Quale fenomenologia per i ν ?

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Torino - 23 Novembre 2004

Experimental Data

Experiment	Observable (# Data)	Measured/SM
Chlorine	Average Rate (1)	[CC]=0.30 ± 0.03
SAGE+GALLEX/GNO[†]	Average Rate (1)	[CC]=0.52 ± 0.03
Super-Kamiokande	Zenith Spectrum (44)	[ES]=0.406 ± 0.013
SNO (pure D_2O phase)	Day-night Spectrum (34)	[CC]=0.31 ± 0.02
		[ES]=0.47 ± 0.05
		[NC]=1.01 ± 0.13
SNO (salt phase)	Average Rates (3)	[CC]=0.28 ± 0.02
		[ES]=0.38 ± 0.05
		[NC]=0.90 ± 0.08
KamLAND	Spectrum (13)	[CC]=0.66 ± 0.06
CHOOZ	Spectrum (14)	[CC] = 1.01 ± 0.04
K2K	Spectrum (6)	[CC](ν_μ) = $0.70^{+0.11}_{-0.10}$
Atmospheric	Zenith Angle (55)	[0.5-1.0]

hep-ph/0406294

2 ν Oscillation Interpretation

"The data of the atmospheric SK and K2K experiments are perfectly described if we assume that ν_μ ($\bar{\nu}_\mu$) survival probability has the standard two-neutrino form

$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \frac{1}{2}\,\sin^2 2\,\theta_{23}\,(1 - \cos\frac{\Delta m^2_{32}\,L}{2E}), \quad (1)$$

where E is the neutrino energy, L is the distance between neutrino source and neutrino detector and $\Delta m^2_{ik} = m^2_i - m^2_k$ (m_i, m_k are neutrino masses, $m_1 < m_2 < m_3$).

The data of the reactor KamLAND experiment are well described if we assume that oscillations of the reactor $\bar{\nu}_e$'s are driven by Δm^2_{21} and $\bar{\nu}_e$ survival probability has the two-neutrino form

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \frac{1}{2}\,\sin^2 2\,\theta_{12}\,(1 - \cos\frac{\Delta m^2_{21}\,L}{2E}). \quad (2)$$

Let us notice that there are the following two reasons, why existing neutrino oscillations data are described by the two-neutrino expressions (1) and (2) :

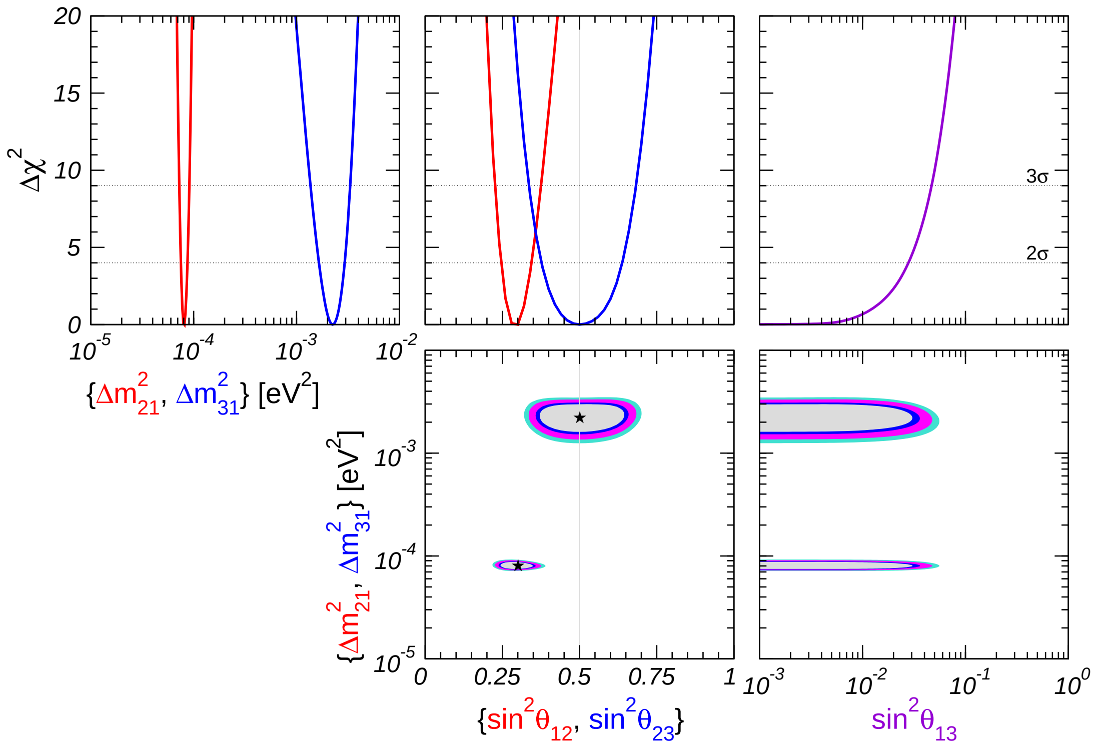
1.
$$\Delta m^2_{21} \ll \Delta m^2_{32}. \quad (3)$$

2.
$$|U_{e3}| \ll 1 \quad (4)$$

This last inequality follows from the negative result of the reactor CHOOZ experiment ."

hep-ph/0411117

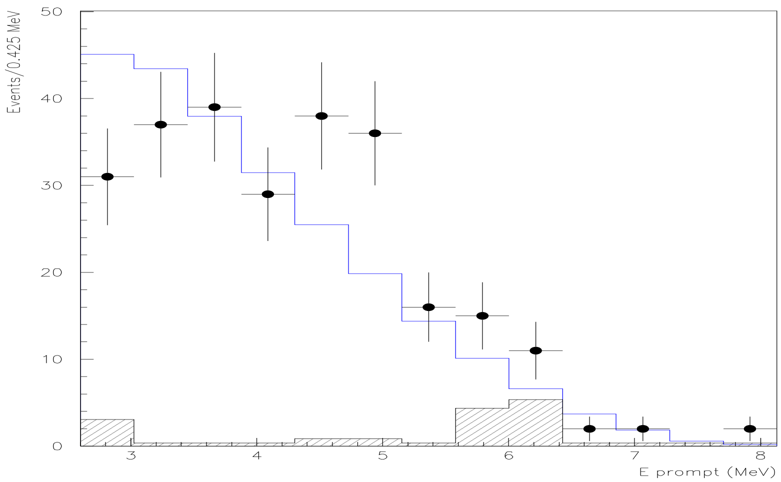
Status of global $3\,\nu$ fits: Bilarge

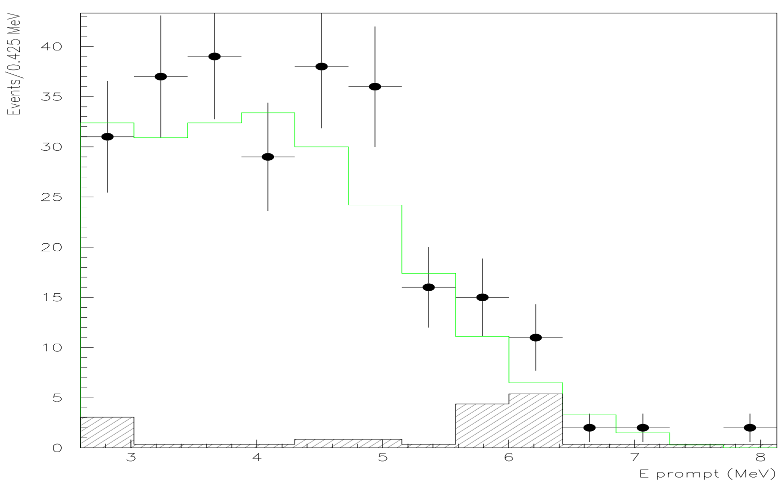


parameter	best fit	2σ	3σ
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	8.1	7.5–8.7	7.2–9.1
$\Delta m^2_{31}\ [10^{-3}\mathrm{eV}^2]$	2.2	1.7–2.9	1.4–3.3
$\sin^2\theta_{12}$	0.30	0.25–0.34	0.23–0.38
$\sin^2\theta_{23}$	0.50	0.38–0.64	0.34–0.68
$\sin^2\theta_{13}$	0.000	$\leq$ 0.028	$\leq$ 0.047

hep-ph/0405172 v3

KAMLAND: which evidence of spectral distorsion ?





