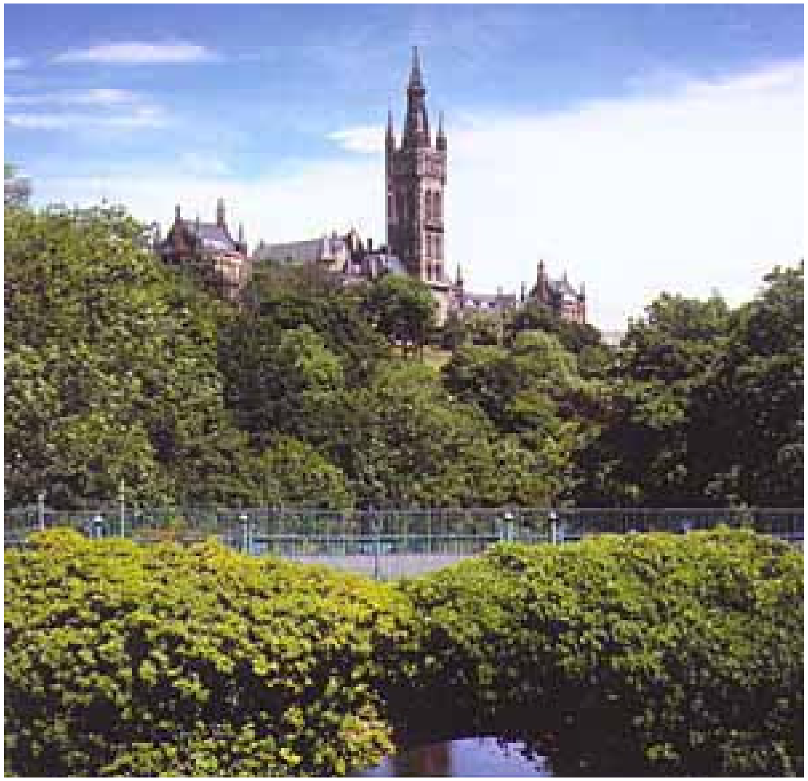
Detectors for a Neutrino Factory



Neutrino Horizons
RAL Forum
18 April 2008
Paul Soler

University of Glasgow

Outline

1. Motivation: neutrino mixing, oscillations, degeneracies and unknown parameters
2. ISS detector requirements
3. MIND
4. Liquid argon
5. Emulsion
6. Near detector
7. R&D plans: EuroNu, DevDet

Neutrino mixing

- Weak eigenstates do not have to coincide with mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

Neutrino mixing matrix (Pontecorvo-Maki-Nakagawa-Sakata, PMNS matrix) similar to CKM matrix of quark sector.

$$U_{MNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

States: $|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$ where $\alpha = e, \mu, \tau$ and $i = 1,2,3$

Neutrino oscillations

- Matter oscillation results for three neutrinos: (MSW effect)

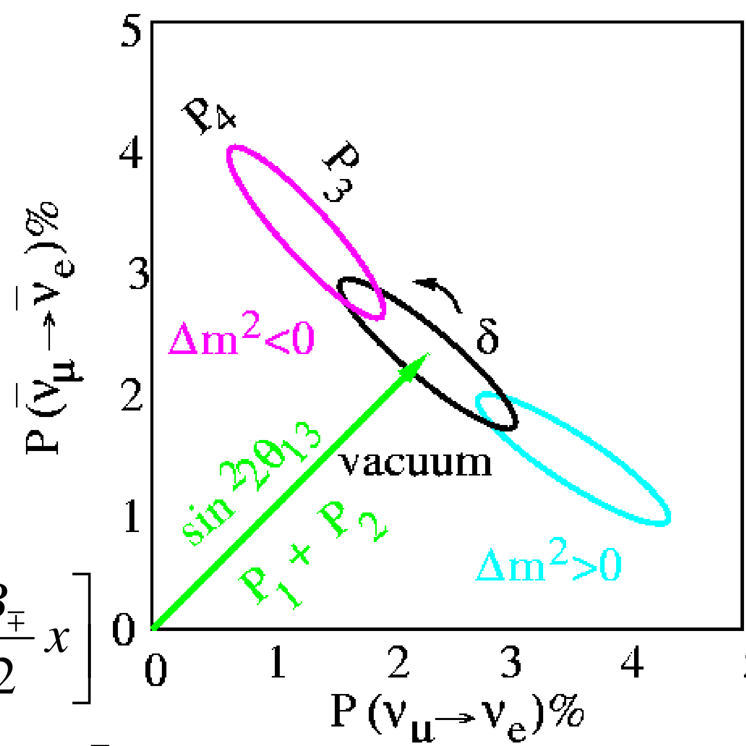
$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)}(x) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = s_{23}^2 \sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\mp}\right)^2 \sin^2\left[\frac{B_\mp}{2}x\right]$$

$$P_2 = c_{23}^2 \sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left[\frac{A}{2}x\right]$$

$$P_3 = \tilde{J}\cos\delta\cos\left[\frac{\Delta_{13}}{2}x\right]\left(\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_\mp}\right)\sin\left[\frac{A}{2}x\right]\sin\left[\frac{B_\mp}{2}x\right]$$

$$P_4 = \pm\tilde{J}\sin\delta\sin\left[\frac{\Delta_{13}}{2}x\right]\left(\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_\mp}\right)\sin\left[\frac{A}{2}x\right]\sin\left[\frac{B_\mp}{2}x\right]$$



Minakata & Nunokawa JHEP 2001

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E} \qquad A \equiv \sqrt{2}G_F n_e$$ where $\pm$ is for $\nu, \bar{\nu}$ $$\tilde{J} \equiv c_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$$

with $B_\mp \equiv \sqrt{(\Delta_{13}\cos 2\theta_{13} \mp A)^2 + \Delta_{13}^2 \sin^2 2\theta_{13}} \approx |\Delta_{13} \mp A|$

Neutrino oscillations

- Matter oscillation results for three neutrinos: (MSW effect)

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)}(x) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\mp} \right)^2 \sin^2 \left[\frac{B_\mp}{2} x \right]$$

Only one term in equation

$$P_2 = c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A} \right)^2 \sin^2 \left[\frac{A}{2} x \right]$$

$$P_3 = \tilde{J} \cos\delta \cos\left[\frac{\Delta_{13}}{2} x \right] \left(\frac{\Delta_{12}}{A} \frac{\Delta_{13}}{B_\mp} \right) \sin\left[\frac{A}{2} x \right] \sin\left[\frac{B_\mp}{2} x \right]$$

$$P_4 = \pm \tilde{J} \sin\delta \sin\left[\frac{\Delta_{13}}{2} x \right] \left(\frac{\Delta_{12}}{A} \frac{\Delta_{13}}{B_\mp} \right) \sin\left[\frac{A}{2} x \right] \sin\left[\frac{B_\mp}{2} x \right]$$

Magic baseline:

$$\frac{Ax}{2} = \pi \Rightarrow x \approx 7300 - 7600 \text{ km}$$

Clean determination of θ_{13}

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E} \qquad A \equiv \sqrt{2} G_F n_e$$

where $\pm$ is for $\nu, \bar{\nu}$

$$\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$

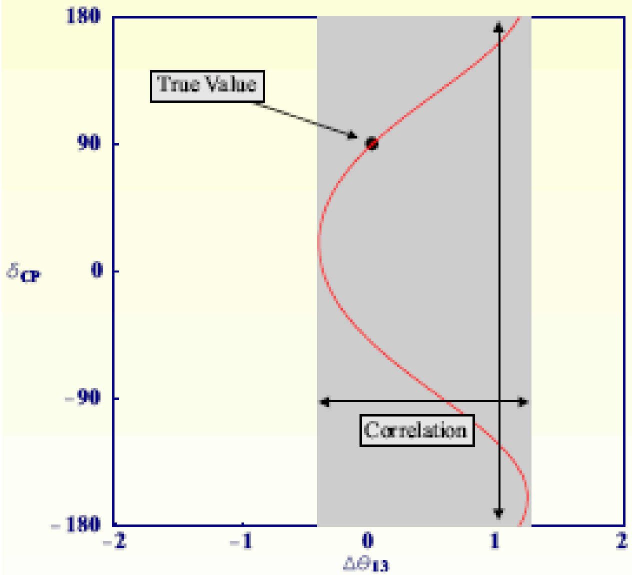
with $B_\mp \equiv \sqrt{(\Delta_{13} \cos 2\theta_{13} \mp A)^2 + \Delta_{13}^2 \sin^2 2\theta_{13}} \approx |\Delta_{13} \mp A|$

Degeneracies

- Intrinsic degeneracy:

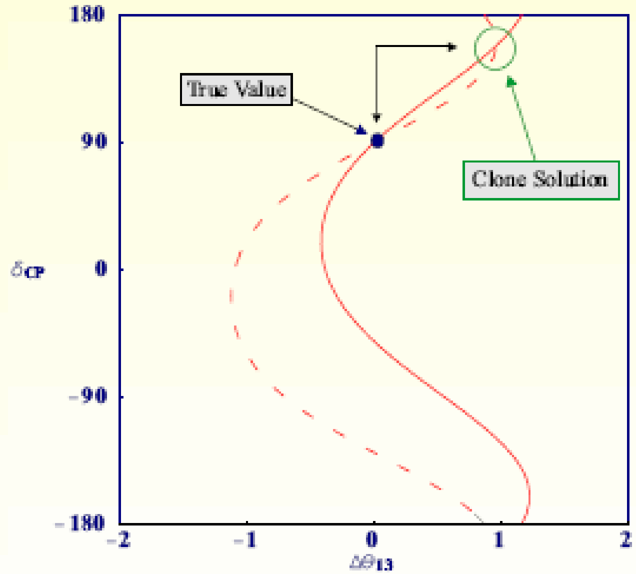
One expt, only ν

$$P_+(\bar{\theta}_{13},\bar{\delta}) = P_+(\theta_{13},\delta)$$

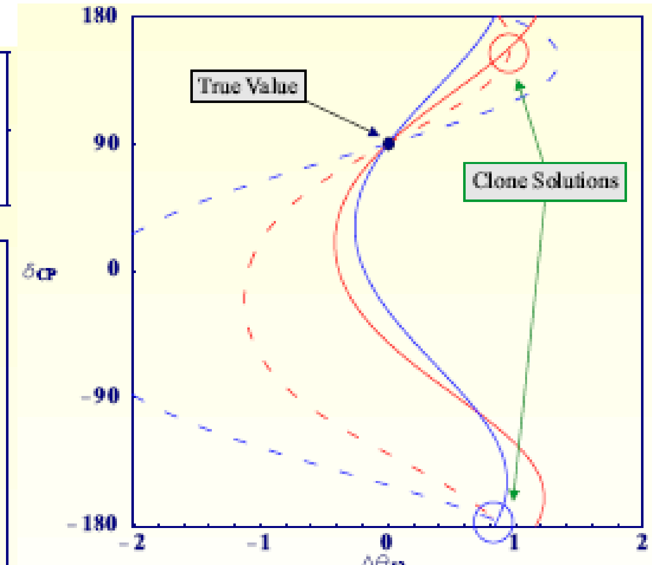


One expt., ν and anti-ν

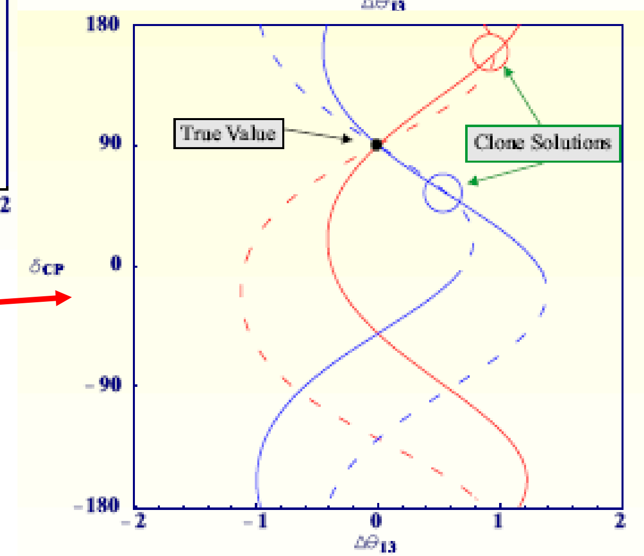
$$P_+(\bar{\theta}_{13},\bar{\delta}) = P_+(\theta_{13},\delta)$$
$$P_-(\bar{\theta}_{13},\bar{\delta}) = P_-(\theta_{13},\delta)$$



Two expts., diff. L/E
ν and anti-ν



Golden $\nu_e \to \nu_\mu$ and
Silver $\nu_e \to \nu_\tau$ channels

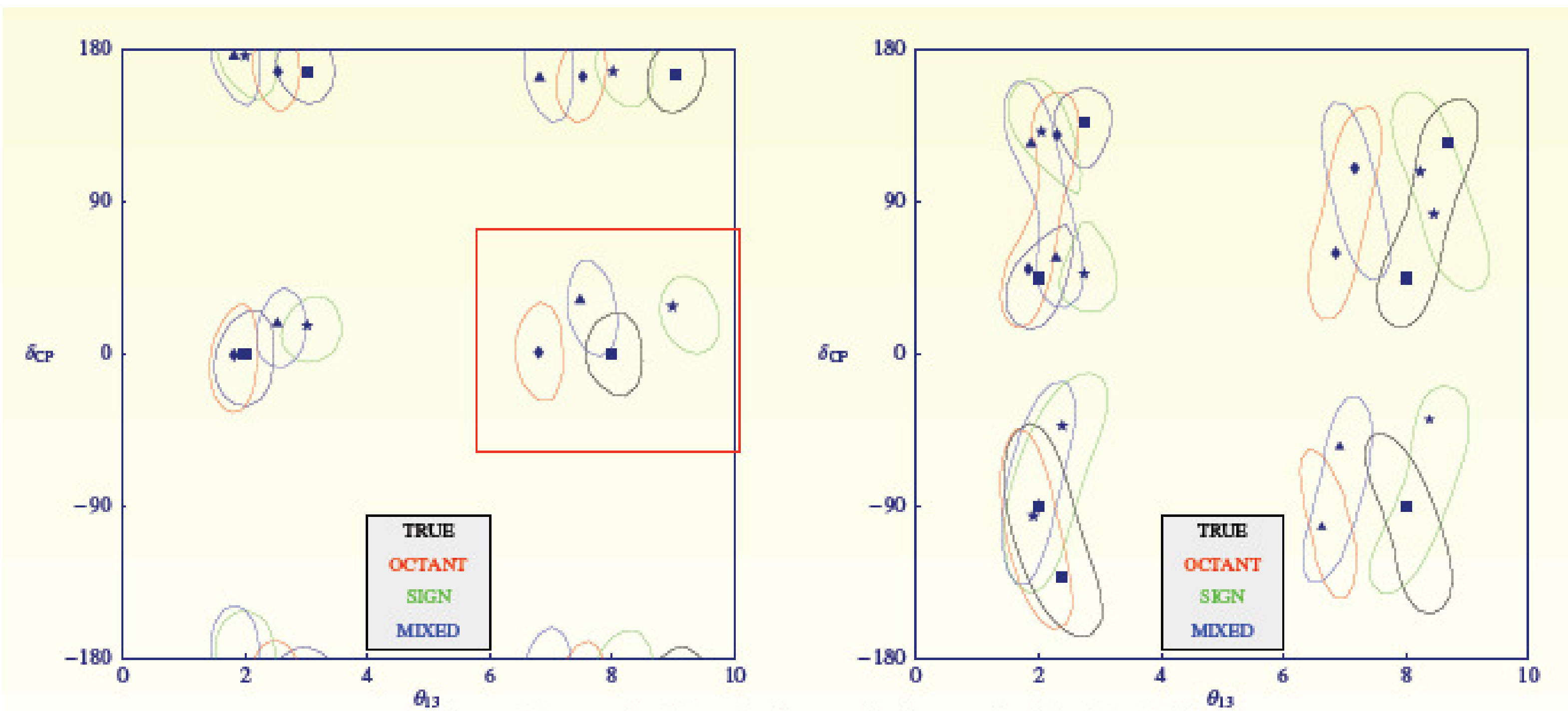


Degeneracies

- Eightfold degeneracy:
  - The sign of the atmospheric mass difference $s_{atm} = \mathrm{sign}(\Delta m^2_{23})$
  - The octant of the atmospheric angle $s_{oct} = \mathrm{sign}(\tan 2\theta_{23})$

