Next Generation Accelerator Neutrino Projects - Long and Short Baseline

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Why do we care about neutrinos?

- We are all thrilled and enthusiastic about the Higgs boson discovery
- ...but still no sign of new physics
- The clearest signal of physics beyond the SM is given by the neutrino masses:
- Either new right-handed states (no SM charge, who ordered them ?) or Majorana masses and lepton number violation
- Neutrinos might be our best window on GUT physics

H. Murayama hep-ph/0312008

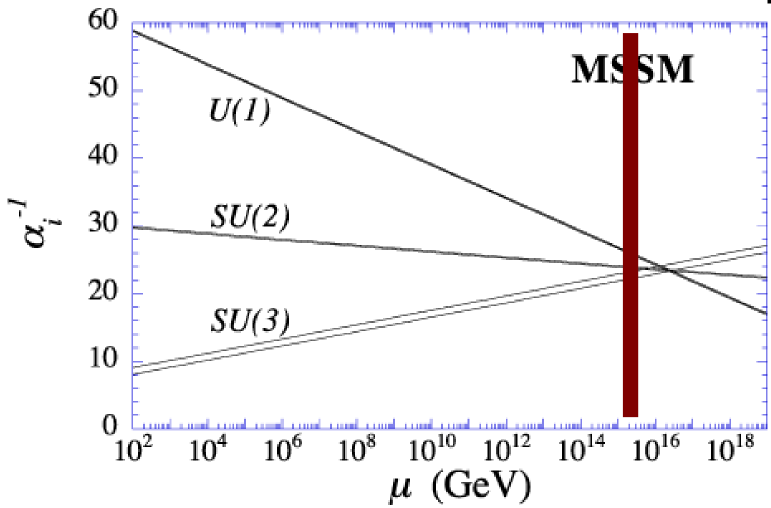
Beyond the Standard Model with neutrinos

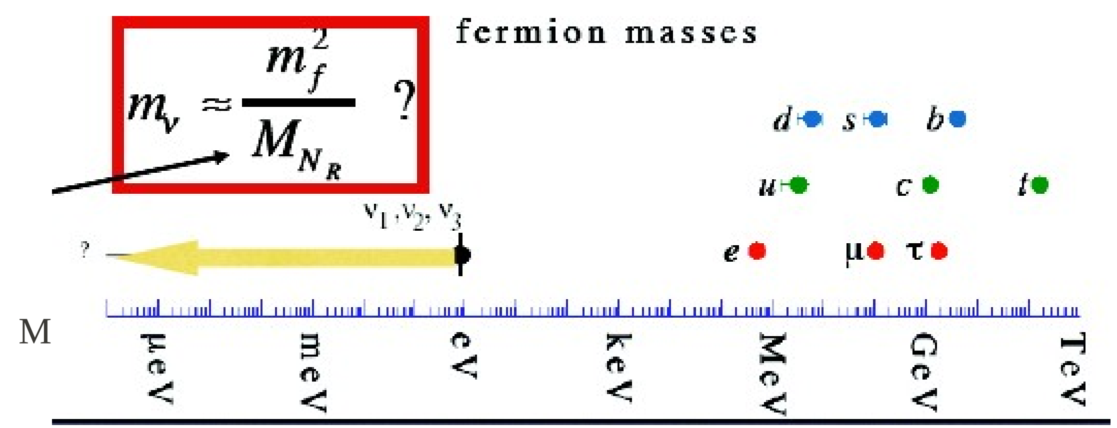
- Standard Model = Gauge symmetry group+Lorentz+renormalizability
- Give up the renormalizability
- Effects of physics beyond the SM as effective operators
- Can be classified systematically (Weinberg)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

Lowest order effect of physics at short distances !

$$\mathcal{L}_5 = (LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

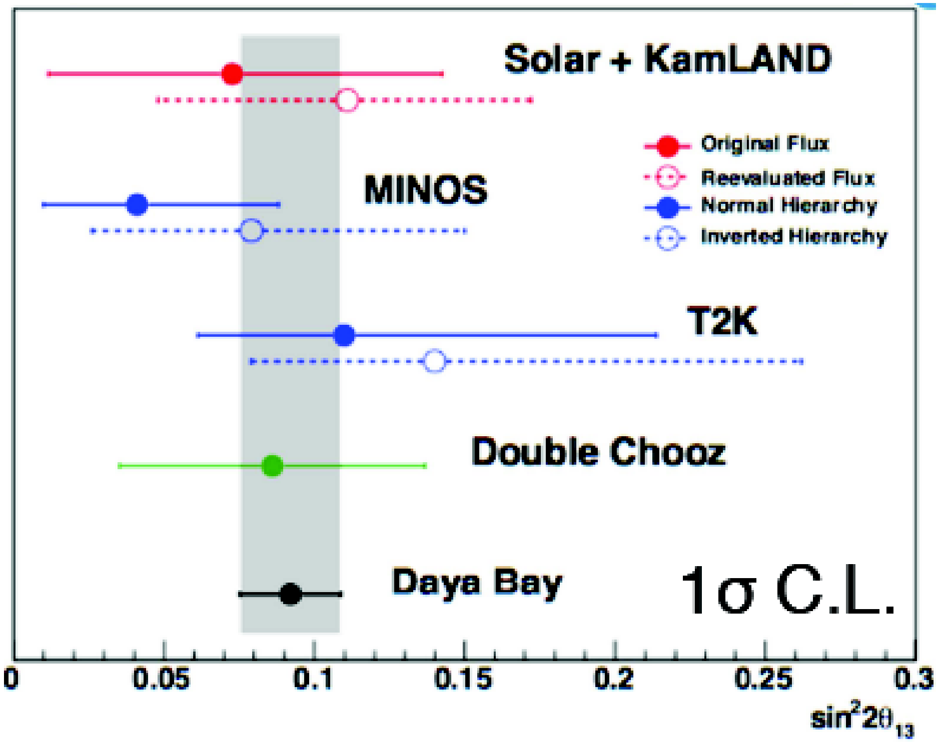




A decade after CHOOZ: the θ_{13} revolution

- T2K (Jun 2011):
  $\sin^2 2\theta_{13} = 0.03 - 0.34$ (90% CL).
  T2K Collaboration, Phys.Rev.Lett. 107 (2011) 041801
- MINOS (July 2011):
  $\sin^2 2\theta_{13} \neq 0$ at 89% CL.
  MINOS Collaboration, Phys.Rev.Lett. 107 (2011) 181802
- Double CHOOZ (Dec 2011):
  $\sin^2 2\theta_{13} = 0.017 - 0.16$ (90% CL).
  Double CHOOZ Collaboration, arXiv: 1112.6353 [hep-ex].
- Daya Bay (Mar 2012):
  $\sin^2 2\theta_{13} \neq 0$ at 5.2σ (!),
  best-fit = 0.092.
  Daya Bay Collaboration, arXiv: 1203.1669 [hep-ex].
- Reno (April 2012):
  exclude no oscillations at 4.9σ

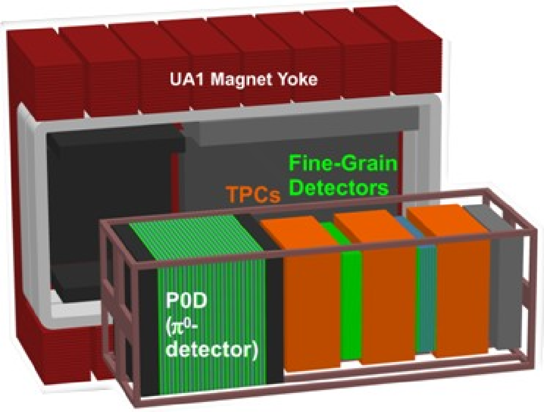
See talk by GL Fogli

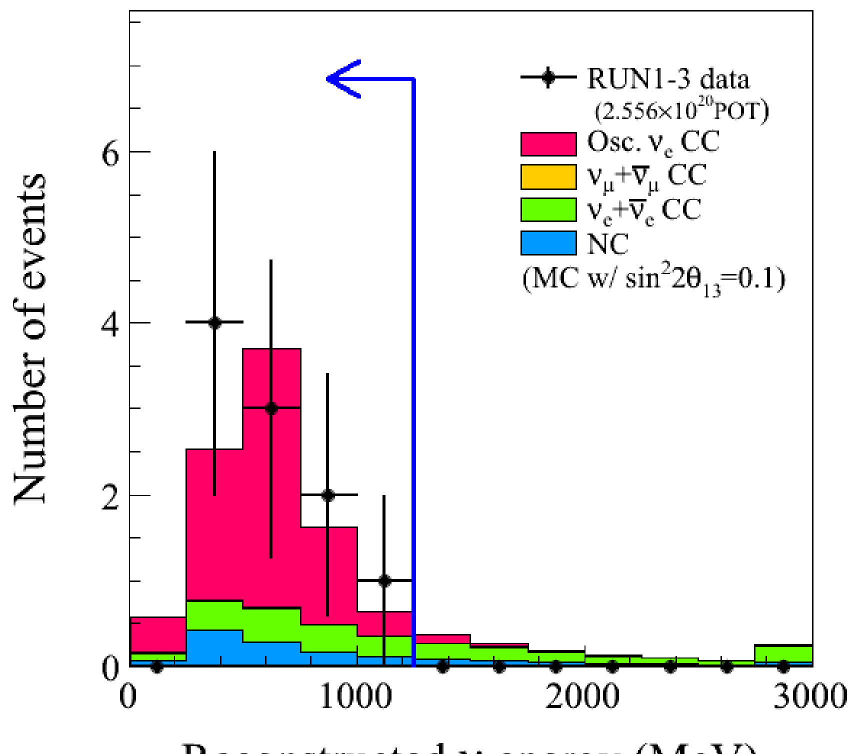


$$\sin^2(2\theta_{13}) = 0.092 \pm 0.016(stat) \pm 0.005(syst)$$

$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat) \pm 0.019(syst)$$

T2K : the θ_{13} appearance measurement



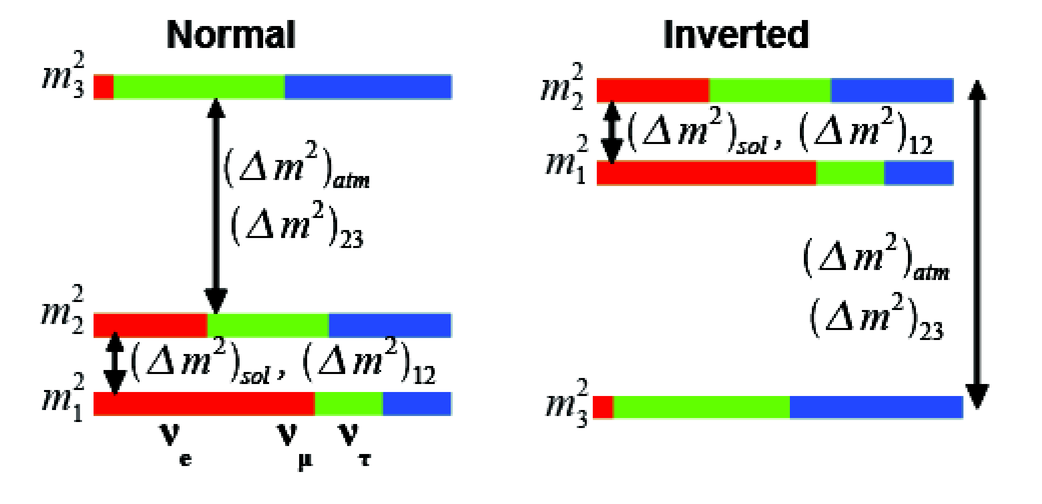


- **First indication and then confirmation of large θ_{13}**
- **First clean appearance experiment**
- **Large European effort**
- **Near detector + production cross section in NA61 → accurately measured ν beam**
- **$\nu_\mu \to \nu_e$: main channel for CPV exploration**

