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"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Short and Long Baseline Neutrino Experiments

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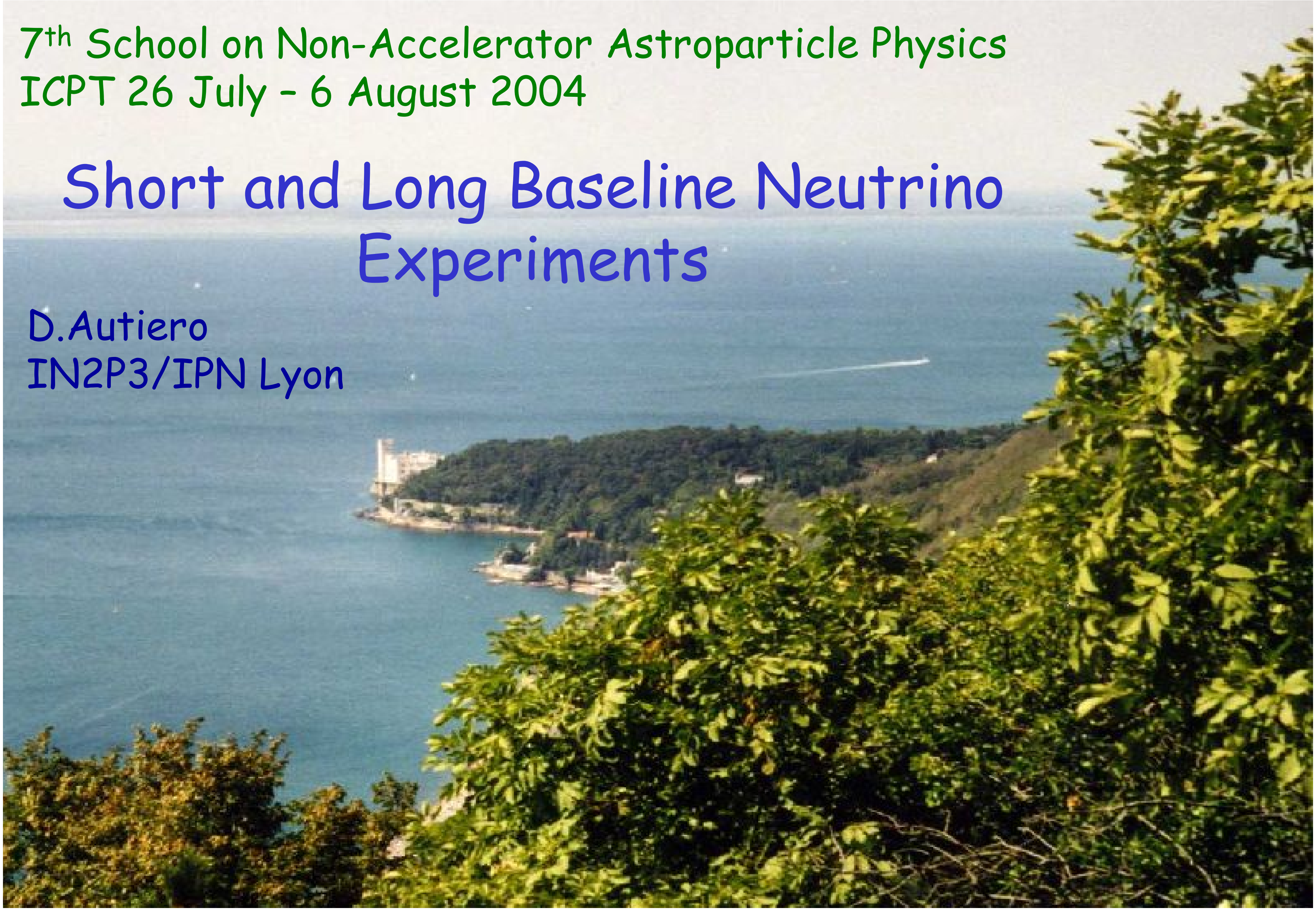

7th School on Non-Accelerator Astroparticle Physics
ICPT 26 July – 6 August 2004

Short and Long Baseline Neutrino Experiments

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Outline

Two lectures on the past and current neutrino oscillation experiments with man-made neutrino sources: Accelerators (mainly) and nuclear Reactors

Presented following an historical approach:

Lecture 1

- ✓ Introduction: neutrino oscillations and experiments
- ✓ The CERN Short Baseline experiments NOMAD, CHORUS
- ✓ LNSD and KARMEN
- ✓ MINIBOONE
- ✓ CHOOZ

Lecture 2

- ✓ K2K
- ✓ MINOS
- ✓ The CNGS program OPERA, ICARUS
- ✓ Outlook

Neutrino oscillations

Neutrino mixing (Pontecorvo 1958; Maki, Nakagawa, Sakata 1962):

3 neutrinos framework, neutrinos are massive particles and they mix similarly to quarks; the flavour eigenstates ν_e, ν_μ, ν_τ are not mass eigenstates but linear superpositions of the mass eigenstates ν_1, ν_2, ν_3 with eigenvalues m_1, m_2, m_3:

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

$\alpha = e, \mu, \tau$ (flavor index)

$i = 1, 2, 3$ (mass index)

$U_{\alpha i}$= **unitary mixing matrix**

Today favorite parametrization of U: in terms of 3 mixing angles θ_{12} θ_{23} θ_{13} and one Dirac-like CP phase δ (two extra phases in case of Majorana neutrinos):

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

Atmospheric ν oscillations **Solar ν oscillations**

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

where: $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$.

Considering the time evolution of a flavour eigentstate ν_α produced at $t = 0$:

$$|\nu(t)\rangle = e^{i\mathbf{p}\cdot\mathbf{r}} \sum_k U_{\alpha k}\, e^{-iE_k t} |\nu_k\rangle \qquad E_k = \sqrt{p^2 + m_k{}^2}$$

The phases: $e^{-iE_k t}$ will be different if $m_j \neq m_k$

Projecting $\nu(t)$ on the flavor basis one can obtain the probability of finding other flavours:

→ **Appearance of the flavour $\nu_\beta \neq \nu_\alpha$ for t > 0**

Simplified case: two neutrinos mixing

Only one mixing angle θ is needed

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

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

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

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

Probability of detecting ν_β at the instant t if $\nu(0) = \nu_\alpha$:

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

$$\hbar = c = 1$$

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

Oscillatory behaviour of $P_{\alpha\beta}$ with time ruled by two parameters:

θ is related to the amplitude of the oscillation

Δm² is related to the wavelength

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

For m<<p, and assuming propagation in vacuum:

$$E = \sqrt{p^2 + m^2} \approx p + \frac{m^2}{2p}$$

In more empirical units:

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

Δm² [eV²]

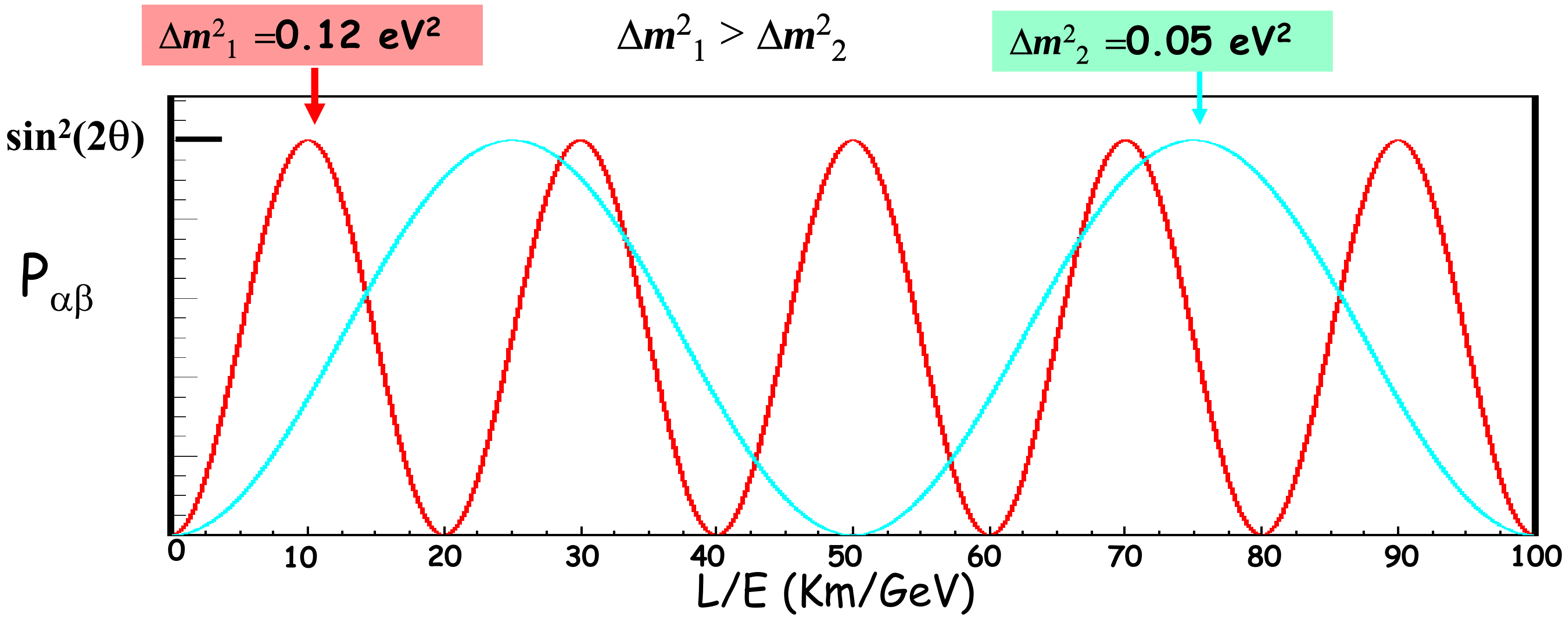
L=ct [km] (distance among the neutrino source and the detector)

E [GeV] (neutrino energy)

Given *Δm²* the experimental quantity for the study of neutrino oscillations is the ratio L/E [km/GeV]: first oscillation maximum at L/E ~ 1.24 / *Δm²*

$$P_{\alpha\beta}(L) = \sin^2(2\theta)\sin^2\left(\pi\frac{L}{\lambda}\right) \qquad \lambda = 2.48\frac{E}{\Delta m^2}$$

Oscillation wavelength


$\Delta m^2_1 = 0.12\ eV^2$ $\qquad \Delta m^2_1 > \Delta m^2_2 \qquad$ $\Delta m^2_2 = 0.05\ eV^2$

For very large Δm^2 the oscillations become very fast and average over the dimensions of the source and of the detector:

→ $\langle \sin^2(1.267\ \Delta m^2\ L/E)\rangle = 1/2 \qquad P=(1/2)\sin^2(2\theta)$

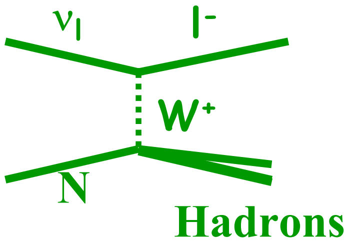
The baseline is related to the L/E ratio of the experimental setup:

Short Baseline experiments: sensistive to large Δm^2 (> 1 eV^2)

Long Baseline experiments: sensitive at least to Δm^2 of interest for the atmospheric neutrino anomaly (<10^{-2} eV^2), L/E > 100 Km/GeV

Reactors:	L>0.3 Km, E~3 MeV
Accelerators:	L>100 Km, E~1 GeV

Most important neutrino interactions with matter in the accelerators energy range



(CC) Charged current interactions ($W^{\pm}$ exchange)

Quasi elastic scattering

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

$\nu_\mu + n \rightarrow \mu^- + p \quad \bar{\nu}_\mu + p \rightarrow \mu^+ + n$ $E_{Threshold}$: ~112 MeV

$\nu_\tau + n \rightarrow \tau^- + p \quad \bar{\nu}_\tau + p \rightarrow \tau^+ + n$ $E_{Threshold}$: ~3.46 GeV

$\sigma_{QE}(\nu_\mu + n) \sim 0.9 \times 10^{-38}$ cm² (far from threshold)

Deep inelastic scattering (DIS)

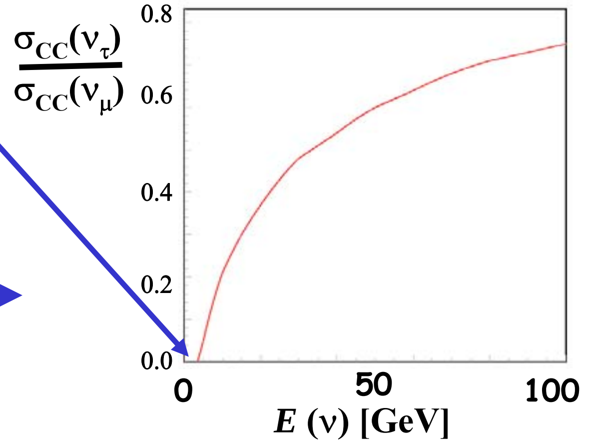
$\nu_e + N \rightarrow e^- + \text{hadrons} \quad \bar{\nu}_e + N \rightarrow e^+ + \text{hadrons}$ (N: p,n)

$\nu_\mu + N \rightarrow \mu^- + \text{hadrons} \quad \bar{\nu}_\mu + N \rightarrow \mu^+ + \text{hadrons}$

$\nu_\tau + N \rightarrow \tau^- + \text{hadrons} \quad \bar{\nu}_\tau + N \rightarrow \tau^+ + \text{hadrons}$

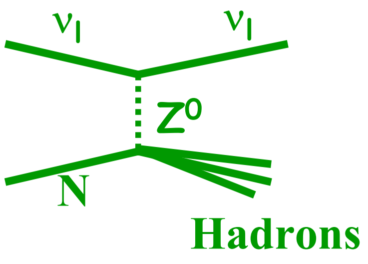
$\sigma_{DIS} \sim 0.68 E \times 10^{-38}$ cm² (E in GeV), $\sigma_{DIS}(\bar{\nu}) \sim 1/2\, \sigma_{DIS}(\nu)$

τ mass kinematic suppression



(NC) Neutral current interactions (Z^0 exchange)

Elastic and DIS, similar for the 3 neutrinos



$\nu + N \rightarrow \nu + \text{hadrons} \quad \bar{\nu} + N \rightarrow \bar{\nu} + \text{hadrons}$

$\sigma_{NC}(\nu) \approx 0.3\, \sigma_{CC}(\nu)$
$\sigma_{NC}(\bar{\nu}) \approx 0.37\, \sigma_{CC}(\bar{\nu})$

Possible neutrino oscillation experiments

Disappearance experiments:

Measure the survival probability at a certain distance from the source of the neutrino flavour produced at the source:

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

Typical examples:

Experiments at nuclear Reactors:

E_ν ~ a few MeV, below threshold for μ or τ production

Experiments at Accelerators studying $\nu_\mu \rightarrow \nu_\tau$ oscillations with low energy beams (MINOS, K2K) below τ production threshold

These experiments rely on the knowledge of the initial neutrino flux at the source to which they have to compare in order to claim an effect.
This knowledge is the main systematic limitation which can be improved by measuring the flux with a near detector

Disappearance experiments can also measure at a certain L the oscillatory dependence of $P_{\alpha\alpha}$ on E (energy spectral distortion), which is an important signature

Appearance experiments:

Measurement of the probability of detecting a neutrino flavour ν_β not produced at the source (beam of ν_α) at a certain distance L from the source:

Typical examples:

ν_e Appearance at accelerators:

Detection of the reaction $\nu_e + \mathrm{N} \rightarrow e^- + \textbf{hadrons}$ with a ν_μ beam

ν_τ Appearance at accelerators:

Detection of the reaction $\nu_e + \mathrm{N} \rightarrow e^- + \textbf{hadrons}$ with a ν_μ high energy beam

These experiments rely on the knowledge of the purity of the initial neutrino flux at the source and on the control of the background processes in the detector which could mimic the appearance of a new flavour.

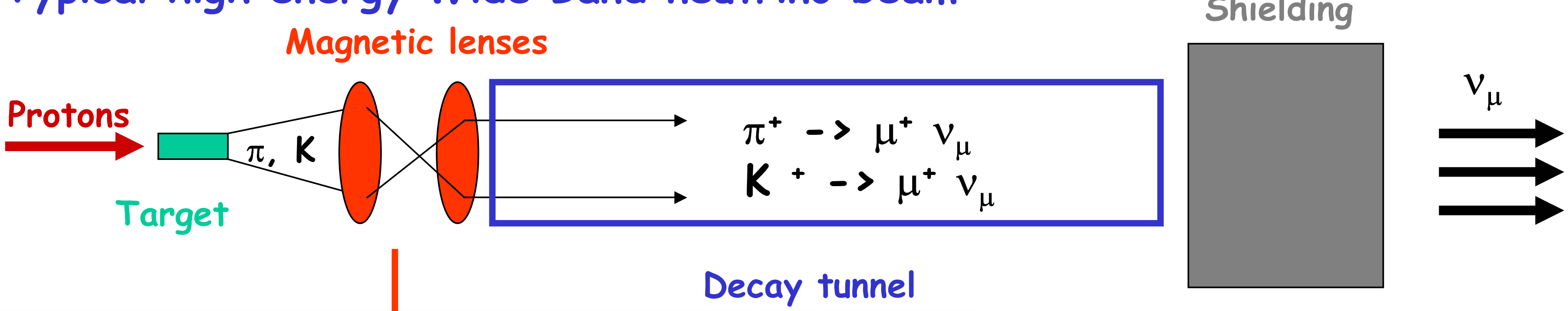
Neutrino beams at accelerator are almost pure ν_μ beams, ν_τ are practically absent, ν_e are present at the level of 1% (a two detector setup improves the syst. uncertainty)

Advantages neutrino beams at accelerators:

man-made neutrino sources of:

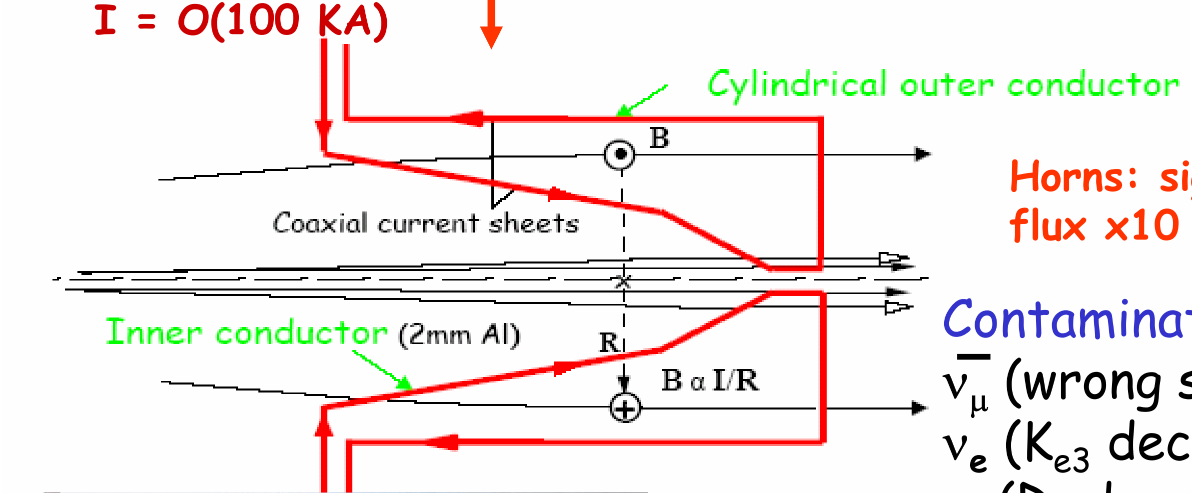
- **high purity**
- **high intensity**
- **high energy (O(10 MeV) – O(100 GeV))**

