Neutrino Masses, Mixing and Oscillations: Experimental Issues

Agnieszka Zalewska
Neutrino Day, Warsaw, 14.01.2014

Oscillations of three active neutrinos

- Present experimental landscape
- Mass hierachy and δ_{CP} measurements – present and future projects
- Specific experimental requirements

Sterile neutrinos

- Follow up of the LSND effect

Partially based on the ICFA European Neutrino Town Meeting, Paris, 8-10.1.2014

Oscillations of three active neutrinos

Present experiments, especially for θ_{13} measurements

How to measure neutrino mass hierarchy and δ_{CP}?

Oscillations - parametrization for 3 ν flavours

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

For three neutrino flavours and three mass states – there are six oscillation parameters: three mixing angles θ_{12}, θ_{23}, θ_{13}, two differences of mass squared Δm^2_{21}, Δm^2_{32} and one phase δ_{CP}

atmospheric neutrinos and accelerator neutrinos

CP phase

solar neutrinos and reactor neutrinos

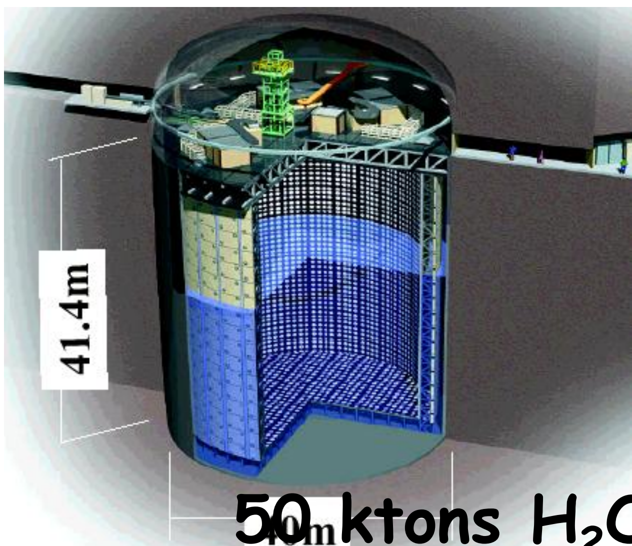
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

connects solar and atmospheric regions

If $\delta \neq 0, \pi, 2\pi$...then CP is violated for leptons (like for quarks), θ_{13} is a gateway to a measurement of δ

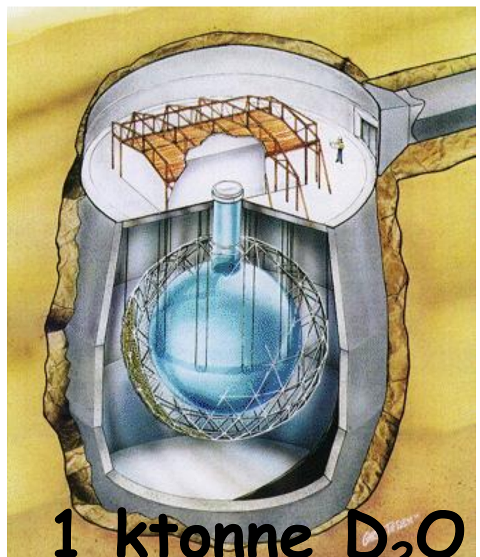
Oscillation parameters – present experimental input

- LBL accelerator experiments: K2K + T2K + MINOS
- Atmospheric neutrino data: SuperK
- Solar experiments: Davis's, Gallium exps, SuperK, SNO
- LBL reactor experiment: KamLAND
- SBL reactor experiments: Dchooz + RENO + Daya Bay



50 ktons H_2O

SuperKamiokande



1 ktonne D_2O

SNO

1 ktonne, scintillator

KamLAND

Oscillation parameters – result of a global fit using all the available data

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. See also Fig. 3 for a graphical representation of the results. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH. The CP violating phase is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$. The overall χ^2 difference between IH and NH is insignificant ($\Delta\chi^2_{\mathrm{I-N}} = +0.3$).

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.08	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.44	2.38 – 2.52	2.30 – 2.59	2.22 – 2.66
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.40	2.33 – 2.47	2.25 – 2.54	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.16 – 2.56	1.97 – 2.76	1.77 – 2.97
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.39	2.18 – 2.60	1.98 – 2.80	1.78 – 3.00
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.25	3.98 – 4.54	3.76 – 5.06	3.57 – 6.41
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.37	4.08 – 4.96 $\oplus$ 5.31 – 6.10	3.84 – 6.37	3.63 – 6.59
δ/π (NH)	1.39	1.12 – 1.72	0.00 – 0.11 $\oplus$ 0.88 – 2.00	—
δ/π (IH)	1.35	0.96 – 1.59	0.00 – 0.04 $\oplus$ 0.65 – 2.00	—

Fractional uncertainties (defined as 1/6 of 3σ ranges):

δm^2	2.6 %
Δm^2	3.0 %
$\sin^2\theta_{12}$	5.4 %
$\sin^2\theta_{13}$	8.5 %
$\sin^2\theta_{23}$	~ 11 %

E.Lisi, ICFA 2014

Experimental aspect
- disappearance vs appearance measurements

Appearance experiment:

$$P(\nu_\alpha \to \nu_\beta) \geq 0$$

Disappearance experiment:

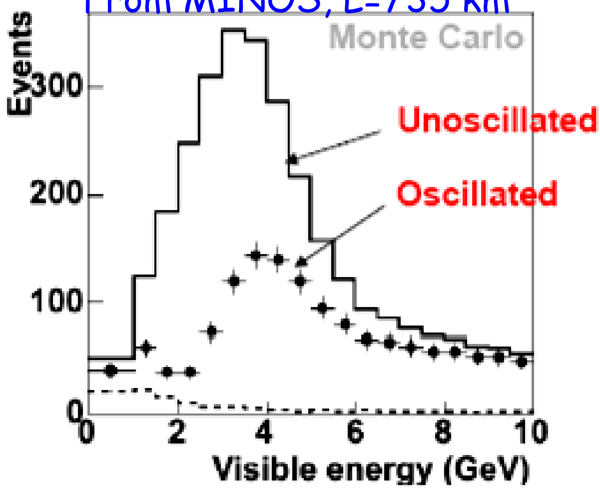
$$P(\nu_\alpha \to \nu_\alpha) \leq 1$$

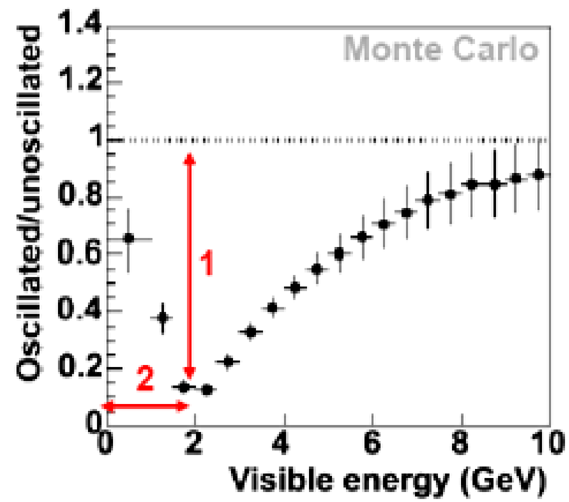
The equalities hold for the case of no oscillations; the sum equals 1.

In a disappearence experiment:

$$P(\nu_\mu \to \nu_\mu) = 1 - \underbrace{\sin^2 2\theta}_{1} \sin^2(1.267 \underbrace{\Delta m^2}_{2} L / E)$$

From MINOS, L=735 km



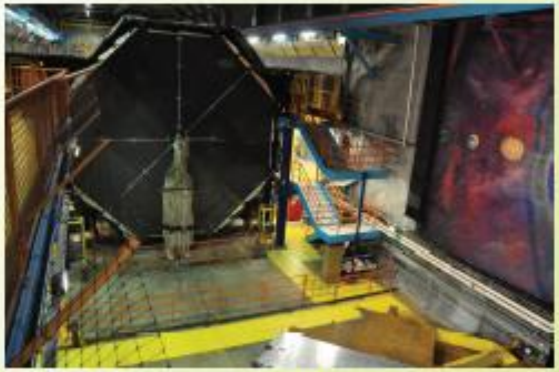


Note: in an appearance experiment the minimum is replaced by a maximum.

Present exp. approach: look for both flavour appearance and disappearance

Best measurement of $|\Delta m^2_{32}|$

The MINOS(+) Experiment

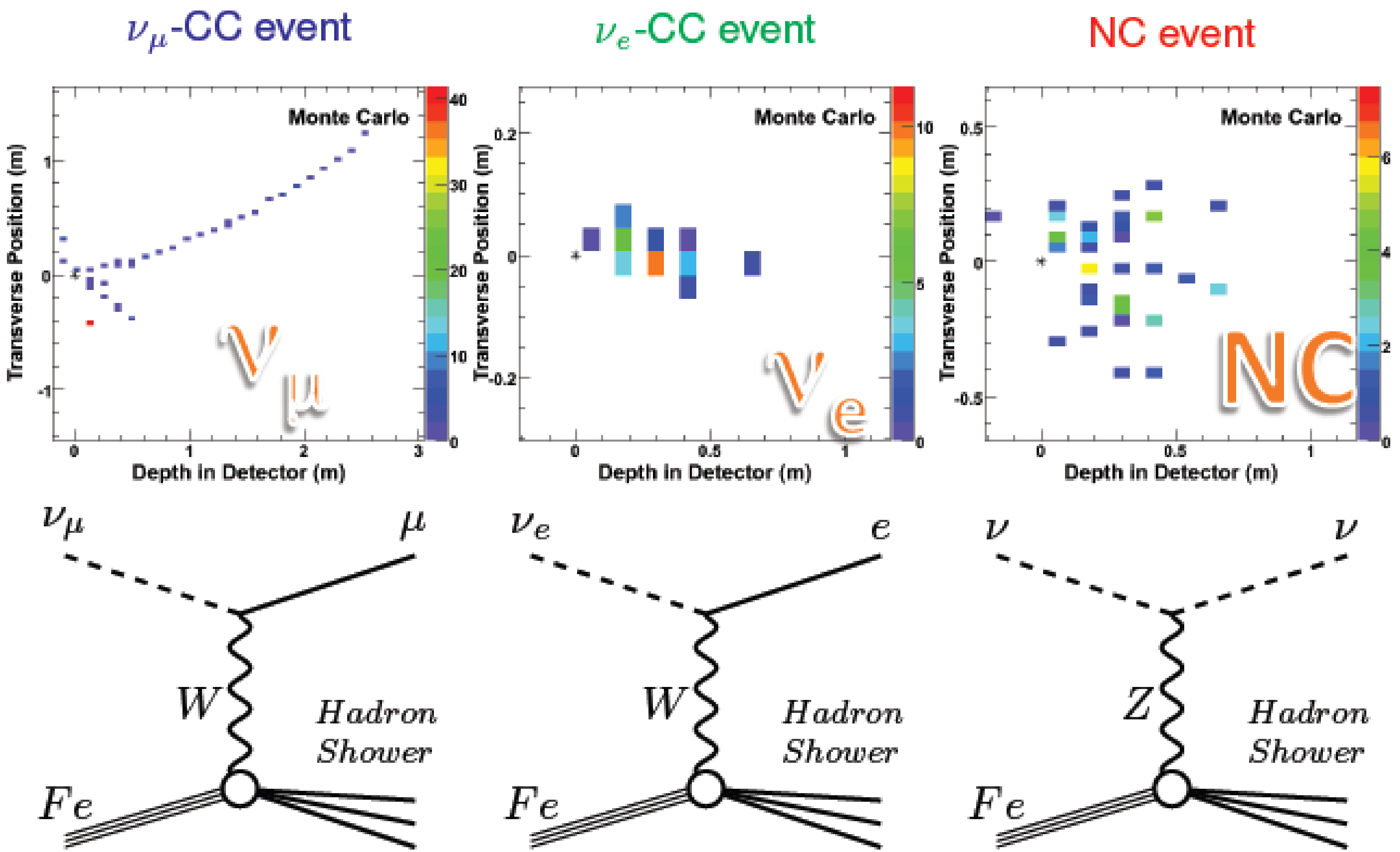


- Two detectors mitigate systematic effects
  - beam flux mis-modeling
  - Neutrino x-sec uncertainties
- L/E ~150-250 km/GeV
- Magnetized:
  - muon energy from range/curvature
  - distinguish μ^+ from μ^-

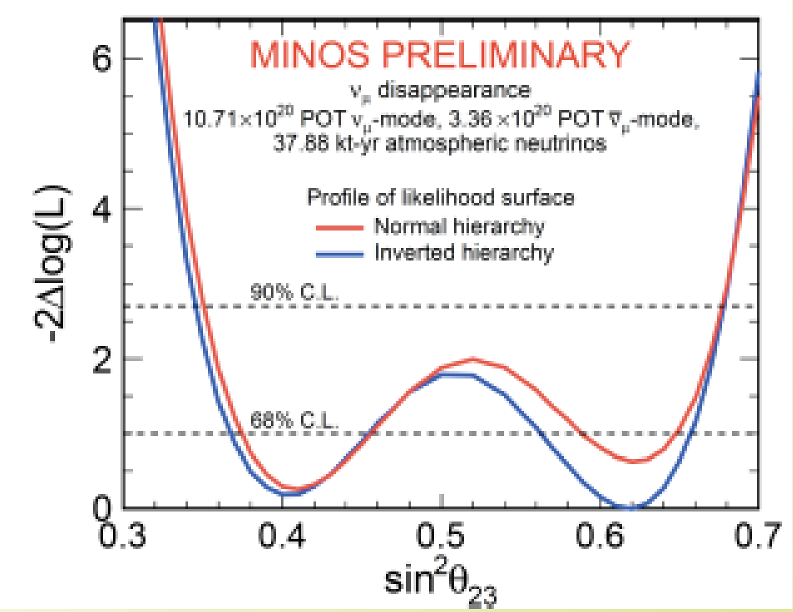
- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick (1.4 X_0)
  - scintillator strips 4.1 cm wide (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)

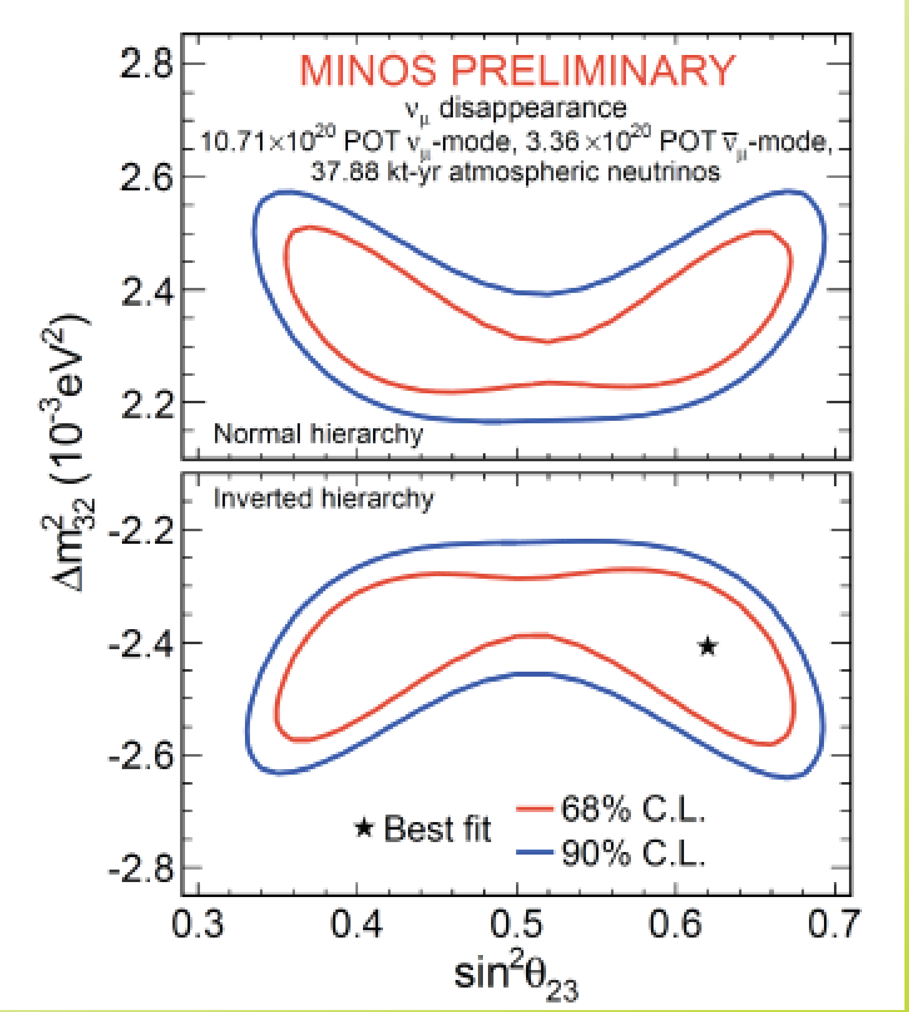
J.Thomas, ICFA 2014

MINOS event topology



3 flavor analysis of disappearance





- These contours combine atmospheric and beam ν_μ data
- Everyone should make THESE contour plots

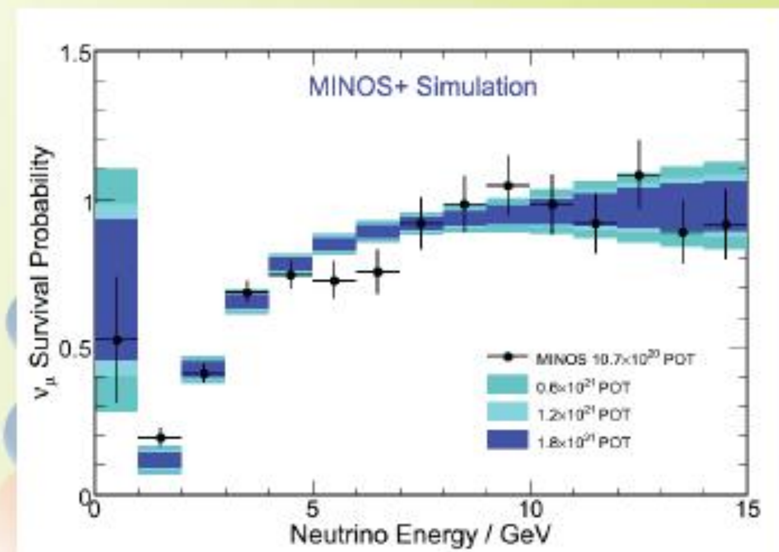
Hint for non-maximal value of θ_{23}

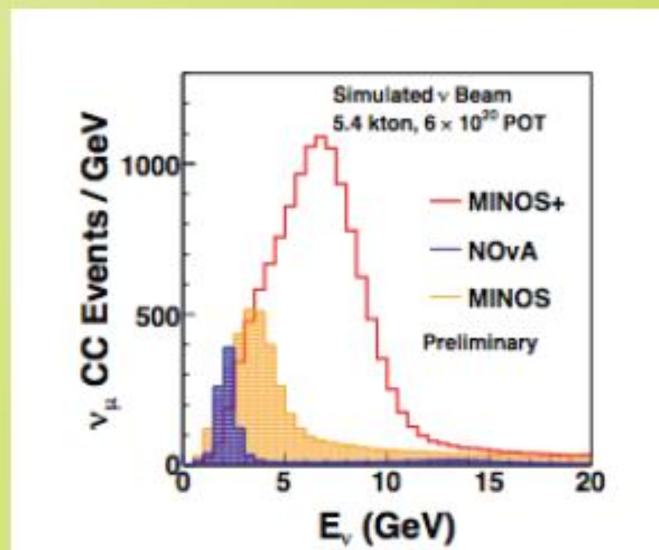
J.Thomas, ICFA 2014

Started in September 2013 for three years

MINOS+

- The overarching reason to run MINOS in the NuMI-NOvA beam is to look for "non-standard" physics in a previously "unexplored" region :
  - Precision will be significantly increased (factor 60 in statistics in 3 years)
  - Where else would you look for evidence of non-3x3 effects?
    - Not at the oscillation maximum, main oscillation dominates
- 3000 events/year between 4-10 GeV near oscillation maximum





Measurements of θ_{13}

I. By measuring $\bar{\nu}_e$ disappearance in the new generation SBL reactor experiments DoubleChooz, Reno and Daya Bay with two (DCh, R) or eight (DB) detectors at two (DCh, R) or more (DB) distances between reactors and detectors in order to significantly reduce systematic uncertaintes related to $\bar{\nu}_e$ flux, cross section and reactor thermal power – almost pure measurement of θ_{13}

$$1 - P_{\bar{e}\bar{e}} \cong \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + O(\alpha^2)$$

II. By searching for $\nu_\mu \leftrightarrow \nu_e$ (and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$) in LBL accelerator experiments: T2K and NOvA – very complicated analysis because P(ν_μ-> ν_e) depends on all oscillation parameters (correlations + degeneracies), but due to that it offers a possibility to measure also sign of Δ^2_{32} (mass hierarchy) and δ_{CP} (if θ_{13} is not too small) – **one needs, however, measurements at different baselines and to use both ν_μ and $\bar{\nu}_\mu$ beams**

