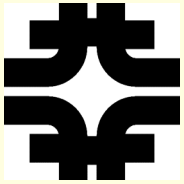
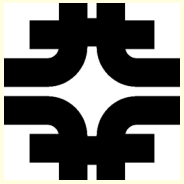


U.S. Future Long Baseline Study - II

Gina Rameika

Fermilab



Outline

- Scope of the Study
  - Beams/Detectors
  - How it evolved to ⇒This talk
- The Decision Tree
  - Phase I ⇒ Phase II evolution
- Study Results
- Summary & Conclusions

Scope of the Study

The charge to the Study participants (Montgomery/Dawson)

- Compare the neutrino physics oscillation potential of :
  - Broadband beam to a DUSEL site
  - Next Generation Off-Axis options
    - Liquid Argon Detector
      - At DUSEL or
      - As a second NOνA detector
  - Proton options
    - ~ 1 MW from exiting accelerator complex
    - 1 - 2 MW
    - Proton Driver (~2MW)

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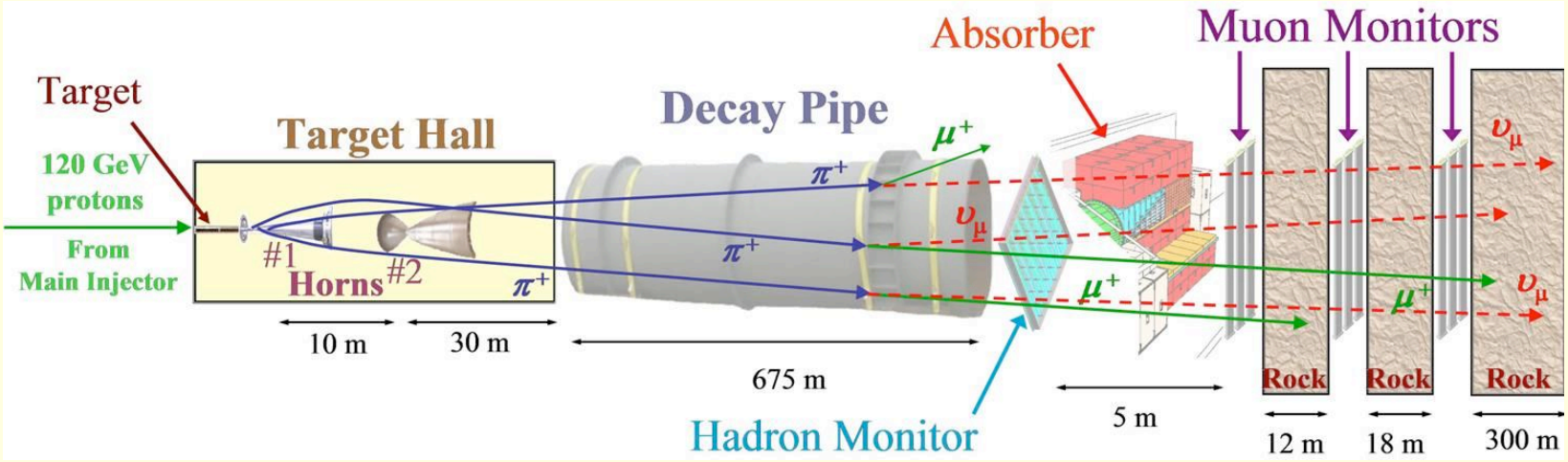
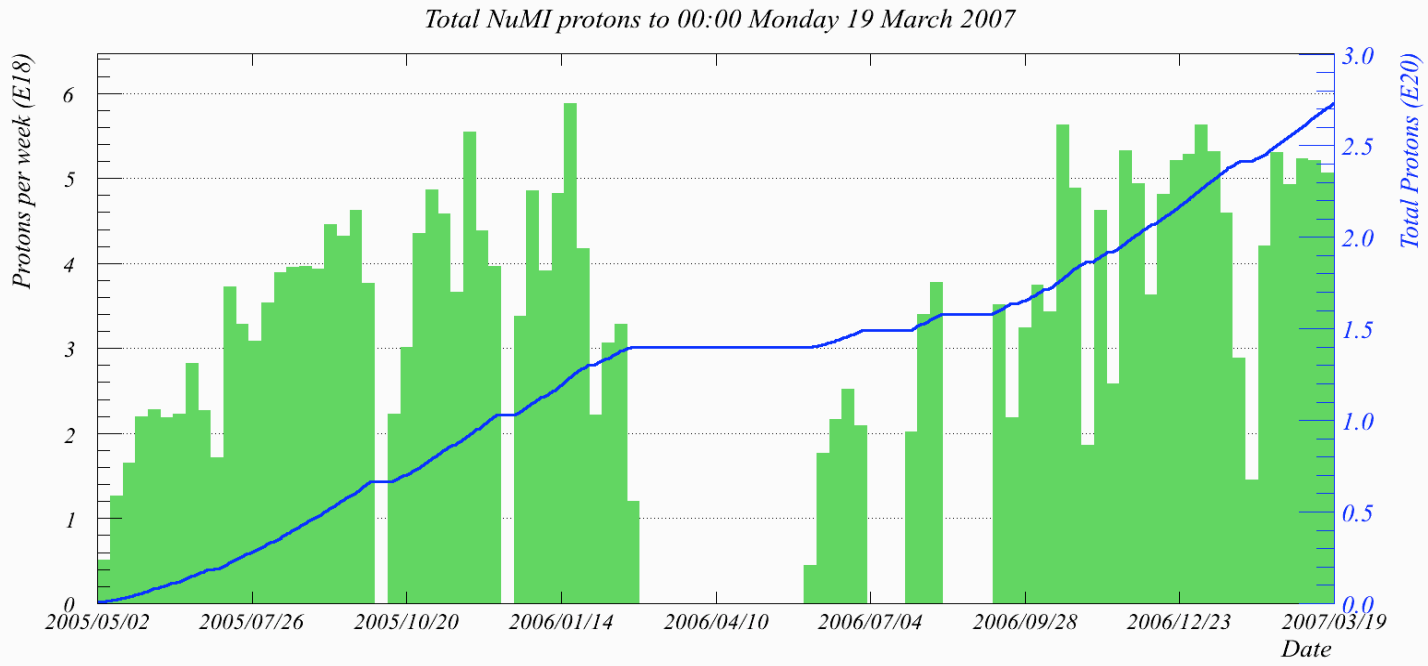
    - ~ 1 MW from exiting accelerator complex
    - 1 - 2 MW
    - Proton Driver (~2MW)

For a discussion of the R&D and technology issues see : http://nwg.phy.bnl.gov/~diwan/nwg/fnal-bnl/report.pdf

The NuMI Beam

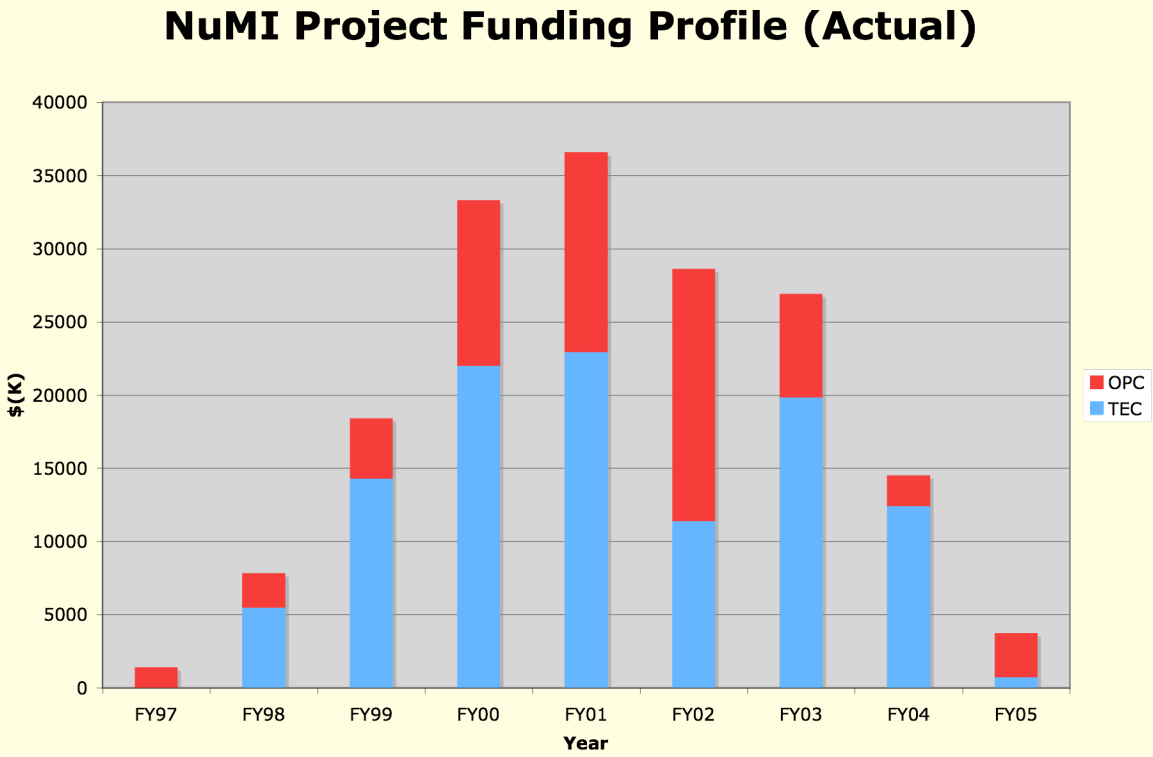


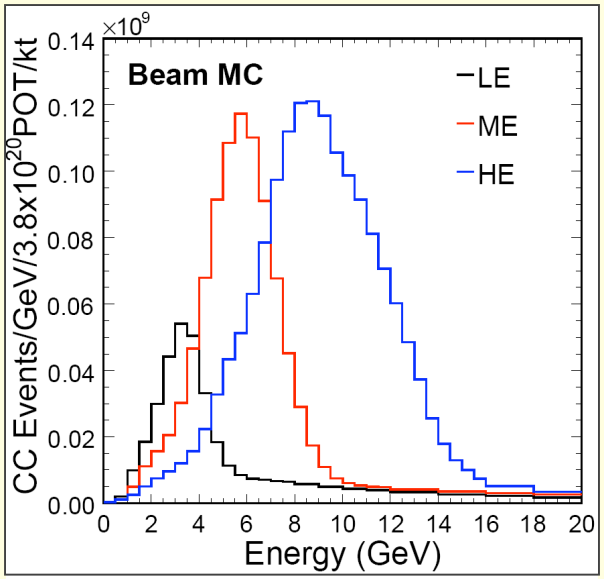


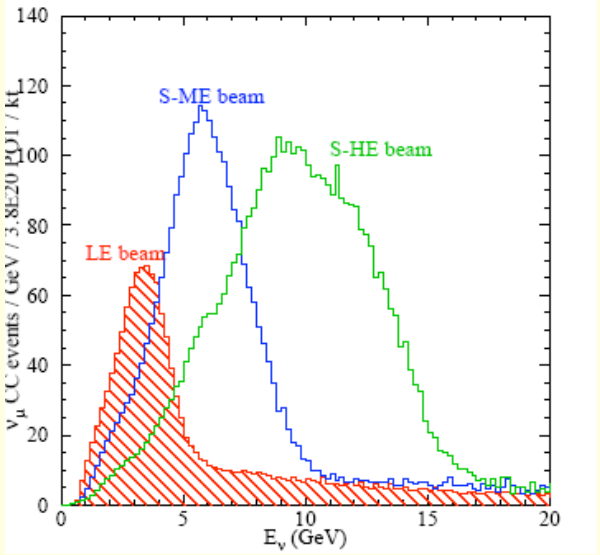
- Physics data set since May 2005 : **2.744E20**
- Since June 2006 : 1.35E20
- This physical year : 1.066E20

