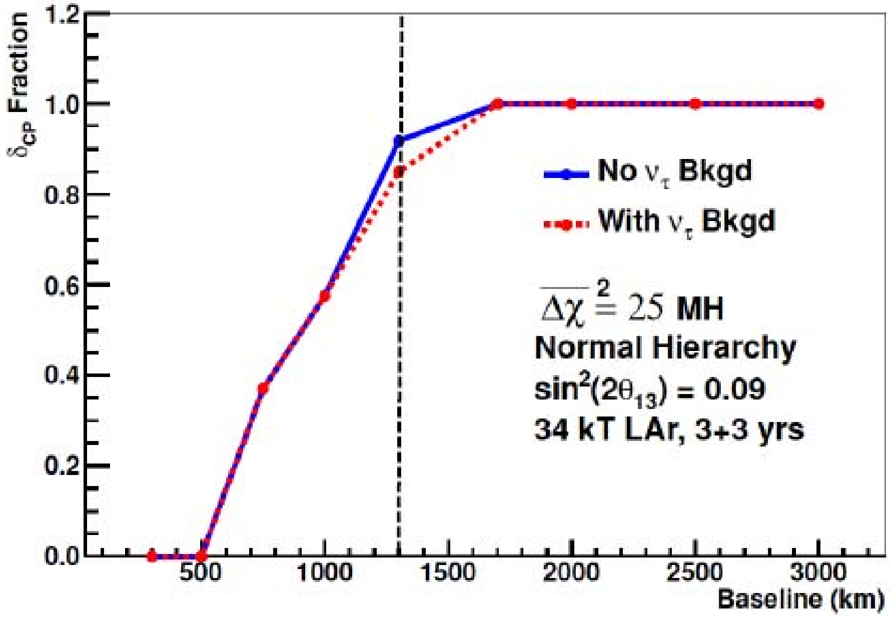


- >1000 km is needed to break the degeneracy between CP and matter effects. Statistics at both nodes improve sensitivity.
- At >2000 km suppression of events in one polarity is very high: nu/anu asymmetry measurement a challenge.