The mixing matrix PMNS

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{23}e^{-i\delta} \\ 0 & 0 & 0 \\ -s_{23}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Parameter	Best fit	1σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.34 – 2.50
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.32 – 2.49
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.45	2.14 – 2.79
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.46	2.15 – 2.80
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.98	3.72 – 4.28
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.08	3.78 – 4.43
δ/π (NH)	0.89	0.45 – 1.18
δ/π (IH)	0.90	0.47 – 1.22



Fractional 1σ accuracy [defined as 1/6 of $\pm 3\sigma$ range]

δm^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	Δm^2
2.6%	5.4%	13%	13%	3.5%

Progress since the last strategy plan

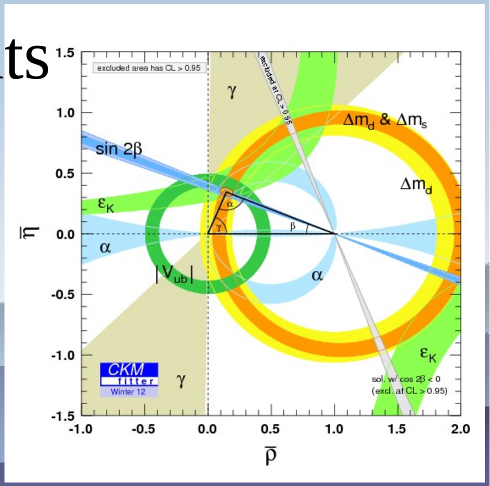
- Measurement of θ_{13} : major unknown measured
- European design studies : EUROnu, LAGUNA and LAGUNA-LBNO (>300 physicists, 4 years)
- Feasibility studies of new neutrino beam technologies, detectors and underground labs
- Neutrino Town meetings : input from the community
- Recommended options to this forum
- We are ready and organized to submit well thought proposals to the strategy process!

Remaining part of this talk

1) Long baseline projects in Europe and elsewhere: complete the study of the PMNS paradigm, check unitarity
2) Short baseline projects : test the existence of new neutrino states

PMNS: the next steps

- The CP violation phase δ, mass hierarchy, θ_{23} can be measured with a long baseline neutrino experiment
- The CP violation in the neutrino sector could help explaining the matter-antimatter asymmetry (and mystery) in the Universe
- In the end, we would like to explore PMNS to the same level of accuracy as CKM (eg. Unitarity, cf new physics potential of $B_s \to \mu^+\mu^-$)
- This calls for a complete set of precision measurements
- NB: J(PMNS) = 0.29 sin δ vs J(CKM) = $3\ 10^{-5}$



Long baseline : the consensus

- The currently approved experiments (T2K, NovA) will not be able to fully explore the PMNS matrix
- We need a new experimental facility : beam + far detector
- The first step of this program can be realized with a conventional neutrino beam
- An underground detector is both a must and a bonus as it opens a rich astrophysical program related to PMNS and GUT studies
- The modest CP asymmetry requires good control of the systematics: a full experimental program is needed, including a hadroproduction experiment, a near detector, possibly additional cross-section measurements
- A novel detector technology beyond Water Cherenkov is the key for a breakthrough in this field

The study of PMNS with a long baseline experiment

- Let us focus on the appearance probability P(ν_μ -> ν_e)

Vacuum LBL: $\nu_\mu \rightarrow \nu_e$

$$P_{\mu\rightarrow e} \approx |\, \sqrt{P_{atm}}\, e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}\, |^2$$

$\Delta_{ij} = \delta m^2_{ij} L/4E$ CP violation !!!

where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13}\ \sin\Delta_{31}$

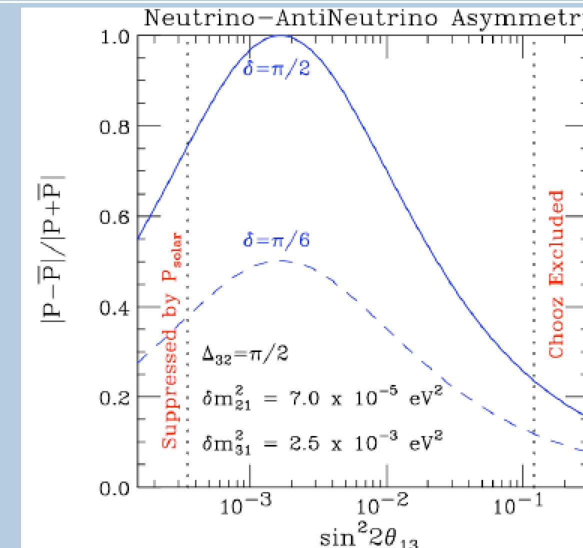
and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12}\ \sin\Delta_{21}$

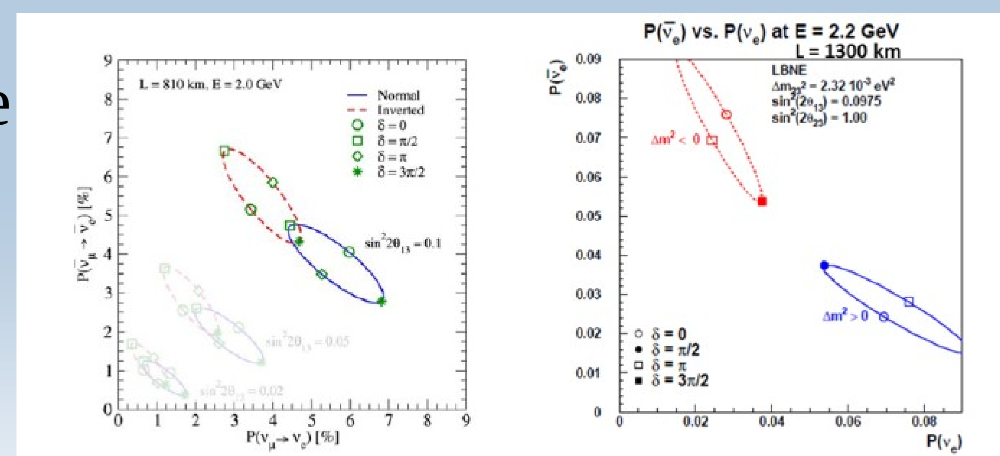
$$P_{\mu\rightarrow e} \approx P_{atm} + 2\sqrt{P_{atm}P_{sol}} \cos(\Delta_{32}\pm\delta) + P_{sol}$$

- The simple study of the CP asymmetry is obscured (or enriched) by matter effects (interaction of n with e in the traversed matter) that mimic a CP effect
- This complication can be seen as a challenge or an opportunity : clean measurement of mass hierarchy

Large theta13 : experimental challenges

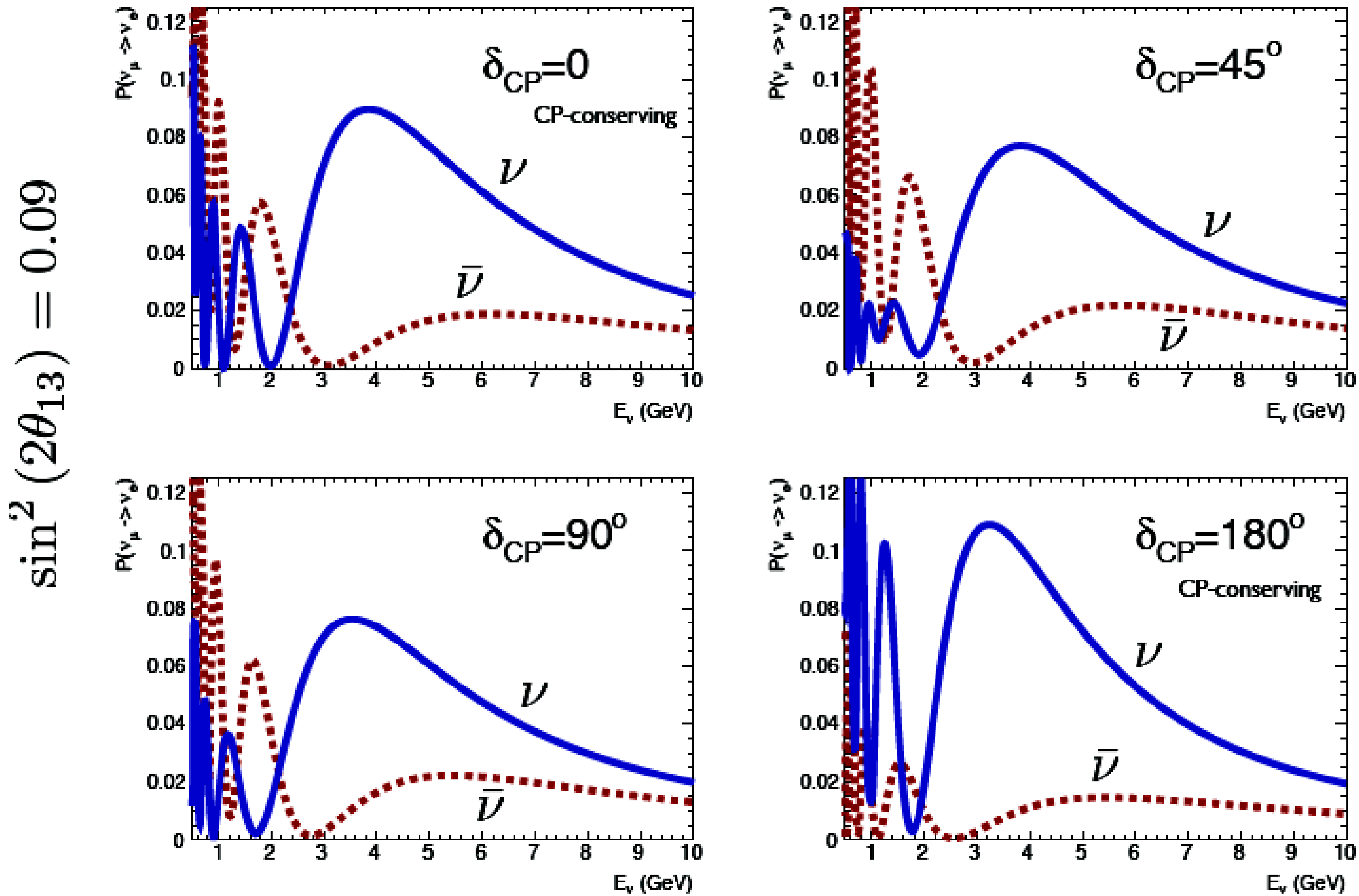
- Large theta13 means small asymmetry (~25%) : need to control the systematics to 5 % or better for a precision measurement
- A full program of cross-section, beam flux measurement, Near Detector
- Mass hierarchy and CPV effects are entangled





