Accelerator-based Neutrino Physics

University of Glasgow

Lecture 3

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Outline

Lecture 3: the future?

4. Future neutrino beams
    - 4.1 Remaining questions in neutrino oscillation physics
    - 4.2 Conventional accelerator-based Super-Beam experiments: CERN-Gran Sasso, T2HK, LBNE, LBNO
    - 4.3 Beta-beams: neutrinos from the decay of radioactive isotopes
    - 4.4 nuSTORM: neutrinos from a muon storage ring
    - 4.5 Neutrino Factory, the ultimate neutrino facility

4.1 Remaining question in neutrino oscillation physics

What have we learned so far?

- More than 50 years of neutrino experiments have established a "standard model" for neutrinos
  - Neutrino oscillations have been established
  - Neutrinos have mass: so far only measured the Δm_{ij}^2
  - We have established neutrino mixing and the parameters of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

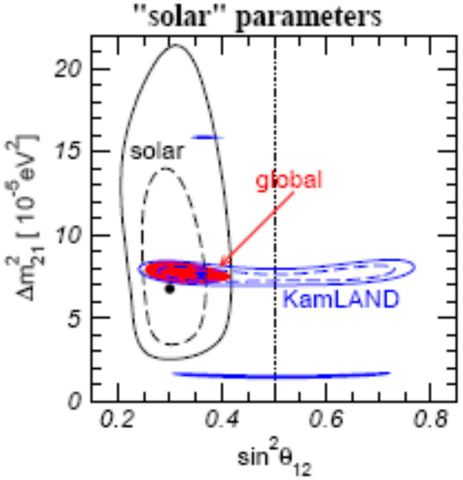
$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

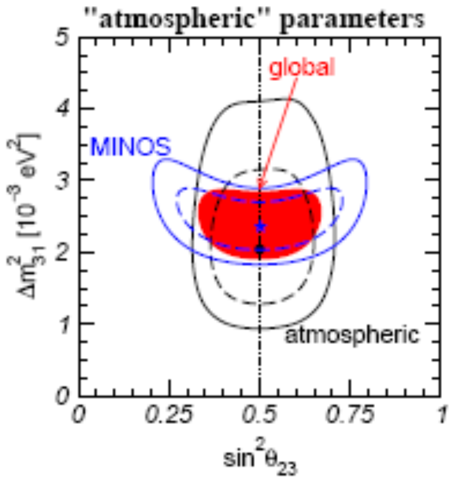
$$where\ c_{ij} = \cos\theta_{ij},\ and\ s_{ij} = \sin\theta_{ij}$$

  - We would like to achieve similar level of precision to the quark sector (CKM matrix) on the mixing parameters
  - We also want to determine CP violation and the phase δ

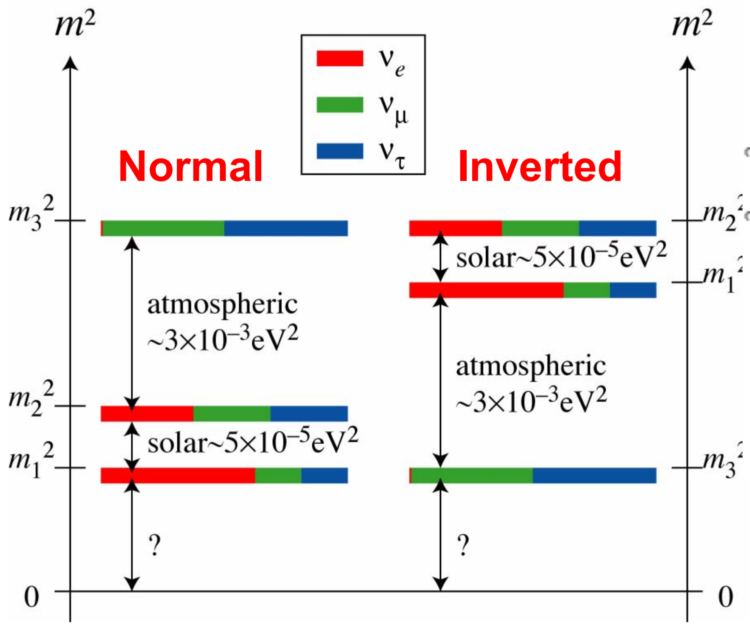
What have we learned so far?

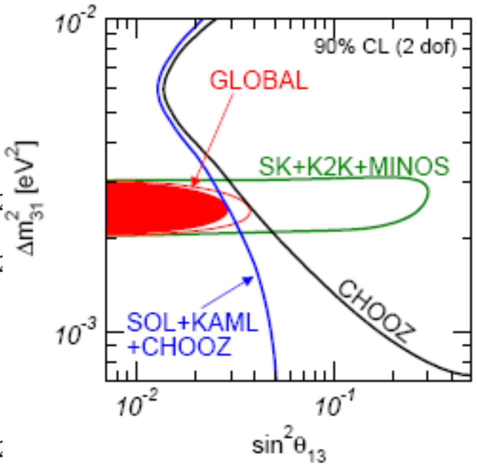
- Consistent picture emerging
- Global fit provides: Schwetz
  - $\sin^2\theta_{12}=0.32\pm0.023$
  - $\Delta m_{12}^2 = 7.6\pm0.20\times10^{-5}$ eV^2
  - $\sin^2\theta_{23}=0.50\pm0.063$
  - $\Delta m_{23}^2=2.40\pm0.15\times10^{-3}$ eV^2
  - $\sin^2 2\theta_{13}=0.092\pm0.016$





- Unknown quantities:
  - Mass hierarchy: sign Δm_{13}^2
  - CP violation phase δ
  - Absolute mass scale
  - Majorana nature





Neutrino oscillations in vacuum

- Oscillations of three neutrino families, if: $|\Delta m^2_{12}| << |\Delta m^2_{23}|, |\Delta m^2_{13}| \approx |\Delta m^2_{23}|$

$$P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)}(x) = s^2_{23} \sin^2 2\theta_{13} \sin^2\left[\frac{\Delta m^2_{13}}{4E} x\right]$$

$$P_{\nu_e \nu_\tau (\bar{\nu}_e \bar{\nu}_\tau)}(x) = c^2_{23} \sin^2 2\theta_{13} \sin^2\left[\frac{\Delta m^2_{13}}{4E} x\right]$$

$$P_{\nu_\mu \nu_\tau (\bar{\nu}_\mu \bar{\nu}_\tau)}(x) = c^4_{13} \sin^2 2\theta_{23} \sin^2\left[\frac{\Delta m^2_{13}}{4E} x\right]$$

Nucl. Phys. B579 (2000), 17

with $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$

- Oscillations, if $|\Delta m^2_{12}|$ not negligible:

$$P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)}(x) = s^2_{23} \sin^2 2\theta_{13} \sin^2\left[\frac{\Delta m^2_{13}}{4E} x\right] + c^2_{23} \sin^2 2\theta_{12} \sin^2\left[\frac{\Delta m^2_{12}}{4E} x\right] +$$

$$+ \tilde{J} \cos\left[\pm\delta - \frac{\Delta m^2_{13}}{4E} x\right]\left(\frac{\Delta m^2_{12}}{4E} x\right) \sin\left[\frac{\Delta m^2_{13}}{4E} x\right]$$

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

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

(Jarlskog coefficient for CP violation)

Oscillations in matter (MSW effect)

- Matter oscillations for two neutrinos (MSW effect):
  - In vacuum:

$$P_{\nu_e\nu_\mu}(x) = \left|\langle \nu_\mu | \nu_e(x)\rangle\right|^2 = \sin^2 2\theta_{12} \sin^2\left[\frac{\Delta m_{12}^2}{4E} x\right] = \sin^2 2\theta_{12} \sin^2\left[\pi \frac{x}{L_{12}}\right]$$

  - In matter:

$$P_{\nu_e\nu_\mu}(x) = \left|\langle \nu_\mu | \nu_e(x)\rangle\right|^2 = \sin^2 2\theta_M \sin^2\left[\frac{\Delta \tilde{m}_{12}^2}{4E} x\right] = \sin^2 2\theta_M \sin^2\left[\pi \frac{x}{L_M}\right]$$

Due to CC interactions of ν_e with electrons in matter: $A \equiv 2E\sqrt{2} G_F n_e$

A new effective mixing angle in matter arises: $\tan 2\theta_M = \dfrac{\Delta m_{12}^2 \sin 2\theta_{12}}{\Delta m_{12}^2 \cos 2\theta_{12} - A}$

with new effective mass eigenstates:

$$\tilde{m}_{1,2}^2 = \frac{1}{2}\left(\left(m_1^2 + m_2^2 + A\right) \mp \sqrt{\left(\Delta m_{12}^2 \cos 2\theta_{12} - A\right)^2 + \Delta m_{12}^4 \sin^2 2\theta_{12}}\right)$$

At resonance $A = \Delta m_{12}^2 \cos 2\theta_{12}$ mixing can be maximal: $\theta_M = \pi/4$

Oscillation length: $L_M = L_{12} \dfrac{\Delta m_{12}^2}{\sqrt{\left(\Delta m_{12}^2 \cos 2\theta_{12} - A\right)^2 + \Delta m_{12}^4 \sin^2 2\theta_{12}}} \approx \dfrac{L_{12}}{\sin 2\theta_{12}}$

Oscillations in matter (MSW effect)

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

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

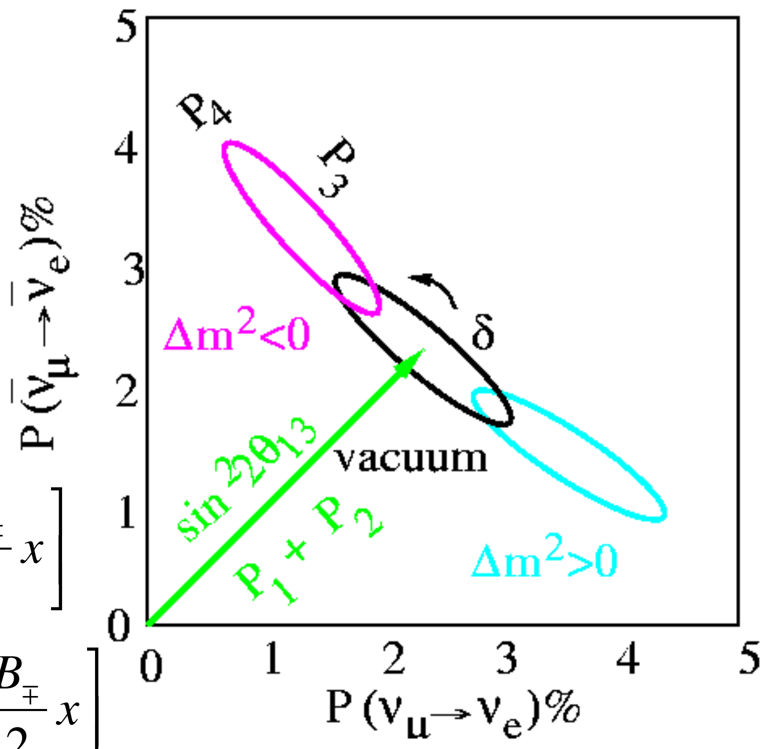
$$P_1 = s_{23}^2 \sin^2 2\theta_{13}\left(\frac{\Delta m_{13}^2}{2EB_\mp}\right)\sin^2\left[\frac{B_\mp}{2}x\right]$$

$$P_2 = c_{23}^2 \sin^2 2\theta_{12}\left(\frac{\Delta m_{12}^2}{A}\right)\sin^2\left[\frac{A}{4E}x\right]$$

$$P_3 = \tilde{J}\cos\delta\cos\left[\frac{\Delta m_{13}^2}{4E}x\right]\left(\frac{\Delta m_{12}^2}{A}\frac{\Delta m_{13}^2}{2EB_\mp}\right)\sin\left[\frac{A}{4E}x\right]\sin\left[\frac{B_\mp}{2}x\right]$$

$$P_4 = \pm\tilde{J}\sin\delta\sin\left[\frac{\Delta m_{13}^2}{4E}x\right]\left(\frac{\Delta m_{12}^2}{A}\frac{\Delta m_{13}^2}{2EB_\mp}\right)\sin\left[\frac{A}{4E}x\right]\sin\left[\frac{B_\mp}{2}x\right]$$

with $B_\mp \equiv \frac{1}{2E}\sqrt{\left(\Delta m_{13}^2\cos 2\theta_{13} \mp A\right)^2 + \Delta m_{13}^4 \sin^2 2\theta_{13}} \approx \frac{\left|\Delta m_{13}^2 \mp A\right|}{2E}$



Minakata & Nunokawa JHEP 2001

$A \equiv 2\sqrt{2}G_F n_e E$

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

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

- Magic baseline: $\frac{Ax}{4E} = \frac{G_F n_e}{\sqrt{2}} = \pi \Rightarrow x = 7300 - 7600\ km \quad P_2 = P_3 = P_4 = 0$

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)}(x) = s_{23}^2 \sin^2 2\theta_{13}\left(\frac{\Delta m_{13}^2}{2EB_\mp}\right)\sin^2\left[\frac{B_\mp}{2}x\right]$$

Independent of CP phase δ

4.2 Conventional accelerator-based Super Beam experiments

Super beams

- Super beams are defined as conventional neutrino beams but with target powers that exceed 1 MW
- The EUROnu project studied and compared the performance of three types of future neutrino facilities
  - A Super Beam from CERN to a water Cherenkov detector established in the Frejus tunnel in France
  - A Beta Beam facility at CERN, also pointing to Frejus
  - A Neutrino Factory facility
- The EUROnu project studied the CERN to Frejus facility **Phys.Rev. STAB 16, 021002 (2013)**

CERN-Frejus Super Beam

- Based on CERN Superconducting Proton Linac (SPL) design: 4-5 GeV protons, with 4 MW power
- Split power into four 1 MW Ti pebble bed target stations with 4 horns

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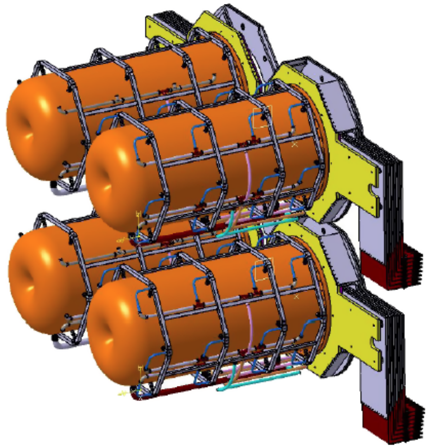
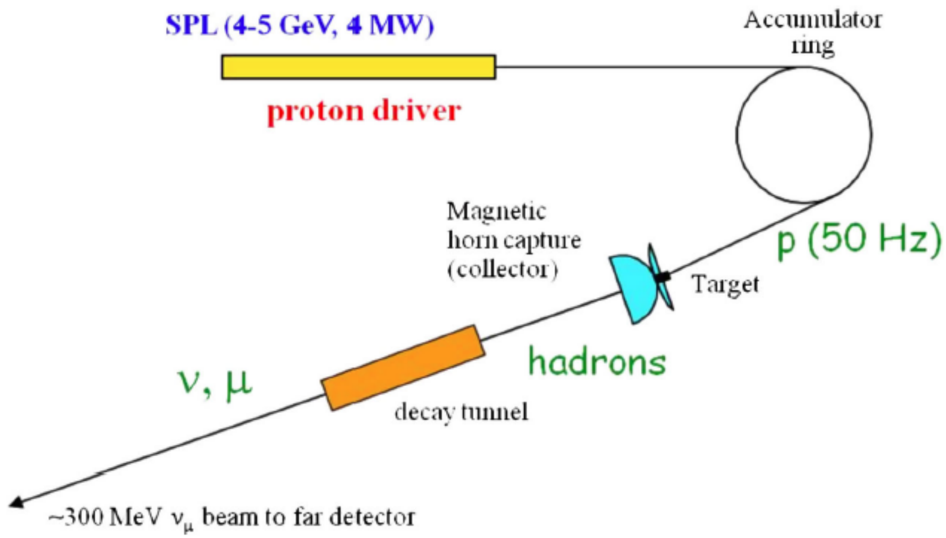
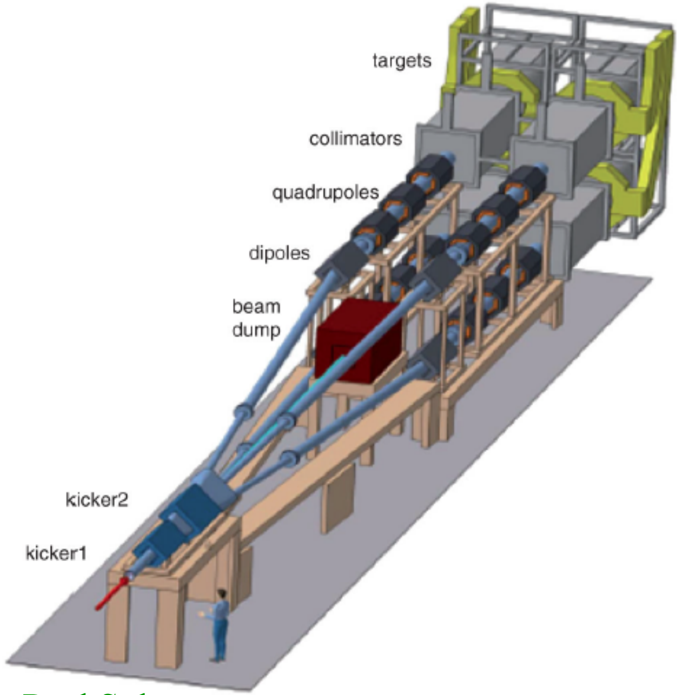
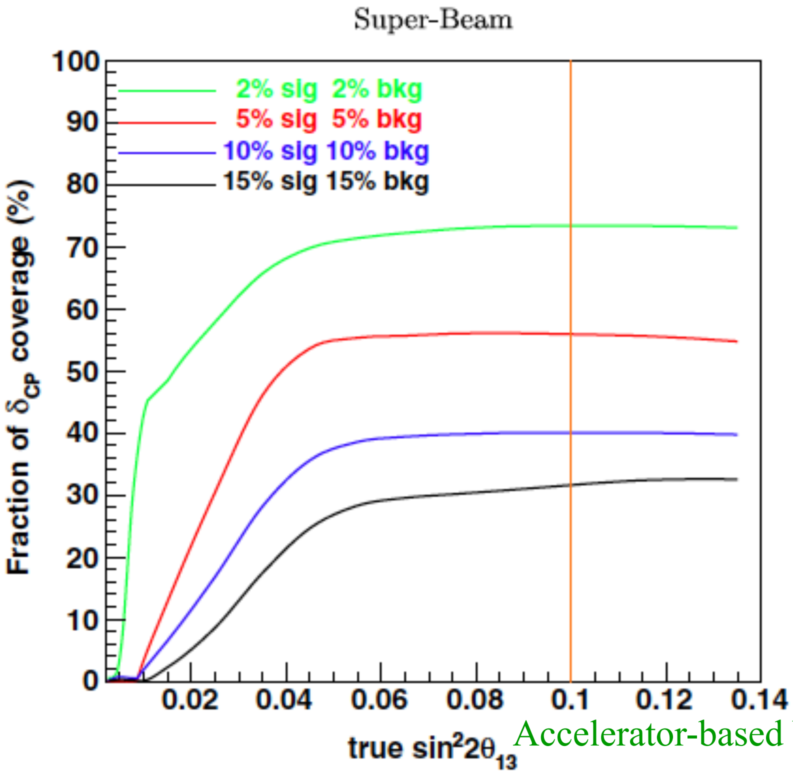


