Future (Possible) Off-Axis and On-Axis long baseline ν oscillation experiments

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Outline

- The **"Ultimate"** goal in **neutrino oscillation physics** (at least for the next decade)…
- The **"Ingredients"** needed in order to achieve the **"Ultimate"** goal.
- R&D steps needed to go **from small/medium** to very **large scale LAr detectors** and their **physics capabilities**
- Summary / Conclusions

The "Ultimate" Goal in neutrino 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

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

Majorana phases

✓

Do "man made" νμ's oscillate?

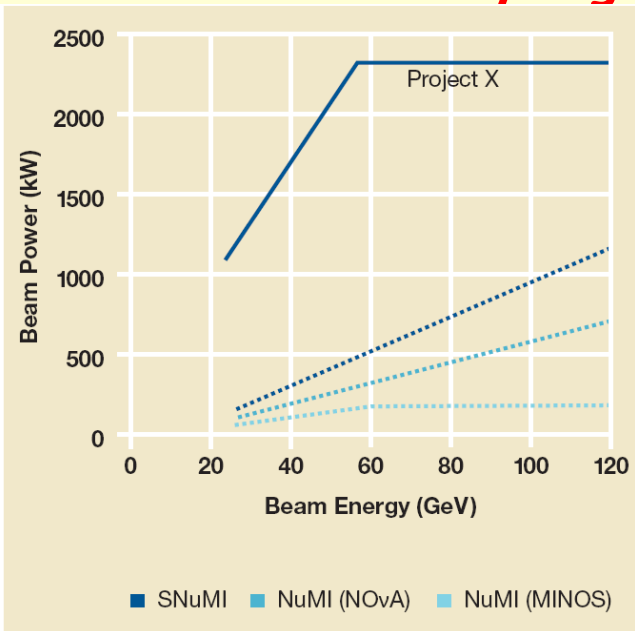
- What is "precisely" the mass squared difference and the mixing angle? (K2K - MINOS)

- Are neutrinos and anti neutrinos the same ?? (Majorana particles) (neutrino-less double beta decays)

The ingredients for achieving the ultimate goal (1)

One needs:
First, Statistics…especially if θ_{13} "small"…

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



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

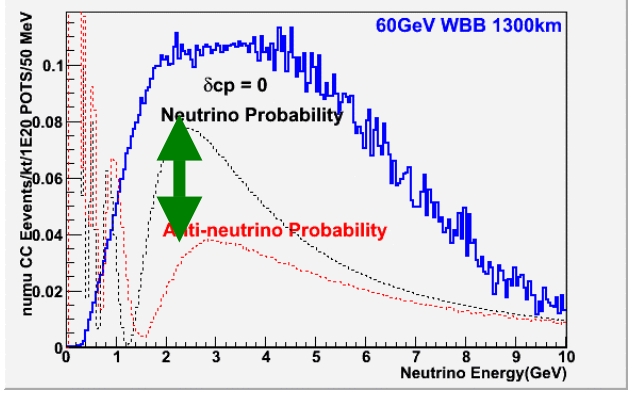
The ingredients for achieving the ultimate goal (2)

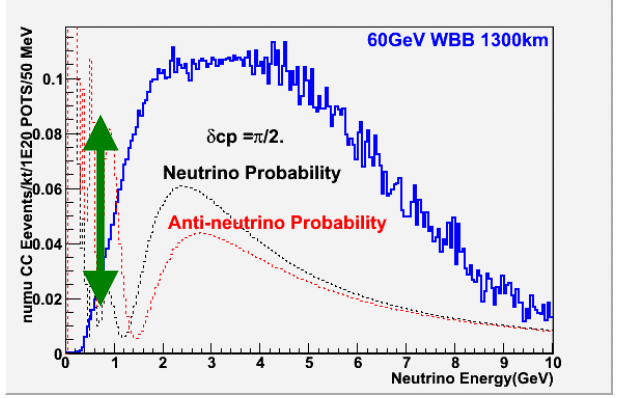
One needs:

Third, 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.

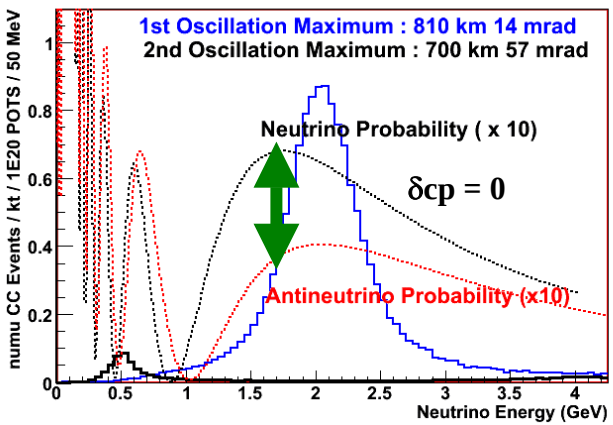
(Other options like beta-beams or neutrino factories are also possible but perhaps will take more time)

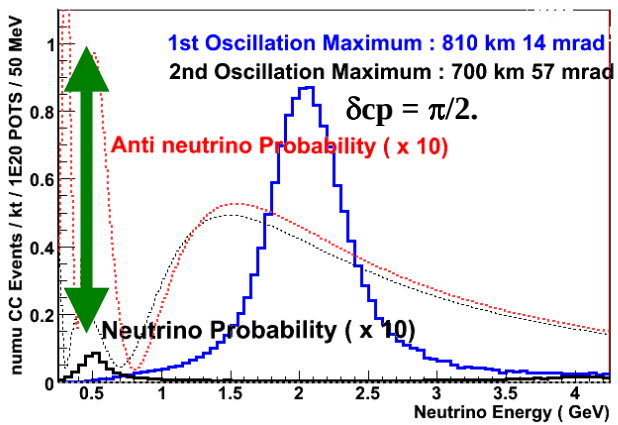
ON AXIS WBB : 1st and 2nd Oscillation Maxima 1 Detector





