Extrapolation Neutrino Flux measured at Near Detector to the Far Detector

Near Detector Workshop,
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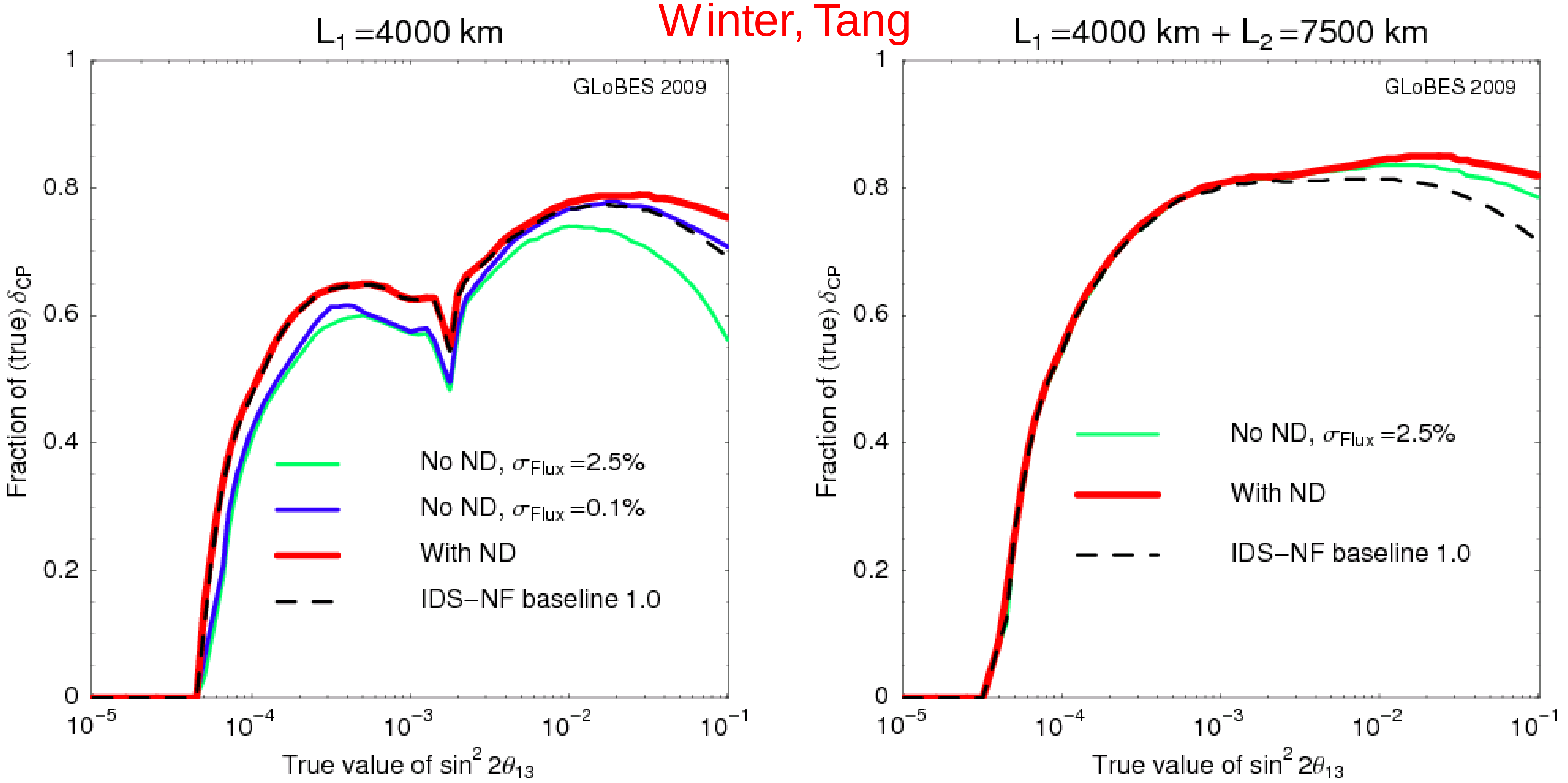
Outline

- Near detector flux systematics at neutrino factory
- Near detector location and spectra
- Neutrino oscillation fits and sensitivities
- Near to Far extrapolation method
- Near to Far extrapolation simulations
- Near to Far extrapolation results

Near Detector Flux systematics

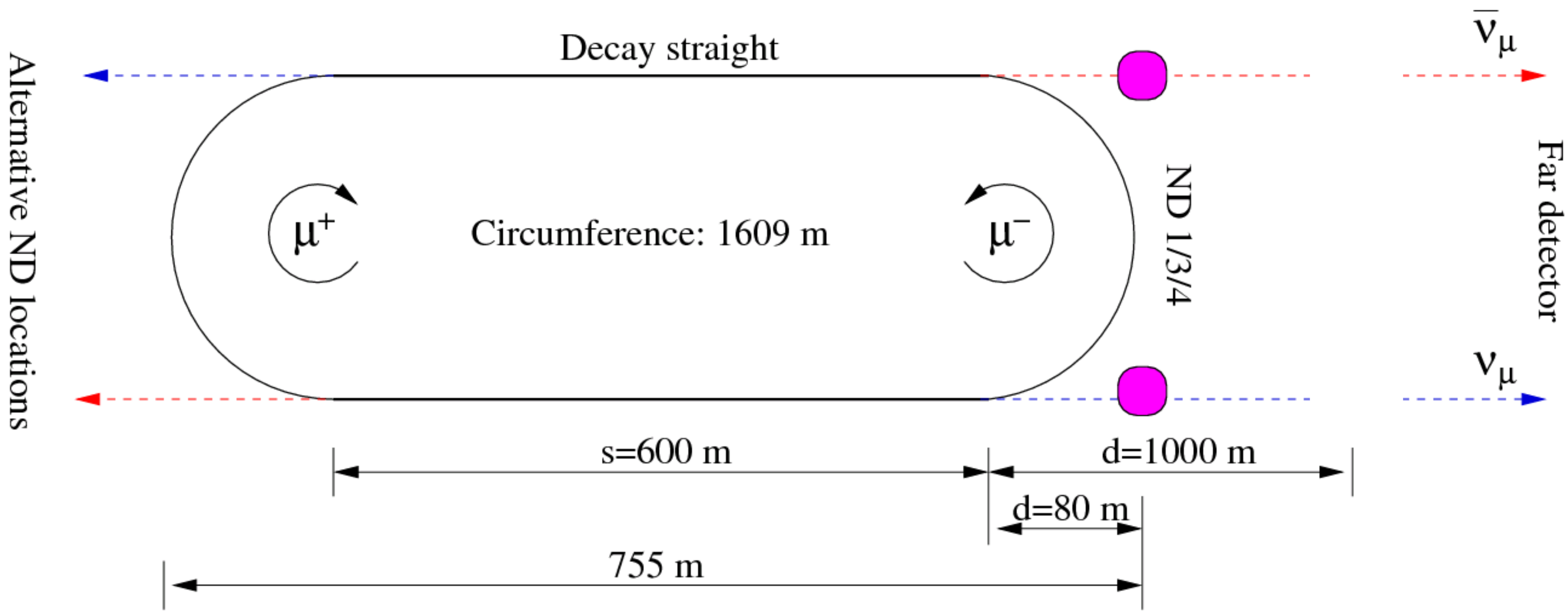
- Importance of Near Detector for systematics
- 2.5% error on flux makes big difference in CP coverage
- Better to reduce error in flux below 1% if possible

