# Project X and Neutrino Oscillation Physics

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# Outline

- The **"Ultimate"** goals in **neutrino oscillation physics.**
- The **"Ingredients"** needed in order to achieve the **"Ultimate"** goals.
- A phased neutrino oscillation program at Fermilab with Project X
- Summary / Conclusions

***I am not going to discuss:***

- ***Technological issues related to neutrino beams***
- ***Technological issues related to detector options***
- ***Non neutrino oscillation physics***

# The "Ultimate" Goals in neutrino oscillations Physics

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

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)

???

Cross Mixing

Majorana phases

$$U = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & -s_{23} \\ 0 & s_{23} & c_{23} \end{bmatrix}}_{\text{Atmospheric}} \begin{bmatrix} c_{13} & 0 & -s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Solar}} \underbrace{\begin{bmatrix} e^{ia_1/2} & 0 & 0 \\ 0 & e^{ia_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{0\nu\beta\beta \text{ decays}}$$

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

# The "Ultimate" Goals in neutrino oscillations Physics

**EXPERIMENT (ACCELERATOR $\nu$'s)**

What is the value of the third mixing angle $\theta_{13}$ ?

Do neutrinos violate CP symmetry ?

Which neutrino is the heaviest one?

**EXPERIMENT (natural $\nu$'s)**

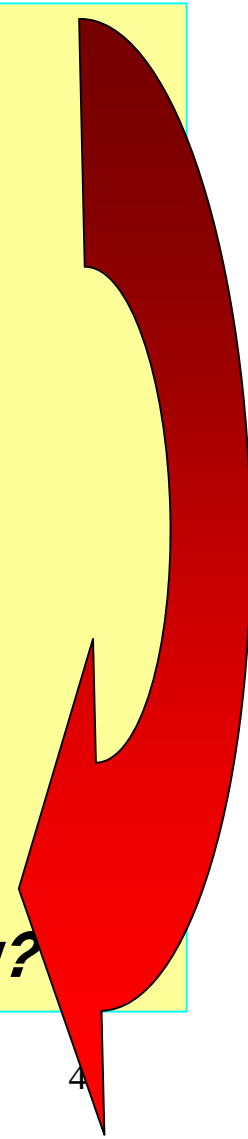
What are the neutrino masses ?

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?***

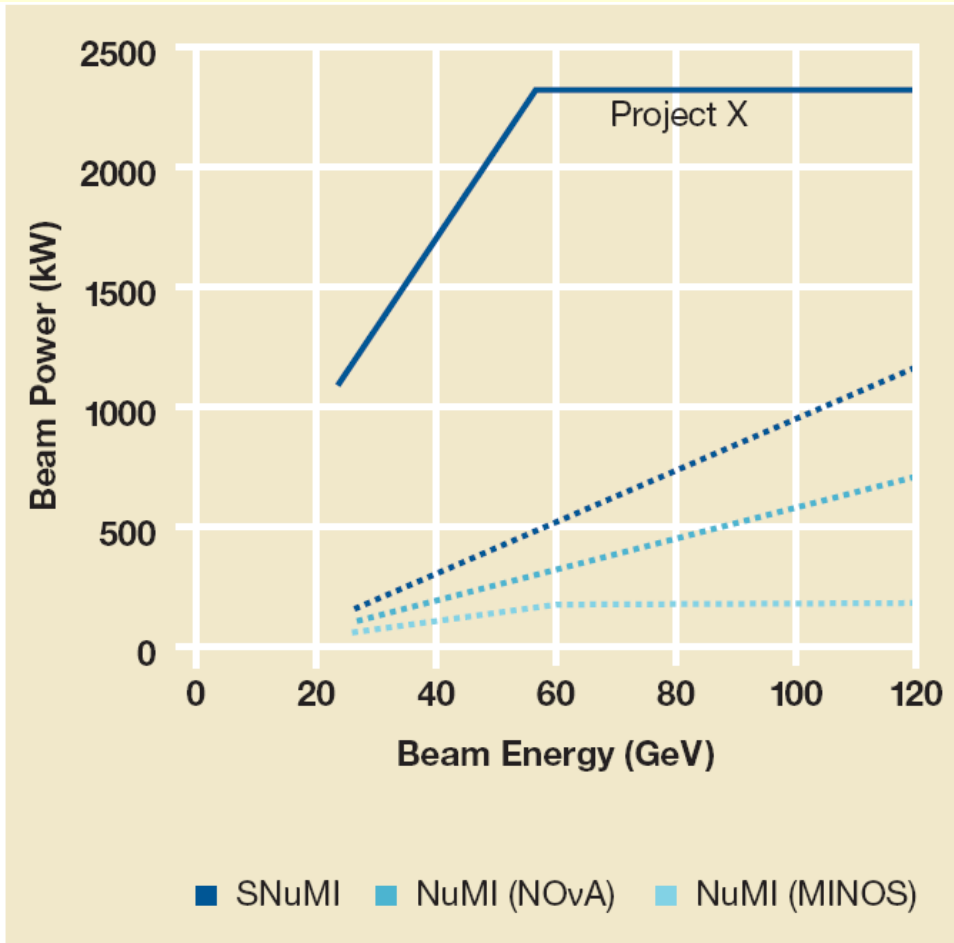


# Ingredients for achieving the ultimate goals (1)

One needs:

First, Statistics…especially if $\theta_{13}$ "small"…

**1) Powerful neutrino beams of very high intensity : Project X**

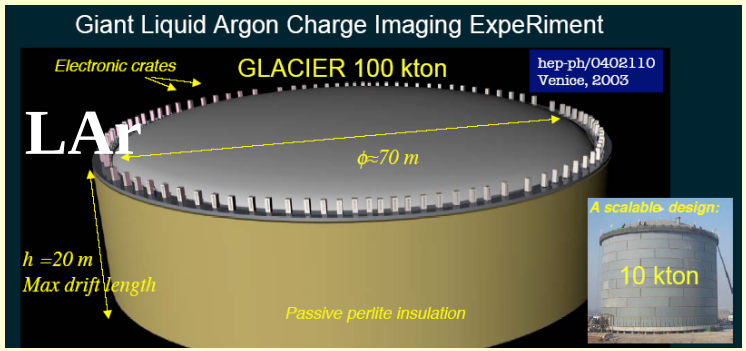


# Ingredients for achieving the ultimate goals (2)

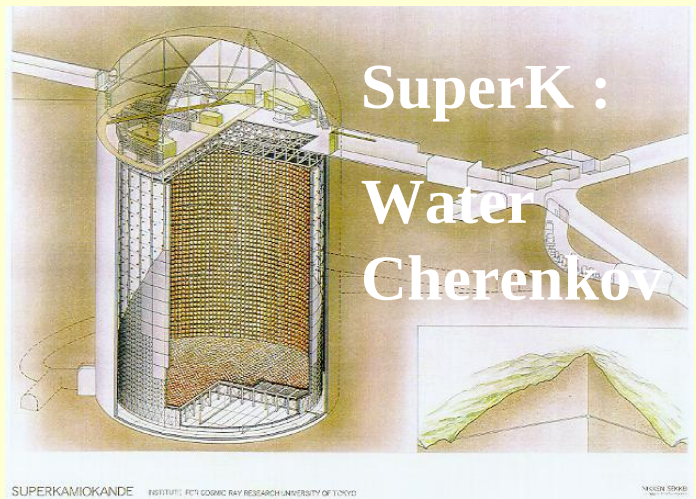
One needs:

