Physics Potential of the DUSEL Program

Outline:

Introduction

- **ν Oscillations**
- **p Decay**
- **Supernova, Relic, Solar ν's**

Summary/Conclusion

N. Saoulidou, Fermilab

Physics **A**dvisory **C**ommittee , 3rd November 2008

Introduction : ν Oscillations

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?

ν Oscillation Sensitivities vs Time

All Scenarios assume, at any point in time, equal running in neutrinos and anti-neutrinos.

All Scenarios assume 10 years of total running

Scenario 1:

Detector Mass : Additional "**Detector Module**" **every 2 years** up **to a total of three "Detector Modules"**.

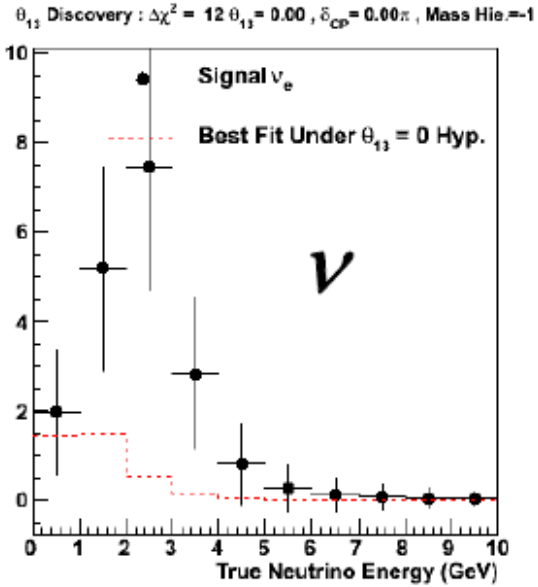
Beam Intensity : **700 KW**

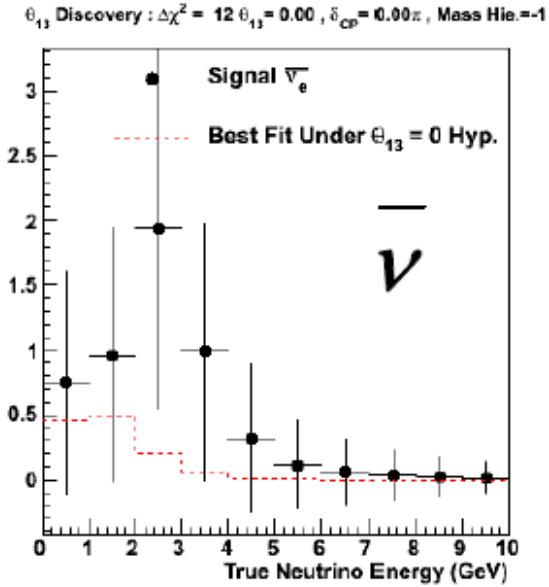
Scenario 2:

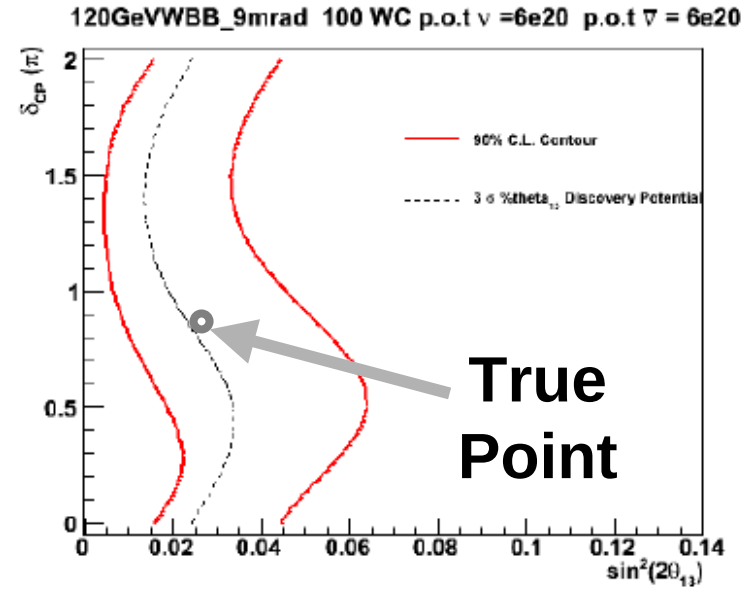
Detector Mass : Additional "**Detector Module**" **every 2 years** up **to a total of three "Detector Modules"**

Beam Intensity : **700 KW for the first 4 years and then 2.1 MW for the remaining 6 years.**

ν Oscillations : Example of measurement







Black : Data

Black Dotted Line : 3 σ Sensitivity

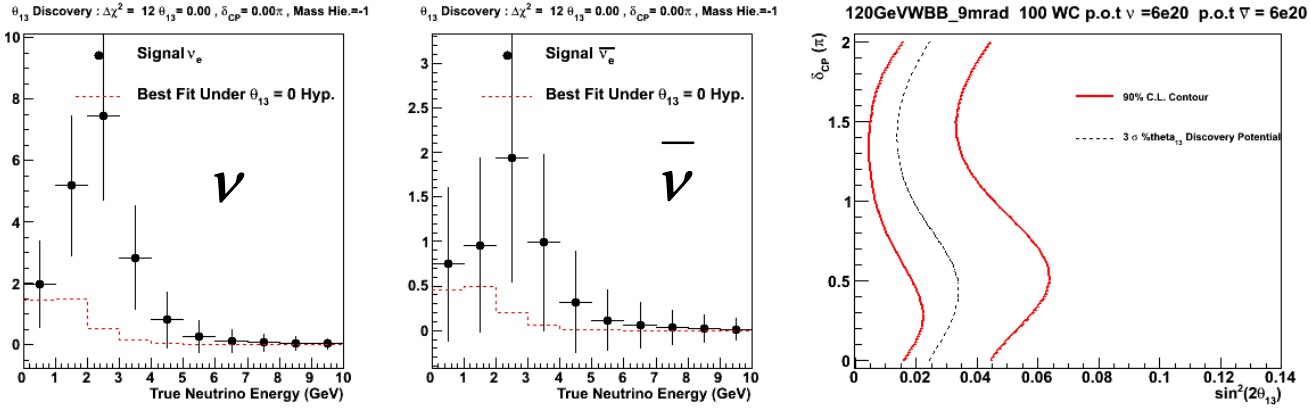
Red Dotted : Null Hypothesis (θ_{13} = 0)

Red Lines : 90% C.L. contour from the fit to the data on the left

With this data we are able to exclude the hypothesis that θ_{13} = 0 to high significance : $\Delta\chi^2$ = 12 => Significance = 3.5 σ

This is why this **true point we choose** is to the **right of the 3 σ sensitivity curve on the right panel, and quite close to the 3 σ limit.**

