Magnetized Iron Neutrino Detectors at Neutrino Factories

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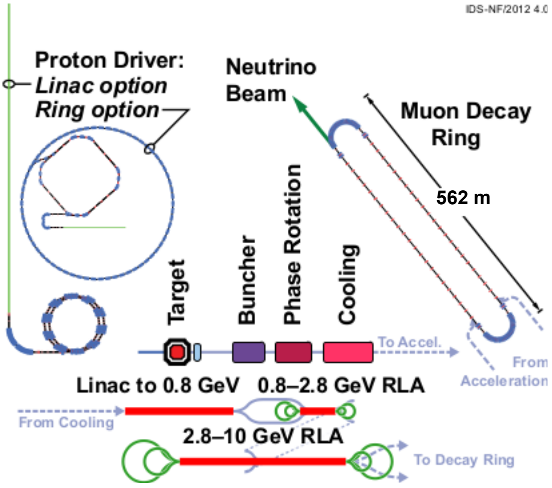
Outline

A 10 GeV 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.
- See talk by P. Soler (Tues PM WP3).



Neutrino Oscillations at a Neutrino Factory

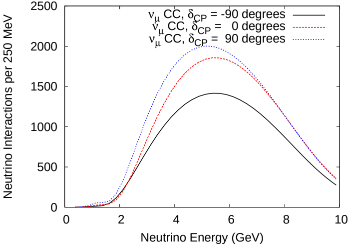
Accessible Oscillation Channels

	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	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$	$\nu_\mu \rightarrow \nu_\tau$

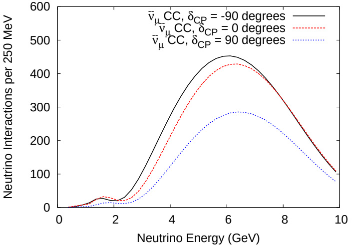
- We know [a]
  - $\sin^2 2\theta_{13} = 0.095 \pm 0.010$
  - $\sin^2 2\theta_{12} = 0.857 \pm 0.024$
  - $\sin^2 2\theta_{23} > 0.95$
  - $\Delta m^2_{12} = (7.65 \pm 0.20) \times 10^{-5}$ eV^2
  - $\Delta m^2_{23} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}$ eV^2
- Effect of δ_{CP} on oscillated NF spectrum from $5{\times}10^{21}$ stored μ decays shown.

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

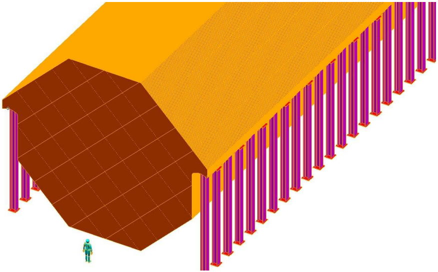
ν_μ CC interaction rate with perfect 100 kt detector



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

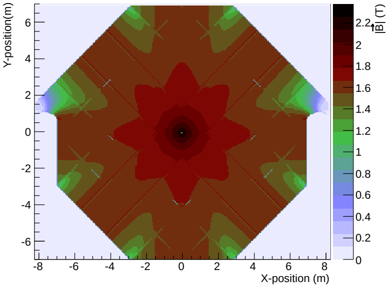


MIND: A Magnetized Iron Neutrino Detector



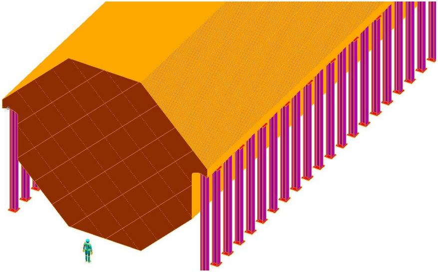
- Octagonal cross-section 14×14 m^2
- Fe plates 3 cm thick
- Space points from paired array of Scint bars 3×1 cm^2

- 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: A Magnetized Iron Neutrino Detector



