Physics Opportunities in a NuMI Offaxis Experiment

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Outline

- Introductory Comments
- Advantages of an Off-axis Beam
- Important Physics Issues
- NuMI Capabilities

Introduction

Introductory Comments

The current generation of long and medium baseline terrestial ν oscillation experiments is designed to:

1. Confirm SuperK results with accelerator ν's (K2K)
2. Demonstrate oscillatory behavior of ν_μ's (MINOS)
3. Make precise measurement of oscillation parameters (MINOS)
4. Demonstrate explicitly $\nu_\mu \rightarrow \nu_\tau$ oscillation mode by detecting ν_τ's (OPERA, ICARUS)
5. Improve limits on $\nu_\mu \rightarrow \nu_e$ subdominant oscillation mode, or detect it (MINOS, ICARUS)
6. Resolve the LSND puzzle (MiniBooNE)
7. Confirm indications of LMA solution (KamLAND)

Many issues in neutrino physics will then still remain unresolved. Next generation experiments will try to address them.

The Physics Goals

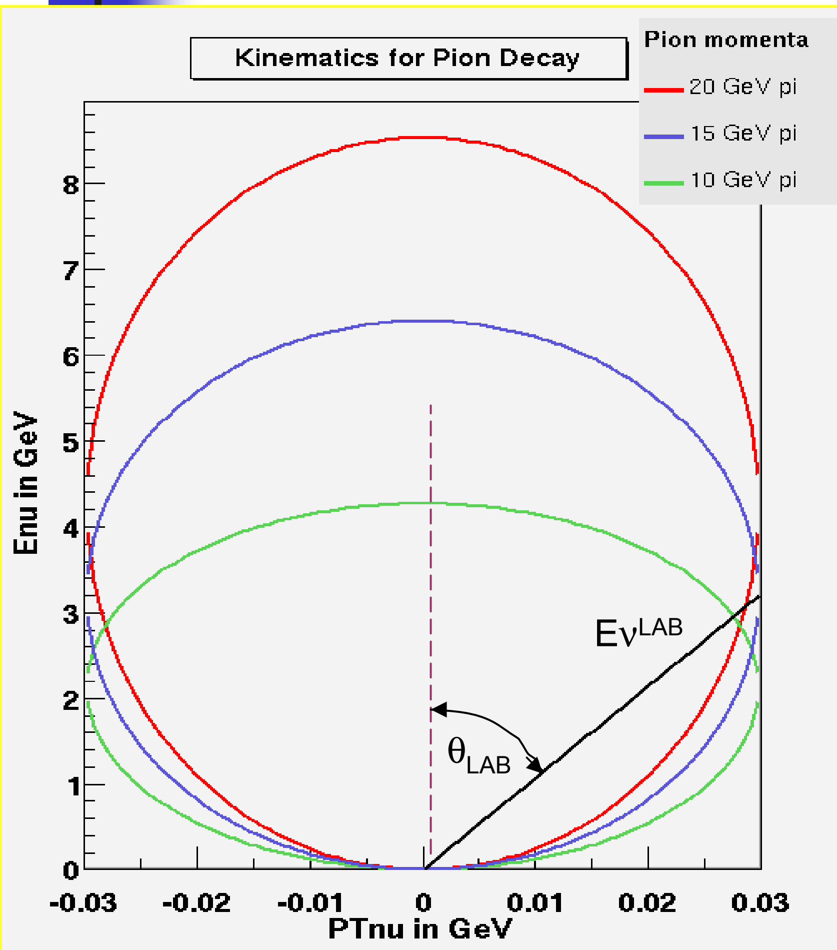
- Observation of the transition $\nu_\mu \rightarrow \nu_e$
- Measurement of θ_{13}
- Determination of mass hierarchy (sign of Δm_{23})
- Search for CP violation in neutrino sector
- Measurement of CP violation parameters
- Testing CPT with high precision

Offaxis Beam Advantages

The Off-axis Situation

- The physics issues to be investigated are clearly delineated
- The dominant oscillation parameters are known reasonably well
- One wants to maximize flux at the desired energy (near oscillation maximum)
- One wants to minimize flux at other energies
- One wants to have narrow energy spectrum

Kinematics of π Decay



Compare E_ν spectra from 10,15, and 20 GeV π's

- Lab energy given by length of vector from origin to contour
- Lab angle by angle wrt vertical
- Energy of ν is relatively independent of π energy
- Both higher and lower π energies give ν's of somewhat lower energy
- There will be a sharp edge at the high end of the resultant ν spectrum
- Energy varies linearly with angle
- Main energy spread is due to beam divergence

Kinematics Quantitatively

$$p_{\rm L} = \gamma(p^*\cos\Theta^* + \beta p^*)$$
$$p_{\rm T} = p^*\sin\Theta^*$$

$$\Theta = \frac{R}{L} = \frac{1}{\gamma}\frac{\sin\Theta^*}{1+\cos\Theta^*},$$

$$E_\nu(R) = \frac{2\gamma p^*}{1+(\gamma\frac{R}{L})^2}$$

$$\Phi_\nu(R) = \frac{\frac{\gamma^2}{\pi L^2}}{(1+(\gamma\frac{R}{L})^2)^2}$$

The decisive feature is:

$$\frac{\partial E_\nu}{\partial\gamma} = 0$$

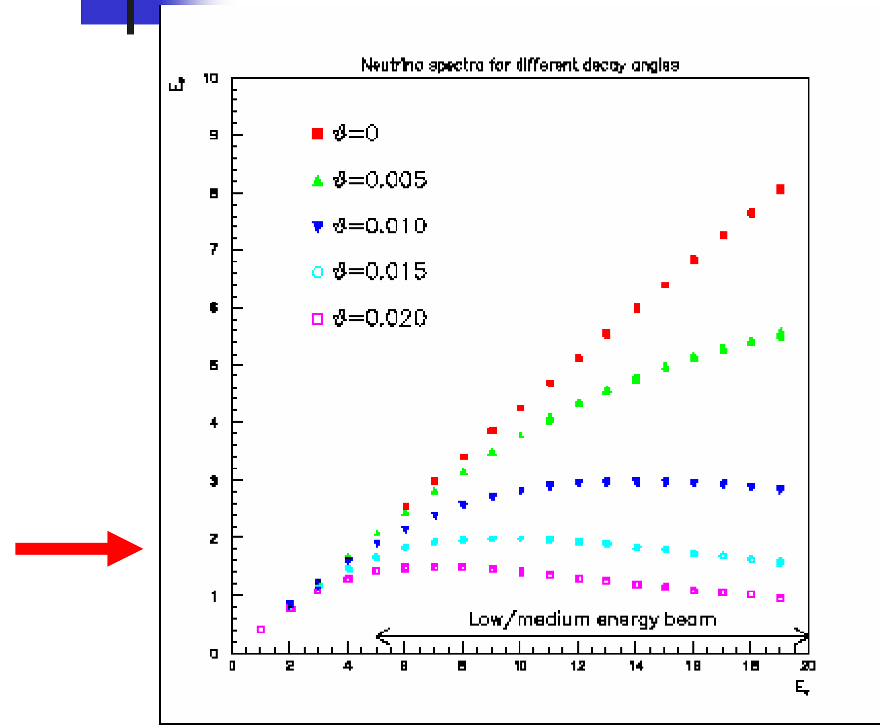
at the 'magic' angle

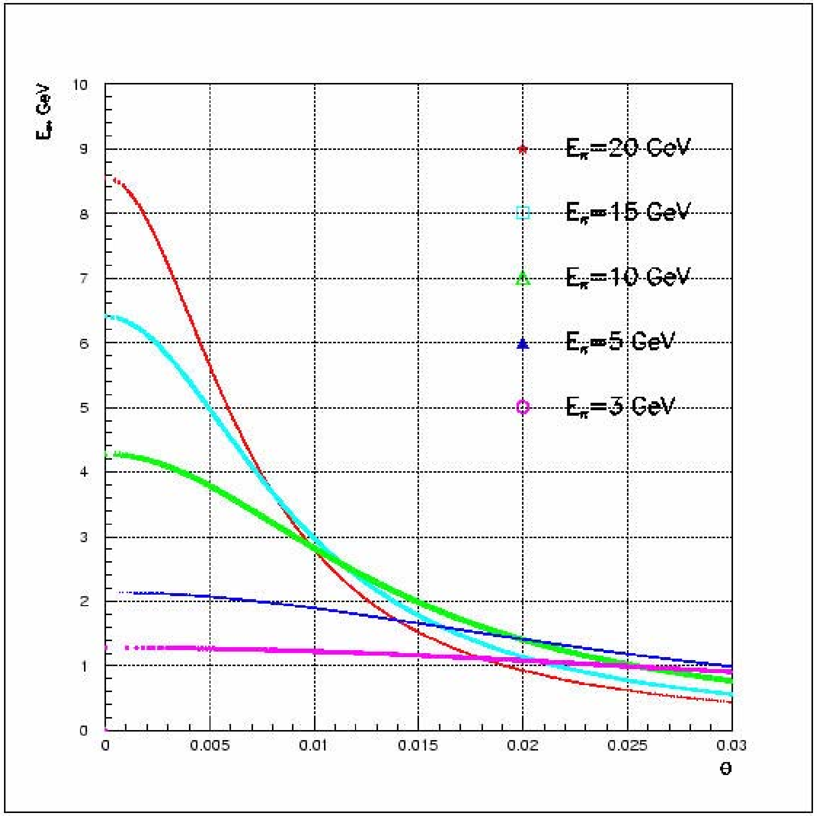
$$\Theta = 1/\gamma\,.$$

Optimization of off-axis beam

- Choose optimum E_ν (from L and Δm_{23}^2)
- This will determine mean E_π and θ_{LAB} from the 90^o CM decay condition
- Tune the optical system (target position, horns) so as to accept maximum π meson flux around the desired mean E_π

Off-axis 'magic'
(D.Beavis at al. BNL Proposal E-889)

