FNAL->DUSEL Discovery potential for ν oscillation physics : Initial results and future plans

N. Saoulidou, Fermilab

Thursday , 14 August 2008

Outline

- The **ultimate** goals in **ν physics** and in particular in **ν oscillation physics**
- Phase I experiments and the **plan for Phase II.**
- Ultimate physics potential of an FNAL -> DUSEL neutrino oscillation program.
- Phase I physics potential of the FNAL -> DUSEL neutrino oscillation program.
- Assumptions/Limitations of physics potential calculations so far (Detector/Modeling/Systematics)
- Needed Next Steps
  - *Beam and Detector Simulation*
  - *Reconstruction*
  - *Event Identification*
  - *Systematics*
- Summary Conclusions

The ultimate goals in ν physics

EXPERIMENT (Accelerator ν's)

What is the value of the third mixing angle θ_{13} ?

Do neutrinos violate CP symmetry ?

Which neutrino is the heaviest one?

EXPERIMENT (natural ν's)

What are the neutrino masses ?

Are neutrinos their own anti-particles? (Majorana-Dirac)

THEORY

How do neutrino masses relate to quark masses?

How does neutrino mixing relates to quark mixing?

Origin of Matter – antimatter asymmetry in the Universe?

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

- Numerous studies over the past several years have laid out options for achieving the *ultimate goals :*
  - *Extend θ_{13} reach beyond Phase I ($\sin^2 2\theta_{13}$ below 0.01)*
  - *Study of CP Violation in the neutrino sector*
  - *Extend neutrino mass hierarchy reach beyond Phase I ($\sin^2 2\theta_{13}$ below 0.05)*
- In the Future Long Baseline Neutrino Study (Joint Fermilab – BNL study) we explored **indicative configurations of detectors (and detector masses), off axis and on-axis locations and protons on target (beam power).**
- In the context of the Fermilab Steering Group **we also explored capabilities using the 2.3 MW beam power of Project X**.

PHASE I is : DCHOOZ, Daya Bay, T2K, NOvA

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.

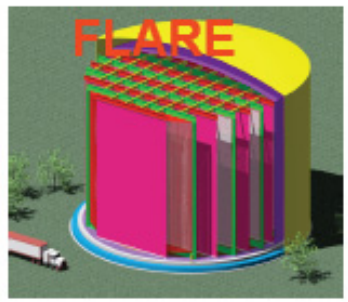
Ingredients for achieving the ultimate goals (1)

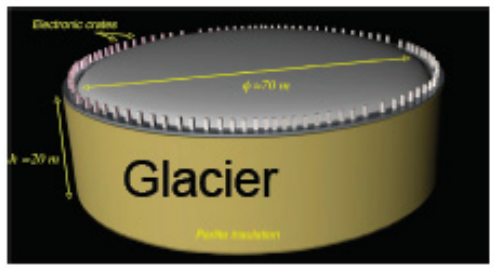
One needs:

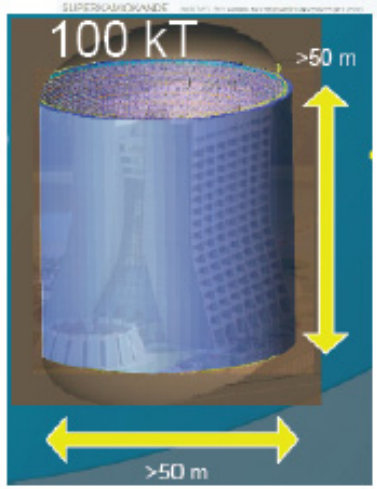
First : Statistics

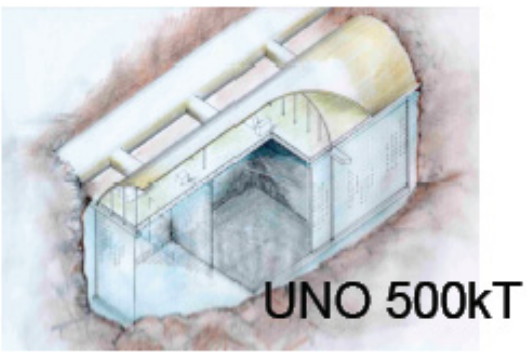
Massive Detectors (Liquid Argon,Water Cherenkov, Liquid Scintillator, etc) that are scalable in the XXX Kt scale

Water Cerenkov And Liquid Argon









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(?)

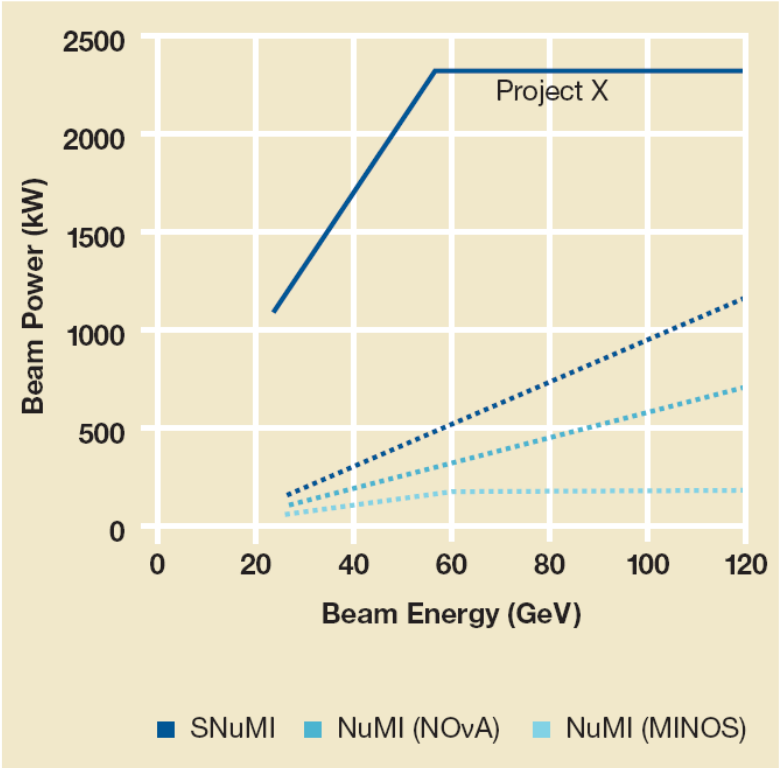
Not proven
technology at large scale

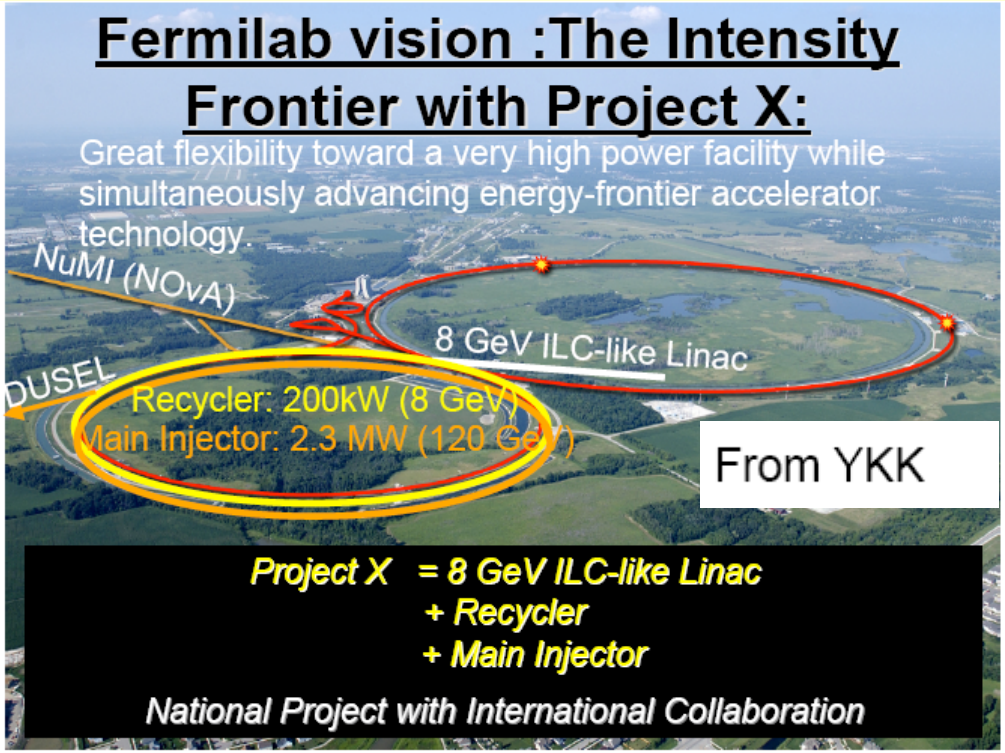
Ingredients for achieving the ultimate goals (2)

One needs:

Second : Statistics

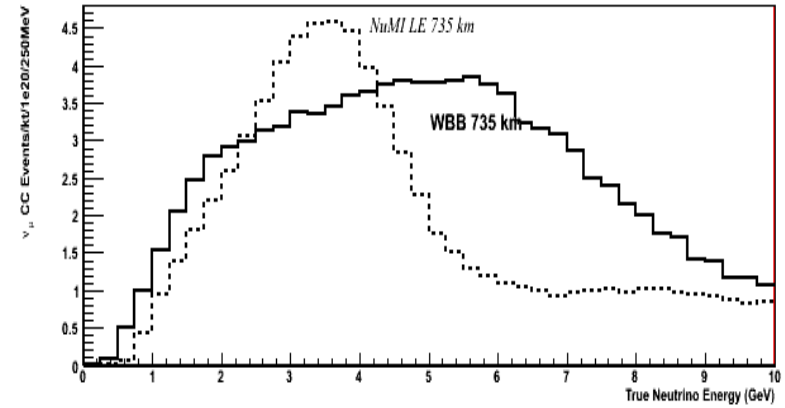
Powerful neutrino beams of very high intensity, like Project X

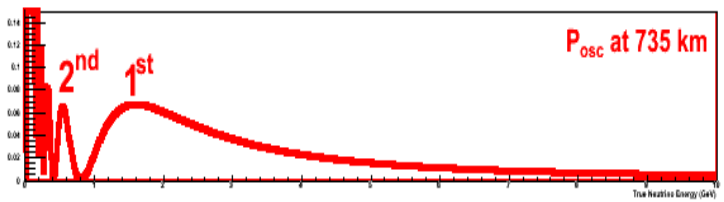


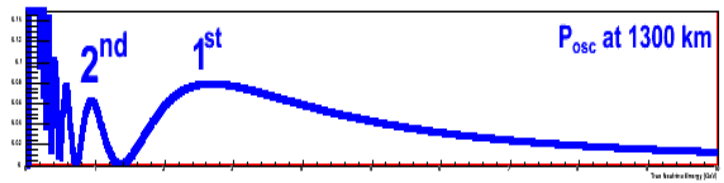


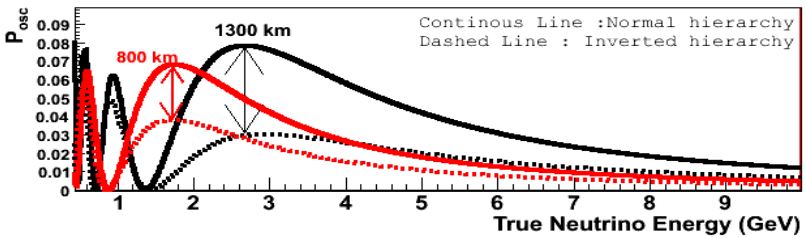
Ingredients for achieving the ultimate goals (3)

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

Sensitivities :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**

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

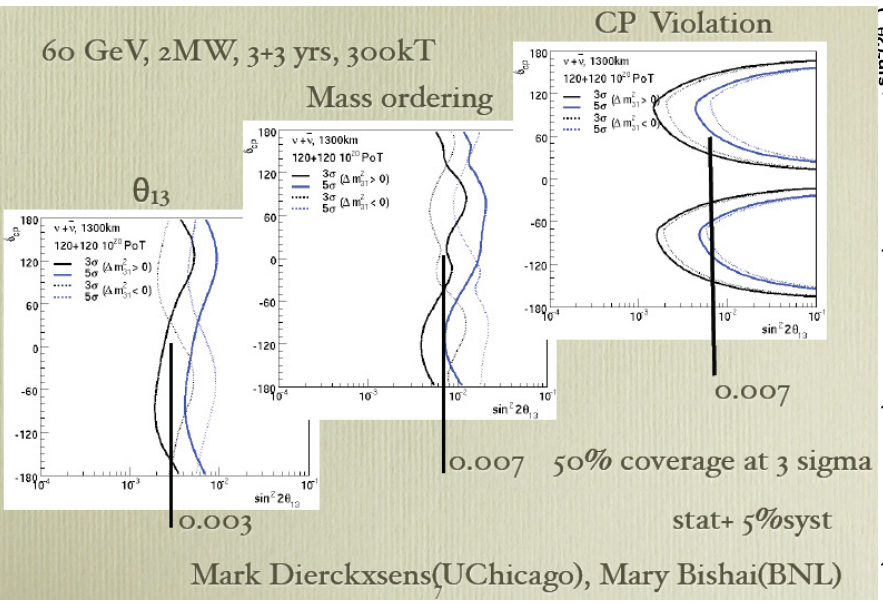
****We do not fix the mass hierarchy in any of the Discovery Potentials shown, which corresponds to the "worst case scenario".***

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

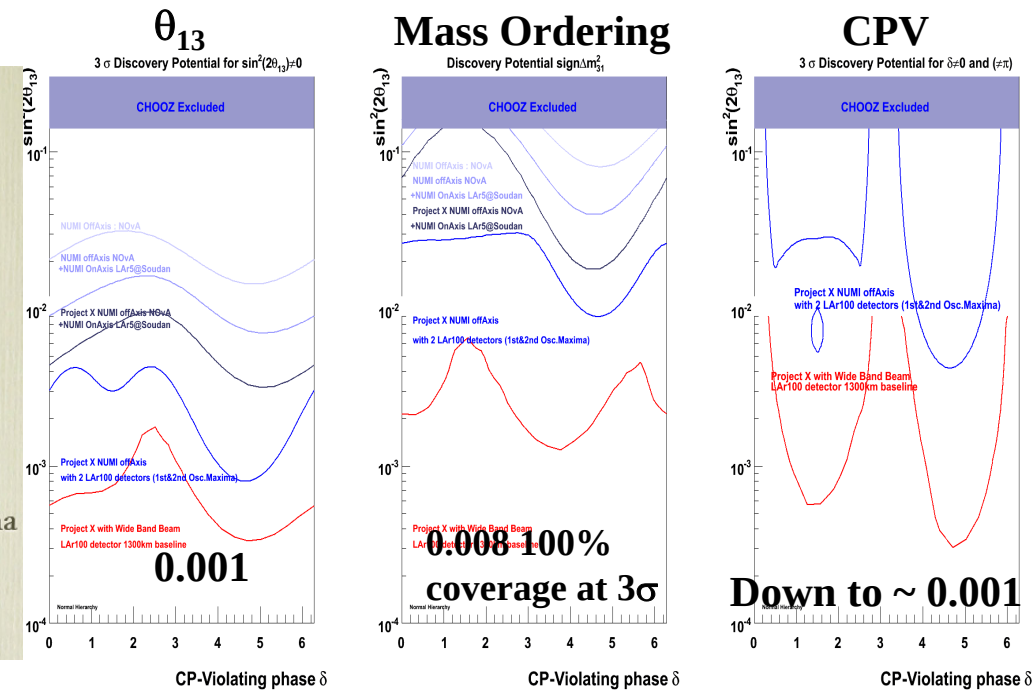
****** We do not let the rest of the oscillation parameters float.***

Ultimate physics potential of an FNAL->DUSEL neutrino oscillation program

M. Diwan P5 2008



Young-Kee Kim P5 2008



Globes Software *N.S. Software*

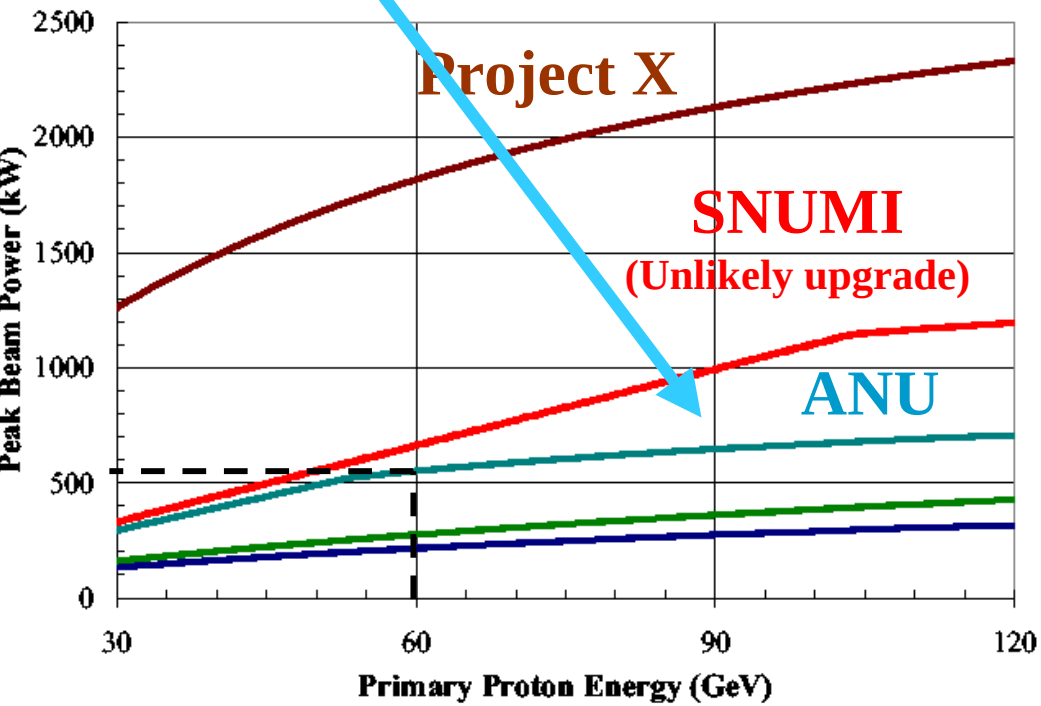
Very massive detectors (300KT WC , 100KT LAr)