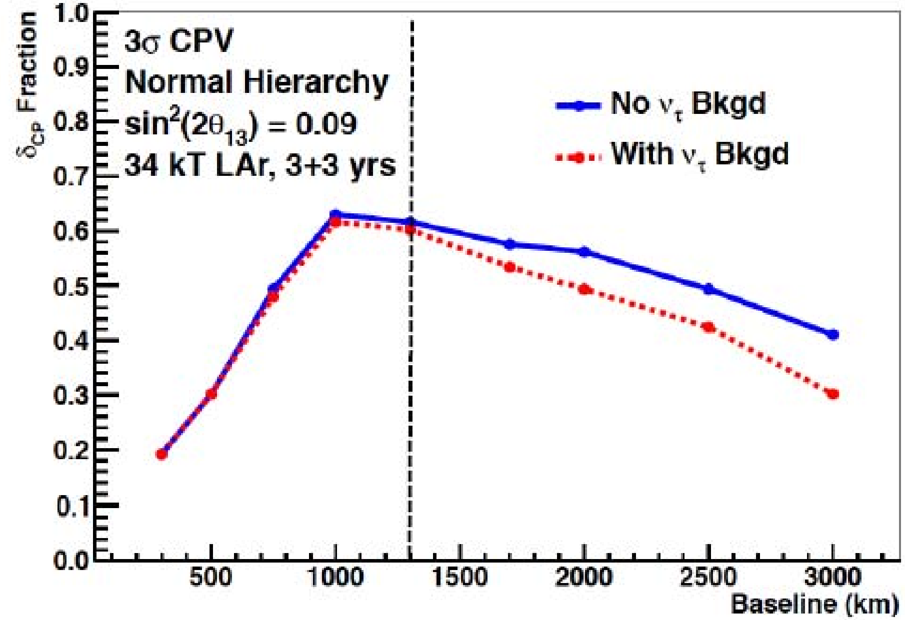
arXiv:1311.0212

Baseline Optimization

Mass Hierarchy



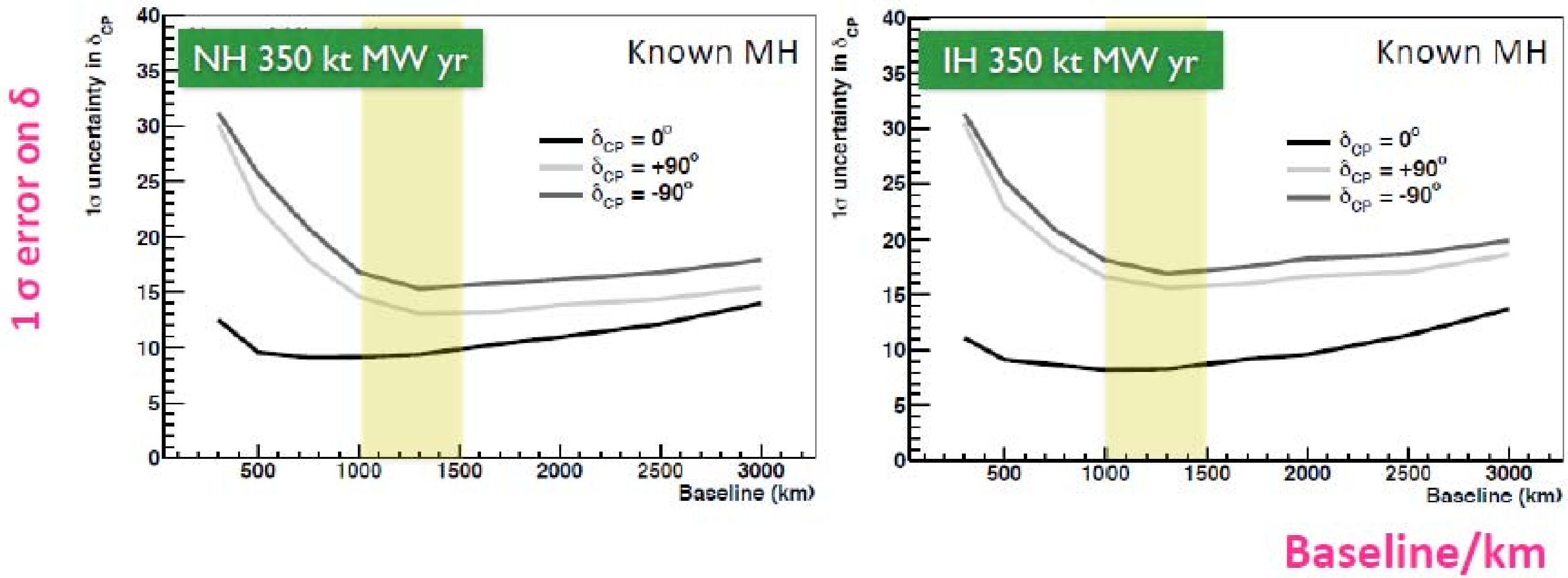
CP Violation



- **Based on simulations for Fermilab NuMI 120-GeV, 1.2 MW proton beam**
  - Target-1st horn distance tuned to cover 1st oscillation node + part of 2nd
  - Decay pipe length tuned (280-580 m)
  - For short baselines (<1000 km) use off-axis beam simulation to produce most flux
- **Baselines 1000-1300 km near optimal**

