Neutrino Oscillations:
Experimental Status and Outlook

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- Neutrino Masses and Mixing
- 2 Flavor Neutrino Oscillation Experiments
  - MINOS, OPERA
- **Measurement of 3rd Mixing Angle θ_{13}**
  Double Chooz, Daya Bay , Reno, MINOS, T2K
- Mass Hierarchy (and CP-phase)
  - Long Baseline Projects: LAGUNA
  - Reactor Neutrinos: Daya Bay 2
- Solar Neutrinos:
  - Borexino
  - Future Project: LENA
- Summary

Neutrino Masses and Mixing

3 massive neutrinos: ν_1, ν_2, ν_3 with masses: m_1, m_2, m_3

Flavor-Eigenstates $\nu_e, \nu_\mu, \nu_\tau \neq$ Mass-Eigenstates

Example: $$\left|\nu_e\right\rangle = U_{e1}\left|\nu_1\right\rangle + U_{e2}\left|\nu_2\right\rangle + U_{e3}\left|\nu_3\right\rangle$$

Neutrino Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Parametrisation of Neutrino Mixing

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:

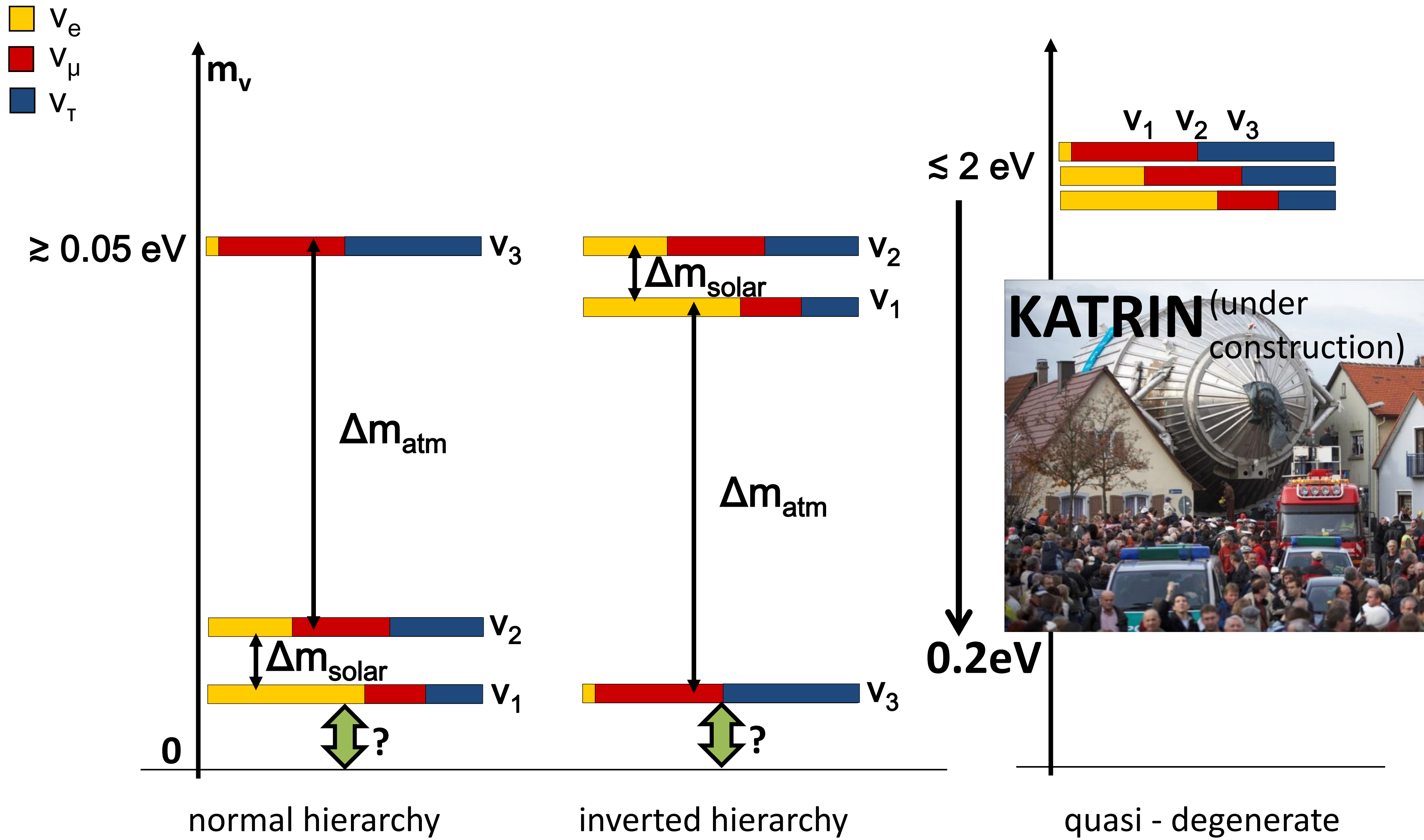
- 3 mixing angles: θ_{12}, θ_{23}, θ_{13} **SINCE 2012: all measured!**
- 1 Dirac-phase (CP violating): δ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\Theta_{23} \approx 45^o$	$\Theta_{13} \approx 9^o$, δ ?	$\Theta_{12} \approx 33^o$
atmospheric neutrinos, neutrino beams	reactor neutrinos, neutrino beams	solar neutrinos, reactor neutrinos

What do we know about neutrino masses?

$\Delta m^2_{solar} \approx 8 \cdot 10^{-5} eV^2$, $\Delta m^2_{atm} \approx 2 \cdot 10^{-3} eV^2$



Neutrino Oscillations

Simplified Picture: 2 Flavor Oscillations

$$P(\nu_\mu \to \nu_\tau) = \sin^2\left(2\theta_{23}\right)\cdot \sin^2\left(1.267\,\frac{\Delta m_{23}^2\left(\text{in eV}^2\right)\cdot L\left(\text{in km}\right)}{E\left(\text{in GeV}\right)}\right)$$

Präzisionsmessung der Neutrino-Oszillationen

The MINOS Experiment

A large detector at Soudan

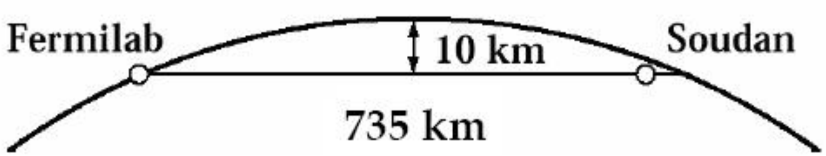
- > The "far detector" or FD

A smaller detector at Fermilab

- > The "near detector" or ND

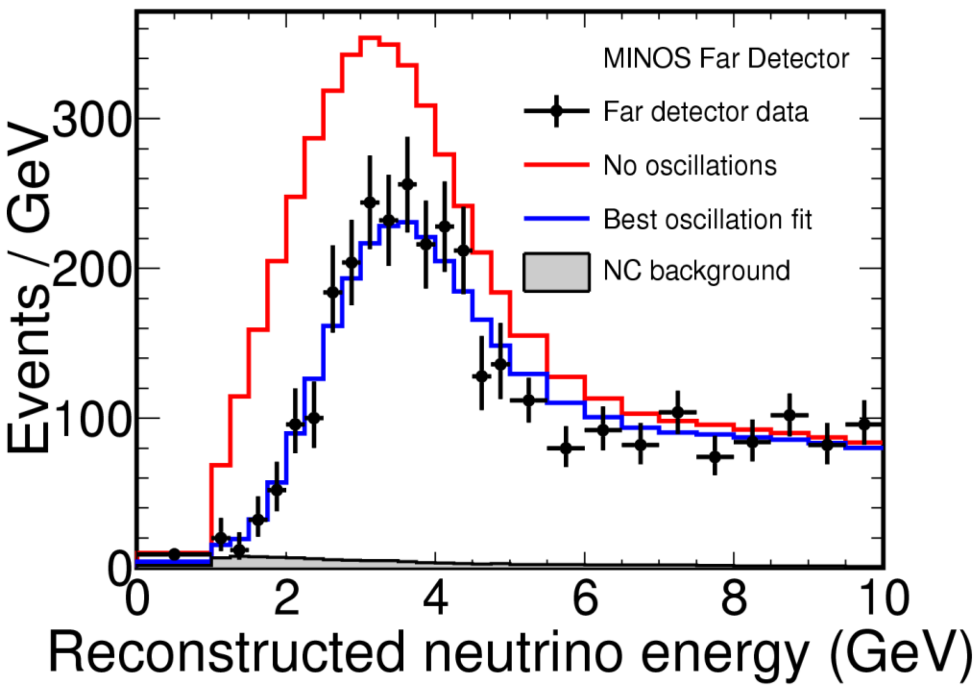
Measure the beam and neutrino energy spectrum near the source

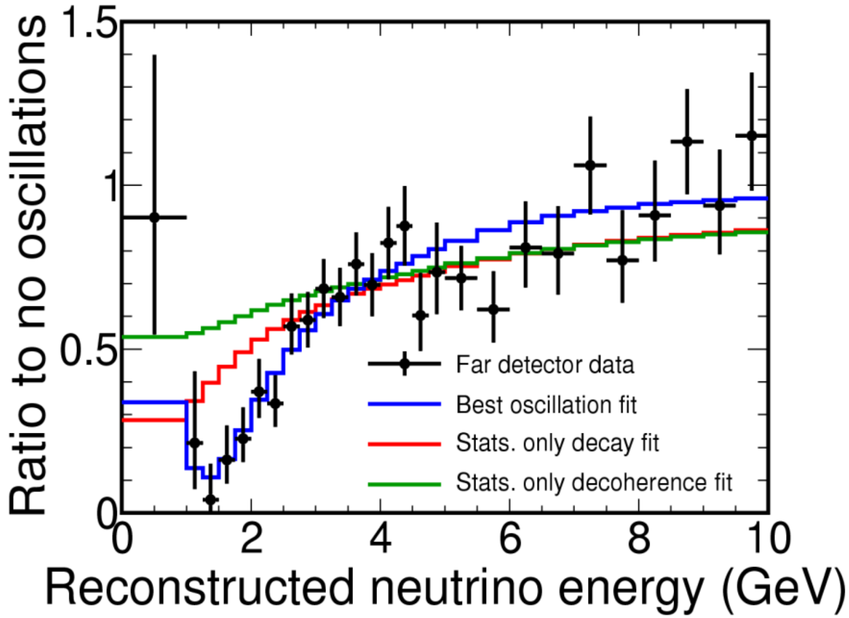
- > See how it differs far away



MINOS: Disappearance of ν_μ

for $7.25 \cdot 10^{20}$pot



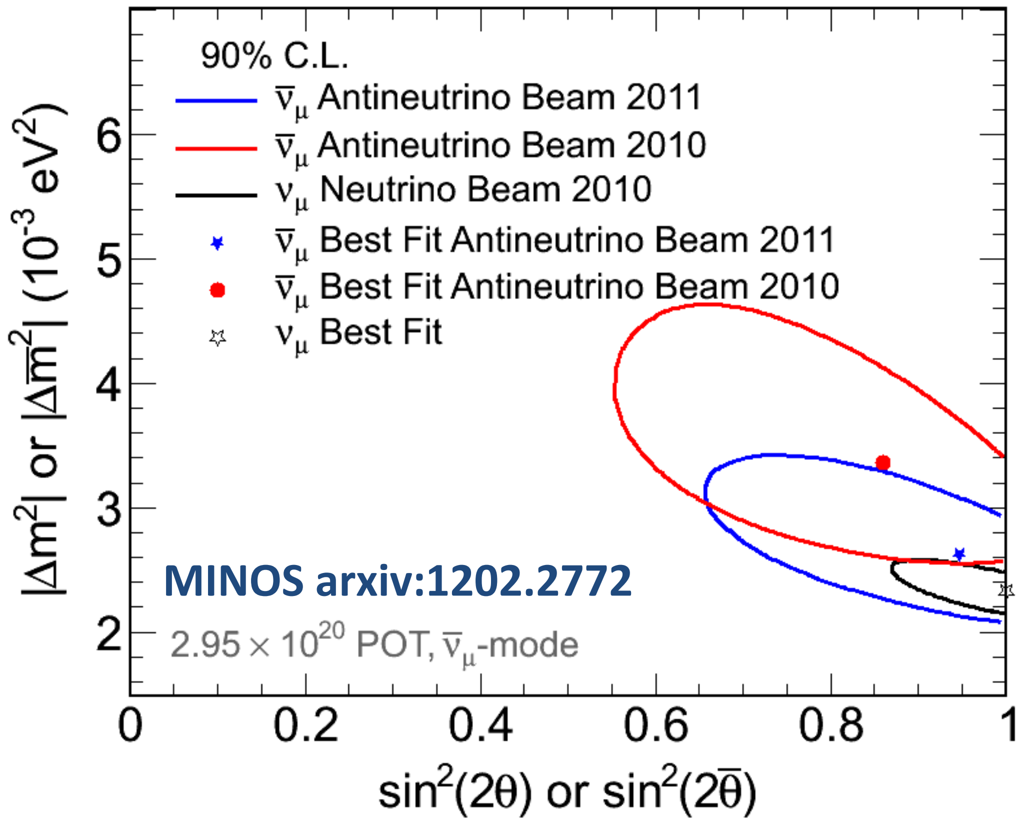


$$\left|\Delta m^2_{32}\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3} \mathrm{eV}^2 \quad (90\%\mathrm{CL})$$

$$\sin^2 2\theta_{23} > 0.90 \qquad (90\%\mathrm{CL})$$

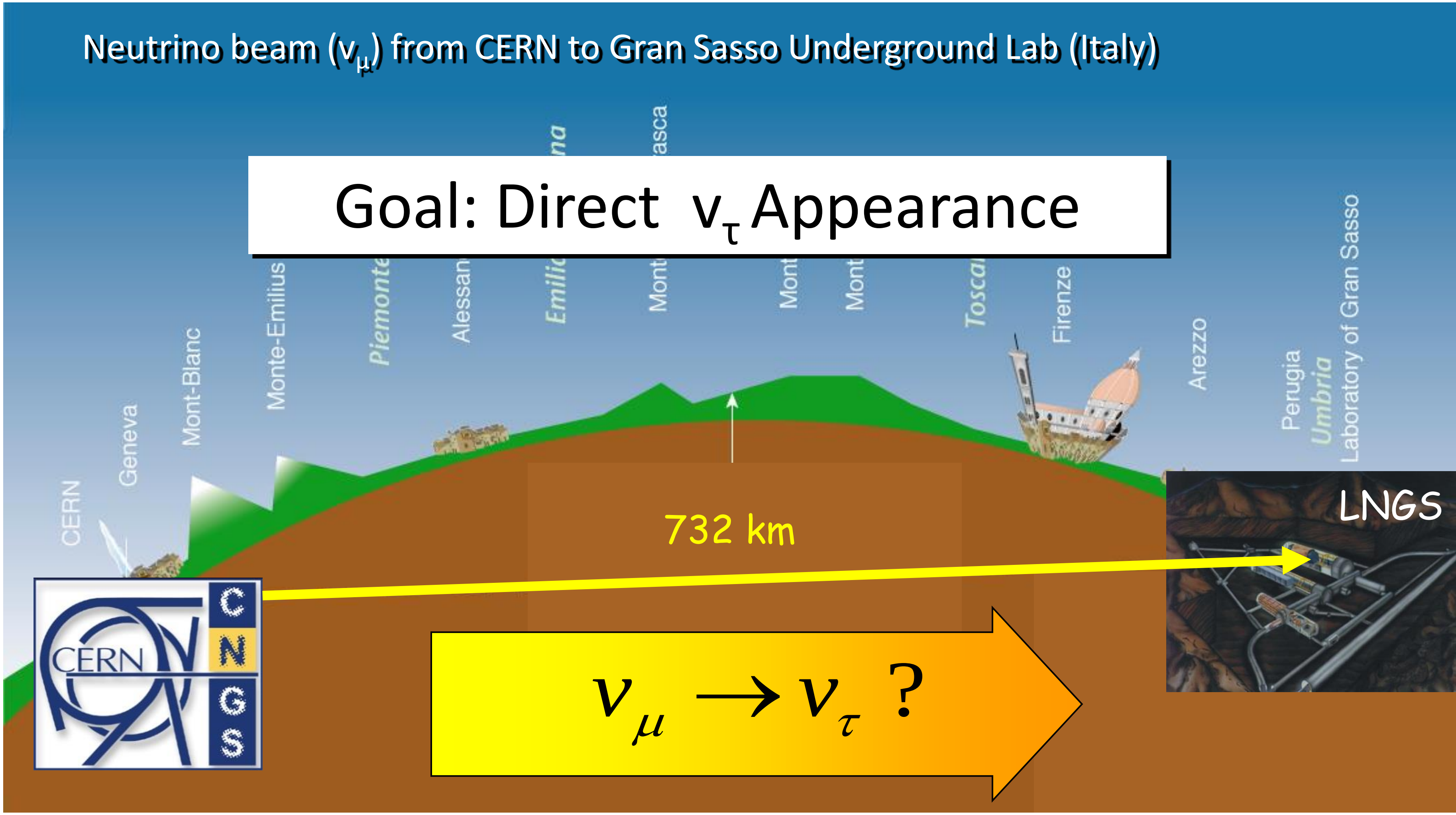
"Measurement of the neutrino mass splitting and flavor mixing by MINOS "
MINOS Coll., Phys.Rev.Lett.106:181801,2011 (arXiv:1103.0340)

MINOS: Anti-Neutrinos



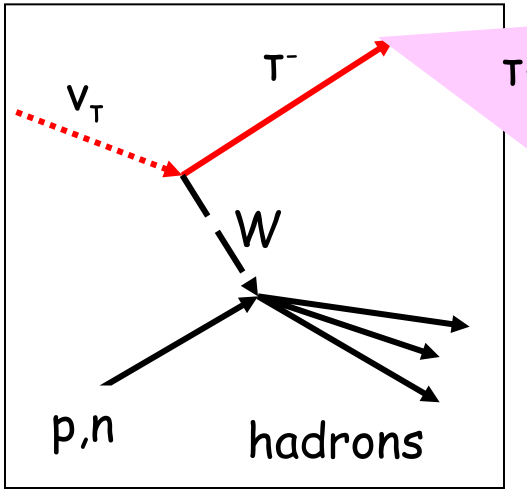
Old Analysis (2010) „Tension“ between Neutrino and Antineutrino result
New Analysis (2011) for 2.95×10^{20} pot: **good agreement of Neutrinos and Antineutrinos!**

OPERA:
Oscillation Project with Emulsion tRacking Apparatus



Physics runs: 2008, 2009, 2010, 2011, 2012 completed.

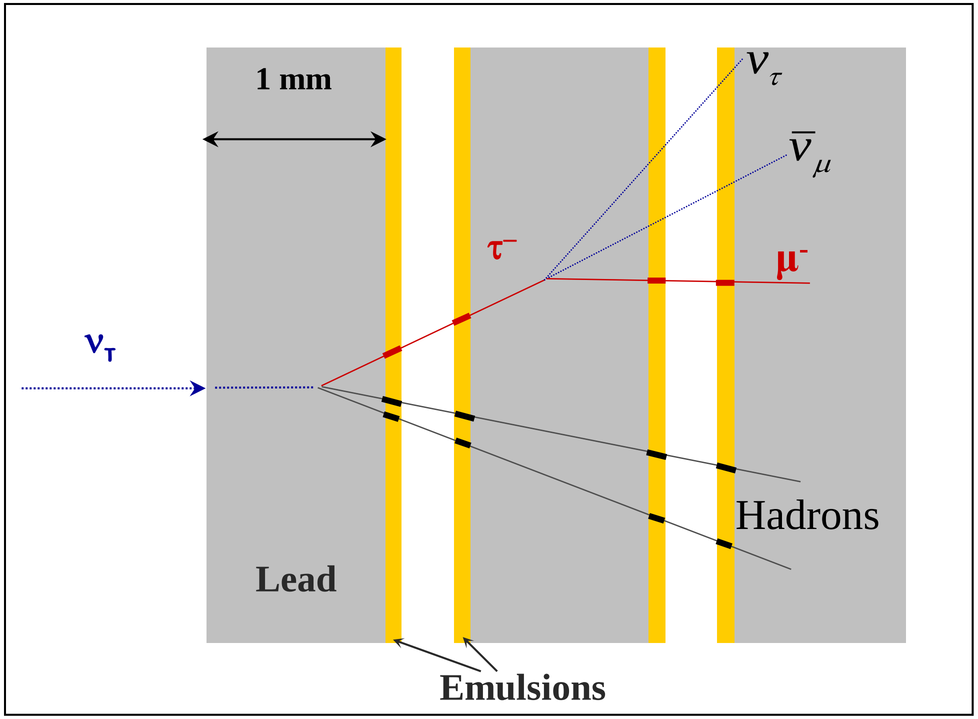
OPERA: ν_τ Detection Method



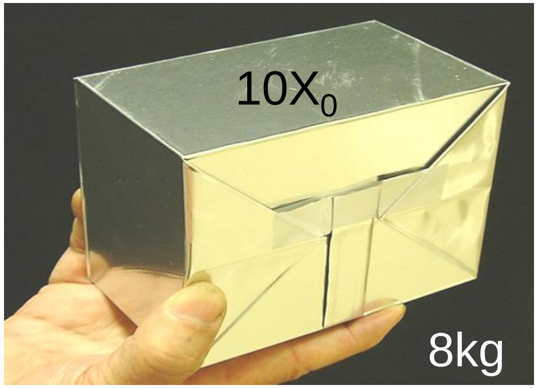
τ-decay:

$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau$	17.7%
$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau$	17.8%
$\tau^- \to \text{hadron} + \nu_\tau$	49.5%
$\tau^- \to \pi^-\pi^-\pi^+(n\pi^0) + \nu_\tau$	15.0%

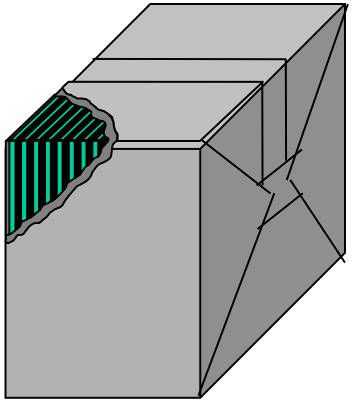
Typical topology of τ-decay:
"Kink" within 1mm from vertex

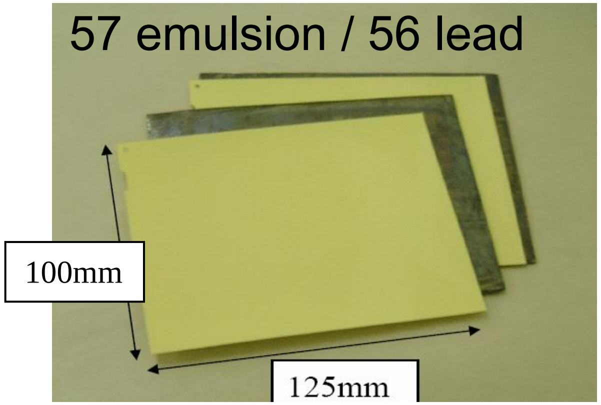


OPERA Target: Lead-Emulsion-Bricks



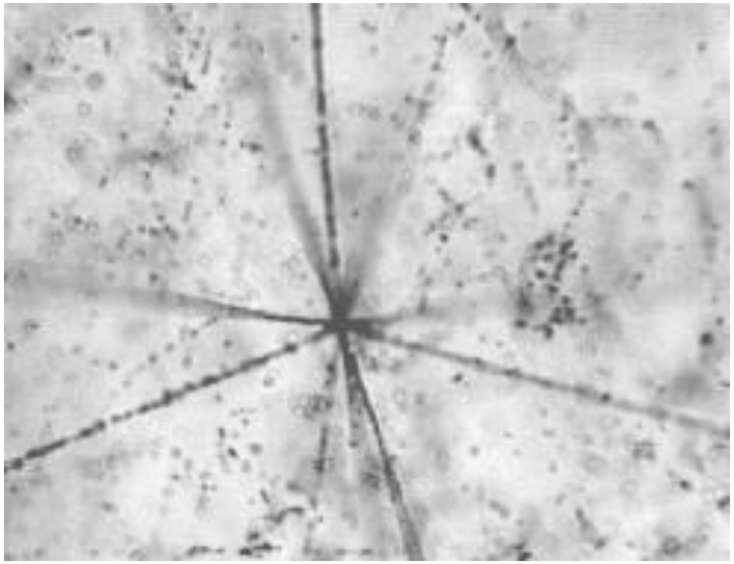
Lead-Emulsion-Bricks
(total ≈ 150.000)





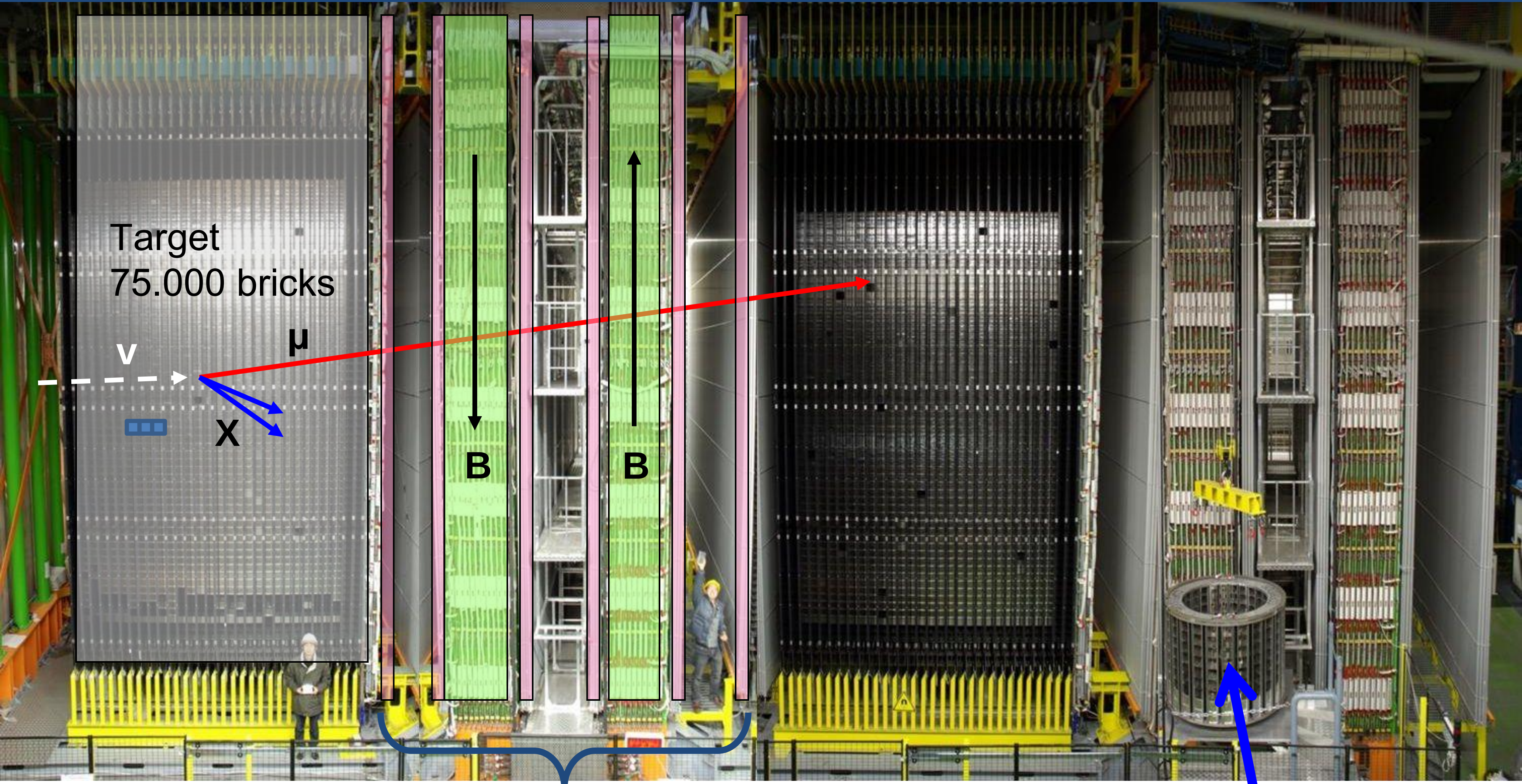
Target Mass:
≈ 1,25 kton

105000 m^2 of lead surface
111000 m^2 of film surface
(9 million films)



„Emulsion Cloud Chamber“ (ECC)

OPERA - Detector



Magnetic Spectrometer:

Magnet-Region:
Iron & RPCs

Precision Tracker:
6 Planes of Drifttubes

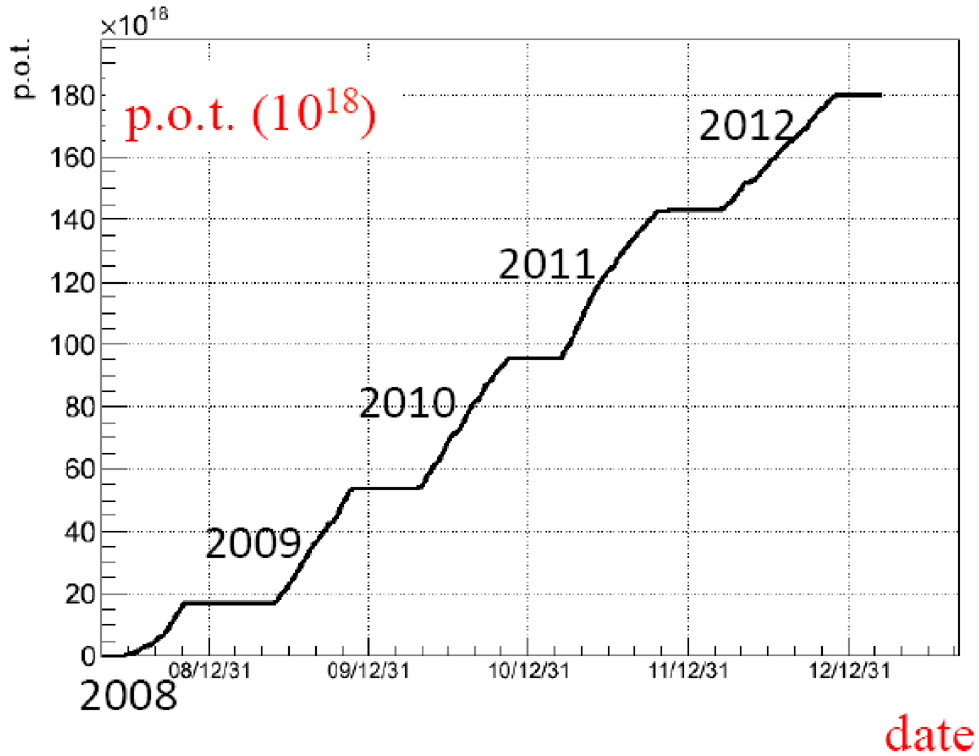
BMS robot
to remove bricks

OPERA Statistics and Scanning Status

CNGS neutrino beam operation terminated (12/2012).

