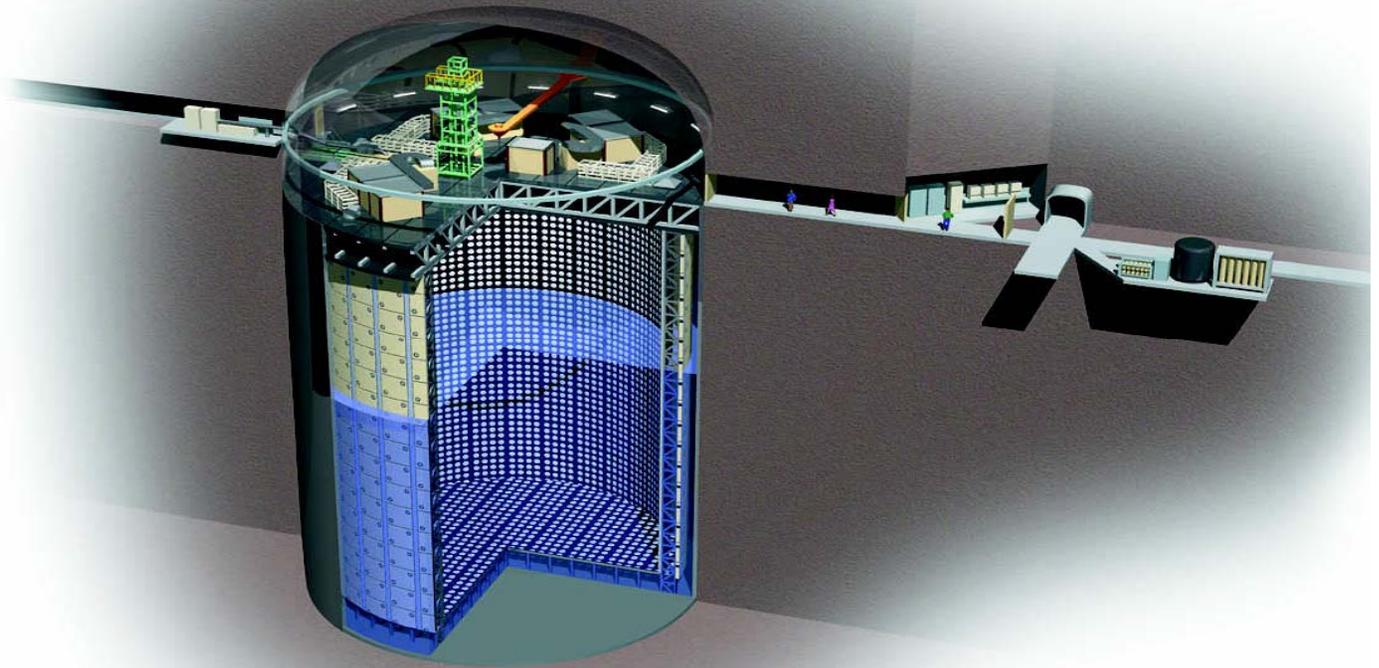


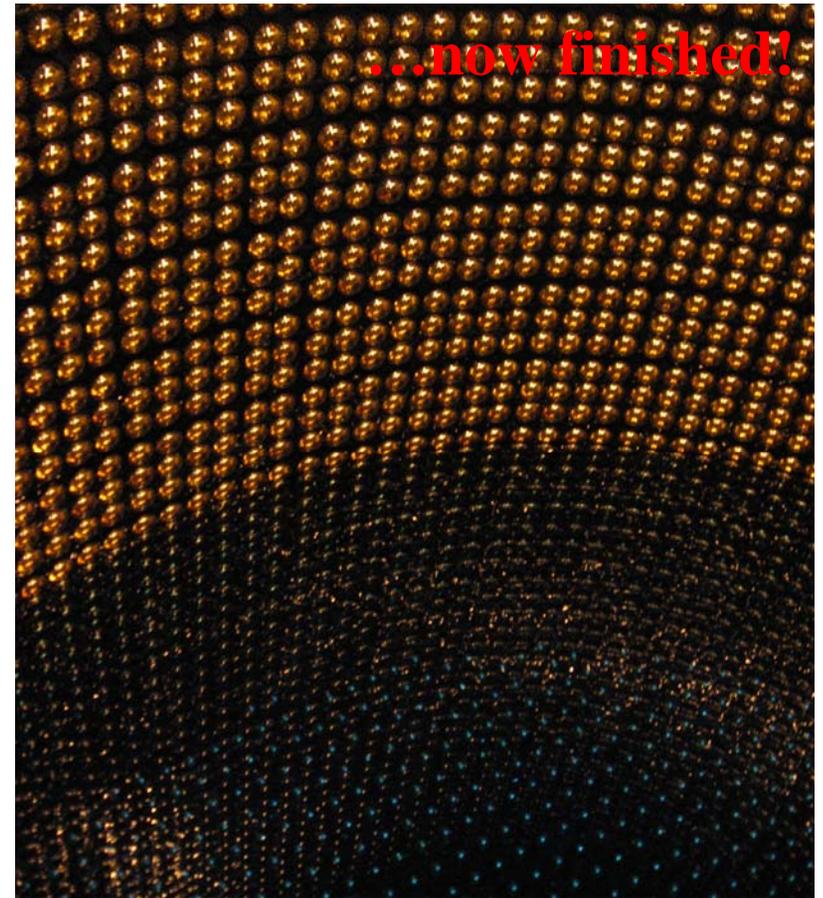


Super-Kamiokande

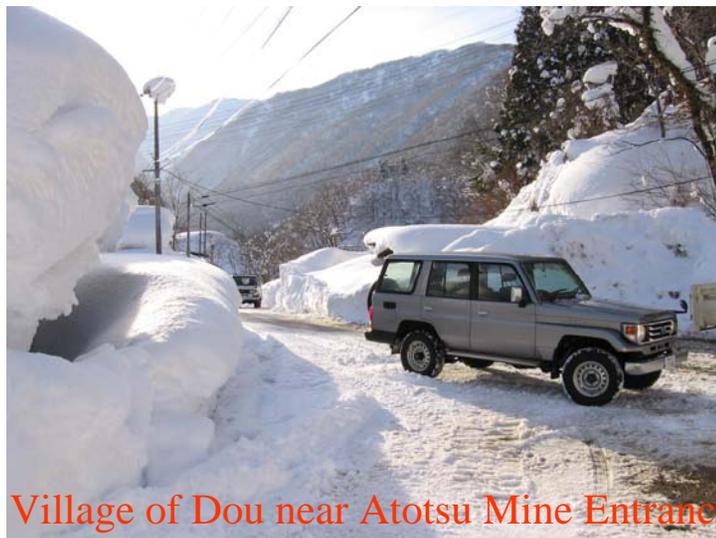
- 50kt Water Cherenkov Detector with 11,146 20" ϕ PMTs
- located in Kamioka mine at 36.43°N latitude and 137.31° longitude $\sim 2,400$ m.w.e underground
- April 1996-July 2001: (SK-I) Accident in November 2001 during maintenance Jan. 2003-Oct. 2005: SK-II
(half PMT density) July 2006 – (SK-III)
- many physics topics; solar, atmospheric & accelerator ν 's, proton decay



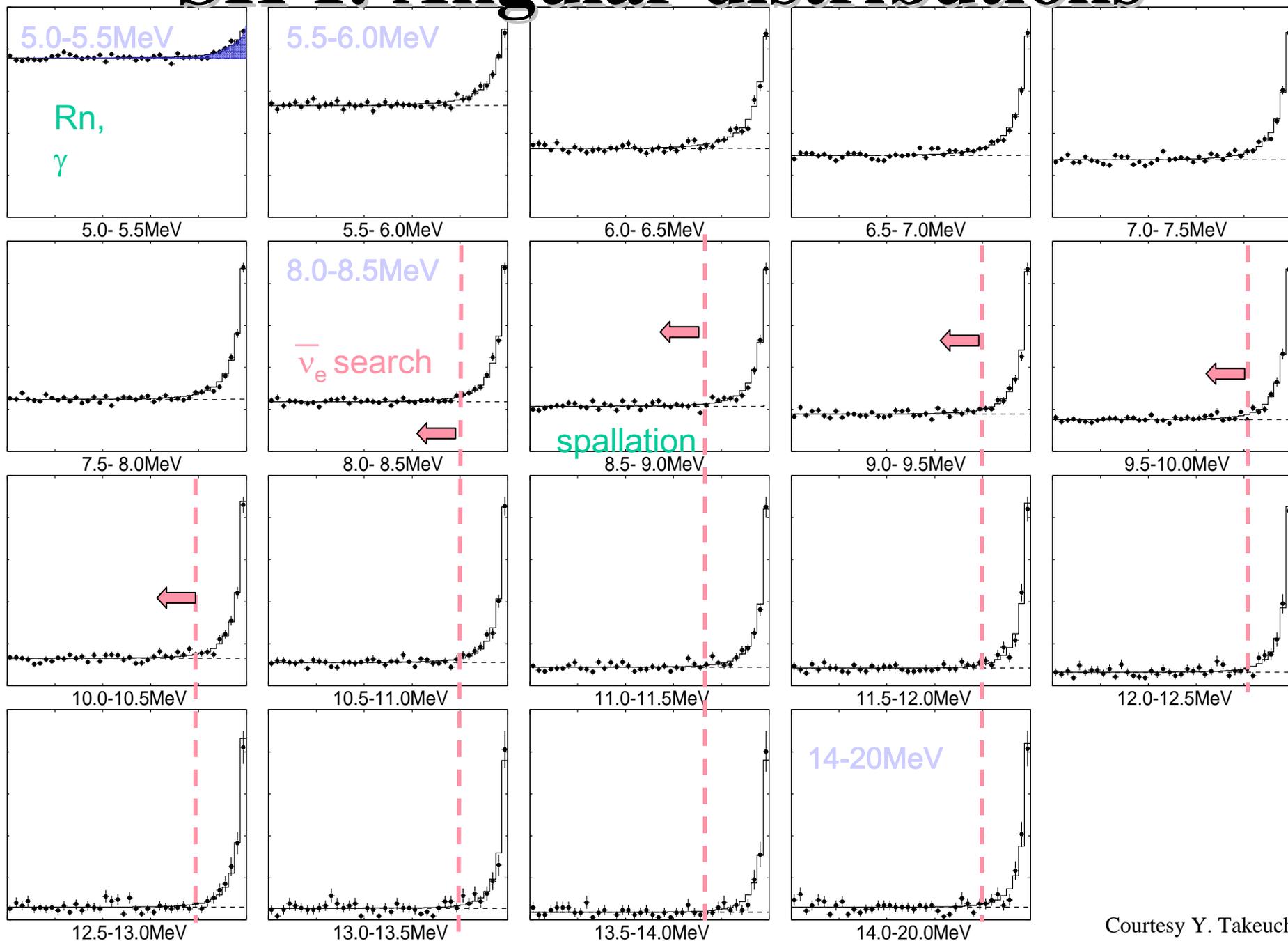
Super-K Is Repaired!



...despite
some
weather
problems!



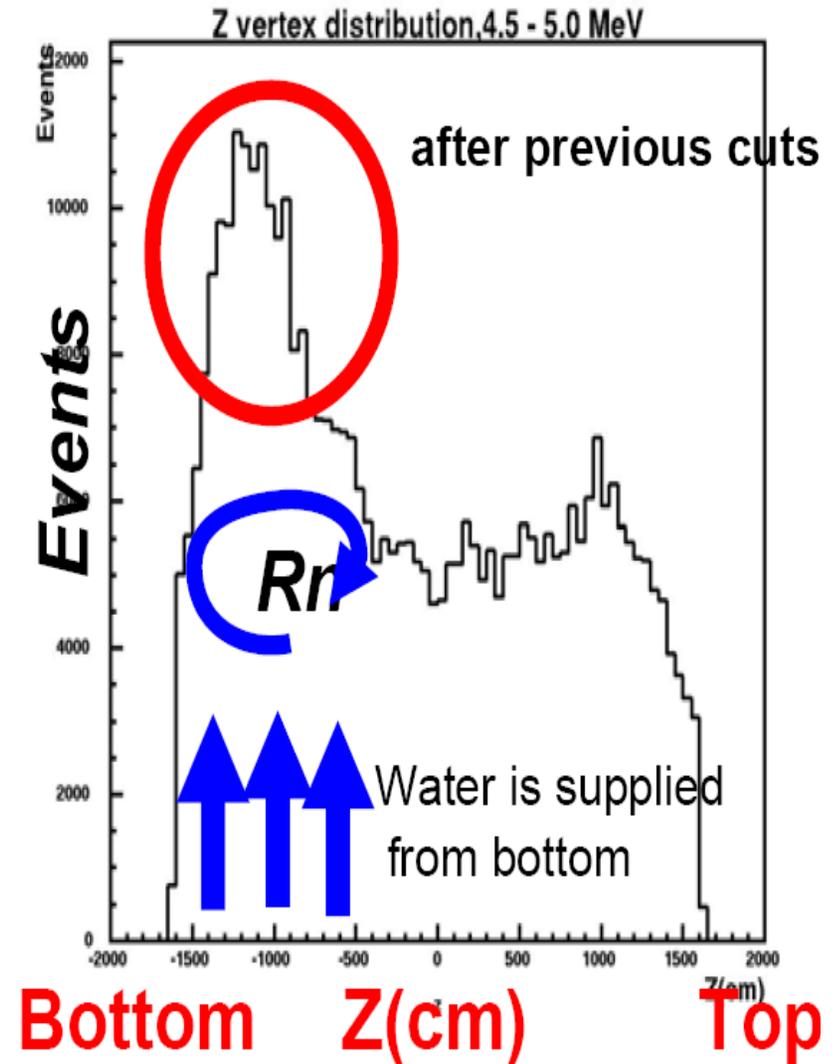
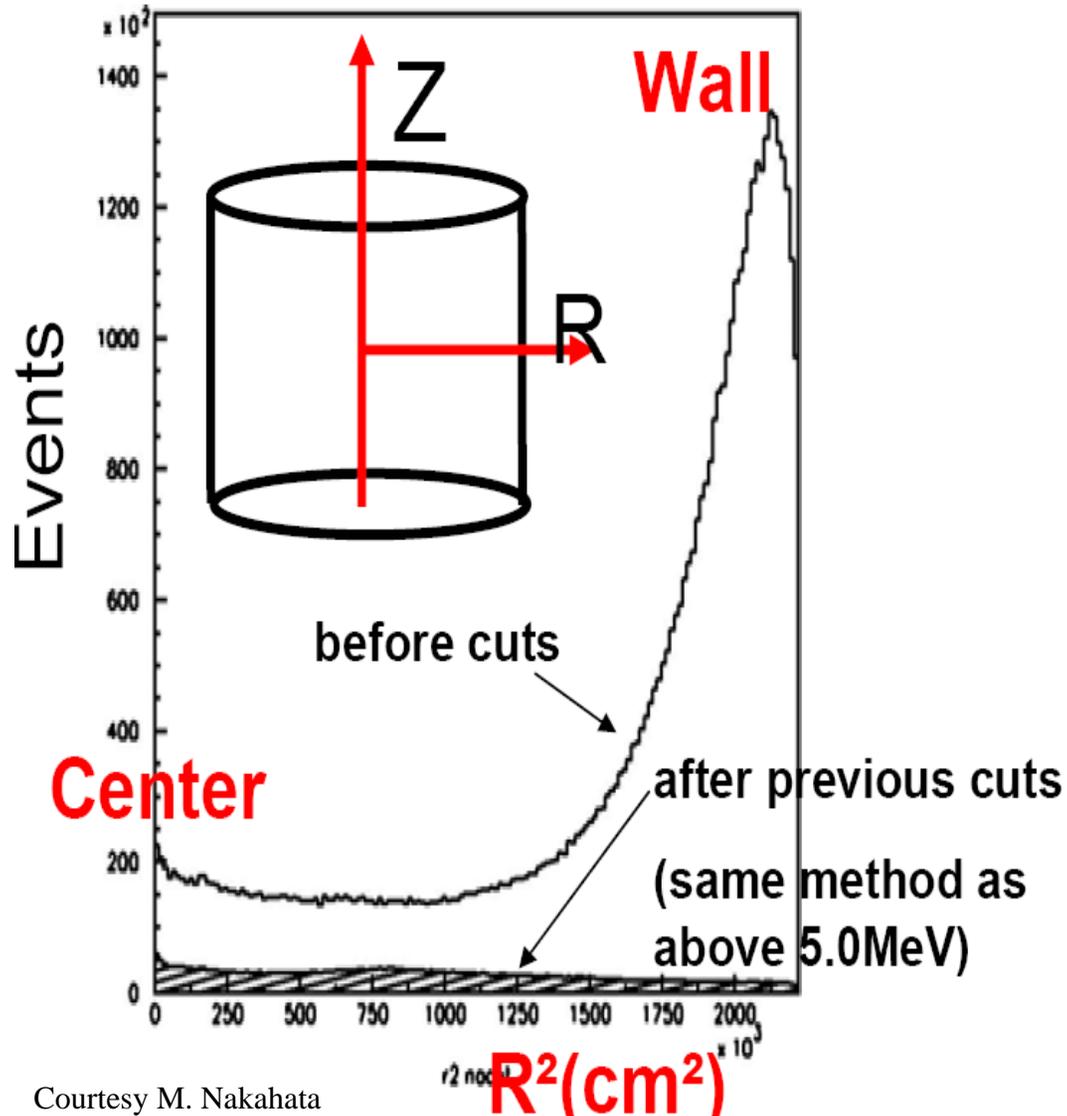
SK-I: Angular distributions



