MIND:
A Detector for Probing CP Violation at a Neutrino Factory

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Experimental Particle Physics

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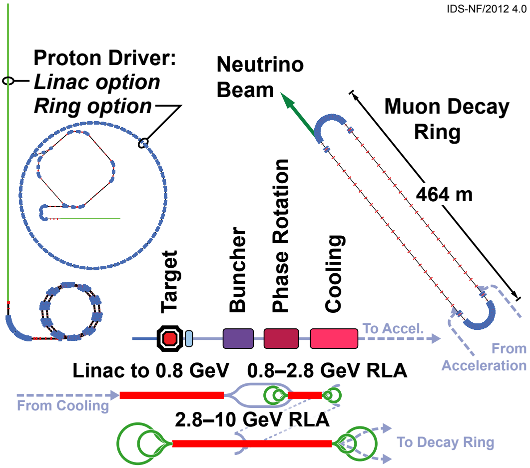
Full Luminosity Neutrino Factory

- Use a single 2000 km baseline with 10 GeV stored $\mu^{\pm}$
- Neutrinos from a cooled muon beam
  - Known flavour content
  - Known energy distribution
  - Reduced beam uncertainties (< 1%)
- Magnetized detector needed for charge separation.



Neutrino Oscillations at a Neutrino Factory

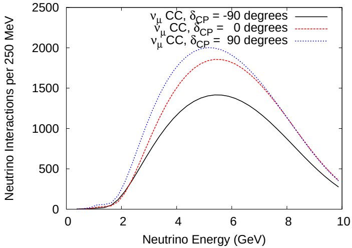
Accessible Oscillation Channels

	Store μ^+	Store μ^-
Golden Channel	$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$
ν_e Disappearance Channel	$\nu_e \rightarrow \nu_e$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$
Silver Channel	$\nu_e \rightarrow \nu_\tau$	$\bar{\nu}_e \rightarrow \bar{\nu}_\tau$
Platinum Channel	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$
ν_μ Disappearance Channel	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_\mu$
Dominant Oscillation	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$	$\nu_\mu \rightarrow \nu_\tau$

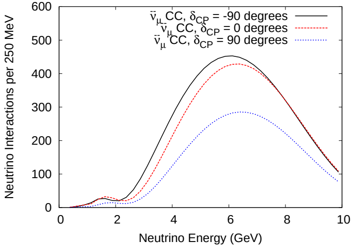
- We know [a]
  - $\sin^2 2\theta_{13} = 0.095 \pm 0.010$
  - $\sin^2 2\theta_{12} = 0.857 \pm 0.024$
  - $\theta_{24} > 0.95$
  - $\Delta m^2_{12} = (7.65 \pm 0.20) \times 10^{-5} eV^2$
  - $\Delta m^2_{23} = (2.32^{+0.12}_{-0.08}) \times 10^{-3} eV^2$
- Effect of δ_{CP} on NF spectrum from 5×10^{20} stored μ decays/yr shown.

[a] J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)

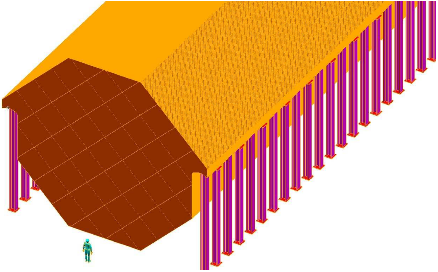
ν_μ CC interaction rate with perfect 100 kt detector



$\bar{\nu}_\mu$ CC interaction rate with perfect 100 kt detector

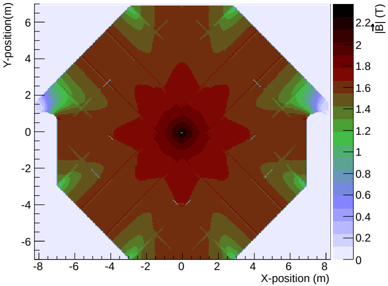


MIND: A Magnetized Iron Neutrino Detector



- Octagonal cross-section 14×14 m^2
- Fe plates 3 cm thick
- Space points from paired array of Scint bars 3×1 cm^2

