THE INTERNATIONAL DESIGN STUDY FOR THE NEUTRINO FACTORY

Neutrino Factory Detectors

NEU2012 Meeting,
CNRS, Paris

Paul Soler, 10 May 2011

University of Glasgow

Baseline for a Neutrino Factory: MIND

- Golden channel signature: appearance of “wrong-sign” muons in magnetised iron calorimeter

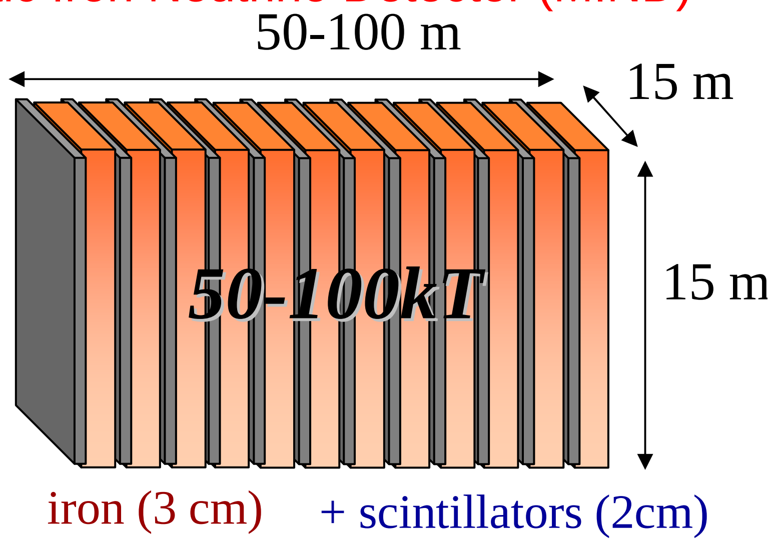
Magnetic Iron Neutrino Detector (MIND)

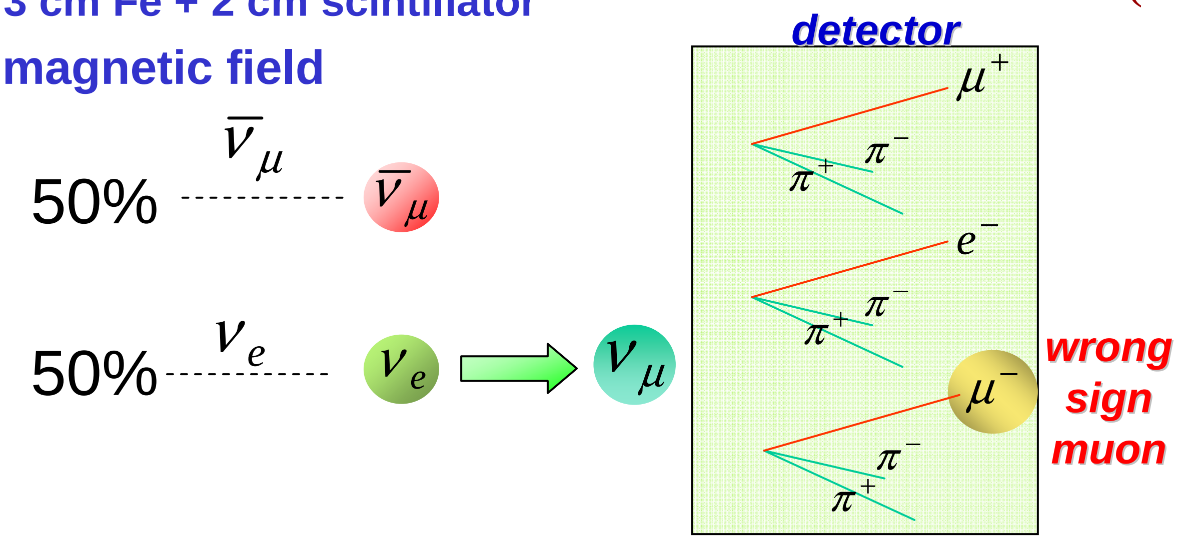
IDS-NF baseline for 25 GeV NuFact:

- **Two far detectors:**
  - **2500-5000 km baseline: 100 kton**
  - **7000-8000 km (magic) baseline: 50 kton**
- **Appearance of “wrong-sign” muons**
- **Segmentation:**
  - **3 cm Fe + 2 cm scintillator**
- **1 T magnetic field**

ν beam

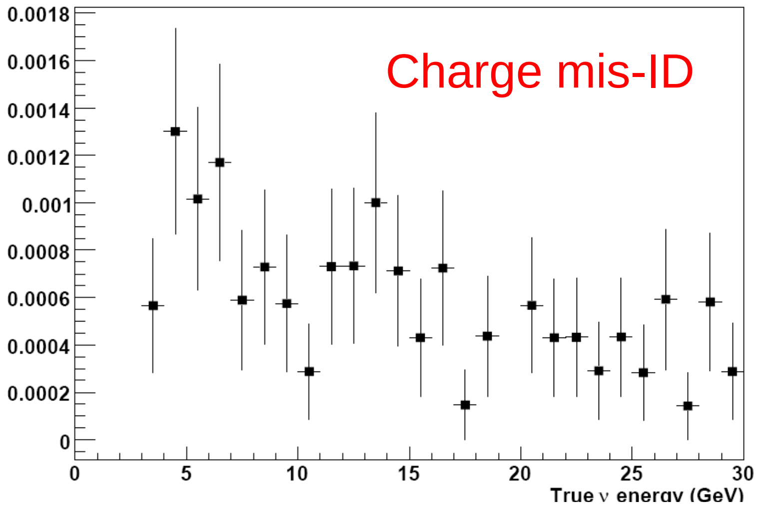
B=1 T

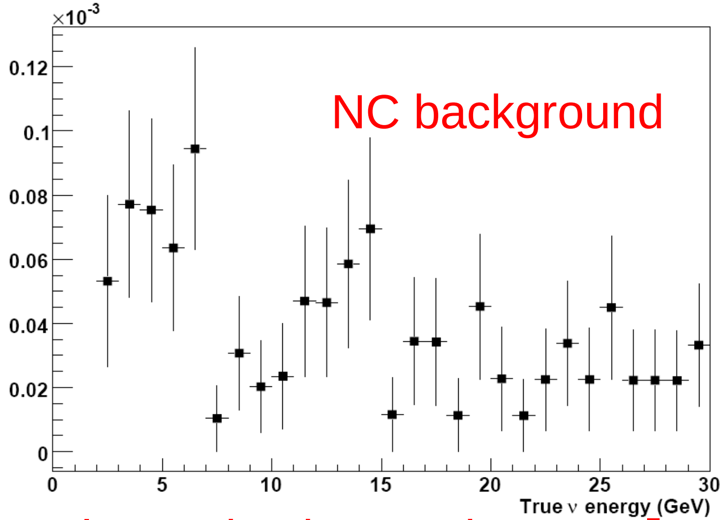




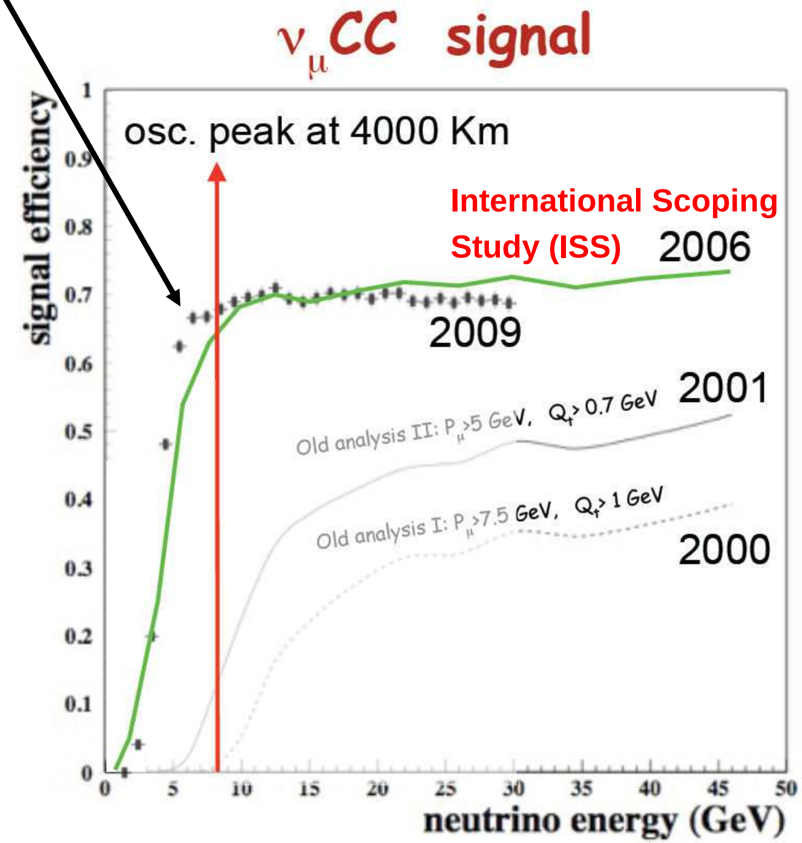
History of Wrong-Sign Muon Analysis

- Latest GEANT3 analysis (2009): **NIMA 624, (2010) 601 (arXiV:1004.0358)**
  - New feature – full reconstruction for the first time





Also: ν_e background ~ $4x10^{-5}$

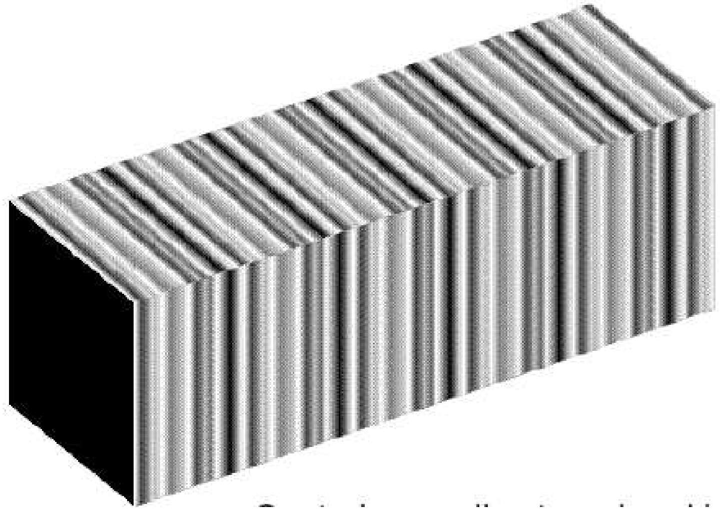


Other important output: full response (migration) matrices for signal and background: sensitivity and systematic studies

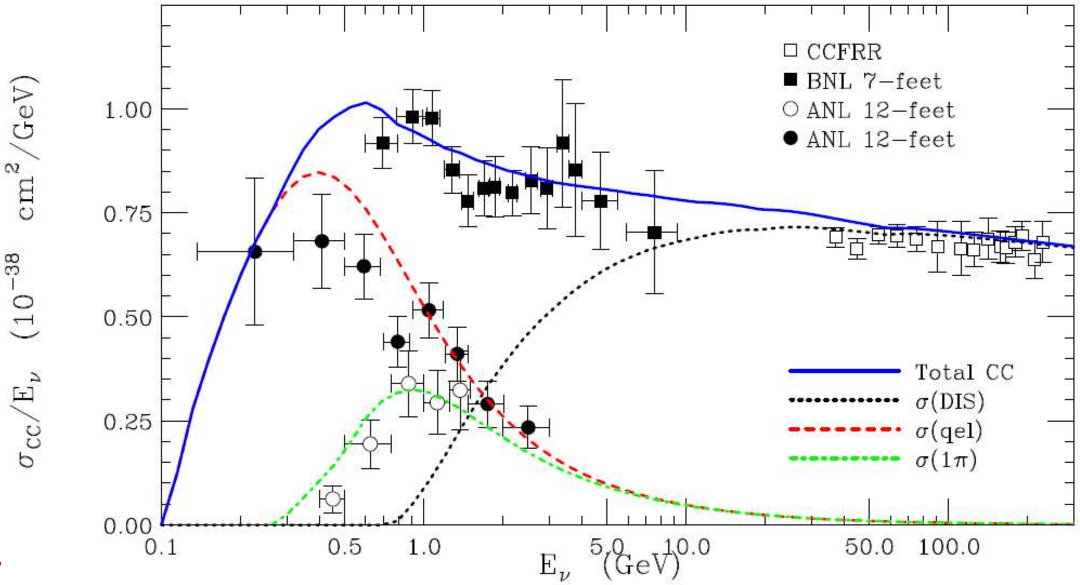
MIND: new GEANT4 analysis

- Improvements MIND analysis with full GEANT4 simulation
  - **A. Laing, PhD thesis, University of Glasgow**
- Add quasi-elastics and resonance production (NUANCE)
- Non DIS processes dominant at low energies
- Should improve low energy efficiency
- Published in IDS-NF Interim design Report

Results to be shown use 3 cm of iron and one 2 cm thick polystyrene plane.