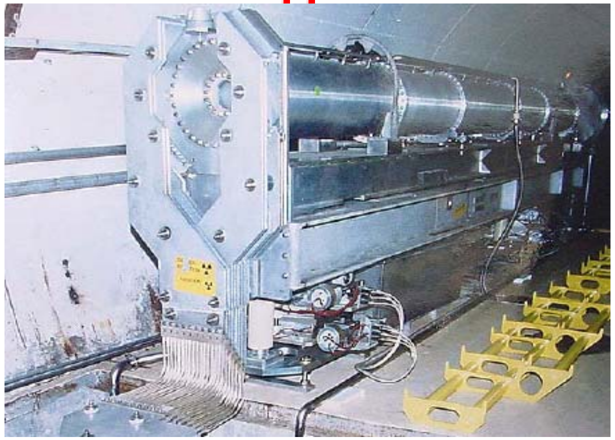
Typical high energy Wide Band neutrino beam



$\pi^+ \to \mu^+ \nu_\mu$

$K^+ \to \mu^+ \nu_\mu$





Horns: sign selection, focalization: flux x10

Contaminations:

$\bar{\nu}_\mu$ (wrong sign parents)	O(5%)
ν_e (K_{e3} decays, μ decays)	O(1%)
ν_τ (D_s decays)	O(10^{-6})

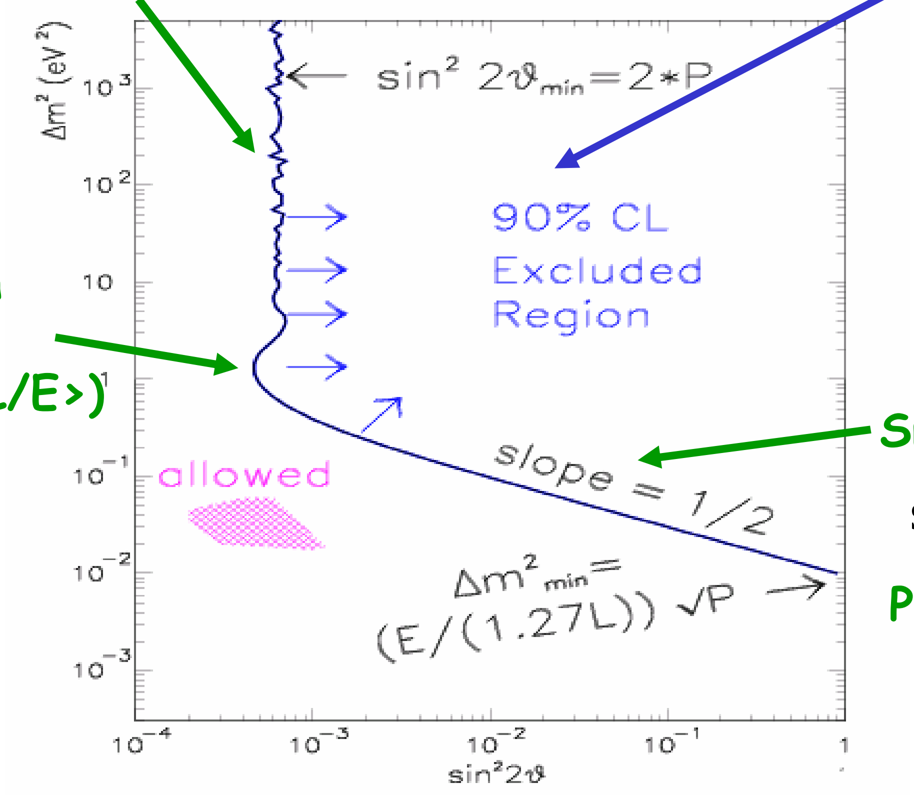
Note that the π/K abundances and spectra at the target are not easy to predict: to reduce systematics perform ad hoc hadron-production experiments (Spy, Harp etc …)

Interpretation of the experimental results

Observation of an oscillation signal:
allowed region in the plane of the parameters $[\Delta m^2, \sin^2(2\theta)]$ compatible with the measured $P_{\alpha\beta}$ (defined by $P_{\alpha\beta}$ and the L/E of the experiment)

Negative result:
upper limit on $P_{\alpha\beta}$ ($P_{\alpha\beta} < P$ at a certain confidence level) → excluded region

Large Δm^2: oscillations averaged



First oscillation maximum
$(\pi/2) / (1.27\langle L/E\rangle)$

Small Δm^2: long λ

$$\sin\left(\pi \frac{L}{\lambda}\right) \approx \pi \frac{L}{\lambda}$$

$$P \sim \sin^2(2\theta)\,(1.27\,\Delta m^2\, L/E)^2$$

Neutrino oscillation searches at the beginning of 90s

(long time ago in neutrino physics, not so much in everydays life …)

U.S. new president in 1993

- The long standing (since 1968) problem of the solar neutrino deficit opened by the Homestake measurements (+ Kamiokande since 1986)
  In 1992 first Gallex results confirm the deficit also for neutrinos from the pp cycle

- Atmospheric neutrino anomaly still quite weak

The controlled observation of neutrino oscillations with an accelerator neutrino beam would have been a great discovery, where to search ?

Prejudice towards small mixing angles and large Δm^2

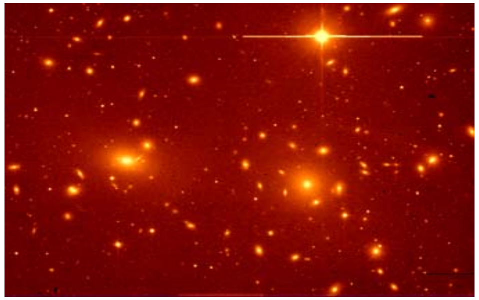
✓Take the MSW solution of the solar neutrino deficit: $\Delta m^2_{\mu e} \sim 10^{-5}$ eV^2

✓Assume a strong hierarchy: $m_{\nu e} \ll m_{\nu\mu} \ll m_{\nu\tau} \rightarrow m_{\nu\mu} \sim 3\times10^{-3}$ eV

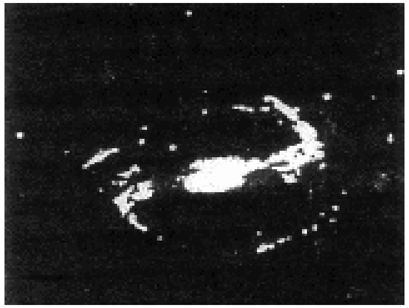
✓Assume the See-Saw mechanism: $m(\nu_i)=m^2(f_i)/M$
M=very large Majorana mass $m(f_i)$= e.g. quark masses

Then: $m_{\nu\tau} \sim 30$ eV (Cosmological relevance)

Dark matter (see lectures of P.Ullio)

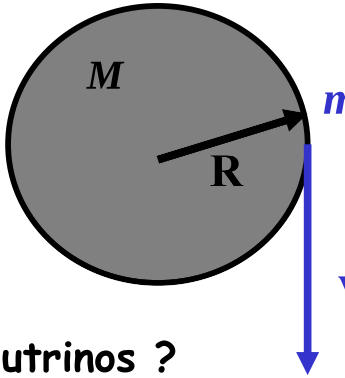


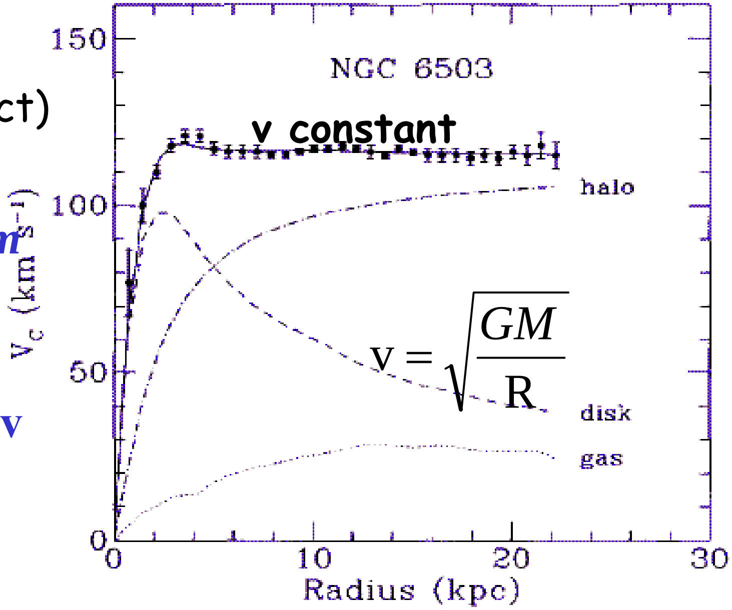
Coma cluster of galaxies, application of the virial theorem by F. Zwicky (1933)
velocity dispersion, geometric size → **total mass (x400 luminous mass)**



Rotational velocity curves
of galaxies (Hydrogen, doppler effect)

$$m\frac{v^2}{R} = \frac{GMm}{R^2}$$





$$v = \sqrt{\frac{GM}{R}}$$

Could it be due to the BIG BANG relic neutrinos ?
112 ν/ cm³ per flavour

if $\sum m_i \approx 52$ eV then $\Omega_\nu = 1$

« ν are an important component of the dark matter » ~ a few 10 eV
Harari PLB 1989

1992 first measurements from the COBE satellite $\Omega \sim 1$

J. Ellis PLB 292 1992 $\Omega_{HDM} = 0.3$, $\Omega_{CDM} = 0.7$

Recent cosmological results: $\sum m\nu < 2.5 eV$ 90% CL

With $m_{\nu\tau}$ ~ 30 eV cosmological neutrinos important component of dark matter
$\Delta m^2_{\mu\tau}$ O(100 eV^2)

Look for $\nu_\mu \rightarrow \nu_\tau$ with short baseline experiments at accelerators, high energy beam

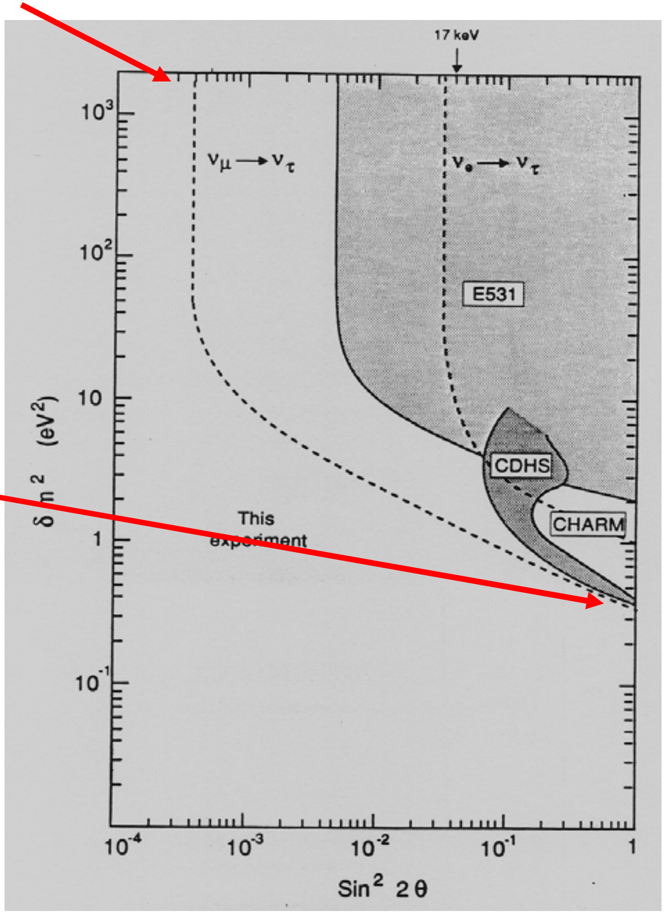
CERN ν_τ appearance experiments:

Search for ν_τ appearance from oscillations in the CERN wide band neutrino beam (WANF)

Pioneers of the technique also for long baseline experiments, important samples of neutrino interactions well measured

sensitive down to:

$P_{\mu\tau}$~ 1.5x10^{-4} (90% CL) (x10) improvement



<E_ν>=24 GeV
<L>=600 m
sensitive to:
1 eV^2 < Δm^2

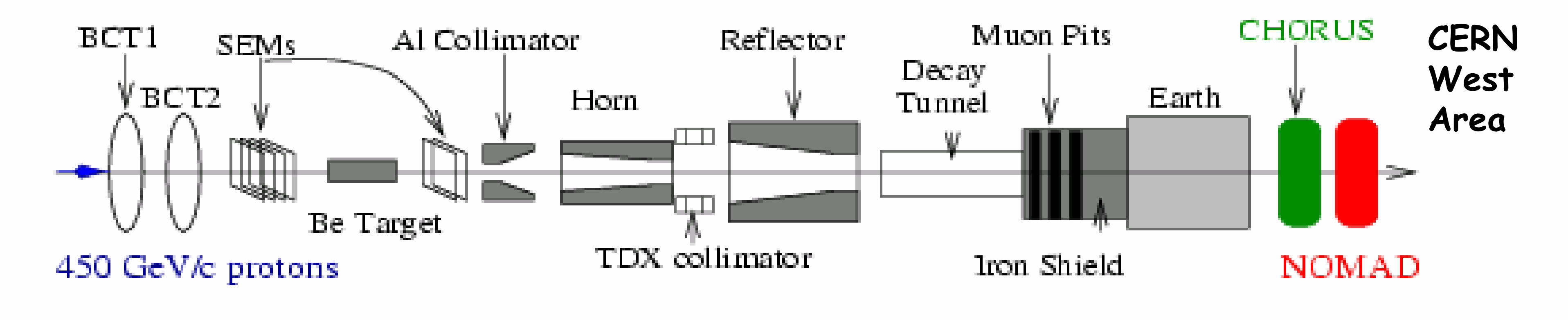
NOMAD:

- Proposal 1991
- Detector 1995
- Data-taking 95-98 (1.35 M ν_μ CC)

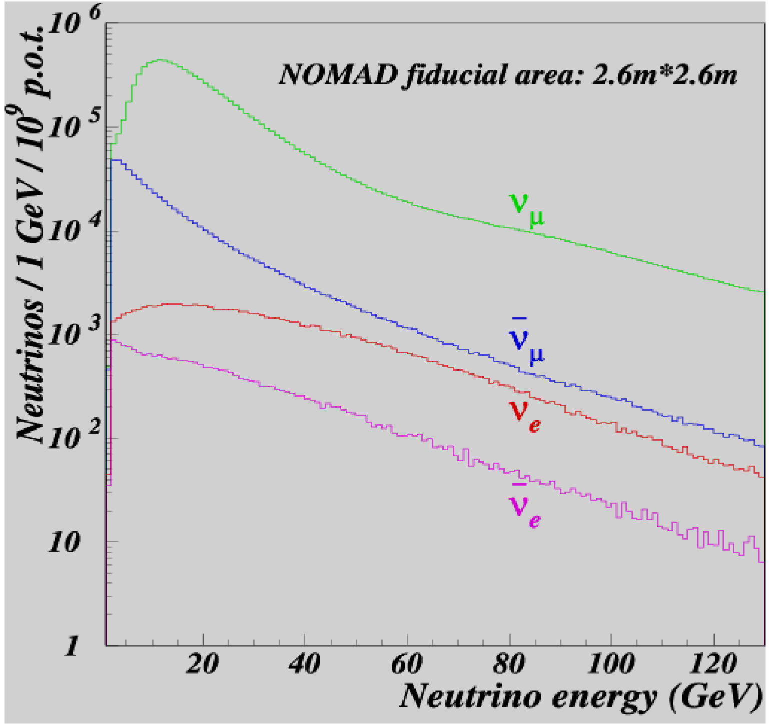
CHORUS:

Data-taking 1994-1997 (0.71 M ν_μ CC)

The CERN WANF neutrino beam



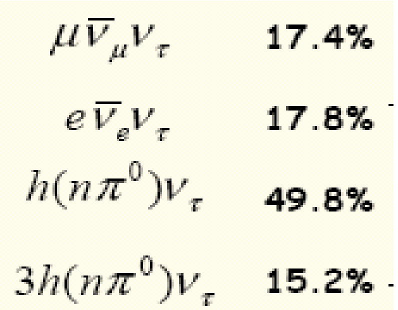
Flavour	$\langle E_\nu \rangle$(GeV)	rel.abun.
ν_μ	23.5	1.0
$\bar{\nu}_\mu$	19.2	0.061
ν_e	37.1	0.0094
$\bar{\nu}_e$	31.3	0.0025
ν_τ	35	$5\text{x}10^{-6}$



$\langle L\rangle/\langle E\rangle = 3 \times 10^{-2}$ Km/GeV

Search for τ appearance

The ν_τ are searched for through their charged current interaction followed by the τ decay.

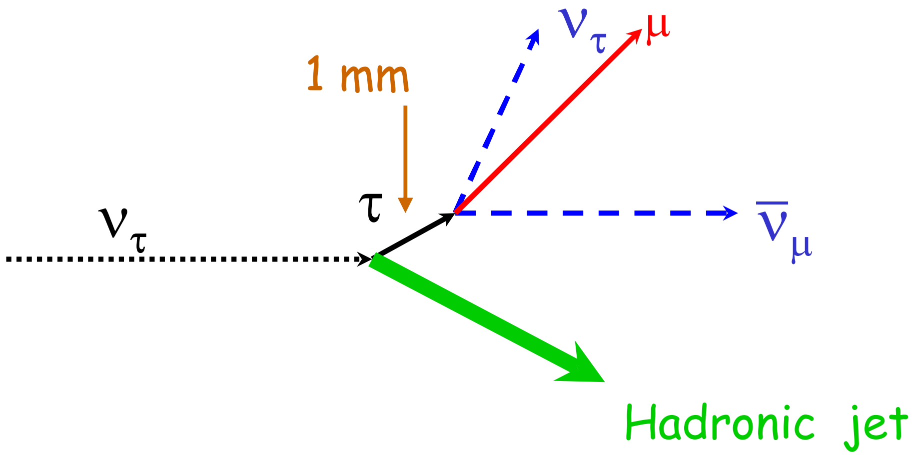


$\mu\bar{\nu}_\mu\nu_\tau$	17.4%
$e\bar{\nu}_e\nu_\tau$	17.8%
$h(n\pi^0)\nu_\tau$	49.8%
$3h(n\pi^0)\nu_\tau$	15.2%

This decay can be identified using two different methods :

- Identification of the τ decay kink : CHORUS (high space resolution, emulsions) (main channel: muonic tau decay)
- Measurement of the KINEMATIC of the τ decays :NOMAD

presence of neutrino(s) in the final state, missing P_t , visible decay daughters (tracking, calorimetry) (main channel: electronic tau decay)

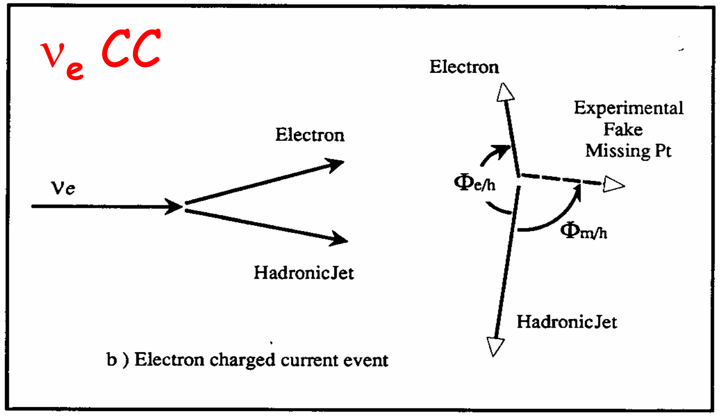


Use of kinematics to extract a ν_τ signal:

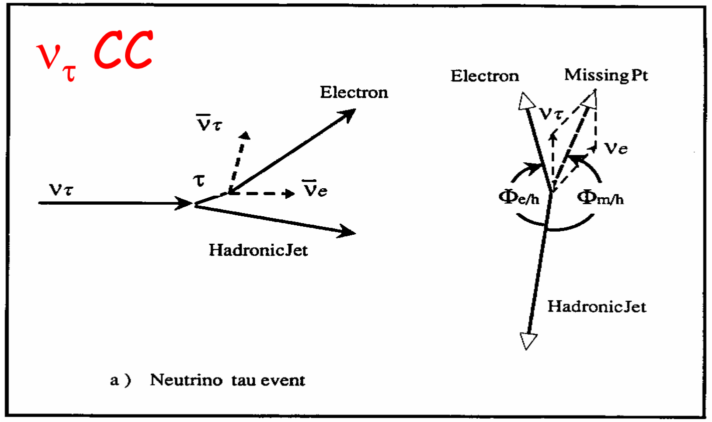
(First proposed by Albrigth and Shrock P.L.B. 1979)

