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26 July - 6 August 2004

## Short and Long Baseline Neutrino Experiments

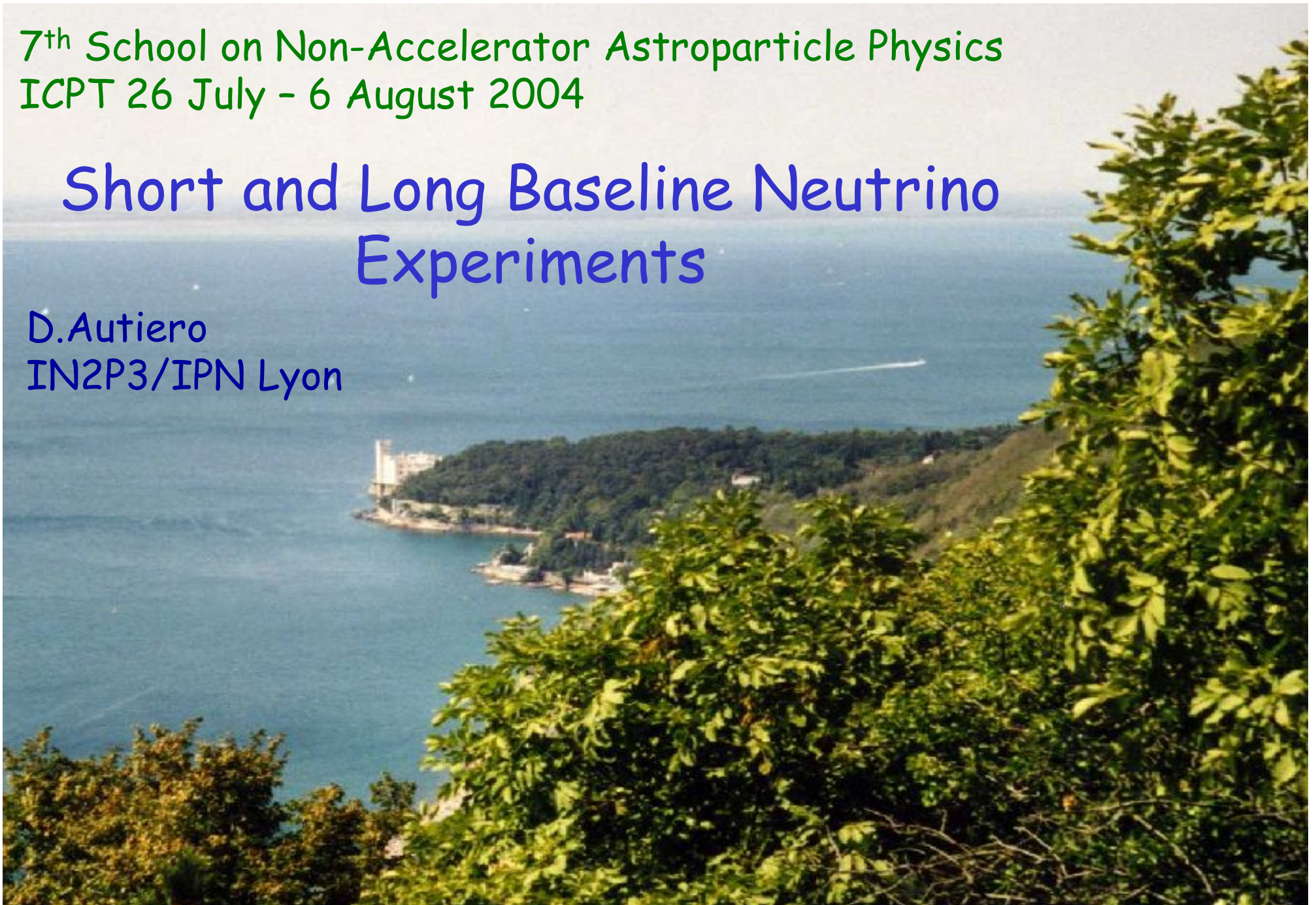
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7<sup>th</sup> School on Non-Accelerator Astroparticle Physics  
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# Short and Long Baseline Neutrino Experiments

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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  $\nu_e, \nu_\mu, \nu_\tau$  are not mass eigenstates but linear superpositions of the mass eigenstates  $\nu_1, \nu_2, \nu_3$  with eigenvalues  $m_1, m_2, m_3$ :

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

$\alpha = e, \mu, \tau$  (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  $\theta_{12}, \theta_{23}, \theta_{13}$  and one Dirac-like CP phase  $\delta$  (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  $\nu$  oscillations
Solar  $\nu$  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 eigenstate  $\nu_\alpha$  produced at  $t = 0$ :

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

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  $\theta$  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  $\nu_\beta$  at the instant  $t$  if  $\nu(0) = \nu_\alpha$ :

$$P_{\alpha\beta}(t) = \left| \langle \nu_\beta | \nu(t) \rangle \right|^2 = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 t}{4E}\right) \quad \hbar = c = 1$$

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

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

$\theta$  is related to the amplitude of the oscillation  
 $\Delta m^2$  is related to the wavelength

For  $m \ll p$ , and assuming propagation in vacuum:

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

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

In more empirical units:

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

$\Delta m^2$  [eV<sup>2</sup>]

