Neutrino Detector R&D in Europe

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University of Warwick
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EuroNu

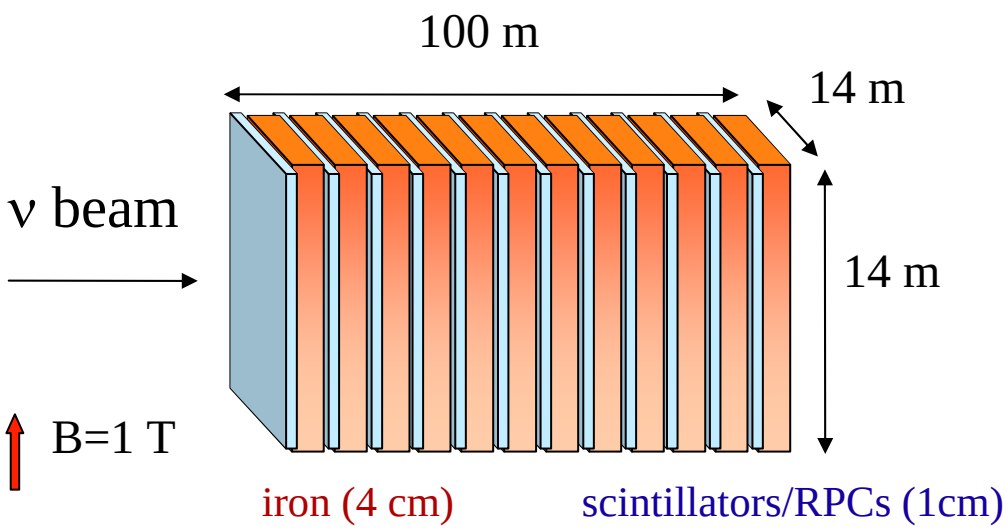
- Europe aspires to host a major neutrino accelerator facility (Neutrino Factory, beta beam, or a future Superbeam project) or to host large neutrino detectors for neutrino oscillations or neutrino astrophysics
- EuroNu was approved by the EU as a Design Study for “A High Intensity Neutrino Oscillation Facility in Europe”, recognising the large European community interested in carrying these projects
- EuroNu will carry out a design study for:
  - **Super-Beam: design of a 4 MW proton beam (SPL), target and collection system for a conventional neutrino beam**
  - **Neutrino factory: define design for muon front-end, acceleration scheme, spent proton beam handling and component integration in an end-to-end neutrino factory simulation**
  - **Beta beam: following from EURISOL, study production, collection and decay ring of beta beam for high Q isotopes (^{8}Li, ^{8}B)**
  - **Neutrino detectors: study Magnetised Neutrino Iron Detector (MIND) performance for golden measurement at a neutrino factory, water Cherenkov detector for beta and super beams and near detectors for all facilities**
  - **Physics: comparison of physics performance, systematic errors and optimisation for all facilities**

Detector tasks in EuroNu

- Define the baseline detector options needed to deliver the physics for each of the neutrino facilities.
- Priorities include baseline detector options from ISS
  - Magnetised Iron Neutrino Detector (MIND) for the golden channel at a Neutrino Factory,
  - Water Cherenkov detector for the Super-Beam and Beta Beam facilities
  - Performance of a near detector at each of the facilities for absolute flux normalisation, measurement of differential cross sections and detector backgrounds.
- Desirable studies: extensions to the baseline options
  - Totally Active Scintillator Detector (TASD) and Emulsion Detectors for the platinum and silver channels
  - Define beam instrumentation and shielding requirements for the near detector.

Detector tasks in EuroNu

1. Coordination task: Leading the task, with responsibility for the coordination work
2. MIND task: Simulation of the magnetic iron neutrino detector (MIND), Neutrino Factory baseline from ISS, including implementation of a toroidal field, optimisation of the geometry, event selection, efficiency as a function of threshold, background evaluation and cost estimate

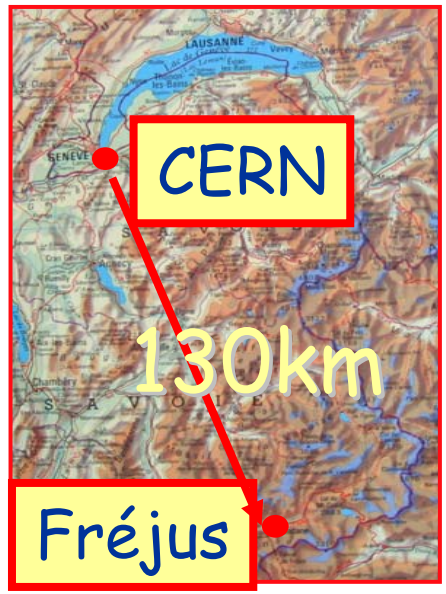


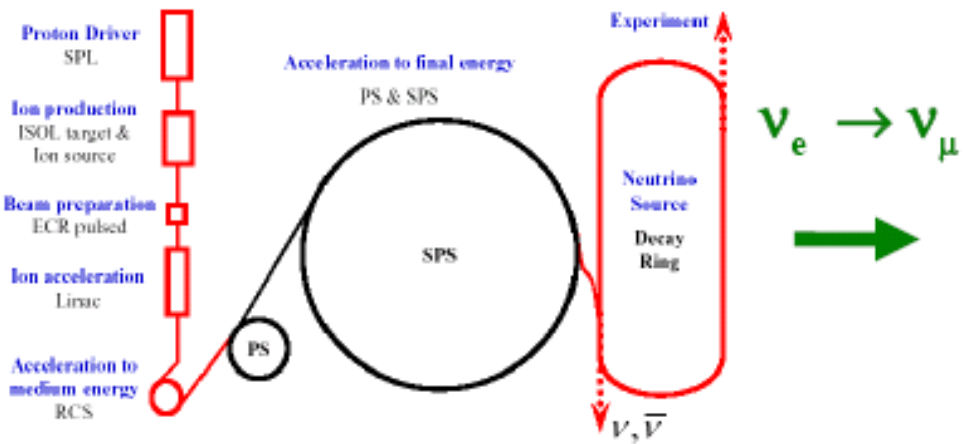
M~100 KTon

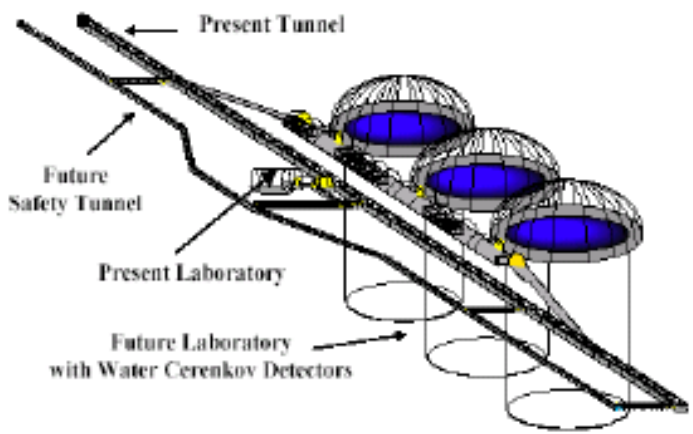
1cm transverse resolution

Detector tasks in EuroNu

3. Water Cherenkov task: Define performance of water Cherenkov detectors for Super-Beam and Beta Beams, including efficiency as a function of threshold and background, and cost estimate