Motivation for the NuMI Off-axis option

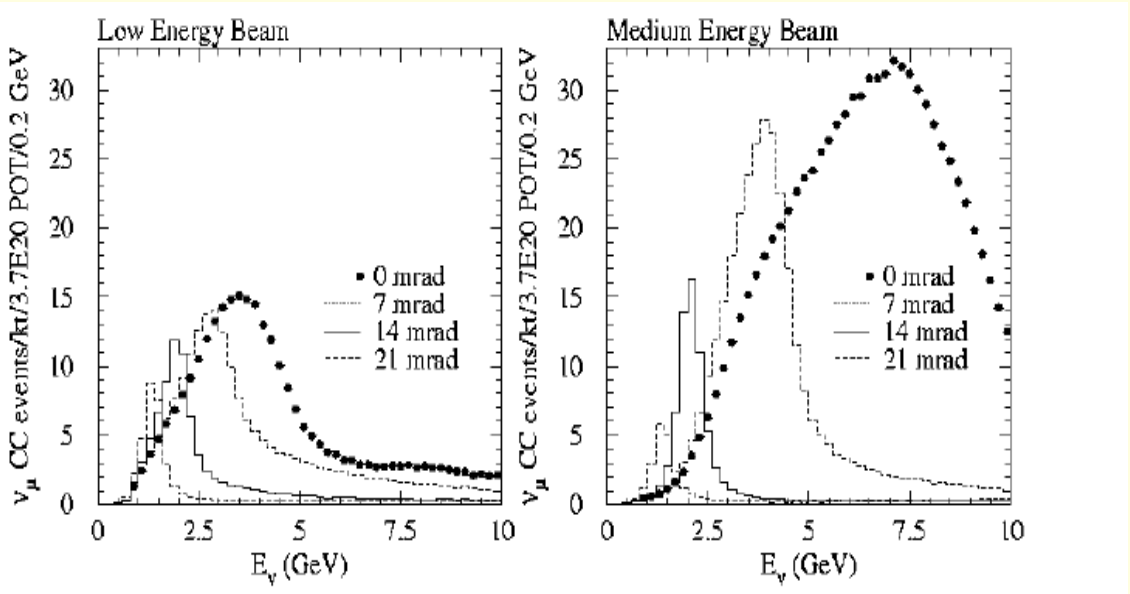
- Exploit our ***investment*** in an ***existing facility***
  - NuMI project took 9 years to construct and commission
  - TEC (civil + beam) = $109 M



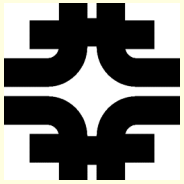




- Exploit the ***flexibility*** of the NuMI Beam
  - Energy tunable wide band and narrow band beams
  - Detector locations can be chosen for the desired L-E combination



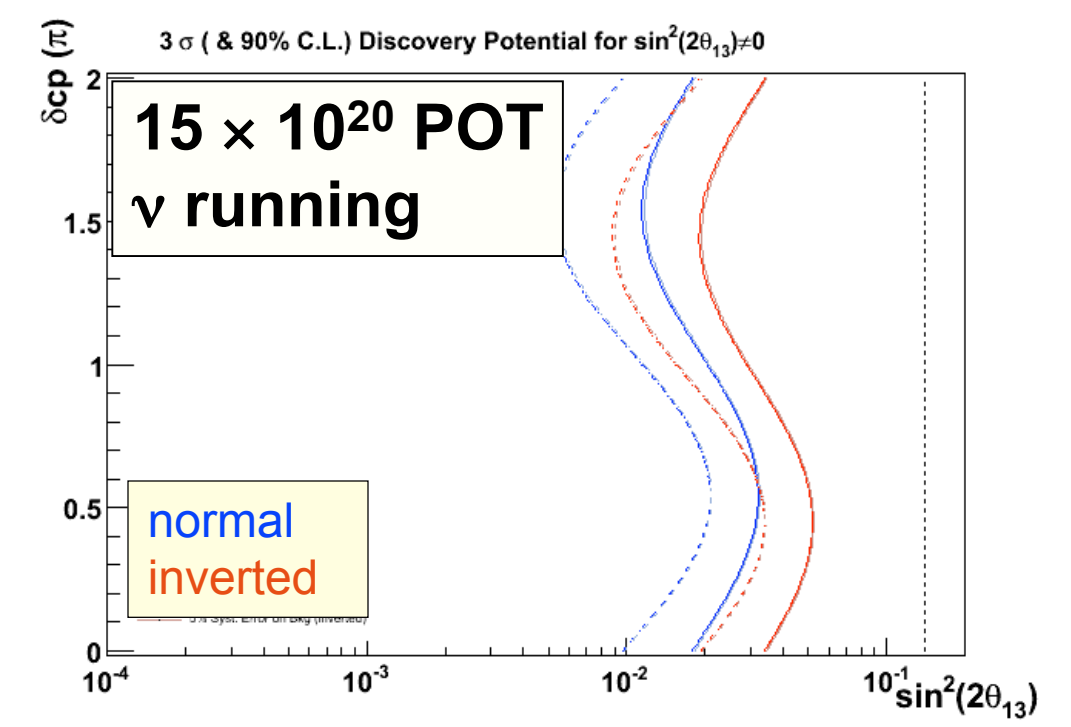
$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta_{ab} \sin^2(1.27\Delta m_{ab}{}^2 L/E)$$



- Exploit the ***opportunity*** for ***incremental*** program development
  - Phase I : NOνA (includes Accelerator and NuMI Upgrades)
    - First results from NOνA and other experiments will help plan next steps
  - Develop plans for increasing proton intensity
  - Do R&D on improved detector technology

Phase I : a.k.a. NOνA

- Sensitivity plots made for a given detector mass + POT
- Define a new parameter
  - **eMpot** = effective mass(kton) x protons on target (1e20)
- Assume 30% efficiency for NOvA
  - 20 kton Mass ~ 6 kton eMass



NOνA sensitivity for eMpot = 90

If $\sin^2 2\theta_{13} > 0.03 - 0.05$ (depending on hierarchy) NOνA can measure it by…

By…

- Time scale depends on how quickly we can get to the eMpot = 90…

Outlook for Protons

- More protons with Collider (<2009)
  - 9/11 slip-stacked Booster Batches (2 batches for anti-protons)
  - Repetition rate = 0.8 s (Booster) + 1.4 s (MI ramp) = 2.2 s
  - **3.4 x 10^{20} protons/year**

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- Post-Collider era w/ Recycler (2010-2011)
  (Accelerator and NUmI Upgrade [ANU])
  - 11 batches
  - use Recycler (1.33 s cycle)
  - **6 x 10 ^{20} protons/year**

Included in The NOvA Project

Results come from Mass * POT

Year	07	08	09	10	11	12	13	14	15	16	17	18	19	20
NOvA	Design	Construction & Installation				Phase I					Begin Phase II			
ANU (old PP2)	Design, R&D, Procurement, Construction				Install	Medium Energy Beam - neutrino mode					Run : ?			
NOvA Mass (kton)					5	10	**20**							
NOvA Effective Mass (eMass) (kton)					2	3	6							
NOvA POT/yr (700kw)						5	5	6	6	6	6	6	6	6
NOVA POT Sum (700kw)						5	10	16	22	28	34	40	46	52
NOvA sumPOT*eMass						14	59	**95**	131	**167**	**203**	239	275	311

NOνA, along with results from Reactors and T2K tell us whether $\sin^2 2\theta_{13}$ is large (> 0.03) or small (<0.03)

