Next Generation Accelerator Neutrino Projects - Long and Short Baseline

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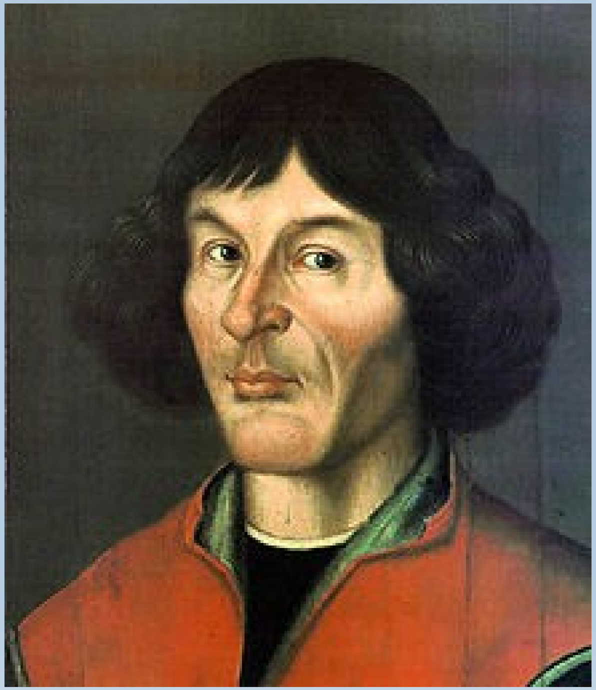
Standing on the shoulders of giants ...

N. Copernicus, studied in Kracow



E. Majorana

S. van der Meer in front of his horn

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

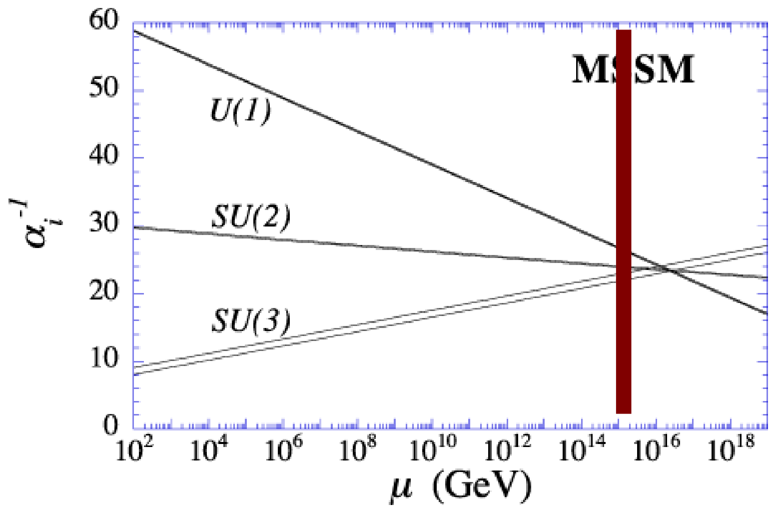
Beyond the Standard Model with neutrinos

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

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

Lowest order effect of physics at short distances !

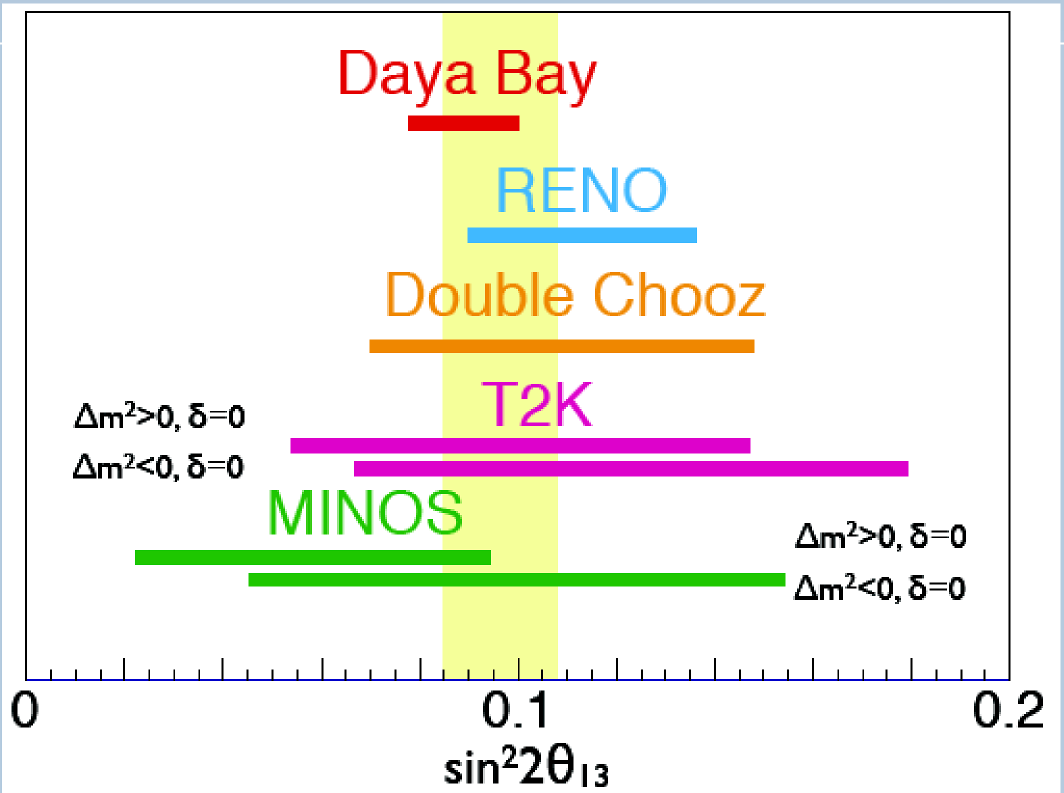
$$\mathcal{L}_5 = (LH)(LH) \rightarrow \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$



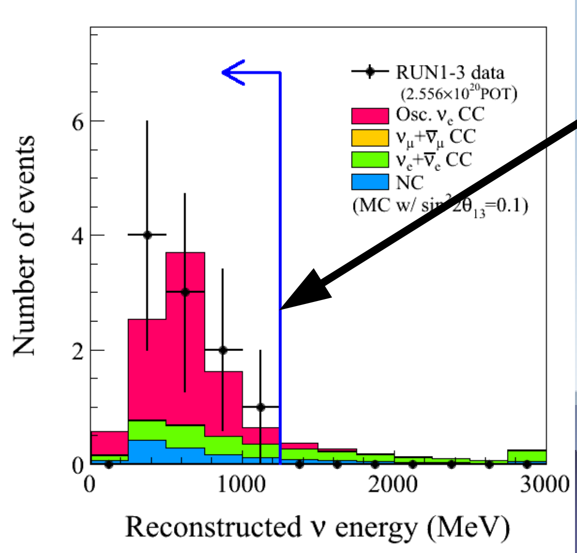
Progress since the last strategy plan

- Measurement of θ_{13} : major unknown measured
- European design studies : EUROnu, LAGUNA and LAGUNA-LBNO (>300 physicists, >4 years)-> conclusions from these studies in this presentation
- Feasibility studies of new neutrino beam technologies, detectors and underground labs
- Neutrino Town meetings : input from the community and recommended options to this forum. This talk is based on Contribution ID 81 by the Town Meeting Program Committee
- We are ready and organized to present well thought out projects to the strategy process!

The θ_{13} revolution



- Good agreement between the experiments
- This angle is sizable : θ_{13} ~ 9°
- We can proceed with the next steps

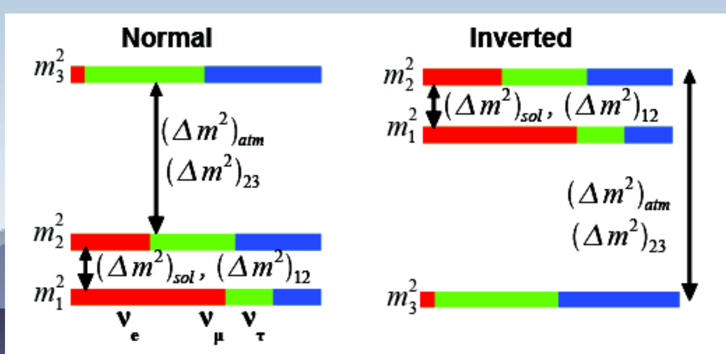


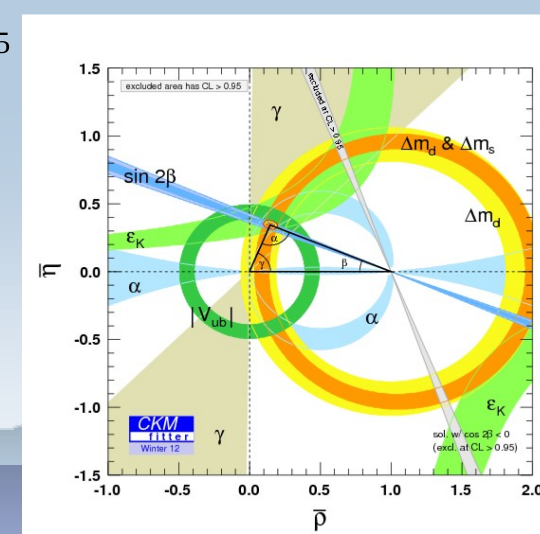
- T2K signal: 10 ev (2.7 exp. background)
- $\nu_\mu \to \nu_e$: main channel for CPV exploration
- First clean appearance experiment
- Large European effort

The mixing matrix PMNS

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

- The next step: discovery of the CP violation phase **δ** and mass hierarchy, precise measurement of θ_{23}
- In the end, we would like to explore PMNS to the same level of accuracy as CKM
- This calls for a complete set of precision measurements
- NB: Jarlskog invariant : J(PMNS) = 0.29 sin δ vs J(CKM) = 3 10^{-5}





Remaining part of this talk

1) Long baseline projects in Europe and elsewhere: towards the discovery of Mass Hierarchy and CP Violation, test of the PMNS paradigm
2) Short baseline projects : test the existence of new neutrino states

$\nu_\mu \to \nu_e$: beyond the leading term

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2} \sin^2((\hat{A}-1)\Delta)$$

"Atmospheric" term

$$+\alpha \frac{8 J_{CP}}{\hat{A}(1-\hat{A})} \sin(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)$$

CP violating term

$$+\alpha \frac{8 I_{CP}}{\hat{A}(1-\hat{A})} \cos(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)$$

$$+\alpha^2 \frac{\cos^2\theta_{23} \sin^2\theta_{12}}{\hat{A}^2} \sin^2(\hat{A}\Delta)$$

"Solar" term

$$J_{CP} = 1/8 \sin\delta_{CP} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

Jarlskog invariant

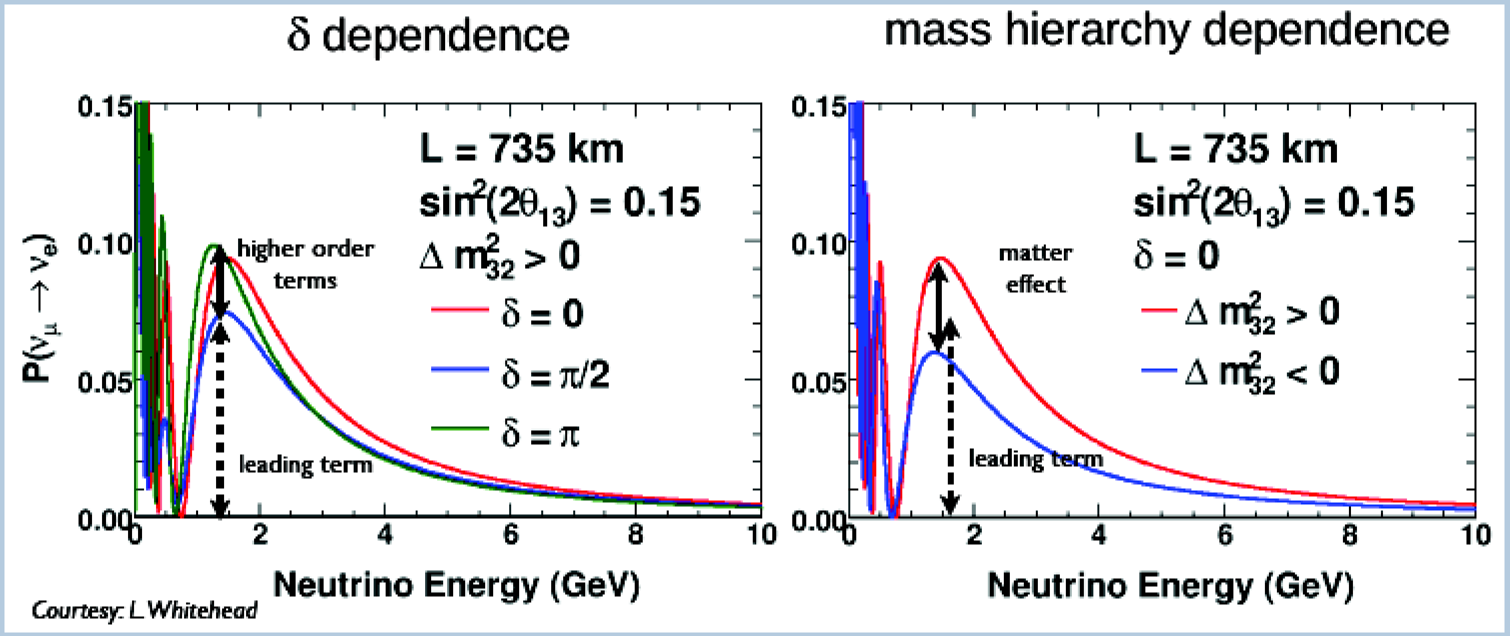
$$I_{CP} = 1/8 \cos\delta_{CP} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$\alpha = \Delta m^2_{21} / \Delta m^2_{31}, \Delta = \Delta m^2_{31} L / 4E$$