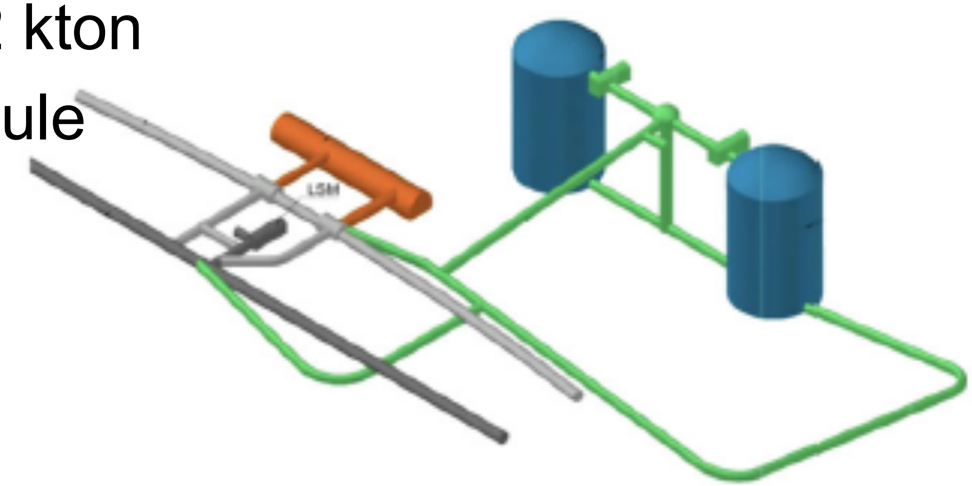


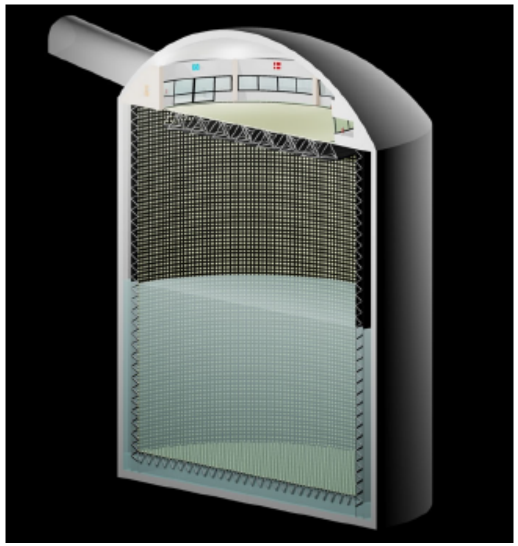


MEMPHYS

- The detector proposed in Frejus is a Megaton Mass Physics (MEMPHYS) water Cherenkov detector: two modules 103 m depth, 65 m diameter – 572 kton
- 120,000 12” PMTs per module
- Coverage of δ_{CP}:

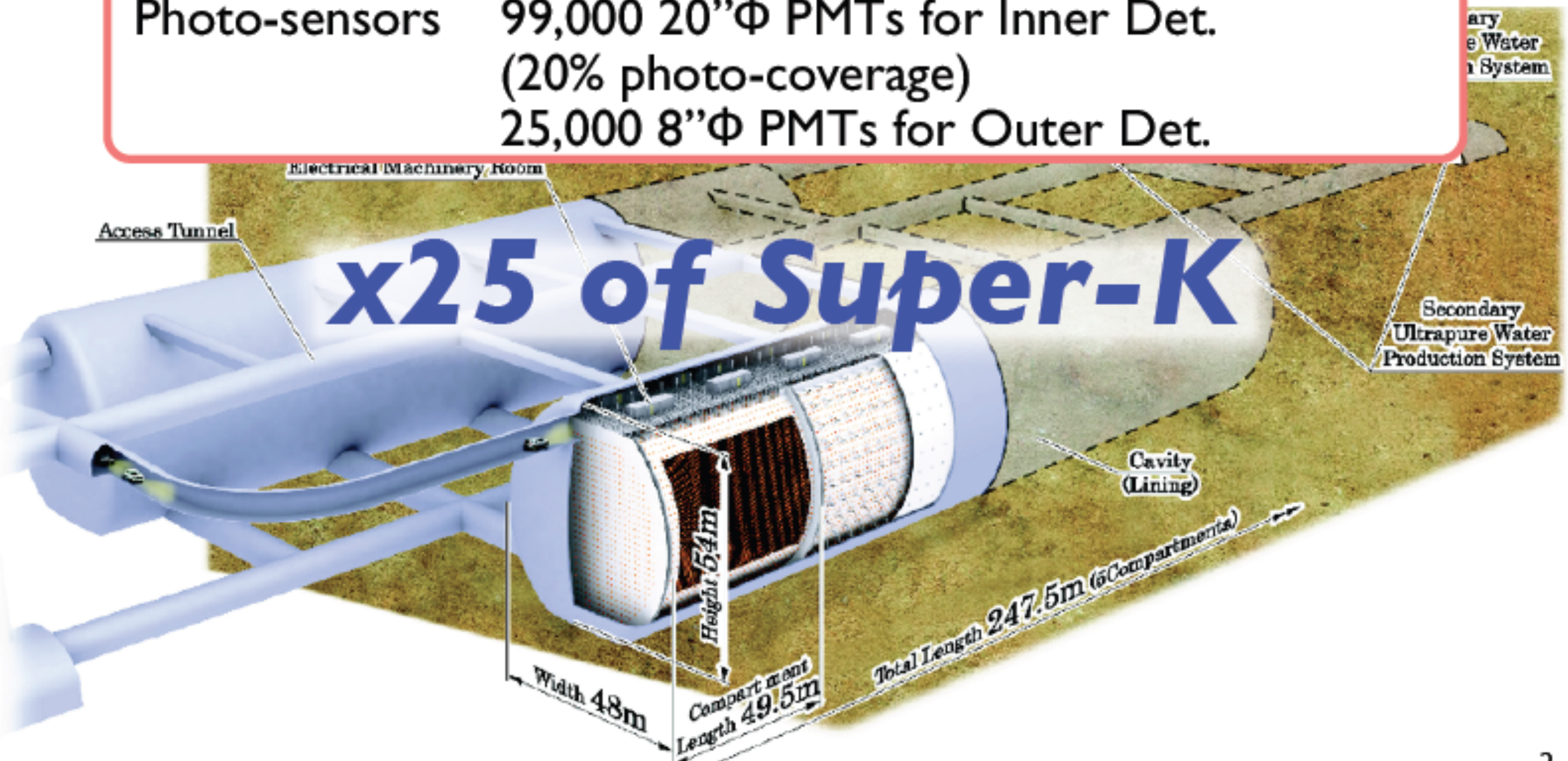






Hyper-Kamiokande

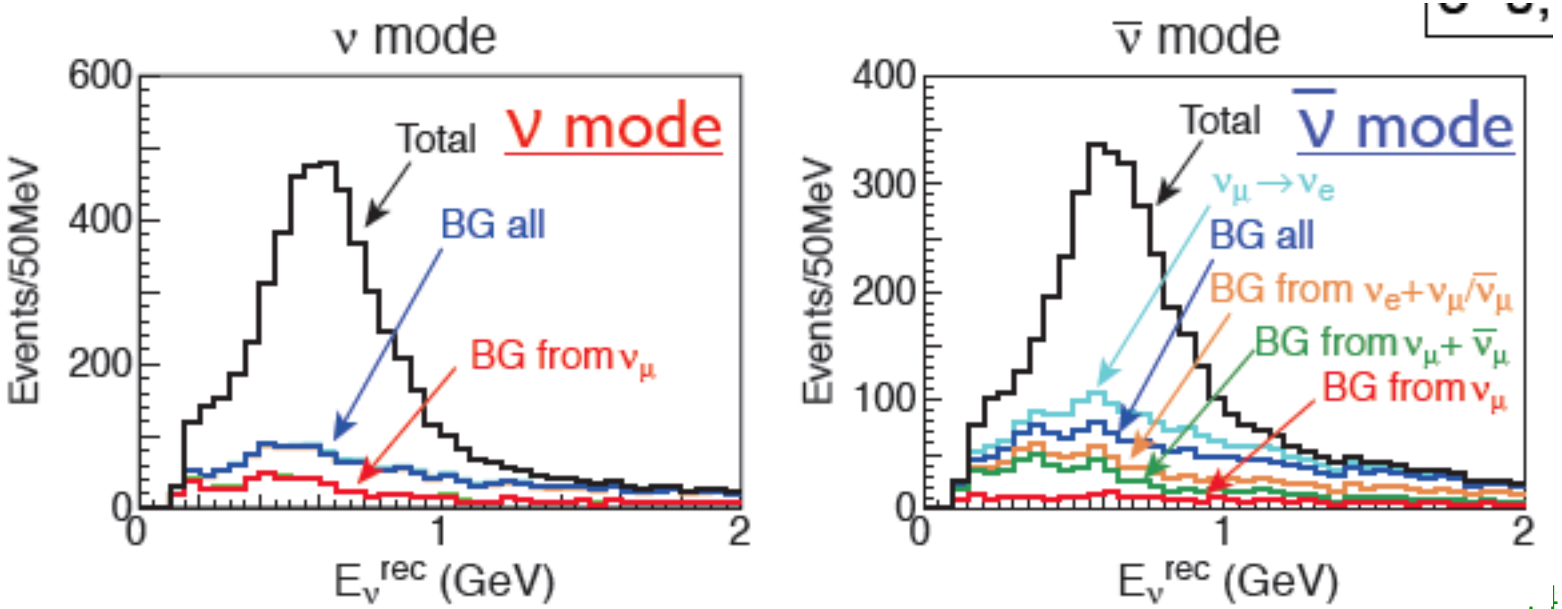
Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	99,000 20”Φ PMTs for Inner Det. (20% photo-coverage) 25,000 8”Φ PMTs for Outer Det.



Hyper-Kamiokande

- Tokai to Hyper-Kamiokande: 295 km baseline at 2.5º off-axis
  - Measure $\nu_\mu \rightarrow \nu_e$ oscillations:

	Signal ($\nu\mu \rightarrow \nu e$ CC)	Wrong-sign appearance	Beam $\nu\mu/\bar{\nu}\mu$ CC	Beam $\nu e/\bar{\nu}e$ CC	NC
ν-mode (0.75kW x 3yrs)	3,560	46	35	880	649
$\bar{\nu}$-mode (0.75kW x 7yrs)	1,959	380	23	878	678



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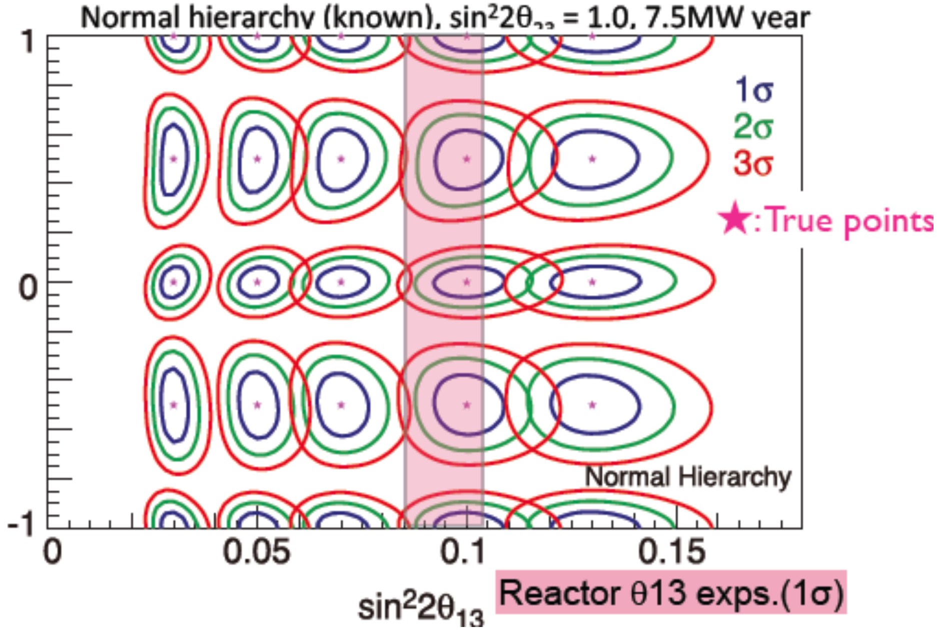
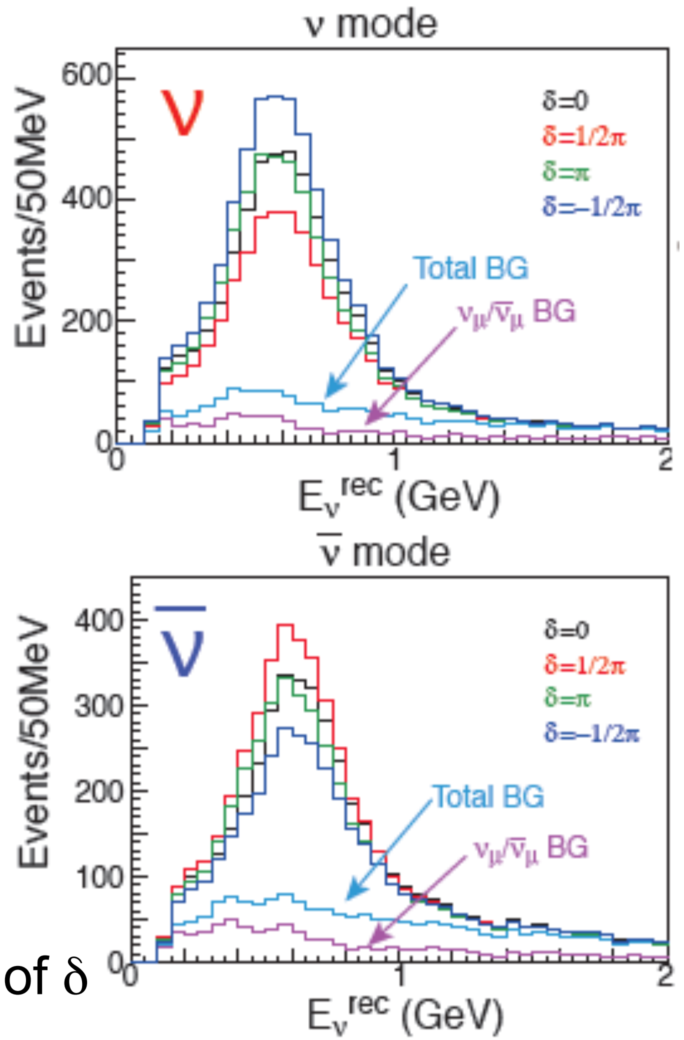


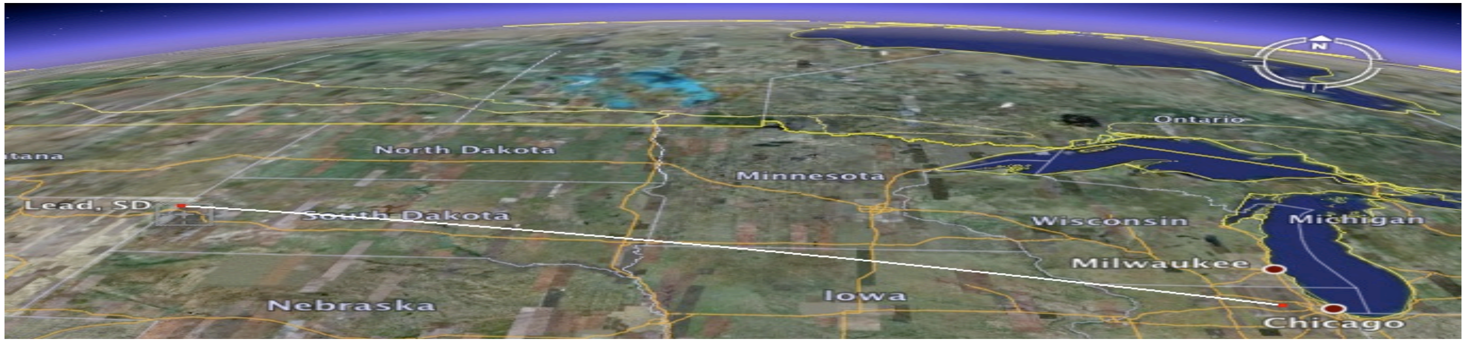
δ precision (1σ error size)
< 20° at δ=90°
< 10° at δ=0°

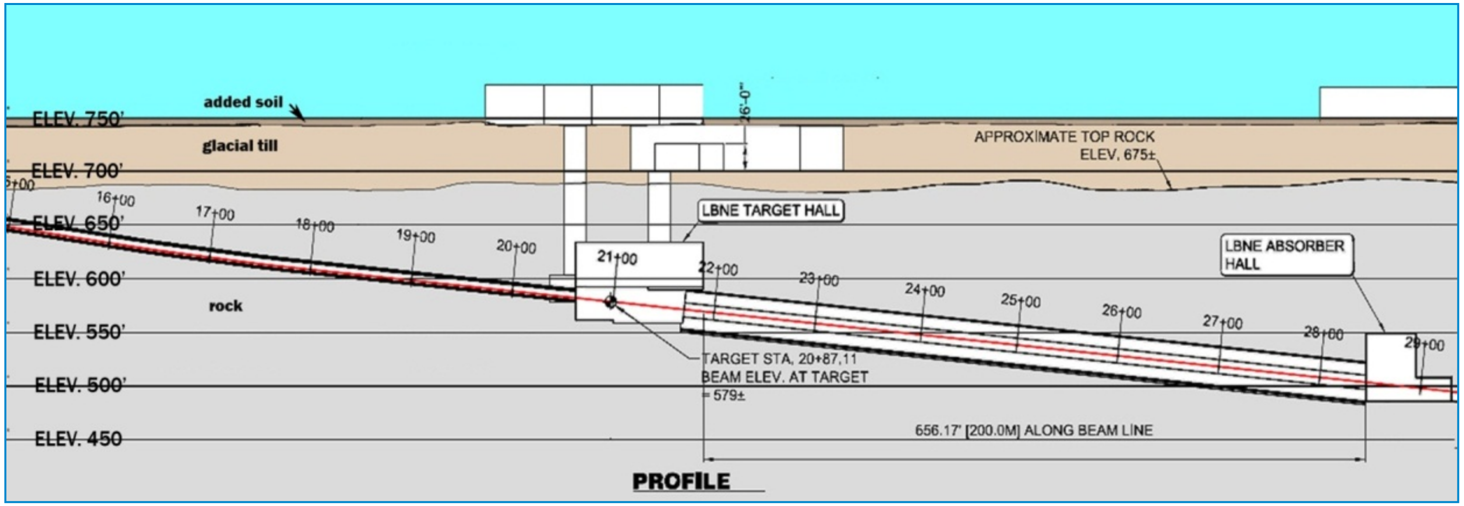


  - CPV discovery >3σ (5σ) in 74% (55%) of δ
  - Mass hierarchy and θ_{23} octant with >3σ

LBNE

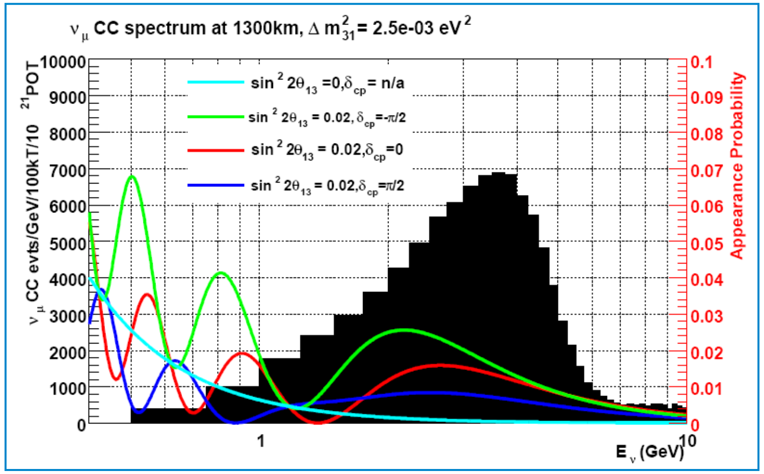
- Long Baseline Neutrino Experiment (LBNE): Fermilab-Sanford Lab, SD (formerly Homestake or DUSEL)
  - CD0 approval Jan 2010 – 1300 km