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

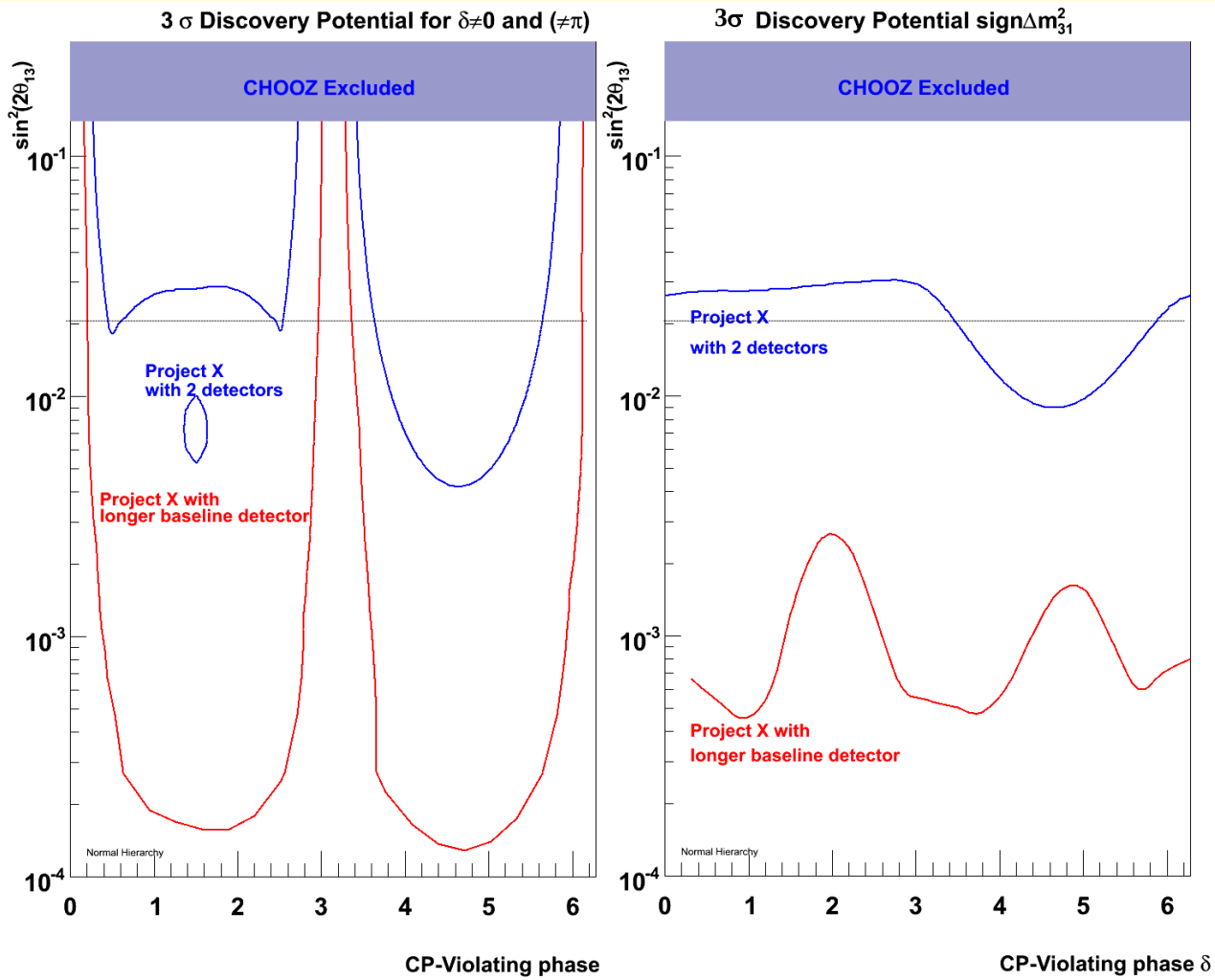




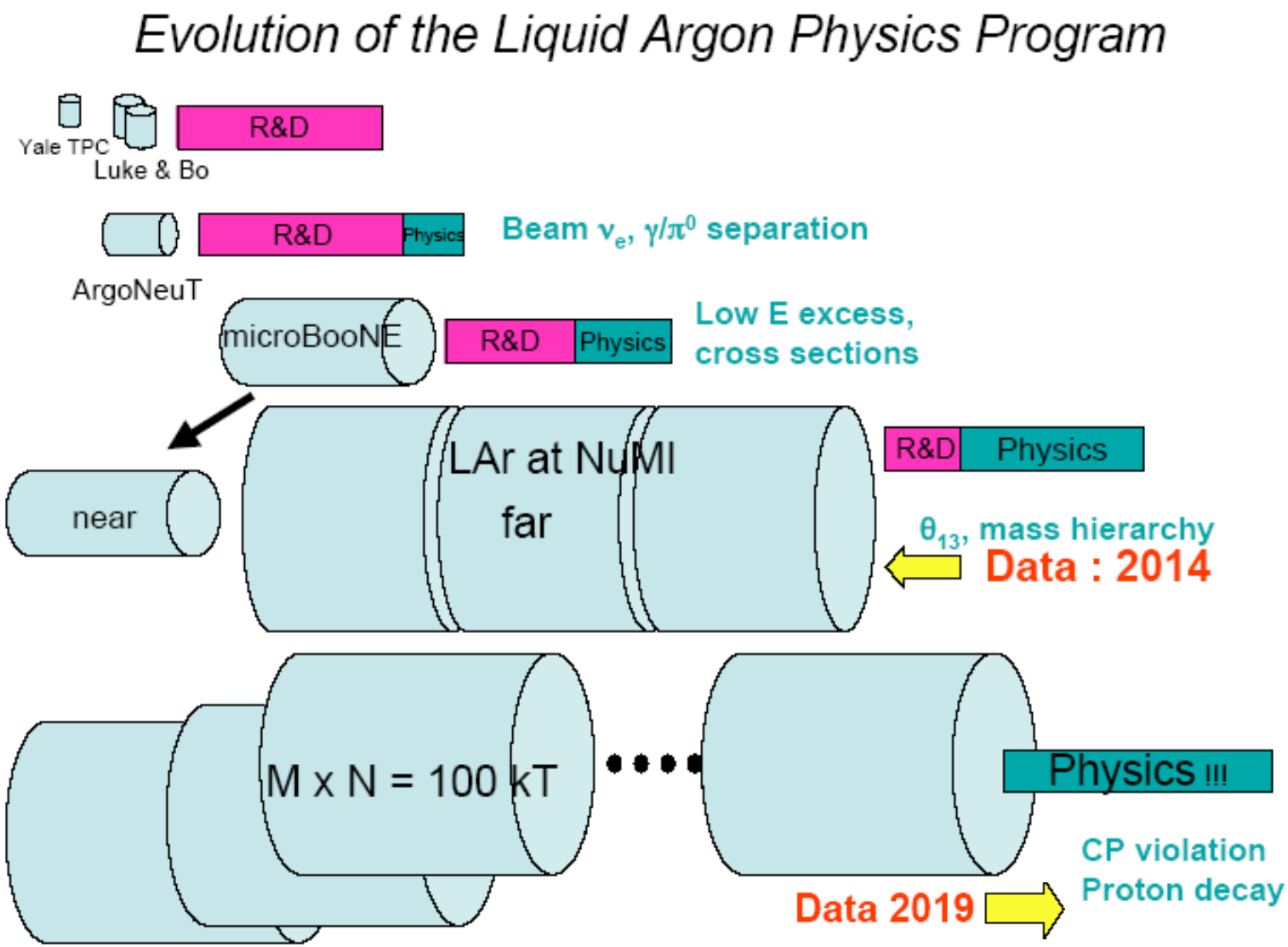
The "ultimate" Goal in neutrino oscillations Physics

Consider the following scenario: (Upgrade detector and upgrade Neutrino Beam)

New Wide Band Beam with ProjectX, longer baseline and more powerful detector technology (100 kt of LAr)



R&D Steps needed in order to build large scale LAr detectors



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.***

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 .

For the NBB no energy binning is used

For the WBB 250 MeV bins are used

ALL RESULTS FROM NOW ON ARE PRELIMINARY!!!

Cases studied

a) 5 kt LAr* with *NuMI Low Energy (LE) Narrow Band (off axis)

15×10^{20} pots in ν mode + 15×10^{20} pots in in ν-bar mode

b) 5 kt Lar NuMI Medium Energy (ME) Narrow Band Beam (off axis)

15×10^{20} pots in ν mode + 15×10^{20} pots in in ν-bar mode

c) 5 kt LAR NuMI Low Energy (LE) On Axis Beam @ Soudan Mine (where MINOS is currently)

15×10^{20} pots in ν mode + 15×10^{20} pots in in ν-bar mode

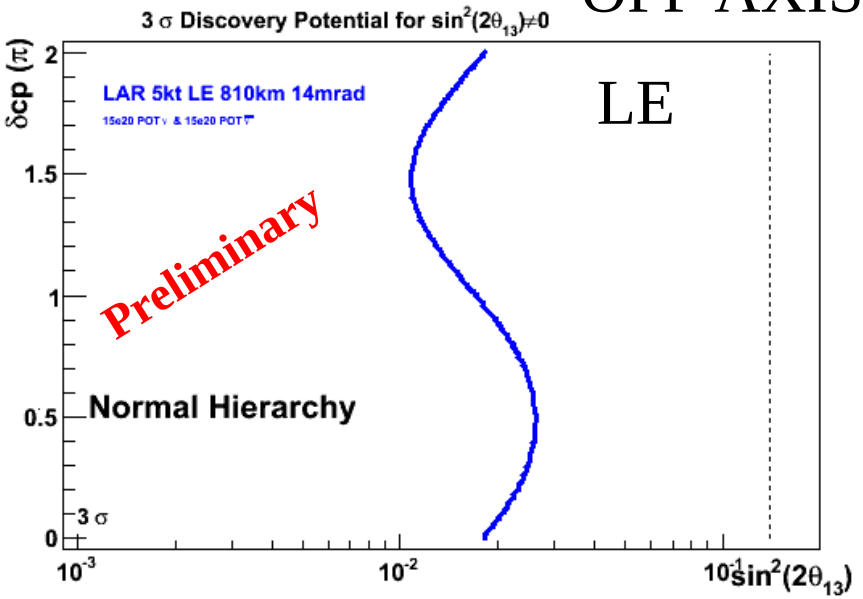
d) 5 kt LAR NuMI Medium Energy (ME) On Axis Beam @ Soudan Mine (where MINOS is currently)