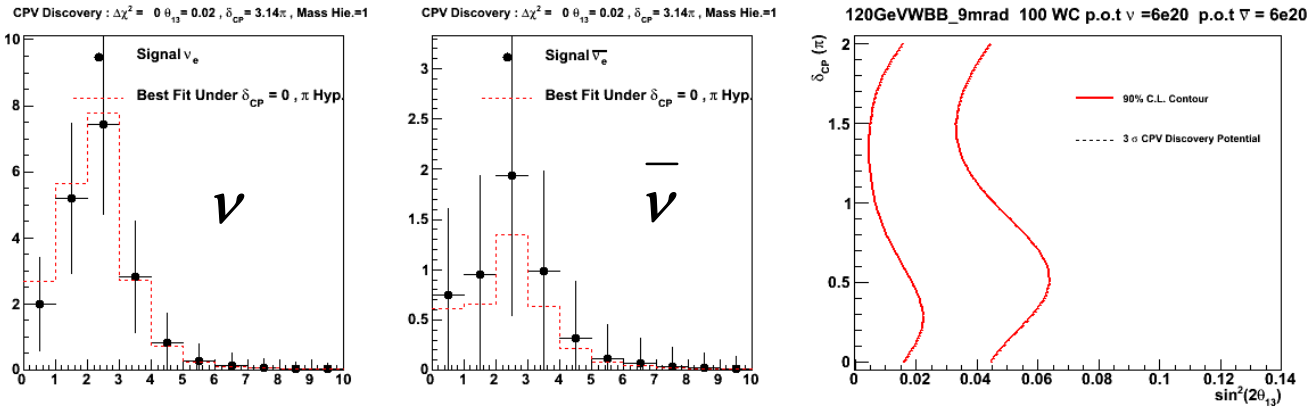
ν Oscillations : Example of measurement



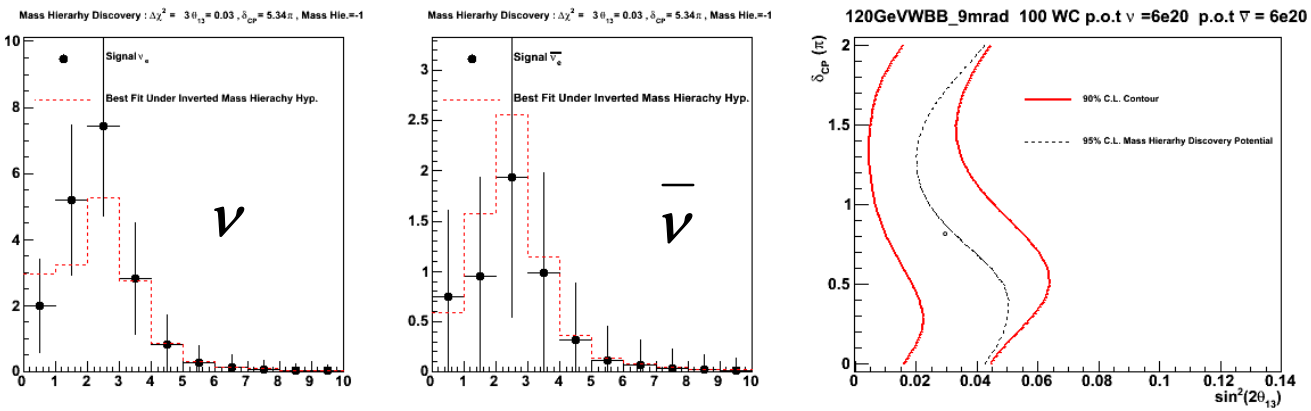
Black : Data

Red : Null Hypothesis

Parameter	Discovery
θ_{13}	**YES**

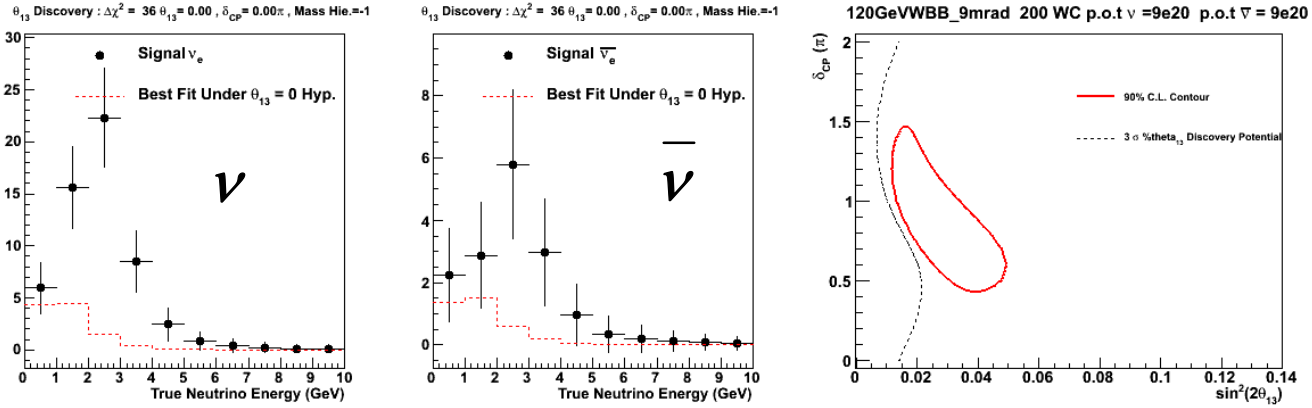


CPV	**NO**



Mass Hierarchy	**NO**

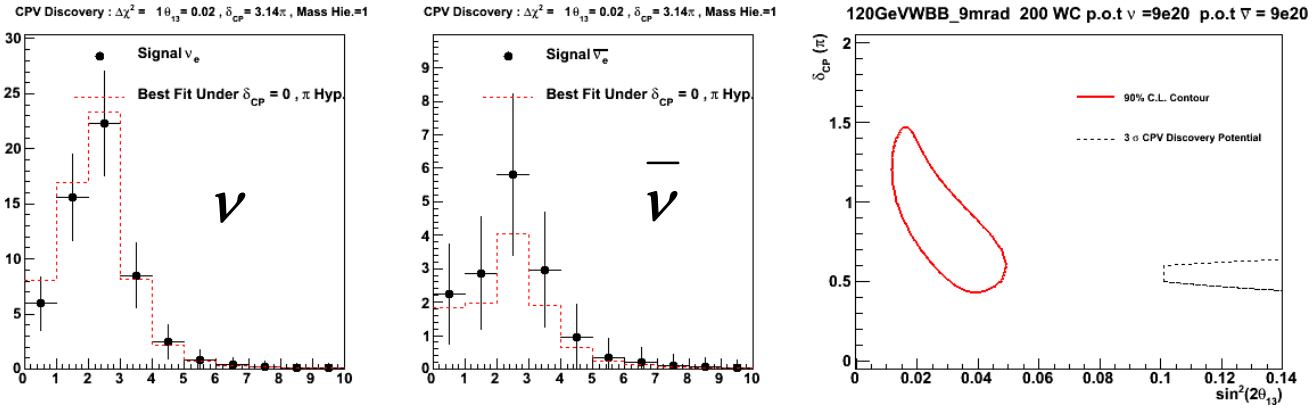
ν Oscillations : Example of measurement



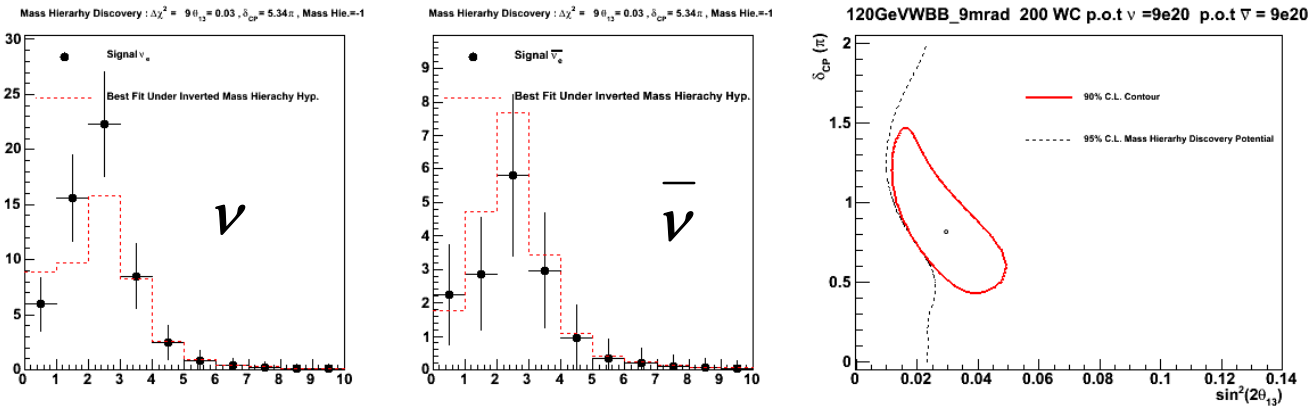
Black : Data

Red : Null Hypothesis

Parameter	Discovery
θ_{13}	YES

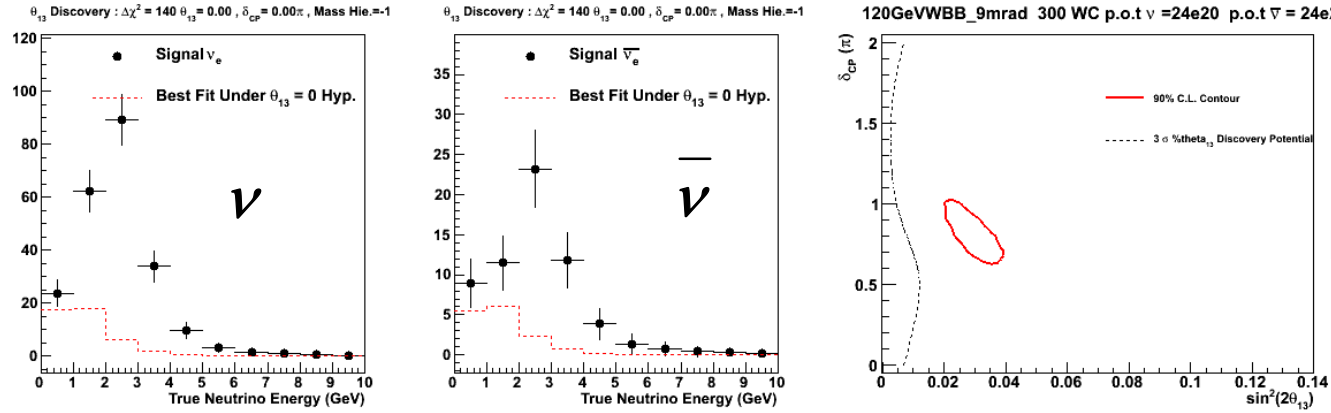


CPV	NO



Mass Hierarchy	YES

ν Oscillations : Example of measurement



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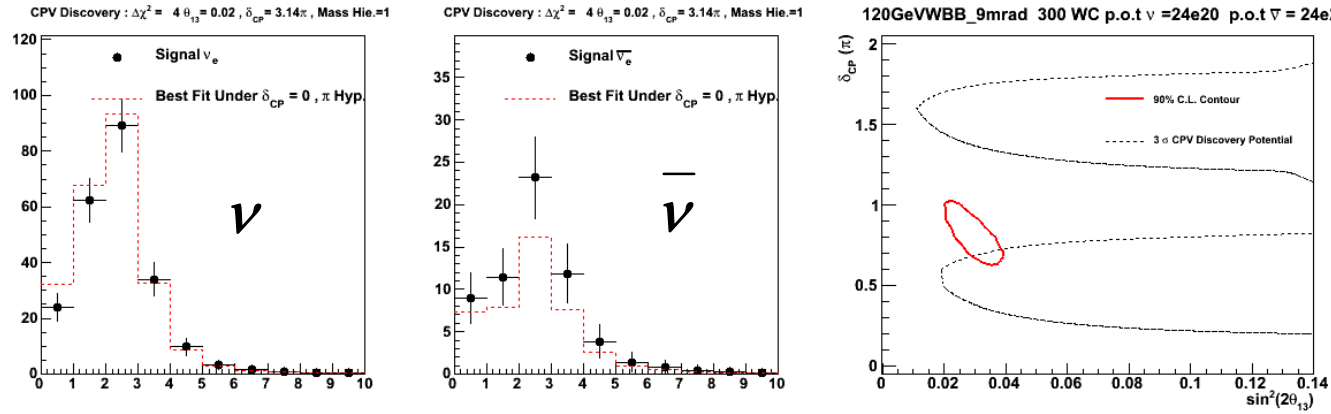
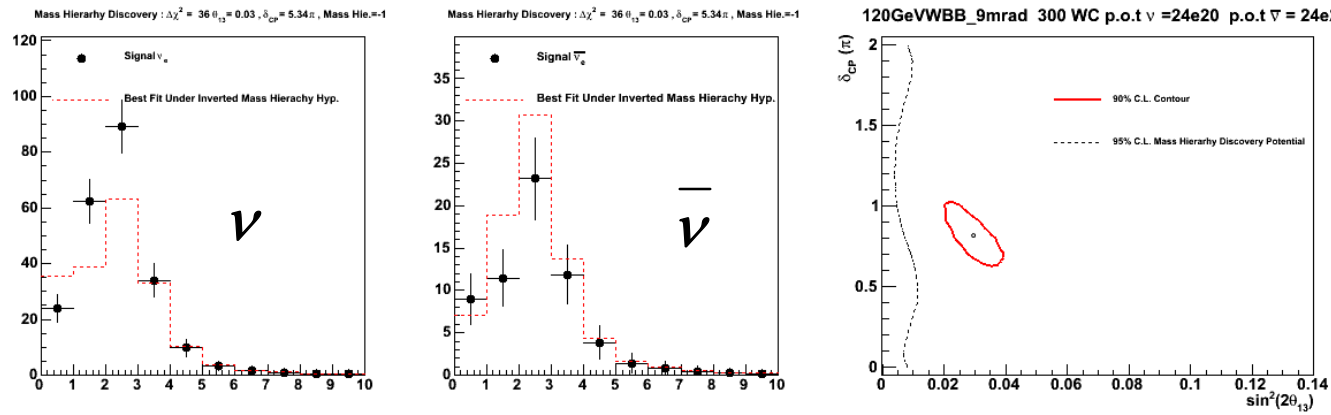
Red : Null Hypothesis

Parameter	Discovery
θ_{13}	YES

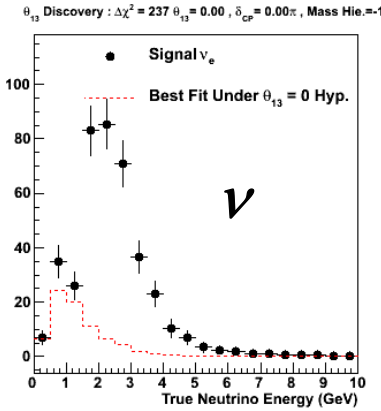


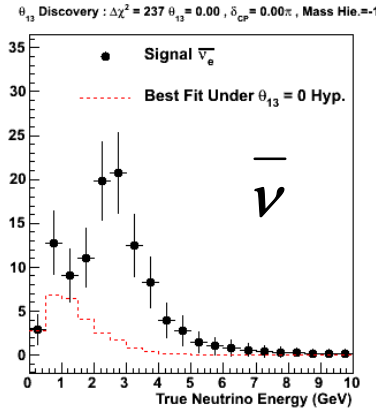
CPV	NO

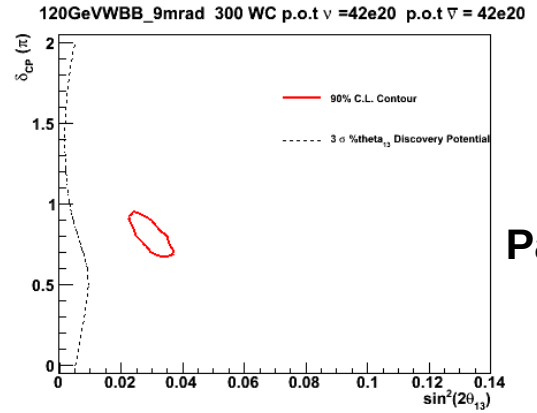


Mass Hierarchy	YES

ν Oscillations : Example of measurement







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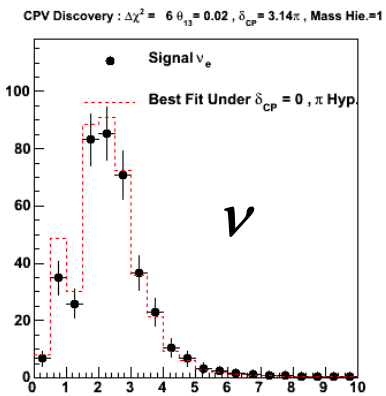
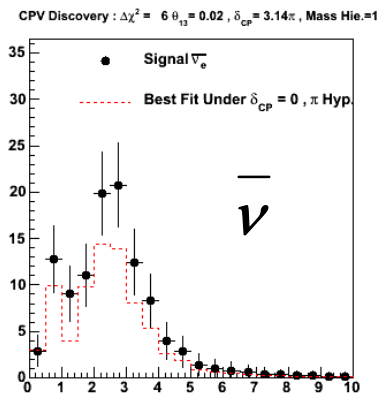
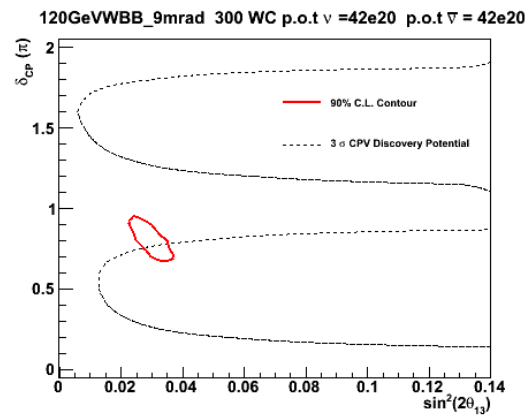
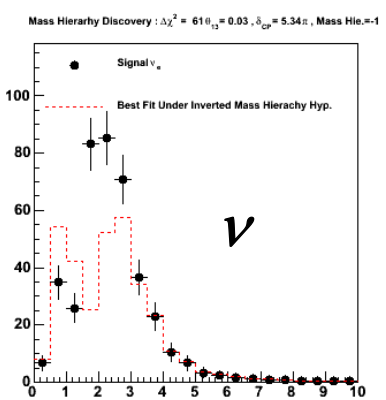
Parameter	Discovery
θ_{13}	YES

