European Neutrino Beam Plans

NNN08, Paris
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Outline

1. Motivation: neutrino mixing, oscillations, degeneracies and unknown parameters
2. Super-beams
3. Neutrino Beta-beam
4. Neutrino Factory
5. Magnetised Iron Neutrino Detector (MIND)
6. Totally Active Scintillator Detector (TASD)
7. Near detector
8. R&D plans in Europe
9. Neutrino Facility roadmap

Neutrino mixing

- Weak eigenstates do not have to coincide with mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow \boldsymbol{U} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} e^{-i\alpha_1} & 0 & 0 \\ 0 & e^{-i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

Ignoring Majorana phases α_1 and α_2, the neutrino mixing matrix (Pontecorvo-Maki-Nakagawa-Sakata, PMNS matrix) is similar to CKM matrix for quarks.

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

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)

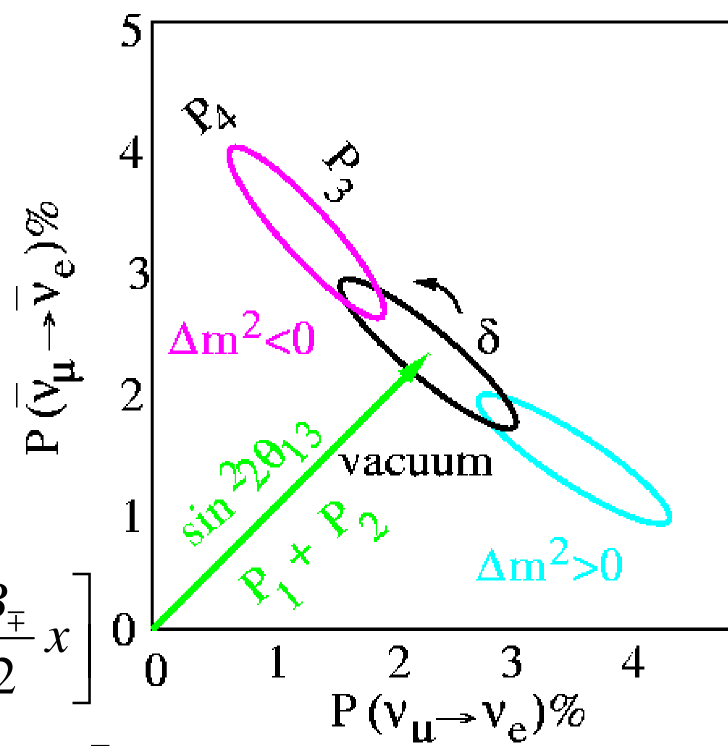
$$P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)}(x) = P_1 + P_2 + P_3 + P_4$$

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

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

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

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



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

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Only one term in equation

Magic baseline:

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

Clean determination of θ_{13}

However, there are up to 8 degeneracies and correlations between variables that need to be determined.

Strategy: different experiments at different baselines and energies to solve degeneracies

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

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

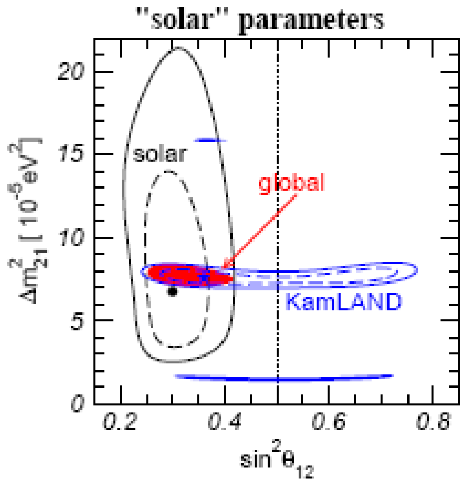
$$\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$

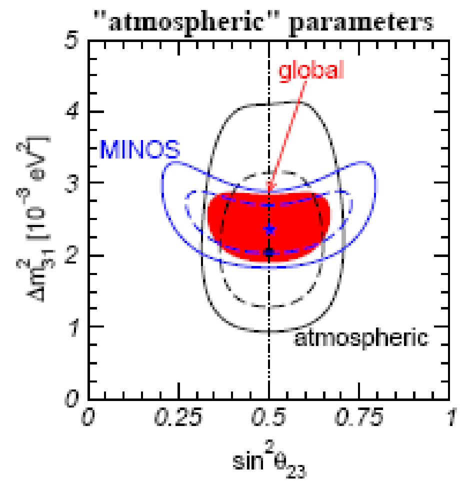
with $B_\mp \equiv \sqrt{(\Delta_{13}\cos 2\theta_{13} \mp A)^2 + \Delta_{13}^2 \sin^2 2\theta_{13}} \approx |\Delta_{13} \mp A|$

Unknown parameters

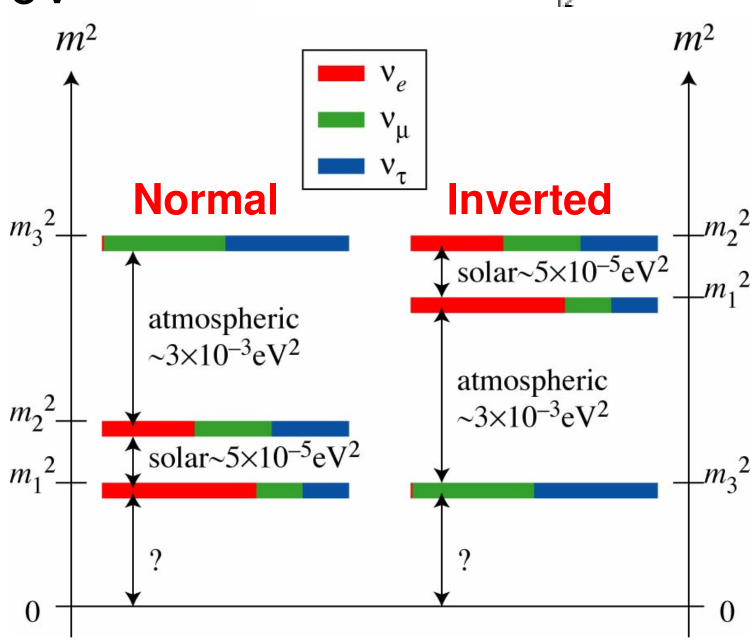
- Consistent picture emerging
- Global fit provides:
  - $\sin^2\theta_{12}=0.32\pm0.23$
  - $\Delta m_{12}^2 = 7.6\pm0.20\times10^{-5}$ eV^2
  - $\sin^2\theta_{23}=0.50\pm0.063$
  - $\Delta m_{23}^2=2.4\pm0.15\times10^{-3}$ eV^2

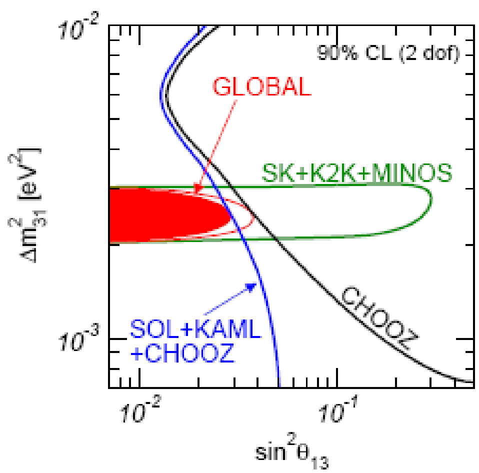
Schwetz





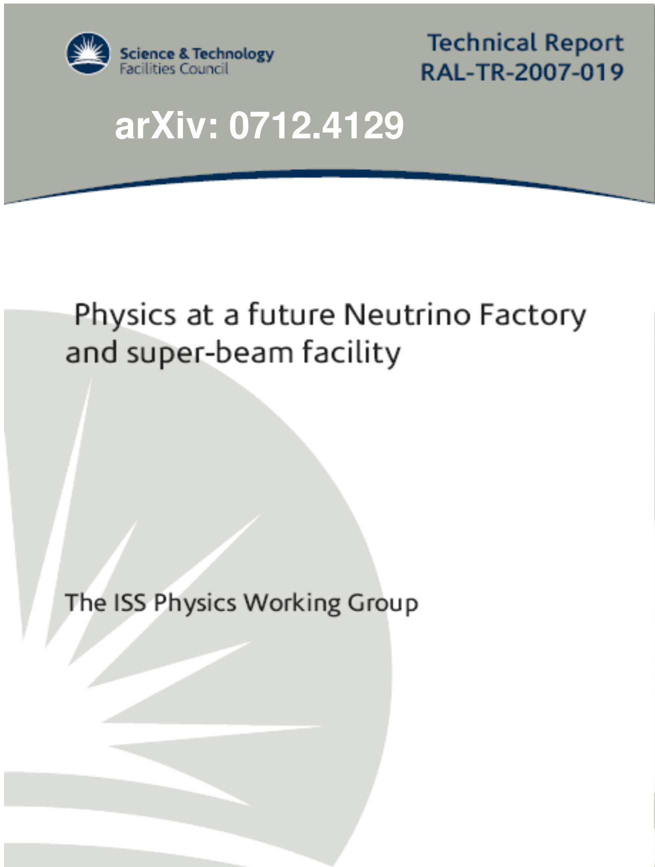
- Unknown quantities:
  - $\sin\theta_{13}<0.224$ (@3σ),
  - Mass hierarchy: sign Δm_{13}^2
  - CP violation phase δ

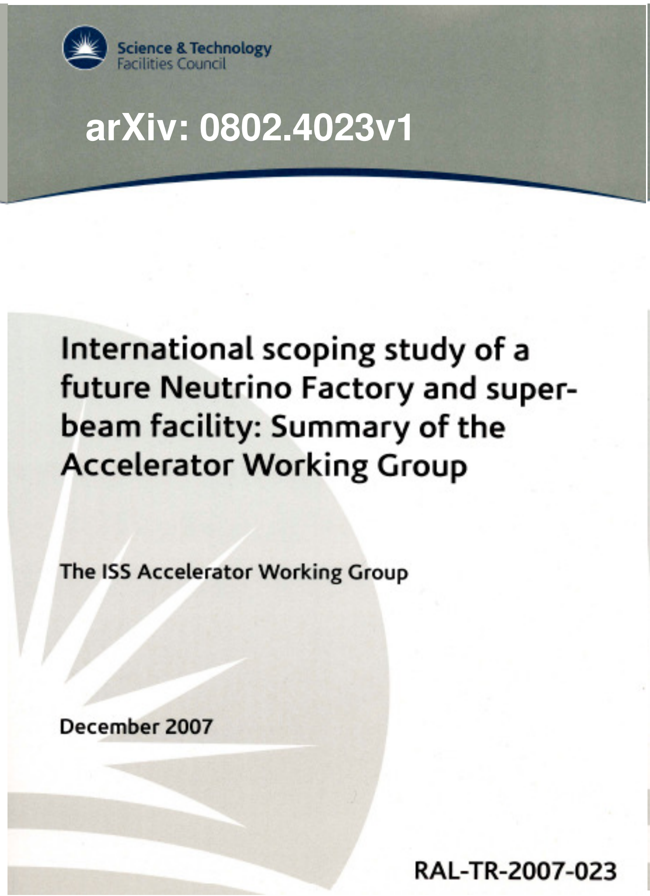


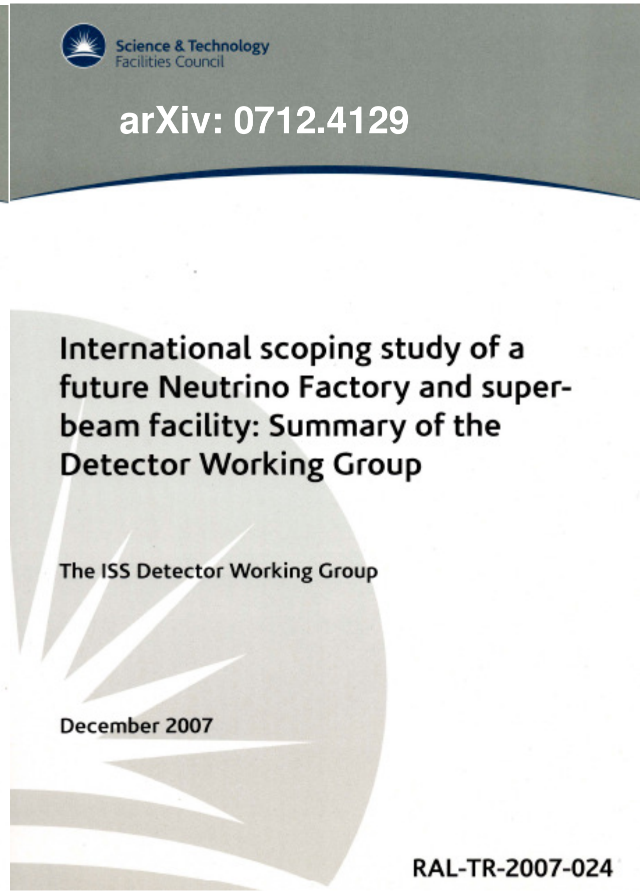


International Scoping Study

- The International Scoping Study looked at the physics, accelerator and detector prospects for future neutrino oscillation facilities to determine remaining unknown oscillation parameters
- Outcomes have been published as three reports:







International Scoping Study (Detectors)

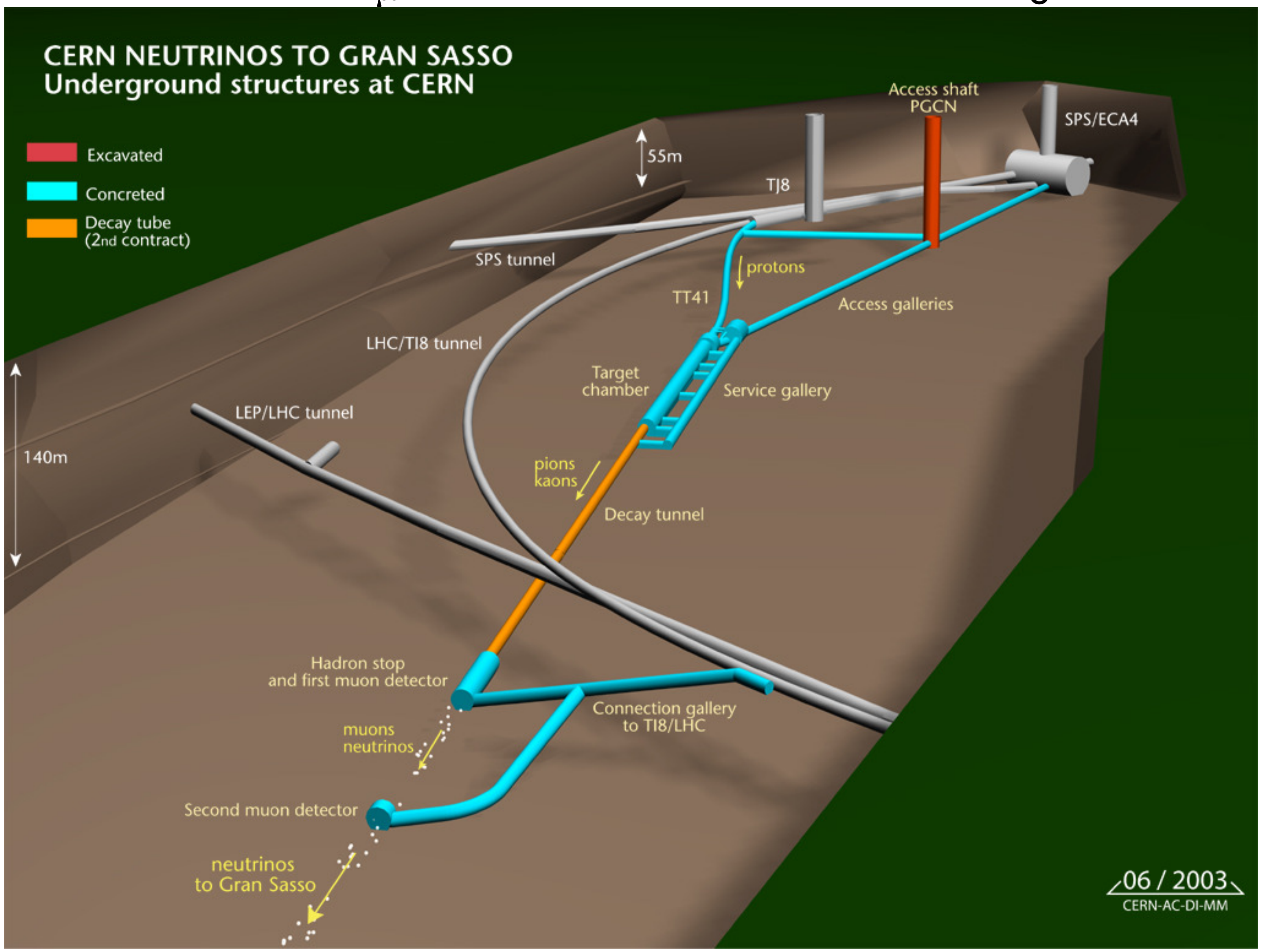
- Baseline detector requirements from International Scoping Study
  - Two detectors at 4000 km and 7500 km to solve degeneracies
- For a Neutrino Factory facility:
  - Magnetised Iron Neutrino Detector (MIND) of 50 kton fiducial for ν_μ appearance channel (gold channel) at each baseline +
  - Magnetised Emulsion Cloud Chamber (MECC) of 10 kton for ν_τ appearance (silver channel) at 4000 km
- Beyond the baseline improvements for Neutrino Factory include ν_e appearance (platinum) channels (R&D needed):
  - Magnetised Liquid Argon: 10-100 kton
  - Magnetised Totally Active Scintillating Detector (TASD): 20-30 kton
- For a Super-Beam or Beta-beam facility: do not need magnetisation
  - Baseline is Water Cherenkov detector (~500 kton)
  - Other options: Liquid Argon or Totally Active Scintillating Detector (ie. non-magnetised, à la Noνa)