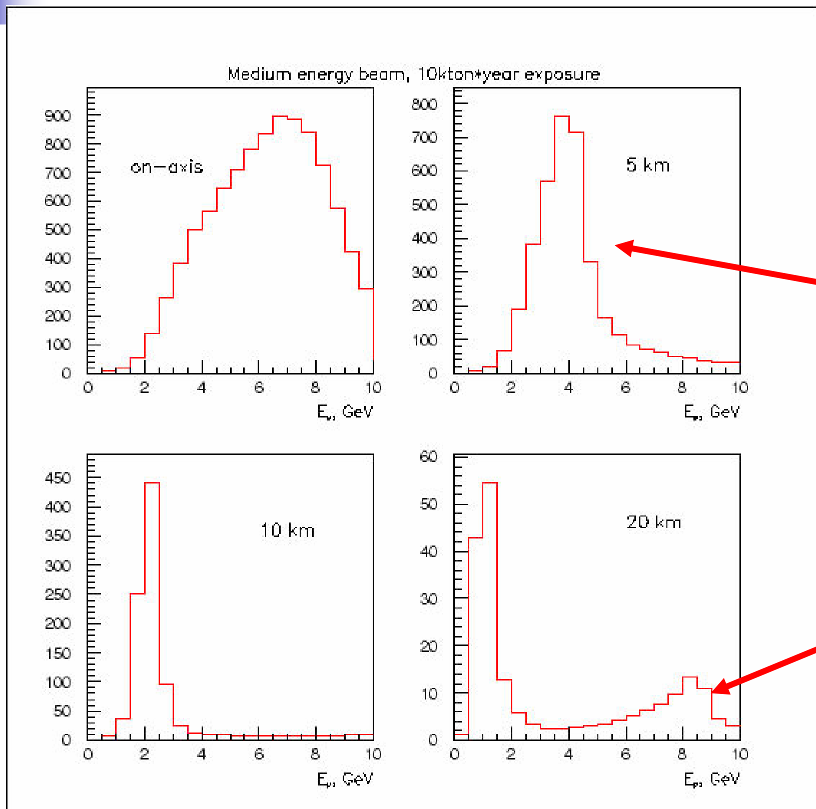




NuMI beam can produce 1-3 GeV intense beams with well defined energy in a cone around the nominal beam direction

$$Flux = \left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2 \frac{A}{4\pi z^2}$$

Medium Energy Beam



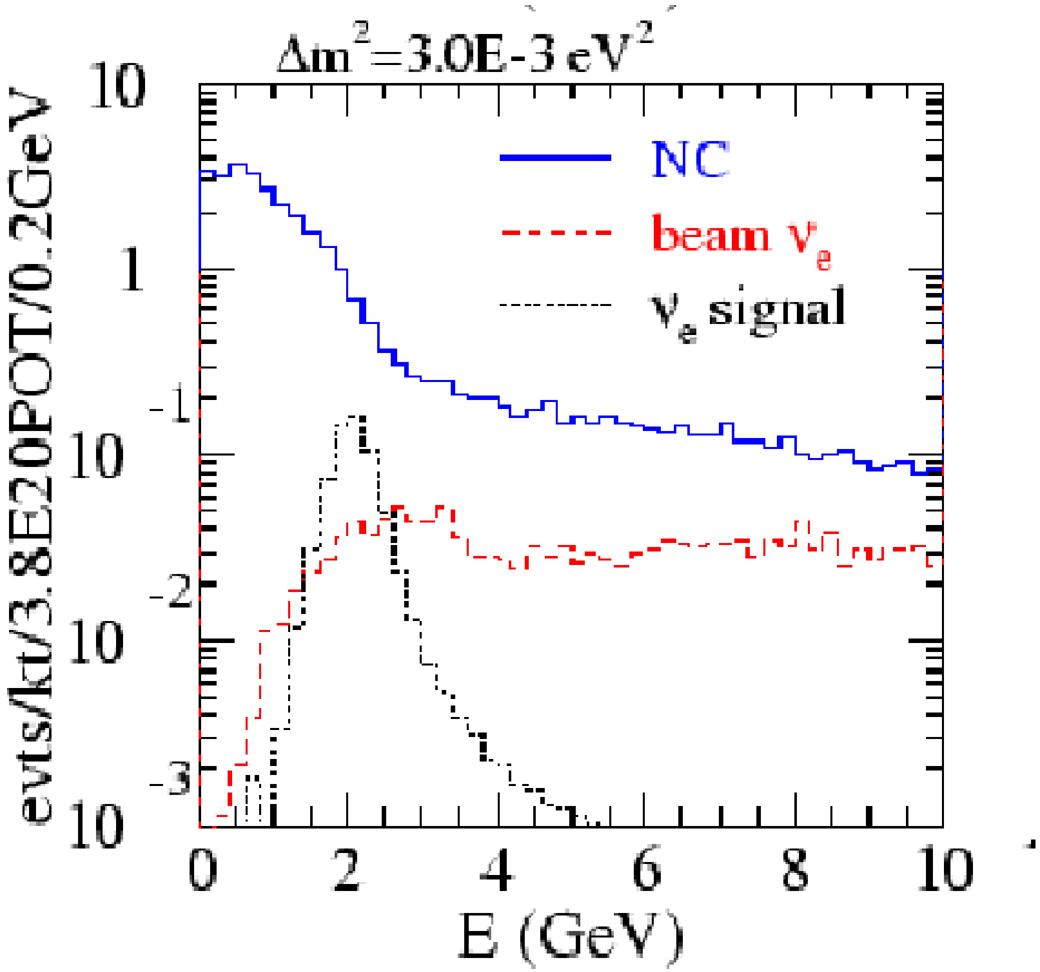
A. Para, M. Szleper, hep-ex/0110032

More flux than low energy on-axis (broader spectrum of pions contributing)