NOMAD: fully reconstruct 1.7 M neutrino interactions, with good resolution, at single particles level:

→ Kinematics closure on the transverse plane



b) Electron charged current event



a) Neutrino tau event

Find ντ down to $P_{\mu\tau} \sim 10^{-4}$ in a large background:

1.3 M νμ CC

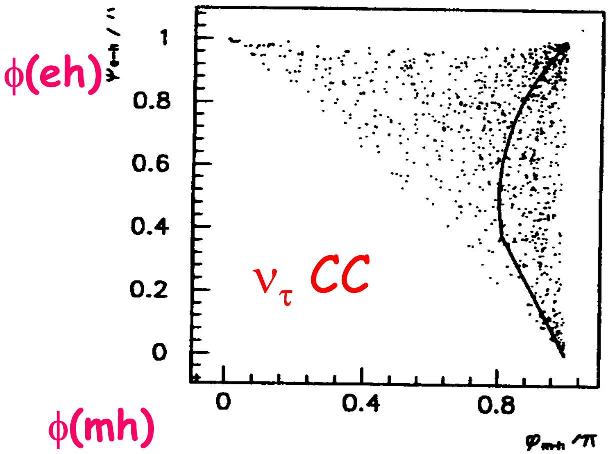
0,4 M νμ NC

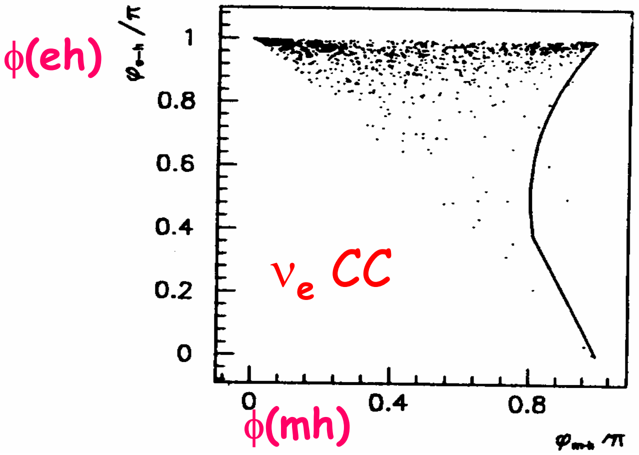
13 K νe CC

Exploit the small νe background:

τ->e channel: electron id

The φ- φ plot:

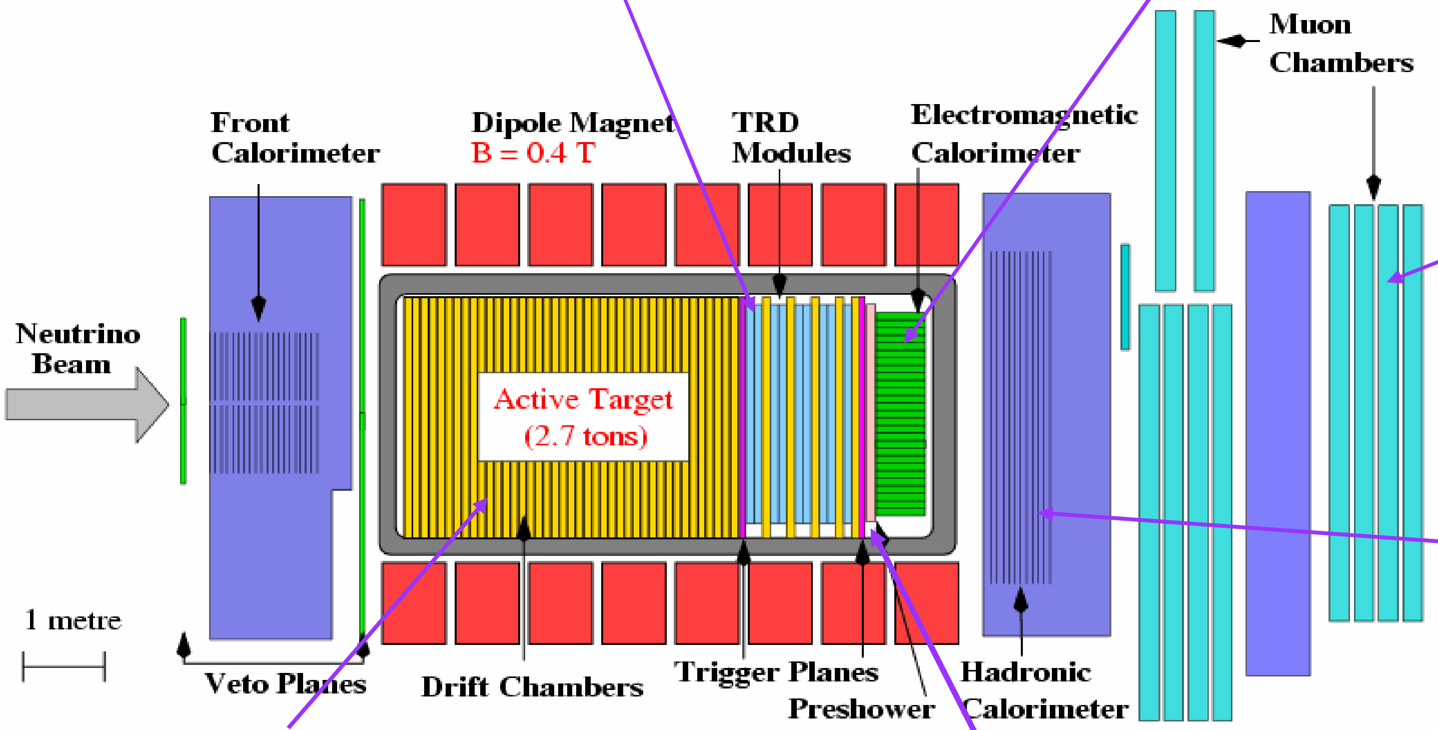




The NOMAD detector

Transition Radiation Detector (TRD) (e identification) 9 modules (315 radiator foils followed by straw tubes plane) π rejection ~ 10^3 for electron efficiency > 90%

Electromagnetic Calorimeter (measurement of energy and position of e.m. shower)



Muon Chambers (μ identification) ε~ 97% for $p_\mu > 5$ GeV/c

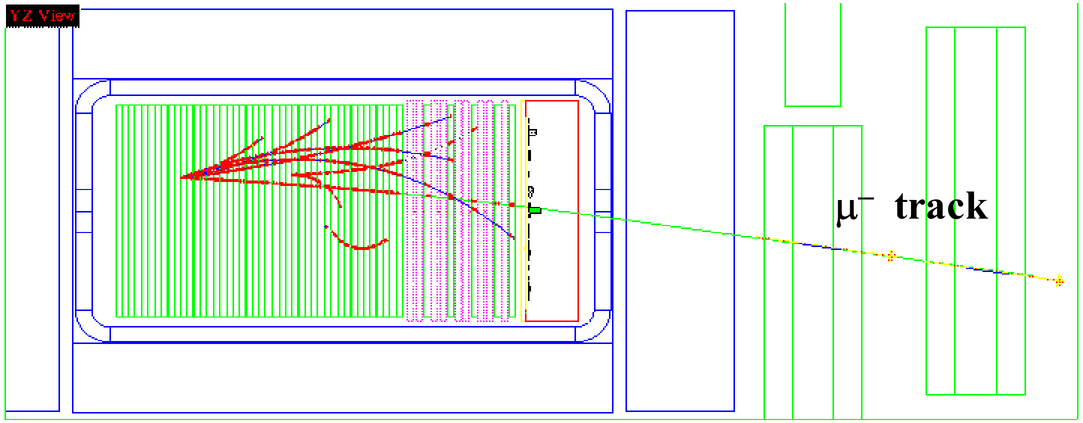
Hadronic calorimeter (n and k^0_L veto)

Drift chambers (target and momentum measurement) Fiducial mass 2.7 tons with average density 0.1 g/cm^3 44 chamber + 5 chambers in TRD region, momentum resolution 3.5% ~ (p < 10 GeV/C)

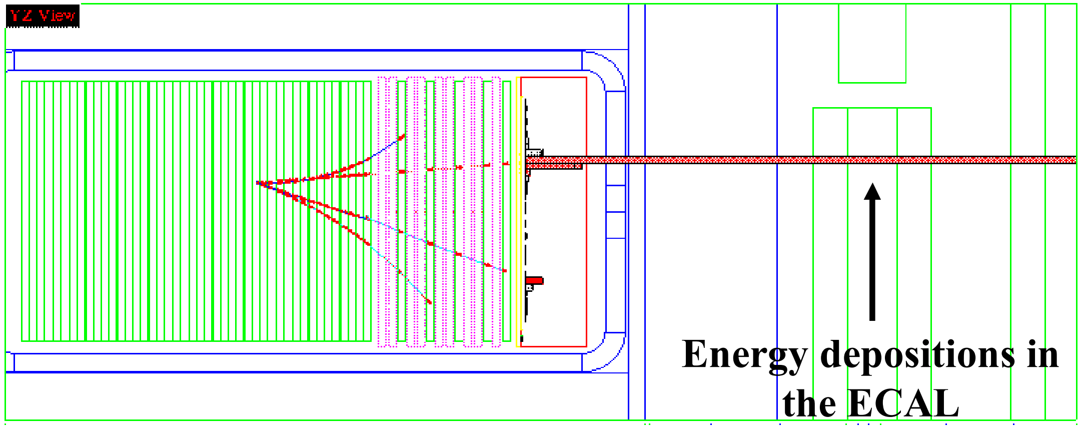
Preshower (e and γ detection) additional π rejection ~ 10^2 for electron efficiency > 90% precise γ position measurement $\sigma(x)$, $\sigma(y)$ ~ 1cm

Nomad typical events:

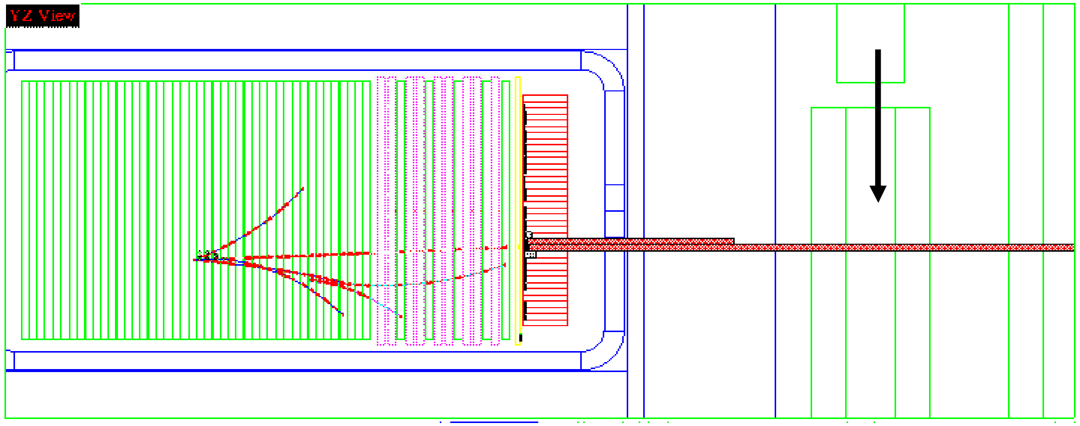
$\nu_\mu + N \rightarrow \mu^- + X$

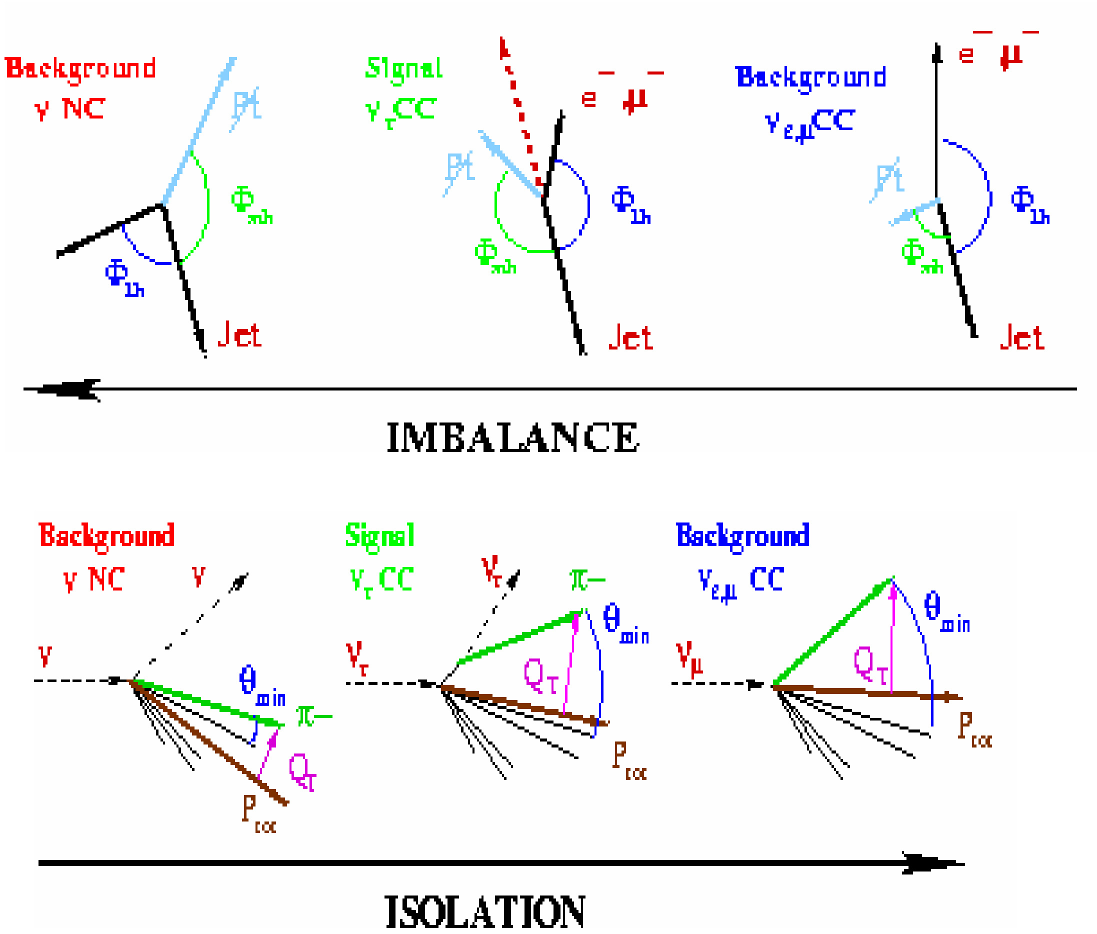


$\nu_e + N \rightarrow e^- + X$



$\overline{\nu}_e + N \rightarrow e^+ + X$





There is not a single miracle cut achieving a 10^5 rejection

The signal is half way between CC and NC background for what concerns the imbalance of the event and the isolation of the tau daughters

Combine the pdf of many variables in order to build likelihood functions for the signal and background

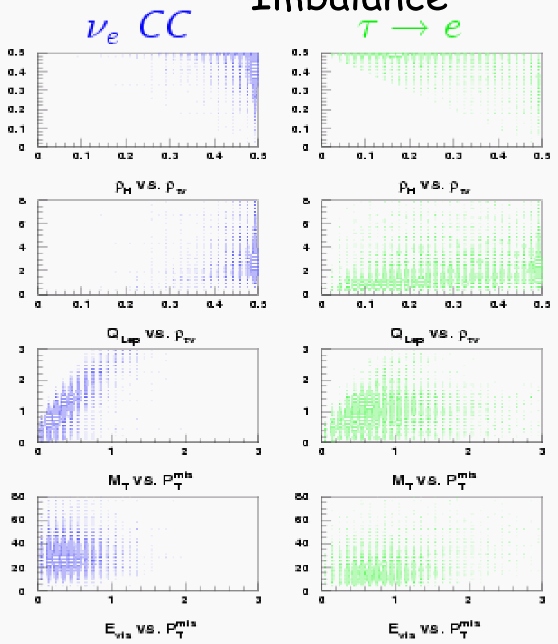
Cut on the likelihood ratio $\ln(L_S/L_B)$

Two likelihood ratios can be used in a correlated way: one to reject NC based on the isolation and one to reject CC based on the imbalance

Corrections to the Monte Carlo predictions are evaluated from the data themselves by looking at the differences between data and MC for the ν_μ CC events, the muonic decay channel is sacrified

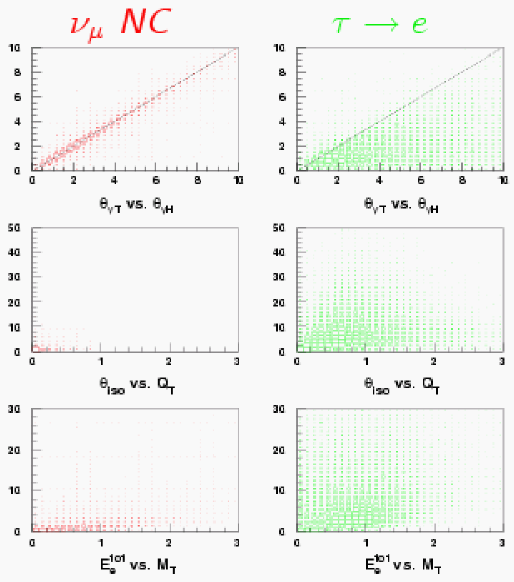
The analysis is performed in a blind way by not looking at the interesting region with good S/B ratio (blind box), data can be looked elswhere, the search is performed as cross-check also for the τ^+ (purely background sample)

Imbalance

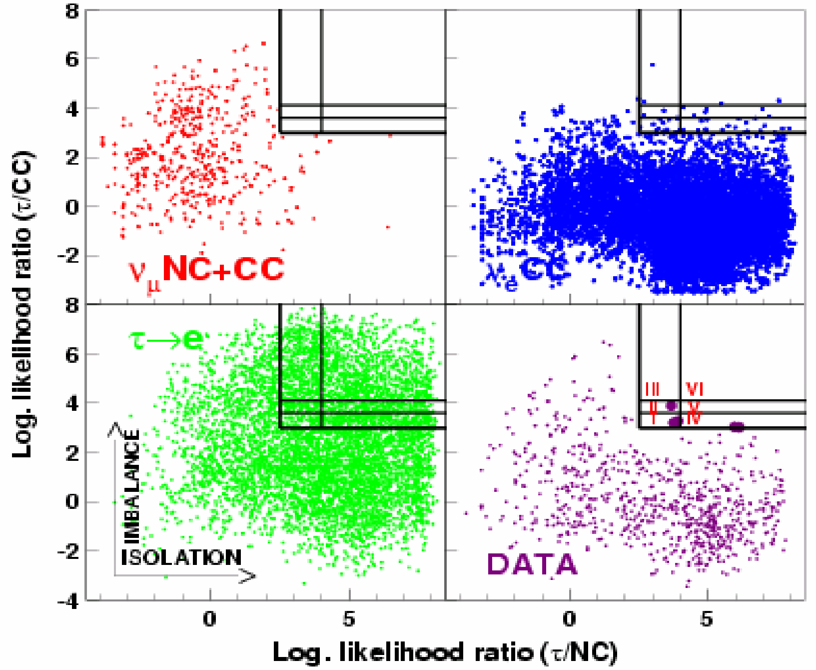


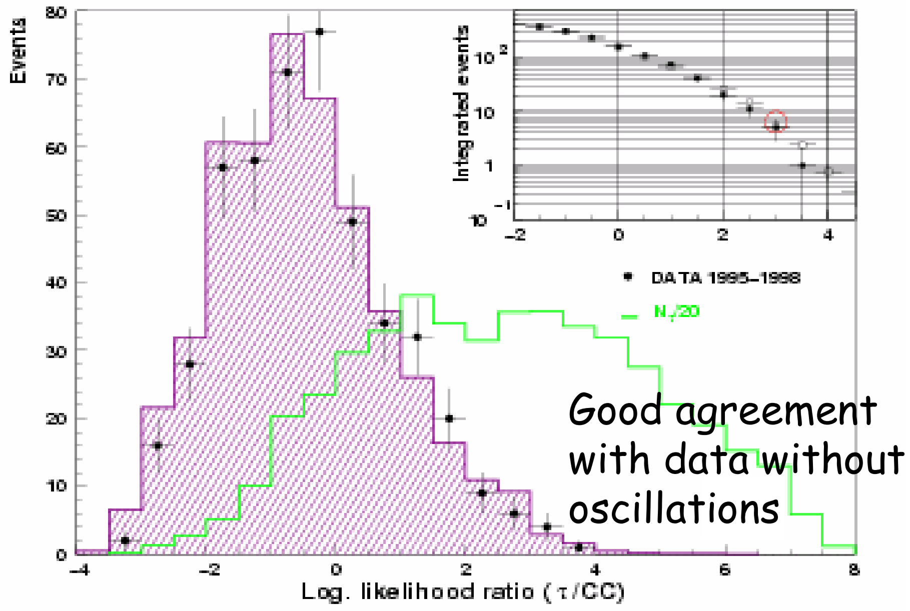
ρ_l	Electron transverse momentum normalized to the sum of transverse momenta $P_T^l + P_T^H + \not{P}_T$;
ρ_h	Hadronic jet transverse momentum normalized to the sum of transverse momenta;
Q_{lep}	Electron momentum component ⊥ to the hadronic jet momentum.
E_{vis}	Total visible energy in the event;