Courtesy Y. Takeuchi

SK-I Backgrounds

Vertex position distribution of background (4.5 – 5.0 Me



How To Lower Threshold

- Must reduce backgrounds...
- Reduced Radon emission due to blast shields
- Reduced Radon due to water flow change
- Software Improvements:
 - Event Reconstruction
 - Event Selection
 - Background Studies

Ridotto flusso osservato → Oscillazioni dei neutrini ?

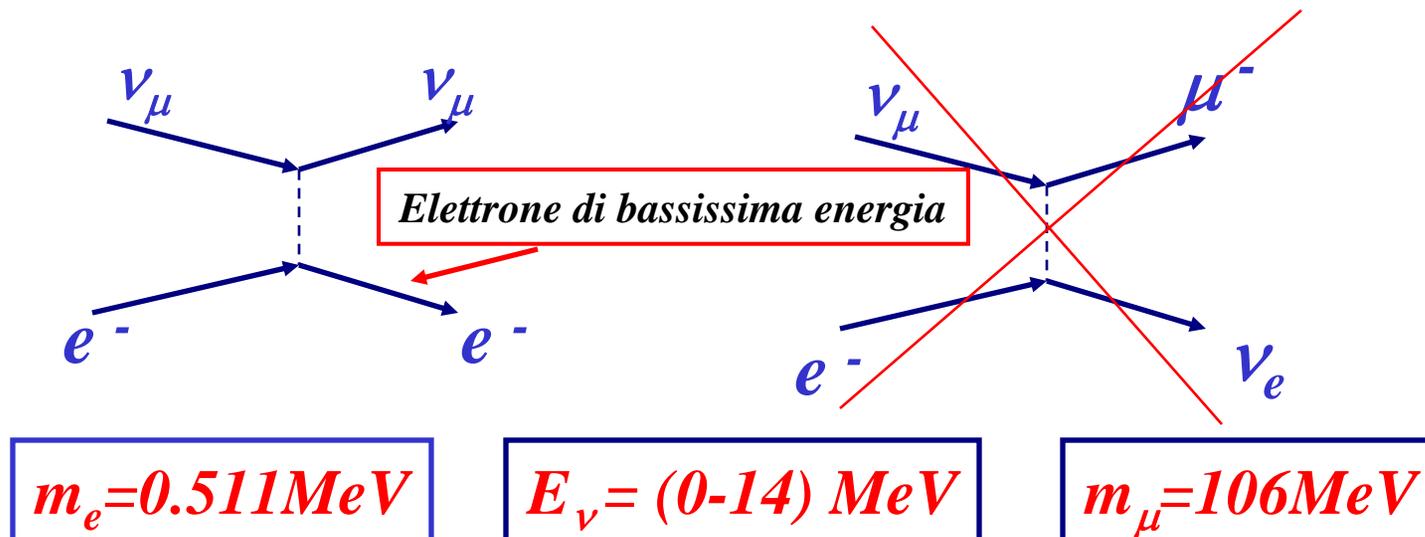
Generati nel Sole: ν_e

Oscillazioni: $\nu_e \rightarrow \nu_\mu$ \circ $\nu_e \rightarrow \nu_\tau$

Effetto proporzionale al quadrato della distanza

Inversamente prop. all'inverso del quadrato dell'energia

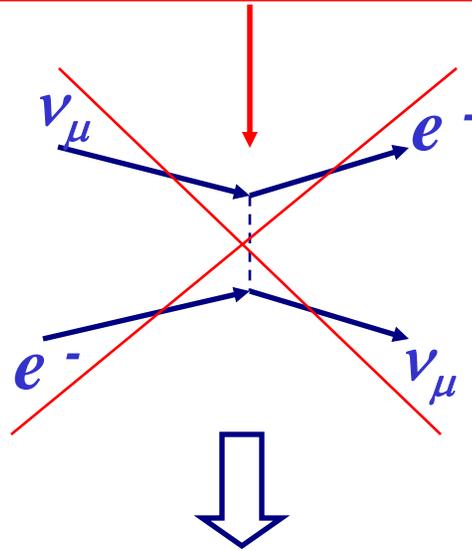
Un ν_μ o ν_τ prodotto non puo' avere interazioni di corrente carica su elettrone (solo corrente neutra) poiche' l'energia del neutrino e' < della massa del leptone (μ o τ) prodotto



Oscillazioni dei neutrini ?

Un ν_μ o ν_τ risultante dall'oscillazione non puo' esser rivelato

Violazione del numero leptonico ad entrambi i vertici



*Neutrino non rivelabile
(ma vedasi piu' giu')*

*INVERSE β -PROCESSES AND NON-CONSERVATION
OF LEPTON CHARGE**

B.Pontecorvo

Joint Institute for Nuclear Research, Dubna

*Proposta da Bruno
Pontecorvo nel 1957*

Not long ago the question was raised [1] as to whether there exist neutral particle mixtures, other than K^0 mesons [2], that is particles for which the transition particle \rightarrow antiparticle is not strictly forbidden, although the particle at issue is an entity distinct from the corresponding antiparticle. It was noted that neutrino may be such a particle mixture and consequently that there is a possibility of real transitions neutrino \rightarrow antineutrino in vacuum, provided that the lepton (neutrino) charge [3] is not conserved. In the present note we consider in more detail this possibility, which became of some interest in connection with new investigations of inverse β -processes.

Recently there came to our attention a paper by Davis [4], who investigated the production of ^{37}Al from ^{37}Cl under bombardment of neutral leptons emitted by a powerful reactor. Davis' result — a measurable probability of the investigated process — if it is confirmed, definitely indicates that neutrino charge is not strictly conserved. Below it is assumed that: a) the neutrino (ν) and antineutrino ($\bar{\nu}$) emitted in the processes

$$\begin{aligned} p &\rightarrow n + \beta^+ + \nu \\ n &\rightarrow p + \beta^- + \bar{\nu} \end{aligned} \quad (1)$$

are not identical particles;

b) the neutrino charge is not strictly conserved, from which it follows that processes

$$\begin{aligned} p &\rightarrow n + \beta^+ + \bar{\nu} \\ n &\rightarrow p + \beta^- + \nu \end{aligned}$$

are possible, although by definition they are less probable than processes (1).

The physical reason of the distinguishability of neutrino and antineutrino is not discussed here; it could be connected with the non-strict conservation law for some kind of quantum number (neutrino charge?) in analogy with K^0 and \bar{K}^0 mesons, the

*JINR Preprint P-95, Dubna, 1957.

ν oscillations[1]

Oscillazioni di neutrini

Ipotesi: “mixing” di neutrini

(Pontecorvo 1958; Maki, Nakagawa, Sakata 1962)

ν_e, ν_μ, ν_τ non sono autostati di massa ma combinazioni lineari di autostati di massa ν_1, ν_2, ν_3 con autovalori m_1, m_2, m_3 :

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

$\alpha = e, \mu, \tau$ (indice di “flavour”)
 $i = 1, 2, 3$ (indice di massa)

$U_{\alpha i}$: matrice unitaria di mixing

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

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

ν oscillations[2]

Evoluzione temporale di un neutrino in un autostato dell'impulso creato nell'autostato di "flavour" ν_α all'istante $t = 0$

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

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

$$E_k = \sqrt{p^2 + m_k^2} \longrightarrow \text{le fasi } e^{-iE_k t} \text{ sono diverse se } m_j \neq m_k$$

\longrightarrow apparizione di "flavour" $\nu_\beta \neq \nu_\alpha$ per $t > 0$

Mixing di due neutrini

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

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

$\theta \equiv$ angolo di mixing

Se $\nu = \nu_\alpha$ alla produzione ($t = 0$):

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

ν oscillations[3]

Probabilità di rivelare ν_β all'istante t se $\nu(0) = \nu_\alpha$:

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

$$\hbar = c = 1$$

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

Nota: per $m \ll p$ $E = \sqrt{p^2 + m^2} \approx p + \frac{m^2}{2p}$ (nel vuoto!)


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

In unità più familiari:

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

$L = ct$ distanza tra sorgente di neutrini e rivelatore

Unità: Δm^2 [eV²]; L [km]; E [GeV] (oppure L [m]; E [MeV])

NOTA: $P_{\alpha\beta}$ dipende da Δm^2 (non da m). Tuttavia, nell'ipotesi $m_1 \ll m_2$ (vera nel caso di leptoni carichi e quarks), $\Delta m^2 \equiv m_2^2 - m_1^2 \approx m_2^2$

ν oscillations[4]

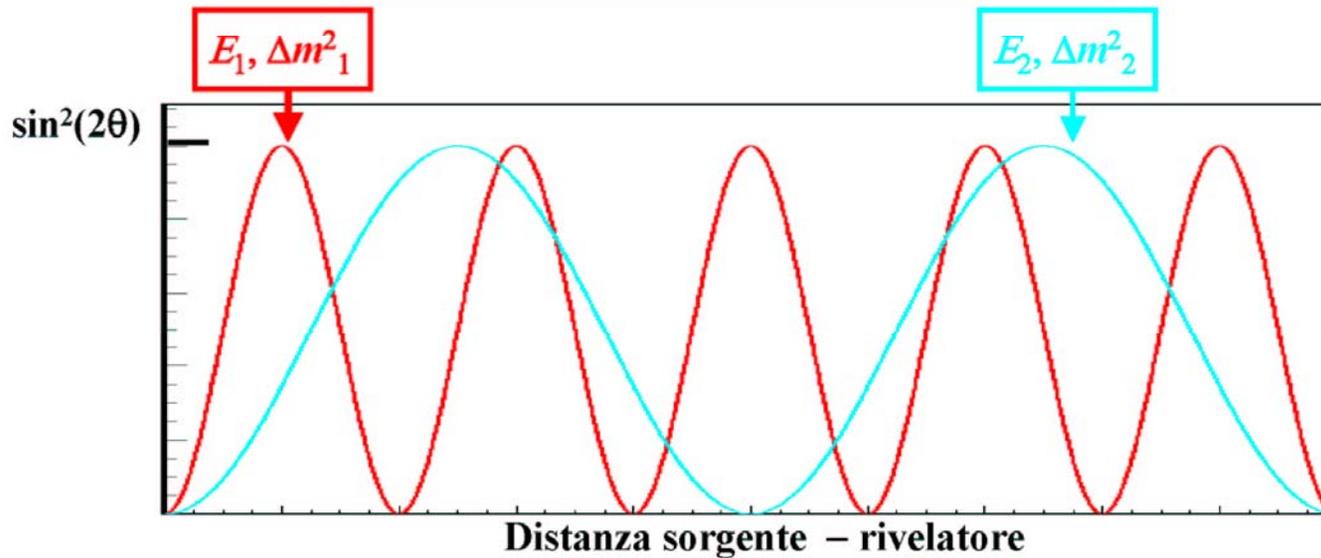
Definizione di lunghezza d'oscillazione λ :

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

Unità: λ [km]; E [GeV]; Δm^2 [eV²]
(oppure λ [m]; E [MeV])



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



$$E_1 < E_2 \text{ e/o } \Delta m^2_1 > \Delta m^2_2$$

ν oscillations[5]

Esperimenti di scomparsa

Sorgente di ν_α , misura del flusso di ν_α a distanza L dalla sorgente

Quantità misurata:
$$P_{\alpha\alpha} = 1 - \sum_{\beta \neq \alpha} P_{\alpha\beta}$$

Esempi:

- **Esperimenti con $\bar{\nu}_e$ da reattori nucleari**
($E_\nu \approx$ pochi MeV: sotto soglia per produzione di μ o τ)
- **Rivelazione di ν_μ presso acceleratori o nella radiazione cosmica** (ricerca di oscillazioni $\nu_\mu \Rightarrow \nu_\tau$ se E_ν è inferiore alla soglia di produzione di τ)

Incertezza sistematica dominante: conoscenza del flusso di neutrini in assenza di oscillazioni \Rightarrow uso di due rivelatori (se possibile)



ν oscillations[6]

Esperimenti di apparizione

Sorgente di ν_α , rivelazione di ν_β ($\beta \neq \alpha$) a distanza L dalla sorgente

Esempi:

- Rivelazione di $\nu_e + N \rightarrow e^- + \text{adroni}$ in un fascio di ν_μ
- Rivelazione di $\nu_\tau + N \rightarrow \tau^- + \text{adroni}$ in un fascio di ν_μ
(Energia alla soglia ≈ 3.5 GeV)

La contaminazione di ν_β alla sorgente deve essere conosciuta con precisione (tipicamente $\nu_e/\nu_\mu \approx 1\%$ in fasci di ν_μ da acceleratori di alta energia)

ν oscillations[7]

Nell'ipotesi di mixing di due neutrini:

- Osservazione di un segnale di oscillazione \rightarrow definizione di regioni di parametri nel piano $[\Delta m^2, \sin^2(2\theta)]$ compatibili col segnale misurato
- Risultato negativo \rightarrow limite superiore $P_{\alpha\beta} < P \rightarrow$ regione di esclusione

Δm^2 grande \rightarrow lunghezza d'oscillazione λ corta

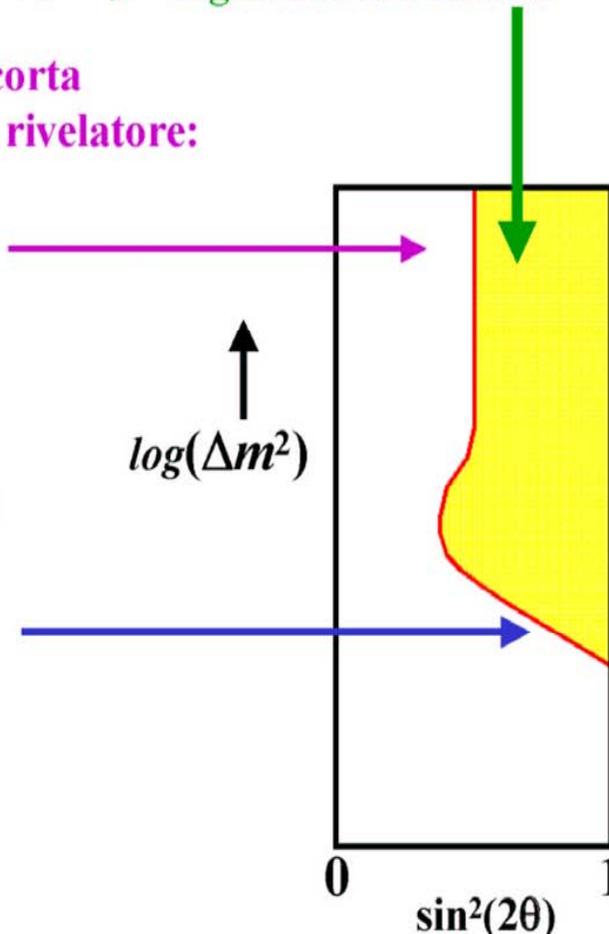
Media sulle dimensioni della sorgente e del rivelatore:

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

Δm^2 piccola \rightarrow λ lunga: $\sin\left(\pi \frac{L}{\lambda}\right) \approx \pi \frac{L}{\lambda}$

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

(inizio della prima oscillazione)



ν oscillations[8]

RICERCHE DI OSCILLAZIONI: PARAMETRI SPERIMENTALI

Sorgente ν	Flavour	Distanza L	Energia ν	Minimo Δm^2 accessibile
Sole	ν_e	$\sim 1.5 \times 10^8$ km	0.2 – 15 MeV	$\sim 10^{-11}$ eV ²
Raggi cosmici	$\frac{\nu_\mu}{\nu_e}$	10 km – 13000 km	0.2 GeV – 100 GeV	$\sim 10^{-4}$ eV ²
Reattori nucleari	$\bar{\nu}_e$	20 m – 250 km	$\langle E \rangle \approx 3$ MeV	$\sim 10^{-1} - 10^{-6}$ eV ²
Acceleratori	$\frac{\nu_\mu}{\nu_e}$	15 m – 730 km	20 MeV – 100 GeV	$\sim 10^{-3} - 10$ eV ²

EVIDENZA / INDIZI DI OSCILLAZIONI:

- **Deficit di neutrini solari: scomparsa di ν_e tra il Sole e la Terra**
Evidenza convincente, misura dei parametri di oscillazione, conferma recente da un esperimento con reattori nucleari
- **Scomparsa di ν_μ di origine “atmosferica” su distanze dell’ordine del diametro terrestre**
Evidenza convincente, misura dei parametri di oscillazione

Oscillazioni di $\nu_e \rightarrow \nu_x$ dagli esperimenti GALLEX, SAGE, SK (2001)

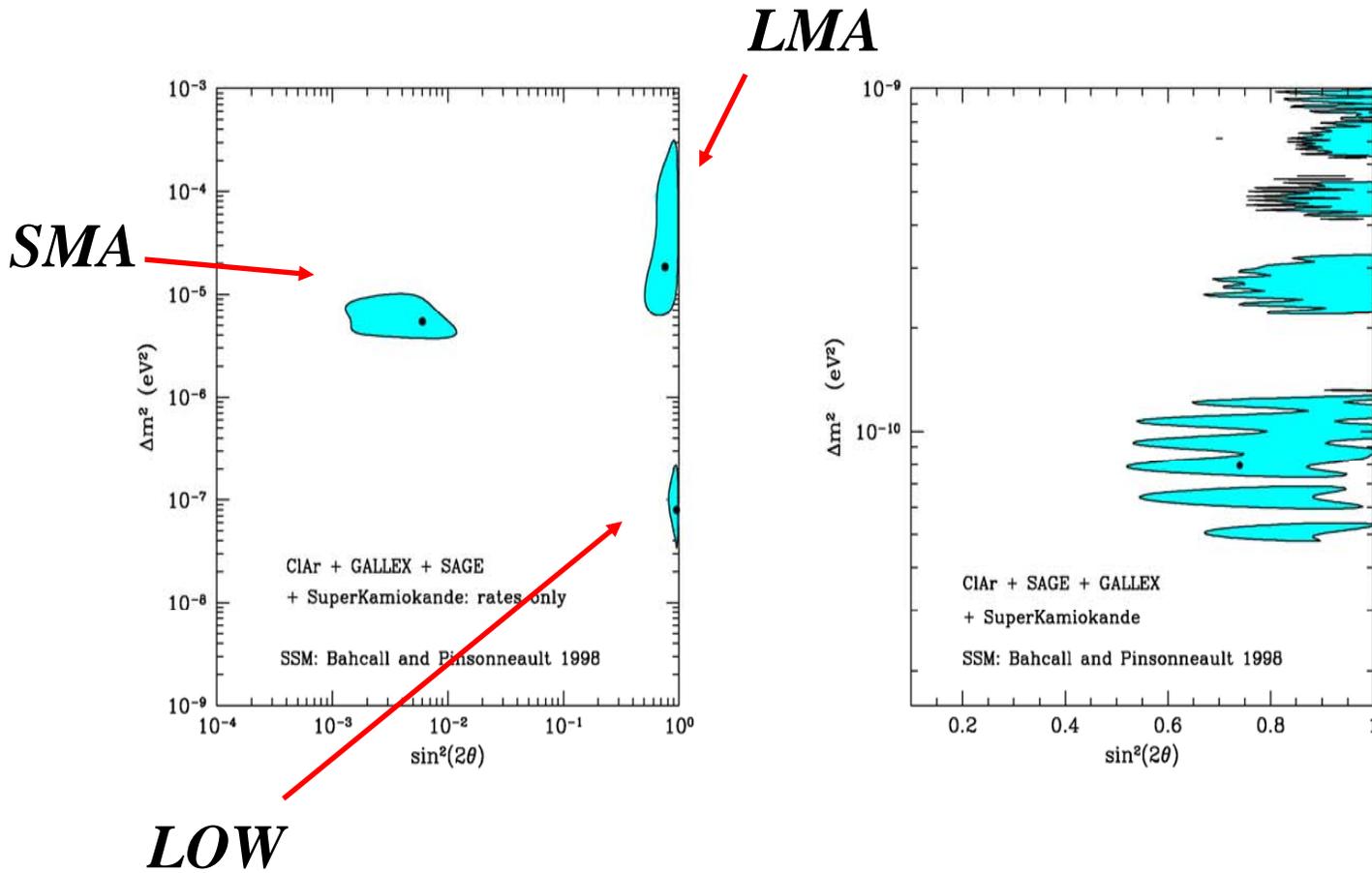


Fig. 6. Allowed regions (99 % C.L.) on the plane $(\sin^2 2\theta, \Delta m^2)$, as obtained in ref.³⁵ from a combined two-flavour analysis of the total rate results in the chlorine, SAGE, GALLEX and Super-Kamiokande experiments, for oscillations in matter (left) and in vacuum (right).

Neutrini atmosferici

6.1. Atmospheric Neutrino Flux and Neutrino Oscillations

Atmospheric neutrinos are produced in the decay of secondary particles created in the interaction of primary cosmic rays^j with the Earth's atmosphere. If the energy of the secondary particles is sufficiently low ($\lesssim 2 \text{ GeV}$) that all of them decay, we have:

$$\begin{aligned} p + \mathcal{N} &\longrightarrow \pi^\pm + X \\ \pi^\pm &\longrightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \\ \mu^\pm &\longrightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu) \end{aligned} \quad (45)$$

Assuming that no effect can change the flavour composition of the shower before it is measured on Earth, Eq.(45) implies that:

$$\mathcal{R} = \frac{\mathcal{N}_{\nu_\mu} + \mathcal{N}_{\bar{\nu}_\mu}}{\mathcal{N}_{\nu_e} + \mathcal{N}_{\bar{\nu}_e}} \sim 2 \quad (46)$$

Doppio rapporto

$$\mathcal{R}' \equiv \frac{\mathcal{R}_{DATA}}{\mathcal{R}_{MC}} = \frac{\left[\frac{\mathcal{N}_{\nu_\mu} + \mathcal{N}_{\bar{\nu}_\mu}}{\mathcal{N}_{\nu_e} + \mathcal{N}_{\bar{\nu}_e}} \right]_{DATA}}{\left[\frac{\mathcal{N}_{\nu_\mu} + \mathcal{N}_{\bar{\nu}_\mu}}{\mathcal{N}_{\nu_e} + \mathcal{N}_{\bar{\nu}_e}} \right]_{MC}},$$

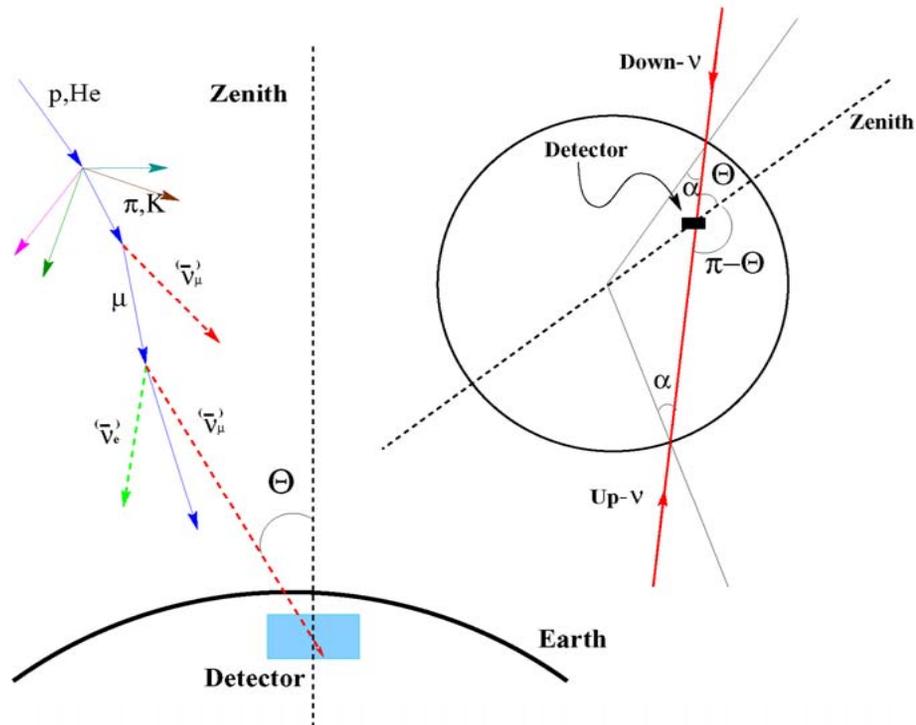


Fig. 11. Sketch of the atmospheric neutrinos detection principles.

Metodo sperimentale

Rivelazione dei neutrini atmosferici

$\nu_\mu + \text{Nucleone} \rightarrow \mu + \text{adroni}$: presenza di una traccia lunga al minimo della ionizzazione (il muone)

$\nu_e + n \rightarrow e^- + p$, $\bar{\nu}_e + p \rightarrow e^+ + n$: presenza di uno sciame elettromagnetico (interazioni ν_e con produzione multipla di adroni in pratica indistinguibili dalle interazioni di Corrente Neutra)

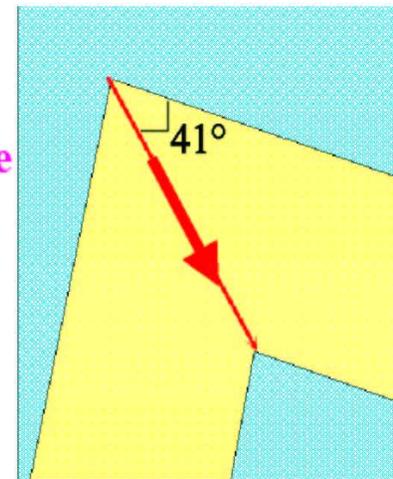
Identificazione in contatori Čerenkov ad acqua

traccia muonica:

dE/dx compatibile col minimo della ionizzazione
anello di luce Čerenkov con bordi ben definiti

sciame elettromagnetico:

dE/dx elevato (molti elettroni secondari)
bordi dell'anello di luce Čerenkov mal definiti
(dall'apertura angolare dello sciame)



Misura della discriminazione elettrone/muone in un contatore Čerenkov ad acqua di 1000 tonn. (copia ridotta di Super-K) esposto a fasci di elettroni e muoni presso acceleratori. Probabilità di identificazione erronea misurata $\sim 2\%$

Misura del rapporto ν_μ/ν_e : primi indizi di un fenomeno nuovo

Contatori Čerenkov ad acqua: Kamiokande (1988), IMB (1991), Super-K (1998)

Calorimetri convenzionali (lastre di ferro + tubi proporzionali): Soudan2 (1997)

$$R = \frac{(\nu_\mu/\nu_e)_{\text{misurato}}}{(\nu_\mu/\nu_e)_{\text{predetto}}} = 0.65 \pm 0.08$$

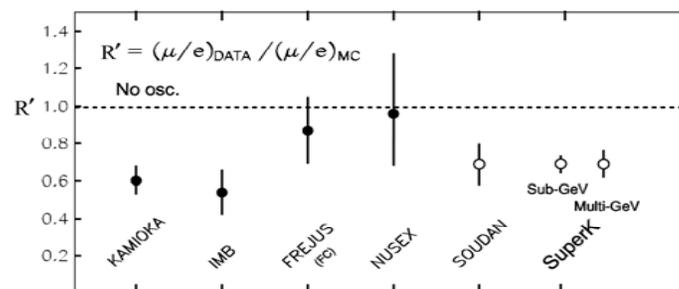


Fig. 12. Compilation of the \mathcal{R}' ratio (see text) measured by several atmospheric neutrino experiments (from ref.⁴⁷).

