Neutrino Oscillations - a brief overview

For two family oscillations, take the mixing matrix to be:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

At production ($t = 0$:)

$$|\nu_\mu(0)\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

At a later time:

$$|\nu_\mu(t)\rangle = -\sin\theta e^{-iE_1 t}|\nu_1\rangle + \cos\theta e^{-iE_2 t}|\nu_2\rangle$$

And the $\nu_\mu \leftrightarrow \nu_e$ oscillation probability is:

$$\begin{aligned} P_{osc} &= |\langle\nu_e|\nu_\mu(t)\rangle|^2 \\ &= \frac{1}{2}\sin^2 2\theta[1 - \cos(E_2 - E_1)t] \end{aligned}$$

Use $E_1 = \sqrt{p^2 - m_1^2} \approx p + m_1^2/2p$ (and same for E_2) and $(t/p) = (tc)/(pc) = L/E$

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

Neutrino Oscillations - a brief overview

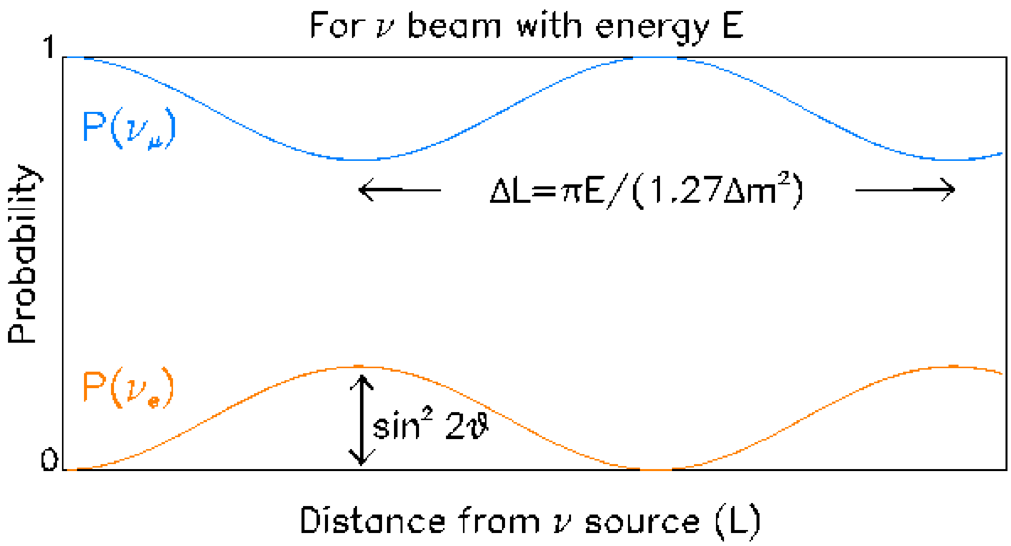
$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

P_{osc} depends upon two experimental parameters:

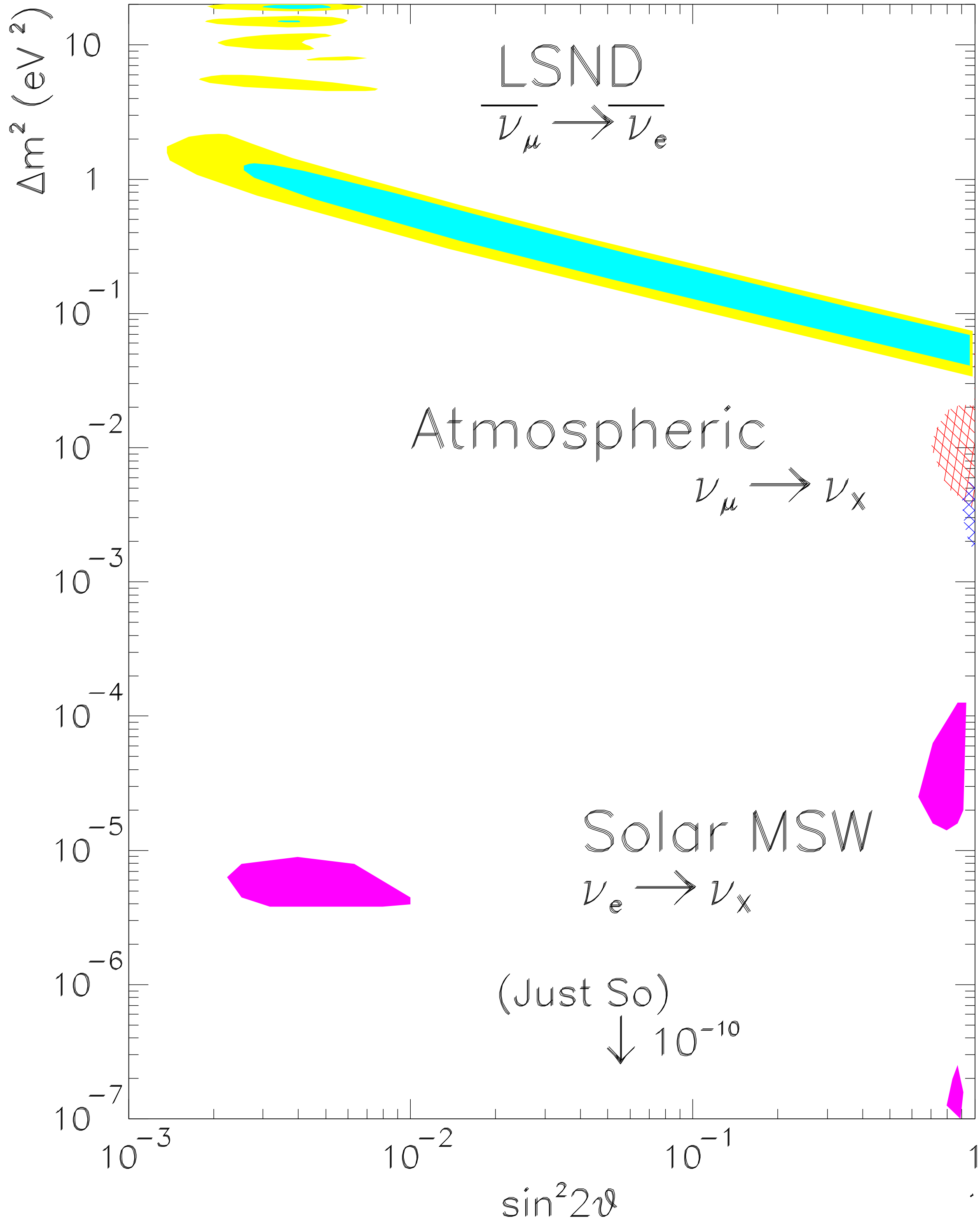
- L – The distance from the ν source to detector
- E – The energy of the neutrinos

And P_{osc} depends on two fundamental parameters:

- $\Delta m^2 = m_1^2 - m_2^2$
- $\sin^2 2\theta$



Evidence for neutrino oscillations



The LSND Experiment

- LAMPF 800 MeV proton beam on targets and beam stop
- Detector 30 m from beam stop
- 167 tons of liquid scintillator, surrounded by 1220 phototubes

Decay-at-rest Analysis

$$\text{stopped } \pi^+ \to \nu_\mu \, \mu^+$$
$$\hookrightarrow e^+ \, \overline{\nu}_\mu \, \nu_e$$

