Report of the US long baseline neutrino study Part II

Gina Rameika

Fermilab

March 29, 2007

Talk to the FNAL Physics Advisory Committee

Outline

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

Scope of the Study

The charge to the Study participants (Montgomery/Dawson)

- Compare the neutrino oscillation physics 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 existing accelerator complex
    - 1 - 2 MW
    - Proton Driver (~2MW)

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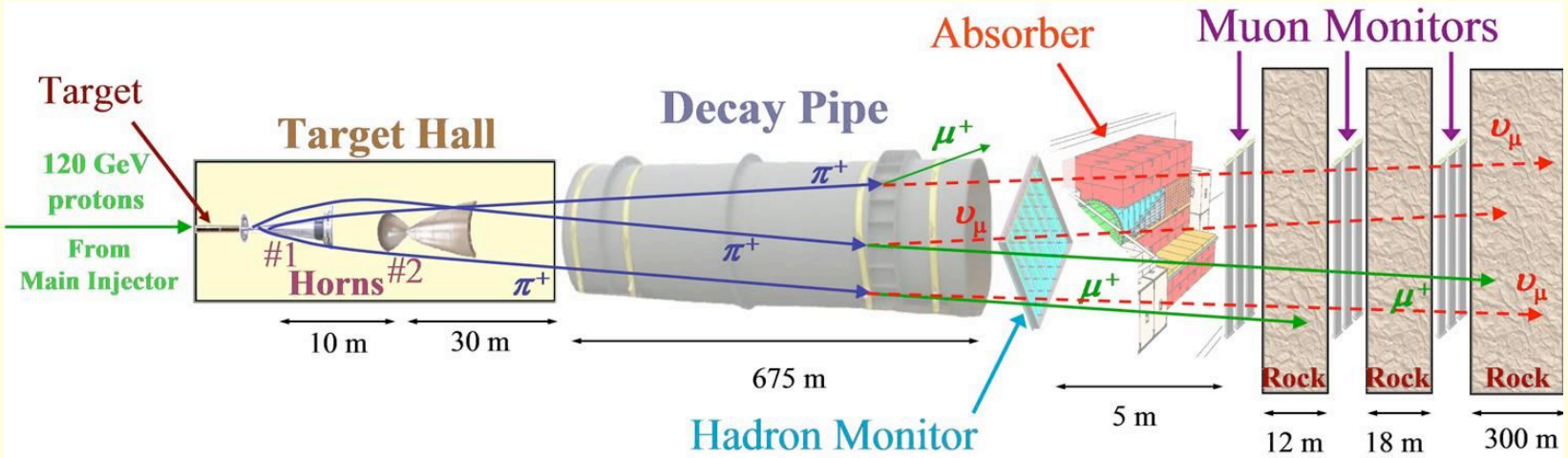
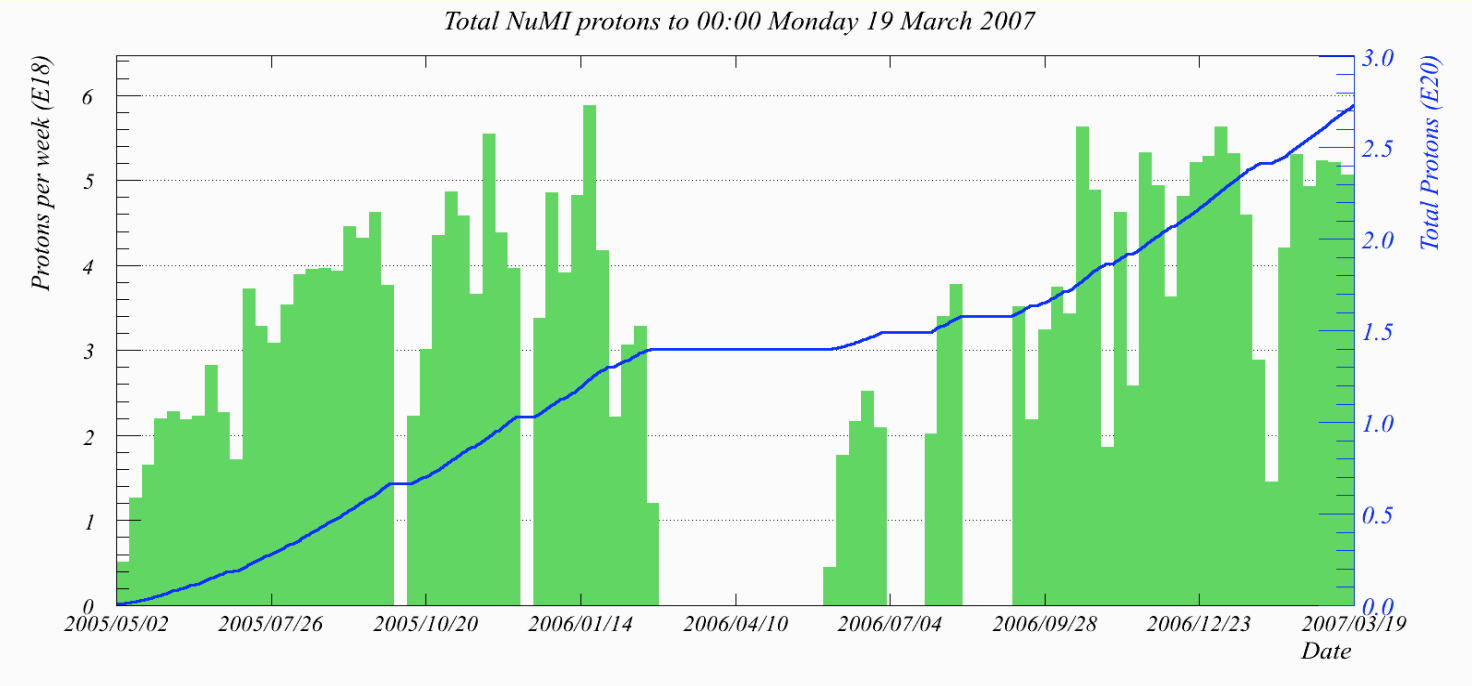
* For a discussion of the R&D and technology issues see : http://nwg.phy.bnl.gov/~diwan/nwg/fnal-bnl/report.pdf

The NuMI Beam

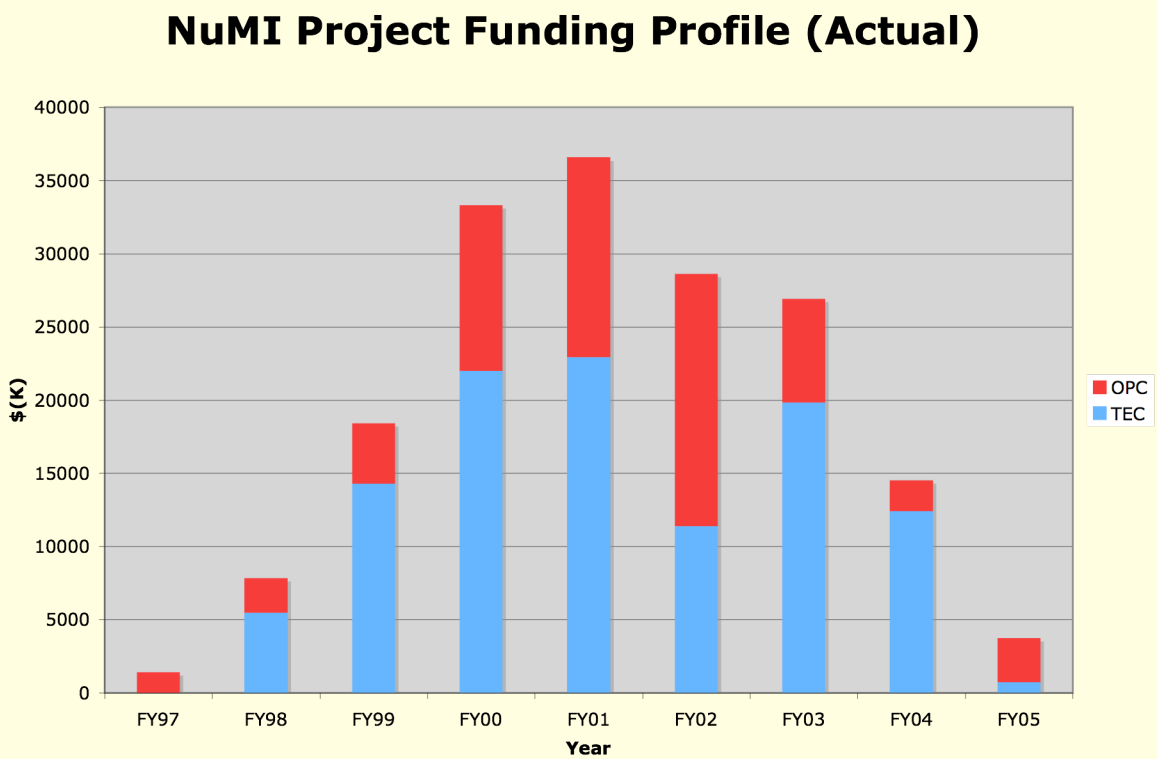




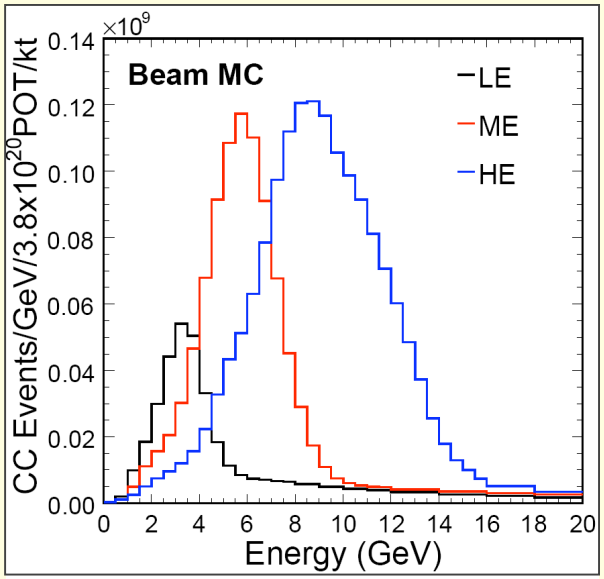
- Physics data set since May 2005 : **2.744E20**
- Since June 2006 : 1.35E20
- This fiscal year : 1.066E20

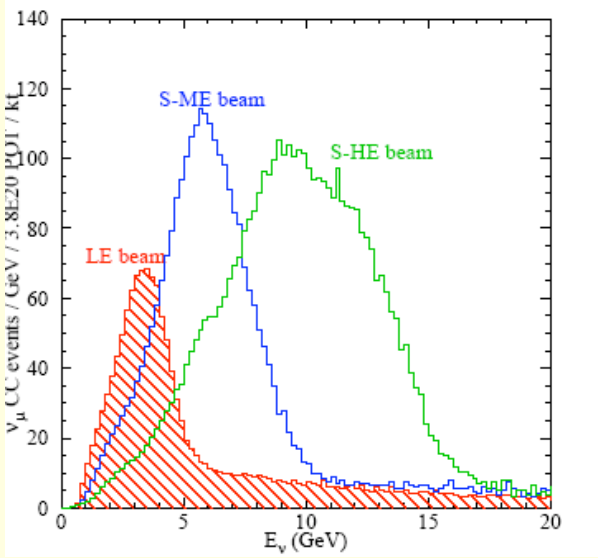
Motivation for the NuMI Off-axis option

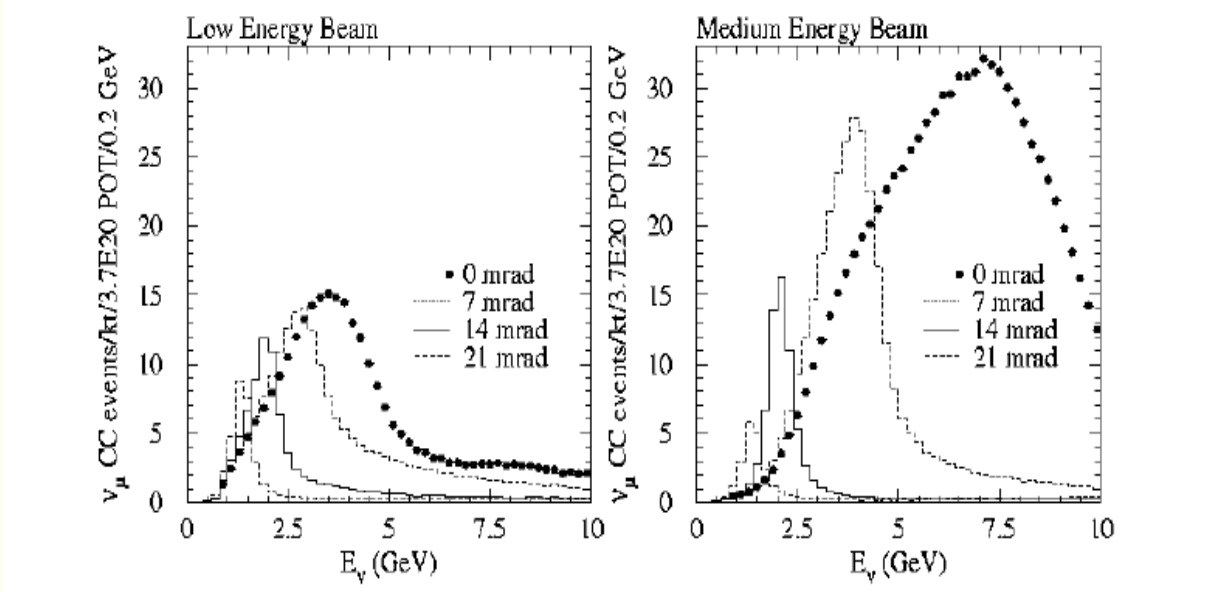
- Exploit our ***investment*** in an ***existing facility***
  - NuMI project took 9 years to construct and commission
  - TEC (civil + beam) = $109 M