Winter, Tang



Near Detector Location

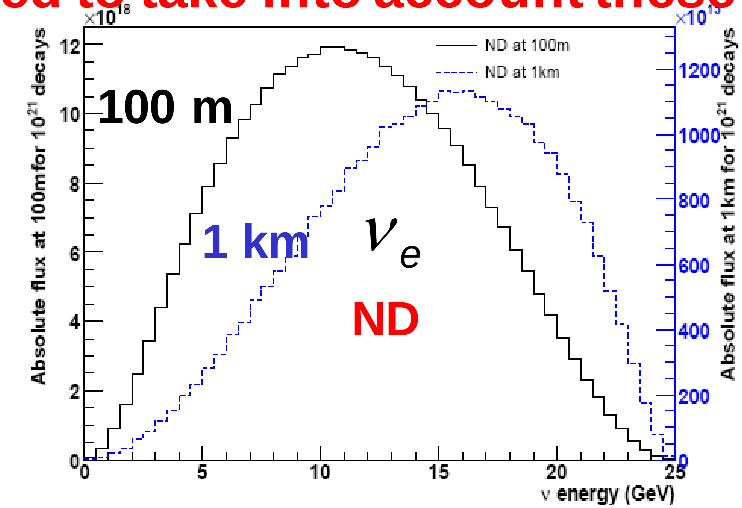
- Assume one ND per straight per ring (ie 4 detectors)
- The idea is to have ND 80-100 m from end of each straight to measure flux and possibly also measure divergence ~0.1/γ

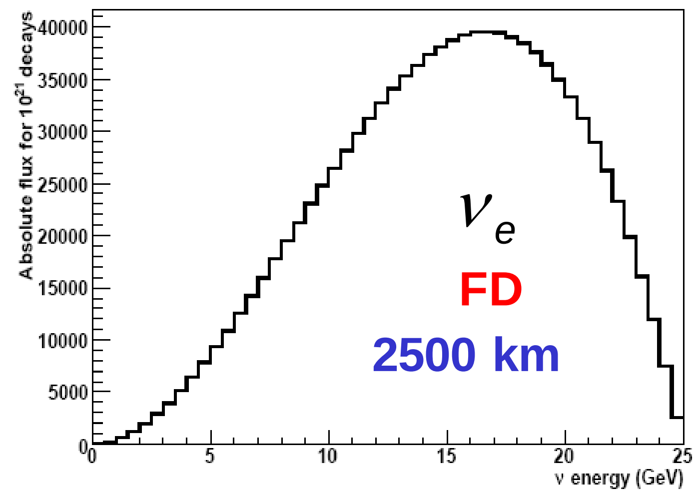


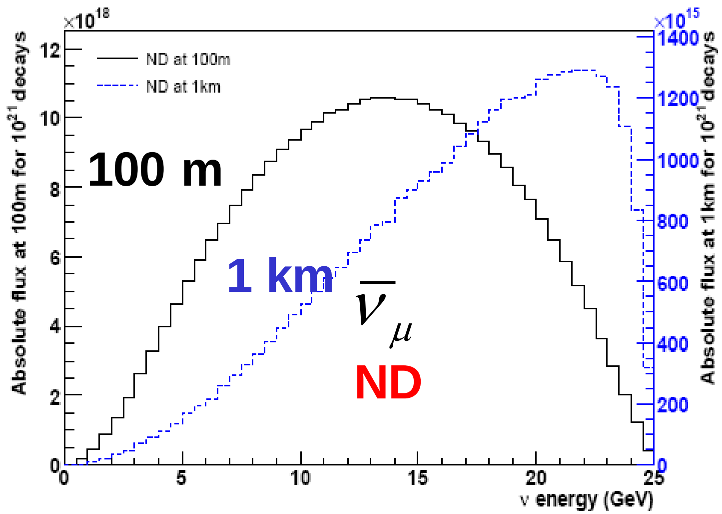
Spectra at Near Detector

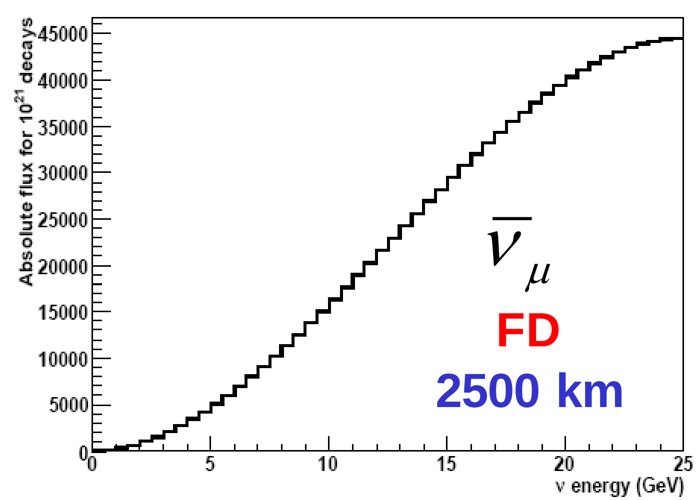
- Near Detector sees a line source (600 m long decay straight)
- Far Detector sees a point source

