Beyond T2K and NOvA : Super Beams with Super Detectors

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NUSS 15-JULY-2009 Fermilab

Outline

- The **ultimate** goals in **ν physics** and in particular in **ν oscillation physics**
- Phase I experiments and the **plan for Phase II**
- The **"Ingredients"** needed in order to achieve the **ultimate** goals:
  - Neutrino Beams
  - Neutrino Detectors
- A possible phased neutrino oscillation program in JAPAN and US for the next decade(s)
- Summary / Conclusions

The ultimate goals in ν physics

EXPERIMENT (Accelerator ν's)

What is the value of the third mixing angle θ_{13} ?

Do neutrinos violate CP symmetry ?

Which neutrino is the heaviest one?

EXPERIMENT (natural ν's)

What are the neutrino masses ?

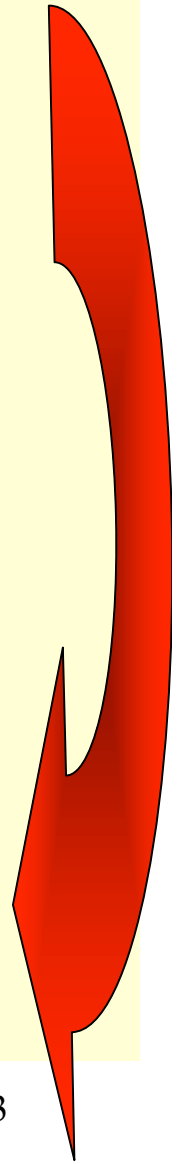
Are neutrinos their own anti-particles? (Majorana-Dirac)

THEORY

How do neutrino masses relate to quark masses?

How does neutrino mixing relates to quark mixing?

Origin of Matter – antimatter asymmetry in the Universe?



The ultimate goals in ν oscillations physics

1)What is the value of the "third" mixing angle (Reactor experiments, NOVA, T2K…)

2)Is there CP violation in the neutrino sector ?? (which might explain why we are here !!!)

3) What is the ordering of the neutrino masses!!!! (NOvA)

Are there sterile neutrinos??? (MiniBoone) ✓

What is after all, the neutrino MASS?? (absolute value not mass squared difference) (kinematics of beta decay)

Atmospheric ??? Cross Mixing Solar $0\nu\beta\beta$ decays

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & -s_{23} \\ 0 & s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & -s_{13}e^{-i\delta} \\ 0 & 1 & \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{ia_1/2} & 0 & 0 \\ 0 & e^{ia_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Majorana phases

- Do "man made" ν_μ's oscillate? ✓
- What is "precisely" the mass squared difference and the mixing angle? (K2K-MINOS)
- Are neutrinos and anti neutrinos the same ?? (Majorana particles)(neutrino-less double beta decays)

ν_μ -> ν_e oscillations

To a good approximation oscillation probability:

$$P(\nu_\mu -> \nu_e) \cong \sin^2 2\theta_{13} T_1 - \alpha \sin 2\theta_{13} T_2 - \alpha \sin 2\theta_{13} T_3 + \alpha^2 T_4$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

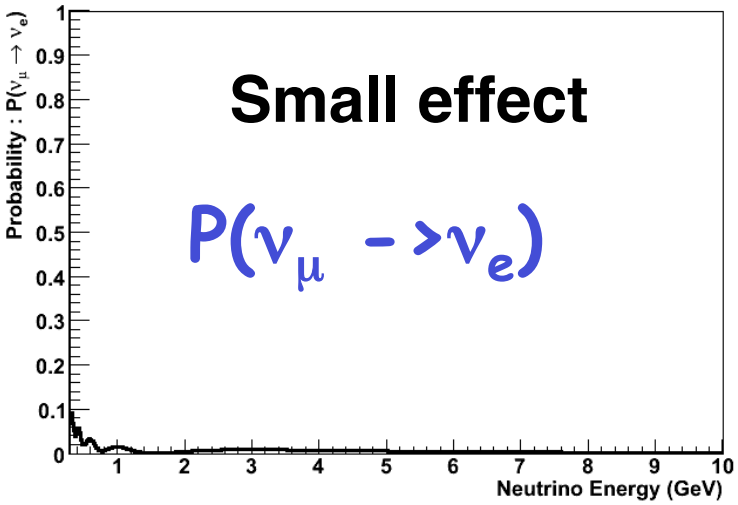
$$T_2 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$ **CP Violating**

$$T_3 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$ **CP Conserving**

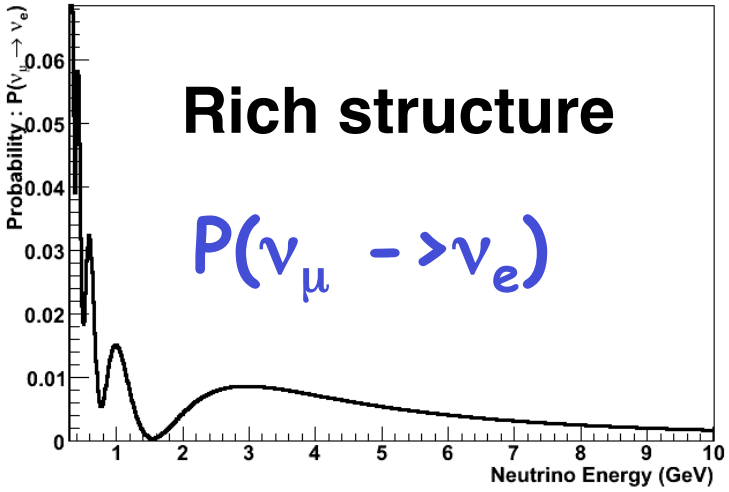
$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

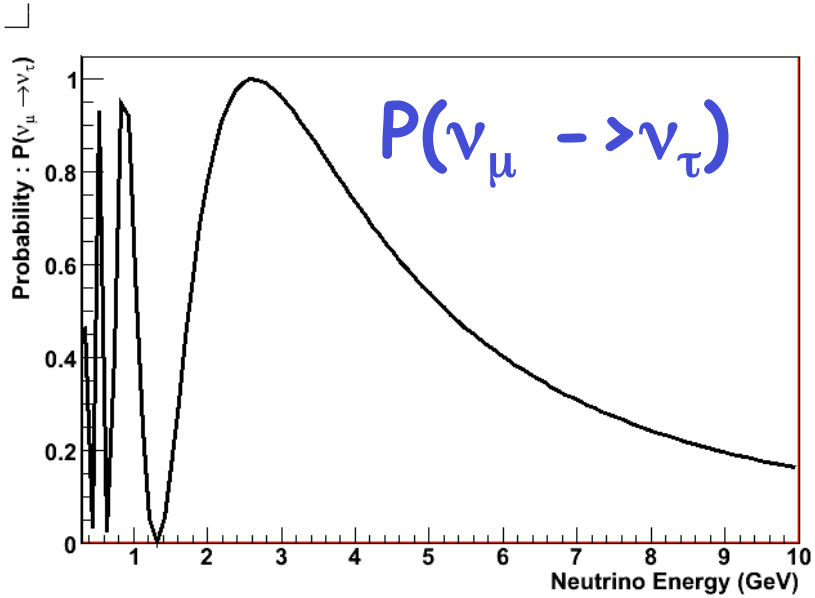
$$\Delta = \frac{\Delta m^2_{31} L}{4E_\nu} \quad x = \frac{2\sqrt{2} G_F N_e E_\nu}{\Delta m^2_{31}}$$ **Matter Effects**

$P(\nu_\mu \rightarrow \nu_e)$ not as simple as $P(\nu_\mu \rightarrow \nu_\tau)$ …



ZOOM IN





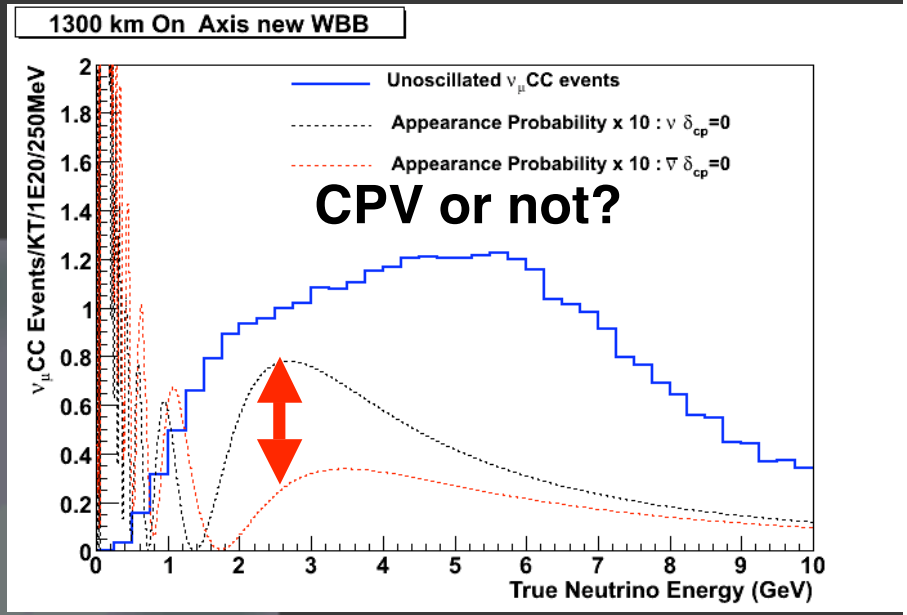
Large effect simple structure

Degeneracies (ghost solutions) …

Oscillation Probability depends on, at least, 3 parameters

θ_{13} , δ_{cp}, sign(Δm^2_{31})

Multiple Combinations of the 3 parameters can yield the "same" number of events, especially if parameters are "doing" similar things (like CPV and matter effects)



WHAT DO WE NEED :

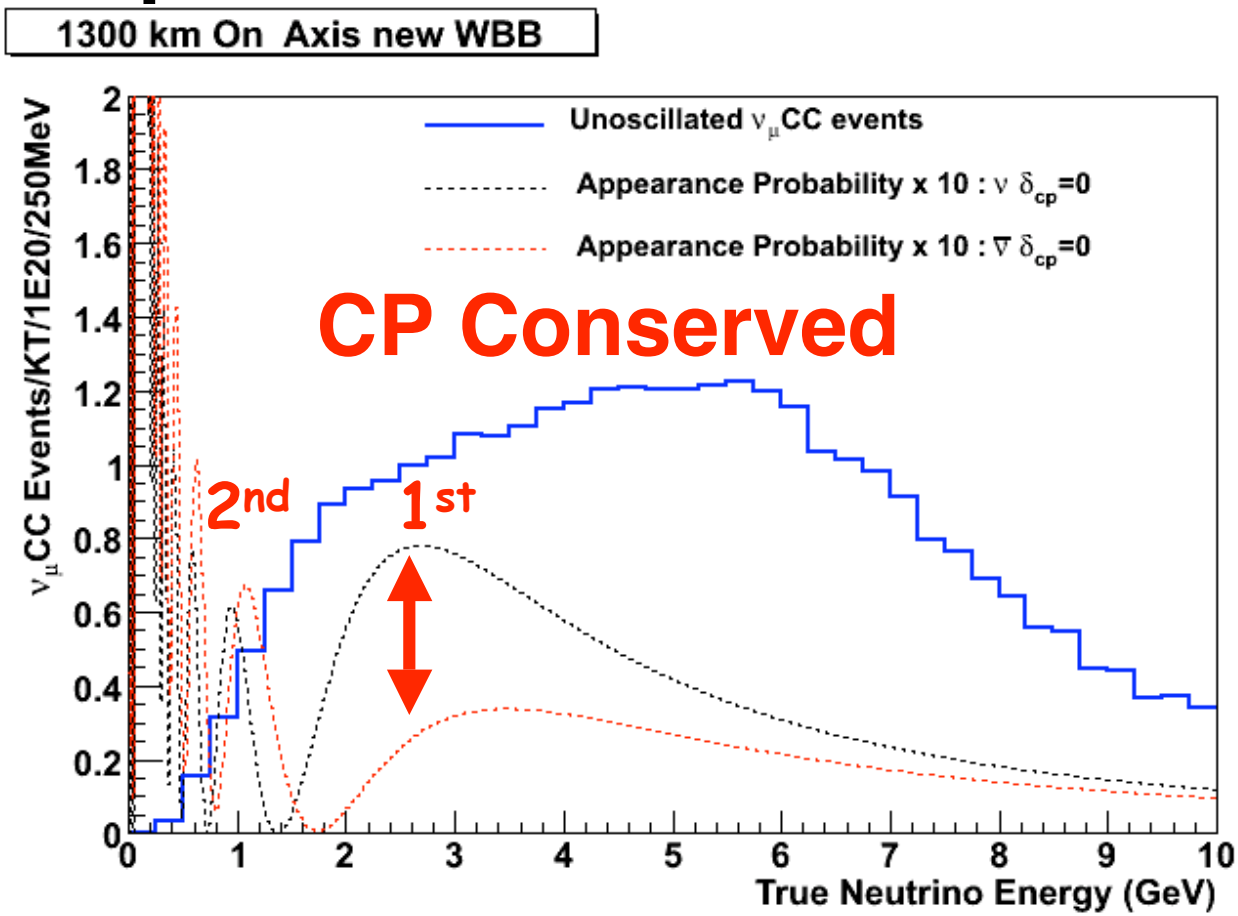
a) Large Number of neutrinos since we know the effects are small ($\theta_{13} < 11^0$)

b) Multiple measurement of number of events as a function of energy , E , and as a function of distance, L.

c) Longer Baselines to enhance matter effects

d) Nature to be kind to us !!!

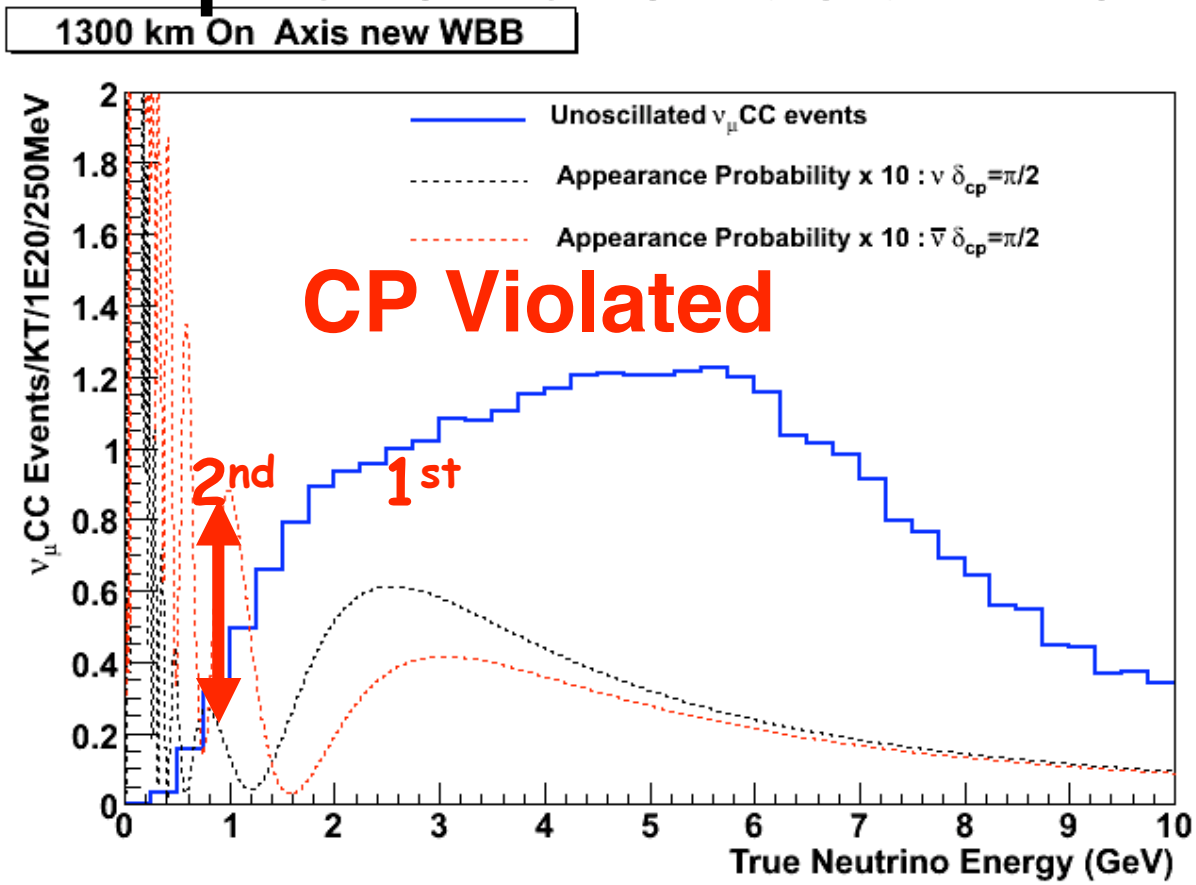
We need to study oscillation phenomenon as a function of energy



1st Maximum : Is telling us the neutrino mass hierarchy

2nd Maximum : Is telling us if CP Violated

We need to study oscillation phenomenon as a function of energy



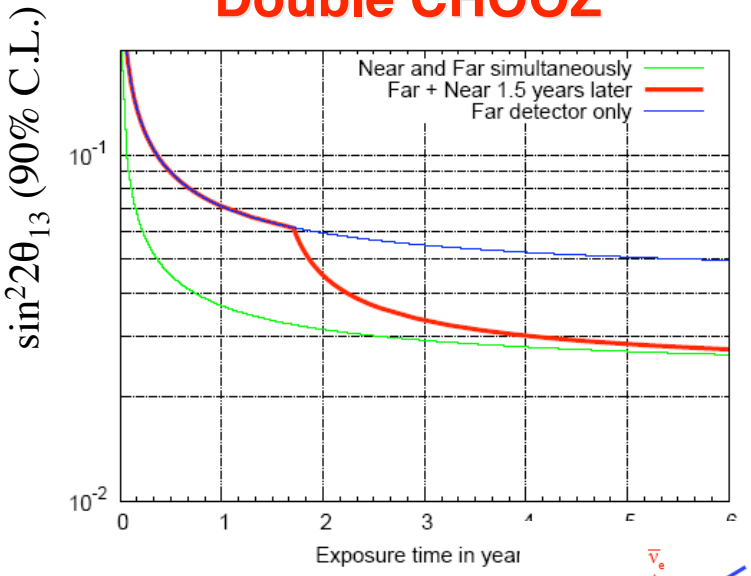
1st Maximum : Is telling us the neutrino mass hierarchy

2nd Maximum : Is telling us if CP Violated

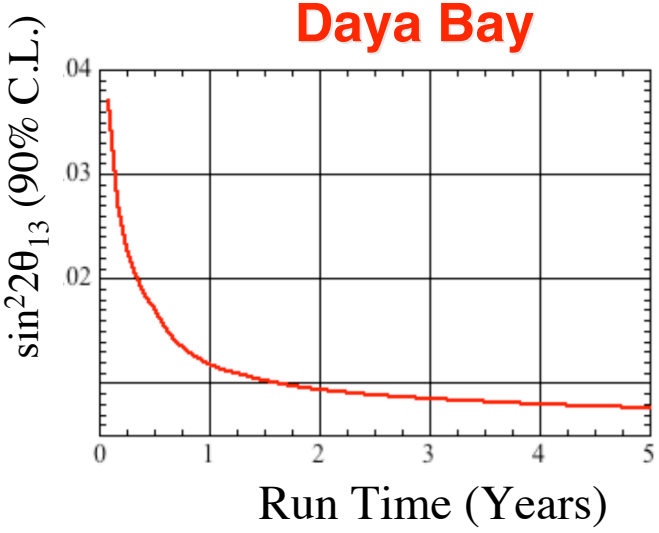
Hunt for a non-zero θ_{13} ("cleanly"): PHASE I

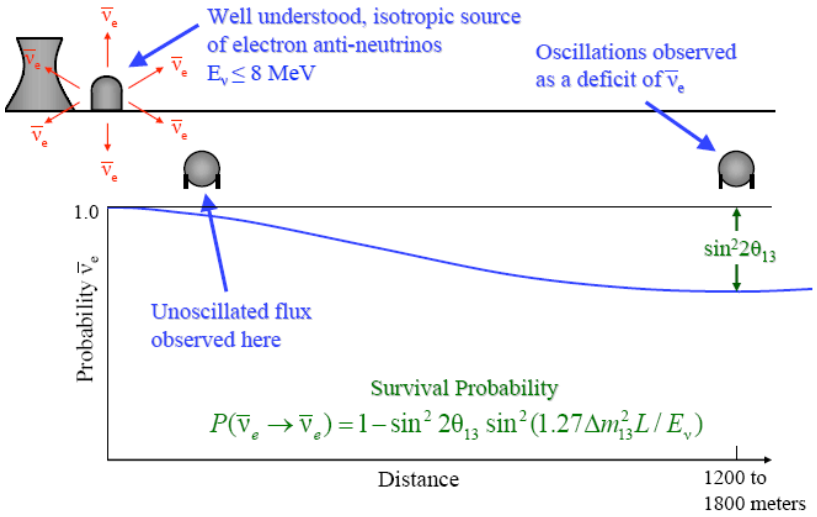
Reactor Experiments : Double CHOOZ & Daya Bay