Zeller: hep-ex/0312061

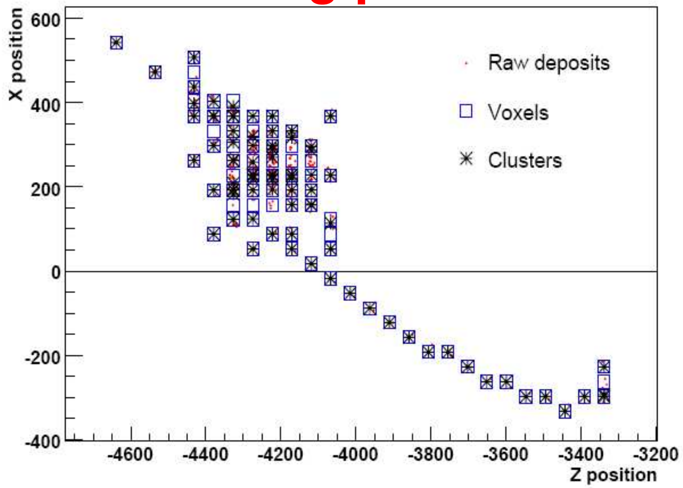


Benchmark of NUANCE with data

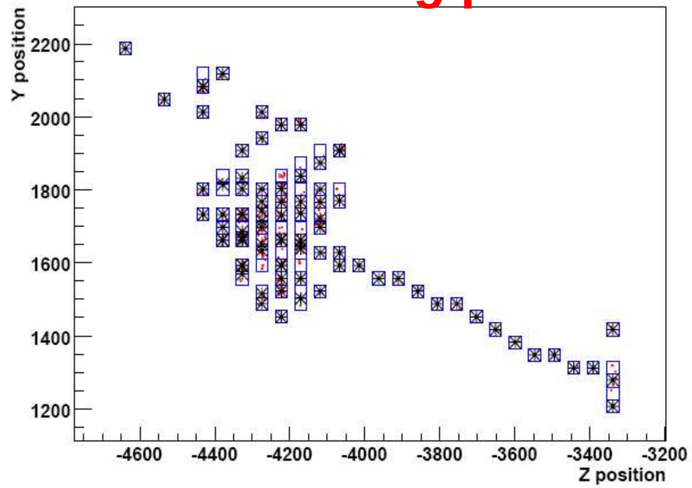
MIND: neutrino event generation

- Energy smearing with hadronic energy resolution: $\frac{\delta E_{had}}{E_{had}} = \frac{0.55}{\sqrt{E_{had}}} + 0.03$
- Digitisation and clustering with ~1cm spatial resolution $\delta\theta = \frac{10.4}{\sqrt{E_{had}}} + 10.1$

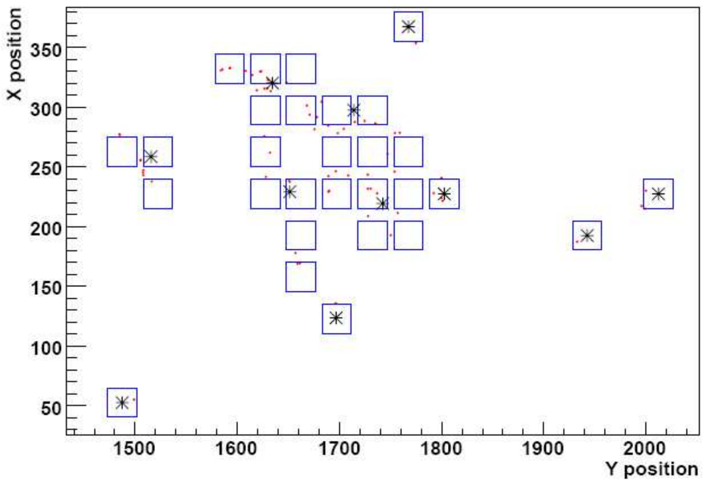
Bending plane



Non-bending plane



Front x-y view

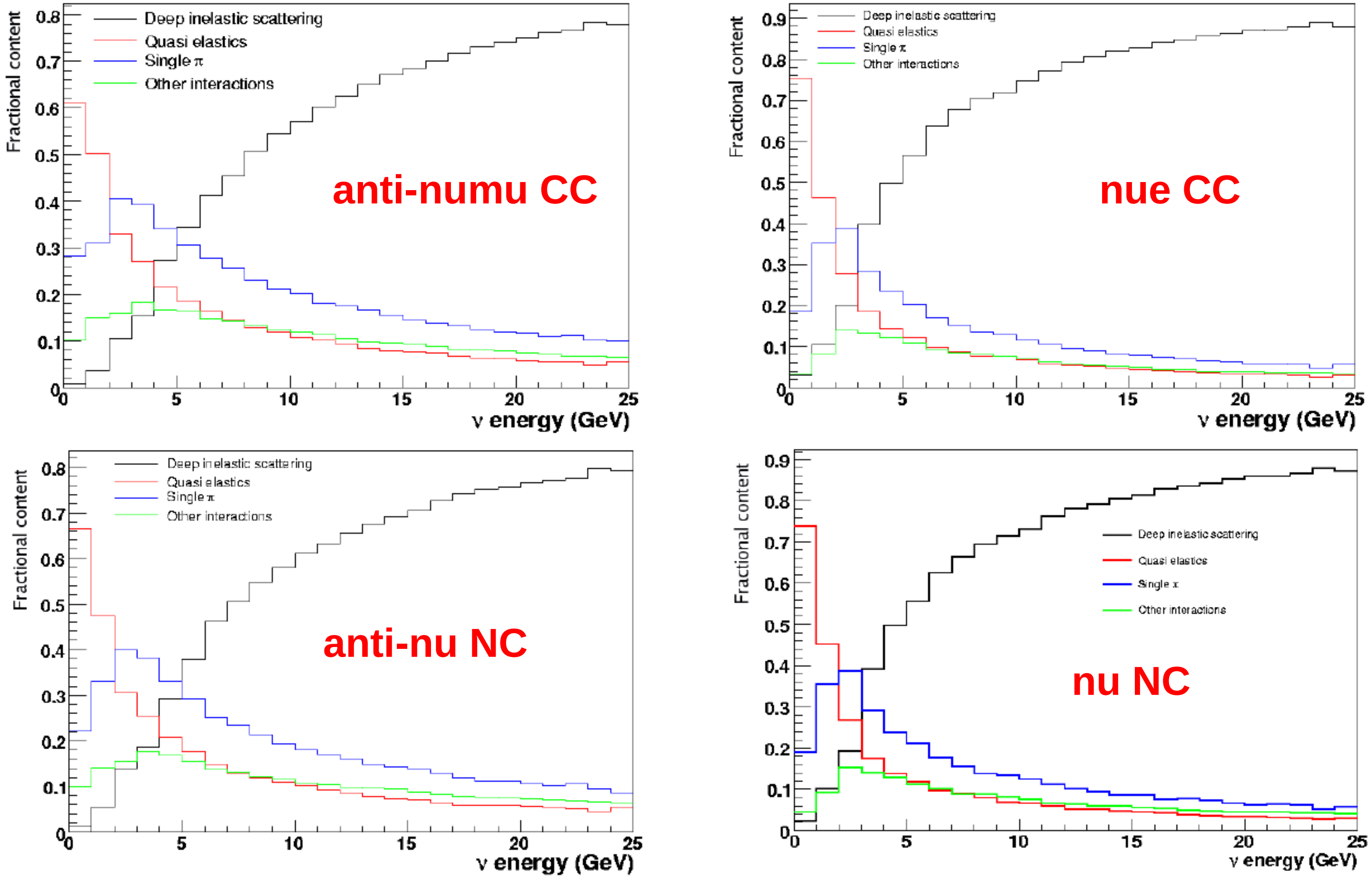


Expected neutrino event rates in MIND

Event rates 100 kton MIND at 4000 km (for 10^{21} μ decays)

$\sin^2 2\theta_{13}$	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_\mu + \nu_e$ NC	ν_μ signal
4×10^{-2}	2.5×10^5	7.0×10^5	3.1×10^5	1.2×10^4
5×10^{-5}	2.5×10^5	7.2×10^5	3.2×10^5	2.2×10^2