Neutrinos from K decays

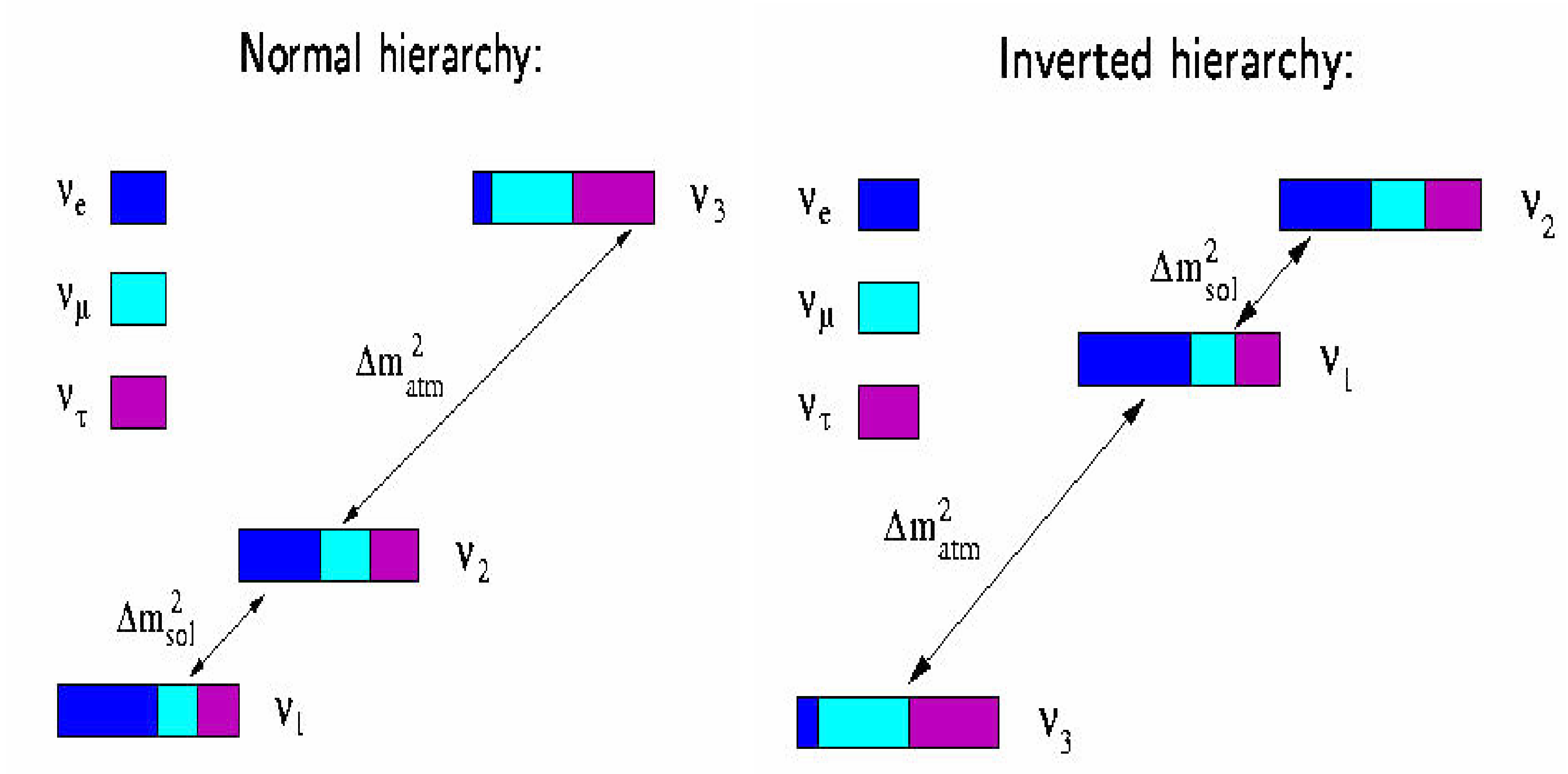
Neutrino event spectra at putative detectors located at different transverse locations

Experimental Challenge



Physics

2 Mass Hierarchy Possibilities



$\nu_\mu \Rightarrow \nu_e$ transition equation

$$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2\theta_{23}\sin^2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23}\sin^2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu};$$

$$A = \sqrt{2}G_F n_e;$$

$$B_\pm = |A \pm \Delta_{13}|;$$

$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

A. Cervera et al., Nuclear Physics B 579 (2000) 17 – 55, expansion to second order in θ $\theta_{13}, \frac{\Delta_{12}}{\Delta_{23}}, \frac{\Delta_{12}}{A}, \Delta_{12}L$

Several Observations

- First 2 terms are independent of the CP violating parameter δ
- The last term changes sign between ν and $\overline{\nu}$
- If θ_{13} is very small ($\leq 1^{o}$) the second term (subdominant oscillation) competes with 1st
- For small θ_{13}, the CP terms are proportional to θ_{13}; the first (non-CP term) to θ_{13}^2
- The CP violating terms grow with decreasing E_ν (for a given L)
- There is a strong correlation between different parameters
- CP violation is observable <u>only if all</u> angles $\neq 0$

