MICE as a Step towards Cool Muon Beams for Particle Physics

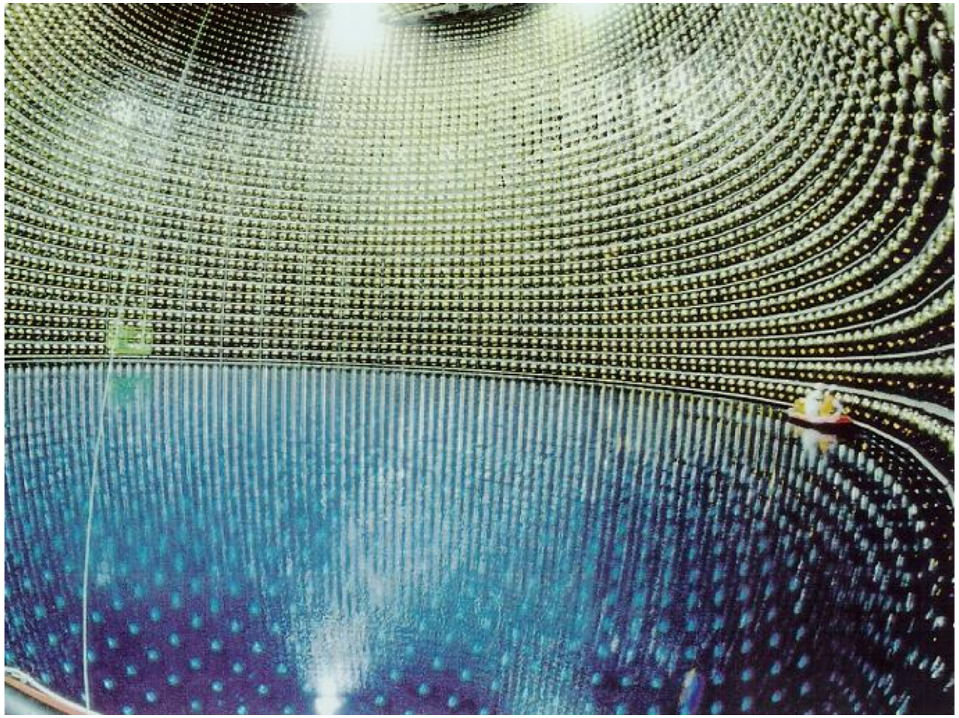
MICE Celebration Event

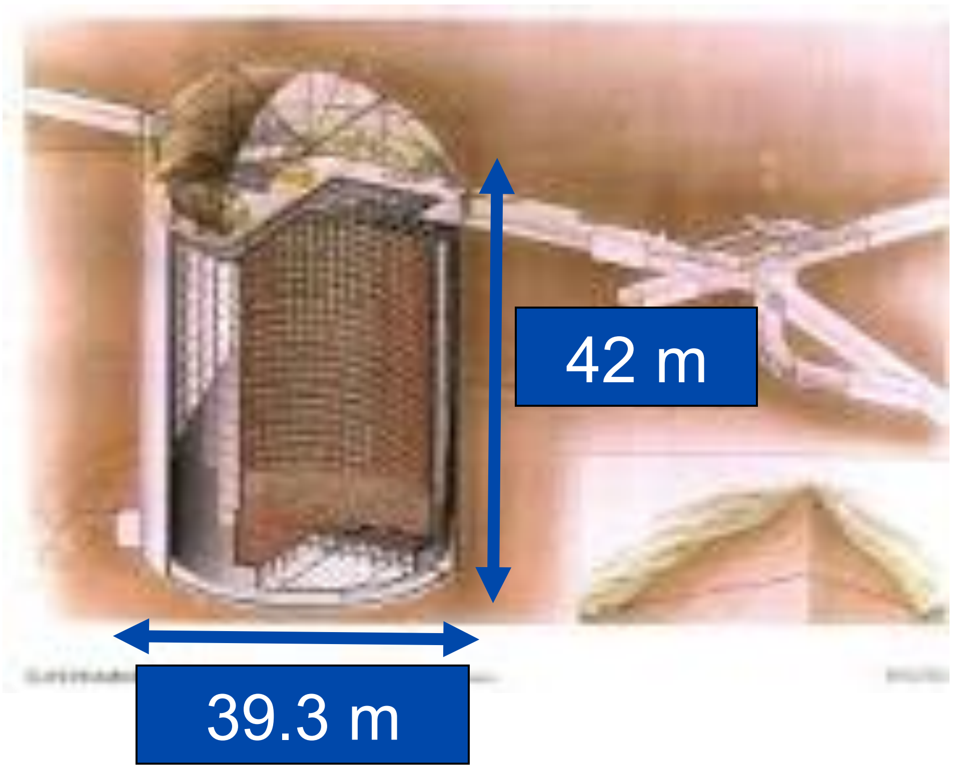
RAL, 25 June 2015

Paul Soler
University of Glasgow

Neutrino Oscillations

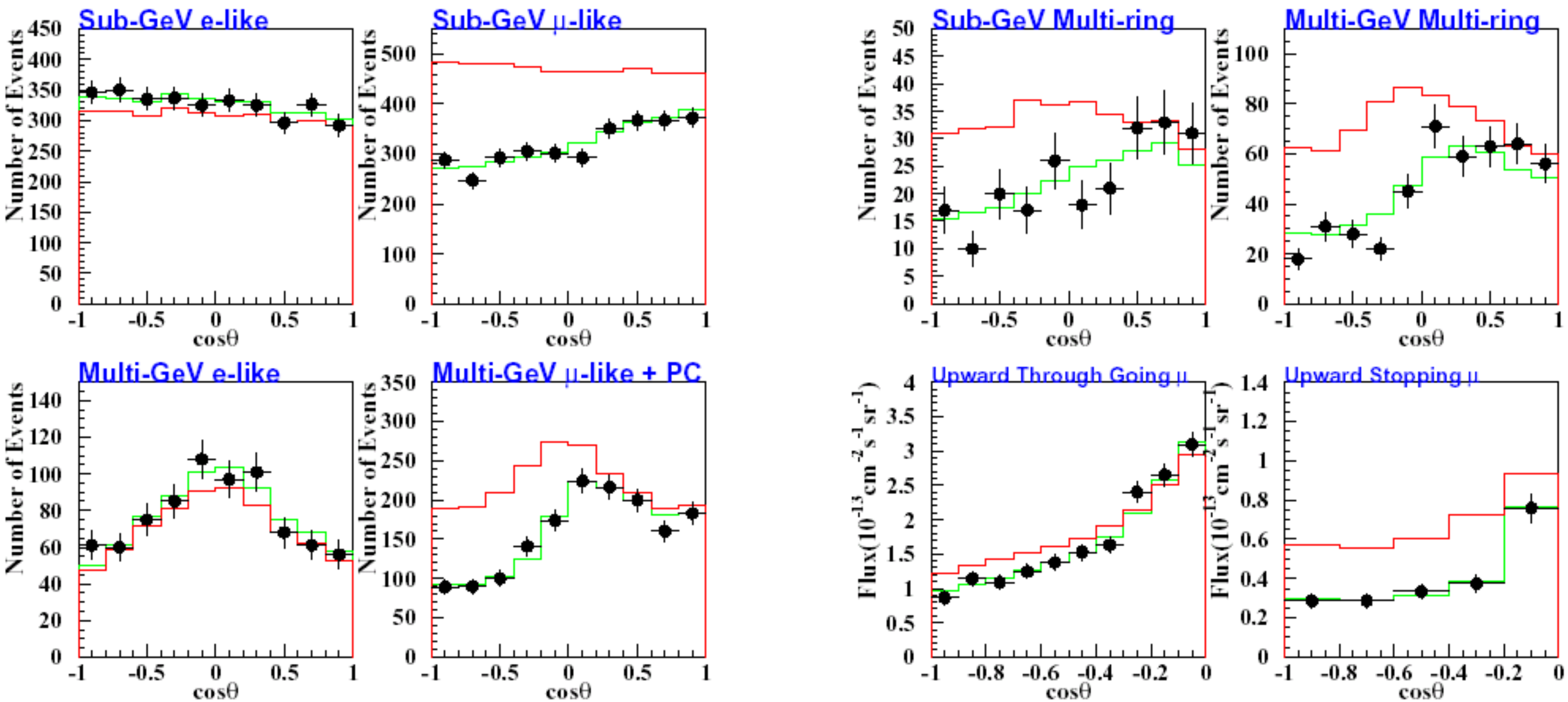
- Neutrino Oscillations:
  - Revolution of 1998: discovery of neutrino oscillations at the Super-KamiokaNDE water Cherenkov detector in Japan (50,000 tons water, 11,000 photomultiplier tubes)





Neutrino Oscillations

- Neutrino Oscillations:
  - Discovery of neutrino oscillations by Super-KamiokaNDE from atmospheric neutrinos (1998): $\nu_\mu \rightarrow \nu_\tau$

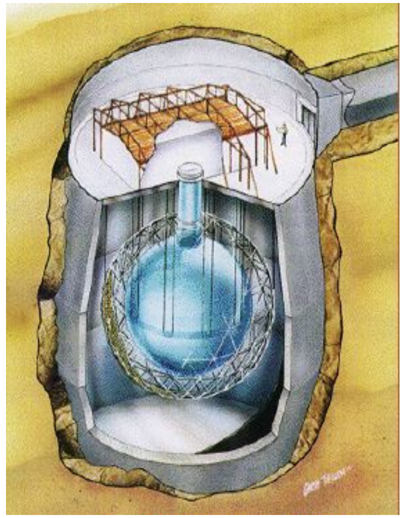


Neutrino Oscillations

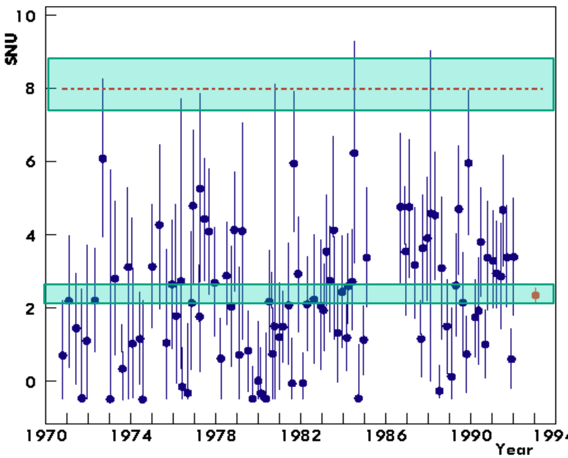
- Neutrino Oscillations: $\nu_e \rightarrow \nu_\mu$
  - Confirmation that solar neutrino problem due to resonant neutrino oscillations in the sun by Sudbury Neutrino Observatory (2002)