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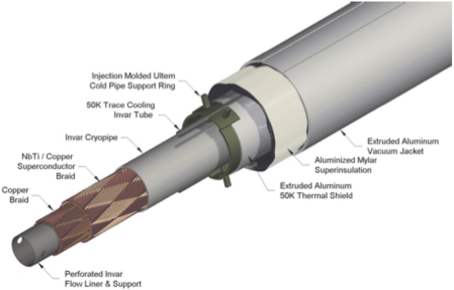
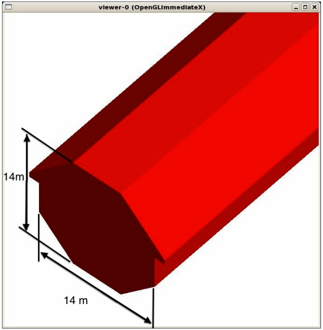


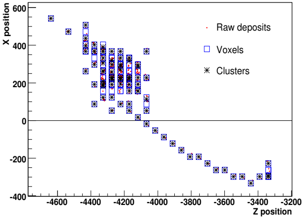
MIND Simulation

- Events simulated using GENIE.

Detector simulated using GEANT4.

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





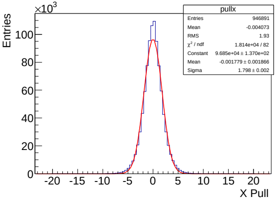
Simple digitization applied to events.

- 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

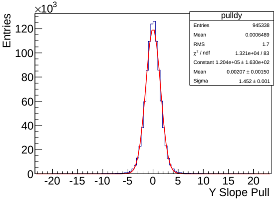
Muon Reconstruction within MIND

Position Pull

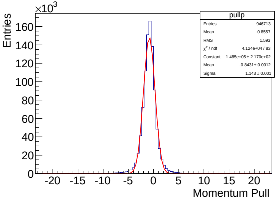


- Trajectories identified using Kalman filter.
- Multiple trajectories identified per event.
- Helix fit to trajectory with Kalman fit $(x, y, \frac{\partial x}{\partial z}, \frac{\partial y}{\partial z}, \frac{q}{p})$.
- Longest trajectory selected as the muon.
- Energy reconstructed as $E_\nu = E_\mu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

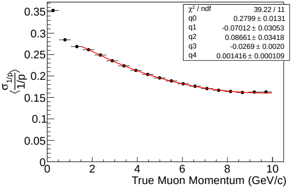
Direction Pull



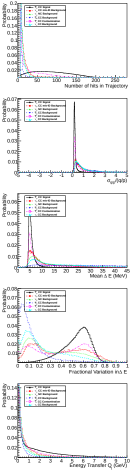
Curvature Pull



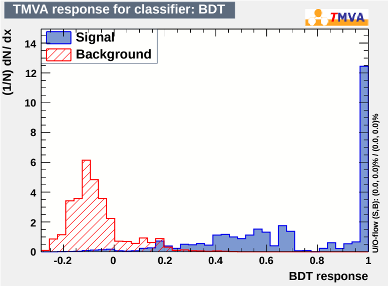
Momentum Resolution

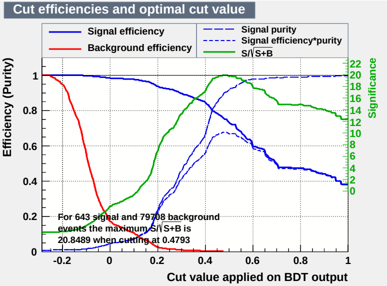


Analysis



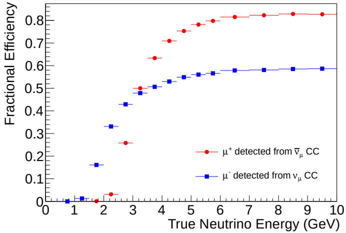
- Five variables with potential correlations used.
- Adopted TMVA package.
- Multiple methods tested i.e. Boosted Decision Trees (BDT), k-Nearest Neighbour (KNN), etc.
- Train CC (signal) to NC (background) separately for stored μ^+ and μ^-.