	scaled spectrum	best LMA
χ^2/dof	25.7/11	13.8/10
Prob.	7.2×10^{-3}	1.8×10^{-1}

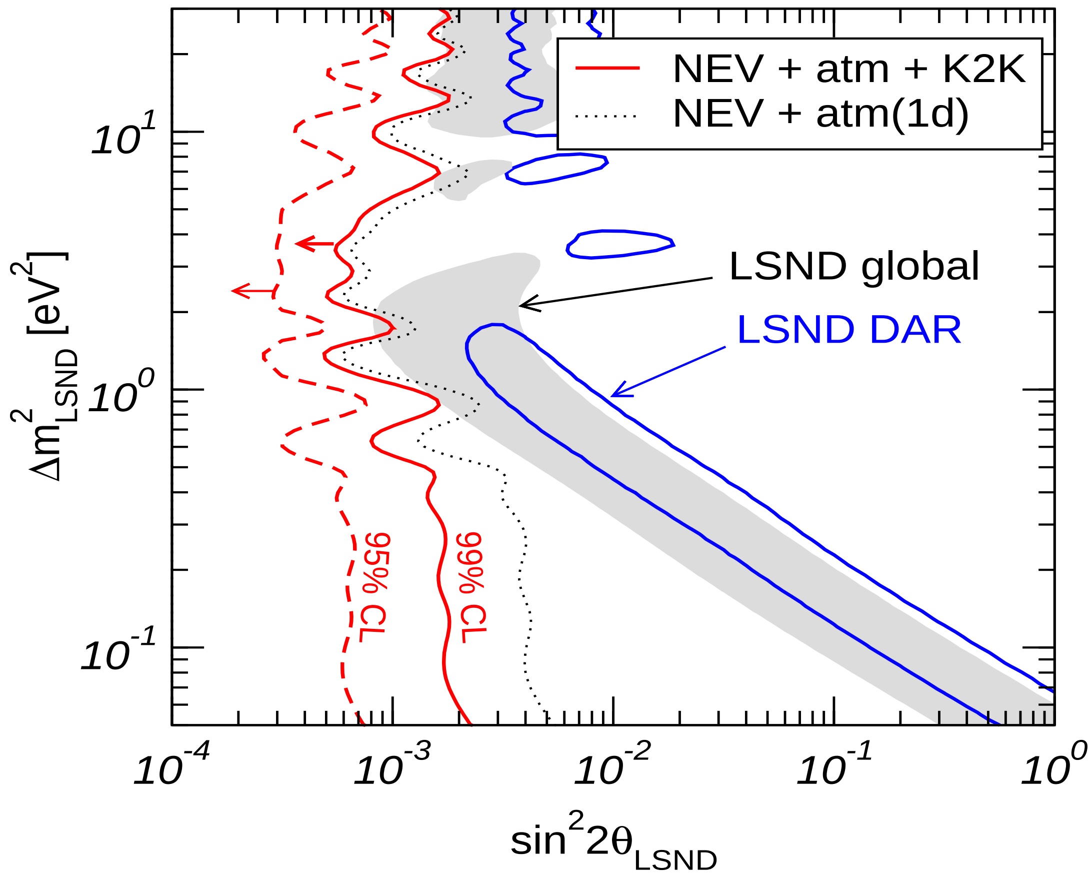
add more data : SBL experiments

Experiment	Oscillation Channels
Bugey	$\bar{\nu}_e \to \bar{\nu}_e$
CDHS	$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$
CCFR	$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu, \overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e, \overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\tau, \overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$
LSND	$\bar{\nu}_\mu \to \bar{\nu}_e, \nu_\mu \to \nu_e$
KARMEN	$\bar{\nu}_\mu \to \bar{\nu}_e$
NOMAD	$\nu_\mu \to \nu_e, \nu_\mu \to \nu_\tau, \nu_e \to \nu_\tau$
CHORUS	$\nu_\mu \to \nu_\tau, \nu_e \to \nu_\tau$
NuTeV	$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$

"Some years ago the oscillations indicated by the LSND experiment could be accommodated together with solar and atmospheric neutrino oscillations in the framework of four-neutrino mixing, in which there are three light active neutrinos and one light sterile neutrino. However, the global fit of recent data in terms of four-neutrino mixing is not good, disfavoring such possibility."

hep-ph/0310238

Status of global $3 + 1\,\nu$ fits: disfavoured



scheme	SOL	ATM	LSND	NEV	$\chi^2_{\rm PG}$	PG
(3+1)	0.0	0.4	5.7	10.9	17.0	1.9×10^{-3} (3.1σ)
(2+2)	5.3	20.8	0.6	7.3	33.9	7.8×10^{-7} (4.9σ)

“Although KamLAND on its own is insensitive to a sterile neutrino contamination (η_s), it contributes indirectly to the bound because of the better determination of $\Delta m^2_{\rm SOL}$ and $\theta_{\rm SOL}$. The combined analysis leads to the 99% C.L. bound (hep-ph/0405172 v3)

$$\eta_s \leq 0.25 \qquad \text{(solar + KamLAND, BP04).}$$

2004 : indication of $\beta\beta_{0\nu}$ decay

$\beta\beta_{0\nu}$ decay is allowed for such even-even nuclei for which the usual β decay is forbidden by the conservation of energy. The most sensitive method to search for $\beta\beta_{0\nu}$ signal comes from the decay (E. Fiorini, 1967)

$$^{76}Ge_{32} \rightarrow {}^{76}Se_{34} + e^- + e^- \qquad E(e_1^-) + E(e_2^-) = 2039\,keV$$

Heidelberg-Moskow experiment

The detector consists of 5 cristals of 86 % enriched ^{76}Ge (solid state detectors) with total mass about 11 Kg. Fraction of ^{76}Ge in natural Ge is $\sim 7.7\%$. Cristals are surrounded by anticoincidence counters and installed in the very low background environment of the LNGS. The experiment ran for 13 years and the collected statistics is 71.7 Kg y. The background index is 0.11 events/ kg y keV and the energy resolution is 3.27 KeV FWHM .

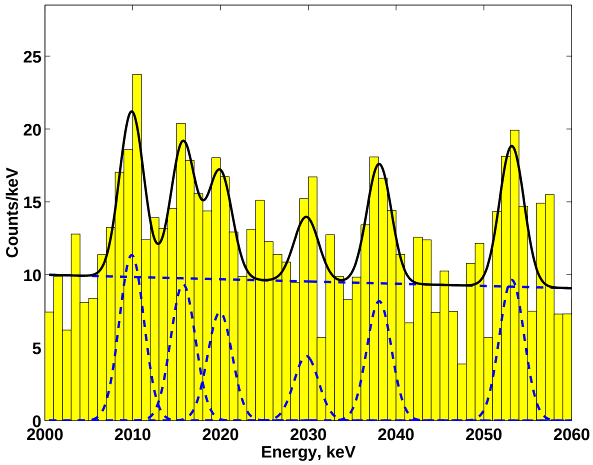
Part of the collaboration reported positive evidence of the signal with a claimed 4.2σ significance. The signal is 28.8 ± 6.9 events over a background of ~ 60 events , corresponding to an half-life :

$$T_{1/2} = (0.69 - 4.18) \times 10^{25}\,yr \quad (3\sigma \quad \mathrm{range})$$

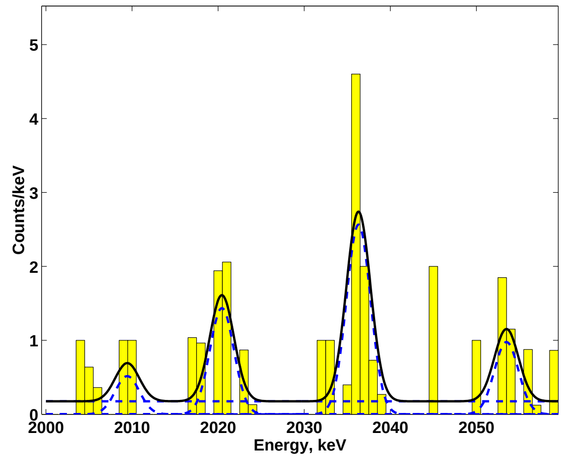
and effective neutrino mass $\langle m_{ee} \rangle$:

$$\langle m_{ee} \rangle = (0.1 - 0.9)\,\mathrm{eV} \quad (99.73\% \quad C.L.)$$

allowing a $\pm 50\%$ uncertainty in the nuclear matrix element.



period 1990-2003



period 1995-2003 : SSE analysis

hep-ph/0404088

In the region between 2000 and 2060 keV, the analysis of 2004 found a total of 6 peaks. Four of these were attributed to ^{214}Bi (2010.7, 2016.7, 2021.8, 2052.9 keV), one was attributed to $\beta\beta_{0\nu}$ decay (2039 keV). The candidate line at ~ 2030 keV could originate from electron conversion of the 2118 keV γ-line from ^{214}Bi .

