US Future Long Baseline Neutrino Experiment Study

Joint FNAL – BNL Study

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Outline

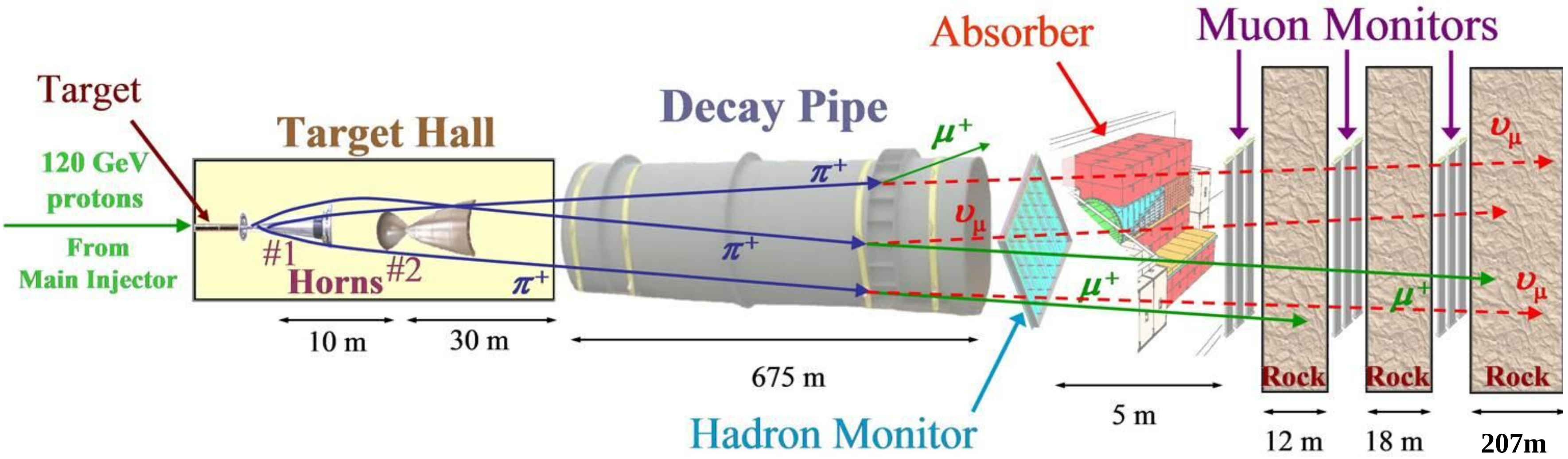
- Discussion of Advantages & Capabilities of the NUMI Neutrino Beam

- Phase II : Develop a Plan based on Phase I Results (NOvA, T2K, Double-Chooz & Daya Bay will inform us of $\sin^2 2\theta_{13}$ down to ~0.02 by ~ 2012-2014)

  - $\sin^2 2\theta_{13}$ very close to the Chooz limit (> ~0.05)
  - $0.02 < \sin^2 2\theta_{13} < \sim 0.05$
  - $\sin^2 2\theta_{13} < \sim 0.02$

- Summary / Conclusions

NuMI Neutrino Beam Capabilities & Advantages



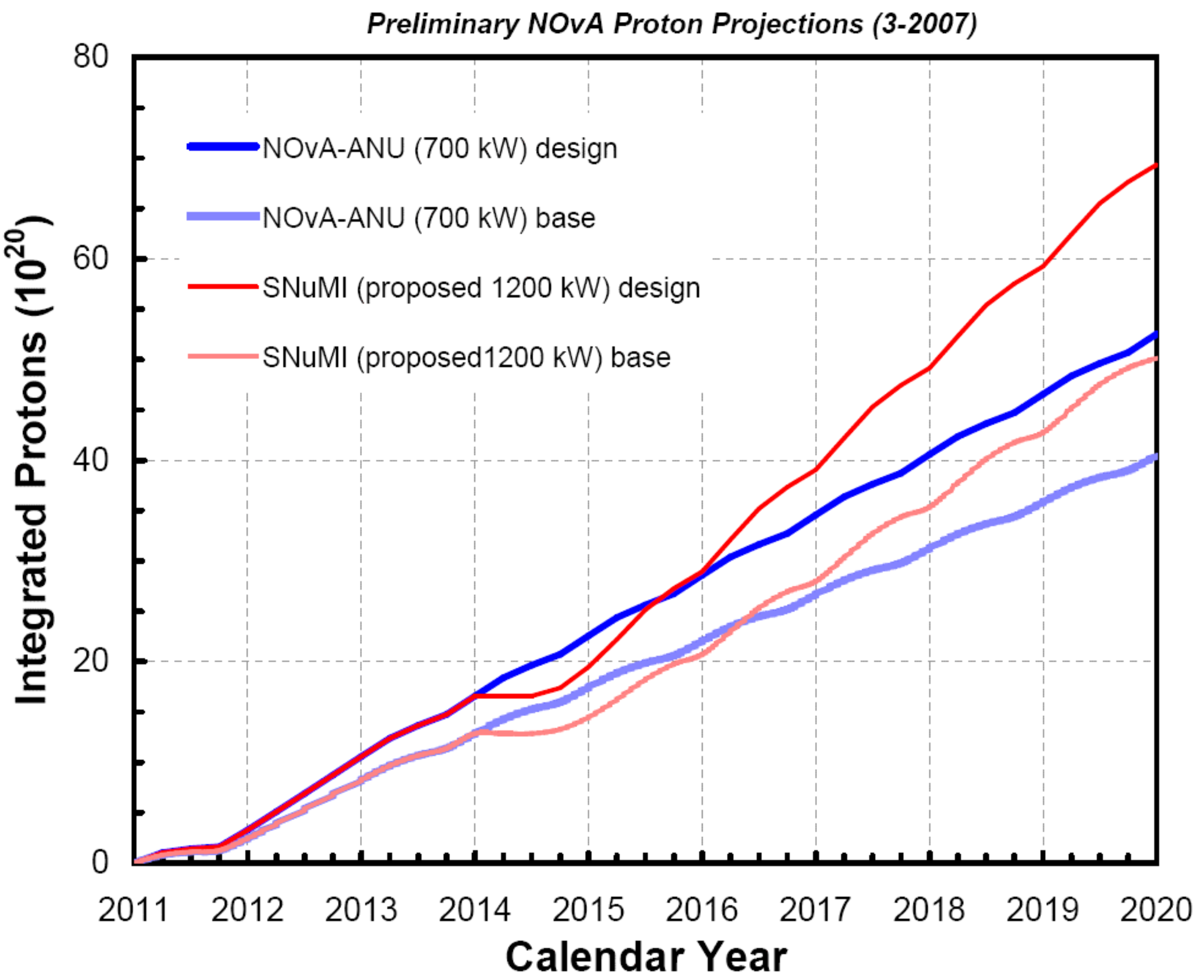
CURRENT STATUS OF NUMI BEAM RUNNING

- 120 GeV protons strike the graphite target
- Current intensity 2.5 x 10^{13} ppp every 2.2 sec