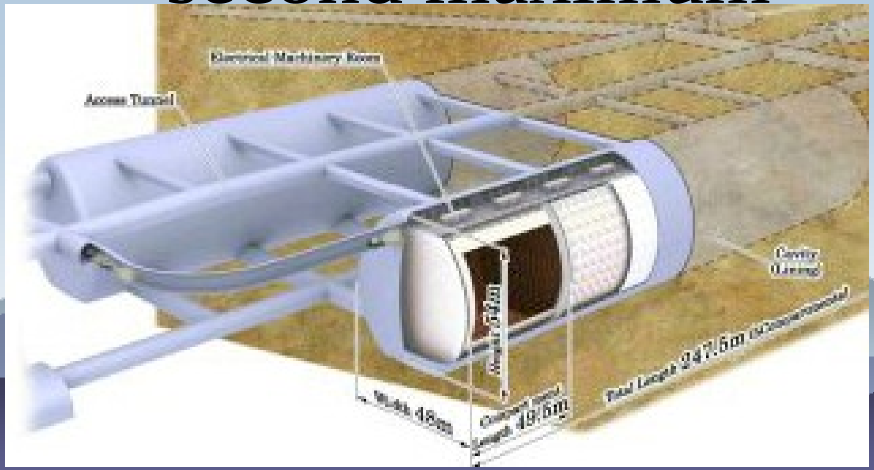
CERN-Pyhäsalmi: oscillations

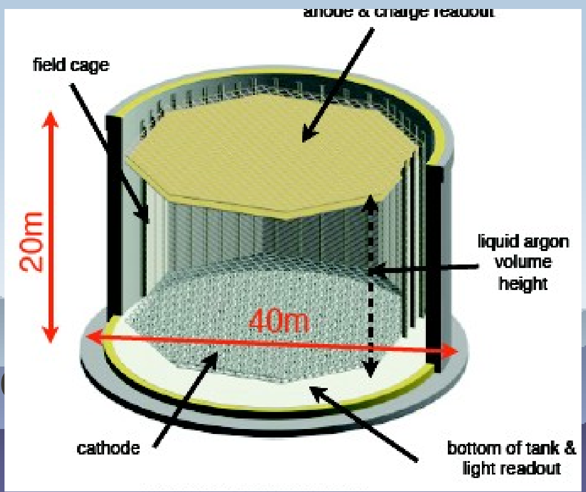
★ Normal mass hierarchy   L=2300 km



The two strategies towards CP violation

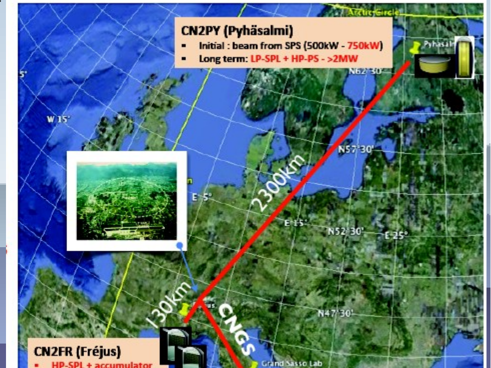
- Short baseline (~100-300 km), lower energy (<1 GeV), narrow beam, large Water Cherenkov (~500 kT). Concentrates on $\nu/\bar{\nu}$ asymmetry, "counting" experiment.
- Longer baseline (>1000 km), higher energy (>1 GeV), wide beam, Liquid Argon TPC. All final states accessible, E/L oscillation pattern and second maximum





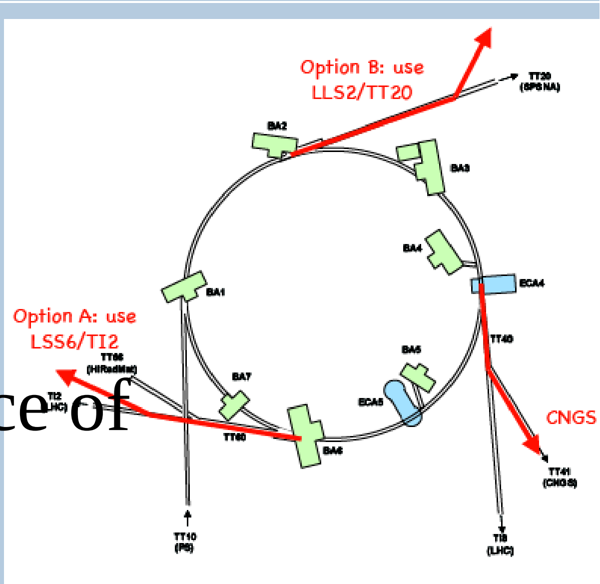
LAGUNA-LBNO

- The LAGUNA-LBNO consortium proposes to create a new European underground laboratory at Pyhäsalmi (Finland) at 2300 km from CERN
- The choice is based on scientific, technological and practical advantages of the site
- The laboratory can host a 50+50 kT liquid Argon detector combined with a 50 kT magnetized Fe detector for the detection of beam nu
- The first phase of the incremental program would be the operation of a new ν beam based on SPS (500 kW)
- The project has a rich astroparticle physics program (depth, low background) that can be fully exploited in conjunction with a 50 kt Liquid scintillator
- Recently submitted EOI to SPSC (230 authors, 51 labs)



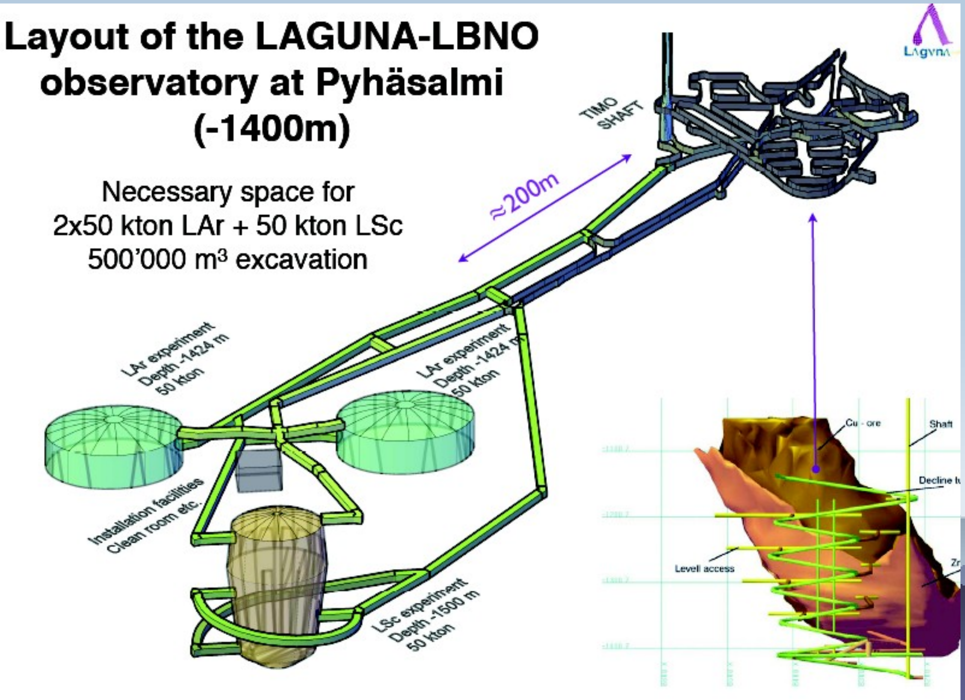
LAGUNA-LBNO beam

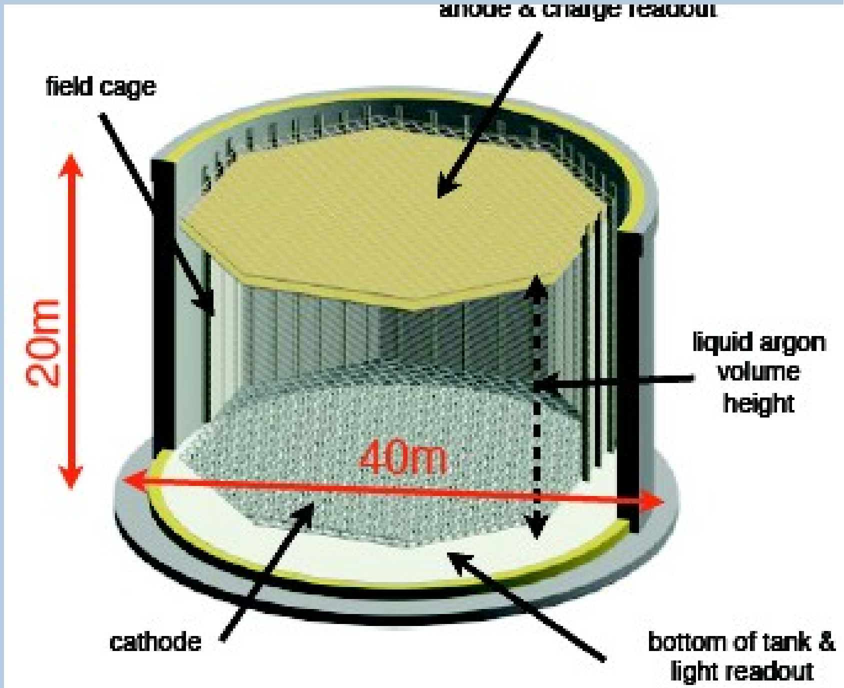
- Phase I : use the 400 GeV SPS proton beam
- Horn focused neutrino beam, based on CNGS technology
- (0.8-1.3)10**20 pot from improved performance of injectors + SPS
- Target station and tunnel in NA
- Near detector at 500-800 m
- Upgrade path with HP-PS with significant power improvement
- Under study by CERN team in LAGUNA-LBNO WP4