Super-Beams

- The first European Super-Beam: CERN to Gran Sasso (CNGS)

ν_μ's: $\pi^+ \rightarrow \mu^+ \nu_\mu$, $K^+ \rightarrow \mu^+ \nu_\mu$

ν_e's: $\mu^+ \rightarrow e^+ \nu_e \nu_\mu$, $K^+ \rightarrow \pi^0 e^+ \nu_e$



Super-Beams

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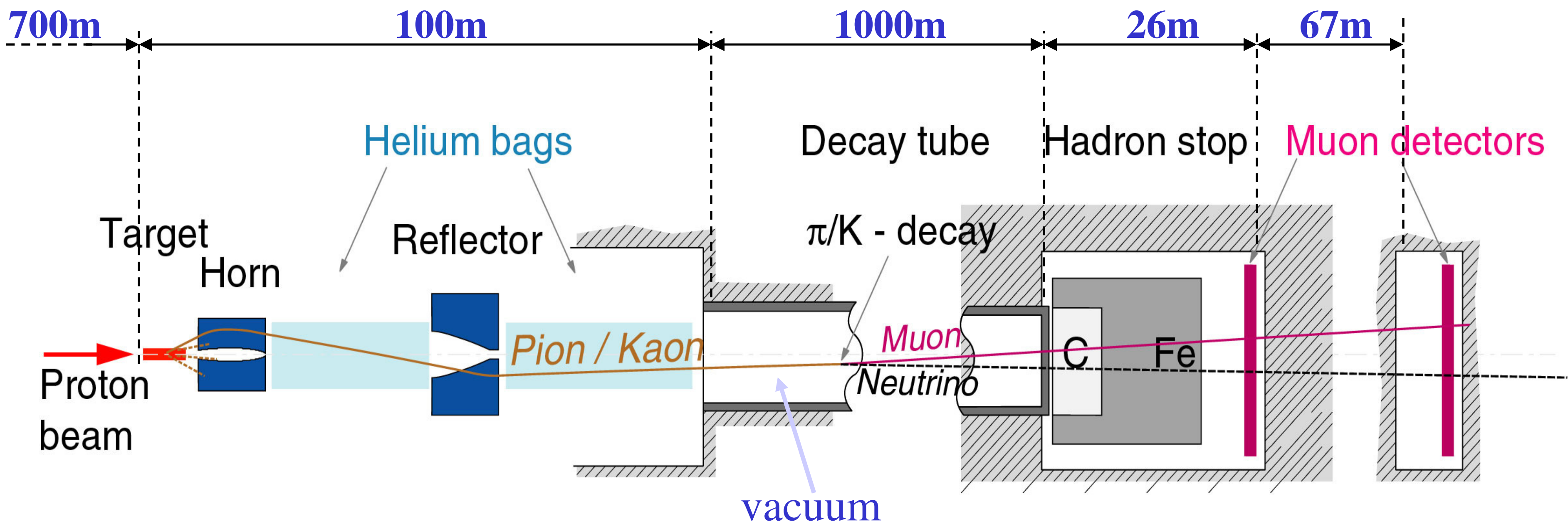
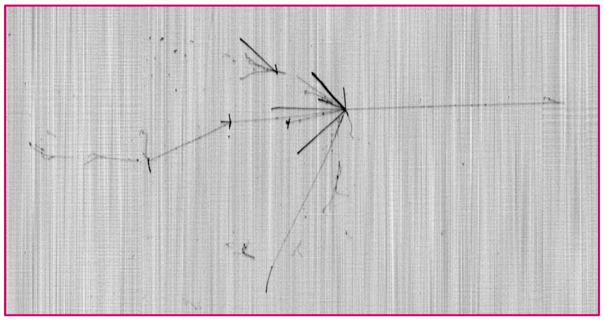


$$p + C \rightarrow \text{(interactions)} \rightarrow \pi^+,\ K^+ \rightarrow \text{(decay in flight)} \rightarrow \mu^+ + \nu_\mu$$

Super-Beams

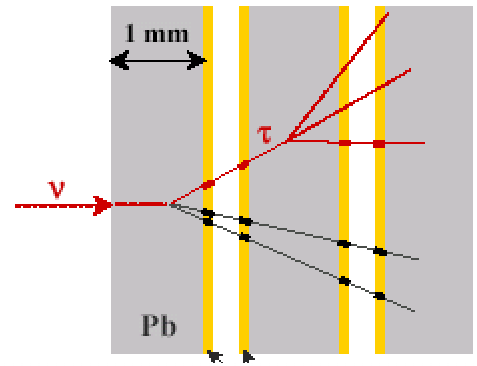
- Detectors at CNGS: OPERA and ICARUS ν_τ appearance

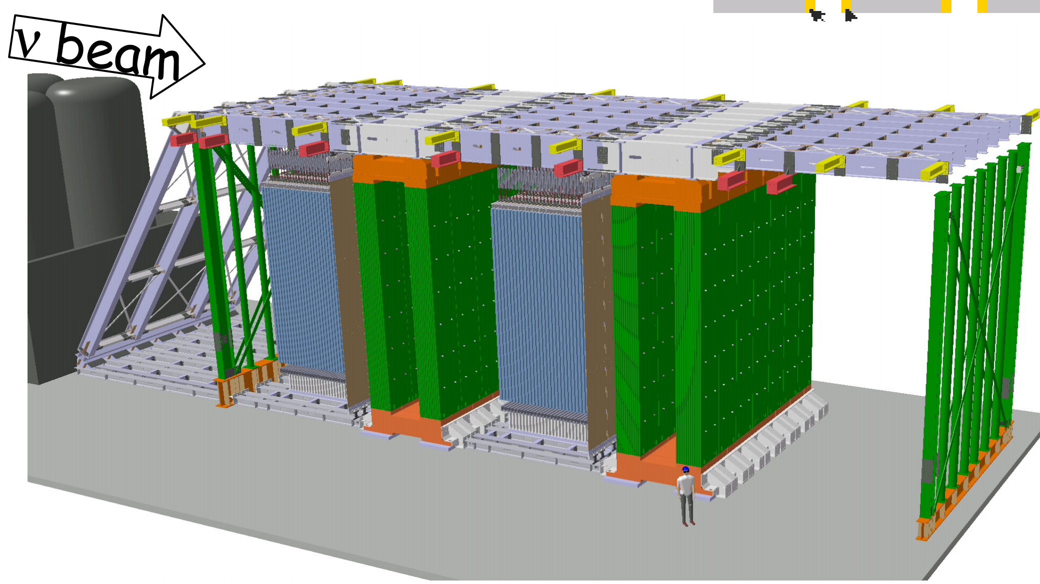
ICARUS (600 ton liquid argon TPC): kinematic selection of ν_τ



OPERA (1.8 kton emulsion based ν_τ appearance search).

6.6 ν_τ signal events
(Δm^2=1.9x10^{-3}eV^2)



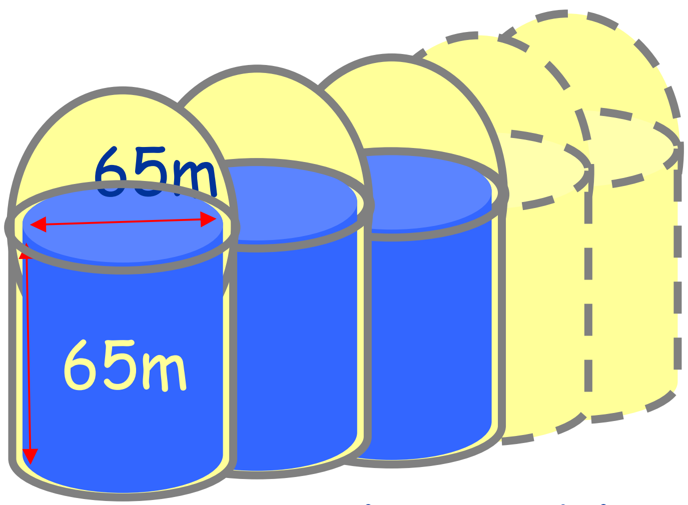


Super-Beams

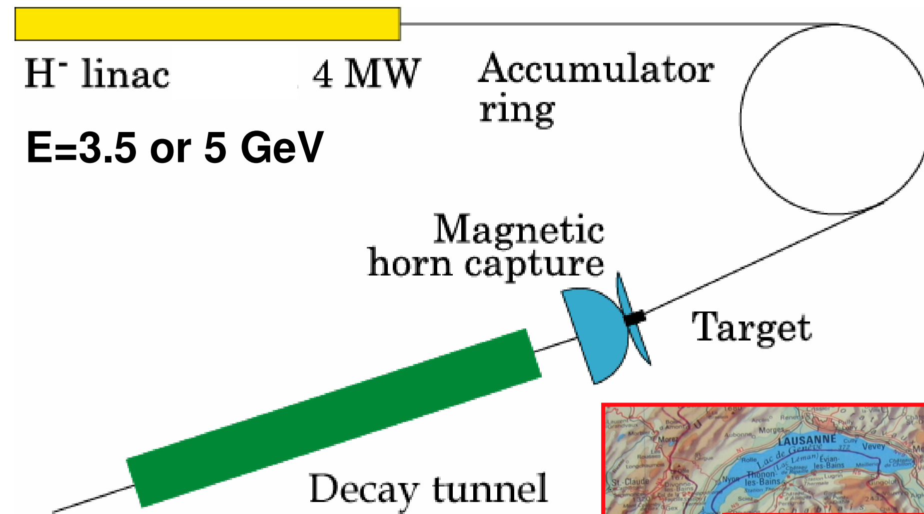
- SPL: Super-conducting Proton LINAC

Memphys

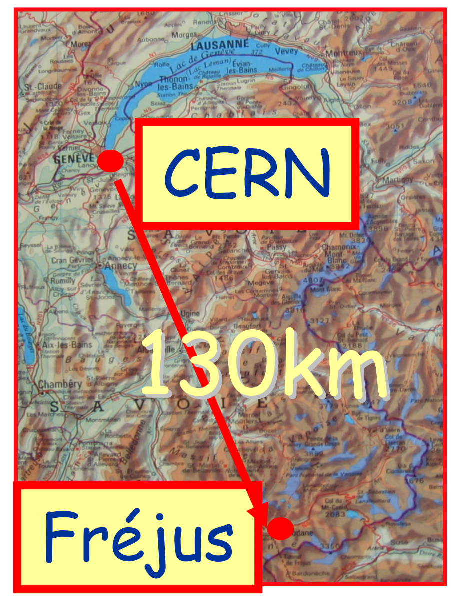
~440 kton



Water Cerenkov modules at Fréjus



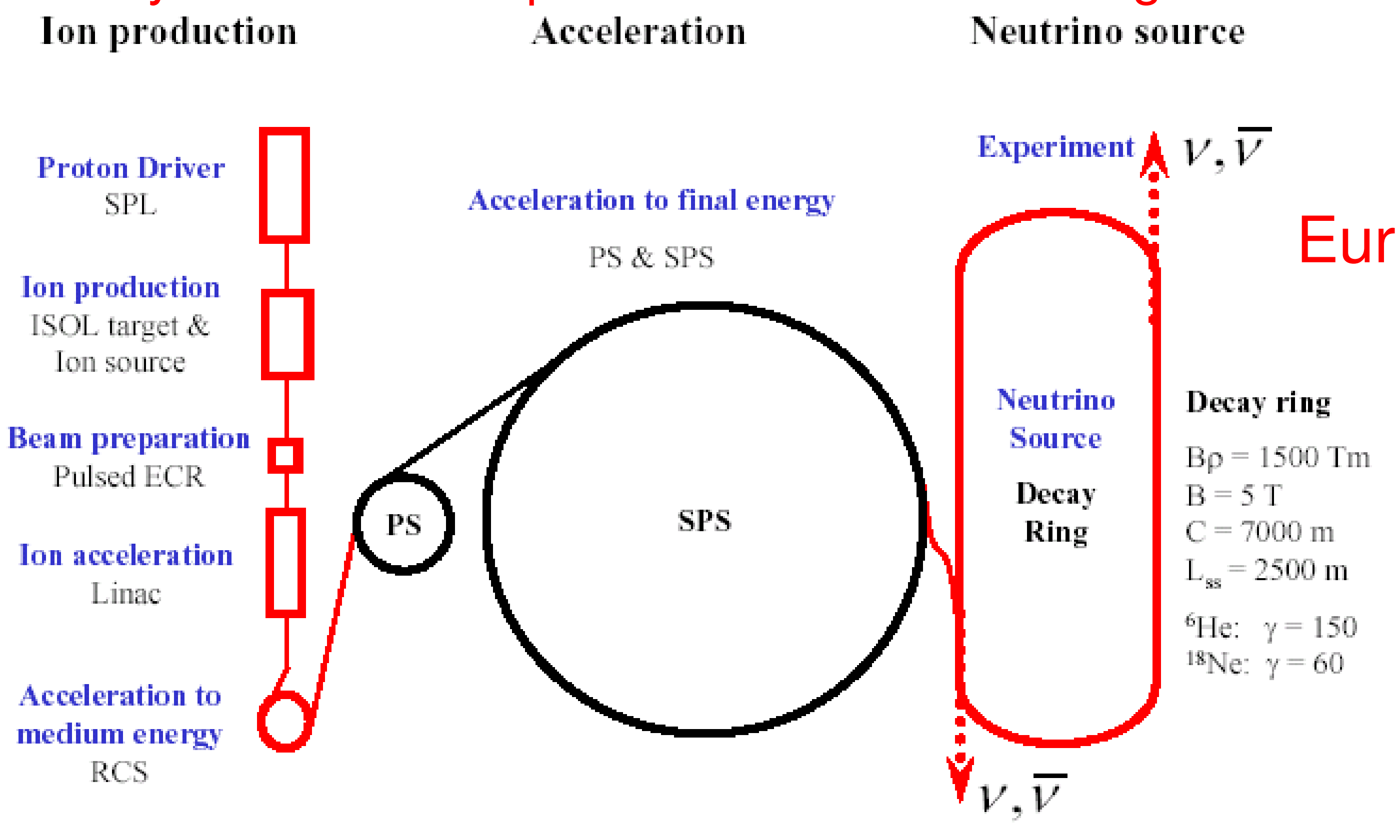
130 km



Beta Beams

- Beta beam: beta decay of accelerated radioactive nuclei (P. Zucchelli, Phys. Lett. B, 532 (2002), 166-172.)
  - He-6 for neutrino production: γ ~ 100 $^{6}_{2}He \rightarrow ^{6}_{3}Li + e^{-} + \bar{\nu}_e$
  - Ne-18 for antineutrino production: γ ~ 60 $^{18}_{10}Ne \rightarrow ^{18}_{9}F + e^{+} + \nu_e$

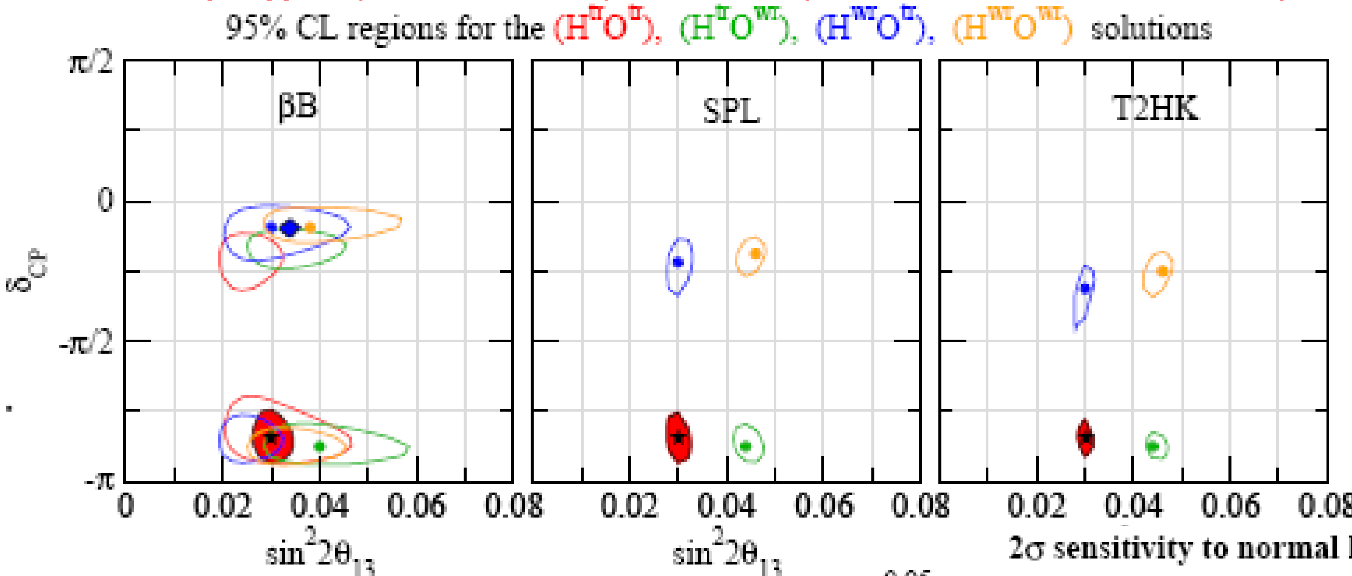
Only one neutrino species → do not need magnetic detector!