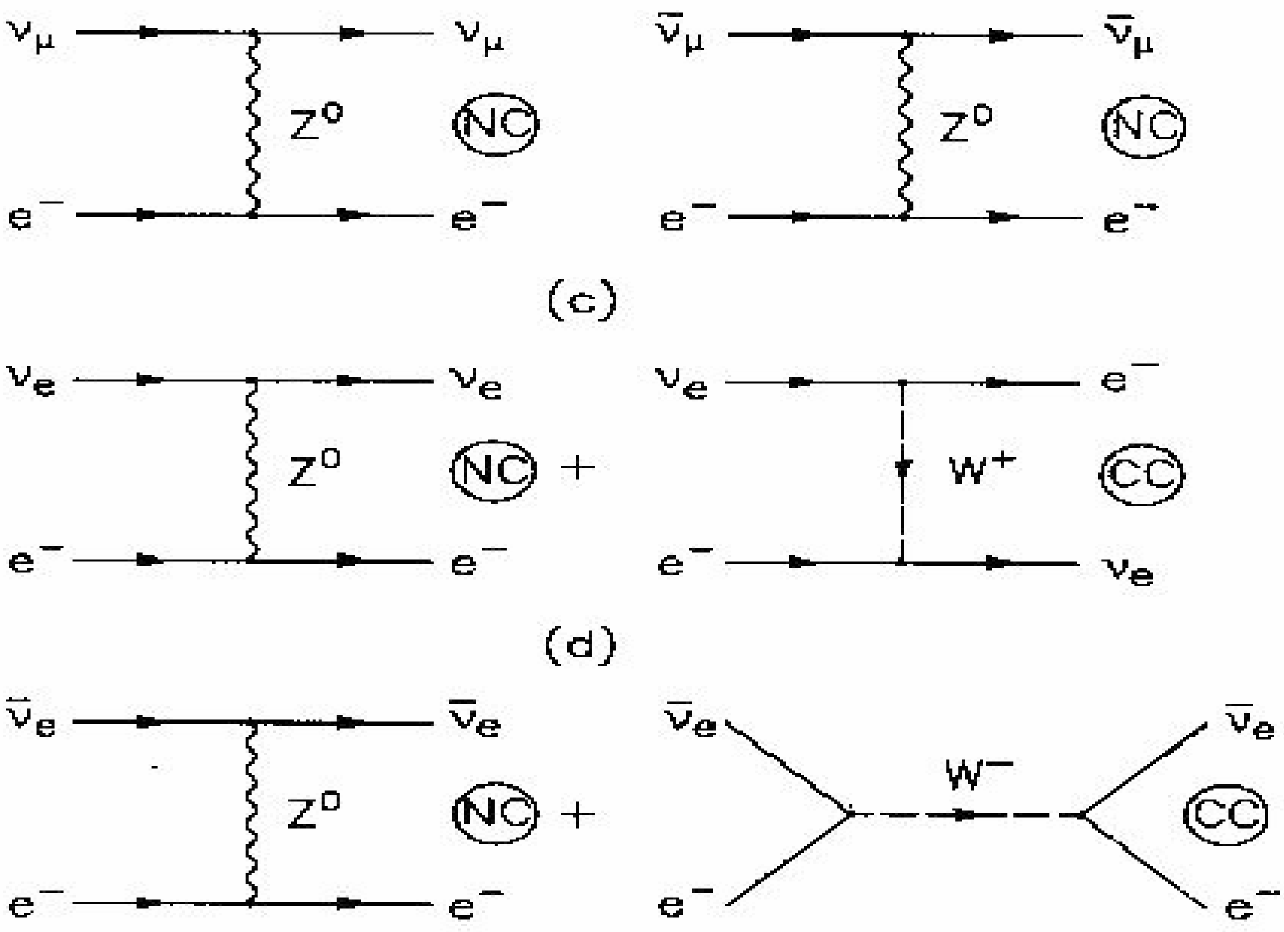
θ_{13} Issue

- The measurement of θ_{13} is made complicated by the fact that oscillation probability is affected by matter effects and possible CP violation
- Because of this, there is not a unique mathematical relationship between oscillation probability and θ_{13}
- Especially for low values of θ_{13}, sensitivity of an experiment to seeing $\nu_\mu \rightarrow \nu_e$ depends very much on δ
- Several experiments with different conditions and with both ν and $\bar{\nu}$ will be necessary to disentangle these effects
- The focus of next generation oscillation experiments is to observe $\nu_\mu \rightarrow \nu_e$ transition
- θ_{13} needs to be sufficiently large if one is to have a chance to investigate CP violation in ν sector

Matter Effects

- The experiments looking at ν_μ disappearance measure Δm_{23}^2
- Thus they cannot measure sign of that quantity ie determine <u>mass hierarchy</u>
- The sign can be measured by looking at the rate for $\nu_\mu \rightarrow \nu_e$ for both ν_μ and $\overline{\nu_\mu}$.
- The rates will be different by virtue of different ν_e-e^- CC interaction in matter, independent of whether CP is violated or not
- At L = 750km and oscillation maximum, the size of the effect is given by $A = 2\sqrt{2}\, G_F\, n_e\, E_\nu / \Delta m_{23}^2 \sim 0.15$

Source of Matter Effects



Scaling Laws (CP and Matter)

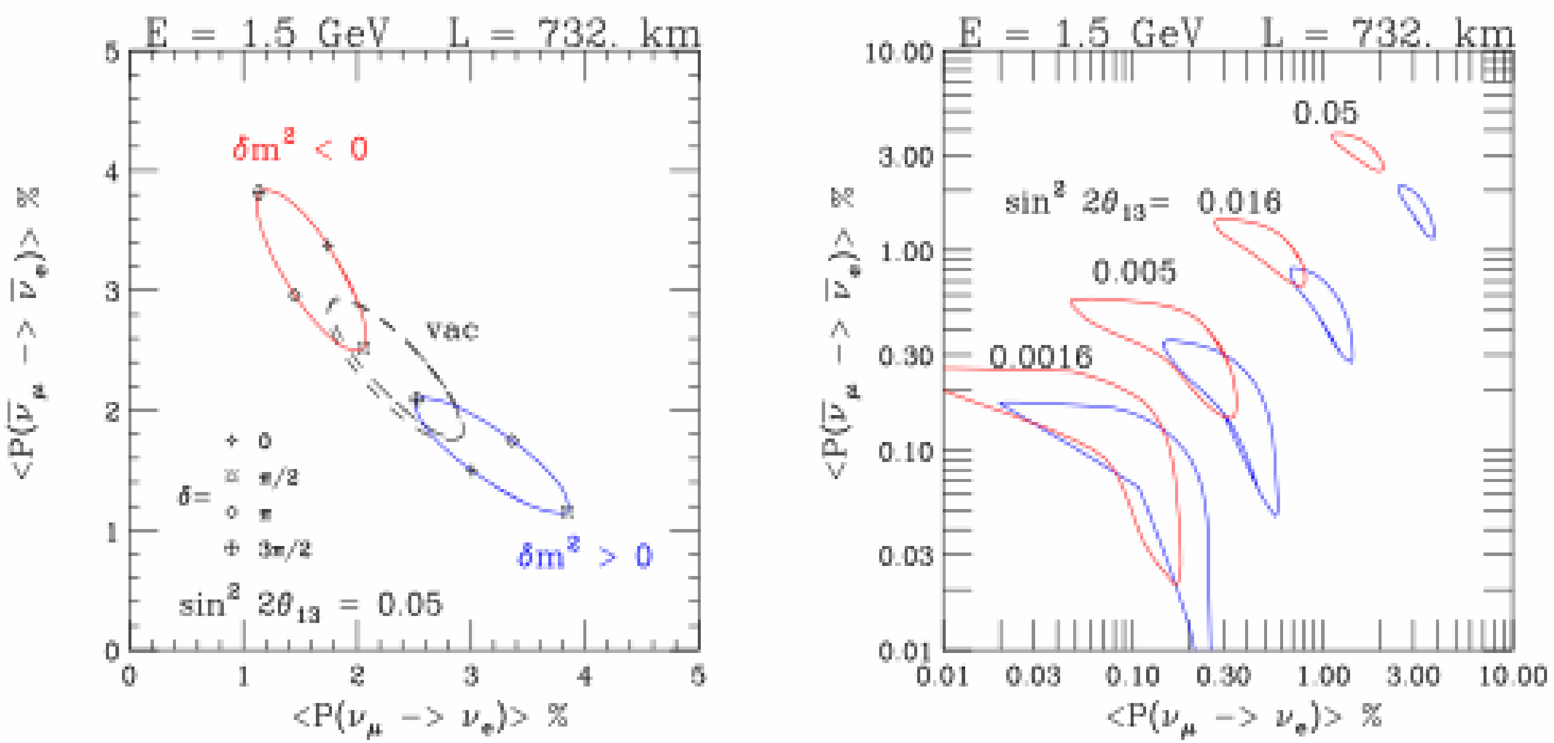
- Both matter and CP violation effects can be best investigated if the dominant oscillation phase ϕ is maximum, ie $\phi = n\pi/2$, n odd (1,3,…)
- Thus $E_\nu \alpha L / n$
- For practical reasons (flux, cross section) relevant values of n are 1 and 3
- Matter effects scale as $\theta_{13}^2 E_\nu$ or $\theta_{13}^2 L/n$
- CP violation effects scale as $\theta_{13} \Delta m_{12}^2 n$