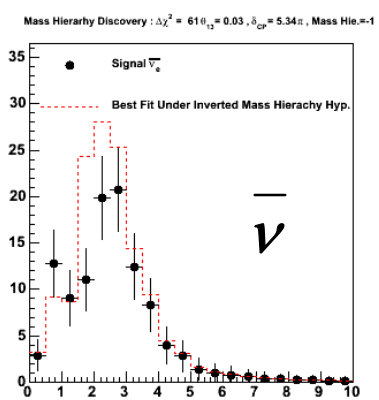


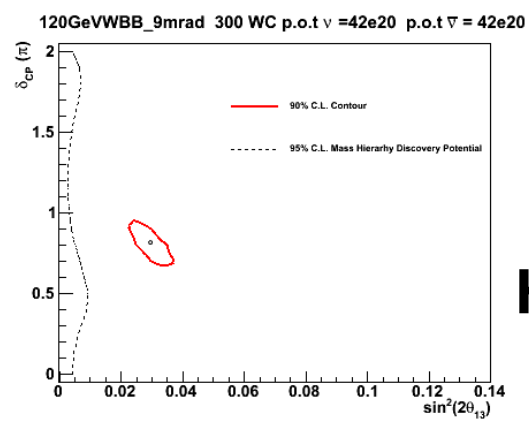




CPV	NO

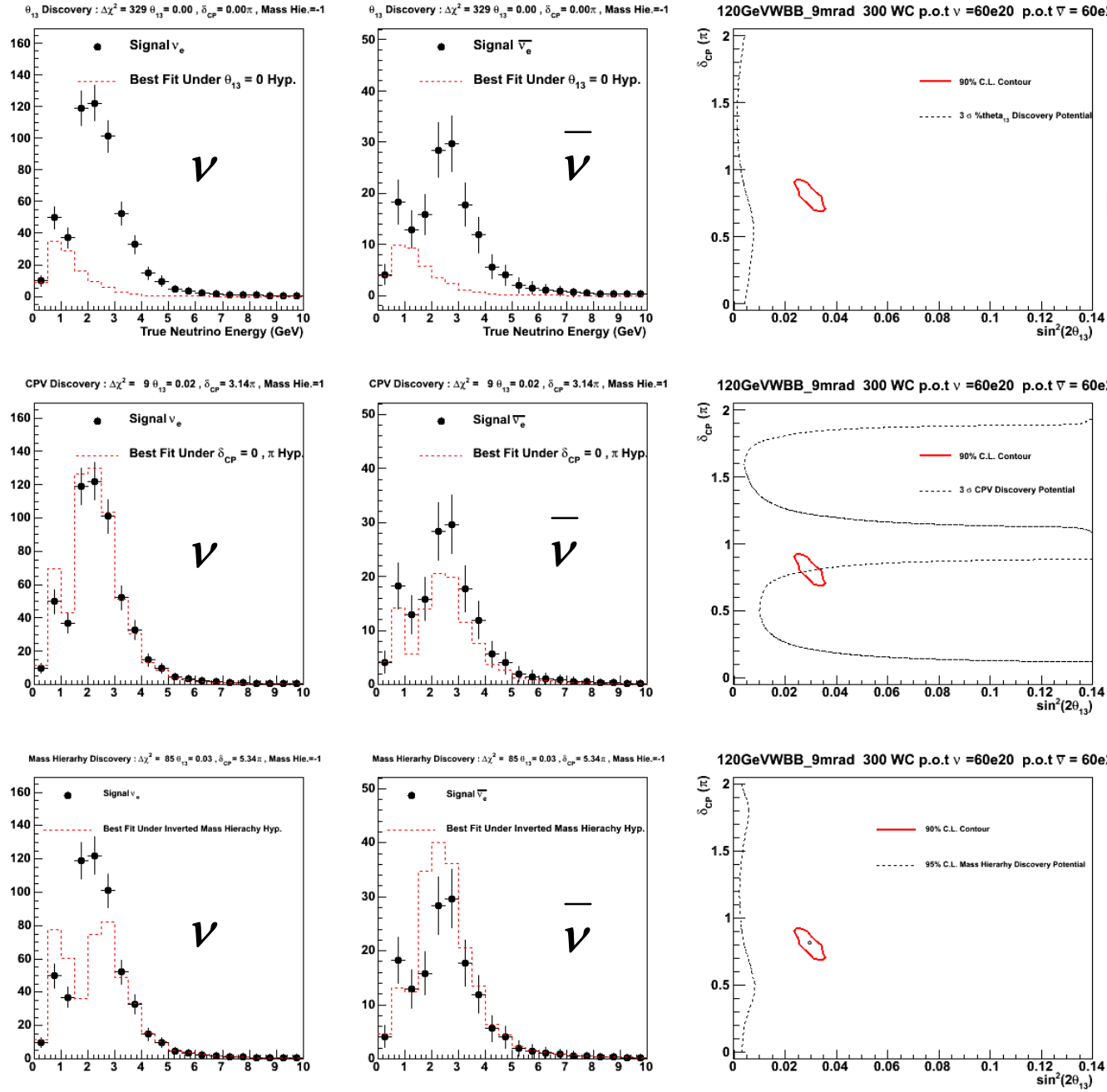






Mass Hierarchy	YES

ν Oscillations : Example of measurement



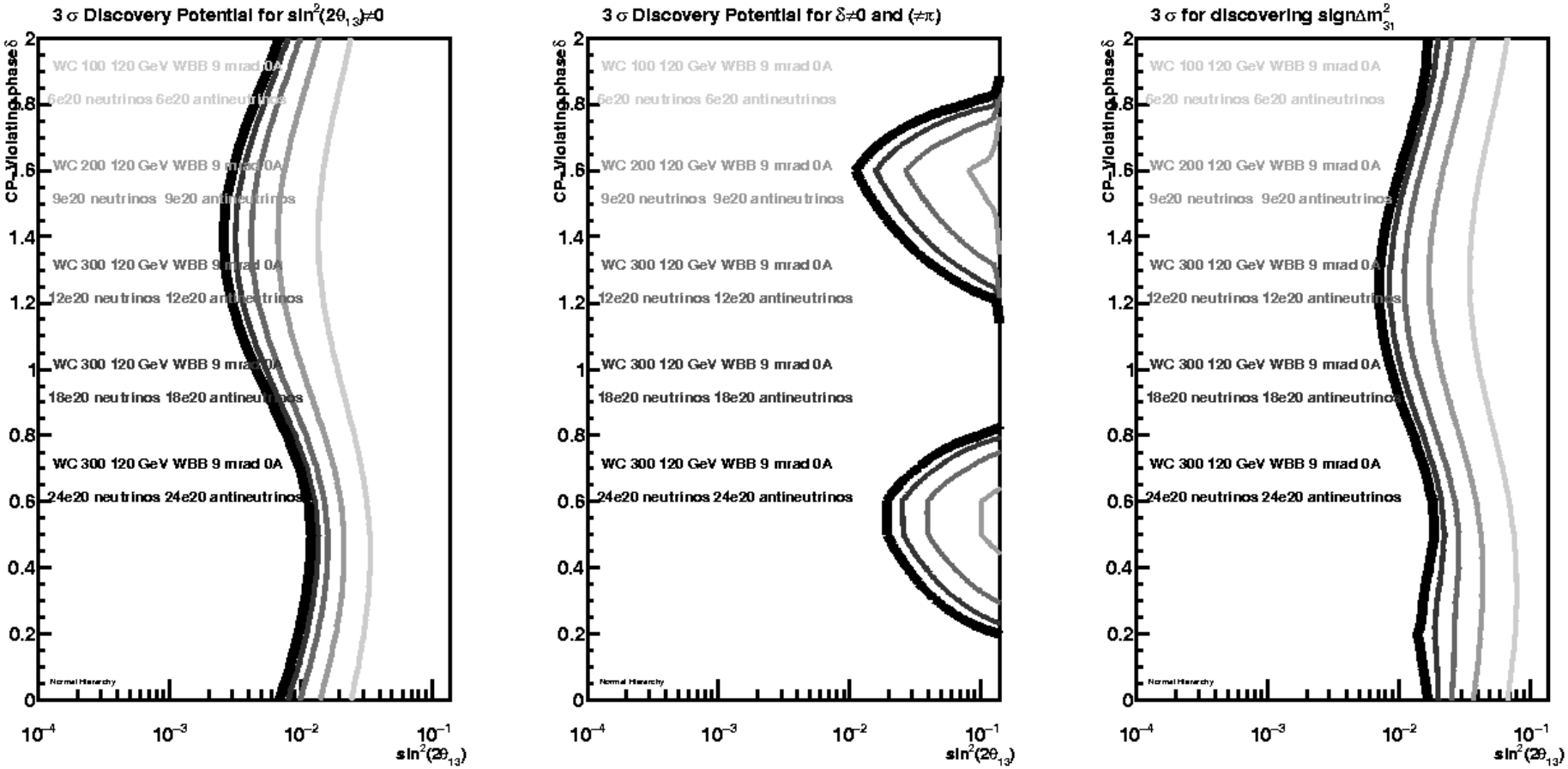
Black : Data

Red : Null Hypothesis

Parameter	Discovery
θ_{13}	YES
CPV	YES
Mass Hierarchy	YES

Sensitivities for Water Cherenkov Detector :

Scenario 1 "Detector Module" = 100 KT



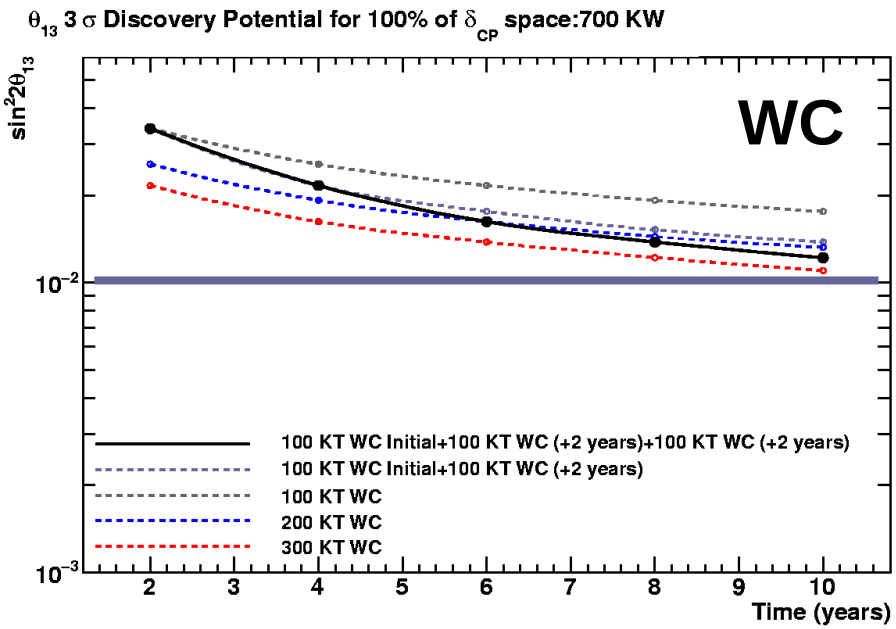
The 5 Curves correspond to the five 2 year intervals for the total 10 year period.

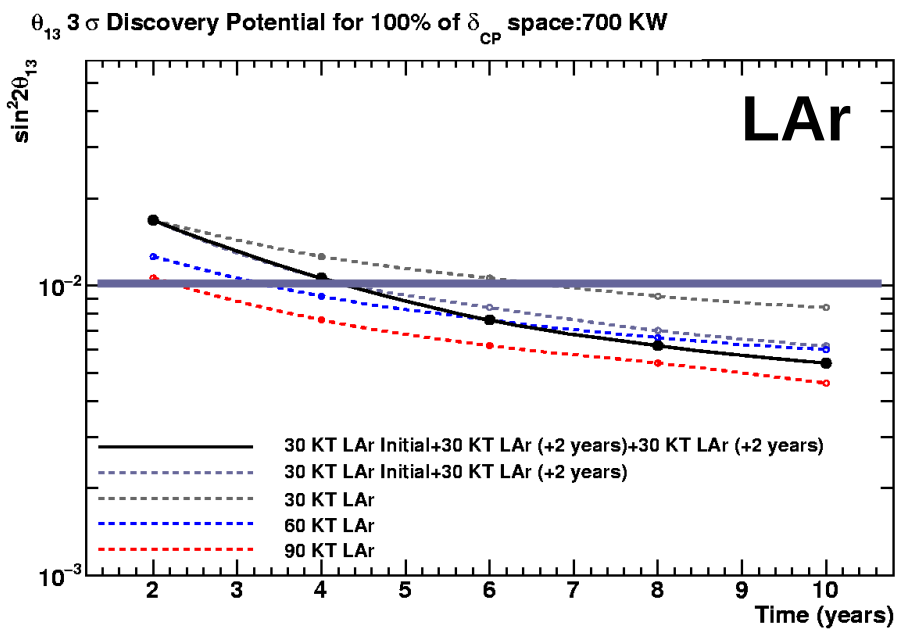
First curve is discovery potential after 2 years of running, second curve is discovery potential after 4 years of running etc.

Sensitivities vs Time for WC (LAr) Detector :

Scenario 1 "Detector Module" = 100 (30) KT

θ_{13} Discovery Potential for all values of δ_{cp} (100%)





The black curve is the "nominal" scenario 1
The dotted curves are :

100 (30) KT total with no further addition of mass
100 (30) KT +100 (30) KT with no further addition of the 3rd Module
200 (60) KT total from day 1
300 (90) KT total from day 1

No significant reach is gained when starting from Day 1 with the total Detector Mass, compared to adding Modules every 2 years.

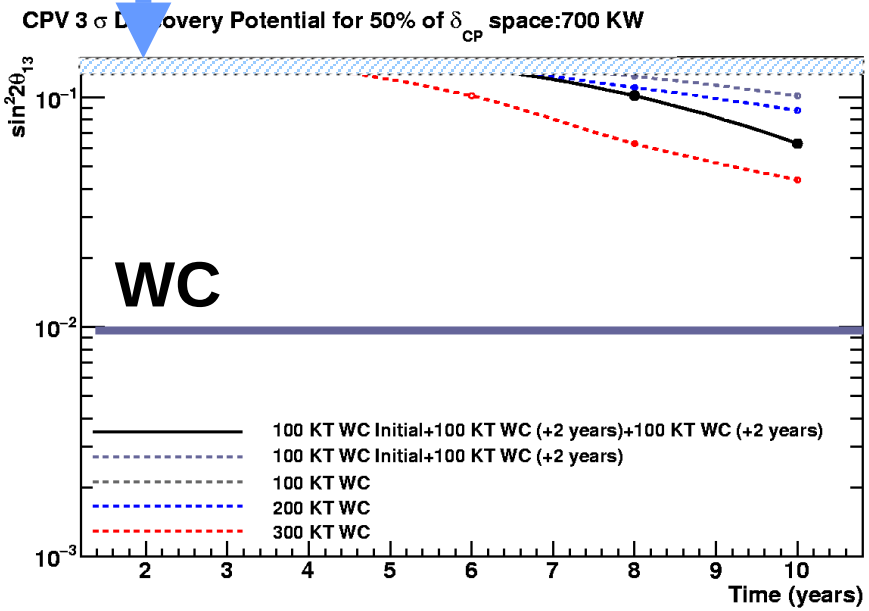
The WC – LAr mass equivalence is 1 – 6 (optimistic) to 1 –3 (very pessimistic)

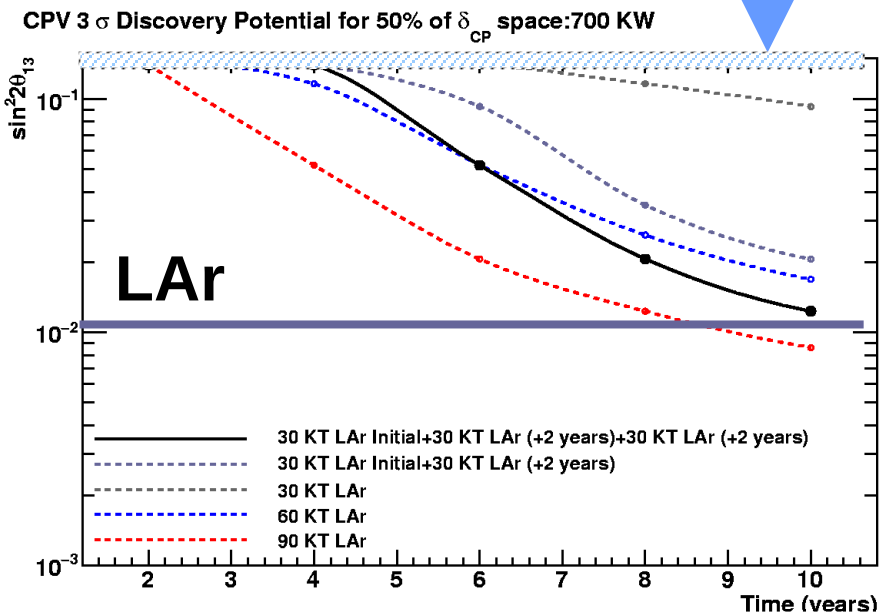
Sensitivities vs Time for WC (LAr) Detector :
Scenario 1 "Detector Module" = 100 (30) KT

CHOOZ Limit

CPV Discovery Potential for 50% of δ_{cp}

CHOOZ Limit





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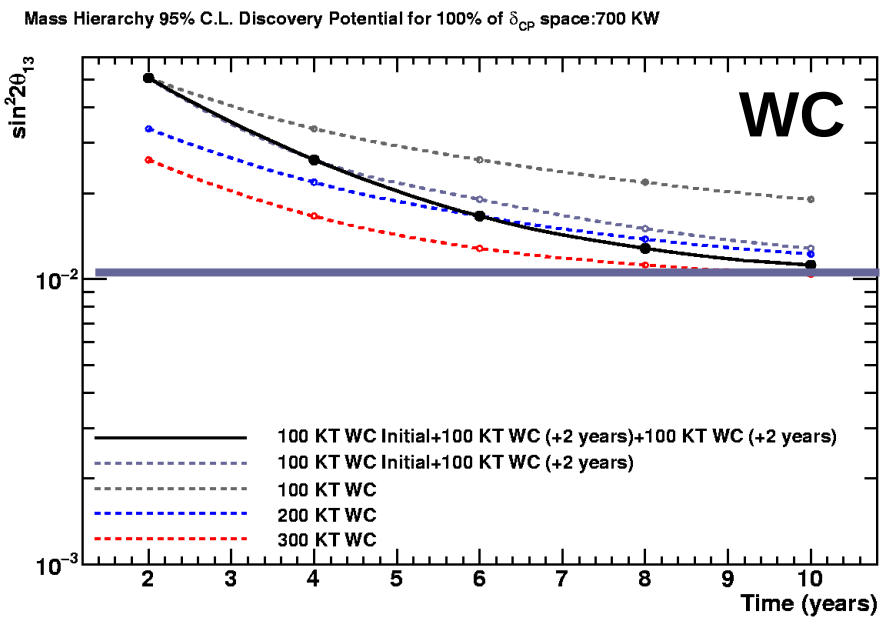
100 (30) KT total with no further addition of mass
100 (30) KT +100 (30) KT with no further addition of the 3rd Module
200 (60) KT total from day 1
300 (90) KT total from day 1

