Neutrino beams: On and Off-axis

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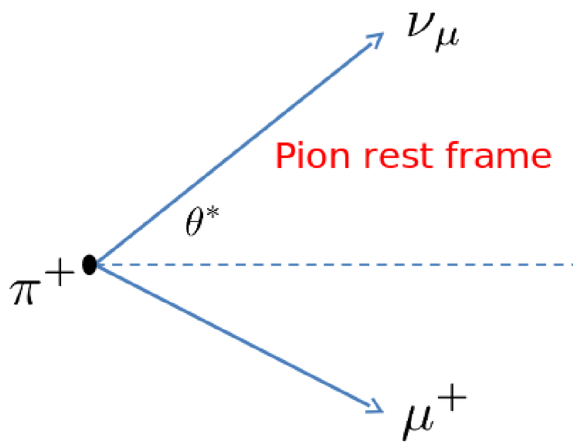
Kinematics of On/Off Axis Beams

Source: hep-ex/0111033



- Conserve 4-mometum in the pion rest frame and the lab frame
- Boost to the lab frame: $m_\mu^2 = m_\pi^2 - 2E_\nu^* m_\pi$

$$\begin{aligned} p_{\mu_\nu} &= (E_\nu, E_\nu \sin\theta, 0, E_\nu \cos\theta) \\ &= (\gamma E_\nu^*(1+\beta\cos\theta^*), E_\nu^* \sin\theta^*, 0, E_\nu^*(\beta + \cos\theta^*)) \end{aligned}$$

- Using the components $\frac{p_{\nu_1}}{p_{\nu_3}}$ can get the relationship

$$\tan\theta = \frac{E_\nu^* \sin\theta^*}{\gamma E_\nu^* (\beta + \cos\theta^*)} \approx \frac{E_\nu^* \sin\theta^*}{E_\nu}$$

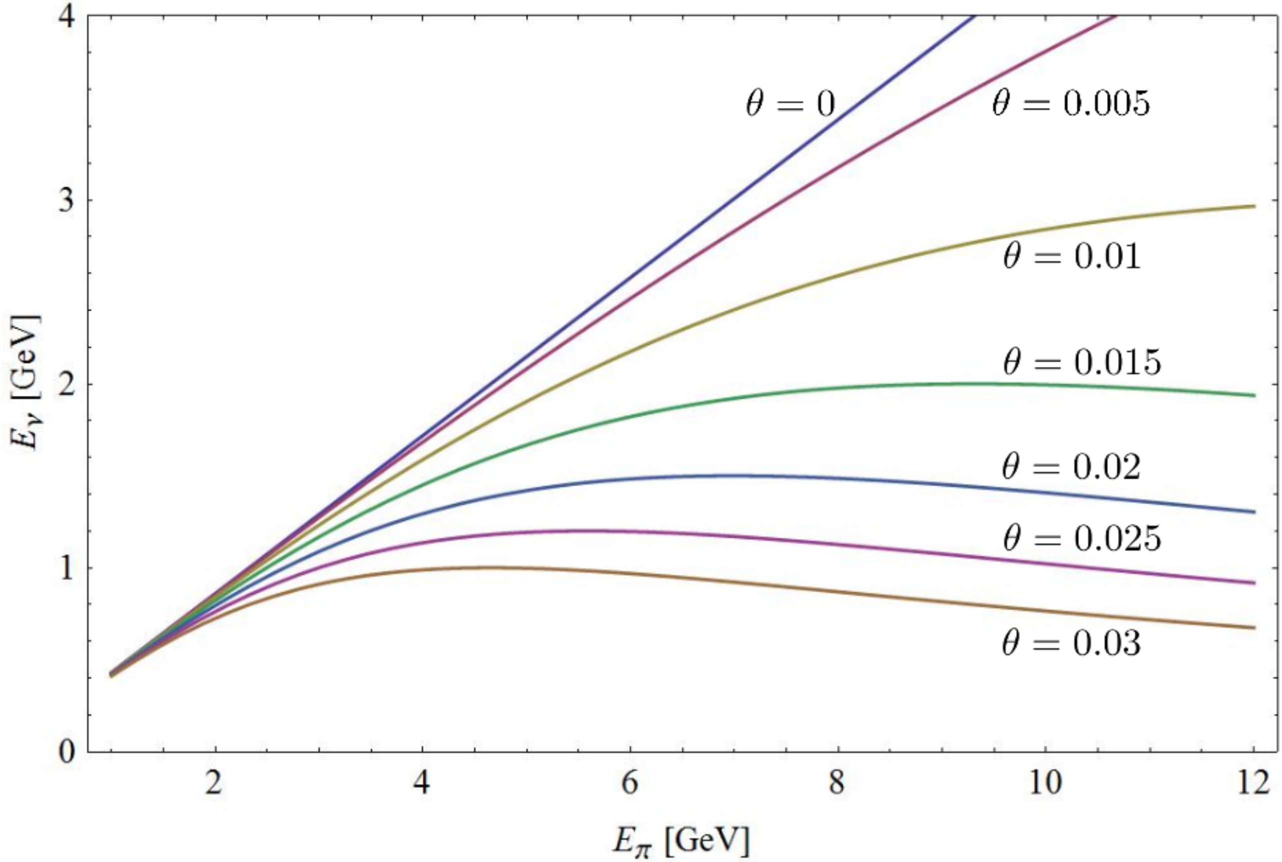
- We assume an ultra-relativistic neutrino where $\beta \approx 1$
- Now we can get neutrino energies as a function of pion energies and angle θ with which the beam is off-axis

$$\gamma = \frac{E_\pi}{m_\pi} \approx \frac{E_\nu}{E_\nu^* (1 + \cos\theta^*)}$$

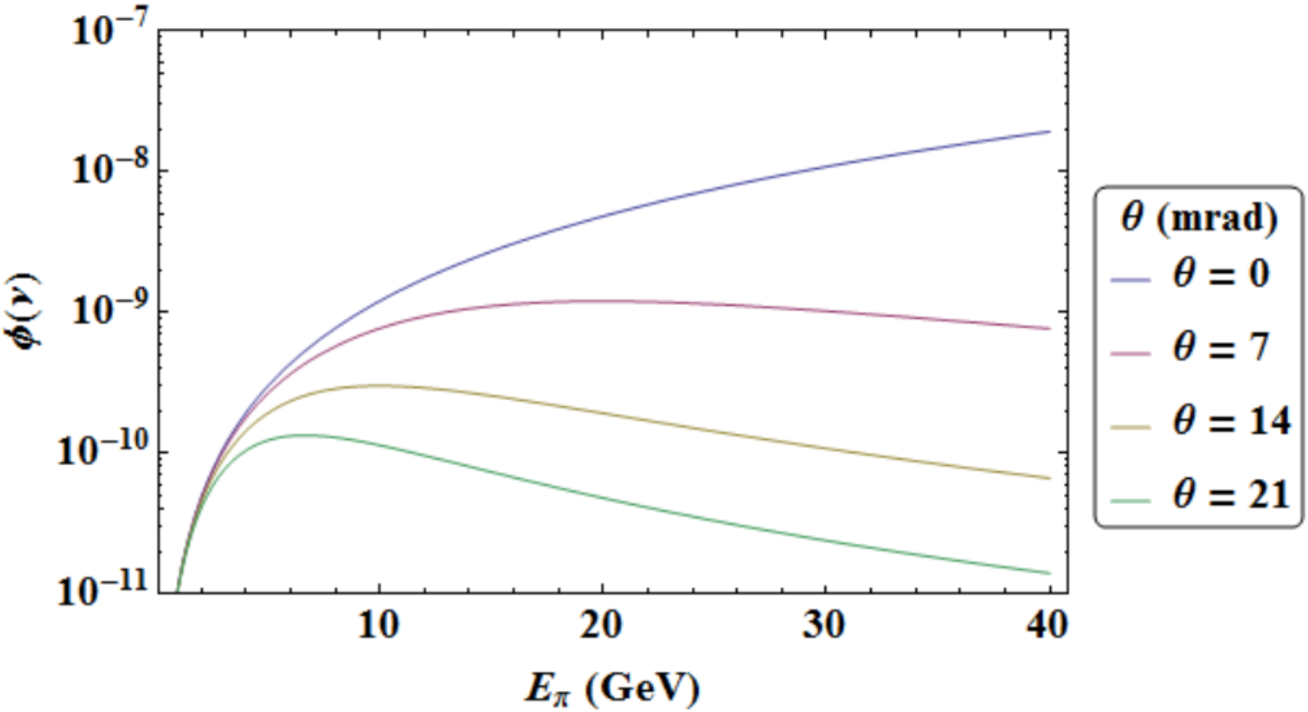
Where:

$$\cos\theta^* \approx \sqrt{1 - \frac{E_\nu^2}{E_\nu^{*2}} \tan^2\theta}$$

$$E_\nu^* = 30\mathrm{MeV}$$



4
3
2
1
0
2
4
6
8
10
12
E_ν [GeV]
E_π [GeV]
$\theta = 0$
$\theta = 0.005$
$\theta = 0.01$
$\theta = 0.015$
$\theta = 0.02$
$\theta = 0.025$
$\theta = 0.03$



This graph of the neutrino flux vs. the parent pion energy show how the neutrino flux peaks as the off axis angle is increased.