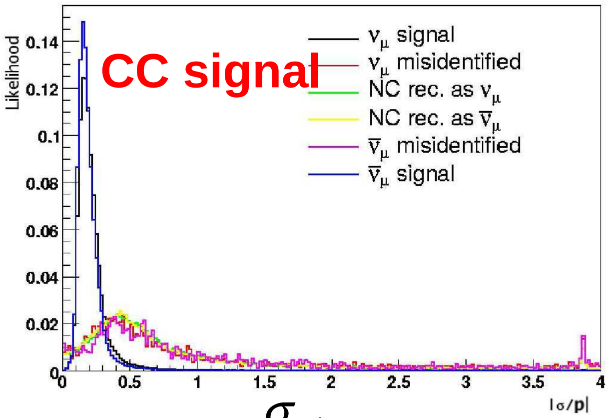
Need 10^{-4} bkg suppression

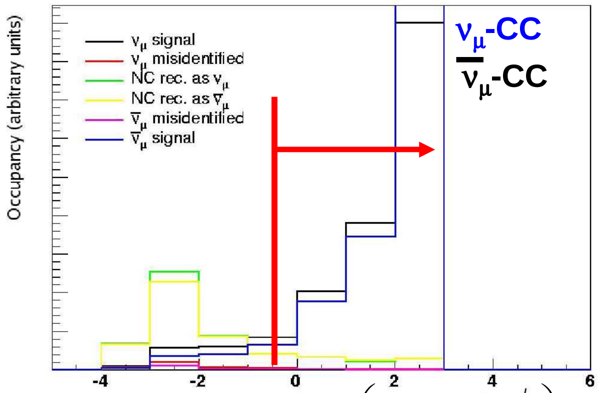


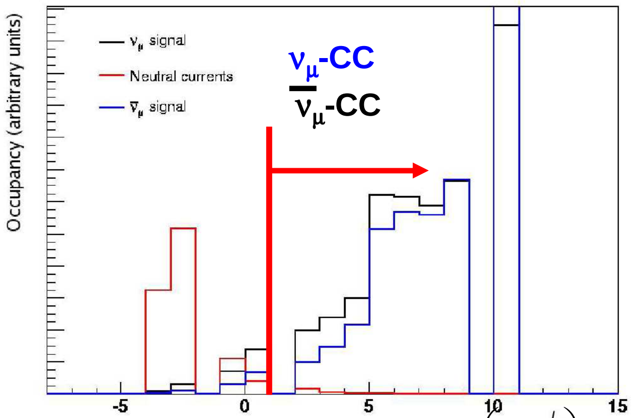
MIND: likelihood analysis

- Curvature error (CC rejection) and NC rejection

Num hits > 150

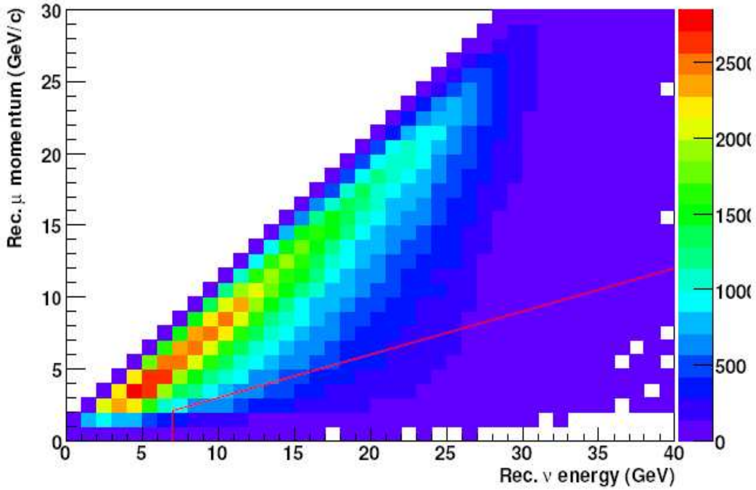


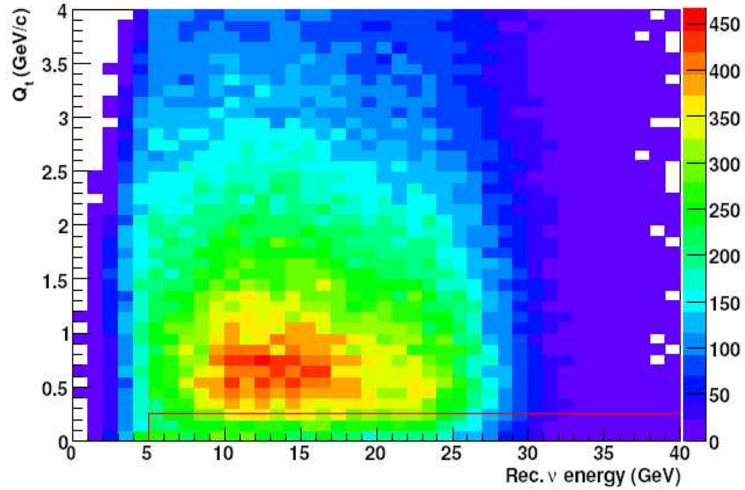




$$\frac{\sigma_{q/p}}{q/p} \text{ log likelihood} > -0.5 \qquad \mathcal{L}_{q/p} = \log\left(\frac{\ell_{q/p-correct}}{\ell_{q/p-incorrect}}\right) \qquad \mathcal{L}_1 = \log\left(\frac{\ell_{1CC}}{\ell_{1NC}}\right)$$

- Kinematic cuts: Neutrino energy ($E_\nu = E_\mu + E_{had}$) vs $Q_t = P_\mu \sin^2\theta_{had}$



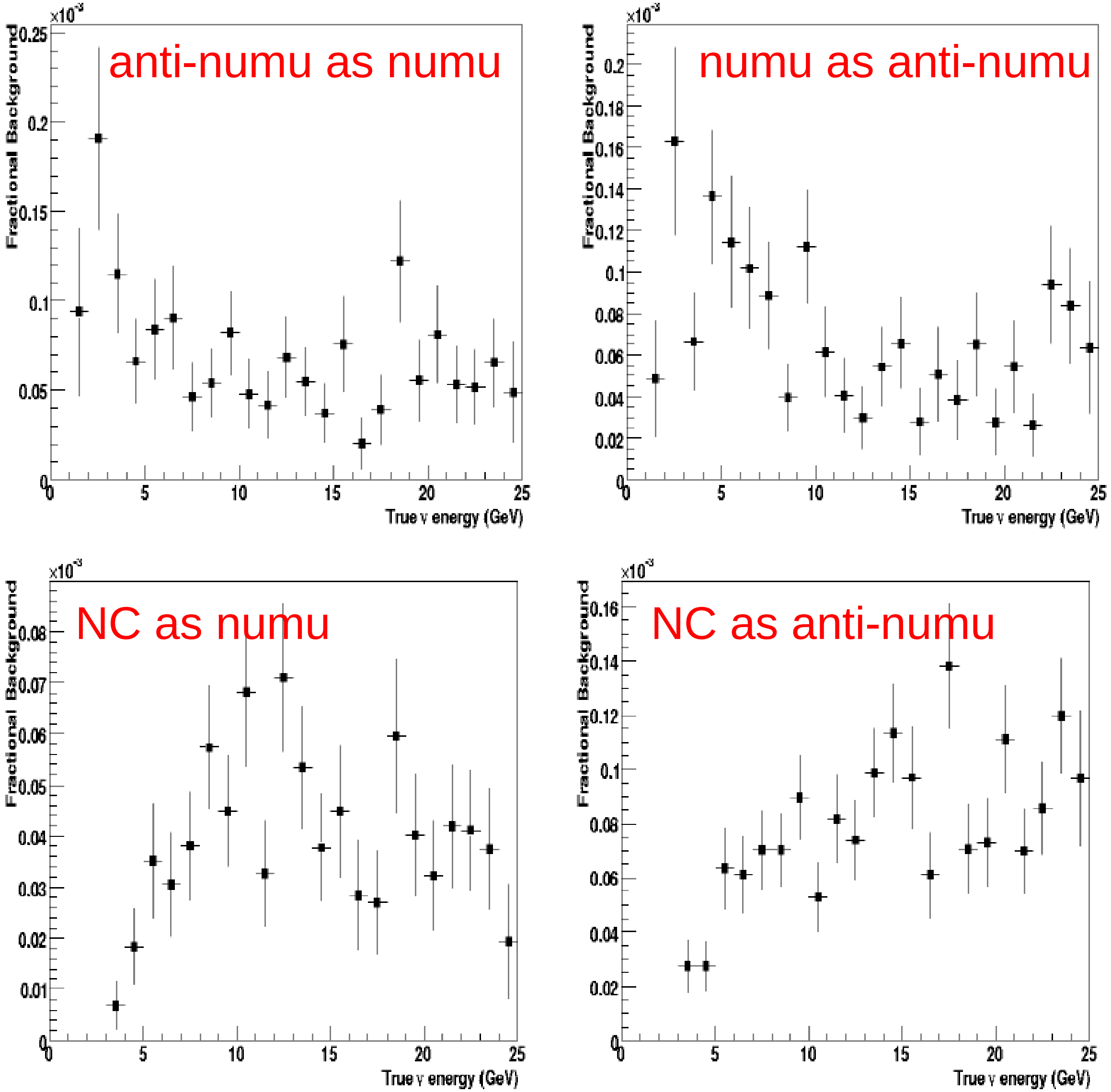


MIND: CC and NC background

- New analysis with Nuance and GEANT4:

CC background

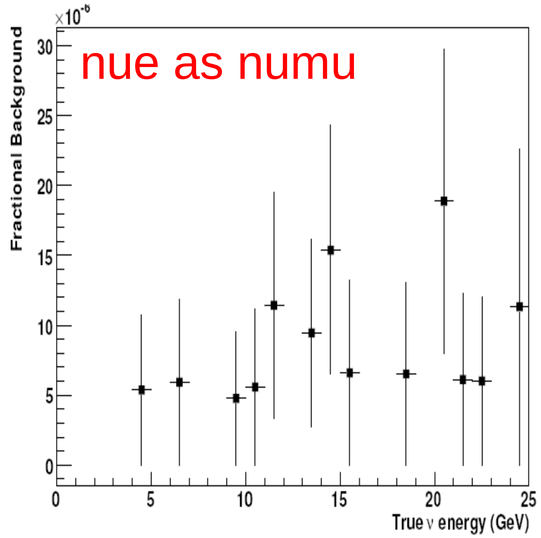
NC background

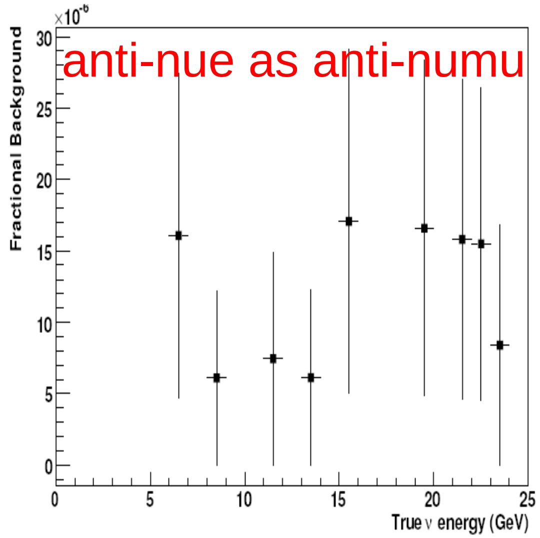


MIND: ν_e background and signal

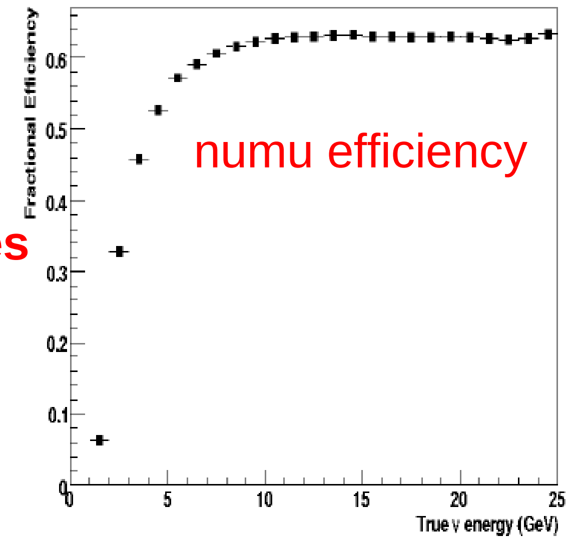
- New analysis with Nuance and GEANT4:

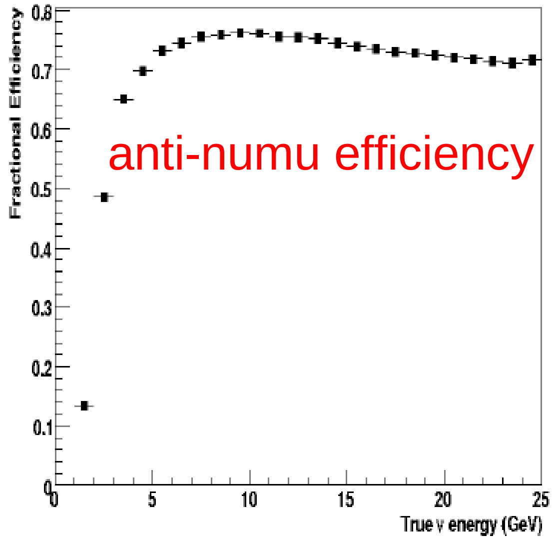
nue background





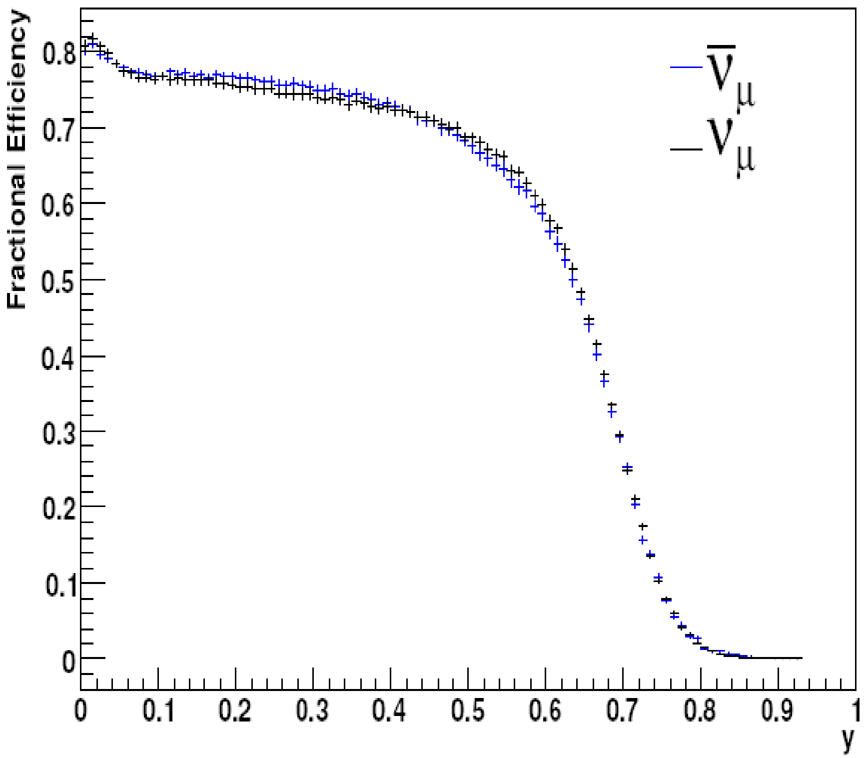
Signal efficiencies

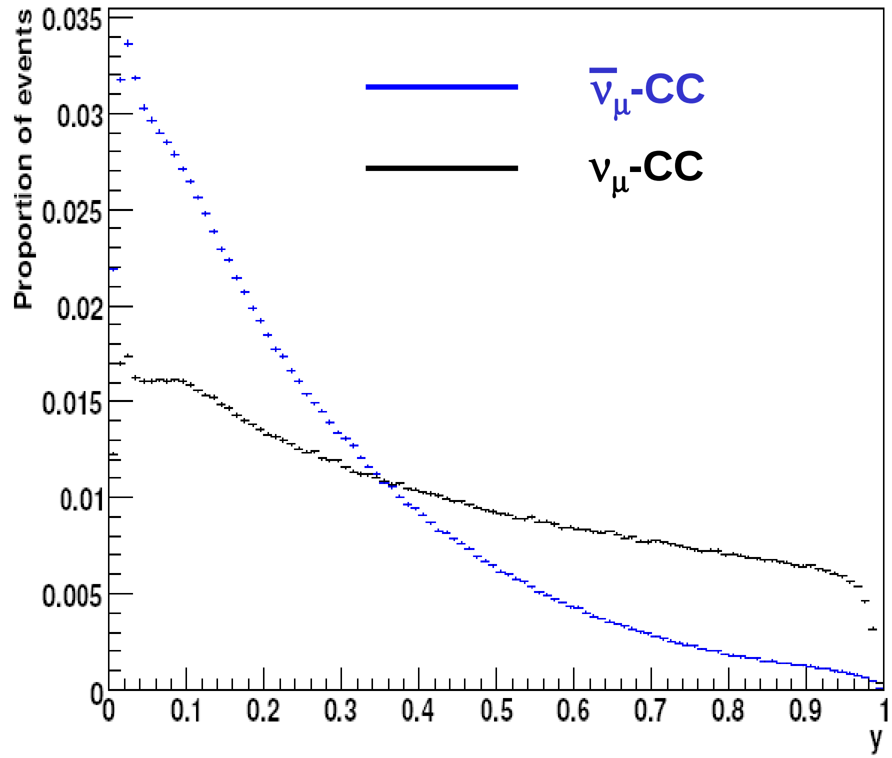




MIND: signal efficiency

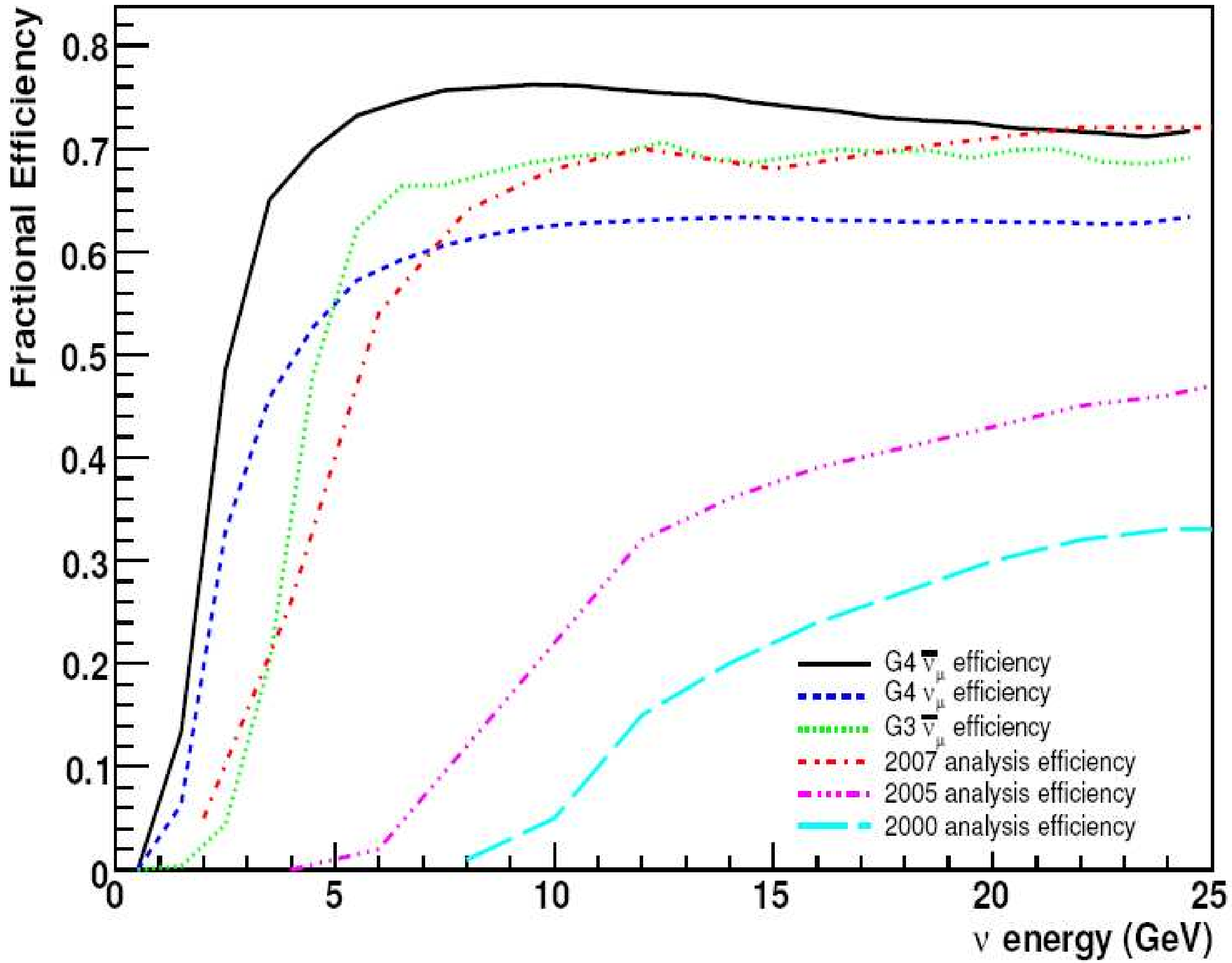
- Difference in numu and anti-numu efficiencies: effectively only because of Bjorken *y* distribution (inelasticity) of neutrinos and antineutrinos





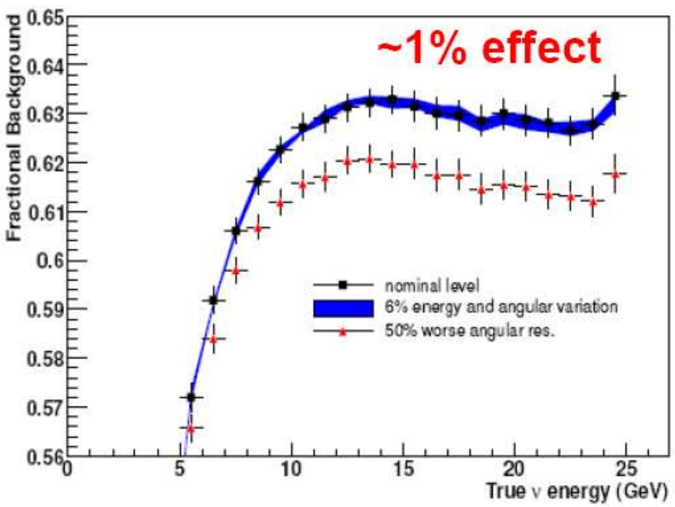
MIND: signal efficiency

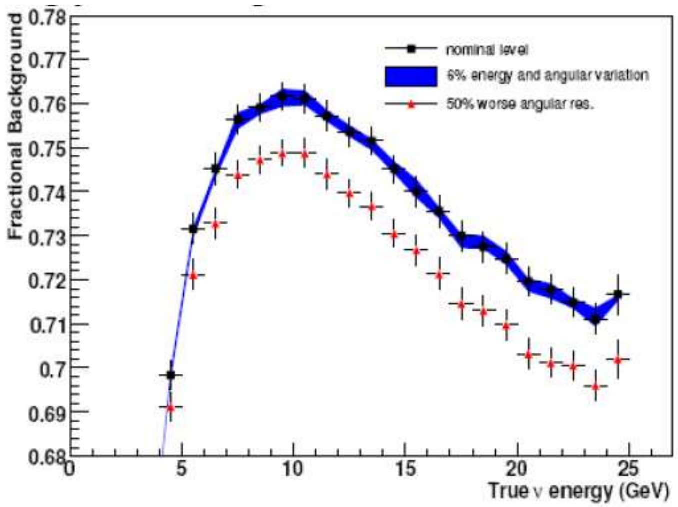
- New analysis with Nuance and GEANT4: better efficiencies at low energies, due to addition of QES and RES events



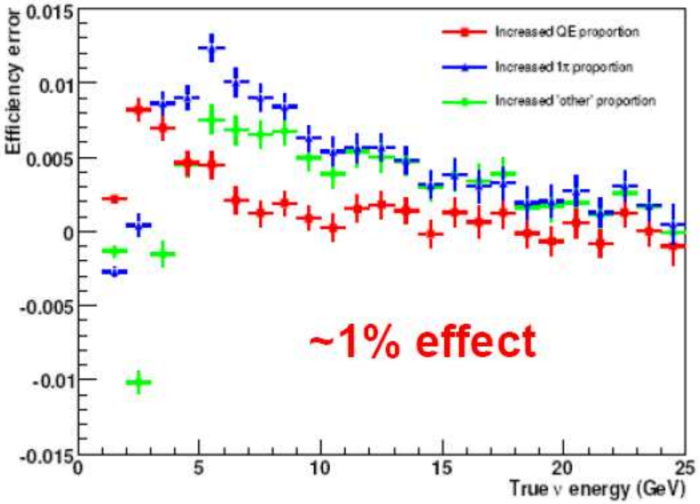
MIND: systematic errors

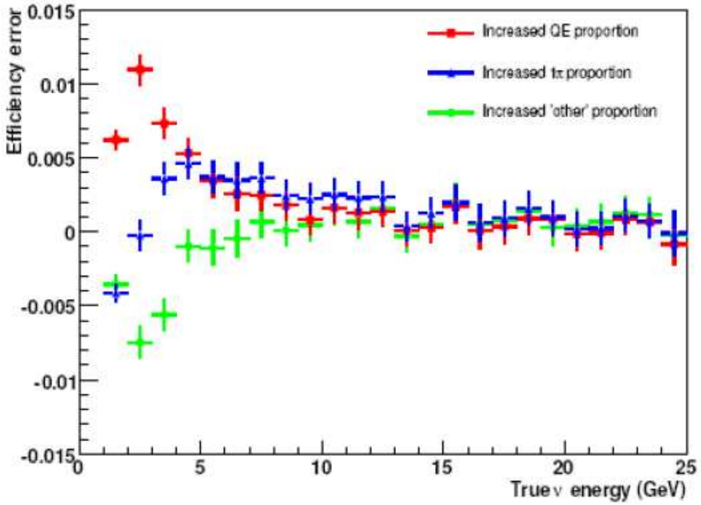
- Systematic errors: hadronic energy & angular resolution