Very intense wide band neutrino beam (2 MW)

Very long baseline (1300 km)

START of an FNAL->DUSEL neutrino oscillation program : Less Beam Power, Smaller Detectors

Plot courtesy : B. Zwaska



Start with :

700 KW Beam Power at 120 GeV
(540 KW Beam Power at 60 GeV)
100 KT Water Cherenkov
30 KT Liquid Argon

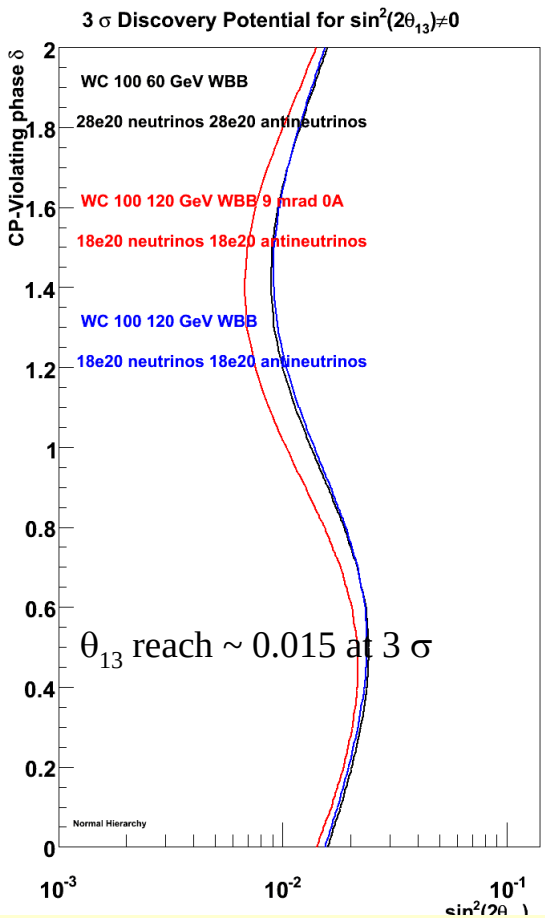
Nominal Running Time:

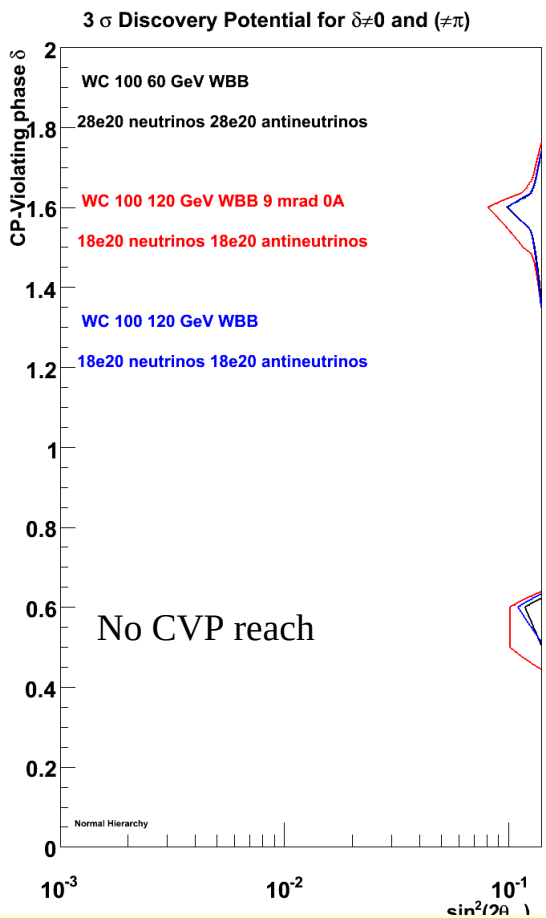
3 years of neutrino +
3 years of anti-neutrinos

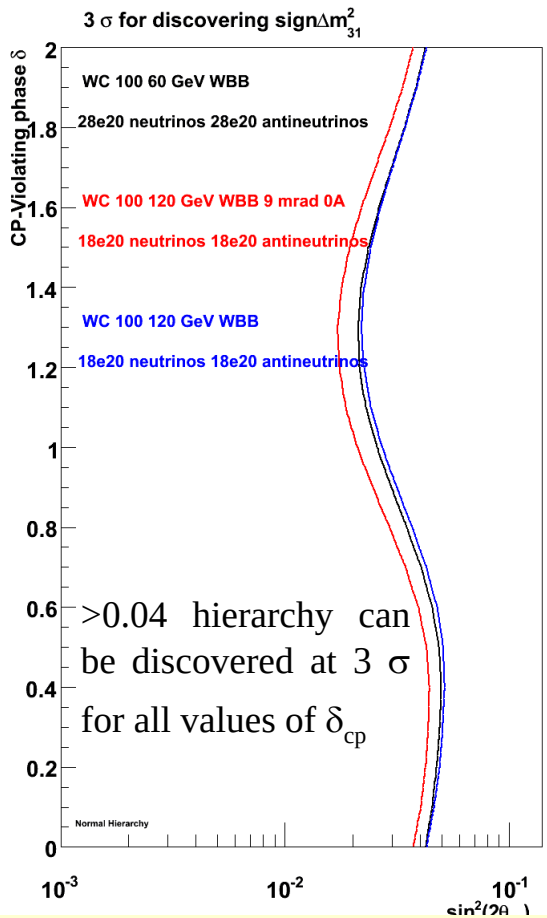
Beam Running Scenarios:

WBB 120 GeV p On Axis
WBB 120 GeV p 0.5° Off Axis
WBB 60 GeV p On Axis

Physics potential of an FNAL->DUSEL neutrino oscillation program : 100 KT WC



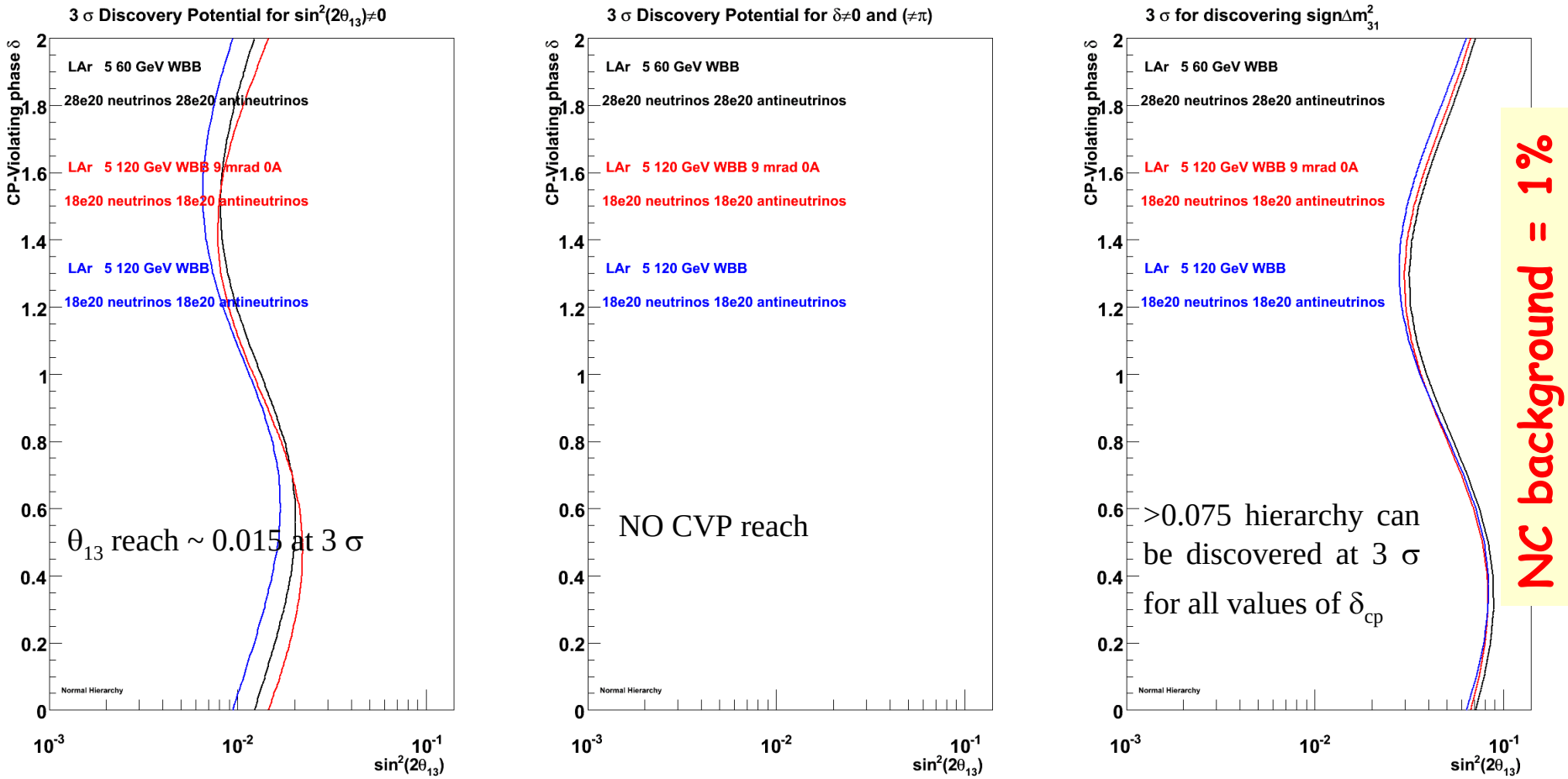




120 GeV 700 KW 9 mrad off Axis (red) gives better results than 120 GeV 700 KW on Axis (blue) due to less NC background

60 GeV 540 KW on axis (black) gives ~ the same results as 120 GeV 700 KW on Axis. 60 GeV 540 KW on axis has slightly less events than 120 GeV 700 KW on axis.

Physics potential of an FNAL->DUSEL neutrino oscillation program : 5 KT LAr



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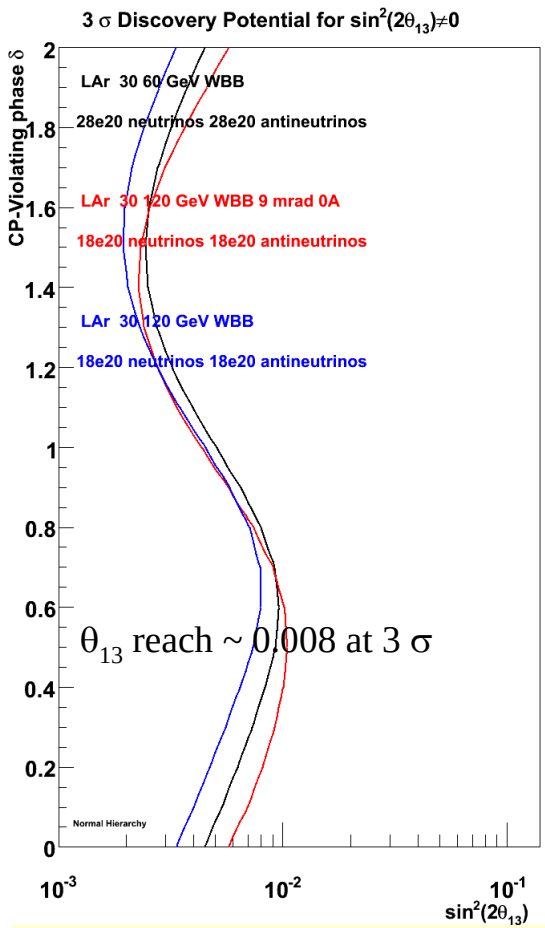
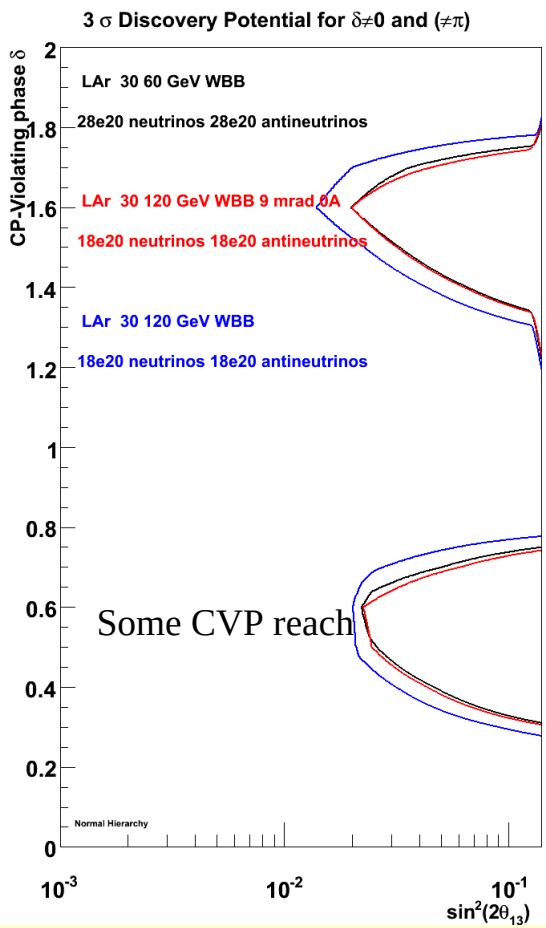
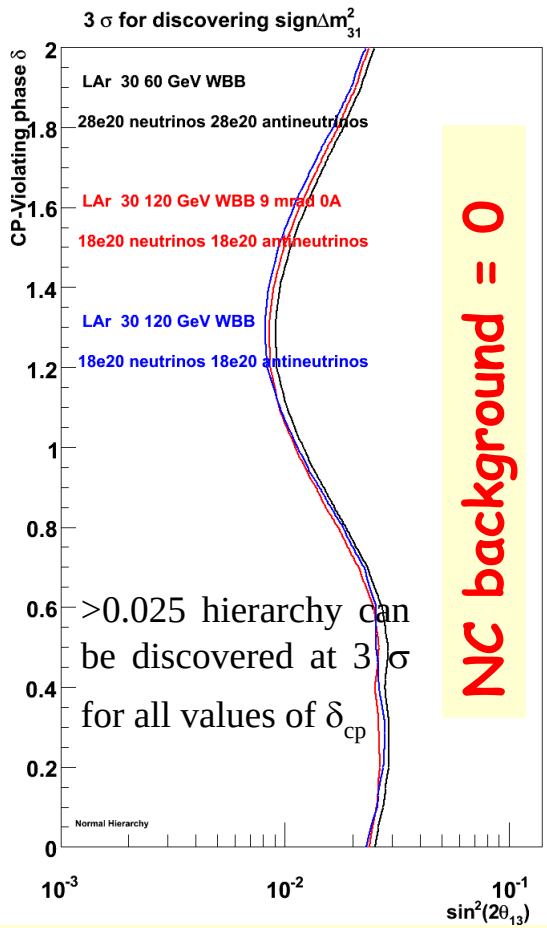
60 GeV 540 KW on axis (black) gives similar results.

Physics potential of an FNAL->DUSEL neutrino oscillation program : 30 KT LAr







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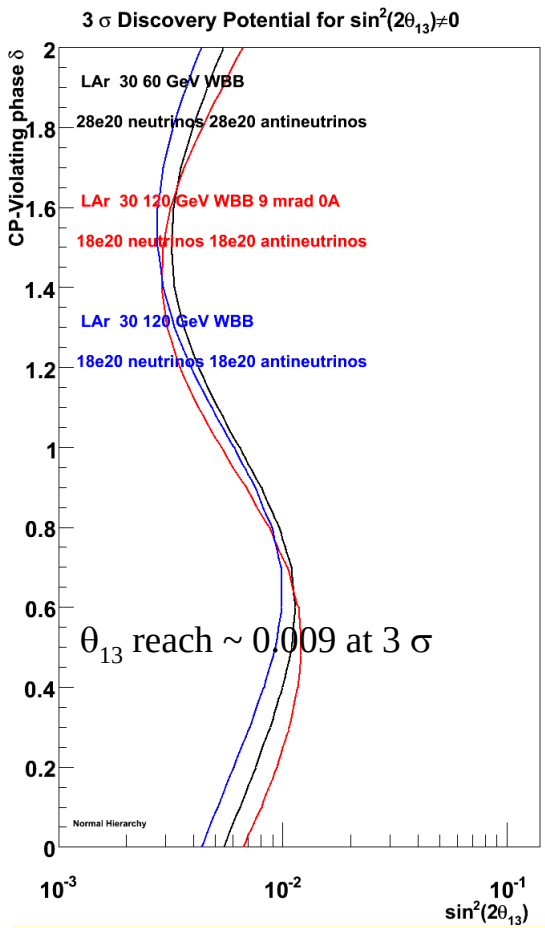
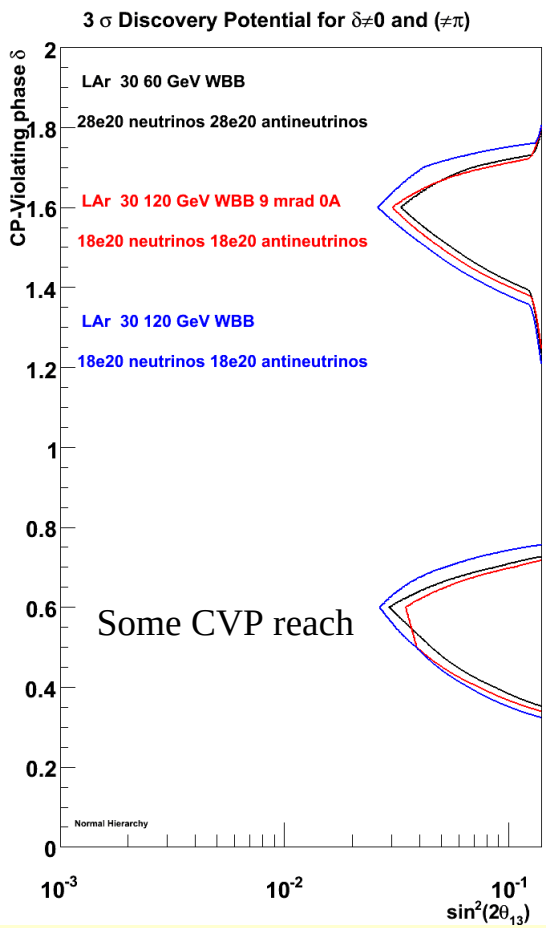
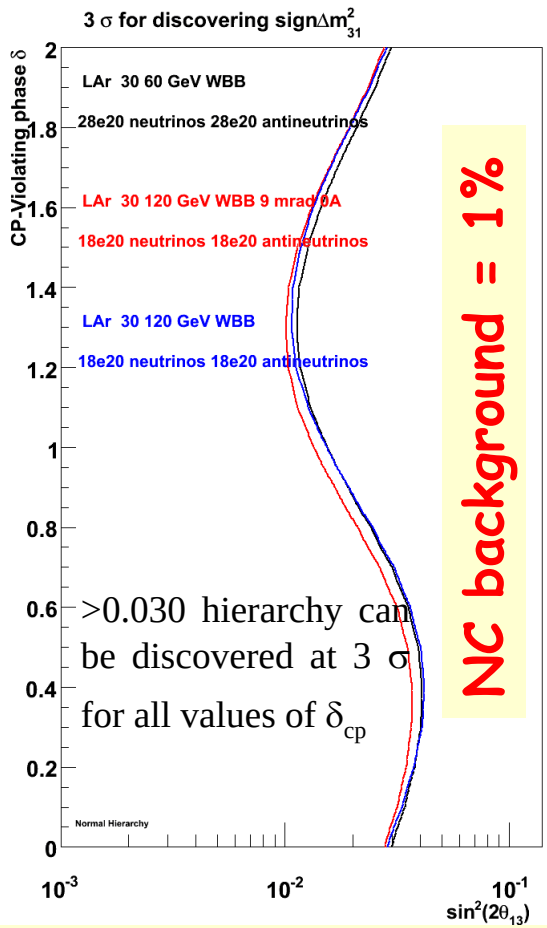
Physics potential of an FNAL->DUSEL neutrino oscillation program : 30 KT LAr







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60 GeV 540 KW on axis (black) gives similar results.

