Near-to-far extrapolation method and low-ν method

IDS-NF Meeting,
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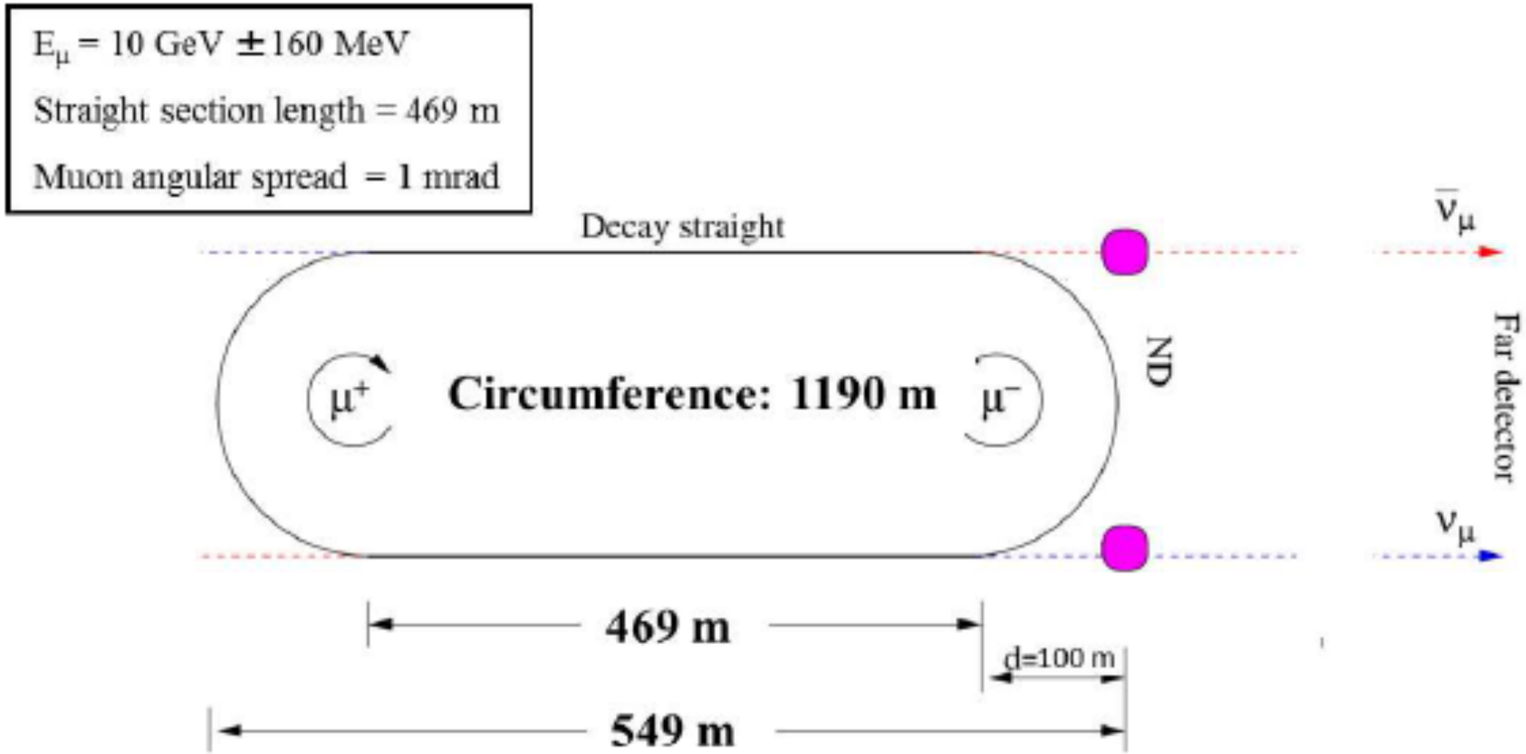
Outline

- Near to Far extrapolation method developed for IDR
- How to use ν-e scattering data to extract flux as function of E
- Alternative: low-ν method to extract neutrino flux

Near Detector Location

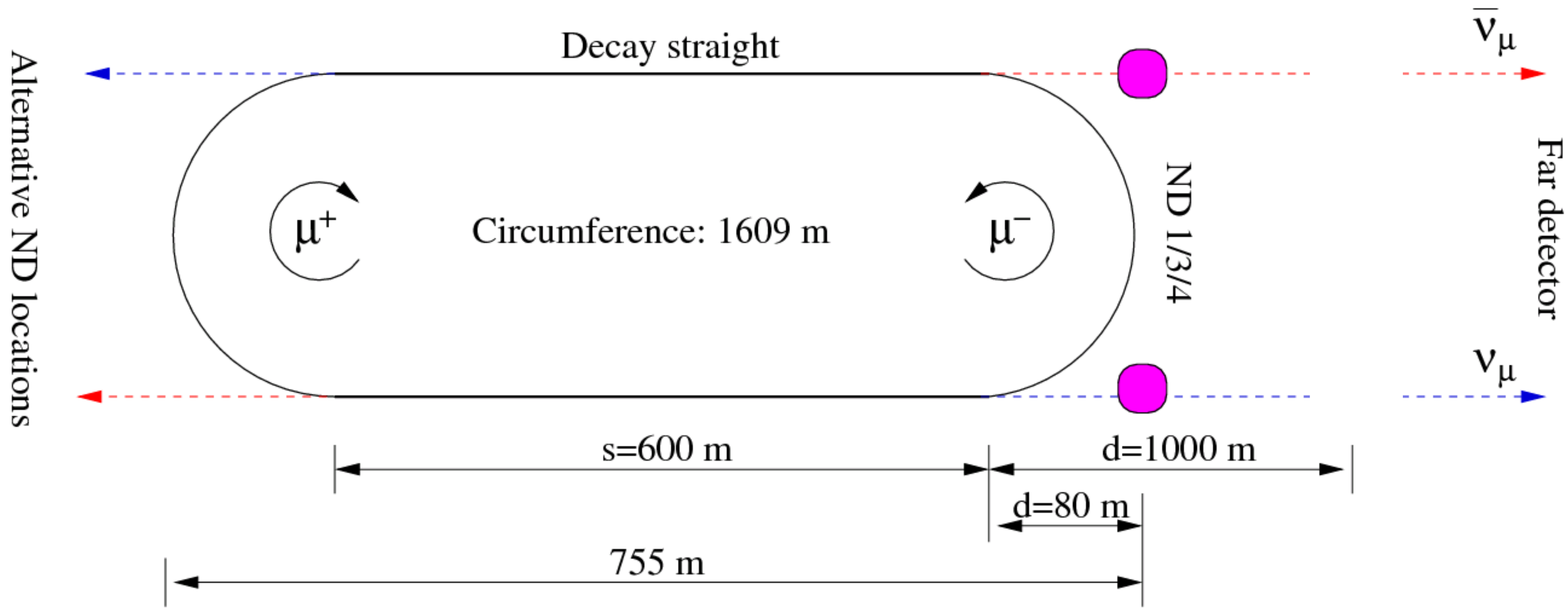
- For new 10 GeV Neutrino Factory, we need one Near Detector per decay straight (ie 2 detectors)