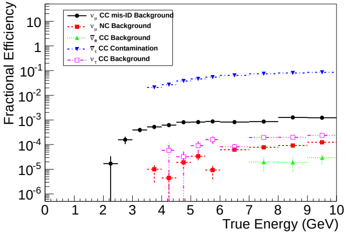
Event Selection Efficiency

Efficiency

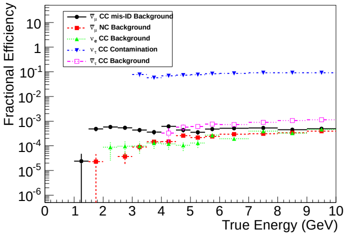


- Clear difference between beam polarity (both physics and training).
- Different MVA have different low energy behaviour
  - Compare **BDT** to KNN

Background (stored μ^-)



Background (stored μ^+)



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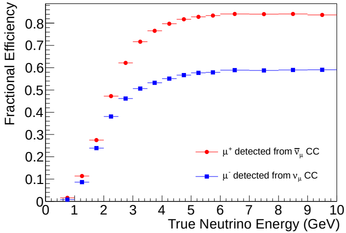
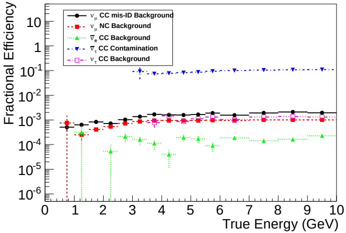
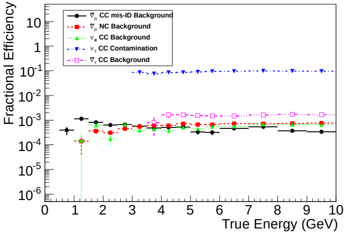


Background (stored μ^-)



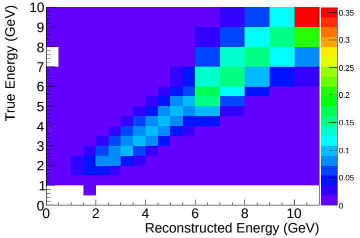
Background (stored μ^+)



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

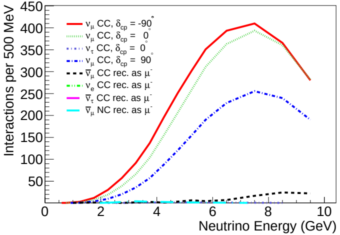
Rates After Selection

Det. response for ν_μ *CC* sample

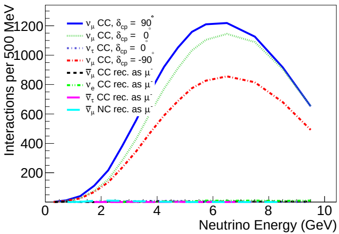


- GLoBeS package used to turn Det. response into detector rates
- Assume 100 kt detector, 2000 km baseline.
- Use 5×10^{20} μ^+/yr and 5×10^{20} μ^-/yr
- Assume 10 years running.

Rate in detector for stored μ^-



Rate in detector for stored μ^+



Rates After Selection

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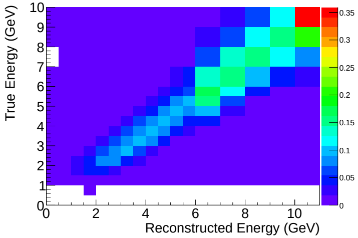

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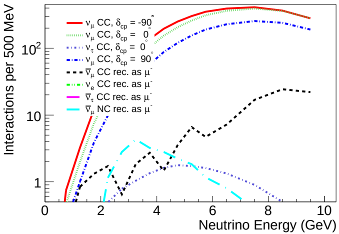
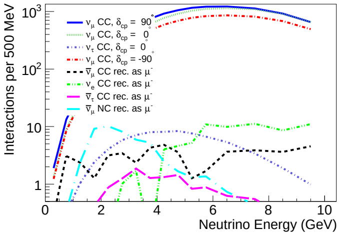
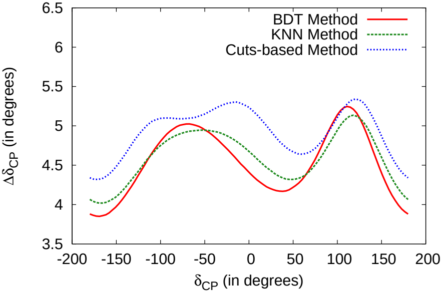