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

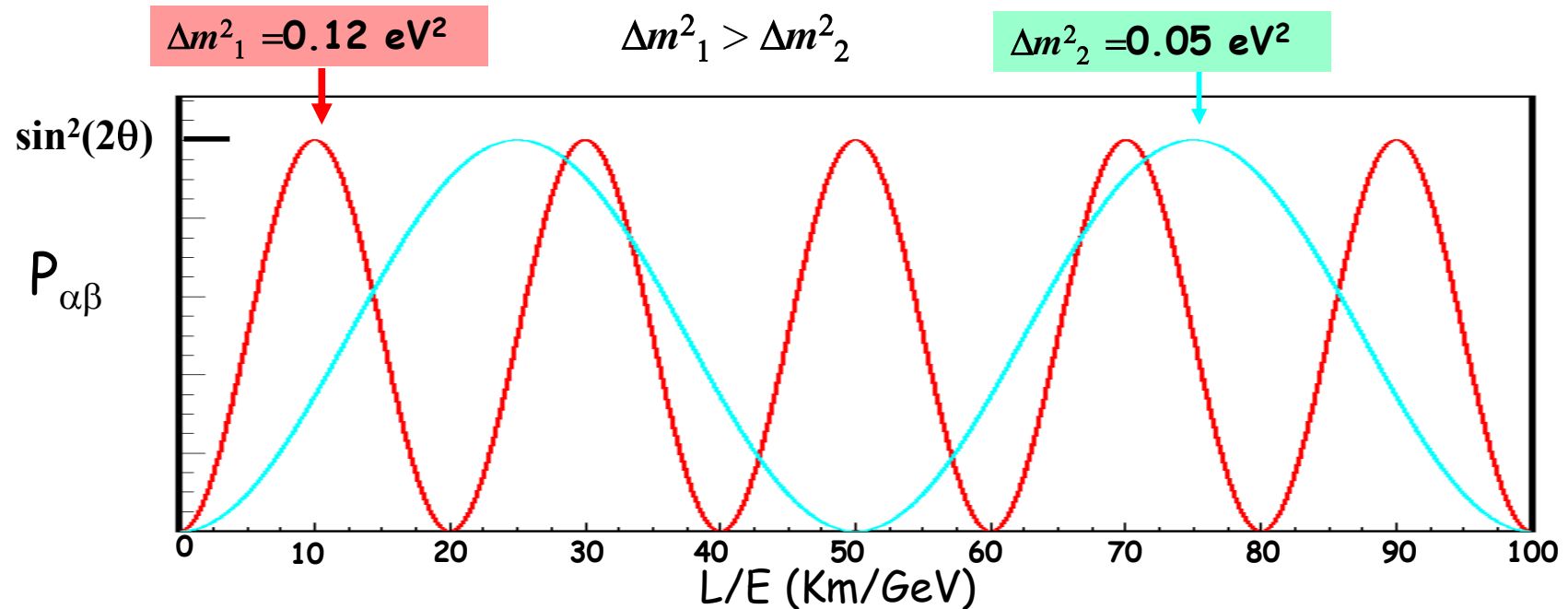
$E$  [GeV] (neutrino energy)

Given  $\Delta m^2$  the experimental quantity for the study of neutrino oscillations is the ratio  $L/E$  [km/GeV]: first oscillation maximum at  $L/E \sim 1.24 / \Delta m^2$

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

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

Oscillation wavelength



For very large  $\Delta m^2$  the oscillations become very fast and average over the dimensions of the source and of the detector:

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

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

**Short Baseline experiments:** sensitive to large  $\Delta m^2$  ( $> 1 \text{ eV}^2$ )

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

Reactors:      $L > 0.3 \text{ Km}$ ,  $E \sim 3 \text{ MeV}$

Accelerators:      $L > 100 \text{ Km}$ ,  $E \sim 1 \text{ GeV}$

# Most important neutrino interactions with matter in the accelerators energy range

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

Quasi elastic scattering

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

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

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

$$\sigma_{\text{QE}}(\nu_\mu + n) \sim 0.9 \times 10^{-38} \text{ cm}^2 \text{ (far from threshold)}$$

Deep inelastic scattering (DIS)

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

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

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

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

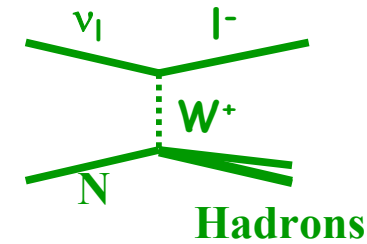
## (NC) Neutral current interactions ( $Z^0$ exchange)

Elastic and DIS, similar for the 3 neutrinos

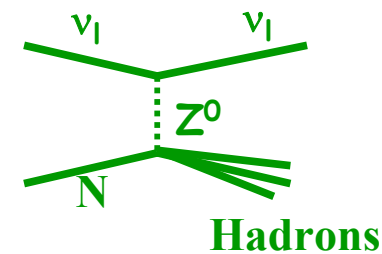
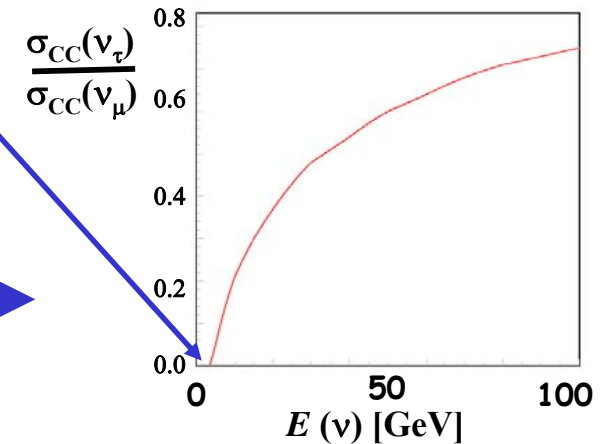
$$\nu + N \rightarrow \nu + \text{hadrons} \quad \bar{\nu} + N \rightarrow \bar{\nu} + \text{hadrons}$$

$$\sigma_{\text{NC}}(\nu) \approx 0.3 \sigma_{\text{CC}}(\nu)$$

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



$\tau$  mass kinematic suppression





# 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:

$E_\nu \sim$  a few MeV, below threshold for  $\mu$  or  $\tau$  production

Experiments at Accelerators studying  $\nu_\mu \rightarrow \nu_\tau$  oscillations with low energy beams (MINOS, K2K) below  $\tau$  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  $\nu_\beta$  not produced at the source (beam of  $\nu_\alpha$ ) at a certain distance  $L$  from the source:

Typical examples:

$\nu_e$  Appearance at accelerators:

Detection of the reaction  $\nu_e + N \rightarrow e^- + \text{hadrons}$  with a  $\nu_\mu$  beam

$\nu_\tau$  Appearance at accelerators:

Detection of the reaction  $\nu_e + N \rightarrow e^- + \text{hadrons}$  with a  $\nu_\mu$  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.