- 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





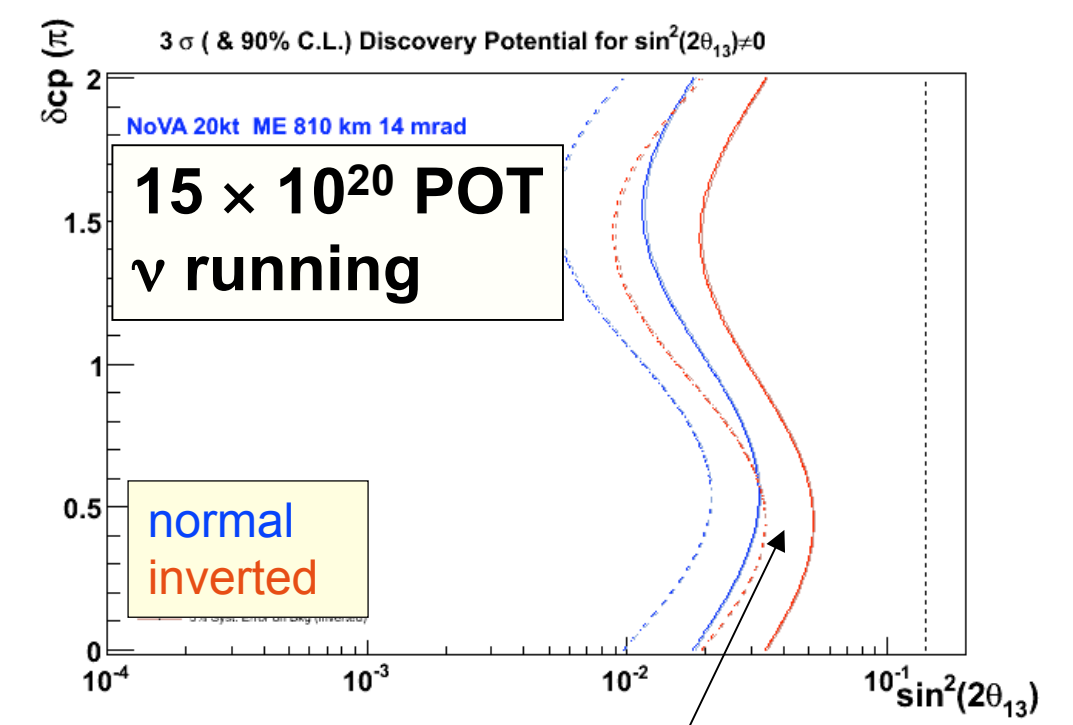


$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta_{ab} \sin^2(1.27\Delta m_{ab}{}^2 L/E)$$

- 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 NOνA
  - 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…

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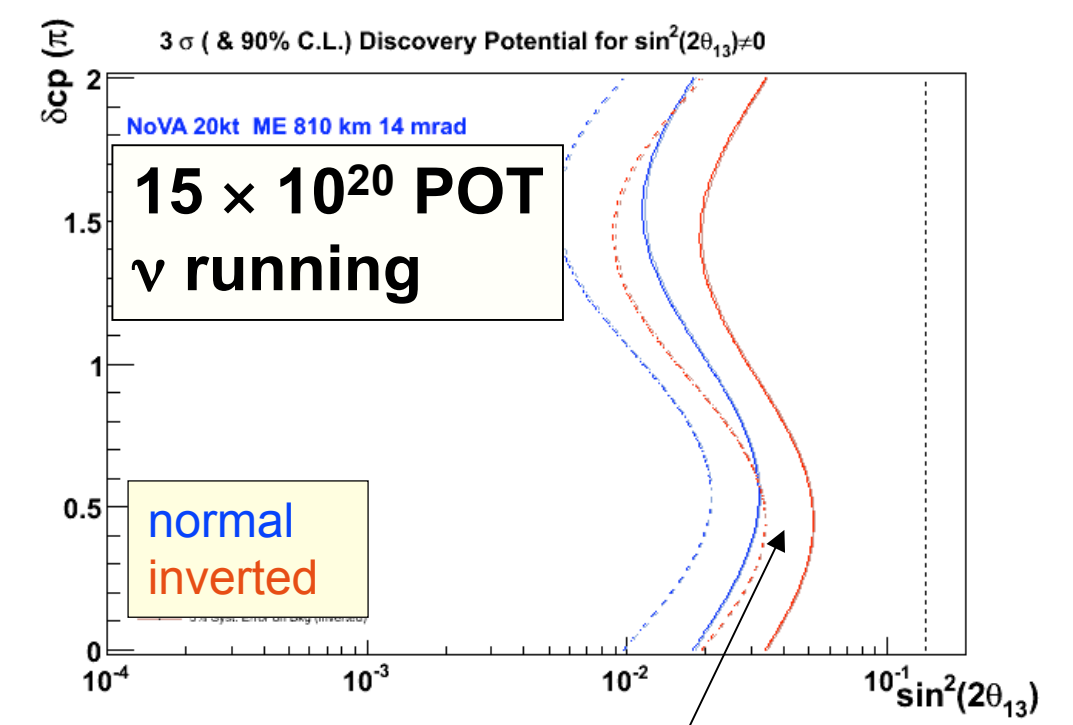
Note : NOνA plots come from our study and have not been cross-checked against the latest calculations being done for the NOνA TDR - we believe they are consistent



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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
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- Post-Collider era w/ Recycler (2010-2011)
  (Accelerator and NuMI Upgrade [ANU])
  - 11 batches
  - use Recycler (1.33 s cycle)
  - **6×10^{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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This is an important decision point …

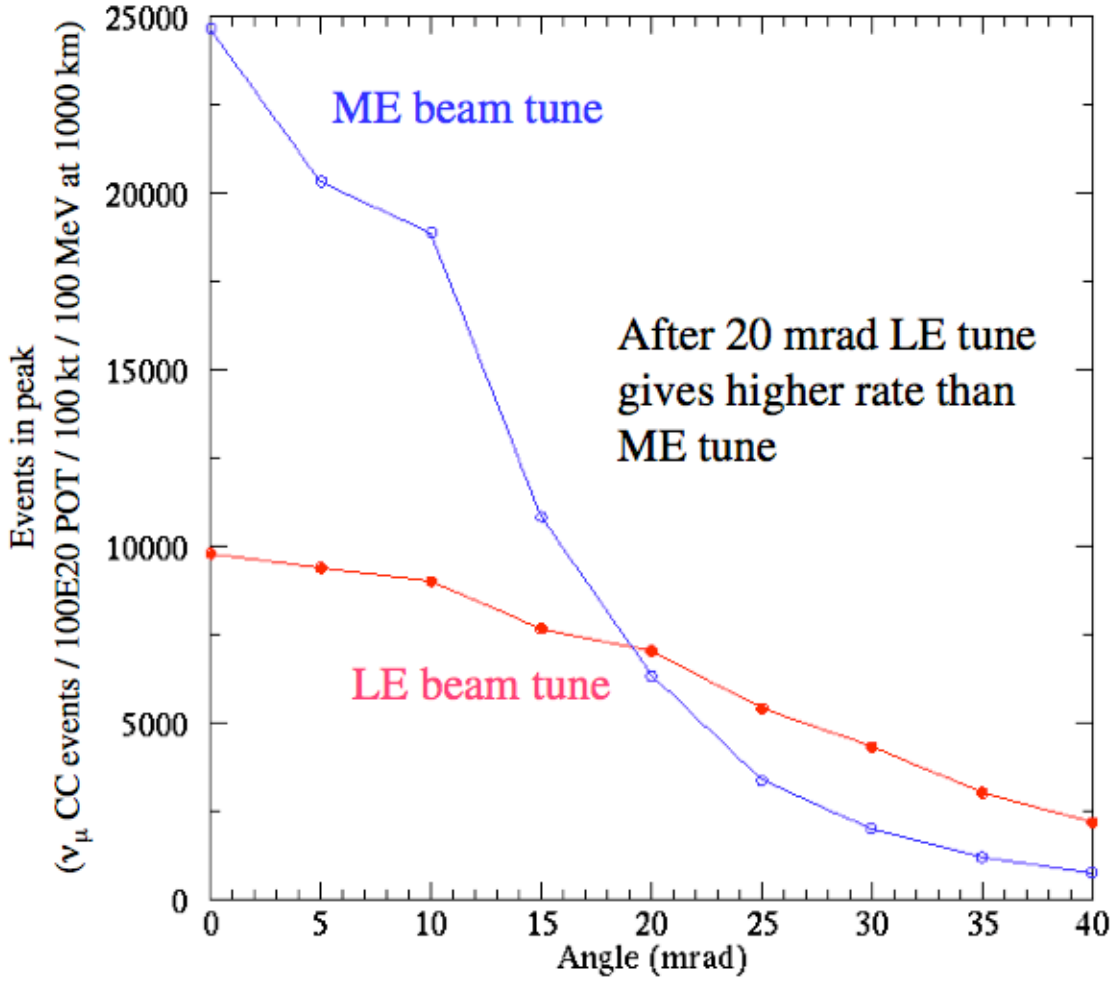
Decision Points

- Based on the expected capability of the NuMI beam, detector capability (both NOνA and LAr) and timescales on which measurements can be achieved, we have determined that the following categories of $\sin^2 2\theta_{13}$ sensitivity make sense to consider
  - $\sin^2 2\theta_{13} > 0.03$
  - $0.01 < \sin^2 2\theta_{13} < 0.03$
  - $0.001 < \sin^2 2\theta_{13} < 0.01$
  - $\sin^2 2\theta_{13} < 0.001$
- Once a definitive non-zero determination of θ_{13} has been made, the goal is to make 2 measurements :
  - Determine the neutrino mass hierarchy
  - Determine the value of δ_{CP} (it may be 0)