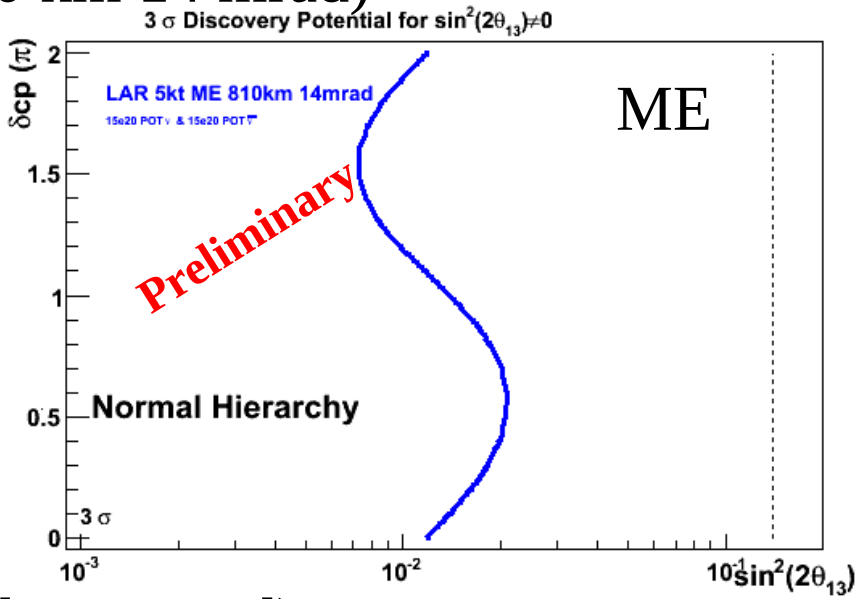
15×10^{20} pots in ν mode + 15×10^{20} pots in in ν-bar mode

With LAr detector technology one can examine on axis options since NC background could be significantly reduced (or eliminated) by detector identification capabilities.

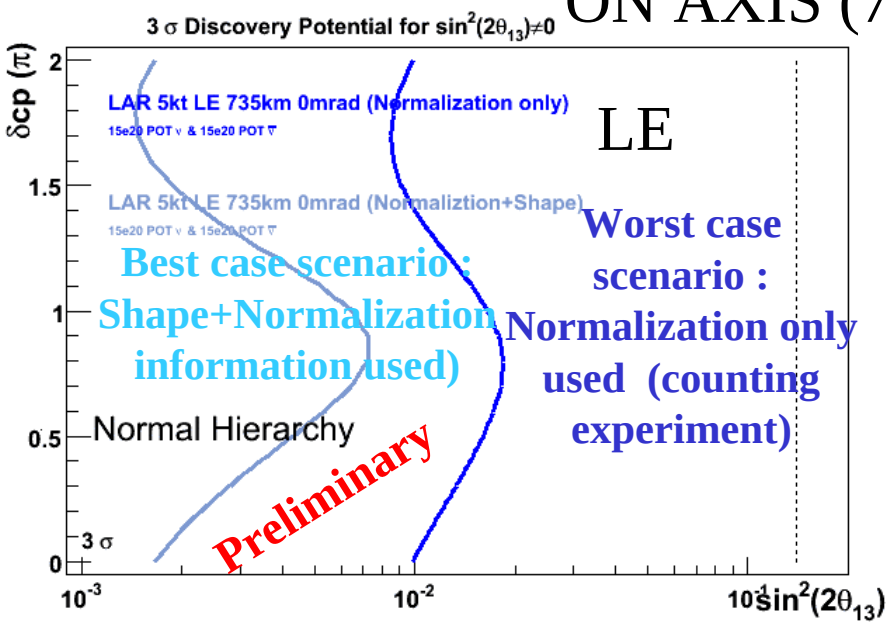
Discovery potential for θ_{13} for all 4 options

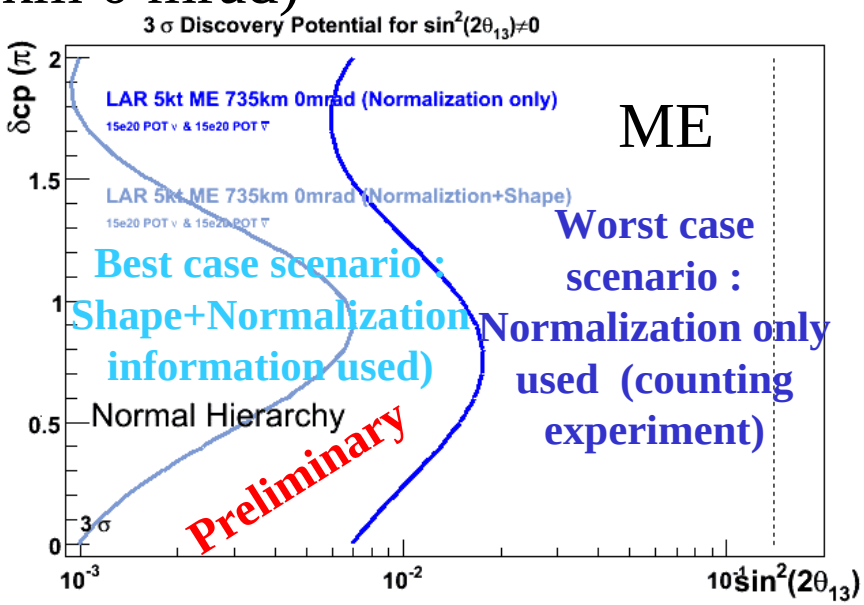
OFF AXIS (810 km 14 mrad)