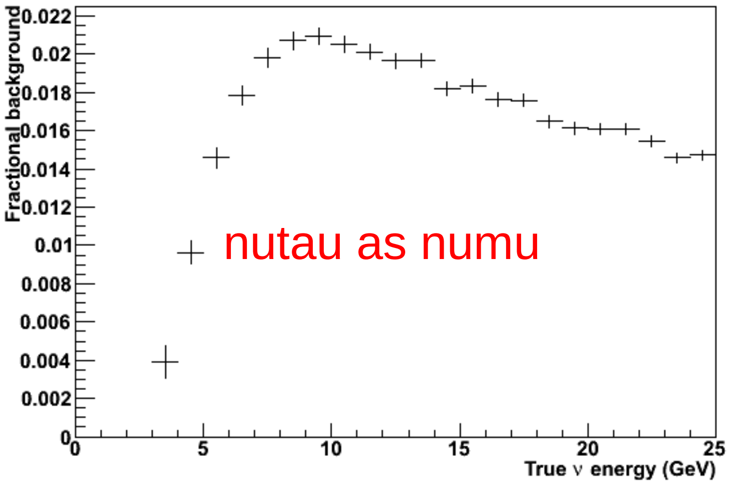
- Systematic errors: ratio of QES/DIS, 1π/DIS, "Other"/DIS

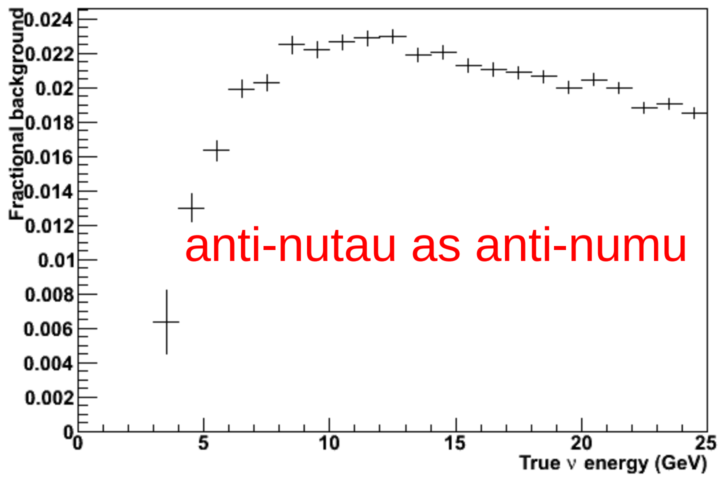




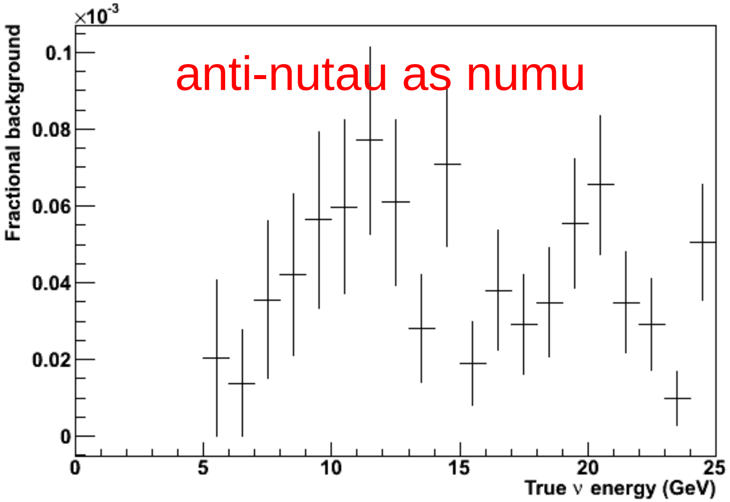
MIND: tau contamination

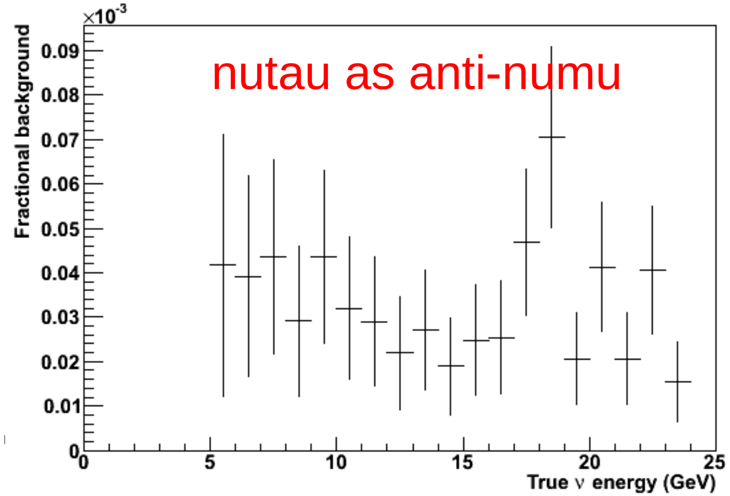
- Tau neutrino simulations using GENIE already implemented
  - **New plots:** ν_τ signal right-sign





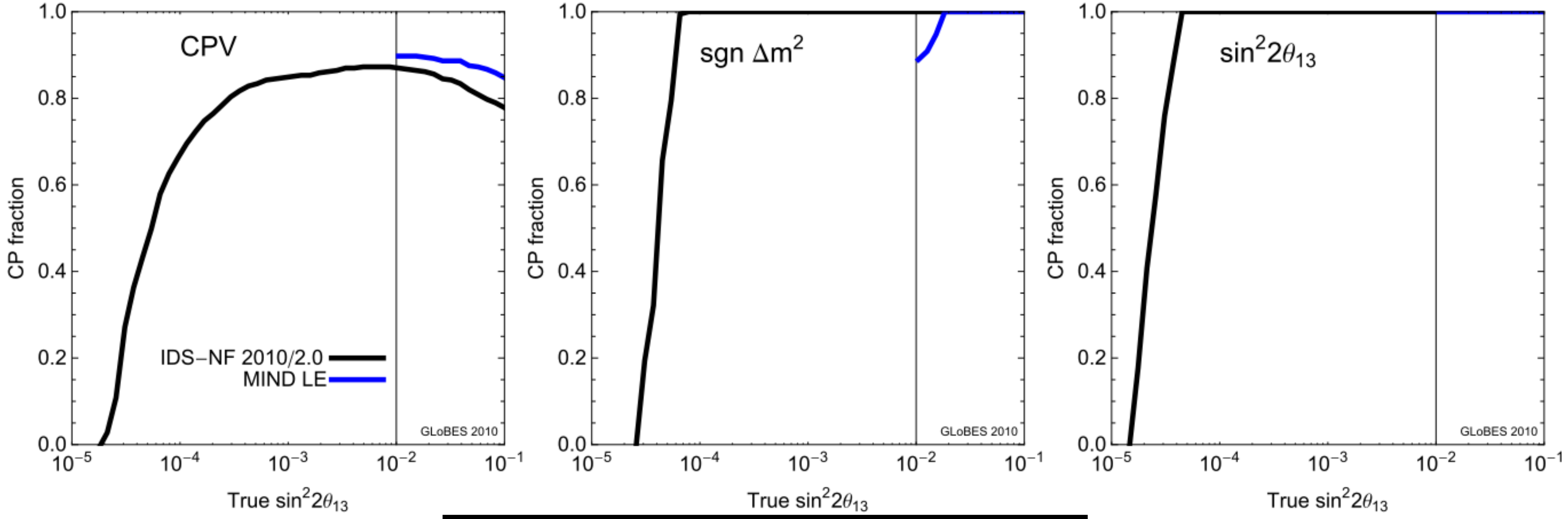
  - **New plots:** ν_τ signal wrong-sign

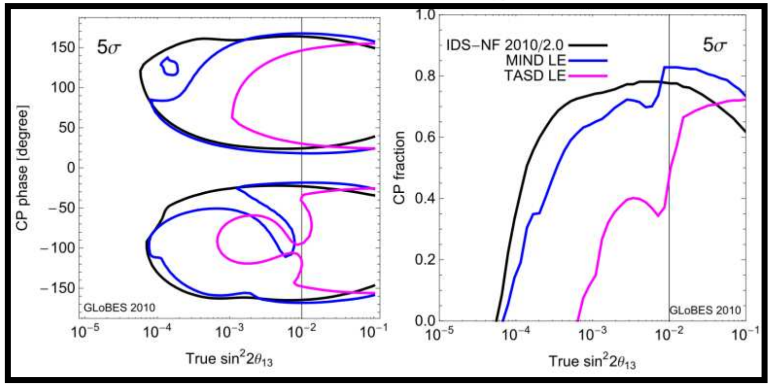




Neutrino Factory performance

- Based on migration matrices derived from this analysis
  - Neutrino Factory outperforms all other facilities
  - MIND can also be used at lower energies ie. 10 GeV NF for large θ_{13}

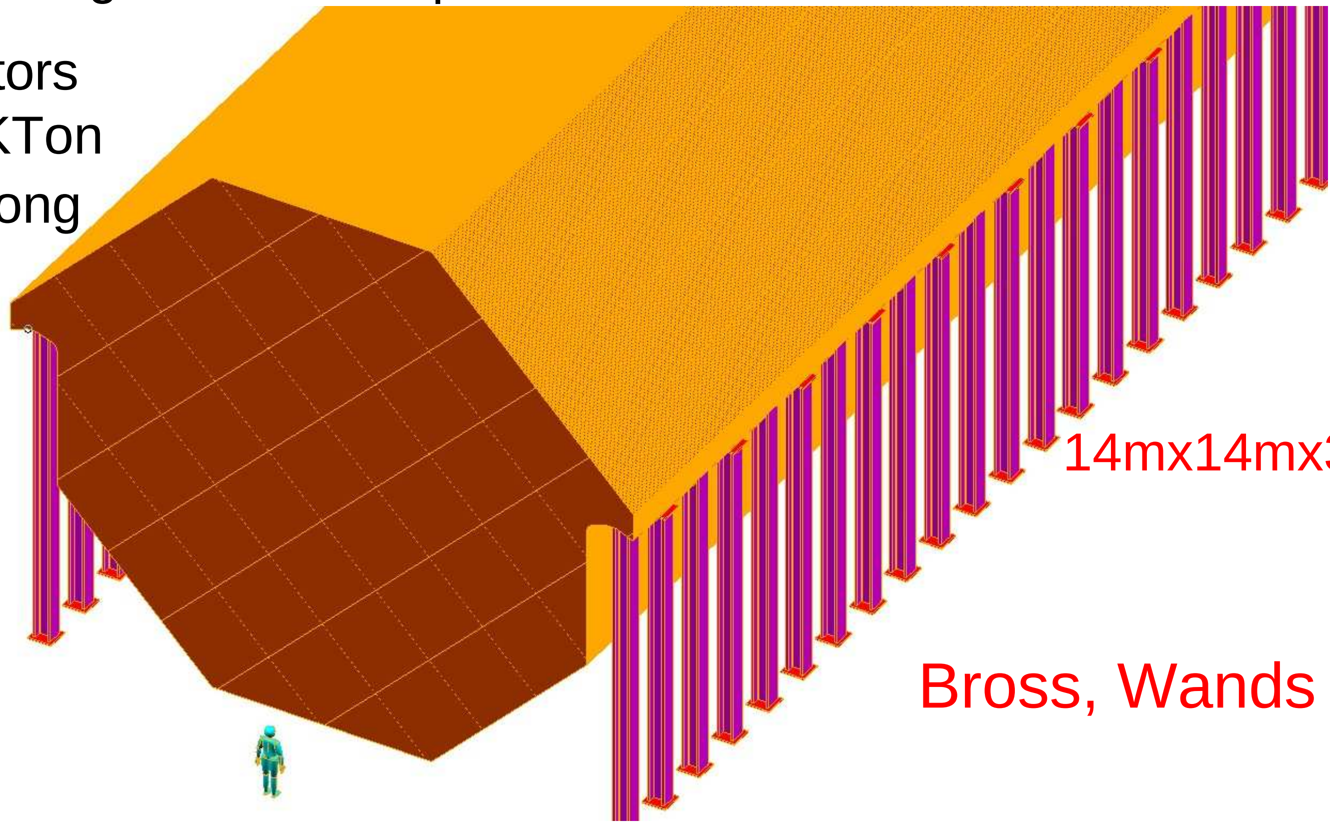




MIND: realistic geometry

- Dipole field not realistic due to cost of implementation
- Toroidal field and octagonally shaped detector (as in MINOS) more realistic
  - Fermilab engineers well advanced in finding valid engineering solution and magnetic field map

