Future Possibilities with Fermilab Neutrino Beams

N. Saoulidou, Fermilab

NEUTRINO08, Christchurch, New Zealand

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 phased neutrino oscillation program at Fermilab 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 · 0νββ decays · Majorana phases

$$U=\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & -s_{23}\\ 0 & s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & -s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ s_{13}e^{-i\delta} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}$$

- Do "man made" νμ'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**

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

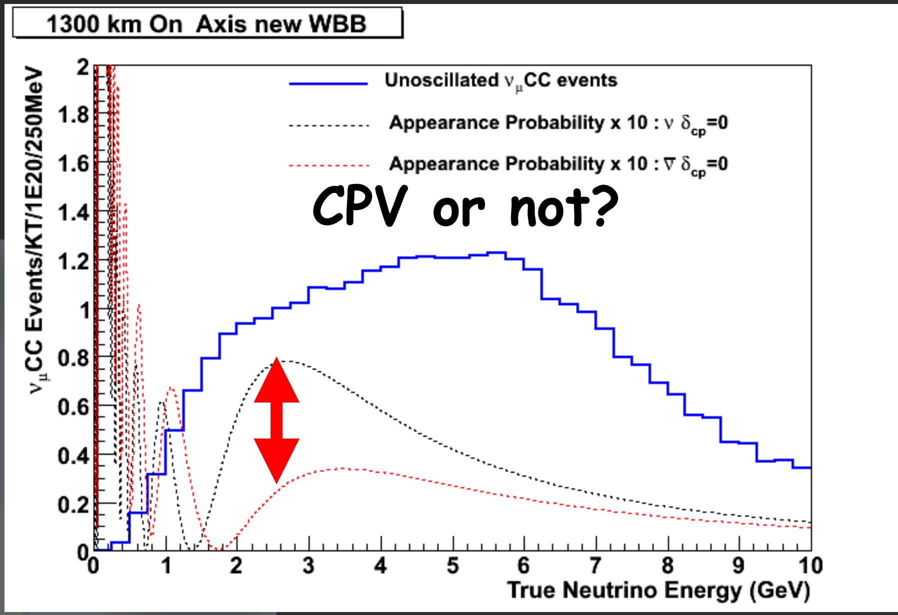
$$\Delta = \frac{\Delta m^2{}_{31} L}{4E_\nu} \qquad x = \frac{2\sqrt{2} G_F N_e E_\nu}{\Delta m^2{}_{31}}$$ **Matter Effects**

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 (θ_{13} < 11 ^{0})

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

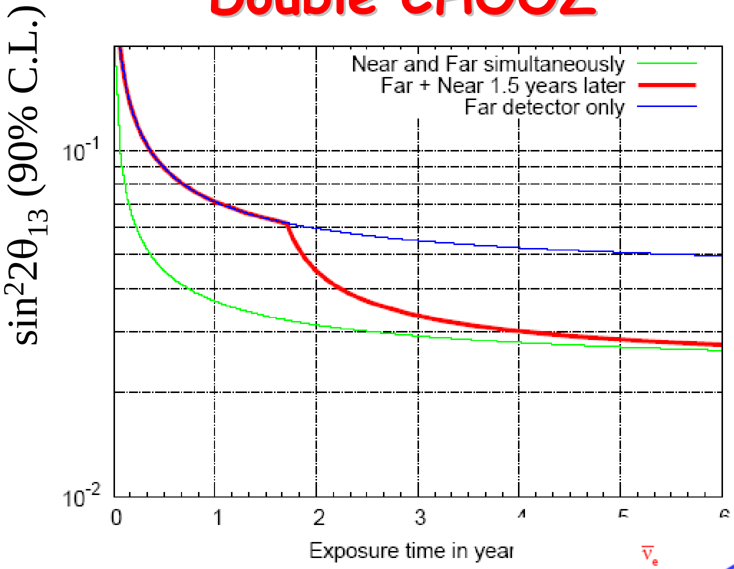
c) Longer Baselines to enhance matter effects

d) Nature to be kind to us !!!

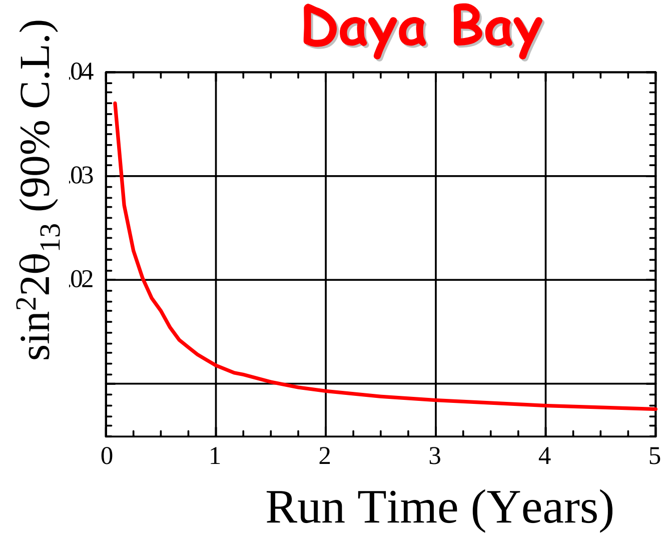
Hunt for a non-zero θ_{13} ("cleanly"): PHASE I

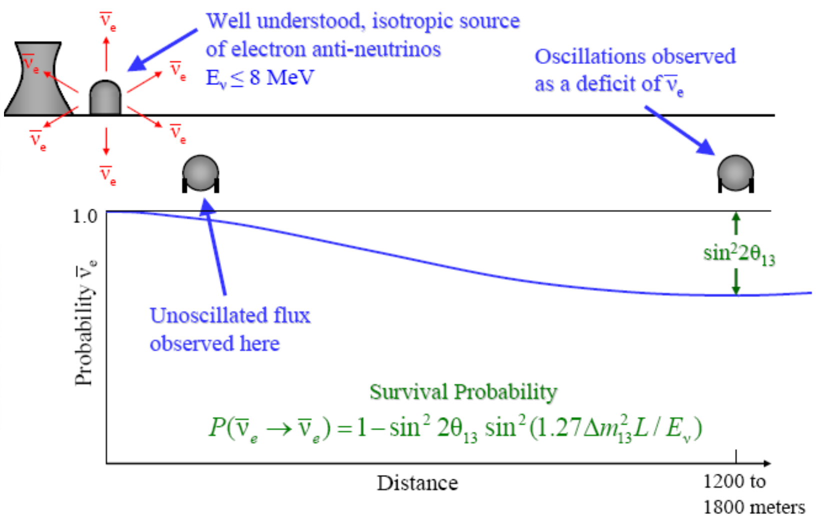
Reactor Experiments : Double CHOOZ & Daya Bay

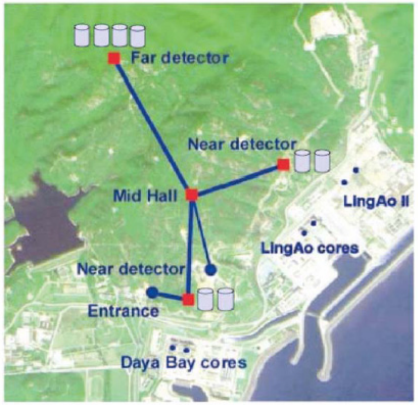
Double CHOOZ



Daya Bay

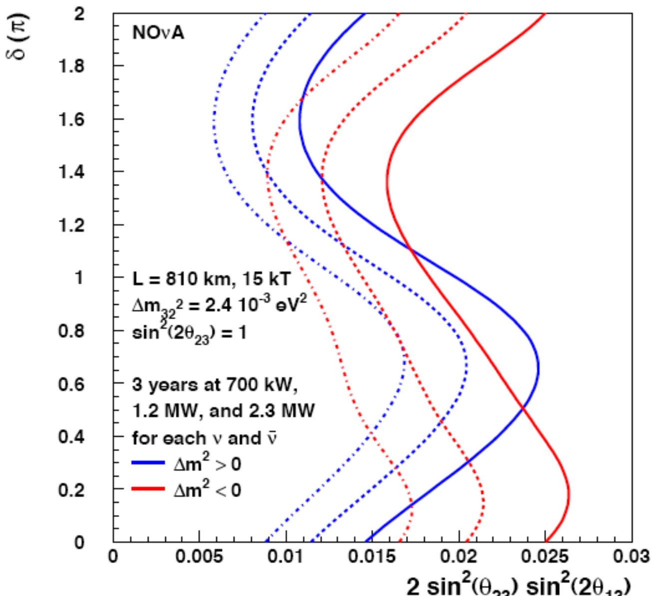




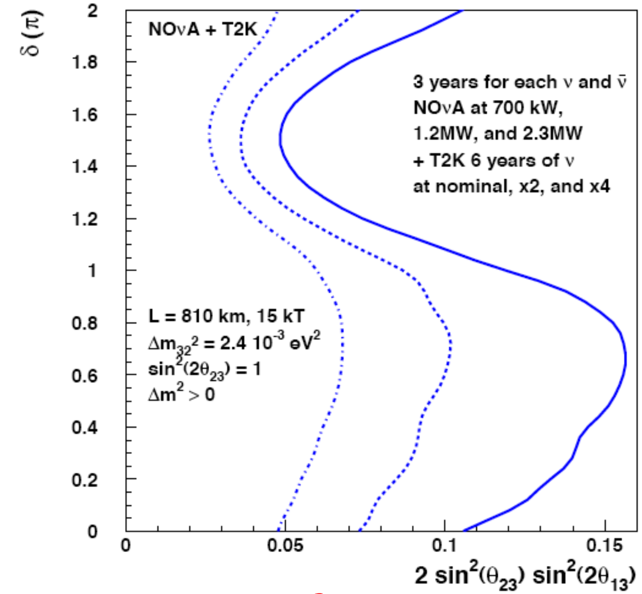


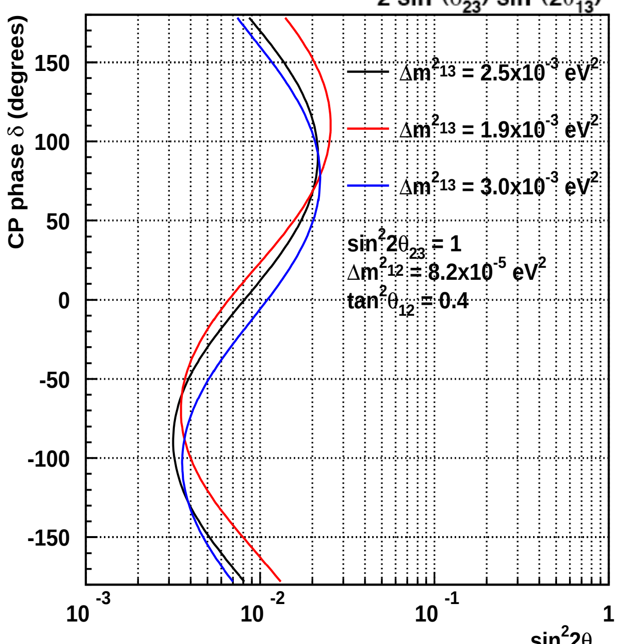
Hunt for a non-zero θ_{13} (+more): PHASE I
Accelerator Experiments : NOνA & T2K

3 σ Sensitivity to $\sin^2(2\theta_{13}) \neq 0$



NOνA





T2K

BONUS from NOνA 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)**.
- In the context of the Fermilab Steering Group **we also explored capabilities using the 2.3 MW beam power of Project X**.