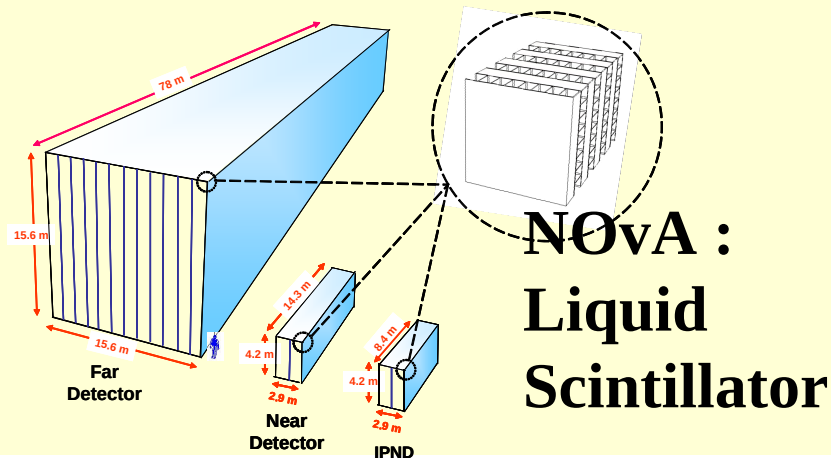
Second , Statistics…especially if $\theta_{13}$ "small"…

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







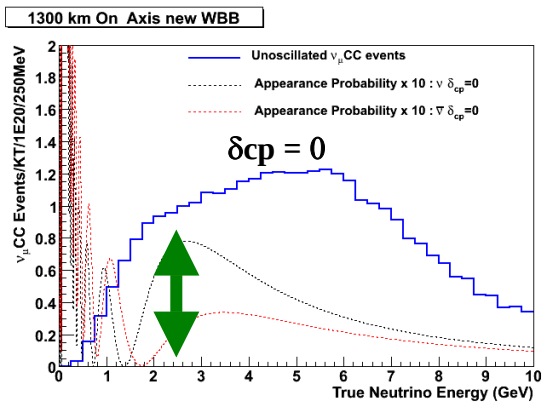
# Ingredients for achieving the ultimate goals (3)

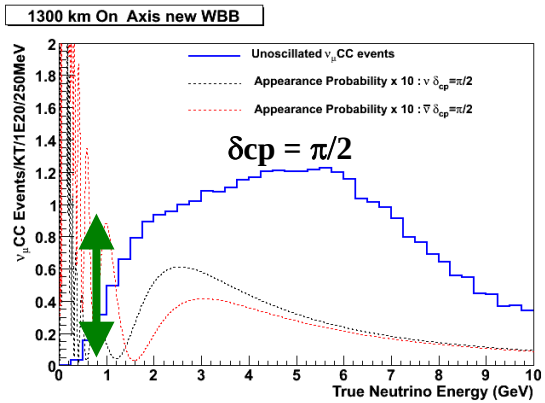
One needs:

Eventually, the capability to study both 1st and 2nd oscillation maxima in a long baseline experiment in order to break inherent degeneracies between CPV phenomenon and matter effects.

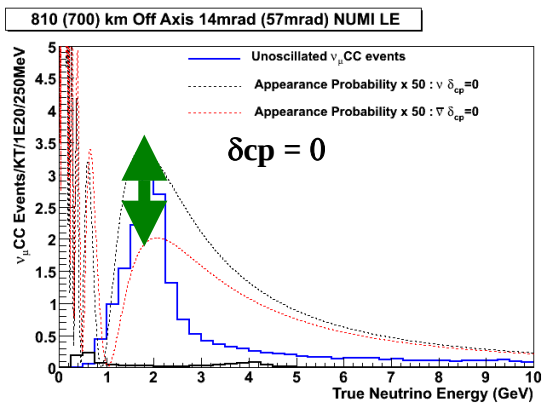
*(Other options like beta-beams or neutrino factories are also possible but perhaps will take more time)*

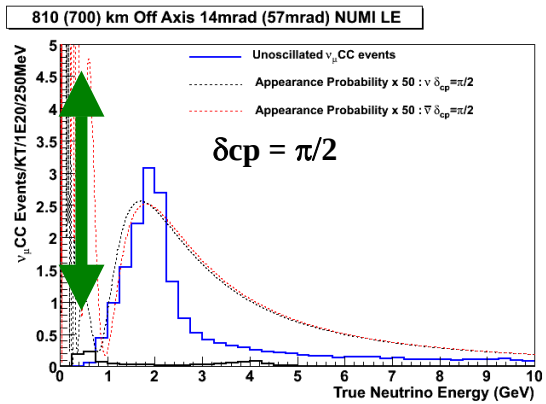
## ON AXIS WBB : 1st and 2nd Oscillation Maxima 1 Detector



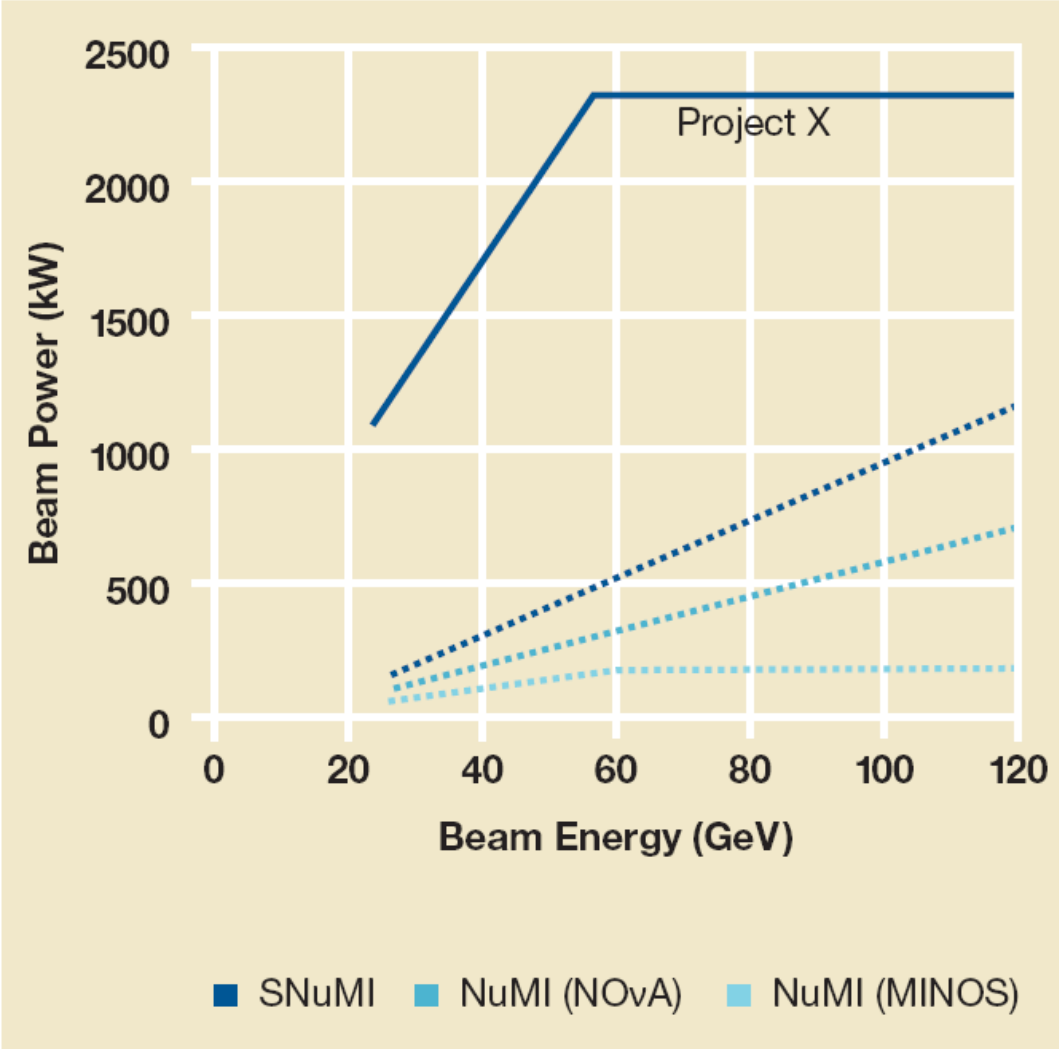




## NuMI OFF AXIS : 1st and 2nd Oscillation Maxima 2 Detectors



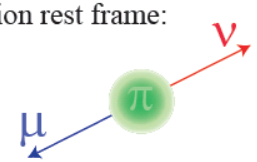
# NuMI Neutrino Beam: Capabilities & Advantages