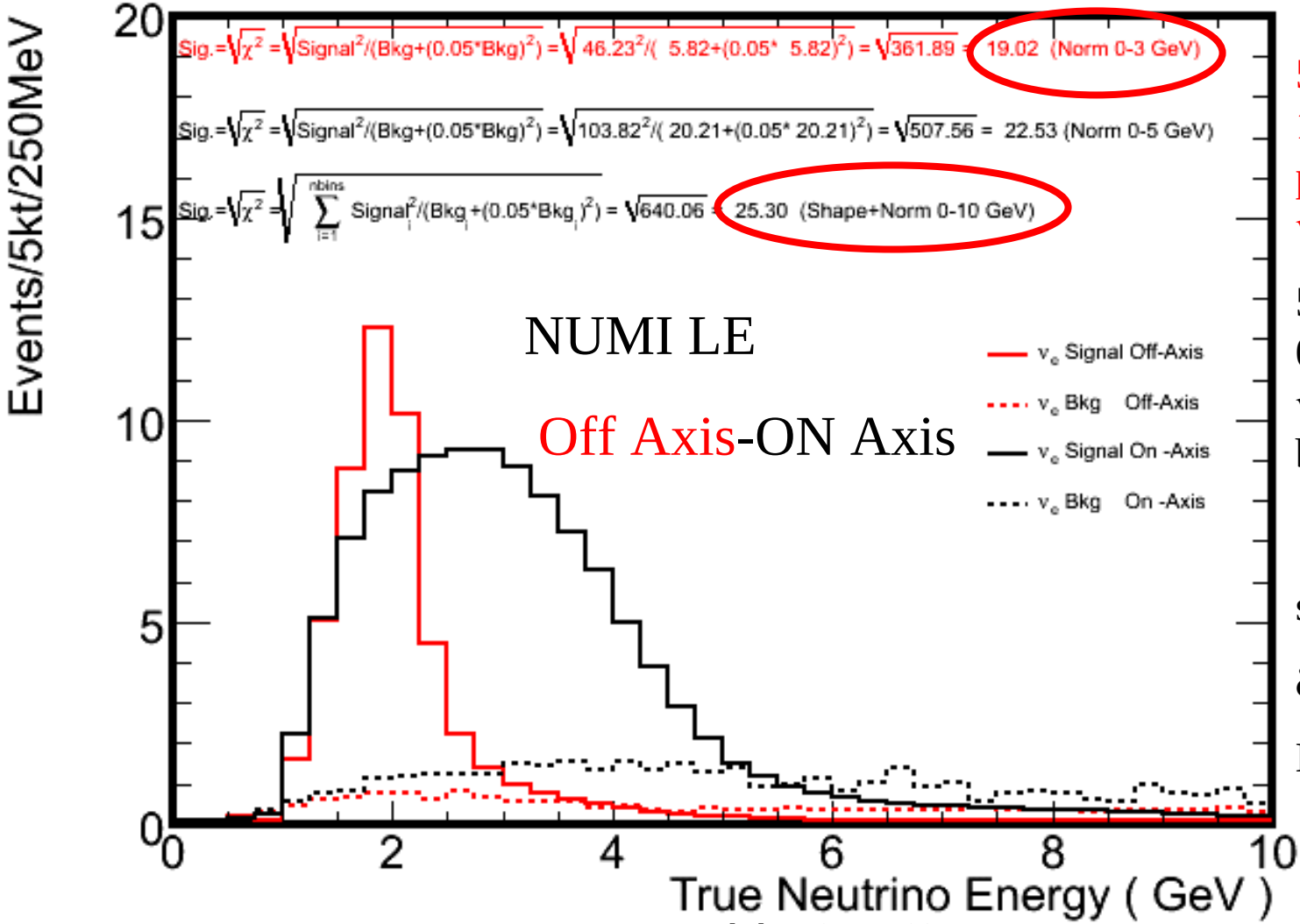


ON AXIS (735 km 0 mrad)





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

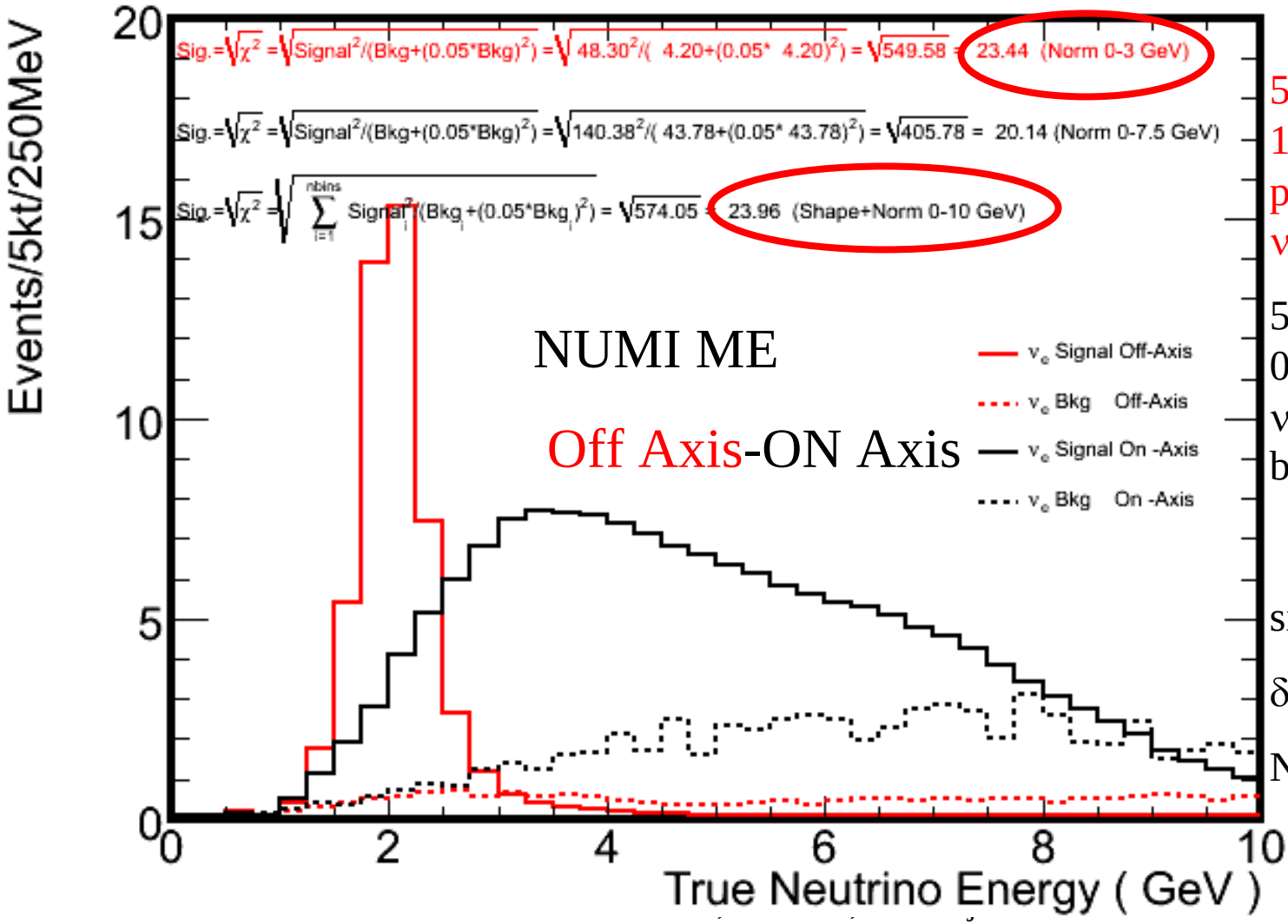
5kt LAr at 735 km 0 mrad :15e20 pots ν +15e20 pots ν-bar

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

$\delta_{cp}=0$

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

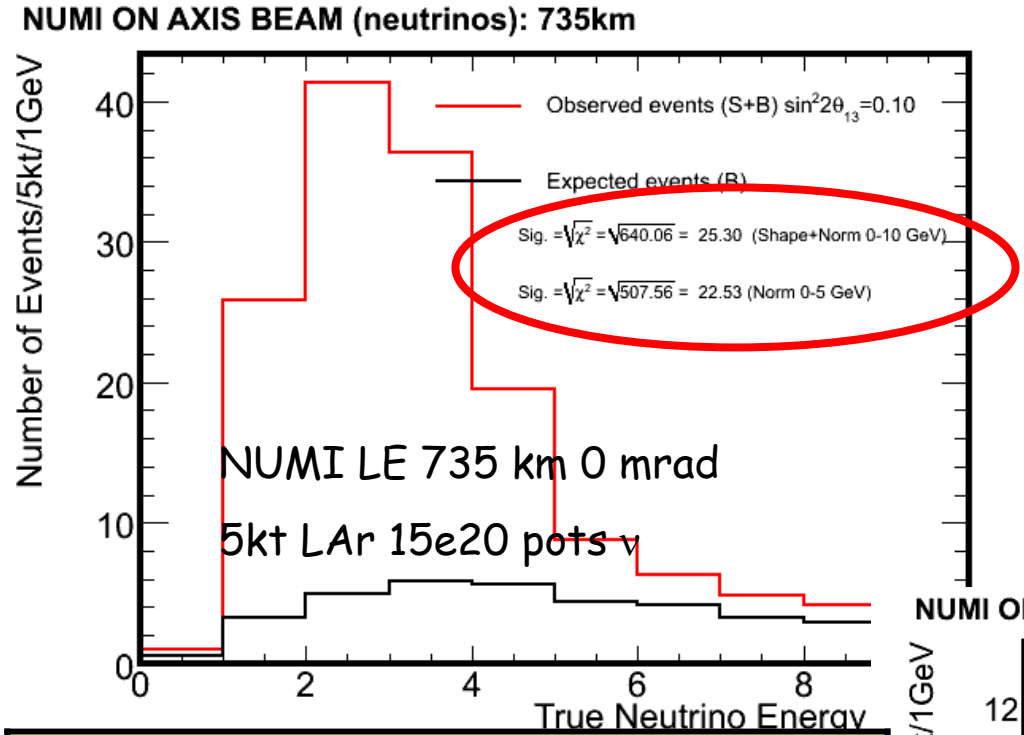
5kt LAr at 735 km 0 mrad :15e20 pots ν +15e20 pots ν-bar

