THE INTERNATIONAL DESIGN STUDY FOR THE NEUTRINO FACTORY

Magnetized Iron Neutrino Detector (MIND)

ICFA Neutrino European Meeting

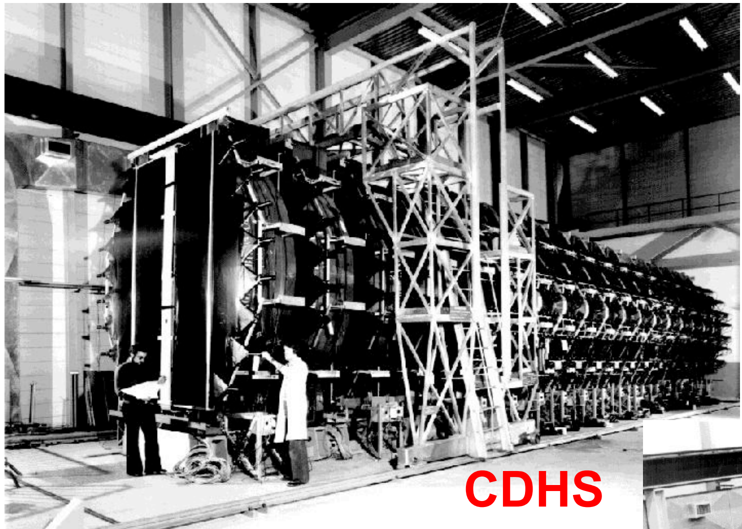
APC, Paris Diderot University

Paul Soler, 8-10 January 2013

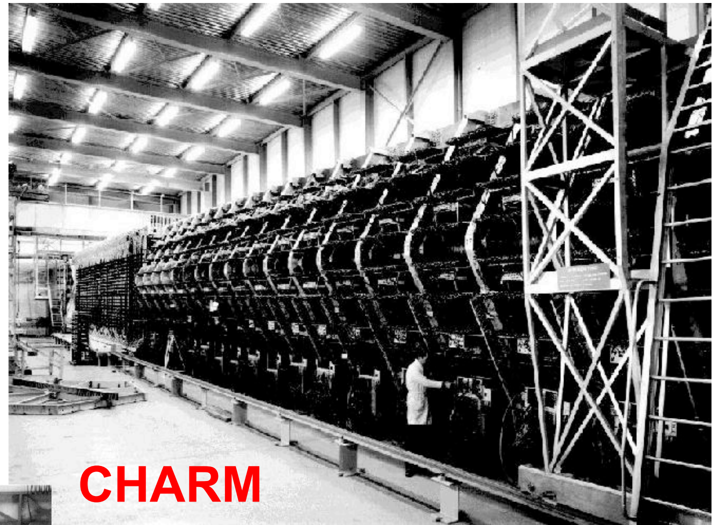
University of Glasgow

Magnetized Iron Neutrino Detectors

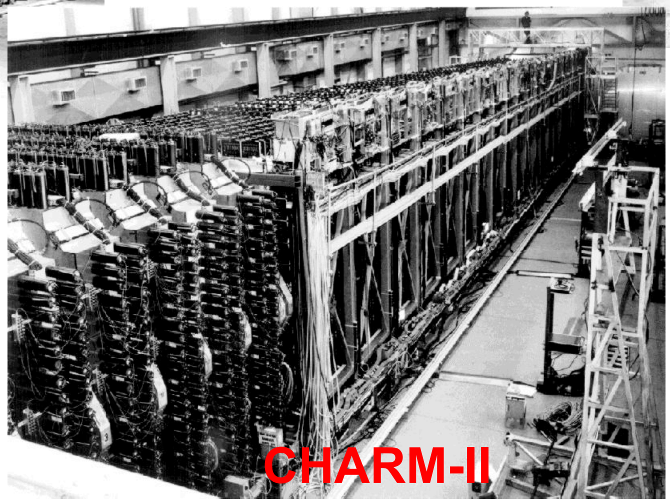
- Distinguished history of “magnetized iron neutrino detectors”
  - CERN-Dortmund-Heidelberg-Saclay-Warsaw (CDHSW): 1250 tons, 1976-84
  - CERN-Hamburg-Rome-Moscow (CHARM) and CHARM-II detectors had marble (180 tons) and glass (692 ton) targets but with magnetized iron spectrometer for muon momentum



CDHS



CHARM



CHARM-II

Magnetized Iron Neutrino Detectors

- Distinguished history of "magnetized iron neutrino detectors"
  - CalTech-Columbia-Fermilab-Rochester (CCFR) (1982-88) and NuTeV (1996-97): 695 tons
  - MINOS: two detectors (980 tons and 5.4 kton) from 2005 onwards

CCFR/NuTeV

MINOS

Advantages/disadvantages

- Why do we still consider large iron detectors?
- Is it not a technology of the 1970s?
- Main advantages:
  - Magnetisation: charge separation/momentum measurement
  - Good muon identification
  - Large mass in reasonable volume (ρ=7.87 ton/m^3)
  - Good ν_μ CC identification and NC background reduction
- Main disadvantages:
  - Generally worse spatial resolution
  - Large multiple scattering, increasing momentum resolution
  - High energy threshold for muon identification (~1 GeV)
  - Poor electron identification

Advent of neutrino factories

- Why do we still consider large iron detectors?
- Large magnetized iron detectors became relevant for neutrino factories due to the need to identify sign of muon with high efficiency ("wrong-sign muon" signature)
- "Golden measurements" paper highlighted power of an iron neutrino detector at a neutrino factory for CP violation

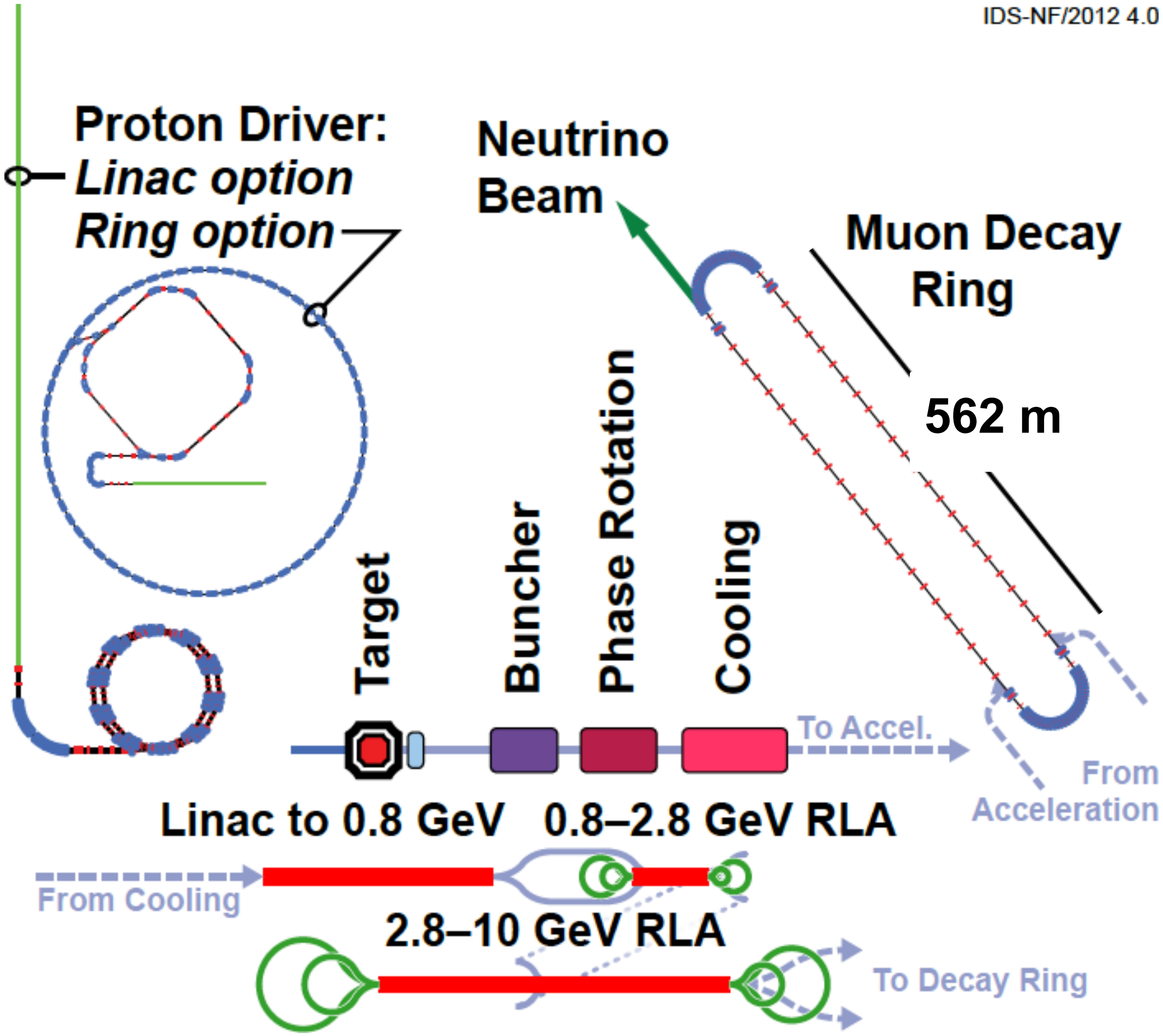
hep-ph/0002108

Nucl Phys B 579 (2000) 17-55

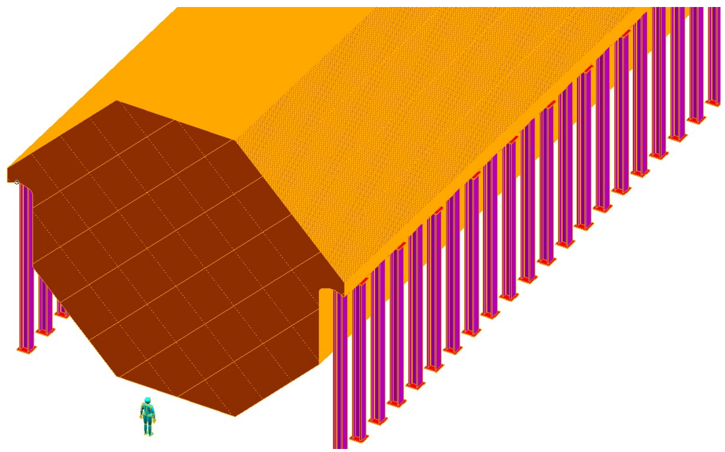
Golden measurements at a neutrino factory

