NEUTRINO OSCILLATIONS

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- **Formalism of neutrino oscillations in vacuum**
- **Solar neutrinos**
- **Neutrino oscillations in matter**
- **The KAMLAND reactor experiment**
- **“Atmospheric” neutrinos**
- **The Chooz reactor experiment**
- **Long baseline oscillation searches at accelerators**
- **Future projects: measurement of the θ_{13} mixing angle**
- **Puzzling results: LSND and MiniBooNE experiments**

Neutrino oscillations in vacuum

Hypothesis: neutrino mixing

(Pontecorvo 1958; Maki, Nakagawa, Sakata 1962)

ν_e ν_μ ν_τ are not mass eigenstates but linear superpositions of mass eigenstates ν_1 ν_2 ν_3 with eigenvalues m_1 m_2 m_3

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

$\alpha =$ e, μ, τ (flavour index)

i = 1, 2, 3 (mass index)

$U_{\alpha i}$: unitary mixing matrix

$$|\nu_i\rangle = \sum_\alpha V_{i\alpha} |\nu_\alpha\rangle$$

$$V_{i\alpha} = (U_{\alpha i})^*$$

Time evolution of a neutrino with momentum p produced in the flavour eigenstate ν_α at time $t = 0$

$$|\nu(t)\rangle = e^{i\mathbf{p}\cdot\mathbf{r}} \sum_k U_{\alpha k} e^{-iE_k t} |\nu_k\rangle$$

Note: $|\nu(0)\rangle = |\nu_\alpha\rangle$

$E_k = \sqrt{p^2 + m_k{}^2}$ ➡ the complex phases $e^{-iE_k t}$ are different if $m_j \neq m_k$

➡ **appearance of new flavour $\nu_\beta \neq \nu_\alpha$ at time $t > 0$**

Example for two – neutrino mixing

$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_\beta\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

$\theta \equiv$ **mixing angle**

If $\nu = \nu_\alpha$ at production ($t = 0$):

$$|\nu(t)\rangle = e^{i(\mathbf{p}\cdot\mathbf{r} - E_1 t)} \left\{ \cos\theta|\nu_1\rangle + e^{-i(E_2 - E_1)t} \sin\theta|\nu_2\rangle \right\}$$

For $m << p$ $$E = \sqrt{p^2 + m^2} \approx p + \frac{m^2}{2p}$$ **(in vacuum!)**

$$\Rightarrow \quad E_2 - E_1 \approx \frac{m_2^{\,2} - m_1^{\,2}}{2p} \approx \frac{m_2^{\,2} - m_1^{\,2}}{2E} \equiv \frac{\Delta m^2}{2E}$$

Probability to detect ν_β at time t if $\nu(0) = \nu_\alpha$:

$$\mathcal{P}_{\alpha\beta}(t) = \left|\langle \nu_\beta | \nu(t) \rangle\right|^2 = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 t}{4E}\right)$$

$$\hbar = c = 1$$

$$\Delta m^2 \equiv m_2^{\,2} - m_1^{\,2}$$

Using units more familiar to experimentalists:

$$\mathcal{P}_{\alpha\beta}(L) = \sin^2(2\theta)\sin^2\left(1.267\,\Delta m^2 \frac{L}{E}\right)$$

$L = ct$ distance between neutrino source and detector

Units: Δm^2 [eV^2]; L [km]; E [GeV] (or L [m]; E [MeV])

NOTE: $\mathcal{P}_{\alpha\beta}$ depends on Δm^2 (not on m).

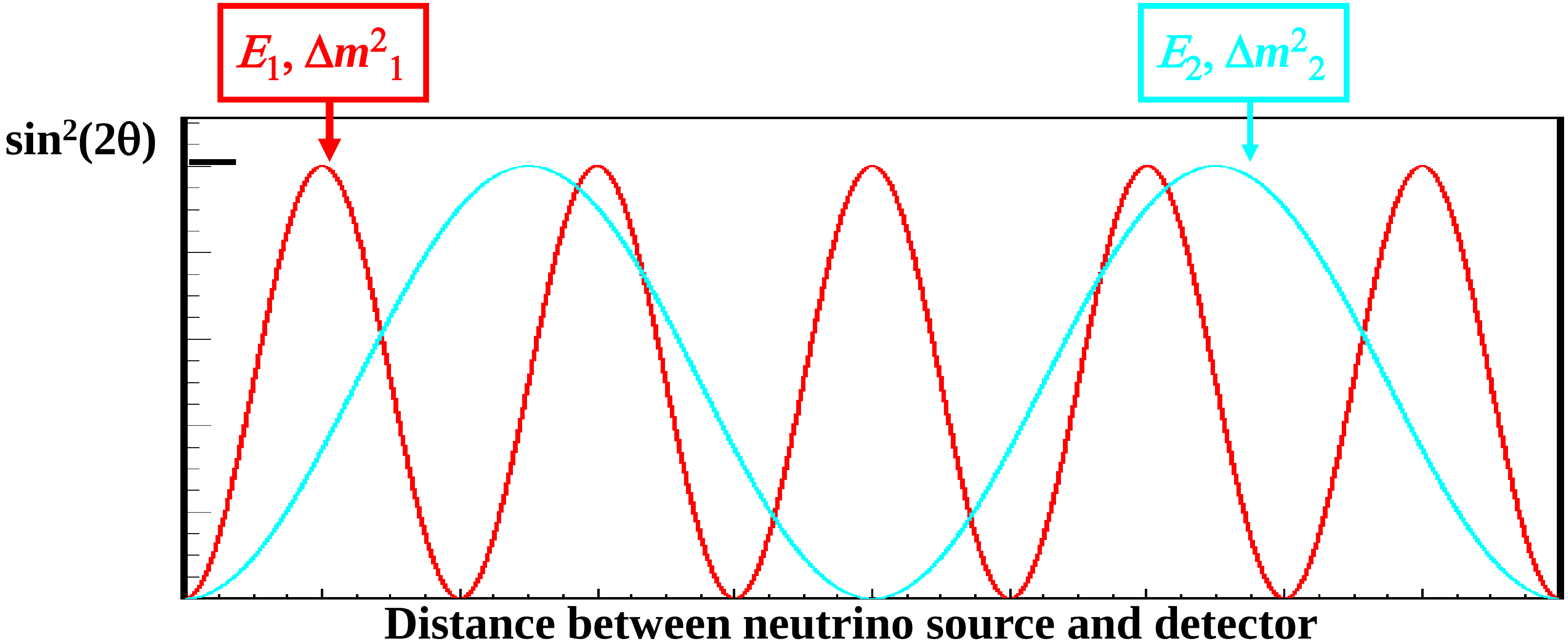
If $m_1 << m_2$, $\Delta m^2 \equiv m_2^{\,2} - m_1^{\,2} \approx m_2^{\,2}$

Definition of oscillation length λ:

$$\lambda = 2.48 \frac{E}{\Delta m^2}$$

Units: λ [km]; E [GeV]; Δm^2 [eV^2]
(or λ [m]; E [MeV])

$$\mathcal{P}_{\alpha\beta}(L) = \sin^2(2\theta)\sin^2\left(\pi\frac{L}{\lambda}\right)$$



$E_1 < E_2$ and/or $\Delta m^2_1 > \Delta m^2_2$

Disappearance experiments

Use ν_α source, measure ν_α flux at distance *L* from source

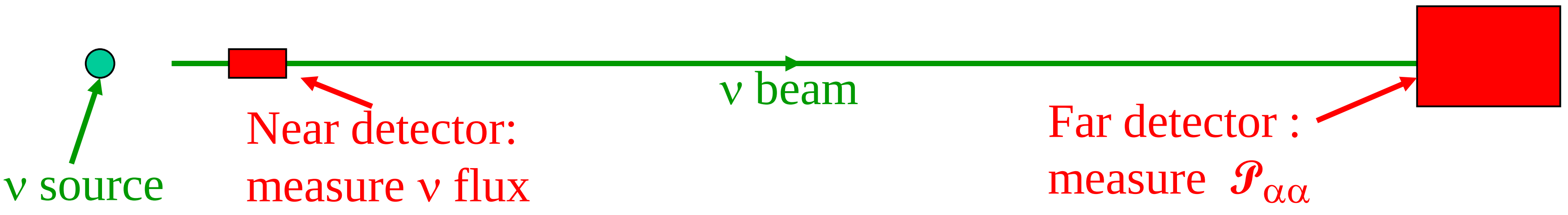
Disappearance probability $$\mathcal{P}_{\alpha\alpha} = 1 - \sum_{\beta \neq \alpha} \mathcal{P}_{\alpha\beta}$$

Examples:

- **Experiments using $\bar{\nu}_e$ from nuclear reactors**
  ($E_\nu \approx$ few MeV: under threshold for μ or τ production)

- **ν_μ detection at accelerators or in the cosmic radiation**
  (search for $\nu_\mu \Rightarrow \nu_\tau$ oscillations if E_ν lower than τ production threshold)

The main source of systematic uncertainties: knowledge of the neutrino flux in the absence of oscillations ⟹ use two detectors if possible



Appearance experiments

Neutrino source: ν_α . Detect ν_β $(\beta \neq \alpha)$ at distance *L* from source

Examples:

- **Detect $\nu_e + N \rightarrow e^- +$ hadrons in a ν_μ beam**
- **Detect $\nu_\tau + N \rightarrow \tau^- +$ hadrons in a ν_μ beam**
  (Threshold energy $\approx$ 3.5 GeV)

The ν_β contamination at source must be precisely known

(typically $\nu_e/\nu_\mu \approx 1\%$ in ν_μ beams from high-energy accelerators)

$\rightarrow$ a near detector is often very useful

Under the hypothesis of two – neutrino mixing:

- Observation of an oscillation signal → allowed parameter region in the [Δm^2 , $\sin^2(2\theta)$] plane consistent with the observed signal

- No evidence for oscillation → upper limit $\mathcal{P}_{\alpha\beta} < P$ → exclusion region

Very large $\Delta m^2 \rightarrow$ very short oscillation length λ
$\rightarrow$ average over source and detector dimensions:

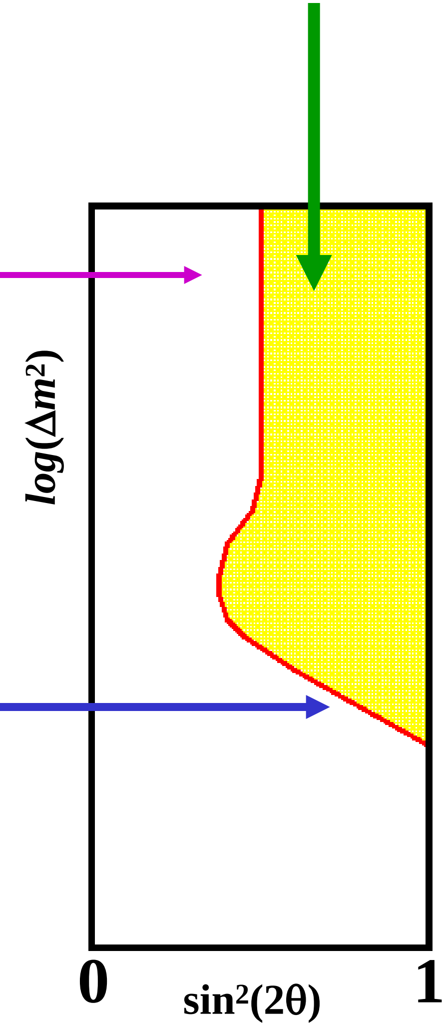
$$\mathcal{P}_{\alpha\beta}(L) = \sin^2(2\theta)\left\langle \sin^2(\pi \frac{L}{\lambda}) \right\rangle \approx \frac{1}{2}\sin^2(2\theta)$$

small $\Delta m^2 \rightarrow$ long λ : L<<λ $\rightarrow$ $\sin(\pi \frac{L}{\lambda}) \approx \pi \frac{L}{\lambda}$

$$\mathcal{P}_{\alpha\beta} < P \approx 1.6\left(\Delta m^2\right)^2 \sin^2(2\theta)\left(\frac{L}{E}\right)^2$$

(onset of the first oscillation)

$$\left(\lambda = 2.48 \frac{E}{\Delta m^2} \right)$$



Searches for neutrino oscillations: experimental parameters

ν source	Flavour	Distance L	Energy	Min. accessible Δm^2
Sun	ν_e	~1.5×10^8 km	0.2-15 MeV	~10^{-11} eV^2
Cosmic rays	ν_μ $\bar{\nu}_\mu$ ν_e $\bar{\nu}_e$	10 – 13000 km	0.2 – 100 GeV	~10^{-4} eV^2
Nuclear reactors	$\bar{\nu}_e$	20m – 250 km	$\langle E \rangle \approx 3$ MeV	~10^{-6} eV^2
Accelerators	ν_μ $\bar{\nu}_\mu$ ν_e $\bar{\nu}_e$	15m – 730 km	20 MeV – 100 GeV	~10^{-3} eV^2

EXPERIMENTAL EVIDENCE / HINTS FOR NEUTRINO OSCILLATIONS

- **Solar neutrino deficit: ν_e disappearance between Sun and Earth**
  Convincing experimental evidence
  Confirmation from a nuclear reactor experiment
  Measurement of the oscillation parameters

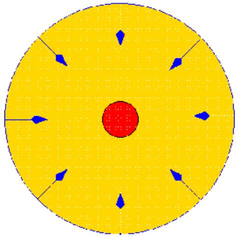
- **"Atmospheric" neutrino deficit: ν_μ , $\bar{\nu}_\mu$ disappearance in the cosmic radiation over distances of the order of the Earth diameter**
  Convincing experimental evidence
  Confirmation from long baseline accelerator experiments
  Measurement of the oscillation parameters

- **LSND experiment at Los Alamos (1996): $\bar{\nu}_e$ excess in a mixed ν_μ , $\bar{\nu}_\mu$, ν_e beam**
  To be confirmed – experimental results from the MiniBoone experiment at Fermilab (designed to verify LSND) unclear and confusing

Solar neutrinos

Birth of a star: gravitational contraction of a primordial gas cloud (mainly ~75% H_2, ~25% He) $\Rightarrow$ density, temperature increase in the star core $\Rightarrow$ NUCLEAR FUSION

Hydrostatic equilibrium between pressure and gravity



Final result from a chain of fusion reactions in the Sun core:

$$4p \rightarrow He^4 + 2e^+ + 2\nu_e$$

Average energy produced as electromagnetic energy in the Sun core:

$$Q = (4M_p - M_{He^4} + 2m_e)c^2 - \langle E(2\nu_e)\rangle \approx 26.1 \text{ MeV}$$

($2e^+ + 2e^- \rightarrow 4\gamma$)

($\langle E(2\nu_e)\rangle \approx 0.59$ MeV)

Solar luminosity: $\mathcal{L}_\odot = 3.846\text{x}10^{26}$ W $= 2.401\text{x}10^{39}$ MeV/s

Neutrino emission rate: $dN(\nu_e)/dt = 2\,\mathcal{L}_\odot/Q \approx 1.84\text{x}10^{38}\ s^{-1}$

Average neutrino flux on Earth: $\Phi(\nu_e) \approx 6.4\text{x}10^{10}\ cm^{-2}\ s^{-1}$

(average Sun – Earth distance = $1.496\text{x}10^{11}$ m)

STANDARD SOLAR MODEL (SSM)

(developed in 1960 and continuously updated by J.N. Bahcall and collaborators)

Assumptions:
- hydrostatic equilibrium
- energy production by nuclear fusion
- thermal equilibrium (power output = luminosity)
- energy transport inside the Sun by radiation

Input data:
- cross-sections for fusion reactions
- "opacity" (photon mean free path) as a function of distance from the Sun center

Method:
- choice of initial parameters
- evolution to present epoch ($t = 4.6 \times 10^9$ years)
- compare predicted and measured quantities
- modify initial parameters if necessary

TODAY'S SUN:

Luminosity $\mathcal{L}_\odot = 3.846 \times 10^{26}$ W

Radius $R_\odot = 6.96 \times 10^8$ m

Mass $M_\odot = 1.989 \times 10^{30}$ kg

Core temperature $T_c = 15.6 \times 10^6$ K

Surface temperature $T_s = 5773$ K

Hydrogen in Sun core = 34.1% (initially 71%)

Helium in Sun core = 63. 9% (initially 27.1%)

} as measured at the surface

Two reaction cycles

p – p cycle (0.985 $\mathcal{L}_\odot$)

85%

$$p + p \rightarrow e^+ + \nu_e + d \qquad p + p \rightarrow e^+ + \nu_e + d \quad \text{OR (0.4\%): } p + e^- + p \rightarrow \nu_e + d$$

$$p + d \rightarrow \gamma + He^3 \qquad p + d \rightarrow \gamma + He^3$$

$$He^3 + He^3 \rightarrow He^4 + p + p \quad \text{OR } (\sim 2\times10^{-5})\text{: } He^3 + p \rightarrow He^4 + e^+ + \nu_e$$

15%

$$p + p \rightarrow e^+ + \nu_e + d$$

$$p + d \rightarrow \gamma + He^3$$

$$He^3 + He^4 \rightarrow \gamma + Be^7$$

$$e^- + Be^7 \rightarrow \nu_e + Li^7$$

$$p + Li^7 \rightarrow He^4 + He^4$$

OR (0.13%)

$$p + Be^7 \rightarrow \gamma + B^8$$

$$B^8 \rightarrow Be^8 + e^+ + \nu_e$$

$$Be^8 \rightarrow He^4 + He^4$$

CNO cycle (two branches)

$$p + N^{15} \rightarrow C^{12} + He^4 \qquad p + N^{15} \rightarrow \gamma + O^{16}$$

$$p + C^{12} \rightarrow \gamma + N^{13} \qquad p + O^{16} \rightarrow \gamma + F^{17}$$

$$N^{13} \rightarrow C^{13} + e^+ + \nu_e \qquad F^{17} \rightarrow O^{17} + e^+ + \nu_e$$

$$p + C^{13} \rightarrow \gamma + N^{14} \qquad p + O^{17} \rightarrow N^{14} + He^4$$

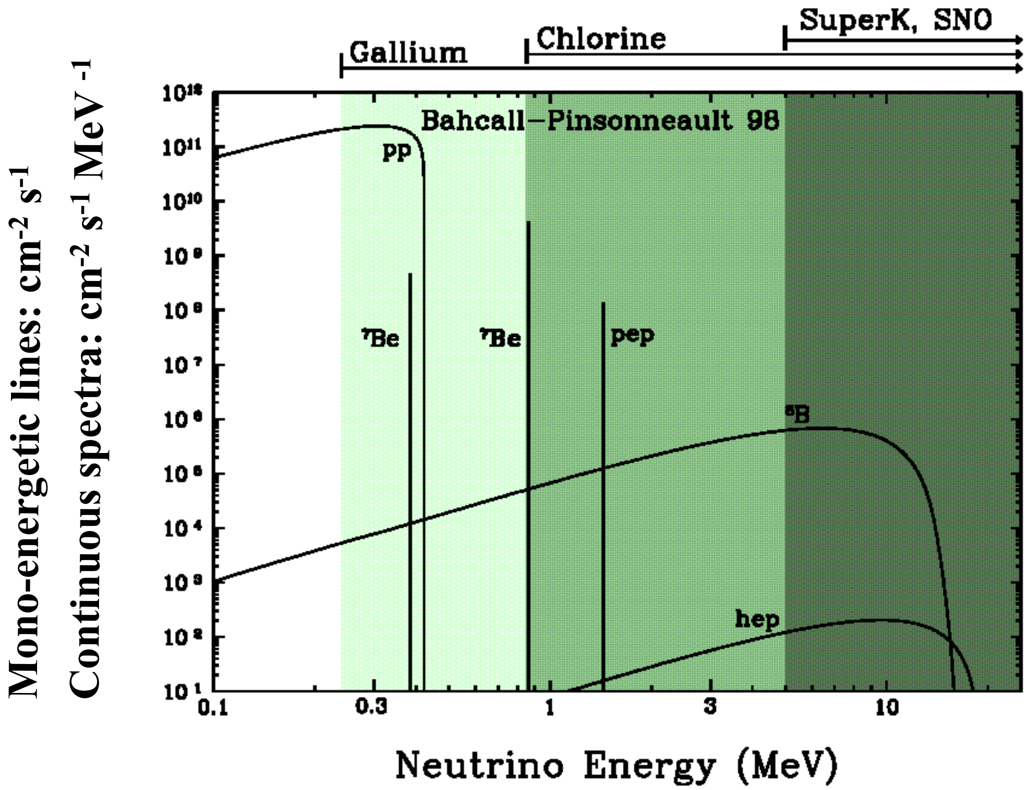
$$p + N^{14} \rightarrow \gamma + O^{15}$$

$$O^{15} \rightarrow N^{15} + e^+ + \nu_e$$

NOTE #1: for both cycles $4p \rightarrow He^4 + 2e^+ + 2\nu_e$

NOTE #2: source of today's solar luminosity: fusion reactions occurring In the Sun core ~ 10^6 years ago (the Sun is a "main sequence star, practically stable over ~10^8 years).

Predicted solar neutrino flux and energy spectrum on Earth (p – p cycle)



Notations

pp : $p + p \rightarrow e^+ + \nu_e + d$

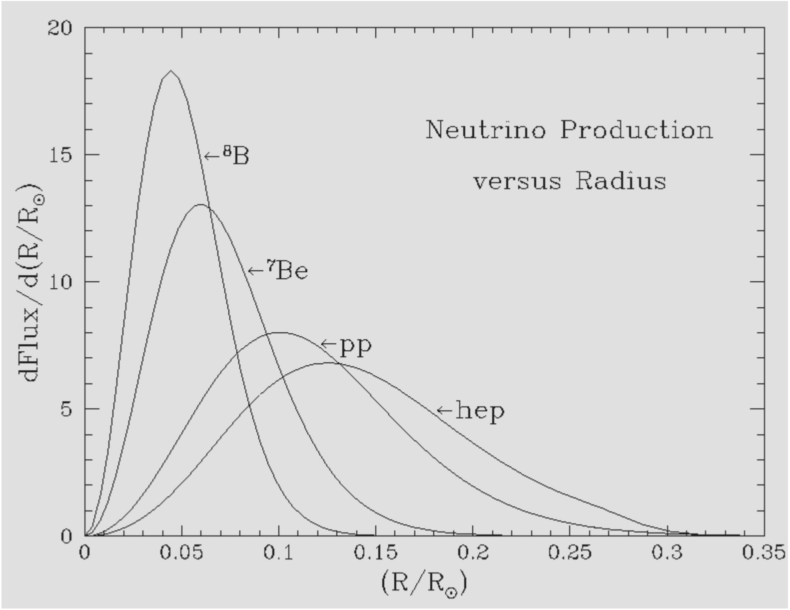
^{7}Be : $e^- + Be^7 \rightarrow \nu_e + Li^7$

pep : $p + e^- + p \rightarrow \nu_e + d$

^{8}B : $B^8 \rightarrow Be^8 + e^+ + \nu_e$

hep : $He^3 + p \rightarrow He^4 + e^+ + \nu_e$

Predicted radial distribution of ν_e production in the Sun core



The Homestake experiment (1970–1998): first detection of solar neutrinos

A radiochemical experiment (R. Davis, University of Pennsylvania)

$\nu_e + Cl^{37} \rightarrow e^- + Ar^{37}$ **Energy threshold $E(\nu_e) = 0.814$ MeV**

Detector: 390 m^3 C_2Cl_4 (perchloroethylene) in a tank installed in the Homestake gold mine (South Dakota, U.S.A.) under 4100 m water equivalent (m w.e.)

(fraction of Cl^{37} in natural Chlorine = 24%)

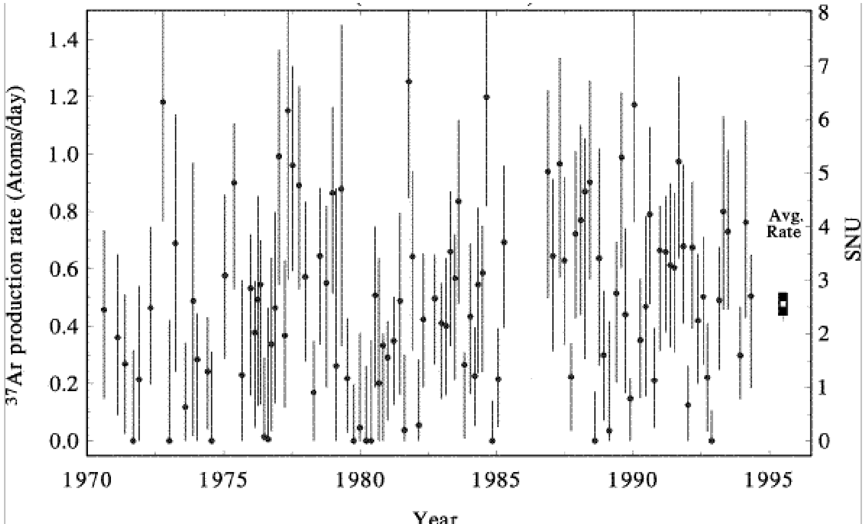
Expected production rate of Ar^{37} atoms ≈ 1.5 per day

Experimental method: every few months extract Ar^{37} by N_2 flow through tank, purify, mix with natural Argon, fill a small proportional counter, detect radioactive decay of Ar^{37}: $e^- + Ar^{37} \rightarrow \nu_e + Cl^{37}$ (half-life $\tau_{1/2} = 34$ d)

(Final state excited Cl^{37} atom emits Augier electrons and/or X-rays)

Check efficiencies by injecting known quantities of Ar^{37} into tank

Results over more than 20 years of data taking



SNU (Solar Neutrino Units): the unit to measure event rates in radiochemical experiments:

1 SNU = 1 event s^{-1} per 10^{36} target atoms

Average of all measurements:

$R(Cl^{37}) = 2.56 \pm 0.16 \pm 0.16$ SNU

(stat) (syst)

SSM prediction: $7.6^{+1.3}_{-1.1}$ SNU

Solar Neutrino Deficit

"Real time" experiments with water Čerenkov counters

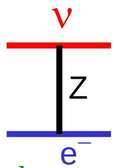
Neutrino – electron elastic scattering: $\nu + e^- \rightarrow \nu + e^-$

Detect Čerenkov light emitted by electrons in water

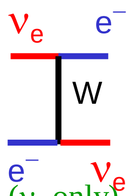
Energy threshold ~5 MeV (5 MeV electron residual range in $H_2O \approx 2$ cm)

Cross-sections: $\sigma(\nu_e) \approx 6\,\sigma(\nu_\mu) \approx 6\,\sigma(\nu_\tau)$

W , Z exchange | Z exchange only



(all three ν types)



(ν_e only)

Two experiments:

Kamiokande (1987 – 94)

Fiducial volume: 680 m^3 H_2O

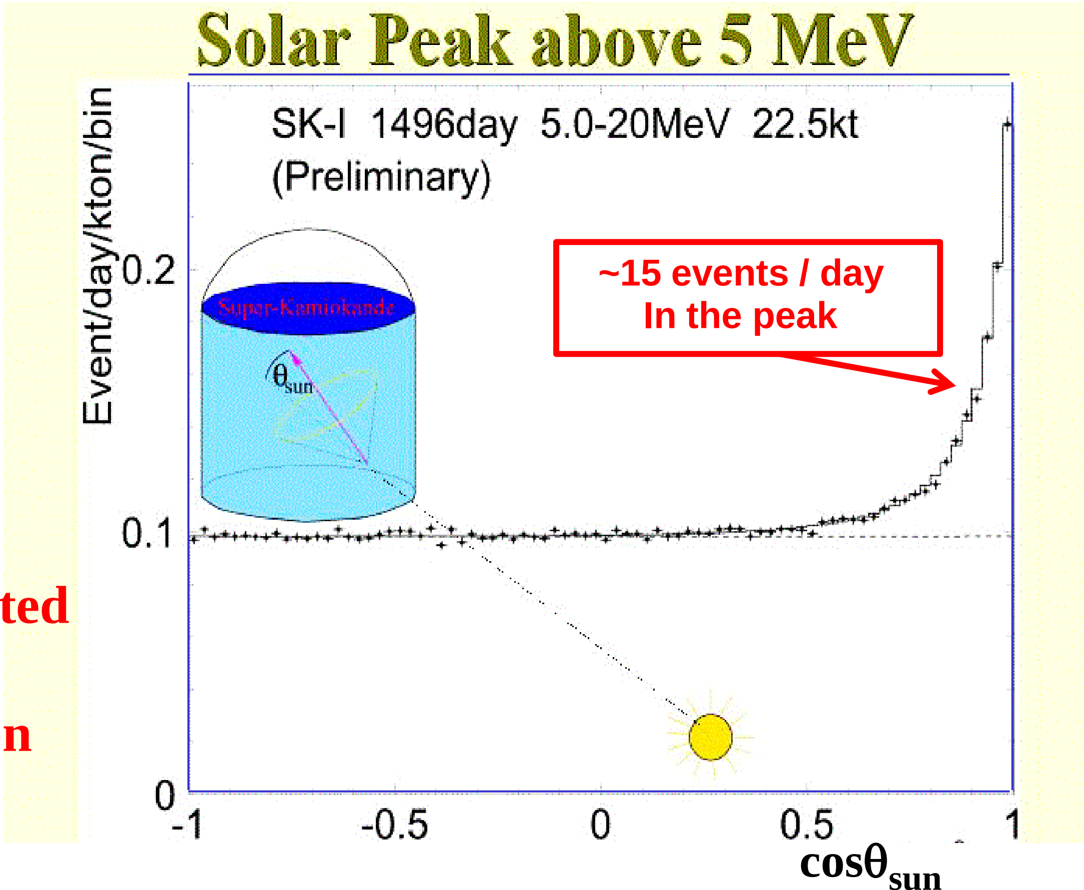
Super-Kamiokande (1996 –)

Fiducial volume: 22500 m^3 H_2O

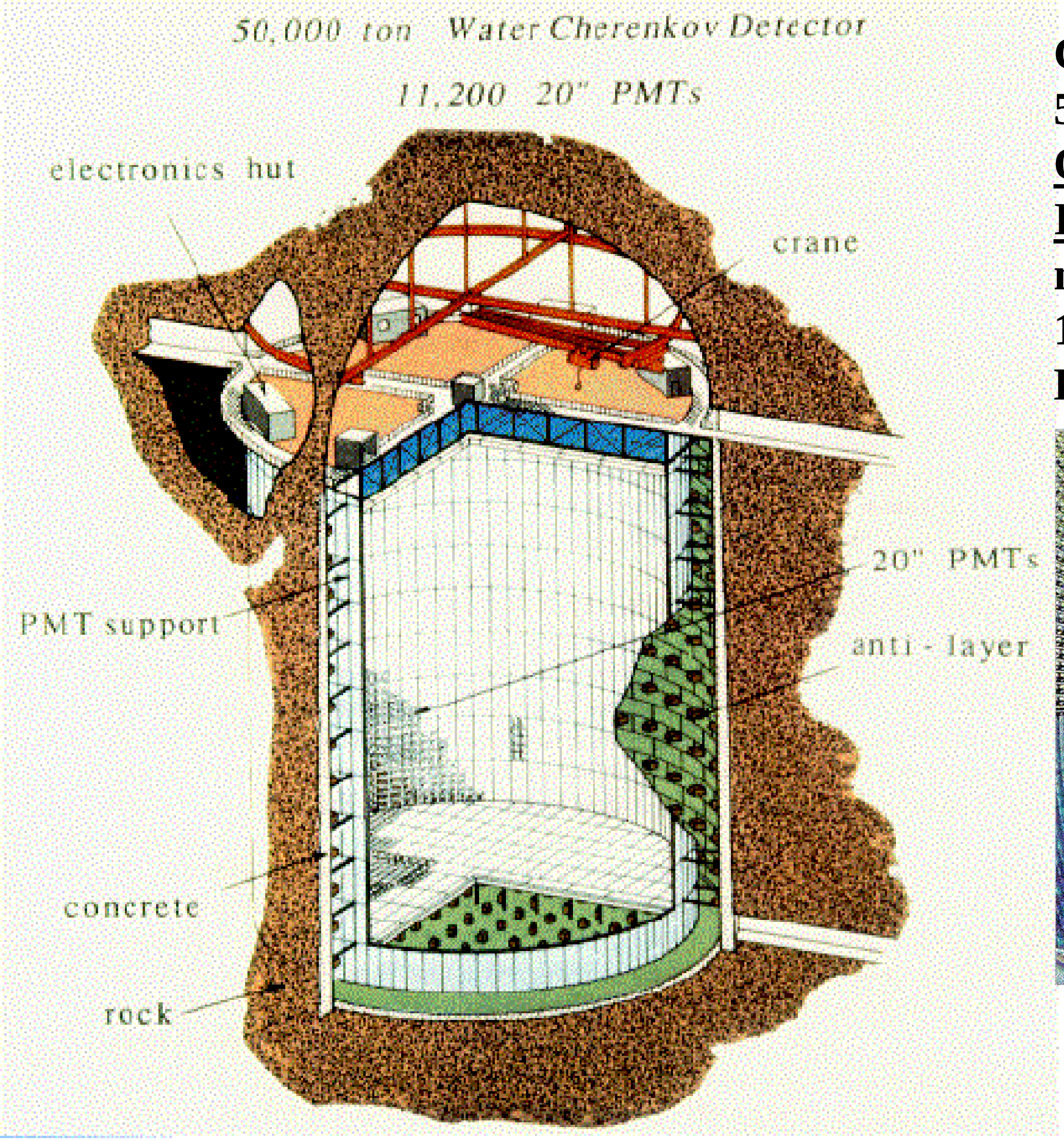
in theKamioka mine (Japan)

Depth 2670 m H_2O eq.

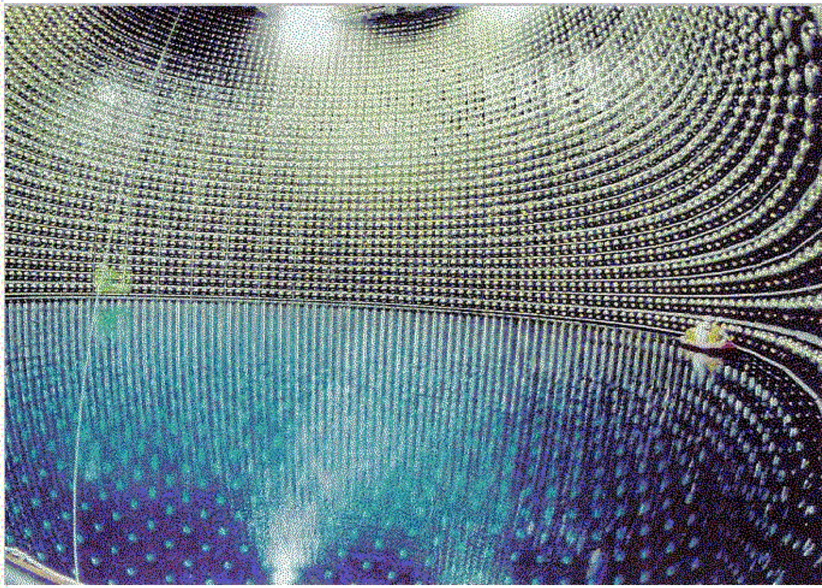
The signal solar origin is demonstrated by the angular correlation between the directions of the detected electron and the incident neutrino



Super-Kamiokande detector

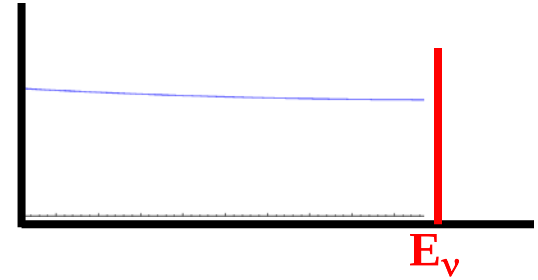


Cylinder, height=41.4 m, diam.=39.3 m
50 000 tons of pure water
Outer volume (veto) ~2.7 m thick
Inner volume: ~ 32000 tons (fiducial mass 22500 tons)
11200 photomultipliers, diam.= 50 cm
Light collection efficiency ~40%

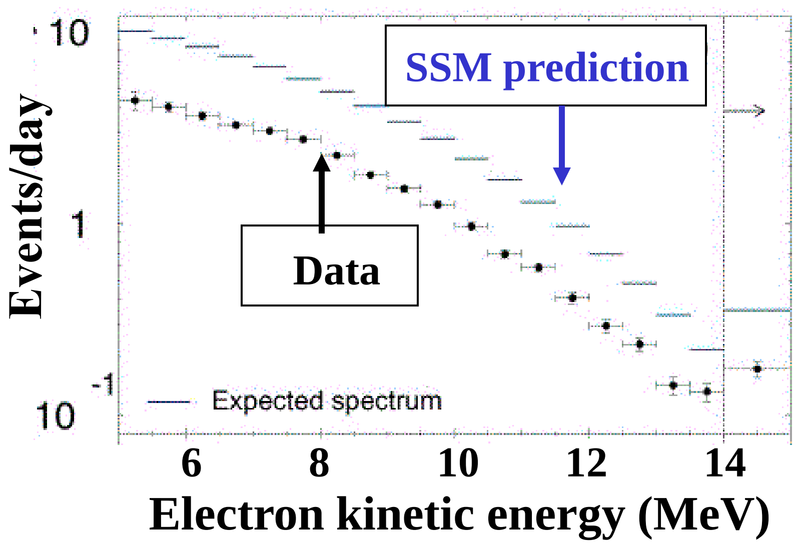


Inner volume while filling

Recoil electron kinetic energy distribution from ν_e – e elastic scattering of mono-energetic neutrinos is almost flat between 0 and $2E_\nu/(2 + m_e/E_\nu)$



→ convolute with predicted spectrum to obtain SSM prediction for electron energy distribution



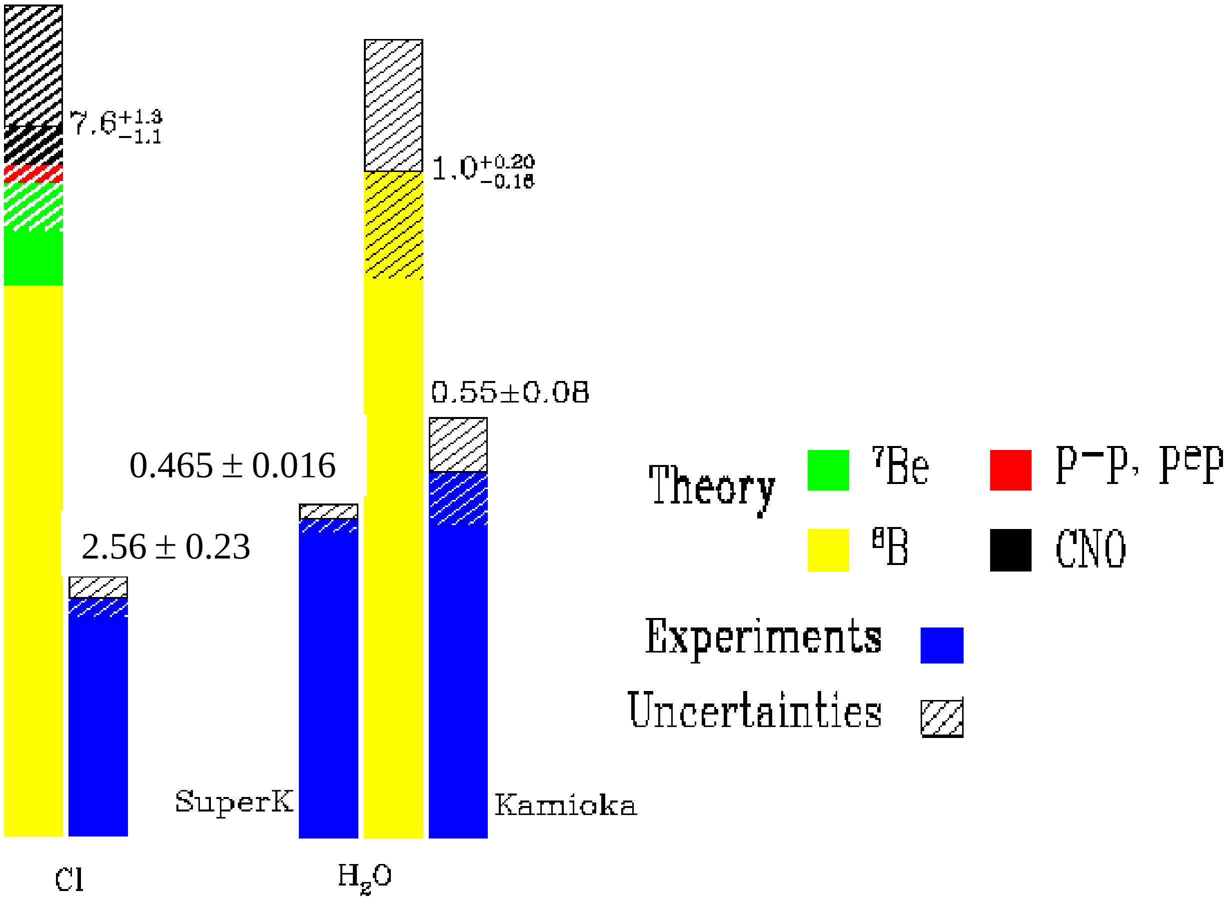
<u>Results from 22400 events (1496 days of data taking)</u>

Measured neutrino flux (assuming all ν_e): $\Phi(\nu_e) = (2.35 \pm 0.02_{(stat)} \pm 0.08_{(syst)}) \times 10^6\ cm^{-2}\ s^{-1}$

SSM prediction: $\Phi(\nu_e) = (5.05\ ^{+1.01}_{-0.81}) \times 10^6\ cm^{-2}\ s^{-1}$

Data/SSM = $0.465 \pm 0.005_{(stat)}\ ^{+0.093}_{-0.074}$ (including theoretical error) ← **ν_e DEFICIT**

Comparison of Homestake and Kamioka results with SSM predictions



Homestake and Kamioka results were known since the late 1980's.
However, the solar neutrino deficit was not taken seriously at that time.
Why?

The two main solar ν_e sources in the Homestake and water experiments:

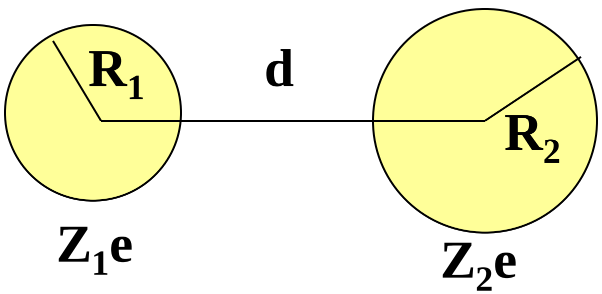
$He^3 + He^4 \rightarrow \gamma + Be^7$

$p + Be^7 \rightarrow \gamma + B^8$

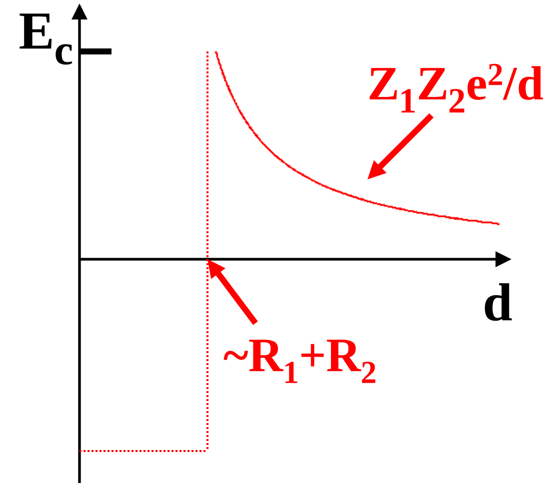
$e^- + Be^7 \rightarrow \nu_e + Li^7$ (Homestake)

$B^8 \rightarrow Be^8 + e^+ + \nu_e$ (Homestake, Kamiokande, Super-K)

Fusion reactions strongly suppressed by Coulomb repulsion



Potential energy:



$$E_c = \frac{Z_1 Z_2 e^2}{R_1 + R_2} = \frac{e^2}{\hbar c}\frac{\hbar c Z_1 Z_2}{R_1 + R_2} \approx \frac{197 \text{ MeV fm}}{137}\frac{Z_1 Z_2}{R_1 + R_2 \text{ fm}} \text{ MeV}$$

$E_c \approx 1.4$ MeV for $Z_1Z_2 = 4$, $R_1+R_2 = 4$ fm

Average thermal energy in the Sun core $<E> = 1.5\, k_BT_c \approx 0.002$ MeV (T_c=15.6 MK)

k_B (Boltzmann constant) = 8.6 x 10^{-5} eV/deg.K

Nuclear fusion in the Sun core occurs by tunnel effect and depends strongly on T_c

Nuclear fusion cross-section at very low energies

$$\sigma(E) = \frac{1}{E} e^{-2\pi\eta} \mathcal{S}(E)$$

Tunnel effect: $\eta = \frac{Z_1 Z_2 e^2}{\hbar v}$

v = relative velocity

Nuclear physics term difficult to calculate measured at energies ~0.1– 0.5 MeV and assumed to be energy independent

Predicted dependence of the ν_e fluxes on T_c:

From $e^- + Be^7 \rightarrow \nu_e + Li^7$: $\Phi(\nu_e) \propto T_c^{8}$

From $B^8 \rightarrow Be^8 + e^+ + \nu_e$: $\Phi(\nu_e) \propto T_c^{18}$

$\Phi \propto T_c^{N}$ ⟶ $\Delta\Phi/\Phi = N\, \Delta T_c/T_c$

How precisely do we know the temperature T of the Sun core?

Search for ν_e from $p + p \rightarrow e^+ + \nu_e + d$ (the main component of the solar neutrino spectrum, constrained by the Sun luminosity)

➡ **very little theoretical uncertainties**

Gallium experiments: radiochemical experiments to search for

$$\nu_e + Ga^{71} \rightarrow e^- + Ge^{71}$$

Energy threshold $E(\nu_e) > 0.233$ MeV ➡ reaction sensitive to solar neutrinos from $p + p \rightarrow e^+ + \nu_e + d$ (the dominant component)

Three experiments:

- **GALLEX (Gallium Experiment, 1991 – 1997)**
- **GNO (Gallium Neutrino Observatory, 1998 –)**

} In the Gran Sasso National Lab 150 km east of Rome Depth 3740 m w.e.

- **SAGE (Soviet-American Gallium Experiment)**

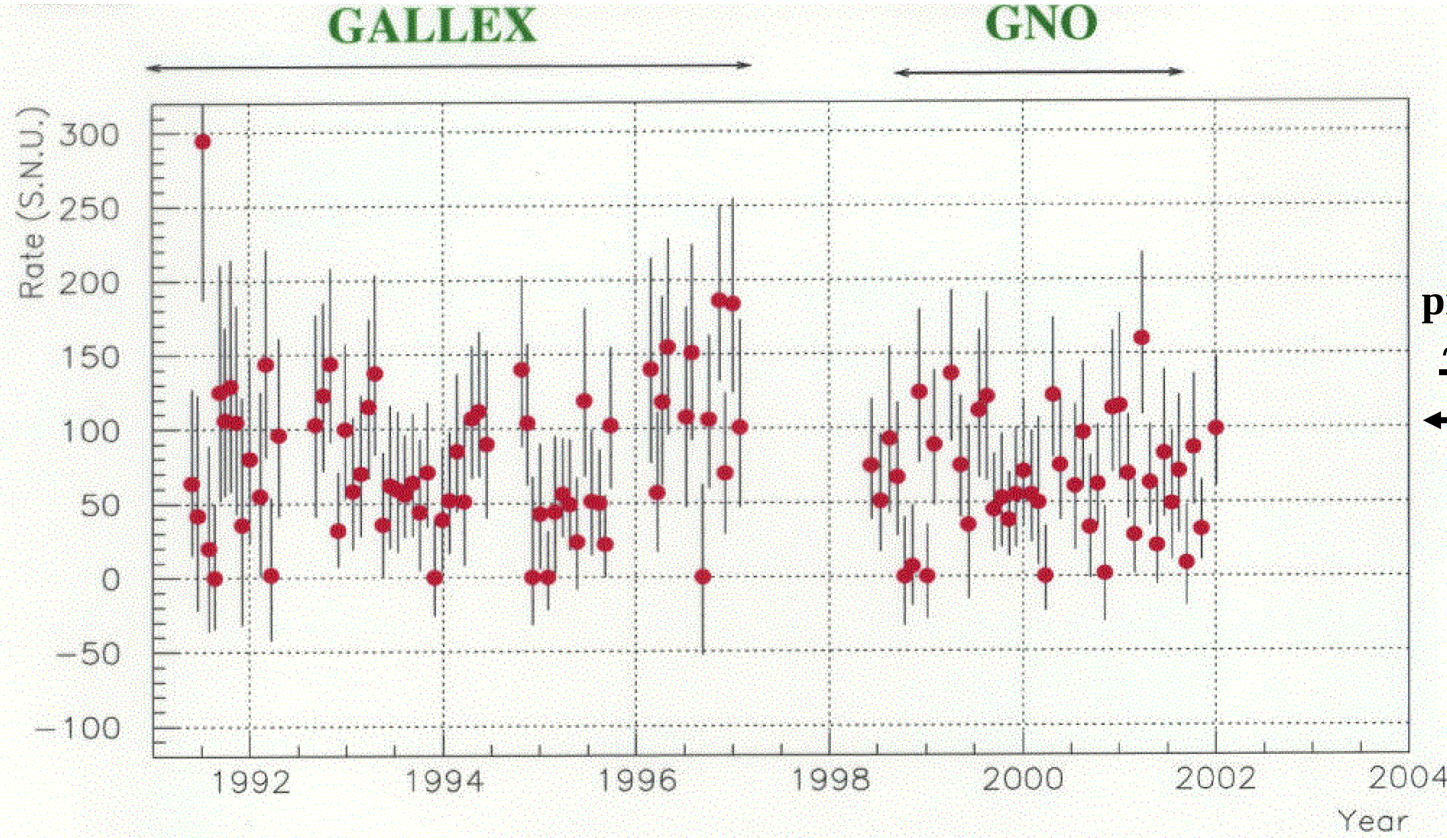
In the Baksan Lab (Russia) under the Caucasus. Depth 4640 m w.e.