Risultati iniziali di SK ed indicazioni da altri esperimenti

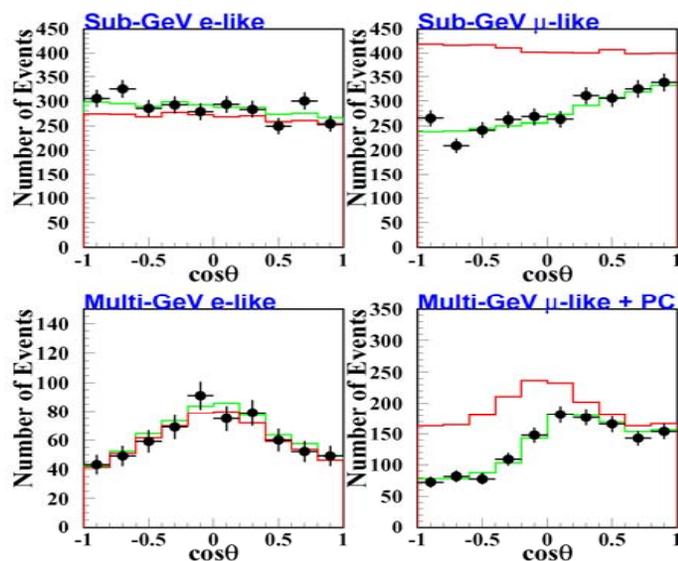
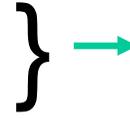


Fig. 17. Distribution of the cosine of the zenith angle obtained by Super-Kamiokade from 1289 live days data, for electron-like and muon-like contained events (from ref.⁸⁴). The solid line is the distribution expected in absence of oscillations, while the hatched histogram is for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the two-flavour mixing scheme, with maximal mixing and $\sin^2 2\theta = 2.5 \times 10^{-3} eV^2$.

Risultati di Superkamiokande

$R'=0.638 \pm 0.017 \pm 0.050$ (Sub GeV)

$R'=0.675 (+0.034/-0.032) \pm 0.080$ (Multi GeV)



diverso da 1 per 7 σ

σ e' la deviazione standard

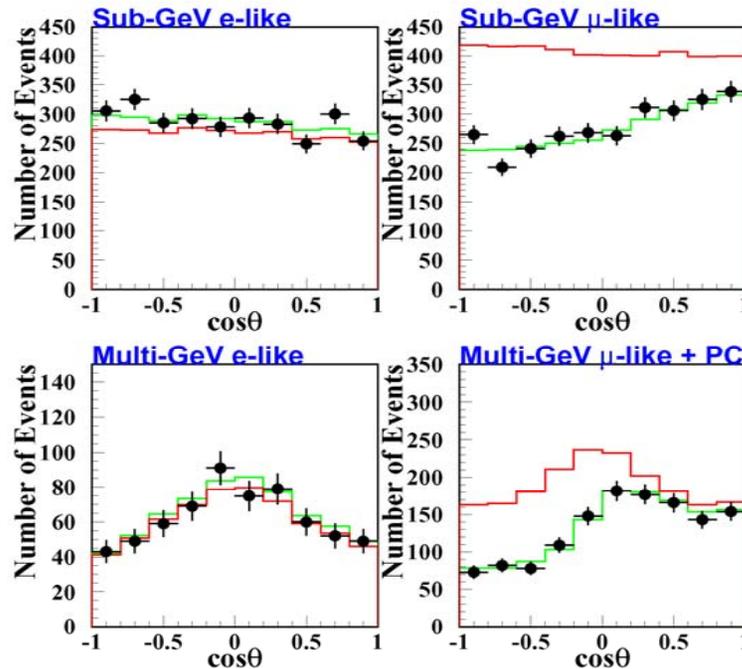


Fig. 17. Distribution of the cosine of the zenith angle obtained by Super-Kamiokande from 1289 live days data, for electron-like and muon-like contained events (from ref.⁸⁴). The solid line is the distribution expected in absence of oscillations, while the hatched histogram is for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the two-flavour mixing scheme, with maximal mixing and $\sin^2 2\theta = 2.5 \times 10^{-3} eV^2$.

SK

U= upward going ($\cos \theta < -0.2$)

D= downward going ($\cos \theta > +0.2$)

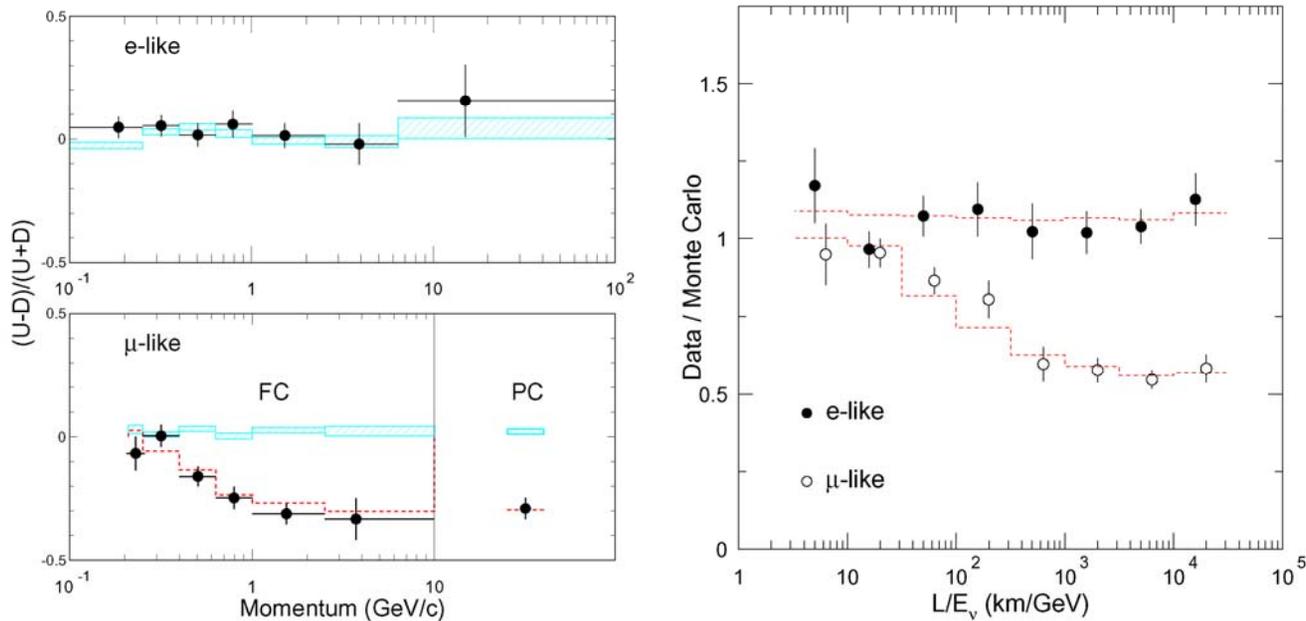


Fig. 18. Super-Kamiokande (1144 days) up-down asymmetry for electron-like and muon-like events, as a function of the particle momentum(left) and ratio between observed and expected number of electron-like and muon-like events as a function of L/E (right). The dashed lines correspond to $\nu_\mu \rightarrow \nu_\tau$ oscillations with maximal mixing and $\Delta m^2 = 3.2 \times 10^{-3} \text{ eV}^2$, while the hatched boxes indicate no-oscillation expectations (figures from ref.⁵⁹).

SK up-down asymmetry

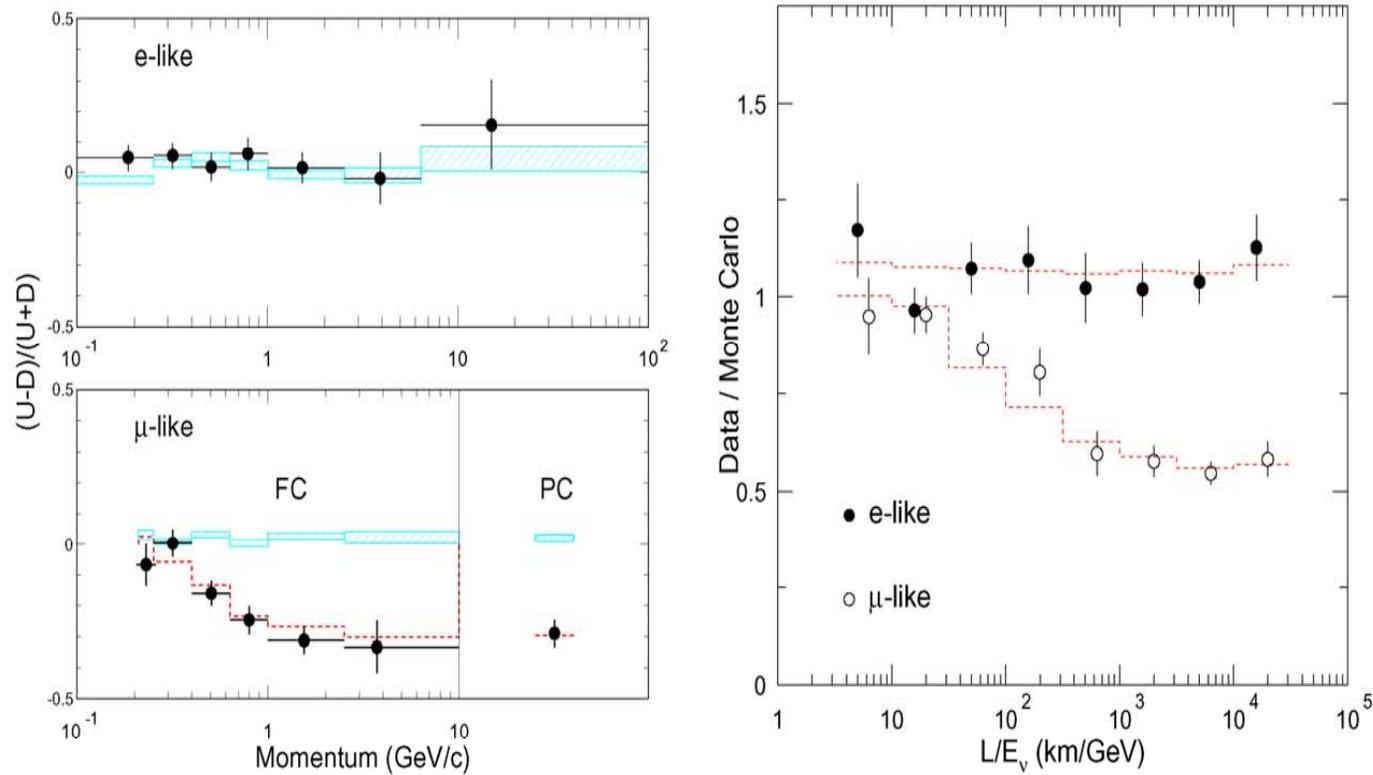


Fig. 18. Super-Kamiokande (1144 days) up-down asymmetry for electron-like and muon-like events, as a function of the particle momentum (left) and ratio between observed and expected number of electron-like and muon-like events as a function of L/E (right). The dashed lines correspond to $\nu_\mu \rightarrow \nu_\tau$ oscillations with maximal mixing and $\Delta m^2 = 3.2 \times 10^{-3} \text{ eV}^2$, while the hatched boxes indicate no-oscillation expectations (figures from ref.⁵⁹).

SK electrons vs muons

Conclusione:

i ν_e sono in accordo con quanto atteso dal calcolo dei flussi

i ν_μ sono soppressi, in accordo con quanto prevedibile da oscillazioni:

$\nu_\mu \rightarrow \nu_\tau$ oppure $\nu_\mu \rightarrow \nu_e$

Neutrini Solari + Atmosferici: Sommario

Soppressione dei ν_e dal Sole: compatibile con oscillazioni $\nu_e \rightarrow \nu_x$ ($x = \mu / \tau$)

$$\delta m^2 \sim 10^{-5} \quad ; \quad \sin^2 2\theta \sim 1$$

+ effetto “risonante” nella materia solare

Soppressione dei ν_μ atmosferici: $\nu_\mu \rightarrow \nu_x$ ($x = e / \tau$)

$$\text{SK: } 1.9 \cdot 10^{-3} \text{ eV}^2 < \delta m^2 < 3.0 \cdot 10^{-3} \text{ eV}^2 \quad ; \quad \sin^2 2\theta > 0.90$$

$$\nu_\mu \rightarrow \nu_e \text{ oppure } \nu_\mu \rightarrow \nu_\tau ???$$

se $\nu_\mu \rightarrow \nu_e$ deve esistere con uguali parametri

$$\bar{\nu}_e \rightarrow \bar{\nu}_\mu \quad (\text{Ricerca con antineutrini ad un reattore})$$

Esperimenti con Reattori

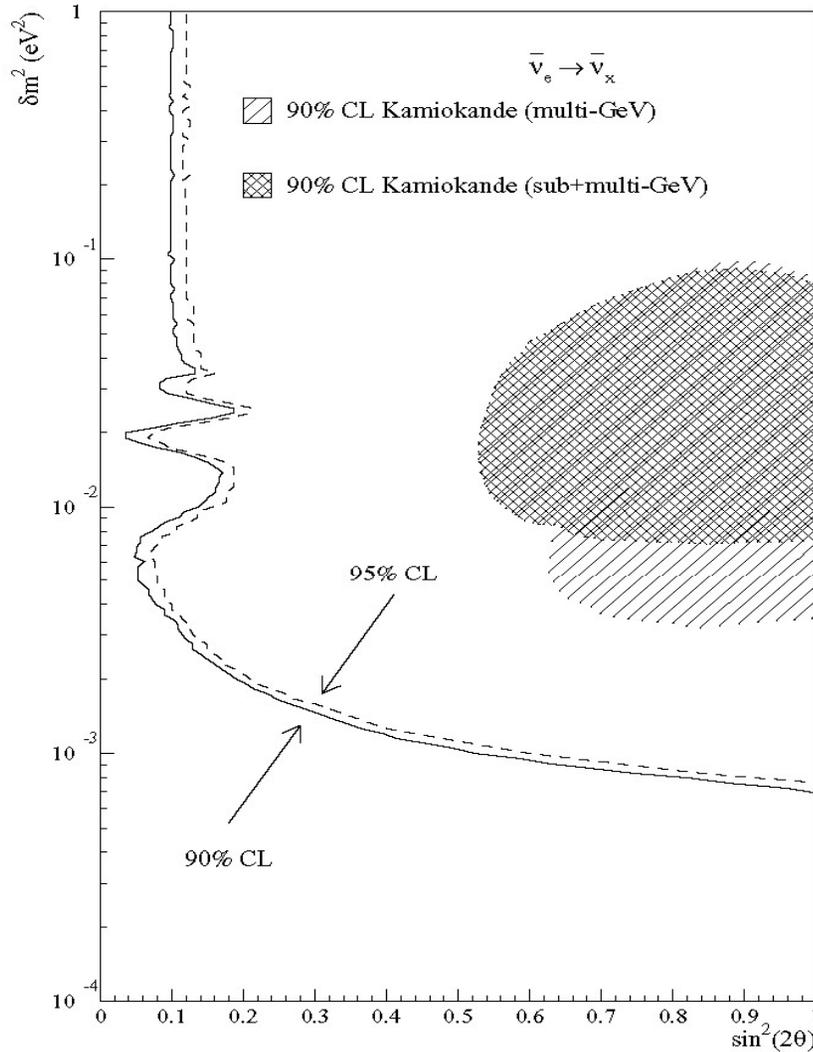


Ingredients...