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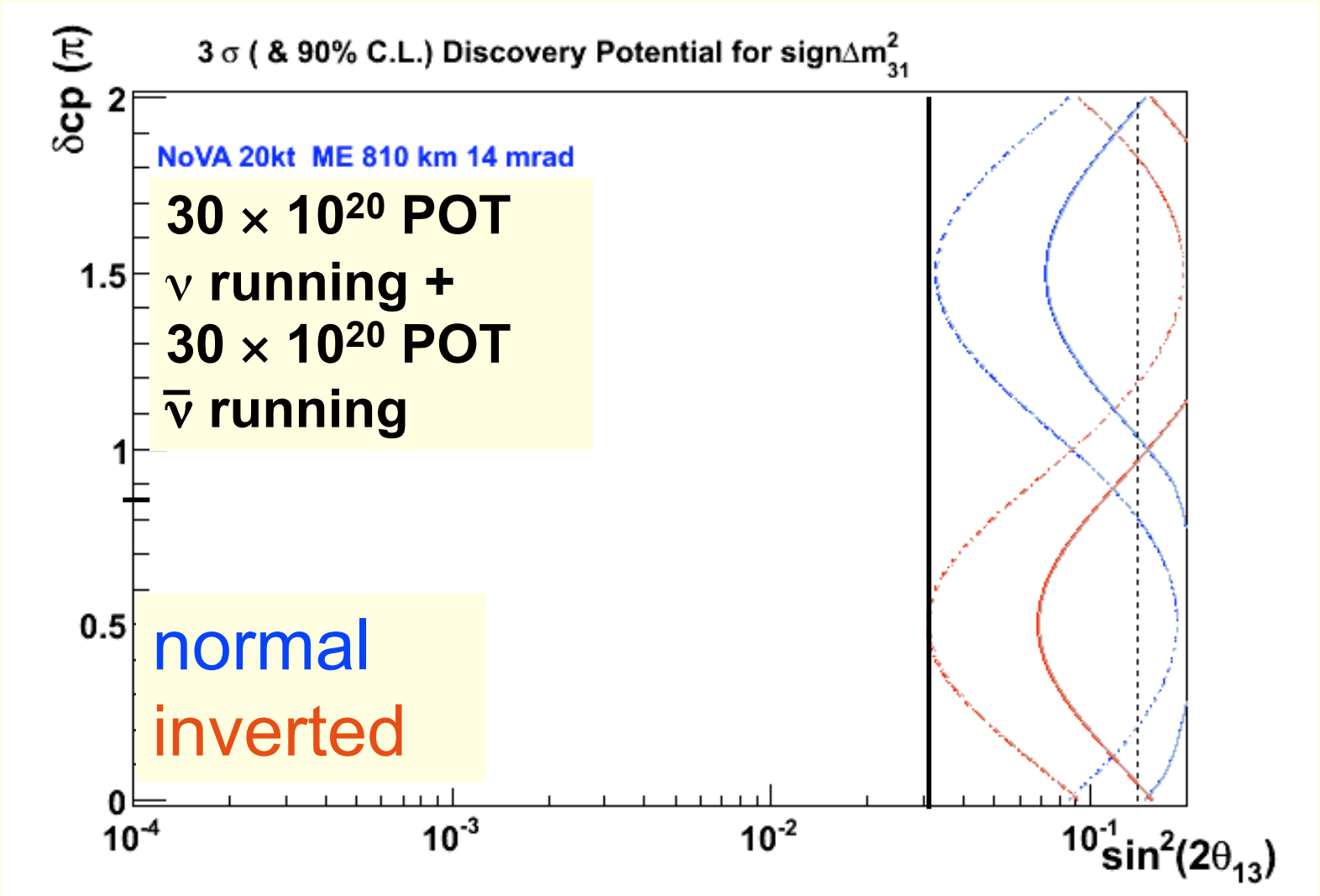
NOνA, along with results from Reactors and T2K tell us whether $\sin^2 2\theta_{13}$ is large (> 0.03) or small (<0.03)

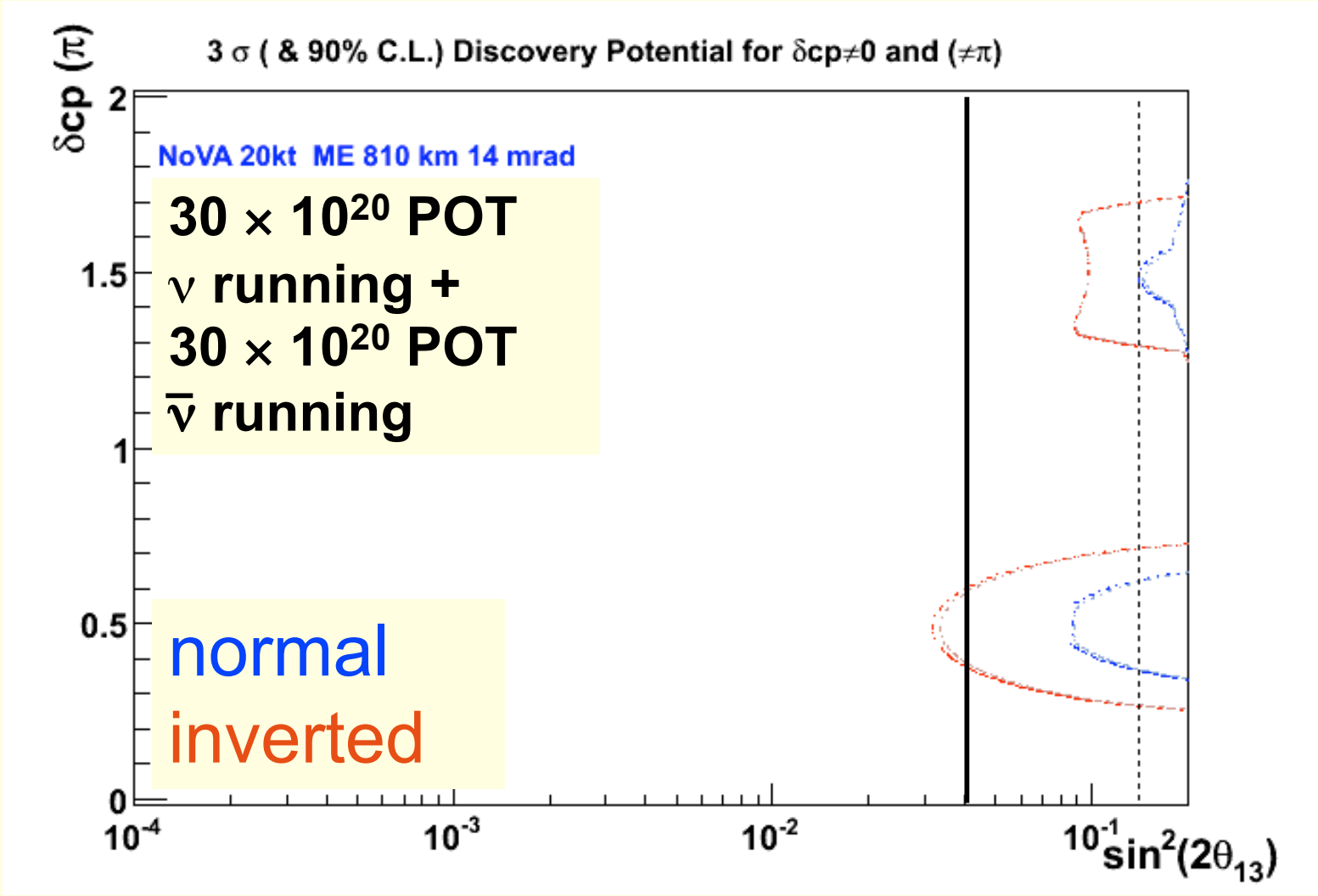
This is an important decision point …

$\sin^2 2\theta_{13} > 0.03$



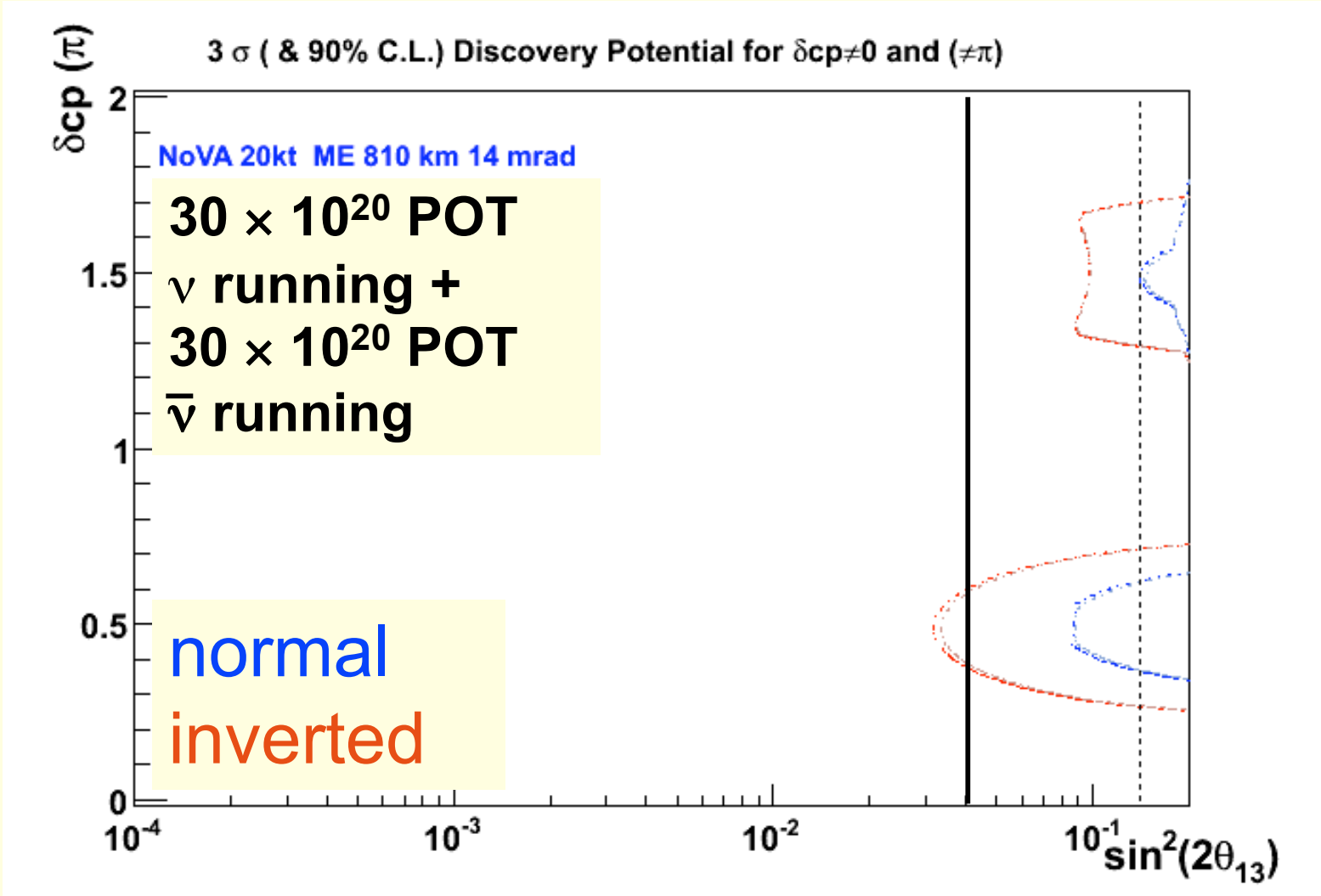
NOνA determines the mass hierarchy (90%CL) …