$$\hat{A} = 2VE / \Delta m^2_{31} \approx (E_\nu / GeV)/11$$

Approximate formula with matter effect:
M. Freund hep-ph/0103300

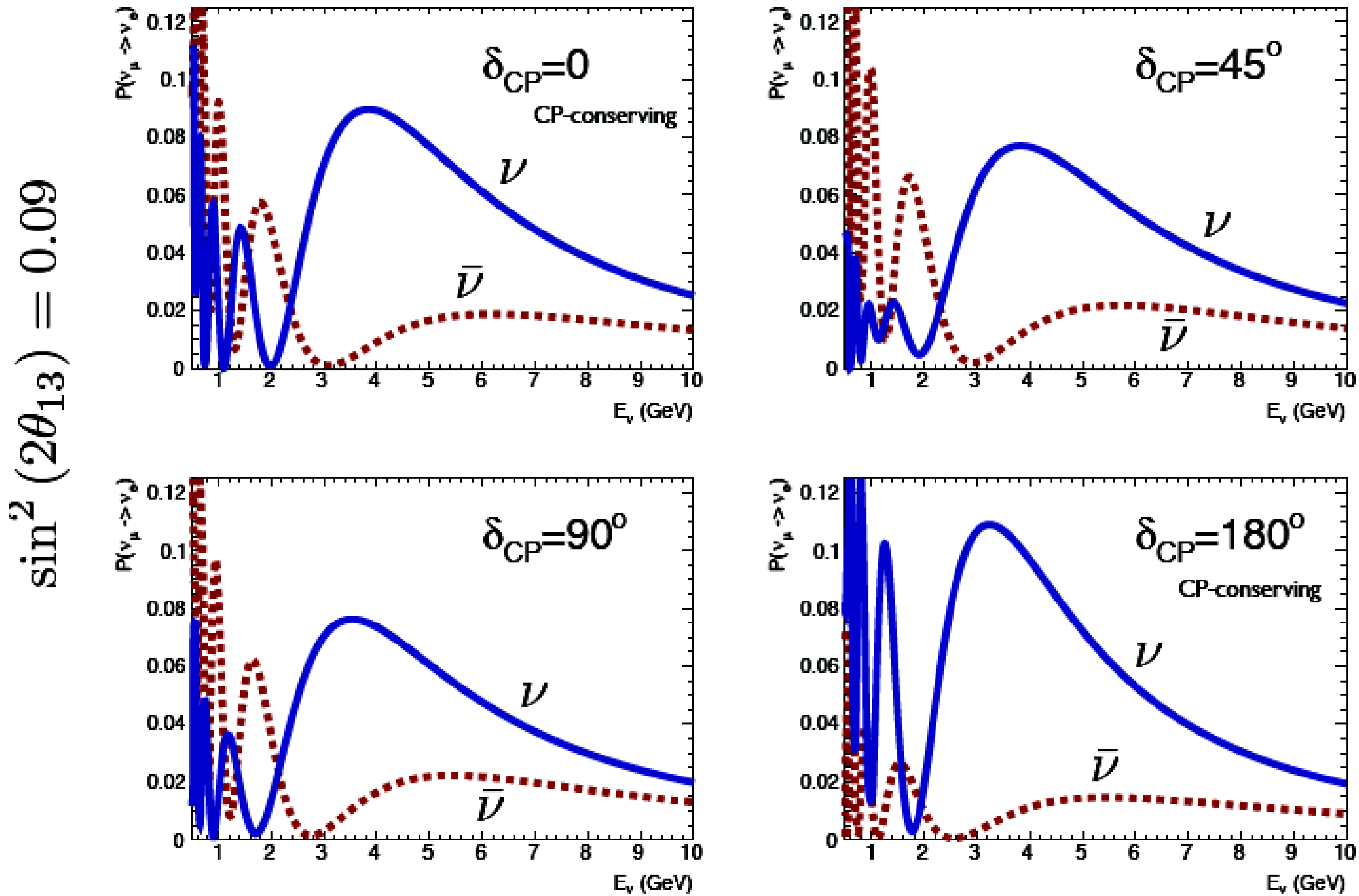
Interplay of CP and Matter Effects



- The simple study of the CP asymmetry is obscured (or enriched) by matter effects (interaction of ν 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

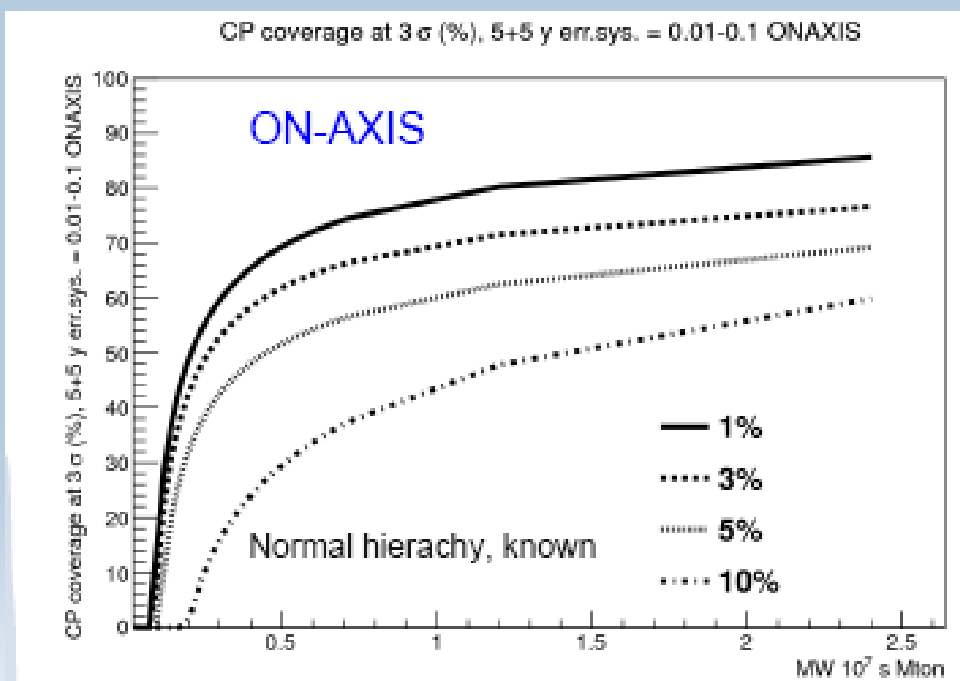
CERN-Pyhäsalmi: oscillations

★Normal mass hierarchy L=2300 km

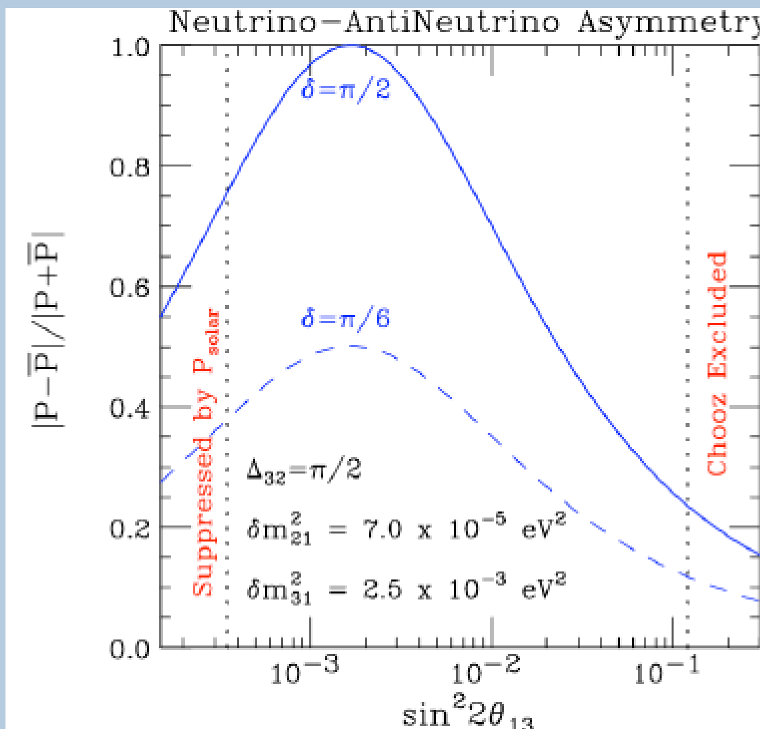


The experimental challenge of large θ$_{13}$

Large θ$_{13}$ means small asymmetry (~20% at most) : need to control the systematics to 5% or better for a precision measurement



A. Longhin@nuTurn



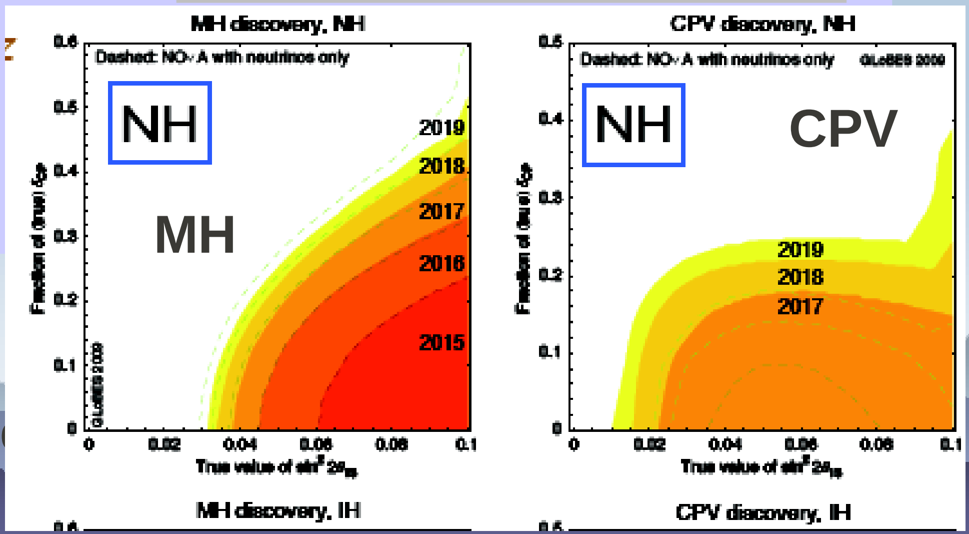
S. Parke

Long baseline : the consensus

- The currently approved/running experiments (T2K, N0vA) will not be able to fully explore the PMNS matrix
- We need a new experimental facility : beam + far detector
- First step of this program: a conventional neutrino beam
- An underground detector is both a must and a bonus: rich astrophysical program related to PMNS and GUT studies
- Control of the systematics: a hadroproduction experiment, a near detector, possibly additional cross-section measurements

