Near Detector Flux Estimates

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Paul Soler (Glasgow)
on behalf of Sofia Group:
Roumen Tsenov, Rosen Matev, Yordan Karadzhov

University of Glasgow

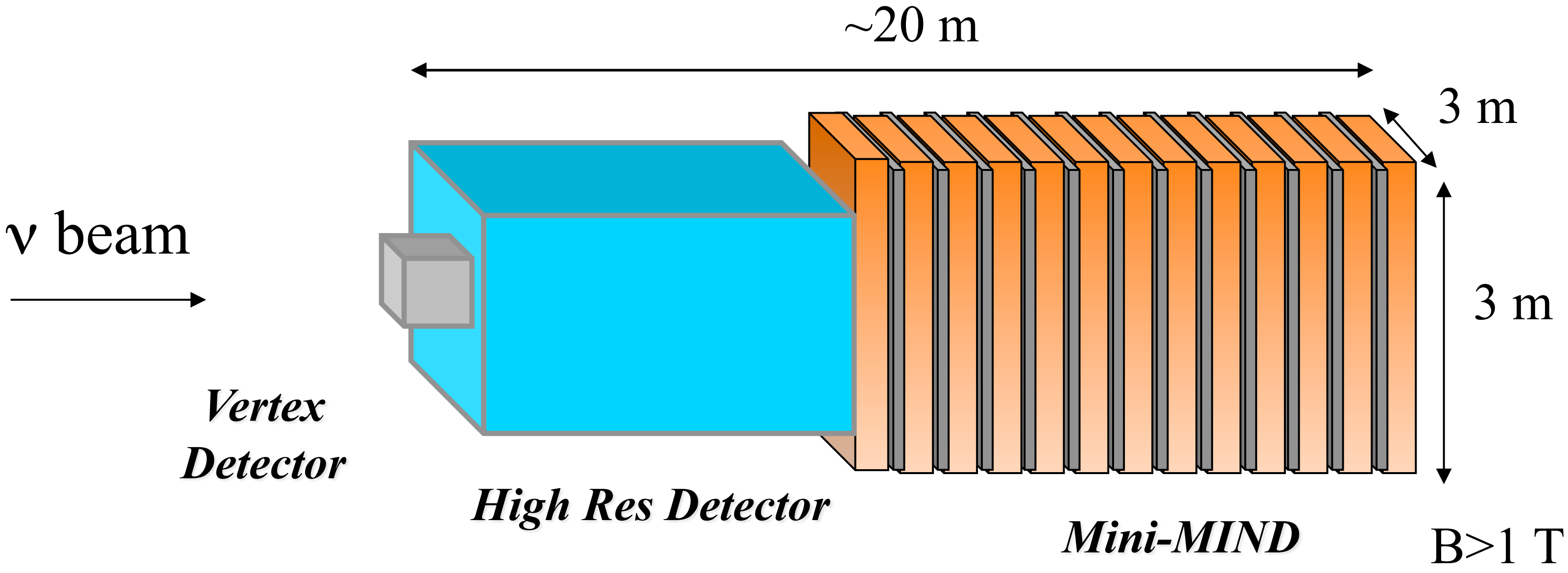
University of Sofia

Near Detectors

- We have learned that near detectors are essential for neutrino oscillation physics:
  - We need measurement of neutrino flux with ~1% precision to perform extrapolation to the Far Detector;
  - We need measurement of charm production for neutrino factory (one of the backgrounds to the oscillation signal at a NF);
  - Cross-section measurements: DIS, QEL, RES scattering; comparison of ν_μ and ν_e cross-sections
- Other measurements with Near Detector
  - Fundamental electroweak and QCD physics (ie PDFs, $\sin^2\theta$W)
  - Search for Non Standard Interactions (NSI) from taus

Near Detector Baseline

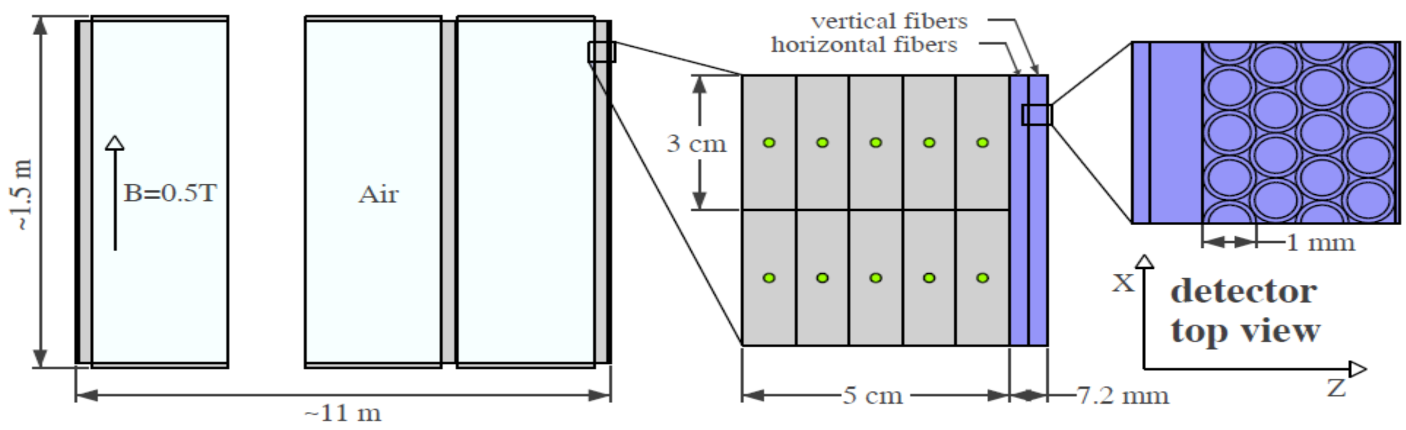
- Near Detector baseline (for Neutrino factory):
  - High resolution section (SciFi tracker) for leptonic flux measurement (baseline EUROnu) – alternative was HiRes straw tube tracker as in LBNE
  - Mini-MIND detector for flux and muon measurement
  - Vertex detector for charm/tau measurement at the front.



- Near Detector for Beta Beam or Super-beam: remove vertex detector, include water targets as part of detector

Scintillating Fibre Tracker

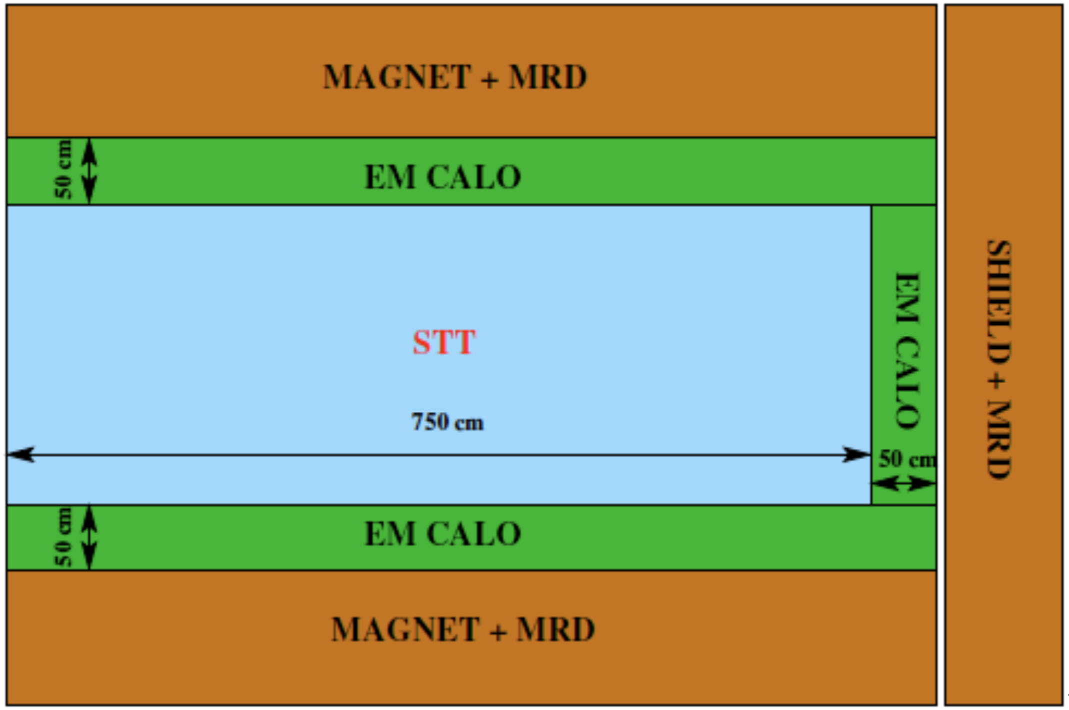
- Detector design:
  - 20 tracker stations
  - Each station consists of 4 horizontal and 4 vertical layers of 1 mm diameter scintillating fibres shifted with respect to each other
  - 5 cm thick active absorber, divided into 5 slabs for more precise measurement of recoil energy near the event vertex;
  - 12 000 fibres per station (240 000 in total);
  - Air gaps are closed by a layer of scintillating bars;
  - Overall detector dimensions: 1.5 x 1.5 x 11 m^3 (2.7 tons of polystyrene);



