5KT LAr Detector for ν oscillation physics

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3rd Project X Workshop 06-07-08

Outline

- The **"Ultimate"** goal in **neutrino oscillation physics** (at least for the next decade)…
- How to achieve the ultimate goal with LAr Detector technology
- ~5 KT LAr as an important intermediate step to do both:
  - Necessary R&D needed to go **from small/medium** to very **large scale LAr detectors**
  - And interesting ν **oscillation physics**
- Summary / Conclusions

The ultimate goals in ν 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)

???

Atmospheric ??? Cross Mixing Solar 0νββ decays

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

Majorana phases

✓

- Do "man made" νμ'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)

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:

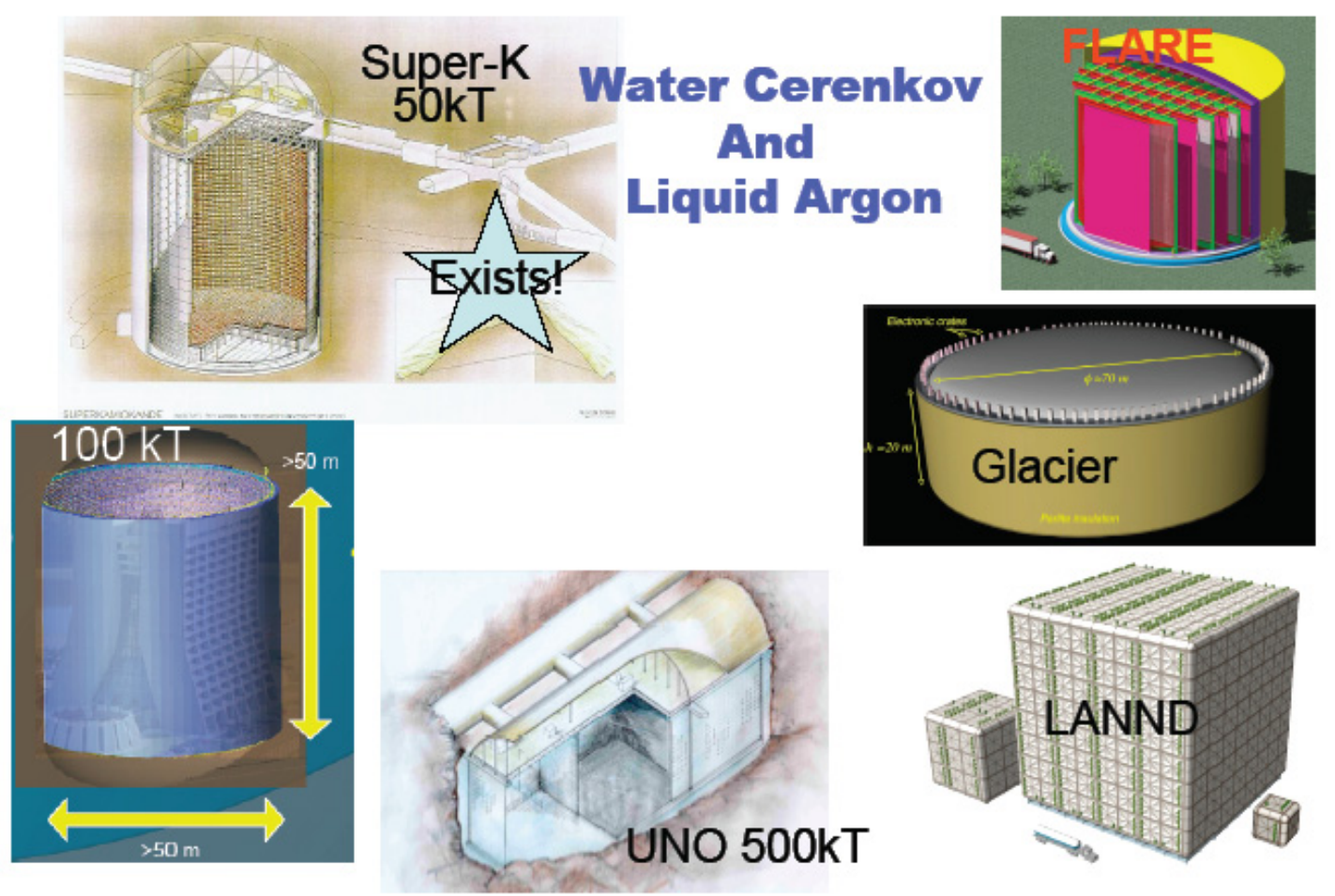
- Massive cost effective detectors that are larger than those of Phase I (> 20 KT)
- Intense neutrino beams with intensity possibly higher than that of Phase I (> 700 KW)
- The ability to break inherent degeneracies between genuine CP violation and "Fake CP violation" from matter effects.

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

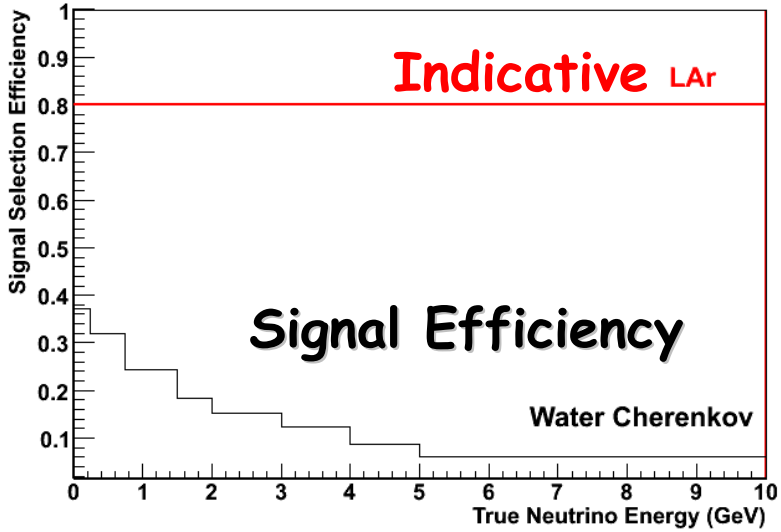
Given their assumed efficiencies and background rejections the following :

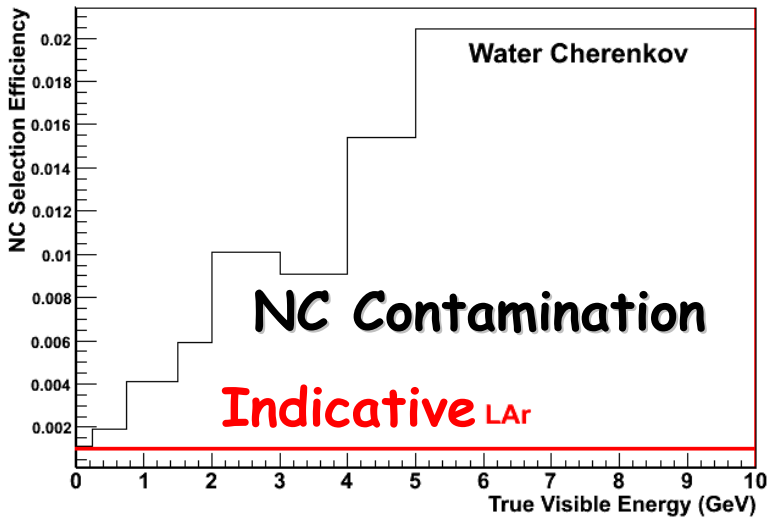
"Detector Mass Equivalent Law" holds, which has been independently checked by two groups (BNL and FNAL)