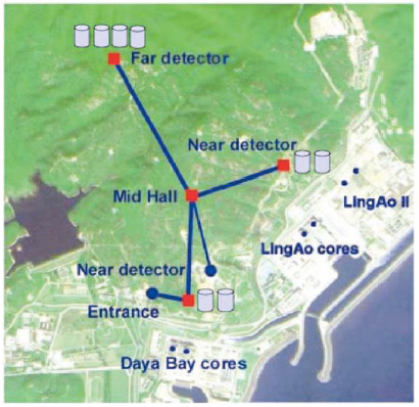
Double CHOOZ



Daya Bay

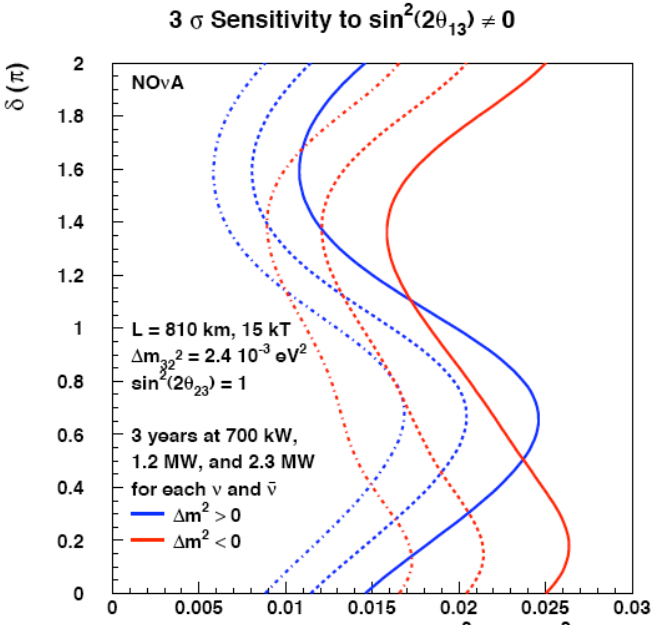




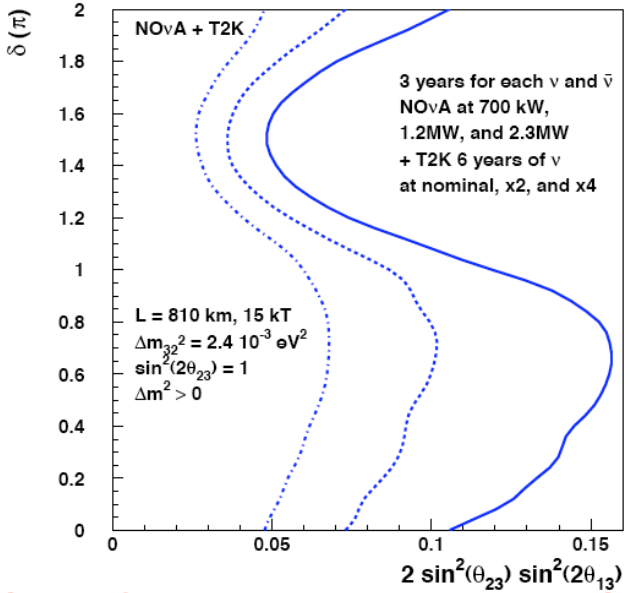


Hunt for a non-zero θ_{13} (+more): PHASE I

Accelerator Experiments : NOvA & T2K

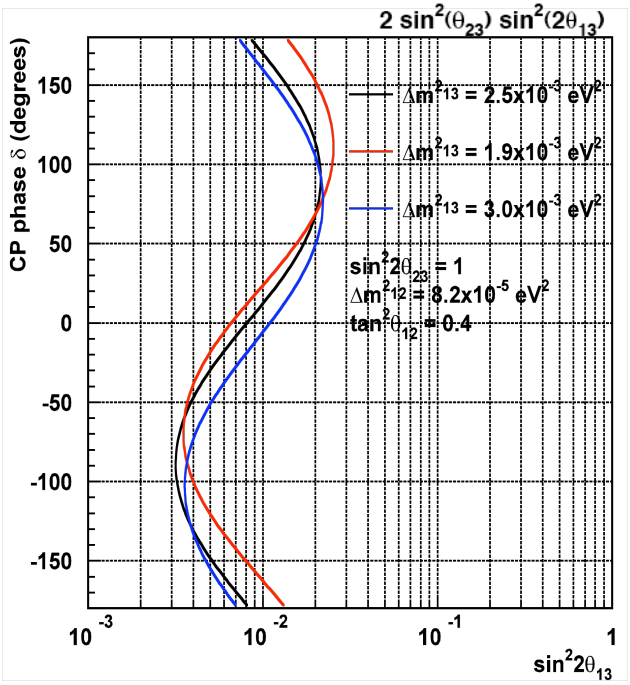


NOvA



T2K

BONUS from NOvA Experiment : Depending on the value of the third mixing angle NOνA is the only Phase I experiment that could determine the neutrino mass hierarchy (and generally speaking anything additional to θ_{13})



PHASE II: Measure CPV, extend θ_{13} reach, extend neutrino mass hierarchy reach

- Numerous studies over the past several years have laid out options for achieving the *ultimate goals :*
  - *Extend θ_{13} reach beyond Phase I ($\sin^2 2\theta_{13}$ below 0.01)*
  - *Study of CP Violation in the neutrino sector*
  - *Extend neutrino mass hierarchy reach beyond Phase I ($\sin^2 2\theta_{13}$ below 0.05)*
- In the Future Long Baseline Neutrino Study (Joint Fermilab – BNL study) we explored **indicative configurations of detectors (and detector masses), off axis and on-axis locations and protons on target (beam power).**
- **The same exercise has been done from our Japanese Colleagues as well with respect to future extensions of the JPARC current neutrino program**

PHASE II: Measure CPV, extend θ_{13} reach, extend neutrino mass hierarchy reach

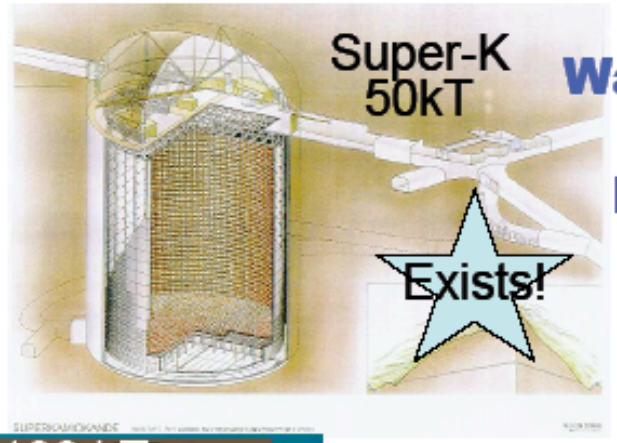
Conclusions from all studies are the same. In order to achieve the goals of Phase II one needs:

- Massive cost effective detectors that are larger than those of Phase I (> 20 KT)
- Intense neutrino beams with intensity possibly higher than that of Phase I (> 700 KW)
- The ability to break inherent degeneracies between genuine CP violation and "Fake CP violation" from matter effects.

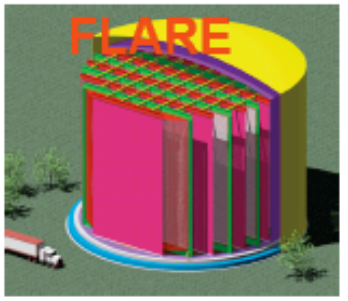
Ingredients for achieving the ultimate goals (1)

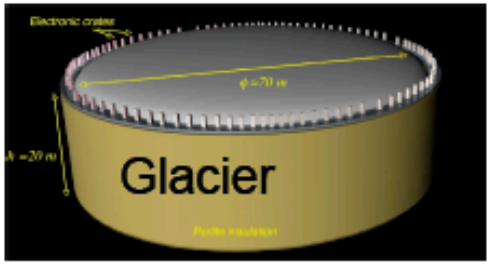
We need Statistics : Massive Detectors!

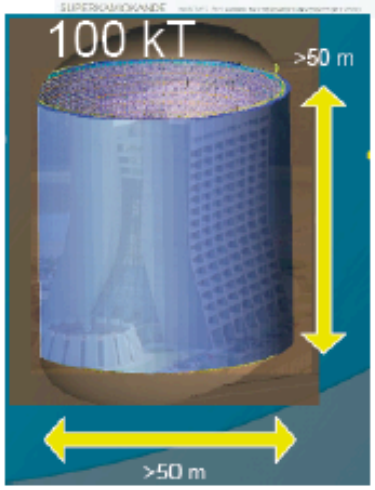
Massive Detectors (Liquid Argon,Water Cherenkov, Liquid Scintillator, etc) that are scalable in the XXX Kt scale

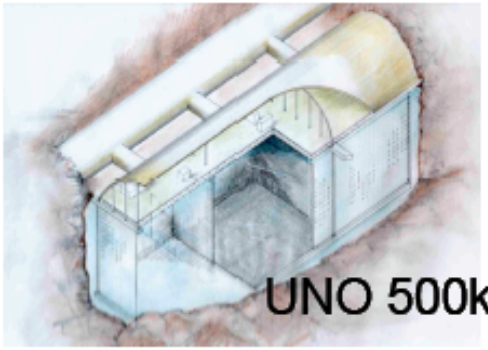


Water Cerenkov And Liquid Argon









LAr Neutrino Events : (MC)

π^o Background

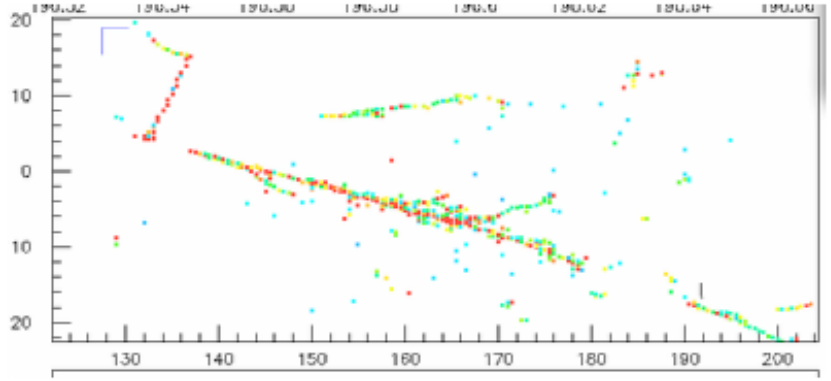


Figure 4.1: A simulated neutral current event with a 1 GeV π^0 ($\nu_\mu + n \rightarrow \nu_\mu + \pi^+ + \pi^- + \pi^0 + n$). Sampling rate is every 3.5% of a radiation length in all three views.

ν_e Signal

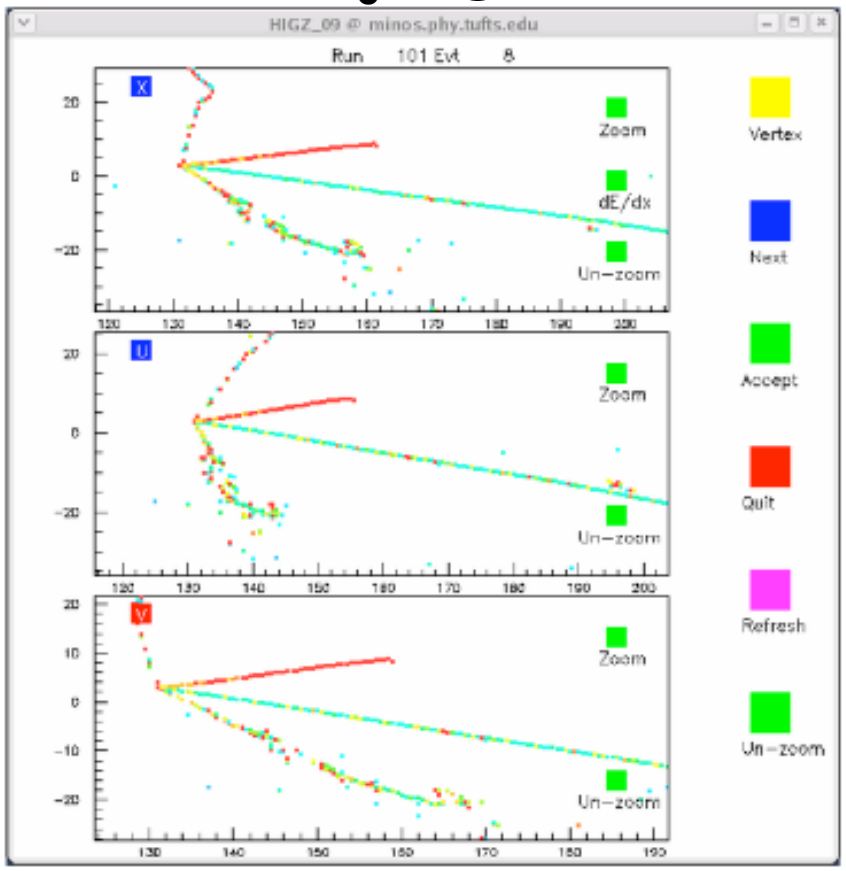
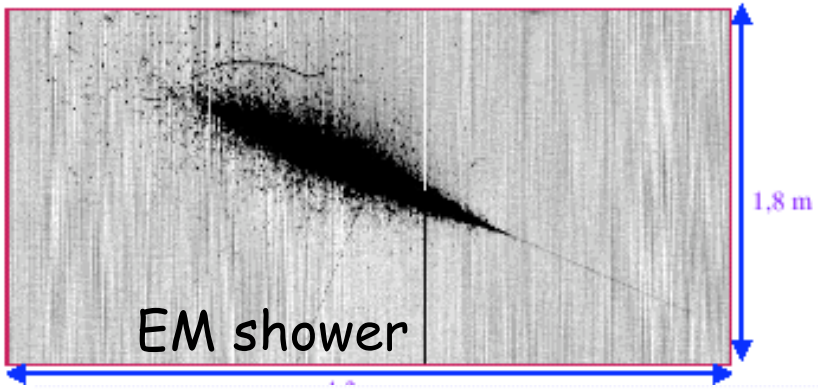
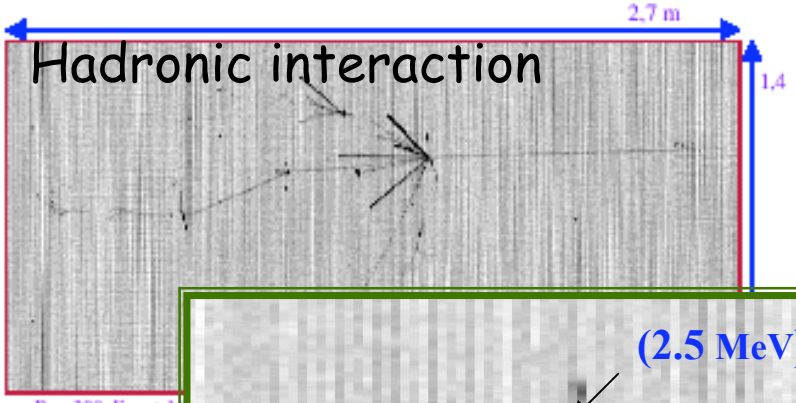
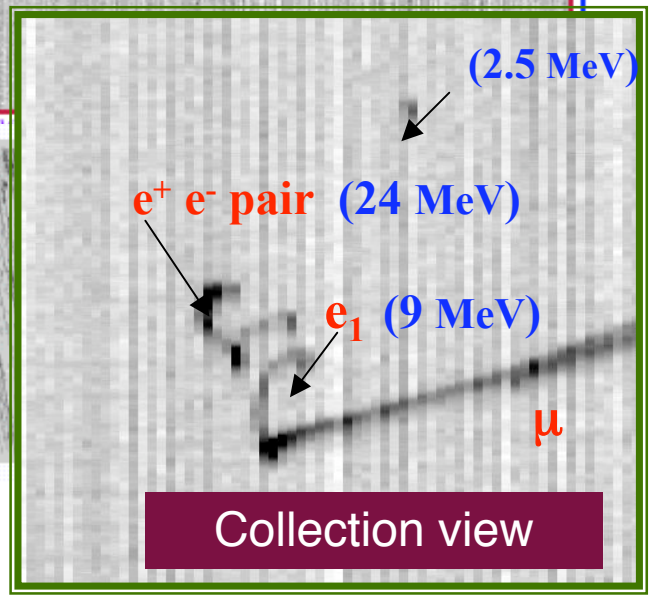


Figure 4.7: Signal event selected, 2.2 GeV DIS ν_e CC with y=0.89. The electron shower is clearly visible.

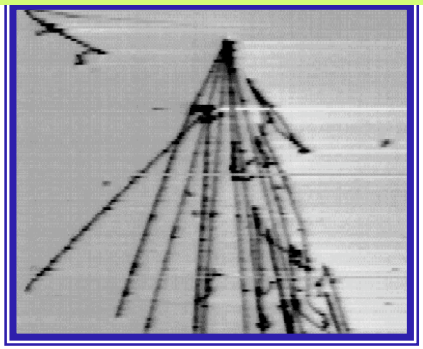
ICARUS T600 : Neutrino Events (Data)



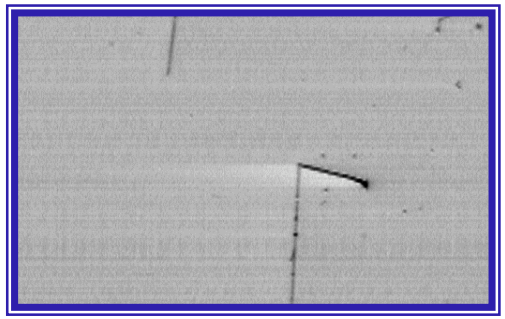




$\nu_\mu + X \rightarrow \mu^- + Shw.$

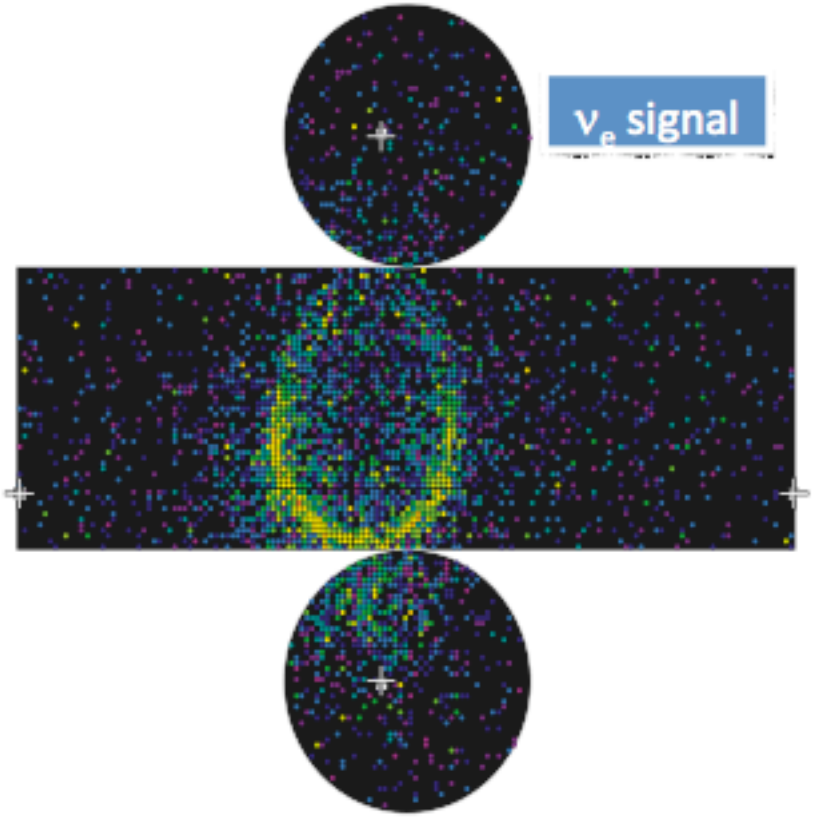


$\nu_\mu + n \rightarrow \mu^- + p$

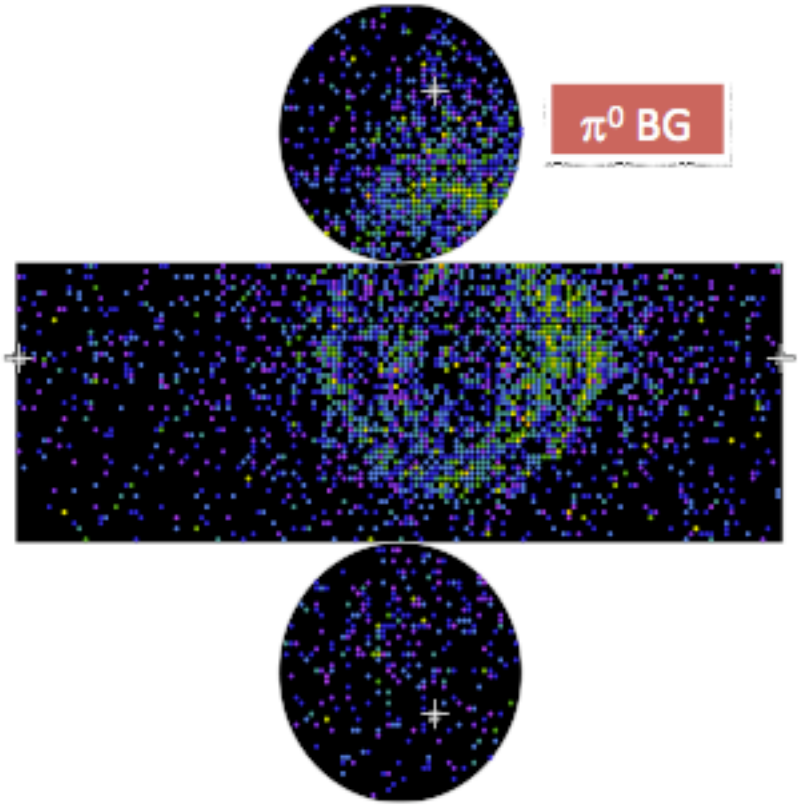


Water Cherenkov : Neutrino Events (MC)

ν_e Signal



π^o Background



Water Cherenkov vs Liquid Argon Detectors

All detector technologies are challenging, for the sizes we are interested in, and both have :

Advantages AND Disadvantages

Water Cherenkov:

Proven technology @ 50kT Scale : SuperK

Low efficiency
Low Background Rejection
Need large underground caverns

Liquid Argon :

High efficiency
High Background Rejection
Need smaller underground caverns
Working on shallower depths or in the surface(?)