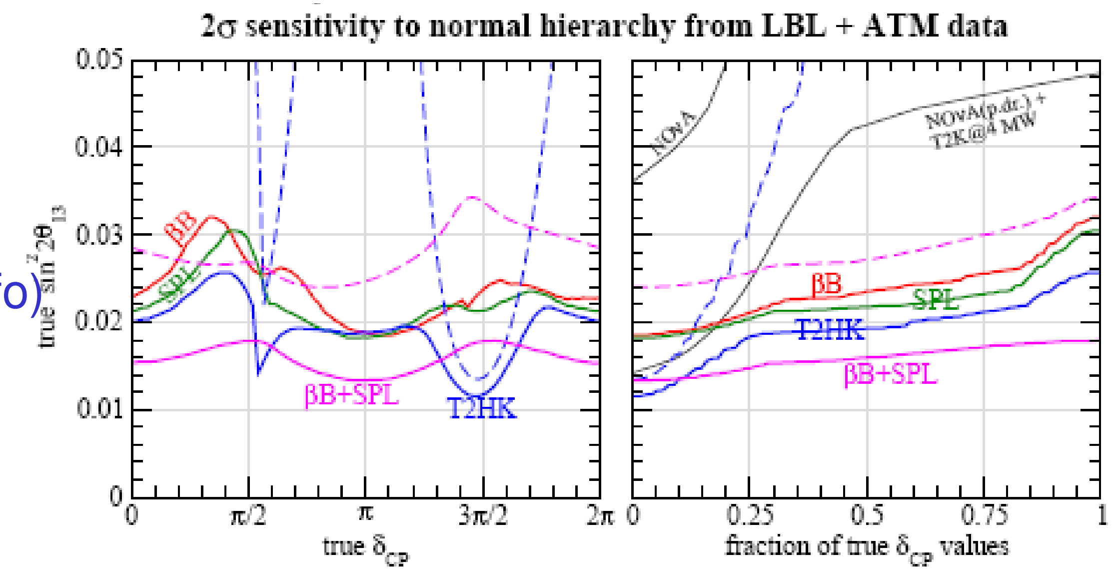
Eurisol study

Resolving degeneracies

- Physics reach of Memphys+SPL; Betabeam+SPL and T2HK:
  Campagne, Mezzetto, Maltoni, Schwetz JHEP 04 (2007) 003.



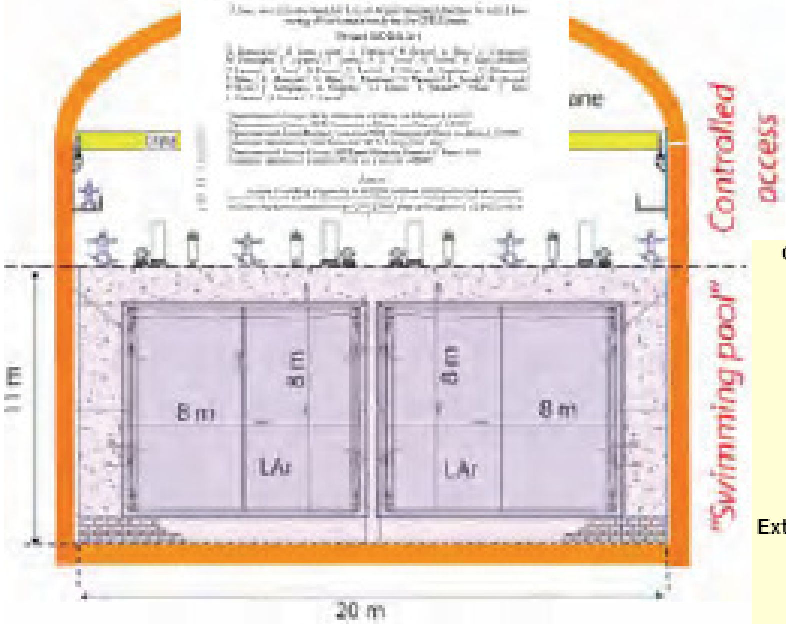
- Resolve degeneracies by combining with atmospherics
- βB: cannot solve degeneracies (no ν_μ and insufficient spectral info)
- βB+SPL, SPL+ATM & T2HK can resolve degeneracies

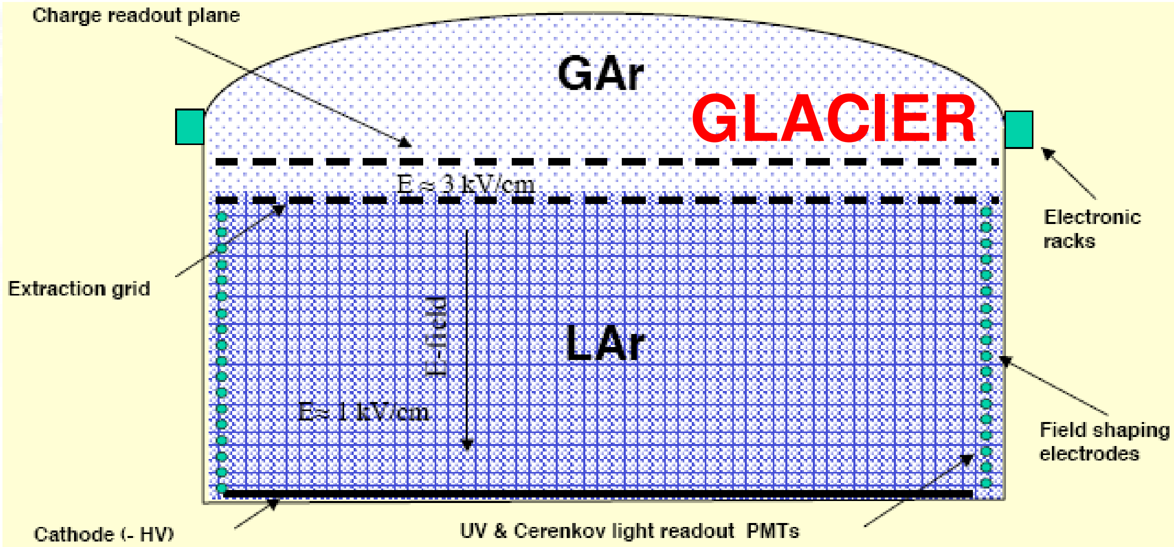


Liquid Argon TPC

- Different approaches for large (~50-100 kton) Liquid Argon TPCs
  - Glacier 2003 (Europe)
  - Flare 2004 (Fermilab, USA)
  - Modular 2007 (Europe)

MODULAR





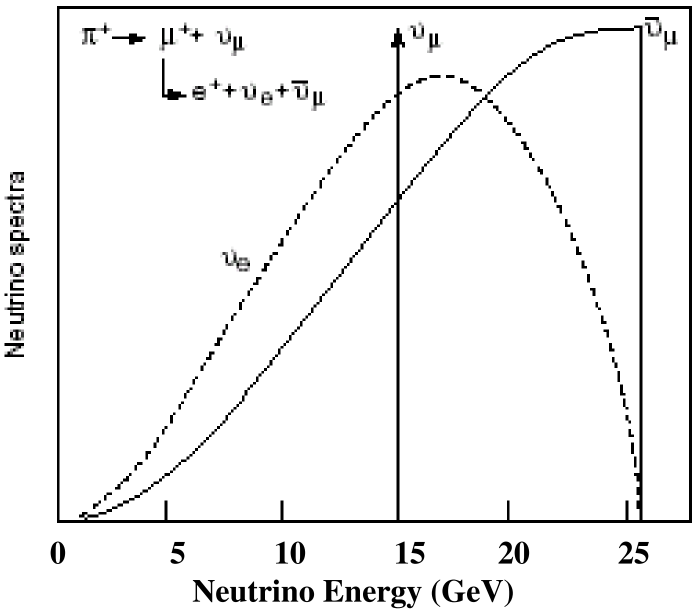
Neutrino Factory

- Neutrino Factories produce neutrinos from muon decays in a storage ring.
- Rate calculable by kinematics of decay (Michel spectrum)

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$$

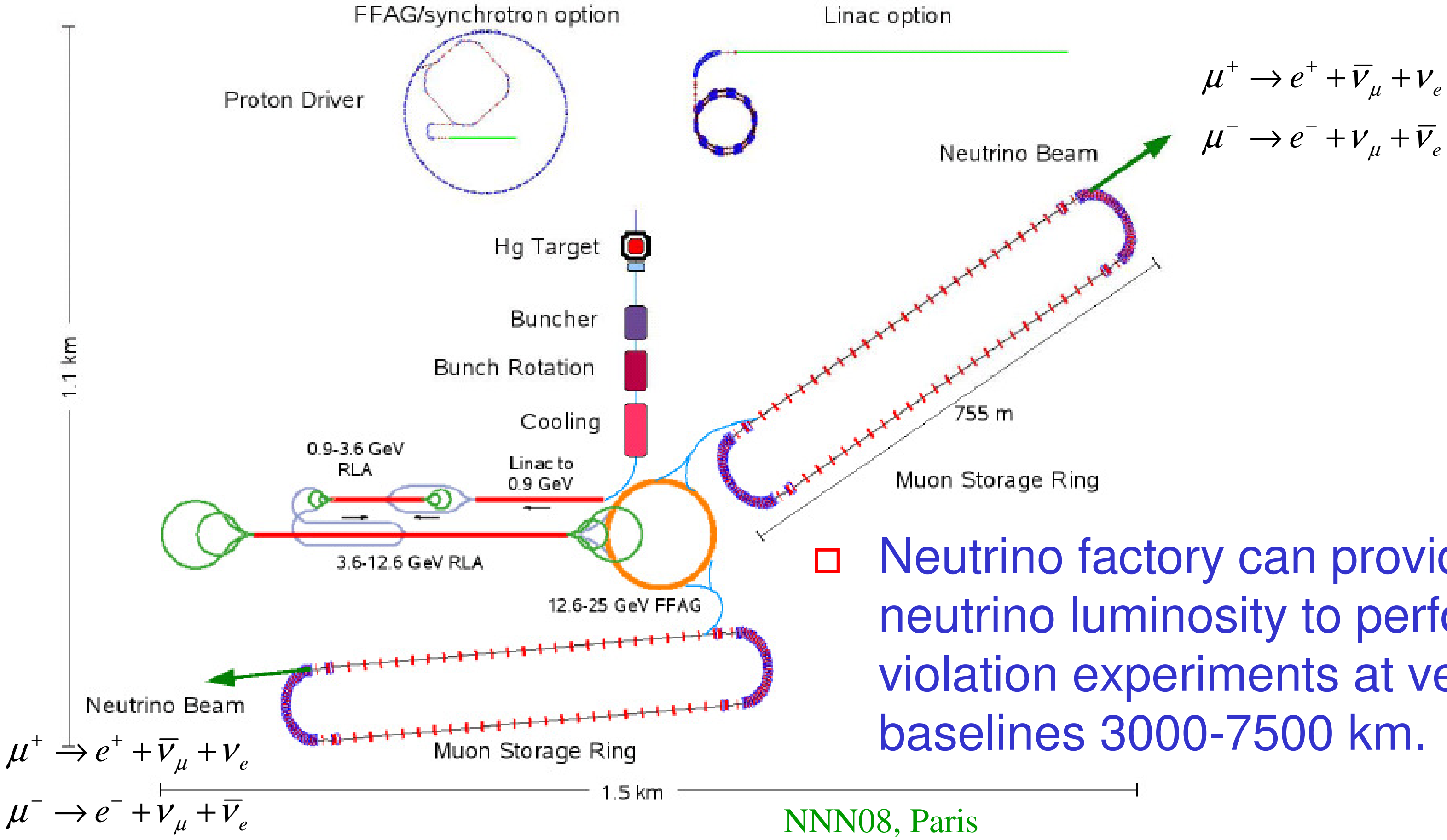
- For example, if μ^+ accelerated to 25 GeV (ISS baseline):



- Defines detector requirements:
  - Since muon and electron neutrino and anti-neutrino species are produced simultaneously we need to determine the charge and lepton identity to separate from background $\to$ Magnetic detectors.

Neutrino Factory

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



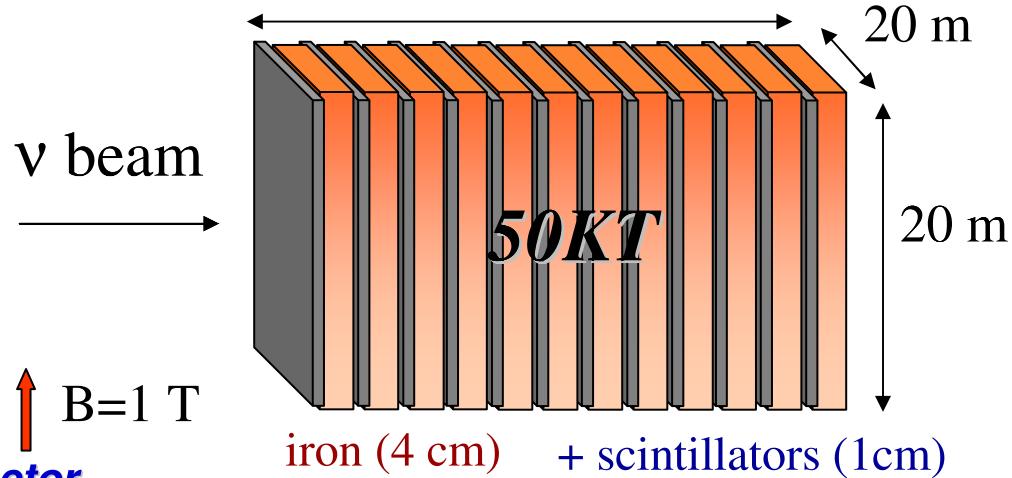
- Neutrino factory can provide sufficient neutrino luminosity to perform CP violation experiments at very long baselines 3000-7500 km.