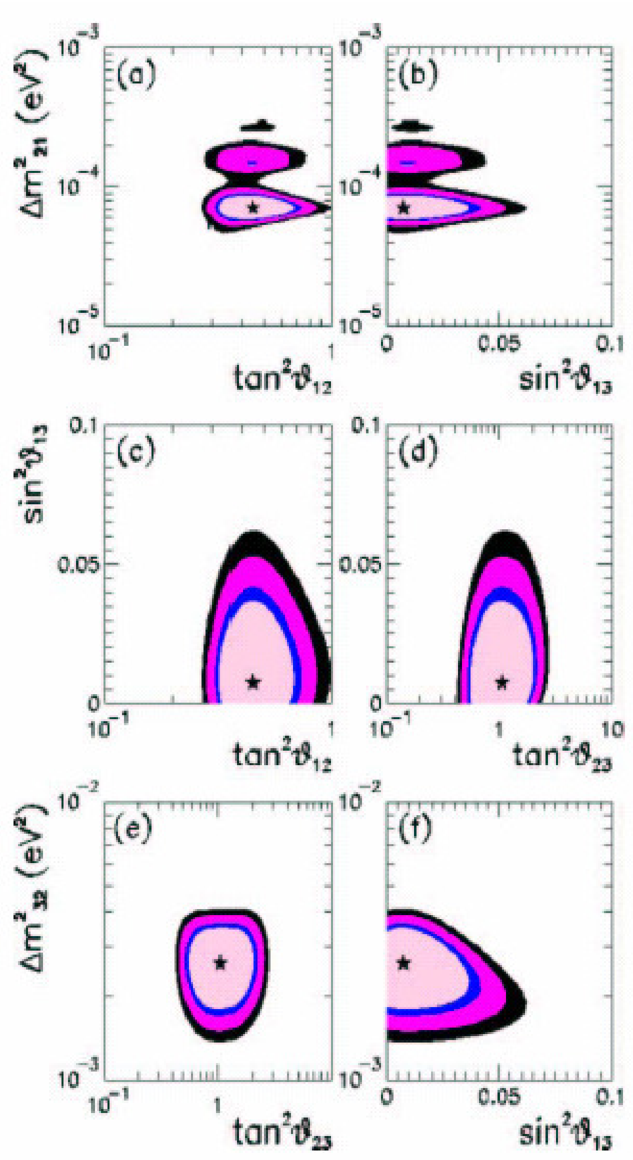
$$N_i^{\pm}\underbrace{(\bar{\theta}_{13}, \bar{\delta}; \bar{s}_{atm}, \bar{s}_{oct})}_{\text{“true parameters”}} = N_i^{\pm}\underbrace{(\theta_{13}, \delta; s_{atm}, s_{oct})}_{\text{“guessed parameters”}}$$

Strategies: different experiments to resolve degeneracy problem

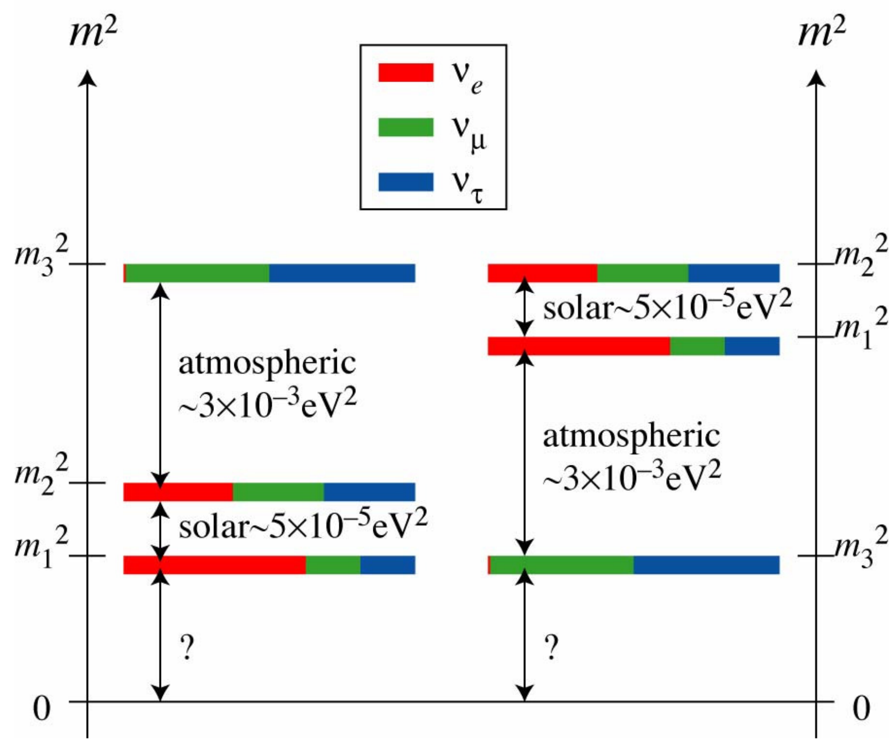


(plots from A. Donini et al, hep-ph/0406132)

Unknown parameters



- Consistent picture emerging
- Global fit provides θ_{23}, θ_{12}, Δm_{12}^2 and Δm_{23}^2
- θ_{13} not known, mass hierarchy not known,CP violation phase δ not known.



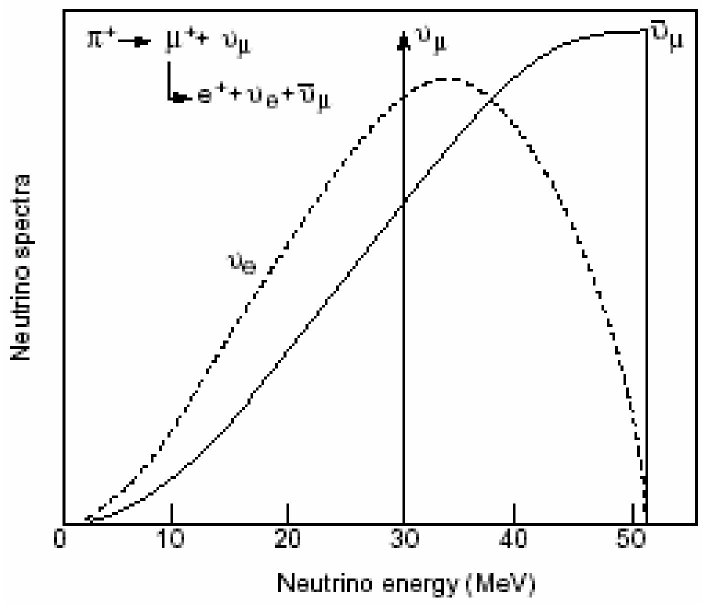
Neutrino factory concept

- Neutrino Factories offer one of the most promising ways to be able to observe CP violation in the neutrino sector.
- Neutrinos produced from muon decay in storage ring. Rate calculable by kinematics of decay (Michel spectrum)

$$\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$$

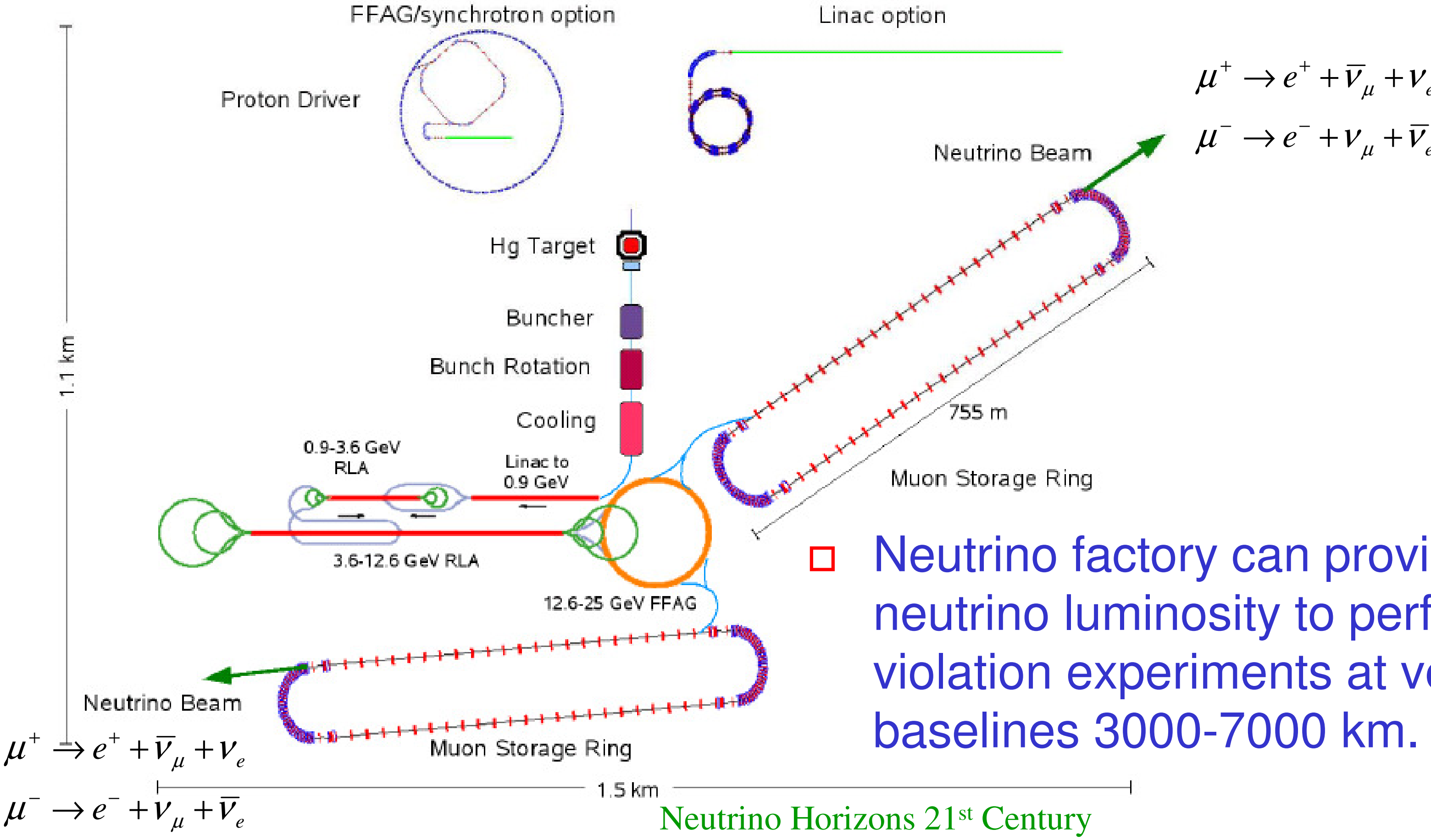
$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e$$

- For example, if μ^+ accelerated to 50 GeV:



Neutrino factory concept

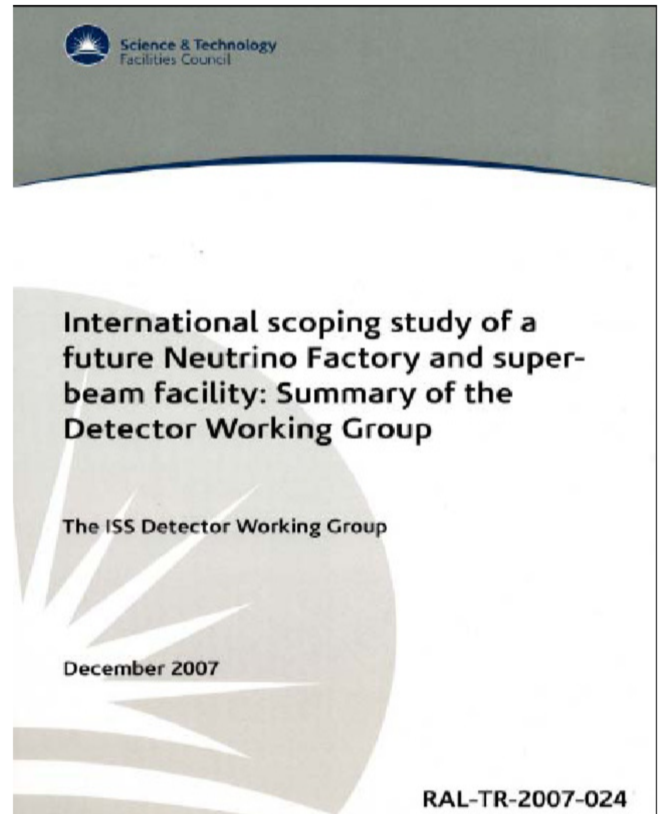
- Baseline design for a Neutrino Factory from International Design Study
- Design can fire neutrino beams to two different detectors at two different baselines



- Neutrino factory can provide sufficient neutrino luminosity to perform CP violation experiments at very long baselines 3000-7000 km.

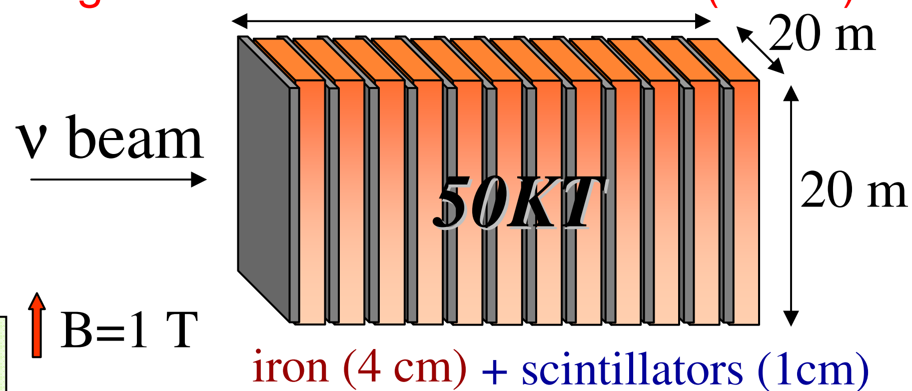
Detector requirements

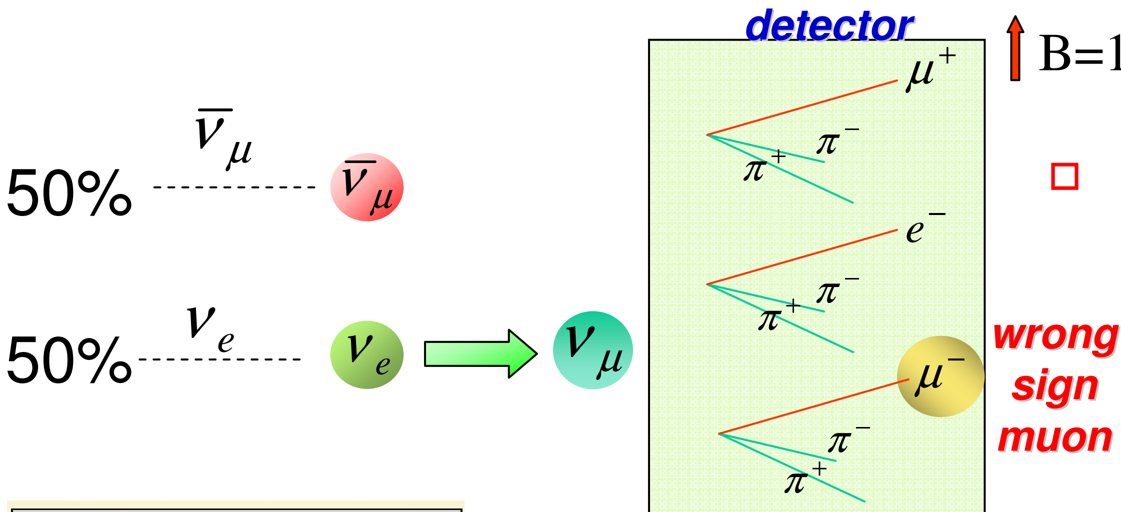
- Detector requirements established by International Scoping Study for a Neutrino Factory Detector Report
  (RAL report: RAL-TR-2007-024 (arxiv:0712.4129v1 [physics.ins-det])
- Baseline detector requirements are:
  - Two detectors at 4000 km and 7500 km
  - Magnetised Iron Neutrino Detector (MIND) of 50 kton fiducial (gold channel)
  - Possible addition of Magnetised Emulsion Cloud Chamber (MECC) of 10 kton (silver)
- Beyond the baseline improvements for platinum channels (R&D needed):
  - Magnetised Liquid Argon: 10-100 kton
  - Magnetised Totally Active Scintillating Detector (TASD): 20-30 kton
- Near detectors: magnetised detector to measure flux and hadronic background