Some notes in CPV Discovery Potential

CPV discovery potential does not scale as square root of Number of Events as a function of $\sin^2(2\theta_{13})$

It is almost scaling linearly with Number of Events as a function of $\sin^2(2\theta_{13})$ (Both my results and BNL Globes results support that)

It is true that CP asymmetry increases (up to a certain point) as $\sin^2(2\theta_{13})$ decreases but IT IS NOT TRUE that the measurement of CP Violation is independent of θ_{13} => CPV Discovery potentials clearly show that.

Limitations in Current Analyses

- So far all discovery potentials are preliminary and are done (more or less) with "parameterized analyses", namely :

  Without real beam, cross section and detector simulation (for example WC Monte Carlo used is for atmospheric neutrino flux weighted for the beam flux, and for an SKI (40% coverage) type detector)

  Without event or energy reconstruction (especially for LAr detector)

  Without event identification (especially for LAr detector)

  Without any optimization studies (ie how does WC performance varies as a function of PMT coverage) and with (good) guesstimates on how systematic uncertainties will evolve

Needed Future Steps

Natural next steps for both detector technologies are:

We need a <u>Simulation/Monte Carlo Group:</u>

1) To develop realistic Monte Carlo using the Wide Band Beam flux, the NEUGEN (or other) neutrino cross sections, and detailed detector simulation

We need a <u>Reconstruction Group</u>

2) To develop reconstruction algorithms

We need an <u>Analysis/Optimization Group</u>

3) To develop automated event identification algorithms

4) To try to realistically study and take into account systematic uncertainties in the analysis chain that will yield the measurements of interest

Summary/Conclusions (1)

- **The next generation of accelerator neutrino oscillation experiments will try to DEFINITIVELLY address the following very challenging questions:**
  - **What is the value of the third mixing angle θ_{13} ?**
  - **Is θ_{23} exactly 45 degrees or not?**
  - **What is the ordering of the neutrino masses ?**
  - **Is CP Violated in the neutrino sector ?**
- To address the above questions we need **very intense neutrino beams** , **massive detectors** and **longer baselines**

Summary/Conclusions (2)

- *The initial/qualitative analyses show that DUSEL Phase I Experiments can have a good discovery potential for the neutrino mass hierarchy (for $\sin^2(2\theta_{13}) >= 0.045$ and all values of δ_{CP}) for a 100 KT fiducial WC detector.*
- *If a 30 KT fiducial LAr detector is present one can have better reach for the neutrino mass hierarchy and also start to have some CPV discovery potential.*
- *We NEED to proceed to the next detailed phase of simulations, reconstruction, event identification and analysis in order to both do optimization studies AND also obtain more detailed/realistic/mature results.*

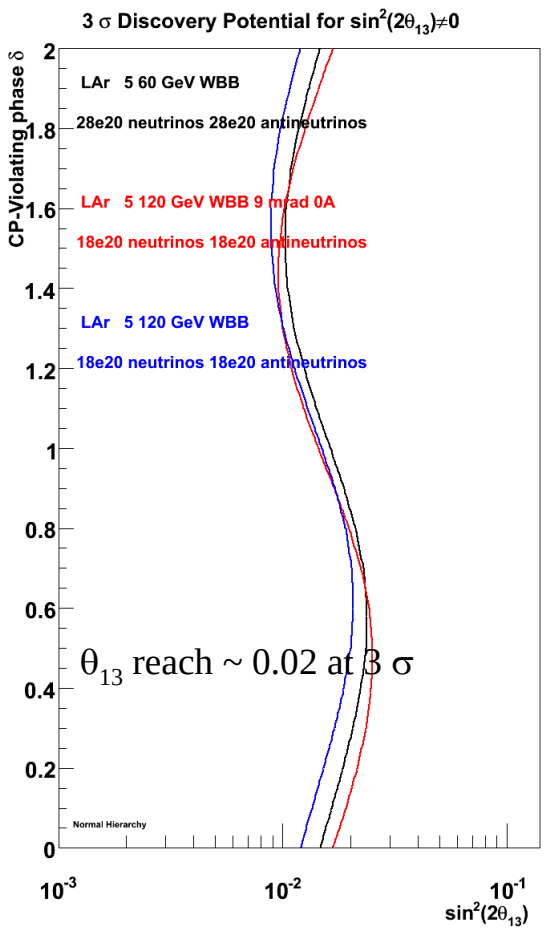
DISCOVERY POTENTIALS CAN ONLY GO ONE WAY FROM WHERE WE ARE NOW … GET WORSE…

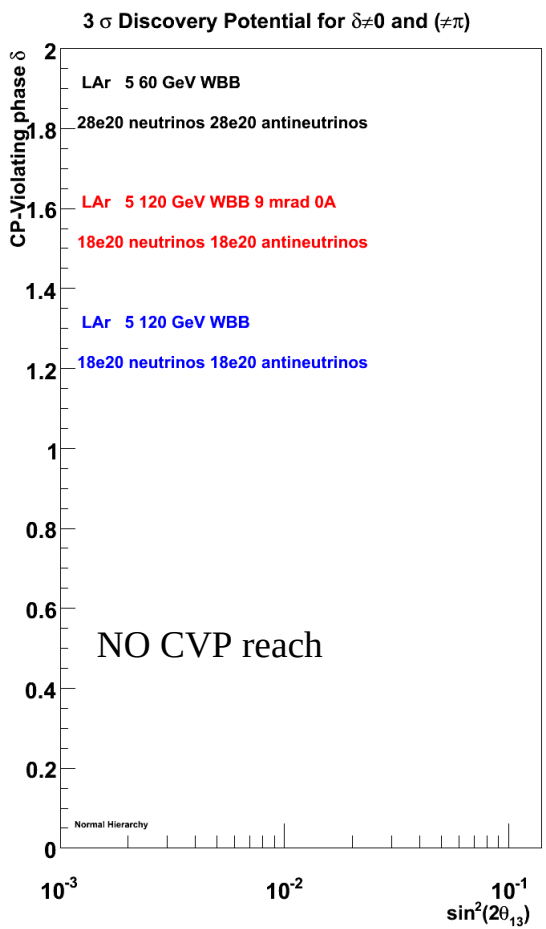
WE NEED TO FIGURE OUT IF THAT IS THE CASE (GETTING WORSE) AND IF YES BY HOW MUCH…

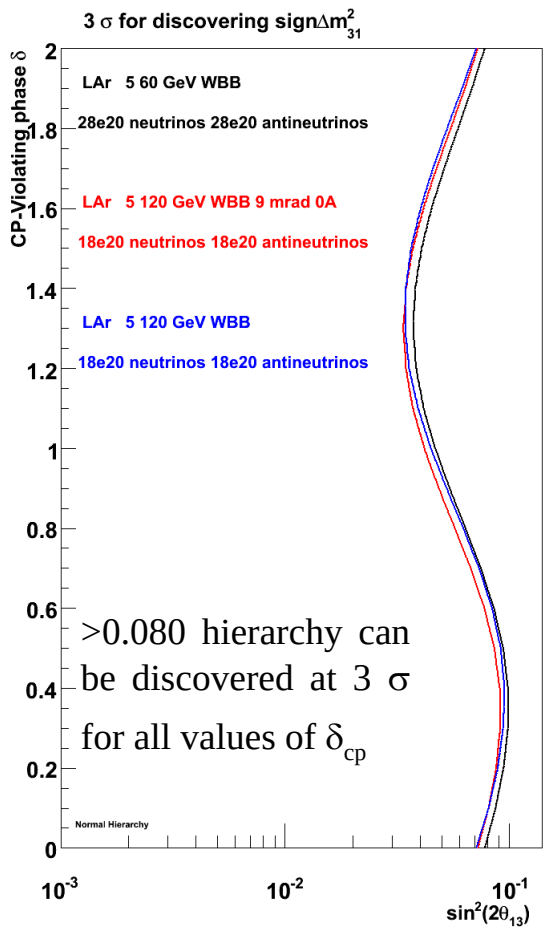
BACKUP

Sensitivities for 5 kt fiducial LAr Detector

NC background = 0.01







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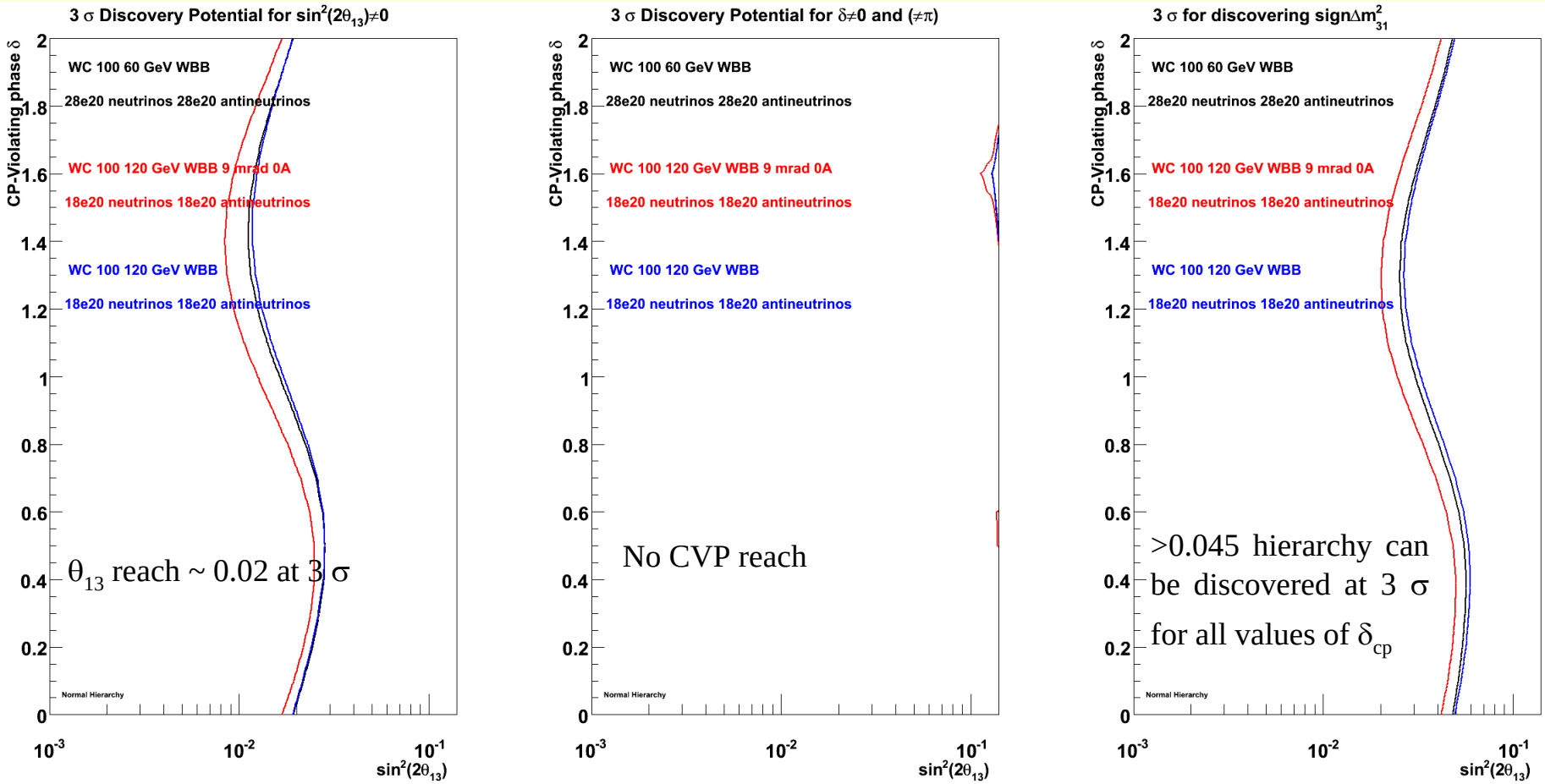
60 GeV 540 KW on axis (black) gives similar results.

Sensitivities for 100kt fiducial Water Cherenkov

"Nominal" NC background x 1.6



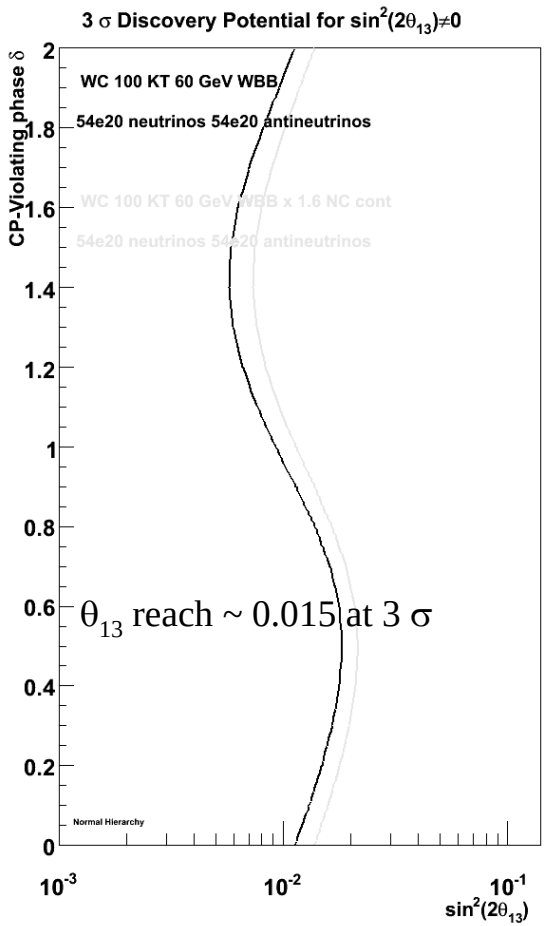
120 GeV 700 KW 9 mrad off Axis (red) gives better results than 120 GeV 700 KW on Axis (blue) due to less NC background

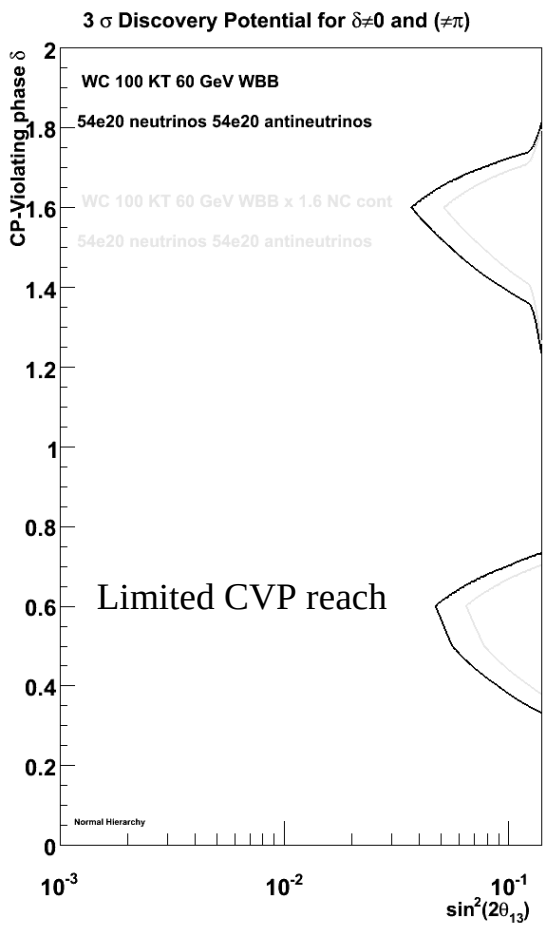
60 GeV 540 KW on axis (black) gives ~ the same results as 120 GeV 700 KW on Axis

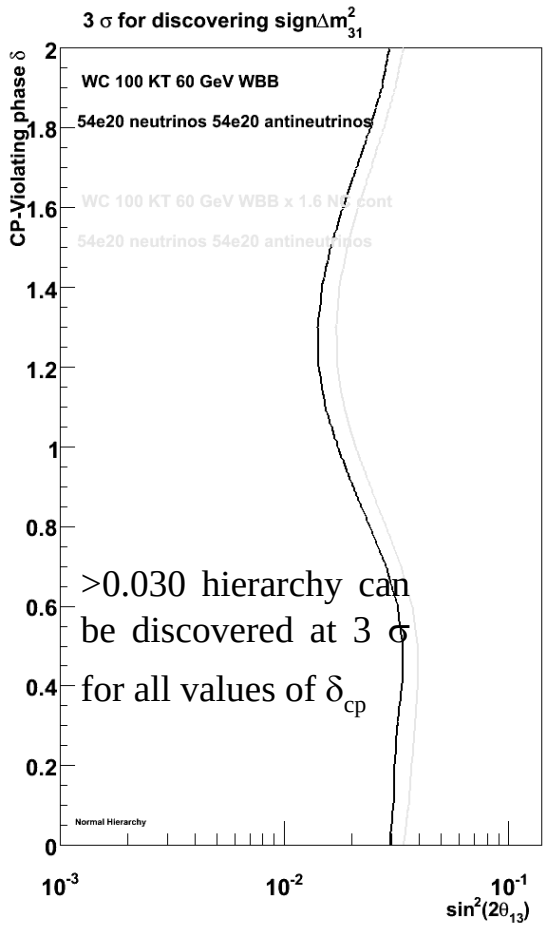
Increasing NC background affects mostly CPV reach.