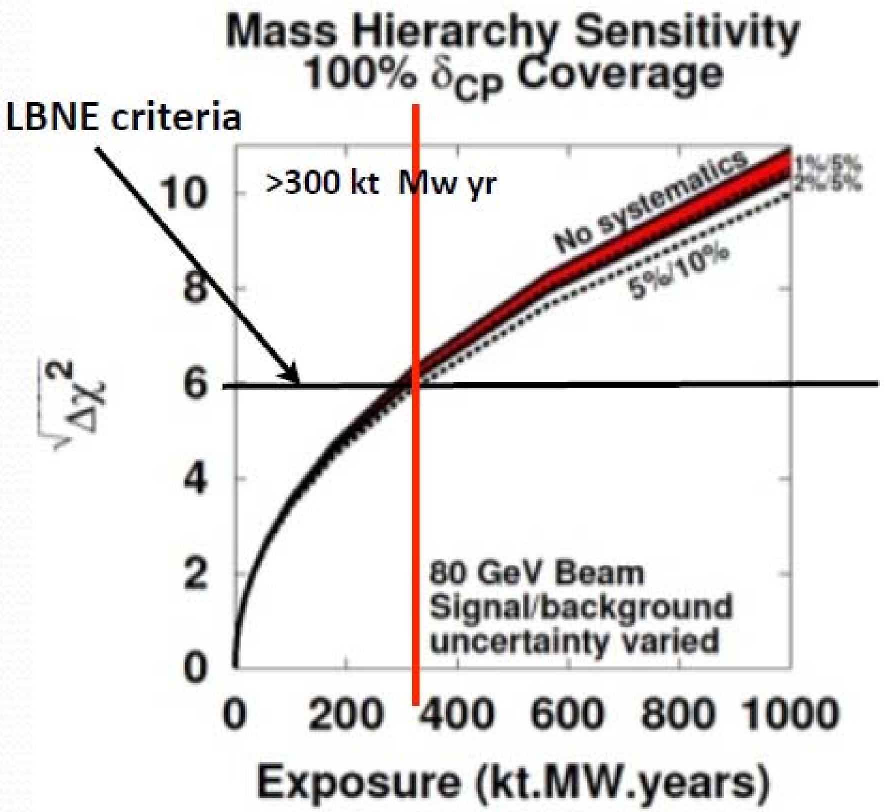
Further optimization of the beam will improve these results but not change baseline conclusions.

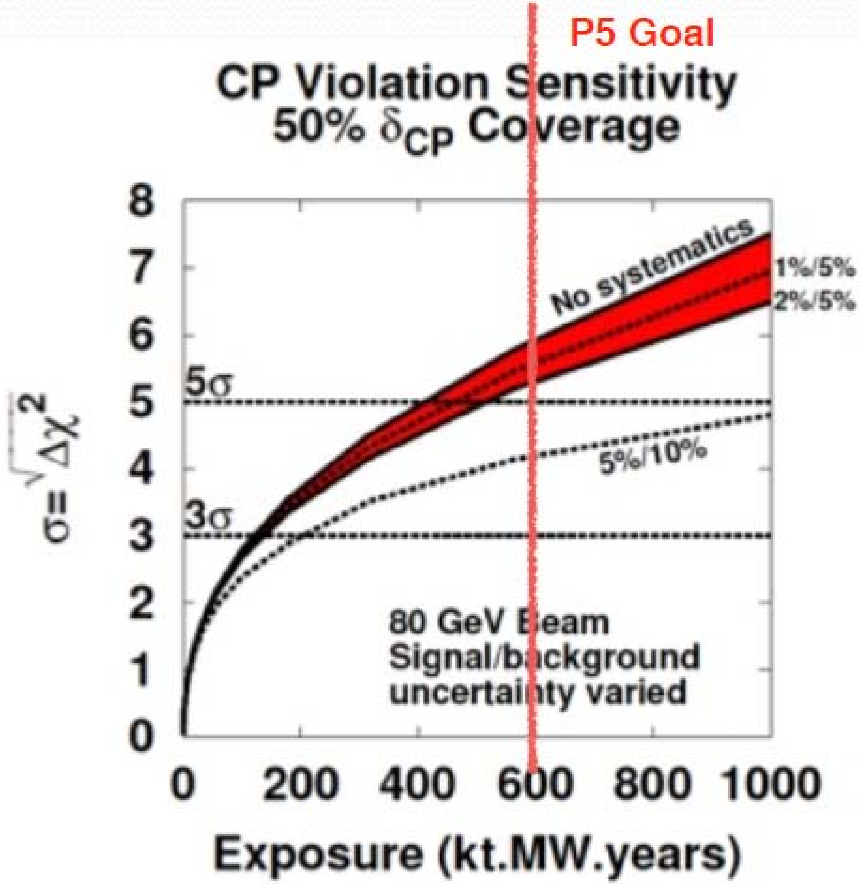
Baseline Optimization



- The phase resolutions calculated as a function of exposure as well as baseline length. An optimum is obtained for phase resolution when there is sufficient shape information and statistics.