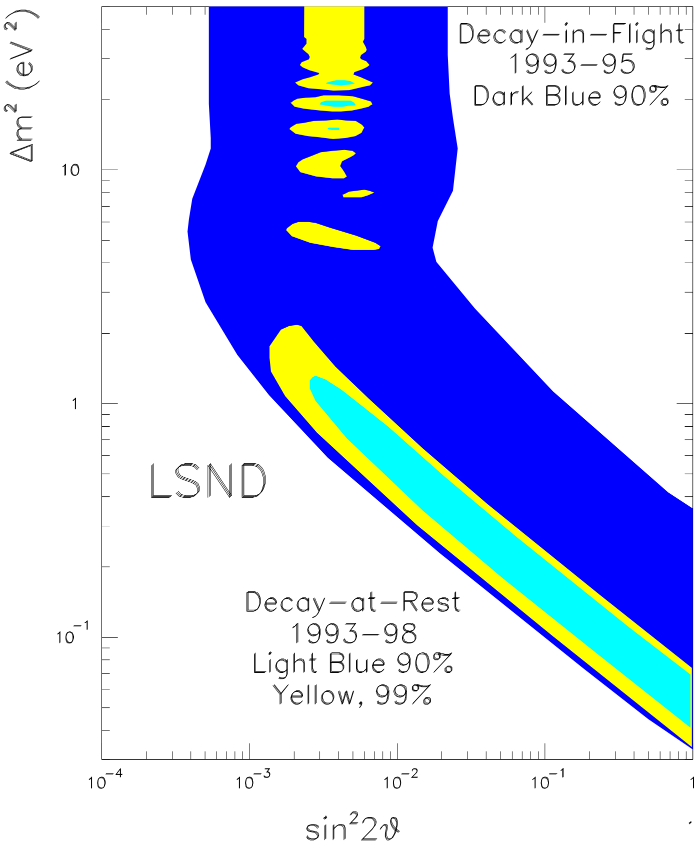
$$\overline{\nu}_\mu \to \overline{\nu}_e \quad \Rightarrow \quad \overline{\nu}_e p \to e^+ n \quad \Rightarrow \quad np \to d\gamma$$

Positron detected in delayed coincidence with a 2.2 MeV γ from neutron capture.

LSND Decay-in-flight Analysis

$$\pi^+ \to \nu_\mu \, \mu^+ \quad \Rightarrow \quad \nu_\mu \to \nu_e \quad \Rightarrow \quad \nu_e \text{ quasielastic scatter}$$