Year	Beam days	P.O.T. (10^{19})
2008	123	1.74
2009	155	3.53
2010	187	4.09
2011	243	4.75
2012	257	3.86
Total	**965**	**17.97**

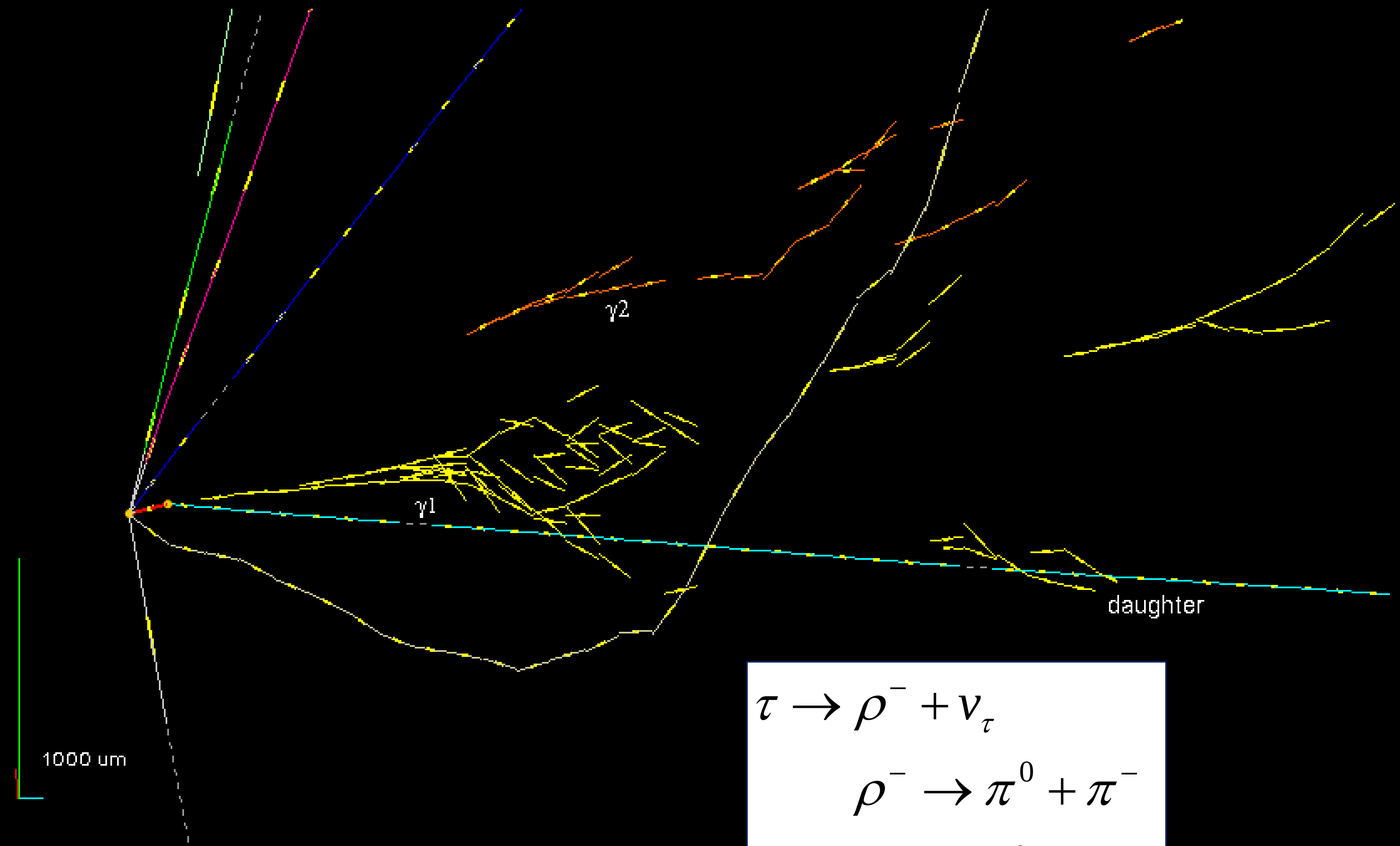
(Proposal: $22.5 \cdot 10^{19}$ p.o.t)



ca. 18000 events collected in electronic detectors,
brick extraction still ongoing,
Scanning of data still ongoing (next 1-2 years), present status: 5844 located interactions
(2008-2009 completed, 2010-2012 ongoing with optimized strategy)

First ν_{Tau} Candidate Event (22/08/2009)

Opera Coll., “Search for nu-mu - nu-tau oscillation with the OPERA experiment in the CNGS beam”, New J. Phys. 14 (2012) 033017



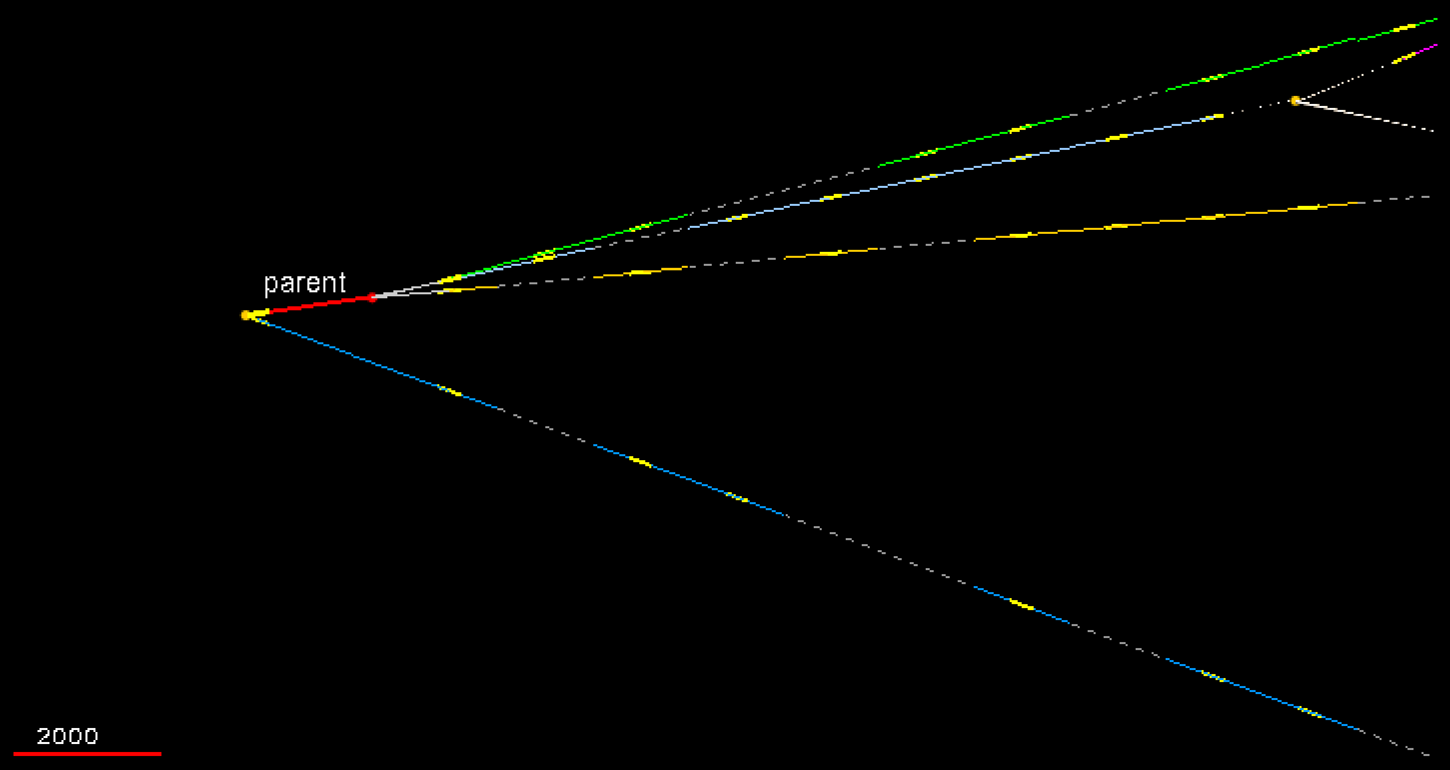
$$\tau \rightarrow \rho^- + \nu_\tau$$

$$\rho^- \rightarrow \pi^0 + \pi^-$$

$$\pi^0 \rightarrow \gamma\gamma$$

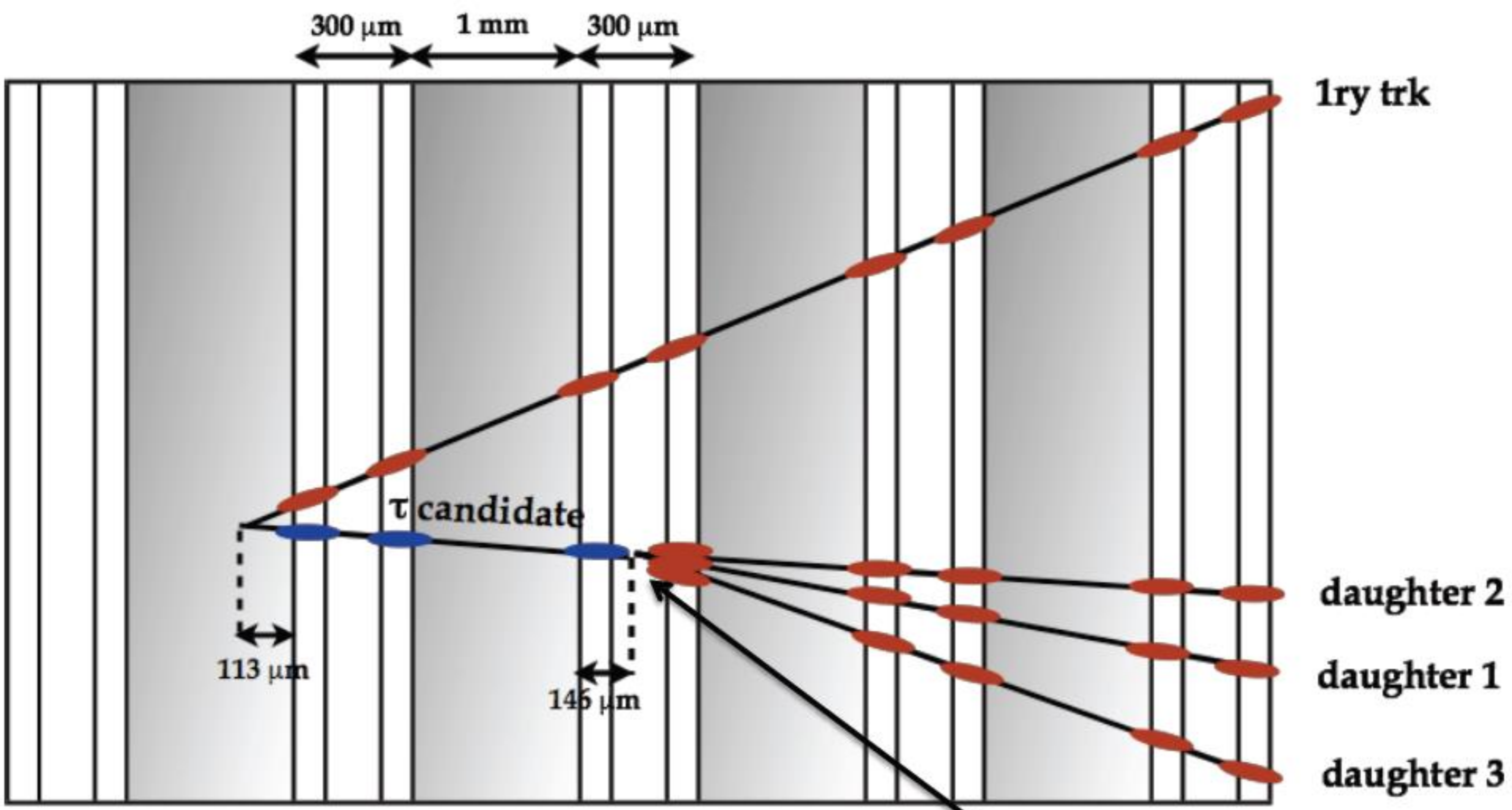
2nd ν_{Tau} Candidate Event (23/04/2011)

$$\tau \rightarrow \nu_{\tau} + h + h + h$$



2nd ν_{Tau} Candidate Event (23/04/2011)

$$\tau \rightarrow \nu_\tau + h + h + h$$

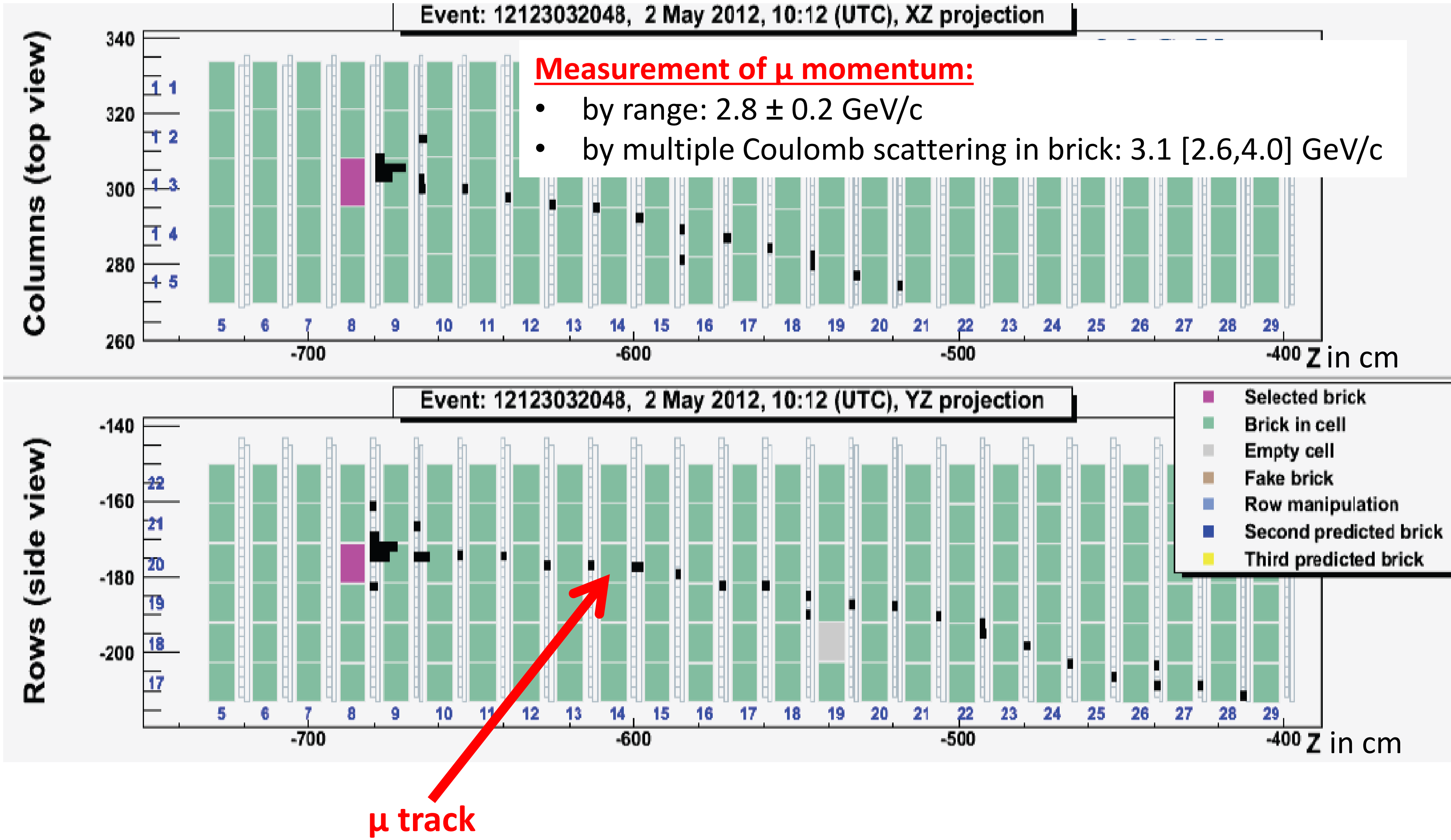


Decay vertex in plastic base
flight length 1.54mm

Publication in preparation

NEW: 3rd ν_{Tau} Candidate Event (02/05/2012): $\tau \to \mu\, \nu_\tau$

(presented at LNGS 26/03/2013)

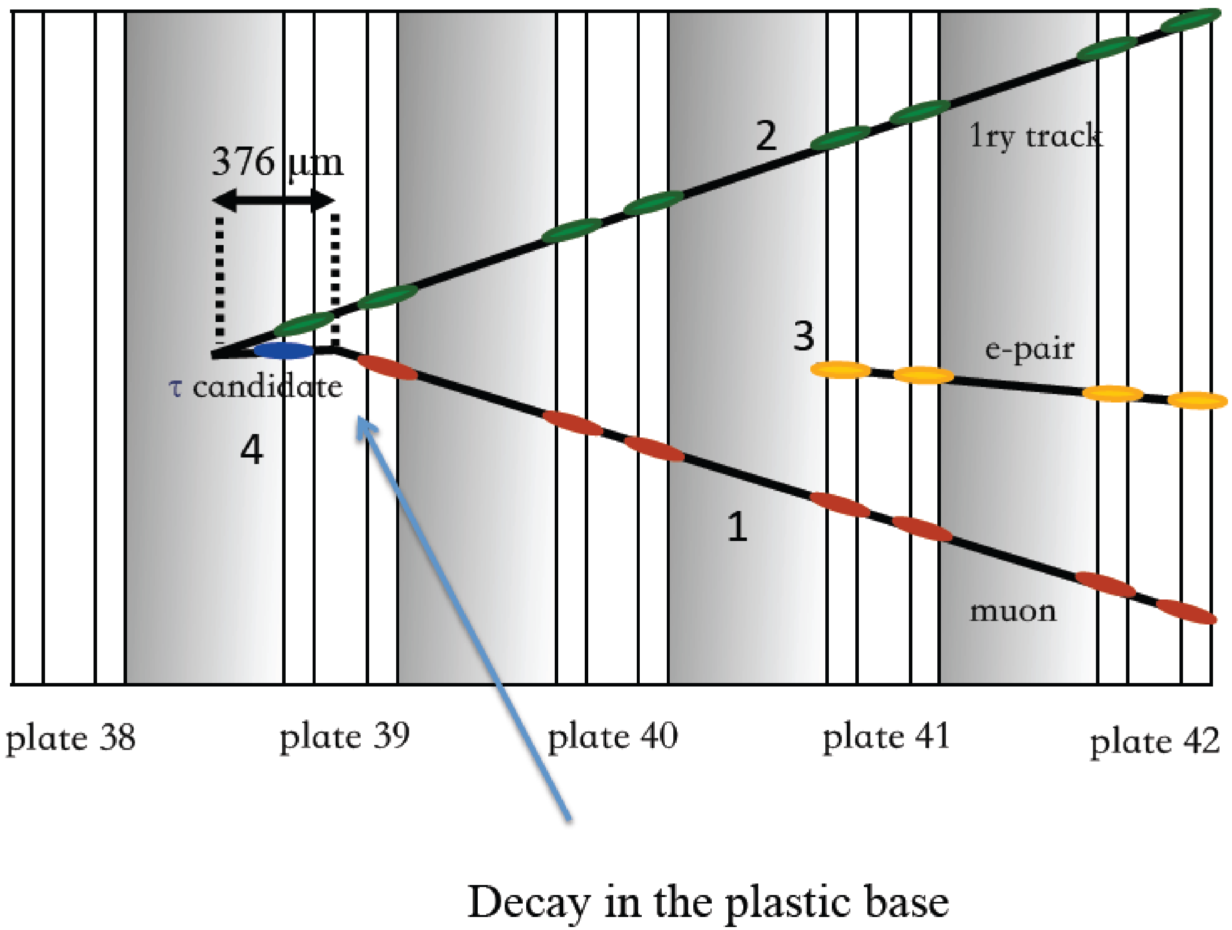


Measurement of μ momentum:

- by range: 2.8 ± 0.2 GeV/c
- by multiple Coulomb scattering in brick: 3.1 [2.6,4.0] GeV/c

3rd ν_{Tau} Candidate Event (02/05/2012): $\tau \rightarrow \mu\ \nu_\tau$

Zoom into the brick:



OPERA Background and Estimate of Significance

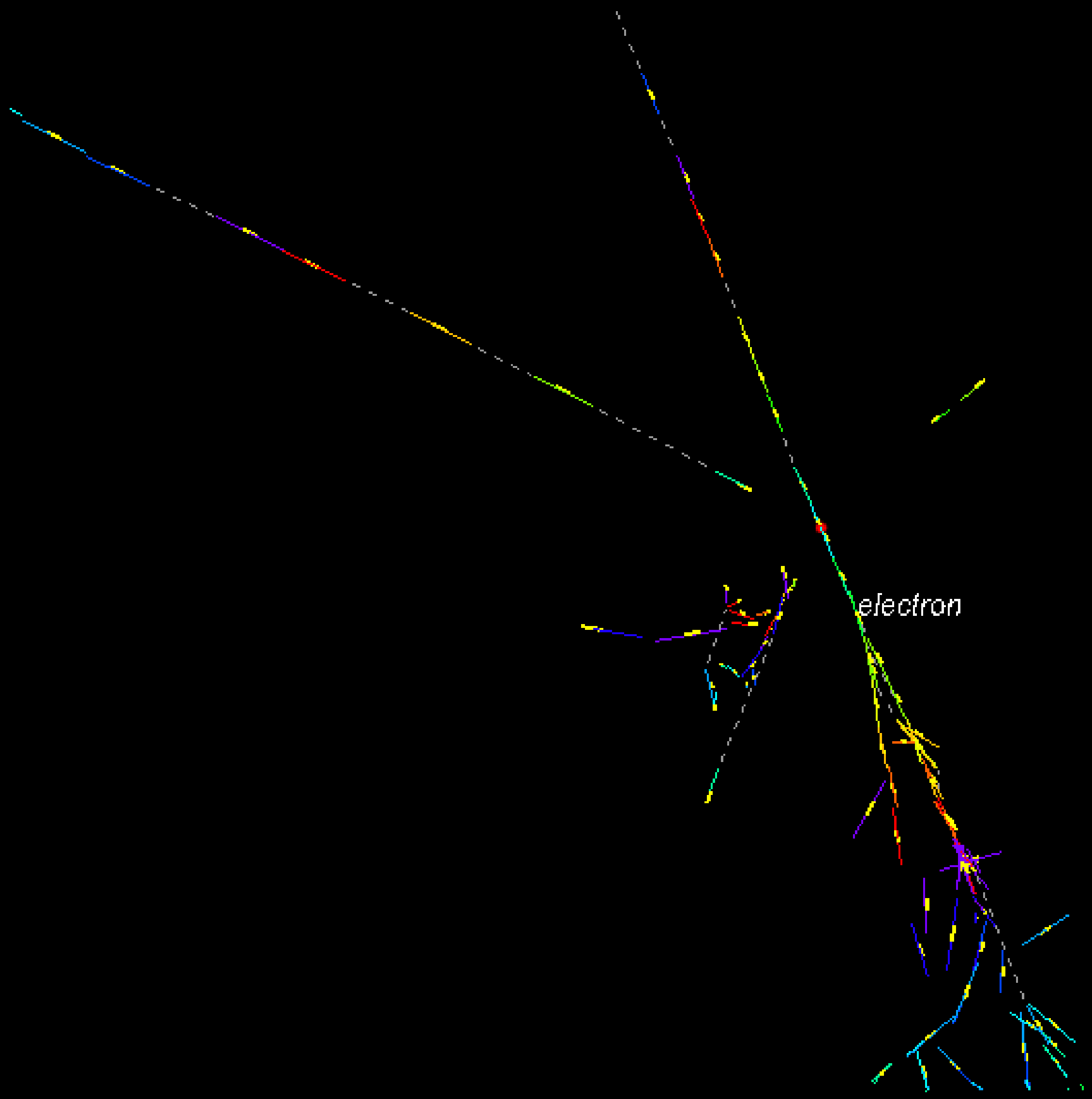
Extended sample (including the 3 tau candidates)

