Neutrino Factory δ_{CP} Sensitivity if θ_{13} is Large

The Big Neutrino Oscillation Physics Questions

1. Is three-flavor mixing the whole story ?
   If no → big discovery !

2. How big is θ_{13} (order of magnitude) ?
   Key to accessibility of the oscillation physics parameters. Discriminates between models. If very small may indicate a new conservation law.

3. Is the neutrino mass hierarchy normal or inverted ?
   Discriminates between models. Key to viability of neutrinoless $\beta\beta$-decay experiments.

4. Is CP violated in the lepton sector ?
   Clue to Leptogenesis. Discriminates between models.

What if θ_{13} is large ?

The physics reach at a Neutrino Factory when θ_{13} is small has been well studied → full oscillation physics program for $\sin^2 2\,\theta_{13}$ down to $O(10^{-4})$!   This motivates Neutrino Factory R&D.

What if θ_{13} is large ? Superbeams will presumably establish the magnitude of θ_{13}, determine the mass hierarchy, and begin the search for CP Violation.

If θ_{13} is large, can Neutrino Factories significantly extend the search for CP Violation and/or better test the oscillation framework ?

Prior Work - 1

Past studies have :

Established that ambiguities can be resolved with the right set of measurements → unique regions of oscillation parameter space (see O. Mena's talk for example, & the work of Huber, Lindner & Winter)

Indicated that if θ_{13} is large Neutrino Factories might enable CP Violation to be observed over an extended range of δ_{CP} parameter space.

However :

The analyses have tended to be complicated. Lets accept that ambiguities can be resolved and try a simpler analysis to try to gain some insight into the ultimate CP-Violation reach at a Neutrino Factory and how things change with energy and baseline.

Prior Work – Huber, Lindner, Winter

Experiment/Combination	LMA-I ($\Delta m^2_{21} = 7 \cdot 10^{-5}\,\mathrm{eV}^2$) $\delta_{CP} = 0°$	$\delta_{CP} = 90°$	$\delta_{CP} = 180°$	$\delta_{CP} = 270°$
$\sin^2 2\theta_{13} = 0.1$				
JHF-HK	2° (17°)	8° (51°)	2° (17°)	9° (53°)
NuFact-II@3 000 km	31° (119°)	41° (123°)	23° (105°)	33° (119°)
JHF-HK+NuFact-II@3 000 km	1° (11°)	6° (45°)	1° (10°)	6° (47°)
NuFact-II@3 000 km+NuFact-II@7 500 km	10° (72°)	18° (91°)	10° (68°)	12° (75°)
JHF-SK+Reactor-II	126° (360°)	125° (360°)	111° (360°)	165° (360°)
NuMI+Reactor-II	294° (360°)	283° (360°)	328° (360°)	215° (360°)
JHF-SK$_{oc}$+NuMI$_{oc}$	127° (360°)	132° (360°)	125° (360°)	125° (289°)
$\sin^2 2\theta_{13} = 0.01$				
JHF-HK	14° (127°)	29° (125°)	15° (141°)	36° (104°)
NuFact-II@3 000 km	10° (67°)	20° (80°)	4° (39°)	20° (85°)
JHF-HK+NuFact-II@3 000 km	3° (26°)	8° (53°)	2° (21°)	9° (54°)
NuFact-II@3 000 km+NuFact-II@7 500 km	5° (42°)	6° (49°)	3° (28°)	4° (39°)
JHF-SK+Reactor-II	328° (360°)	221° (360°)	324° (360°)	190° (360°)
NuMI+Reactor-II	360° (360°)	360° (360°)	360° (360°)	232° (360°)
JHF-SK$_{oc}$+NuMI$_{oc}$	329° (360°)	228° (360°)	316° (360°)	177° (360°)

The errors in δ_{CP} for $\Delta m^2_{21} = 3 \cdot 10^{-3}\,\mathrm{eV}^2$, $\sin^2 2\theta_{23} = 1$, and $\sin^2 2\theta_{12} = 0.8$. The errors are defin