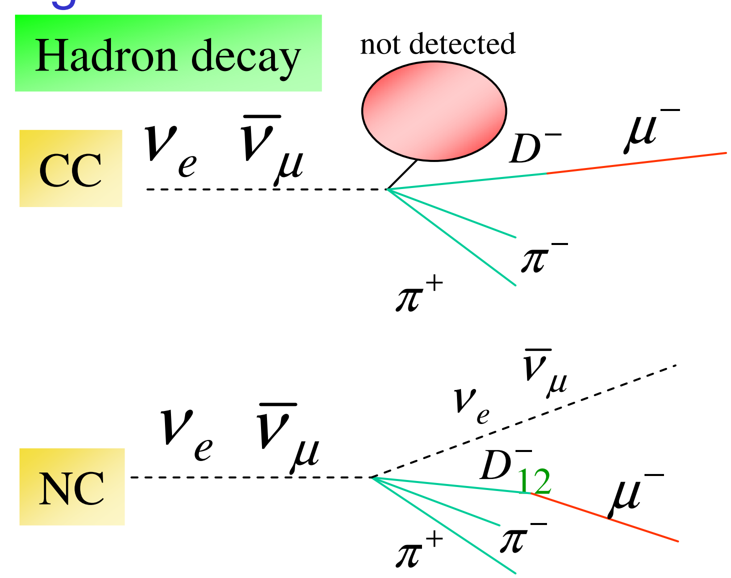
Magnetised Iron Neutrino Detector (MIND)

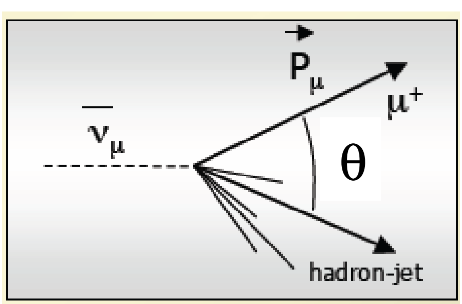
- Golden channel signature: "wrong-sign" muons in magnetised calorimeter
  (Cervera et al. 2000)
- Far detector (3000-7000 km) can search for "wrong-sign" muons in appearance mode (for example, Large Magnetic Detector)





- Background: charm production, charge misidentification.





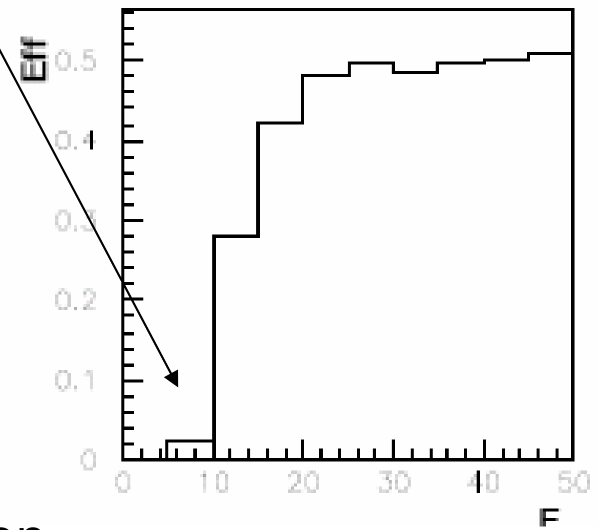
$$Q_t = P_\mu \sin^2\theta$$

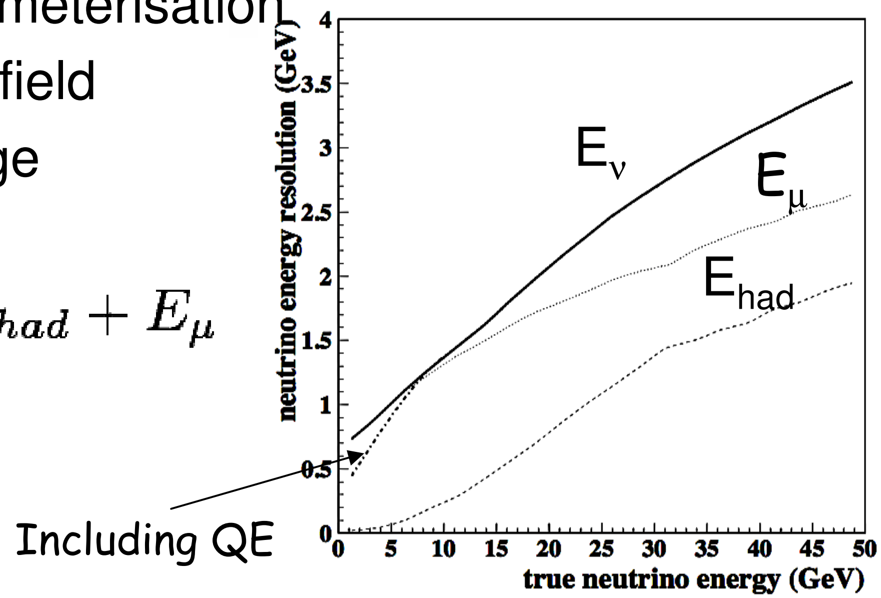
- Eliminates background at 10^{-6}

Magnetised Iron Neutrino Detector (MIND)

- "Golden" paper (Cervera et al, 2000) was optimised for a low value of θ_{13}, so efficiency at low energy cut severely
- Used fast simulations and detector parameterisation
- MIND analysis redone (Cervera 2007)
  - Improved event selection,
  - Still fast simulation
  - Perfect pattern recognition
  - Reconstruction based on parameterisation
  - Dipole field instead of toroidal field
  - Fully contained muons by range
  - Scraping muons by curvature
  - Hadron shower: $E_\nu^{recon} = E_{had} + E_\mu$

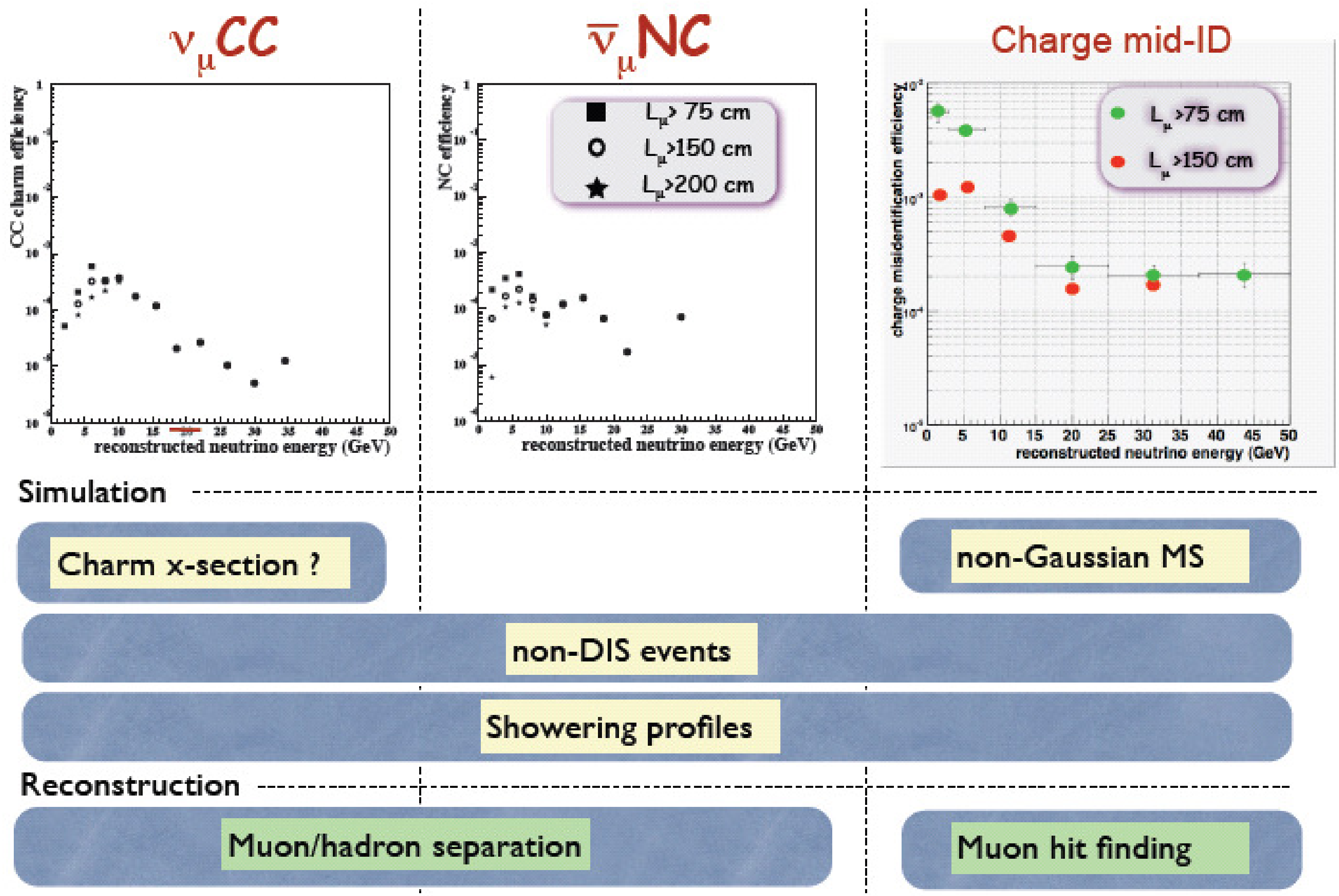
$$\left(\frac{\delta E}{E}\right)_{had} = \frac{0.55}{\sqrt{E_{had}}}$$





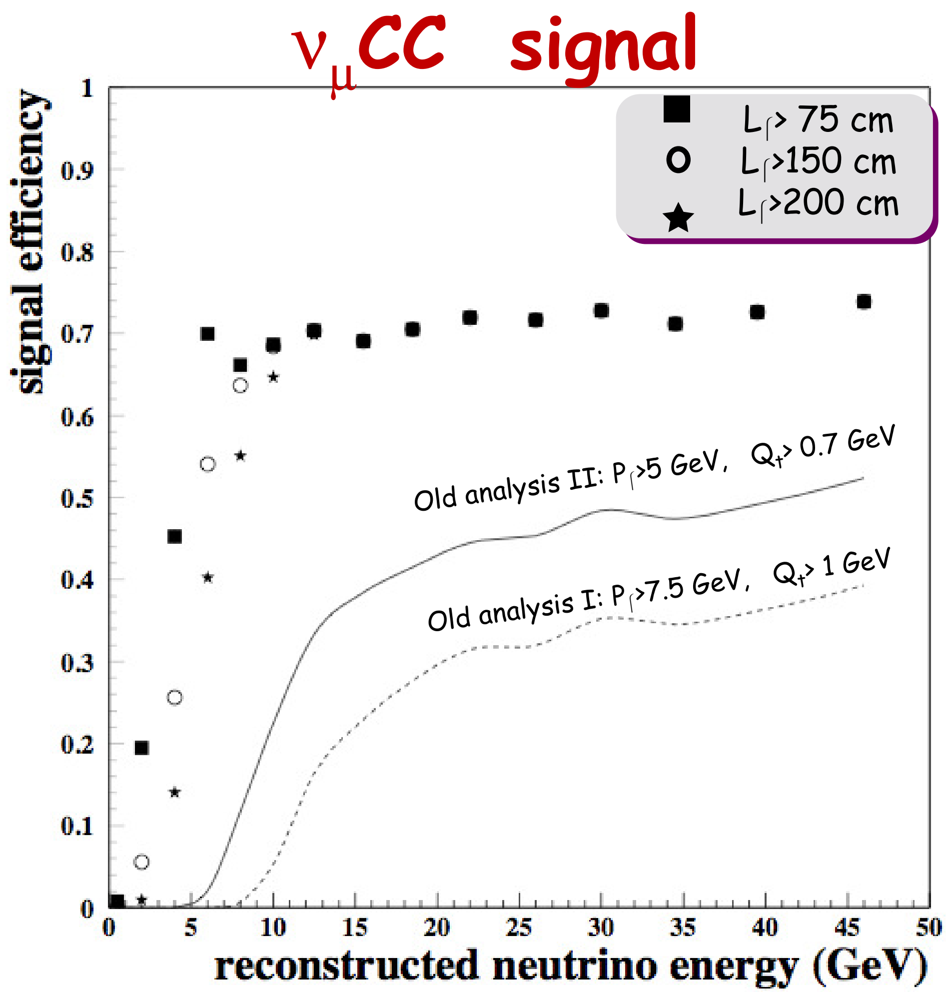
Magnetised Iron Neutrino Detector (MIND)

- Backgrounds from charm, NC and charge misidentification



Magnetised Iron Neutrino Detector (MIND)

- Signal efficiency:
  - Efficiency plateau between 5 and 8 GeV
  - Baseline: L_μ > 150 cm
  - Ensures charge mis-ID below 10^{-3}



Magnetised Iron Neutrino Detector (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

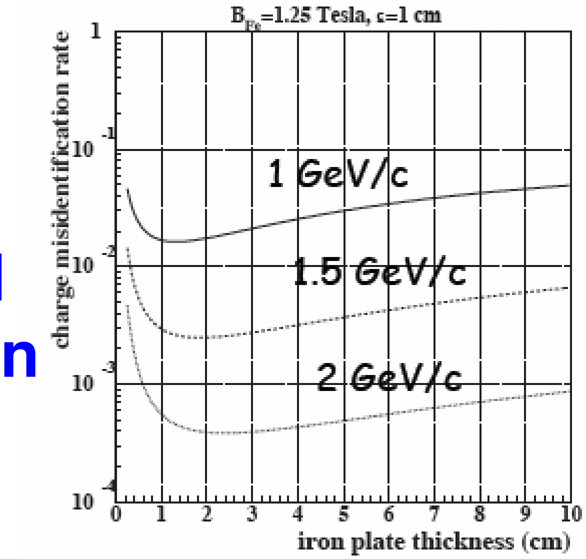
Magnetised Iron Neutrino Detector (MIND)

- Event generators:
  - Only DIS interactions as coming from LEPTO have 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

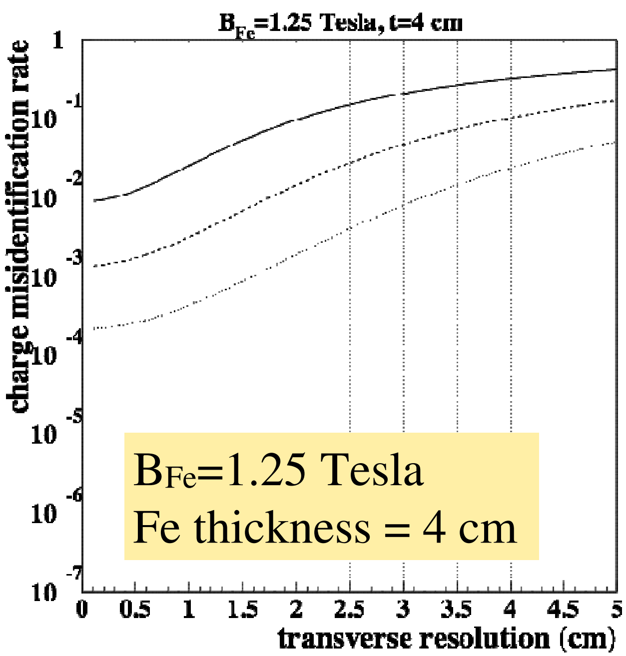
Magnetised Iron Neutrino Detector (MIND)