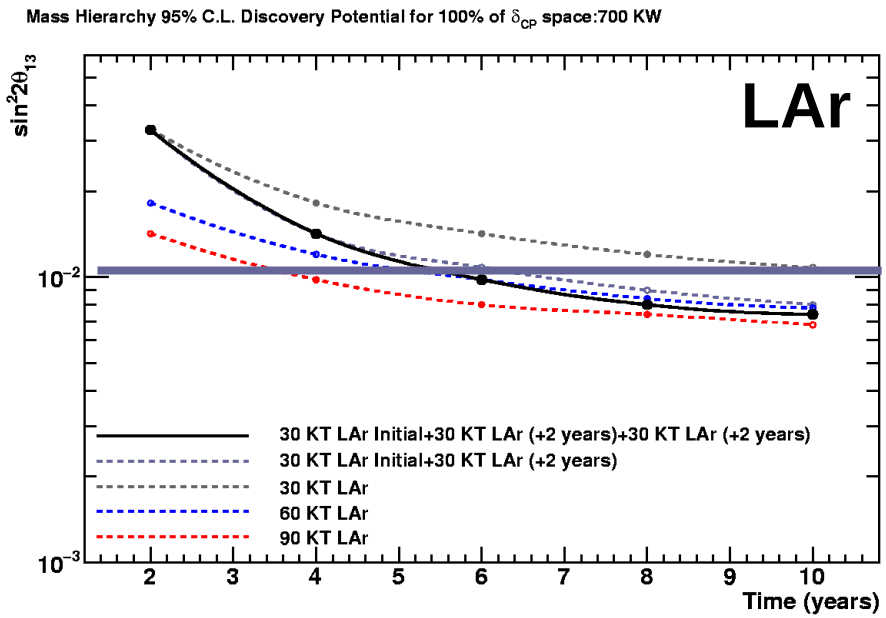
For CVP Discovery we need more than 100 KT WC. 200 KT is not enough either unless θ_{13} is large

The WC – LAr mass equivalence is 1 – 6 (optimistic) to 1 –3 (very pessimistic)

Sensitivities vs Time for WC (LAr) Detector :
Scenario 1 "Detector Module" = 100 (30) KT

Mass Hierarchy Discovery Potential for all values of δ_{cp} (100%)





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100 (30) KT +100 (30) KT with no further addition of the 3rd Module
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300 (90) KT total from day 1

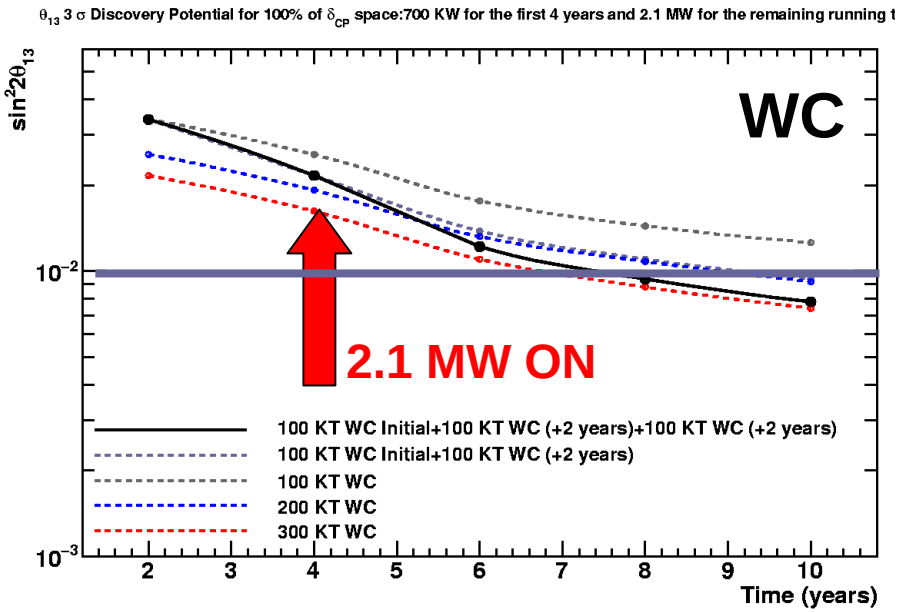
No significant reach is gained when starting from Day 1 with the total Detector Mass, compared to adding Modules every 2 years.

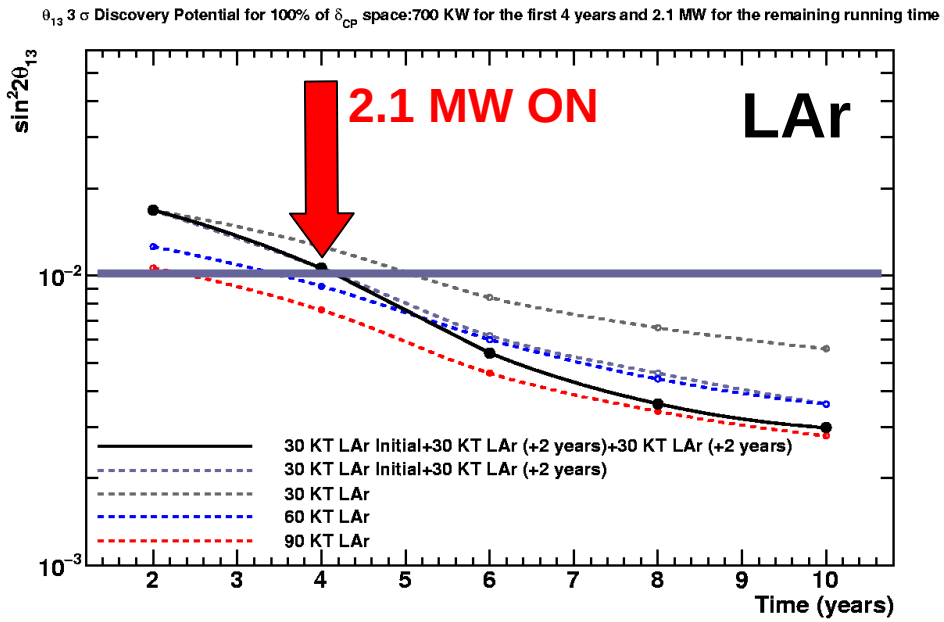
The WC – LAr mass equivalence is 1 – 6 (optimistic) to 1 –3 (very pessimistic)

Sensitivities vs Time for WC (LAr) Detector :

Scenario 2 "Detector Module" = 100(30) KT

θ_{13} Discovery Potential for all values of δ_{cp} (100%)





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100 (30) KT +100 (30) KT with no further addition of the 3rd Module
200 (60) KT total from day 1
300 (90) KT total from day 1

ProjectX with a 2.1 MW beam helps a lot!

No significant reach is gained when starting from Day 1 with the total Detector Mass, compared to adding Modules every 2 years.

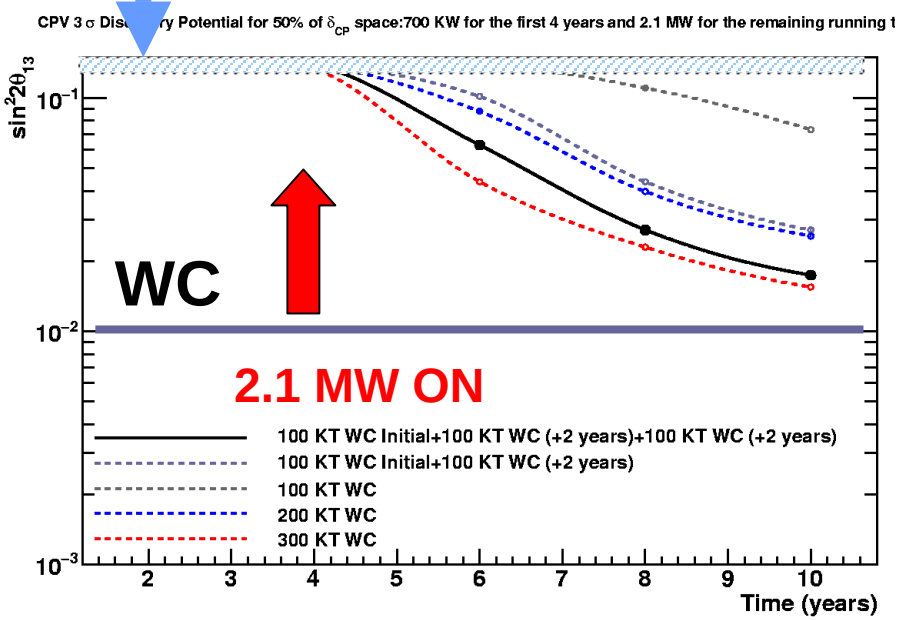
The WC – LAr mass equivalence is 1 – 6 (optimistic) to 1 –3 (very pessimistic)

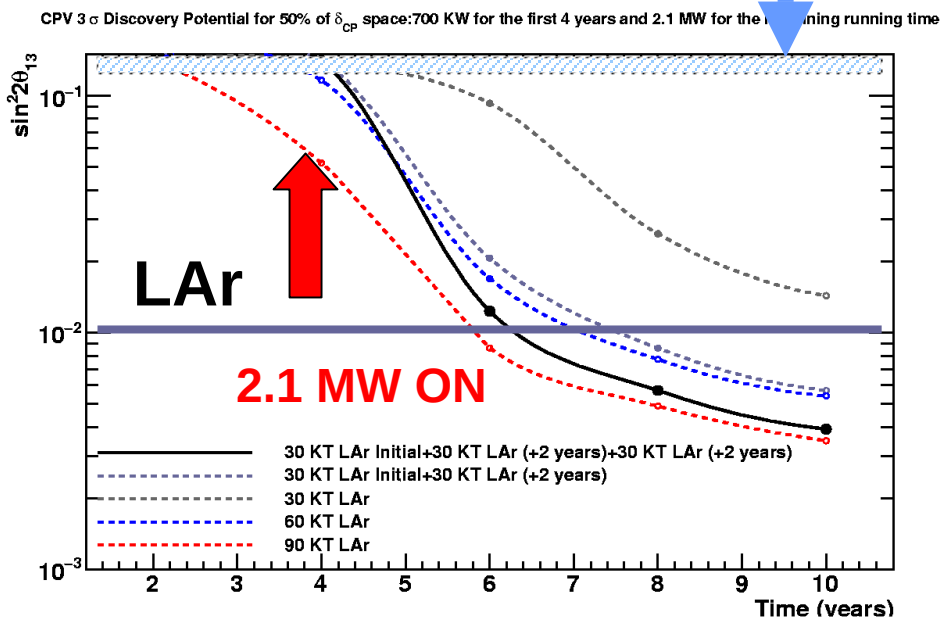
Sensitivities vs Time for WC (LAr) Detector :
Scenario 2 "Detector Module" = 100 (30) KT

CHOOZ Limit

CPV Discovery Potential for 50% of δ_{cp}

CHOOZ Limit





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100 (30) KT +100 (30) KT with no further addition of the 3rd Module
200 (60) KT total from day 1
300 (90) KT total from day 1

For CPV Discovery we need more than 100 KT WC.

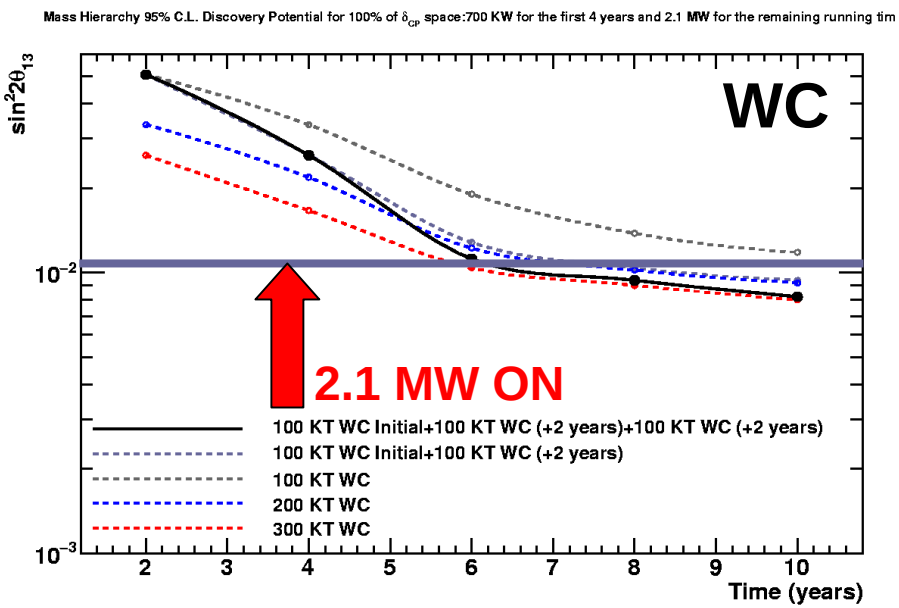
For CPV Discovery 30 KT LAr could be adequate.

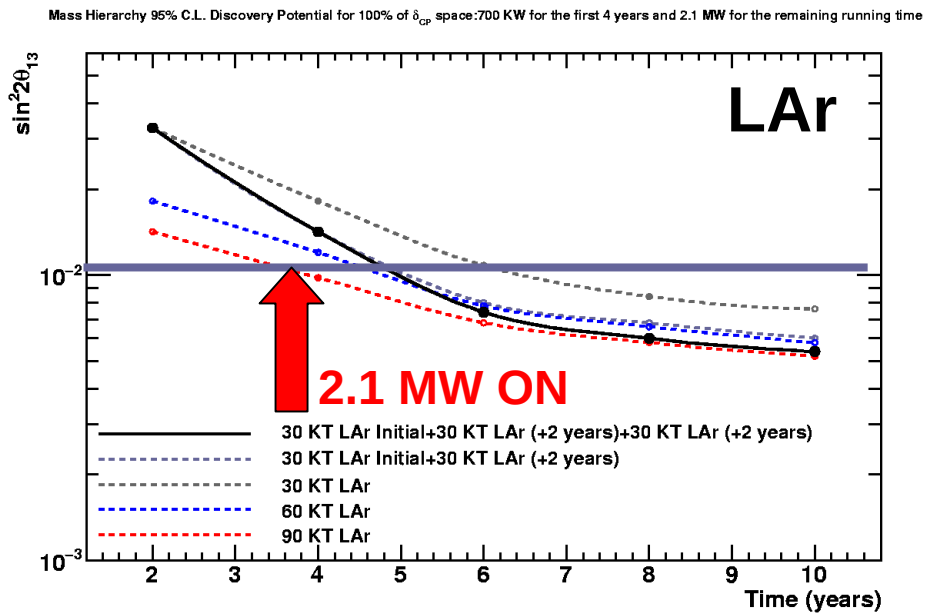
ProjectX with a 2.1 MW beam helps a lot!