Two detectors
M~50-100 KTon
50-100 m long



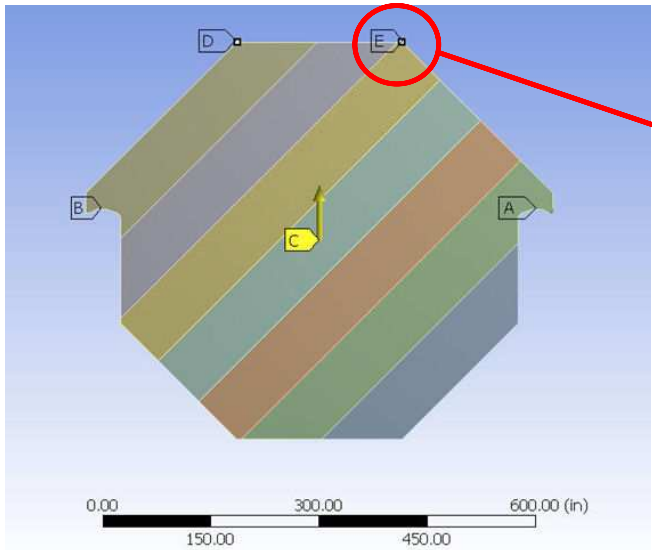
14mx14mx3cm plates

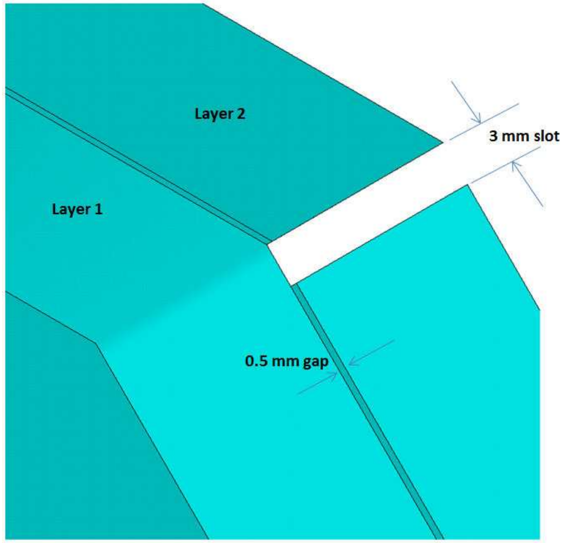
Bross, Wands (FNAL)

MIND: realistic geometry

- Plate engineering:

Plates: two welded layers (0.5mm gaps) 3 mm slots between Plates (2 m wide)

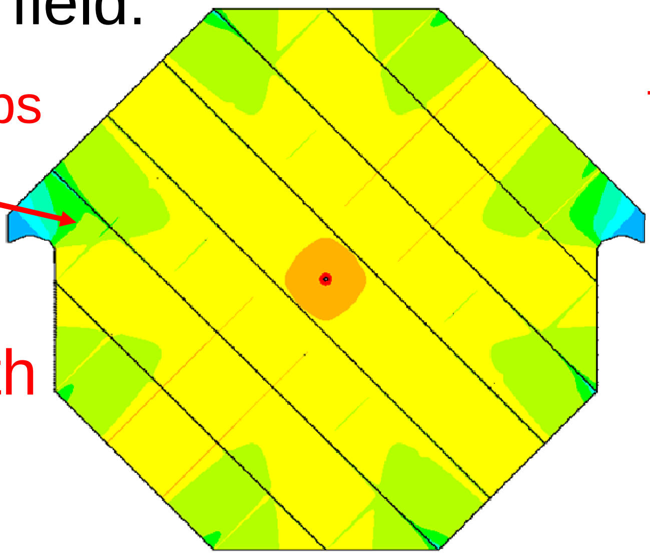




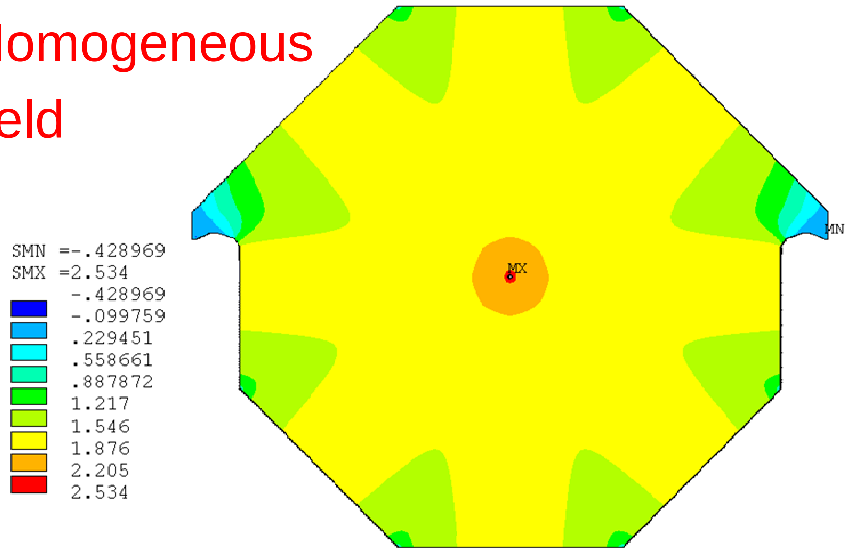
- Toroidal field:

Small field gaps and jumps

1.2-2.2 T with 100 kA turn

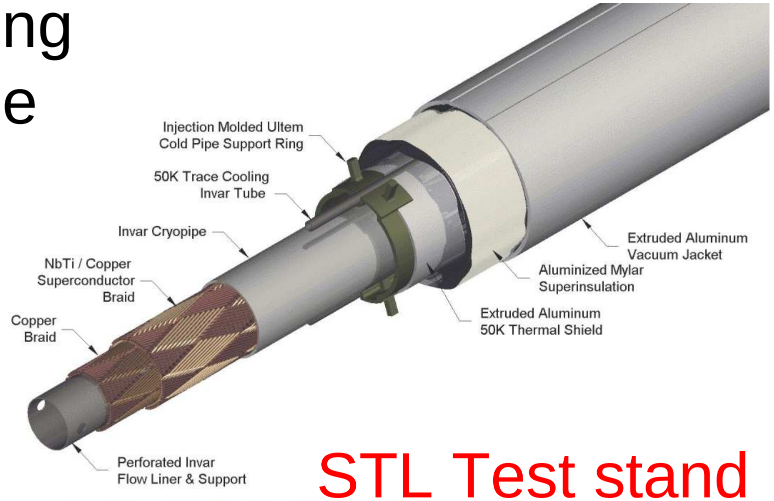


Homogeneous field

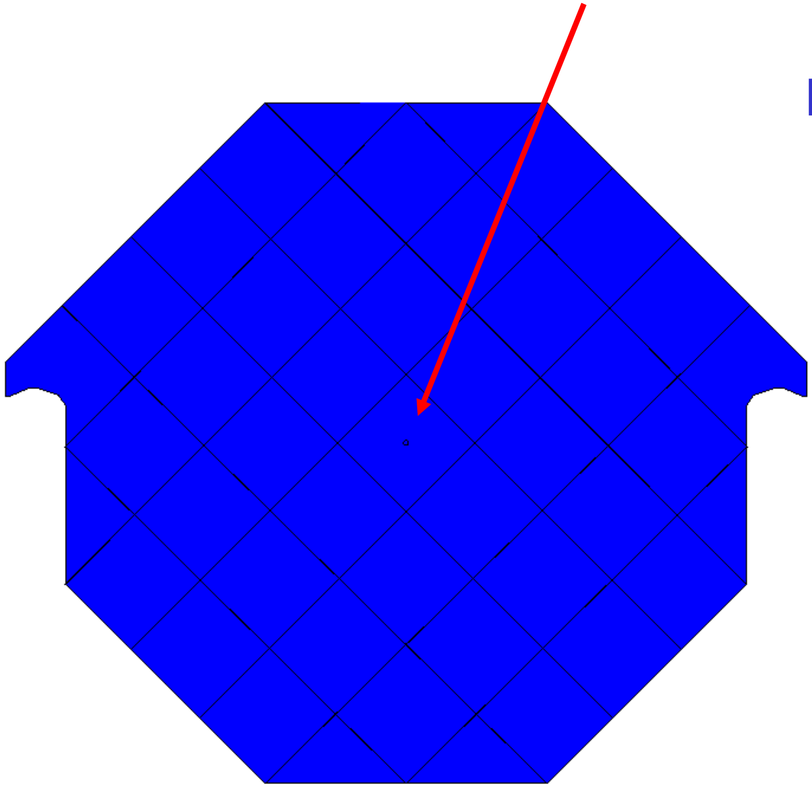


MIND magnetisation

- Magnetisation can be achieved using Superconducting Transmission Line (STL) developed for VLHC:
  - Can carry 100 kA turn
  - Only need 10 cm diameter hole