Strategy Considerations

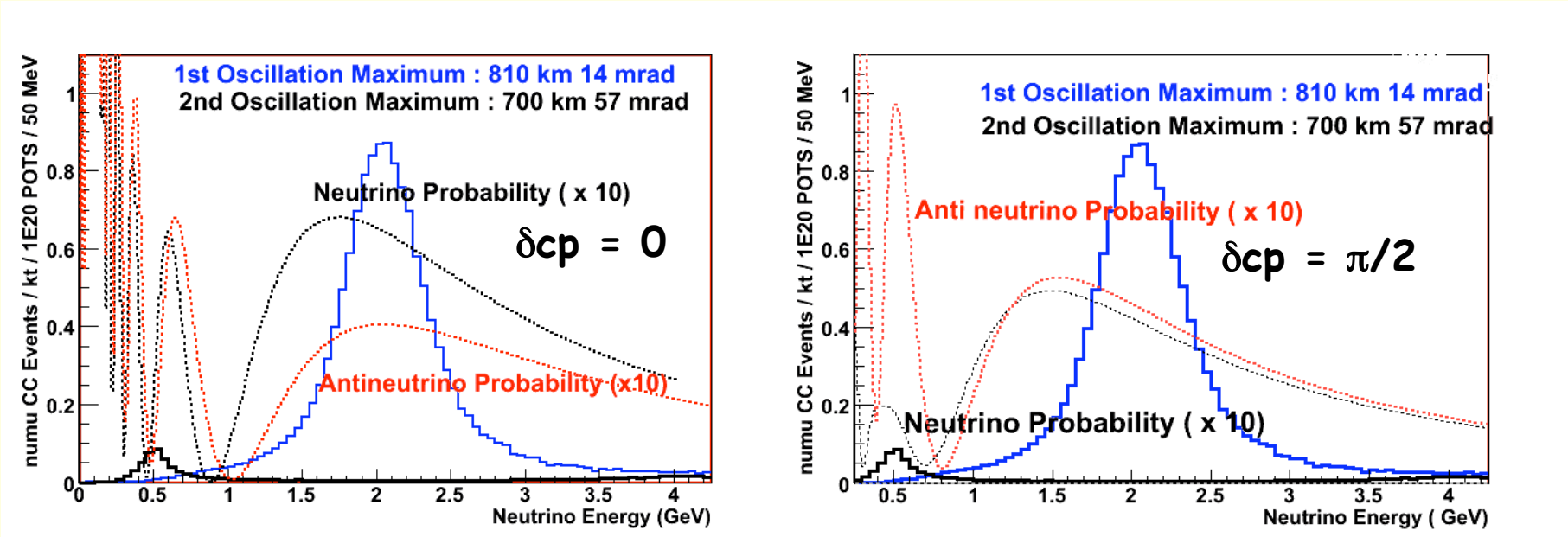
- Off-axis technique lends itself to a counting experiment (as opposed to fitting events to a spectrum)
- Event rates and energy are a strong function of the off-axis angle
- Matter effects can be used to extract the mass hierarchy by running both neutrinos and anti-neutrinos (affected oppositely by matter)
  - Increases with energy and baseline
- CP also affects neutrino and anti-neutrino oppositely
  - CP and matter can get “confused” → ambiguities

Comparing event rates as function of off-axis position



Plot by M. Messier

1st and 2nd "maximum"



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

Advantage

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

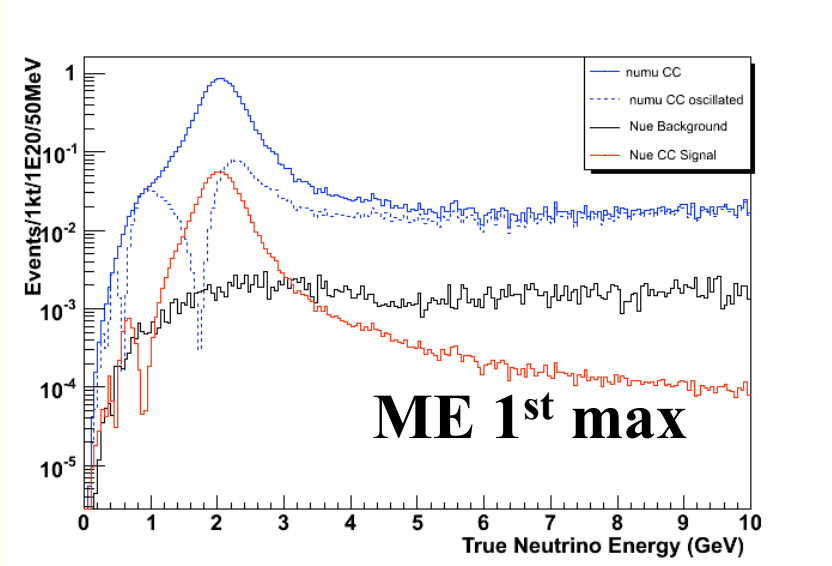
Disadvantage

- Neutrino Flux @ 2nd Maximum is low.
- Optimization studies were performed placing Detectors @ both Locations.

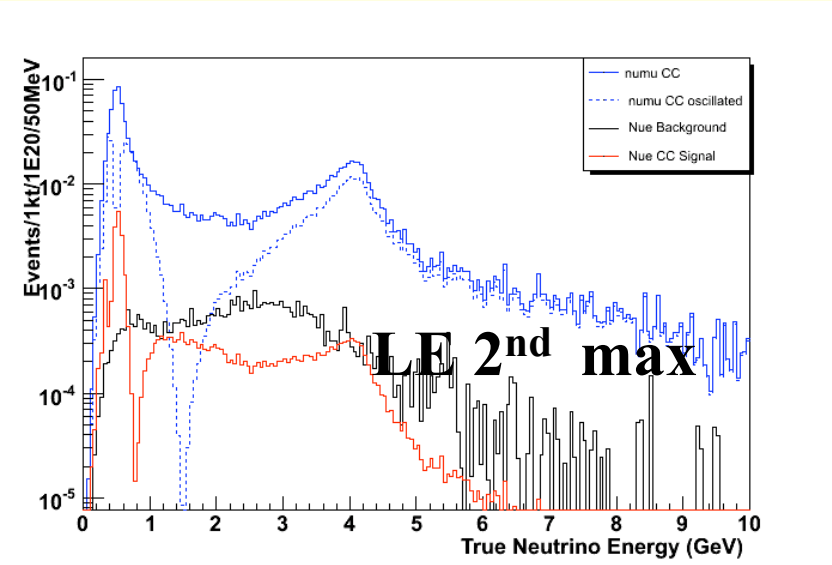
Off-axis Options

- 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)



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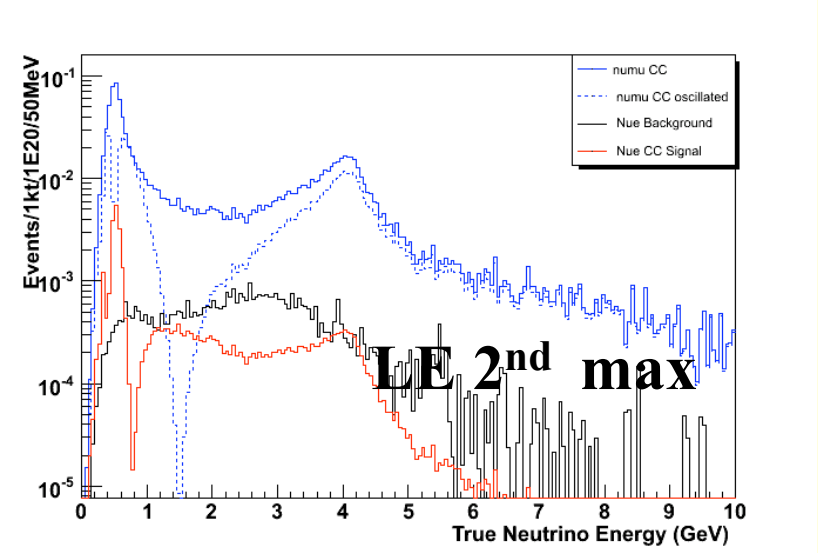
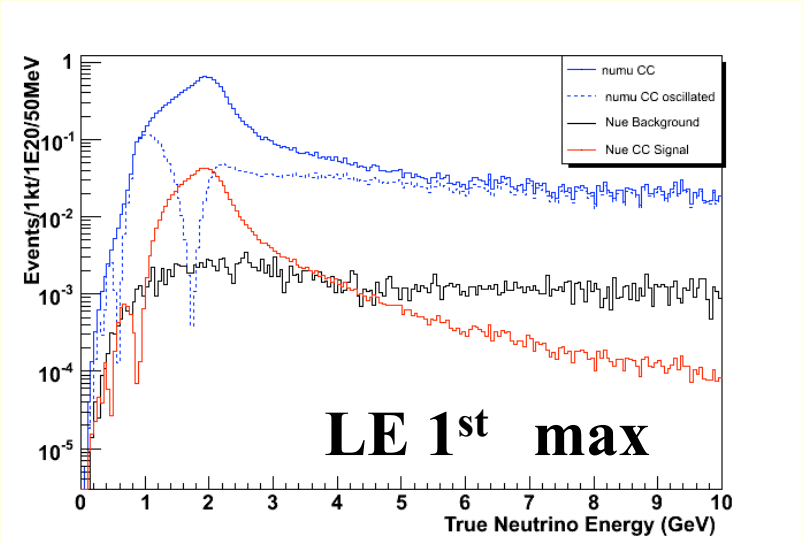
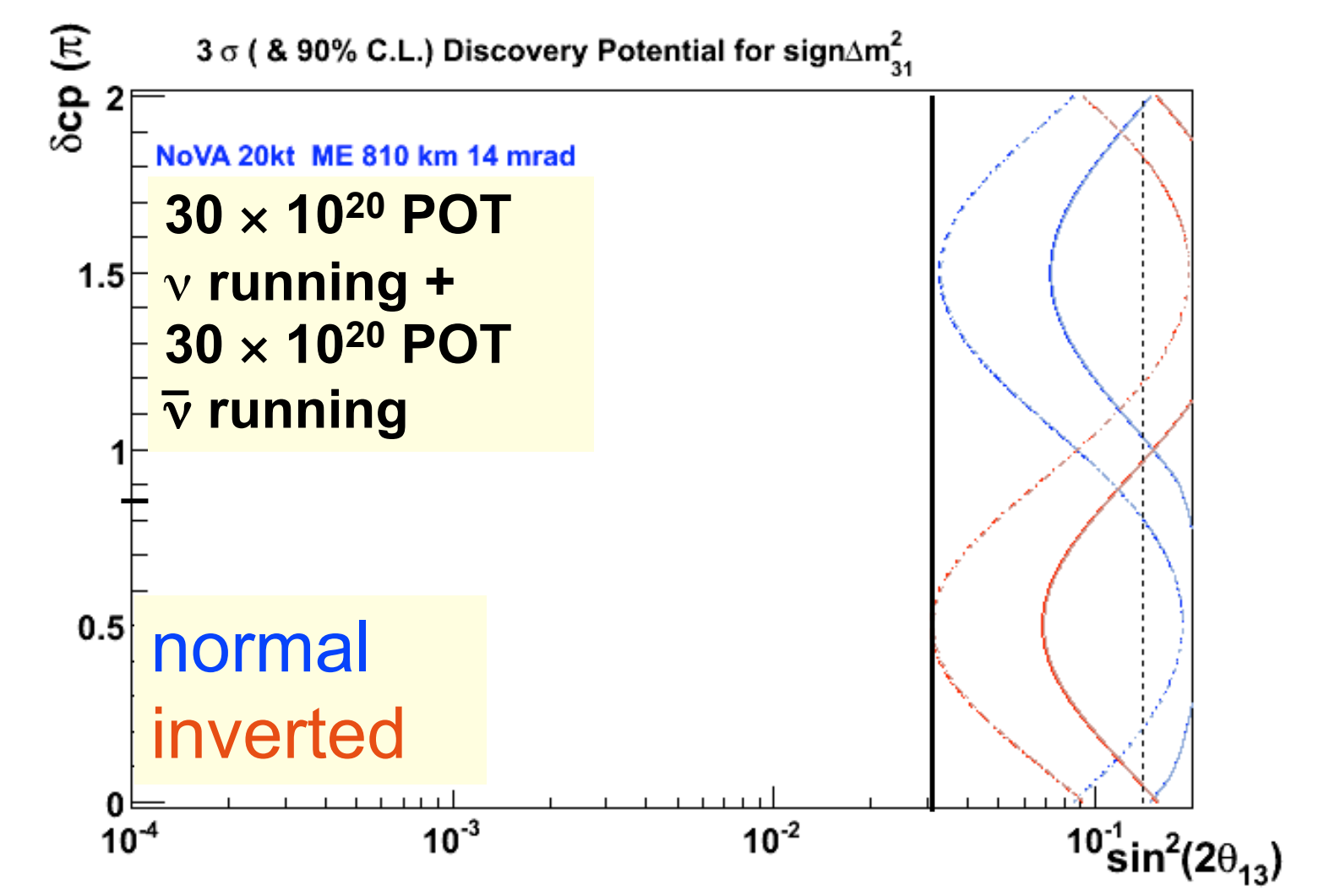