A. Cervera [a,1], A. Donini [b,2], M.B. Gavela [b,3], J.J. Gomez Cádenas [a,4], P. Hernández [c,5], O. Mena [b,6], S. Rigolin [d,7]

MIND at a Neutrino Factory



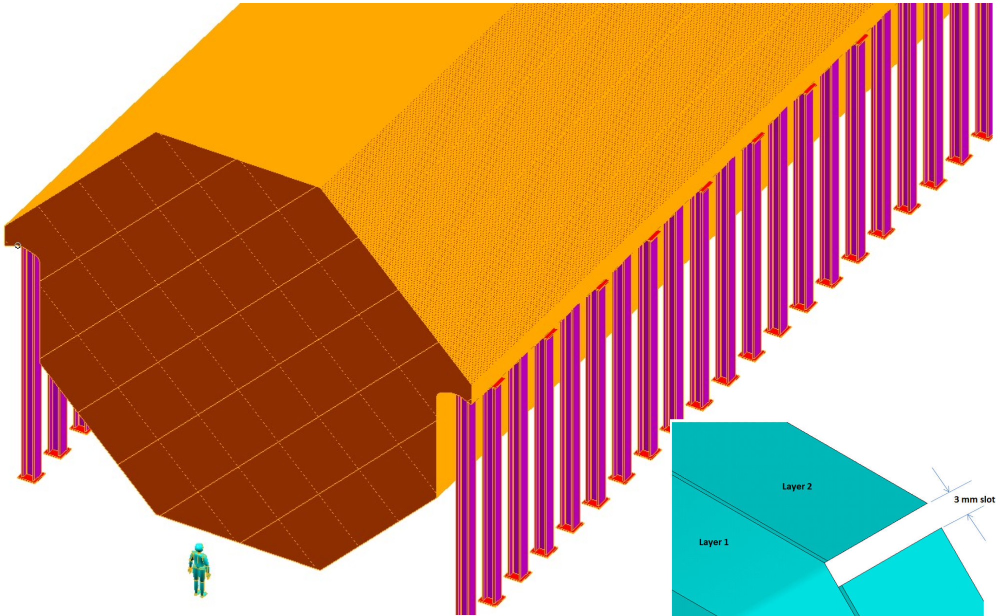
International Design Study for a Neutrino Factory (IDS-NF) Determined optimum design: 10 GeV muons with 100 kton MIND at 2000 km, optimised for large θ_{13} results



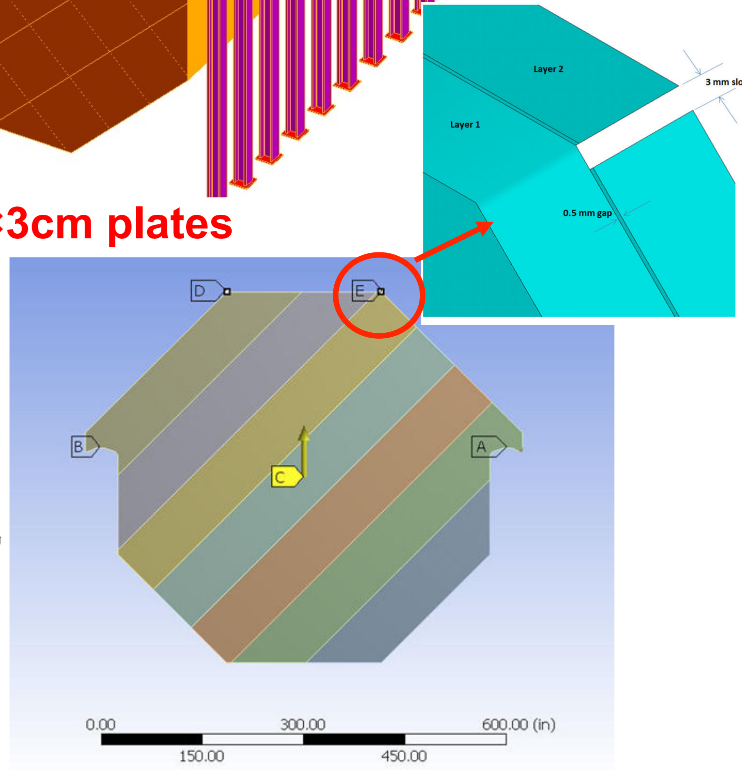
IDS-NF Reference Design Report (RDR), to be published within 1-2 months

MIND at a Neutrino Factory

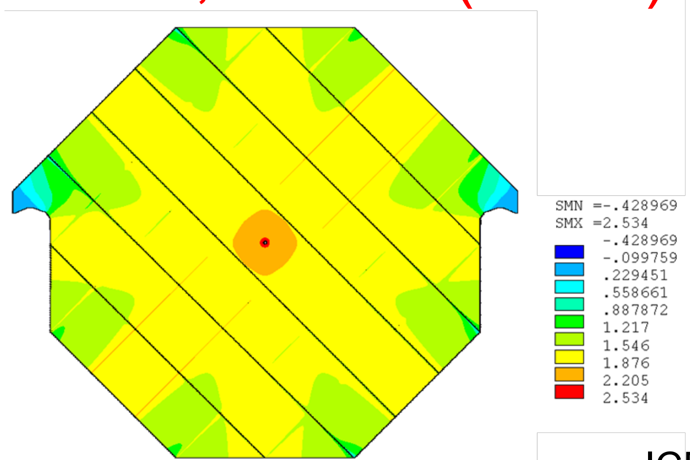
- Magnetised Iron Neutrino Detector (MIND): 100 kton
- Octagonal plates and toroidal field (as in MINOS)
- Engineering metal plates
- Magnetic field 1.2-2.2 T delivered by 100 kA current

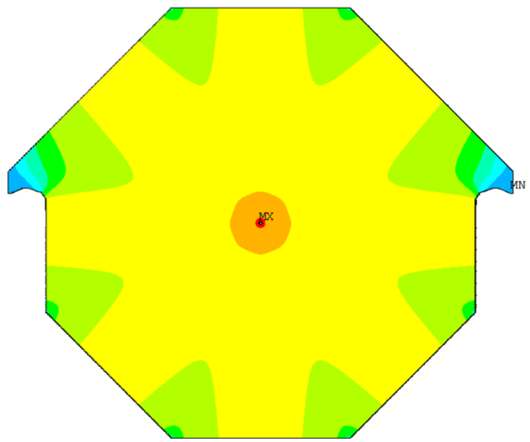


14m×14m×3cm plates



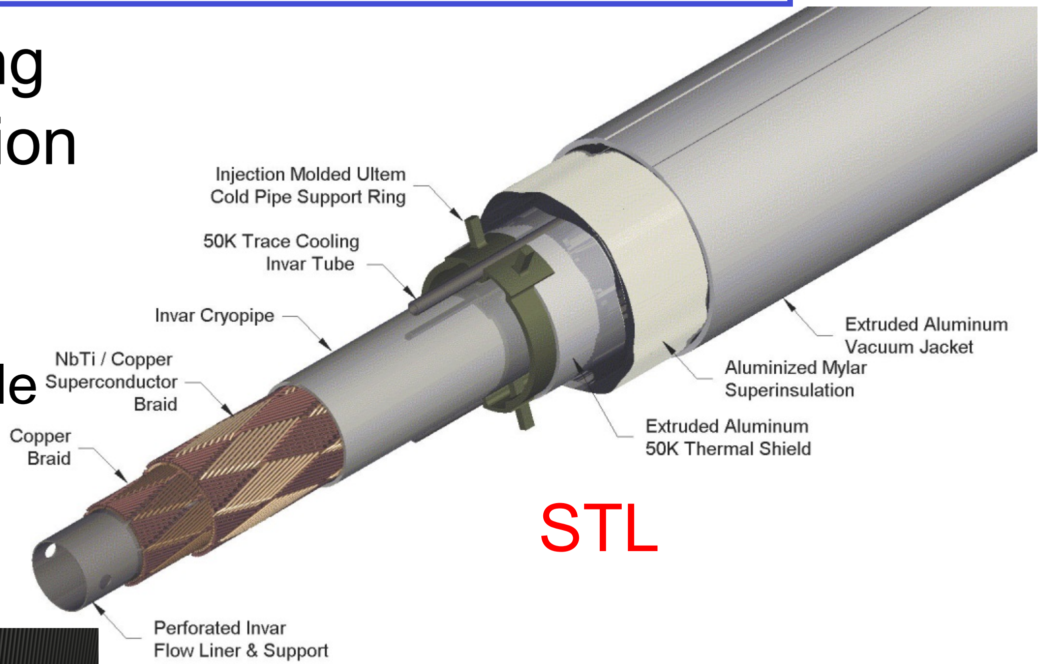
Bross, Wands (FNAL)