1 : ~4

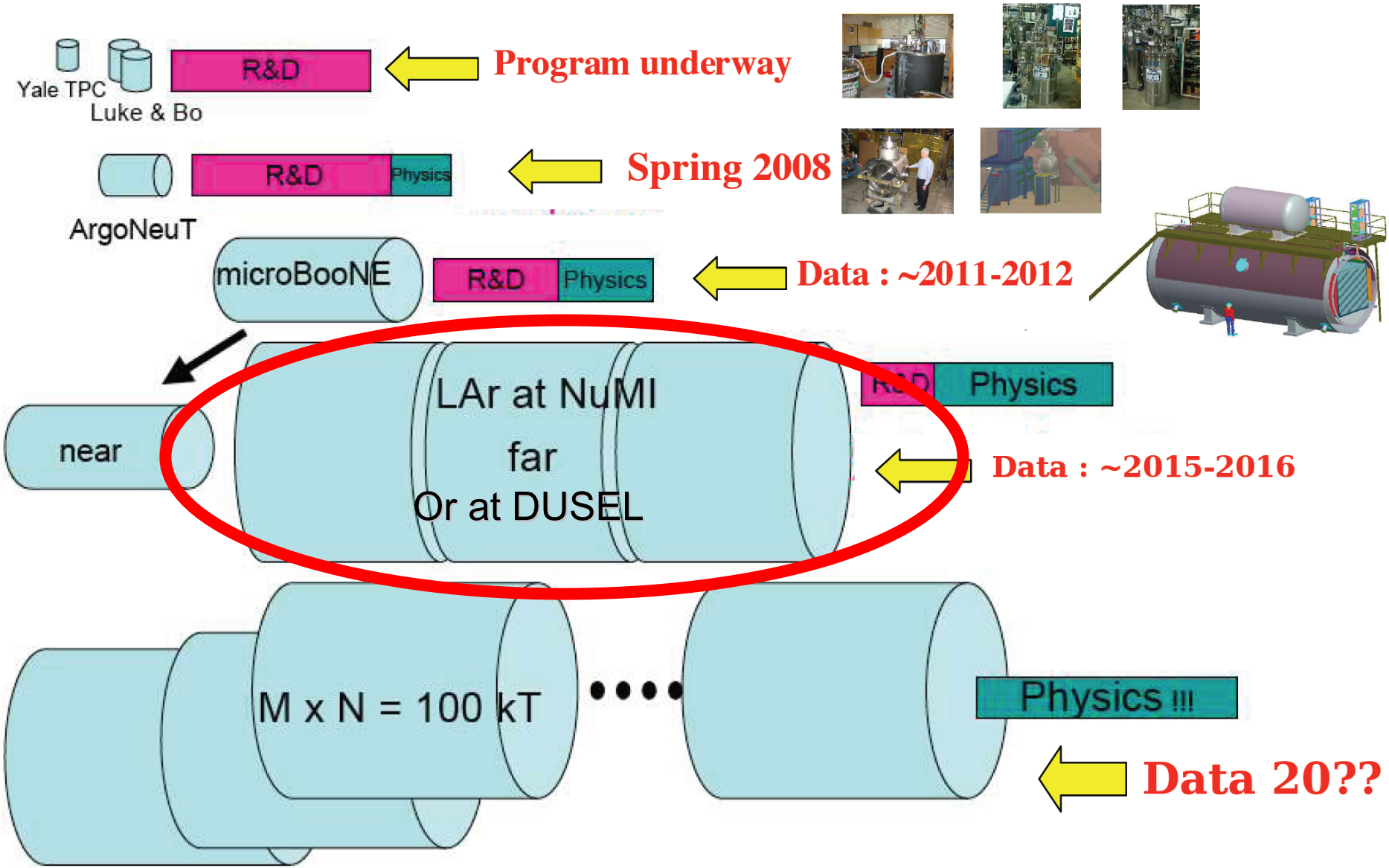
OR

100kt LAr ~ 400 kt WC





Liquid Argon TPC R&D Path in the US

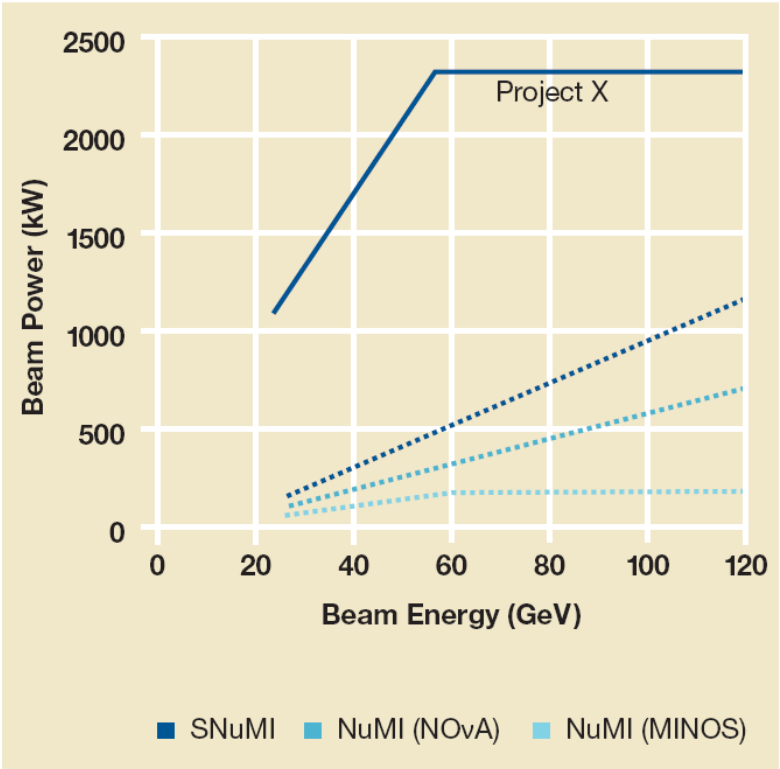


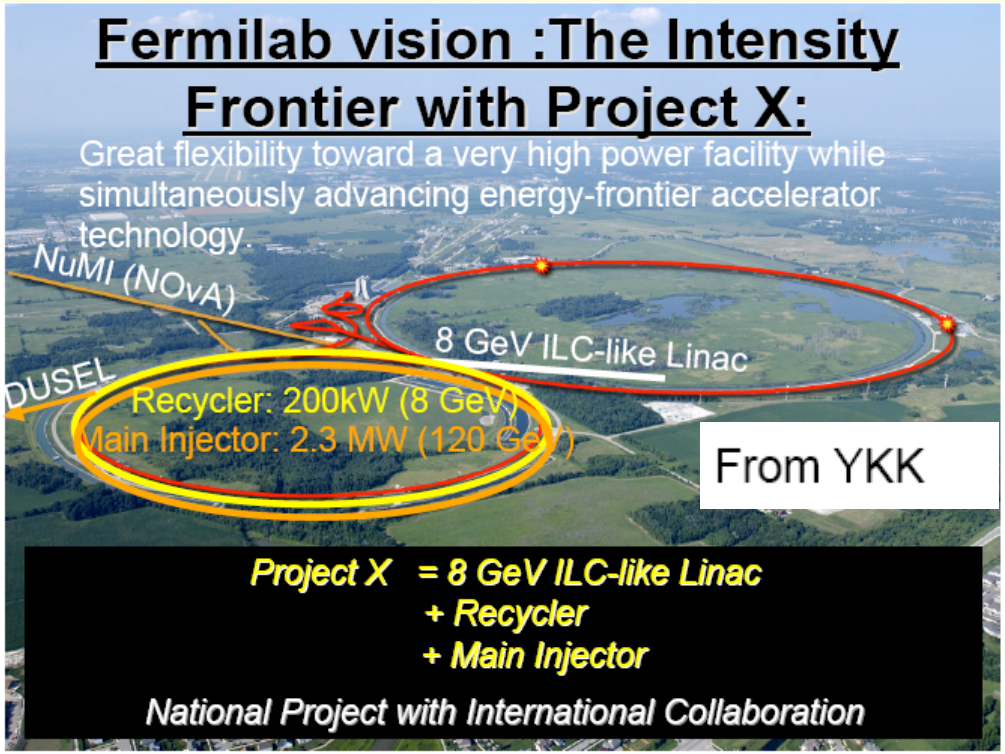
Ingredients for achieving the ultimate goals (2)

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 :

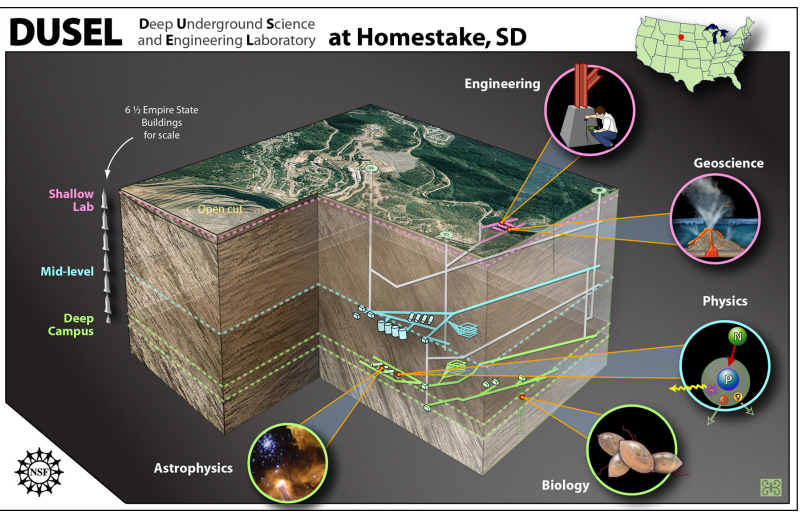
Water Cherenkov detectors not an option for that reason.