	Signal	Background	Charm	μ scattering	had int
$\tau \rightarrow h$	0.66	0.045	0.029		0.016
$\tau \rightarrow 3h$	0.61	0.090	0.087		0.003
$\tau \rightarrow \mu$	0.56	0.026	0.0084	0.018	
$\tau \rightarrow e$	0.49	0.065	0.065		
total	2.32	**0.226**	0.19	0.018	0.019

- 3 observed events (in $\tau \rightarrow h$, $\tau \rightarrow 3h$, $\tau \rightarrow \mu$ channels)
- Pvalue = $P_0 = 1.125 \cdot 10^{-4}$
- Probability to be explained by background = $7.29 \cdot 10^{-4}$

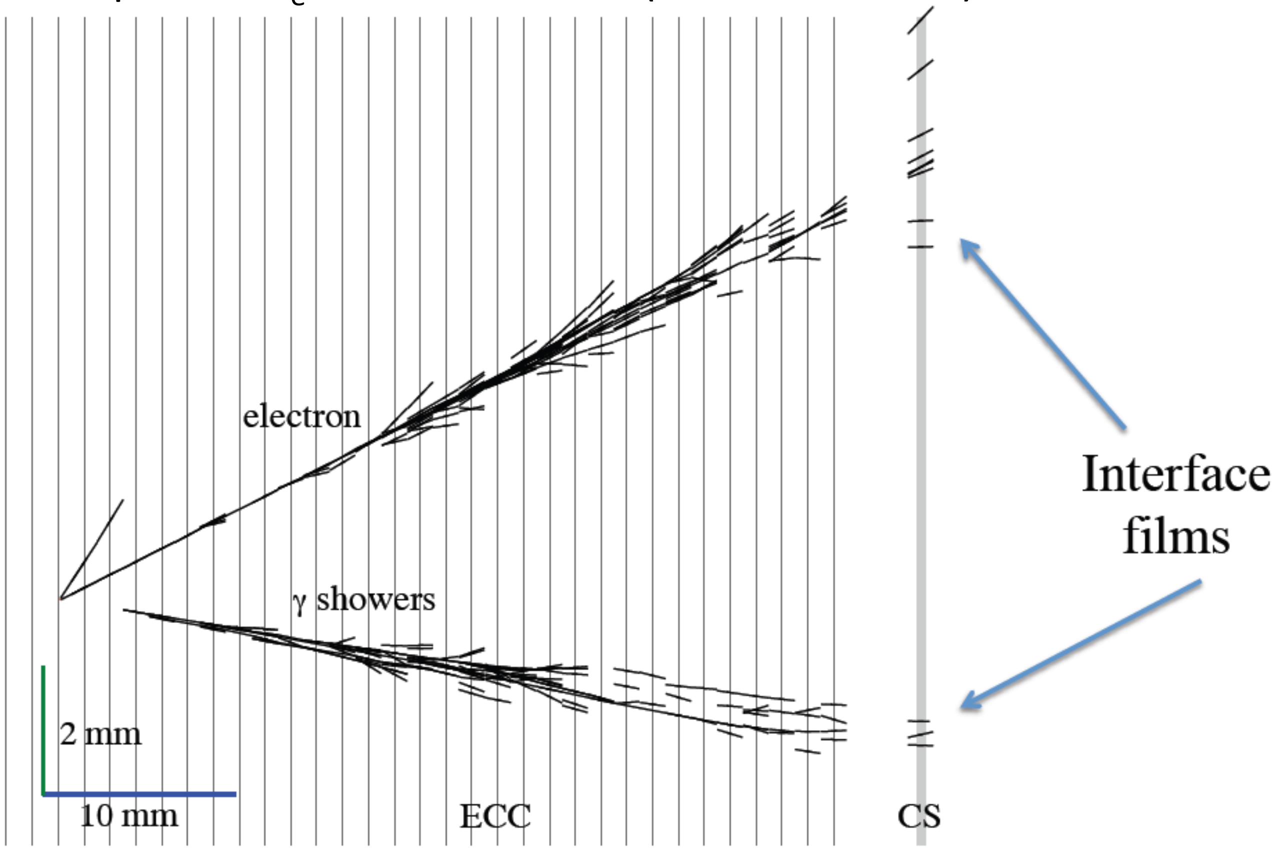
- **Significance of non-null observation: 3.2σ**

Search for $\nu_\mu \rightarrow \nu_e$ Oscillations (Data 2008-2009)



Search for $\nu_\mu \rightarrow \nu_e$ Oscillations (Data 2008-2009)

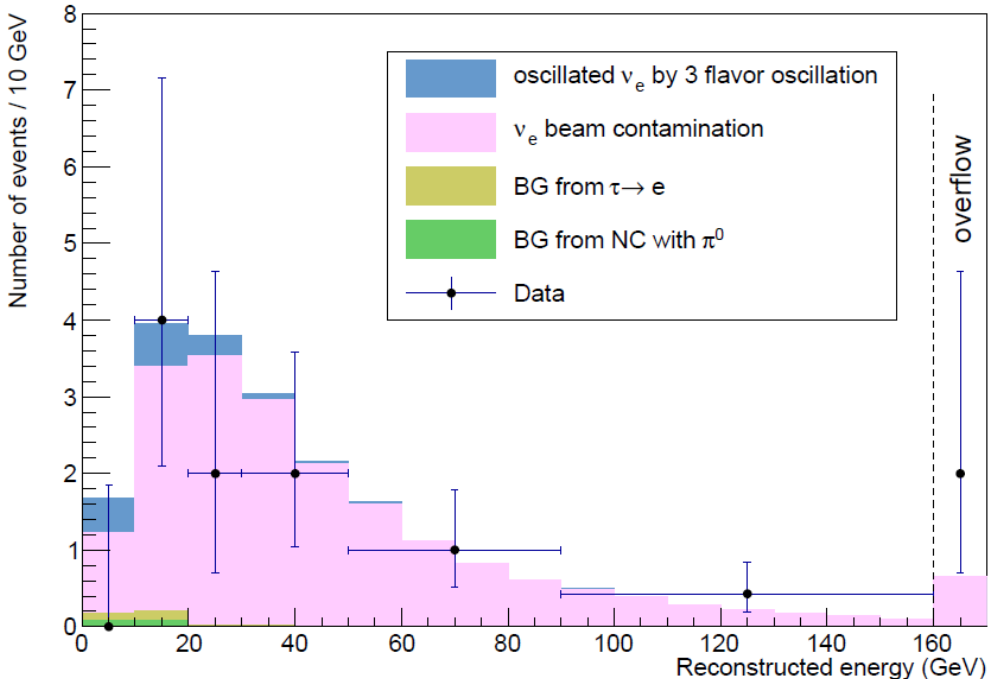
Example of a ν_e candidate event (emulsion tracks):



19 events found in sample of 505 neutrino interactions without muon

Search for $\nu_\mu \rightarrow \nu_e$ Oscillations (Data 2008-2009)

arXiv1303.3953: Opera Coll., „Search for $\nu_\mu \rightarrow \nu_e$ oscillations with the OPERA experiment in the CNGS beam", submitted to JHEP



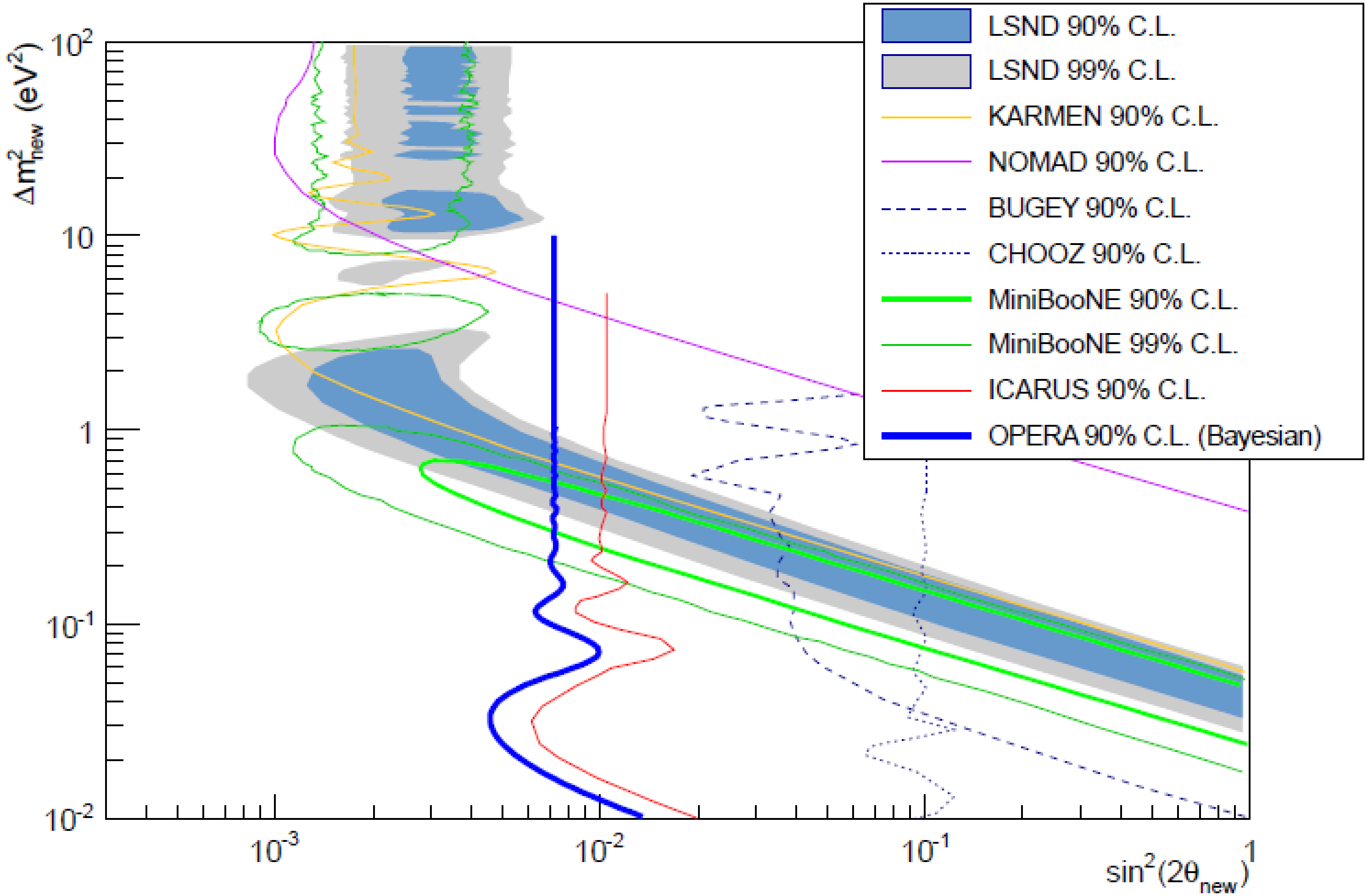
4 events observed
4.6 events expected

→ $\sin^2(2\theta_{13}) < 0.44$ (90% C.L.)

Energy cut		20 GeV	30 GeV	No cut
BG common to both analyses	BG (a) from π^0	0.2	0.2	0.2
	BG (b) from $\tau \rightarrow e$	0.2	0.3	0.3
	ν_e beam contamination	4.2	7.7	19.4
Total expected BG in 3-flavour oscillation analysis		**4.6**	8.2	19.8
	ν_e via 3-flavour oscillation	**1.0**	1.3	1.4
Data		**4**	6	19

Analysis for $\nu_\mu \rightarrow \nu_e$ non-standard oscillations

$$P_{\nu_\mu \to \nu_e} = \sin^2(2\theta_{new}) \cdot \sin^2(1.27\Delta m^2_{new} L(\mathrm{km})/E(\mathrm{GeV}))$$



OPERA Summary

- CNGS beam stopped 12/2012.
- Data Analysis ongoing (2015).
- So far: **3 tau-neutrino candidate events found** (2.3 expected) corresponding to ≈3σ.
- First results of electron-neutrino search .

Most Important Result of Neutrino Physics in 2012: θ_{13}

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

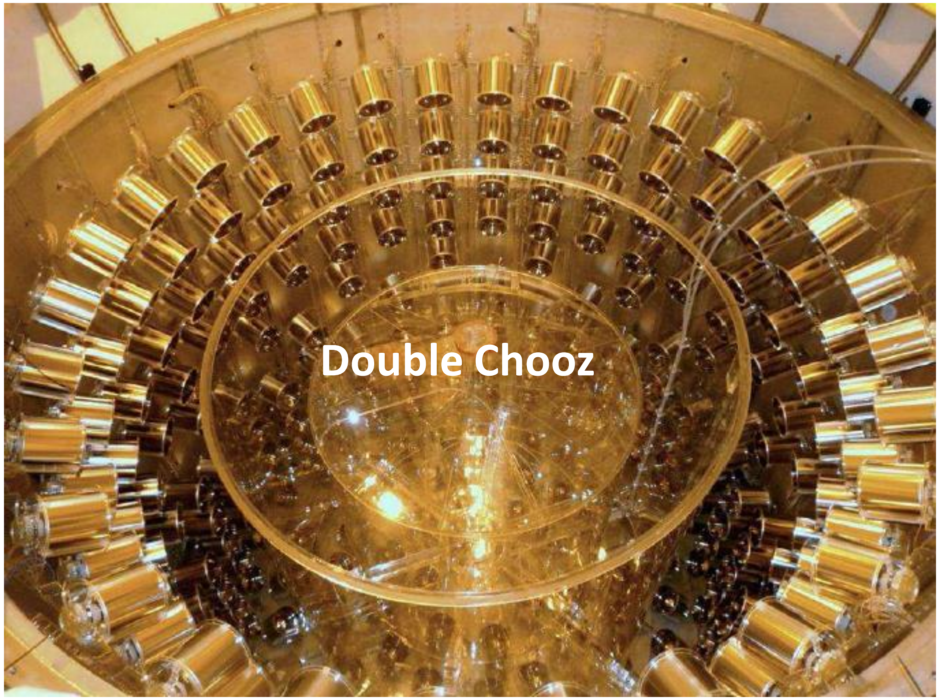
Status 2011: CHOOZ (and Palo Verde) reactor neutrino experiments:

$$\sin^2(2\theta_{13}) < 0.15 \text{ for } |\Delta m^2_{31}| = 2.5 \times 10^{-3}\mathrm{eV}^2$$

Measurement of θ_{13} (method A)

A) **Disappearance of $\bar{\nu}_e$** from nuclear reactors

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \cdot \sin^2\left(1.267 \frac{\Delta m^2_{atm}(\text{in eV}^2) \cdot L(\text{in m})}{E(\text{in MeV})}\right)$$

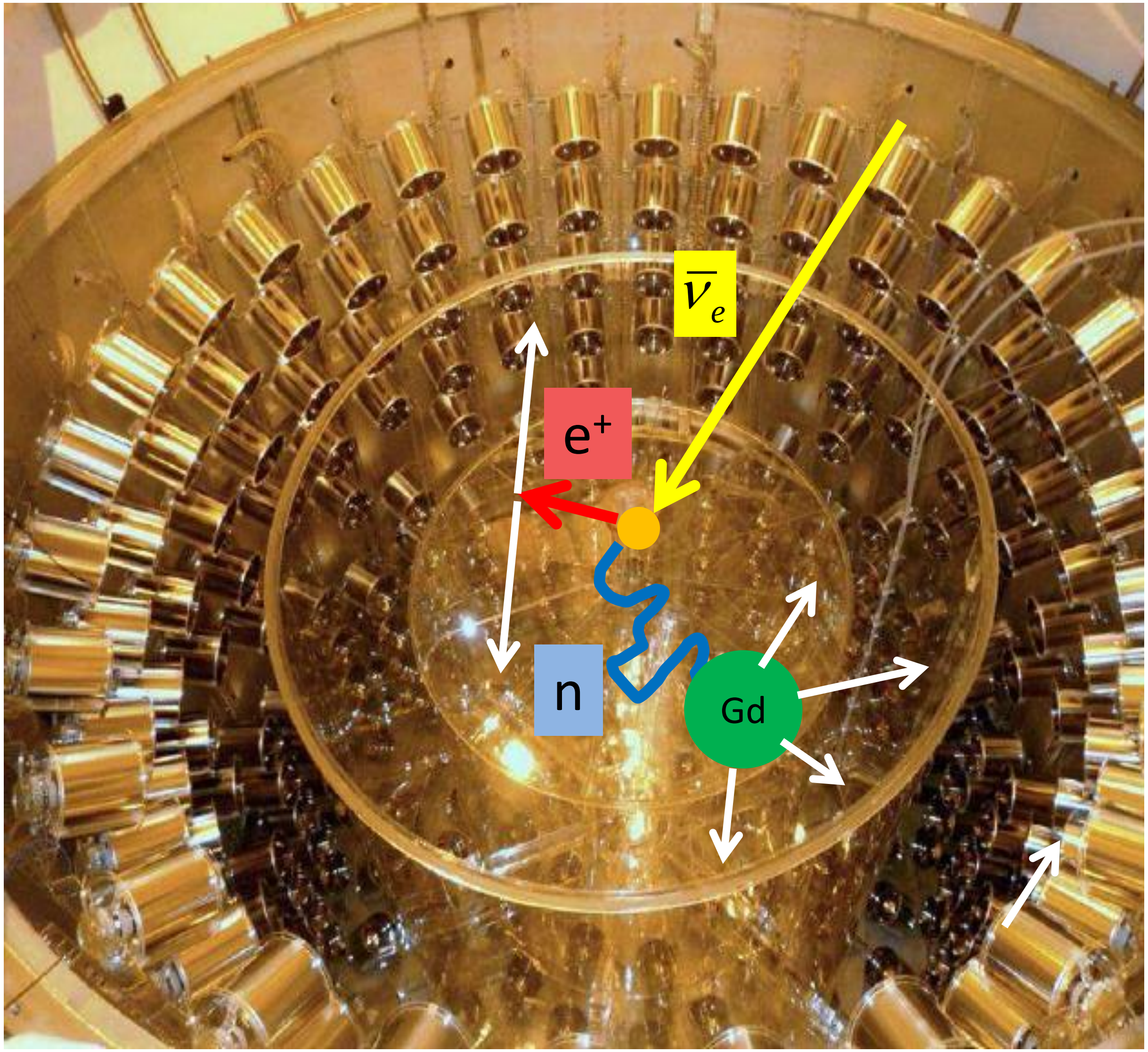


Compare rates of
near detector (few 100m)
and far detector (1km)

Running Experiments:

- Double Chooz (France)
- Daya Bay (China)
- RENO (South Korea)

Antineutrino Detection in Reactor Experiments



Inverse Beta Decay:

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

Prompt Event: e^+

gives neutrino energy E_ν

$$E_\nu = E_{vis} + 1.8\text{MeV} - 2m_e$$

Delayed Event: n

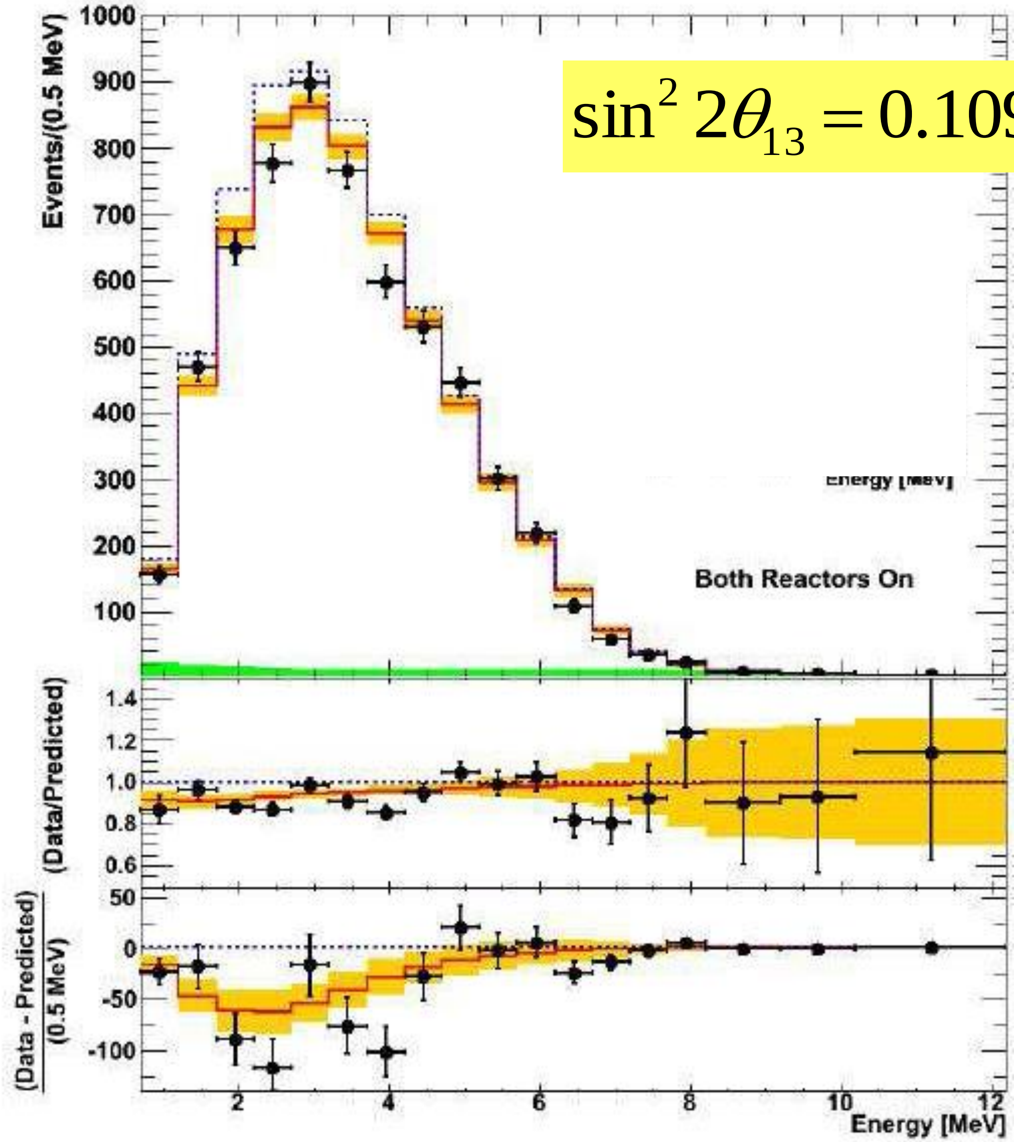
capture on Gd

(8MeV γ-emmission)

Delay: ca. 30µs

Double Chooz experiment

Double Chooz: Result



$$\sin^2 2\theta_{13} = 0.109 \pm 0.030(\mathrm{stat}) \pm 0.025(\mathrm{syst})$$

fit of rate and spectral shape

Double Chooz Coll.,
"Reactor anti ν_e Disappearance in the Double Chooz experiment",
Phys. Rev. D 86, 052008 (2012),
arXiv:1207.6632

New: Analysis using neutron capture on Hydrogen

$$\sin^2 2\theta_{13} = 0.097 \pm 0.034(\mathrm{stat}) \pm 0.034(\mathrm{syst})$$

"First Measurement of θ_{13} from Delayed Neutron Capture on Hydrogen in the Double Chooz Experiment",
arXiv:1301.2948

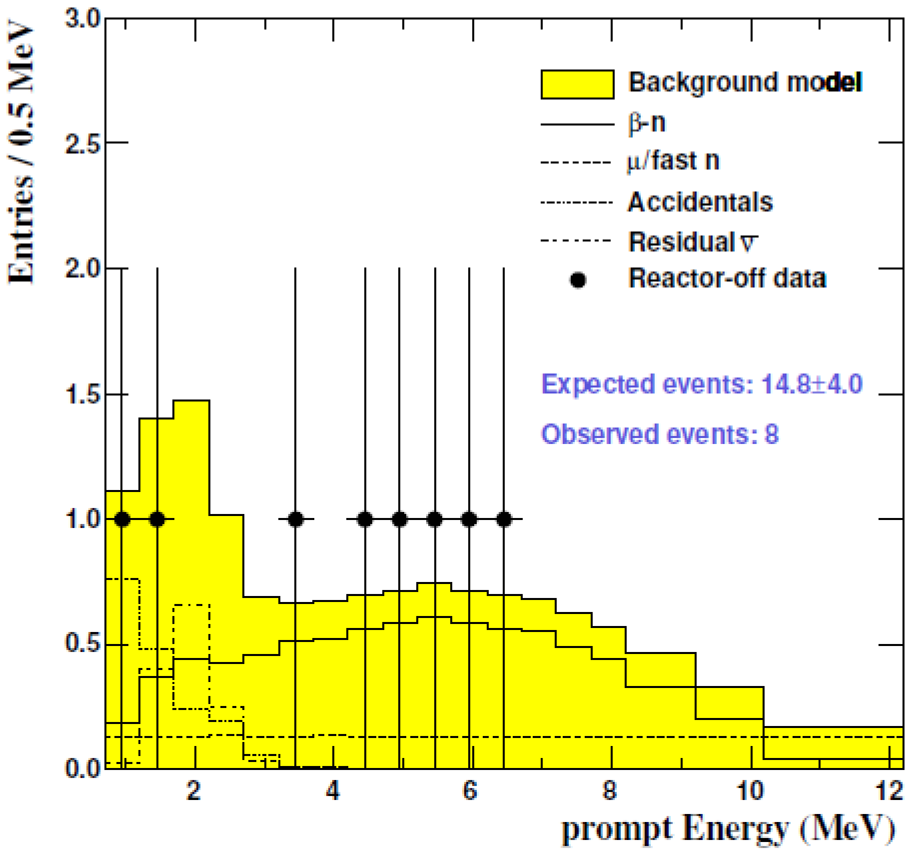
Double Chooz: Background

7.53 days (2011 und 2012),
during which **both reactors had been switched off → background measurement!**

Dominant background contributions:

- Spallation products induced by cosmic μ's (9Li and 8He) cause β-n events.
  Estimate: 1.25 ± 0.54 per day
- Stopping muons and
- Fast neutrons
  Estimate: 0.44 ± 0.20 per day
- Accidental coincidences
  Estimate: 0.26 ± 0.02 per day

Estimated BG : 2.0 ± 0.6 per day
Measured BG: 1.0 ± 0.4 per day



Double Chooz Coll., "Direct Measurement of Backgrounds using Reactor-Off Data in Double Chooz", arxiv:1210.3748

Status of Near Detector in Double Chooz

Under construction, start data taking in 2014

The Daya Bay Experiment

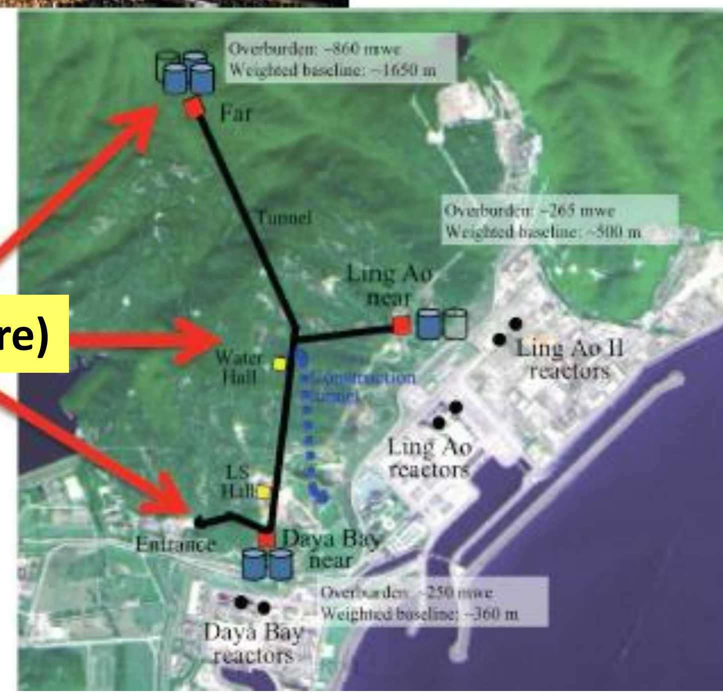
Adjacent mountains with horizontal access provide 860 (250) m.w.e cosmic shielding.