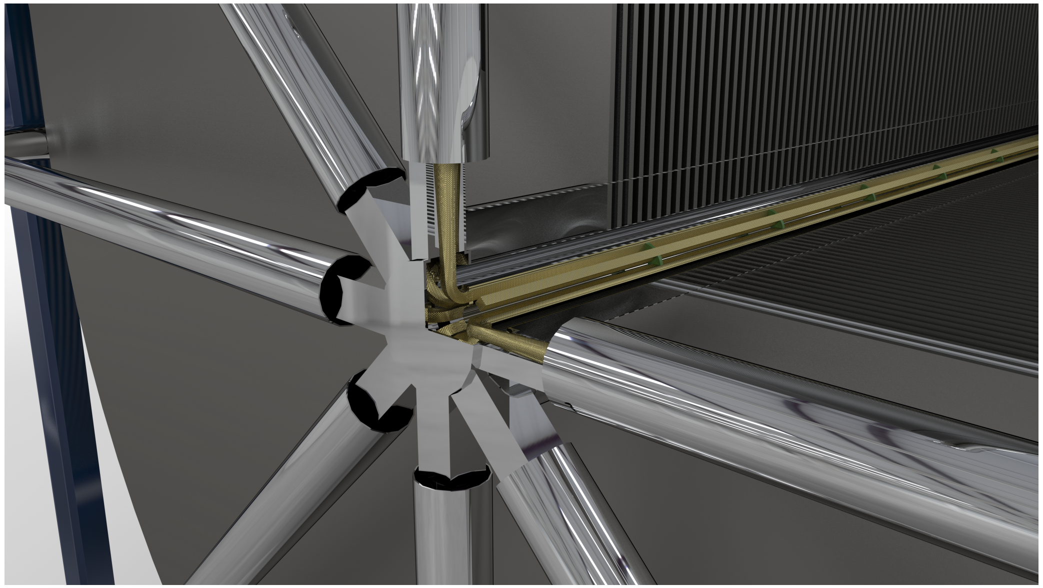




MIND magnetisation

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





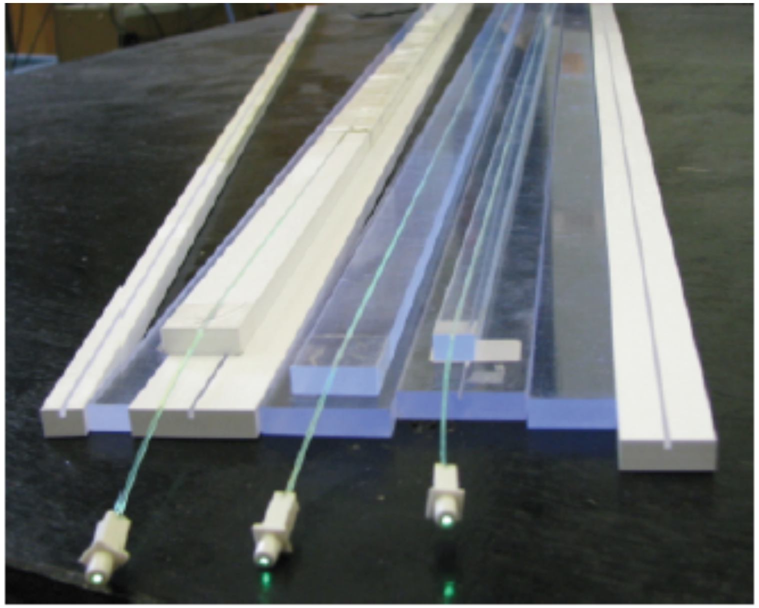
- Multiple coil scheme:
  - More efficient to have 8 STL coils to limit power supplies to <15 kA
  - Diameter hole: 20 cm

Detector readout

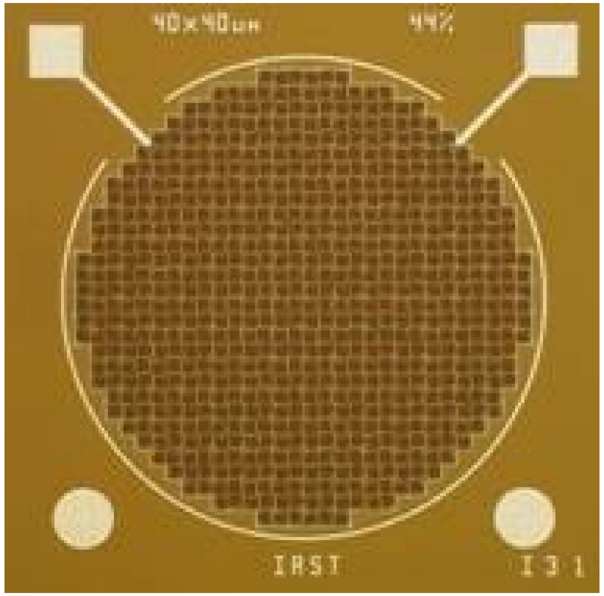
- Extruded scintillator:
  - Mature technology
  - Enough to achieve σ ~1 cm
  - Read out with Kuraray wavelength shifting fibre

- Photon detector:
  - SiPMT (or MPPC) is also now becoming a mature technology
  - Insensitive to magnetic fields
  - Has already been used extensively for T2K ND280 detector

How to teach an old dog new tricks!



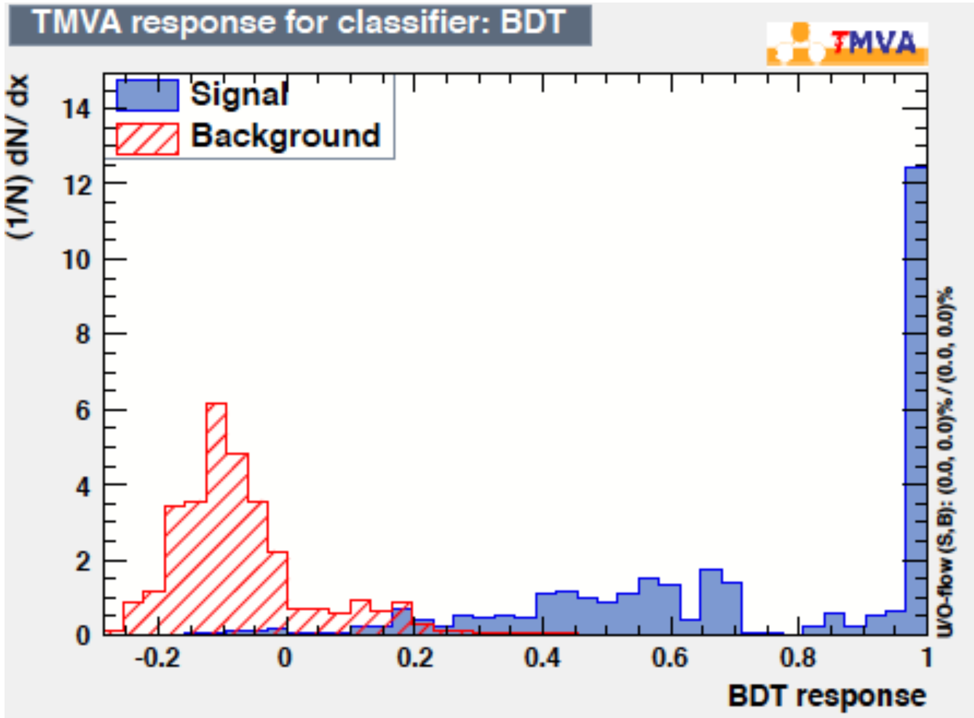
Scintillator and WLS fibre

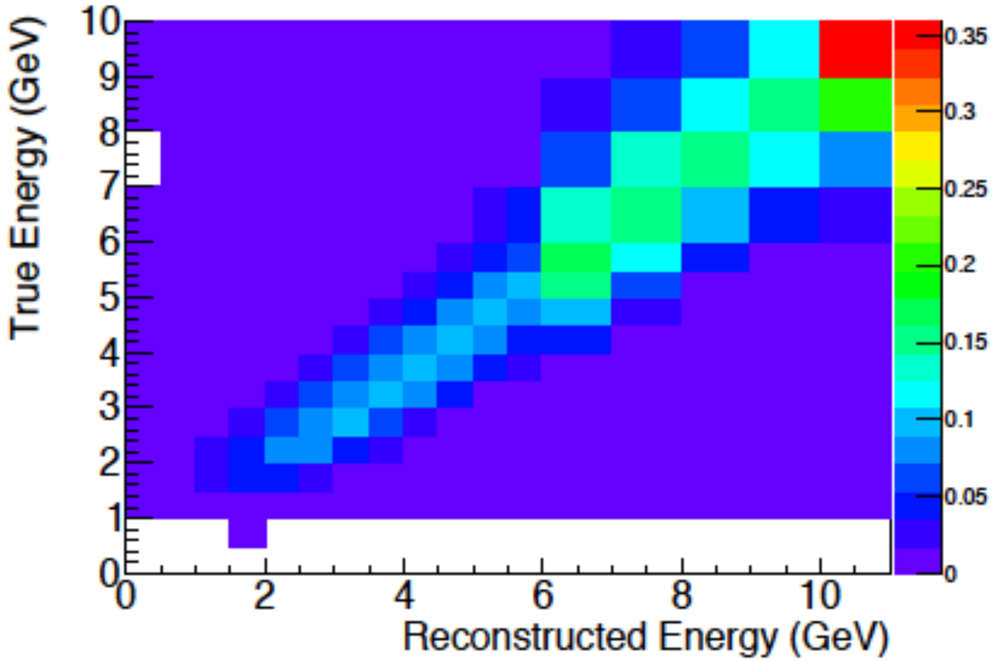


SiPMT

Neutrino Factory MIND analysis

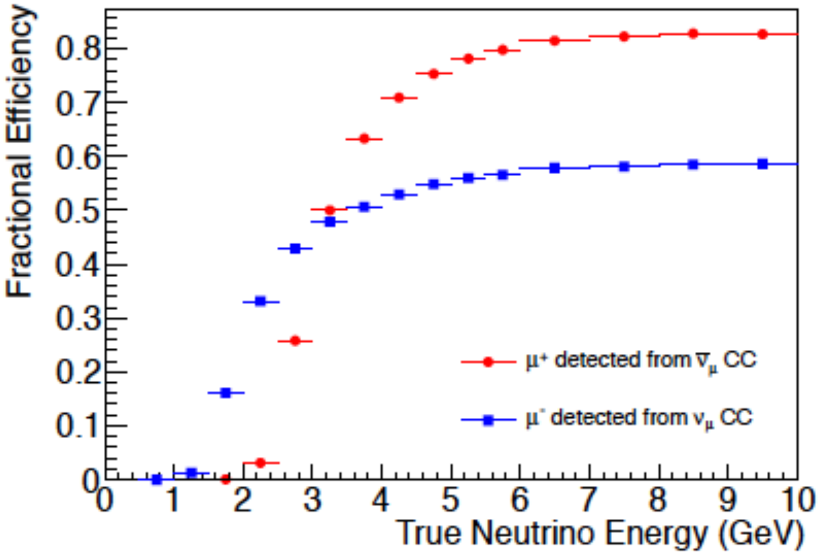
- GENIE generator, GEANT4 simulation and event reconstruction
- Multi-variate analysis (MVA) performed with five variables, tuned for best value of $\sin^2 2\theta_{13}$~0.1
- Boosted Decision Tree (BDT) and K-Nearest Neighbour (KNN) give best performance of MVA methods
- Migration matrices give 2D response of true vs recon energy