- Toroidal magnetic field in steel.
- Field induced by 100 kA-turns.
- Current carried by multiple turns of STL through detector axis.[a]



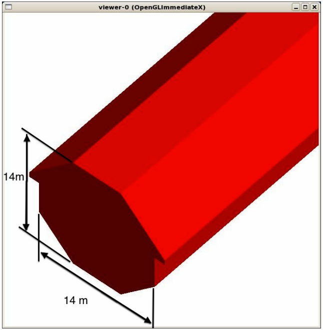
[a] IDS-NF-020, Interim Design Report

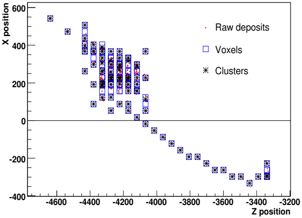
MIND Simulation

- Events simulated using GENIE.

Detector simulated using GEANT4.

- Events products propagated through detector volume.
- Energy deposition recorded in 2 cm thick scintillator plane.





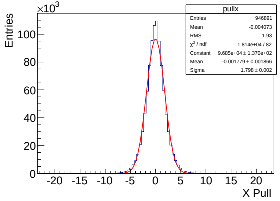
Simple digitization applied to events.

- Deposition grouped into 3×3 cm^2 voxels.
- 5 m attenuation length applied to energy.
- Smearing applied to hit position.[a]

[a] arxiv:1208.2735

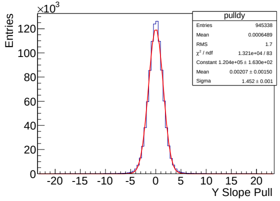
Muon Reconstruction within MIND

Position Pull

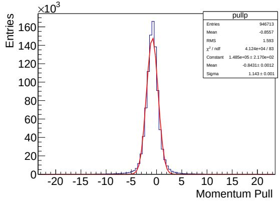


- Trajectories identified using Kalman filter.
- Multiple trajectories identified per event.
- Helix fit to trajectory with Kalman fit $(x, y, \frac{\partial x}{\partial z}, \frac{\partial y}{\partial z}, \frac{q}{p})$.
- Longest trajectory selected as the muon.
- Energy reconstructed as $E_\nu = E_\mu + E_{had}$ or using Quasi elastic approximation.

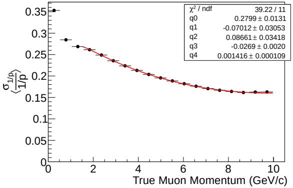
Direction Pull



Curvature Pull

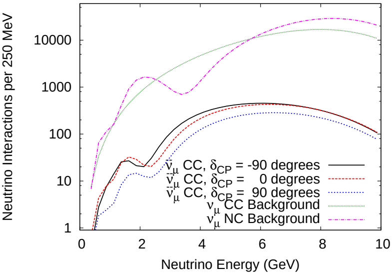


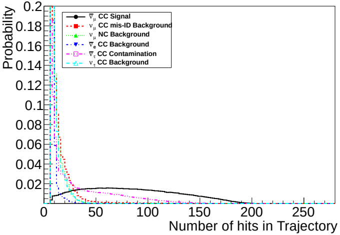
Momentum Resolution



Event Selection

- Must select $\nu_\mu(\bar{\nu}_\mu)$ CC events from backgrounds
  - NC events
  - Charge misidentified $\nu_\mu(\bar{\nu}_\mu)$ CC events.
  - Flavour misidentified ν_e and ν_τ events.
- Suppression $<$0.1% is required.





Quantities for Event Selection

- Number of hits in event.
- Quality of track fit
- Mean energy deposited in track.
- Variation in energy deposition along track
- Separation between muon and hadron.

