Long & Very Long Baseline Neutrino Oscillation Studies at Intense Proton Sources

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Outline

- A highly selective neutrino primer
- Oscillations (what & why we believe)
  - > LSND saved for a later talk
- Neutrino Sources (Now & Future)
  - > Beams – It's just the beam power…
  - > Current concepts & proposals for next decade and beyond
- What will we be studying in 10 years?
  - > Long Baseline & Very Long Baseline
  - > Where an EIC proton injector fits into this future

Cliffs Notes on Neutrinos

- There are only 3 “light” active neutrino flavors (from Z width)
  - > Electron, muon, & tau types
  - > Cosmological mass limits imply $\sum m_{\nu} < 0.7$ eV (WMAP + Ly-a)
  - > Oscillations imply at least one neutrino great than 0.04 eV (more later)
- Basic types of interactions => basic signatures
  - > Cross sections crudely linear with energy
  - > Charged current (CC)
    - The produced lepton tags the neutrino type
    - Has an energy threshold
    - Neutrino’s energy converted to “visible” energy
  - > Neutral current (NC)
    - No information about the neutrino type
    - No energy threshold
    - Some energy carried away by an out-going neutrino
  - > Electron scattering (ES)

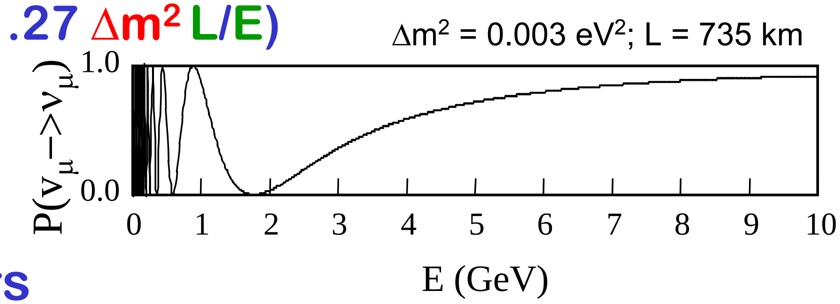
Oscillation Formalism

- With 2 neutrino basis (weak force & mass) there can be flavor oscillations $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$
- The probability that a neutrino (e.g. ν_μ) will look like another variety (e.g. ν_τ) will be

$$P(\nu_\mu \rightarrow \nu_\tau; t) = |\langle \nu_\tau | \nu_\mu(t) \rangle|^2$$

- A 2-component unitary admixture characterized by θ results in

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \, \sin^2(1.27 \, \Delta m^2 \, L/E)$$



- Experimental parameter

L (km) /E (GeV)

- Oscillation (physics) parameters

$\sin^2 2\theta$ (mixing angle)

$\Delta m^2 = m_\tau^2 - m_\mu^2$ (mass squared difference, eV^2)

3-Flavor Oscillation Formalism

- In 3 generations, the mixing is given by $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

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

  > Where, $s_{jk} \equiv \sin\theta_{jk}$ and $c_{jk} \equiv \cos\theta_{jk}$

  > There are 3 Δm^2's (only 2 are independent)

$$\Delta m^2_{12} = m^2_1 - m^2_2 \quad , \quad \Delta m^2_{23} = m^2_2 - m^2_3 \quad , \quad \Delta m^2_{31} = m^2_3 - m^2_1$$

  > 2 independent signs of the mass differences

  > There are also 3 angles and 1 CP violating phase

- Predicts: CPV, sub-dominate oscillations (all 3 flavors)
- Matter effects (MSW)

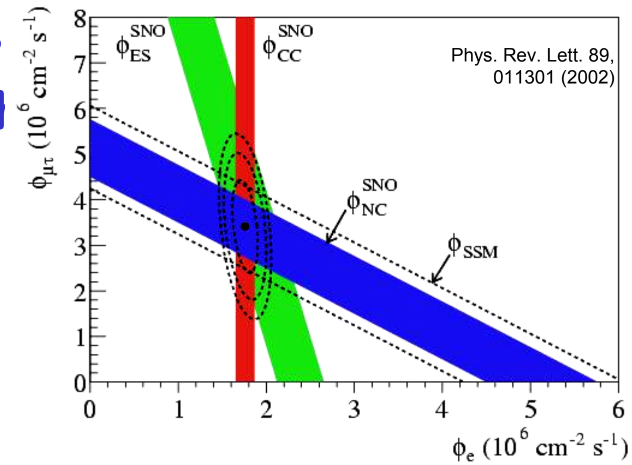
  > Electron neutrinos see a different potential due to electrons in matter

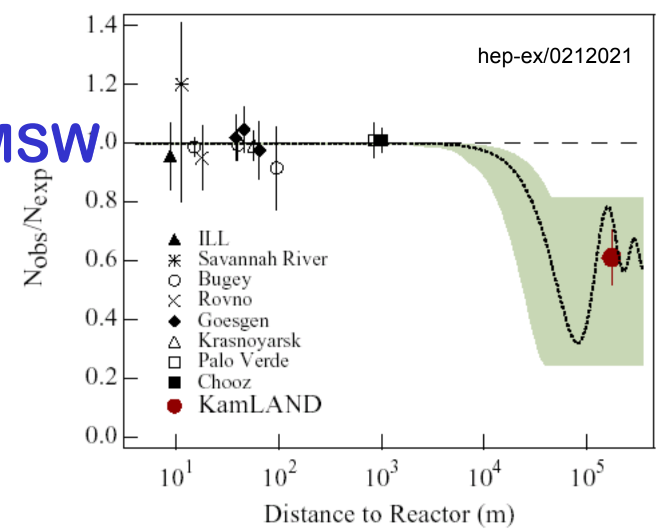
How do we know what we know?