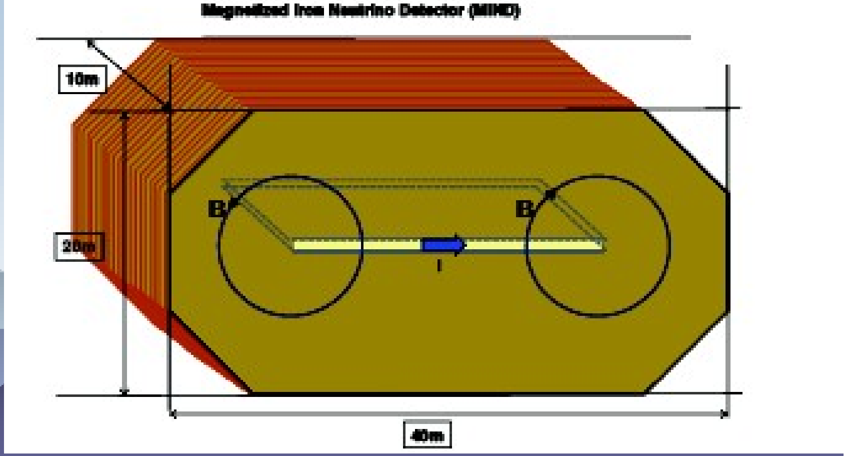


LAGUNA-LBNO underground lab and detector

- Detector complex at -1400 m
- Excellent quality of the rock and mine infrastructure
- Initial configuration : 20 kT + magnetized iron detector

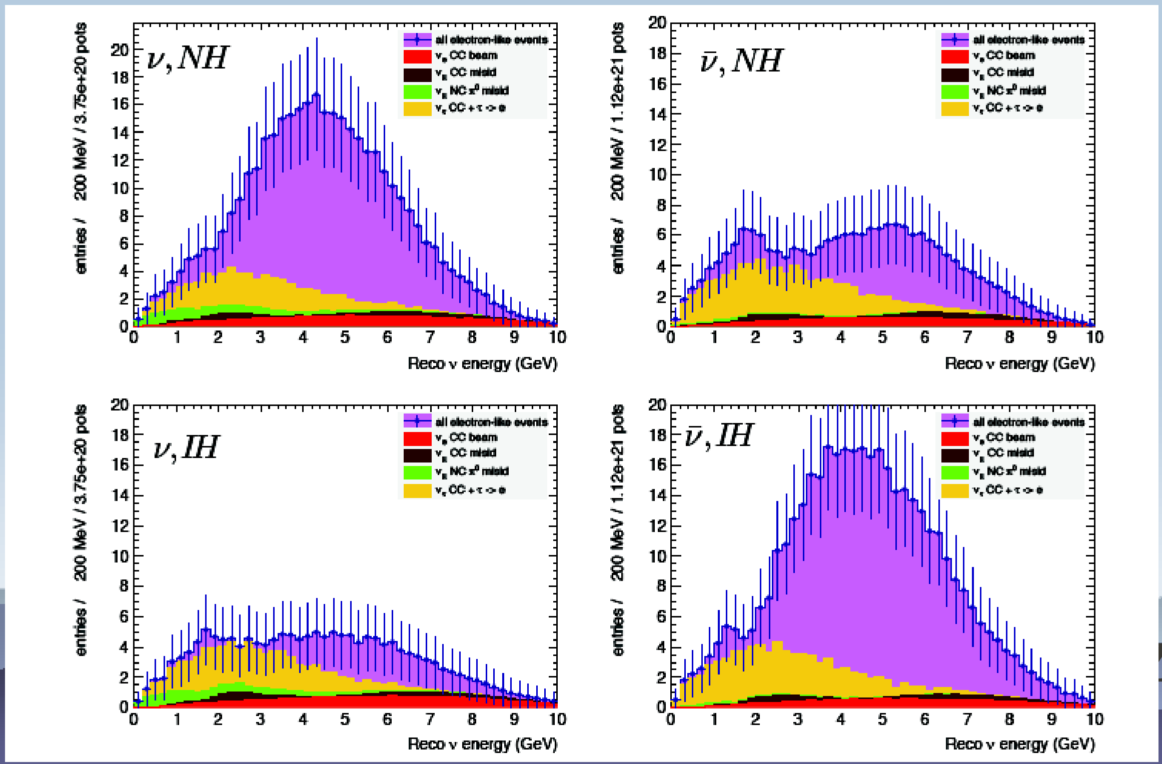


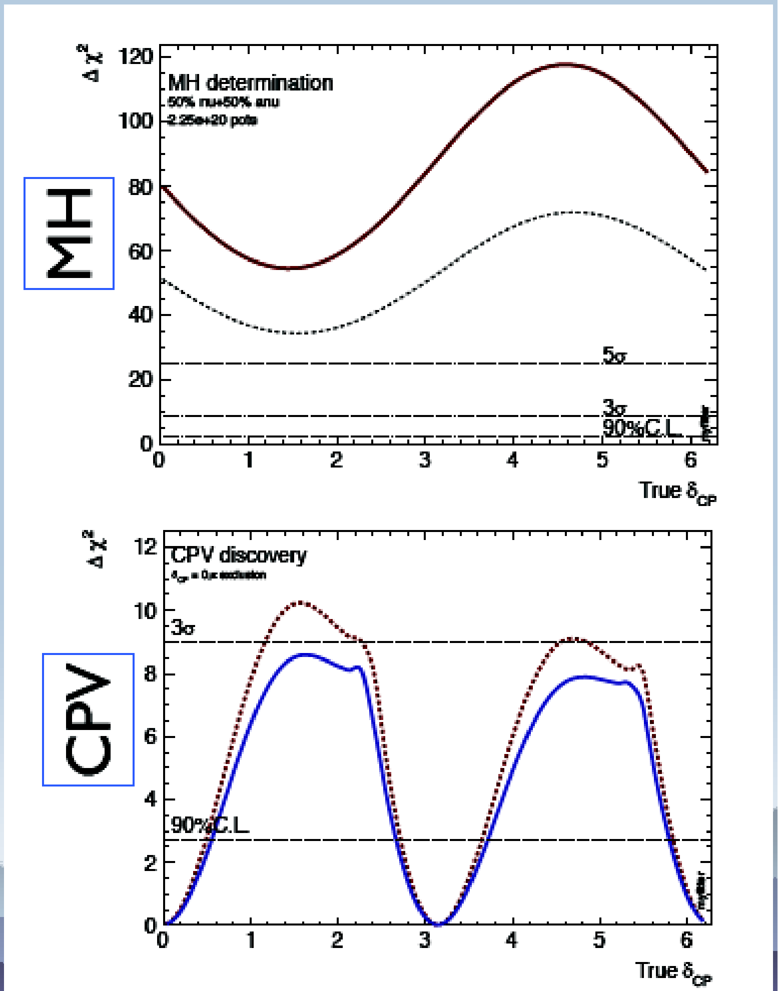




LAGUNA-LBNO : physics reach

- Mass hierarchy : 100 % coverage at 5 σ in a few years
- CPV: 60 % coverage in 10 years



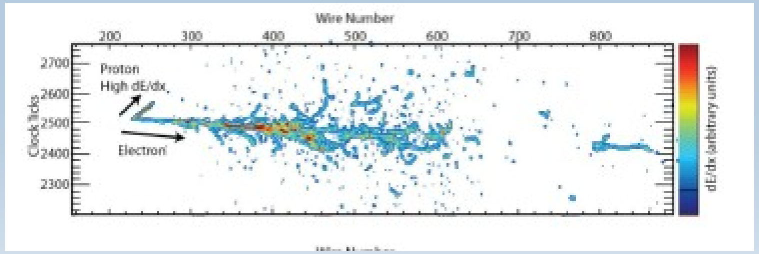


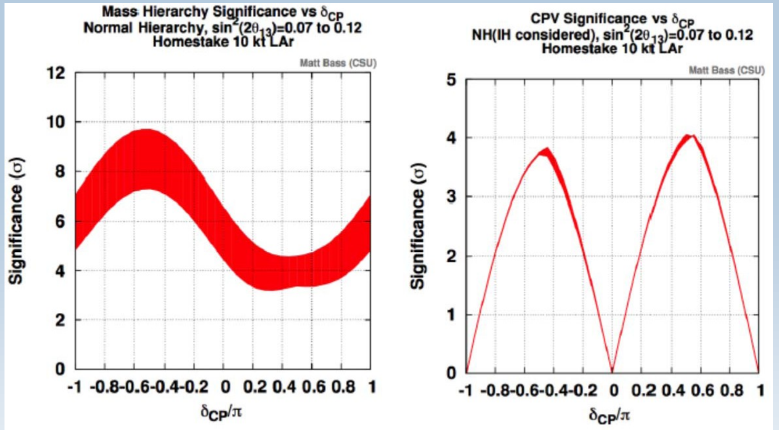
LAGUNA-LBNO : reach and plans

- All transitions (ν_e $\nu_\mu \nu_\tau$) in neutrino/antineutrino mode in a single experiment, with wide L/E range
- Clean and direct matter effects for a conclusive mass hierarchy and CP violation sensitivity
- Proton decay and astrophysical reach (SN)
- Clear upgrade path. Baseline adopted by the NF/Euronu studies
- Call to CERN to support design of the beam and detector R/D