$\sin^2 2\theta_{13} > 0.03$



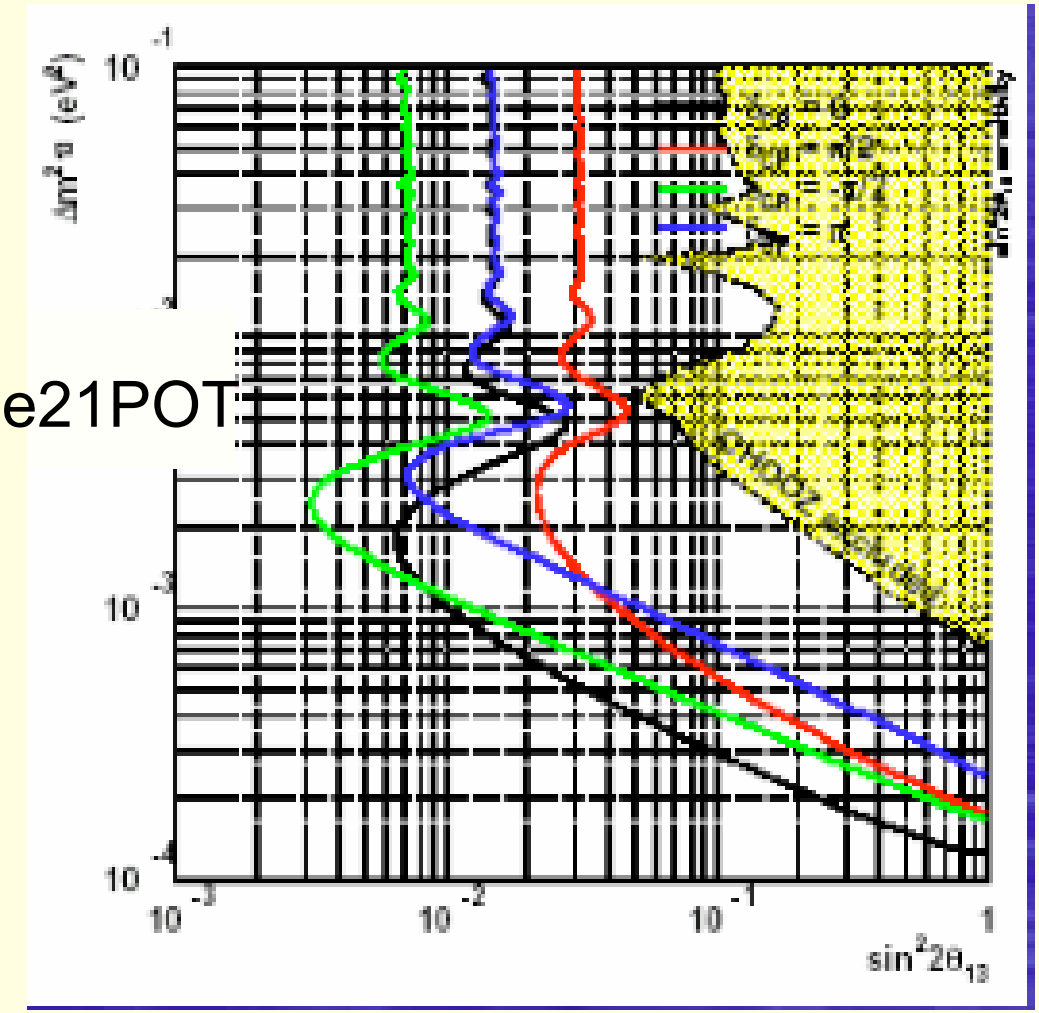
But has small sensitivity to CP…

$\sin^2 2\theta_{13} > 0.03$



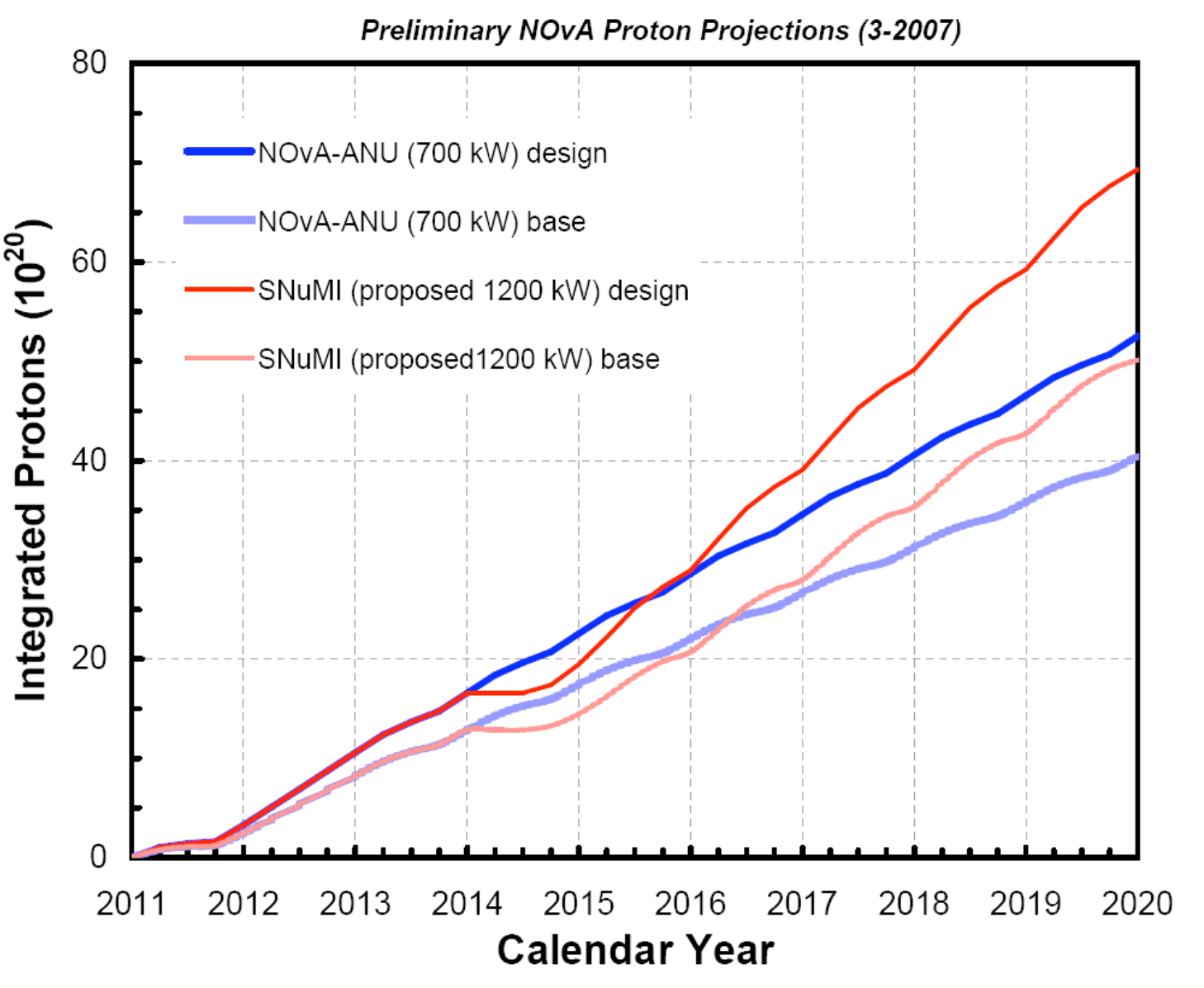
But has small sensitivity to CP… but combined with T2K

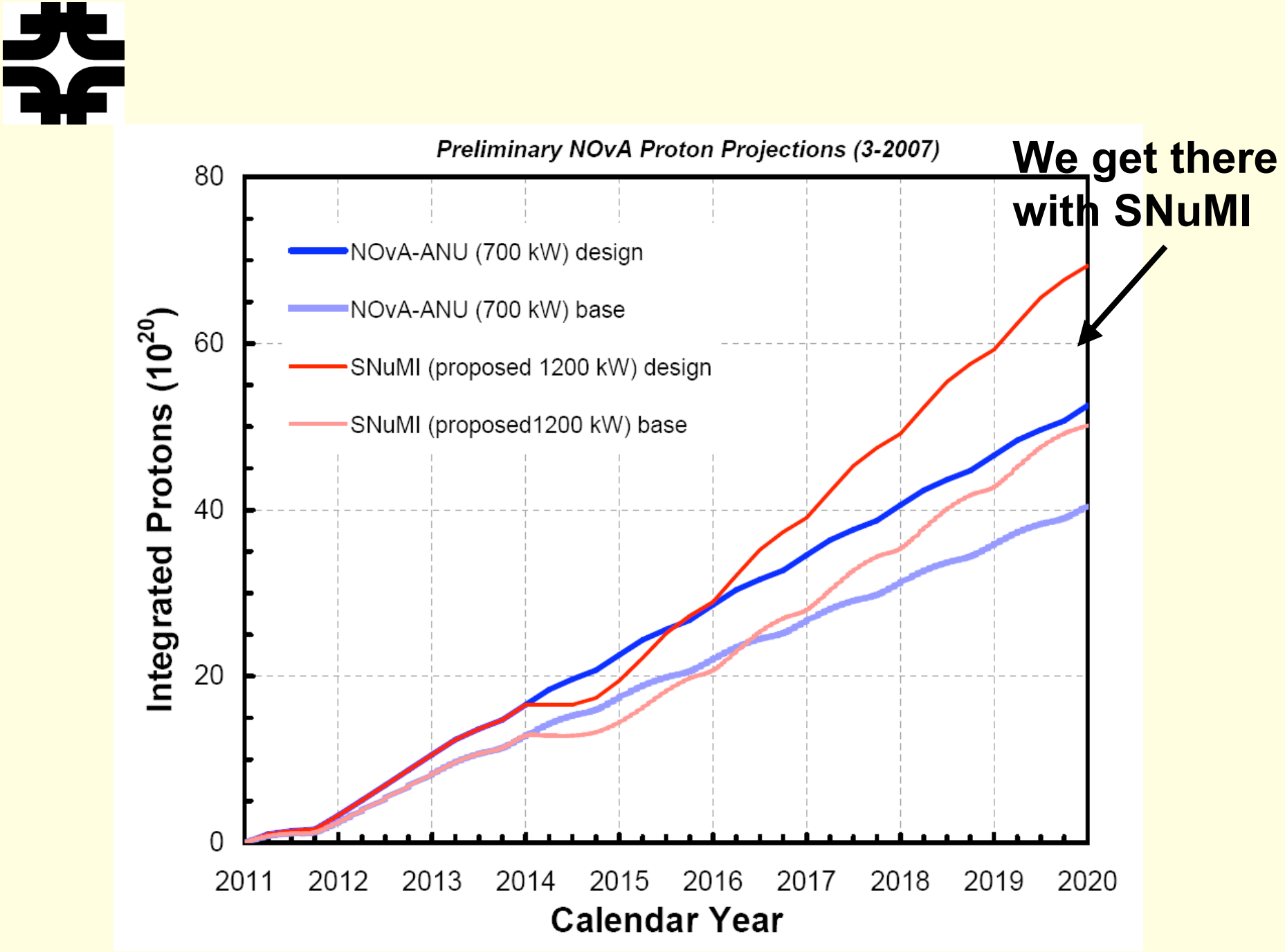
$\sin^2 2\theta_{13} > 0.03$



Good sensitivity to δ_{CP}

Background uncertainty	10%
$\delta_{CP} = 0$	
$\delta_{CP} = \pi/2$	
$\delta_{CP} = -\pi/2$	
$\delta_{CP} = \pi$	