Isolation



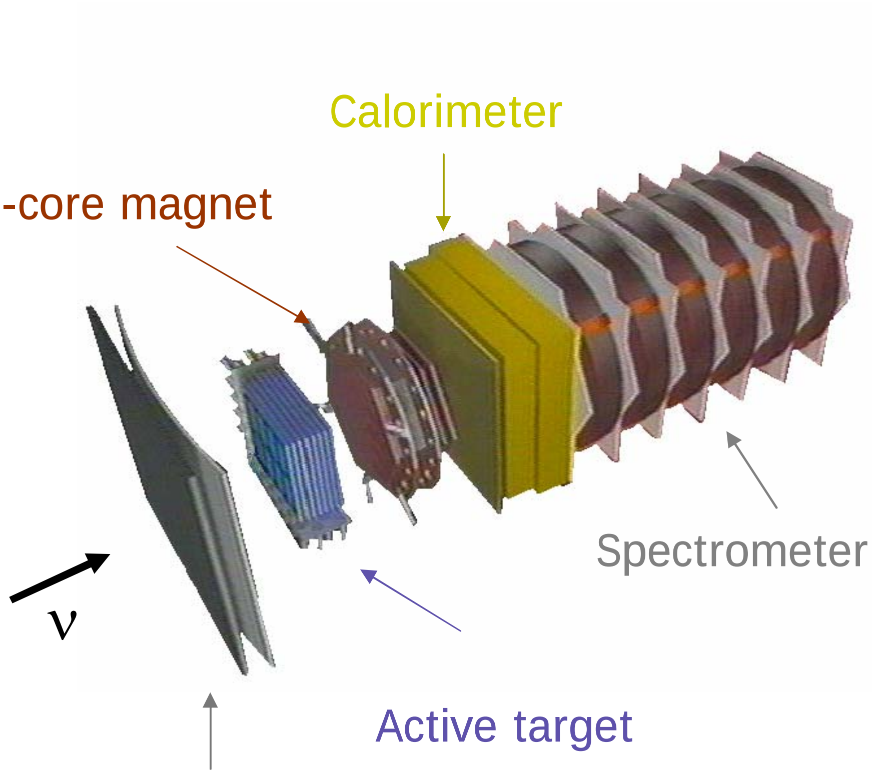
$\theta_{\nu T}$	Angle between the direction of the incident ν and the total momentum of the event;
$\theta_{\nu H}$	Angle between the direction of the incident ν and the hadronic jet momentum;
θ_{iso}	Minimum opening angle between the electron and any other track in the hadronic system;
E_e^{tot}	Electron energy.





Good agreement with data without oscillations

CHORUS



Calorimeter

Air-core magnet

Spectrometer

Veto

Active target

- Nuclear emulsion
- Sci-Fi tracker

Target: 800 kg of nuclear emulsions

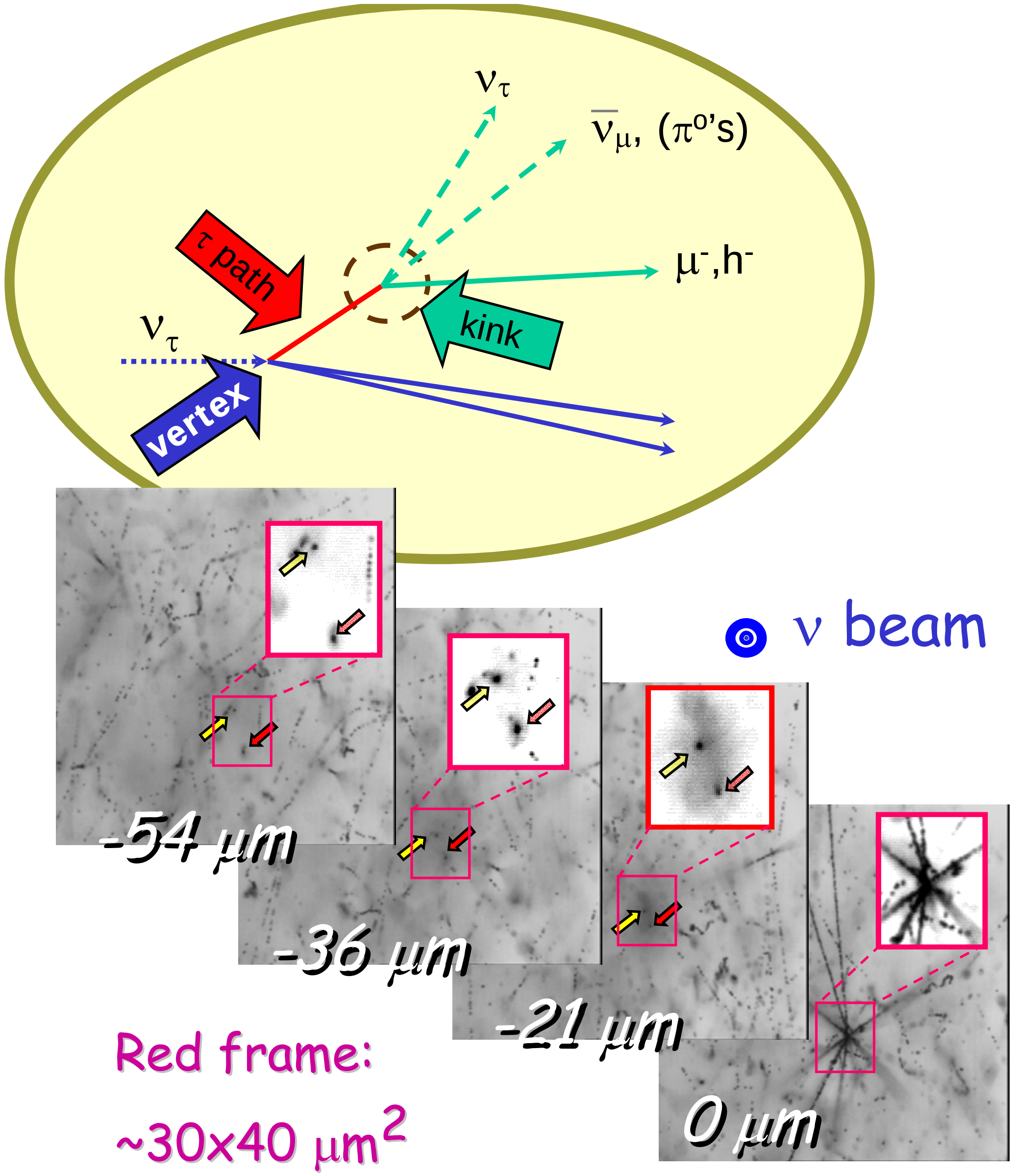
Scintillating fibers tracker: high space resolution for the localization of the neutrino interaction in the emulsions

Magnetic spectrometer and calorimeters: measurements of momentum and energy of secondary particles

Automatic scanning microscopes for the analysis of the data recorded by the nuclear emulsions

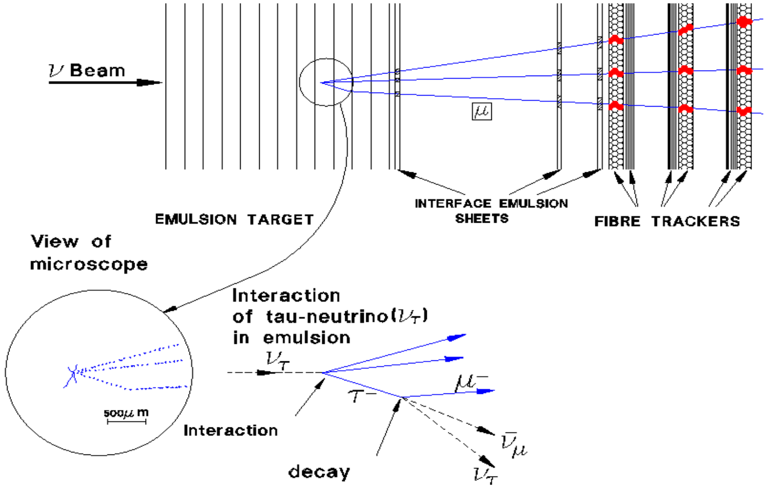
Cleanest channel: muonic tau decay.

Main background: production of charmed particles in CC events with primary lepton missed

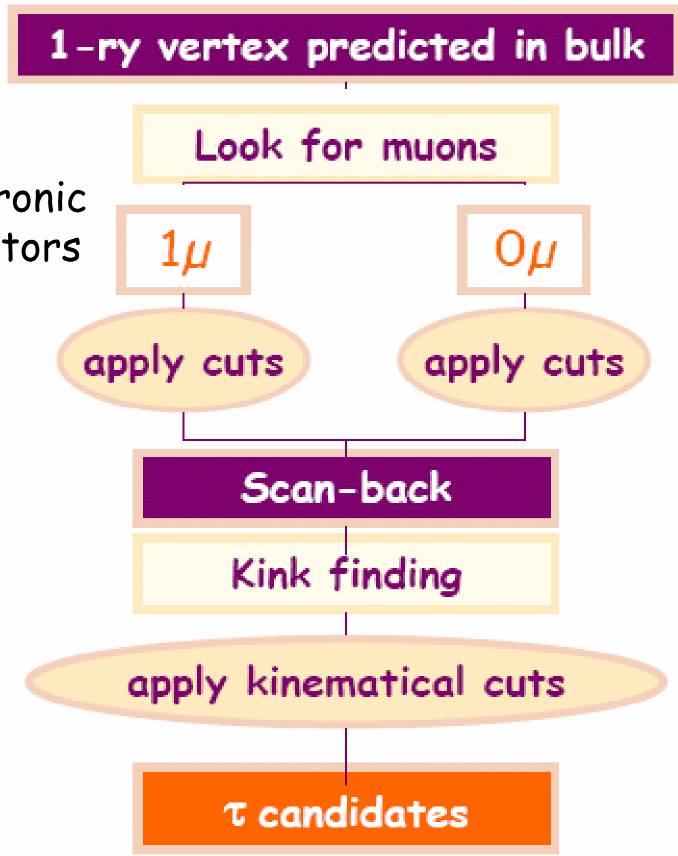


Red frame:

~30x40 μm^2



Electronic detectors



1-ry vertex predicted in bulk

Look for muons

1μ — apply cuts

0μ — apply cuts

Scan-back

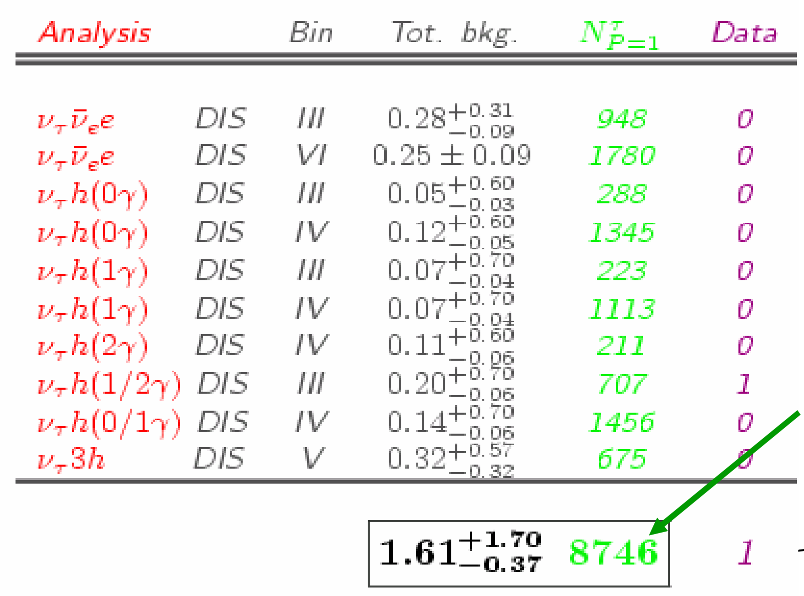
Kink finding

apply kinematical cuts

τ candidates

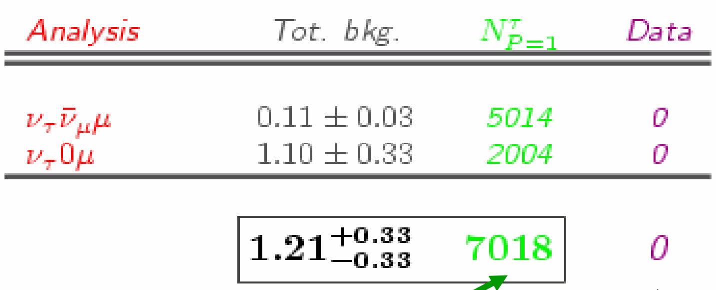
Location efficiency 40% 1μ
27% 0μ

NOMAD (completed)



Analysis		Bin	Tot. bkg.	$N^{\tau}_{P=1}$	Data
$\nu_\tau \bar{\nu}_e e$	DIS	III	$0.28^{+0.31}_{-0.09}$	948	0
$\nu_\tau \bar{\nu}_e e$	DIS	VI	0.25 ± 0.09	1780	0
$\nu_\tau h(0\gamma)$	DIS	III	$0.05^{+0.60}_{-0.03}$	288	0
$\nu_\tau h(0\gamma)$	DIS	IV	$0.12^{+0.60}_{-0.05}$	1345	0
$\nu_\tau h(1\gamma)$	DIS	III	$0.07^{+0.70}_{-0.04}$	223	0
$\nu_\tau h(1\gamma)$	DIS	IV	$0.07^{+0.70}_{-0.04}$	1113	0
$\nu_\tau h(2\gamma)$	DIS	IV	$0.11^{+0.60}_{-0.06}$	211	0
$\nu_\tau h(1/2\gamma)$	DIS	III	$0.20^{+0.70}_{-0.06}$	707	1
$\nu_\tau h(0/1\gamma)$	DIS	IV	$0.14^{+0.70}_{-0.06}$	1456	0
$\nu_\tau 3h$	DIS	V	$0.32^{+0.57}_{-0.32}$	675	0
			$1.61^{+1.70}_{-0.37}$	8746	1

CHORUS (Phase I)



Analysis	Tot. bkg.	$N^{\tau}_{P=1}$	Data
$\nu_\tau \bar{\nu}_\mu \mu$	0.11 ± 0.03	5014	0
$\nu_\tau 0\mu$	1.10 ± 0.33	2004	0
	$1.21^{+0.33}_{-0.33}$	7018	0

Number of signal events expected in case of full mixing

No evidence of $\nu_\mu - \nu_\tau$ oscillations

Chorus Phase II:

New location method (increase by 60K the sample)

Scan a volume of 1.5x1.5x6.3 mm^3 around already located events

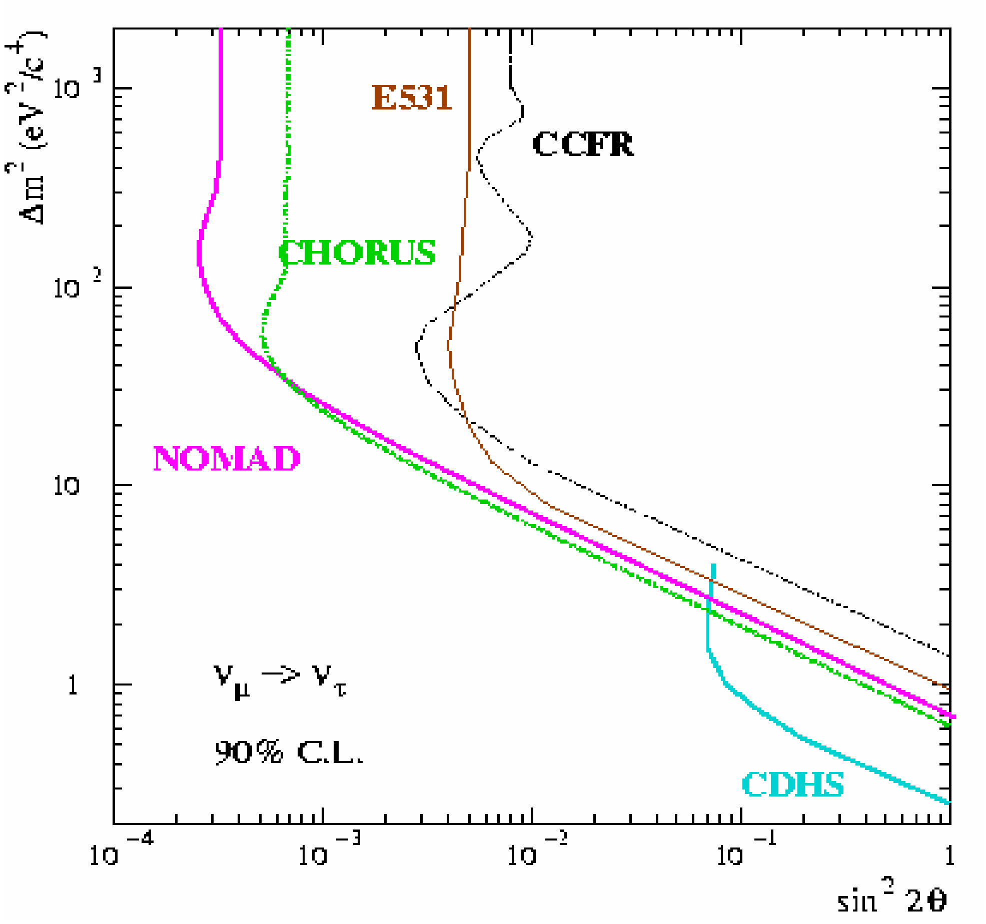
Decay search not limited to just the scan-back track