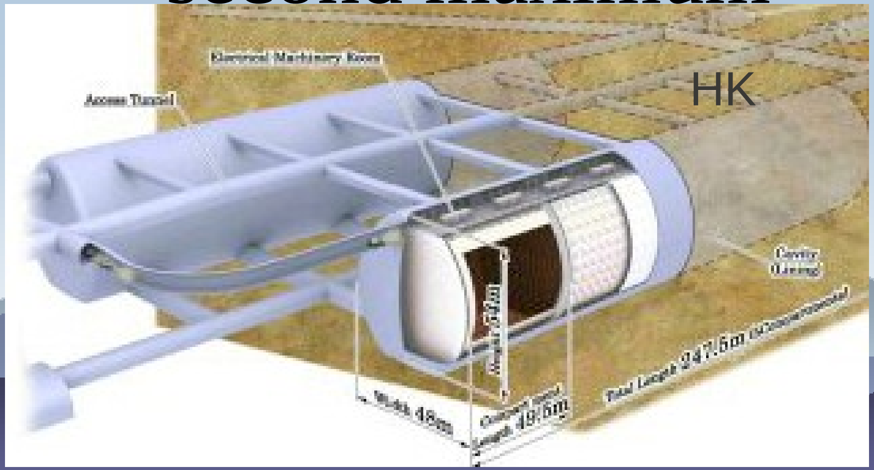
P. Huber et al: JHEP0911:044

Recently completed 1st NOvA block

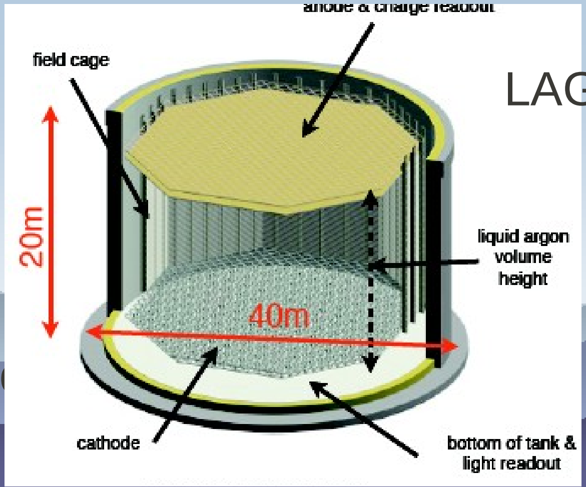


The two strategies towards CP violation

- 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



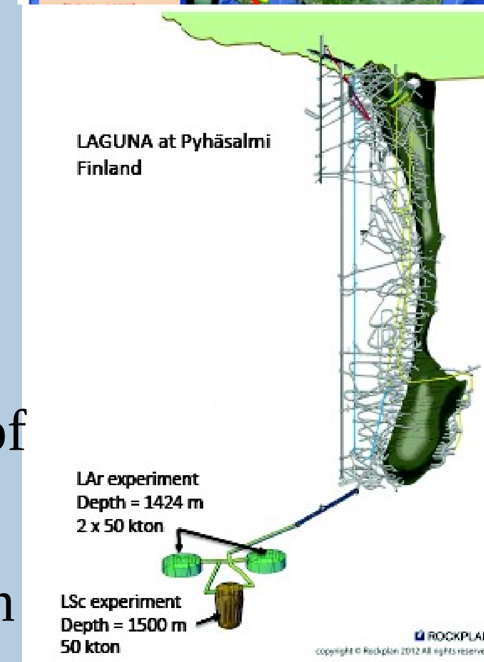
HK

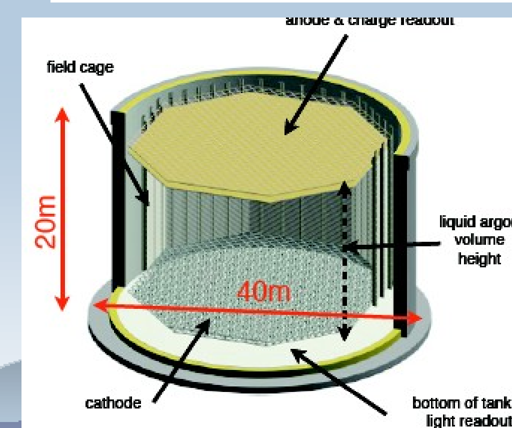


LAGUNA

LAGUNA-LBNO

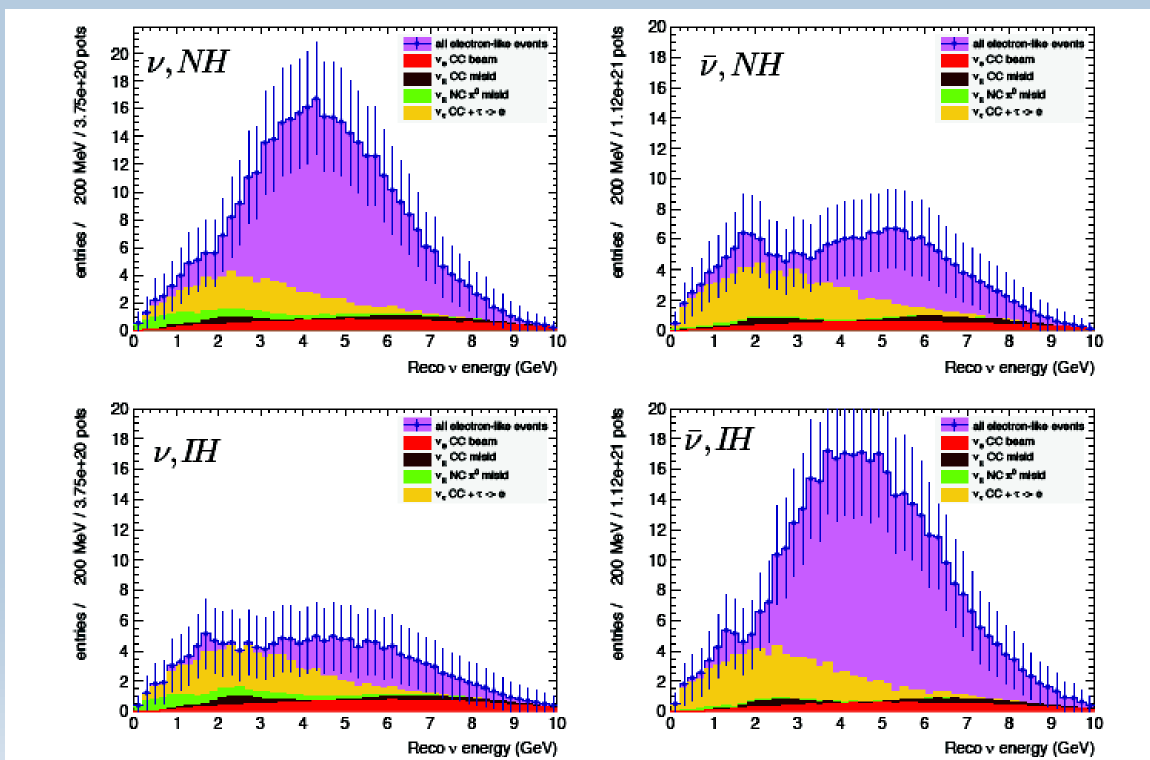
- The LAGUNA-LBNO consortium proposes to create a new European underground laboratory at Pyhäsalmi (Finland) at 2300 km from CERN
- The choice is based on scientific, technological and practical advantages of the site
- The laboratory can host a 50+50 kT liquid Argon detector combined with a 50 kT magnetized Fe detector for the detection of beam ν
- 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 that can be fully exploited together with a 50 kt Liquid scintillator
- Recently submitted EOI to SPSC (230 authors, 51 labs)



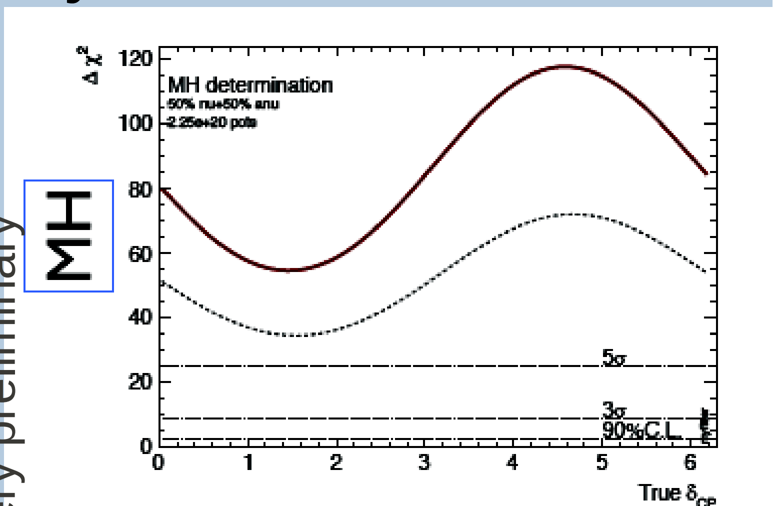


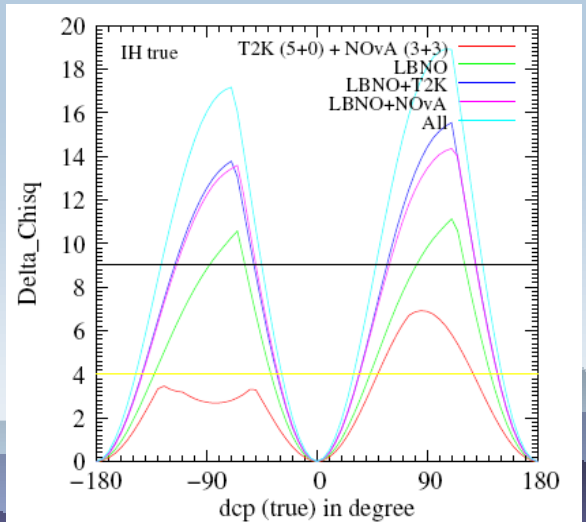
LAGUNA-LBNO : physics reach

- Mass hierarchy : 100 % coverage at 5 σ in a few years
- CPV: 71 (44) % coverage at 90% (3σ)in 10 years



S. Agarwalla, A. Rubbia Very preliminary



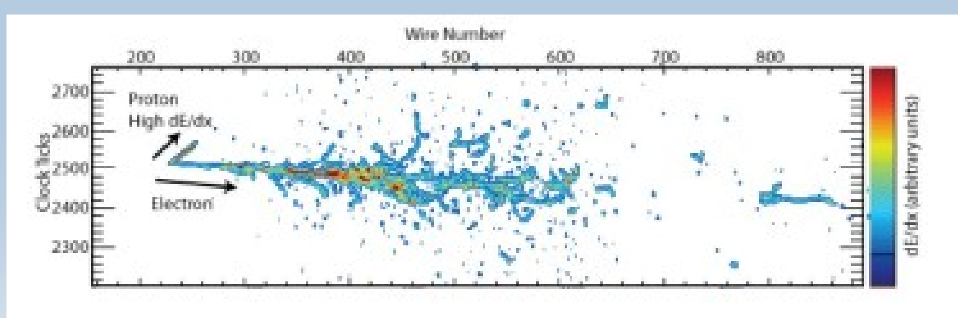


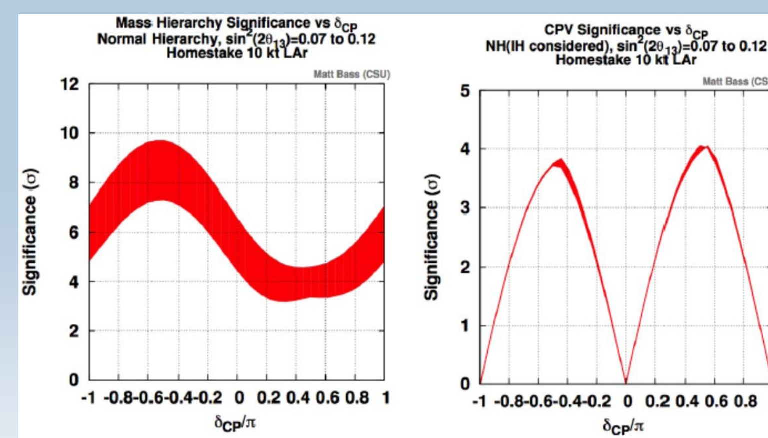
LAGUNA-LBNO : reach and plans

- 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)
- <u>Clear upgrade path</u>. Baseline adopted by the Neutrino Factory/Euronu studies
- Call to CERN to support design of the beam and detector R/D