Target: 30.3 tons of Gallium in HCl solution (GALLEX, GNO)
50 tons of metallic Gallium (liquid at 40°C) (SAGE)

Experimental method: every few weeks extract Ge^{71} in the form of $GeCl_4$ (a highly volatile substance), convert chemically to gas GeH_4, inject gas into a proportional counter, detect radioactive decay of Ge^{71}: $e^- + Ge^{71} \rightarrow \nu_e + Ga^{71}$ (half-life $\tau_{1/2} = 11.43$ d)
(Final state excited Ga^{71} atom emits X-rays: detect K and L atomic transitions)

Check of detection efficiency:

- **Introduce a known quantity of As^{71} in the tank (decaying to Ge^{71}: $e^- + As^{71} \rightarrow \nu_e + Ge^{71}$)**
- **Install an intense radioactive source producing mono-energetic ν_e near the tank: $e^- + Cr^{51} \rightarrow \nu_e + V^{51}$ (prepared in a nuclear reactor, initial activity 1.5 MCurie equivalent to 5 times the solar neutrino flux), $E(\nu_e) = 0.750$ MeV, half-life $\tau_{1/2} = 28$ d**



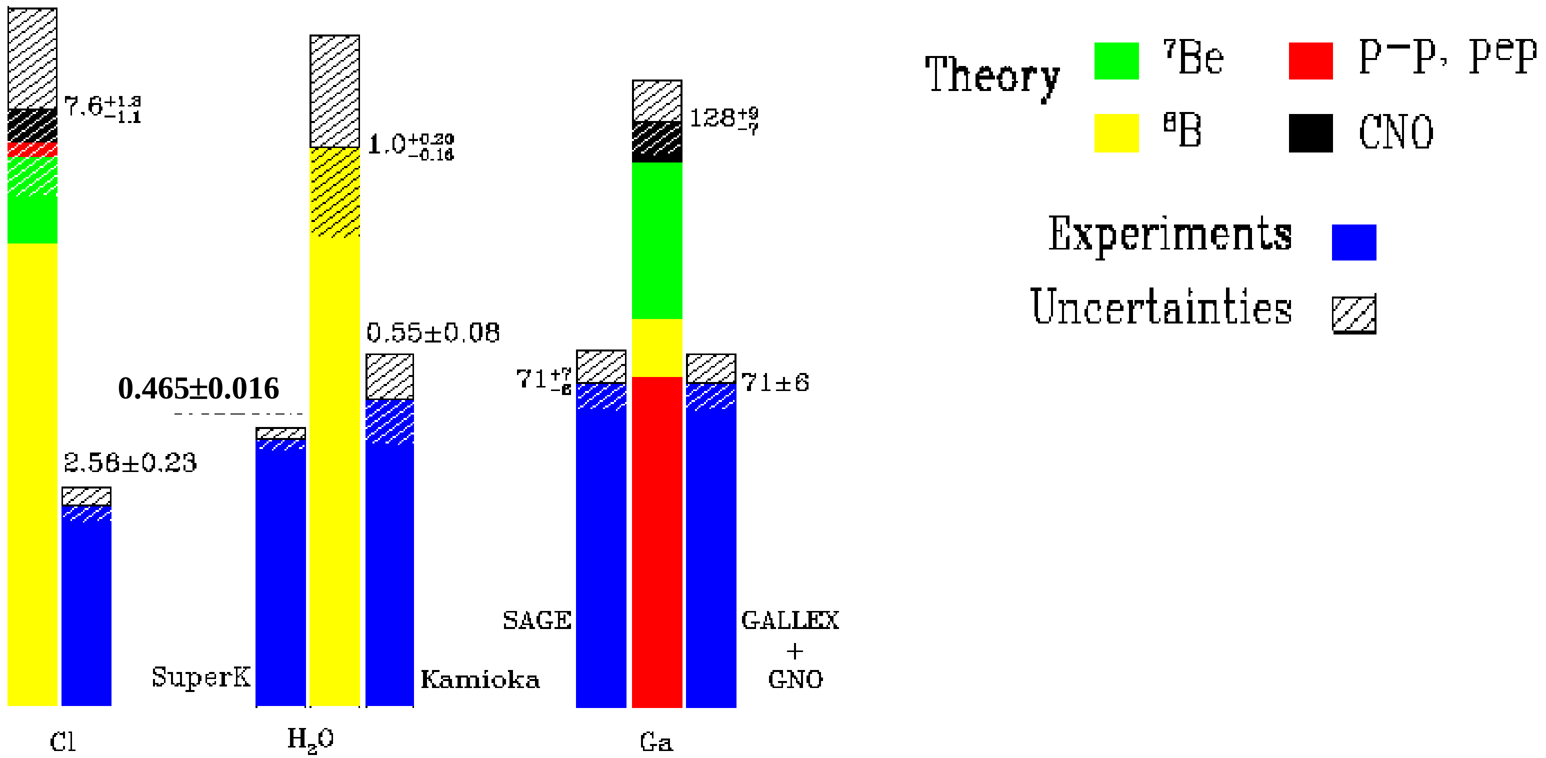
Ge^{71} production rate ~1 atom/day

GALLEX	**65 SR**	**77.5 +– 6.2 (stat) +– 4.5 (sys) SNU**
GNO	**43 SR**	**65.2 +– 6.4 (stat) +– 3.0 (sys) SNU**
GNO+GALLEX	**108 SR**	**70.8 +– 4.5 (stat) +– 3.8 (sys) SNU**

SAGE (1990 – 2001) $70.8^{+6.5}_{-6.1}$ **SNU**

SSM PREDICTION: 128^{+9}_{-7} **SNU**

Data/SSM = 0.56 ± 0.05

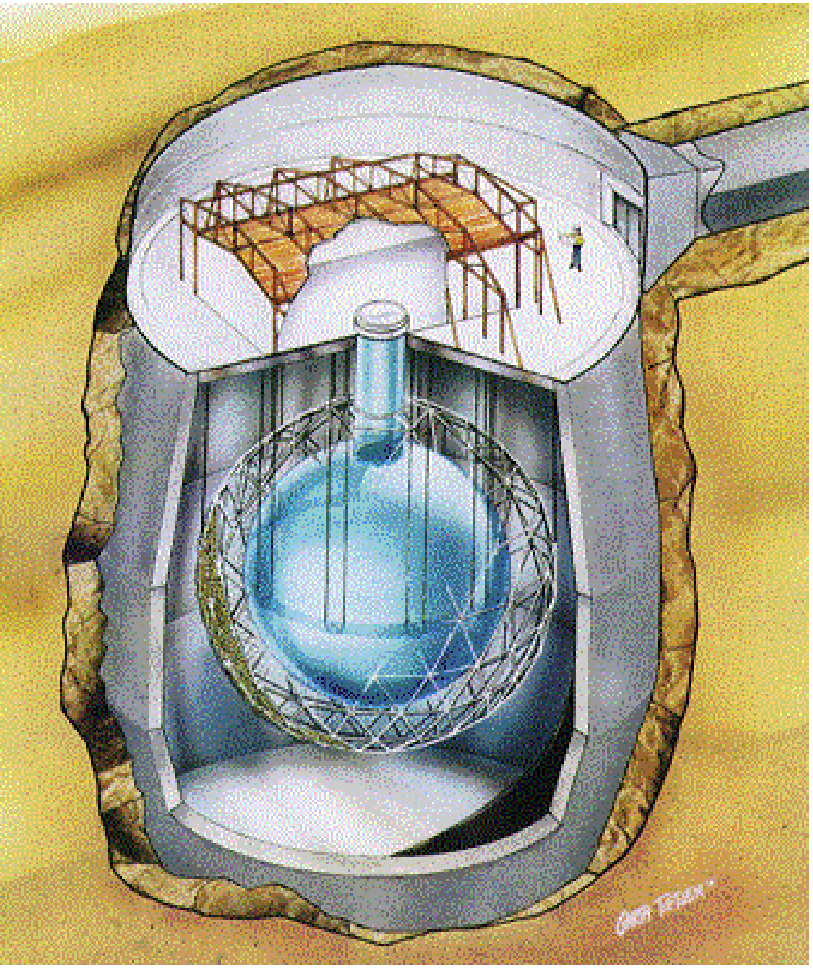


7.6 +1.3 −1.1
2.56±0.23
Cl
0.465±0.016
SuperK
1.0 +0.20 −0.16
0.55±0.08
Kamioka
H2O
128 +9 −7
71 +7 −6
SAGE
71±6
GALLEX
+
GNO
Ga
Theory
7Be
P−P, PeP
8B
CNO
Experiments
Uncertainties

SNO

Concluding evidence for solar neutrino oscillations

(Sudbury Neutrino Observatory, Sudbury, Ontario, Canada)



SNO: detector of Čerenkov light produced in 1000 tons of ultra-pure heavy water D_2O contained in an acrylic sphere (diam. 12 m), surrounded by 7800 tons of ultra-pure water H_2O

Light collection: 9456 photomultipler tubes, diam. 20 cm, on a spherical surface of 9.5 m radius

Depth: 2070 m (6010 m H_2O eq.) in a Nickel mine

Detection energy threshold: 5.5 MeV
(reduced to 3.5 MeV in a recent analysis)

Reconstruct the event position
from the measurement of the photomultiplier signal relative timings

Solar neutrino detection in the SNO experiment

(ES) **Neutrino – electron elastic scattering :** $\nu + e^- \rightarrow \nu + e^-$

Directional, $\sigma(\nu_e) \approx 6\,\sigma(\nu_\mu) \approx 6\,\sigma(\nu_\tau)$ (as in Super-K)

(CC) $\nu_e + d \rightarrow e^- + p + p$

Electron angular distribution $\propto 1 - \frac{1}{3}\cos(\theta_{sun})$

Measurement of the ν_e energy (most of the ν_e energy is transferred to the electron)

(NC) $\nu + d \rightarrow \nu + p + n$

Identical cross-section for all three neutrino flavours

$\Rightarrow$ measurement of the total neutrino flux from $B^8 \rightarrow Be^8 + e^+ + \nu$ independent of oscillations

DETECTION OF $\nu + d \rightarrow \nu + p + n$

Detect neutron capture after “thermalization”

- **Phase I (November 1999 – May 2001):**

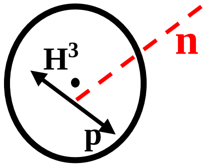
  $n + d \rightarrow H^3 + \gamma$ (E_γ= 6. 25 MeV, σ = 5x10^{-4} b); $\gamma \rightarrow$ Compton electron, e^+e^- pair

- **Phase II (July 2001 – September 2003): add 2 tons of ultra-pure *NaCl* to D_2O**

  $n + Cl^{35} \rightarrow Cl^{36}$ + several γ's ($\langle N_\gamma \rangle \approx 2.5$, $\Sigma E_\gamma \approx 8.6$ MeV, $\sigma = 44$ b)

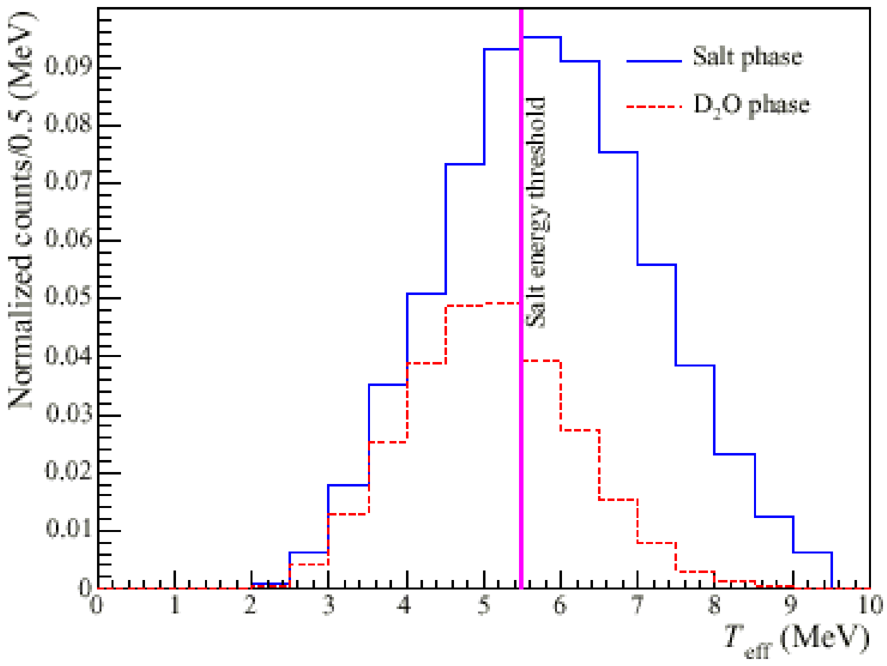
- **Phase III (November 2004 – November 2006: insert in the D_2O volume an array of cylindrical proportional counters (diameter 5 cm) filled with He^3**

  $n + He^3 \rightarrow p + H^3$ (0.764 MeV mono-energetic signal, σ = 5330 b)



Neutron detection efficiency in Phase I and II

Efficiency measurement using a Cf ^{252} neutron source
(spontaneous fission, $\tau_{1/2}$ = 2.6 years)
Average over a spherical volume of radius R = 550 cm
(50 cm from the edge of the D_2O sphere)



Detection efficiency for neutrons from $\nu + d \rightarrow \nu + p + n = 0.407 \pm 0.005^{+0.009}_{-0.008}$

Efficiency without *NaCl* ≈ 0.14

An additional advantage of Phase II with respect to Phase I

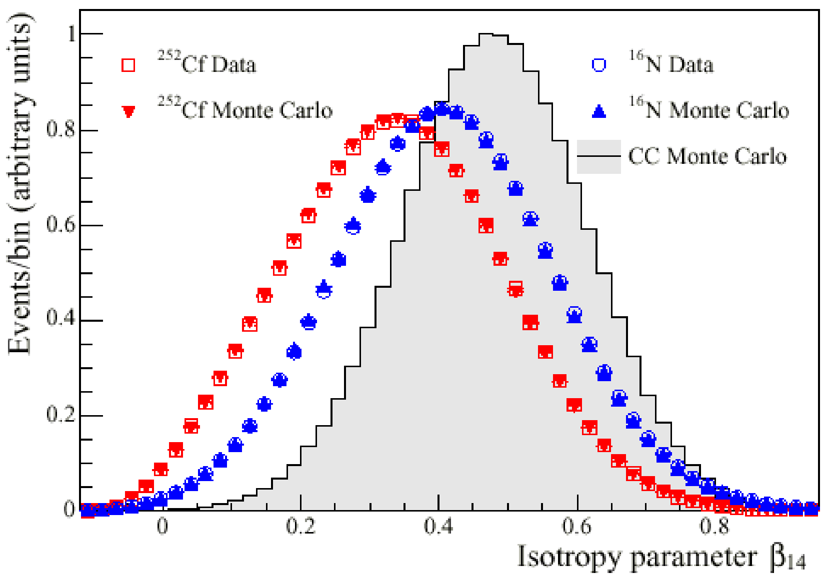
n + *Cl* ^{35} → *Cl* ^{36} + several γ' s (on average, $N_\gamma = 2.5$)

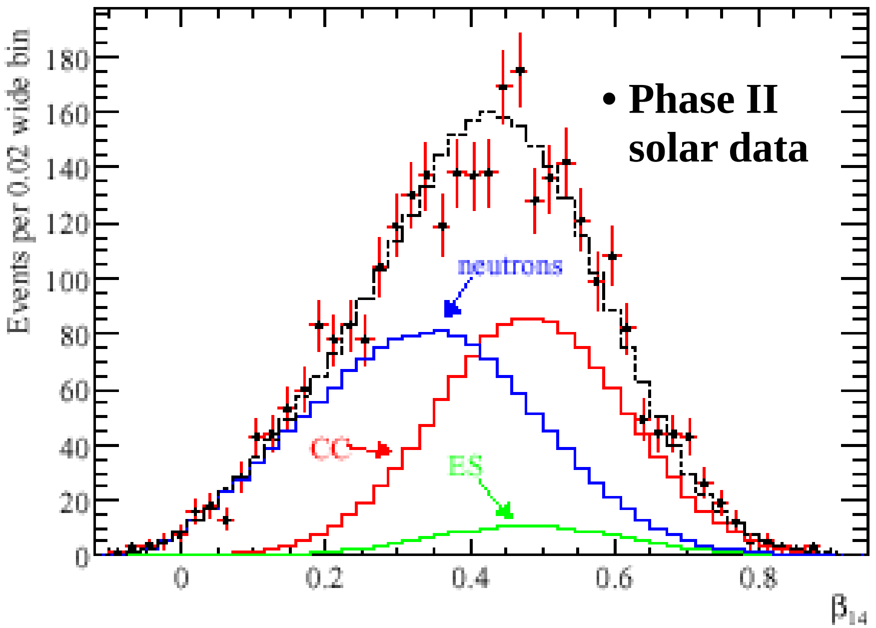
The Čerenkov light is more isotropic with respect to the CC and ES reactions which have only one electron in the final state

To measure the isotropy of the light emitted in each event define an an "isotropy parameter" β_{14} using the space distribution of photomultiplier hits

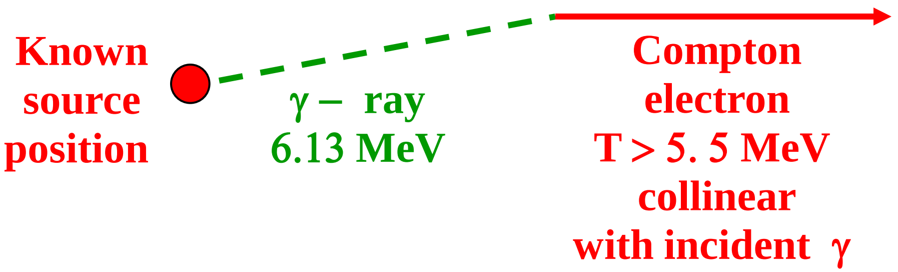
^{252}Cf: neutron source (neutron energy: few MeV)

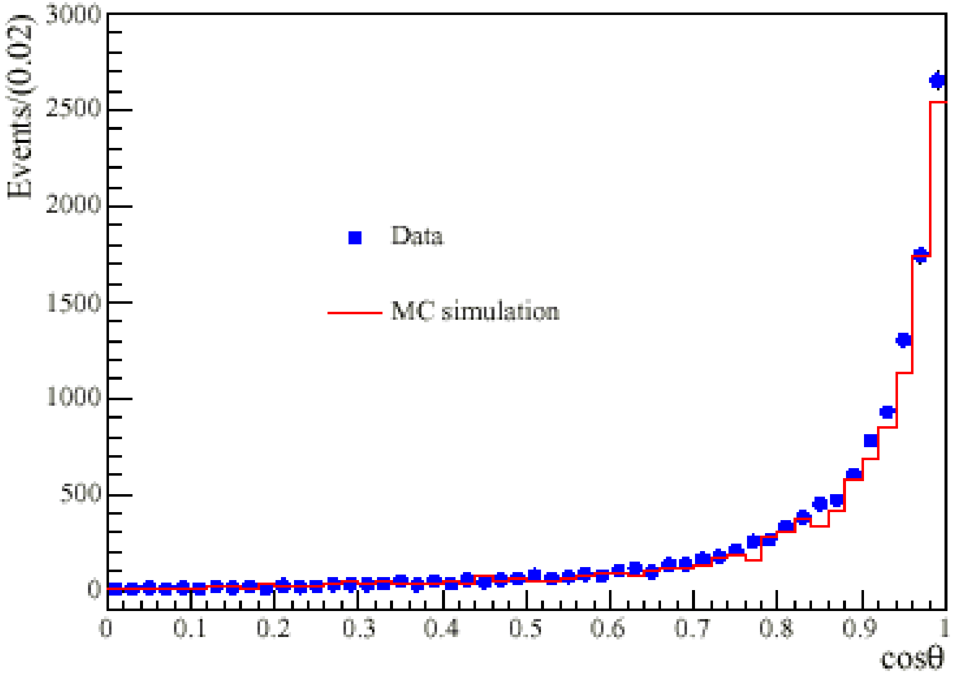
^{16}N: γ – ray source (6.13 MeV) → Compton electron, collinear e^+e^- pair



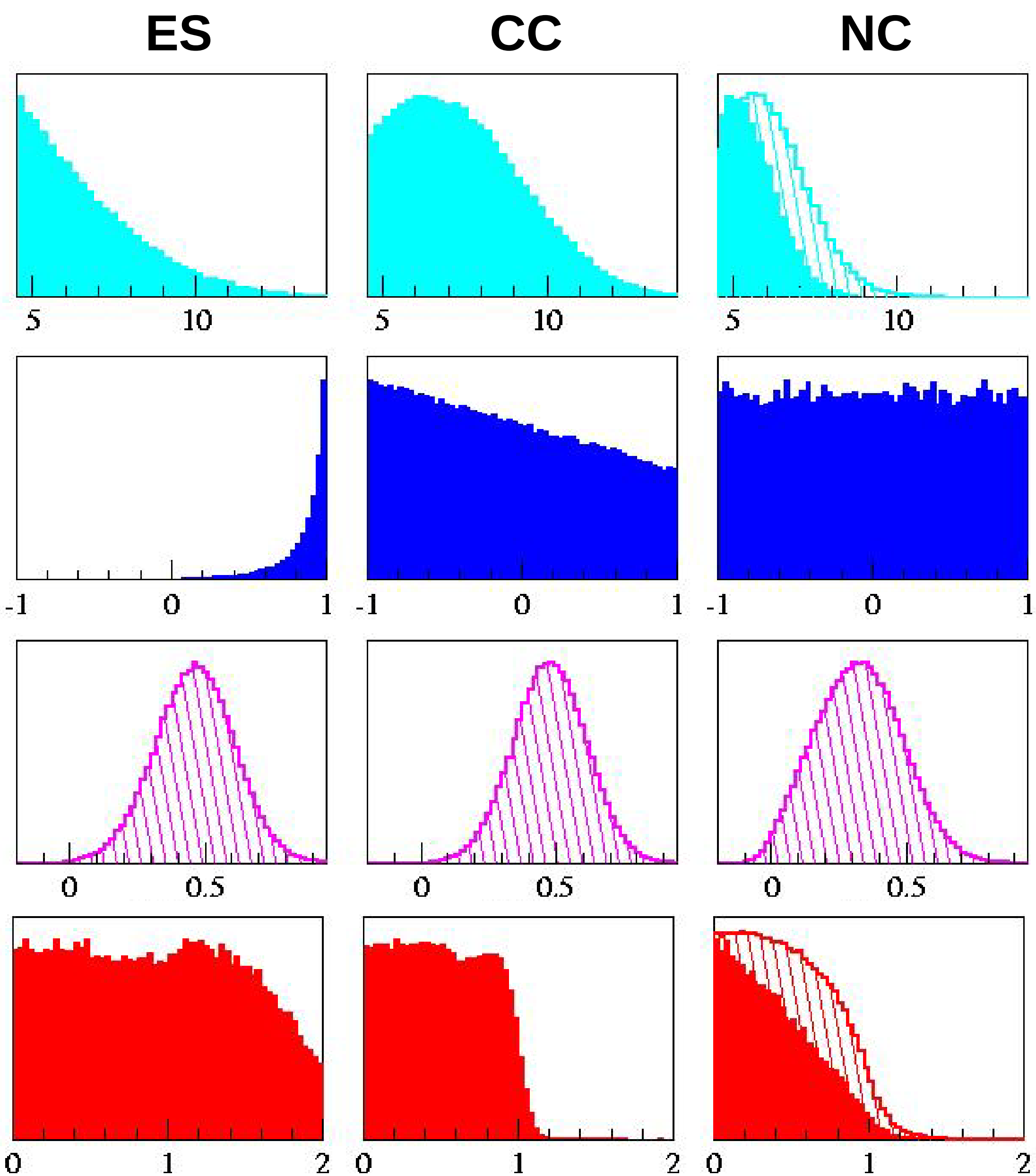


Direct measurement of the electron angular resolution using the ^{16}N γ – ray source





Use four independent variables to separate the three reactions



(Hatched histograms correspond to Phase II)

T_{eff}
Energy distribution
(from signal amplitude)

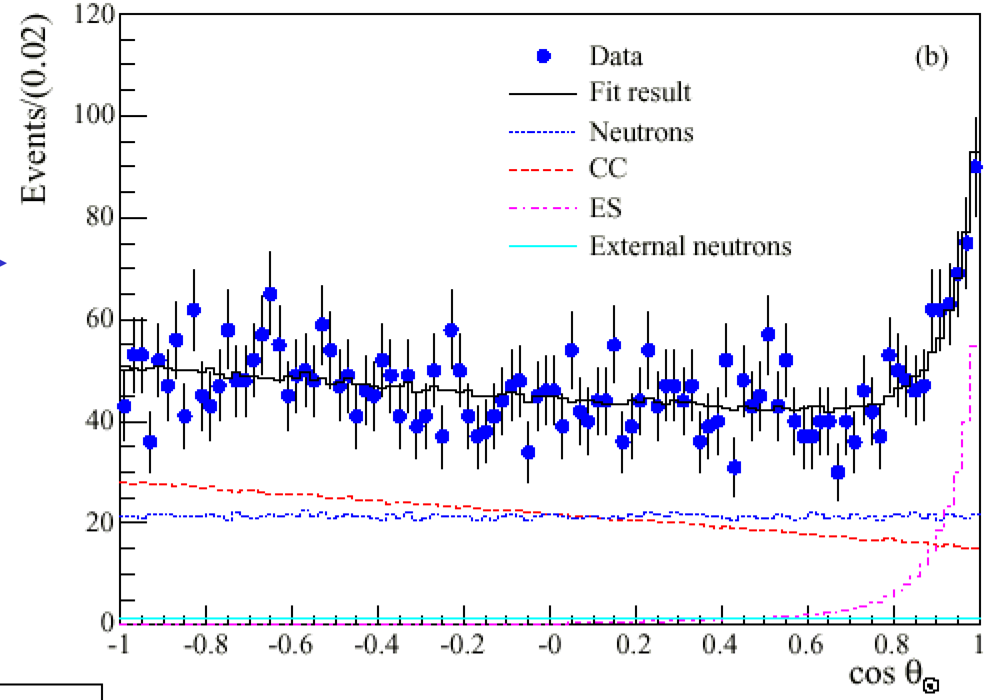
$\mathbf{Cos\theta_{sun}}$
Directionality

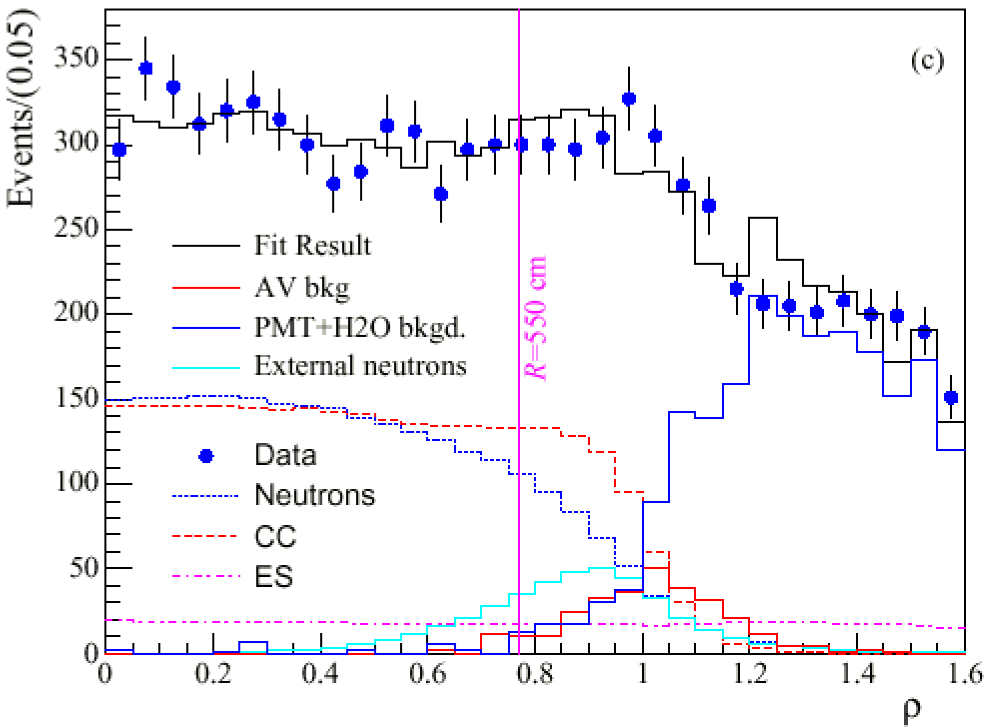
β_{14}
Isotropy parameter

$\rho = (R/R_0)^3$
Event radial position
R_0 = 600.5 cm
radius of the D_2O sphere

DATA

cos θ_{sun} distribution



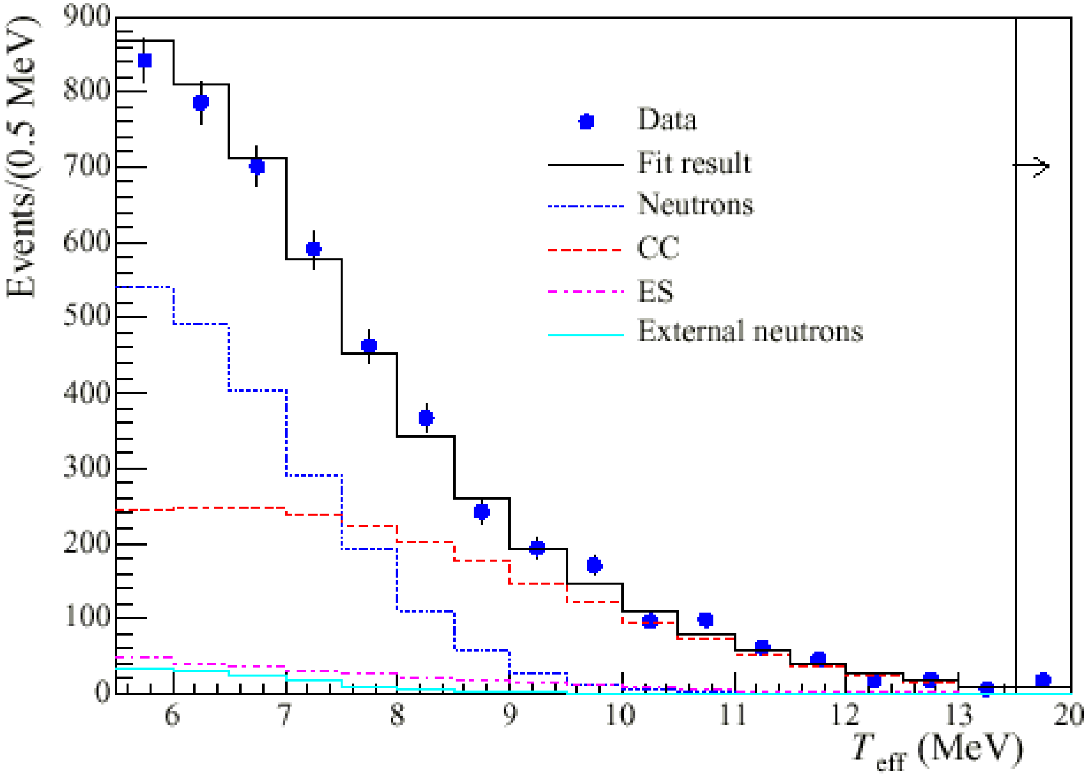


Event position: distribution of distance from center

$\rho = (R / R_0)^3$

$R_0 = 600.5$ cm

radius of D_2O sphere



Energy distribution (from signal amplitude)

Extract all components (ES, CC, NC, background) by maximum likelihood method

Number of events:

CC: 2176 ± 78

ES: 279 ± 26

NC: 2010 ± 85

Background from external neutrons: 128 ± 42

Solar neutrino fluxes, as measured from the three signals:

$$\Phi_{CC} = (1.72 \pm 0.05 \pm 0.11) \times 10^{6}\ \text{cm}^{-2}\ \text{s}^{-1}$$

Note: $\Phi_{CC} \equiv \Phi(\nu_e)$

$$\Phi_{ES} = (2.34 \pm 0.23\ ^{+0.15}_{-0.14}) \times 10^{6}\ \text{cm}^{-2}\ \text{s}^{-1}$$

← Calculated assuming that all incident neutrinos are ν_e

$$\Phi_{NC} = (4.81 \pm 0.19\ ^{+0.28}_{-0.27}) \times 10^{6}\ \text{cm}^{-2}\ \text{s}^{-1}$$

⟺ $\Phi_{SSM}(\nu) = 5.05\ ^{+1.01}_{-0.81} \times 10^{6}\ \text{cm}^{-2}\text{s}^{-1}$

(stat) (syst)

$$\frac{\Phi_{CC}}{\Phi_{NC}} = 0.358 \pm 0.021\ ^{+0.028}_{-0.029}$$

differs from 1 by 10 standard deviations

- **The TOTAL solar neutrino flux agrees with SSM predictions**
  (determination of the solar core temperature to ~ 0.5% precision)
- **Composition of solar neutrino flux on Earth:**
  ~ 36% ν_e ; ~ 64% $\nu_\mu + \nu_\tau$ (ratio ν_μ / ν_τ unkown)

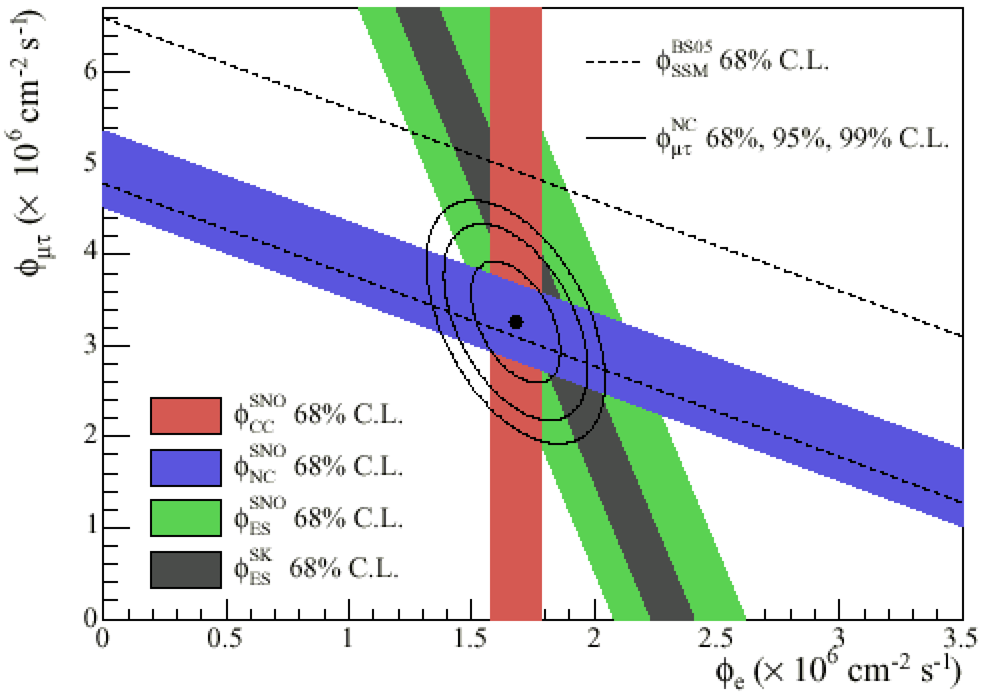
DEFINITIVE EVIDENCE OF SOLAR NEUTRINO OSCILLATIONS

Difference between the measured values of Φ_{CC} and Φ_{ES}

$$\Phi_{CC} = \Phi(\nu_e) \equiv \Phi_e$$

$$\Phi_{NC} = \Phi(\nu_e) + \Phi(\nu_\mu) + \Phi(\nu_\tau) \equiv \Phi_e + \Phi_{\mu\tau}$$

$$\Phi_{ES} = \Phi(\nu_e) + \frac{\sigma_{ES}(\nu_{\mu,\tau})}{\sigma_{ES}(\nu_e)}\left[\Phi(\nu_\mu) + \Phi(\nu_\tau)\right] \approx \Phi_e + \frac{1}{6}\Phi_{\mu\tau}$$

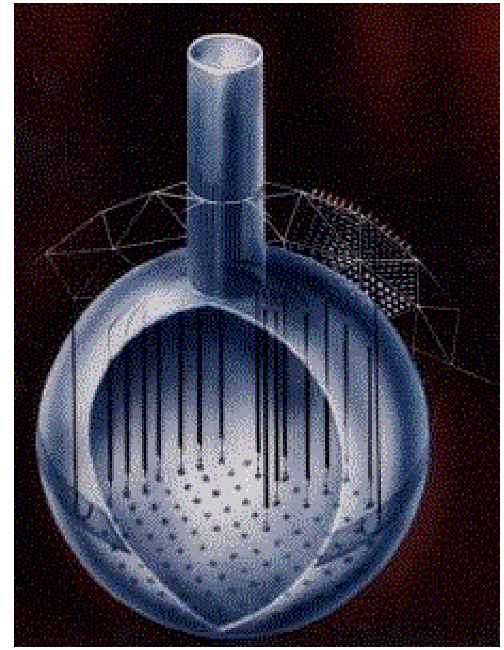


SNO phase III

B. Aharmim et al., Phys. Rev. Lett. 101, 111301 (2008)

Insert 40 cylindrical proportional counters filled with He3 (NCD) vertically in the D_2O volume (no salt)

36 Tubes filled with 85% He3, 15% CF_4;
4 tubes filled with 85% He4, 15% CF_4
Pressure 2.5 bar
Ultra-pure Nickel tubes, diam. 5.08 cm
Tube wall thickness 370 μm
Variable length

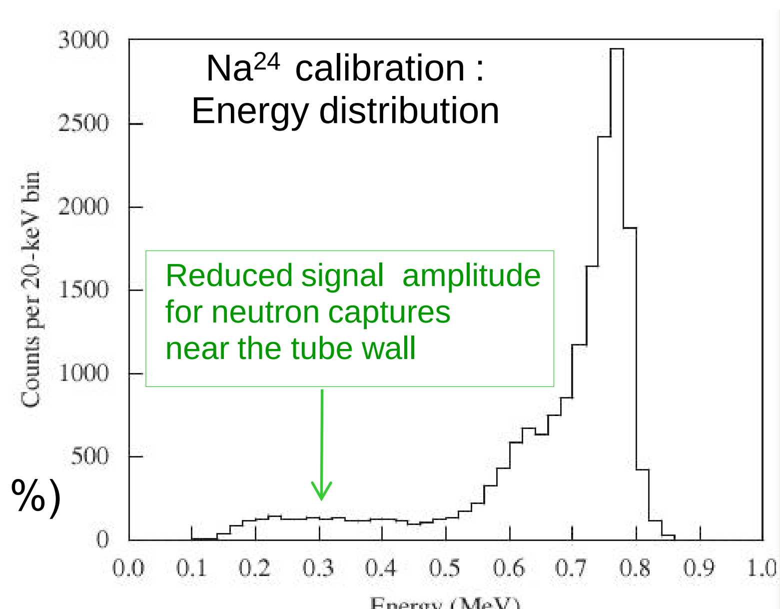


Detect neutrons from NC process $\nu + d \rightarrow \nu + p + n$ from capture by He^3 after thermalization

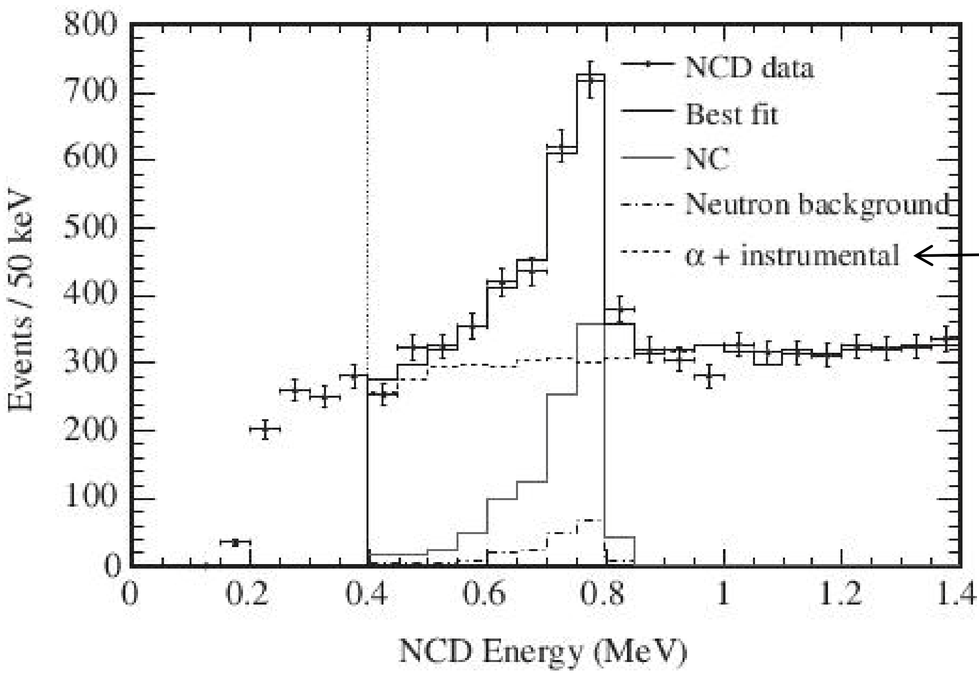
$n + He^3 \rightarrow p + H^3 + 764$ KeV

- mono-energetic signal
  (~ 20,000 electron – ion pairs in gas)
- detection efficiency ~18%
  measured using Na^{24} sources (γ, 2.754 MeV) inserted in the D_2O volume:
  $$\gamma + d \rightarrow p + n$$

(neutron detection efficiency from $n + d \rightarrow H^3 + \gamma \approx 4.9$ %)



NCD energy distribution during Phase III data - taking (November 2004 – november 2006)



Contamination from α radioactivity in the Nickel walls measured by the four counters filled with He^4

Number of solar neutrino events:

Neutrons: 983 ± 77 (NCD); 267 ± 23 ($n + d \rightarrow H^3 + \gamma$)

Electrons from CC events : 1867^{+91}_{-101} **; electrons from ES events:** 171 ± 24

Background neutrons: 185 ± 24 (NCD); 77 ± 12 ($n + d \rightarrow H^3 + \gamma$)

$$\frac{\Phi_{CC}}{\Phi_{NC}} = 0.301 \pm 0.033$$

Measurement of the solar ν_e deficit using an independent method with different systematic effects

Solar ν_e disappearance: interpretation

Hypothesis: two – neutrino mixing

Vacuum oscillations

ν_e energy spectrum measured on Earth $\Phi(\nu_e) = \mathcal{P}_{ee}\,\Phi_0(\nu_e)$

($\Phi_0(\nu_e) \equiv \nu_e$ energy spectrum at production)

Probability to detect ν_e on Earth :

$$\mathcal{P}_{ee} = 1 - \sin^2(2\theta)\sin^2(1.267\Delta m^2 \frac{L}{E}) \approx 0.33$$

$$\begin{pmatrix} L\ [\text{m}] \\ E\ [\text{MeV}] \\ \Delta m^2\ [\text{eV}^2] \end{pmatrix}$$

Solar neutrino energy in SNO, Super-K experiments $E = 5 – 15$ MeV

Variation of Sun – Earth distance during data taking

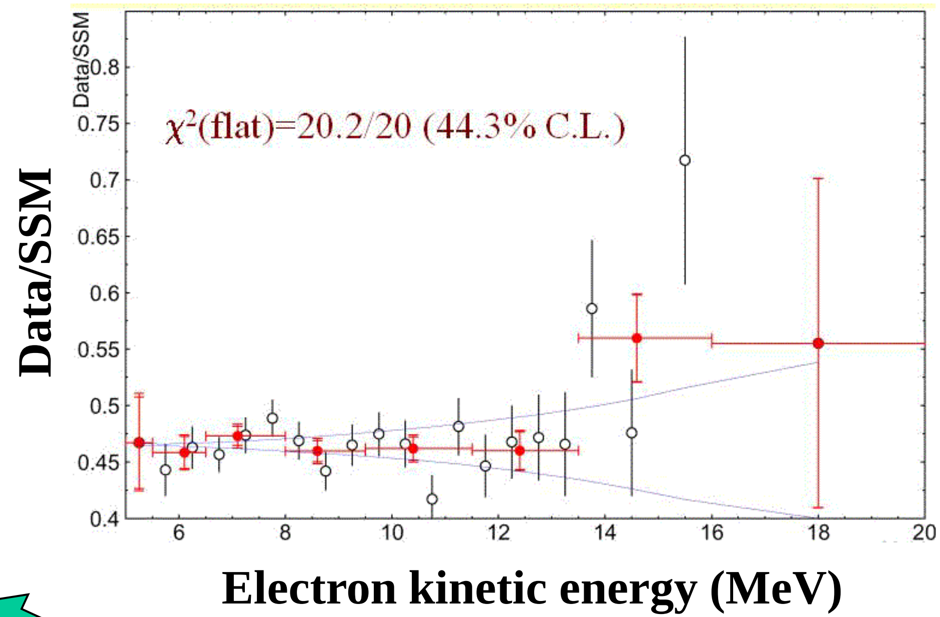
(the Earth orbit is an ellipse) $\Delta L = 5.01 \times 10^9$ m

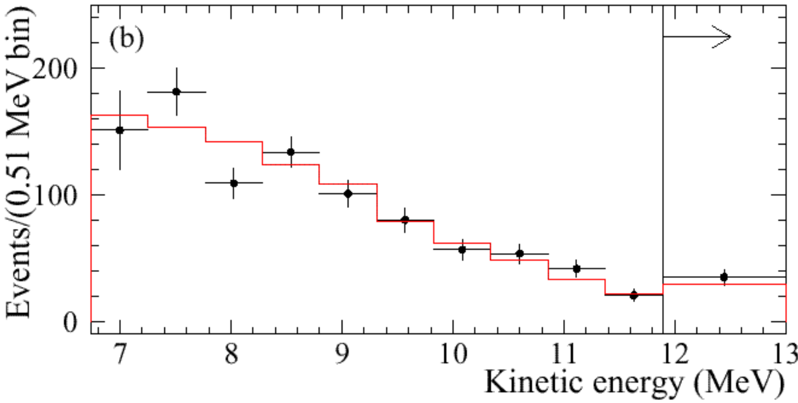
($\langle L \rangle = 149.67 \times 10^9$ m)

→ **Check dependence of $\mathcal{P}_{ee}$ on E and L**

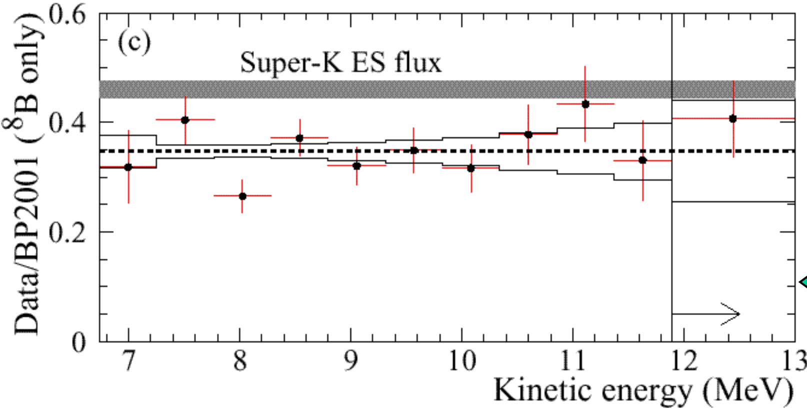
Spectral distortions

Super-K 2002





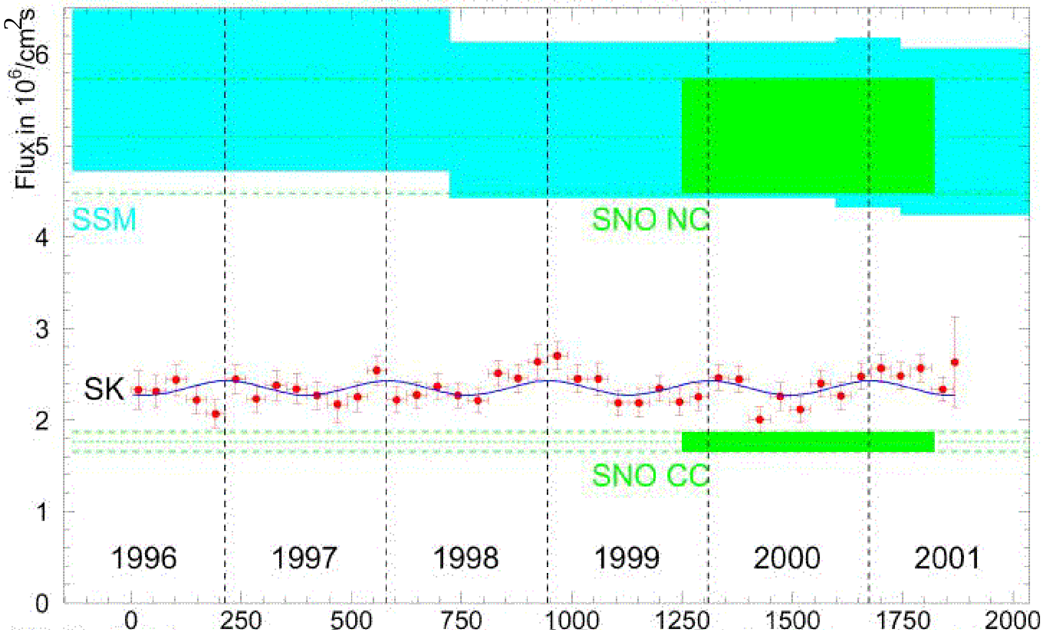
SNO: $\nu_e + d \to e^- + p + p$
electron energy distribution



SNO: data / SSM prediction

ν_e deficit independent of energy within measurement errors (no spectral distortions)

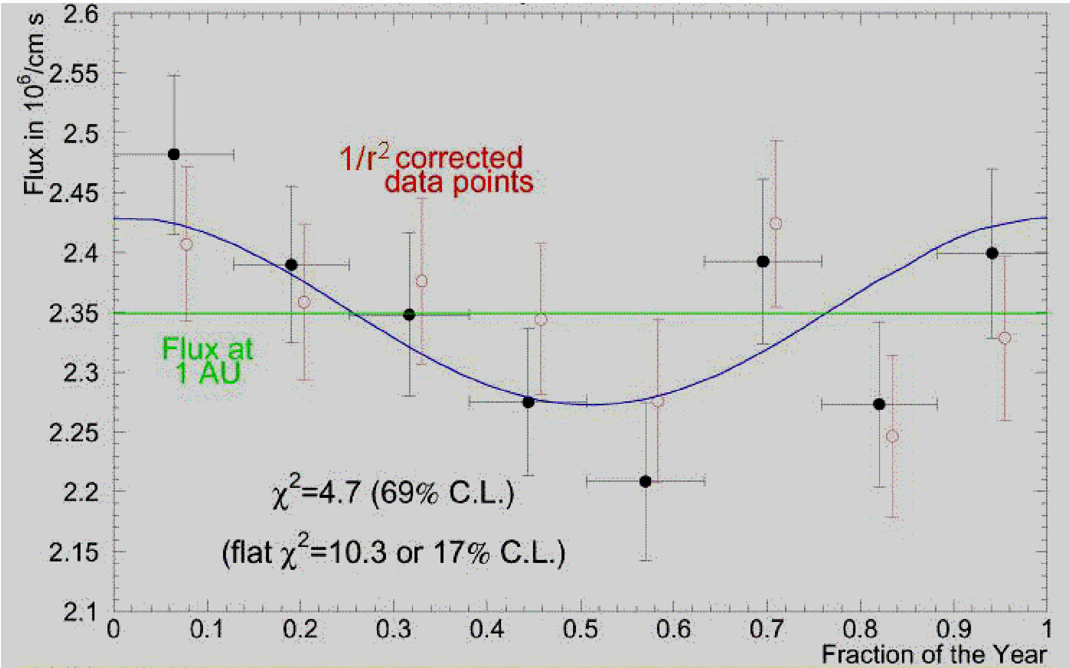
Seasonal modulation



Yearly variation of the Sun - Earth distance: 3.3% $\Rightarrow$ seasonal modulation of the solar neutrino flux

Expected seasonal variation from the variation of solid angle in the absence of oscillations: ~ 6.6%

The observed effect is consistent with the expected solid angle variation



$$\mathscr{P}_{ee} = 1 - \sin^2(2\theta)\sin^2\left(1.267\Delta m^2 \frac{L}{E}\right) = 1 - \sin^2(2\theta)\sin^2\left(\pi\frac{L}{\lambda}\right) \approx 0.33$$

$$\begin{pmatrix} L \text{ [m]} \\ E \text{ [MeV]} \\ \Delta m^2 \text{ [eV}^2\text{]} \end{pmatrix}$$

For oscillation lengths $\lambda \ll \nu$ source dimension ($\sim 0.15\ R_O \approx 1 \times 10^8$ m);
$\ll$ Earth diameter ($\sim 1.3 \times 10^7$ m)

$\mathscr{P}_{ee}$ is independent of *E* and *L* :

$$\mathscr{P}_{ee} = 1 - \sin^2(2\theta)\left\langle \sin^2\left(\pi\frac{L}{\lambda}\right)\right\rangle = 1 - \frac{1}{2}\sin^2(2\theta) \geq 0.5$$

in disagreement with the experimental result ~ 0.33

Neutrino oscillations in vacuum
do not describe
the observed solar ν_e deficit

NEUTRINO OSCILLATIONS IN MATTER

Neutrino refractive index in matter

(L. Wolfenstein, 1978)

$$n = 1 + \varepsilon = 1 + \frac{2\pi}{p^2} N f(0)$$

p: neutrino momentum
N: density of scattering centers
f(0): scattering amplitude at θ = 0°