Off-axis tunes event rates

From NOνA : arxiv.org/0503053

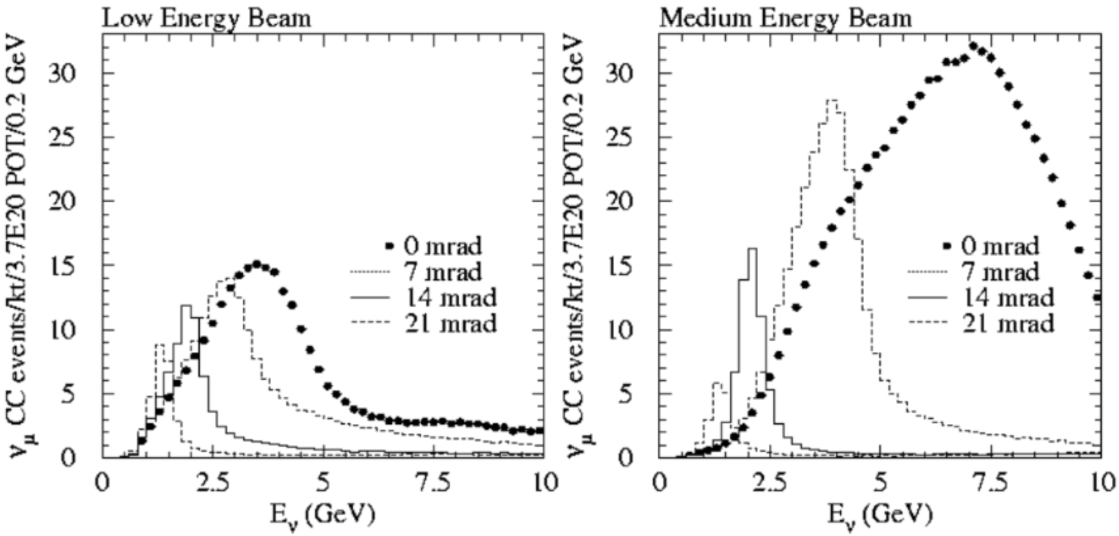


Fig. 4.4: CC ν_μ event rates expected under a no-oscillation hypothesis at a distance of 800 km from Fermilab and at various transverse locations for the NuMI low-energy beam configuration (left) and medium-energy beam configuration (right).

Putting Off-Axis Flux and Event Probabilities Together

From T2K: arxiv/1211.0469v3

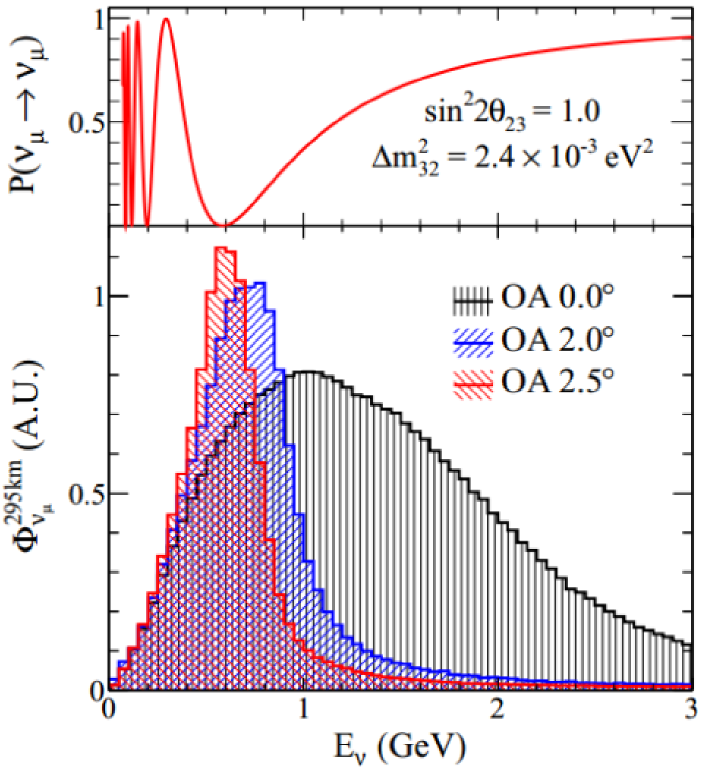


FIG. 1: Muon neutrino survival probability at 295 km and neutrino fluxes for different off-axis angles.

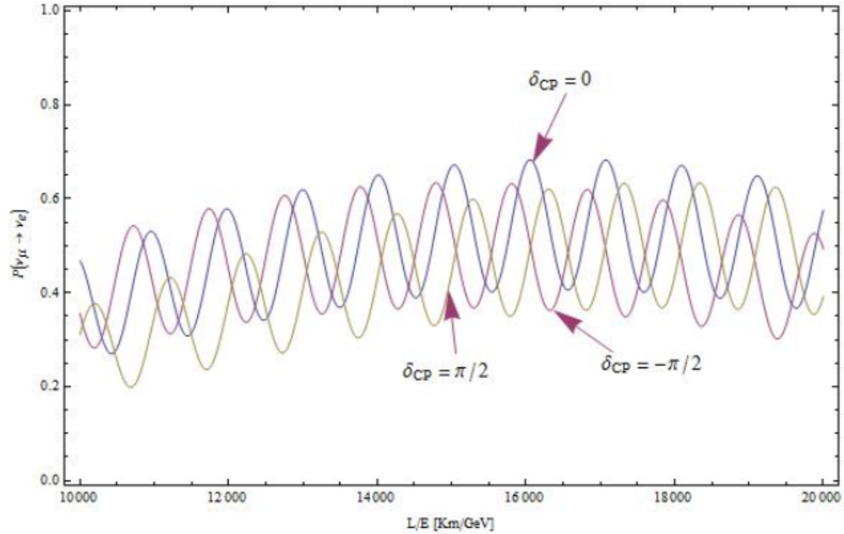
Picking L/E For Tests of CPV

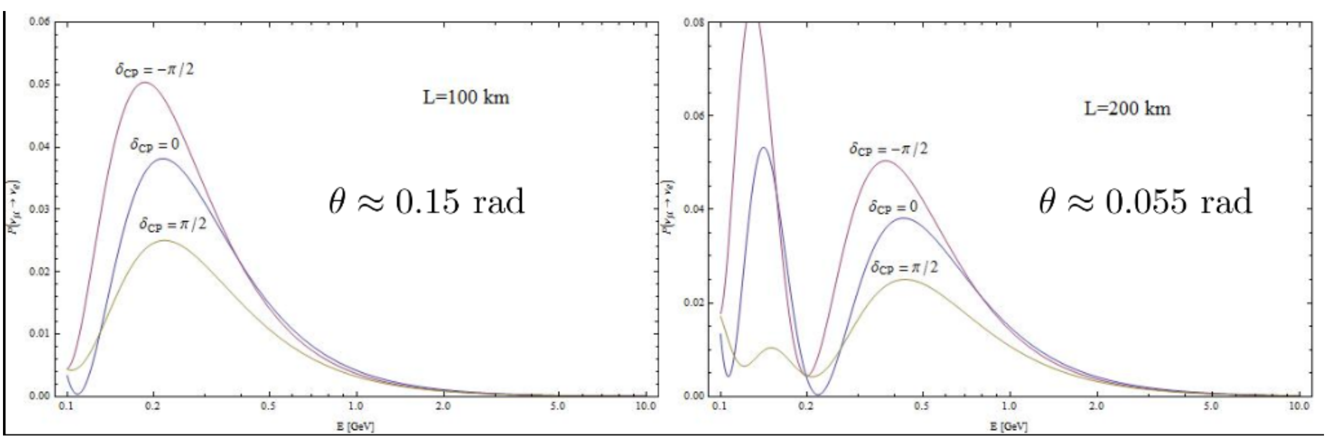
- Want a medium baseline experiment to eliminate matter effects which are dependent on the hierarchy
  - K2K or T2k
- Can look at vacuum oscillations $\nu_\mu \to \nu_e$ and tune L/E to the points in the spectrum where the probability differences are the largest for different CP phases

$$P_{\mu e}(L/E) = -4\sum_{i>j}\mathrm{Re}(U^*_{\mu i}U_{ei}U^*_{ej}U_{\mu j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j}\mathrm{Im}(U^*_{\mu i}U_{ei}U^*_{ej}U_{\mu j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