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

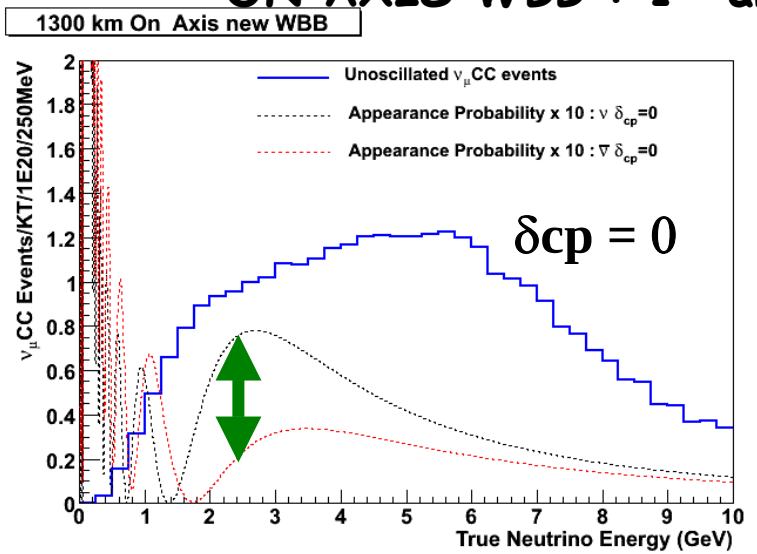
(Homestake Mine 300 ft level, or ~ surface)

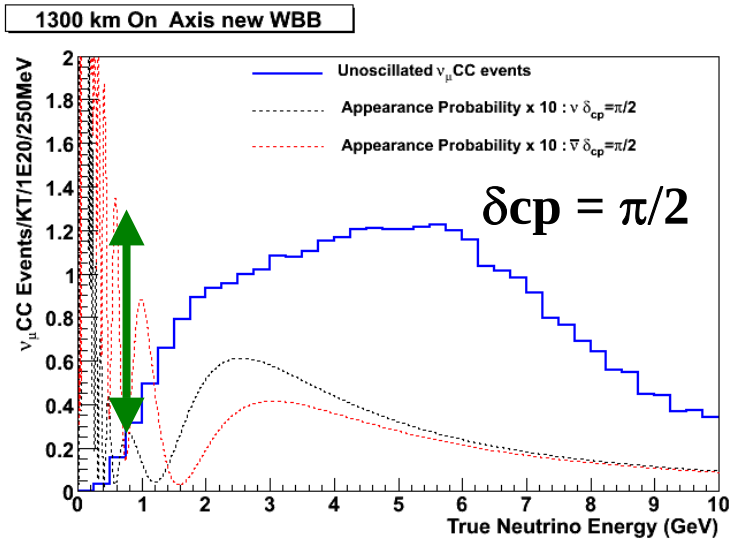
Implications on ν beam :

New beam has to be designed and constructed

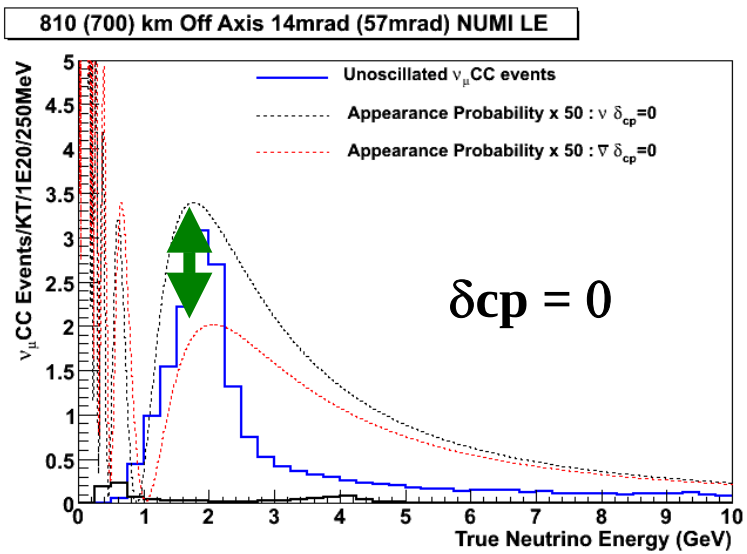
Wide Band Neutrino Beam: Advantages

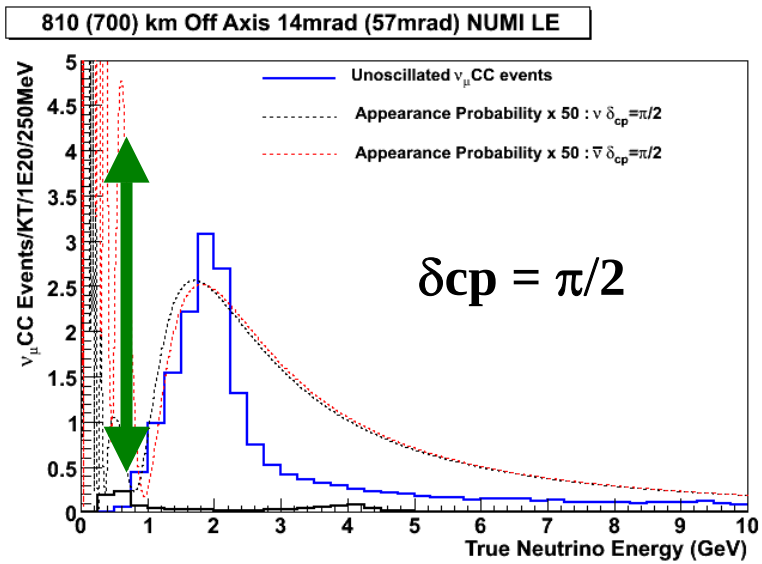
ON AXIS WBB : 1st and 2nd Oscillation Maxima 1 Detector



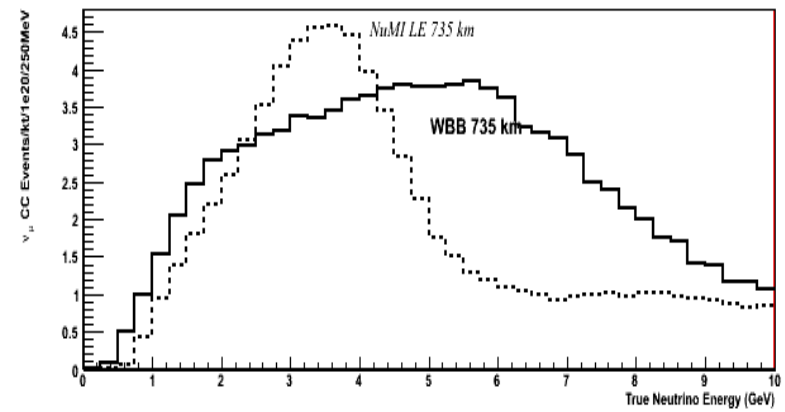


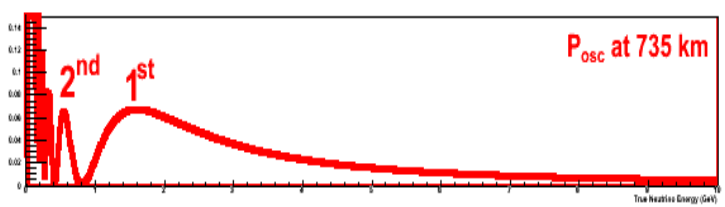
NuMI OFF AXIS : 1st and 2nd Oscillation Maxima 2 Detectors

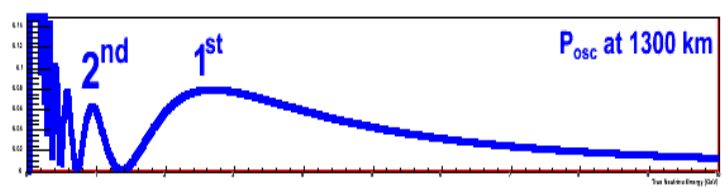


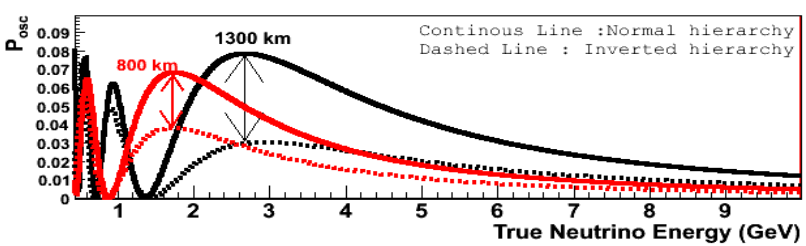


Longer baseline (>>L) AND a new Wide Band Beam









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

Technical Issues (as discussed by all members of the LAr community world-wide)