The LSND Experiment

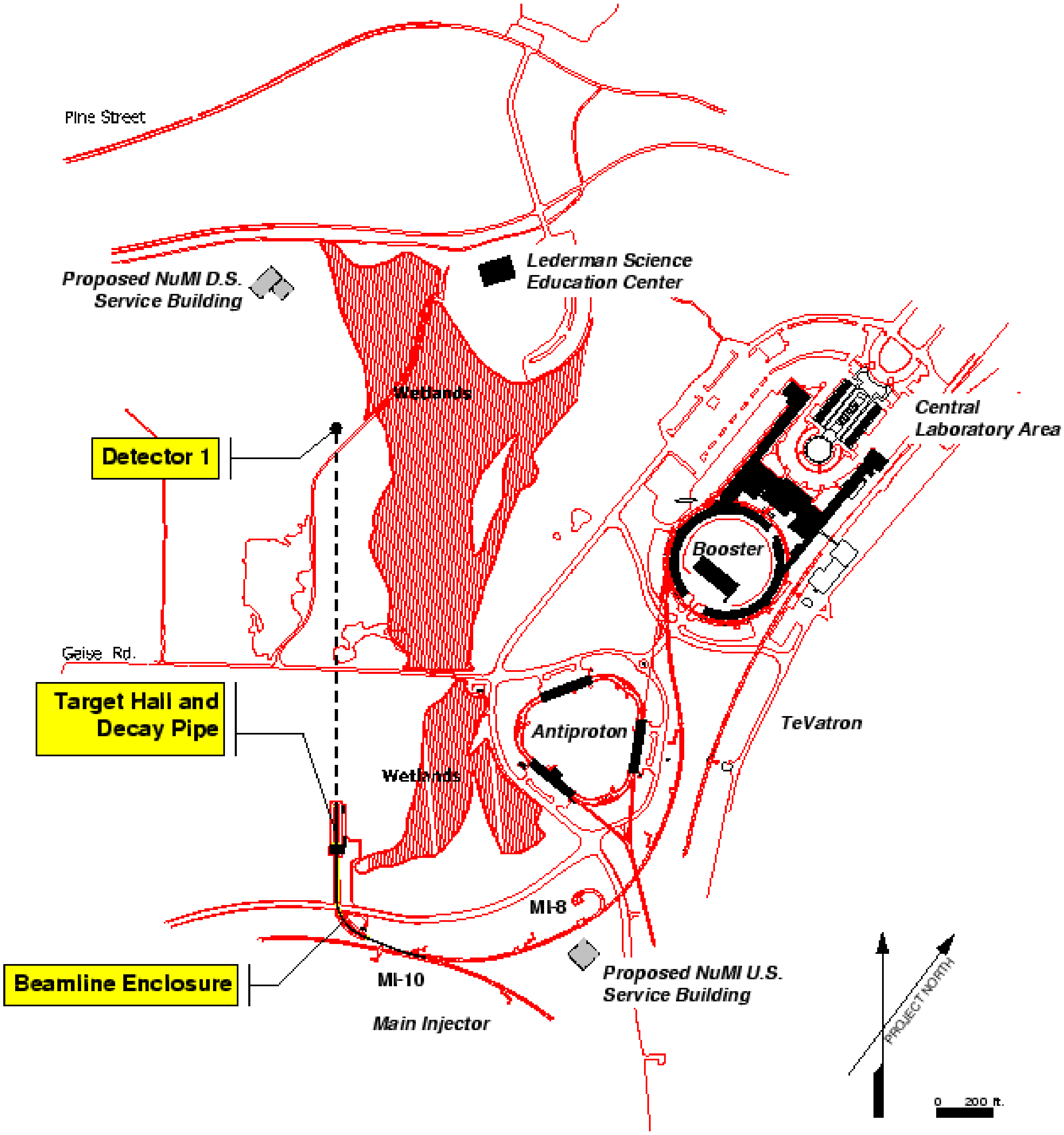


Decay-in-flight and Decay-at-rest results are consistent, but different analyses were used.

- ν_μ rather than $\overline{\nu_\mu}$
- Upstream targets as well as DIF in beamstop (different L)
- Higher energy neutrinos
- Different event signature (no neutron)
- Different backgrounds

The Goal of the MiniBooNE experiment is to confirm or deny the LSND results

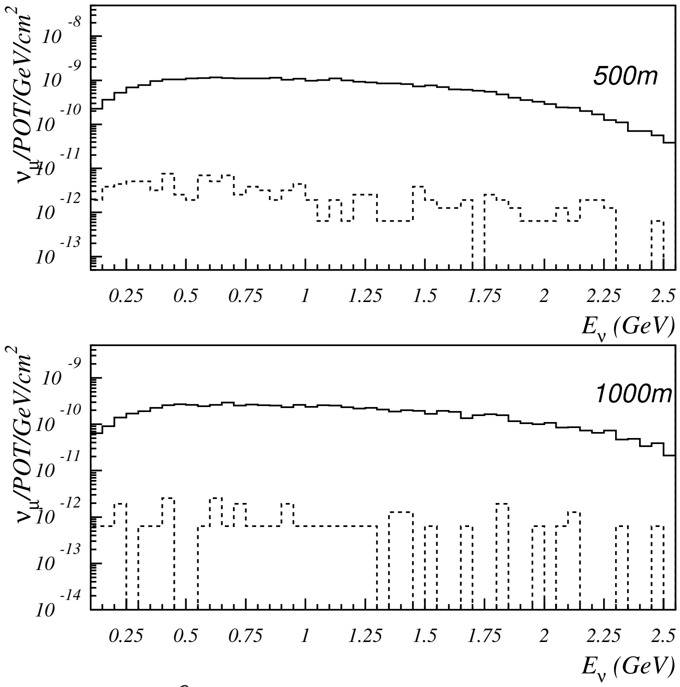
The MiniBooNE Site



General Beam Design Considerations

- Maximize the flux

Full Geant Simulation: Solid – ν_μ flux, Dashed – ν_e background



- & Minimize the ν_e content & sys uncertainty...
  - $\Rightarrow$ μ decays
  - $\Rightarrow$ K decays