Subdominant oscillation in accelerator experiments

$\theta_{13} = 0$	$P(\nu_e \to \nu_\mu) = c_{23}^2 \sin^2 2\theta_{12} \sin^2(\frac{\Delta m_{12}^2 L}{4E})$	solar
$\theta_{13} \neq 0$	$P(\nu_e \to \nu_\mu) = c_{23}^2 \sin^2 2\theta_{12} \sin^2(\frac{\Delta m_{12}^2 L}{4E})$	solar
	$+ s_{23}^2 \sin^2 2\theta_{13} \sin^2(\frac{\Delta m_{23}^2 L}{4E})$	atmospheric
	$+ J \cos(\pm\delta - \frac{\Delta m_{23}^2 L}{4E}) \frac{\Delta m_{12}^2 L}{4E} \sin(\frac{\Delta m_{23}^2 L}{4E})$	interference

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

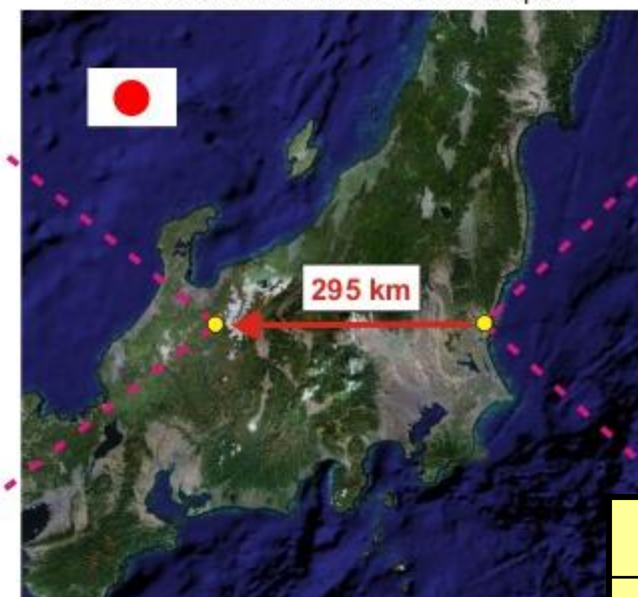
T2K (Tokai to Kamioka) experiment

T2K (start in 2009) – aiming at a very intensive neutrino beam (first superbeam) due to very intensive proton beam from the new synchrotron at JPARC, off-axis configuration of the detectors (kinematical squeezing of the neutrino energy spectrum),

ND280 near detector – a complex magnetic spectrometer,
the SuperKamiokande detector as a far detector

Super Kamiokande
50,000 tons of water
10,000 phototubes

Neutrino beam directed across Japan



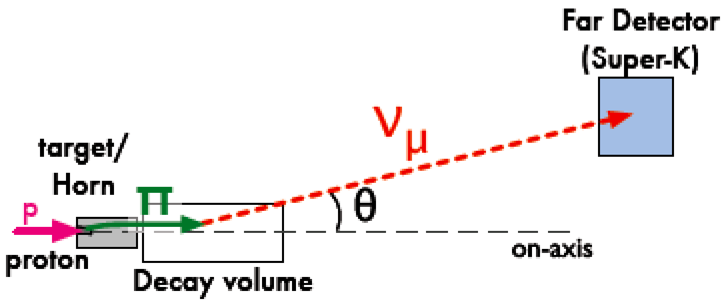
Tokai accelerator complex and location of near detector (ND280)

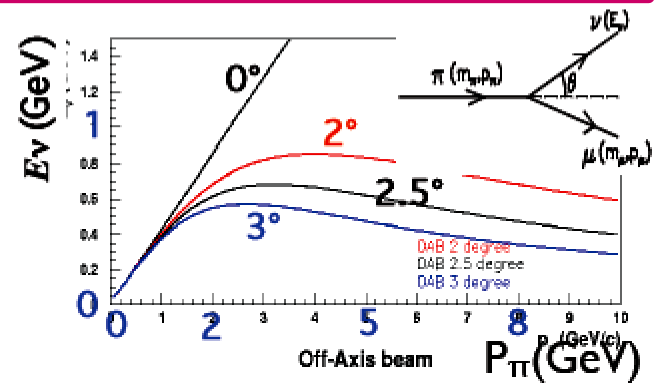
	T2K	K2K
E(GeV)	50 (30 @t=0)	12
Int.(10^{12}ppp)	330	6
Power(MW)	0.75	0.0052

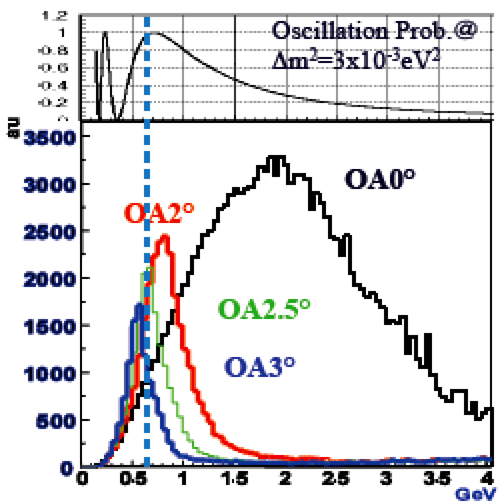
The data taking started in January 2010

T2K experiment

Off-axis beam : intense & narrow-band beam







Beam energy at oscillation max.

E_ν ~ 0.6 GeV (based on Δm^2_{23} & L=295km)

→ T2K off-axis angle is 2.5°

(maximize physics sensitivity)

Small high energy tail

→ small background

Important to keep beam direction stable

(Keep the peak energy stable)

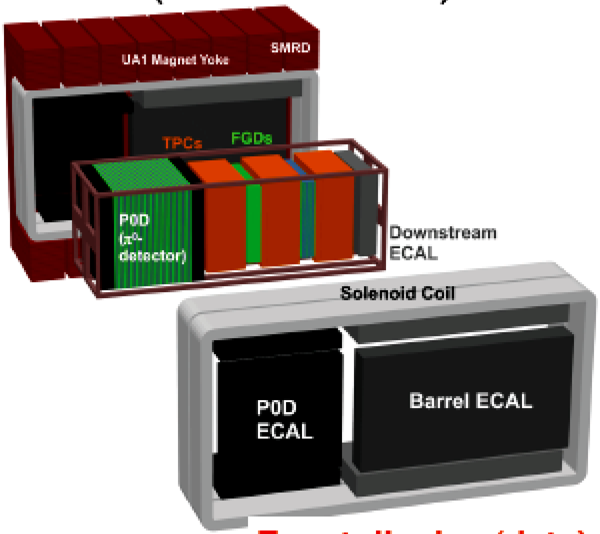
K.Sakashita, KEK, 2011

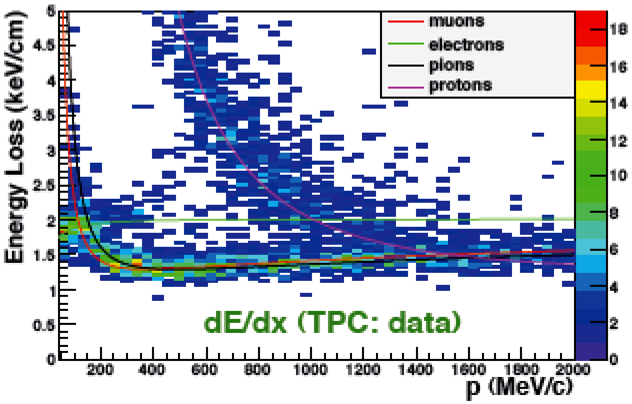
T2K experiment

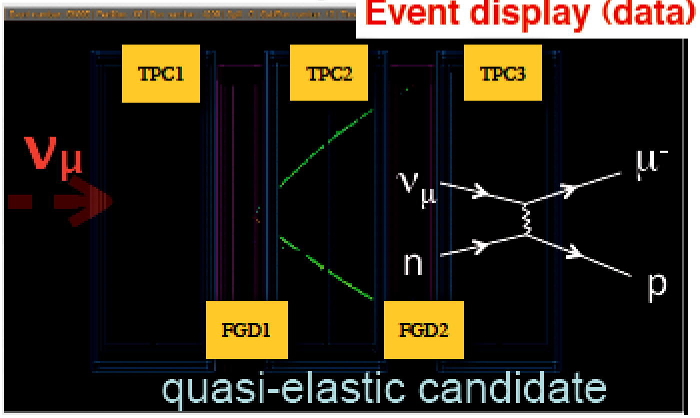
Off-axis Near Detector (ND280)

ν_μ CC events rate measurement in present analysis

- 0.2 T UA1 magnet
- Fine Grained Detector (FGD)
  - scintillator bars target (water target in FGD2)
  - 1.6ton fiducial mass for analysis
- Time Projection Chambers (TPC)
  - better than 10% dE/dx resolution
  - 10% momentum resolution at 1GeV/c



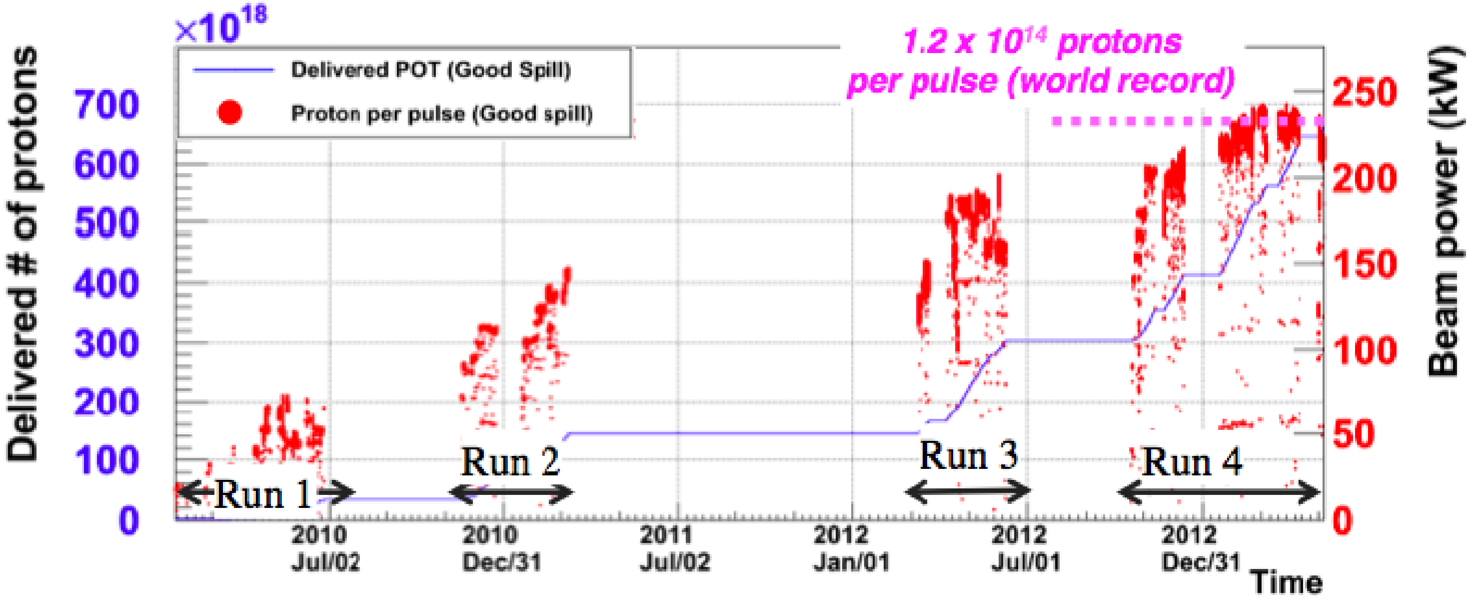




K.Sakashita, KEK, 2011

T2K Datasets

Data-taking started in January 2010. Data have been collected in 4 running periods.



Period	Exposure (proton on target) for oscillation physics analyses
Run 1	0.323×10^{20}
Run 1-2	1.431×10^{20}
Run 1-3	3.010×10^{20}
Run 1-4	6.570×10^{20}

- Steady improvement of beam power
- Run 4: Routine operation at $\sim$230 kW.
- Total exposure of 6.570×10^{20} protons on target for physics analysis

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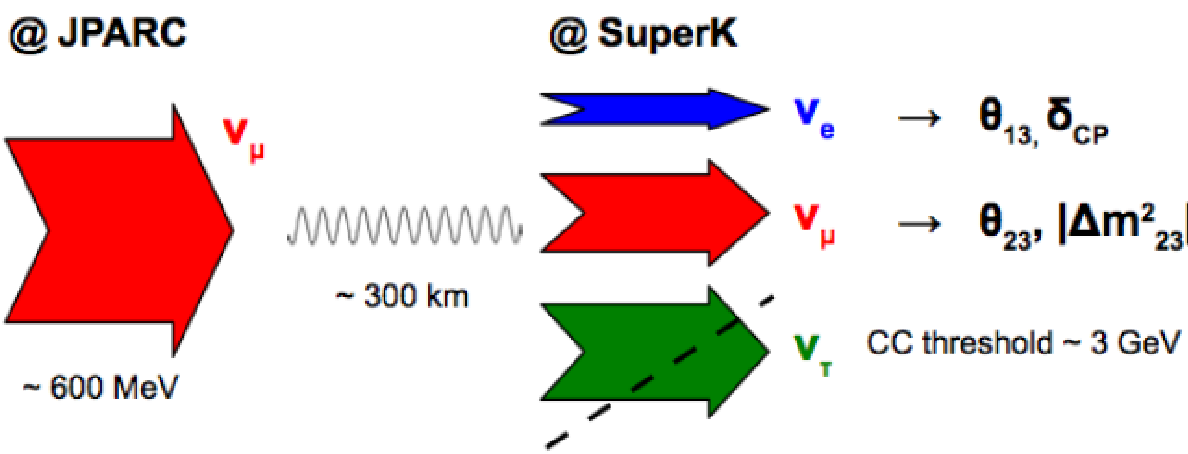
Neutrino oscillation signatures in T2K

Muon-neutrino disappearance ($\nu_\mu \to \nu_\mu$)

$$P(\nu_\mu \to \nu_\mu) = 1 - cos^4\theta_{13} \cdot sin^2 2\theta_{23} \cdot sin^2(\frac{\Delta m^2_{31} L}{4E}) + \text{sub-leading terms}$$

Electron-neutrino appearance ($\nu_\mu \to \nu_e$)

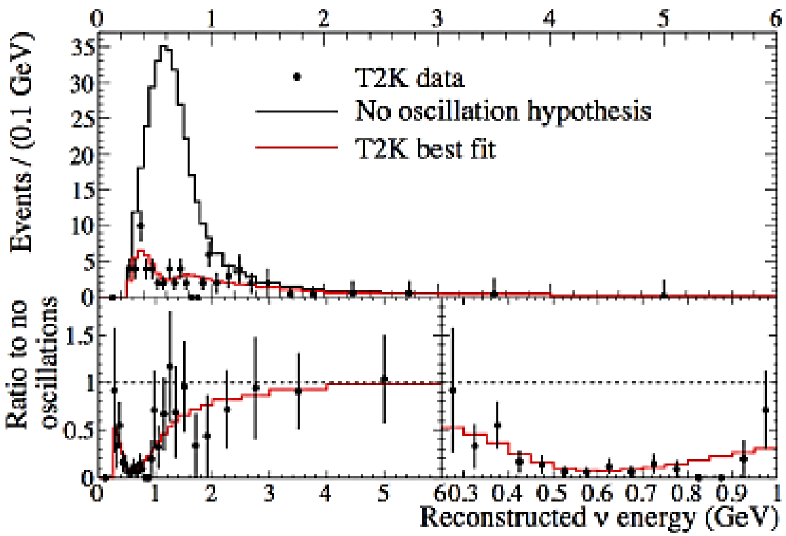
$$P(\nu_\mu \to \nu_e) = 4 \cdot cos^2\theta_{13} \cdot sin^2\theta_{13} \cdot sin^2\theta_{23} \cdot sin^2(\frac{\Delta m^2_{31} L}{4E}) + \text{sub-leading terms}$$



- **Oscillation results**
  - ν_e appearance (accepted by PRL; arXiv:1311.4750)
  - ν_μ disappearance (PRL 111 (2013) 211803; arXiv:1308.0465)

T2K ν_μ disappearance with Run 1-3 data (*)

205 ± 17 (syst.) single-ring μ-like events expected in absence of oscillations, but only 58 events were observed. The observed deficit is strongly energy-dependent.

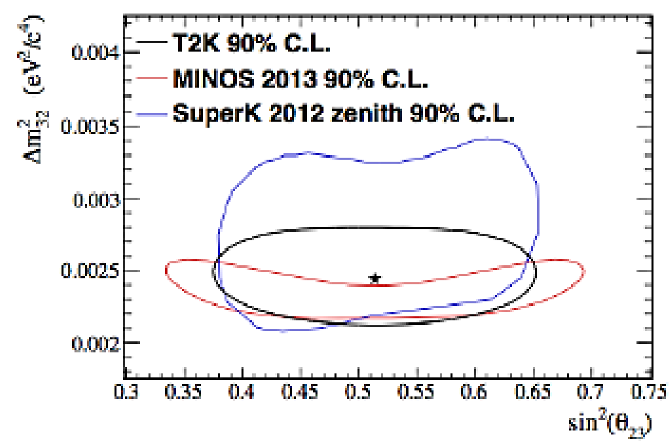


- Dramatic deficit allows us to place stringent constraints on ν_μ disappearance parameters.
- Assuming NH: $|\Delta m^2_{32}| = 2.44^{+0.17}_{-0.15} \times 10^{-3} eV^2/c^4$ and $\sin^2\theta_{23} = 0.514 \pm 0.082$

(*) Analysis of Run 1-4 data (with ×2 statistics) in final stages of internal T2K review. Result would be made public within the next few weeks.

Effect of systematics on the number of events (assuming $|\Delta m^2_{32}|$=2.4×10^{-3} eV^2/c^4, $\sin^2\theta_{23}$=0.5)
All 48 systematics were allowed to float in the fit.

Source of uncertainty (no. of parameters)	$\delta n^{exp}_{SK} / n^{exp}_{SK}$
ND280-independent cross section (11)	6.3%
Flux & ND280-common cross section (23)	4.2%
Super-Kamiokande detector systematics (8)	10.1%
Final-state and secondary interactions (6)	3.5%
Total (48)	13.1%



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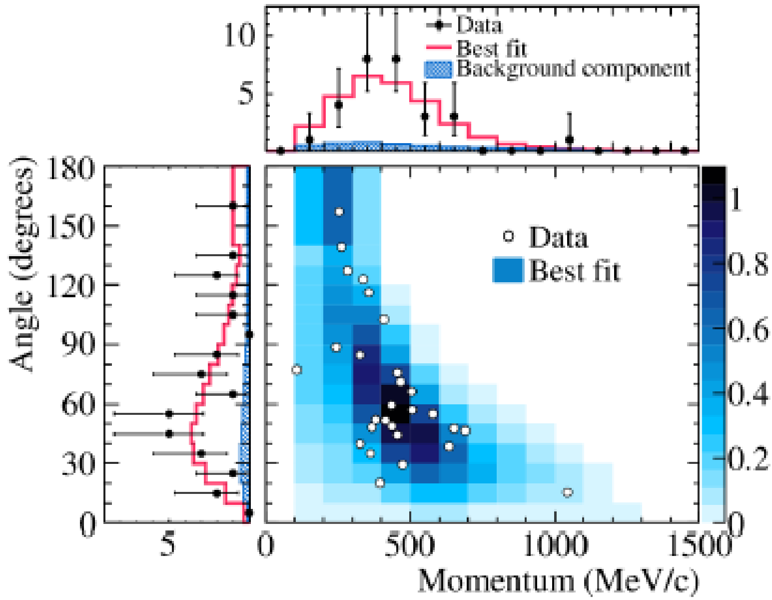
T2K ν_e appearance with Run 1-4 data

28 single-ring e-like events were observed, with an expected bkg of 4.92 ± 0.55 (syst) events.
The significance of the excess is 7.3σ (first ever observation of an explicit appearance signal).