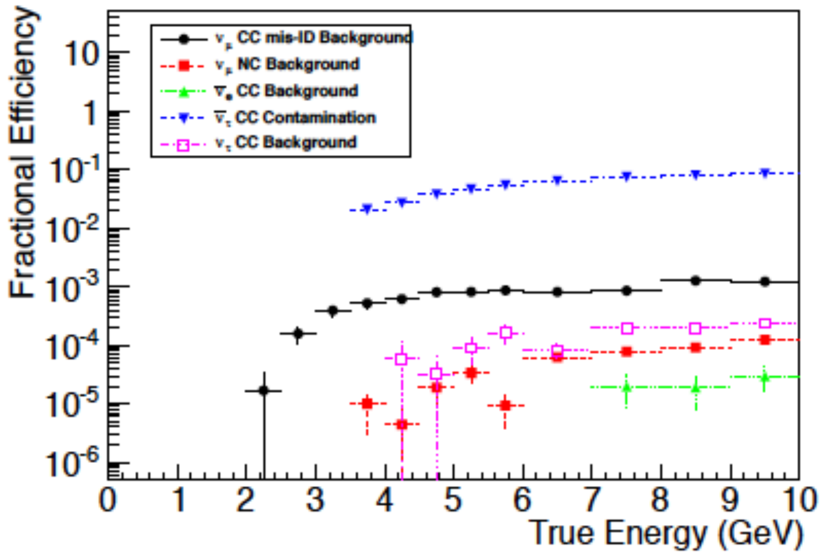


MIND efficiencies and background

BDT efficiency, focussing μ^+

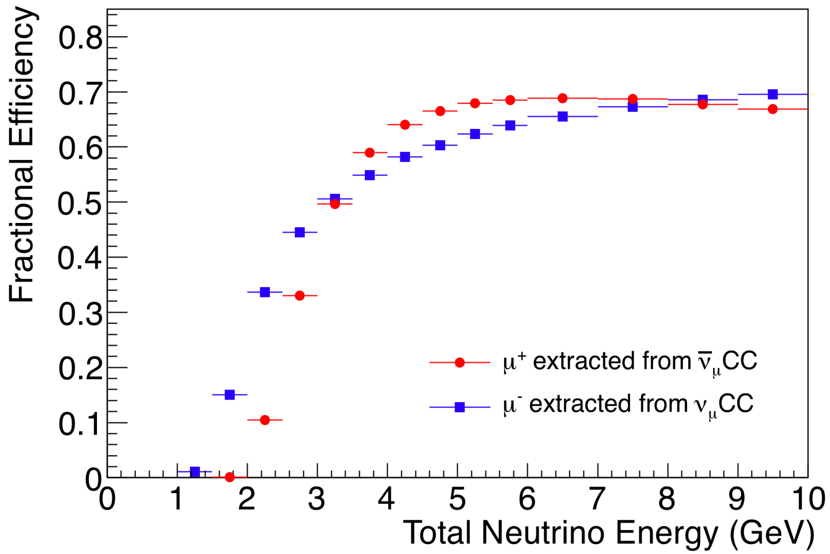


BDT background (stored μ^-, focussing μ^+)

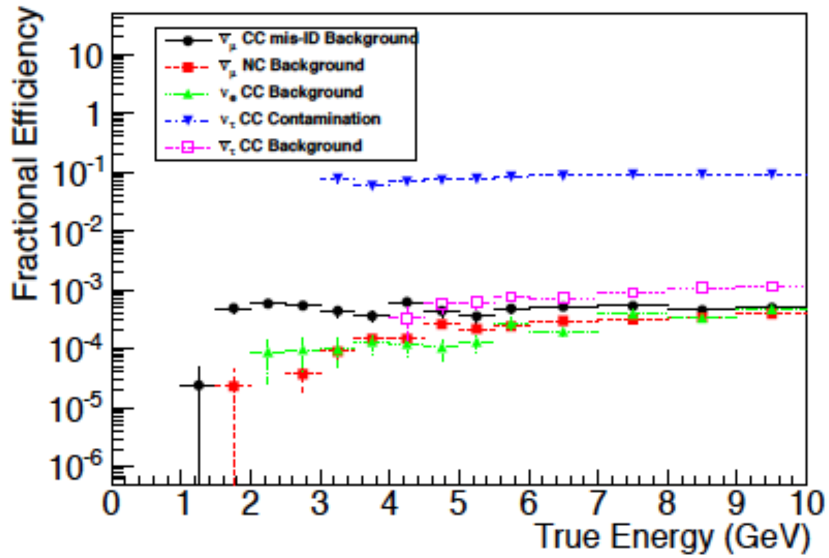


Courtesy R. Bayes

BDT efficiency, focussing μ^-



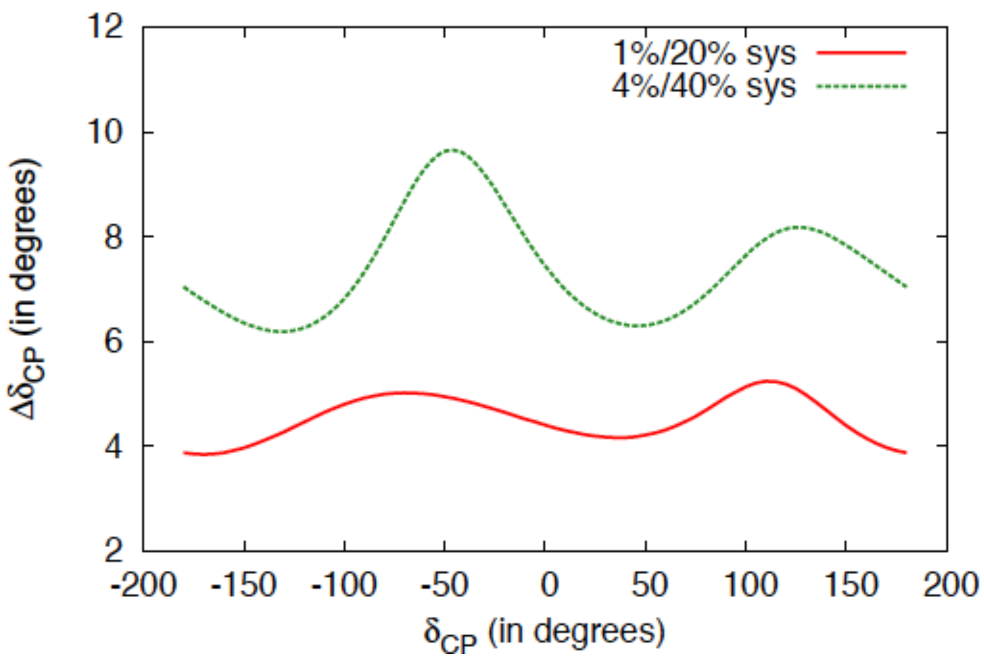
BDT background (stored μ^+, focussing μ^+)

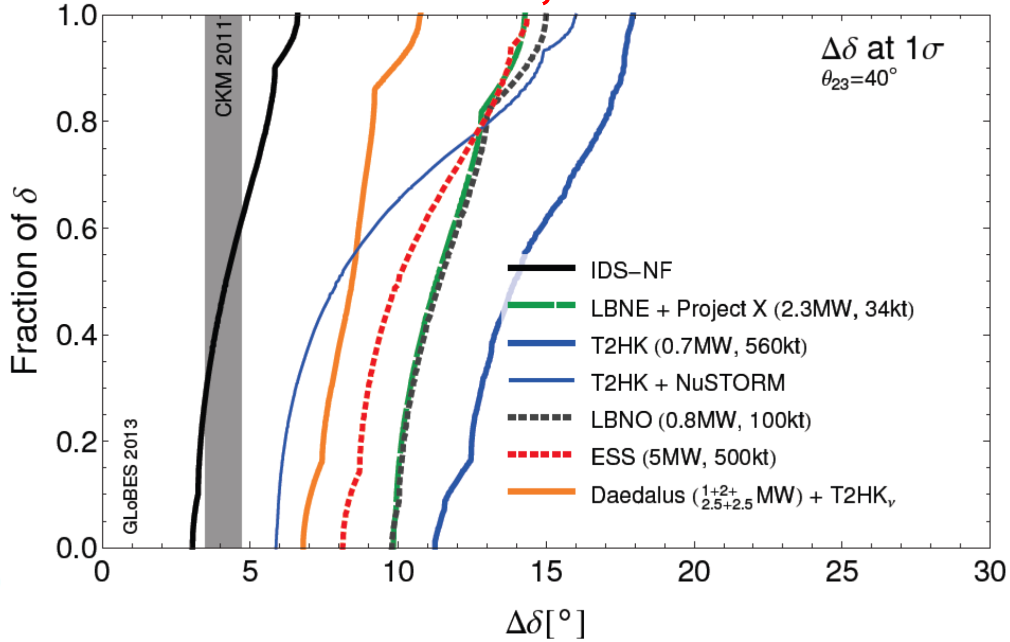


MIND CP sensitivities

- Final sensitivities with GLoBES (1.4% signal and 20% back syst.)
- Precision in δ depends on systematic errors
- Neutrino factory offers best facility for controlling systematic errors and has best sensitivity out of all possible future facilities