- The straight is shorter for the 10 GeV NF: 469 m

Near Detector Location

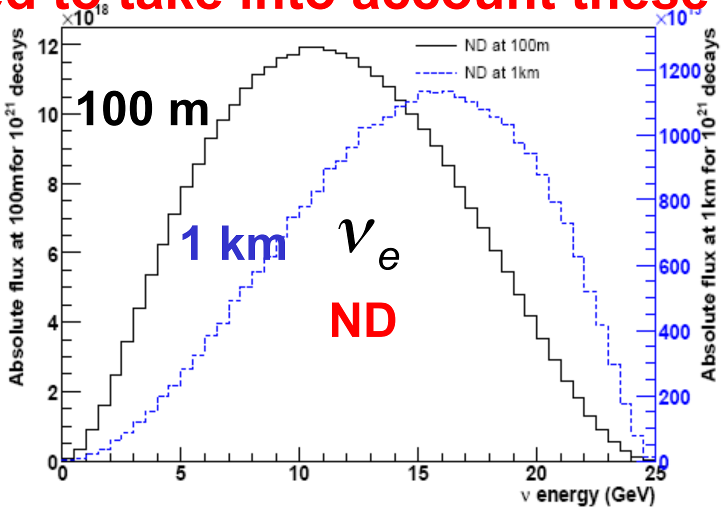
- However, for the 25 GeV Neutrino Factory, the straight was longer (600 m)
- A method for extrapolating near-to-far was developed for the IDR (A. Laing, P.S) based on this configuration

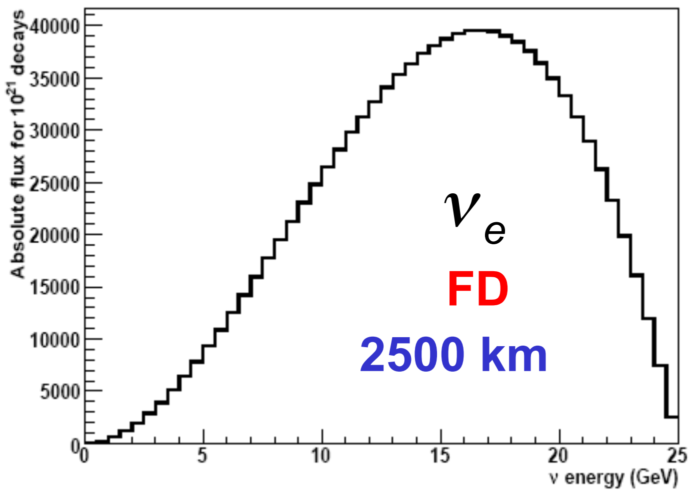


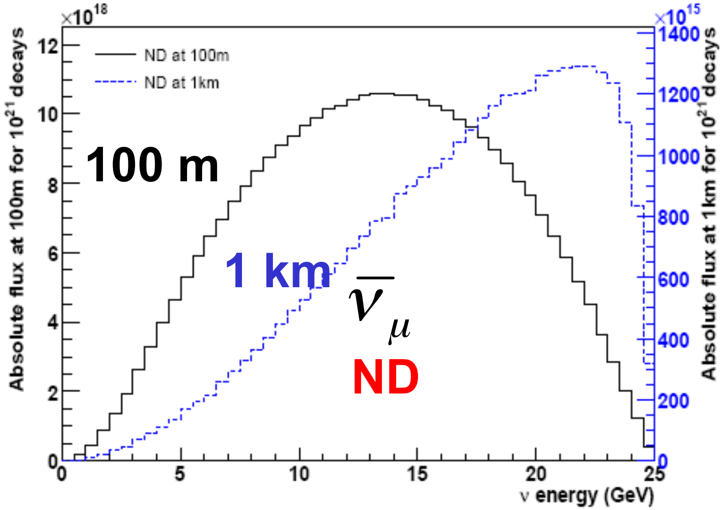
Spectra at Near Detector

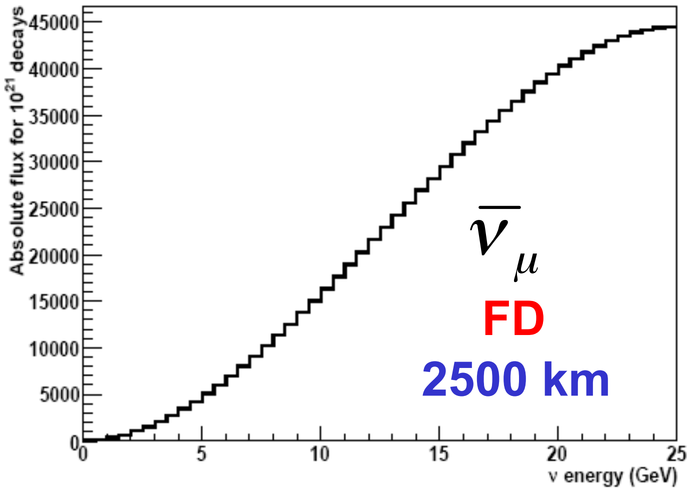
- Near Detector sees a line source (600 m long decay straight)
- Far Detector sees a point source

Need to take into account these differences for flux measurement









Fitting Far Detector Sensitivity

- For A. Laing'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:

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

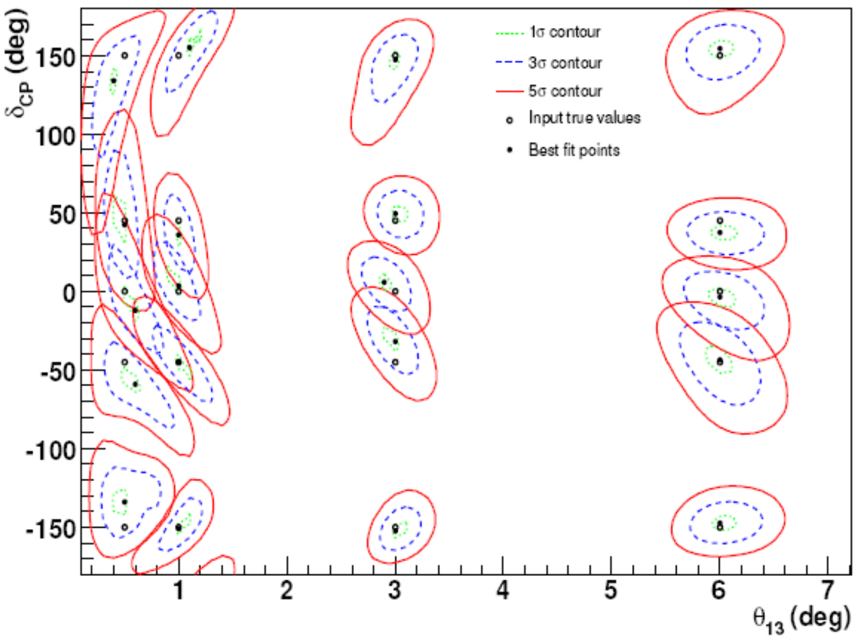
$n^e_{i,j}$=$Data_{sim}$, $N^e_{i,j}$ = predicted spectrum, e=energy bin;

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

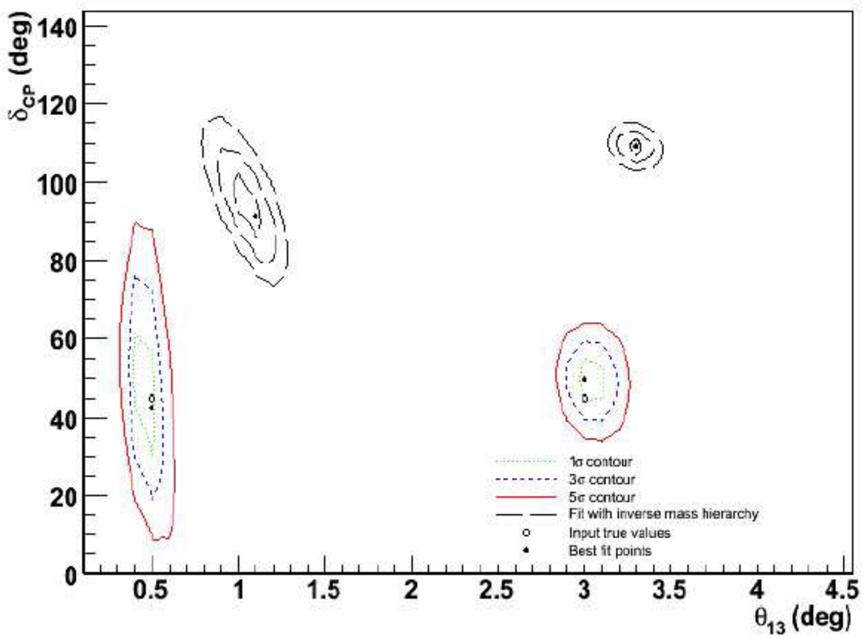
*J. Burguet-Castell et al. NPB 608:301, 2001; NPB 646:301, 2002; NPB725:306, 2005.

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

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:

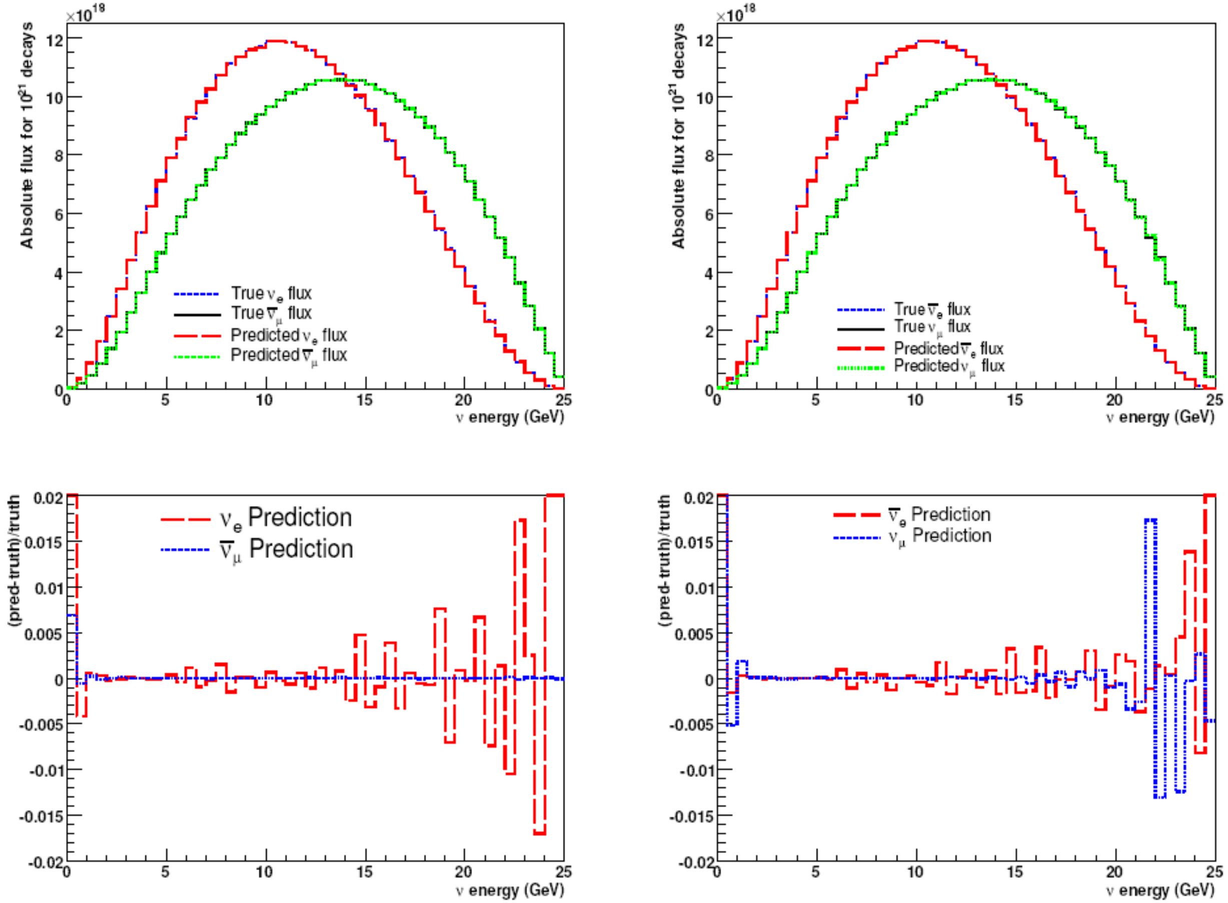
$$\frac{\Delta E(\nu_\mu)}{E(\nu_\mu)} = \frac{20\%}{\sqrt{E(GeV)}}$$