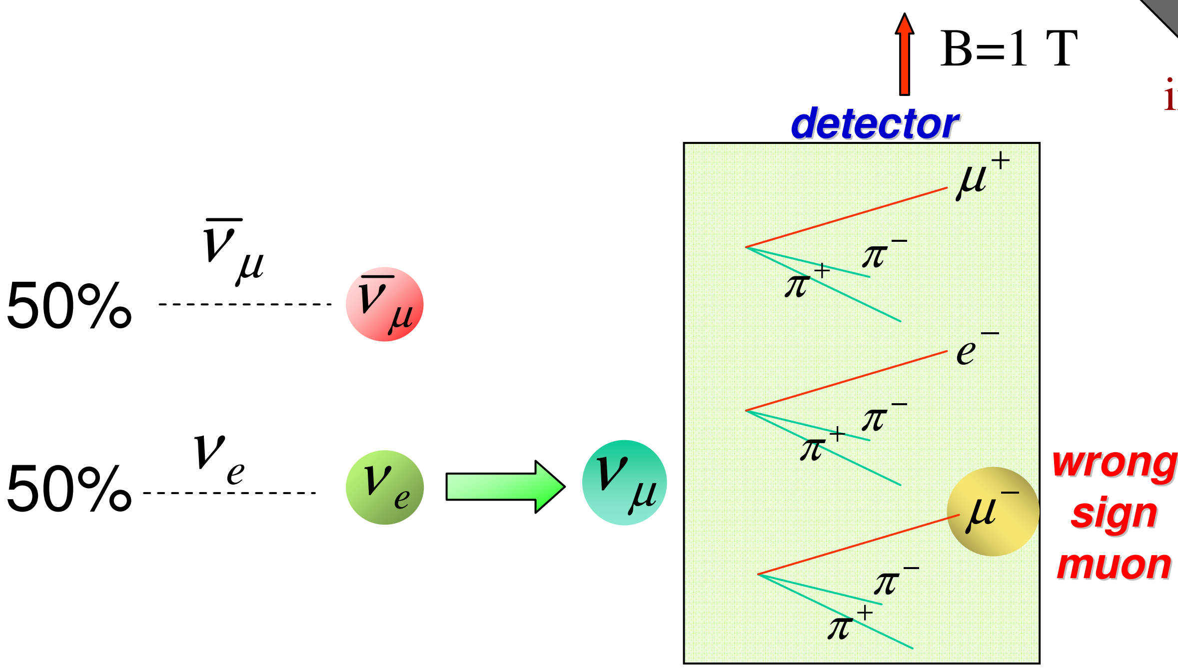
Magnetised Iron Neutrino Detector (MIND)

- 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)

Magnetic Iron Neutrino Detector (MIND)





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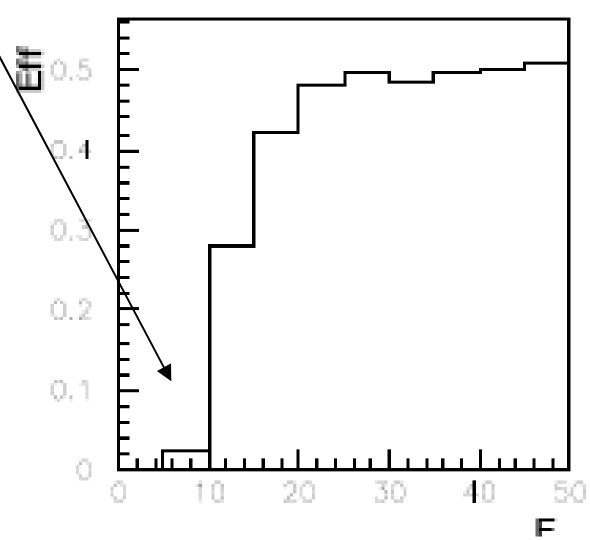
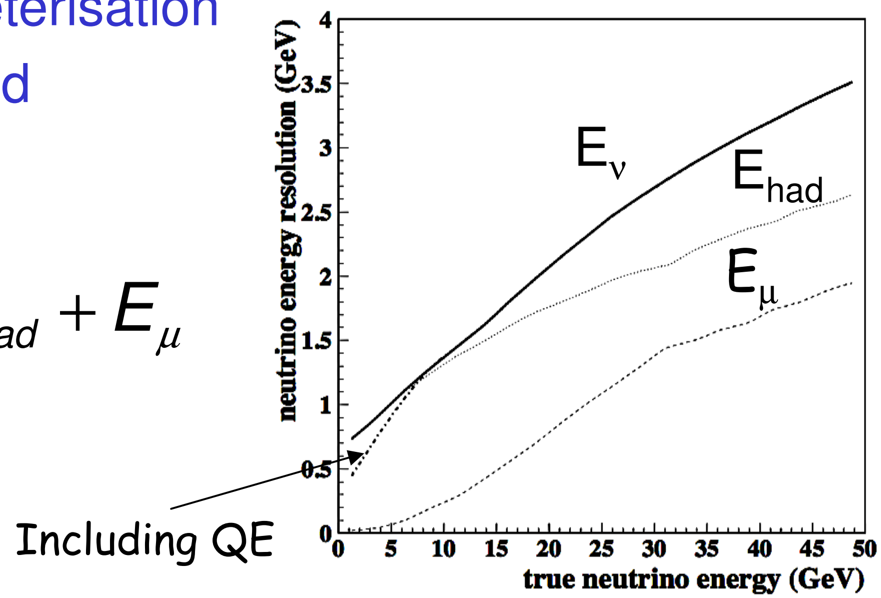
MIND analysis

- "Golden" paper (Cervera et al, 2000) was optimised for a small value of θ_{13}, so efficiency at low energy cut severely
- Used fast simulations and detector parameterisation
- MIND analysis redone for ISS (Cervera 2007)
  - Improved event selection,
  - 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: $E_\nu^{recon} = E_{had} + E_\mu$

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

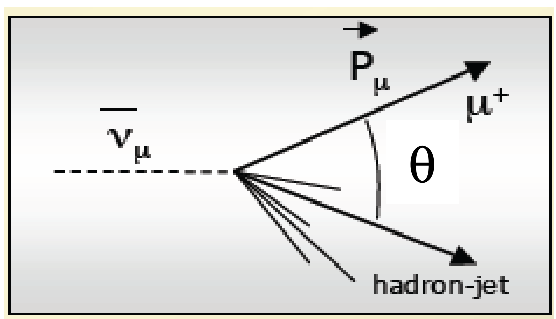


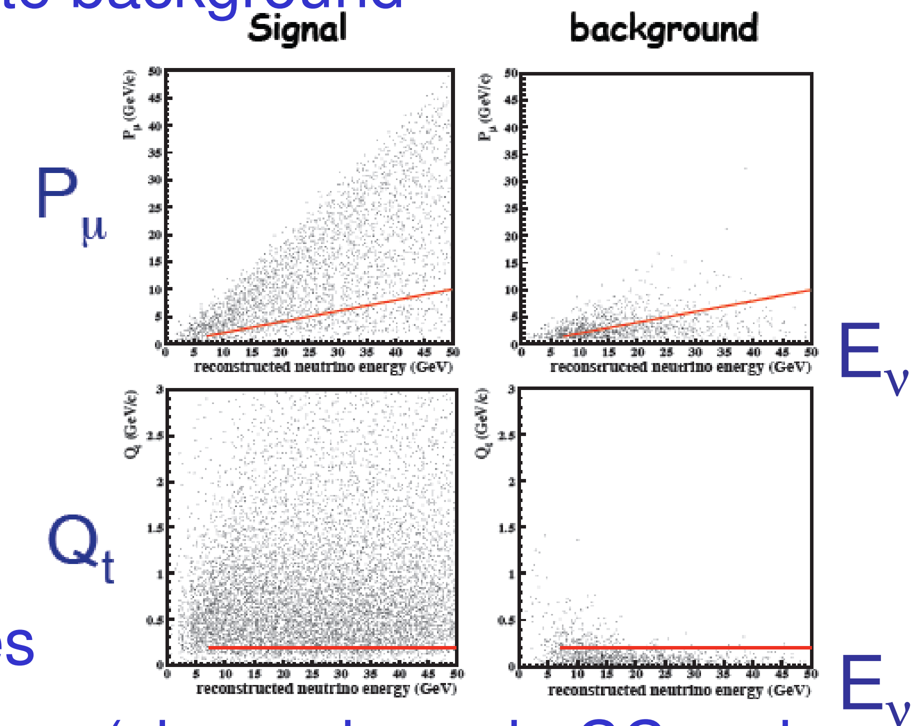


MIND analysis

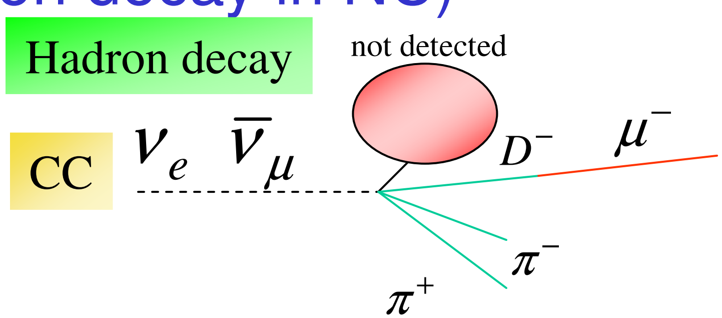
- Kinematic analysis to eliminate background
- Variables used:

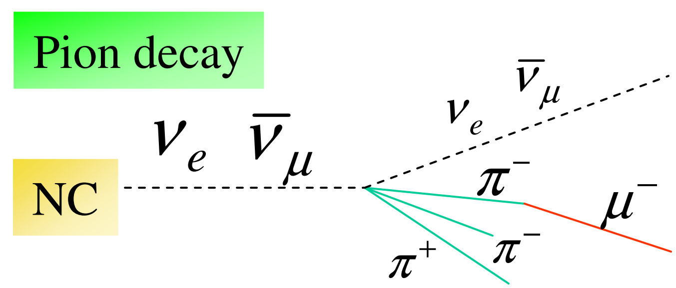
$$P_\mu = |P_\mu| \qquad Q_t = P_\mu \sin^2\theta$$





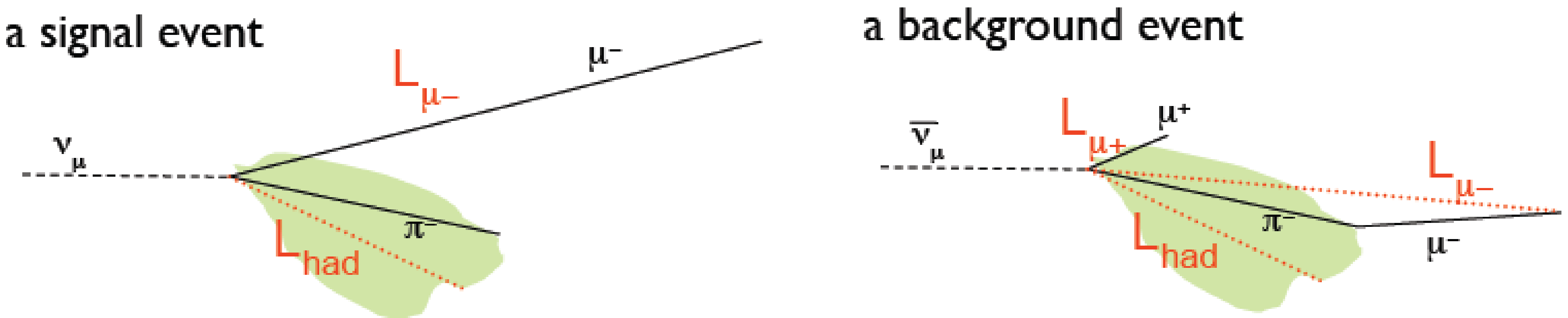
- Cuts in E_ν-P_μ and E_ν-Q_t planes
- Main background: hadron decay (charm decay in CC and pion decay in NC)



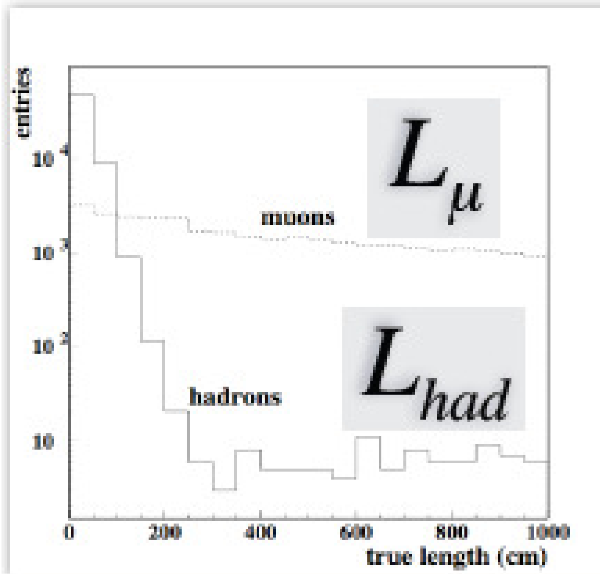


MIND event selection

- Muons go beyond the hadron shower
- They can be identified by range



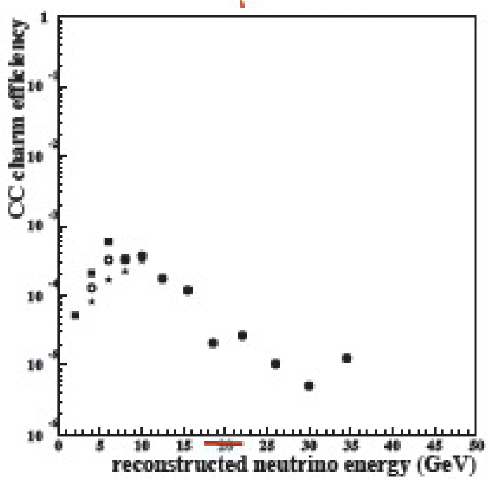
- Classification of Charged Current events depends on muon ID
- Muon identification criteria attempted:
  - $L_\mu - L_{had} > 75$ cm
  - $L_\mu - L_{had} > 150$ cm
  - $L_\mu - L_{had} > 200$ cm



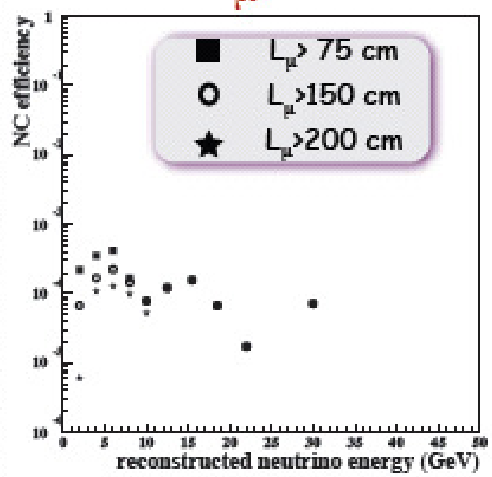
MIND background

- Backgrounds from charm, NC and charge misidentification

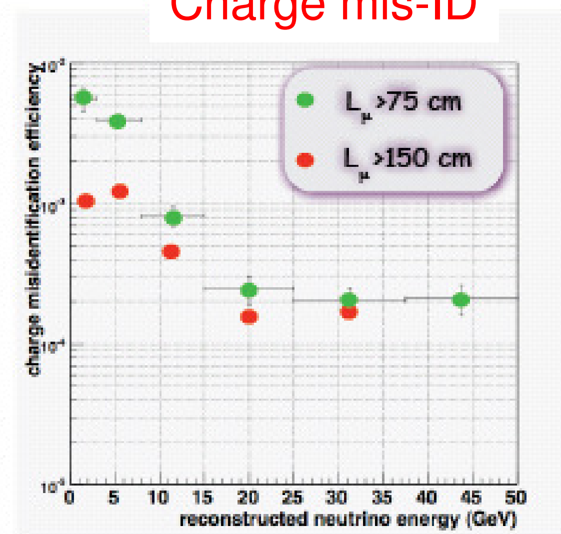
$\nu_\mu CC$



$\bar{\nu}_\mu NC$



Charge mis-ID



Simulation

Charm x-section ?