In vacuum: $E = \sqrt{p^2 + m^2}$

Plane wave in matter: $\Psi = e^{i(n\mathbf{p}\cdot\mathbf{r} - E't)}$

$$E' = \sqrt{(np)^2 + m^2} \approx E + \frac{p^2}{E}\varepsilon \qquad (|\varepsilon| << 1)$$

Energy conservation:

$$E = E' + V$$

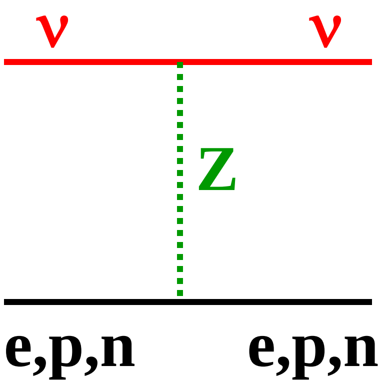
V ≡ neutrino potential energy in matter

$$V = -\frac{p^2}{E}\varepsilon = -\frac{2\pi}{E} N f(0)$$

$V < 0$: attractive potential ($n > 1$)
$V > 0$: repulsive potential ($n < 1$)

Neutrino potential energy in matter

1. Z-boson exchange (the same for the three neutrino types)



$$V_Z(p) = -V_Z(e) = \frac{\sqrt{2}}{2} G_F N_p (1 - 4\sin^2\theta_w)$$

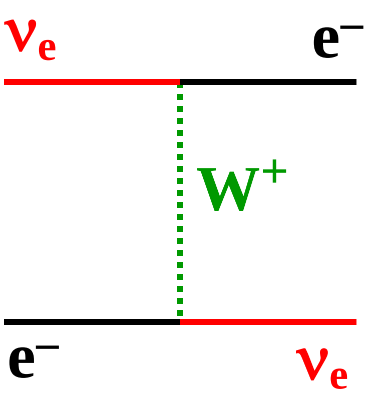
$$V_Z(n) = -\frac{\sqrt{2}}{2} G_F N_n$$

G_F: Fermi constant

N_p (N_n): proton (neutron) density

θ_w: weak mixing angle

2. W- boson exchange (only for ν_e!)



$$V_W[eV] = \sqrt{2} G_F N_e \approx 7.63 \times 10^{-14} \frac{Z}{A} \rho$$

N_e: electron density

ρ: matter density [g/cm^3]

NOTE: $V(\nu) = -V(\bar{\nu})$

Example: $\nu_e - \nu_\mu$ **mixing in a constant density medium**

(identical results for $\nu_e - \nu_\tau$ mixing)

In the "flavour" representation: $\nu = \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$

Evolution equation: $H\nu = i\dfrac{\partial \nu}{\partial t}$

H: **2x2 matrix**

$$H = (E + V_Z)\begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} + \frac{1}{2E}\begin{vmatrix} M_{ee}{}^2 & M_{e\mu}{}^2 \\ M_{\mu e}{}^2 & M_{\mu\mu}{}^2 \end{vmatrix} + V_W \begin{vmatrix} 1 & 0 \\ 0 & 0 \end{vmatrix}$$

(Remember: $\sqrt{p^2 + M^2} \approx p + \dfrac{M^2}{2p} \approx E + \dfrac{M^2}{2E}$ **for** $M << p$**)**

$$M_{ee}{}^2 = \frac{1}{2}(\mu^2 - \Delta m^2 \cos 2\theta)$$

$$M_{e\mu}{}^2 = M_{\mu e}{}^2 = \frac{1}{2}\Delta m^2 \sin 2\theta$$

$$M_{\mu\mu}{}^2 = \frac{1}{2}(\mu^2 + \Delta m^2 \cos 2\theta)$$

$$\mu^2 = m_1{}^2 + m_2{}^2$$

$$\Delta m^2 = m_2{}^2 - m_1{}^2$$

NOTE: m_1, m_2, θ are defined in vacuum

$$H = (E + V_Z)\begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} + \frac{1}{2E}\begin{vmatrix} M_{ee}{}^2 + 2EV_W & M_{e\mu}{}^2 \\ M_{\mu e}{}^2 & M_{\mu\mu}{}^2 \end{vmatrix}$$

diagonal term:
no mixing

Term inducing ν_e–ν_μ mixing

ρ = constant ⟶ H is time - independent

H diagonalization ⇒ eigenvalues and eigenvectors

Eigenvectors in matter

$$M^2 = \frac{1}{2}(\mu^2 + \xi) \pm \frac{1}{2}\sqrt{(\Delta m^2 \cos 2\theta - \xi)^2 + (\Delta m^2)^2 \sin^2 2\theta}$$

$$\xi \equiv 2EV_W \approx 1.526 \times 10^{-7} \frac{Z}{A} \rho E \quad [\text{eV}^2]$$

(ρ in g/cm^3, E in MeV)

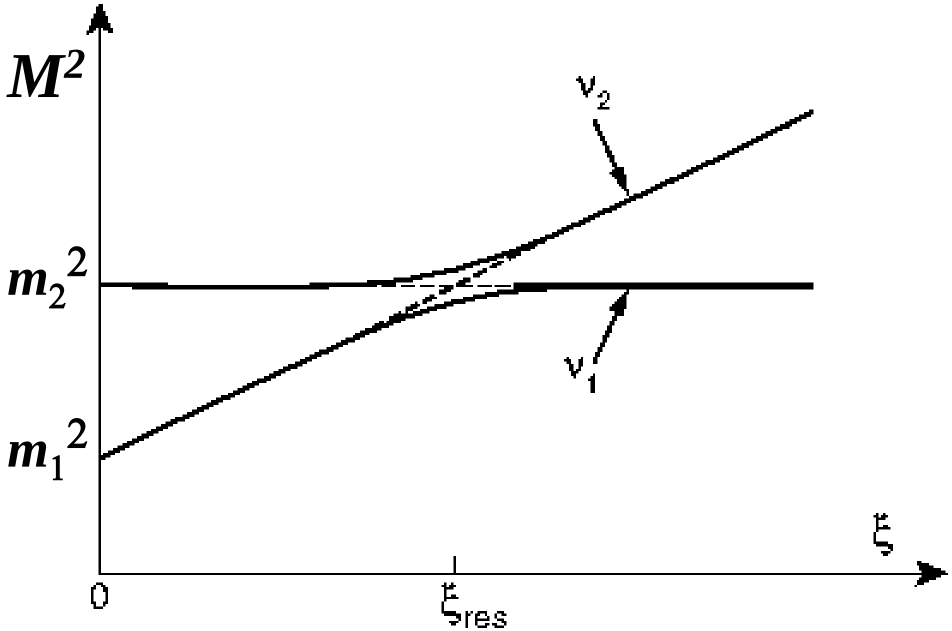
Mixing angle in matter:

$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - \xi}$$

$\xi = \Delta m^2 \cos 2\theta \equiv \xi_{res}$ ⇒ maximum mixing (θ_m = 45°) even if the mixing angle in vacuum is very small: "MSW resonance "

(discovered by Mikheyev and Smirnov in 1985)

Mass eigenvalues as a function of ξ



$$\xi \equiv 2EV_W \approx 1.526\times 10^{-7}\,\frac{Z}{A}\,\rho E$$

$$\xi_{res} = \Delta m^2 \cos 2\theta$$

Oscillation length in matter:

$$\lambda_m = \lambda \frac{\Delta m^2}{\sqrt{(\Delta m^2 \cos 2\theta - \xi)^2 + (\Delta m^2)^2 \sin^2 2\theta}}$$

(λ ≡ oscillation length in vacuum)

For $\xi = \xi_{res}$: $\lambda_m = \dfrac{\lambda}{\sin 2\theta}$

NOTE: for ν_e oscillations the MSW resonance exists only if $\Delta m^2 \cos 2\theta > 0$

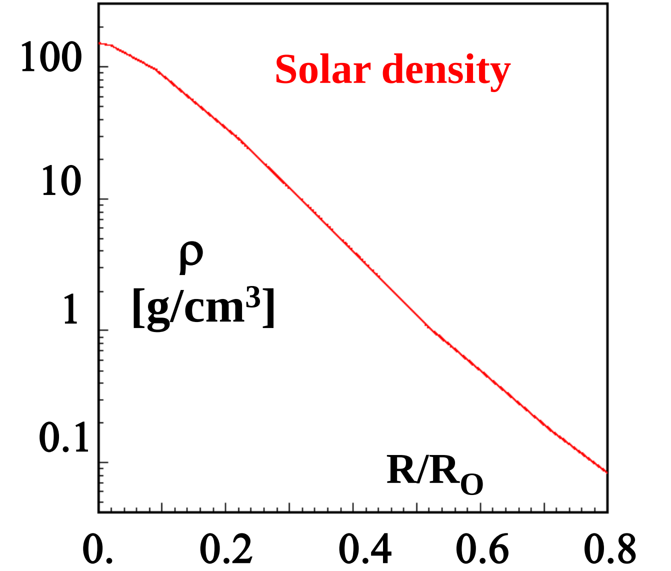
$\Delta m^2 > 0$, $\cos 2\theta > 0$ ($\theta < 45^o$) or $\Delta m^2 < 0$, $\cos 2\theta < 0$ ($\theta > 45^o$)

DEFINITION (to remove the ambiguity): $\Delta m^2 = m_2^2 - m_1^2 > 0$

Matter effects in solar neutrino oscillations

Solar neutrinos are produced in a high – density medium (the solar core).

Variable density along the neutrino path: $\rho = \rho(t)$



Oscillations in solar matter

Time evolution: $H\nu = i\,\partial\nu / \partial t$

H (2 x 2 matrix) depends on time via $\rho(t)$

→ H has no eigenvectors

Numerical solution of the evolution equation:

$$\nu(0) = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$ (pure ν_e at production)

$$\nu(\delta) = \nu(0) + \left(\frac{\partial\nu}{\partial t}\right)_{t=0} \delta = \nu(0) - iH(0)\nu(0)\delta$$ (δ = very small time interval)

....

$$\nu(t+\delta) = \nu(t) + \left(\frac{\partial\nu}{\partial t}\right)_{t} \delta = \nu(t) - iH(t)\nu(t)\delta$$

....

(until the neutrino emerges from the Sun)

“Adiabatic solutions”

(Negligible variation of matter density ρ over an oscillation length)

$$\nu(t) = a_1(0)\nu_1(t) + a_2(0)\nu_2(t)$$

$\nu_1(t)$, $\nu_1(t)$: “local” mass eigenstates obtained by setting ρ = constant = local density at time *t* in the evolution Hamiltonian

$$a_1(0) = \cos\theta_m^0;\ a_2(0) = \sin\theta_m^0$$ constant along the whole path inside the Sun

$$\theta_m^0 = \theta_m(0)$$ mixing angle in matter at neutrino production point (in the Sun core)

Assumption: mixing angle in vacuum $\theta < 45° \rightarrow \cos\theta > \sin\theta$; $\cos 2\theta > 0$

Mixing angle in matter:

$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - \xi} \qquad \xi \equiv 2EV_W \approx 1.526\times 10^{-7}\,\frac{Z}{A}\,\rho[\mathrm{g/cm^3}]\,E[\mathrm{MeV}]$$

$$\text{If}\ \ \xi > \xi_{res} = \Delta m^2 \cos(2\theta):\ \ \theta_m > 45^0 \Rightarrow a_1(0) = \cos\theta_m^0 < \sin\theta_m^0 = a_2(0)$$

→ at production $\left|\langle \nu_2 | \nu_e \rangle\right| > \left|\langle \nu_1 | \nu_e \rangle\right|$

$\xi > \xi_{res}$ → $$E[MeV] > \frac{\xi_{res}}{2V_W} \approx \frac{6.6\times 10^6\,\Delta m^2 \cos 2\theta}{(Z/A)\rho}$$

(Δm^2 [eV^2], ρ [g/cm^3])

In case of "adiabatic" solutions, at exit from Sun ($t = t_E$):

$$\nu(t_E) = \cos\theta_m^0 \nu_1(t_E) + \sin\theta_m^0 \nu_2(t_E)$$

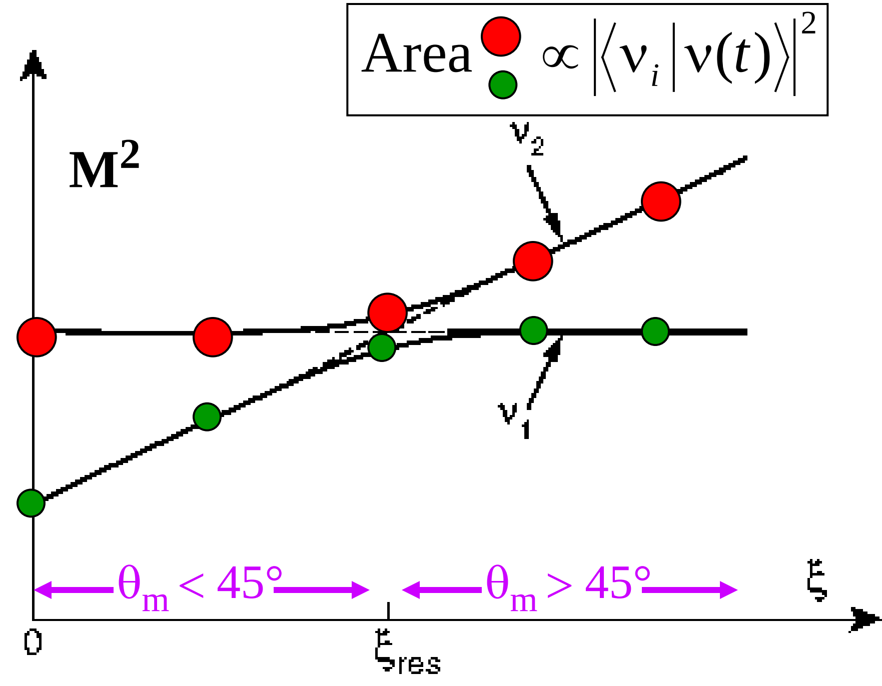
$\nu_1(t_E)$, $\nu_2(t_E)$ **: mass eigenstates** **in vacuum**

$$\text{For } \theta_m^0 > 45^0 \quad \left|\langle \nu_\mu | \nu(t_E)\rangle\right| > \left|\langle \nu_e | \nu(t_E)\rangle\right|$$

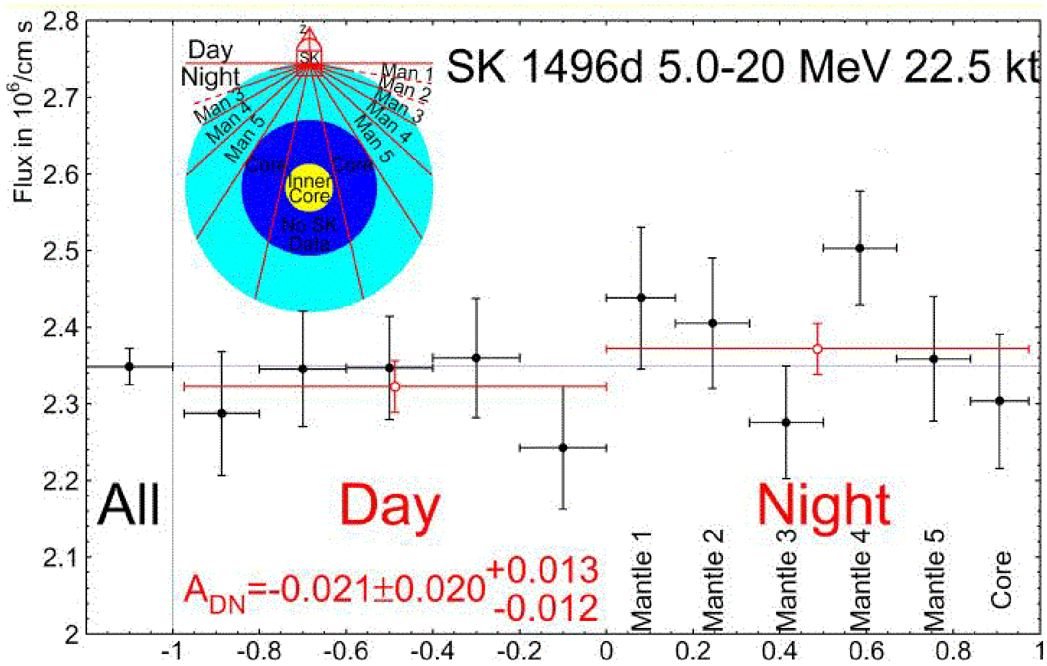
$$\text{because in vacuum } \left|\langle \nu_\mu | \nu_2\rangle\right| > \left|\langle \nu_e | \nu_2\rangle\right|$$

In vacuum, at exit from Sun ($t = t_E$):

➡ **ν_e DEFICIT**



Day – night modulation (from matter effects on neutrino oscillations through Earth at night → ν_e flux increase at night for some values of the oscillation parameters)

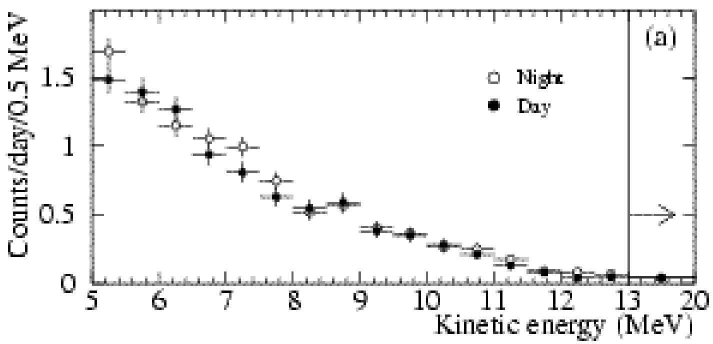


cos(Sun zenith angle)

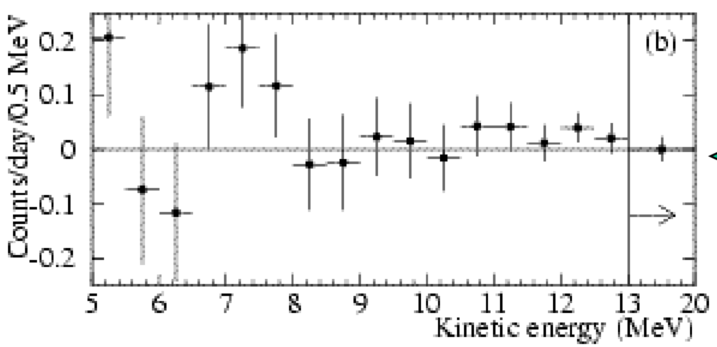
Study ν_e deficit as a function of path inside Earth (length and density) subdividing the night spectrum in bins of zenith angle

(with respect to local vertical axis)

$$A_{DN} = \frac{D - N}{0.5(D + N)}$$



SNO: Day and Night spectra (CC events)



Day – night difference

"Best fit" to SNO data

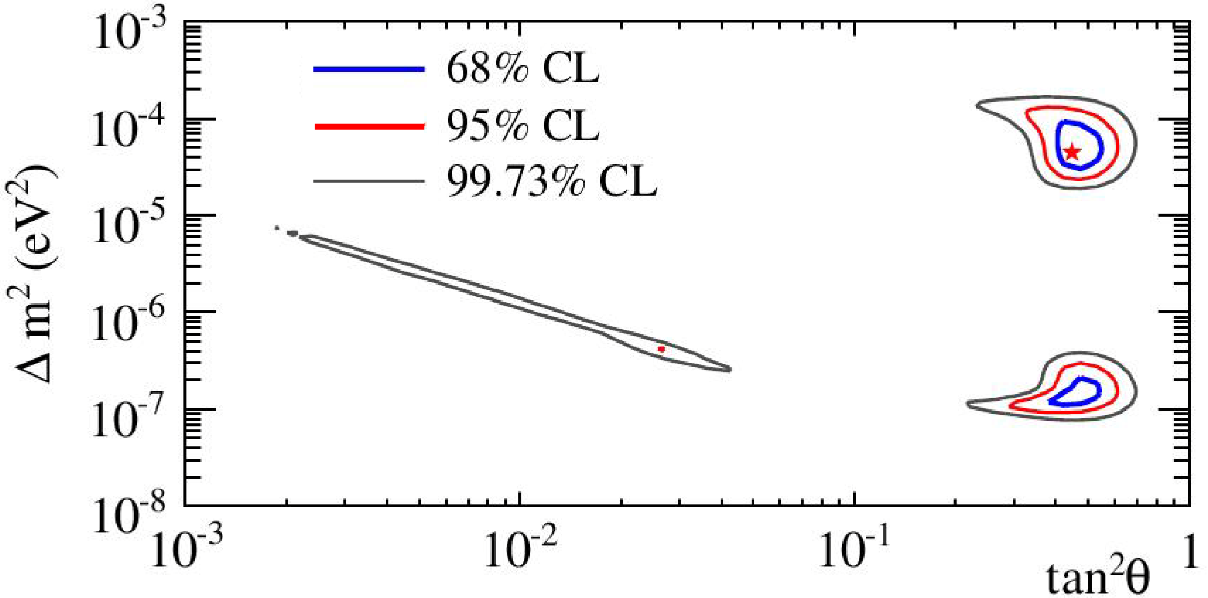
★ **Best fit:**

$$\Delta m^2 = 4.57\times10^{-5}\ \mathrm{eV}^2$$

$$\tan^2\theta = 0.447$$

$$\chi^2 / N_{dof} = 73.8/72$$

Confidence levels for two-parameter fits CL	$\Delta\chi^2=\chi^2-\chi^2_{min}$
68.27%	2.30
90%	4.61
95%	5.99
99%	9.21
99.73%	11.83



<u>NOTE</u>: $\tan^2\theta$ is used instead of $\sin^2 2\theta$ because $\sin^2 2\theta$ is symmetric around $\theta = 45°$

$$\sin 2(45^0-\theta) = \sin(90^0-2\theta) = \sin(90^0+2\theta) = \sin 2(45^0+\theta)$$

MSW solutions exist only if $\theta < 45°$

Best fit to all solar neutrino experiments

including a recent re-analysis of SNO Phase I and II data with detection threshold reduced to 3.5 MeV

B.Aharmim et al., Phys. Rev. **C81**, 055504 (2010)

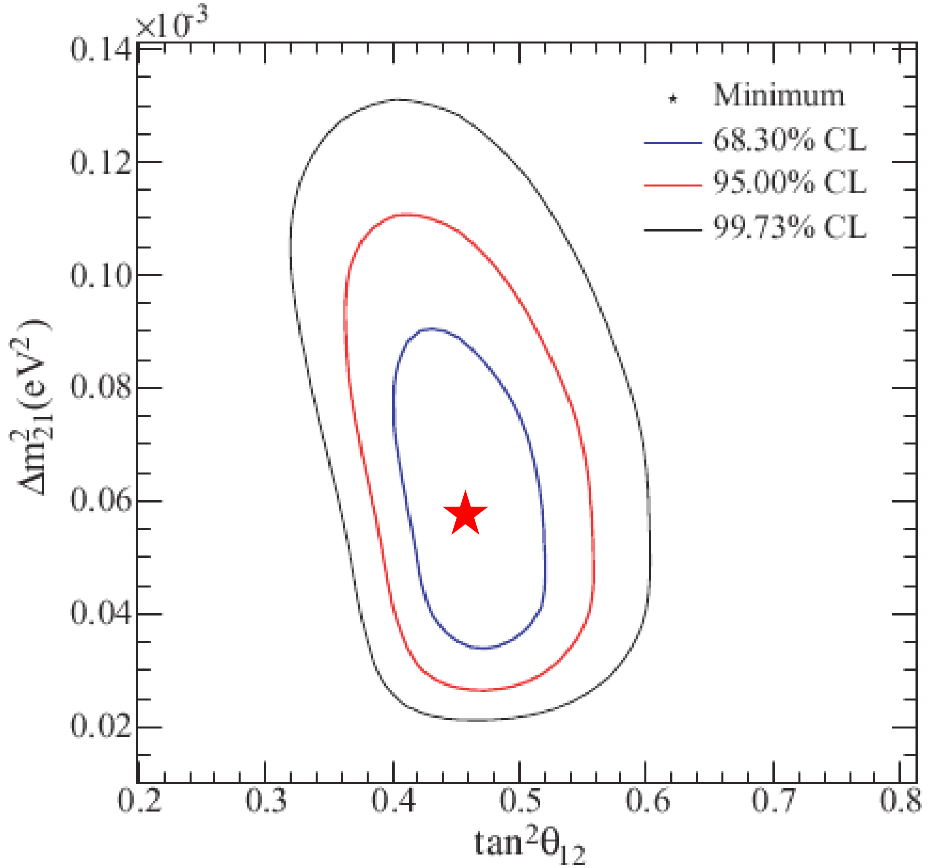
★ **Best fit:**

$$\Delta m^2 = (5.89^{+2.13}_{-2.16}) \times 10^{-5}\ \mathrm{eV}^2$$

$$\tan^2\theta = 0.457^{+0.038}_{-0.041}$$

$$\theta = (32.82^{+1.07}_{-1.24})^\circ$$

$$\chi^2 / N_{dof} = 67.5 / 89$$



KamLAND

Confirmation of solar ν_e oscillations using antineutrinos from nuclear reactors

CPT invariance: $\mathscr{P}_{osc}(\nu_\alpha - \nu_\beta) = \mathscr{P}_{osc}(\bar{\nu}_\beta - \bar{\nu}_\alpha)$

→ **same disappearance probability for ν_e and $\bar{\nu}_e$**

Nuclear reactors: strong, isotropic $\bar{\nu}_e$ sources from β – decay of fission fragments

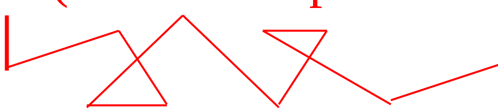
Energy spectrum ($E \leq 10$ MeV, $\langle E \rangle \approx 3$ MeV) known from experiments.

$\bar{\nu}_e$ production rate : $1.9 \times 10^{20}\ P_{th}\ s^{-1}$ P_{th}: reactor thermal power (GW)

Systematic uncertainty on $\bar{\nu}_e$ flux : ±2.7 %

Detection:

$\bar{\nu}_e + p \rightarrow e^+ + n$ (on the free protons of hydrogen–rich liquid scintillator)



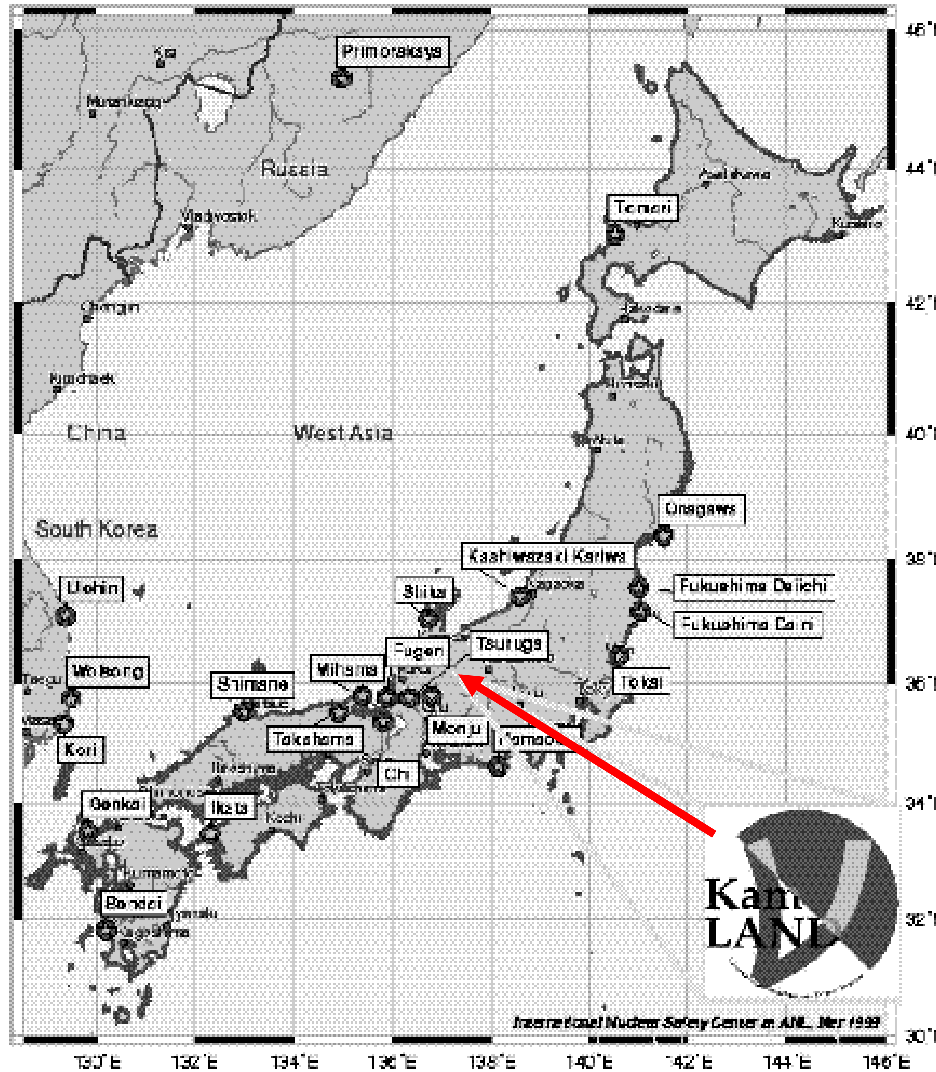
$e^+ e^- \rightarrow 2\gamma$
prompt signal
$E = E(e^+) + 2m_e$
$E_\nu = E + 0.782$ MeV

"thermalization" from multiple collisions ($\langle t \rangle \approx 180\ \mu s$), followed by capture
$n + p \rightarrow d + \gamma$ ($E_\gamma = 2.2$ MeV)
delayed signal

KamLAND (KAMioka Liquid scintillator Anti-Neutrino Detector)

$\bar{\nu}_e$ source : nuclear reactors in Japan

Total thermal power 70 GW
>79% of the $\bar{\nu}_e$ flux from
26 reactors, 138 < *L* < 214 km
Distance weighted average:
<*L*>: 180 km (weight = $\bar{\nu}_e$ flux)

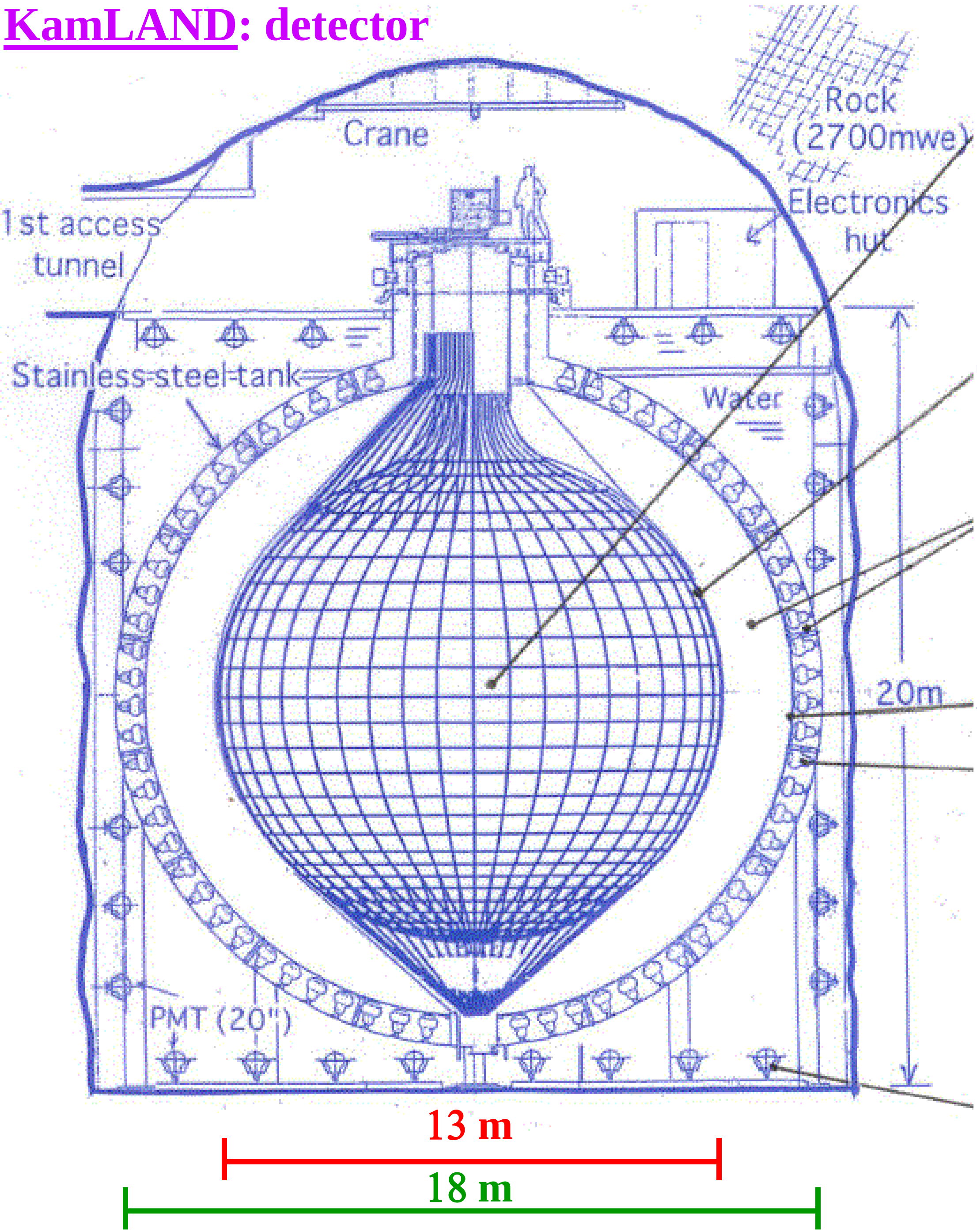


Expected $\bar{\nu}_e$ flux ≈ 1.3 x 10^6 cm^{-2} s^{-1}
(all reactors at full power,
no oscillations)

Expected oscillation length
for $\Delta m^2 = 5 \times 10^{-5}$ eV ^{2} :

$$< \lambda_{osc} > \approx 160 \text{ km}$$

KamLAND: detector



1000 tons liquid scintillator

Transparent nylon balloon

Mineral oil

Acrylic sphere

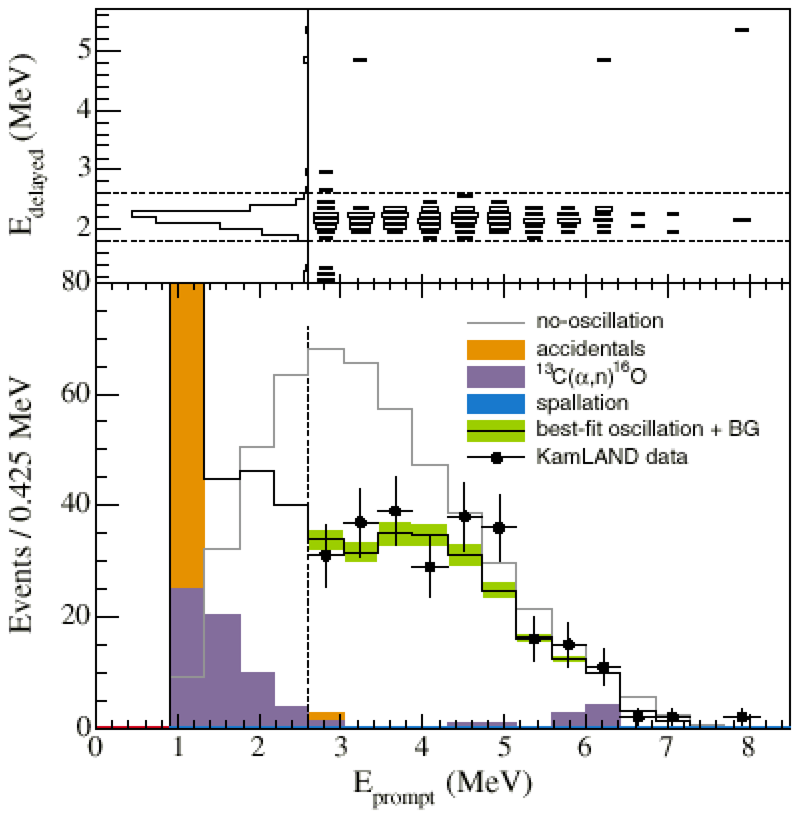
Photomultipliers (1879)
(coverage: 35% of 4π)

External anticoincidence against cosmic rays (pure H_2O)
225 photomultipliers

KamLAND: event selection

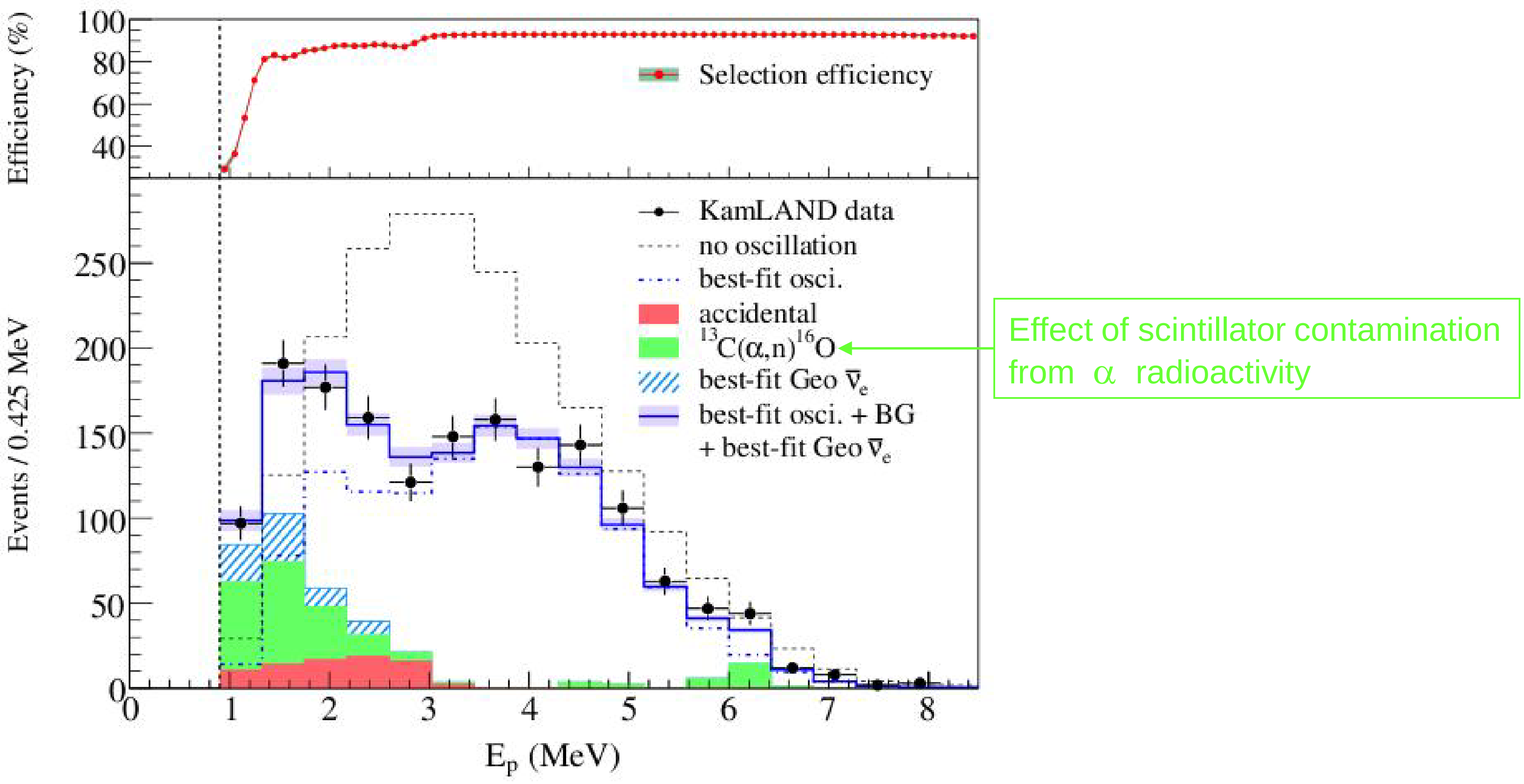
Prompt signal: 2.6 < E < 8. 5 MeV, distance from center < 5.5 m

Delayed signal: 0. 5 < Δt < 660 μs, ΔR < 1.6 m with respect to the prompt signal



KamLAND: final results

S. Abe et al., Phys. Rev. Lett. **100**, 221803 (2008)



Expected number of events for no oscillation : 2179 ± 89 (syst.)

Background: 276.1 ± 23.5 events

Number of observed events: 1609

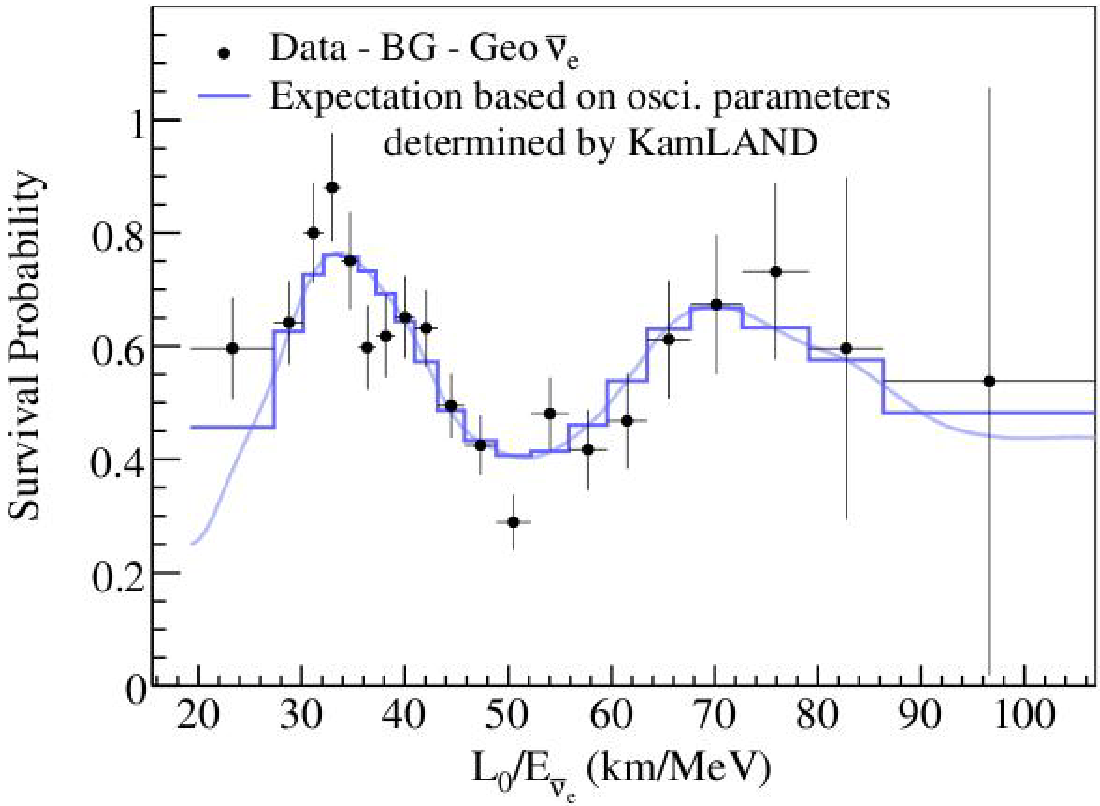
KamLAND: $\bar{\nu}_e$ disappearance probability

$$\mathscr{P}_{ee} = 1 - \sin^2(2\theta)\sin^2(1.267\Delta m^2 \frac{L_0}{E})$$

Best fit

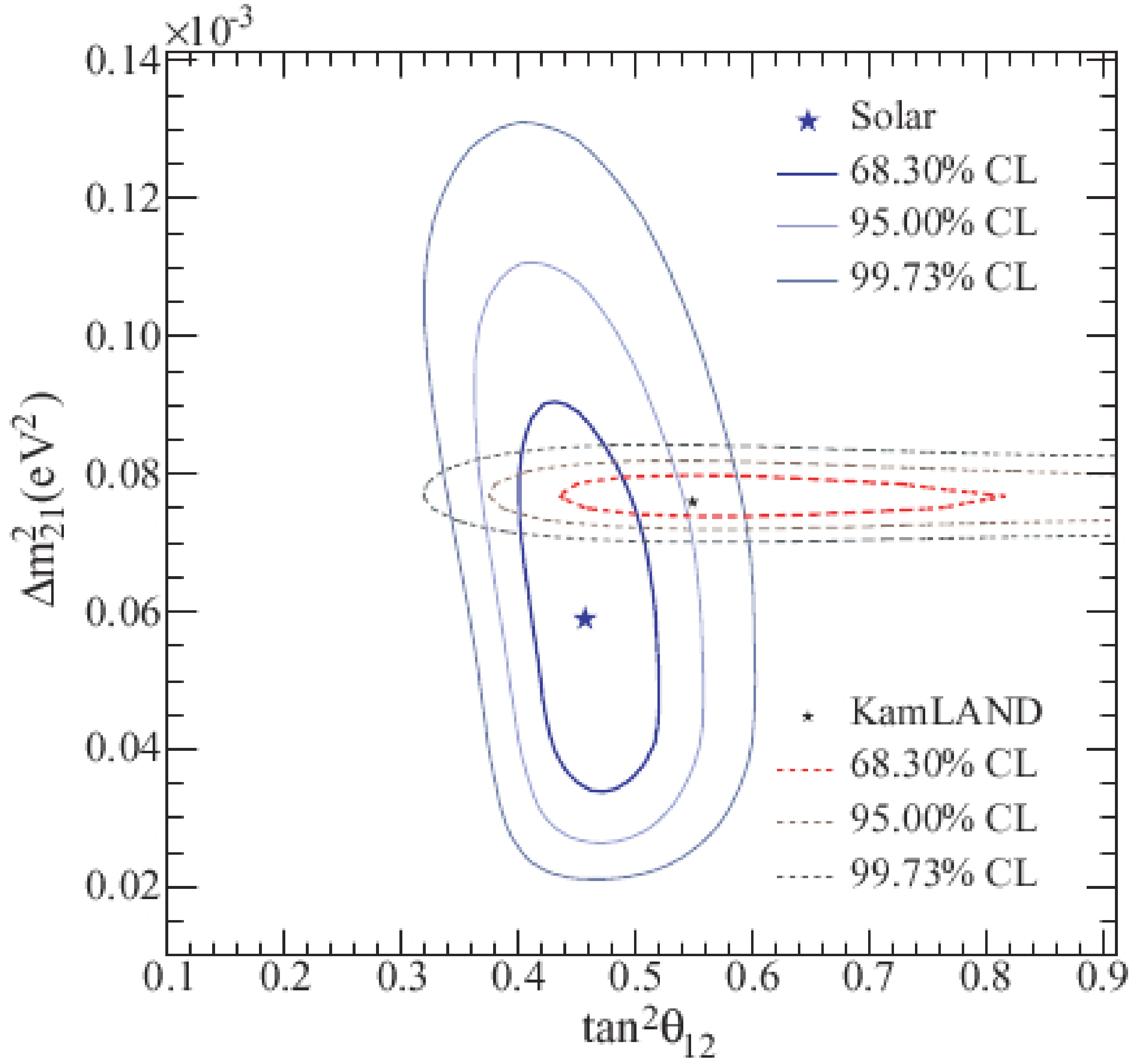
$$\Delta m^2 = (7.58^{+0.14}_{-0.13} \pm 0.15) \times 10^{-5}\ \mathrm{eV}^2$$

$$\tan^2\theta = 0.56^{+0.10}_{-0.07}(\mathrm{stat})^{+0.10}_{-0.06}(\mathrm{syst})$$

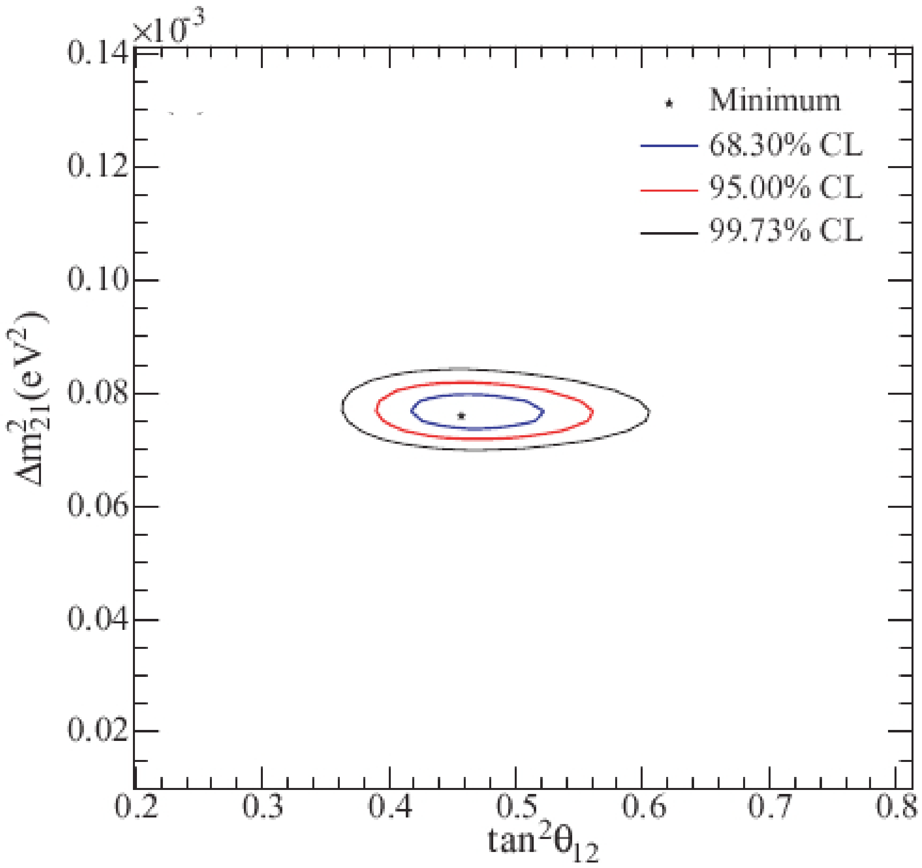


L_0 = 180 km source - detector average distance

Solar – KamLAND fit comparison



Best fit to all solar neutrino data + KamLAND



Combined best fit : $\Delta m^2 = (7.59 \pm 0.21) \times 10^{-5}\ \mathrm{eV}^2$

$$\tan^2\theta = 0.457^{+0.040}_{-0.029} \Rightarrow \theta = 34.06°^{+1.16°}_{-0.84°}$$

$$\chi^2 / N_{dof} = 81.4 / 106$$

Solar ν_e disappearance
Summary

Oscillation length in vacuum
= 5.06×10^4 m for E_ν = 1 MeV;
= 5.06×10^5 m for E_ν = 10 MeV.

$$\lambda(m) = 2.48 \frac{E(MeV)}{\Delta m^2 (eV^2)}$$

Oscillation length in matter $\lambda_m < \dfrac{\lambda}{\sin 2\theta} \approx 1.09\lambda$