Recently we reached 4.05 x 10^{13} ppp every 2.2 sec

- Goal for 2007 is to run stably at ~ 2.5 x 10^{13} ppp every 2 sec.
- (2008-9) expected rate ~ 3.4 x 10^{20} protons/year

NuMI Neutrino Beam: Capabilities & Advantages



- **There exists a well defined upgrade plan for the NUMI Beam**

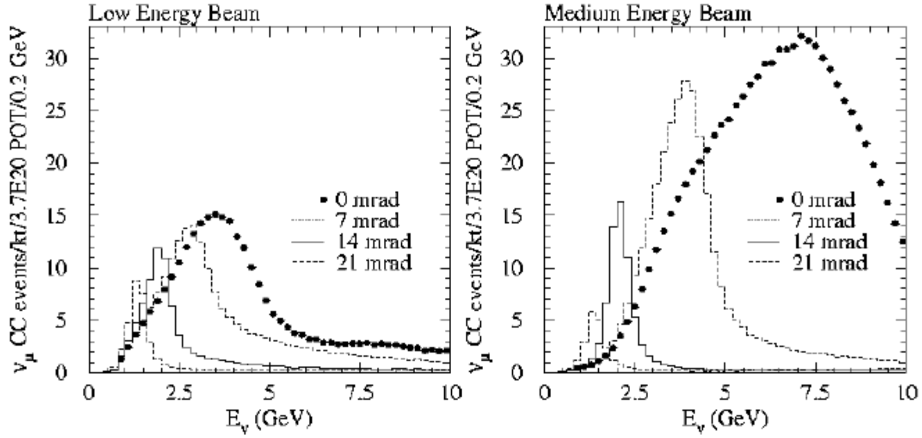
NuMI Neutrino Beam: Capabilities & Advantages

By using a conventional, albeit more intense, neutrino beam:

$$\pi^+ \rightarrow \mu^+ \nu_\mu \quad < 1\% \nu_e$$

In an Off-Axis detector location

$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2 \theta^2}$$



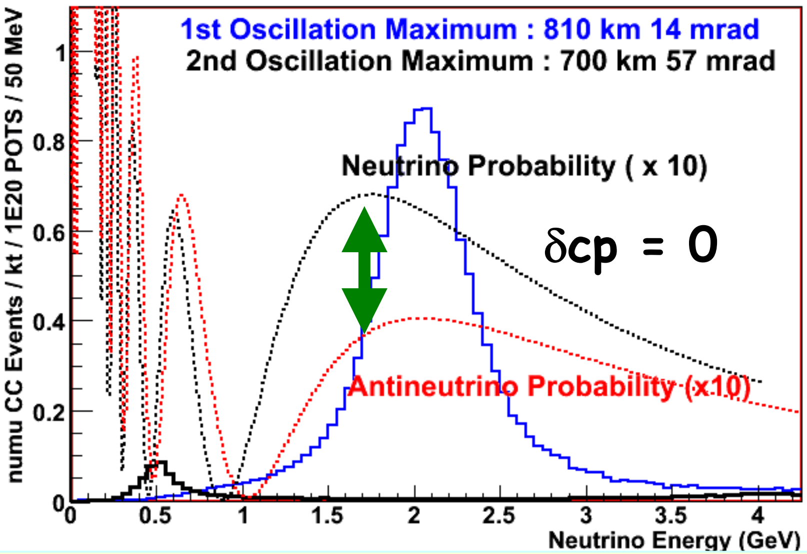
Advantages

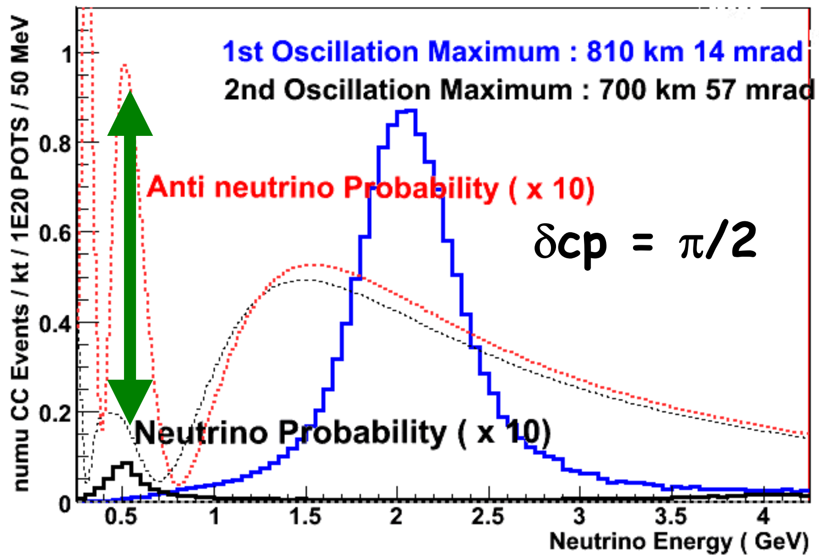
- The Beam Exists and performs well (NUMI Beam took 6 years to be built and cost ~ 110M$)

- 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.

NuMI Neutrino Beam : 1st & 2nd Oscillation Maxima





• Off Axis Beam is a Narrow Band Beam but if we choose to place 2 detector @ different off axis angles we get an off - axis "Pseudo - Wide Band Beam"

Advantage

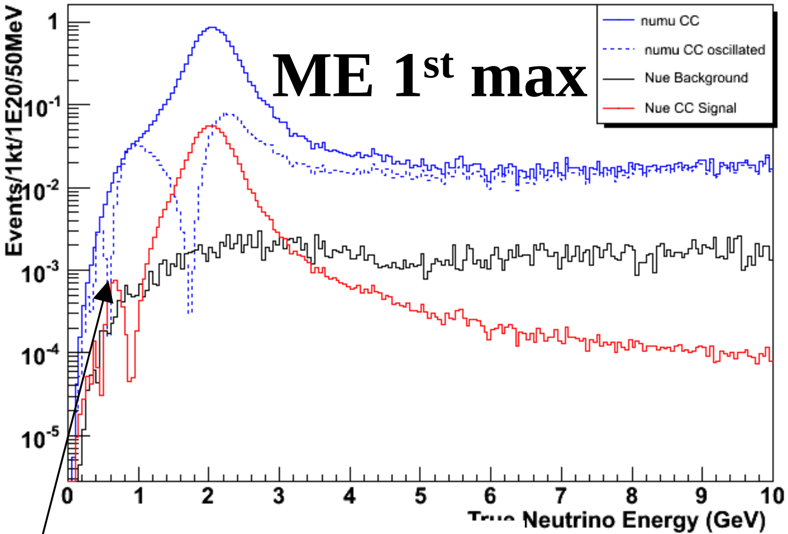
- Matter effects important @ 1st Oscillation Maximum but not @ 2nd Oscillation Maximum = > Combination of measurement helps in better determination of mass hierarchy and δcp.