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:

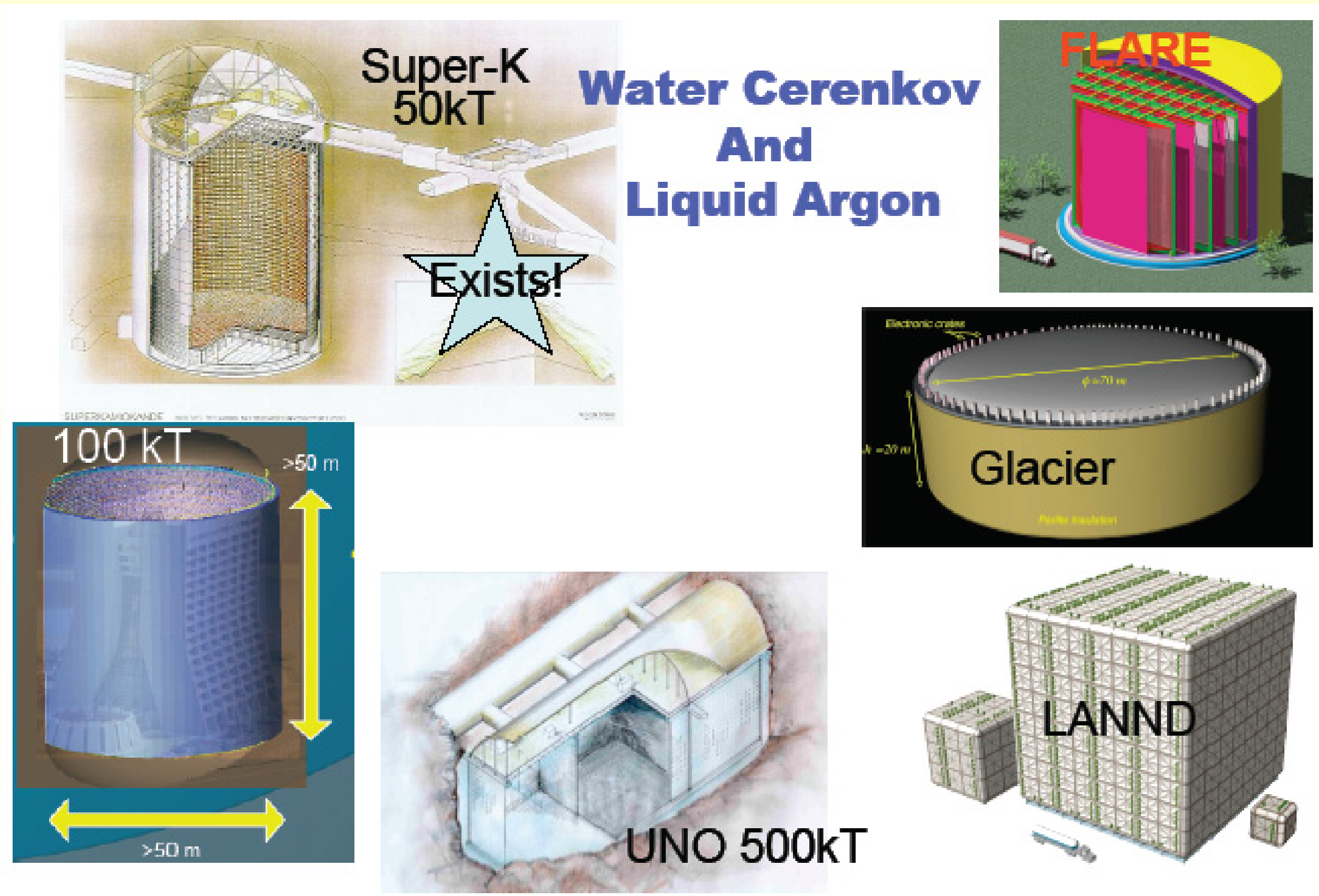
- Massive cost effective detectors that are larger than those of Phase I (> 20 KT)
- Intense neutrino beams with intensity possibly higher than that of Phase I (> 700 KW)
- The ability to break inherent degeneracies between genuine CP violation and "Fake CP violation" from matter effects.

Ingredients for achieving the ultimate goals (1)

One needs:

First : Statistics

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



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

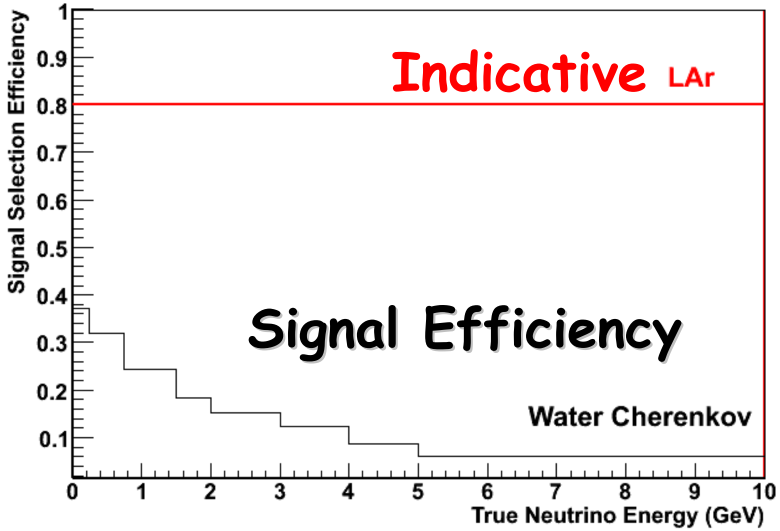
Given their assumed efficiencies and background rejections the following :

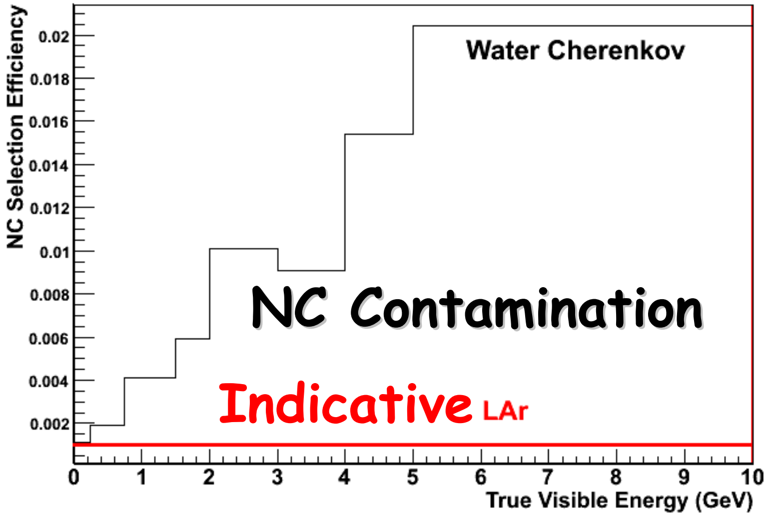
"Detector Mass Equivalent Law" holds, which has been independently checked by two groups (BNL and FNAL)

1 : ~4

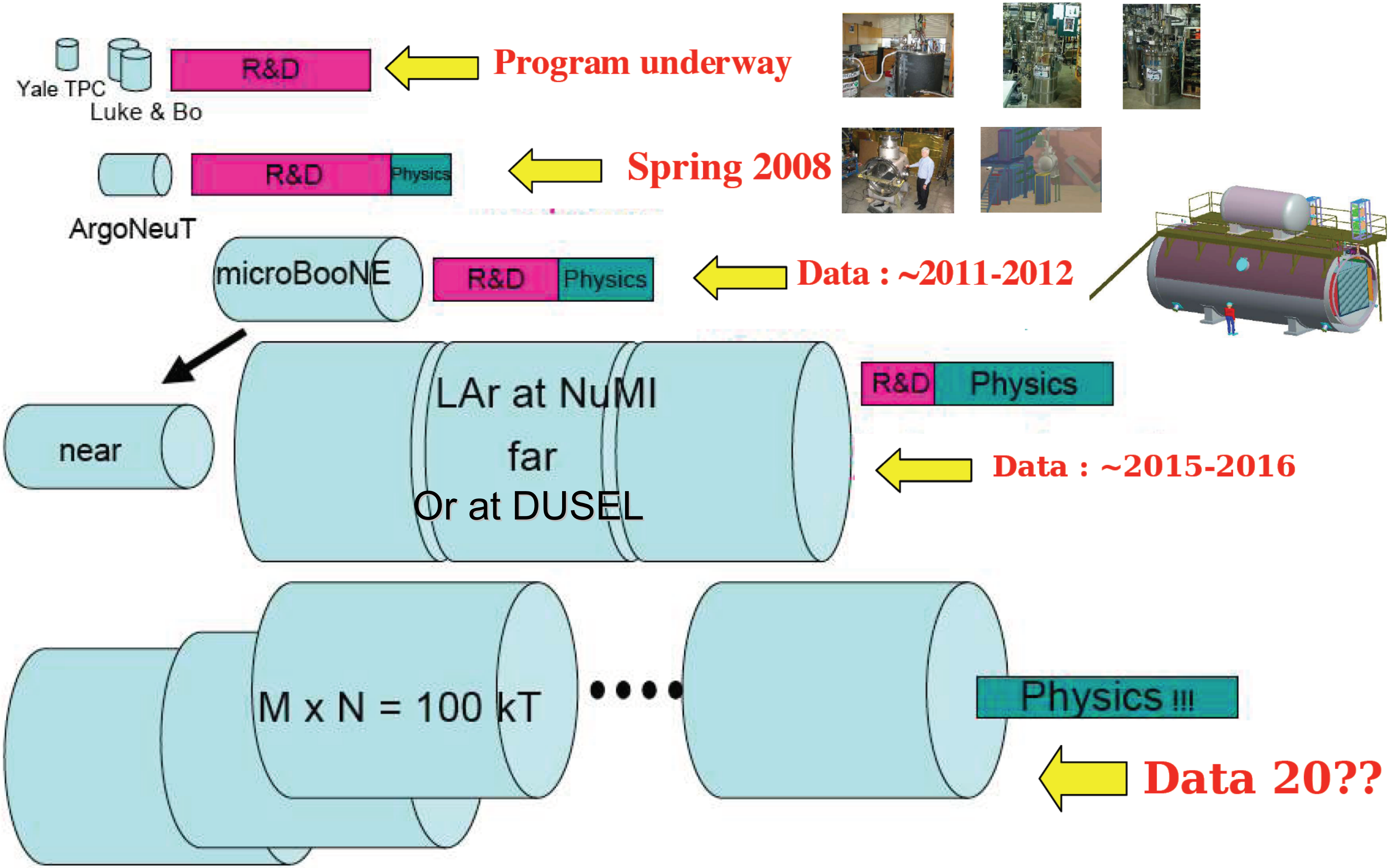
OR

100kt LAr ~ 400 kt WC





Liquid Argon TPC R&D Path in the US



Water Cherenkov R&D Path in the US

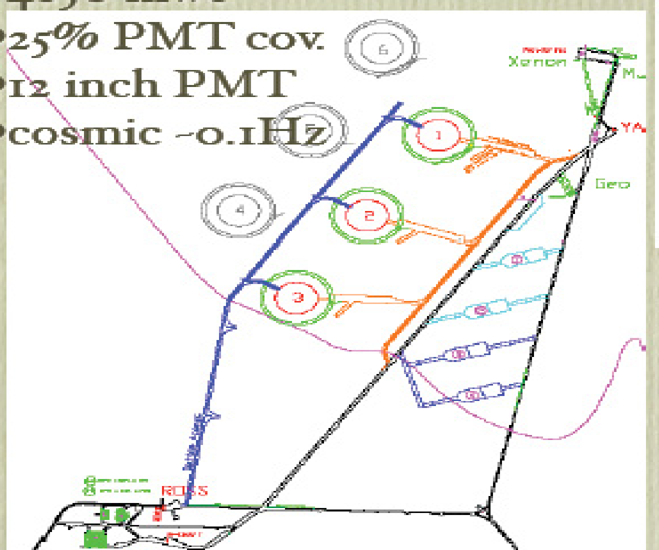
Ongoing R&D on PMT technical requirements in order to reduce cost while keeping the same detection efficiency

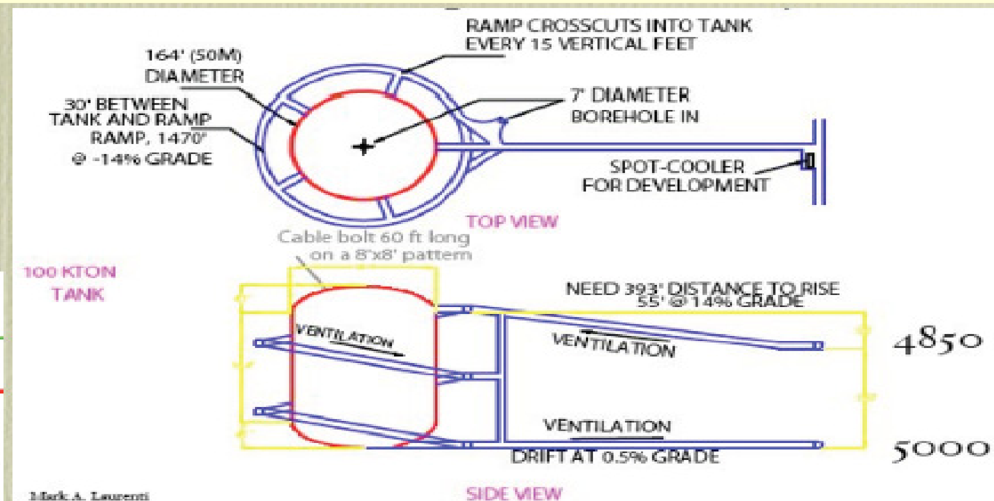
Ongoing R&D on Large Cavern Construction since Water Cherenkov detectors, due to lower efficiency and lower background rejection, need to be more massive.