- nuclear reactors: Vs
- hills for overburden (L)
- detectors... many!!
- ...and us: physicists!

Chooz

$$\mathcal{P}(\nu_\alpha \rightarrow \nu_\alpha) = \mathcal{P}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\alpha) \quad (\text{CPT conserved}).$$



$$\nu_\mu \rightarrow \nu_e = \bar{\nu}_e \rightarrow \bar{\nu}_\mu$$

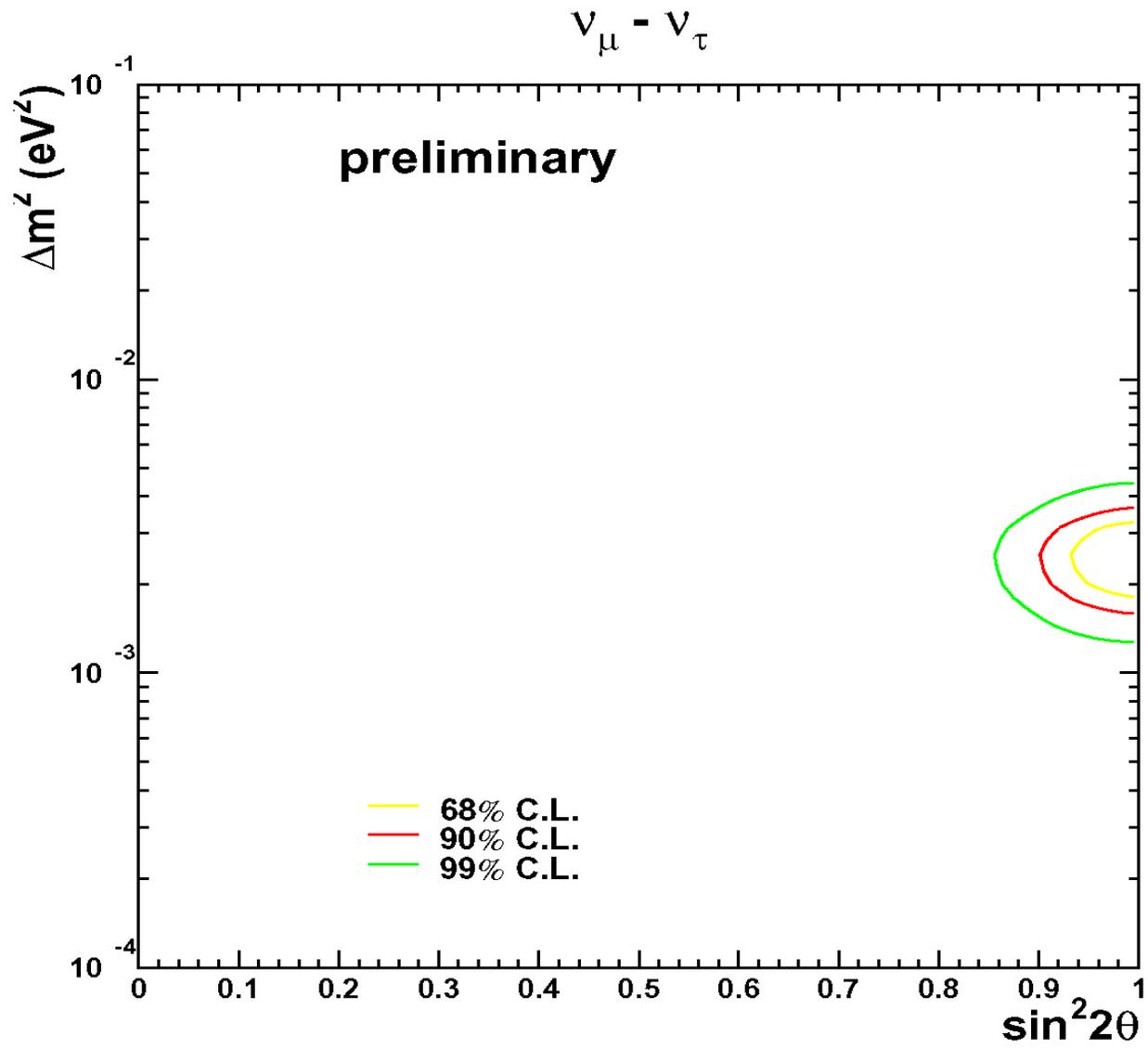
La regione permessa

da SK per $\nu_\mu \rightarrow \nu_e$ o $\nu_\mu \rightarrow \nu_\tau$

e' esclusa da Chooz per $\nu_e \rightarrow \nu_x$

Figure 9: Exclusion plot for the oscillation parameters based on the absolute comparison of measured vs. expected positron yields.

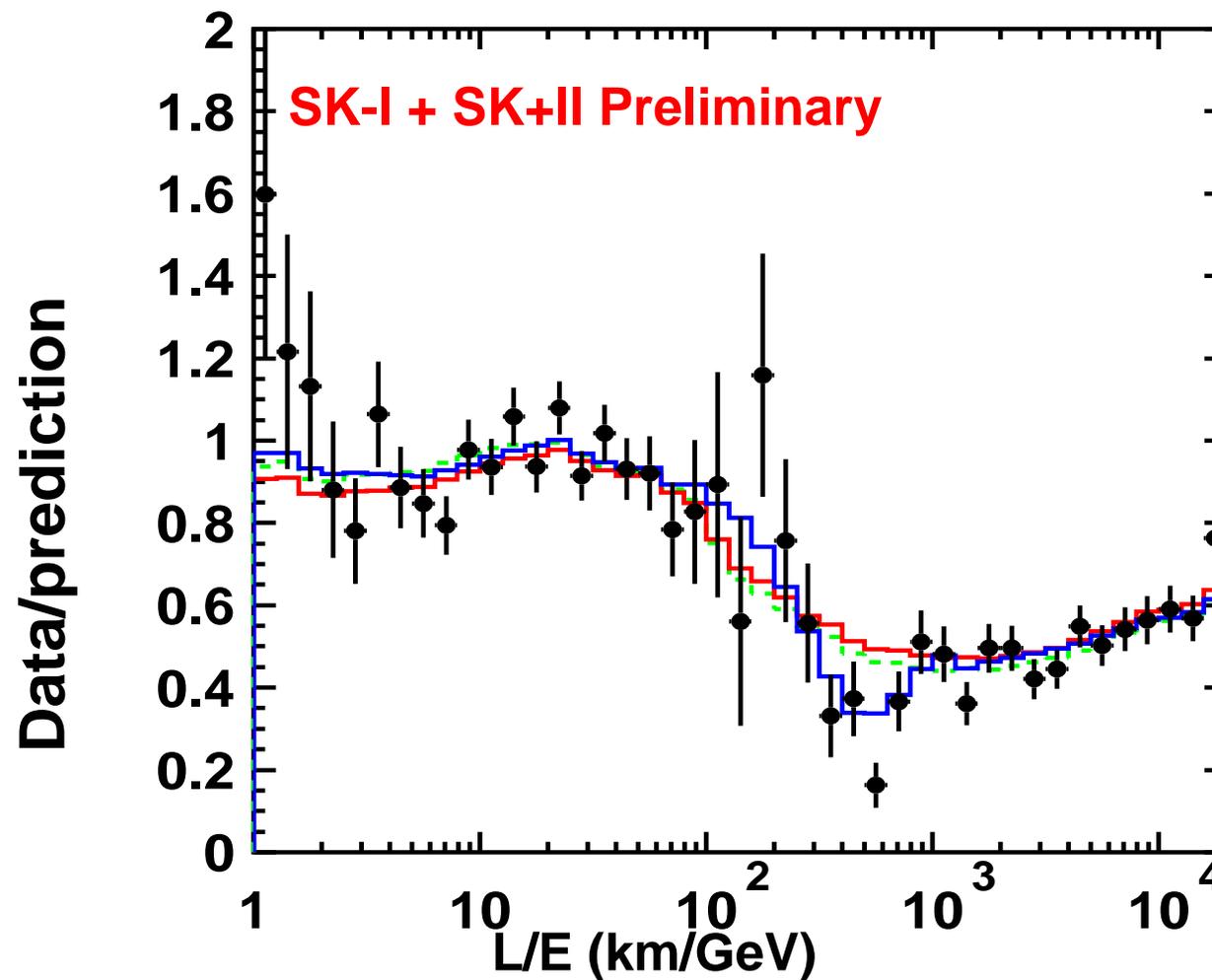
SK solution



Evidenza dell'oscillazione (superK)

Lepton-Photon symposium
June 2005

Flusso dei ν_μ
in funzione di L/E
e
confronto con previsioni
Montecarlo



Evidenza dell'oscillazione (superK)

SuperK.
Physical Rev. Lett.
24 Giugno 2004

$1.9 \cdot 10^{-3} \text{ eV}^2 < \Delta m^2 < 3.0 \cdot 10^{-3} \text{ eV}^2$
 $\sin^2 2\theta > 0.90$
90% CL

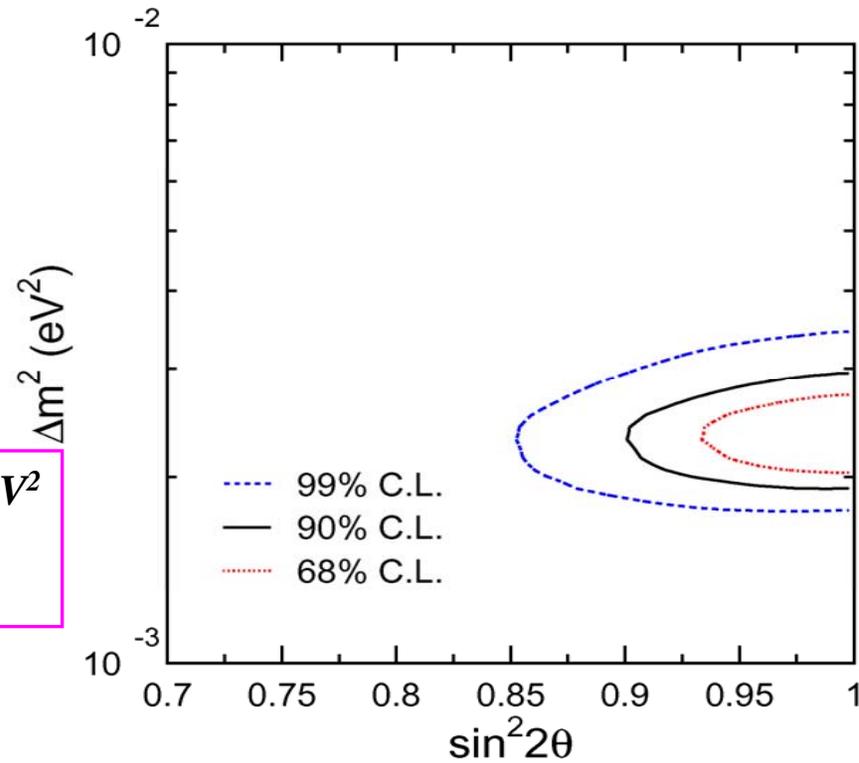


FIG. 5: 68, 90 and 99% C.L. allowed oscillation parameter regions for 2-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations obtained by the present analysis.

Flusso dei neutrini solari

Misure di flussi di ν_e insufficienti (dubbi sul modello solare)

Necessaria una misura del flusso assoluto di TUTTI i neutrini

$$\nu_e + \nu_\mu + \nu_\tau$$

La reazione: $\nu_e + n \rightarrow e^- + p$ (CC) misura il flusso dei soli ν_e

*La reazione: $\nu_{e/\mu/\tau} + e^- \rightarrow \nu_{e/\mu/\tau} + e^-$ (ES) riceve contributi dai ν_e ,
ma anche (in piccola misura) dai ν_μ e ν_τ*

*La reazione: $\nu_{e/\mu/\tau} + p \rightarrow \nu_{e/\mu/\tau} + p$ (NC) misura il flusso di tutti i
neutrini con ugual peso*

(segnatura pero' difficile !)

Ma, in D2: $\nu_{e/\mu/\tau} + d \rightarrow \nu_{e/\mu/\tau} + p + n$ (NC)

abbiamo anche un neutrone nello stato finale (rivelabile!)