Not proven technology at large scale

Comparison of Water Cherenkov and LAr detector technologies

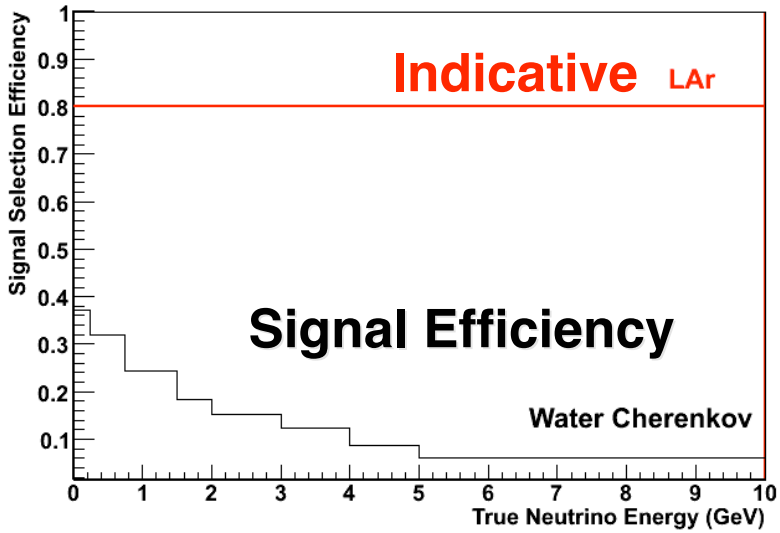
Given their assumed efficiencies and background rejections the following :

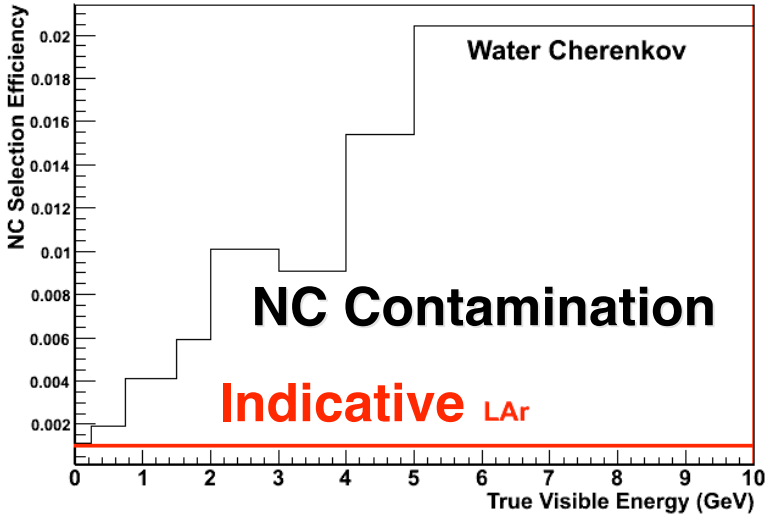
"Detector Mass Equivalent Law" holds, which has been independently checked by two groups (BNL and FNAL)

1 : ~4

OR

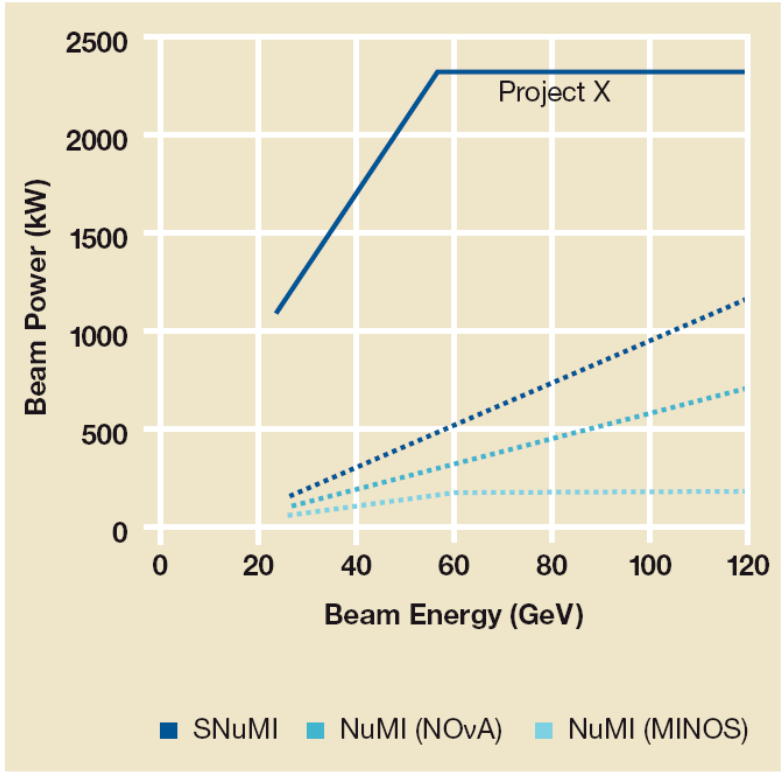
100kt LAr ~ 400 kt WC

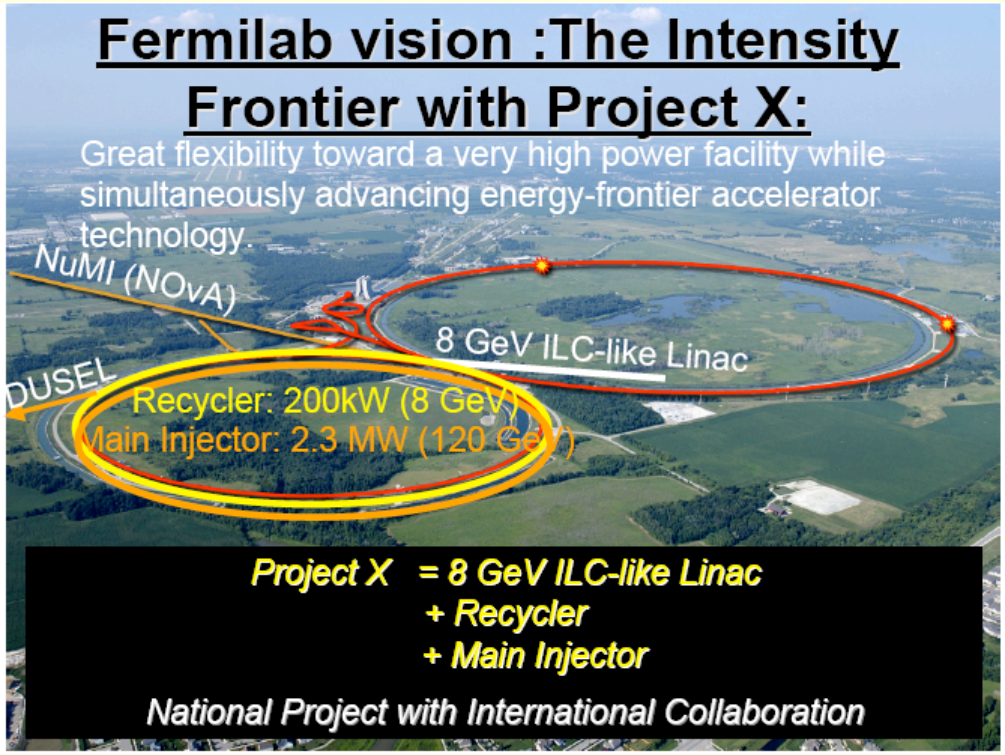




Ingredients for achieving the goals of Phase II: Powerful Neutrino Beams, Project X (US)

We need Statistics : Powerful Beams!





Two options for neutrino beams and experiment baselines exist in the US since it is a big country…

Ingredients for achieving the goals of Phase II: Powerful Neutrino Beams, JPARC (JAPAN)

Plan for Improving Neutrino Beam Intensity by Main-Ring Upgrade

Slide by A.Suzuki, KEK Roadmap Review Committee, March 2008

Assumed in most part of this talk

Linac : 181 MeV to 400 MeV

0.60MW 0.28 Hz → 0.91 MW 0.57 Hz → **1.66MW 0.52 Hz**

- Shorten acceleration time
- More RF system
- Magnet power system

- More beam per pulse
- Operation of 3 GeV RCS in harmonic number =1

Neutrino beam and experiment baselines : Two Options for Baselines,two Beams(US)

(A) L ~800 Km and

NuMI Off Axis Narrow Band Beam.

Implications on Detector Technology:

If detector not in Soudan Mine, then it has to be on the ~ surface :

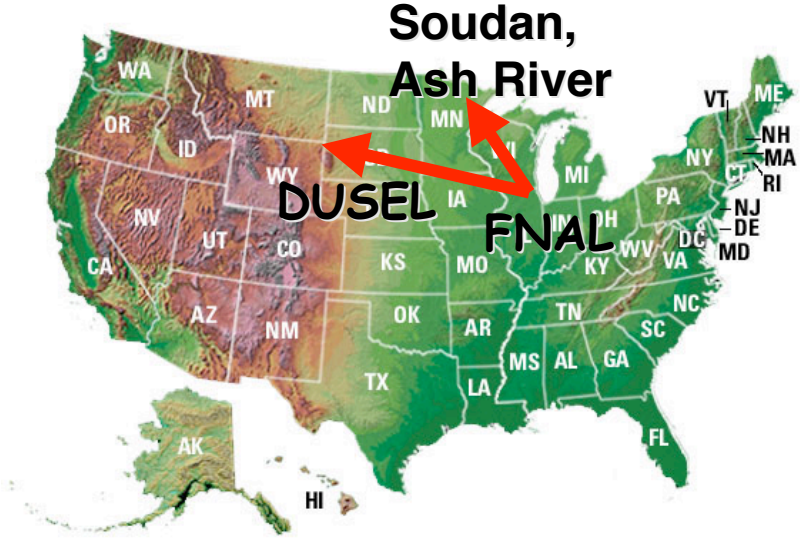
Water Cherenkov detectors not an option for that reason.

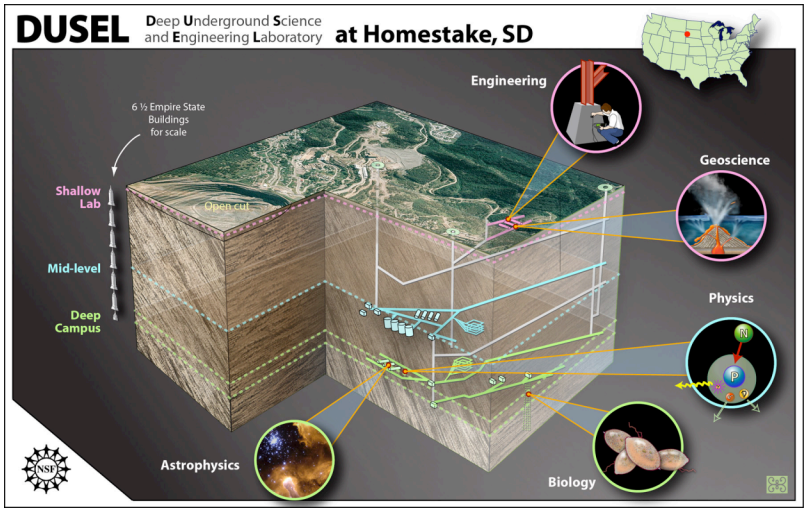
LAr TPCs need to be able to operate ~ surface.

Implications on ν beam and baseline :

If L >>> 800 km then NuMI beam axis many km above ground, so beam can only be off Axis Narrow Band Beam.

Neutrino beam and experiment baselines : Two Options for Baselines,two Beams(US)





(B) L ~ 1300 Km (Fermilab-> *DUSEL*)

New On Axis Wide Band Beam

Implications on Detector Technology:

Water Cherenkov

(Homestake Mine at 4850 ft level)

OR LAr TPC

(Homestake Mine 300 ft level, or ~ surface)

Implications on ν beam :

New beam has to be designed and constructed

Neutrino Beams and Experiment Baselines: Three options for Baselines, One beam (JAPAN)

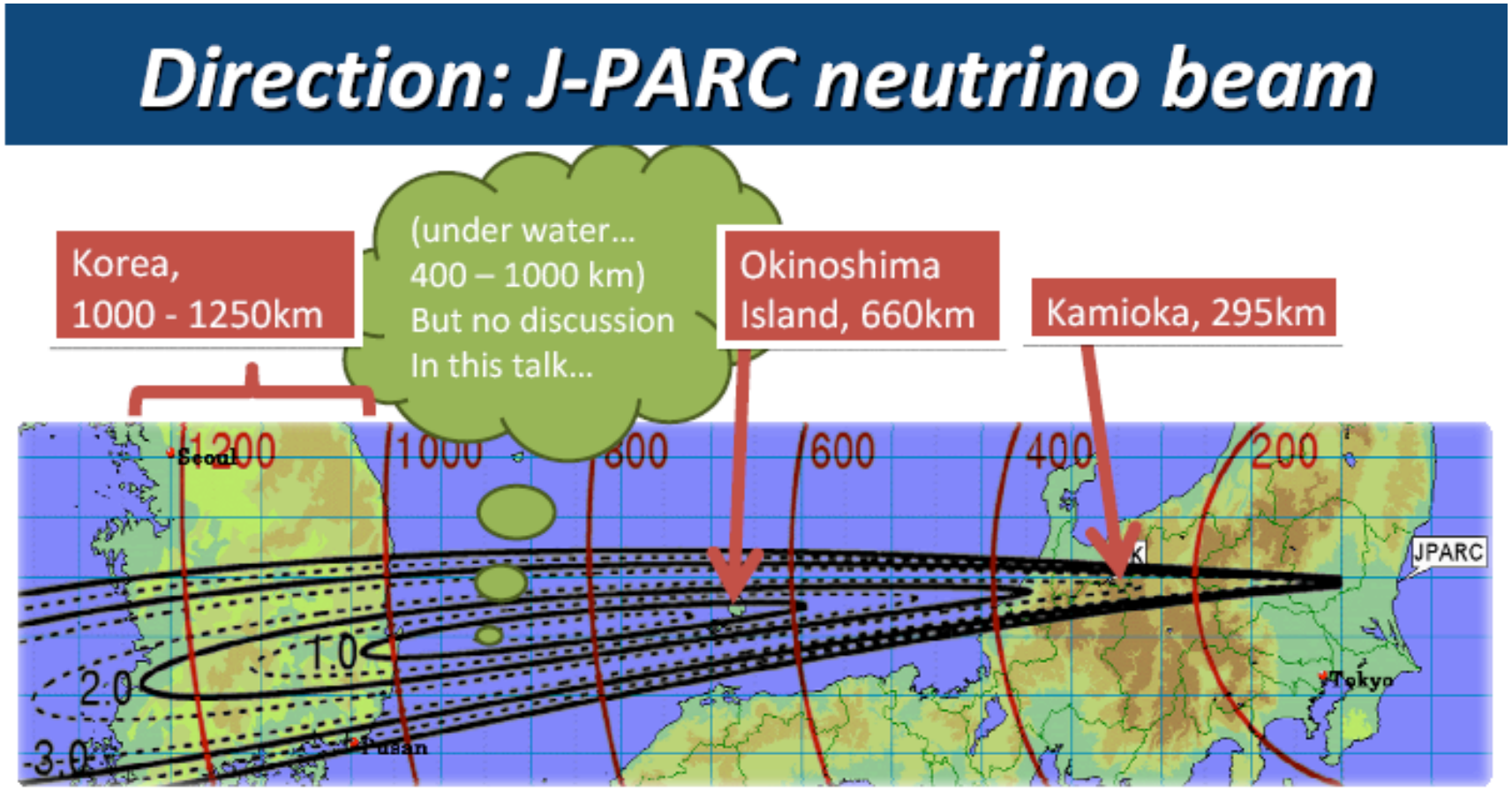
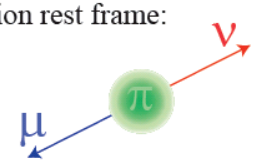


Fig: Senda NP04

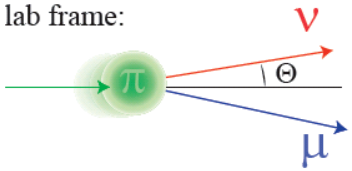
Off Axis Neutrino Beam: Capabilities & Advantages

In pion rest frame:

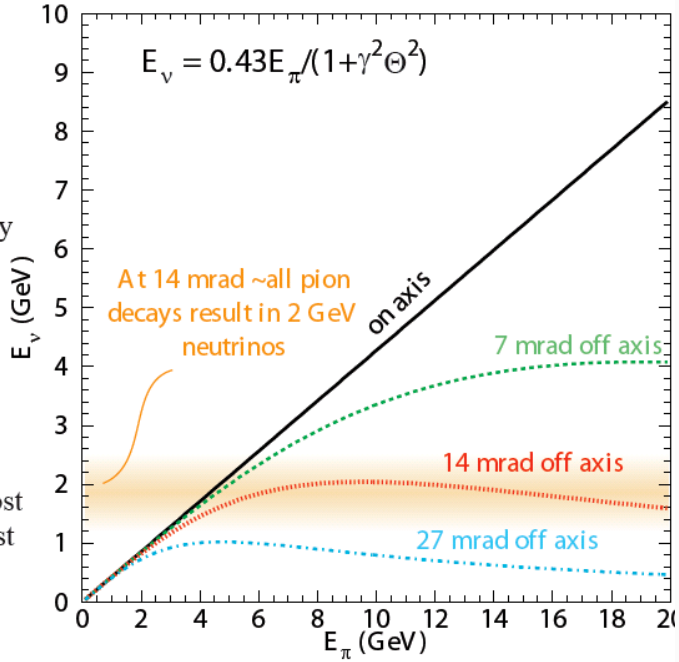


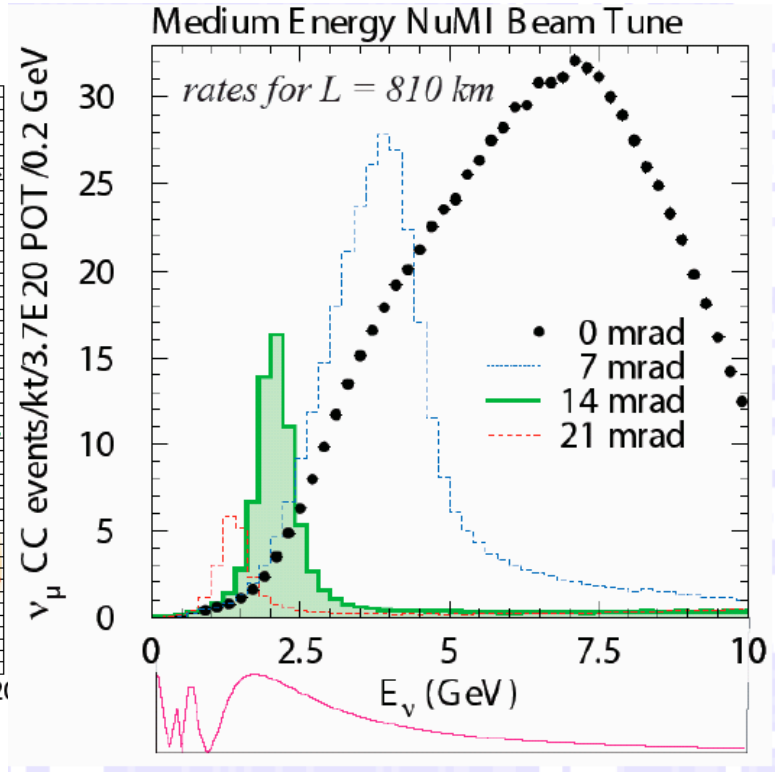
Neutrino and muon energy completely determined by energy conservation