Detector at Homestake

Modular Detector

- ~53m dia/h
- 100kT fiducial
- 4850 mwe
- 25% PMT cov.
- 12 inch PMT
- cosmic ~0.1Hz





Studies ~50m cavity stable in HS rock

- ✓Initial detector 3 modules
- ✓Space can be planned for 10
- ✓ Cost estimate $115M/module
- ✓6 yrs construction to first 100kT
- ✓8 yrs to full 300 kT.

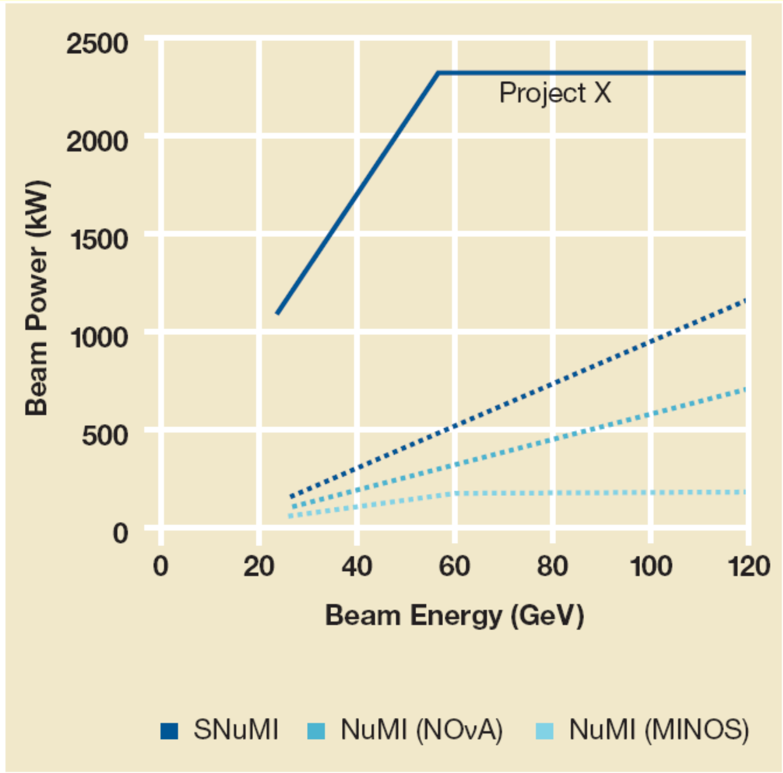
Fiducial vol depends on rock stability studies and PMT pressure rating.

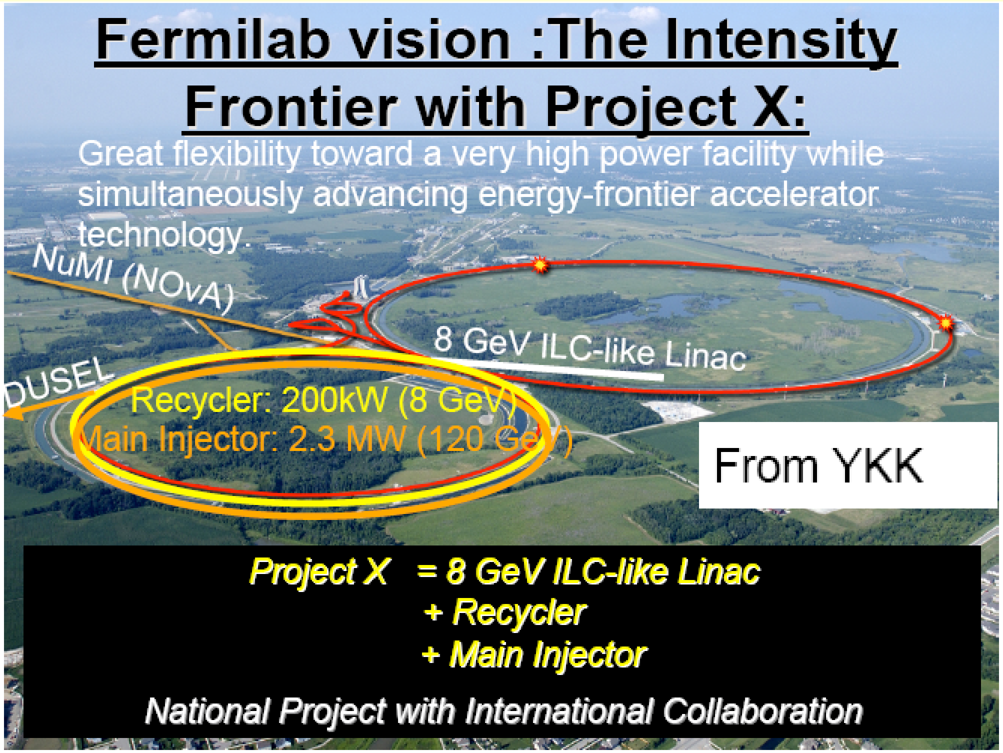
Ingredients for achieving the ultimate goals (2)

One needs:

Second : Statistics

Powerful neutrino beams of very high intensity, like Project X





Two options for neutrino beams and experiment baselines exist:

Neutrino beam and experiment baselines : ~ Two Options

(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 :

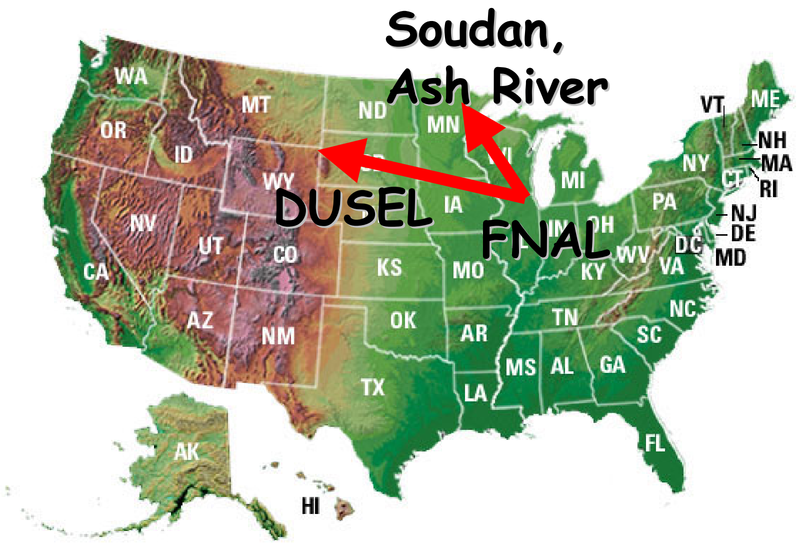
Water Cherenkov detectors not an option for that reason.

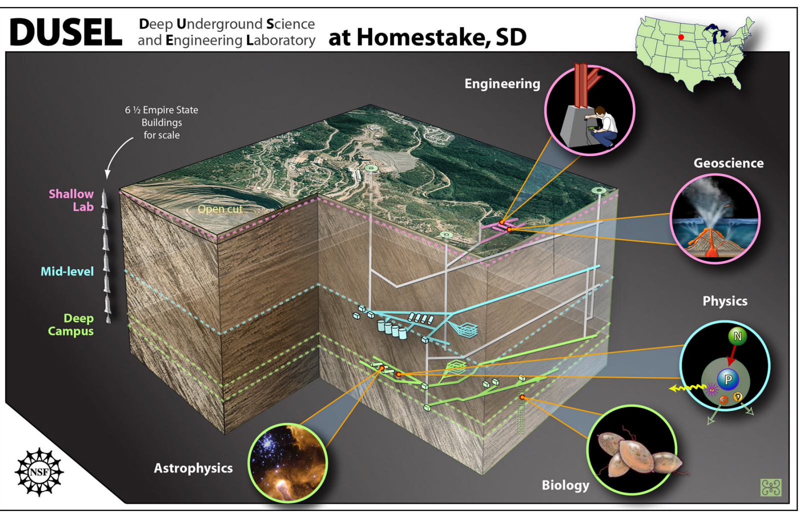
LAr TPCs need to be able to operate ~ surface.

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





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

New On Axis Wide Band Beam

Implications on Detector Technology:

Water Cherenkov

(Homestake Mine at 4850 ft level)

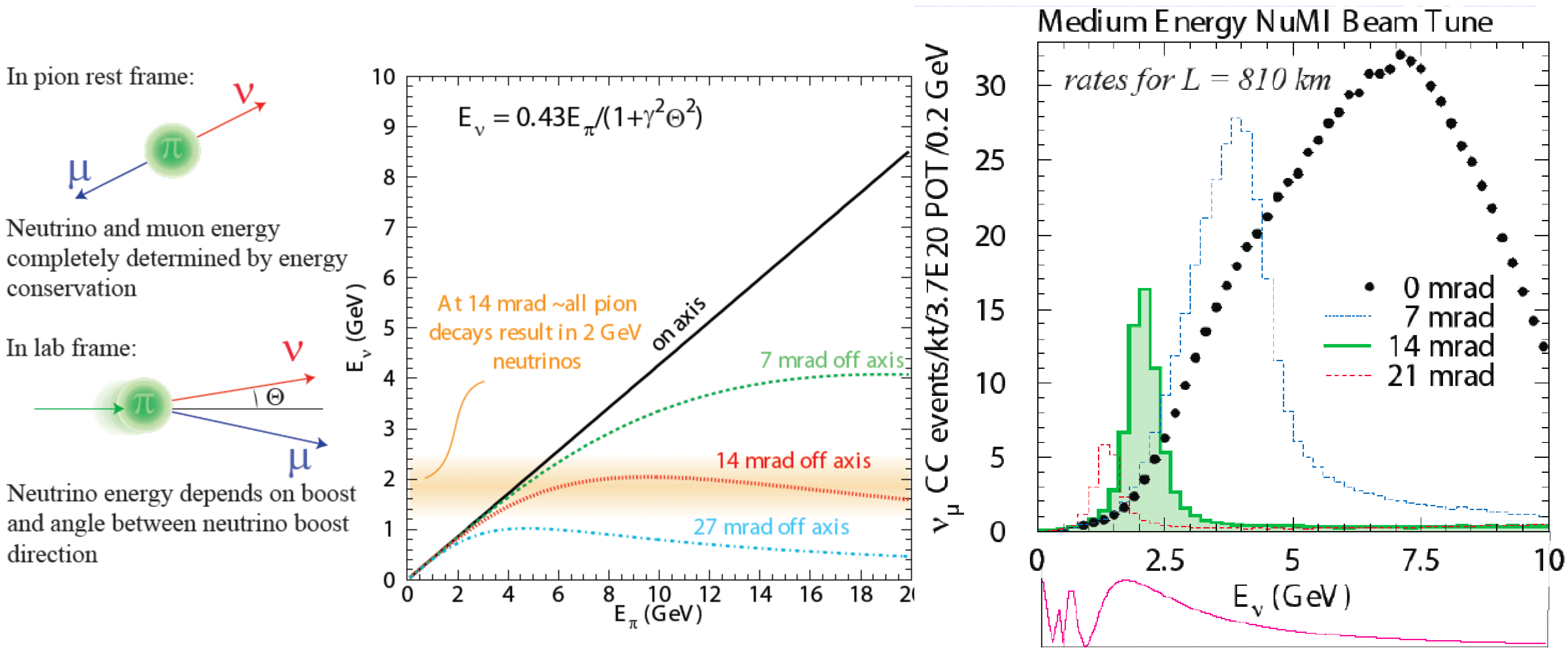
OR LAr TPC

(Homestake Mine 300 ft level, or ~ surface)