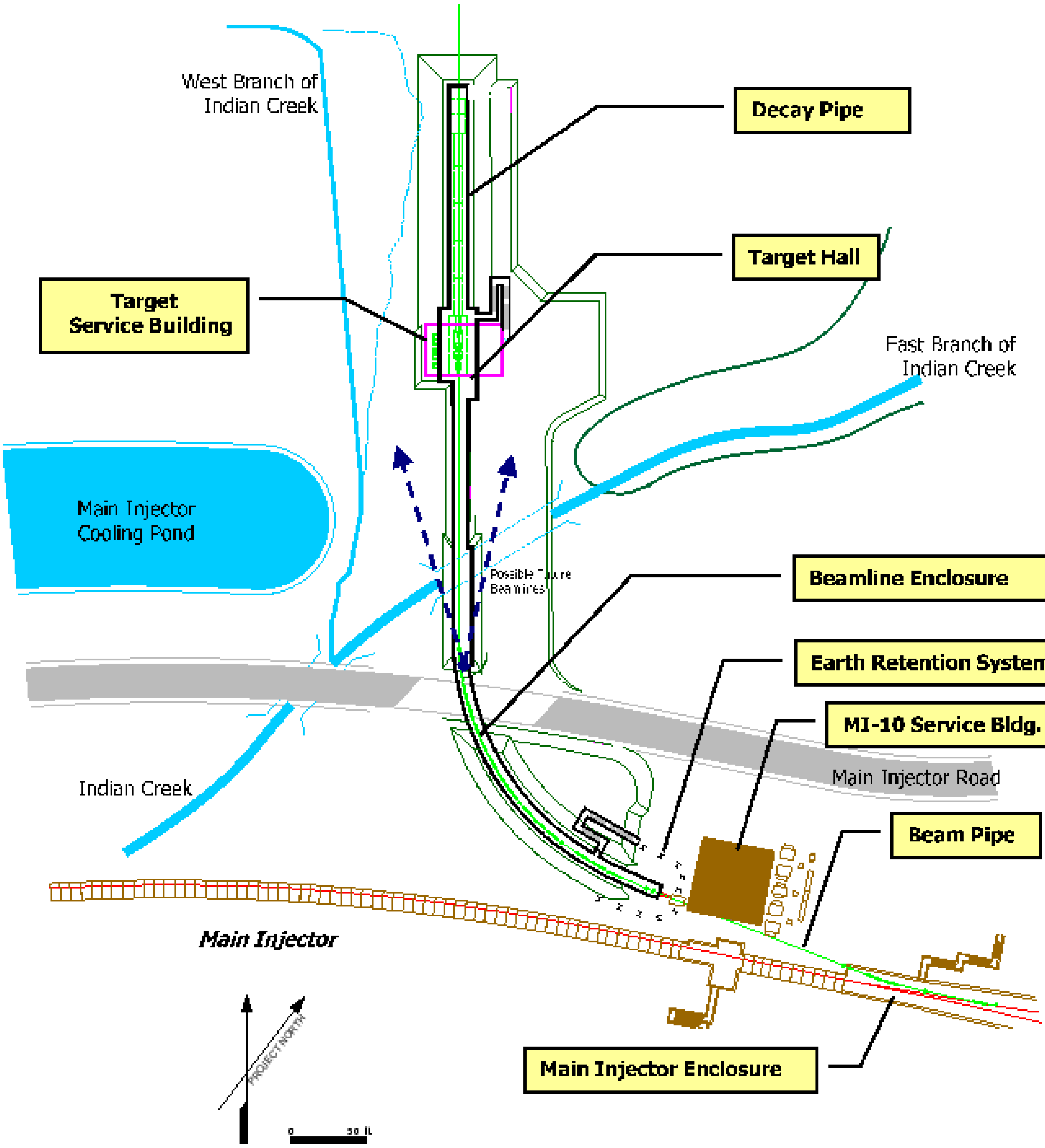
- Enhance the low E region
  - $\Rightarrow$ Reduces neutral current π^0 production in detector
  - $\Rightarrow$ Improves reach in Δm^2