Rate in detector for stored μ^+



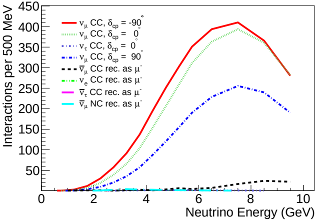
Precision of CP Violation Measurements



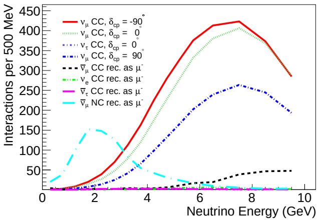
- Assume
  - 1.4% Signal systematic uncertainty (Flux× Cross-Section)
  - 20% Background systematic uncertainty (Ditto).
- Precision between 4° and 5°.
- ≈85% coverage of $\Delta\delta_{CP}$ at 3σ.

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

BDT Method

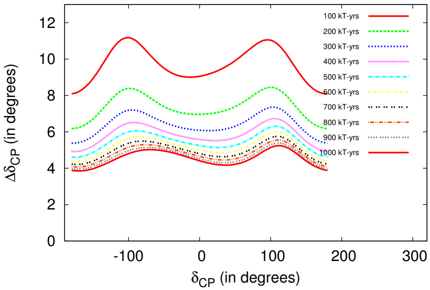


KNN Method



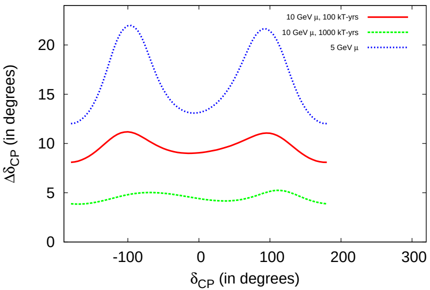
CP Violation for Modified Experiments

Intermediate Exposure



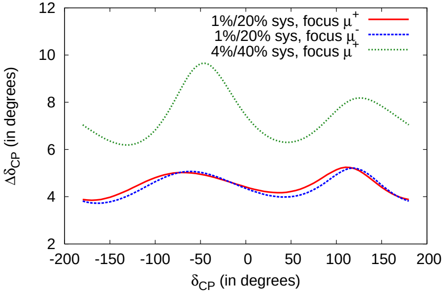
- Partial exposure parametrized as product of mass by years.
- Gains in $\Delta\delta_{CP}$ small after 600 kT·yrs.

5 GeV E_μ, 1300 km baseline



- Re-optimized analysis for 5 GeV NF.
- Identical exposure to 10 GeV NF given 1000 kT·yr.

Systematics for a Neutrino Factory Experiment



- Two systematics cases studied.
  - "Known" from MINOS
  - Expected for NF

Detector Construction Uncertainties

Uncertainty	Known Measures		Expected Contribution	
	Signal	Bkgd	Signal	Bkgd
EM Model	2%	0	0.5%	0
Magnetic Field	$<$1%	$<$1%	0.2%	3%
Steel	0.2%	0.2%	0.2%	0.2%

Beam and Theoretical Systematic Uncertainties

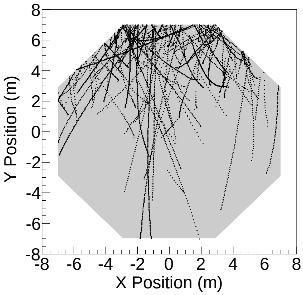
Uncertainty	Known Measures		Expected Contribution	
	Signal	Background	Signal	Background
Source luminosity	0.1%	0.1%	0.1%	0.1%
Cross section	4%	40%	0.5%	5%
Hadronic Model	0	15%	0	8%

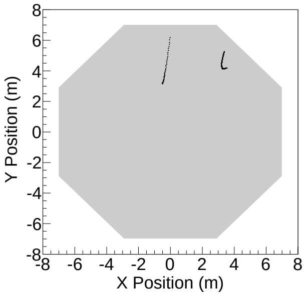
- $\Delta\delta_{CP}$ between 6° and 10° for "known" systematics case.