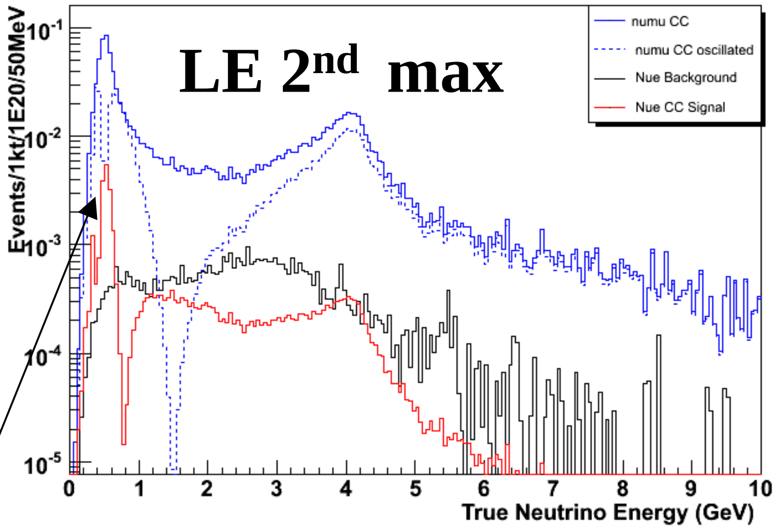
Disadvantage

- Neutrino Flux @ 2nd Oscillation Maximum is low.

Optimization studies were performed placing Detectors @ both Locations.

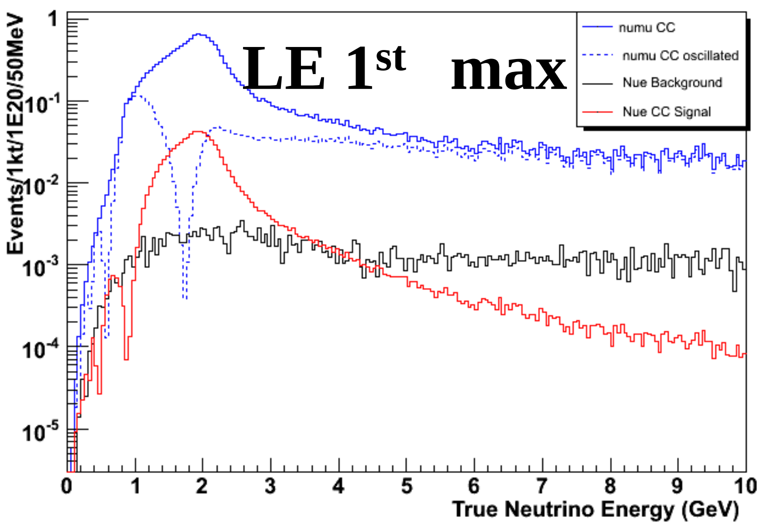
NuMI Neutrino Beam : 1st & 2nd Oscillation Maxima





- Best location for 1st Oscillation Maximum (off axis beam) is 810 km 14 mrad & best beam energy is ME (medium energy)
(rate for 2nd oscillation maximum is low)

- Best location for 2nd Oscillation Maximum (off axis beam) is 700 km 57 mrad & best beam energy is LE (low energy) (rate for 2nd oscillation maximum increases by a factor of 10)



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".

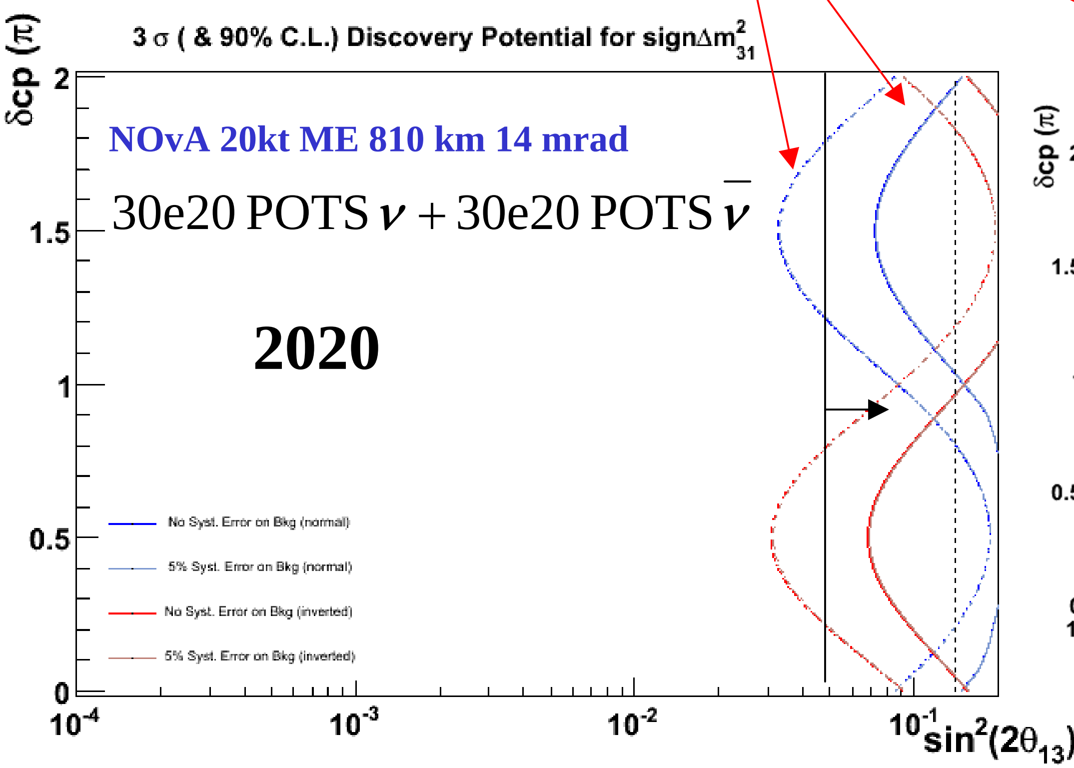
***** We assume 5% systematic error on the background***

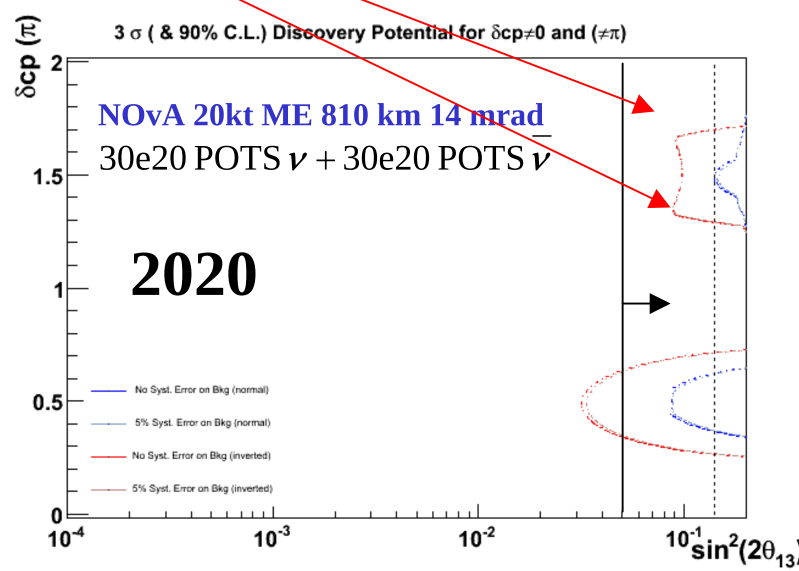
****** We do not let the rest of the oscillation parameters float.***

Phase II : Phase I says $\sin^2 2\theta_{13}$ > 0.05

- We want to measure the rest: Mass Hierarchy and δcp
- In this scenario NOvA and T2K can do the physics

(Combining the measurements will give even better results)





Phase II:Phase I says $0.02 < \sin^2 2\theta_{13} < 0.05$

- We want to measure the rest: Mass Hierarchy and δcp

- In this scenario we have to consider a more powerful detector technology that:

1) Has very high efficiency and very high background rejection capabilities for low energy neutrinos (0.5-3 GeV)

2) Can operate on (or close to) the surface (for the distances of interest the NUMI off axis beam is close to the surface too)

- An obvious solution that satisfies the above requirements is a Liquid Argon Detector.