Huber, Coloma

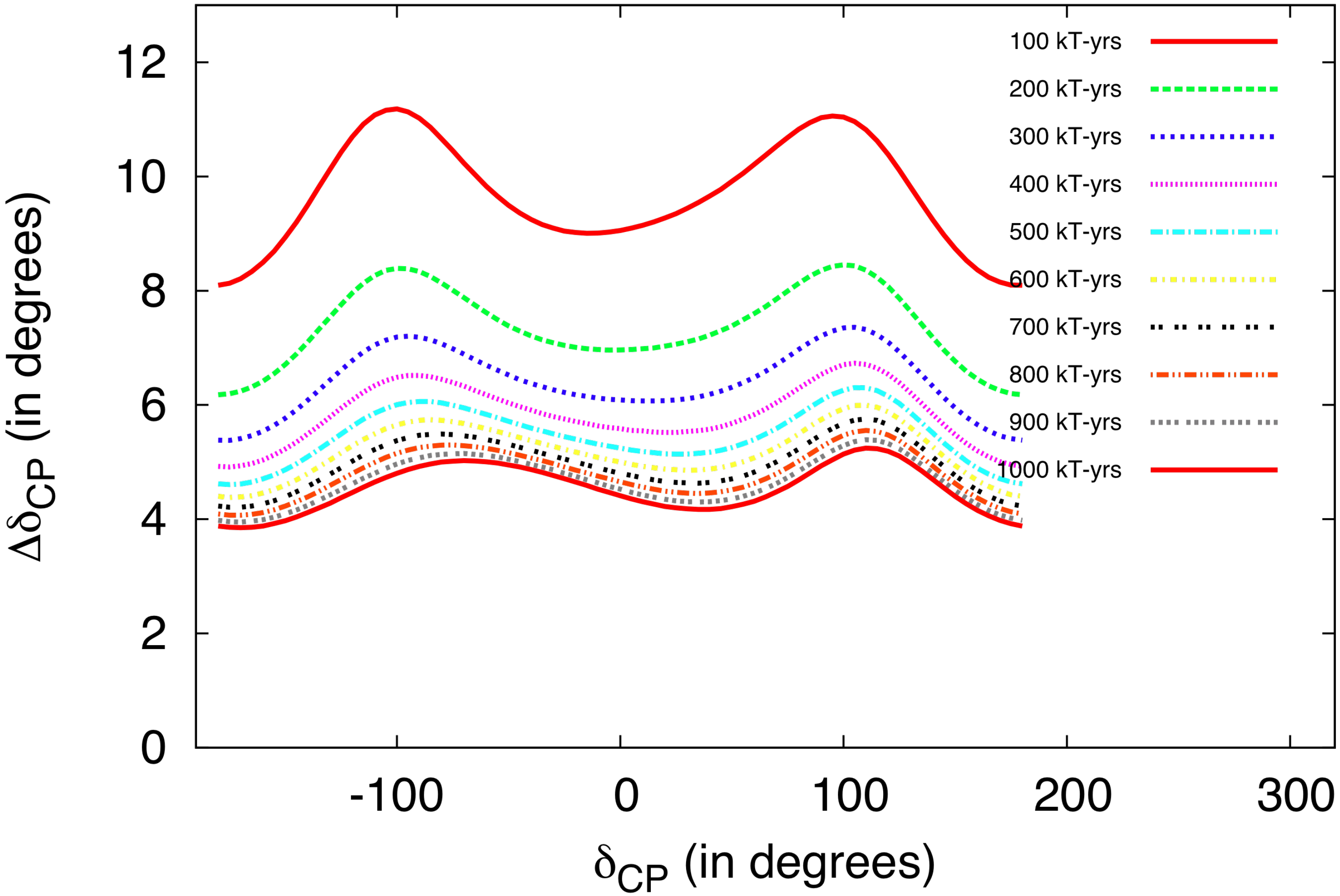




NF yields $\Delta\delta$~4°-5°, regardless of value of δ

MIND CP sensitivities

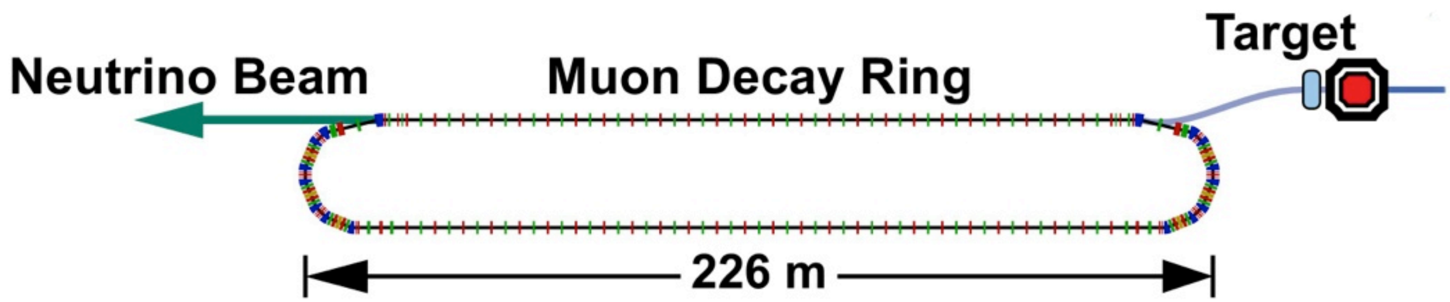
- Facility can be staged: precision as function of exposure:



Precision moves from $\Delta\delta$~8°-11°, to $\Delta\delta$~4°-5°

MIND in nuSTORM

- nuSTORM facility: muon decay ring (3.8 GeV) with no cooling



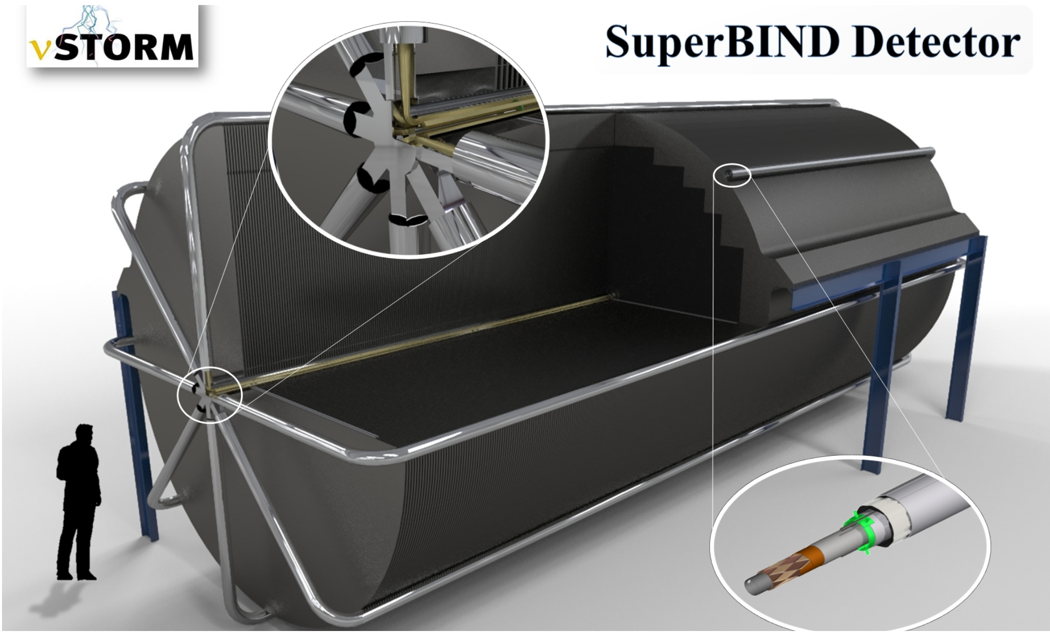
- Physics goals:
  - Resolve short baseline large Δm^2 light sterile neutrino evidence
  - Measure neutrino cross-sections (including ν_e cross-sections) with unprecedented precision
  - Provide accelerator R&D facility for 6D muon cooling experiment
- For sterile neutrino search: two magnetised iron detectors ("SuperBIND") for $\nu_e \rightarrow \nu_\mu$ appearance and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ disappearance search

MIND in nuSTORM

- The $\nu_e \rightarrow \nu_\mu$ appearance probability from $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

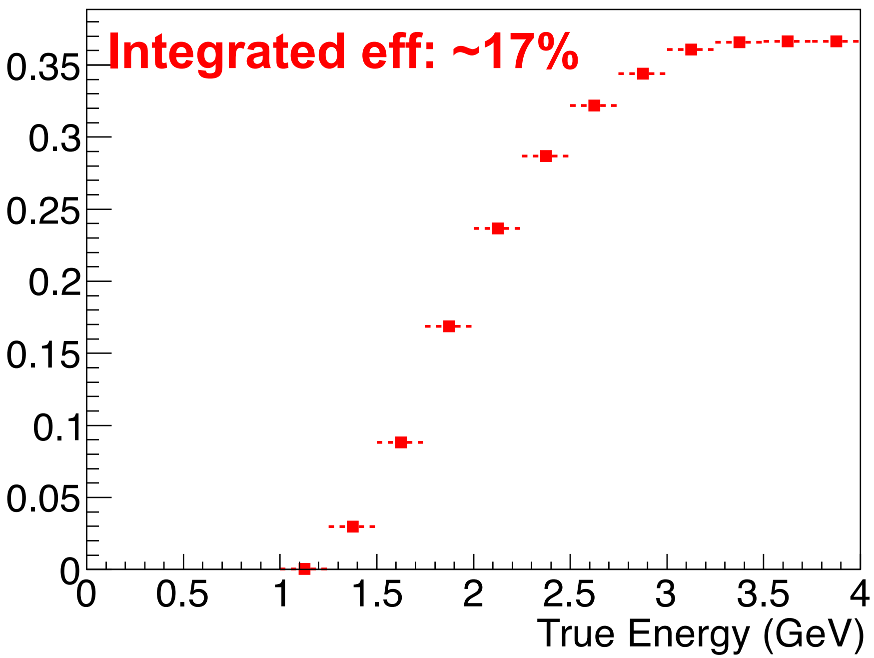
$$P_{e\mu} = \sin^2\theta_{e\mu} \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \qquad \sin^2\theta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