In lab frame:



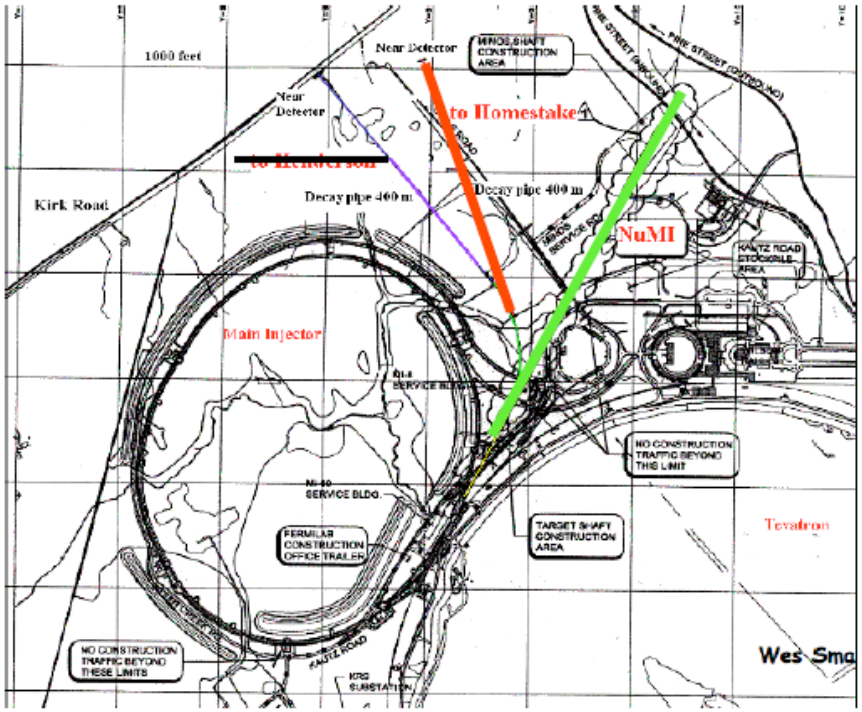
Neutrino energy depends on boost and angle between neutrino boost direction





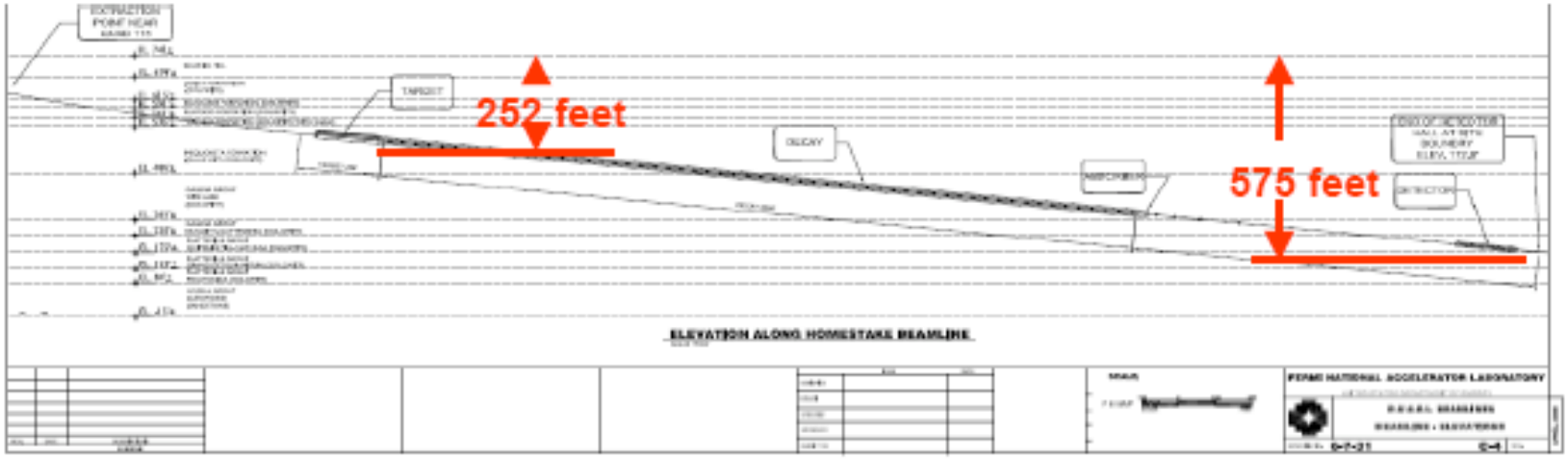
- **The Beams (NUMI and JPARC) exists**
- **There is a well defined upgrade plan**
- **The off – axis idea of obtaining a NBB is attractive: It reduces the NC background resulting from high energy neutrinos.**

Wide Band Neutrino Beam in the US : Status



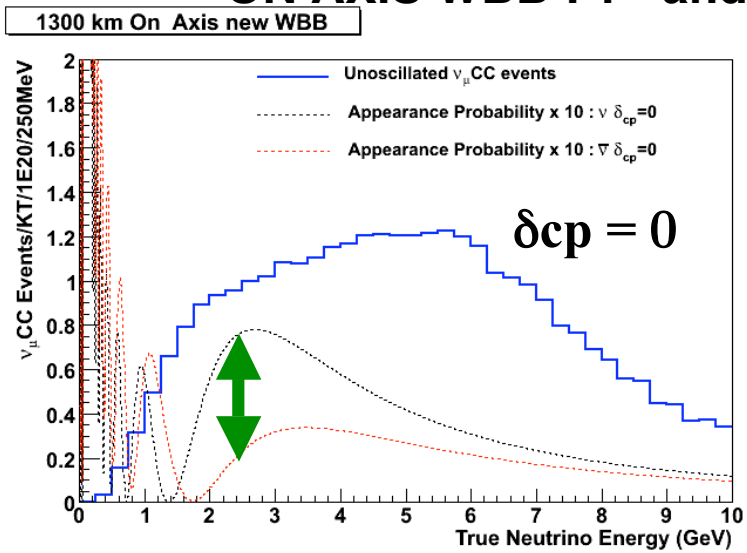
- ***Such beam does not exist, but is in the design phase.***

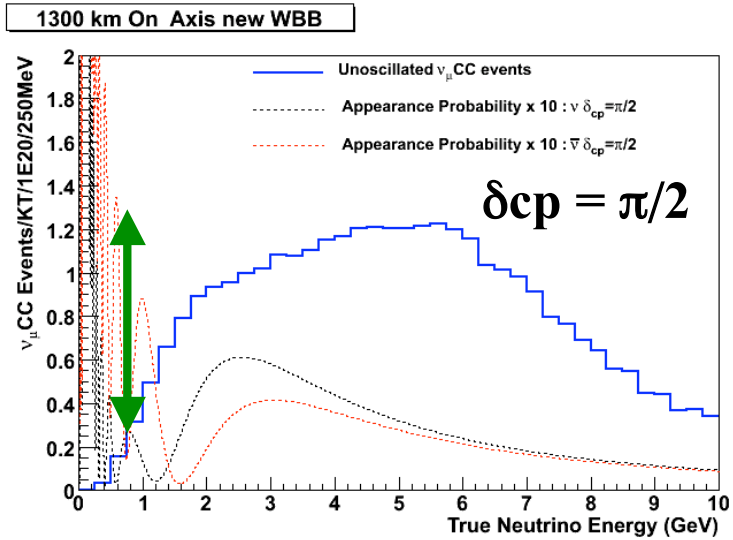
- ***In general, design of target station and horns for beam power > 1 MW non trivial (R&D needed)***



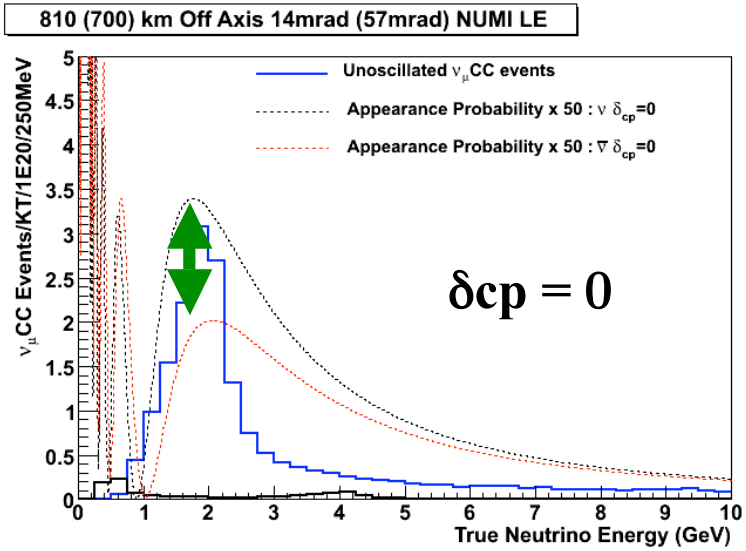
Wide Band Neutrino Beam: Advantages

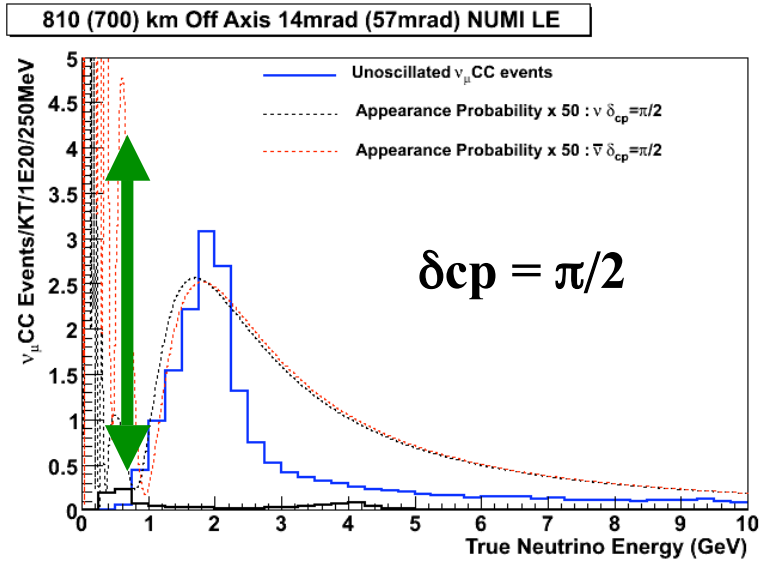
ON AXIS WBB : 1st and 2nd Oscillation Maxima 1 Detector



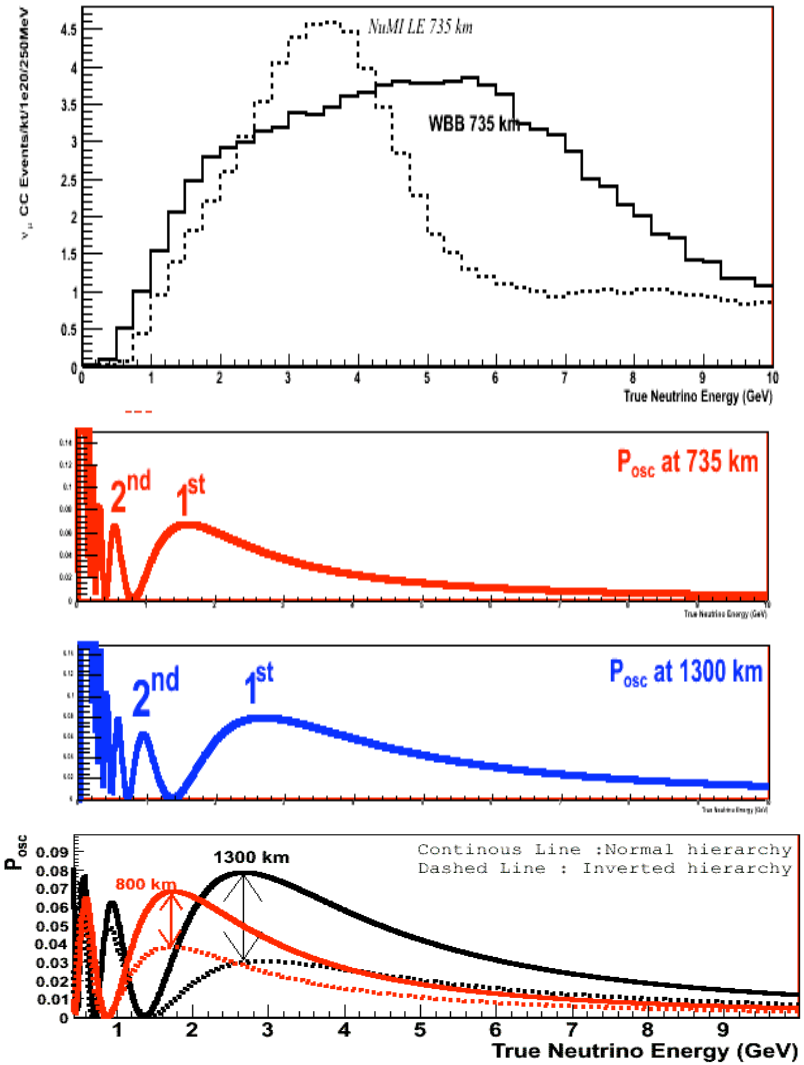


OFF AXIS NBB : 1st and 2nd Oscillation Maxima 2 Detectors





Longer baseline (>>L) AND a new Wide Band Beam : What can they do for us???



With new Wide Band Beam :

1)Increase "useful" flux (at first and second oscillation maxima)

2)With increasing L oscillation maxima "appear" in more "favourable" positions in the neutrino energy spectra

3)Thus study of first and second oscillation maxima is easier (one detector instead of two, higher rates, etc)

4) With increasing L matter effects increase and hence potential for mass hierarchy determination is increasing

Discovery Potentials:Technical details

θ_{13} Discovery Potential :

Null hypothesis : $\theta_{13} = 0$

Both δ_{cp} and sign of Δm^2_{31} allowed to float in the fit

δ_{cp} Discovery Potential :

Null hypothesis : $\delta_{cp} = 0$ **or** $\delta_{cp} = \pi$ **(take worst χ^2)**

Both θ_{13} and sign of Δm^2_{31} allowed to float in the fit

Mass Hierarchy Discovery Potential :

Fit the energy spectrum to θ_{13} , **δcp and both signs of Δm^2_{31} in order to determine**

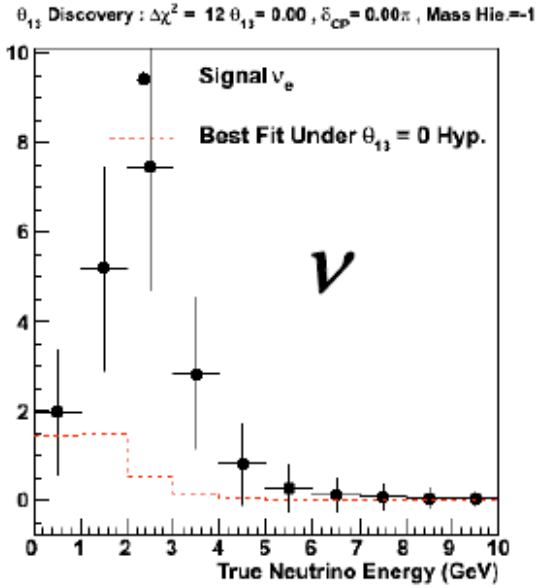
$$\Delta\chi^2 = \chi^2_{\text{true hierarchy}} - \chi^2_{\text{false hierarchy}}$$

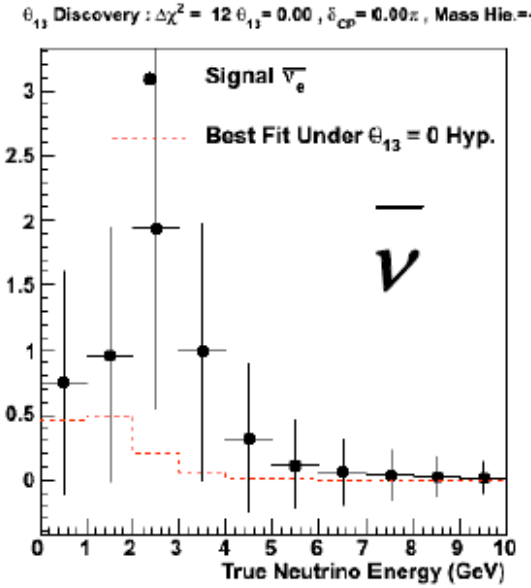
We do not fix the mass hierarchy in any of the Discovery Potentials shown, which corresponds to the "worst case scenario".

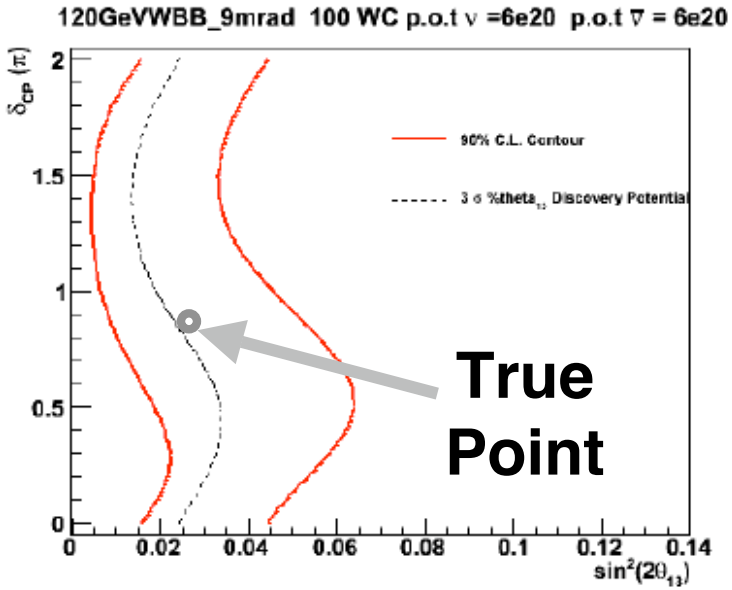
*** We assume 5% systematic error on the background***

**** We do not let the rest of the oscillation parameters float.***

ν Oscillations : Example of measurement







Black : Data

Red Dotted : Null Hypothesis ($\theta_{13} = 0$)

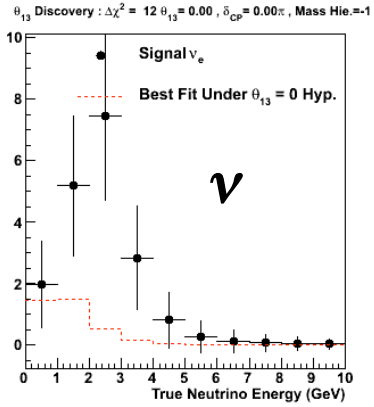
Black Dotted Line : 3 σ Sensitivity

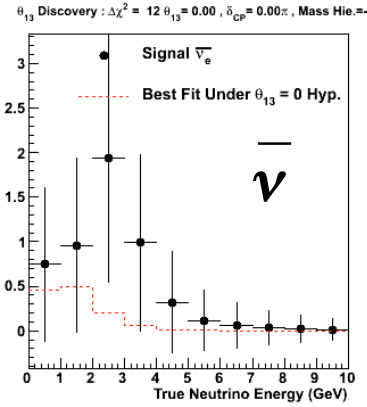
Red Lines : 90% C.L. contour from the fit to the data on the left

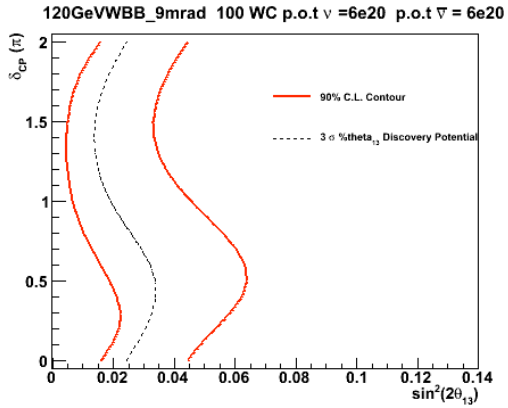
With this data we are able to exclude the hypothesis that $\theta_{13} = 0$ to high significance : $\Delta\chi^2 = 12$ => Significance = 3.5 σ