Sensitivities for 100kt fiducial Water Cherenkov

60 GeV ~1 MW, 1300 km on axis





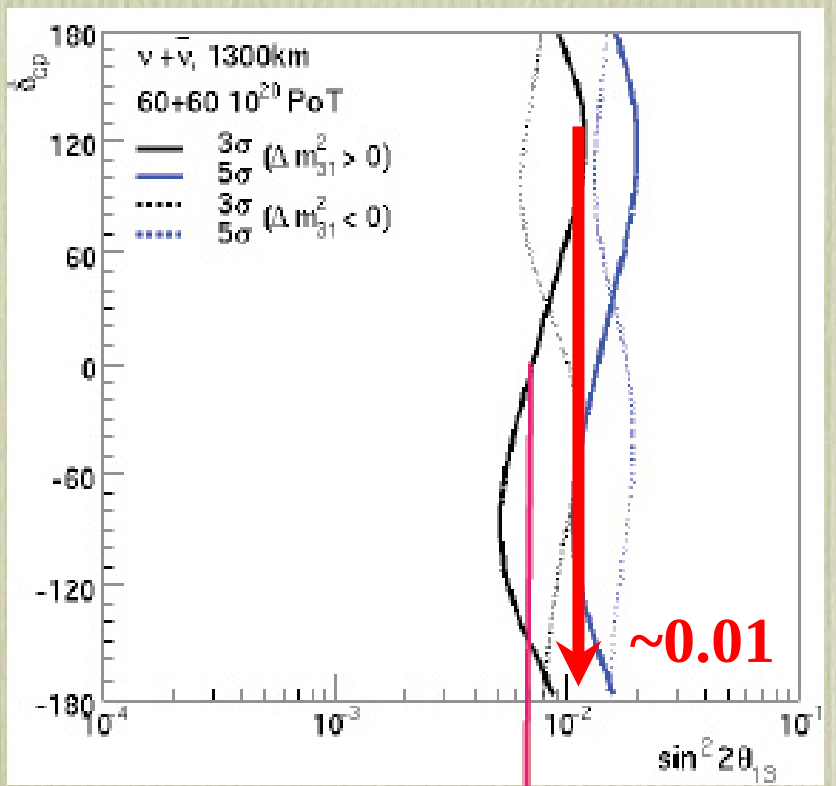


Results are in general agreement with the BNL Group (see next page)

BNL Group Results from talk presented at 2008 P5 meeting at SLAC

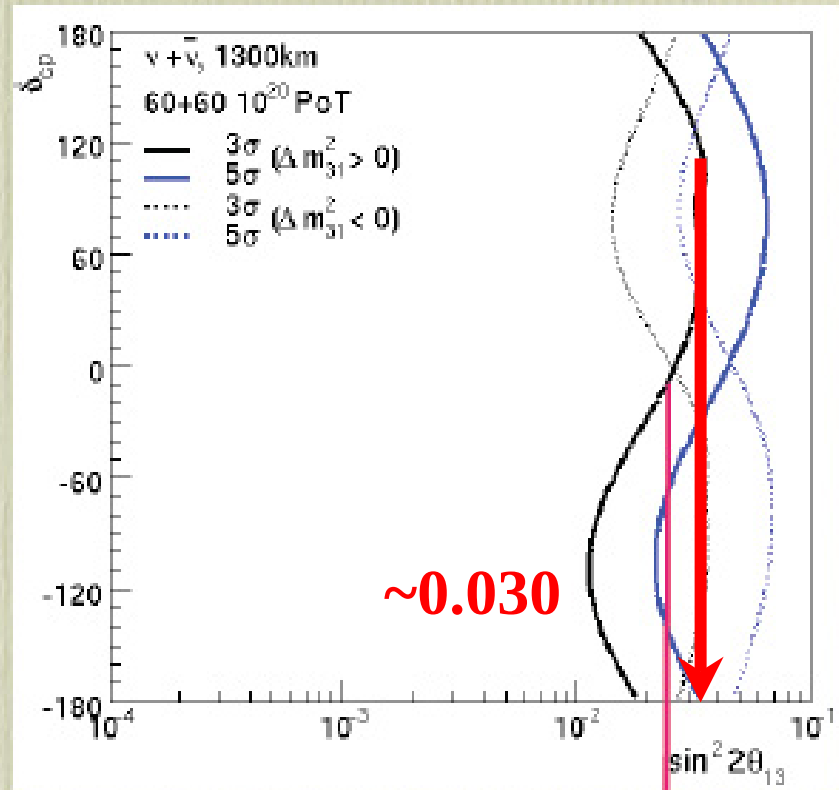
60 GeV, 1MW, 3+3 yrs, 100kT

θ_{13}



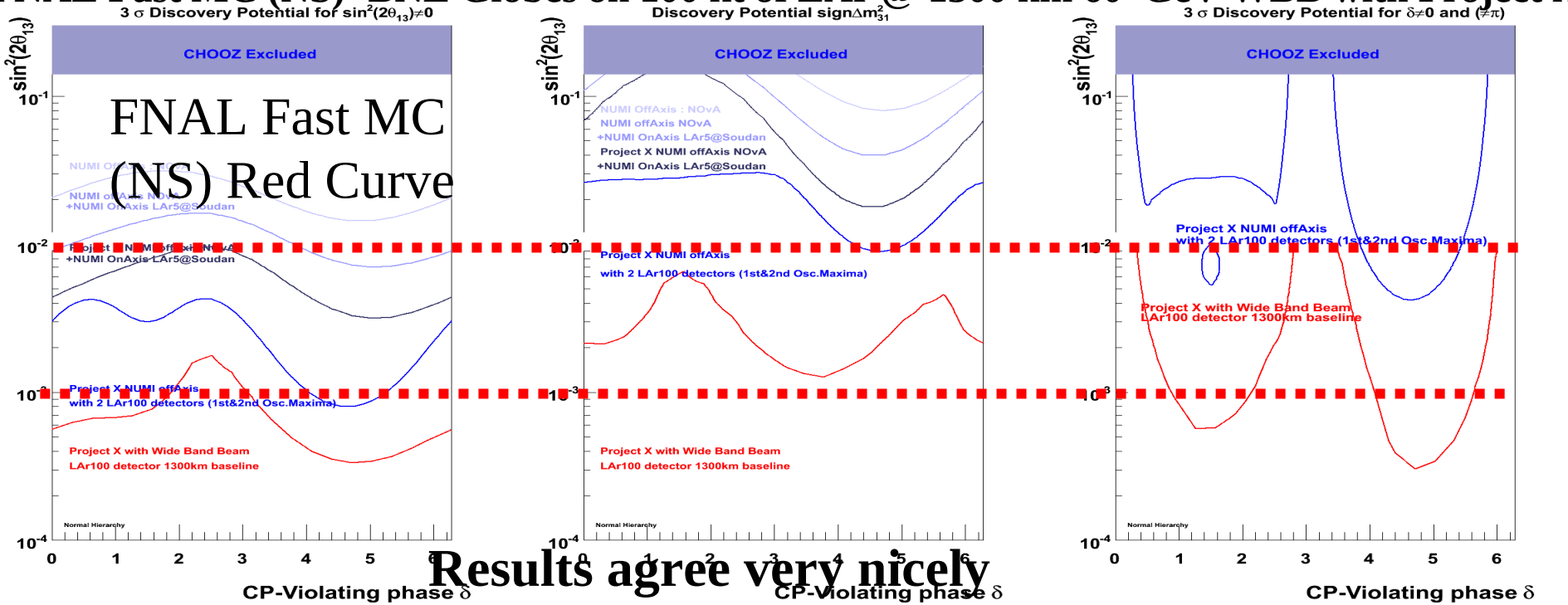
0.008

Mass ordering

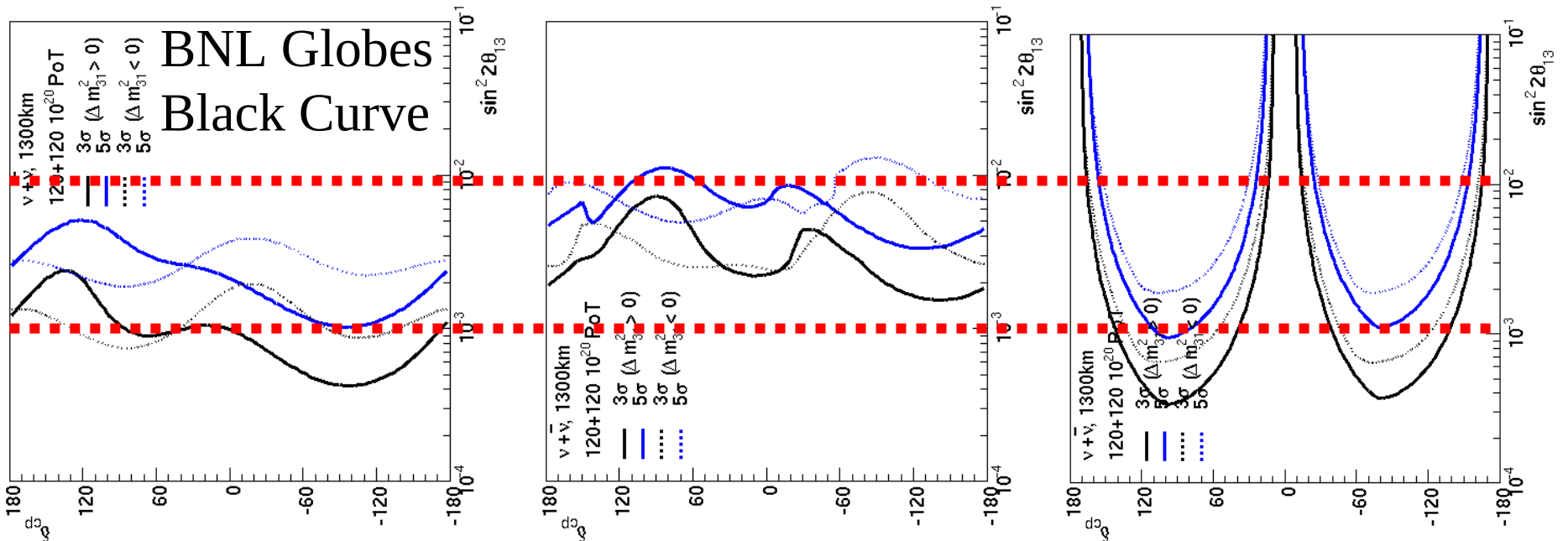


0.025

FNAL Fast MC (NS)- BNL Globes on 100 kt of LAr @ 1300 km 60 GeV WBB with Project X



Results agree very nicely



Work on Water Cherenkov Detector Simulation and Sensitivities

- BNL Group has done a lot of work (also in the context of the BNL-FNAL long baseline neutrino experiment study) with respect to the simulation and sensitivities of Water Cherenkov Detectors.

- The Signal efficiency and Background rejection as developed by the BNL group (in particular by C.Yanagisawa and independently by F.Dufour) are the ones used for the study presented in this talk.

- Also the neutrino fluxes for a wide band neutrino beam as developed by B.Viren and M.Bishai are the input neutrino fluxes used for the study presented in this talk.

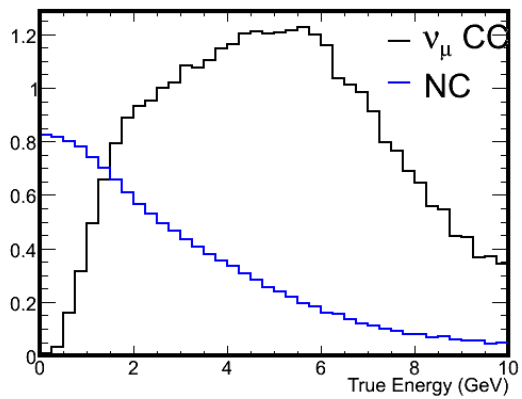
Details of Modeling of Neutral Current (NC) Visible Energy Spectrum

- Start with neutrino fluxes as given by B.Viren and M.Bishai.
- Use NEUGEN NC total cross sections as a function of true neutrino energy.
- Obtain from : **Flux x NC cross sections**, the **True Neutrino Energy spectrum of Neutral Current interactions (from 0->120 GeV or 0->60 GeV)**
- Use an approximate Y distribution, which is flat from 0 to 1 (pretty good approximation) in order to obtain the **True Visible Energy spectrum of NC interactions = True Neutrino Energy (NC) x Y**
  (*Y = (True Visible Energy)/True Neutrino Energy*)
- If everything is done correctly, the ratio of total NC/CC distributions should be ~ 1/3 and the NC Visible Energy Spectrum should have an ~ exponential shape.

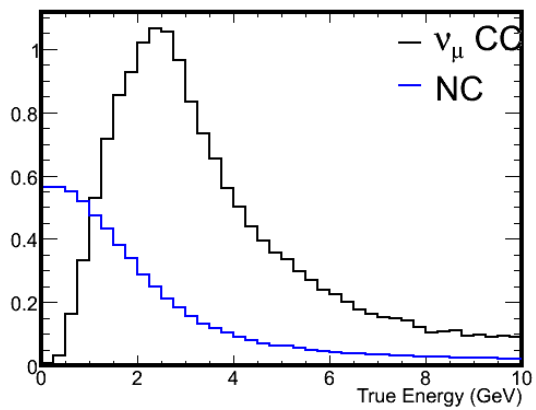
Details of Modeling of Neutral Current (NC) Visible Energy Spectrum con't

- If everything is done correctly, the ratio of total NC/CC distributions should be ~ 1/3 and the NC Visible Energy Spectrum should have an ~ exponential shape.

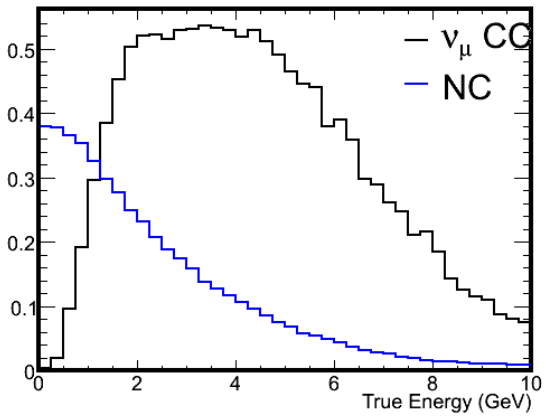
WBB 120 GeV ON AXIS



WBB 120 GeV OFF AXIS



WBB 60 GeV ON AXIS



Note : different scale

Shape and number of NC interactions as expected for all three different beam configurations.