Daya Bay

Ling Ao I + II

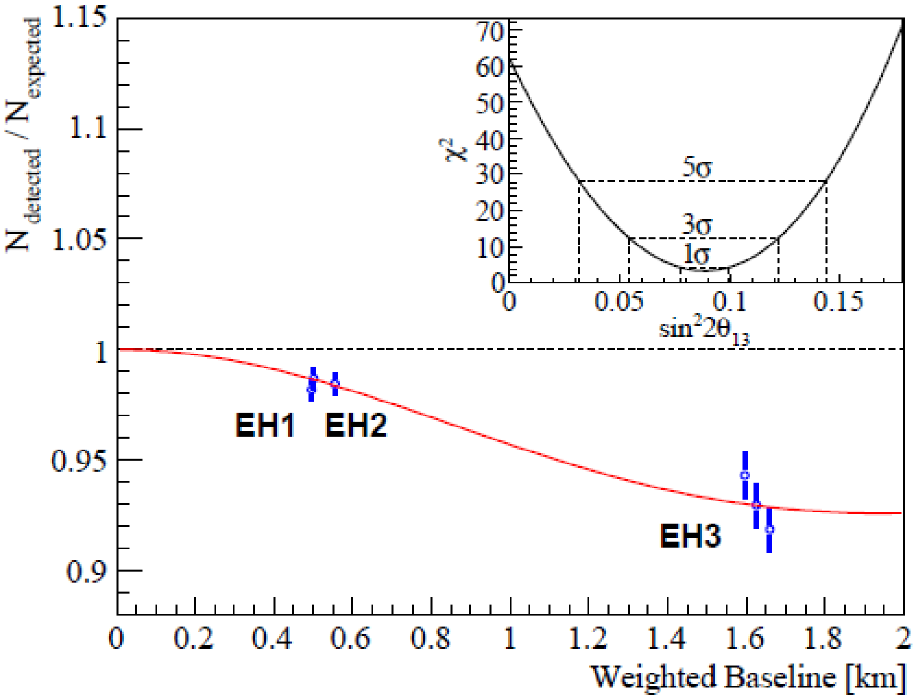
6 commercial reactor cores with 17.4 GW_{th} total power.

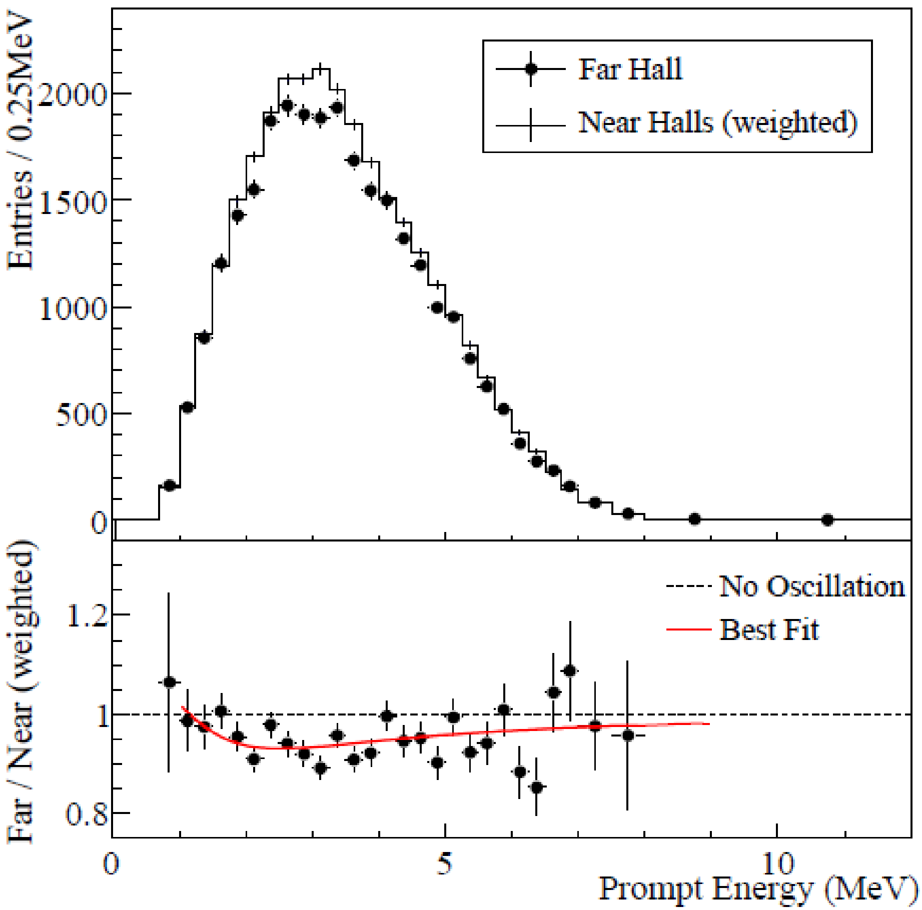
6 Antineutrino Detectors (ADs) **+2 (Future)** give 120 tons total target mass.



Daya Bay: Result

$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\mathrm{stat}) \pm 0.005(\mathrm{syst})$ (obtained by fit to rate, spectral shape not used)





Daya Bay Coll., "Improved Measurement of Electron Antineutrino Disappearance at Daya Bay", submitted and accepted by Chinese Physics C, arxiv:1210.6327

Measurement of θ_{13} (and δ_{CP}) (Method B)

B) **Appearance of ν_e** in a beam of ν_μ

Oscillation probability P($\nu_\mu \rightarrow \nu_e$) is approximately given by:

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) \approx\ & \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta) \\ & +\alpha\frac{\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta) \\ & +\alpha\frac{\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta) \\ & +\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta) \end{aligned}$$

- Potential to measure θ_{13} and δ_{CP} !
- All other parameters have to be known with high precision

with:

$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2 << 1$

$\Delta = \Delta m_{31}^2 L / 4E$

matter dependent quantities :

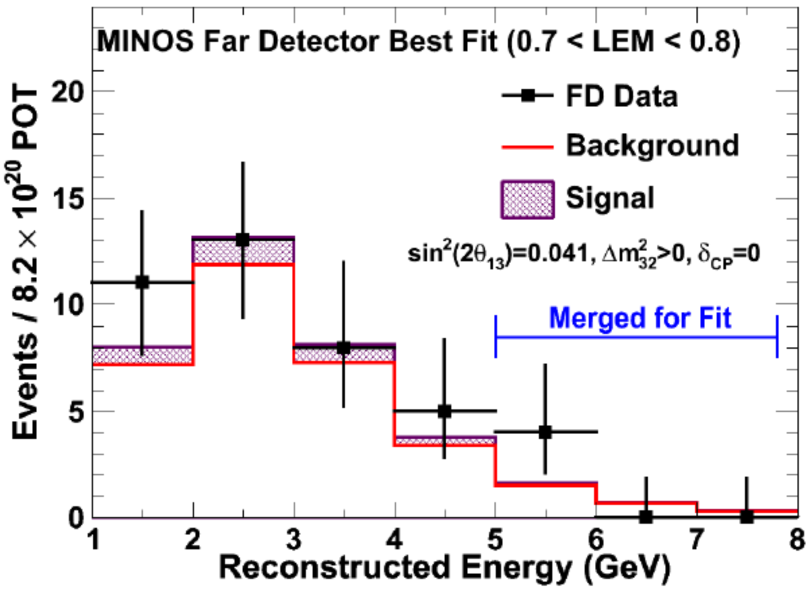
$\hat{A} = 2VE / \Delta m_{31}^2$

$V = \sqrt{2} G_F n_e$, with electronen density n_e

MINOS: Electron Neutrino Appearance

First result:

Phys. Rev. Lett. 107, 181802 (2011)

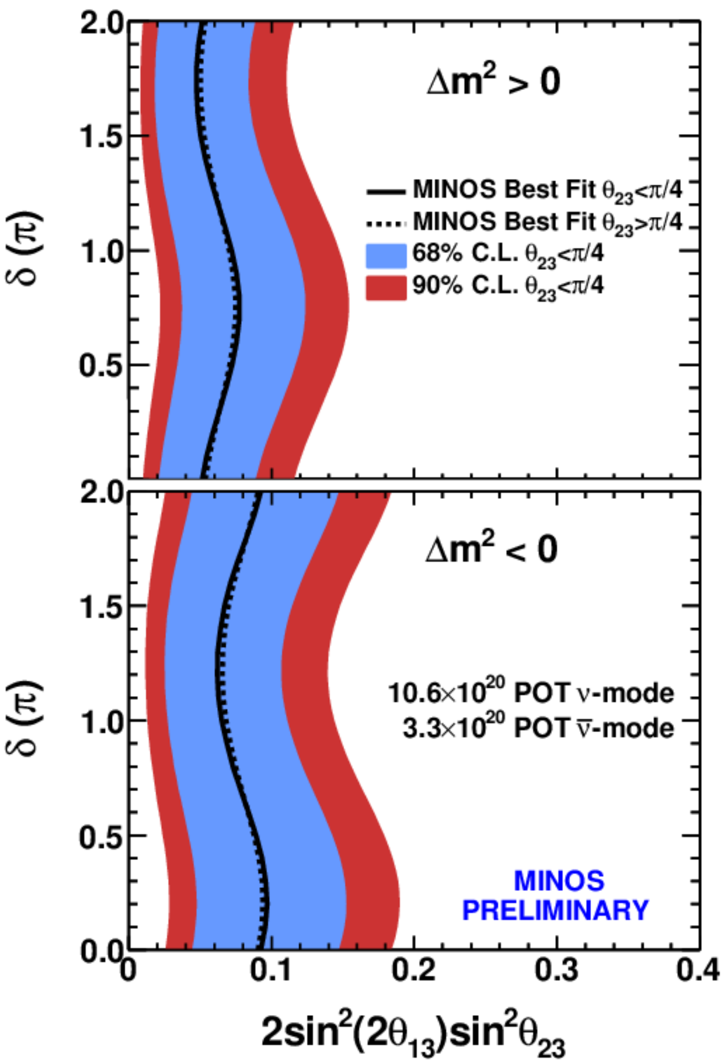


Expected background ($\theta_{13}=0$):

49.6 +- 2.7 (syst) +- 7.0 (stat)

Observed data: **62**

Update summer 2012:

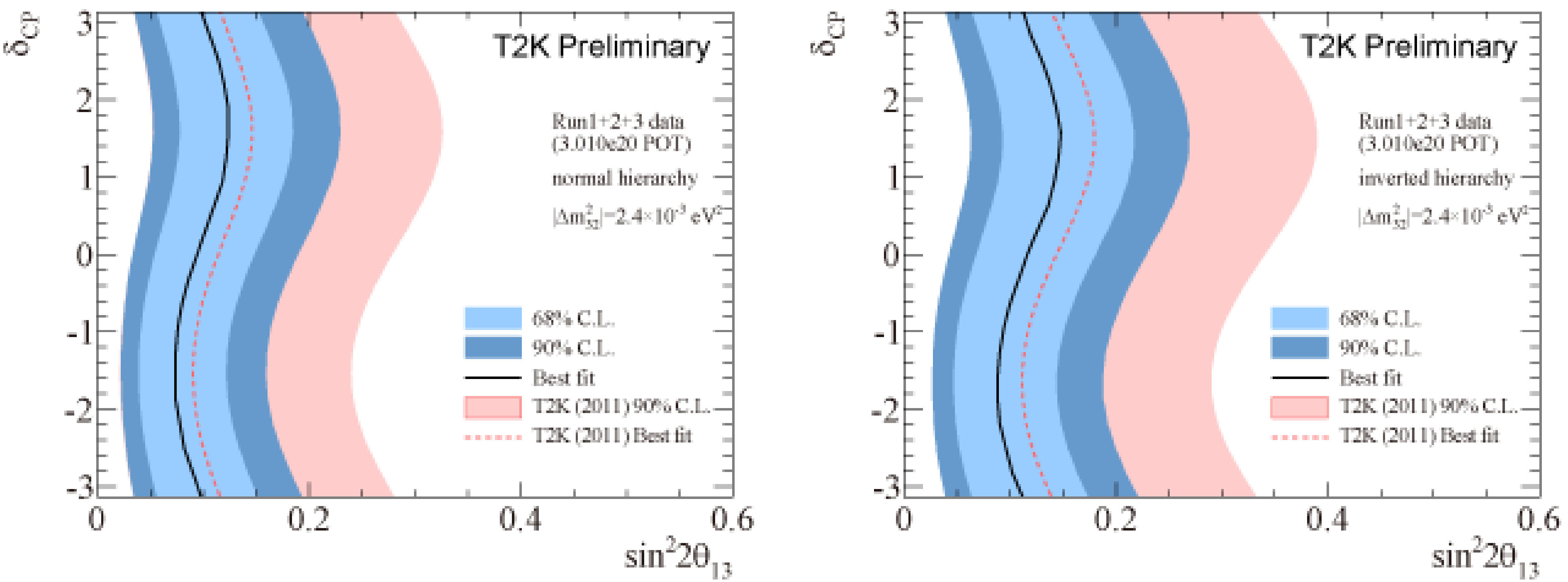


T2K: Electron Neutrino Appearance

First Result in 2011 (1.43×10^{20}) : **T2K Coll., "Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam"**, arXiv:1106.2822v1

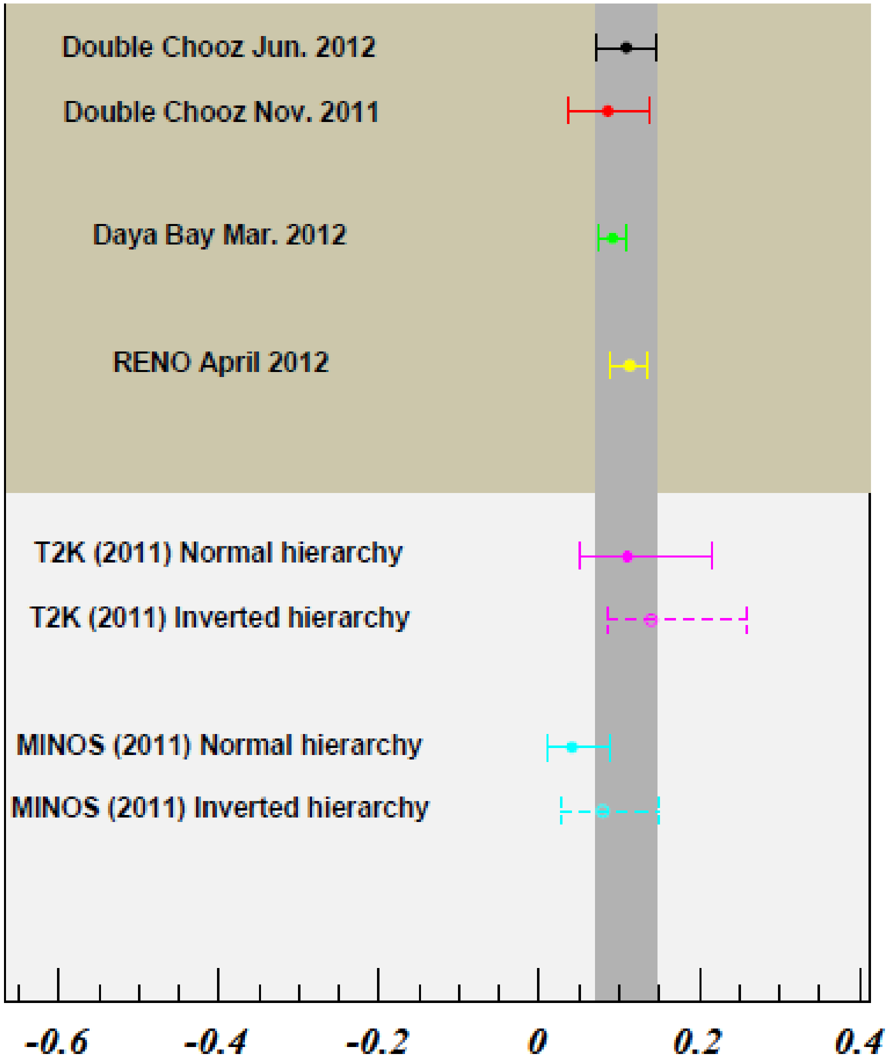
Update for 3.01×10^{20} p.o.t. (summer 2012)

Normal Hierarchy | Inverted Hierarchy



Best Fit: $\sin^2(2\theta_{13}) = 0.094^{+0.053}_{-0.040}$ (NH) , $\sin^2(2\theta_{13}) = 0.116^{+0.063}_{-0.049}$ (IH)
with $\delta_{CP} = 0$, $\Delta m^2_{23} = 2.4\times10^{-3}$ eV^2, $\theta_{23} = \pi/4$.

Comparison of θ_{13} results



Theta13 measured!

<u>Open Questions:</u>

- Mass hierarchy?
- CP phase?

Global Fit to Data of all Neutrino Experiments

Example: Fogli et al., arxiv:1205.5254

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. 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.

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)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49	2.27 – 2.55	2.19 – 2.62
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31 – 2.49	2.26 – 2.53	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66	1.93 – 2.90	1.69 – 3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67	1.94 – 2.91	1.71 – 3.15
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10	3.48 – 4.48	3.31 – 6.37
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70 – 4.31	3.53 – 4.84 $\oplus$ 5.43 – 6.41	3.35 – 6.63
δ/π (NH)	1.08	0.77 – 1.36	—	—
δ/π (IH)	1.09	0.83 – 1.47	—	—

relative precision of globally determined neutrino parameters:

δm^2 (2.6%), Δm^2 (3.0%),
$\sin^2{}_{12}$ (5.4%), $\sin^2{}_{13}$ (10%), and $\sin^2{}_{23}$ (14%)

How to determine the mass hierarchy:

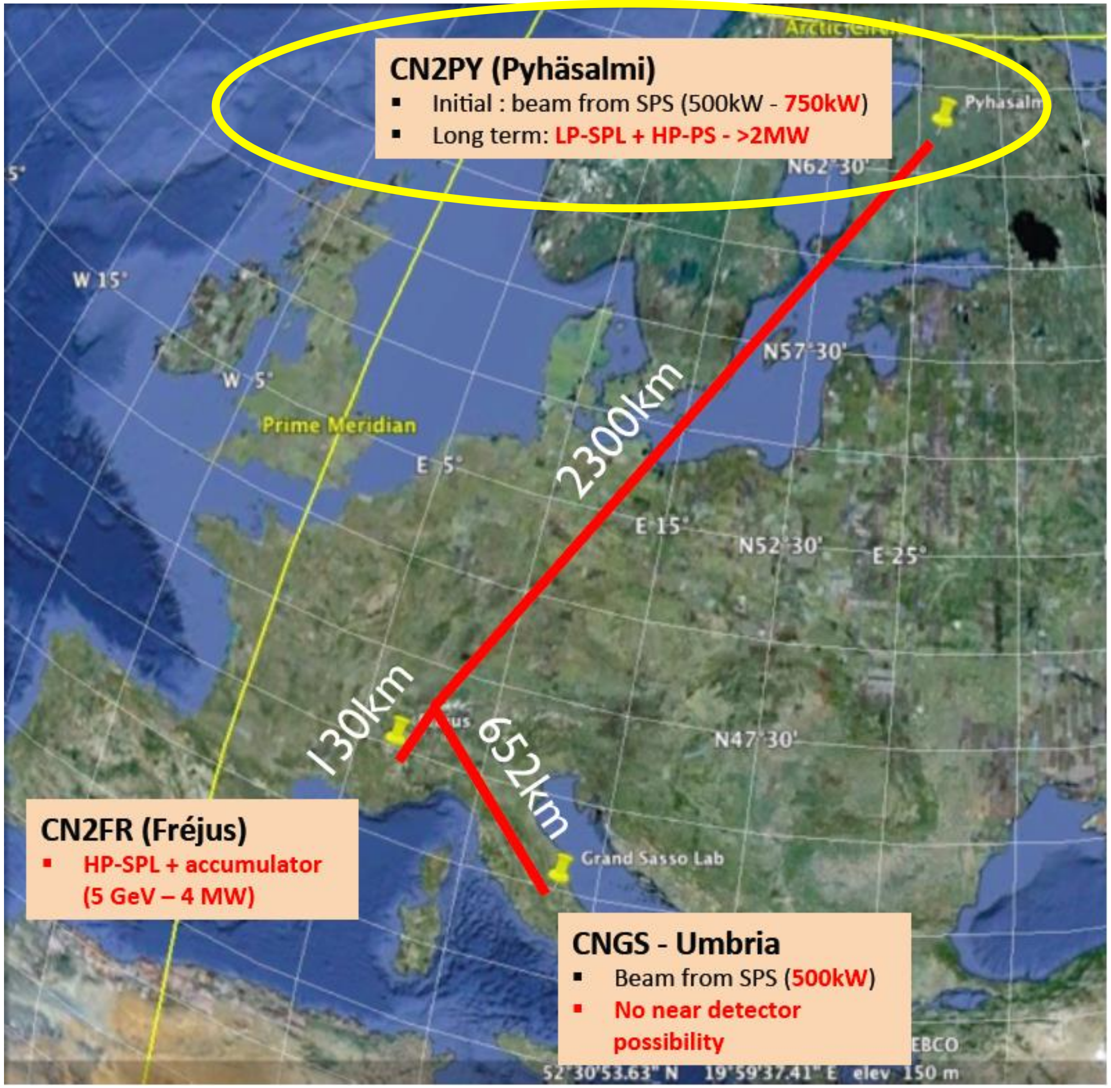
Long Baseline Oscillation (>1000km)
Detectors: Liquid Argon, Water Cerenkov, Liquid Scintillator
Europa: LAGUNA, USA: LBNE, Japan: HyperKamiokande

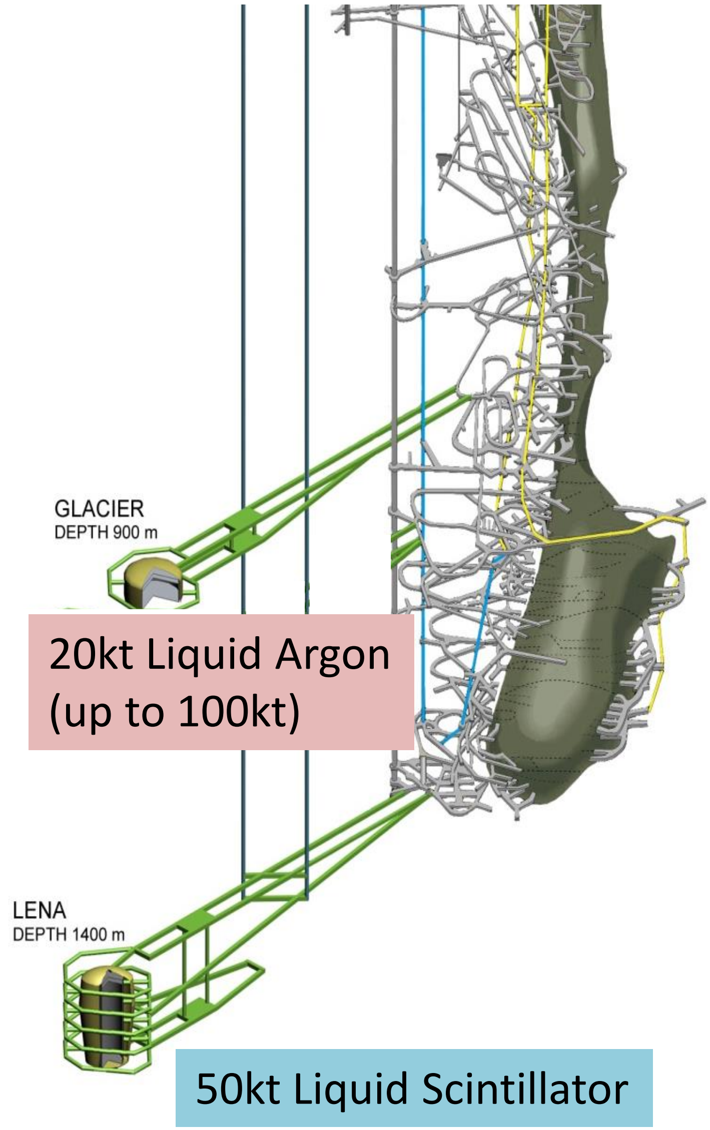
Reactor Experiment ?
@60km with 20kt Liquid Scintillator

Supernova Neutrinos ?