EM Calorimeter

- ECAL surrounding tracker now needed to determine energy of electrons:
  - No details of what this ECAL should be, but a lead-glass calorimeter or CsI calorimeter would work
  - Similar to LBNE HiRes detector: assume same energy resolution

$$\frac{\Delta E}{E} = \frac{6\%}{\sqrt{E/GeV}}$$



Near Detector Location

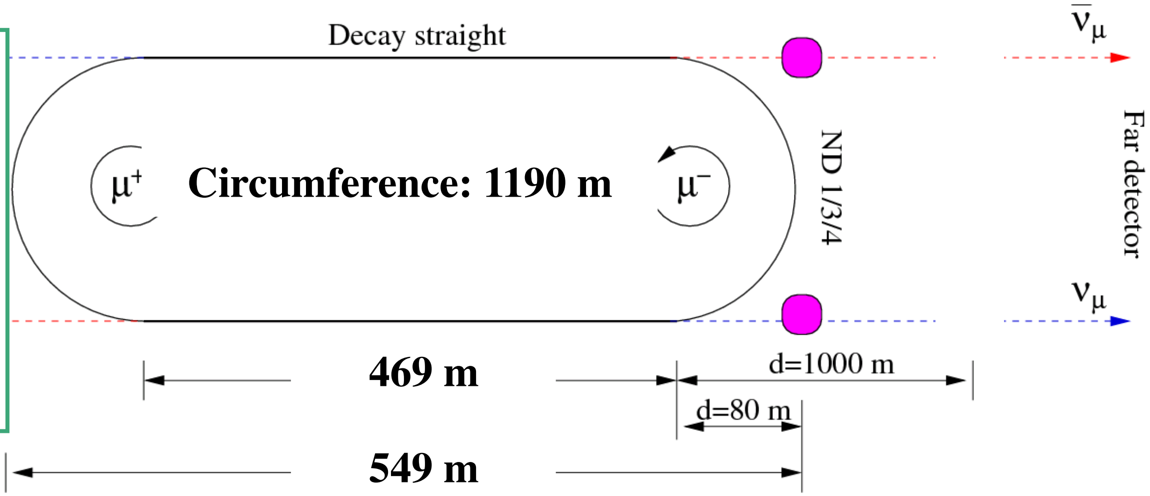
- For Neutrino Factory: one detector per new 10 GeV decay straight: ie. 2 detectors

E_μ = 10 GeV ±35 MeV

Straight section length = 469 m

Muon angular spread 0.5 mrad

5×10^{20} muon decays/per charge/ per year



- Decay straight dip is 10° → two near detectors will be at depth of ~100 m.
- For Beta Beams: one detector at end of straight
- For Super-beam: one detector at end of decay pipe

Method for flux extraction

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

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

  - Elastic neutrino scattering:
    - Neutral Current:

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

    - Interference Charged Current/Neutral Current:

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

- These processes have cross-sections about 10^{-3} of total CC cross-section but can still expect ~10^6 events in a near detector at a neutrino factory

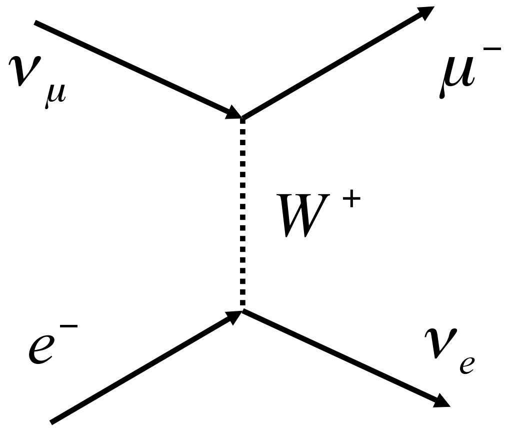
Near Detector Flux

For 25 GeV NuFact ν-e CC quasi-elastic scattering with *single muon in the final state*:

Absolute cross-section calculated with enough confidence (0.1%)

Two processes of interest (available only for neutrinos from ***μ⁻ decays***):

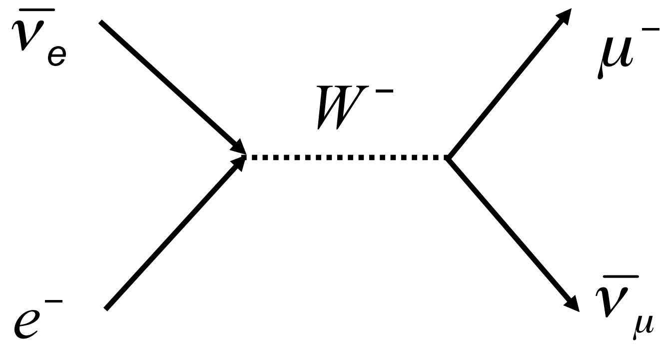
Inverse Muon Decay (IMD)



$$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$$

$$\sigma^{CC}_{\nu_\mu e^-}(E) = \frac{G_F^{\,2}}{\pi}\frac{(s - m_\mu^2)^2}{s}$$

Muon production via annihilation



$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$$

$$\sigma^{CC}_{\bar{\nu}_e e^-}(E) = \frac{G_F^{\,2}}{\pi}\frac{(s - m_\mu^2)^2}{s}\left(E_e E_\mu + \frac{1}{3}E_{\nu_1}E_{\nu_2}\right)$$

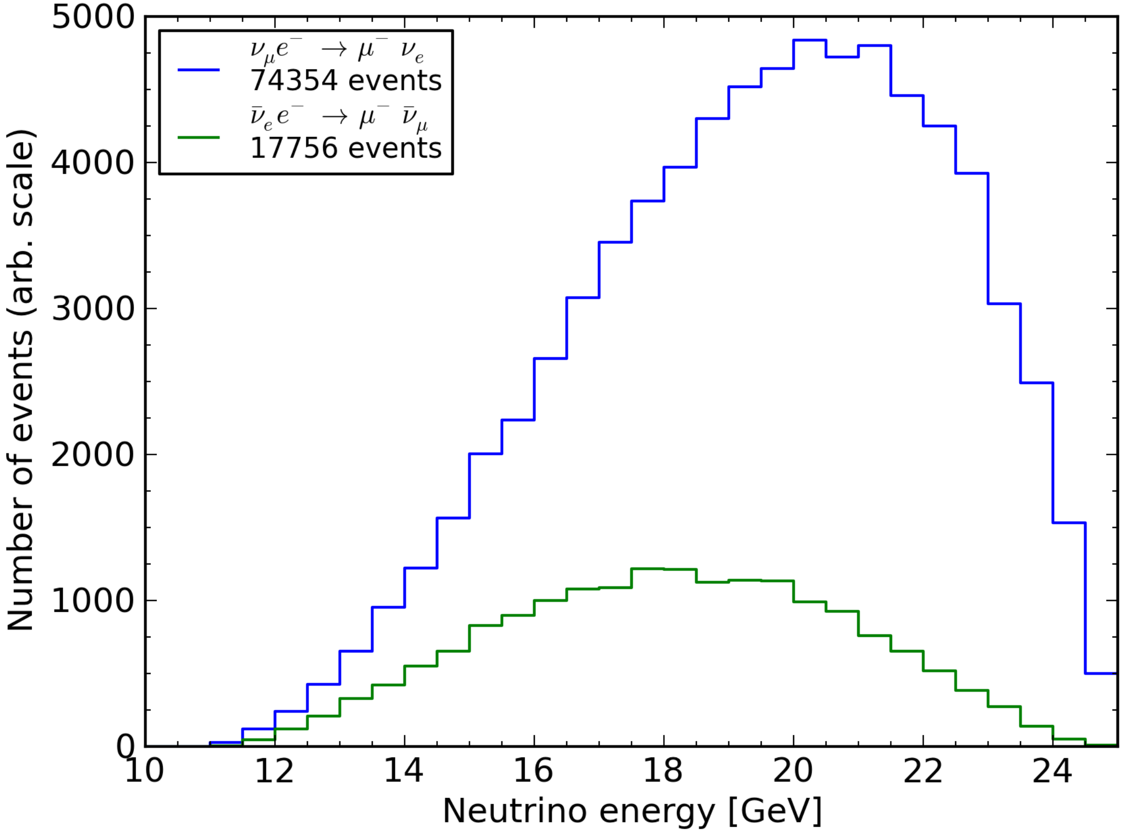
Cross-section ~1.7×10^{-41} E(GeV) cm^2 but threshold E_ν > 11 GeV