"Double-beta decay produces two electrons that have a short range in solid Ge. Therefore, the energy deposit is inherently localized. Background process, such as the γ rays from ^{214}Bi, tend to produce multiple energy deposits. The pulse waveform can be analyzed to distinguish single site events (SSE) from multiple site events. Such an analysis tends to indicate that the Bi lines behave as multiple site events, whereas the $\beta\beta_{0\nu}$ candidate events behave as SSE. Note, however, that the statistics are still poor for the experimental lines and this conclusion has a large uncertainty. Nonetheless, this feature of the data is very intriguing and clearly a strength of the analysis." hep-ph/0405078

$\beta\beta_{0\nu} \Leftrightarrow$ Majorana ν mass

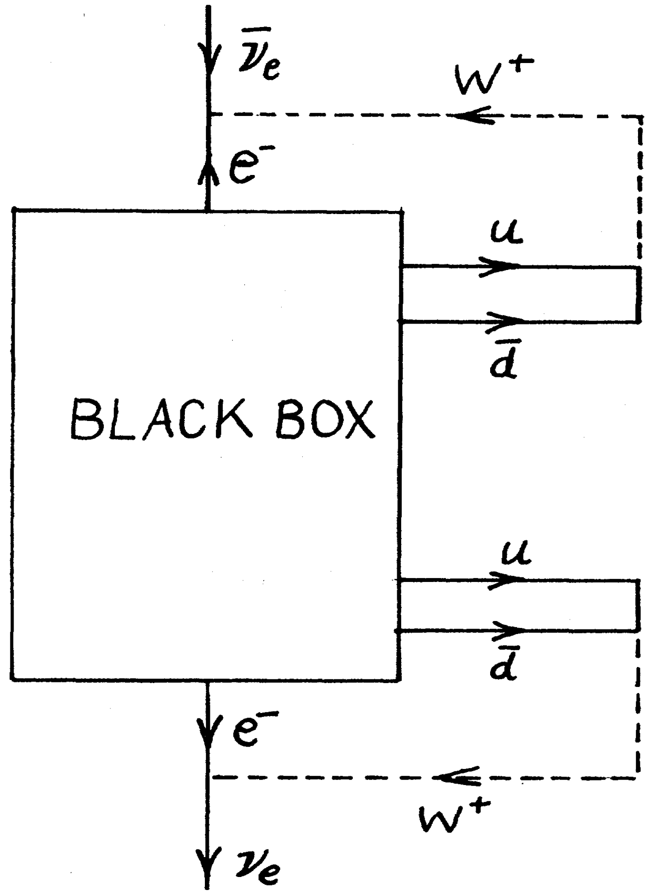


FIG. 2. Diagram showing how any neutrinoless double-β decay process induces a $\bar{\nu}_e$-to-ν_e transition, that is, an effective Majorana mass term.

"The observation of $\beta\beta_{0\nu}$ decays implies the existence of a Majorana mass term for the neutrino ? For a "natural" gauge theory we argue that this is indeed the case."

PRD 25 (1982) 2951 J.Schehter and J.Valle

$\beta\beta_{0\nu}$ and ν mixing

mass term	$\beta\beta_{0\nu}$	oscillation type
Dirac + Majorana	allowed	active-active active-sterile
Majorana	allowed	active-active
Dirac	forbidden	active-active

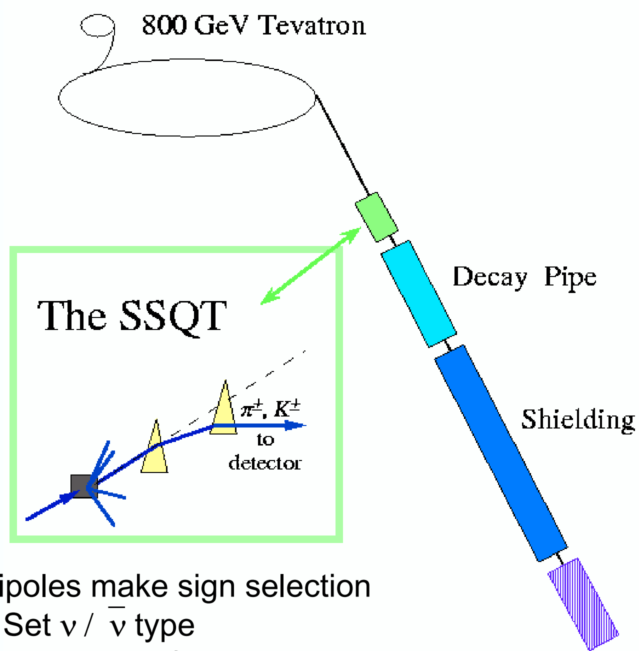
"It is interesting to note that, in principle, one can distinguish the first scheme from the second and third one by studyng the oscillations. Indeed, suppose that the neutrinos are detected by observation of the processes of ν-nucleon NC scattering. Let the initial beam of neutrinos consists of ν_μ. If $N_0^{NC}(R,p)$ is the number of events expected in absence of oscillations, the number of events $N^{NC}(R,p)$ at distance R from the source of ν_μ will be :

$$N^{NC}(R,p) = \sum_{l=e,\mu,\tau} P_{\nu_\mu \to \nu_l}(R/p) \cdot N_0^{NC}(R,p) < N_0^{NC}(R,p)$$

if the neutrino mass term is of Dirac-Majorana type. In this case the quantity $\sum_{l=e,\mu,\tau} P(\nu_\mu \to \nu_l)$ may be smaller than 1 and may depend on R/p. Therefore the observation of neutrino oscillation effects in experiments in which neutrinos are detected through the processes of NC elastic and/or DIS ν-nucleon scattering would be a proof of the existence of sterile neutrinos. It also would imply that the number of massive neutrinos exceeds the numbers of neutrino flavours.

Rev. Mod. Phys.59 (1987) p. 699 S.M. Bilenky and S.T. Petcov

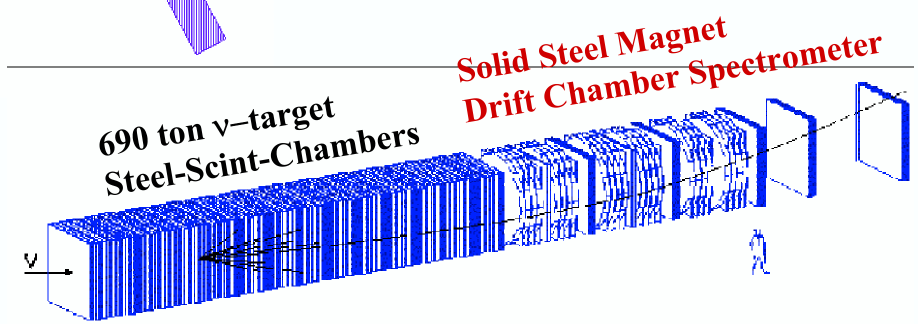
NUTEV EXP



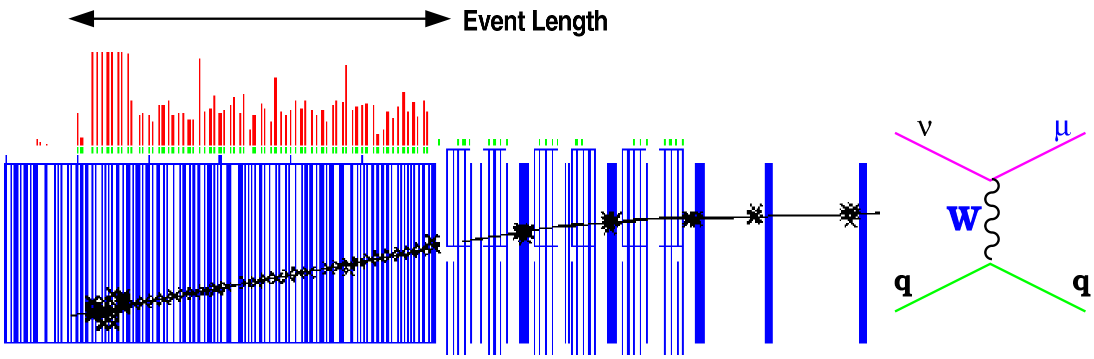
Dipoles make sign selection
- Set ν / $\bar{\nu}$ type
- Remove ν_e from K_{long}