Atmospheric Neutrinos ?
(Pingu, Orca)

LAGUNA-LBNO Design Study FP7 (2011-2014)

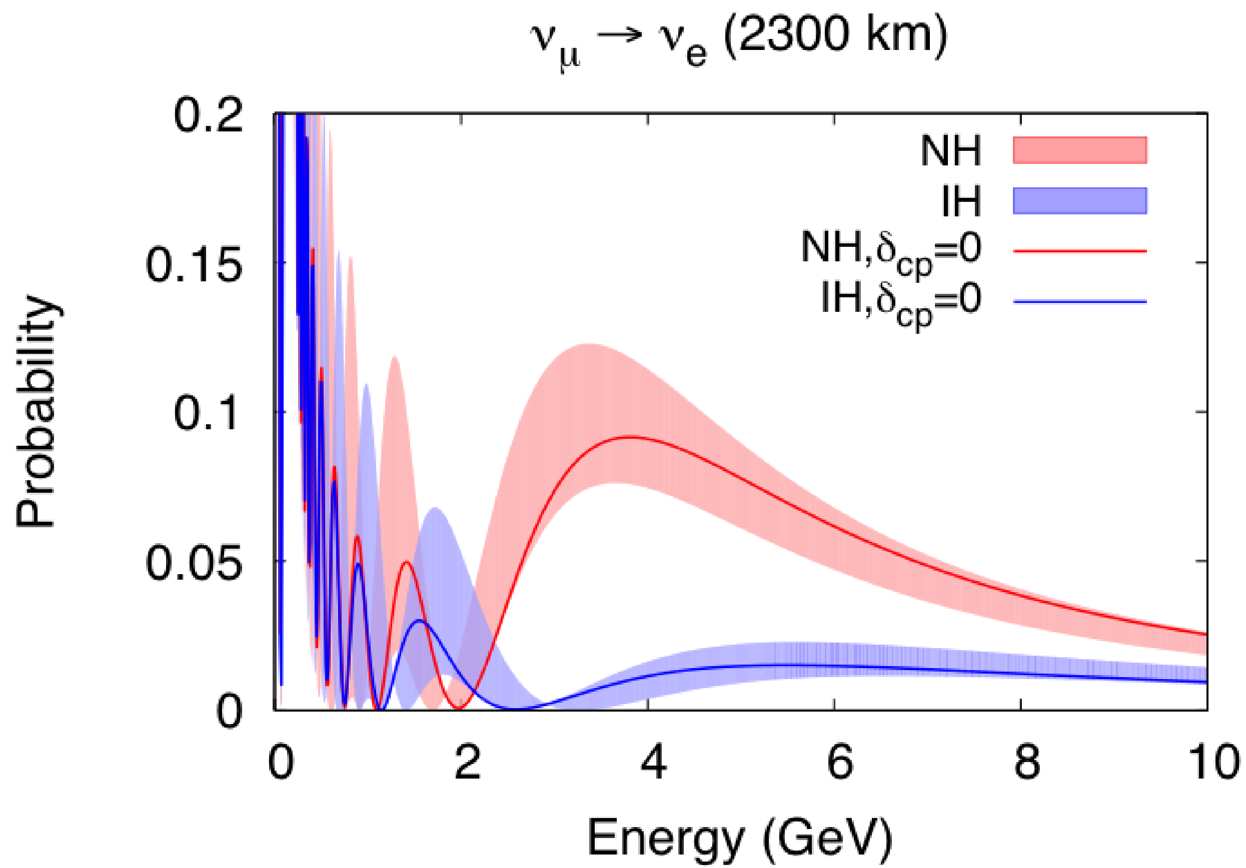




DESY - Pyhäsalmi (1500km), Protvino – Pyhäsalmi (1100km)

CN2PY (2300km): Mass Hierarchy

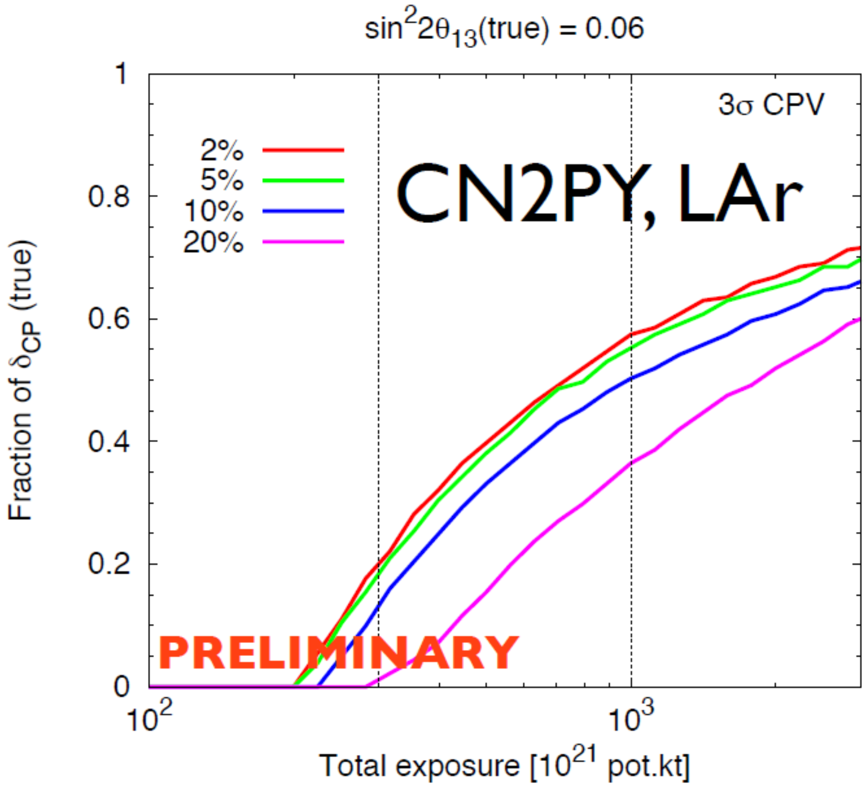
Very long baseline -> large matter effect

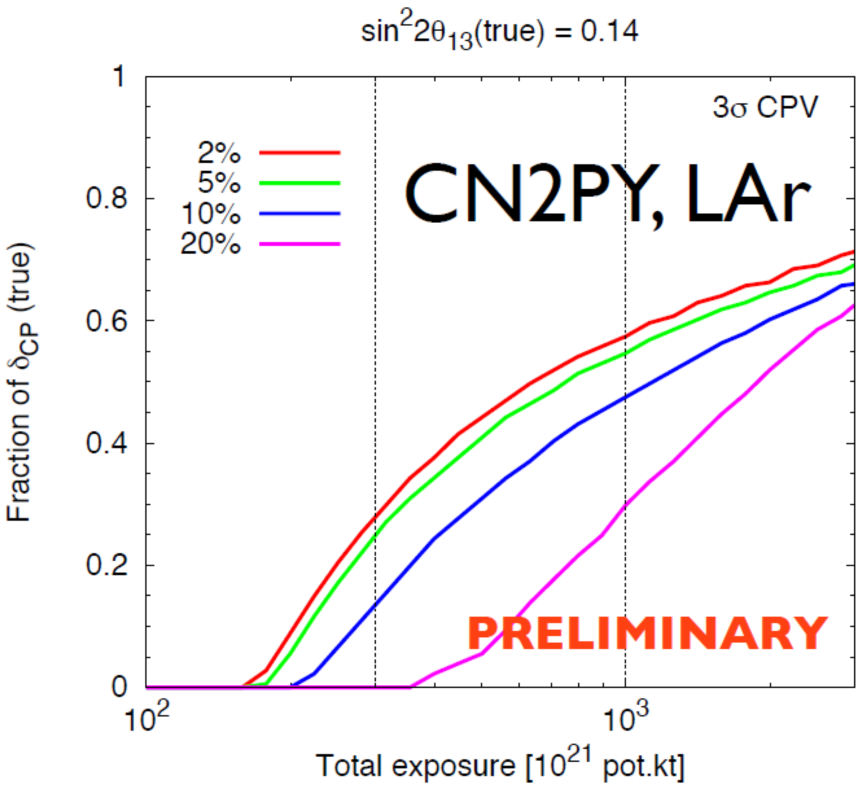


Mass hierarchy could be measured with > 5σ
(By Liquid Argon and Liquid Scintillator Detectors)

Potential to determine CP-Phase with CN2PY

colors = uncertainties of Earth density profile (2%-10%)





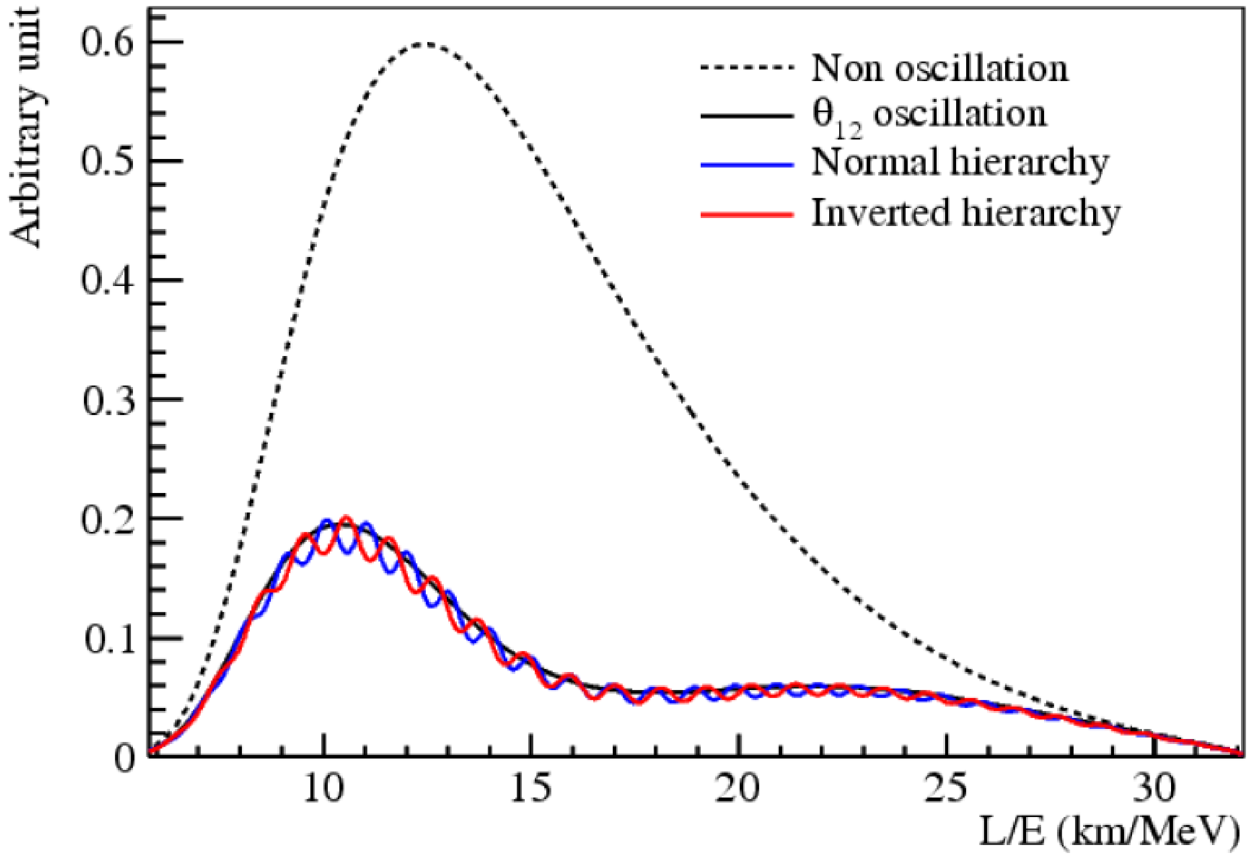
S.Pascoli NOW2012

Determination of Mass Hierarchy in a Reactor Neutrino Experiment

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

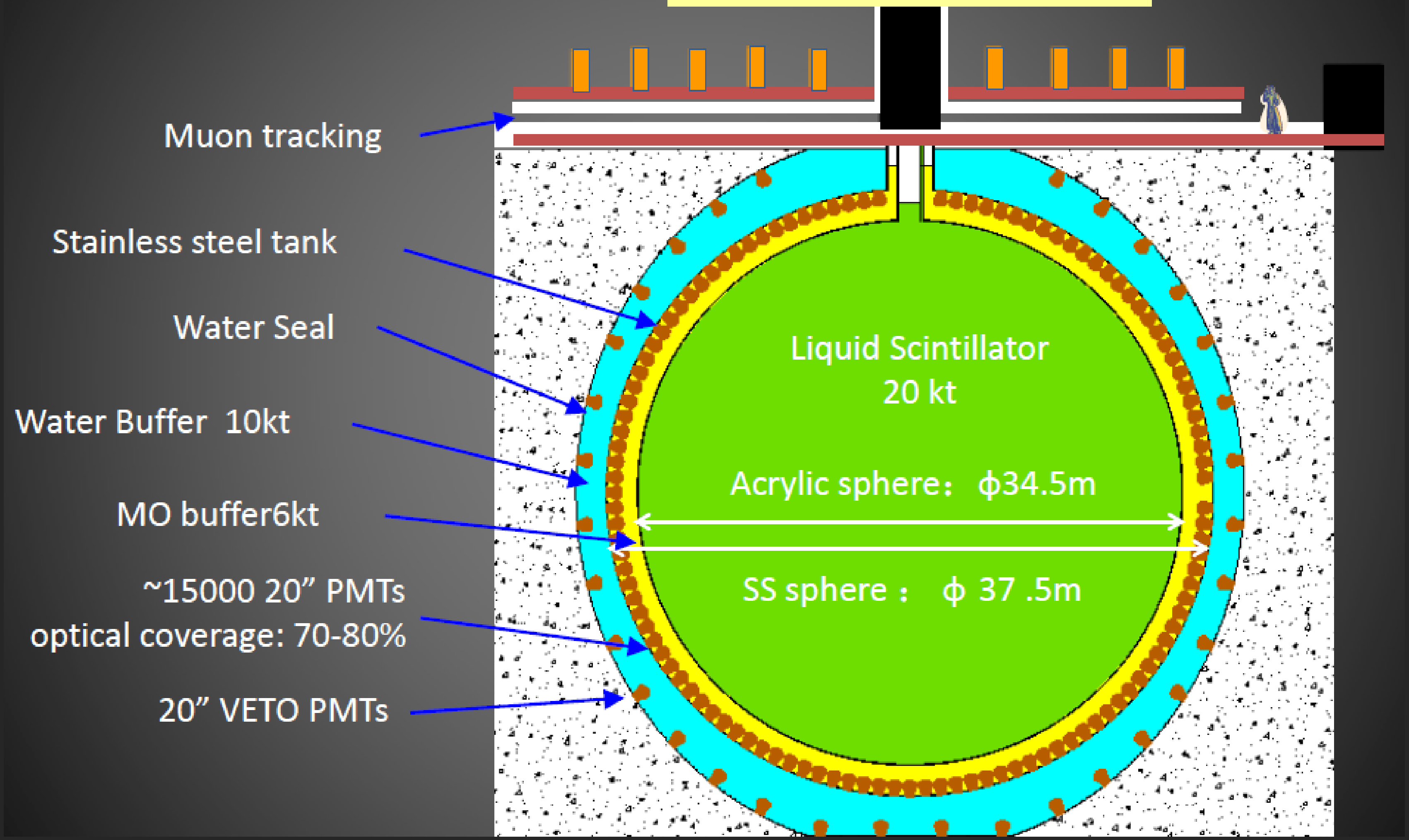
$$
\boxed{
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\text{NH}: \; |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\
\text{IH}: \; |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}|
\end{aligned}
}
$$

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



Daya Baya II

- **20kt Liquid Scintillator**
- 3%/√E energy resolution
- overburden: > 1000mwe
- Thermal power 35GW



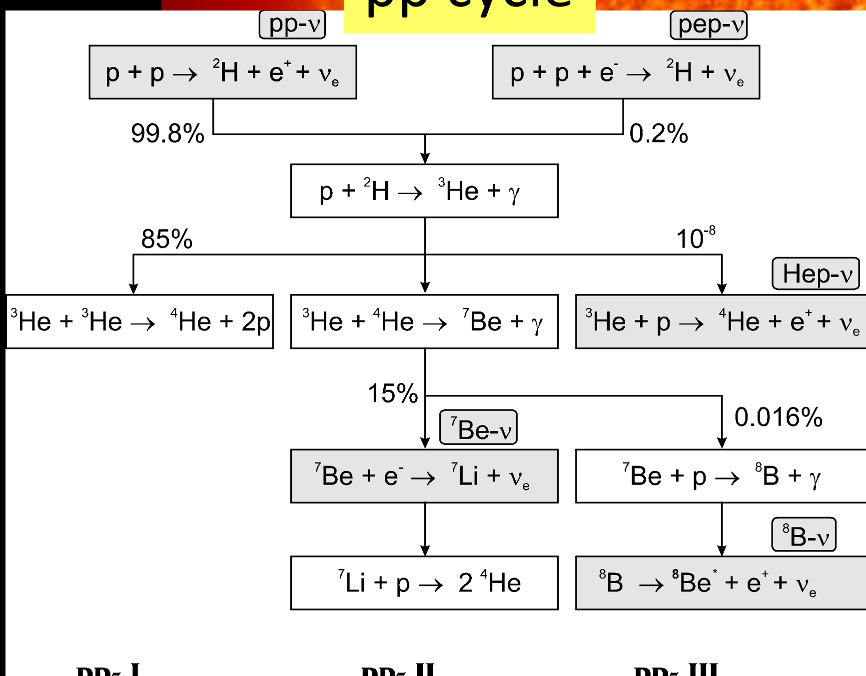
From NOW2012

Solar Neutrinos

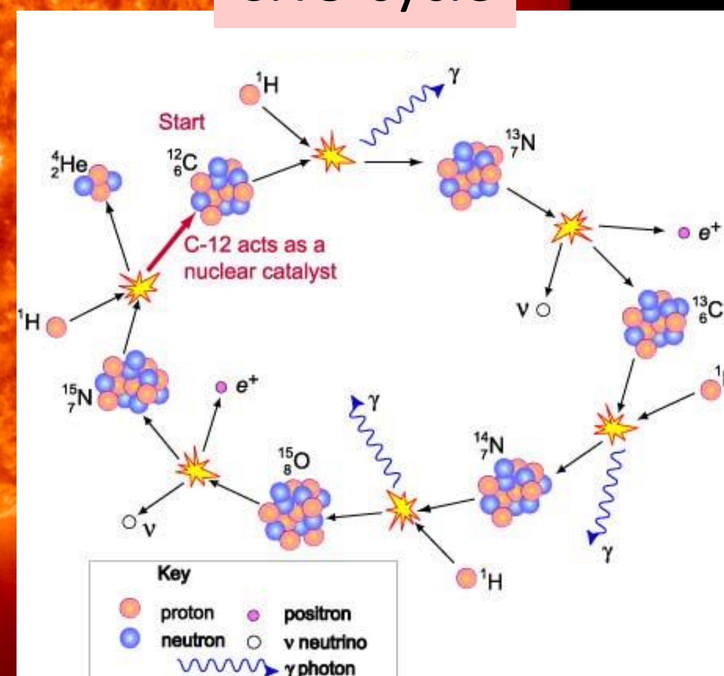
$$4p \rightarrow \mathrm{He}^4 + 2e^+ + 2\nu_e + 26.7\,\mathrm{MeV}$$

$6.5 \cdot 10^{10}\ \nu_e/\mathrm{cm}^2\mathrm{s}$

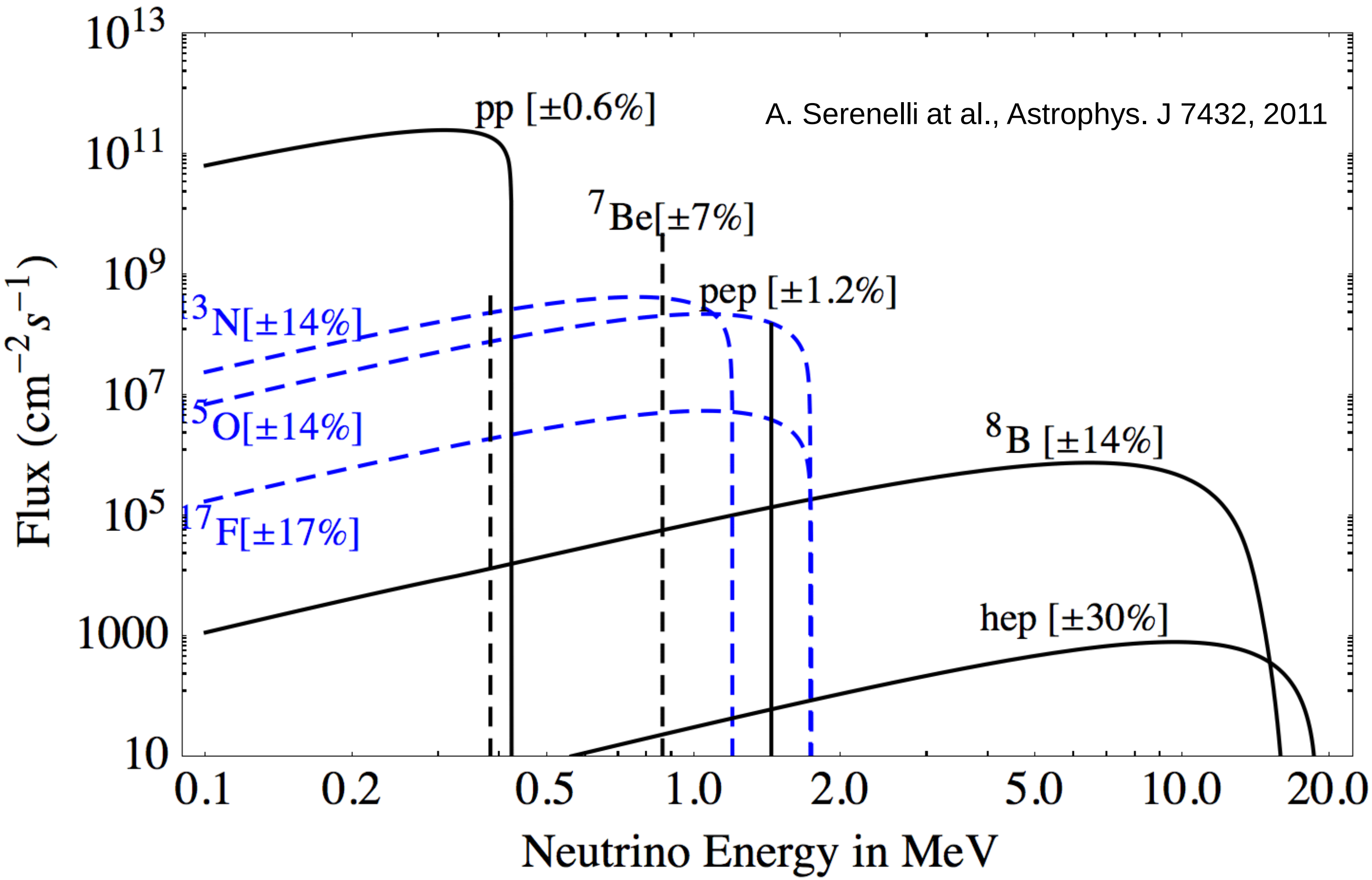
pp cycle



CNO cycle



Energy Spectrum of Solar Neutrinos



Solar Neutrino Experiments

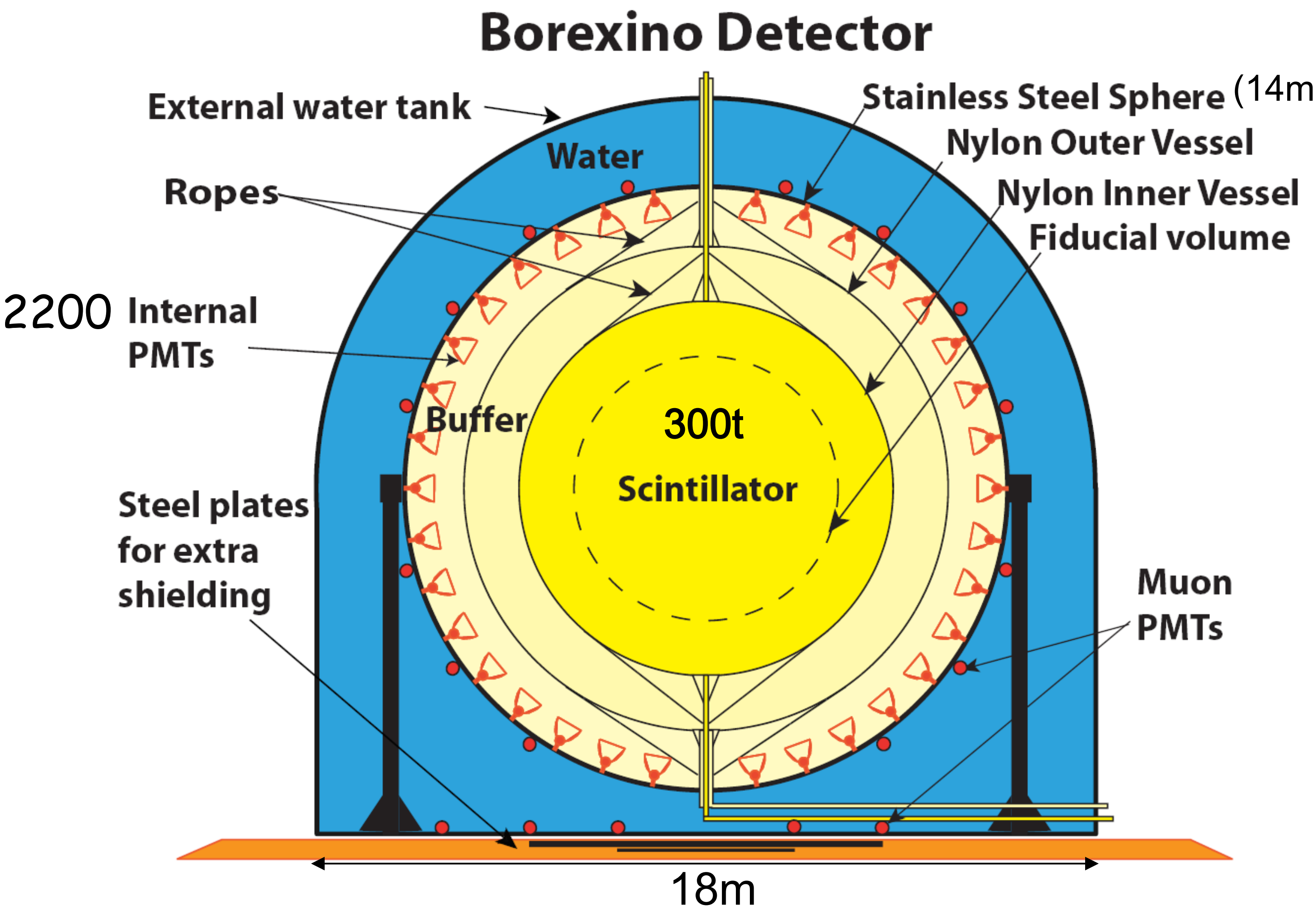
Measure Δm^2_{12} and (at present) most precise value of θ_{12}