Implications on ν beam :

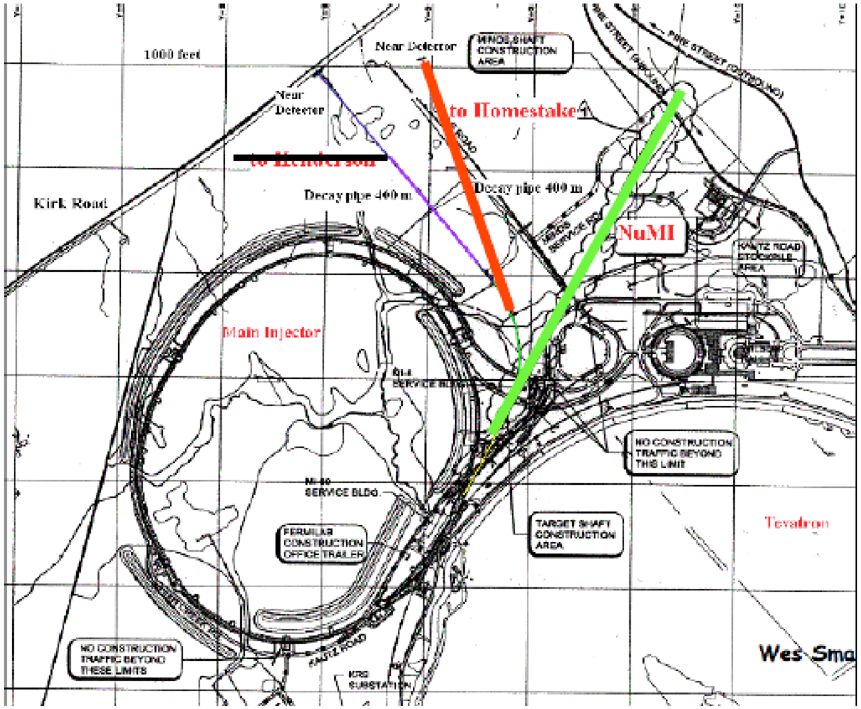
New beam has to be designed and constructed

NuMI Neutrino Beam: Capabilities & Advantages

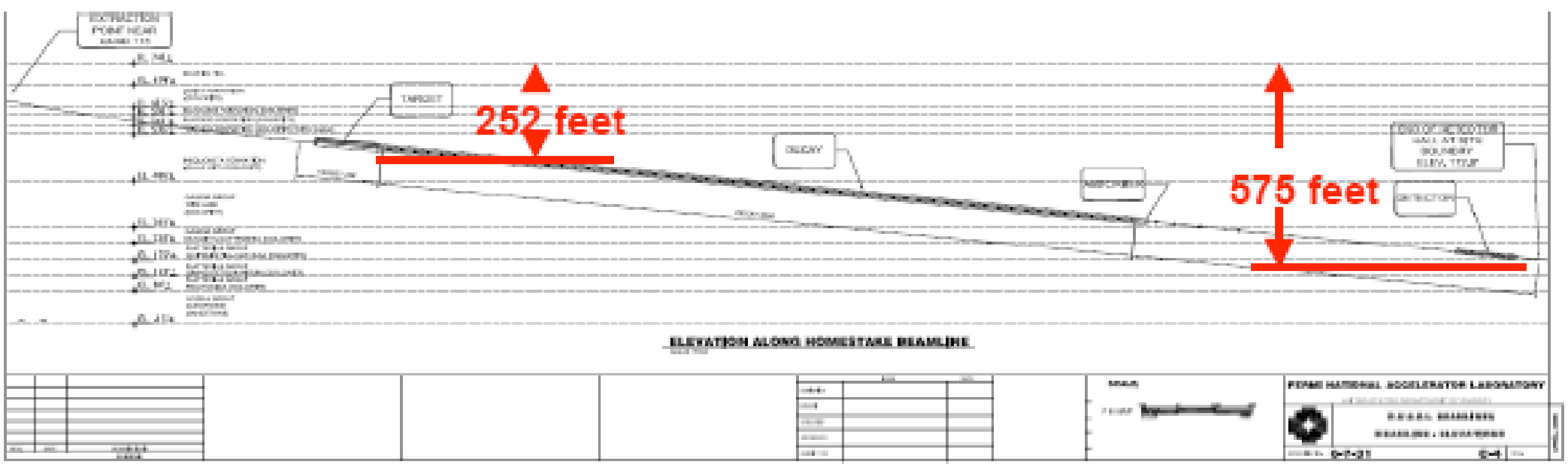


- The Beam Exists and performs well
- There is a well defined upgrade plan
- The off – axis idea of obtaining a NBB is attractive: It reduces the NC background resulting from high energy neutrinos.

Wide Band Neutrino Beam : Status

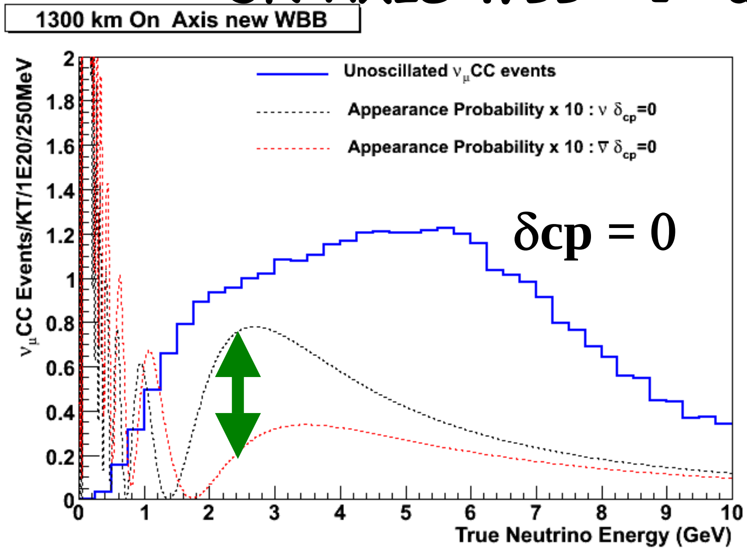


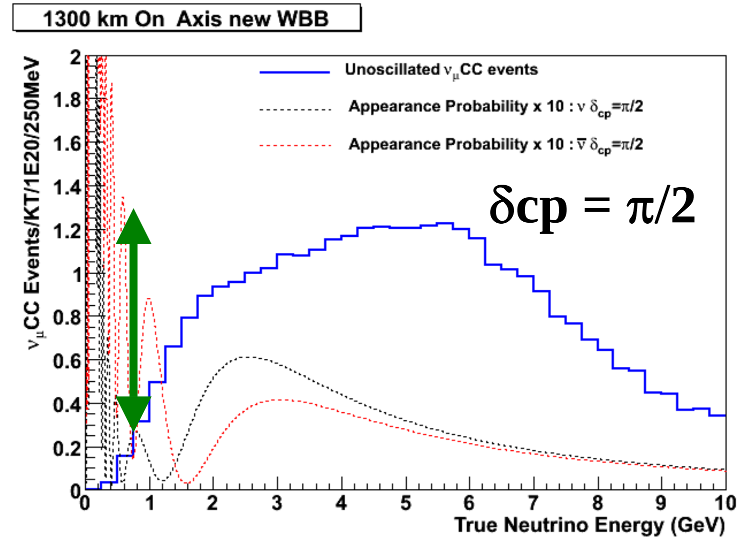
- *Such beam does not exist, but is in the design phase.*
- *In general, design of target station and horns for beam power > 1 MW non trivial (R&D needed)*



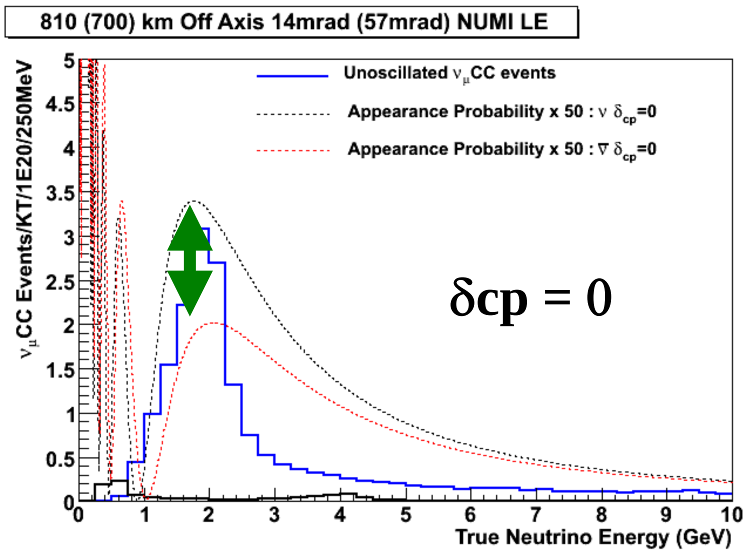
Wide Band Neutrino Beam: Advantages

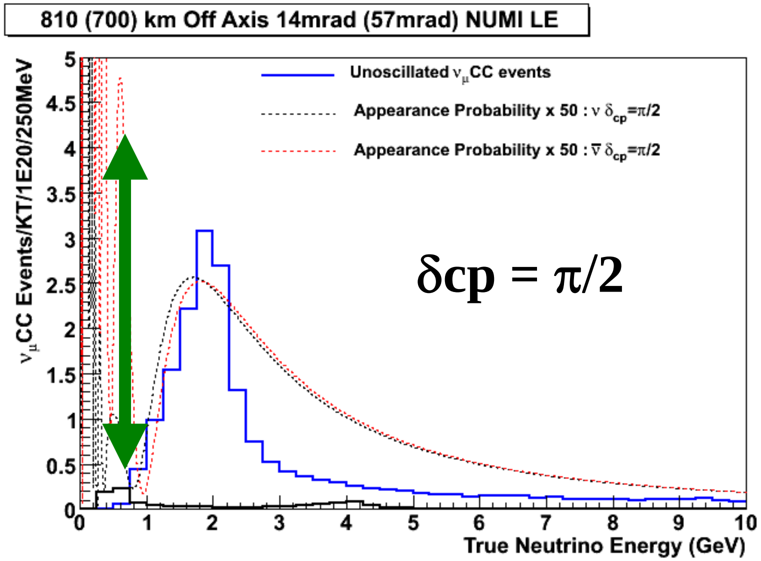
ON AXIS WBB : 1st and 2nd Oscillation Maxima 1 Detector



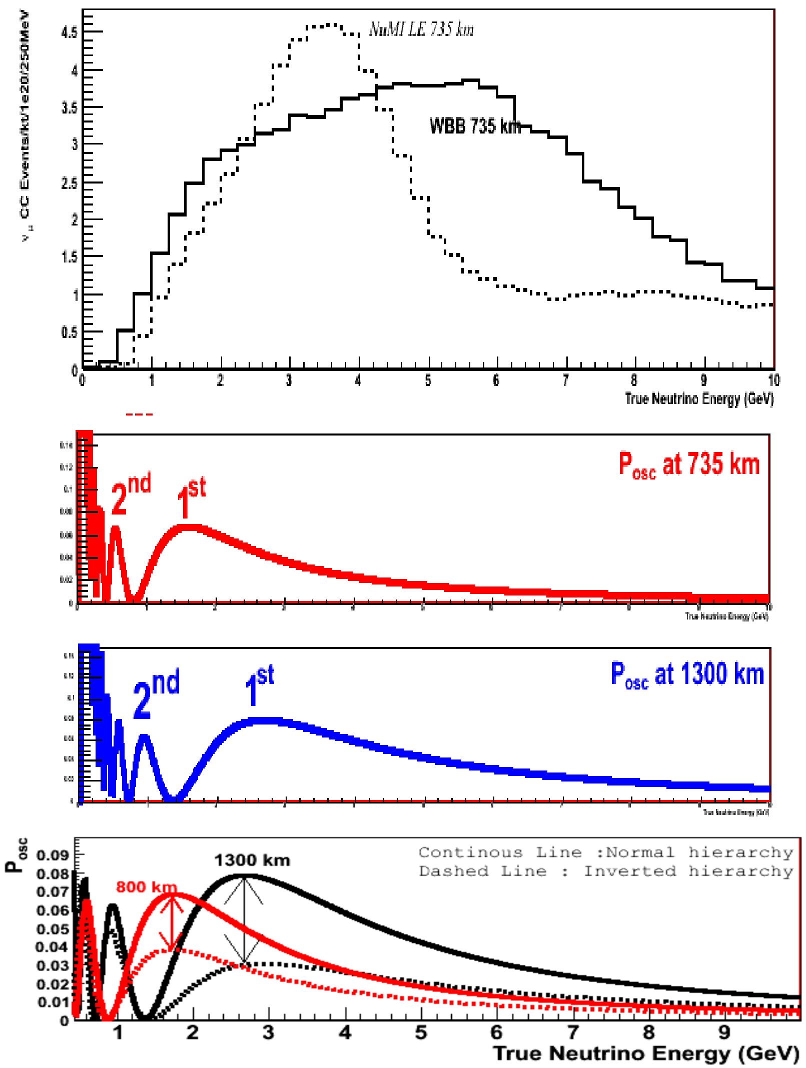


NuMI OFF AXIS : 1st and 2nd Oscillation Maxima 2 Detectors





Longer baseline (>>L) AND a new Wide Band Beam



With new Wide Band Beam :