- In the past decades there have been many oscillation experiments in many forms
- Neutrino sources
  - > Reactor neutrinos
  - > Solar neutrinos
  - > Supernovae
  - > Atmospheric neutrinos (cosmic rays)
  - > Heavy elements concentrated in the Earth’s core
  - > Accelerator neutrinos
- Luckily we are converging to just a few important facts…

Solar Neutrinos: Case Closed

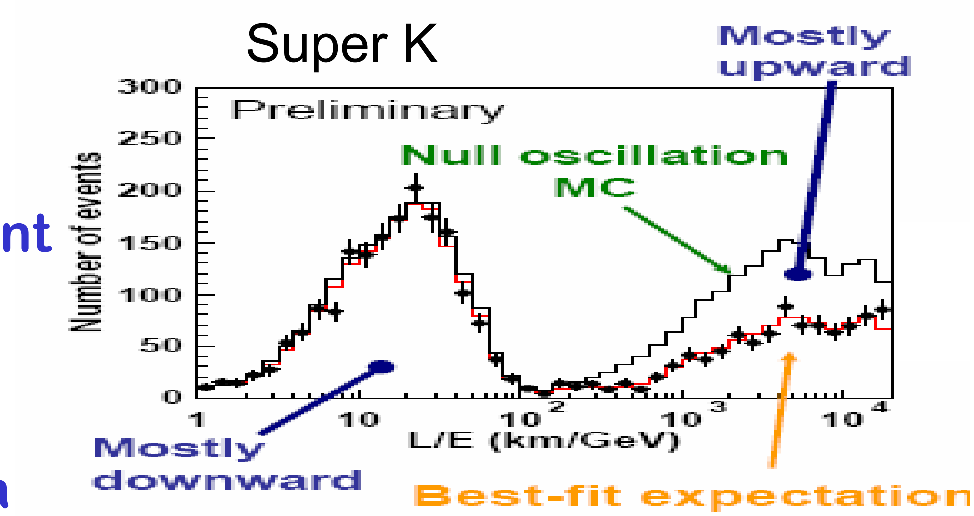
- Sun emits neutrinos while converting H to He
  - > The overall neutrino production rate is well known based on the amount of ligl emitted by the sun
  - > There are too few electron neutrinos; seen by a number of experiments
  - > From SNO's NC sample we know the overall solar flux is bang on
  - > Looks like $\nu_e \Rightarrow \nu_{active}$ oscillations w/MSW
- KamLand, a ~100 km baseline reactor experiment, confirms
- A very consistent picture

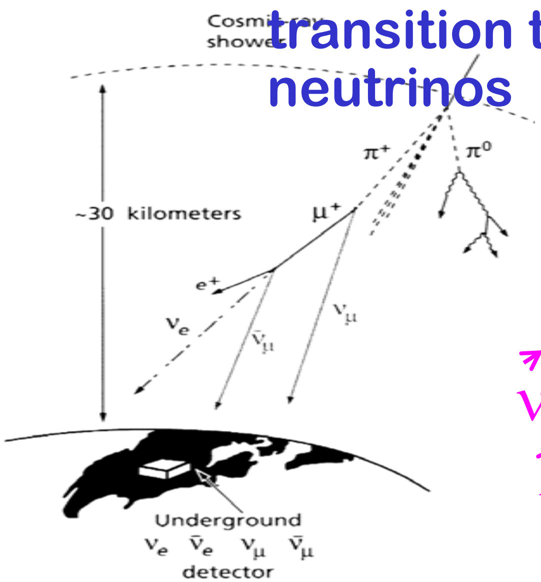


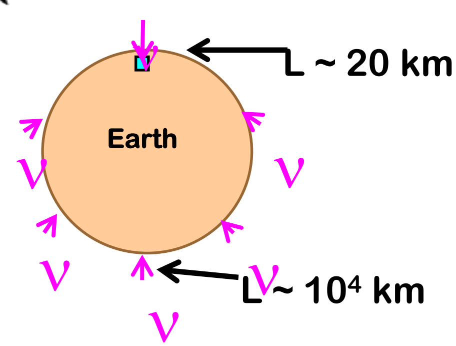


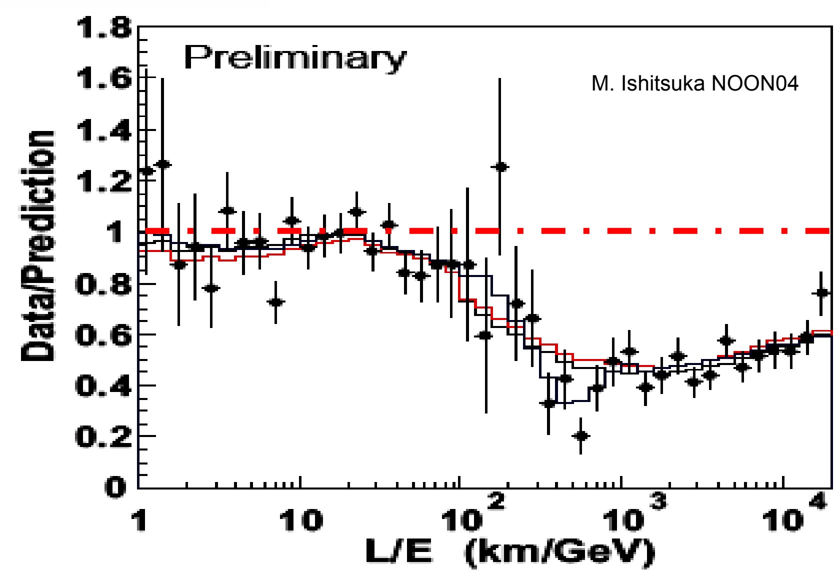
Atmospheric Neutrinos

- Consistent results
  - > Super K results are the standard; other experiments are consistent
  - > Electrons show no effect
    - Reactors give the best limits
  - > Matter effects tell us it's a transition to normal neutrinos