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

$\delta_{cp}=0$

Normal hierarchy

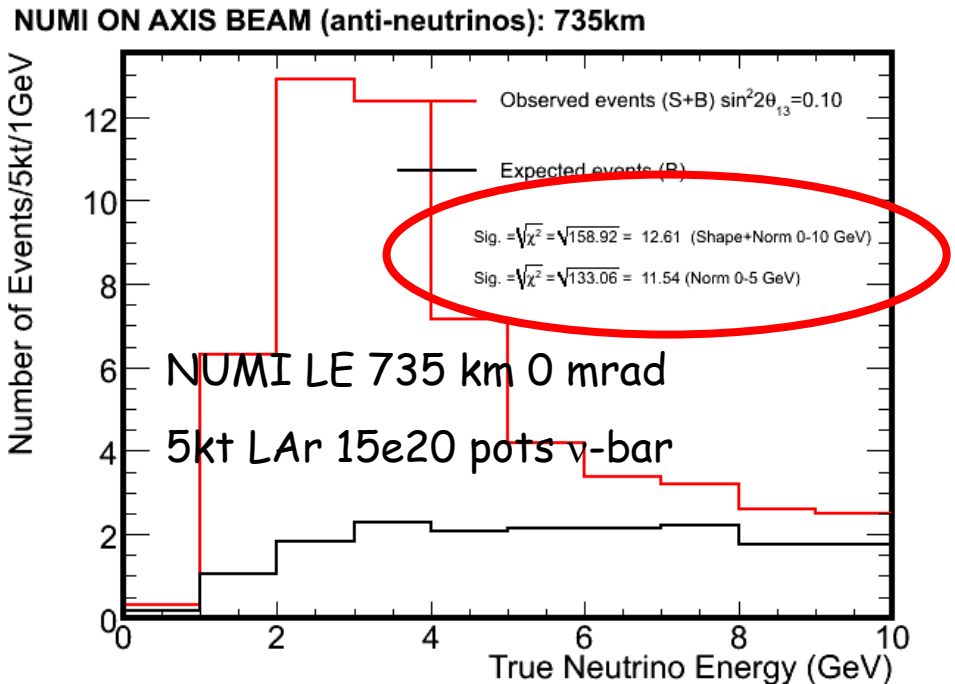
Example for $\sin^2 2\theta_{13}$= 0.10 (Chooz limit) using Normalization alone or Shape+Normalization



Using normalization only integrates information over all energy bins into 1 bin :

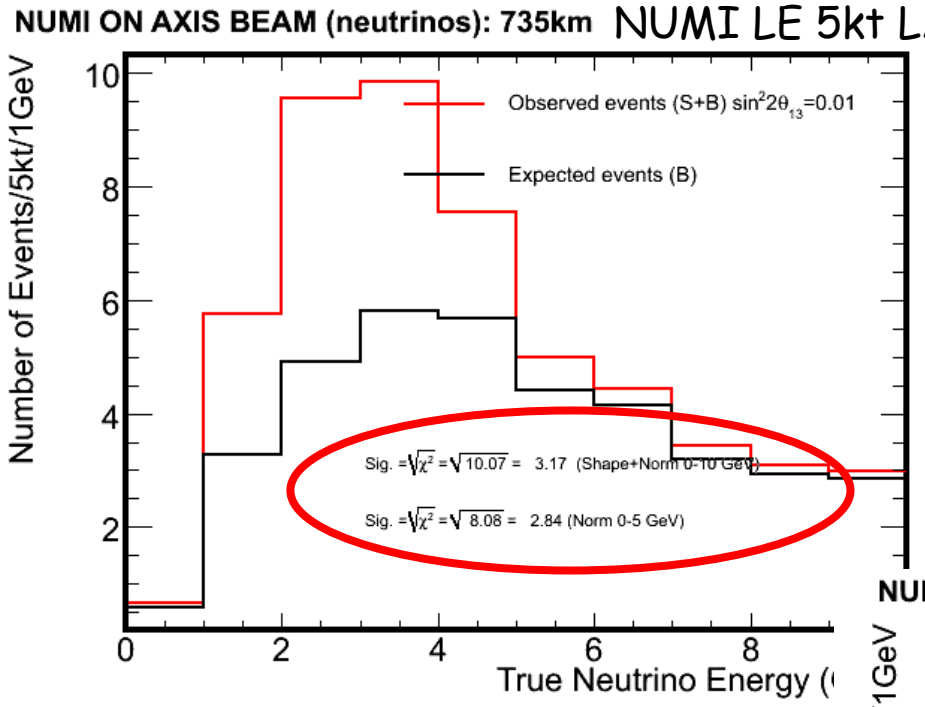
Lose of Spectral information (significance per energy bin)

Neutrinos (0-5 GeV for event #)			
Signal	Bkg	Sig. (Norm)	Sig. (Norm+Shape)
103	20	22	25
Anti neutrinos (0-5 GeV for event #)			
32	7	12	13
Overall Significance (ν+ν-bar)			
135	27	25	28



Example for $\sin^2 2\theta_{13}$= 0.01 (Chooz limit) using Normalization alone or Shape+Normalization

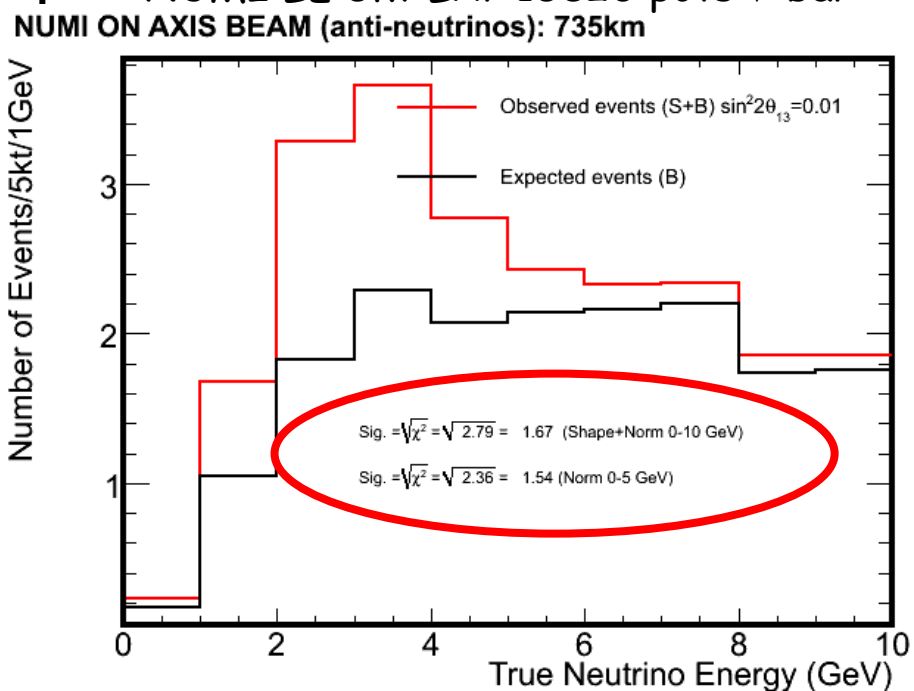
NUMI LE 5kt LAr 15e20 pots ν



Using normalization only integrates information over all energy bins into 1 bin :

Lose of Spectral information (significance per energy bin)