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

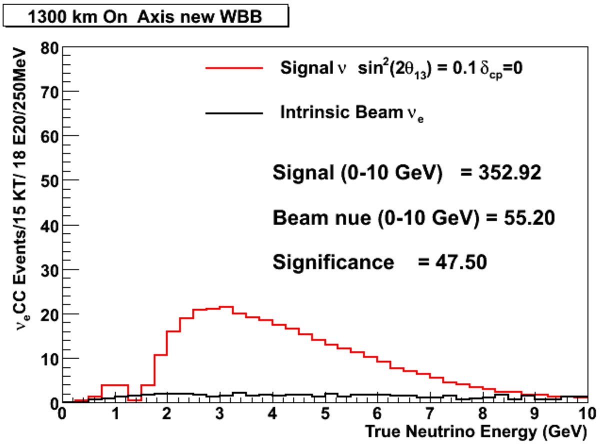
2)With increasing L oscillation maxima "appear" in more "favourable" positions in the neutrino energy spectra

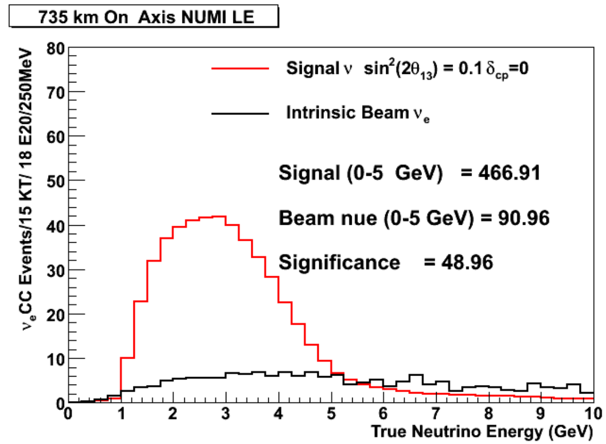
3)Thus study of first and second oscillation maxima is easier (one detector instead of two, higher rates, etc)

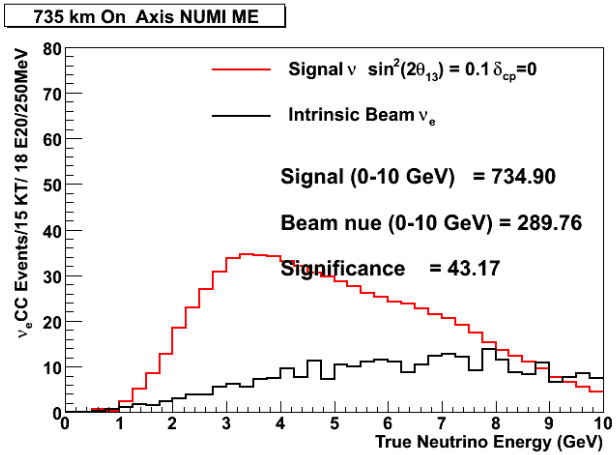
4) With increasing L matter effects increase and hence potential for mass hierarchy determination is increasing

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**

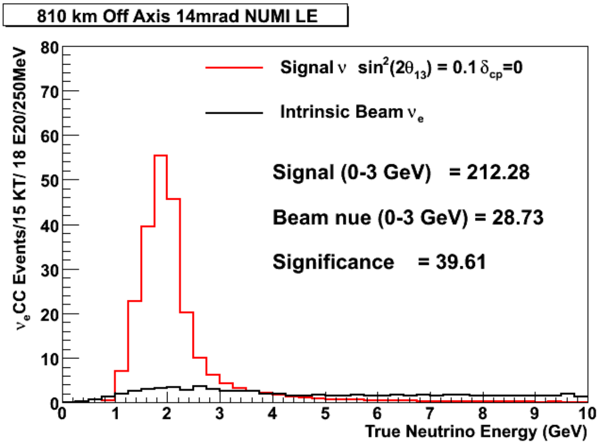






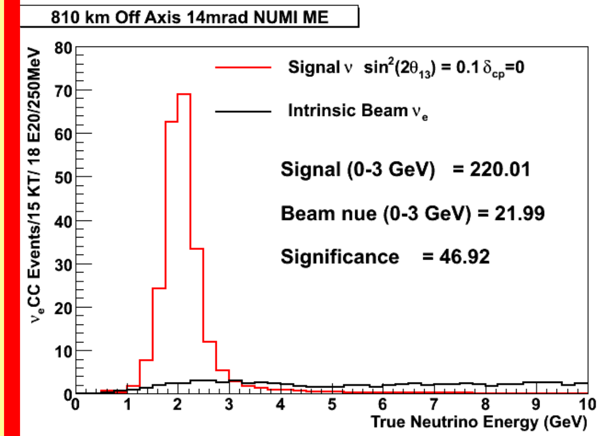
Disappearance minimum (appearance maximum) at given Δm_{23}^2:
Signal events do not scale as $1/L^2$, backgrounds do.

Off Axis NuMI LE

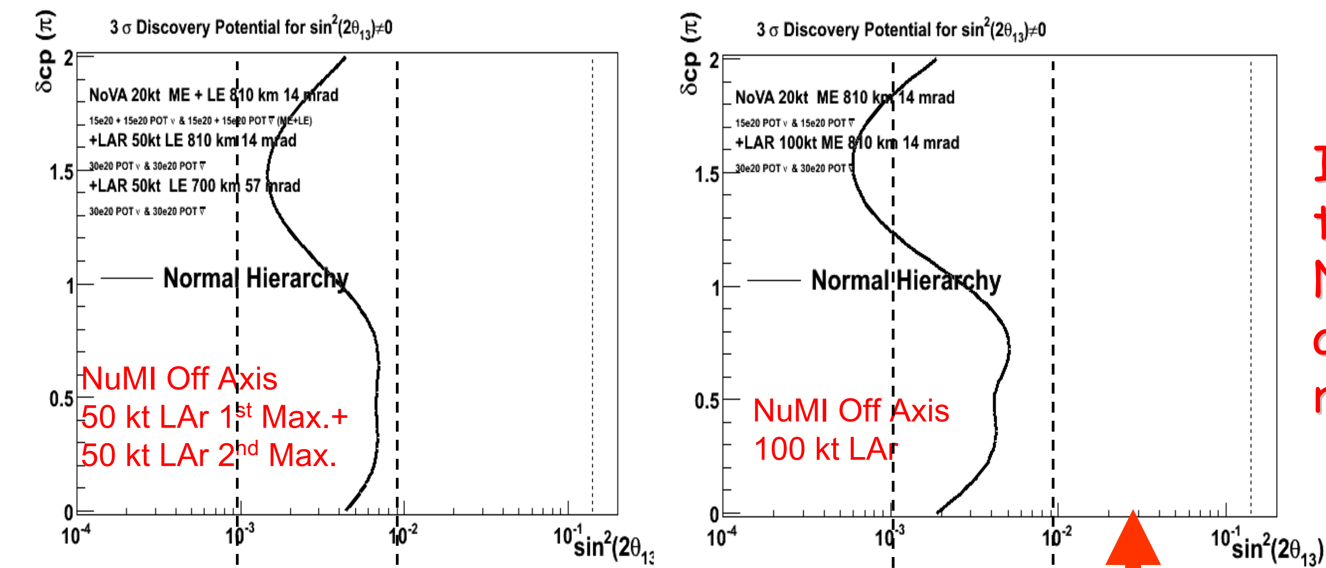


Considered all these options with various Detector Technologies and Beam Powers and concluded on a possible staged approach to get to the physics of interest