-This is a challenging technology and therefore progress has to be made (R&D) while Phase I (~ 2014) is ongoing.

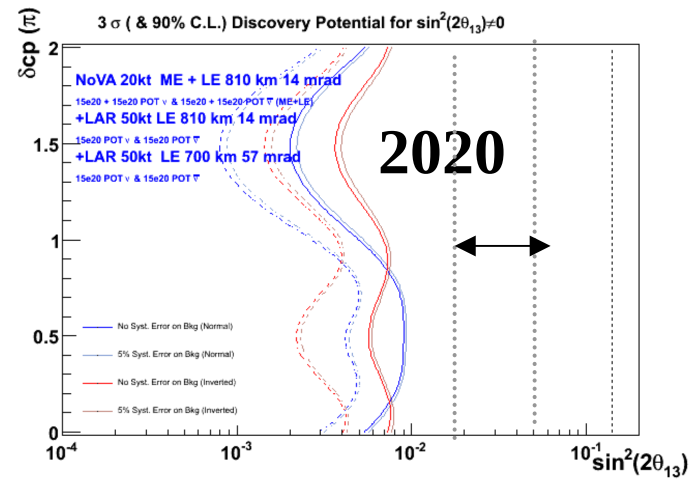
Phase II:Phase I says 0.02 < $\sin^2 2\theta_{13}$ < 0.05

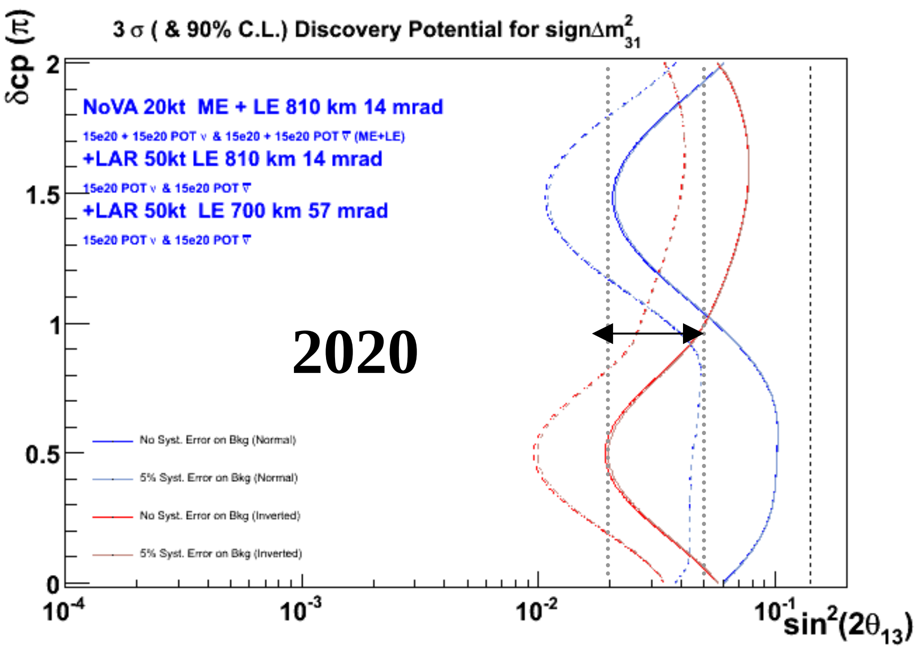
Consider the following scenario :

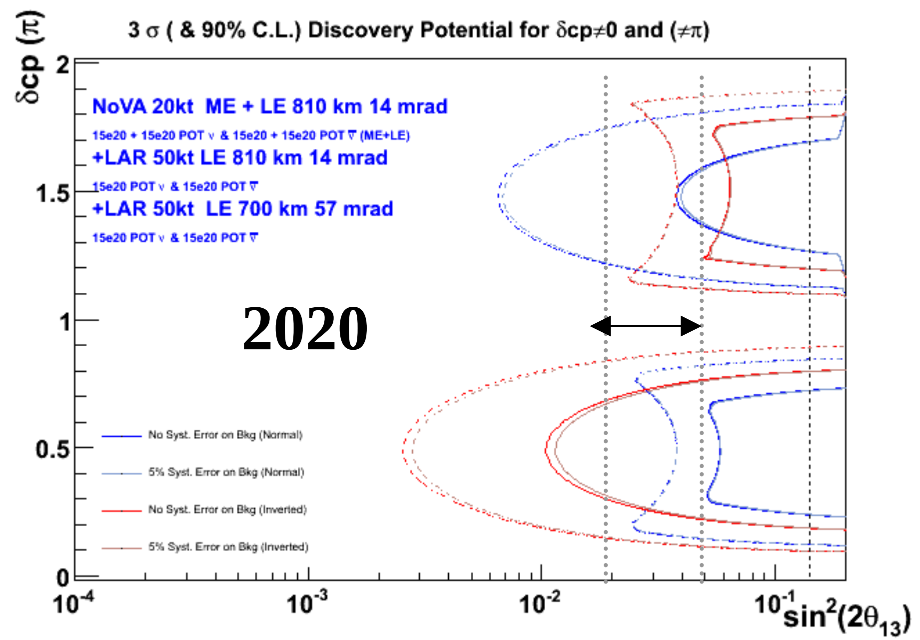
<u>Switch to Low Energy Running</u>

1) Place 50 kT of LAR at the 1st oscillation Maximum (810 km 14 mrad, matter effects important)

2) Place 50 kT of LAR at the 2nd oscillation Maximum (700 km 57 mrad, matter effects not important)