This is why this **true point we choose** is to the **right of the 3 σ sensitivity curve on the right panel, and quite close to the 3 σ limit.**

ν Oscillations : Example of measurement

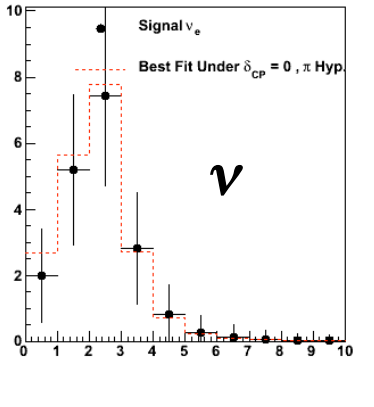


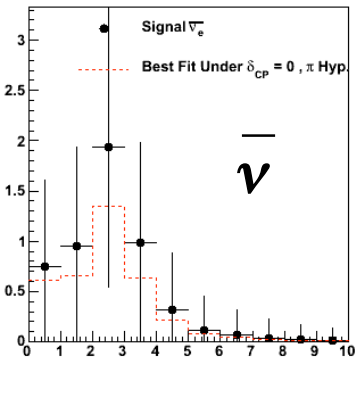


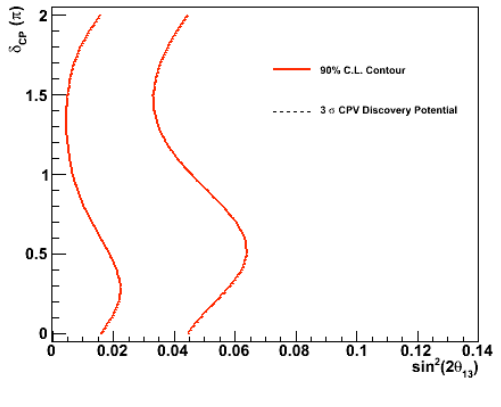


Black : Data
Red : Null Hypothesis

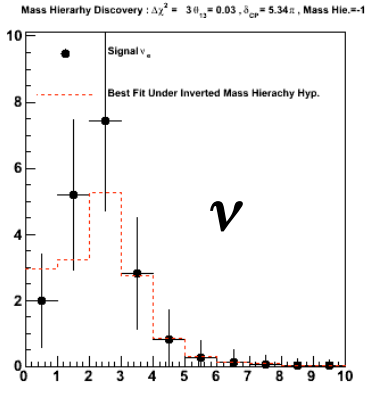
Parameter	Discovery
θ_{13}	**YES**

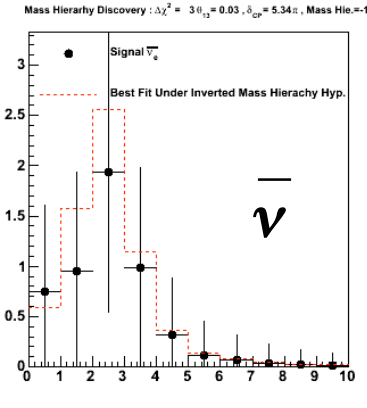


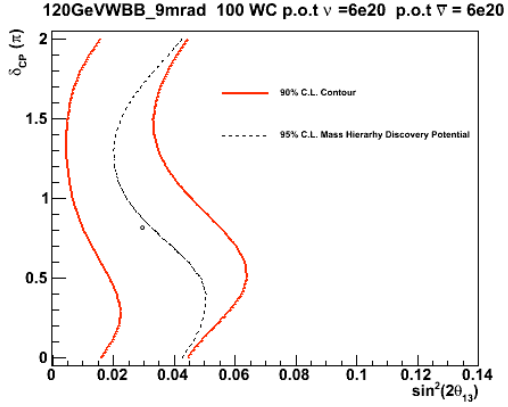




CPV	**NO**

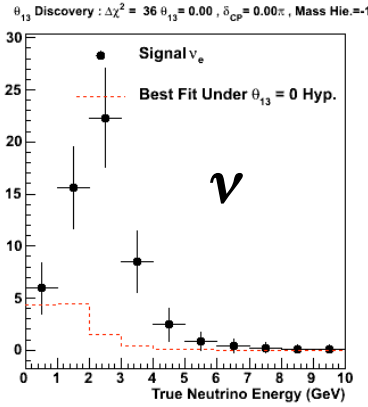


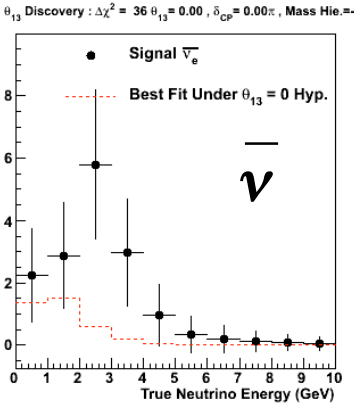


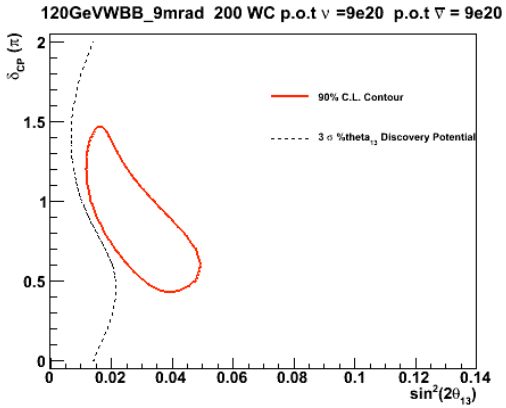


Mass Hierarchy	**NO**

ν Oscillations : Example of measurement

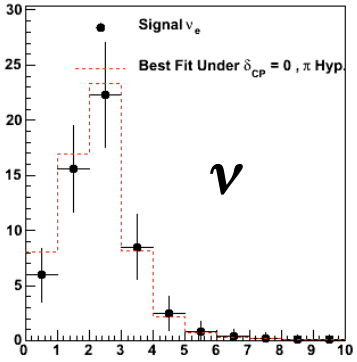


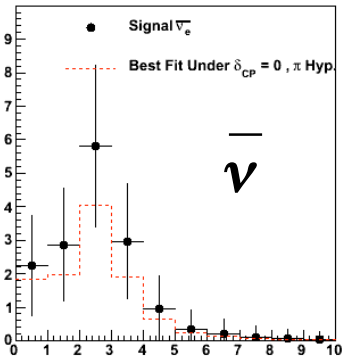


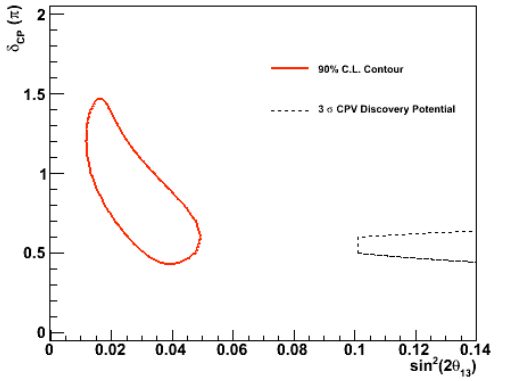


Black : Data
Red : Null Hypothesis

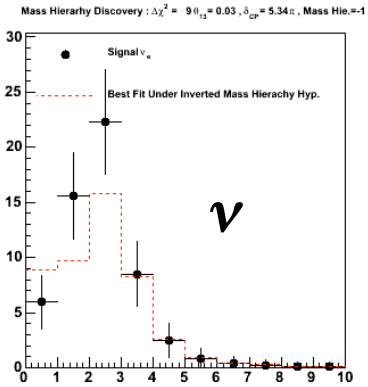
Parameter	Discovery
θ_{13}	YES

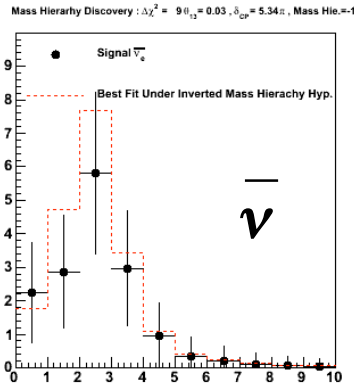


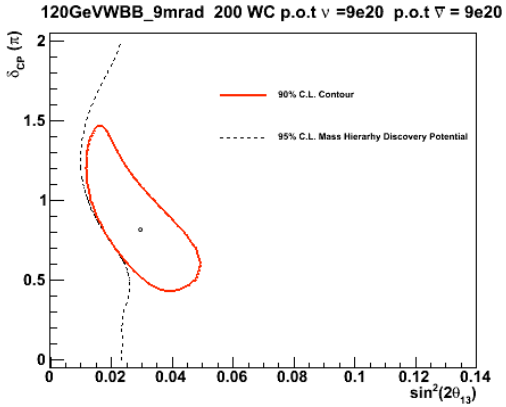




CPV	NO

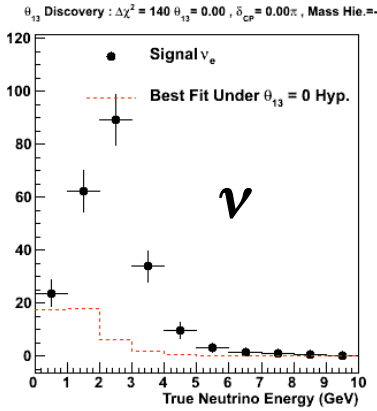


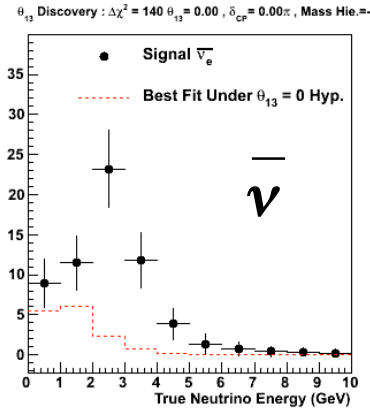


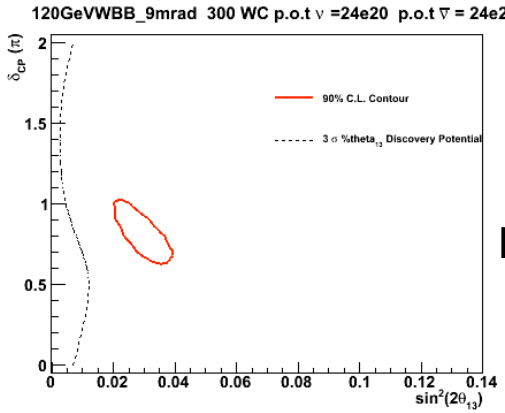


Mass Hierarchy	YES

ν Oscillations : Example of measurement



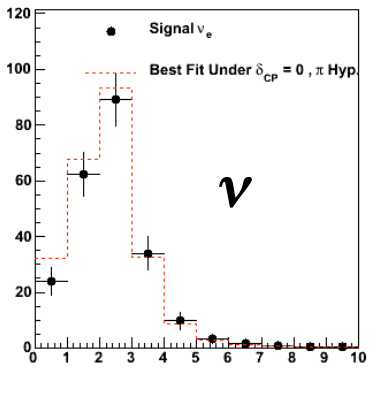


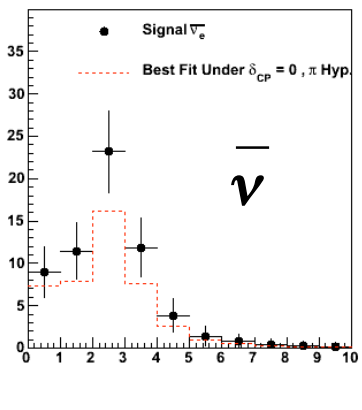


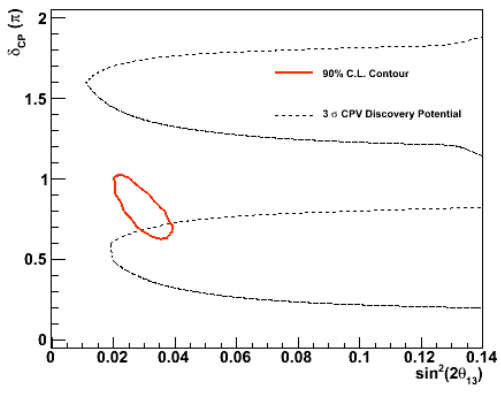
Black : Data

Red : Null Hypothesis

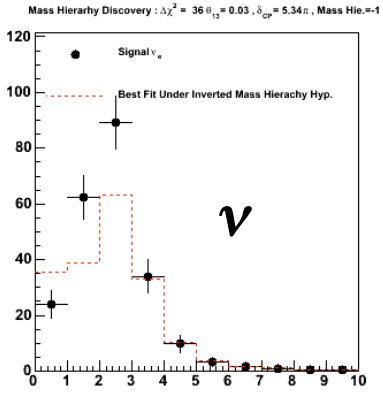
Parameter	Discovery
θ_{13}	YES

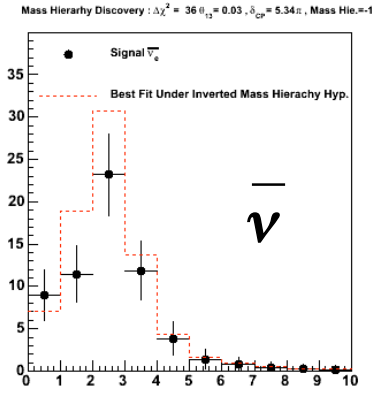


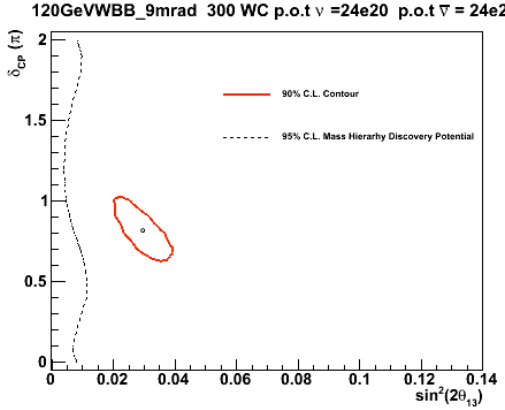




CPV	NO

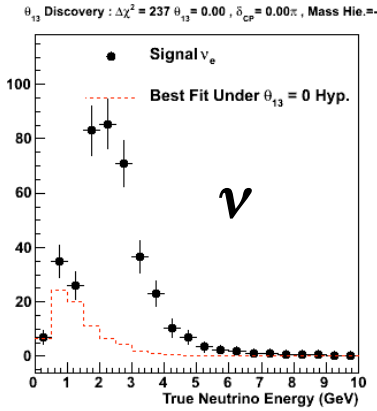


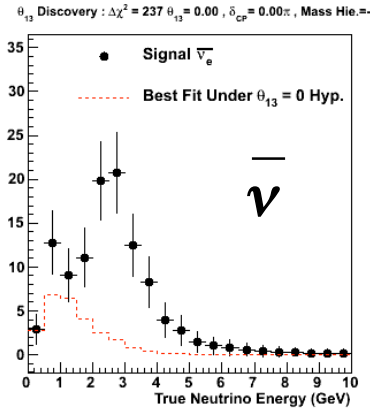


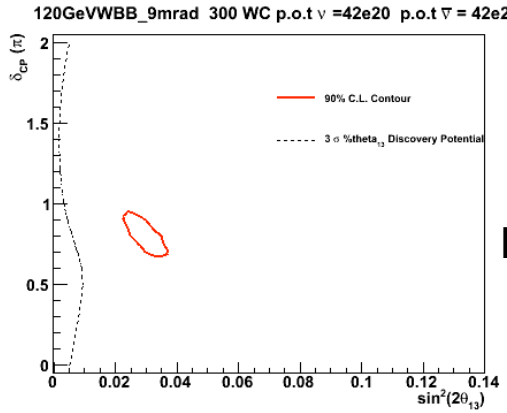


Mass Hierarchy	YES

ν Oscillations : Example of measurement



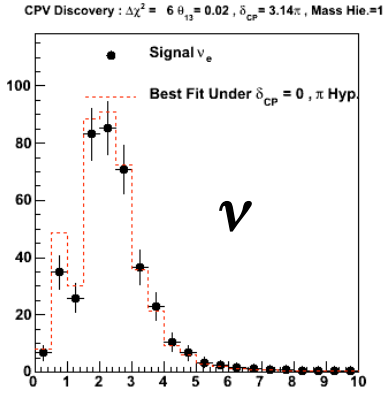


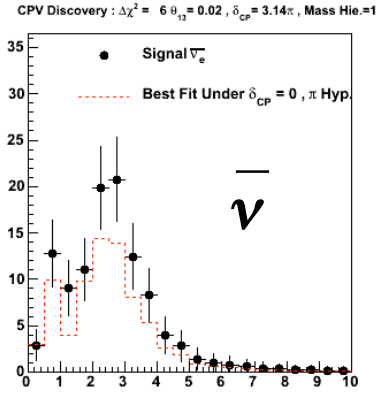


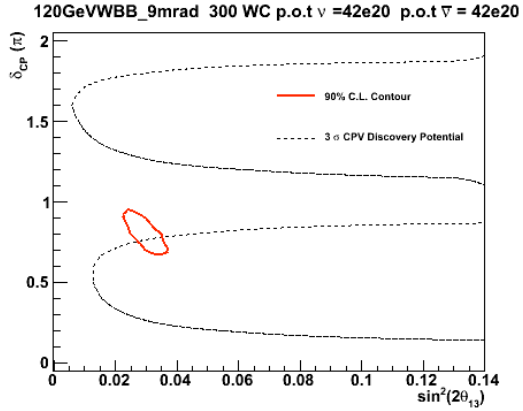
Black : Data

Red : Null Hypothesis

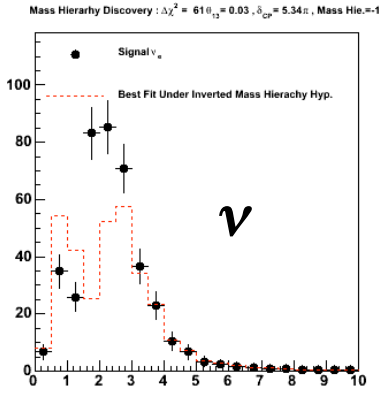
Parameter	Discovery
θ_{13}	YES

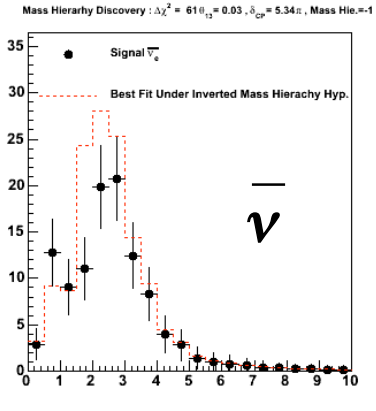


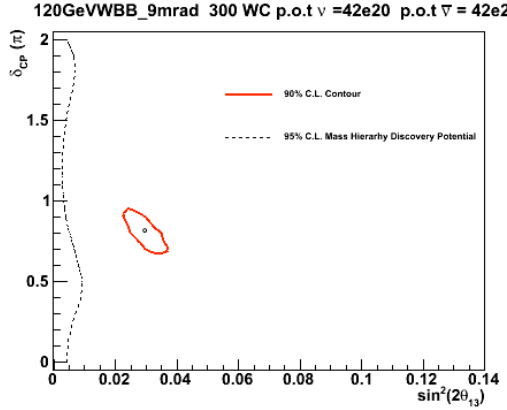




CPV	NO

