MIND Far Detector Simulation

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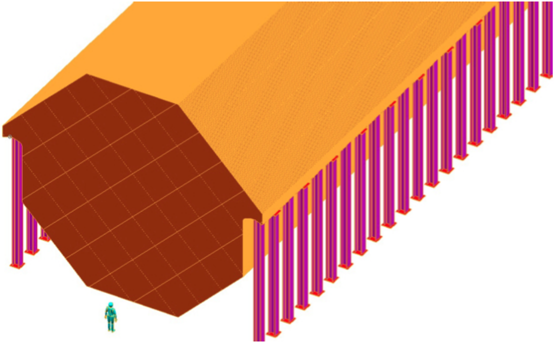
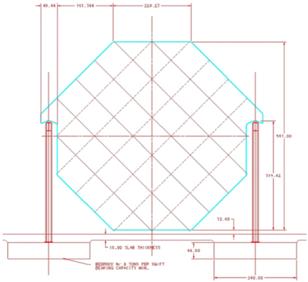
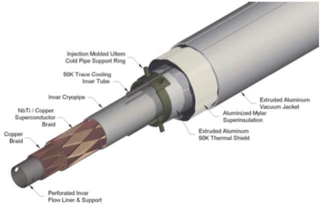
Outline

MIND Design for Neutrino Factory





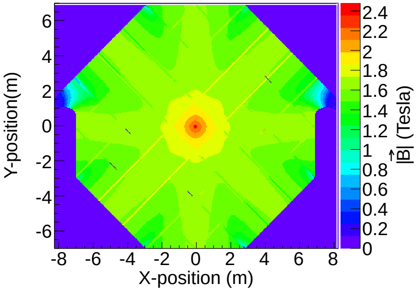
Superconducting Transmission Line

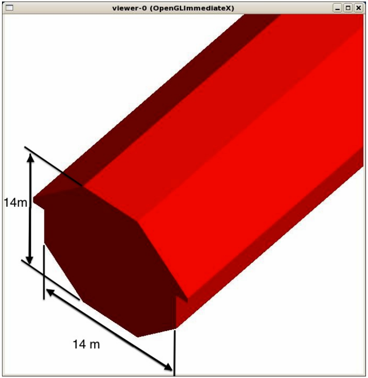


- 100 kTon detector
- 14 m$\times$14 m$\times$140 m.
- X and Y views from 2 cm thick lattice of 1 cm$\times$3.5 cm scintillator bars.
- $\vec{B}$ field from 3 cm Fe plates, induced by 120 kA current carried by 7 cm diameter SCTL

MIND Simulation

- Events simulated with GENIE.
- Full geometry & $\vec{B}$ field in GEANT 4
- Realistic field map generated by Bob Wands at FNAL
  - default positive focussing.



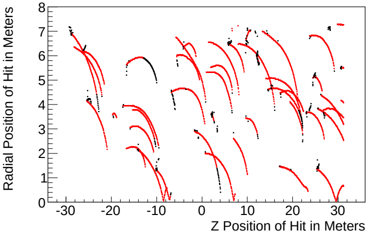


- Dimensions of detector easily altered for
  - optimization.
  - testing variations.

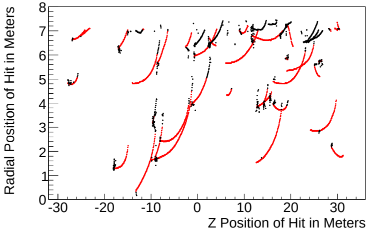
Reconstruction With RecPack

- Simulated events digitized.
  - Hits positions smeared and energy deposition attenuated.
  - Edep clustered into 3.5 cm$\times$3.5 cm units.
- Tracks identified by Kalman Filter or Cellular automata.
- Kalman fitting used to determine momentum and charge.
- Simulated field map used here.
- Algorithms from RecPack.
  - supported by Cervera-Villanueva *et al.*

- 50 $\bar{\nu}_\mu$ CC events.



- 50 ν_μ CC events.



- Fitted hits in red others in black.