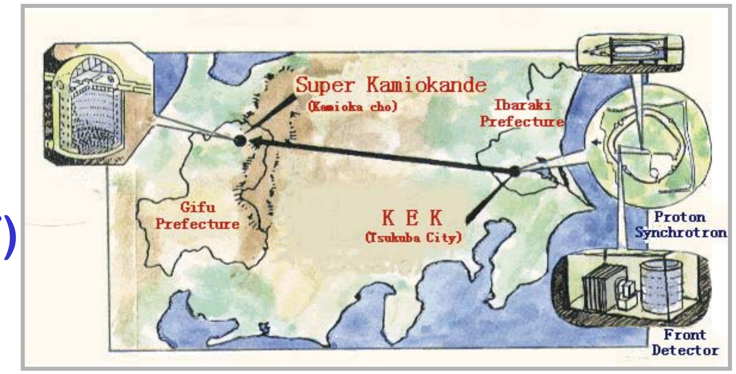


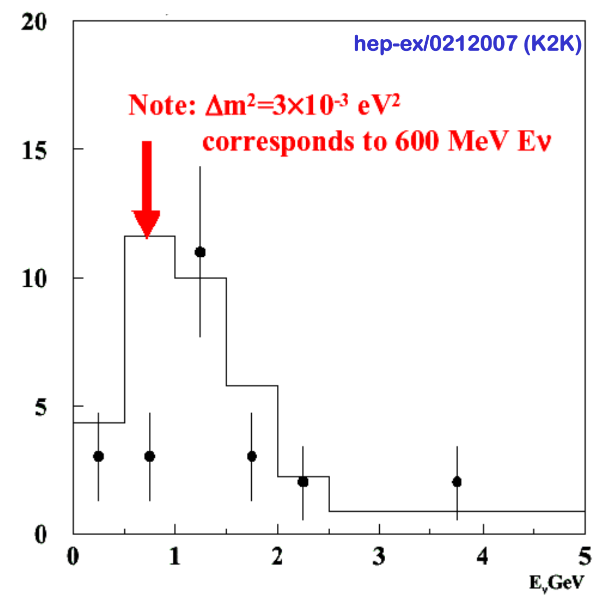




K2K Experiment
Man-Made Neutrinos

- Neutrinos from KEK to SuperK
  - > P_p = 12 GeV
  - > Goal of 10^{20} protons on target (POT)
  - > 5 kW beam power
  - > Baseline of 250 km
  - > Running since 1999
  - > 50 kT detector
- They see 44 events
  - > Based on near detector extrapolations, they expected 64 ± 6 events
    without oscillations
- Results are consistent with atmospheric data but not yet statistically compelling





The Next 5 Years

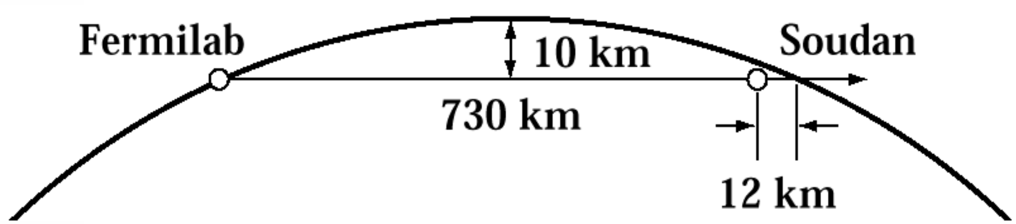
- **The current generation of oscillation experiments are designed to**
  - > Confirm atmospheric results with accelerator ν's (K2K)
  - > Resolve sterile neutrino situation (MiniBooNE; more later)
  - > Demonstrate oscillatory behavior of ν_μ's (MINOS)
  - > Refine the solar region (KamLAND)
  - > Demonstrate explicitly $\nu_\mu \rightarrow \nu_\tau$ oscillation mode by detecting ν_τ appearance (OPERA)
  - > Precise (~10%) measurement of ATM parameters (MINOS)
  - > Improve limits on $\nu_\mu \rightarrow \nu_e$ subdominant oscillation mode, or detect it (MINOS, ICARUS)

Long Baseline Example: MINOS Detectors & NuMI Beam

A 2-detector long-baseline neutrino oscillation experiment in a beam from Fermilab's Main Injector

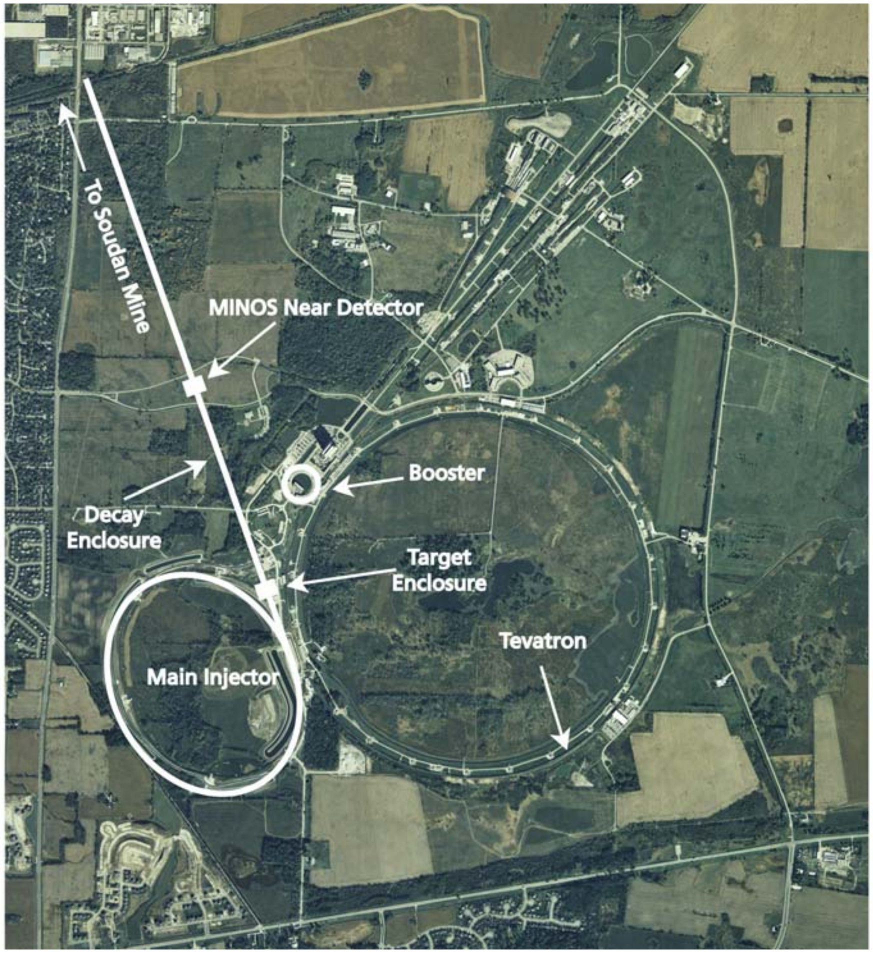
Near Detector: 980 tons

Far Detector: 5400 tons



On the Fermilab Site

- 120 GeV Main Injector's (MI) main job is stacking antiprotons and as an injector in the Tevatron
- Most bunches are not used required for p-bar production
- So…
  - > Put them on a target and make neutrinos
- Same thing is also done with the 8 GeV booster