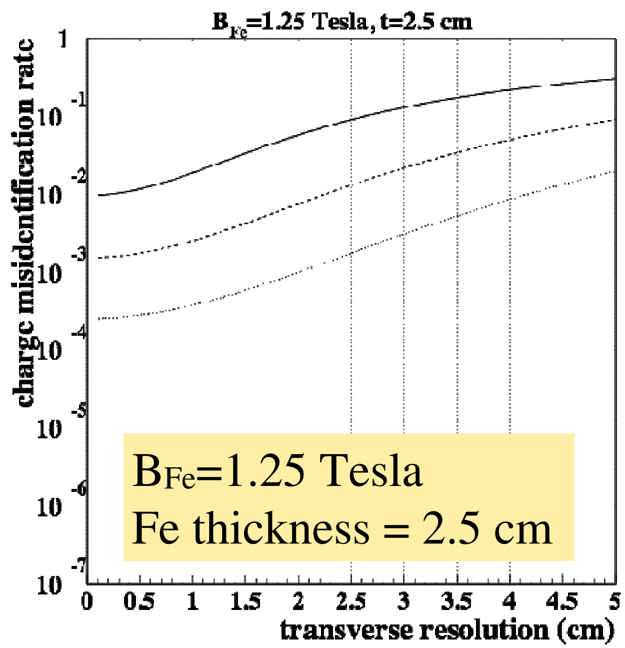
- Optimal segmentation:
  - Assume transverse segmentation of 1 cm

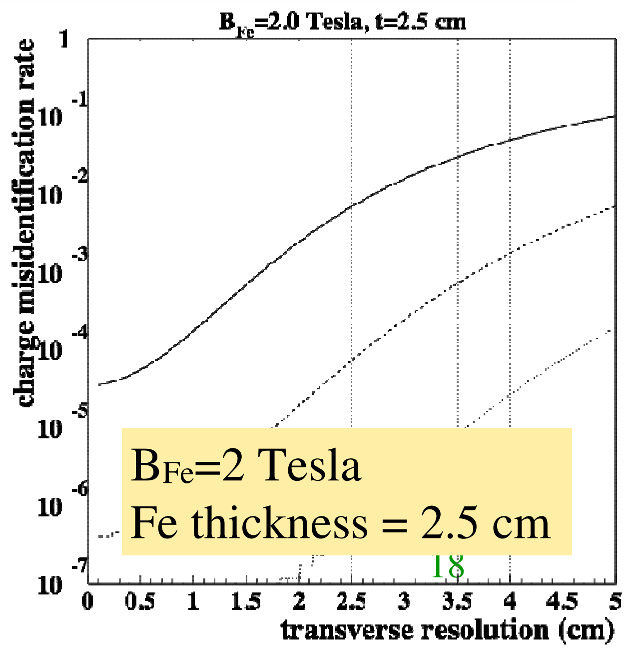
Longitudinal segmentation



Transverse segmentation

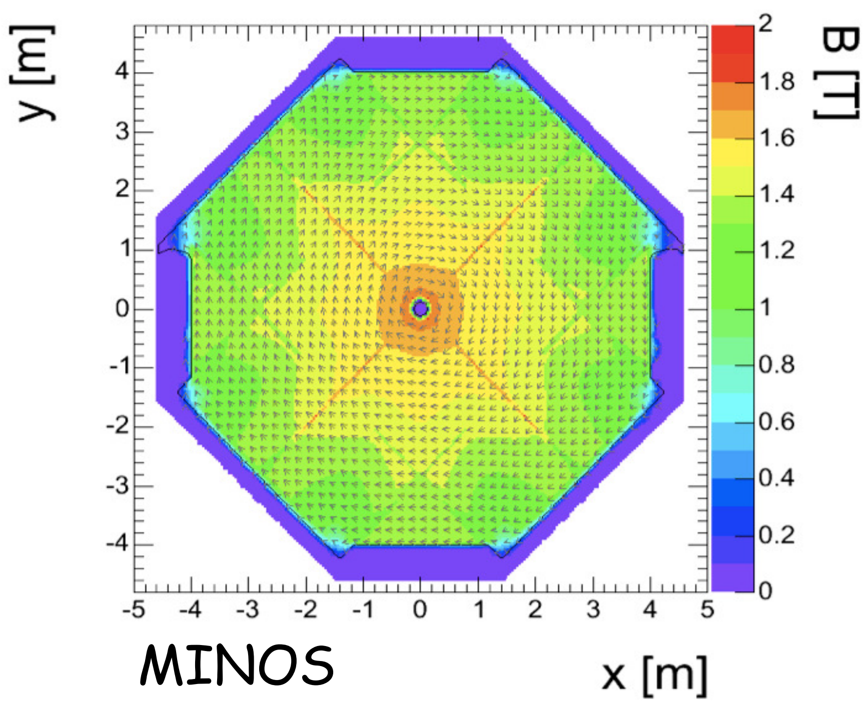


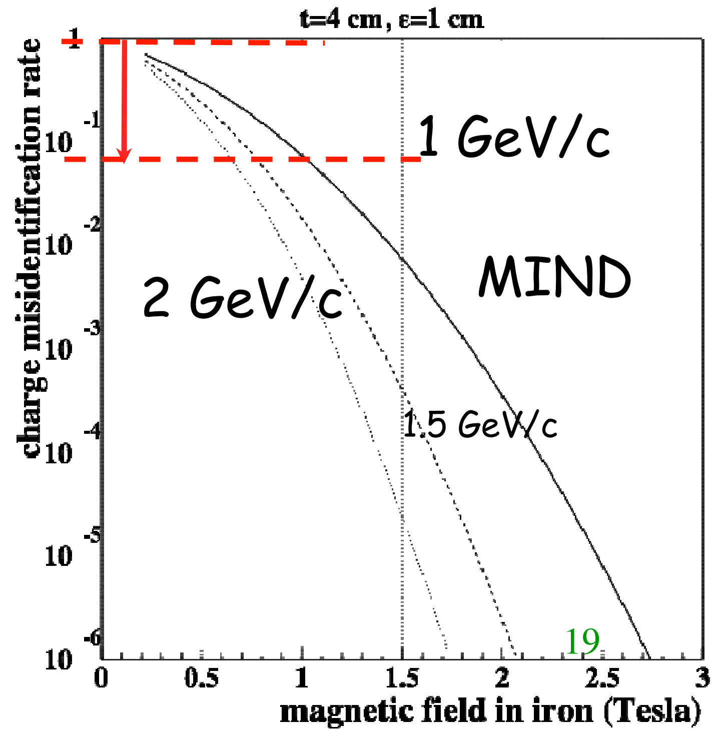




Magnetised Iron Neutrino Detector (MIND)

- 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

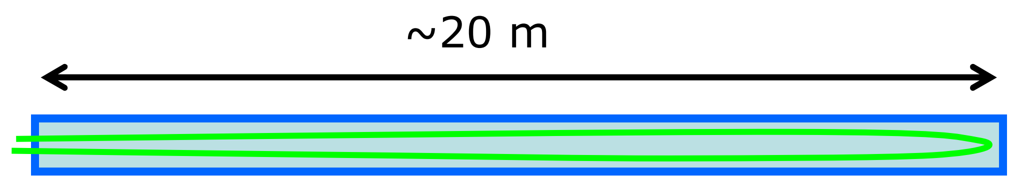


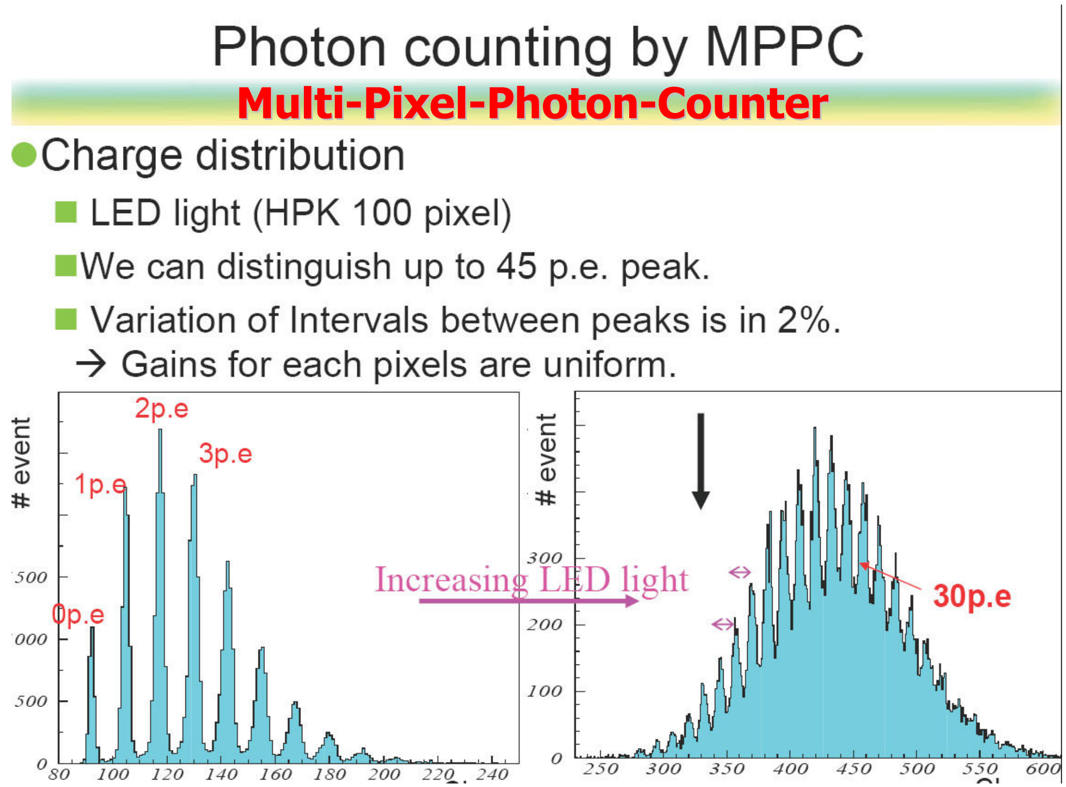


Magnetised Iron Neutrino Detector (MIND)

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

Extruded scintillator: pioneered Fermilab

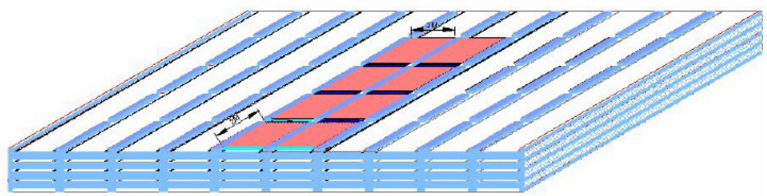


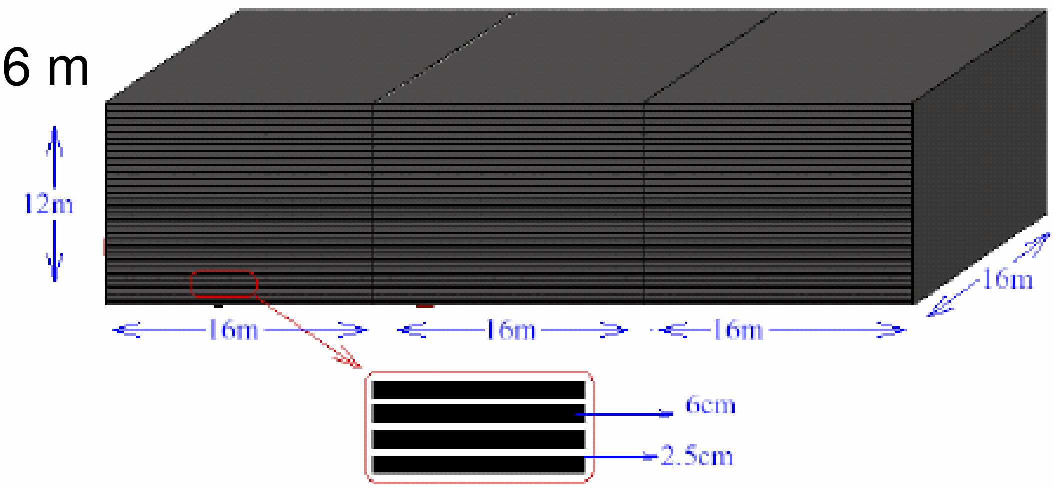


- Photon detectors: APD, MPPC …
- Build prototype for test beam
- Engineering: Magnetic field

Indian Neutrino Observatory

- Indian Neutrino Observatory (INO) in advanced stage of planning
- Recommended for funding
- Detector size: 48 m x 16 m x 16 m
- Readout: RPCs
- B=1.5 T



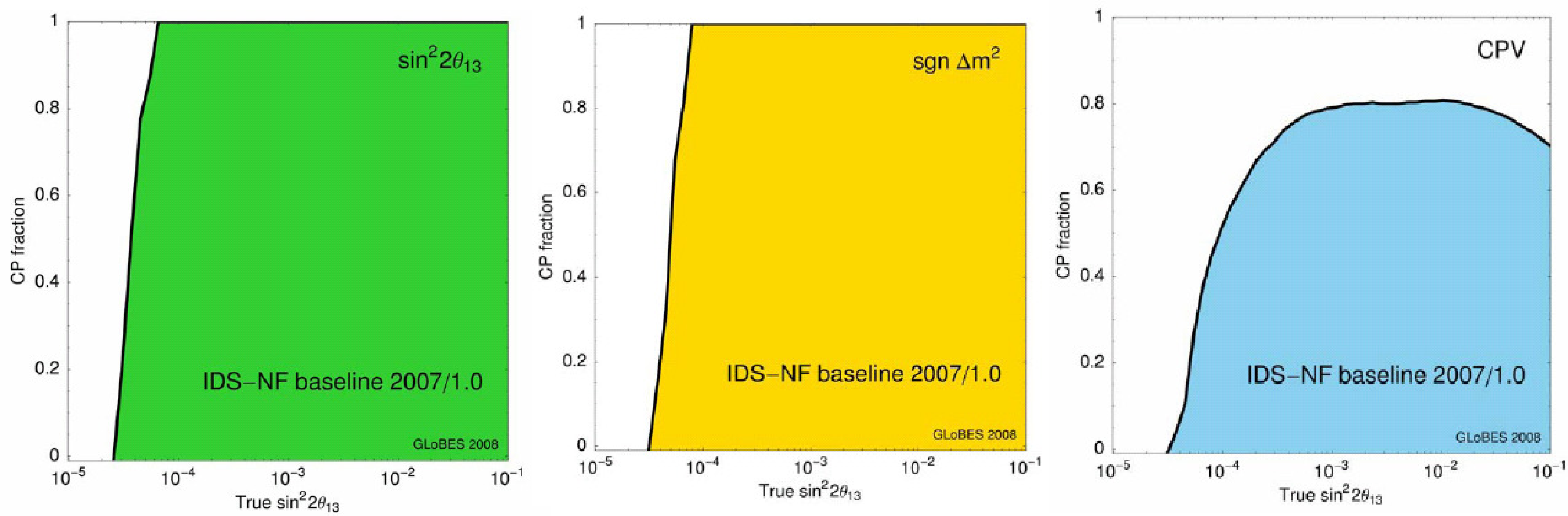


- Physics case: atmospheric oscillations with magnetised detector, matter effects, sign Δm^2_{23}, θ_{23}, CP, CPT, ultrahigh energy ν and μ
- Far detector at magic baseline of neutrino factory

- CERN to INO distance = 7152 km
- JPARC to INO distance = 6556 km
- RAL to INO distance = 7653 km

Magnetised Iron Neutrino Detector (MIND)

- Performance of IDS-NF baseline detectors (two MIND detectors, one at 4000 km and one at 7500 km) at 3σ