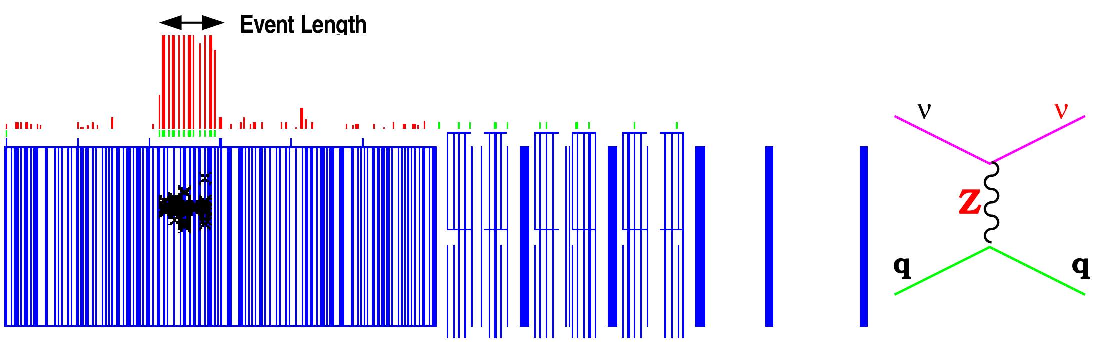
- Beam is almost pure ν or $\bar{\nu}$ ($\bar{\nu}$ in ν mode 3×10^{-4}, ν in $\bar{\nu}$ mode 4×10^{-3})
- Beam only has ~1.6% electron neutrinos

  $\Rightarrow$ Important background for isolating true NC event

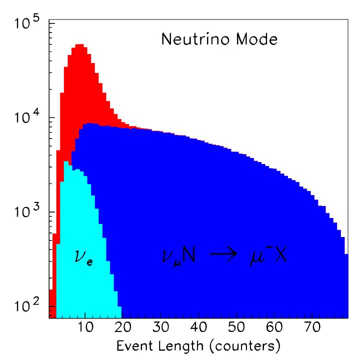


NUTEV NC/CC event separation



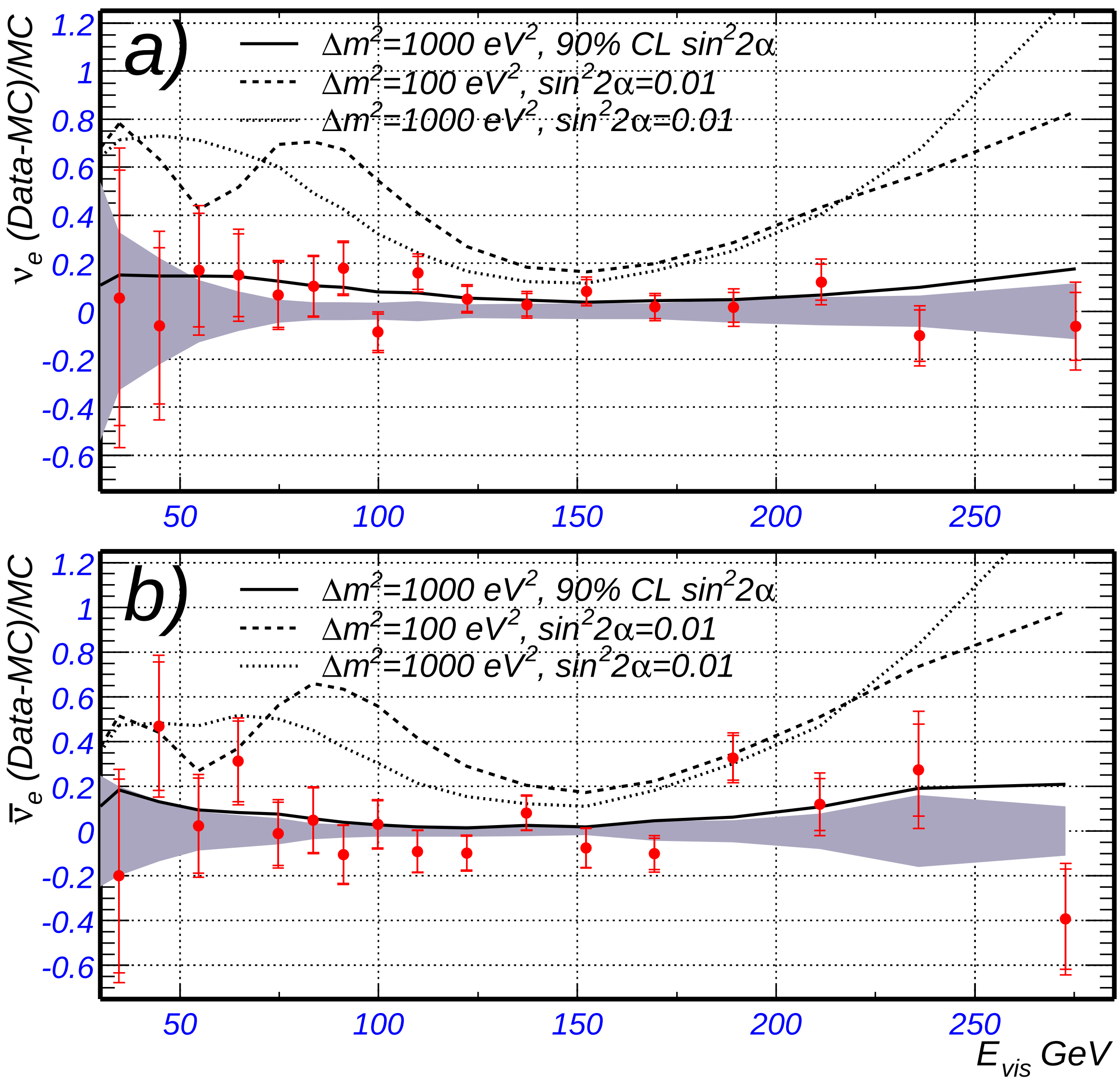


Statistical separation of NC and CC events based on ("event length").



$$R_{\text{exp}} = \frac{\text{SHORT events}}{\text{LONG events}} = \frac{\text{NC candidates}}{\text{CC candidates}}$$

NUTEV ν_e measurement



hep-ex/0203018

NUTEV result

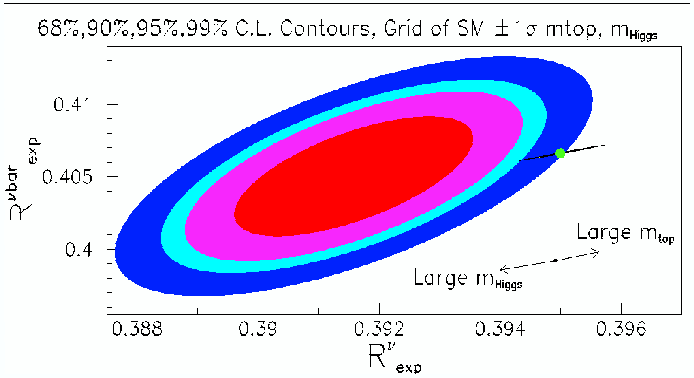
$$\sin^2\theta_W^{(on-shell)} = 0.2277 \pm 0.0013\,(stat.) \pm 0.0009\,(syst.)$$
$$= 0.2277 \pm 0.0016$$

Phys.Rev.Lett. 88,91802 (2002)

- NuTeV result:
  - Error is statistics dominated
  - Is ×2.3 more precise than previous νN experiments where $\sin^2\theta_W = 0.2277 \pm 0.0036$ and syst. dominated

- Standard model fit (LEP-EWWG): **0.2227** ± **0.00037**

  A 3σ discrepancy ....



$$R^{\nu} = \frac{\sigma^{\nu}_{NC}}{\sigma^{\nu}_{CC}} \quad \text{and} \quad R^{\bar{\nu}} = \frac{\sigma^{\bar{\nu}}_{NC}}{\sigma^{\bar{\nu}}_{CC}}$$

$\frac{dR^{\nu}_{\exp}}{d\sin^2\theta_W}$ large $\quad$ $\frac{dR^{\bar{\nu}}_{\exp}}{d\sin^2\theta_W}$ small

$R^{\nu}_{\exp} \rightarrow \sin^2\theta_W$ $\quad$ $R^{\bar{\nu}}_{\exp} \rightarrow$ systematics (i.e. m_c)

$$\boxed{\begin{array}{lll} R^{\nu}_{\exp} = 0.3916 \pm 0.0013 & (SM : 0.3950) & \Leftarrow 3\sigma \ difference \\ R^{\bar{\nu}}_{\exp} = 0.4050 \pm 0.0027 & (SM : 0.4066) & \Leftarrow Good \ \ agreement \end{array}}$$