Event category	The predicted number of events $\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	4.92	21.56
ν_e signal	0.40	17.30
ν_e background	3.37	3.12
ν_μ background	0.94	0.94
$\overline{\nu}_\mu$ background	0.05	0.05
$\overline{\nu}_e$ background	0.16	0.15

	$\sin^2 2\theta_{13} = 0$		$\sin^2 2\theta_{13} = 0.1$	
Error source	w/o ND280 fit	w/ ND280 fit	w/o ND280 fit	w/ ND280 fit
BANFF	21.7	4.8	25.9	2.9
ν int. (other than BANFF)	6.8	6.8	7.5	7.5
SK+FSI	7.3	7.3	3.5	3.5
Total	24.0	11.1	27.2	8.8
2012 analysis	21.0	13.0	24.2	9.9

Best fit value of $\sin^2 2\theta_{13}$
(for $\delta_{CP} = 0$, $|\Delta m^2_{32}| = 2.4 \times 10^{-3} eV^2/c^4$ and $\sin^2 \theta_{23} = 0.5$):

- $\sin^2 2\theta_{13} = 0.14$ (Normal)
- $\sin^2 2\theta_{13} = 0.17$ (Inverted)

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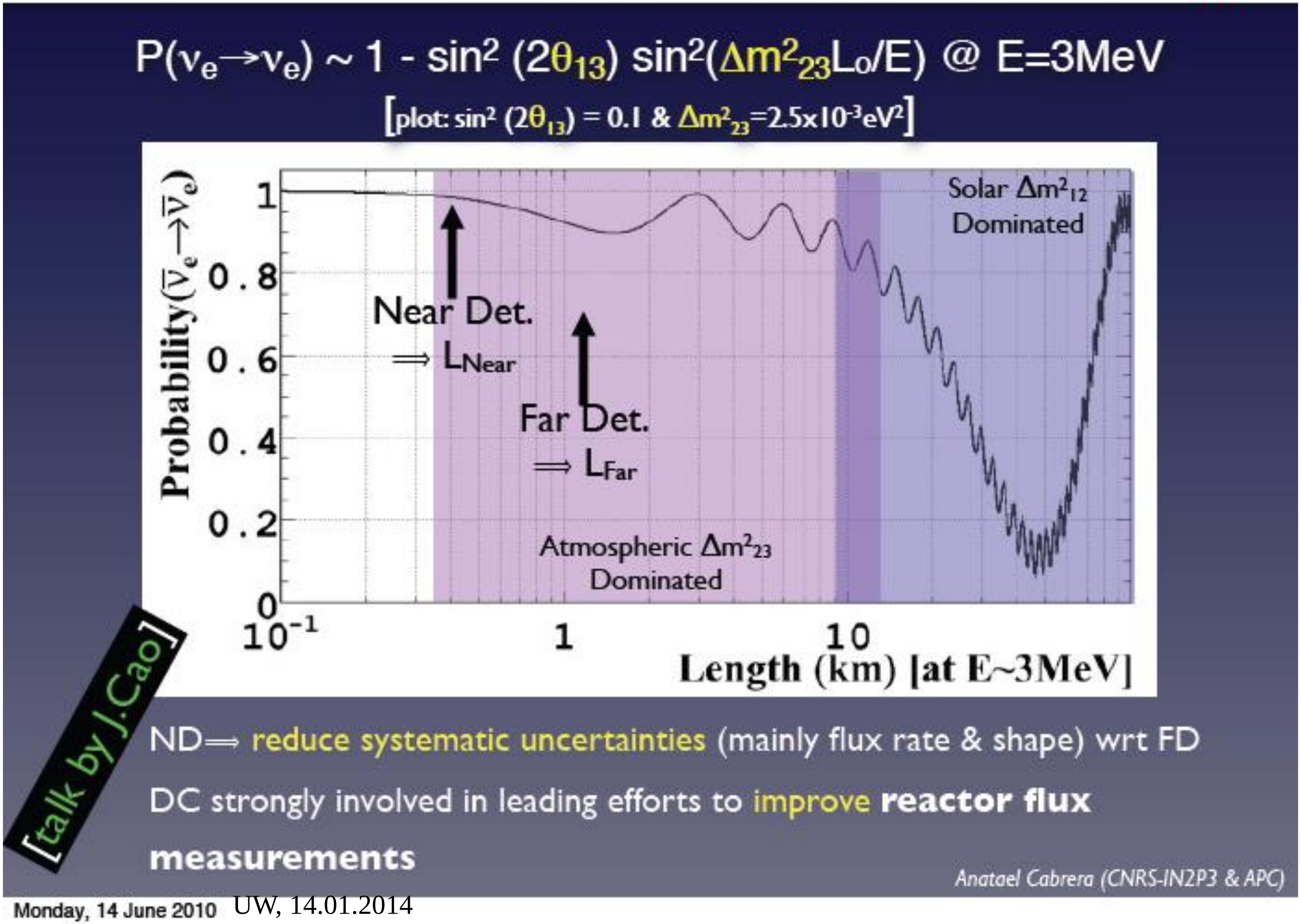
θ_{13} in reactor experiments: Double Chooz, RENO and Daya Bay

strategy...



Antineutrino Detection

Inverse β-decay (IBD):

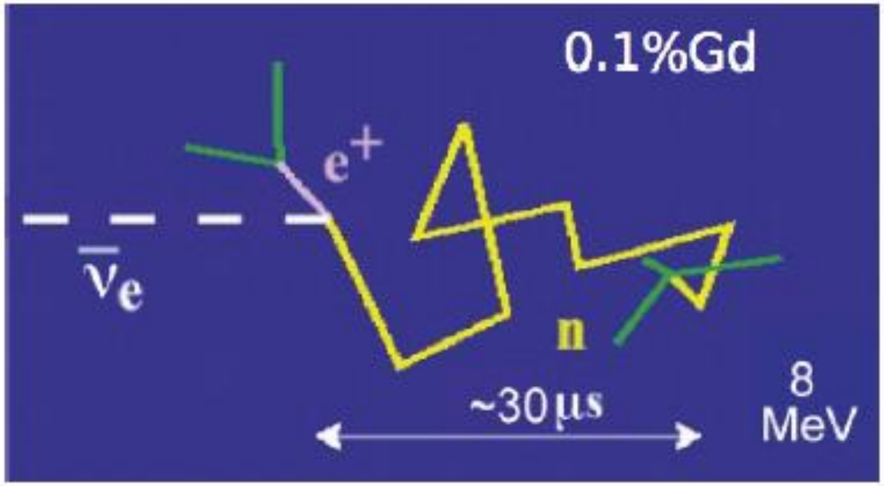
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma s$$

Prompt positron:

Carries antineutrino energy

$E_{e+} \approx E_\nu - 0.8$ MeV



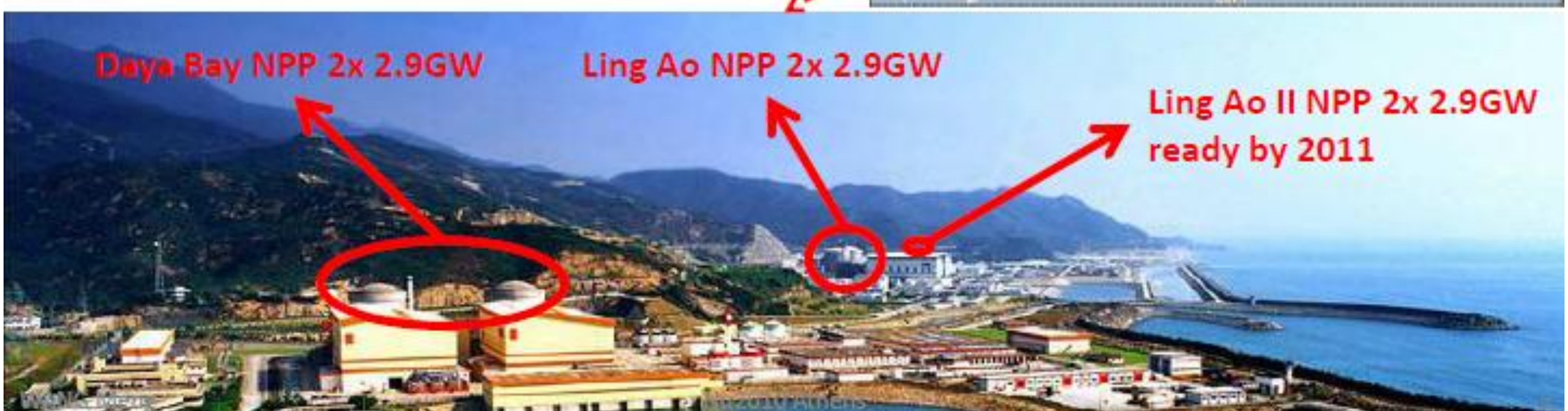
Delayed neutron capture:

Efficiently tags antineutrino signal

Prompt + Delayed coincidence provides distinctive signature

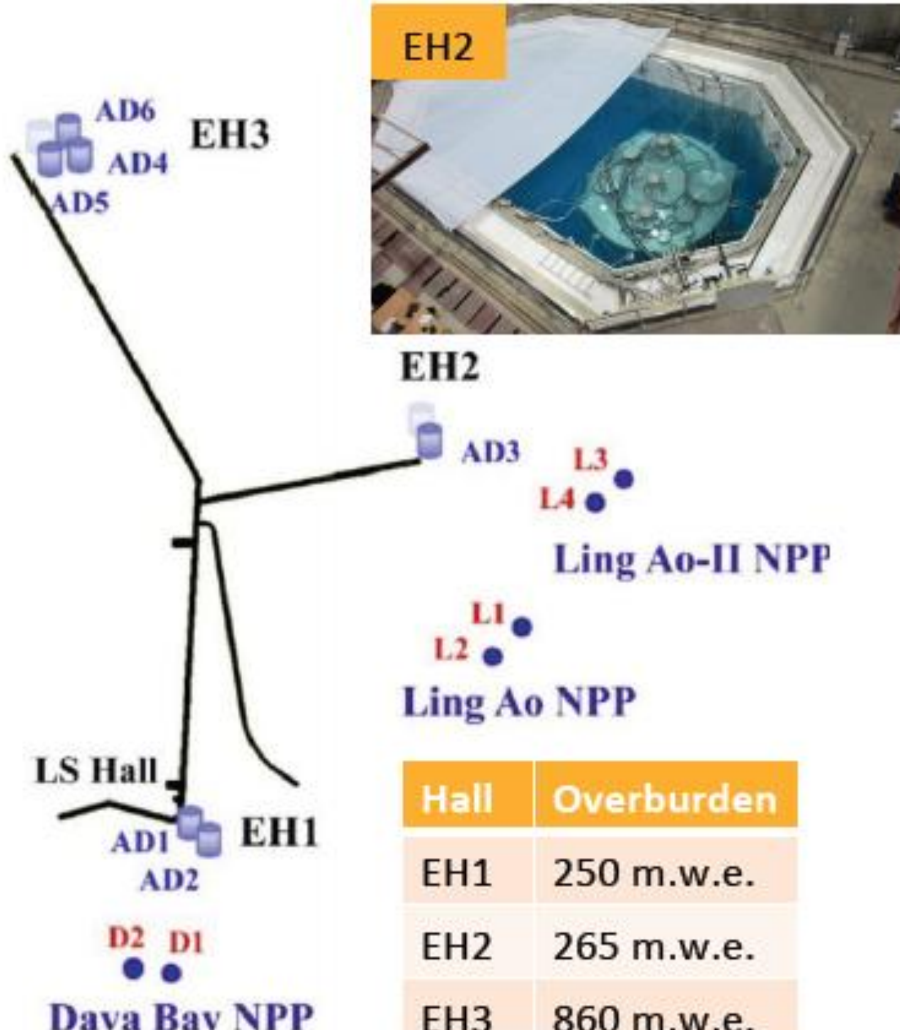
where is Daya Bay

- in Shenzhen, southern China; ~55km to HK.
- very powerful nuclear power complex:
  - Daya Bay NPP (nuclear power plant)
  - Ling Ao NPP
  - Ling Ao II NPP (*start to run in October 2010*)
- adjacent to mountain
  - is easy to build underground labs with tunnel access.
  - provide sufficient overburden to suppress cosmic rays.



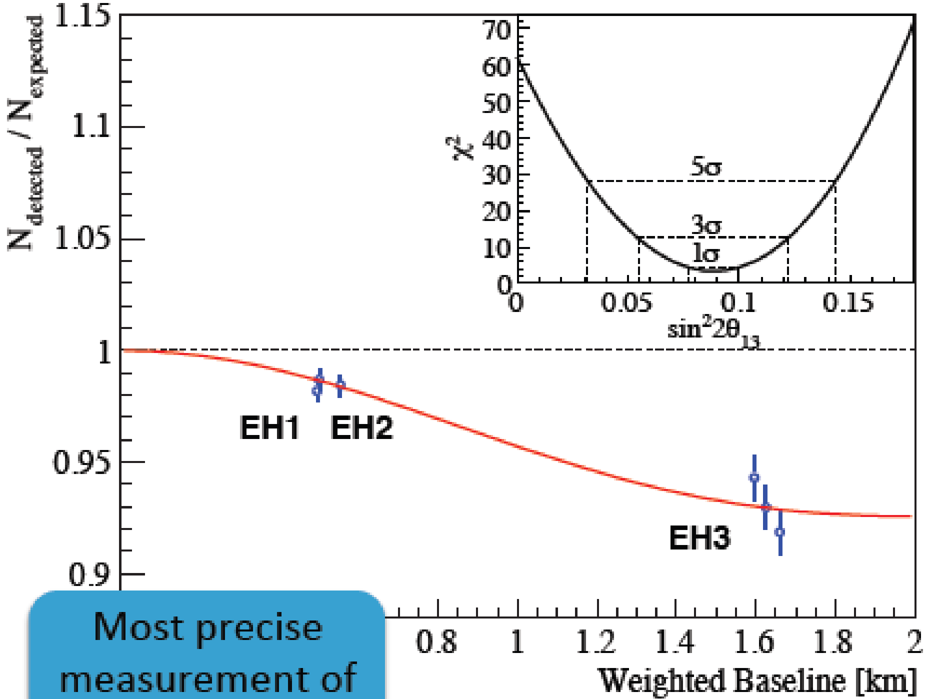
M.Wang

Experiment Layout



Hall	Overburden
EH1	250 m.w.e.
EH2	265 m.w.e.
EH3	860 m.w.e.

$\sin^2(2\theta_{13})$: Rate Analysis

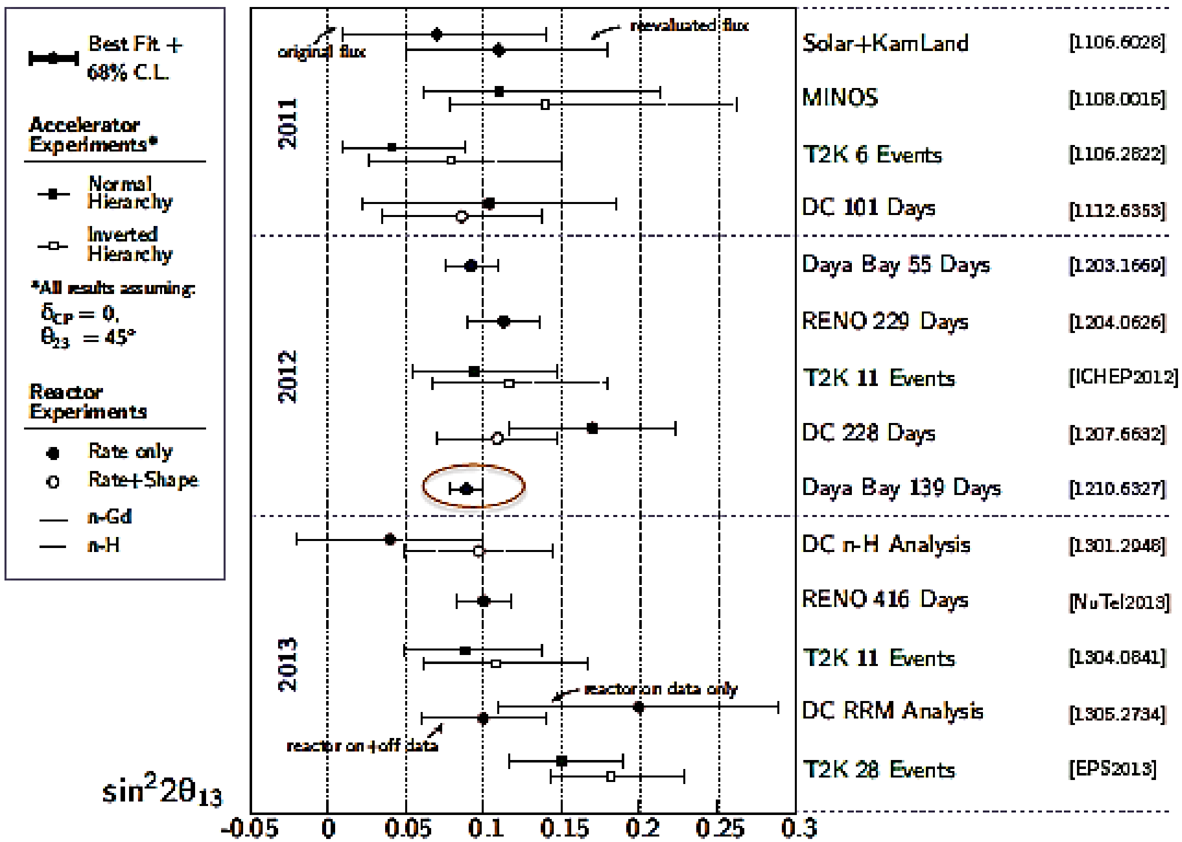


- Uses standard χ^2 approach
- Far vs. near relative measurement
- Absolute rate is **not** constrained
- Consistent results obtained by independent analyses, different reactor flux models

Most precise measurement of $\sin^2 2\theta_{13}$ to date

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010\ (\text{stat}) \pm 0.005\ (\text{syst})$$

$\sin^2(2\theta_{13})$: Global Results



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Neutrino oscillations – open questions

How close to 45^0 is θ_{23}?

Measure all parameters more precisely!

Is there a new symmetry of Nature hidden behind the scheme of neutrino mixing?

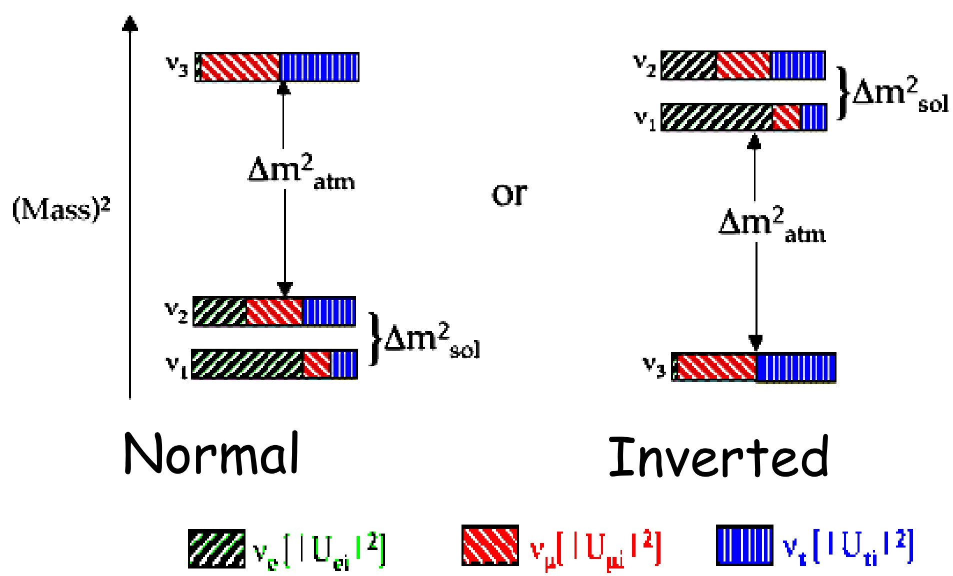
⇓ LEPTON MIXING IS "WEIRD" ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

Old values

Which is the hierarchy of neutrino masses?

Is CP violated for neutrinos?