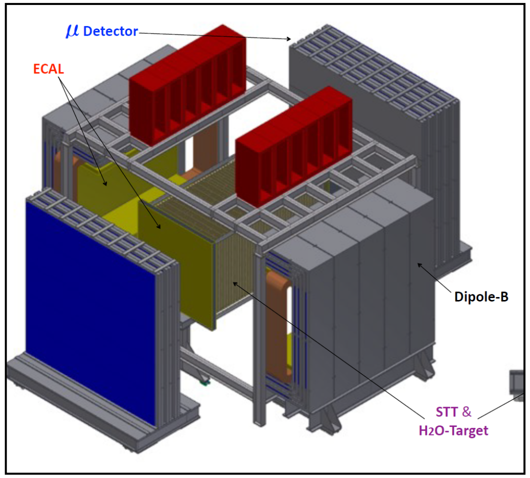


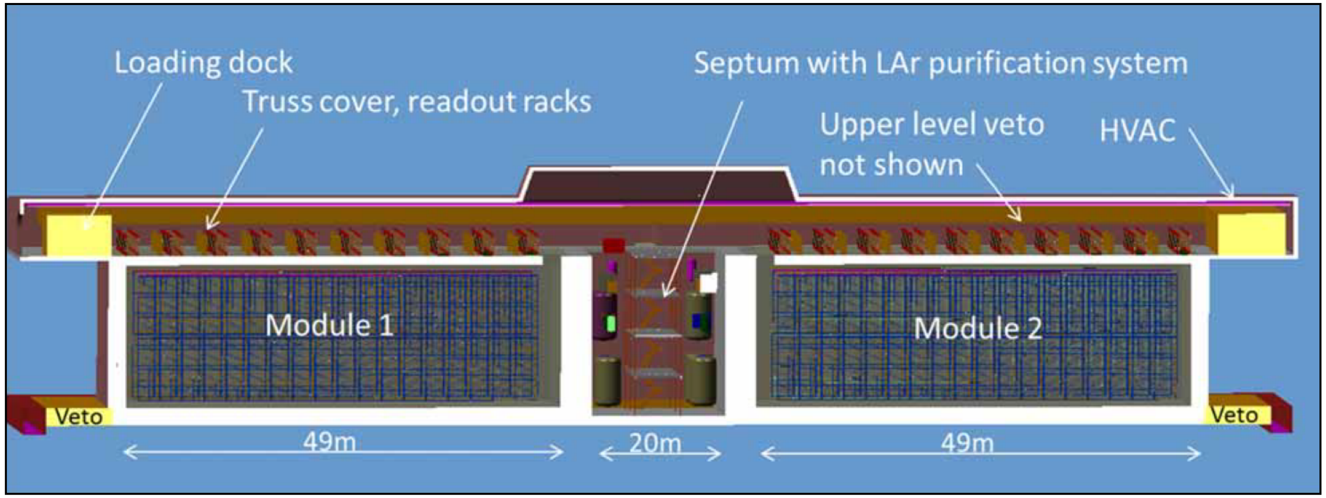


LBNE

- Long Baseline Neutrino Experiment (LBNE):
  - Wide band beam: multiple oscillation maxima ν_e appearance
  - Far detect: 34 kton Liquid Argon TPC
  - Fine grained near detector







LBNE

- Long Baseline Neutrino Experiment (LBNE):
  - For cost reasons, needs to be staged: 10 kton Liquid Argon
  - Measure $\nu_\mu \rightarrow \nu_e$ oscillations: goal is mass hierarchy and CP

10 kt:	Signal Events	Background Events				
	ν_e	ν_μ NC	ν_μ CC	ν_e Beam	ν_τ CC	Total
Neutrino Normal Hierarchy	222	19	24	42	14	99
Neutrino Inverted Hierarchy	98	19	23	44	15	100
Anti-neutrino Normal Hierarchy	54	11	11	23	9	54
Anti-neutrino Inverted Hierarchy	80	11	11	23	9	54

LBNE

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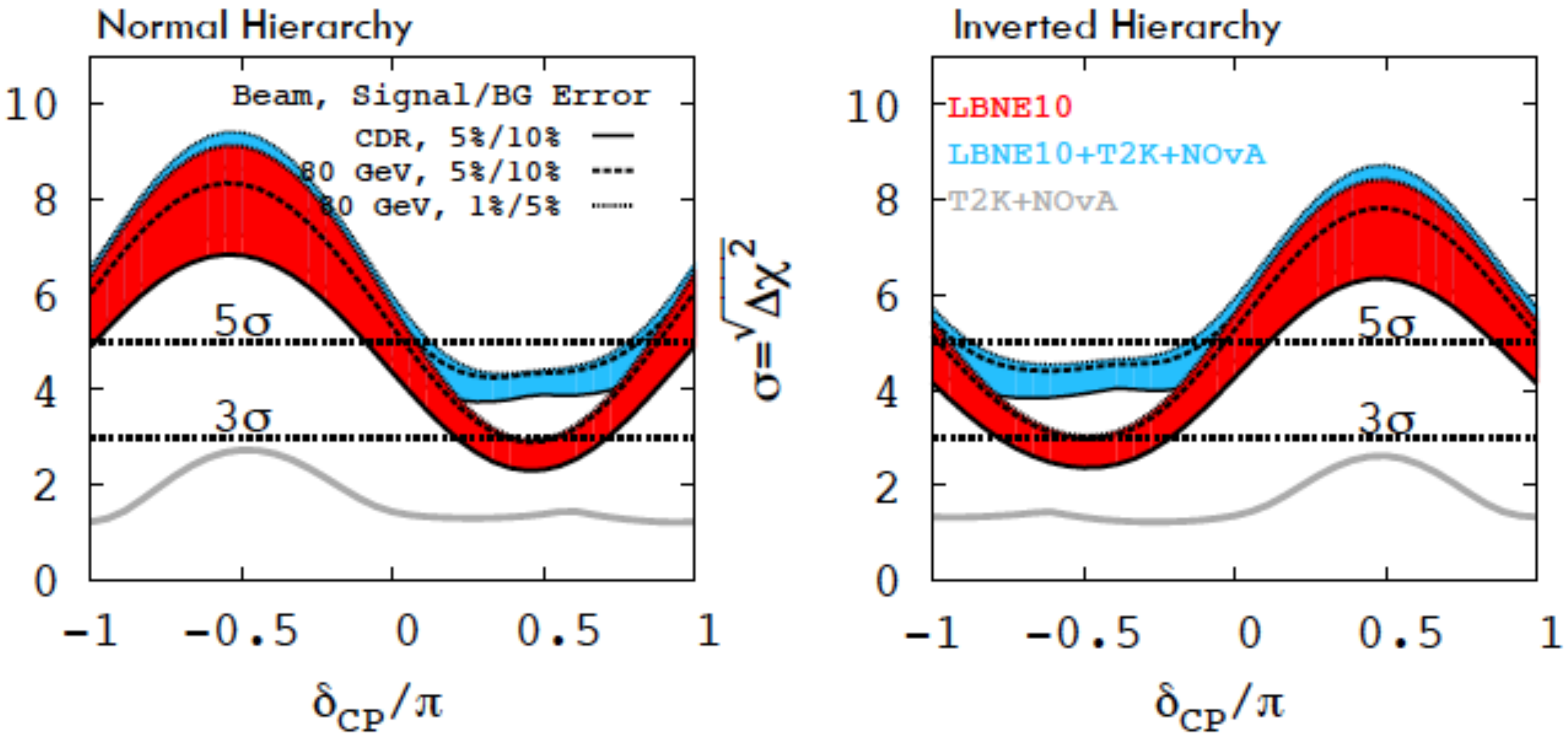

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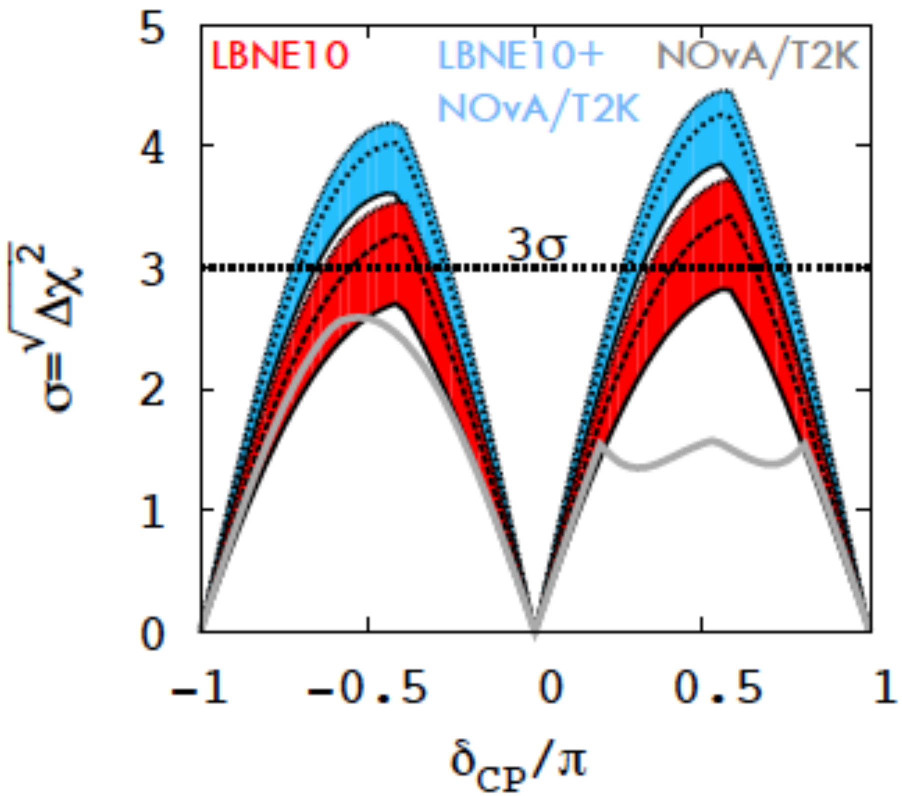
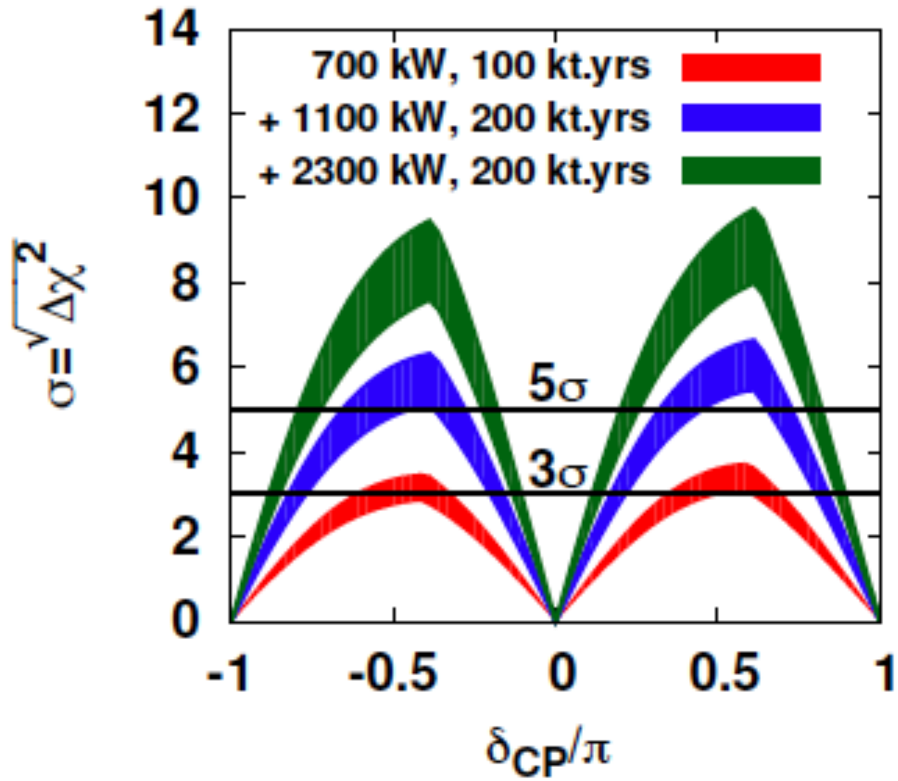
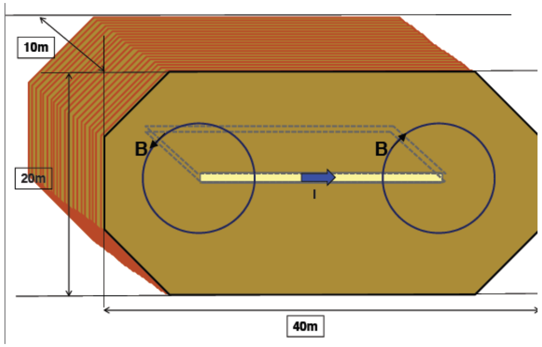
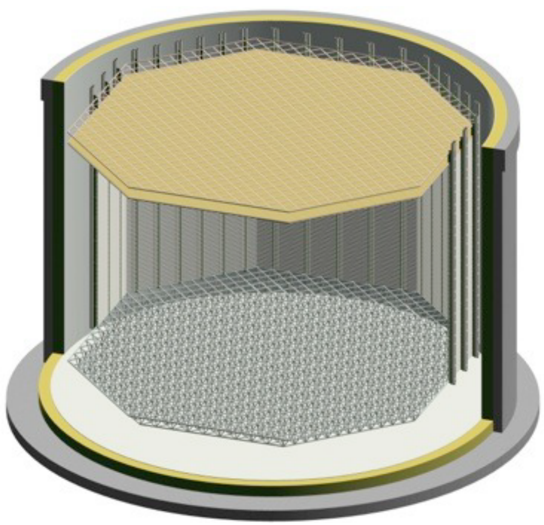


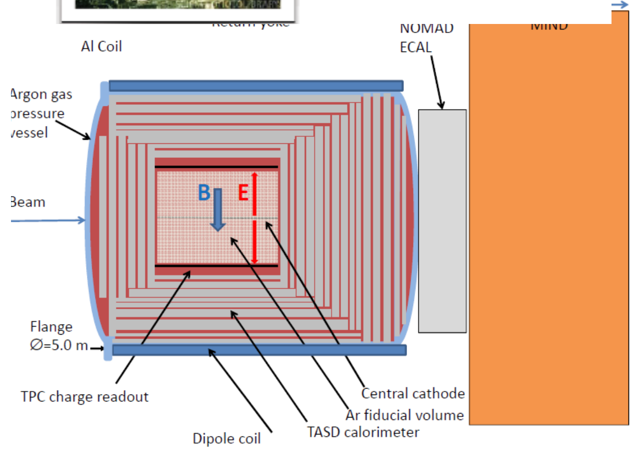


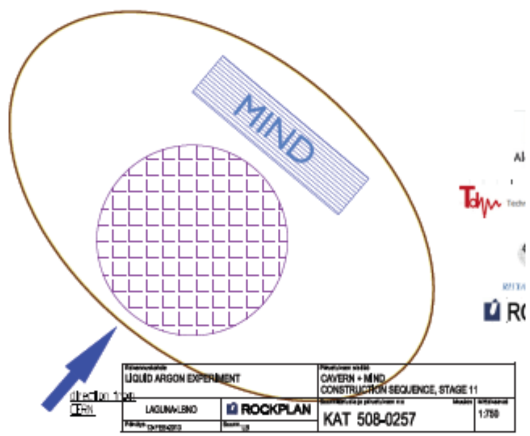
LBNO in Europe

- Similar to LBNE, with 20-100 kton Liquid Argon and Magnetised Iron Neutrino Detector (MIND) for muon catcher
- CERN-Pyhasalmi (Finland): 2300 km
- Near detector: high pressure gas LAr TPC