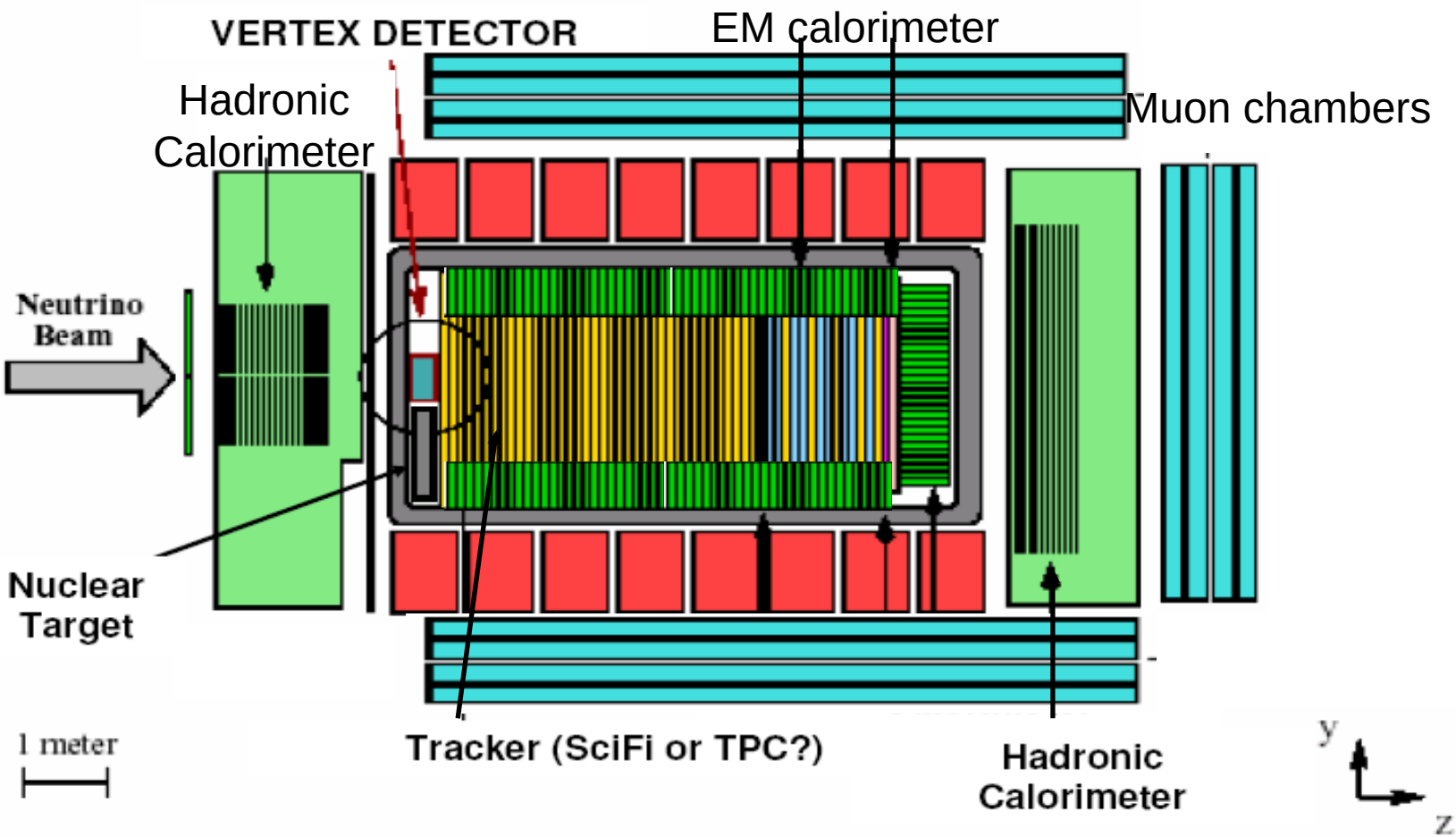






Detector tasks in EuroNu

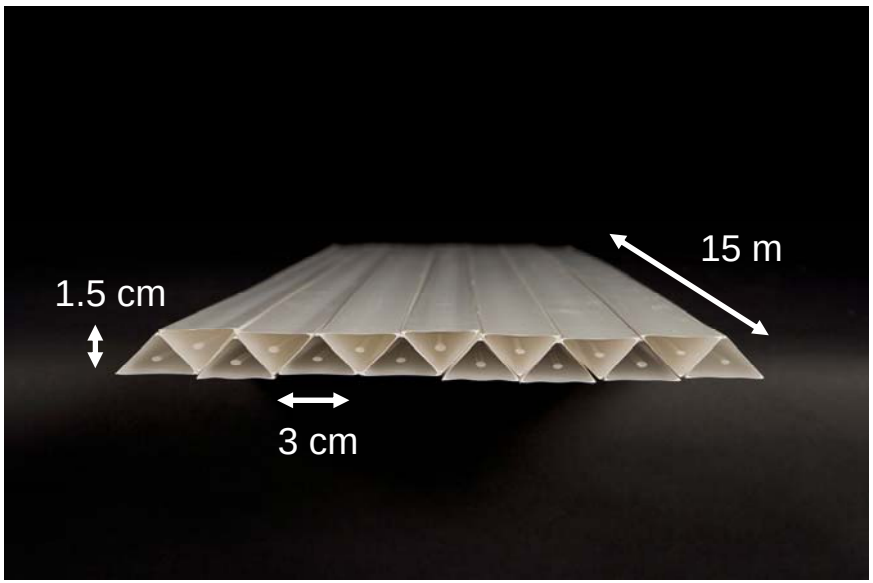
4. Near detector task: Design for the near detector in order to measure the absolute flux normalisation, differential neutrino cross sections, backgrounds to the far detector, and cost estimate

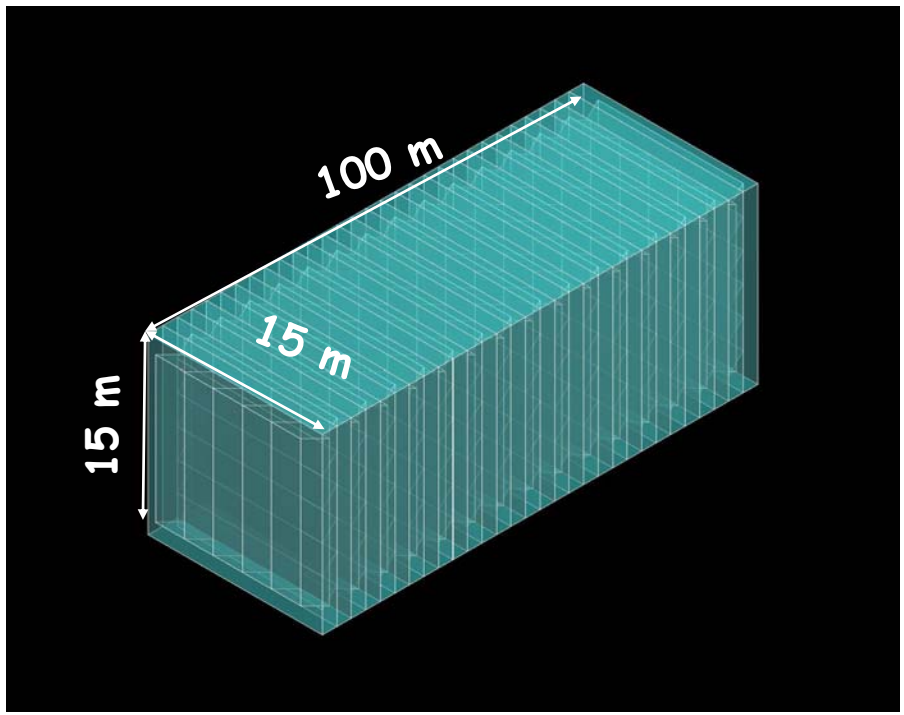


Other desirable studies in EuroNu

Possible improvement: Totally Active Scintillating Detector (TASD) using Nova and Minerva concepts

Reduction threshold: access second oscillation maximum and electron identification (platinum channel)





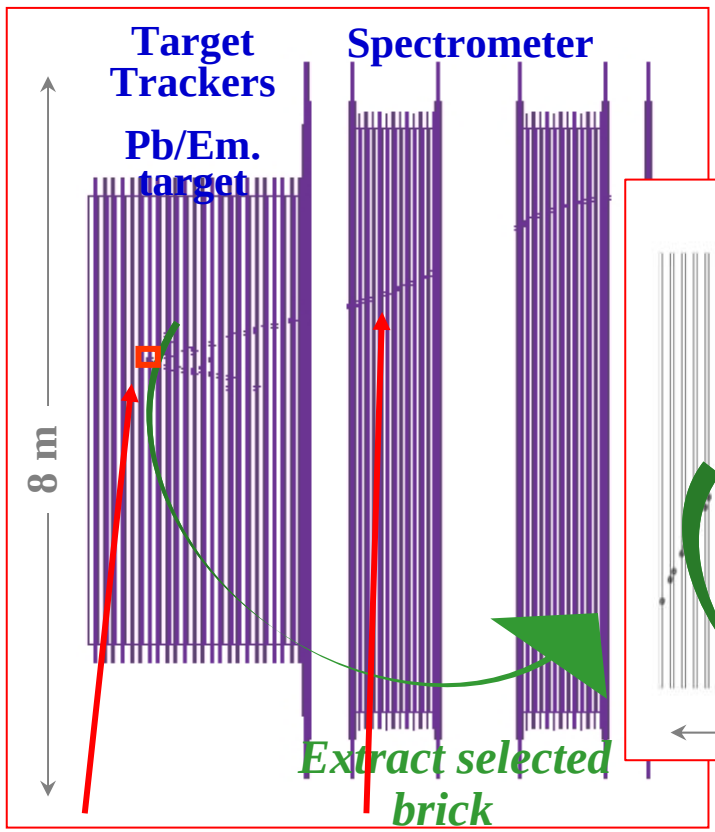
Other desirable studies in EuroNu

Hybrid emulsion-scintillator far detector (like Opera)

- For 60 walls emulsion ⇨ 1.1M bricks ⇨ 4.1 kton
- Total length of detector is: ~ 150 m

Golden and silver channels simultaneously!