Preliminary NOvA Proton Projections (3-2007)
Integrated Protons (10^{20})
Calendar Year
NOvA-ANU (700 kW) design
NOvA-ANU (700 kW) base
SNuMI (proposed 1200 kW) design
SNuMI (proposed1200 kW) base
0
20
40
60
80
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020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NOvA-ANU (700 kW) design
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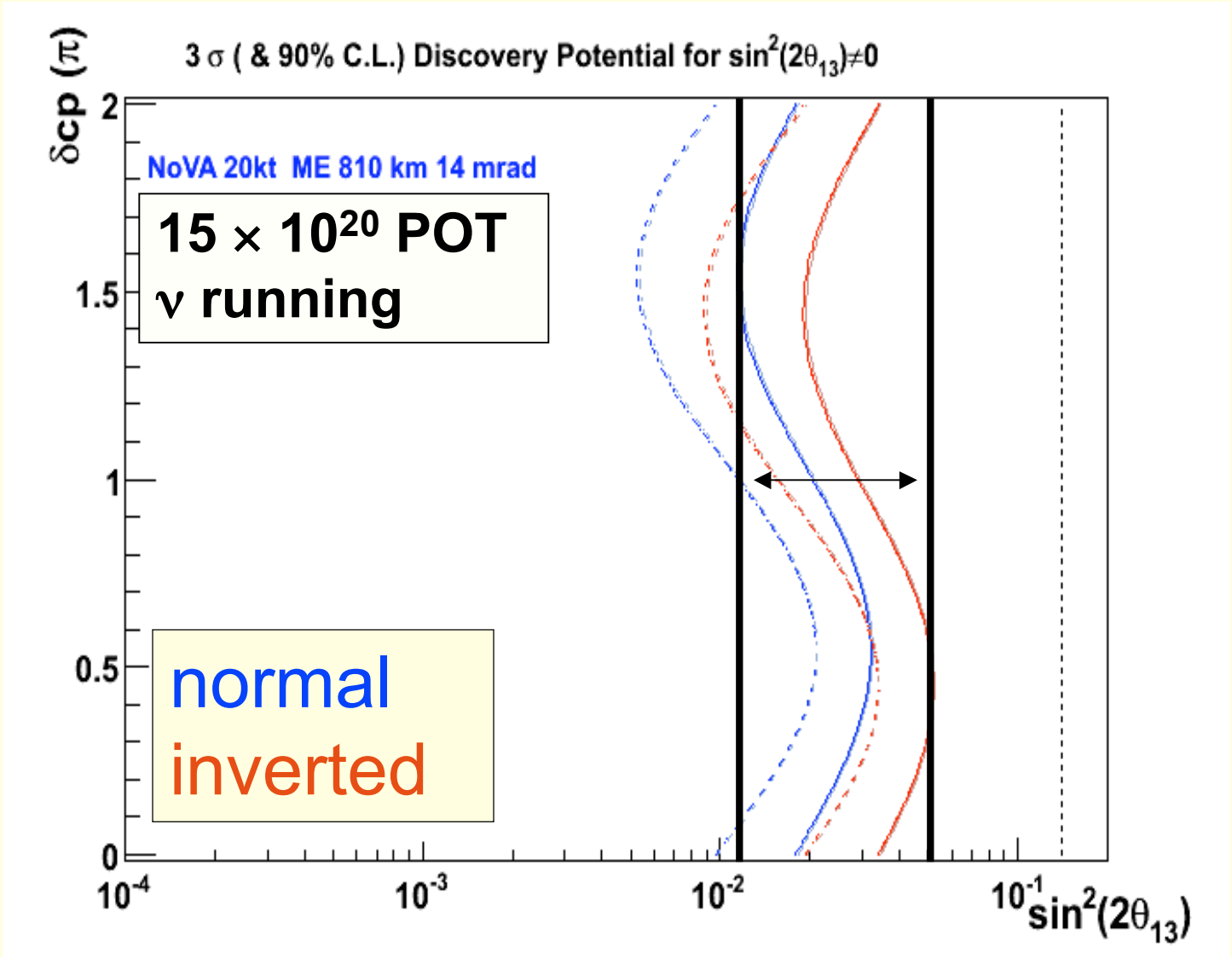
Integrated Protons (10^{20})
0
20
40
60
80
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
Calendar Year

Phase I tells us :
$.01 < \sin^2 2\theta_{13} < 0.05$



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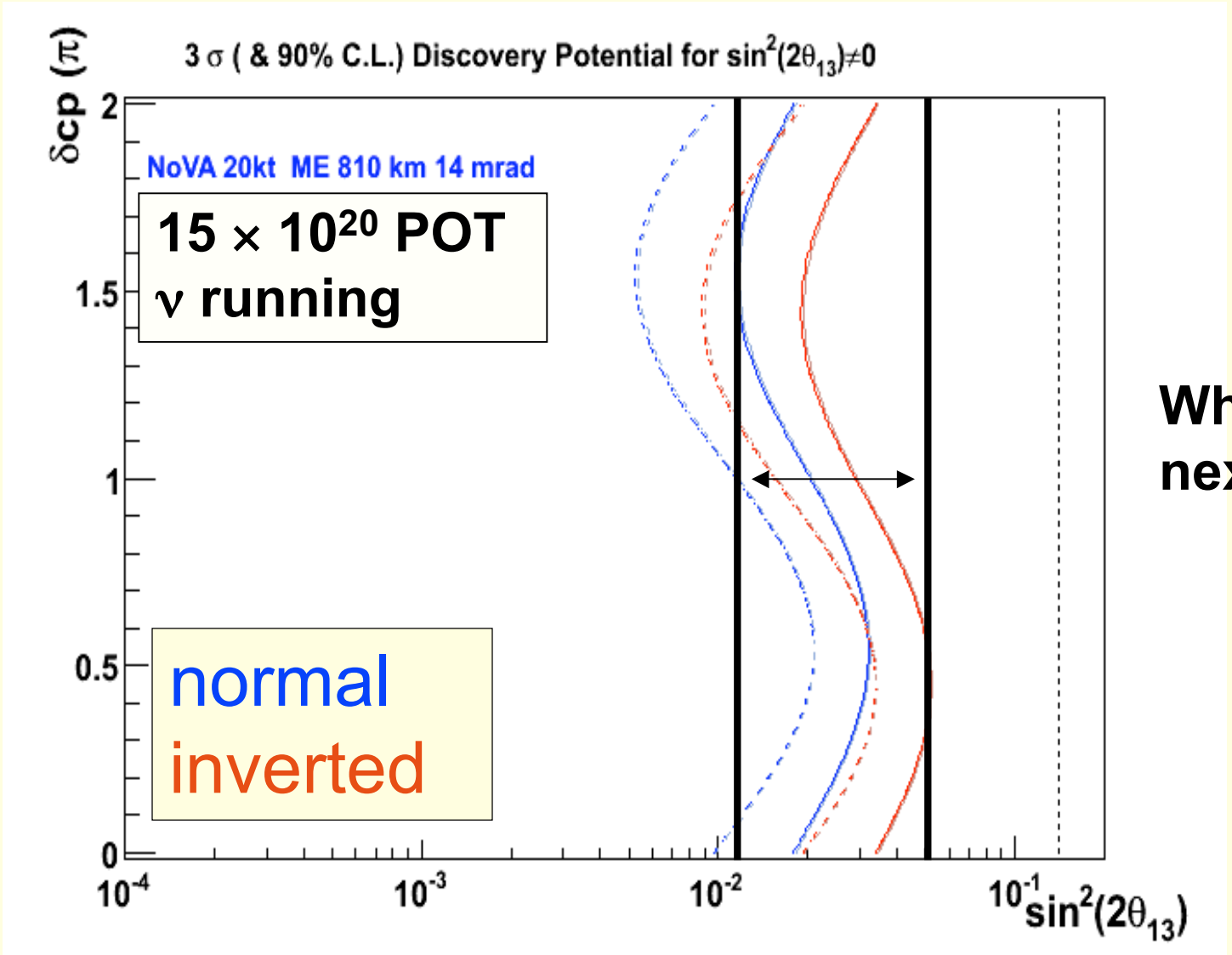
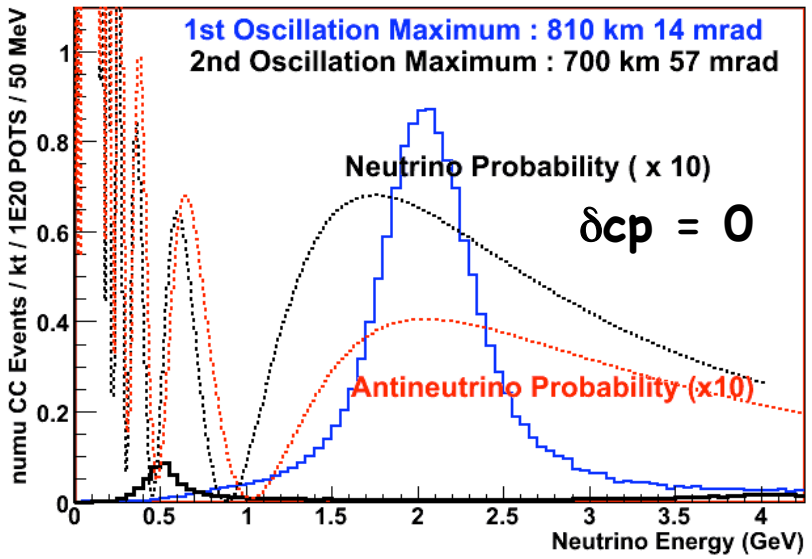
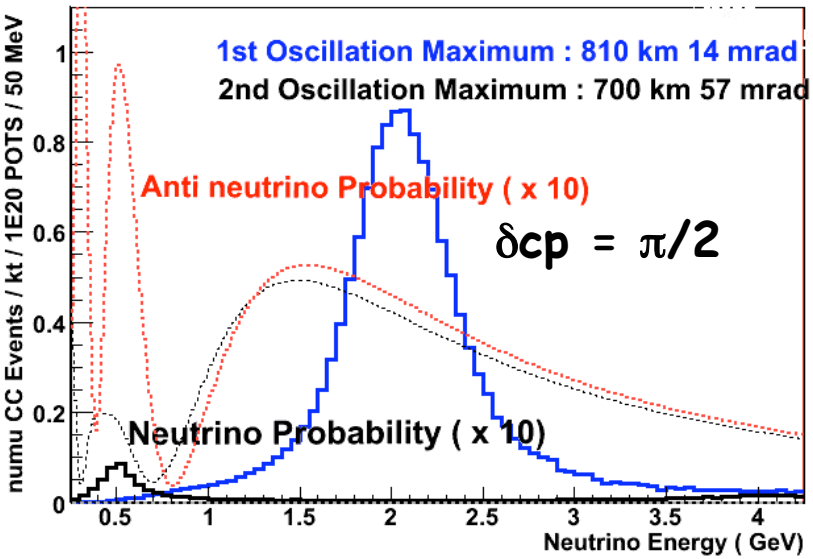