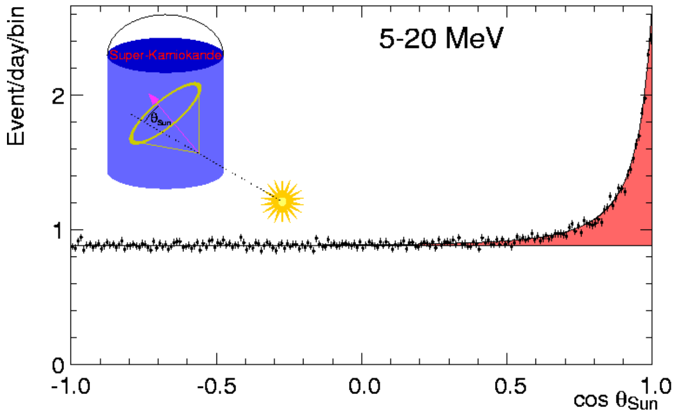
Homestake

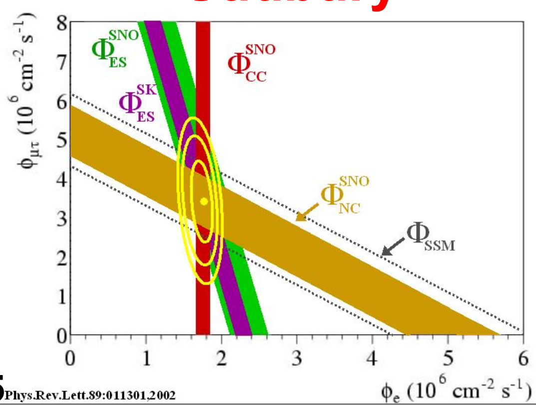
Super-Kamiokande



Sudbury



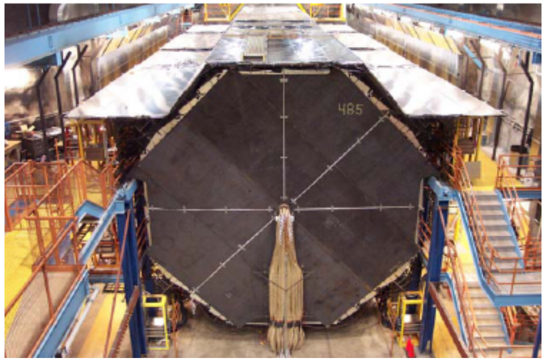


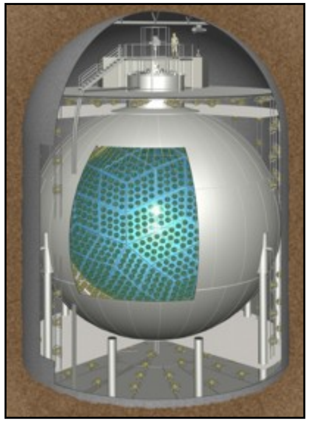


Phys.Rev.Lett.89:011301,2002

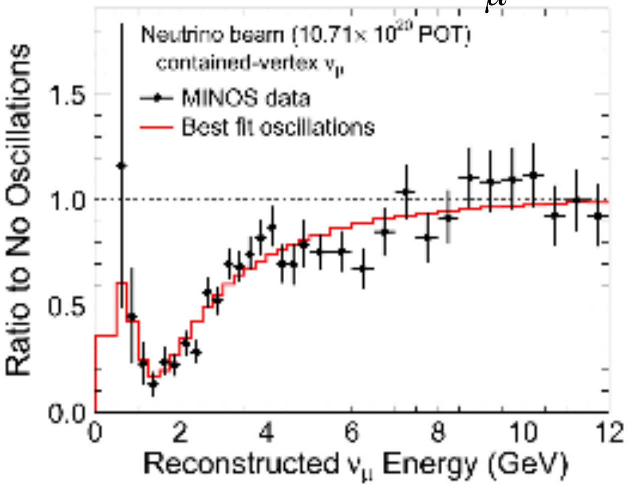
Neutrino Oscillations

- Neutrino Oscillations:
  - Further confirmation of neutrino oscillations at accelerators (K2K, MINOS) and reactors (KamLAND)

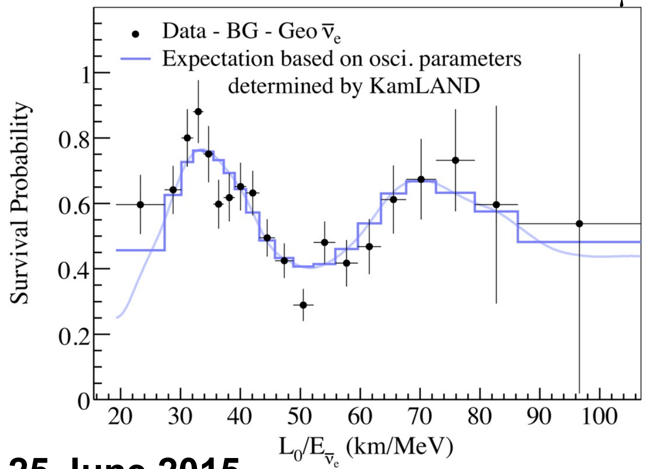




MINOS $\nu_\mu \rightarrow \nu_\tau$



KamLAND $\overline{\nu}_e \rightarrow \overline{\nu}_\mu$

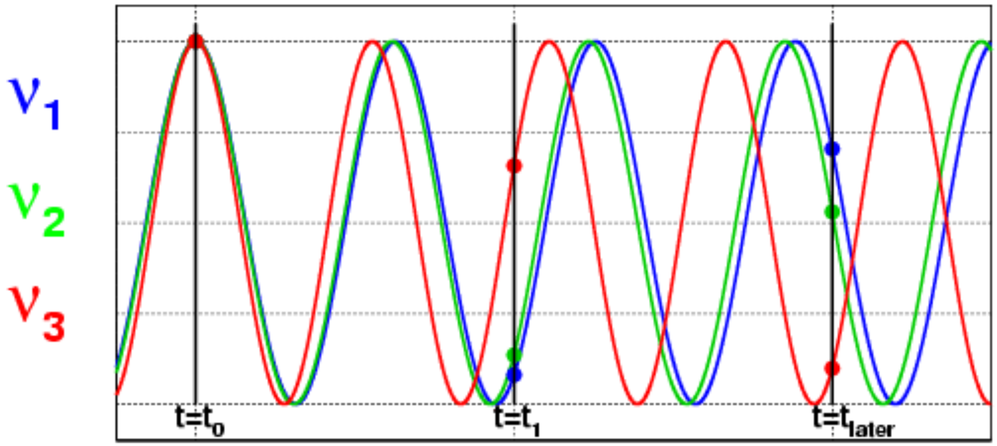


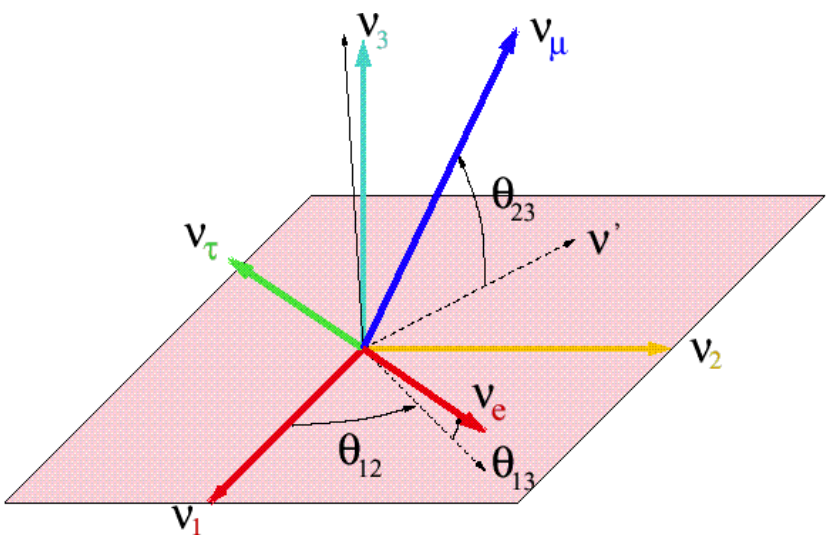
Neutrino Mixing

- Neutrino mass states mix to make up three neutrino flavour states by PMNS matrix:

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

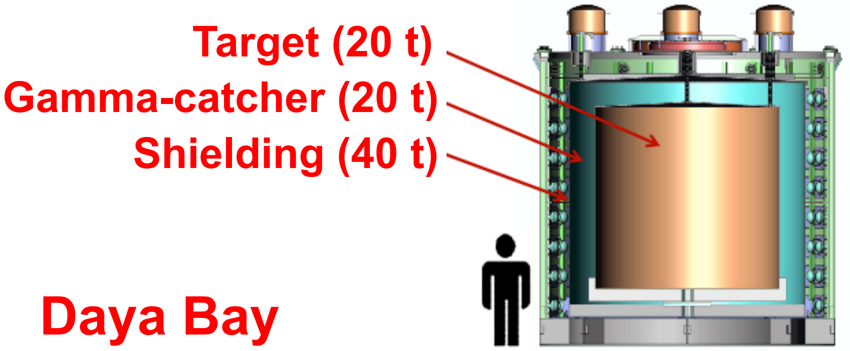
$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$



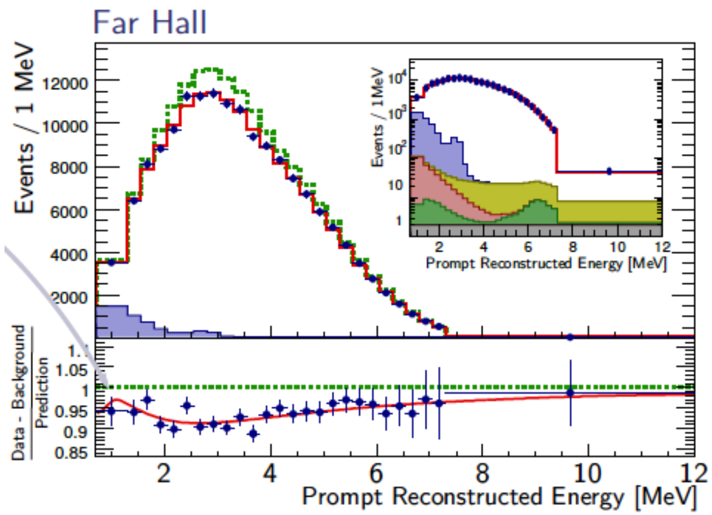


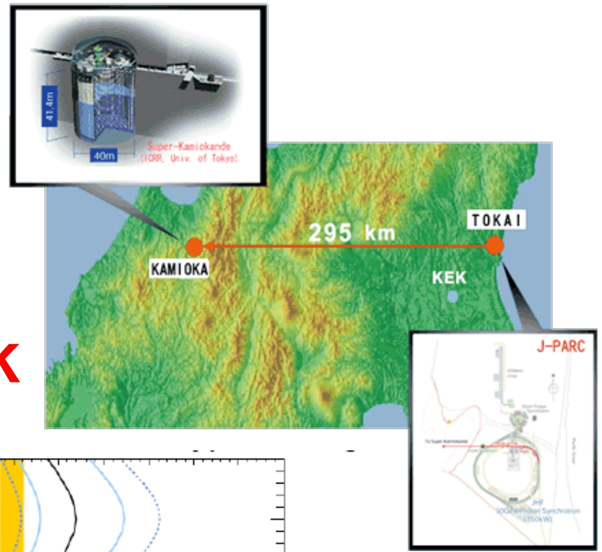
Sub-dominant Neutrino Oscillations

- Neutrino Oscillations:
  - Discovery of θ_{13} from reactor experiments (Daya Bay, RENO) and at long-baseline accelerator (T2K)