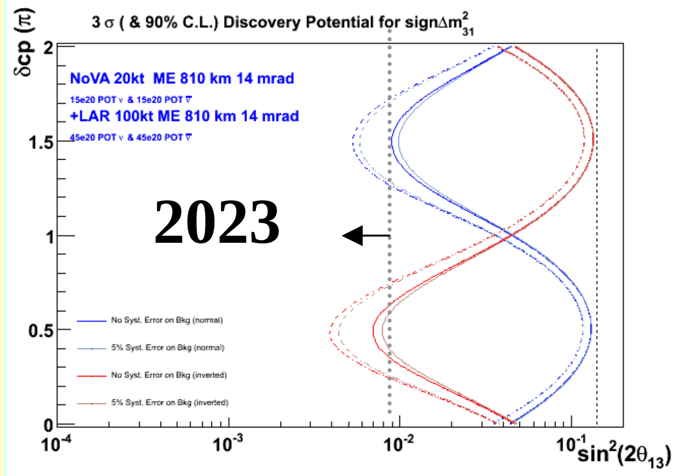


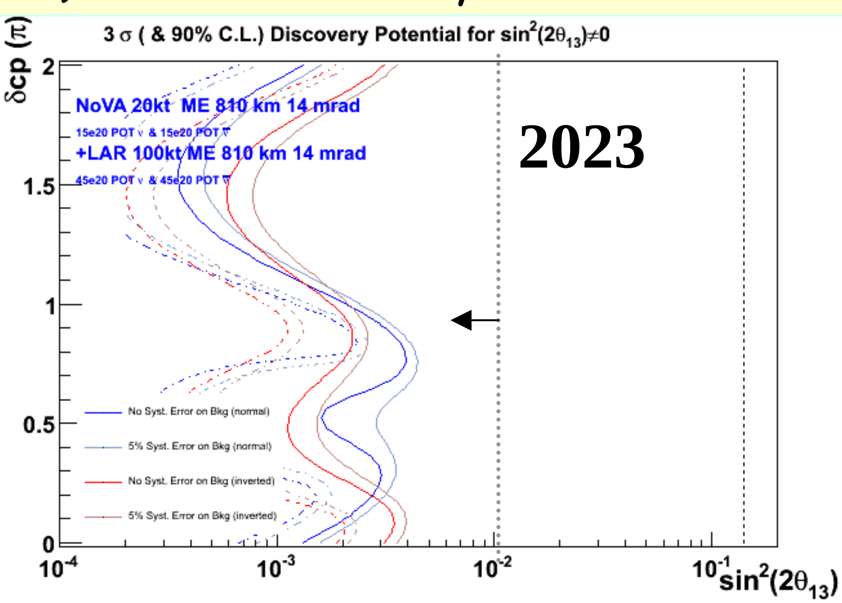


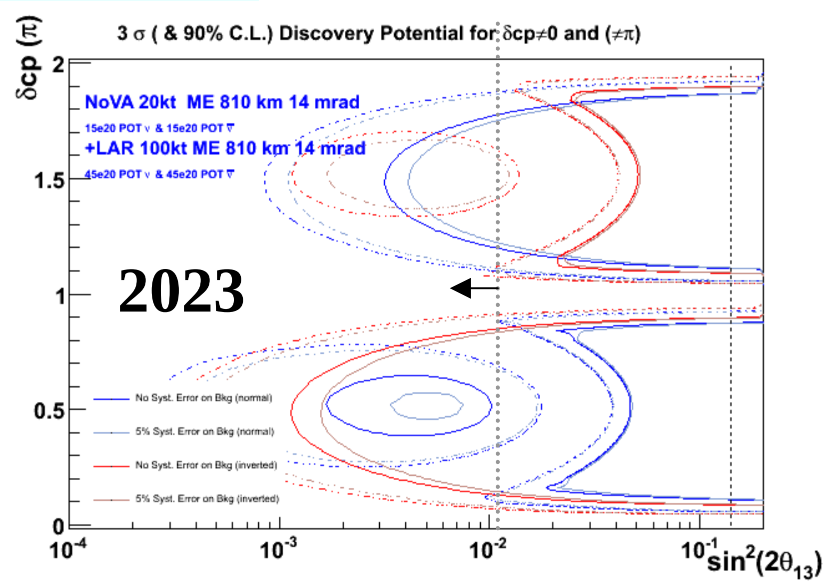
Phase II: Phase I says $\sin^2 2\theta_{13} < 0.02$

Consider the following scenario:

- Try to push the θ_{13} limit further and measure CP violation with existing NUMI Beam and LAR Detector at the 1st Maximum (Medium energy beam)
- Or consider other options :
  a) New beam and longer baselines (the Protons on target needed and the construction time lead to approximately the same time ~ 2023)
  b) Neutrino Factory etc…







Summary - Conclusions

- The NUMI Beam is operating as we speak and there is a well defined plan for upgrades that would make it even more powerful.

- If θ_{13} > ~ 0.05 mass hierarchy and δcp can be measured by the NOvA experiment (~ 2020)

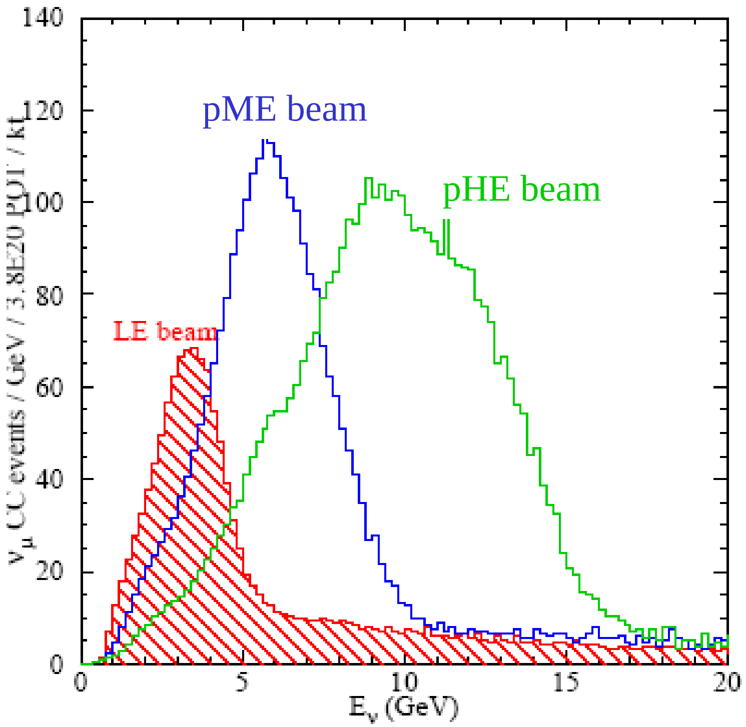
- If ~ 0.02 < θ_{13} <0.05 mass hierarchy and δcp can be measured with the existing NUMI Beam and LAR detector technology (~ 2020) with detectors at both 1^{st} and 2^{nd} maxima

- If 0.001 < θ_{13} <0.02 then θ_{13} and δcp can be measured with the existing NUMI beam (SNUMI upgrades) and LAR detector technology (~2023) with large(r) detector at the 1^{st} maximum

- Beyond that point (ie 0.001 < θ_{13}) one perhaps needs to consider the other options (a WBB to a longer baseline, a neutrino factory etc)