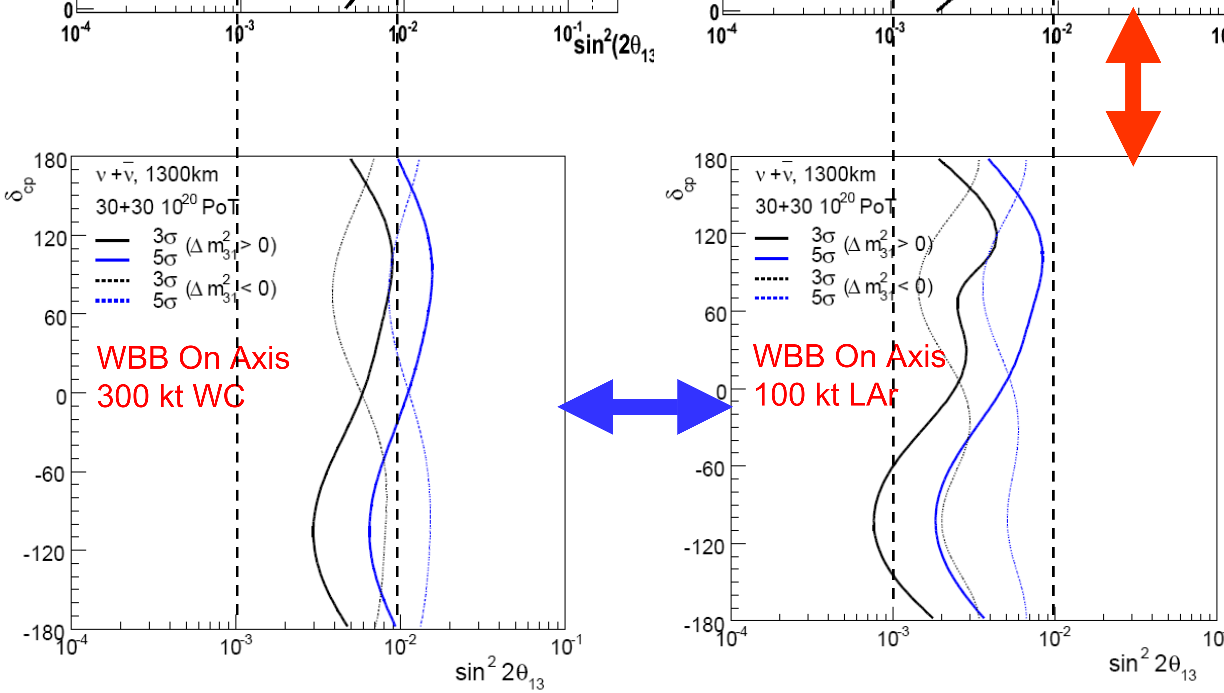
Off Axis NuMI ME



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

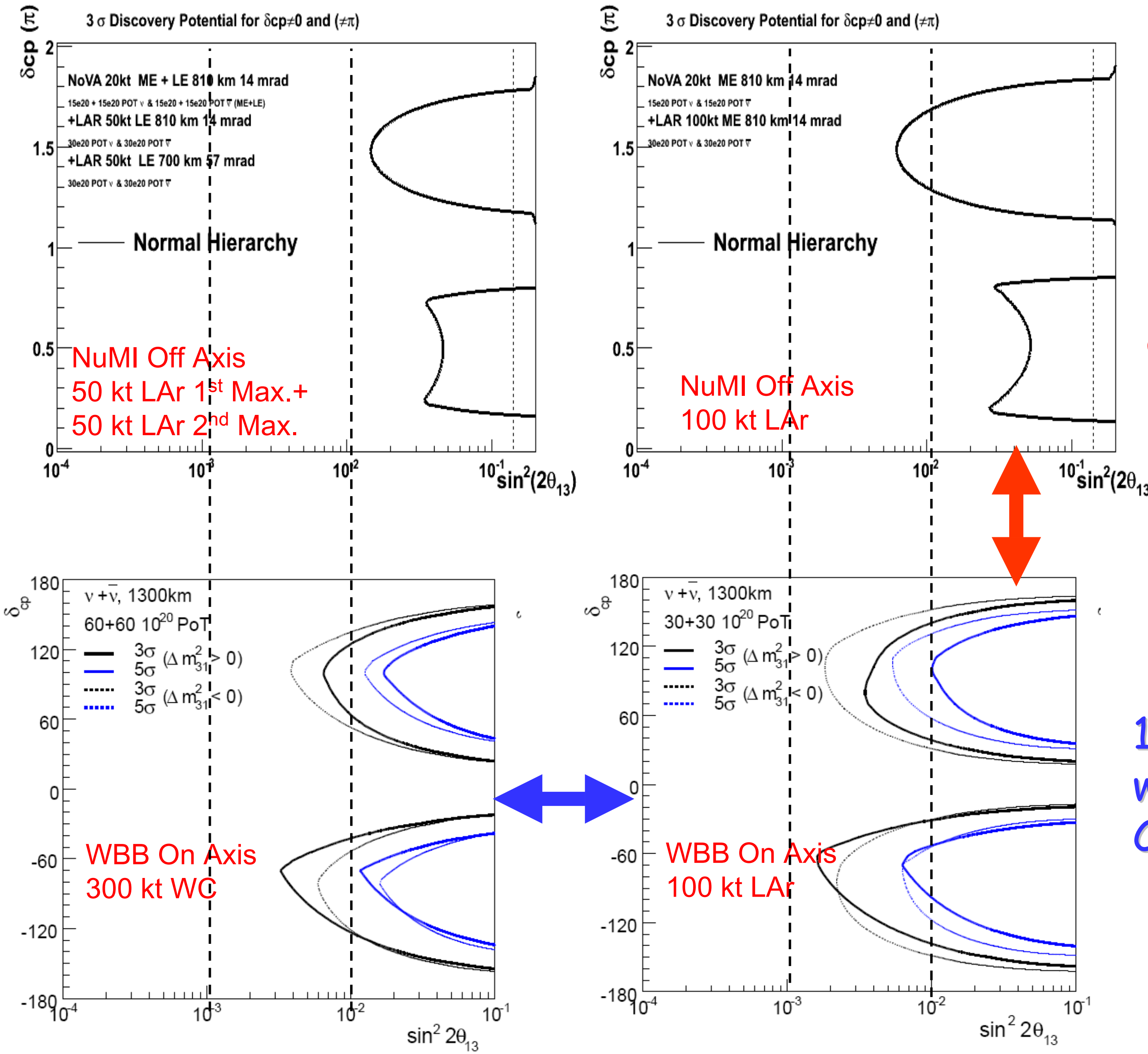


If the same detector technology used , off axis NBB and on axis WBB approaches give ~similar reach



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

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



If the same detector technology used :

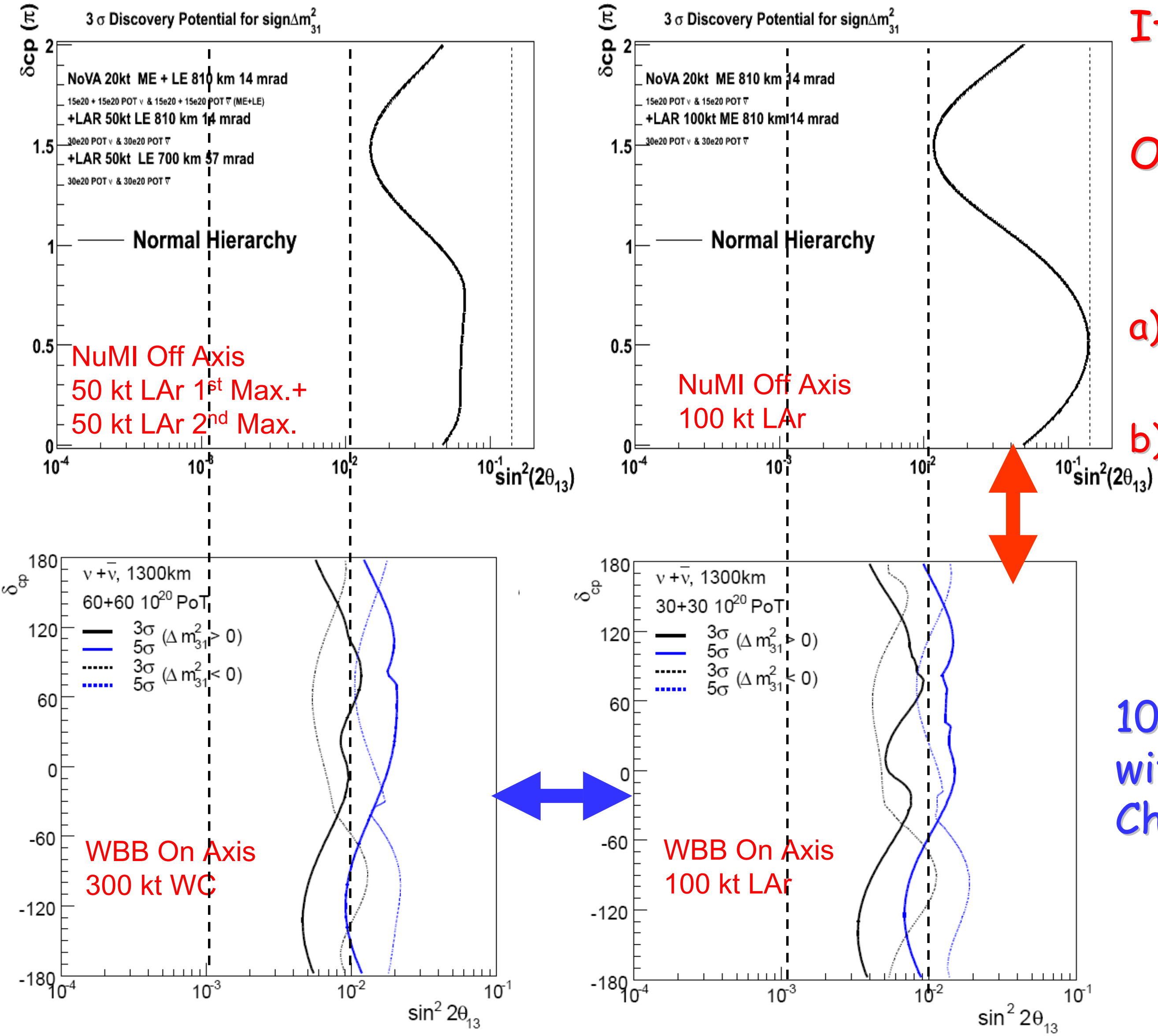
On Axis WBB has much higher reach on CP Violation due to

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

Staged approach to achieve the ultimate goals

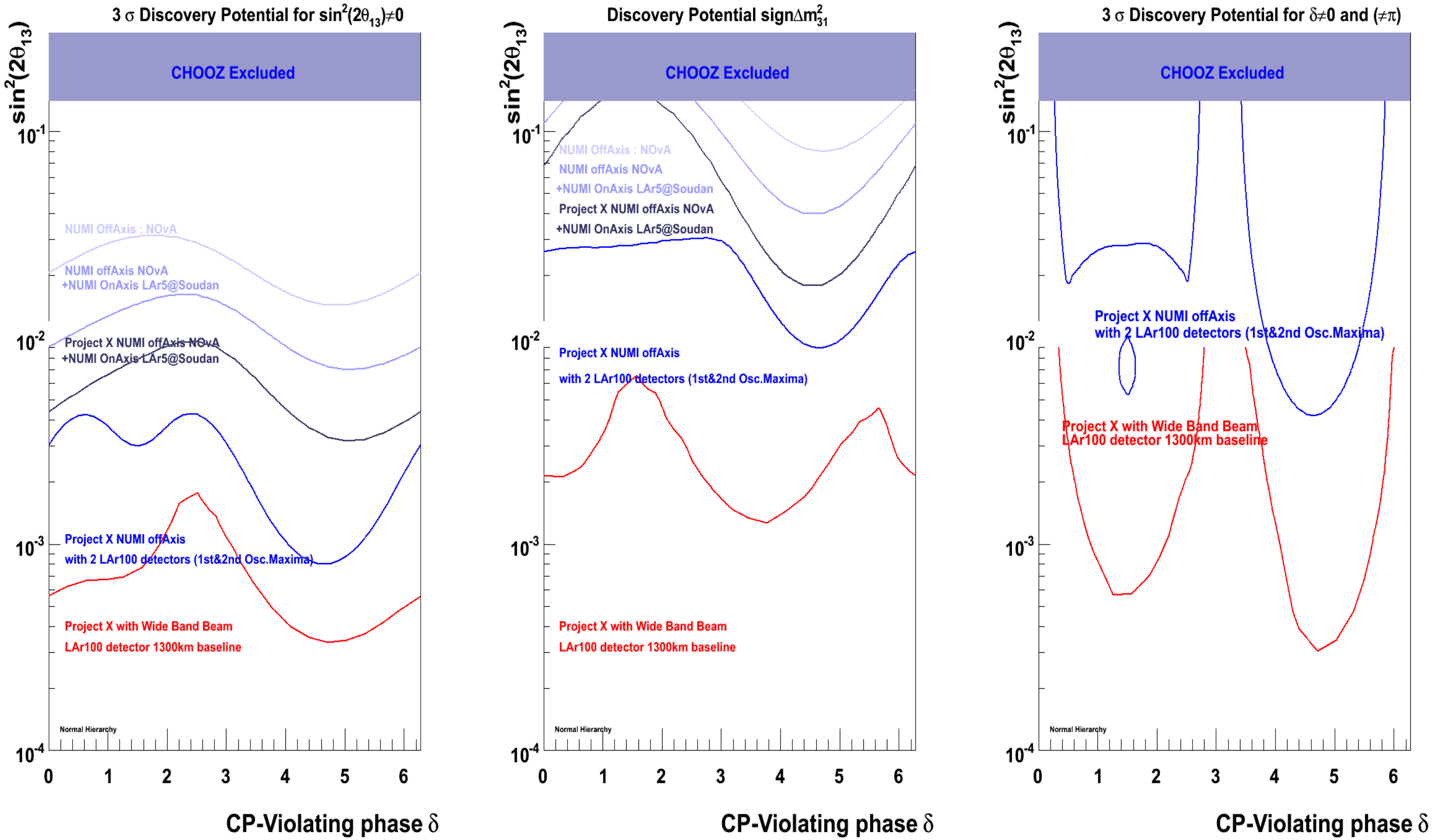
1) Start with NuMI off Axis beam at 810 km (NOvA) and 700 KW

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 , (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

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

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**.