Offline data analysis

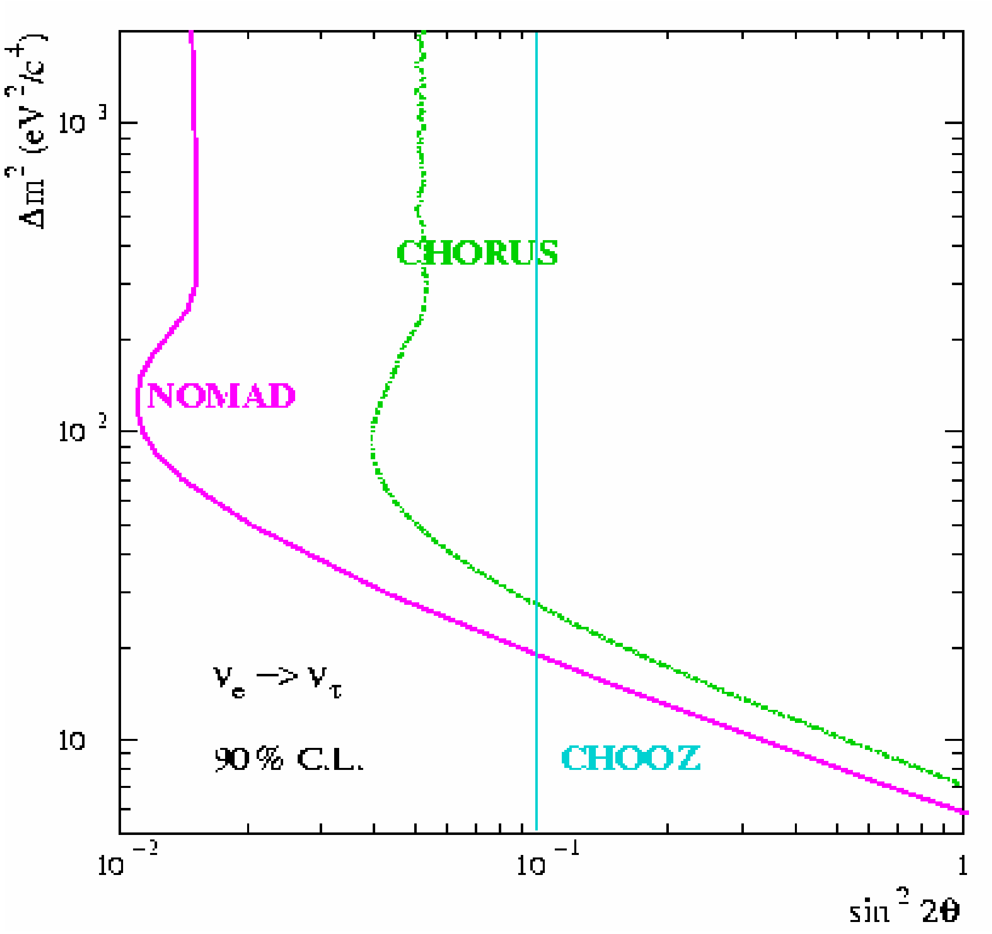
In Progress

Status of short baseline oscillation searches into ν_τ

$\nu_\mu - \nu_\tau$



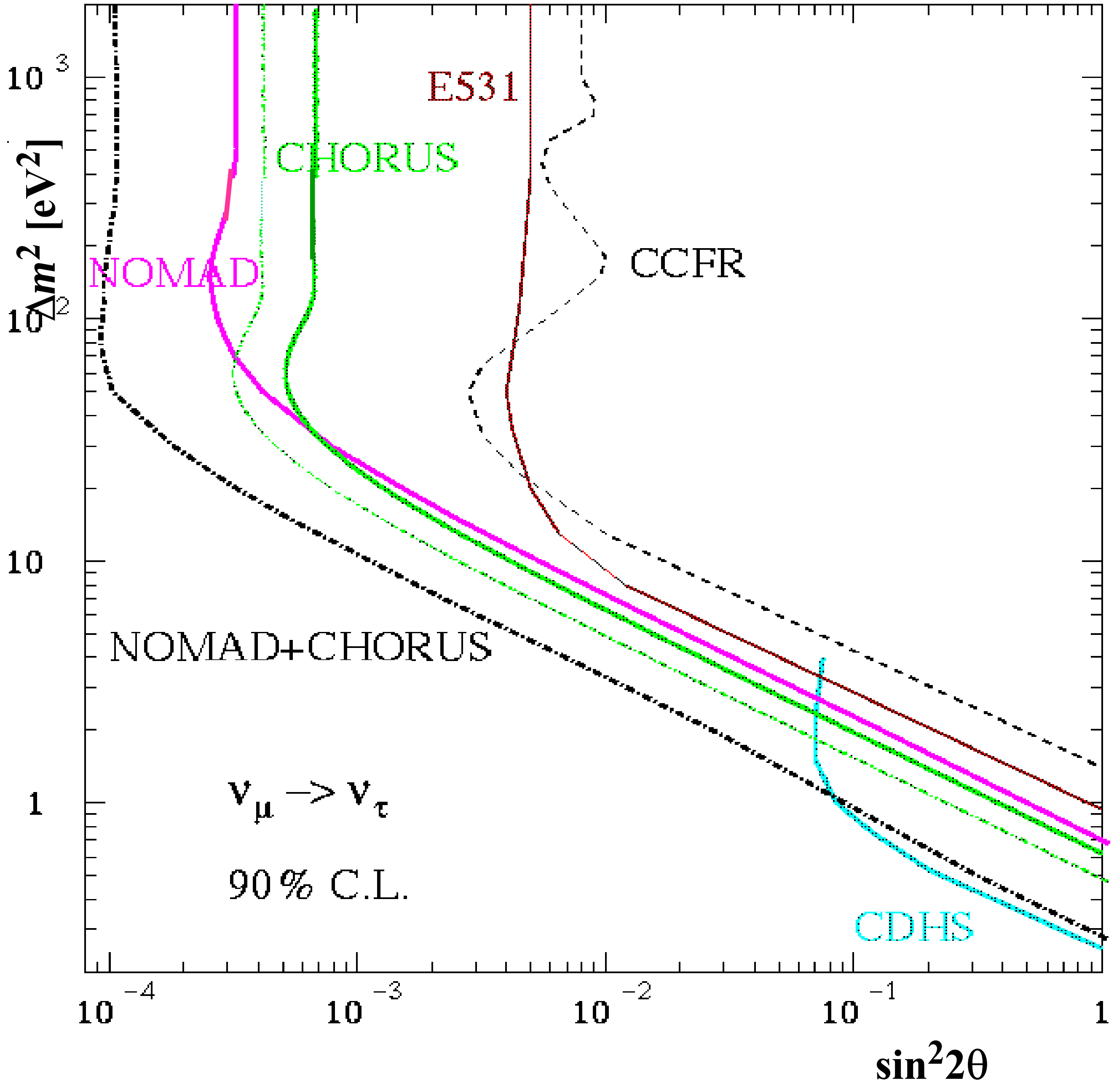
$\nu_e - \nu_\tau$



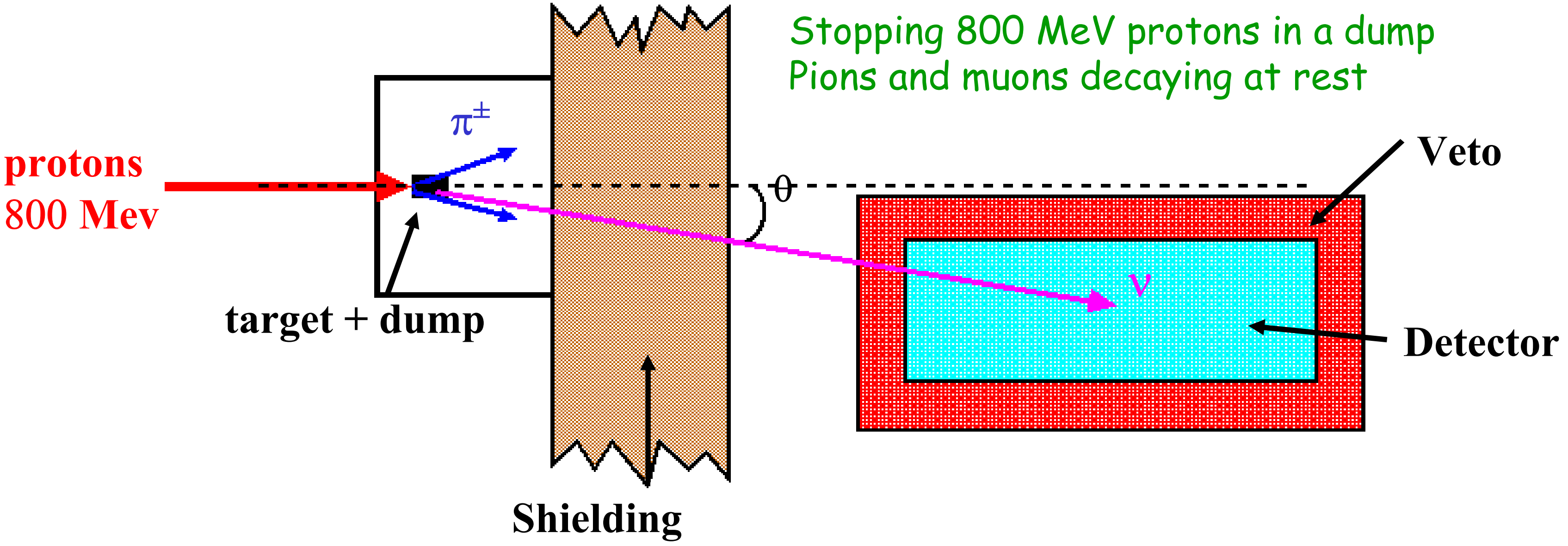
NOMAD data: final - CHORUS phase-II not yet finished

Combined
NOMAD-CHORUS limit

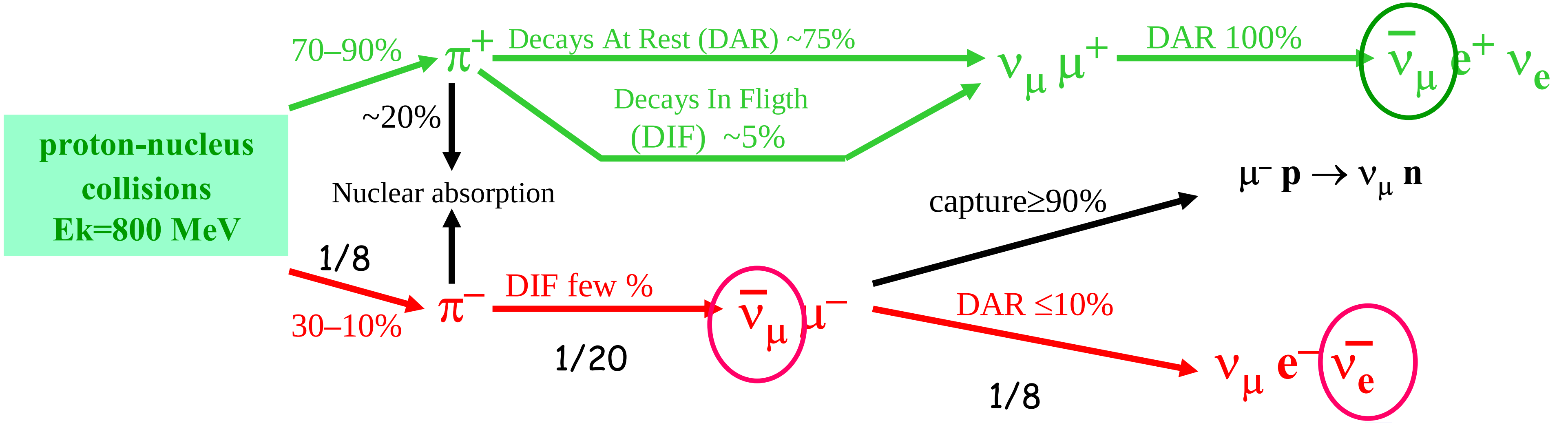
Upper limit on the
oscillation probability for
$\nu_\mu \rightarrow \nu_\tau$: 0.5 10^{-4}



The LSND and Karmen experiments (1993-2001)



Stopping 800 MeV protons in a dump
Pions and muons decaying at rest



proton-nucleus collisions
Ek=800 MeV

70–90% π^+

π^+ Decays At Rest (DAR) ~75% $\nu_\mu \mu^+$

Decays In Fligth (DIF) ~5%

$\nu_\mu \mu^+$ DAR 100% $\bar{\nu}_\mu e^+ \nu_e$

~20%

Nuclear absorption

1/8

30–10% π^-

π^- DIF few % $\bar{\nu}_\mu \mu^-$

1/20

capture≥90% $\mu^- p \to \nu_\mu n$

DAR ≤10% $\nu_\mu e^- \bar{\nu}_e$

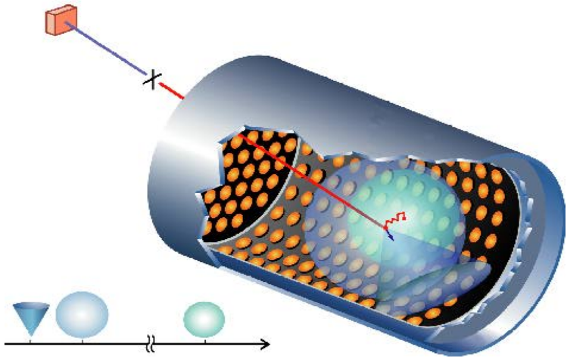
1/8

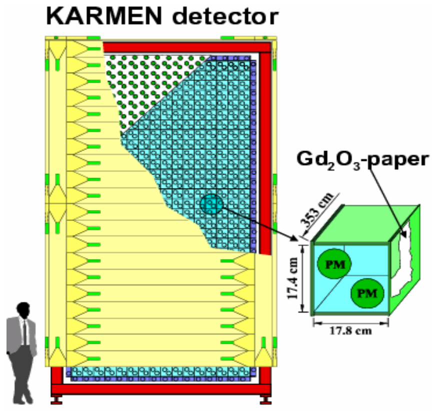
Goal: search for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations

The only source of $\bar{\nu}_e$

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

	LSND	KARMEN
Accelerator	Los Alamos Neutron Science Centre	Neutron Spallation Facility ISIS , R.A.L. (U.K.)
Protons kinetic energy	800 MeV	800 MeV
Current	1000 μA	200 μA
Detector	Tank of liquid scintillator Scintillation and Čerenkov light	512 indipendent cells filled with liquid scintillator
Target mass	167 ton	56 ton
Event localization	PMT time	cell dimensions
Distance from the source	29 m	17 m
Neutrino angle wrt the Incoming protons	11°	90°
Data-taking	1993 – 98	1997 – 2001
Protons on target	4.6×10^{23}	1.5×10^{23}





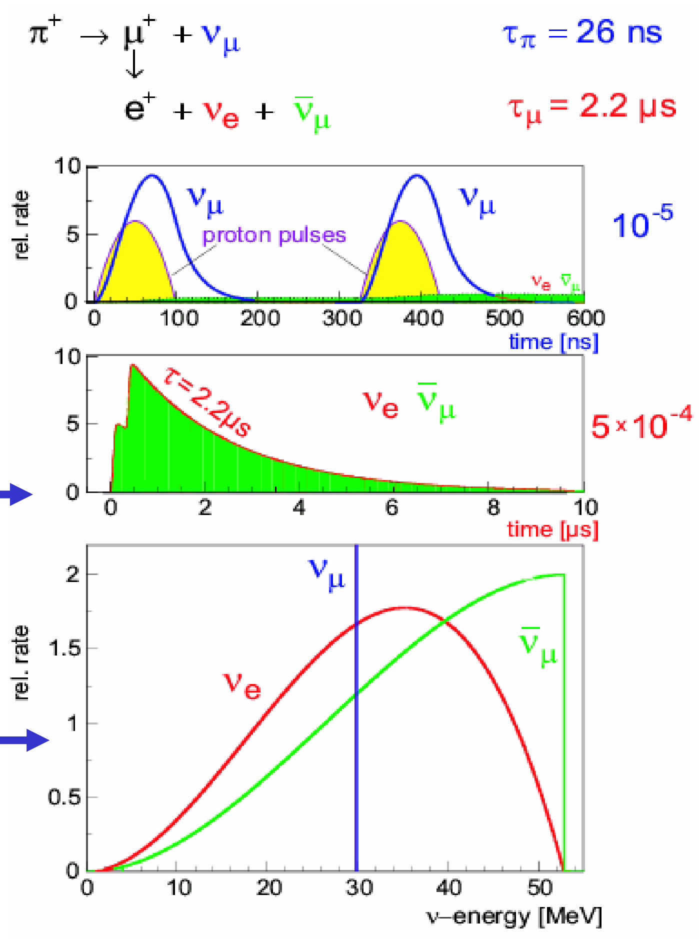
$\bar{\nu}_e$ detection

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

Delayed signal from neutron capture
$np \to \gamma d$ ($E_\gamma = 2.2$ MeV)

KARMEN: paper sheets doped with Gadolinium in between the cells
Increase of neutron capture probability, $\Sigma E_\gamma = 8.1$ MeV

Prompt signal



KARMEN: time structure of the beam
Repetition rate 50 Hz

Oscillation signal $\bar{\nu}_\mu \to \bar{\nu}_e$
Expected within ~10 μs from the beam (handle not exploitable in LSND)

Neutrino energy spectra from DAR (LNSD,KARMEN)

$\pi^+ \to \mu^+ \nu_\mu$
$\hookrightarrow e^+ \nu_\mu \bar{\nu}_e$

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

Signal: Positrons with 20 < *E* < 200 MeV correlated in space and in time with the γ rays of 2.2 MeV expected from the neutron capture:

N(“beam-on”) – N(“beam-off”) = 117. 9 ± 22.4 events

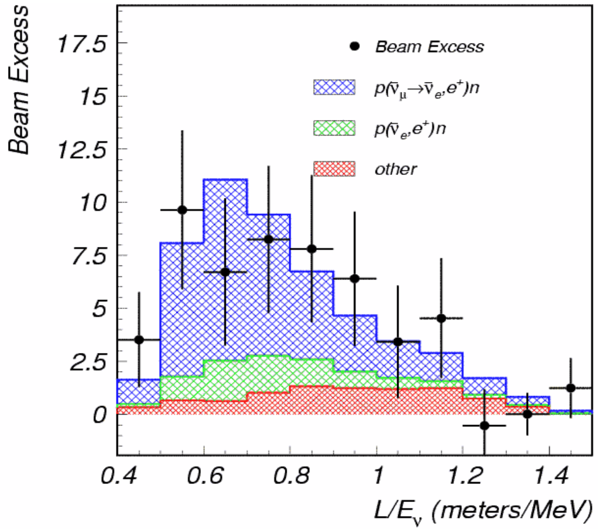
Background due to μ^- DAR = 19.5 ± 3.9

Background from π^- DIF + $(\nu_\mu \mp p \rightarrow \mu^+ + n)$ = 10.5 ± 4.6

Signal $\bar{\nu}_e$ = 87. 9 ± 22.4 ± 6.0 events 3.8 σ effect

(stat.) (syst.)