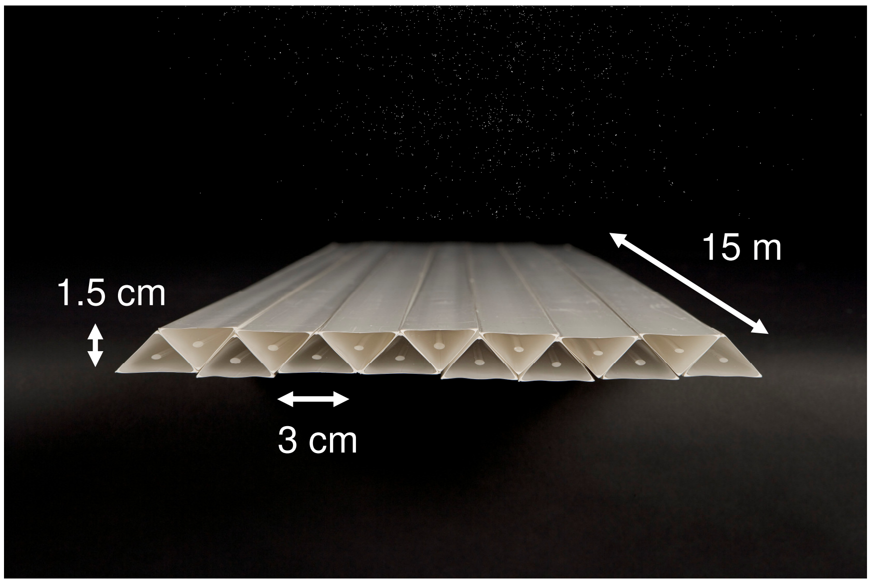


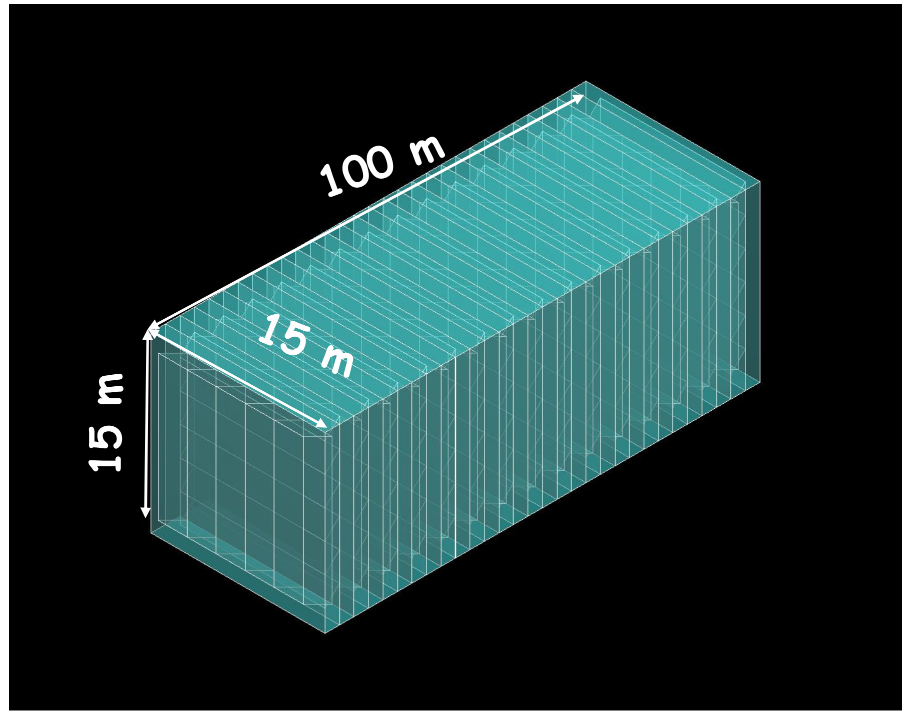
Totally Active Scintillating Detectors (TASD)

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

Ellis, Bross

- 3333 Modules (X and Y plane)
- Each plane contains 1000 slabs
- Total: 6.7M channels



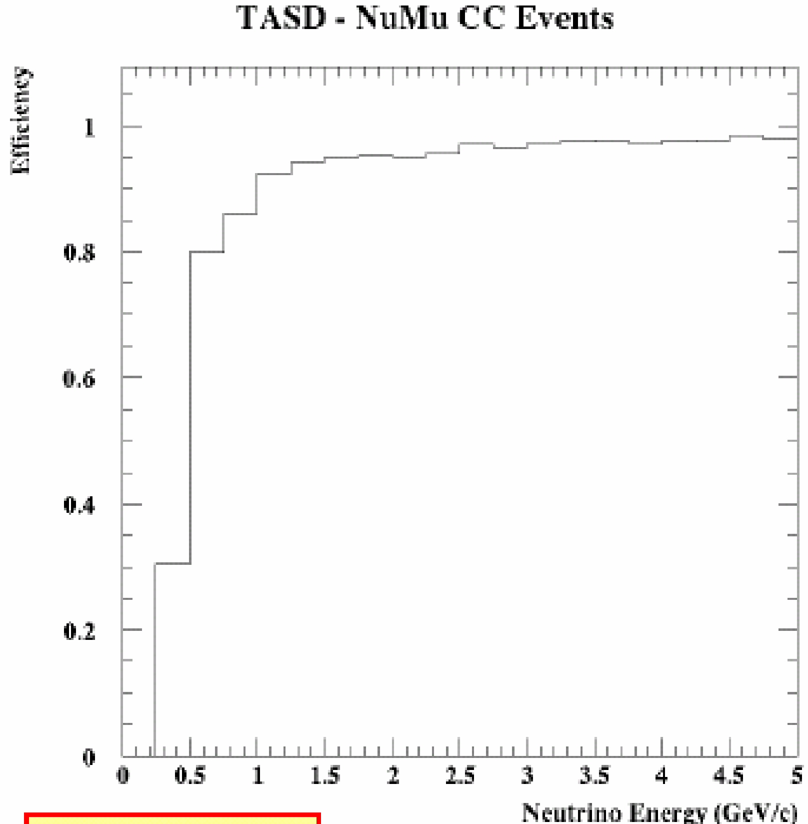


- Momenta between 100 MeV/c to 15 GeV/c
- Magnetic field considered: 0.5 T
- Reconstructed position resolution ~ 4.5 mm

Reduction threshold: access second oscillation maximum and electron identification

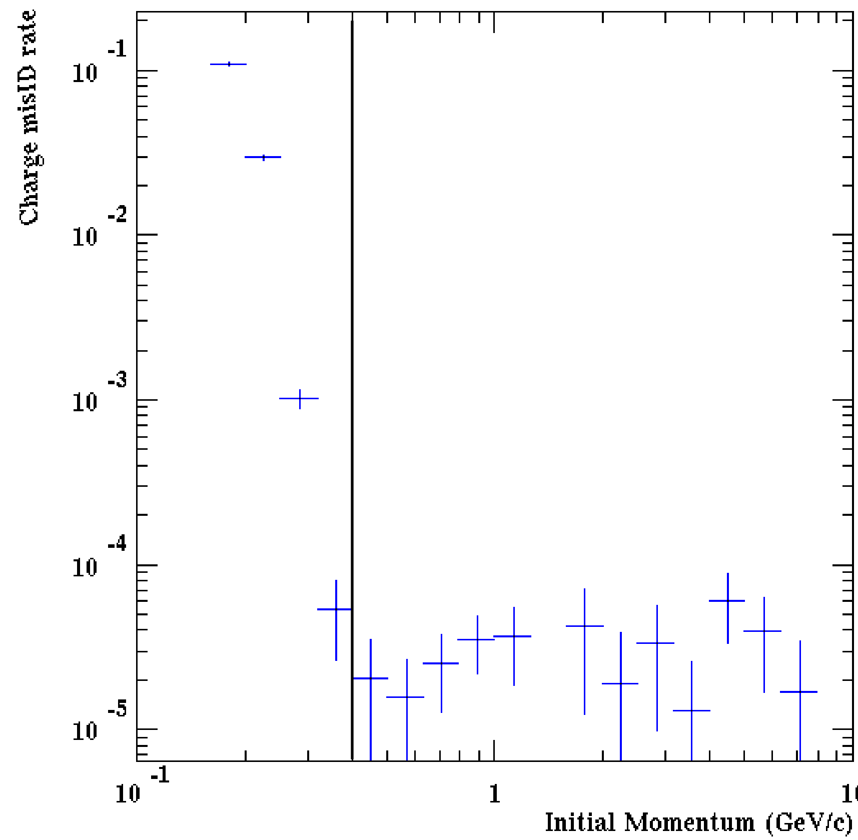
Totally Active Scintillating Detectors (TASD)

Neutrino CC reconstructed efficiency



Excellent σ_E

Muon charge mis-ID rate



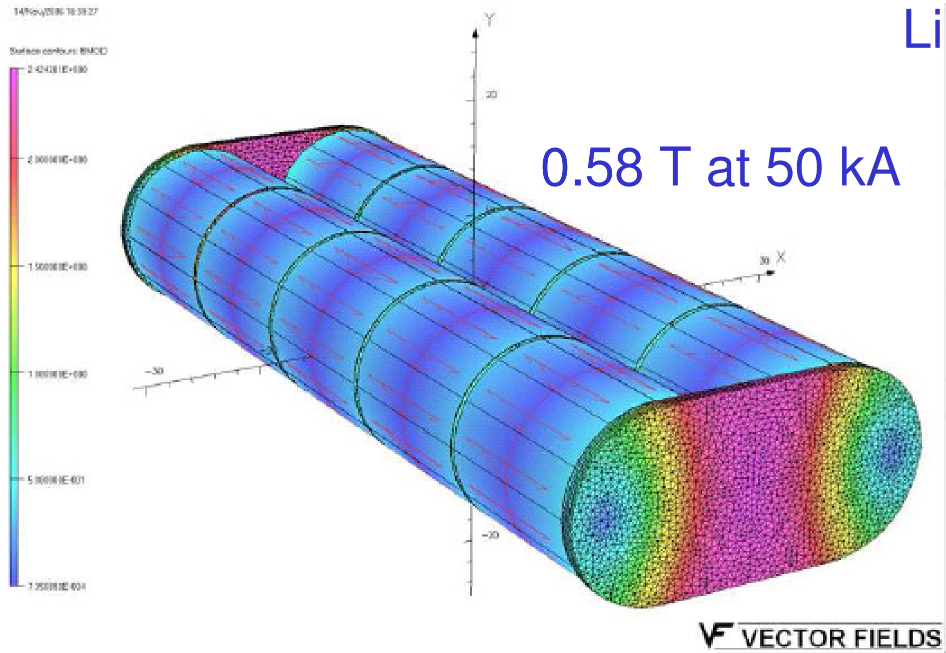
Main problem: magnetisation of huge volume
Difficulty and cost!

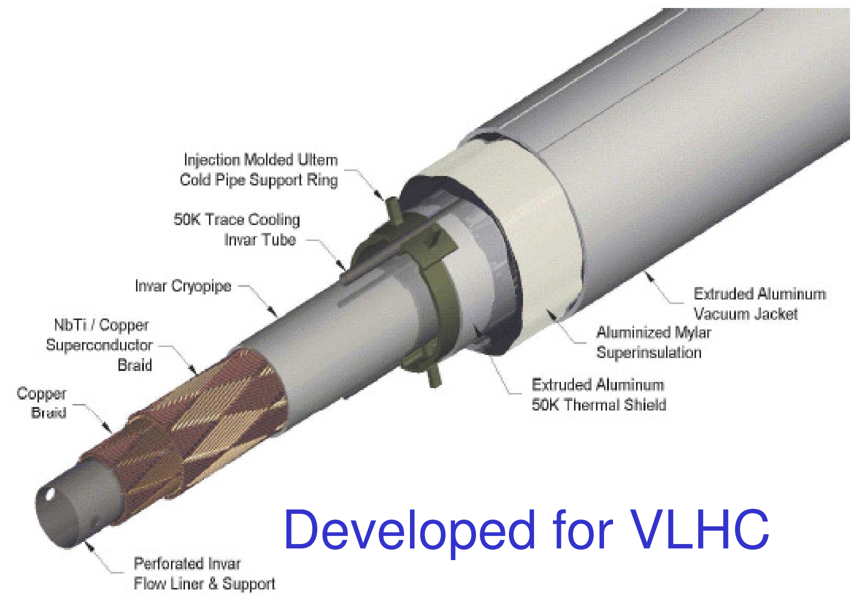
Totally Active Scintillating Detectors (TASD)

However, possible magnetisation can be achieved using magnetic cavern concept (10 modules with 15m x 15 m diameter)

Bross

Use Superconducting Transmission Line (STL): cable has its own cryostat!





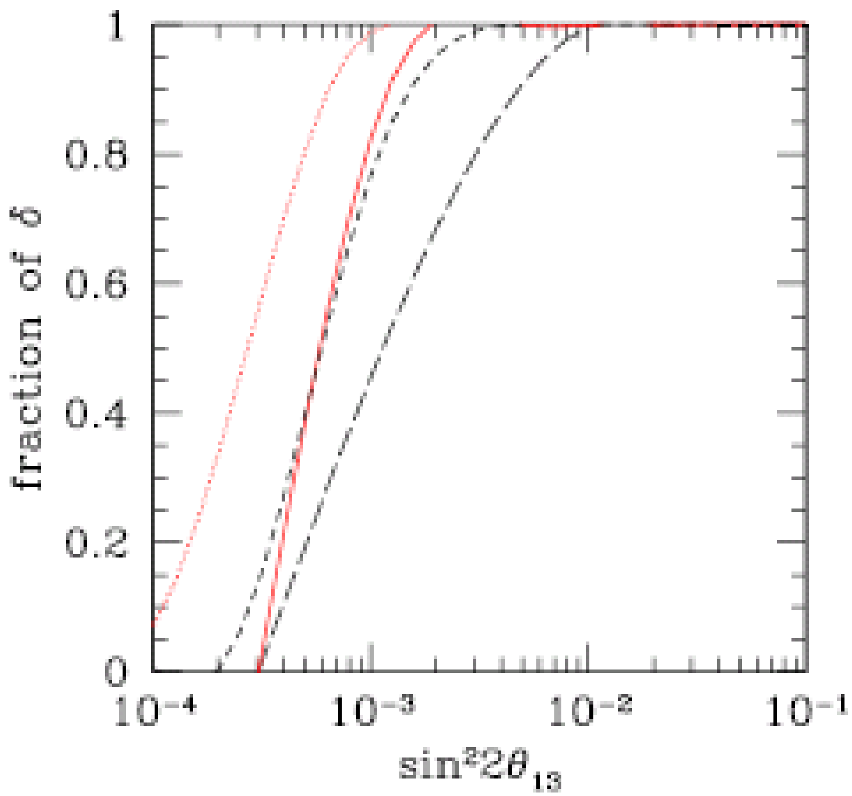
Developed for VLHC

R&D needed to develop concept!!