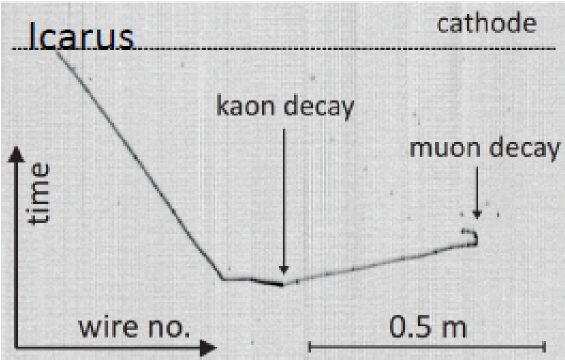
Impact of Normalization Uncertainties





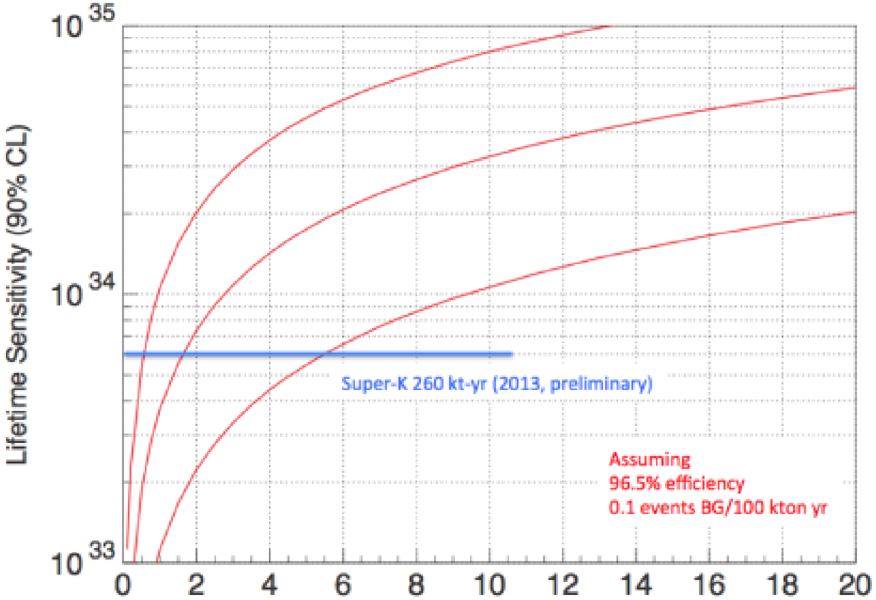
- <3% errors appear realistic with recent progress.
- The systematic precision is required to be better than the expected statistics at each stage of the experiment. High precision is needed after 200kt*MW*yr.
- MH relatively insensitive to systematics; but further study needed.
- MINOS appearance result has achieved better than 5%/5% systematics.

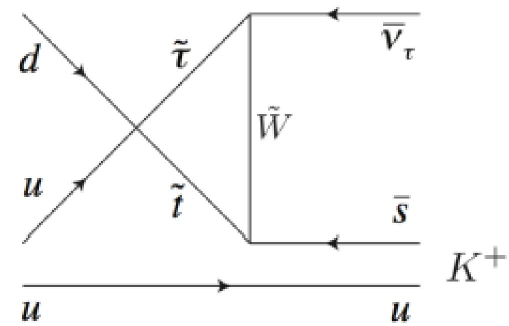
Proton Decay Search with a LAr TPC Detector



Nucleon decays

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





Kaon modes in LAr with high efficiency and low background, leading to high s/b.