non-Gaussian MS

non-DIS events

Showering profiles

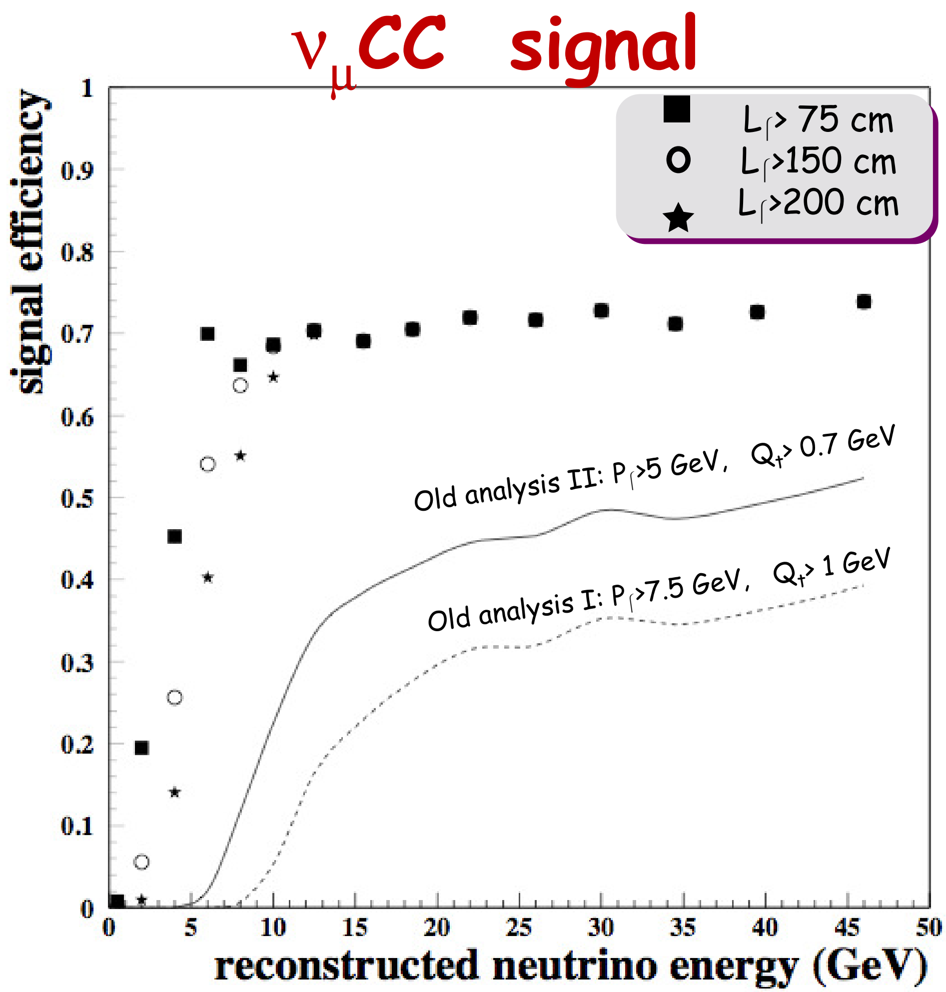
Reconstruction

Muon/hadron separation

Muon hit finding

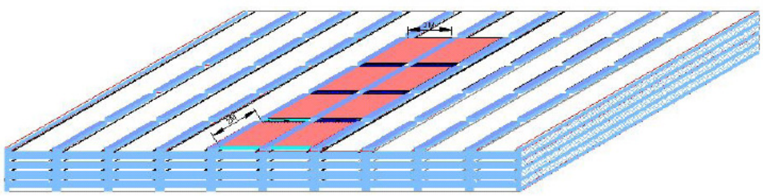
MIND Efficiency

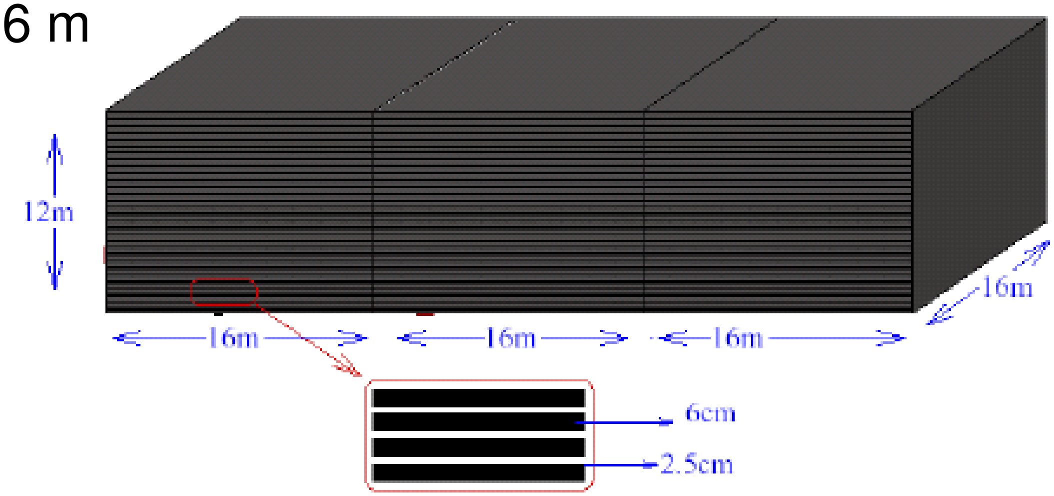
- Signal efficiency: International Scoping Study (ISS) report
  - Efficiency plateau between 5 and 8 GeV
  - Baseline: $L_\mu > 150$ cm
  - Ensures charge mis-ID below 10^{-3}
- Optimal segmentation:
  - Transverse: ~1 cm
  - Longitudinal: 3cm Fe + 2 × 1cm scint
- Improvements to study: MIND analysis with full GEANT4 reconstruction



Indian Neutrino Observatory

- Indian Neutrino Observatory (INO) in advanced stage of planning
- Recommended for funding — I. Dharmavaran to report at this meeting
- Detector size: 48 m x 16 m x 16 m
- Readout: RPCs
- B=1.5 T



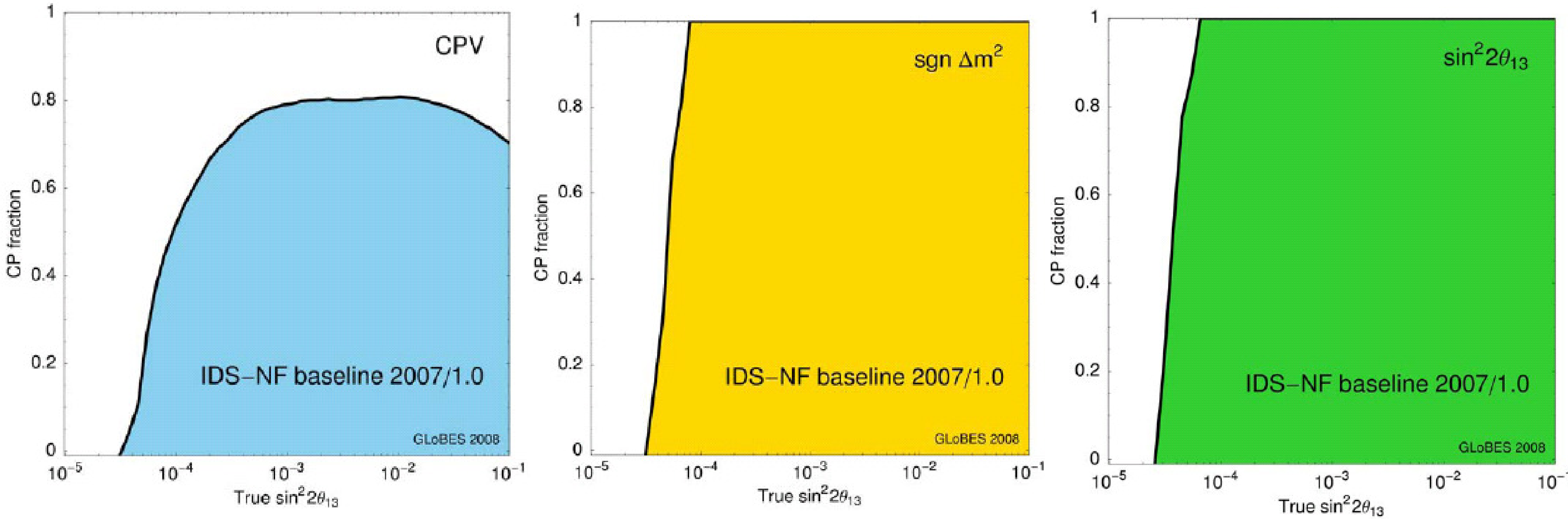


- Physics case: atmospheric oscillations with magnetised detector, matter effects, sign Δm^2_{23}, θ_{23}, CP, CPT, ultrahigh energy ν and μ, ...
- Far detector at magic baseline of neutrino factory for most facilities:
  - CERN to INO: distance = 7152 km
  - JPARC to INO: distance = 6556 km
  - RAL to INO: distance = 7653 km

INO is MIND at the magic baseline!

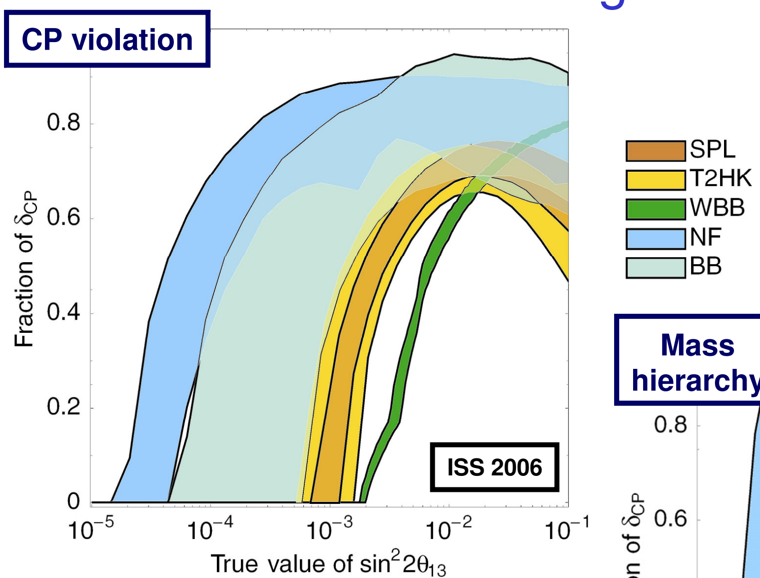
MIND sensitivity

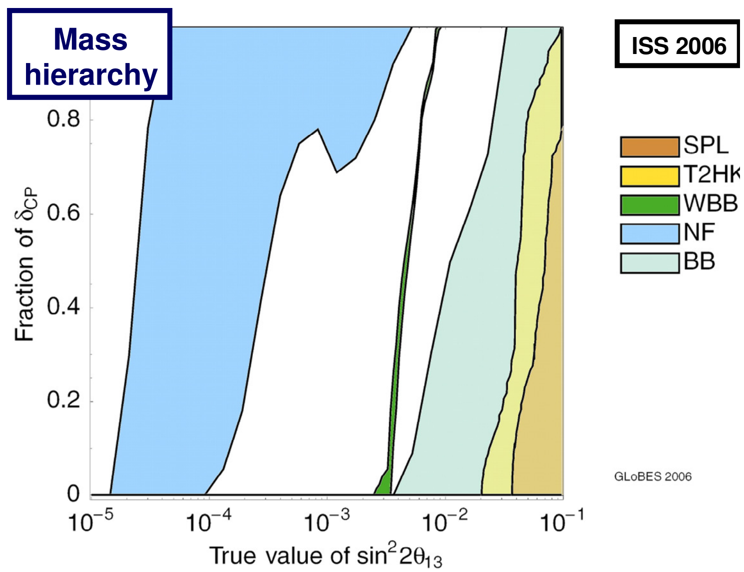
- Performance of IDS-NF baseline detectors (two MIND detectors, one at 4000 km and one at 7500 km) at 3σ (Huber, Winter, ISS 2007)
- Efficiencies and background used are those from latest MIND analysis

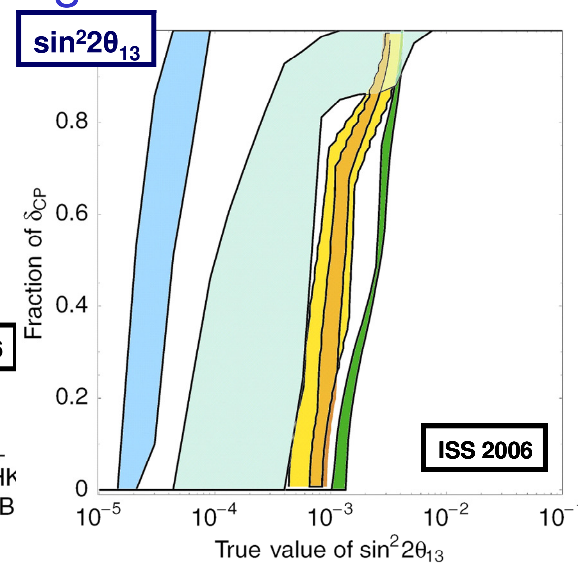


ISS Conclusions

- Comparison of facilities from International Scoping Study:
  - If $\sin^2 2\theta_{13} > 10^{-2}$ super-beam and beta-beam facility compatible with neutrino factory to explore CP violation but accuracy might be issue
  - If $\sin^2 2\theta_{13} < 10^{-2}$, a neutrino factory with two detectors at ~7500 km and ~4000 km gives optimal CP violation coverage



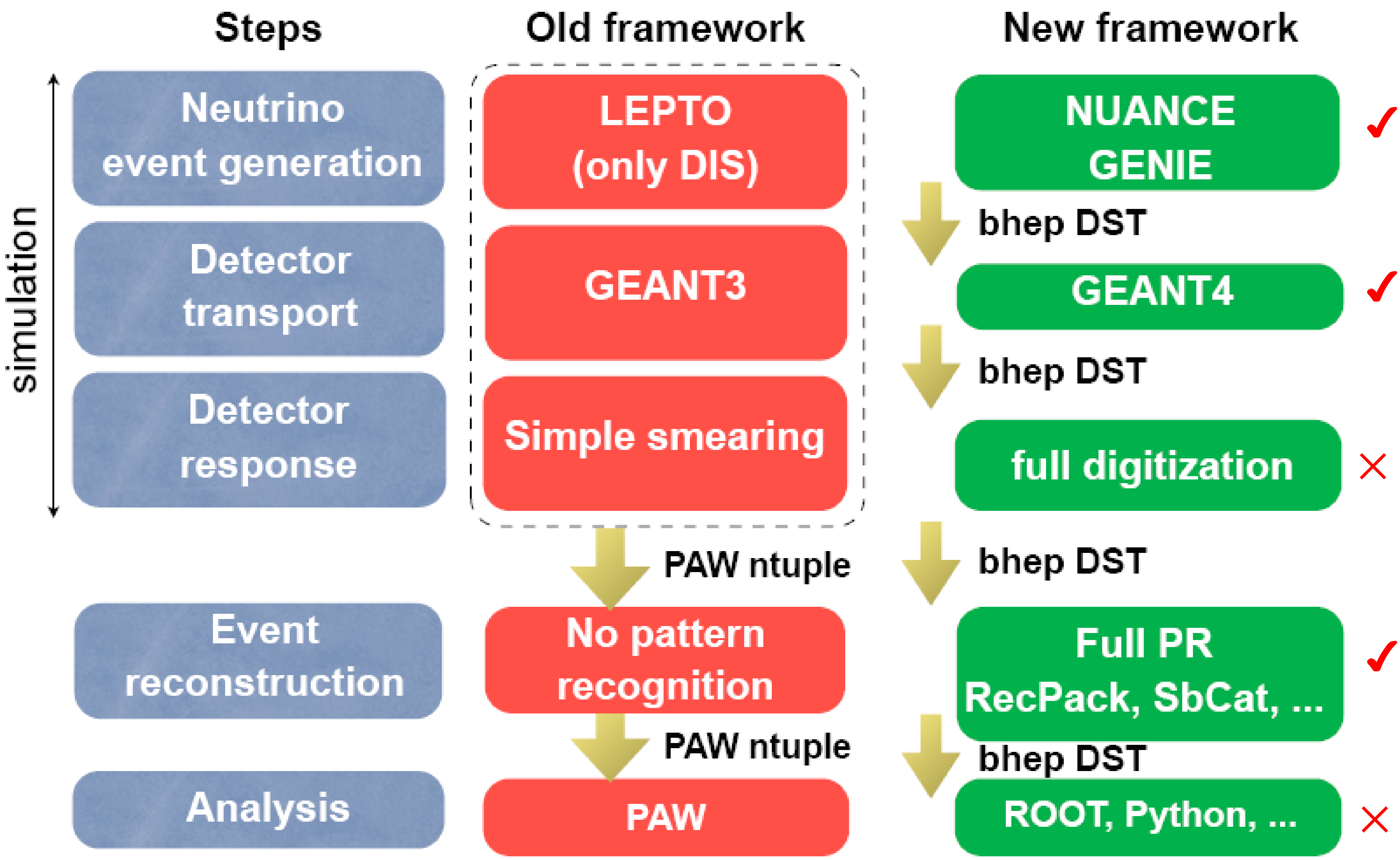




MIND: new developments

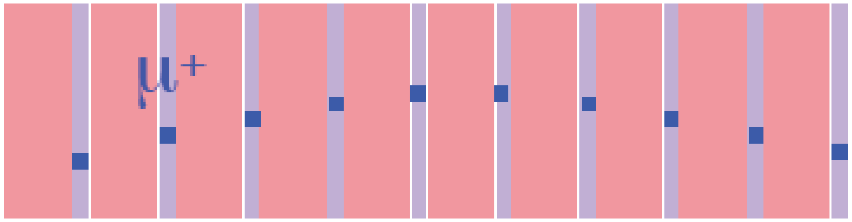
- Improvements MIND analysis with full GEANT4 reconstruction
  - Demonstrate that for $E_\nu < 10$ GeV
    - Backgrounds are below 10^{-3}
    - The efficiency can be increased with respect to fast analysis
  - Compute:
    - Signal and backgrounds efficiency as a function of energy
    - Energy resolution as a function of energy
  - Optimise segmentation and B field based on the above parameters and taking into account feasibility and cost
  - Add Quasi-Elastic (QE) and Resonance (RES) production to Deep Inelastic (DIS) events