LBNE : the US long baseline project

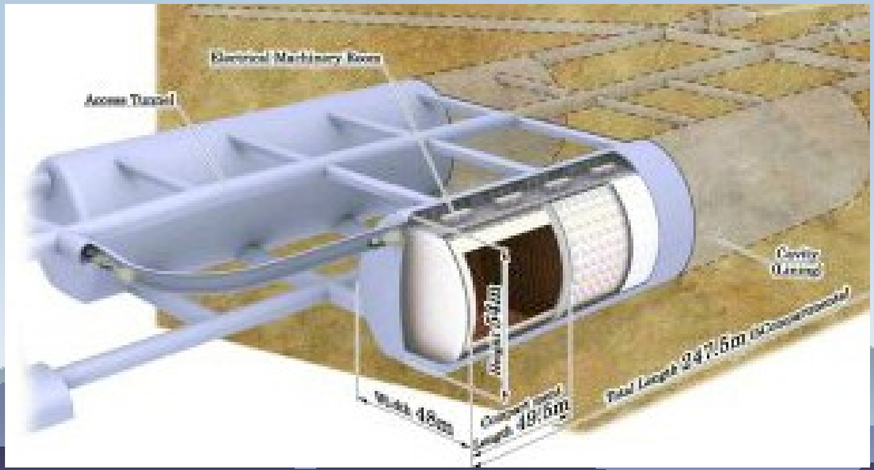
- New 700 kW beamline from Fermilab to Homestake (1300 km) with a 10 kt Liquid Argon detector (on surface, and without Near Detector unless additional funds)
- The project underwent recently a reconfiguration phase
- The further stages include a Near Detector, an underground Far Detector (up to 35 kt)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

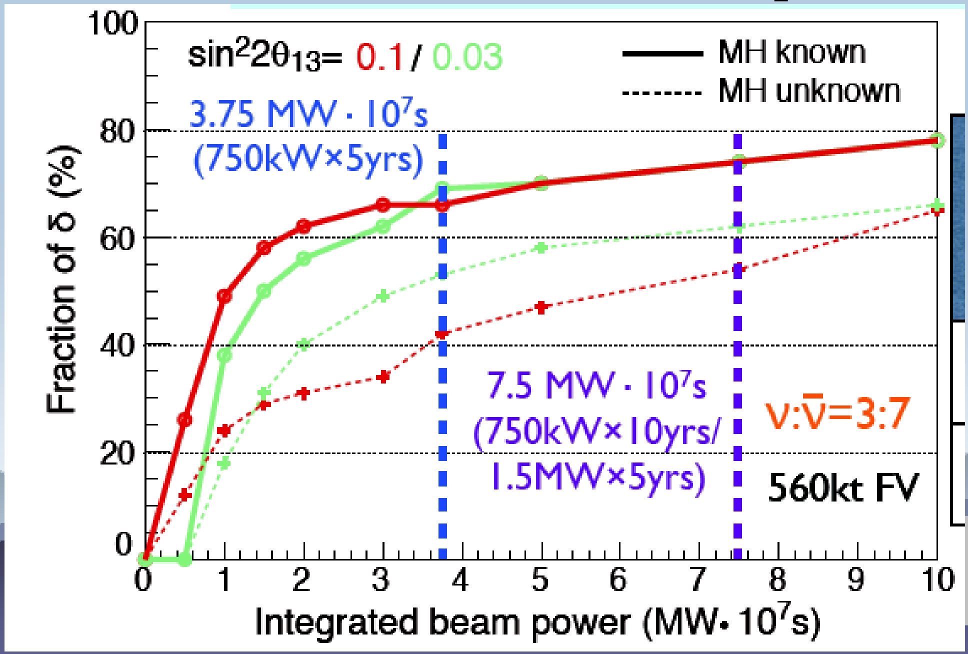




Long baseline in Japan

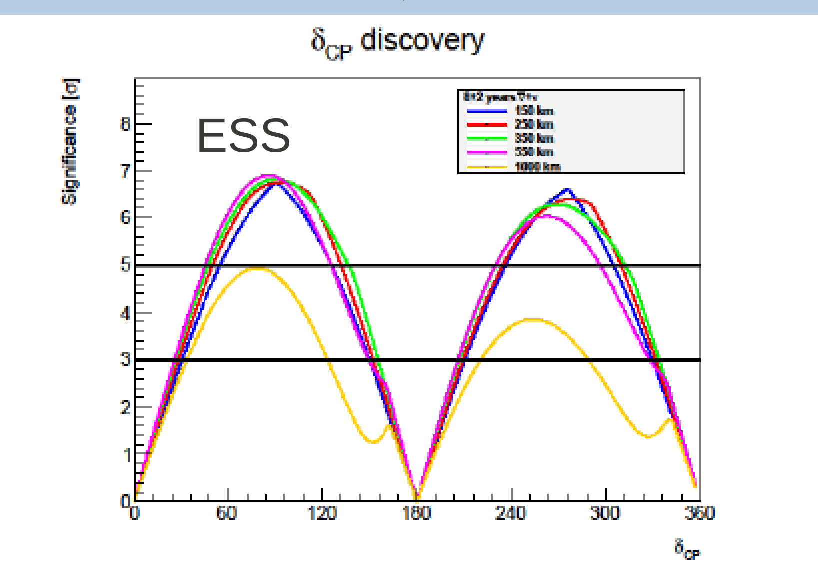
- T2HK :Very large Water Cherenkov with fiducial mass 0.56 Mton (25xSK)
- Two caverns (248x54x48 m^3, 99 000 20" PMT)
- 750 kW beam from JPARC : 295 km baseline
- 74% (55%) CP coverage (3σ) if MH known (unknown)
- Other option: Tokai to Okinoshima : 650 km with Liquid Argon Far Detector



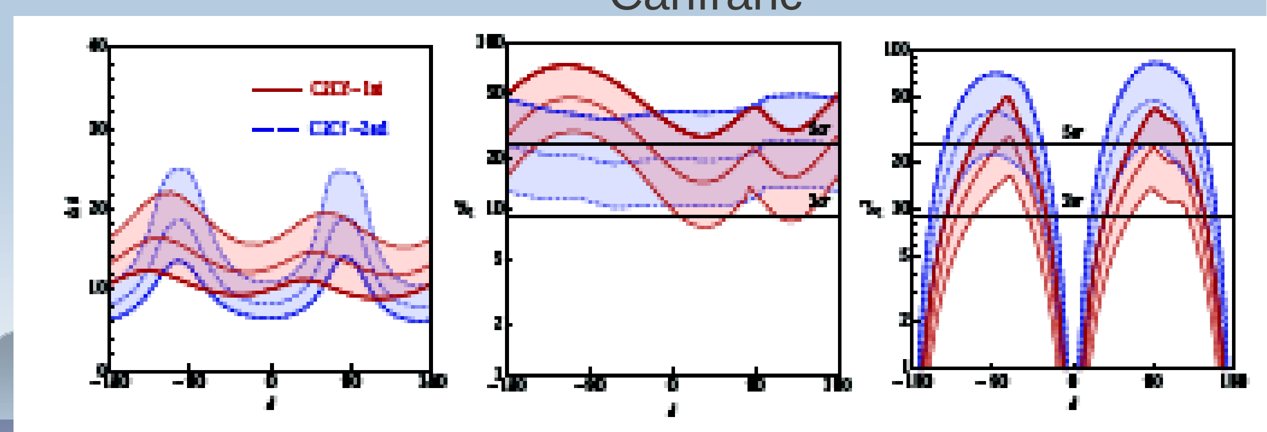


Other ideas in Europe

- 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)



Canfranc

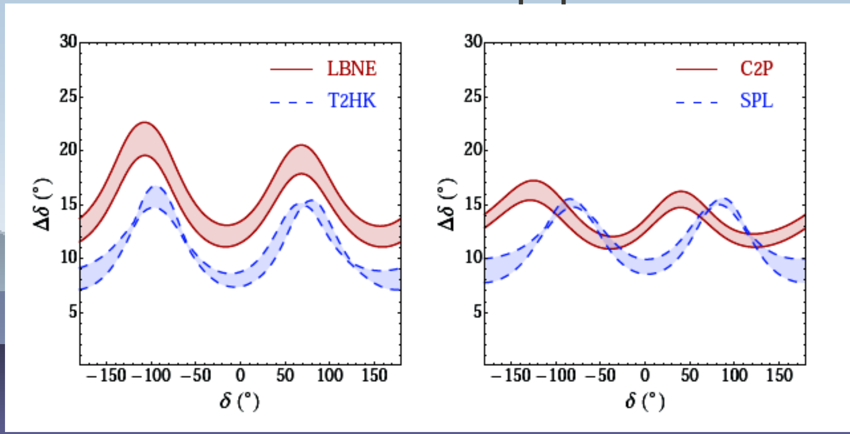


Long baseline projects

Project	Beam power MW	Fiducial Mass kt	Baseline km	MH	CPV 90%CL, (3σ)	Physics starts	Astrophysical program
LBNO	0.8	20->100	2300	Excellent	71 (44)	2023	Yes
T2HK	0.75	500	295	Little	86 (74)*	2023	Yes
LBNE	0.7	10	1300	OK	69 (43)	2022	No
Lund	5	440	365	Some	86 (70)	>2019	Yes
CERN-Canfranc	0.8-4	440	650	Some	80-88(80)	>2020	Yes

*: if mass hierachy is known

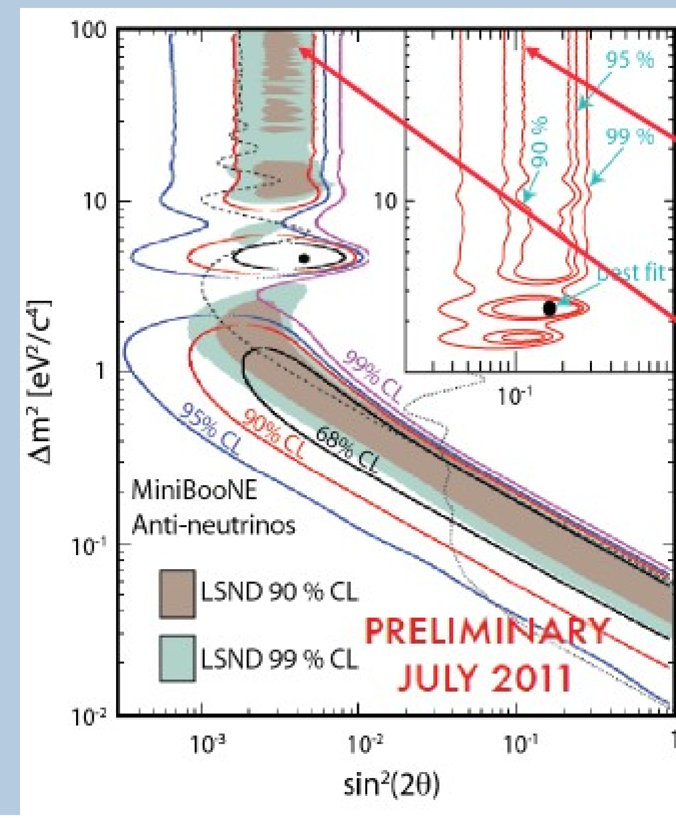
P. Coloma et al.hep-ph:1203.5651

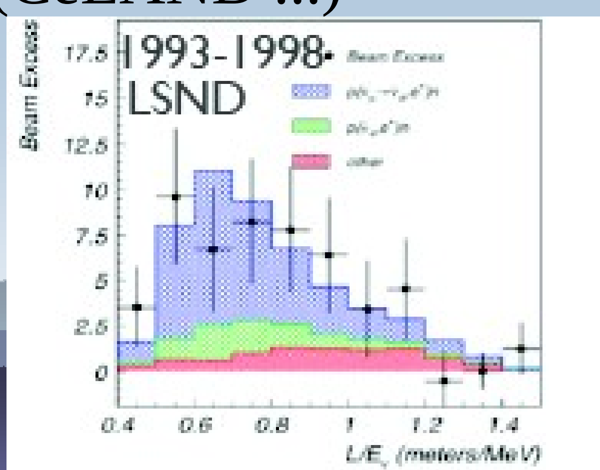


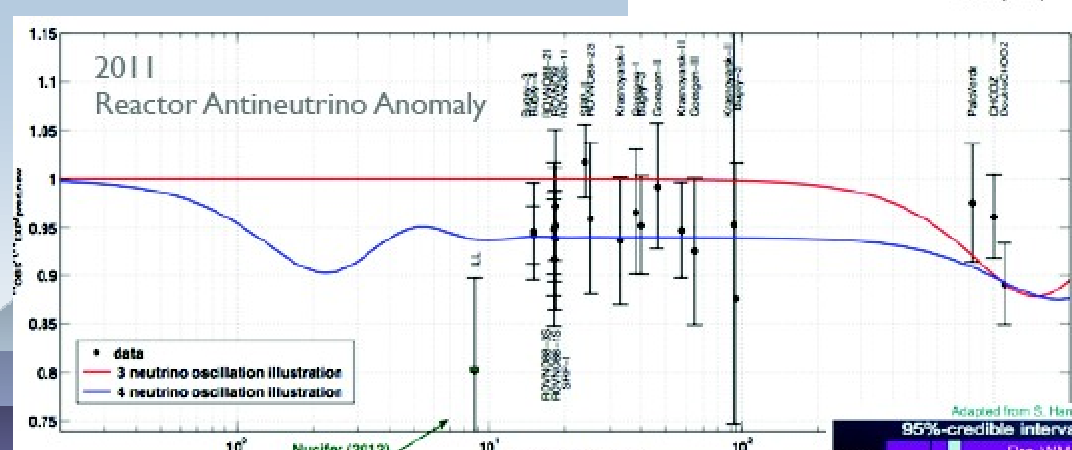
T2HK: 4MW, 500 kt
LBNE: 0.8 MW,33 kt
C2P=LBNO : 0.8 MW, 100 kt

Neutrino anomalies

- There are hints of possible new states beyond the three observed neutrinos:
- LSND anomaly in $\nu_\mu \rightarrow \nu_e$ channel
- The neutrino deficit in reactor fluxes
- Is there a new ν with $\Delta m^2 \sim 1\ eV^2$?
- Many experimental approaches: reactor exp., strong sources close to an existing det. (CeLAND ...)