Near Detector Flux

Added muon production by annihilation into GENIE, which will be included in GENIE version 2.8.0 – service to community

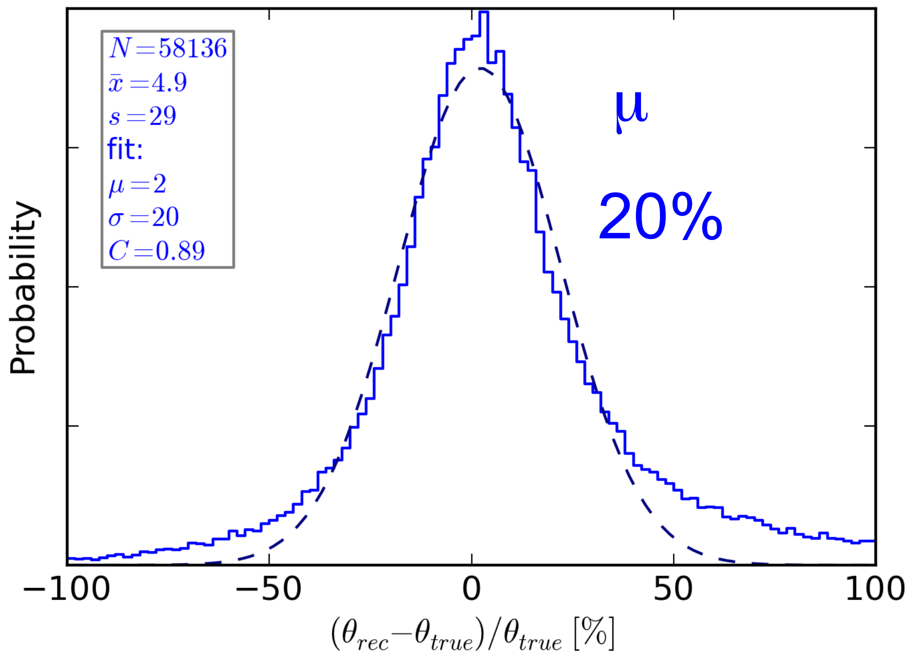
Adds 25% to IMD signal

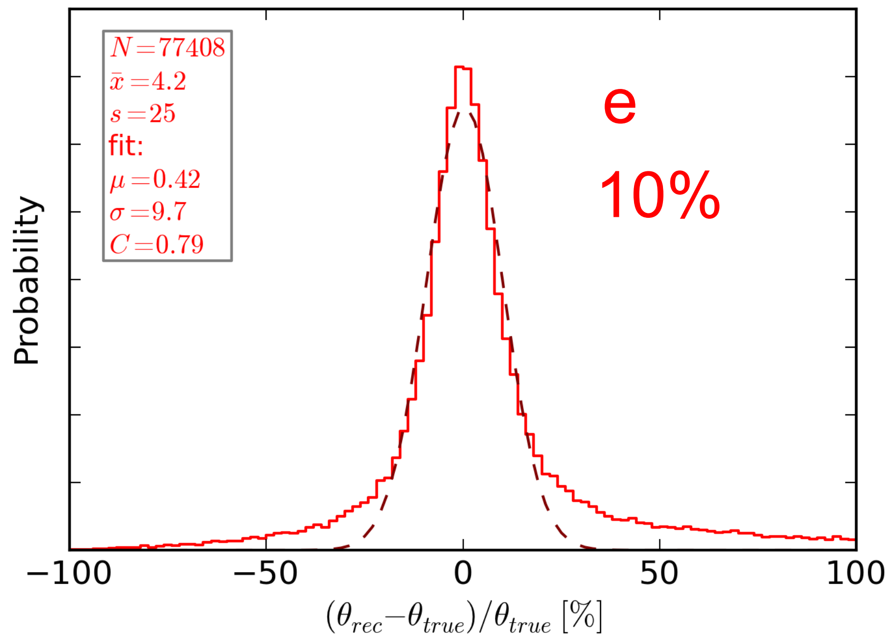
Rosen Matev



Near Detector resolutions

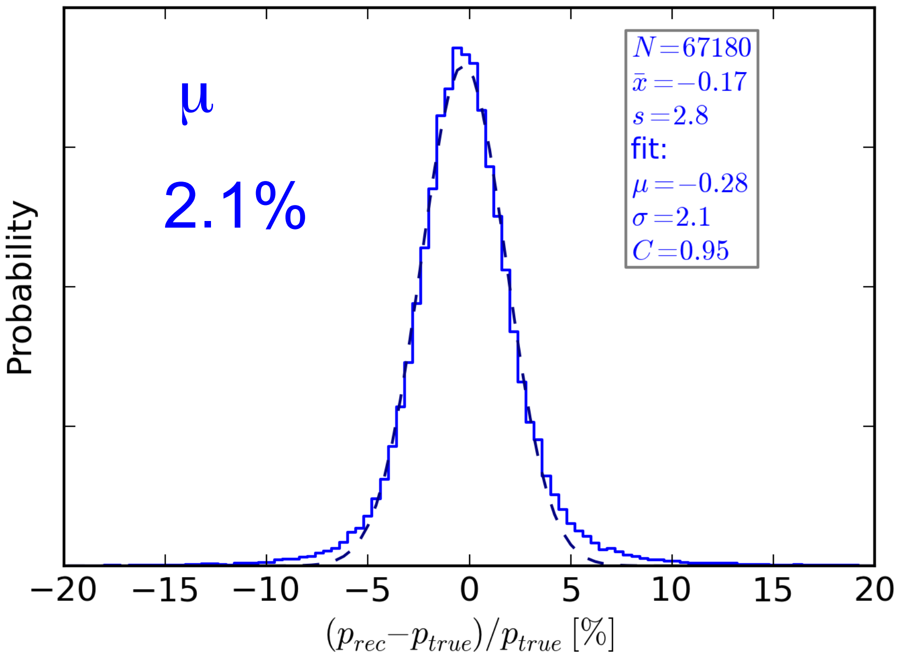
- Angular resolution

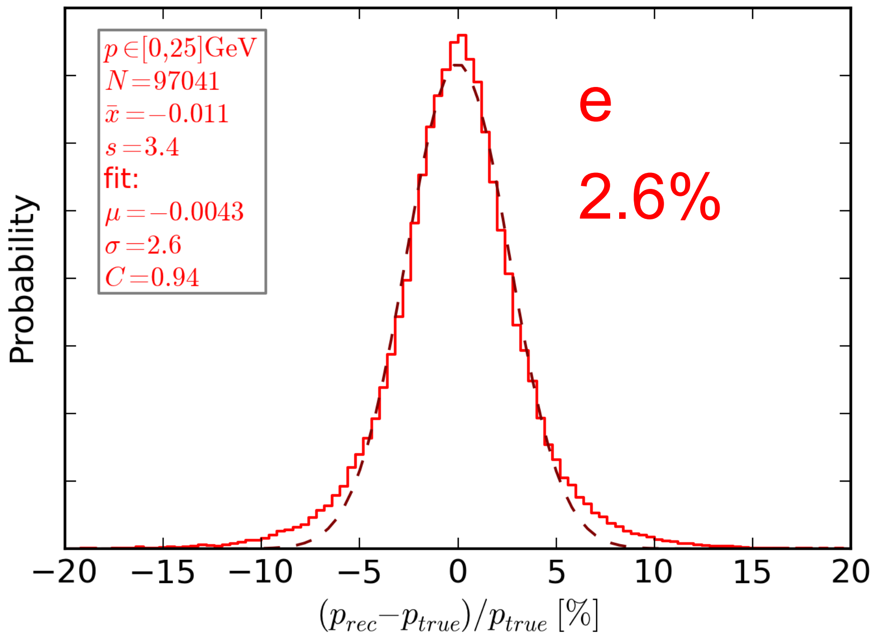




Near Detector resolutions

- Momentum resolution

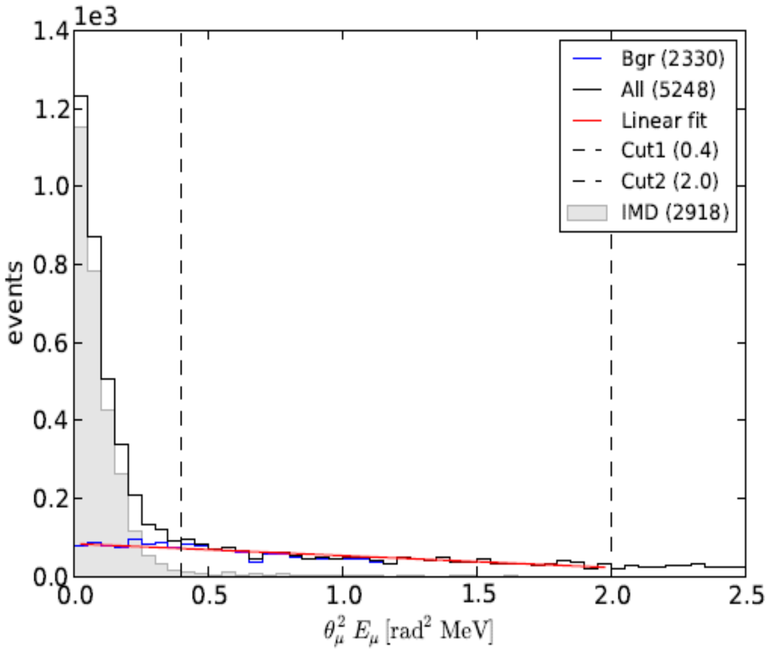


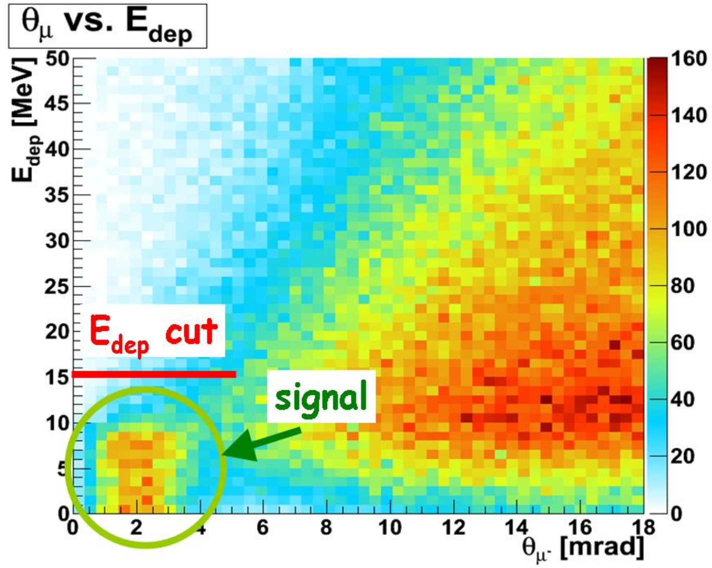


Near Detector IMD events

IMD signal extraction

Use linear extrapolation of event rates in region between cut1 and cut2 to estimate background under the signal peak.

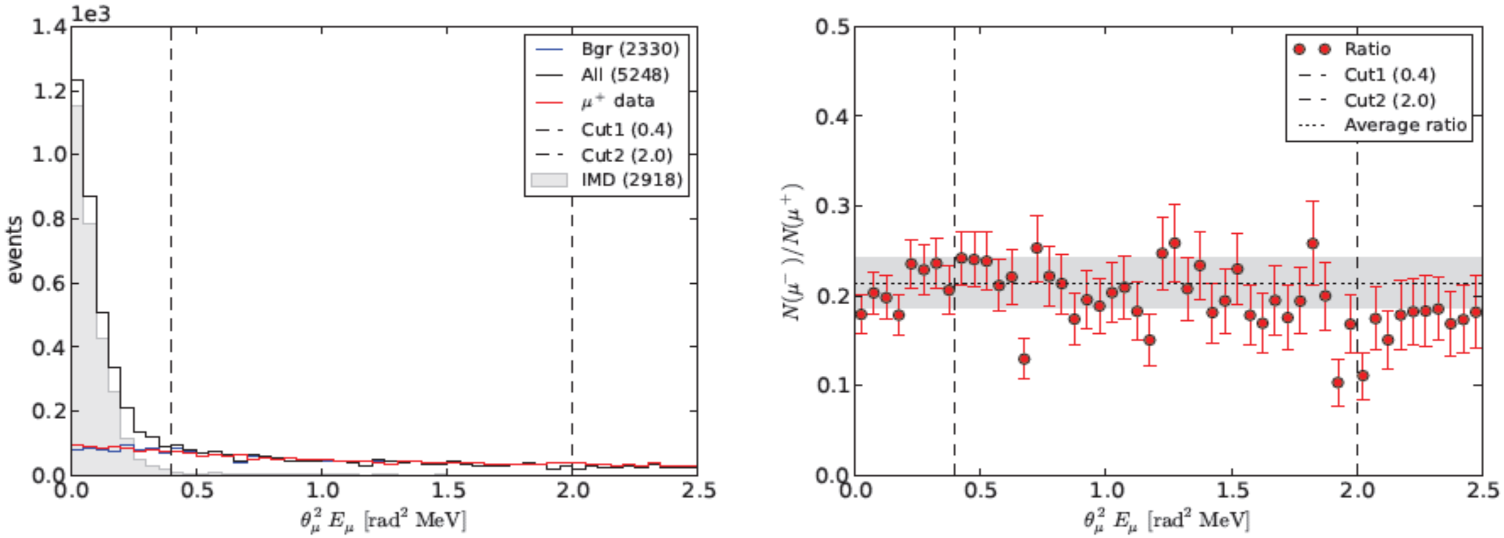




bgrrej&cut eff	overall eff	purity	all events	signal events	signal events from fit	μ decays
86 %	46 %	81 %	3498	2844	2880 ± 59	2.3×10^{19}

IMD background subtraction with anti-ν_μ