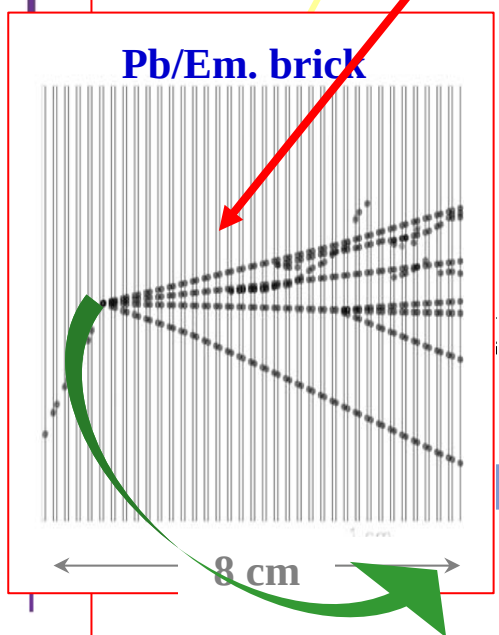
Electronic detectors:



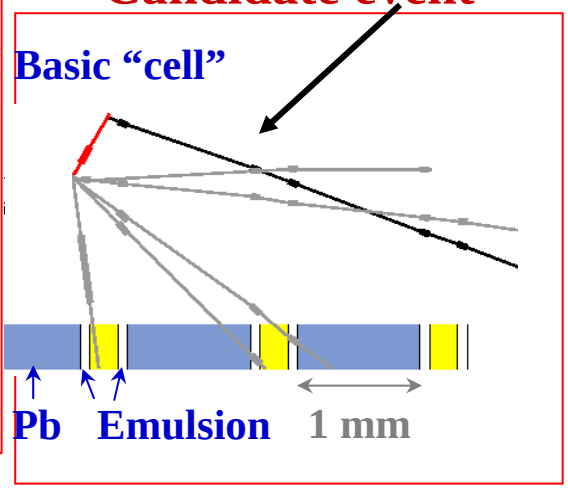
Brick finding, muon ID, charge and p

ECC emulsion analysis:

Vertex, decay kink e/γ ID, multiple scattering, kinematics



Link to muon ID,
Candidate event



Δp/p<20%

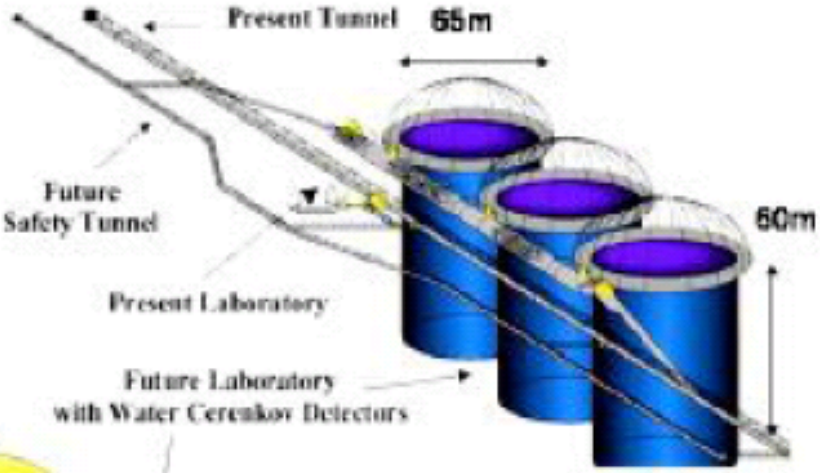
Laguna

- Laguna (Large Apparatus for Grand Unification and Neutrino Astrophysics) is a design study to detect the feasibility of building large underground detectors for neutrino physics and proton decay.
- Typical size of detectors: 10^5-10^6 tonnes
- Very large underground infrastructures
- It covers three potential technologies: very large water Cherenkov detectors (~0.5 Mtonne Memphys), liquid scintillator detectors (LENA - Low Energy Neutrino Astronomy) or liquid Argon detectors (GLACIER – Giant Liquid argon Charge Imaging ExpeRiment) .
- Physics motivation:
  - Proton decay
  - Low energy astrophysics: supernova (SN) explosions, diffuse background of SN neutrinos, solar neutrinos and geoneutrinos.
  - Detectors can also carry out high statistics atmospheric neutrino searches and for neutrino oscillation experiments (reactor and accelerator)
  - Coordination office for Linear Collider

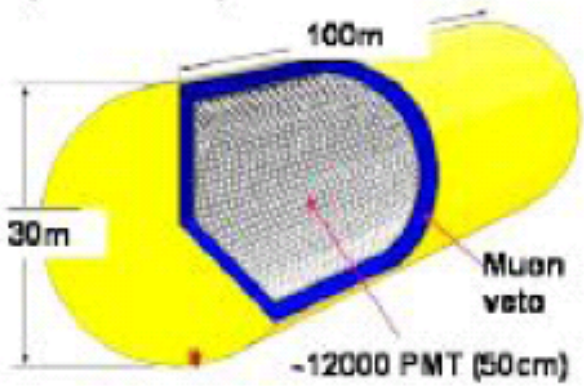
Laguna

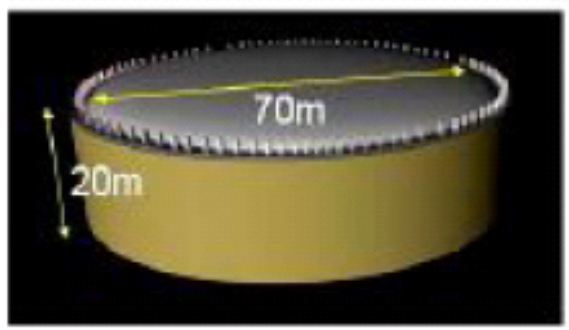
Three liquids: water (MEMPHYS), scintillator (LENA), liquid argon (GLACIER)

MEMPHYS:
Water Cherenkov,
(420 kton -1 Mton)



LENA:
Liquid Scintillator
(30-70 kton)





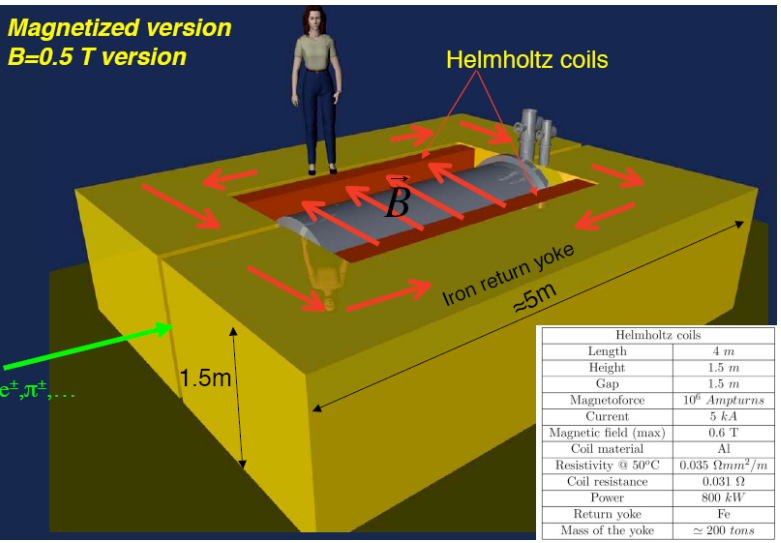
GLACIER: Liquid Argon (50 -100 kton)

DevDet

- DevDet is a new Integrating Activity proposal across Europe to coordinate "Detector Development Infrastructures for Particle Physics Experiments"
- It is a 37.8 M€ proposal to the European Union (EU) with a requested EU contribution of 11.0 M€. It has 87 participants from 21 different countries
- It includes the luminosity-upgraded LHC (SLHC), future Linear Colliders (ILC/CLIC), future accelerator-driven facilities and B-physics facilities (Super-B)
- The proposal covers:
  - Development of common software
  - Development of common microelectronics tools
  - Coordination office for Linear Collider
  - Coordination office for Neutrino facilities
  - Test beam infrastructures at CERN and DESY
  - Irradiation facilities at CERN and other European countries
  - Transnational access to all facilities
- The Neutrino community will benefit since a coordination office for Neutrino Facilities will coordinate R&D from other work packages (common software, common microelectronics and test beam infrastructures for neutrino facilities).

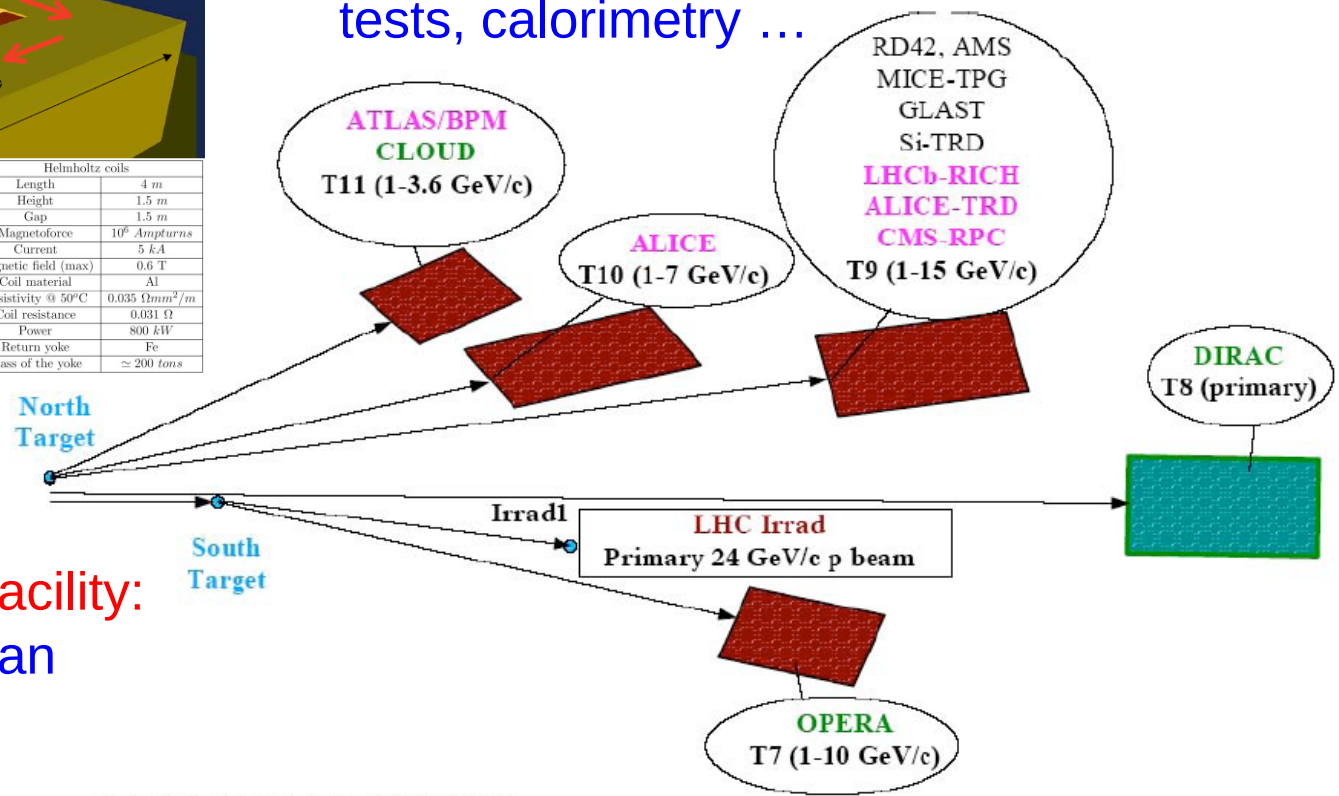
DevDet

- Possible dedicated Neutrino Detector R&D test beam either in East Area at the CERN PS, or North Area at SPS: fixed dipole magnet