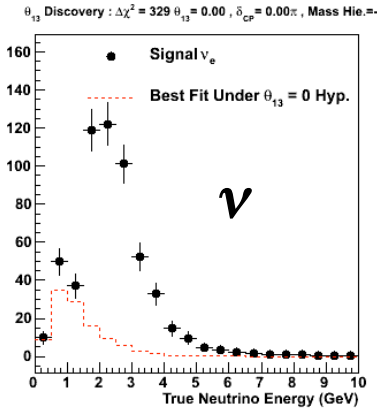


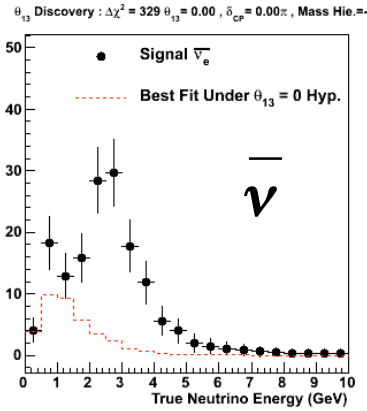


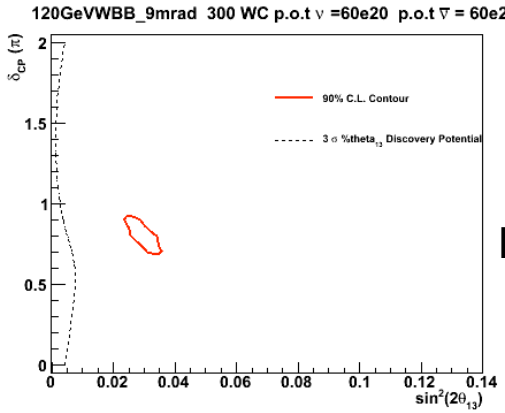


Mass Hierarchy	YES

ν Oscillations : Example of measurement



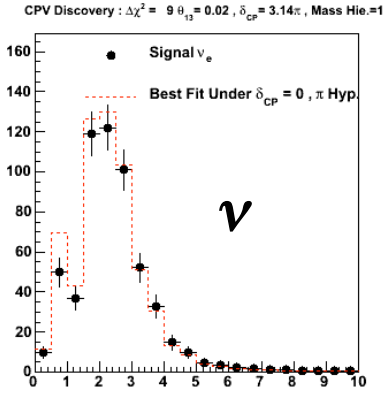


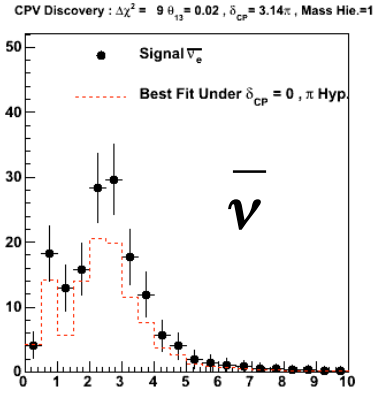


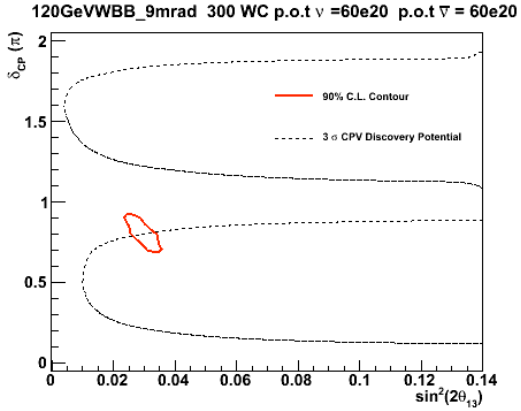
Black : Data

Red : Null Hypothesis

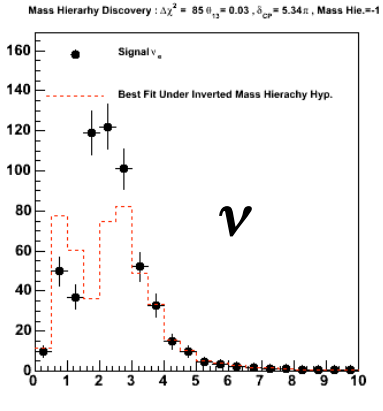
Parameter	Discovery
θ_{13}	YES

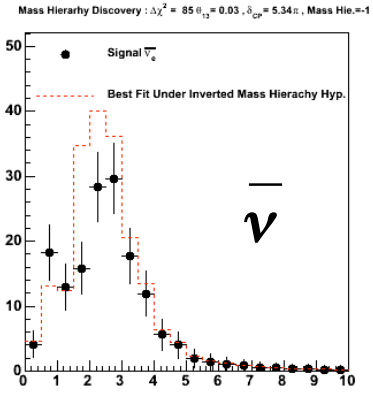


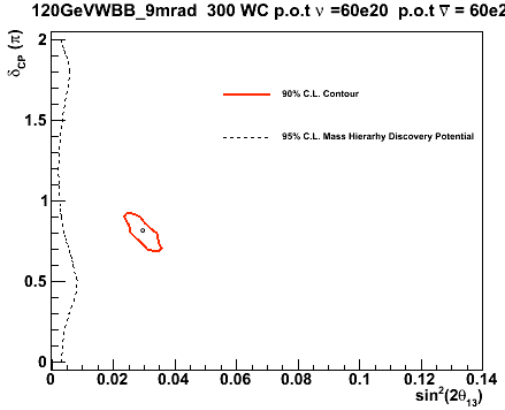




CPV	YES



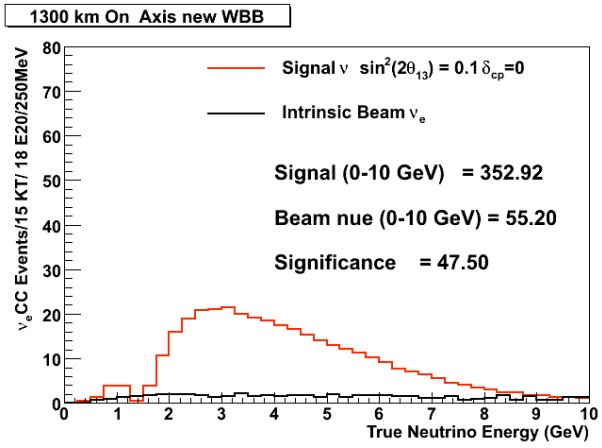




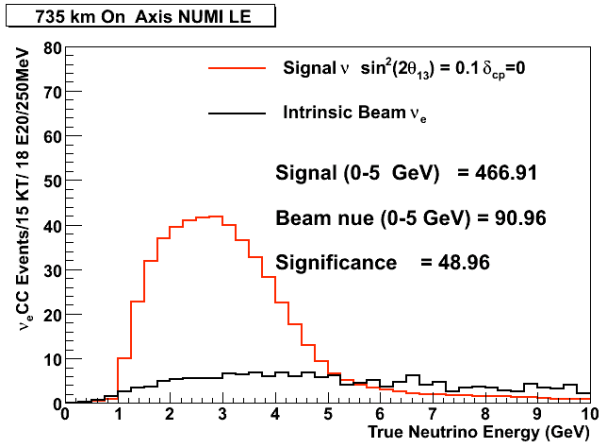
Mass Hierarchy	YES

Neutrino beams @ different on–off axis locations we consider in order to define the Future Strategy (US)

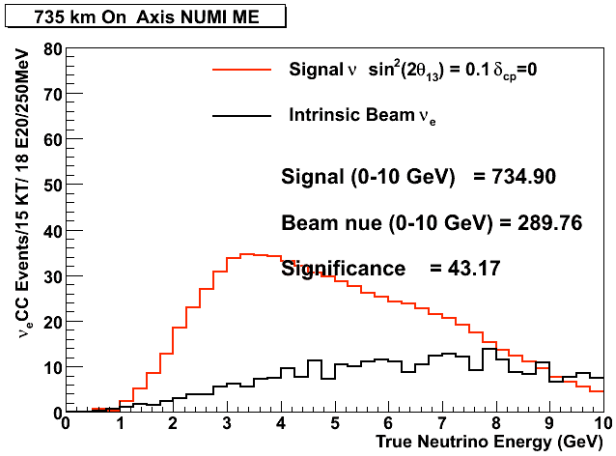
On-Axis 1300km new WBB



On Axis 735km NuMI LE



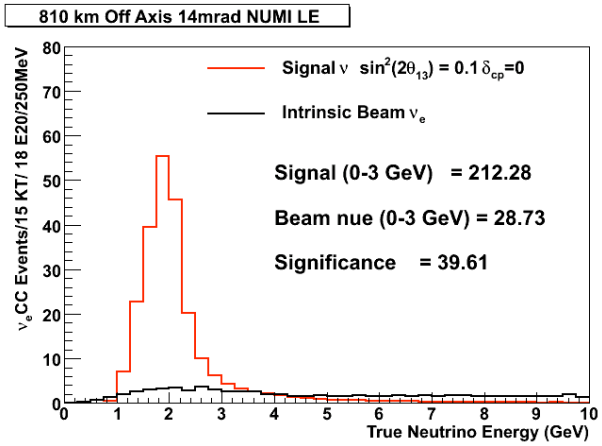
On Axis 735km NuMI ME



Disappearance minimum (appearance maximum) at given Δm_{23}^2:

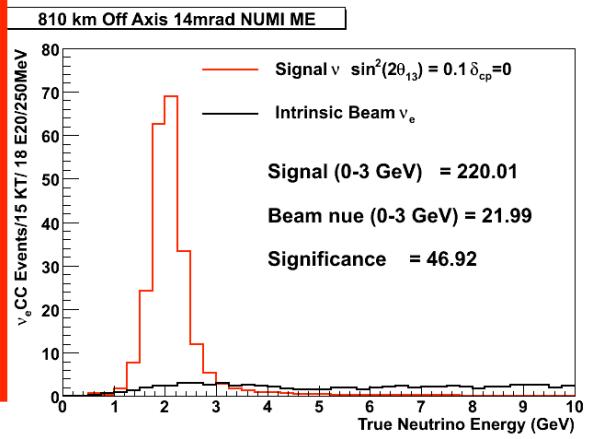
Signal events do not scale as $1/L^2$, backgrounds do.

Off Axis NuMI LE



Considered all these options with various Detector Technologies and Beam Powers and concluded on a possible staged approach to get to the physics of interest

Off Axis NuMI ME



Staged approach to achieve the ultimate goals (US)

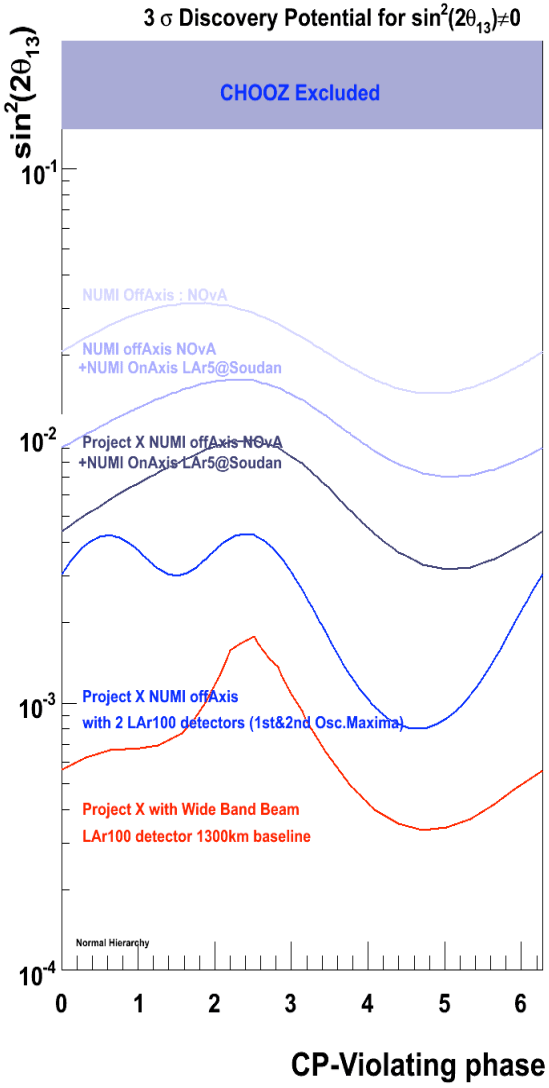
1) Start with NuMI off Axis beam at 810 km (NOvA) and 700 KW

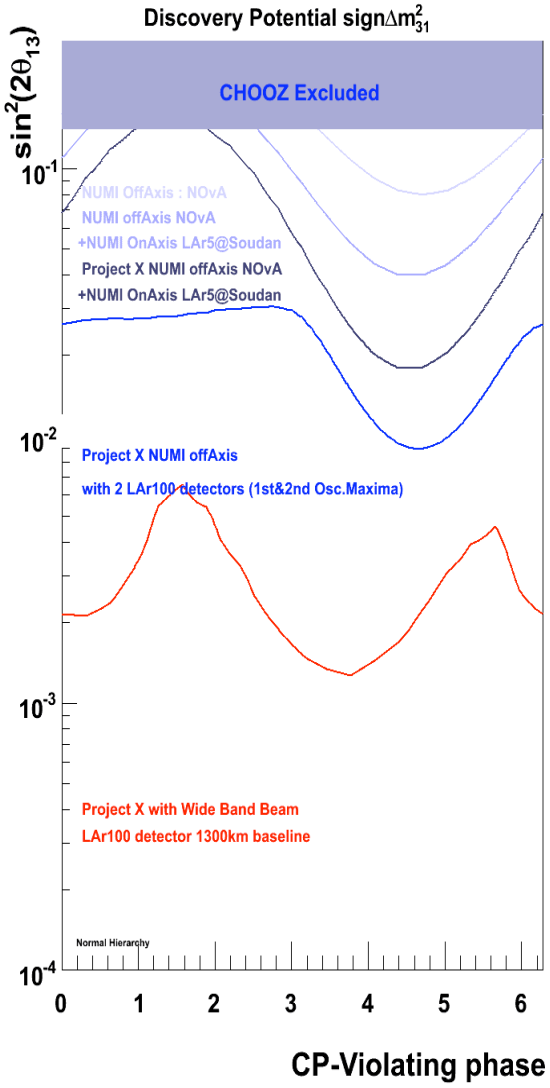
2) Upgrade detector, ie add 5kt LAr with NuMI on Axis Beam at 735 km and 700 KW (*equivalent to increasing statistics. Equivalent to ~doubling NOvA, with the benefit of proving or not a promising detector technology that is scalable*)

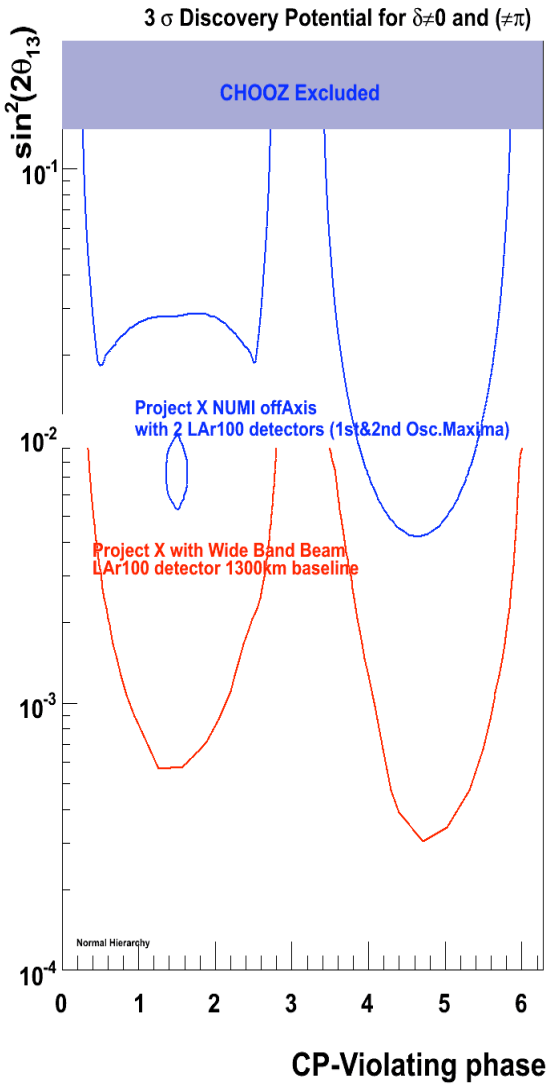
3) Increase Beam Power : Project X yields 2.3 MW , *(equivalent to increasing statistics)*

4) Improve the Neutrino Beam (new WBB), Increase Detector Mass (*equivalent to increasing statistics*) and Increase Baseline

Physics Reach : FNAL with one 100KT Lar Detector in DUSEL







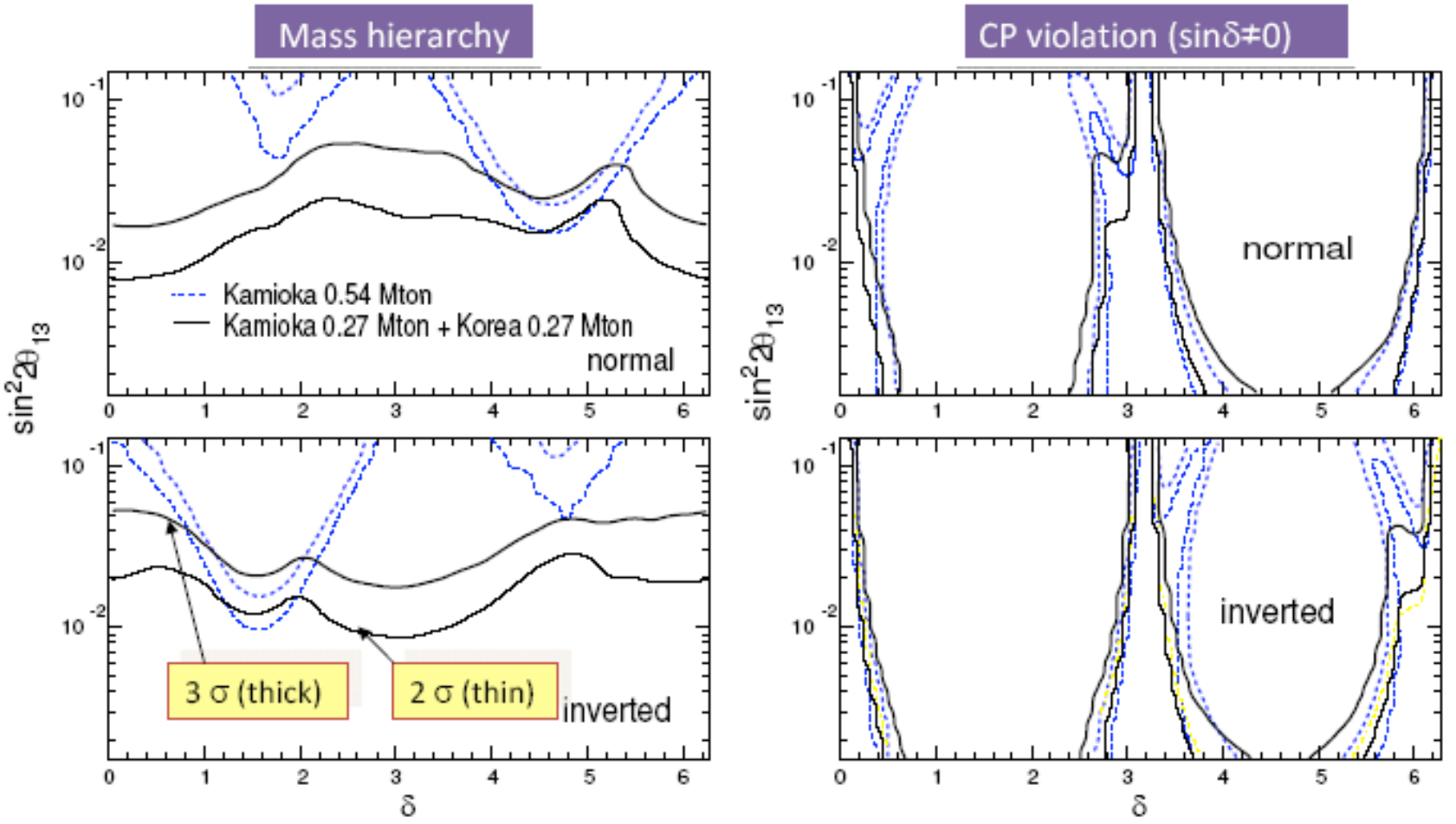
NOvA - NOvA+5ktLAr - NOvA+5ktLAr+PX - NOvA+100kt LAr +PX