LBNE : the US long baseline project

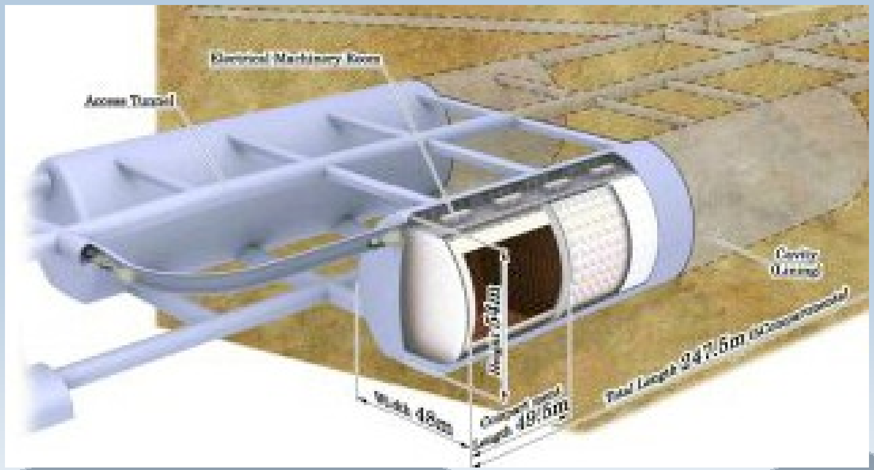
- New 700 kW beamline from Fermilab to Homestake (1300 km) with a 10 kt Liquid Argon detector (on surface, and without ND unless additional funds)
- The project underwent recently a reconfiguration phase
- The further phases include a Near Detector, an underground Far Detector (up to 35 kt) and a 2.3 MW beam (Project X)

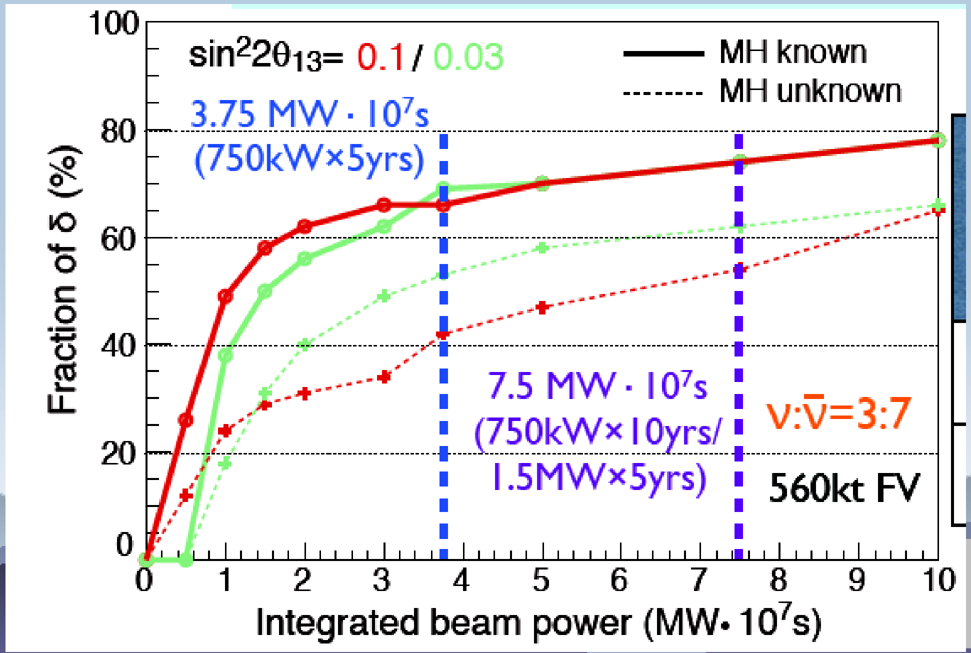




T2HK : long baseline in Japan

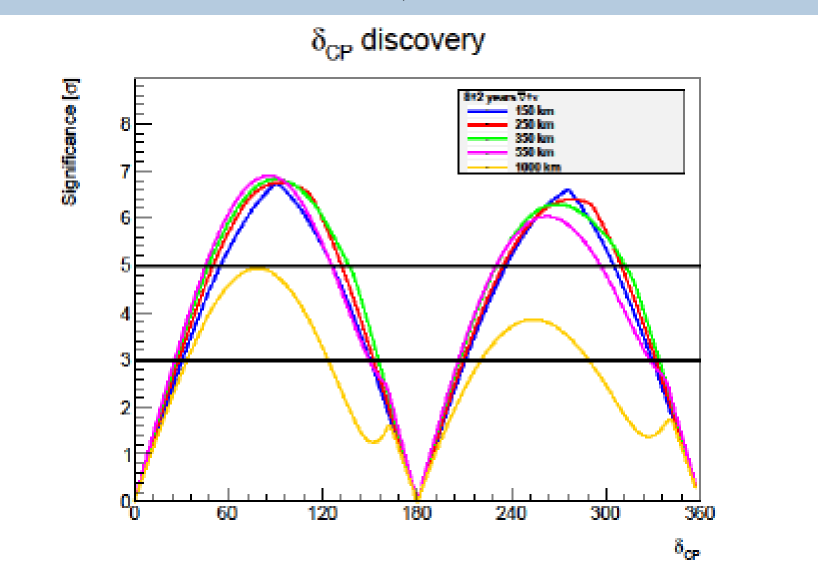
- Very large Water Cherenkov with fiducial mass 0.56 Mton (25xSK)
- Two caverns (248x54x48 m**3, 99 000 20" PMT)
- 750 kW beam from JPARC : 295 km baseline
- 74% (55%) CP coverage if MH known (unknown)

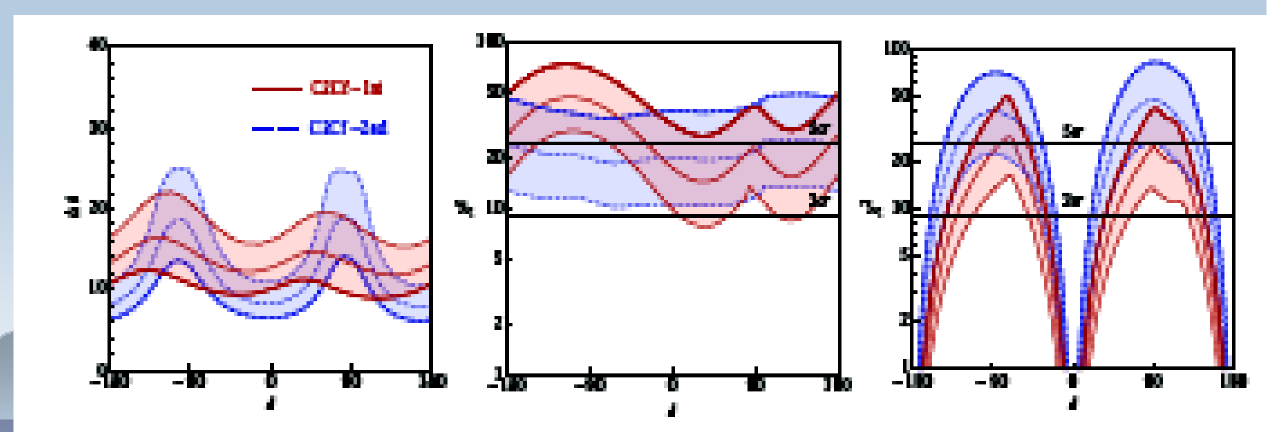




Other proposals in Europe

- Ideas based on a large Water Cherenkov (440 kt) as far detector (MEMPHYS studies)
- Based on ESS facility (Lund, Sweden, ready in 2019) to produce a 5 MW beam with a baseline of 365 km (Zinkruvan mine, Sweden)
- Or the detector would be located in Canfranc (Spain) and the beam based either on SPS (800 kW, 1st osc. maximum) or on SPL (4 MW, 2nd osc. max)

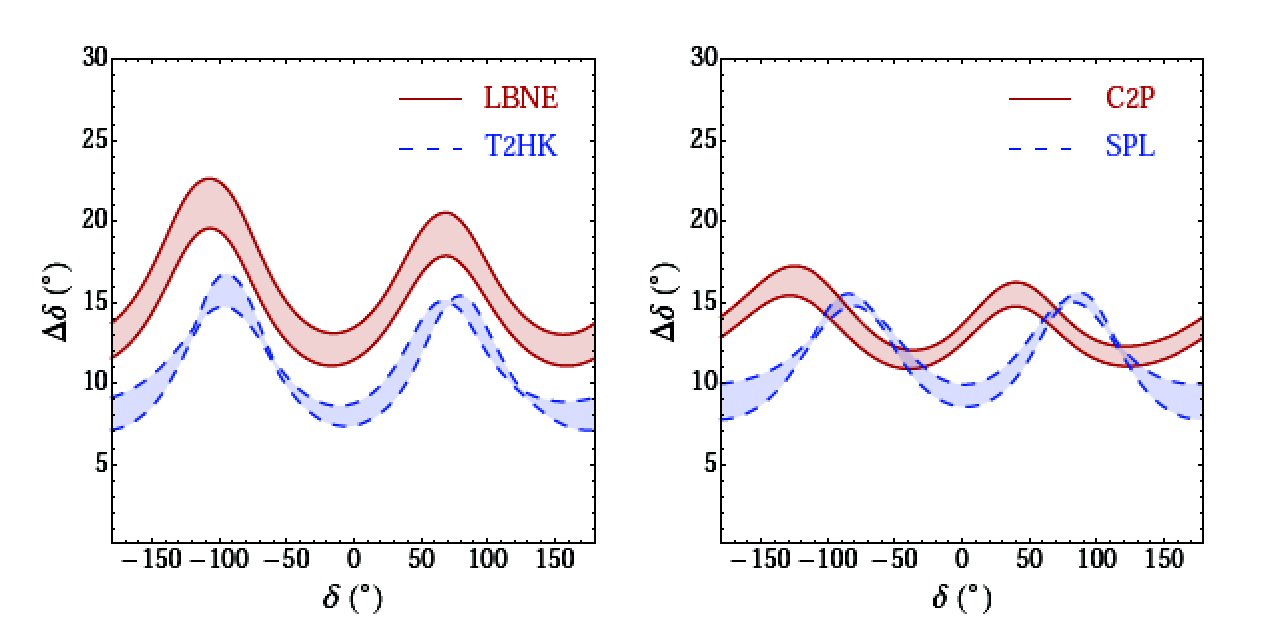




Long baseline scenarios

Project	Beam power MW	Fiducial Mass kt	Baseline km	MH	CPV 90%CL, in %	Physics starts	
LBNO	0.8	20->100	2300	Excellent	60	2023	
T2HK	0.75	500	295	No	55 (74)	2023	
LBNE	0.7	10	1300	OK		2022	
Lund	5	440	365	Some	86	>2019	
CERN-Canfranc	0.8-4	440	650	Some	80-88	>2020	