Helmholtz coils	
Length	4 m
Height	1.5 m
Gap	1.5 m
Magnetoforce	10^6 $Ampturns$
Current	5 kA
Magnetic field (max)	0.6 T
Coil material	Al
Resistivity @ 50°C	0.035 $\Omega mm^2/m$
Coil resistance	0.031 Ω
Power	800 kW
Return yoke	Fe
Mass of the yoke	$\simeq$ 200 $tons$

Prototype MIND, Liquid Argon tests, beam telescopes for silicon pixel and SciFi tests, calorimetry …



EAST AREA LAYOUT
(2006 Situation)

Neutrino detector test facility: resource for all European neutrino detector R&D

Need very low intensity ≈ 1000 /spill

Status MIND

- MIND analysis redone for NUFACT07, June 2007 (Cervera) with improved event selection, efficiency, but still fast simulation
  - Detector effects not simulated
  - Perfect pattern recognition
  - Reconstruction based on parameterisation
  - Dipole field instead of toroidal field

$$E_\nu^{recon} = E_{had} + E_\mu$$

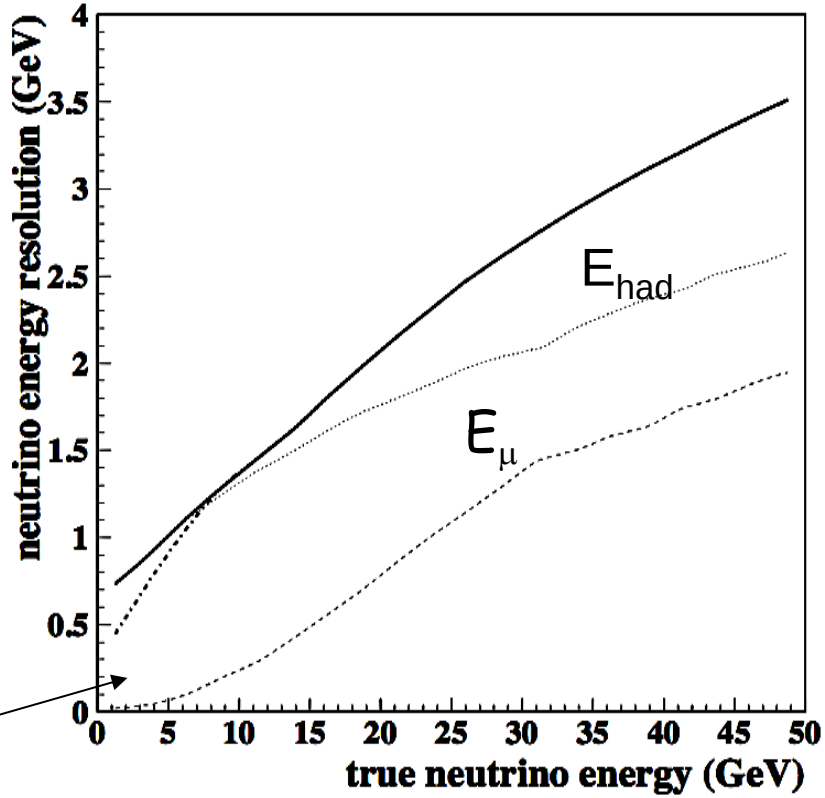
Essential to measure the oscillation pattern

Crucial to solve degeneracies

- Fully contained muons by range
- Scaping muons by curvature
- Hadron shower:

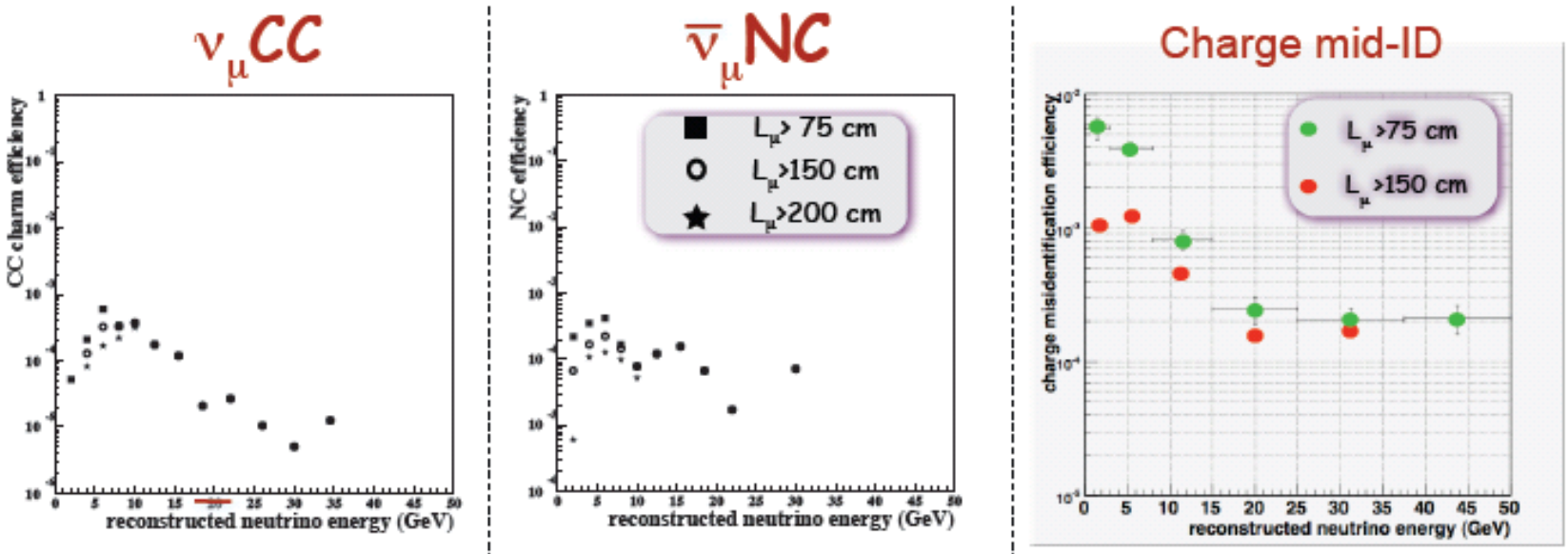
$$\left(\frac{\delta E}{E}\right)_{had} = \frac{0.55}{\sqrt{E_{had}}}$$

Including QE



Status MIND

- Backgrounds from charm, NC and charge misidentification



Simulation

Charm x-section ?