Reazioni indotte dai neutrini solari

Reazione (a): $\nu_e + d \rightarrow e^- + p + p$ (CC) [soglia 1.4 MeV]

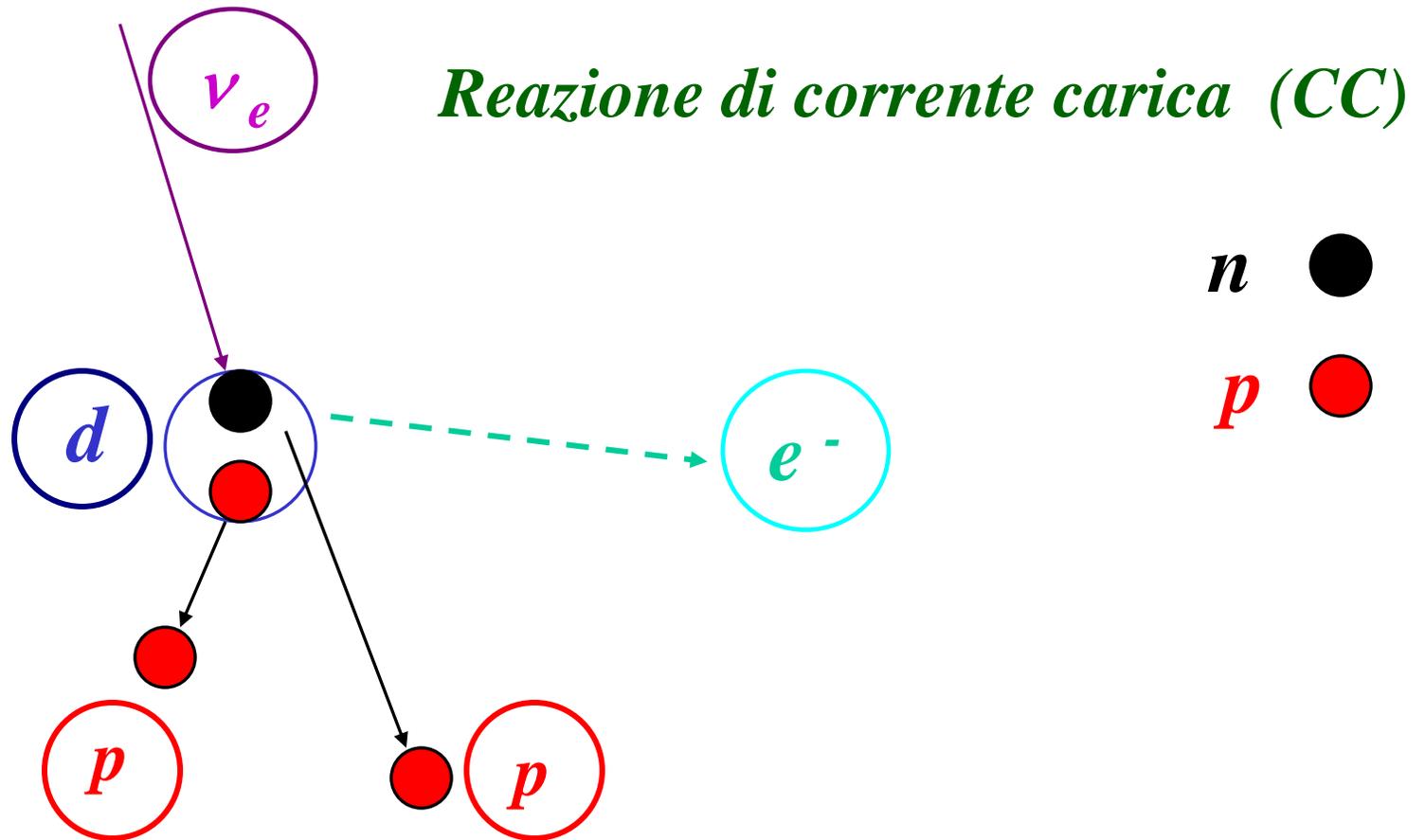
Reazione (b): $\nu_x + e^- \rightarrow \nu_x + e^-$ (ES)

Reazione (c): $\nu_x + d \rightarrow n + p + \nu_x$ (NC) [soglia 2.2 MeV]

Neutrone nello stato finale rivelabile:

- 1) nel solo deuterio \rightarrow cattura neutronica con emissione γ da 6.25 MeV*
- 2) con aggiunta di NaCl \rightarrow cattura neutronica da parte del Cl con emissione γ da 8.6 MeV*
- 3) con contatori ad He^3 per neutroni*

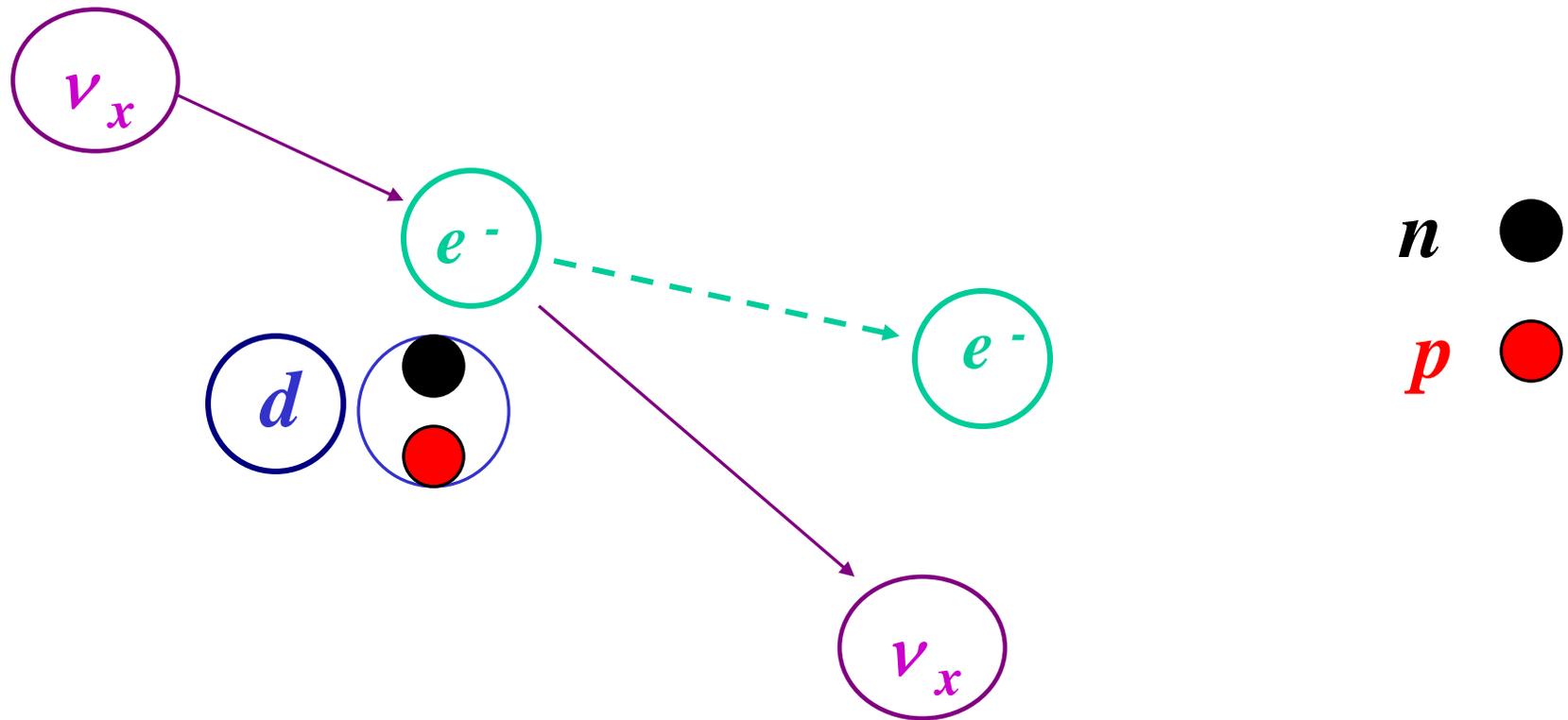
Reazione di corrente carica (CC)



[possibile solo per ν_e]

Protoni nello stato finale non rivelabili (energia troppo bassa)

Reazione di scattering elastico (ES)

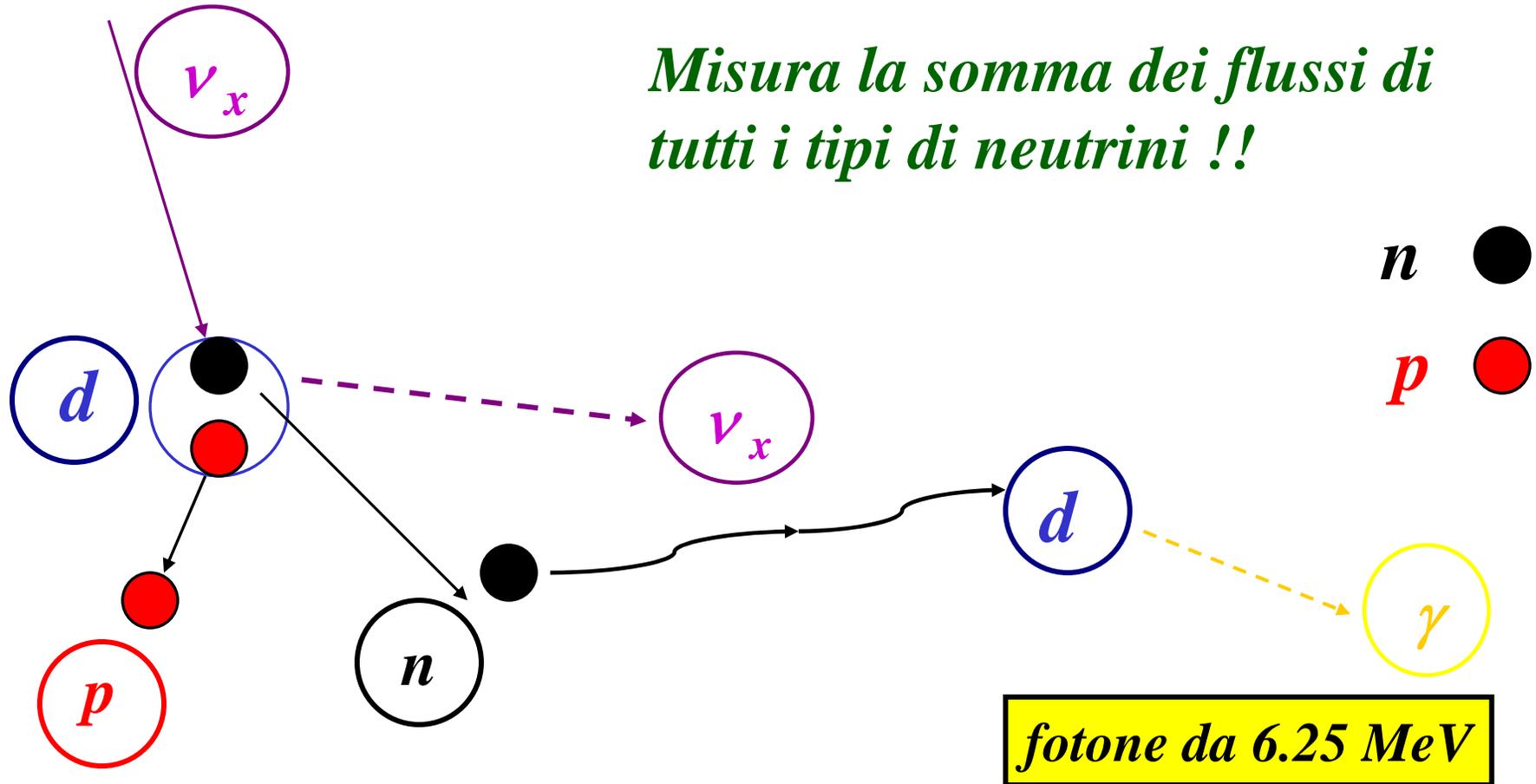


$\nu_{e/\mu/\tau} e^- \rightarrow e^- \nu_{e/\mu/\tau}$ [possibile per tutti i flavours -

- ma contribuiscono soprattutto i ν_e]

Reazione di corrente neutra (NC)

Misura la somma dei flussi di tutti i tipi di neutrini !!



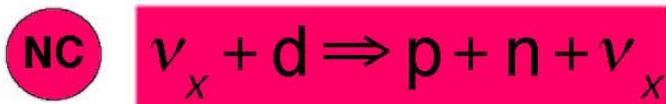
Neutrone nello stato finale rivelabile (cattura in deuterio)

SNO

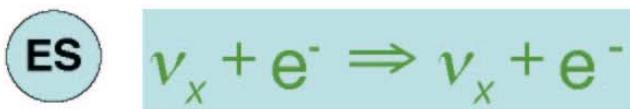
Sudbury Neutrino Observatory



- Gives ν_e energy spectrum well
- Weak direction sensitivity $\propto 1 - 1/3 \cos(\theta)$
- ν_e only.



- Measure total ${}^8\text{B}$ ν flux from the sun.
- Equal cross section for all ν types



- Low Statistics
- Mainly sensitive to ν_e , some sensitivity to ν_μ and ν_τ
- Strong direction sensitivity

Key physics signatures

$$\frac{\Phi_{\text{CC}}}{\Phi_{\text{NC}}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

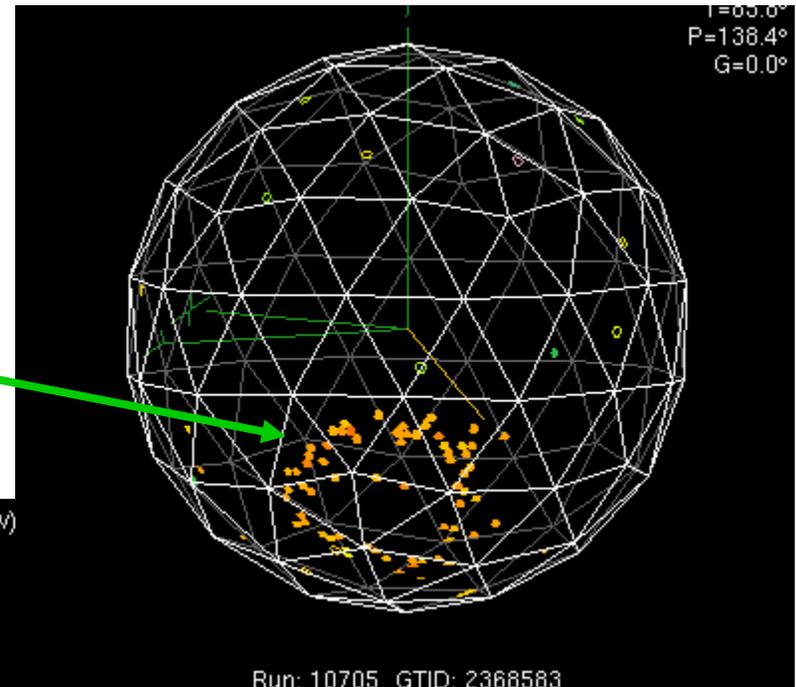
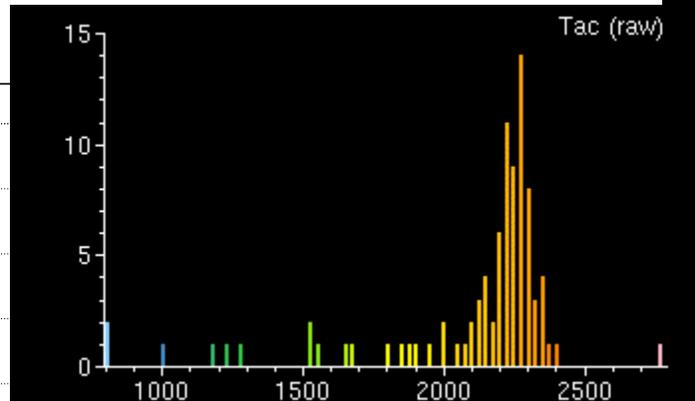
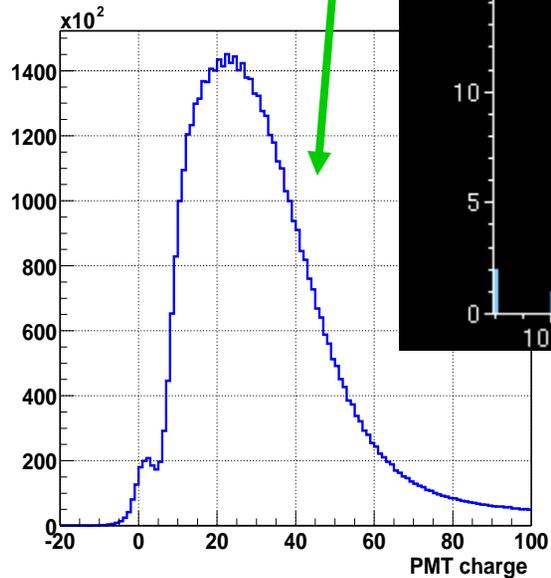
$$\frac{\Phi_{\text{CC}}}{\Phi_{\text{ES}}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)}$$