- Understand particle production well $\rightarrow$ monitoring (ν_μ disappearance)

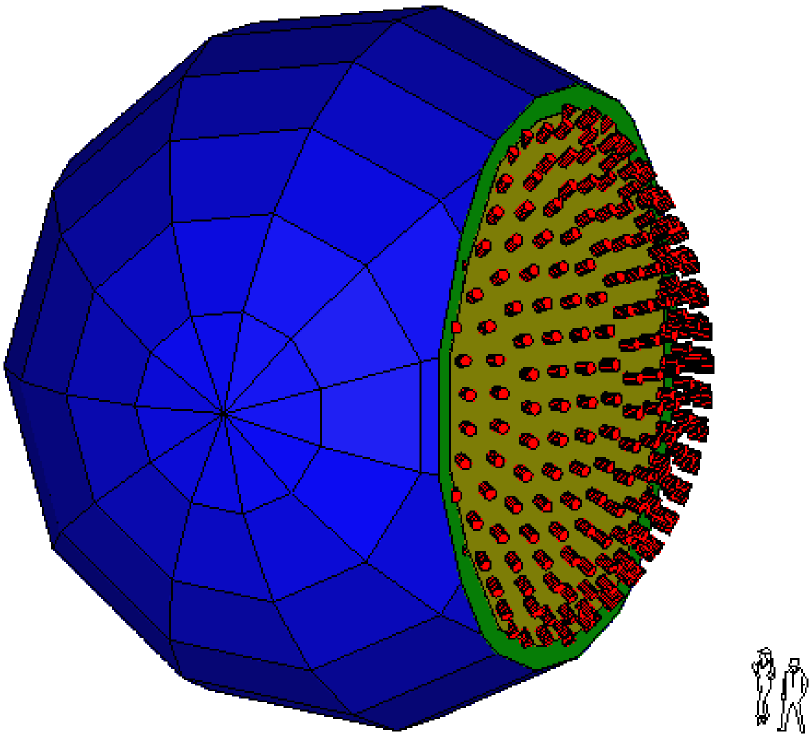
- Run in ν and $\overline{\nu}$ modes
  - $\Rightarrow$ Change in backgrounds $\rightarrow$ understand systematics
  - $\Rightarrow$ Search for CP violation in oscillation signal