Many technical issues need to be addressed for the large (~100 KT) scale detectors

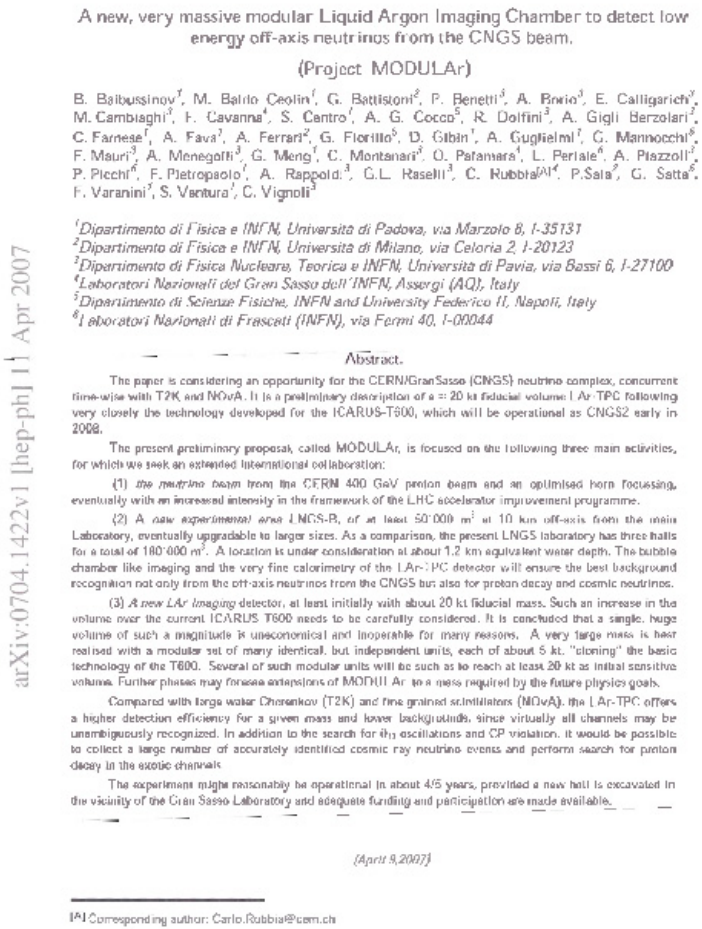
- **Design Considerations**
  - Liquid Argon purity → maximum drift →
  - Thermal insulation → Operation cost
  - Location : surface/underground
    - Mechanical stability and safety → cryostat design
    - Cosmic ray backgrounds
  - ....

- **Scaling considerations**
  - Modularity
  - Shape
  - Total-Fiducial-Active volume ratio
  - Number of electronic channels
  - Surface-to-volume ratio (heat input and wall outgassing)
  - Cryostat thermal insulation techniques
  - Materials and construction techniques

Why a 5 kiloton step?

- **Various opinions on the size of the "intermediate step" detector exist within the LAr community *(some Colleagues would even strongly argue that no intermediate step is needed…)***
- The step after the 100 - 200 t detector, could be 1 to 5 kilotons
  - The main technical purpose of this step is to determine construction techniques and the scaling laws, especially in regards to cost
- Location of 1 - 5 kilotons
  - *1 KT in a near location gets lots of events; does near detector physics - no oscillation physics,*
  - *1 KT potentially can be constructed faster/cheaper than a larger detector with a goal to do oscillation physics?*
  - **5 KT in a far location is about the smallest one can build and have decent sensitivity to physics measurements**

Similar idea evolving in Europe :Project MODULAr



A new, very massive modular Liquid Argon Imaging Chamber to detect low energy off-axis neutrinos from the CNGS beam.

(Project MODULAr)

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Abstract.

The paper is considering an opportunity for the CERN/GranSasso (CNGS) neutrino complex, concurrent time-wise with T2K and NOvA. It is a preliminary description of a ≈ 20 kt fiducial volume LAr-TPC following very closely the technology developed for the ICARUS-T600, which will be operational as CNGS2 early in 2008.

The present preliminary proposal, called MODULAr, is focused on the following three main activities, for which we seek an extended international collaboration:

(1) *the neutrino beam* from the CERN 400 GeV proton beam and an optimised horn focussing, eventually with an increased intensity in the framework of the LHC accelerator improvement programme.

(2) A *new experimental area* LNGS-B, of at least 50'000 m^3 at 10 km off-axis from the main Laboratory, eventually upgradable to larger sizes. As a comparison, the present LNGS laboratory has three halls for a total of 180'000 m^3. A location is under consideration at about 1.2 km equivalent water depth. The bubble chamber like imaging and the very fine calorimetry of the LAr-TPC detector will ensure the best background recognition not only from the off-axis neutrinos from the CNGS but also for proton decay and cosmic neutrinos.

(3) *A new LAr imaging* detector, at least initially with about 20 kt fiducial mass. Such an increase in the volume over the current ICARUS T600 needs to be carefully considered. It is concluded that a single, huge volume of such a magnitude is uneconomical and inoperable for many reasons. A very large mass is best realised with a modular set of many identical, but independent units, each of about 5 kt, "cloning" the basic technology of the T600. Several of such modular units will be such as to reach at least 20 kt as initial sensitive volume. Further phases may foresee extensions of MODULAr to a mass required by the future physics goals.

Compared with large water Cherenkov (T2K) and fine grained scintillators (NOvA), the LAr-TPC offers a higher detection efficiency for a given mass and lower backgrounds, since virtually all channels may be unambiguously recognized. In addition to the search for θ_{13} oscillations and CP violation, it would be possible to collect a large number of accurately identified cosmic ray neutrino events and perform search for proton decay in the exotic channels.

The experiment might reasonably be operational in about 4/5 years, provided a new hall is excavated in the vicinity of the Gran Sasso Laboratory and adequate funding and participation are made available.

(April 9,2007)

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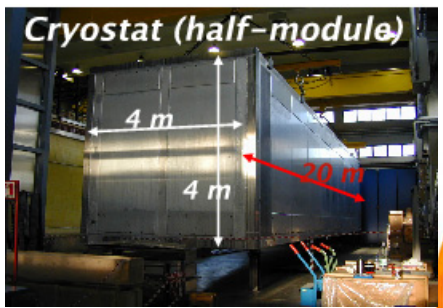
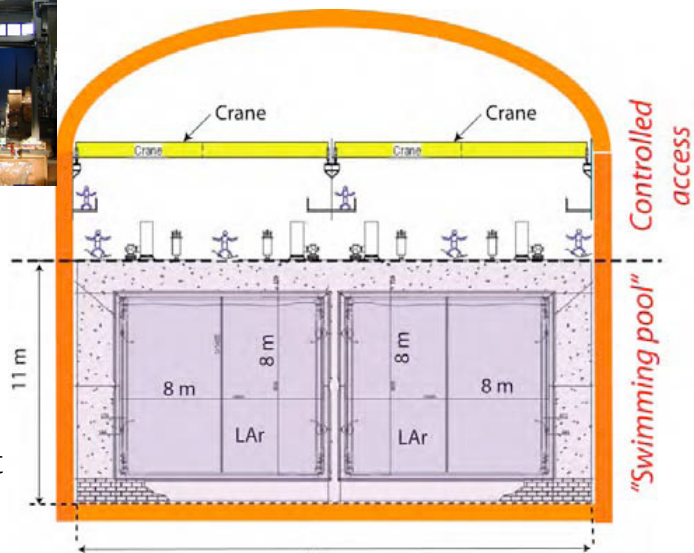
- ~20kT fiducial volume, modeled after ICARUS T-600
  - Upgraded neutrino beam from the 400 GeV CERN SPS
  - New experimental area 10 km off-axis of CNGS neutrino beam
  - Multiple 5kT LArTPCs
    - (8x8x60m^3 per 5kT unit)





Advantages and disadvantages for NuMI option

ADVANTAGES:

- The NuMI beam exists; it will be upgraded to 700kW for NOvA
- Soudan
  - The SOUDAN cavern + laboratory infrastructure exists.
  - The underground location eliminates the concern about surface operation (which in principle is possible, but likely to lead to additional challenges).
    - Any detector constructed for proton decay will need to be at depth
    - This 5kT may be able to make a contribution to the $p \rightarrow K\nu$ search
- Physics reach is comparable to NOvA => ~Doubling the mass

DISADVANTAGES:

Reach in mass hierarchy limited by length of baseline and by less optimized L/E (given that we now know Δm^2)

Advantages and disadvantages for DUSEL option

ADVANTAGES :