non-Gaussian MS

non-DIS events

Showering profiles

Reconstruction

Muon/hadron separation

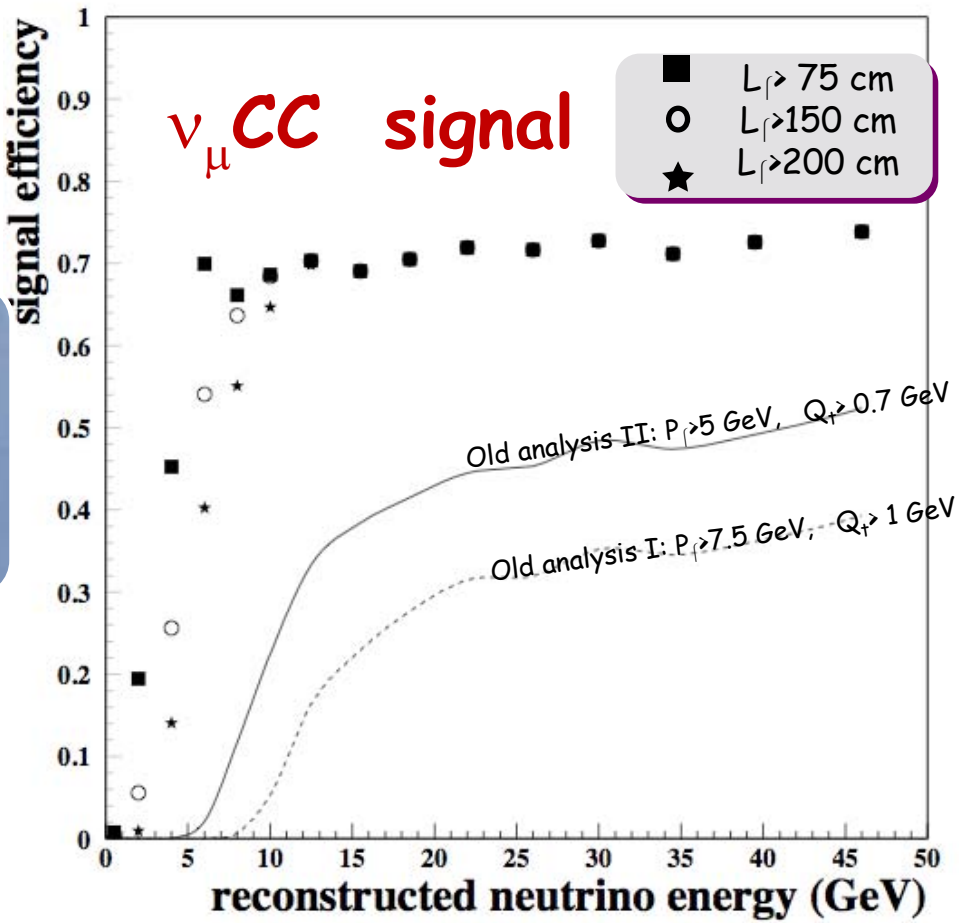
Muon hit finding

Status MIND

- Signal efficiency

- Efficiency plateau between 5 and 8 GeV depending on L_μ^{cut}

- baseline: $L_\mu > 150$ cm
- Ensures charge mis-ID below 10^{-3}



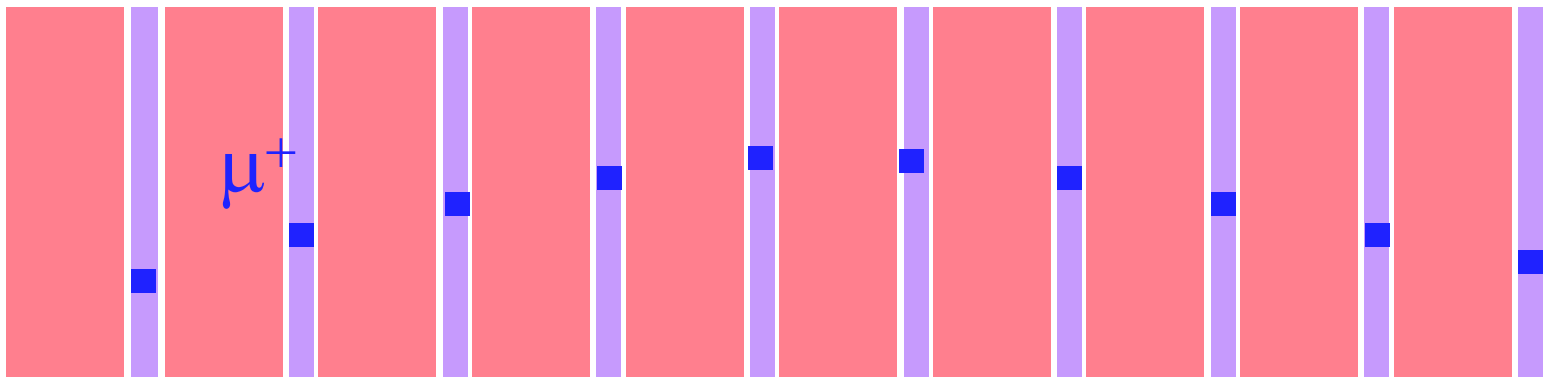
Status MIND

- Improvements: MIND analysis with full GEANT4 reconstruction
  - Demonstrate that for $E_\nu < 10$ GeV
    - Backgrounds are below 10^{-3}
    - The efficiency can be increased with respect to fast analysis
  - Compute:
    - Signal and backgrounds efficiency as a function of energy
    - Energy resolution as a function of energy
  - Identify crucial parameters to be optimised to maximise the sensitivity to the osc. parameters
  - Optimise segmentation and B field based on the above parameters and taking into account feasibility and cost

Improvements MIND

- For example, muon reconstruction:
  - Muon is followed until it stops, decays or escapes the detector
  - The position of all hits is recorded
  - And also its 3-momentum

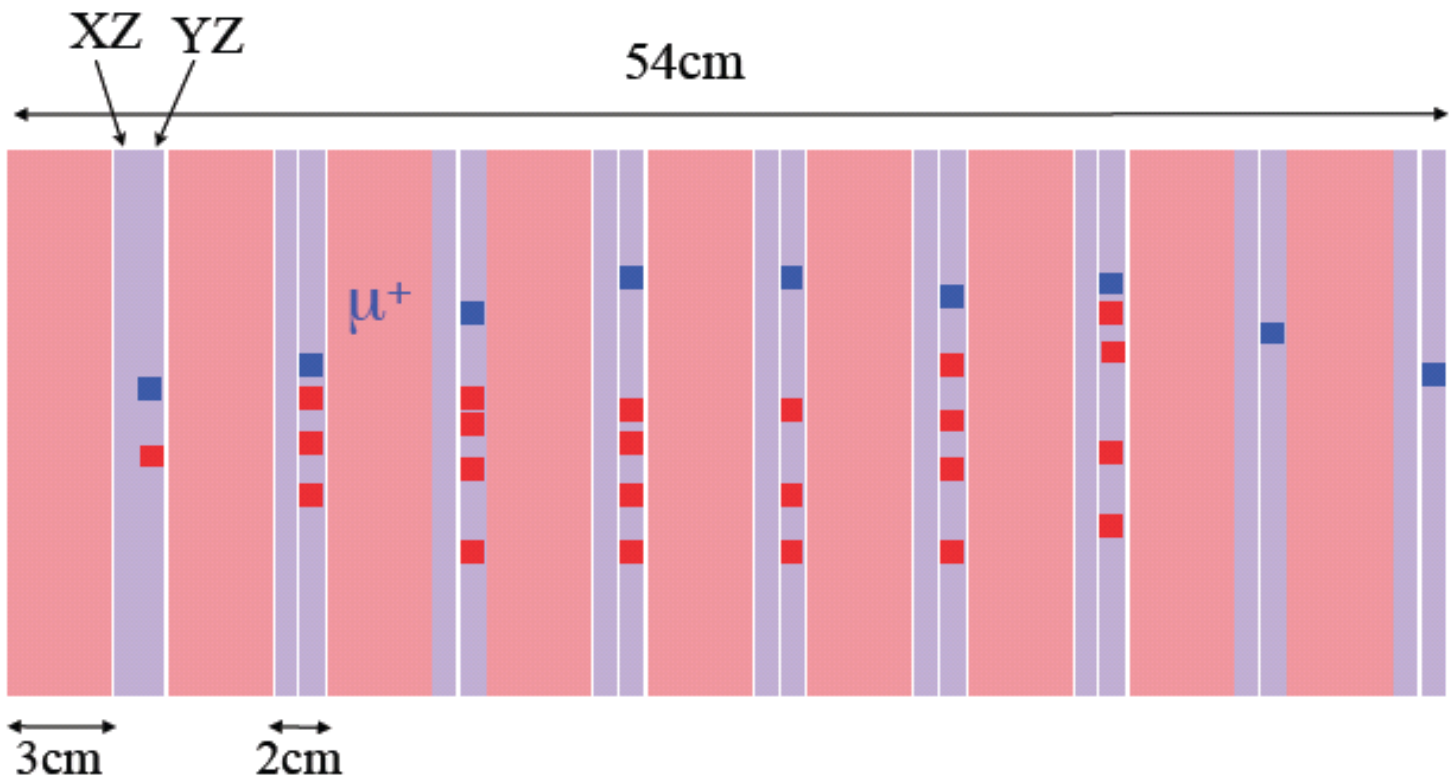
Fast analysis



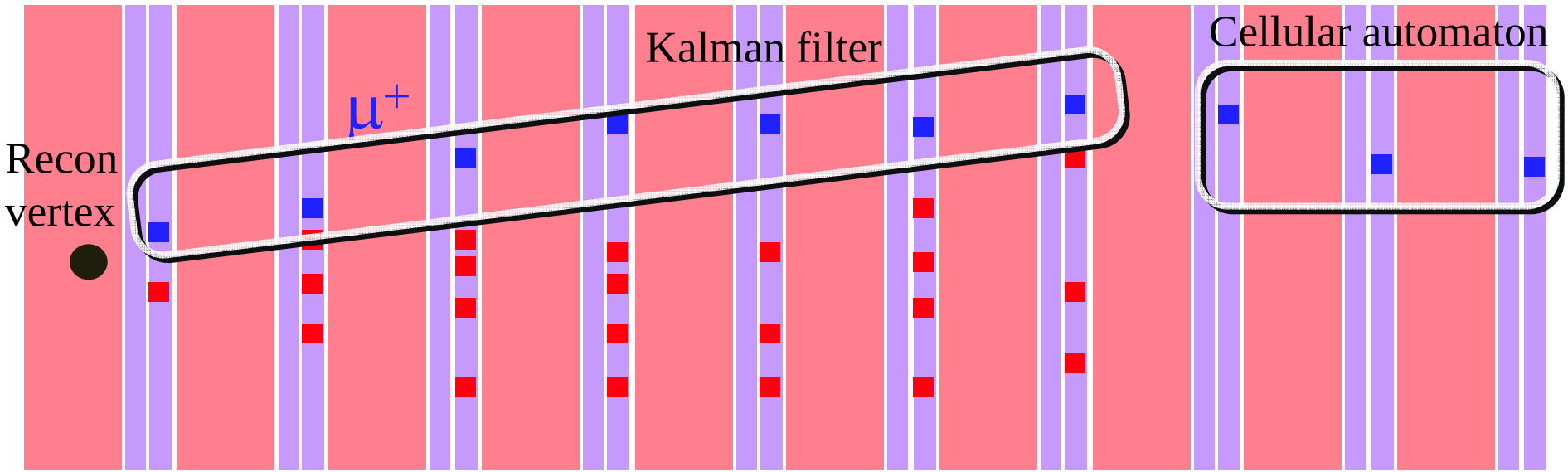
  - Muon hits are smeared with 1cm transverse resolution
  - A track fit gives its charge
  - For the kinematical analysis the muon momentum is smeared according to Gluckstern formula + MS term

Improvements MIND

- In real life:
  - The muon is not isolated: pattern recognition
  - 2 independent views XZ and YZ that should be matched
  - The event sense can be computed from timing (?)