Detector Efficiencies and Background Rejection : Water Cherenkov

- For Water Cherenkov Detector used analysis by :
  F.Dufour : http://hep.bu.edu/~fdufour/paper/fnal_report.pdf

  There are three sets of sequential cuts used for both Signal Selection and Background Rejection:

  (A) Fiducial Volume Cuts : **Use Super Kamiokande fiducial volume efficiency of 50% since I could not find in any document any other number for Water Cherenkov Detectors**

  (B) Pre – Selection cuts : Simple Set of cuts to select neutrino interactions

  (C) Selection cuts : Likelihood analysis to separate Signal from Backgrounds

Detector Efficiencies : Water Cherenkov (1)

- For Water Cherenkov Detector used analysis by :
  F.Dufour : http://hep.bu.edu/~fdufour/paper/fnal_report.pdf

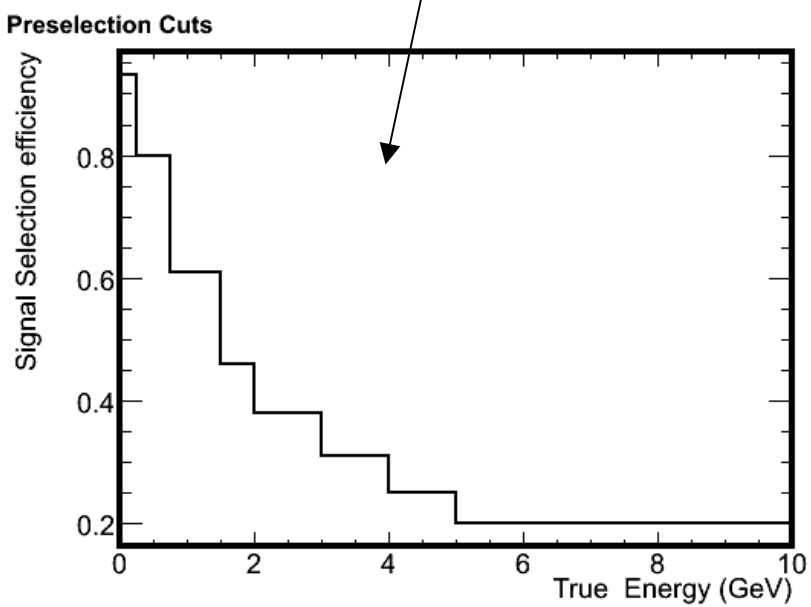
Pre Selection Cuts (Signal , Beam Nues)

	Signal			Background	
Energy (true)	ν_e (avg)	QE ν_e	non-QE ν_e	NC	ν_μ mis-ID
0 - 350 MeV	93%	94%	*NA*	0.2%	*NA*
350 - 850 MeV	80%	94%	41%	4%	0.6%
850 MeV - 1.5 GeV	61%	92%	36%	10%	0.7%
1.5 - 2.0 GeV	46%	86%	29%	11%	0.8%
2.0 - 3.0 GeV	38%	81%	26%	12%	0.9%
3.0 - 4.0 GeV	31%	78%	23%	11%	1.0%
4.0 - 5.0 GeV	25%	70%	19%	11%	0.6%
5.0 - 10.0 GeV	20%	62%	16%	10%	1.0%

Table 1 Efficiency of pre-cuts as applied to neutrino interactions in the fiducial volume of the Super-Kamiokande detector simulation. The charged current ν_e interactions are broken down separately for quasi-elastic and non-quasi-elastic samples. The NC sample includes elastic scattering in the denominator of the efficiency calculation.

F.Dufour Table

What I used



Detector Efficiencies : Water Cherenkov (2)

- For Water Cherenkov Detector used analysis by :
  F.Dufour : http://hep.bu.edu/~fdufour/paper/fnal_report.pdf

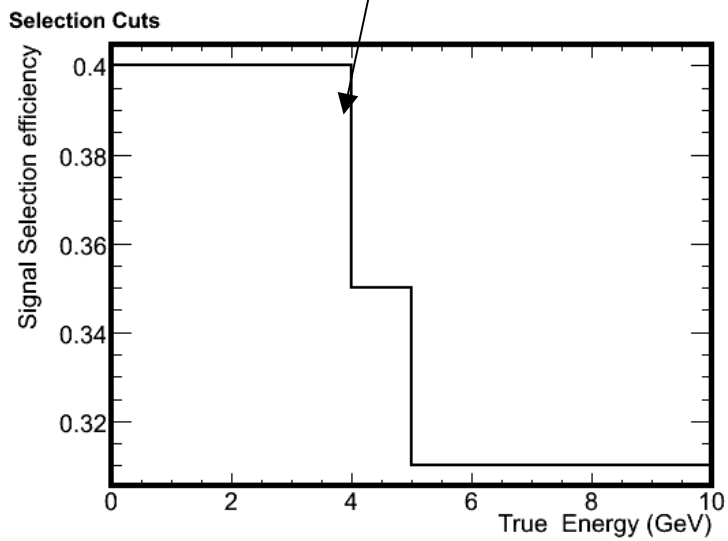
Selection Cuts (Signal, Beam Nues)

	Cut at zero			Cut keeps 40% of signal		
Energy (rec)	ν_e	NC	ν_μ mis-ID	ν_e	NC	ν_μ mis-ID
0 - 350 MeV	87.1%	10.9%	10.4%	41.4%	1.1%	0.6%
350 - 850 MeV	80.8%	22.1%	25.2%	36.8%	1.9%	2.5%
850 MeV - 1.5 GeV	78.6%	23.4%	25.6%	44.5%	4.1%	9.5%
1.5 - 2.0 GeV	72.6%	24.6%	11.1%	43.8%	5.9%	4.0%
2.0 - 3.0 GeV	73.2%	34.9%	14.6%	38.7%	10.1%	2.2%
3.0 - 4.0 GeV	69.6%	41.8%	20.0%	40.7%	9.1%	9.9%
4.0 - 5.0 GeV	78.7%	34.9%	52.9%	35.8%	15.4%	7.0%
5.0 - 10.0 GeV	83.7%	51.4%	22.2%	31.3%	20.4%	5.5%

Table 2 Efficiency for the likelihood cut, at zero and at cut position that keeps approximately 40% of the signal. These efficiencies are calculated for events which have already passed the pre-cuts, and are calculated based on reconstructed energy.

What I used

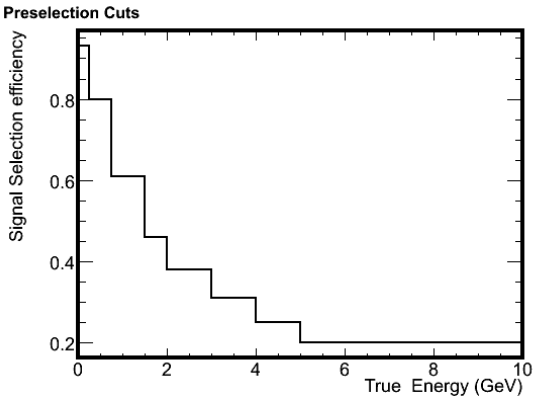
F.Dufour Table



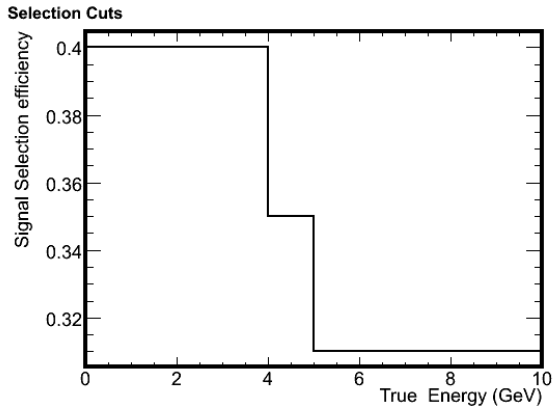
Detector Efficiencies : Water Cherenkov (3)

- For Water Cherenkov Detector used analysis by :
  F.Dufour : http://hep.bu.edu/~fdufour/paper/fnal_report.pdf

Overall Efficiency **After Fiducial** (which I assumed to be 50%) (Signal, Beam Nues)



X



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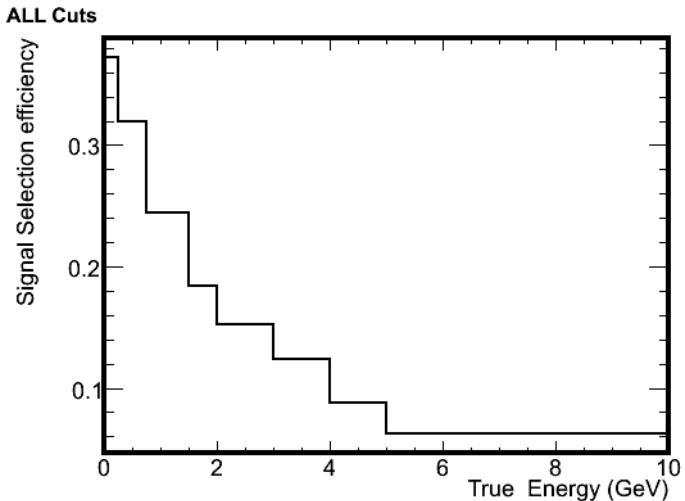

Detector Bkg Rejection : Water Cherenkov (1)

- For Water Cherenkov Detector used analysis by :
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Pre Selection Cuts (NC interactions)

	Signal			Background	
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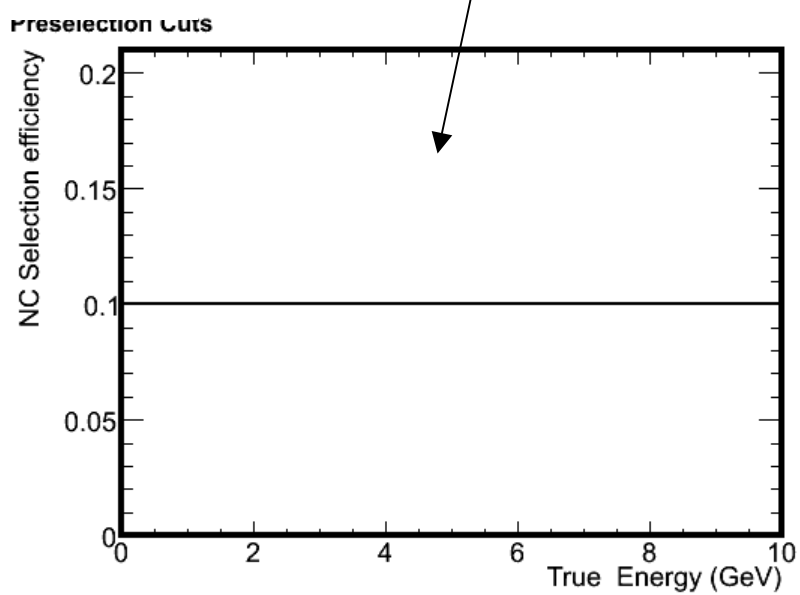
Table 1 Efficiency of pre-cuts as applied to neutrino interactions in the fiducial volume of the Super-Kamiokande detector simulation. The charged current ν_e interactions are broken down separately for quasi-elastic and non-quasi-elastic samples. The NC sample includes elastic scattering in the denominator of the efficiency calculation.

F.Dufour Table

What I used



Detector Bkg Rejection : Water Cherenkov (2)

- For Water Cherenkov Detector used analysis by :
  F.Dufour : http://hep.bu.edu/~fdufour/paper/fnal_report.pdf

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2.0 - 3.0 GeV	73.2%	34.9%	14.6%	38.7%	10.1%	2.2%
3.0 - 4.0 GeV	69.6%	41.8%	20.0%	40.7%	9.1%	9.9%
4.0 - 5.0 GeV	78.7%	34.9%	52.9%	35.8%	15.4%	7.0%
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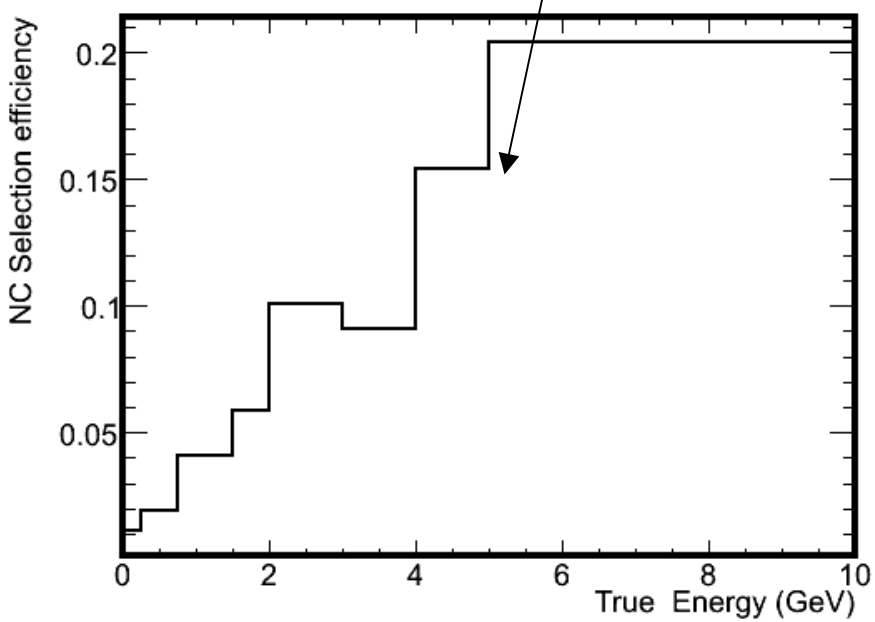
Table 2 Efficiency for the likelihood cut, at zero and at cut position that keeps approximately 40% of the signal. These efficiencies are calculated for events which have already passed the pre-cuts, and are calculated based on reconstructed energy.

What I used

F.Dufour Table



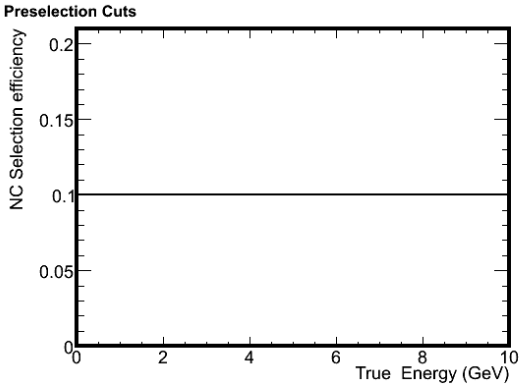
N. Saoulidou

Detector Bkg Rejection : Water Cherenkov (3)

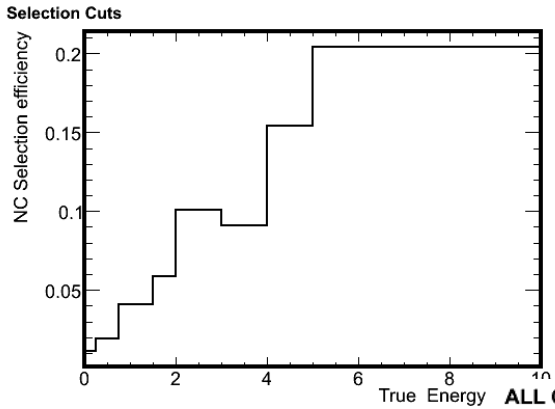
- For Water Cherenkov Detector used analysis by :
  F.Dufour : http://hep.bu.edu/~fdufour/paper/fnal_report.pdf

Overall NC Bkg Rejection **After Fiducial Cuts** (fiducial volume efficiency I assumed to be 50% like Super Kamiokande)

These numbers are percentage of NC interactions remaining in the Signal-Like sample.



X



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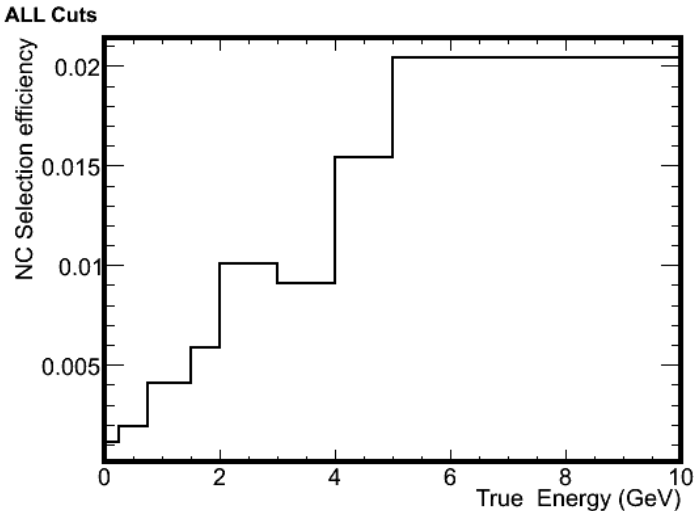
NC Background rejection for Water Cherenkov detector >= 99% below 4 GeV.

=



Detector Efficiencies and Background Rejection : Liquid Argon

- For Liquid Argon Detector used:

http://www.hep.net/nusag_pub/May2006/Fleming_NuSAG_may2006.pdf

LArTPCs
- Total absorption calorimeter
- 5mm sampling
  -> 28 samples/rad length
- energy resolution

→ ν_e efficiency
NC rejection

First pass studies using hit level MC show
~80 ± 7 % ν_e efficiency and
NC rejection factor ~70 (99 ± 1% eff.)

Studies from groups
working on T2K LAr indicate 85-95% ν_e efficiency

Fiducial volume efficiency (worst case) : 70% (Input from B.Fleming)

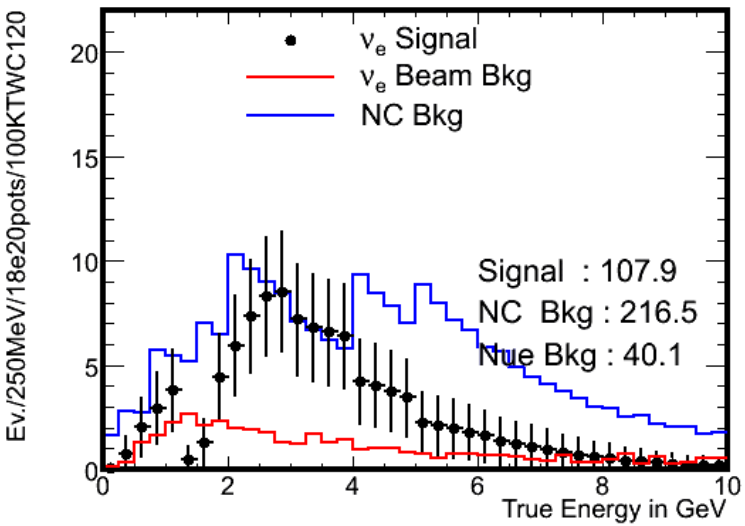
Signal Selection Efficiency (from visual Scan of Tufts group) : 80%flat in true neutrino energy.