MIND software framework

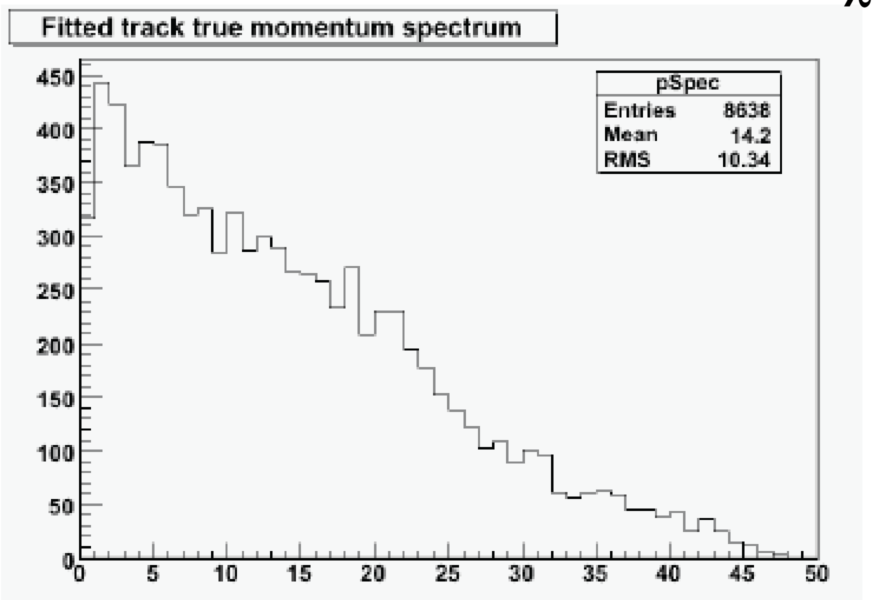


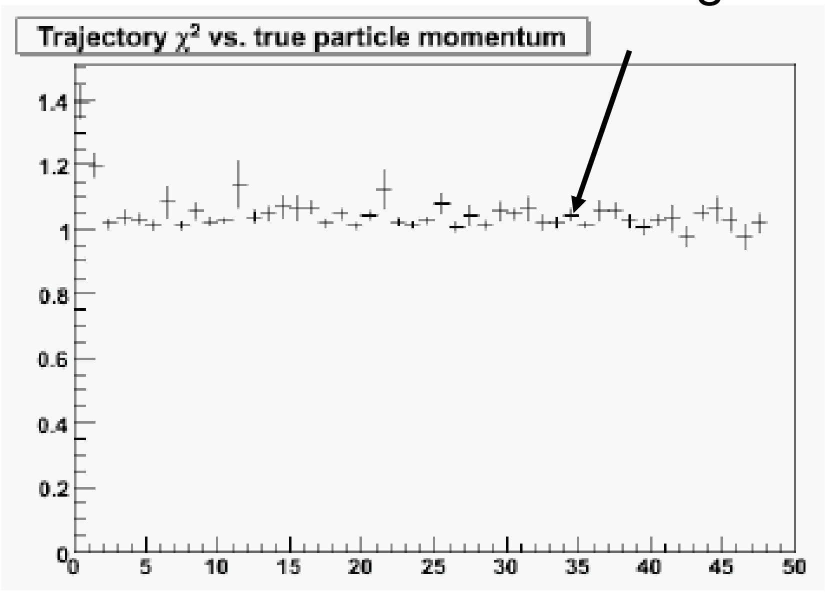
Kalman filter (RecPack)

- Pattern recognition and Kalman filter already implemented
  - Kalman filter algorithm takes into account multiple scattering and energy loss



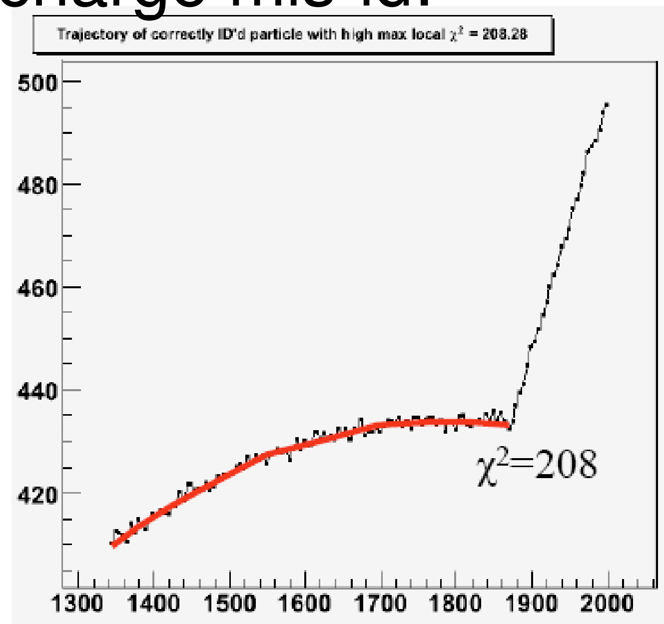
χ^2/DOF ~ 1 shows model working well

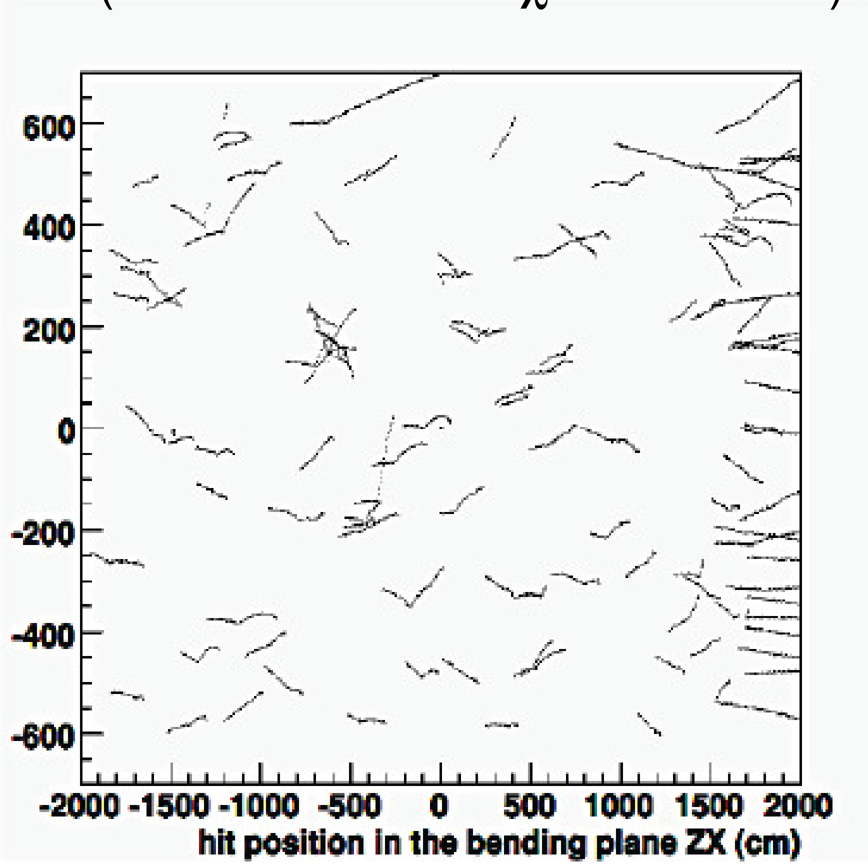


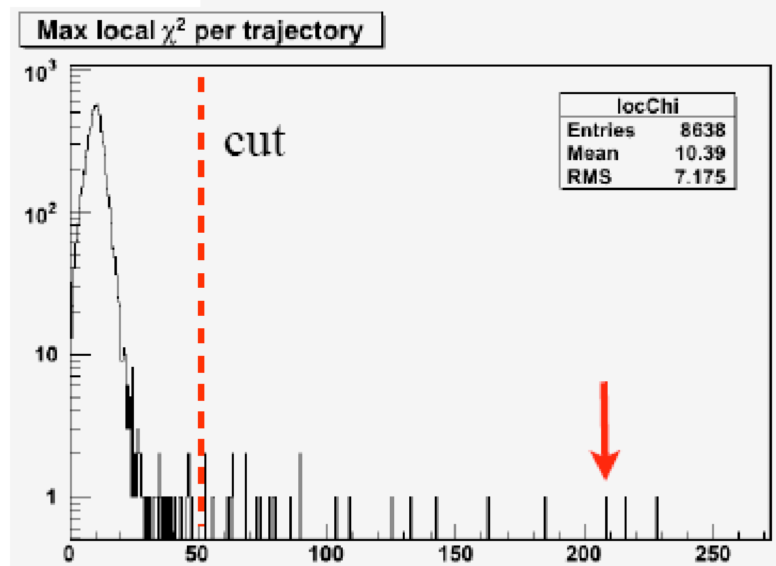


Kink rejection

- Further rejection background due to charge mis-id:
  - 70-80% events due to hard scatters (kinks)
  - Rest due to Non-Gaussian MS
  - Established kink finding algorithm (cut on maximum χ^2 hit of track)





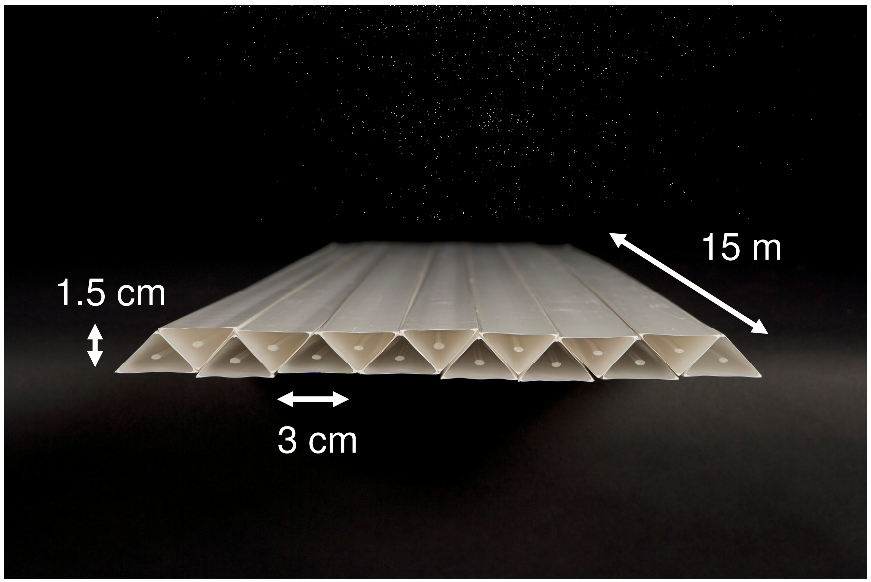


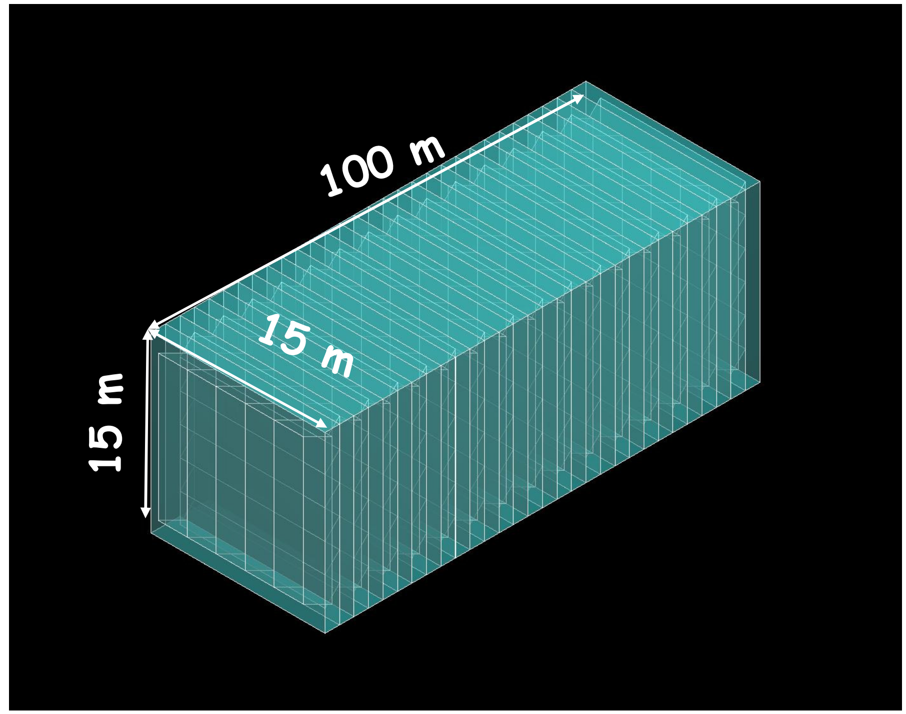
Totally Active Scintillating Detectors (TASD)

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



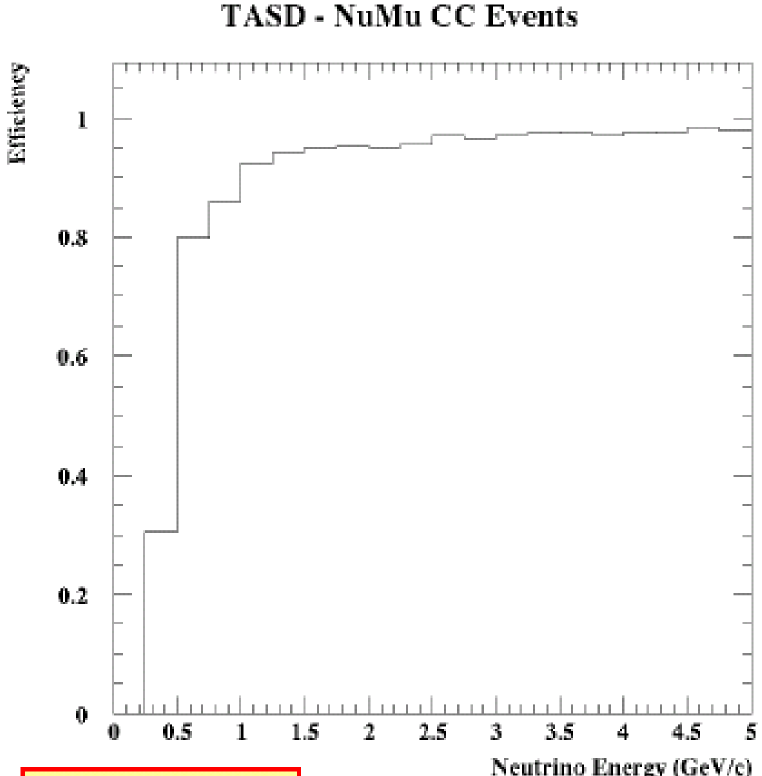


- Momenta between 100 MeV/c to 15 GeV/c
- Magnetic field considered: 0.5 T
- Reconstructed position resolution ~ 4.5 mm

Reduction threshold: access second oscillation maximum and electron identification