Bross

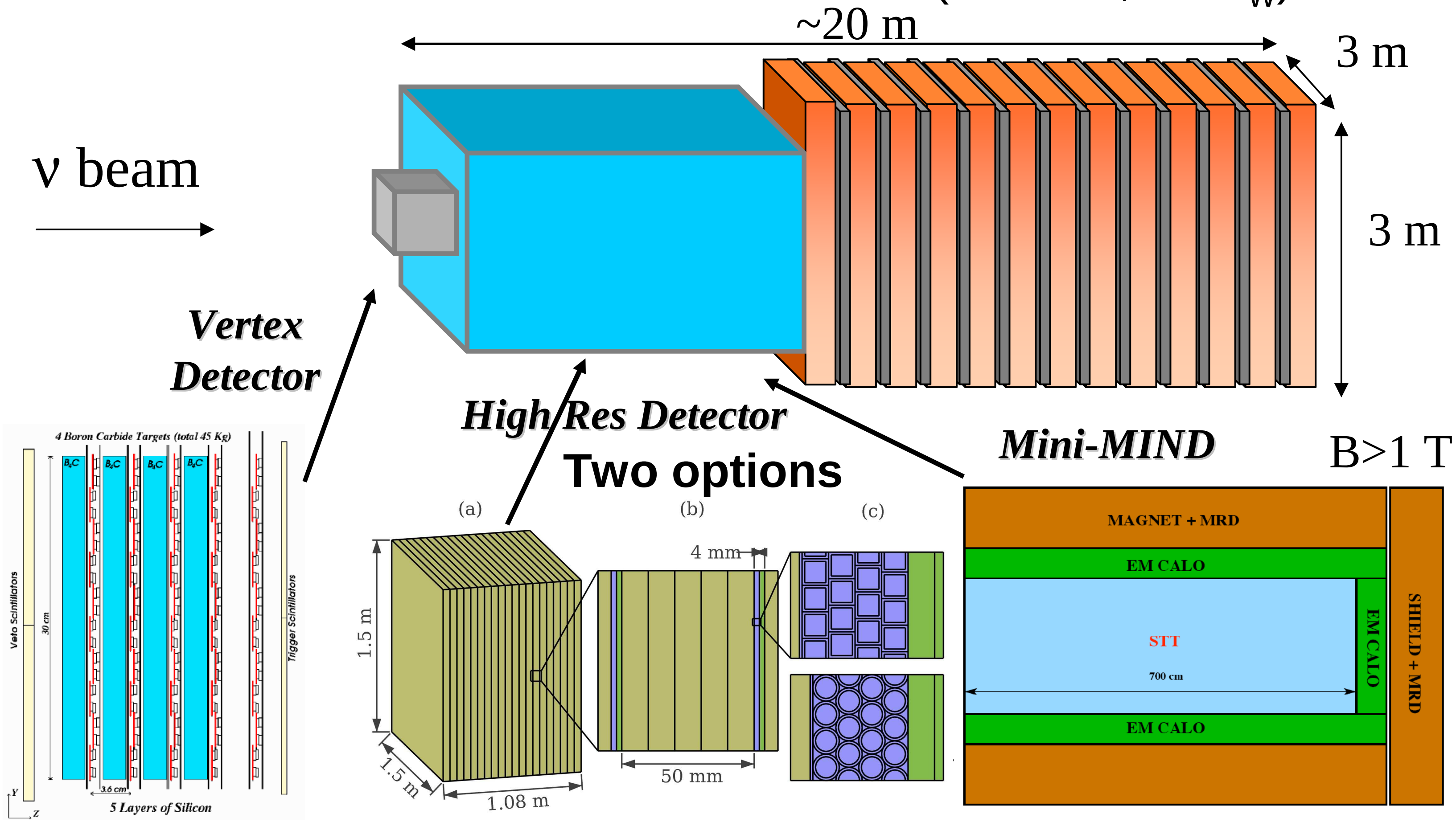


STL Test stand

The test apparatus used at MW-9 for developing the transmission line.

Near Detectors

- Near detector tasks:
  - Neutrino flux (<1% precision) and extrapolation to far detector
  - Charm production (main background) and taus for Non Standard Interactions (NSI) searches
  - Cross-sections and other measurements (ie PDFs, $\sin^2\theta_W$)



Near Detector Location

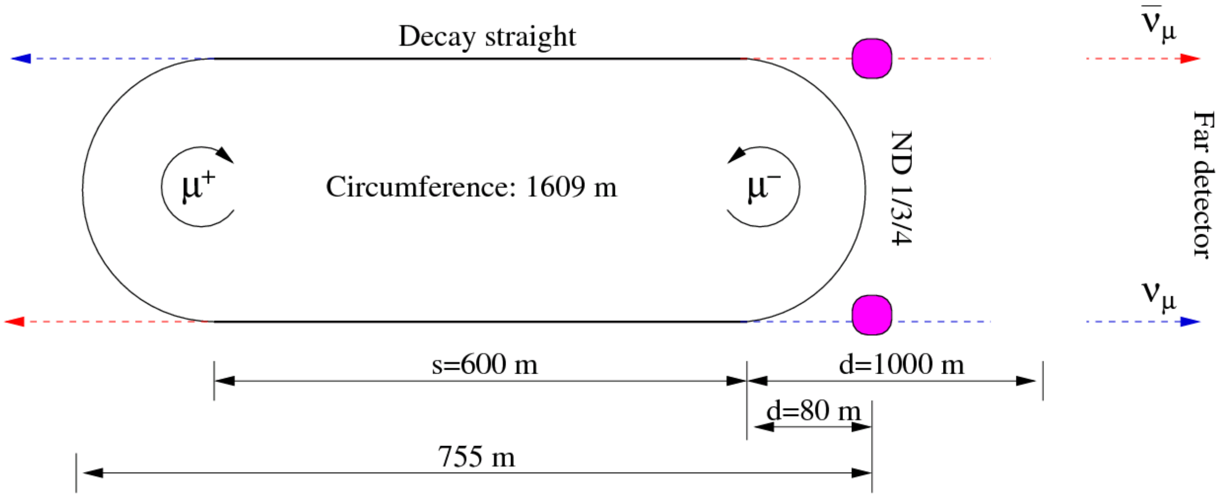
- For Neutrino Factory, baseline is to have one Near Detector per decay straight per ring (ie 4 detectors)

E_μ = 25 GeV ±80 MeV

Straight section length = 600 m

Muon angular spread 0.5 mrad

2.5×10^{20} muon decays/per charge/per year

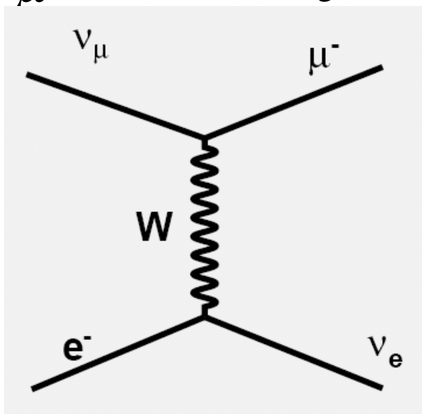


- Need to check if one ND can measure beam divergence ~0.1/γ
- Questions:
  - What is optimum distance?
  - How much shielding do we need?

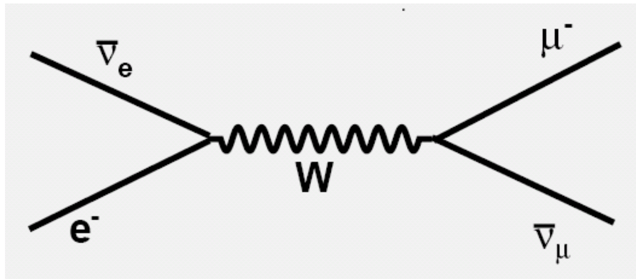
Near Detector Flux

- Quasi-elastic scattering off electrons (at NF):
  - Can be used to measure the flux
  - Absolute cross-section calculated theoretically with high precision.
  - Two processes of interest for neutrinos from μ^- decays are Inverse Muon Decay (IMD) and muon production through annihilation:

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



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



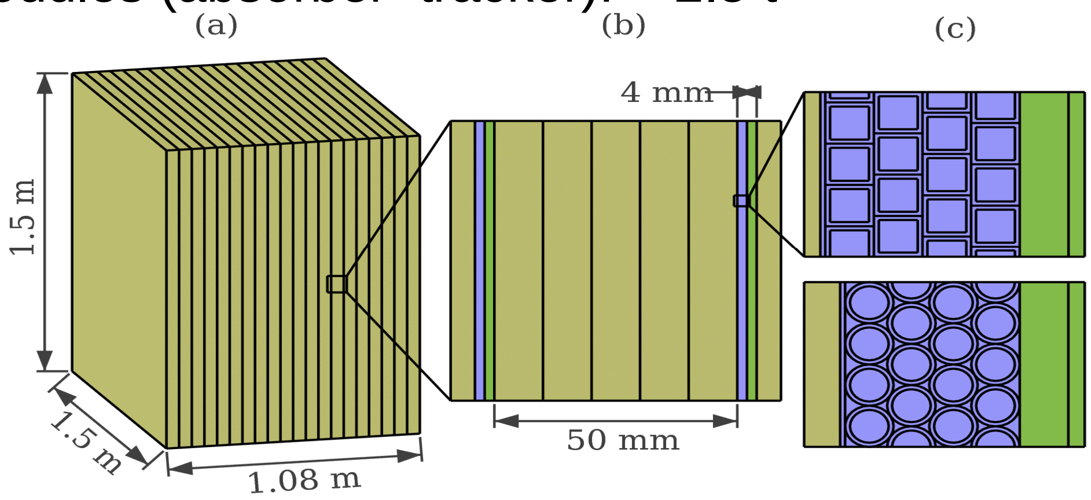
$$\sigma = \frac{G_F^2}{\pi}\frac{\left(s - m_\mu^2\right)^2}{s} = 4\times10^{-41}cm^2$$

$$\sigma = \frac{2G_F^2}{\pi}\frac{\left(s - m_\mu^2\right)^2 (E_e E_\mu + \frac{1}{3}E_{\nu 1}E_{\nu 2})}{s^2}$$

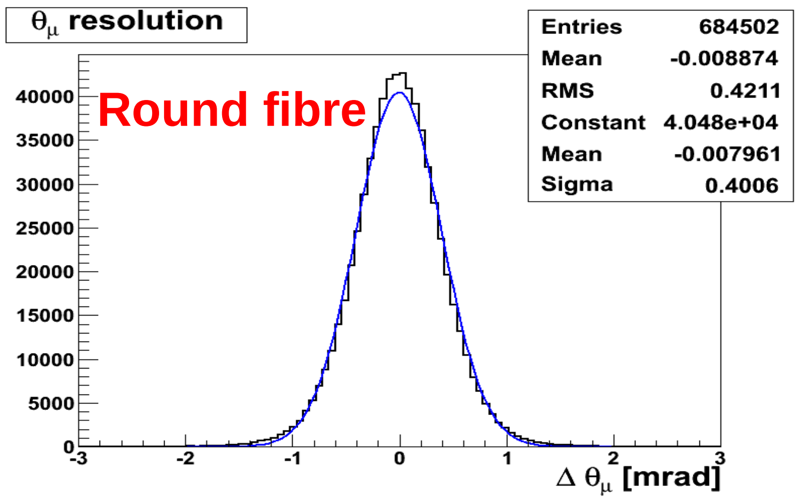
For 15 GeV ν_μ: ~10^{-3} of $\sigma_{total}(\nu N)$

Near Detector design

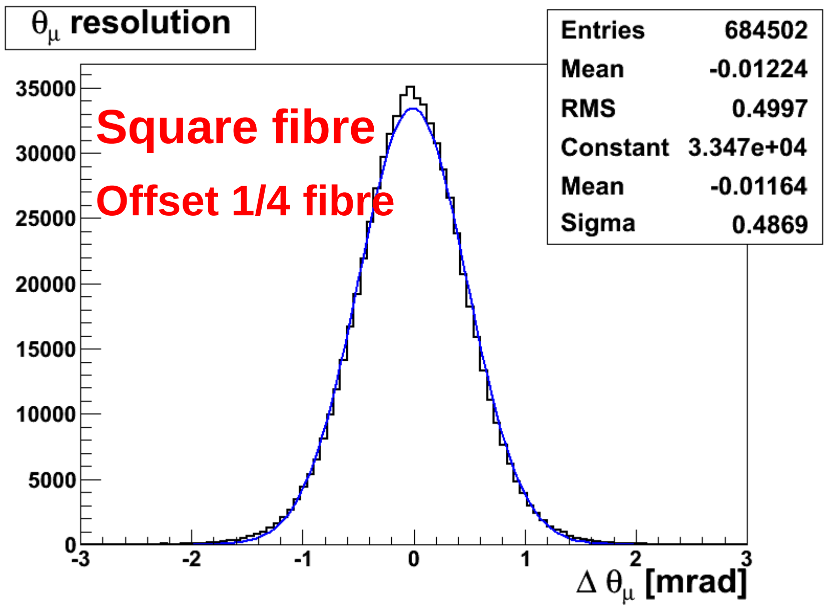
- Detector requirements:
  - To provide sufficient interaction rate: **solid detector;**
  - To reconstruct polar angle of scattered muon: **low Z tracker;**
  - To measure hadron recoil energy to few MeV: **precise calorimeter**
- Baseline detector design:
  - Tracker station – 4 fibre planes (vertical and horizontal)
    Scintillating fibres – 0.5 mm width (round or square)
  - 24000 fibres per station
  - Absorber is 5 cm thick polysterene (5 slabs)
  - 20 modules (absorber+tracker): ~ 2.5 t