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

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

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

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

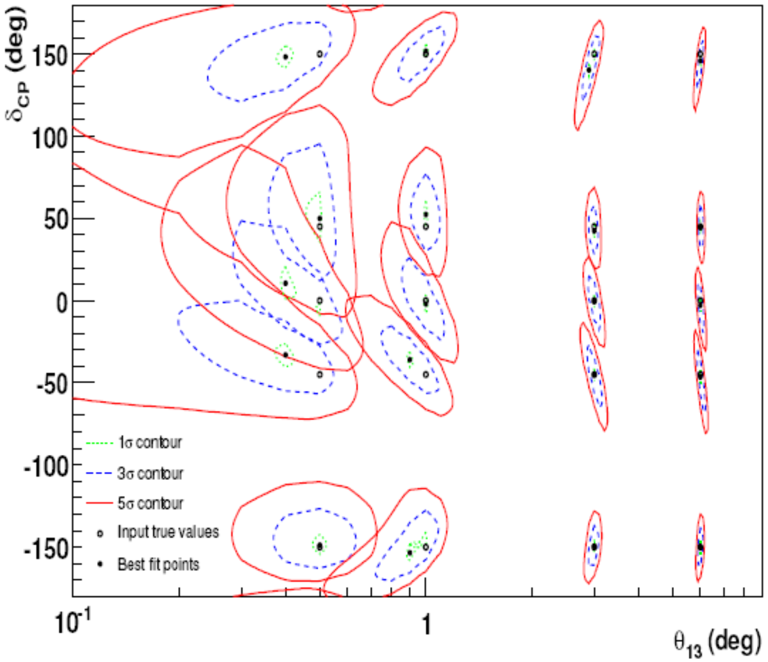


Prediction of flux from response matrices

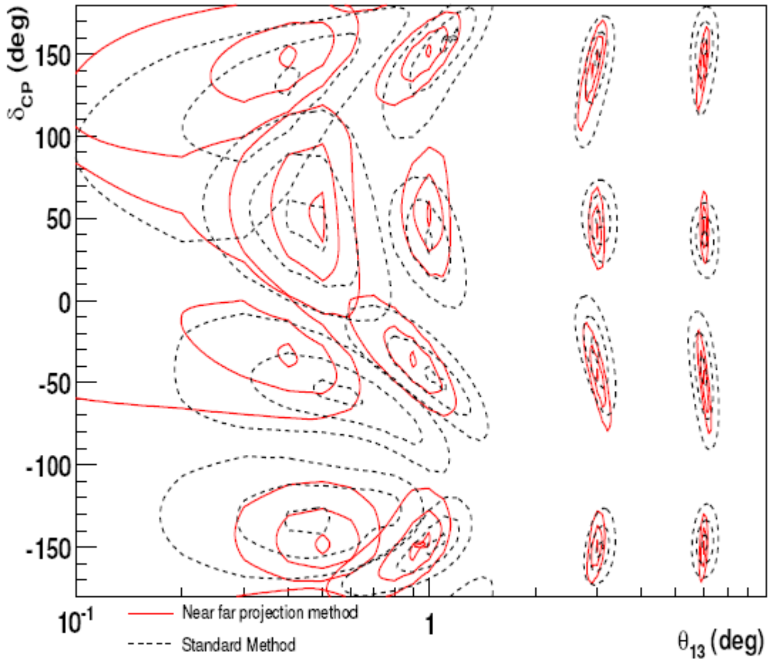
Flux extrapolation results

- 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:

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



Fits using near-far projection method



Fits assuming standard flux error 1%

Flux extrapolation results

- Extrapolation near-to-far at Neutrino Factory:
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  - Fit FD spectrum to predicted spectrum from ND:

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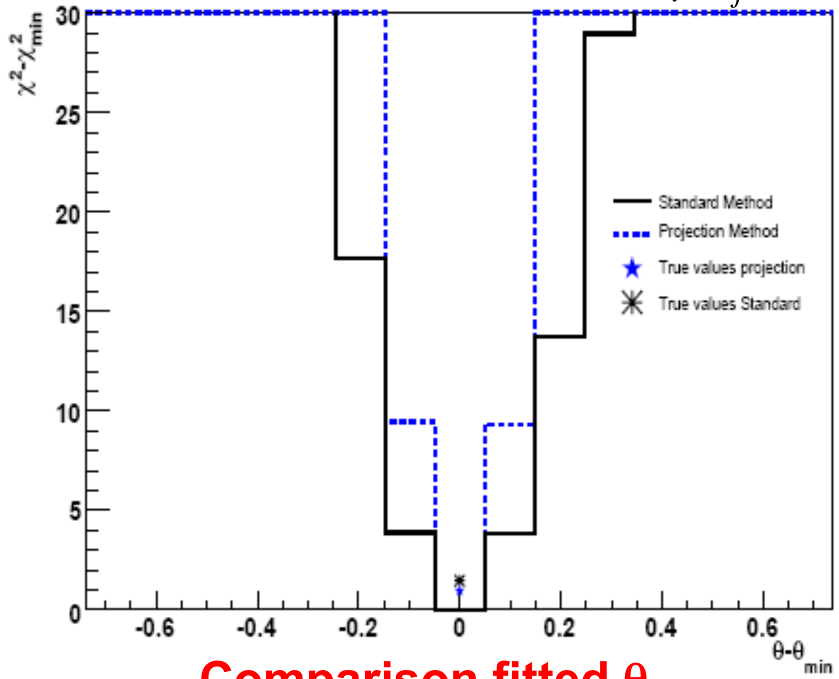
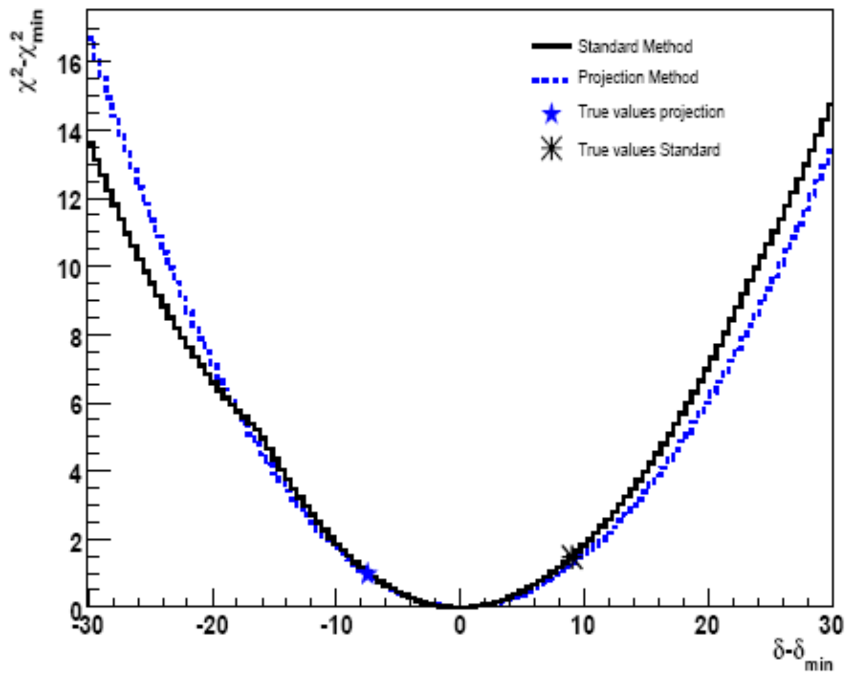


Comparison fitted θ_{13} and δ with true values

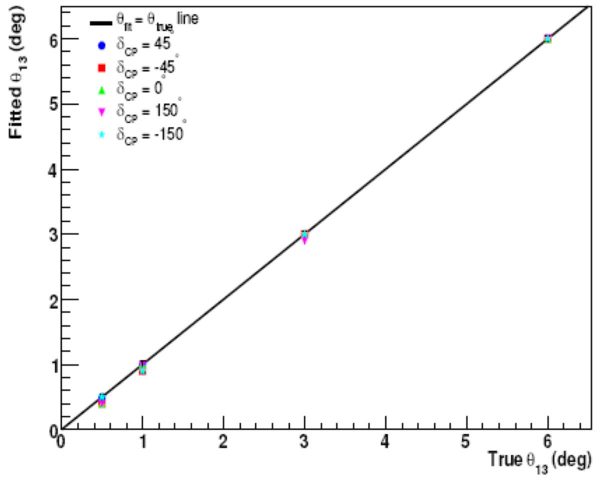


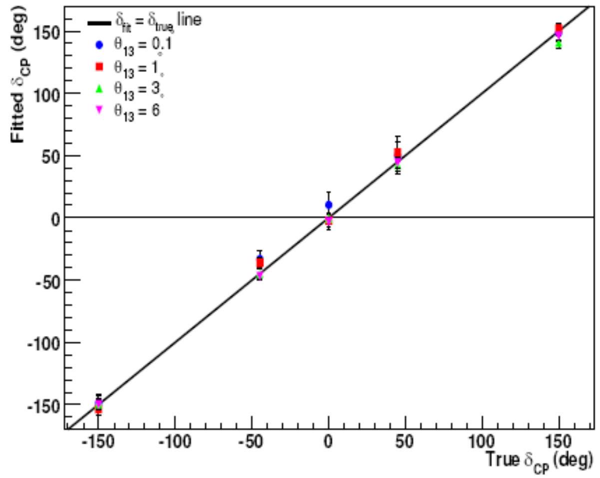
Fit improves at 3σ level

Flux extrapolation results

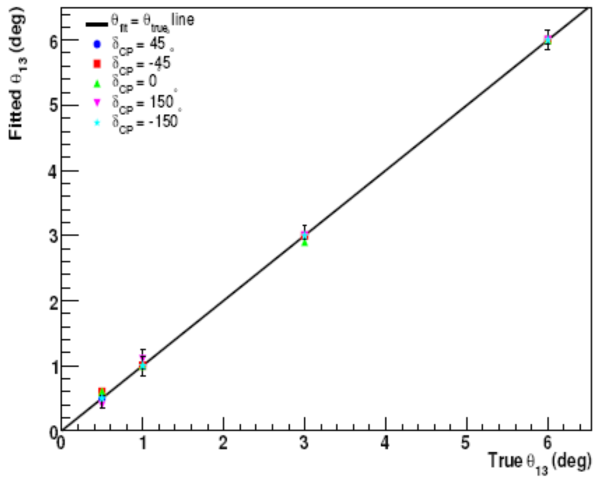
- Fitted vs true values of θ_{13} and δ_{CP}: no observed biases

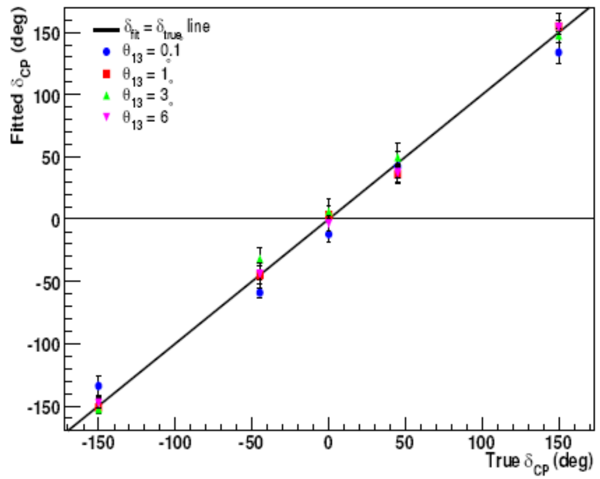
Fitted θ_{13} vs true value





Fitted δ_{CP} vs true value





- Need to reproduce these results with 10 GeV NF

Flux from ν-e scattering

- How to extract the neutrino factory flux from the measurements of IMD and elastic neutrino scattering?
- Use channels with very small theoretical error in the cross-sections and measure them at near detector:
  - Inverse muon decay (Charged Current): threshold ~ 11 GeV

$$\nu_\mu + e^- \to \nu_e + \mu^- \qquad \bar{\nu}_e + e^- \to \bar{\nu}_\mu + \mu^-$$

$$N_1(E) = \phi_{\nu_\mu}(E)\sigma^{CC}_{\nu_\mu e^-}(E) \qquad N_2(E) = \phi_{\bar{\nu}_e}(E)\sigma^{CC}_{\bar{\nu}_e e^-}(E)$$