Experimental Scenario

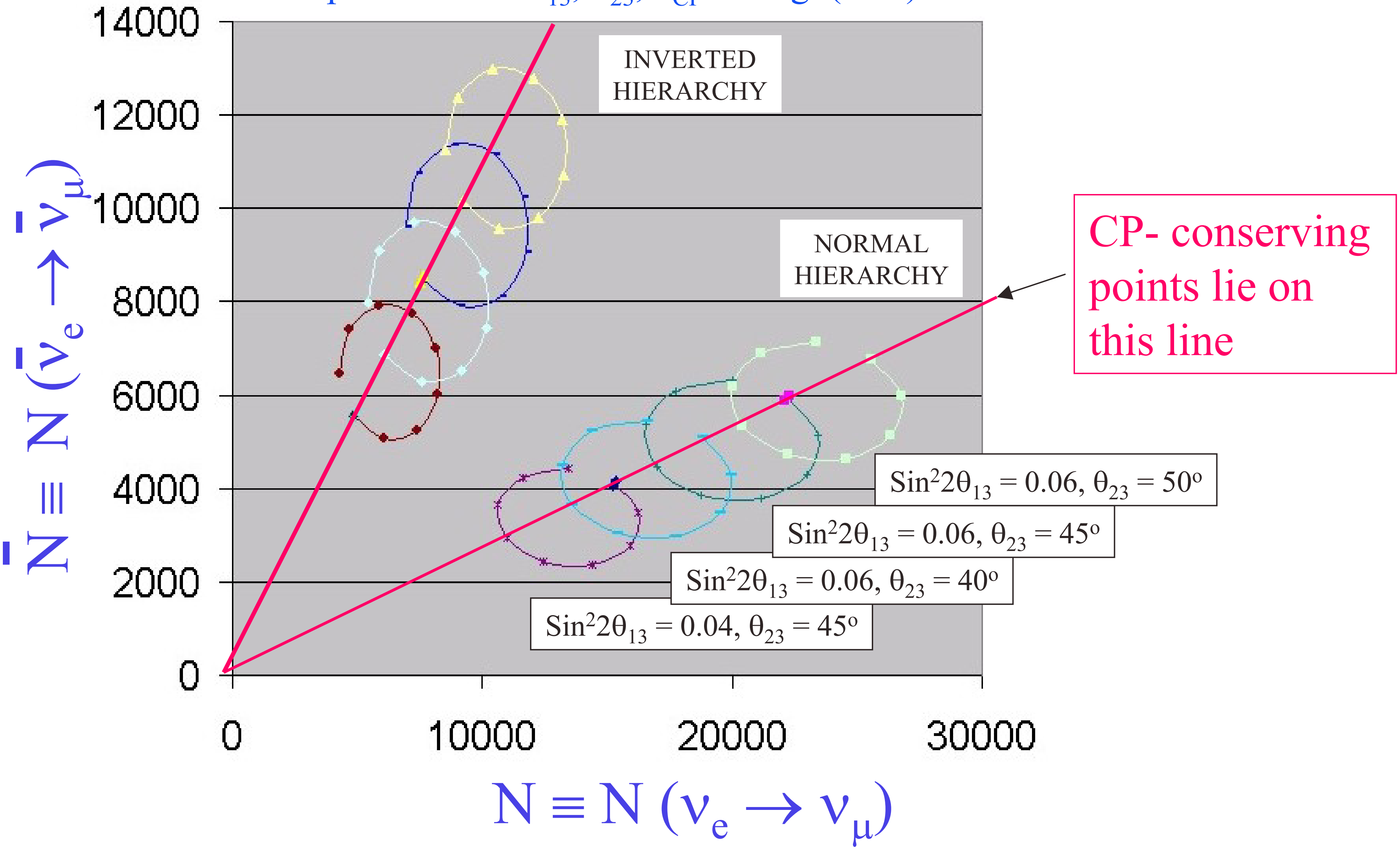
Want to understand how close can δ_{CP} be to 0 or π and CP Violation still be observed at a Neutrino Factory.

Adopt an aggressive (but plausible) set of values for the ultimate Neutrino Factory intensity and experiment parameters :

2×10^{20} μ^+ and 2×10^{20} μ^- useful decays / year
10 years of data taking
$M_{fiducial} = 100$ kt

Example 1: $E_\mu = 16$ GeV, $L = 2000$ km

Dependence on θ_{13}, θ_{23}, δ_{CP} and sgn(Δm^2)