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

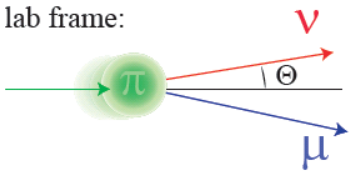
# NuMI Neutrino Beam: Capabilities & Advantages

In pion rest frame:

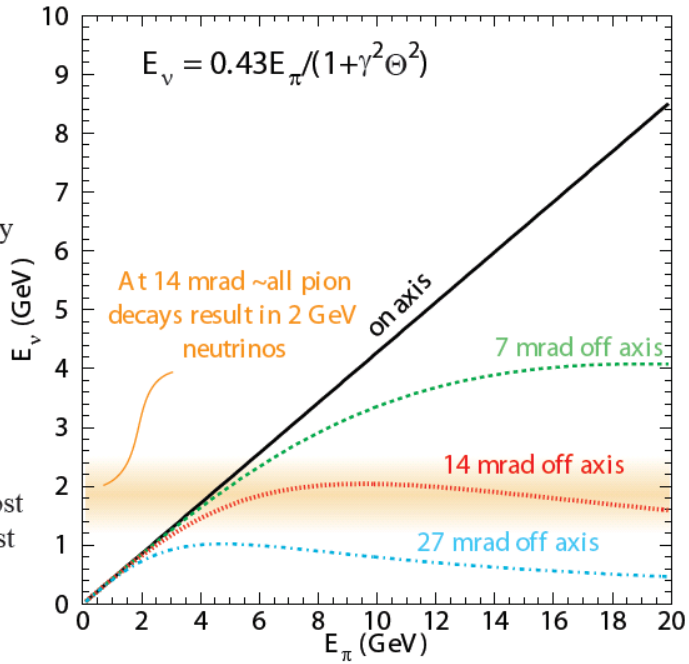


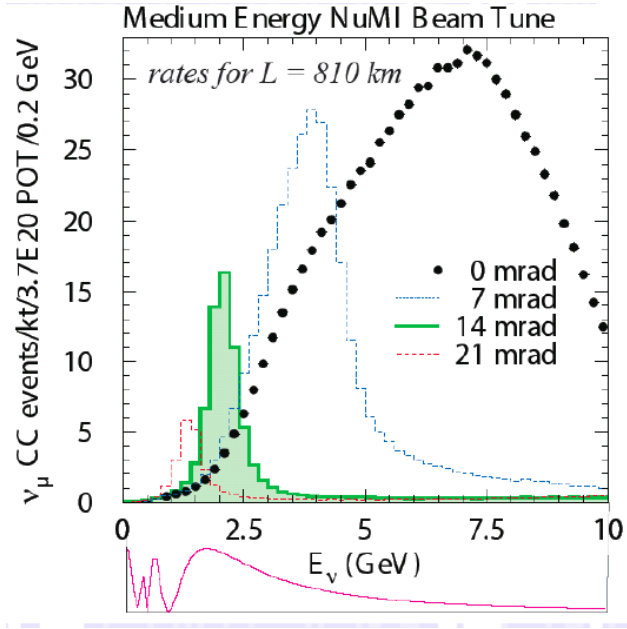

Neutrino and muon energy completely determined by energy conservation

In lab frame:




Neutrino energy depends on boost and angle between neutrino boost direction

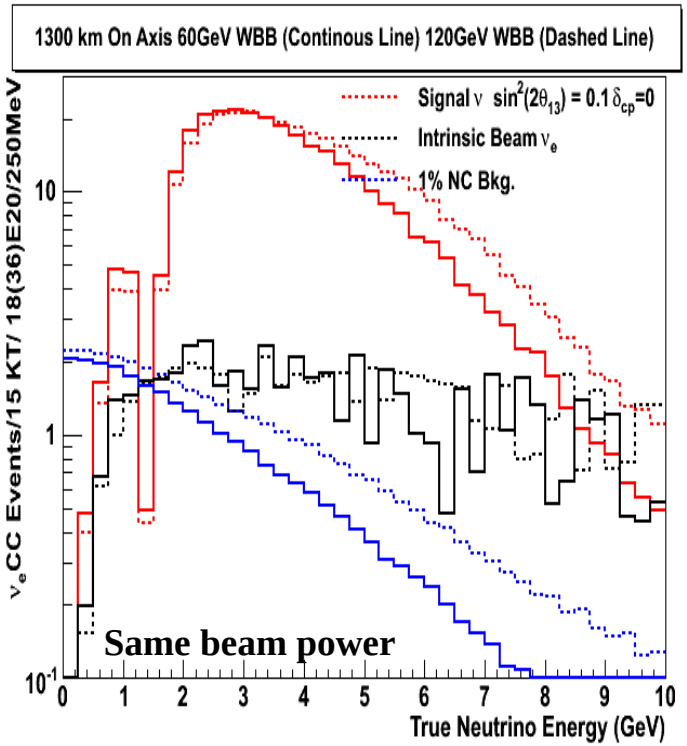


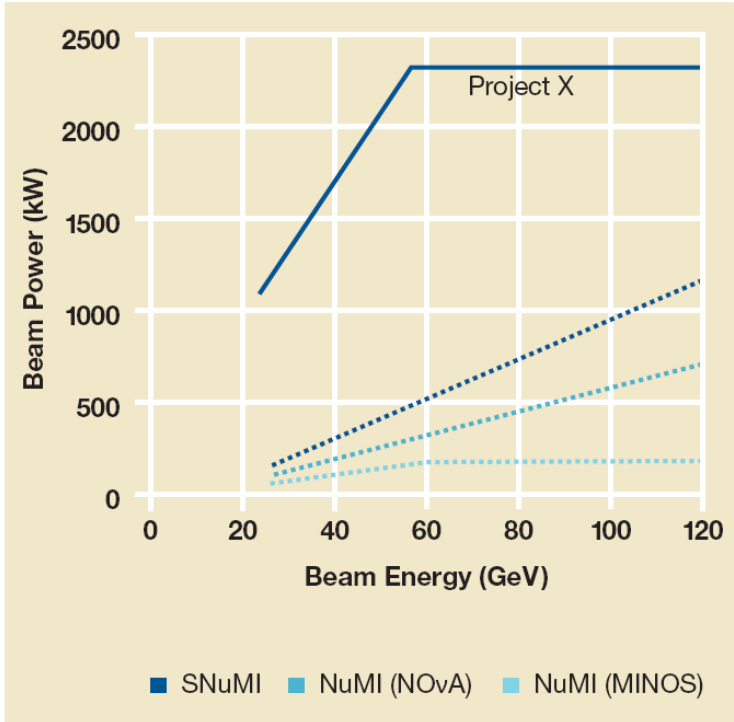




## Advantages

- The Beam Exists and performs well
- 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: Capabilities & Advantages




- This type of neutrino beam might require optimization at **lower proton energies** in order to **reduce NC backgrounds (necessary depending on detector technology) and increase signal :**