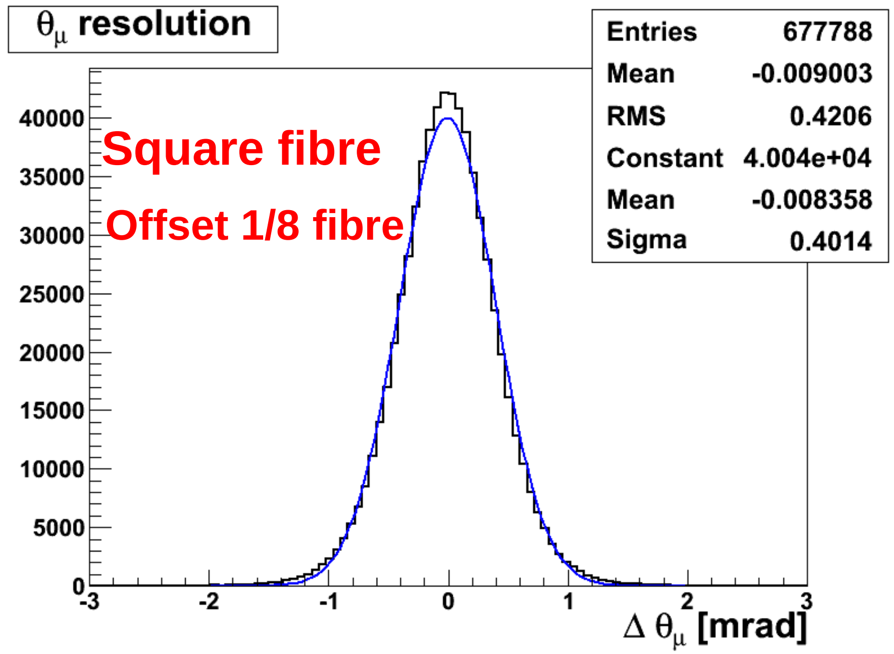


Near Detector polar angle



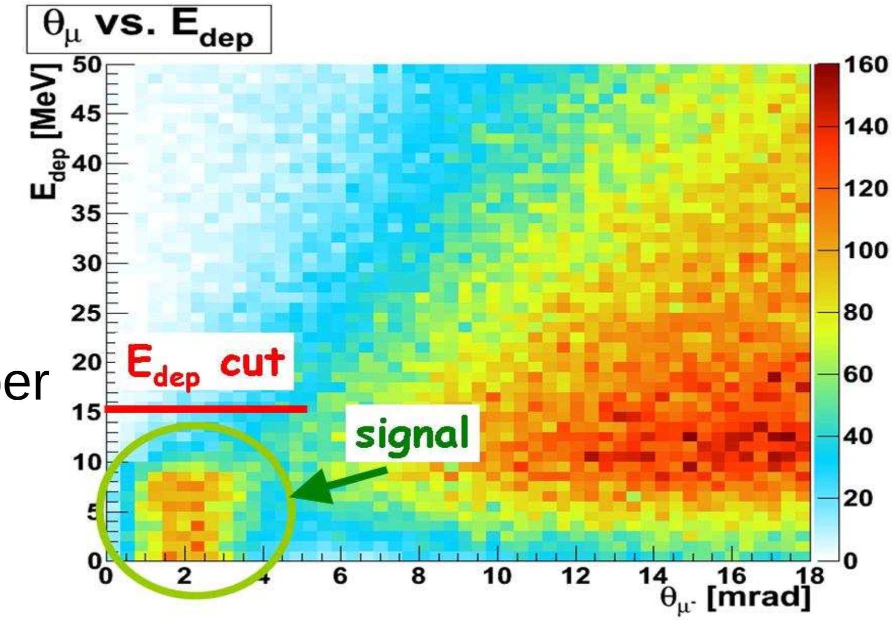
- Configuration with 0.5 mm round fibres (top)
- Two configurations with 0.5 mm square fibres (bottom)
- Resolution ~ 0.5 mrad in all setups

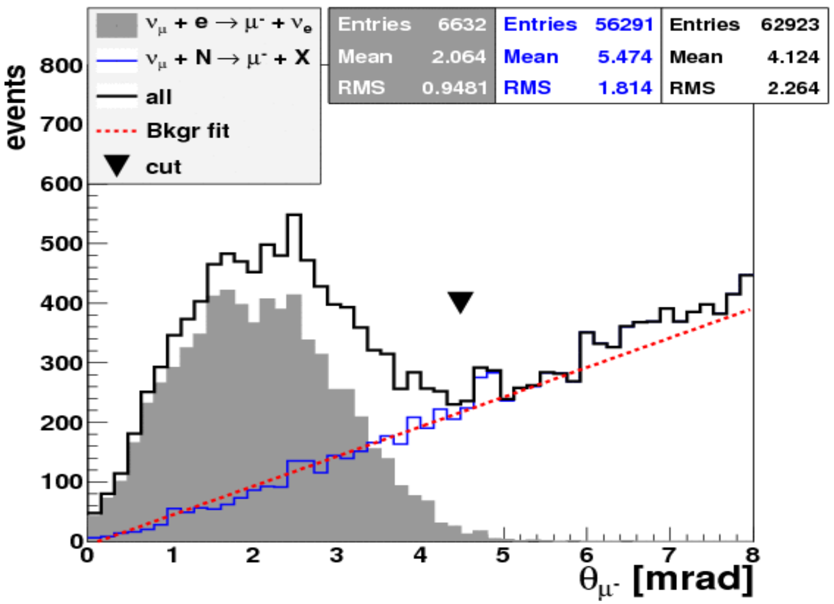


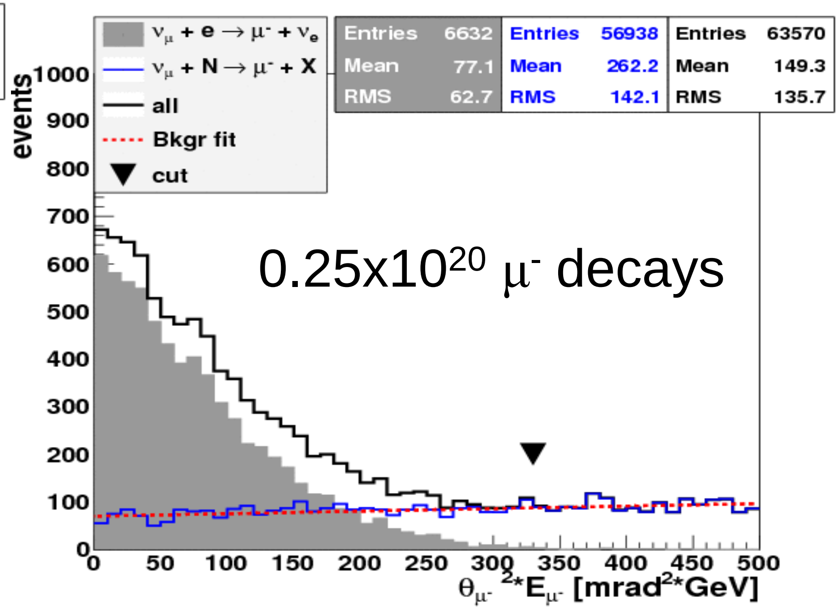


Near Detector IMD events

- IMD event selection:
  - Muon scattering angle θ_μ
  - $E_\mu \theta_\mu^2 =\sim (1-y)$, y – inelasticity
  - Muon p_T^2
  - Energy deposition in first absorber (5 cm thick) vs. Θ_μ
  - Flux accuracy: 1% in one year

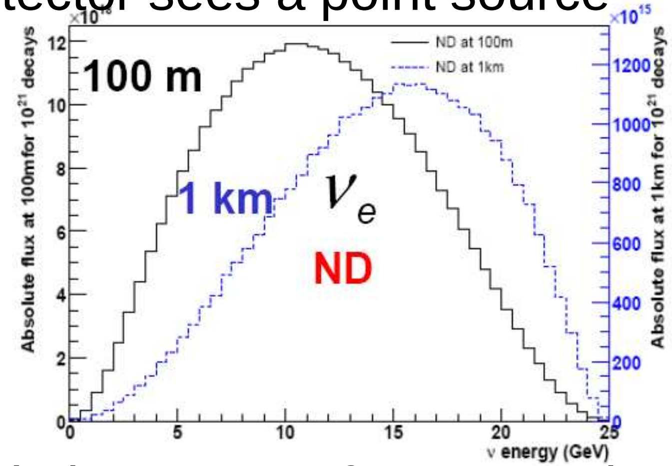


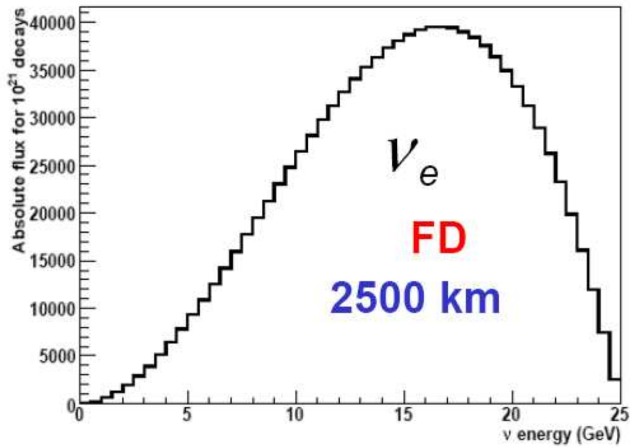




Flux Near Detector at Neutrino Factory

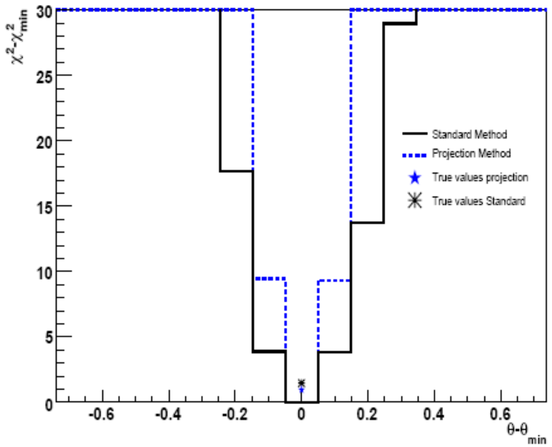
- At a NF, the Near Detector sees a line source (600 m long decay straight)
- Far Detector sees a point source

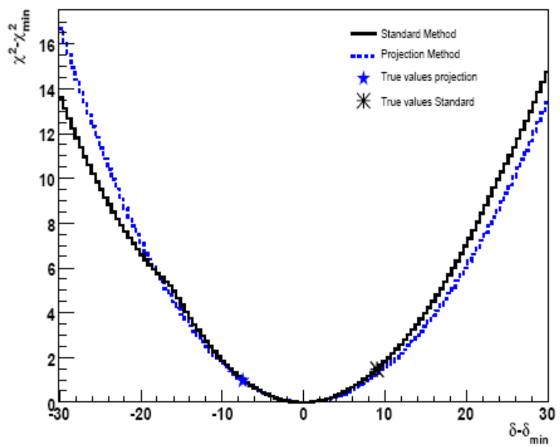




- Extrapolation near-to-far at Neutrino Factory:
  - Matrix method similar to MINOS: $N_{FD} = M_{FD} P_{osc}(\theta_{13}, \delta_{CP}) M_{nOsc} M_{ND}^{-1} N_{ND}$
  - Fit FD spectrum to predicted spectrum from ND:

Fit improves at 3σ level





Conclusions

- Two Magnetised Iron Neutrino Detectors (MIND) at standard Neutrino Factory (25 GeV) is baseline:
  - 2500-5000 km with100 kton mass
  - 7000-8000 km (magic baseline) with 50 kton
- New analysis with Nuance, Geant4, full pattern recognition and reconstruction achieved, with full migration matrices for GLoBES outperforms all other facilities in θ_{13} and CP coverage.
- Efficiencies higher in the plateau and lower threshold than previous analyses (mainly due to addition of QEL+RES events)
- Engineering realistic concept well under way
- Conceptual design for Near Detector being established
  - Flux measured with IMD with accuracy of 1% in one year NF