Background Rejection (from visual Scan of Tufts group) : 99-100% flat in true visible energy

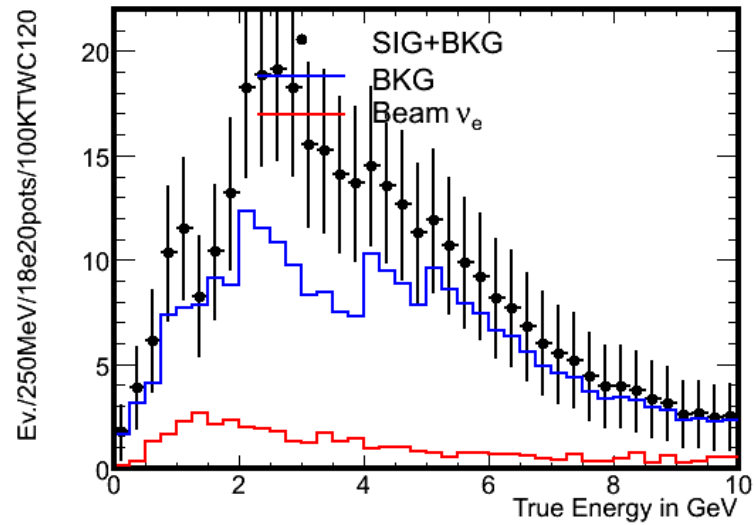
Neutrino Energy Spectra :

120 GeV,700 KW @1300 km, 18×10^{20} pots , $\sin^2(2\theta_{13}) = 0.04$ $\delta_{cp} = 0$

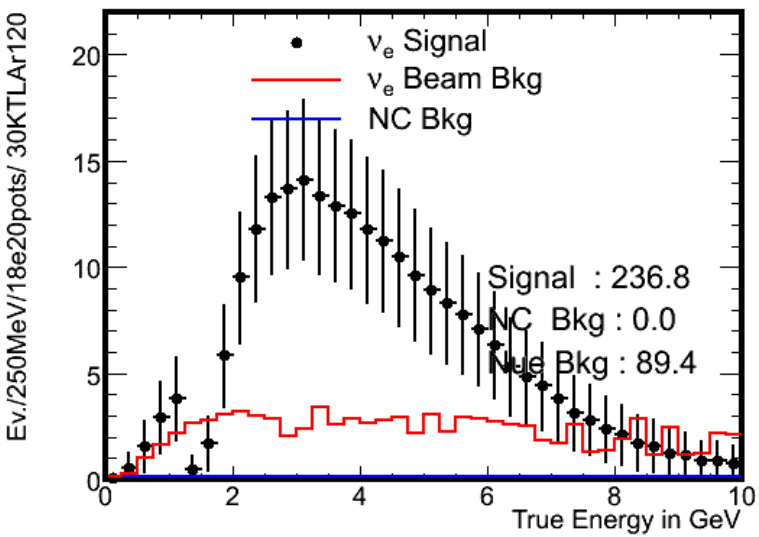
100 kt fiducial WC



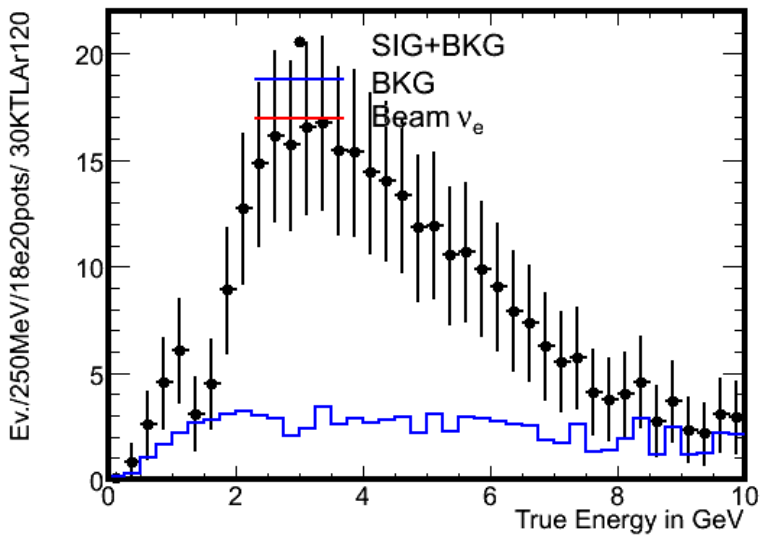
100 kt fiducial WC



30 kt fiducial LAr



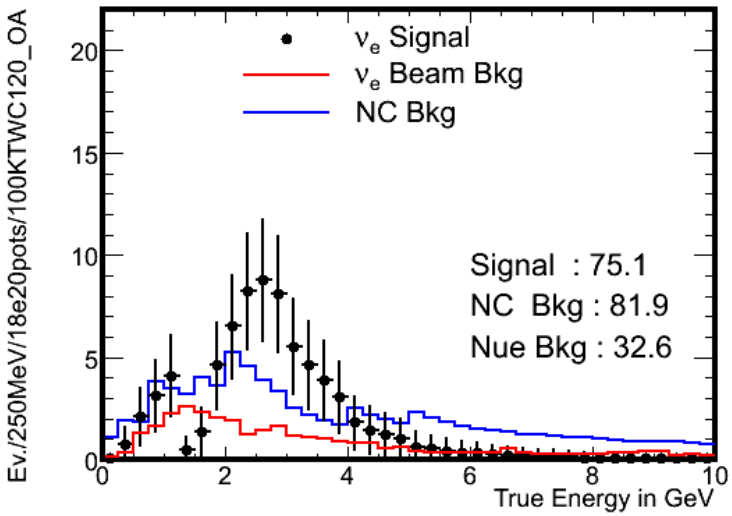
30 kt fiducial LAr



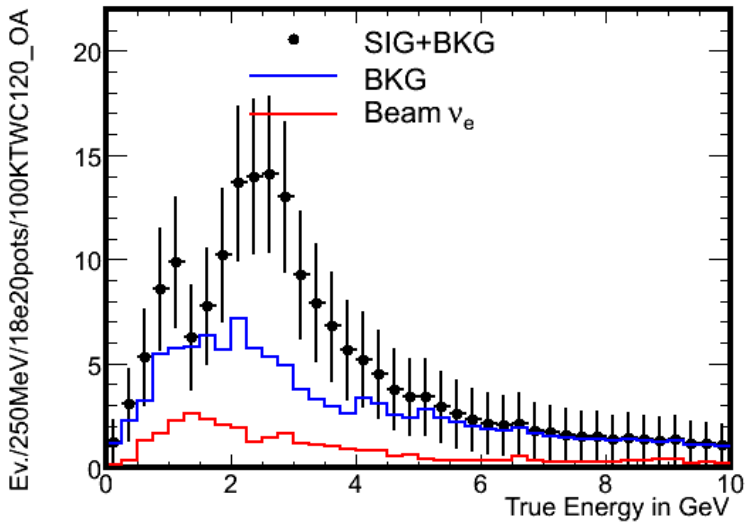
Neutrino Energy Spectra :

120 GeV,700 KW 9 mrad Off Axis @1300 km, 18×10^{20} pots , $\sin^2(2\theta_{13}) = 0.04$ $\delta_{cp} = 0$

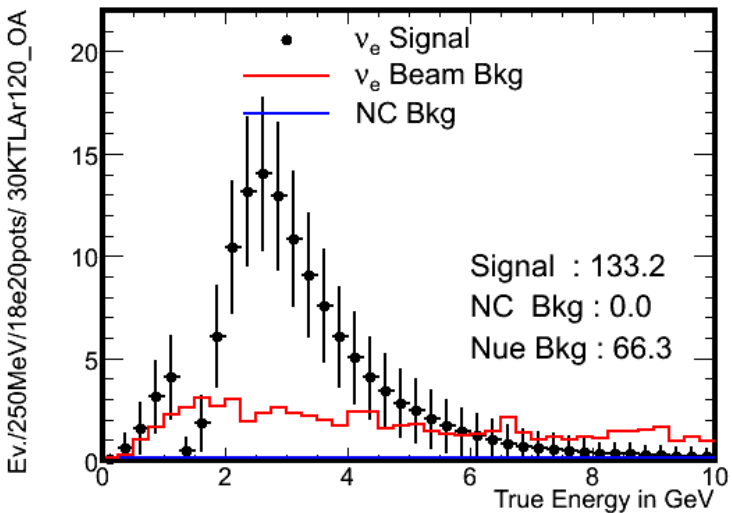
100 kt fiducial WC



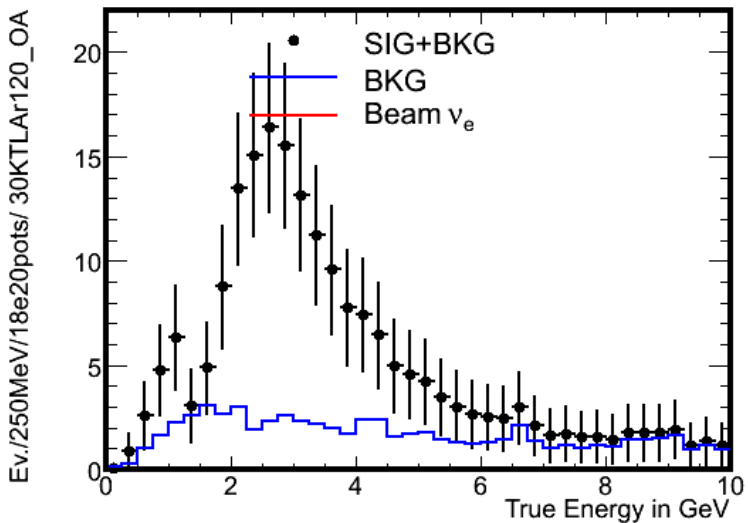
100 kt fiducial WC



30 kt fiducial LAr



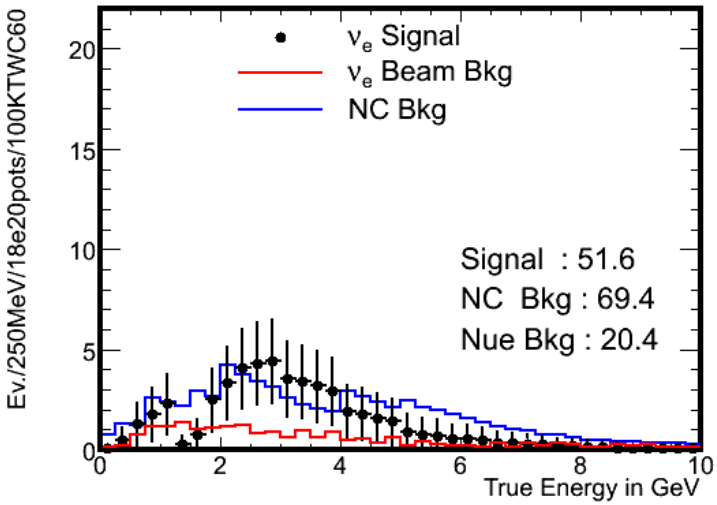
30 kt fiducial LAr



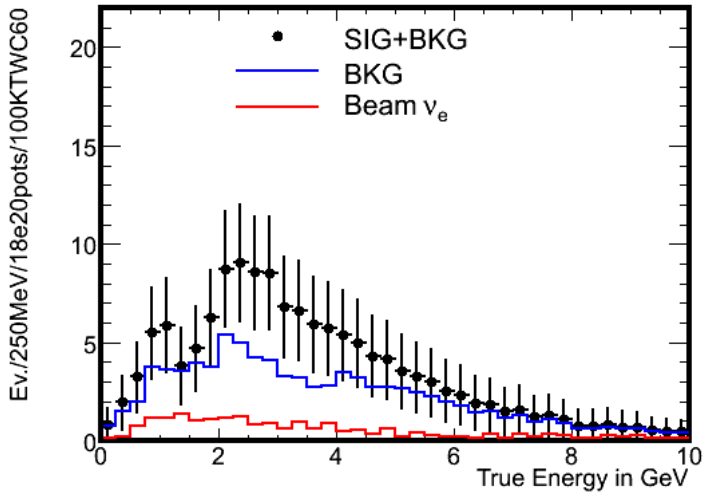
Neutrino Energy Spectra :

60 GeV,350 KW @1300 km, 18×10^{20} pots , $\sin^2(2\theta_{13}) = 0.04$ $\delta_{cp} = 0$

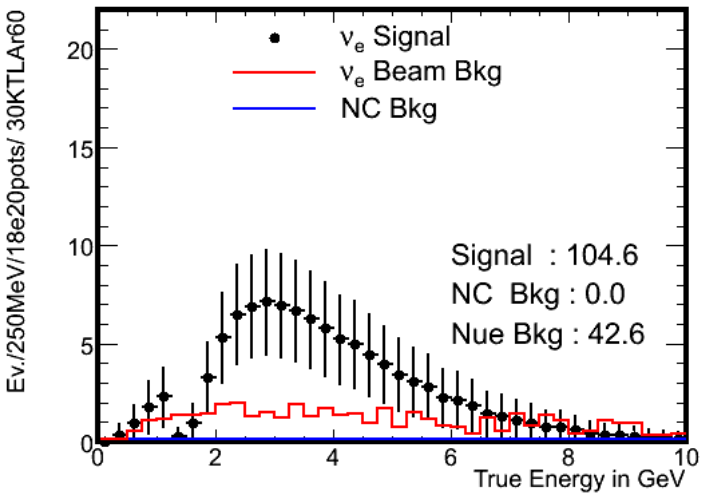
100 kt fiducial WC



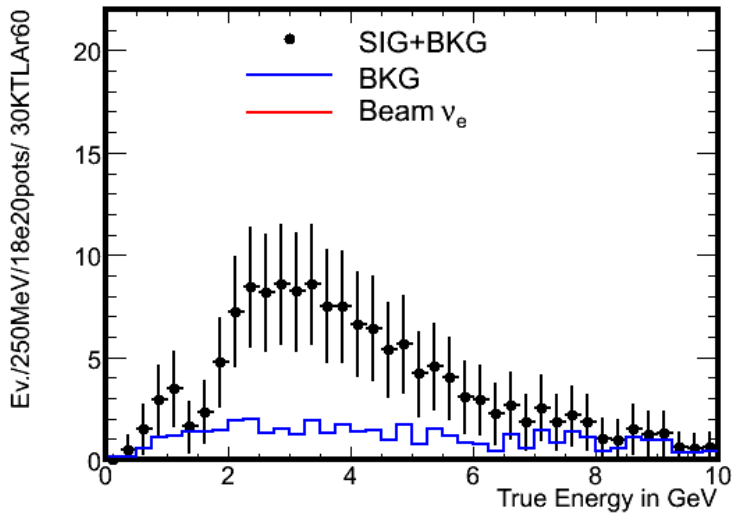
100 kt fiducial WC



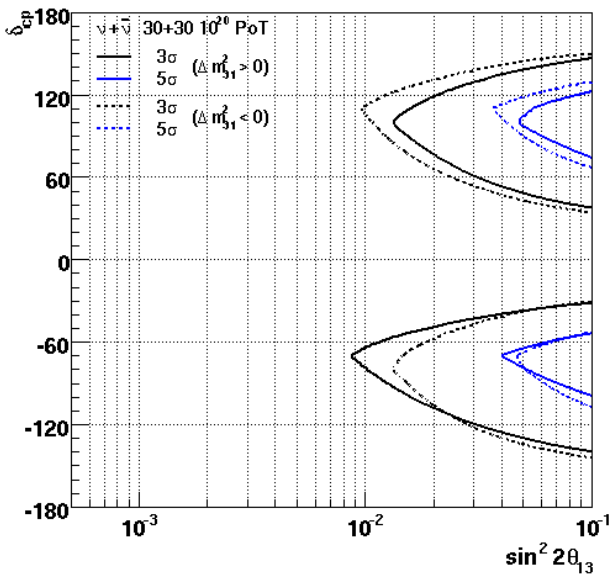
30 kt fiducial LAr



30 kt fiducial LAr



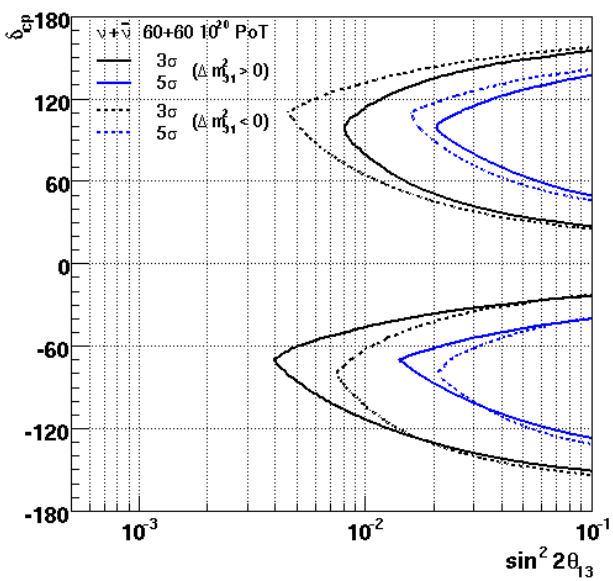
How Does CPV Reach Scale with Number of Events?