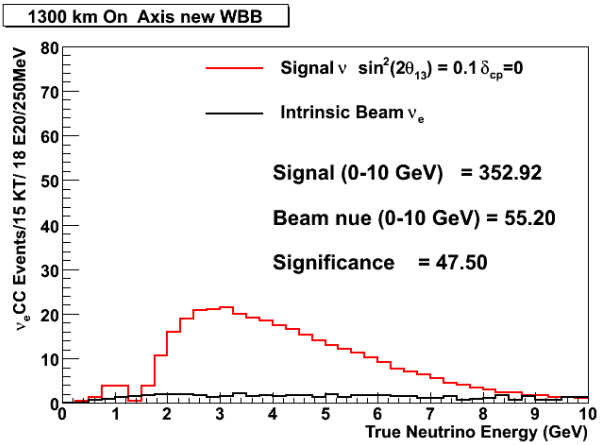
- Longer baseline and better optimized beam (L/E) give higher reach in mass hierarchy (and similar reach in θ_{13})
- Detector will be in the location that the next , PHASE II, large detectors will eventually be placed

DISADVANTAGES :

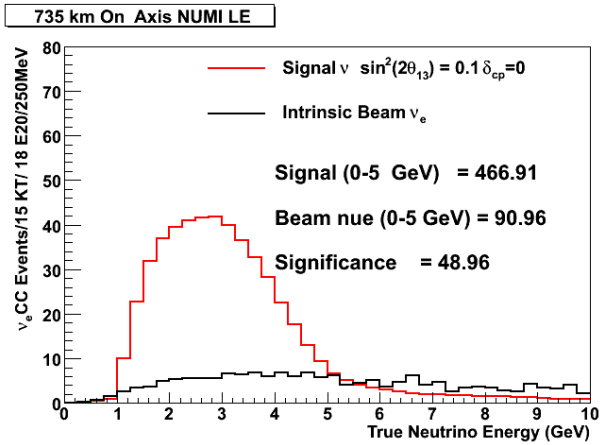
- The DUSEL beam doesn't exist …
- The cavern does not exist…

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

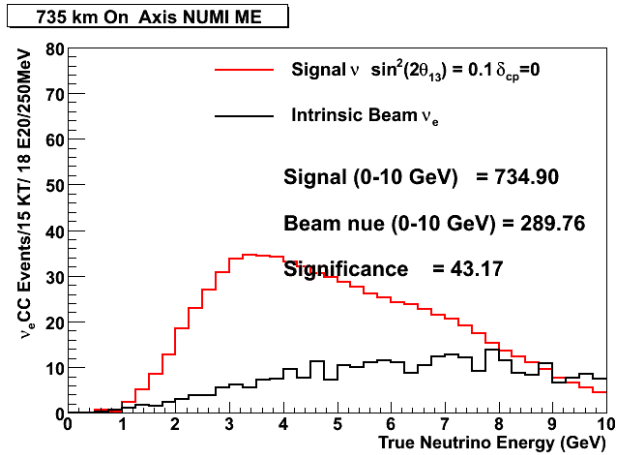
On-Axis 1300km new WBB



On Axis 735km NuMI LE

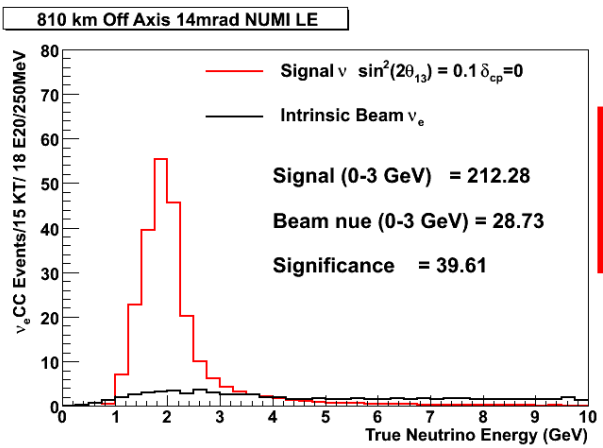


On Axis 735km NuMI ME



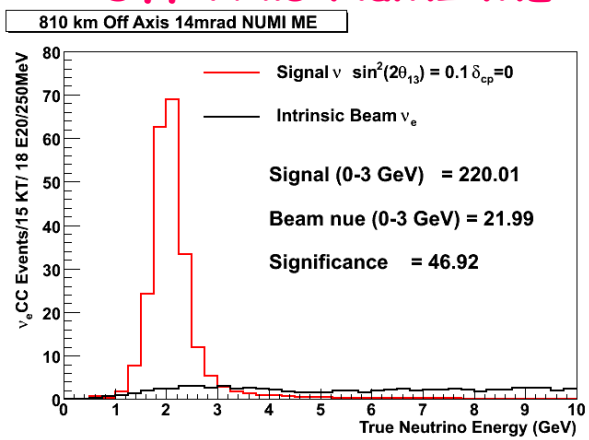
Disappearance minimum (appearance maximum) at given Δm_{23}^2:
Signal events do not scale as $1/L^2$, backgrounds do.

Off Axis NuMI LE



Considered all these 5 options

Off Axis NuMI ME



Assumptions on Detector Capabilities

For the Sensitivities shown next we used a 5kt LAR Detector with:

Signal selection efficiency : 80%

Beam ν_e selection efficiency : 80%

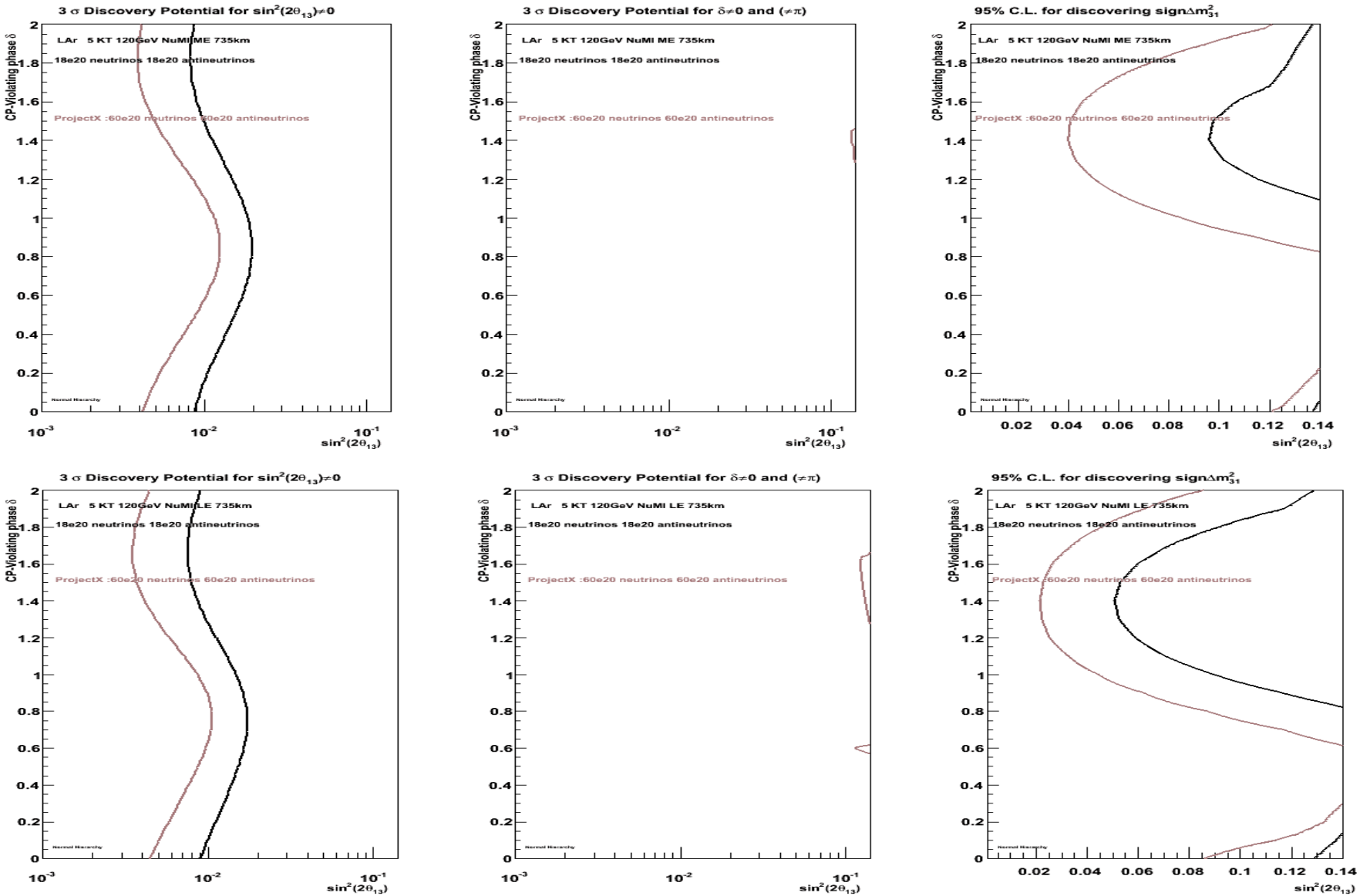
No NC contamination

Systematic uncertainties on the Background : 5%

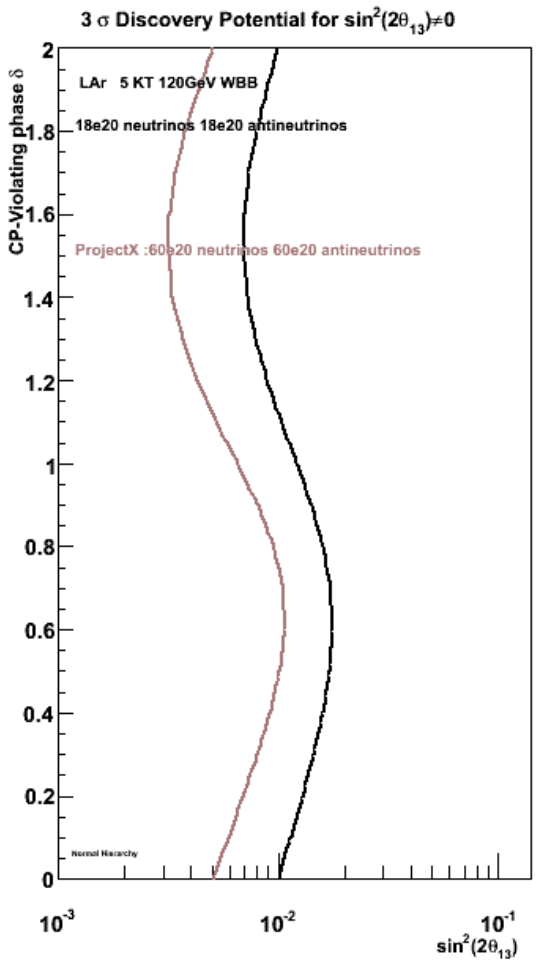
No energy smearing (true neutrino energy used), no reconstruction .

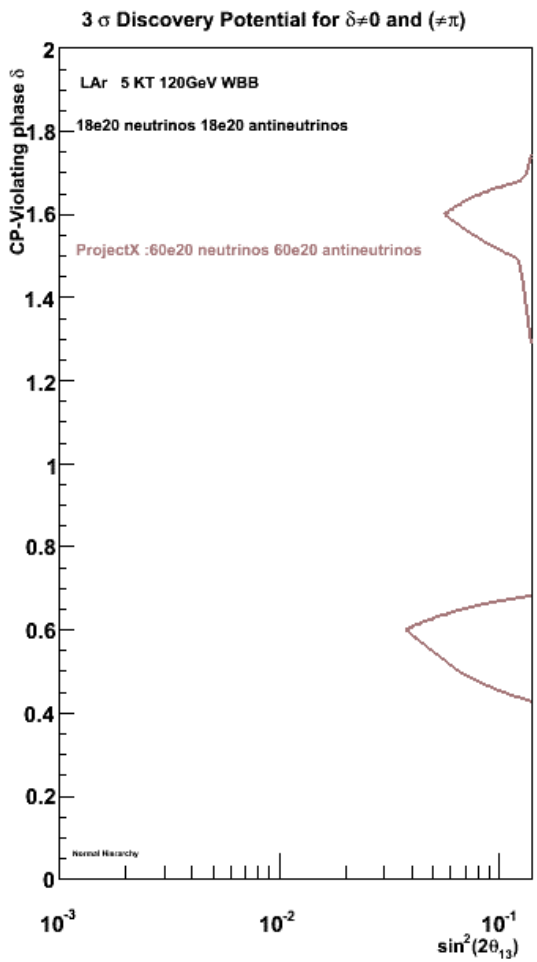
250 MeV bins are used in true neutrino energy

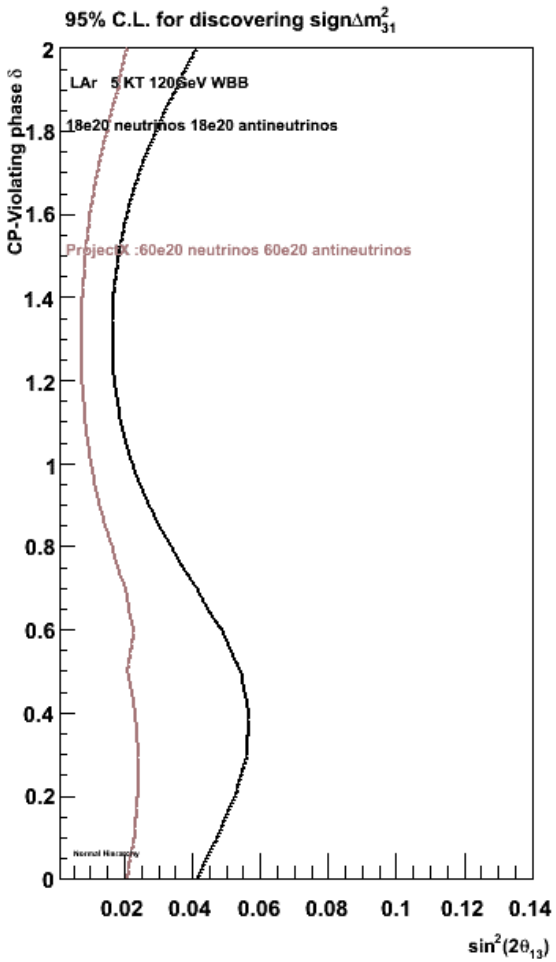
LAr5 @ SOUDAN (ME-LE)



LAr5 @ L = 1300 km







Summary - Conclusions

- The **"ultimate" goal** (given what we know at the moment) on **ν oscillation physics** is to construct and operate world class **CPV experiments.**

- If we want to achieve the "ultimate" goal we need:

  - **A) Powerful (very intense) neutrino beams : Project X**

  - B) Massive (at the XXX kt scale) and powerful (in signal selection and background rejection) detectors : LAr or Water Cherenkov

- **LAr detector technology** is extremely **attractive (for both ν-physics and proton decay)** but **not proven in large scale:** ***Need to follow a well defined R&D path while on the same time doing interesting ν-oscillation physics…***

- A 5kt LAr detector would **significantly increase the physics reach of PHASE I** while on the same time it would be **a major step on the LAr R&D path towards the "ultimate" goal …**

BACKUP SLIDES

Discovery Potentials:Technical details

θ_{13} Discovery Potential :