NUTEV : possible interpretation

Reduced Background from $\nu_e \rightarrow \nu_s$ *Osc.*

- Neutrino oscillations to Sterile Neutrinos
  (Giunti et al. hep-ph/0202152;)
  - $\nu_e \rightarrow \nu_s$ oscillation make real ν_e background subtraction smaller giving NuTeV anomaly
    - Requires high Δm^2 and ~20% mixing
  - Is this consistent with other oscillation limits
    - For (3+1) model inconsistent with Bugey reactor limits

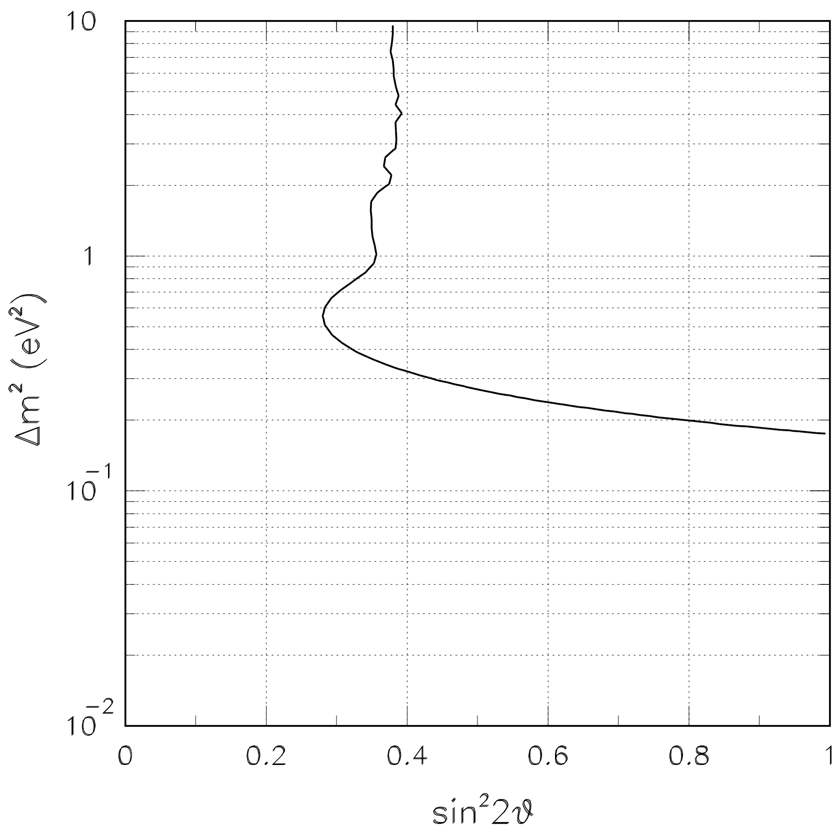
M.Shaevitz Nobel Symposium Aug 2004

NUTEV : ν_e content in beam

"Recent BNL-E865 measurement of K+e3 branching ratio is 6% higher than the PDG value used in the NuTeV analysis; higher branching ratio would INCREASE NuTeV discrepancy by roughly 1 σ; appears to be confirmed by recent KTeV (hep-ex/0406002) , KLOE results ."

http://home.fnal.gov/ gzeller/nutev.html#nue

$\nu_e \to \nu_s$ 90 % C.L. limit from ^{51}Cr test exp



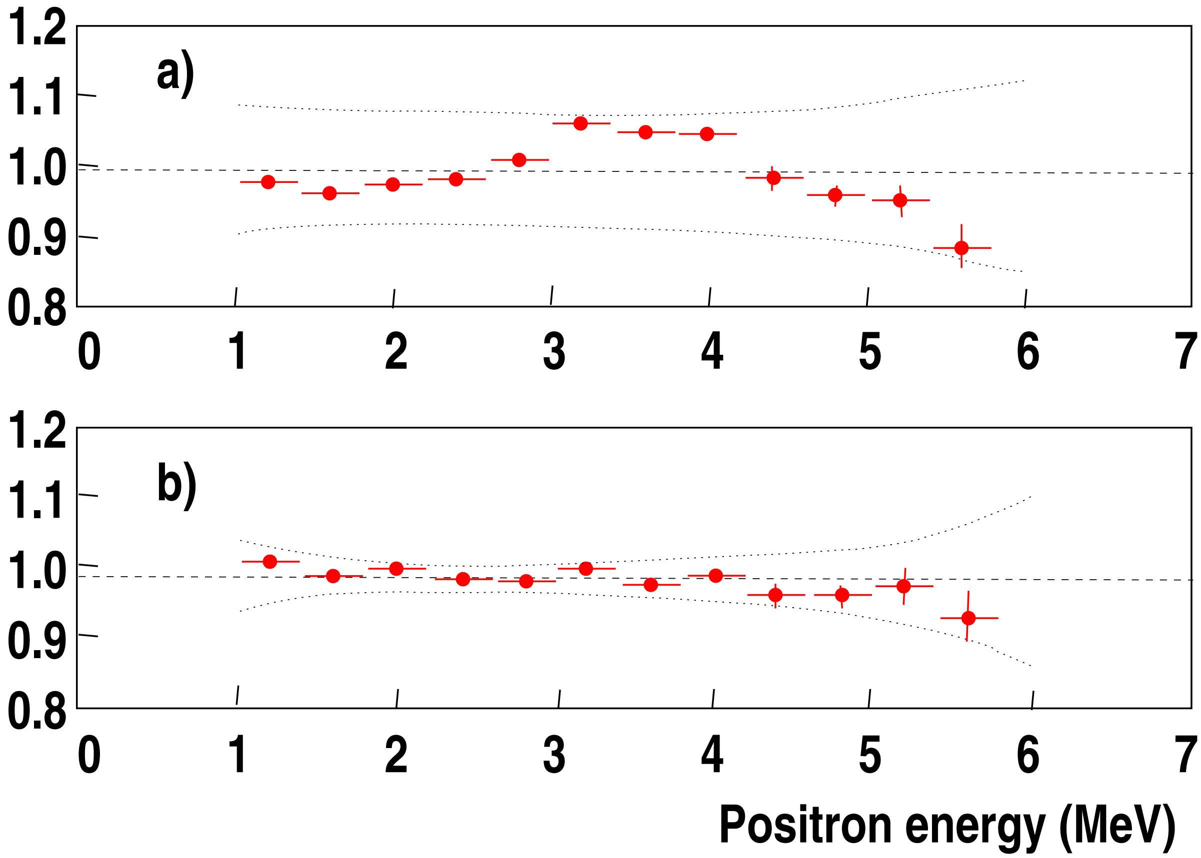
hep-ex/9411414

The value for the mixing angle in the $\nu_e \to \nu_s$ oscillation interpretation of NUTEV data (hep-ph/0202152) is:

$$sen^2 2\theta = 0.42 \pm 0.14 \quad (1\sigma)$$

$$10 \leq \Delta m^2 \leq 100\,\mathrm{eV}^2$$

DATA/MC comparison at BUGEY



hep-ph/0107277

In a) the measurements are compared to the calculations of Klapdor and Metzinger . In b) Bugey 3 data is compared to the prediction obtained using the β spectra measurements of Schreckenbach and Hahn. The dashed envelopes are estimates of the overall systematics.

" The ultimate check of the accuracy of the prediction outlined above consists in comparing the results in terms of $\bar{\nu}_e$ energy spectrum with the measurements performed in SBL reactor oscillation experiments."'

NOMAD detector

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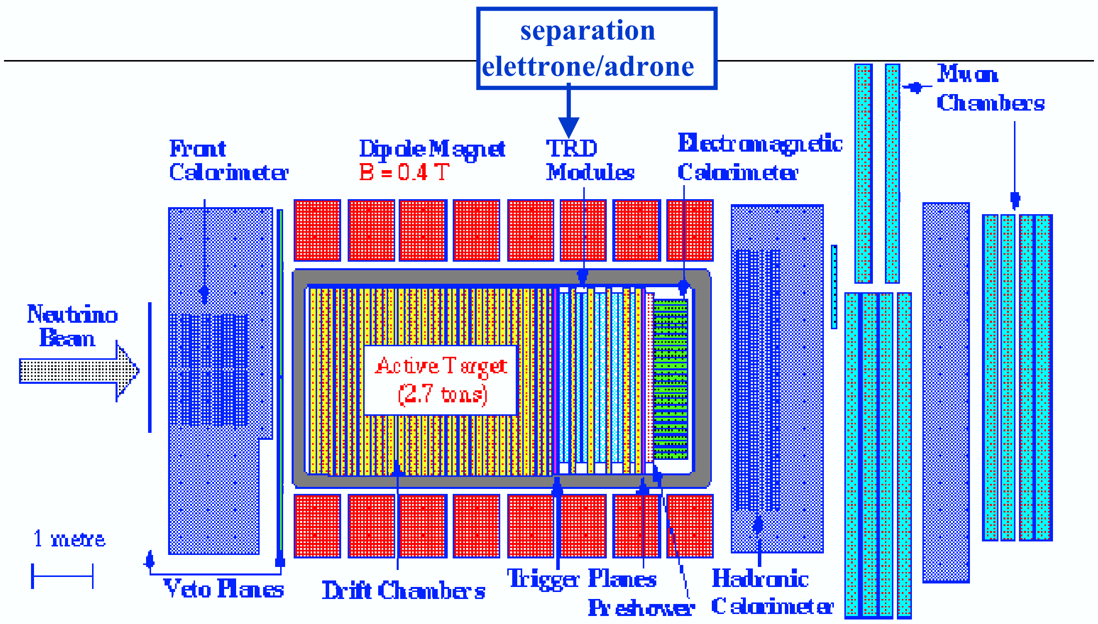
Rivelatore NOMAD