Scaling Laws (2)

- If θ_{13} is small, eg $\sin^2 2\theta_{13} < 0.02$, then CP violation effects obscure matter effects
- Hence, performing the experiment at 2nd maximum (n=3) might be a best way of resolving the ambiguity
- Good knowledge of Δm_{23}^2 becomes then critical
- Several locations (and energies) are required to determine all the parameters

Detector	L(km)	E(GeV)	Relative matter effect	Relative CP effect
JHF	295	0.6	1.0	1.0
NuMI Phase I	712	1.4	2.9	1.0
NuMI Phase II	985	0.7	1.1	3.0

CP and Matter Effects

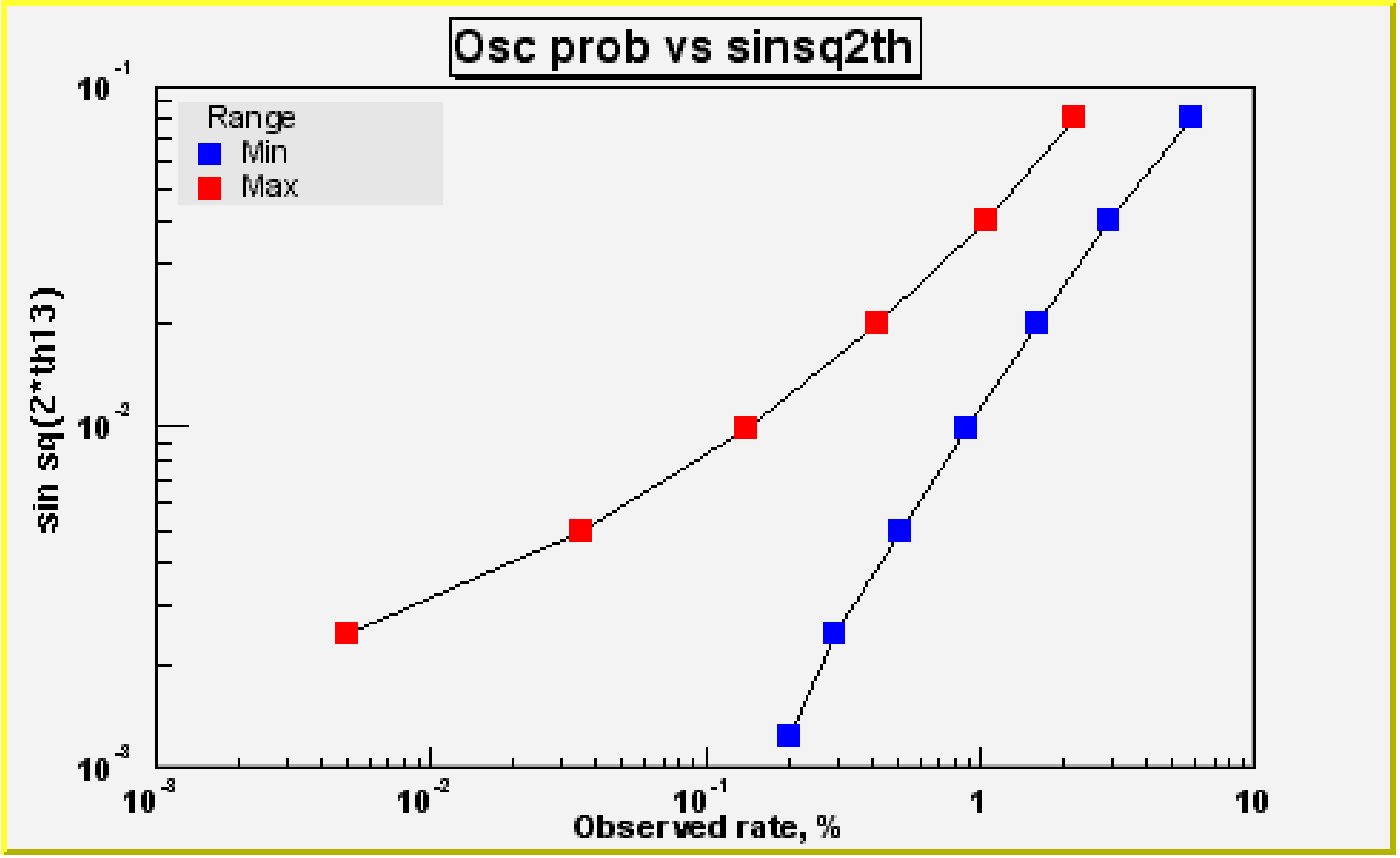


NuMI Capabilities

Important Reminder

- Oscillation Probability (or $\sin^2 2\theta_{\mu e}$) is not unambigously related to <u>fundamental</u> parameters, θ_{13} or U_{e3}^2