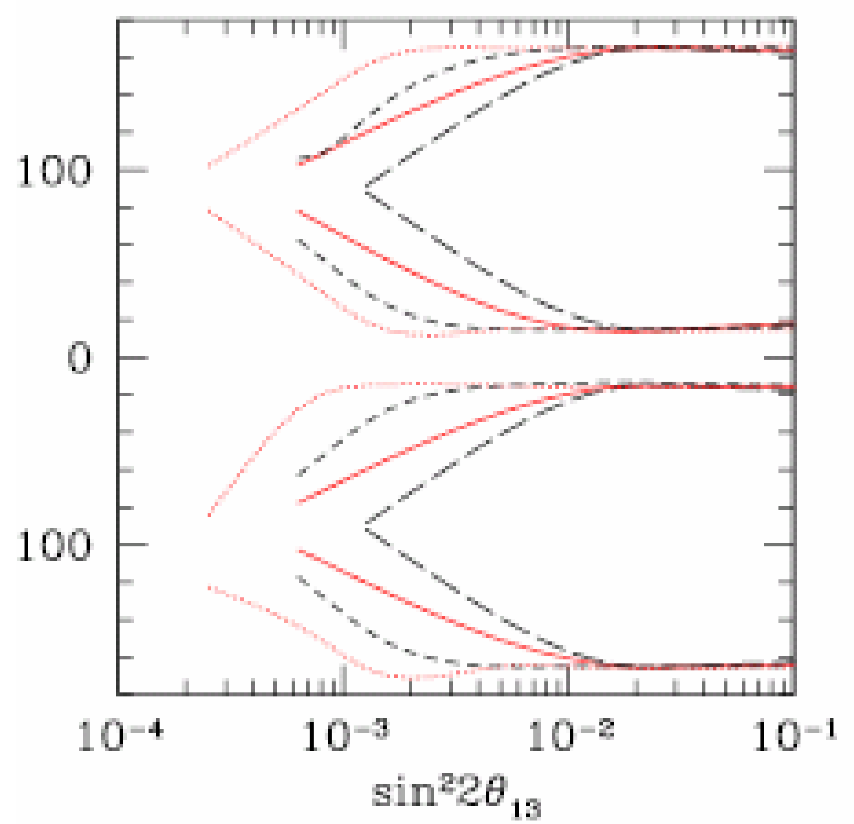
Totally Active Scintillating Detectors (TASD)

- Possible use of TASD opens up possibility of running at a low energy neutrino factory (4 GeV)   Bross, Ellis, Geer, Mena, Pascoli

95% CL mass hierarchy at 1480 km

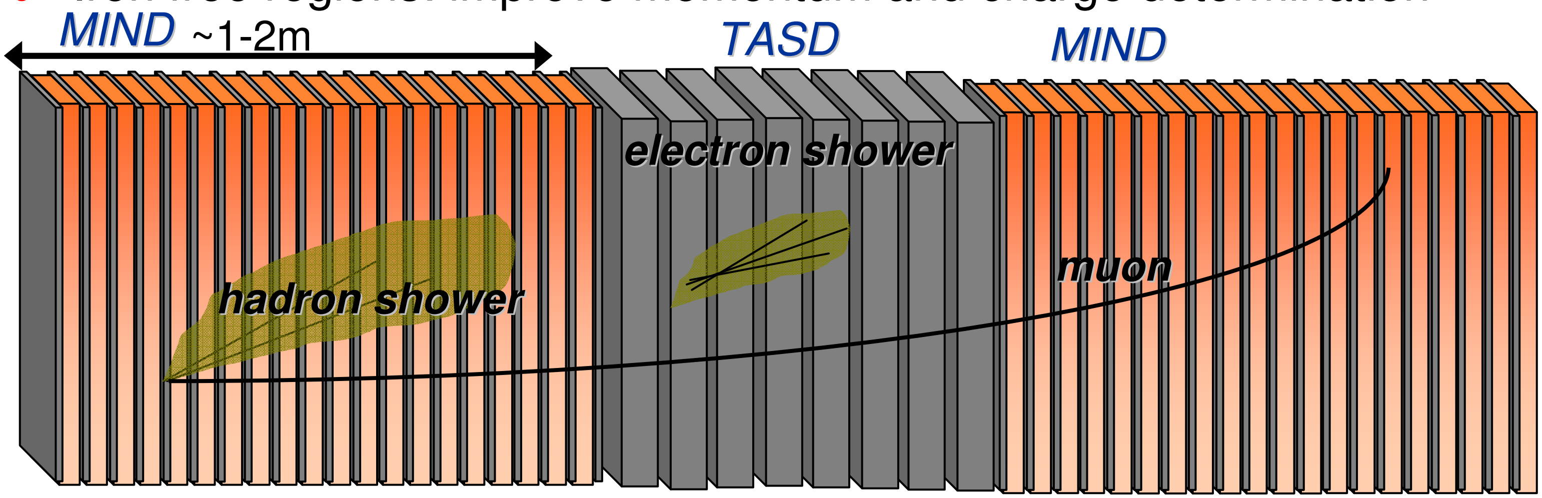


95% CL CP violation at 1480 km

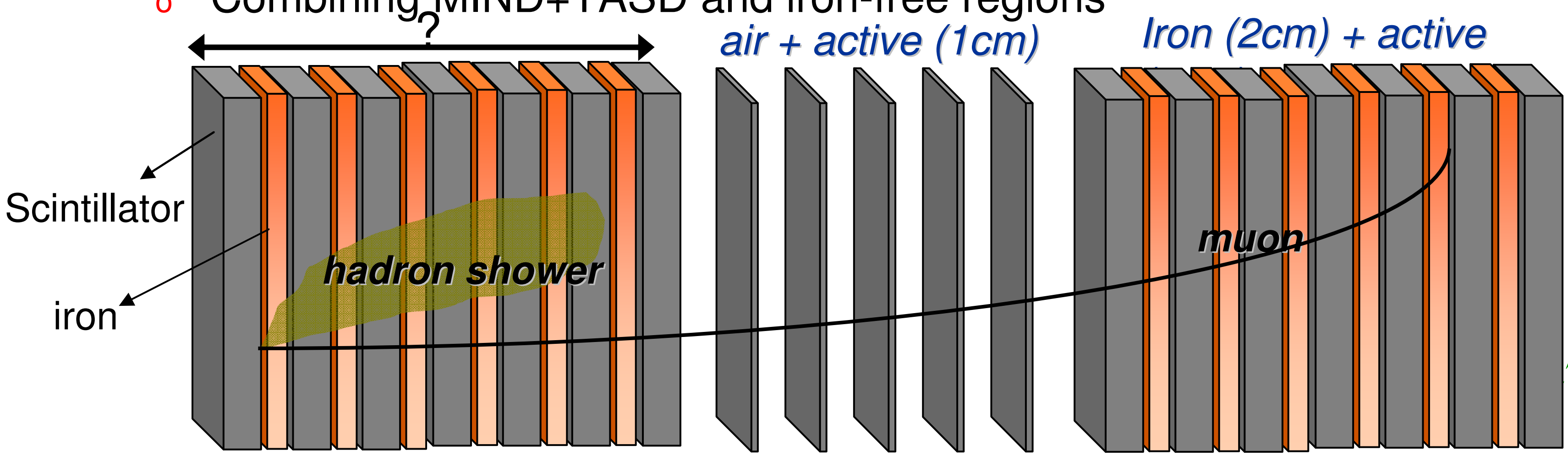


Hybrid detectors MIND+TASD?

- Compromise between MIND and TASD concepts? Optimisation of geometry not done
  - Iron free regions: improve momentum and charge determination

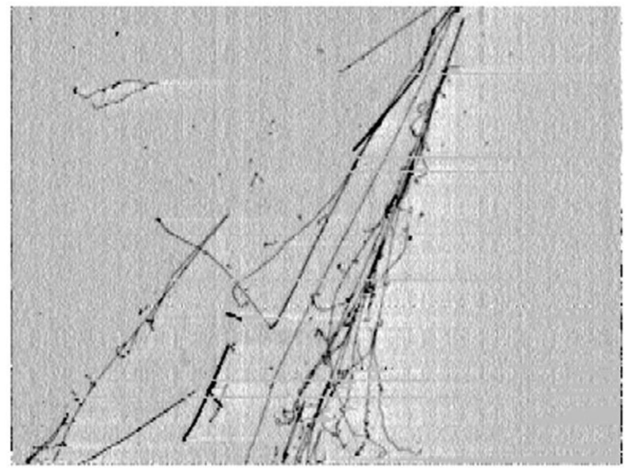


  - Combining MIND+TASD and iron-free regions



Liquid Argon TPC

- Liquid argon detector is the ultimate detector for ν_e ("platinum channel") and ν_τ appearance ("silver channel"). Simultaneous fit to all wrong and right sign distributions.
- Liquid argon is a mature technology: ICARUS has constructed 2x300 t modules and observed images

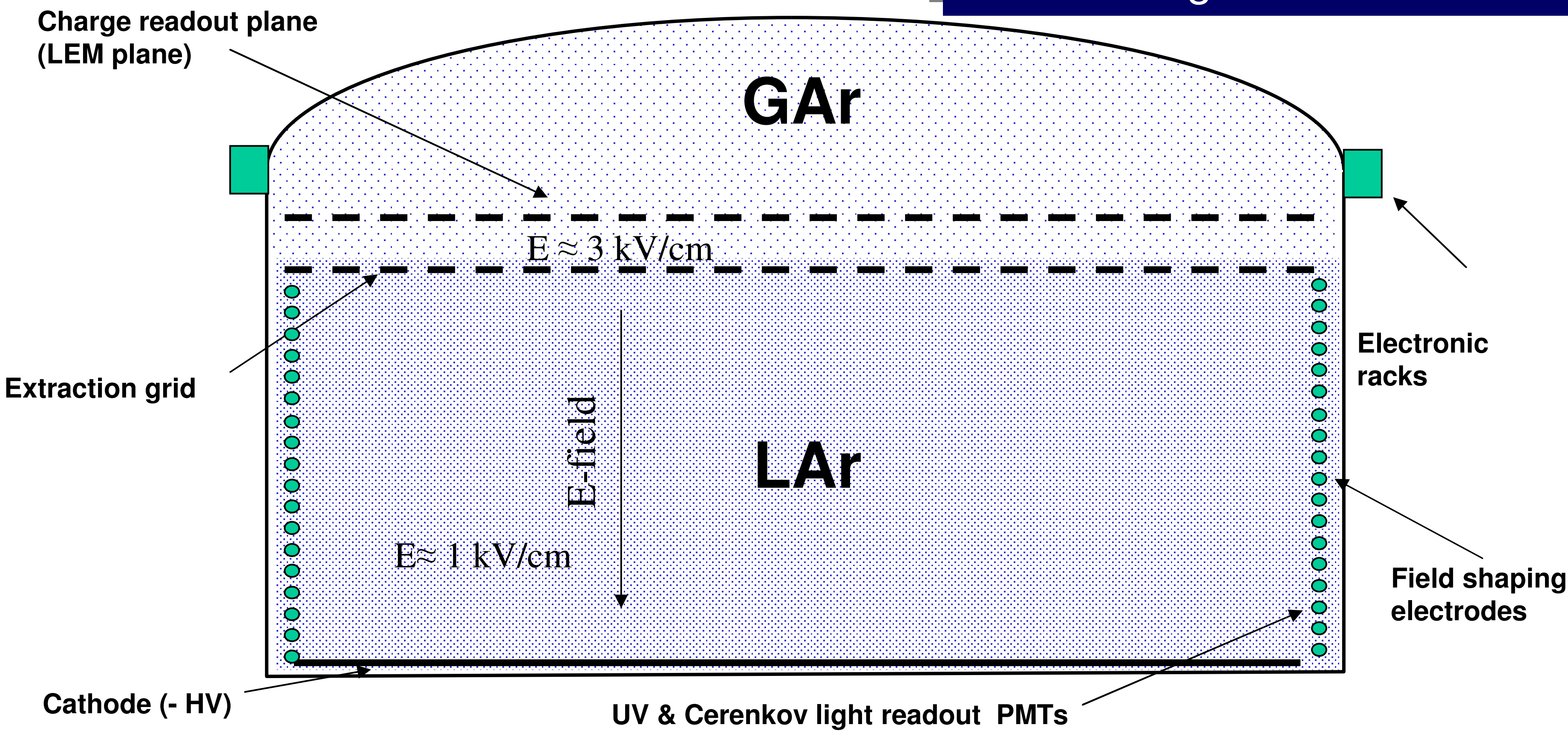


- Main issues: inclusion of a magnetic field, scalability to ~15-100 kT
- Two main R&D programmes: Europe & US

Liquid Argon TPC

A tentative detector layout (GLACIER)

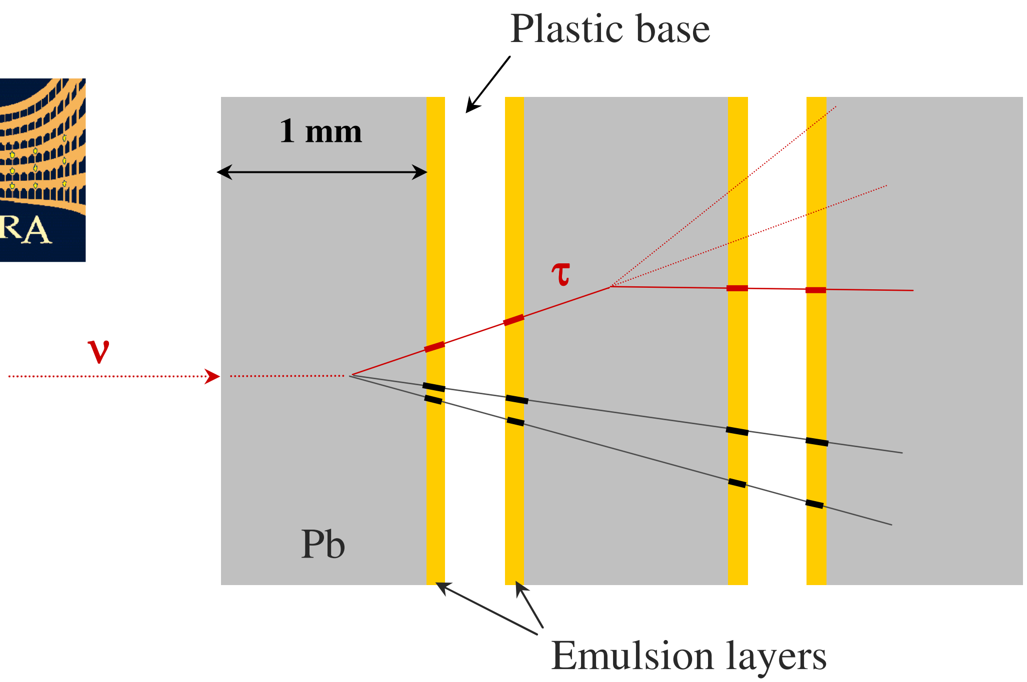
Single detector: charge imaging, scintillation, possibly Cerenkov light

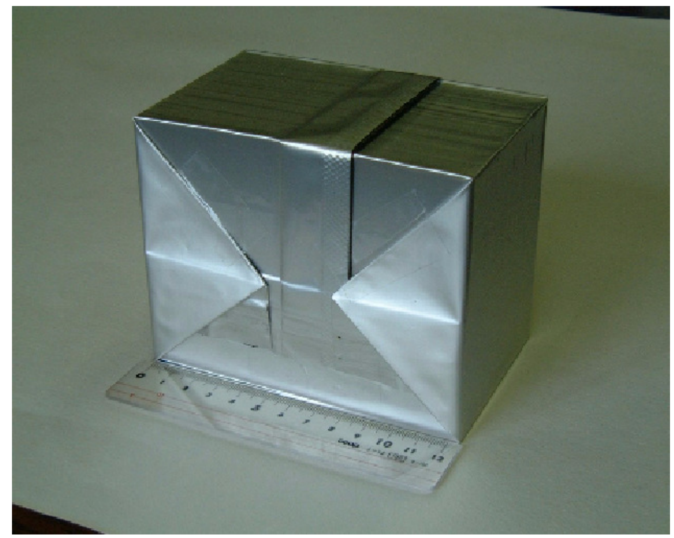


Magnetic field problem
Field 0.1-1 T?