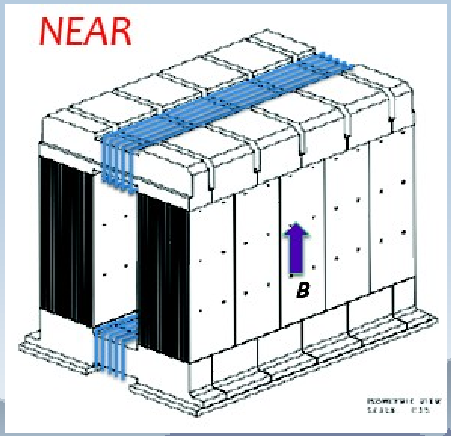




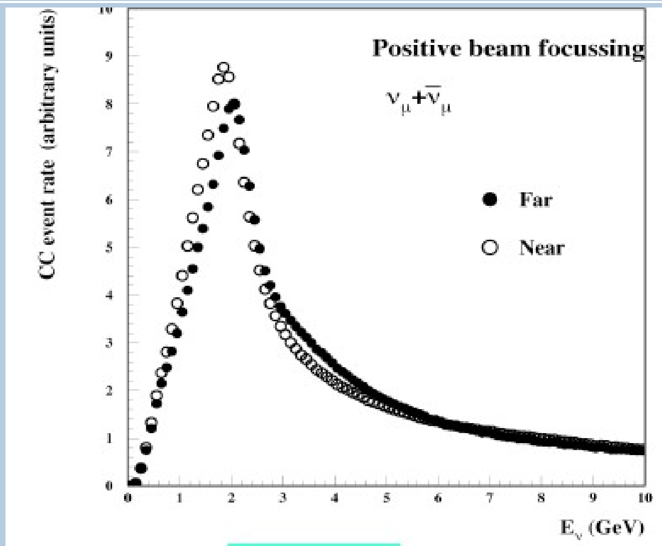


SPSC-P-347 (Icarus-Nessie)

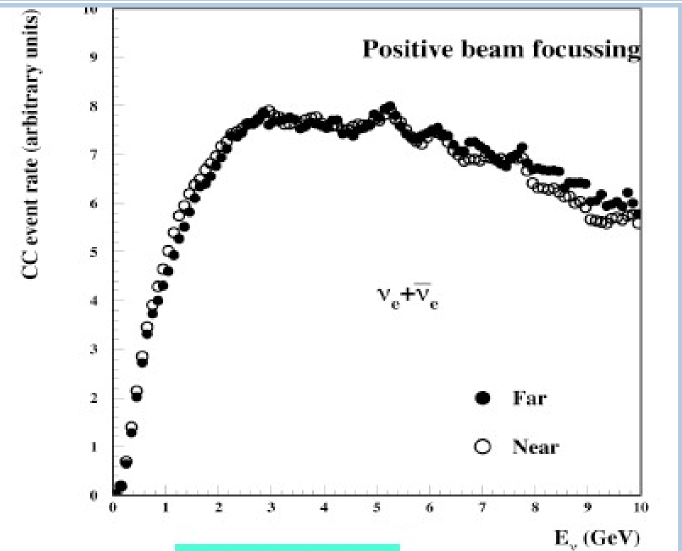
- Proposal (SPSC-P-347, 150 authors) of a comprehensive search for new neutrino states around $\Delta m^2 \sim 1 eV^2$ using a SPS 110 GeV proton beam in the NA
- with two LAr detectors, at 1600 m (ICARUS T600 now at Gran Sasso) and 300m (T150), supplemented by two spectrometers
- Method : two identical detectors, with imaging properties and complete final state reconstruction



SPSC-P-347

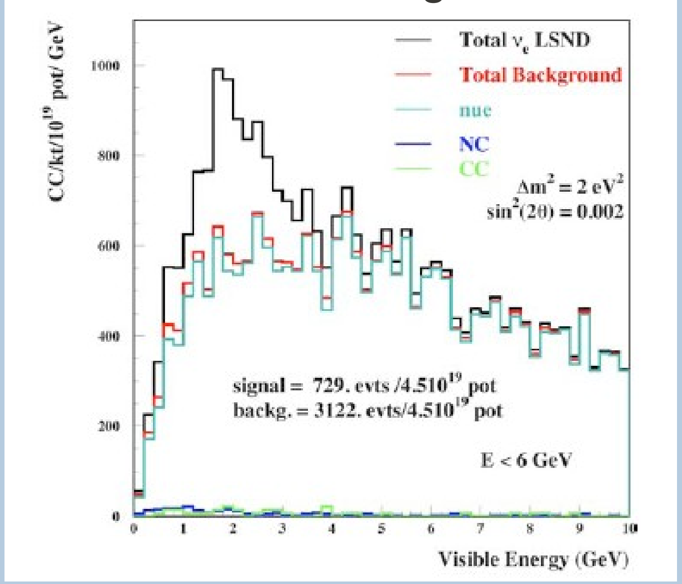


CC muons



CC electrons

Possible "LSND" signal 1500ev

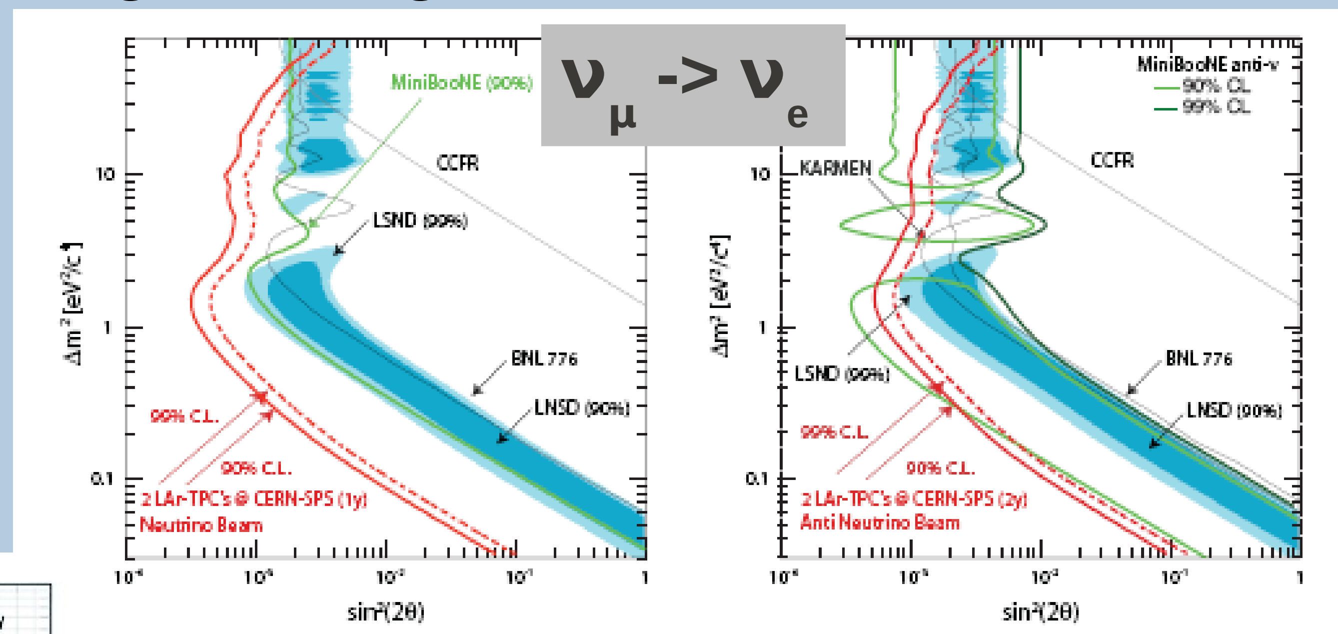


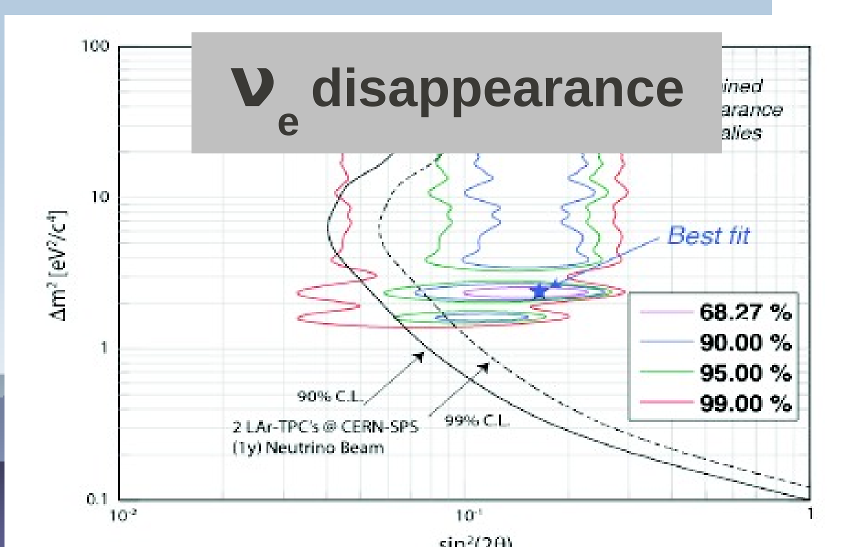
One year of data-taking in negative focusing (ν)

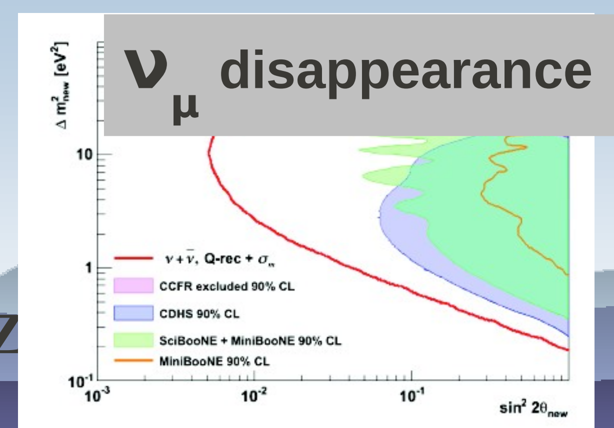
		NEAR (ν-bar)	NEAR(ν)	FAR(ν-bar)	FAR(ν)
produced	$\nu_e + \nu_e$-bar (LAr)	35 K	54 K	4.2 K	6.4 K
	$\nu_\mu + \nu_\mu$-bar (LAr)	2000 K	5250 K	270 K	670 K
	Appear. test point	590	1900	360	910
detected	ν_μ (LAr+NESSiE)	230 K	1200 K	21 K	110 K
	ν_μ (NESSiE)	1150 K	3600 K	94 K	280 K
	ν_μ-bar (Lar+NESSiE)	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