Risoluzione in impulso: $\Delta p/p = \pm 3.5\%$ per $p < 10$ GeV/c
Risoluzione in energia del Calorimetro Elettromagnetico:

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus 1\% \quad (E \text{ in GeV})$$

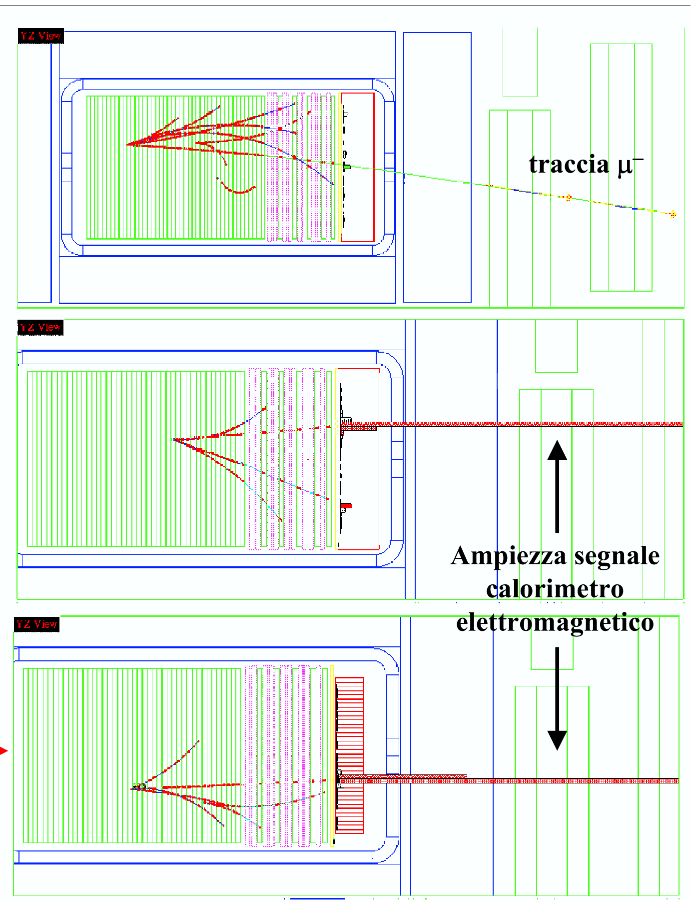
NOMAD events

Tre eventi tipici in NOMAD

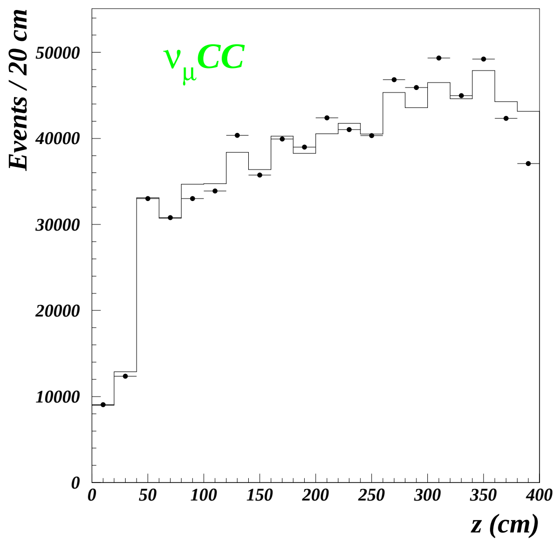
$\nu_\mu + N \rightarrow \mu^- + \text{adroni}$

$\nu_e + N \rightarrow e^- + \text{adroni}$

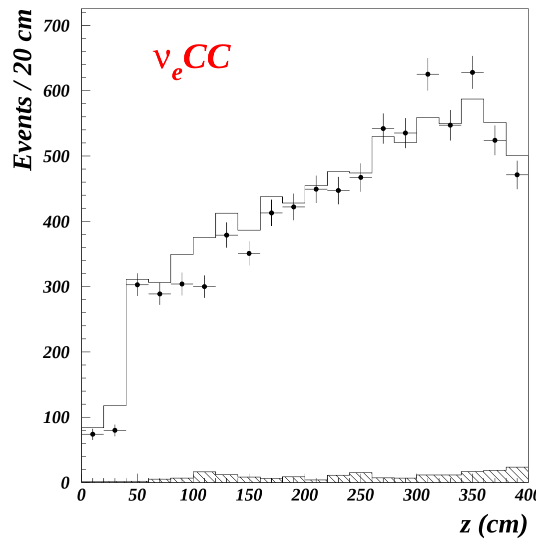
$\bar{\nu}_e + N \rightarrow e^+ + \text{adroni}$



NOMAD event distributions and cuts



cut : $z > 184$ cm

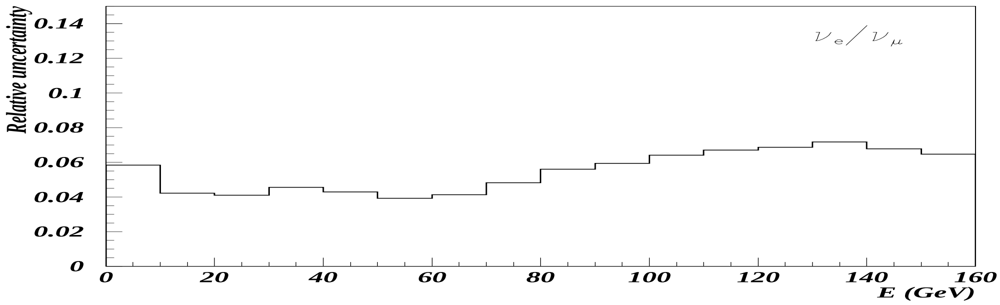


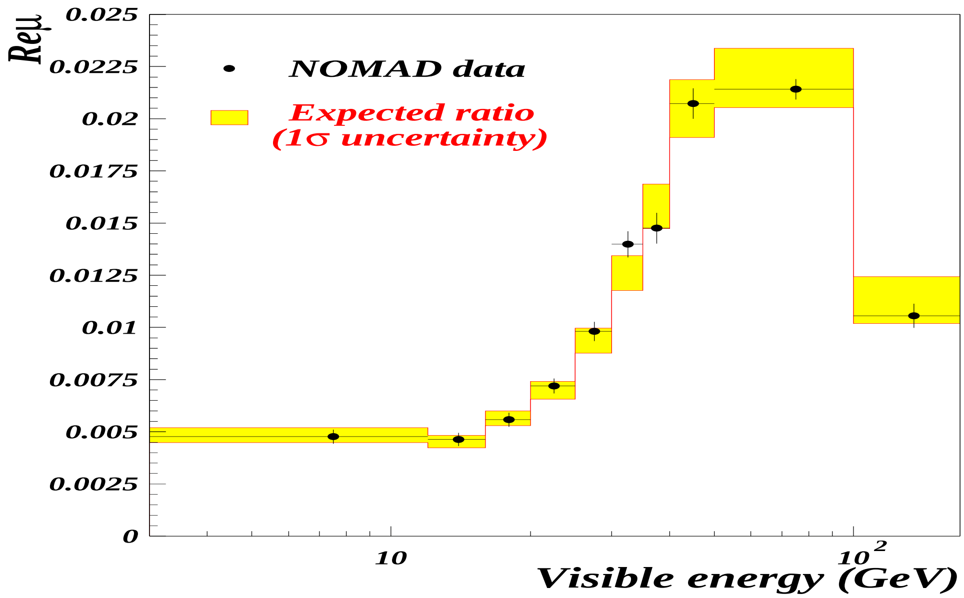
cut : $z > 184$ cm

“ We therefore decided to restrict the analysis to events occurring in the 72 downstream planes of drift chambers by requiring $z > 184$ cm. This restriction resulted in a loss of about 30% of the ν_e CC events and 35% of the ν_μ CC events. It should be noted that any oscillation effects could not manifest themselves over this distance since the point of origin of the neutrinos is spread over more than 300 m. A total of 5.584 ν_eCC and 472.378 ν_μ CC events were retained.”