- At low values of $\sin^2 2\theta_{13}$ (~0.01), the uncertainty could be as much as a factor of 4 due to matter and CP effects
- Measurement precision of <u>fundamental</u> parameters can be optimized by a judicious choice of running time between ν and $\overline{\nu}$

CP/mass hierarchy/θ_{13} ambiguity



Neutrinos only, L=712 km, E_ν=1.6 GeV, Δm_{23}^2 = 2.5

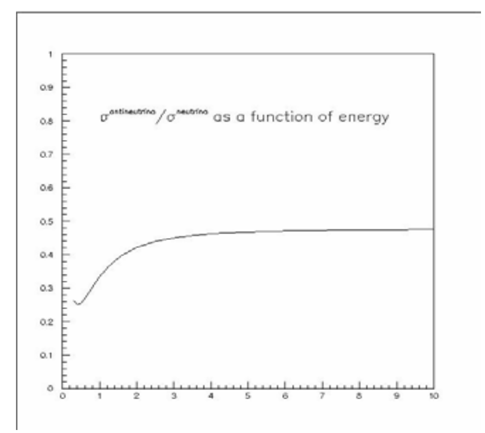
Antineutrinos help greatly

Antineutrinos are crucial to understanding:

- Mass hierarchy
- CP violation
- CPT violation

High energy experience: antineutrinos are ‘expensive’.

For the same number of POT ← Ingredients: $\sigma(\pi^+) \sim 3\sigma(\pi^-)$ (large x)



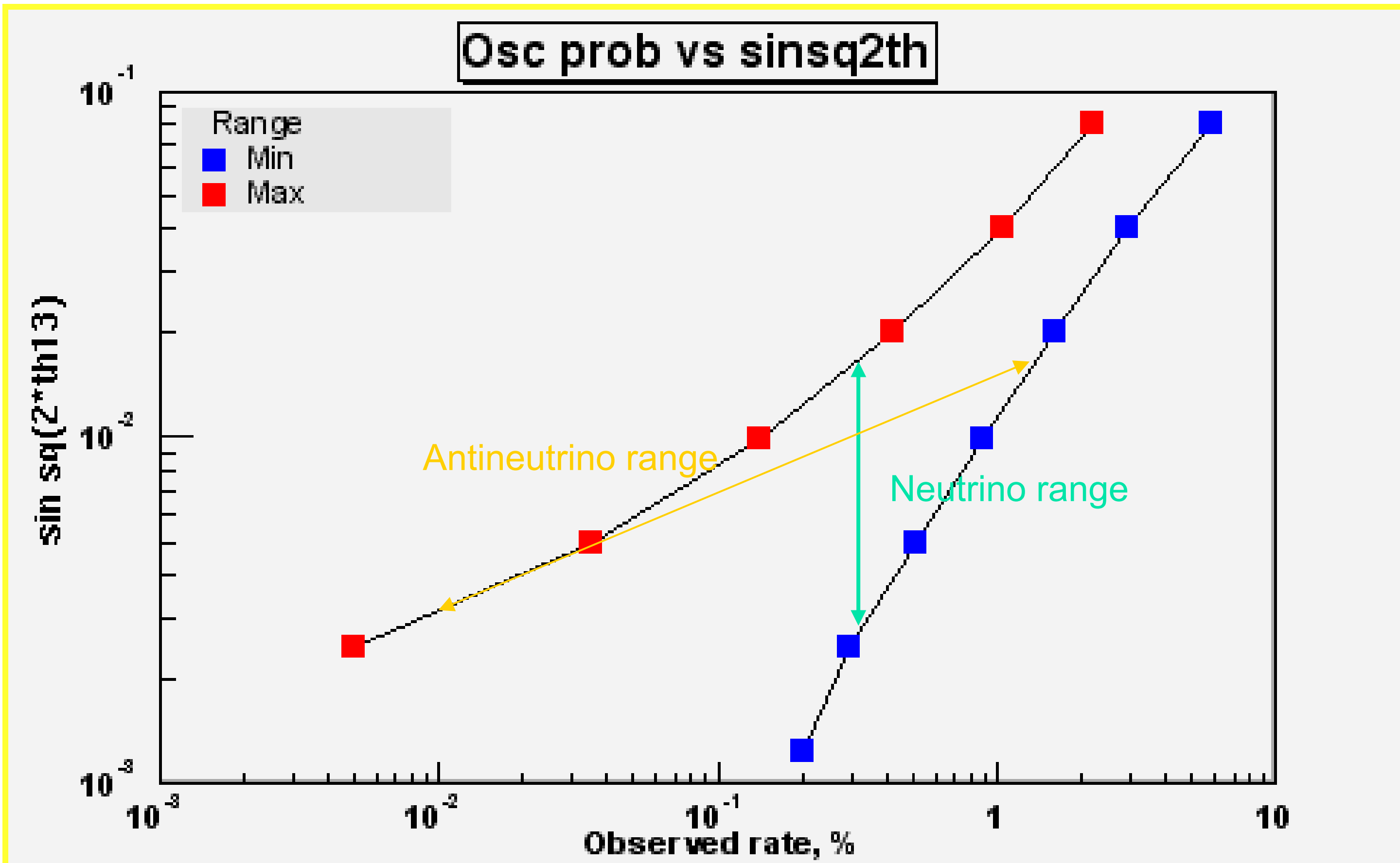
(no Pauli exclusion)