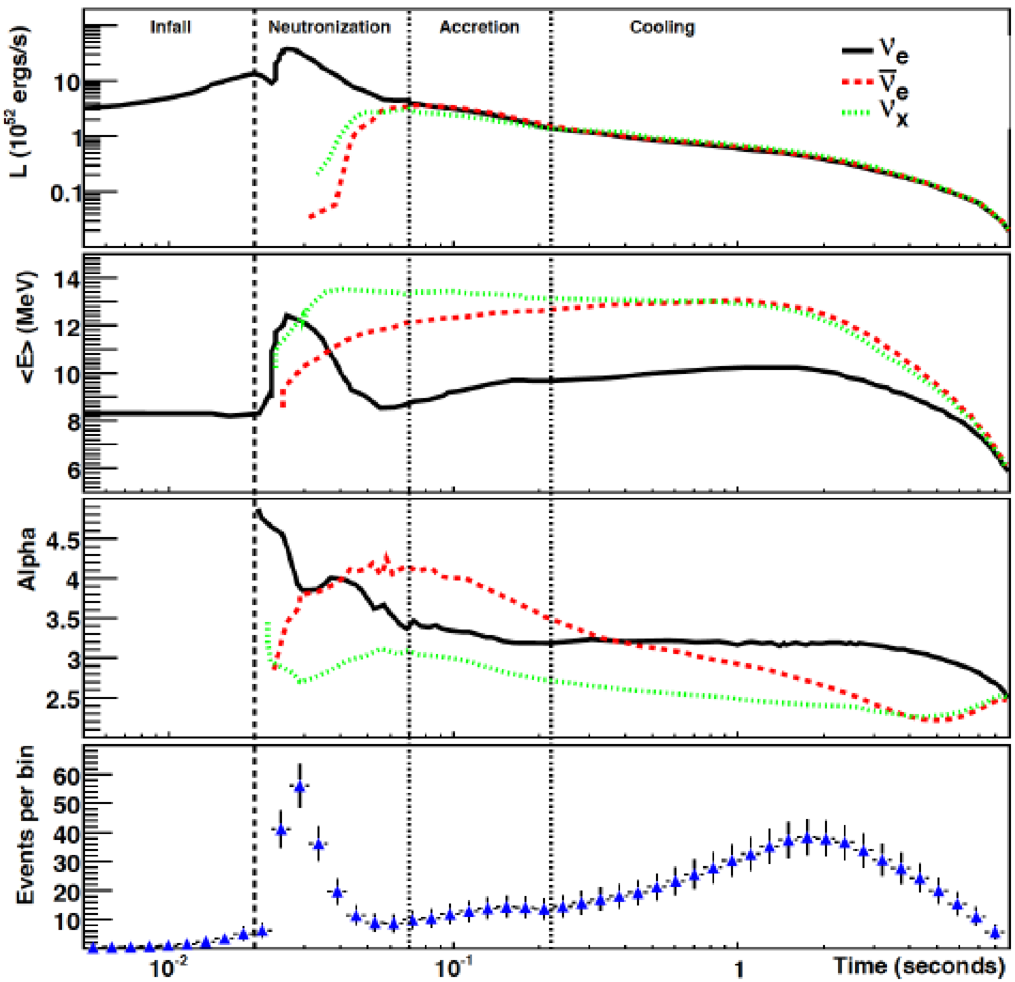
Example: SUSY models

Examination in 2008 concluded that 4850 ft depth is sufficient

Supernova burst

$$e^- + p \rightarrow n + \nu_e$$

LAr mainly sensitive to electron neutrinos.
(water is sensitive to anti-electron-neutrinos)