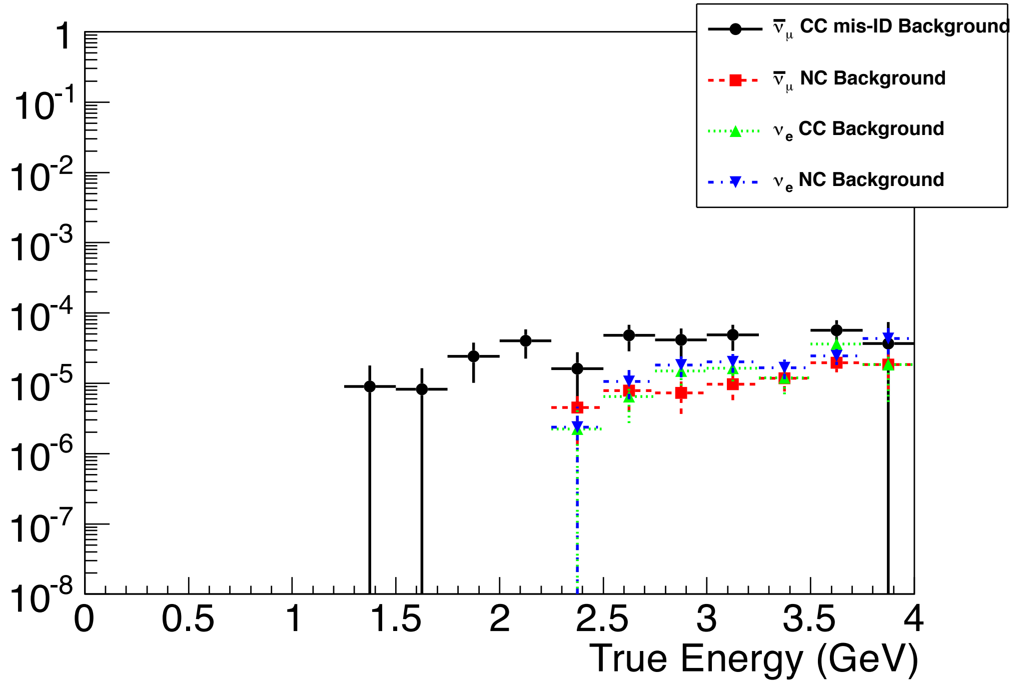
- Near detector ~ 30 m, far detector ~2 km
- SuperBIND: iron slabs 2 cm thick, scintillator 2×1 cm thick
- Multi-variate analysis in both appearance and disappearance



MIND in nuSTORM

- Neutrino appearance efficiency: ~35% for 10^{-5} background acceptance using Boosted Decision Tree (BDT) analysis
  - Expected 73 events with 6 events background (10^{21} pot)





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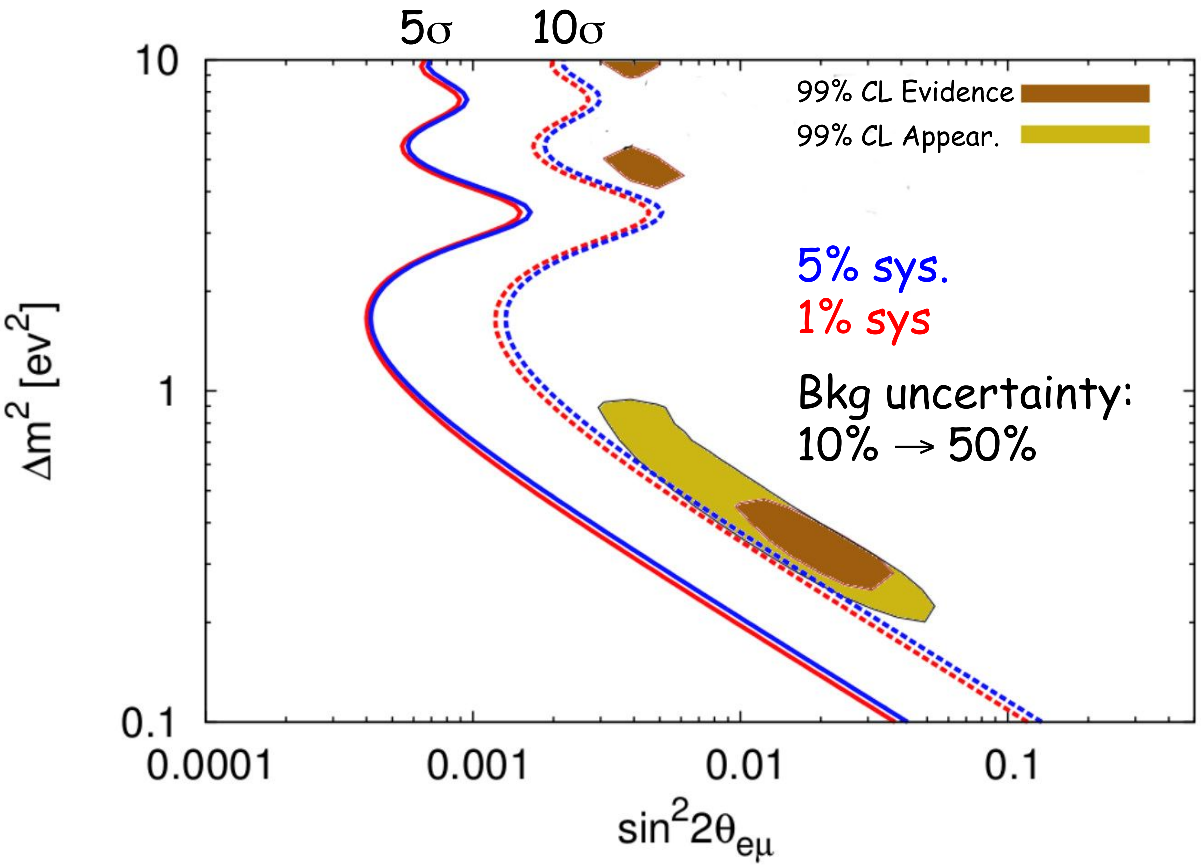


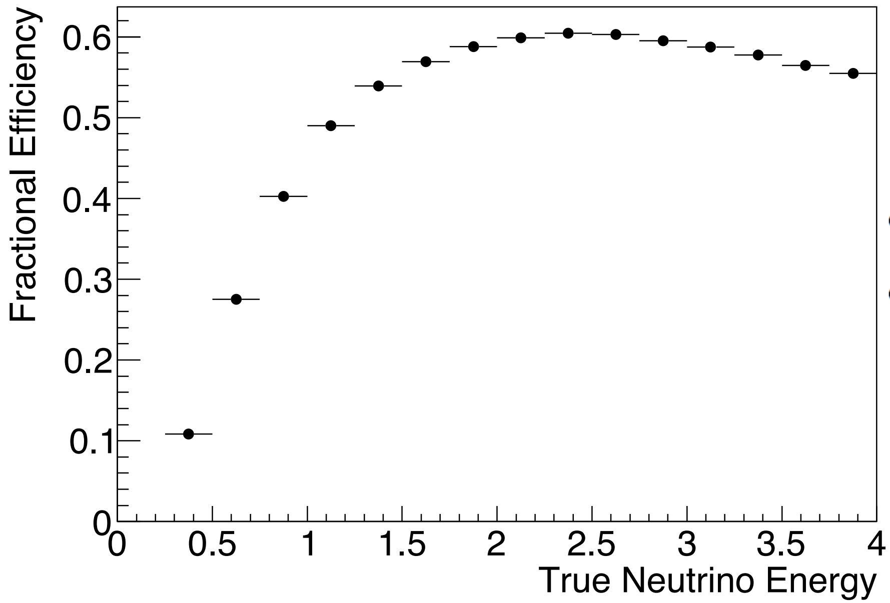
Global fit from: J. Kopp, P. A. N. Machado, M. Maltoni, and T. Schwetz, 392 JHEP 1305, 050 (2013)

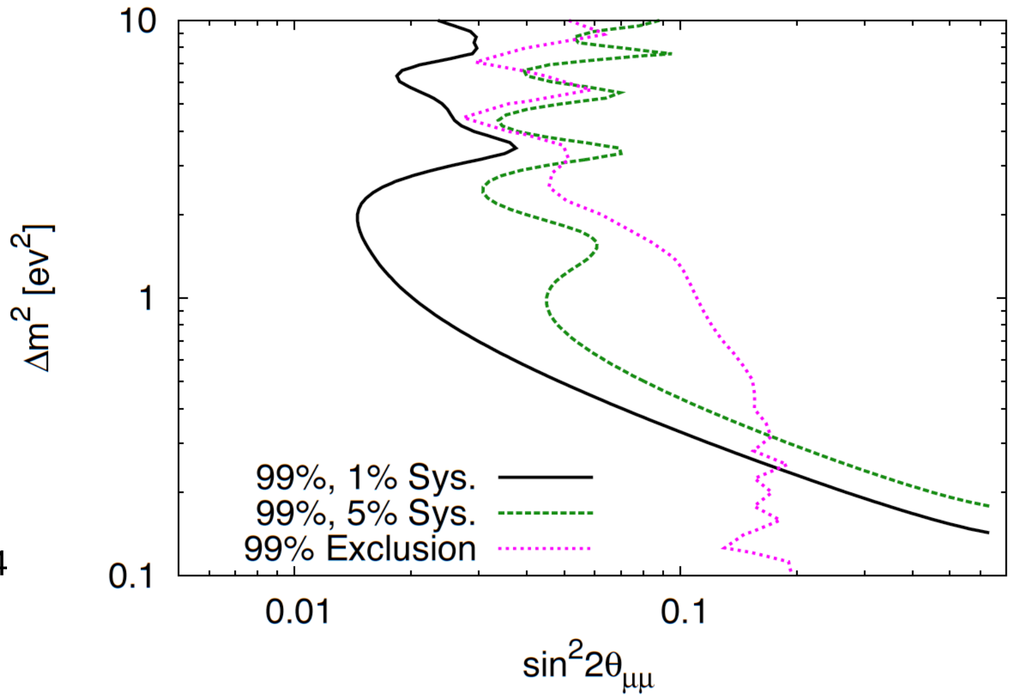
MIND in nuSTORM

- Neutrino disappearance efficiency: ~60% for 10^{-2} background

$$P_{\mu\mu} = 1 - \sin^2\theta_{\mu\mu}\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \qquad \sin^2\theta_{\mu\mu} = 4|U_{\mu 4}|^2\left(1 - |U_{\mu 4}|^2\right)$$