$$\Phi_{\text{day}} \quad \text{vs} \quad \Phi_{\text{night}}$$

SNO observables

PMT Measurements

- position
- time
- charge



Reconstructed event

- vertex
- direction
- energy
- isotropy

SNO Collaboration



The SNO Collaboration



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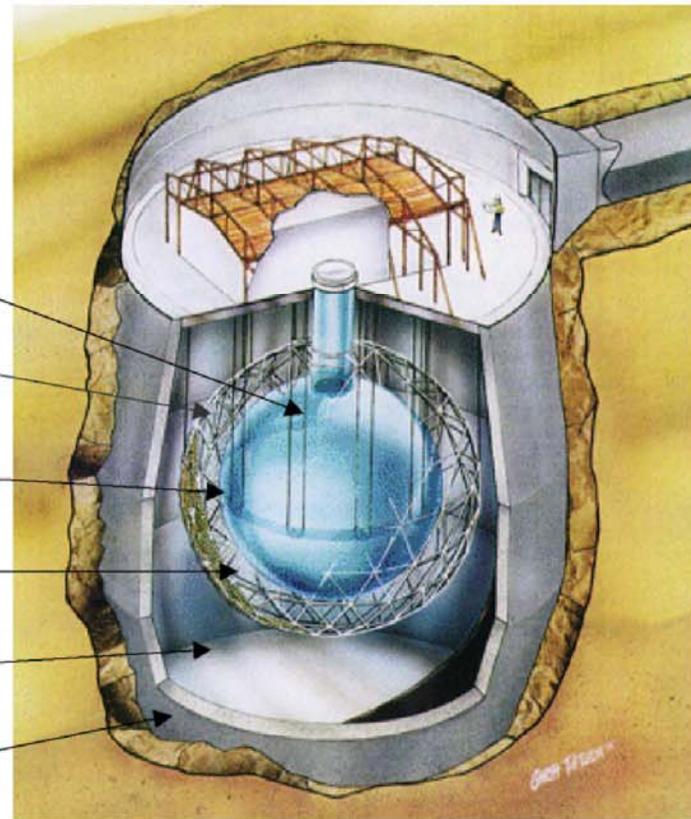
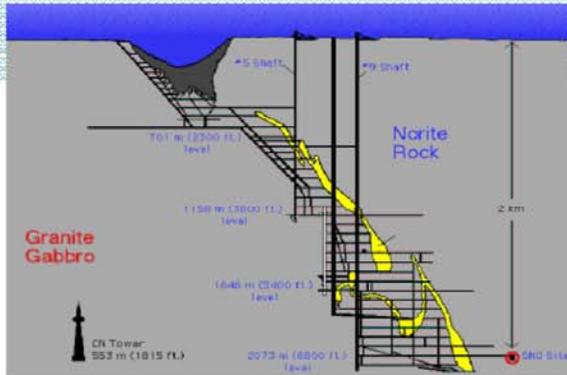
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SNO detector

Sudbury Neutrino Observatory



1000 tonnes D_2O

Support Structure
for 9500 PMTs,
60% coverage

12 m Diameter
Acrylic Vessel

1700 tonnes Inner
Shielding H_2O

5300 tonnes Outer
Shield H_2O

Urylon Liner and
Radon Seal

neutron detection methods

SNO - 3 neutron detection methods

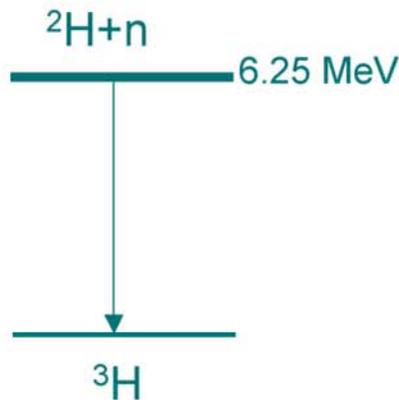
Intro



Phase I (D₂O)

Nov. 99 - May 01

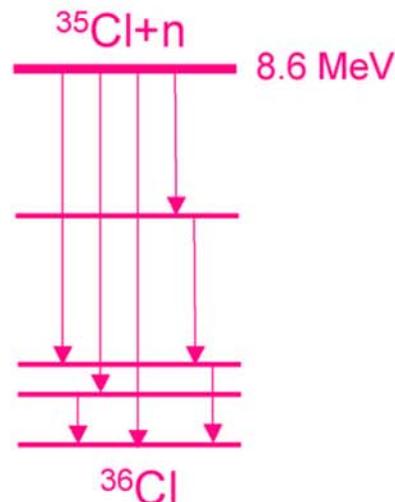
n captures on
 $^2\text{H}(n, \gamma)^3\text{H}$
 $\sigma = 0.0005 \text{ b}$
 Observe 6.25 MeV γ
 PMT array readout
 Good CC



Phase II (salt)

July 01 - Sep. 03

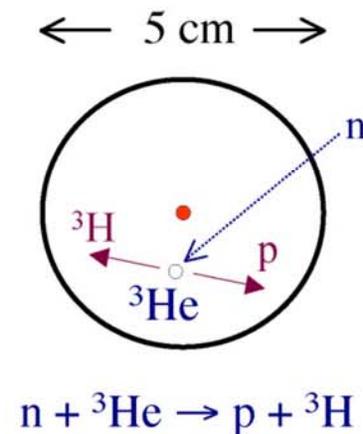
2 t NaCl. n captures on
 $^{35}\text{Cl}(n, \gamma)^{36}\text{Cl}$
 $\sigma = 44 \text{ b}$
 Observe multiple γ 's
 PMT array readout
 Enhanced NC



Phase III (^3He)

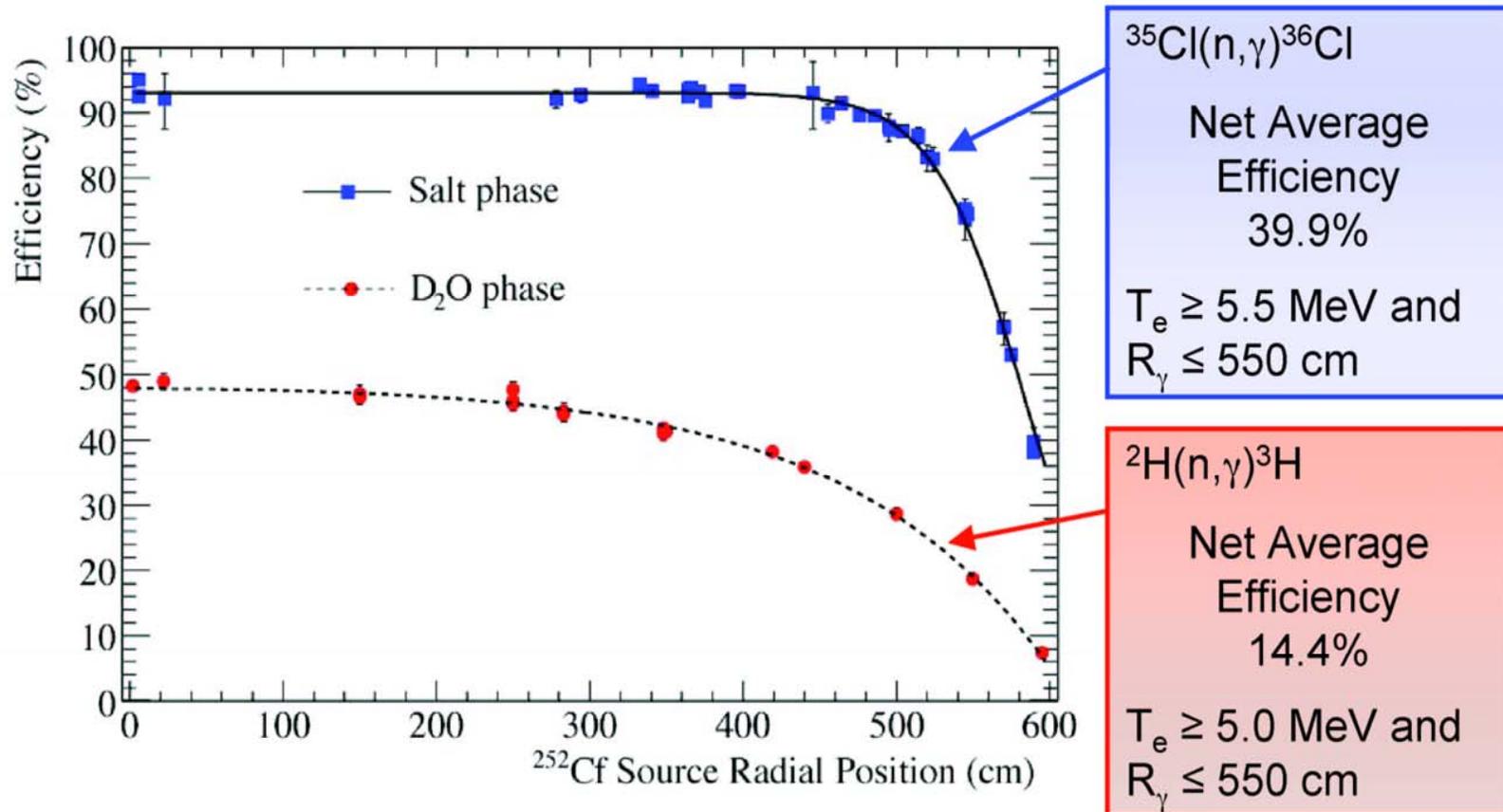
Summer 04 - Dec. 06

40 proportional counters
 $^3\text{He}(n, p)^3\text{H}$
 $\sigma = 5330 \text{ b}$
 Observe p and ^3H
 PC independent readout
 Event by Event Det.



efficienza di cattura dei neutroni

Neutron Capture Efficiency in SNO



Metodo di separazione dei tre tipi di eventi

Reazione (a) : $\nu_e + d \rightarrow e^- + p + p$ (CC) (produce singoli γ)

Reazione (b): $\nu_x + e^- \rightarrow \nu_x + e^-$ (ES) (produce singoli γ)

Reazione (c): $\nu_x + d \rightarrow n + p + \nu_x$ (NC) (produce diversi γ)

→ maggiore isotropia della luce che arriva ai fotomoltiplicatori nella (c)

Parametro di isotropia dell'evento β_{14} utilizzato per la separazione di eventi CC ed NC

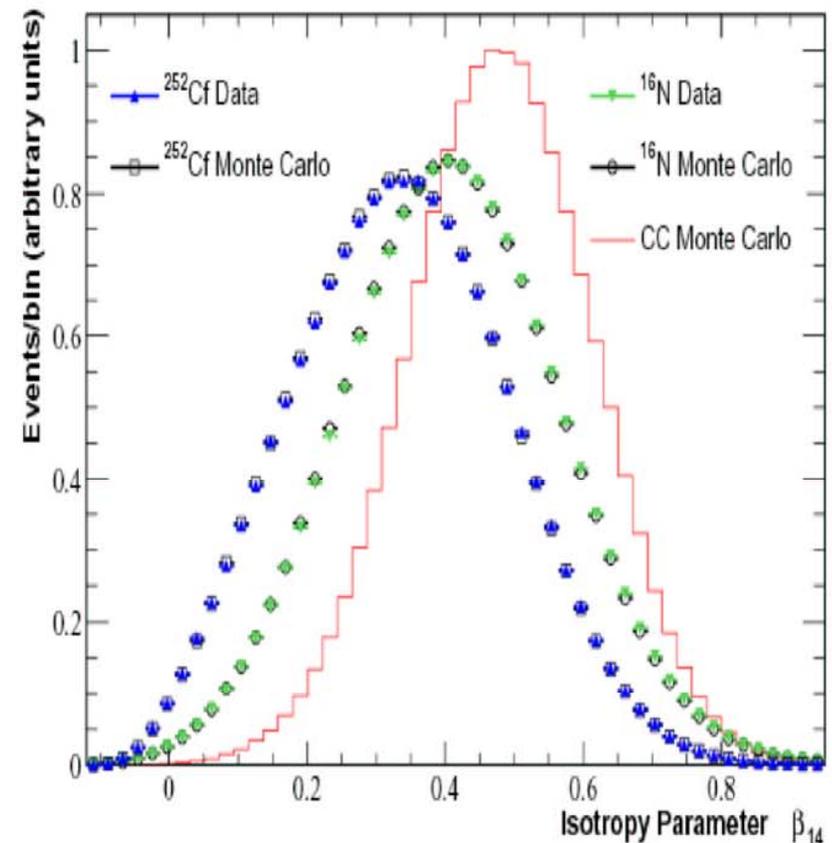
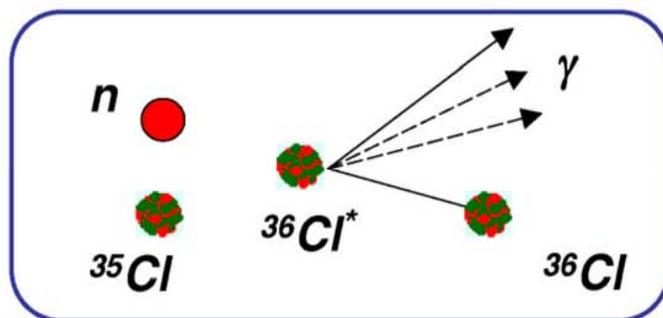
Vantaggi del sale[1]

Advantages of Salt

Salt
Phase



- Neutrons capturing on ^{35}Cl provide higher neutron energy above threshold.
- Higher capture efficiency
- Gamma cascade changes the angular profile.