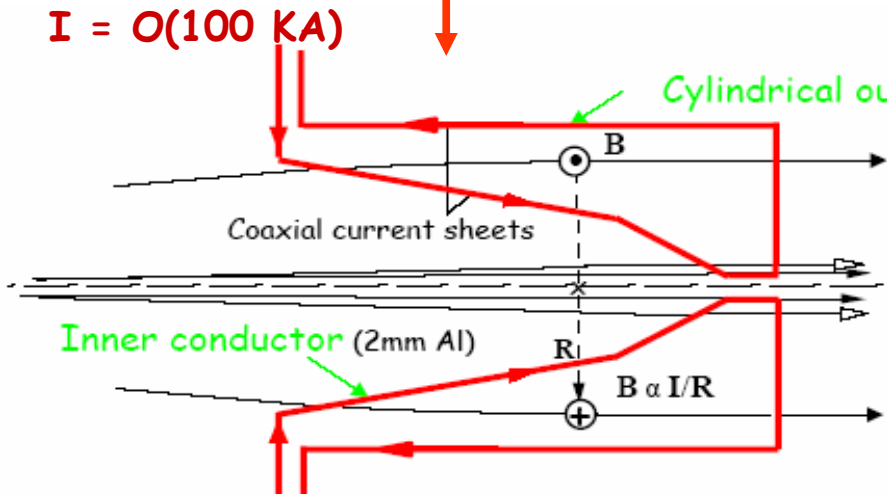
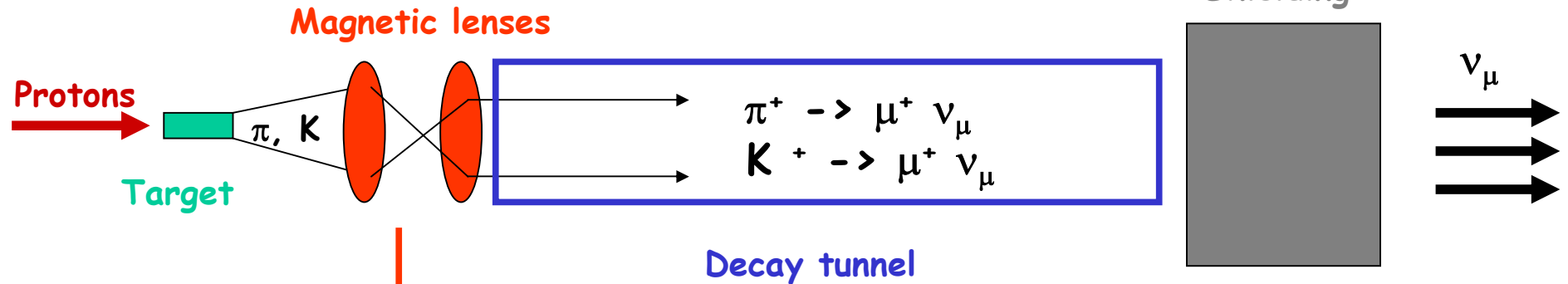
Neutrino beams at accelerator are almost pure  $\nu_\mu$  beams,  $\nu_\tau$  are practically absent,  $\nu_e$  are present at the level of 1% (a two detector setup improves the syst. uncertainty)

**Advantages neutrino beams at accelerators:**

**man-made neutrino sources of:**

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

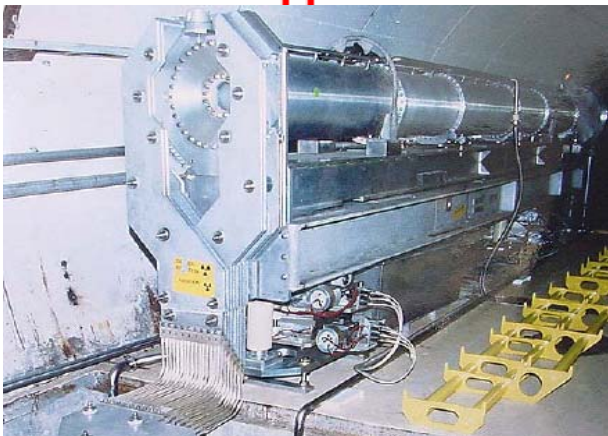
# Typical high energy Wide Band neutrino beam



**Horns: sign selection, focalization: flux x10**

### Contaminations:

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



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

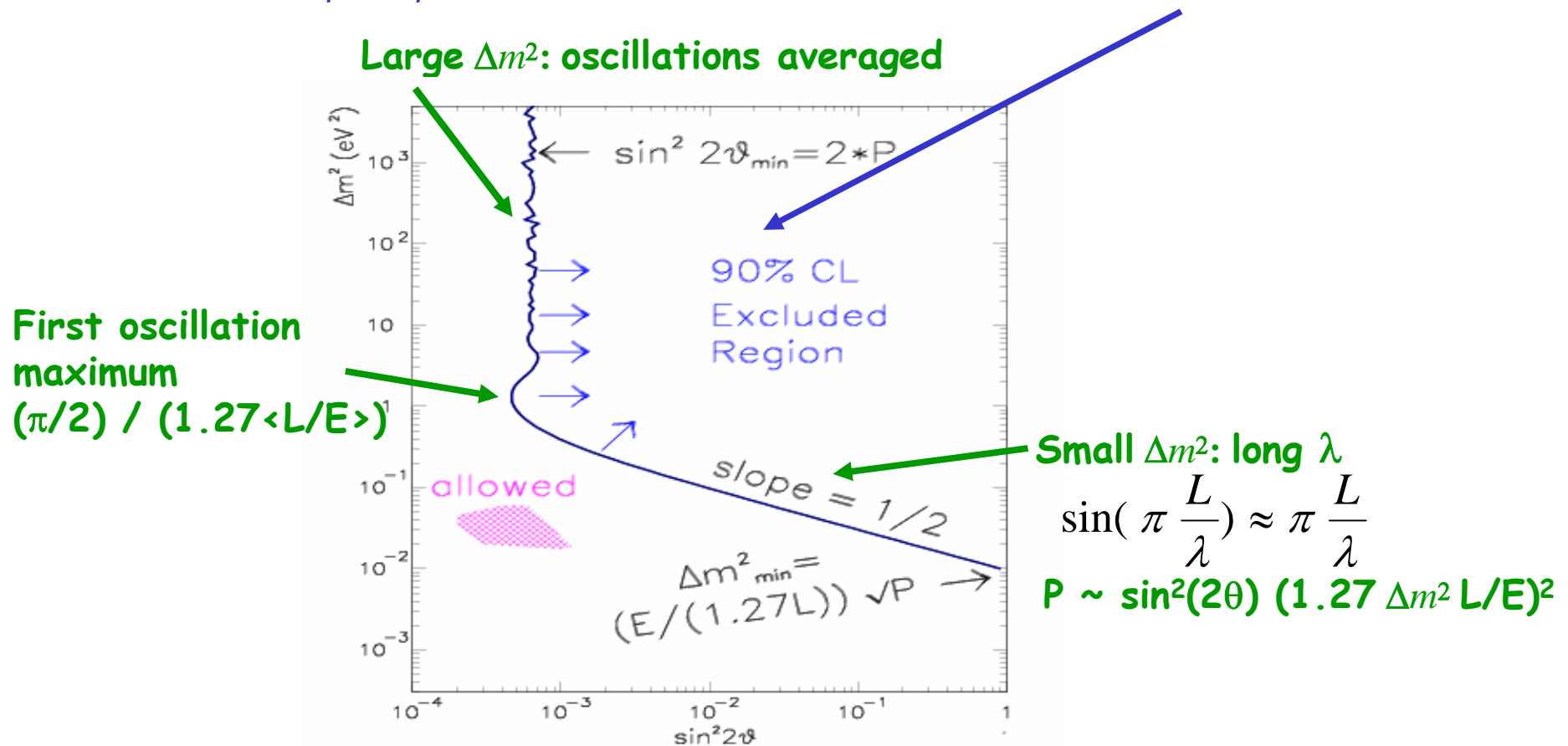
# Interpretation of the experimental results