The WC – LAr mass equivalence is 1 – 6 (optimistic) to 1 –3 (very pessimistic)

Sensitivities vs Time for WC (LAr) Detector :
Scenario 2 "Detector Module" = 100 (30) KT

Mass Hierarchy Discovery Potential for all values of δ_{cp} (100%)





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Introduction : p Decay

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

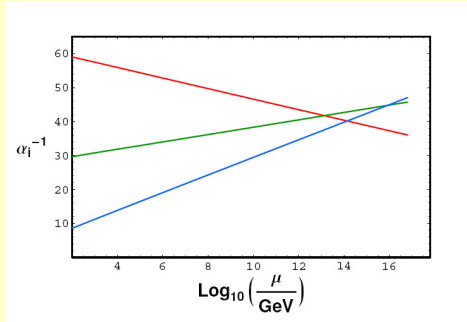
Unity of All Elementary-Particle Forces

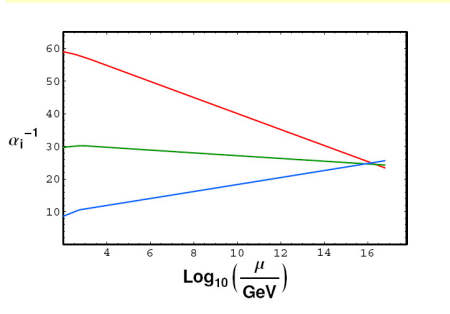
Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

Grand **U**nified **T**heories (**GUTs**)

$p \rightarrow e^+\pi^o$ $\quad$ $p \rightarrow K^+\nu$





Is Baryon Number Conserved?

Jogesh C. Pati*
International Centre for Theoretical Physics, Trieste, Italy, and Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

and

Abdus Salam
International Centre for Theoretical Physics, Trieste, Italy, and Imperial College, London, England
(Received 3 August 1973)

We suggest that baryon-number conservation may not be absolute and that an integrally charged quark may disintegrate into two leptons and an antilepton with a coupling strength $G_B m_p^2 \lesssim 10^{-9}$. On the other hand, if quarks are much heavier than low-lying hadrons, the decay of a three-quark system like the proton is highly forbidden (proton lifetime $\gtrsim 10^{38}$ y). Motivation for these ideas appears to arise within a unified theory of hadrons and leptons and their gauge interactions. We emphasize the consequences of such a possibility for real quark searches.

PHYSICAL REVIEW D VOLUME 10, NUMBER 1 1 JULY 1974

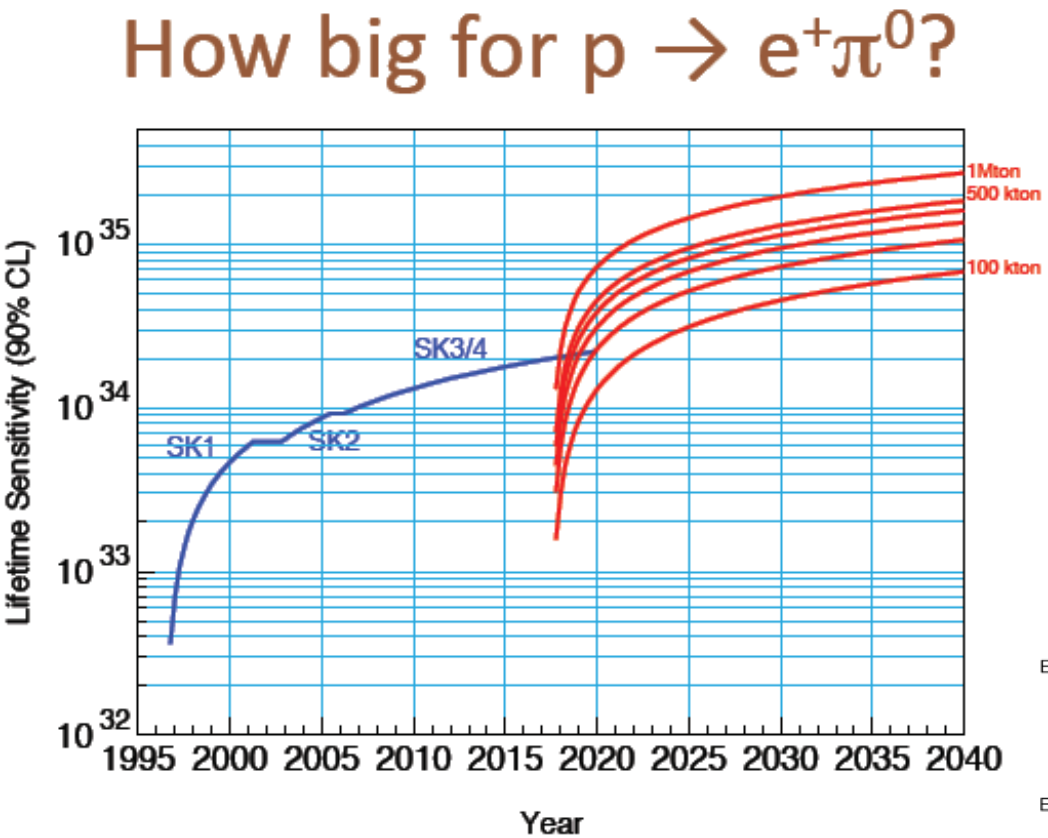
Lepton number as the fourth "color"

Jogesh C. Pati*
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

Abdus Salam
International Centre for Theoretical Physics, Trieste, Italy and Imperial College, London, England
(Received 25 February 1974)

Universal strong, weak, and electromagnetic interactions of leptons and hadrons are generated by gauging a non-Abelian renormalizable anomaly-free subgroup of the fundamental symmetry structure $SU(4)_L \times SU(4)_R \times SU(4')$, which unites three quartets of "colored" baryonic quarks and the quartet of known leptons into 16-folds of chiral fermionic multiplets, with lepton number treated as the fourth "color" quantum number. Experimental consequences of this scheme are discussed. These include (1) the emergence and effects of exotic gauge mesons carrying both baryonic as well as leptonic quantum numbers, particularly in semileptonic processes, (2) the manifestation of anomalous strong interactions among leptonic and semileptonic processes at high energies, (3) the independent possibility of baryon-lepton number violation in quark and proton decays, and (4) the occurrence of $(V+A)$ weak-current effects.

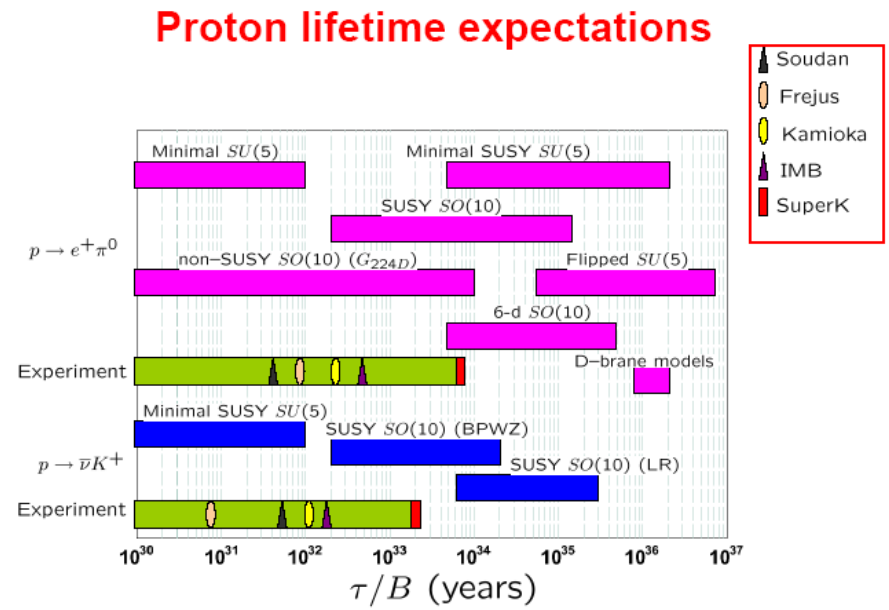
p Decay



Plot Courtesy: E. Kearns

Goal : Increase p Decay reach by an order of magnitude.

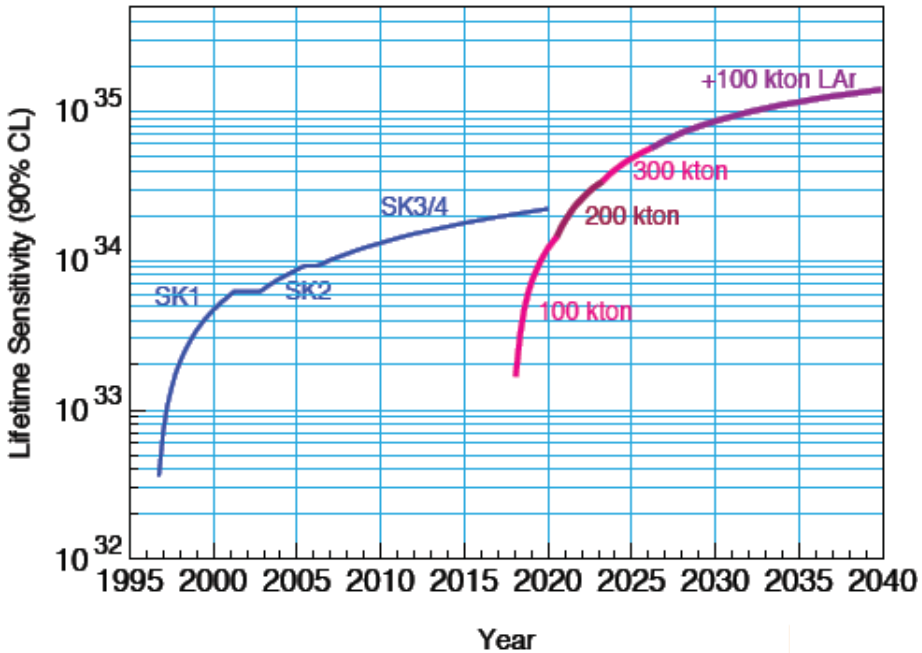
For that, 100 KT of WC not enough.



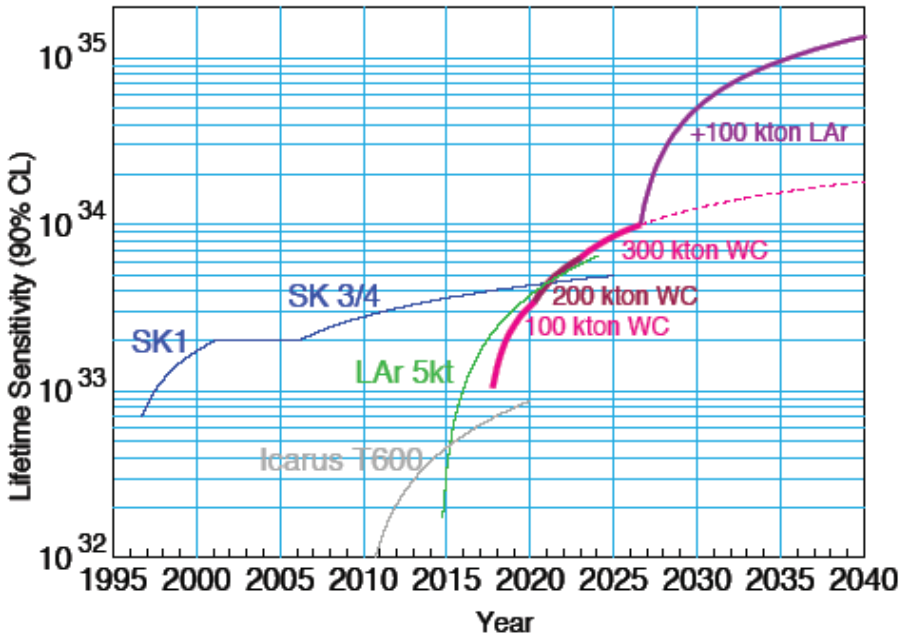
Plot Courtesy : K.S. Babu

p Decay

$p \rightarrow e^{+}\pi^{0}$



$p \rightarrow K^{+}\nu$



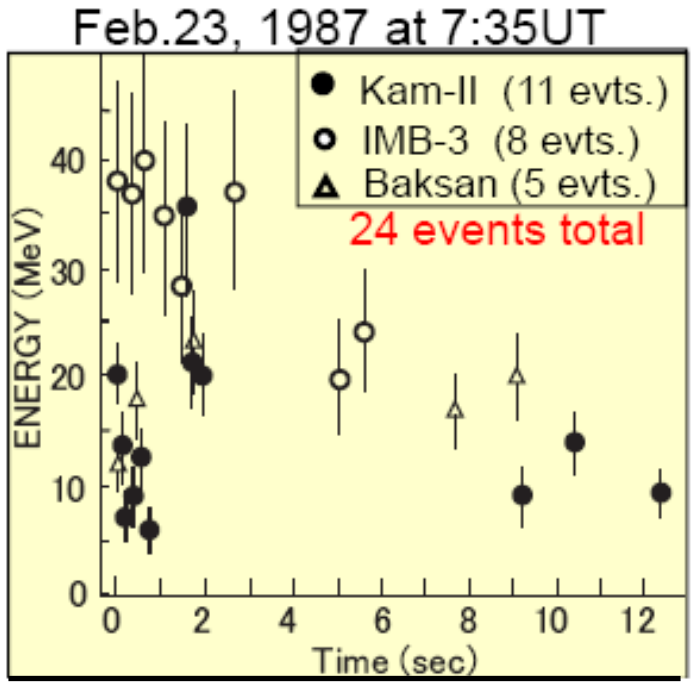
If Supersymmetry is discovered at the LHC, the neutrino mode becomes extremely important and LAr has a significant advantage over WC.