Ultimate CPV sensitivity

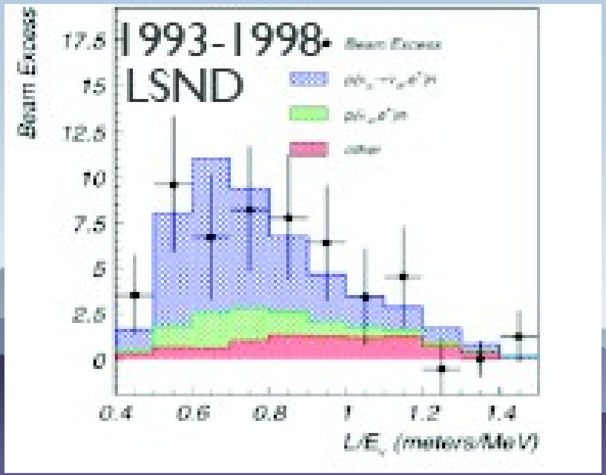


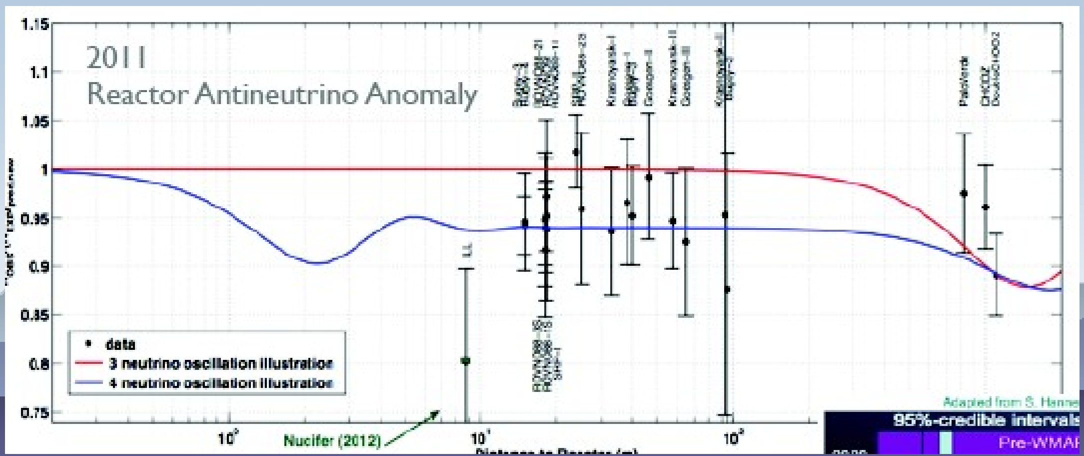
T2HK: 4MW, 500 kt
LBNE: 0.8 MW,33 kt
C2P : 0.8 MW, 100 kt

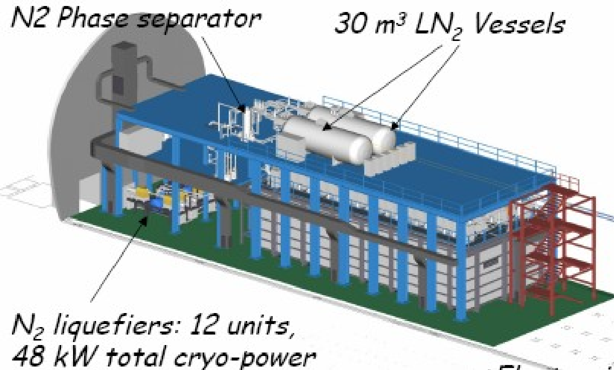
Neutrino anomalies

There are hints of possible new states beyond the three observed neutrinos:

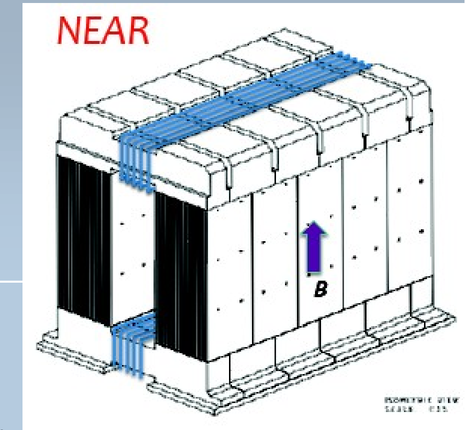
- LSND anomaly in ν_μ -> ν_e channel
- The neutrino deficit in reactor fluxes
- Is there a new ν with $\Delta m^2 \sim 1\ eV^2$?



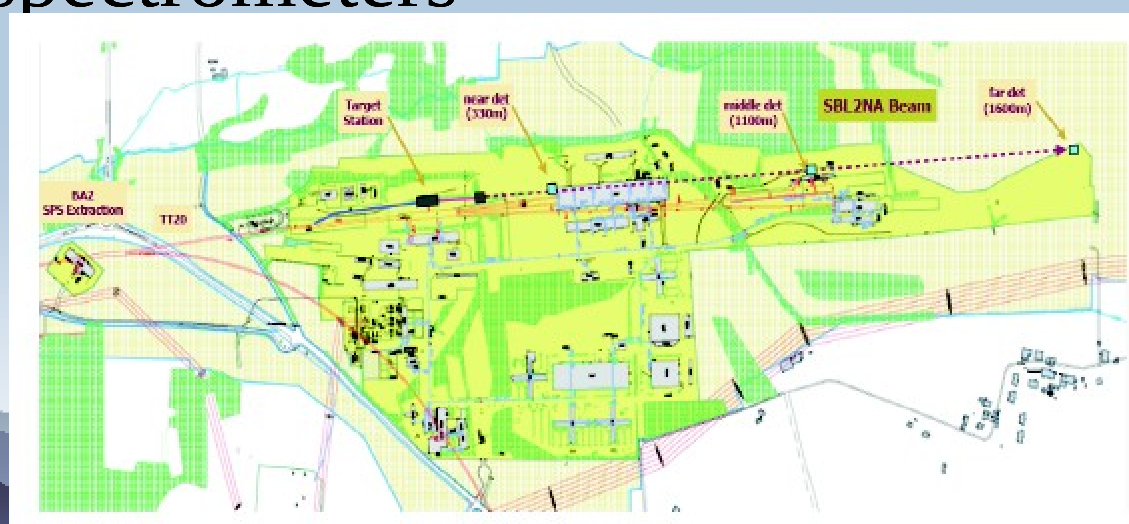




SPSC-P-347
Icarus-Nessie

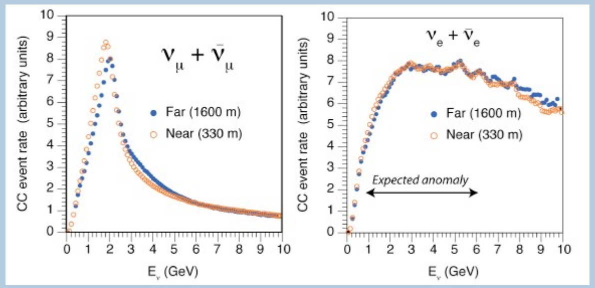


- Proposal (SPSC-P-347) of a comprehensive search for new neutrino states around $\Delta m^2 \sim 1eV^2$ using a SPS 110 GeV proton beam in the NA
- with two identical LAr detectors, at 1600 m (ICARUS T600) and 300m (T150), supplemented by two spectrometers



P347: beam detector

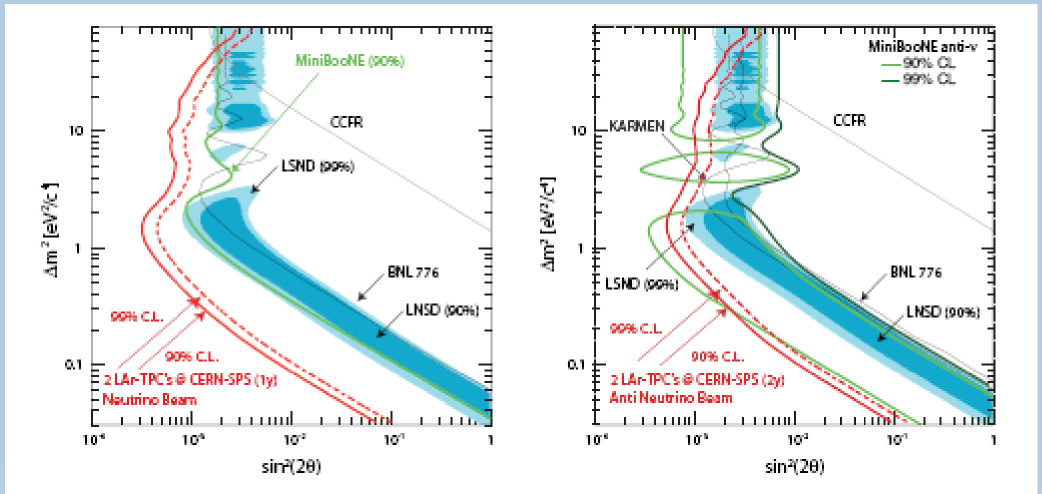
- Method : two identical detectors, with imaging properties and complete final state reconstruction
- High statistics