- **ProjectX can produce ~2.3 MW neutrino beams for proton energies >= 50 GeV.**

# 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)

# Comparison of Water Cherenkov and LAr detector technologies

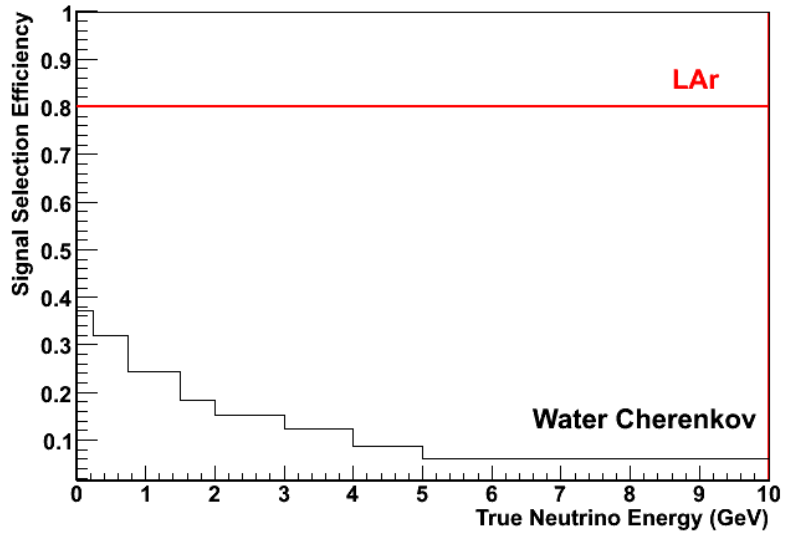
• Both detector technologies have advantages and disadvantages.

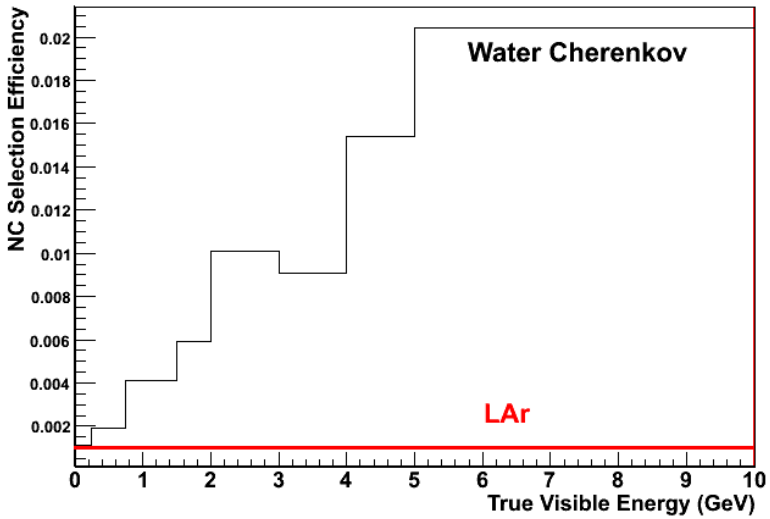
•Given their assumed efficiencies and background rejections **the following "Detector Mass Equivalent Law" holds, which has been independently checked by two groups (BNL and FNAL)**

**1 : 5**

**OR**

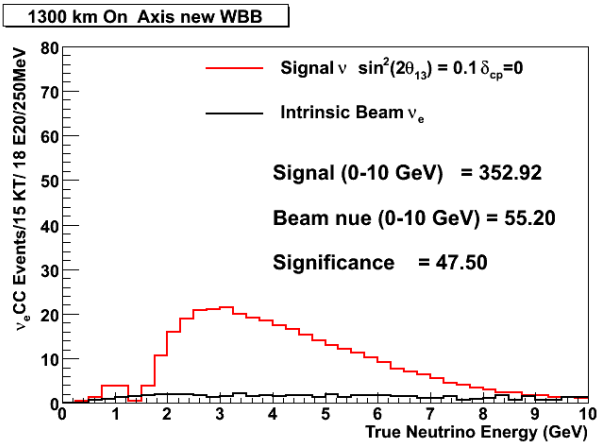
**100kt of LAr ~ 500kt WC**

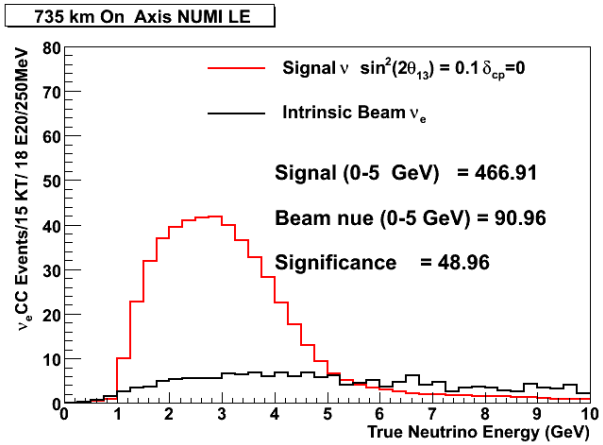


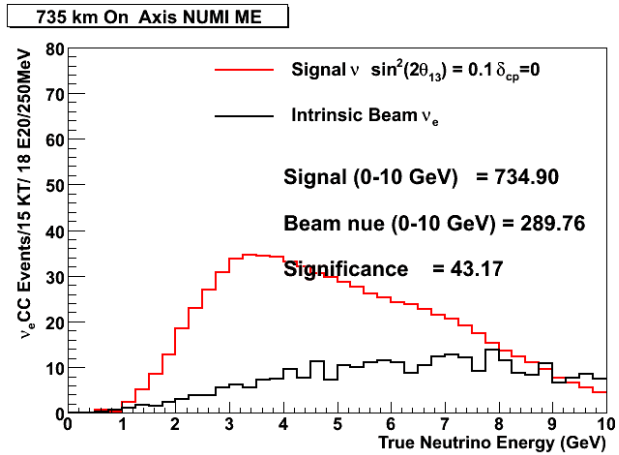



# Combinations of different neutrino beams @ different on-off axis locations that we considered

**On-Axis 1300km new WBB** **On Axis 735km NuMI LE** **On Axis 735km NuMI ME**

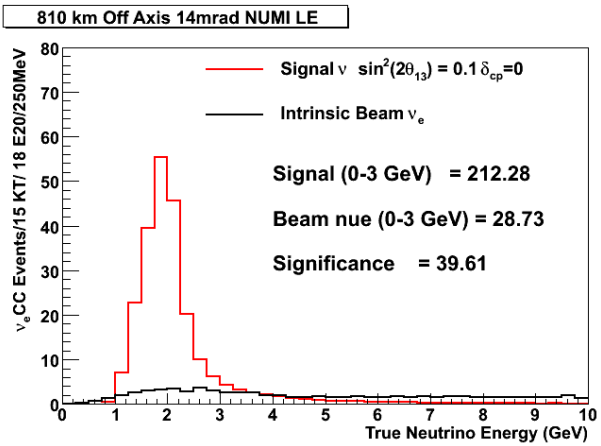


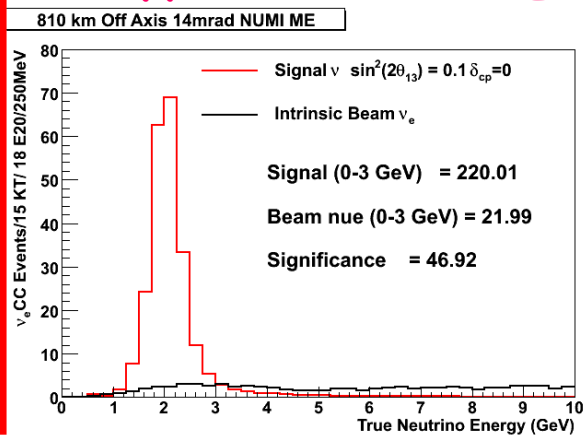




*Disappearance minimum (appearance maximum) at given $\Delta m_{23}^2$: Signal events do not scale as $1/L^2$, backgrounds do.*