  - Elastic neutrino scattering:
    - Neutral Current:

$$\nu_\mu + e^- \to \nu_\mu + e^- \qquad \bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$$

$$N_3(E) = \phi_{\nu_\mu}(E)\sigma^{NC}_{\nu_\mu e^-}(E) \qquad N_4(E) = \phi_{\bar{\nu}_\mu}(E)\sigma^{NC}_{\bar{\nu}_\mu e^-}(E)$$

    - Interference Charged Current/Neutral Current:

$$\nu_e + e^- \to \nu_e + e^- \qquad \bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$$

$$N_5(E) = \phi_{\nu_e}(E)\sigma^{CC+NC}_{\nu_e e^-}(E) \qquad N_6(E) = \phi_{\bar{\nu}_e}(E)\sigma^{CC+NC}_{\bar{\nu}_e e^-}(E)$$

Combination of all channels

- For a 25 GeV NF, above 11 GeV, we can include data from IMD and electron channels together:
  - For the NF decay: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

$$N_1(E) + N_2(E) = \phi_{\nu_\mu}(E)\sigma^{CC}_{\nu_\mu e^-}(E) + \phi_{\bar{\nu}_e}(E)\sigma^{CC}_{\bar{\nu}_e e^-}(E)$$

$$N_3(E) + N_6(E) = \phi_{\nu_\mu}(E)\sigma^{NC}_{\nu_\mu e^-}(E) + \phi_{\bar{\nu}_e}(E)\sigma^{CC+NC}_{\bar{\nu}_e e^-}(E)$$

  - We can extract the fluxes when we have IMD and elastic scattering:

$$\phi_{\nu_\mu}(E) = \frac{\sigma^{CC+NC}_{\bar{\nu}_e e^-}(N_1 + N_2) - \sigma^{CC}_{\bar{\nu}_e e^-}(N_3 + N_6)}{\sigma^{CC+NC}_{\bar{\nu}_e e^-}\sigma^{CC}_{\nu_\mu e^-} - \sigma^{CC}_{\bar{\nu}_e e^-}\sigma^{NC}_{\nu_\mu e^-}}$$

$$\phi_{\bar{\nu}_e}(E) = \frac{\sigma^{NC}_{\nu_\mu e^-}(N_1 + N_2) - \sigma^{CC}_{\nu_\mu e^-}(N_3 + N_6)}{\sigma^{CC+NC}_{\bar{\nu}_e e^-}\sigma^{CC}_{\nu_\mu e^-} - \sigma^{CC}_{\bar{\nu}_e e^-}\sigma^{NC}_{\nu_\mu e^-}}$$

Below 11 GeV we cannot resolve fluxes since we have N_3+N_6

  - For the negative muon beam: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

$$N_5(E) + N_4(E) = \phi_{\nu_e}(E)\sigma^{CC+NC}_{\nu_e e^-}(E) + \phi_{\bar{\nu}_\mu}(E)\sigma^{NC}_{\bar{\nu}_\mu e^-}(E)$$

We cannot resolve fluxes since we have N_5+N_4

Low-ν method

- Therefore, for a 10 GeV Neutrino Factory we need to resolve the flux ambiguity by using electron channels only, so use:
  - Different shape distributions of $\bar{\nu}_\mu$ and ν_e and fit for the fluxes
  - Another method to extract flux, such as Low-ν method
- What is low-ν method?
  - It is a method developed by S. Mishra for CCFR to determine neutrino flux from DIS interactions:

$$N(E_\nu : E_{had} < \nu_0) = C\phi(E_\nu) f\left(\frac{\nu_0}{E_\nu}\right)$$

  - By selecting low ν=E−E' interactions, the error associated to the hadronic energy is small, and the interaction rate becomes proportional to the flux, except for a correction to be determined
- Normally used in DIS interactions but A. Bodek (NUFACT12) showed that it can also be used in the context of quasi-elastic, resonant and coherent interactions

Low-ν method

Sanjib Mishra
IDS-NF meeting Glasgow

LOW-ν_0 METHOD ⇐Shape of ν_μ or Anti-ν_μ Flux

✦ *Relative flux vs. energy from low-ν_0 method:*

$$N(E_\nu : E_{\text{HAD}} < \nu^0) = C\Phi(E_\nu) f(\frac{\nu^0}{E_\nu})$$

⇐SRM(1990): Used by CCFR, NOMAD, NuTeV, MINOS..

the correction factor $f(\nu^0/E_\nu) \to 1$ *for* $\nu^0 \to 0$.

$\Longrightarrow$ *Need precise determination of the muon energy scale and good resolution at low ν values*

✦ *Fit Near Detector $\nu_\mu, \bar{\nu}_\mu$ spectra:*

- *Trace secondaries through beam-elements, decay;*
- *Predict $\nu_\mu, \bar{\nu}_\mu$ flux by folding experiental acceptance;*
- *Compare predicted to measured spectra $\Longrightarrow \chi^2$ minimization*

$$\frac{d^2\sigma}{dx_F dP_T^2} = f(x_F) g(P_T) h(x_F, P_T)$$

- *Functional form constraint allows flux prediction close to $E_\nu \sim \nu^0$.*