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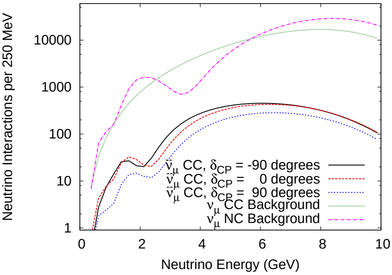

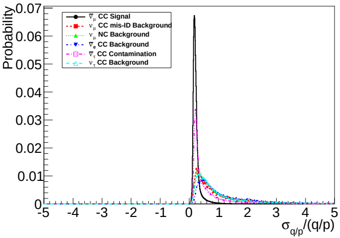

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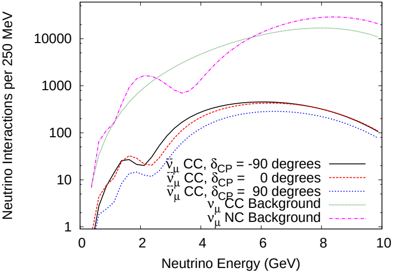

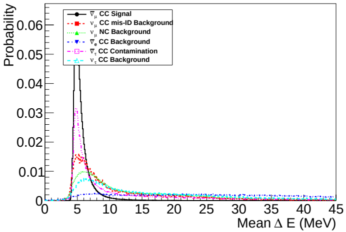

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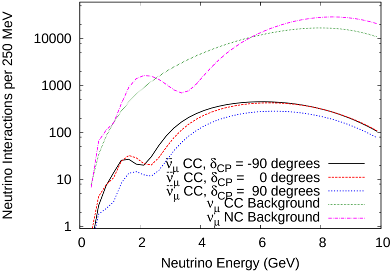

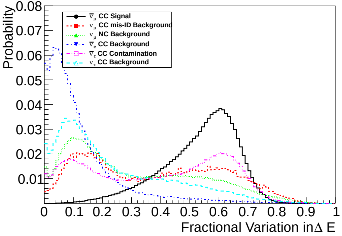

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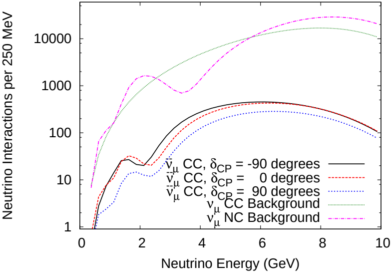

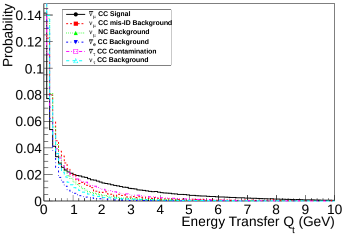

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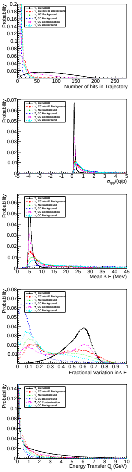
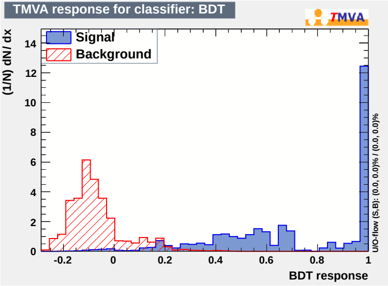
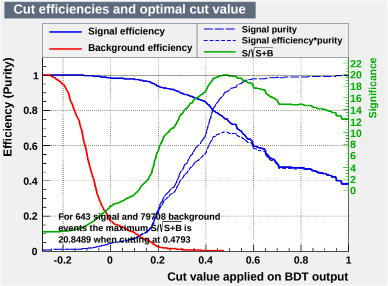
Multivariate Analysis for Event Selection



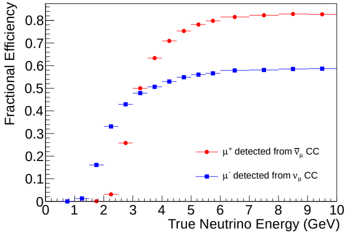
- Five variables with potential correlations used.
- Adopted TMVA package.
- Multiple methods tested i.e. Boosted Decision Trees (BDT), k-Nearest Neighbour (KNN), etc.
- Train CC (signal) to NC (background) separately for stored μ^+ and μ^-.