**Off Axis NuMI LE** **Off Axis NuMI ME**




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



# Staged approach to get to the physics of interest

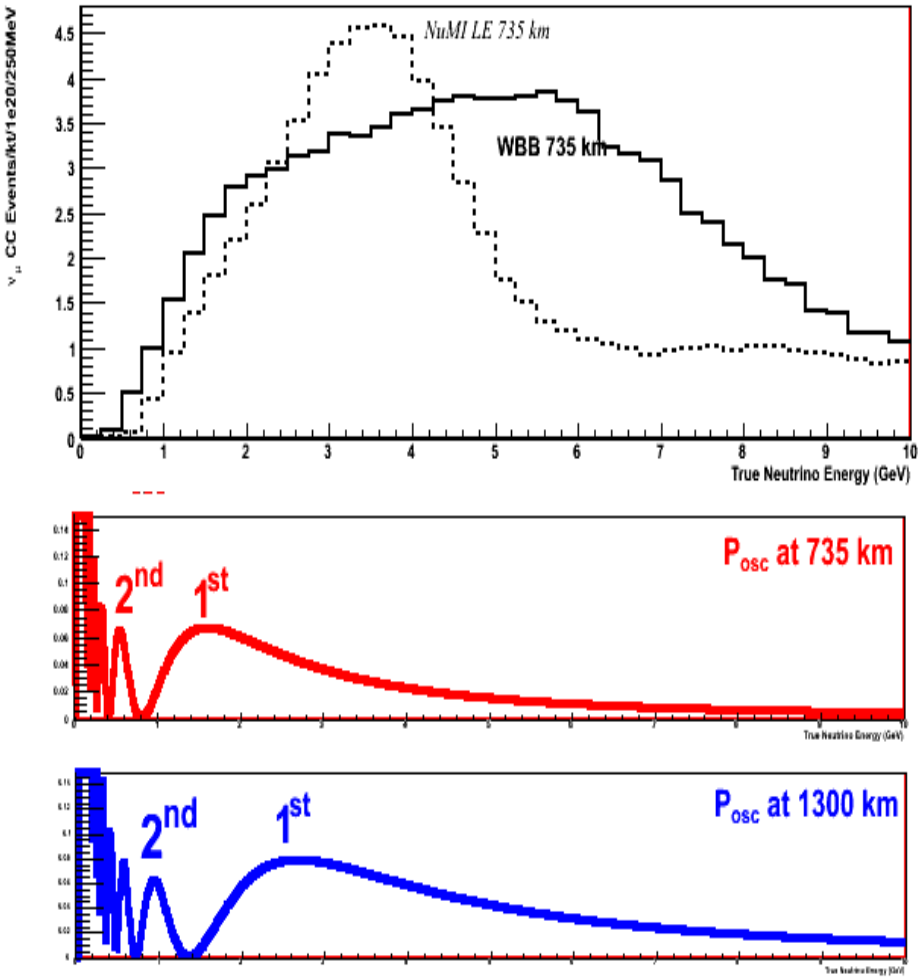
1) Start with NuMI off Axis beam at 810 km (NOvA) and 700 KW

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

3) Increase Beam Power : Project X yields 2.3 MW , (SNUMI could yield 1.2 MW) *(equivalent to increasing statistics)*

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

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




*With new Wide Band Beam :*

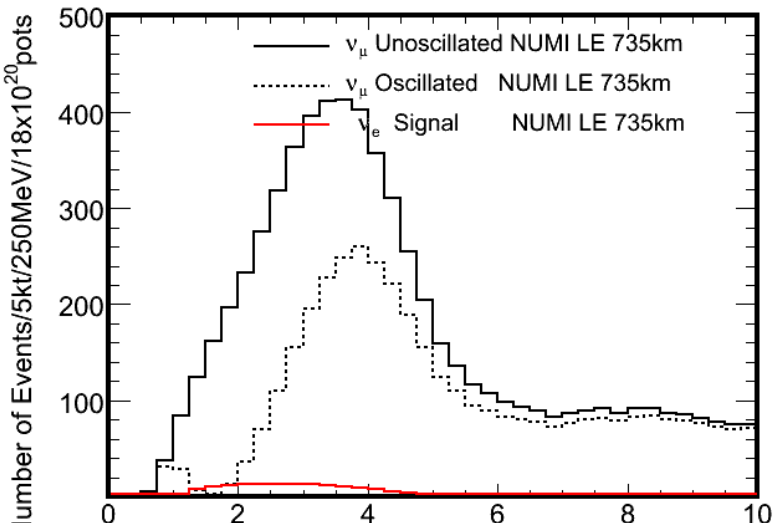
*Increase "useful" flux (at first and second oscillation maxima)*

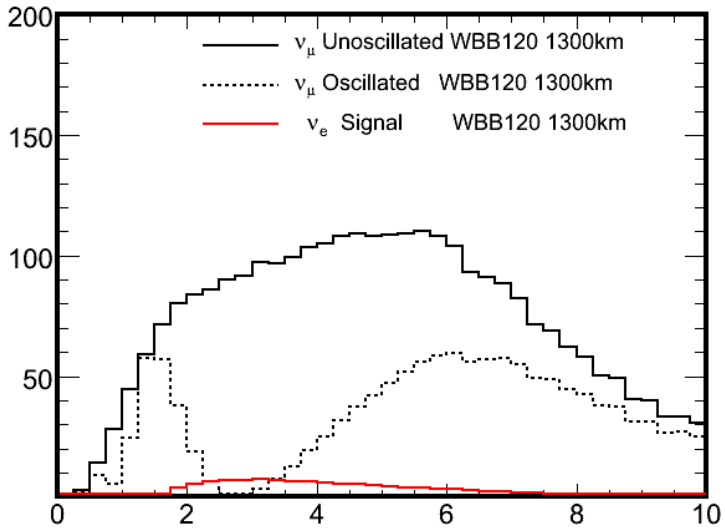
*Decrease backgrounds (depending on proton energy and off axis angle)*

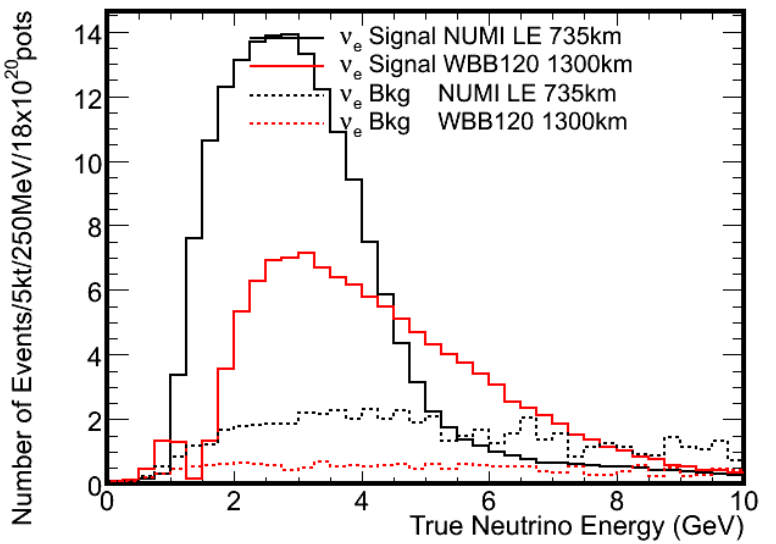
*With increasing L matter effects increase and hence mass hierarchy determination is improving*

*With increasing L oscillation maxima (and minima) "appear" in more "favourable" positions in the neutrino energy spectra*