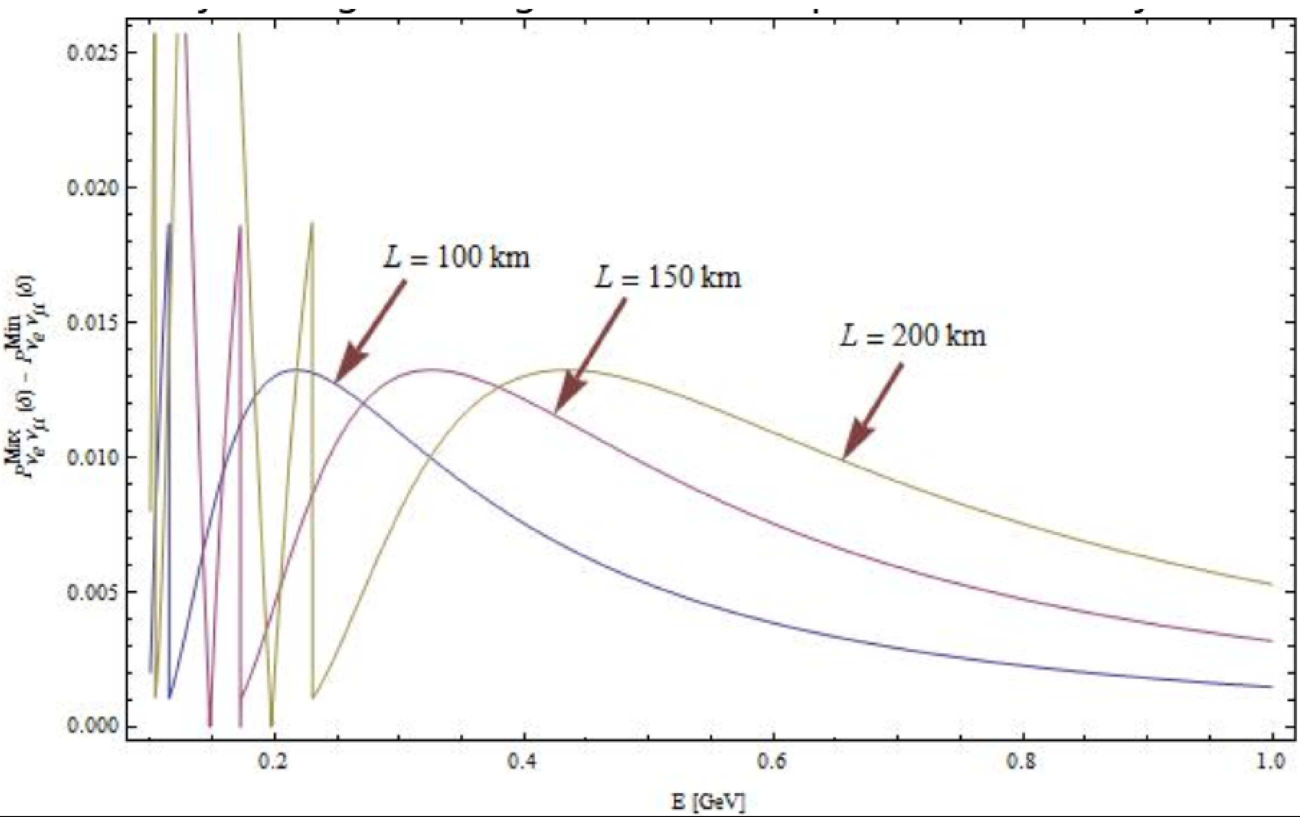
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

- For the choice of L for the detector, tune the off-axis angle to produce at the max of the oscillations
- Pick L $\approx$ 100 so that the neutrino energy is $\geq$ 100 MeV



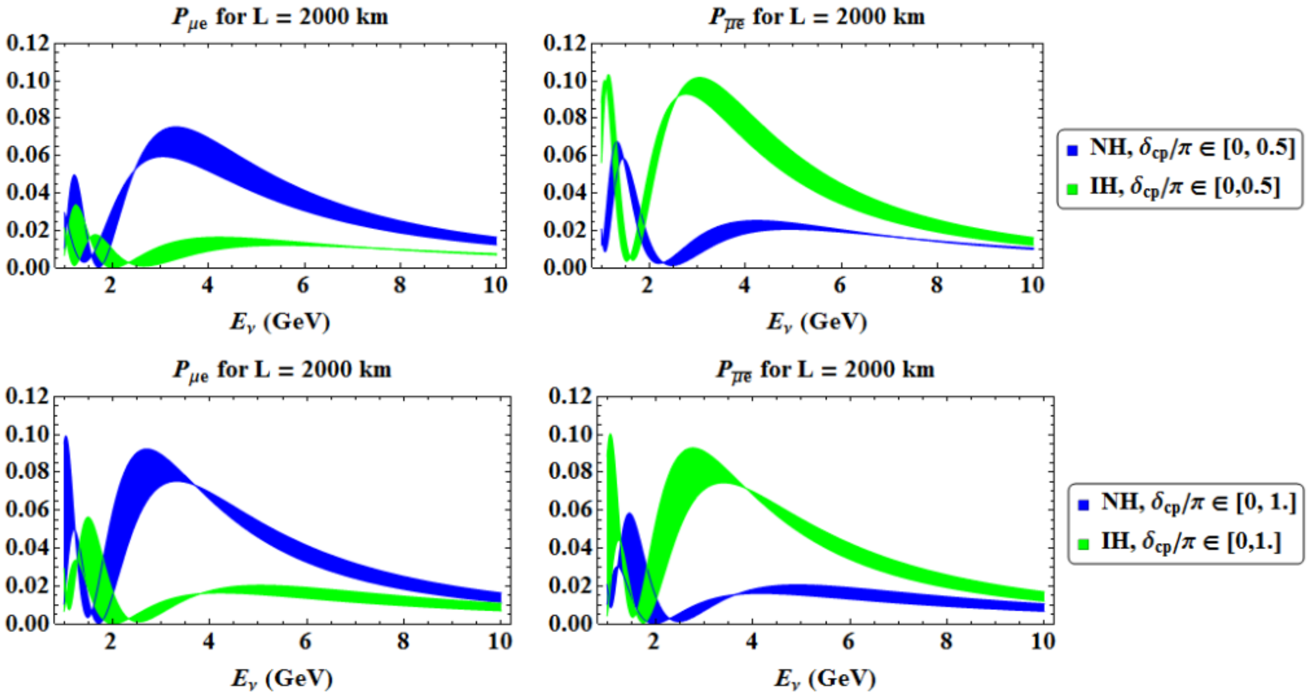


It has been suggested (arXiv:1301.4333) that the CP asymmetry given by $P^{\max}_{\nu_\mu \nu_e} - P^{\max}_{\nu_\mu \nu_e}$ may be a good diagnostic for CP phase sensitivity.



Picking L/E For Tests of MH

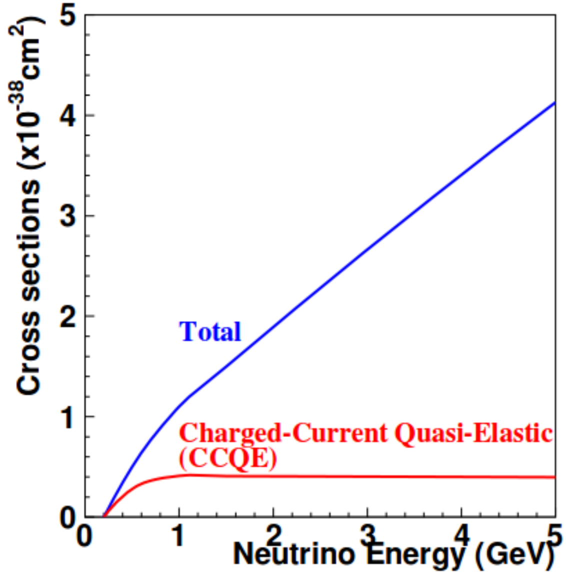
- Need Large L/E
- Search for ν_e appearance from a ν_μ source
- CP effects are then small corrections to MH effects
- NOνA and LBNE



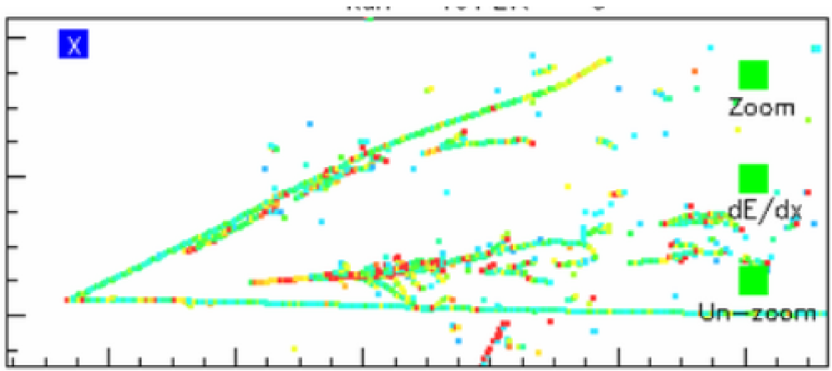
The difference between NH and IH at the first oscillation maximum becomes more distinct as L increases. NOνA and the LBNE are experiments that have the baseline to make this type of measurement. NOνA benefits from off-axis spectrum tuning because it has a shorter baseline than LBNE which is on axis.