BACKUP SLIDES

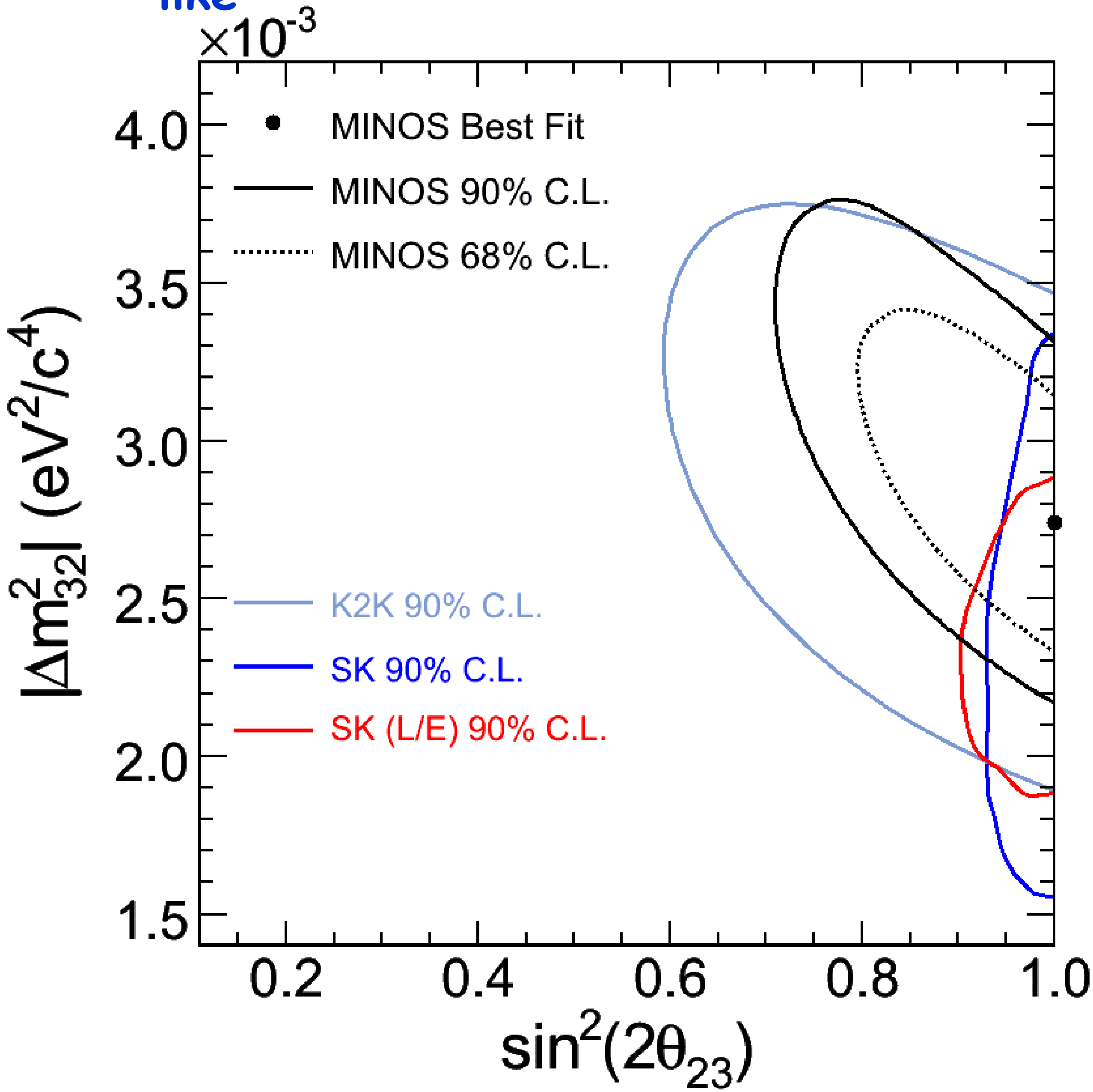
NuMI Neutrino Beam configurations



Running in the LE configuration we expected ~390 ν_μ CC events for $1x10^{20}$/year in the 5.4kt FAR detector (in the FAR fiducial region and in the absence of oscillations).

- **One can also obtain different neutrino spectra by just moving the target (fast, have taken data already for three different energy configurations).**
- **LE, pME and pHE data (and another 2 intermediate positions) used to perform systematic studies in the Near Detector and tune our Monte Carlos (more about this later).**

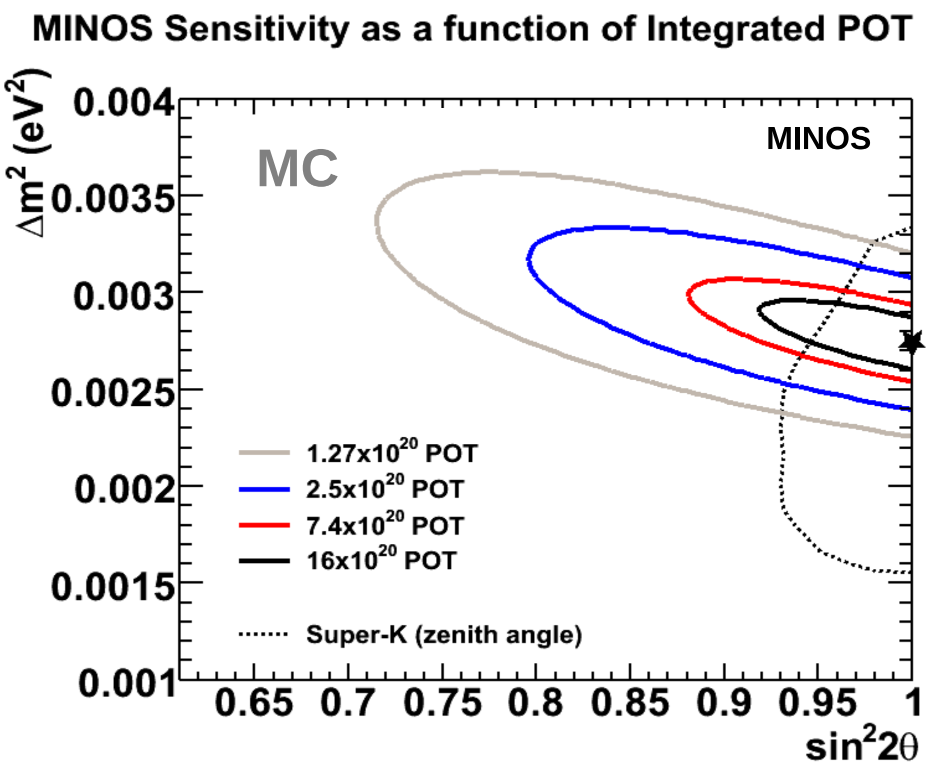
FD CC_{like} Events: MINOS Allowed Region