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

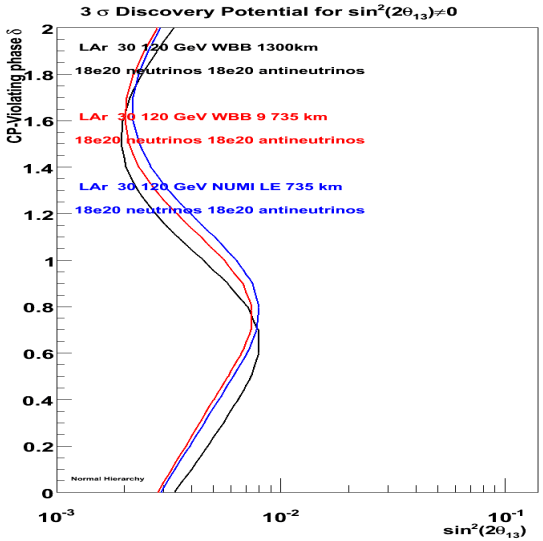


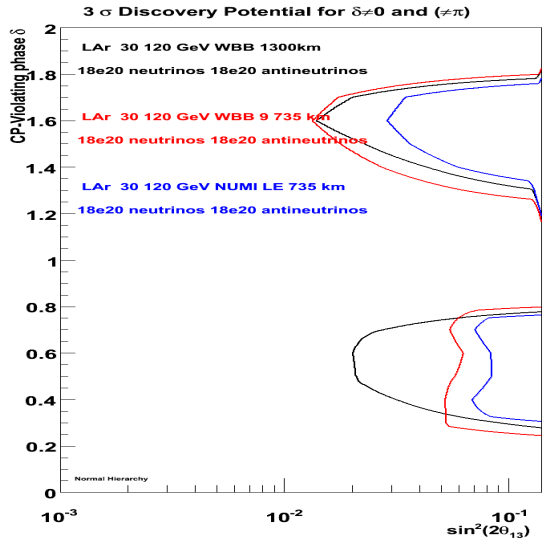



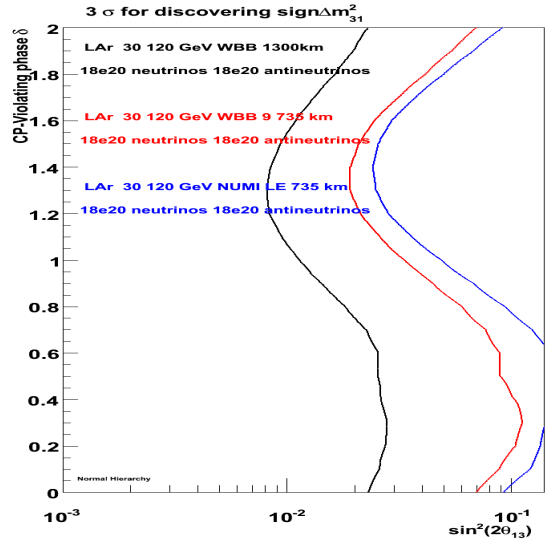




- *With increasing L oscillation maxima (and minima) "appear" in more "favourable" positions in the neutrino energy spectra (higher energies),*
- *Thus study of first and second oscillation maxima is easier (one detector instead of two, higher rates, etc)*

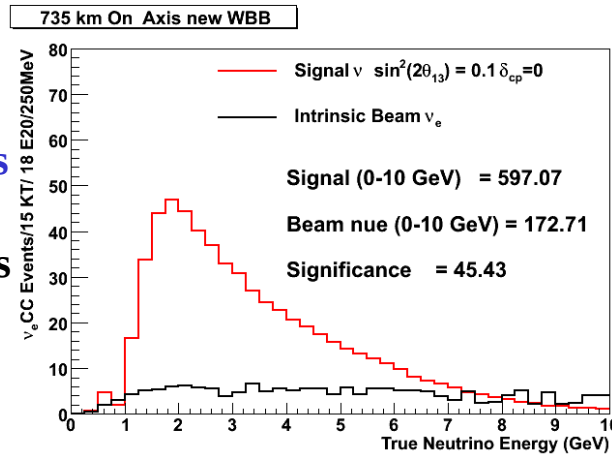
# The effect of longer baseline (>>L) and a new Wide Band Beam with the same detector : 30 kt of LAr