NuMI ME beam energies:

$\sigma(\pi^+) \sim 1.15\sigma(\pi^-)$ (charge conservation!)

Neutrino/antineutrino events/proton ~ 3

How antineutrinos can help resolve the CP/mass hierarchy/θ_{13} ambiguity

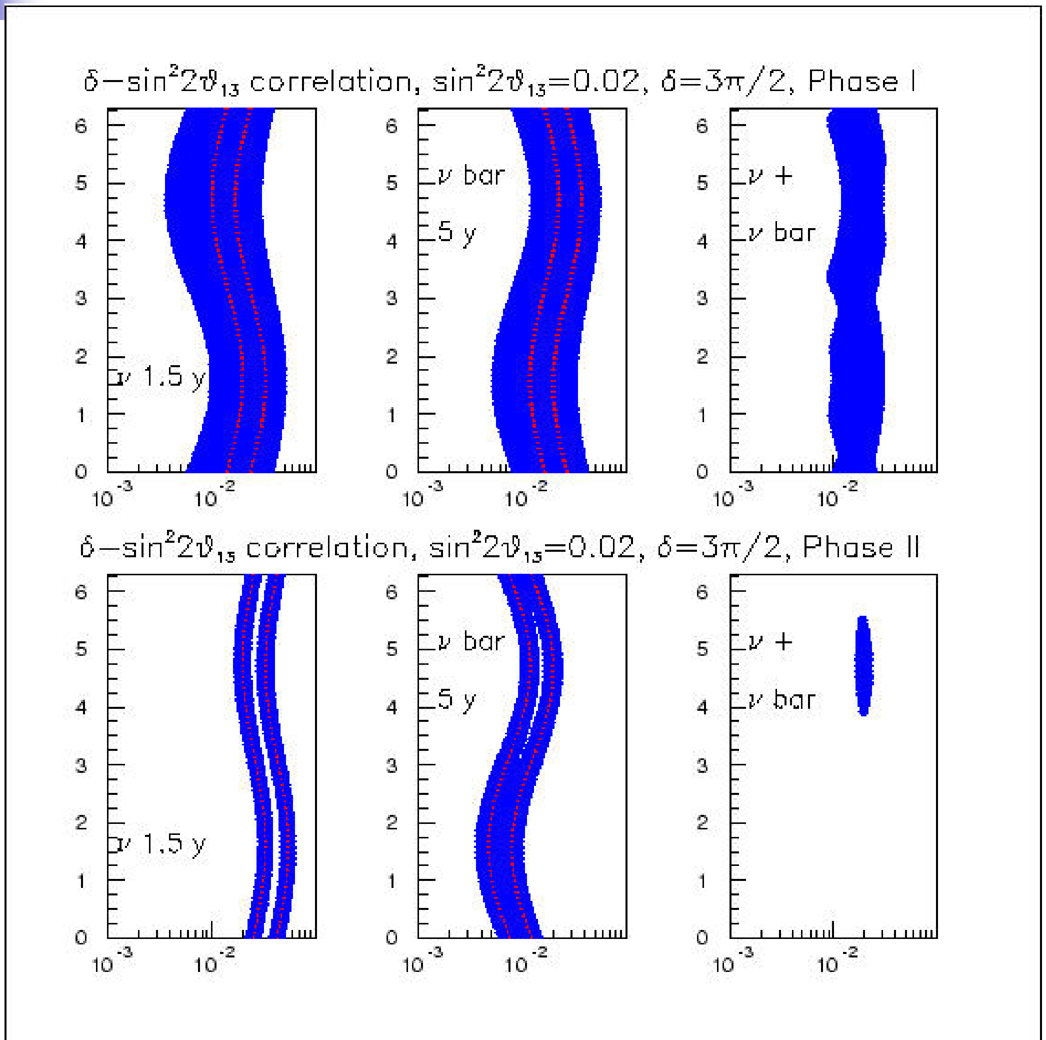


$L=712$ km, $E_\nu=1.6$ GeV, $\Delta m_{23}^2 = 2.5$

Optimum Run Strategy

- Start the experiment with neutrinos
- Run in that mode until either:
  - A definite signal is seen, or
  - Potential sensitivity with antineutrinos could be significantly higher (x 2?) than with neutrinos
- Switch to antineutrinos and run in that mode until either:
  - A definite signal is seen
  - Potential sensitivity improvement from additional running would be better with neutrinos

Sensitivy for Phases I and II (for different run scenarios)



We take the Phase II to have 25 times higher POT x Detector mass

Neutrino energy and detector distance remain the same

Concluding Remarks

- Neutrino Physics appears to be an exciting field for many years to come
- Most likely several experiments with different running conditions will be required
- Off-axis detectors offer a promising avenue to pursue this physics
- NuMI beam is excellently matched to this physics in terms of beam intensity, flexibility, beam energy, and potential source-to-detector distances that could be available
- We have great interest in forming a Collaboration that could work on these opportunities