## 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)  $\rightarrow$  excluded region



# Neutrino oscillation searches at the beginning of 90s

(long time ago in neutrino physics, not so much in everyday 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  $\Delta m^2$**

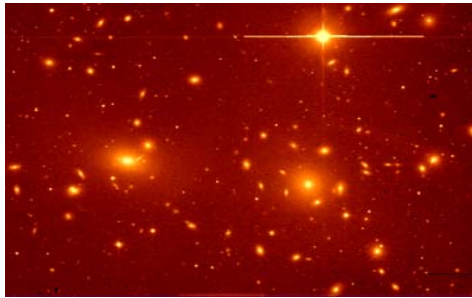
✓ Take the MSW solution of the solar neutrino deficit:  $\Delta m_{\mu e}^2 \sim 10^{-5} \text{ eV}^2$

✓ Assume a strong hierarchy:  $m_{\nu e} \ll m_{\nu \mu} \ll m_{\nu \tau} \rightarrow m_{\nu \mu} \sim 3 \times 10^{-3} \text{ eV}$

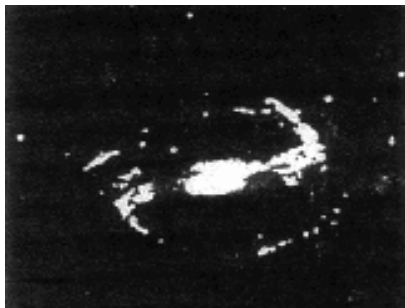
✓ Assume the See-Saw mechanism:  $m(\nu_i) = m^2(f_i)/M$   
 $M = \text{very large Majorana mass}$   $m(f_i) = \text{e.g. quark masses}$

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

# Dark matter (see lectures of P.Ullio)

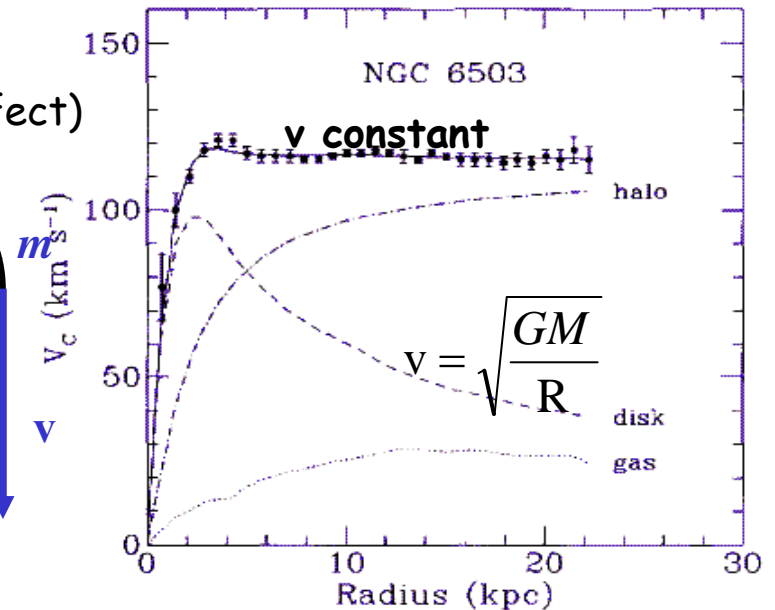
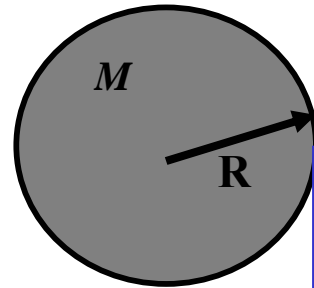


Coma cluster of galaxies, application of the virial theorem by F. Zwicky (1933)  
 velocity dispersion, geometric size → **total mass (x400 luminous mass)**



Rotational velocity curves of galaxies (Hydrogen, doppler effect)

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



Could it be due to the **BIG BANG** relic neutrinos ?  
 112  $\nu$  /  $\text{cm}^3$  per flavour

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

«  $\nu$  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  $\Omega_{\text{HDM}} = 0.3$ ,  $\Omega_{\text{CDM}} = 0.7$

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

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

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

## CERN $\nu_\tau$ appearance experiments:

Search for  $\nu_\tau$  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

### NOMAD:

- Proposal 1991
- Detector 1995
- Data-taking 95-98 (1.35 M  $\nu_\mu$  CC)

### CHORUS:

Data-taking 1994-1997 (0.71 M  $\nu_\mu$  CC)

sensitive down to:

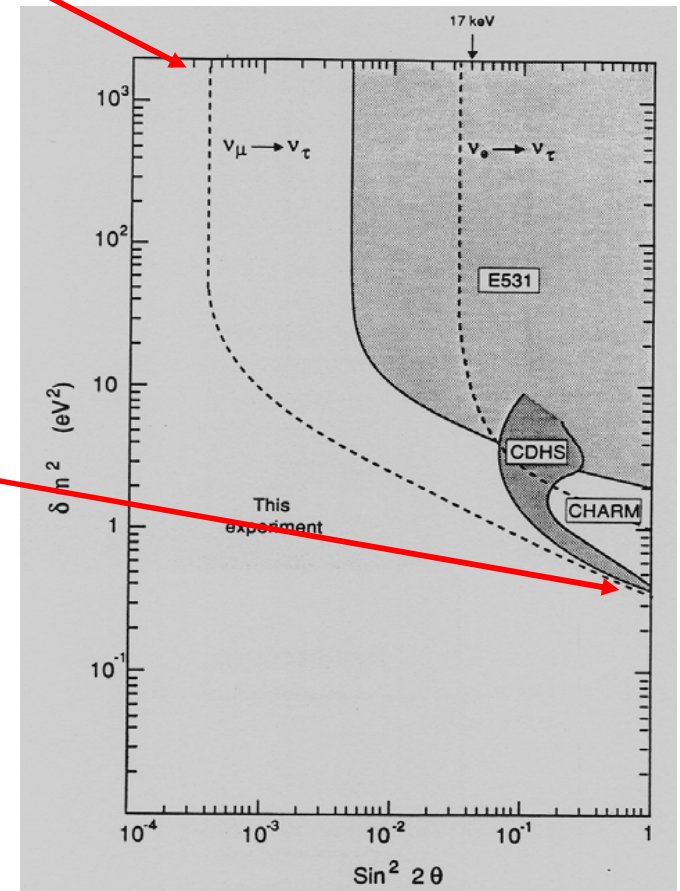
$P_{\mu\tau} \sim 1.5 \times 10^{-4}$  (90% CL) (x10) improvement