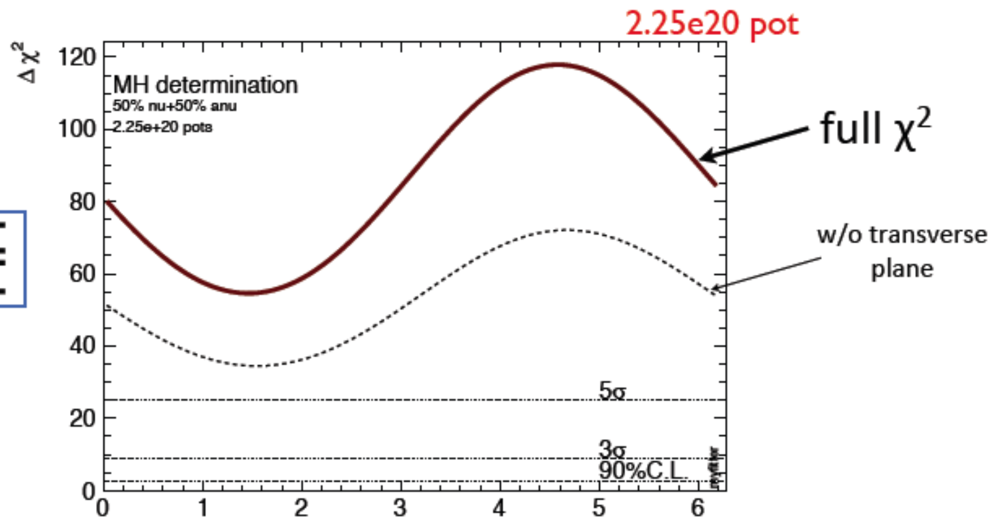


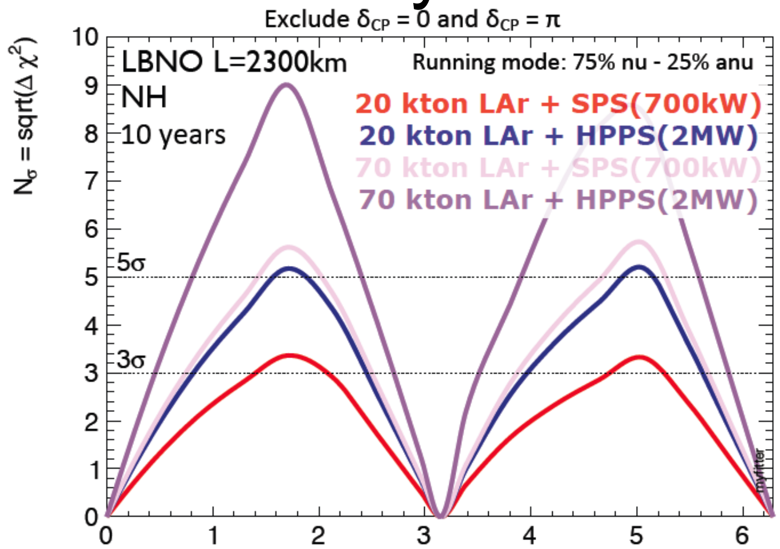


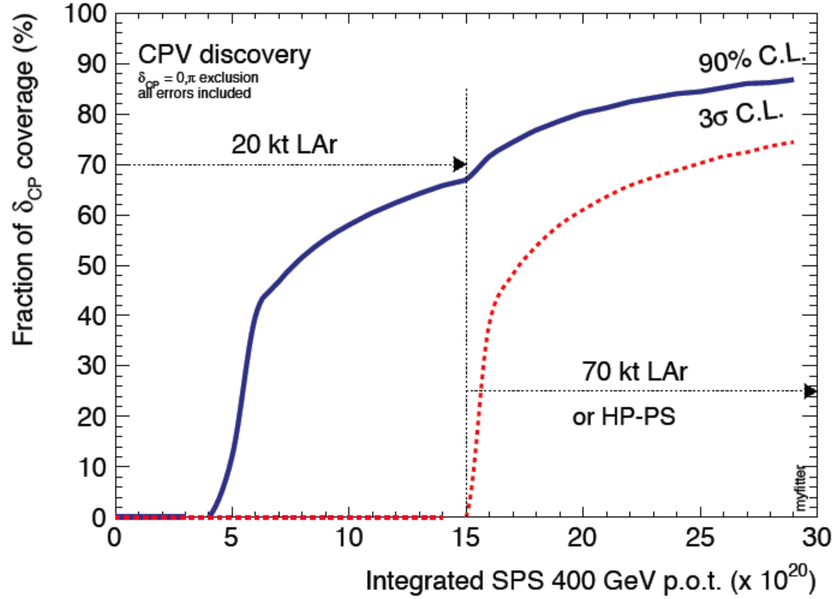
LBNO in Europe

- Mass hierarchy and CP violation sensitivity of LBNO

MH



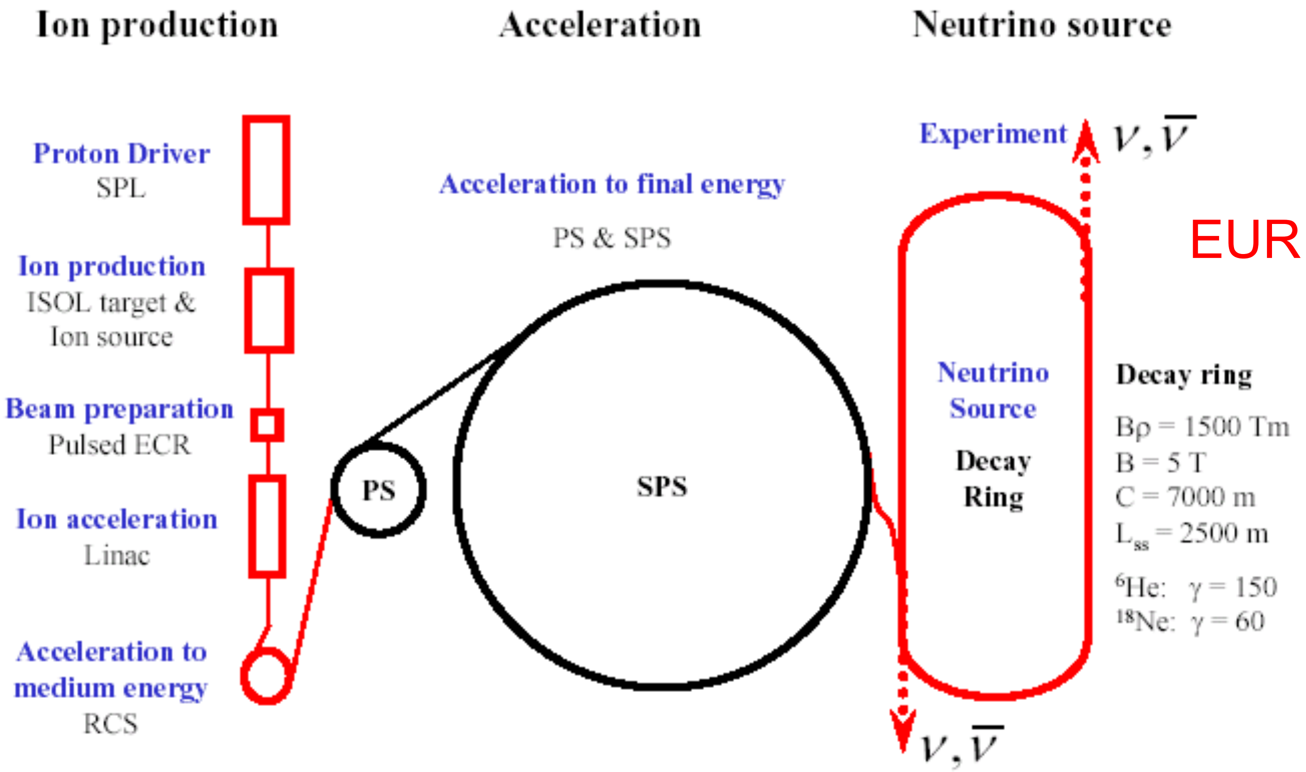




4.2 Beta Beam experiments: beams from the decay of radioactive isotopes

Beta beam

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



EURISOL study

Beta beam

- New beta beam study during EUROnu study

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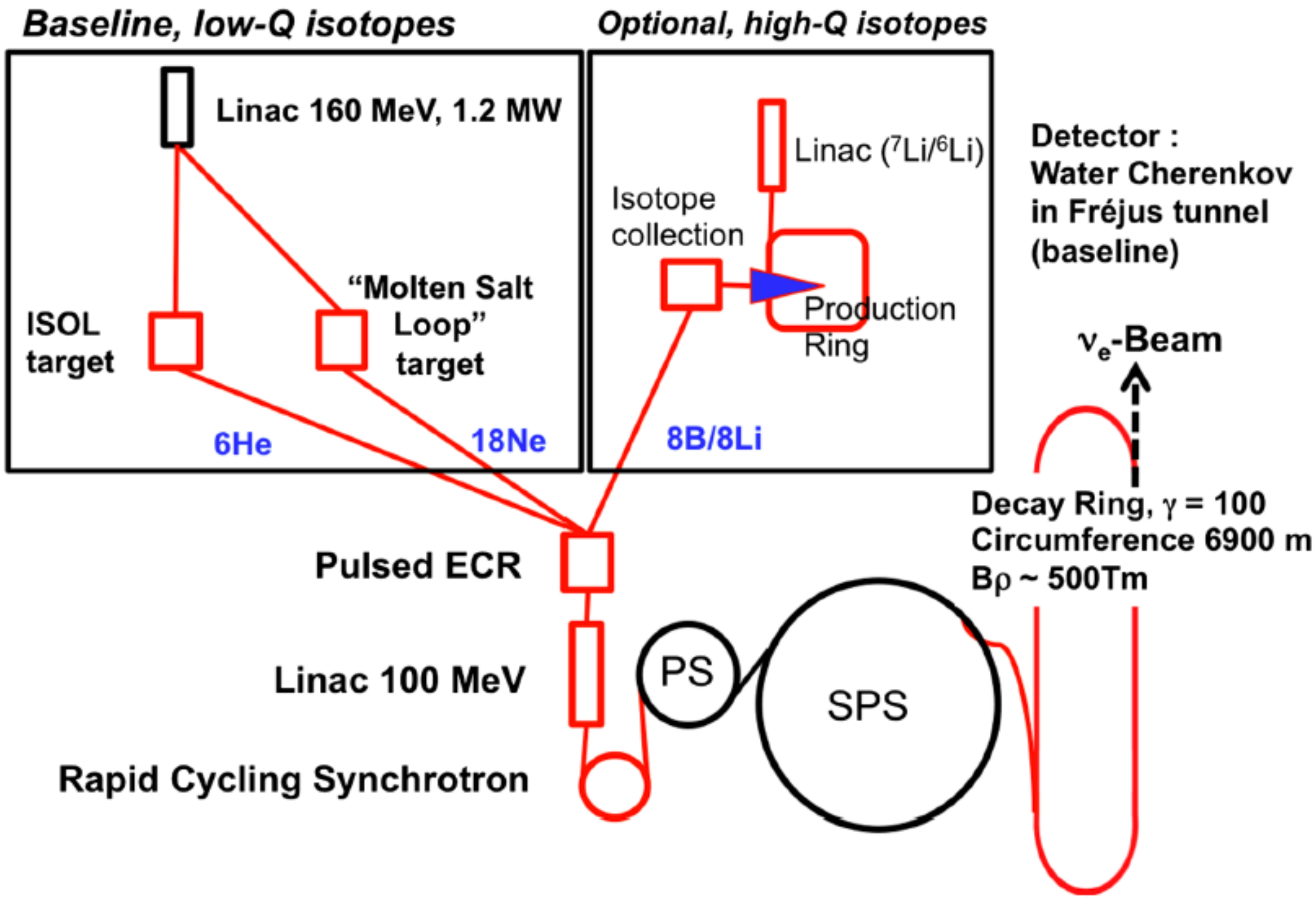
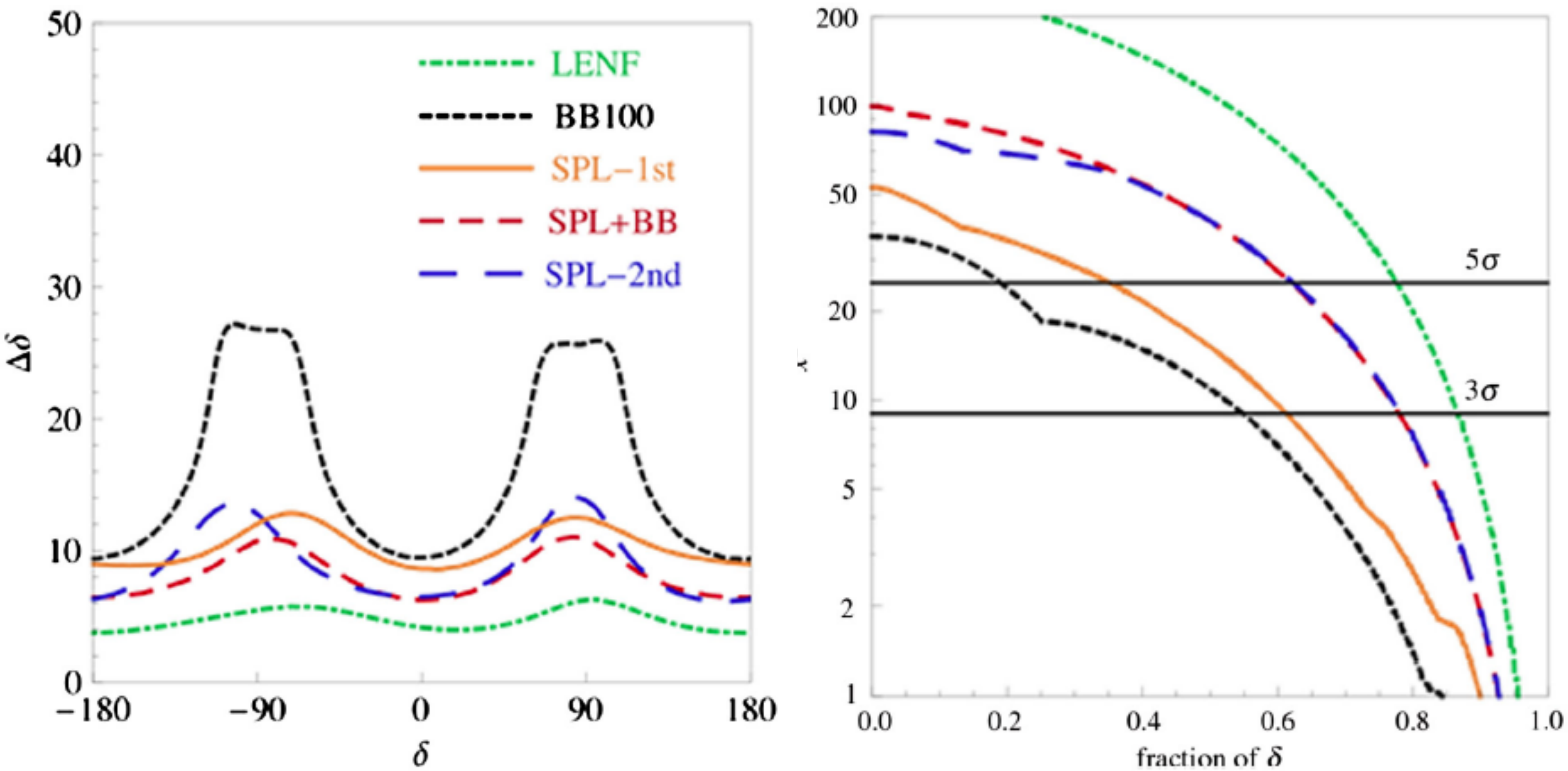


Beta beam

- Use the 572 kton MEMPHYS water Cherenkov at Frejus
- Coverage of δ_{CP}:

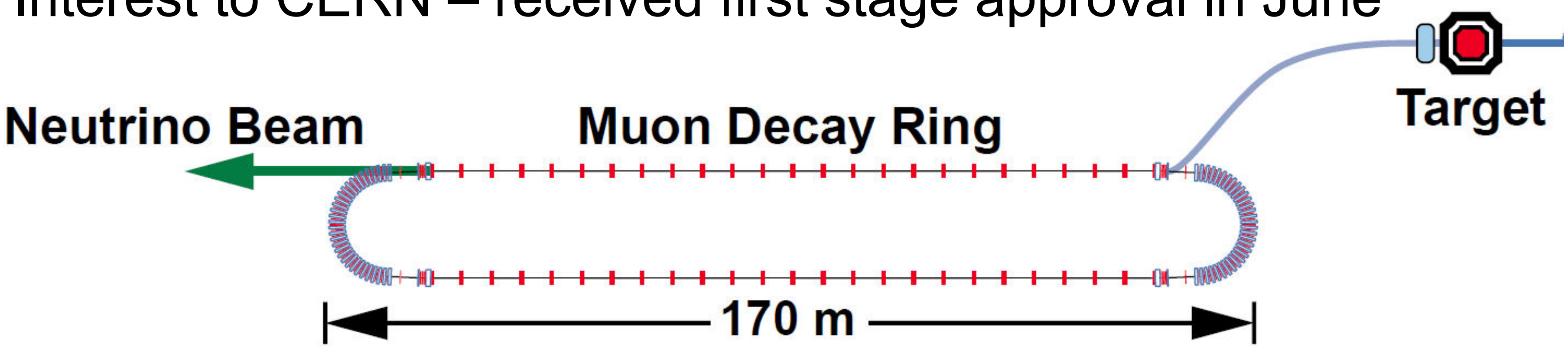


- Performance improves by comlementing with Super Beam data: neutrino factory (LENF) has best sensitivity

4.4 nuSTORM: neutrinos from stored muons

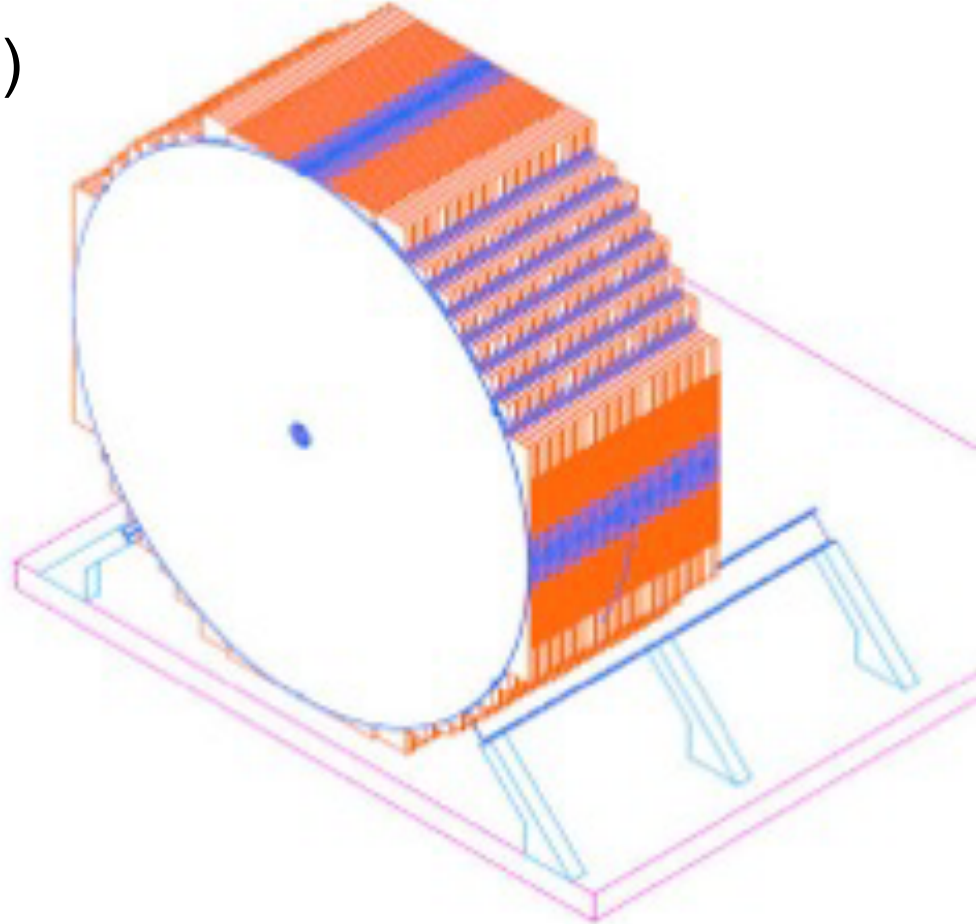
nuSTORM

- First mini-Neutrino Factory could be nuSTORM (Neutrinos from Stored Muons) – 3.8 GeV muons
- Physics goals: sterile neutrino search, cross-section measurement and R&D for Neutrino Factory, facility where a 6D ionization cooling experiment could be carried out for muon collider
- Letter of Intent and Proposal to Fermilab, Expression of Interest to CERN – received first stage approval in June



nuSTORM

- Magnetised iron (Super BIND) far detector
- Scintillator-iron calorimeter
- Far detector: 1.3 kton at 2 km
- Near detector: 200 ton
- Magnetic field: 1.5-2.6 T
- Current = 240 kA by STL

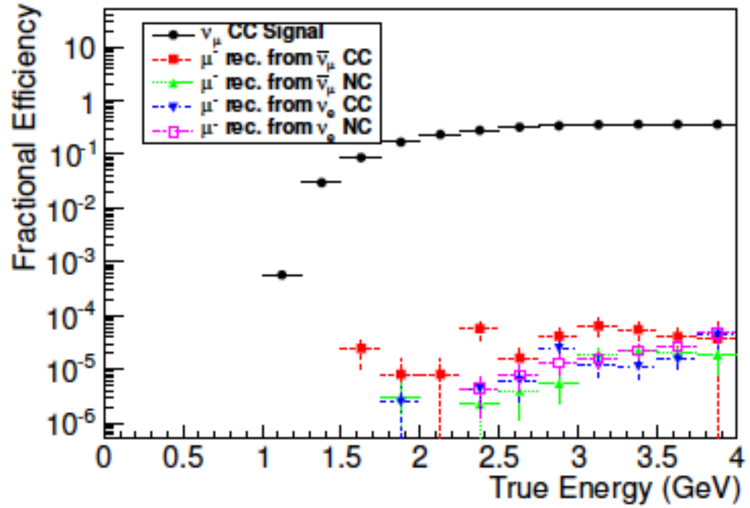


nuSTORM

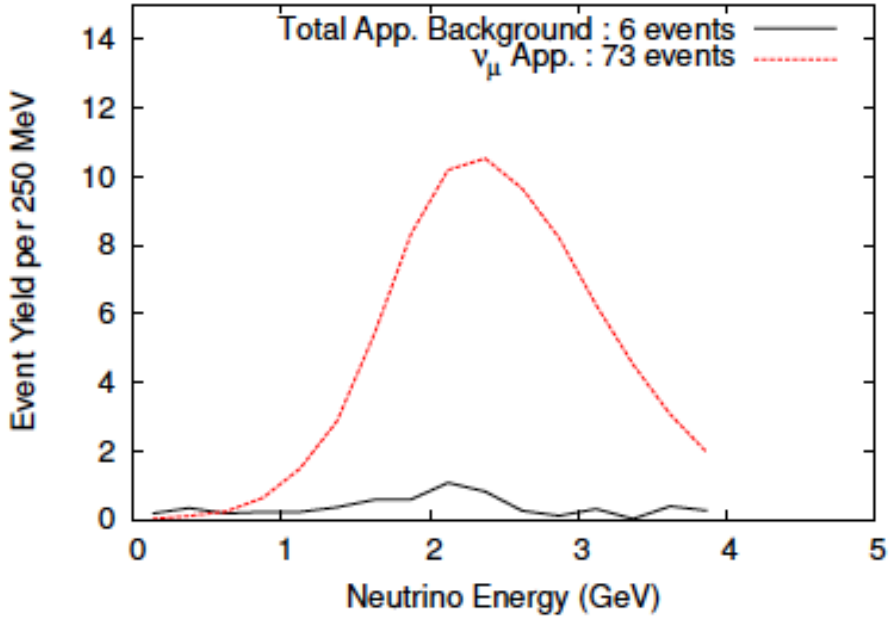
- Performed appearance and disappearance analyses:

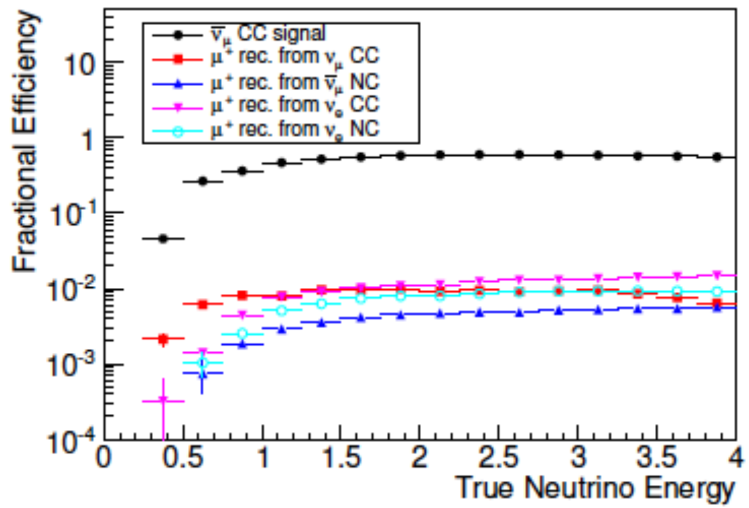
$$P_{\nu_e \nu_\mu}(x) = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\left(\frac{m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{e\mu})\sin^2\left(\frac{m_{14}^2 x}{4E}\right)$$

$$P_{\mu\mu}(x) = 4|U_{\mu 4}|^2\left(1-|U_{\mu 4}|^2\right)\sin^2\left(\frac{m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{\mu\mu})\sin^2\left(\frac{m_{14}^2 x}{4E}\right)$$



(a)Appearance efficiencies





(b)Disappearance efficiencies

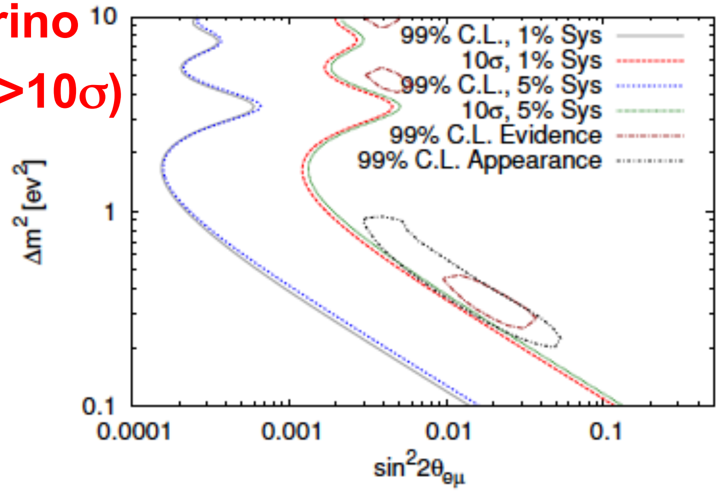
nuSTORM

- Performed appearance and disappearance analyses:

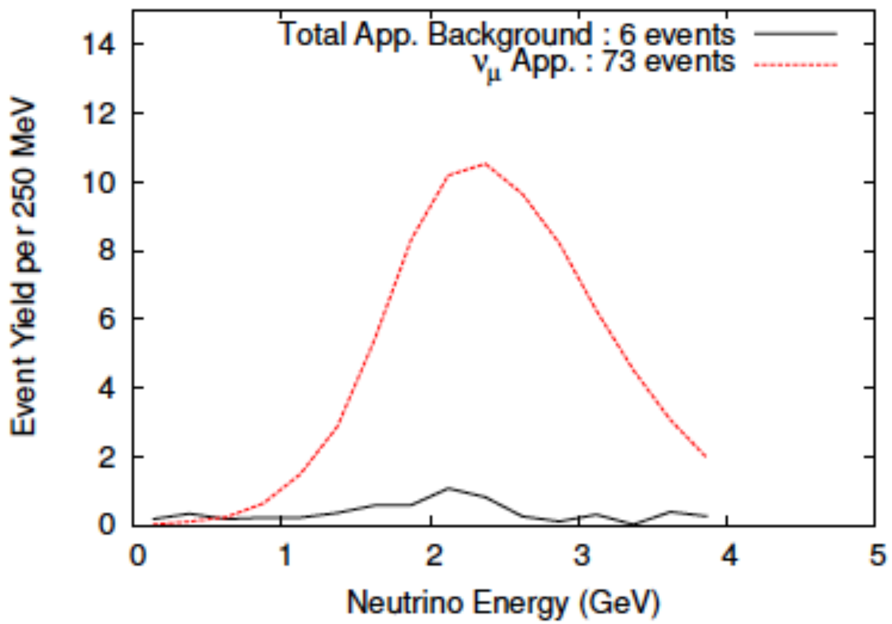
Sterile neutrino Sensitivity (>10σ)

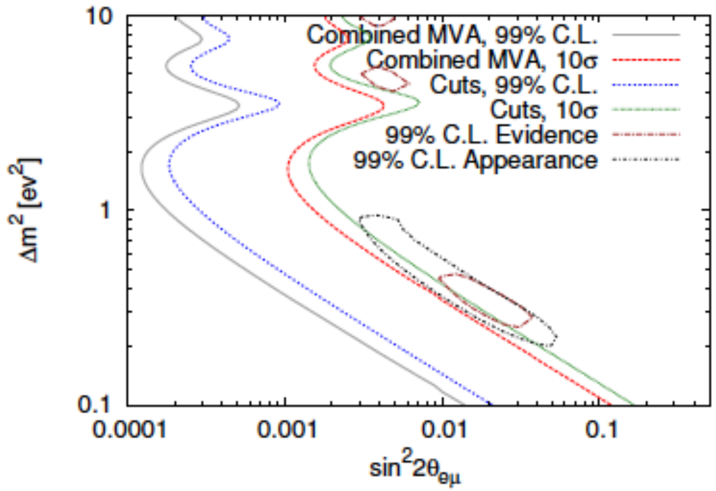
$$P_{\nu_e \nu_\mu}(x) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{e\mu})\sin^2\left(\frac{m_{14}^2 x}{4E}\right)$$

$$P_{\mu\mu}(x) = 4|U_{\mu 4}|^2\left(1-|U_{\mu 4}|^2\right)\sin^2\left(\frac{m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{\mu\mu})\sin^2\left(\frac{m_{14}^2 x}{4E}\right)$$



(a) Sensitivity of appearance experiment using BDT analysis.





(b) Sensitivities of appearance experiment using cuts-based analysis and of a combined experiment with MVA methods.

4.5 Neutrino Factory: the ultimate neutrino facility

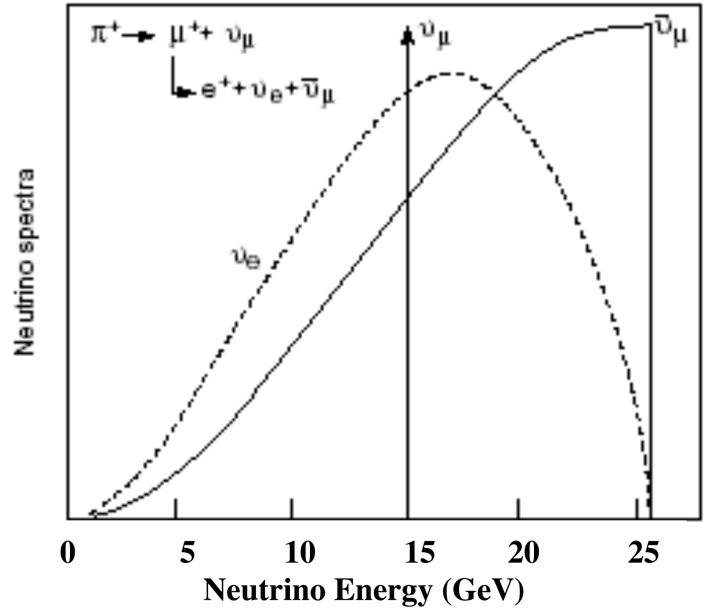
Neutrino Factory

- 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:



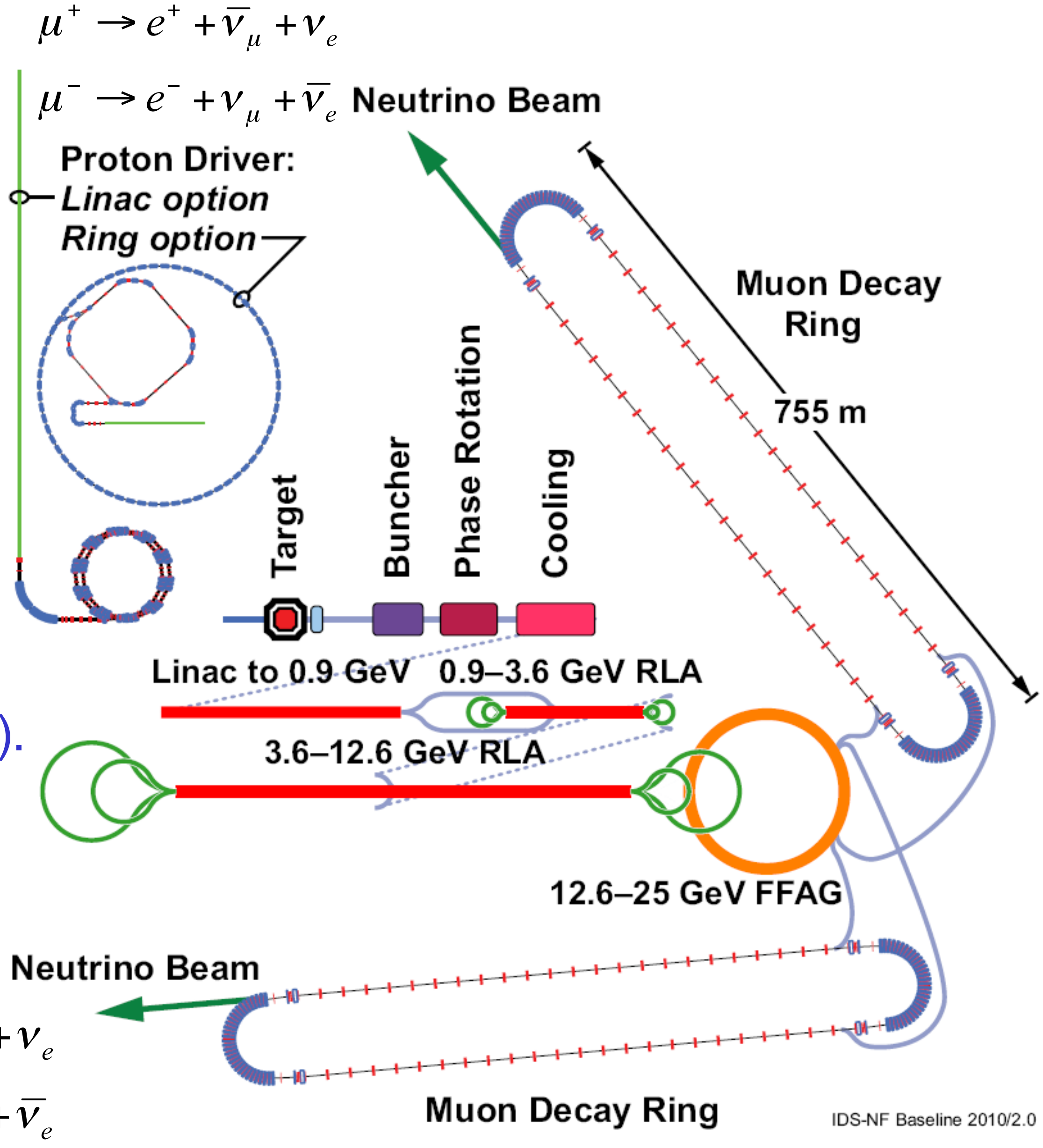
- Defines detector requirements:
  - Since muon and electron neutrino and anti-neutrino species are produced simultaneously we need to determine the charge and lepton identity to separate from background $\rightarrow$ Magnetic detectors.

International Design Study

- International Design Study for a Neutrino Factory (IDS-NF)
  - Principal objective: deliver Reference Design Report by 2013
    - Physics performance of the Neutrino Factory
    - Specification of each of the accelerator, diagnostic, and detector systems that make up the facility
    - Schedule and cost of the Neutrino Factory accelerator, diagnostics, and detector systems.
  - Co-sponsored by EU through EUROnu
  - Web site: **https://www.ids-nf.org/wiki/FrontPage**
- Interim Design Report: IDS-NF-020 **arXiv:1112.2853** delivered 2011
- Reference Design Report that itemises facility, accelerator and detector performance and physics reach will be published by the end of the year

Neutrino Factory

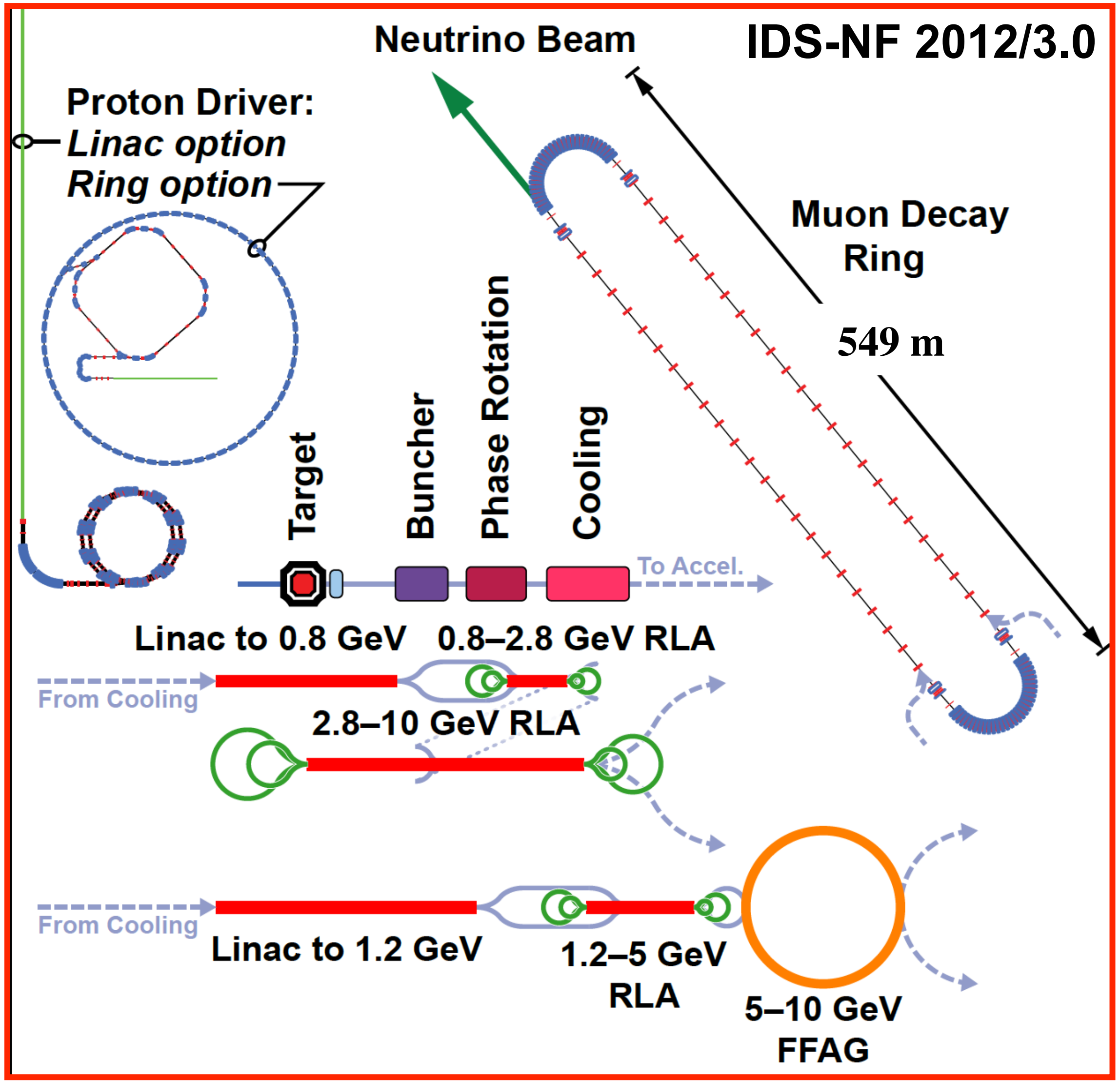
- Before θ_{13} discovery, baseline design for a Neutrino Factory had two storage rings and energy was 25 GeV
- Two different detectors at two different baselines to reduce ambiguities in θ_{13} vs δ fits
- One baseline was ~3000 km and the other was ~7500 km (magic baseline).