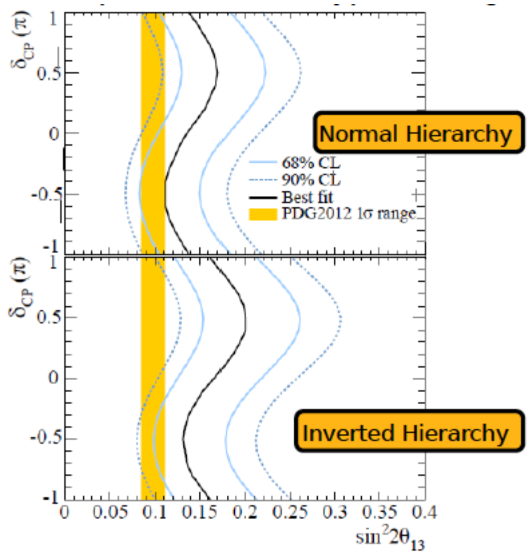


Daya Bay



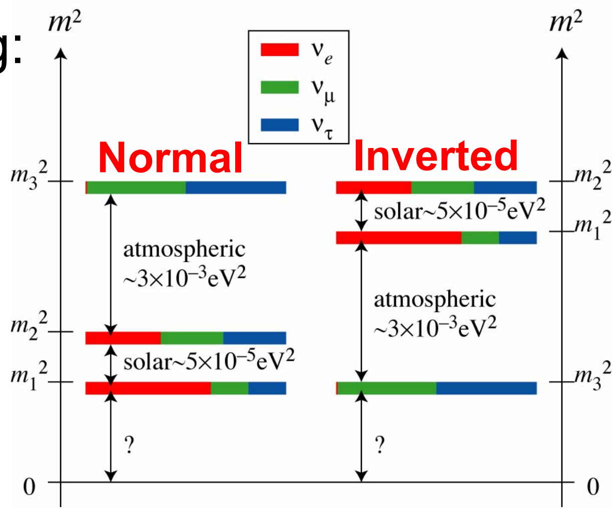


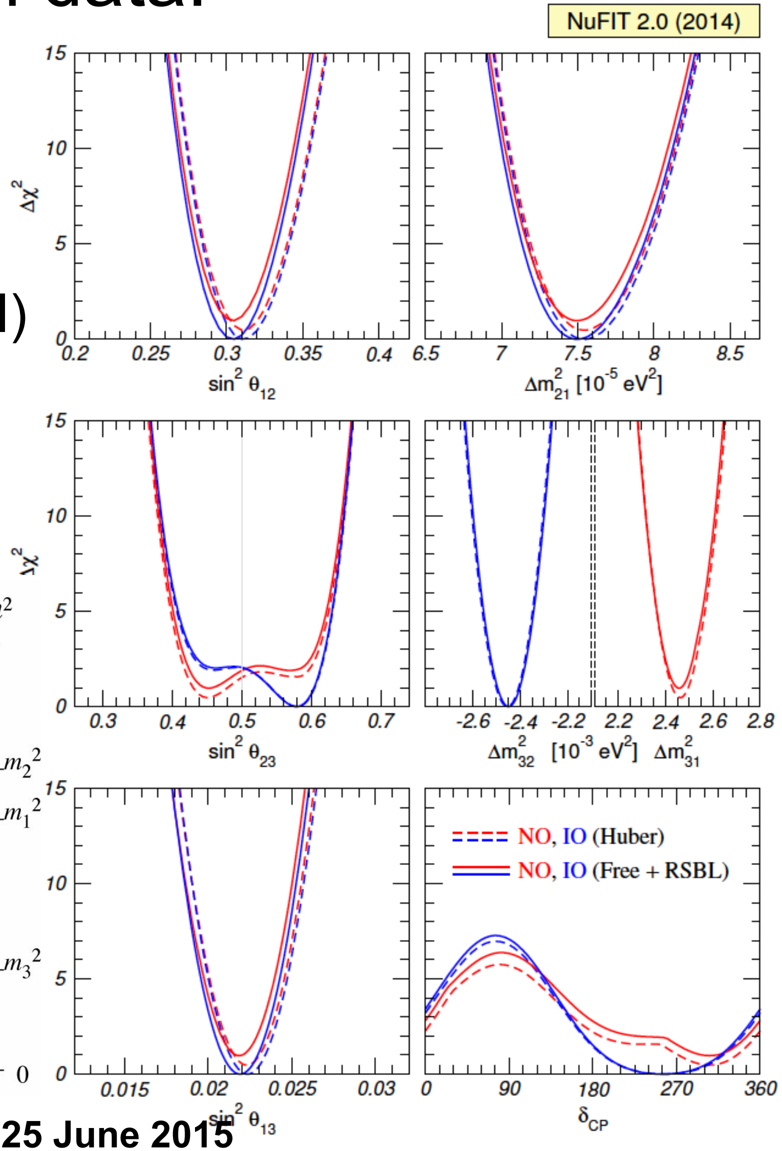
T2K



Neutrino Oscillation Physics

- Global fits to neutrino oscillation data: arXiv:1409.5439
  - Consistent picture:
    - $\sin^2\theta_{12}$=0.304±0.013
    - Δm_{12}^2 =(7.50±0.19)×10^{-5} eV^2
    - $\sin^2\theta_{23}$=0.452±0.052(N), 0.579±0.037(I)
    - Δm_{23}^2=(2.45±0.05)×10^{-3} eV^2
    - $\sin^2\theta_{13}$=0.0218±0.0010
  - Unknown quantities:
    - Mass ordering: sign Δm_{13}^2
    - Quadrant θ_{23}
    - CP phase δ



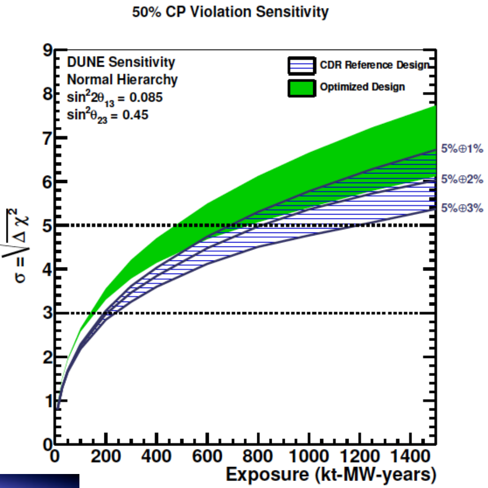


Possible key to explain matter-antimatter asymmetry of universe

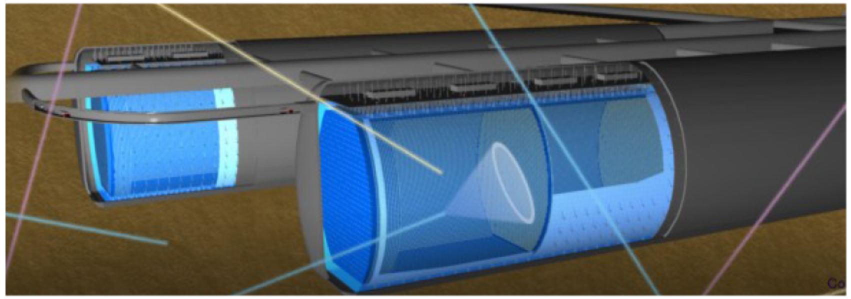
Future Neutrino Oscillation Experiments

- The search for CP violation in neutrinos:
  - Two large-scale projects currently being considered

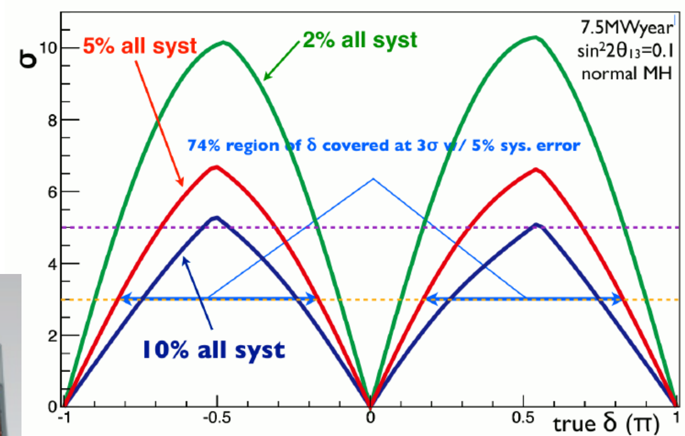
DUNE at LBNF (Fermilab to SURF in SD)