Lessons from Example 1

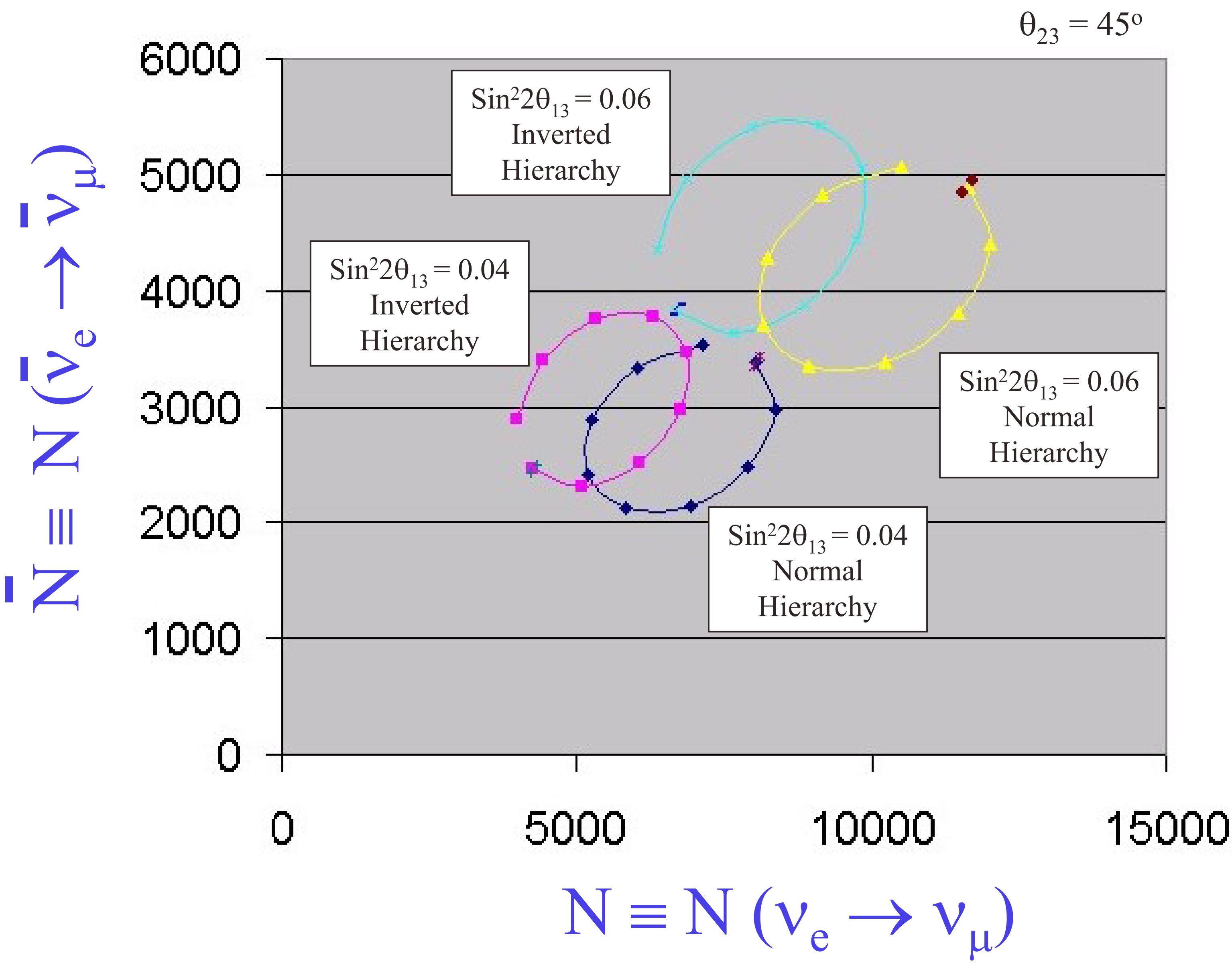
The two measured wrong-sign muon rates (N, $\bar{N}$) are sensitive to the mass hierarchy, and the oscillation parameters θ_{13}, θ_{23}, δ_{CP}.

However:

1. The statistical errors are tiny compared to separation between the predictions for the two mass hierarchies …. determining the hierarchy is easy.

2. As θ_{13} and θ_{23} change the CP-conserving points move along a fixed line in (N,$\bar{N}$)-space … uncertainties in θ_{13} and θ_{23} do not degrade the sensitivity to small CP-violating values for δ_{CP} (just need to determine whether measured rates are on the CP-conserving line or not).