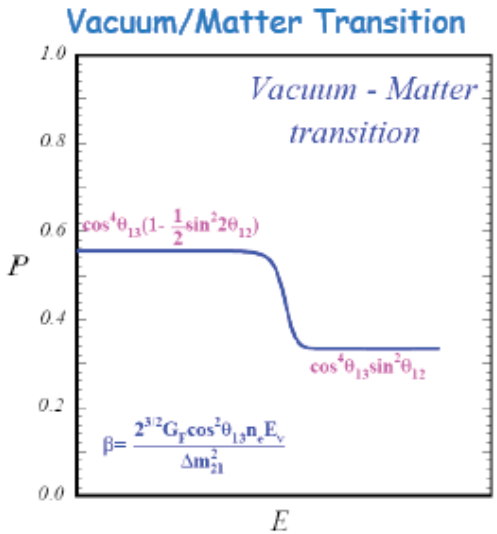
LAr and WC detectors are complementary,

Plots Courtesy: E. Kearns

Introduction : Supernova, solar ν's

(Hubble image)

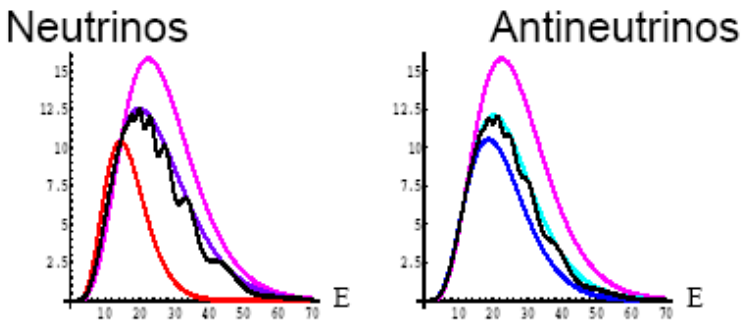




- **Supernova cooling mechanism**
- **ν Oscillations**
- **Early signal important for astrophysics : ν's arrive 6-24 h earlier than light**

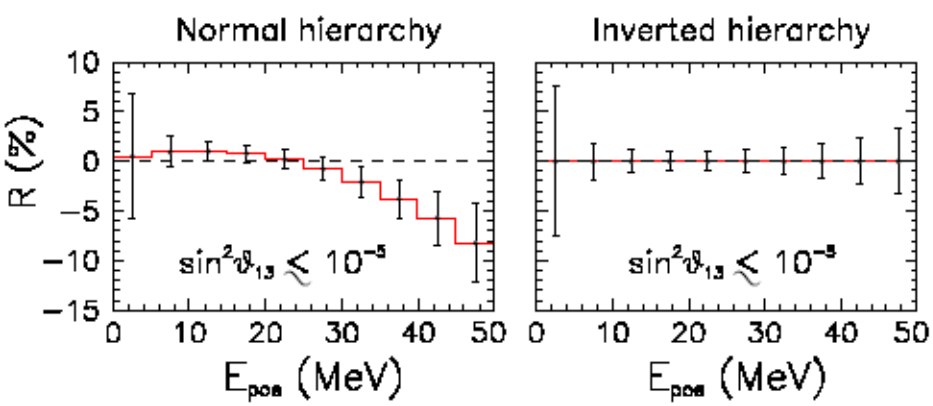
Supernova, Relic, Solar ν's

Earth Mater Effects



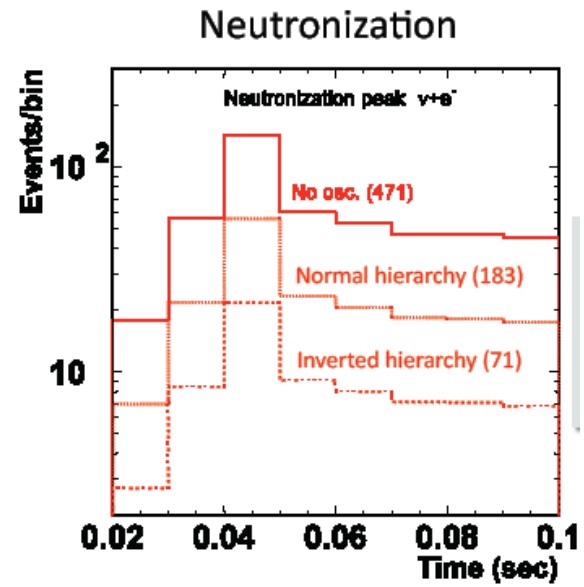
(ν_e, ν_x, mixed ν) ($\bar{\nu}_e$, $\bar{\nu}_x$, mixed $\bar{\nu}$)

$$R \equiv \frac{N(shadowed) - N(unshadowed)}{N(unshadowed)}$$



B.Dasgupta, AD, A. Mirizzi, arXiv:0802.1481

SN Mater Effects



Day/Night Effect : Solar ν's

$$A = \frac{2(\phi_{\nu_e}^{night} - \phi_{\nu_e}^{day})}{\phi_{\nu_e}^{night} + \phi_{\nu_e}^{day}}$$

Statistics for 300kTon on integral asymmetry good enough for ~0.7% measurement, expect 2% asymmetry

Spectral information could play bigger role for LAr…

…and can we see CC interactions on Ar? If yes, even better

J.Klein UDIG Workshop, BNL

Summary/Conclusions

- There are many very important physics topics to be studied with large detectors at DUSEL :

  - **ν oscillations**, **p decay**, **supernova ν's , solar ν's**

- For **both ν oscillations** and **p decay** detectors with masses **> 100 KT WC** or **>30 KT LAr** are **required**.

- Starting with the **"total" detector mass** from the **beginning** or following a **"modular" approach does not make a difference.**

- **Project X helps significantly especially for the CPV discovery potential.**

- Water Cherenkov and Liquid Argon detectors show great complementarity for nearly all physics topics.

BACKUP

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.

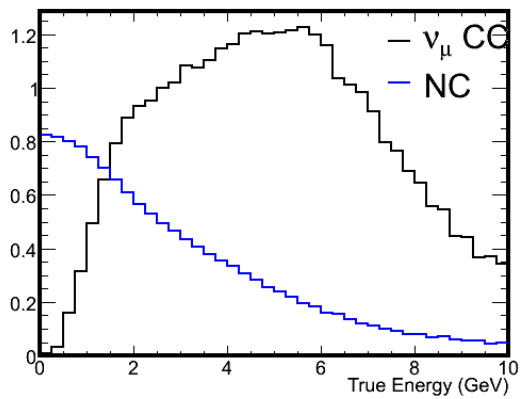
Details of Modeling of Neutral Current (NC) Visible Energy Spectrum

- 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.

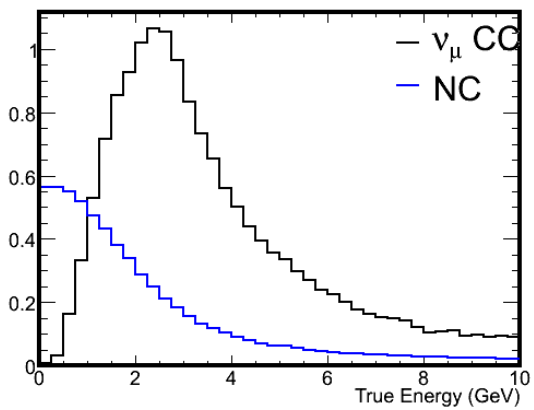
Details of Modeling of Neutral Current (NC) Visible Energy Spectrum con't

- 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.

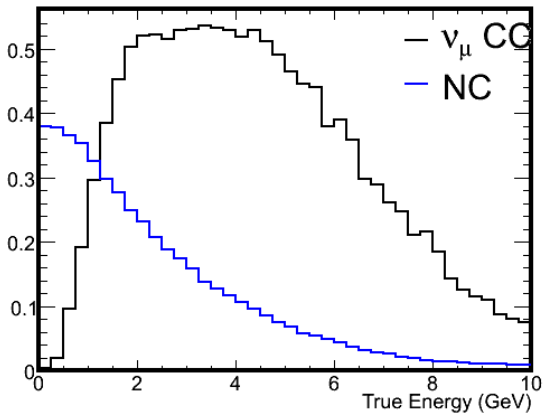
WBB 120 GeV ON AXIS



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

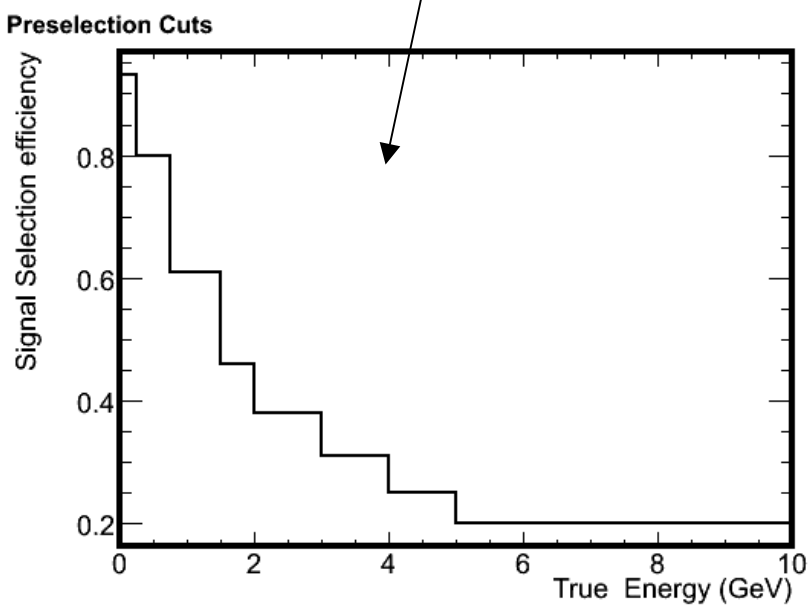
Pre Selection Cuts (Signal , Beam Nues)

	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

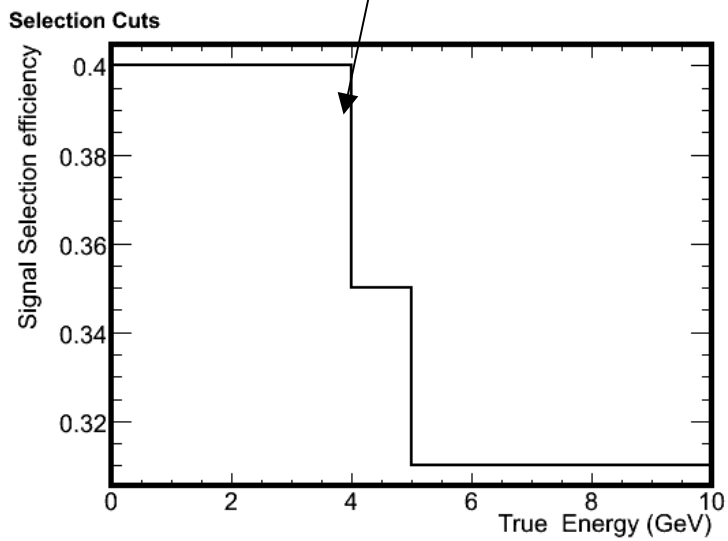
Selection Cuts (Signal, Beam Nues)

	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

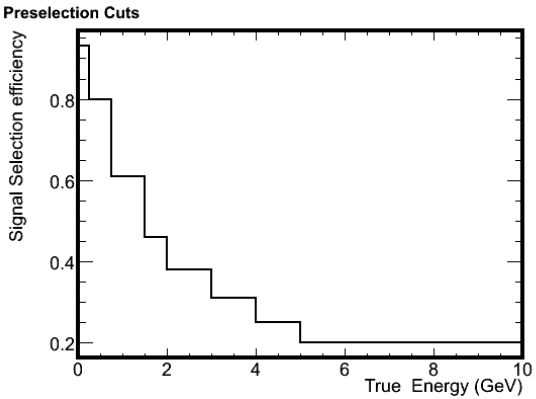
F.Dufour Table



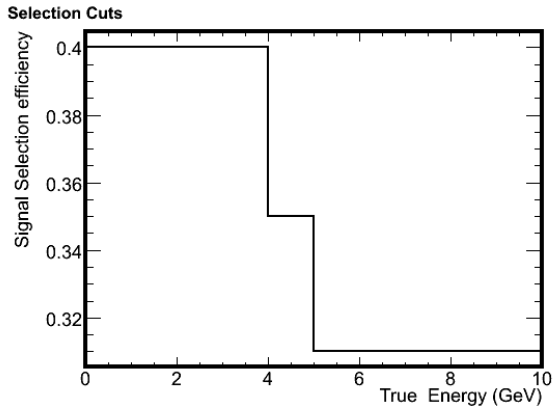
Detector Efficiencies : Water Cherenkov (3)

- 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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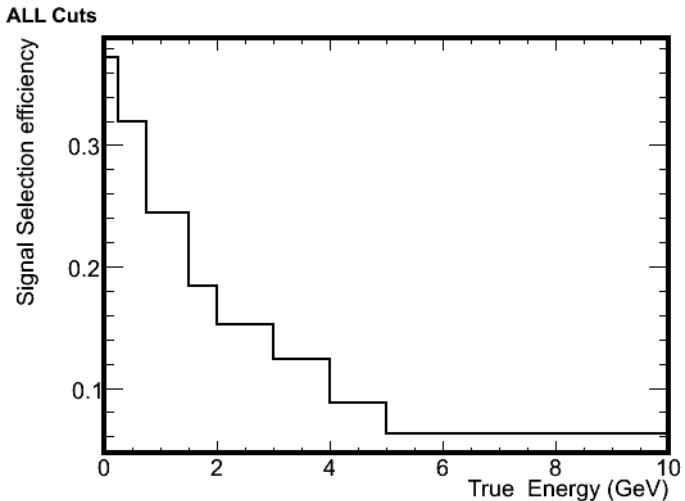

Detector Bkg Rejection : Water Cherenkov (1)

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

Pre Selection Cuts (NC interactions)

	Signal			Background	
Energy (true)	ν_e (avg)	QE ν_e	non-QE ν_e	NC	ν_μ mis-ID
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F.Dufour Table

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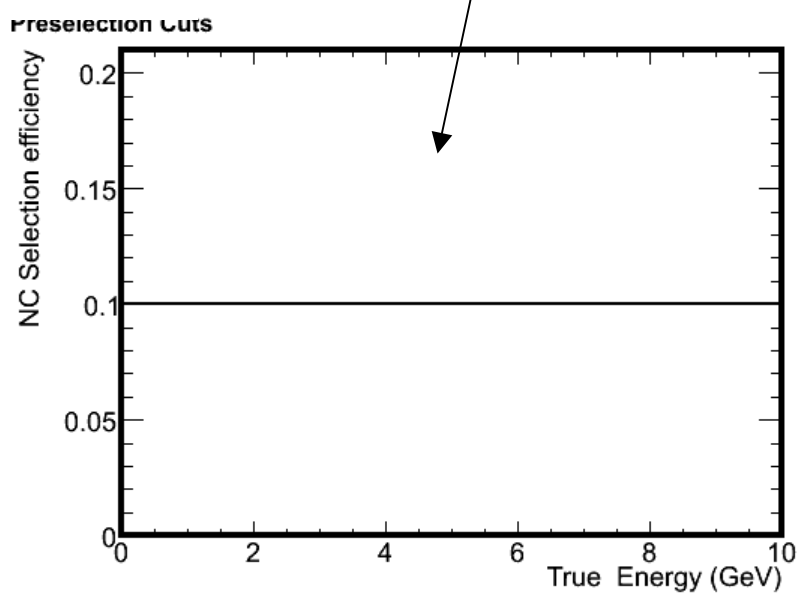

Detector Bkg Rejection : Water Cherenkov (2)

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

Pre Selection Cuts (NC interactions)

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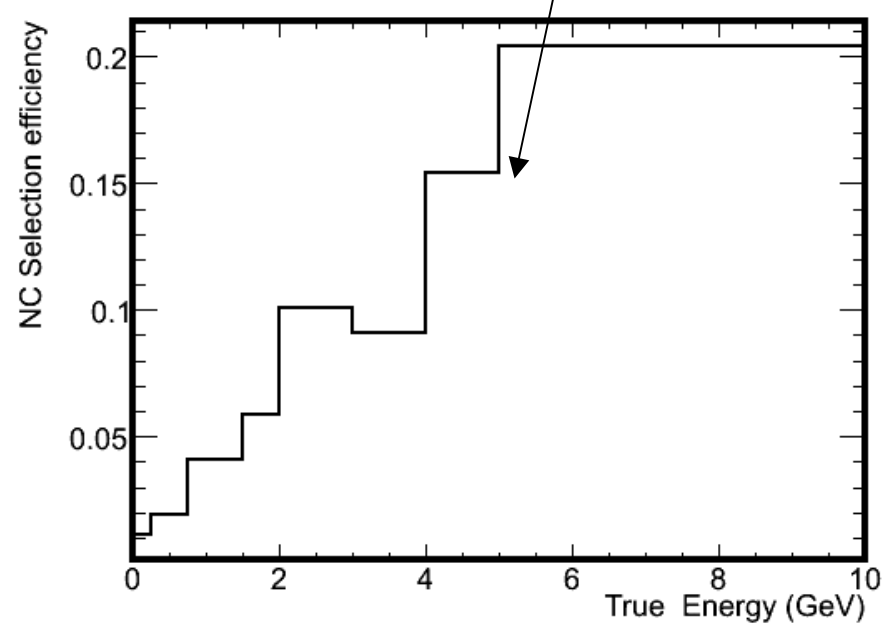
Table 2 Efficiency for the likelihood cut, at zero and at cut position that keeps approximately 40% of the signal. These efficiencies are calculated for events which have already passed the pre-cuts, and are calculated based on reconstructed energy.