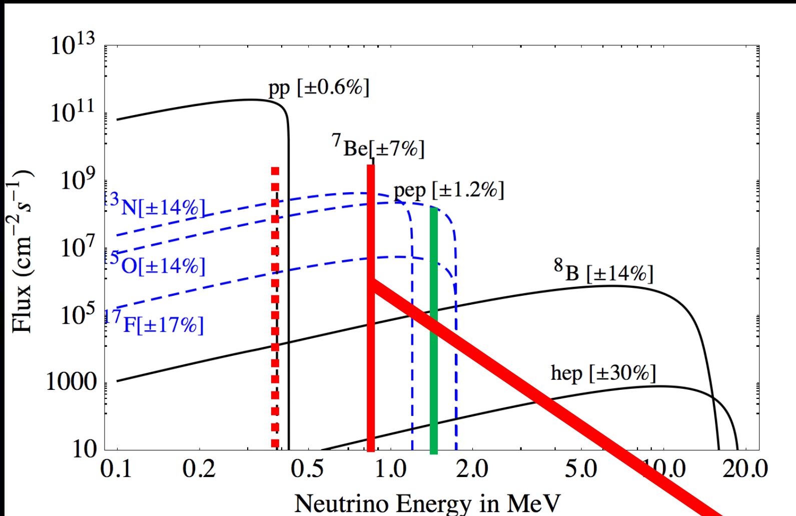
Detector	Target mass	Threshold [MeV]	Data taking
Homestake	615 tons C_2Cl_4	0.814	1970-1994
Kamiokande	3ktons H_2O	7.5	1983-1990
SAGE	50tons molted metal Ga	0.233	**1989-present**
GALLEX	30.3tons $GaCl_3$-HCl	0.233	1991-1997
GNO	30.3tons $GaCl_3$-HCl	0.233	1998-2003
Super-Kamiokande	22.5ktons	4.5 6.5 4.5 4	1996-2001 2003-2005 2006-2008 **2008-present**
SNO	1kton D_2O	5[3.5]	1999-2006
Borexino	300ton C_9H_{12}	0.2 MeV	**2007-present**

Compilation shown by Aldo Ianni at NOW2012

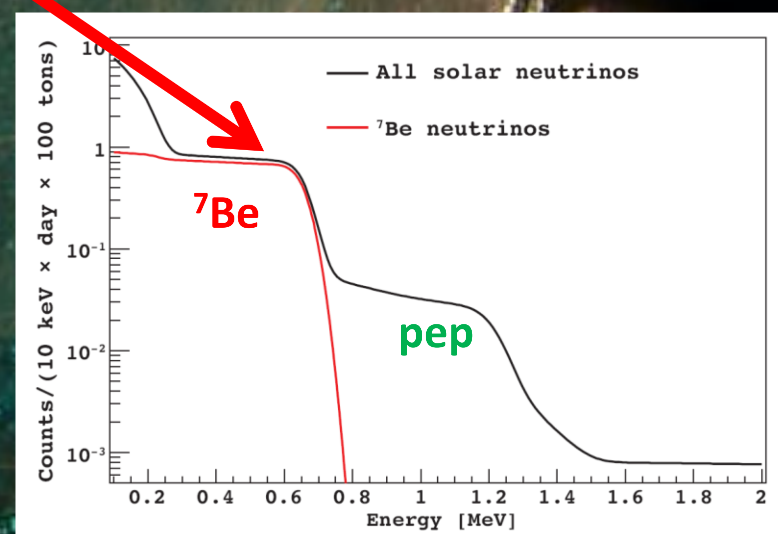
BOREXINO @ LNGS

Main Measurement: Flux of ^{7}Be Neutrinos

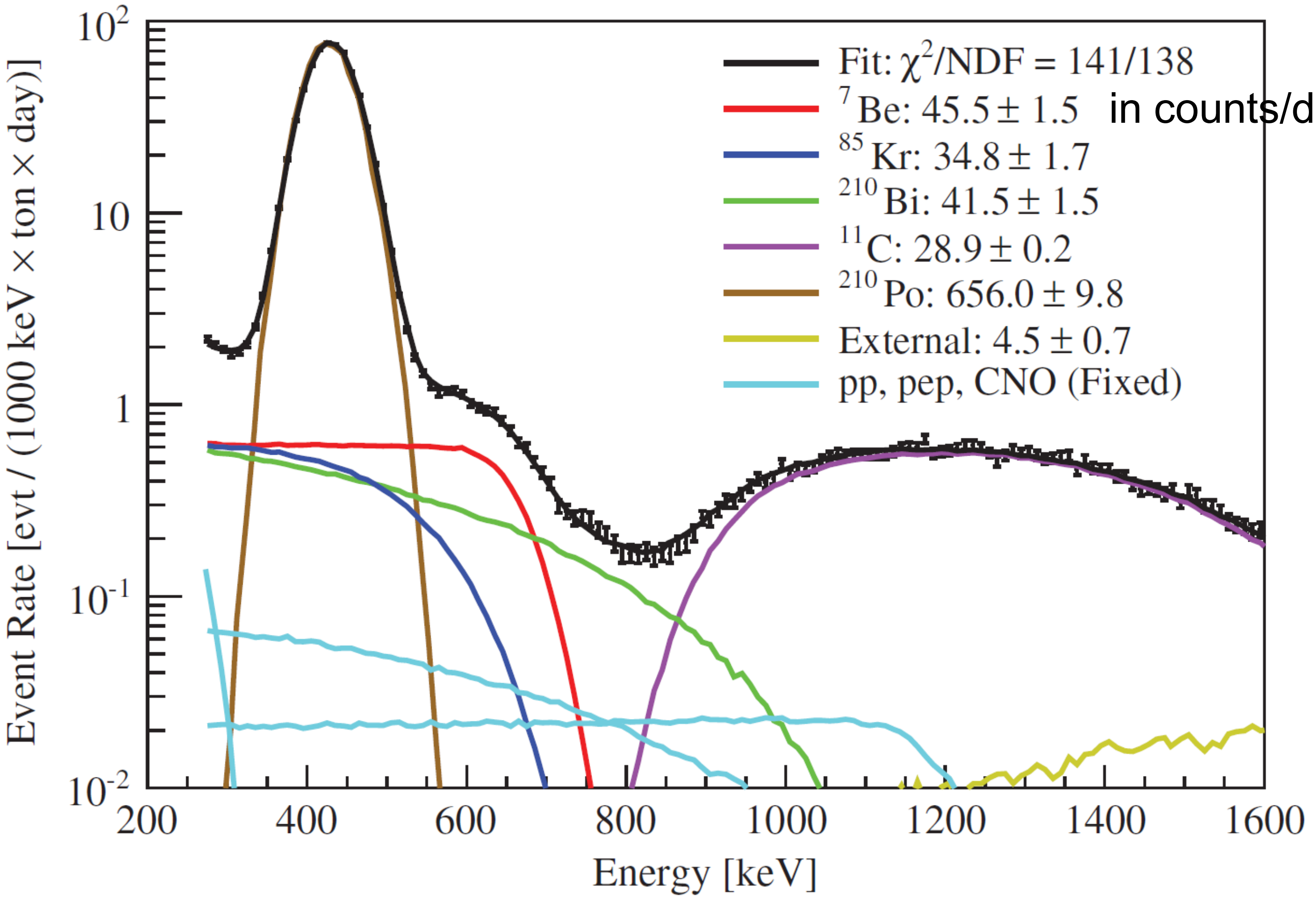




elastic scattering of neutrinos on electrons:
neutrino „lines" → Compton-like edge in spectrum of recoil electrons



Main Borexino Result: Flux of 7Be Neutrinos



in counts/day/100t

Borexino Coll. „precision measurement of the 7Be solar neutrino interaction rate in Borexino“, PRL 107, 141301 (2011)

Borexino Highlight 2012:
First Observation of pep-Neutrinos (+ best limit on CNO)

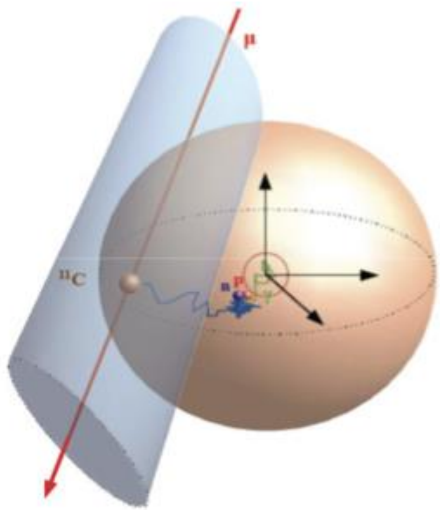
$\mu + {}^{12}\mathrm{C} \rightarrow \mu + {}^{11}\mathrm{C} + n$

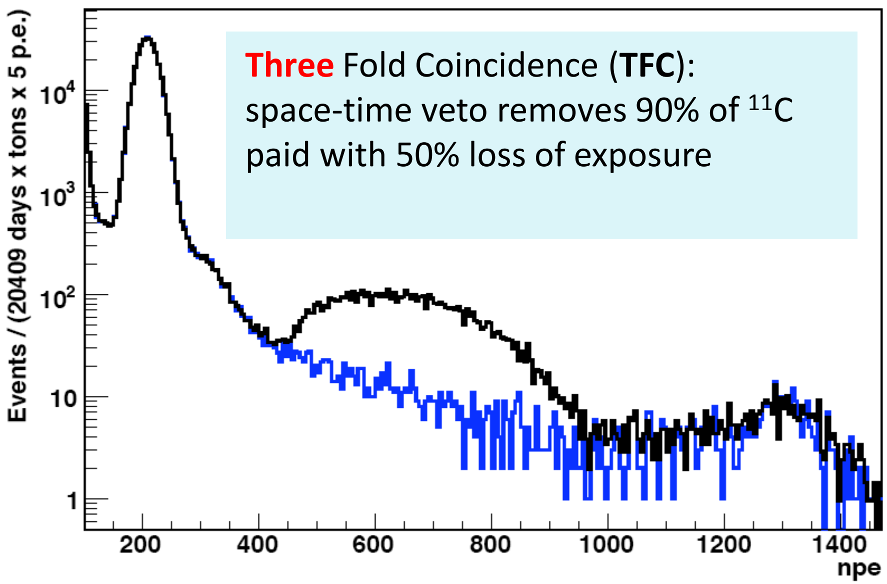
$\boxed{\tau \sim 260\ \mu s}$

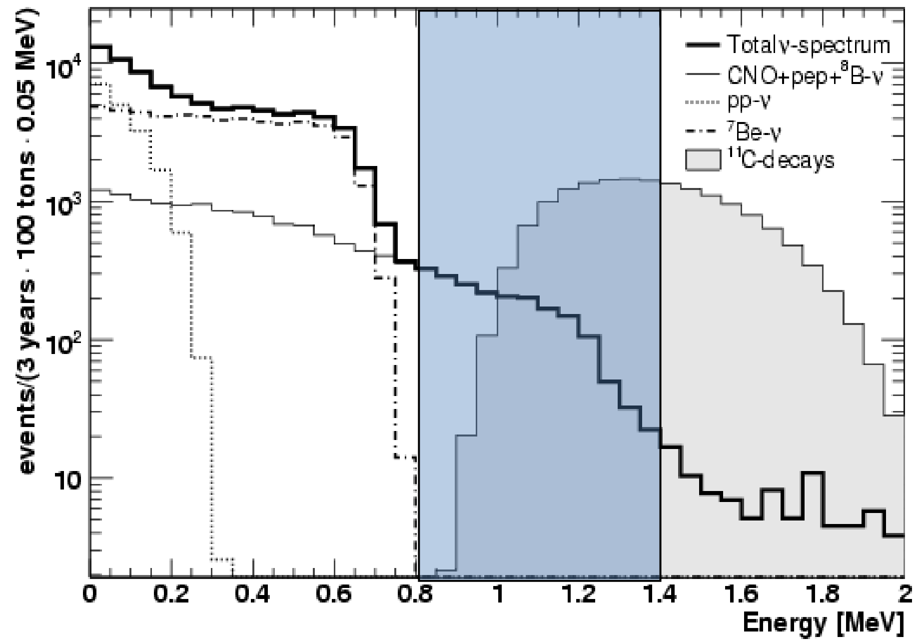
$\hookrightarrow + p \rightarrow d + \gamma$

${}^{11}\mathrm{C}$: $\tau \sim 30$ min

$\rightarrow {}^{11}\mathrm{B} + e^{+} + \nu_e$







G. Bellini et al., *"First evidence of pep solar neutrinos by direct detection in Borexino"*,
Phys. Rev. Lett. 108, 051302, 2012

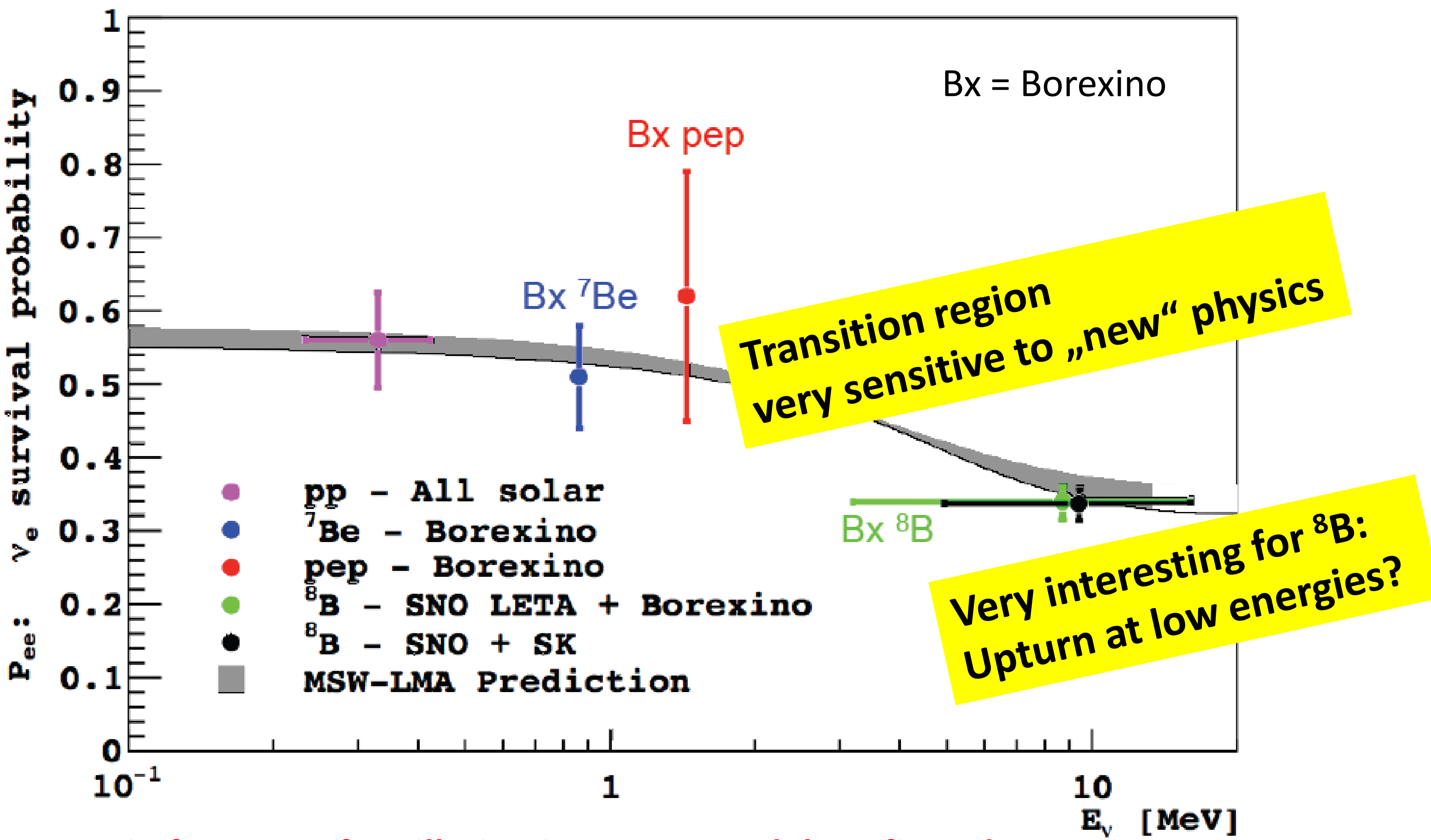
Solar Neutrino Flux: Theory vs Experiment

Source	Flux $[cm^{-2}s^{-1}]$ SSM-GS98	Flux $[cm^{-2}s^{-1}]$ SSM-AGSS09	Flux (Borexino) $[cm^{-2}s^{-1}]$ Data
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	$6.06(1^{+0.003}_{-0.01})\times10^{10}$
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	$1.60(1\pm0.19)\times10^{8}$
^{7}Be	$5.00(1\pm0.07)\times10^{9}$	$4.56(1\pm0.07)\times10^{9}$	$4.84(1\pm0.05)\times10^{9}$
^{8}B	$5.58(1\pm0.13)\times10^{6}$	$4.59(1\pm0.13)\times10^{6}$	$5.40(1\pm0.031)\times10^{6}$
^{13}N	$2.96(1\pm0.15)\times10^{8}$	$3.76(1\pm0.15)\times10^{8}$	$<6.7\times10^{8}$
^{15}O	$2.23(1\pm0.16)\times10^{8}$	$1.56(1\pm0.16)\times10^{8}$	$<3.2\times10^{8}$
^{17}F	$5.52(1\pm0.18)\times10^{6}$	$3.40(1\pm0.16)\times10^{6}$	$<59\times10^{6}$
CNO	5.24×10^{8}	3.76×10^{8}	**$<7.7\times10^{8}$ (2σ)**

Next Goal: First measurement of CNO flux

(2004 prediction was 10.8×10^{8})

Transition from Oscillations in Vacuum to Oscillations in Matter

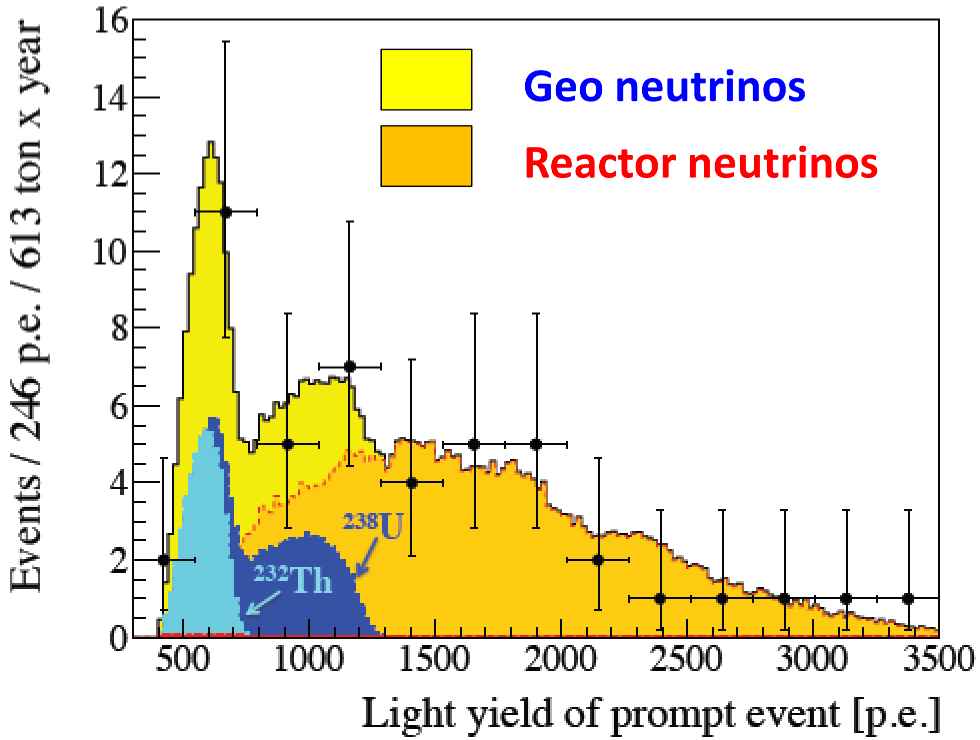


Main features of oscillation in matter model confirmed

More data points in transition region needed! (BSM and/or solar physics)

Borexino: Geo Neutrinos (New)

Borexino Coll., „Measurement of geoneutrinos from 1353 days of Borexino“, Phys. Lett. B, April 2013, arXiv:1303.2573
Exposure x2.4 compared to first publication: Borexino Coll., Phys. Lett. B 687 (2010) 299.



Conversion: 500 p.e. ≈ 1MeV

Assume chondritic ratio U/Th = 3.9:
Geo neutrino flux: **38.8 ± 12.0 TNU** (terristrial neutrino units)
1TNU = 1 event / year / 10^{32} protons
First time: U, Th contribution and mantle signal e

Still big uncertainties, agreement with geophysical models

Next Generation Liquid Scintillator Detector: 50kt
LENA (Low Energy Neutrino Astronomy)

Liquid Scintillator
ca. 69kt LAB

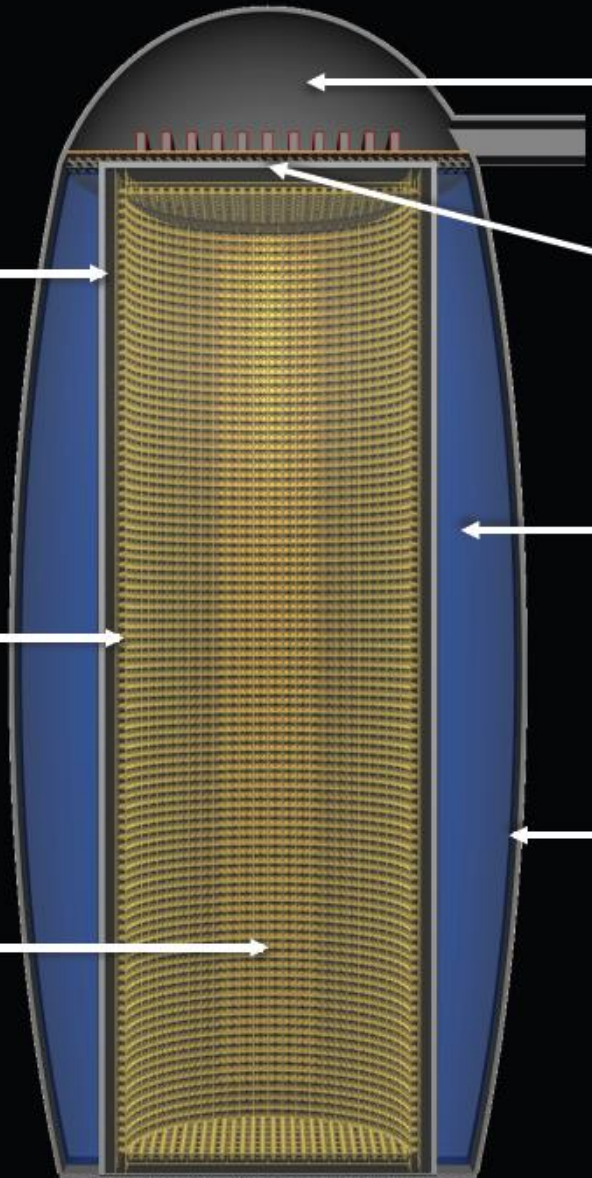
Concrete Tank
r = 16m, h = 100m

PMT support structure
radius: 14m

32,000 12“-PMTs
Winston cones
optical coverage: 30%

Optical shield

Active volume
ca. 50kt of LAB



Electronics Hall
dome of 15m height

Top Muon Veto
gas/solid scint. panels
vertical muon tracking

Water Cherenkov Veto
2000 PMTs, $\Delta r > 2$m
fast neutron shield
inclined muons

Egg-Shaped Cavern
about 10^5 m^3

Rock Overburden
at least 4000 mwe

Michael Wurm (UHH)

LENA Physics Program

Neutrinos at low energies

- Galactic Supernovae ν's
- DSNB
- Solar neutrinos
- Dark matter annihilation
- Geoneutrinos
- Reactor neutrinos
- Radioactive sources
- Pion decay-at-rest beams

GeV energies

- Long-baseline neutrino beam
- Atmospheric neutrinos
- Proton decay

→ Astrophysical neutrino sources

- stellar core collapse/fusion processes
- Earth heat flow, elemental composition

→ Neutrino physics

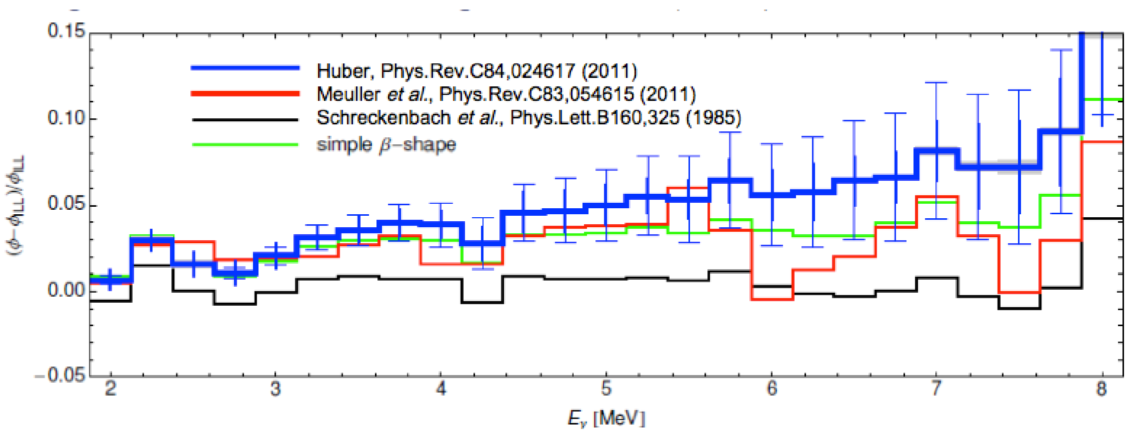
- mixing parameters
- neutrino mass hierarchy
- sterile flavors
- neutrino-antineutrino conversion
- non-standard interactions

→ Particle physics

- baryon number violation
- light dark matter

The Reactor Neutrino Anomaly

- Improved Reactor Neutrino Energy Spectra: +3,5% Flux Increase
  Müller et al., Phys.Rev.RC83, 054615 (**2011**), Huber, Phys.Rev.C84, 024617 (**2011**)
  gegenüber Schreckenbach et al. , Phys.Lett.B160, 325 (**1985**)

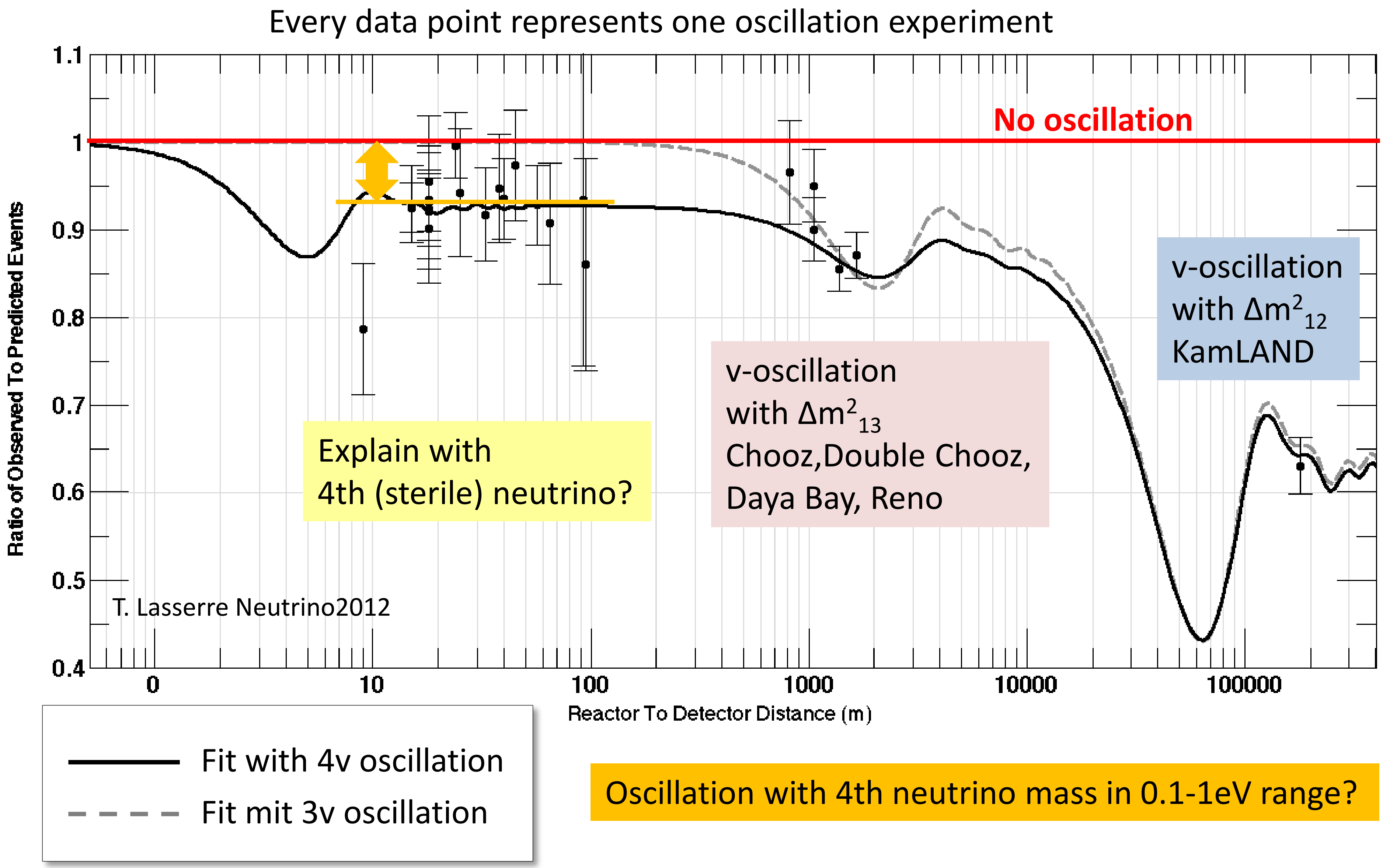


- New calculation of σ(inverse β decay): +1%
  (new value of neutron lifetime)
- Taking into account long lived Isotopes: +1%

Flux(SBL Experiments)/New Flux = 0.94 ± 0.02

G.Mention et al., Phys.Rev.D83:073006,2011

Sterile Neutrinos and Reactor Neutrino Anomaly



Oscillation with 4th neutrino mass in 0.1-1eV range?