SPSC-P-347

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



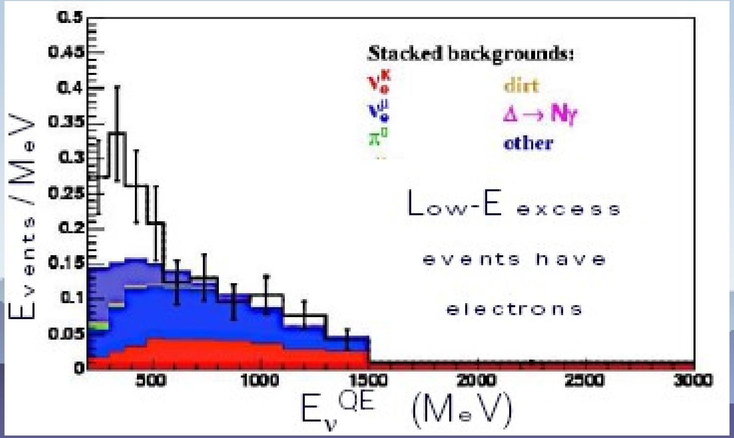


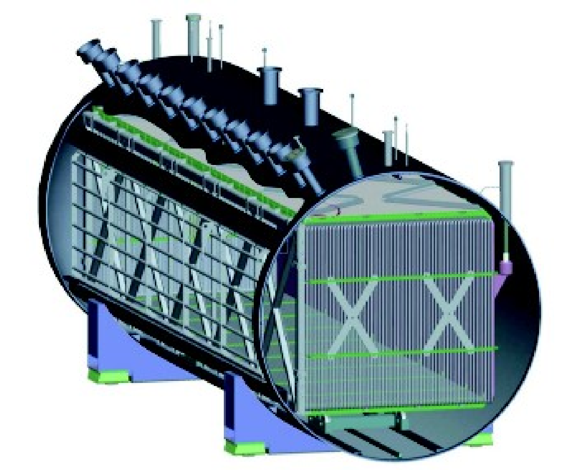


Contribution ID149

MICROBooNE

- 70 ton Liquid Argon detector under construction (completion end 2013) on the Booster neutrino beam line at FNAL
- Same baseline as MiniBooNE : 500 m, E=0.7 GeV
- Study of the low energy excess of MiniBooNe: electron or photons ? 5 (e) or 4 (γ) σ possible in 2-3 years
- Possible construction of 1 kton Liquid Argon TPC (LAr1) to investigate the MiniBoone antineutrino anomaly

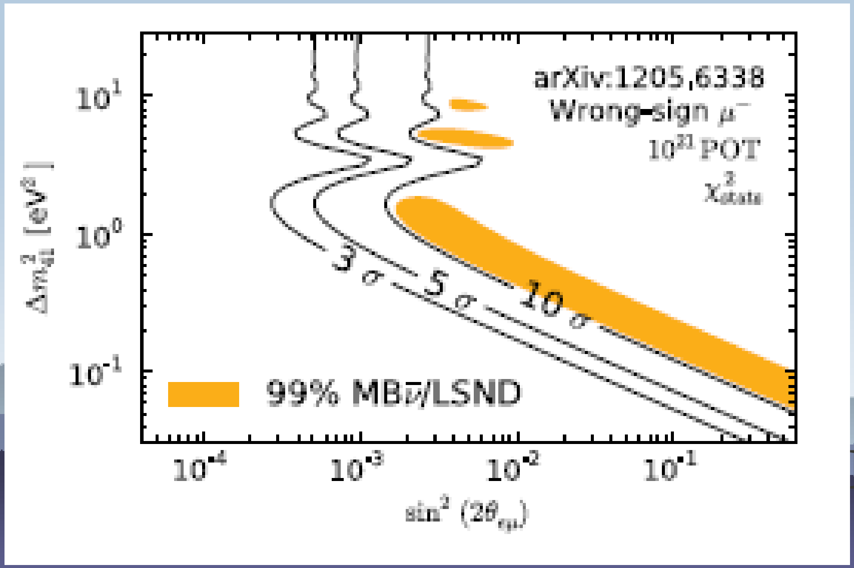


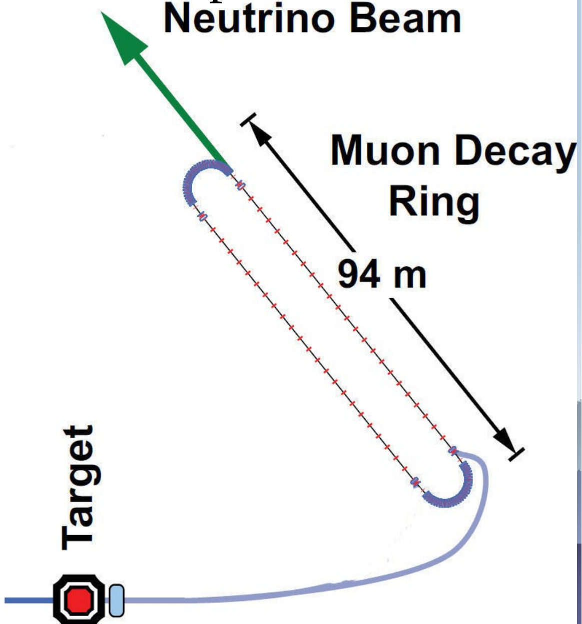


Contribution ID108

νSTORM

- LOI submitted to FNAL PAC
- Use a muon decay ring to produce with $\mu\text{->}e\ \nu_\mu\ \bar{\nu}_e$ a precisely known beam aimed at a magnetized iron detector to
- Investigate the LSND signal in the T conjugated mode $\nu_e \text{->} \nu_\mu$ 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, on the EUROnu road map





Conclusions-1

- Clear conclusions from the Town Meeting summarized here
- 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 existing CERN accelerator, and a longer term vision with this baseline optimized for the Neutrino Factory
- Europe needs this new long baseline facility to stay at the frontier of the field

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" (from Town Meeting Summary Document)
- 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

P. Huber @ Town Meeting

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?

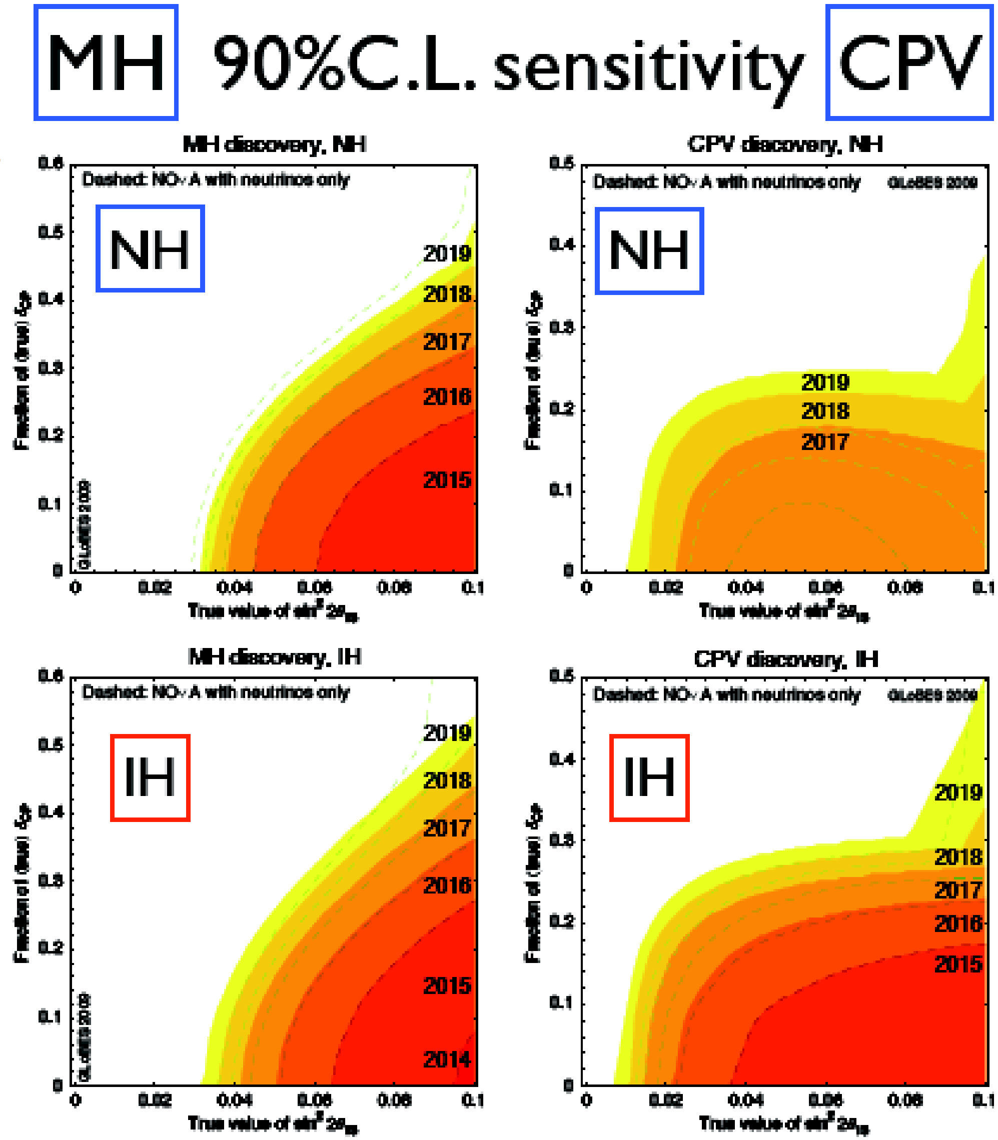
It is very difficult to rank those measurements in their relative importance

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.

P. Huber – VT-CNP – p. 2

T2K and NOvA: in the future

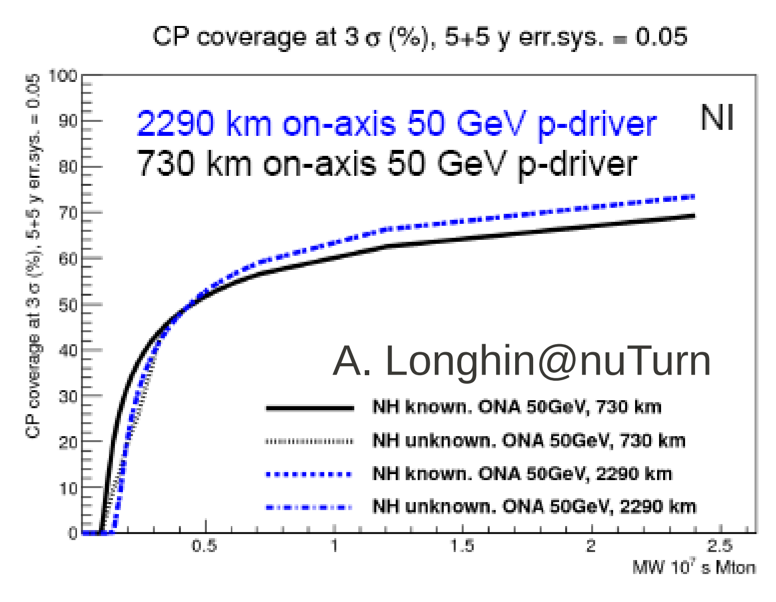
- Preliminary estimation of sensitivity of T2K and NOvA *See talk by Schwetz*
- Nominal beam power scenarios (750kW). Need to check beam power assumptions.
- For $\sin^2 2\theta_{13}=0.1$, approximately (at 90%C.L.):
  - MH: ≈50% coverage
  - CPV: ≈30-40% coverage (robustness vs MH ?)
- Is 90% C.L. enough ? 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.



Huber et al., JHEP 0911:044,2009

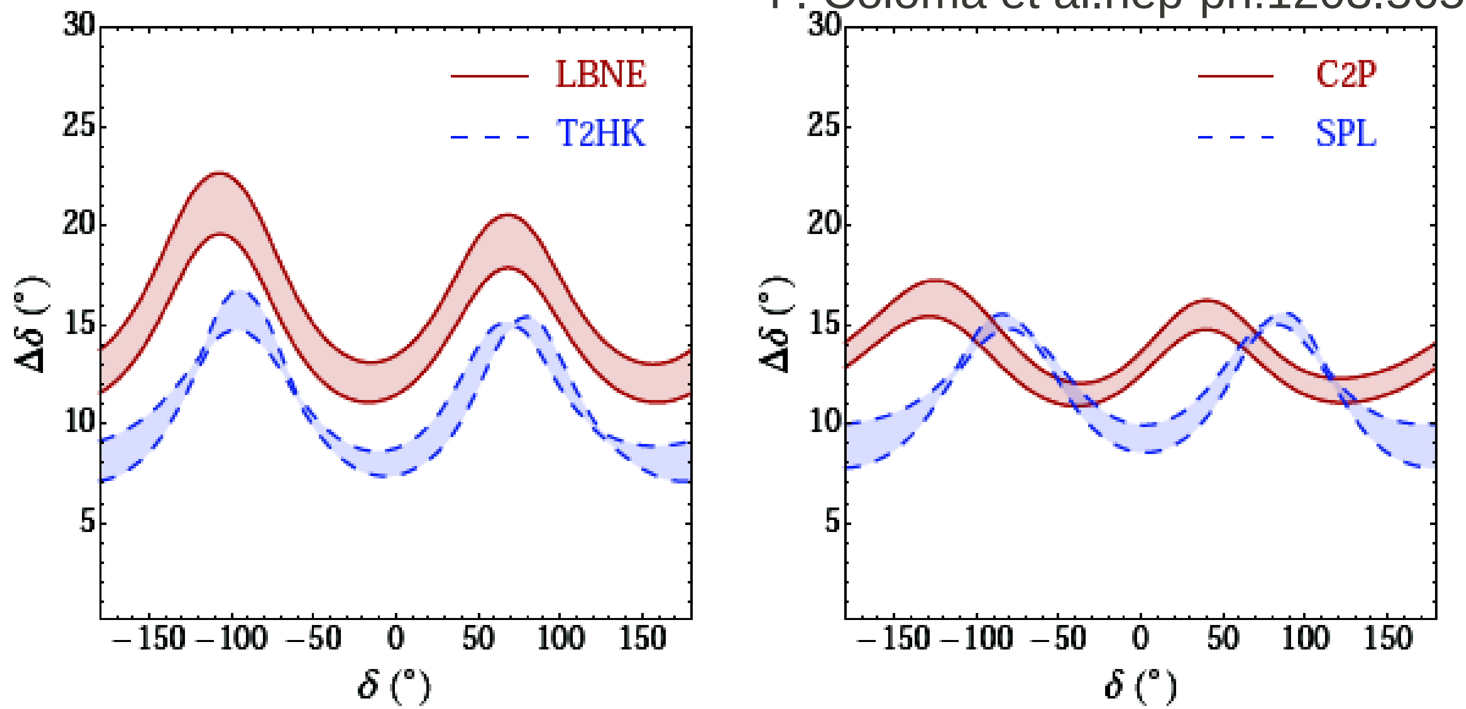
CPV and the baseline issues

- CPV sensitivity is mainly driven by the total exposure (MW Mt year) and by the control of systematic uncertainties
- The baseline has a relatively mild effect
- For ultimate exposure, the sensitivity to the second maximum is at premium