100ktLAr (OR 500kt WC) +New WBB+PX at DUSEL

Physics Reach : JPARC with two 0.27 MT WC in Kamioka and Korea

hep-ph/0504026

0.27 Mton fid. Mass at Kamioka and Korea (water Ch)
4 years ν beam + 4 years anti-ν beam, 4MW, 2.5 deg Off-axis

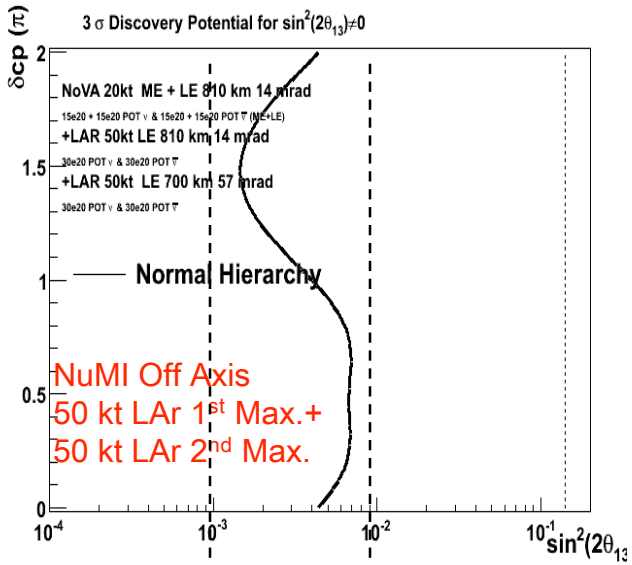


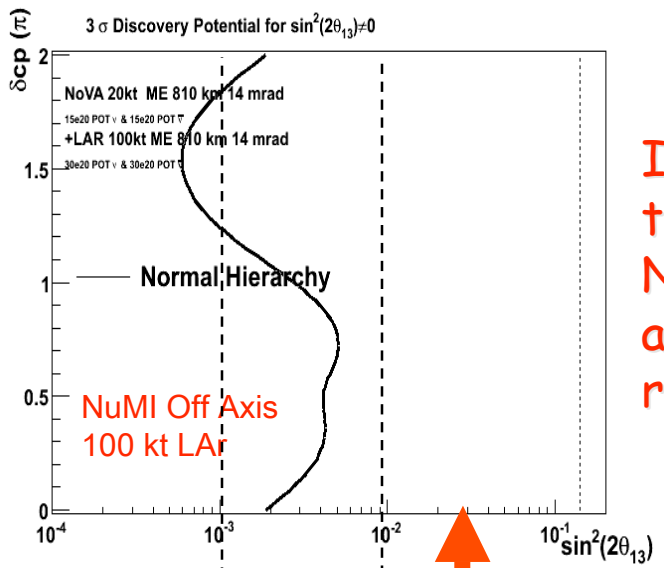
Summary

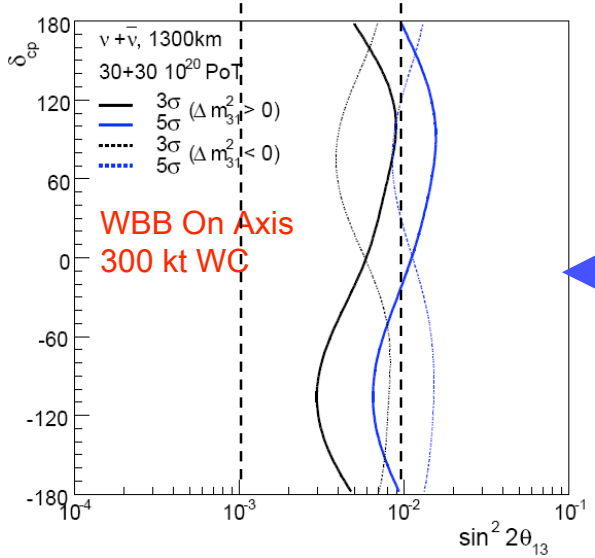
- We have learned (and are still learning) a lot with respect to neutrino masses and mixings …
- In the near future we hope to have **new "POSITIVE"** results on θ_{13} from Double CHOOZ , Day Bay, T2K and NOvA.
- **The next generation of accelerator neutrino oscillation experiments will try to DEFINITIVELLY address the following very challenging questions:**
  - **What is the value of the third mixing angle θ_{13} ?**
  - **Is θ_{23} exactly 45 degrees or not?**
  - **What is the ordering of the neutrino masses ?**
  - **Is CP Violated in the neutrino sector ?**
- To address the above questions we need **very intense neutrino beams** and **massive detectors**. Both JAPAN and US are developing future strategies in order to perform these measurements should Nature turns out to be kind and **θ_{13} is not "experimentally" zero …**

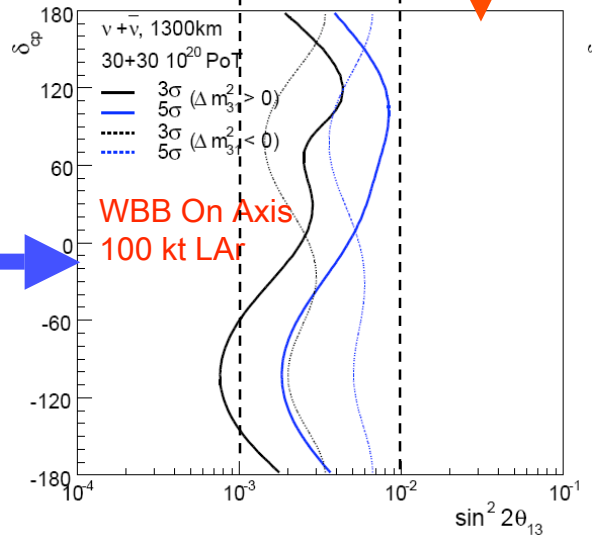
Backup

BNL- FNAL Joint Study: θ_{13} discovery potential





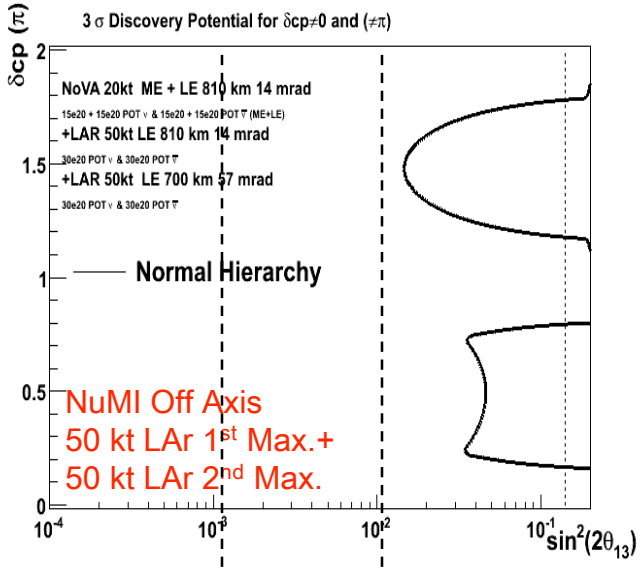


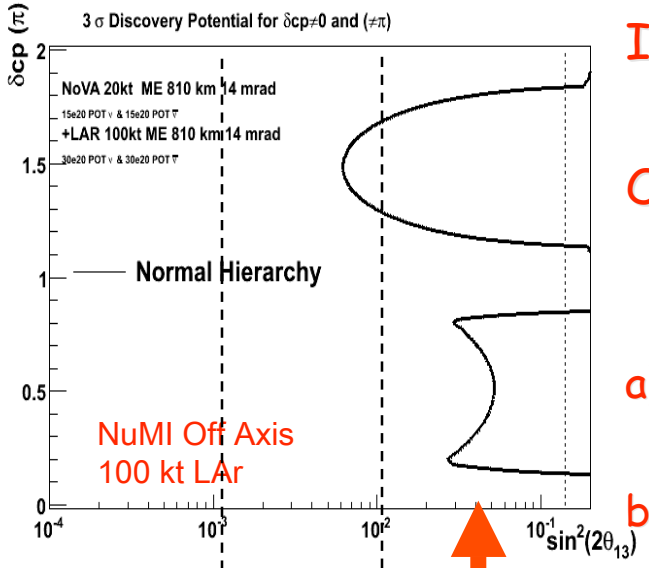


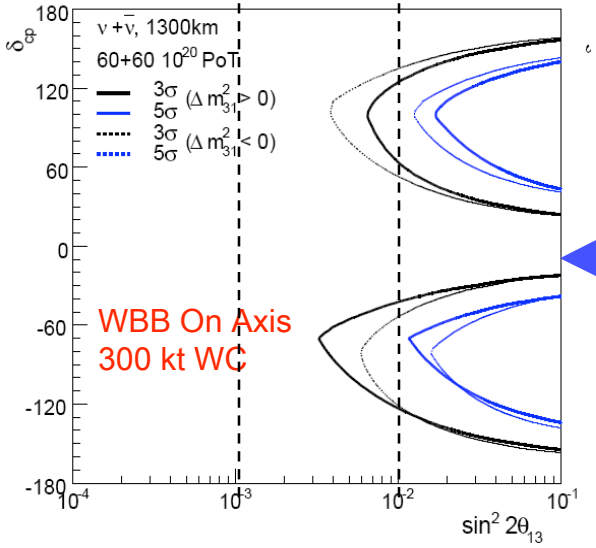
If the same detector technology used , off axis NBB and on axis WBB approaches give ~similar reach

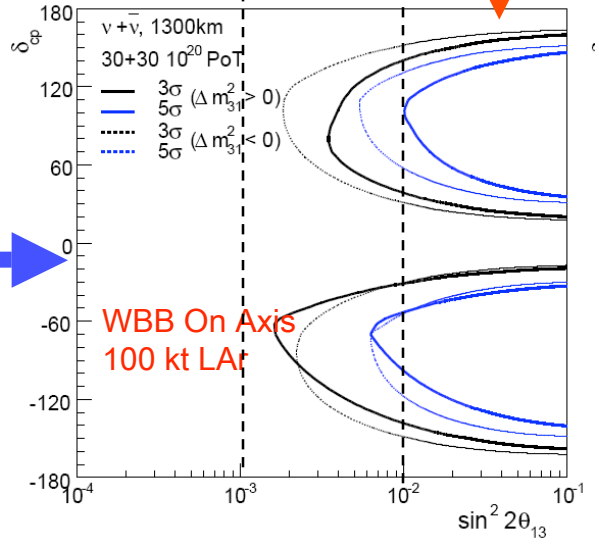
100kt of LAr equivalent with > 300 kt of Water Cherenkov

BNL- FNAL Joint Study: δ_{CP} discovery potential









If the same detector technology used :

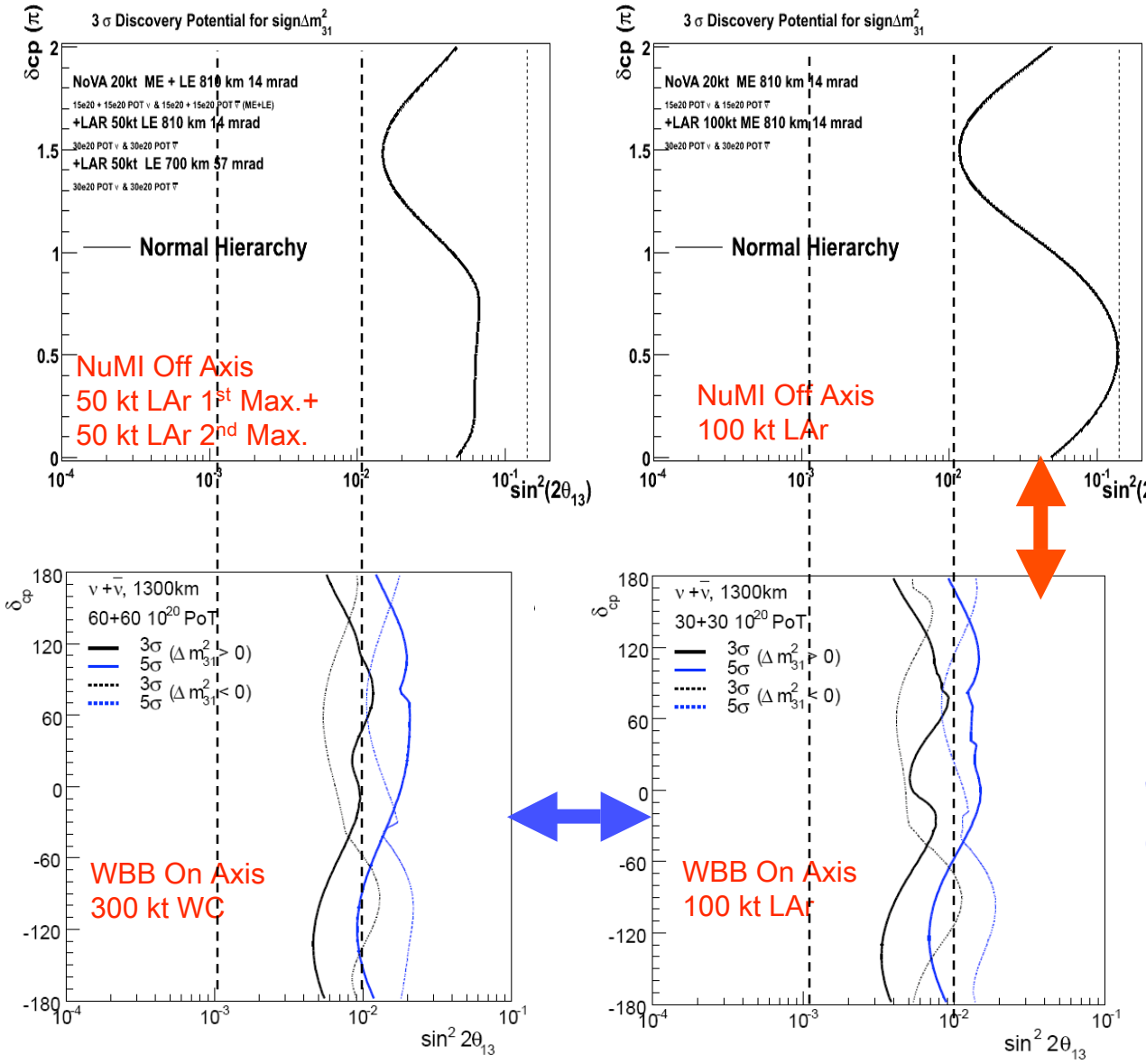
On Axis WBB has much higher reach on CP Violation due to

a) more information on 2nd oscillation maximum and

b) higher L that increase matter effects.

100kt of LAr equivalent with > 300 kt of Water Cherenkov

BNL- FNAL Joint Study: mass hierarchy discovery potential



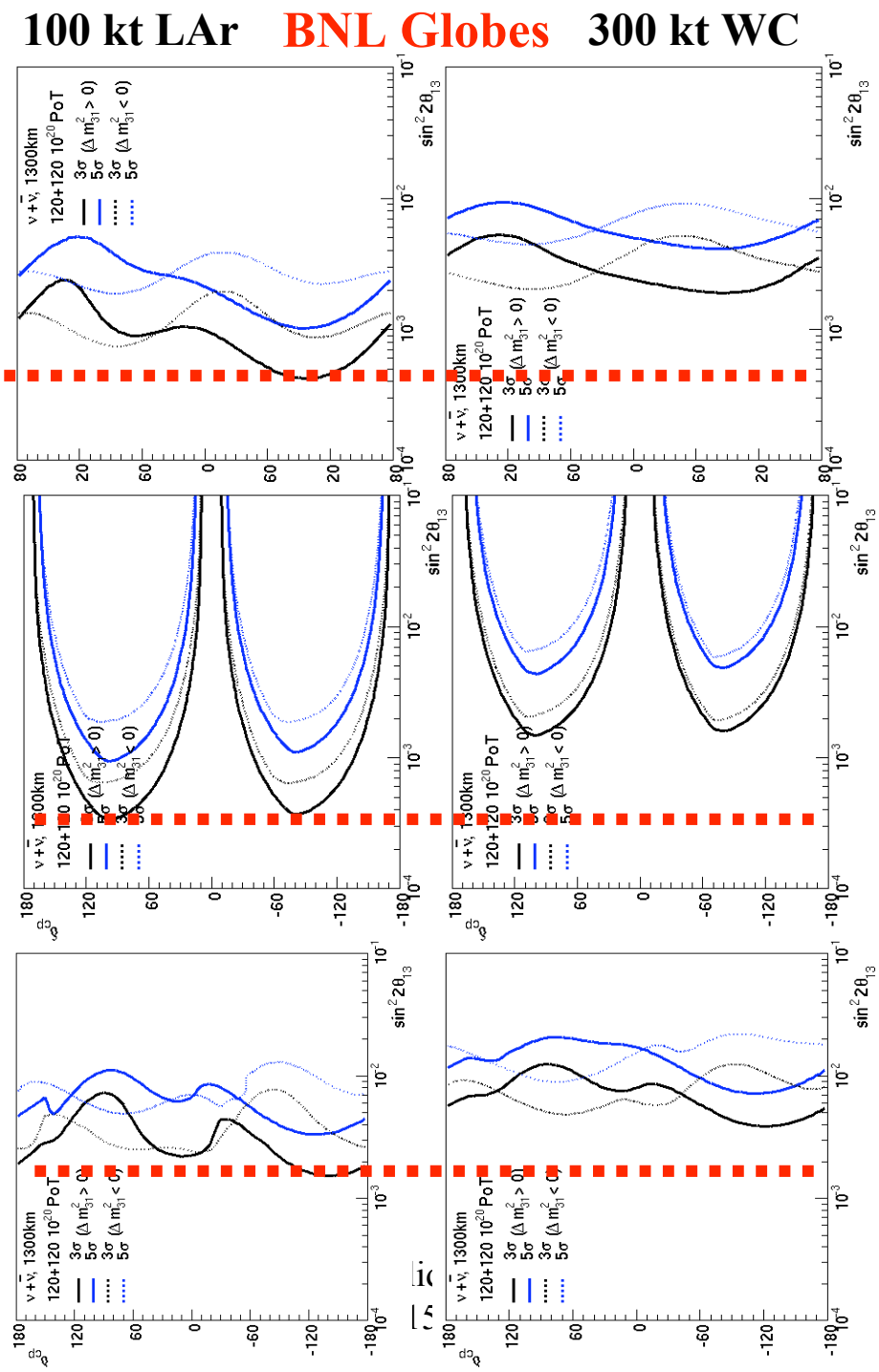
If the same detector technology used :

On Axis WBB has much higher reach on the mass hierarchy due to

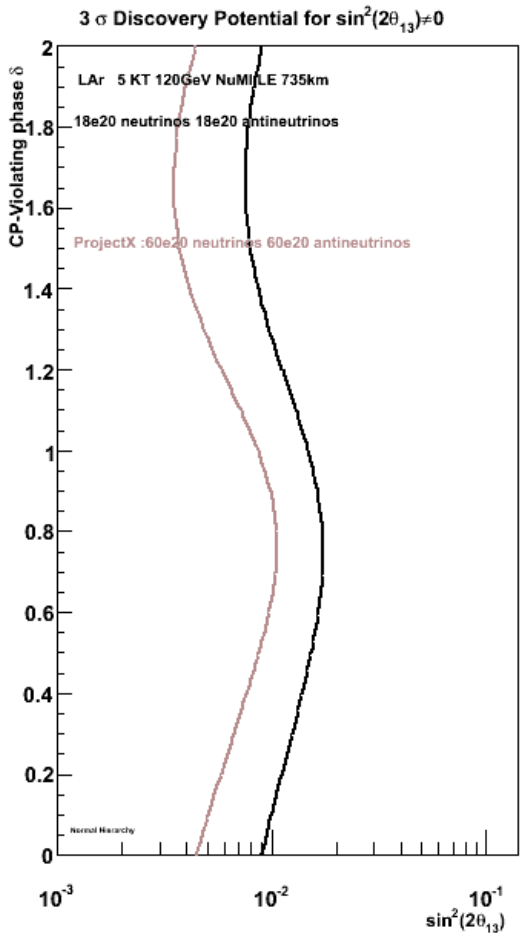
a) more information on 2nd oscillation maximum and

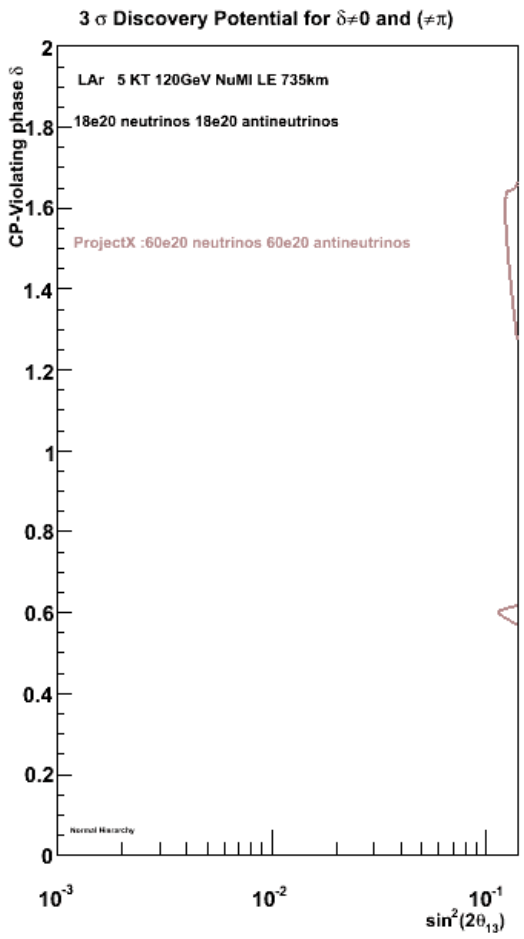
b) higher L that increase matter effects.