$\langle E_\nu \rangle = 24 \text{ GeV}$

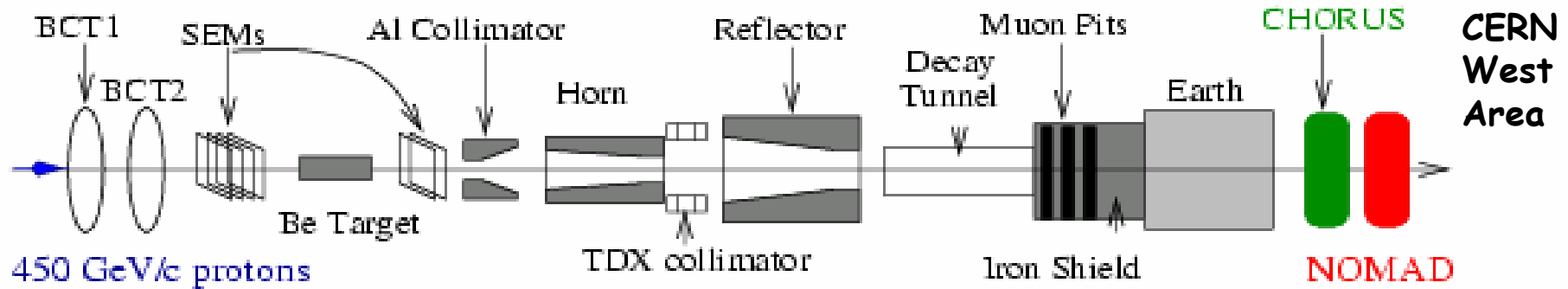
$\langle L \rangle = 600 \text{ m}$

sensitive to:

$1 \text{ eV}^2 < \Delta m^2$

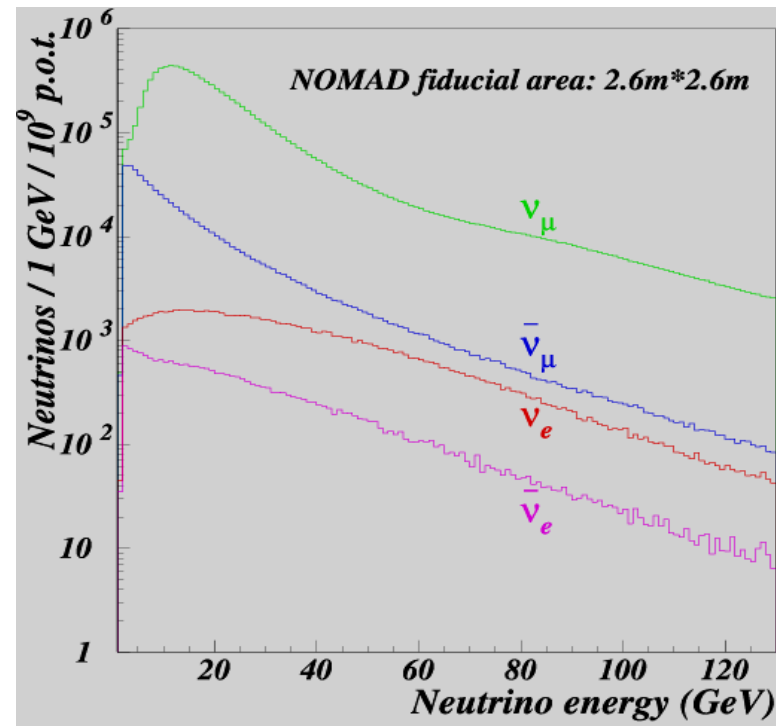


# The CERN WNF neutrino beam



Flavour	$\langle E_\nu \rangle$ (GeV)	rel.abun.
$\nu_\mu$	23.5	1.0
$\bar{\nu}_\mu$	19.2	0.061
$\nu_e$	37.1	0.0094
$\bar{\nu}_e$	31.3	0.0025
$\nu_\tau$	35	$5 \times 10^{-6}$

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





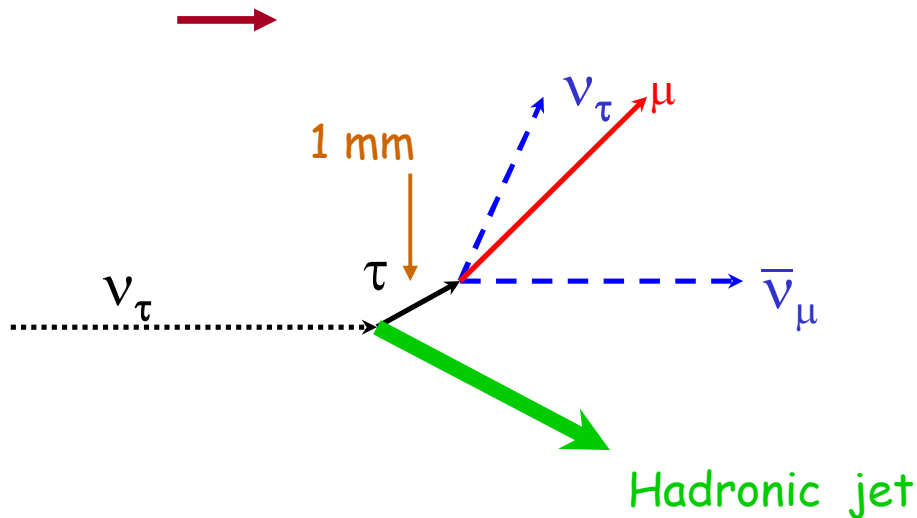
# Search for $\tau$ appearance

The  $\nu_\tau$  are searched for through their charged current interaction followed by the  $\tau$  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  $\tau$  decay kink : CHORUS (high space resolution, emulsions) (main channel: muonic tau decay)
- Measurement of the KINEMATIC of the  $\tau$  decays : NOMAD  
presence of neutrino(s) in the final state, missing  $P_+$ , visible decay daughters (tracking, calorimetry) (main channel: electronic tau decay)