What I used

F.Dufour Table

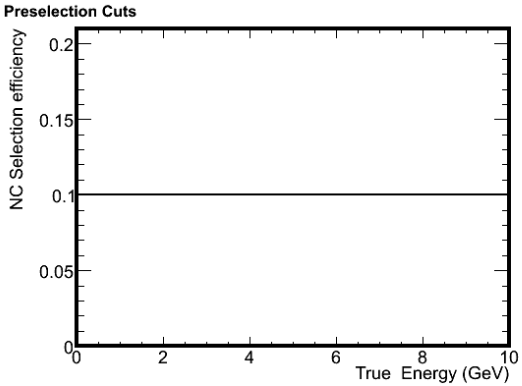


Detector Bkg. Rejection : Water Cherenkov (3)

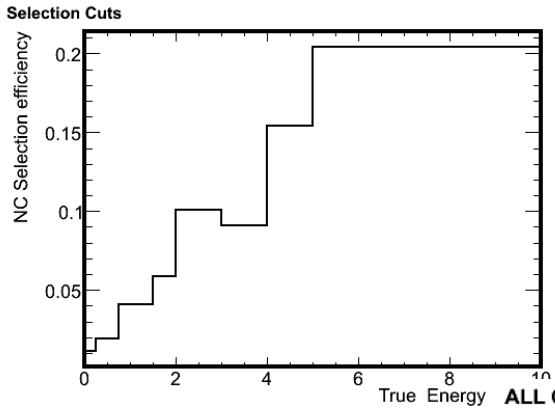
- For Water Cherenkov Detector used analysis by :
  F.Dufour : http://hep.bu.edu/~fdufour/paper/fnal_report.pdf

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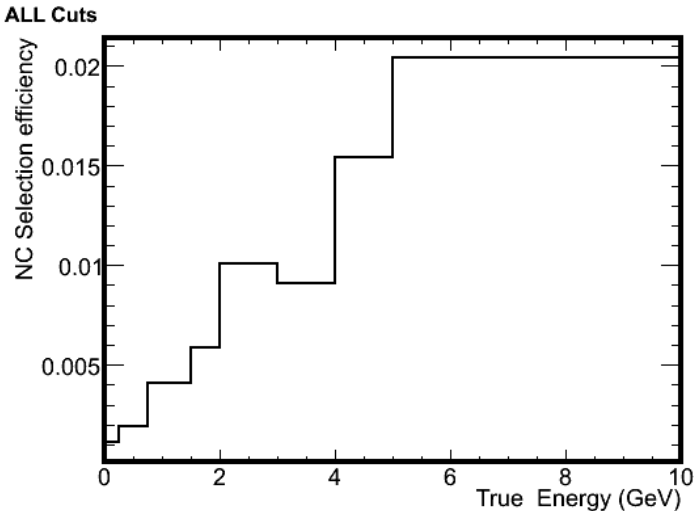
NC Background rejection for Water Cherenkov detector >= 99% below 4 GeV.

=



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% (1% contamination) flat in true visible energy

These are preliminary and need to be refined with more detailed analysis

General Assumptions

- Systematics on the Backgrounds (both beam electron neutrinos and Neutral Current events) are taken into account in the fit.
- The assumption for all the sensitivities is that systematics are understood at the 5% level.
- Energy bins are 250 MeV. No smearing is performed in the true neutrino energy (or true visible energy for the Neutral Currents)

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.***

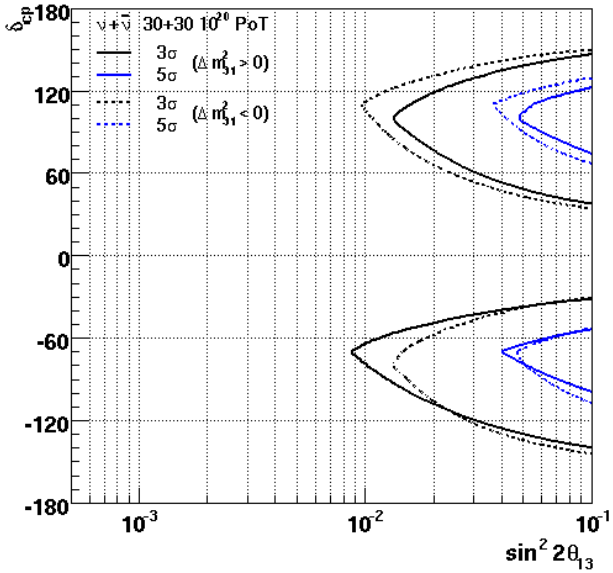
Before any Sensitivities are shown :
How does CPV reach scale with Number of Events?

It does not scale as square root of Number of Events (which many Colleagues are using)

It is almost scaling linearly with Number of Events

Both my results and BNL Globes results support that (see back up slides on this issue)

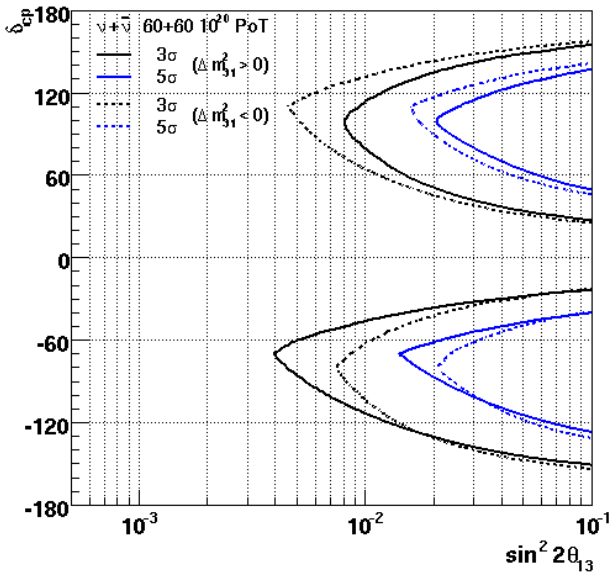
How Does CPV Reach Scale with Number of Events?



CP reach ~ 0.009

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

$$\sqrt{2} = 1.4$$



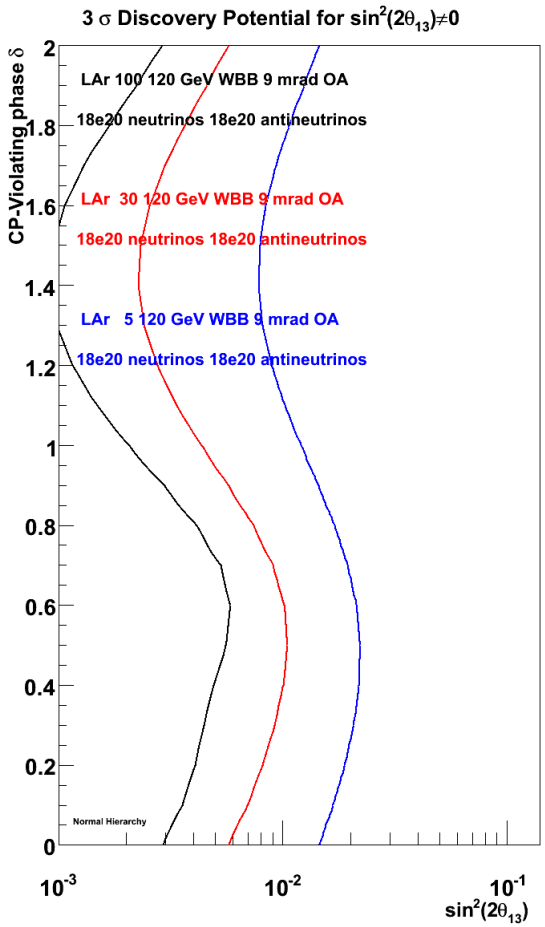
Stat x 2

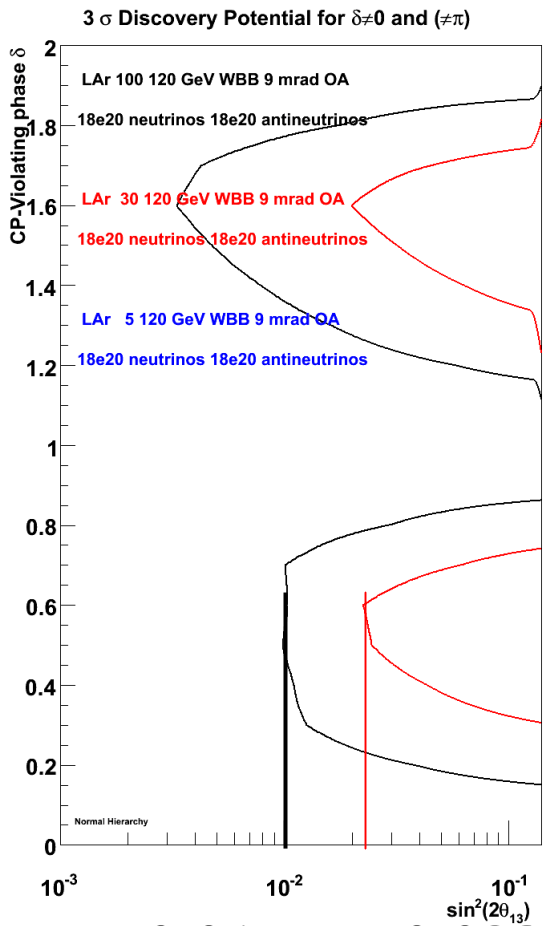
CP reach ~ 0.004

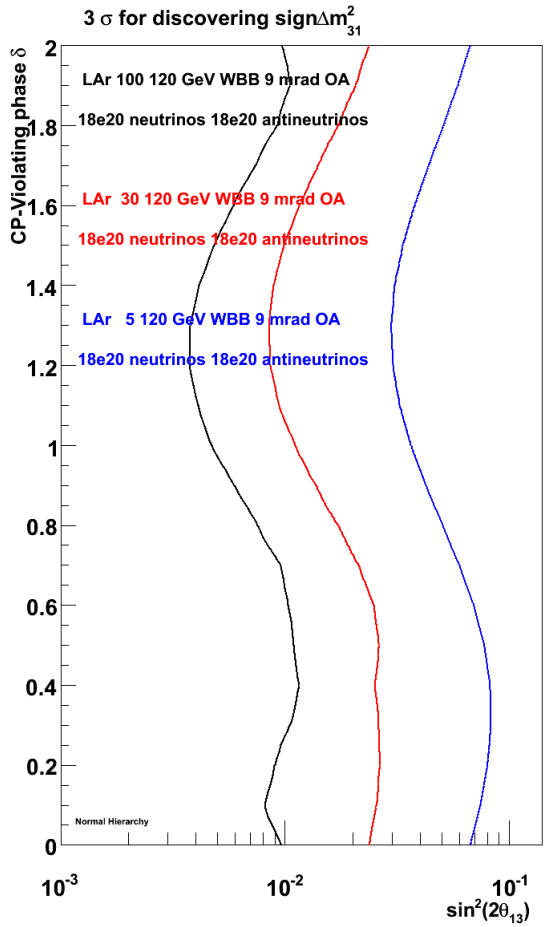
BNL Globes WC 300 kt fiducial, 120 GeV 9 mrad OA 60e20neutrinos+60e20 antineutrinos

How Does CPV Reach Scale with Number of Events?