ν events: some are better than others. CC vs. NC

- More neutrino events is the name of the game for δ_{CP} and MH experiments. But, not all neutrino events are "good"
- Charged current events do not have a neutrino as their end product: $\rightarrow$ collecting all the energy in the event will be easier $\rightarrow$ Better energy reconstruction
- CC has a lepton as a product: can tag the neutrino and determine if μ or e $\rightarrow$ will result in better analysis with smaller systematics

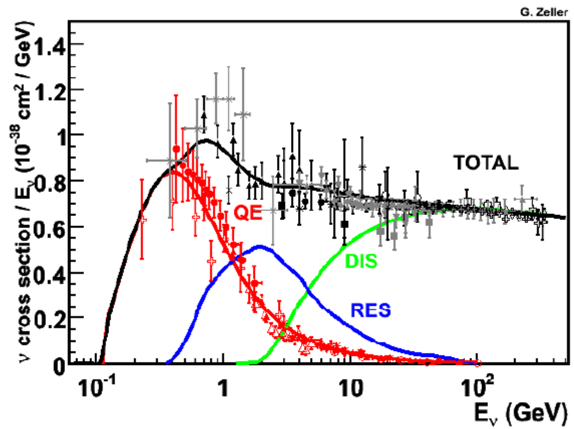


NC: ν scatters off something (proton, electron, ...)
In a Cherenkov detector: only an e-like signal could be produced.
$\rightarrow$ But this e event could just as well have come from a muon NC eventIn a LAr detector:
Can detect "all" NC events
More details on event because of tracking!
Argon atoms are big and complicated! Need to better study what is going on in the nucleus



ν events: some are better than others. QE and the rest

Furthermore, not all CC events are nice:
Higher energy ν s will undergo more complex interactions.
Detectors cannot interpret very well what is going on with non-QE events.
$\rightarrow$ energy not reconstructed correctly



CC QE:

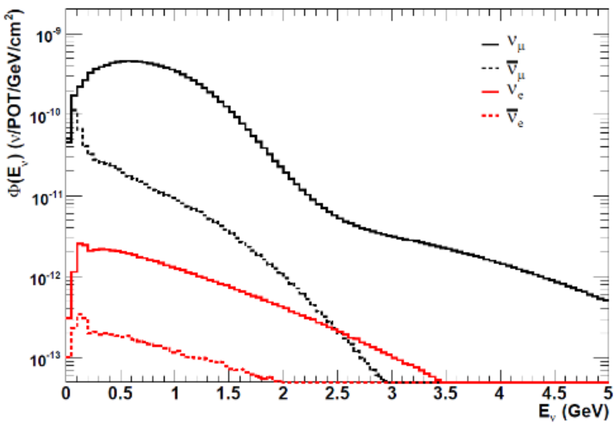
$$\nu_\mu + n \rightarrow \mu^- + p$$

Resonant π Production:

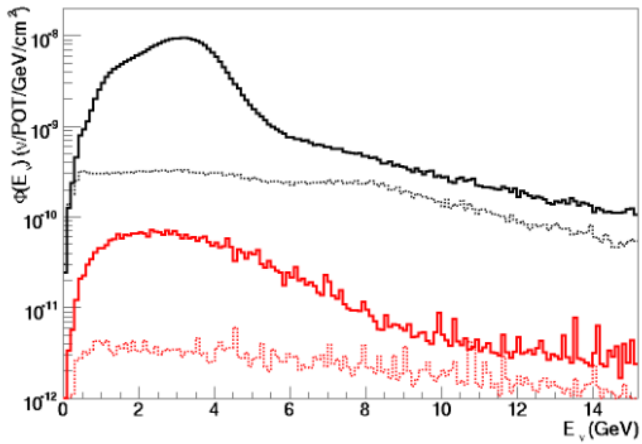
$$\nu_\mu + N \rightarrow \mu^- + N^* \rightarrow \mu^- + \pi + N'$$

Beam Composition

MiniBooNE



MINOS ND



As θ varies the composition of the beam is changing as well.

ν_e product of secondary decays $\rightarrow$ kinematics are different $\rightarrow$ spectrum changes differently than ν_μs

A change in ratio ν_e/ν_μ of a few % can have large consequences.

P_{osc} small $\rightarrow$ 10 osc / 100 bkgd very different from 10 osc / 50 bkgd.

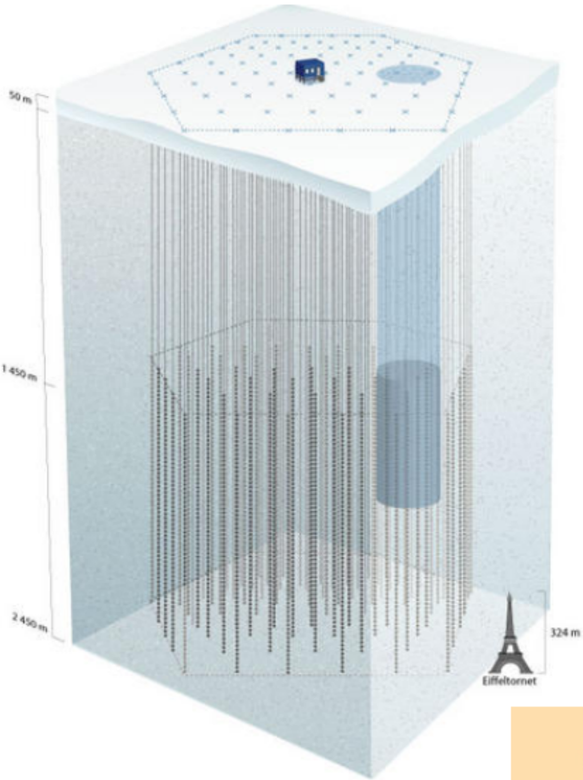
Pros and Cons: Summary

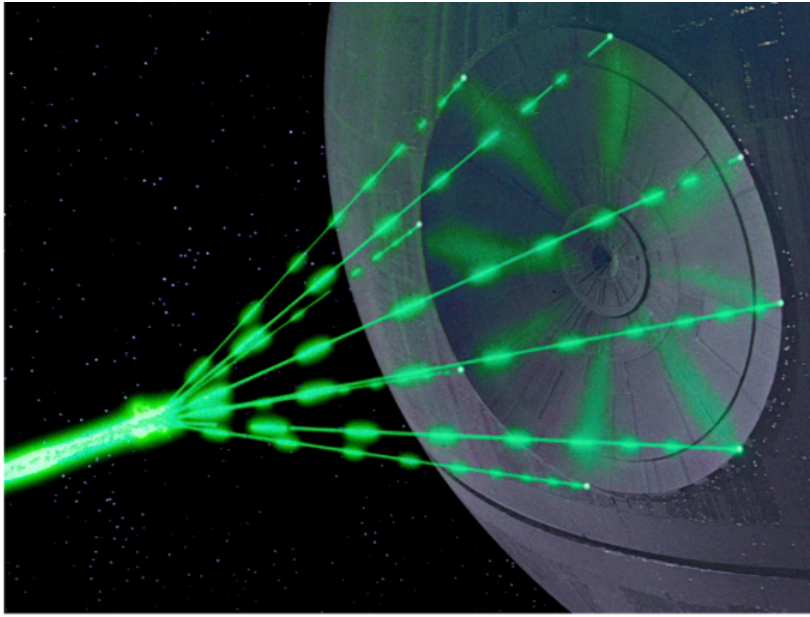
Off-Axis:

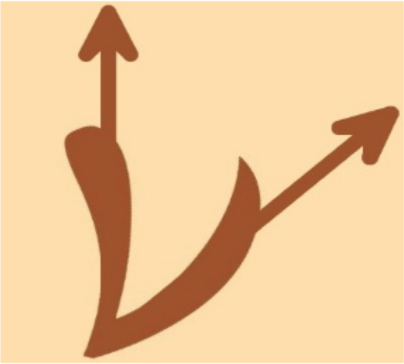
- Lower ν_e backgrounds.
- Can only measure oscillation at a single value of L/E (or requires multiple detectors).
- Fewer high energy events (less complicated interactions, fewer NC events).

On-Axis:

- Larger ν flux.
- Not a counting experiment (shape fitting).
- Requires good energy resolution: Resolving E is necessary for figuring out L/E. Lower resolution of E makes it harder to determine oscillations.


50 m
1 450 m
2 450 m
324 m
Eiffeltornet





Backup

ν s of the future: superbeam

This is the Intensity, not the Energy frontier! Large Energy νs not needed or desired because:
- Can always change L
- In a ν_μ beam, at large E_ν, intrinsic ν_e fluxes are higher
- Large E neutrinos lead to more complicated interactions

$\rightarrow$ in fact, as shown previously, one would like to keep the ν energy to less than 2 GeV

The main problem with off-axis experiments is that while they may be at the sweetspot for oscillations, the ν flux is much smaller.