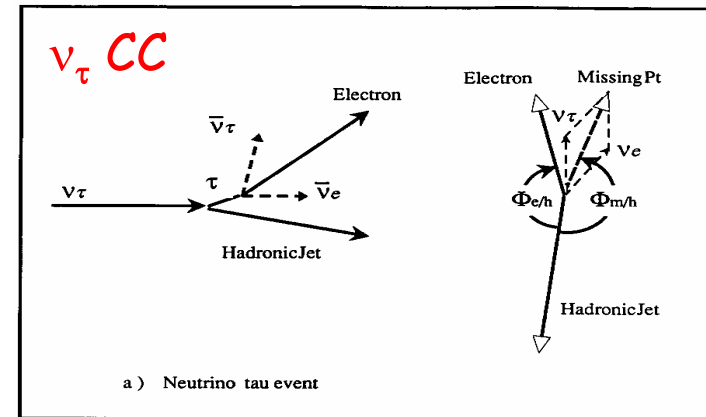
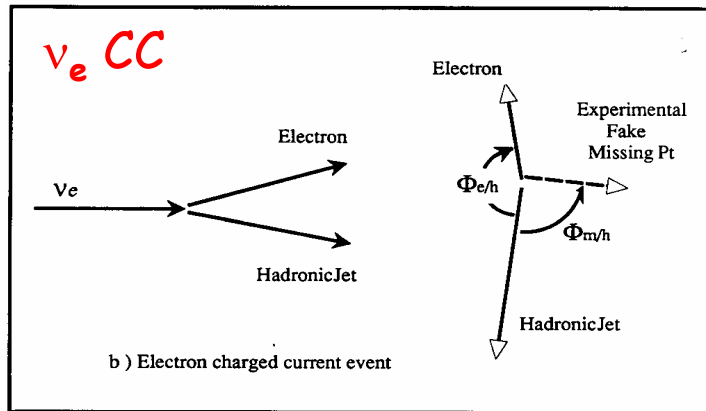


# Use of kinematics to extract a $\nu_\tau$ signal:

(First proposed by Albright 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



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

background:

1.3 M  $\nu_\mu$  CC

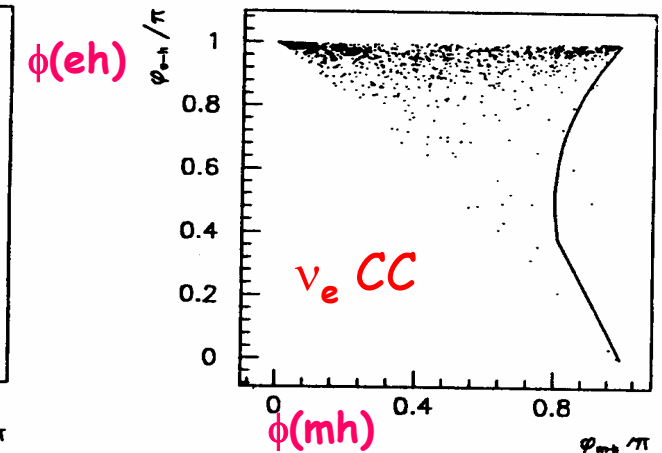
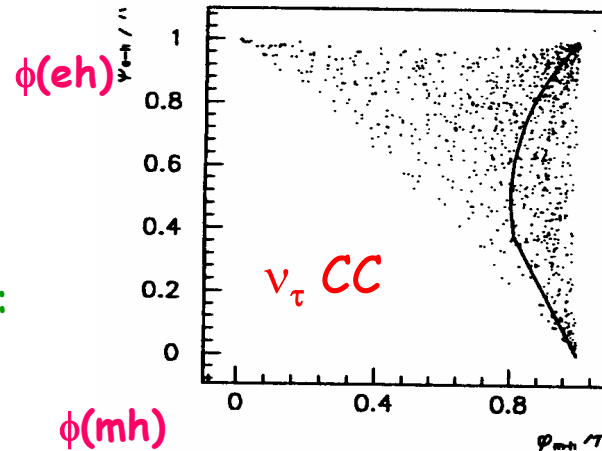
0,4 M  $\nu_\mu$  NC

13 K  $\nu_e$  CC

Exploit the small  $\nu_e$  background:

$\tau \rightarrow e$  channel: electron id

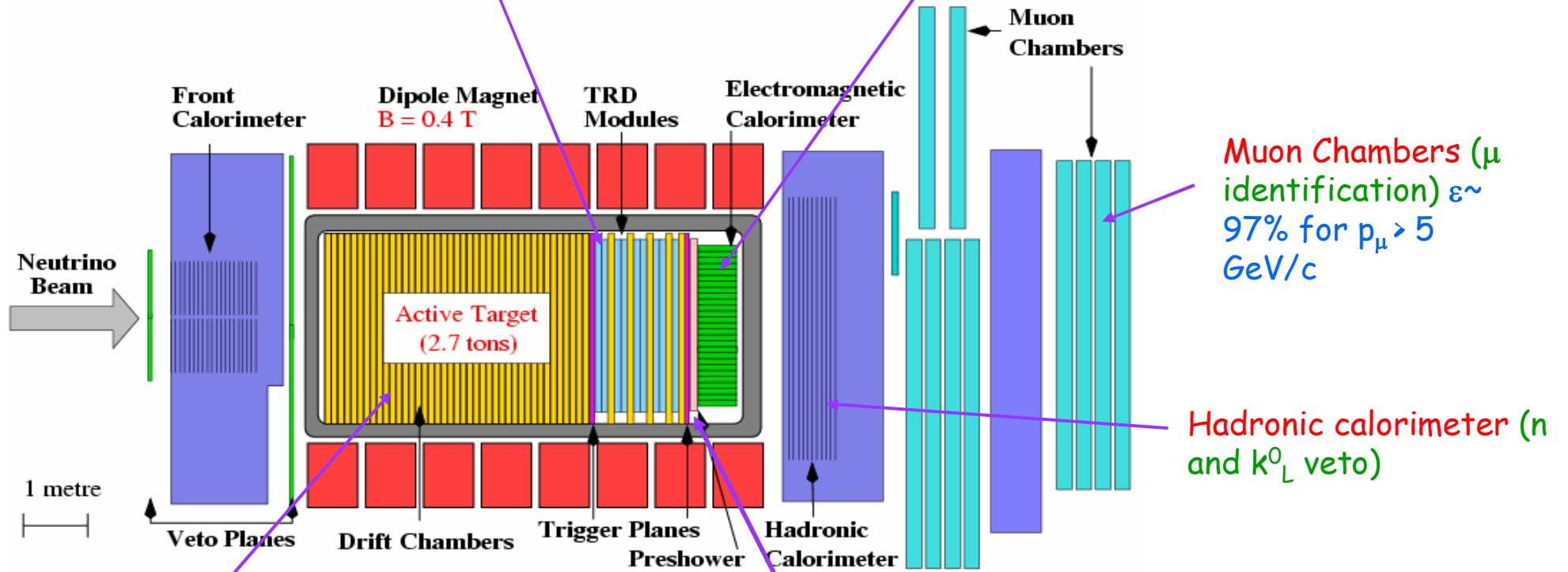
The  $\phi$ - $\phi$  plot:



# The NOMAD detector

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

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



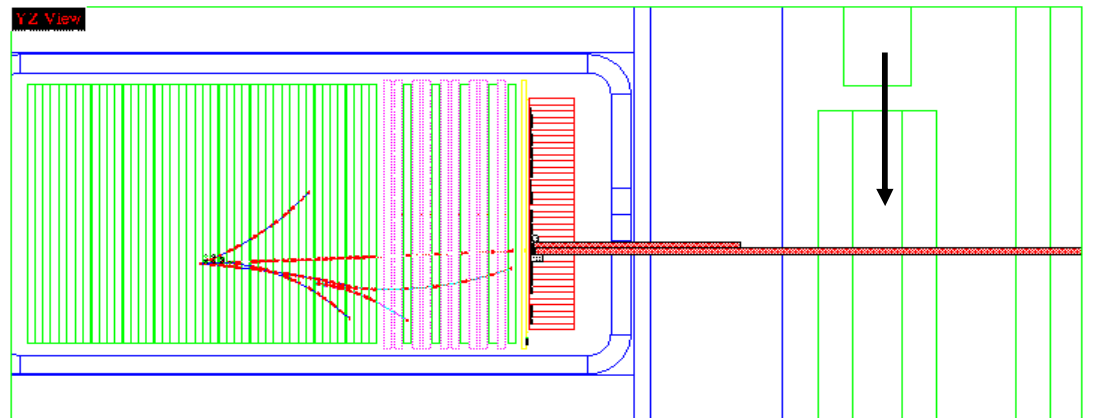
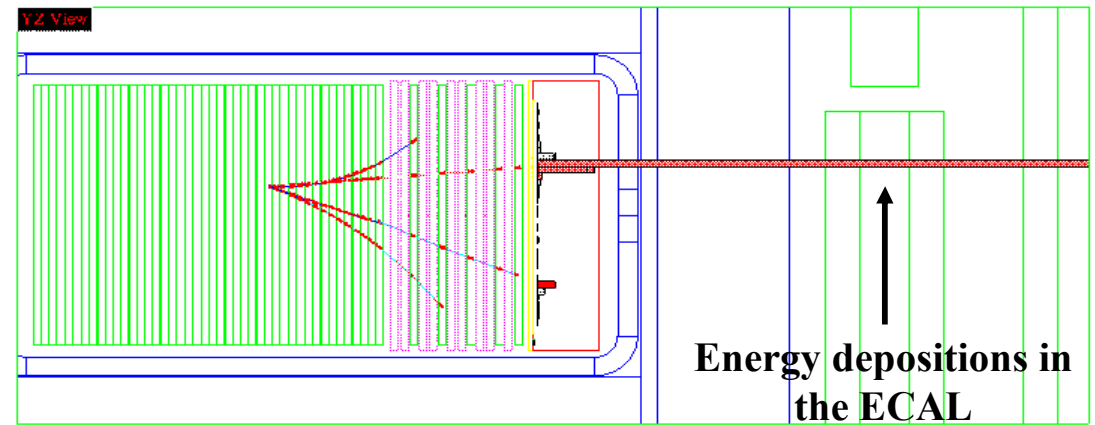
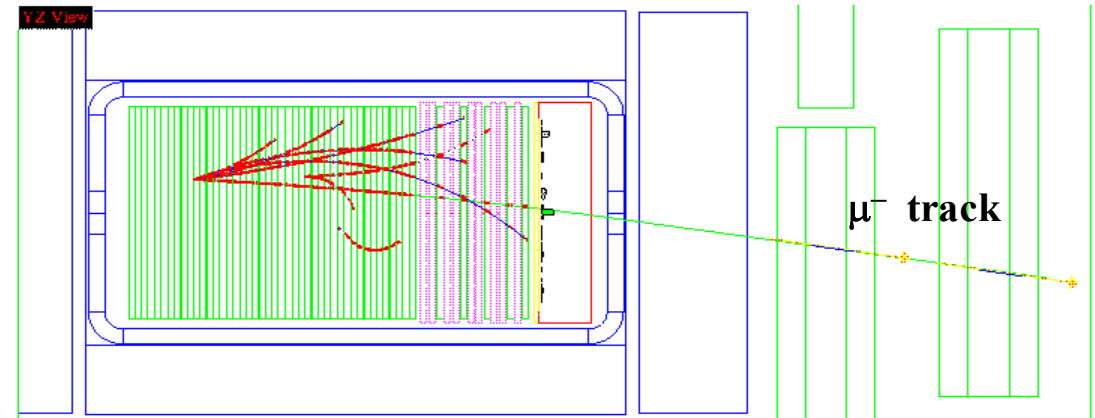
Muon Chambers ( $\mu$  identification)  $\epsilon \sim 97\%$  for  $p_\mu > 5$  GeV/c

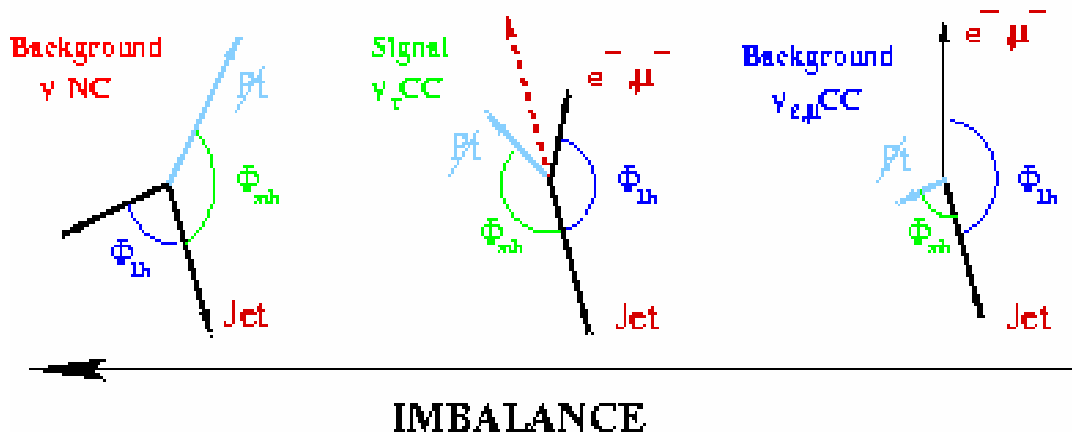
Hadronic calorimeter ( $n$  and  $k_L^0$  veto)