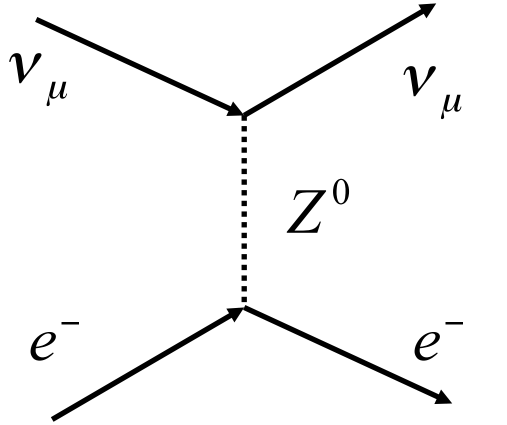
Use μ^+ events to estimate background under the IMD peak. Number of μ^+ events is normalized to μ^- events by the average ratio between cut1 and cut2.

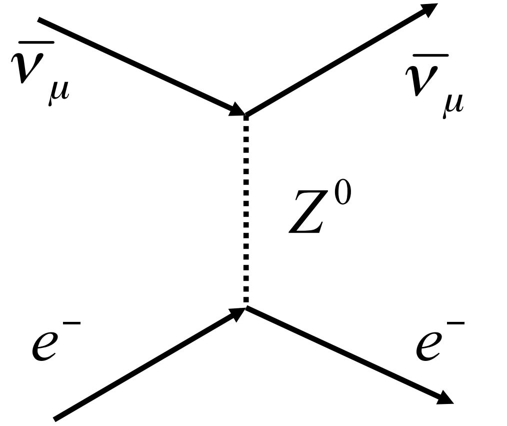


bgrrej&cut eff	overall eff	purity	all events	signal events	signal events from fit	μ decays
86 %	46 %	81 %	3498	2844	2820 ± 60	2.3×10^{19}

Muon-neutrino electron scattering

- Neutral current processes:





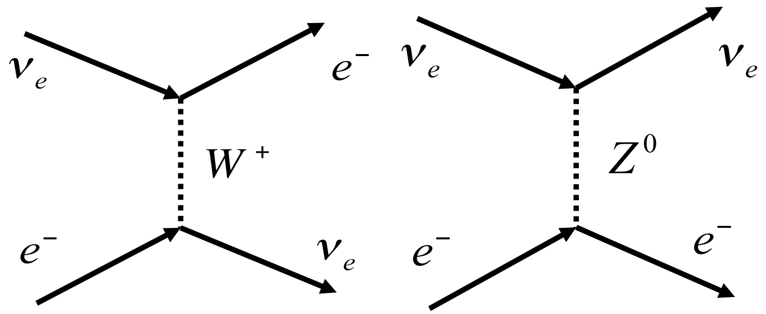
$$\nu_\mu + e^- \rightarrow \nu_\mu + e^- \qquad \bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$

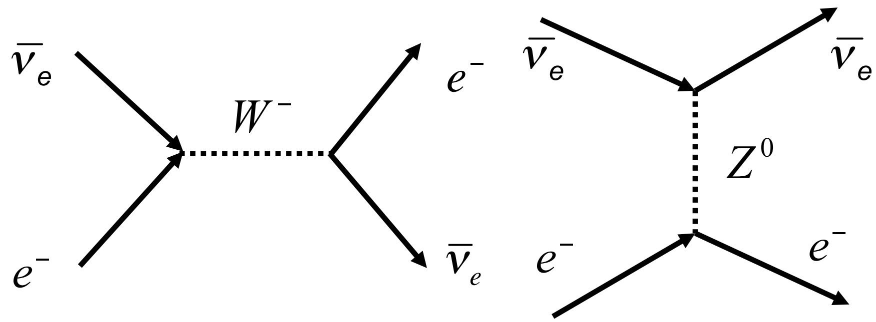
$$\sigma^{NC}_{\nu_\mu e^-}(E) = \frac{G_F{}^2 s}{\pi}\left[\left(-\frac{1}{2}+\sin^2\theta_W\right)^2 + \frac{1}{3}\sin^4\theta_W\right] \qquad \sigma^{NC}_{\bar{\nu}_\mu e^-}(E) = \frac{G_F{}^2 s}{\pi}\left[\frac{1}{3}\left(-\frac{1}{2}+\sin^2\theta_W\right)^2 + \sin^4\theta_W\right]$$