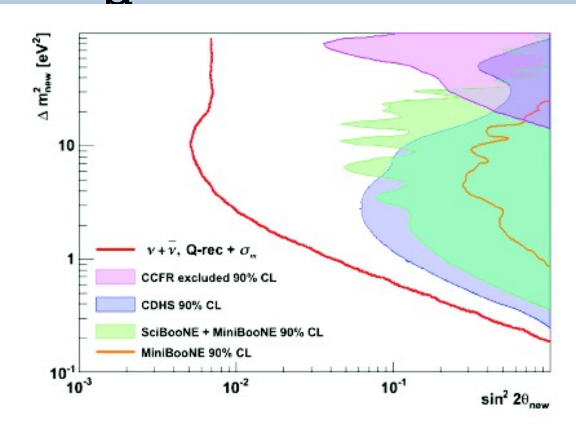


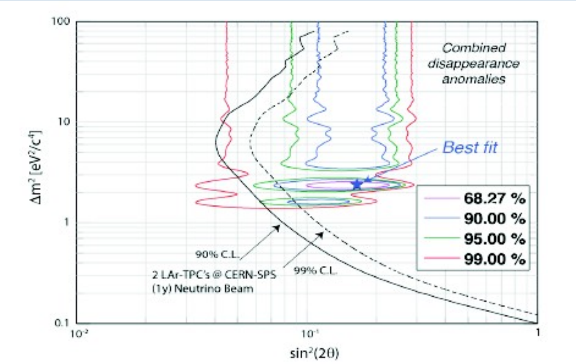
		NEAR (ν-bar)	NEAR(ν)	FAR(ν-bar)	FAR(ν)
produced	$\nu_e + \nu_e$-bar (LAr)	35 K	54 K	4.2 K	6.4 K
	$\nu_\mu + \nu_\mu$-bar (LAr)	2000 K	5250 K	270 K	670 K
	Appear. test point	590	1900	360	910
detected	ν_μ (LAr+NESSiE)	230 K	1200 K	21 K	110 K
	ν_μ (NESSiE)	1150 K	3600 K	94 K	280 K
	ν_μ-bar (Lar+NESSiE)	370 K	56 K	33 K	6.9 K
	ν_μ-bar (NESSiE)	1100 K	300 K	89 K	22 K
	Disappear. test point	1800	4700	1700	5000

SBL

- With two years negative and one year positive focusing, the following channels can be studied in neutrino and antineutrino modes
- $\nu_\mu \rightarrow \nu_e$
- ν_e disappearance
- ν_μ disappearance

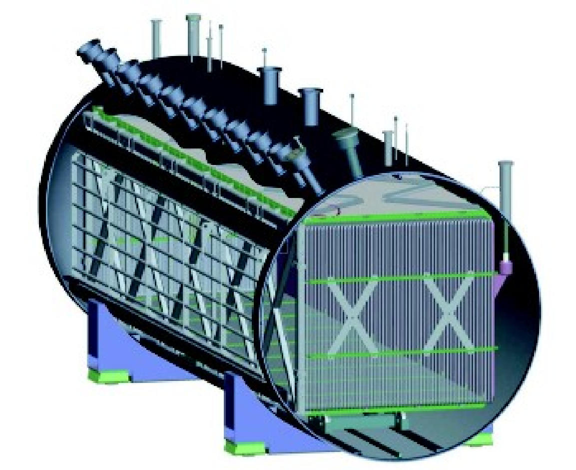






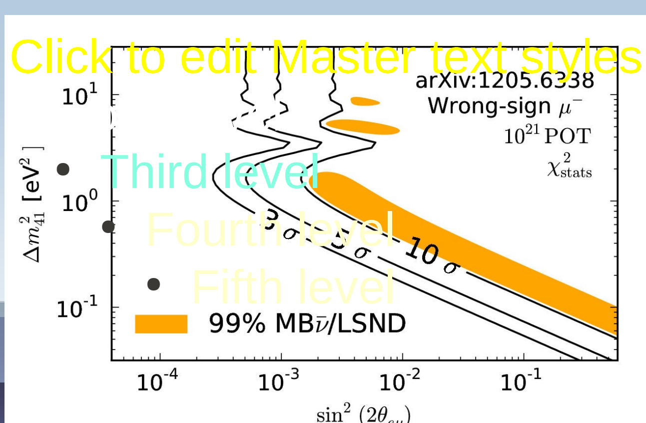
MICROBooNE

- 70 ton Liquid Argon detector <u>under construction</u> (completion end 2013) on the Booster neutrino beam line at FNAL
- Same baseline as MiniBooNE
- Study of the low energy excess of MiniBooNe: electron or photons ?
- Possible construction of 1 kton Liquid Argon TPC (Lar1) to investigate the MiniBoone antineutrino anomaly



νSTORM

- Use a muon decay ring to produce with $\mu^- \to e\, \nu_\mu\, \bar{\nu}_e$ a precisely known beam aimed at a magnetized iron detector to
- Investigate the LSND signal at 10 σ
- Study ν_e and ν_μ disappearance
- And precisely (1%) measure ν_μ and ν_e cross-sections
- Accelerator R/D towards the Neutrino Factory



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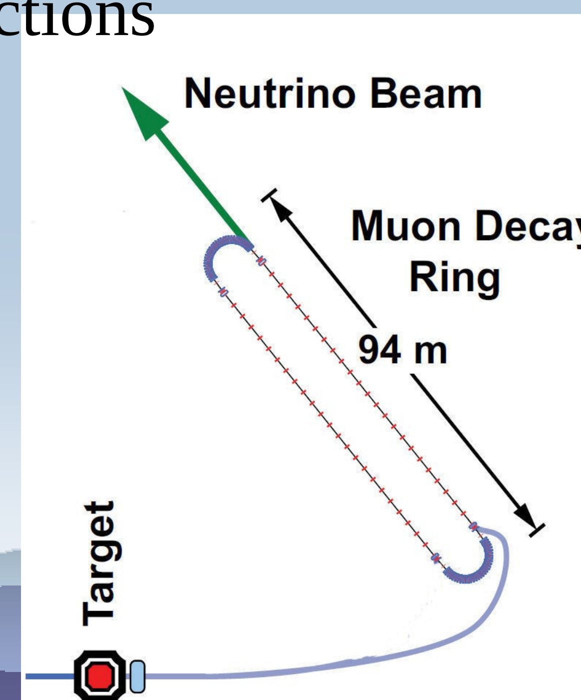
- Third level
- Fourth level
- Fifth level



The next facility : questions

- Long Baseline (LB) : what facility has the best overall program and long term vision ? Balance breakthrough, technological risks, physics competitiveness and overall physics program
- Should Europe fully explore the opportunities studied by the neutrino community and supported by a large consensus ?
- If we want a LB facility, prepare a full package, including beam and det. R/D, etc
- Prepare next steps : high power R/D, novel ν beams
- Short vs long baseline : synergies and compatibility
- Short baseline : reactor vs Strong sources vs accelerator

My conclusions-1

- The strong (~750 physicists) European neutrino community calls for neutrino physics to be at the highest priority levels on the strategy document
- The study of the PMNS mixing mechanism, CP violation and mass hierarchy is of fundamental importance in today particle physics as it could reveal the shape of physics beyond the SM
- Europe has a world class opportunity with the LAGUNA-LBNO project and its unique features, including the baseline, the mine, the LAr technology and CERN accelerator, and a longer term vision
- Europe needs this new long baseline facility to stay in the frontier of the field

My conclusions-2

- The experimental anomalies related to the search for new neutrino states need a clarification
- The Icarus-Nessie proposal is among the most comprehensive and competitive studies of the field
- Compatibility with the long baseline scenario in terms of protons and timeline must be ensured
- Precision EW physics requires a precise understanding of the neutrino beam and cross-section and a full program of accelerator and detector R/D where CERN can play a central role

- After theoretical introduction on the importance of further measurements of the neutrino properties, in particular the oscillation parameters, the session will focus on a discussion of the proposed experiments and where the European effort should go. We will also discuss the longer-term strategy towards even more capable programmes and what R&D and other efforts are needed in the near term. We need input on what support experiments (neutrino cross-sections, hadron production measurements, etc.) we should be preparing. There is also the question of short-baseline indications of sterile neutrinos, where the experimental situation has become more complex since the last strategy. We will discuss proposed experiments to address these questions and, once again, where European effort should be focused.

What we want to learn

In the context of long baseline neutrino experiments

- δ_{CP}
- mass hierarchy
- $\theta_{23} = \pi/4$, $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$?
- New physics?

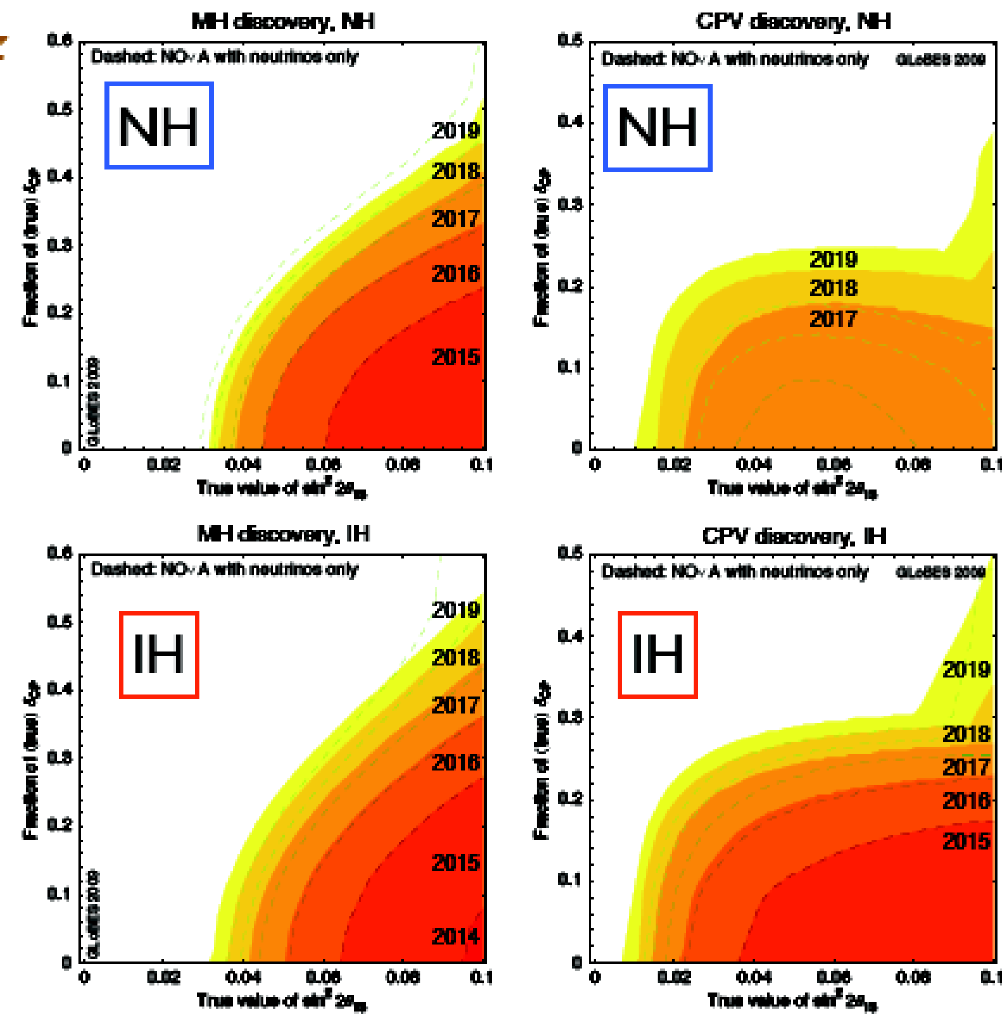
It is very difficult to rank those measurements in their relative importance

Given the current state of the theory of neutrinos we can not say with confidence that any one quantity is more fundamental than any other.