CP reach ~ 0.009

BNL Globes WC 300 kt fiducial, 120 GeV 9 mrad OA 30e20neutrinos+30e20 antineutrinos

$$\sqrt{2} = 1.4$$



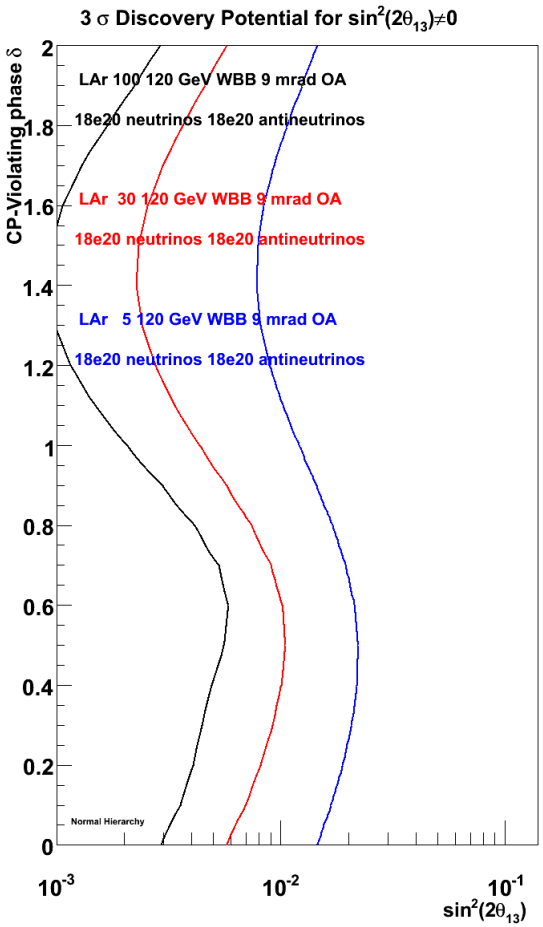
Stat x 2

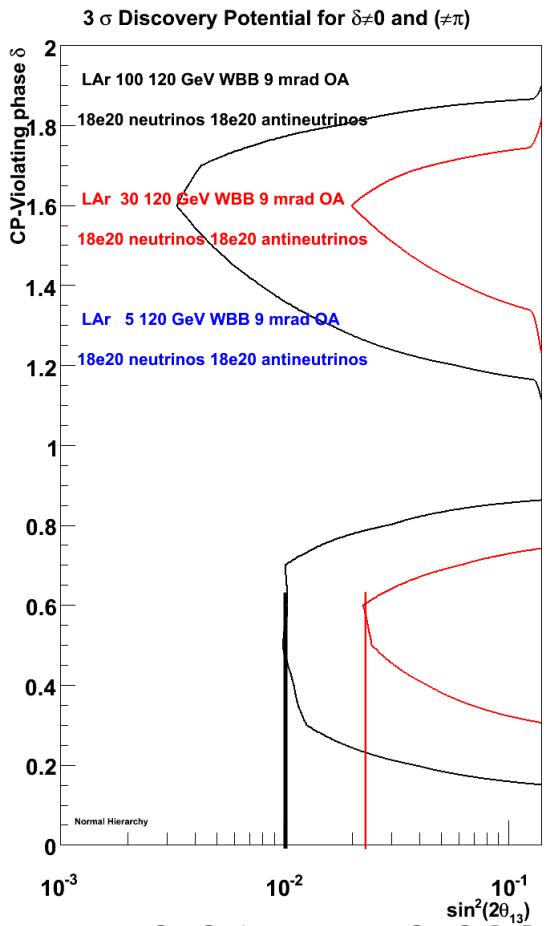
CP reach ~ 0.004

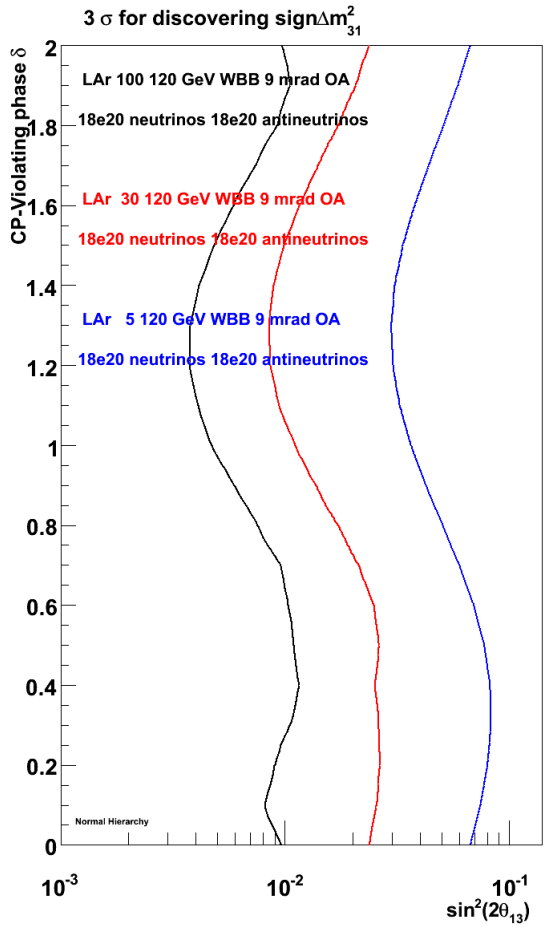
BNL Globes WC 300 kt fiducial, 120 GeV 9 mrad OA 60e20neutrinos+60e20 antineutrinos

How Does CPV Reach Scale with Number of Events?

FNAL Fast MC (NS)







0.01 0.023

Stat x 3.33

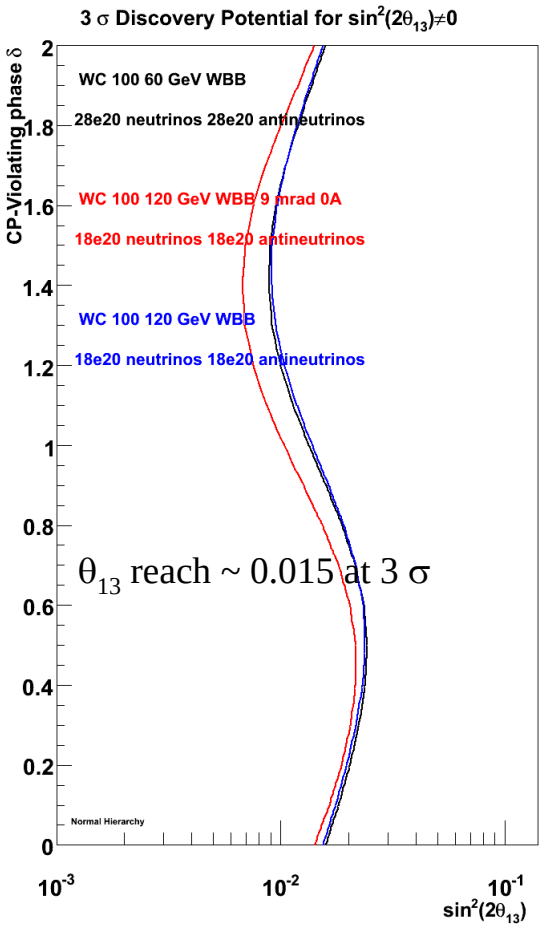
$$\sqrt{3.3} = 1.8$$

Need to increase # bins in deltacp to get smoother curves.

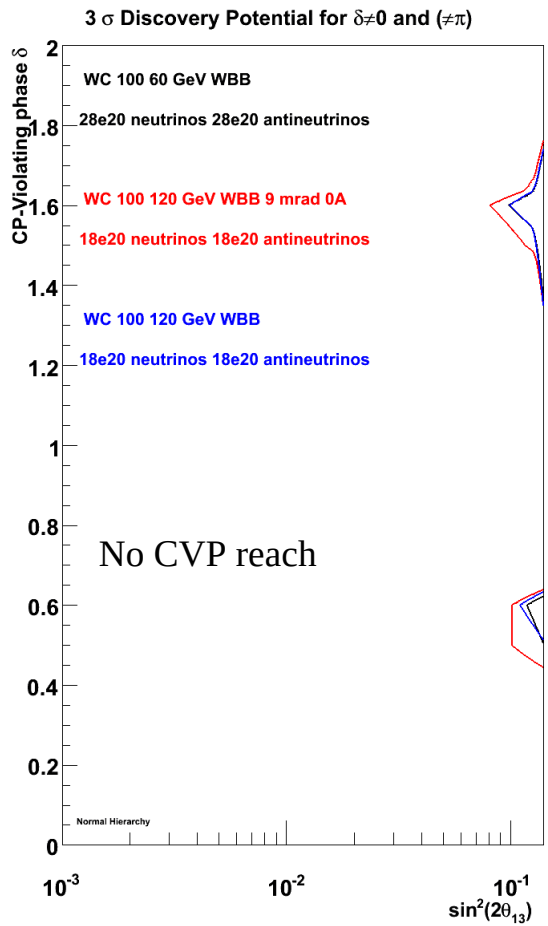
Sensitivities with 95% C.L. for the mass hierarchy in linear scale

Sensitivities for 100kt fiducial Water Cherenkov

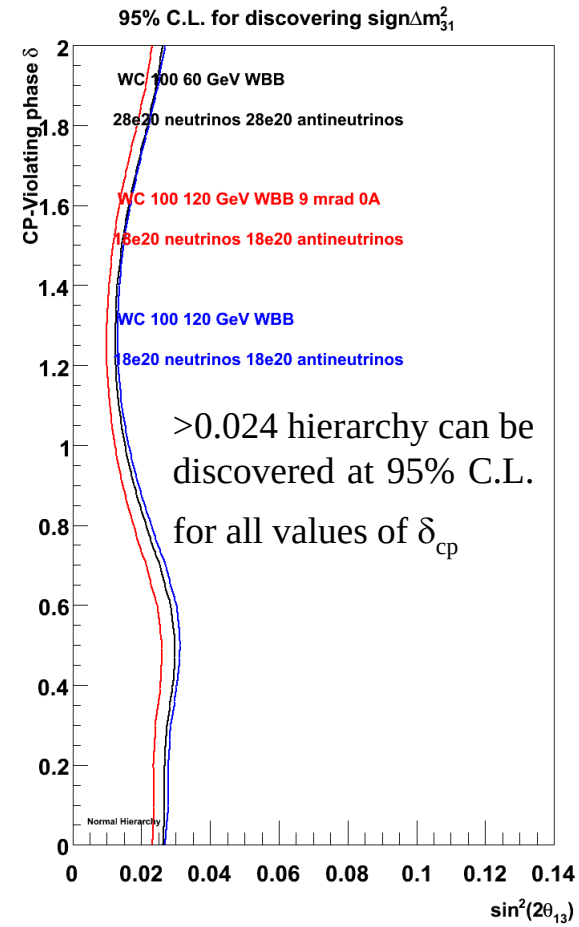
"Nominal" NC background



θ_{13} reach ~ 0.015 at 3 σ



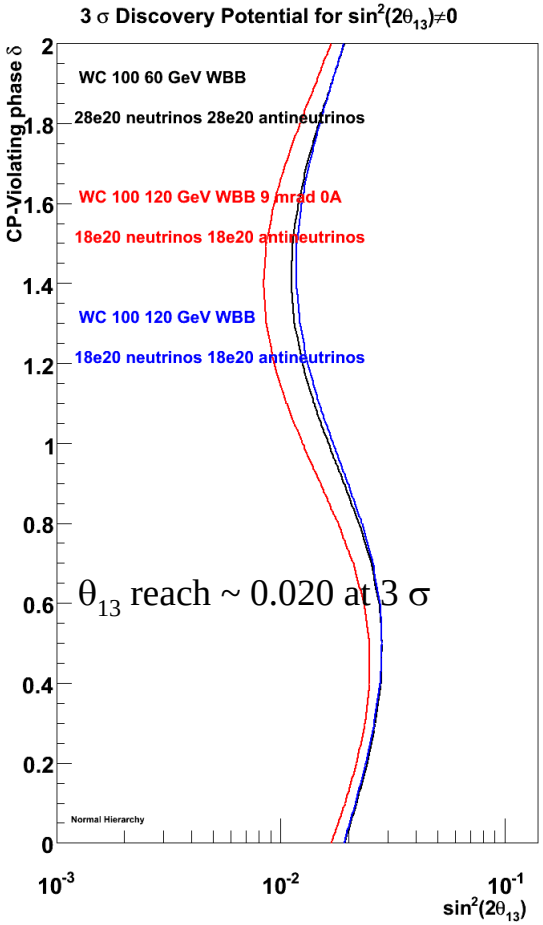
No CVP reach

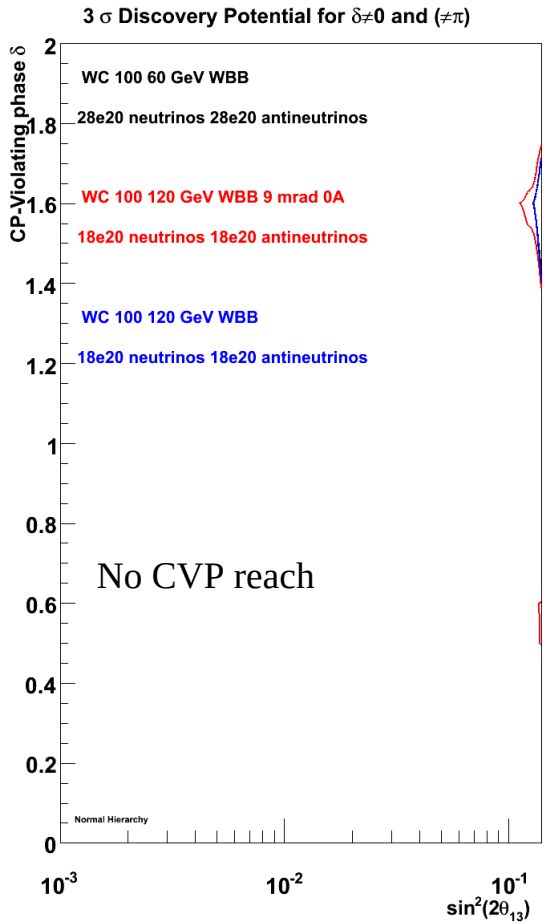


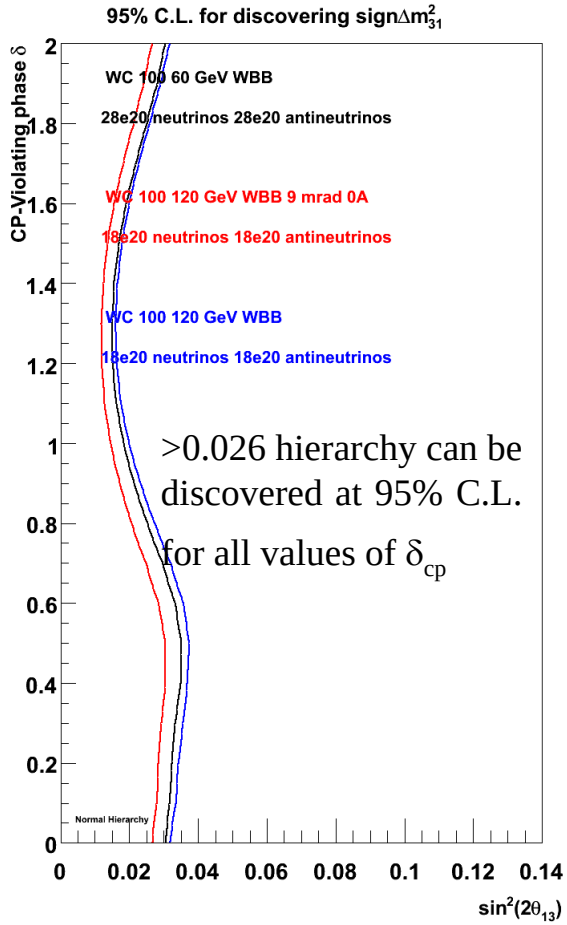
>0.024 hierarchy can be discovered at 95% C.L. for all values of δ_{cp}