$P_{osc}(\bar{\nu}_\mu - \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045) \times 10^{-2}$



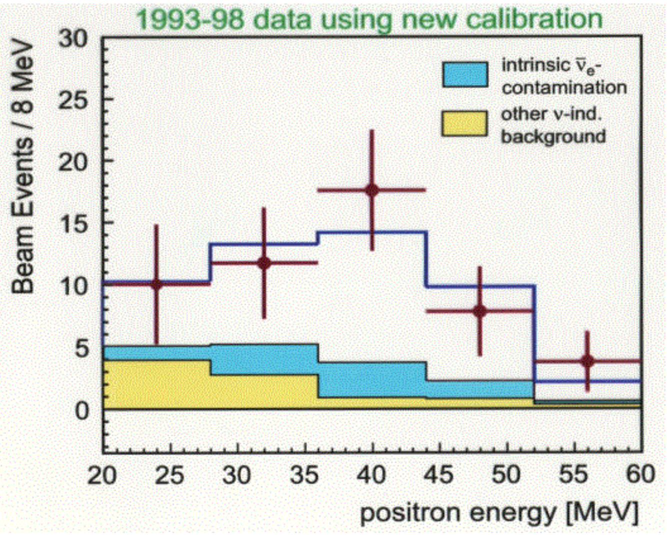
Sample with reduced background:

Positrons with 20 < *E* < 60 MeV, more stringent neutron correlation cut

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

Neutrino background = 16. 9 ± 2.3 events

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



KARMEN final result

correlation in space and time between the prompt and delayed signals,
time correlation of prompt signal with proton beam,

$16 < E(e^+) < 50$ MeV

Data: 15 events after cuts with a total background of 15.8 ± 0. 5 events

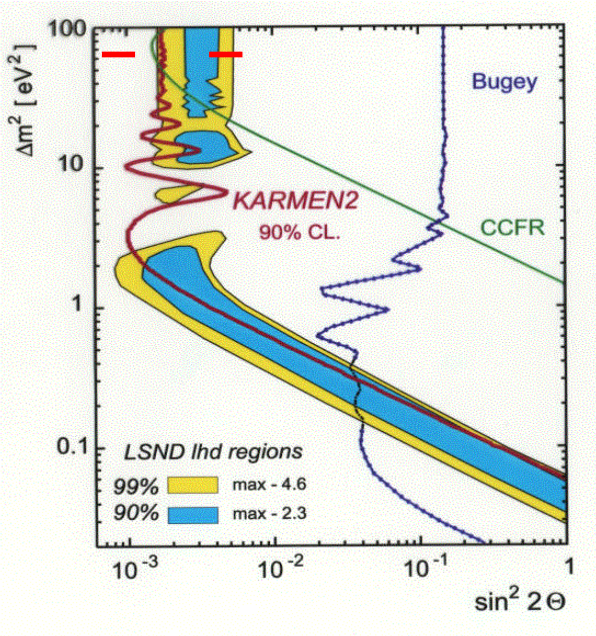
Backgrounds:

Cosmics: 3.9 ± 0.2 events

Random coincidences $\nu_e \to e^-$: 5.1 ± 0.2

Random coincidences among $\nu_e \to e^-$ **and uncorrelated** γ: 4.8 ± 0. 3

Intrinsic contamination of $\bar{\nu}_e$ **in the beam :** 2.0 ± 0. 2



No evidence for oscillations:

$P_{osc}(\bar{\nu}_\mu - \bar{\nu}_e) < 0.085 \times 10^{-2}$ (90% C.L.)

The two experiments are still compatible in a region of the parameters due to the different L (29 m LSND, 17 m KARMEN)

The oscillation signal $\bar{\nu}_\mu - \bar{\nu}_e$ in LSND complicates the global scenario: with 3 neutrinos only two independent Δm^2 are possible:

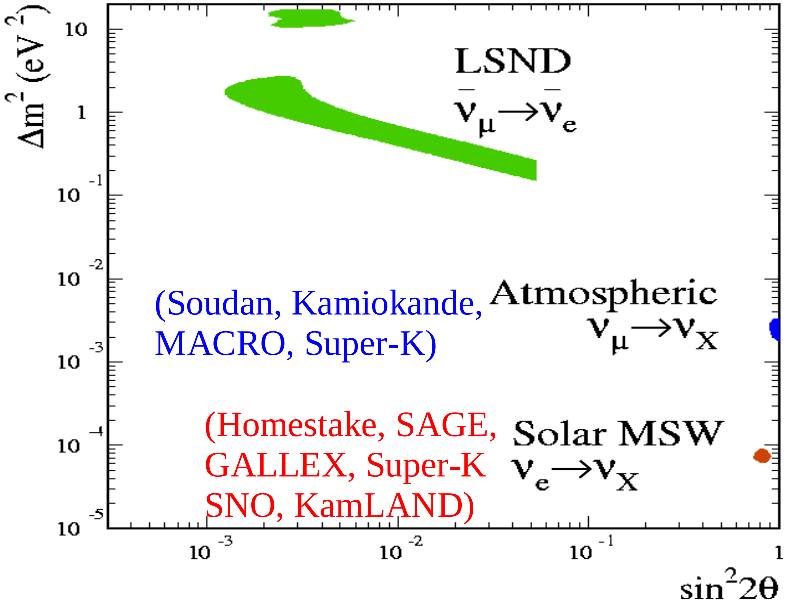
$$\Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 = 0$$

$$\Delta m^2_{solar} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$$

Oscillation signals:

- **Solar:** $\Delta m_{12}^2 \approx 7 \times 10^{-5}$ eV^2
- **Atmosperic:** $\Delta m_{23}^2 \approx 2.5 \times 10^{-3}$ eV^2
- **LSND:** $|\Delta m_{31}^2| = 0.2 — 2$ eV^2

$$|\Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2| = 0.2 — 2 \text{ eV}^2$$



- ➢ At least 4 neutrinos are needed to reconcile all the results, from LEP it is known that the number of active light neutrinos is 3, so the other neutrinos must be sterile
- ➢ Even under this assumption the global fit of oscillation signals is poor:oscillations involving sterile neutrinos are disfavoured for the Atmospheric and Solar neutrinos, more sophisticate mechanisms like CPT violation must be advocated

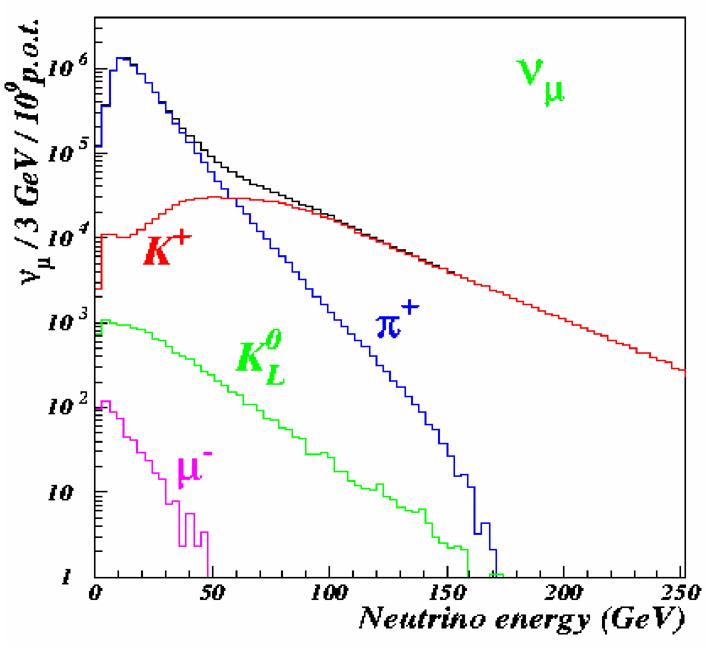
Search for ν_μ–ν_e oscillations in NOMAD (1995-2002)

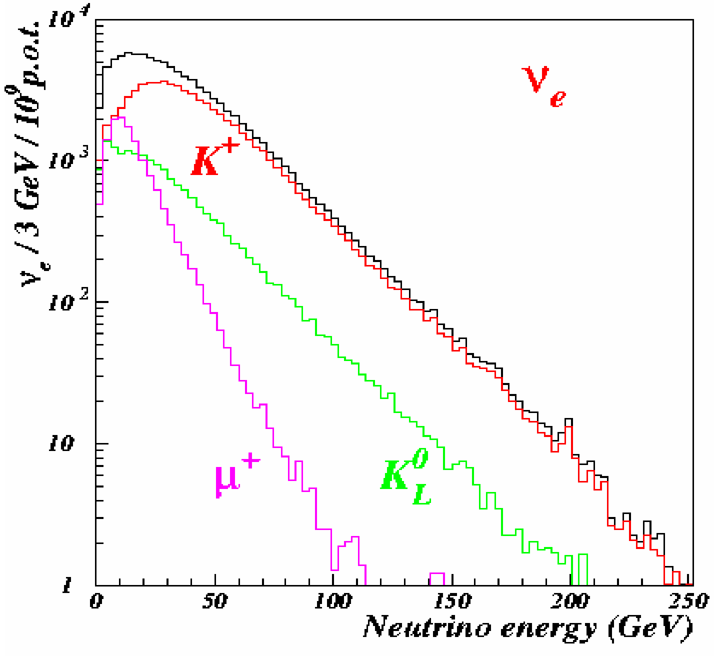
Motivated by LSND result

Due to electron neutrino component in beam (1%) – careful simulation of beam line needed (<5% syst. uncertainty achieved on the ratio among the ν_μ and ν_e spectra)

Exploit powerful electron identification

Study energy spectra (enhanced at low energy) and radial distributions (enhanced in the center)

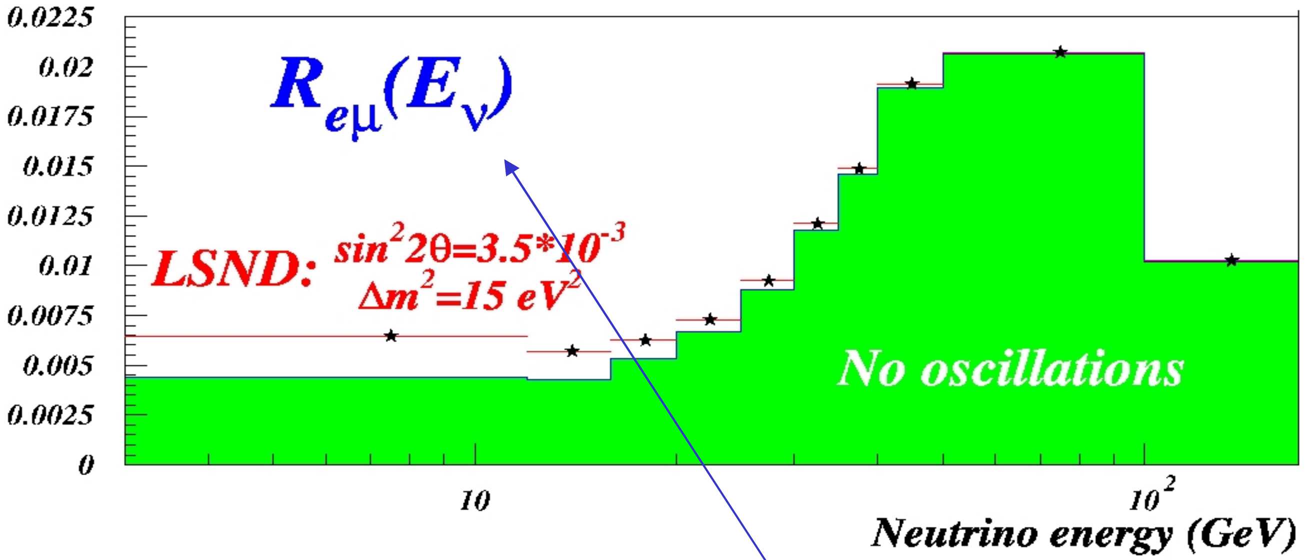




NOMAD can also study ν_μ -> ν_e oscillations:

- Good electron ID
- Low ν_e contamination in the beam (1%)

→ ν_e appearance



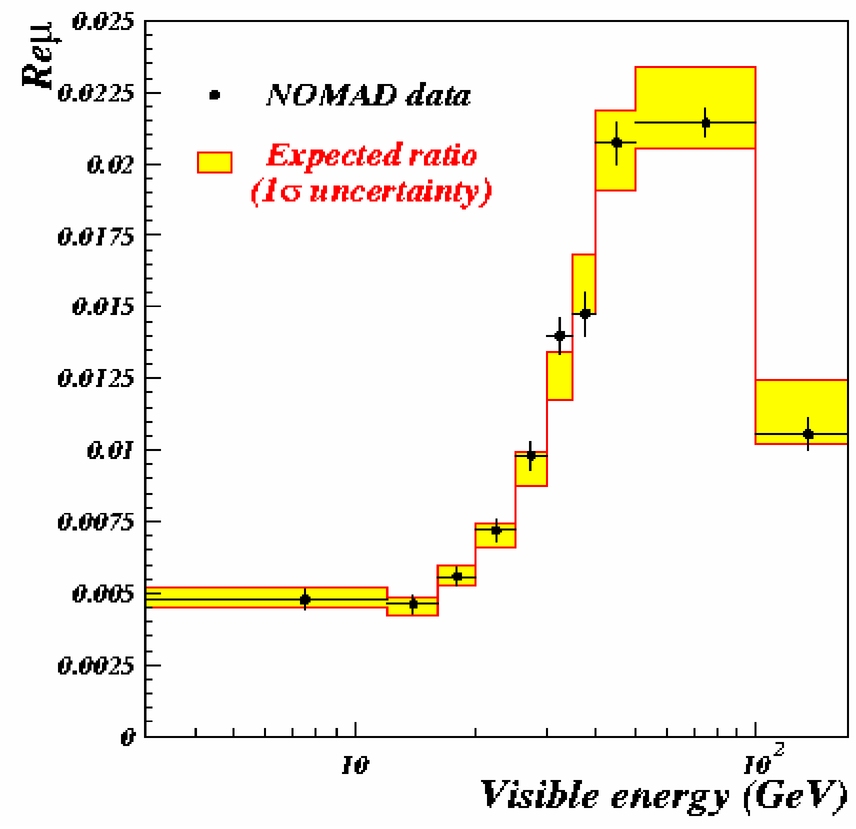
To reduce systematics study the ratio $R_{e\mu}$:

$$R_{e\mu} = \frac{\nu_e CC}{\nu_\mu CC}(E, r)$$

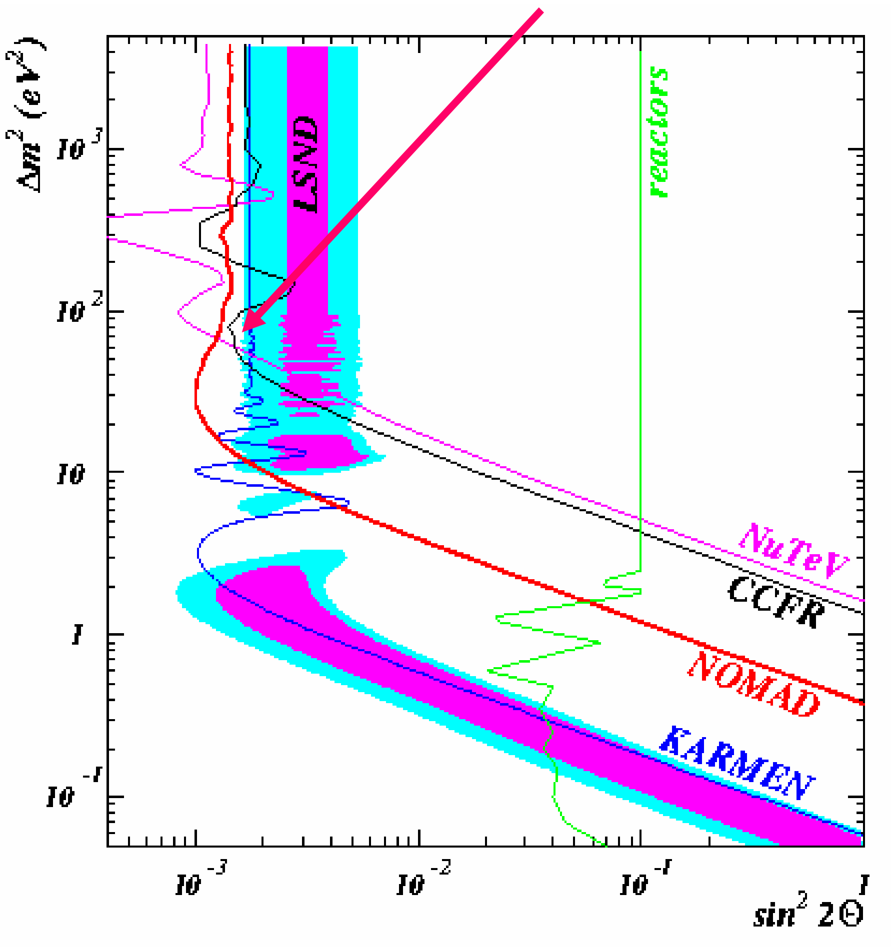
ν_μ -> ν_e at 10^{-3} results in a 10% increase in ν_e flux.

The oscillated ν_e have also a lower energy, narrower radial distribution than the original ν_e

Final results



NOMAD result rules out the LSND allowed region with Δm^2 above 10 eV^2

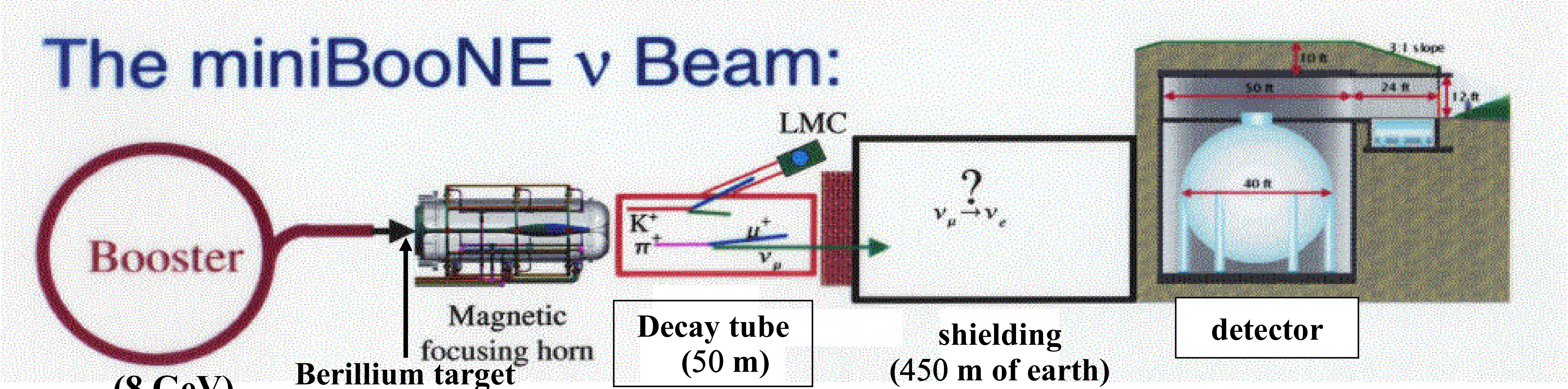


Data are compatible with known sources, No evidence for oscillations

MiniBooNE (Booster Neutrino Experiment at Fermilab)

Goal: confirm LSND claim (with different syst. , energy, statistics)

- **first phase: search for $\nu_\mu - \nu_e$ oscillation;**
- **second phase: search for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations;**
- **in case of LSND confirmation, measurement with a second detector at different *L***



The miniBooNE ν Beam:

Decay tube (50 m)

shielding (450 m of earth)