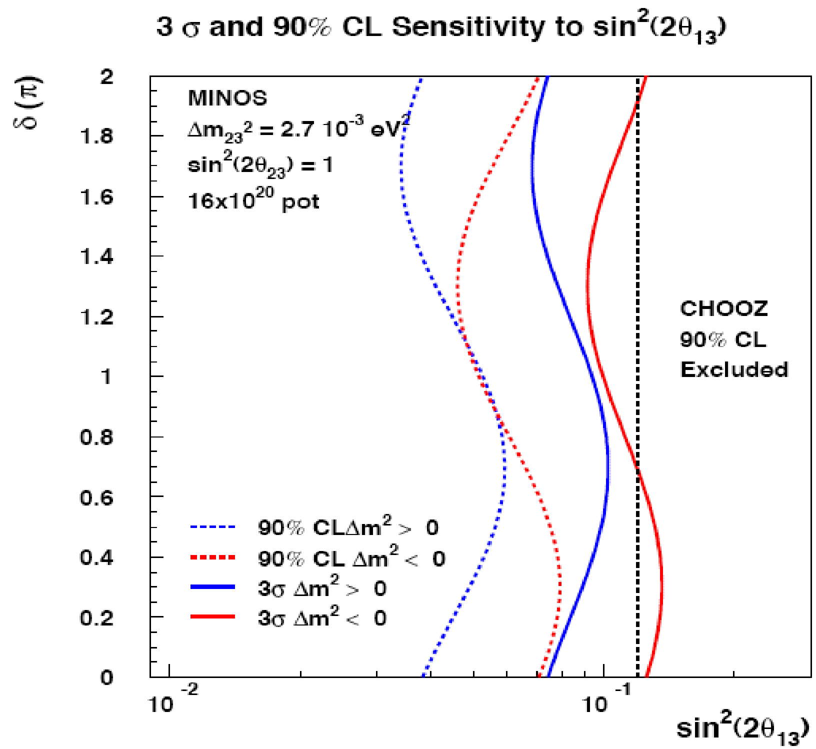


Projected Sensitivity of MINOS

ν_μ disappearance

$\nu_\mu \rightarrow \nu_e$





- With increased statistics :

  -Improve precision on $|\Delta m^2_{32}|$ and $\sin^2(2\theta_{23})$ and test/rule out alternate models such as neutrino decay.

  - Could make first measurement on θ_{13} or improve current best limit set by CHOOZ

3-Flavor Oscillation Formalism

What do we know so far

If neutrinos oscillate, then the interaction eigenstates (what we observe) can be expressed in terms of the mass eigenstates as follows:

$$\nu_{e(\mu)(\tau)} = \sum_{i=1}^{3} U^{*}_{e(\mu)(\tau)i}\, \nu_i$$

Atmospheric — Cross-Mixing — Solar

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

Majorana phases

$$\begin{bmatrix} e^{ia_1/2} & 0 & 0 \\ 0 & e^{ia_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

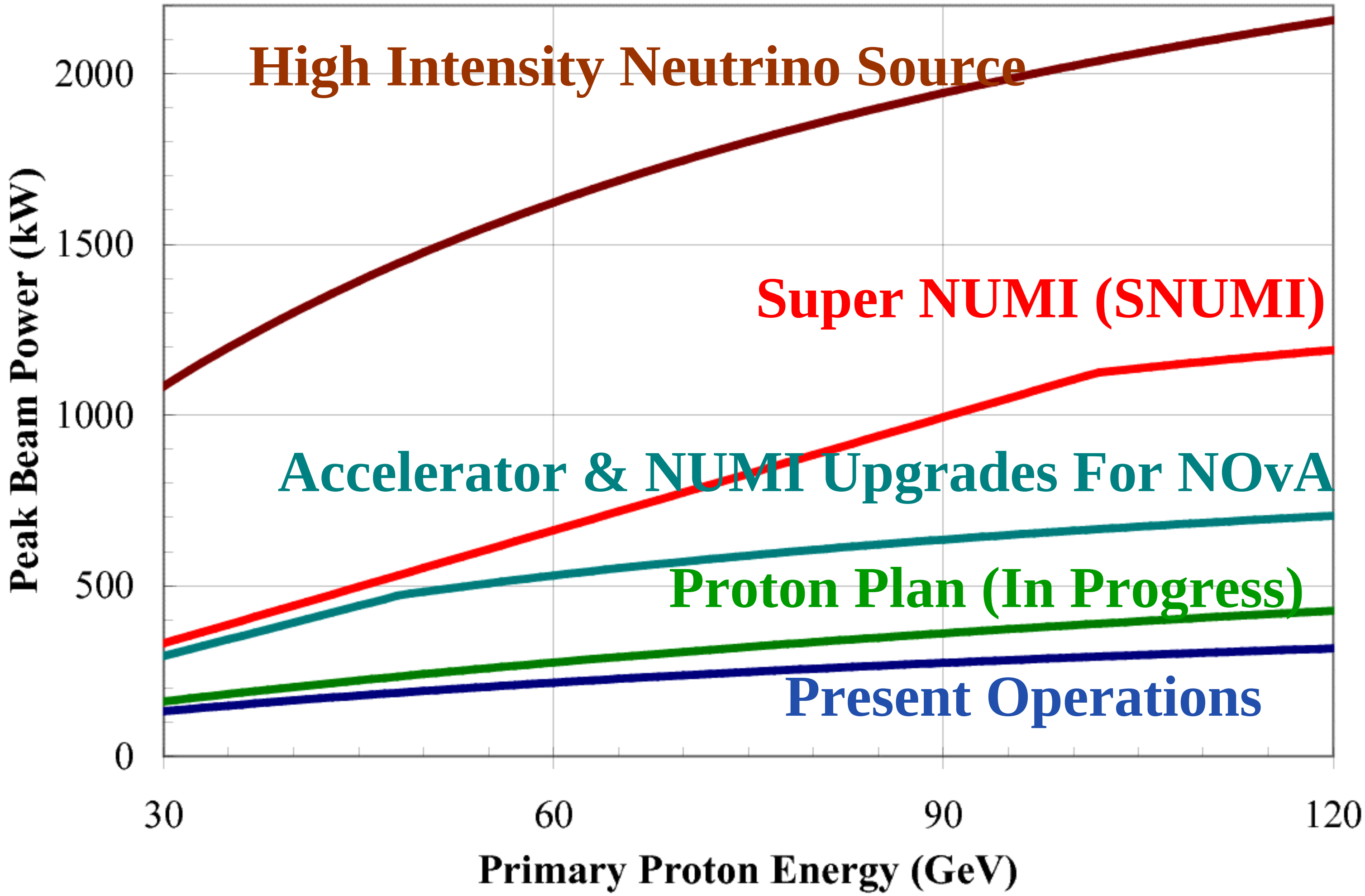
???