- Insertable beam absorber at 25 meters

The 8 GeV Beamline and MiniBooNE Target Area



The MiniBooNE Detector Tank

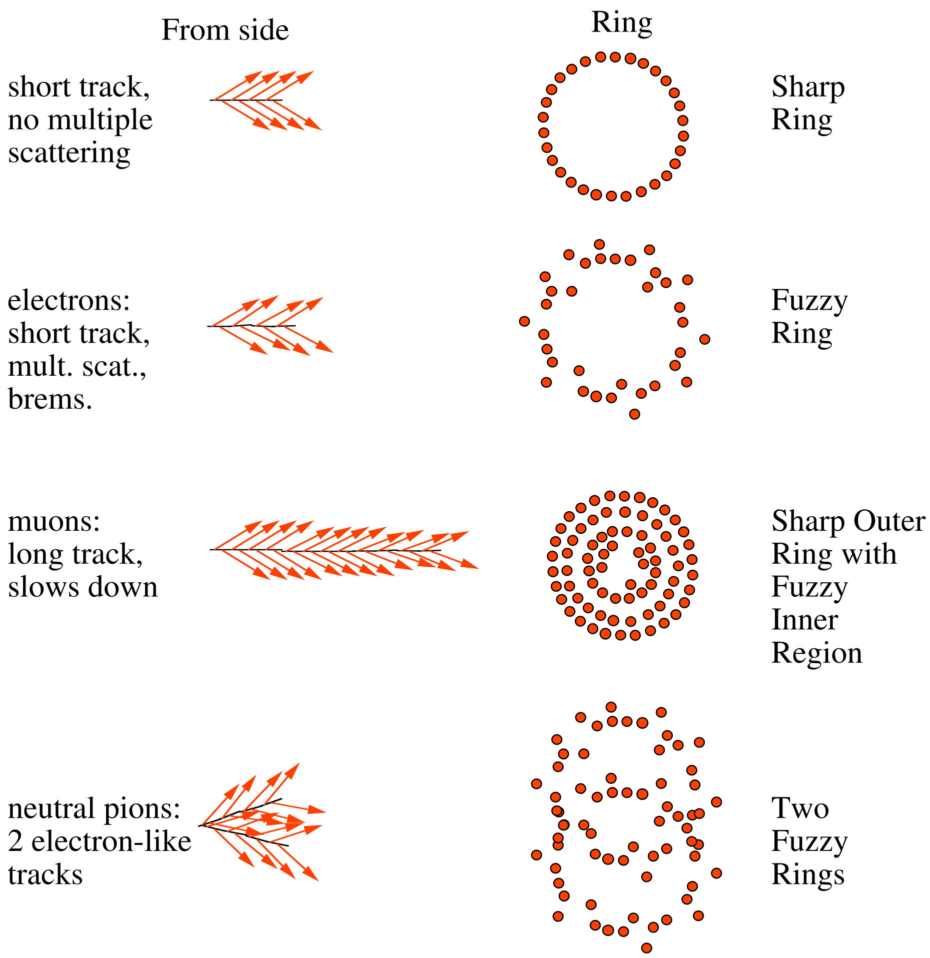


- 1280 phototubes in detector located at 5.75m radius, and 240 phototubes in veto
- Fiducial volume: 445 tons (5.75m radius sphere)
  Total volume: 807 tons (6.1m radius sphere)
- Pure mineral oil in detector & veto
- Opaque shield between veto and detector region.

The basics of particle identification...

Cerenkov Light:

Prompt signal in the form of rings



Scintillation Light:

Later signal and isotropic

Estimated Signal

After running for 1 year (2×10^7s, 5×10^{20} pot)...

- $\nu_\mu\ C \to \mu^-\ N$ — 700,000 events

  Assuming 50% electron ID efficiency and 100% $\nu_\mu \to \nu_e$ transmutation then...

- $\nu_e\ C \to e^-\ N$ — 400,000 events

  If $\Delta m^2 = 0.4\text{eV}^2$ and $sin^2 2\theta = 0.02$ then

- $\nu_e\ C \to e^-\ N$ — 960 events
- Intrinsic ν_e — 960 events
- μ^- Misidentification — <400 events
- π^0 Misidentification — 400 events

Methods for Testing a Signal

- Vary meson decay length from 50 m to 25 m

Example: assume a 600 event excess after 2.5×10^{20} p.o.t.:

Decay Pipe Length (m)	ν_μ events	$\nu_\mu \to \nu_e$ (oscillation events) $\propto L_{decay}$	if due to ν_e bkgnd: $\pi \to \mu \to \nu_e \propto L^2_{decay}$ K decays constant
50	700,000	600 ± 50	600 ± 50
25	390,000	334 ± 35	174 ± 32