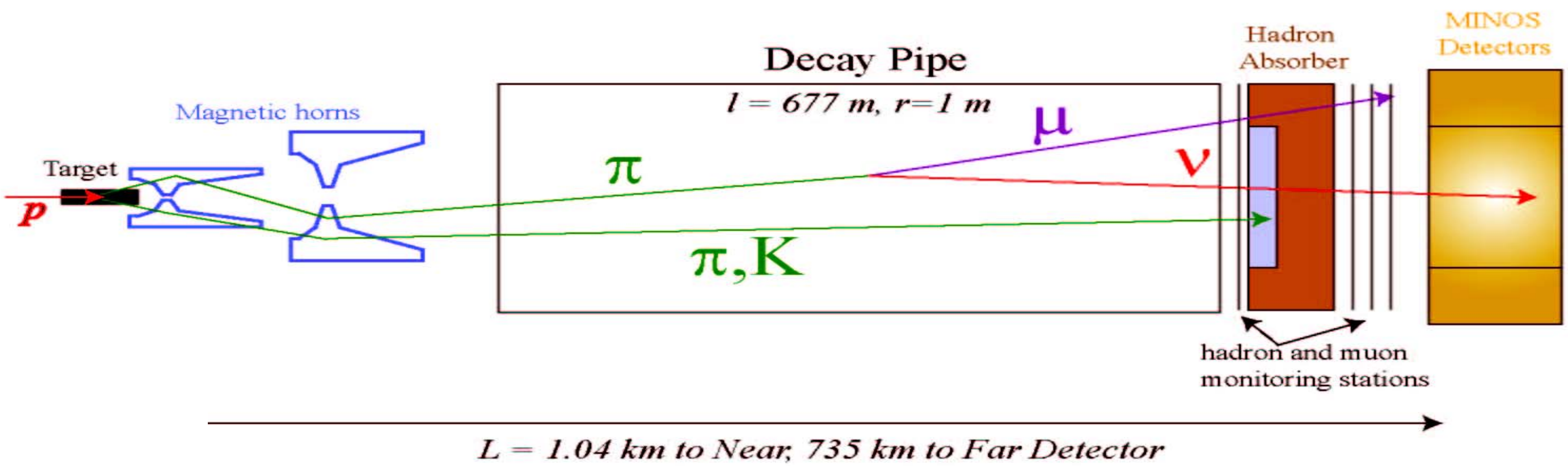


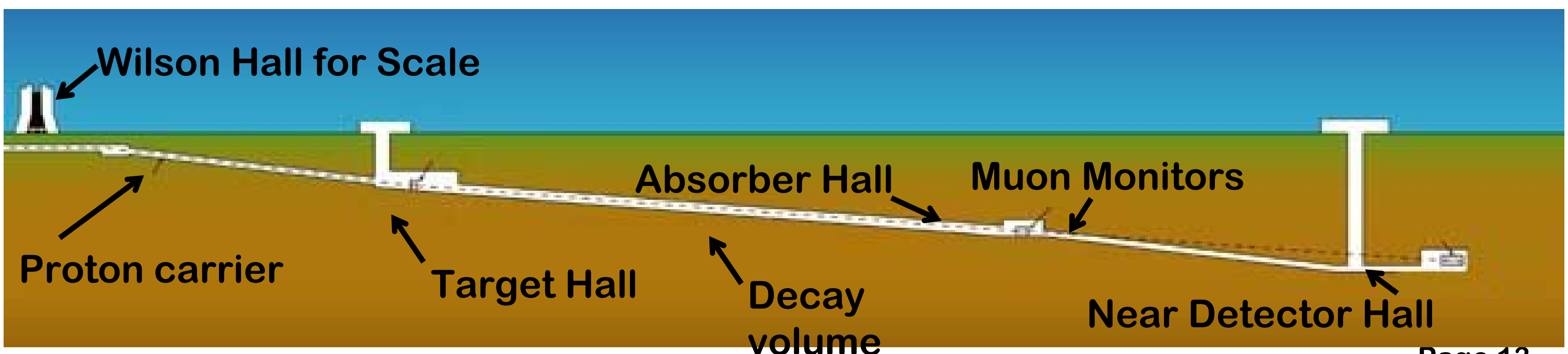
Making a Neutrino Beam

120 GeV/c protons strike graphite target

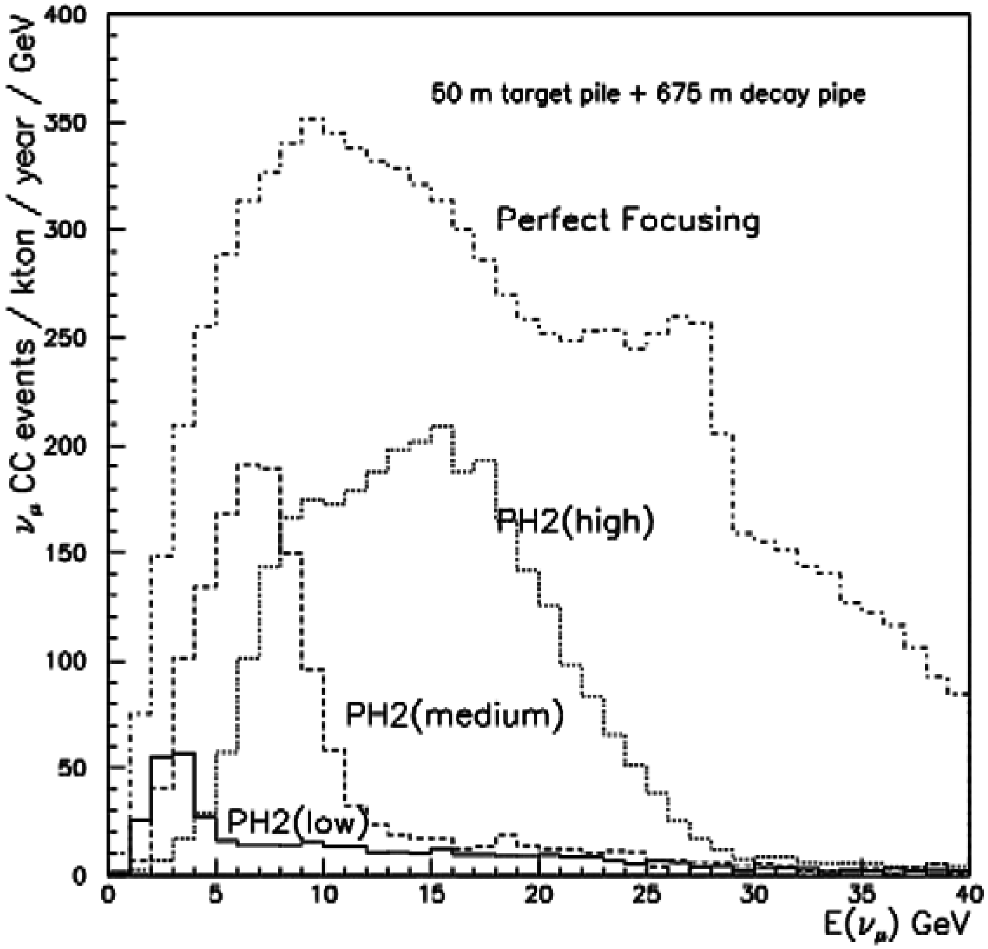
Magnetic horns focus charged mesons (pions and kaons)