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

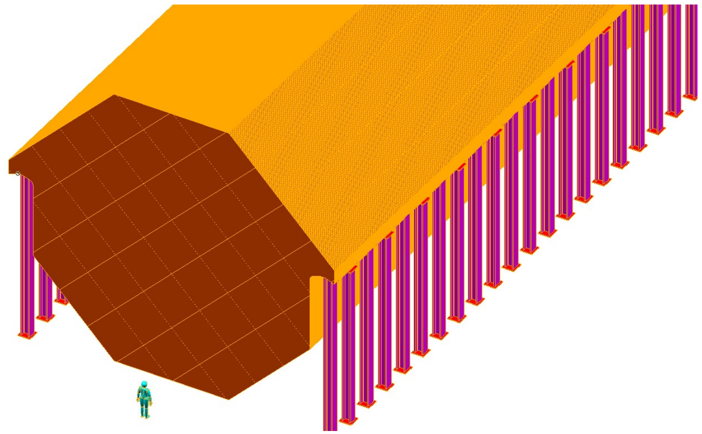
$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$$

Neutrino Factory Baseline



Baseline reviewed last year: from 25 GeV to 10 GeV muons and only one storage ring with detector at ~2000 km, due to large θ_{13} results

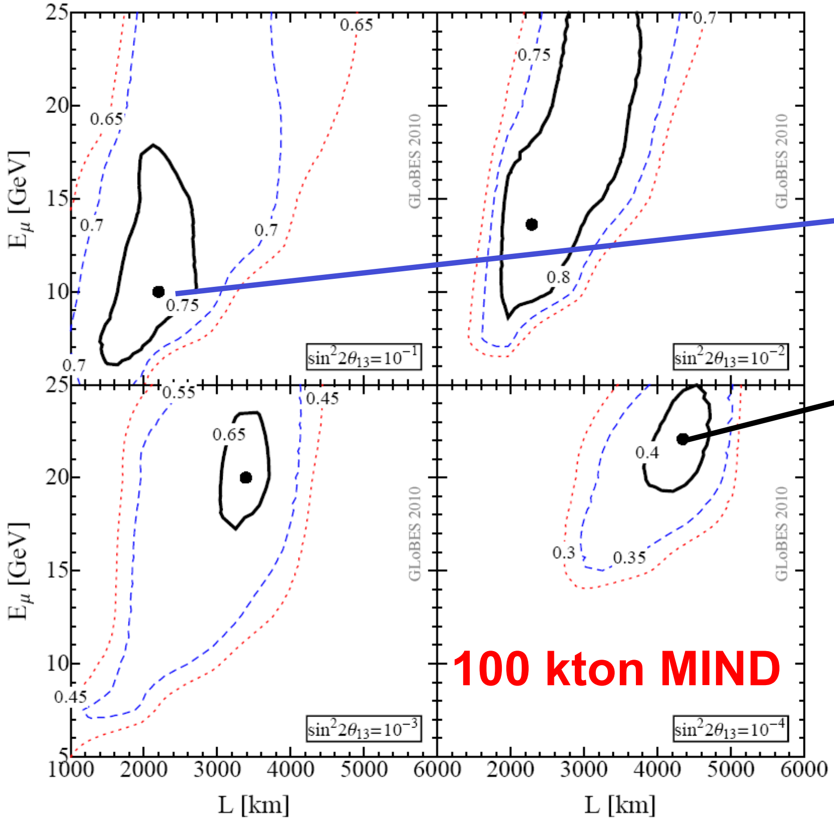
- Magnetised Iron Neutrino Detector (MIND):
  - 100 kton at ~2000 km

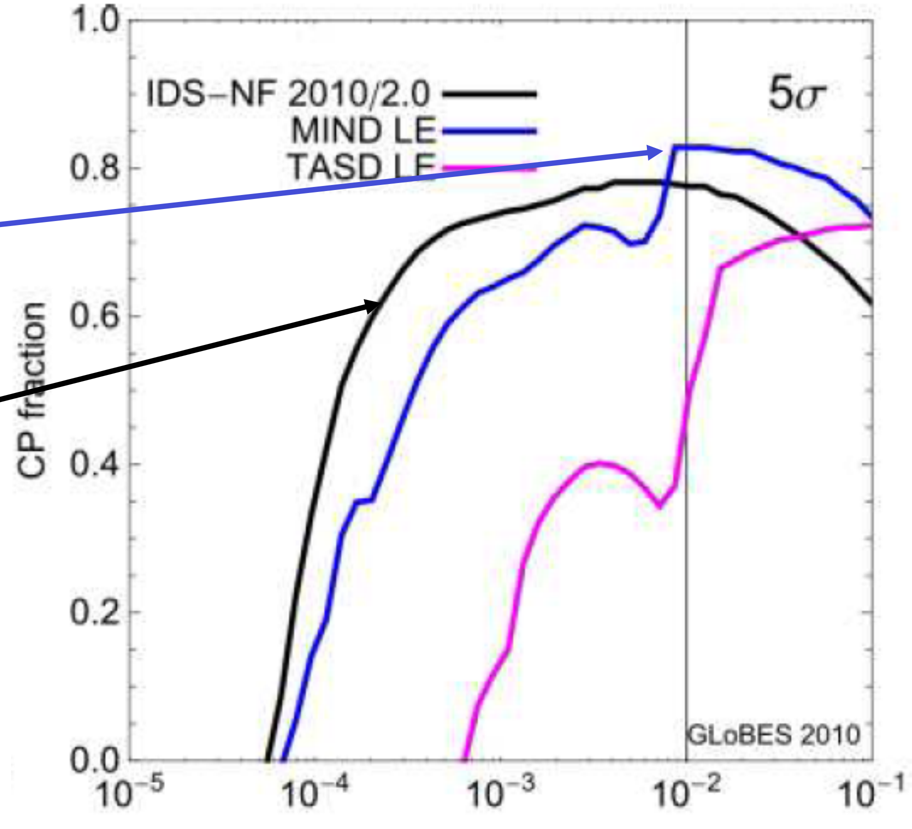


Optimisation of Neutrino Factory

- Optimisation for high θ_{13}: only one baseline

Contours of CP coverage



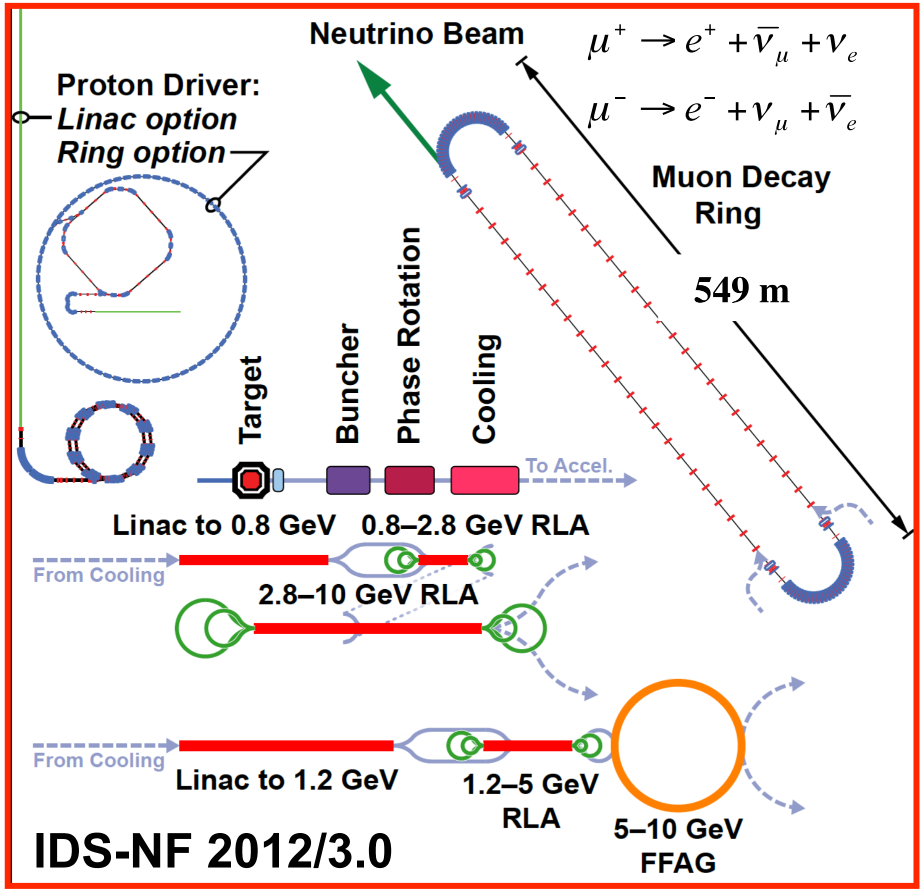


For small θ_{13}: Energy ~25 GeV, Baseline ~4000 km

For large θ_{13}: Energy 10 GeV, Baseline ~2000 km

Neutrino Factory Baseline

- Proton driver
  - Proton beam ~8 GeV on target
- Target, capture and decay
  - Create π, decay into μ (MERIT)
- Bunching and phase rotation
  - Reduce ΔE of bunch
- Cooling
  - Reduce transverse emittance (MICE)
- Acceleration
  - 120 MeV→ 10 GeV with RLAs or additional FFAG (EMMA)
- Decay ring
  - Store for ~100 turns
  - Long straight sections

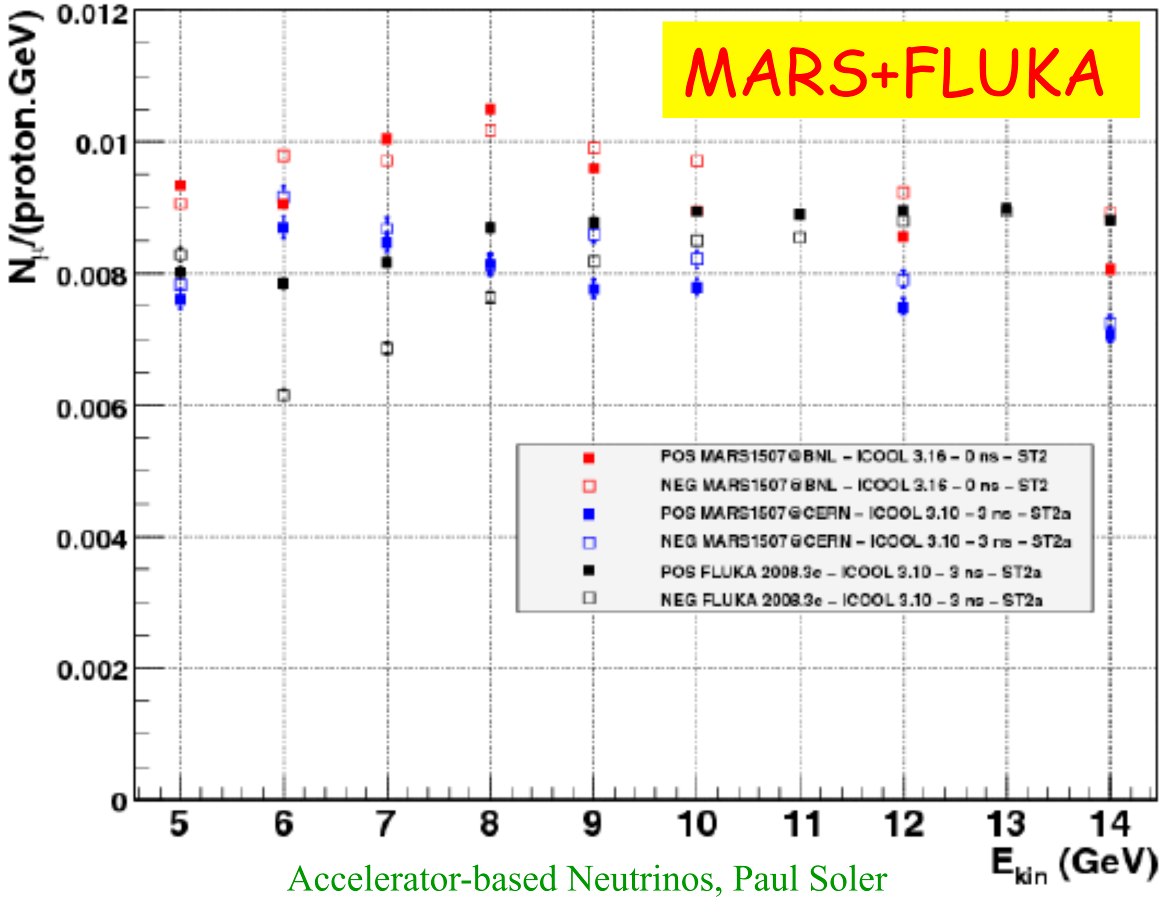


Optimum energy proton driver

- Optimum beam energy

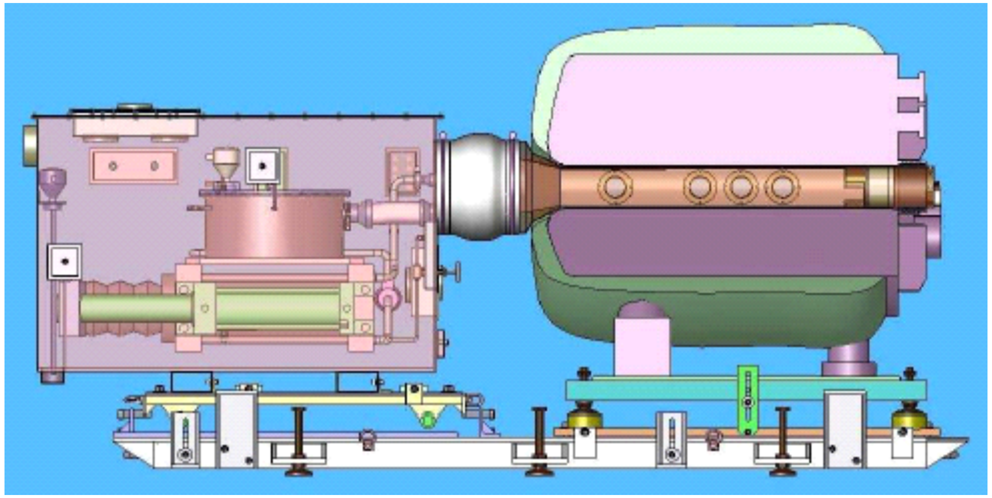
Adopted 10 ± 5 GeV

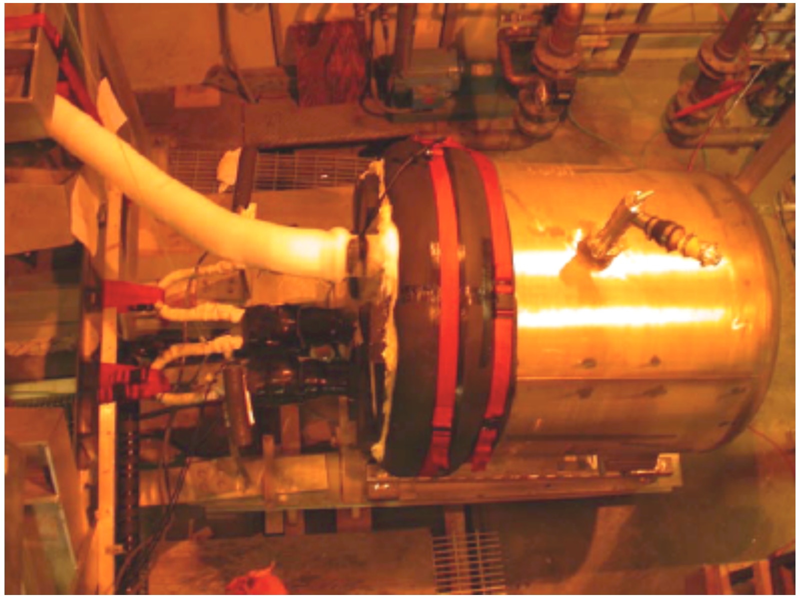
  - Depends on choice of target
  - Optimum energy for high-*Z* targets around 8 GeV
  - Results validated by HARP hadron production experiment



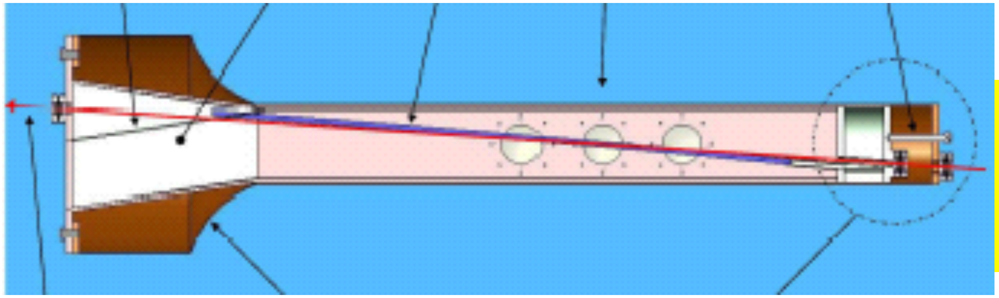
Target R&D: MERIT

- MERIT experiment tested Hg jet in 15-T solenoid
  - 24 GeV proton beam from CERN PS
    - Ran Autumn 2007





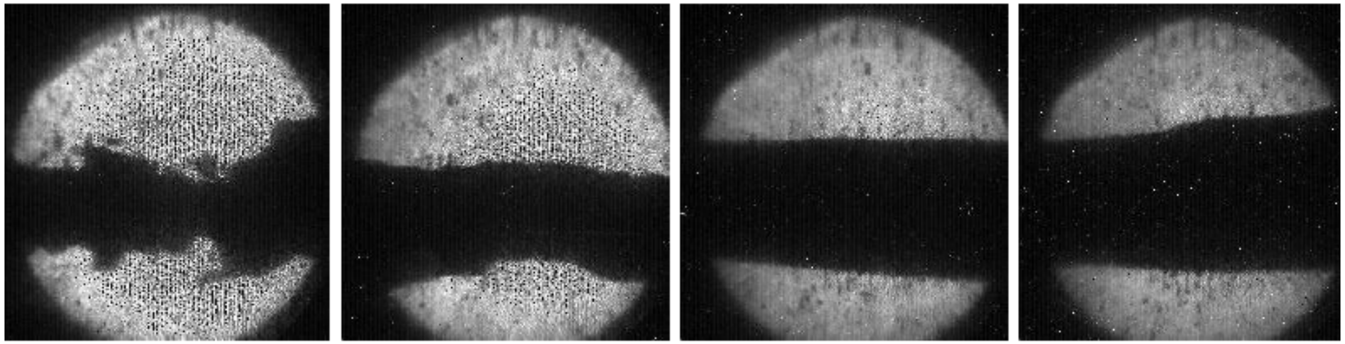
15-T solenoid during tests at MIT



MERIT experiment showed proof-of-principle of Hg jet system in magnetic field – rated up to 8 MW

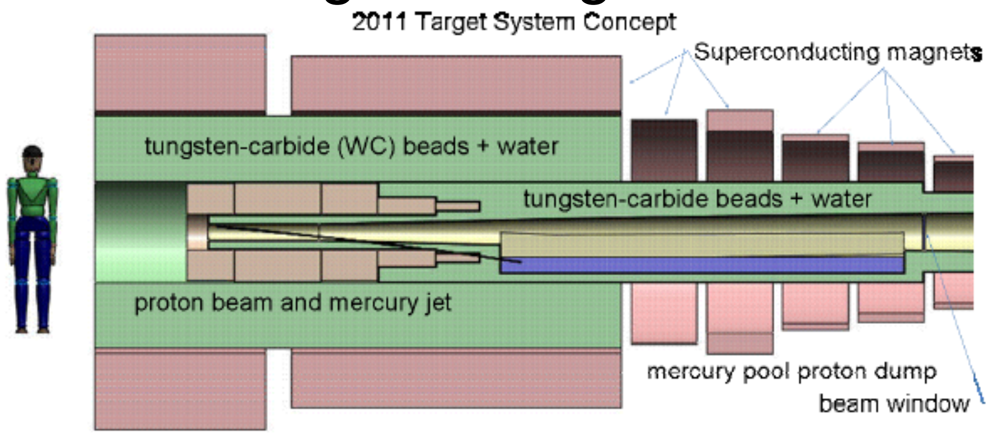
MERIT and Target

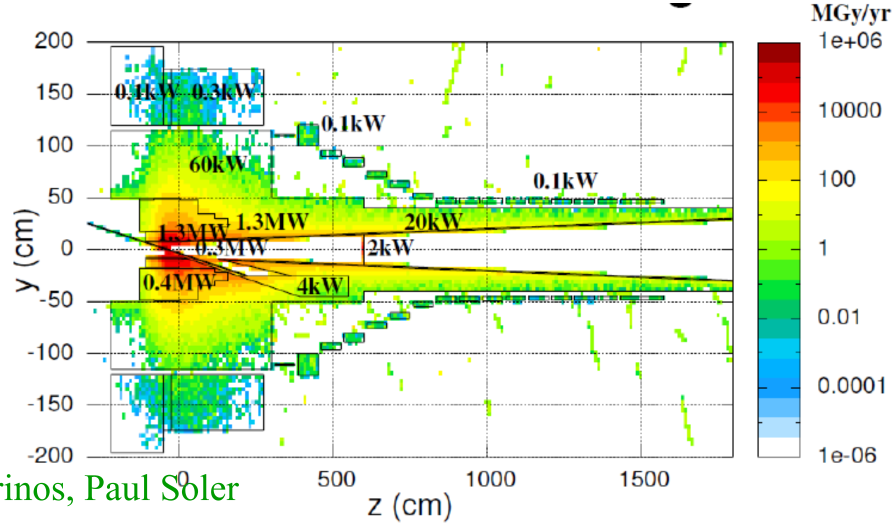
- Results MERIT:
  - Hg jet target operated at 8 MW in 15 T magnetic field with v=15 m/s