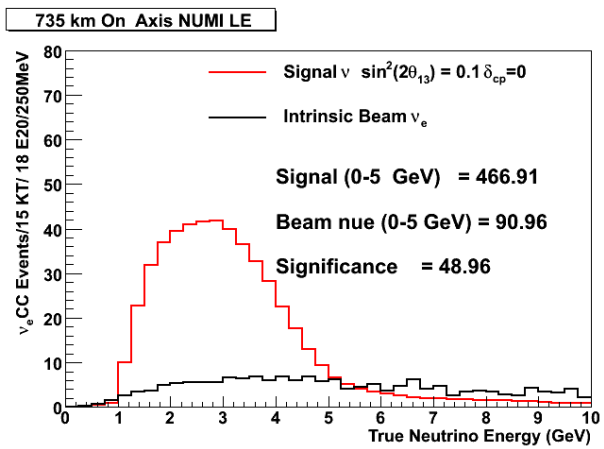



**BLUE : NuMI 735 km On Axis**
**RED : WBB 735 km On Axis**
**BLACK : WBB 1300 km On Axis**



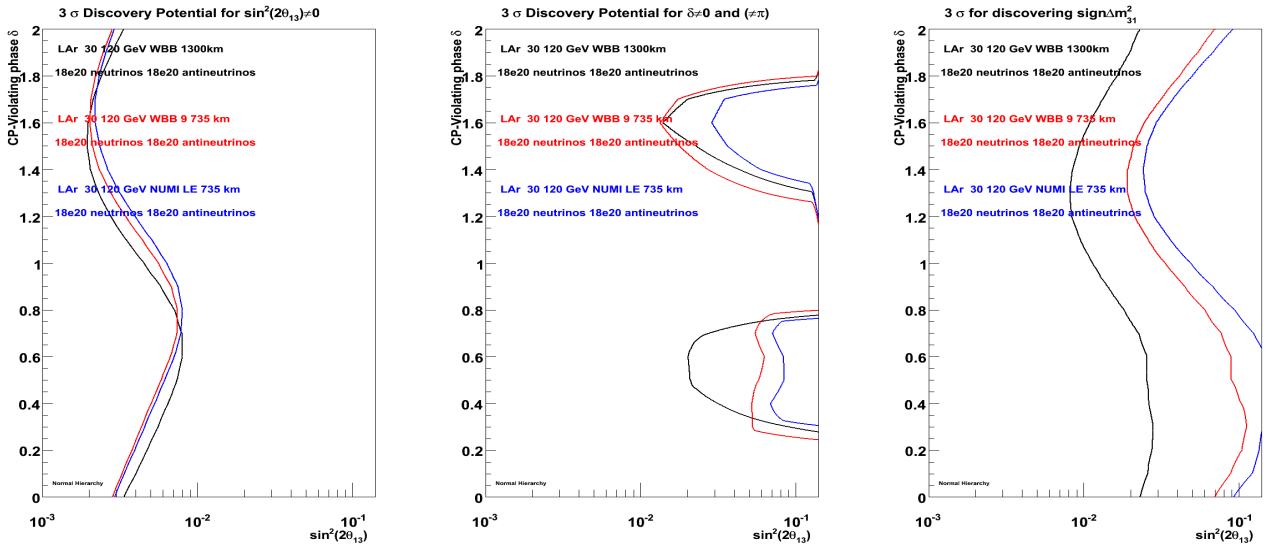



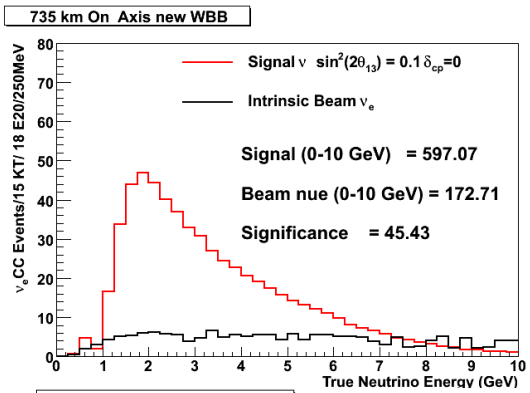

**New WBB** vs **NuMI beam** at 735 km :

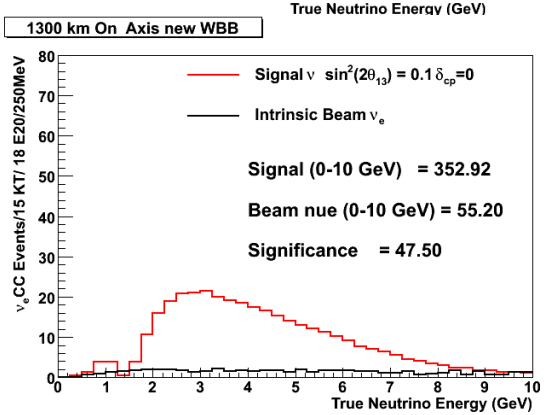
1) More events

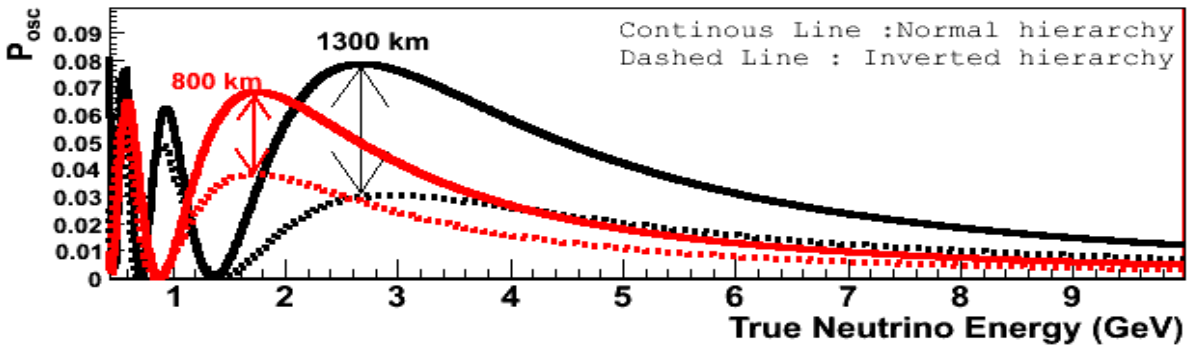
2) Start to have information on first and second oscillation maxima.

# The effect of longer baseline (>>L) and a new Wide Band Beam with the same detector : 30 kt of LAr




**BLUE : NuMI 735 km On Axis**

**RED : WBB 735 km On Axis**

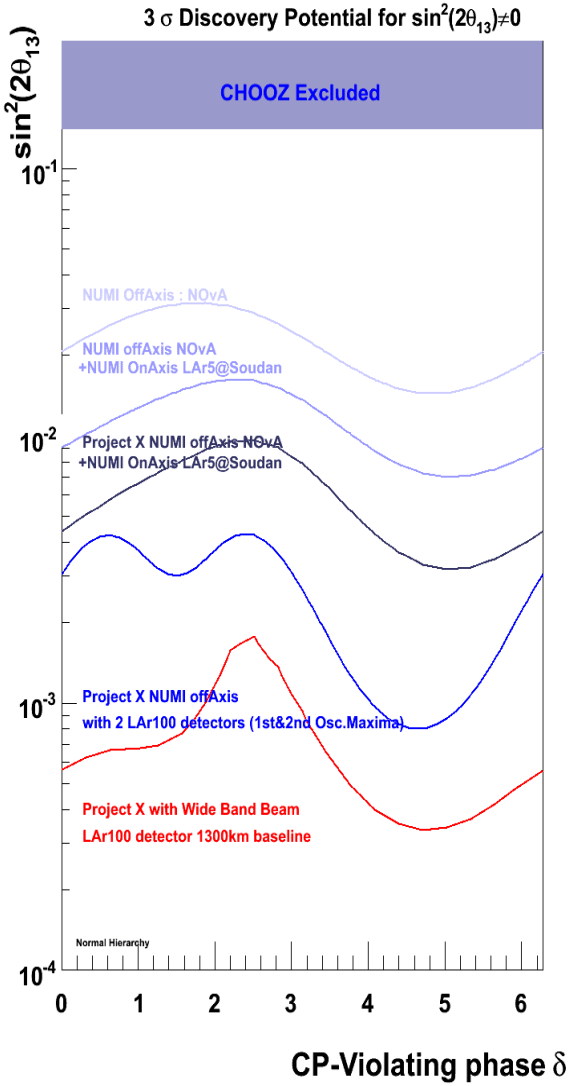
**BLACK : WBB 1300 km On Axis**

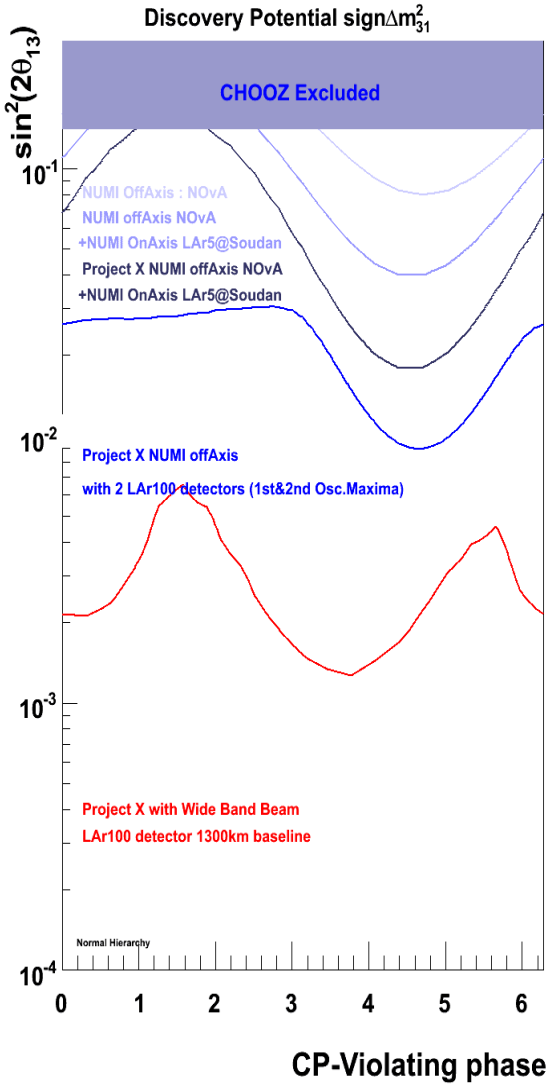
**WBB at 735 km** vs **WBB beam** at 1300 km :

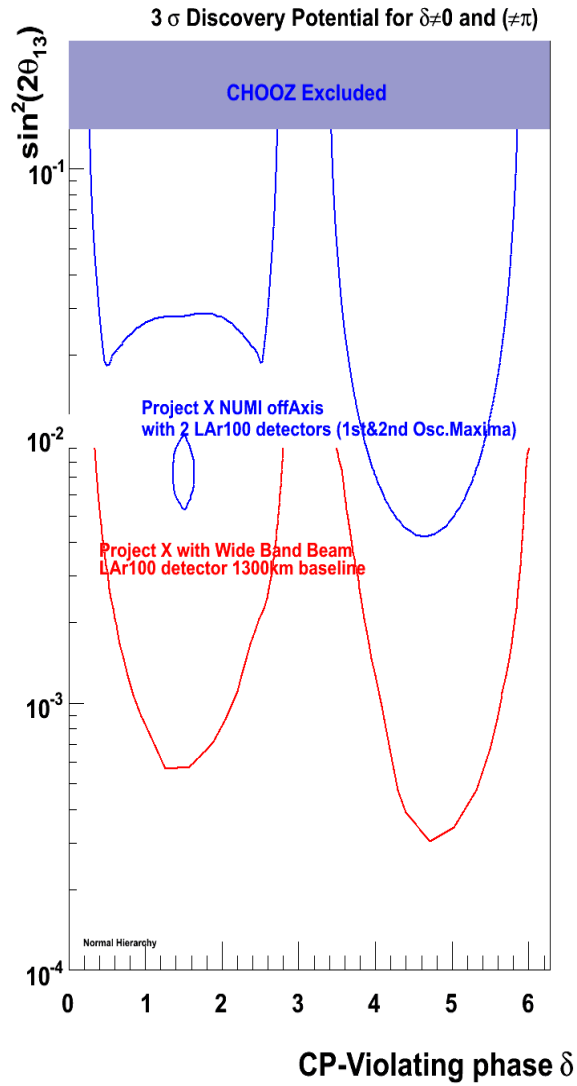
1) More matter effects

2) More information on second oscillation maxima, which results in breaking the inherent degeneracies, and less background.