- Low energy beam does not significantly hurt the event rate at the 1st maximum

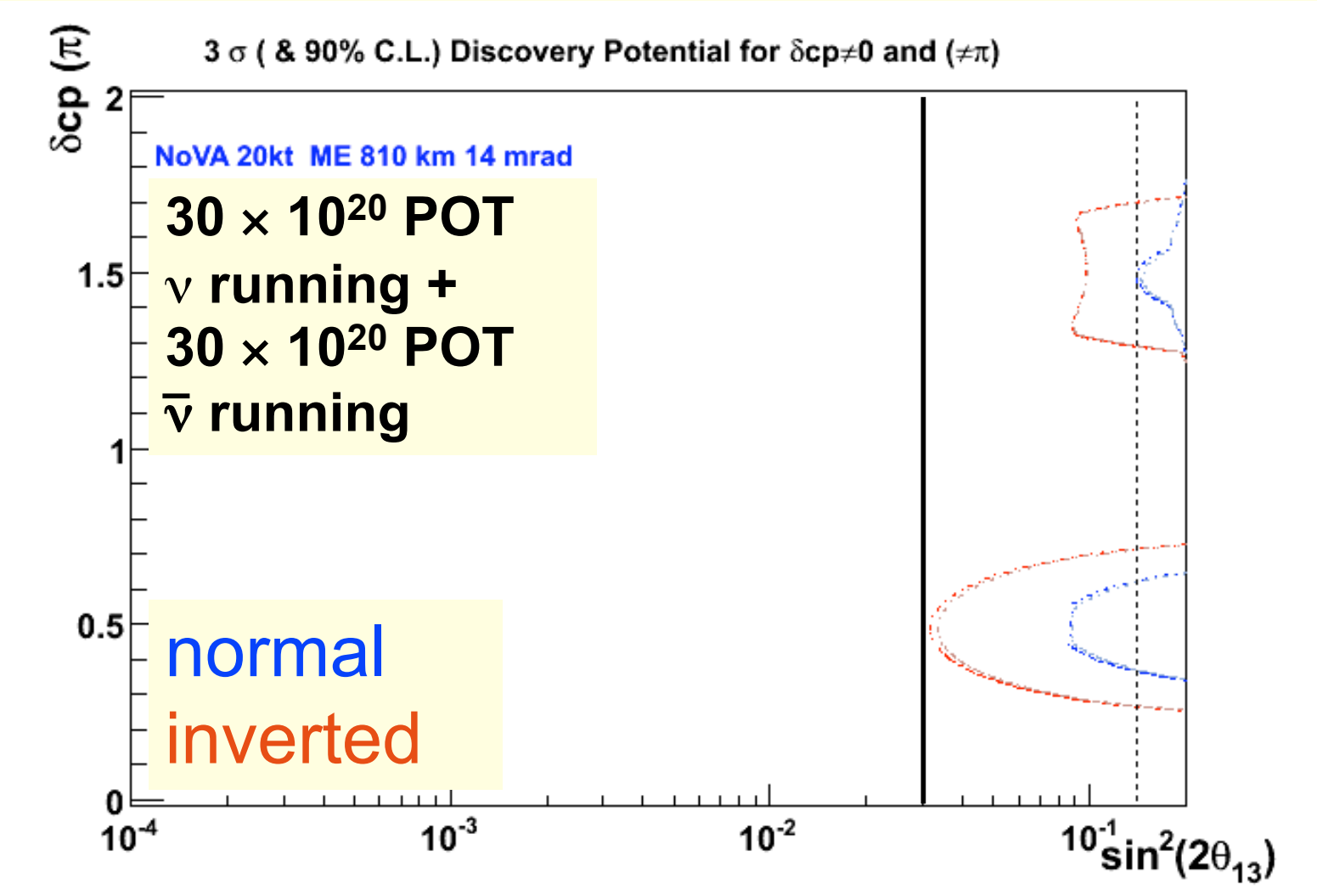


$\sin^2 2\theta_{13} > 0.03$



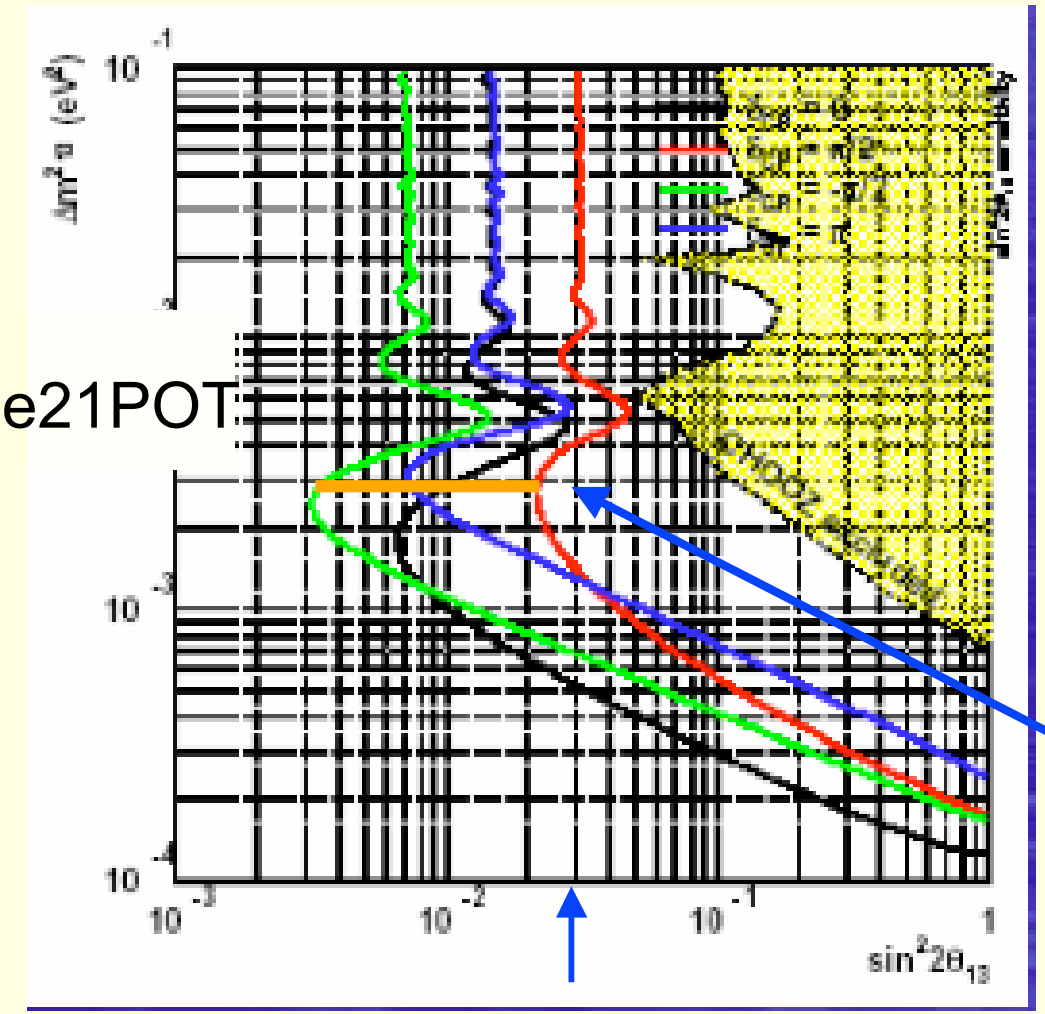
NOνA can try to measure the mass hierarchy (90%CL) …

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



But has low (no?) sensitivity to CP…

T2K 90% CL



A modest turn-on and continuous improvement in beam power gets to 5e21 ~ 2014.

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

Good sensitivity to δ_{CP} for all values if θ_{13} is large; degeneracies in parameter determination exist →multiple measurements are needed including anti-neutrinos

If nature is kind…(large θ_{13})

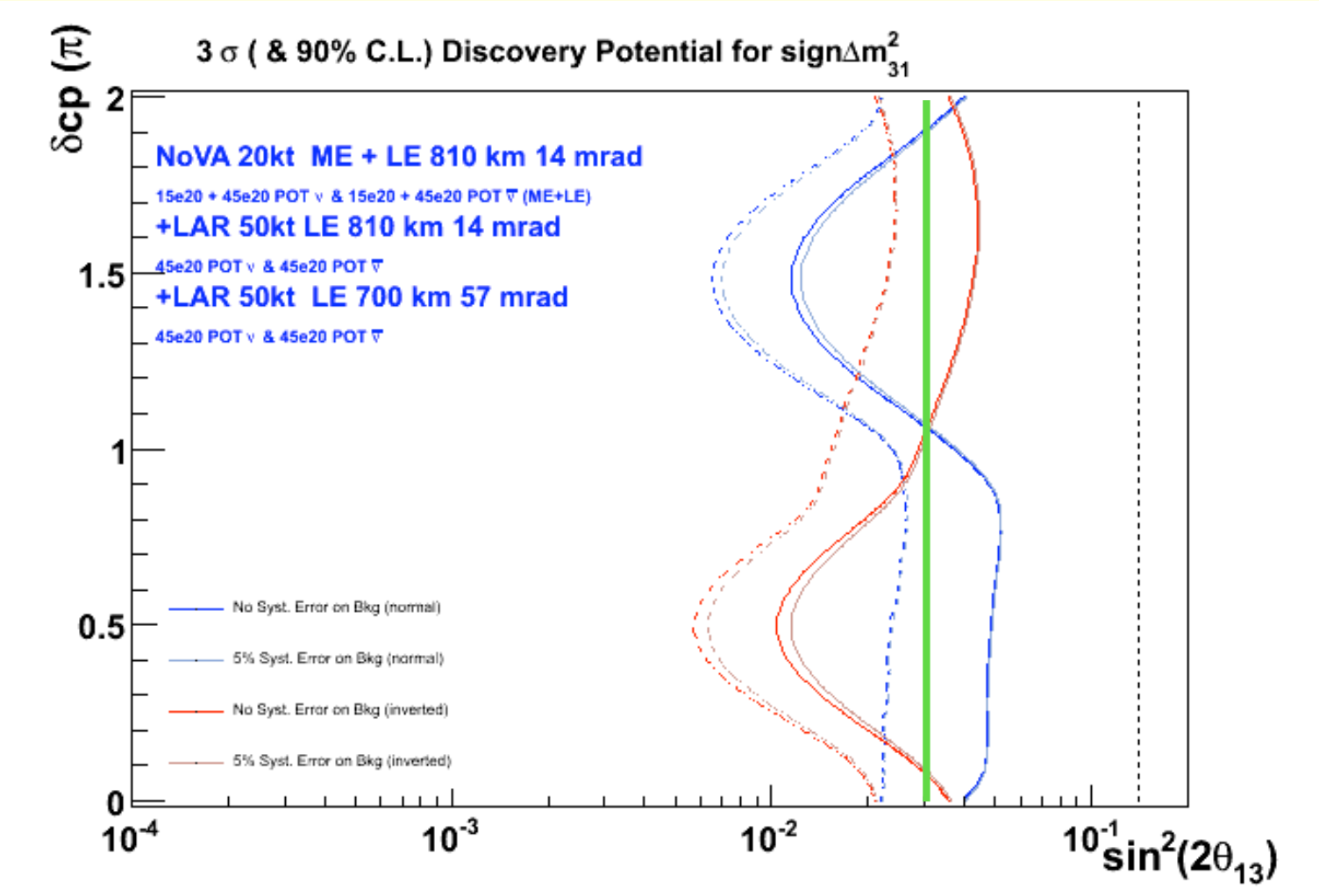
- NOνA can run anti-neutrinos and try to determine the mass hierarchy; success depends on nature's value of δ_{CP}
- To **definitively** determine the mass hierarchy using the NuMI off-axis option we have to consider a more powerful detector technology (than NOνA) that:

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

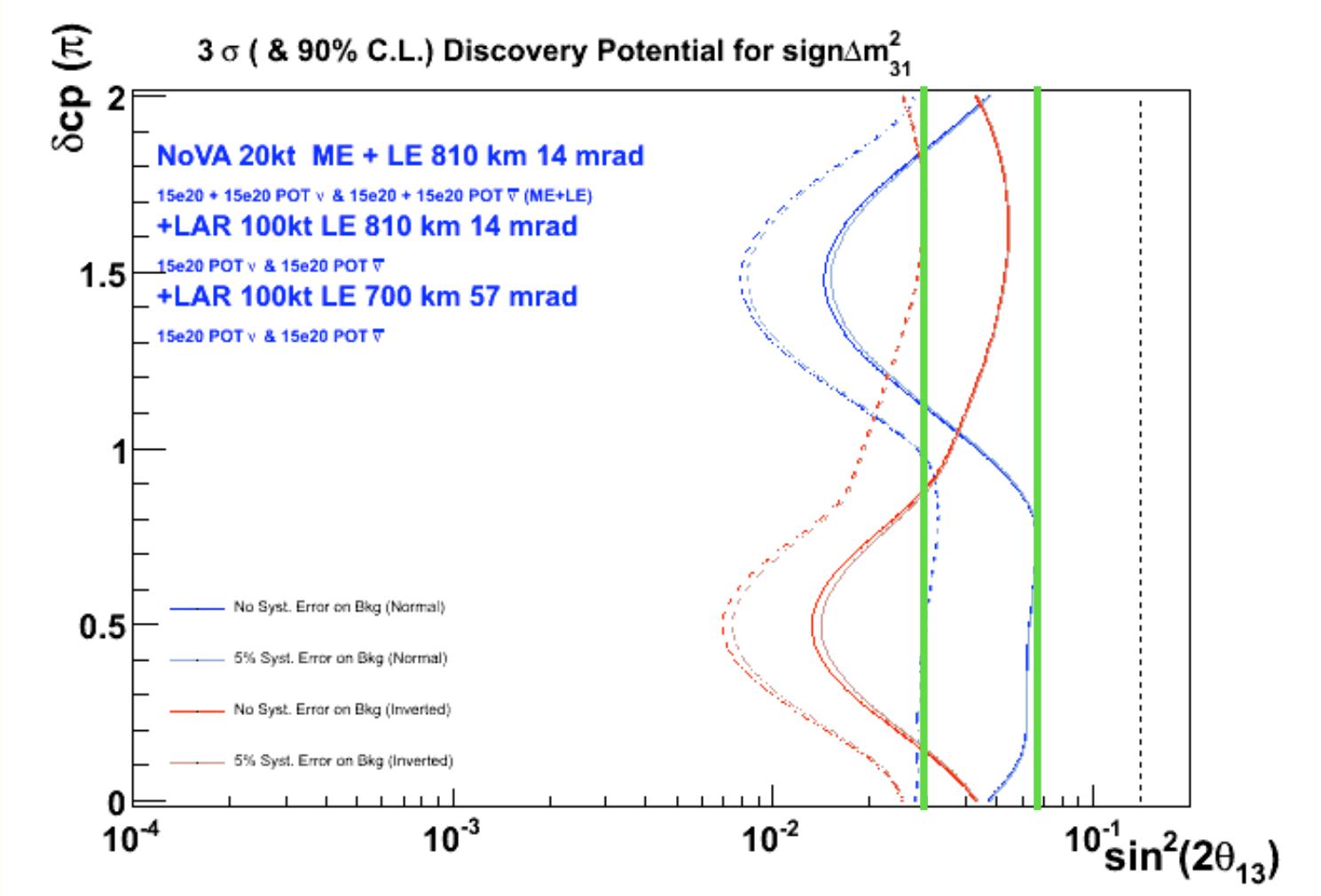
  2) Has very high efficiency and very high background rejection capabilities for low energy neutrinos (0.5-3 GeV)

  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 with many criteria to satisfy along the way to a large detector and therefore progress has to be made (R&D) while Phase I is ongoing.

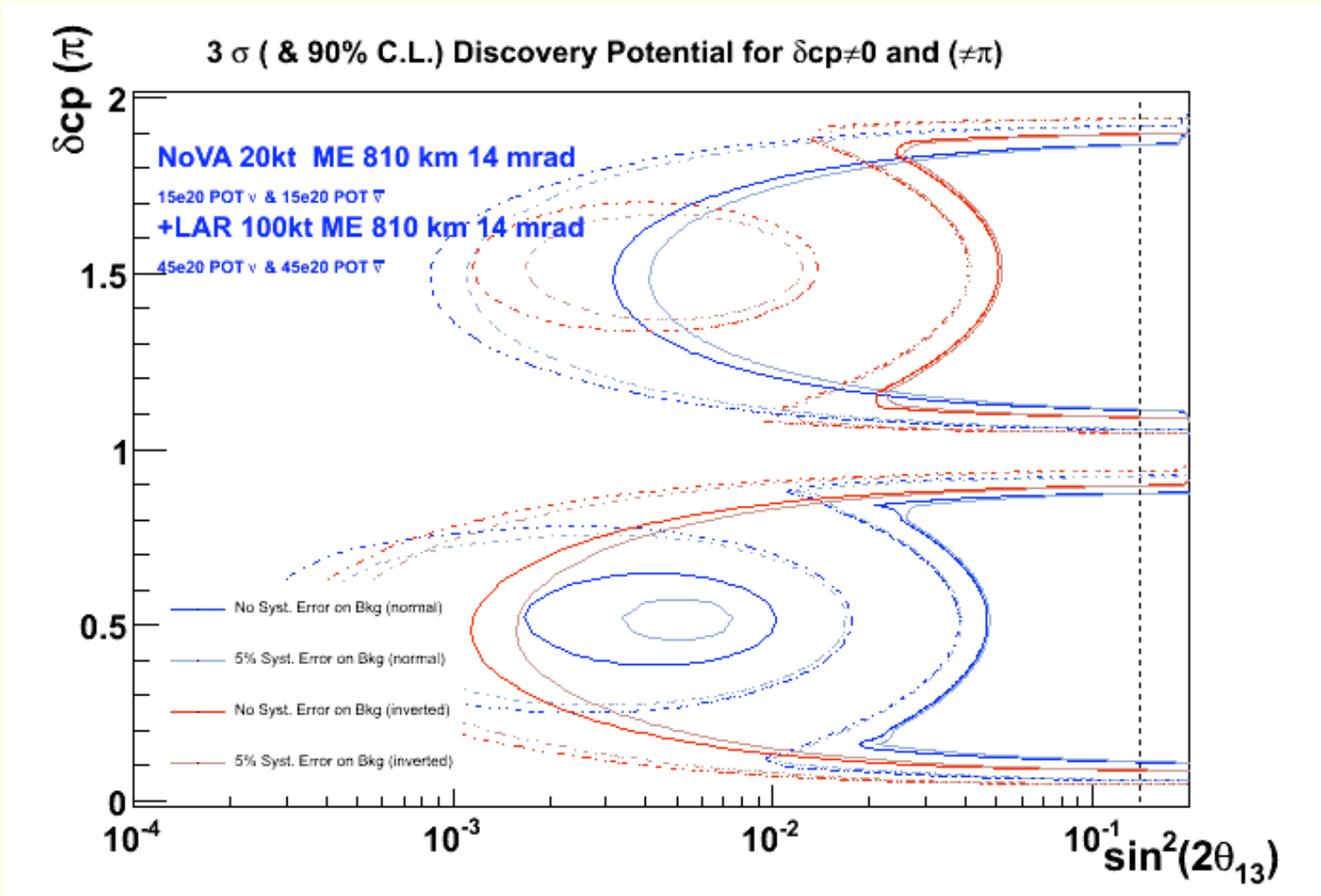
Add mass, efficiency and POT



Add *more* mass, efficiency and fewer POT (less time)