Need to take into account these differences for flux measurement









Fitting Far Detector Sensitivity

- For Andrew's thesis, carried out sensitivity plots by fitting spectra with NuTS framework developed by Valencia group*

$$Data_{sim} = smear\left(M^{i}_{sig} N^{i,j}_{sig} + \sum_k M^{i,k}_{back} N^{i,j,k}_{back} \right)$$

where M^i is response matrix and $N^{i,j}$ is interaction matrix

i= channel; j=baseline; k=background channel

- Fitting for θ_{13} and δ_{CP} simultaneously, minimise χ^2:

$$\chi^2 = \sum_j \{ 2 \times \sum_e^{E_\mu} \left(A_j x_j N^e_{+,j}(\theta_{13}, \delta_{CP}) - n^e_{+,j} + n^e_{+,j} \log\left(\frac{n^e_{+,j}}{A_j x_j N^e_{+,j}(\theta_{13}, \delta_{CP})} \right) \right.$$
$$\left. + A_j N^e_{-,j}(\theta_{13}, \delta_{CP}) - n^e_{-,j} + n^e_{-,j} \log\left(\frac{n^e_{-,j}}{A_j N^e_{-,j}(\theta_{13}, \delta_{CP})} \right) \right)$$
$$+ \frac{(A_j - 1)^2}{\sigma_A} + \frac{(x_j - 1)^2}{\sigma_x} \}$$

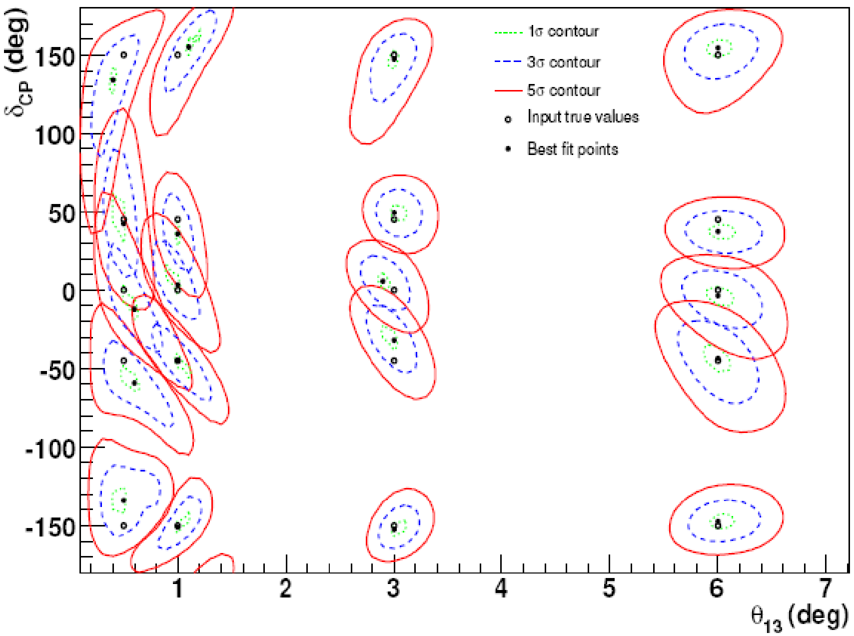
$n^e_{i,j}$=$Data_{sim}$, $N^e_{i,j}$ = predicted spectrum, e=energy bin;

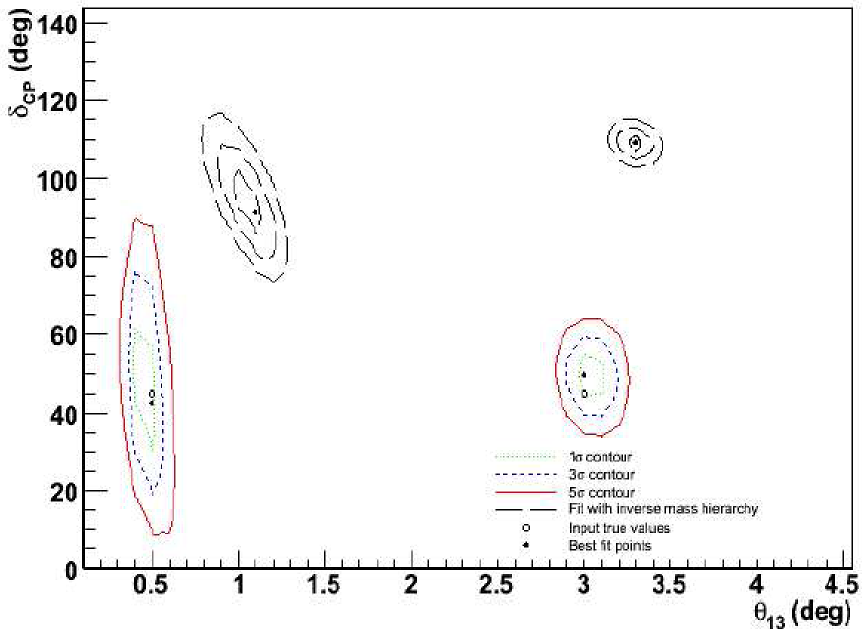
A_j=rate factor (fiducial mass), x_j=ratio cross sections; σ_A=0.05; σ_x=0.01.

*J. Burguet-Castell et al. *Nucl. Phys.*, B608:301, 2001; *Nucl.Phys.*, B646:301, 2002; *Nucl. Phys.*, B725:306, 2005.

Far detector sensitivity

- Set up grid of points in θ_{13} and δ_{CP} and fit sensitivity contours:





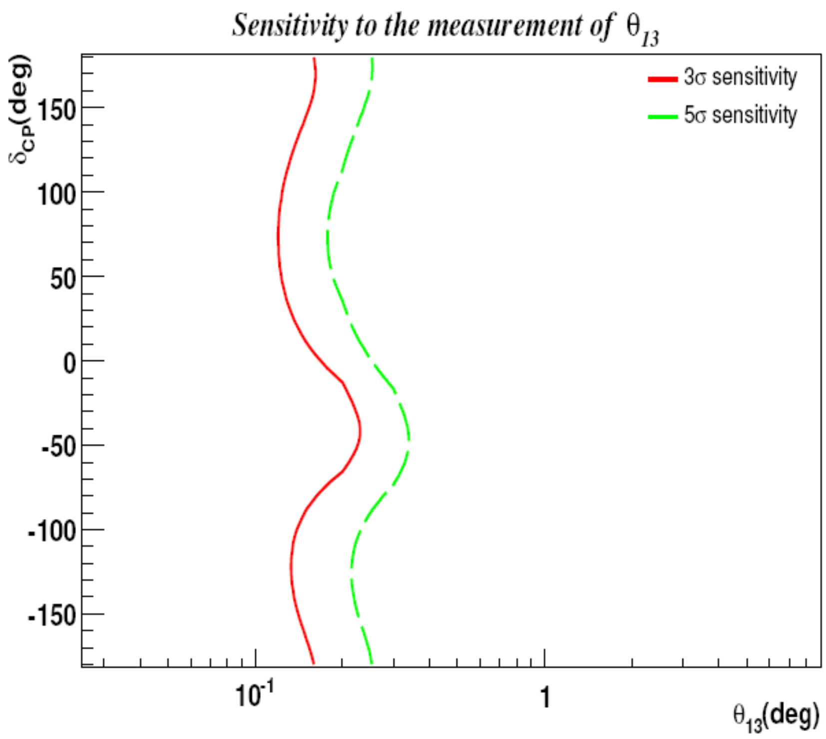
Normal mass hierarchy fitted with NH assumption

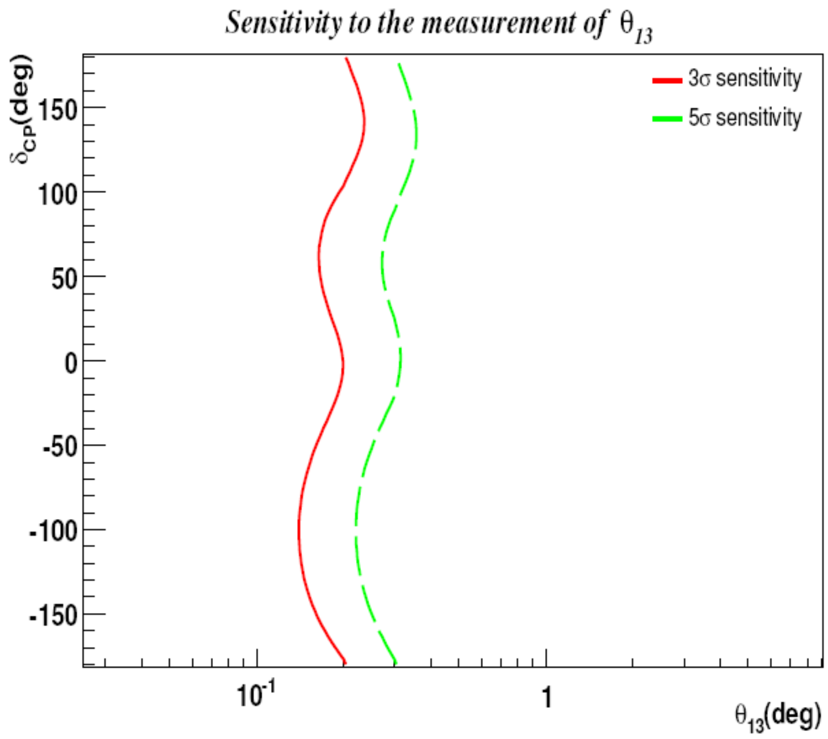
NH contours fitted with wrong mass hierarchy: χ^2 values much worse