Hybrid Emulsion Detectors

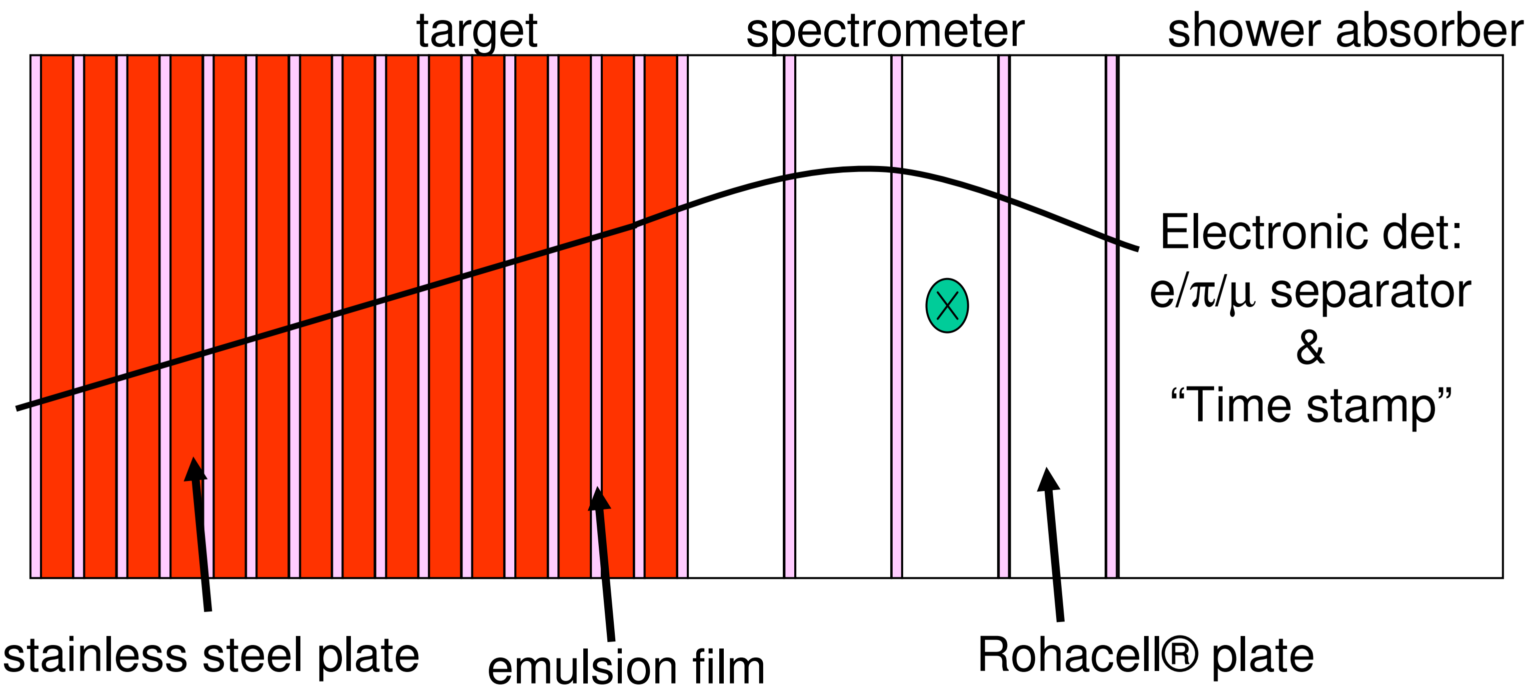
- Emulsion detector for ν_τ appearance, a la OPERA: "silver channel"
  Emulsion Cloud Chamber (ECC)



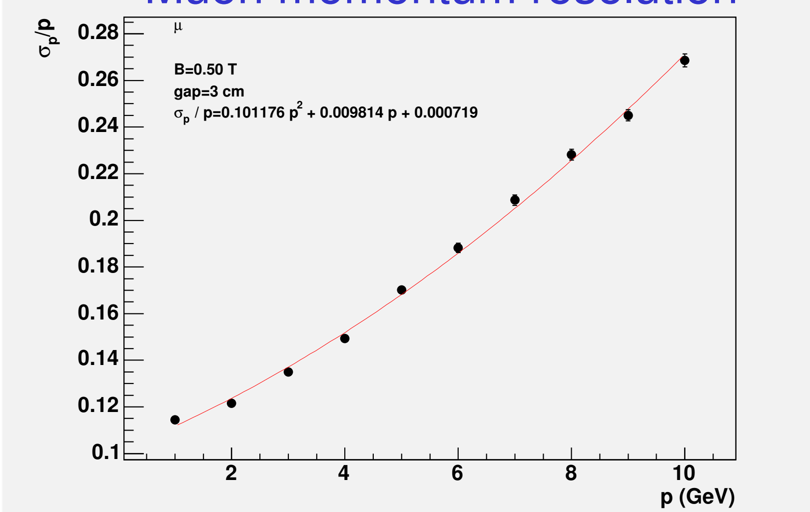


- Issues: high rate, selected by choosing only "wrong sign" $\tau \rightarrow \mu$ events
- Assume a factor of two bigger than OPERA (~4 kt)

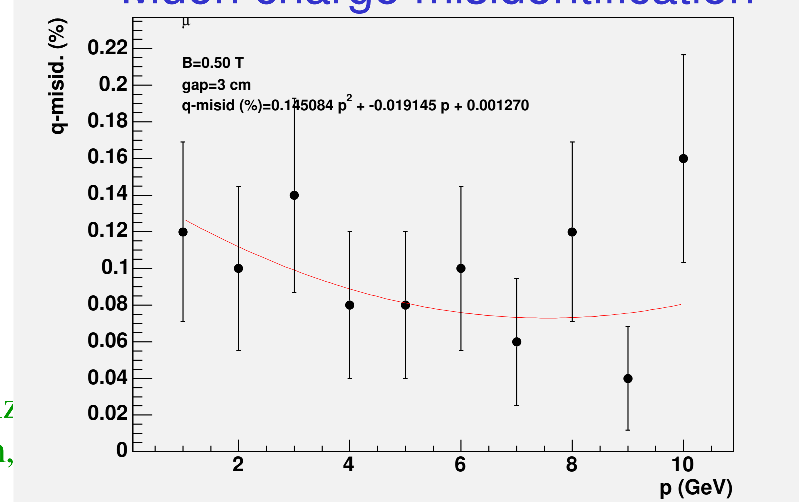
Magnetised Emulsion Cloud Chamber



Muon momentum resolution



Muon charge misidentification

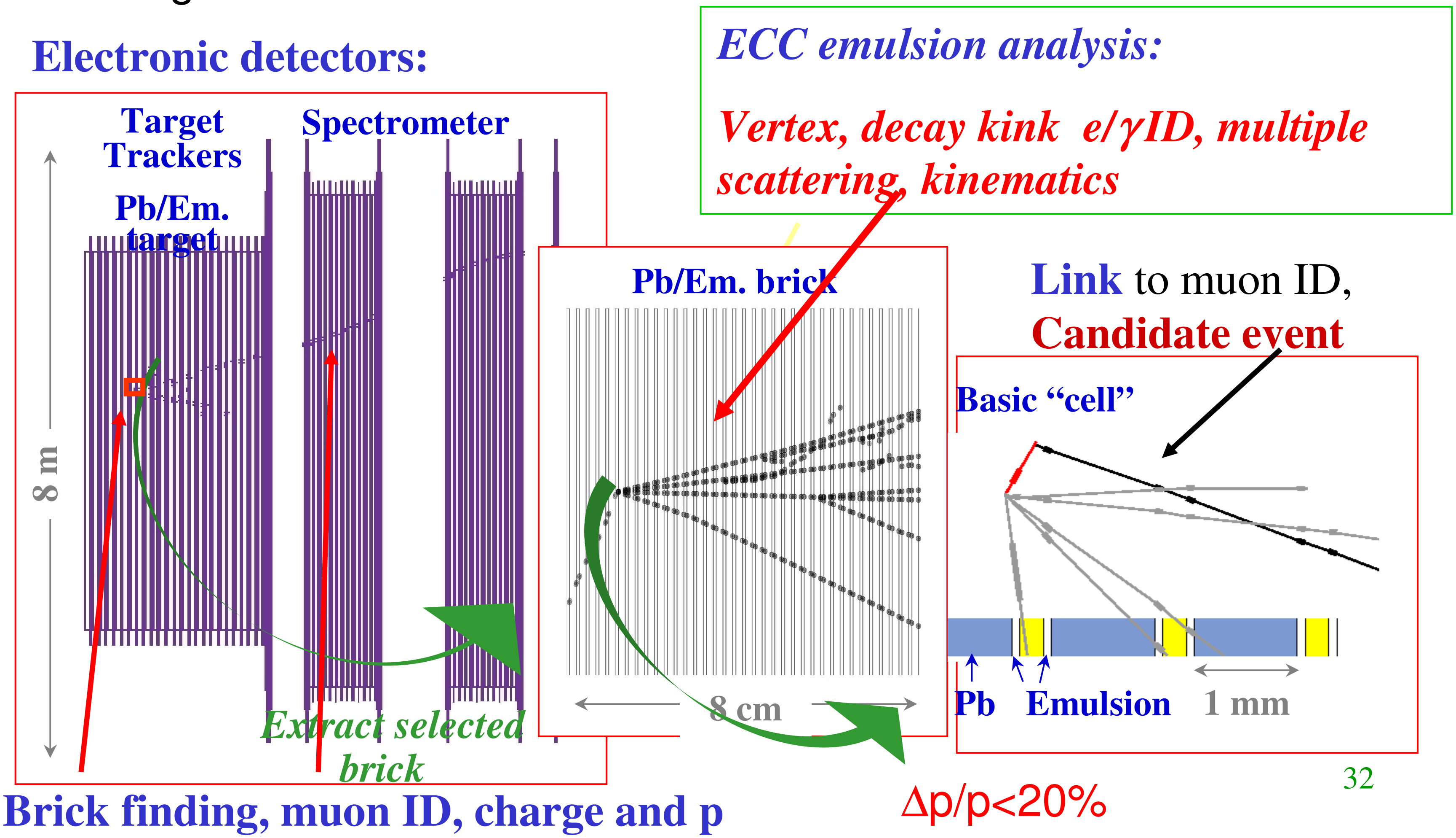


Hybrid Emulsion Detectors

Possible design hybrid emulsion-scintillator far detector

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

Golden and silver channels simultaneously!



Near detector

What needs to be measured

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

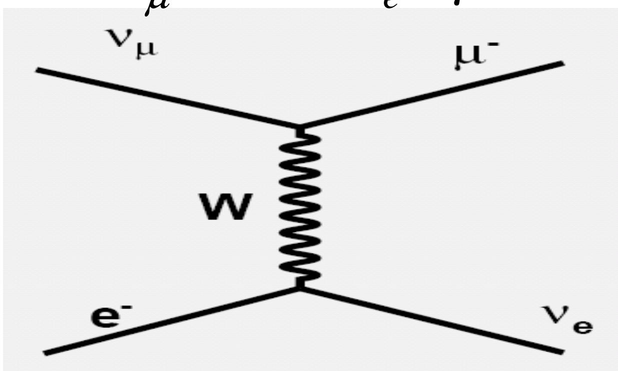
$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e \qquad \bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$$

- 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.

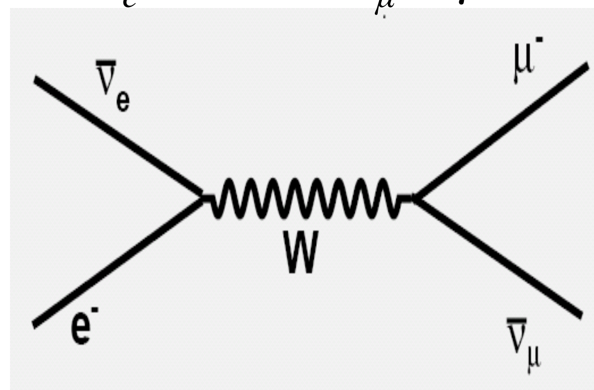
Flux Measurement at Near Detector for NF

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

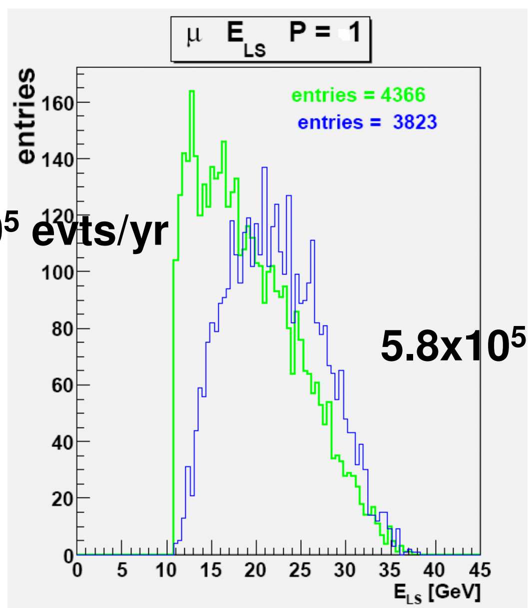
$$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$$



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

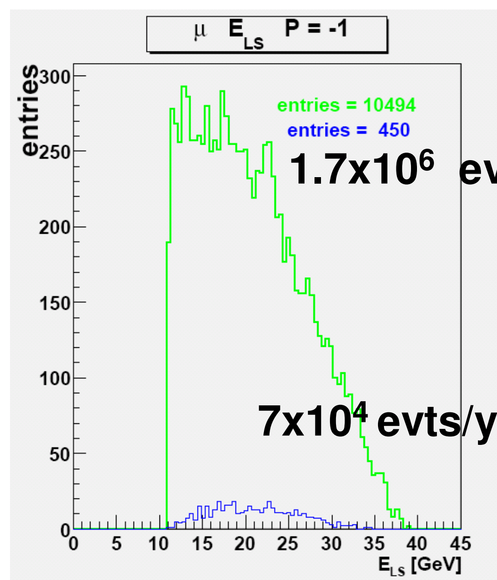


- Rates in 1 ton Near Detector for 10^{21} muons/yr



6.9×10^5 evts/yr

5.8×10^5 evts/yr



1.7×10^6 evts/yr

7×10^4 evts/yr

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

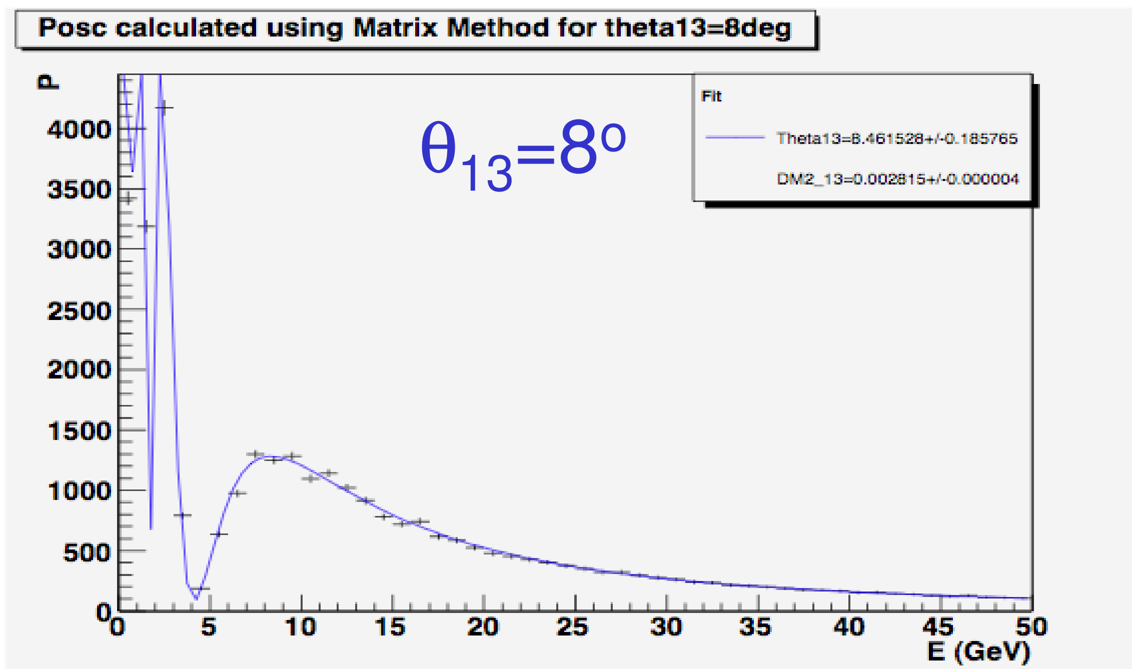
  M_2=matrix relating event rate and flux of ν_μ at FD

  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

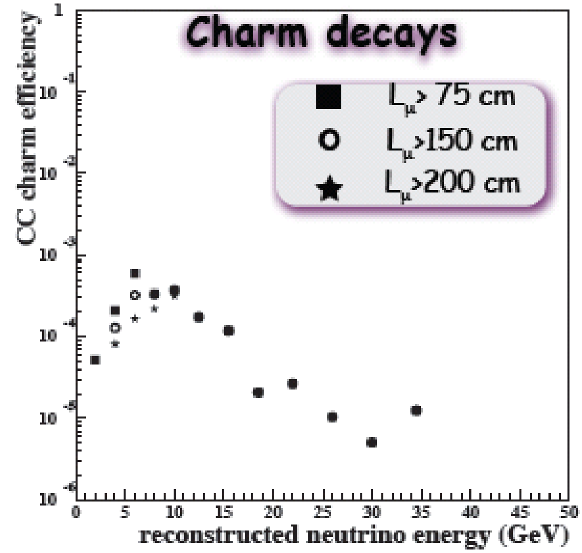
- Proof of principle works for Neutrino Factory near detector but need to extract syst errors of method:

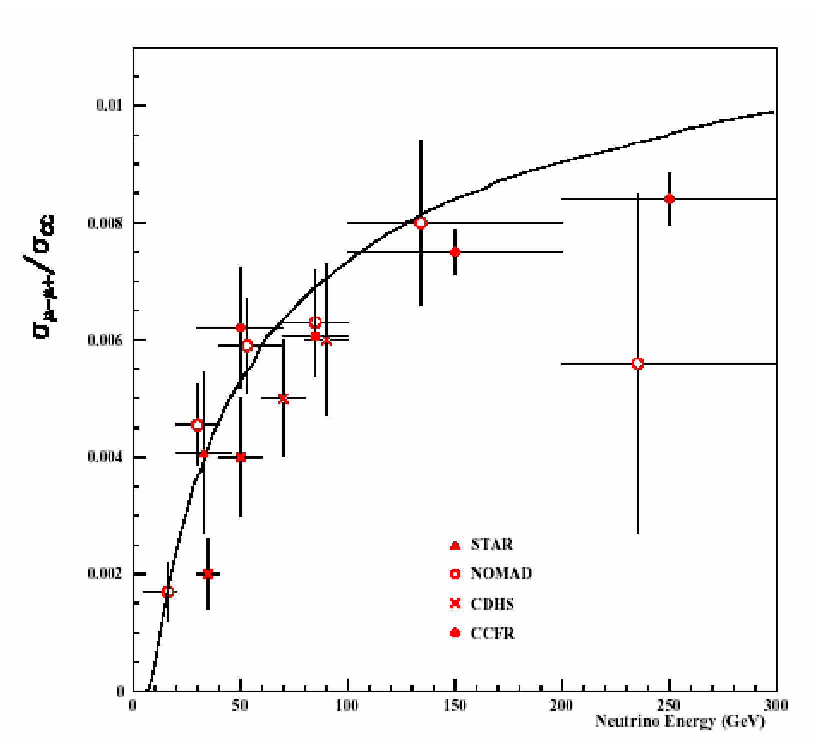
Probability of oscillation determined by matrix method under "simplistic" conditions. Need to give more realism to detector and matter effects.