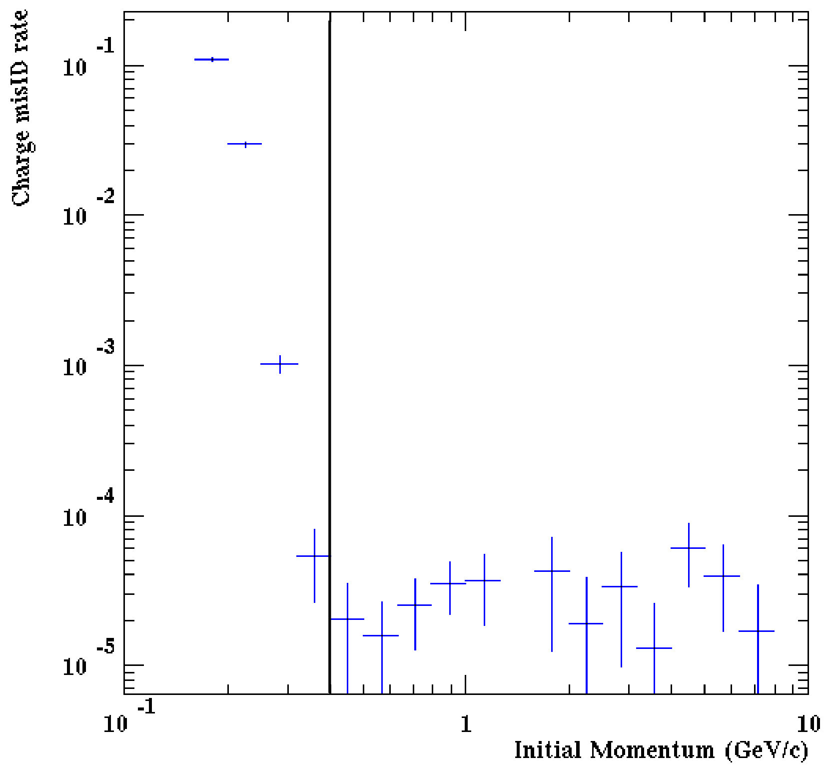
Totally Active Scintillating Detectors (TASD)

Neutrino CC reconstructed efficiency



Excellent σ_E

Muon charge mis-ID rate



A. Bross reported promising electron efficiency (~80%) based on "visual" scans at NUFACT08 – need proper algorithm to automate

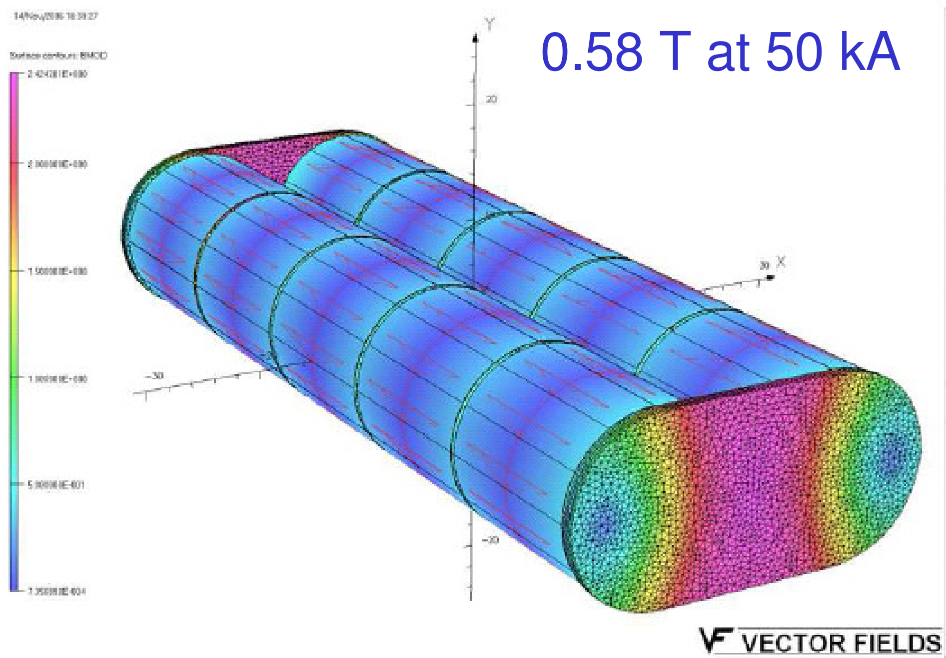
Totally Active Scintillating Detectors (TASD)

Main problem: magnetisation of huge volume (difficulty and cost)

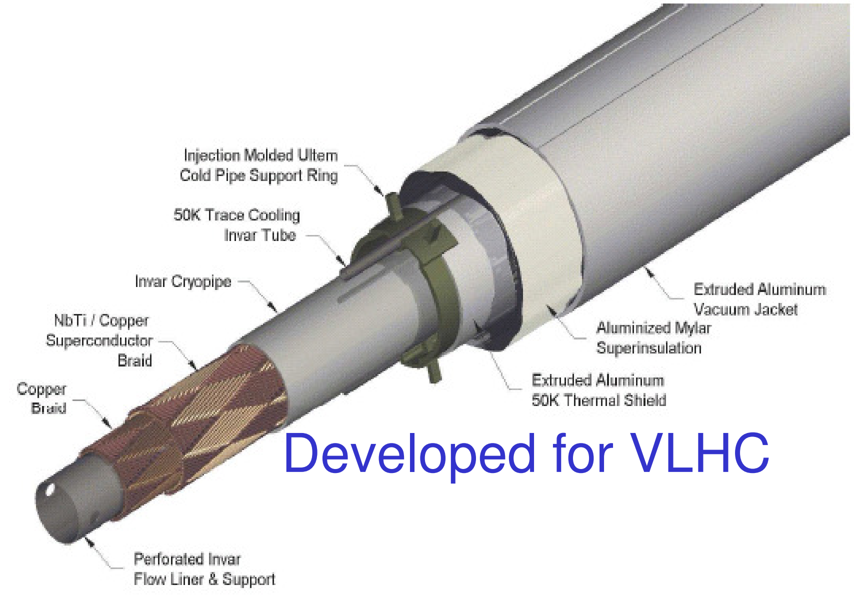
However, possible magnetisation can be achieved using magnetic cavern concept (10 modules with 15m x 15 m diameter)

Bross

0.58 T at 50 kA



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



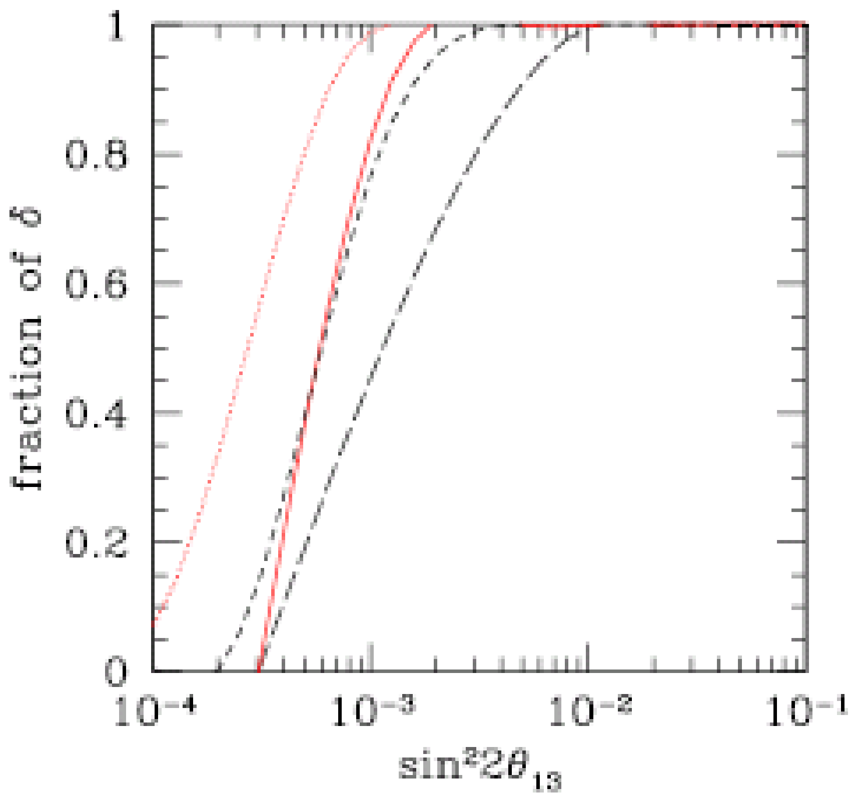
Developed for VLHC

R&D needed to develop concept!!

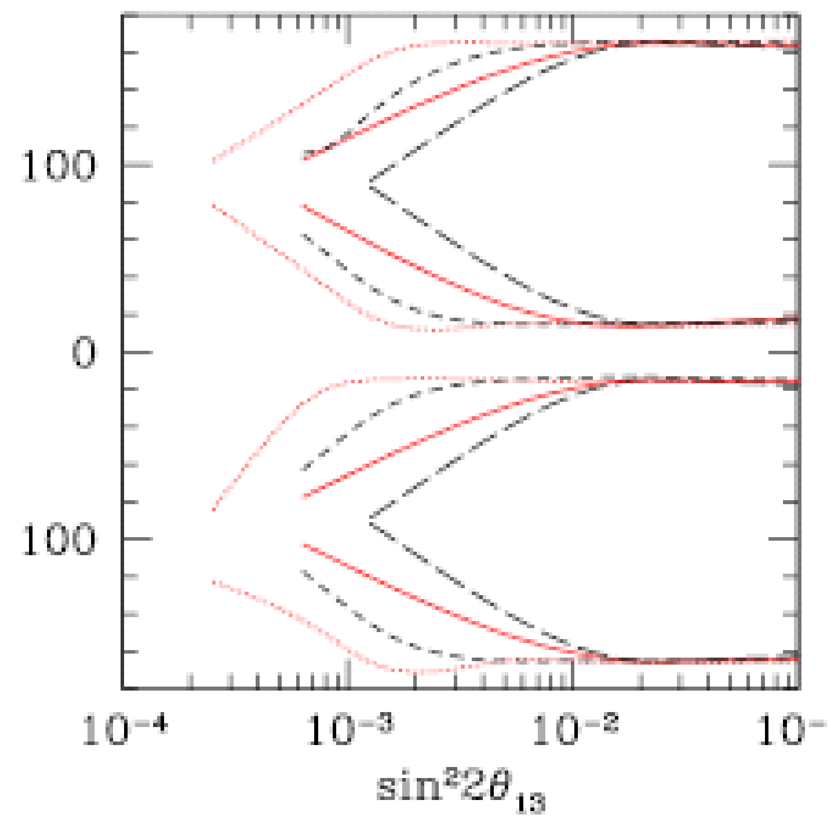
Totally Active Scintillating Detectors (TASD)

- 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



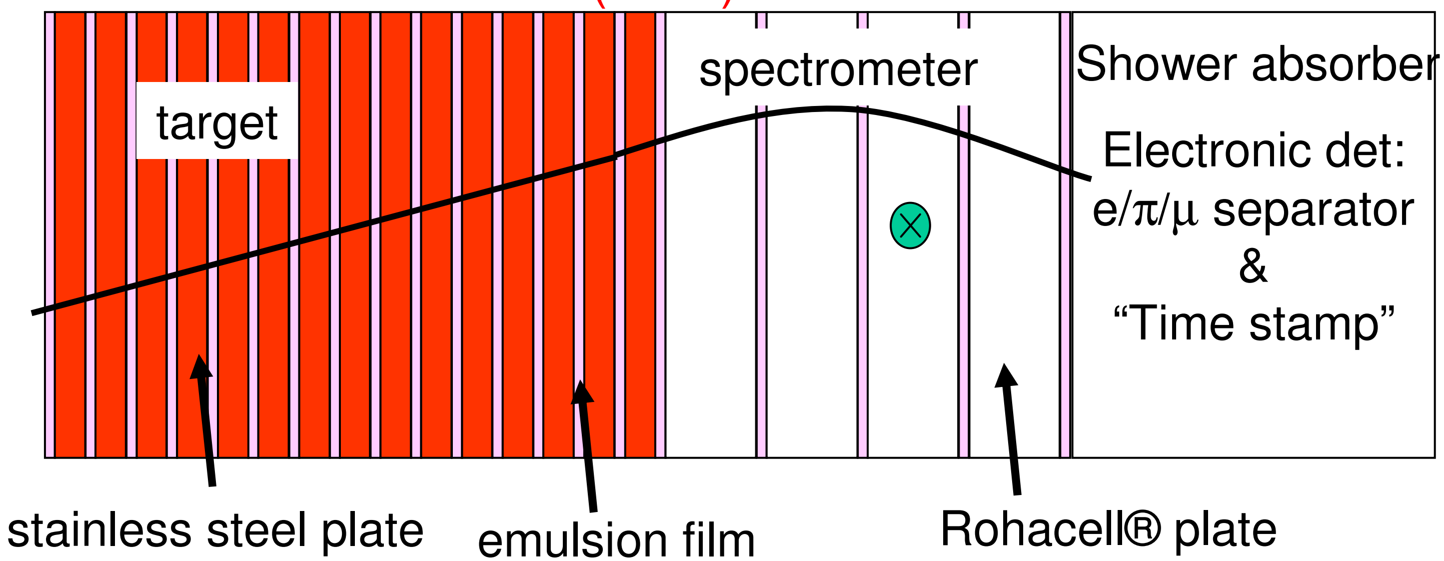
95% CL CP violation at 1480 km

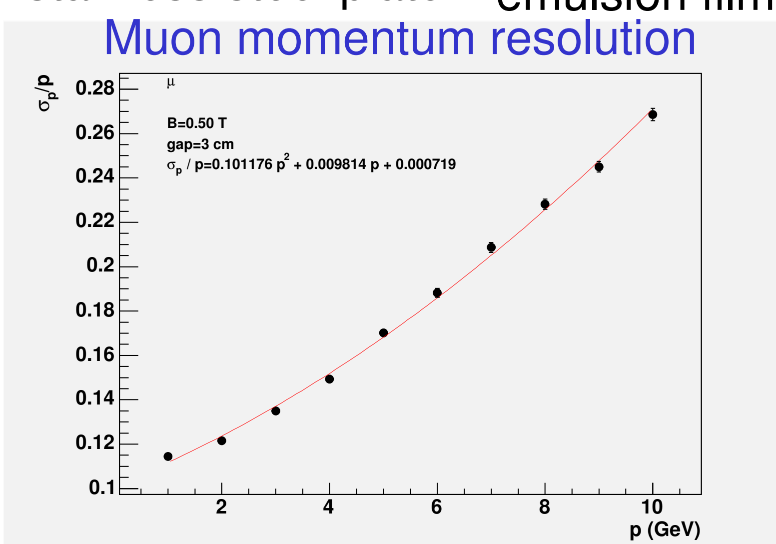


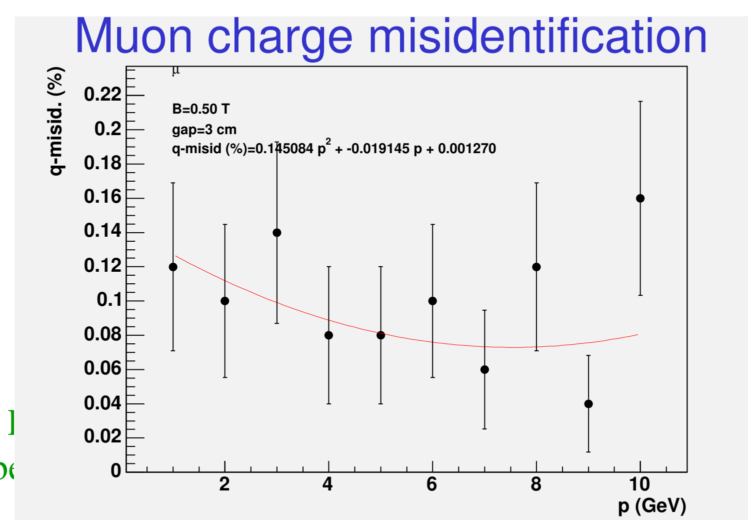
Magnetised Emulsion Cloud Chamber

- Emulsion detector for ν_τ appearance, à la OPERA: “silver channel”

Emulsion Cloud Chamber (ECC)