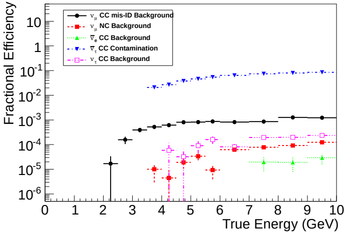
Efficiencies and Backgrounds in MIND

Efficiency

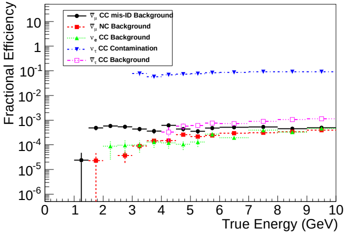


- Clear difference between beam polarity (both physics and training).
- Different MVA have different low energy behaviour
  - Compare BDT to KNN

Background (stored μ^-)



Background (stored μ^+)



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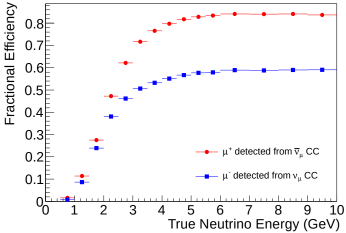
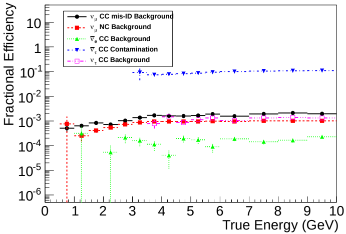
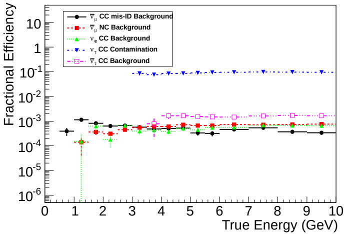


Background (stored μ^-)



Background (stored μ^+)



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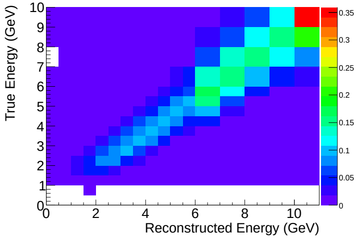
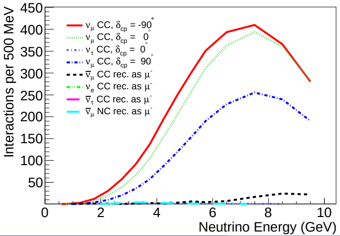
Expected Rates

Det. response for ν_μ *CC* sample

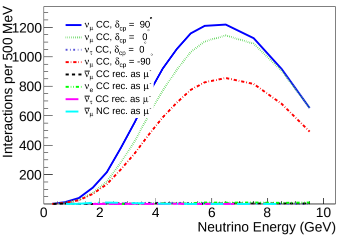


- GLoBeS package used to turn Det. response into detector rates
- Assume 100 kt detector, 2000 km baseline.
- Use 5×10^{20} μ^+/yr and 5×10^{20} μ^-/yr
- Assume 10 years running.

Rate in detector for stored μ^-



Rate in detector for stored μ^+



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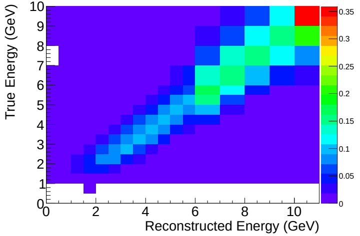

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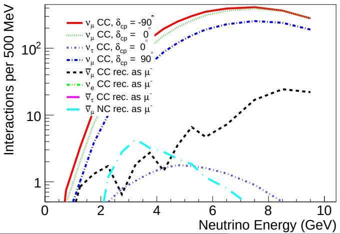
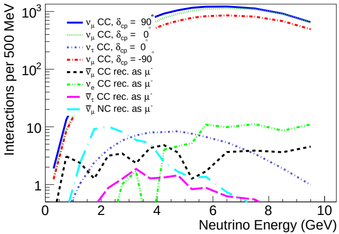