Improvements MIND



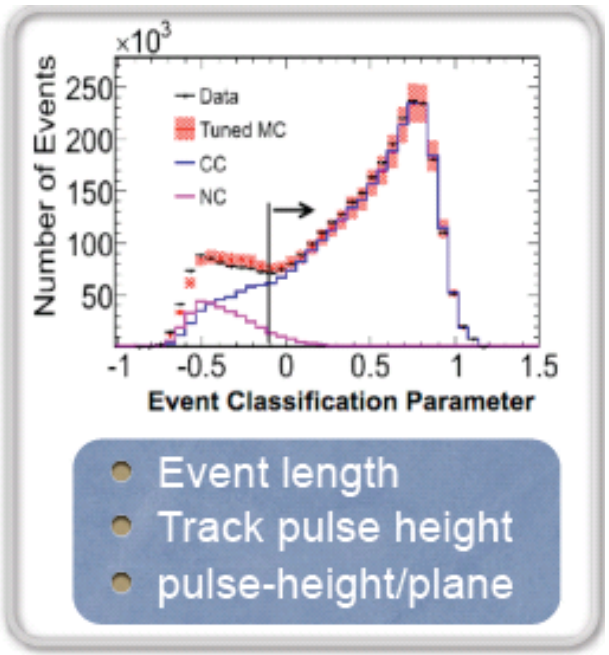
1. Reconstruct the vertex from event topology
2. Cellular automaton or Hough transform for planes with small activity
3. Match X and Y views in planes with small activity
4. Find approximate muon parameters based on these planes and vertex
5. Incremental Kalman Filter from the end of the track towards vertex

- Multiple scattering, energy loss and B field map

Improvements MIND

- Likelihood functions for event selections:

1. Likelihood method (à la MINOS) to discriminate between ν_μ CC and NC, a la MINOS, maximising the purity of NC
   - Cut should depend on neutrino energy



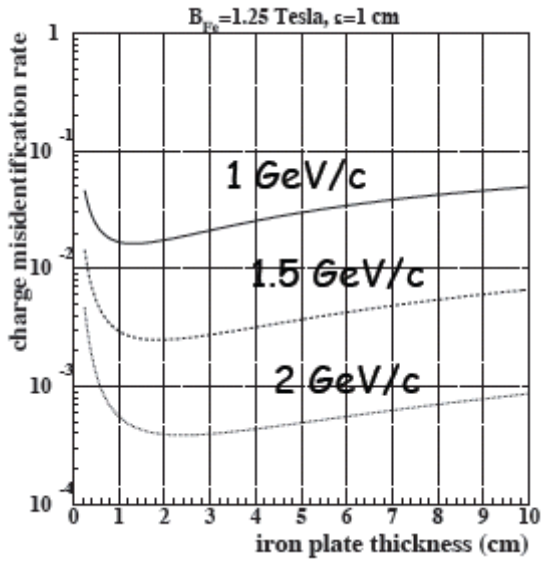
2. If NC → reject
3. If ν_μ CC:
   - A. Muon reconstruction based on previous method
   - B. if μ^+ or kink → reject
   - C. if μ^- with no kink
     - reconstruct hadron shower
     - compute muon momentum and neutrino energy
     - kinematical analysis

Improvements MIND

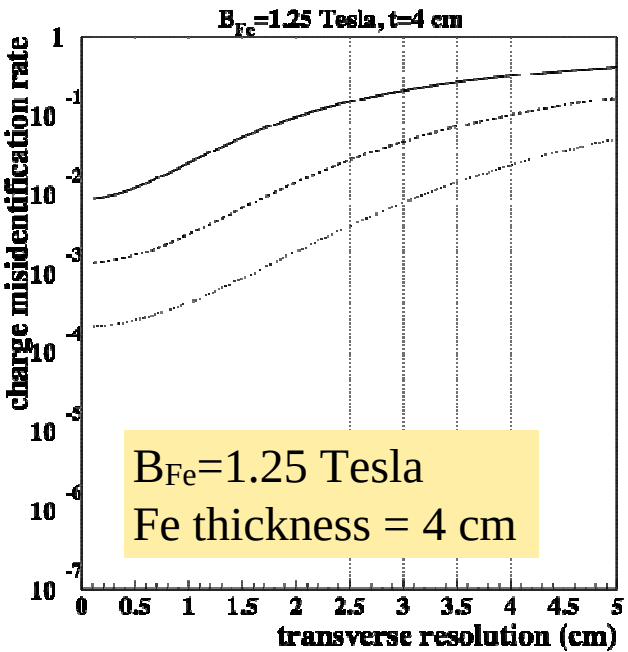
- Event generators:
  - Only DIS interactions as coming from LEPTO has been generated so far
  - Including QE and RES should have a big impact at low neutrino energies:
    - No hadron shower:
      - Easy pattern recognition
      - Better neutrino energy resolution
    - Help in improving the threshold energy and reduce backgrounds
  - Generators: Nuance, Neut, Neugen, Genie

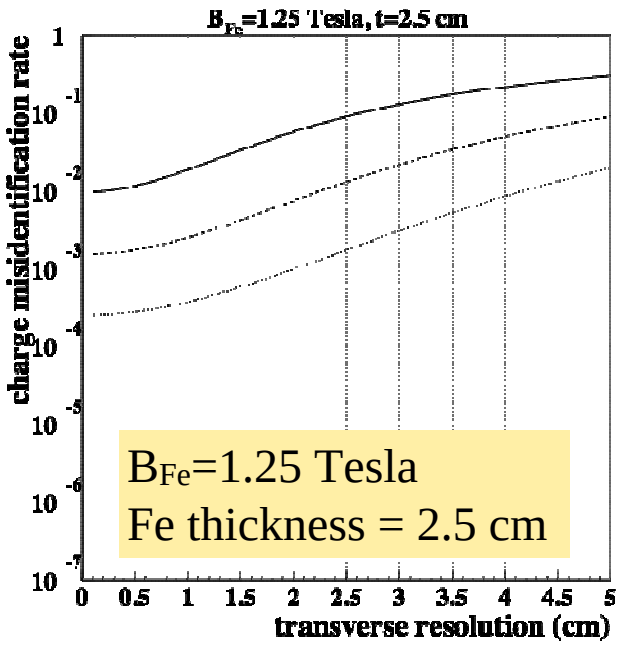
Improvements MIND

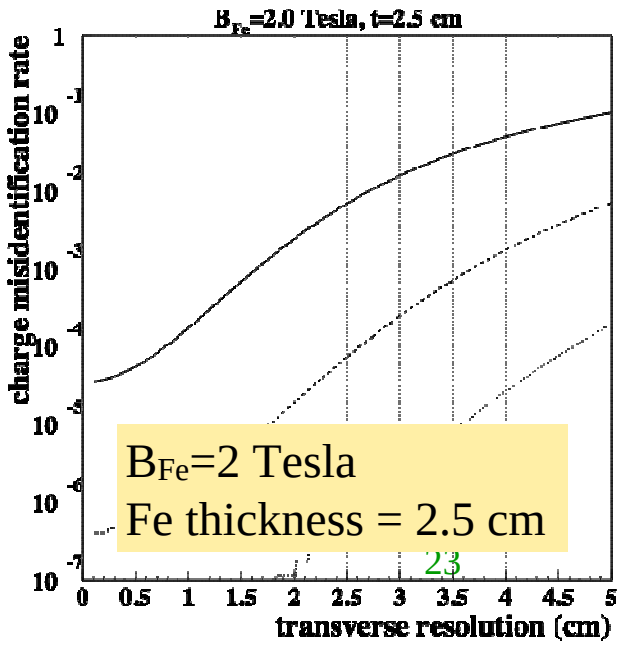
- Optimal segmentation:
  - Assume transverse segmentation of 1 cm