Low-ν method

Sanjib Mishra
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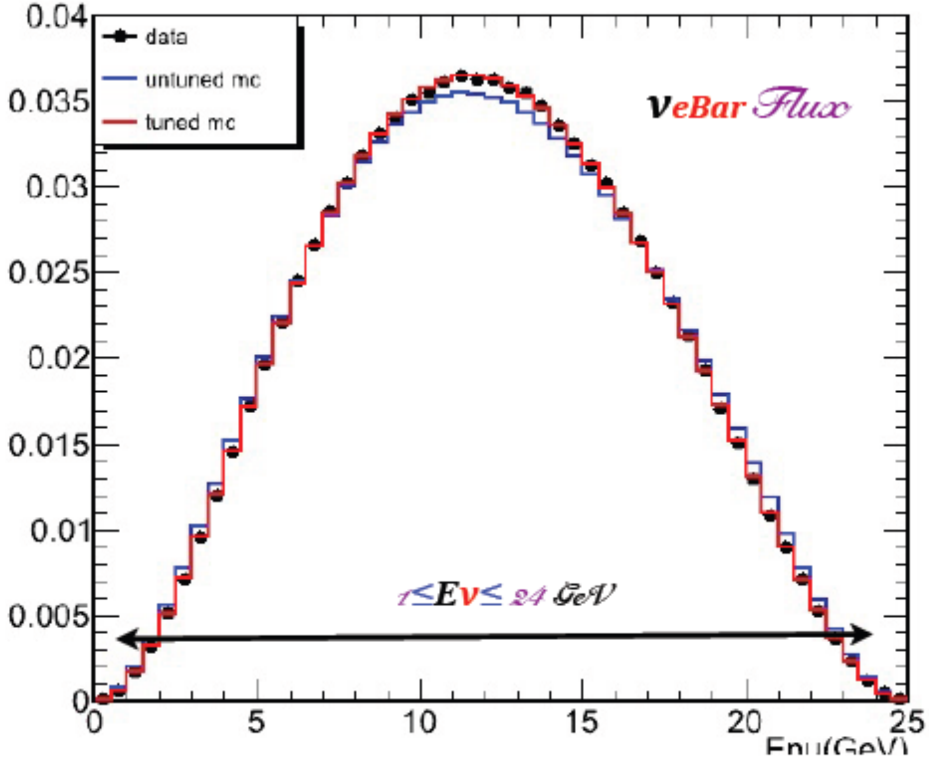
Low-ν0:

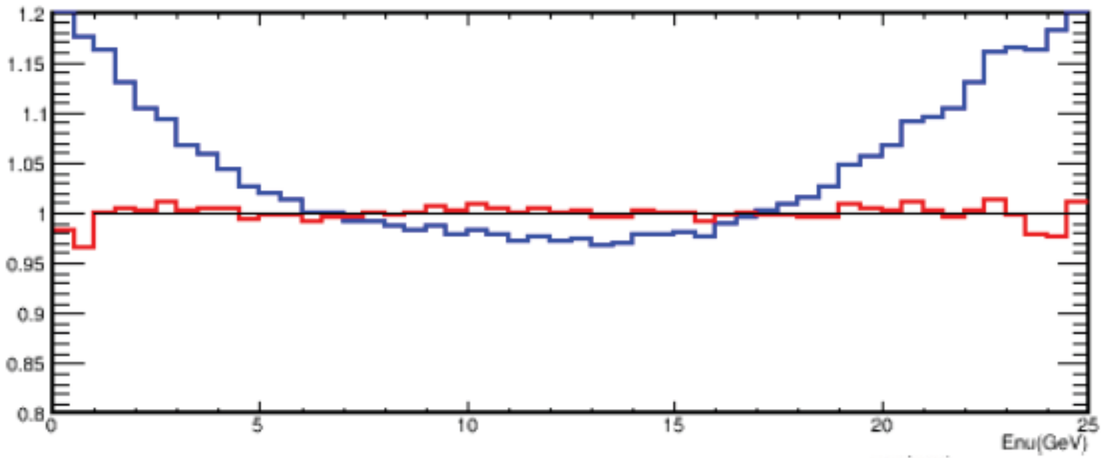
$\nu_e Bar + N \rightarrow e^{+} + X$ (Ex<0.5 GeV)

Observation ⇒ The Low-ν0 method should permit flux determination of ν_μ and ν_eBar within ± ~1-% at ND;

Ditto for (ν_e and $\nu_\mu Bar$).