$\rightarrow$ can compensate this by using a high-intensity beam $\rightarrow$ SuperBeam!

To get the ν intensities needed need a few MW beam power.

$\rightarrow$ Project-X !?

ν s of the future: ν factory

A Superbeam is a more powerful and more expensive version of what we already know how to build.
Another option is a different type of ν source: muon accelerator.
Muons produced in the same way as for a ν beam, but then captured and accelerated in circular accelerator. Do this FAST!
Then let muons decay...
Can capture μ^+ and μ^-. What is so nice about this?
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \rightarrow$ 50% ν_e, $\bar{\nu}_\mu$
$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e \rightarrow$ 50% ν_μ, $\bar{\nu}_e$
$\rightarrow$ Great for oscillations!
Intrinsic backgrounds from beam $\approx 10^{-4}$ effect, not 1% $\rightarrow$ more sensitive
Can do muon appearance, not electron appearance $\rightarrow$ bkgd further reduced
SO MUCH MORE PHYSICS!!!

From NOνA : arxiv.org/0503053

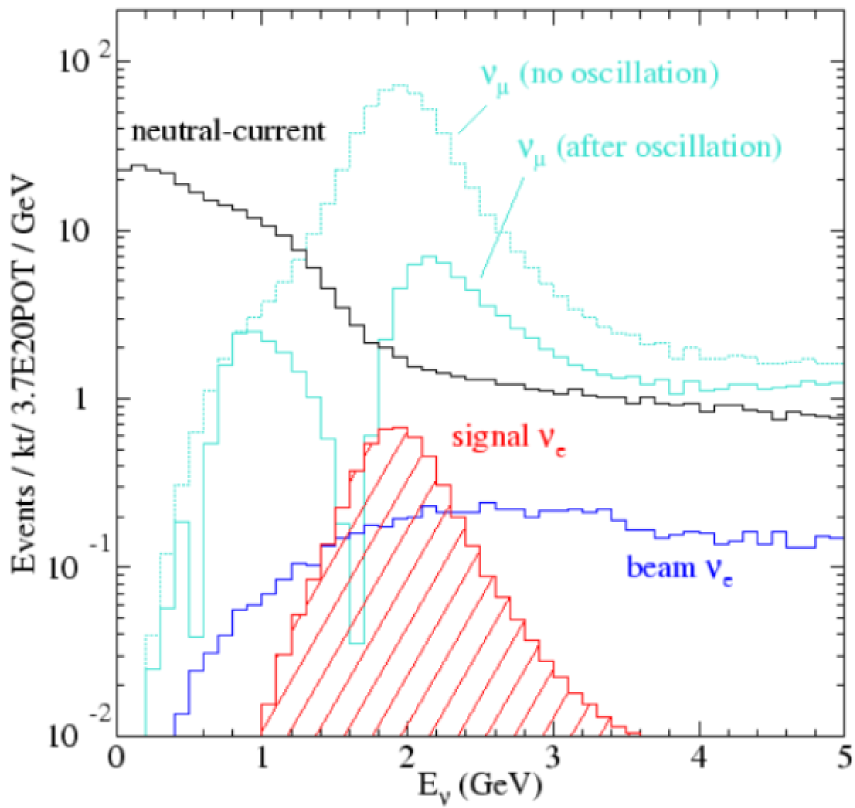
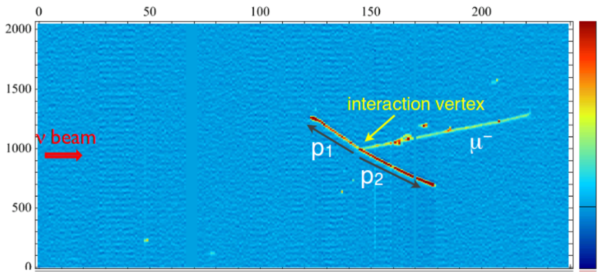


Fig. 4.5: Simulated energy distributions for the ν_e oscillation signal, intrinsic beam ν_e events, neutral-current events and ν_μ charged-current events with and without oscillations. The simulation used $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2, $\sin^2(2\theta_{23}) = 1.0$, and $\sin^2(2\theta_{13}) = 0.04$. An off-axis distance of 12 km at 810 km was assumed.

How to Decide: Detector Technology

Liquid Argon:



Great tracking capabilities

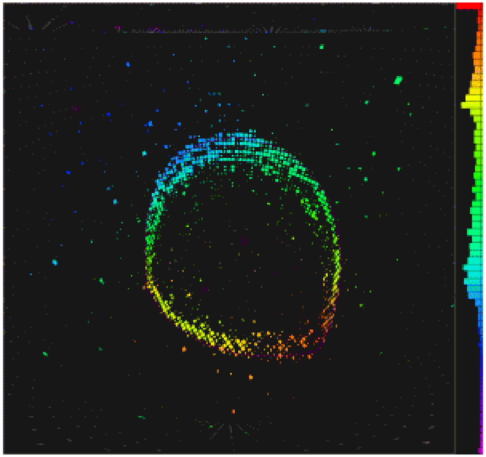
→ can distinguish events well

Energy deposition (dE/dx)

→ good energy reconstruction

New technology: needs testing to see how good it can perform Can it be expanded to huge experiments?

Cherenkov Light:



We know how to cover huge areas with PMTs

Backgrounds hard to reduce

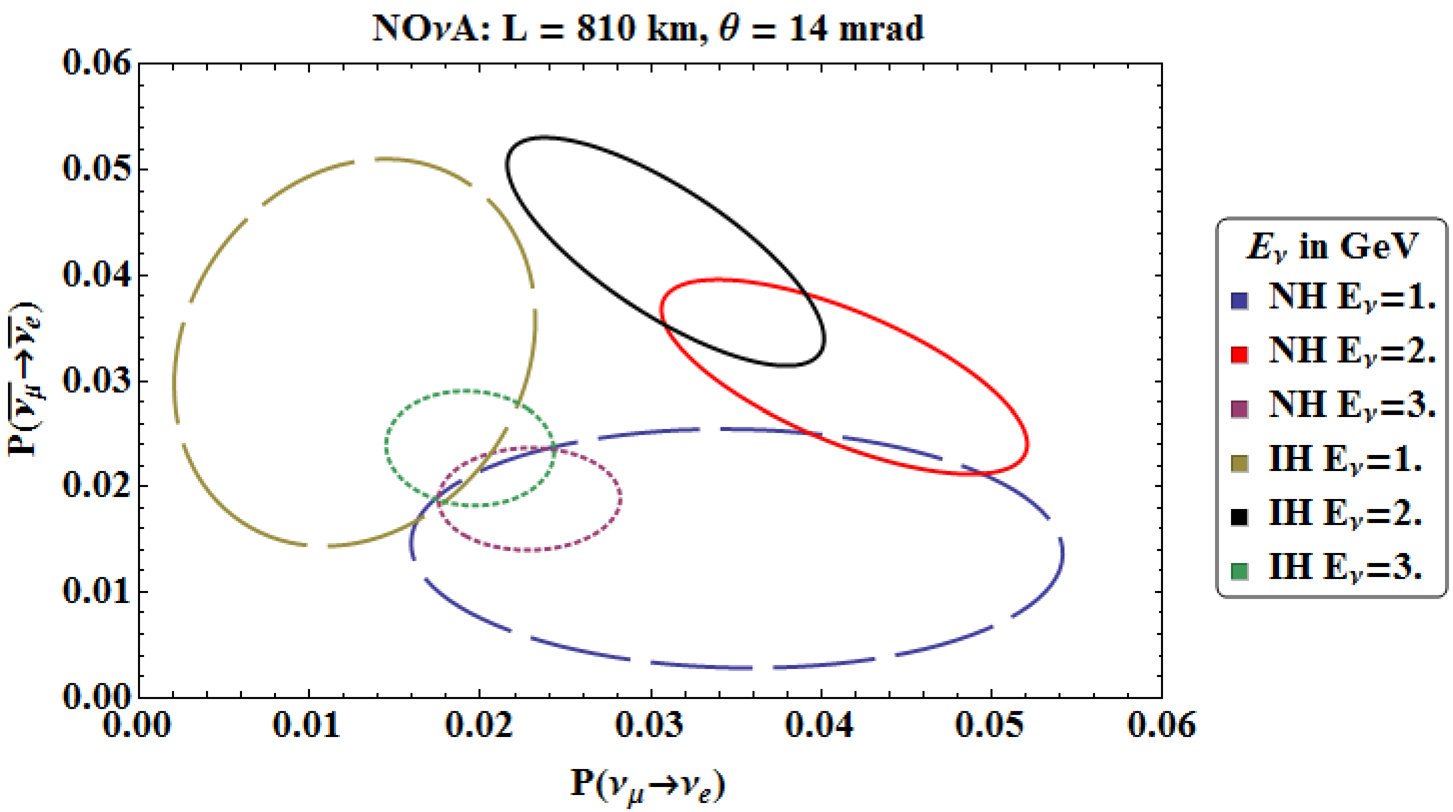
→ need large statistics

How to Decide: What ν sources?