Tests in Future Experiments

Complementary Methods:

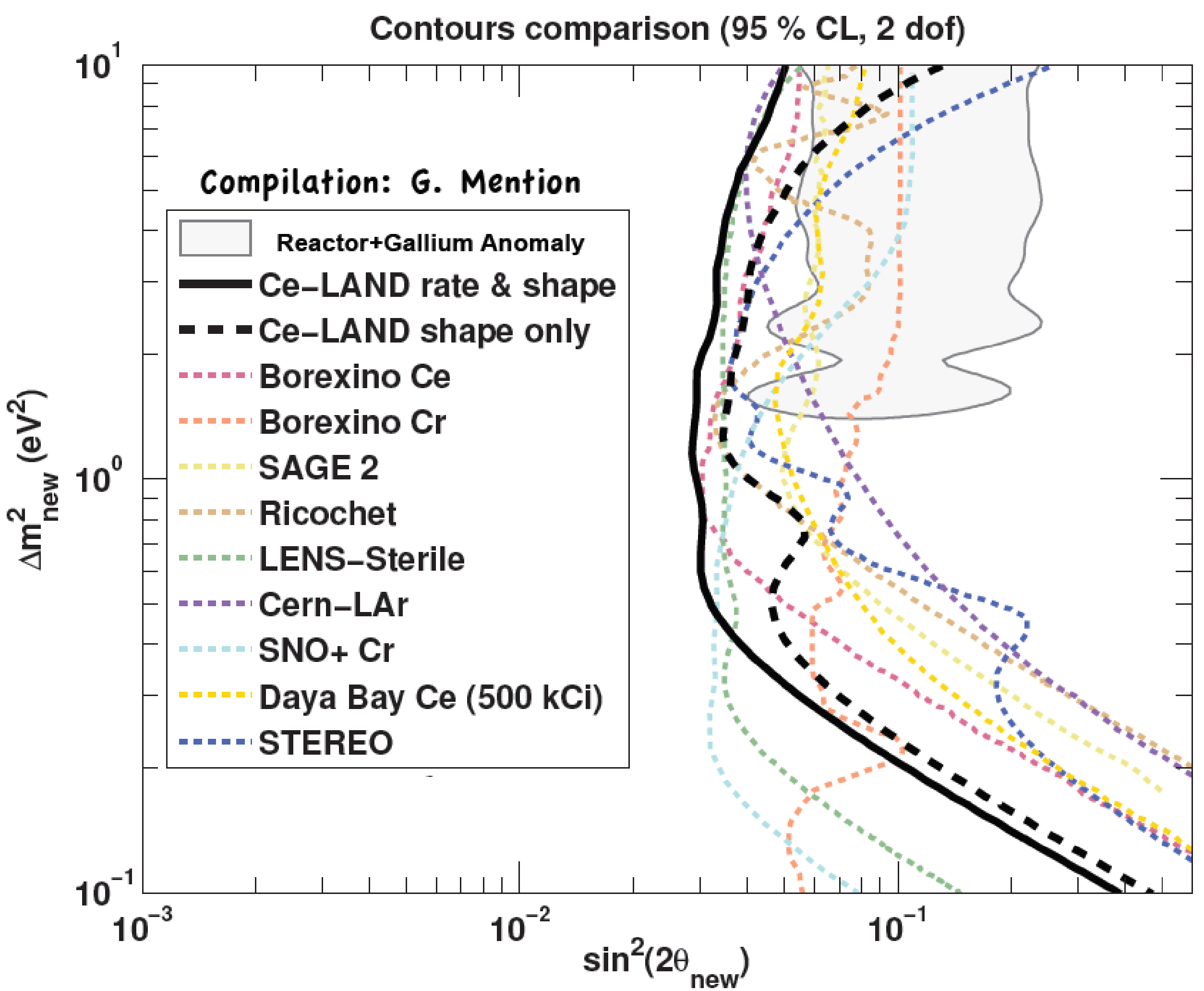
- Neutrino flux very close (<15m) to reactor core
  e.g. NUCIFER at Osiris reactor (CEA/Saclay)

- „Short Baseline" O(1km) neutrino beam
  e.g. Icarus & Nessie proposal at CERN

- Strong radioactive neutrino sources
  - ^{51}Cr neutrino source O(MCi)
    inside detector: Baksan, LENS, SNO+
    outside detector: Borexino
  - ^{144}Ce-^{144}Pr Anti neutrino source O(10kCi)
    inside: CeLAND, Borexino
    outside: Daya Bay

arXiv:1204.5379: „Light Sterile Neutrinos: A White Paper"

Sensitivity of planned Experiments



from arXiv:1204.5379: „Light Sterile Neutrinos: A White Paper“

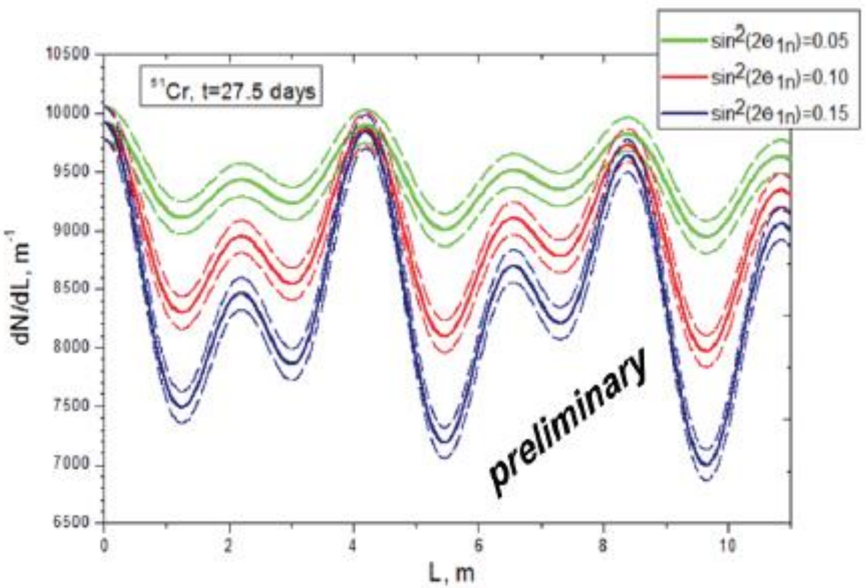
Neutrino Oscillometry in LENA

Radioactive neutrino sources

- anti-ν_e (monoenergetic) from EC sources: ^{51}Cr, ^{37}Ar
- ν_e (E=1.8-2.3MeV) from ^{90}Sr (^{90}Y)
- large activity necessary: 1MCi or more

Oscillation baseline

- for Δm^2_{32} (θ_{13}): 750m for ^{51}Cr (747keV)
- for Δm^2_{41} (sterile): 1.3m

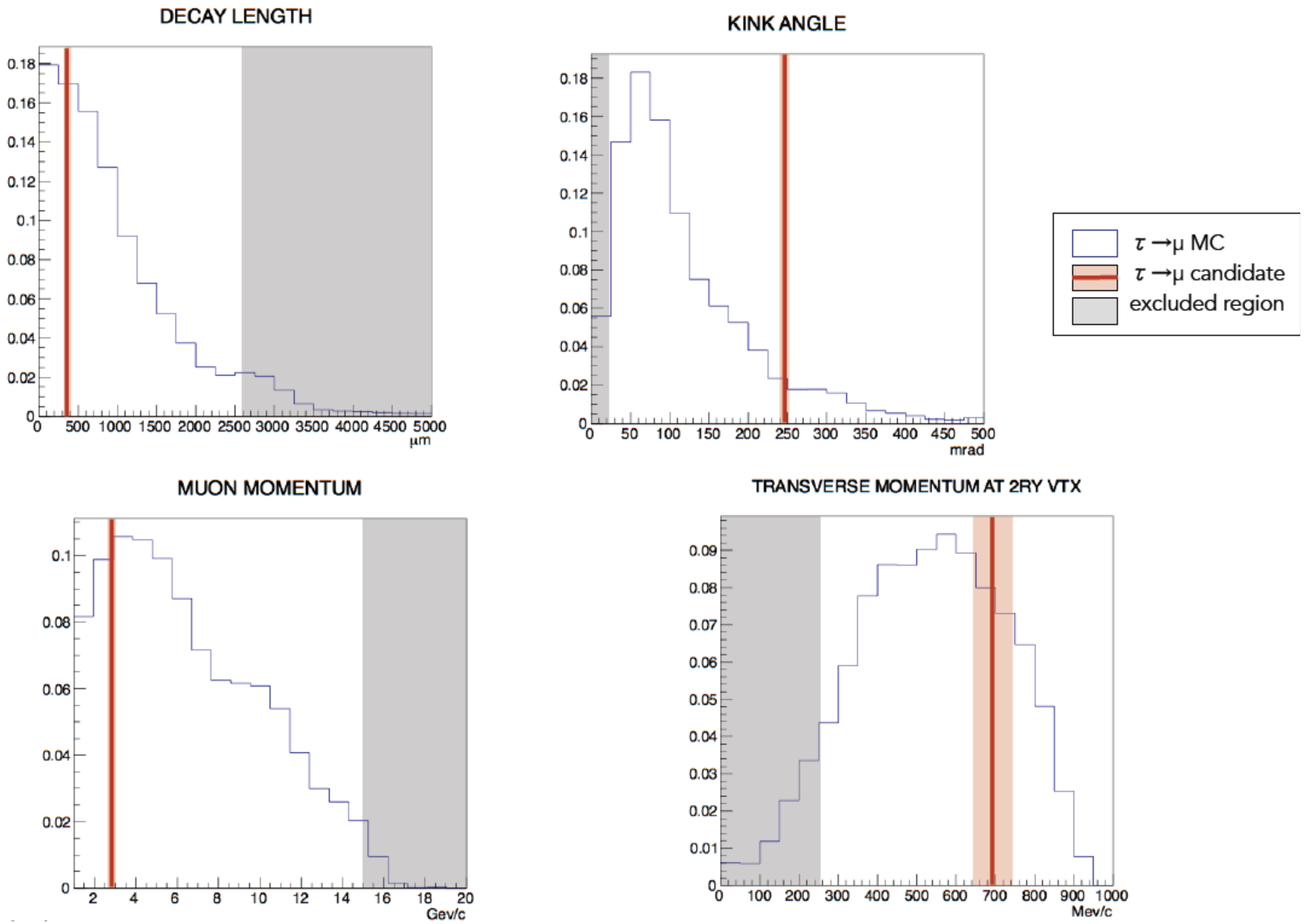


Summary:

- Neutrino Oscillationes have been observed in a large variety of experiments.
- The 2 mass differences have been measured.
- All 3 mixing angles have been measured.
- The mixing matrix of quarks and leptons
  has a very different structure.
- Goals for next generation of oscillation experiments:
  - Mass hierarchy
  - CP-phase
  - Clarification of MiniBoone/LSND
    and Reactor/Gallium anomaly (sterile neutrinos?)
- Use neutrinos as probes for Sun, Earth, Supernovae…
- Upcoming: GERDA will announce first result in June

3rd ν_{Tau} Candidate Event (02/05/2012): $\tau \rightarrow \mu\, \nu_\tau$

Event passes all cuts on kinematical variables



Double Chooz: Aufbau Ferndetektor

Outer Veto (OV)
plastic scintillator strips

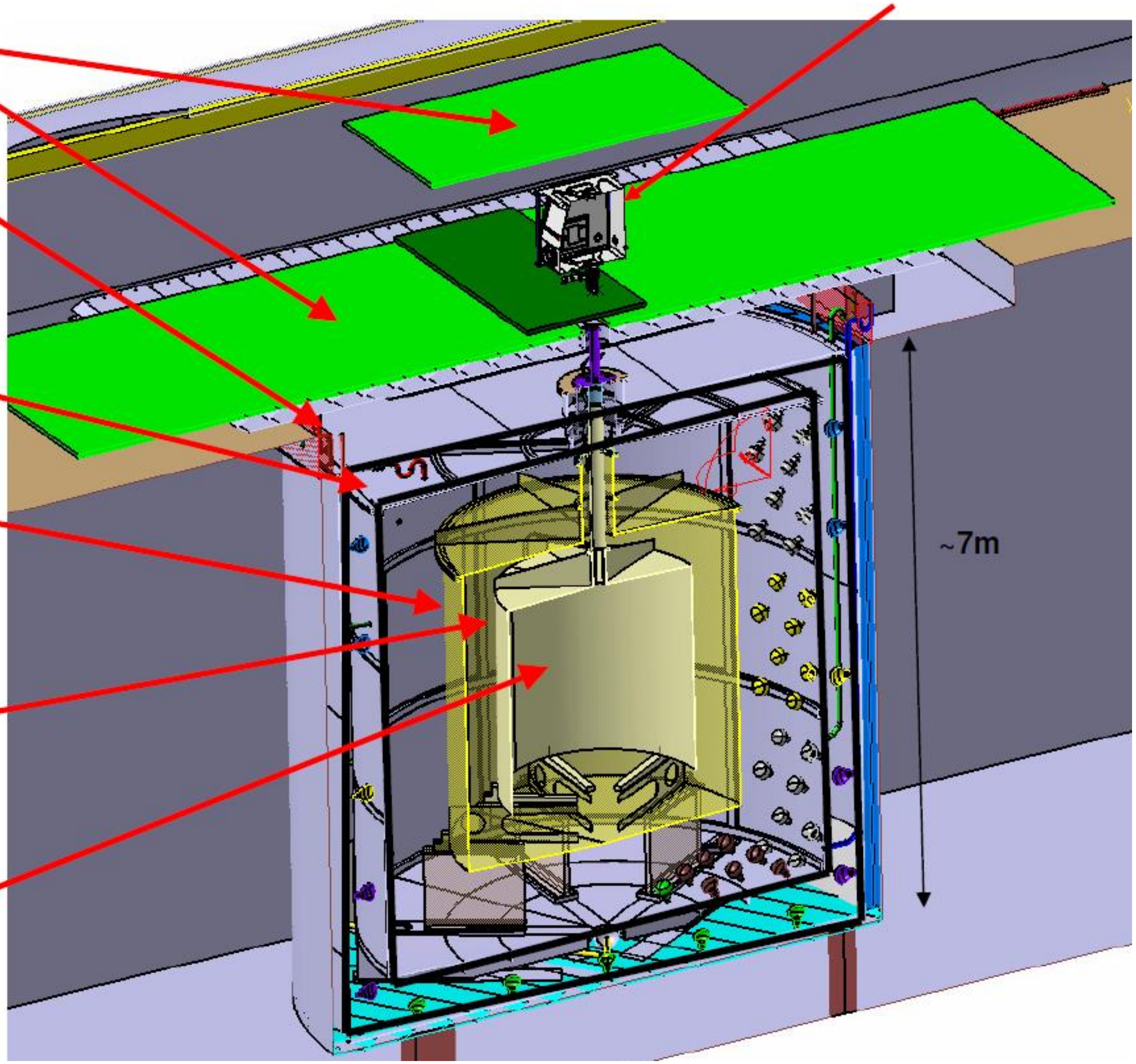
Outer Steel Shielding
250 t steel (15 cm)

Inner Veto (IV)
90 m^3 of scintillator in a steel vessel (10 mm) equipped with 78 PMTs (8 inches)

Buffer
110 m^3 of mineral oil in a steel vessel (3 mm) equipped with 390 PMTs (10 inches)

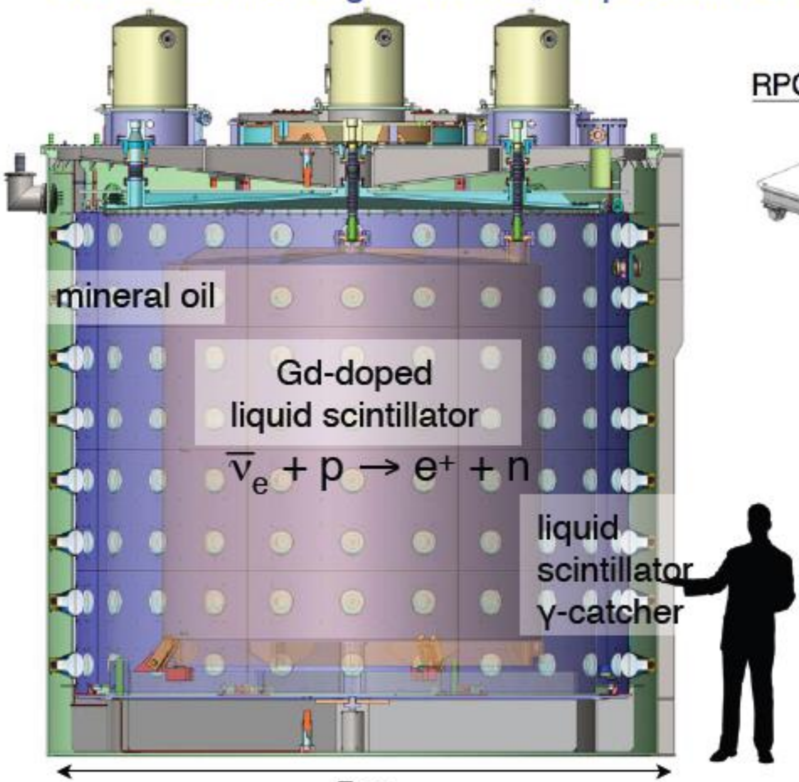
γ-Catcher (GC)
22.3 m^3 scintillator in an acrylic vessel (12 mm)

Target
10.3 m^3 scintillator doped with 1g/l of Gd compound in an acrylic vessel (8 mm)



Daya Bay Neutrino Detektoren

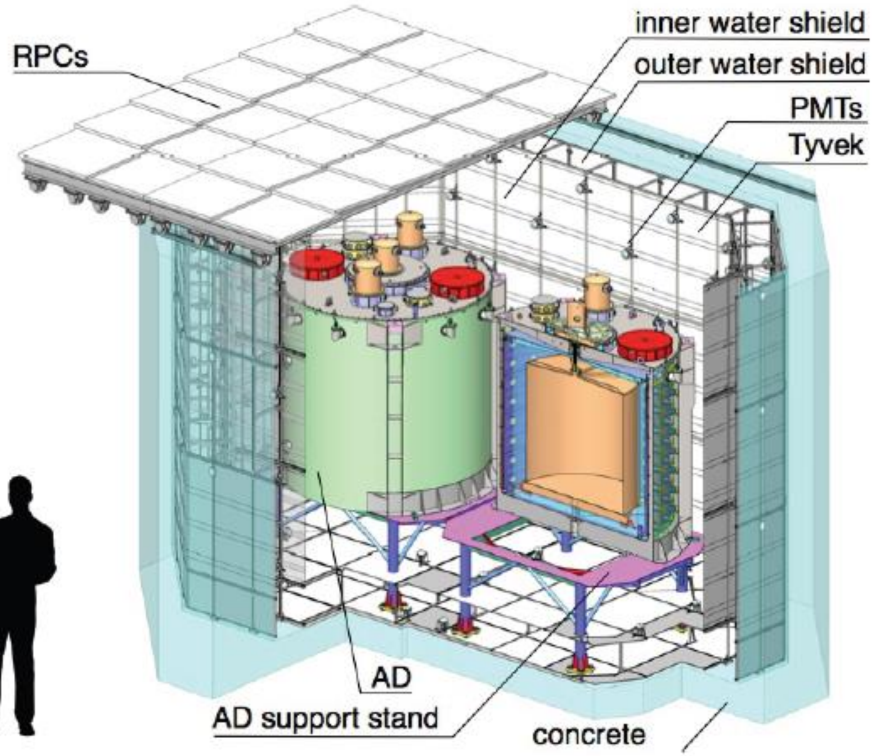
6 "functionally identical" detectors
Gd-LS defines target volume, no position cut



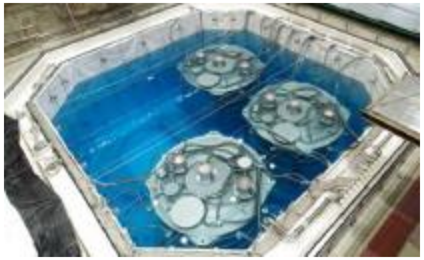
5 m

target mass: 20 ton per AD
photosensors: 192 8"-PMTs
energy resolution: (7.5 / √E + 0.9)%

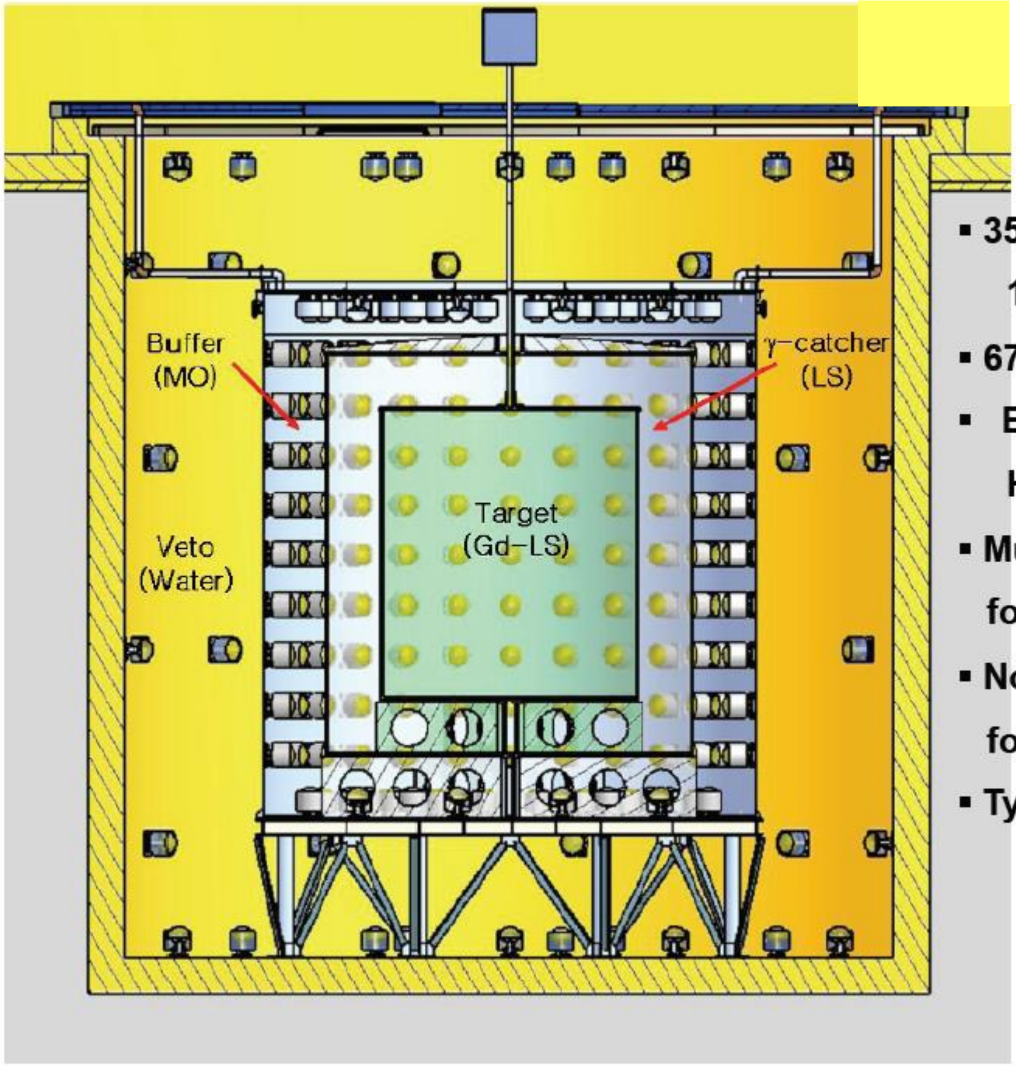
Dual tagging systems: 2.5 meter water shield and RPCs