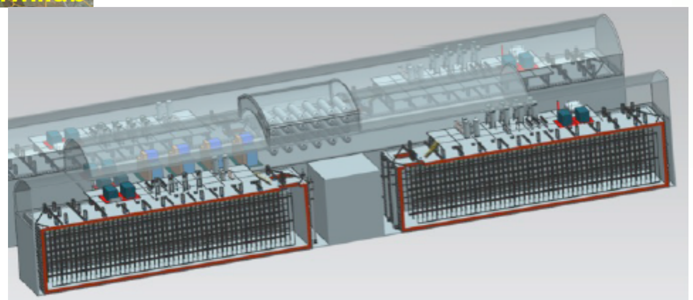
Hyper-Kamiokande



1 Mt Water Cherenkov



40 kt Liquid Argon

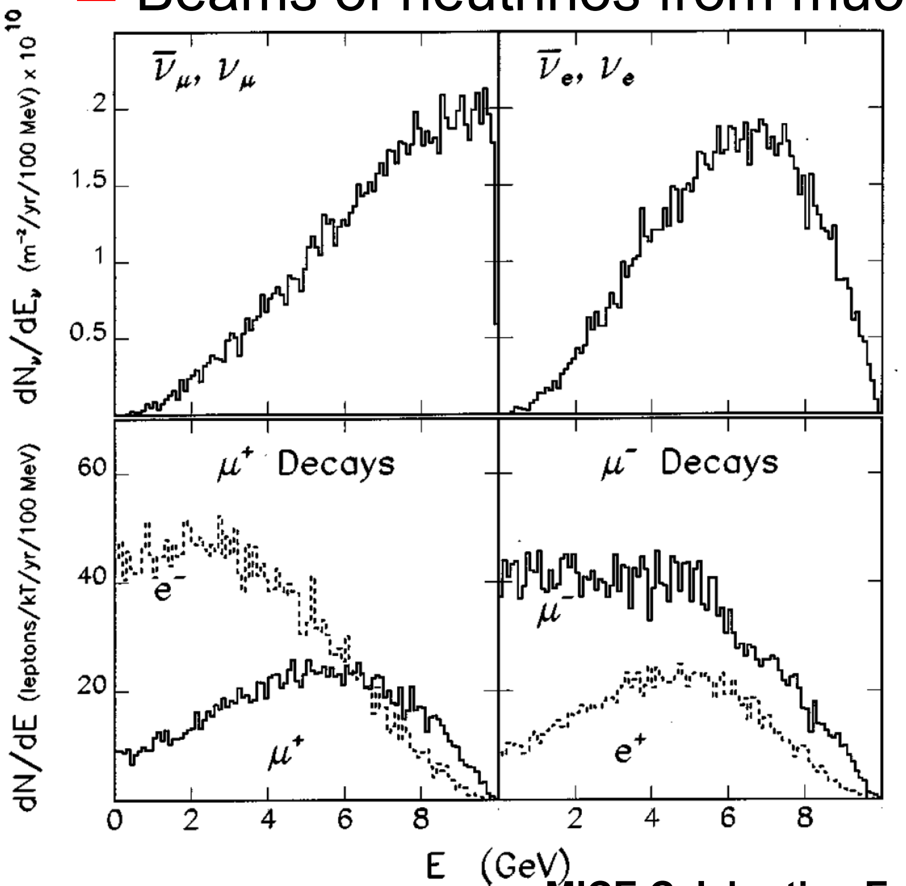


Neutrino Physics and Neutrino Factories

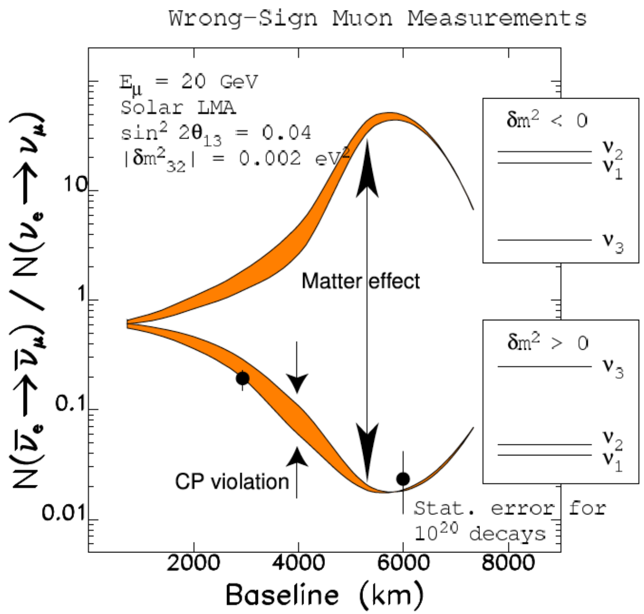
- Neutrino Factory:
  - S. Geer: Phys Rev D57, 6989 (1998) – birth of the modern concept of a neutrino factory
  - Beams of neutrinos from muon decay

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

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

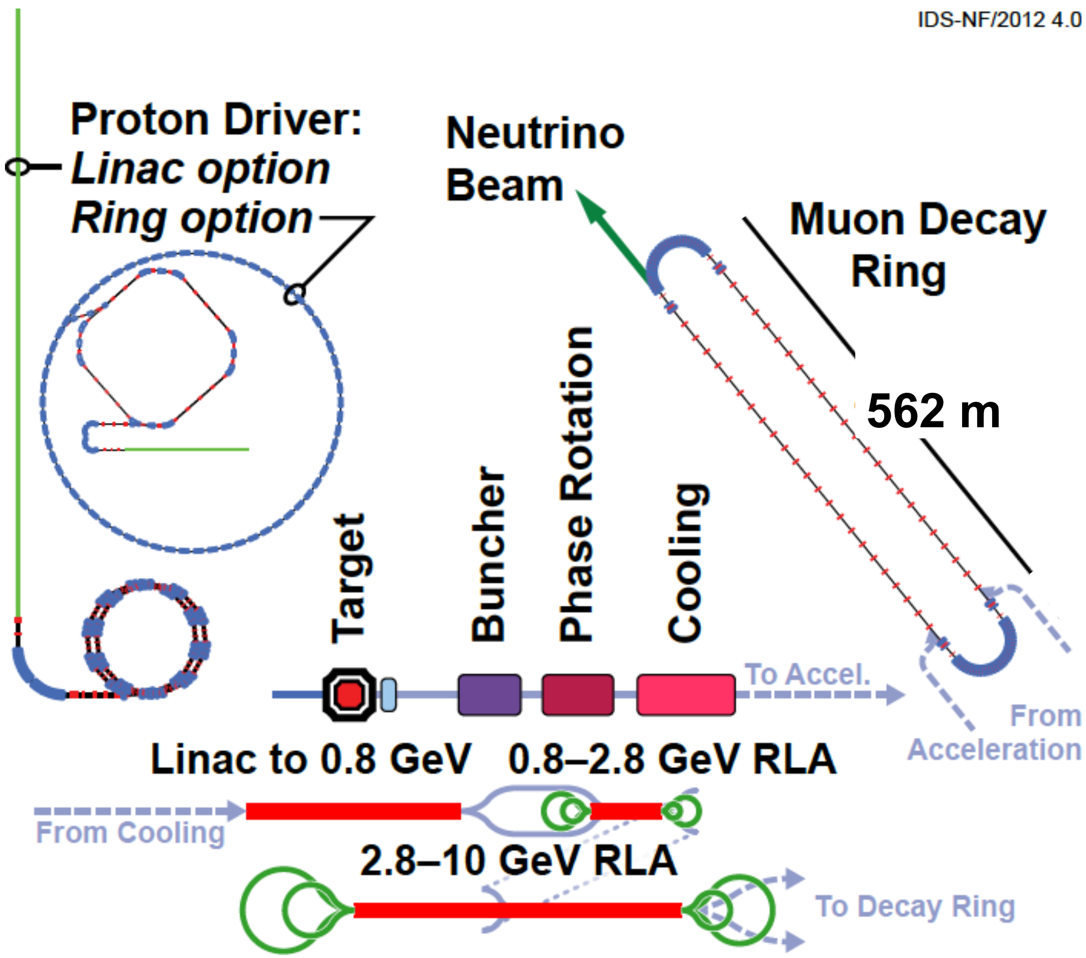


  - Search for CP violation by comparing $\nu_e \to \nu_\mu$ to $\bar{\nu}_e \to \bar{\nu}_\mu$



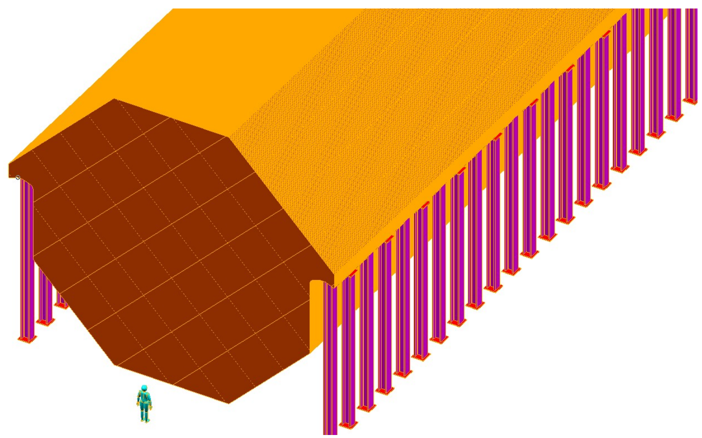
Neutrino Physics and Neutrino Factories

- International Design Study for a Neutrino Factory (IDS-NF):
  - Optimum generic Neutrino Factory



Optimum: 10 GeV muons
Detector: ~2000 km

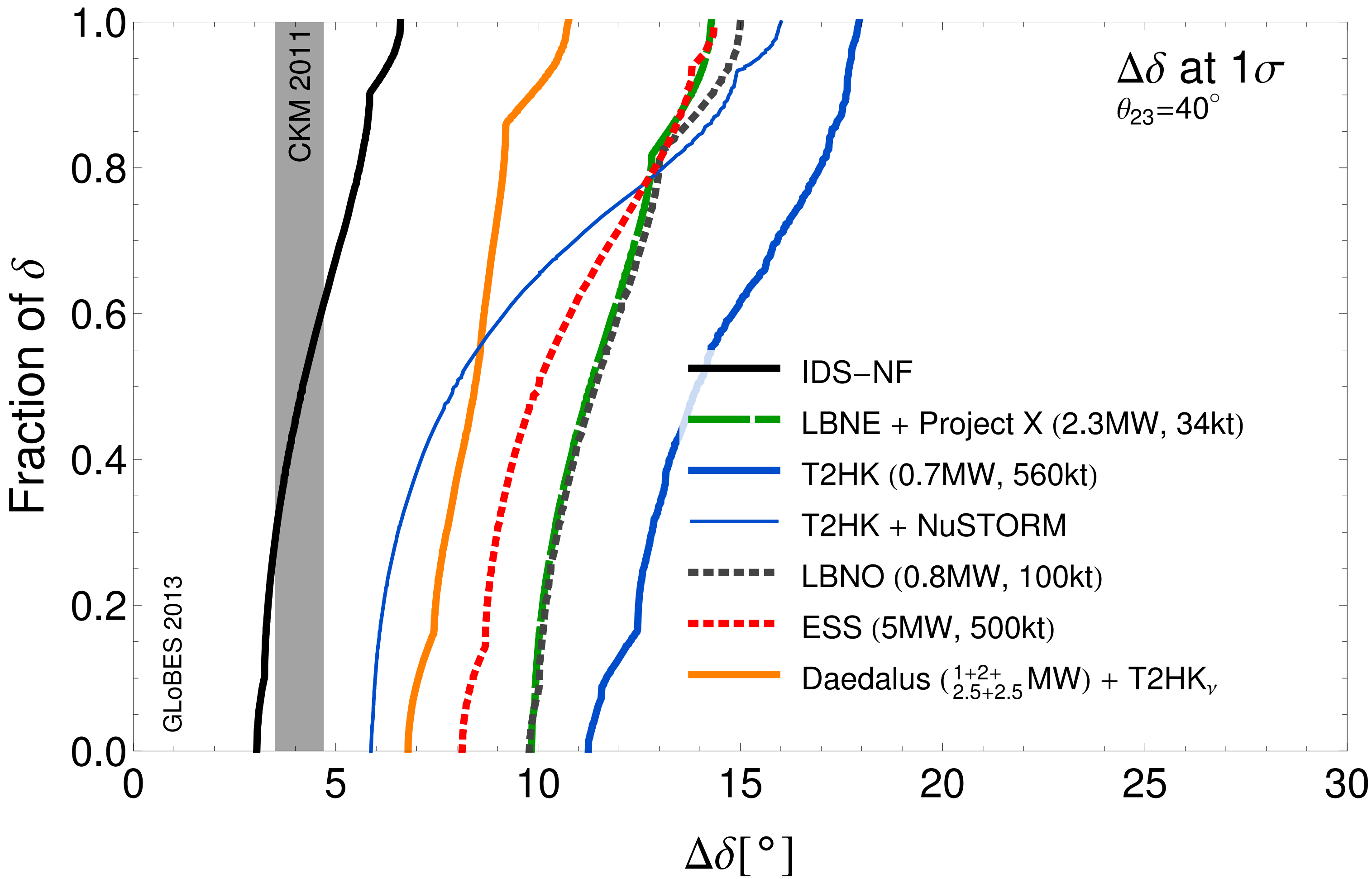
- Magnetised Iron Neutrino Detector (MIND):
  - 100 kton at ~2000 km