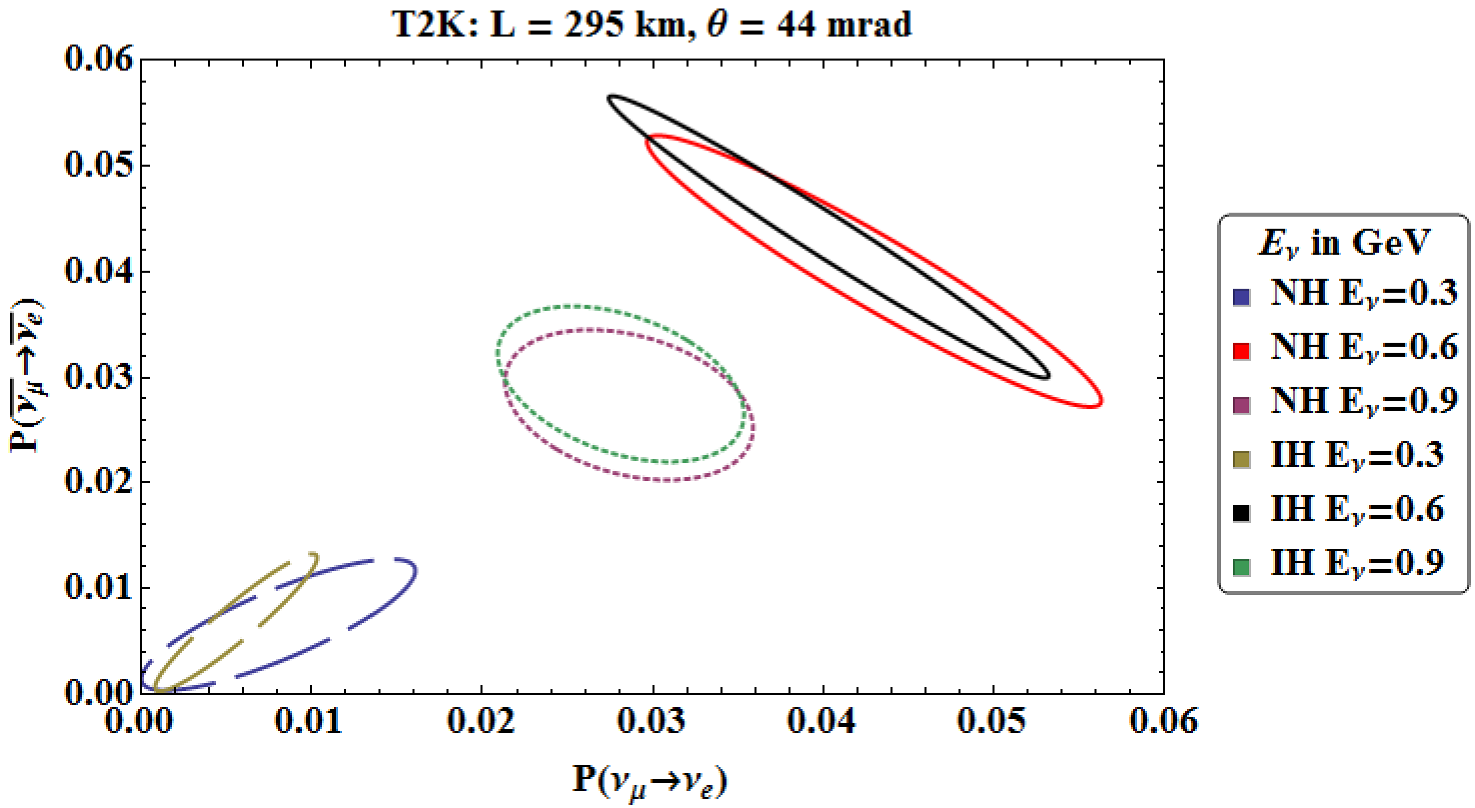
Need one or more L/E. Can set E by
1) changing proton E
2) change beam angle
L is variable for surface experiment (crazy!). Otherwise set by available mines/excavation cost.
Available beams:
- Cern Neutrino to Gran Sasso: 4.5×10^19 POT/year @ 400 GeV
- NuMI: 2×10^20 POT/year @ 8 GeV (upgrades can bring POT up x2)
-J-PARK: 1.44×10^20 POT/year @ 30 GeV then upgraded to 50 GeV
Future:
- Projext X
- muon collider

LBL Experiments

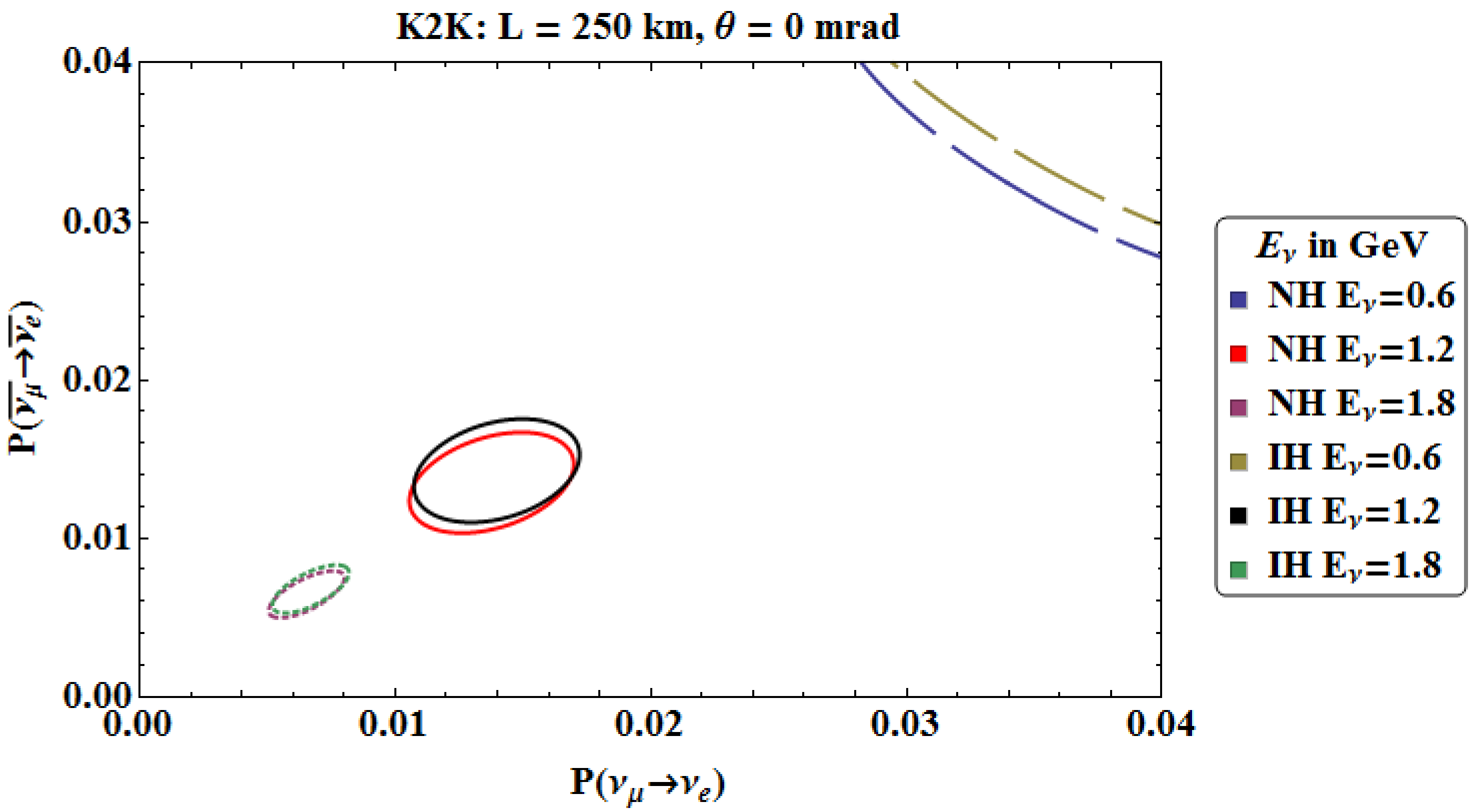
Name	BL	Enu (GeV)	PS Energy (GeV)	L (km)	Theta
NOvA	LBL	2	120	810	15 mrad
T2K	LBL	0.6	50	295	2-3 deg
K2K	LBL	1.2	12	250	0
OPERA	LBL	17	400	730	0
MINOS	LBL	3.3	120	735	0
LBNE (future)	LBL	1-10	60-100	1300	0
miniBooNE	LBL	~1	8	450	33.5 mrad