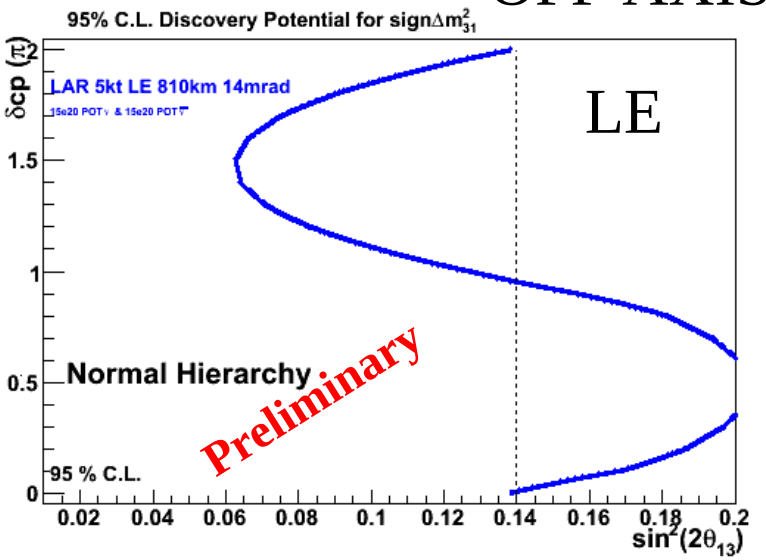
NUMI LE 5kt LAr 15e20 pots ν-bar

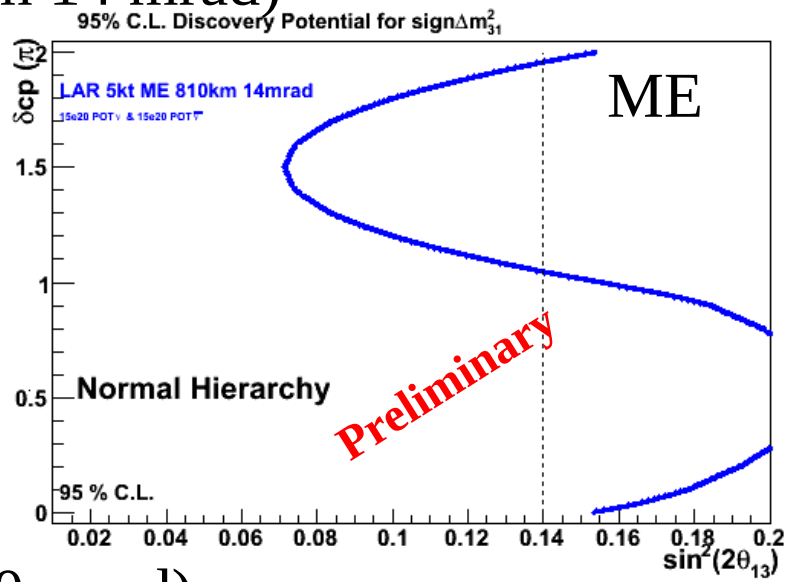


Neutrinos(0-5 GeV for event #)			
Signal	Bkg	Sig. (Norm)	Sig. (Norm+Shape)
13	20	2.8	3.1
Anti neutrinos(0-5 GeV for event #)			
4	7	1.5	1.7
Overall Significance (ν+ν-bar)			
17	27	3.2	3.6

Discovery potential for the ν mass hierarchy for all 4 options

OFF AXIS (810 km 14 mrad)





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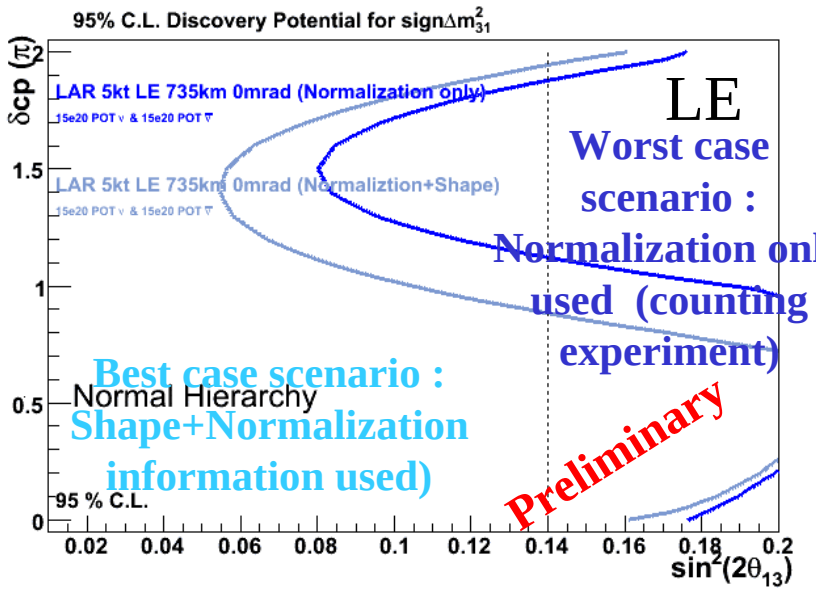

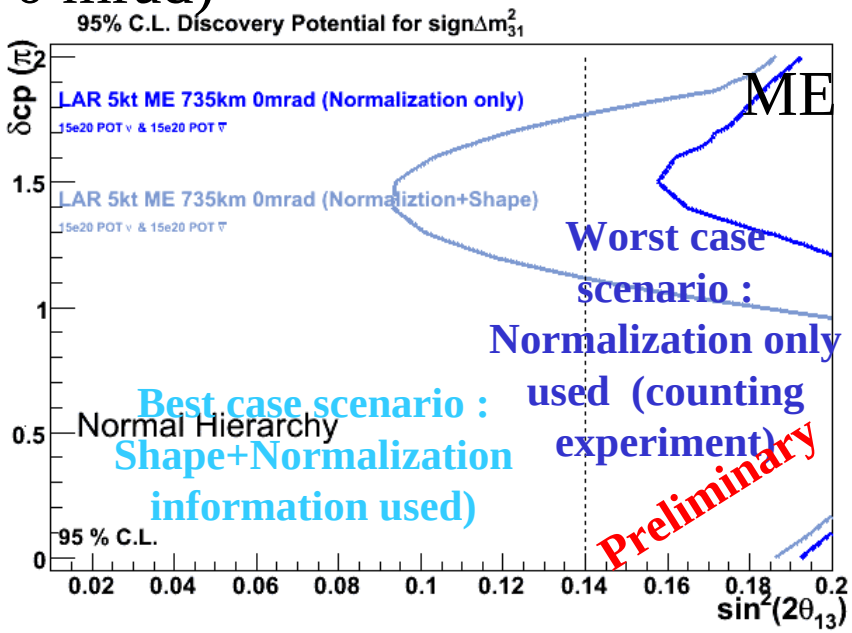

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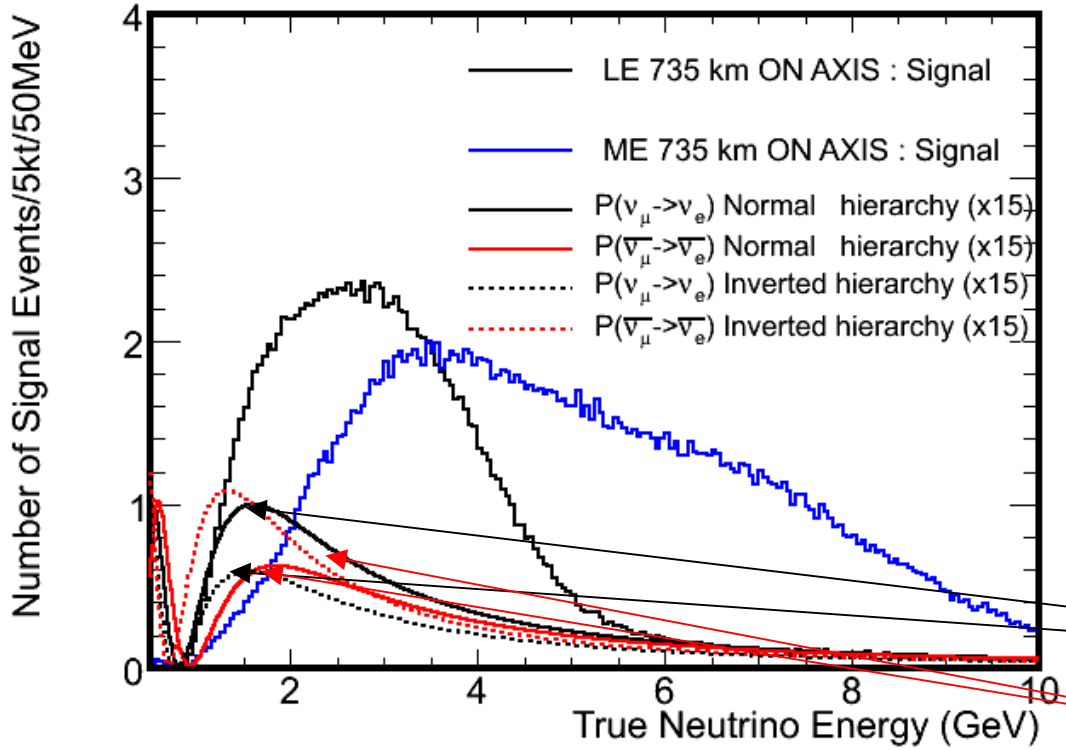
Discovery potential for the ν mass hierarchy : Why LE on axis better than ME on axis