What's the next step?

1st and 2nd "maximum" strategy





- 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 "Wide Band Beam"

Advantage

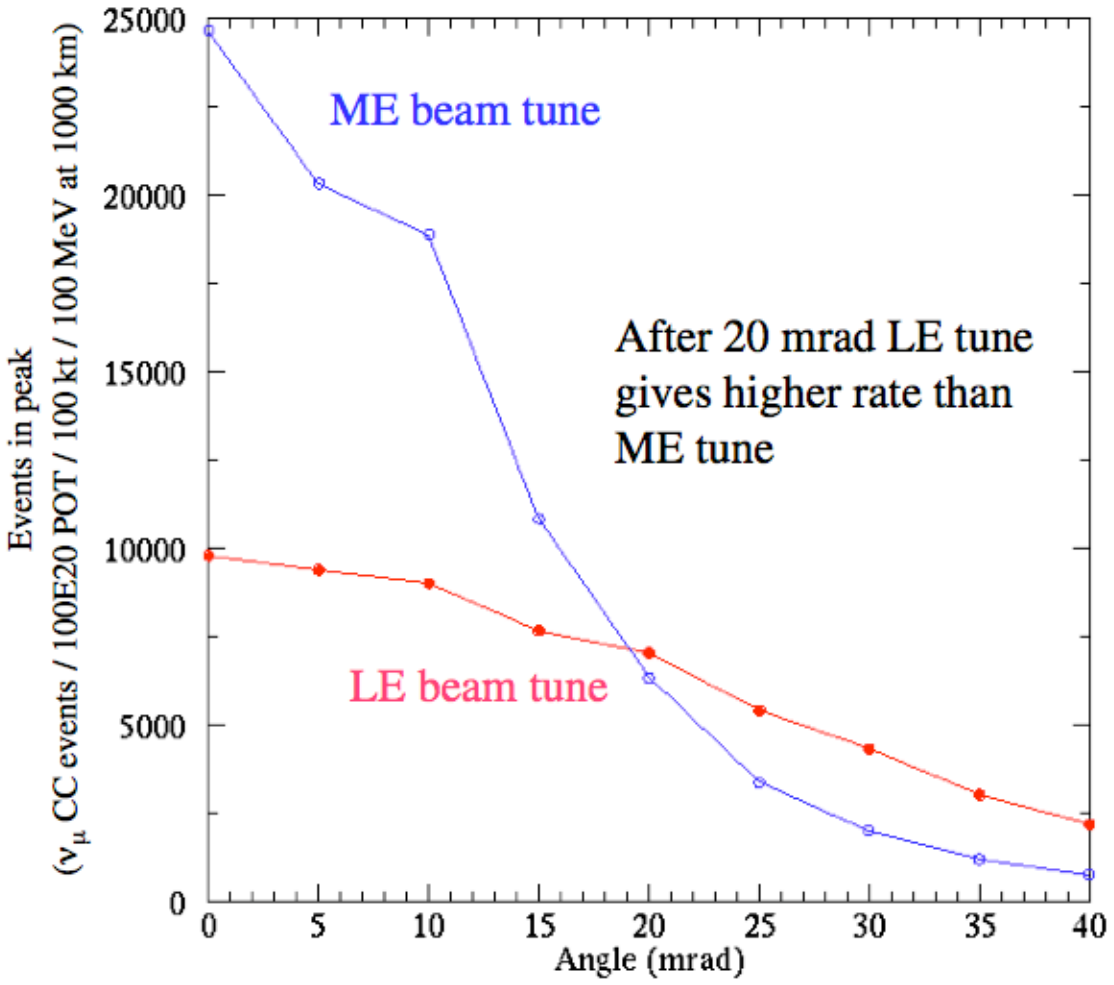
- Matter effects important @ 1st Oscillation Maximum but not @ 2nd Oscillation Maximum = > Combination of measurement helps in better determination of mass hierarchy and δcp.

Disadvantage

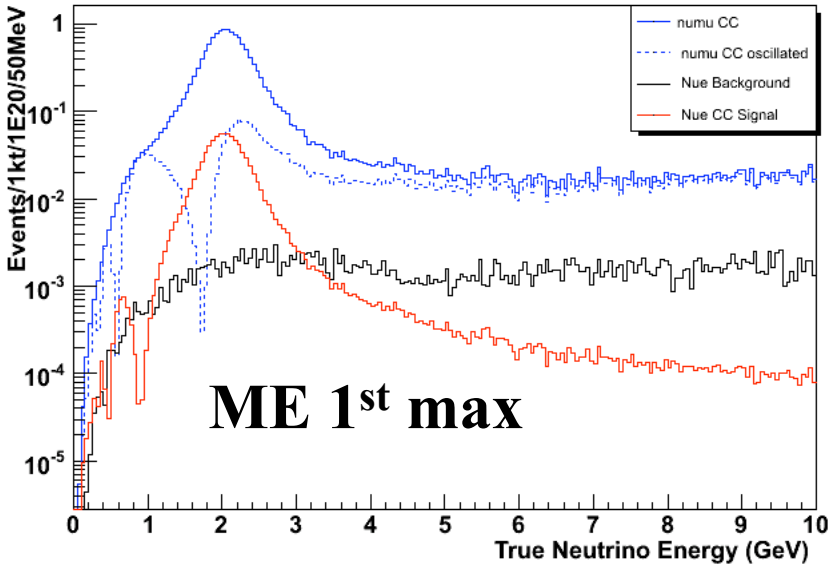
- Neutrino Flux @ 2nd Oscillation Maximum is low.

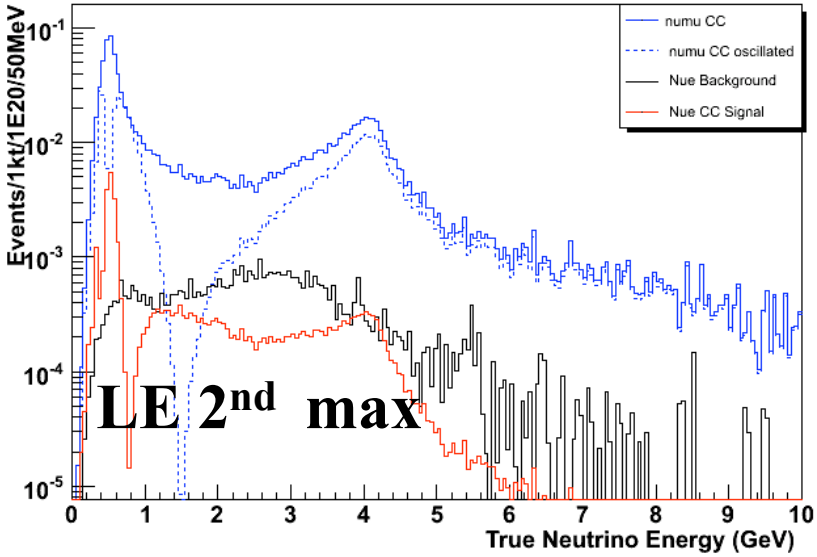
Optimization studies were performed placing Detectors @ both Locations.

Comparing event rates as function of off-axis position

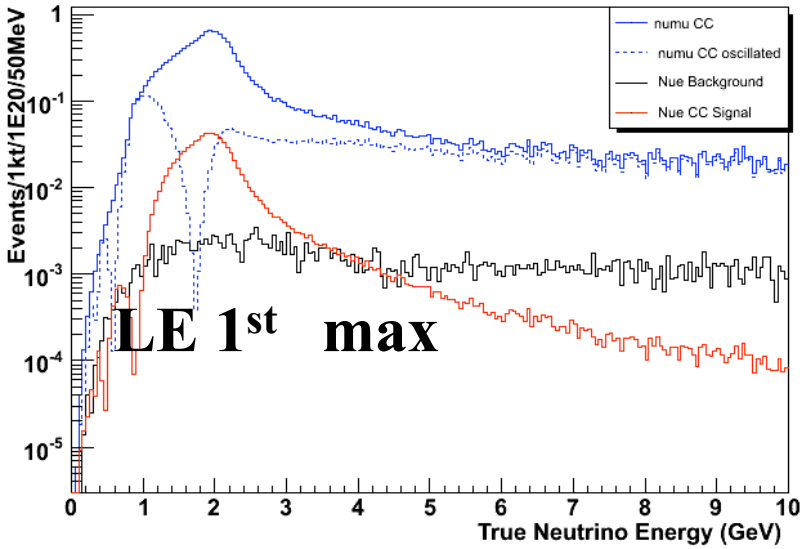


Off-axis Options





- 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)



$.01 < \sin^2 2\theta_{13} < 0.05$

- In this case we have to consider a more powerful detector technology (than NOνA) that:

  1) Can be constructed to give high mass (perhaps modular)

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

  3) 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 is ongoing.