Seeding Algorithm

A rudimentary momentum seed is calculated for Kalman Filtering

Momentum

- Calculated from the length (or extent) of a track using range tables

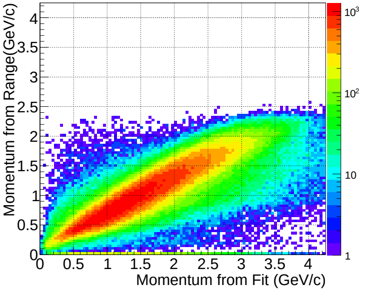
Charge

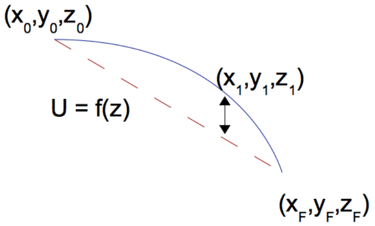
- Define bending coordinate i.e.

$$u = \vec{r} \cdot (\hat{z} \times \hat{B})$$

- In a positive focussing field

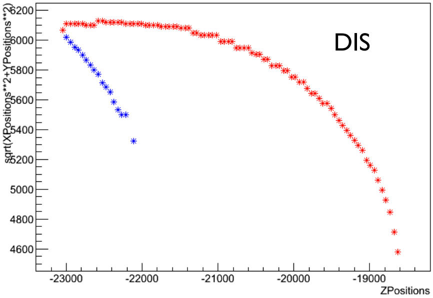
$$q = sign\left(\sum_{i=0}^{F}(f(z_i) - u_i)\right)$$

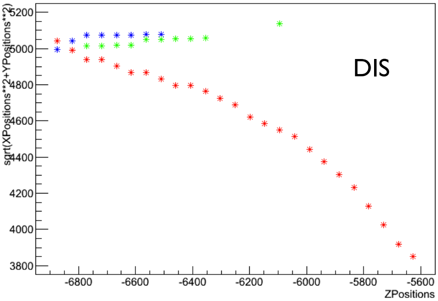




Reconstruction of Multiple Tracks

- Isolate muon track
  - Use length of track as well as number of hits to select muon
  - Reduce energy threshold imposed to reduce charge mis-id
- Reconstruct hadron direction for multiple tracks
  - Can be used to isolate low energy muon tracks.
  - i.e. parallel low energy reconstructed from showers.
- Isolate hits pertinent to hadron energy for energy reconstruction





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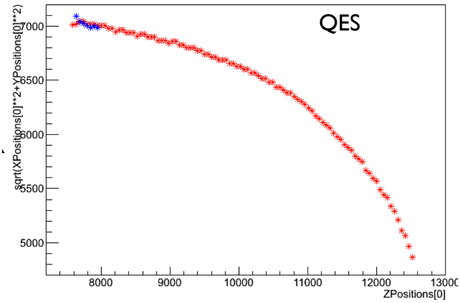
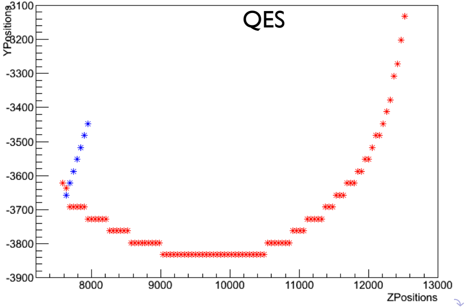
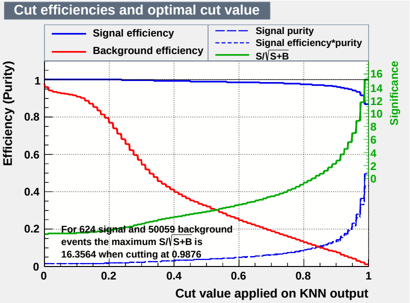




Multi-variate Analysis

- Investigating use of TMVA package for MIND.
- Provides vetted optimization algorithm.
- Have written (but not tested) TMVA analysis for multiple tracks.
- Requires stable reconstruction and input variables including
  - Muon Trajectory Selection.
  - Hadron Reconstruction.
  - Energy Deposition Calculation.
  - Deposition Fraction.
  - Deposition Variation.