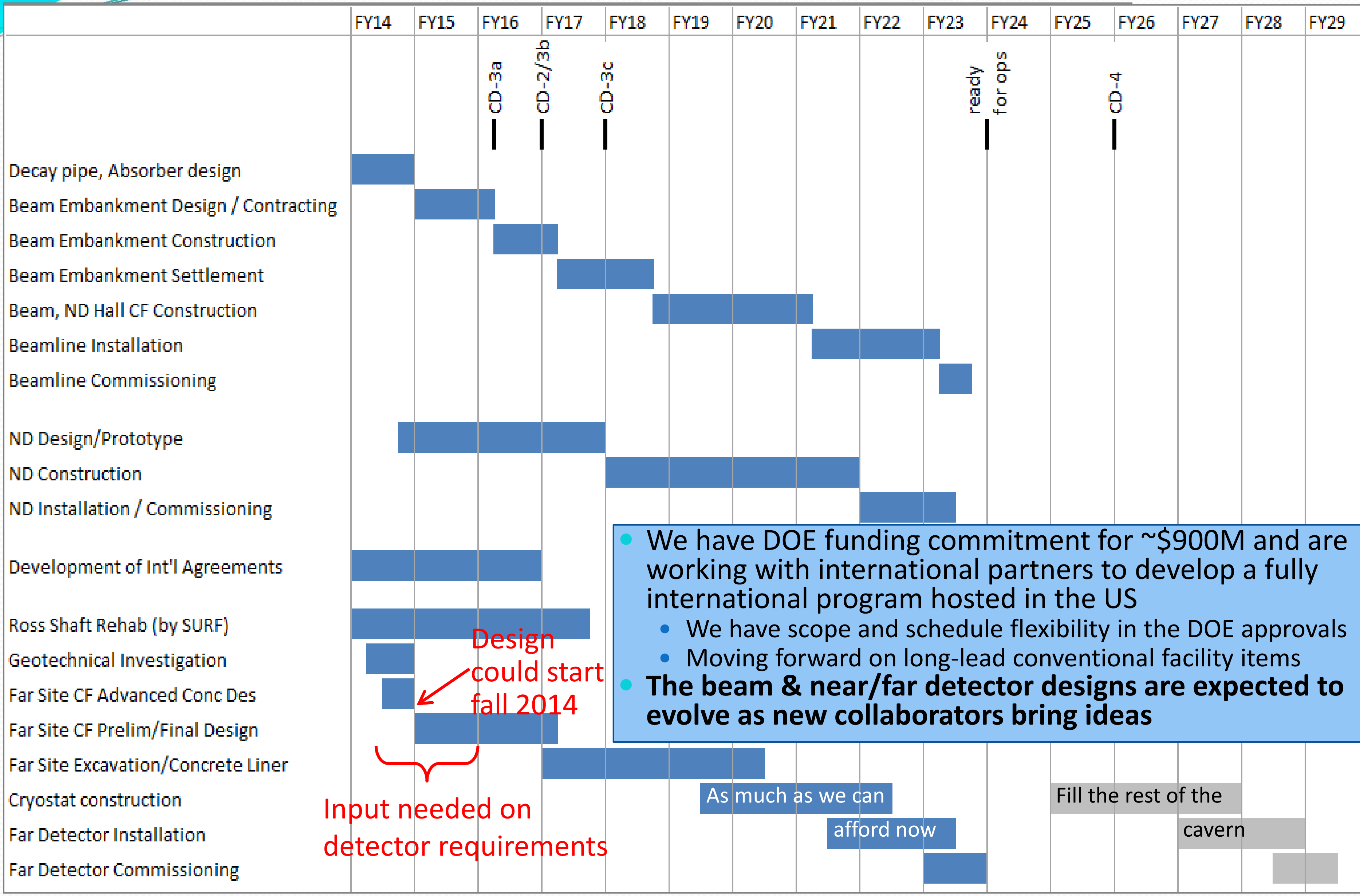
A large theory effort is underway to understand neutrino related dynamics of the supernova. Both oscillations, mass, and self-interactions have large effects on observables.

e.g. mass hierarchy could have very distinct effects on the spectrum.

Precision astrophysics and cosmology needs precise laboratory data on neutrinos so that correlations can be resolved.

Estimated rate: ~3000 evts @ 10 kpc for 34 kt LAr TPC

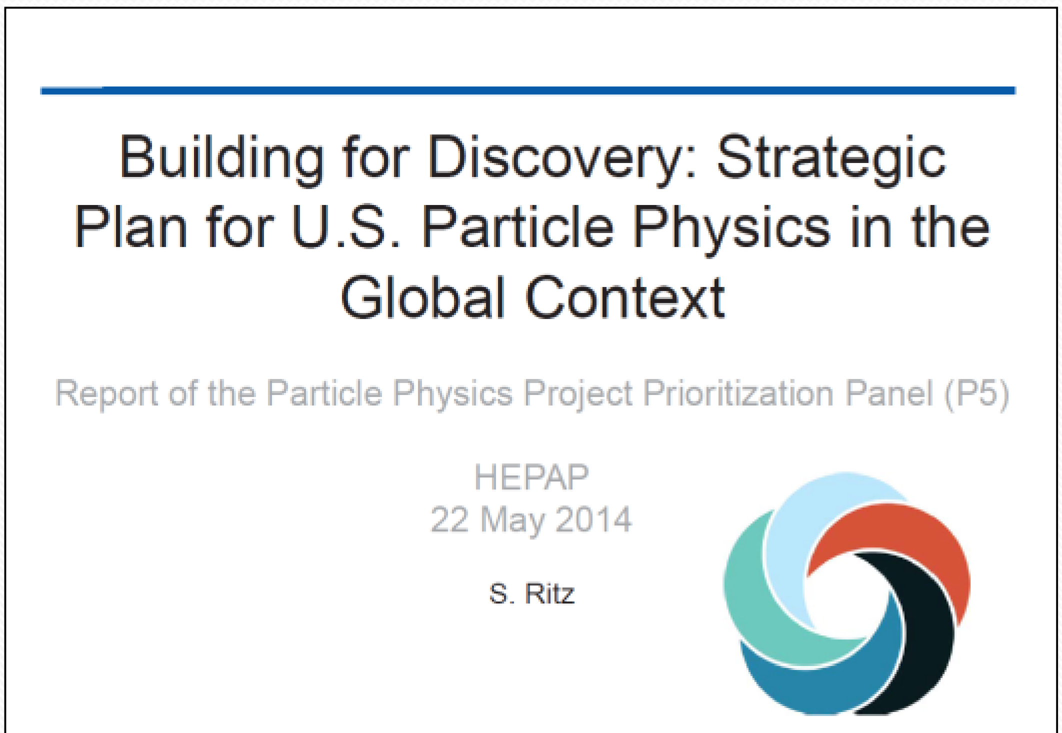
Technically Limited Schedule for International LBNE