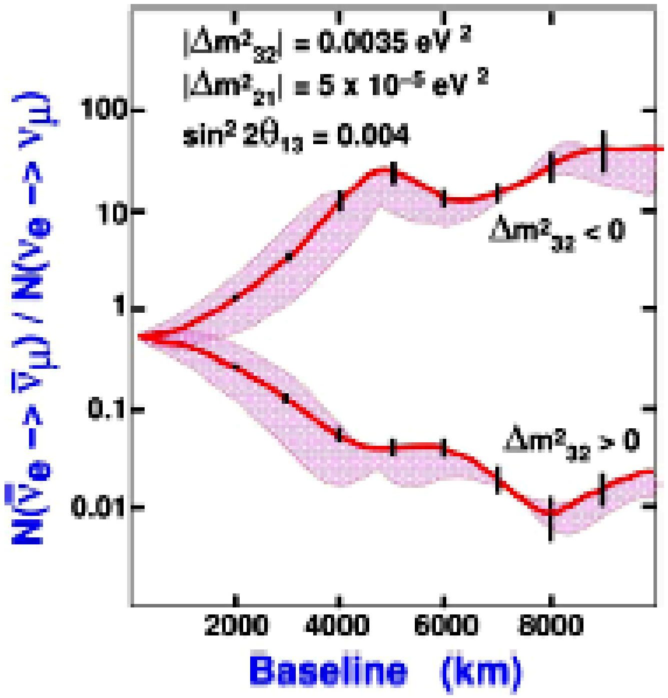


Mass hierarchy and CP determination in LBL experiments

Experimental strategies:

Mass hierarchy:

- Use both the neutrino and antineutrino beams
- Longer baselines are better
- Off-axis configuration may be helpful

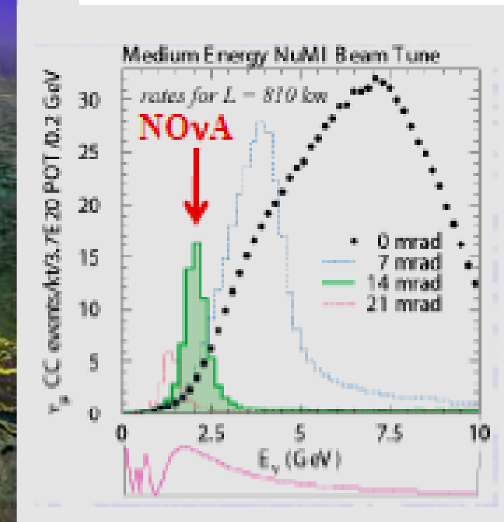


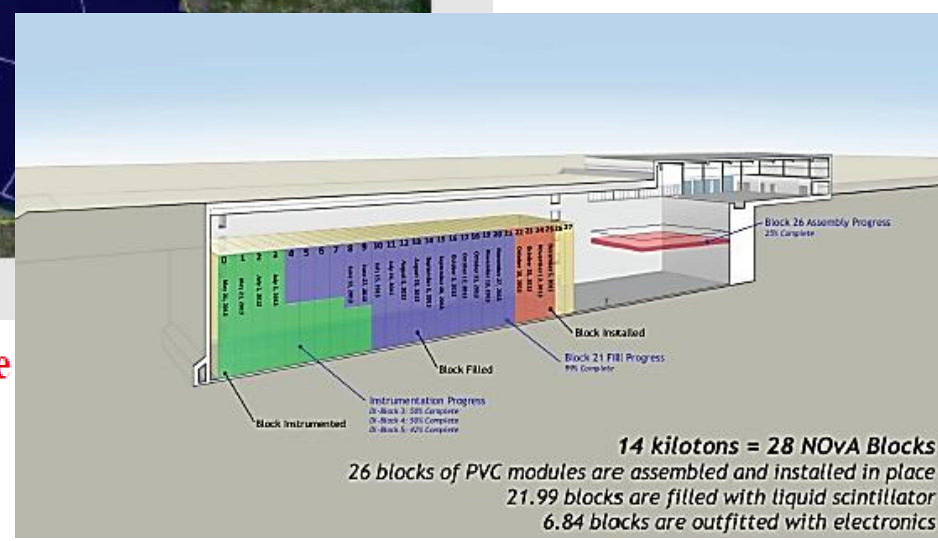
CP:

- Use both the neutrino and antineutrino beams
- Study the L/E dependence for wide band beams
- Use the second oscillation maximum

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

NOvA exp.- started in Sept.2013 for 6-10 years





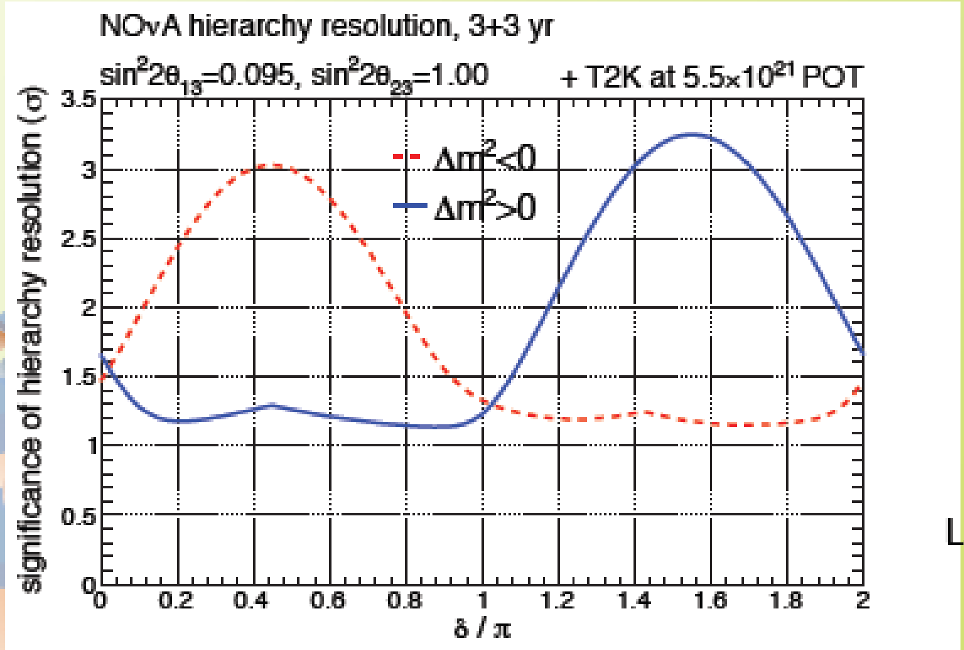
- **NOvA's unique feature 810 km long baseline**

➡ Sensitive to neutrino mass ordering.

- Measures θ_{13} and θ_{23}

NOνA+T2K mass hierarchy reach

- NOVA is experiment in the best available place RIGHT NOW!
- Reach is improved slightly with T2K



Period	Integ. No. of Proton on Target	Beam Power (kW)	
-Jun.2012	3.1E+20	170	
-Jun.2013	7.8E+20	200	
-Jun.2014	1.2E+21	250	*2
-Jun.2015	1.8E+21	250	
-Jun.2016	2.5E+21	300	
-Jun.2017	3.2E+21	300	
-Jun.2018	3.9E+21	300	
-Jun.2019	5.5E+21	700	*1
-Jun.2020	7.1E+21	700	
-Jun.2021	8.8E+21	700	

*1 Completion time of MR upgrade (assumed to be 2018) is suject to change, depending on economical situation, readiness and so on.

*2 LINAC upgrade completed

* Beam Energy 30GeV

LATEST T2K projection is 8.8e21 by 2021

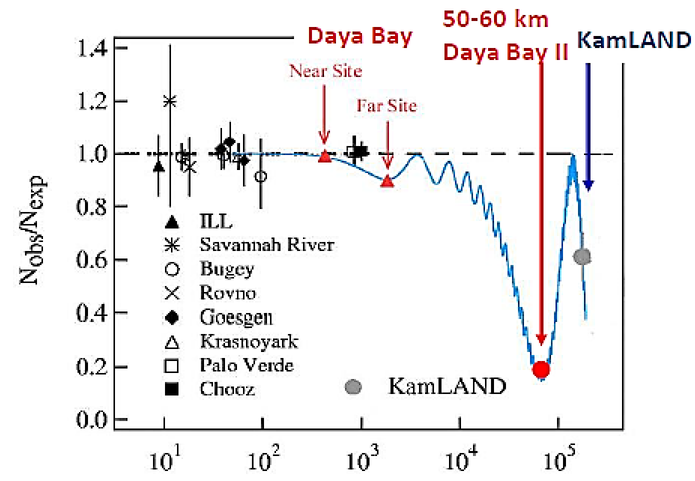
JUNO (Daya Bay II) for MH determination

The site: Kaiping county, Jiangmen City

	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	**17.4 GW**	**18.4 GW**

Daya Bay II

- 20 kton LS detector
- 2-3 % energy resolution

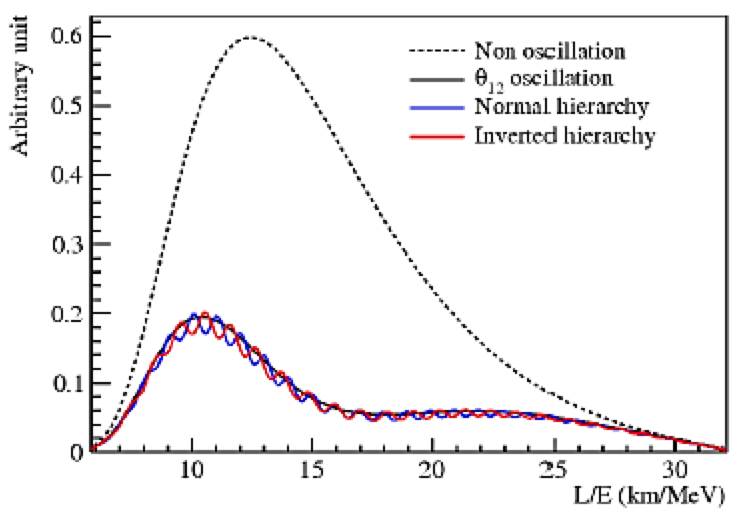


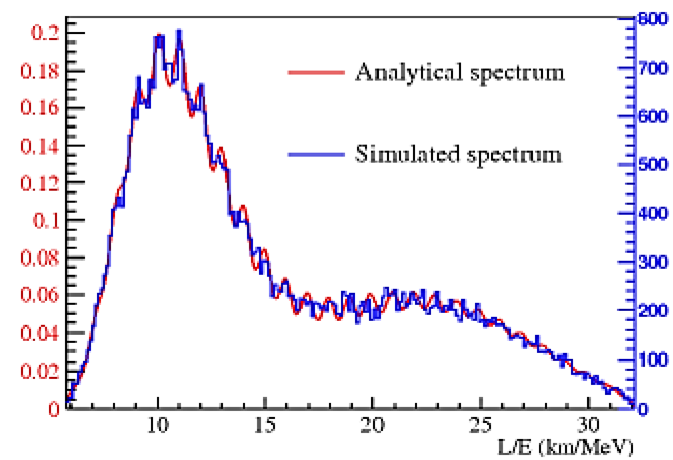
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\mathrm{NH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\
\mathrm{IH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}|
\end{aligned}
$$

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022 L.

Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008
PRD79:073007, 2009





50000 events

Future projects based on Superbeams

Superbeams (ν_μ's from π, K decays) but based on proton beams of up to 4-5 MW power

A few remarks:

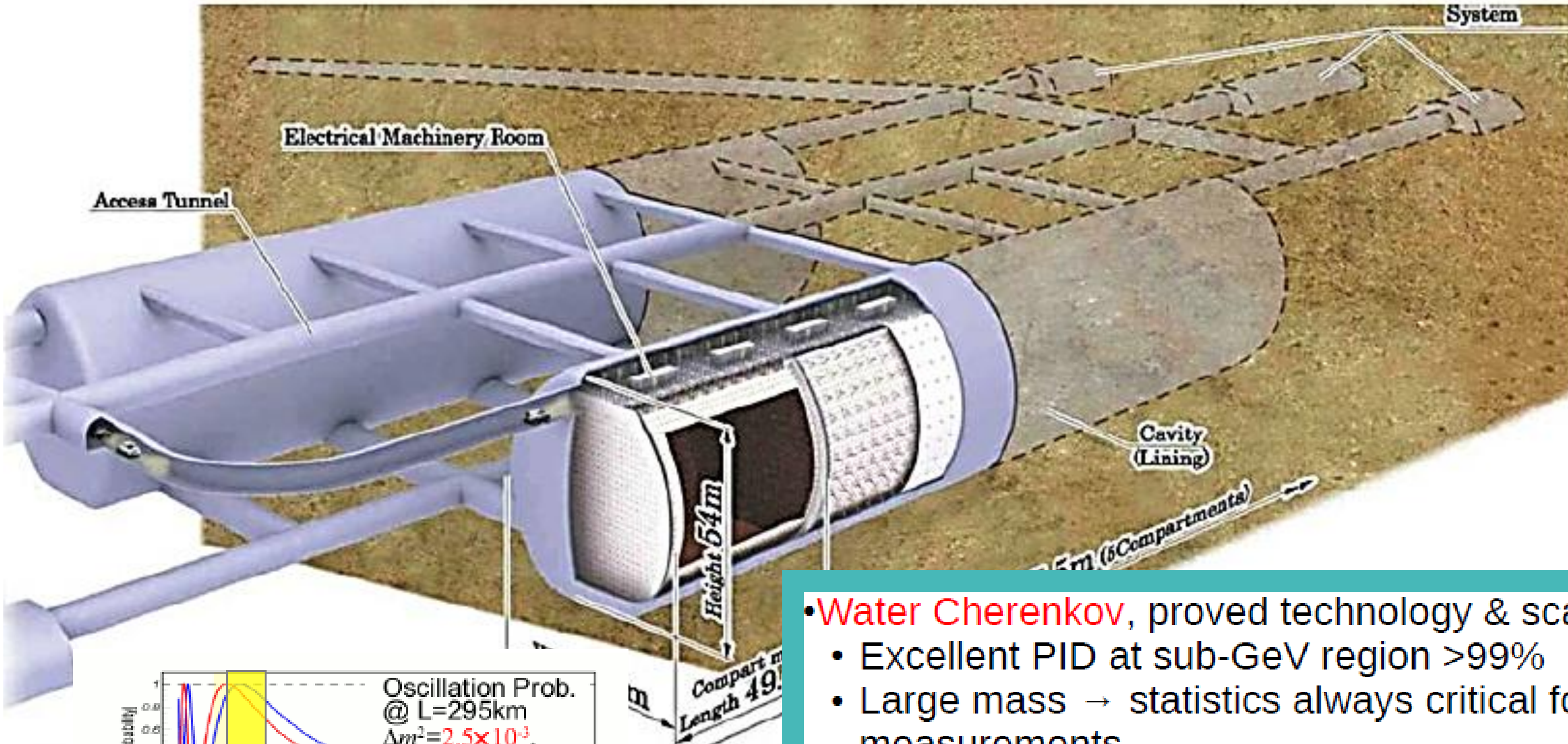
- Much larger detectors than the SuperKamiokande detector are needed to improve searches for proton decays and studying low energy neutrinos from astrophysical sources.

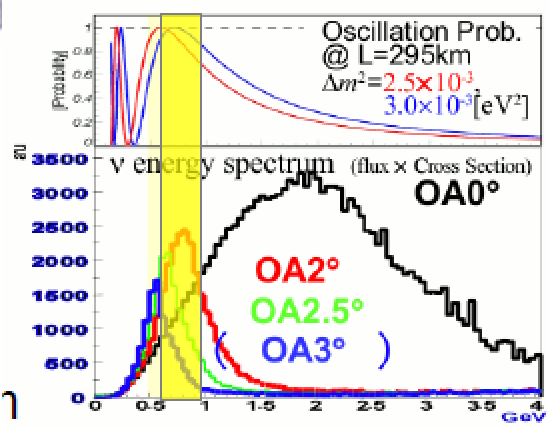
-Nowadays these studies cannot be separated from LBL accelerator neutrino experiments to study neutrino oscillations.

- No one of the existing infrastuctures in the world is able to host future detectors → studies in Japan, USA and Europe.

HyperKamiokande in Japan

25 times SuperKamiokande





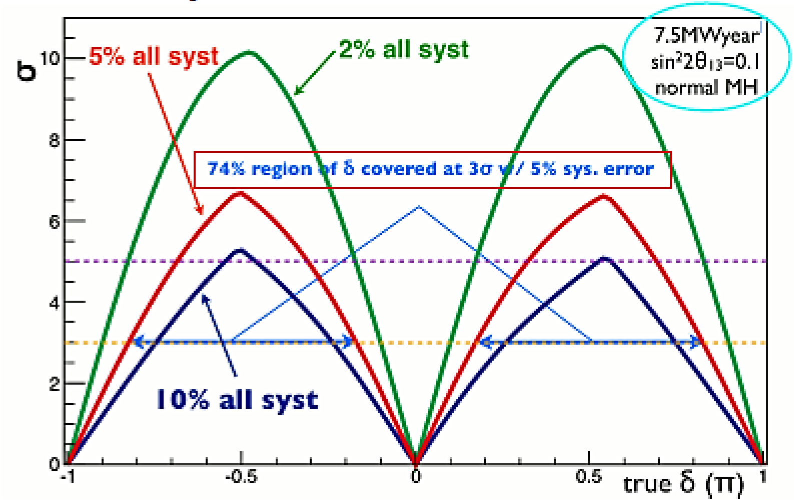
- Water Cherenkov, proved technology & scalability:
  - Excellent PID at sub-GeV region >99%
  - Large mass → statistics always critical for any measurements.

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 Detector (ID) (20% photo-coverage) 25,000 8”Φ PMTs for Outer Detector (OD)
Tanks	2 tanks, with egg-shape cross section 48m (w) × 50m (t) × 250 m (l)

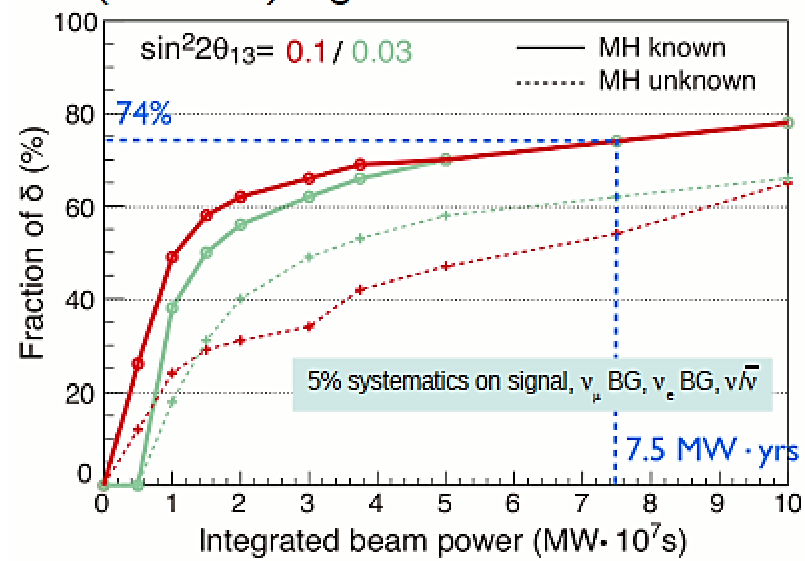
F.di LodovicoM. ICFA 2014

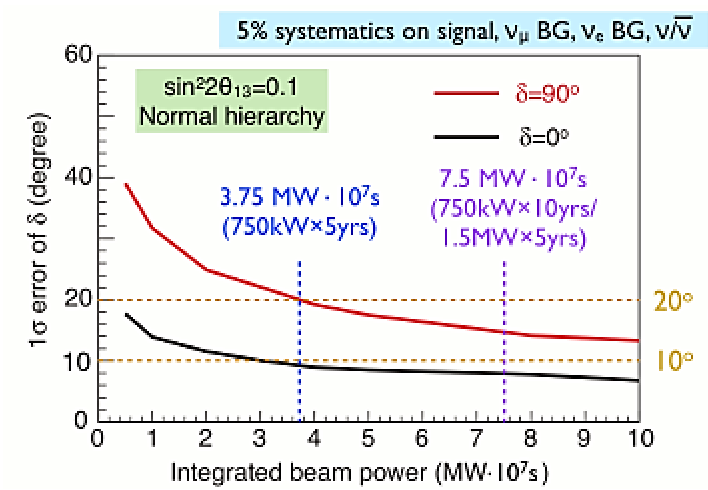
Expected Sensitivity to CP Violation

CPV discovery sensitivity w/ mass hierarchy known.



Fractional region of δ(%) for which the CPV (sin δ ≠0) significance is > 3σ





δ coverage:

CPV > 3σ (5σ) for 74%(55%) of δ

1σ uncertainty of δ as a function of the beam power:

< 20°(10°) for δ = 90°(0°)

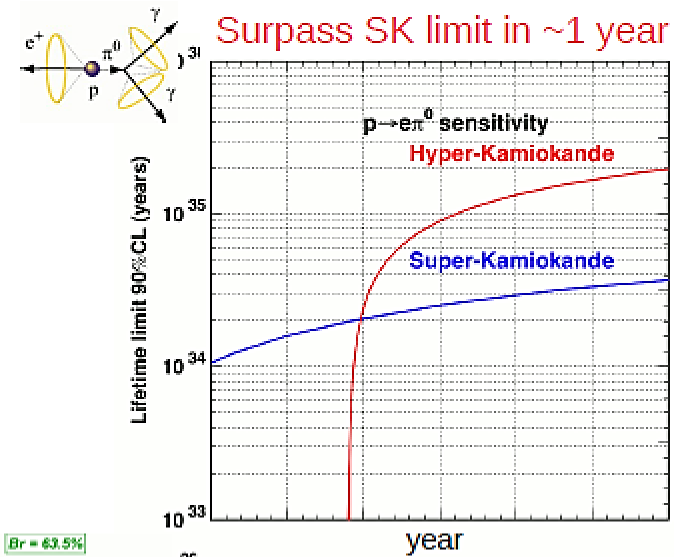
Modest dependence on θ_{13}

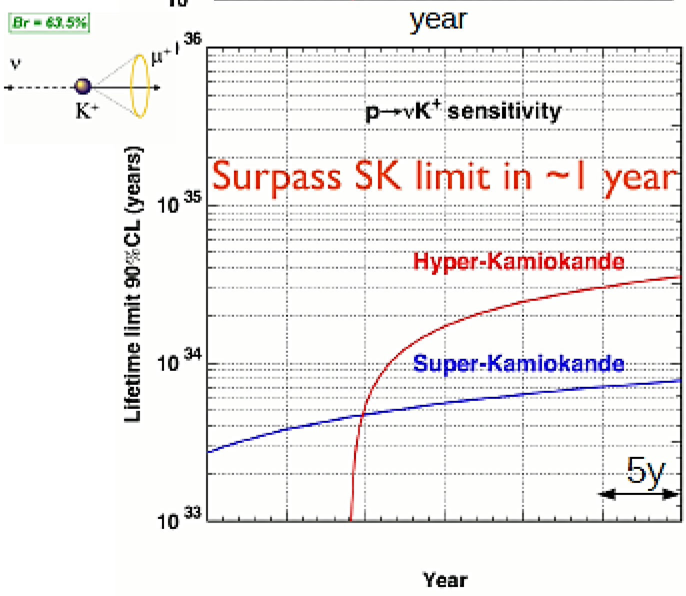
F.di LodovicoM. ICFA 2014

Three Possible Scenario Studied at NP08 Workshop

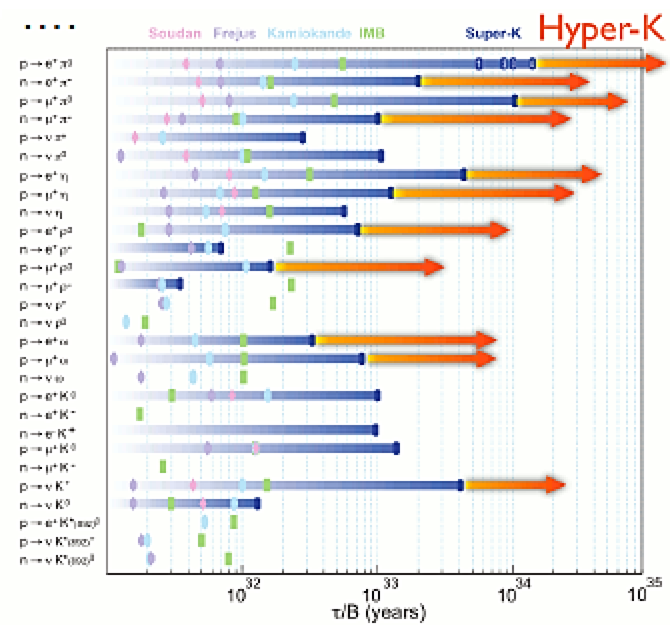
500 kton Water Cherenkov or 100 kton Liquid Argon detector at the 2nd maximum in Korea

Proton Decay Sensitivities





- 10 times better sensitivity than Super-K
- Hyper-K surpasses SK limits in ~1y
  - $p\rightarrow e\pi^0$: 1.3×10^{35} y at 90%CL
  - $p\rightarrow \nu K^+$: 2.5×10^{34} y at 90%CL
  - Many other modes:
    - $P(n\rightarrow e,\mu) + (\pi,\rho,\omega,\eta)$; 10^{14}-10^{35}
    - K^0 modes
    - $\nu\pi^0$, $\nu\pi^+$
    - ….