0T 5 T 10 T 15 T

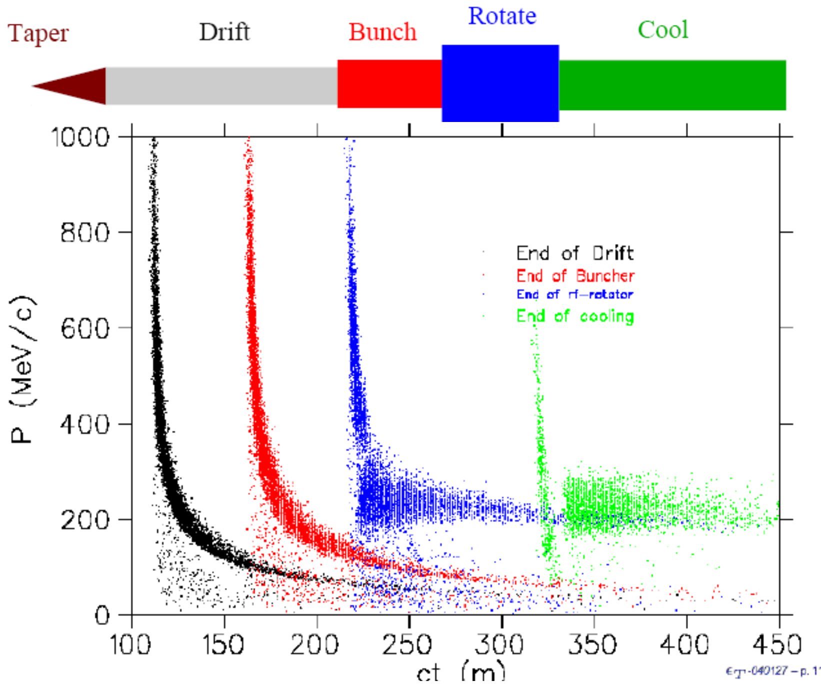
- Had to increase radiation shielding in solenoid surrounding new design for target station

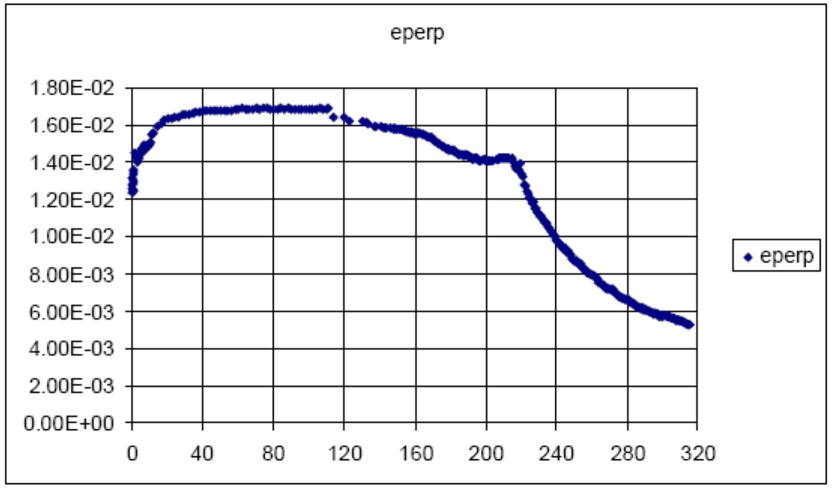




Muon Front End

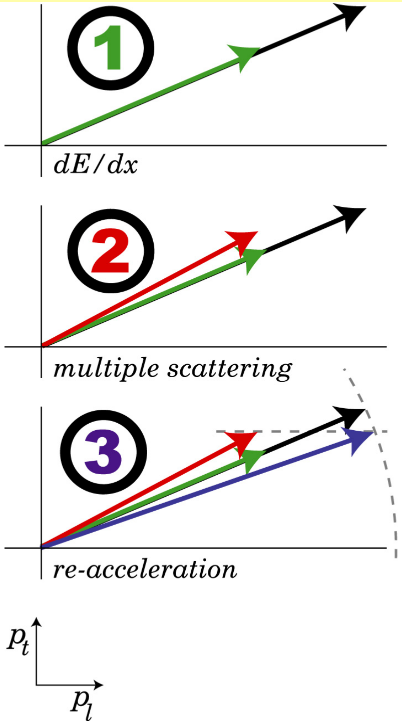
- Adiabatic B-field taper from Hg target to longitudinal drift
- Drift in ~1.5 T, ~100 m solenoid
- Adiabatically bring on RF voltage to bunch beam
- Phase rotation using variable frequencies
  - High energy front sees -ve E-field
  - Low energy tail sees +ve E-field
  - End up with smaller energy spread
- Ionisation Cooling
  - Try to reduce transverse beam size
  - Prototyped by MICE



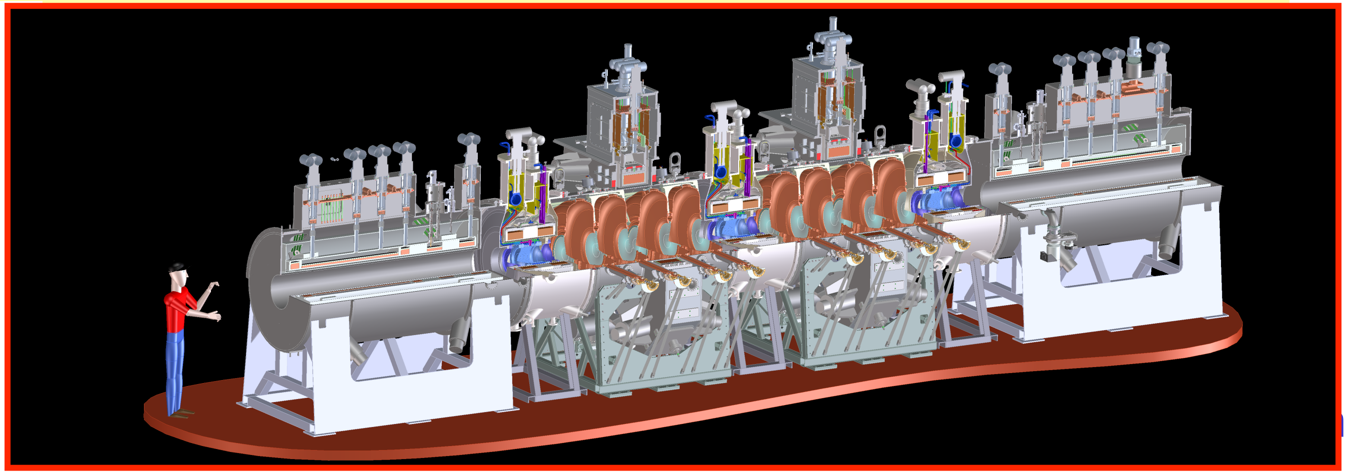


Ionization Cooling

Principle



Practice



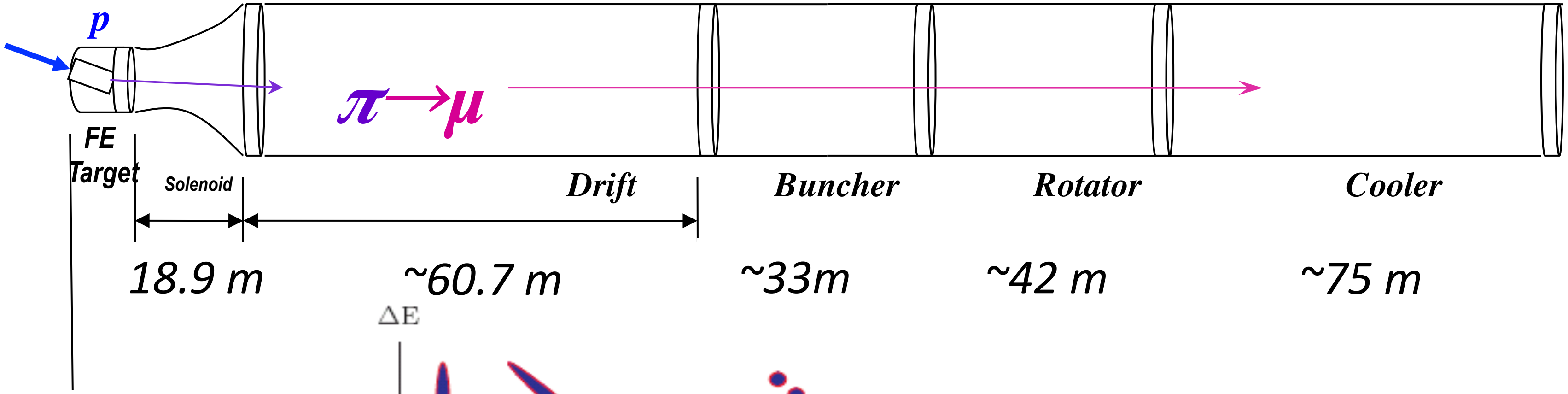
$$\frac{d\varepsilon}{dz} \approx -\frac{\varepsilon}{E_\mu \beta^2}\frac{dE_\mu}{dz} + \frac{\beta_\perp}{2m\beta^3}\frac{(13.6\,MeV)^2}{E_\mu X_0}$$

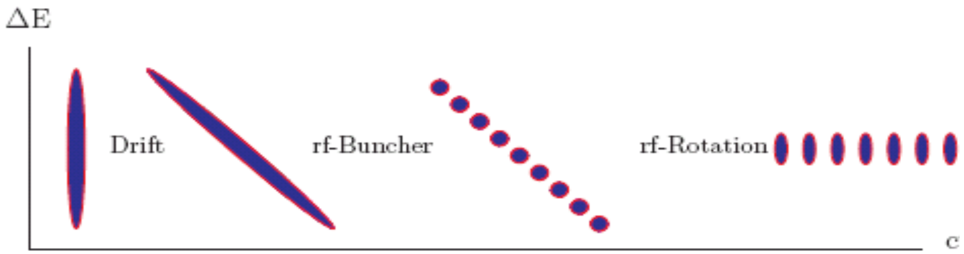
Ionization: cooling term

Multiple scattering: heating term

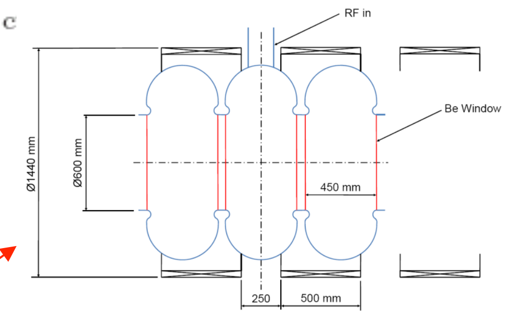
- Goals of MICE:
  - design, engineer, and build a section of cooling channel
  - measure performance under different beam conditions
  - show that design tools (simulation codes) agree with experiment
  - demonstrate operation LH_2 close to high gradient RF in high B fields

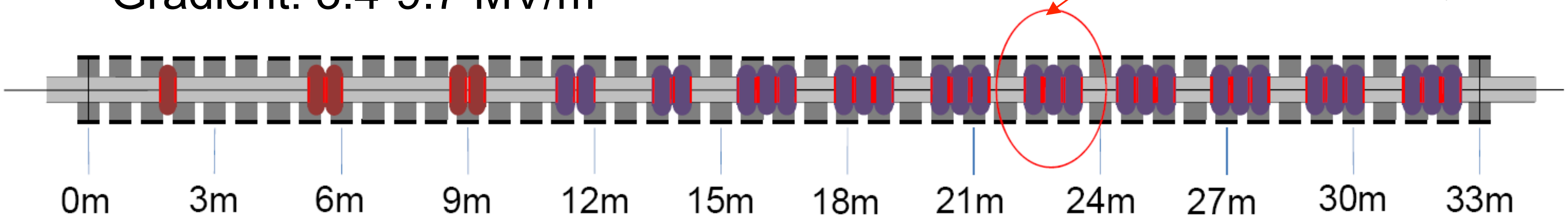
Muon Front End



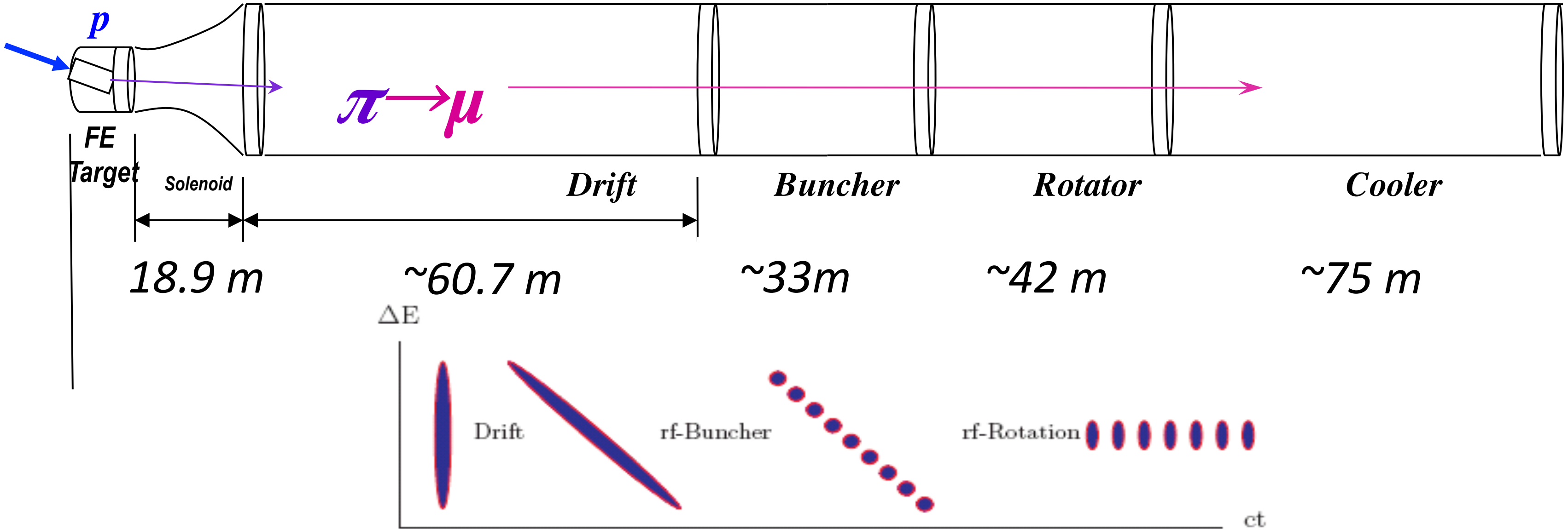


- Buncher:
  - 33 normal conducting RF cavities
  - RF frequency: 320-234 MHz
  - Gradient: 3.4-9.7 MV/m

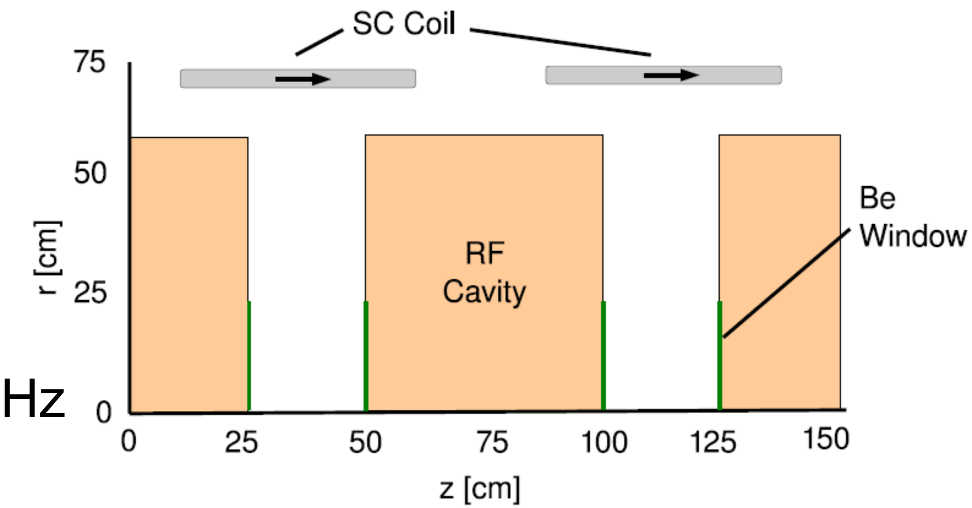




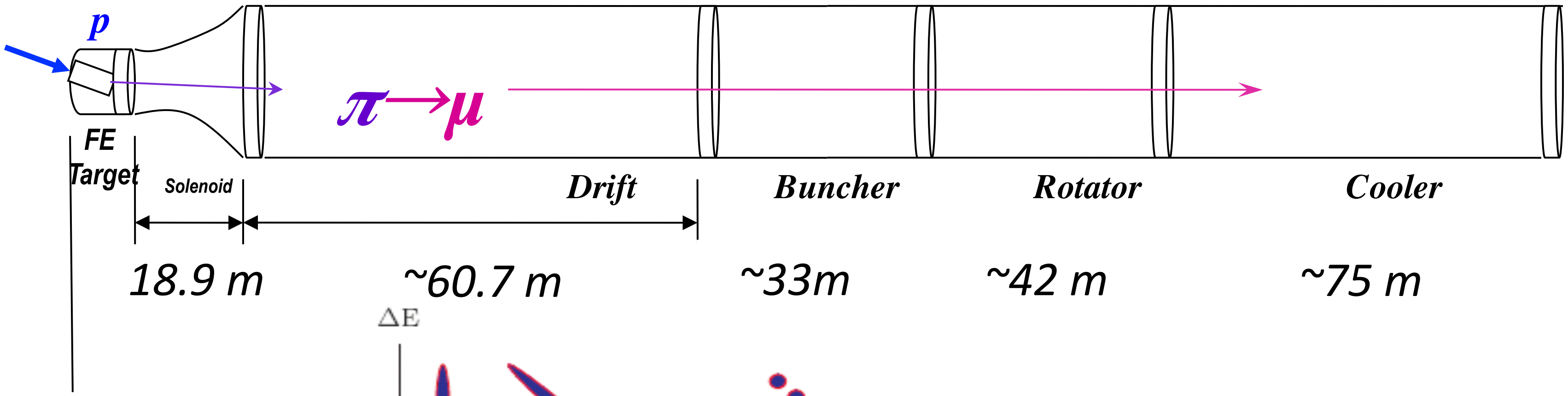
Muon Front End

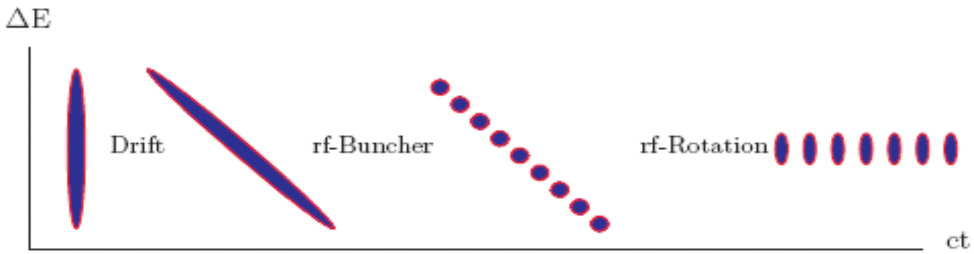


- Phase rotation:
  - 56 cells of 0.75 m length
  - Total length: 42 m
  - 56 normal conducting RF cavities with SC coils
  - RF frequency 230.2- 202.3 MHz
  - Gradient 12 MV/m