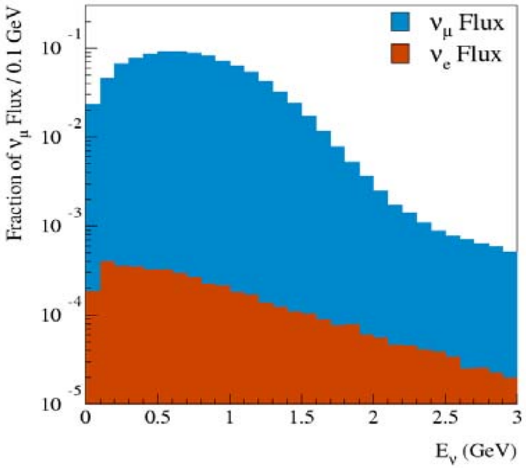
detector

Berillium target

**(8 GeV)
PS at Fermilab**

–L=540 m ~10x LSND

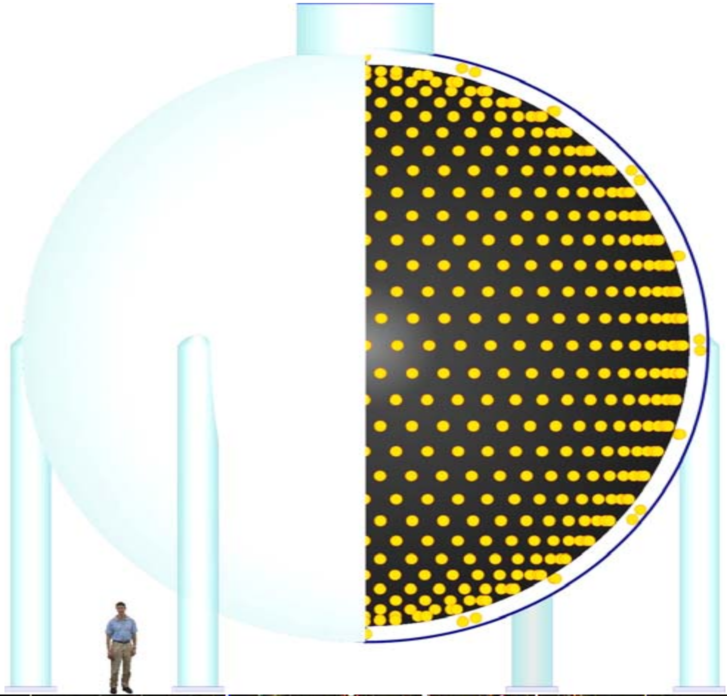
–E~500 MeV ~10x LSND

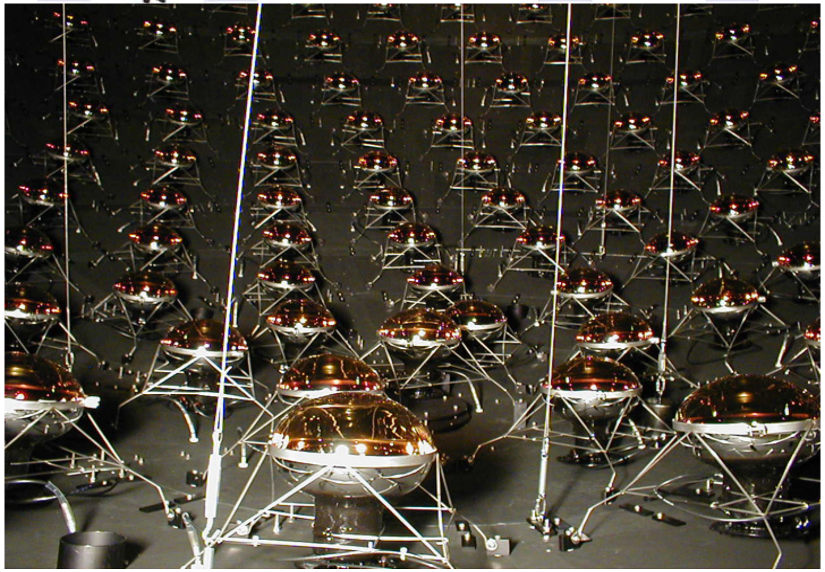


Expected ν fluxes

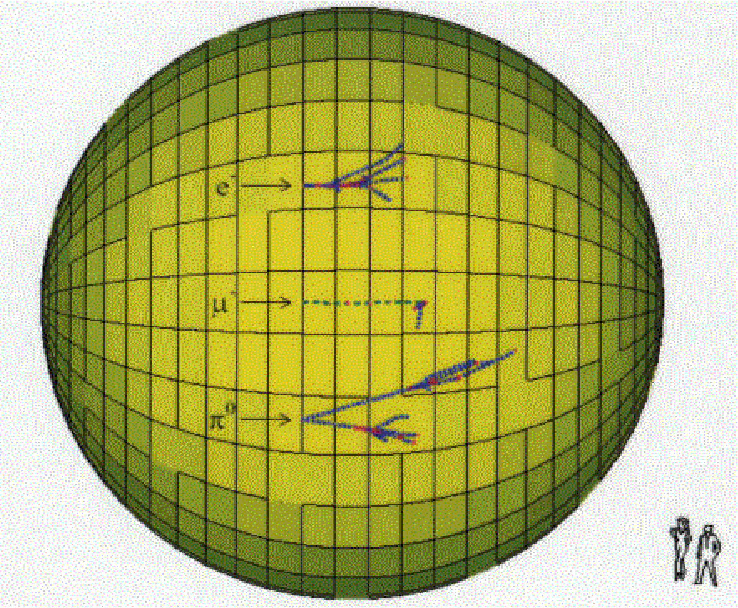
The MiniBooNE detector

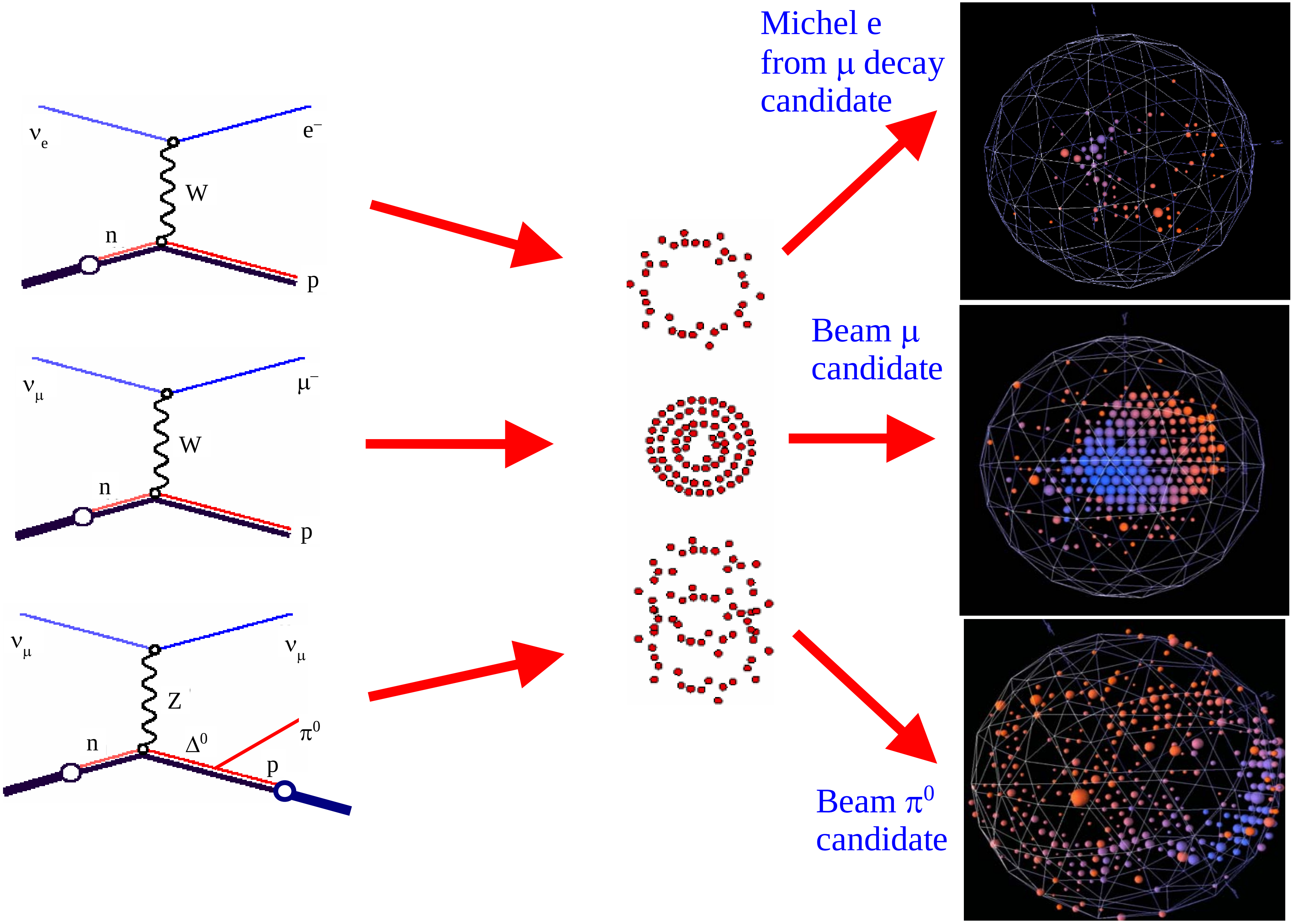
- Sphere 12 m diameter
- 807 ton mineral oil. Čerenkov ligth + delayed scintillation ligth.
- Fiducial mass 445 ton
- Internal volume optically insulated (1280 PM, diam. 20 cm)
- External veto volume (240 PM)





Identification of secondary particles
Based on different behavior of electrons, muons, pions and on the pattern of Čerenkov rings





Michel e
from μ decay
candidate

Beam μ
candidate

Beam π^0
candidate

MiniBooNE results with two years of data-taking

(10^{21} protons on target: 20% already taken, results in 2005,)

~500K events $\nu_\mu C \rightarrow \mu^- X$,

~70K events $\nu C \rightarrow \nu X$

Backgrounds to the $\nu_\mu - \nu_e$ oscillation signal:

1500 $\nu_e C \rightarrow e^- X$ events

(ν_e contamination in the beam)

500 events μ^- identified as electrons

500 events $\pi°$ identified as electrons

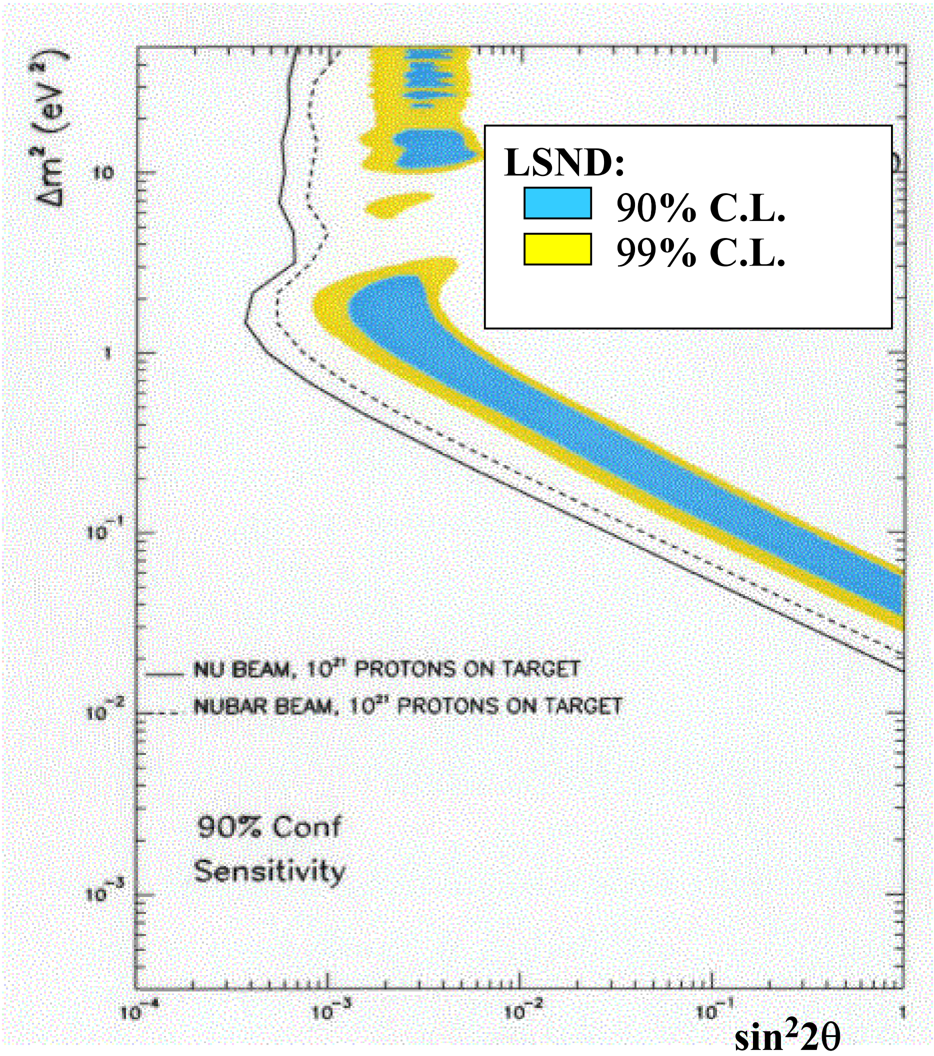
+ 1000 signal events $\nu_e C \rightarrow e^- X$

if the LSND result is correct

The ν_μ and the ν_e contamination in the beam have different energy spectra allowing to better separate the oscillated events from the background

ν_e are coming from muon decays, the muons have the same origin (pion decays) as the ν_μ

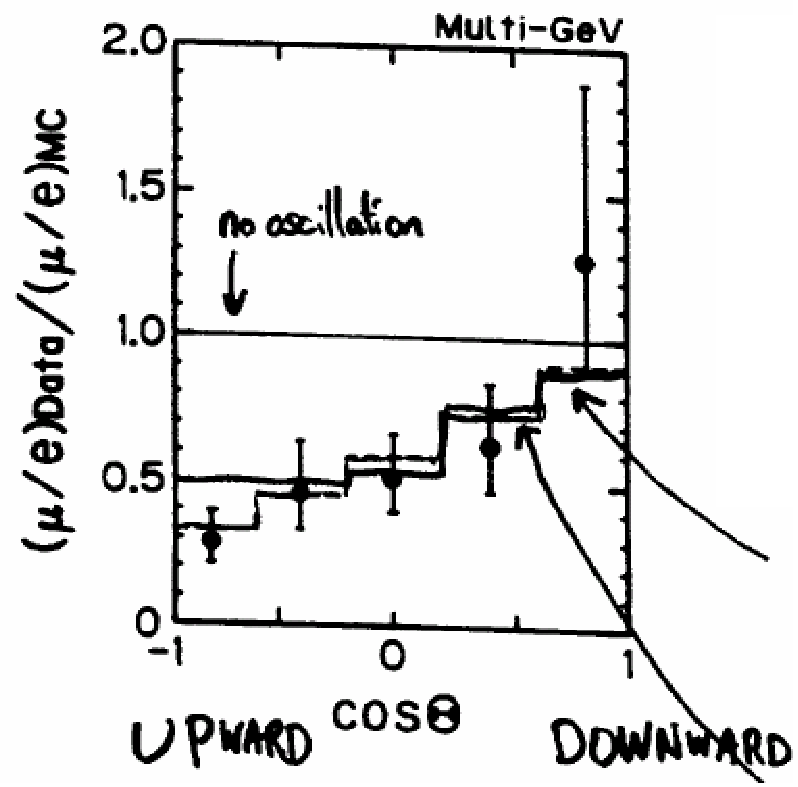
Exclusion plot after two years of data-taking



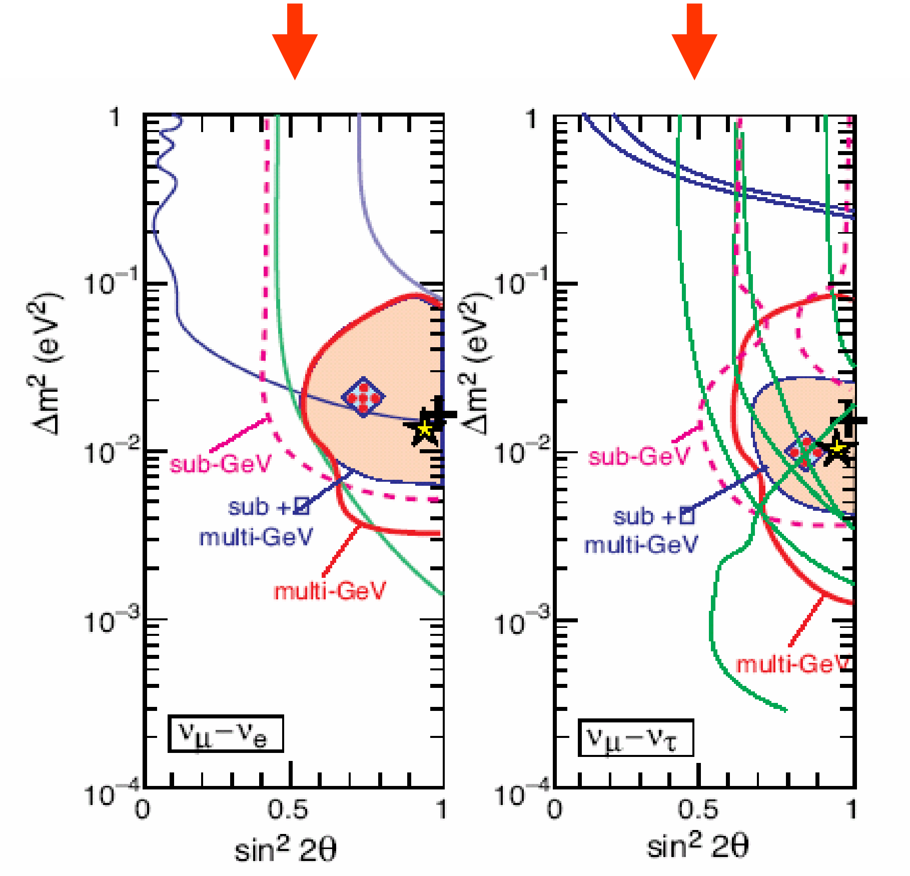
Kamiokande atmospheric neutrinos anomaly 1994 -1997:

$$R = \frac{(\nu_\mu/\nu_e)_{\mathrm{measured}}}{(\nu_\mu/\nu_e)_{\mathrm{expected}}} \sim 0.6$$

Intepretable both in terms of $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations with a **$\Delta m^2 \sim 10^{-2}$ eV^2**



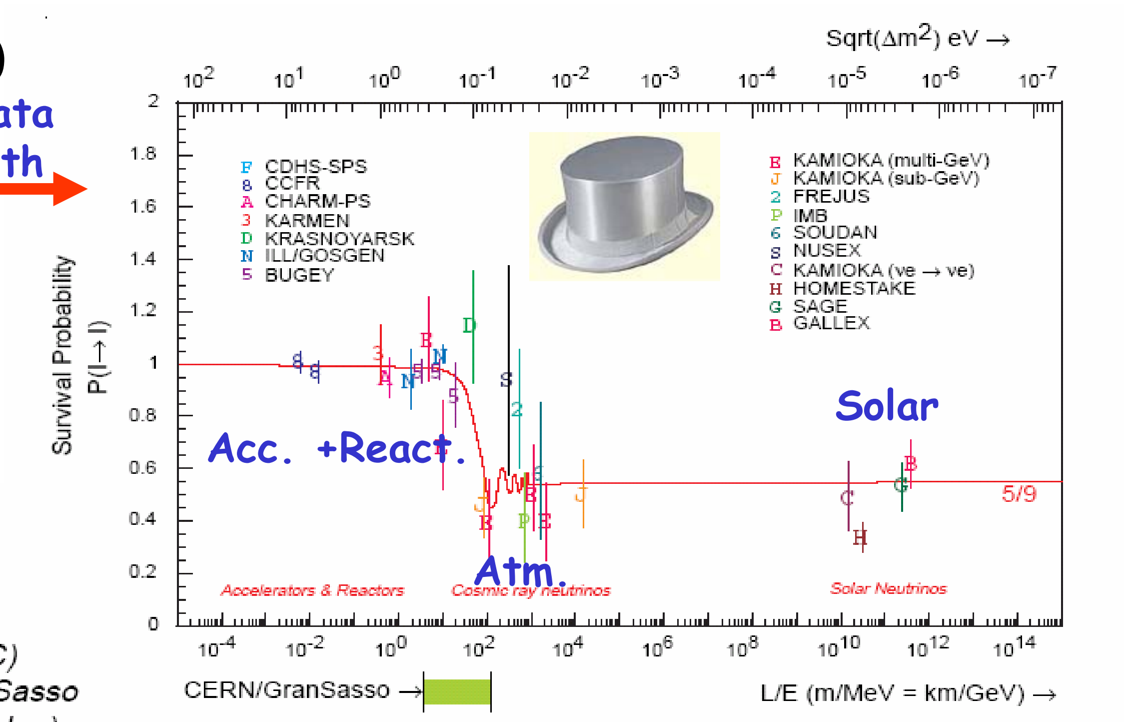
Some first zenith angle dependence

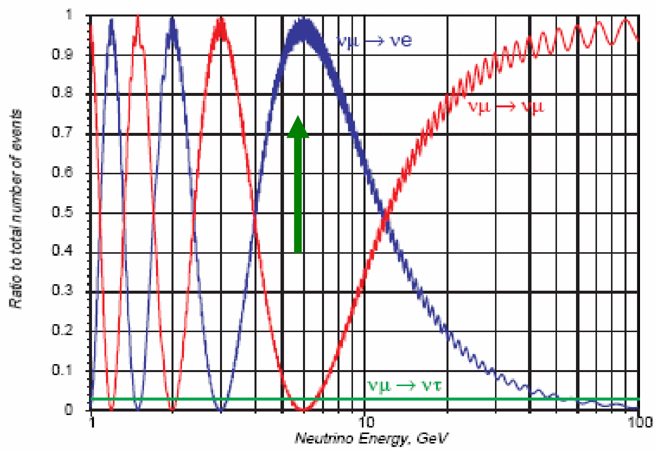


The Perkins plot (PLB 349 1995)