- We have DOE funding commitment for ~$900M and are working with international partners to develop a fully international program hosted in the US
  - We have scope and schedule flexibility in the DOE approvals
  - Moving forward on long-lead conventional facility items
- **The beam & near/far detector designs are expected to evolve as new collaborators bring ideas**

Particle Physics Project Prioritization Panel (P5)

- A sub-panel of the High Energy Physics Advisory Panel (HEPAP)
  - HEPAP is official mechanism for community input to the US Department of Energy Office of High Energy Physics
  - P5 charged to advise on project priorities for the next 10 years in a 20 year context



Slides: *http://science.energy.gov/~/media/hep/hepap/pdf/May%202014/P5MayHEPAP-Ritz.pdf*
P5 Report: *http://science.energy.gov/~/media/hep/hepap/pdf/May%202014/FINAL_DRAFT2_P5Report_WEB_052114.pdf*

Science Drivers

- We distilled the eleven groups of physics questions from Snowmass* into five compelling lines of inquiry that show great promise for discovery over the next 10 to 20 years.
- The Science Drivers:
  - Use the Higgs boson as a new tool for discovery
  - **Pursue the physics associated with neutrino mass**
  - Identify the new physics of dark matter
  - Understand cosmic acceleration: dark energy and inflation
  - Explore the unknown: new particles, interactions, and physical principles
- The Drivers are deliberately not prioritized because they are intertwined, probably more deeply than is currently understood.
- A selected set of different experimental approaches that reinforce each other is required. Projects are prioritized.
- The vision for addressing each of the Drivers using a selected set of experiments – their approximate timescales and how they fit together – is given in the report.

* See Appendix D and http://www.slac.stanford.edu/econf/C1307292/

Summary (3/5)

Several significant changes in direction are recommended:

- Increase the fraction of the budget devoted to construction of new facilities.
- Reformulate the long-baseline neutrino program as an internationally designed, coordinated, and funded program with Fermilab as host.
- Redirect former Project-X activities and some existing accelerator R&D temporarily to improvements of the Fermilab accelerator complex that will provide proton beams with power greater than one megawatt by the time of first operation of the new long-baseline neutrino facility.
- Increase the planned investment in second-generation dark matter direct detection experiments.
- Increase particle physics funding of CMB research and projects in the context of continued multiagency partnerships.
- Realign activities in accelerator R&D with the P5 strategic plan. Redirect muon collider R&D and consult with international partners on the early termination of the MICE muon cooling R&D facility.

Project-specific Recommendations

#12-15:

Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.