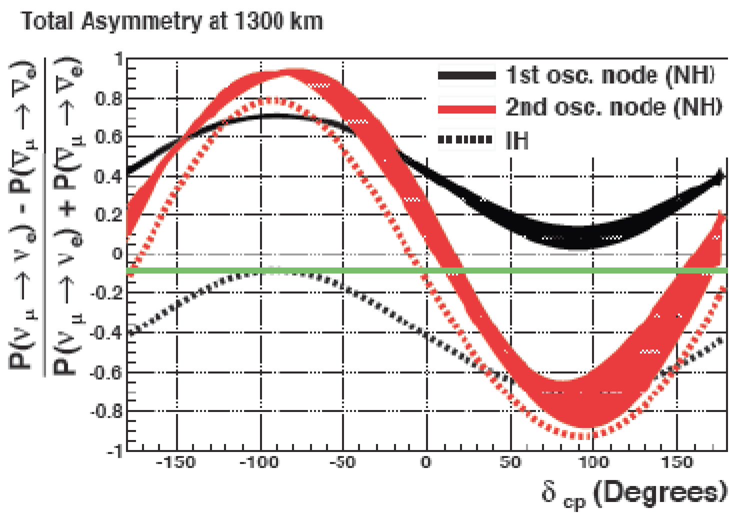
F.di LodovicoM. ICFA 2014

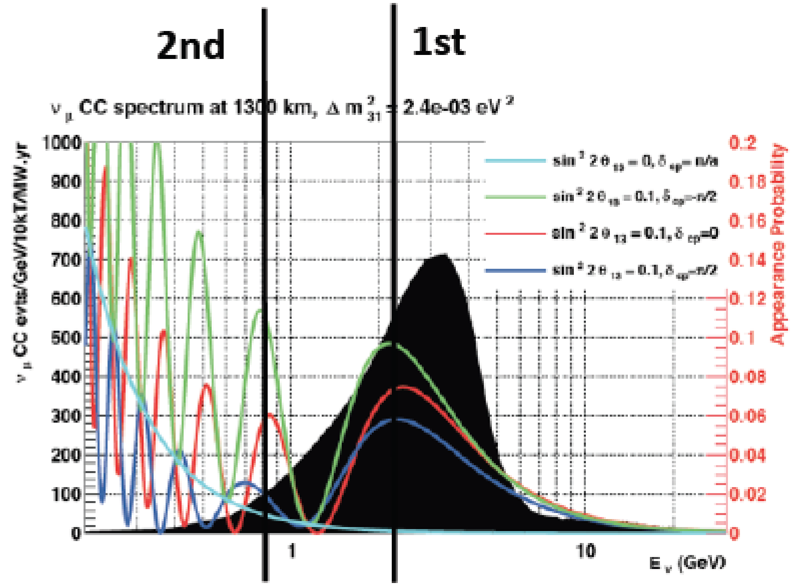
LBNE – Long Baseline Neutrino Experiment in US

LBNE configuration is:

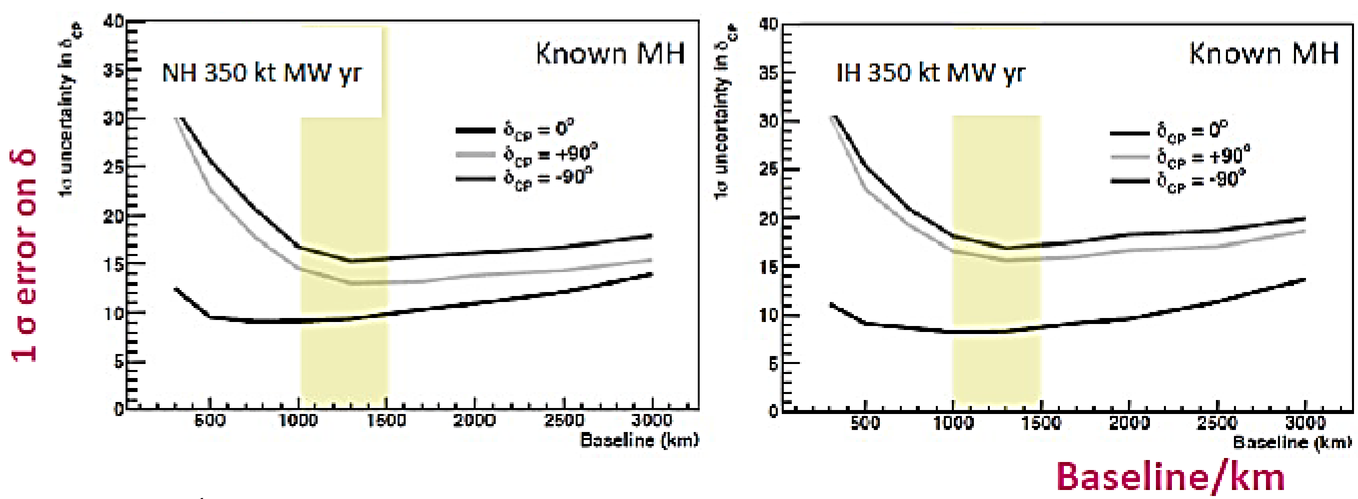
- A horn-produced broad-band beam with 60-120 GeV protons at 700 kw (upgradable to 2.3 MW) from FNAL.
- Planning change: 700 kw → 1.2 MW at LBNE start.
- A baseline of 1300 km towards the Sanford Underground Research Facility in Lead, South Dakota.
- A 35 kt fiducial volume liquid argon time projection chamber located at the 4850 ft level.
- A high resolution near detector at FNAL.
- This configuration will be achieved in a phased manner according to financial constraints.

Neutrino Asymmetries





- **At 1300 km the events from 1st and 2nd maximum (and in-between) can measure the asymmetries from both CP and matter effect.**



The LAGUNA project in Europe (2008-2011)

SITE STUDY

Candidate Sites

- Boulby, UK
- Canfránc, Spain
- Fréjus, France
- Pyhäsalmi, Finland
- Sieroszowice, Poland
- Slanic, Romania
- Caso, Italy

LAGUNA Collaboration

100 scientists
more than 20 institutes
11 European countries

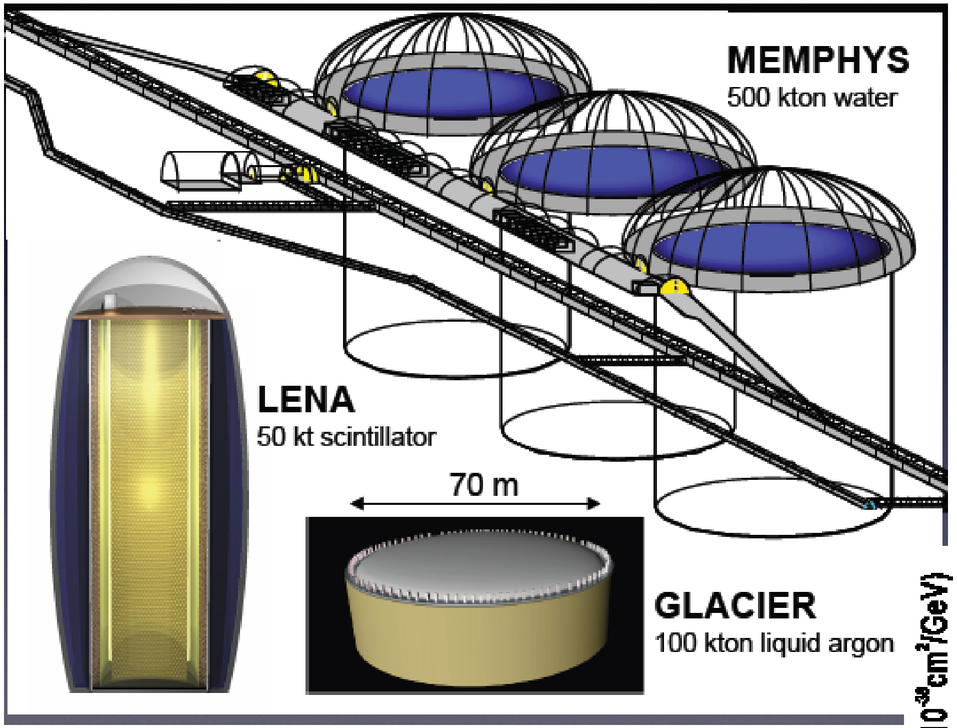
Table 1: Potential sites being studied with the LAGUNA design study.

Location	Type	Envisaged depth m.w.e.	Distance from CERN [km]	Energy 1^{st} Osc. Max. [GeV]
Fréjus (F)	Road tunnel	$\simeq 4800$	130	0.26
Canfranc (ES)	Road tunnel	$\simeq 2100$	630	1.27
Umbria(IT) [a]	Green field	$\simeq 1500$	665	1.34
Sierozsowice(PL)	Mine	$\simeq 2400$	950	1.92
Boulby (UK)	Mine	$\simeq 2800$	1050	2.12
Slanic(RO)	Salt Mine	$\simeq 600$	1570	3.18
Pyhäsalmi (FI)	Mine	up to $\simeq 4000$	2300	4.65

[a] $\simeq$1.0 ° CNGS off axis.

from A.Rubbia

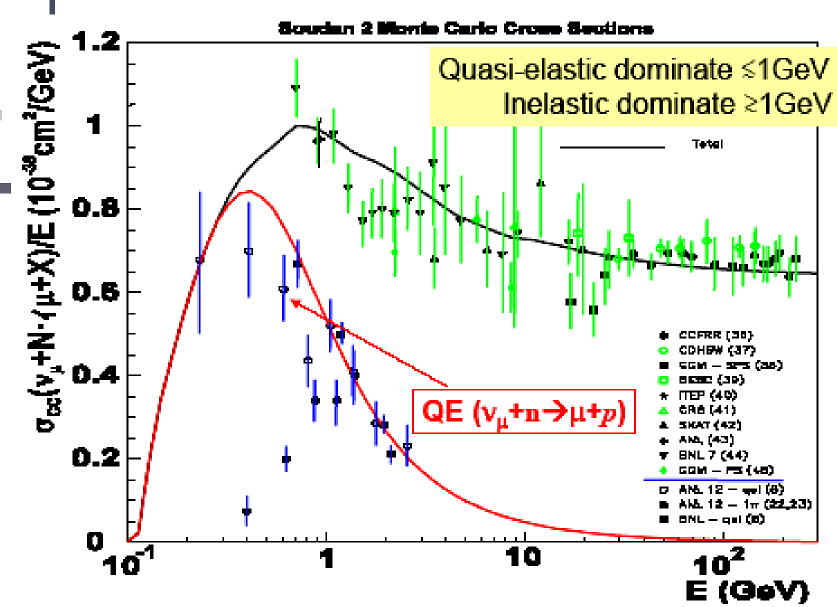
Experimental aspects – choice of detectors



Water Cherenkov detectors -ideal for QE neutrino interactions

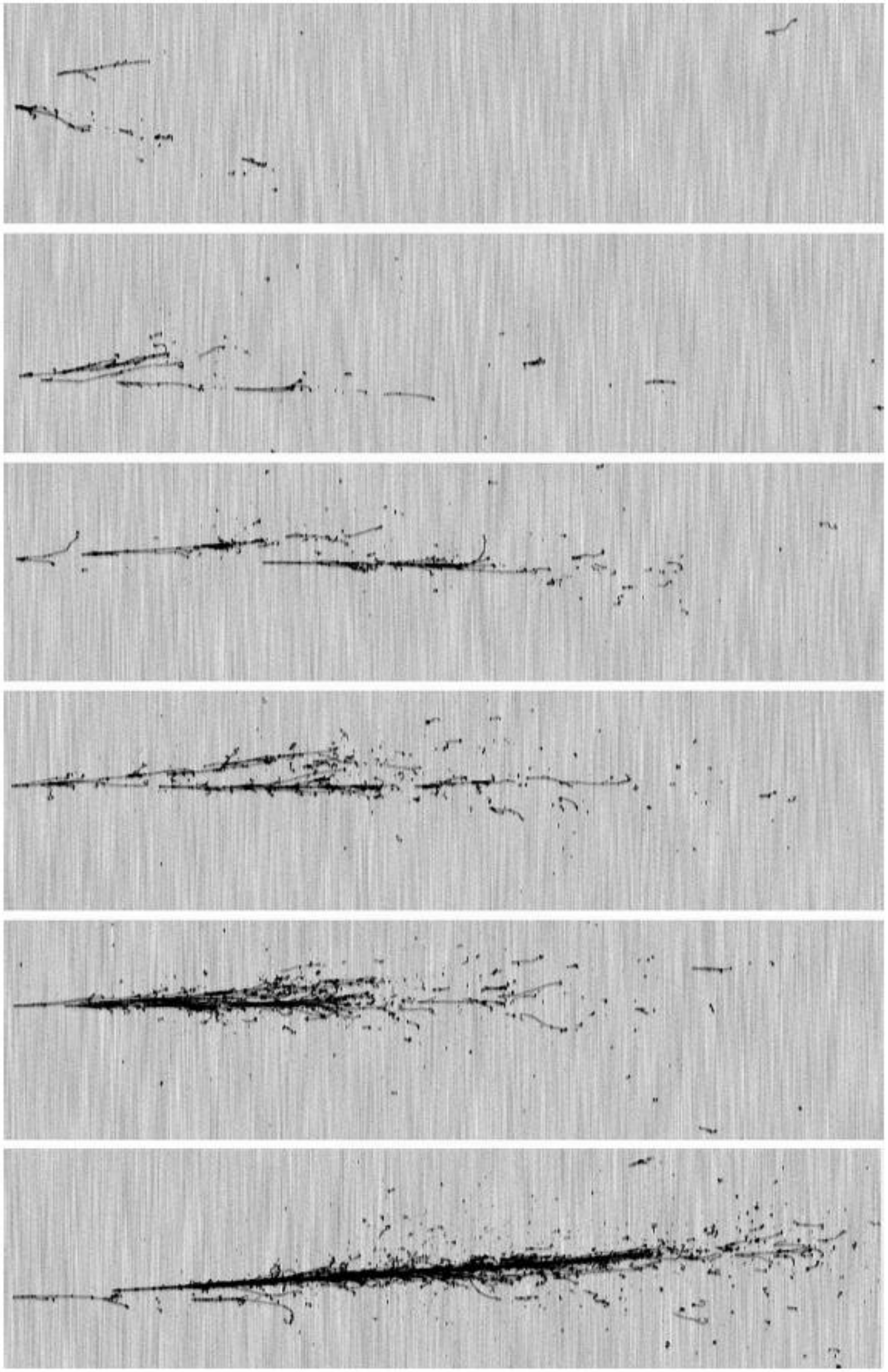
Liquid Argon – better at higher Energies (DIS)

Studies of ν_μ events at higher energies require either muon detector in addtion or a magnetized Liquid Argon detector



But how the detection efficiency for liquid argon changes with energy?

just for illustration simulated π^0's of 0.5, 1, 2, 3, 5, 10 GeV in the ICARUS detector

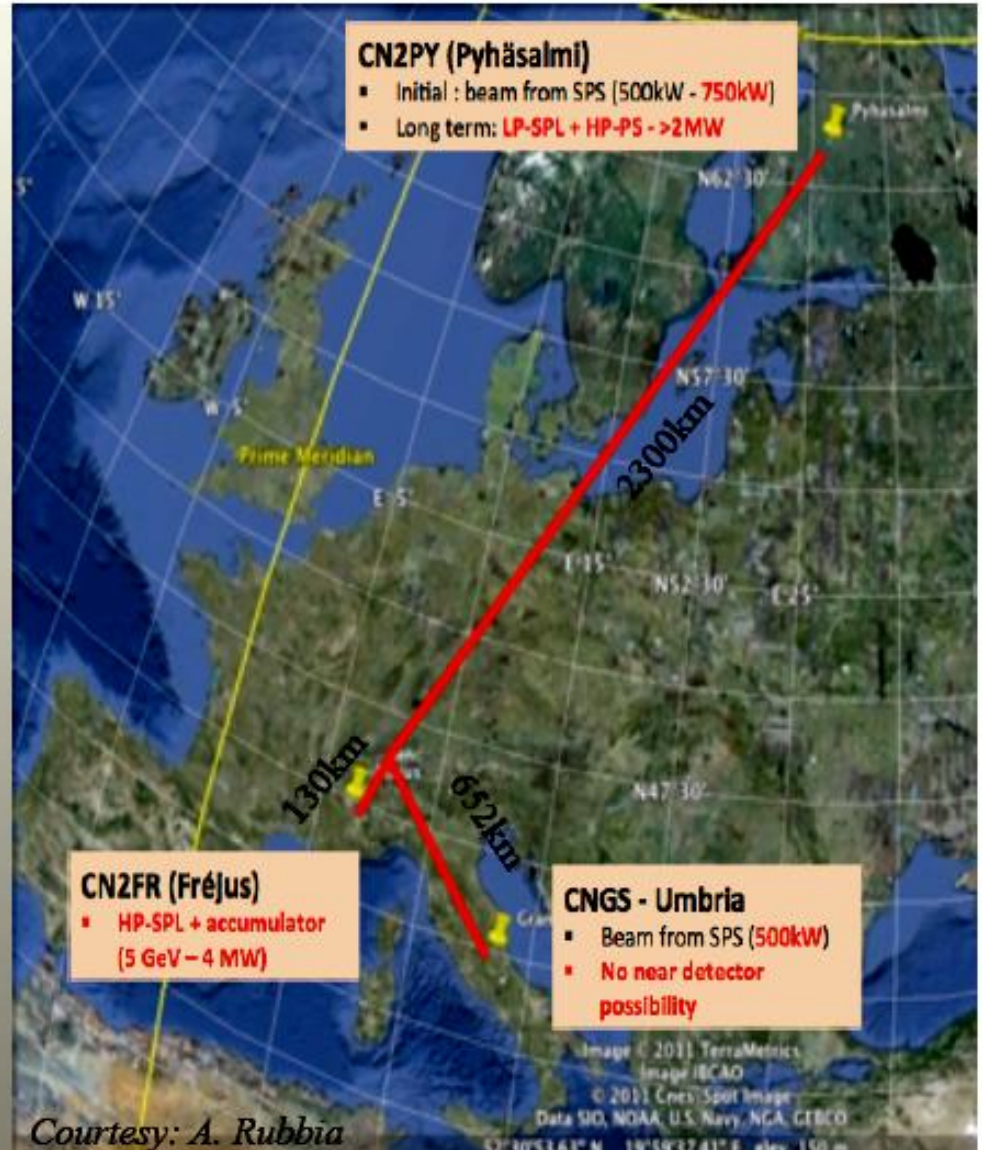


The LAGUNA-LBNO project in Europe (2011-2015)