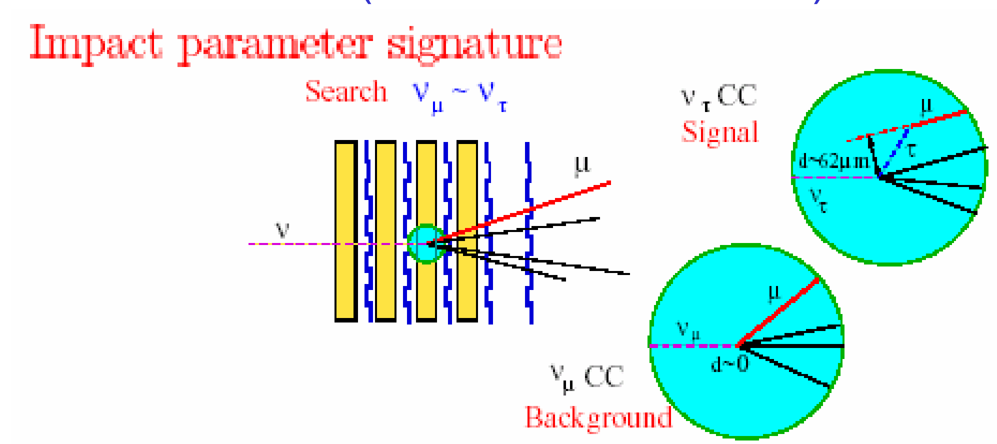
Charm measurement for NF

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



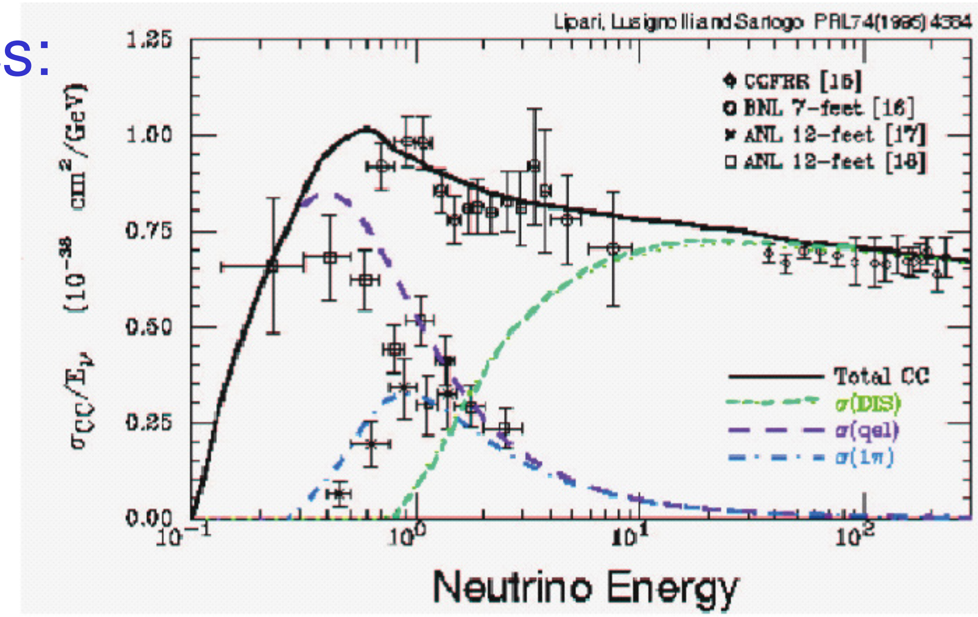


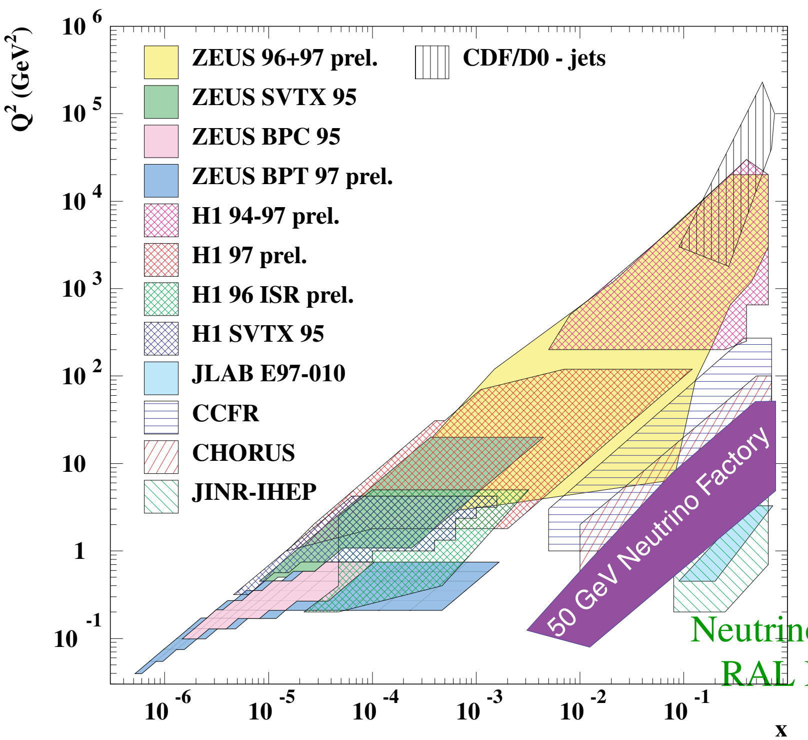
- Semiconductor vertex detector only viable option in high intensity environment (emulsion too slow!)



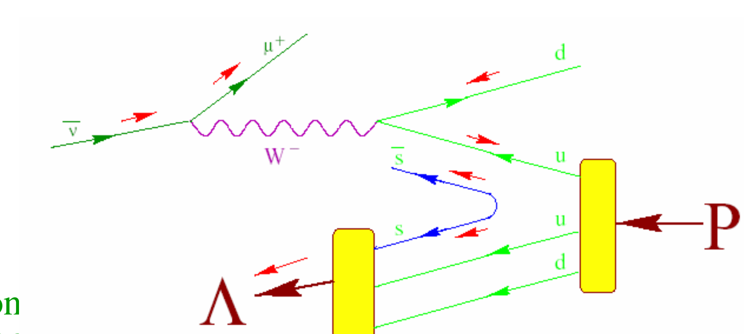
Other measurements Near Detector

- Near detector neutrino physics:
  - Cross-section measurements: DIS, QES, RES scattering
  - $\sin^2\theta_W$ - $\delta\sin^2\theta_W$ ~ 0.0001
  - Parton Distribution Functions, nuclear shadowing
  - α_S from xF_3 - $\delta\alpha_S$~0.003





- Λ polarization: spin transfer from quarks to Λ



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.

EuroNu

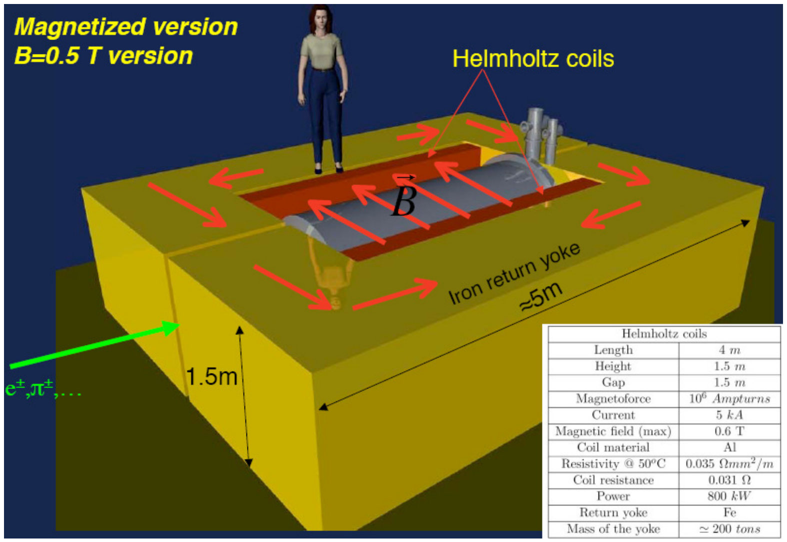
- EuroNu: four year EU Design Study for "A High Intensity Neutrino Oscillation Facility in Europe"
- EuroNu will carry out a design study for Super-beam, Neutrino Factory, Beta-beam, neutrino detectors and physics performance.
- Detector tasks:
  - Define the baseline detector options needed to deliver the physics for each of the neutrino facilities.
  - Priorities: performance and cost of ISS baseline detectors Magnetised Iron Neutrino Detector (MIND) for the Neutrino Factory, water Cherenkov detector for the Super-Beam and Beta Beam facilities and near detector at each of the facilities for absolute flux normalisation, measurement of differential cross sections and detector backgrounds.
  - Desirable other studies: extensions to the baseline options, including Totally Active Scintillator Detector (TASD) and Emulsion Detectors for the platinum and silver channels, beam instrumentation and shielding requirements for the near detector.

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 activities in communication with neutrino community and coordinate neutrino test beam facilities and measurements. Also, liaise with other communities in common software and common microelectronics

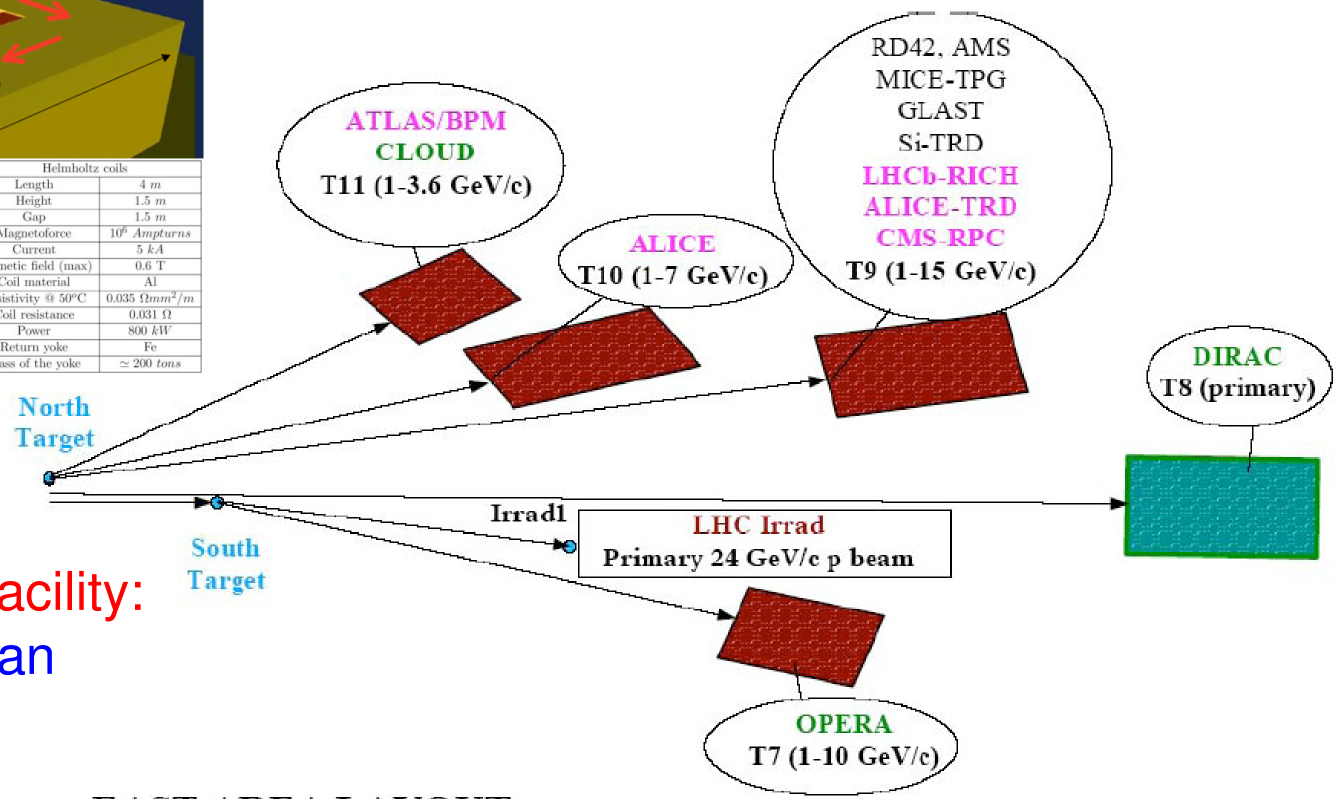
Test Beam Facility for Neutrino Detector R&D

- Request test beam in East Area at the CERN PS, with a fixed dipole magnet for dedicated Neutrino Detector R&D



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 $tons$

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



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

EAST AREA LAYOUT
(2006 Situation)

Need very low intensity ≈ 1000 /spill

MIND prototypes for Test Beam

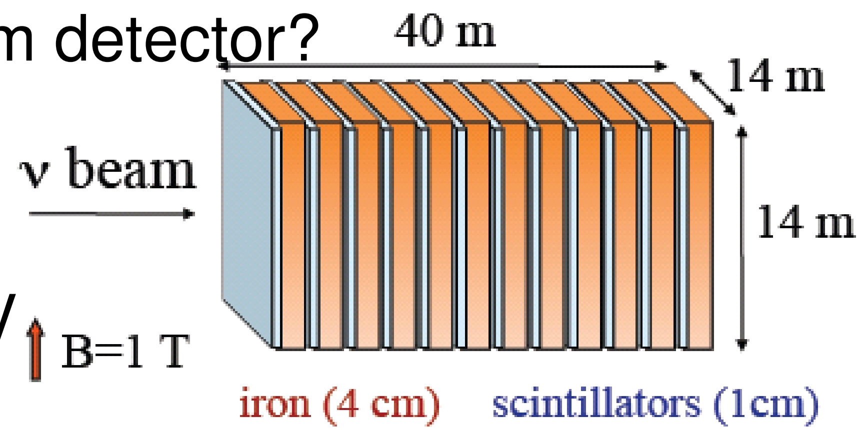
- Prototype MIND ("BabyMind"): A. Cervera

  How big do we make test beam detector?

  Current default is ~2x2x4 m^3

  ie. ~10^{-3} of full MIND

  Important to contain μ < 2 GeV



1cm transverse resolution

- Use of INO test stand in a beam environment:
  - Nearly the same as "BabyMind"
  - Main difference: dipole vs toroidal field
    - Probably not an issue

Conclusions

- 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
  - Laguna also partly funded for investigation very large volume detectors (water Cherenkov, liquid argon and scintillator)
  - 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 for Neutrino Factory Detector R&D?
- If we did, it could be based around the following:

1. Magnetic detector: scintillator and photon readout technology for 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 R&D activities