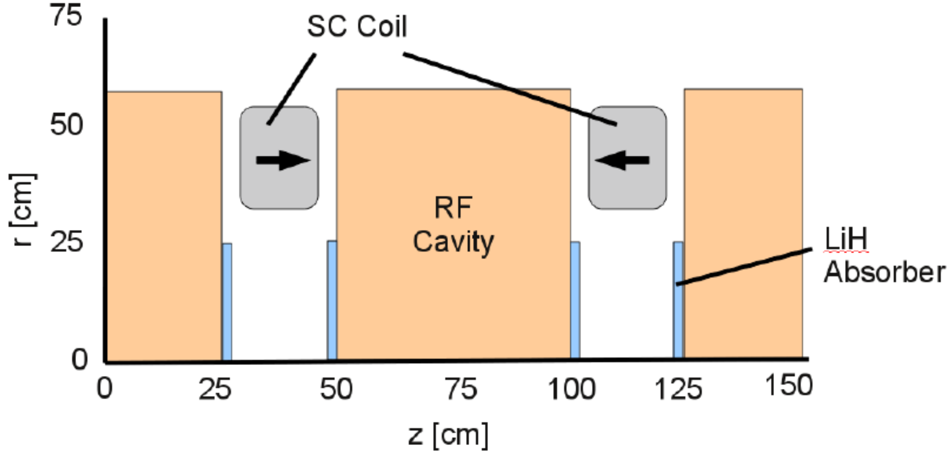


Muon Front End



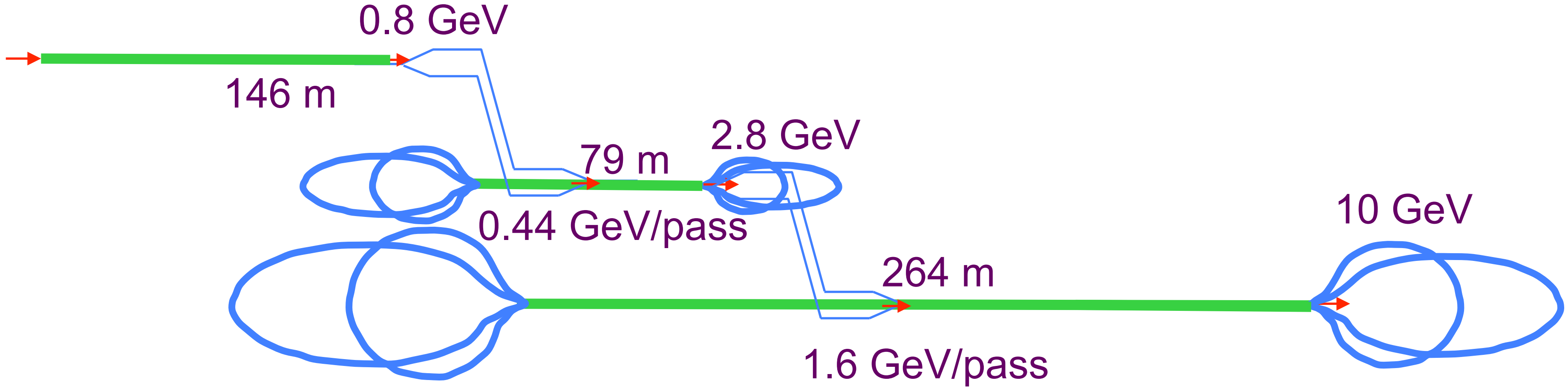


- Cooling channel:
  - 100 cells of 0.75 m length
  - Total length: 75 m
  - 100 normal conducting RF cavities with SC coils
  - RF frequency 201.25 MHz
  - Gradient 15 MV/m
  - LiH absorbers (1.1 cm)

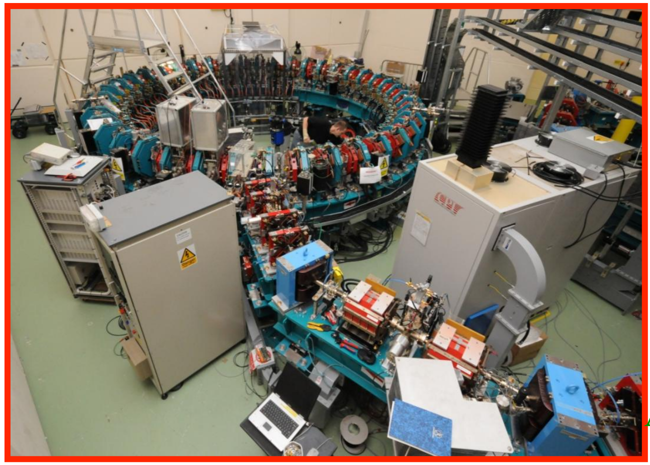


Acceleration

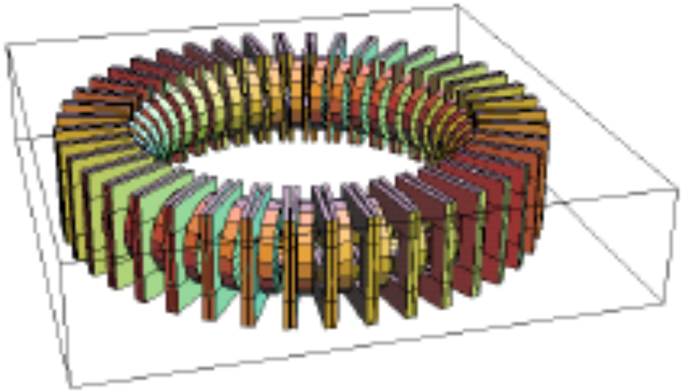
- Redefined baseline after moving to 10 GeV (IDR: 25 GeV)
  - One possibility: Recirculating Linear Accelerators (RLA) up to 10 GeV



  - Another possibility, Fixed Field Alternating Gradient (FFAG): LINAC up to 1.2 GeV, RLA up to 5.0 GeV and FFAG from 5.0 –10.0 GeV

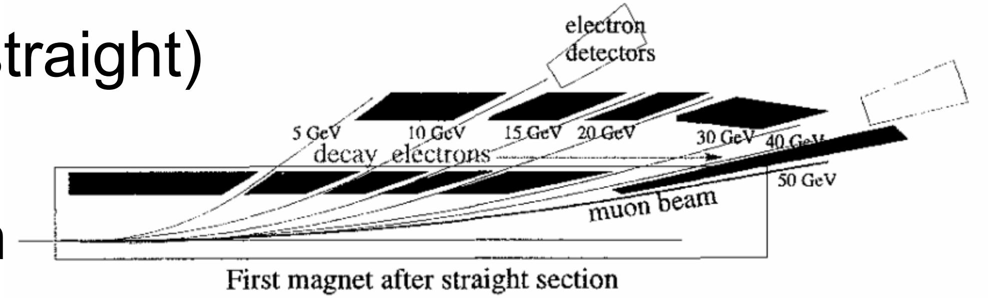


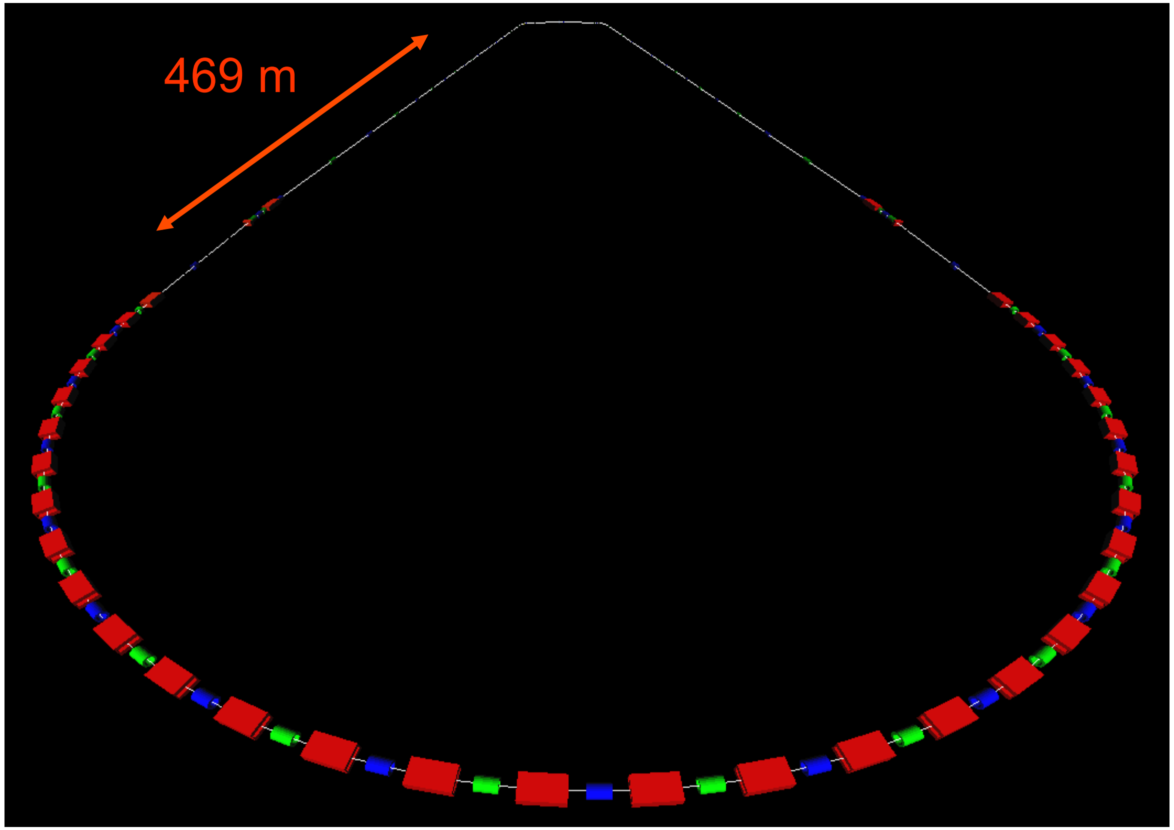
EMMA: first demonstation of non-scaling FFAG with electrons



Decay Ring Geometry

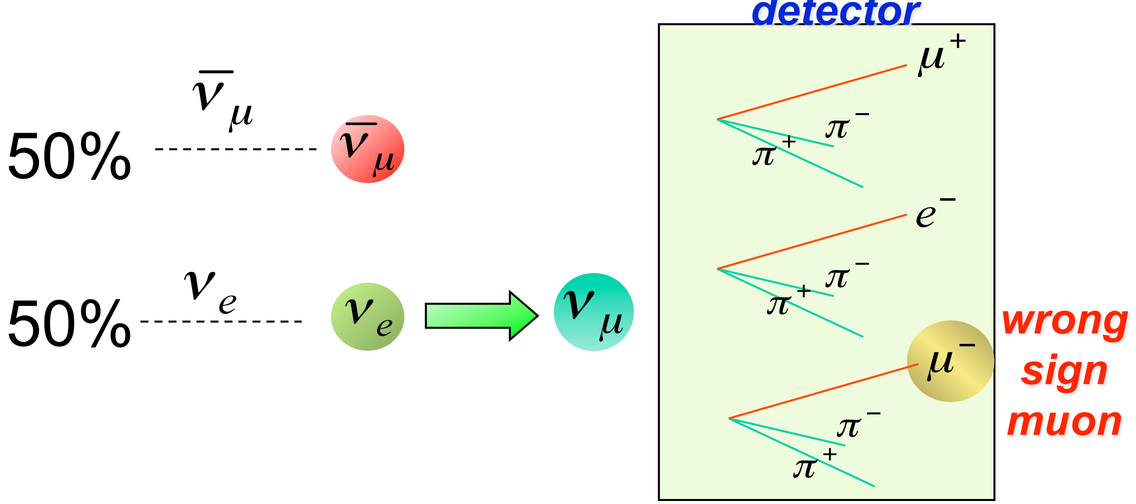
- Racetrack geometry (469 m straight)
- Decay electron energy used to measure muon polarization

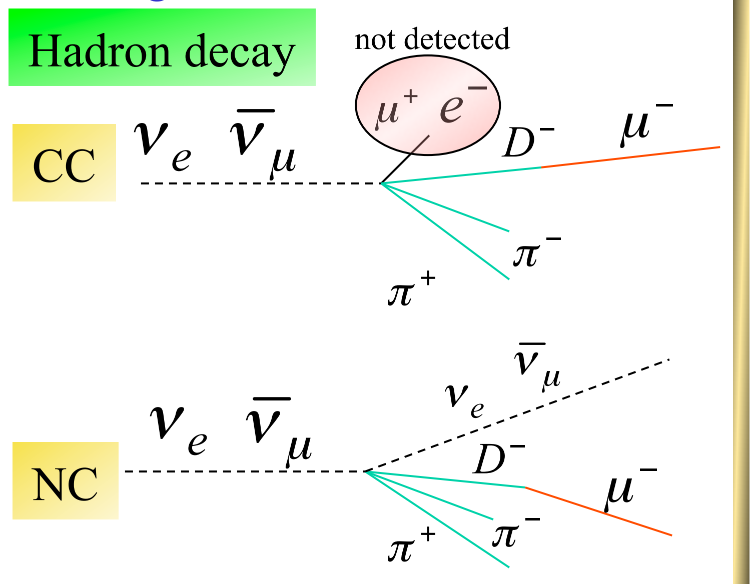




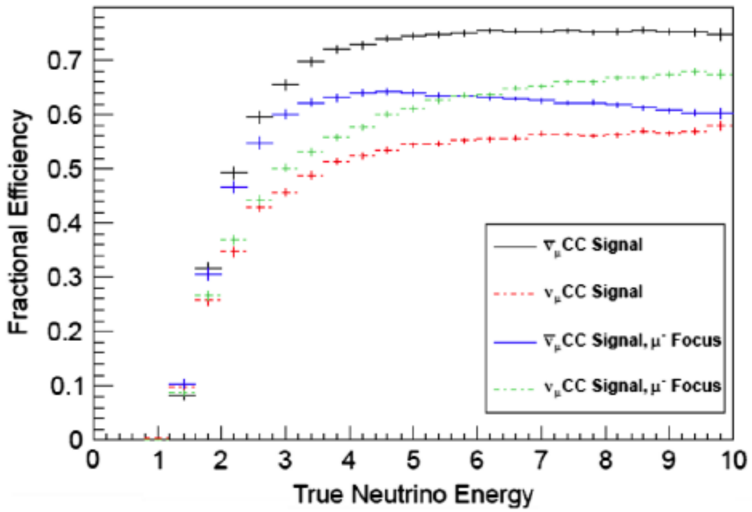
Detector concept and analysis

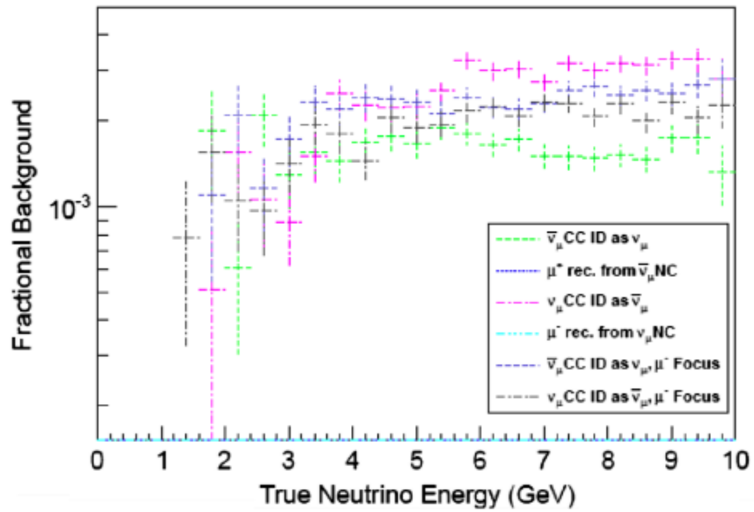
- Far detector searches for “wrong-sign” muons at Magnetised Iron Neutrino Detector (MIND)





- Efficiency 50-70%, background rejection ~10^3:

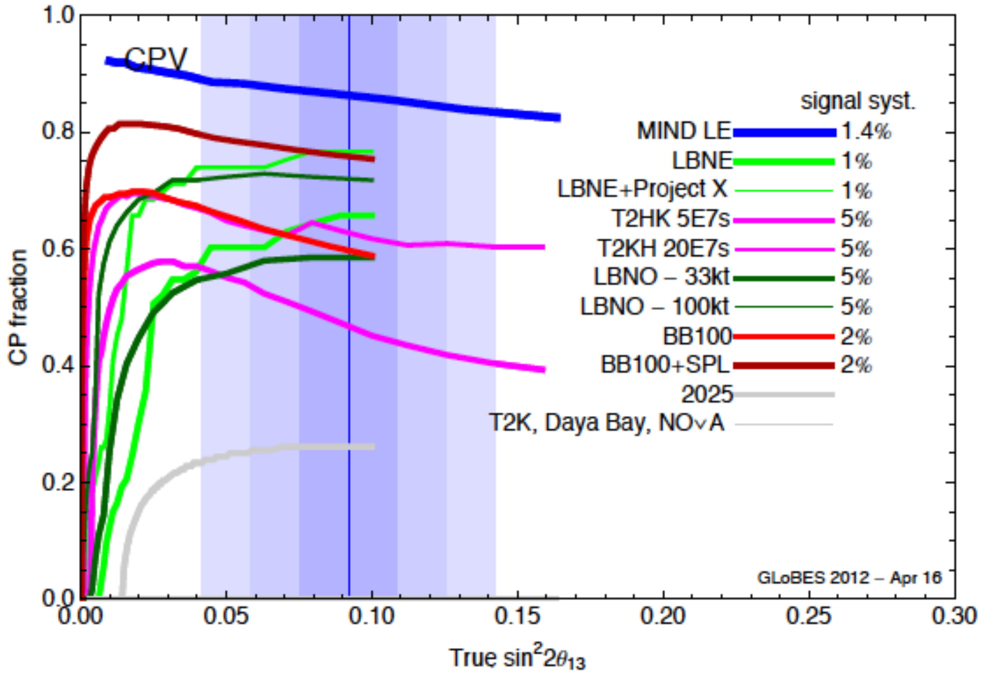


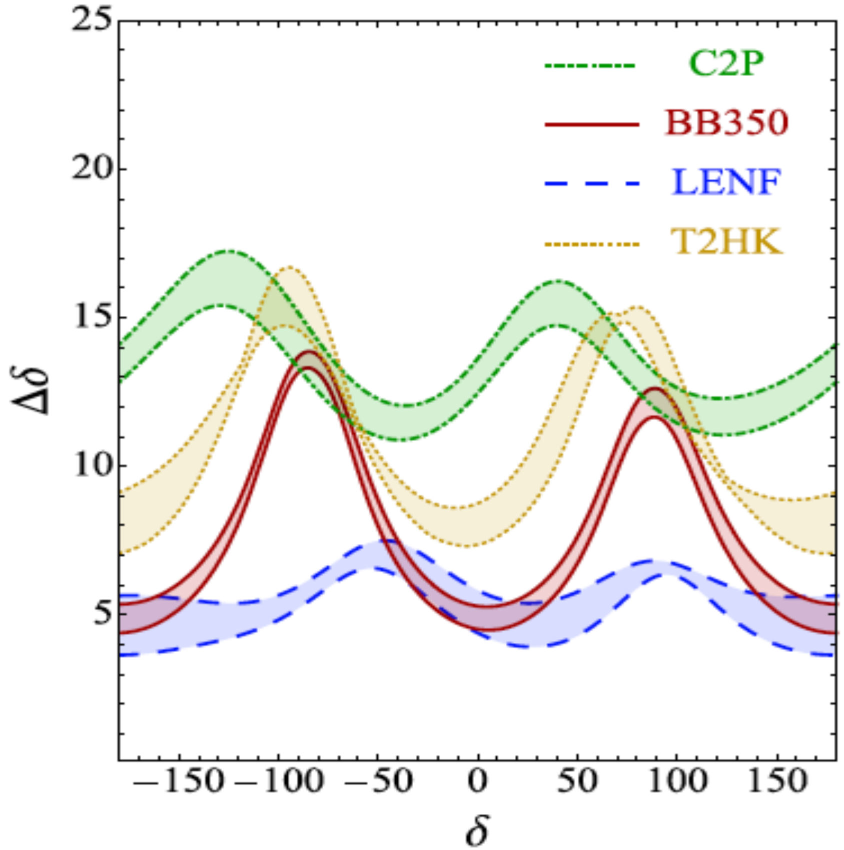


Performance 10 GeV Neutrino Factory

- Optimisation for 10 GeV Neutrino Factory with 100 kton MIND at 2000 km gives best sensitivity to CP violation, even at latest value of $\sin^2 2\theta_{13} \sim 0.09$

arXiv:1203.5651





NF yields Δδ~5°, regardless of value of δ

Conclusions

- Neutrino oscillations so far explains all the atmospheric, solar and long baseline neutrino data
- After discovery of θ_{13}, the mass hierarchy, the θ_{23} octant and CP violation remain the main unanswered questions in neutrino oscillation experiments
- This opens up the possibility of new long baseline experiments that may discover CP violation
- Next generation accelerator experiments: T2K, NOvA
- Future proposals: LBNE, Hyperkamiokande, Beta Beam, Neutrino Factory?
- Short baseline data is still in conflict: LSND and MiniBoone results not clarified yet
- nuSTORM offers best prospects for light sterile neutrino search