Pions and kaons decay giving neutrinos





NuMI Beam & Spectra



ν_μ CC Events/kt/year

Low	Medium	High
470	1270	2740

ν_μ CC Events/MINOS/2 year

Low	Medium	High
5080	13800	29600

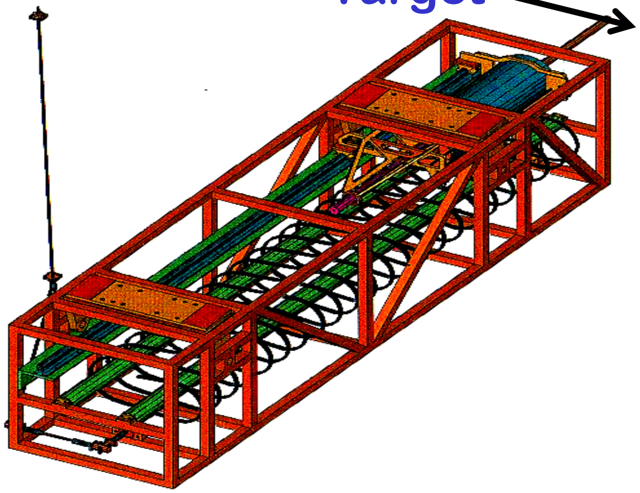
$4x10^{20}$ protons on target/year
$4x10^{13}$ protons/2.0 seconds

0.4 MW beam power

(0.25 MW initially)