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 $>$6 m.



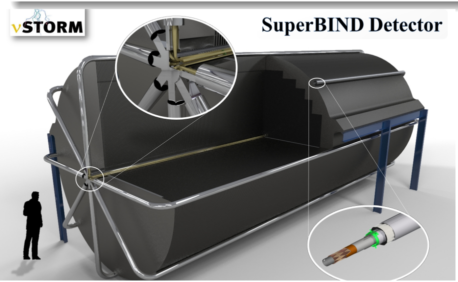


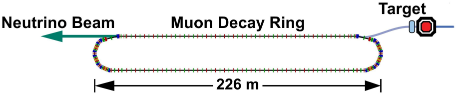
Events in Detector

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

nuSTORM

- 120 GeV proton beam incident on a graphite target produce pions.
- Pions are horn captured, transported, and injected into ring.
  - 52% of pions decay to muons before first turn
- Muons within momentum acceptance circulate in ring.



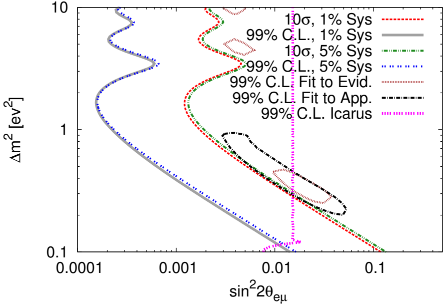


- Study sterile neutrino oscillations
- 1.5 cm steel plates, 1.5 cm thick Scint. plane
- Field induced by 270 kA-turn current in SCTL.

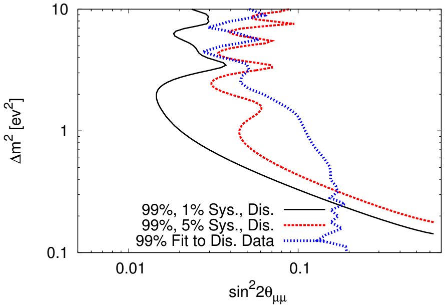
Sterile Sensitivity at nuSTORM [1]

- Assume sample of 1×10^{18} useful μ^+ decays.
- 1.3 kTon iron-scinitillator calorimeter detector, 2 km from ring.
- Assume a 0.5% rate and 0.5% cross-sectional systematic.
- In absence of interaction studies 0.5%→5%.

$\nu_e \rightarrow \nu_\mu$ Appearance Search



$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ Disappearance Search



[1] **D. Adey *et. al.* Phys. Rev. D 89, 071301(R)**

Conclusions

- MIND is a well developed technology suitable for a Neutrino Factory.
- A full simulation of the detector has been developed to evaluate detector performance.
- Excellent charge selection allows for reduction of background below parts in 10^3
- Simulation can (and has) been used to scope variations in the detector technology.
  - Sterile neutrino search at nuSTORM.
  - Reduced energy neutrino factory.
- For IDS-NF design a precision in δ_{CP} between 4° and 5° is achievable

Thank you

- A. Bross, [a]
- A. Cervera-Villanueva, [b]
- M. Ellis, [c]
- T. Ghosh, [3]
- A. Laing, [3]
- F.J.P. Soler,[d]
- R. Wands [2]

[a]Fermilab
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[c]Westpac Institutional Bank, Australia
[d]University of Glasgow

- C. Tunnell [a]
- P. Colomba [b]

[a]NikHEF
[b]Virginia Tech