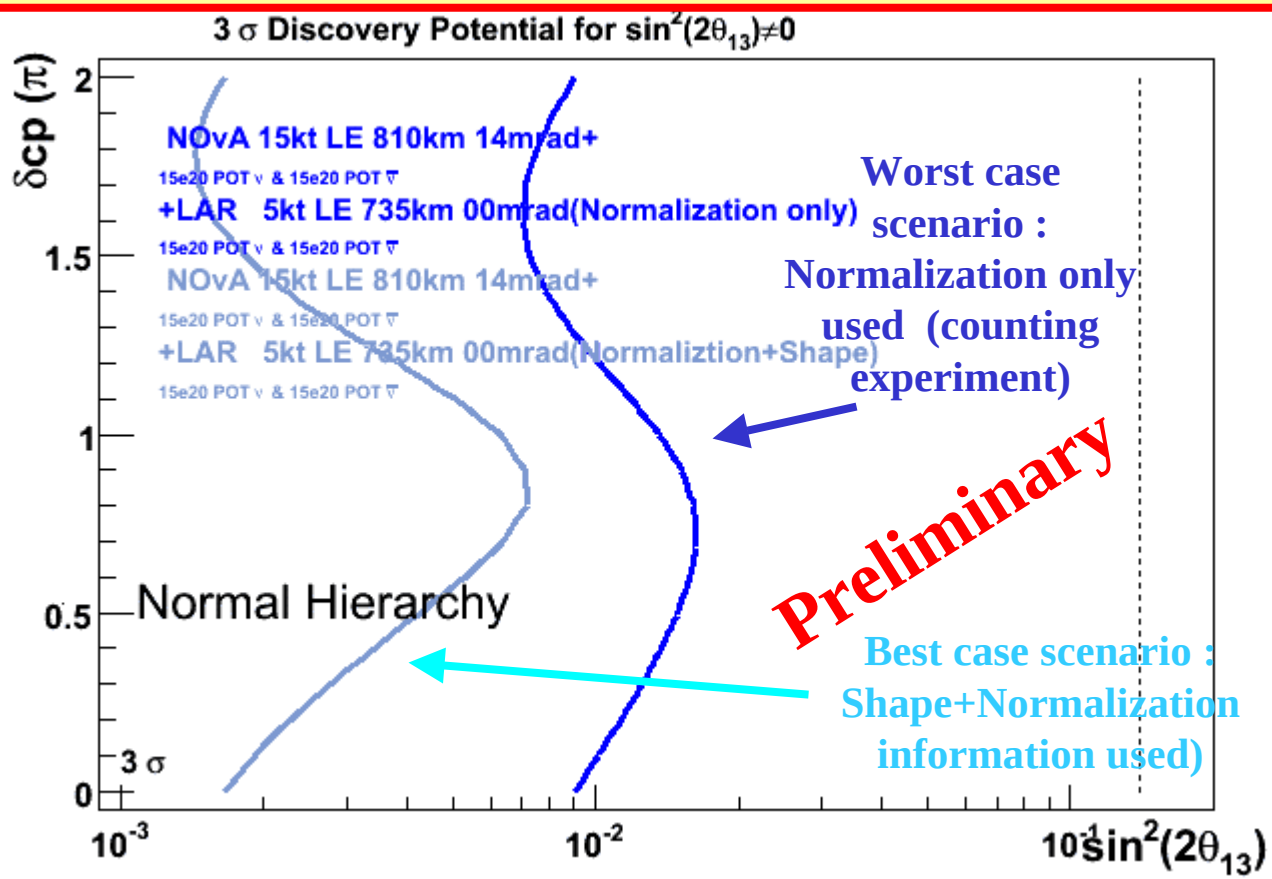


What we measure in ν oscillation experiments are oscillation Probabilities.

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

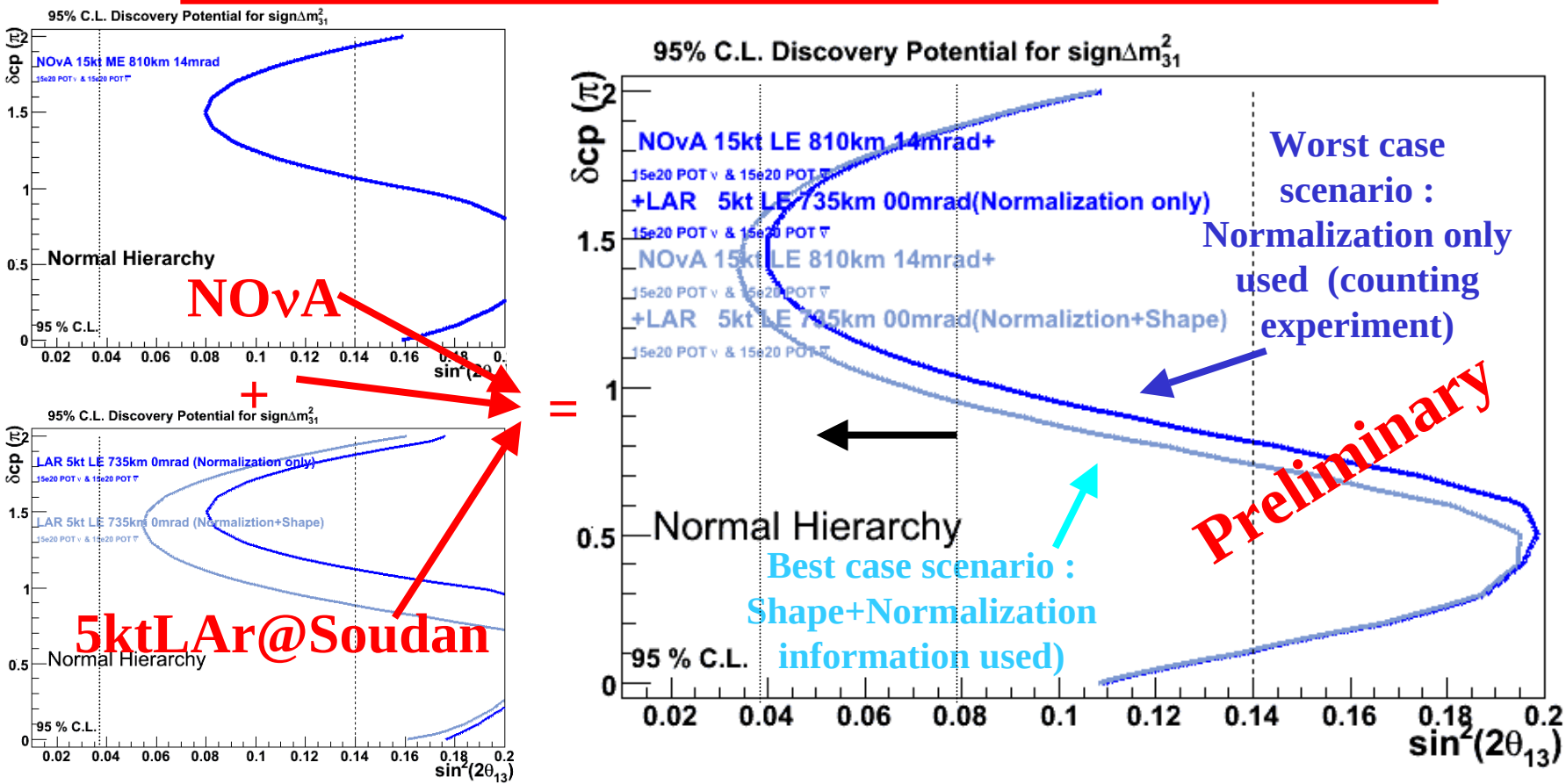
Best Case is 5kt LAr with NUMI LE Wide Band On Axis Beam : What does it add to Phase I physics wise?? (1)

If no-one has measure the third mixing angle, this configuration can extend the physics reach considerable and well below $\sin^2(2\theta_{13})$ of 0.01



Best Case is 5kt LAr with NUMI LE Wide Band On Axis Beam : What does it add to Phase I physics wise?? (2)

If the angle is known from Double CHOOZ (and hence big) the discovery potential for the n mass hierarchy is increased considerably!



Best Case is LE On Axis Beam : What does it add to Phase I R&D – wise ??