Longitudinal segmentation

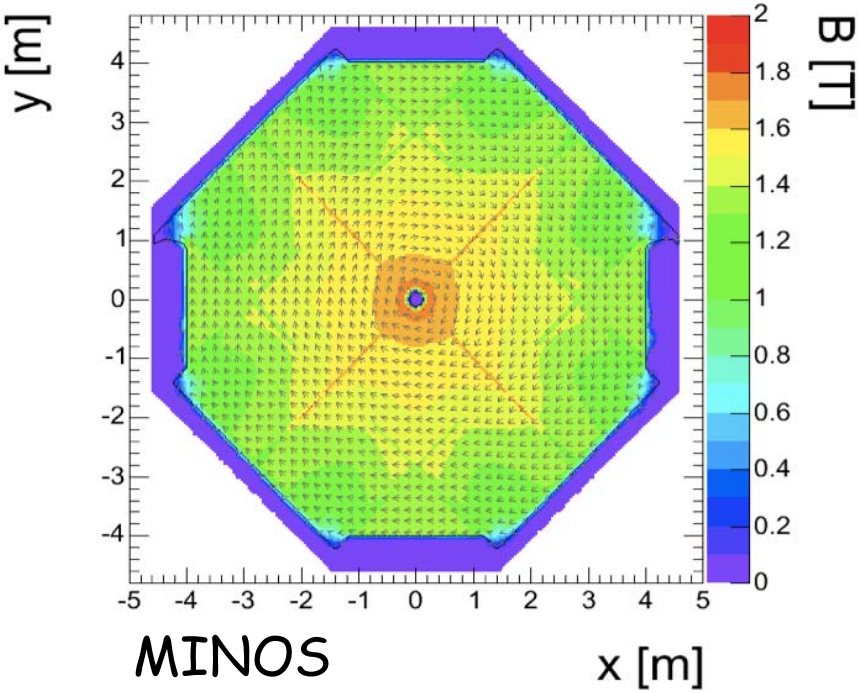


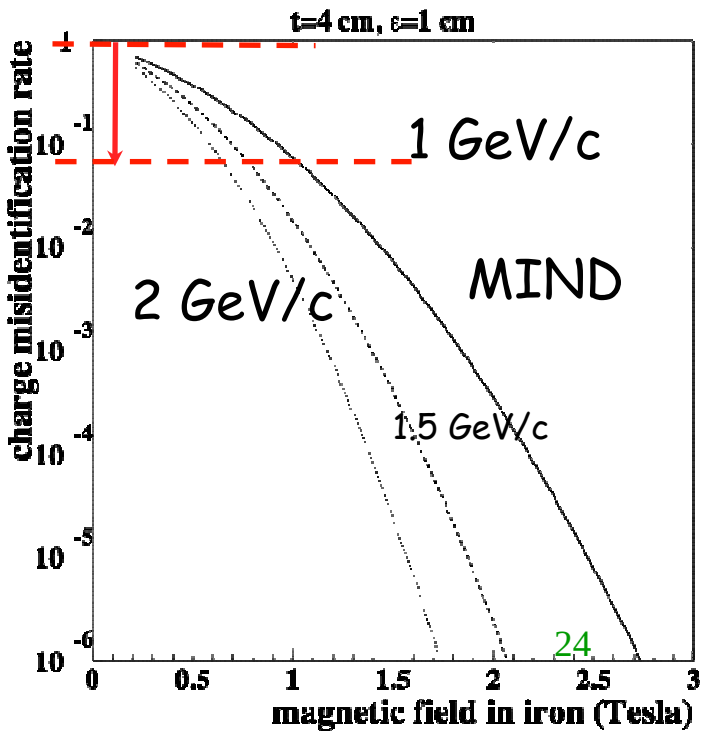




Improvements MIND

- Magnetic field:
  - Even if we are able to isolate a 1 GeV/c muon, the ratio curvature/MS is not sufficient. ~5% charge mis-ID
  - The magnetic field strength is the crucial parameter
    - Going from 1.25 to 1.7 Tesla average is feasible (J. Nelson, Golden07)
    - > 1 o.o.m improvement at 1 GeV/c. 10^{-3} level





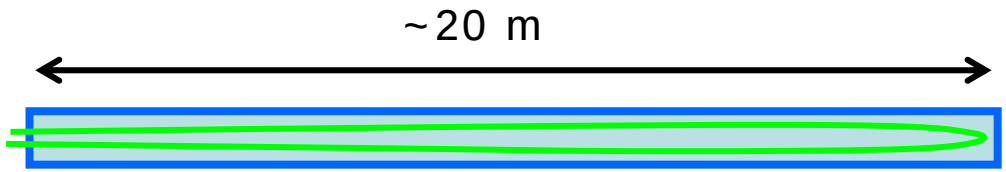
Improvements MIND

- Next steps:
  - Fast simulation/reconstruction very useful so far
  - Time to move forward with a full simulation and reconstruction
  - Established valencia/Brunel/Glasgow collaboraton to move analysis forward (eg A. Laing in Valencia)
  - Procedure:
    - Event simulation (NUANCE)
    - Event transport (GEANT4)
    - Digitisation --> bHEP3
      - hits
      - Dummy digitisation with MIND fast simulation
      - Reconstruction
        - **Event likelihood**
        - **Cellular automaton (import from T2K)**
        - **Kalman filter (RecPack)**

R&D MIND

- R&D: development of scintillator bars and readout system through fibres, electronics …

Extruded scintillator: pioneered Fermilab



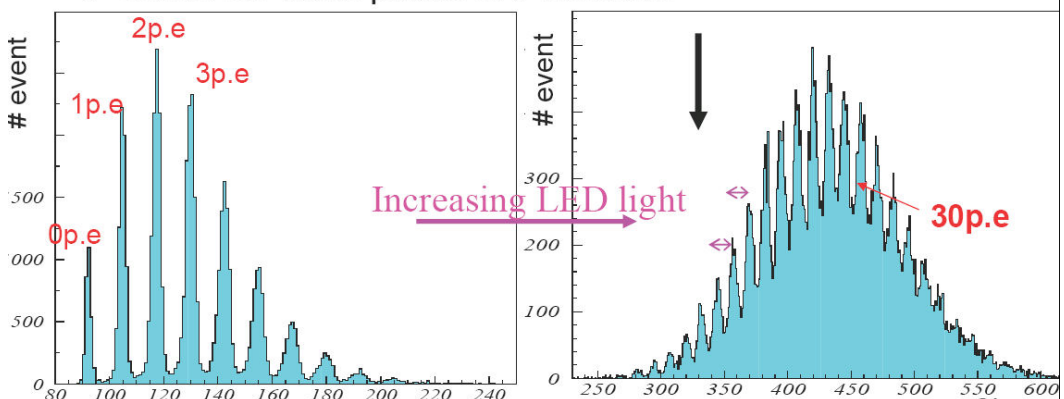
- Photon detectors: APD, MPPC …
- Build prototype for test beam
- Engineering: Magnetic field

Photon counting by MPPC

Multi-Pixel-Photon-Counter

- Charge distribution
  - LED light (HPK 100 pixel)
  - We can distinguish up to 45 p.e. peak.
  - Variation of Intervals between peaks is in 2%.

→ Gains for each pixels are uniform.



Near detector

What needs to be measured

- Near detectors should be able to measure flux and energy of ν_μ and $\overline{\nu}_e$
- Calibration and flux control (inverse muon decay):

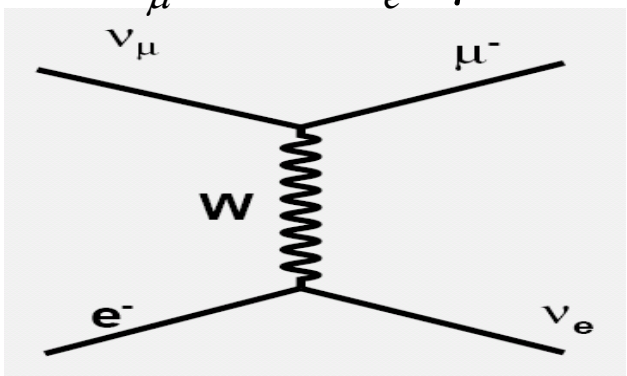
$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e \qquad\qquad \overline{\nu}_e + e^- \rightarrow \overline{\nu}_\mu + \mu^-$$

- High event rate: ~10^9 CC events/year in 50 kg detector
- Measure charm in near detector to control systematics of far detector (main background in oscillation search is wrong sign muon from charm)
- Other physics: neutrino cross-sections, PDF, electroweak measurements, ...
- Possible technology: fully instrumented silicon target in a magnetic detector.

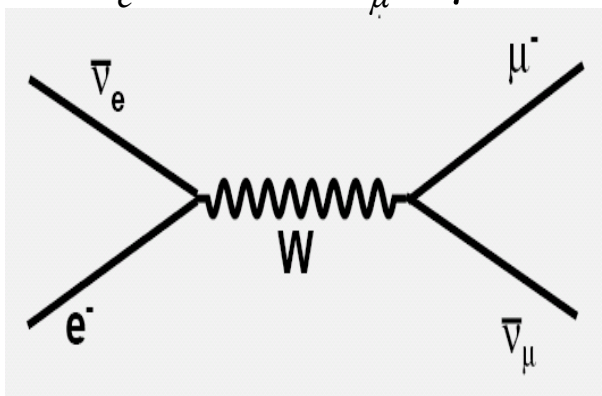
Flux Measurement at Near Detector for NF

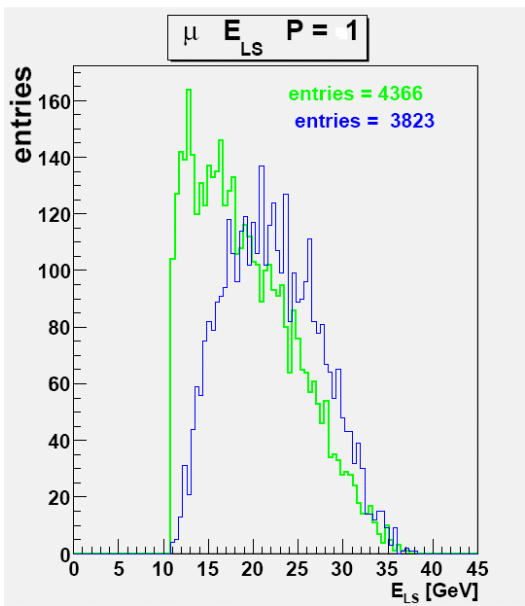
- Best possibility: Inverse Muon Decay: scattering off electrons in the near detector. Known cross-sections