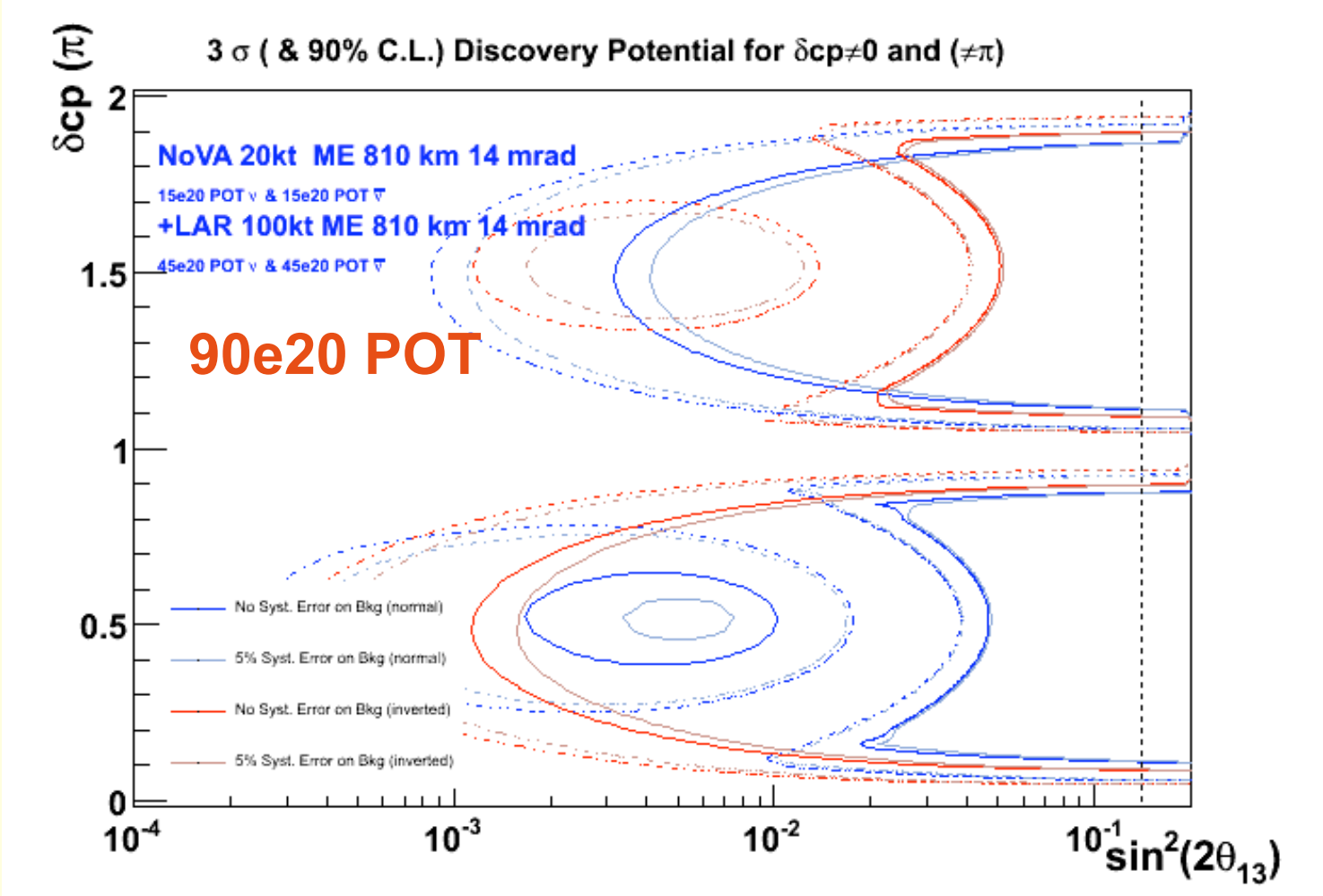


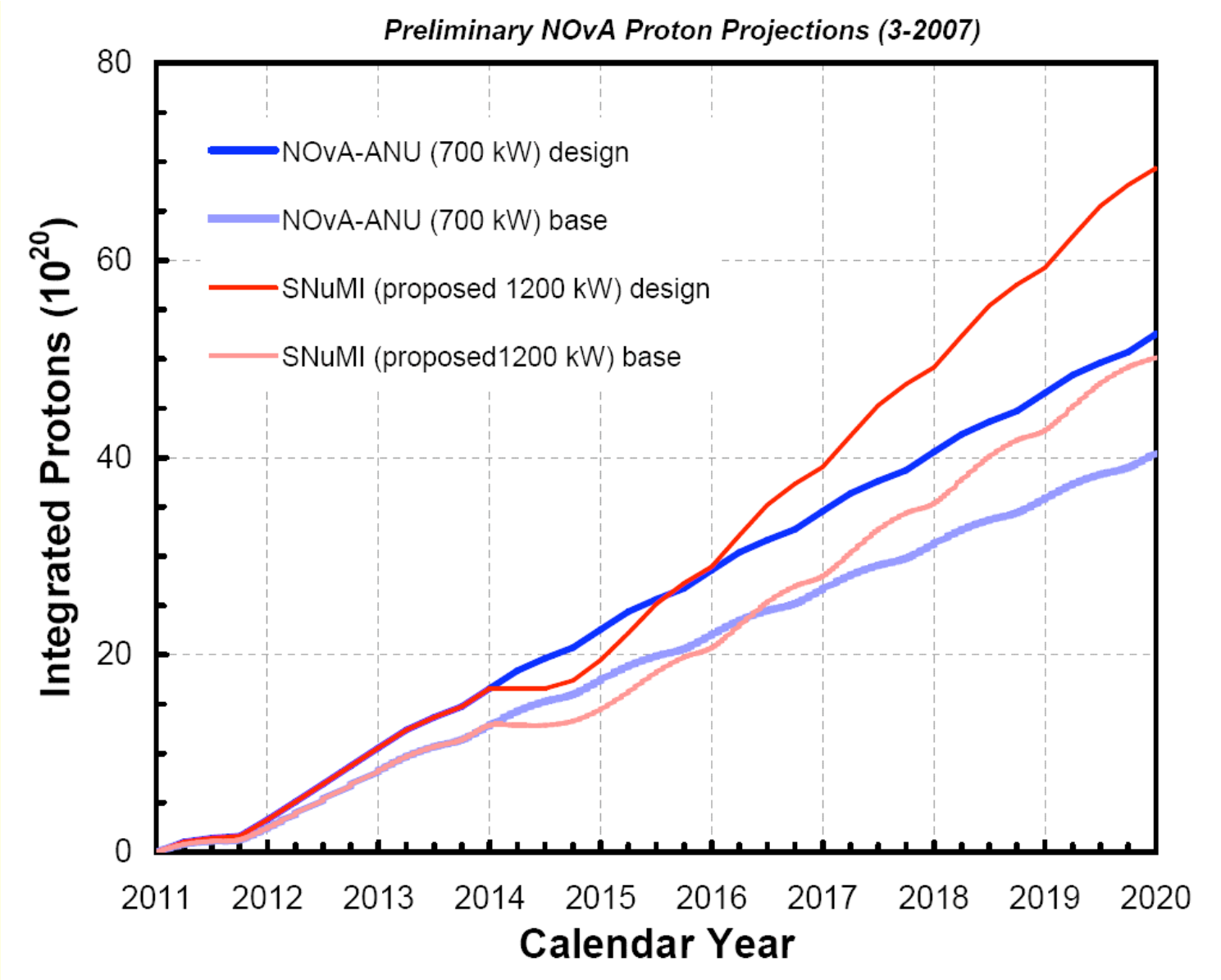
A massive detector at
1st maximum also has good
sensitivity to CP for a large θ_{13}



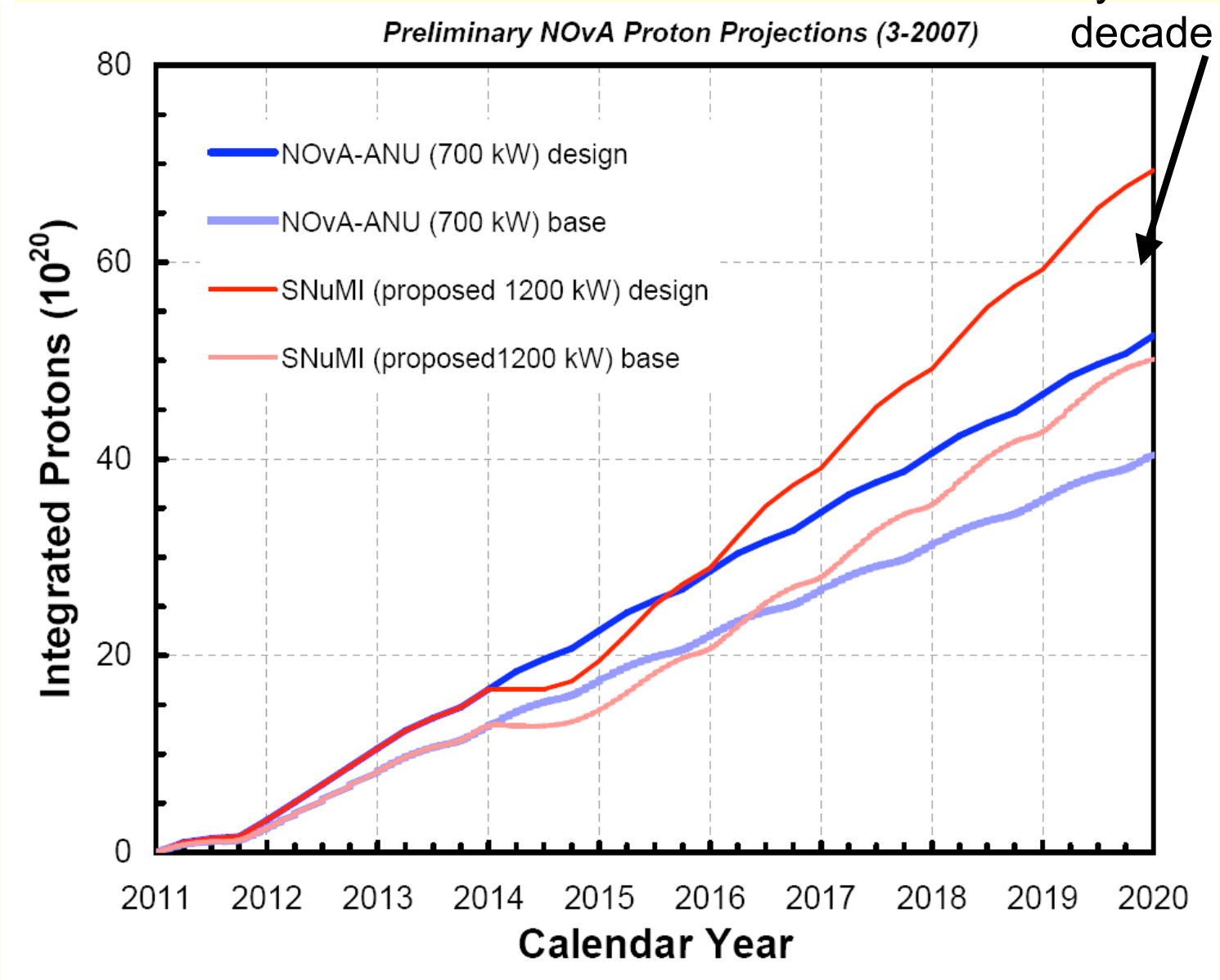
A massive detector at 1st maximum has good sensitivity to CP for a large θ_{13}

But it will take time…

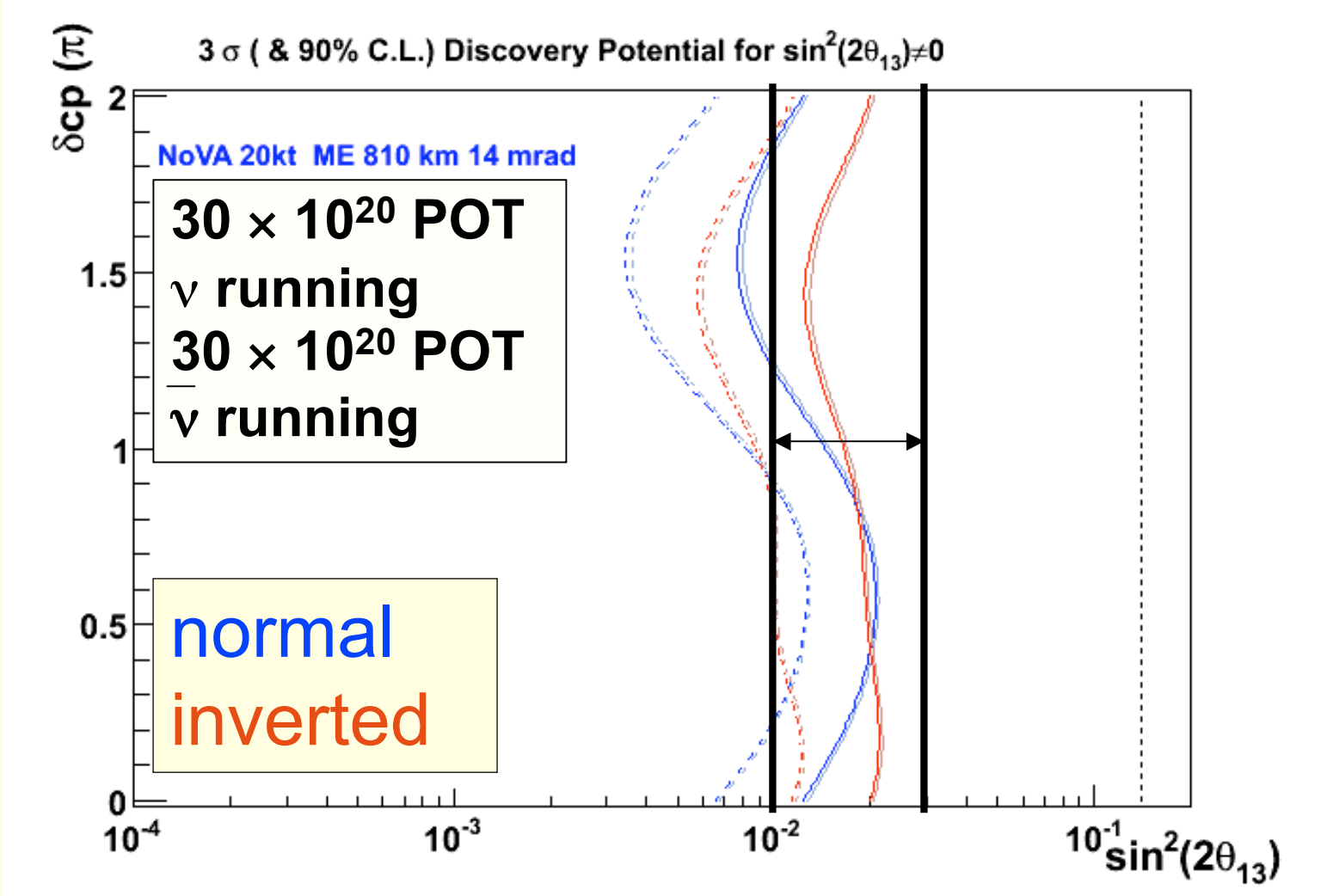



Preliminary NOvA Proton Projections (3-2007)
NOvA-ANU (700 kW) design
NOvA-ANU (700 kW) base
SNuMI (proposed 1200 kW) design
SNuMI (proposed1200 kW) base
Integrated Protons (10^{20})
0
20
40
60
80
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
Calendar Year