(A) Exercise and prove the LAr technology in the kt – Scale, which is essential step in order to be able to think about ~ 100 kt Scales

(B) Exercise and prove kt - Scale LAr detector operation underground which :

1) Might be essential for the smooth operation of such detectors and

2) If successful , can create useful synergies between ν-physics and other important physics like proton decay

(C) Exercise reconstruction, signal selection, background rejection etc. and all of that :

While doing interesting ν-oscillation physics and significantly contributing to PHASE I.

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**

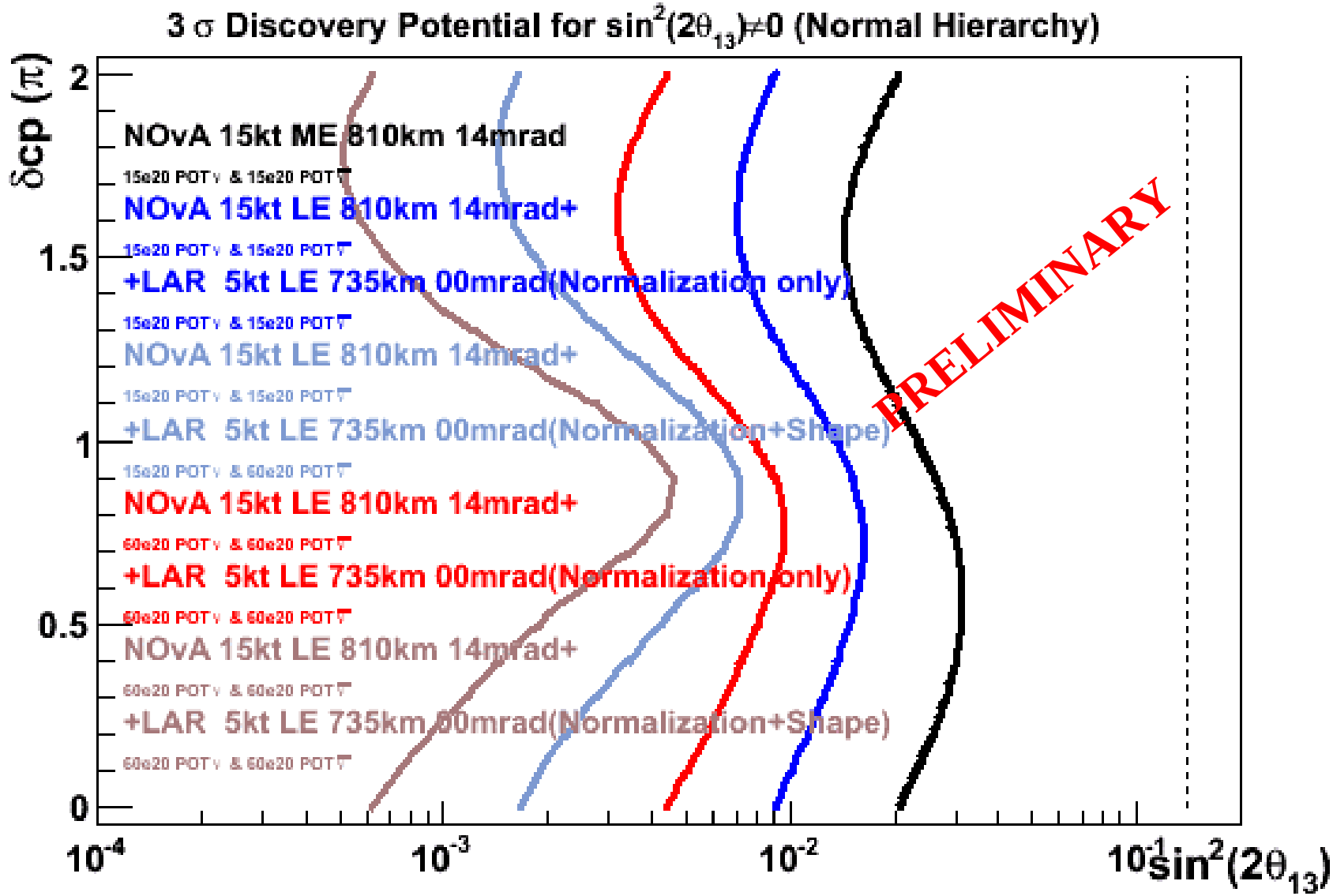
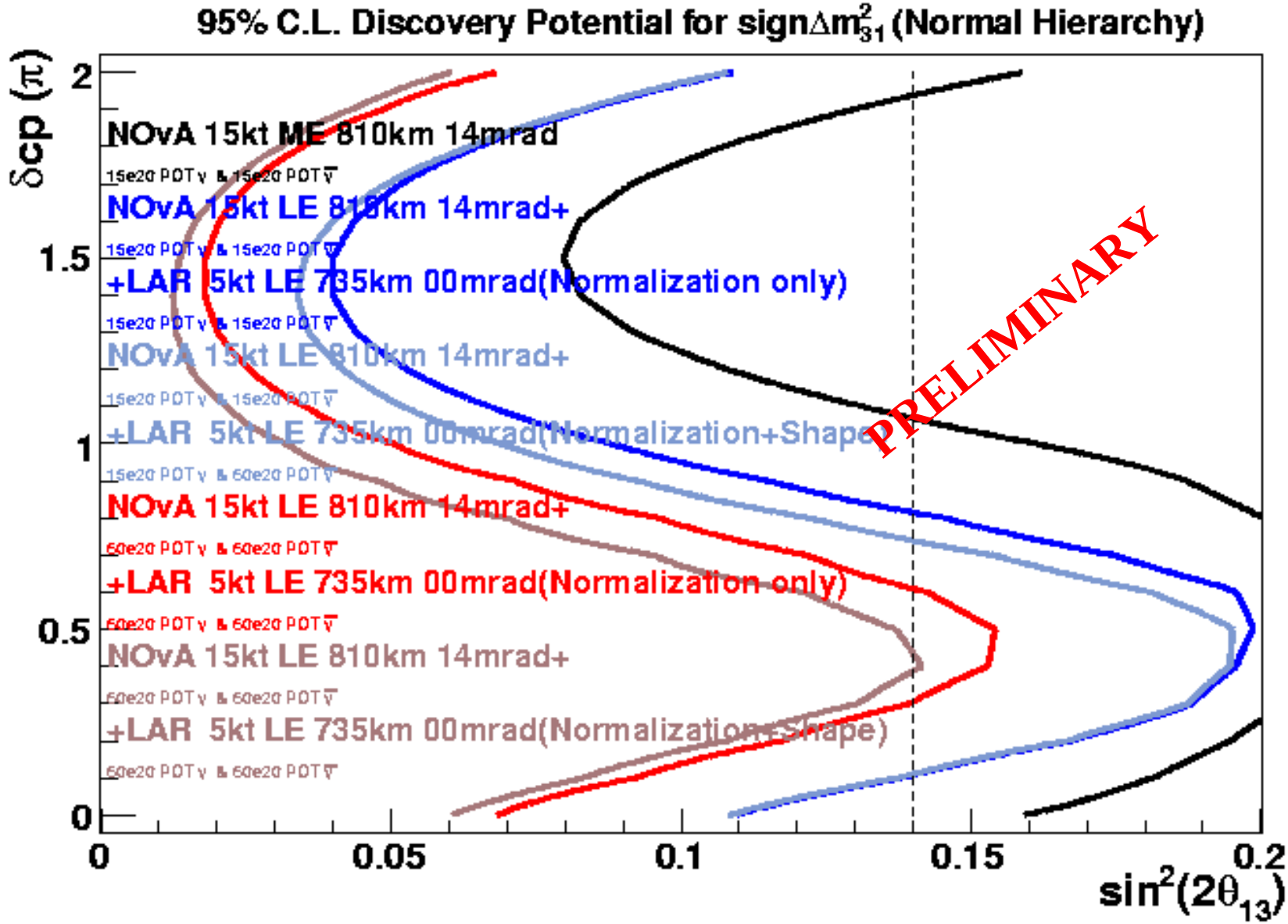
  - B) Massive (at the XXX kt scale) and powerful (in signal selection and background rejection) detectors : LAr or Water Cherenkov

- **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 using the NUMI On Axis Beam at the Soudan mine 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

Sensitivities with PX



Sensitivities with PX