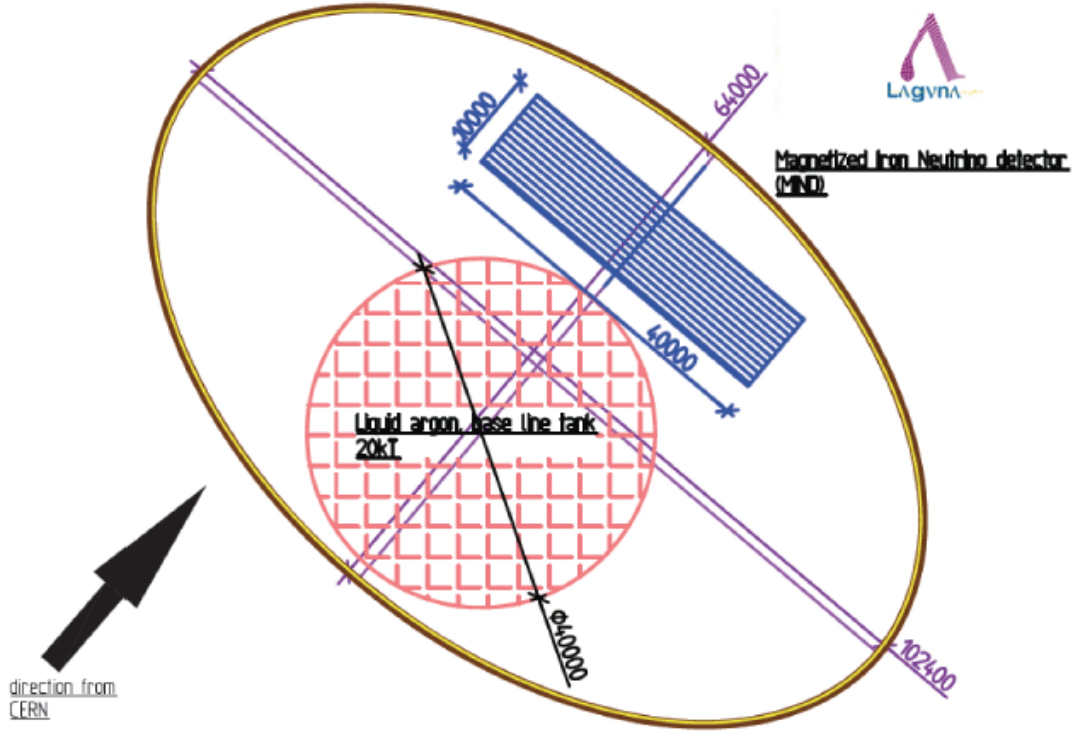
- Combination of two modes allows to test sterile neutrino scenarios and set limits on $|U_{\mu 4}|^2$ and $|U_{e4}|^2$





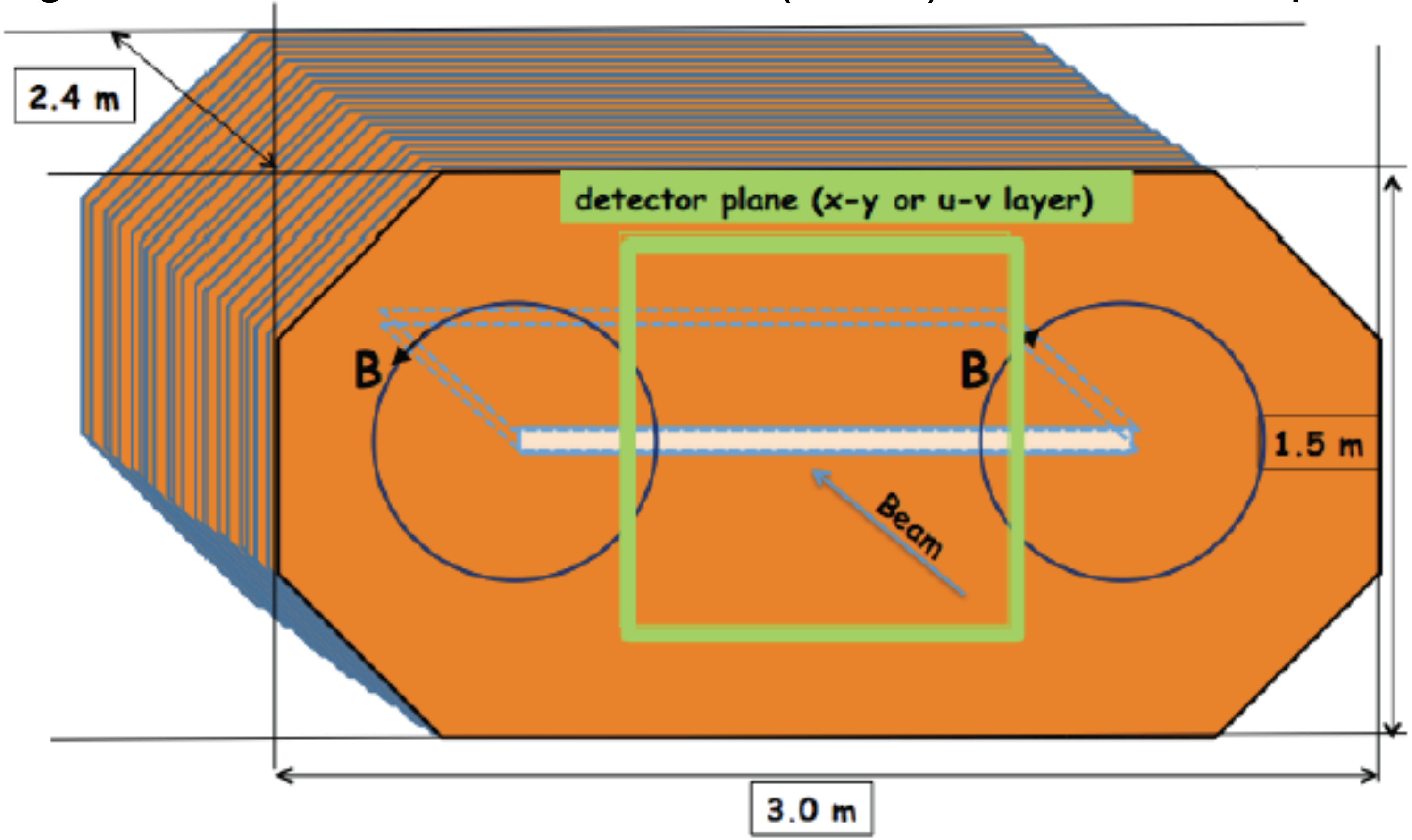
AIDA Test Beam

- Neutrino Factory and nuSTORM analyses rely on GENIE and GEANT4 simulations of interactions and detector
- We need to test assumptions of simulations using test beams
- LAGUNA-LBNO detector also assumes a Magnetized Iron Detector for muon momentum measurement



AIDA Test Beam

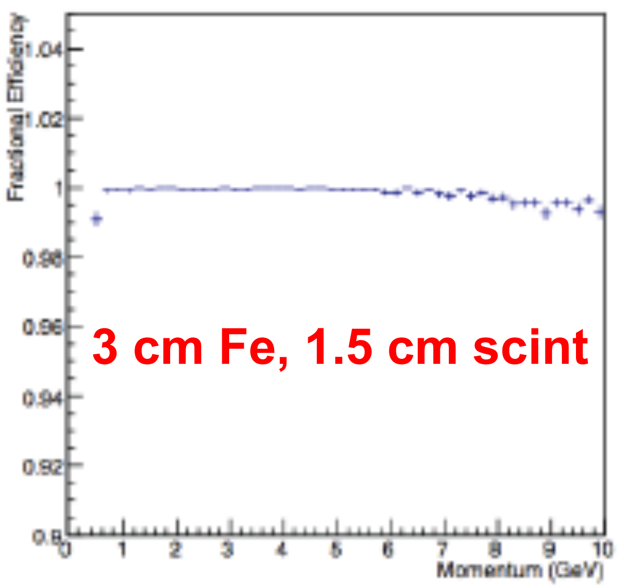
- AIDA (Advanced Infrastructures for Detectors at Accelerators):
  - Develop a new low-energy test beam facility at CERN
  - Build and develop a Totally Active Scintillator Detector (TASD) and Magnetized Iron Neutrino Detector (MIND) for neutrino experiments

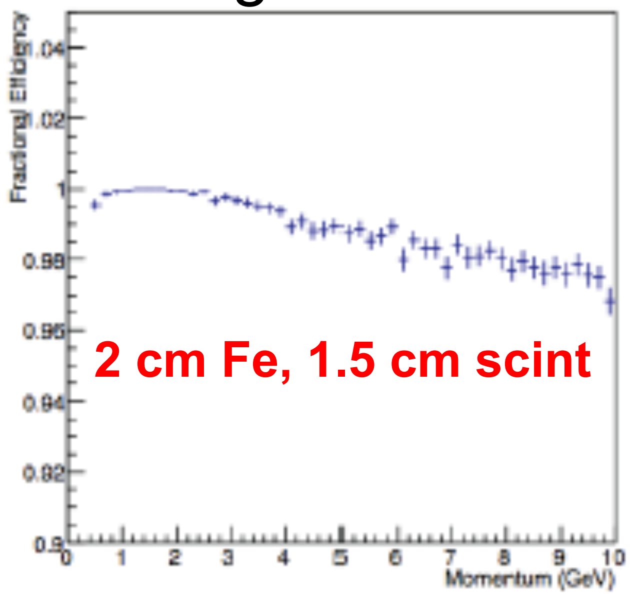


AIDA Test Beam

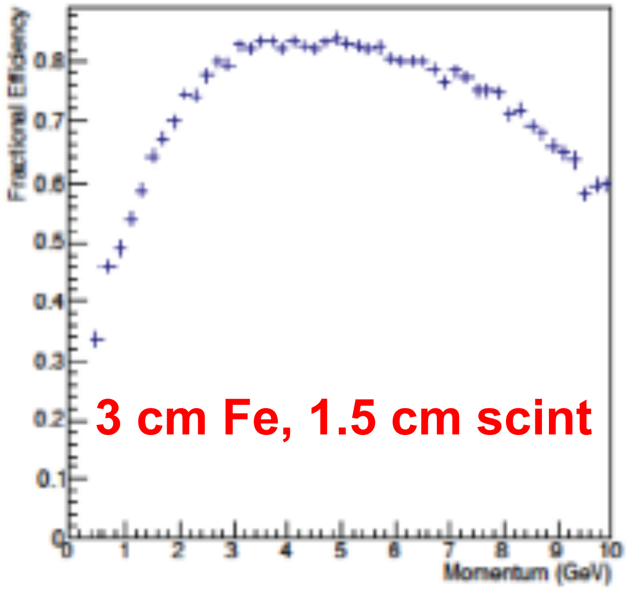
- GEANT4 simulations of different MIND configurations