T2K and NOvA: in the future

- Preliminary estimation of sensitivity of T2K and NOvA *See talk by Schwetz*
- Nominal beam power scenarios (750kW). Need to check beam power assumptions.
- For $\sin^2 2\theta_{13}=0.1$, approximately (at 90%C.L.):
  - MH: ≈50% coverage
  - CPV: ≈30-40% coverage (robustness vs MH ?)
- Is 90% C.L. enough ? at 3σ C.L. sensitivity is highly reduced even with largely increased statistics.
- Atmospherics to the rescue ?
- Official curves to be produced by experiments with revised projections.

MH 90%C.L. sensitivity CPV



Huber et al., JHEP 0911:044,2009

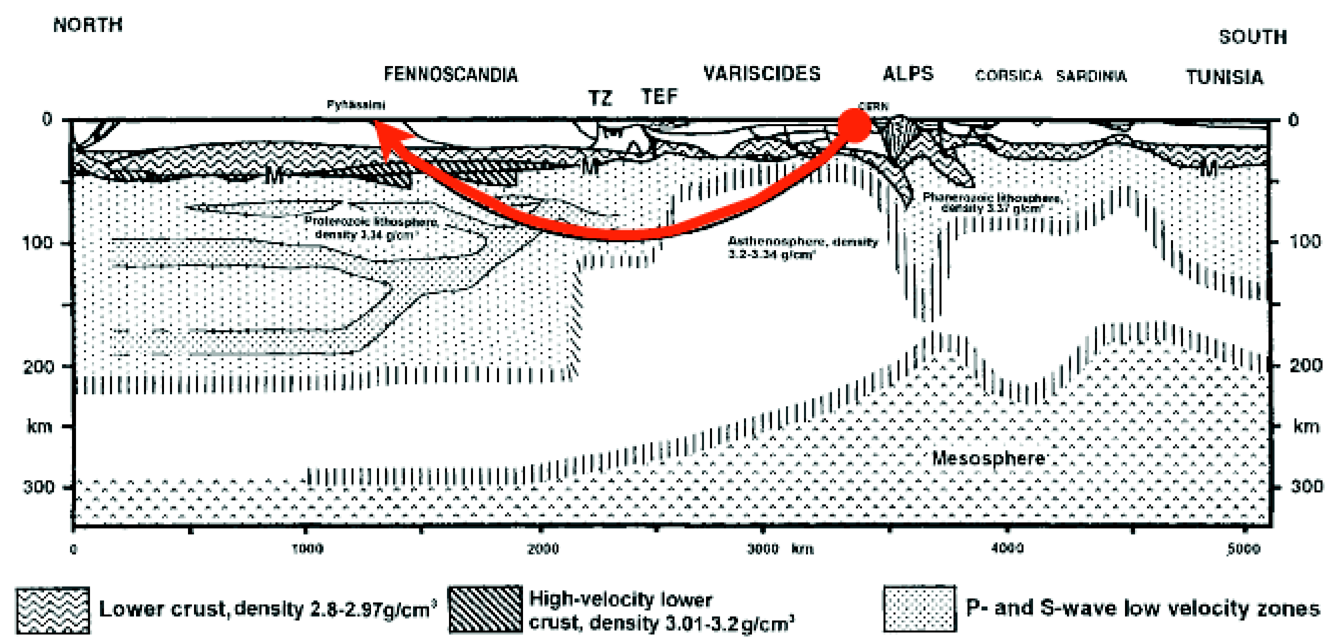
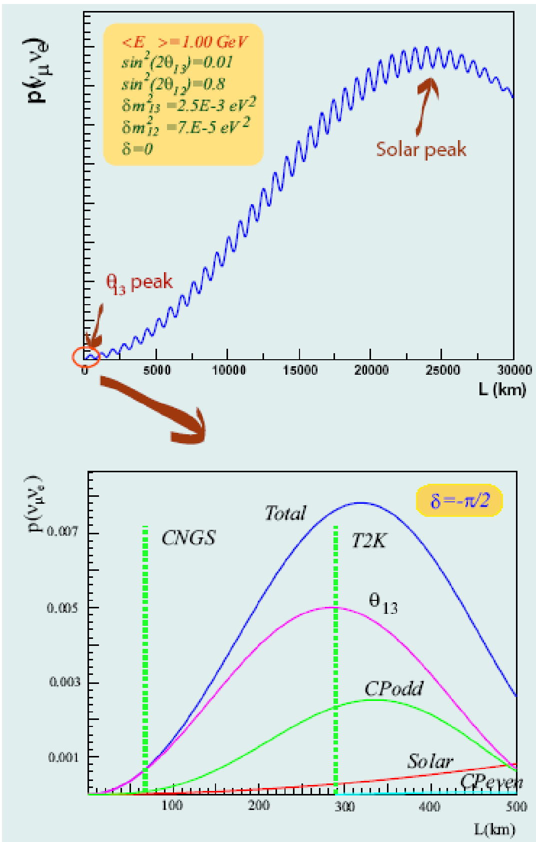


FIG. 18: Trajectory of the CERN-Pyhäsalmi neutrino (red thick line) on the map of main tectonic elements of Western Europe[120].

Sub leading $\nu_\mu - \nu_e$ oscillations

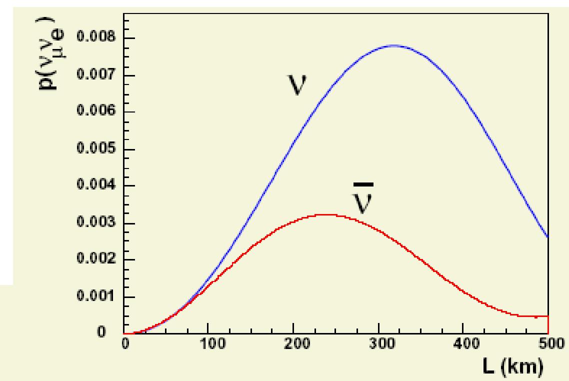


$$
\begin{aligned}
p(\nu_\mu \rightarrow \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} && \theta_{13}\ \text{driven} \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{CPeven} \\
& - 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{CPodd} \\
& + 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{solar driven} \\
& - 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E} (1 - 2s_{13}^2) && \text{matter effect (CP odd)}
\end{aligned}
$$

θ_{13} discovery requires total probability greater than solar driven probability

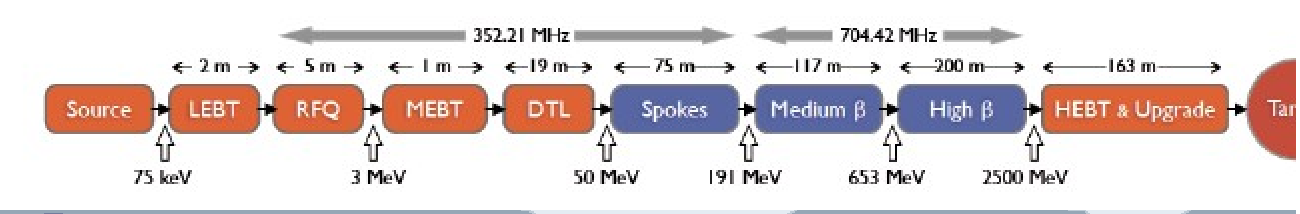
Leptonic CP discovery requires

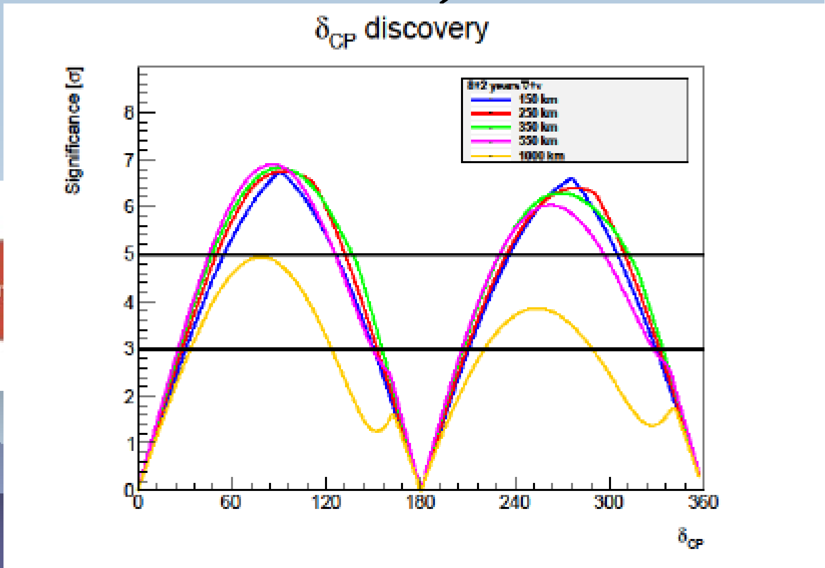
$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)} \neq 0$$



ESS neutrino beam proposal

- Proposal to complement the ESS facility (Lund, Sweden, ready in 2019) to produce a 5 MW 2.5 GeV proton beam
- The neutrinos (~350 MeV/c) would be aimed at the Zinkruvan mine (365 km) in Sweden
- Where a large WC detector (440 kt fiducial) would be located





Marco Zito

CERN to Canfranc proposal

- Proposal to build a new beam from CERN to Canfranc based either on SPS (800 kW, 1st osc. maximum) or on SPL (4 MW, 2nd osc. max)
- With a 500 kt fiducial Water Cherenkov detector in the Canfranc laboratory