Example 2: $E_\mu = 8$ GeV , L = 732 km

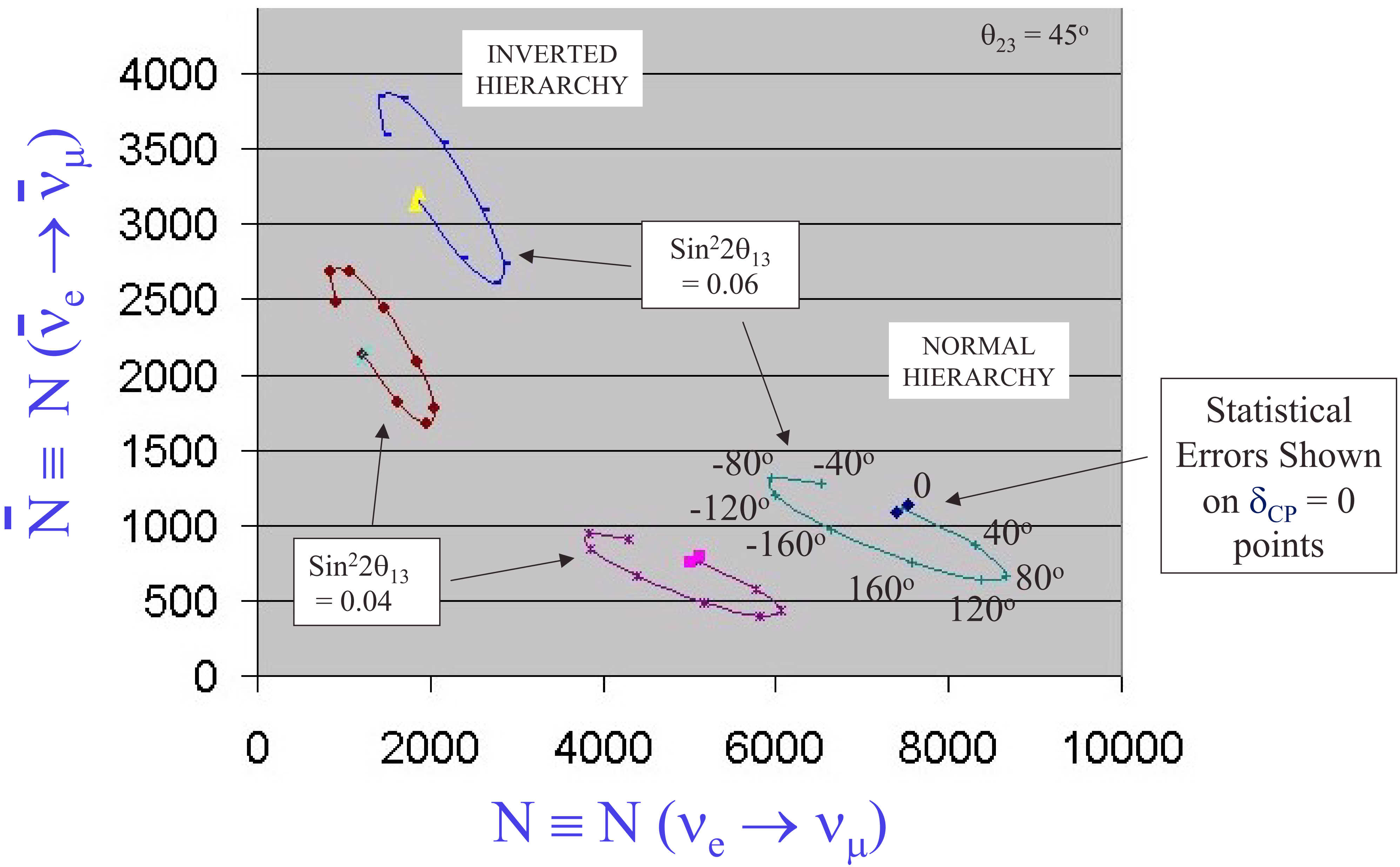


Lessons from Example 2

1. If the baseline is less than about 1000 km the allowed regions of $(N,\bar{N})$ space overlap for the two mass hierarchies. This is not a problem if the mass hierarchy has already been determined … but if it has not, longer baselines are preferred.

2. Suppose our measured $(N,\bar{N})$ rates provide evidence for small but finite CPV corresponding to the true underlying parameter values $(\delta_{CP}, \theta_{13})$. There will be a second solution at $(\pi- \delta_{CP}, \theta_{13})$. If we want to know which solution is the correct one (do we care ?) a comparison of examples 1 and 2 shows that two experiments at different well chosen baselines will resolve the ambiguity. (see Lindner et al, Gomez-Cadenez et al for a much more comprehensive treatment).