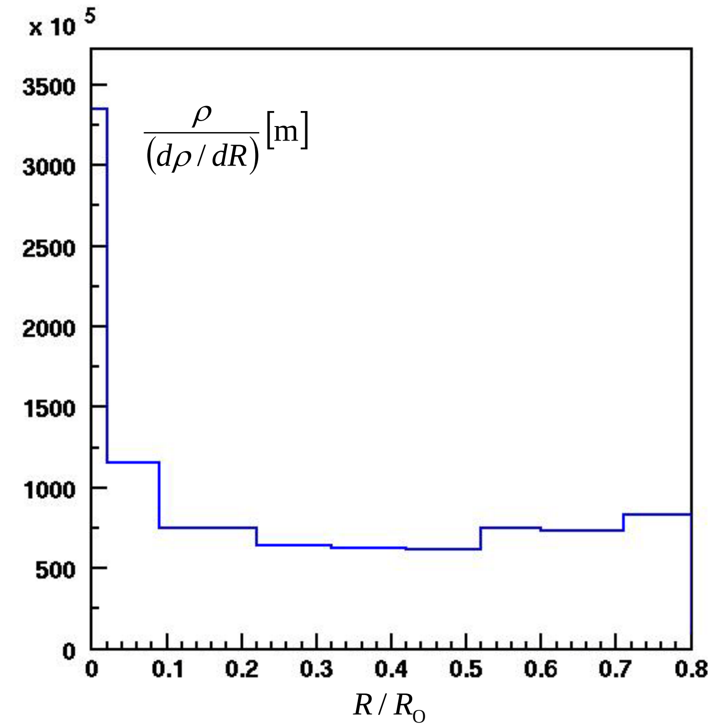
Adiabatic solutions:

Negligible variation of the solar density over an oscillation length

$$\frac{1}{\rho}\frac{d\rho}{dR}\lambda_m << 1$$

(***R*****:** distance from Sun center**)**

$$\lambda_m << \frac{\rho}{(d\rho / dR)}$$



The solar neutrino propagation inside the Sun is described by adiabatic solutions

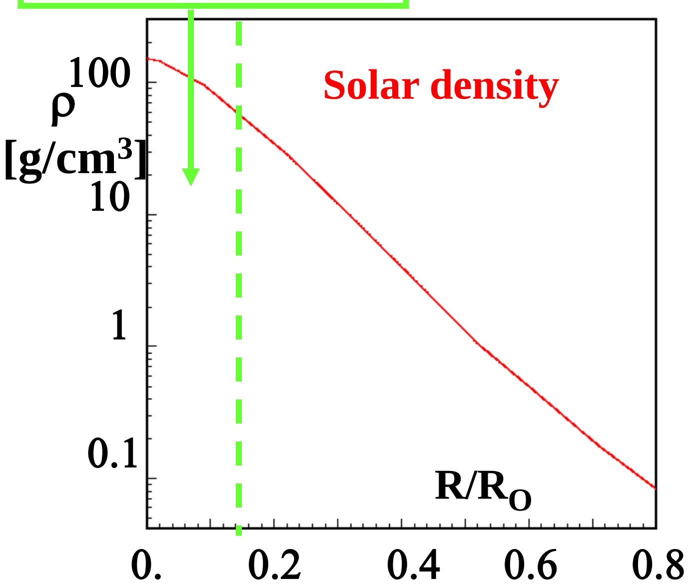
Mixing angle in matter

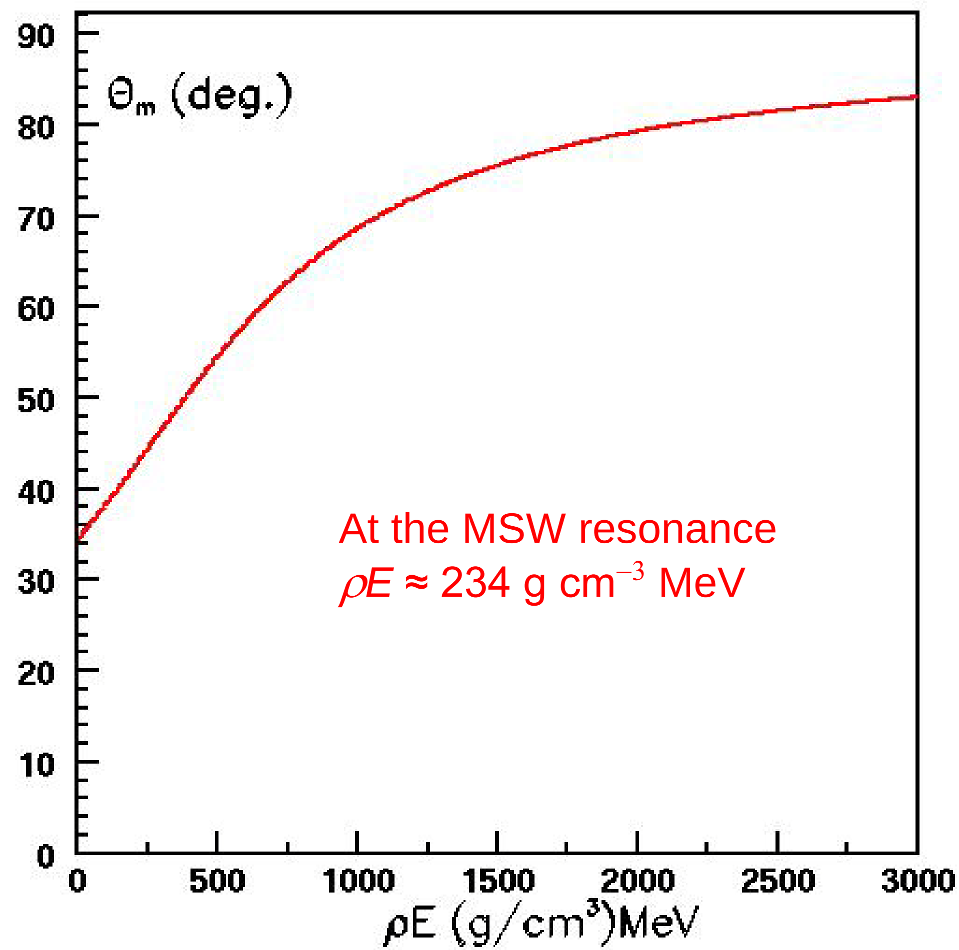
$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - \xi}$$

$$\xi \equiv 2EV_W \approx 1.526 \times 10^{-7} \frac{Z}{A} \rho E \quad [\mathrm{eV}^2]$$ (ρ in g/cm^3, E in MeV)

< Z / A > ≈ 0.77 in the Sun core:
34% H (Z/A = 1), 66% nuclei with Z/A = ½ (mainly He^4)

$R/R_O < 0.15$
solar ν_e
production region
$R_O \approx 6.96 \times 10^5$ km





At the MSW resonance
$\rho E \approx 234$ g cm^{-3} MeV

Solar ν_e detection probability on Earth ($\mathcal{P}_{ee}$)

Assumption: $\nu_e - \nu_\mu$ mixing $\Rightarrow \mathcal{P}_{ee} = 1 - \mathcal{P}_{e\mu}$

At exit from Sun (adiabatic solution):

$$\nu_E = \cos(\theta_m^0)\nu_1 + \sin(\theta_m^0)\nu_2$$

Neutrino propagation to a detector on Earth:

$$\left(E_{1,2} = \sqrt{p^2 + m_{1,2}{}^2} \approx p + \frac{m_{1,2}{}^2}{2E} \right)$$

$$\nu(t) = \cos(\theta_m^0)\nu_1 e^{-iE_1 t} + \sin(\theta_m^0)\nu_2 e^{-iE_2 t}$$

$$\mathcal{P}_{e\mu} = \left| \langle \nu_\mu | \nu(t) \rangle \right|^2 = \left| \langle -\sin(\theta)\nu_1 + \cos(\theta)\nu_2 \,|\, \cos(\theta_m^0)\nu_1 e^{-iE_1 t} + \sin(\theta_m^0)\nu_2 e^{-iE_2 t} \rangle \right|^2 =$$

$$= \left| -\sin(\theta)\cos(\theta_m^0) + \cos(\theta)\sin(\theta_m^0) e^{-i(E_2 - E_1)t} \right|^2 = \left| -\sin(\theta)\cos(\theta_m^0) + \cos(\theta)\sin(\theta_m^0) e^{-i\frac{m_2{}^2 - m_1{}^2}{2E}t} \right|^2 =$$

$$= \left(-\sin(\theta)\cos(\theta_m^0) + \cos(\theta)\sin(\theta_m^0)\cos\left(\frac{\Delta m^2}{2E}t\right) \right)^2 + \left(\cos(\theta)\sin(\theta_m^0)\sin\left(\frac{\Delta m^2}{2E}t\right) \right)^2 =$$

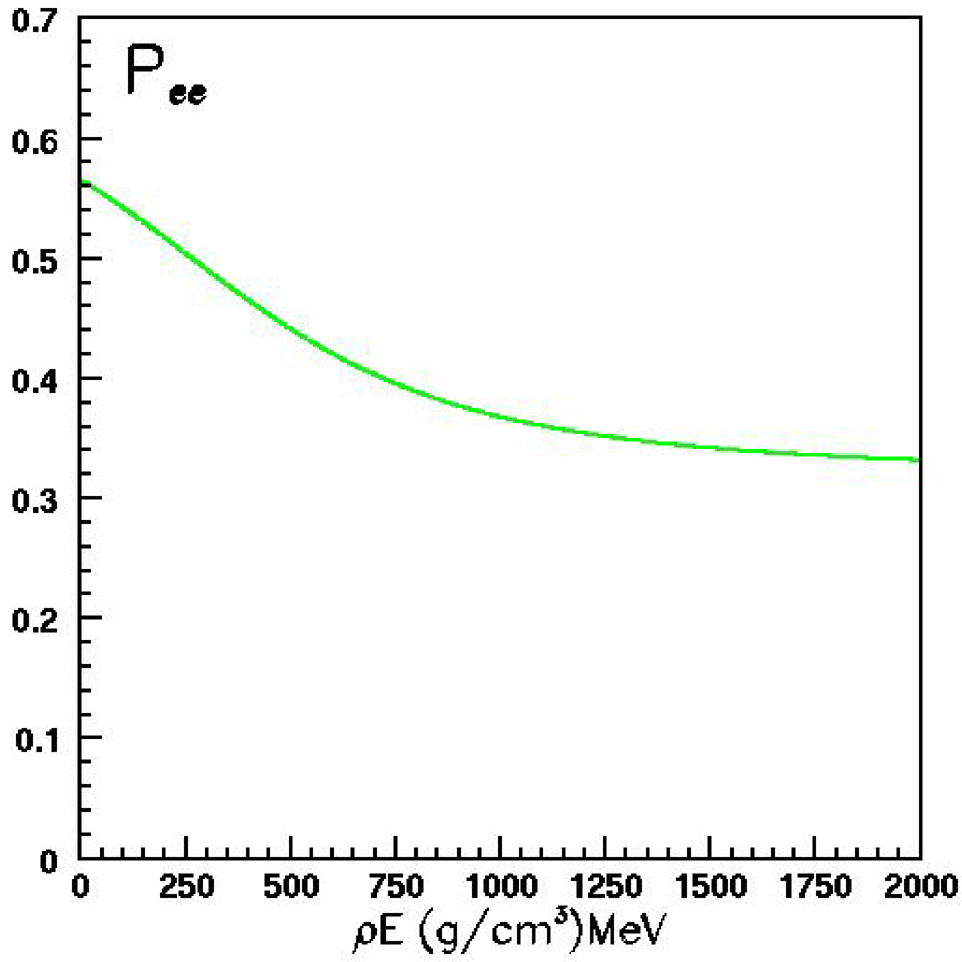
$$= \sin^2(\theta)\cos^2(\theta_m^0) + \cos^2(\theta)\sin^2(\theta_m^0) - 2\sin(\theta_m^0)\cos(\theta_m^0)\sin(\theta)\cos(\theta)\cos\left(\frac{\Delta m^2}{2E}t\right)$$

$$\cos\left(\frac{\Delta m^2}{2E}t\right) = \cos\left(2\pi \frac{L}{\lambda_{osc}}\right)$$

λ_{osc} << Earth diameter / variation of Sun-Earth distance

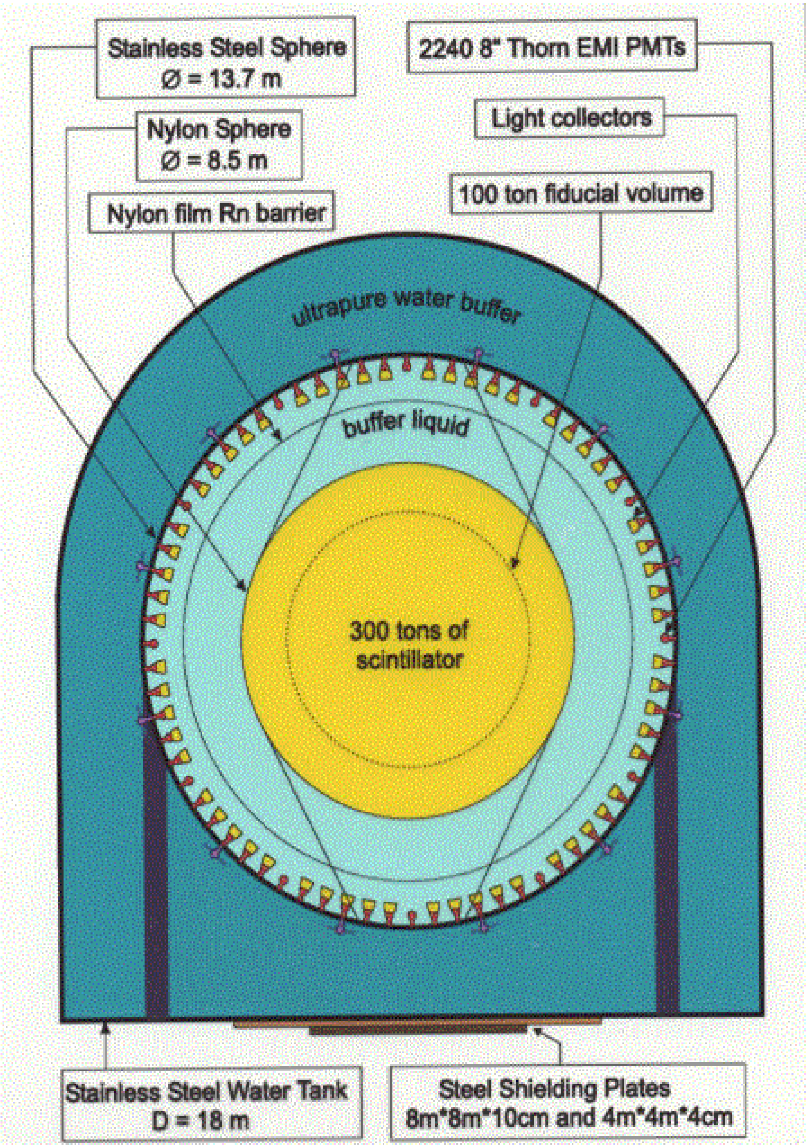
$$\Rightarrow \left\langle \cos\left(2\pi \frac{L}{\lambda_{osc}}\right) \right\rangle = 0$$

$$P_{ee} = 1 - P_{e\mu} = 1 - \sin^2(\theta)\cos^2(\theta_m^0) - \cos^2(\theta)\sin^2(\theta_m^0)$$



BOREXINO

An experiment at the Gran Sasso National Laboratories



Goal:

Detection of elastic scattering process

$\nu + e \rightarrow \nu + e$ (dominated by ν_e)

in liquid scintillator

Scintillation light >> Čerenkov light

→ detection threshold < < 1 MeV

Scintillator: pseudocumene (PC) + PPO;

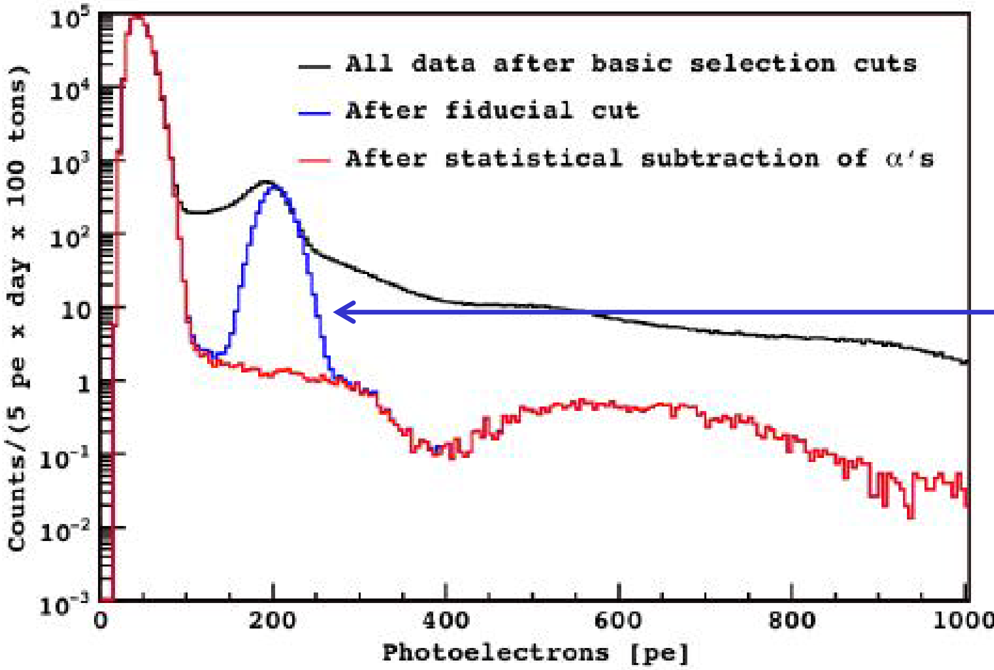
"buffer liquid": PC + DMP (no scintillation)

Real – time experiment

Scintillation light is ISOTROPIC

→ no signal correlation with the Sun direction

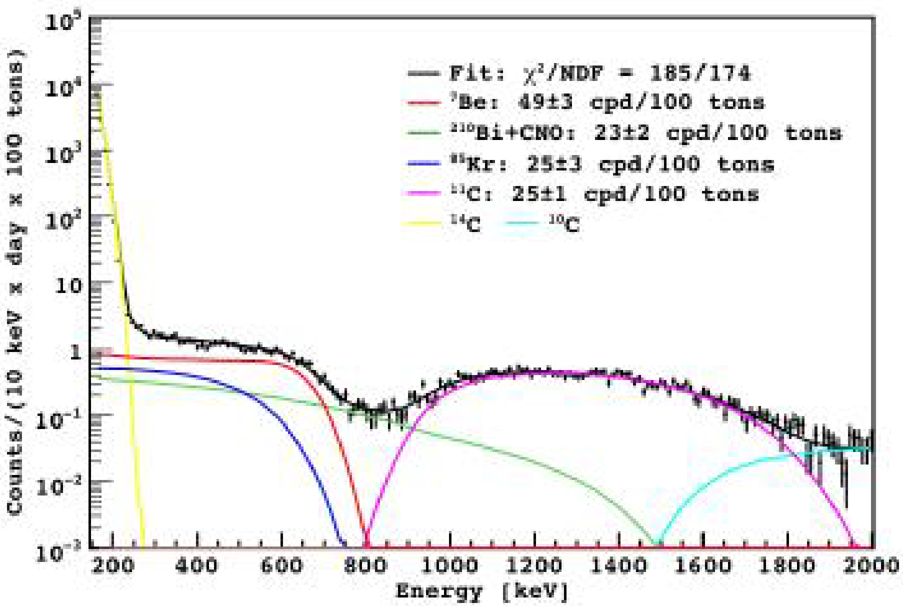
The signal solar origin can be verified after few data-taking years by observing the seasonal modulation induced by the excentricity of the Earth orbit around the Sun



Results after ~ 200 data-taking days

α – radioactive contaminants in scintillator

Signal shape from α-particles differs from electron signal



After background subtraction:

evidence for monoenergetic solar neutrinos from reaction

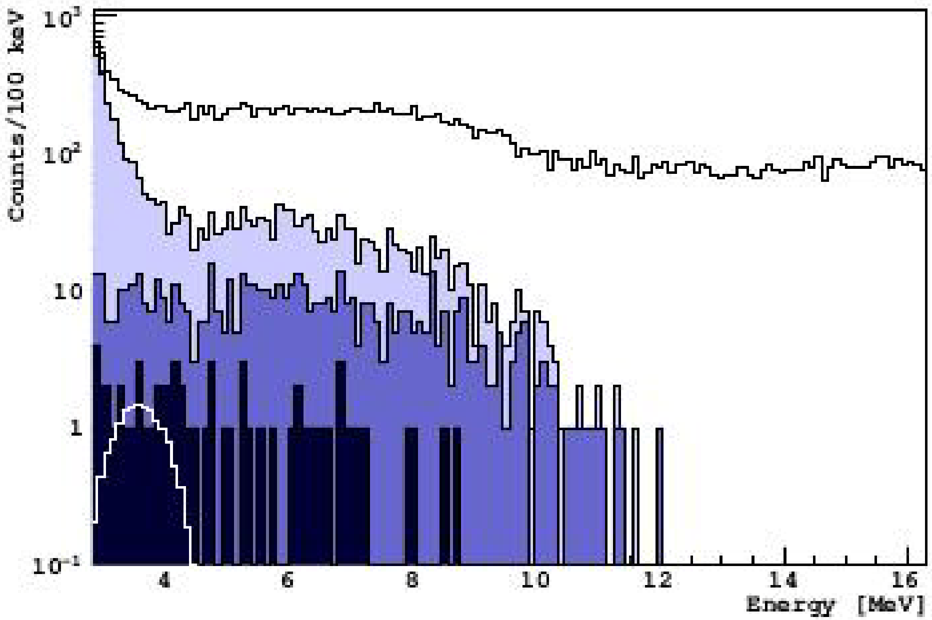
$e^{-} + Be^{7} \rightarrow \nu_e + Li^{7}$

$E(\nu_e) \approx 0.87$ **MeV**

Electron energy distribution from

$\nu_e + e^{-} \rightarrow \nu_e + e^{-}$

practically flat up to ~0.67 MeV



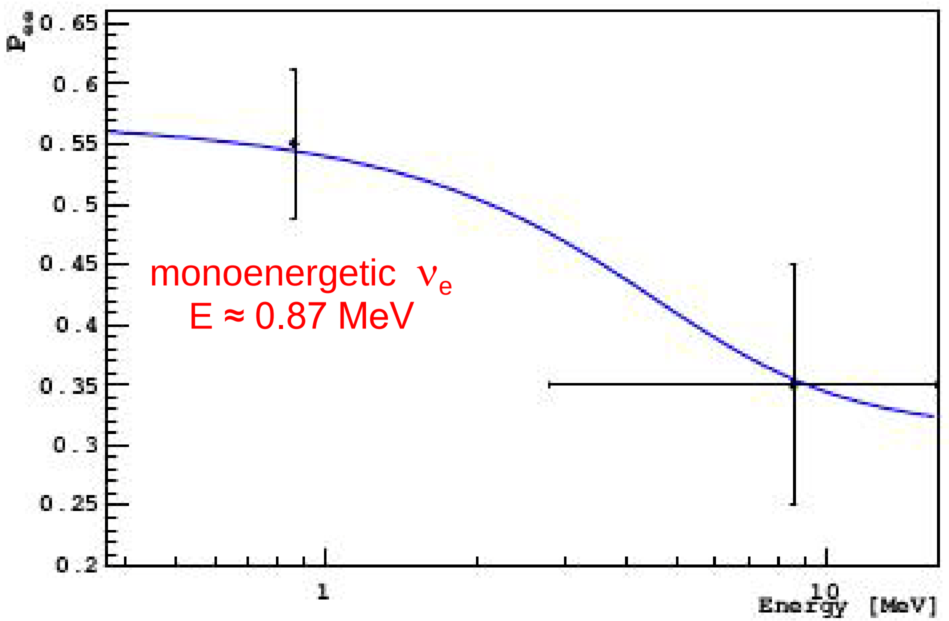
BOREXINO
Measured spectrum, E > 2 MeV

All events

After removal of cosmic rays (external anticoincidence)

Excluding events at < 1m from detector edge

After subtracting background from radioactive contaminants



Measurement of the solar ν_e deficit as a function of energy

$$P_{ee} = \frac{\text{N(measured events)}}{\text{N(SSM prediction)}}$$

Matter effects NEGLIGIBLE
For $E(\nu_e) = 0.87$ MeV

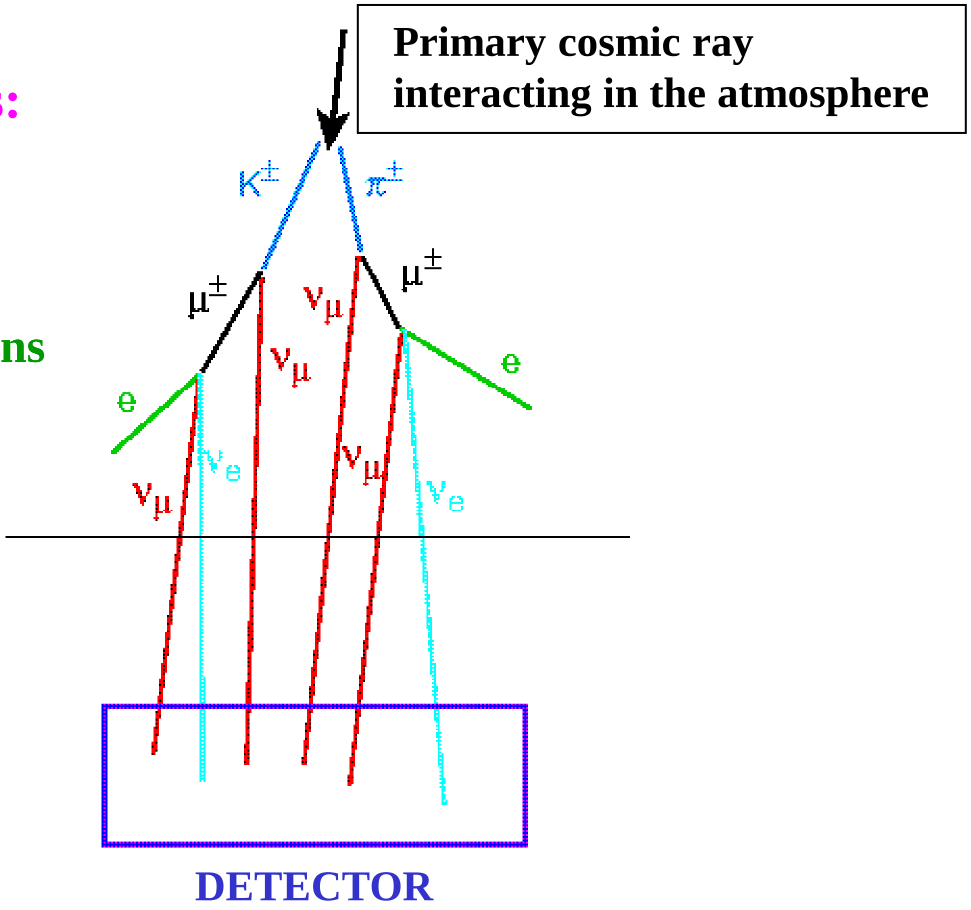
$$P_{ee} = 1 - \frac{1}{2}\sin^2(2\theta) \approx 0.57 \quad \text{(for } \theta = 34^o\text{)}$$

"Atmospheric" neutrinos

Main sources of atmospheric neutrinos:

$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$

$\hookrightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \nu_\mu(\bar{\nu}_\mu)$



For energies $E < 2$ GeV most pions and muons decay before reaching the Earth:

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

At higher energies most muons reach the Earth before decaying:

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} > 2$$

(increasing with E)

Atmospheric neutrino energies: 0.1 — 100 GeV

Very low event rates: ~100 /year for a 1000 ton detector

Typical uncertainty on the atmospheric neutrino fluxes: ± 30%

(from uncertainties on the primary cosmic ray spectrum, on hadron production, etc.)

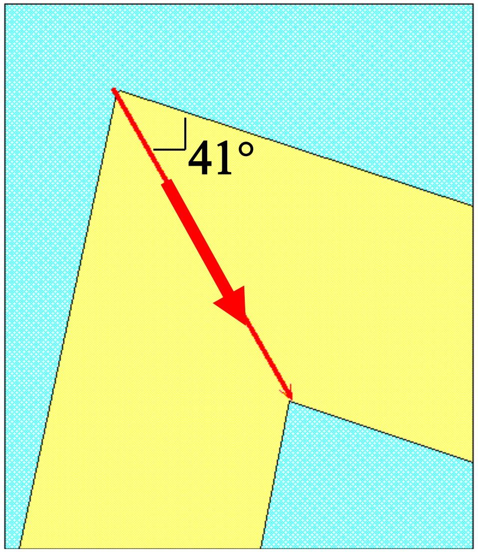
Incertainty on the ν_μ / ν_e ratio : ± 5%

Atmospheric neutrino detection

ν_μ + Nucleon $\rightarrow \mu$ + hadrons: presence of a long, minimum – ionizing track (the muon)

$\nu_e + n \rightarrow e^- + p$, $\bar{\nu}_e + p \rightarrow e^+ + n$: presence of an electromagnetic shower

(ν_e interactions with multiple hadron production cannot be easily distinguished from Neutral Current interactions $\nu + N \rightarrow \nu$ + hadrons)



Event identification in water Čerenkov detectors

Muon track:

d*E*/d*x* consistent with ionization minimum;

well defined edges of Čerenkov light ring

Electromagnetic shower:

high d*E*/d*x* (many secondary electrons);

fuzzy edges of Čerenkov light ring

(from the shower angular aperture)

Direct measurement of the electron / muon separation by exposing a 1000 ton water Čerenkov detector (a small copy of Super-K) to electron and muon beams from a proton accelerator. Measured probability of wrong identification ~2%

Measurement of the ν_μ / ν_e ratio: first hints for a new phenomenon

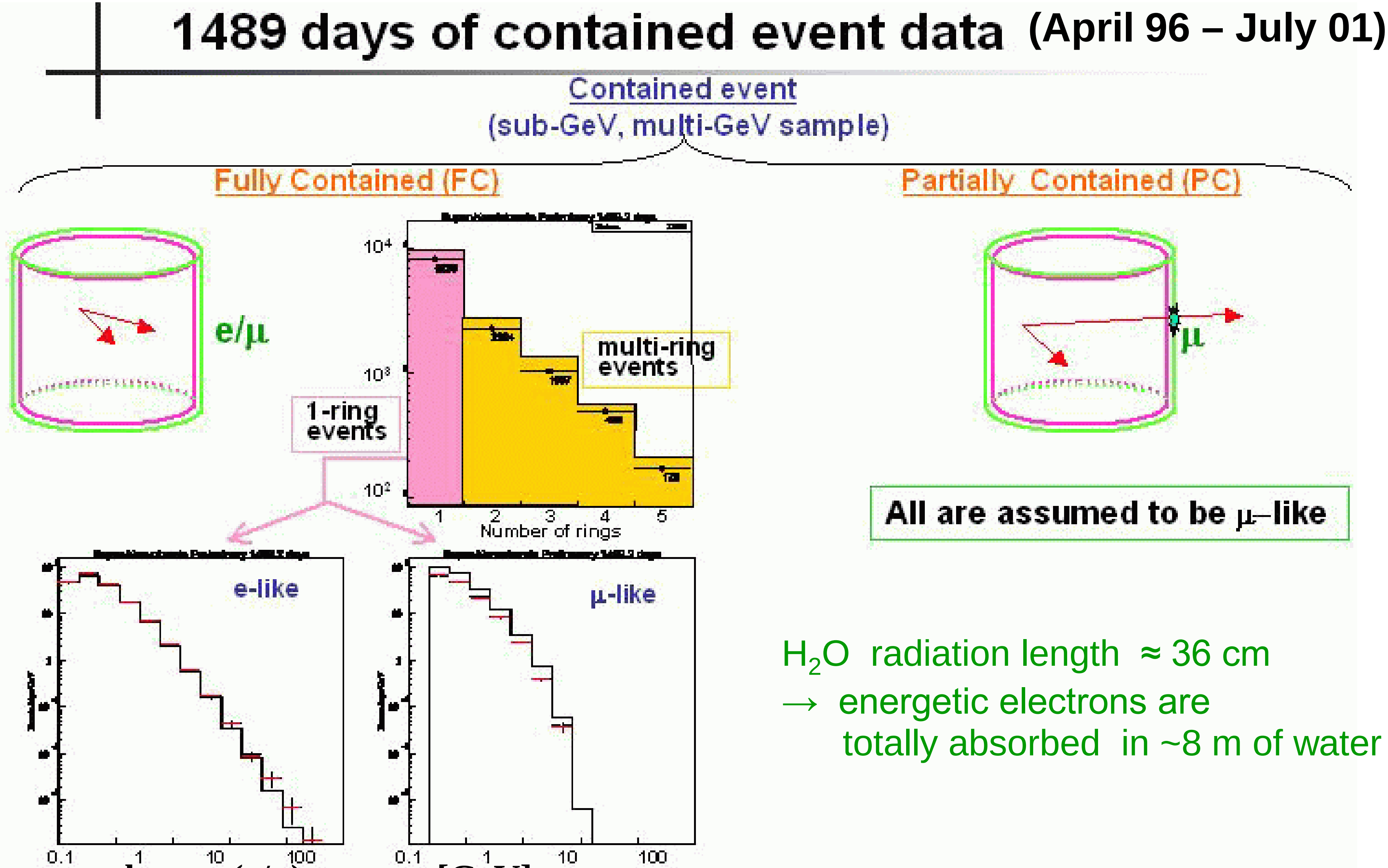
Water Čerenkov detectors: Kamiokande (1988), IMB (1991), Super-K (1998)

Conventional calorimeters (iron plates + proportional tubes): Soudan2 (1997)

$$R = \frac{(\nu_\mu/\nu_e)_{measured}}{(\nu_\mu/\nu_e)_{predicted}} = 0.65 \pm 0.08$$

Atmospheric neutrino events in Super-K

Distance between interaction point and inner detector walls ≥1 meter



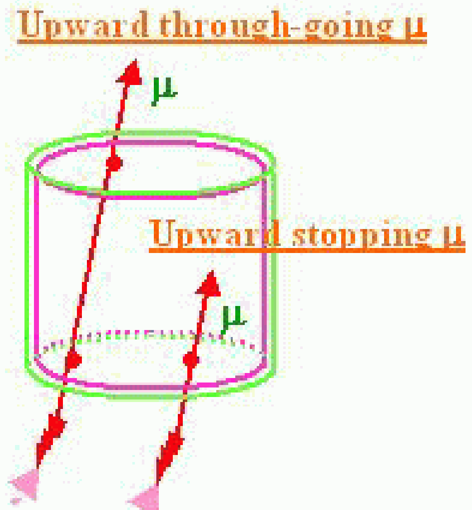
lepton (e/μ) energy [GeV]

H_2O radiation length ≈ 36 cm

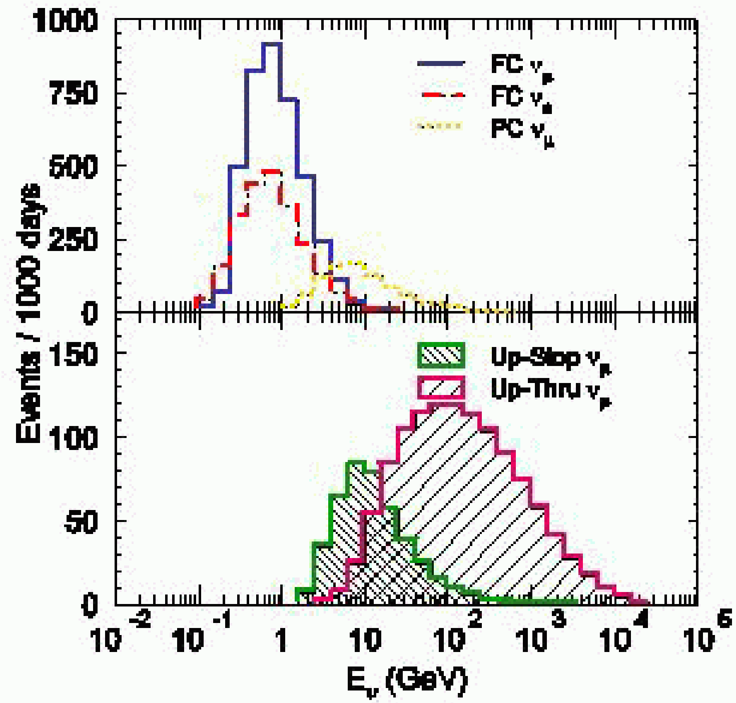
→ energetic electrons are totally absorbed in ~8 m of water

An additional event sample:

Up – going muons from ν_μ interactions in the rock



- different energy scale
- different detection technique



Up through-going μ, 1678days,	Obs. 1.7 +- 0.04 +- 0.02 ($\times 10^{-13} cm^{-2} s^{-1} sr^{-1}$)
	Exp. 1.97+-0.44
Up stopping μ, 1657days,	Obs. 0.41+-0.02+-0.02 ($\times 10^{-13} cm^{-2} s^{-1} sr^{-1}$)
	Exp. 0.73+-0.16

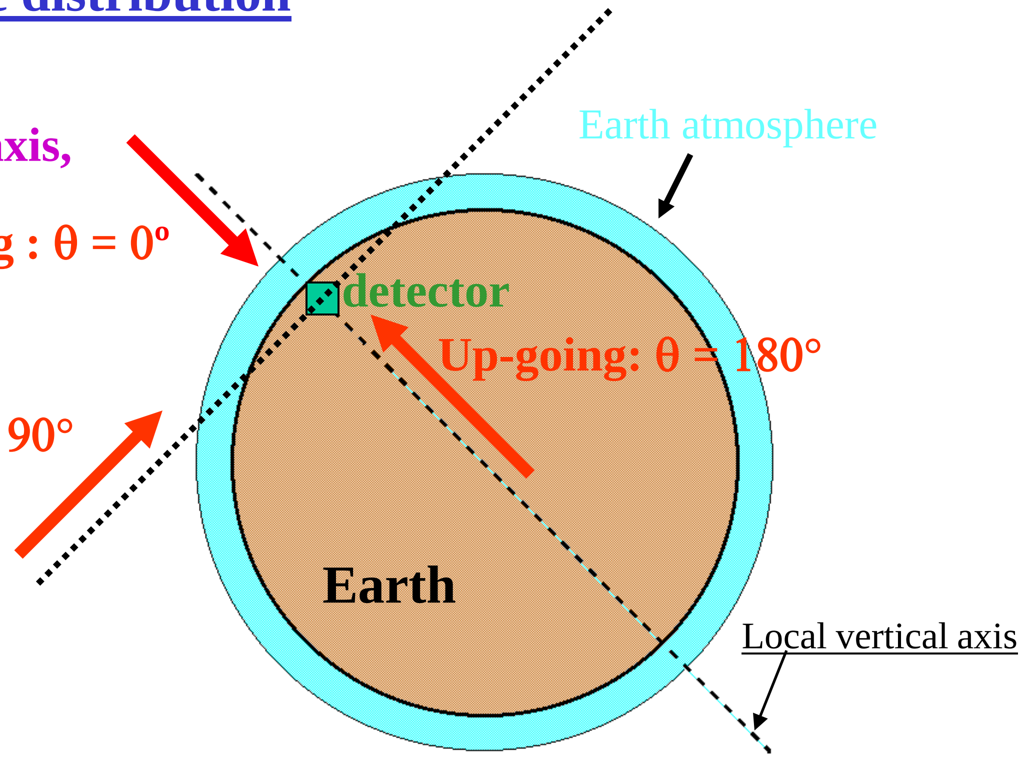
Note: down – going muons are mainly $\pi \to \mu$ decays in the atmosphere traversing the mountain rock and reaching the detector

Measurement of the zenith angle distribution

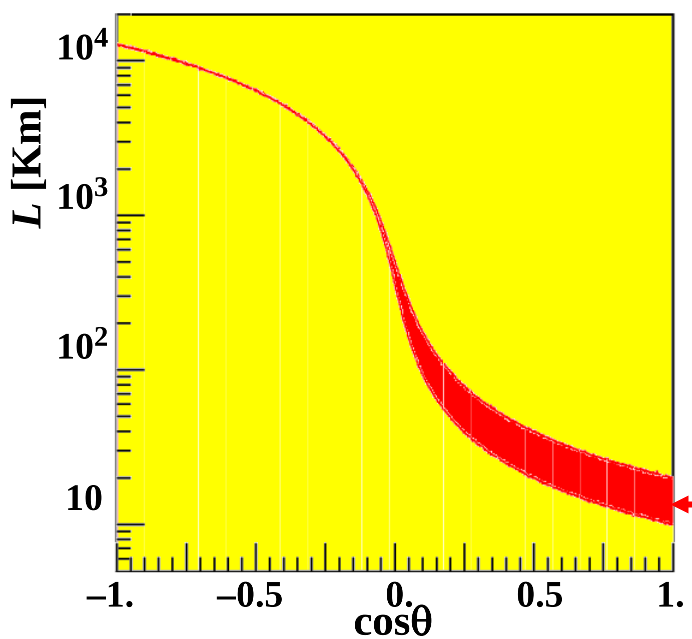
Definition of the zenith angle θ :
Polar axis along the local vertical axis, pointing downwards

Down-going : θ = 0º

Horizontal : θ = 90°



L **(distance between neutrino production point and detector) depends on zenith angle**

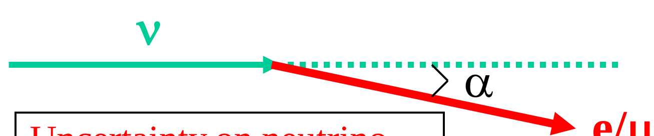


Uncertainty on neutrino production point ±5 km

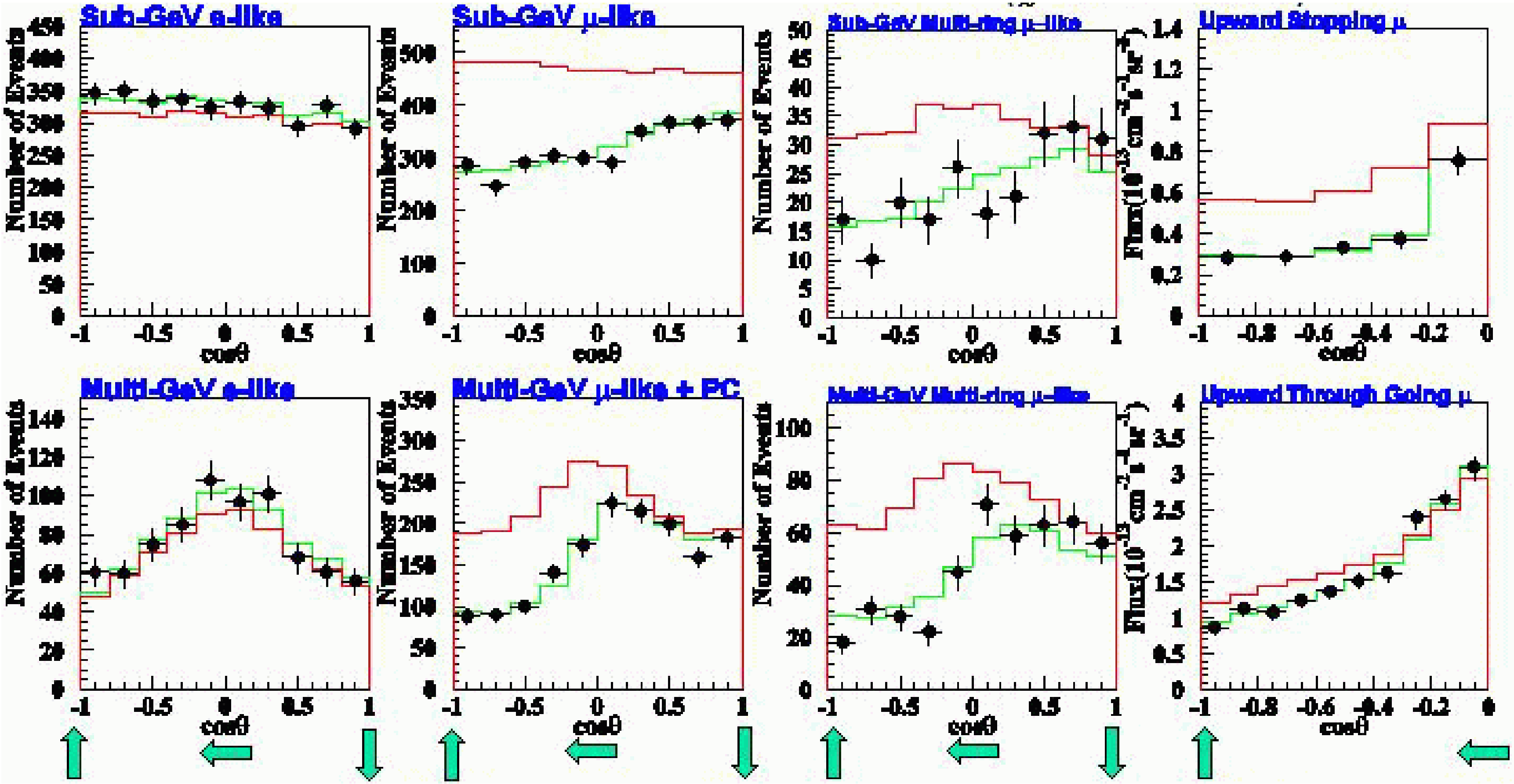
θ = 0º — 180º
L = ~10 — ~12800 km

➡ **Search for oscillations with variable distance *L***

Strong angular correlation between incident neutrino and produced electron/muon for *E* > 1 GeV:
α ≈ 25° at *E* = 1 GeV;
α → 0 for increasing *E*



Zenith angle distribution in Super-K



No oscillation (χ^2 = 456.5 / 172 degrees of freedom)

$\nu_\mu - \nu_\tau$ oscillation (best fit): $\Delta m^2 = 2.5\times10^{-3}$ eV^2, $\sin^2 2\theta = 1.0$

χ^2 = 163.2 / 170 degrees of freedom

Zenith angle distributions in the Super-K experiment:

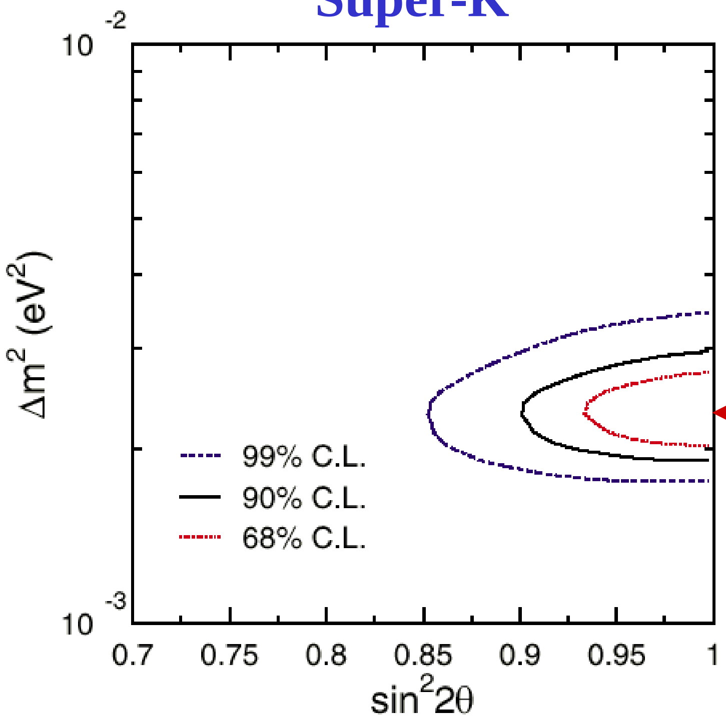
Evidence for ν_μ disappearance over ~1000 — 10000 km distance

Not a $\nu_\mu - \nu_e$ oscillation:

- **ν_e disappearance from oscillations with $\Delta m^2 > 10^{-3}$ eV^2 excluded by the CHOOZ experiment (discussed later)**
- **For $\nu_\mu - \nu_e$ oscillation expect a zenith angle distribution for "e-like" events with opposite asymmetry (excess of up-going "e-like" events) because $\nu_\mu / \nu_e \geq 2$ at production**

The most plausible interpretation: $\nu_\mu - \nu_\tau$ oscillation

Super-K



$\nu_\tau + N \rightarrow \tau + X$ requires $E(\nu_\tau) > 3.5$ GeV;
fraction of $\tau \rightarrow \mu$ decays $\approx 18\%$

Region of oscillation parameters
$1.9 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2
$\sin^2 2\theta > 0.90$
(confidence level 90%)

CHOOZ

Search for $\bar{\nu}_e$ disappearance over ~1 km distance
Sensitivity to $\Delta m^2 > 7 \times 10^{-4}$ eV^2

Two nuclear reactors at the CHOOZ (EDF) power plant
Total thermal power 8.5 GW
L = 998, 1114 m

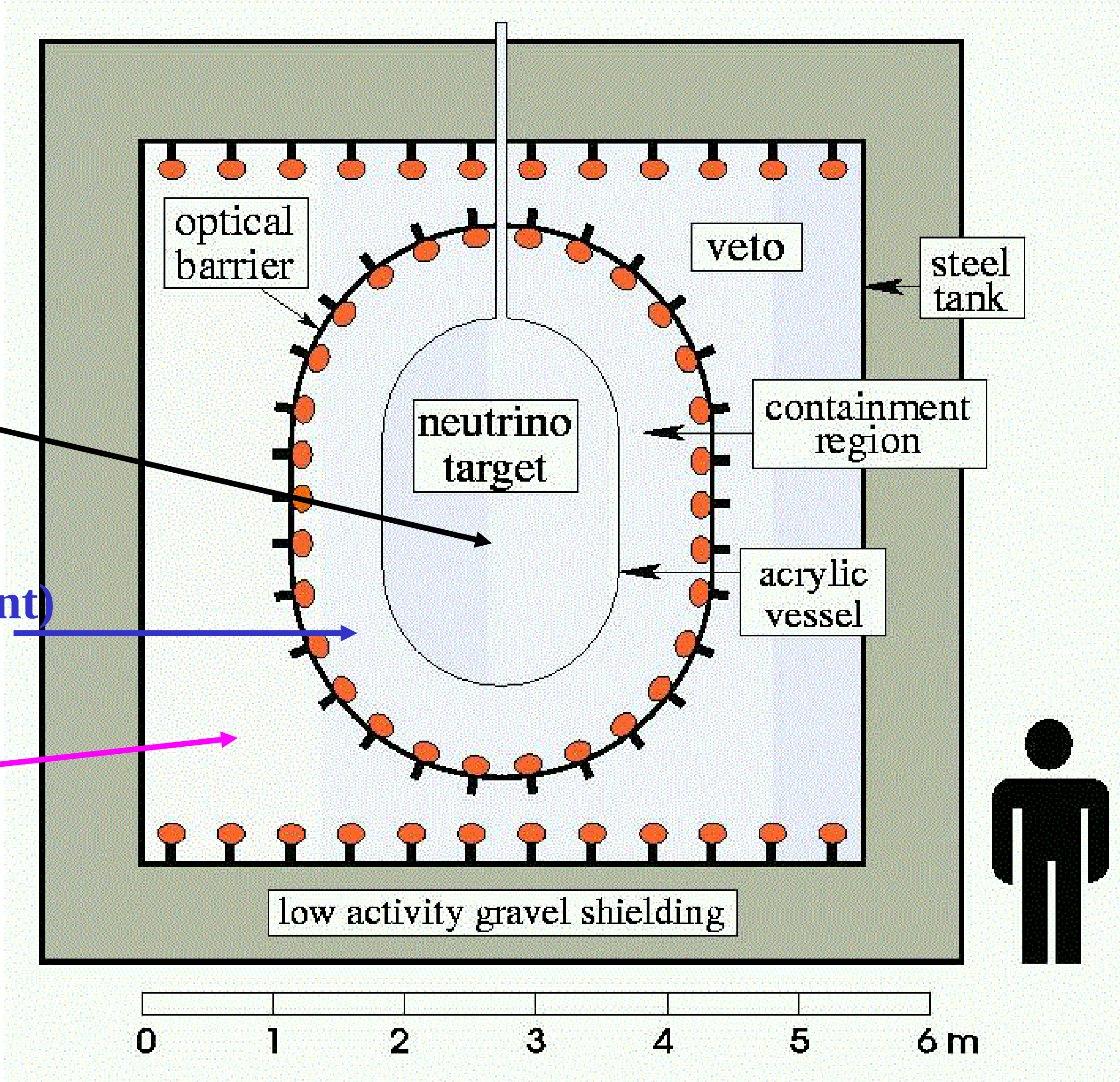
<u>Detector</u>:
5 ton Gadolinium-enriched liquid scintillator
n + Gd → γ rays
Total energy 8.1 MeV