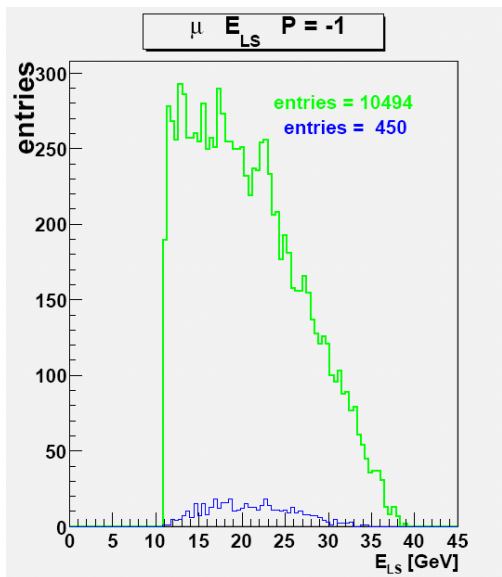
$$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$$



$$\overline{\nu_e} + e^- \rightarrow \overline{\nu_\mu} + \mu^-$$







Near Detector used to extract $P\nu_e\nu_\mu$

- Use matrix method with Near Detector data (even if spectrum not identical in near and far detector!) to extract oscillation probability:

$$P_{\nu_e\nu_\mu} = M_2^{-1} M M_1 M_{nOsc}^{-1}$$

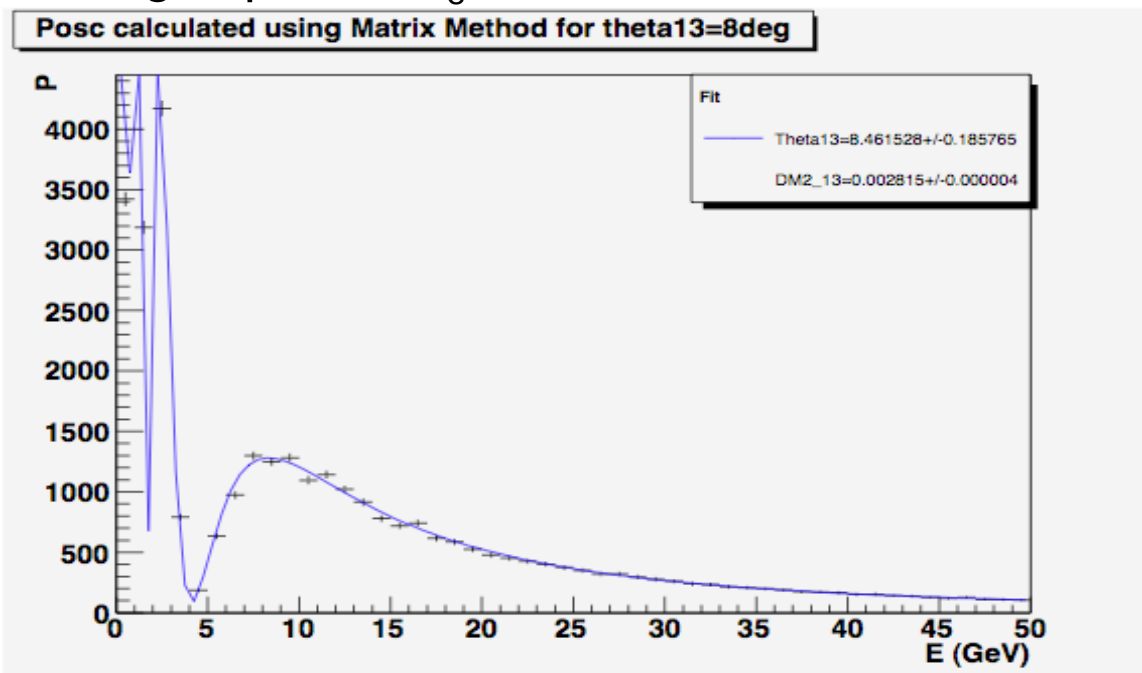
- Where: M_1=matrix relating event rate and flux of ν_e at ND

  M_2=matrix relating event rate and flux of ν_μ at FD

  M=matrix relating measured ND ν_e rate and FD ν_μ rate

  M_{nOsc}=matrix relating expected ν_e flux from ND to FD

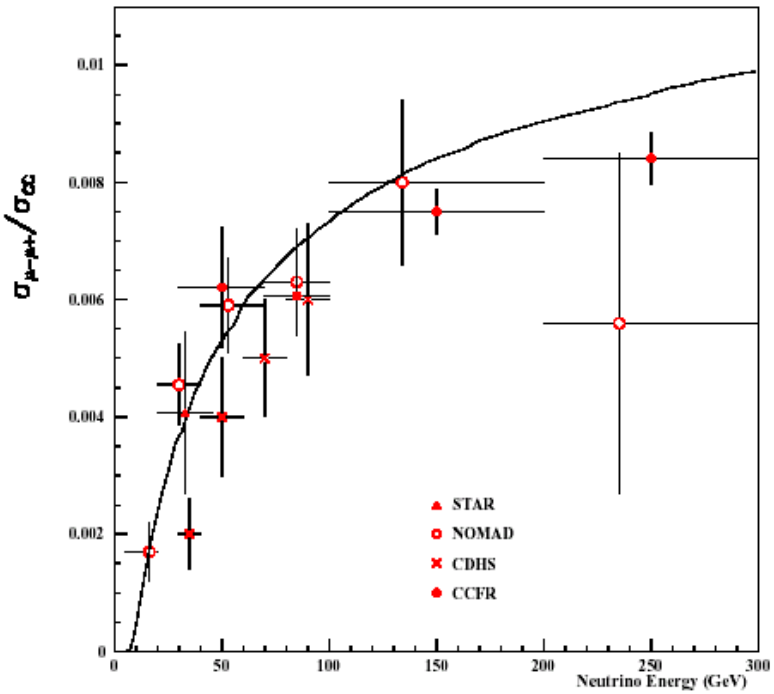
- Method works well but need to extract syst errors of method:

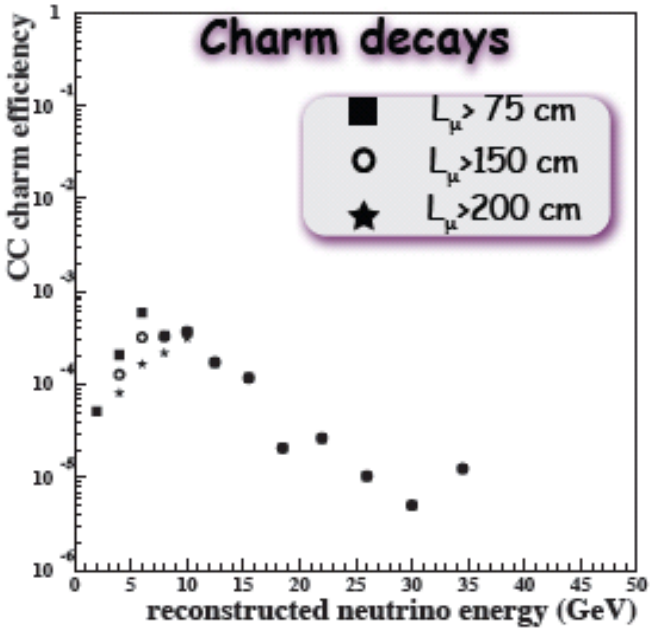


Probability of oscillation determined by matrix method under "simplistic" conditions. Need to give more realism to detector and matter effects.

Charm measurement for NF

- Motivation: measure charm cross-section to validate size of charm background in wrong-sign muon signature
- Charm cross-section and branching fractions poorly known





- Semiconductor vertex detector only viable option in high intensity environment (emulsion too slow!)

Near detector

- R&D programme

1) Vertex detector options: hybrid pixels, monolithic pixels (ie. CCD, Monolithic Active Pixels MAPS or DEPFET) or strips. Synergy with other fields such as Linear Collider Flavour Identification (LCFI) collaboration. Already started testing these detectors at Glasgow.
2) Tracking: gas TPC (is it fast enough?), scintillation tracker (same composition as far detector), drift chambers?, cathode strips?, liquid argon (if far detector is LAr), …
3) Simulations for full design

- Collaboration with theorists to determine physics measurements to be carried out in near detector and to minimise systematic errors in cross-sections, etc.

Conclusion

- A number of European proposals are being catalysts for neutrino detector development and R&D
  - EuroNu: approved, contract still under negotiation (final draft soon): hope to start ~ July (6 months after it was supposed to start)
  - Laguna also funded (but limited scope).
  - DevDet proposal submitted, decision ~July, would not start until well into 2009.
- With STFC funding uncertain, is it the right time to put forward a PDR?
- Probably based around UK activities:

1. Magnetic detector: bid around scintillator and photon readout technology for a MIND or TASD at neutrino factory. Build protype “Baby MIND” to put in test-beam.
2. Near Detector: charm detector (strip vs pixel) and tracker (ie. scintillating fibre) – also to put in test beam.
3. Liquid argon