Physics performance of IDS-NF

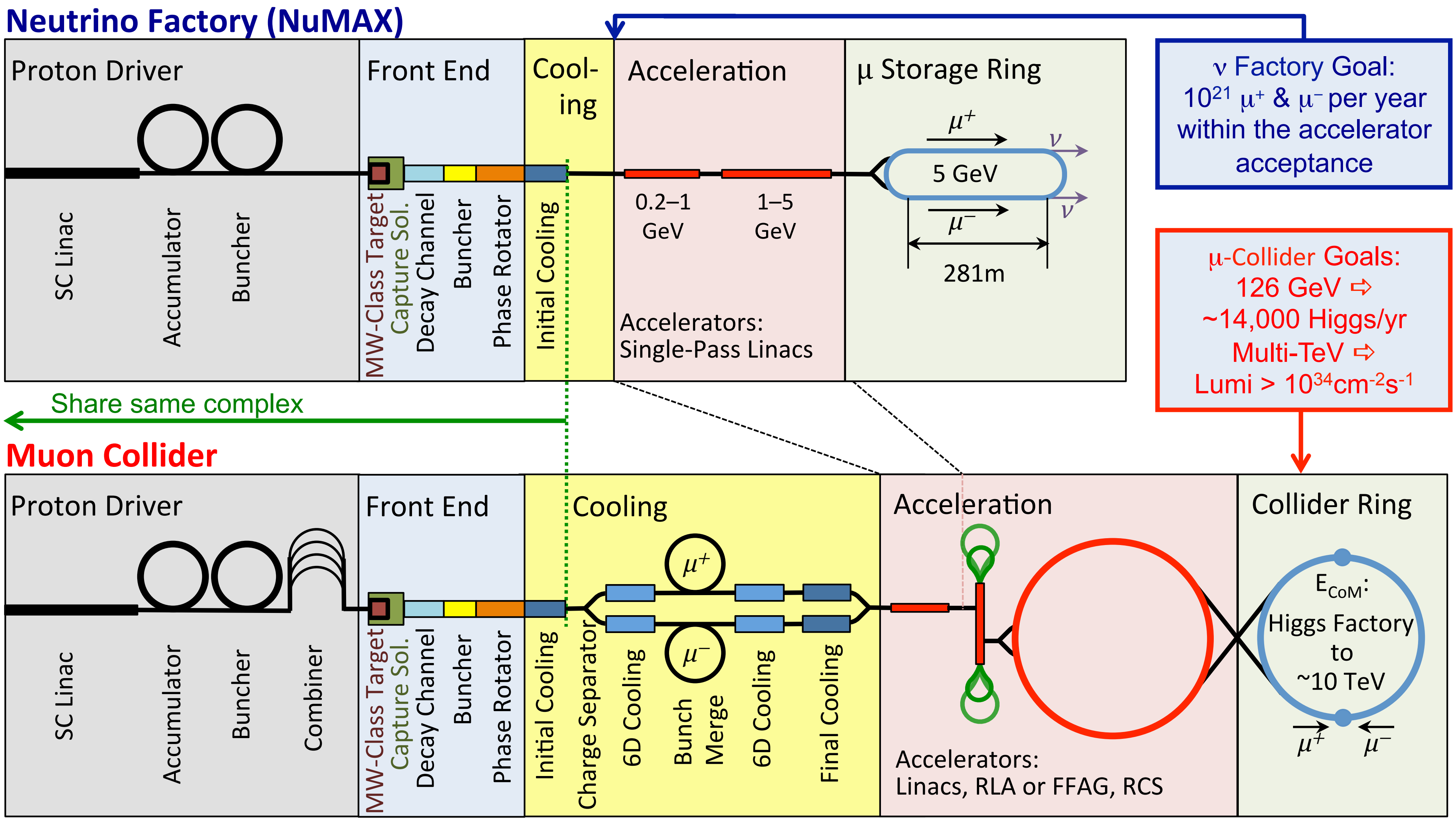
- Physics performance in terms of fraction of CP phase δ with measurement accuracy at or below Δδ

P. Huber



Muon Accelerator Staging Study

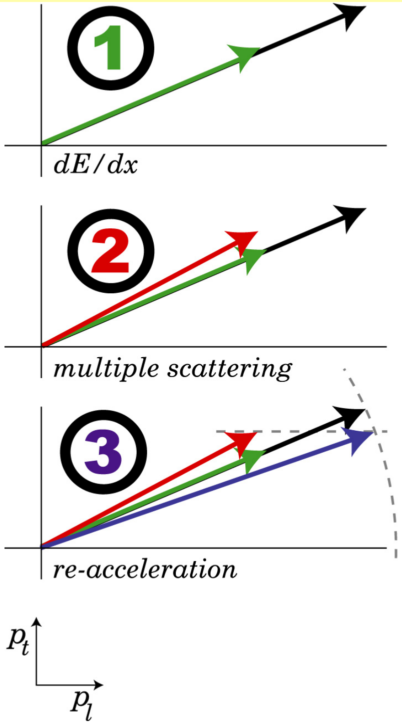
- Staging of Neutrino Factory, leading to a Muon Collider, carried out within the US Muon Accelerator Programme (MAP)

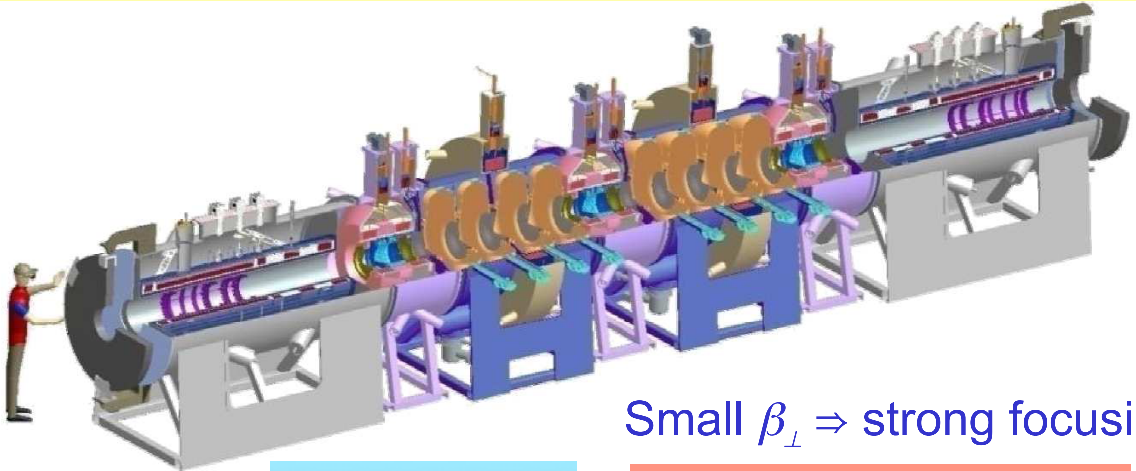


Muon Cooling

- Muon Ionization Cooling:
  - Muon Ionization Cooling is the key technology required to be able to realise a Neutrino Factory and a Muon Collider

Principle | **Practice**





Small $\beta_\perp \Rightarrow$ strong focusing

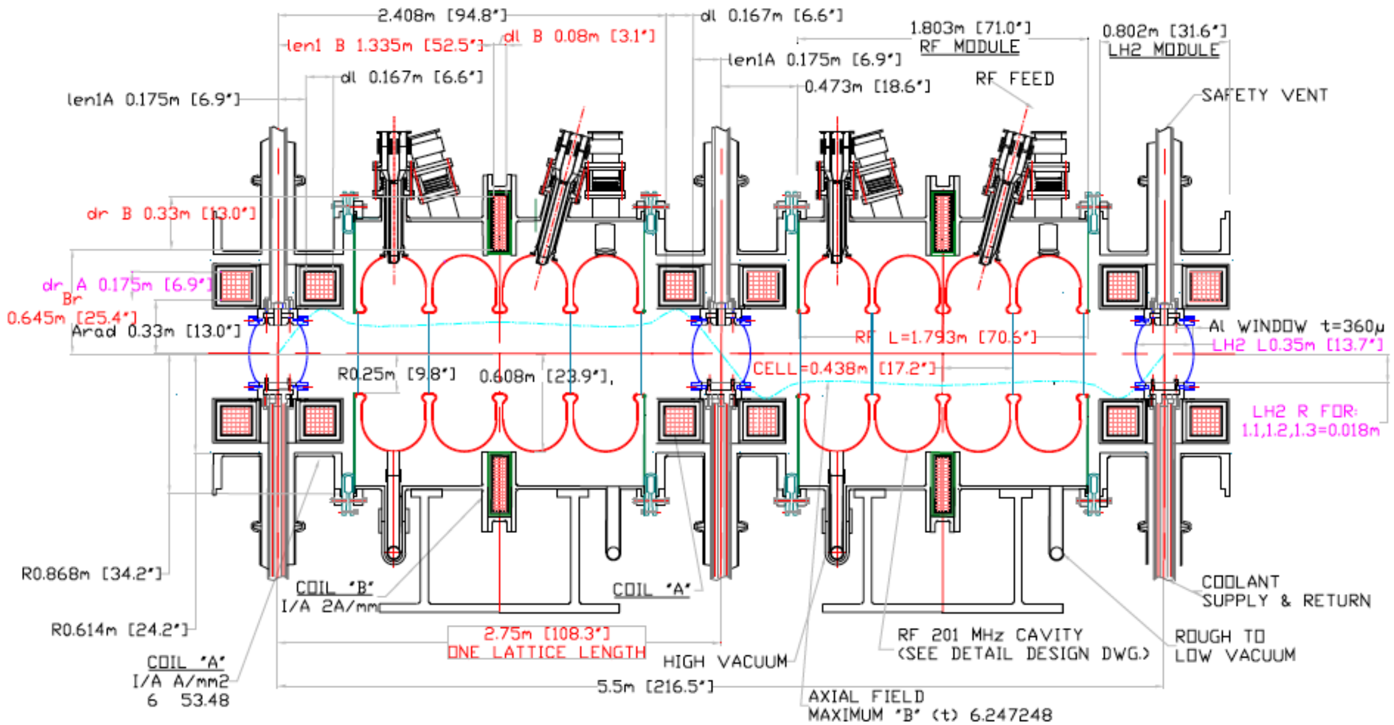
$$\frac{d\varepsilon}{dz} \approx -\frac{\varepsilon}{E_\mu \beta^2}\frac{dE_\mu}{dz} + \frac{\beta_\perp}{2m\beta^3}\frac{(13.6\,MeV)^2}{E_\mu X_0}$$