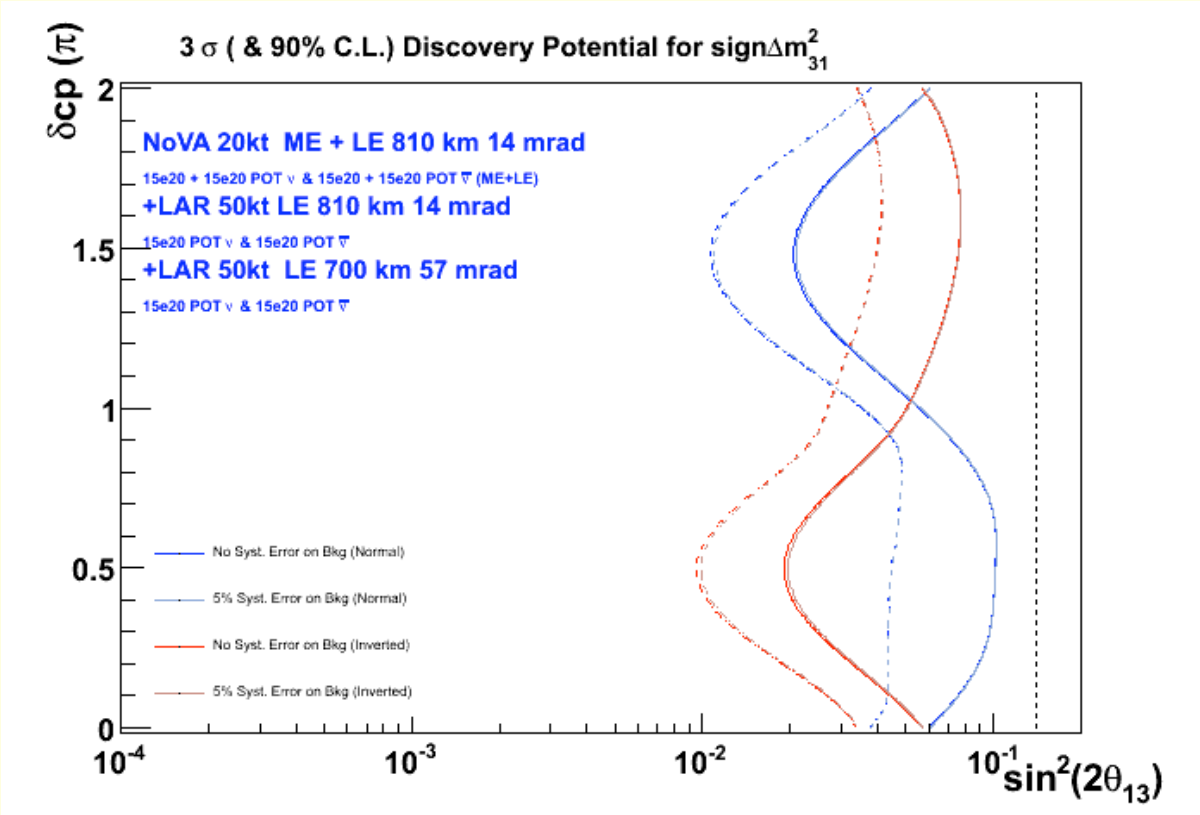
$.01 < \sin^2 2\theta_{13} < 0.05$

We considered the following scenario :