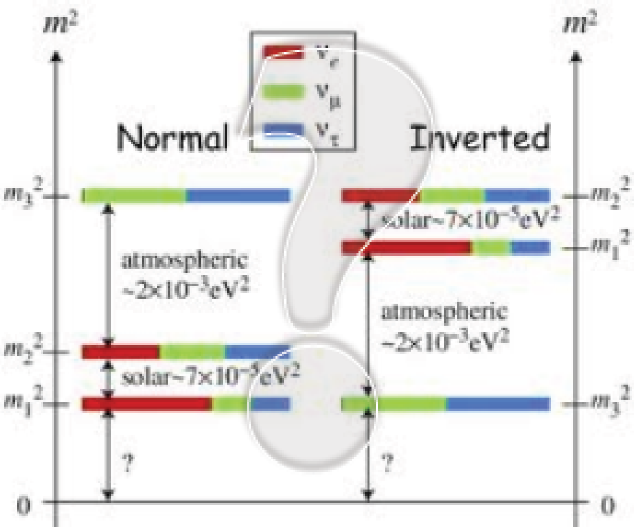
LAGUNA-LBNO sites

New conventional beams to be considered based on CNGS experience

- CERN-Fréjus is a short baseline. It offers good synergy for enhanced physics reach with β-beam at γ=100
- CERN-Pyhäsalmi is the longest baseline. It offers good synergy for enhanced physics reach with a NF
- [CERN-Umbria has an existing beam but is considered at lower priority (missing near detector, limited power upgrade scenarios)]



Mass Hierarchy is a fundamental measurement:



- MH is a **prerequisite** to study leptonic CPV
- Scenarios for lepto-genesis
- Hints for theory development (GUT models)
- Feasibility and interpretation of $0\nu\beta\beta$ experiments
- Interpretation of HDM from cosmology in terms of ν masses

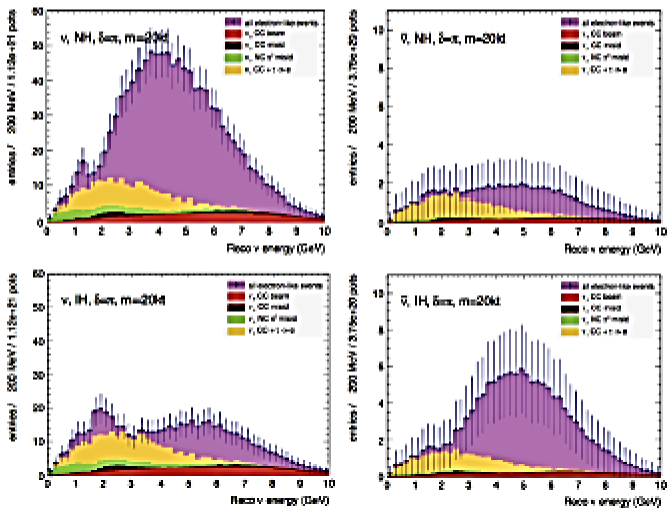
LBNO strategy on MH:

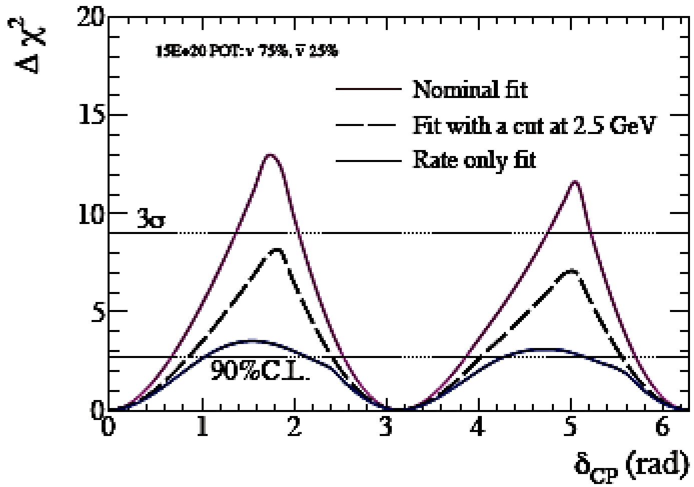
- To guarantee the measure MH on the > 5 σ level one need to go to very long baselines > 2000 km.
- MH should be settled early in the exp. to optimize the ν / $\overline{\nu}$ ratio to maximize CP sensitivity.
- The **median 5 σ sensitivity** (p = 0.5) for LBNO is reached within 2 years of running.
- The **guaranteed 5 σ sensitivity** (p ~ 1) for LBNO is reached within 5 years of running.

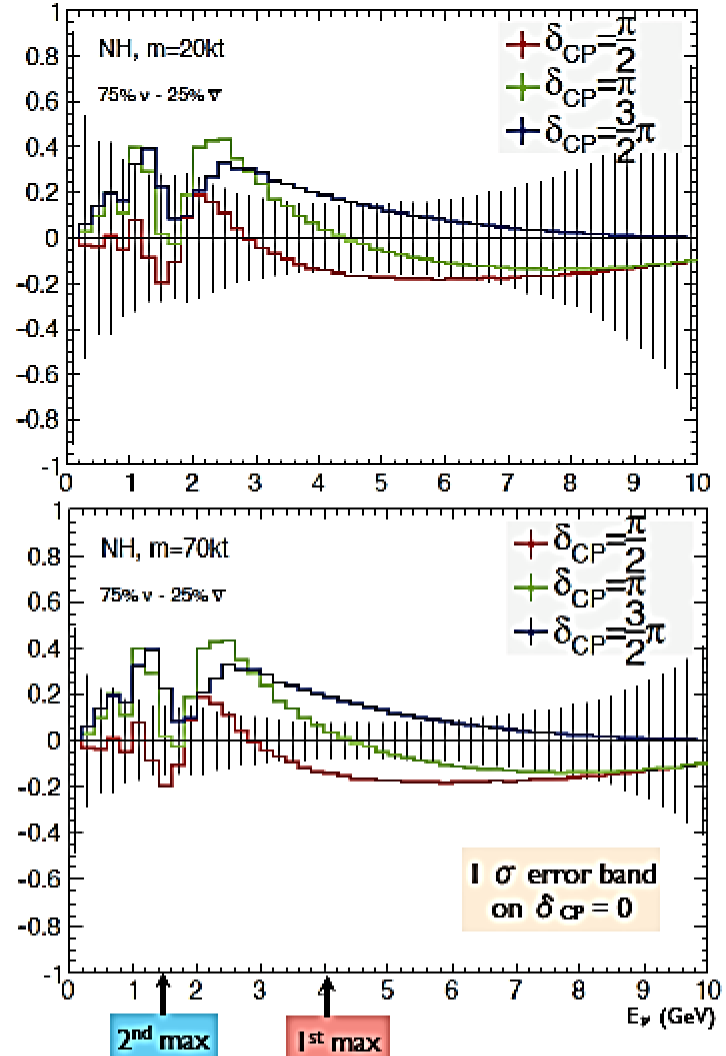
Design value: 75 % ν - 25 % anti-ν

LBNO Strategy on δ_{CP}

Use all spectral information: Rate & Shape for energy range 1st - 2nd max







Once MH determined run for 5 more years with optimized sharing of neutrinos / anti-neutrinos to cover the most possible phase space in δ_{CP}

UPPSALA
UNIVERSITET
1477

An world-unique ESS Based Super Beam for Lepton CP violation discovery

Snowmass White Paper arXiv:1309.7022

Tord Ekelof, Uppsala Univerisity
of behalf of the ESSvSB Collaboration

The ESS 2 GeV proton linac as proton driver for a neutrino Super Beam

EUROPEAN SPALLATION SOURCE

The European Spallation Source (ESS), which is being built in Lund, Sweden, will have a **2 GeV 5 MW (alternatively 2.5 GeV 5MW)** superconduction linac to produce

1.6×10^{16} protons on target/second*

which is two orders of magnitude more than any other planned proton driver for a neutrino beam

- T2HK – JPARK to HyperKamiokande 30 GeV, 0.75 MW ->
- 1.6×10^{14} protons on target/second

- LBNE – FNAL to Sanford Lab 60-120 GeV, 0.7 MW ->
- 1.1×10^{14} protons on target/second

First beams 2019

Full linac power installed 2022

* = Power [W]/(Energy [eV]$\times1.6\times10^{-19}$)

The MEMPHYS detector of the FP7 LAGUNA project;
- Fiducial mass: 440 kt in 3 cylinders 65x65 m
- Readout: 3x81k 12" PMTs, 30% geom. cover.
- Order of magnitude cost : 700 MEuro

10

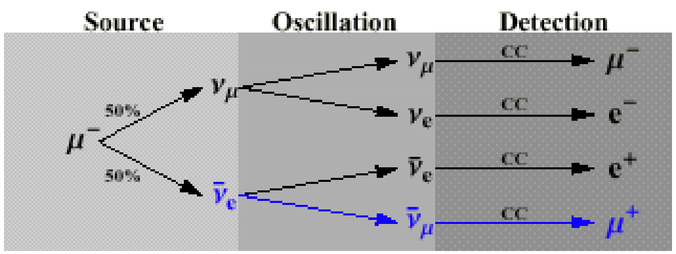
ICFA Neutrino Meeting in Paris
Tord Ekelöf Uppsala University

6

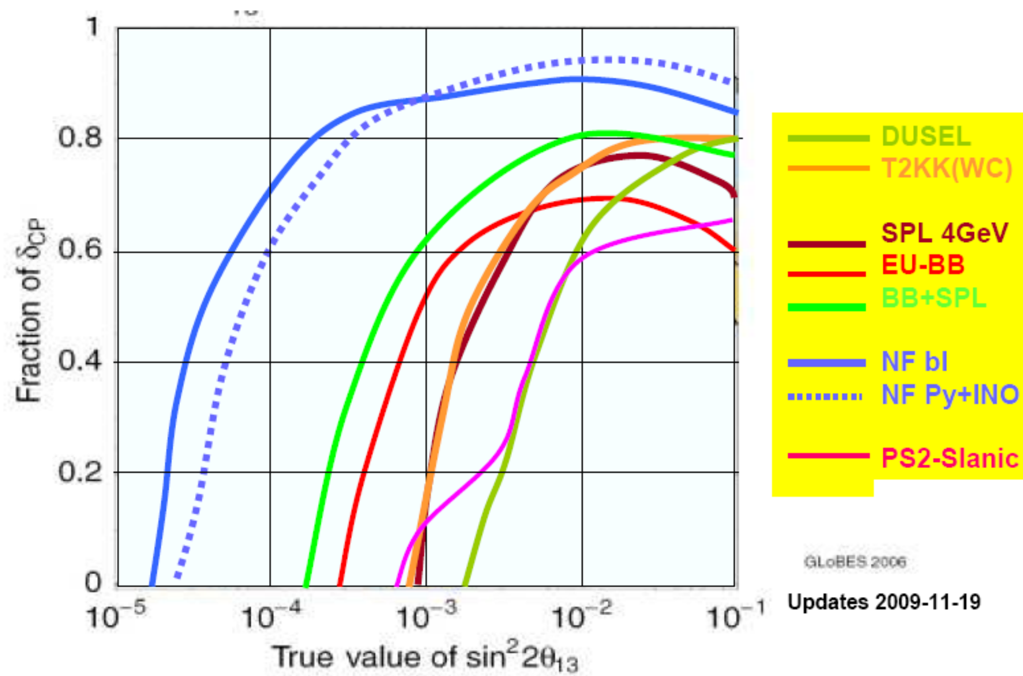
Further future of the CP studies

New sources of neutrinos based on new types of accelerators

Neutrino factories – nuSTORM project as a first step



$\mu^- \to e^- \nu_\mu \bar{\nu}_e$	
Disappearance	**Appearance**
$\bar{\nu}_e \to \bar{\nu}_e \to e^+$	$\bar{\nu}_e \to \bar{\nu}_\mu \to \mu^+$ $\bar{\nu}_e \to \bar{\nu}_\tau \to \tau^+$
$\nu_\mu \to \nu_\mu \to \mu^-$	$\nu_\mu \to \nu_e \to e^-$ $\nu_\mu \to \nu_\tau \to \tau^-$



From the report of the SPC neutrino panel for the CERN Council, March 2010

Steryle neutrinos

Various observed anomalies

Ways to solve them

Is the 3-flavour oscillations scheme fully consistent

?

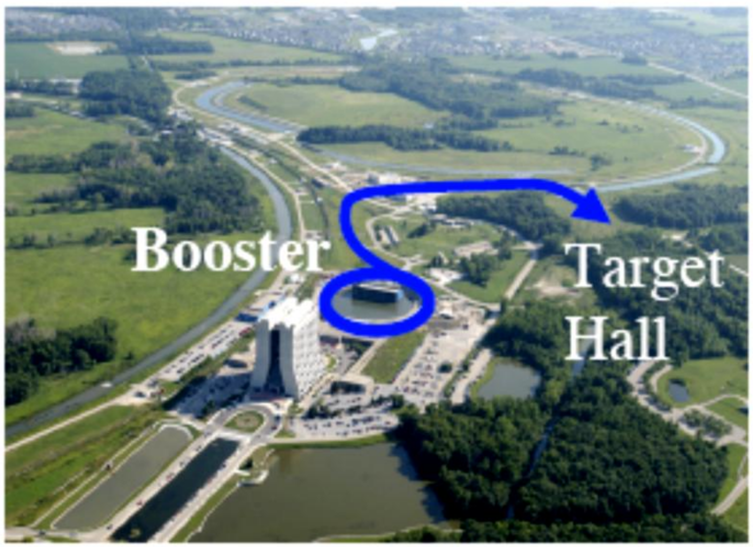
LSND story

- ❑ 3rd region of oscillation parameters was observed in the LSND experiment
- ❑ 3 different values of Δm^2 → more than 3 neutrino species must exist
- ❑ BUT 3 active neutrinos according to the measurements at LEP → other neutrinos of different type „sterile"
- ❑ MiniBooNE experiment was designed to check the LSND effect (different beam, different baseline, different systematics)

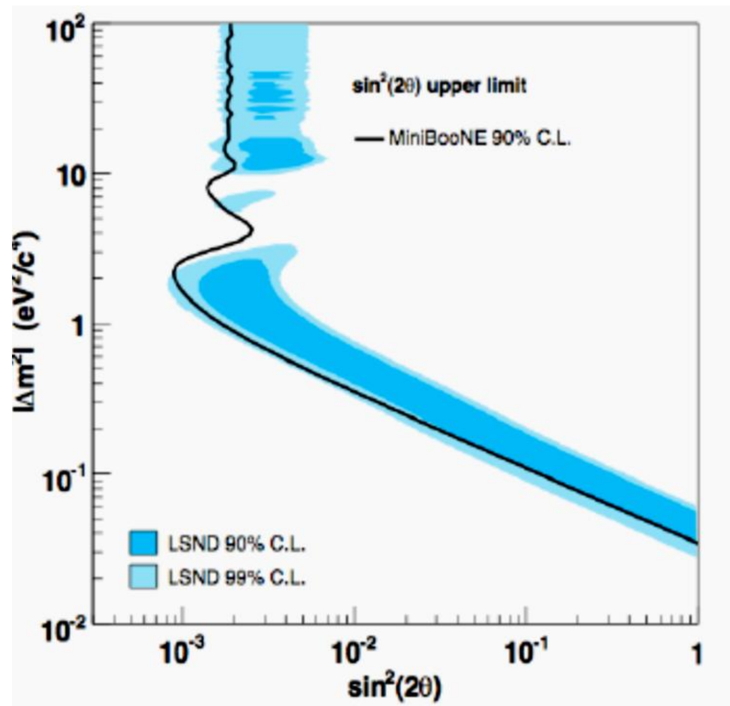
MiniBooNE results for neutrinos

2007 - no need for extra ν species (sterile neutrino(s)):

The result of the MiniBooNE experiment, searching for the $\nu_\mu \leftrightarrow \nu_e$ oscillations for L/E ≈1: L = 500 m, E ≈ 500 MeV (published in 2007), exclusion of the LSND effect.



Another neutrino beam at FNAL



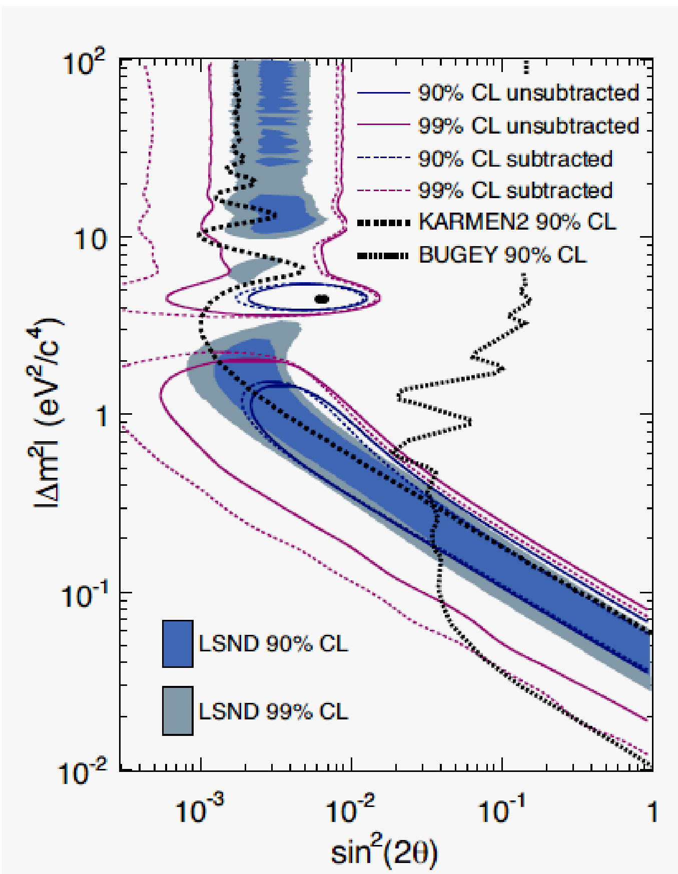
χ^2 probability equal 93% for the hypothesis of no oscillations

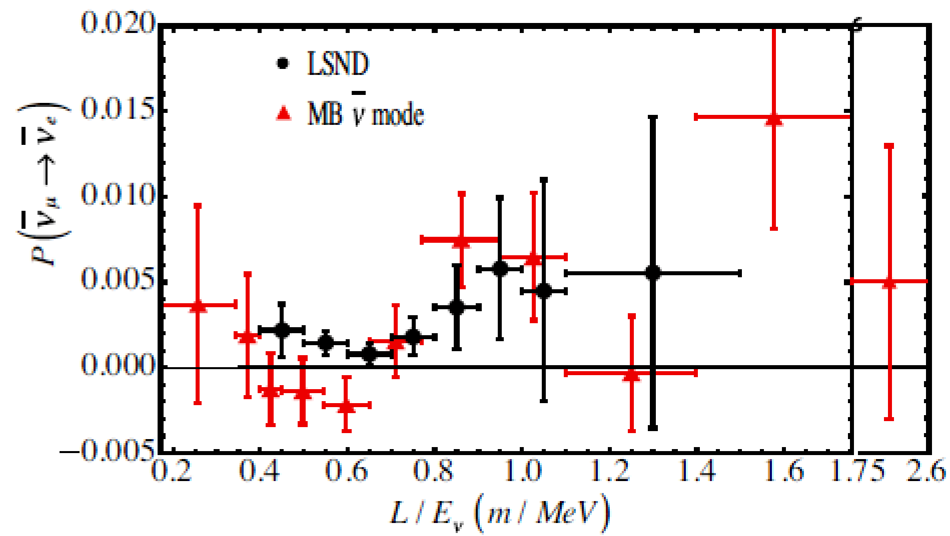
BUT new facts at Neutrino 2010 !!!