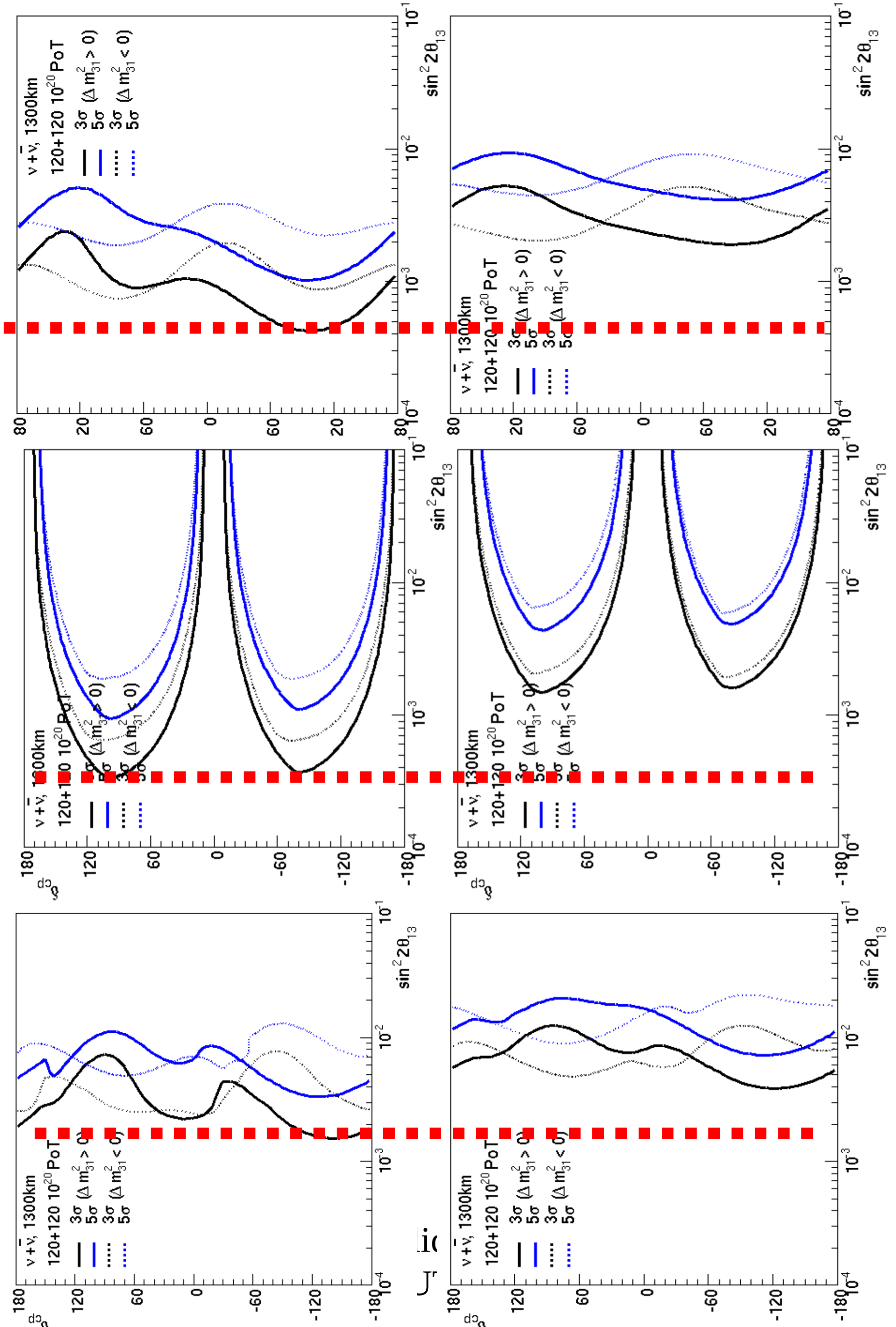
Conclusions

- Fermilab already has the most intense accelerator neutrino beam in the world that is going to be used for Phase I experiments and :
  - The potential of a factor of 3 further increase of beam power with ProjectX
  - An emerging well defined R&D Plan on massive detectors
  - An ongoing effort on designing the next generation Long Baseline Wide Band Neutrino Beam :

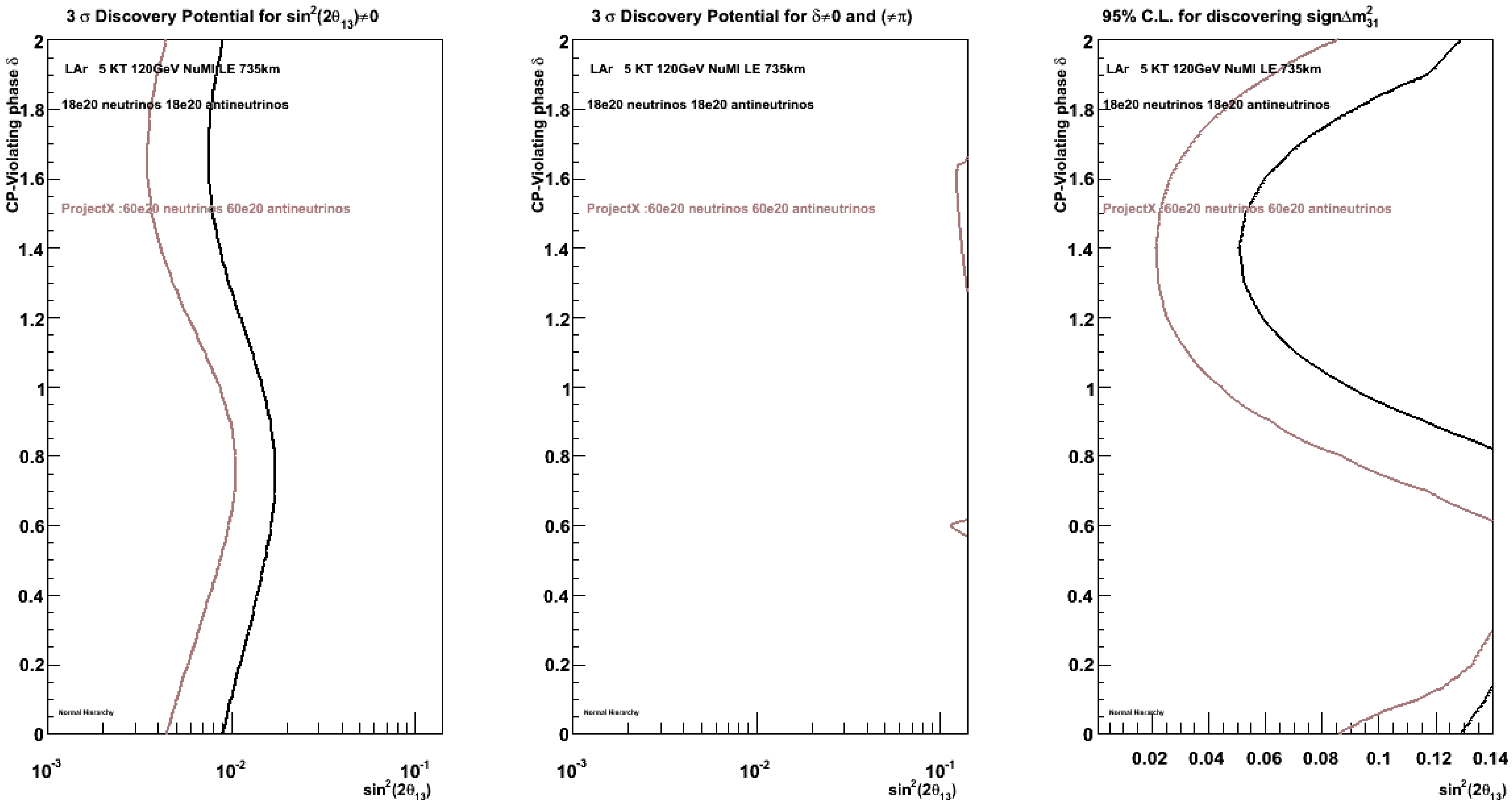
… which is precisely what is needed for the "next generation (Phase II) long baseline neutrino oscillation experiments"

Backup

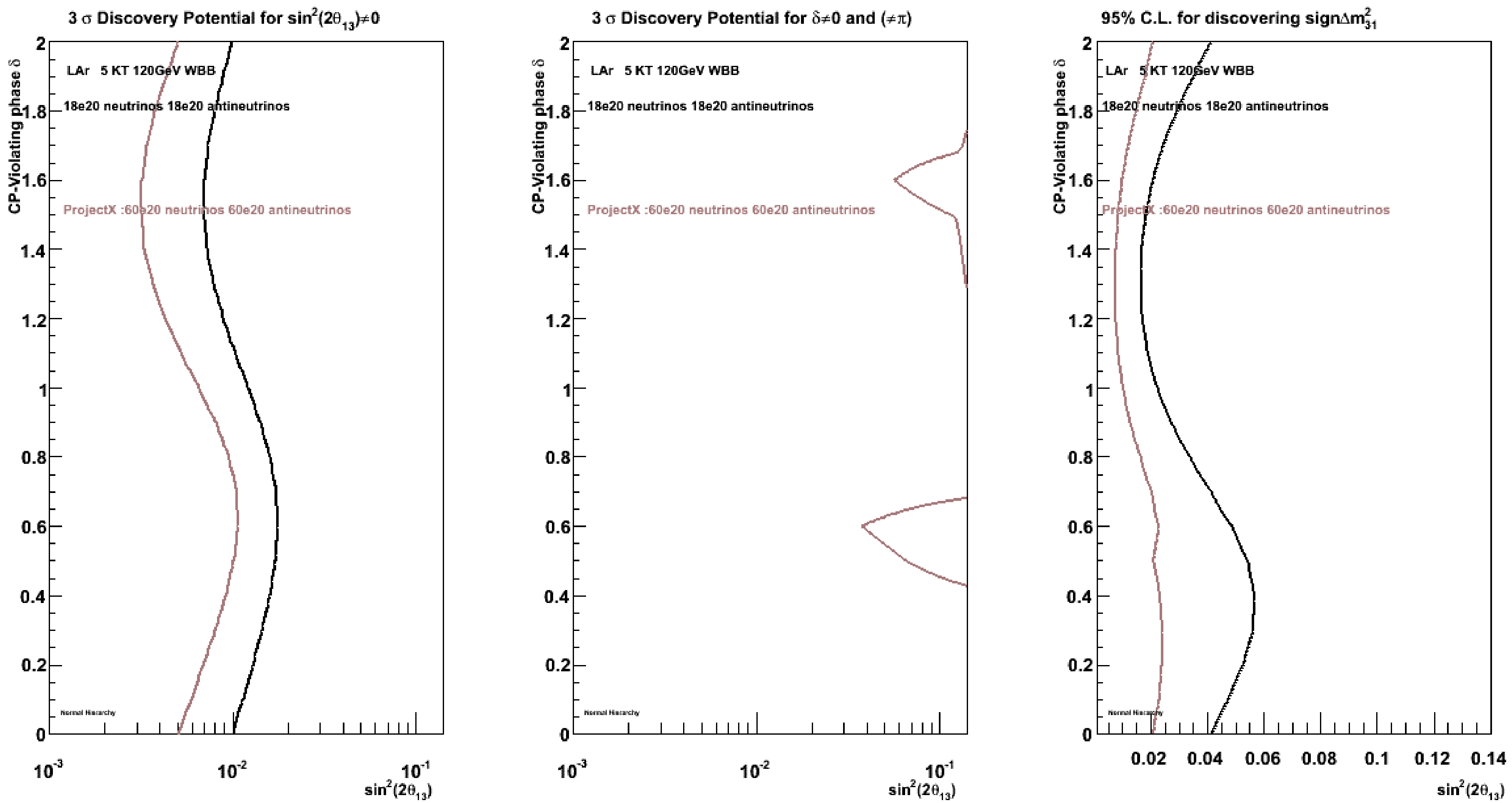
100 kt LAr **BNL Globes** **300 kt WC**



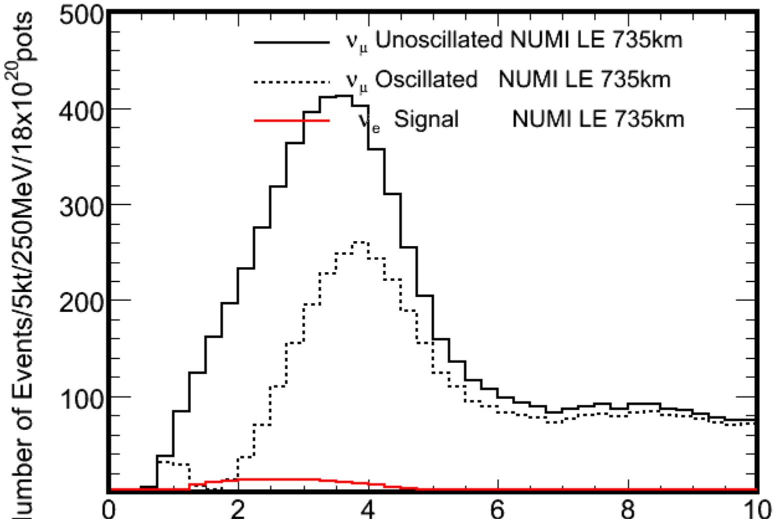
LAr5 @ SOUDAN (LE)