17 ton liquid scintillator without Gd (γ –ray containment)

90 ton liquid scintillator
(cosmic ray veto)

Underground site:
depth 300 m H_2O eq.
(negligible matter effects)

Data – taking : 1997–98
Experiment completed in 1998



Event rate at max. power : 25 / day

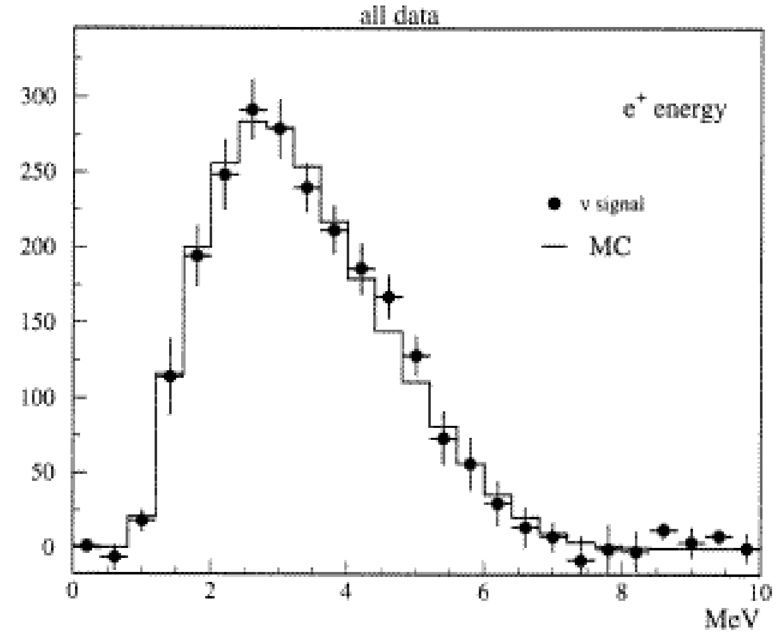
Background (reactors OFF): 1.2 / day

Positron energy spectrum

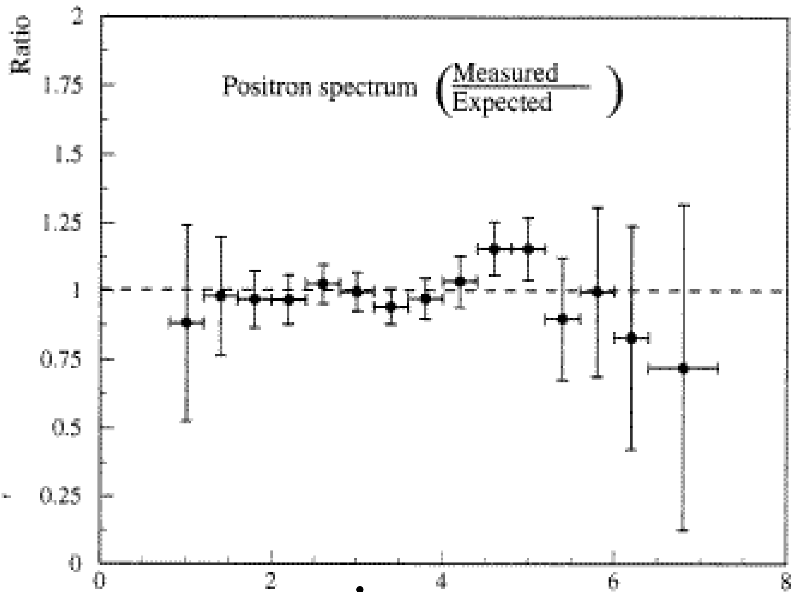
(prompt signal from $\bar{\nu}_e + p \rightarrow n + e^+$)

Comparison with predicted spectrum

for no oscillation



$$\frac{\text{Measured spectrum}}{\text{Predicted spectrum (no oscillation)}}$$



positron energy

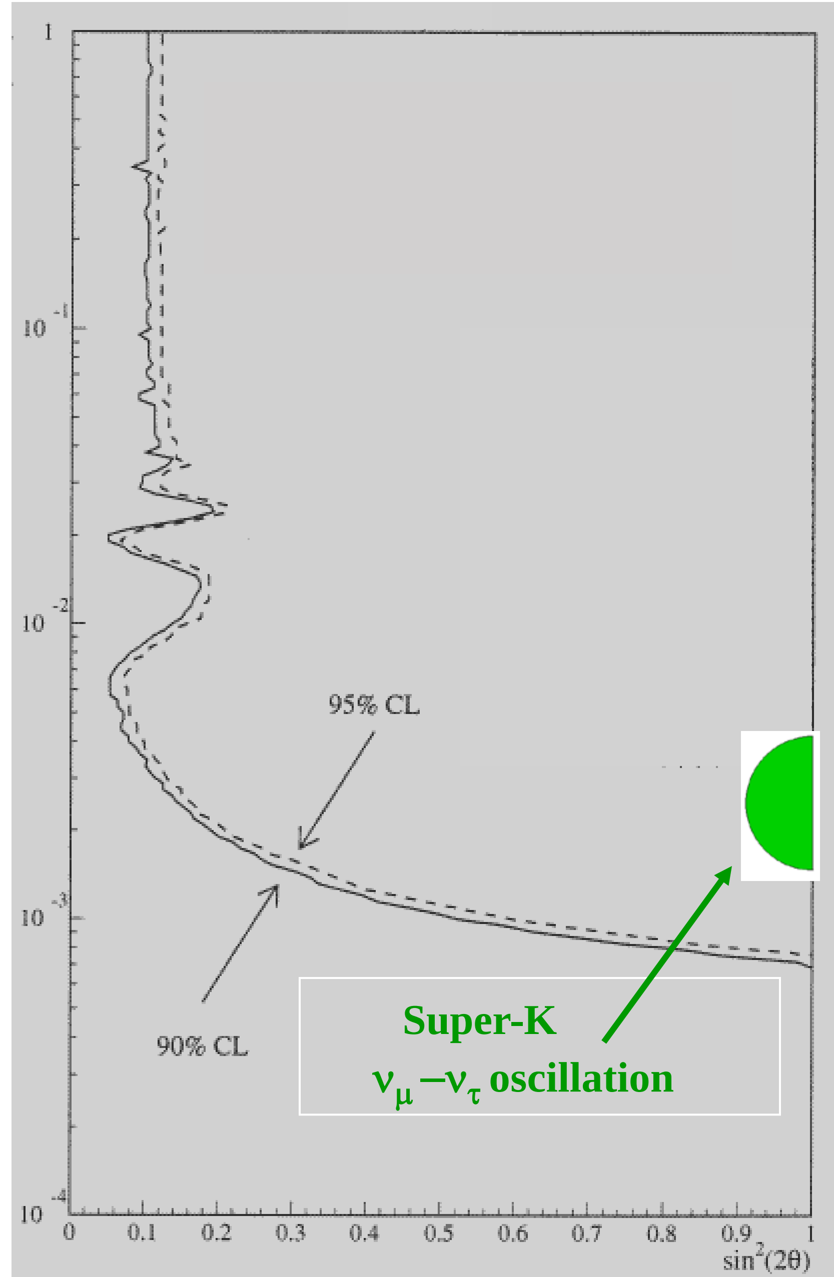
Energy – integrated ratio

= 1.010 ± 0.028 ± 0.027

no evidence for $\bar{\nu}_e$ disappearance

CHOOZ Experiment

$\bar{\nu}_e - \bar{\nu}_\mu$ ($\bar{\nu}_e - \bar{\nu}_\tau$) oscillation: excluded region



Summary

- **Solar ν_e oscillation:**
  $\Delta m^2 \approx 7.6 \times 10^{-5}$ eV^2 , $\theta \approx 34°$

- **Atmospheric ν_μ oscillation:**
  $\Delta m^2 \approx 2.5 \times 10^{-3}$ eV^2 , $\theta \approx 45°$

- **ν_e oscillation with $\Delta m^2 \approx 2.5 \times 10^{-3}$ eV^2**
  <u>not observed</u>: $\theta < 11.5°$

Searches for long baseline oscillations using neutrino beams from accelerators

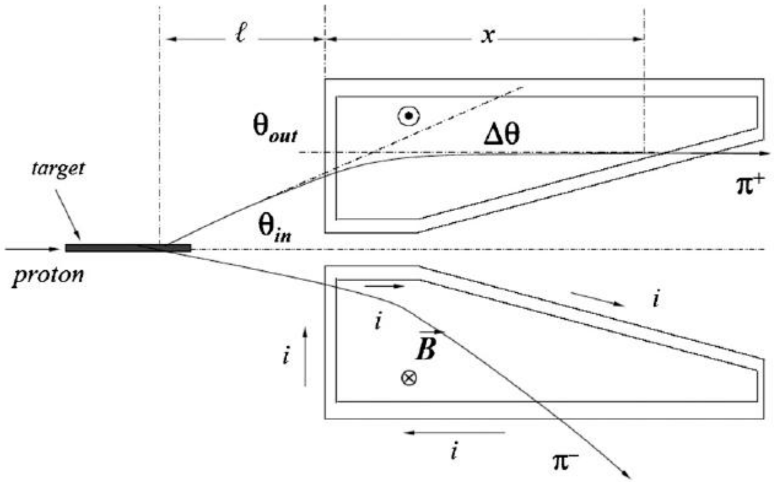
Motivations:

- **Conclusive demonstration that the atmosferic ν_μ deficit is due to neutrino oscillations using ν_μ beams from proton accelerators (directional beams with known energy spectra):**
  - Distortions of the ν_μ energy distribution $\rightarrow$ measurement of Δm^2, $\sin^2 2\theta$;
  - ν_τ appearance at long distance from source in a beam with no ν_τ at production.
- **Measurement of the Neutral Current event rate to distinguish $\nu_\mu - \nu_\tau$ from $\nu_\mu - \nu_s$ oscillations (ν_s: a possible "sterile" neutrino);**
- **Search for $\nu_\mu - \nu_e$ oscillations driven by the Δm^2 value associated with the atmospheric neutrino deficit.**

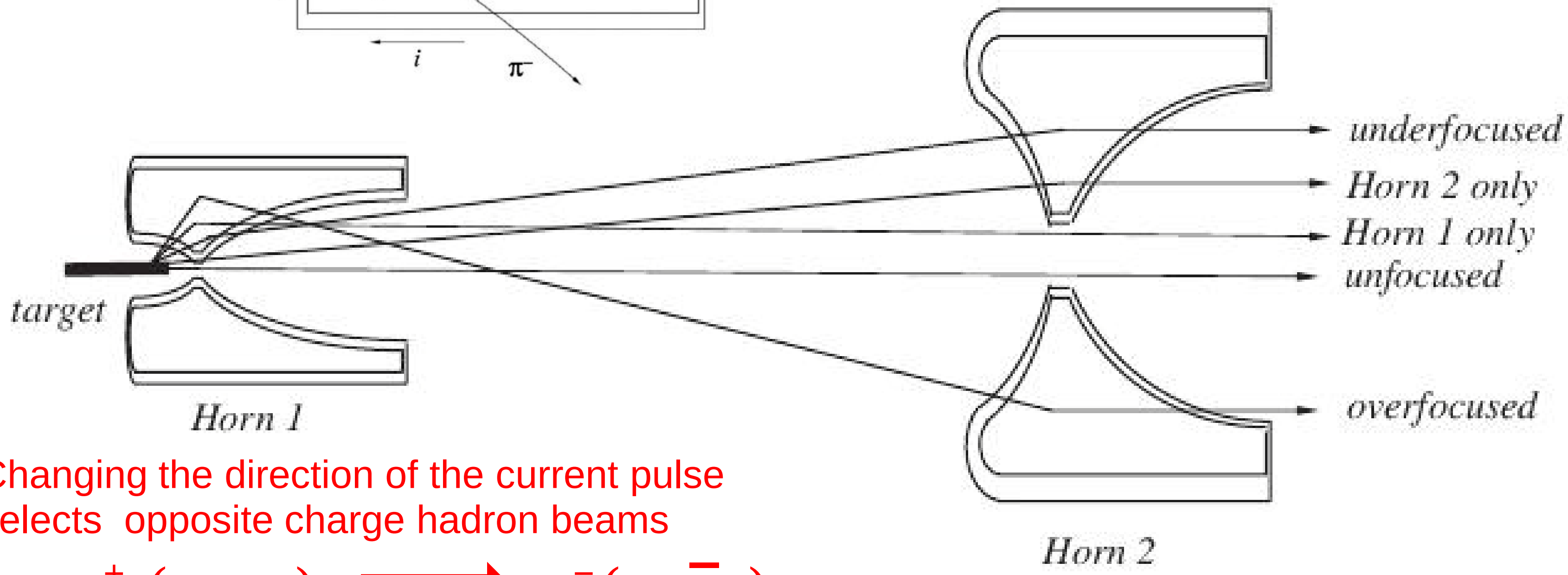
Wide band neutrino beams from accelerators

Focusing of positively or negatively charged hadrons to produce an almost parallel beam with wide momentum distribution using "magnetic horns" (invented at CERN in 1963 by S. Van der Meer)

The horns are followed by a long decay tunnel under vacuum



- Axially symmetric conductors
- Pulsed current
- Cylindrically symmetric magnetic field perpendicular to the hadrons produced in the target

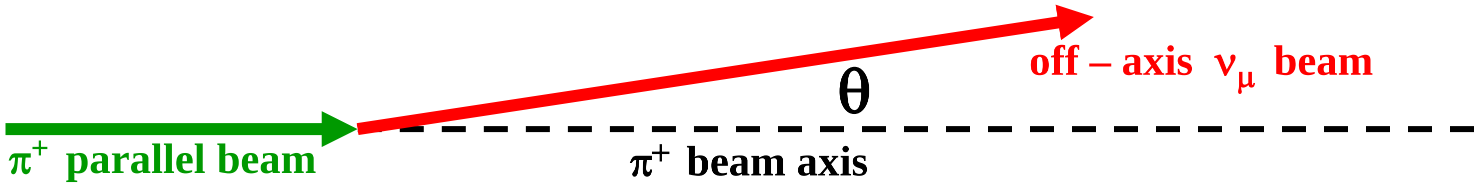


Changing the direction of the current pulse selects opposite charge hadron beams

$\pi^+ \; (\rightarrow \nu_\mu) \;\Rightarrow\; \pi^- (\rightarrow \bar{\nu}_\mu)$

“On – axis” neutrinos (emitted at decay angles $\theta = 0^o$ with respect to the hadron beam) have a wide momentum distribution.

“Off –axis” beams have narrower energy distributions but lower fluxes



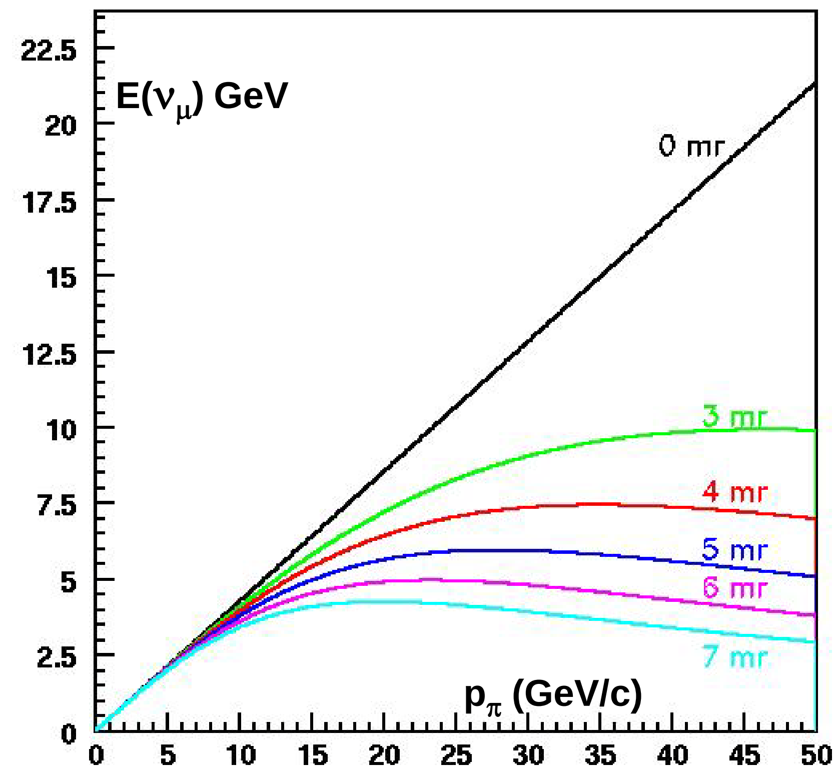
ν_μ energy at <u>fixed</u> θ :
(from Lorentz transformation)

$$E = \frac{E^*}{\gamma_\pi (1 - \beta_\pi \cos\theta)}$$

E^*: ν_μ energy in the π^+ rest frame (0.03 GeV)
$\gamma_\pi = E_\pi / m_\pi$
$\beta_\pi = v_\pi / c$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ decay
ν_μ energy versus π^+ momentum for different ν_μ angles θ

For $\theta > 0$ neutrino beams are enriched in monoenergetic neutrinos but flux is reduced by a factor ~4

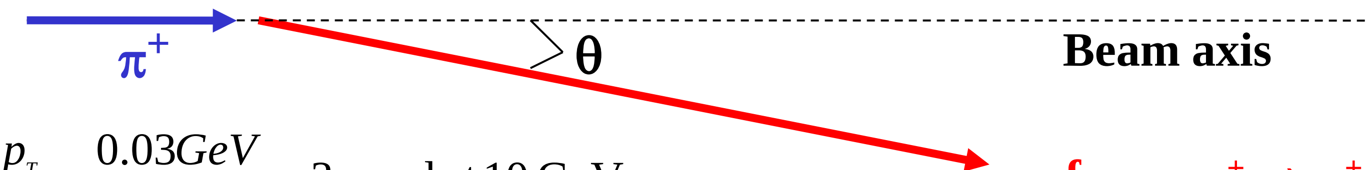


Monoenergetic neutrinos:
first oscillation maximum at $L = \lambda_{osc} / 2$

Project	Distance L	$< E_\nu >$	ν beam type	Status
K2K	250 km	1.3 GeV	on – axis	completed
MINOS	735 km	few GeV	on – axis	data – taking
CNGS	732 km	17 GeV	on – axis	data – taking
T2K	295 km	~0.6 GeV	off – axis	few events
NOνA	810 km	~1.6 GeV	off – axis	under construction

- **Energy threshold for $\nu_\tau + N \to \tau^- + X$: $E_\nu > 3.5$ GeV**
- **Event rate ~1 $\nu_\mu \to \mu^-$ event / year for one ton detector mass**

  ⟶ **need detector masses of several kiloton.**
- **Angular divergence of the ν_μ beam from pion decay :**



$$\theta \approx \frac{p_T}{p_L} \approx \frac{0.03GeV}{E_\nu[GeV]} = 3\,\text{mrad at } 10\,\text{GeV}$$

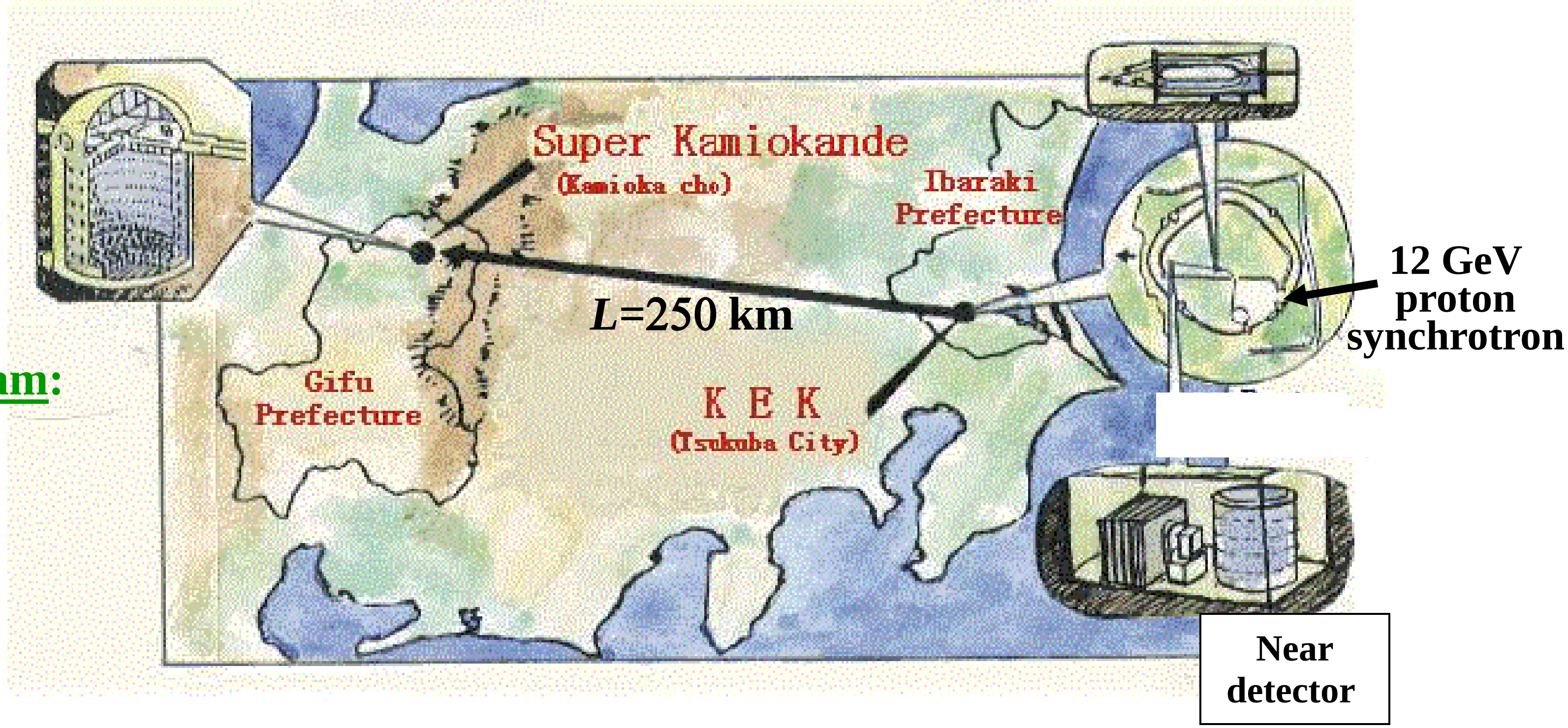
ν_μ from $\pi^+ \to \mu^+ \nu_\mu$ decay

Neutrino beam lateral dimensions: 100 m – 1 km for $L > 100$ km

⟶ **no problem to hit the far detector**

The neutrino flux decreases as L^{-2} at large distance L

K2K



Neutrino beam:
95% ν_μ
4% $\bar{\nu}_\mu$
1% ν_e

Near detector: measurement of ν_μ flux and ν_μ interaction rate in the absence of oscillation

1 kton water Čerenkov counter: similar to Super-K; fiducial mass 25 ton

Muon chambers: measurement of muon energy spectrum from $\pi \rightarrow \mu$ decay

Data - taking: from June 1999 to February 2004 (8.9 x 10^{19} protons on target)

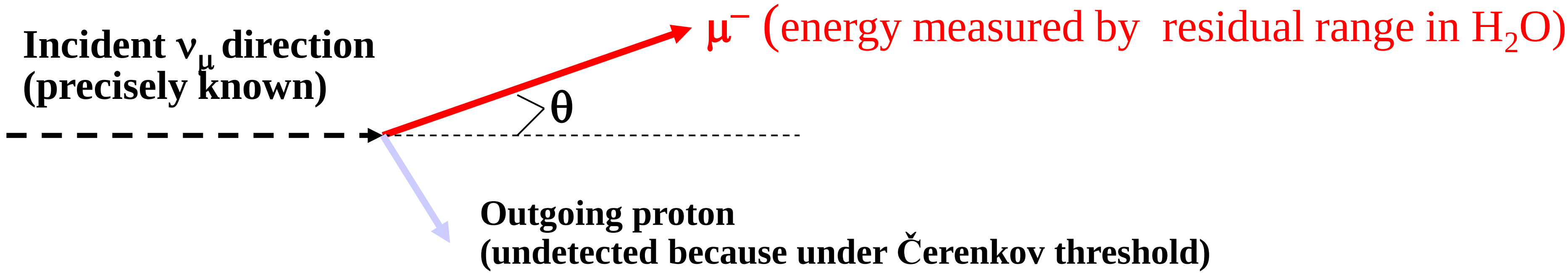
Events fully contained in the Super-K detector, E_{vis} > 30 MeV:

predicted ($\mathscr{P}_{osc} = 0$): 151^{+12}_{-10} events

observed: 107 events

Contained events with only one muon: 57

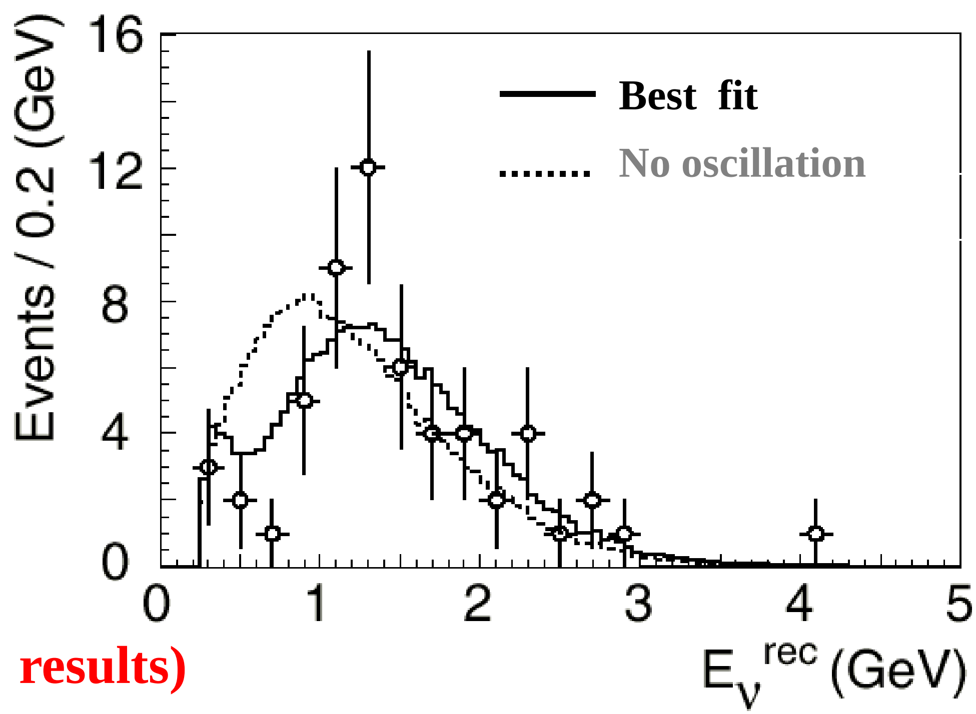
Measurement of the ν_μ energy spectrum in Super-K from the 57 1μ events assuming quasi-elastic scattering $\nu_\mu + n \rightarrow \mu^- + p$



Quasi-elastic scattering kinematics assuming target neutron at rest
⇒ ν_μ energy determination:

$$E_\nu = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu \cos\theta}$$

($M \equiv$ nucleon mass)



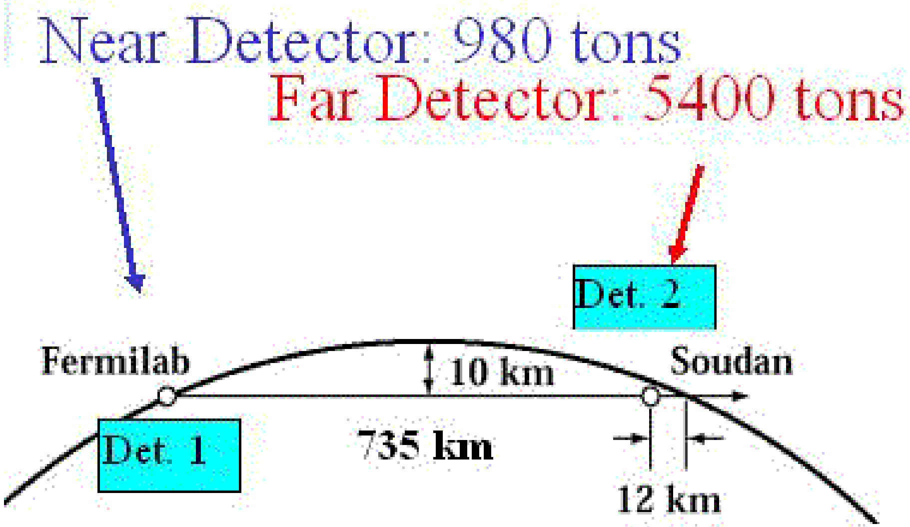
Best fit: $\Delta m^2 = 2.2 \times 10^{-3}$ eV^2
$\sin^2 2\theta = 1$
(in agreement with atmospheric ν_μ results)

Probability of no oscillation 5×10^{-5}

(equivalent to 4 standard deviations)

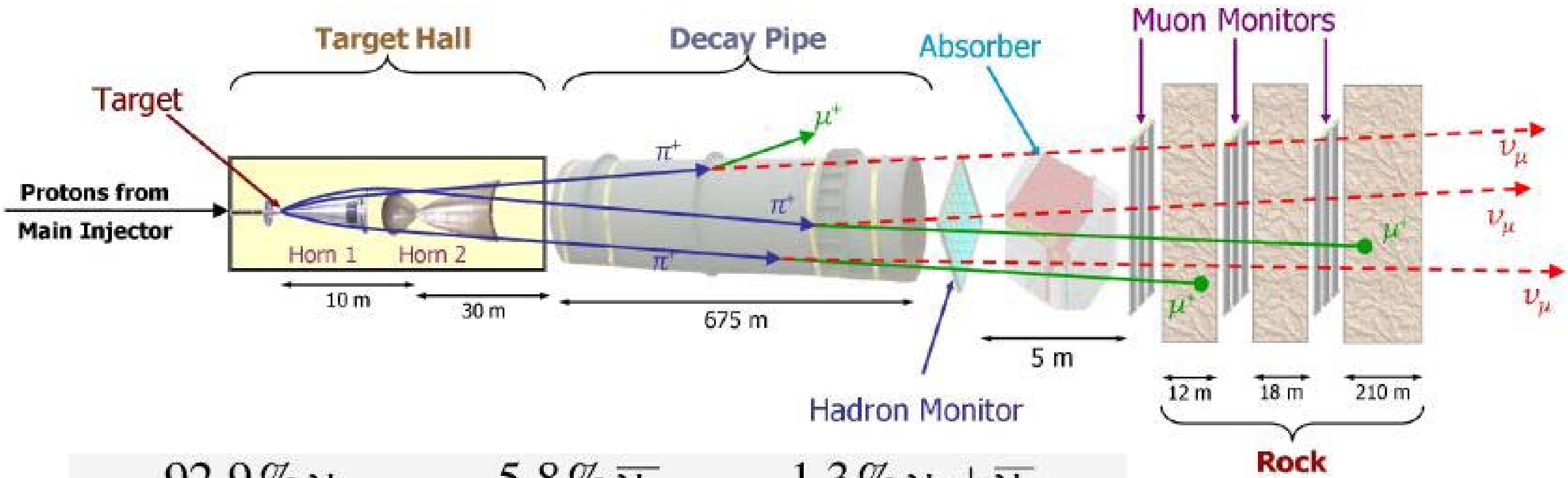
MINOS experiment

Neutrino beam from Fermilab to Soudan (an old iron mine in Minnesota):
***L* = 735 km**



Accelerator:
Fermilab Main Injector (MI)
120 GeV proton synchrotron
High beam intensity (0.4 MW):
$4x10^{13}$ protons per cycle (1.9 s)
$4x10^{20}$ protons / year
Decay tunnel : 700 m

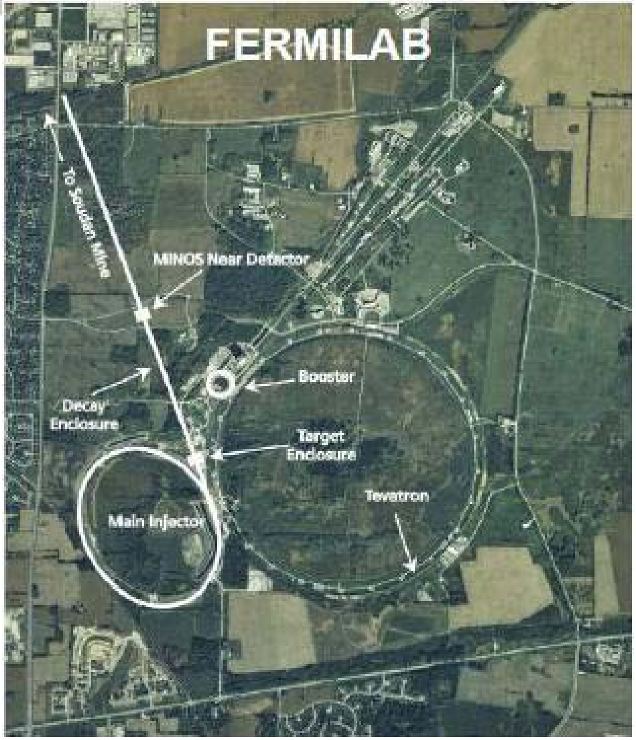
NUMI beam ("Neutrinos from Main Injector")



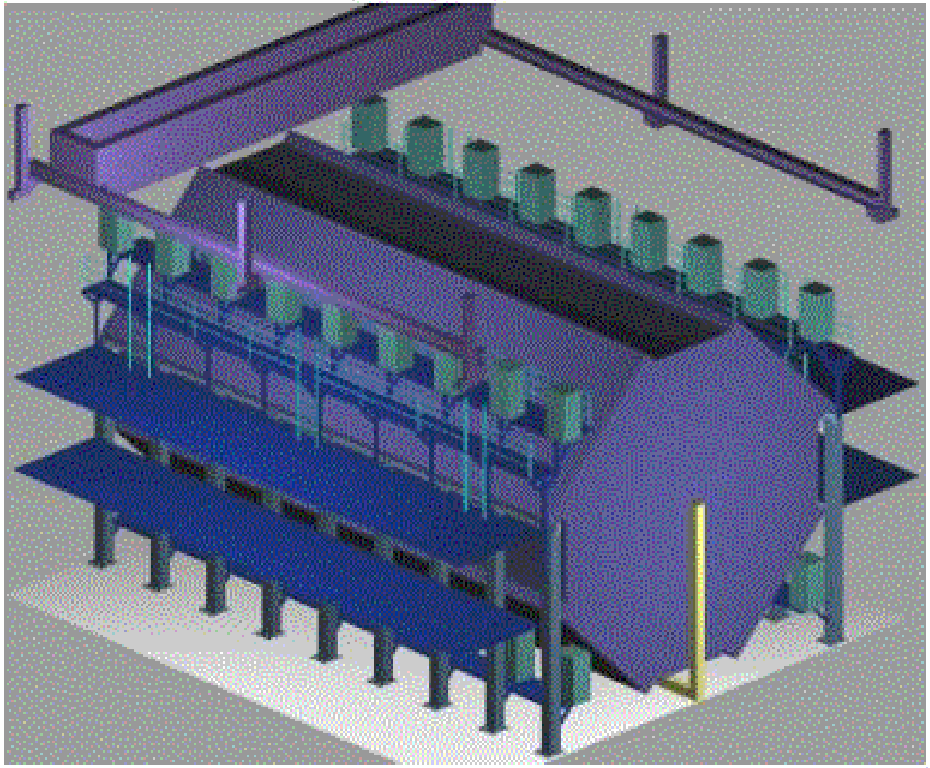
$$92.9\,\%\,\nu_\mu \qquad 5.8\,\%\,\overline{\nu}_\mu \qquad 1.3\,\%\,\nu_e + \overline{\nu}_e$$

The neutrino beam average energy can be changed by varying the target – magnetic horn distance and the horn current

Aerial view
of the Fermilab accelerators →



MINOS: Far detector



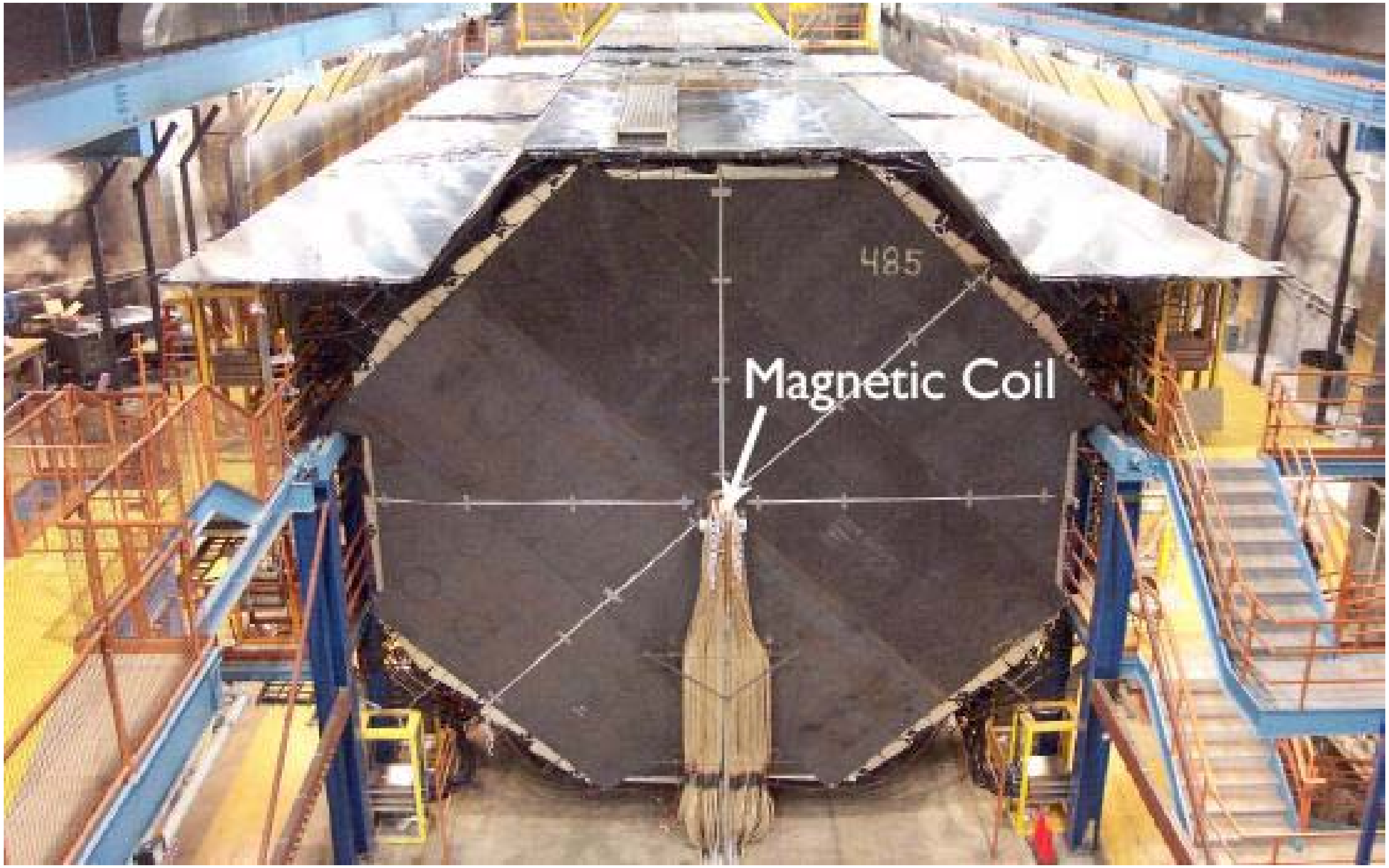
- Octagonal tracking calorimeter diameter 8 m
- Iron plates 2.54 cm thick
- Plastic scintillator 4 cm wide strips between adjacent iron plates
- 2 modules, each 15 m long
- total mass 5400 tons, fiducial mass 3300 tons.
- 484 scintillator planes (26000 m^2)
- Magnetized iron plates: toroidal field, B = 1.5 T

MINOS: Near detector

- "Octagonal" tracking calorimeter , 3.8x4.8 m
- Construction similar to far detector
- 282 magnetized iron plates
- Total mass 980 tons, fiducial mass 100 tons
- Installed 250 m downstream of the decay tunnel end

Start – up of data – taking: 2005

MINOS: far detector



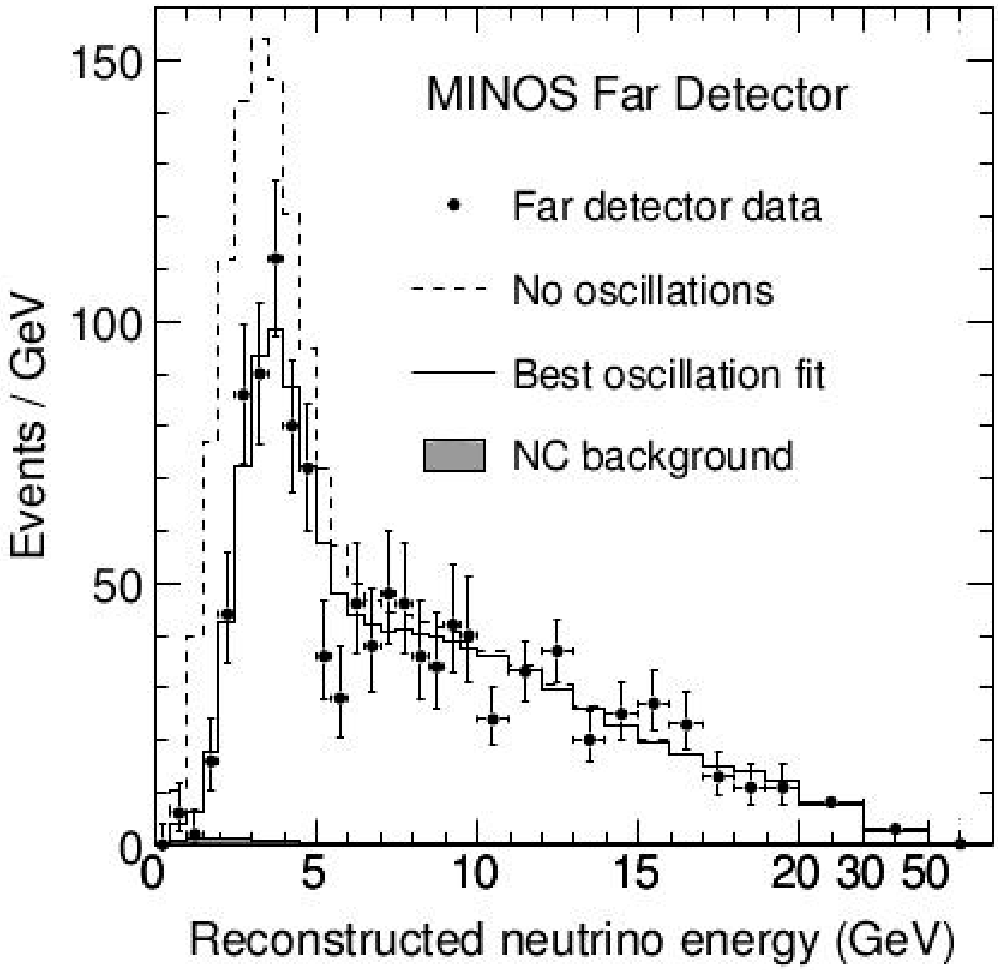
MINOS results (June 2008)

P. Adamson et al., Phys. Rev. Letters 101, 131802 (2008)

3.36 x10^{20} protons on target (May 2005 → July 2007)

Two neutrino beams: low energy (<E_ν> ≈5 GeV); high energy (<E_ν> ≈13 GeV)

ν beam typical composition: 93% ν_μ , 6% $\bar{\nu}_\mu$, 1.2% ν_e , 0.1% $\bar{\nu}_e$

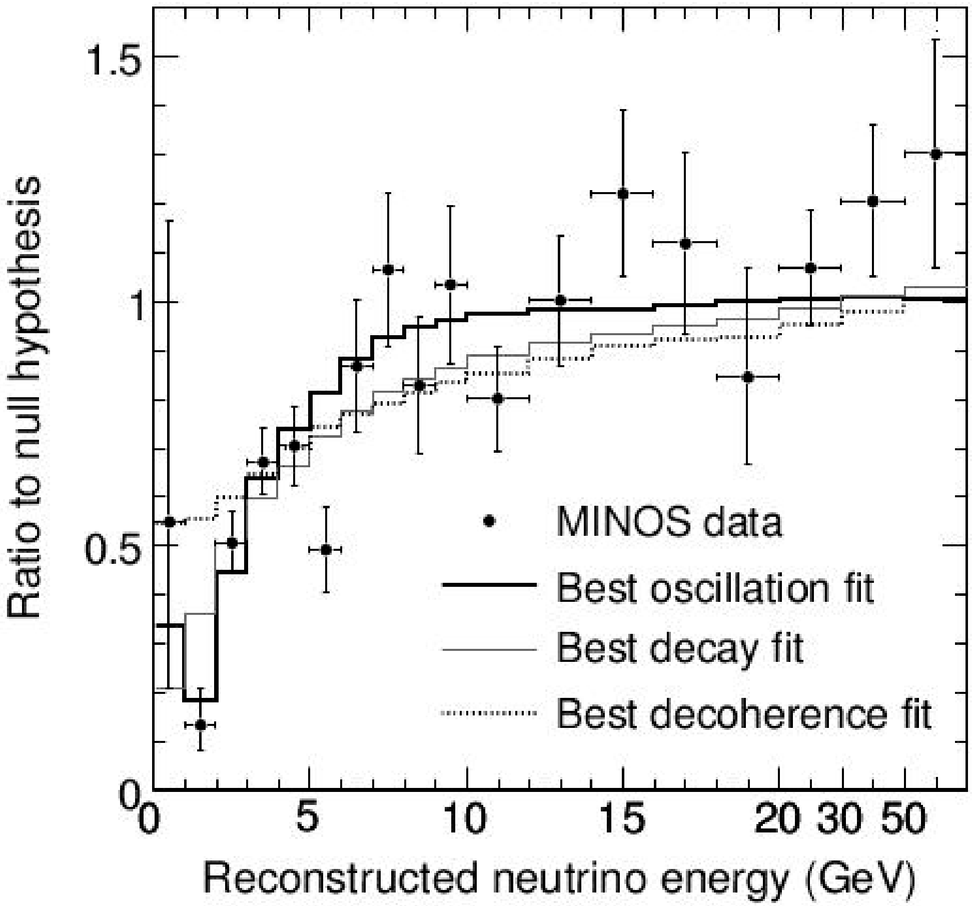


ν_μ + N → μ^- + X events

Low energy beam : 730 events;

High energy beam: 848 events

$$\frac{\textbf{Data}}{\textbf{Prediction} \; (\mathscr{P}_{osc} = 0)}$$



Best fit :

Δm^2 **= (2.43 ± 0.13) x** 10^{-3} **eV**^{2}

$\sin^2(2\theta) > 0.95$

(confidence level 68%)

CNGS (CERN Neutrinos to Gran Sasso)

Search for ν_τ appearance at L = 732 km

Predicted number of $\nu_\tau + N \rightarrow \tau^- + X$ (N_τ) events:

$$N_\tau = A \int_{3.5GeV}^{E_{max}} \Phi_\mu(E) \mathscr{P}_{\mu\tau}(E) \sigma_\tau(E) dE$$

Normalization: depends on detector mass, running time, detection efficiency, etc.