FNAL Fast MC (NS)







0.01 0.023

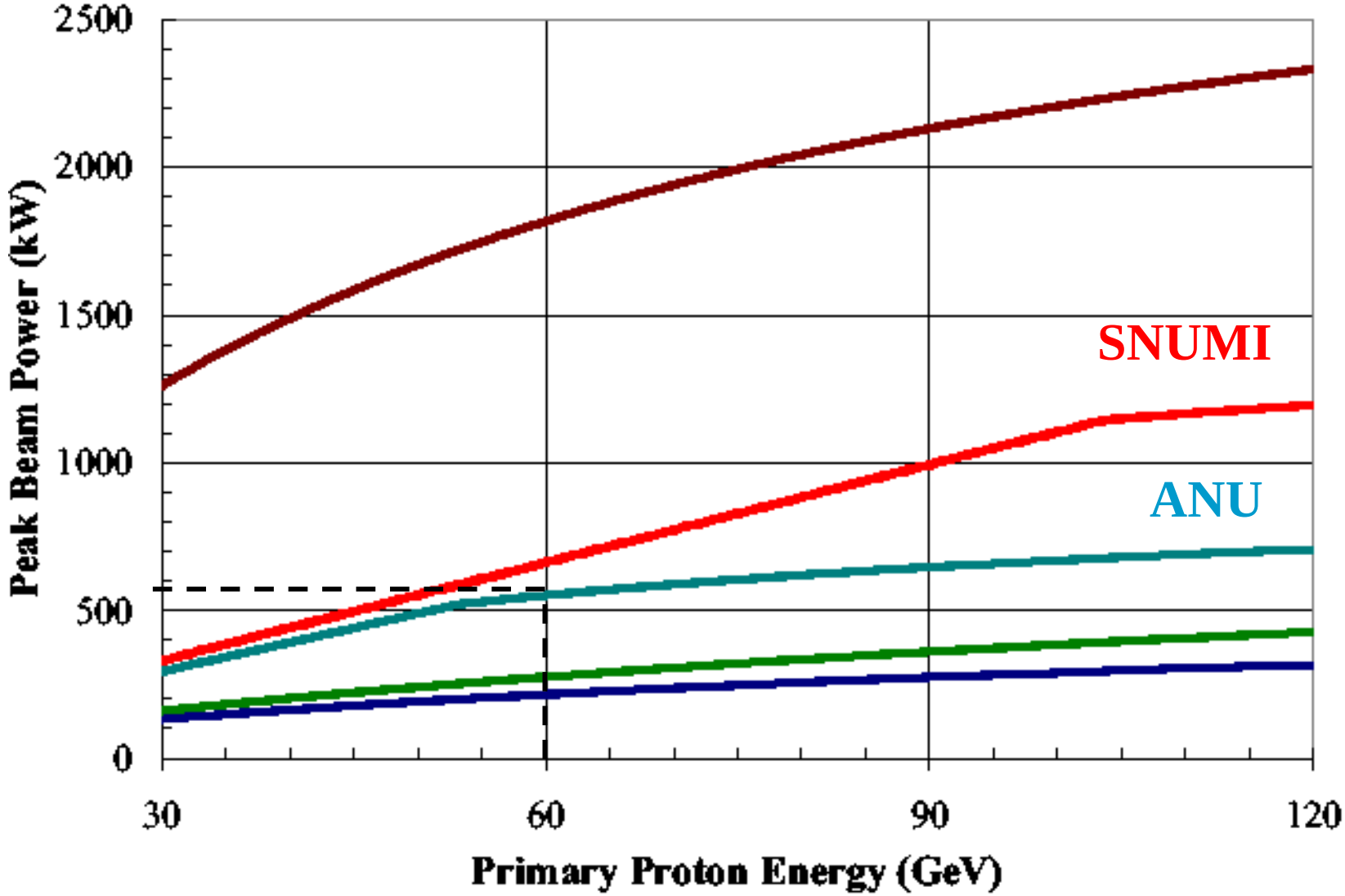
Stat x 3.33

$$\sqrt{3.3} = 1.8$$

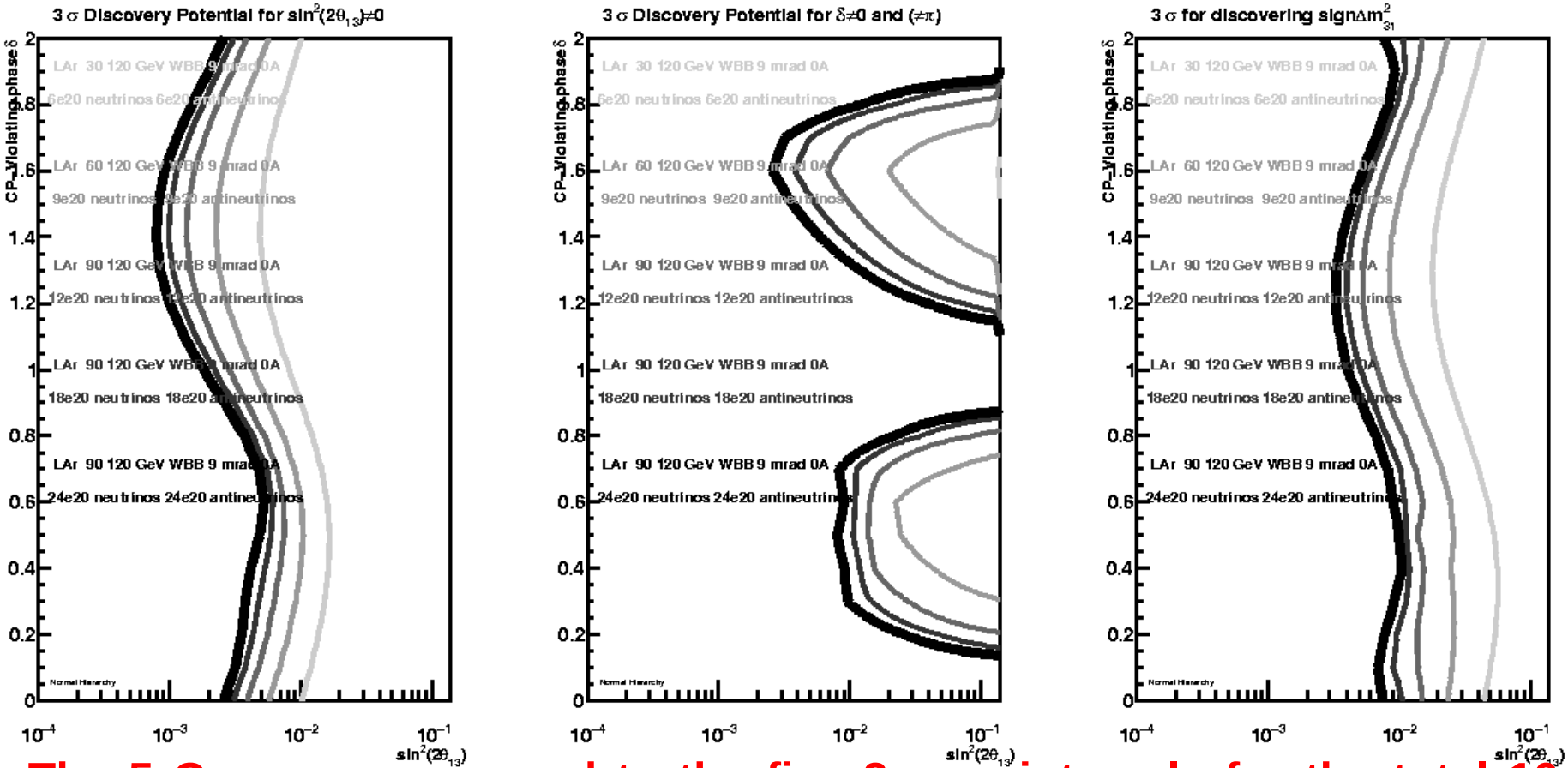
Need to increase # bins in deltacp to get smoother curves.

Beam Power as a function of proton Energy

Plot courtesy : B. Zwaska



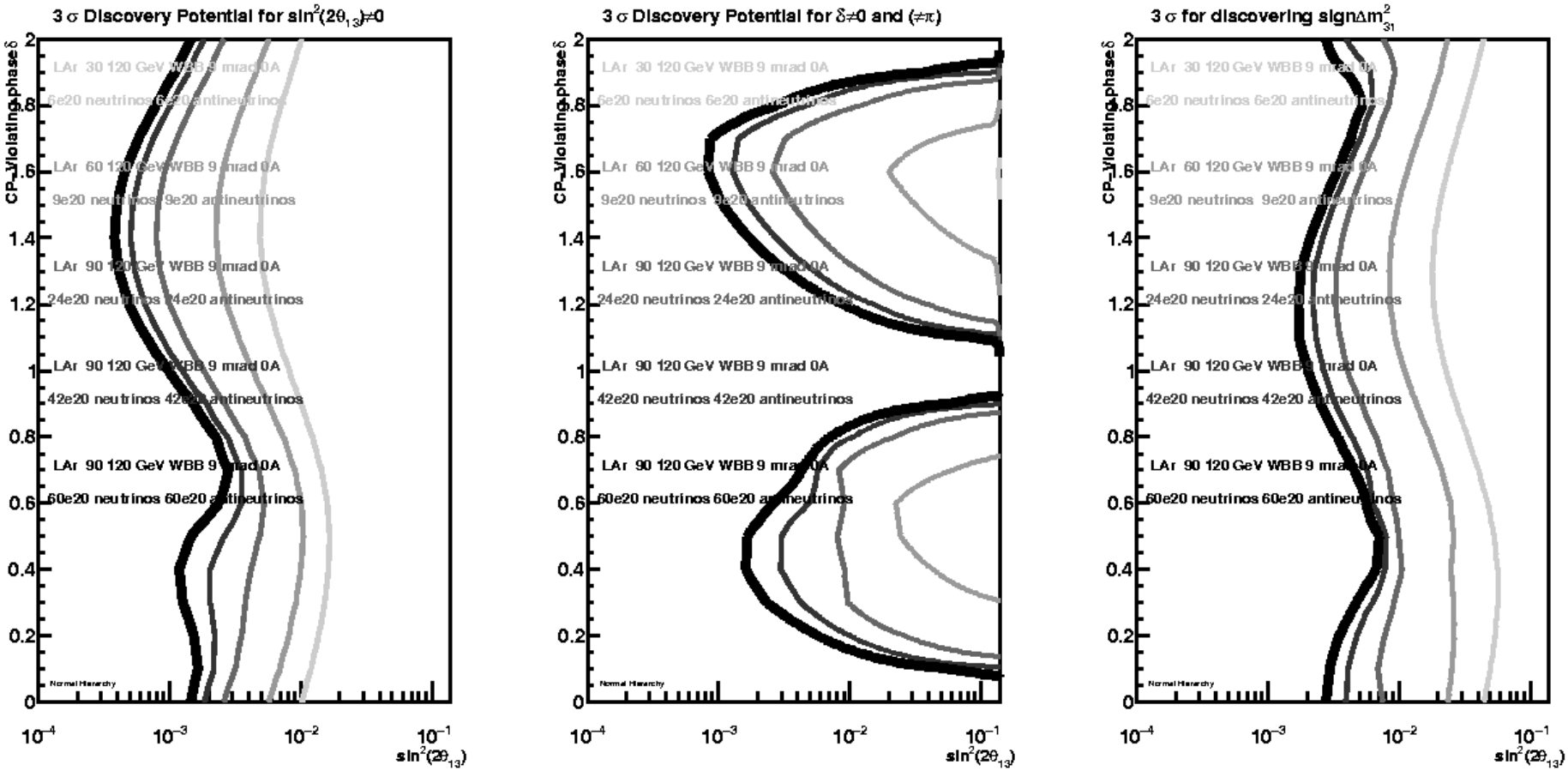
Sensitivities for LAr Detector:
Scenario 1 and "Detector Module" = 30 KT



The 5 Curves correspond to the five 2 year intervals for the total 10 year period.

First curve is discovery potential after 2 years of running, second curve is discovery potential after 4 years of running etc.

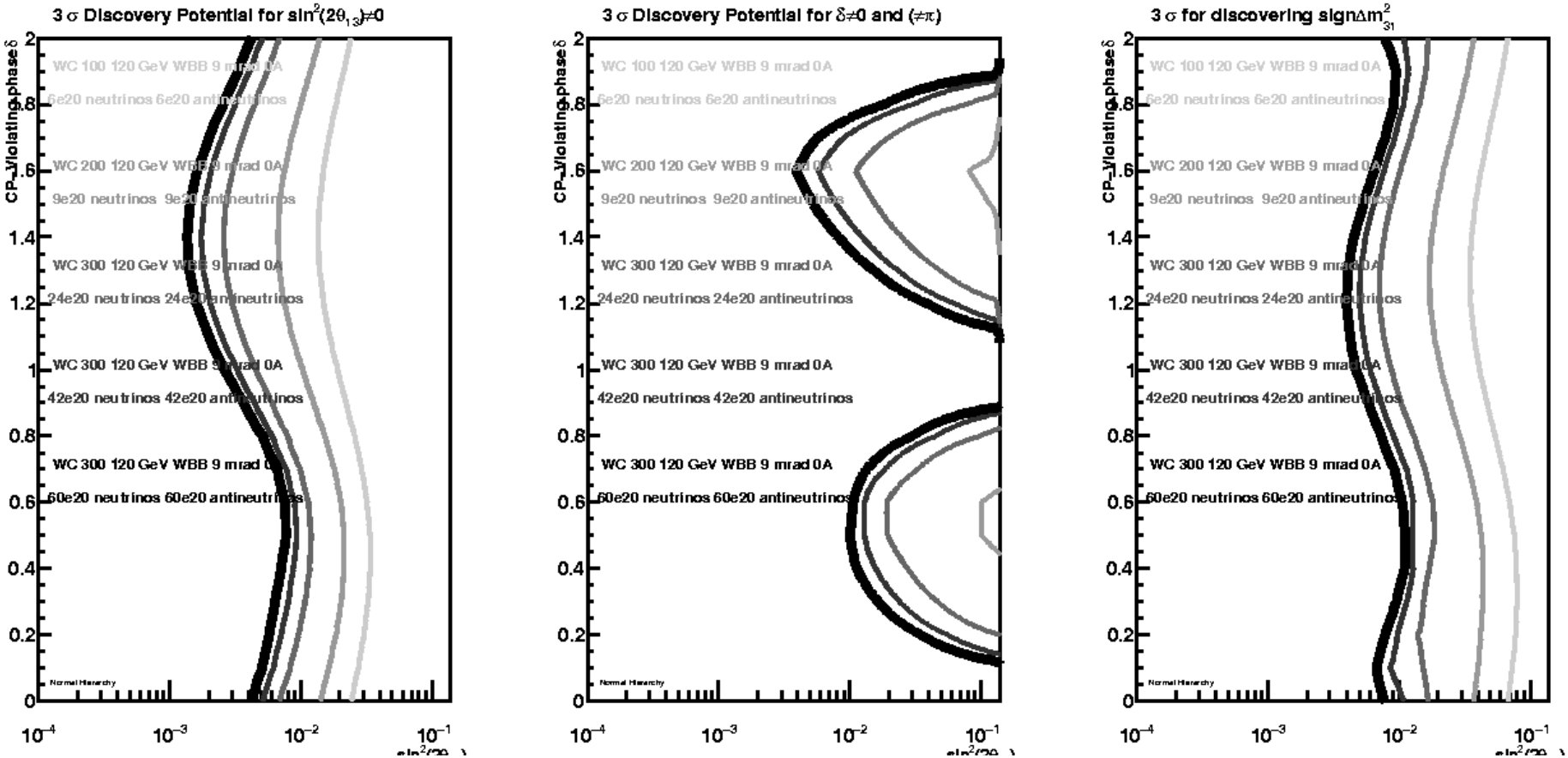
Sensitivities for LAr Detector :
Scenario 2 and "Detector Module" = 30 KT



The 5 Curves correspond to the five 2 year intervals for the total 10 year period. Scenario 2 assumes 2.1 MW after the first 4 years.

Namely, first curve is discovery potential after 2 years of running, second curve is discovery potential after 4 years of running etc.

Sensitivities for Water Cherenkov Detector : Scenario 2 and "Detector Module" = 100 KT



The 5 Curves correspond to the five 2 year intervals for the total 10 year period. Scenario 2 assumes 2.1 MW after the first 4 years.

Namely, first curve is discovery potential after 2 years of running, second curve is discovery potential after 4 years of running etc.