This was all done using migration matrices from MIND analysis

Far detector sensitivity

- Sensitivity to θ_{13}: $$\chi^2(\theta_{13}=0) - \chi^2_{min} \geqslant n^2.$$



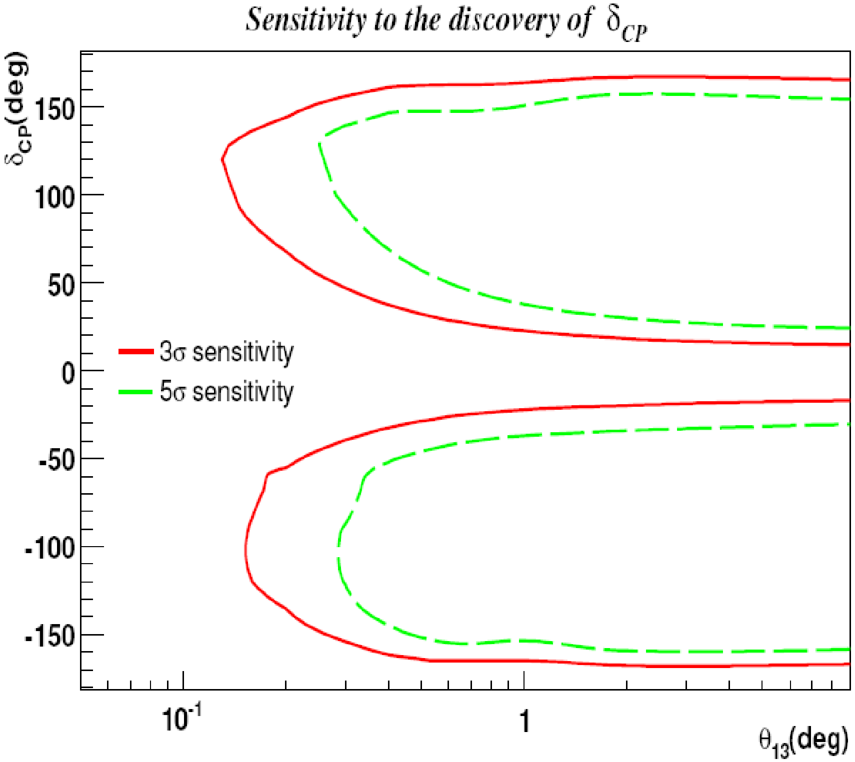


Normal mass hierarchy **Inverted mass hierarchy**

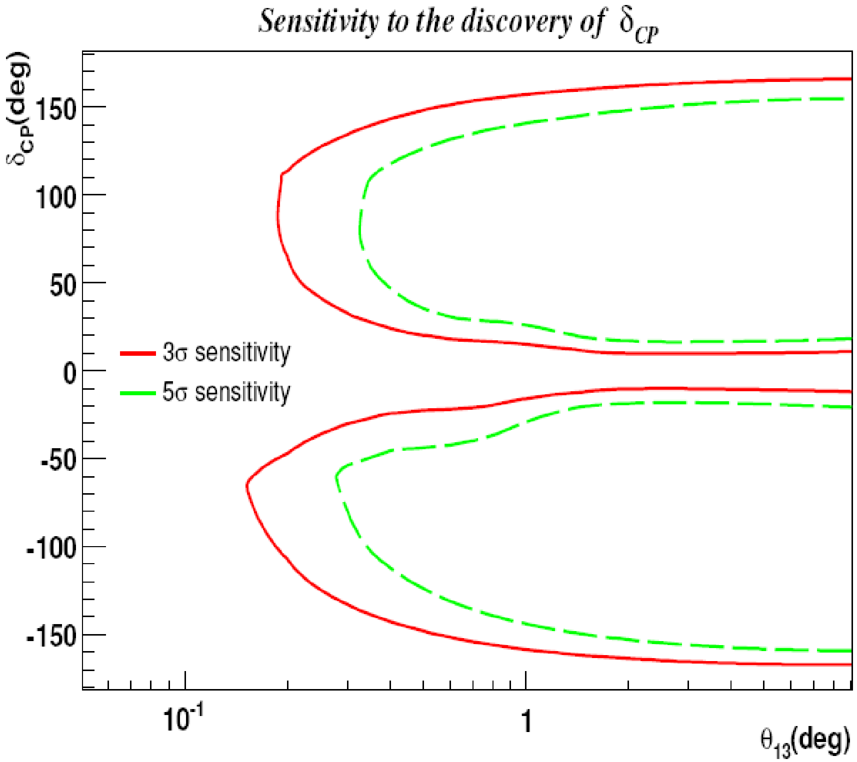
This was all done using migration matrices from MIND analysis

Far detector sensitivity

- Sensitivity to δ_{CP}: $min(\chi^2(\delta_{CP}=0), \chi^2(\delta_{CP}=180), \chi^2(\delta_{CP}=-180)) - \chi^2_{min} \geqslant n^2.$



Normal mass hierarchy

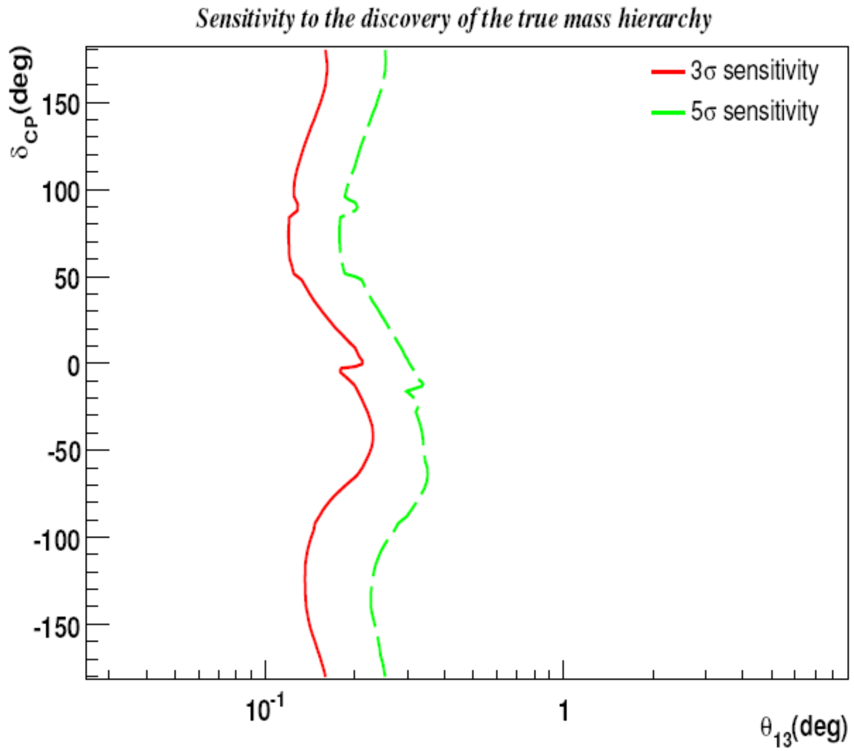


Inverted mass hierarchy

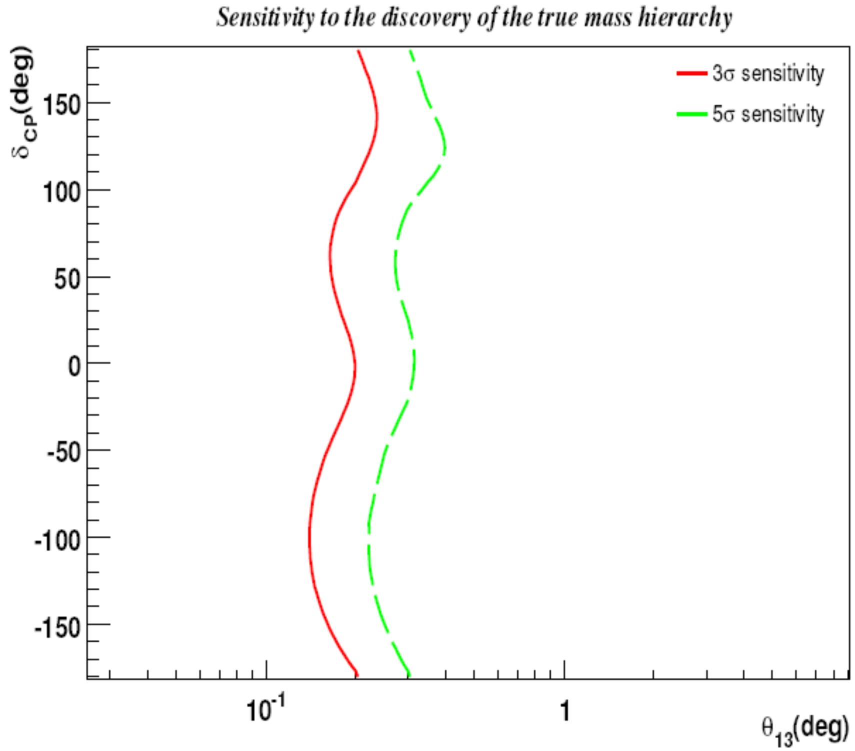
This was all done using migration matrices from MIND analysis

Far detector sensitivity

- Sensitivity to the mass hierarchy: $\chi^2_{min}(-\Delta m^2_{13}) - \chi^2_{min}(\Delta m^2_{13}) \geqslant n^2.$