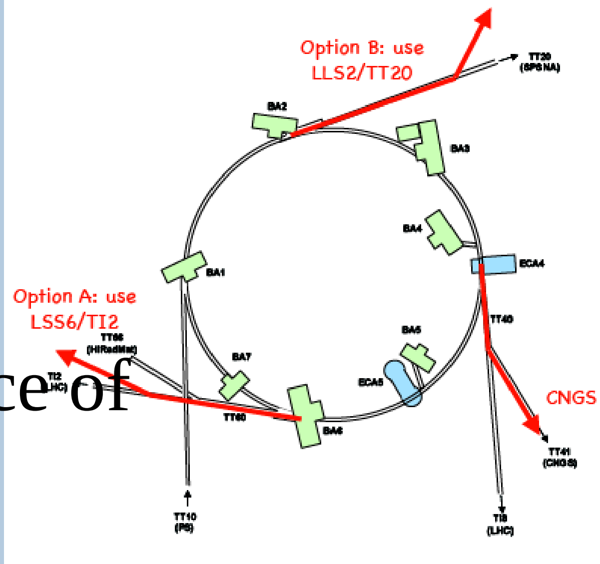
CPV sensitivity

P. Coloma et al.hep-ph:1203.5651



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

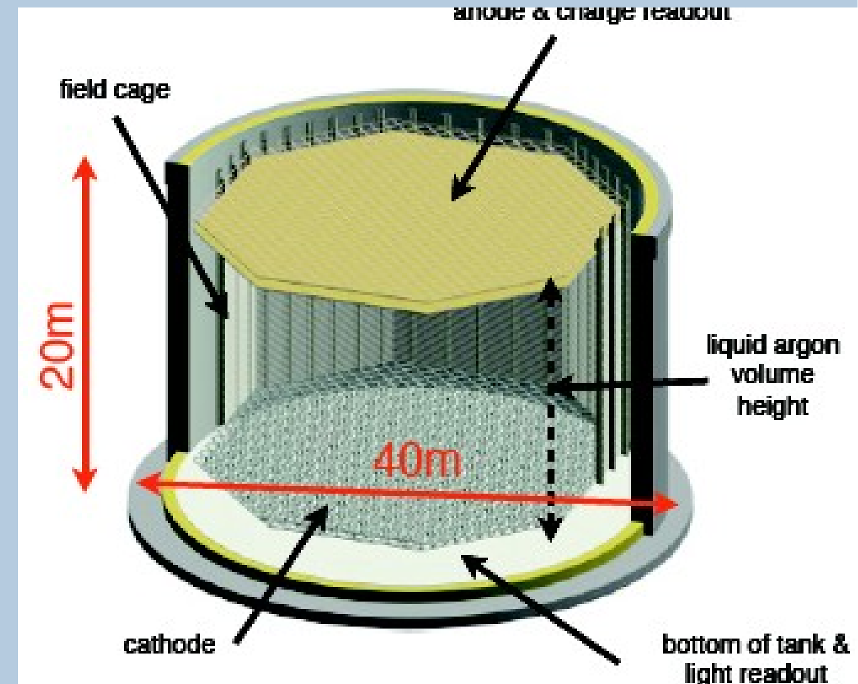
LAGUNA-LBNO beam

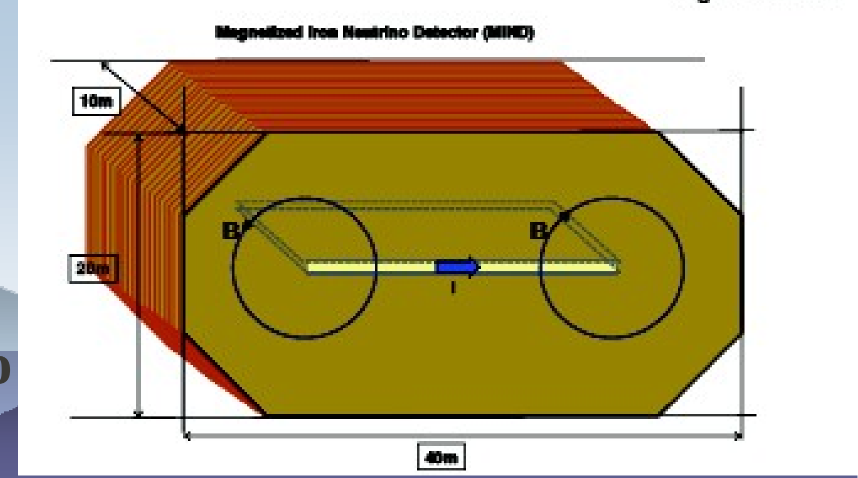


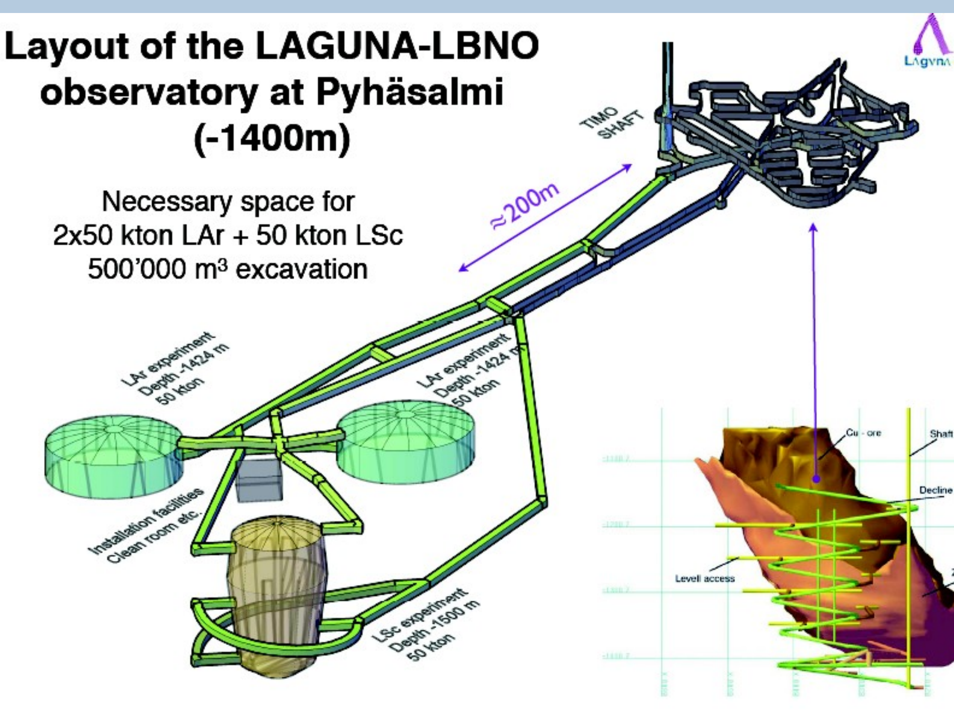
- Phase I : use the 400 GeV SPS proton beam
- Horn focused neutrino beam, based on CNGS technology
- (0.8-1.3)10**20 pot from improved performance of injectors + SPS
- Target station and tunnel in NA
- Near detector at 500-800 m
- Upgrade path with HP-PS with significant power improvement
- Under study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

LAGUNA-LBNO underground lab and detector

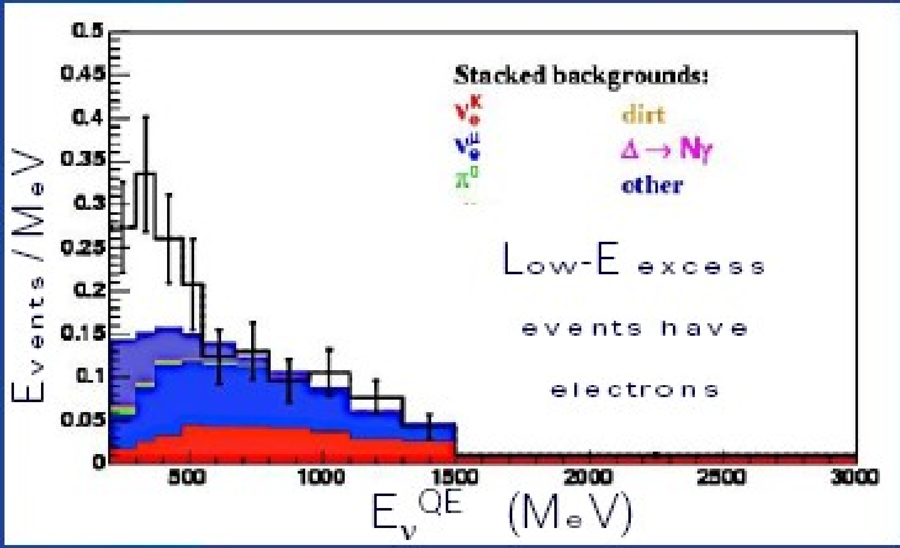
- Detector complex at -1400 m
- Excellent quality of the rock and mine infrastructure
- Initial configuration : 20 kT + magnetized iron detector





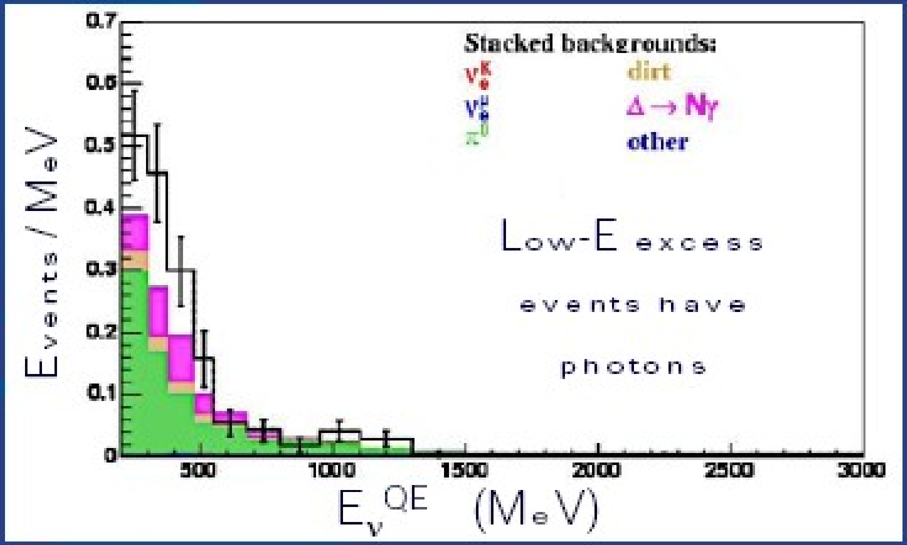


MicroBooNE



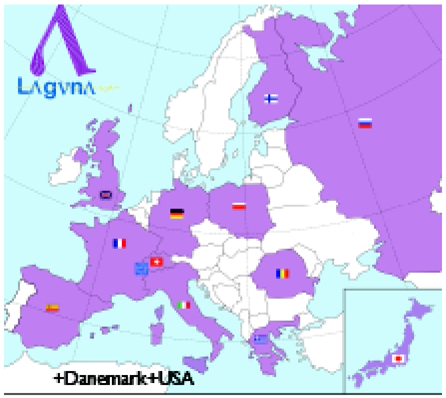
6×10^{20} pot in neutrino mode (2-3 year run, starting 2014)