hep-ex/0306037

NOMAD flux error & result

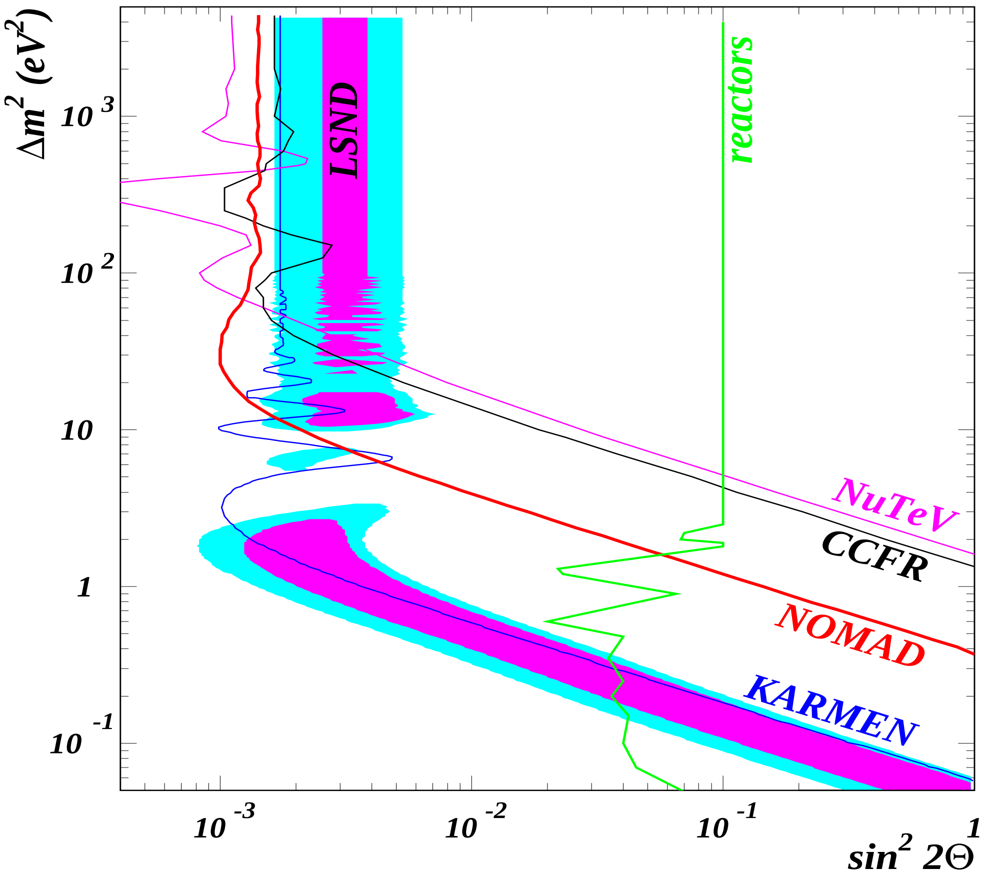




“ The overall uncertainty arising from the knowledge of the beam composition is divided into an energy-independent, or normalization, uncertainty and an energy-dependent one. The normalization uncertainty on $R_{e\mu}$ is 4.2%, while the energy-dependent uncertainty, varies from 4% to 7%.”

hep-ex/0306037

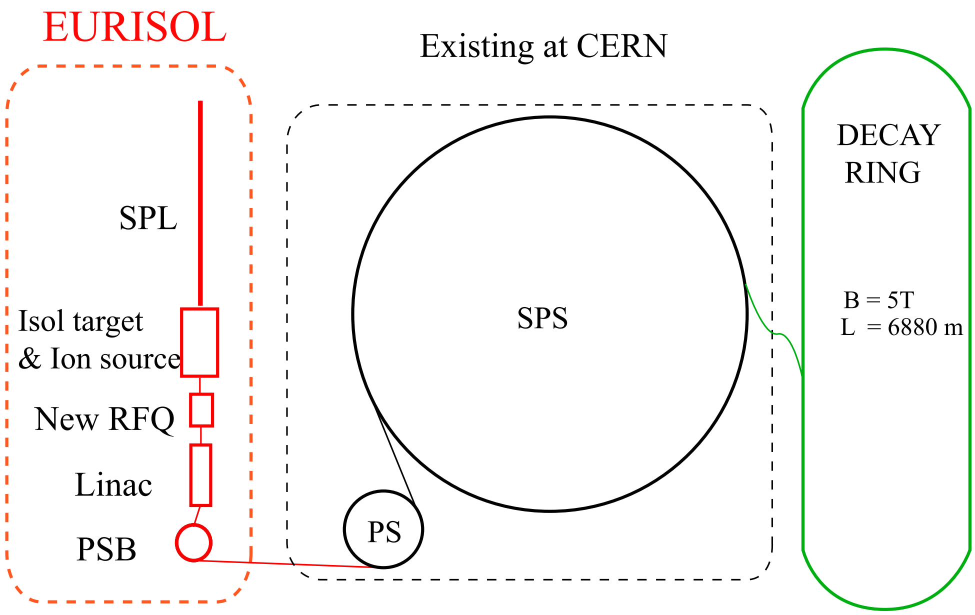
NOMAD $\nu_\mu \to \nu_e$ limit 2003



“No evidence for oscillations was found. The 90% confidence limits obtained are : $\delta m^2 < 0.4$ eV^2 for maximal mixing and $\sin^2 2\theta < 1.4 \times 10^{-3}$ for large δm^2. This result excludes the high δm^2 region of oscillation parameters favoured by the LSND experiment. This resultis less stringent than our preliminary result (EPS 2001) because of a better understanding of the systematic uncertainties arising from the knowledge of the beam composition.”

hep-ex/0306037

Future β beam experiment ?

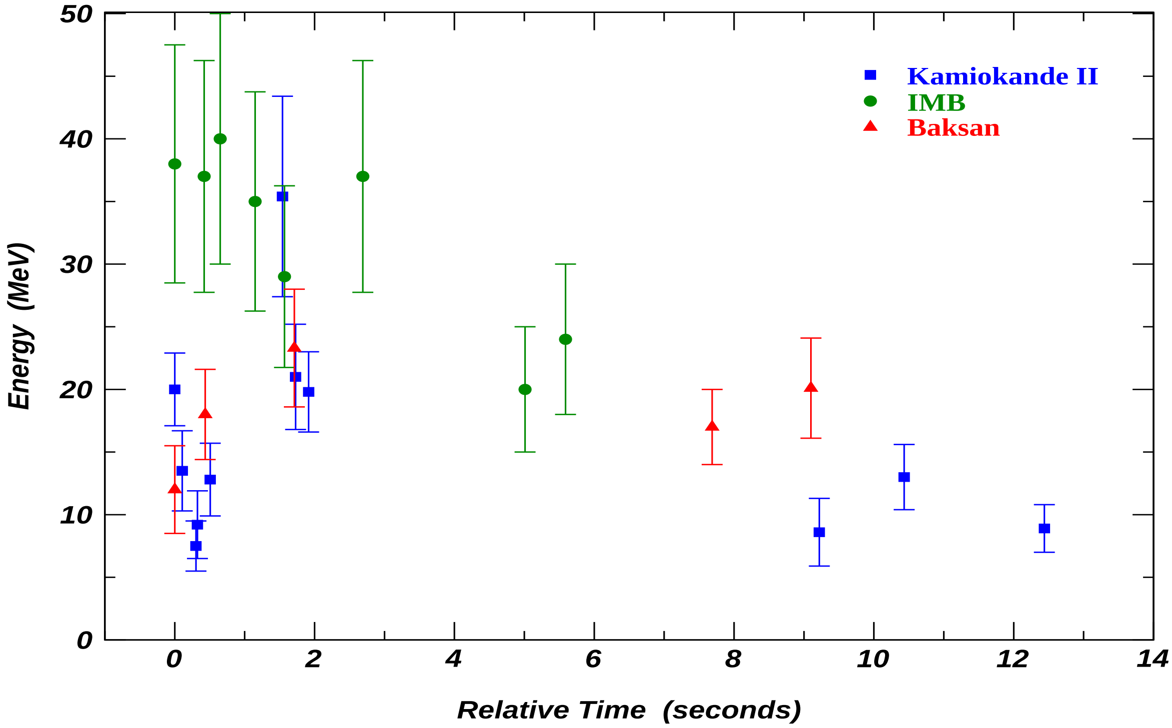


hep-ex/0410083

"Beta Beams have been introduced by Piero Zucchelli in 2001 . The idea is to generate pure, well collimated and intense ν_e and $\bar{\nu}_e$ beams by producing, collecting, accelerating radioactive ions and storing them in a decay ring. The best candidates so far are ^{18}Ne and ^{6}He for ν_e and $\bar{\nu}_e$ respectively.A baseline study for such a BetaBeam complex has been produced at CERN .