Interpretation of solar + atmospheric data in terms of just one $\nu_\mu \rightarrow \nu_e$ oscillation with $\Delta m^2 \sim 10^{-2}$ eV^2

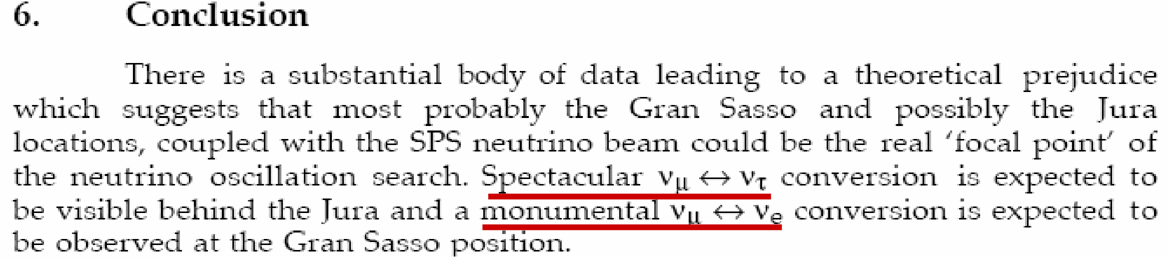
The Acker-Pakvasa 3 flavours model **hep-ph/9611423** included also LSND ($\Delta m^2 \sim 1$ eV^2)





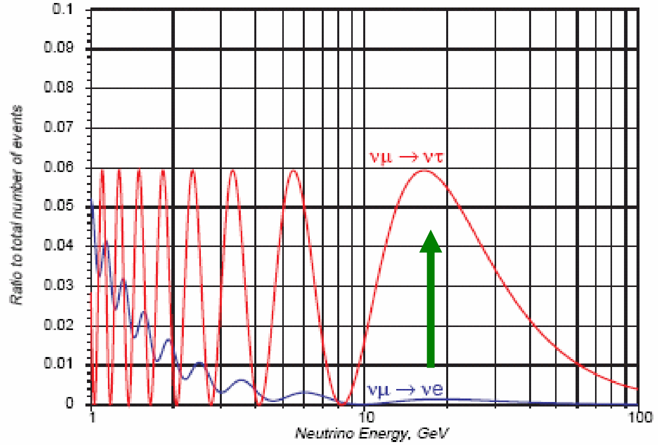
(C)
Gran Sasso
(735 km)

Icarus SPSLC 96/58 P304 19/12/1996



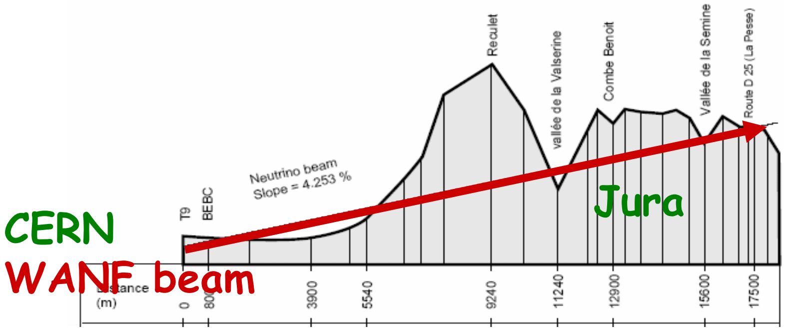
6. Conclusion

There is a substantial body of data leading to a theoretical prejudice which suggests that most probably the Gran Sasso and possibly the Jura locations, coupled with the SPS neutrino beam could be the real 'focal point' of the neutrino oscillation search. Spectacular $\nu_\mu \leftrightarrow \nu_\tau$ conversion is expected to be visible behind the Jura and a monumental $\nu_\mu \leftrightarrow \nu_e$ conversion is expected to be observed at the Gran Sasso position.

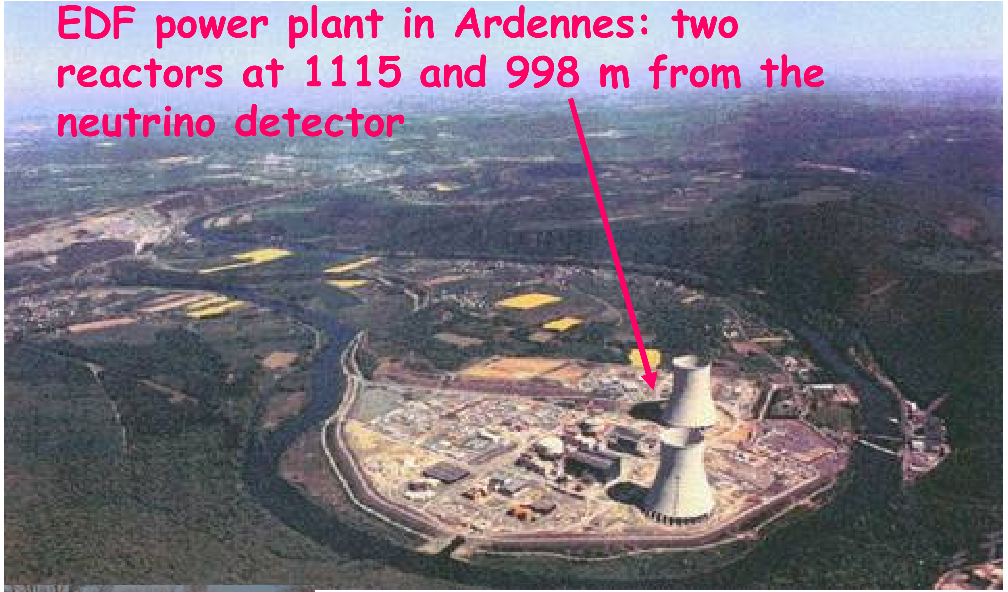


(B)
Behind Jura
(17 km)

Medium-baseline
L/E~1Km/GeV

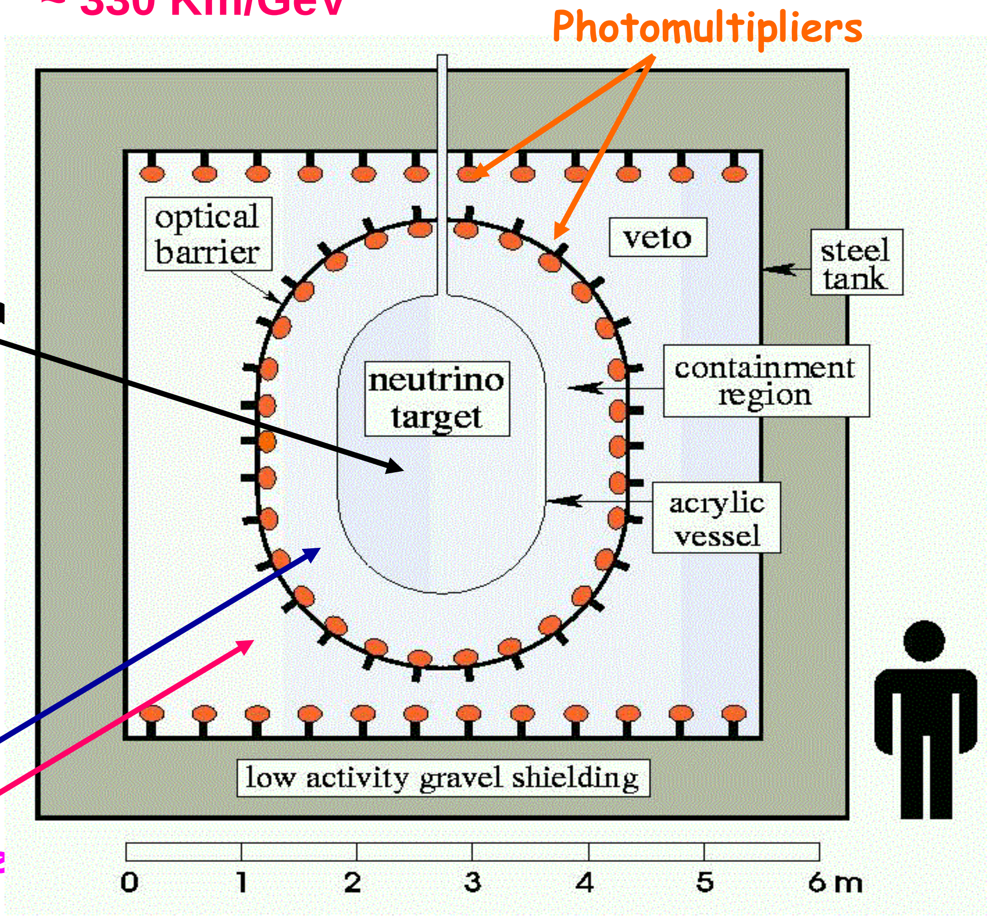


CHOOZ (the first long baseline experiment) 1997-1998


EDF power plant in Ardennes: two reactors at 1115 and 998 m from the neutrino detector

$\bar{\nu}_e \rightarrow \bar{\nu}_e$ (disappearance experiment at nuclear reactor)

P_{th}= 8.5 GW_{th}, 1 detector at L ~ 1 km, overburden equivalent to 300 m H_2O, Reactor neutrino flux known at 2.7 %, L/E ~ 330 Km/GeV



Target: 5 ton liquid scintillator ta with 0.09% Gadolinium

Prompt annihilation signal (γ rays)

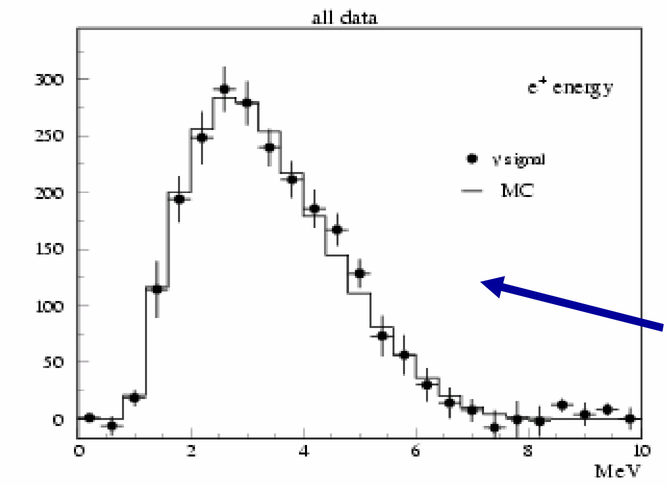
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + Gd \rightarrow \gamma \text{ rays } (E_{tot} \text{ 8.1 MeV})$$

n capture on Gd after thermalization ~30µs

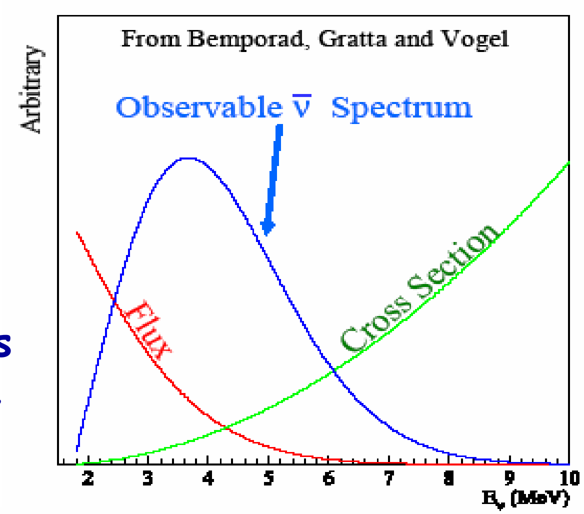
17 ton liquid scint. without Gd (containement of γ rays)

90 ton liquid scint. cosmic rays ve



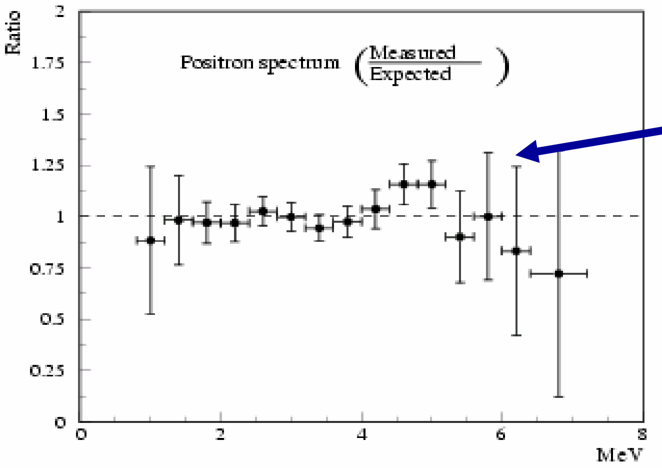
$N(\overline{\nu_e}) \sim 2\ 10^{20}\ s^{-1}/\ GW_{th}$

Signal ~ 25 events/day, background (reactors off) ~ 1.2 events/day



Energy spectrum of the positrons compared with the predicted one (no oscillations)

$E(\overline{\nu_e}) = E(e^+) + 1.8$ MeV



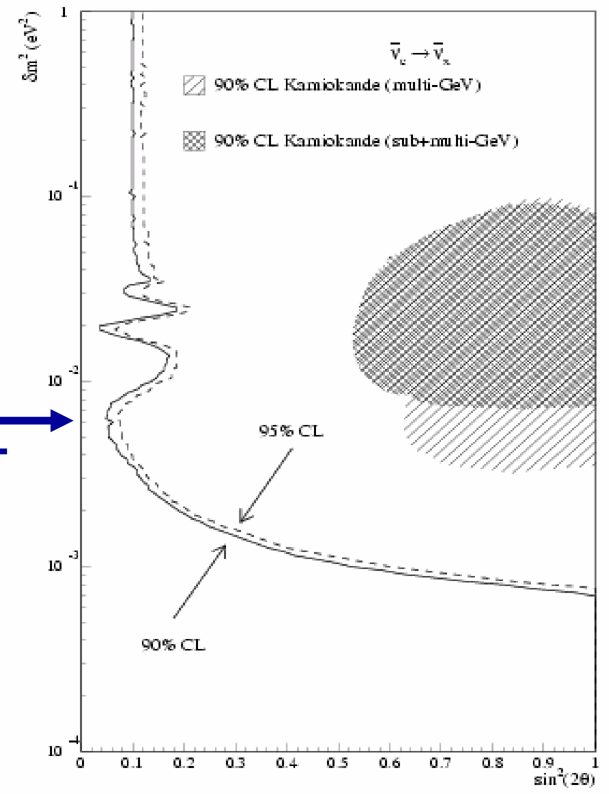
Positron energy (MeV)

Ratio measured/expected

Integrated ratio = $1.01 \pm 0.028 \pm 0.027$

CHOOZ did not observe a significative deficit of ν_e

NO « monumental » $\overline{\nu_e} \to \overline{\nu_\mu}$ conversion

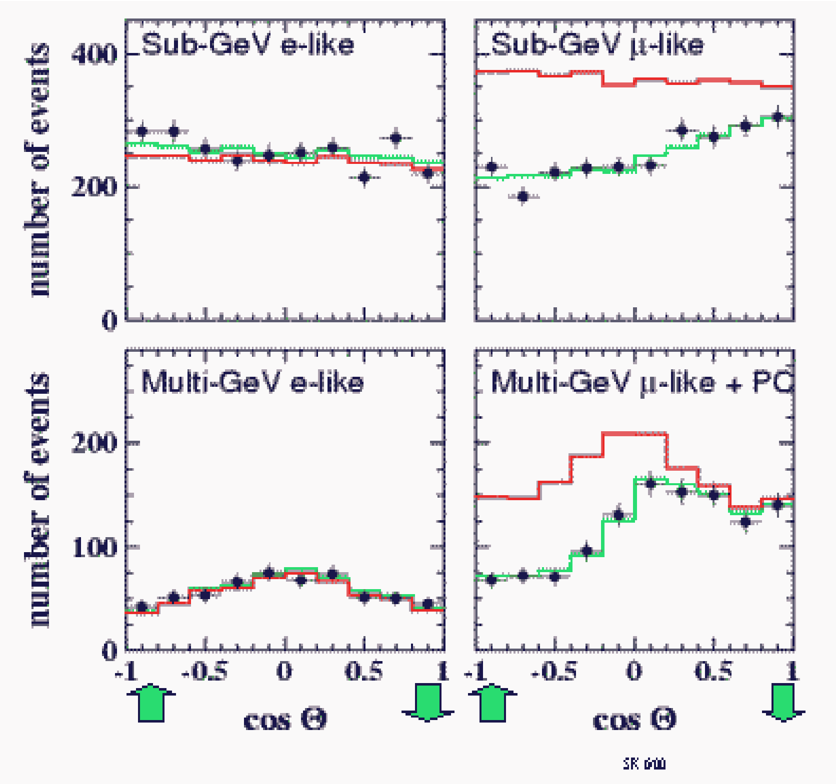


This result was published in 1998 <u>before</u> the Super-Kamiokande results and excluded the atmospheric neutrino anomaly interpretation in terms of $\nu_\mu \to \nu_e$ oscillations

Neutrino 98 Conference in Takayama (June 1998)

(see G. Giacomelli Lectures)

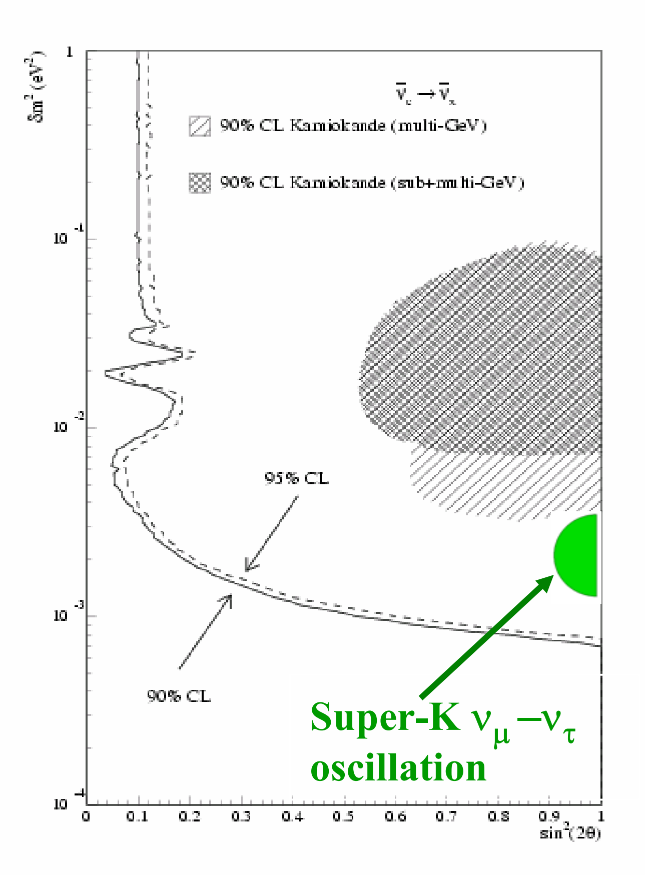
First results from Super-Kamiokande on atmospheric neutrinos, evidence of a zenith angle dependence of ν_μ disappearance, ν_e in agreement with expectations



SK: Atmospheric neutrinos anomaly

intepretable in terms of $\nu_\mu \to \nu_\tau$ oscillations with a $\Delta m^2 \sim$ a few 10^{-3} eV^2

CHOOZ: no $\nu_\mu \to \nu_e$ oscillations, $\Theta_{13} < 11°$



Neutrino oscillations start to be taken seriously as explanatic of the atmospheric neutrinos anomaly

Opens a campaign for a new generation of long baseline experiments to provide a final proof 2nd Lecture