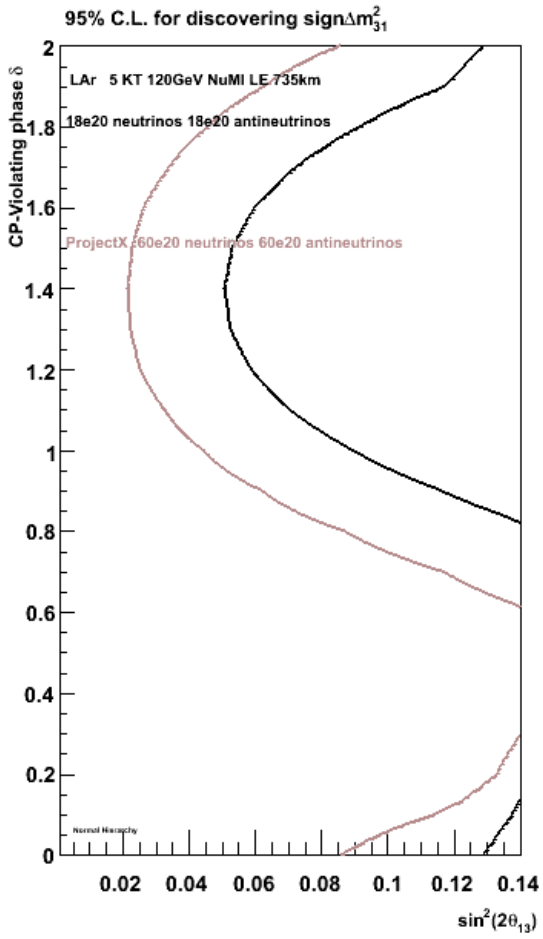
100kt of LAr equivalent with > 300 kt of Water Cherenkov


100 kt LAr
BNL Globes
300 kt WC
ν+ν̄, 1300km
120+120 10^20 PoT
3σ (Δm²31 > 0)
5σ (Δm²31 > 0)
3σ (Δm²31 < 0)
5σ (Δm²31 < 0)
sin²2θ13
δCP

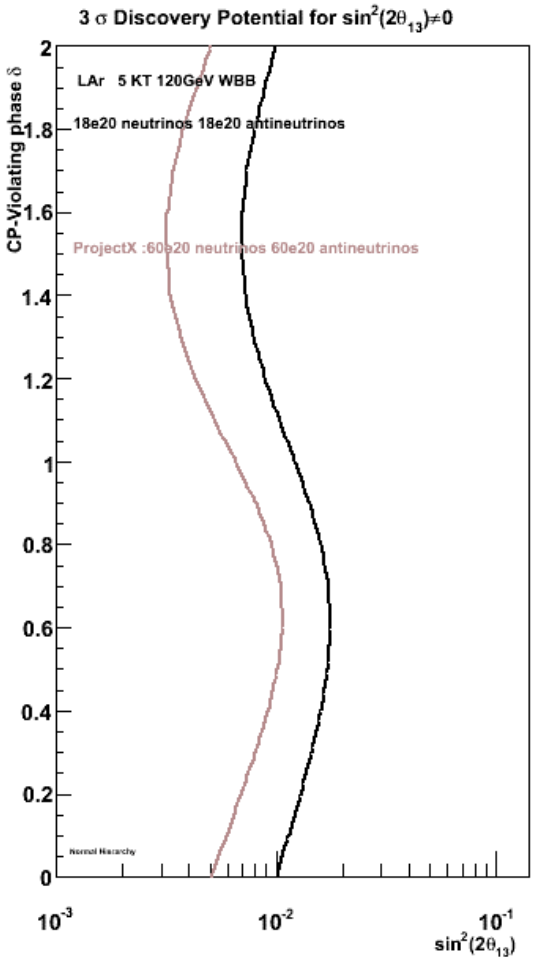
LAr5 @ SOUDAN (LE)

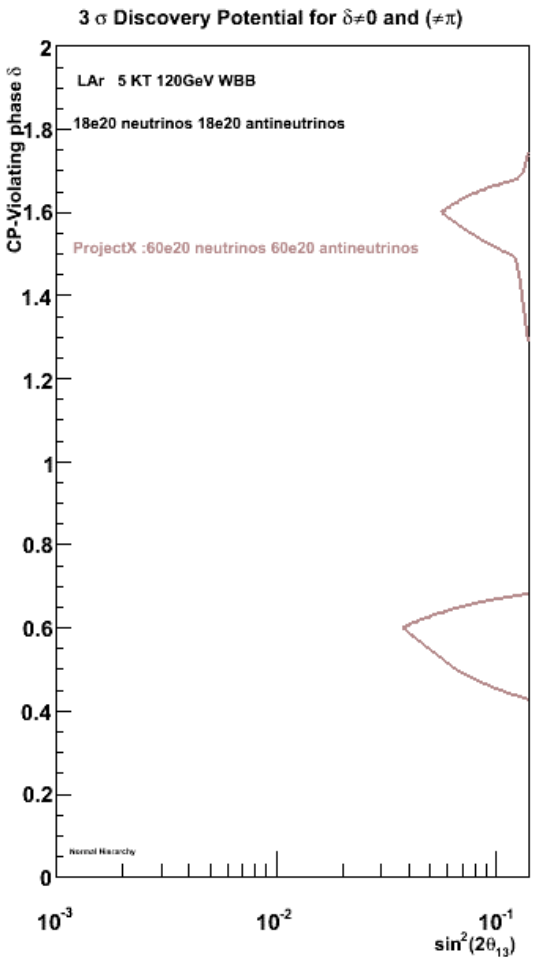


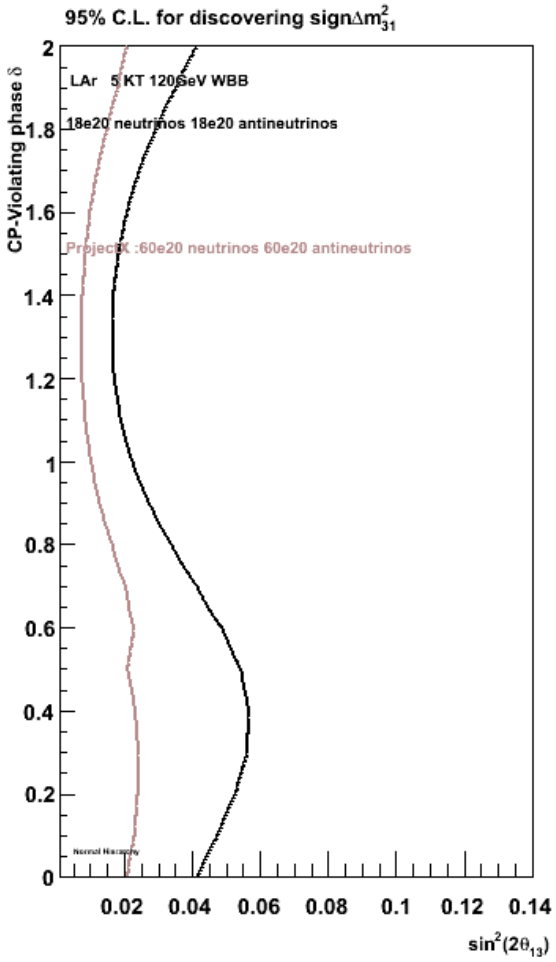




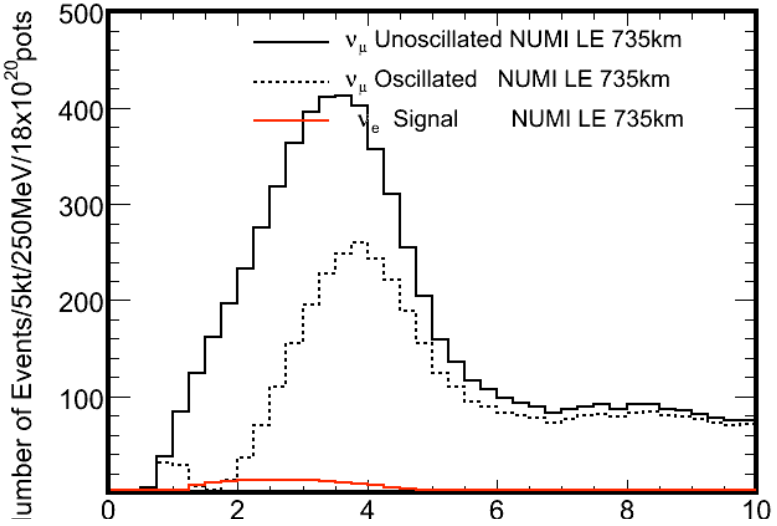
LAr5 @ L = 1300 km

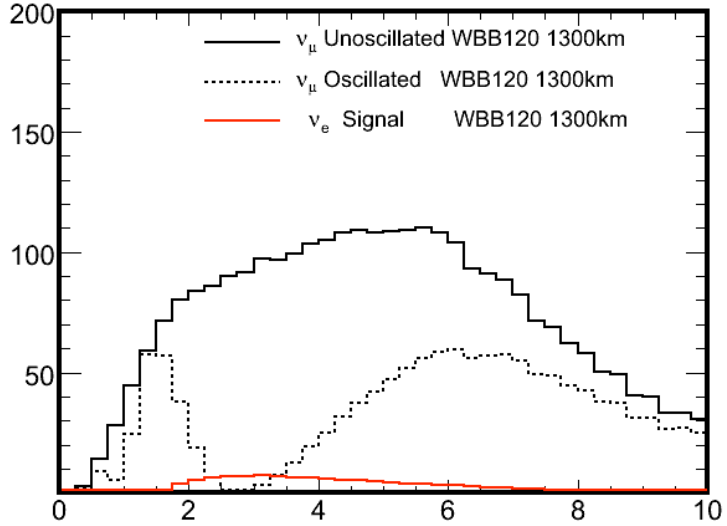


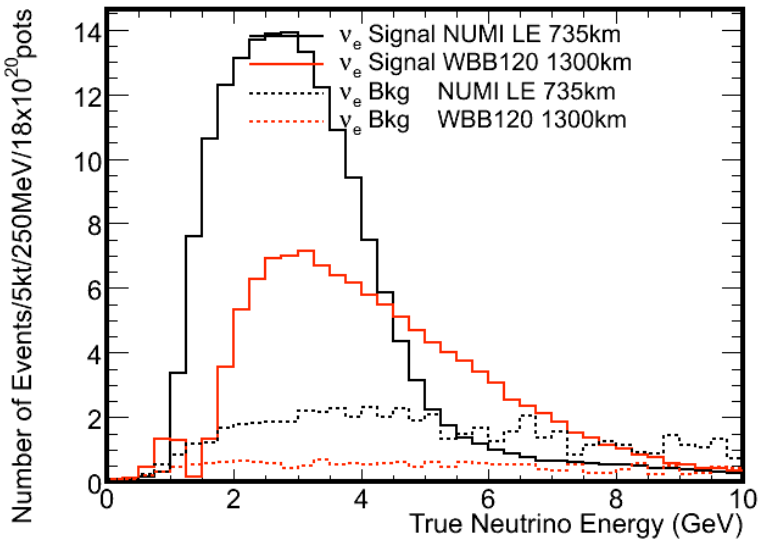




The effect of longer baseline (>>L) and a new Wide Band Beam





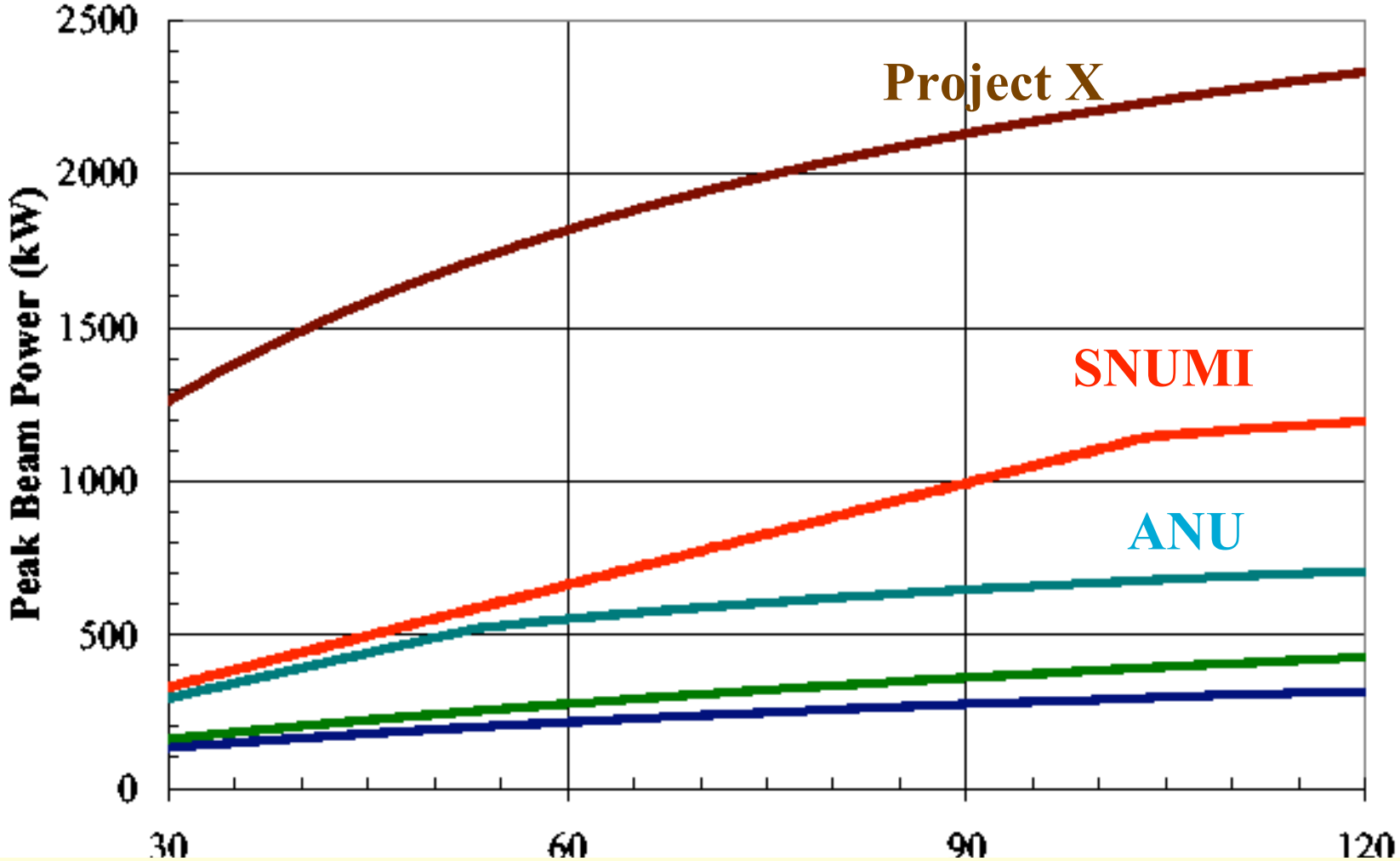


- With increasing L oscillation maxima (and minima) "appear" in more "favourable" positions in the neutrino energy spectra (higher energies),

- Thus study of first and second oscillation maxima is easier (one detector instead of two, higher rates, etc)

NuMI Neutrino Beam: Capabilities & Advantages

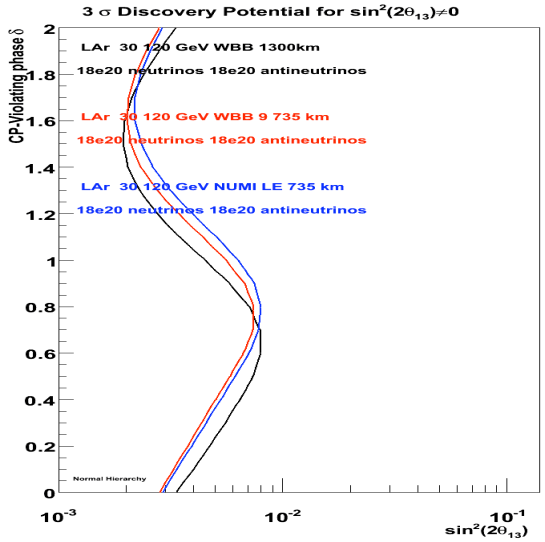
Plot courtesy : B. Zwaska

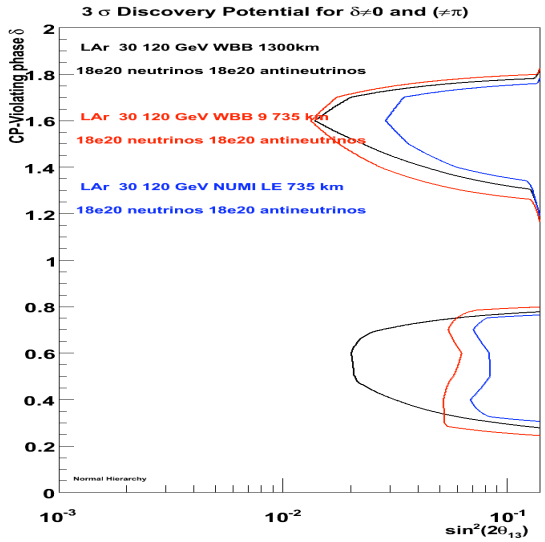


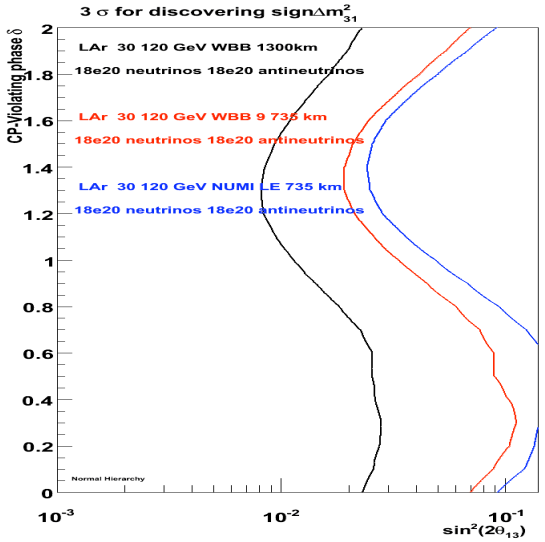
- There exists a well defined upgrade plan for the NuMI Beam
- With Project X, beam power and hence neutrino beam intensity can increase by a factor of 3 with respect to ANU

The effect of longer baseline (>>L) and a new Wide Band Beam with the same detector and the same exposure :

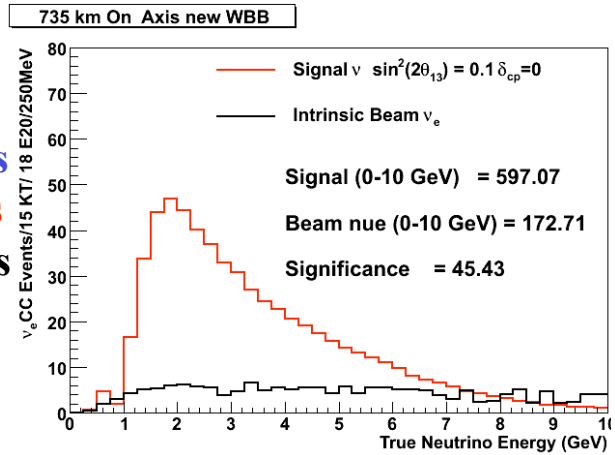
Example : 30 kt of Lar, 700 KW Beam Power, 3 year of neutrino + 3 years of anti-neutrino running

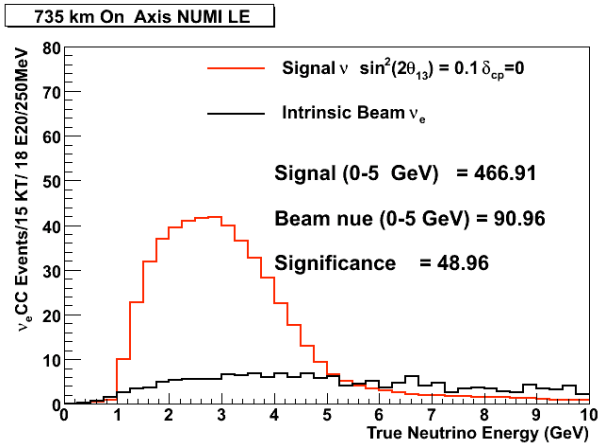






BLUE : NuMI 735 km On Axis
RED : WBB 735 km On Axis
BLACK : WBB 1300 km On Axis





Detector Technologies & Capabilities

Liquid Scintillator (NOvA) :

- Signal selection efficiency : 27% **(fiducial volume efficiency included)**
- NC contamination ~ 0.5% for the off axis Beam concept.

LAr and Water Cherenkov :

- Signal selection efficiency : 80% LAr , ~15% WC **(After fiducial volume)**
- Practically no NC contamination for LAr, NC contamination at the ~ 1-2% for Water Cherenkov (assuming 1-2% NC contamination for LAr as well does not introduce a big difference in sensitivities)

No energy smearing, true visible energies used :

For the NuMI off axis Beam no energy binning is used (normalization information only)

For the WBB 250 MeV bins are used (shape+normalization information)