MiniBooNE results for antyneutrinos

arXiv:1007.1150v3 [hep-ex]
PRL 105 (2010) 181801

2010 – excess of events corresponting to anty-ν_e interactions

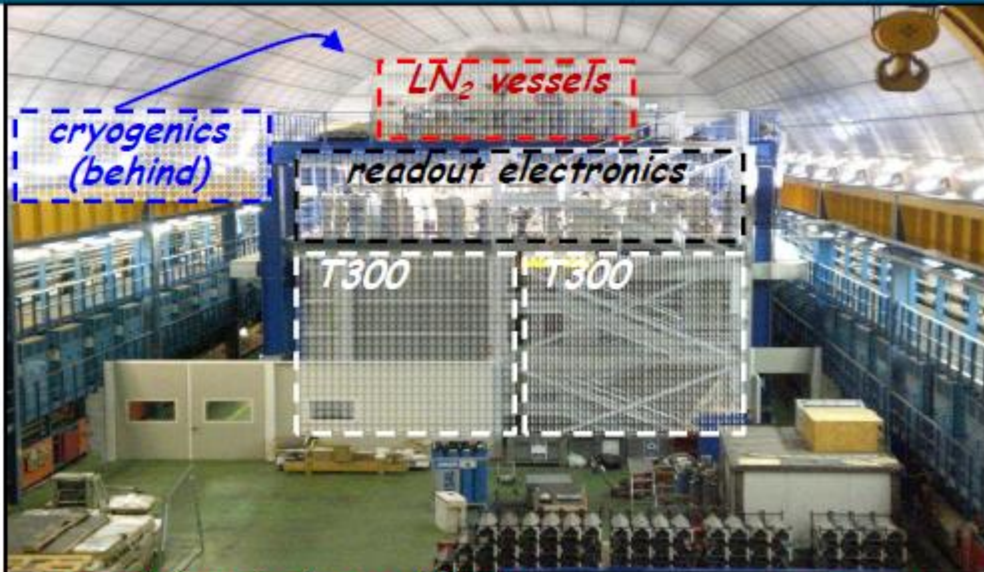


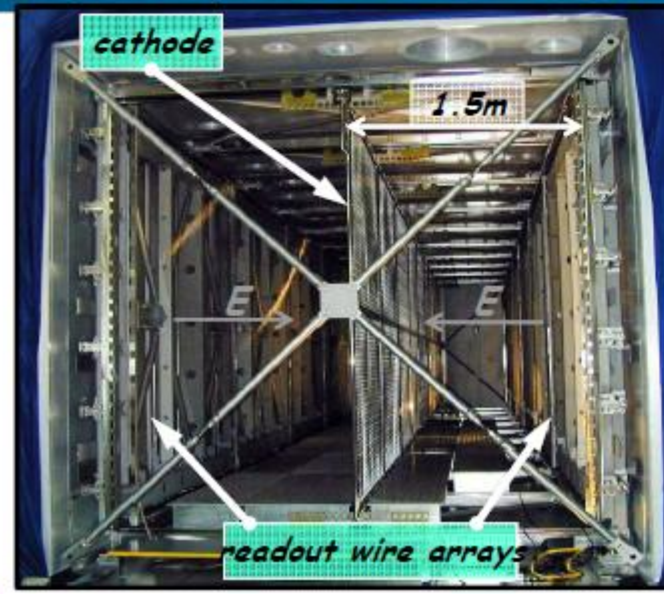


→ Better experiment with two detectors is needed,

→ MicroBooNE LAr exp. approved in the US, 1ktonne detector added in the future

The ICARUS single-phase T600 LAr-TPC at LNGS laboratory

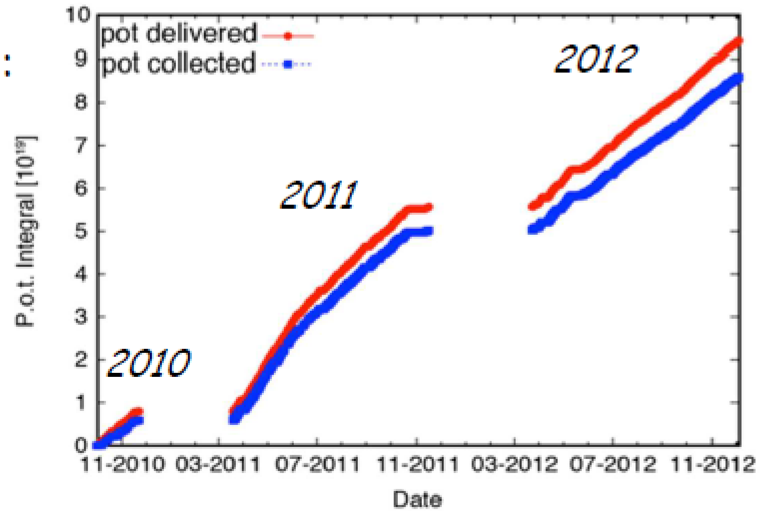




- *Two identical modules*
  - *3.6x3.9x19.6 ≈ 275 m^3 each*
  - *Liquid Ar active mass: ≈476 t*
  - *Drift length = 1.5 m (1 ms)*
  - *HV = -75 kV; E = 0.5 kV/cm*
  - *v-drift = 1.55 mm/µs*
  - *Sampling time 0.4µs (sub-mm resolution in drift direction)*
- *4 wire chambers:*
  - *2 chambers per module*
  - *3 "non-distructive" readout wire planes per chamber wires at 0,±60° (up to 9 m long)*
  - *Charge measurement on collection plane*
  - *≈ 54000 wires, 3 mm pitch and plane spacing*
- *20+54 8" PMTs for scintillation light detection*
  - *VUV sensitive (128nm) with TPB wave shifter*

The ICARUS T600 detector at LNGS Laboratory

- Exposed to CNGS beam up to Dec. 3rd 2012: a 8.6 10^{19} pot event statistics has been collected with a remarkable detector live-time > 93 %.
- In parallel data taking with Cosmics has been conducted to study detector capability for atmospheric ν, p-decay search (0.73 kty exposure).



- T600 decommissioning @ LNGS is successfully proceeding from June 27th
  - cryostats empty on July 25th (740 out of 760 tons LAr recovered); detector @ room temperature on September 1st.
- TPC chambers, cryogenic plant, read-out electronics, chimneys,... and ancillary systems will be recovered.

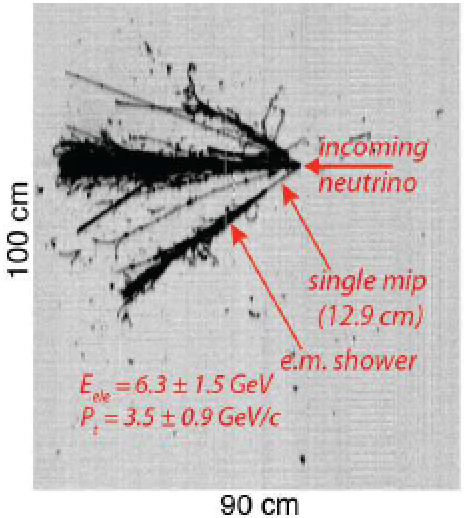
T600 run at LNGS: first publications

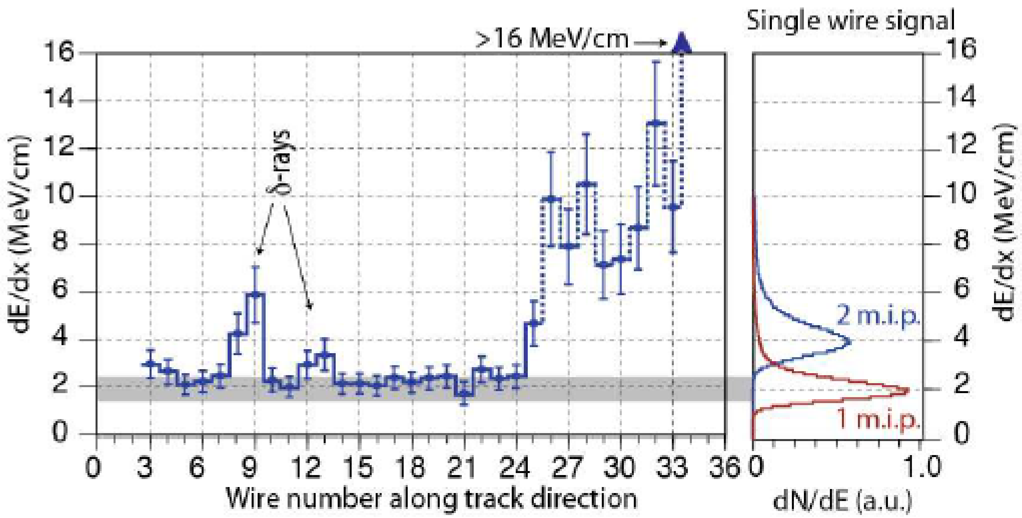
1. "Underground operation of the ICARUS T600 LAr-TPC: first results", JINST **6** (2011) P07011.
2. "A search for the analogue to Cherenkov radiation by high energy neutrinos at superluminal speeds in ICARUS", PLB 711 (2012) 270.
3. "Measurement of neutrino velocity with the ICARUS detector at the CNGS beam", PLB 713 (2012) 17.
4. "Precision measurement of the neutrino velocity with the ICARUS detector in the CNGS beam", JHEP 11 (2012) 049.
5. "Precise 3D Reconstruction Algorithm for the ICARUS T600 Liquid Argon Time Projection Chamber Detector", AHEP 2013 (2013) 260820.
6. "Experimental search for the LSND anomaly with the ICARUS detector in the CNGS neutrino beam", EPJ C73 (2013) 2345.
7. "Search for anomalies in ν_e appearance from ν_μ beam", EPJ C73 (2013) 2599.

Analysis of the large amount of physics data becoming progressively the main activity of the CNGS2 collaboration

The new ICARUS results

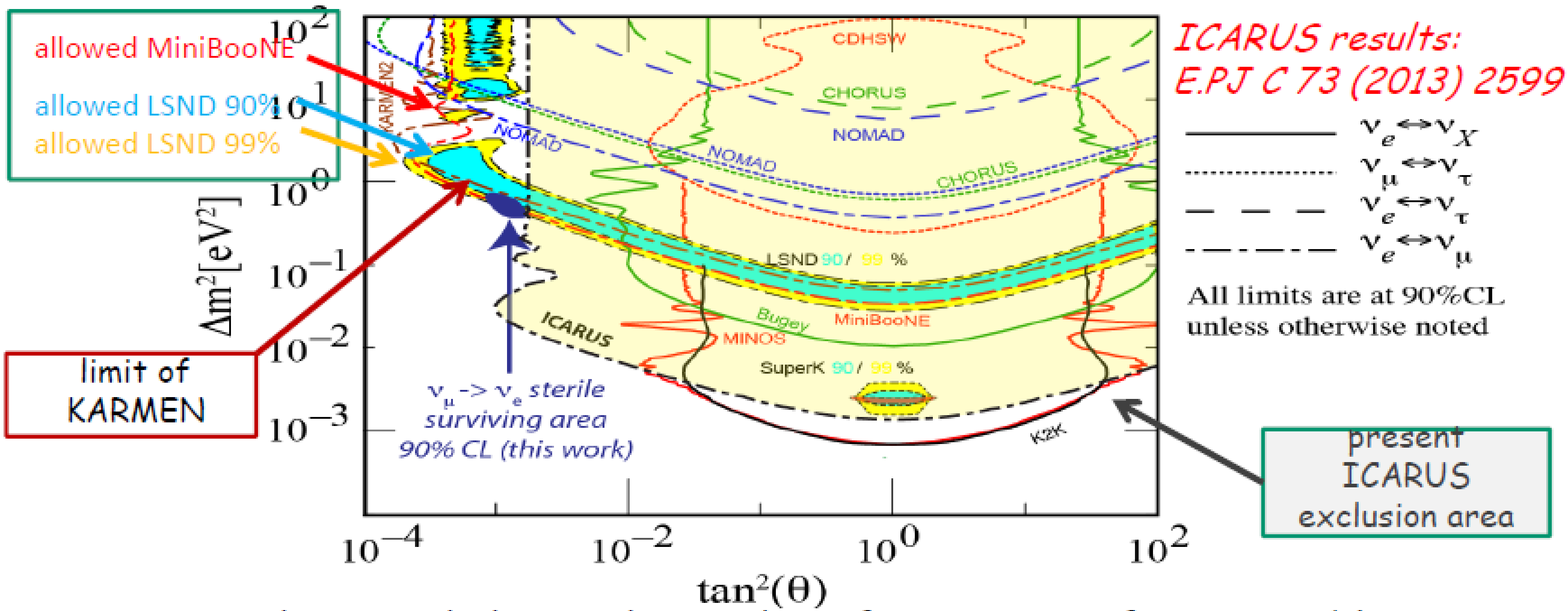
- Experimental pictures of one of the **four events** with a clear electron signature found in the sample of 1995 ν interactions (6.0 10^{19} pot over the full recorded statistics of 8.6 10^{19} pot).
- In all events the single electron shower is opposite to hadronic component in the transverse plane.
- The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is shown along the individual wires.





- The expected number of e- events from intrinsic ν_e beam, θ_{13}~9^0 and ν_μ–ν_τ oscillations is then 6.4±0.9 (syst. only).

LSND-like exclusion from the ICARUS experiment



ICARUS result strongly limits the window of parameters for *a possible* LSND anomaly to a very narrow region *($\Delta m^2 \approx 0.5\ eV^2$ and $\sin^2 2\theta \approx 0.005$)* where there is an overall agreement (90% CL) *of*

- the present ICARUS limit
- the limits of KARMEN
- the positive signals of LSND and MiniBooNE

However the original LSND anomaly requires the direct verification with anti-νs

Instead of conclusions

Neutrino physics fascinating but difficult

Very interesting topics of searches for neutrinoless double beta decays require a separate talk

Neutrino studies offer the best way to find physics beyond the Standard Model?

Neutrino masses and nature

How to weight neutrino?

Dirac or Majorana particle?

How to measure neutrino masses?

- Direct measurements of the ν_e mass based on the end-point of electron energy spectra in beta decays

The best measurement from the end-point of the tritium β decay (2.2 eV limit at present, 0.2 eV in a few years from the KATRIN experiment)

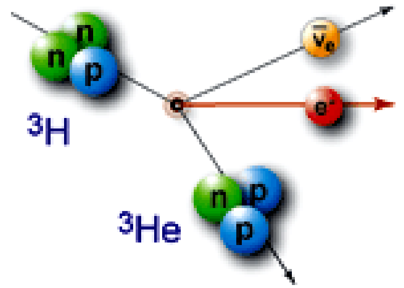
- Measurements based on the lifetime measurements for the neutrinoless double beta decays

Potentially the most sensitive method for the mass determination but neutrino must be a Majorana particle

- Cosmological limits

Resent cosmic microwave background measurements by the Wilkinson Microwave Anisotropy Probe (WMAP) together with different survey experiments give upper limits for a sum of masses of different neutrino species typically below 1 eV but these limits are model dependent

Measurement of ν_e mass from Tritium β decays



$$E_0 = M(^3H) - M(^3He) - m_e$$
$$= 18.6\ keV$$
$$\tau_{1/2} = 12.3\ years$$

$E_0 = E_e + E_\nu$ (+ recoil corrections)

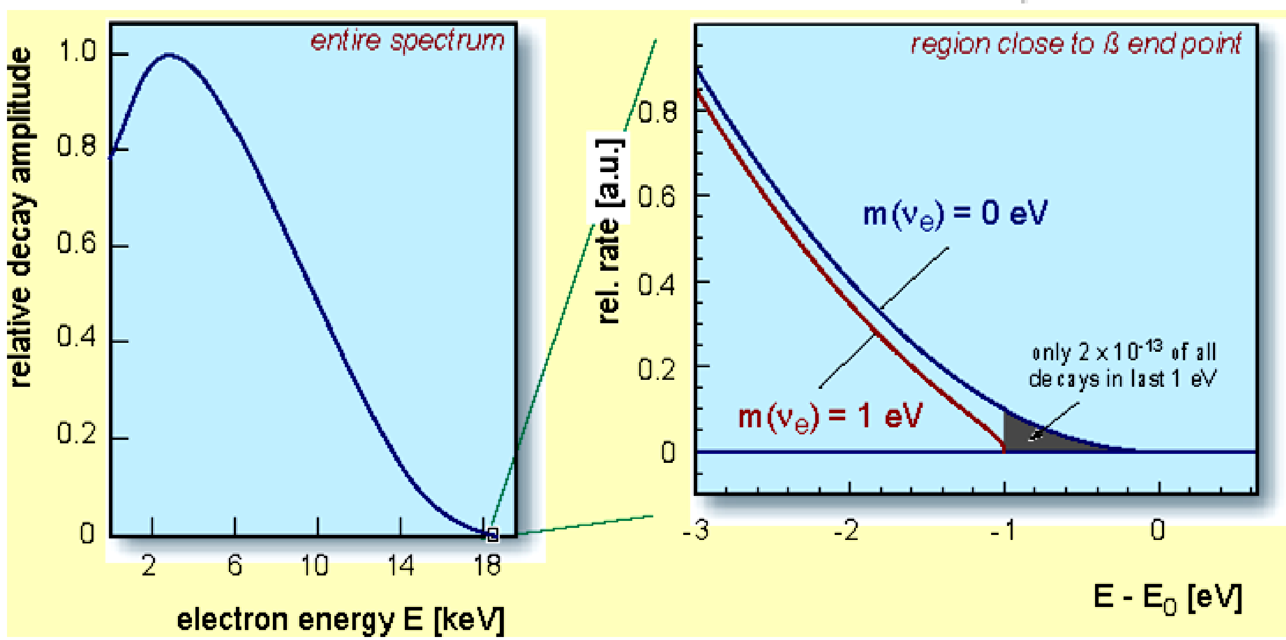
$$\frac{dn}{dE} = F(Z,E)\,p_e E(E_0 - E)\left((E_0 - E)^2 - m_\nu^2\right)^{1/2} \qquad K(E) = \frac{1}{Fp_e E}\frac{dn}{dE}$$

model-independent

squared neutrino mass:

$$m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2$$

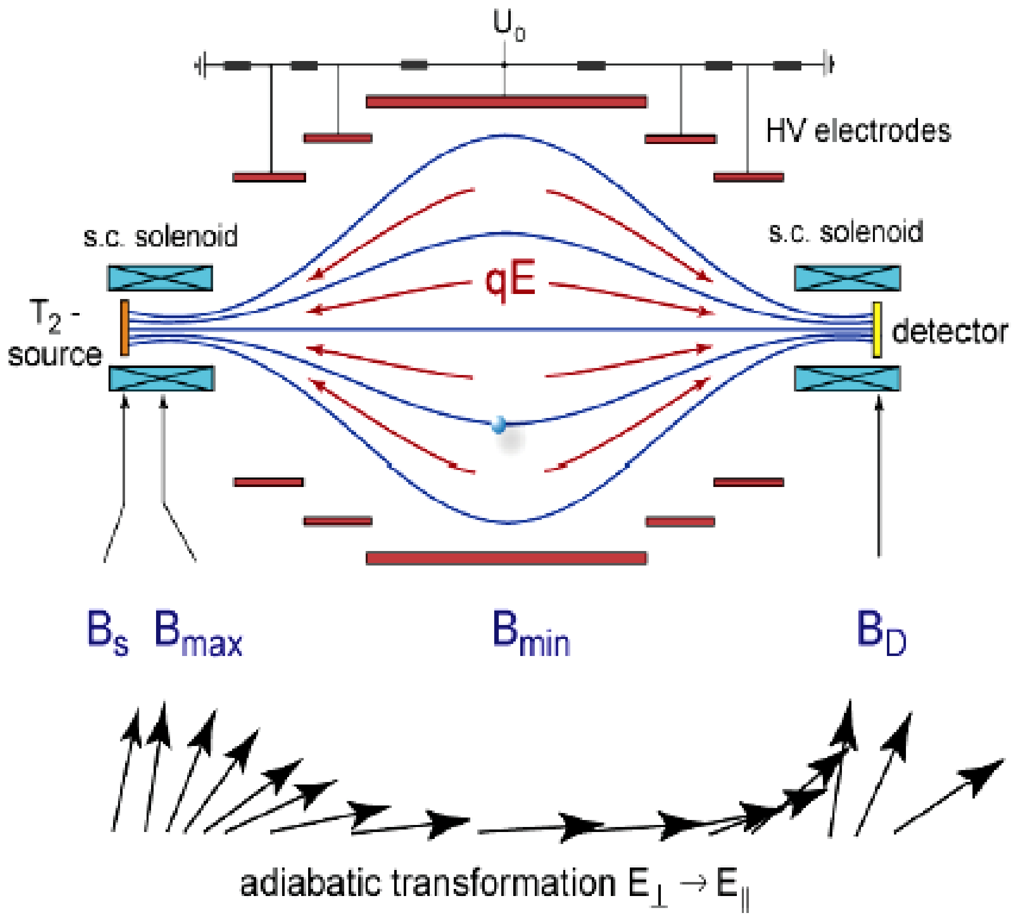
- direct, from kinematics
- status: $m_\nu < 2.3$ eV
- potential: $m_\nu = 200$ meV