Example 3: $E_\mu = 8$ GeV , L = 2000 km

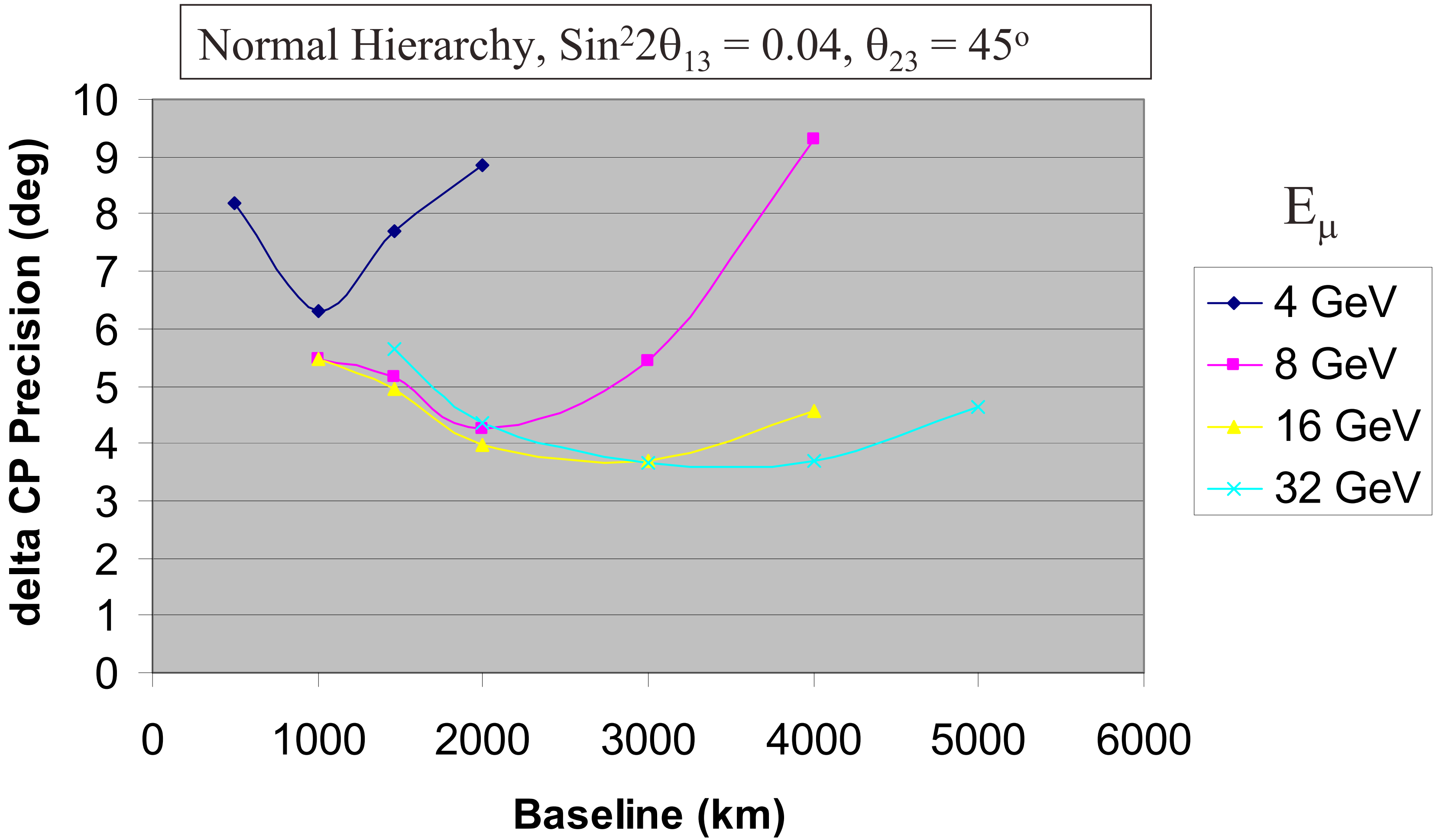


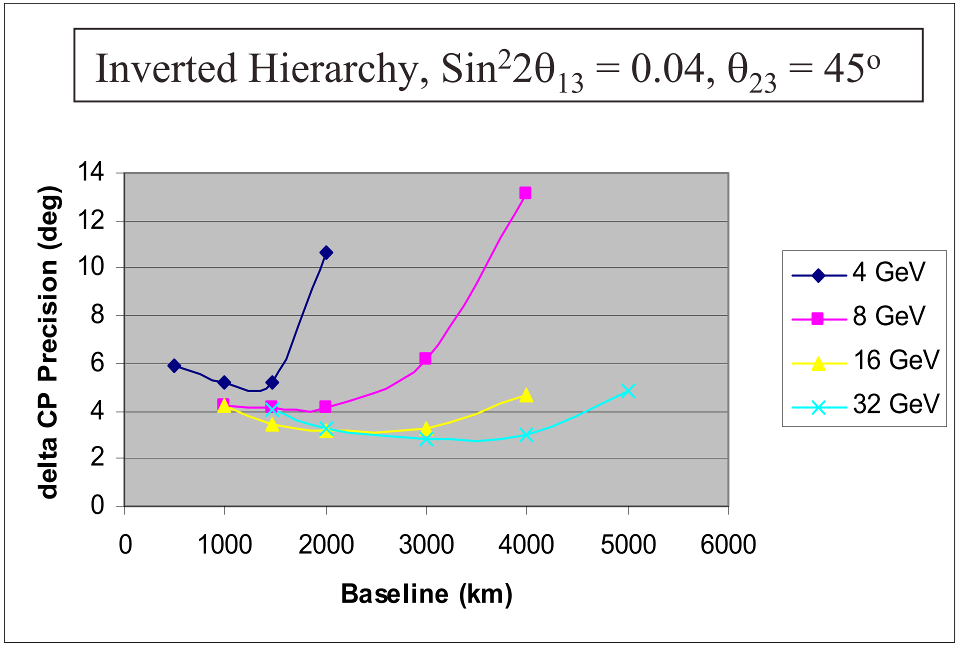
CP Violation Sensitivity

How close can δ_{CP} be to 0 or π before we can no longer observe CP Violation ?