"If the MiniBoone experiment validates the LSND oscillation claim, a beta-beam experiment looking to $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ oscillation could allow unprecedented measurements of oscillations in the region of Δm^2 relevant to astrophysics and cosmology. At the moment, no pure sources of ν_μ or ν_e are available to appearance experiments which have to explore the region characterized by $sen^2 2\theta \approx 10^{-4}$. The technology developed for the ICARUS experiment would probably be suitable for this domain of investigation."

SN 1987A



Time delay of massive neutrinos:

Let us look now at the time delay in the arrival time of a non-zero mass neutrino in comparison to that of a massless one. If the mass is exactly zero, the time of flight for arriving on the Earth from the Supernova is the same for all the neutrinos. It is

$$T_0 = L_{SN}/c = 1.7 \cdot 10^5 \quad years$$

where L_{SN} is the distance of the Supernova from the Earth, and c is the light speed in vacuum. However if the mass m is not zero, then the time of flight is

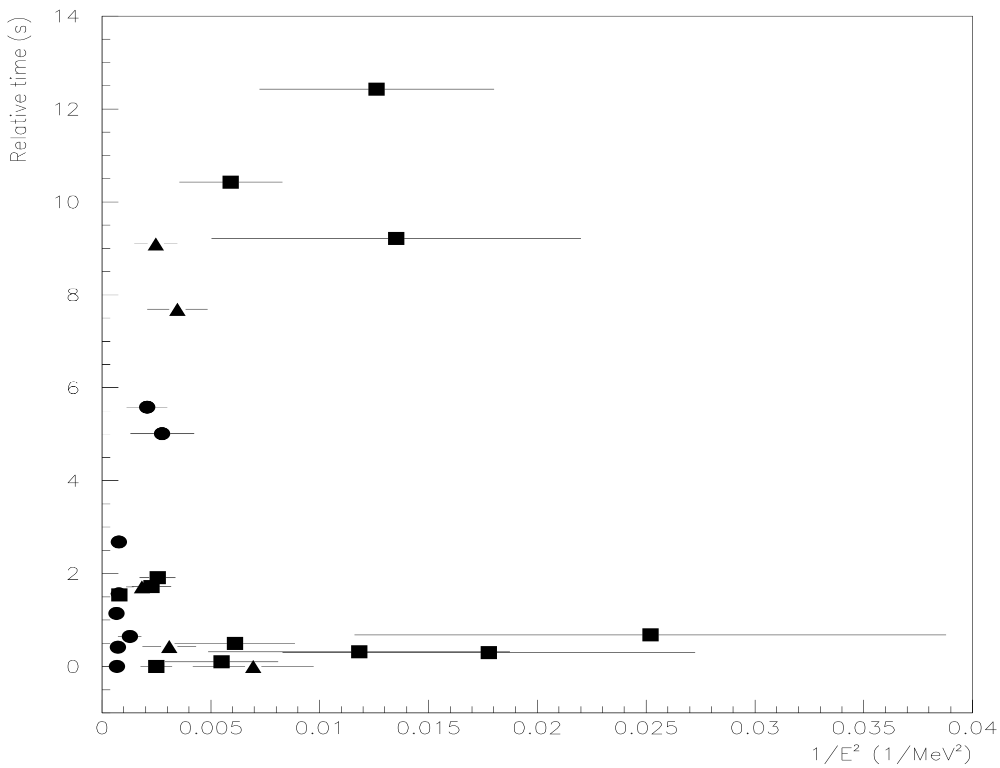
$$T_m = \frac{L_{SN}}{c \cdot \sqrt{1-(m/E)^2}} \sim \frac{L_{SN}}{c} \cdot \{1 + \ 1/2 \cdot (m/E)^2\}$$

SN 1987A

The difference of these two values, *i.e.* the delay in the arrival of a neutrino with mass m in comparison to a massless one, is

$$\Delta T_m = T_m - T_0 \approx 1/2 \cdot T_0 \cdot m^2/E^2$$

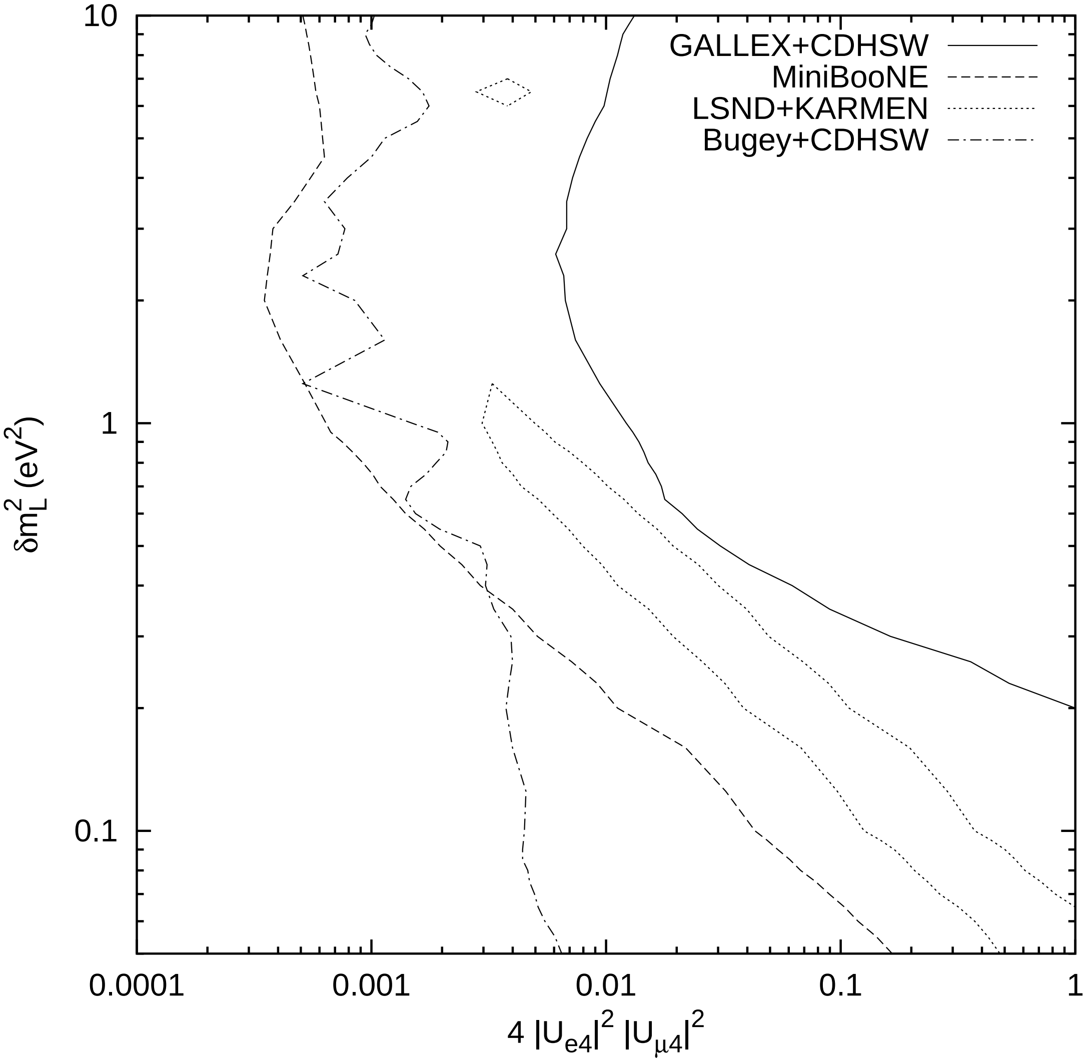
Numerically, a neutrino of energy 5 MeV should delay about one second if the mass is 3 eV and about 10 seconds if the mass is 10 eV.



$$m_1 = 3.4 \pm 0.6\,\mathrm{eV} \qquad m_2 = 22.7 \pm 3.7\,\mathrm{eV}$$

hep-ph/0212337 H. Huzita

3+1 & CPT violation



hep-ph/0308299

Se son rose fioriranno ...