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

Both δcp 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**

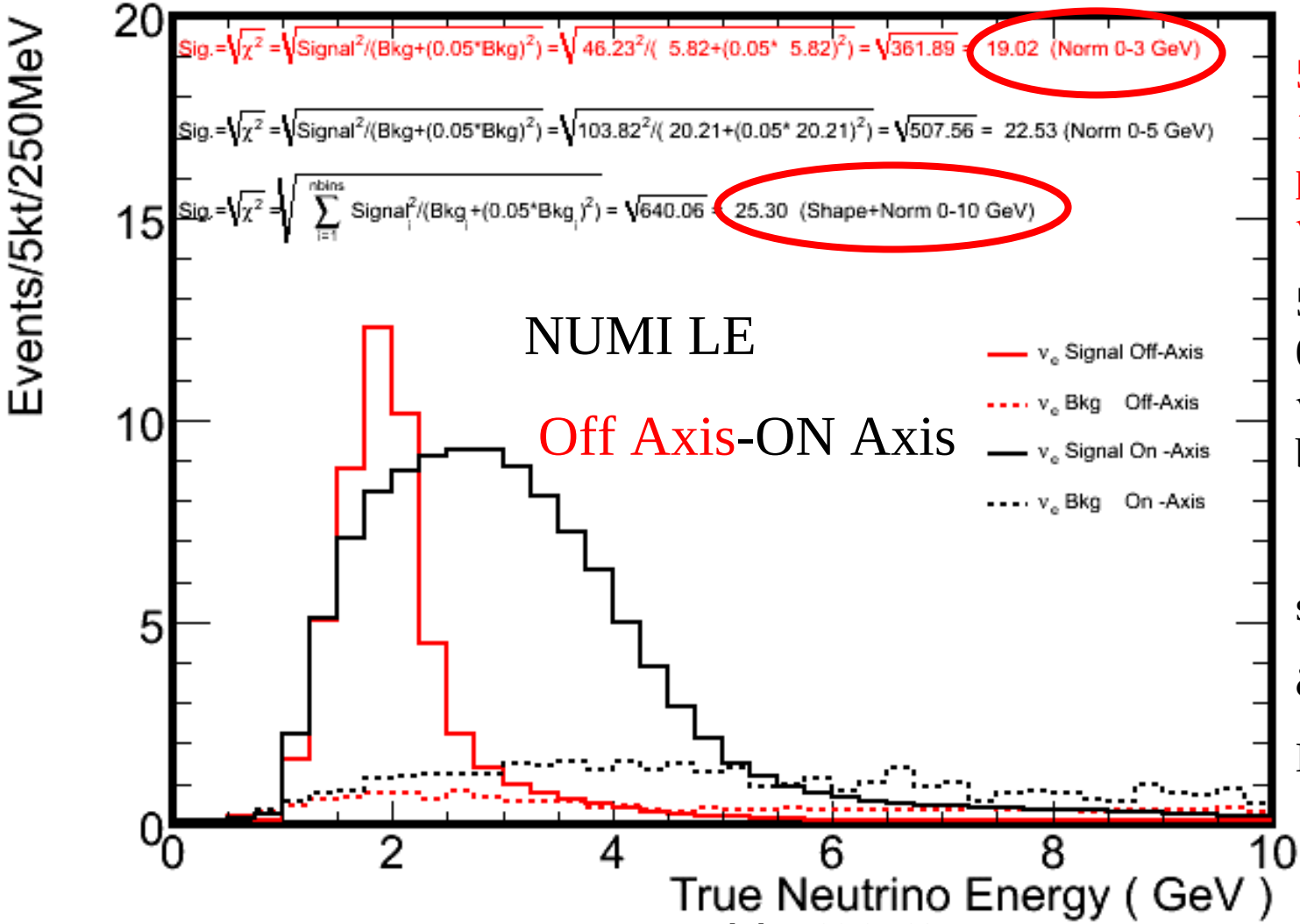
$$\Delta\chi^2 = \chi^2_{\text{true hierarchy}} - \chi^2_{\text{false hierarchy}}$$

****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.***

NUMI LE On Axis - Off axis Signal and Background Spectra Comparisons : On Axis "wins" due to more Signal events



5kt LAr at 810 km 14 mrad : 15e20 pots ν +15e20 pots ν-bar

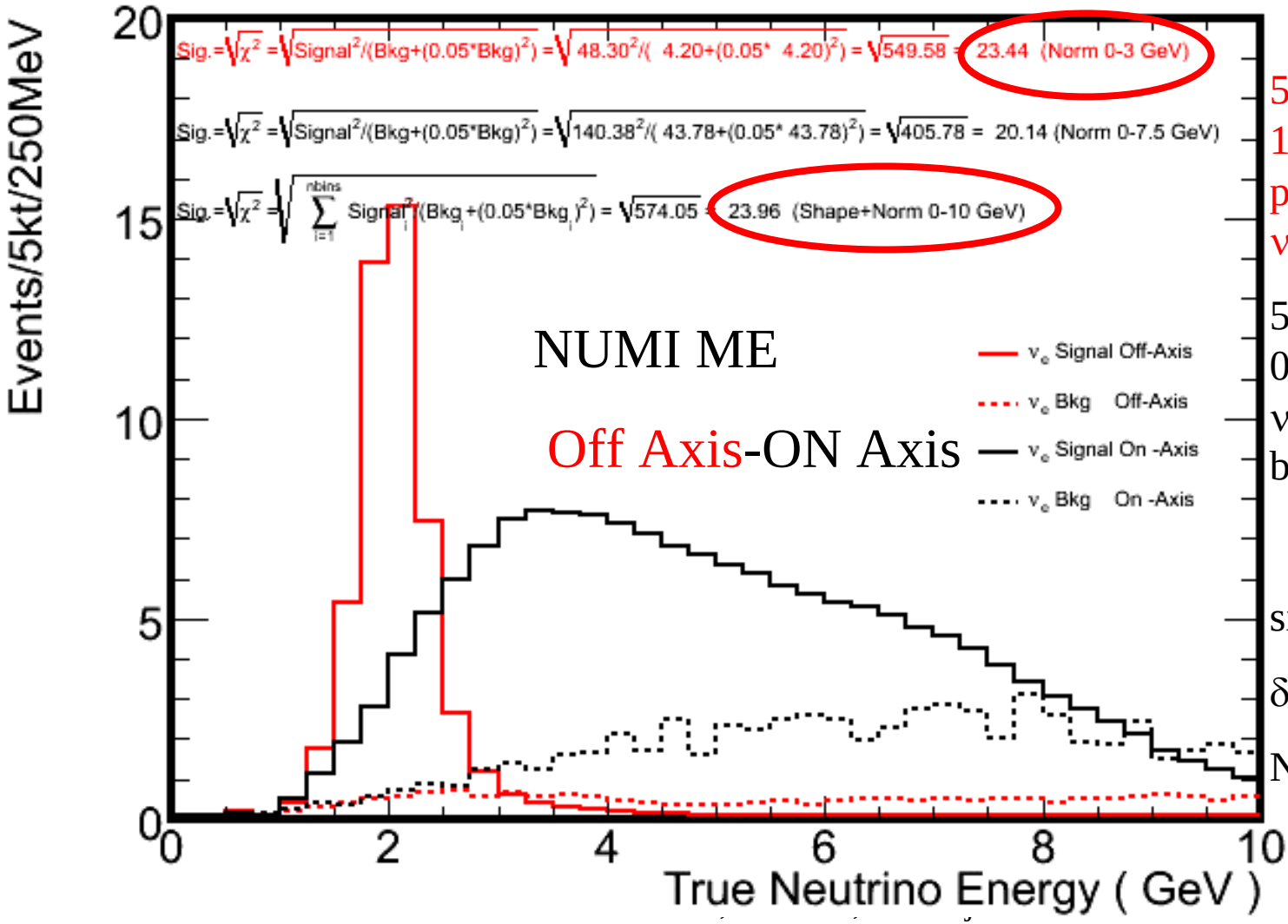
5kt LAr at 735 km 0 mrad :15e20 pots ν +15e20 pots ν-bar

$\sin^2(2\theta_{13})=0.1$

$\delta_{cp}=0$

Normal hierarchy

NUMI ME On Axis - Off axis Signal and Background Spectra Comparisons : On Axis "wins" due to more Signal events



5kt LAr at 810 km 14 mrad : 15e20 pots ν +15e20 pots ν-bar

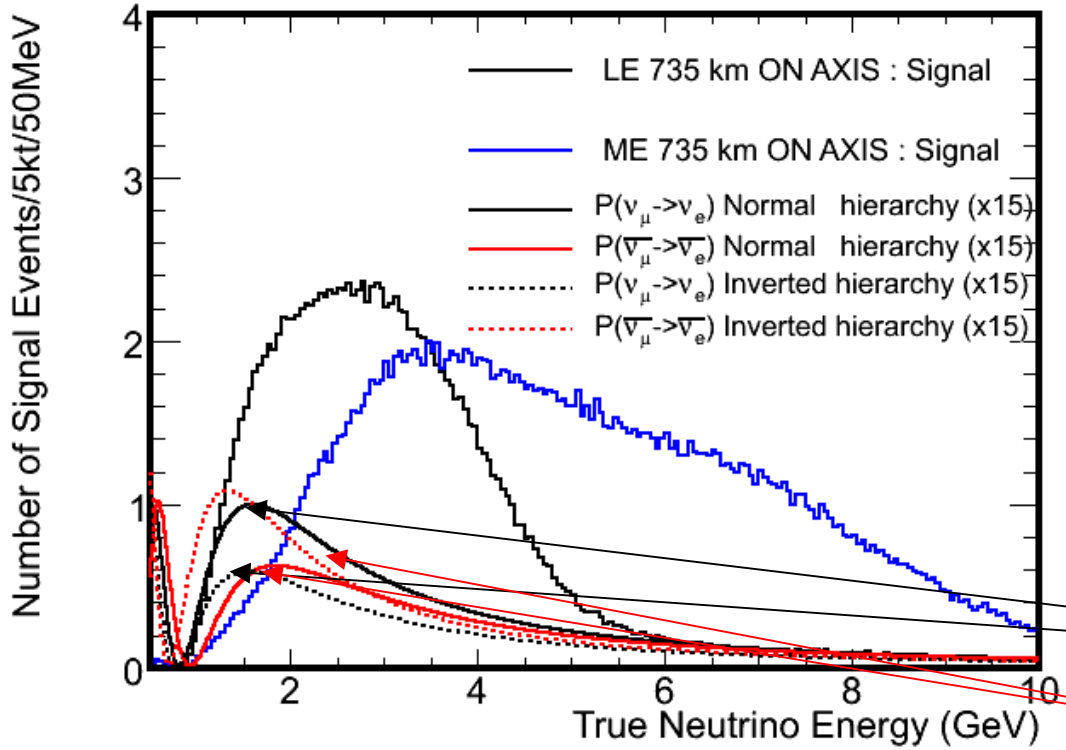
5kt LAr at 735 km 0 mrad :15e20 pots ν +15e20 pots ν-bar