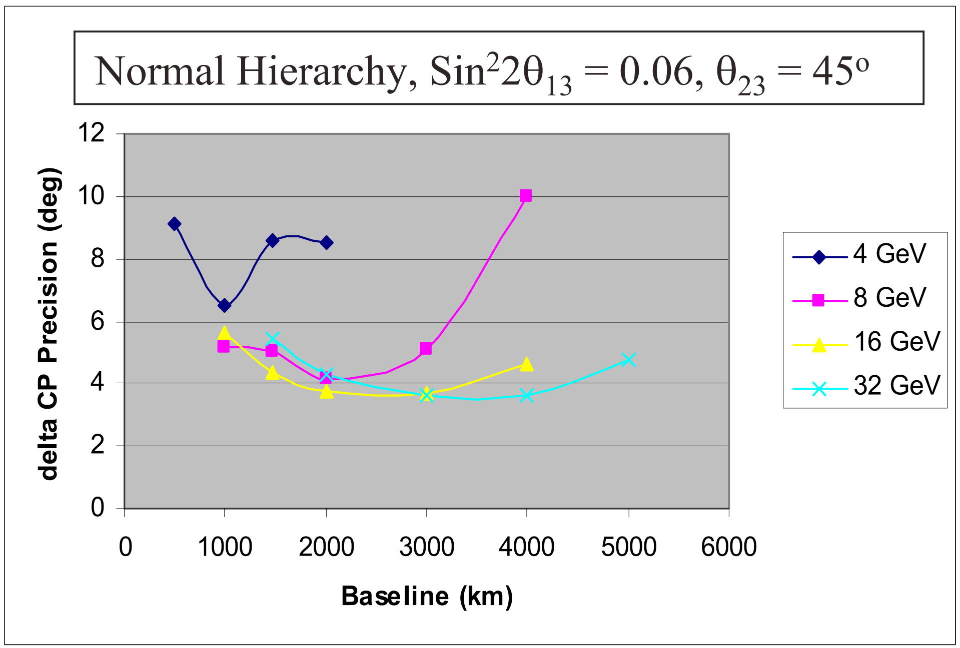
Depends on Neutrino Factory energy and baseline … which choices give the best sensitivity ?

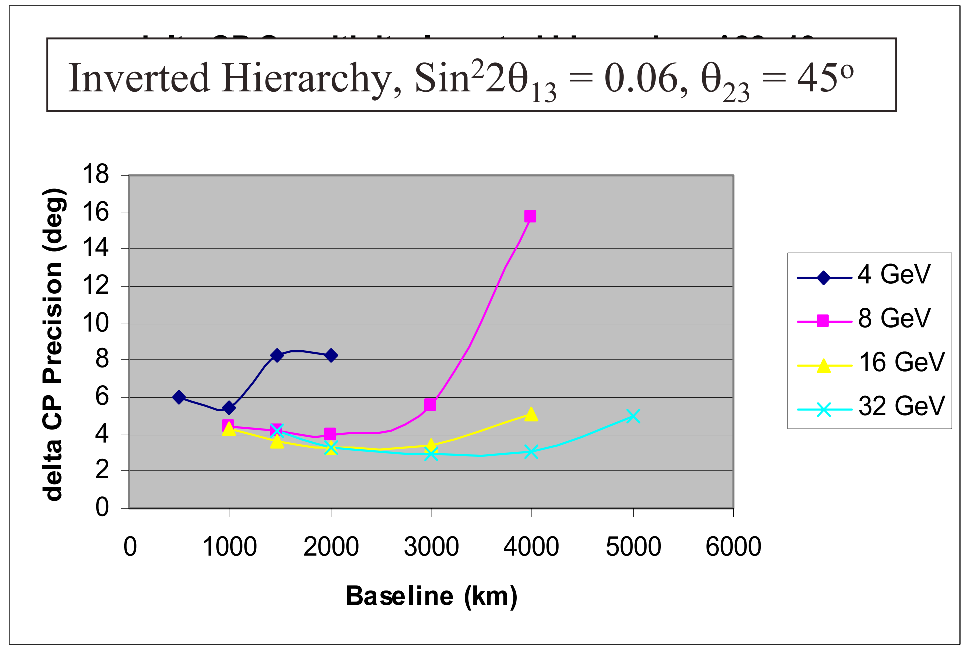
Statistical Precision (1σ) for determining δ_{CP} if δ_{CP} near 0 or π