Hybrid Emulsion Detectors

Possible design hybrid emulsion-scintillator far detector

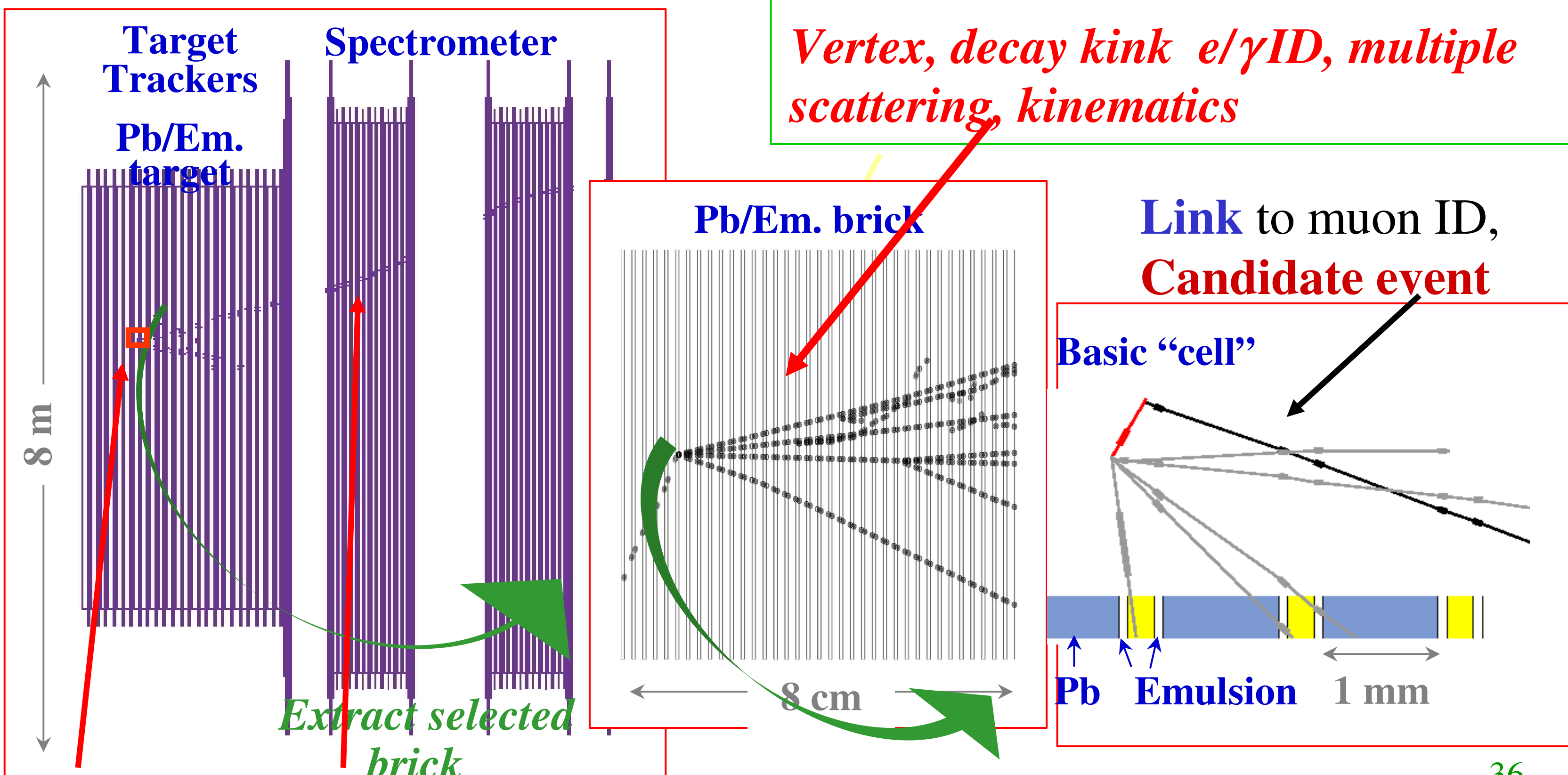
- For 60 walls emulsion ⇨ 1.1M bricks ⇨ 4.1 kton

Golden and silver channels simultaneously!

Electronic detectors:

ECC emulsion analysis:

Vertex, decay kink e/γID, multiple scattering, kinematics



Brick finding, muon ID, charge and p

Δp/p<20%

Near detector

What needs to be measured:

1) Near detectors should be able to measure flux and energy of ν_μ and $\bar{\nu}_e$

Use inverse muon decay: $\nu_\mu + e^- \rightarrow \mu^- + \nu_e \quad \bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$

2) Extraction oscillation probability from ND and FD spectra:

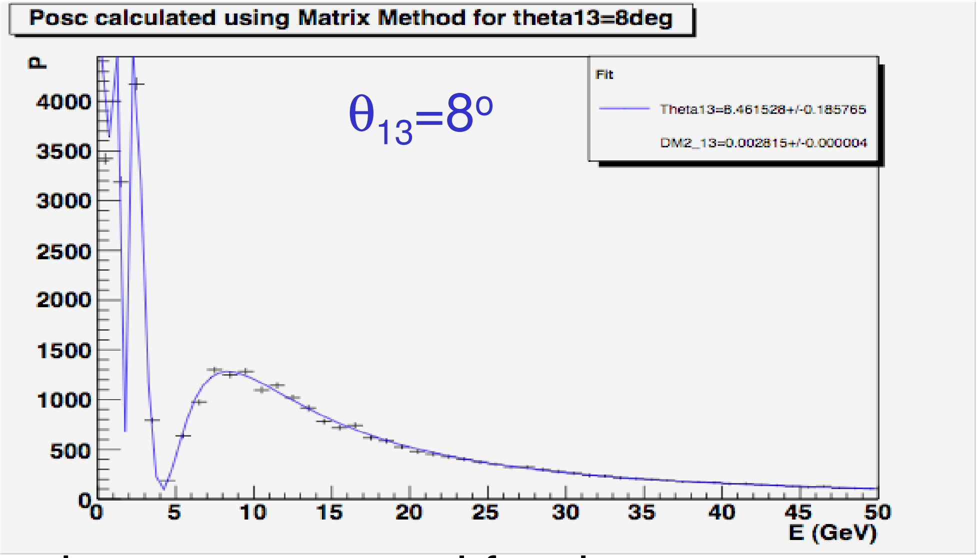
$$P_{\nu_e \nu_\mu} = M_2^{-1} M M_1 M_{nOsc}^{-1}$$

M_1=matrix event rate vs flux of ν_e at ND

M_2=matrix event rate vs flux of ν_μ at FD

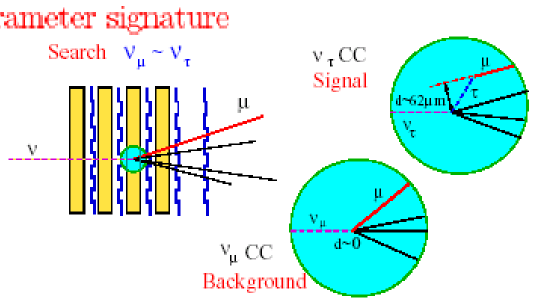
M=matrix ND ν_e rate vs FD ν_μ rate

M_{nOsc}=matrix expected ν_e flux ND vs FD



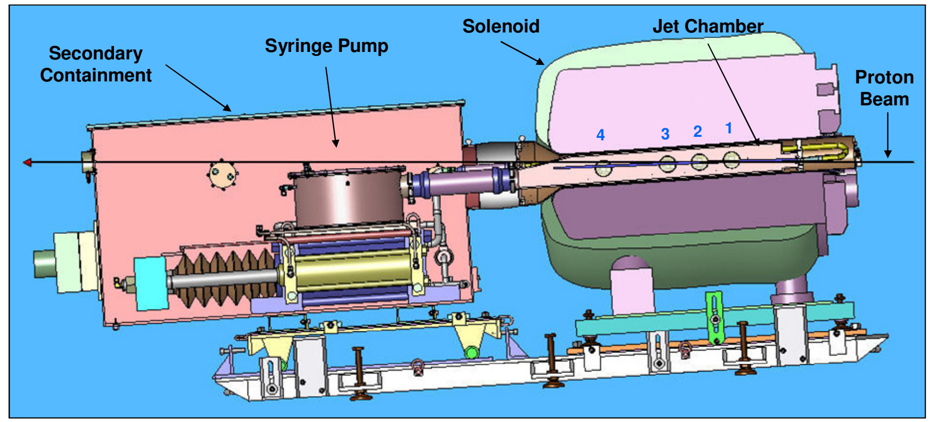
3) Measure charm cross-section in near detector to control far detector background:

Si vertex detector

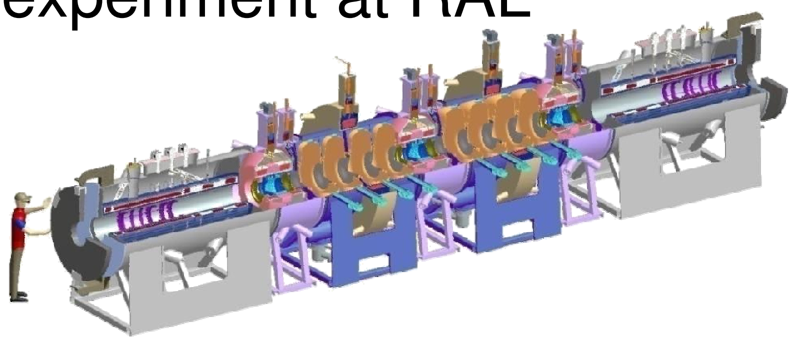


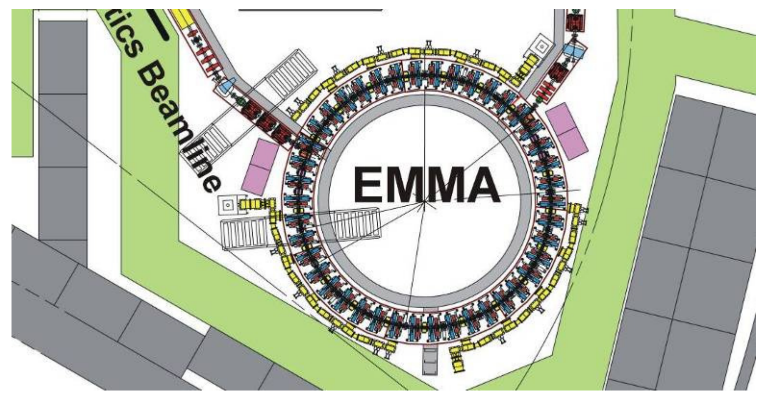
Accelerator R&D effort

- MERIT: liquid Hg target experiment at CERN

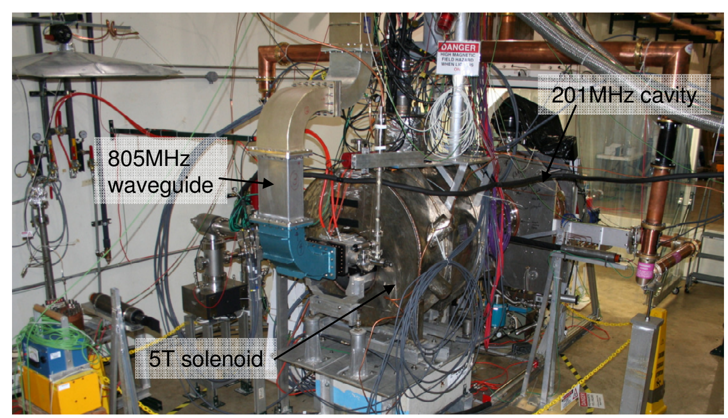


- MICE: ionisation cooling experiment at RAL





- FFAG acceleration: EMMA demonstration at Daresbury

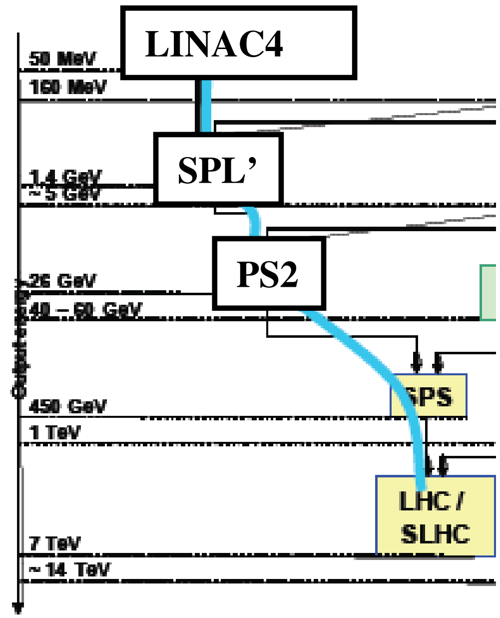


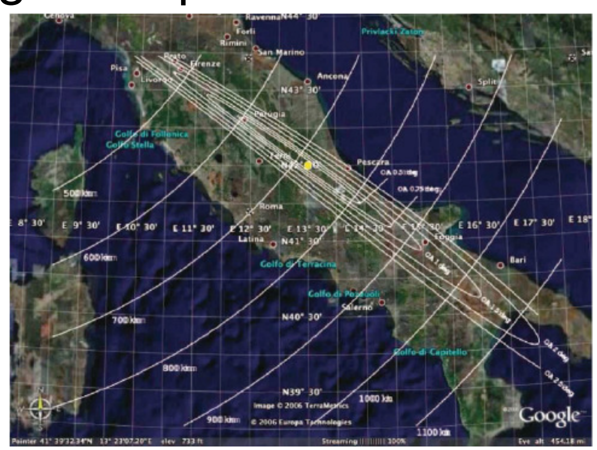
- RF cavities: MuCool cavities in US and UK

Upgrades at CERN

- CNGS: neutrino beam CERN to Gran Sasso
  - Upgrade of CNGS to be studied as part of EuCARD FP7 programme

- Proton complex at CERN:
  - Weakest link in CERN proton complex: LINAC2, PS
  - Step 1: replace LINAC2 by LINAC4 (~2011) to increase injection rate
  - Step 2: New SPL' to 5 GeV and new PS2 up to 50 GeV (~2016).
  - Upgrades are related to SLHC but may be used for neutrino facilities with an upgrade up to 5 MW at 5 GeV in a few more years





EU Projects

- EuroNu: 4 year FP7 EU Design Study
  "A High Intensity Neutrino Oscillation
  Facility in Europe" (started 1 Sept 08)
  - WP1: Management
  - WP2: Super-Beam: design of a 4 MW proton beam (SPL), target and collection system for a conventional neutrino beam
  - WP3: 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
  - WP4: Beta beam: following from EURISOL, study production, collection and decay ring of beta beam for high Q isotopes (^{8}Li, ^{8}B)
  - WP5: Neutrino detectors: study Magnetised Neutrino Iron Detector (MIND) performance for golden measurement at neutrino factory, water Cherenkov detector for beta and super beams and near detectors for all facilities
  - WP6: Physics: comparison of physics performance, systematic errors and optimisation for all facilities

EU Projects

- EuCARD: FP7 Integrating Activity proposal for "European Coordination for Accelerator Research and Development"
  - European R&D on accelerator technologies (LHC upgrade, TeV linear colliders, XFEL, FAIR and neutrino facilities).
  - WP3: NEU2012 (Structuring the accelerator neutrino community): networking activity to define next neutrino accelerator facilities by 2012 (recommended in the "European Strategy for Particle Physics"), successor to BENE
  - WP7: Transnational access to MICE facility to carry out ionization cooling experiments and low energy muon experiments
  - WP12: "Novel accelerator concepts", which includes diagnostic devices for EMMA, the first non-scaling FFAG accelerator:
- DevDet: FP7 Integrating Activity proposal for "Detector Development Infrastructures for Particle Physics Experiments"
  - It includes detector R&D for future accelerator-driven neutrino facilities
  - The aim is to develop test beams for neutrino detector R&D.
  - Unlikely to be funded

Neutrino Facility Roadmap

- Roadmap for future International Neutrino Facilities:
  - The ISS studied options for future facilities and narrowed the list of detector options for each facility
  - EuroNu design study to define parameters for future neutrino facilities
  - Launch of Neutrino Factory International Design Study (IDS)
  - Developed an internationally agreed baseline for the Neutrino Facility complex and for neutrino-detection system
  - Goal: to produce a ‘Reference Design Report’ for an internationally agreed Neutrino Facility by 2012:
    - The RDR is conceived as the document that will allow to consider initiating an internationally agreed Neutrino Facility project
    - Emphasis on engineering to demonstrate technical feasibility and evaluate cost

University of Glasgow

GOLDEN08: 2nd International Workshop on Physics and Detectors at a Neutrino Factory Glasgow, 17-19 November 2008.

Joint meeting with:

1) EuroNu, Physics and Detector Work Packages

2) UKIERI UK-India Education and Research Initiative UKIERI UK-India Neutrino programme