# Putting it all together : A Phased program




**NOvA - NOvA+5ktLAr - NOvA+5ktLAr+PX - NOvA+100kt LAr +PX**
**100ktLAr (OR 500kt WC) +New WBB+PX at DUSEL**

# Without Project X ???

**For A Given Reach :**

**Without Project X same results are obtained with 3 times higher running time. Namely :**

**3+3 YEARS become 9+9 YEARS !!!**

**Without Project X same results in the same time are obtained with 3 times higher Detector Masses. Namely :**

**100 KT LAr become 300 KT LAr !!! OR**

**300 KT WC become 900 kt WC !!!**

**For the same detector masses and running time:**

**Without project X , $\theta_{13}$ reach reduces by ~ a factor of 1.7 , mass hierarchy reach reduces by ~ a factor of 1.7 and CPV reach reduces by ~ 3** ***(CP reach does not scale as sqrt(N) but rather as N)***

***High intensity neutrino beams (Project X) essential for a strong neutrino oscillation program.***

# Summary / Conclusions

- We have learned (and are still learning) a lot with respect to neutrino masses and mixings …
- **The next generation of accelerator neutrino oscillation experiments will try to address the following very challenging questions:**
  - **What is the value of the third mixing angle $\theta_{13}$ ?**
  - **Is $\theta_{23}$ 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**.
- **Fermilab** already has **the most intense accelerator neutrino beam in the world , with the potential of a factor of 3 further increase with Project X …**

**… which is precisely what is needed for the "next generation neutrino oscillation physics experiments"**

# Backup

# Discovery Potentials:Technical details

$\theta_{13}$ Discovery Potential :

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

**Both $\delta$cp and sign of $\Delta m^2_{31}$ allowed to float in the fit**

$\delta_{cp}$ Discovery Potential :

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

**Both $\theta_{13}$ and sign of $\Delta m^2_{31}$ allowed to float in the fit**

**Mass Hierarchy** Discovery Potential :

Fit the energy spectrum to $\theta_{13}$ , $\delta$cp **and both signs of** $\Delta m^2_{31}$ **in order to determine**

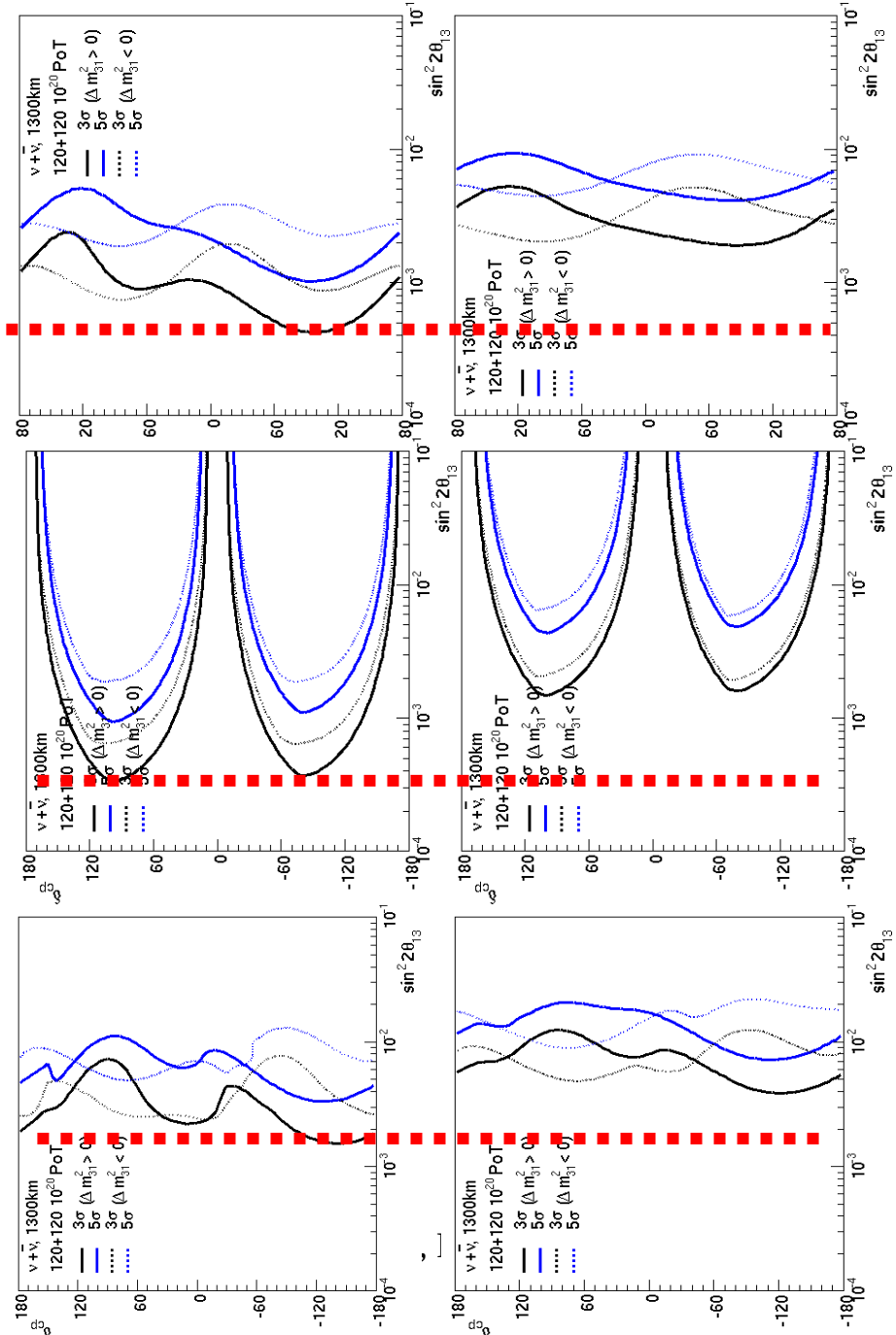
$$\Delta\chi^2 = \chi^2_{\text{true hierarchy}} - \chi^2_{\text{false hierarchy}}$$

***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.***

**100 kt LAr** **BNL Globes** **300 kt WC**



# The "Ultimate" Goals in neutrino oscillations Physics

***Approximate Numbers for quark mixing***

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{12\ \text{quarks}} = 13^0 \quad \theta_{12\ \text{neutrinos}} \sim 35^0$

$\theta_{23\ \text{quarks}} = 2.4^0 \quad \theta_{23\ \text{neutrinos}} \sim 45^0$

$\theta_{13\ \text{quarks}} = 0.2^0 \quad \theta_{13\ \text{neutrinos}} < 11^0$

***Approximate Numbers for neutrino mixing***

$$\begin{pmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

**$\theta_{13}$ ???**

**$\theta_{23}$ how close (or far) from $\pi/4$???**

**Why neutrino mixing so obviously different than quark mixing while both of them seem to follow a pattern ???**

**What is the pattern , how can we connect quark-neutrino mixing ???**

**Does this pattern point to a particular symmetry???**