- Cross-section $0.16\mathrm{x}10^{-41}$ E(GeV) and $0.13\mathrm{x}10^{-41}$ E(GeV) cm^2
- Accuracy of cross-section depends on $sin^2\theta_W$

Electron-neutrino electron scattering

- Interference neutral and charged current processes:





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

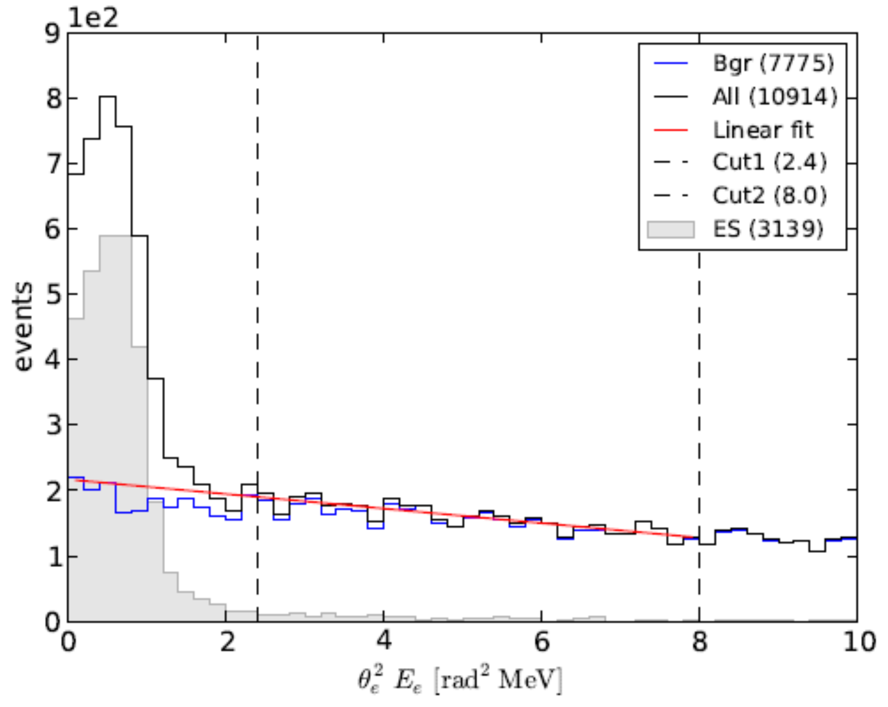
$$\sigma_{\nu_e e^-}^{CC+NC}(E) = \frac{G_F^{\ 2} s}{\pi}\left[\left(\frac{1}{2} + \sin^2\theta_W\right)^2 + \frac{1}{3}\sin^4\theta_W\right] \qquad \sigma_{\bar{\nu}_e e^-}^{CC+NC}(E) = \frac{G_F^{\ 2} s}{\pi}\left[\frac{1}{3}\left(\frac{1}{2} + \sin^2\theta_W\right)^2 + \sin^4\theta_W\right]$$

- Cross-section 0.96×10^{-41} E(GeV) and 0.40×10^{-41} E(GeV) cm^2
- Accuracy of cross-section depends on $sin^2\theta_W$

ν-e elastic scattering

ES signal extraction in μ^- beam

Use linear extrapolation of event rates in region between cut1 and cut2 to estimate background under the signal peak.

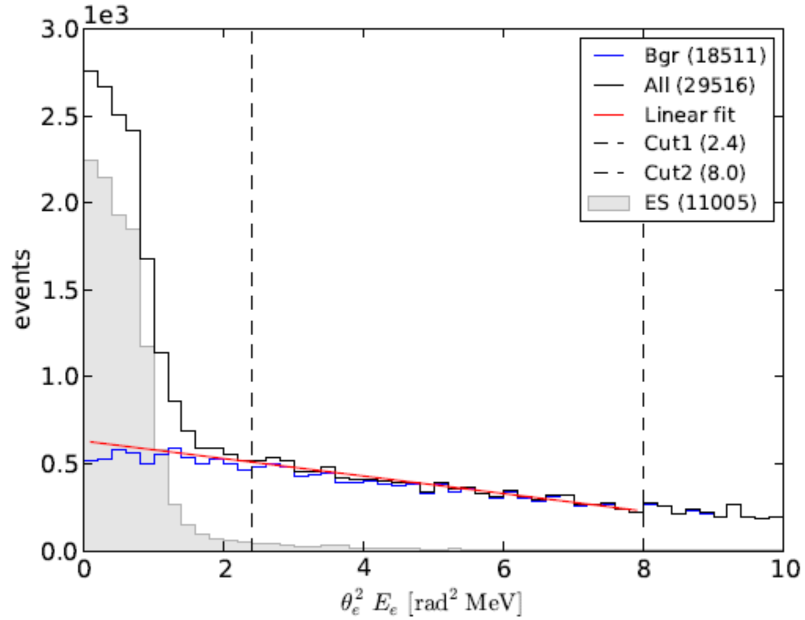


bgrrej&cut eff	overall eff	purity	all events	signal events	signal events from fit	μ decays
47 %	21 %	58 %	5202	2992	2760 ± 72	2.3×10^{19}

ν-e elastic scattering

ES signal extraction in μ^+ beam

Use linear extrapolation of event rates in region between cut1 and cut2 to estimate background under the signal peak.



bgrrej&cut eff	overall eff	purity	all events	signal events	signal events from fit	μ decays
83 %	37 %	63 %	16964	10607	10124 ± 131	2.3×10^{19}

- **With the SciFi tracker we can achieve ~1% uncertainty on the flux normalisation by exploring IMD or ν-e NC elastic scattering.**

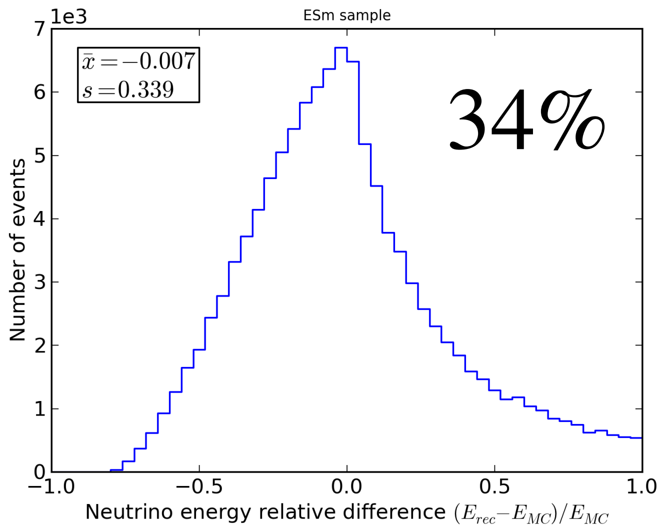
Neutrino energy reconstruction

- Neutrino energy reconstruction:

$$E_\nu = \frac{2E_l m_e - m_l^2 - m_e^2}{2(m_e - E_l + p_l \cos\theta_l')}$$

- If scattering angle is lepton angle

$$\theta_l' = \theta_l$$



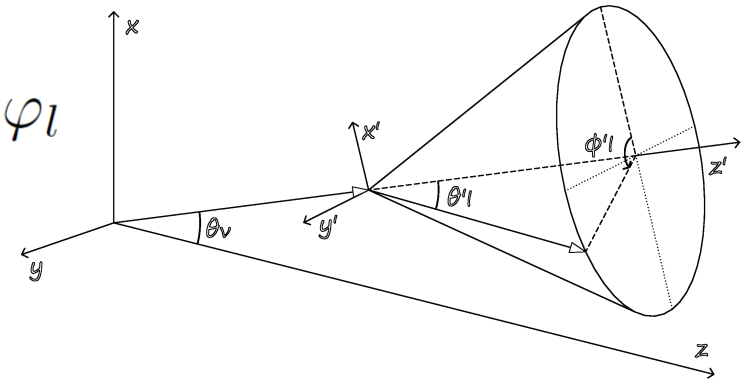
- Since decay position not known, we do not know angle
- Instead, use:

$$\cos\theta_l' = \cos\theta_\nu \cos\theta_l + \sin\theta_\nu \sin\theta_l \cos\varphi_l$$