Normal mass hierarchy



Inverted mass hierarchy

This was all done using migration matrices from MIND analysis

Flux extrapolation method

- Extrapolation near-to-far at Neutrino Factory:
  - Our first idea was to directly use a matrix method similar to MINOS:

$$P_{osc}(\theta_{13},\delta_{CP}) = M_{FD}^{-1} N_{FD} N_{ND}^{-1} M_{ND} M_{nOsc}^{-1}$$

  - Where M_{FD}=matrix of x-section plus response for numu at FD
  - M_{ND}=matrix of x-section plus response for nue at ND
  - M_{nOsc}=matrix of FD nue flux extrapolated from ND nue flux
  - N_{FD}=number of numu events in FD
  - N_{ND}=number of nue events in ND
  - P_{osc} is the probability of oscillation and depends on θ_{13} and δ_{CP}
- However, there are problems with this direct method due to the finite resolution of response matrices: inverting three matrices means that the fit did not converge in many cases

Flux extrapolation method

- Extrapolation near-to-far at Neutrino Factory:
  - We now use indirect method, we extract P_{osc} by fitting this formula:

$$N_{FD} = M_{FD} P_{osc}(\theta_{13}, \delta_{CP}) M_{nOsc} M_{ND}^{-1} N_{ND}$$

  - Where M_{FD}=matrix of x-section plus response for numu at FD
  - M_{ND}=matrix of x-section plus response for nue at ND
  - M_{nOsc}=matrix of FD nue flux extrapolated from ND nue flux
  - N_{FD}=number of numu events in FD
  - N_{ND}=number of nue events in ND
  - P_{osc} is the probability of oscillation and depends on θ_{13} and δ_{CP}
- There is only one ND matrix that we need to invert and because the resolution on this matrix should be better than at the FD, then the fits converge for all values of θ_{13} and δ_{CP}

Flux extrapolation simulation

- Extrapolation near-to-far at Neutrino Factory:
  - Simulate a near detector nue response by assuming:

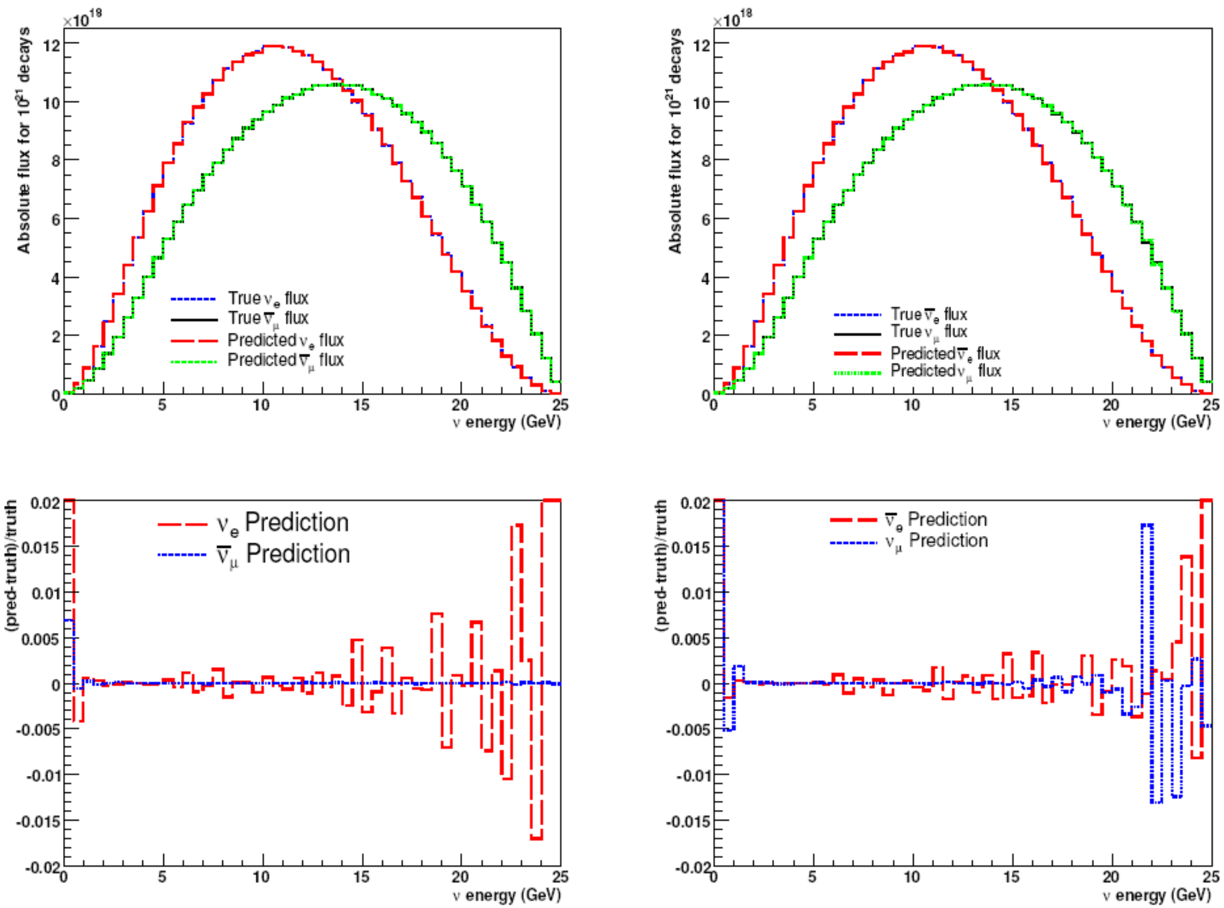
$$\frac{\Delta E(\nu_\mu)}{E(\nu_\mu)} = \frac{20\%}{\sqrt{E(GeV)}}$$

$$\frac{\Delta E(\nu_e)}{E(\nu_e)} = \frac{35\%}{\sqrt{E(GeV)}}$$

$$\varepsilon(\nu_\mu) = \begin{cases} 60\% & E > 4\,GeV \\ 15\% E & E < 4\,GeV \end{cases}$$

$$\varepsilon(\bar{\nu}_\mu) = \begin{cases} 80\% & E > 4\,GeV \\ 20\% E & E < 4\,GeV \end{cases}$$

$$\varepsilon(\nu_e) = \begin{cases} 70\% & E > 4\,GeV \\ 17.5\% E & E < 4\,GeV \end{cases}$$