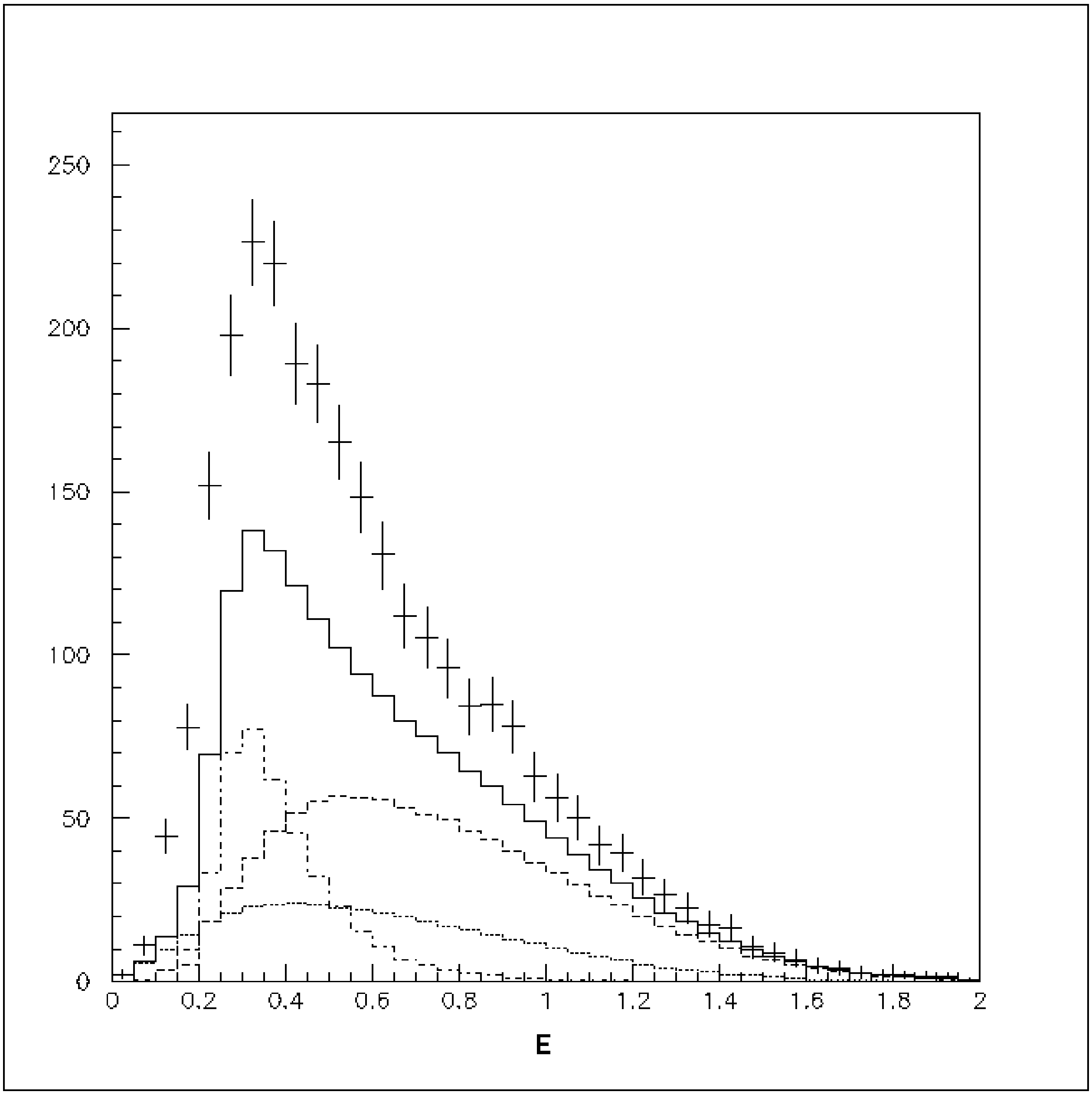
- Run with an antineutrino beam
- Modify the horn system to vary neutrino energy.
  Not easily done!

- Build a second detector ... BooNE!

Visible Energy Distribution for Oscillations at $\Delta m^2 = 0.4\ \text{eV}^2$, $\sin^2 2\theta = 0.02$

+ signal & background
– total background

–.– π^0 background
––– ν_e background
...... μ^- background



Estimated confidence level limits MiniBooNE will reach in one year of running