1) Switch to **Low Energy** Running

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

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



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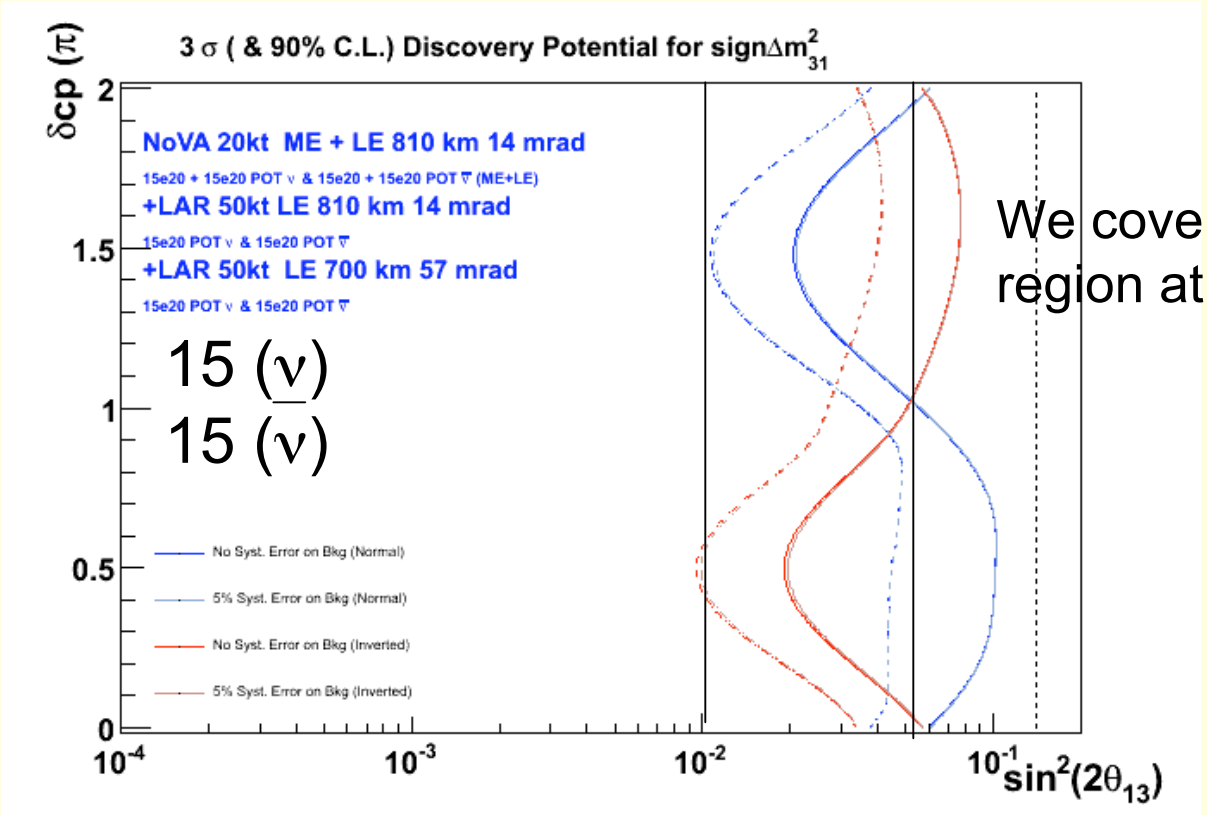
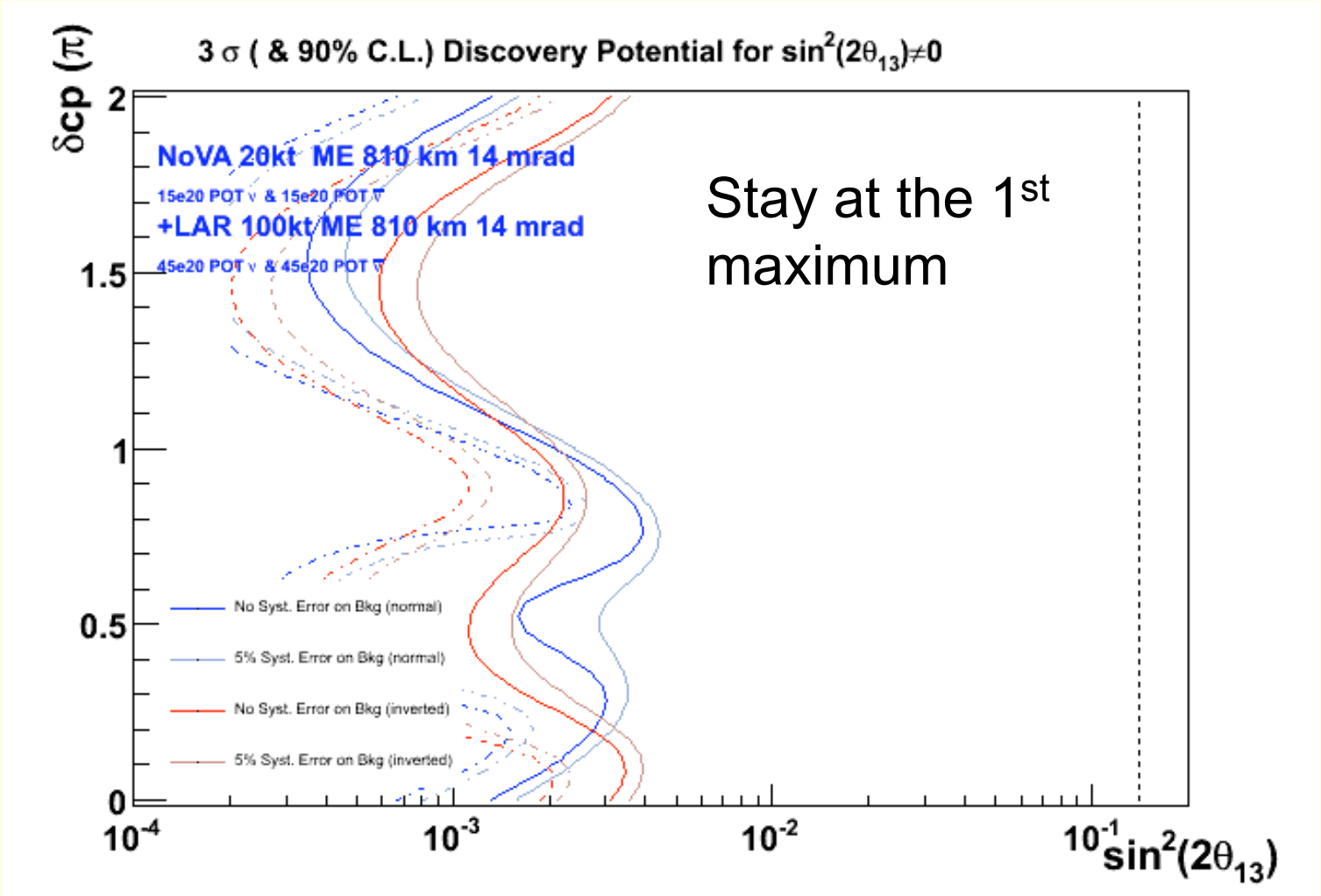
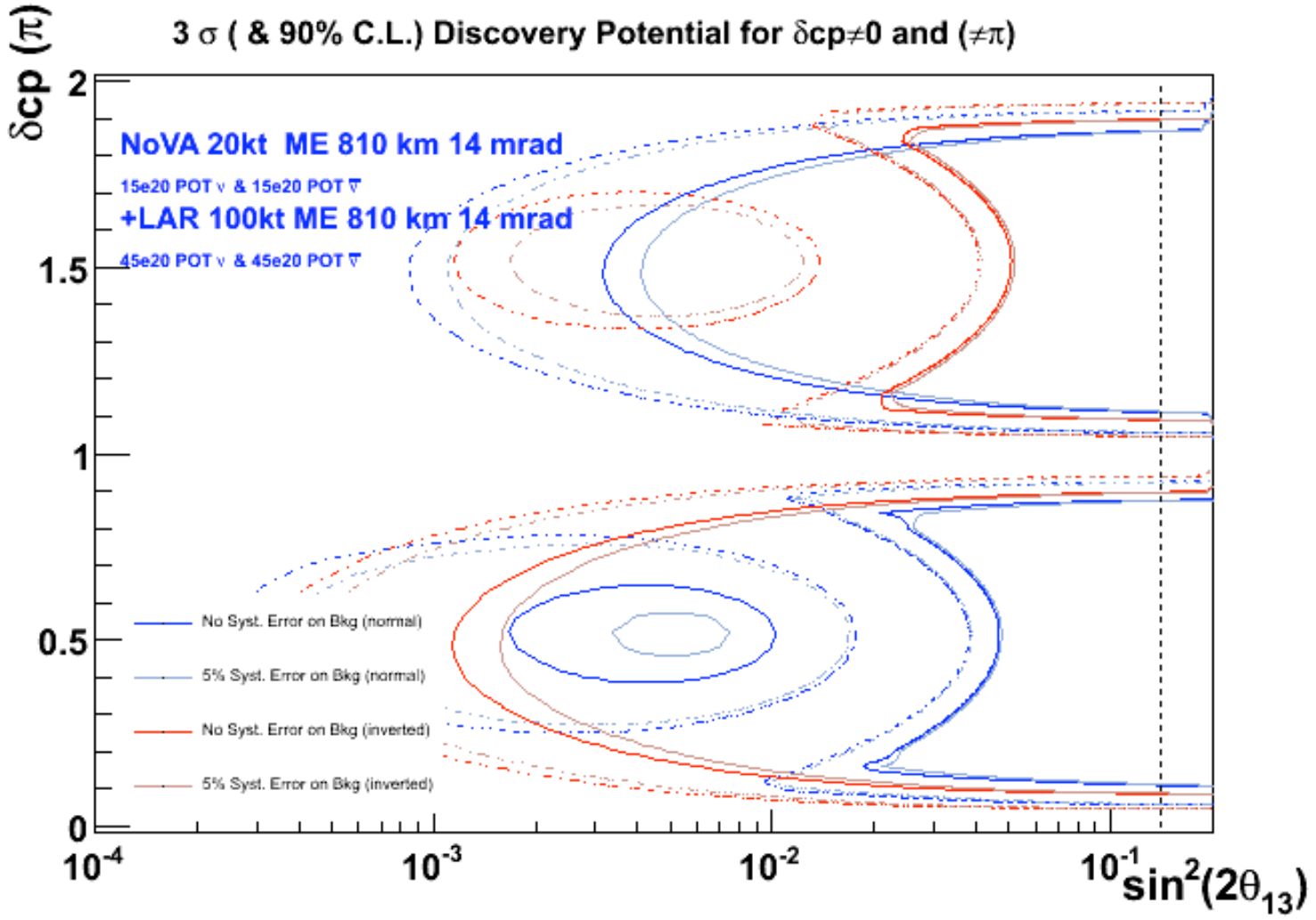
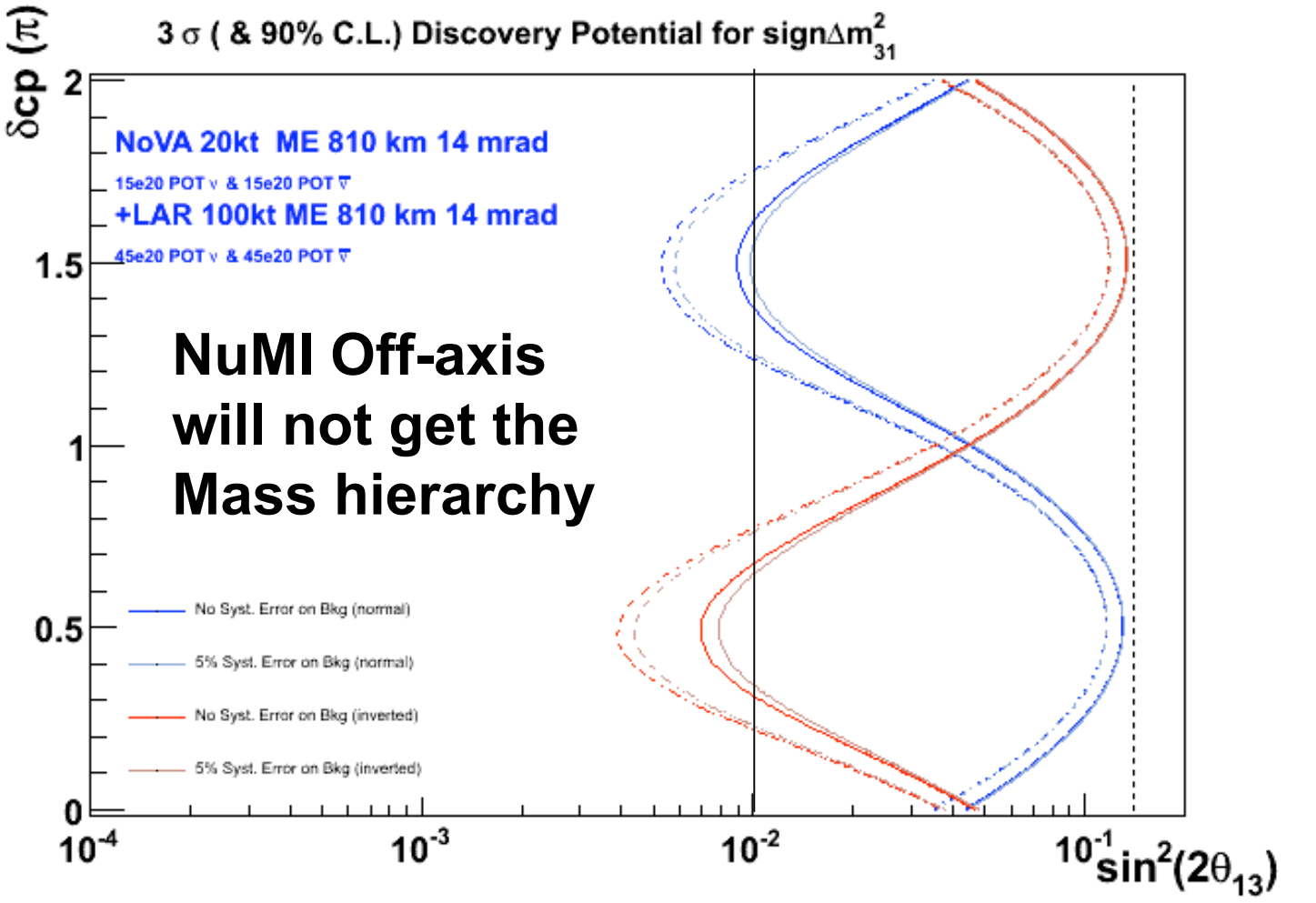


We cover the region at the 90%CL

Phase I : $\sin^2 2\theta_{13} < 0.01$




3 σ (& 90% C.L.) Discovery Potential for δcp≠0 and (≠π)
δcp (π)
NoVA 20kt ME 810 km 14 mrad
15e20 POT ν & 15e20 POT ν̄
+LAR 100kt ME 810 km 14 mrad
45e20 POT ν & 45e20 POT ν̄
No Syst. Error on Bkg (normal)
5% Syst. Error on Bkg (normal)
No Syst. Error on Bkg (inverted)
5% Syst. Error on Bkg (inverted)
2
1.5
1
0.5
0
10^-4
10^-3
10^-2
10^-1
sin^2(2θ13)


3 σ (& 90% C.L.) Discovery Potential for signΔm^2_{31}
δcp (π)
2
1.5
1
0.5
0
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15e20 POT ν & 15e20 POT ν̄
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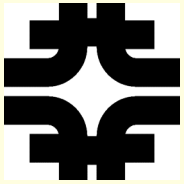
45e20 POT ν & 45e20 POT ν̄
NuMI Off-axis
will not get the
Mass hierarchy
No Syst. Error on Bkg (normal)
5% Syst. Error on Bkg (normal)
No Syst. Error on Bkg (inverted)
5% Syst. Error on Bkg (inverted)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$\sin^2(2\theta_{13})$

Summary and 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.
- The exploitation of an existing, operating and upgradeable facility was a key factor in laying out the scenarios we have studied.
- If **$\sin^2 2\theta_{13} > \sim 0.03\text{-}0.05$**, the angle, the mass hierarchy and δ_{cp} can be determined by a combination of the currently planned experiments : NOνA, T2K and the reactors
- If **$0.01 < \sin^2 2\theta_{13} < \sim 0.03$**, the angle angle and δ_{cp} can be determined by a combination of the currently planned experiments : NOνA, T2K and the reactors; the mass hierarchy could be determined by adding two massive detectors to the NuMI off-axis program - one at the NOνA site and a second at the shorter baseline 2nd oscillation maximum
- If **$0.001 < \sin^2 2\theta_{13} < 0.01$**, the angle can be measured by placing a very large liquid argon detector at the NOνA site; this experiment also has sensitivity to δ_{cp}; in this case, the NuMI beam does not allow for determination of the mass hierarchy
- Timely and significant R&D and prototyping of the Liquid Argon detector is essential to a future program unless nature is very kind.
- A very small value of will require a different approach : possibly a WBB to a longer baseline, or even a Neutrino Factory.



Backup Slides

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  (Accelerator and NUmI Upgrade [ANU])
  - 11 batches
  - use Recycler (1.33 s cycle)
  - **6 x 10 ^{20} protons/year**

- Post-Collider era w/ Accumulator (>2012)
  - Use Accumulator
  - **10 x 10 ^{20} protons/year**

Conceptual Design Only