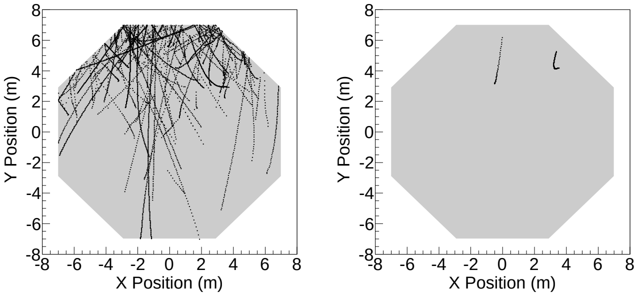
Rate in detector for stored μ^+



Cosmic Ray Backgrounds

Question: Do we need to put this detector underground?

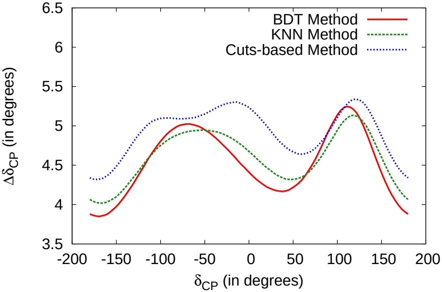
- Simulations done with CRY generator in GEANT4 detector.
- Identical reconstruction and event selection done.
- Apply self vetoing fiducial cuts at 30 cm.
- Detector will need overburden.



Events in Detector

Stored μ^+	
Signal	17802
Bkgd	298
Cosmics	261370
Stored μ^-	
Signal	3166
Bkgd	244
Cosmics	73169

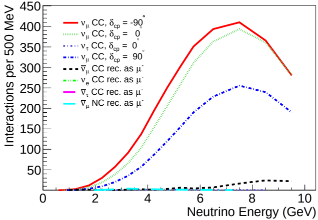
Precision of CP Violation



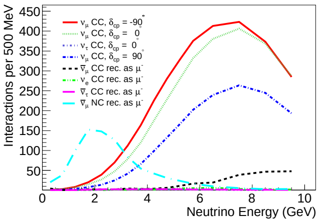
- Assume
  - 1.4% Signal systematic uncertainty (Flux $\times$ Cross-Section)
  - 20% Background systematic uncertainty (Ditto).
- Preferred MVA (BDT) shows precision between 4° and 5°.

- Method choice affects background rejection.
- Background affects result weakly.

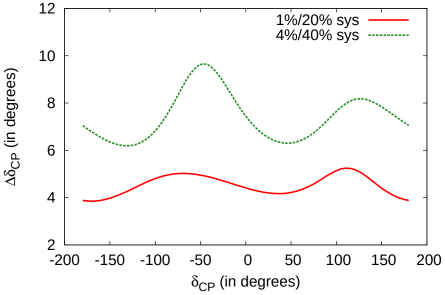
BDT Method

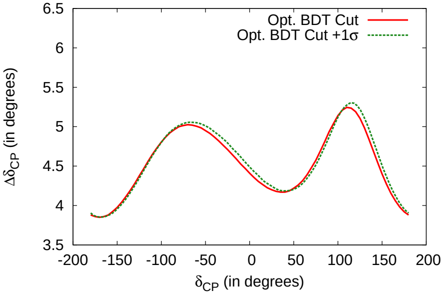


KNN Method



Systematics Explorations





- Consider the case of no improvement in systematic uncertainties
  - Signal systematic: 4%
  - Background systematic: 40%
- $\Delta\delta_{CP}$ between 6° and 10°.

- Consider analysis systematic.
- Increase the threshold on BDT cut so that $S/\sqrt{S+B}$ increases by 1.
- Small change ($< 0.1^\circ$) in precision.

Summary

- Development of simulation and reconstruction for MIND at a neutrino factory is coming to a conclusion.
- Improved reconstruction and event selection algorithms have been introduced
  - multiple track reconstruction
  - multivariate analysis for event selection
- High efficiency achieved while rejecting background at parts in 10^3
- Can achieve precision in δ_{CP} between 4° and 5°