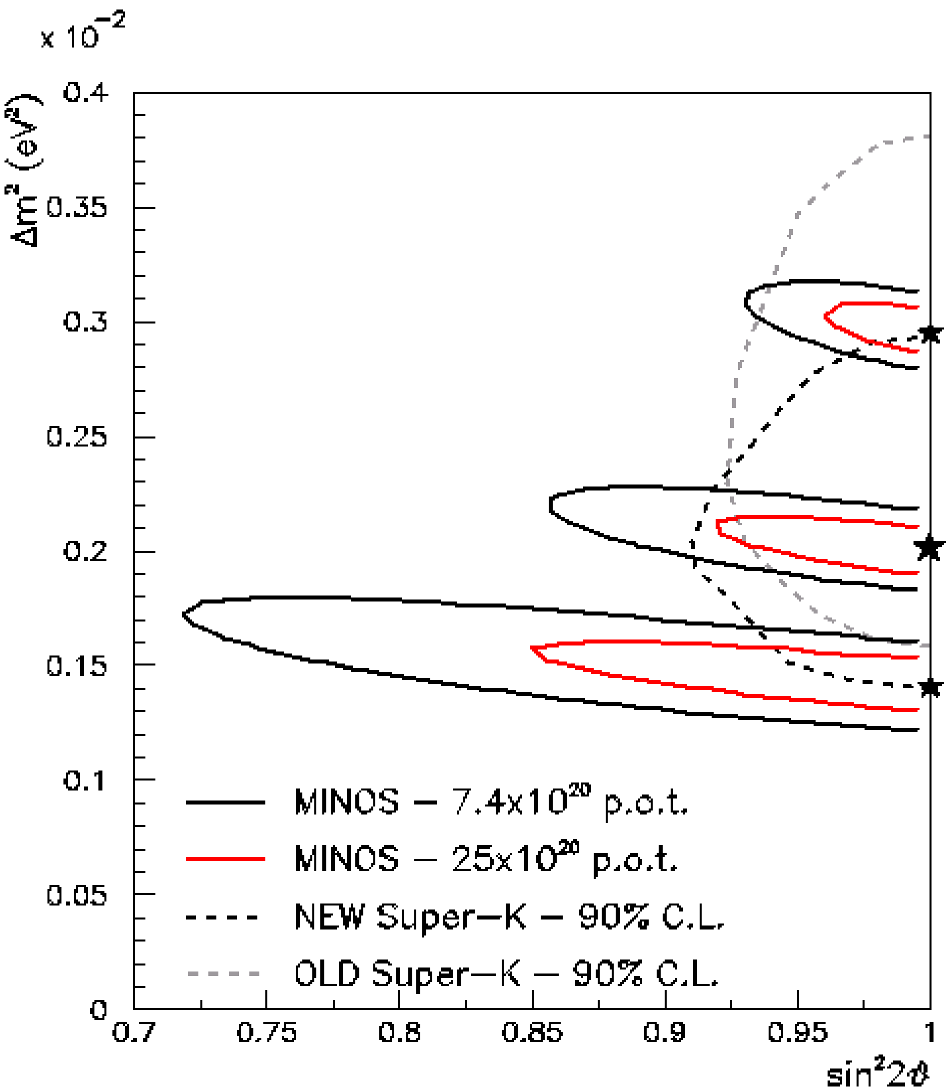
Target & Horn

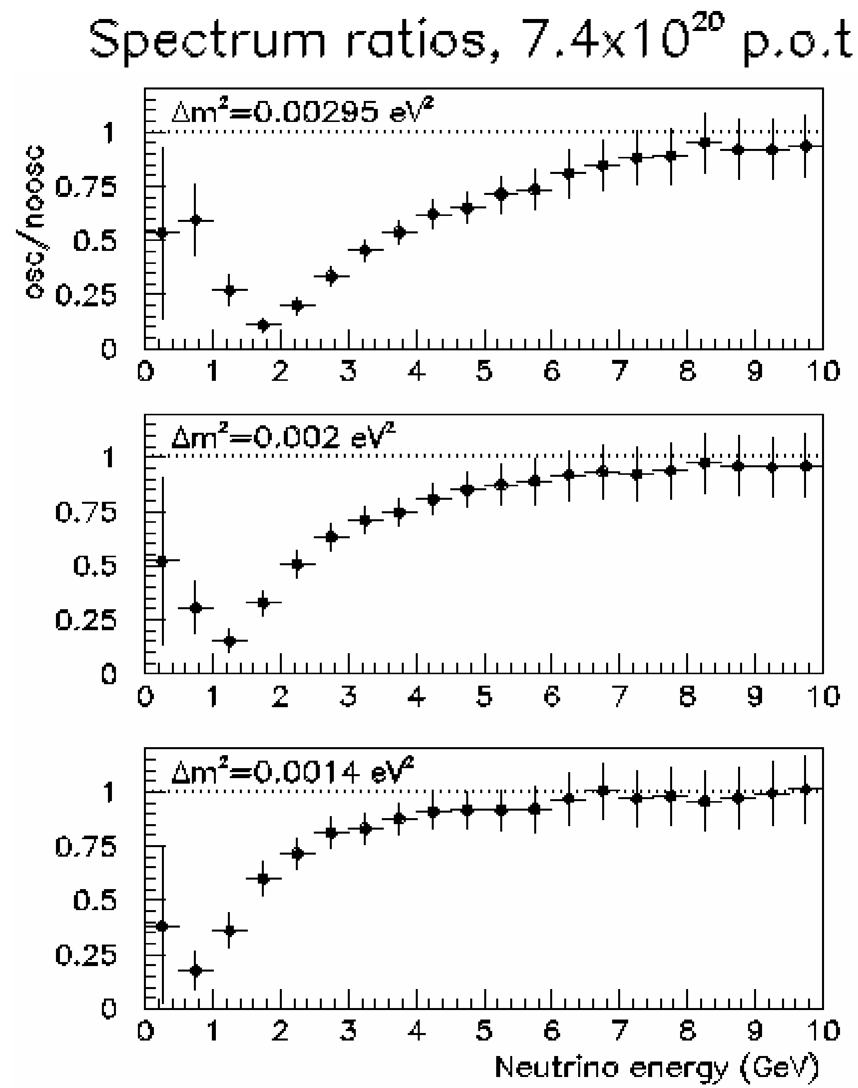
- Graphite target
- Magnetic horn (focusing element
    - 250 kA, 5 ms pulses



NuMI Target Hall

MINOS Charged-Current Spectrum Measurement





Status in ~5 Years

- We will know
  - > Both mass differences (Kamland, MINOS)
  - > 2 of the 3 angles @ 10% (Kamland+SNO; SK+MINOS)
  - > Sign of one of the mass differences (Solar MSW)
  - > First tests of CPT in allowed regions (MINOS, MiniBoo
- Probably still missing
  - > Last angle? *
  - > Confirmation of matter effects *
  - > Sign of the other mass difference; mass hierarchy *
  - > CP in neutrinos *
  - > Absolute mass scale (double beta; cosmology)
  - > Majorana or Dirac (double beta)

* addressable with “super beam” experiments

Super Beam Rules of Thumb

- It's the [proton beam power] x [mass] that matters
  - > Crudely linear dependence of pion production vs E_{proton}
  - > Generally energy & cycle time are related and hence the power is conserved within a synchrotron
  - > Remember that we design an experiment at constant L/E
  - > The beam divergence due to the energy of the pions is balanced by the boost of the pions and the ν cross section

Long Baseline Goals

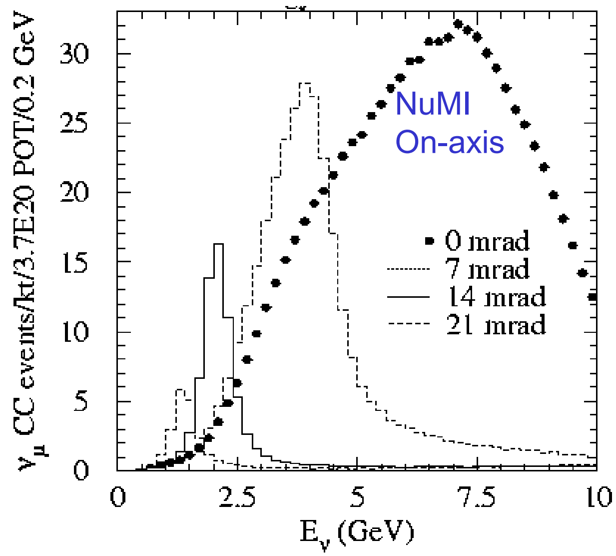
- Find evidence for $\nu_\mu \rightarrow \nu_e$
  - > One small parameter in phenomenology
- Determine the mass hierarchy
  - > Impacts model building
- Is θ_{23} exactly equal to 1??? – test to 1% level
- Precision measurement of the CP-violating phase δ
  - > Cosmological matter imbalance significance
  - > Potentially orders of magnitude stronger than in the quark sector
- Resolve θ ambiguities
  - > Significant cosmological/particle model building implications