If the MiniBooNE low energy excess is due to electrons, MicroBooNE expects a 5σ signal



If the MiniBooNE low energy excess is due to photons, MicroBooNE expects a 4σ excess

LAGUNA-LBNO consortium



14 countries, 47 institutions, ~300 members

Switzerland
University Bern
University Geneva
ETH Zürich (*coordinator*)
Lombardi Engineering*

Finland
University Jyväskylä
University Helsinki
University Oulu
Rockplan Oy Ltd*

CERN

France
CEA
CNRS-IN2P3
Sofregaz*

Germany
TU Munich
University Hamburg
Max-Planck-Gesellschaft
Aachen
University Tübingen

Poland
IFJ PAN
IPJ
University Silesia
Wroklaw UT
KGHM CUPRUM*

Greece
Demokritos

Spain
LSC
UA Madrid
CSIC/IFIC
ACCIONA*

United Kingdom
Imperial College London
Durham
Oxford
QMUL
Liverpool
Sheffield
Sussex
RAL
Warwick
Technodyne Ltd*
Alan Auld Ltd*
Ryhal Engineering*

Romania
IFIN-HH
University Bucharest

Denmark
Aahrus

Italy
AGT*

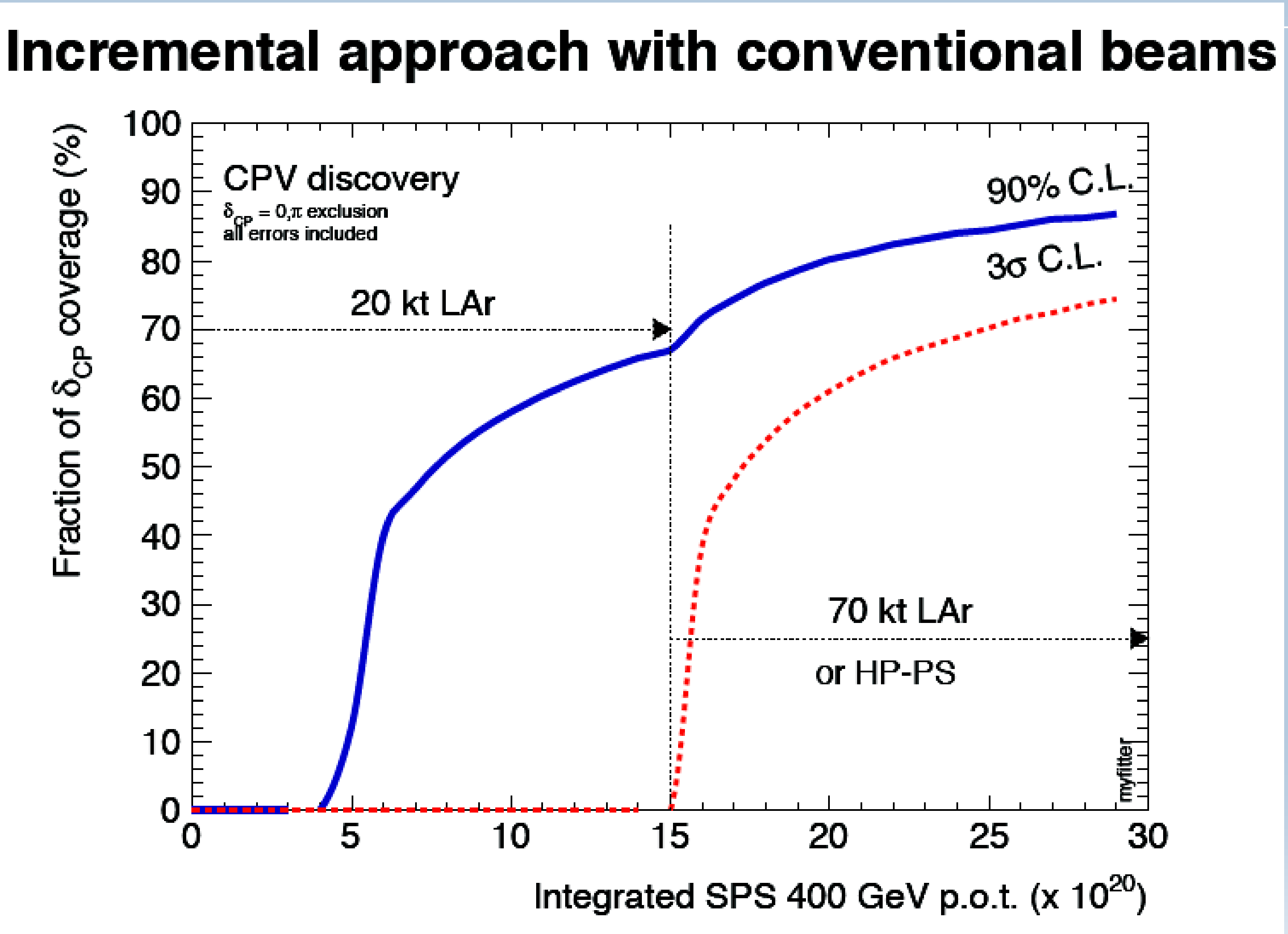
Russia
INR
PNPI

Japan
KEK

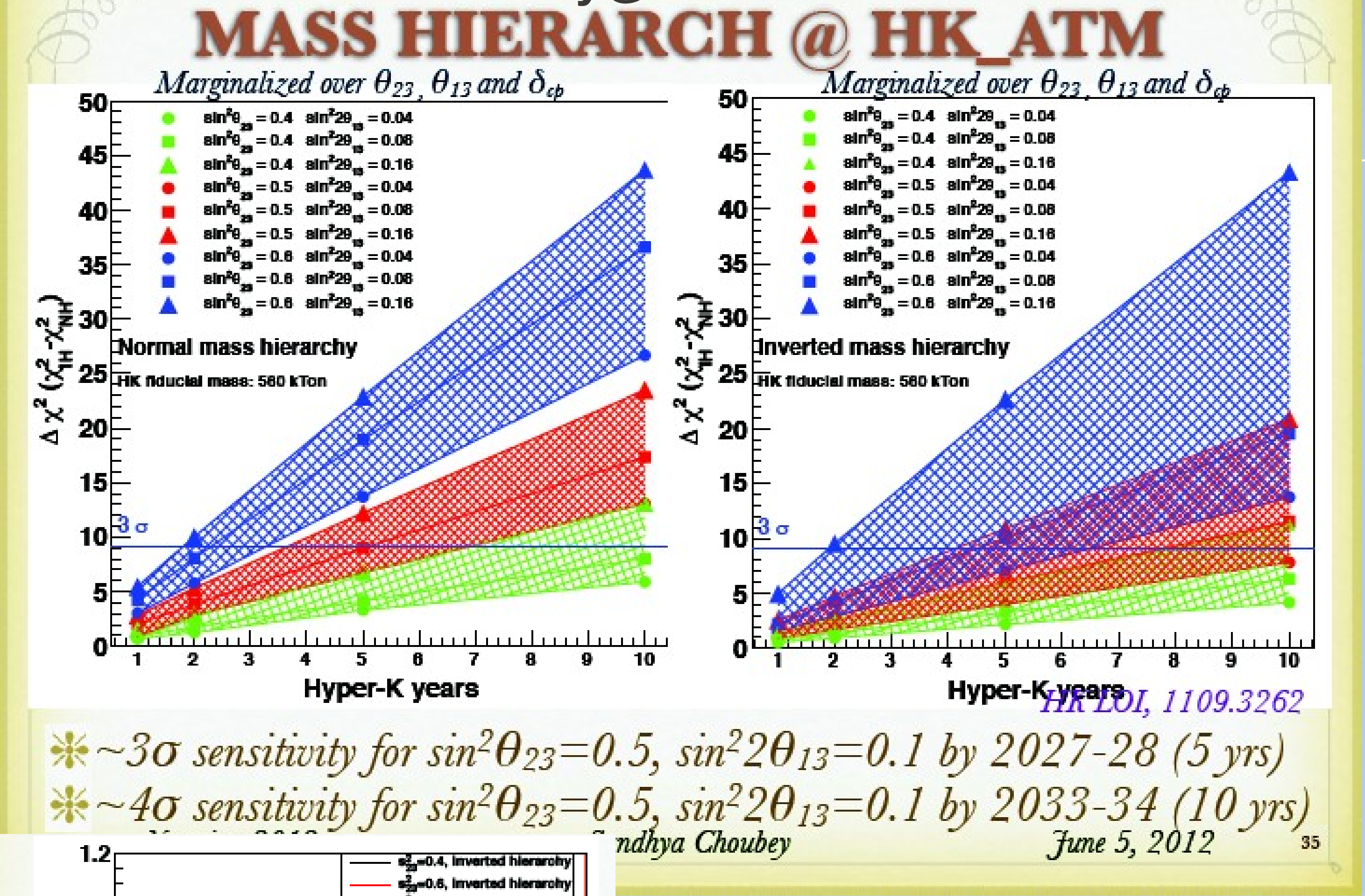
USA
Virginia Tech

(*=industrial partners)

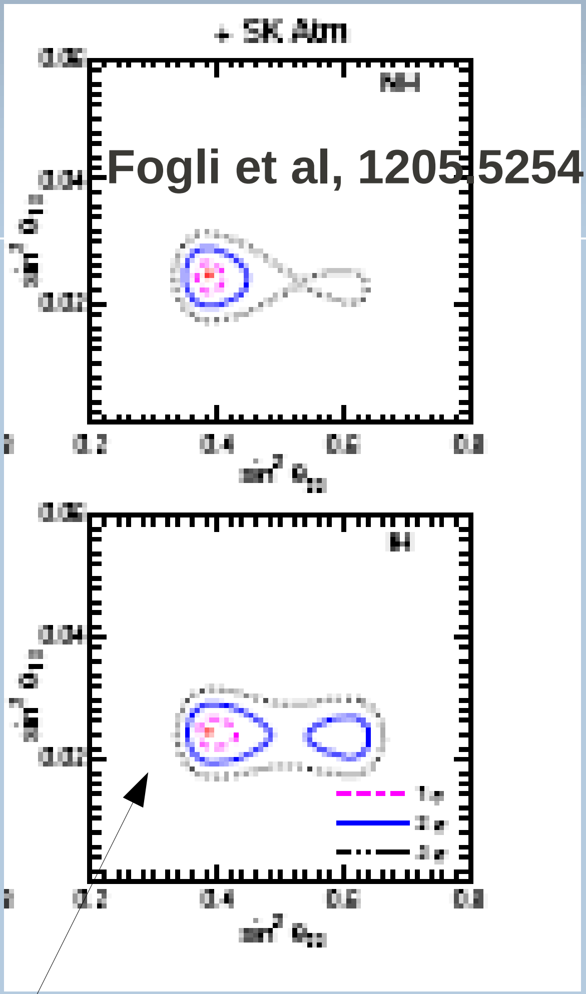
LAGUNA-LBNO CP Coverage

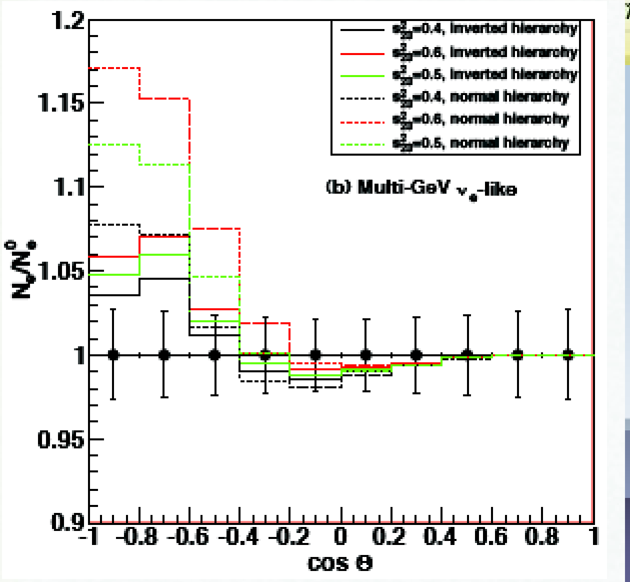


S. Choubey@Neutrino2012



Fogli et al, 1205.5254





What if the worst case scenario $\sin^2(\theta_{23})$~0.4 comes true?