Example KNN Method

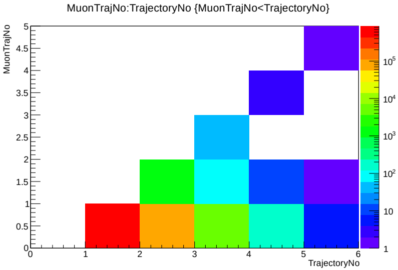


- Attempts to date have been suspicious in oscillation context

Muon Selection and Cuts with Multiple Tracks

Muon Selection

- Find trajectory with most hits.



- Could also use the longest trajectory.
- Still work in progress.

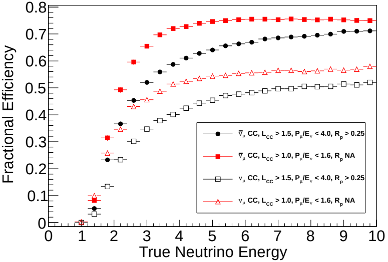
NC Rejection of Muon Track

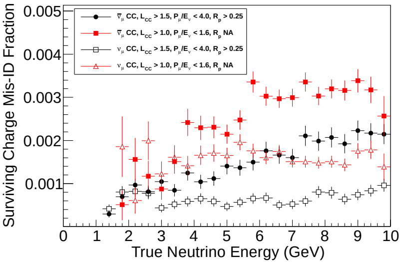
- Muon track fit successful
- $p_\mu < 4.0 \times E_\mu$
- $z_{length} - z_{vertex} > 1$ m
- $\frac{N_{fit}}{N_{cand.}} < 60\%$.
- $R_p = \frac{q_{fit}}{p_{fit}} \times \frac{p_{init}}{q_{init}} > 0.25$
- $\log \frac{P(\sigma_{qp}/qp|CC)}{P(\sigma_{qp}/qp|NC)} > -0.5$
- $\log \frac{P(N_{hit}|CC)}{P(N_{hit}|NC)} > 1.5$

Changes in Cuts and Corrections (So Far)

1. Include a cut on events to prevent the track fitting from switching charge or over-estimating the momentum.
   - Achieved by cutting on the product $R_p = \frac{p_{init}}{q_{init}} \frac{q_{rec}}{p_{rec}}$
   - Duplicates quadratic cut as q_{init} is derived from geometry of track
   - p_{init} derived from range.
   - $R_p > 0.25$ removes low and high energy backgrounds
   - Normalizes upper momentum cut to length of track.
2. Upper momentum cut redundant and biased in energy.
3. Reduce the $\mathcal{L}_{CC}$ threshold from 1 to 1.5 due to change in $\mathcal{L}_{CC}$ distribution.
4. Remove the Kinematic cut as it was only removing signal.

Efficiency of Muon Selection



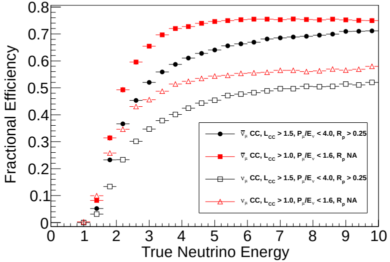


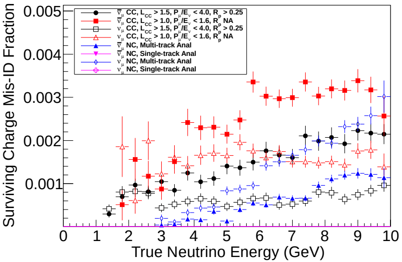
- Red for Single track reconstruction
- Black for Multiple track reconstruction.

Result of Changes

- Reduced signal efficiency.
- Reduced background fraction.
- Energy threshold unchanged.
- Need to calculate $\Delta\delta_{CP}$

Efficiency of Muon Selection





- Red for Single track reconstruction
- Black for Multiple track reconstruction.

Result of Changes

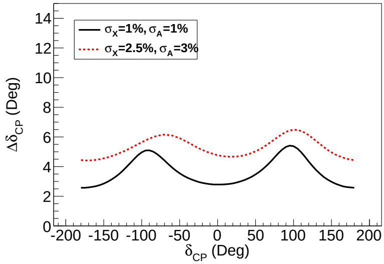
- Reduced signal efficiency.
- Reduced background fraction.
- Energy threshold unchanged.
- Need to calculate $\Delta\delta_{CP}$
- Neutral current backgrounds are significant in multiple track reconstruction.