Ionization: cooling term

Multiple scattering: heating term

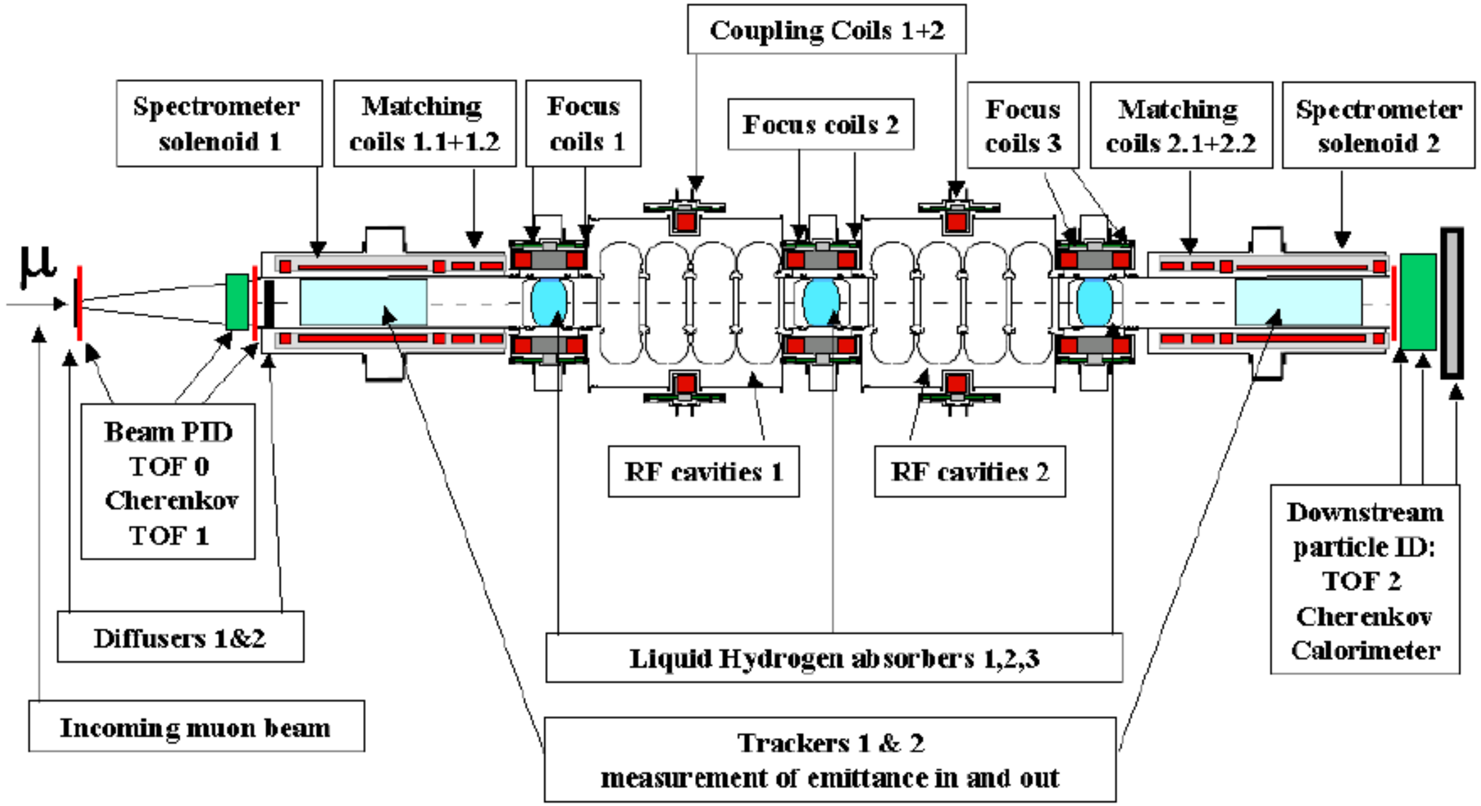
Letter of Intent MICE

- The Muon Ionization Cooling Experiment became a priority to deliver a Neutrino Factory:
  - Letter of Intent for a Muon Cooling experiment (**November 2001**)
  - Two host labs considered: PSI and RAL (A. Blondel will expand)
  - Cooling channel with 201 MHz cavities:



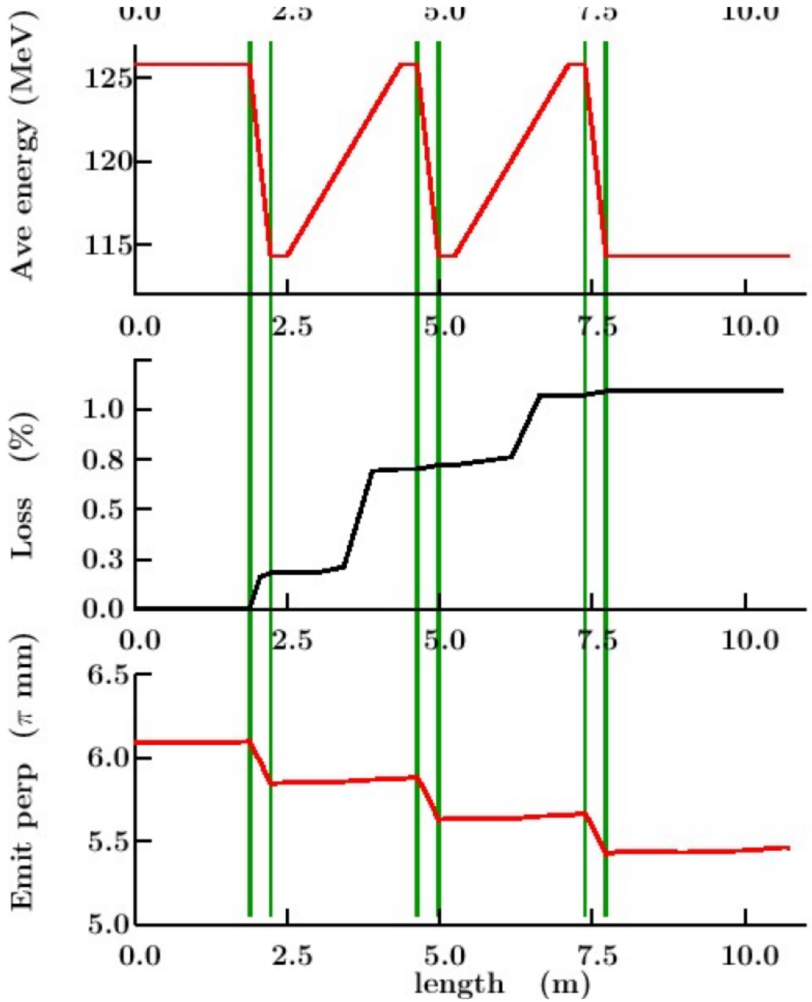
MICE Proposal

- Muon Ionization Cooling Experiment proposal at RAL **(January 2003)**
  - Cooling Channel from US Neutrino Factory Study II
  - Three liquid hydrogen absorbers inside focus coil magnets, two RF cavity modules with coupling coils



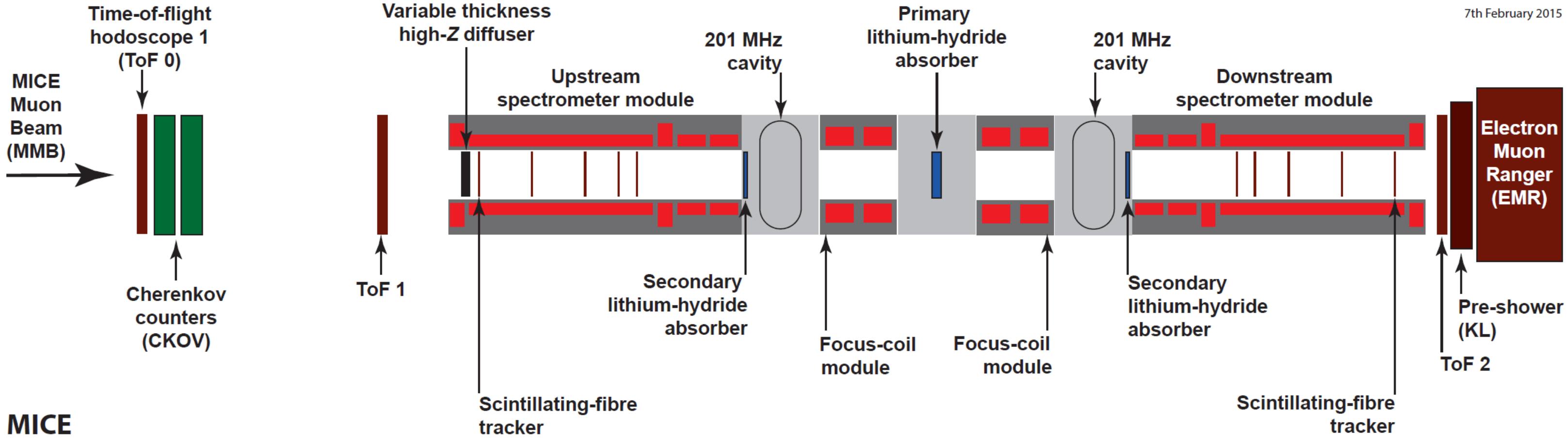
MICE Proposal

- Muon Ionization Cooling Experiment proposed at RAL
  - Spectrometers in solenoid fields upstream and downstream to measure ~10% change in emittance in single particle experiment

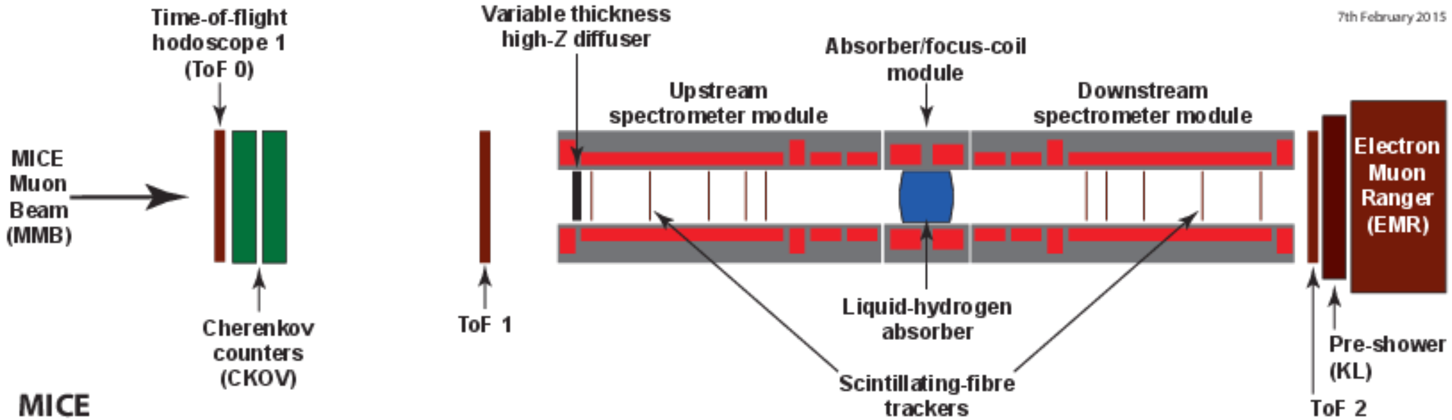


Muon Ionization Cooling Experiment

- Final MICE demonstration of ionization cooling was recently reconfigured after a detailed project review