Sensitivities for 100kt fiducial Water Cherenkov

NC background x 1.6

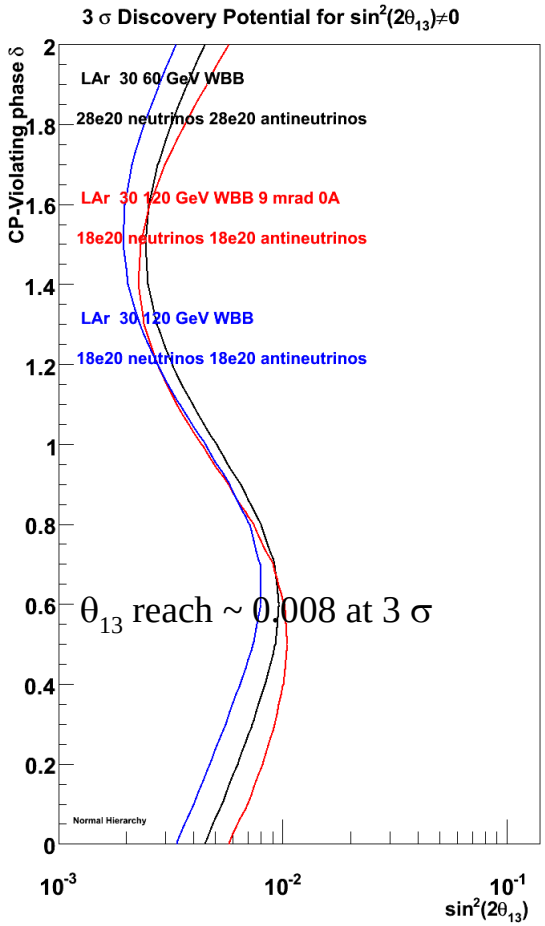




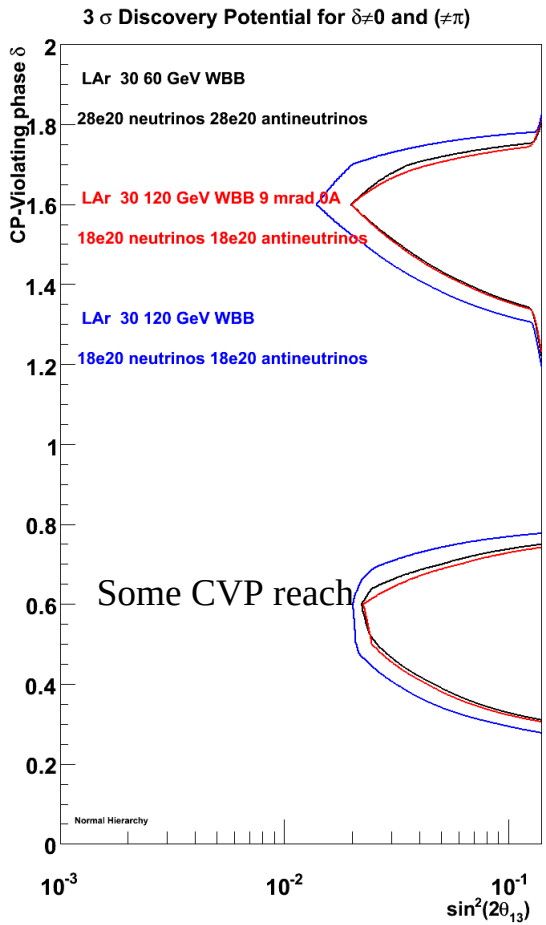


Sensitivities for 30kt fiducial LAr Detector

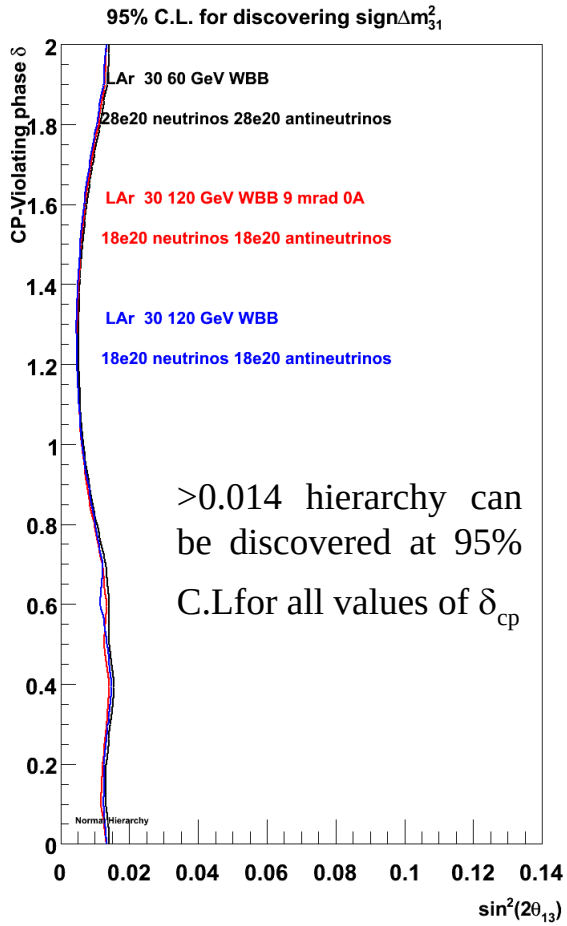
NC background = 0



θ_{13} reach ~ 0.008 at 3 σ



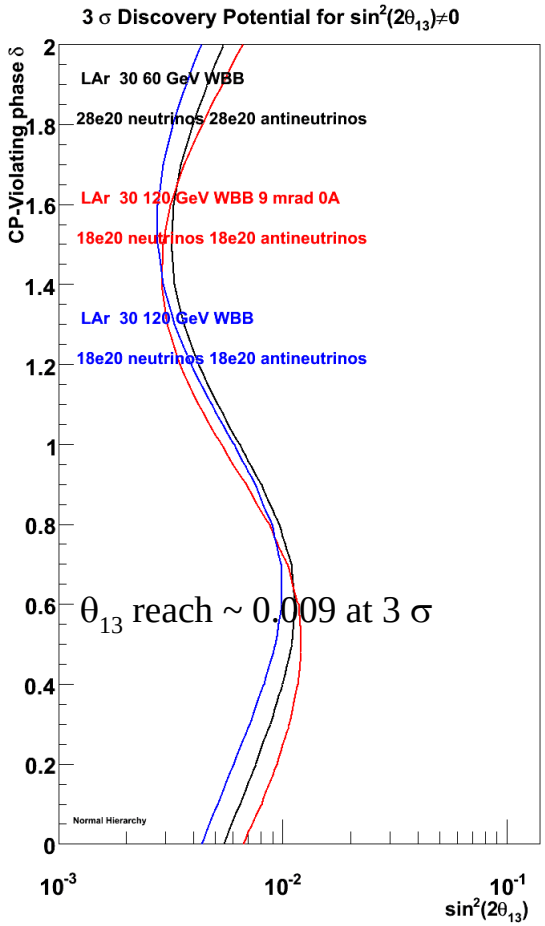
Some CVP reach



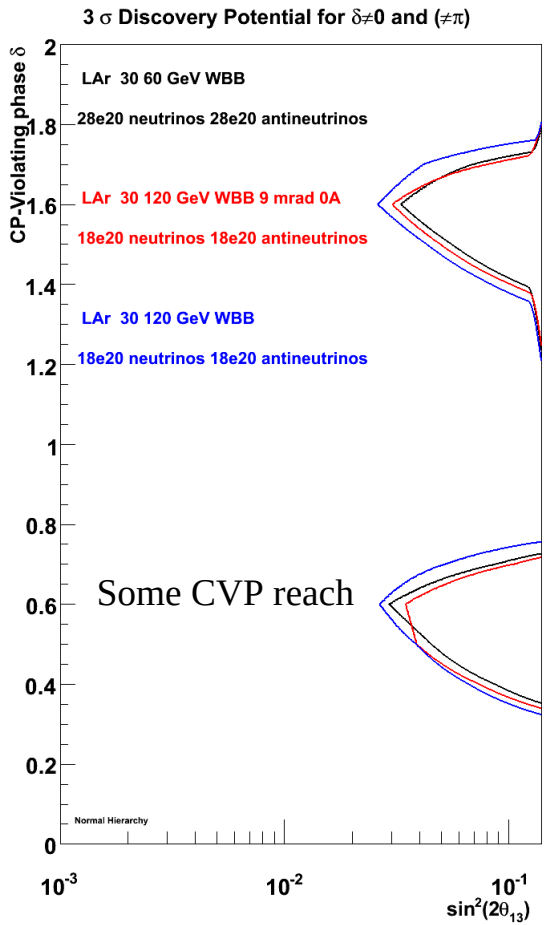
>0.014 hierarchy can be discovered at 95% C.Lfor all values of δ_{cp}

Sensitivities for 30kt fiducial LAr Detector

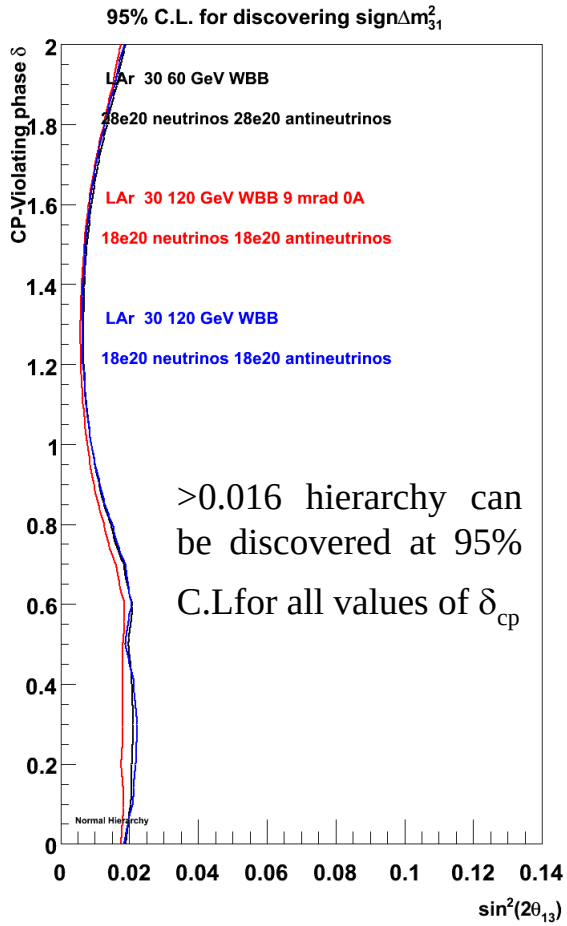
NC background = 0.01



θ_{13} reach ~ 0.009 at 3 σ



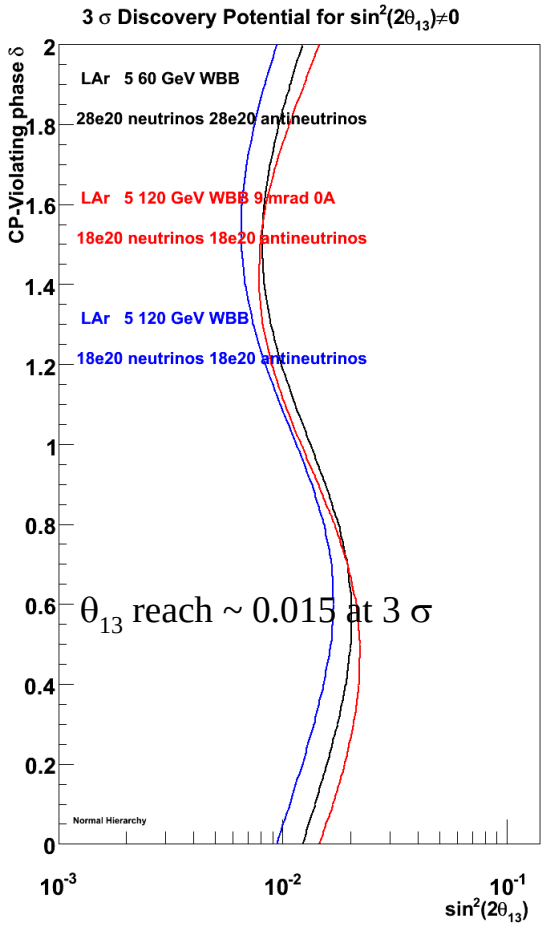
Some CVP reach



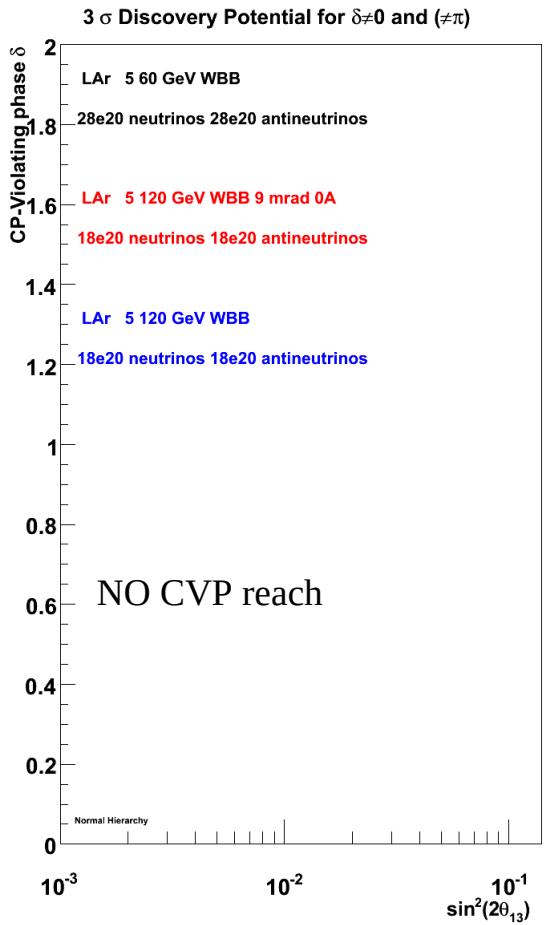
>0.016 hierarchy can be discovered at 95% C.Lfor all values of δ_{cp}

Sensitivities for 5kt fiducial LAr Detector

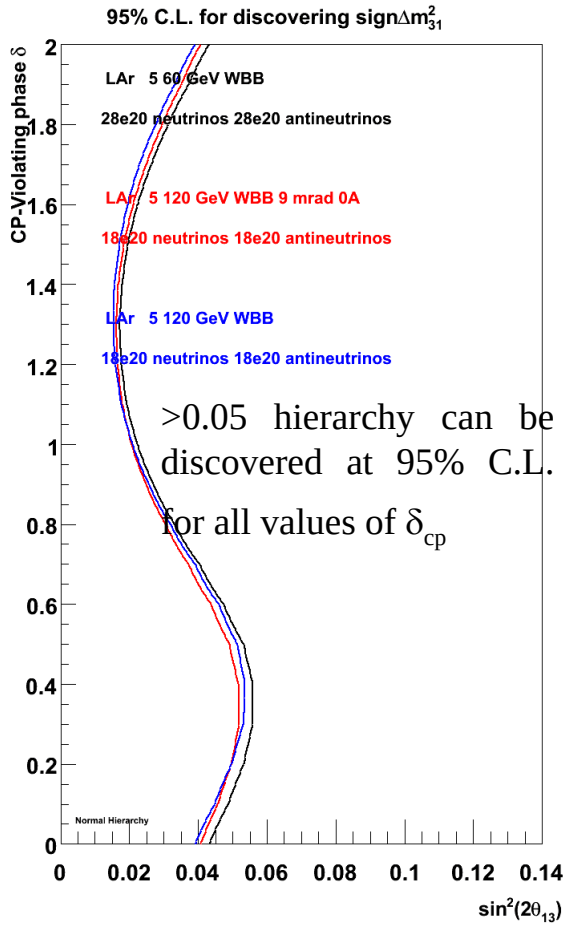
NC background = 0



θ_{13} reach ~ 0.015 at 3 σ



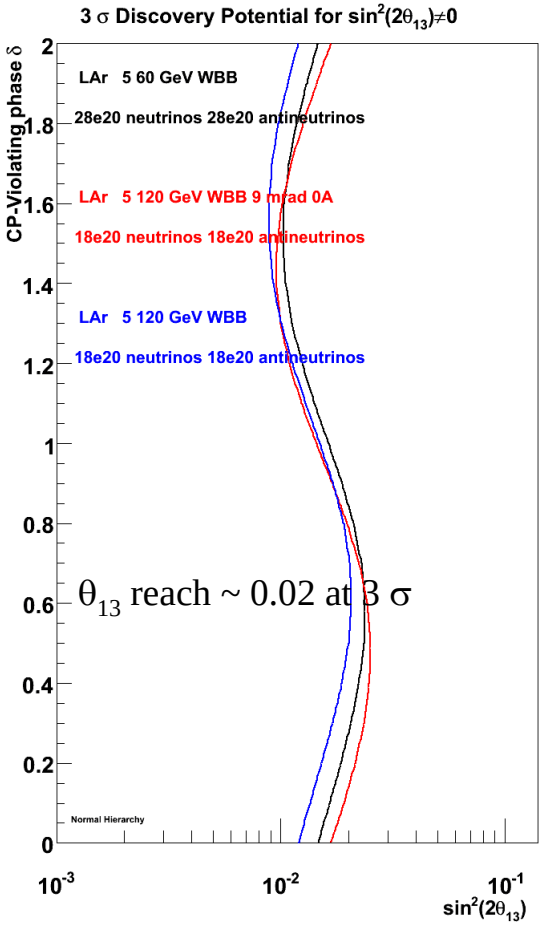
NO CVP reach



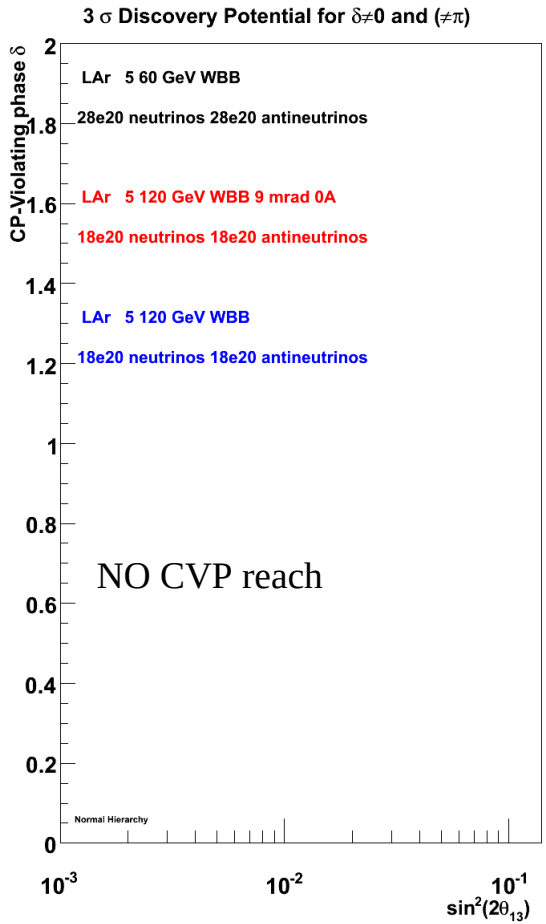
>0.05 hierarchy can be discovered at 95% C.L. for all values of δ_{cp}

Sensitivities for 5kt fiducial LAr Detector

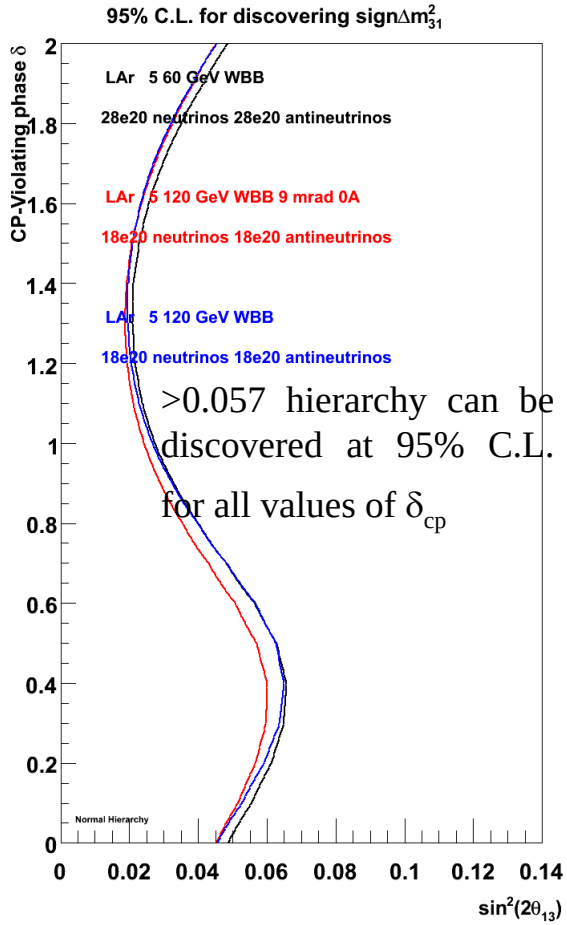
NC background = 0.01



θ_{13} reach ~ 0.02 at 3 σ



NO CVP reach



>0.057 hierarchy can be discovered at 95% C.L. for all values of δ_{cp}