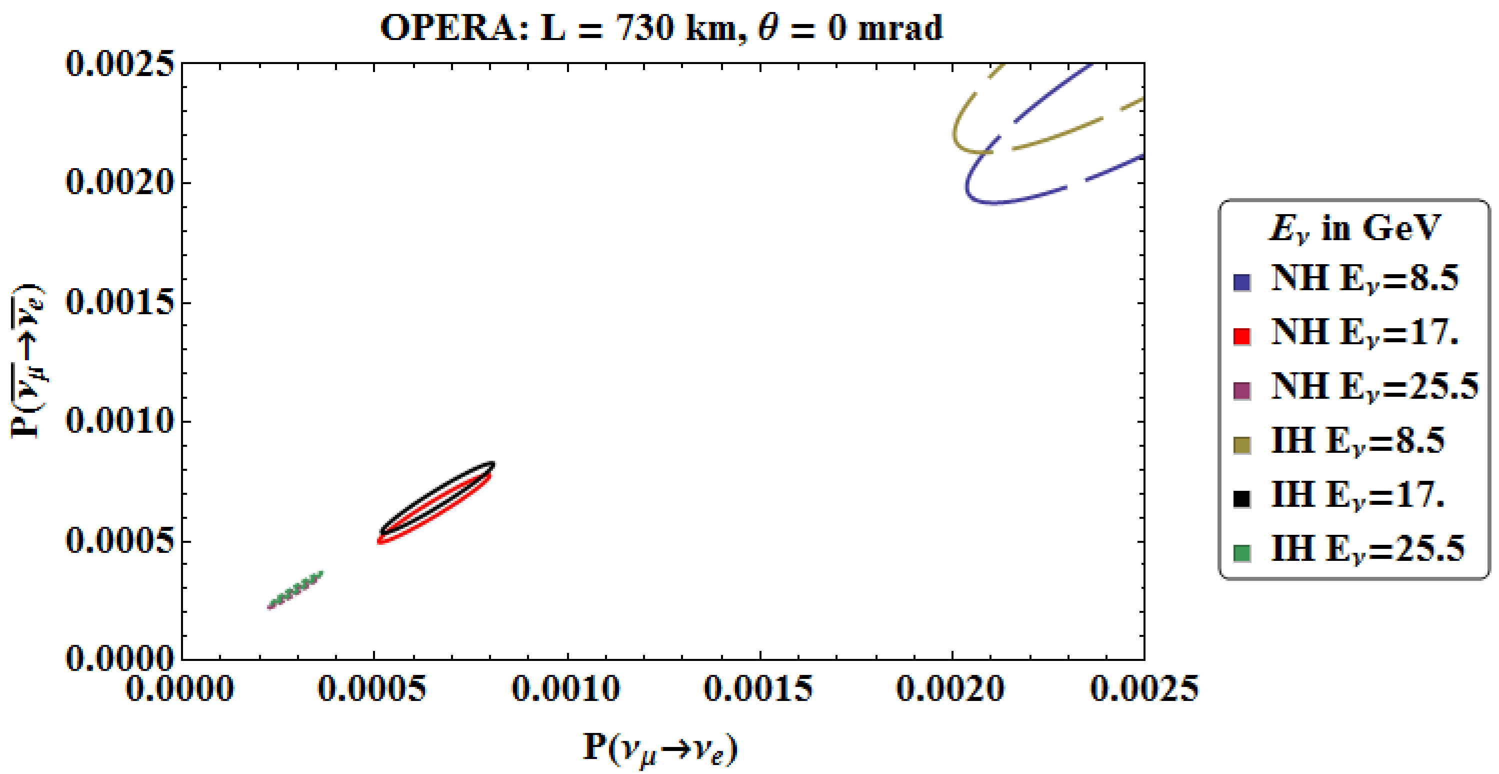


NOνA: L = 810 km, θ = 14 mrad
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.00
0.01
0.02
0.03
0.04
0.05
0.06
P(ν̄μ→ν̄e)
P(νμ→νe)
Eν in GeV
NH Eν=1.
NH Eν=2.
NH Eν=3.
IH Eν=1.
IH Eν=2.
IH Eν=3.

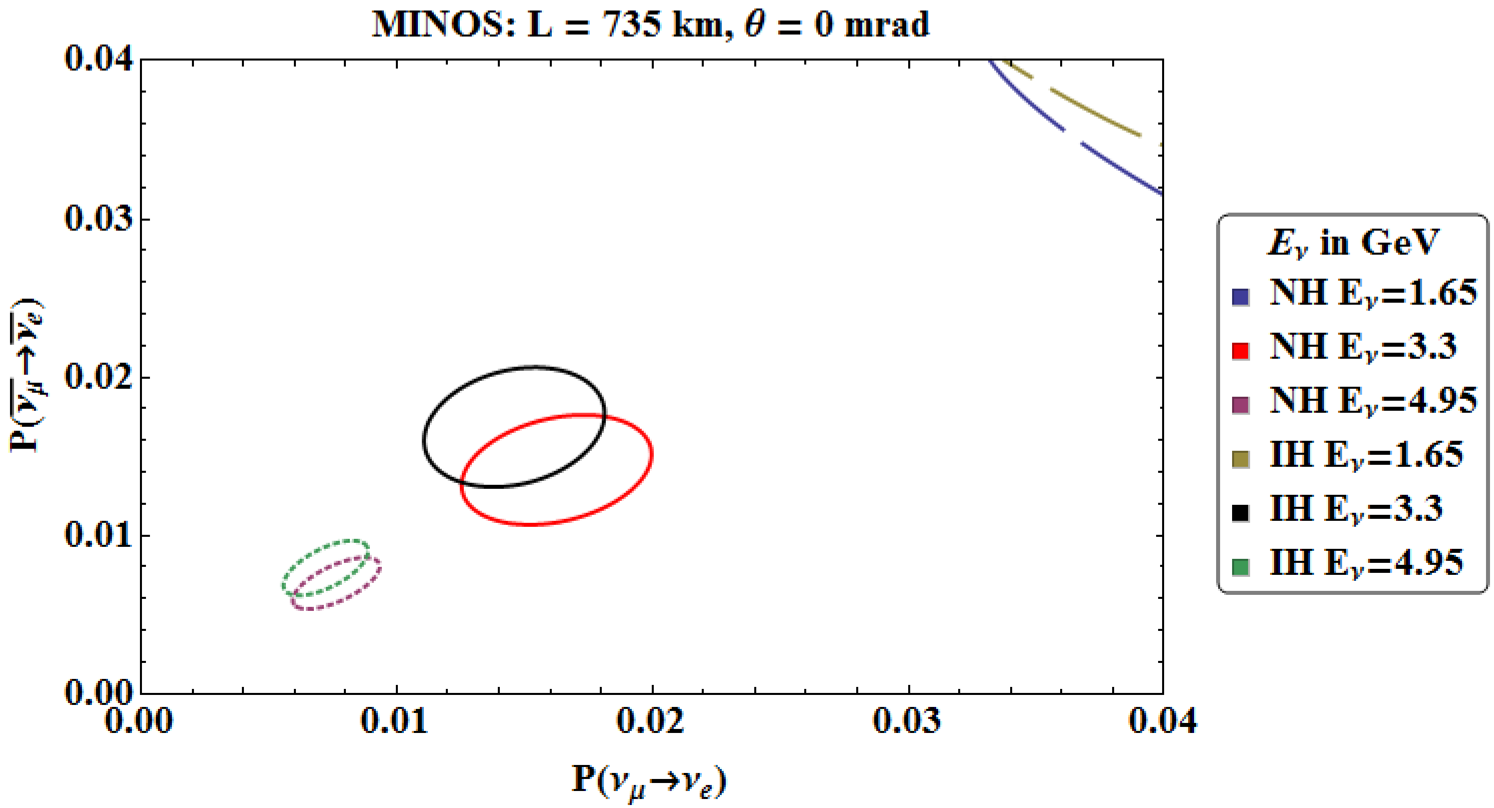


T2K: L = 295 km, θ = 44 mrad
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.00
0.01
0.02
0.03
0.04
0.05
0.06
P(ν̄μ→ν̄e)
P(νμ→νe)
Eν in GeV
NH Eν=0.3
NH Eν=0.6
NH Eν=0.9
IH Eν=0.3
IH Eν=0.6
IH Eν=0.9