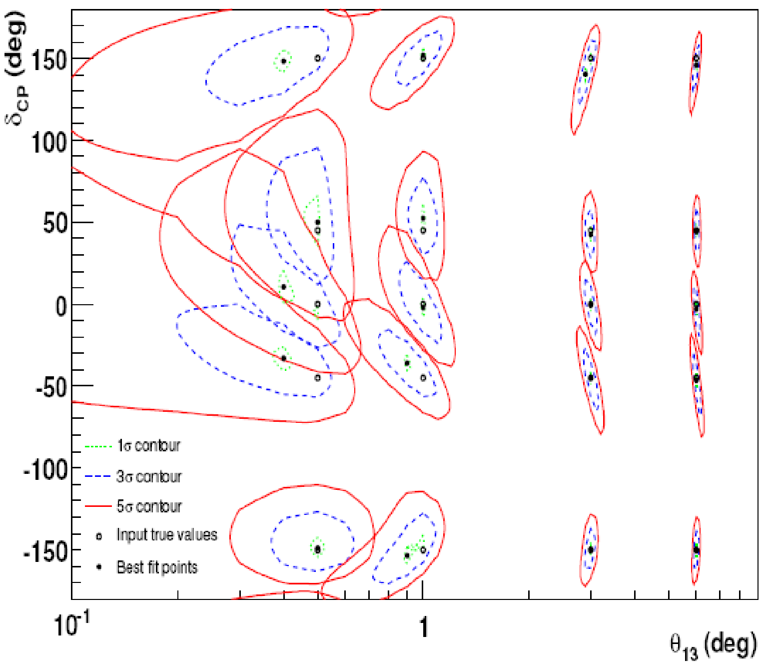


Prediction of flux from response matrices

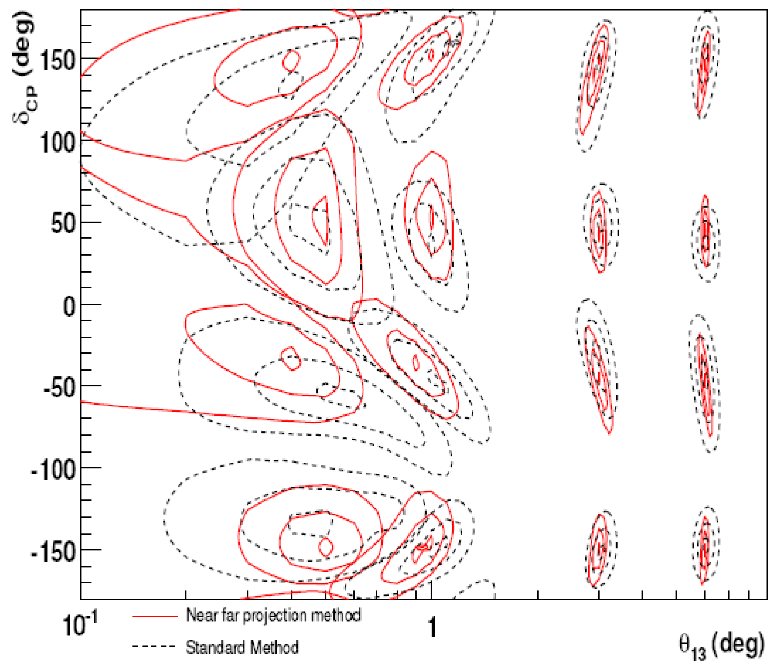
Flux extrapolation results

- Extrapolation near-to-far at Neutrino Factory:
  - Using the FD spectrum formula: $N_{FD} = M_{FD} P_{osc}(\theta_{13}, \delta_{CP}) M_{nOsc} M_{ND}^{-1} N_{ND}$
  - Fit FD spectrum to predicted spectrum from ND:

$$\chi^2 = \sum\sum (N_{ij} - n_{ij}) V_{ij}^{-1} (N_{ij} - n_{ij})^T$$



Fits using near-far projection method

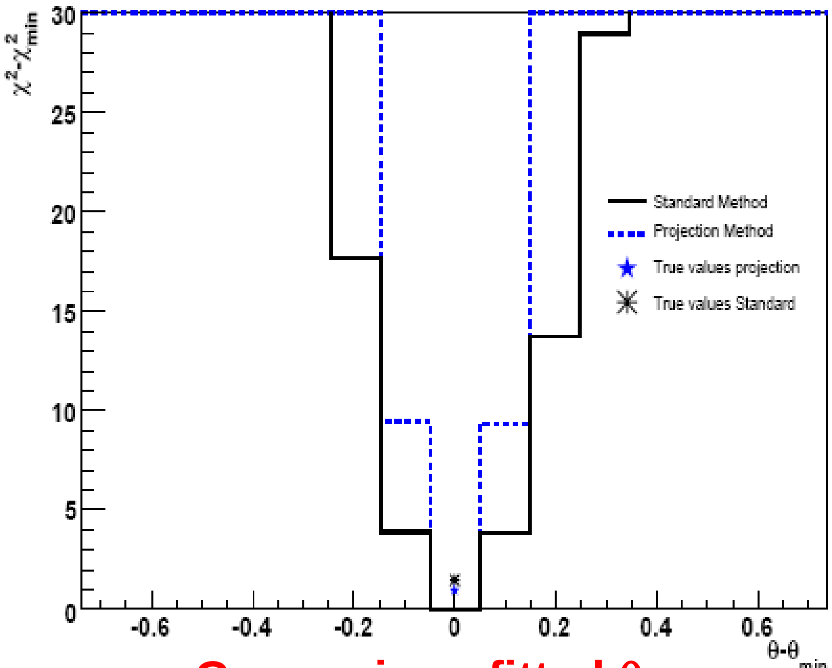


Fits assuming standard flux error 1%

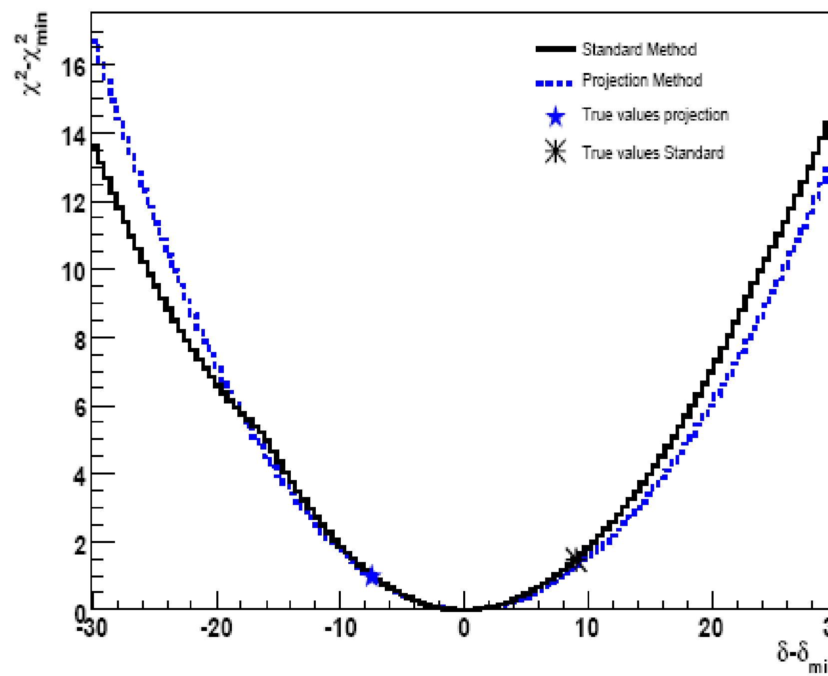
Flux extrapolation results

- Extrapolation near-to-far at Neutrino Factory:
  - Using the FD spectrum formula: $N_{FD} = M_{FD} P_{osc}(\theta_{13}, \delta_{CP}) M_{nOsc} M_{ND}^{-1} N_{ND}$
  - Fit FD spectrum to predicted spectrum from ND:

$$\chi^2 = \sum_i \sum_j \left(N_{ij} - n_{ij}\right) V_{ij}^{-1} \left(N_{ij} - n_{ij}\right)^T$$



Comparison fitted θ_{13} and δ with true values

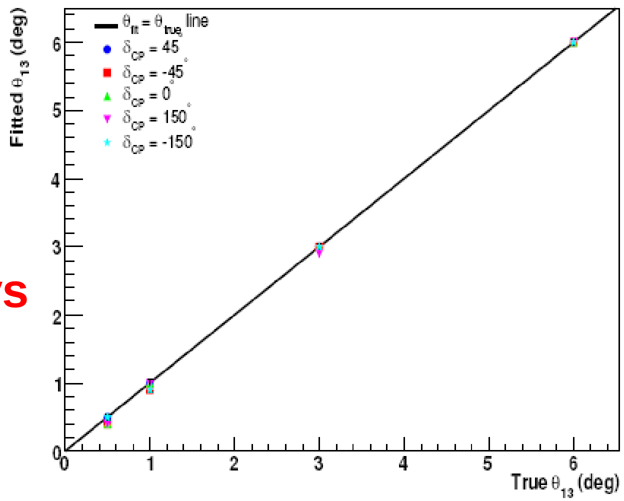


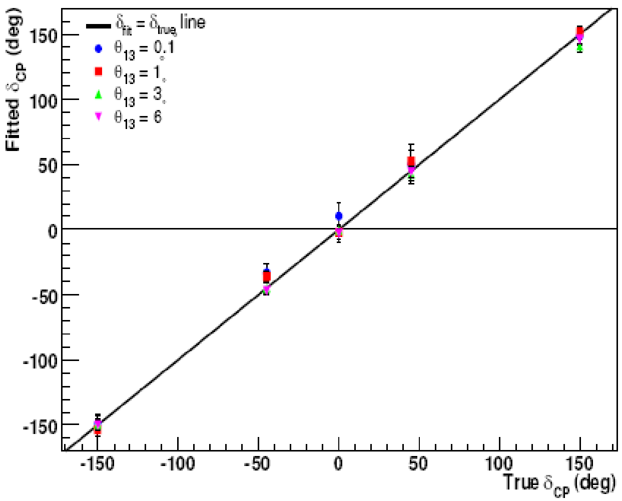
Fit improves at 3σ level

Flux extrapolation results

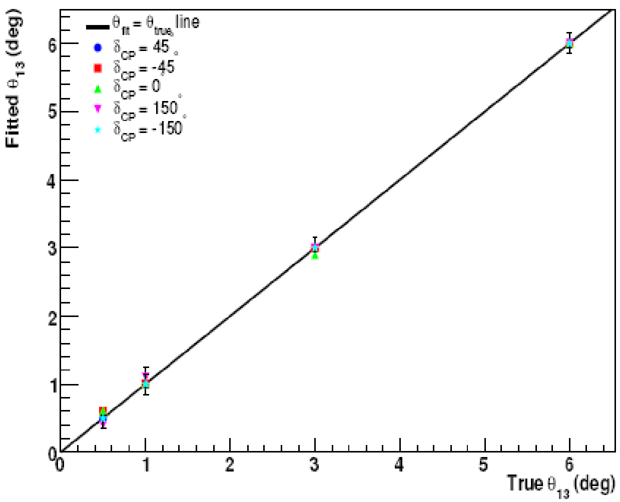
- Fitted vs true values of θ_{13} and δ_{CP}: no observed biases

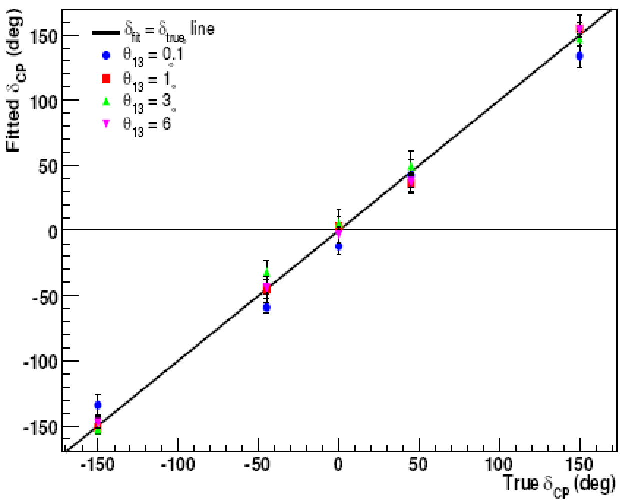
Fitted θ_{13} vs true value





Fitted δ_{CP} vs true value





Conclusions

- Developed extrapolation method for near to far detector
- While fluxes can be calculated accurately at a neutrino factory, fitting the spectrum from near to far detector improves performance especially at the 3σ level
- In my view, the near detector flux measurement and extrapolation to far detector is necessary to go to sub-1% level flux error