Two-zone ultrapure water Cherenkov detector

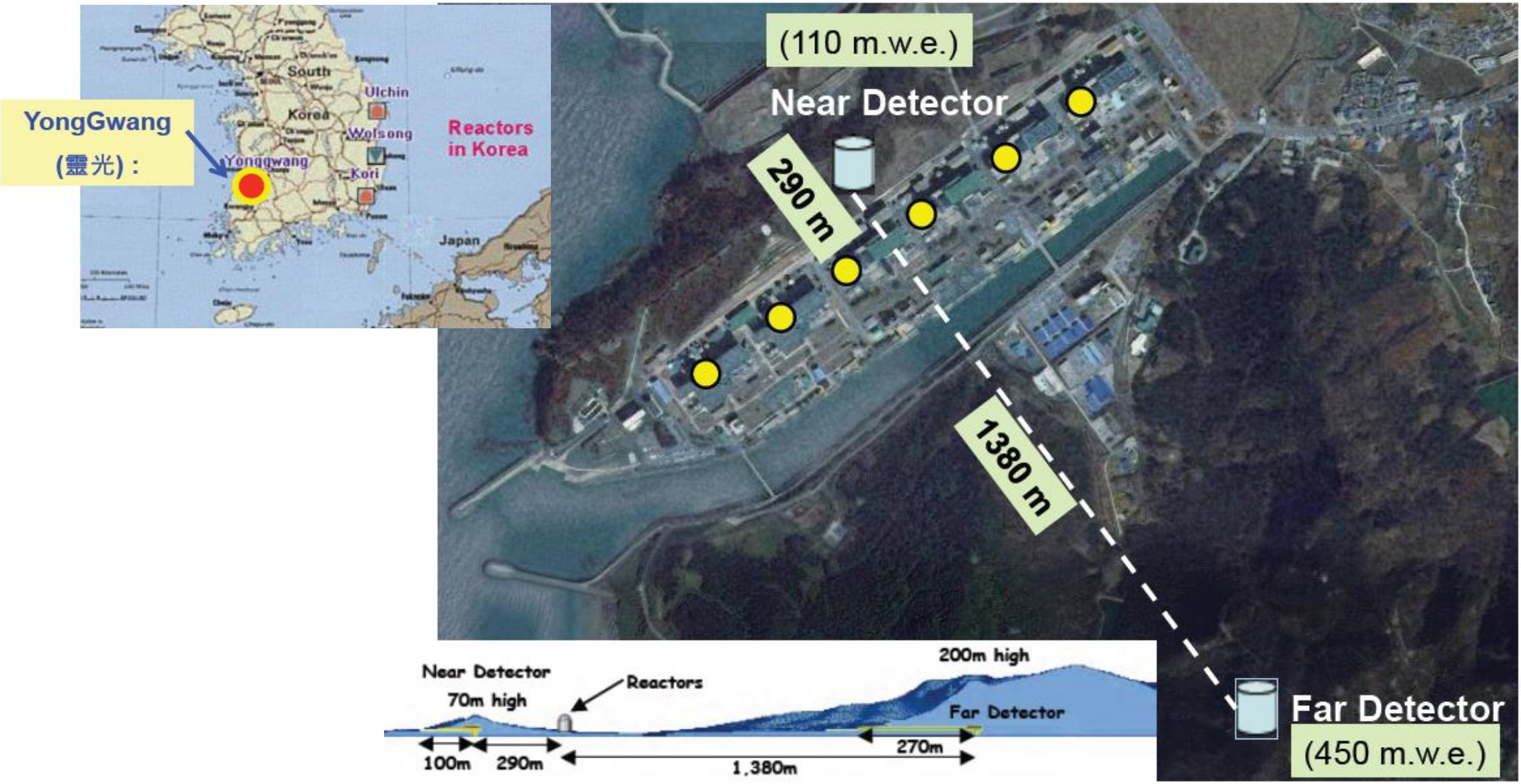


RENO Detektor



- 354 10" ID PMTs :
  14% surface coverage
- 67 10" OD PMTs
- Both PMTs are
  HAMAMATSU, R7081
- Mu-metal shielding
  for each PMT. (-5cm)
- No special reflector
  for ID
- Tyvek reflector at OD

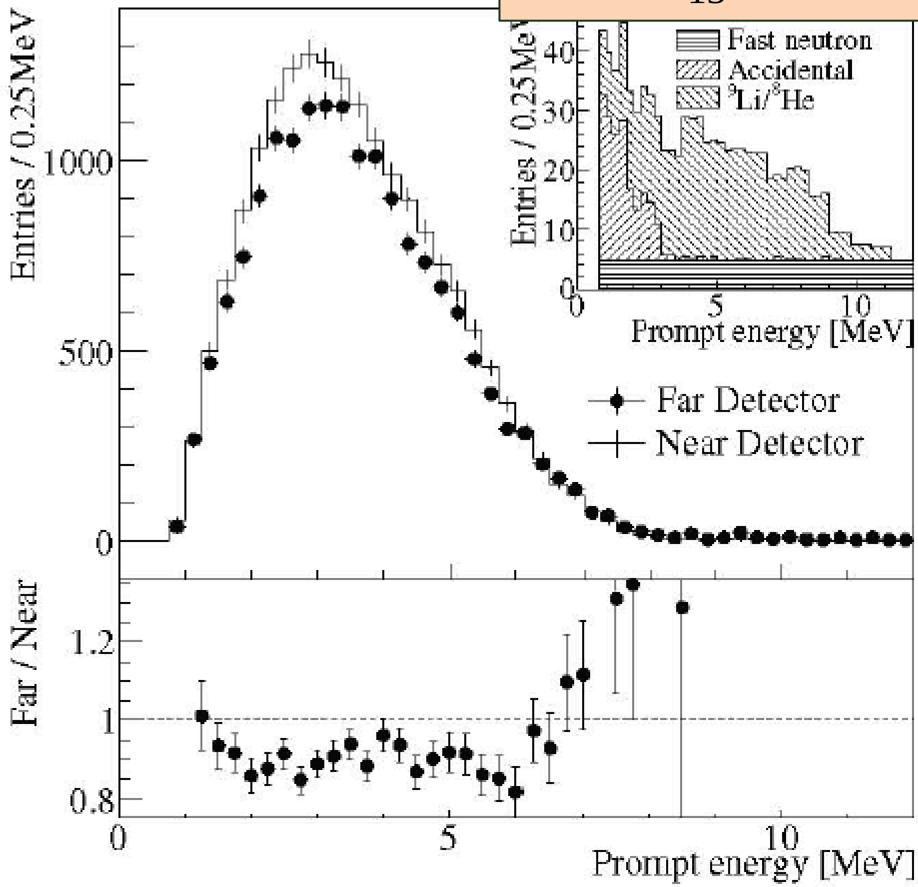
RENO (South Korea)



RENO: Result (220 days)

$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{expected}} = 0.920 \pm 0.009(stat) \pm 0.014(syst)$$

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



- A clear deficit in rate (8.0% reduction)
- Consistent with neutrino oscillation in the spectral distortion
- E>6 MeV distortion is not understood yet.

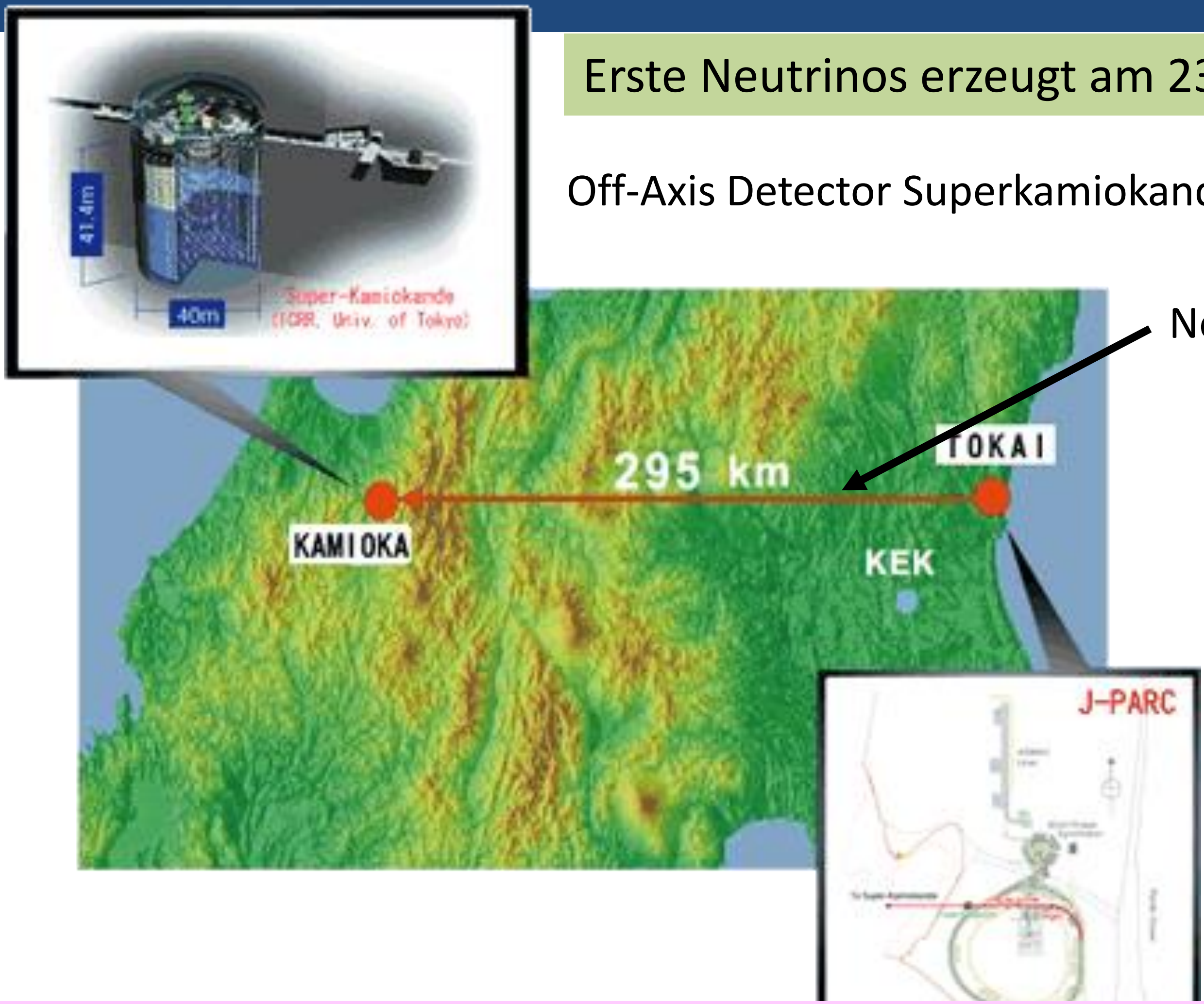
Seeon-He Seo, NOW2012

T2K

Erste Neutrinos erzeugt am 23.April 2009

Off-Axis Detector Superkamiokande

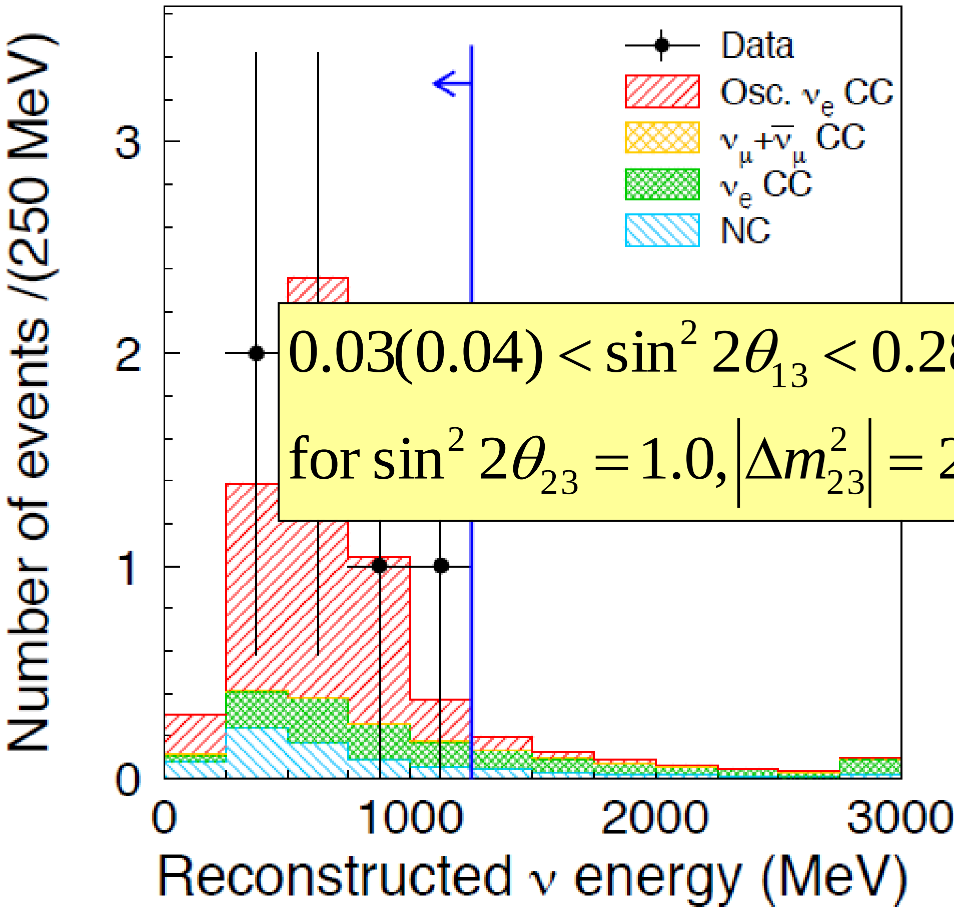
Neutrino Super Beam

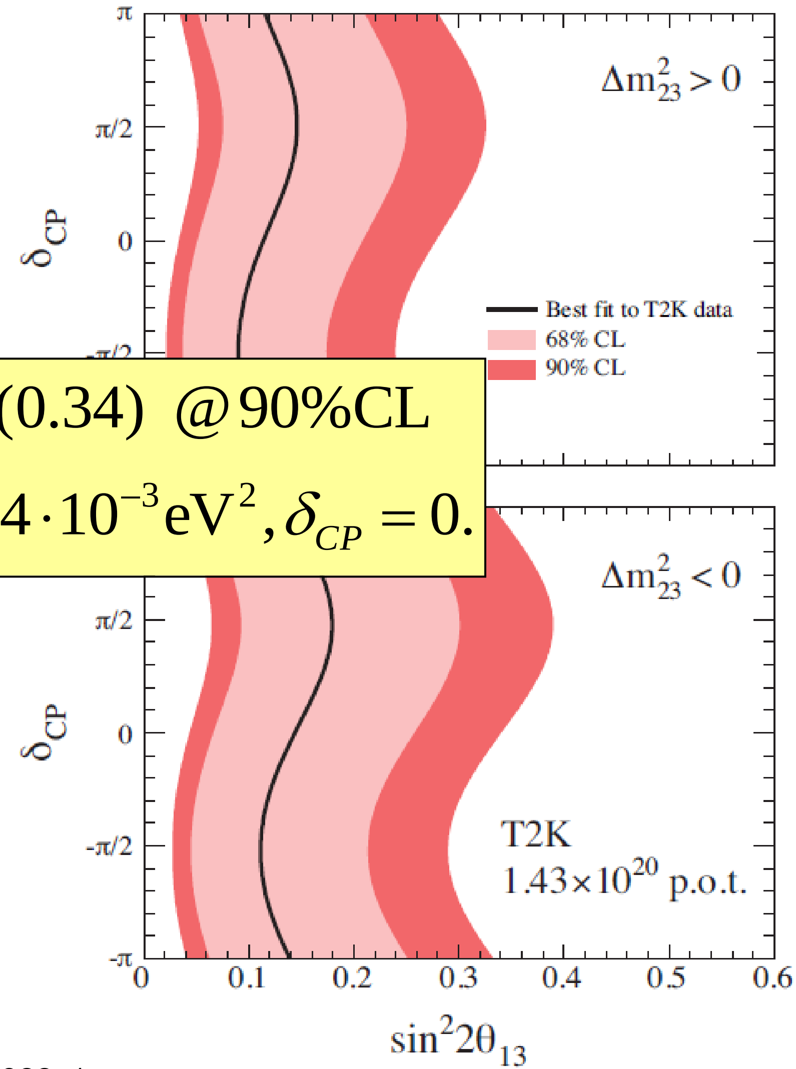


Proton driver

Unterbrochen wegen Erdbeben und Tsunami im März 2011 (Infrastruktur beschädigt)
Beschleuniger im Dezember 2011 wieder gestartet. Datennahme läuft.

T2K: Hinweis auf Erscheinen von ν_e in ν_μ Strahl





$$0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34) \quad @90\%\mathrm{CL}$$

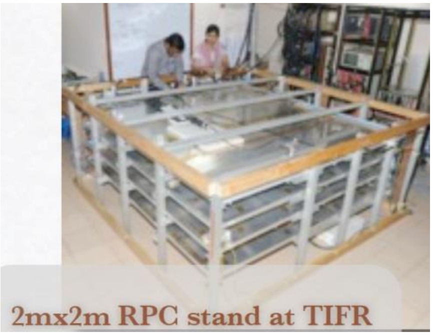
$$\text{for } \sin^2 2\theta_{23} = 1.0, \left|\Delta m^2_{23}\right| = 2.4\cdot10^{-3}\mathrm{eV}^2, \delta_{CP} = 0.$$

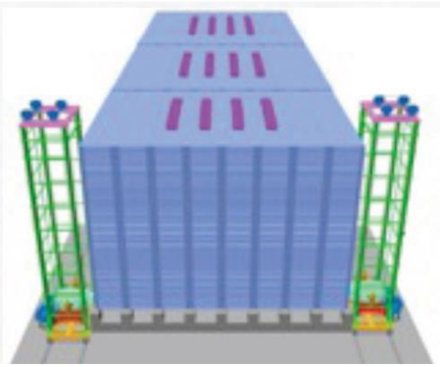
T2K Coll., "Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam", arXiv:1106.2822v1

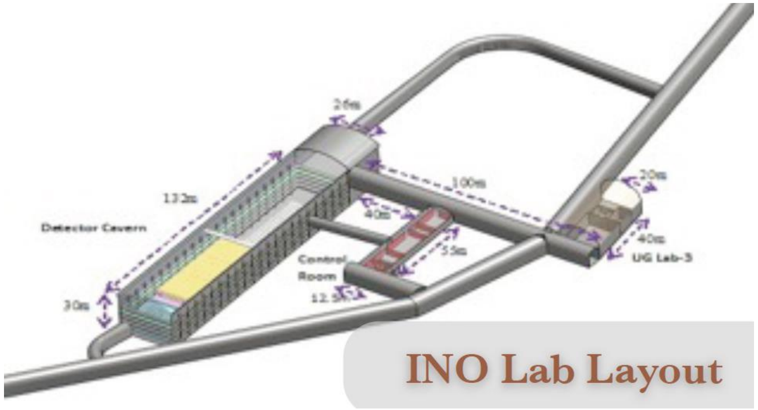
Atmosphärische Neutrinos und Massenhierarchie (1): ICAL @ INO

50kt magnetized iron calorimeter using glass RPCs (ICAL),
Underground Lab INO in Tamil Nadu (India)

Mass hierarchy results possible before 2025, but < 3σ
even with most optimistic assumptions on energy and angular resolution of ICAL (10% and 10°, respectively)





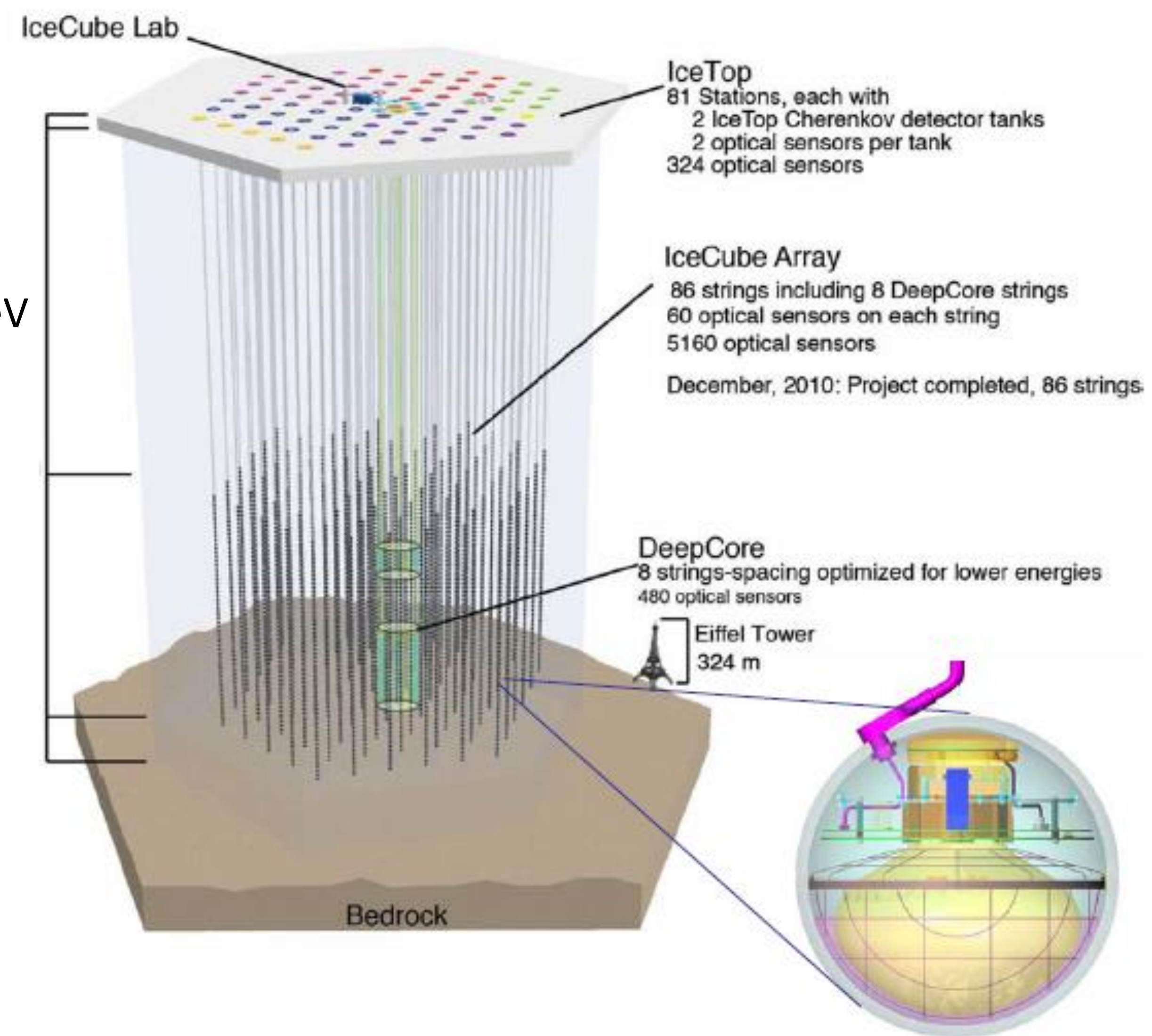


Atmosphärische Neutrinos und Massenhierarchie (2): PINGU (und ähnlich ORCA)

PINGU @ Icecube:

- add 20 strings in DeepCore region
- lower energy threshold: 1 GeV (DeepCore 10GeV)

Timeline:
2012 LOI
2013 proposal



Massenhierarchie mit PINGU/ORCA

Akhmedov, Smirnov, Razzaque (arxiv:1205.7071)

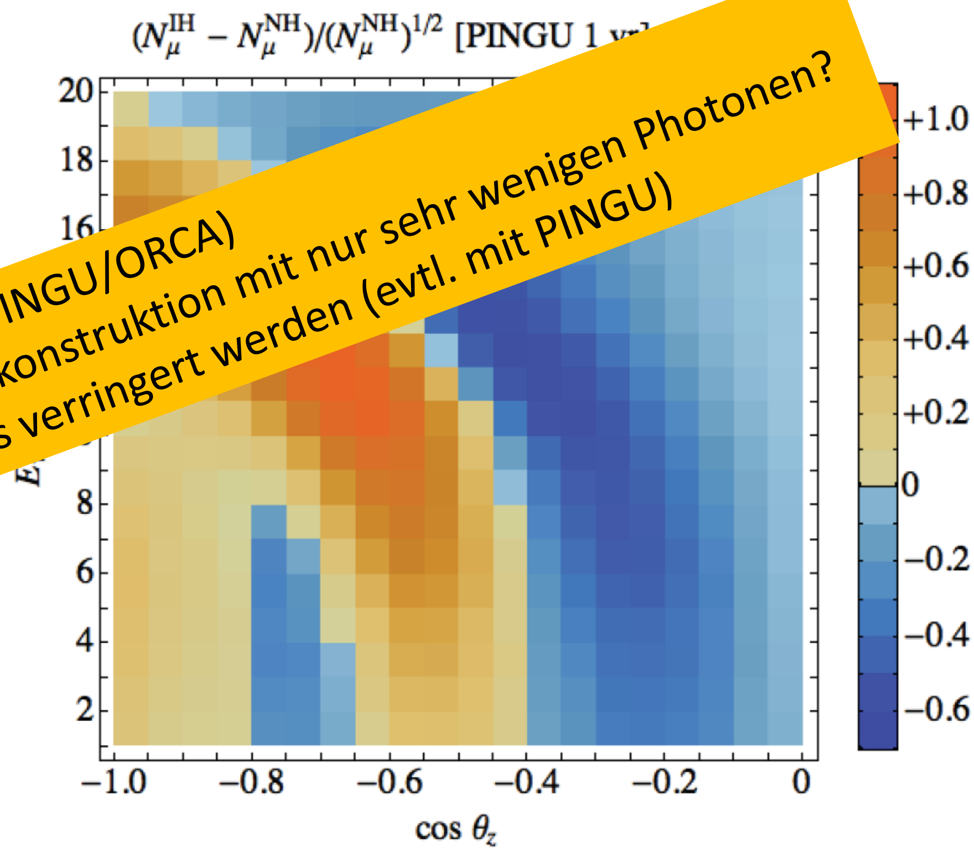
"After 5 years of PINGU 20 operation:
Significance of the determination of the hierarchy can range from 4σ to 11σ
(without taking into account parameter degeneracies),
depending on the accuracy of reconstruction of the neutrino energy and zenith angle."

One example: 5years

$$\sigma_E = 0.3 E_\nu \text{ and } \sigma_\theta = \sqrt{m_p/E_\nu}.$$

f = 10% (uncorrelated syst. Errors)
Total Significance: 7.1σ

Similar ... used
by KM3N...
ORCA feasibility study



Machbarkeitsstudien laufen (PINGU/ORCA)
Probleme: Gelingt die Spurrekonstruktion mit nur sehr wenigen Photonen?
Unsicherheit auf Δm^2_{23} muss verringert werden (evtl. mit PINGU)

Experimente die nicht ins Standard Oszillationsbild passen: LSND/MiniBoone

- LSND:
  Pion-Zerfall in Ruhe,
  Oszillation Anti-Myon-Neutrino in Anti-Elektron-Neutrino beobachtet?

- MiniBoone:
  Short Baseline,
  Oszillation Anti-Myon-Neutrino in Anti-Elektron-Neutrino beobachtet?

Könnten durch 4. Neutrino (steril) im 1eV Bereich erklärt werden.