We get 60e20 with SNuMI by end of next decade



Suppose Phase I tells us : $0.01 < \sin^2 2\theta_{13} < 0.03$



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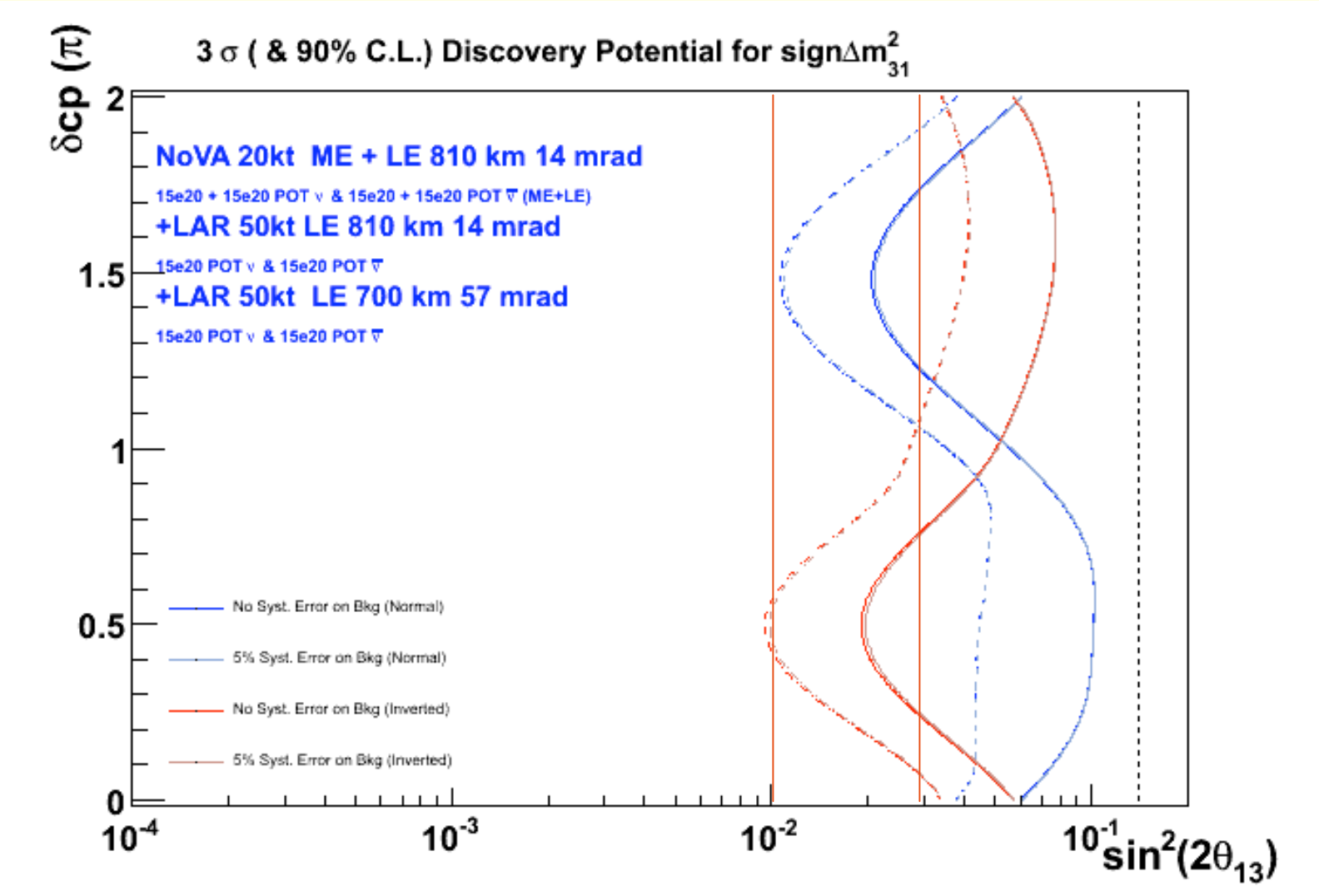

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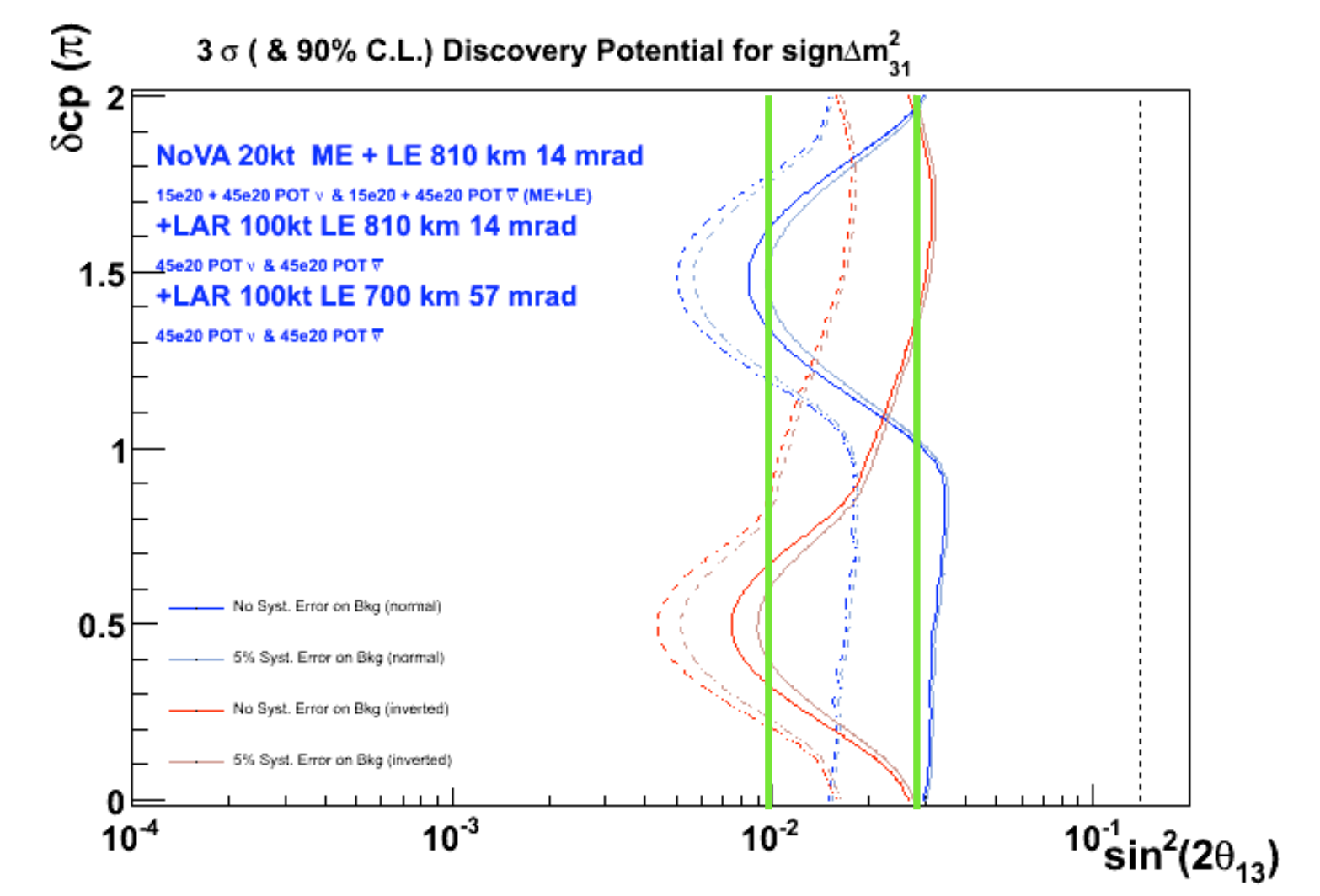