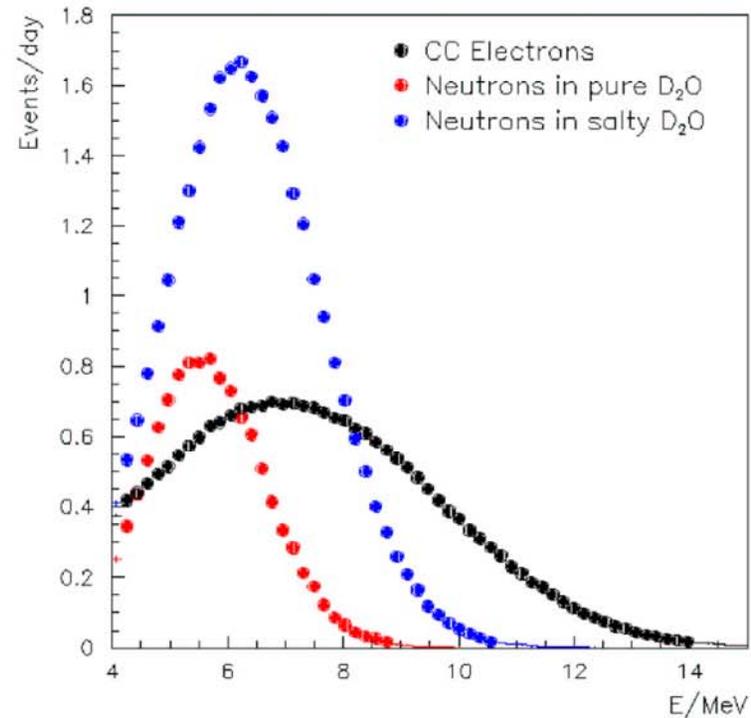


Advantages of Salt

Salt
Phase



- Neutrons capturing on ^{35}Cl provide higher neutron energy above threshold.
- Higher capture efficiency
- Gamma cascade changes the angular profile.



Risultati (Sale)[1]

Event Distributions (PRL 92, 181301, 2004)

Salt
Phase



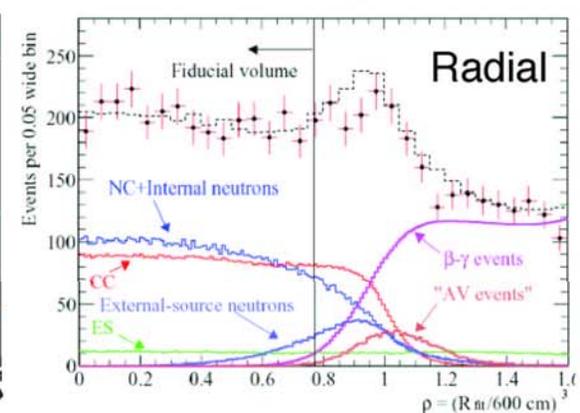
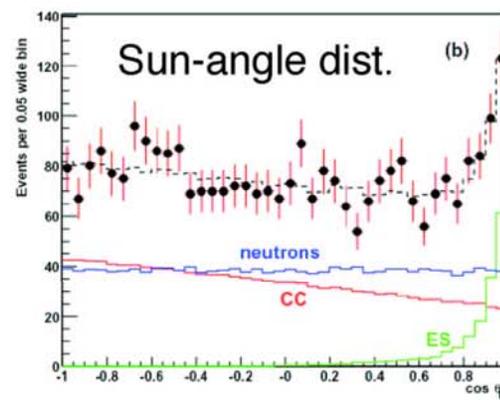
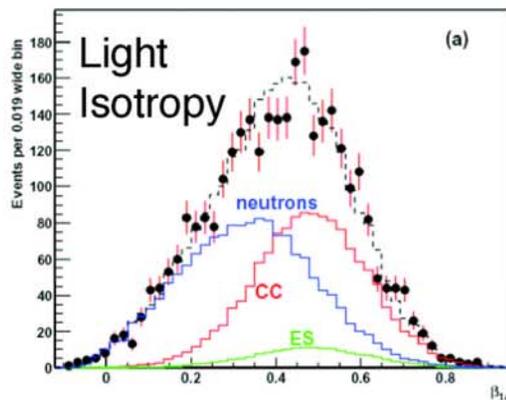
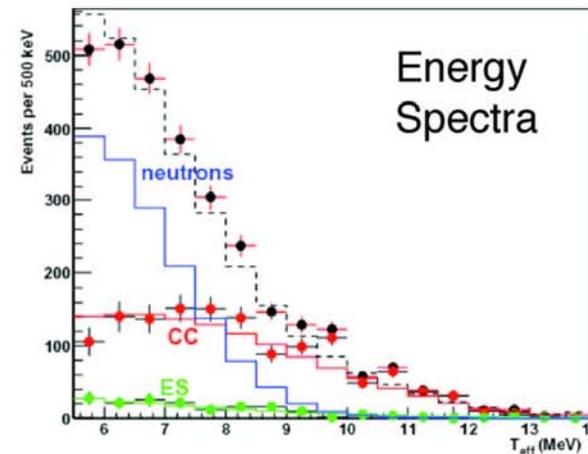
$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.306 \pm 0.026 \text{ (stat)} \pm 0.024 \text{ (syst)}$$

#EVENTS

CC 1339.6 ^{+63.8} _{-61.5}

ES 170.3 ^{+23.9} _{-20.1}

NC 1344.2 ^{+69.8} _{-69.0}



J.F. Wilkerson on behalf of the SNO Collaboration

June 14, 2004

Neutrino 2004

Risultati (Sale)[2]

$$\phi_{\text{CC}}^{\text{SNO}} = 1.59^{+0.08}_{-0.07}(\text{stat})^{+0.06}_{-0.08}(\text{syst})$$

$$\phi_{\text{ES}}^{\text{SNO}} = 2.21^{+0.31}_{-0.26}(\text{stat}) \pm 0.10(\text{syst})$$

$$\phi_{\text{NC}}^{\text{SNO}} = 5.21 \pm 0.27(\text{stat}) \pm 0.38(\text{syst}),$$

and the ratio of the ${}^8\text{B}$ flux measured with the CC and NC reactions is

$$\frac{\phi_{\text{CC}}^{\text{SNO}}}{\phi_{\text{NC}}^{\text{SNO}}} = 0.306 \pm 0.026(\text{stat}) \pm 0.024(\text{syst}).$$

Unita' $10^6 \text{ cm}^{-2} \text{ s}^{-1}$

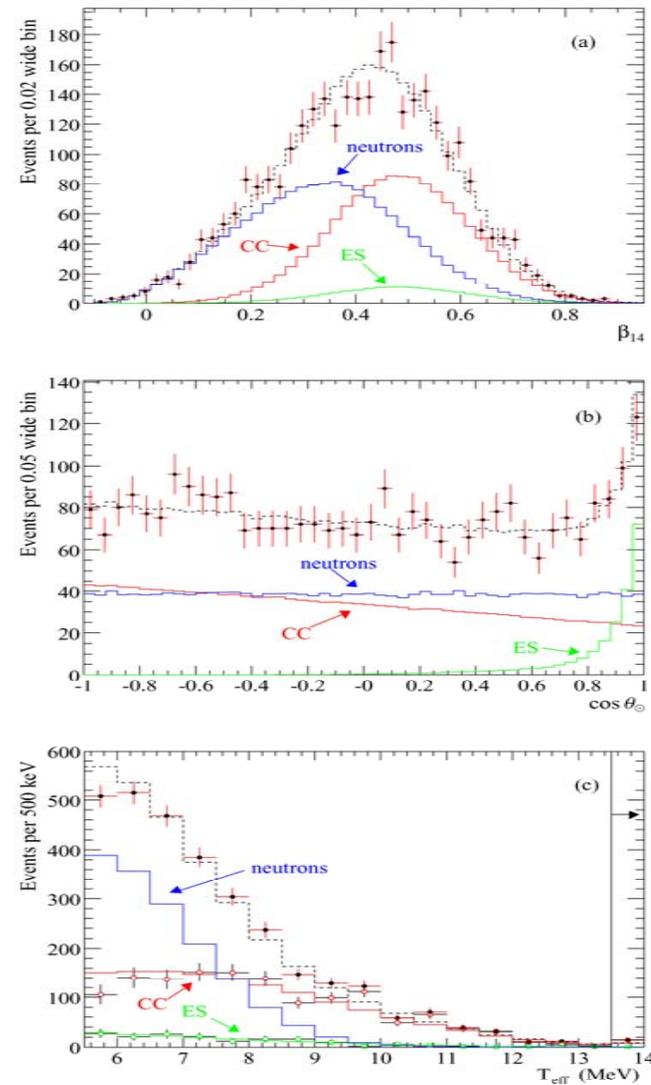


FIG. 2: Distribution of (a) β_{14} , (b) $\cos \theta_0$ and (c) kinetic energy, for the selected events. The CC and ES spectra are extracted from the data using β_{14} and $\cos \theta_0$ distributions in each energy bin. Also shown are the Monte Carlo predictions for CC, ES, NC + internal and external-source neutron events, all scaled to the fit results. The dashed lines represent the summed components. All distributions are for events with $T_{\text{eff}} \geq 5.5$ MeV and $R_{\text{fit}} \leq 550$ cm. Differential systematics are not shown.

Flusso misurato da SNO

In summary, we have precisely measured the total flux of active ^8B neutrinos from the Sun without assumptions about the energy dependence of the electron neutrino survival probability. The flux is in agreement with standard solar model calculations. These results combined with global solar and reactor neutrino results reject the hypothesis of maximal mixing at a confidence level equivalent to 5.4σ .

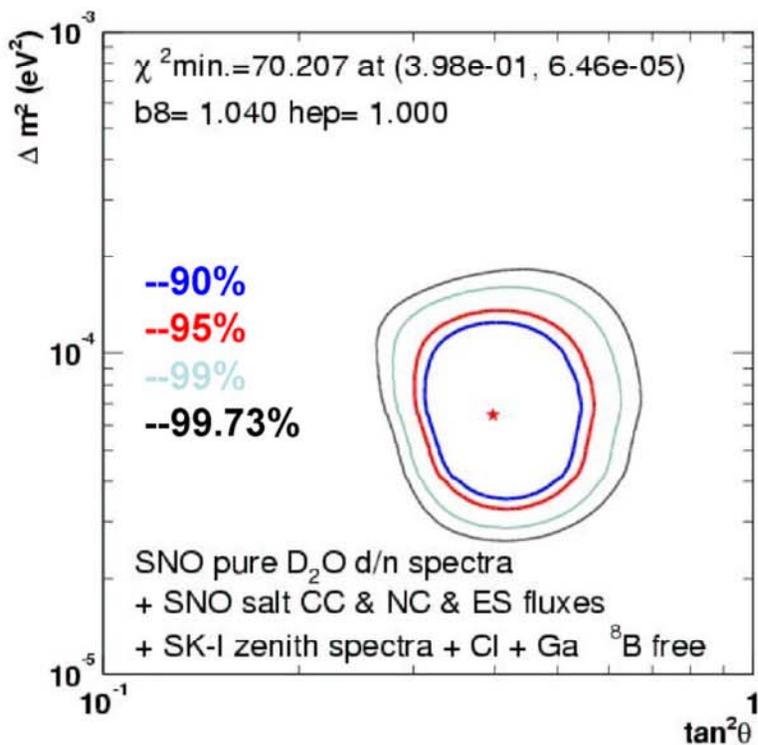
Risultati (Sale)[3]

SNO First Salt Result (PRL 92, 181301, 2004)

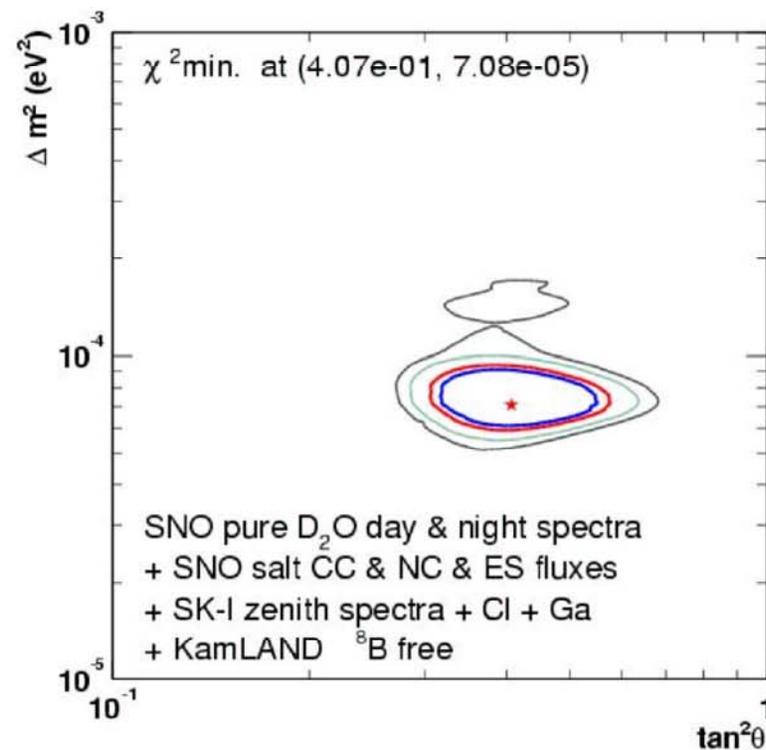
Salt
Phase



$$\phi(^8\text{B})_{\text{meas}} = (0.88 \pm 0.04 (\text{exp}) \pm 0.23 (\text{th})) \phi(^8\text{B})_{\text{SSM}}$$

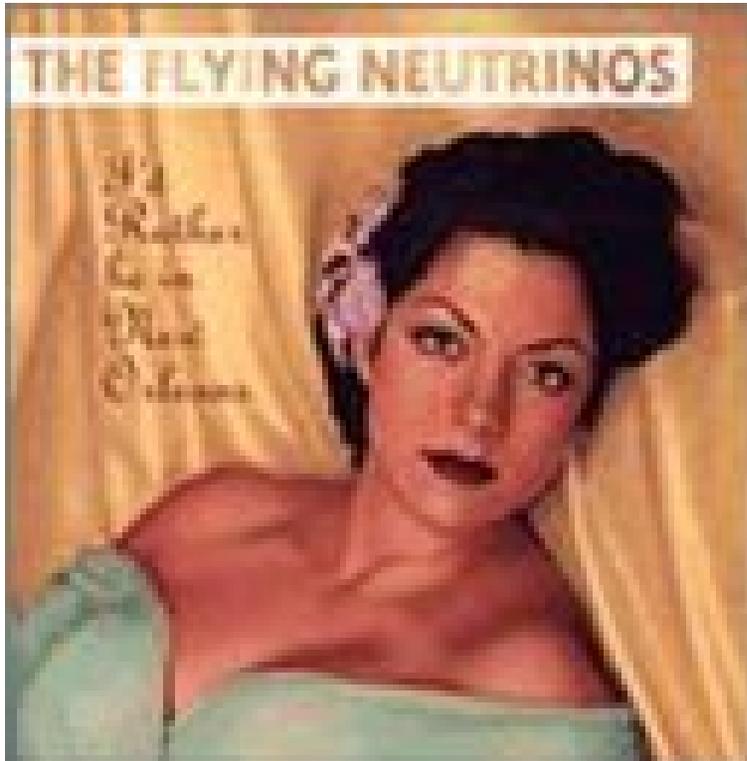


Disfavors maximal mixing
at a level equivalent to 5.4 σ .



LMA I only at > 99% CL

Ingrid Lucia
The flying neutrinos



Floating neutrinos
Zattera assemblata con
materiale di scarto

Floating Neutrinos

First Scrap Raft to Cross the North Atlantic Ocean