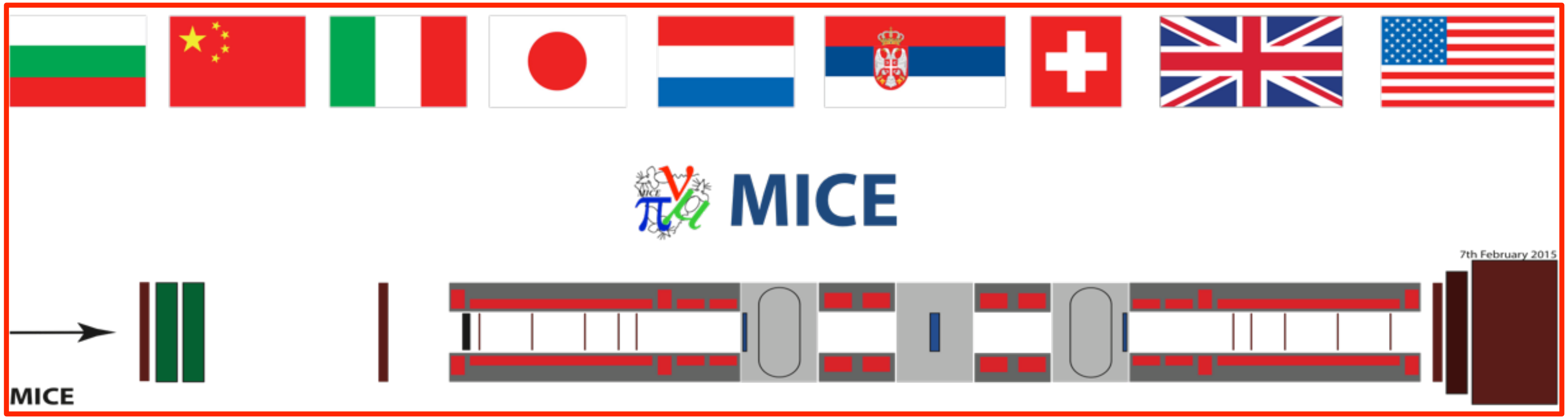


- MICE Step IV: first chance to measure normalised transverse emittance reduction and explore ionization cooling parameters



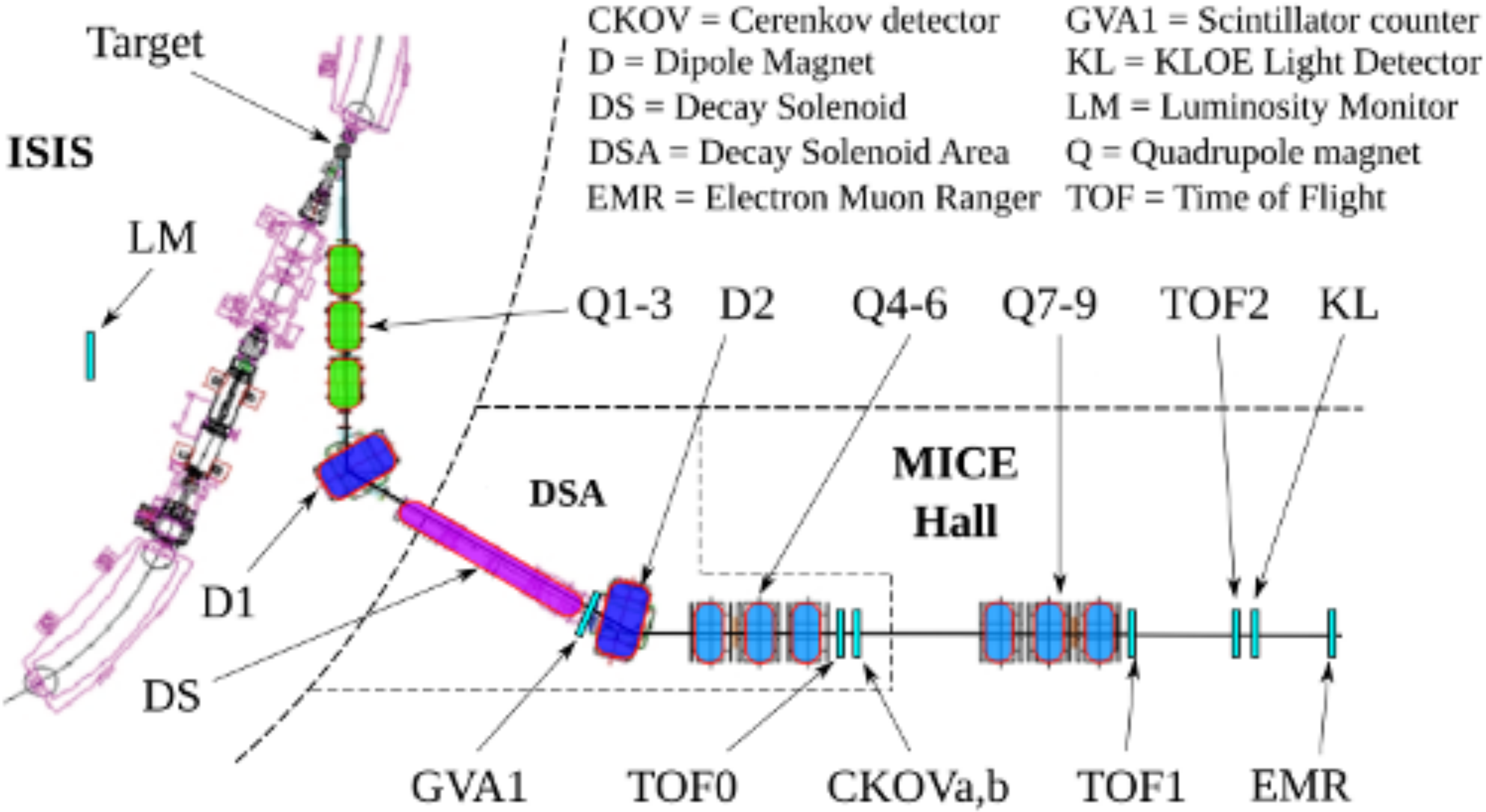
Muon Ionization Cooling Experiment

- We are extremely grateful to all the funding agencies that are contributing and have contributed to MICE
  - STFC (formerly PPARC and CCLRC) from UK
  - NSF and DoE from USA
  - INFN in Italy, Swiss National Science Foundation, European Community, Institutional Funding in Bulgaria, Netherlands, Serbia
  - Japan Society for the Promotion of Science, Chinese Academy of Sciences



MICE Beam

- Muon beam from ISIS: UK responsibility (STFC)

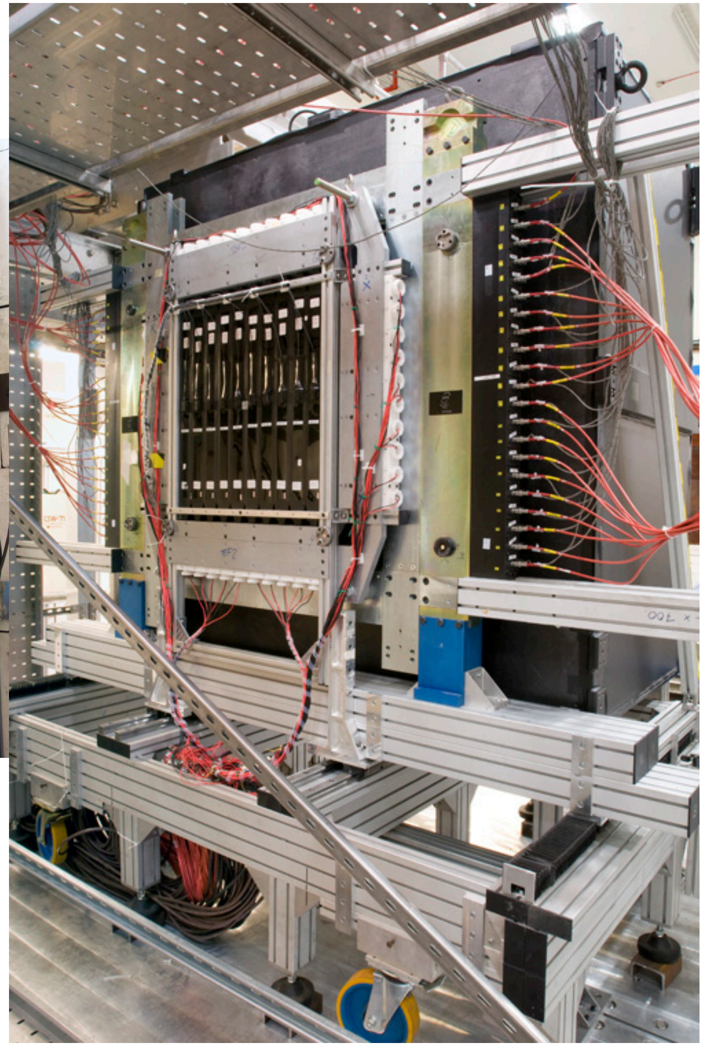


MICE Beam

- Muon beam from ISIS: UK responsibility (STFC)

MICE Detectors

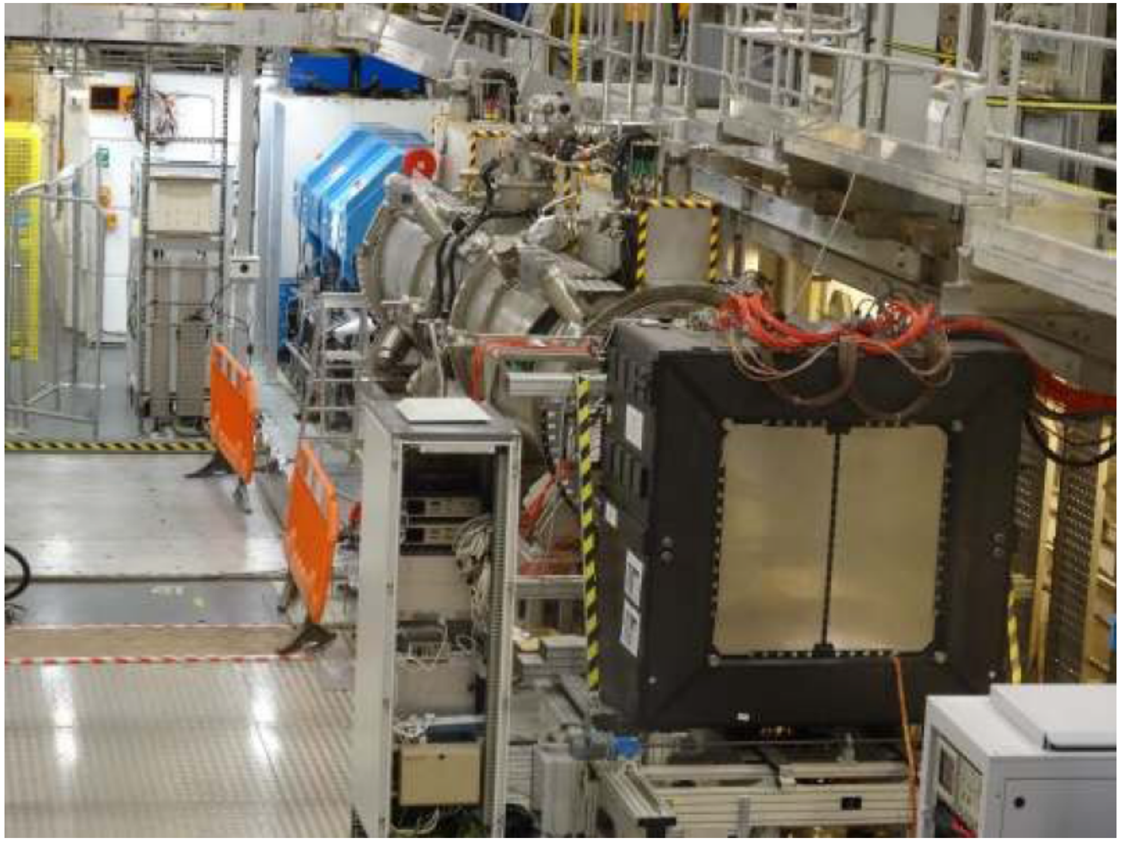
- Time-of-Flight and KL-preshower detector (Italy, INFN)