CP sensitivity from NuTS and GLoBES

- Exp. Definition: 5×10^{21} $\mu^{\pm}$ decays, 2000 km baseline, 100 kTon
- Response matrices from EUROnu report.

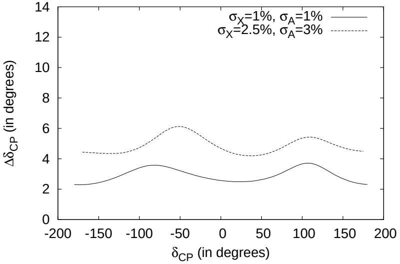
NuTS

- Used the Poisson log likelihood for χ^2.
- Systematic errors: Norm. (1%) and x-sec. ratio (1%)



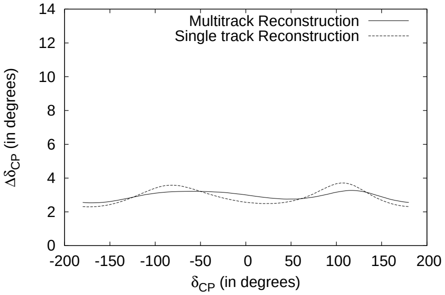
GLoBES

- By default uses extended χ^2
- Systematic error: Norm. (1%) and "tilt"(1%)



$\Delta\delta_{CP}$ optimization with GLoBES

- Default definition of χ^2 assumed.
- Compare new analyses to EUROnu analysis.



- Decreases sensitivity to δ_{CP} by $< 1\%$
- Precision increases on average
- Have tested $\mathcal{L}_{CC} > 1$
  - No significant difference
  - background larger (not shown).

Systematics: Current Status

Assume that only two systematics dominate

- Normalization/Fiducial: $\approx$1%
- Ratio of cross-sections: $\approx$1%

Effects demonstrated to be "small":

- Relative interaction cross-sections ($<$ 0.005).
- Hadron energy and angle resolution ($<$ 0.005).

To do list:

- Implement Poisson likelihood in GLoBES fit.
- Implement systematics (properly) in GLoBES fit.
- Implement Near-Far detector projection.
- Plan to evaluate impact of cosmic ray on analysis.
- Think of other systematic effects.

Summary

Software and Simulation

- Simulation has not changed.
- Reconstruction of multiple tracks now available.
- Analysis has been defined for new reconstruction.
- Further tuning of cuts and track selection attractive (TMVA).

Physics Sensitivity

- Can achieve 4° precision at all angles.
- Multi-track reconstruction makes a small (but noticeable) change.
- Small tuning attempts do not have a significant impact.
- Precision is limited by systematic uncertainty.

Summary (Part deux)

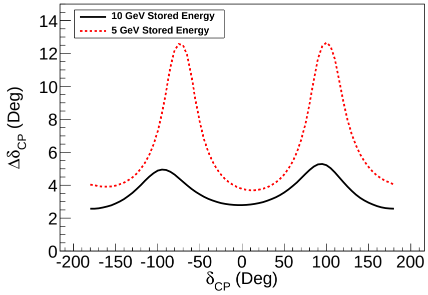
Systematic Considerations

- To date have been estimated.
- Will implement cosmic ray generator soon.
  - Do we need a mine?
- Need numerical estimate of systematics
  - Fiducial sensitivity
  - Field variation effects (i.e. field map is wrong).
  - Cross-section variations (Near Detector?).
  - Other effects...?

5 GeV Staging

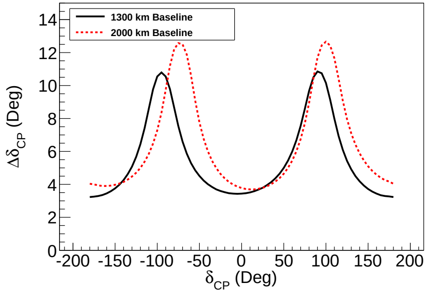
- Used EUROnu MM, Consider 5 GeV at 1300 km and 2000 km.
- Taken from private e-mail,"Re:Break points in muon acceleration", 31 July, 2012

Fixed 2000 km Baseline



- 5 GeV: 66% 5σ CP Coverage.

Fixed 5 GeV Energy



- 1300 km: Covers 80% 5σ CP.