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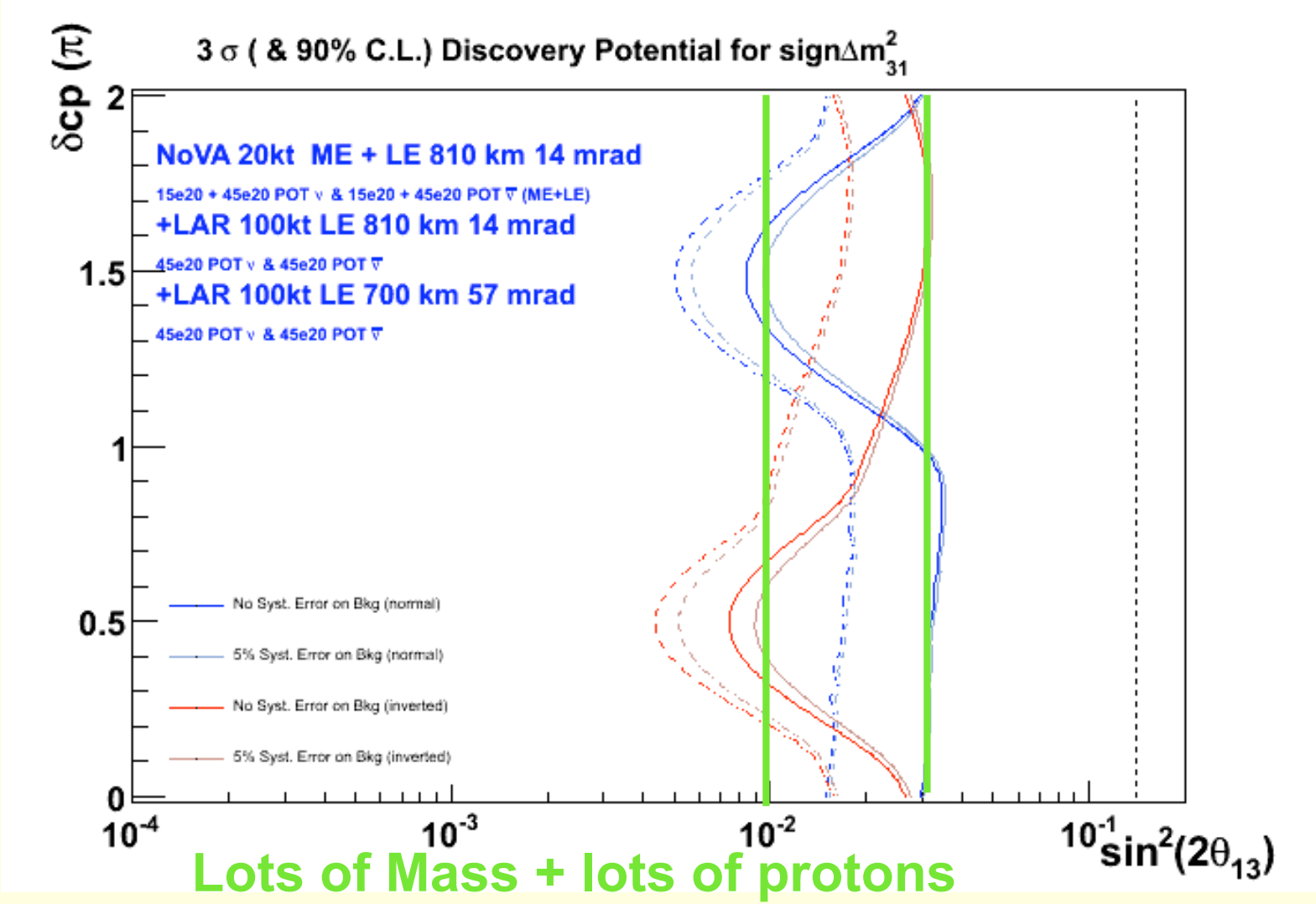
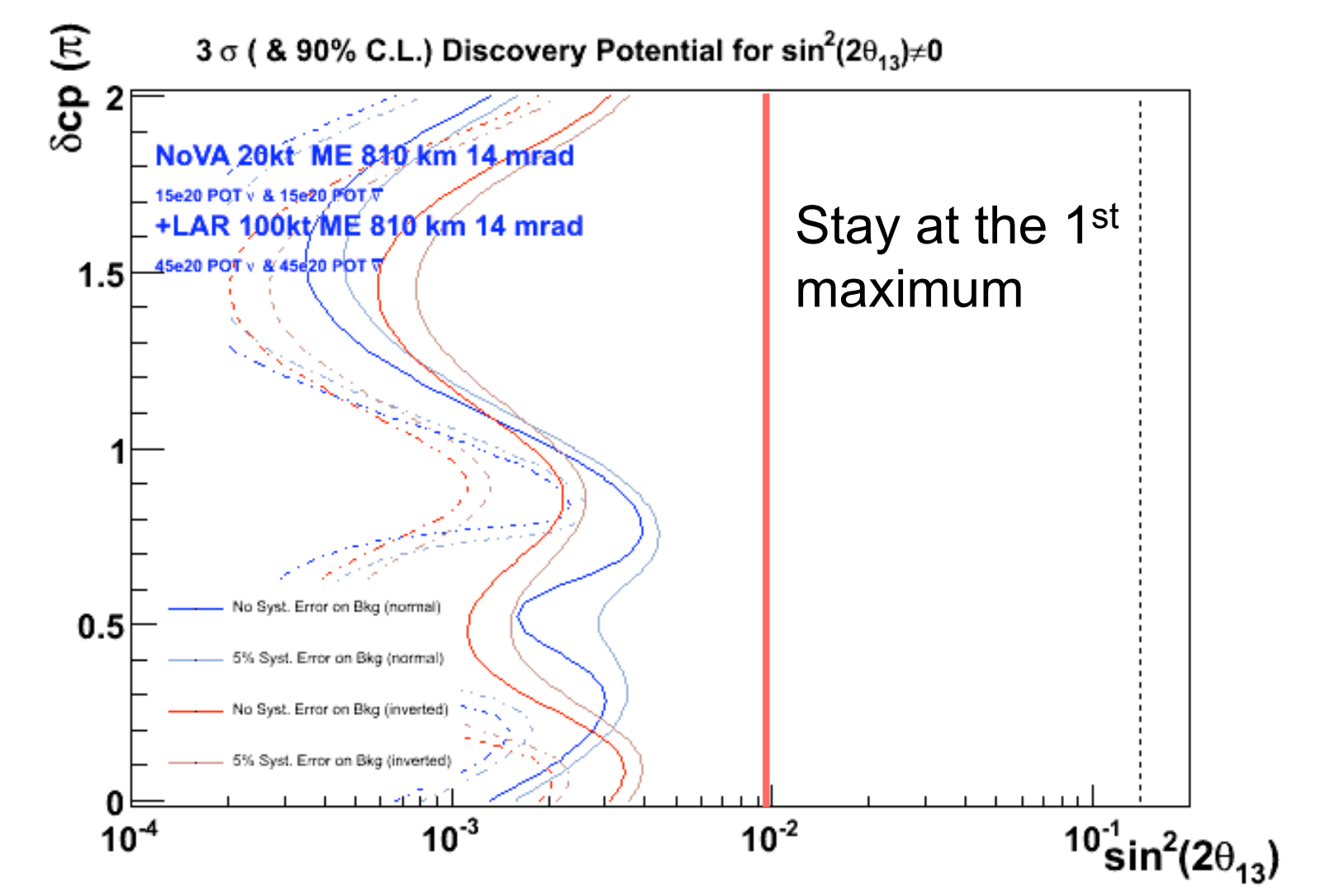
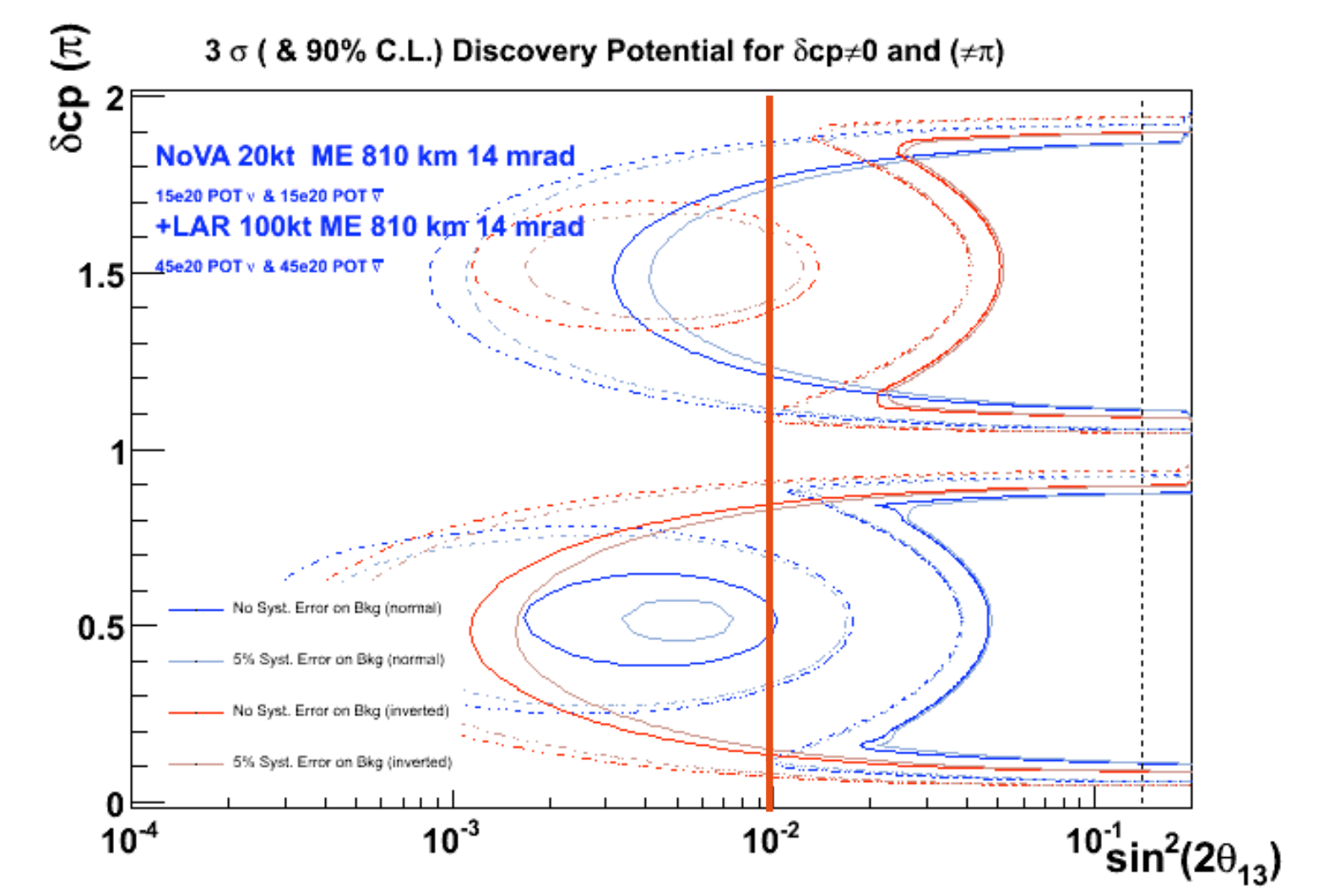


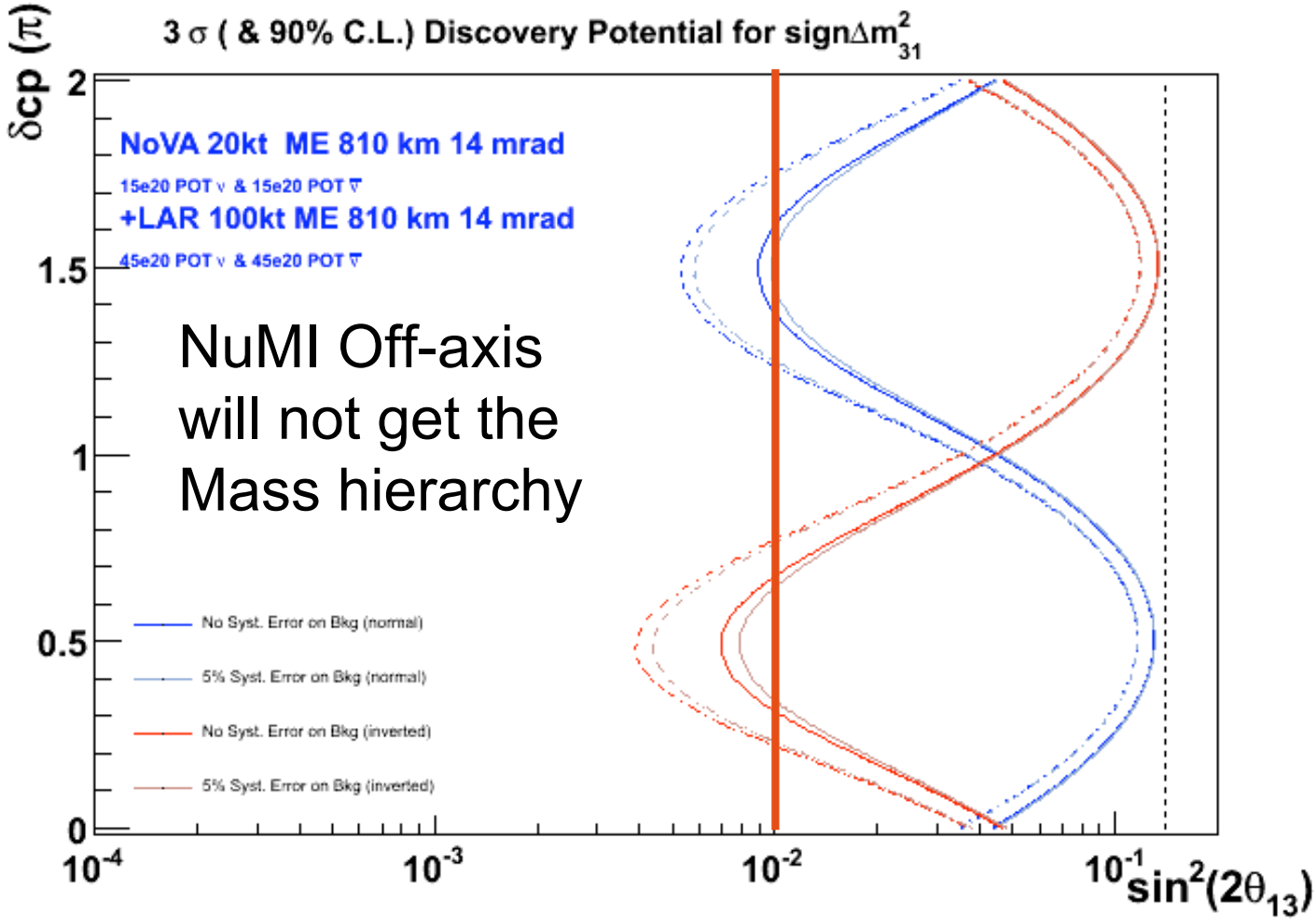
Lots of Mass + lots of protons

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





Some sensitivity to CP



NuMI Off-axis will not get the Mass hierarchy

Conclusions

- If **$\sin^2 2\theta_{13}$ > ~0.03-0.05**, the angle, and indications about δ_{cp} (i.e.≠ 0) can be determined by a combination of the currently planned **Phase I** experiments : NOνA, T2K and the reactors
  - The mass hierarchy can be determined by a program in the NuMI beam, beginning with NOνA; A **Phase II** program with two massive detectors - one at the NOνA site and a second at the shorter baseline 2nd oscillation maximum increase sensitivity over the range of possible values of δ_{cp}
- If **0.01 < $\sin^2 2\theta_{13}$ <~0.03**, the measurements can still be achieved by a combination of the currently planned experiments
  - In a **Phase II** program using the NuMI off-axis beam the mass hierarchy could be determined for some fraction of the CP phase space; this program would benefit from the SNuMI upgrade and requires new detectors
- If **0.001 < $\sin^2 2\theta_{13}$ <0.01**, the angle can be measured in a **Phase II** program 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.
- Ultimately full determination of the parameters will require multiple measurements. Massive detectors and a lot of protons are required.

Status of the Study

- Began 1 year ago
- Just as the study was getting organized:
  - New charge to NuSAG…..
  - Report “completion” driven by NuSAG time line rather than our own
    - Particularly true for the NuMI off-axis option
- The report will be completed within the next several weeks.
  - NuSAG wants to see 3 and 5 sigma sensitivities
- Independent of the report we will continue as time permits to work on
  - Optimizing extraction of Phase I results (work on NOνA)
  - Explore optimization of a Phase II program for the two options :
    - Nature is kind
    - Life is tough

Summary

- 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.
- Our scenarios have used various sequences of running neutrinos and anti-neutrinos to explore sensitivity to the mass hierarchy; the actual way that one would collect data would likely differ, and **depend on what is learned early on**.
- Timely and significant **R&D and prototyping of massive and efficient detectors** is essential to a future program unless nature is very kind.
- Likewise, continued **development and ultimate construction of a HINS** would greatly enhance Fermilab's ability to carry out a long term neutrino program

Backup Slides

- The results we have shown are based on $\chi 2$ calculated assuming no knowledge of any of the parameters, and hence are the worse case scenarios.
- A full set of plots for all scenarios considered can be found in :
  - http://home.fnal.gov/~niki/FutureLongStudy/

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

Conceptual Design Only