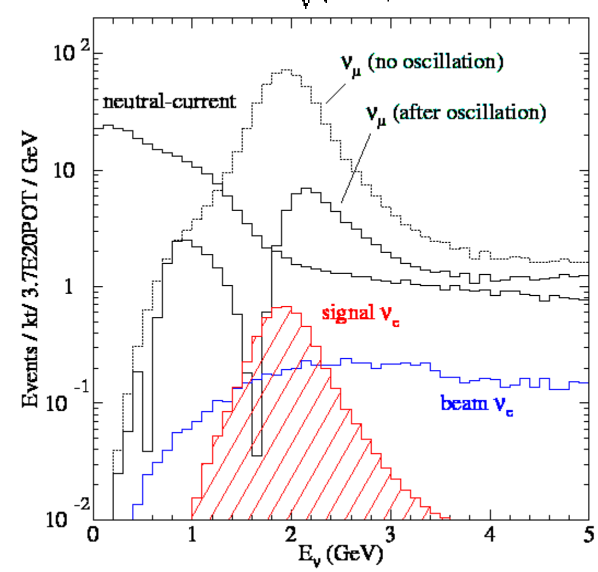
Super Beam Phasing
Part of the DoE Roadmap

- Phase I (~next 5 years)
  - MINOS, OPERA, K2K
- Phase II (5-10 years)
  - > 50kt detector & somewhat less than 1 MW
    - J2K, NOνA, super reactor experiment
- Phase III (10+ years; super beams)
  - > Larger detectors and MW+ beams
    - JPARC phase II + Hyper K (Mton ĉ)
    - NuMI + Proton driver + 2nd 100kt detector
    - CERN SPL + Frejus (0.5 Mton ĉ)
    - BNL super beam + UNO (0.5 Mton ĉ) @ NUSL
- Phase IV (20 years ???)
  - > Neutrino factory based on muon storage ring

Phase II
e.g. Off-Axis Searches for ν_e Appearance

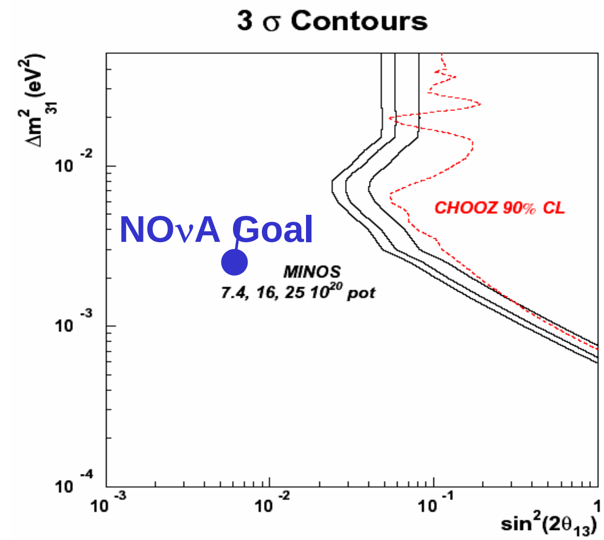
- 2 off-axis programs
  - > JPARC to Super K (T2K; Funded)
  - > NuMI to NOνA (Under Review)
- Main goal
  - > Look for electron appearance <1% (30X current limits)
  - > Off-axis detector site to get a narrow-band beam
  - > Fine-grain detectors to reduce NC π^o background below the intrinsic beam contamination
  - > Statistics limited for most any foreseeable exposure

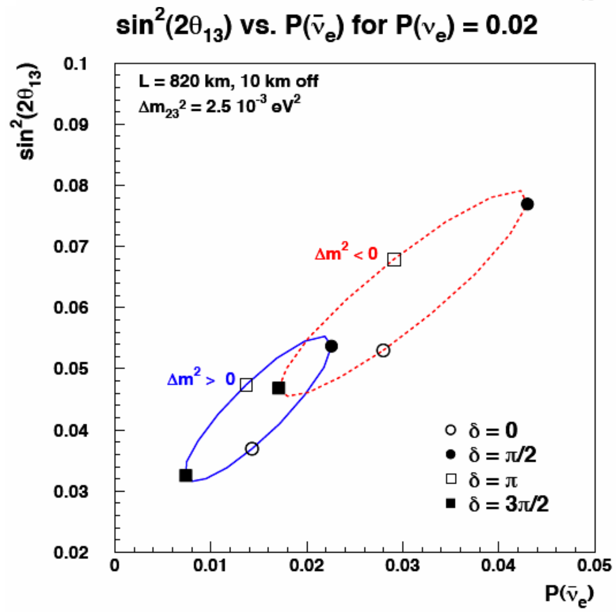




Interpretation of Results

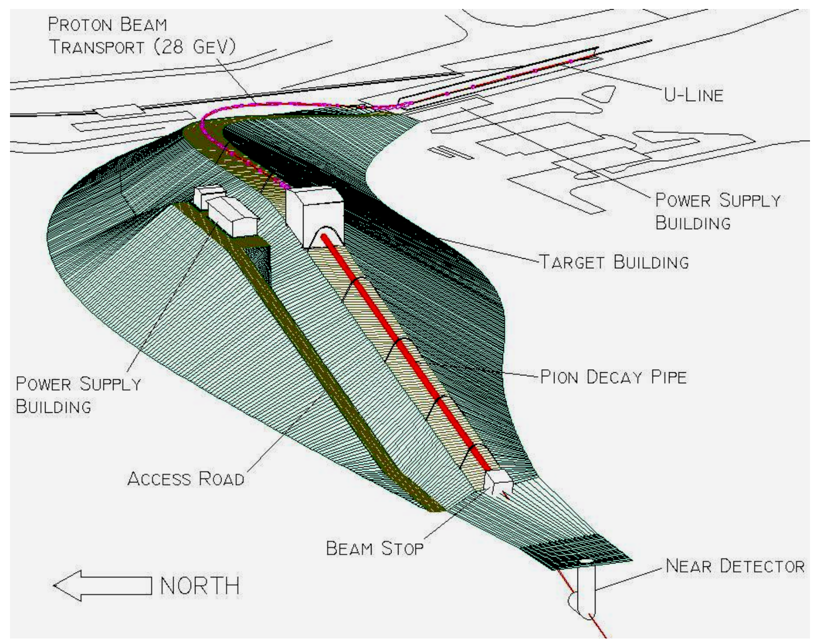
- There are matter effects visible in the 820km range
  - > Provides handle on CP phase, mass hierarchy but…
  - > Ambiguities with just a single measurement
- In addition
  - > If $\sin^2(2\theta_{23}) = 0.95$
  - > $\sin^2(\theta_{23}) = 0.39$ or 0.61
  - > Cosmology cares
- Rough equivalence of reactor & antineutrino measurements
  - > Eventually need 2nd energy (or detector position) in same beam to resolve at narrow-band beam