Project-specific Recommendations

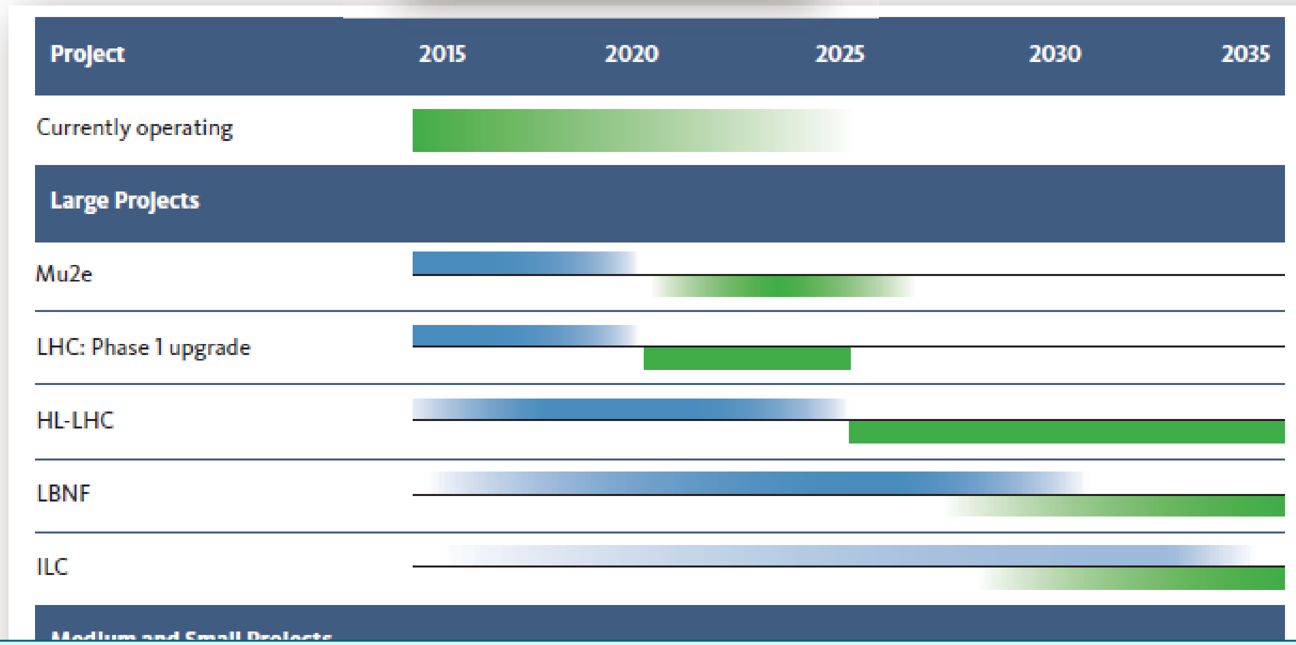
#12-15:

Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

- **LBNE leadership is working with DOE OHEP and Fermilab Director to develop a fully international collaboration at all levels**
  - There will be a series of meetings in the coming months with all “stakeholders” – 1st is “International Meeting on Large Neutrino Infrastructure,” Paris 23-24 June
- **Minimum requirements: 120 kt*MW*yr by 2035 ⇒ 10-12 kt undergrounds w/ 1.2 MW beam**
  - The report recommends to plan for a cavern to accommodate 40 kt fiducial mass and set as a goal 600 kt*MW*yr exposure

Figure 1
Construction and Physics Timeline



- **Timeline indicates how P5 priorities could fit within the budget scenarios in the panel charge**
- **Actual timeline will depend on many factors**
  - Enacted budgets, other factors and constraints within DOE, ***interests and resources of international partners***
- **P5 report was eagerly awaited by the international community, which can now organize to produce an optimized and sustainable global program for High Energy Physics**

(Large [>$200M] in the upper section, Medium and Small [<$200M] in the lower section), shown for Scenario B. The LHC: Phase 1 upgrade is a Medium project, but shown next to the HL-LHC for context. The figure does not show the suite of small experiments that will be built and produce new results regularly.

Meetings to plan the International Long-Baseline Facility

- International Meeting on Large Neutrino Infrastructures, 23-24 June, Paris
- Followup meeting of funding agencies, 14 July, Fermilab
- “Summit” meeting of neutrino scientific leaders, 21-22 July, Fermilab
- LBNE open workshop on Near Detector Design, 28-29 July, Fermilab … *all are welcome to participate*.
- LBNE Collaboration meeting, 30 July – 1 Aug, Fermilab *Everyone interested in this program is invited to participate.*

Summary and Conclusions

- LBNE will perform far-reaching measurements of CP violation, mass hierarchy, non-standard interactions, proton decay and supernova burst neutrinos from intra-galactic distances
- Building on substantial investments already made, an international partnership will deliver:
  - A high-power neutrino beam
  - A high-resolution near detector system
  - A far detector of ≥10 kt fiducial mass in a cavern that can accommodate a ≥ 35 kt detector
- A series of meetings with government agencies, (inter)national laboratories, and researchers is being organized to fully internationalize the design, funding, construction and operation of the facility
- **We hope the world-wide neutrino community will come together to realize this exciting program!**