The MAC-E Filter

Magnetic Adiabatic Collimation with Electrostatic Filter

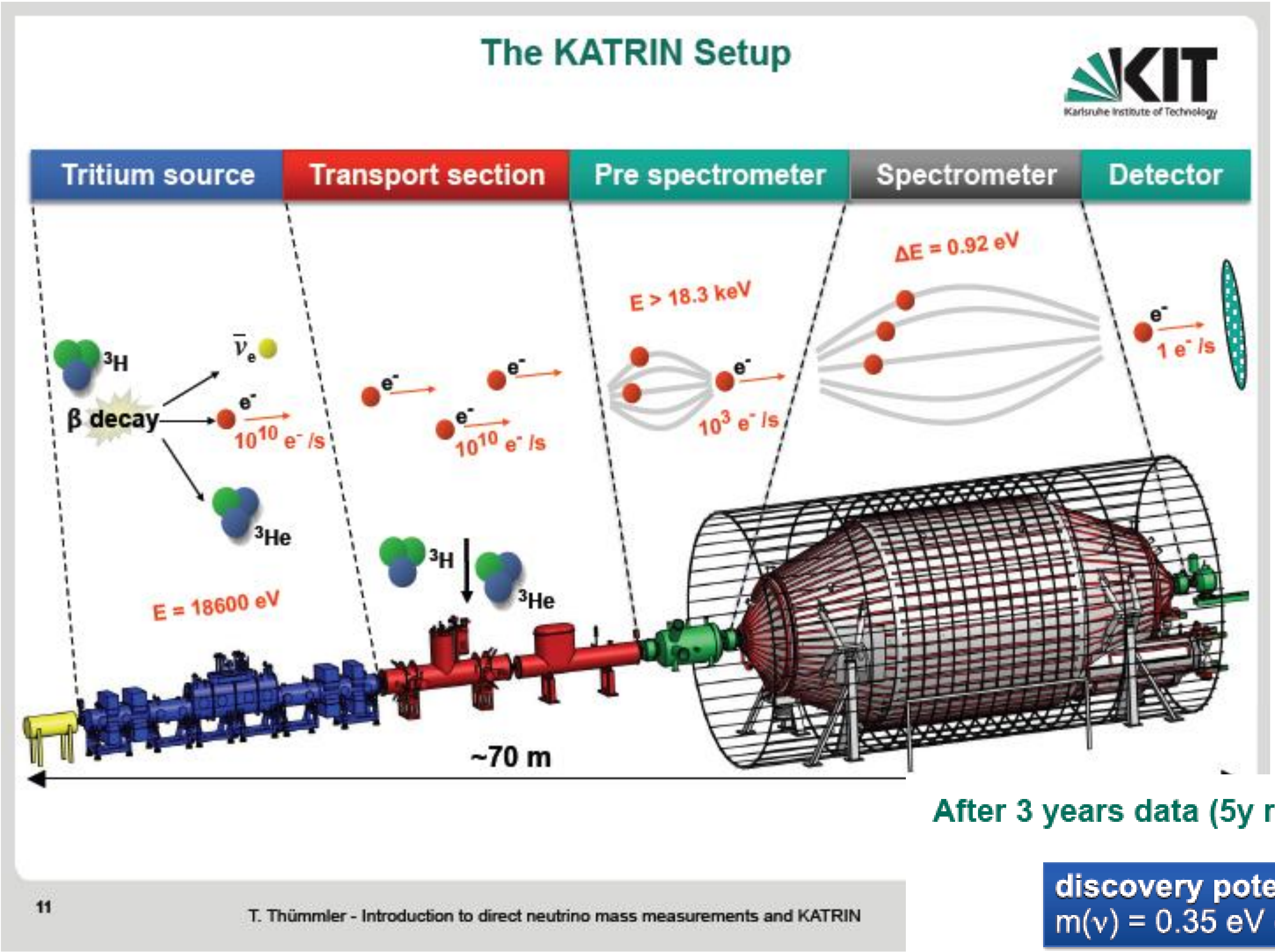
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)



- inhom. magn. guiding field:
  → gradient force:
  adiab. transformation $\mathbf{E_\perp} \rightarrow \mathbf{E_{||}}$
  due to $\boldsymbol{\mu} = \mathbf{E_\perp/B} = \boldsymbol{const.}$
- momentum of e^- || magnetic field
  → el. retarding potential
  → energy analysis

  → **high-pass filter** with a sharp transmission function, no tails!
- high resolution:
  $\Delta E = E \cdot B_{min} / B_{max}$
- magn. adiab. collimation
  → large solid angle (2π)

KATRIN experiment



After 3 years data (5y realtime):

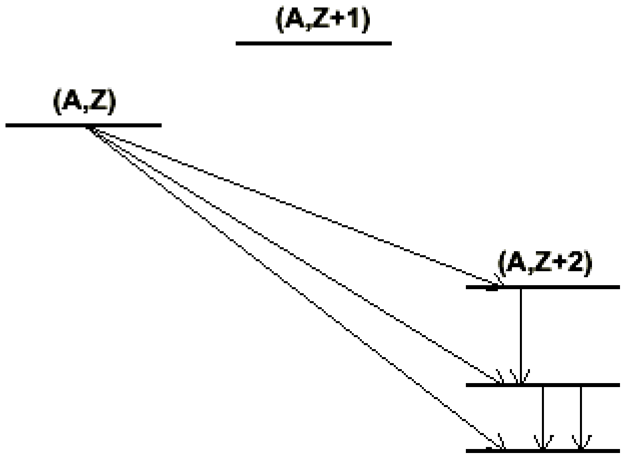
discovery potential
$m(\nu) = 0.35$ eV (5σ)

sensitivity (90% CL)
$m(\nu) < 0.2$ eV

Double beta decay

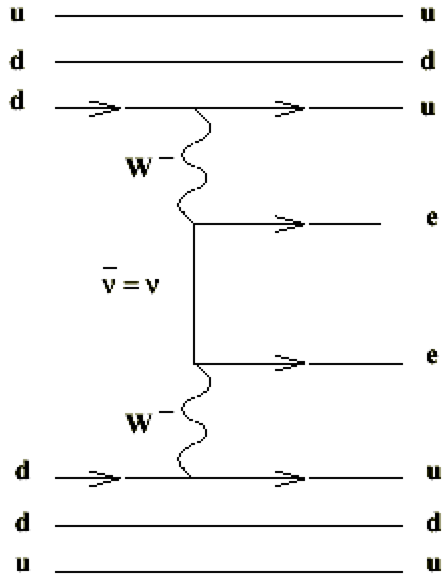
For some even-even nuclei the decay chain

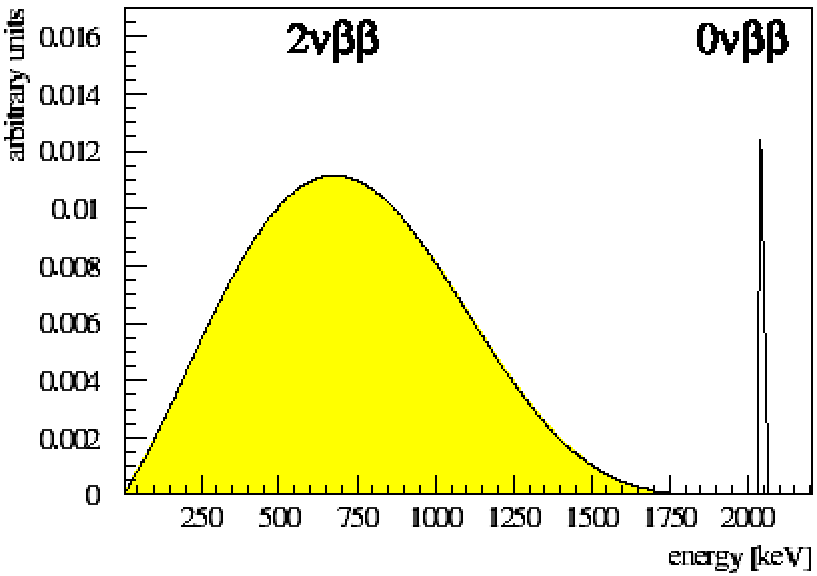
$$(A,Z) \rightarrow \quad (A,Z+1) + e^- + \overline{\nu}_e$$
$$\hookrightarrow (A,Z+2) + e^- + \overline{\nu}_e$$



is forbidden by energy conservation and one could have

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}_e$$
$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$





The most sensitive method but neutrino has to be a Majorana particle

Double β decays – 2νββ and 0νββ

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_\nu\rangle^2$$

$G^{0\nu}$ Phase-space factor

$|M^{0\nu}|^2$ Nuclear matrix element

$\langle m_\nu\rangle^2$ Effective neutrino mass

$$\langle m_\nu\rangle = \sum_k \phi_k m_k U^2_{e,k}$$

Table I A selection of the past and present experiments giving the best result per isotope to date. All given $\tau^{0\nu}_{1/2}$ ($\langle m_\nu\rangle$) are lower (upper) limits with the exception of the Heidelberg-Moscow experiment where the 99.9973% CL value is given. The spread in $\langle m_\nu\rangle$ is due to the uncertainties on the nuclear factor F_N.

isotope	experiment	latest result	$Q_{\beta\beta}$ [keV]	i. a. nat.	enrich.	exposure [kg×y]	technique	material	$\tau^{0\nu}_{1/2}$ [10^{23} y]	$\langle m_\nu\rangle$ [eV]
^{48}Ca	Elegant VI	2004[11]	4271	0.19	–	4.2	scintillator	CaF_2	0.14	7.2÷44.7
^{76}Ge	Heidelberg/Moscow	2004[17]	2039	7.8	87	71.7	ionization	Ge	120.0	0.44
^{82}Se	NEMO-3	2007[22]	2995	9.2	97	1.8	tracking	Se	2.1	1.2÷3.2
^{100}Mo	NEMO-3	2007[22]	3034	9.6	95÷99	13.1	tracking	Mo	5.8	0.6÷2.40
^{116}Cd	Solotvina	2003[12]	2805	7.5	83	0.5	scintillator	$CdWO_4$	1.7	1.7
^{130}Te	Cuoricino	2007[20]	2529	33.8	–	11.8	bolometer	TeO_2	30.0	0.16÷0.84
^{136}Xe	DAMA	2002[23]	2476	8.9	69	4.5	scintillator	Xe	12.0	1.10÷2.9
^{150}Nd	Irvine TPC	1997[14]	3367	5.6	91	0.01	tracking	Nd_2O_3	0.012	3.0
^{160}Gd	Solotvina	2001[13]	1791	21.8	–	1.0	scintillator	Gd_2SiO_5	0.013	26.0

nucl-ex/0707.2216

SENSITIVITY AND CANDIDATES

$$\langle m_{ee}\rangle^2 = \frac{1}{\tau_{1/2}\; G_{0\nu}\,|M_{0\nu}|^2}$$

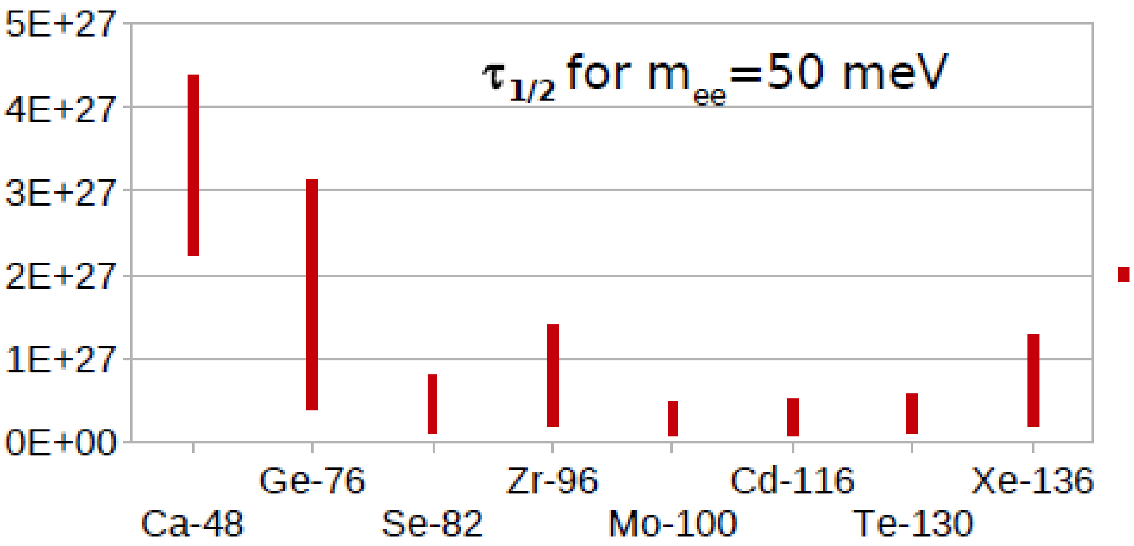
m_{ee} = Majorana mass

$G_{0\nu}\ |M_{0\nu}|^2$ = phase space & NME

$S_{0\nu}$ = 0ν sensitivity

F_N = nuclear factor of merit

Reasonable $F_N \rightarrow$ GOLDEN LIST OF CANDIDATES



NME bibliography:

1 Šimkovic et al., PRC 77 (2008) 045503
2 Civitarese et al., JoP:Conference series 173 (2009) 012012
3 Menéndez et al., NPA 818 (2009) 139
4 Barea and Iachello, PRC 79 (2009) 044301

0νββ signal in the Moskow-Heidelberg experiment?

First announcement in 2002, new publication in 2004, based on the data collected between 1990 and 2003

Klapdor-Kleingrothaus Phys. Lett. B586 (2004) 198

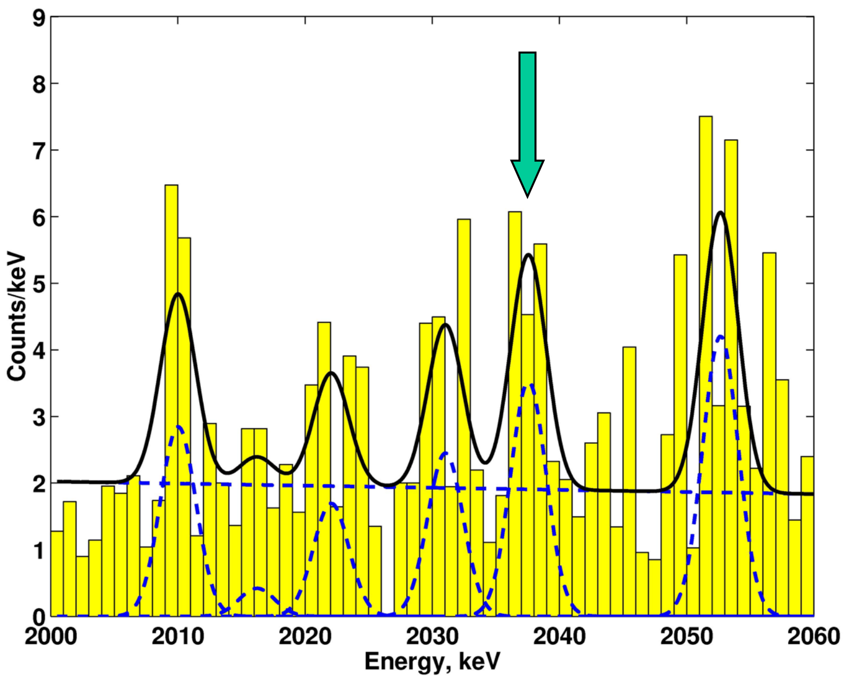


Fig. 31. The single site sum spectrum of the four detectors 2,3,4,5 for the period November 1995 to May 2003 (51.389 kg y), and its fit (see section 3), in the range 2000 - 2060 keV.

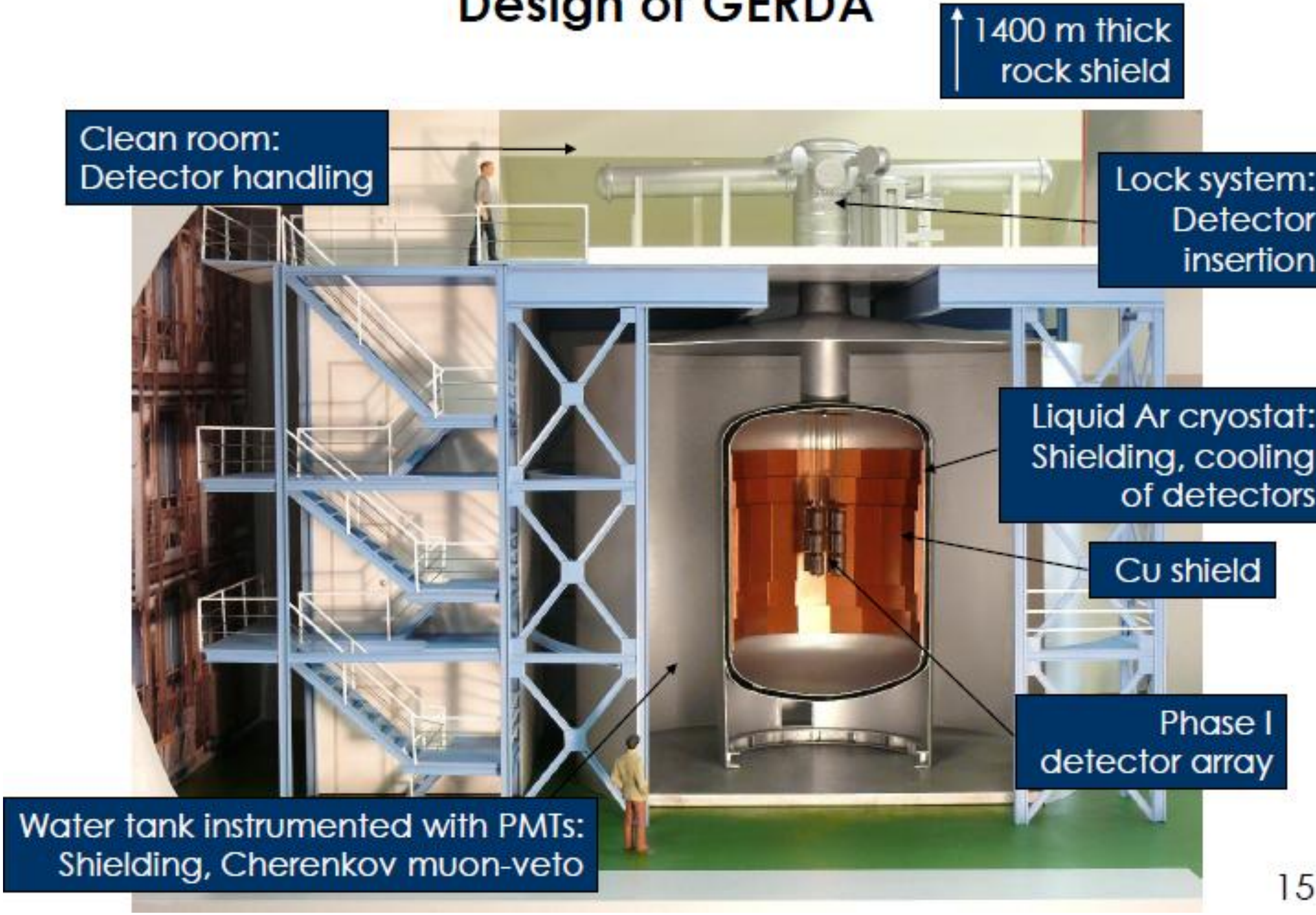
Maximum at 2039 keV

$T_{1/2}$ = 0.6-8.4x10^{25}lat

→ m_ν = 0.17-0.63 eV

This result must be verified by another experiment, e.g. GERDA should achieve the required sensitivity in a few years

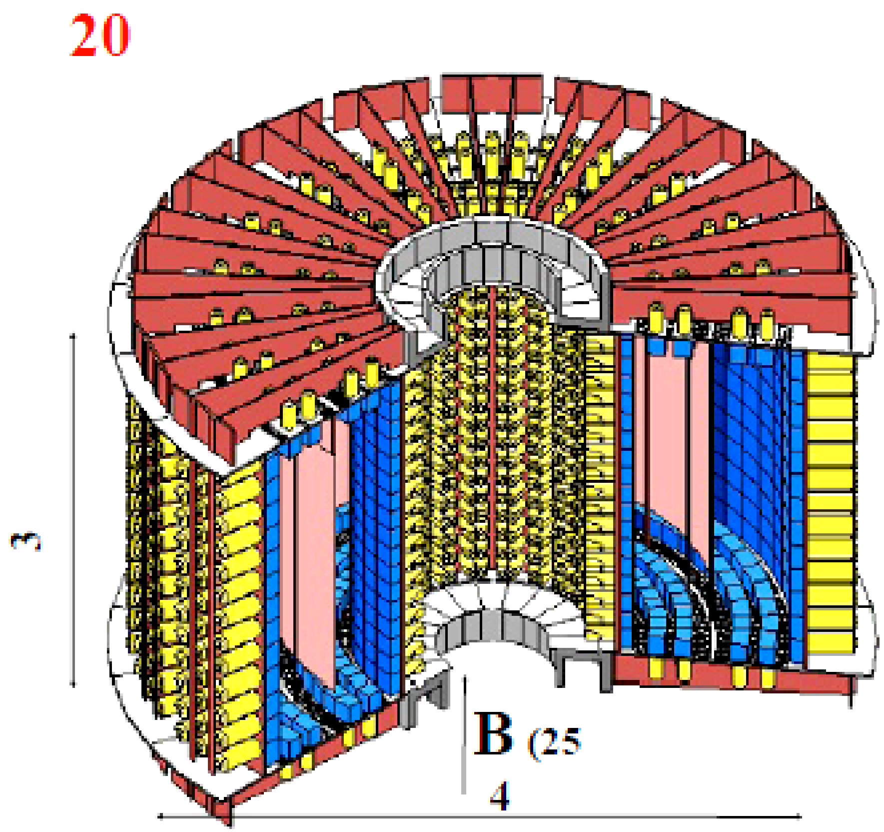
Design of GERDA



The NEMO-3 detector

Neutrino Ettore Majorana Observatory

Modane Underground Laboratory : 4800 m.w.e.



Source: 10 kg of ββ isotopes

7kg of ^{100}Mo, 1kg of ^{82}Se + smaller quantities of ^{130}Te, ^{116}Cd, ^{48}Ca, ^{96}Zr, ^{150}Nd

Tracking detector:

drift wire chamber operating in Geiger mode (6180 cells)

Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:

1940 plastic scintillators coupled to low radioactivity PMTs

CUORICINO: detector

44 TeO_2 crystals 5x5x5 cm^3 + 18 TeO_2 crystals 3x3x6 cm^3

11 modules,
4 crystal each,
5x5x5 cm^3 = 790 g

2 modules
9 crystal each,
3x3x6 cm^3 = 330 g

RUN I April 2003 – October 2003

1.18 kg(^{130}Te) yr

RUN II May 2004 – June 2008

18.57 kg(^{130}Te) yr

Active mass ~ 10 kg(^{130}Te)
Live time ~ 55%
Physics live time ~ 45%