ν_μ flux

τ^- production cross-section

$\nu_\mu - \nu_\tau$ oscillation probability ($\mathscr{P}_{\mu\tau}$):

$$\mathscr{P}_{\mu\tau} = \sin^2(2\theta)\sin^2(1.27\Delta m^2 \frac{L}{E}) \approx 1.27^2 \sin^2(2\theta)(\Delta m^2)^2 \left(\frac{L}{E}\right)^2$$

Good approximation for : L = 732 km, E > 3.5 GeV, $\Delta m^2 < 4\text{x}10^{-3}$ eV^2

$$N_\tau \approx 1.61 \sin^2(2\theta)(\Delta m^2)^2 L^2 \int_{3.5GeV}^{E_{max}} \Phi_\mu(E) \frac{\sigma_\tau(E)}{E^2} dE$$

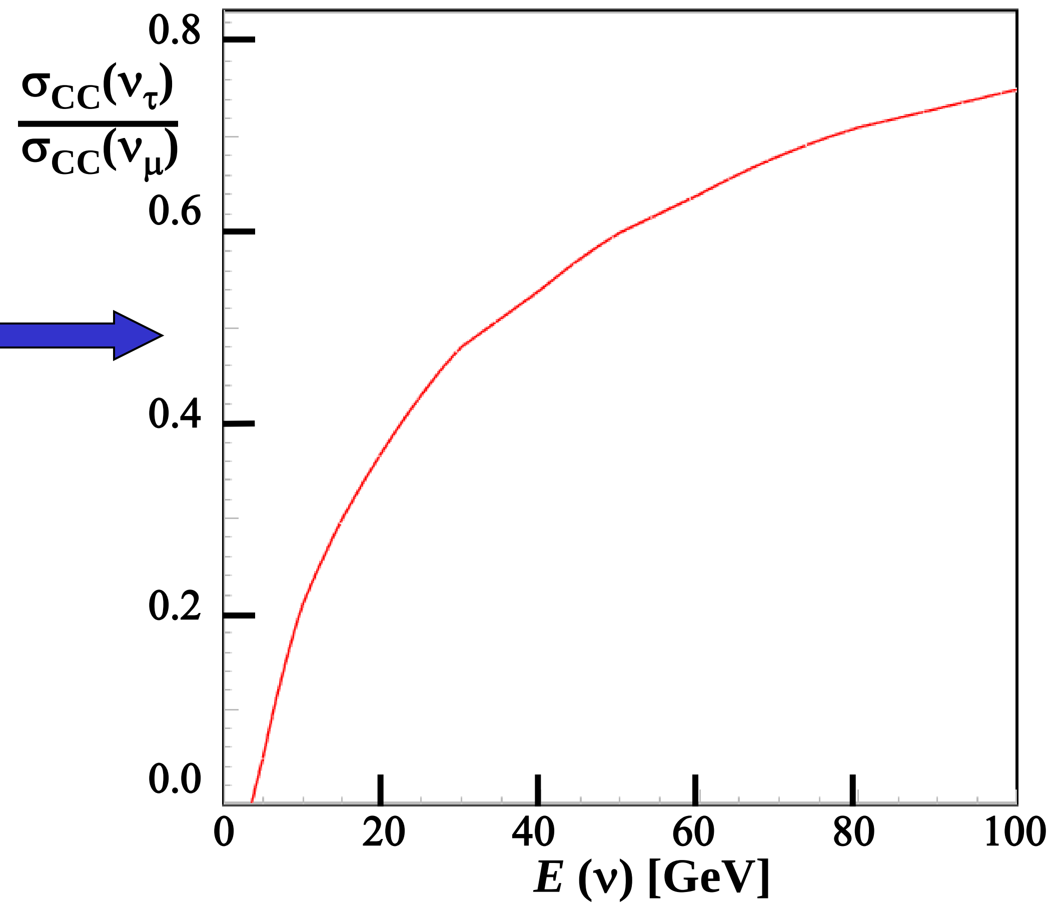
Disadvantages:

- **L = 732 km: distance << $\nu_\mu - \nu_\tau$ oscillation length**
- **N_τ depends on $(\Delta m^2)^2$ $\Rightarrow$ very low event rate at small Δm^2 values**

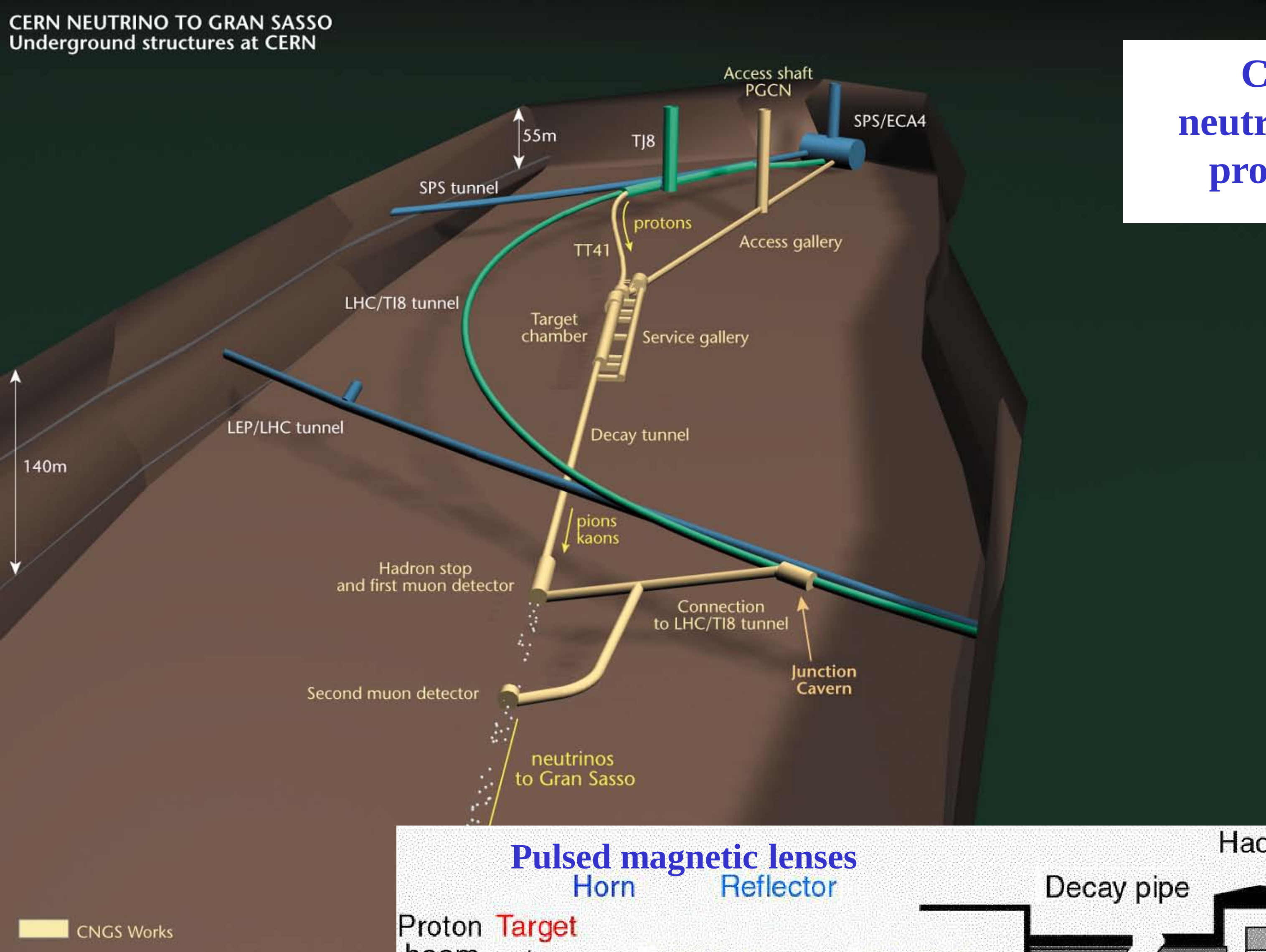
Advantages:

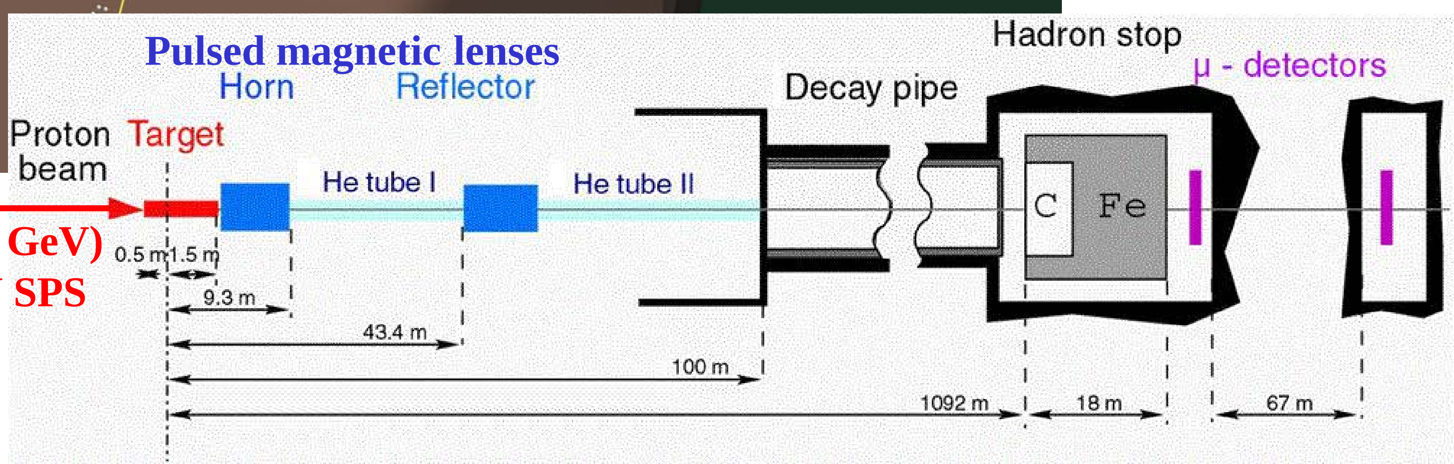
- **Beam optimization independent of Δm^2**

$\nu_\tau + N \rightarrow \tau^- + X$:
suppression factor with respect to
$\nu_\mu + N \rightarrow \mu^- + X$
from τ mass effects



CNGS: neutrino beam production

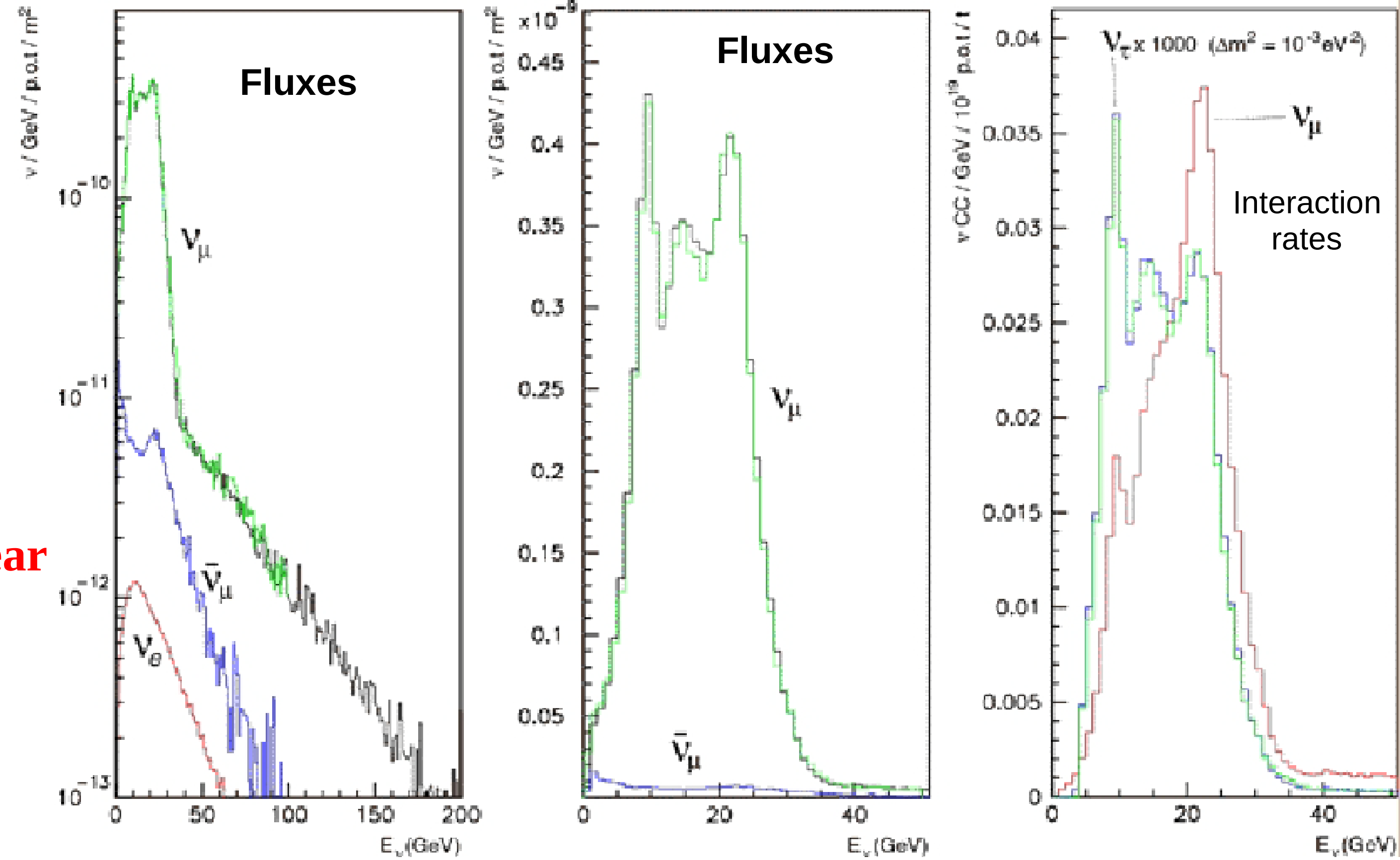




Proton beam (400 GeV) from the CERN SPS

Beam energy spectra and interaction rates at Gran Sasso

Primary protons:
400 GeV;
4x2.3x10[13] / SPS cycle
SPS cycle: 26.4 s
Running efficiency 75%
Data-taking 200 days/year
Protons on target:
4.5 x 10[19] / year



Process	Rates (events/kton/year)
ν_μ CC	2450
$\bar{\nu}_\mu$ CC	49
ν_e CC	20
$\bar{\nu}_e$ CC	1.2
ν NC	823
$\bar{\nu}$ NC	17

No oscillations

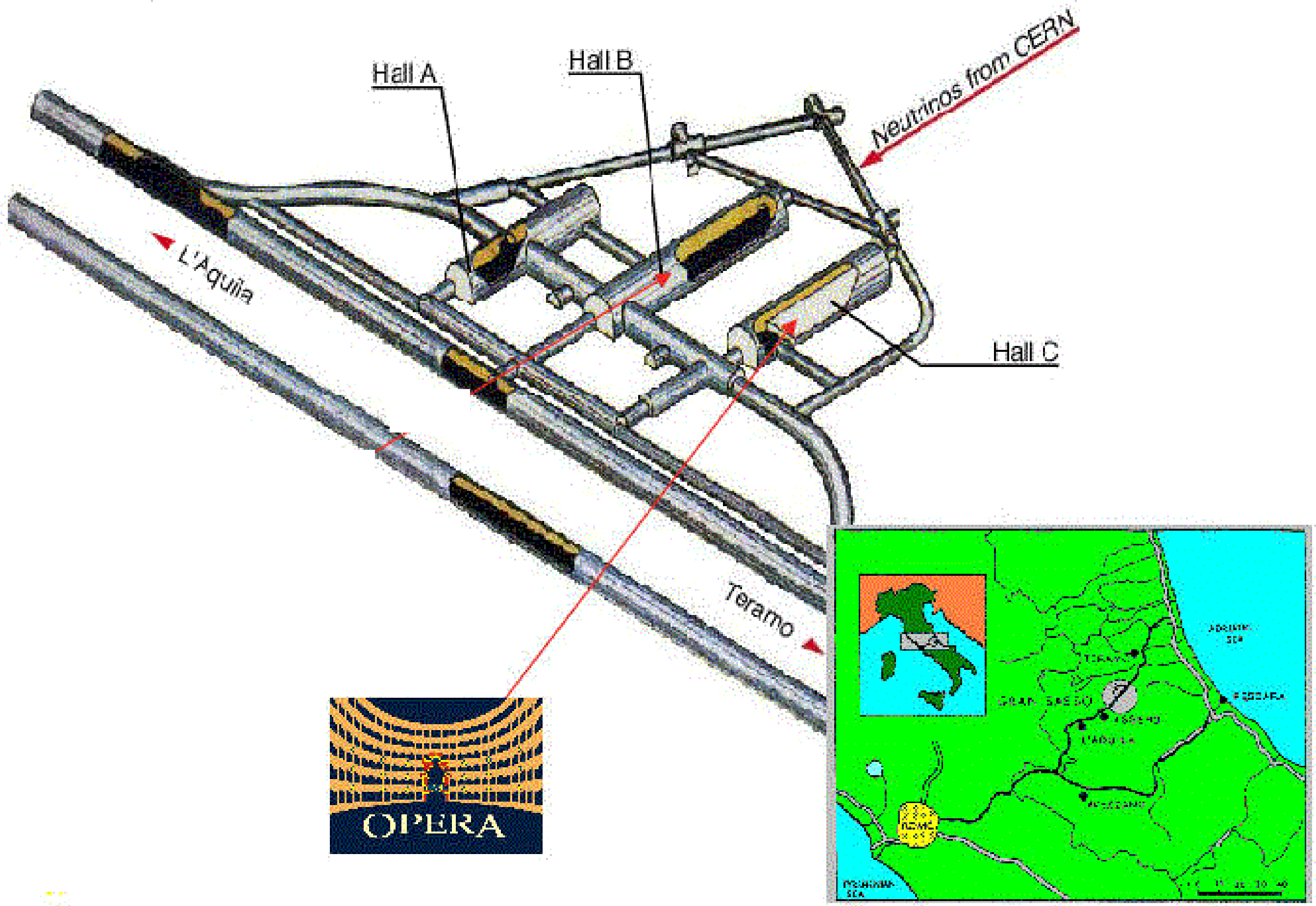
Δm^2 (eV^2)	Rates (events/kton/year)
1×10^{-3}	2.4
2.5×10^{-3}	15.1
3.5×10^{-3}	29.4
5×10^{-3}	58.6
1×10^{-2}	209.0

ν_τ CC event rates

Search for ν_τ appearance at Gran Sasso

OPERA experiment

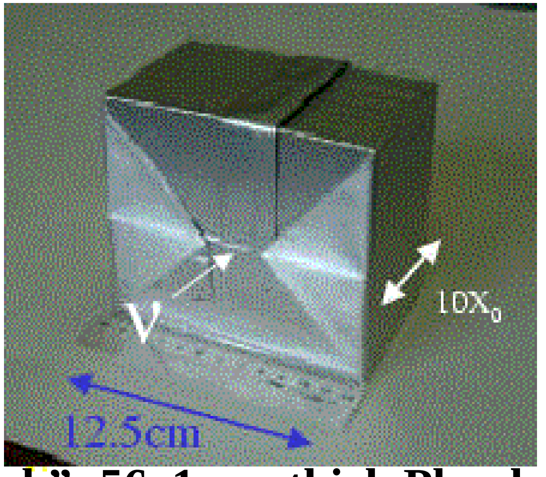
No near detector (negligible ν_τ production at the proton target)



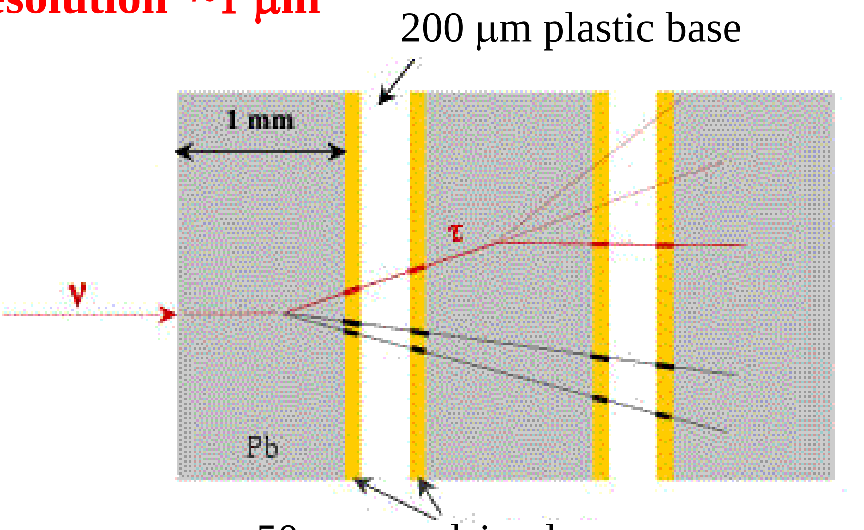
OPERA experiment: detect τ^- by observing its decays to one charged particle(~85%)

Mean τ decay path $\approx$ 1 mm $\Rightarrow$ need very high space resolution

Photographic emulsion: space resolution ~1 μm



"Brick": 56 1mm thick Pb plates interleaved with 57 emulsion films and tightly packed



Brick internal structure

Each brick is followed by a Changeable Sheet (two emulsion films replaced quite often to reduce the scanning load)

"Bricks" arranged into "walls" : one "wall" = 2850 bricks

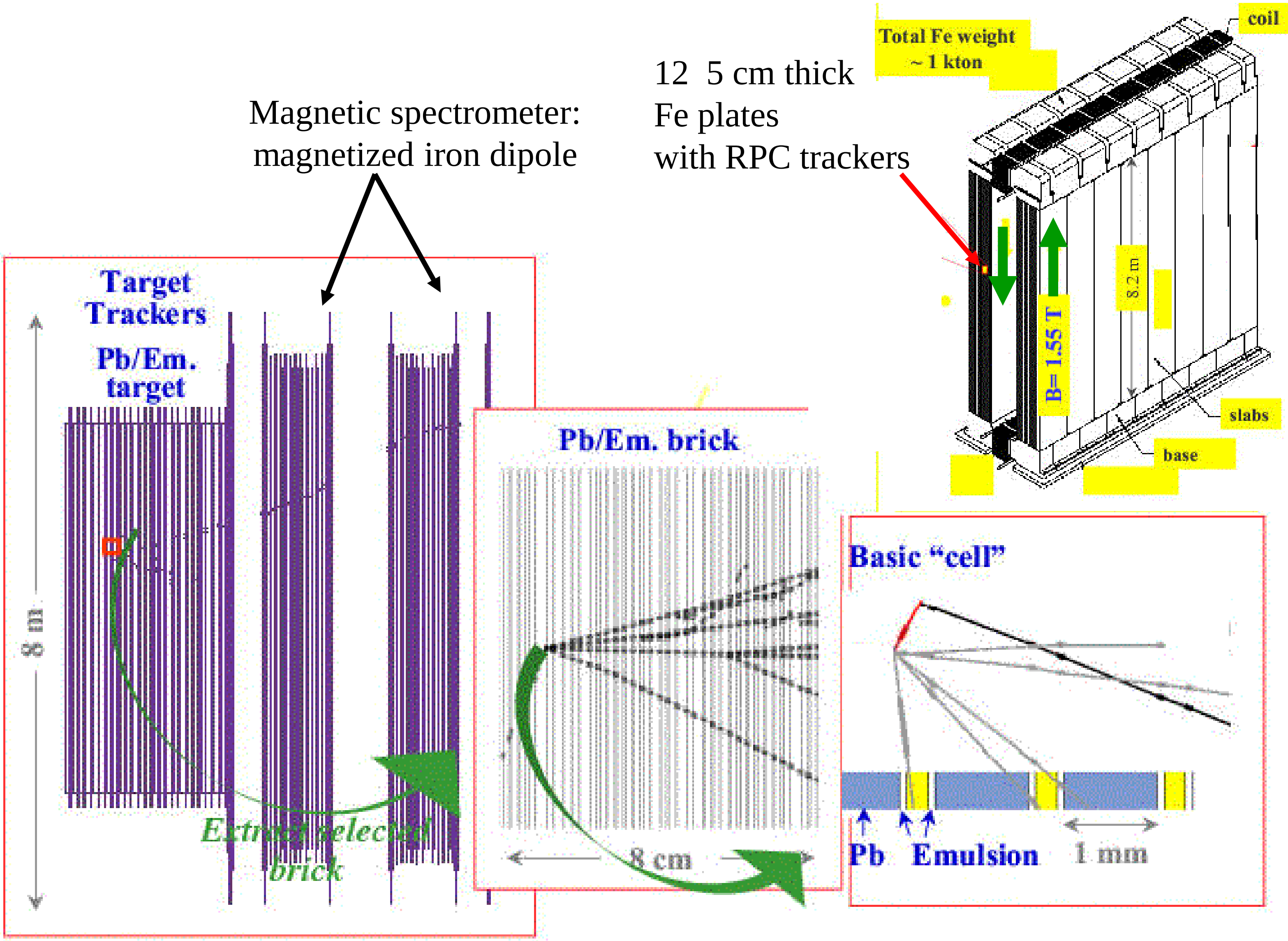
"Walls" arranged into two "super-modules" → ~150,000 bricks ≈ 1.25 ktons in total

Each super-module is followed by a magnetic spectrometer

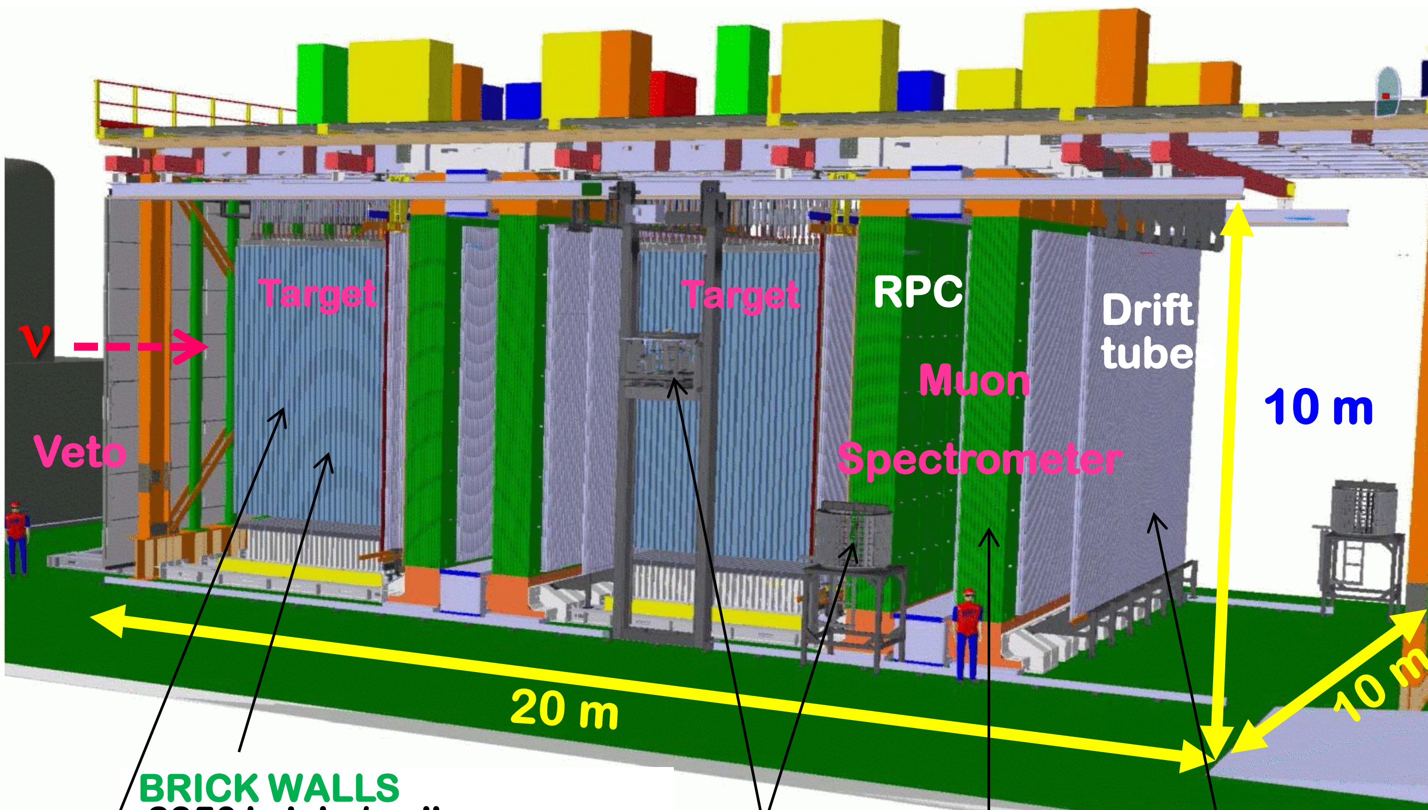
Planes of orthogonal scintillating strips are inserted between walls to provide the trigger and to identify the brick where the neutrino interacted.

Immediate removal of the brick and Changeable Sheet, emulsion development and automatic measurement using computer – controlled microscopes

OPERA super-module



The OPERA detector



→ Electronic Detectors are needed for:

- Triggering, Timing
- Neutrino interactions Location
- Calorimetry
- Muon I.D. and Spectrometry

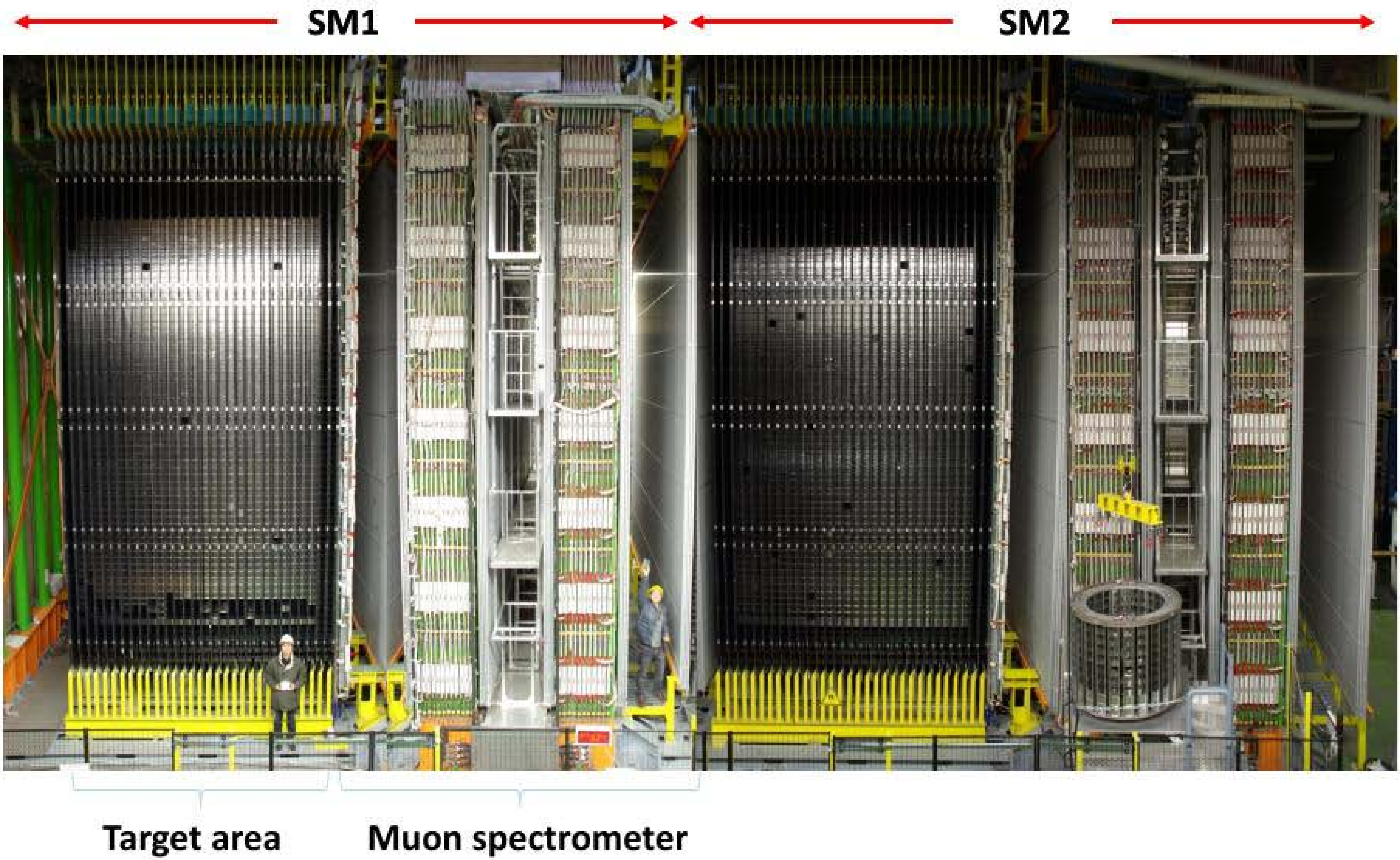
BRICK WALLS
2850 bricks/wall
• 53 walls
•150000 bricks ~ 1.25 kton

BMS
Brick Manipulator System

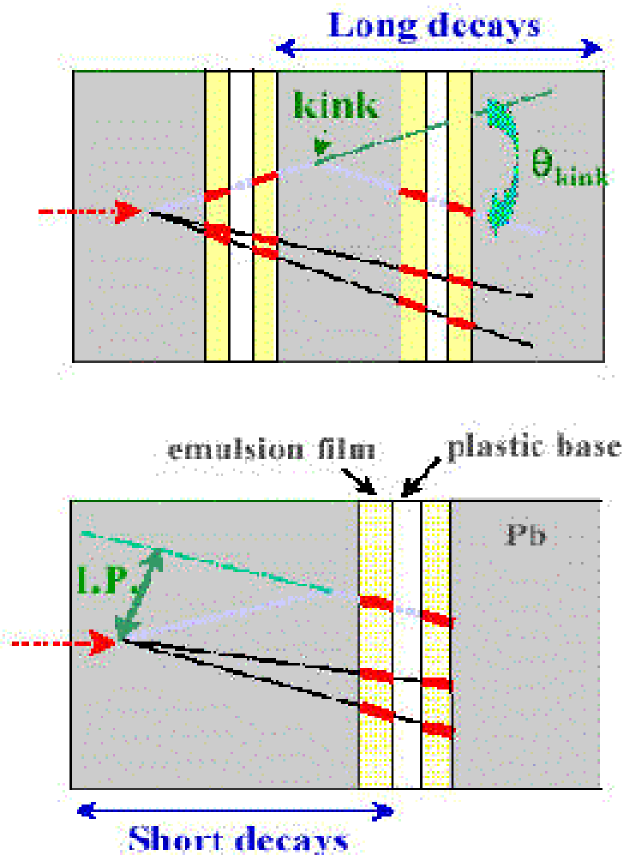
HIGH PRECISION TRACKERS
6 drift-tube layers/spectrometer
spatial resolution < 0.5 mm

TARGET TRACKERS
• 2x31 scintillator strips walls
• 256+256 X-Y strips/wall
• WLS fiber readout
• 64-channel PMTs
• 63488 channels
• 0.8 cm resololution, 99% ε
• rate 20 Hz/pixel @1 p.e.

INNER TRACKERS
• 990-ton dipole magnets
(B= 1.55 T) instrumented with 22 RPC planes
• 3050 m^2, ~1.3 cm resolution


SM1
SM2
Target area
Muon spectrometer

OPERA: signal and backgrounds



Expectations for 5 data – taking years with 4.5×10^{19} protons on target / year

τ decay channel	B.R. (%)	Signal $\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$	Background
$\tau \to \mu$	17.7	2.9	0.17
$\tau \to e$	17.8	3.5	0.17
$\tau \to h$	49.5	3.1	0.24
$\tau \to 3h$	15.0	0.9	0.17
All	BR*eff =10.6%	10.4	0.75

The signal rate depends on $(\Delta m^2)^2$

Main backgrounds:

- Production of charged "charmed" hadrons decaying to only one charged particle in events with unidentified primary lepton (negative muon, electron);
- Primary μ^- large angle elastic scattering near the neutrino interaction point;
- Charged hadron interacting close to the neutrino interaction point, with one or three outgoing charged particles and unidentified primary lepton.

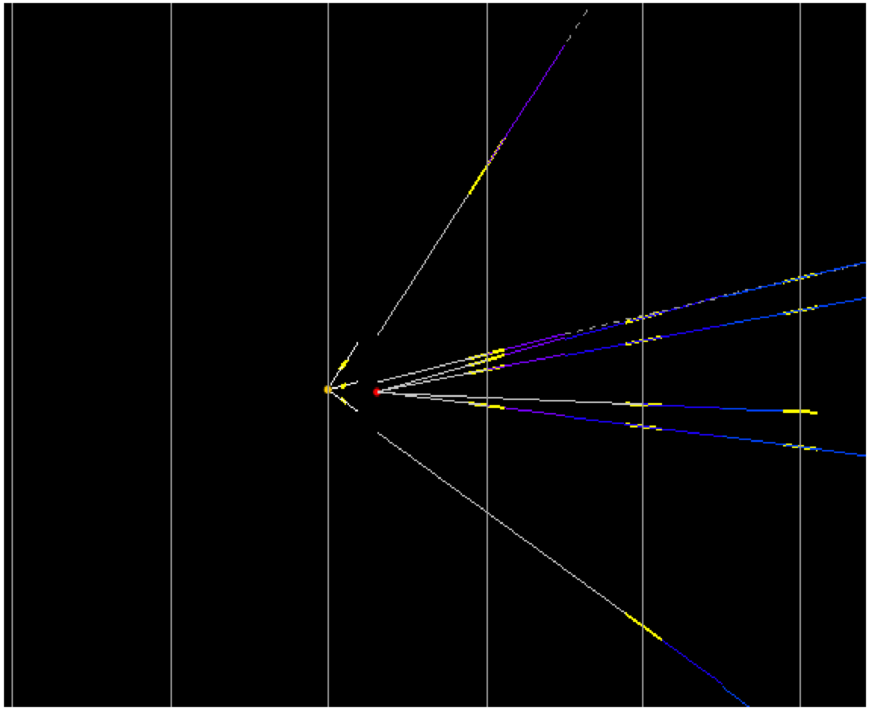
OPERA after two years of data - taking (2008 – 09)

	2008 run	**2009 run**
total	1.782×10^{19} pot	3.522×10^{19} pot
On-time events	10122	21428
candidate in the target	1698	3693

Events with neutrino interaction vertex identified in a brick:

218 with no primary μ^-;

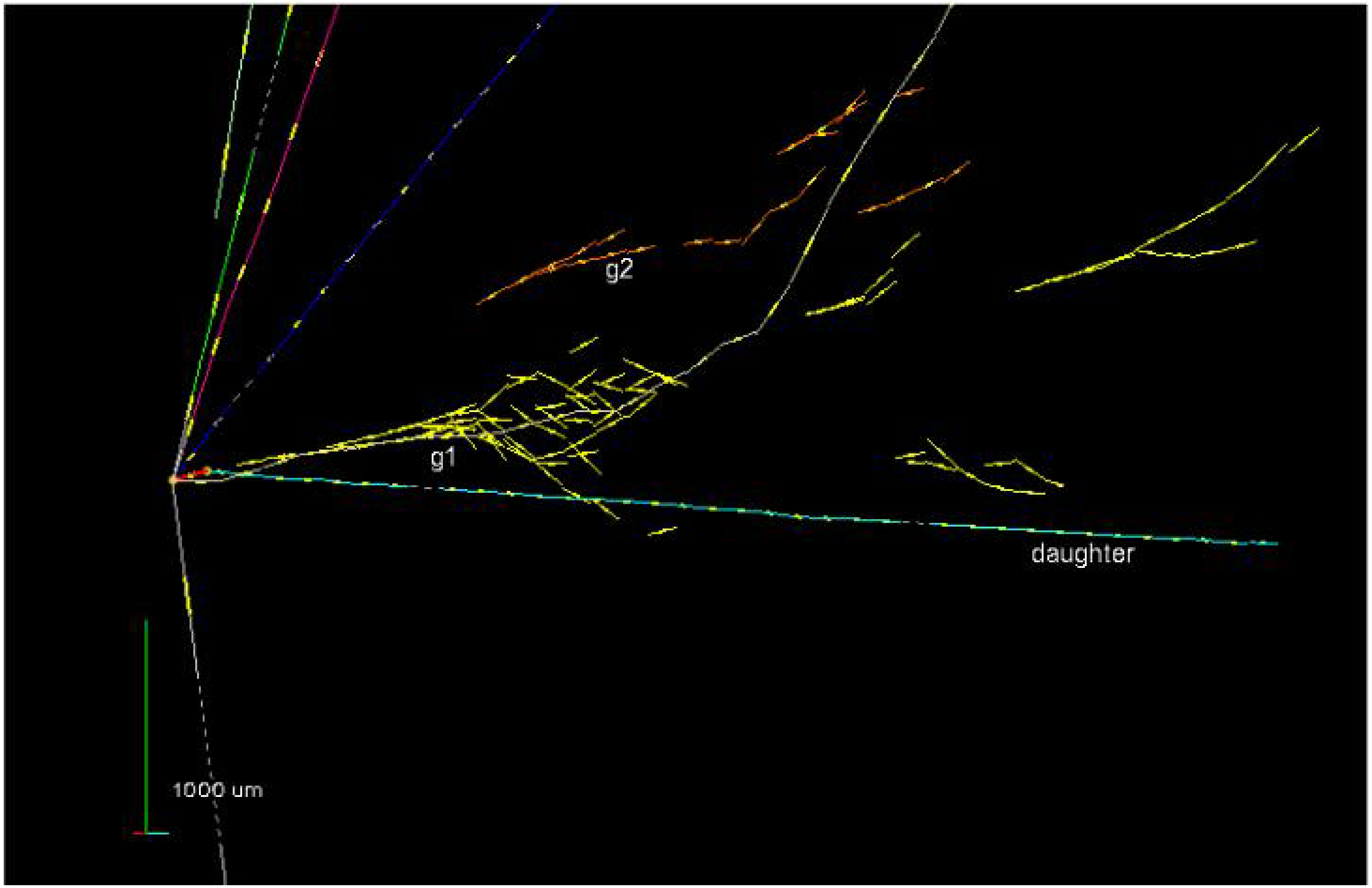
1163 with identified primary μ^-.



Neutral "charmed" hadron decay to four charged particles;
Decay vertex - primary vertex distance 313.1 µm

The first OPERA event consistent with τ^- production

N. Agafonova et al., Phys. Letters B 691 (2010) 138



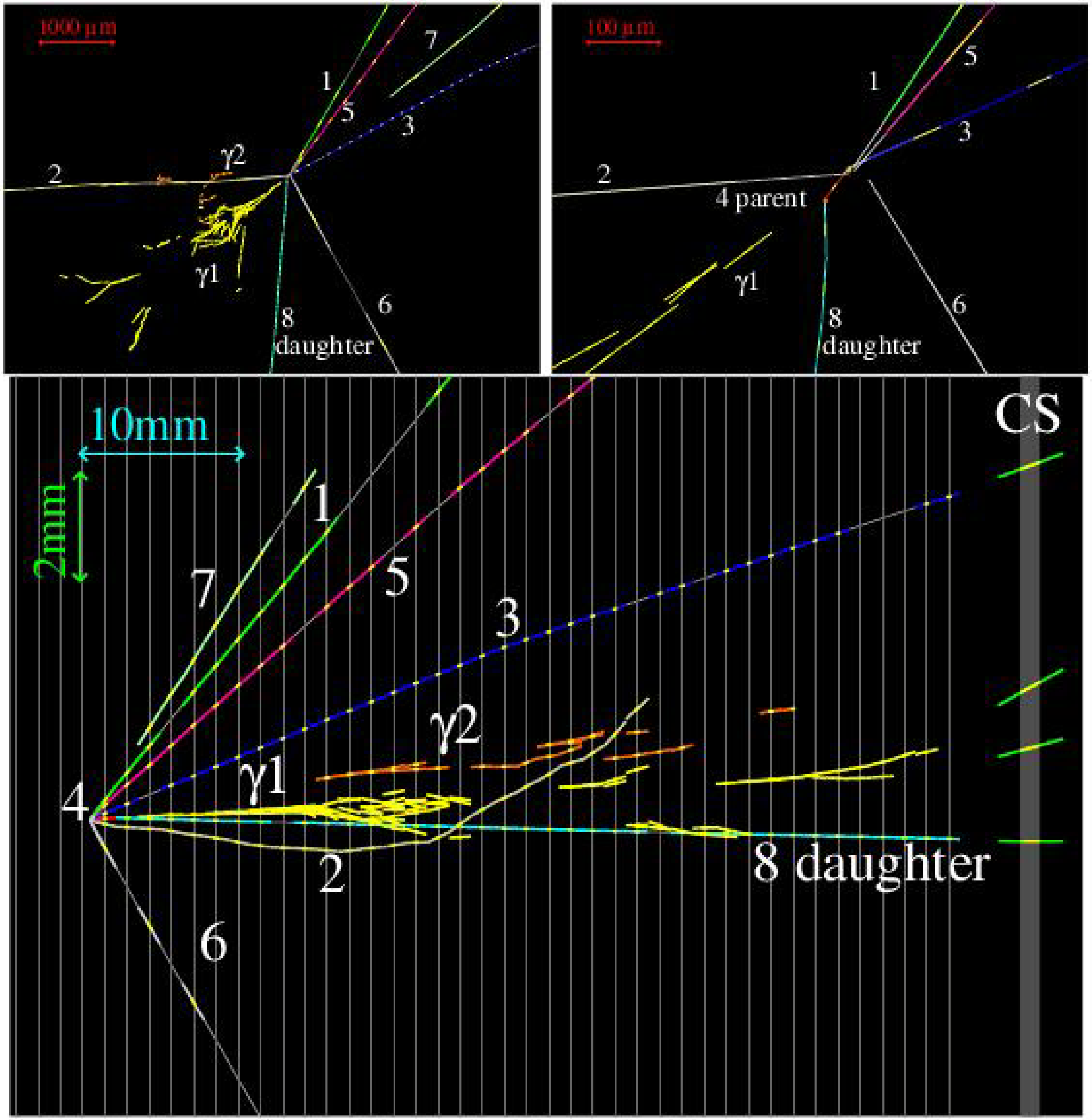
Event interpretation: $\nu_\tau + N \rightarrow \tau^- + \text{hadrons}$

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

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

$\pi^o \rightarrow 2\gamma$

Event projections orthogonal to the neutrino beam direction



Number of $\nu_\mu \rightarrow \nu_\tau \rightarrow \tau^-$ events expected in the analysed event sample:

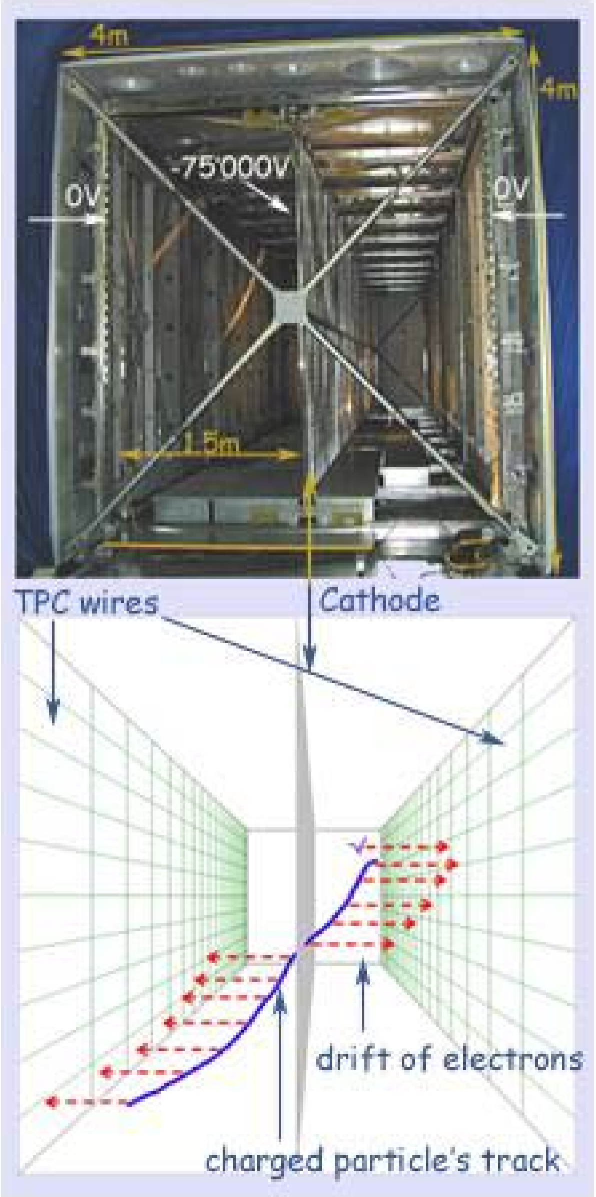
0.54 ± 0.13

Expected background (“charm” events with unidentified primary μ, NC events with Interacting hadron):

0.018 ± 0.007

ICARUS detector (proposed by C. Rubbia in 1977)

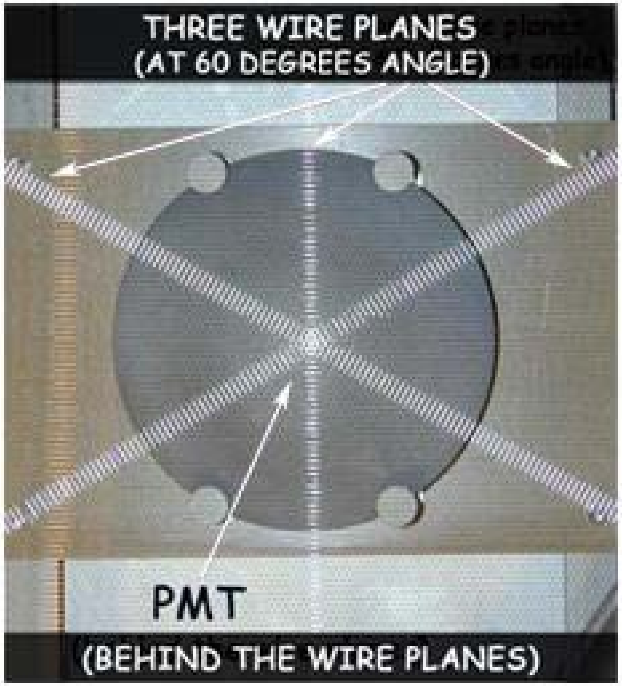
- 600 ton liquid Argon in two adjacent containers
- Container dimensions 3.6 x 3.9 x 19.9 m^3
- Time Projection Chamber (TPC):
  electrons from primary ionization drift in the liquid
  and are collected by read-out wires
  → 3-dimensional event reconstruction
- Number of primary ionization electrons from a charged particle at minimum ionization ~ 6000 / mm of track length
- Electron drift without recombination over lengths of ~1.8 m require ultra-pure Argon (concentration of electro-negative impurities $<10^{-10}$)
- Drift velocity ~ 1.5 mm/μs for electric fields ~ 0.5 kV/cm
- Liquid Argon density 1.4 g/cm^3
- Radiation length 14 cm



**DETECTOR FILLED
AT MID MAY 2010
PRESENTLY TAKING DATA
AT THE GRAN SASSO
NATIONAL LABORATORIES**

ICARUS

UV scintillation light from liquid Argon
is collected by photomultiplier tubes
located behind the read-out wires
The scintillation signal is necessary
to localize the event along the drift direction



ICARUS PHYSICS PROGRAMME

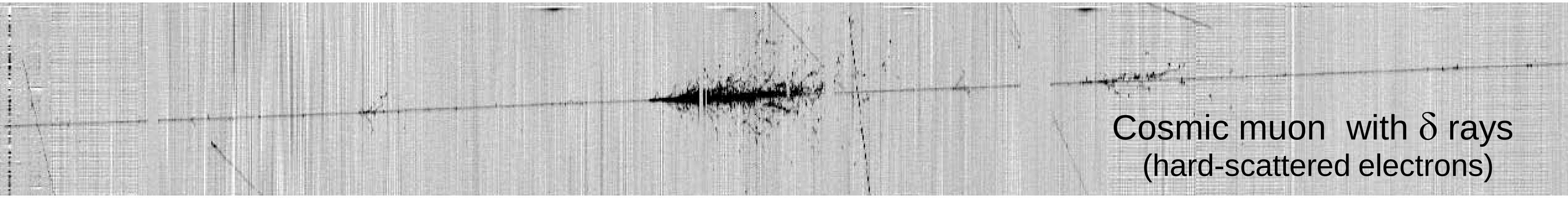
Search for $\nu_\mu \rightarrow \nu_\tau$ oscillations:

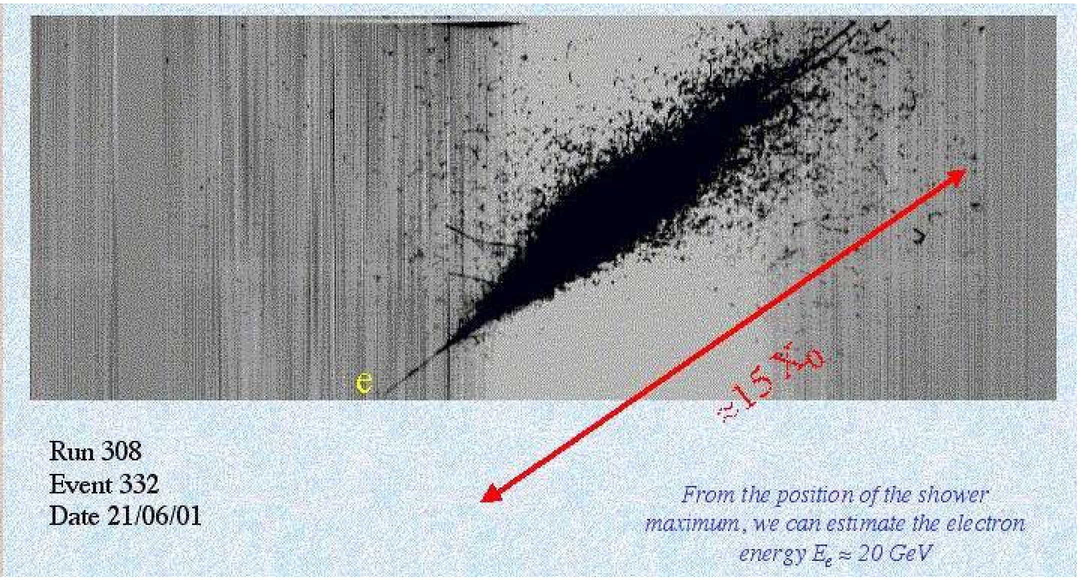
ν_τ appearance by detecting $\tau^- \rightarrow e^- \nu \bar{\nu}$ decays

Event topology similar to ν_e interactions (~1% in the CNGS beam)
but with missing transverse momentum from undetected $\nu \bar{\nu}$

Liquid Argon total mass (600 tons) probably not large enough (~1 event for 5 data – taking years), but useful to demonstrate the detector potential for future, very high mass neutrino detectors