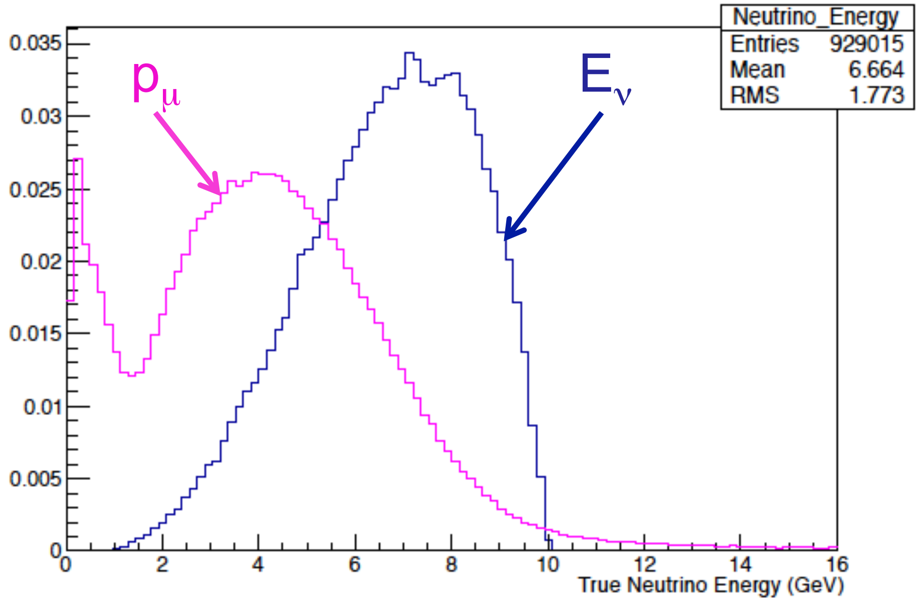
⇒ FD/ND will be more precise

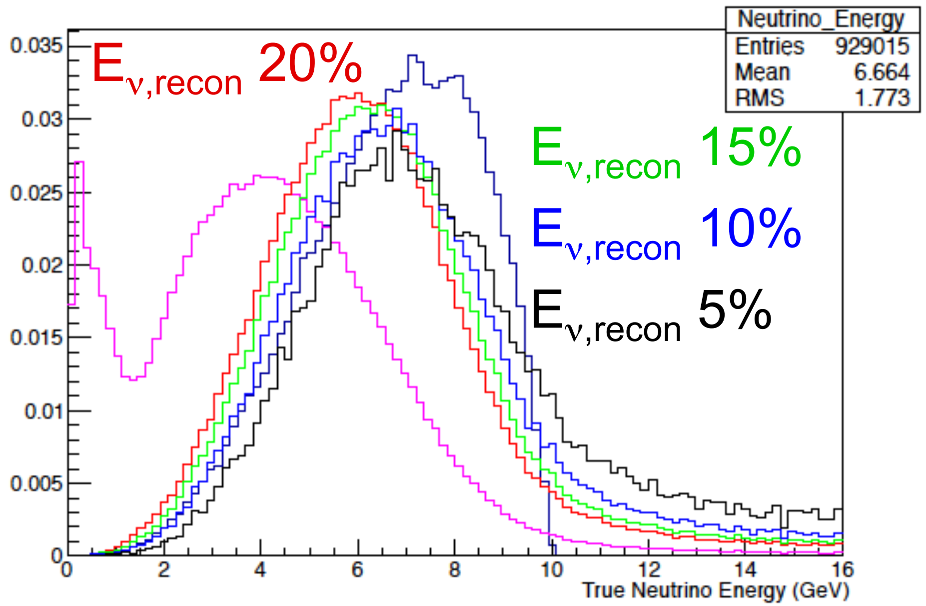




Low-ν method

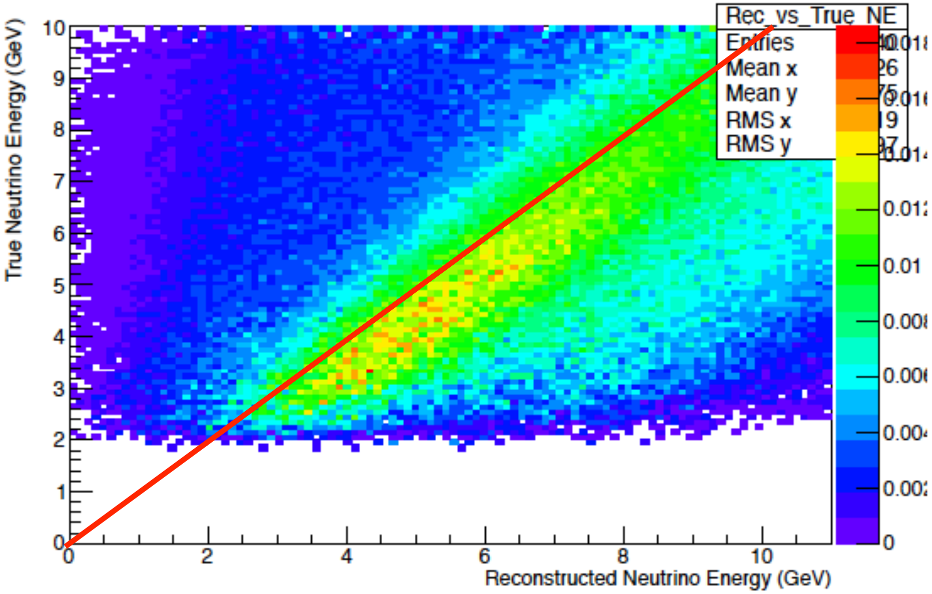
- With Ryan and a summer student (A. De Miquel) we looked at implementing the low-ν method at a near detector of a NF
- Use a mini-MIND detector: 10 m long and 3 m in diameter with a toroidal field similar to SuperBind (nuSTORM) model
- Comparison neutrino energy and reconstructed momentum as a function of low-ν cut (20%, 15%, 10%, 5% of p_μ):

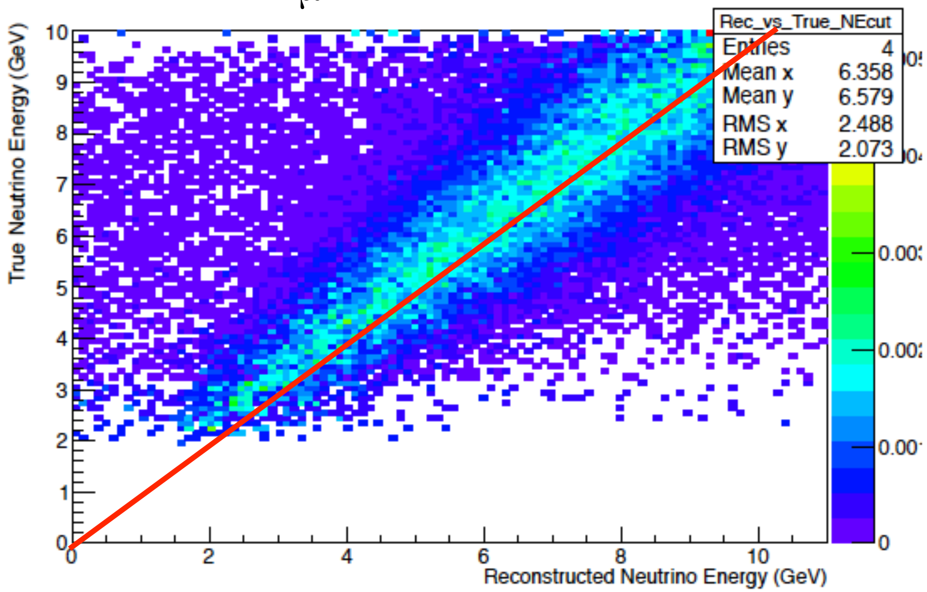




Low-ν method

- Compare true neutrino energy vs neutrino energy reconstruction with and without a 20% p_μ low-ν cut:





$$E_{\nu,recon} = E_\mu + E_{had}$$

$$E_{\nu,recon} = E_\mu + E_{had}$$
$$E_{had} < 0.20\, p_\mu$$

- Low-ν method improves agreement between true neutrino energy spectrum and reconstructed energy – need to develop further to extract the flux

Conclusions

- Developed near-to-far extrapolation method for the IDR at 25 GeV Neutrino Factory
- Need to apply method for new conditions with 10 GeV Neutrino Factory and extract δ and θ_{13} from fits
- Neutrino-electron scattering in near detector can be used to extract flux, but at 10 GeV NF the IMD channel is not available so cannot extract unambiguously flux of all species
- Need to fit to shape of neutrino spectrum or perform alternate method such as low-ν method
- Started applying low-ν method to a Near Detector at a 10 GeV neutrino factory – preliminary results look encouraging