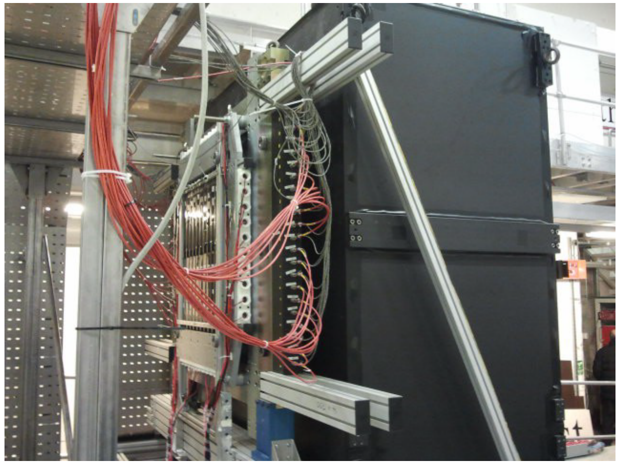


- Cherenkov detectors (NSF, USA)

EMR and Absorber

- Electron Muon Ranger (Switzerland)





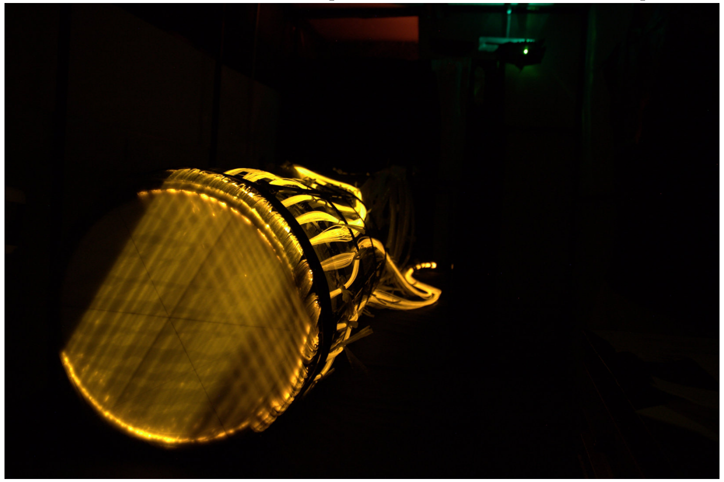
- Hydrogen absorber modules (Japan)

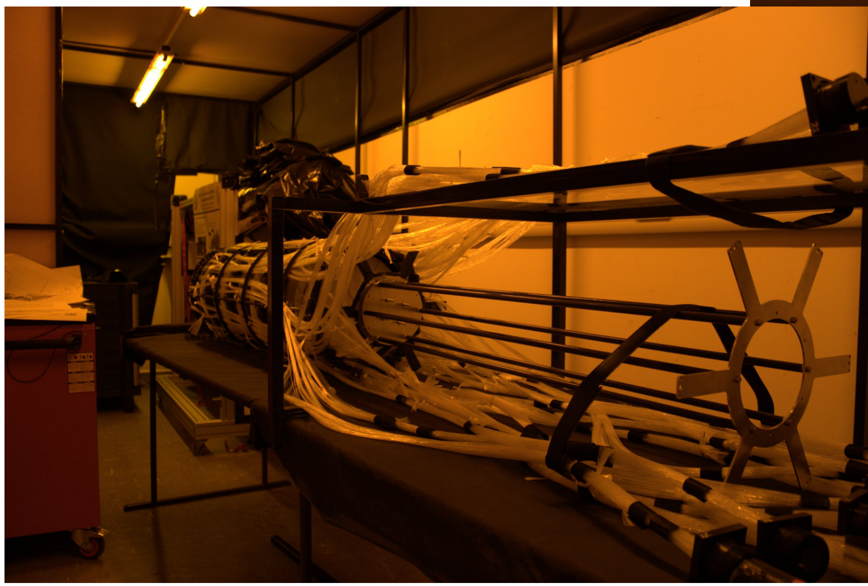
Muon Ionization Cooling Experiment

- Focus Coils (UK, STFC) and Spectrometer Solenoids (USA, DoE)

Muon Ionization Cooling Experiment

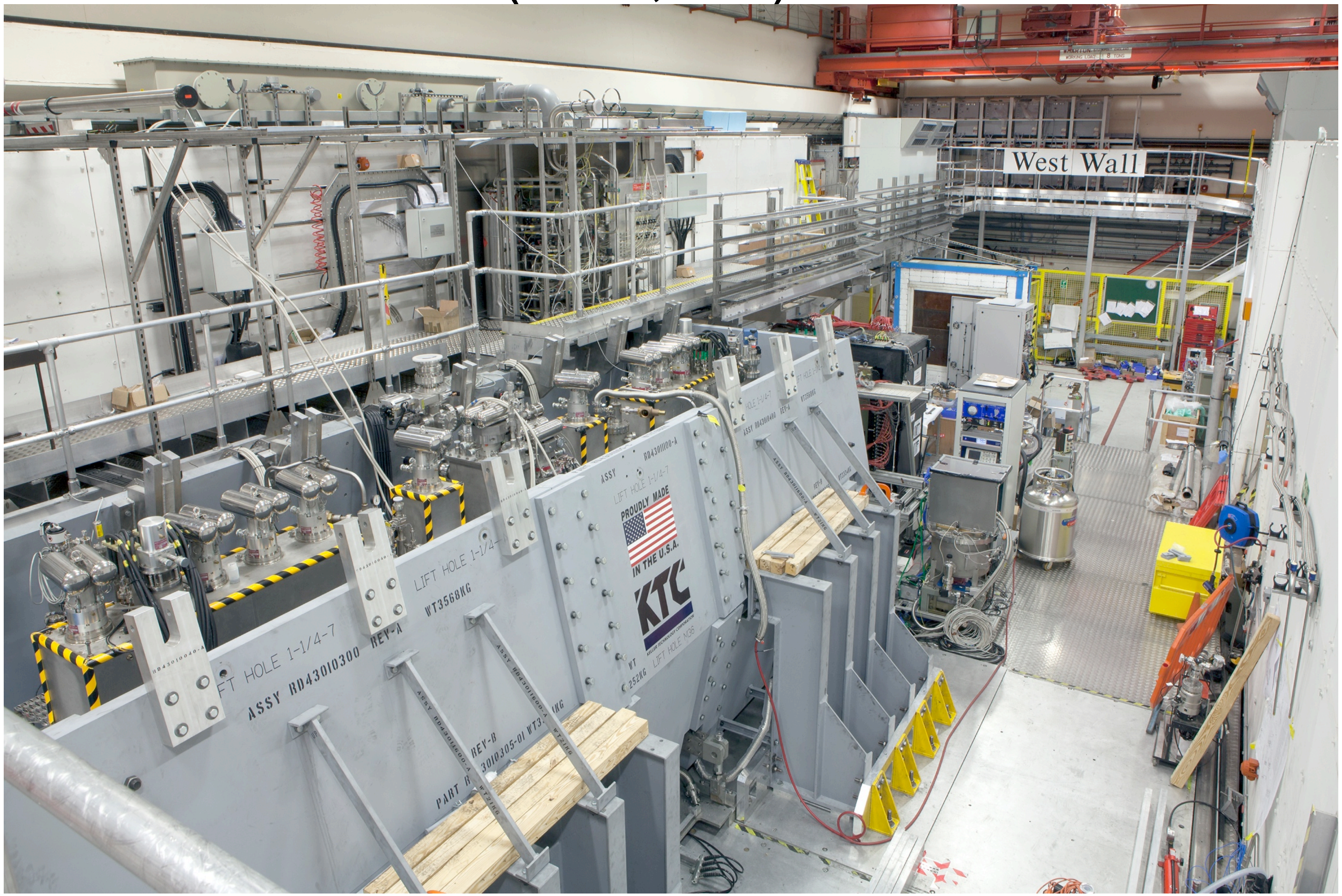
- Scintillating Fibre Tracker (USA, UK)





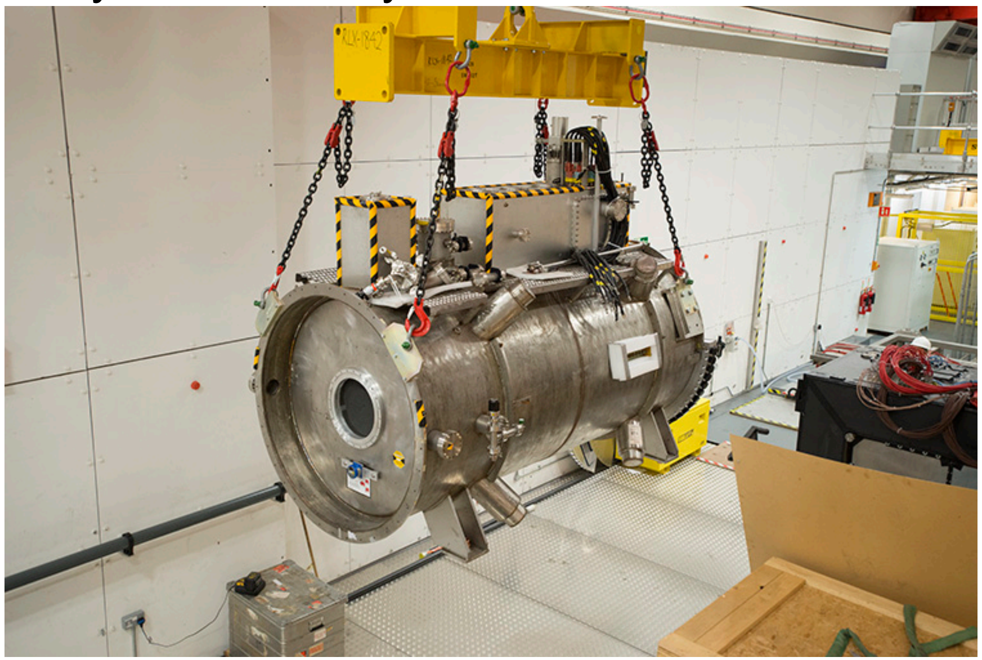
Muon Ionization Cooling Experiment

- Partial Return Yoke (USA, UK)



Painting MICE

- In the 2015-6 academic year we will celebrate the launch of MICE with a science-art project for sixth formers:
  - School groups visit for a day of talks and tours of MICE
  - Schools will design a mural for MICE, based on their visit
  - The winning school will produce their mural in MICE:
    - They will present the mural at the XXVII International Conference on Neutrino Physics and Astrophysics to be held in London in July 2016
    - Prize to be presented by J.Womersley, CEO of STFC



Conclusions

- CP violation in neutrinos could be the key to understanding the matter-antimatter asymmetry of the universe
- A Neutrino Factory offers the best accuracy in determining the CP violation phase δ
- A Muon Collider could pave the way to deliver a high precision Higgs Factory and a multi-TeV lepton-antilepton collider
- Muon ionization cooling is the key technology required to make Neutrino Factories and Muon Colliders viable
- Significant investment, effort (and patience) from all the funding agencies have been paramount in achieving the construction of the Muon Ionization Cooling Experiment at RAL
- MICE is ready to commence its Step IV data taking in order to observe reduction of transverse normalised emittance and characterise the parameters that affect cooling performance