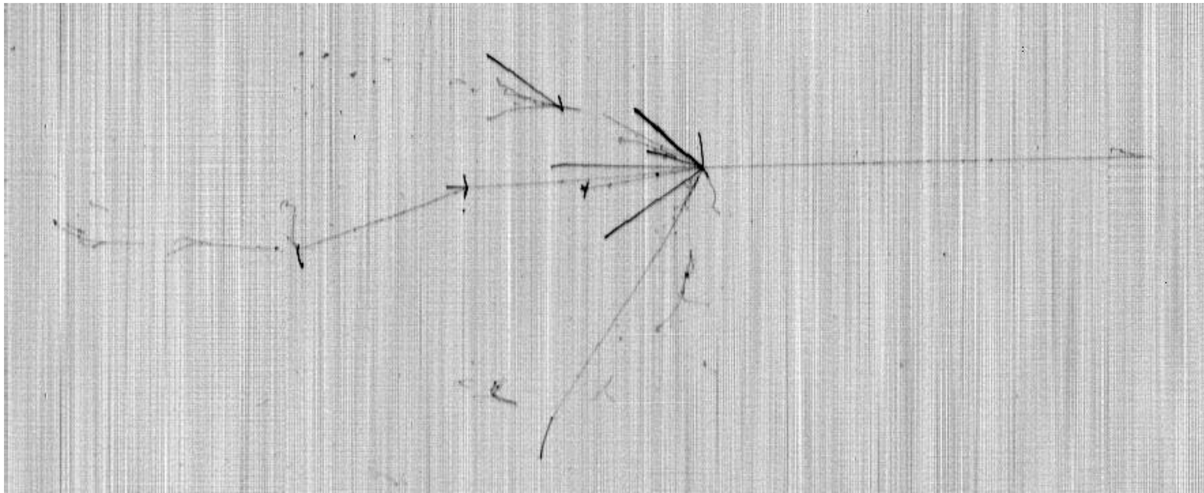
ICARUS tracks recorded during the first detector tests in 2001





Electron shower

Interacting hadron



Future projects

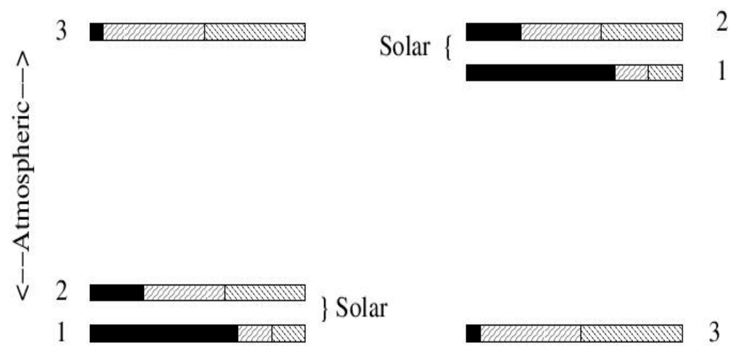
- Precise measurement of the neutrino mixing matrix
- Search for CP violation in neutrino oscillations

Assumption: only three neutrinos $\Rightarrow$ two independent Δm^2 values

Experimental information presently available:

- **Solar neutrino experiments + KAMLAND**
  - $m_2^2 - m_1^2 \equiv \Delta_{12} = (7.59 \pm 0.21) \times 10^{-5}$ eV^2 ($m_2 > m_1$ by definition)
  - Large mixing angle: $\theta = 34.1^\circ \pm 1.0^\circ$
- **Atmospheric neutrino experiments+ K2K + MINOS (ν_μ disappearance)**
  - $|m_3^2 - m_2^2| \equiv |\Delta_{23}| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (MINOS)
  - Large mixing angle: $\theta \approx 45^\circ$ (consistent with maximum mixing)
- **CHOOZ experiment:** no evidence for $\bar{\nu}_e$ disappearance associated with Δ_{23}

Neutrino masses: normal or inverted hierarchy?



normal hierarchy $\Delta_{23} > 0$

inverted hierarchy $\Delta_{23} < 0$

Three – neutrino oscillations are described by three angles ($\theta_{12}, \theta_{13}, \theta_{23}$)
+ a phase angle δ inducing violation of CP – symmetry

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

$$=\begin{pmatrix}c_{12}c_{13}&c_{13}s_{12}&s_{13}e^{-i\delta}\\-c_{23}s_{12}-c_{12}s_{13}s_{23}e^{i\delta}&c_{12}c_{23}-s_{12}s_{13}s_{23}e^{i\delta}&c_{13}s_{23}\\s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta}&-c_{12}s_{23}-c_{23}s_{12}s_{13}e^{i\delta}&c_{13}c_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$c_{ik} \equiv \cos\theta_{ik}$; $s_{ik} \equiv \sin\theta_{ik}$

Unitarity condition:

$$\sum_i \mathbf{U}_{\alpha i}\mathbf{V}_{i\beta}=\sum_i \mathbf{U}_{\alpha i}\mathbf{U}^*_{\beta i}=\delta_{\alpha\beta}$$

inverse matrix $\mathbf{V} = \mathbf{U}^{-1}$

If $s_{13} = 0$ all matrix elements containing the phase δ vanish

Impact of the CHOOZ experiment on the mixing matrix

Evolution of a neutrino produced as ν_e at distance *L* from source:

$$\nu(L) = U_{e1}\nu_1 e^{-iE_1L} + U_{e2}\nu_2 e^{-iE_2L} + U_{e3}\nu_3 e^{-iE_3L}$$

ν_e disappearance probability:

$$\mathscr{P}_{ee} = 1 - \left|\langle \nu_\mu | \nu(L) \rangle\right|^2 - \left|\langle \nu_\tau | \nu(L) \rangle\right|^2$$

$$\langle \nu_\mu | \nu(L) \rangle = e^{-iE_1L}\left(U_{e1}U_{\mu 1} + U_{e2}U_{\mu 2}e^{-i(E_2-E_1)L} + U_{e3}U_{\mu 3}e^{-i(E_3-E_1)L}\right)$$

$$\langle \nu_\tau | \nu(L) \rangle = e^{-iE_1L}\left(U_{e1}U_{\tau 1} + U_{e2}U_{\tau 2}e^{-i(E_2-E_1)L} + U_{e3}U_{\tau 3}e^{-i(E_3-E_1)L}\right)$$

Remember: for *E* >> *m* $\quad E_i - E_k \approx \dfrac{m_i^2 - m_k^2}{2E}$

Ignoring the overall phase *exp(–iE$_1$L)* :

$$\langle \nu_\mu | \nu(L) \rangle = U_{e1}U_{\mu 1} + U_{e2}U_{\mu 2}e^{-i\frac{\Delta_{12}}{2E}L} + U_{e3}U_{\mu 3}e^{-i\frac{\Delta_{13}}{2E}L}$$

$$\langle \nu_\tau | \nu(L) \rangle = U_{e1}U_{\tau 1} + U_{e2}U_{\tau 2}e^{-i\frac{\Delta_{12}}{2E}L} + U_{e3}U_{\tau 3}e^{-i\frac{\Delta_{13}}{2E}L}$$

In the CHOOZ experiment $\langle E \rangle \approx 3$ MeV , $L \approx 1000$ m

$$\frac{\Delta_{12}}{2E} L = 2.534 \frac{\Delta_{12}(\mathrm{eV}^2)}{E(\mathrm{MeV})} L(\mathrm{m}) << 1$$

→ oscillation effects associated with Δ_{12} are negligible

Define: $$\alpha = \frac{\Delta_{12}}{|\Delta_{13}|} \approx 0.03$$

Series expansion of three – flavour ν_e (and $\bar{\nu}_e$) disappearance probability
(E.K. Akhmedov et al., JHEP 04 (2004) 078):

$$\mathcal{P}_{ee} = 1 - \left|\langle \nu_\mu | \nu(L) \rangle\right|^2 - \left|\langle \nu_\tau | \nu(L) \rangle\right|^2 = 1 - \alpha^2 \sin^2 2\theta_{12} - 4\sin^2\theta_{13} \sin^2\left(1.267\Delta_{13}\frac{L}{E}\right)$$

CHOOZ limit: $\mathcal{P}_{ee} < 0.11$ for $|\Delta_{13}| \approx 2.5 \times 10^{-3}$ eV^2 (90% conf. level)

→ $\theta_{13} < 11.5°$

Three – neutrino mixing matrix consistent with all measured oscillation parameters:

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} \cos(34^0) & \sin(34^0) & 0 \\ -\sin(34^0)/\sqrt{2} & \cos(34^0)/\sqrt{2} & 1/\sqrt{2} \\ \sin(34^0)/\sqrt{2} & -\cos(34^0)/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

< 0.2 CHOOZ limit

Solar ν_e oscillations

assuming $U_{e3} = \sin\theta_{13} = 0$

(consistent with the limit from the CHOOZ experiment)

$$\nu(L) = U_{e1}\nu_1 e^{-iE_1L} + U_{e2}\nu_2 e^{-iE_2L}$$

ν_e disappearance probability :

$$\mathcal{P}_{ee} = 1 - \left|\langle \nu_\mu | \nu(L)\rangle\right|^2 - \left|\langle \nu_\tau | \nu(L)\rangle\right|^2$$

$$\langle \nu_\mu | \nu(L)\rangle = U_{e1}U_{\mu 1} + U_{e2}U_{\mu 2} e^{-i\frac{\Delta_{12}}{2E}L}$$

$$\langle \nu_\tau | \nu(L)\rangle = U_{e1}U_{\tau 1} + U_{e2}U_{\tau 2} e^{-i\frac{\Delta_{12}}{2E}L}$$

$\theta_{23} = 45^o \rightarrow \sin(\theta_{23}) = \cos(\theta_{23})$ ⟹

$$\langle \nu_\mu | \nu(L)\rangle = -\langle \nu_\tau | \nu(L)\rangle$$

⟹ **Solar ν_e oscillate to ν_μ and ν_τ with equal probabilities**

Violation of CP symmetry in three – neutrino mixing

CP violation : $\mathcal{P}_{osc}(\nu_\alpha - \nu_\beta) \neq \mathcal{P}_{osc}(\bar\nu_\alpha - \bar\nu_\beta)$

CPT invariance: $\mathcal{P}_{osc}(\nu_\alpha - \nu_\beta) = \mathcal{P}_{osc}(\bar\nu_\beta - \bar\nu_\alpha)$ $(\alpha, \beta = e, \mu, \tau)$

→ $\mathcal{P}_{osc}(\nu_\alpha - \nu_\alpha) = \mathcal{P}_{osc}(\bar\nu_\alpha - \bar\nu_\alpha)$ **(CPT invariance)**

→ **CP violation in neutrino oscillations can only be detected in appearance experiments**

CP violation in $\nu_\mu - \nu_e$ oscillations:

Define: $\mathcal{P}_{\mu e} = \mathcal{P}_{osc}(\nu_\mu \to \nu_e)$; $\bar{\mathcal{P}}_{\mu e} = \mathcal{P}_{osc}(\bar\nu_\mu \to \bar\nu_e)$

Vacuum oscillations:

$$\mathcal{P}_{\mu e} = A\sin^2(1.27\Delta_{23}\frac{L}{E}) + B\sin^2(1.27\Delta_{12}\frac{L}{E}) + C\cos(-\delta - 1.27\Delta_{23}\frac{L}{E})\sin(1.27\Delta_{23}\frac{L}{E})\sin(1.27\Delta_{12}\frac{L}{E})$$

$$\bar{\mathcal{P}}_{e\mu} = A\sin^2(1.27\Delta_{23}\frac{L}{E}) + B\sin^2(1.27\Delta_{12}\frac{L}{E}) + C\cos(\delta - 1.27\Delta_{23}\frac{L}{E})\sin(1.27\Delta_{23}\frac{L}{E})\sin(1.27\Delta_{12}\frac{L}{E})$$

$A = (\sin\theta_{23}\sin 2\theta_{13})^2$

$B = (\cos\theta_{23}\sin 2\theta_{12})^2$

$C = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$ ←

CP – violating terms (note the sign of δ)

CP violation in $\nu_\mu - \nu_e$ oscillations
can only be measured if $\theta_{13} \neq 0$
<u>AND</u> the experiment is simultaneously sensitive
to Δ_{12} and Δ_{23}

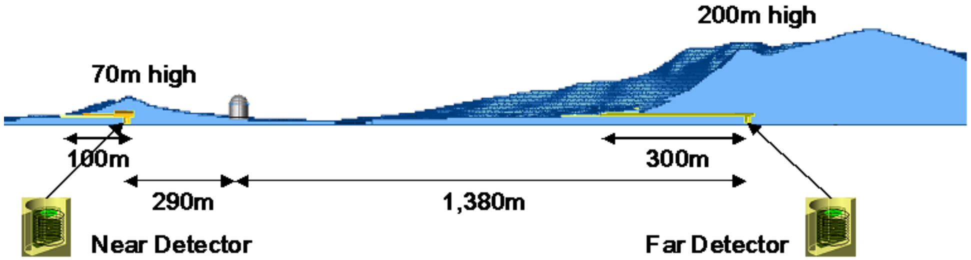
The most urgent problem: to measure precisely θ_{13}

⇒ **need new oscillation experiments**
(ν_e disappearance / $\nu_\mu - \nu_e$ appearance)
more sensitive to θ_{13} than the CHOOZ experiment

$\bar{\nu}_e$ disappearance experiments in preparation

(with near detector to measure directly the $\bar{\nu}_e$ flux)

1. **RENO: two identical underground detectors consisting of 15 ton Gd – doped liquid scintillator (similar to CHOOZ) at the Yonggwang power plant (South-Korea); 6 reactors, total thermal power 16 GW**



Start–up of data – taking : 2011

Expected sensitivity after 3 years: $\sin^2 2\theta_{13} < 0.02$ (CHOOZ limit : $\sin^2 2\theta_{13} < 0.15$)

2. **DOUBLE – CHOOZ (with near detector identical to far detector)**

   Start–up of data – taking : end 2011

3. **Daya Bay (on the East coast of China, 55 km North-East of Hong Kong)**

   Two nuclear power plants 1100 m apart:

   Daya Bay (two reactors, 2 x 2.9 GW)

   Ling Ao (two reactors, 2 x 2.9 GW + 2 under construction)

   Total thermal power 17.4 GW after 2011

   8 identical liquid scintillator detectors (similar to CHOOZ) in 8 different sites (4 near the reactors, 4 at ~2 km distance)

   Start–up of data – taking: 2012

High – sensitivity searches for $\nu_\mu - \nu_e$ oscillations: detector distance $L \approx ½\lambda_{23}$
⇒ require low energy neutrino beams (1 – 2 GeV) for the existing detectors

K2K: **neutrino flux too low despite the very large detector mass (Super-K)**

CNGS: **physics programme optimized for ν_τ appearance**
(beam energy >> τ production threshold, too high for $\nu_\mu - \nu_e$ oscillations ,
no near detector to measure the intrinsic ν_e contamination in the beam)

MINOS: preliminary results (April 2010)

Distance L = 735 km: the neutrino beam traverses the Earth crust ($< \rho > \approx 3$ g/cm^3, Z/A ≈ ½) ⟶ matter effects cannot be neglected

$$\tan 2(\theta_{13})_{matter} = \frac{\Delta m^2_{13} \sin 2\theta_{13}}{\Delta m^2_{13} \cos 2\theta_{13} - \xi} \qquad \xi \equiv 2EV_W \approx 1.526 \times 10^{-4} \frac{Z}{A} \rho E \ (\text{eV}^2)$$

(ρ in g/cm^3, E in GeV)

$$\Delta m^2_{13} = m^2_3 - m^2_1 = (m^2_3 - m^2_2) + (m^2_2 - m^2_1) \approx \Delta m^2_{23}$$

Matter effects depend on the sign of Δm^2_{23}

At the first peak of the $\nu_\mu - \nu_e$ oscillation:

$E \approx 1.4$ GeV ; $\xi \approx 3.3 \times 10^{-4}$ eV^2 ; $\Delta m^2_{13} \cos 2\theta_{13} \approx \pm 2.4 \times 10^{-3}$ eV^2

$\nu_\mu - \nu_e$ oscillations : Series expansions for three-flavor neutrino oscillation probabilities in matter

E.K. Akhmedov et al., JHEP 04 (2004) 078

$$\mathcal{P}(\nu_\mu - \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(A-1)\omega}{(A-1)^2}$$

$$-2\alpha\sin\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta\frac{\sin A\omega}{A\omega}\frac{\sin(A-1)\omega}{A-1}\sin\omega$$

$$+2\alpha\sin\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos\delta\frac{\sin A\omega}{A\omega}\frac{\sin(A-1)\omega}{A-1}\cos\omega$$

$$A = \frac{2EV_W}{\Delta_{13}} = \frac{1.526\times 10^{-4}(Z/A)\rho E}{\Delta_{13}} \qquad \omega = 1.267\Delta_{13}\frac{L}{E} \qquad \alpha = \frac{\Delta_{12}}{\Delta_{13}} \approx \pm 0.03$$

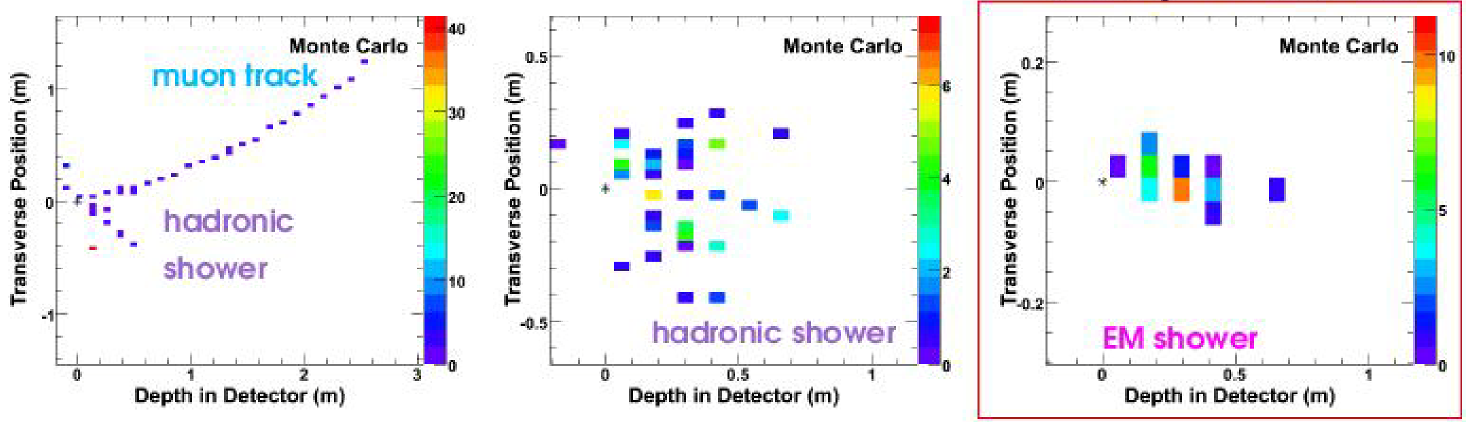
ρ (g/cm^3) ; E (GeV) ; L (km) ; Δ_{ik} (eV^2)

Note the weak dependence on the CP-violating phase δ coming from terms to first order in Δ_{12} ($\alpha \approx \pm 0.03$)

MINOS: search for $\nu_\mu - \nu_e$ oscillations
Preliminary results (April 2010)
7×10^{20} protons on target (May 2005 – August 2009)

Typical neutrino event configurations
(from simulations)

Signal and also
beam ν_e-CC background



Experimental method:

- Select $\nu_e \rightarrow$ electron events from event topology (no muon, presence of an electromagnetic shower consistent with an electron)
- Measure backgrounds in the near detector (no oscillation)
- Predict backgrounds for the far detector
- Compare far detector data with predictions

MINOS
Far detector predictions
for no $\nu_\mu - \nu_e$ oscillation

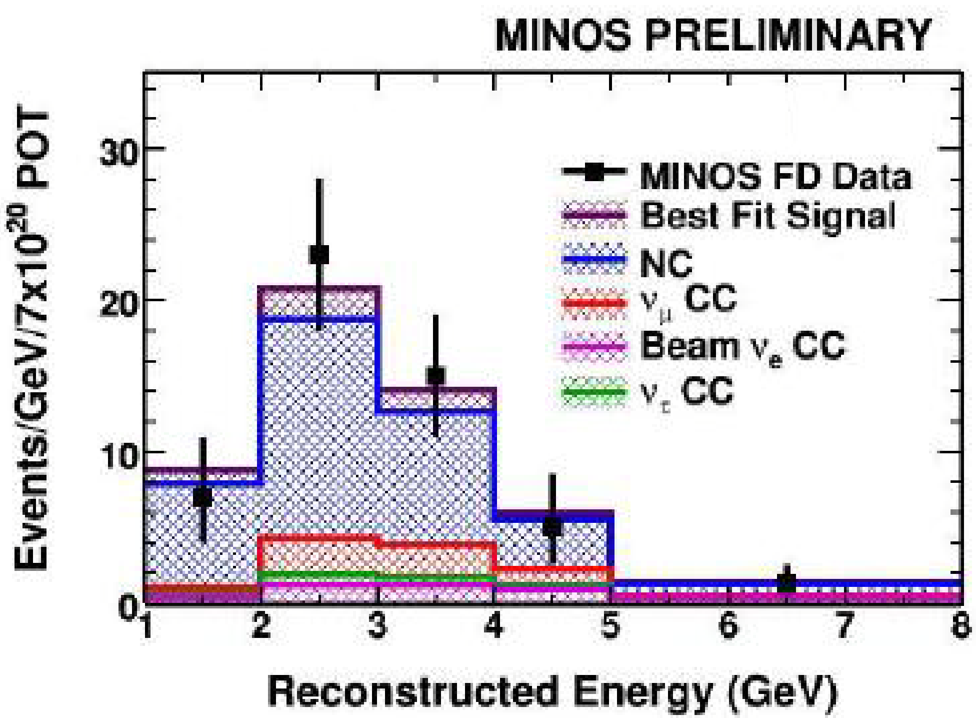
	Total	Stat. Err.	Syst. Err.	NC	CCNuMu	Beam NuE	CcNuTau
N. of events	49.1	7.0	2.7	35.8	6.3	5.0	2.0

Expected number of events for no $\nu_\mu - \nu_e$ oscillation: 49.1 ± 7.0 (stat.) **± 2.7** (sist.)

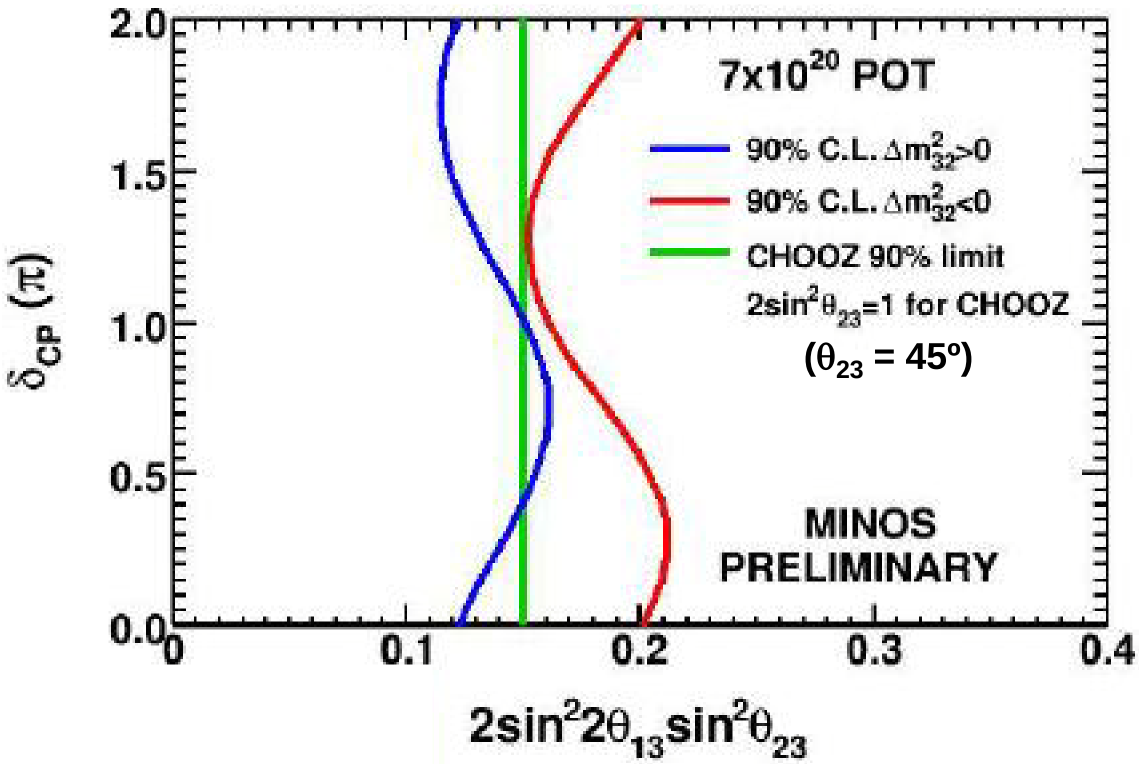
Observed: 54

No evidence for $\nu_\mu - \nu_e$ oscillation

$\nu_e \rightarrow$ electron selected events: Energy distribution in the far detector



Excluded regions in the plane δ, $\sin^2 2\theta_{13}$ for $|\Delta_{23}| = 2.43 \times 10^{-3}$ eV^2



Limits (C.L. 90%) for $\delta = 0$:

- $\Delta_{23} > 0$ (normal hierarchy): $\sin^2 2\theta_{13} < 0.12$; $\theta_{13} < 10.1^o$
- $\Delta_{23} < 0$ (inverted hierarchy): $\sin^2 2\theta_{13} < 0.20$; $\theta_{13} < 13.3^o$

High sensitivity $\nu_\mu - \nu_e$ oscillation searches ($\mathscr{P}_{osc} \propto \sin^2 2\theta_{13}$)

J-PARC (Japan Proton Accelerator Research Complex): 50 GeV high intensity proton synchrotron at JAERI (Tokai) in operation since 2009

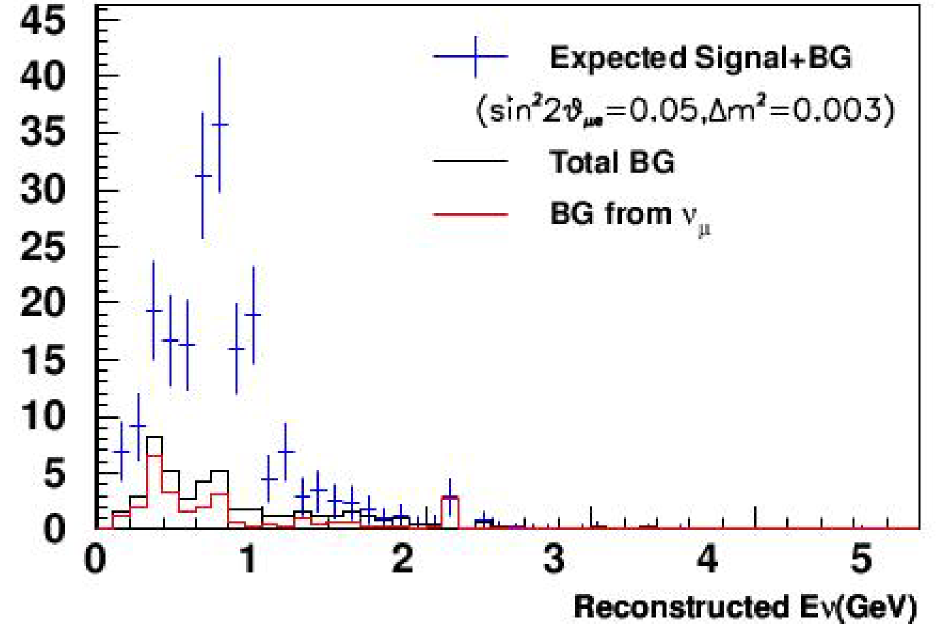
T2K (Tokai to Kamioka): experiment to measure θ_{13} using a 2.5° off-axis neutrino beam of ~0.6 GeV aimed at the Super-K detector (L = 295 km)
T2K includes a near detector

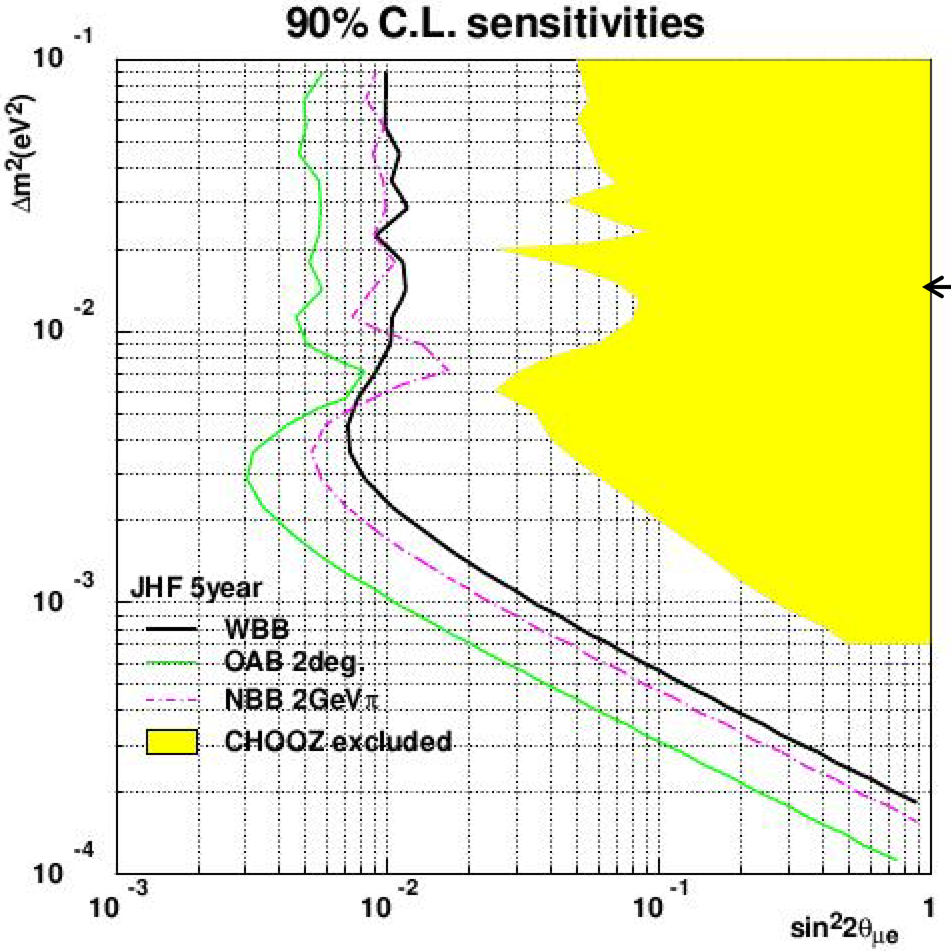
NOνA: esperiment approved in 2008 to use the Fermilab NUMI beam at a distance of 810 km . The detector is located on the surface, 12 km from the beam axis (14.8 mr off – axis). Neutrino beam energy ~1.6 GeV

Detector: 15,000 ton liquid scintillator in plastic rectangular tubes 15.5 m long, section 3.9cm x 6cm

Search for $\nu_\mu \rightarrow \nu_e$ oscillations in the T2K experiment: expectations (from simulations)

Energy distribution of $\nu_e \rightarrow e$ events
8.3 x 10^{21} protons on target at 30 GeV
(5 years of data – taking)





Sensitivity : limit obtained if
N(ν_e events) = N(background)

NOTE:

$\nu_\mu \rightarrow \nu_e$ oscillation probability proportional to

$$\sin^2(2\theta_{\mu e}) = \sin^2(2\theta_{13})\sin^2(\theta_{23}) = \frac{1}{2}\sin^2(2\theta_{13})$$

(θ_{23} = 45º)

January – June 2010 run:
3.3 x10^{19} protons on target
22 fully contained events
observed in the Super-K detector

Measurement of CP violation
(phase angle δ in the mixing matrix)

First – order approximation for $\nu_\mu - \nu_e$ and $\bar{\nu}_\mu - \bar{\nu}_e$ oscillation probabilities:

$$\mathcal{P}\begin{pmatrix}\nu_\mu - \nu_e \\ \bar{\nu}_\mu - \bar{\nu}_e\end{pmatrix} = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(A-1)\omega}{(A-1)^2}$$

$$\mp 2\alpha\sin\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta\frac{\sin A\omega}{A\omega}\frac{\sin(A-1)\omega}{A-1}\sin\omega$$

$$+2\alpha\sin\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos\delta\frac{\sin A\omega}{A\omega}\frac{\sin(A-1)\omega}{A-1}\cos\omega$$

$$A = \frac{2EV_W}{\Delta_{13}} = \pm\frac{1.526\times 10^{-4}(Z/A)\rho E}{\Delta_{13}} \qquad \omega = 1.267\Delta_{13}\frac{L}{E} \qquad \alpha = \frac{\Delta_{12}}{\Delta_{13}} \approx \pm 0.03$$

ρ (g/cm^3) ; E (GeV) ; L (km) ; Δ_{ik} (eV^2)

Matter effects:
Opposite signs for ν , $\bar{\nu}$

Two possible methods:

- Data – taking with ν and $\bar{\nu}$ beams;
- Data – taking with ν beams only, measurement of the $\nu_\mu - \nu_e$ oscillation probability at the first and second oscillation maximum ($\omega \approx \pi/2$, $3\pi/2$).

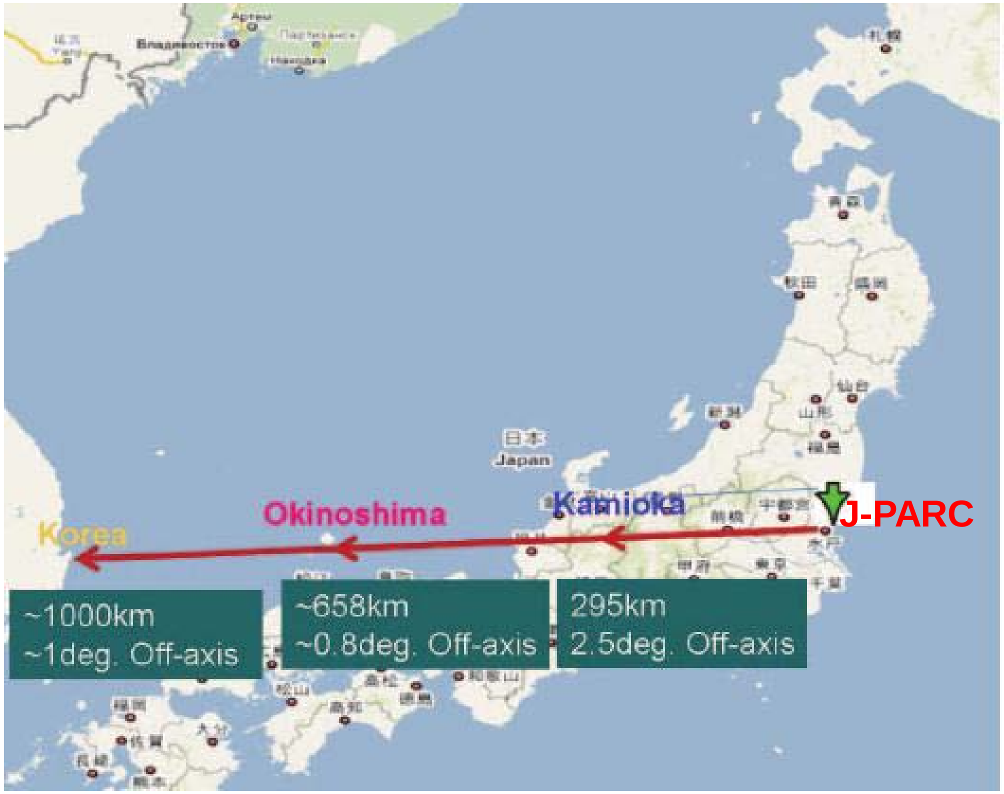
Neutrino energy at the 1st and 2nd $\nu_\mu - \nu_e$ oscillation maximum

Experiment	L (km)	1st maximum	2nd maximum
T2K	295 km	0.58 GeV	0.19 GeV
NOνA	810 km	1.6 GeV	0.53 GeV

For T2K E_ν at 2nd maximum is too low to separate electrons from muons

➡ **need longer baseline distances**

PROPOSAL FOR AN ICARUS-LIKE LIQUID ARGON DETECTOR WITH A 100 KTON MASS IN THE OKINOSHIMA ISLANDS OR IN KOREA

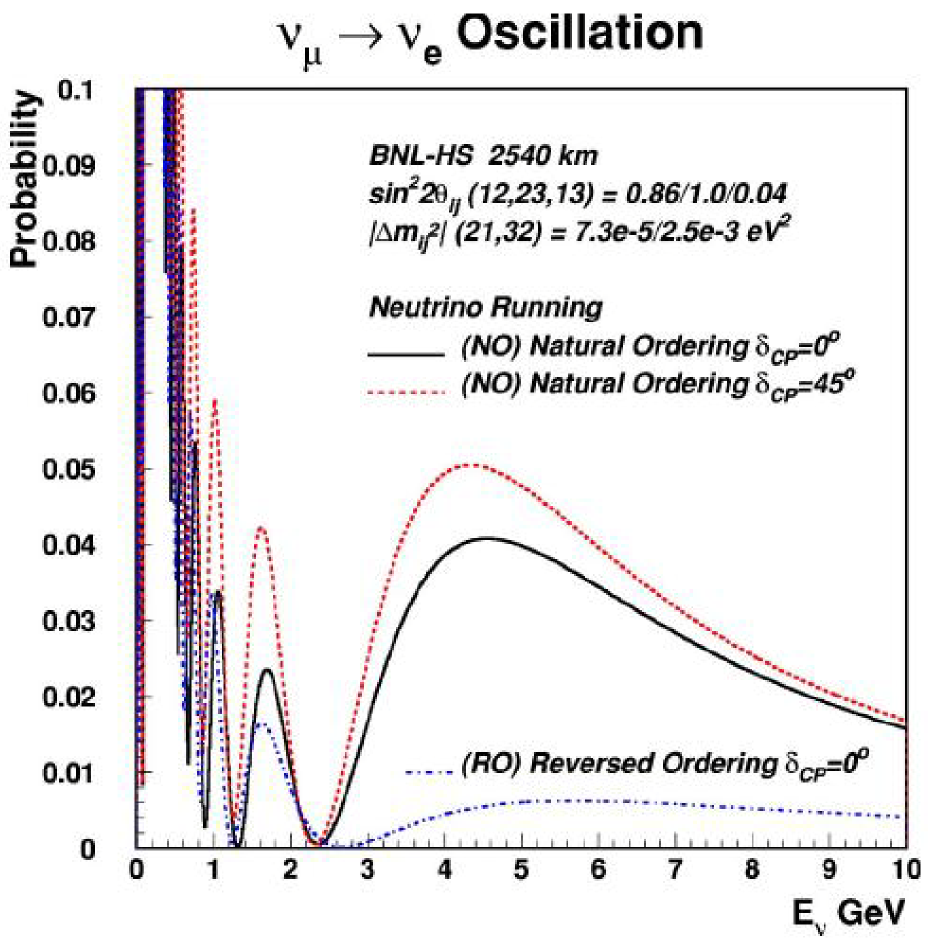


Proposal for a new water Čerenkov detector with 500 kton mass for the new underground laboratory under construction at Homestake (U.S.A.) .

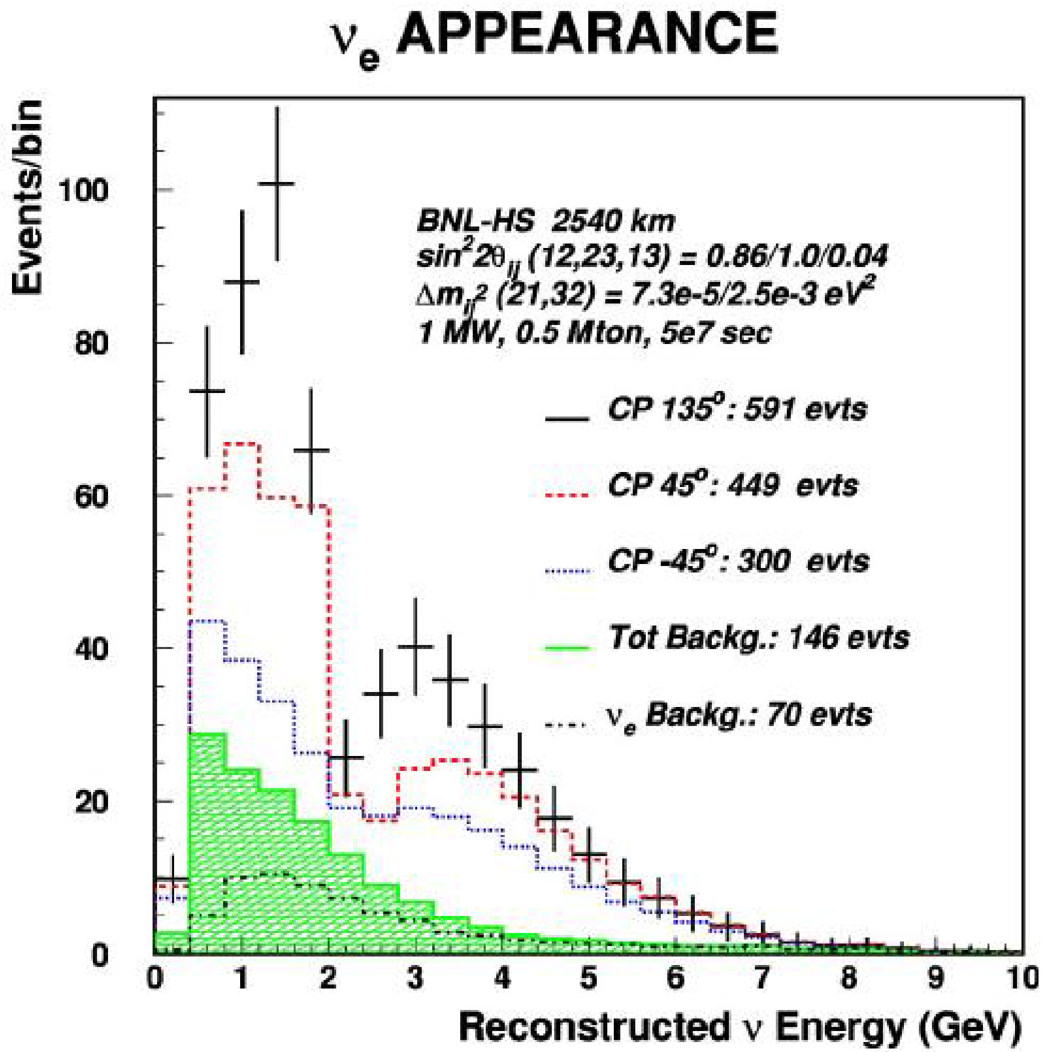
Neutrino beam from the 28 GeV proton synchrotron (AGS) at the Brookhaven National Laboratory (L.I., N.Y., U.S.A.)

L = 2540 km

M.V. Diwan, et al., Phys. Rev. D 68 (2003) 012002



Expectations (from simulations) for 10^{22} protons on target (~ 4 data – taking years)



The new Homestake underground laboratory ("DUSEL") is expected to be operational in 2018

A NEW CONCEPT:
NEUTRINO FACTORY

Muon storage ring with long straight sections pointing to neutrino detectors at large distance. N(μ): ≥10^{21} / year

Components of a Neutrino Factory:

- **High – intensity proton accelerator (up to 10^{15} protons/s, energy few GeV) ;**
- **High – aperture solenoidal magnetic channel following the proton target to capture $\pi^{\pm}$ and $\mu^{\pm}$ from $\pi^{\pm}$ decay;**
- **Muon "cooling" to reduce the muon beam angular spread and momentum interval;**
- **Two or more muon accelerators in series;**
- **A muon magnetic storage ring with long straight sections.**

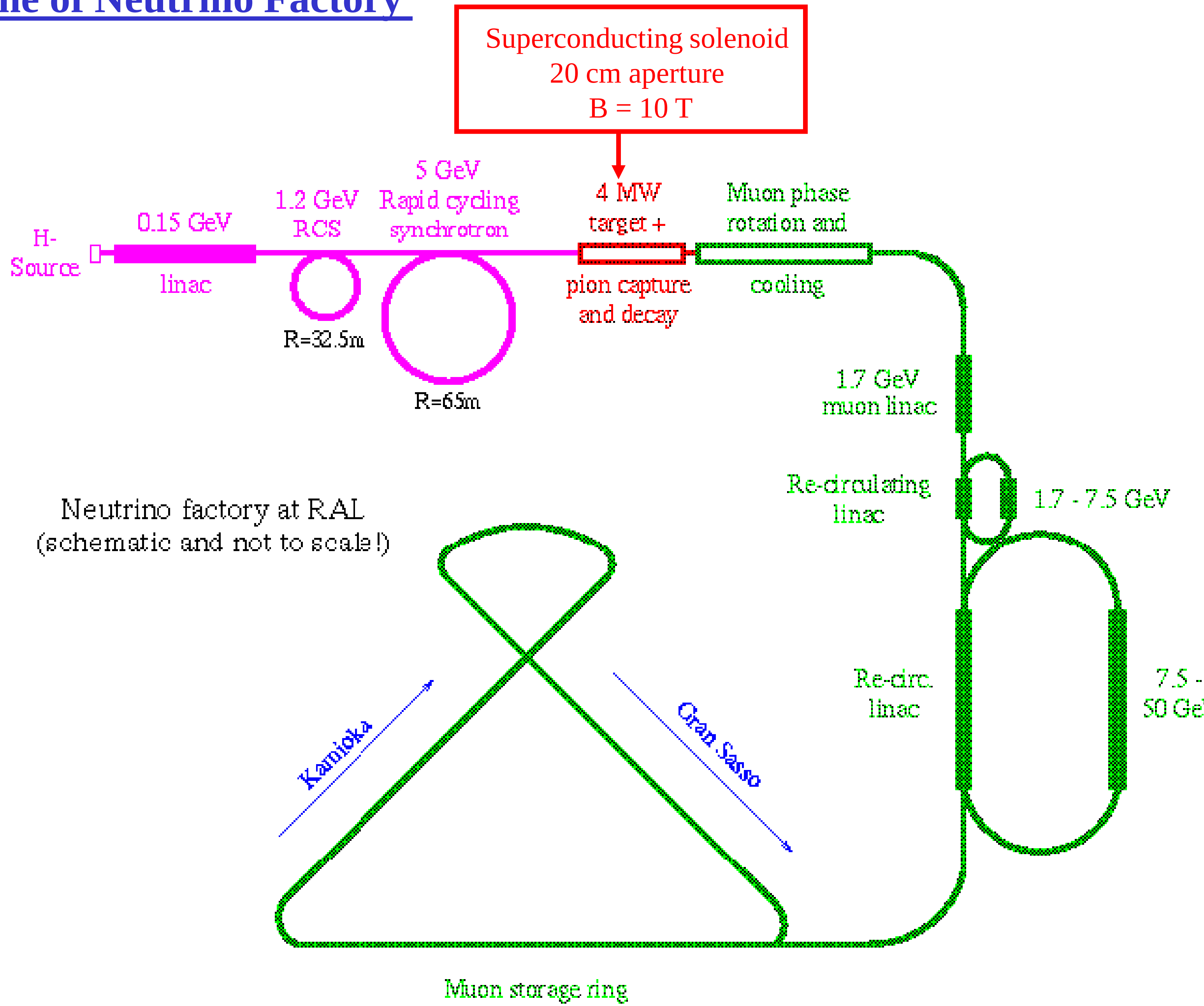
μ^{+} storage ⇒ pure $\bar{\nu}_{\mu}$, ν_{e} beams;

μ^{-} storage ⇒ pure ν_{μ} , $\bar{\nu}_{e}$ beams;

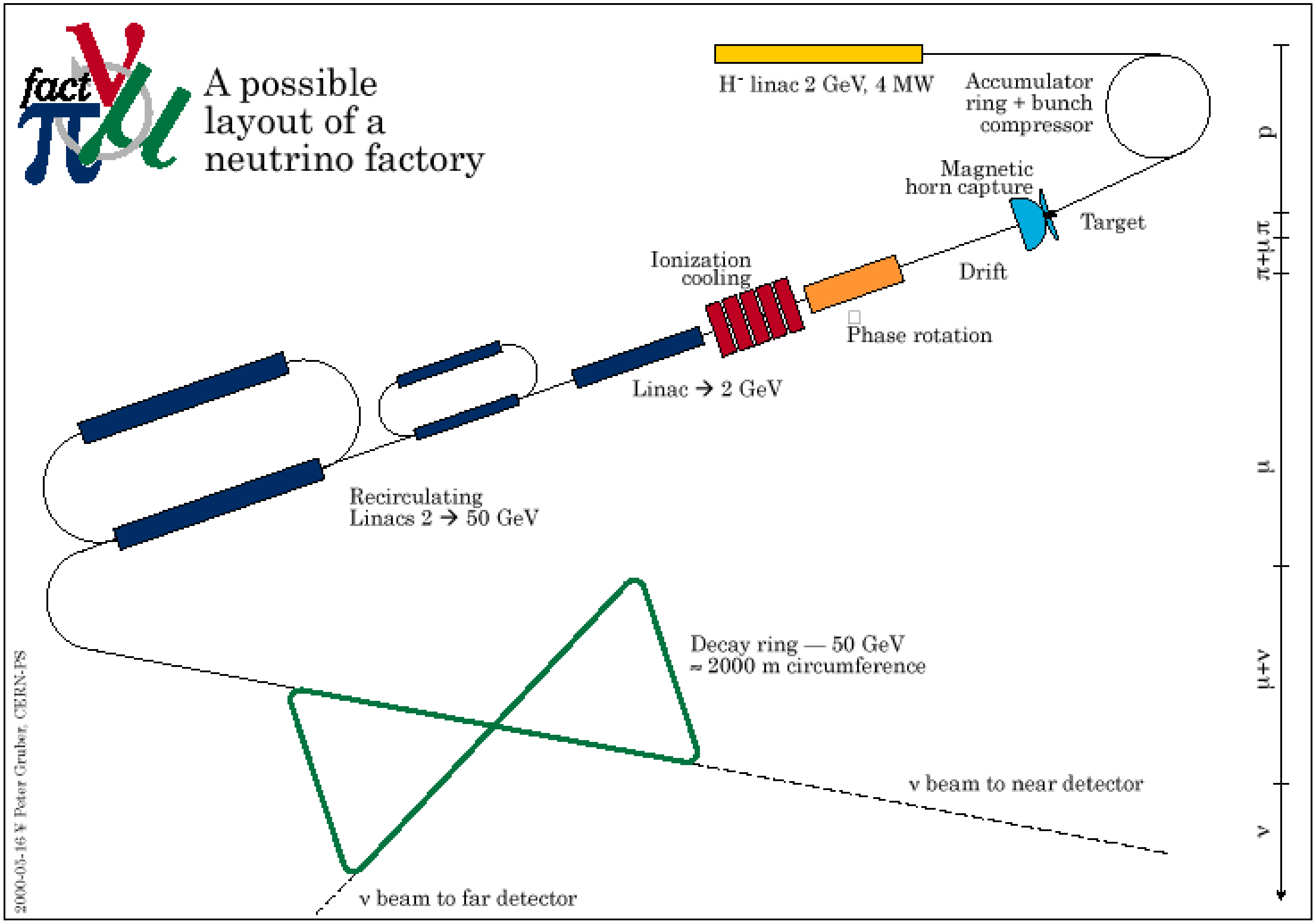
Neutrino fluxes and energy distributions precisely predicted from μ decay kinematics

Search for $\nu_{e} - \nu_{\mu}$ oscillations: detection of "wrong sign" muons (electric charge opposite to charge of stored muons) ⇒ MAGNETIC DETECTOR