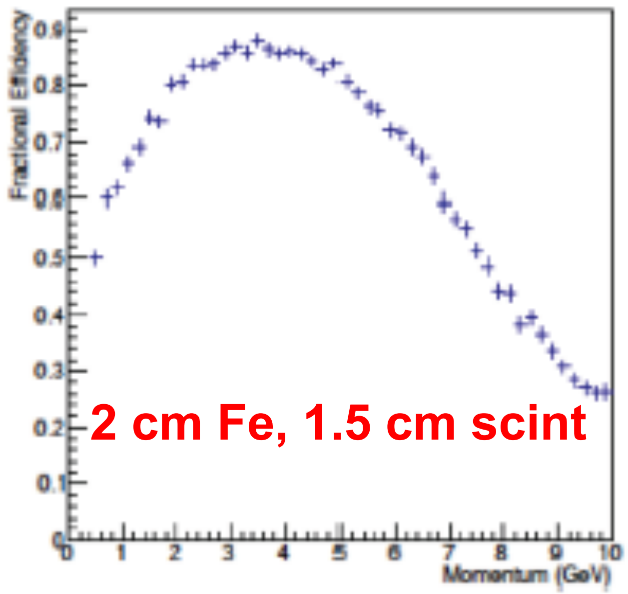
μ^+ reconstruction efficiency





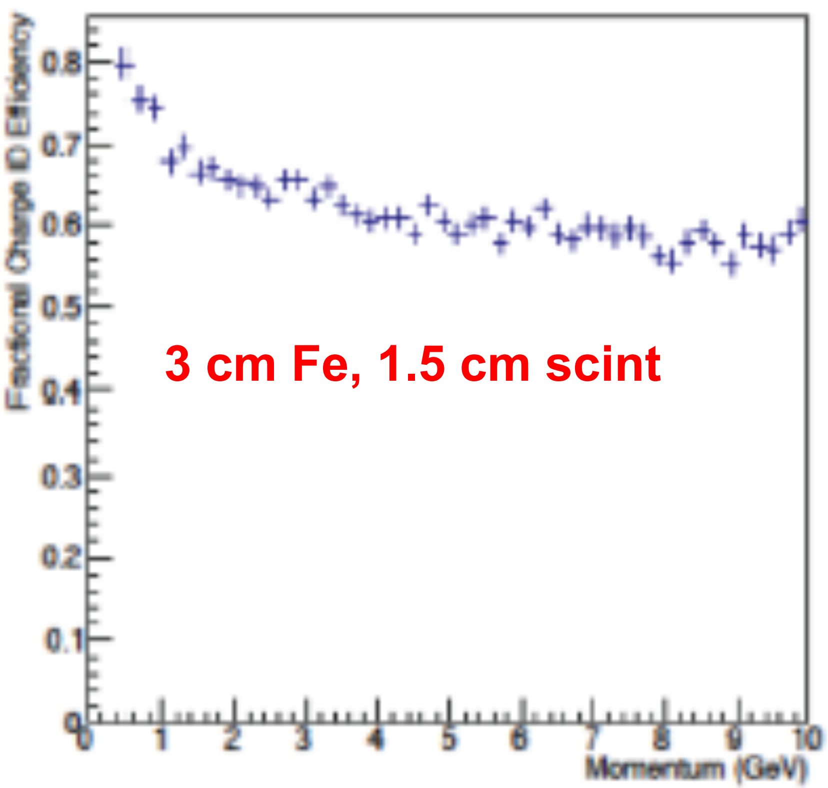
π^+ reconstruction efficiency

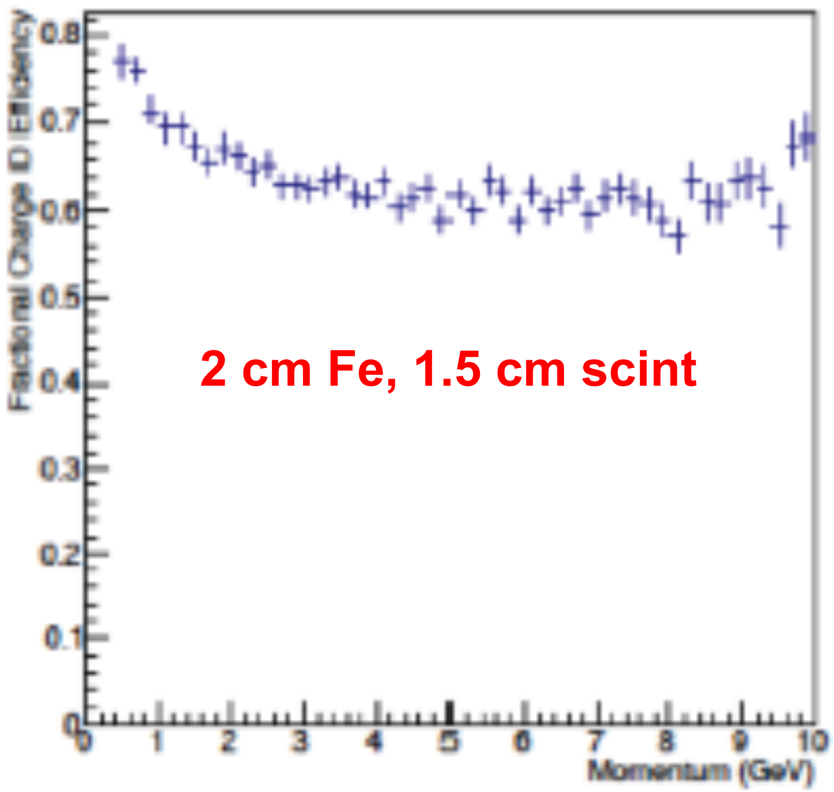




AIDA Test Beam

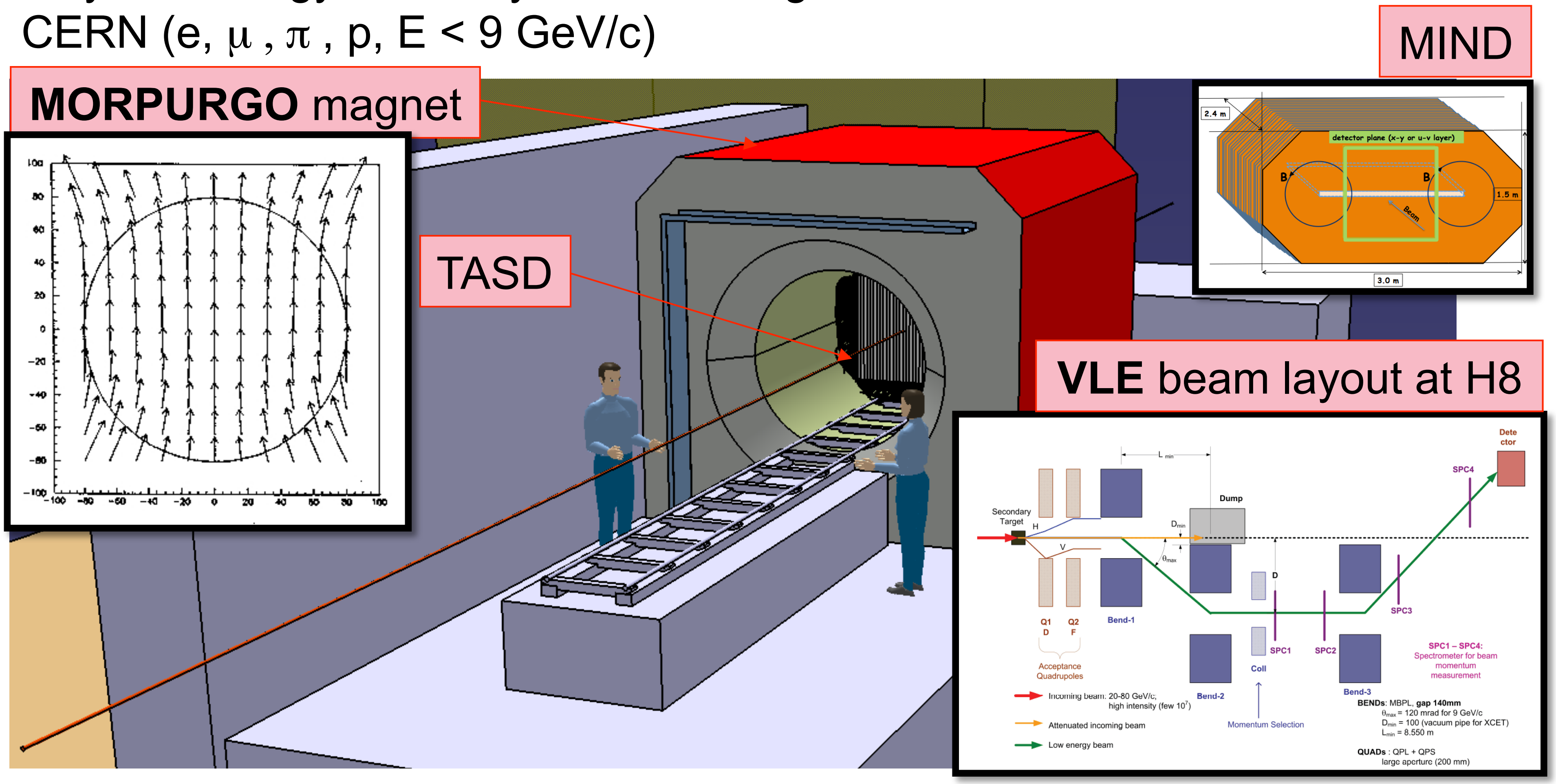
- GEANT4 simulations of different MIND configurations
  - **π^+ charge identification efficiency**





SPS Beam Request for MIND

- Plans to test MIND and TASD prototypes (2015, €400k) presented to SPS committee (June 2013). Formal request for SPS beam time is being finalized for submission.
- Recent study (Nov 2013) under AIDA WP8.2.1 reported feasibility of very low energy beam layout at existing H8 beam line in North Area at CERN (e, μ , π , p, E < 9 GeV/c)



Conclusions

- Magnetized Iron Neutrino Detectors (MIND) are most effective way to provide magnetic field for large neutrino experiments
- Recent studies have shown that:
  - MIND at a Neutrino Factory offers best chance to discover neutrino CP violation
  - MIND at nuSTORM offers best available sensitivity for light sterile neutrino search
  - MIND at LBNO supplies muon catcher for mass hierarchy and first level CP violation search
- Robust detector designs are available, some R&D required to:
  - Track progress in technologies (ie. photosensors, electronics, …)
  - Refine costing models
  - Benchmark assumptions made in the simulations
- AIDA low energy test beam facility at CERN for detector R&D and performance studies