$\sin^2(2\theta_{13})=0.1$

$\delta_{cp}=0$

Normal hierarchy

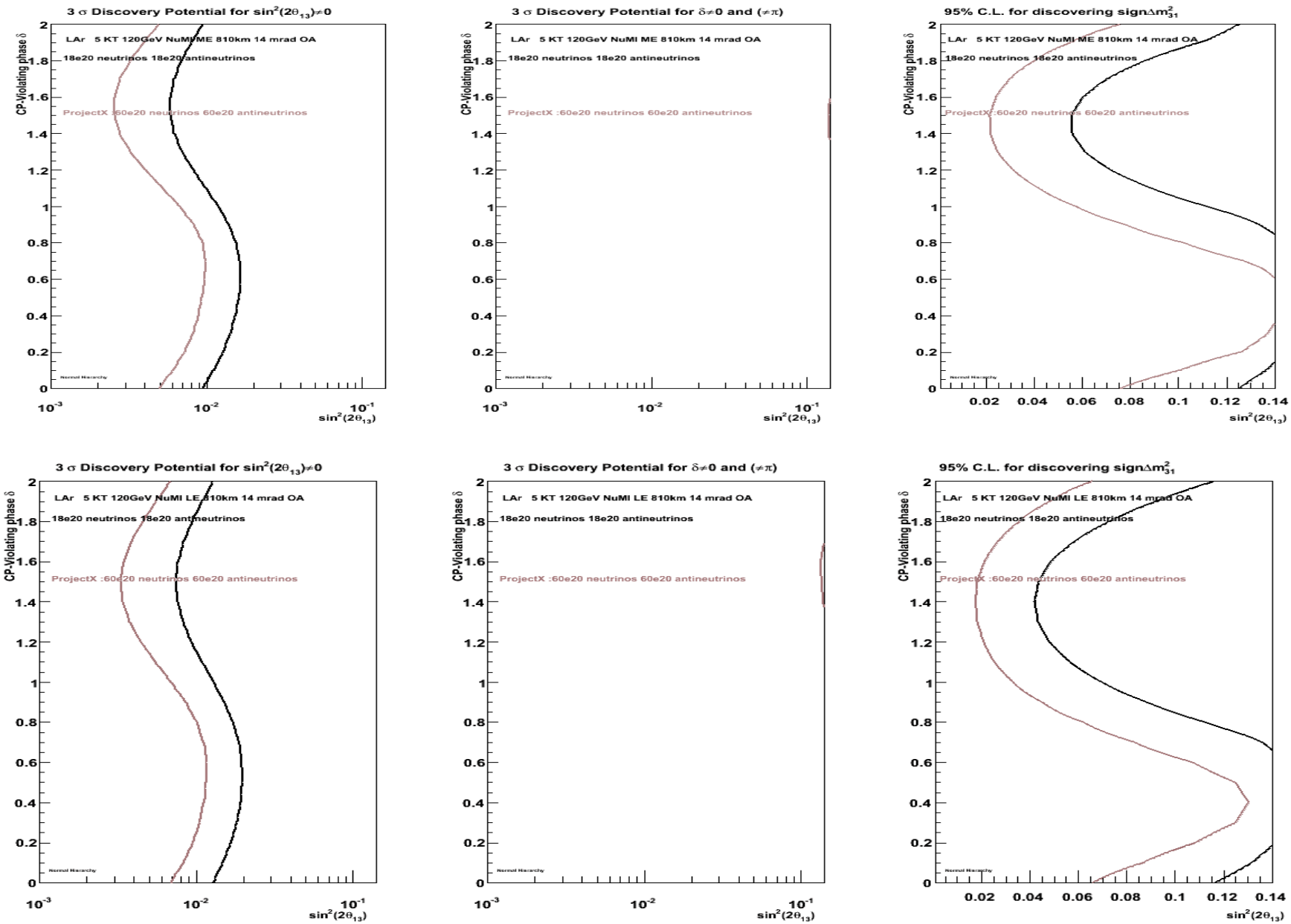
Discovery potential for the ν mass hierarchy : Why LE on axis better than ME on axis



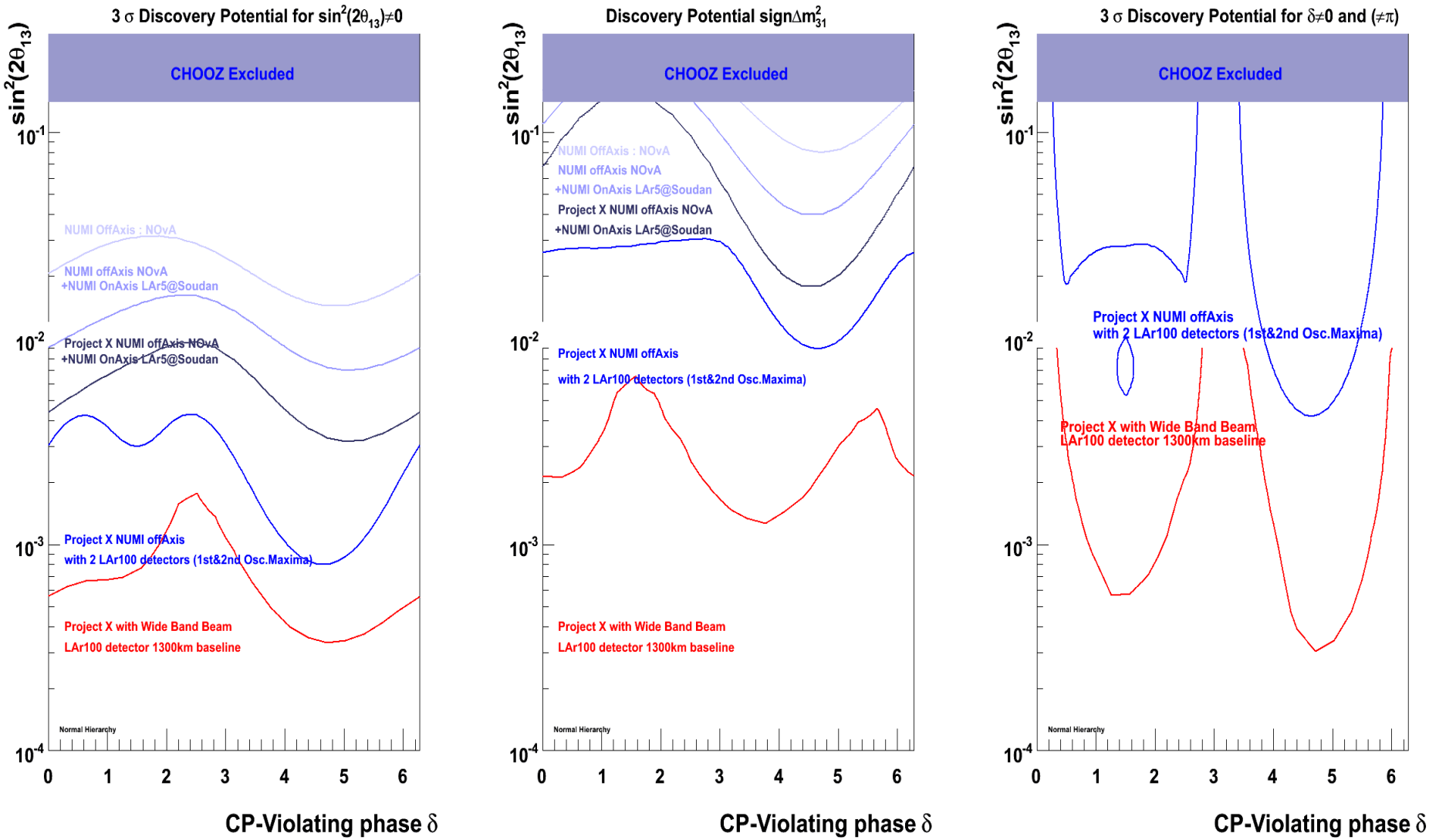
What we measure in ν oscillation experiments are oscillation Probabilities.

The lower the beam energy the better one can experimentally measure with difference between Normal and Inverted hierarchy for both neutrinos and anti-neutrinos

LAr5 @ Ash River (ME - LE)



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