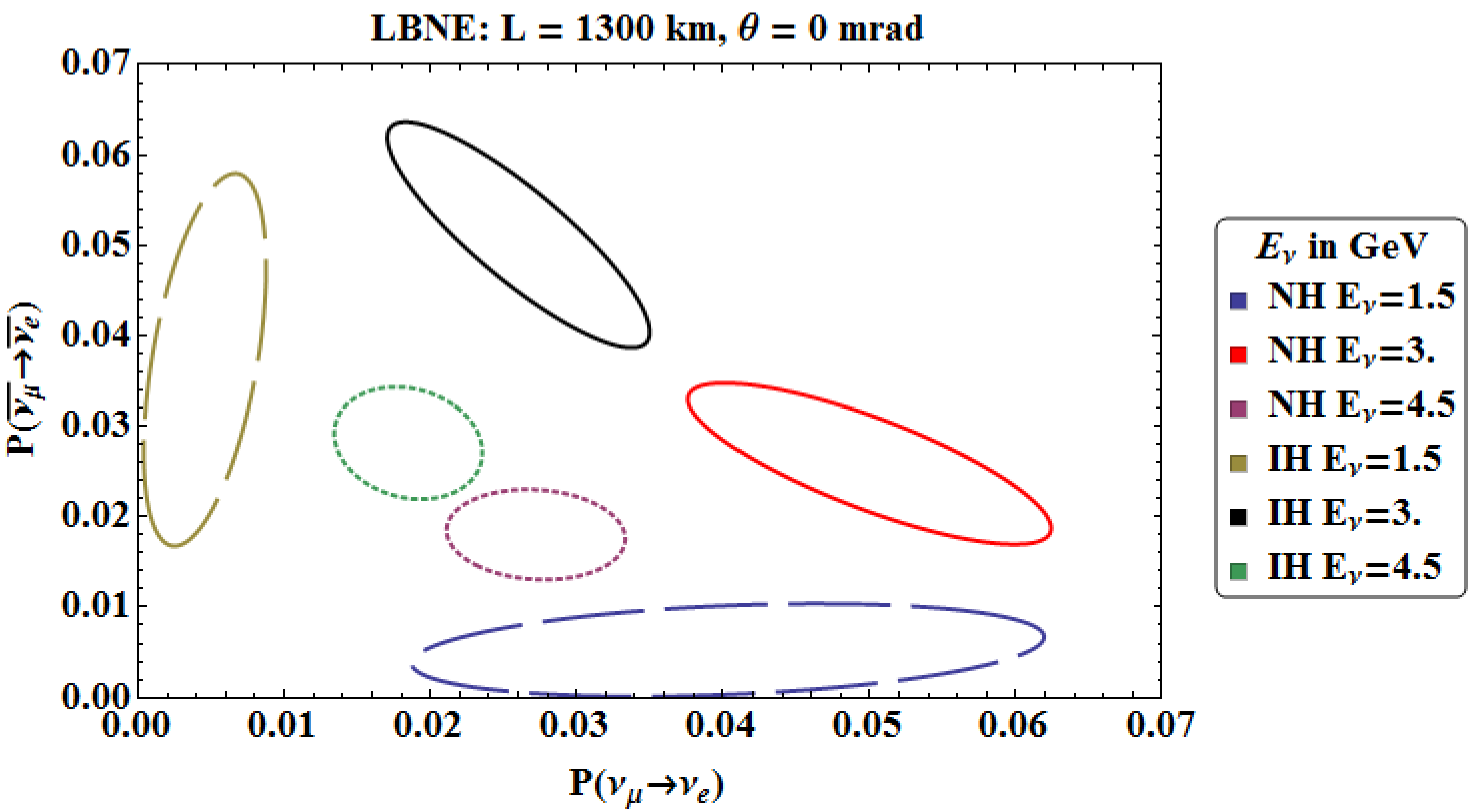

K2K: L = 250 km, θ = 0 mrad
0.04
0.03
0.02
0.01
0.00
0.00
0.01
0.02
0.03
0.04
P(ν̄μ→ν̄e)
P(νμ→νe)
Eν in GeV
NH Eν=0.6
NH Eν=1.2
NH Eν=1.8
IH Eν=0.6
IH Eν=1.2
IH Eν=1.8



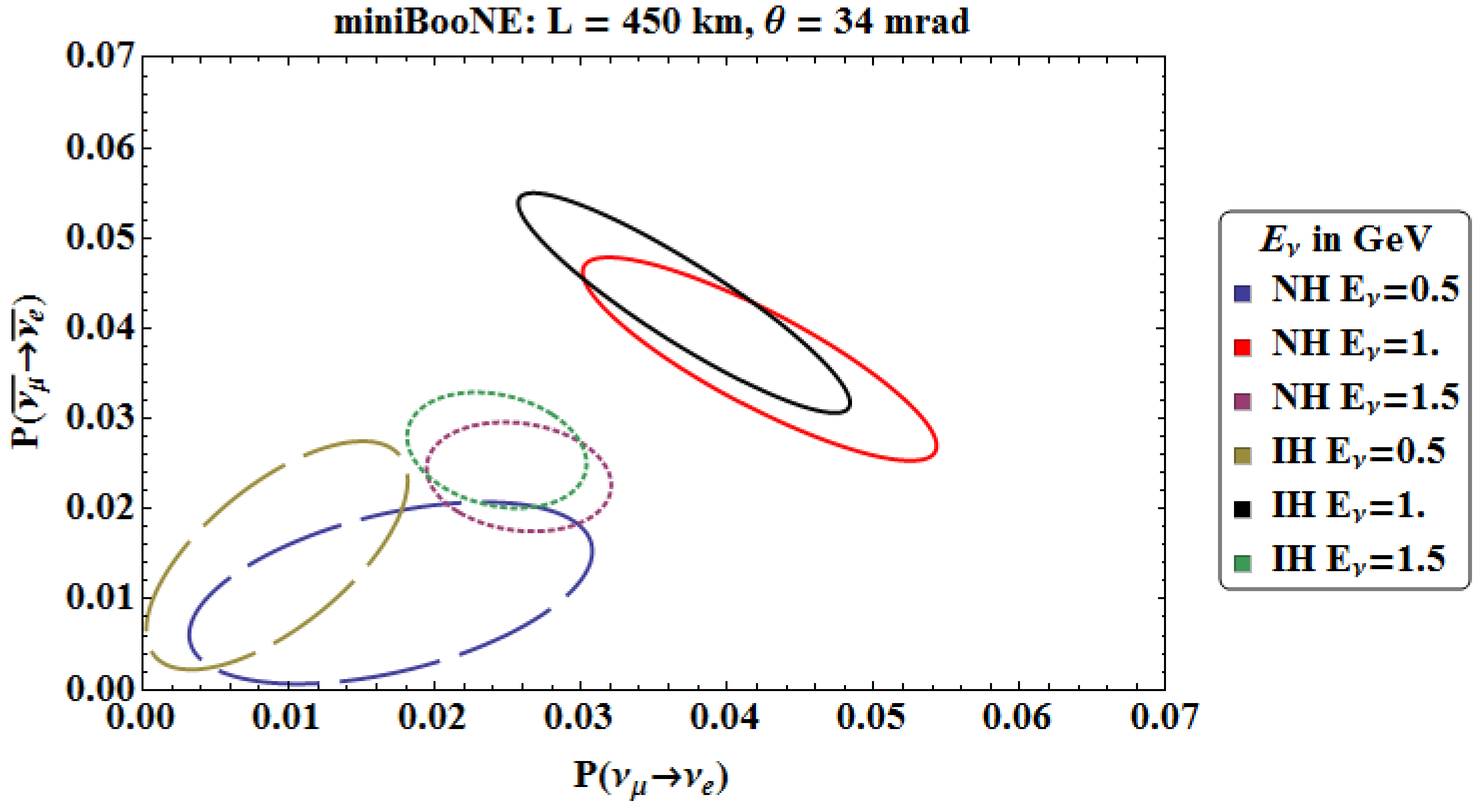
OPERA: L = 730 km, θ = 0 mrad
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
P(ν̄μ→ν̄e)
P(νμ→νe)
Eν in GeV
NH Eν=8.5
NH Eν=17.
NH Eν=25.5
IH Eν=8.5
IH Eν=17.
IH Eν=25.5



MINOS: L = 735 km, θ = 0 mrad
0.00
0.01
0.02
0.03
0.04
P(ν_μ→ν_e)
P($\overline{\nu_\mu}$→$\overline{\nu_e}$)
E_ν in GeV
NH E_ν=1.65
NH E_ν=3.3
NH E_ν=4.95
IH E_ν=1.65
IH E_ν=3.3
IH E_ν=4.95



LBNE: L = 1300 km, θ = 0 mrad
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
$P(\overline{\nu_\mu} \to \overline{\nu_e})$
$P(\nu_\mu \to \nu_e)$
E_ν in GeV
NH E_ν=1.5
NH E_ν=3.
NH E_ν=4.5
IH E_ν=1.5
IH E_ν=3.
IH E_ν=4.5


miniBooNE: L = 450 km, θ = 34 mrad
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
P(ν̄μ→ν̄e)
P(νμ→νe)
Eν in GeV
NH Eν=0.5
NH Eν=1.
NH Eν=1.5
IH Eν=0.5
IH Eν=1.
IH Eν=1.5