- Constrain possible values of:

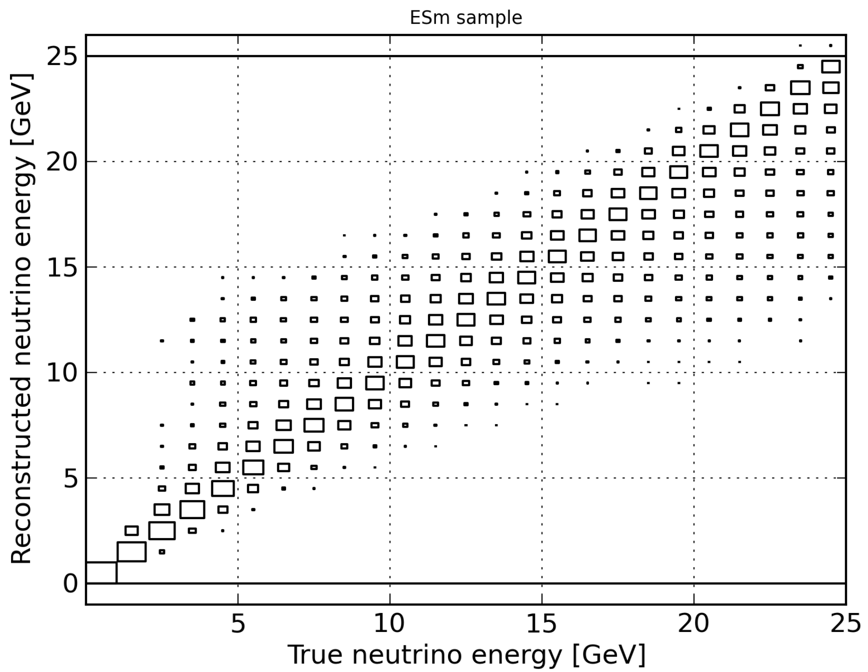
$$E_l,\ \theta_l,\ \varphi_l$$

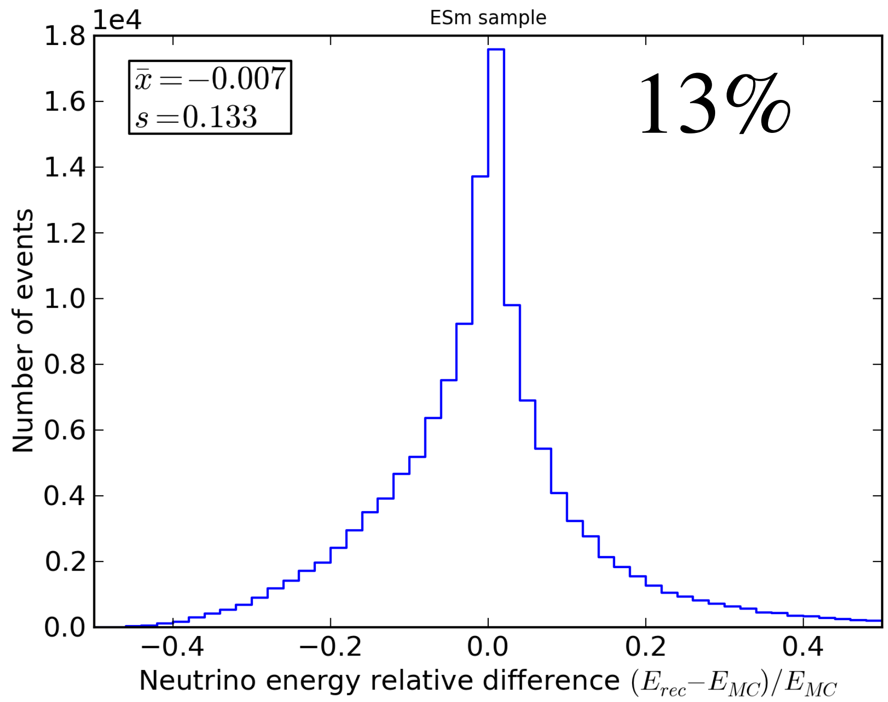
by fitting likelihood function



Neutrino energy reconstruction

- Improved neutrino energy reconstruction:

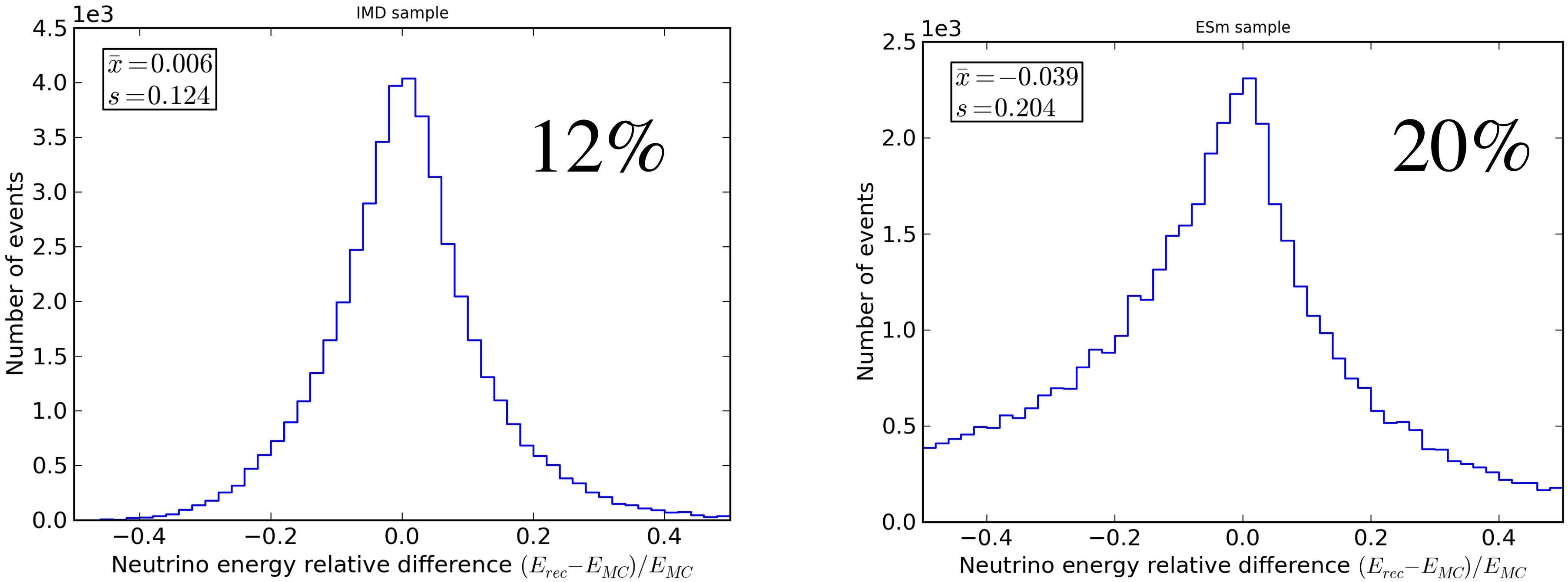




- Neutrino energy reconstruction improves from 34% to 13% with this method

Neutrino energy reconstruction

- Final neutrino energy resolution for IMD and ν-e scattering including reconstructed momentum and angle:



- Allows us to obtain flux as a function of energy

Fluxes from IMD and ν-e scattering

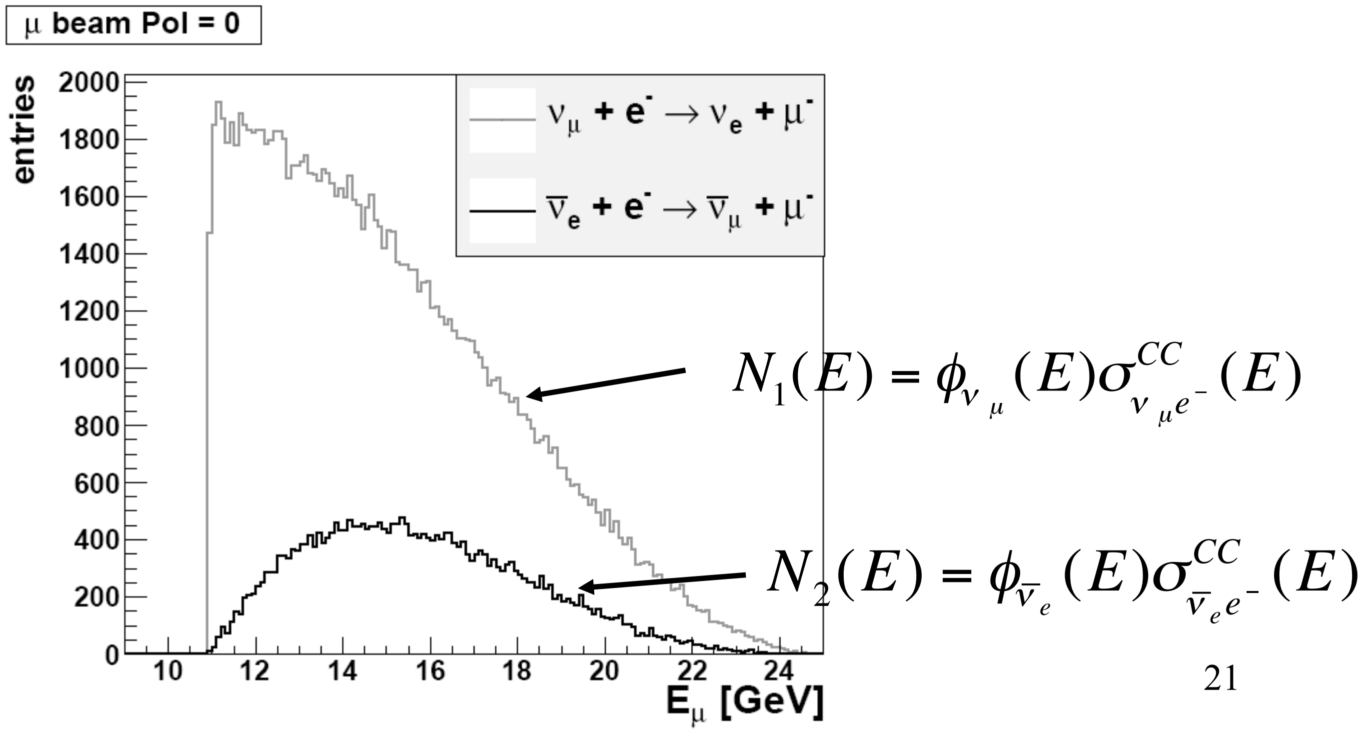
- Charged current processes:

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

- We cannot distinguish between the two channels so we measure $N_1(E) + N_2(E)$:

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

Can only be used for 25 GeV NF above 11 GeV for μ^- channel



Neutrino electron scattering

- Neutral current processes:

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

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

- Interference neutral and charged current processes:

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

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

- We can distinguish between each channel by the sign of the muon decay that produces each of the neutrinos.

Combination of all channels

- So, if we consider the IMD and neutrino elastic scattering channels together we obtain:
  - For the NF decay above 11 GeV: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

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

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

  - 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 since we only have N_3+N_6

Combination of all channels

- For a 10 GeV neutrino factory we do not have IMD, so we can only rely on the ν-e channels:
  - For the NF decay: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

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

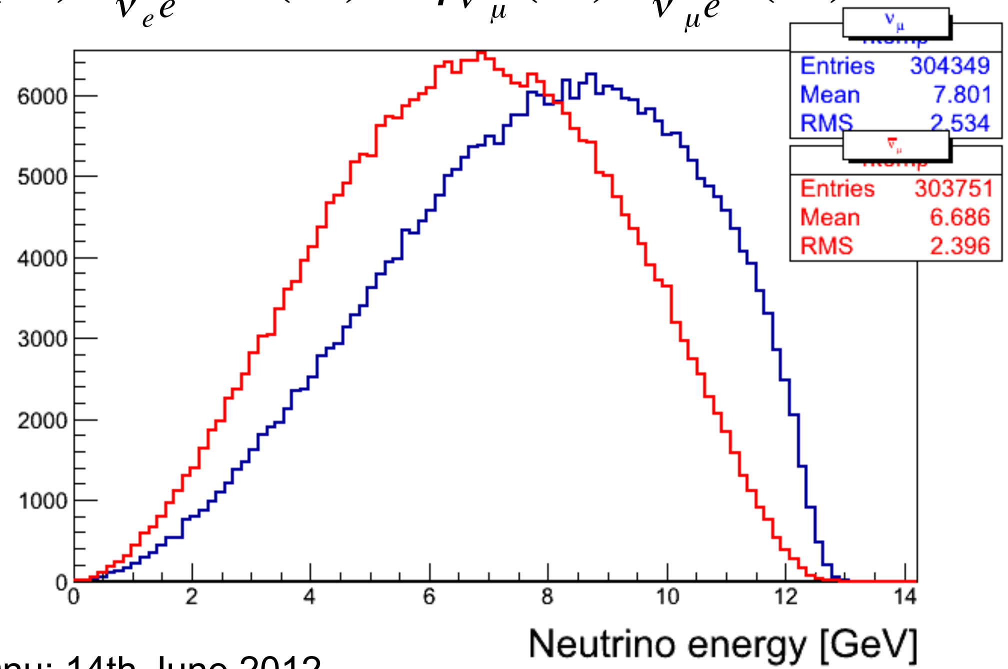
  - For the NF decay: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

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

- We cannot resolve fluxes unambiguously, but we can fit for shape of spectrum with the constraints that:

$$\sum_E \phi_{\nu_e}(E) = \sum_E \phi_{\bar{\nu}_\mu}(E)$$

$$\sum_E \phi_{\nu_\mu}(E) = \sum_E \phi_{\bar{\nu}_e}(E)$$



Flux extrapolation method

- Extrapolation near-to-far at Neutrino Factory:
  - We extract P_{osc} by fitting this formula:

Andrew Laing

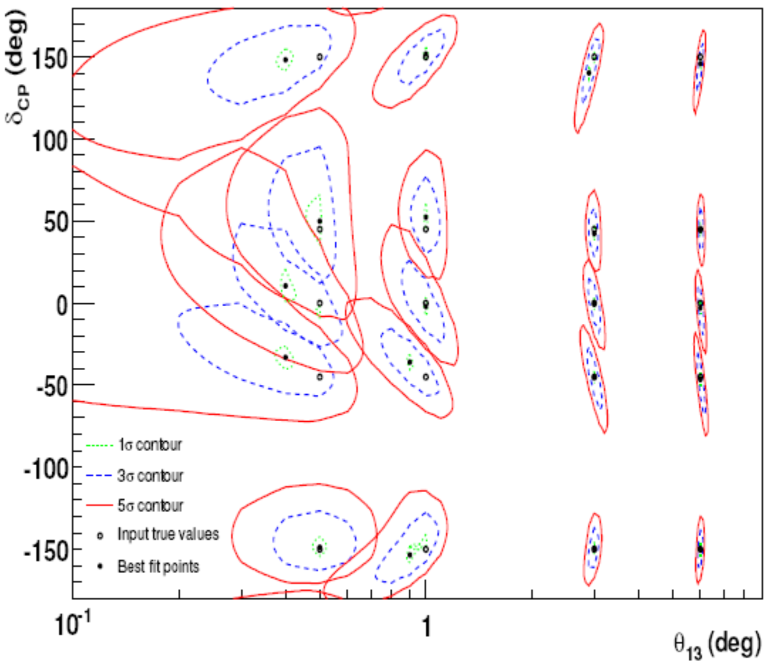
$$N_{FD} = M_{FD} P_{osc}(\theta_{13}, \delta_{CP}) M_{nOsc} M_{ND}^{-1} N_{ND}$$

  - 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: fits converge for all values of θ_{13} and δ_{CP}