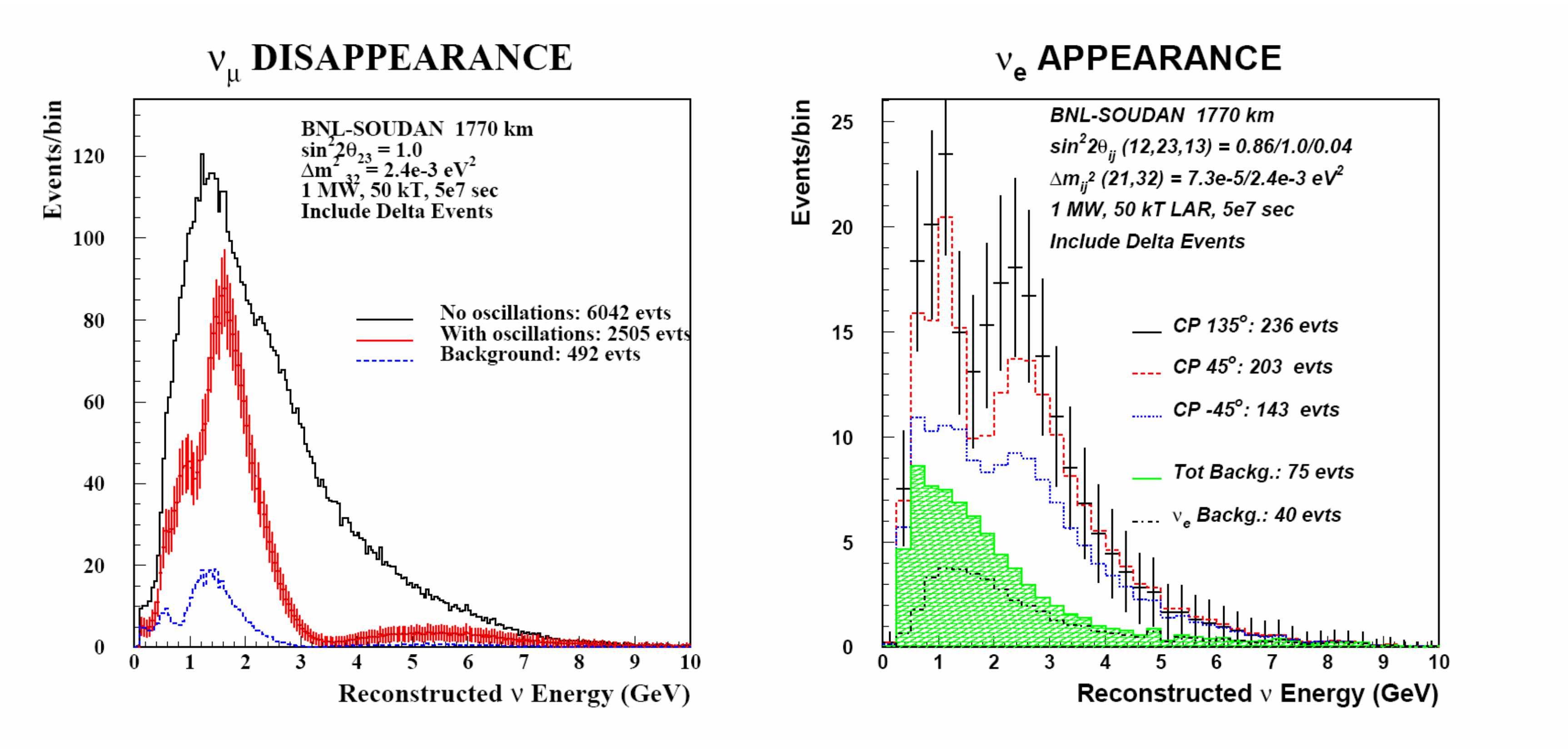
Phase III
e.g. BNL Super Beam + UNO

- **Turn AGS into a MW beam**
  - > 10X in AGS beam power
  - > Not same upgrades as eRHIC
  - > Use a very long baseline and a wide-bean beam
  - > While paper last year
- **Mton-class proton decay detector called UNO envisioned at the National Underground Lab (NUSL)**
  - > Location not picked but any of the possibilities are compatible with this concept
  - > LOI to funding agencies this year



Addressed Issue with Somewhat Improved Reach

Assess to large part of the spectrum gives access to all ambiguities



Current, Planned, & Dream LBL and VLBL Facilities

Program	P_p	E_ν	P (MW)	L (km)	yr
K2K	12	1.5	0.005	250	99
MiniBooNE	8	0.7	0.05	0.5	02
NuMI (initial)	120	3.5	0.25	735	05
NuMI (full design)	120	3.5	0.4	735	08
CNGS	600	17.0	0.2	735	05
JPARC to SK	50	1.0	0.8	295	08
NOνA (NuMI Off-Axis)	120	1.5	0.4	810	09
SNS	1.3	0.1	1.4	0.02	soon
Super Reactor	n/a	MeV	10	1	5 yrs?
JPARC phase II	50	0.8	4	295	
Fermilab Proton driver	120	1.8	1.9	735/1500	
SPL (SC proton linac)	2	0.3	4	130	
AGS Upgrade	30	1-7	2	2500	
eLIC injector	20	1-5	4	2500	

Now/next couple years ~5 years 10-15 years

What about eLIC?

- The distance to the NuSL site is about the same for either BNL or JLab
- Large Injector gets used for few minutes per fill of the collider
  - > Rest of the time could be used for “pinging” a target
  - > Beam power for eLIC proton injector competitive with other super beams
  - > Implies some machine design issues
- Needs 11^{o} angle to hit NUSL
  - > Similar ground water issues to BNL
- Site is potentially restrictive but fortunately the beam line would run nearly parallel to Jefferson Ave (~10^{o})

Summary

- A rich field for investigation of neutrino oscillations using long & very long baselines
  - > Considerable beyond-SM & cosmological implications
- Proton injector for EIC has potential to be a world class neutrino source on a competitive time scale
- Connections between NUSL, neutrino community, and EIC promise broad program embracing different communities with orthogonal uses of the facility