Statistical Precision (1σ) for determining δ_{CP} if δ_{CP} near 0 or π





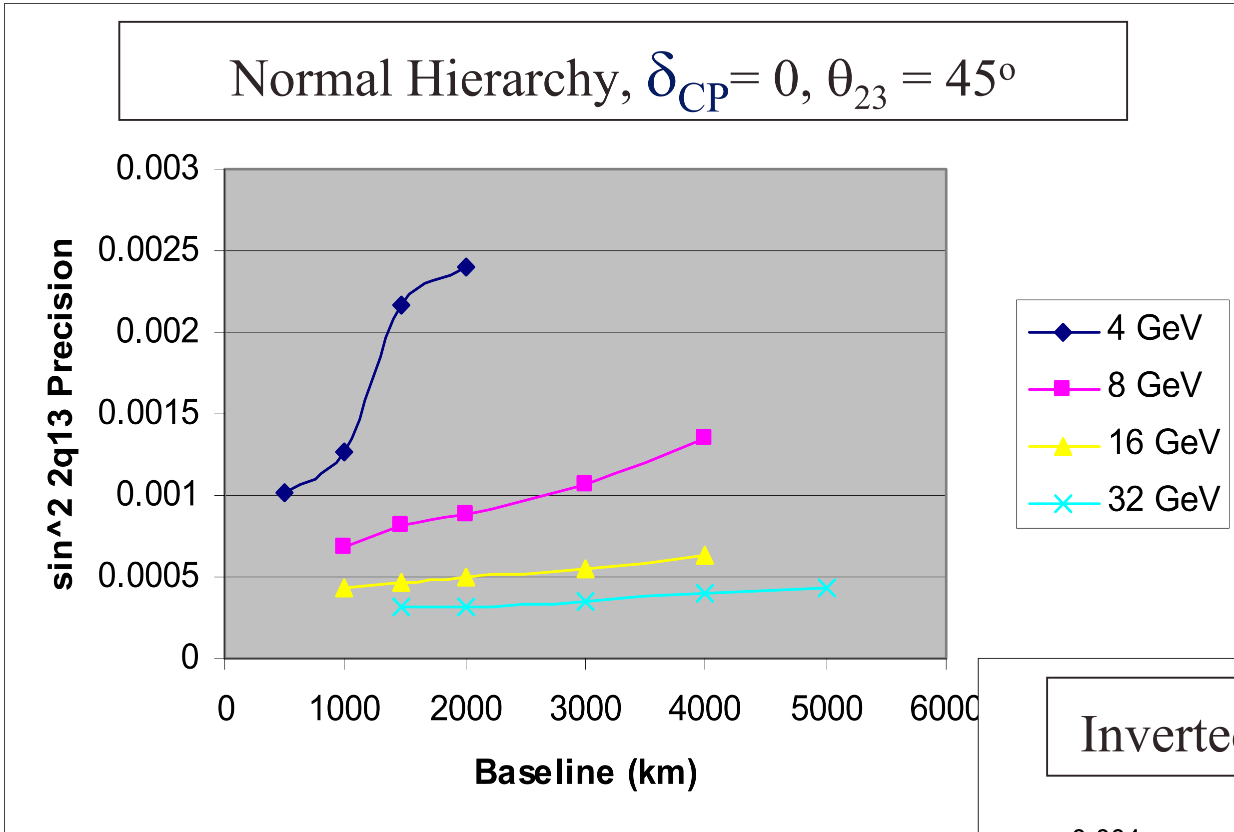
CP Sensitivity Lessons

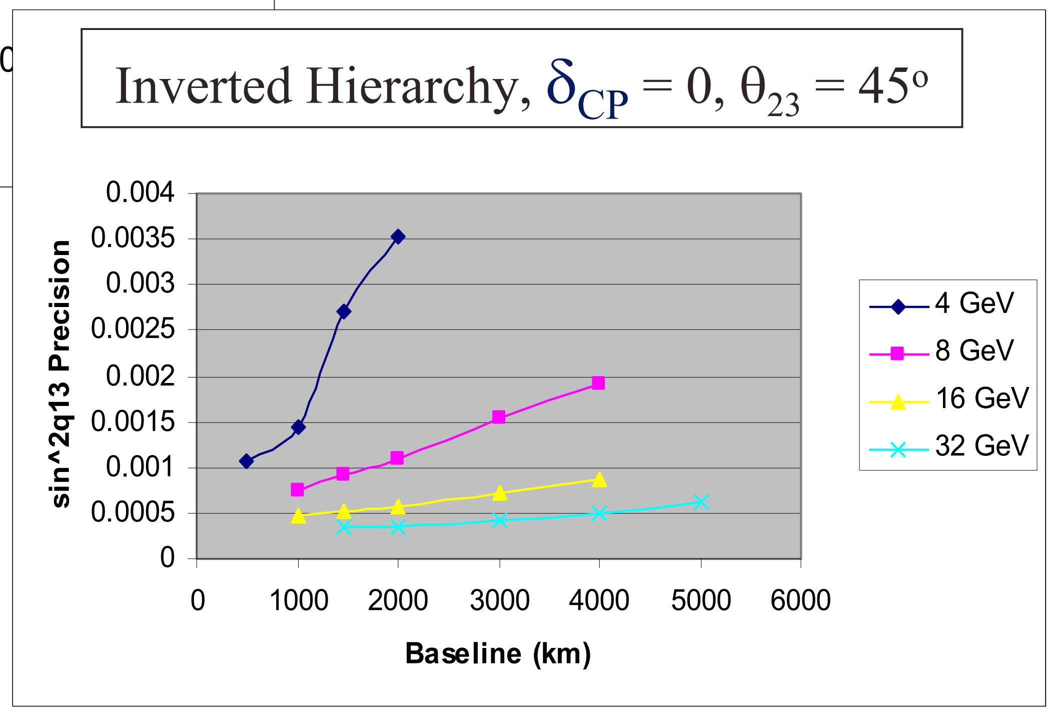
1. The best choices of Energy and Baseline yield $\sigma(\delta_{CP})$ ~ 3 degrees for δ_{CP} close to the CP conserving values (0 and 180 degrees). (Consistent with the expectations for $\sigma(\delta_{CP})$ from the more complete Huber, Lindner, Winter Analysis)

2. The δ_{CP} prescision decreases rapidly for energies less than ~ 8 GeV and improves slowly for higher energies.

3. The baseline dependence shows a very broad minimum.

Statistical Precision (1σ) for determining θ_{13} if δ_{CP} near 0 or π





Lessons

1. The $\sin^2 2\,\theta_{13}$ sensitivity $\sigma(\sin^2 2\,\theta_{13}) \sim 0.0005$ for a broad range of Energies and Baselines.

2. The $\sin^2 2\,\theta_{13}$ sensitivity increases with increasing energy and decreasing baseline.

Background Considerations

Statistical precision at a Neutrino Factory is so good that we need to check the expected wrong-sign muon background rates:

Background / √(Signal) assuming background rate = 10^{-4} total CC rate

Energy (GeV)	Baseline (km) 500	1000	1464	2000	3000	4000	5000
4	0.69	0.40	0.29	0.12			
8		0.97	0.53	0.15	0.14	0.11	
16		4.7	2.6	1.3	0.68	0.35	
32				6.8	3.3	2.0	1.4

Systematic uncertainties from background subtraction are likely to be negligible provided there is a 10^{-4} (or better) rejection against wrong-sign muon backgrounds, baselines are not too short & energies not too high.
This may still be true with an order of magnitude higher statistics.

Very High Performance Neutrino Factory Example

Example: E = 8 GeV, L = 2000 km.

If the integrated beam flux × detector mass increased by a factor of 6 compared to the example we have been considering, then :
background / √ signal ≈ 1 and δ_{CP} precision ≈ 1.7 degree

Conclude that if θ_{13} is large it may be possible one day to obtain a measurement of δ_{CP} with a precision of 1 – 2 degrees which would enable a significant observation of CP Violation if δ_{CP} is greater than ~ 5 degrees !

Conclusions

1. If θ_{13} is large, it may be possible to observe CP Violation at a Neutrino Factory even if δ_{CP} is only a few degrees away from its CP-Conserving values.

2. To do this the required Neutrino Factory energy might be a little less than we have been traditionally considering $\rightarrow$ saves money but we need to be sure we get the 10^{-4} background rejection from the detector.

3. Is this CP violation sensitivity significantly better than that obtainable at a high-performance Superbeam ? Probably … but we may have to wait for the first generation of ν_e appearance searches to understand just how much better.