$0\nu\beta\beta$ decays

$$c_{ij} = \cos\theta_{ij}$$

$$s_{ij} = \sin\theta_{ij}$$

NuMI Neutrino Beam: Capabilities & Advantages



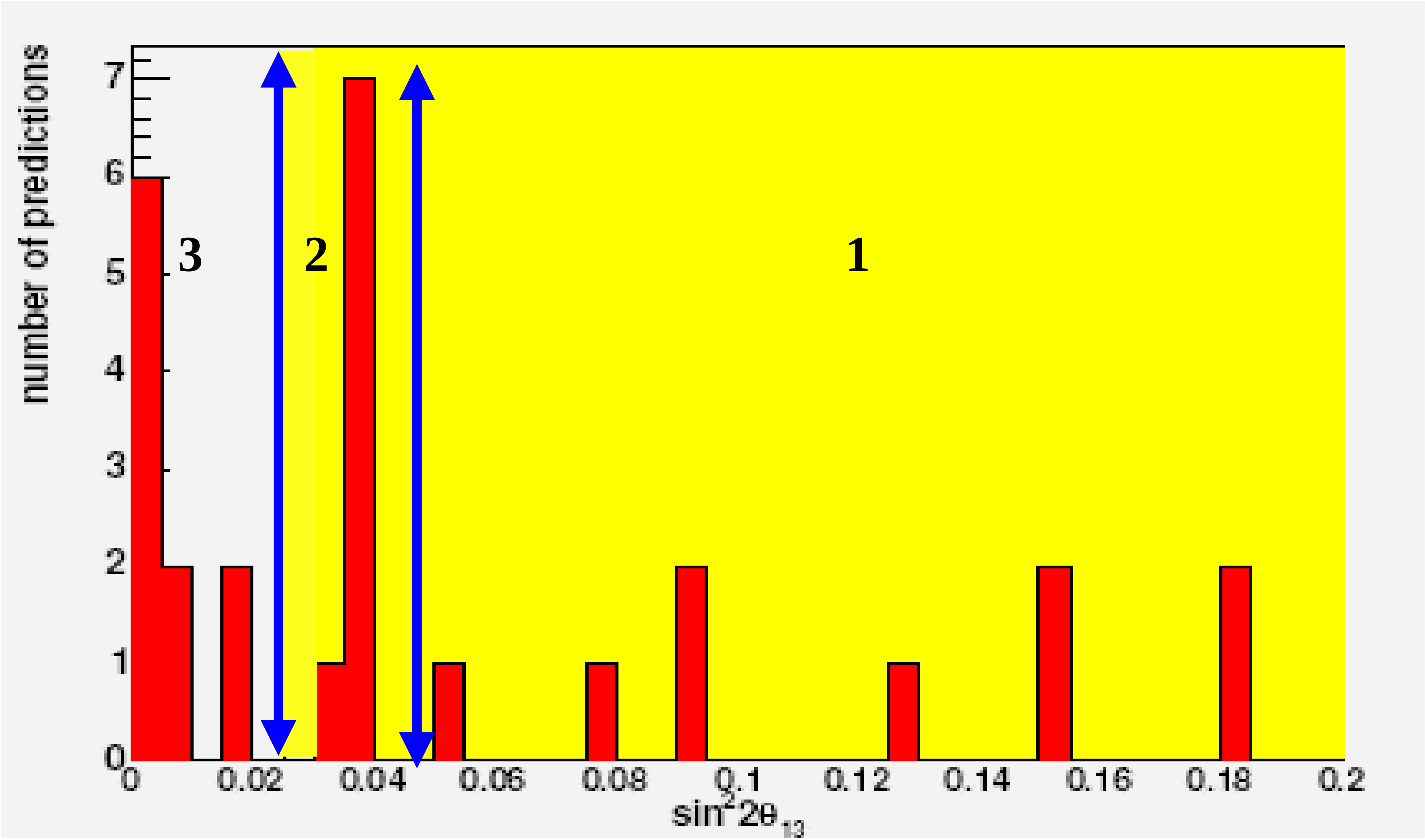
Running @ 120 GeV Protons has the advantage that future possible (or considered) upgrades lead to a more powerful beam :

- from 700 kW (Plan for NOvA) to > 2 MW …

Search for a non zero θ_{13} :

What does theory say??

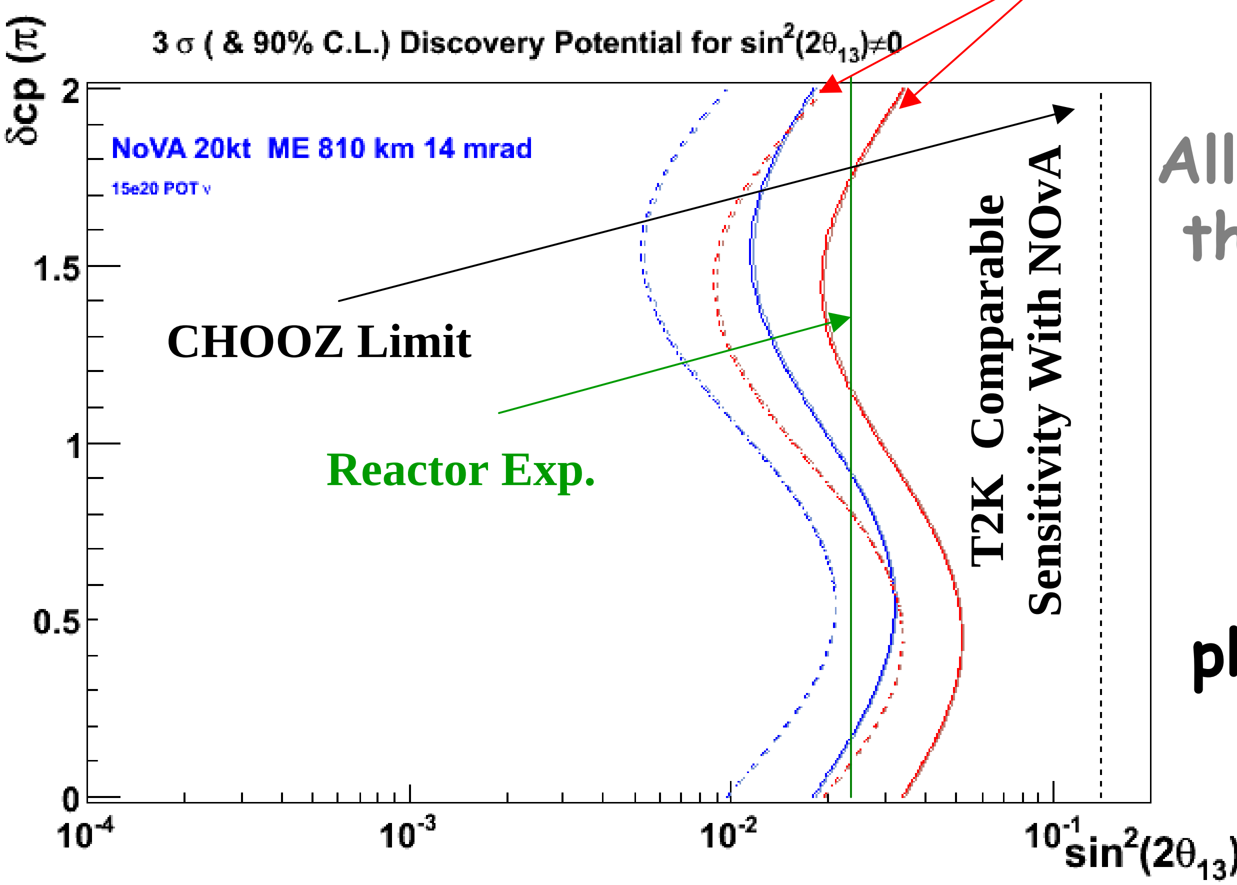
Low Values of θ_{13} not theoretically favoured(!)



Search for a non zero θ_{13}

Push the current limit down but a factor of 10 : Phase I

- Experiments hunting for a non-zero θ_{13} :
  - Reactor experiments : 2CHOOZ and Daya Bay
  - Accelerator experiments : NOvA and T2K



All Experiments obtain the same reach by ~ 2012-2014

These results will greatly help in planning for Phase II