A possible scheme of Neutrino Factory

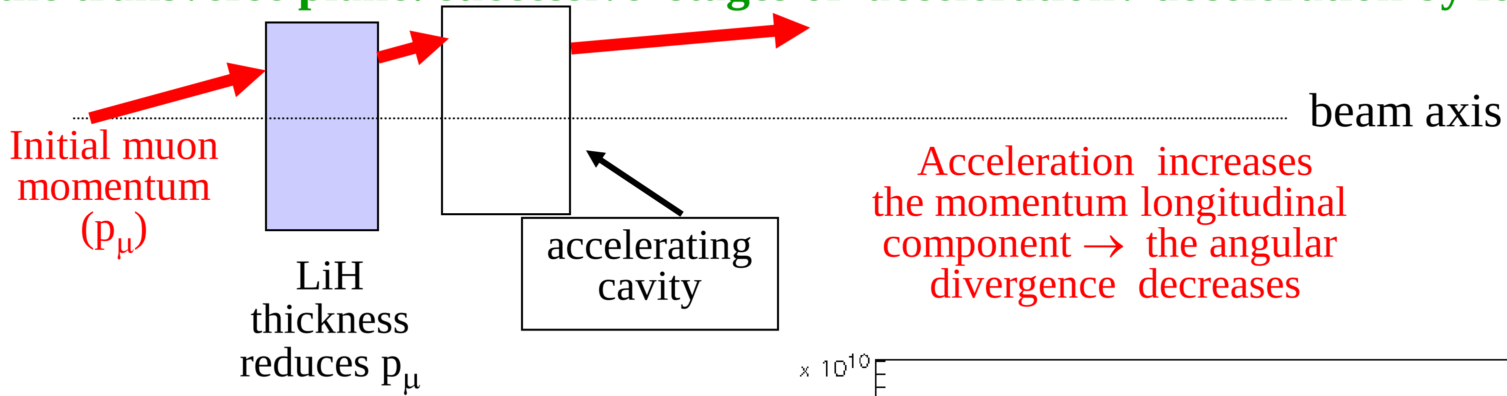


An alternative Neutrino Factory design



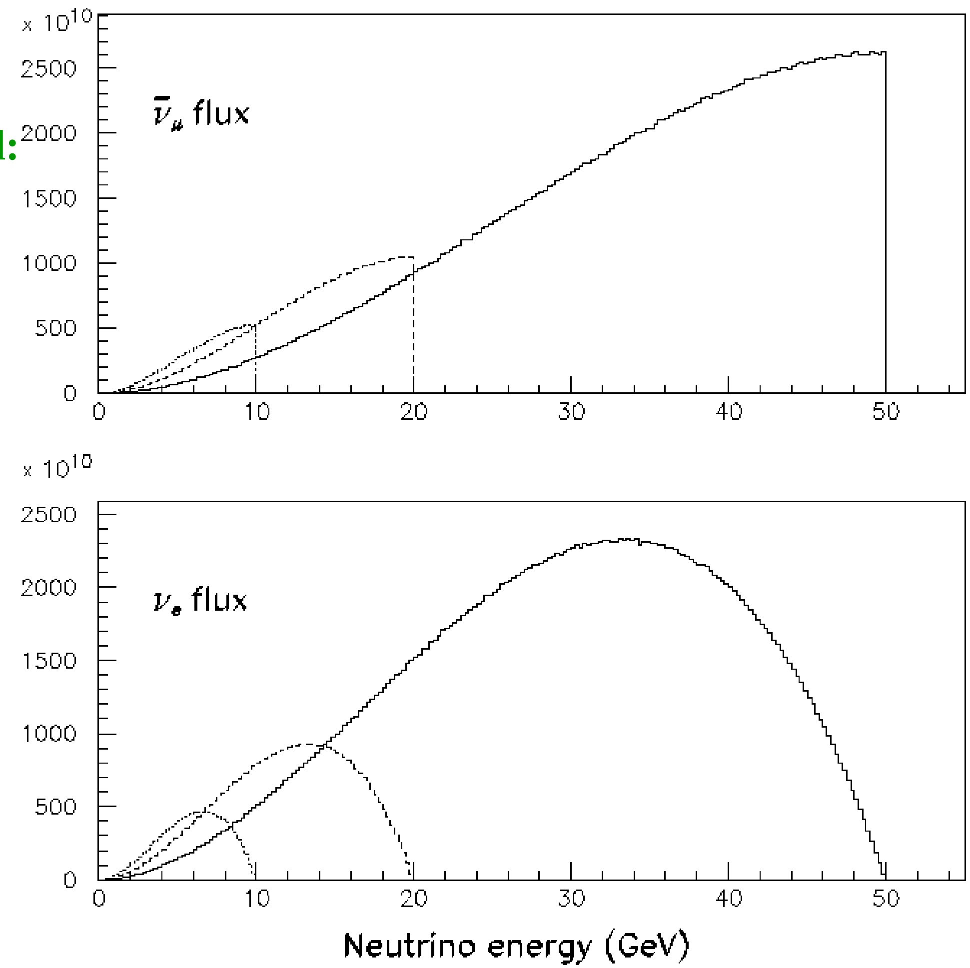
Muon cooling

In the transverse plane: successive stages of acceleration / deceleration by ionization



Reducing the muon beam momentum spread:
Accelerating cavity with modulated electric field:
weak field for early, fast muons;
high field for late, slow muons

Predicted fluxes
(neutrinos / (year x 0.25 GeV)
Detector diameter 10 m
Distance L = 732 km;
μ^+, E_μ = 10, 20, 50 GeV



Measurement of CP violation at a Neutrino Factory

The sensitivity to the phase angle δ decreases rapidly with θ_{13}

$\rightarrow$ no measureable effect for $\theta_{13} < 1°$

Optimum distance to measure the phase angle δ : $L \approx 2000 - 4000$ km:

The neutrino beam traverses the Earth crust

$\rightarrow$ matter effects of opposite sign for neutrinos and antineutrinos

$\rightarrow$ apparent violation of CP symmetry

Matter effects and direct CP violation have different *E* and *L* dependences

$\Longrightarrow$ require two detectors at different distances and study CP violation as a function of the neutrino energy *E*

Number of events / year expected in a 40 kton detector for 2.5×10^{20} μ^+ decays in the straight section of a 50 GeV Neutrino Factory

***L* (km)**	$\bar{\nu}_\mu N \rightarrow \mu^+ X$	$\nu_e N \rightarrow e^- X$	$\nu N \rightarrow \nu X$
730	8.8×10^6	1.5×10^7	8×10^6
3500	3×10^5	6×10^5	3×10^5
7000	3×10^4	1.3×10^5	5×10^4

"Beta" beams

An alternative idea for a Neutrino Factory (P. Zucchelli, 2001)

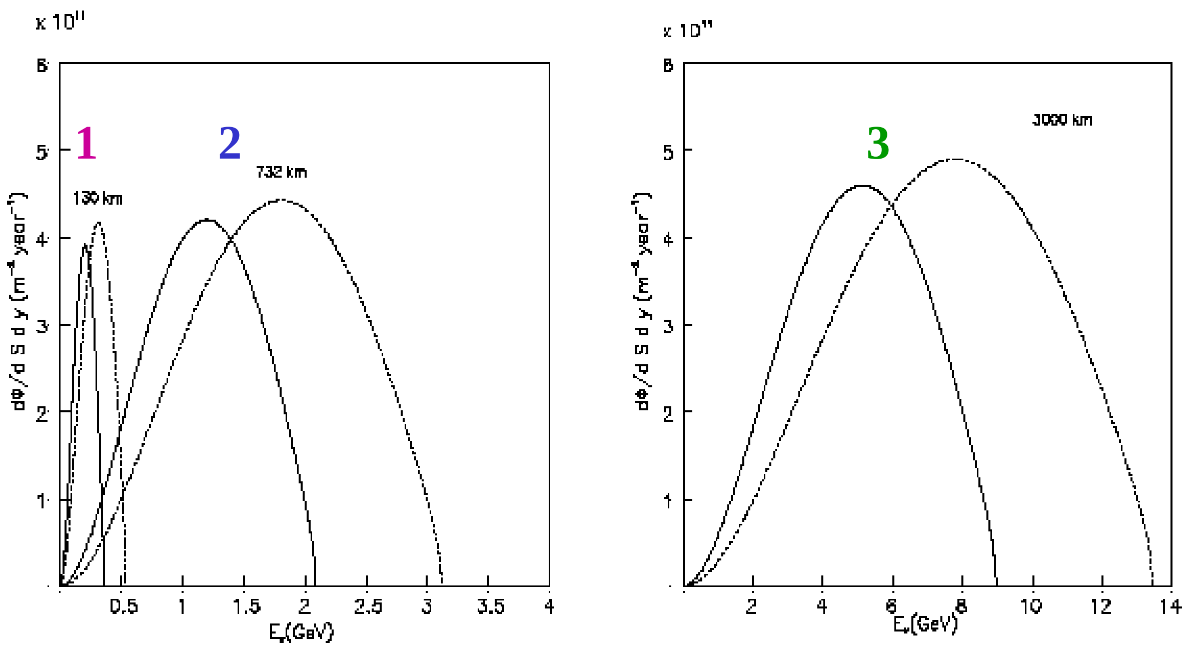
- **Produce intense beams of radioactive isotopes undergoing β decay**
- **Acceleration and injection into a storage ring with long straight sections**

$He^6 \rightarrow Li^6 + e^- + \bar{\nu}_e$: $\langle E(\bar{\nu}_e)\rangle = 1.94$ MeV ; $\tau_{1/2} = 0.807$ s

$Ne^{18} \rightarrow F^{18} + e^+ + \nu_e$: $\langle E(\nu_e)\rangle = 1.86$ MeV; $\tau_{1/2} = 1.672$ s

Conceptual machine schemes studied so far:

1. **Acceleration: $\gamma = 60$ (He^6), $= 100$ (Ne^{18}). $L = 130$ km (CERN – Tunnel Frejus)**
2. **Acceleration: $\gamma = 350$ (He^6), $= 580$ (Ne^{18}). $L = 732$ km (CERN – Gran Sasso)**
3. **Acceleration: $\gamma = 1500$ (He^6), $= 2500$ (Ne^{18}). $L = 3000$ km (CERN – ?)**



Typical event rate:
10 – 800 / year
for a 1000 ton
detector

CONCLUSIONS ON THREE – NEUTRINO MIXING

- **Neutrinos mix and have non – zero masses;**
- **We do not know the neutrino mass absolute scale because oscillations provide information on Δm^2, and not m^2**
  (The present direct limit on the $\bar{\nu}_e$ mass from H^3 β – decay is $m < 2$ eV)
- **The most urgent problem in the study of neutrino oscillations is to measure θ_{13} with much higher sensitivity than CHOOZ and MINOS ;**
- **Only if $\theta_{13} > 1^o$ there is hope of observing CP violation in neutrino mixing;**
- **R&D is in progress on new ideas to produce more intense, higher purity neutrino beams (Neutrino Factories, Beta Beams) .**

However, there are hints from the LSND experiment at Los Alamos in the 1990s, and more recently from the MiniBooNE experiment at Fermilab, that there may be (at least) one more light neutrino:

LSND observes a signal from $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations with $\Delta m^2 \approx 0.2 - 2$ eV^2;

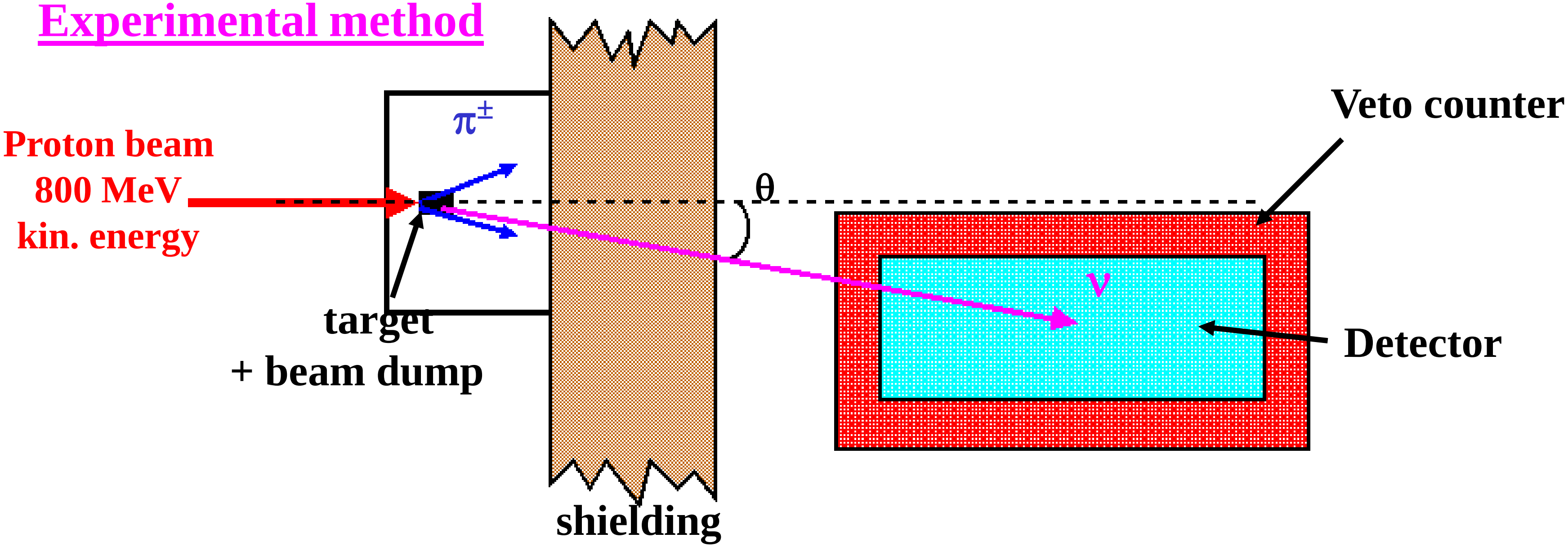
MiniBooNE has a similar signal in $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations , but not in $\nu_\mu - \nu_e$.

The statistical significance is about 3 standard deviations in both experiments.

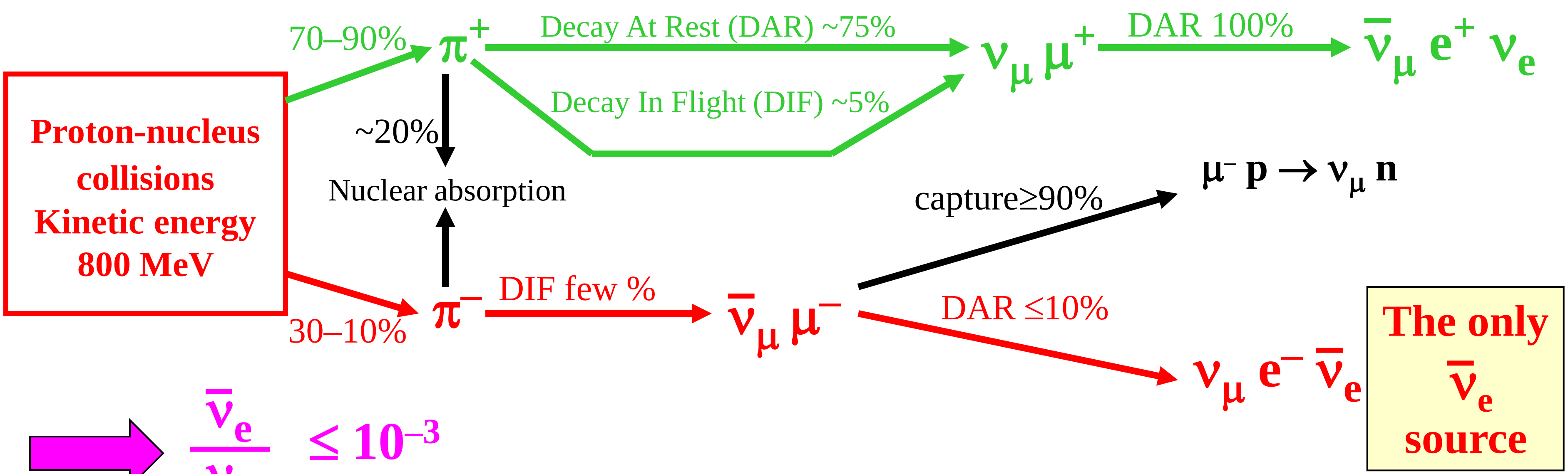
These puzzling results need confirmation from two-detector experiments.

LSND and KARMEN experiments: search for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations

Experimental method



Neutrino sources



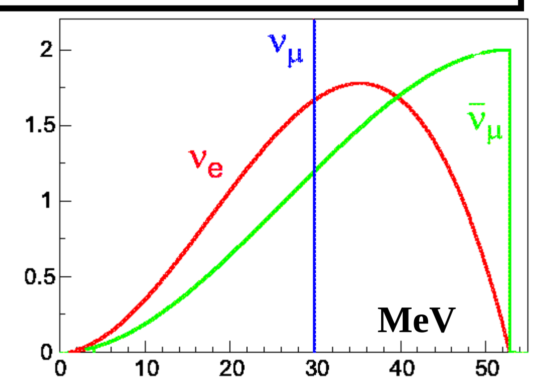
$$\frac{\bar{\nu}_e}{\nu_e} \leq 10^{-3}$$

Parameters of the LSND and KARMEN experiments

	LSND	KARMEN
Accelerator	Los Alamos Neutron Science Centre	Neutron Spallation Facility ISIS ar R.A.L. (U.K.)
Proton kin. energy	800 MeV	800 MeV
Proton current	1000 μA	200 μA
Detector	Single cylindrical tank filled with liquid scintillator Collect both scintillating and Čerenkov light	512 independent cells filled with liquid scintillator
Detector mass	167 tons	56 tons
Event localisation	PMT timing	cell size
Distance from ν source	29 m	17 m
Angle θ between proton and ν direction	11°	90°
Data taking period	1993 – 98	1997 – 2001
Protons on target	4.6×10^{23}	1.5×10^{23}

Neutrino energy spectra from $\pi^+ \to \mu^+ \nu_\mu$ decay at rest

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



ν_e detection: the "classical" way

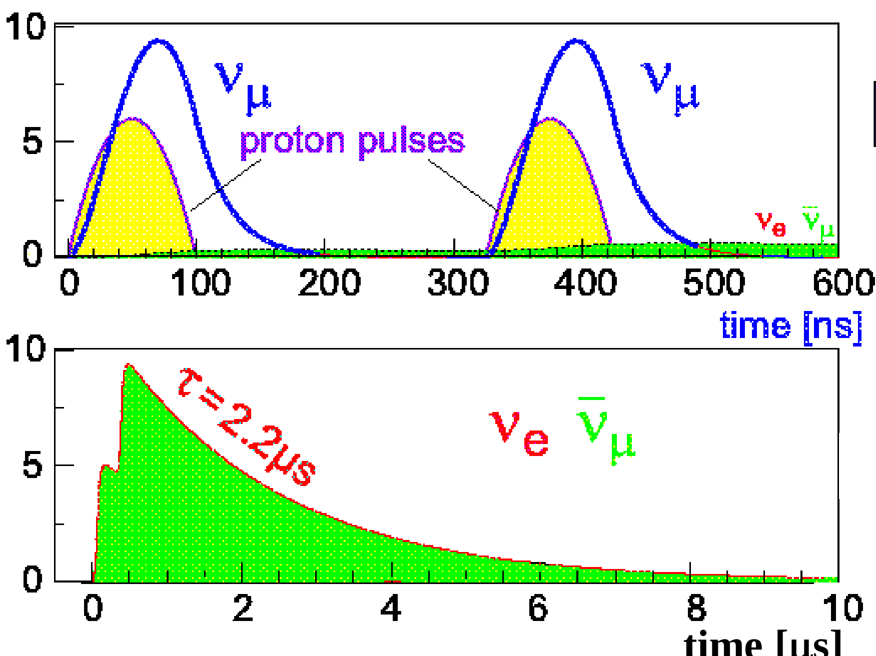
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

delayed signal from np → γd (E_γ = 2.2 MeV)
KARMEN has Gd-loaded paper between adjacent cells → enhanced neutron capture, ΣE_γ = 8.1 MeV

prompt signal

KARMEN beam time structure

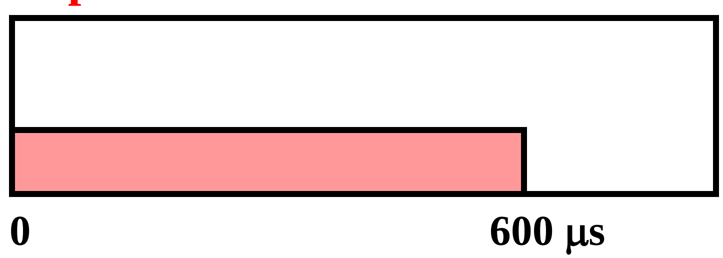
Repetition rate 50 Hz



Expect $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation signal within ~10 μs after beam pulse

LSND beam time structure

Repetition rate 120 Hz



no correlation between event time and beam pulse

LSND: evidence for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations

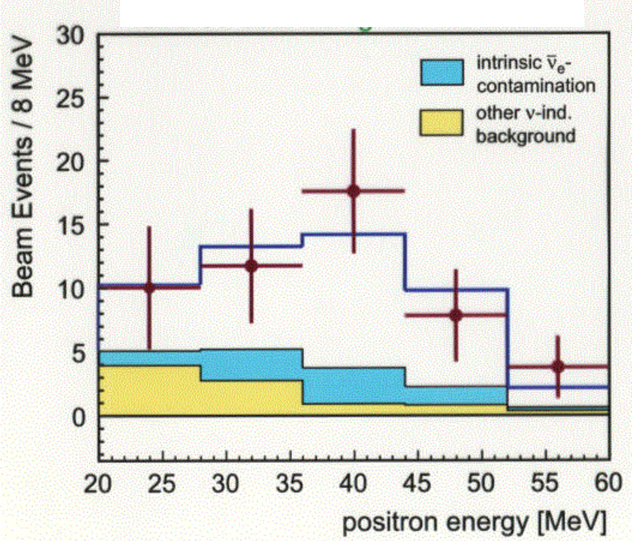
Positrons with 20 < *E* < 60 MeV

N(beam-on) – N(beam-off) = 49.1 ± 9.4 events

Neutrino background = 16. 9 ± 2.3

$\bar{\nu}_e$ signal = 32.2 ± 9.4 events

$$\mathcal{P}_{osc} = (0.264 \pm 0.067 \pm 0.045) \times 10^{-2}$$

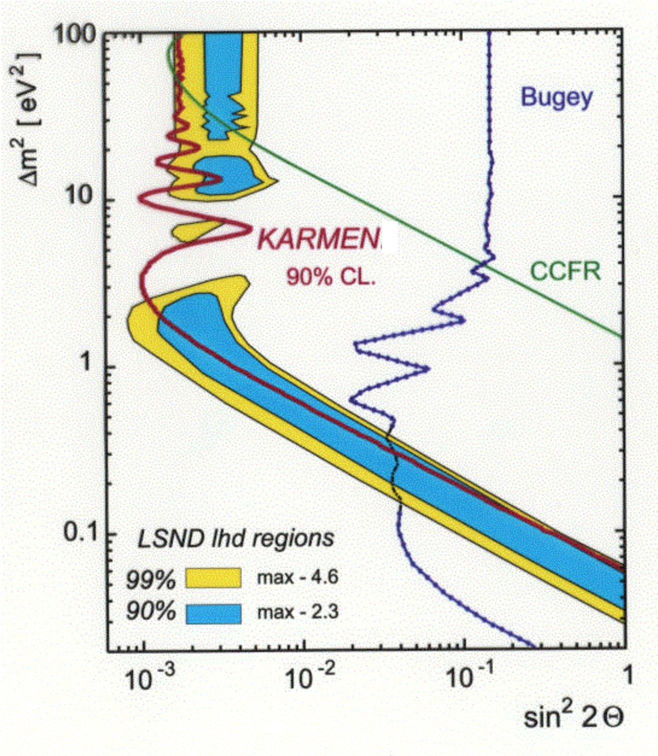


KARMEN: no evidence for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations

Positrons with 16 < *E* < 50 MeV : 15 events

Total background: 15.8 ± 0.5 events

$$\mathcal{P}_{osc} < 0.085 \times 10^{-2} \text{ (conf. level 90\%)}$$



Consistency of KARMEN and LSND results in a limited region of the oscillation parameters because of the different detector distance *L*:

***L* = 29 m (LSND);**

***L* = 17 m (KARMEN)**

The LSND $\nu_\mu - \nu_e$ oscillation signal with $\Delta m^2 \approx 0.2 - 2$ eV^2 requires the existence of a 4th neutrino:

$$(m_2^{\ 2} - m_1^{\ 2}) + (m_3^{\ 2} - m_2^{\ 2}) + (m_1^{\ 2} - m_3^{\ 2}) = 0$$

m_2^2-$m_1^2 \approx 7.6 \times 10^{-5}$ eV^2; $|m_3^2$-$m_2^2| \approx 2.4 \times 10^{-3}$ eV^2

$\rightarrow |m_1^2$-$m_3^2| = |m_3^2$-$m_2^2|\pm(m_2^2$-$m_1^2) << 0.2 - 2$ eV^2

Measurement of the Z – boson width at LEP: number of neutrinos $N_\nu = 2.984 \pm 0.008$

$\Rightarrow$ the 4th neutrino does not couple to W or Z $\Rightarrow$ no interaction with matter:

"sterile neutrino" – the mixing matrix dimensions are at least 4 x 4

$$\nu_\alpha = \sum_{k=1}^{4} U_{\alpha k} \nu_k \qquad \alpha = e, \mu, \tau, s$$

$$P(\nu_\mu - \nu_e) = \left| \sum_{k=1}^{4} U_{ek} U_{\mu k} \exp(-iE_k t) \right|^2 = \left| U_{e1} U_{\mu 1} + \sum_{k=2}^{4} U_{ek} U_{\mu k} \exp\left(-i \frac{\Delta_{k1}}{2E} t \right) \right|^2 \qquad (\Delta_{k1} = m_k^{\ 2} - m_1^{\ 2})$$

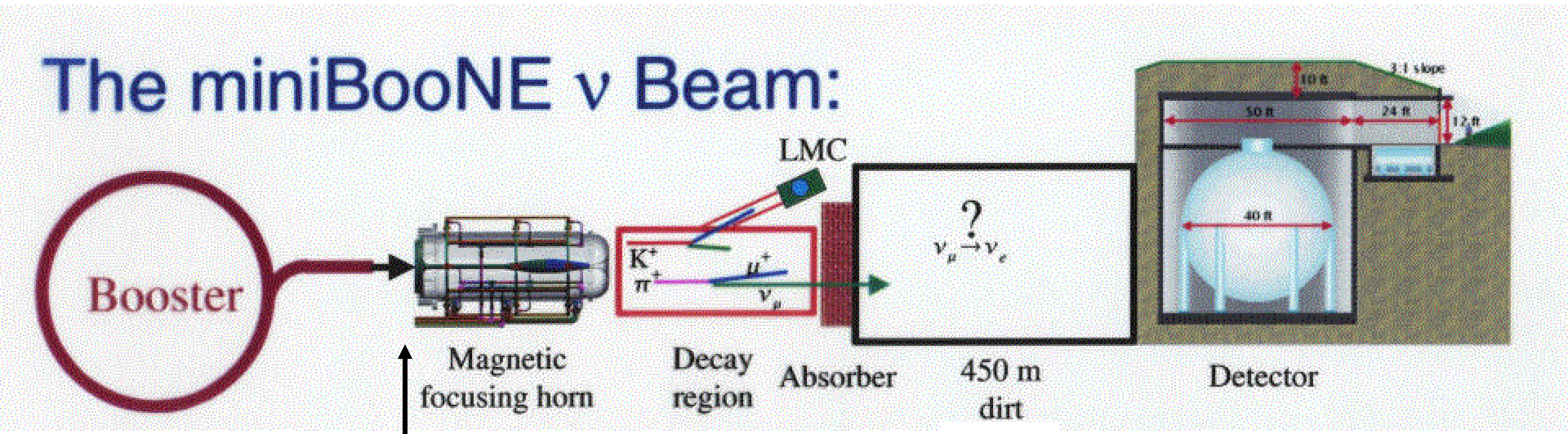
For the LSND experiment oscillation effects associated with Δ_{12} and Δ_{23} are negligible:

$$P(\nu_\mu - \nu_e) = \left| \sum_{k=1}^{3} U_{ek} U_{\mu k} + U_{e4} U_{\mu 4} \exp\left(-i \frac{\Delta_{41}}{2E} t \right) \right|^2 = 4 \left| U_{e4} U_{\mu 4} \right|^2 \sin^2\left(1.267 \Delta_{41} \frac{L}{E} \right) \qquad (L[m];\ E[MeV])$$

$$\left(\sum_{k=1}^{4} U_{e4} U_{\mu 4} = 0 \quad \text{from unitarity} \right)$$

MiniBooNE at Fermilab

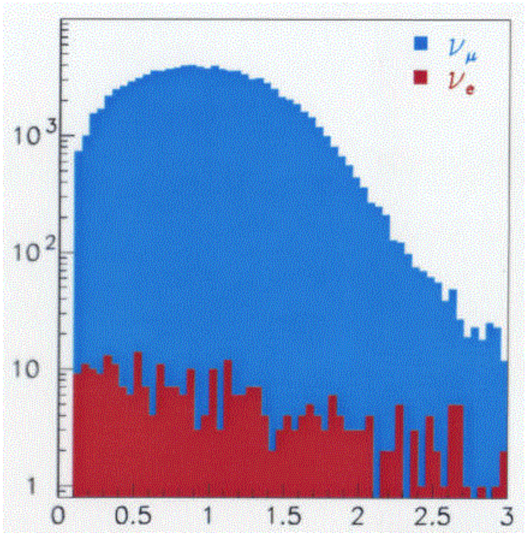
An experiment to verify the LSND oscillation signal



Beryllium target

8 GeV proton synchrotron

Predicted fluxes →



ν flux (arbitrary units)

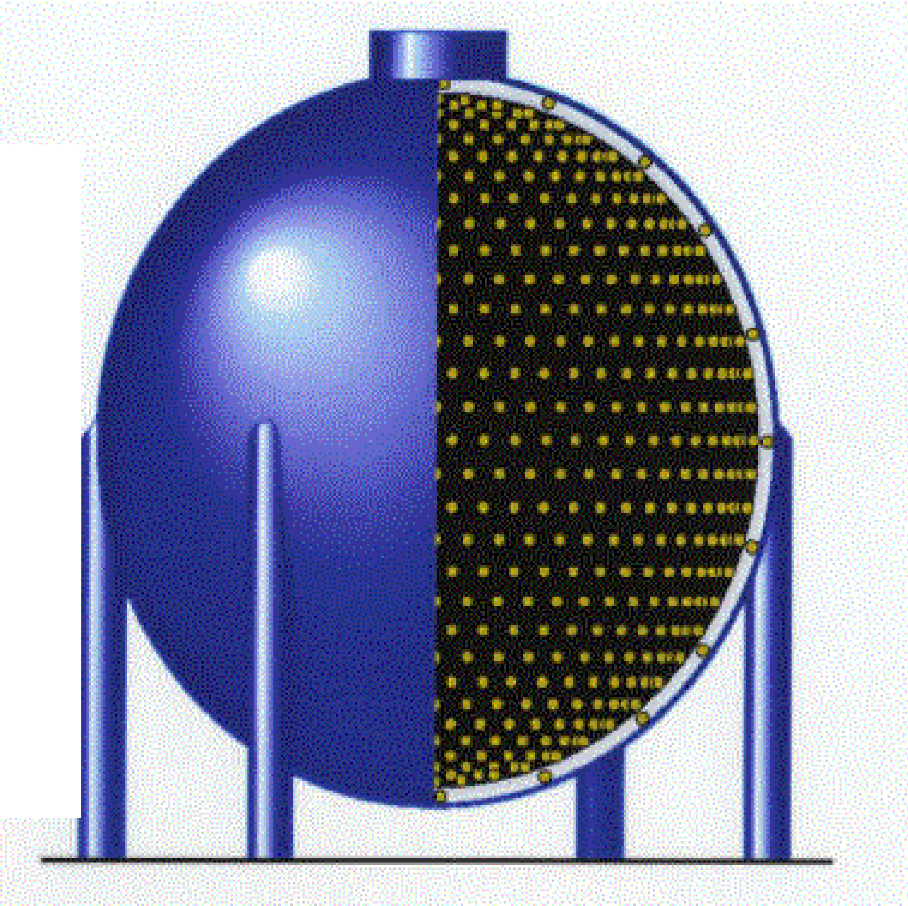
E_ν [GeV]

***L* ≈ 500 m**

$\frac{L}{E}$ similar to LSND experiment

NO NEAR DETECTOR

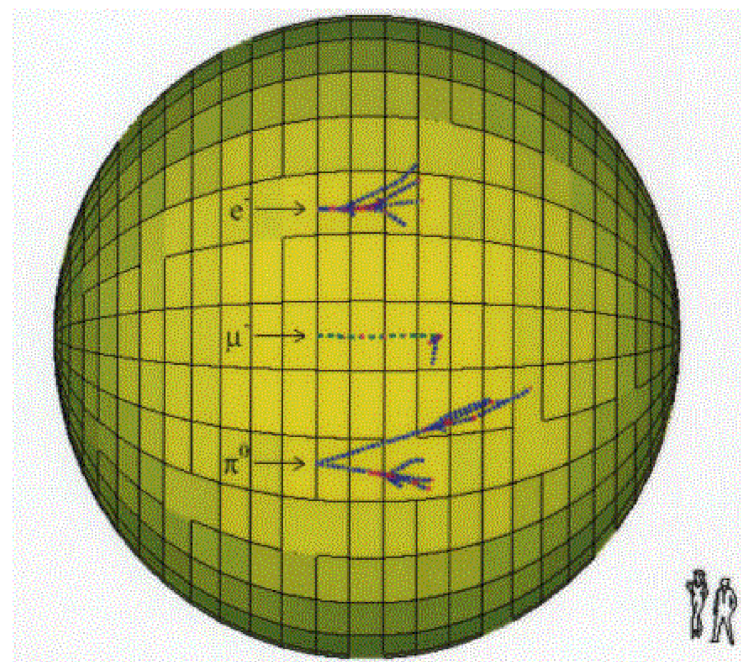
MiniBooNE detector



- Spherical tank, diameter 12 m, filled with 807 ton mineral oil
- Collect both Čerenkov light (directional) and scintillation light.
- Fiducial mass 445 tons
- Optically isolated inner region (1280 photomultiplier tubes, diam. 20 cm)
- External shell used for anticoincidence (240 photomultiplier tubes)

Particle identification

based on the different behaviour of electrons, muons, pions and on the Čerenkov light ring configuration



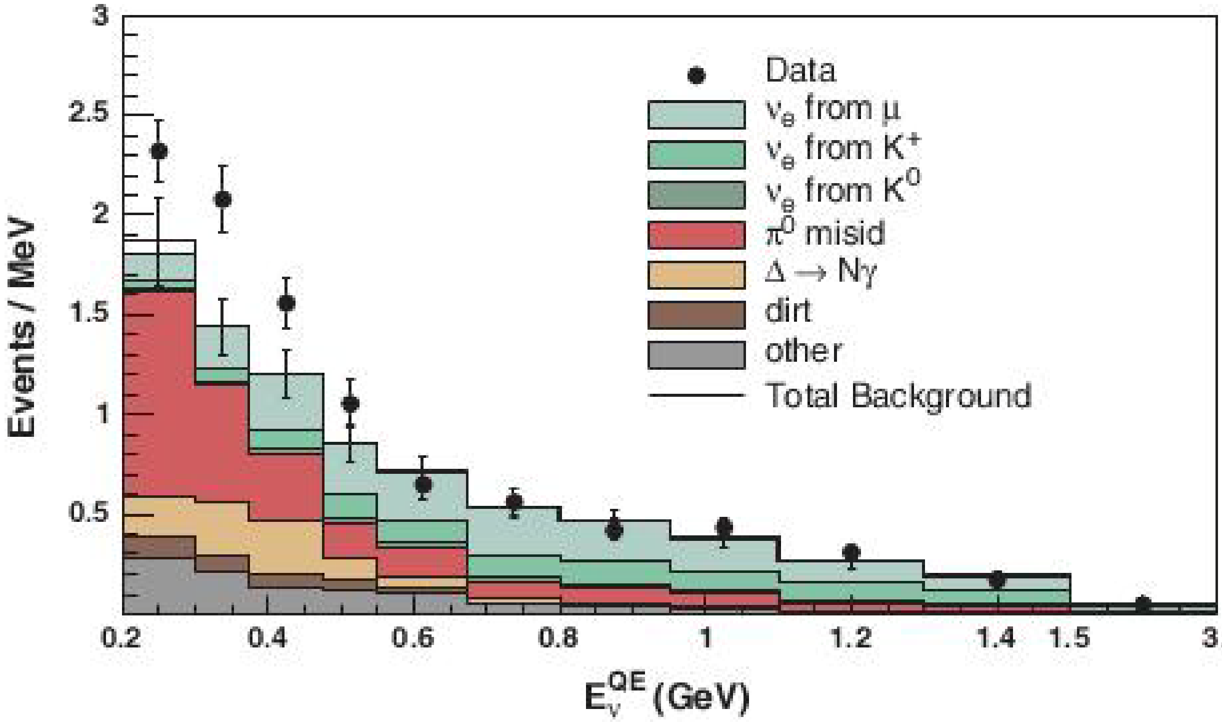
MiniBooNE: search for $\nu_\mu - \nu_e$ oscillations

6.46×10^{20} protons on target

A.A.Aguilar-Arevalo et al., Phys. Rev. Lett. 102, 101802 (2009)

ν_e energy distribution

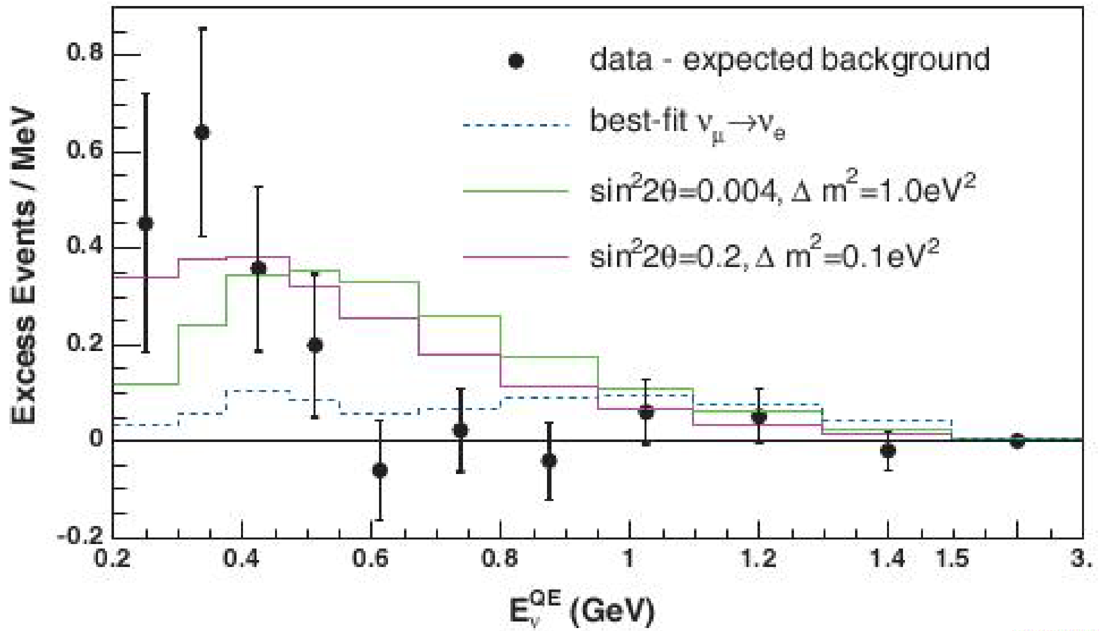
for events consistent with $\nu_e + n \rightarrow e^- + p$



Event excess with $0.2 < E_\nu < 0.475$ GeV: 128.8 ± 43.4 events

The MiniBooNE detector does not distinguish electrons from photons

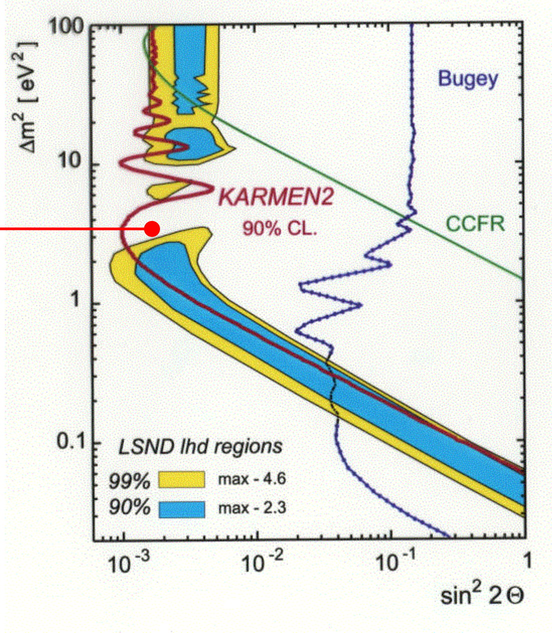
ν_e energy distribution after background subtraction. Comparison with three different $\nu_\mu - \nu_e$ oscillations.



Best fit to $\nu_\mu - \nu_e$ oscillation for 0.2 GeV < E_ν < 2 GeV:

$\sin^2 2\theta = 0.0017$; $\Delta m^2 = 3.14$ eV^2

Parameters excluded by KARMEN

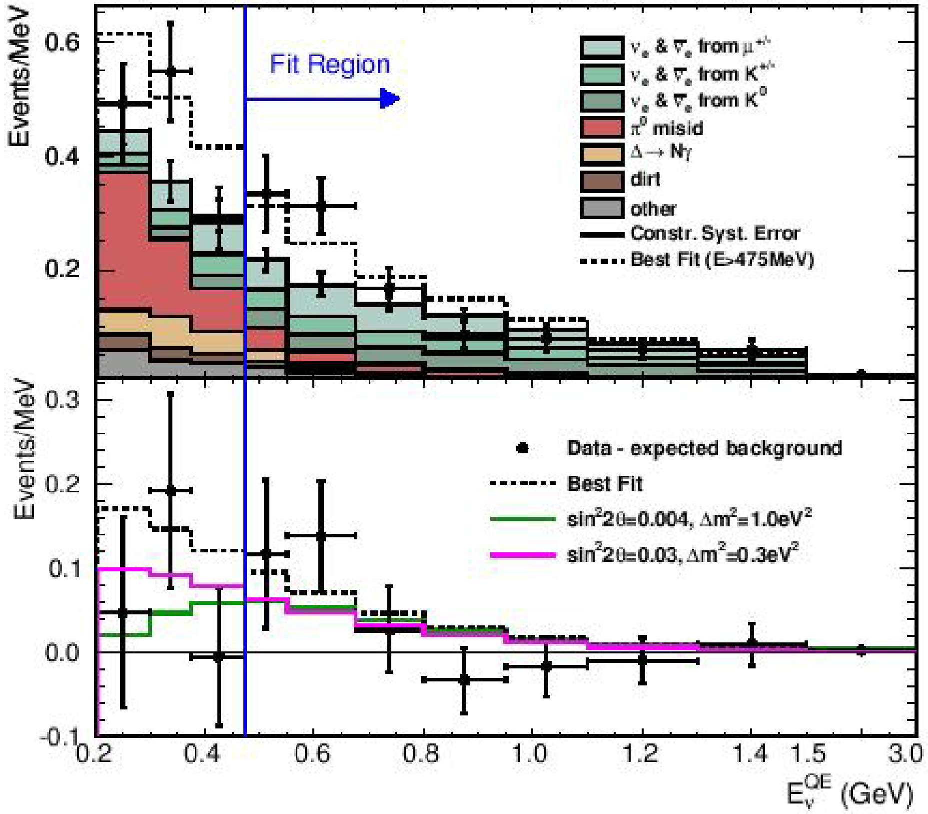


- **MiniBooNE $\nu_\mu - \nu_e$ results inconsistent with the oscillation parameters describing the LSND signal;**
- **Excess of events at low E_ν unexplained**

MiniBooNE: search for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations

5.66 x 10^{20} protons on target

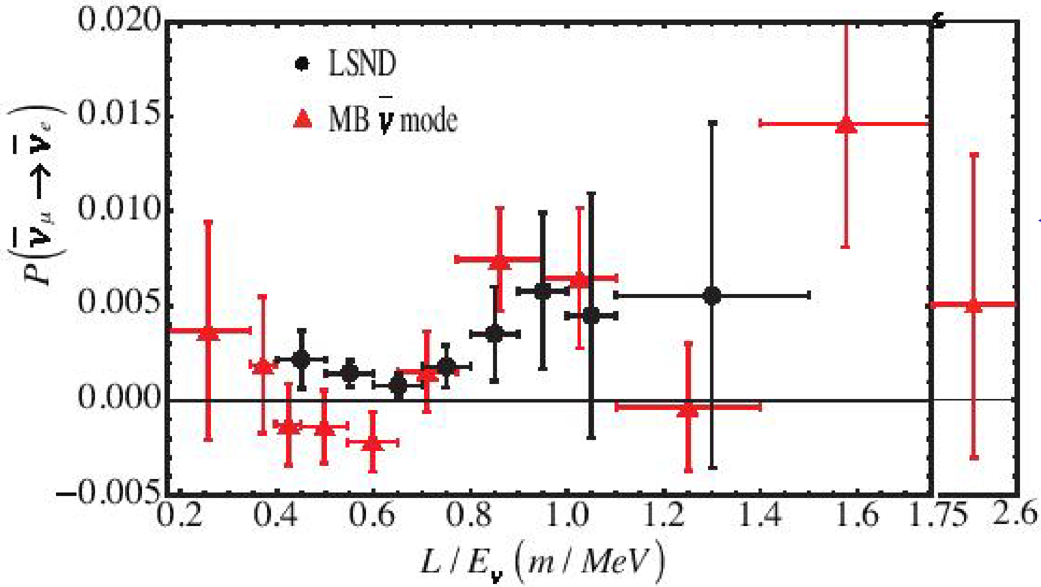
A.A.Aguilar-Arevalo et al., arXiv:1007.1150v3



$\bar{\nu}_e$ energy distribution for events consistent with $\bar{\nu}_e + p \rightarrow e^+ + n$

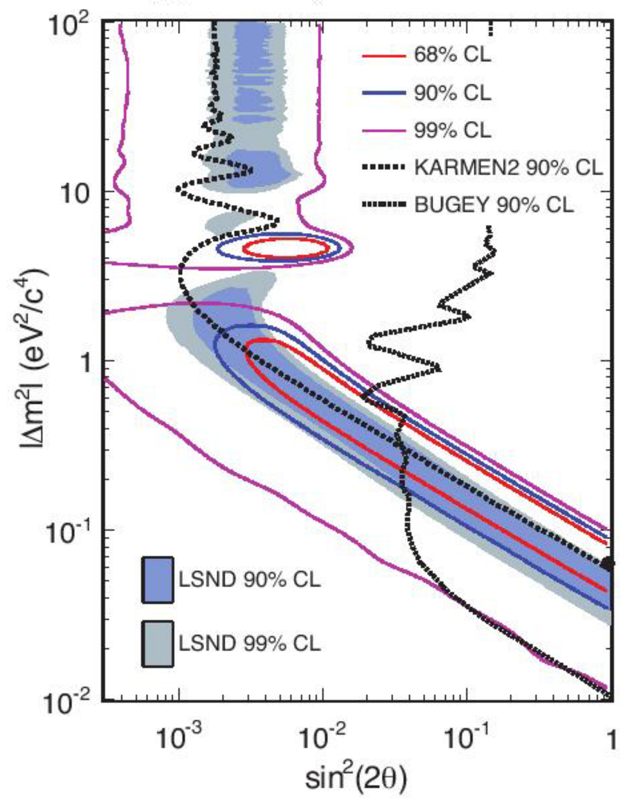
E_ν^{QE} Range	Data	Background	Excess
200 – 475 MeV	119	$100.5 \pm 10.0 \pm 10.2$	18.5 ± 14.3
475 – 675 MeV	64	$38.3 \pm 6.2 \pm 3.7$	25.7 ± 7.2
475 – 1250 MeV	120	$99.1 \pm 10.0 \pm 9.8$	20.9 ± 14.0
475 – 3000 MeV	158	$133.3 \pm 11.5 \pm 13.8$	24.7 ± 18.0
200 – 3000 MeV	277	$233.8 \pm 15.3 \pm 16.5$	43.2 ± 22.5

Excess of events consistent with LSND oscillation signal



$\bar{\nu}_\mu - \bar{\nu}_e$ **oscillation probability versus** ***L / E*** **:**
LSND – MiniBooNE comparison

Best fit assuming two – neutrino mixing



The MiniBooNE antineutrino result (if confirmed) implies:

- **the existence of a 4th sterile neutrino;**
- **violation of CP symmetry in the neutrino mixing matrix**

  (because the probabilities for $\bar{\nu}_\mu - \bar{\nu}_e$ and $\nu_\mu - \nu_e$ oscillations are different)

This result must be confirmed by an experiment which includes a near detector

MINOS: search for $\nu_\mu - \nu_s$ oscillations as a possible mechanism for ν_μ disappearance in the far detector:

measurement of the Neutral Current (NC) event rate

$\nu + N \rightarrow \nu$ + hadrons

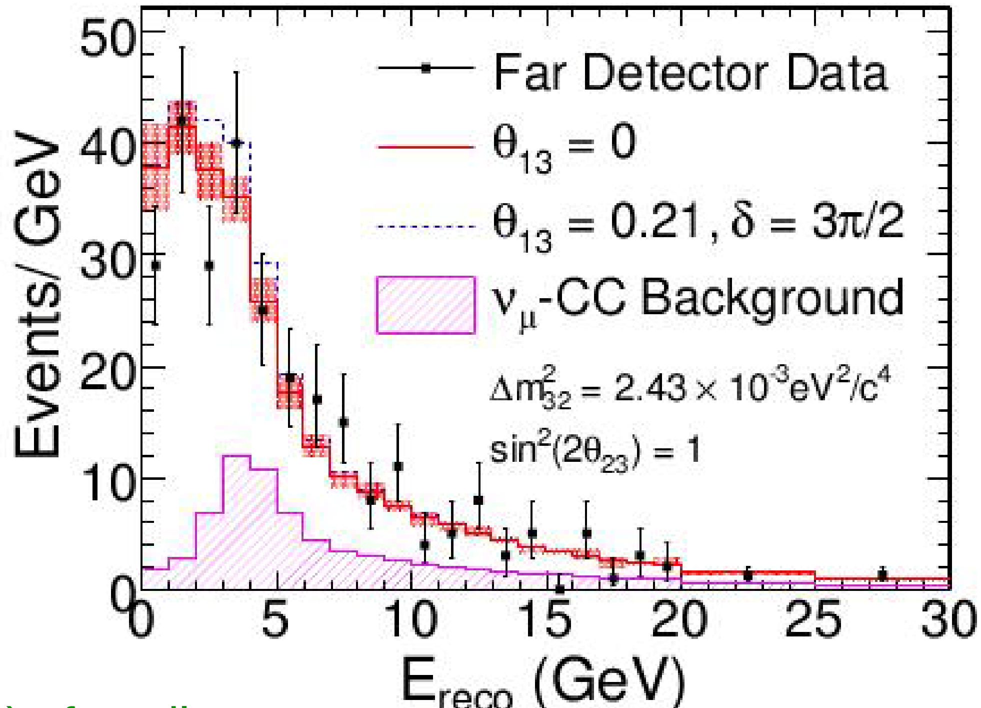
NC events: no muon track $\Rightarrow$ events contained in a limited number of consecutive detector planes (include $\nu_e + N \rightarrow e^- +$ hadron events)

$\nu_\mu - \nu_\tau$ oscillations:

NC event rate unchanged (identical cross-section for the three neutrino types)

$\nu_\mu - \nu_s$ oscillations:

ν_s does not interact with matter
$\Rightarrow$ deficit of NC events



Measured energy distribution consistent with no deficit
$\Rightarrow$ no evidence of ν_s

Results from a fit including a fraction $f(\nu_s)$ of sterile ν :

$f(\nu_s) = 0.28 \pm 0.28$; $f(\nu_s) < 0.68$ (confidence level 90%)