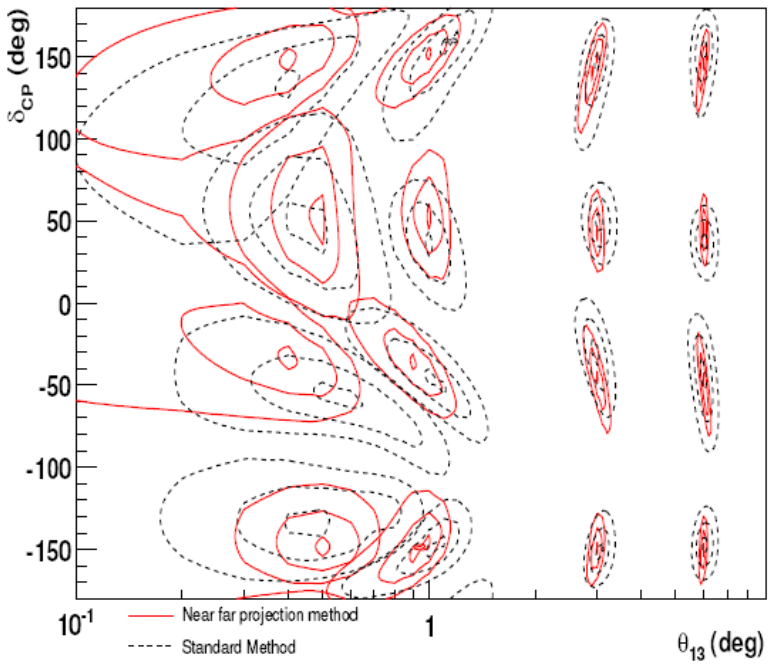
Flux extrapolation results

- 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

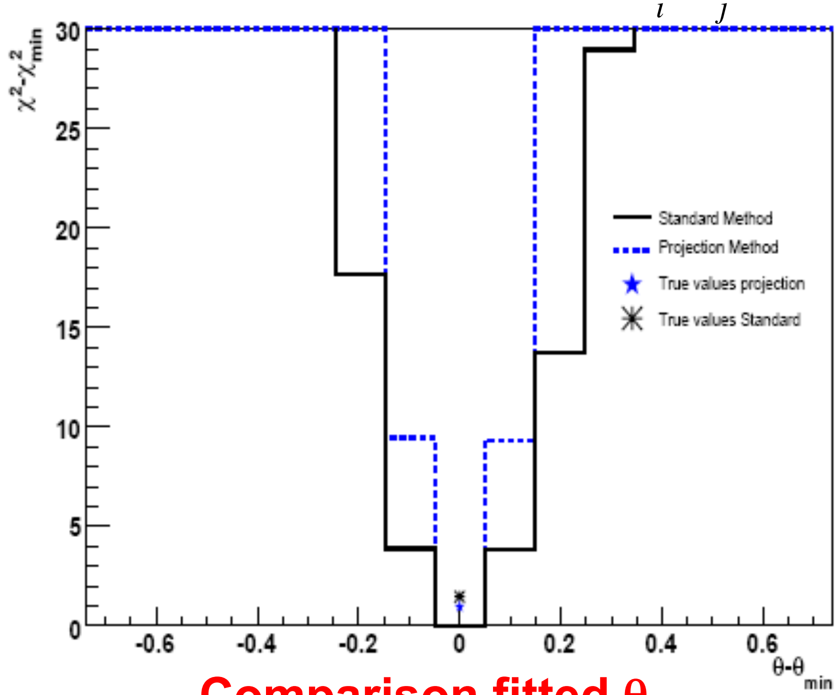


Fits assuming standard flux error 1%

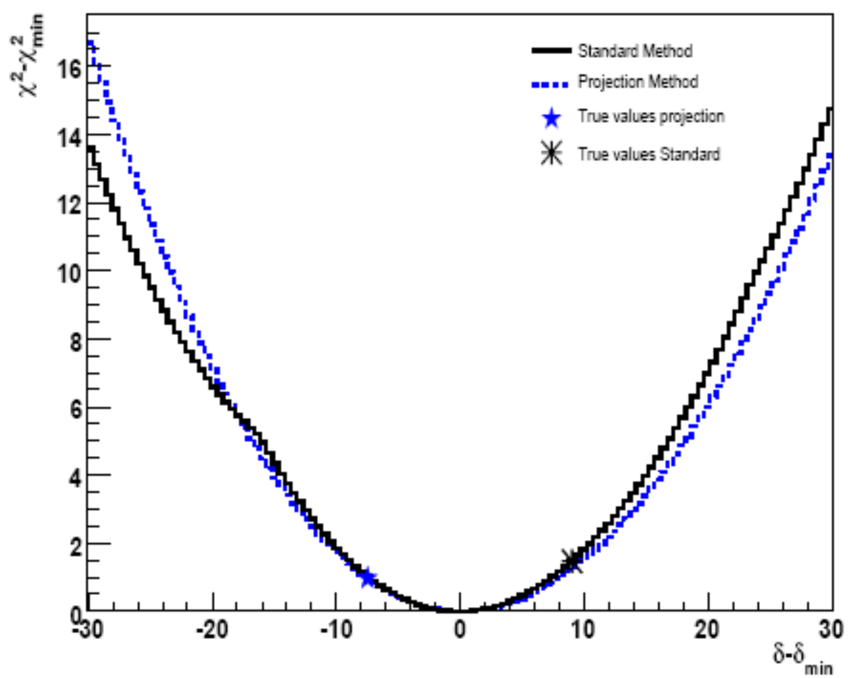
Flux extrapolation results

- Extrapolation near-to-far at Neutrino Factory:
  - 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

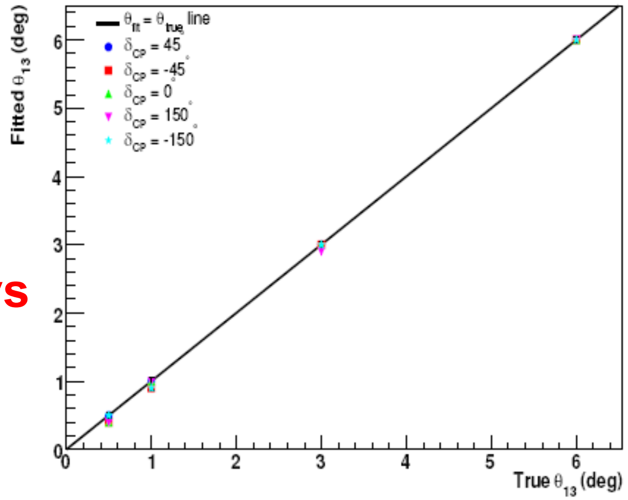


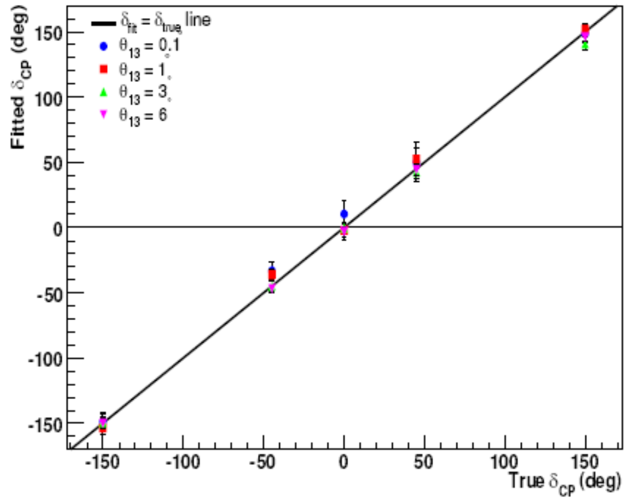
Fit improves at 3σ level

Flux extrapolation results

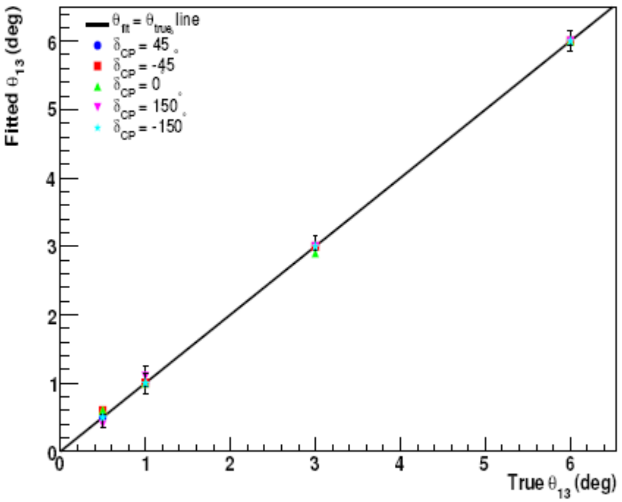
- Fitted vs true values of θ_{13} and δ_{CP}: no observed biases

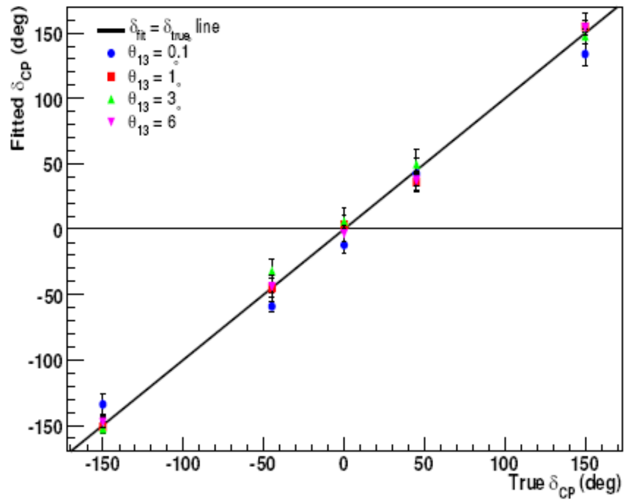
Fitted θ_{13} vs true value





Fitted δ_{CP} vs true value





Conclusions

- Method for extracting neutrino fluxes at NF relies on using channels in which cross-sections are known very well theoretically
- Channels identified include:
  - Inverse Muon Decay
  - Muon-neutrino electron elastic scattering
  - Electron-neutrino electron elastic scattering
- Combination of IMD+neutrino elastic scattering works very well for μ^- decay above IMD threshold (11 GeV)
- For 10 GeV NF we need to fit combination of μ^+ and μ^- decay and rely on fitting the shapes of spectra
- Extrapolation to far detector from near detector can be performed in an unbiased way with "matrix method"