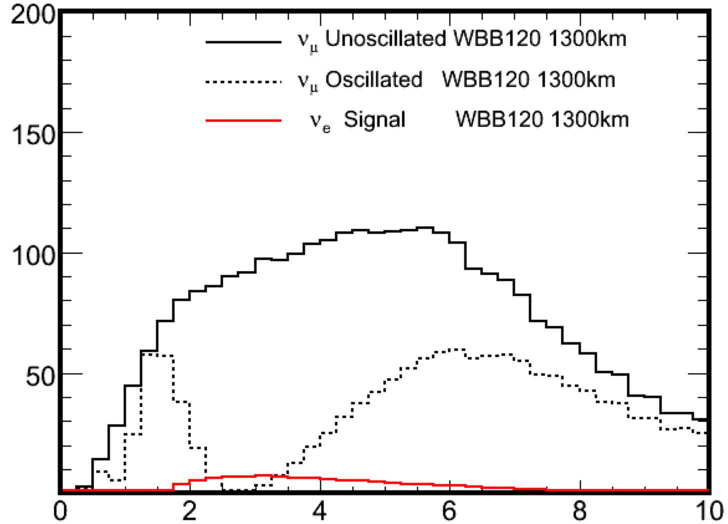


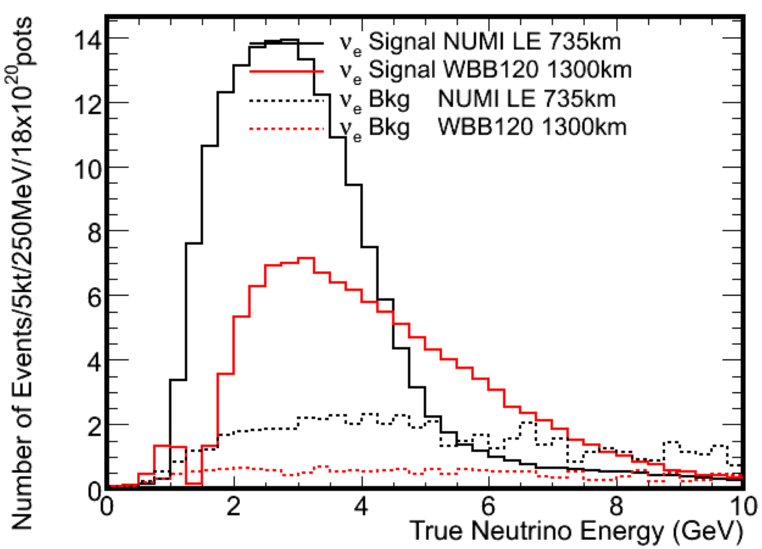
LAr5 @ L = 1300 km



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)

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 !!!

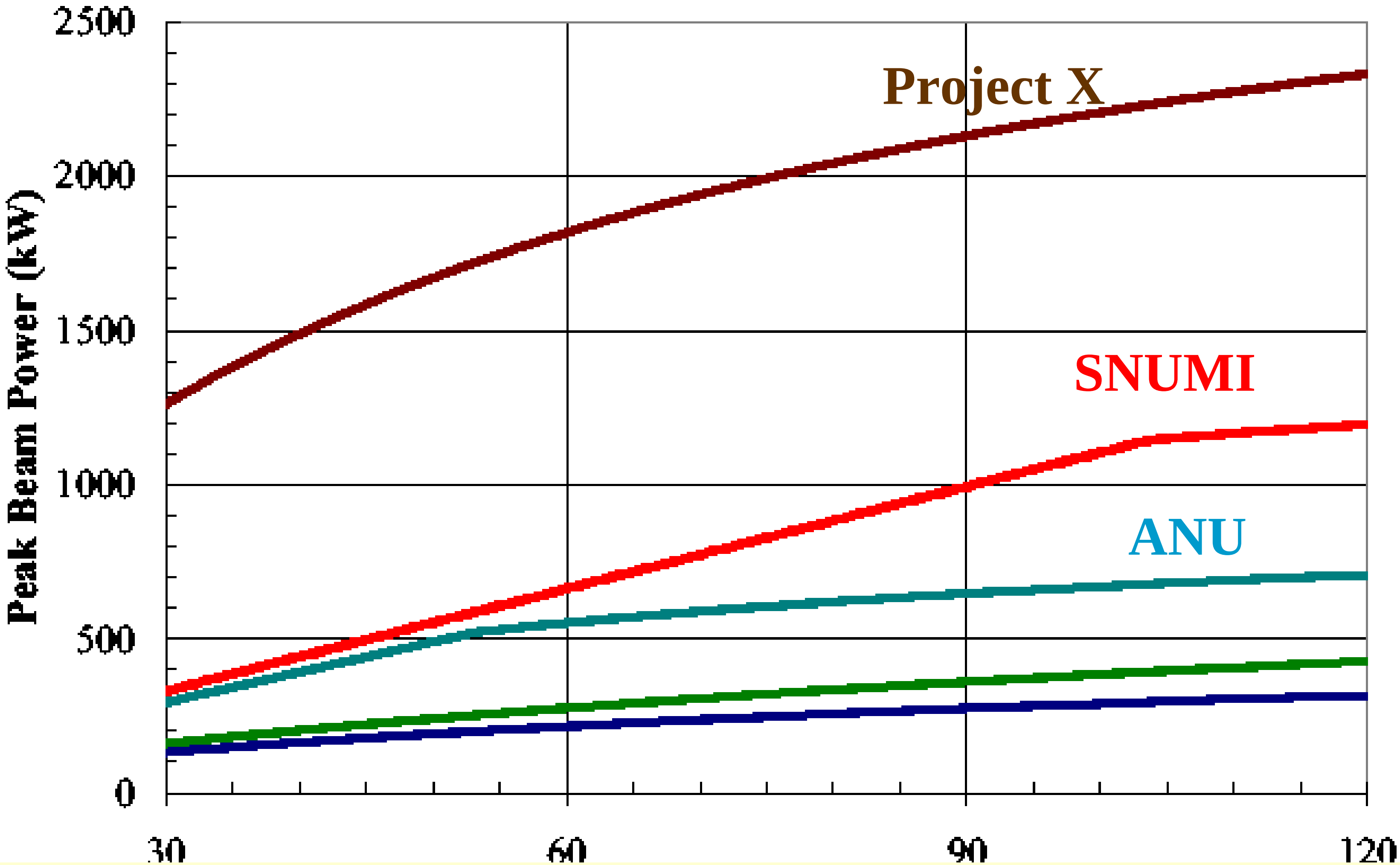
For the same detector masses and running time:

Without project X , θ_{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.

NuMI Neutrino Beam: Capabilities & Advantages

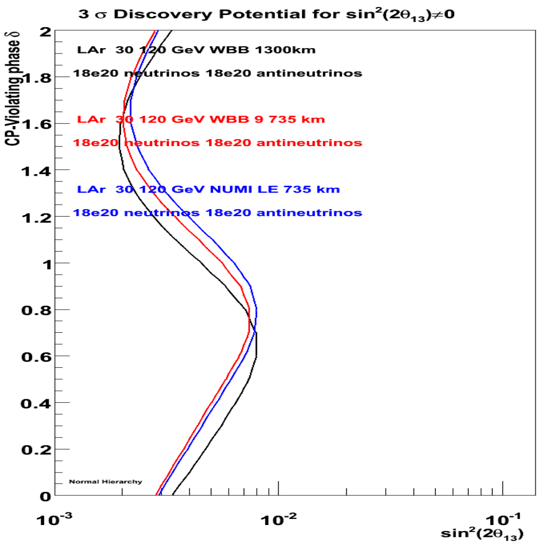
Plot courtesy : B. Zwaska

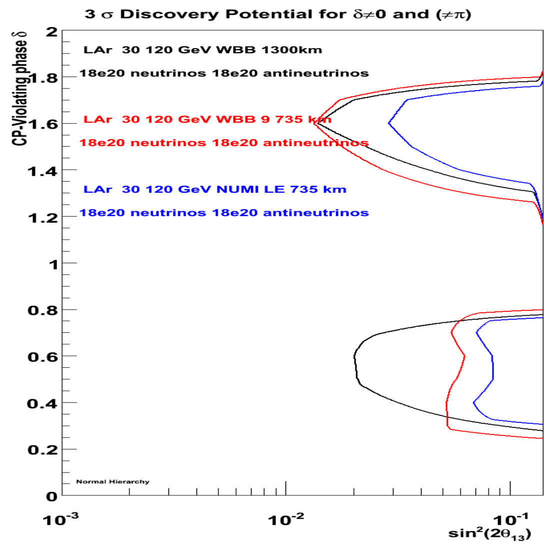


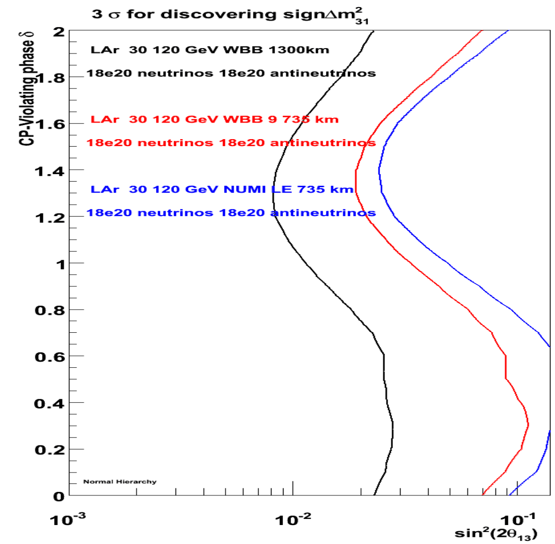
- There exists a well defined upgrade plan for the NuMI Beam
- With Project X, beam power and hence neutrino beam intensity can increase by a factor of 3 with respect to ANU

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

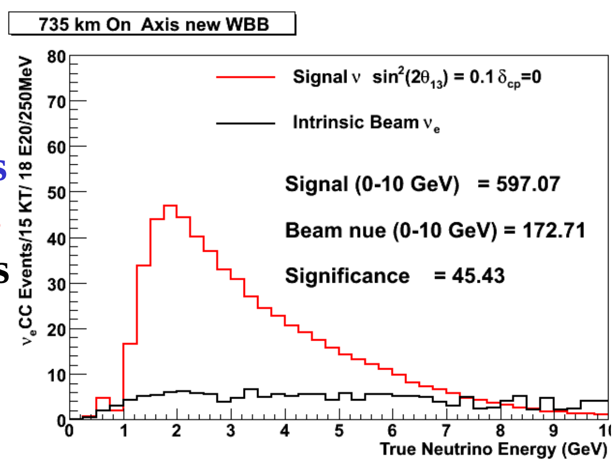
Example : 30 kt of Lar, 700 KW Beam Power, 3 year of neutrino + 3 years of anti-neutrino running

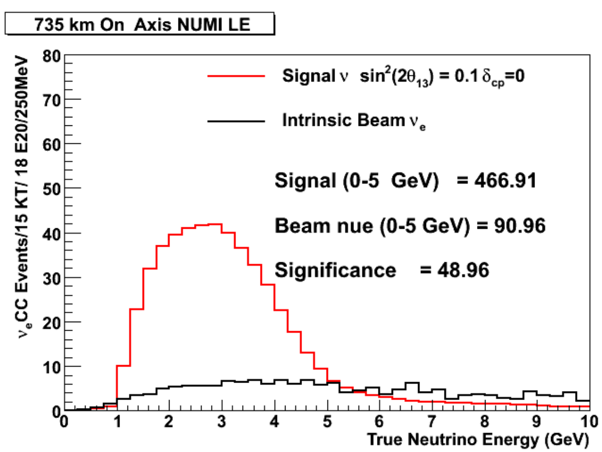






BLUE : NuMI 735 km On Axis
RED : WBB 735 km On Axis
BLACK : WBB 1300 km On Axis





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)

Discovery Potentials: Technical details

θ_{13} Discovery Potential :

Null hypothesis : θ_{13} = **0**

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

δ_{cp} Discovery Potential :

Null hypothesis : δ_{cp} = **0 or** δ_{cp} = π (**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.***