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

Preshower ( $e$  and  $\gamma$  detection) additional  $\pi$  rejection  $\sim 10^2$  for electron efficiency  $> 90\%$  precise  $\gamma$  position measurement  $\sigma(x), \sigma(y) \sim 1 \text{ cm}$

## Nomad typical events:





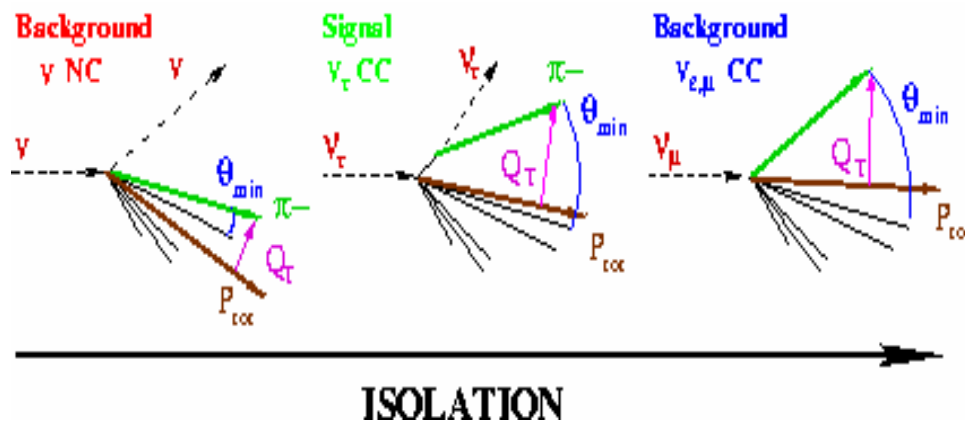
There is not a single miracle cut achieving a  $10^5$  rejection

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  $\ln(L_S/L_B)$

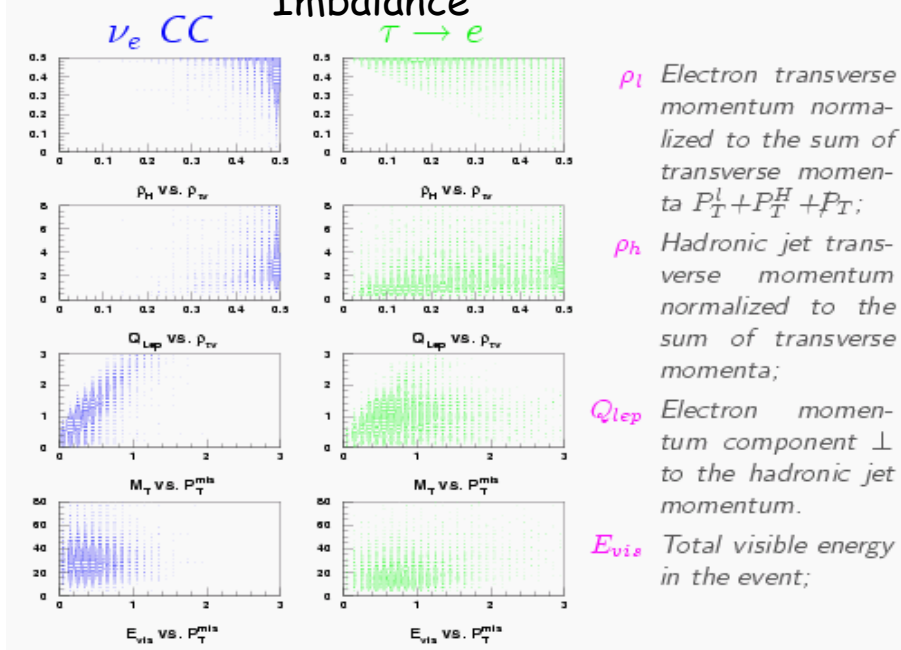
Two likelihood ratios can be used in a correlated way: one to reject NC based on the isolation and one to reject CC based on the imbalance



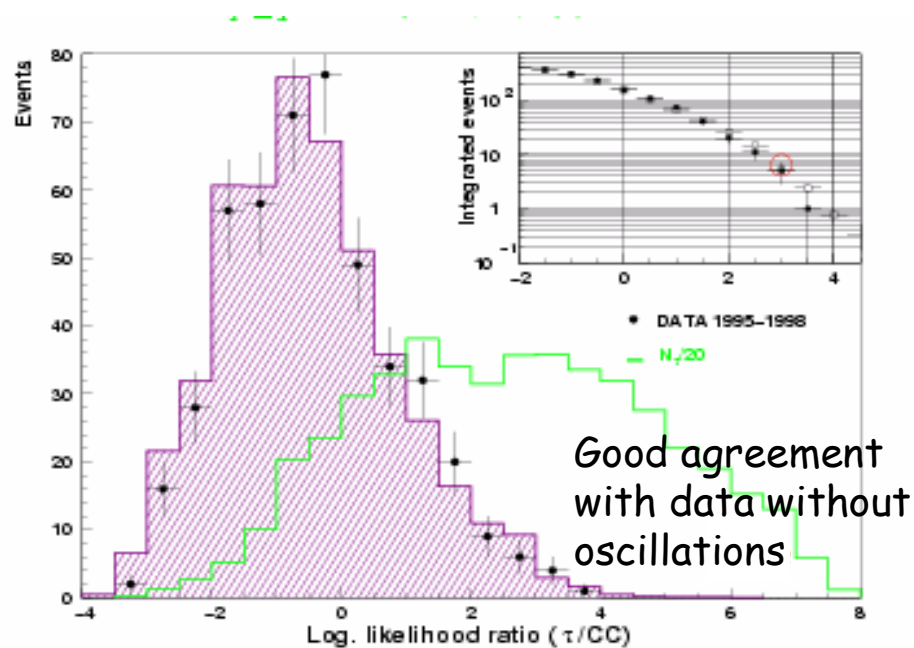
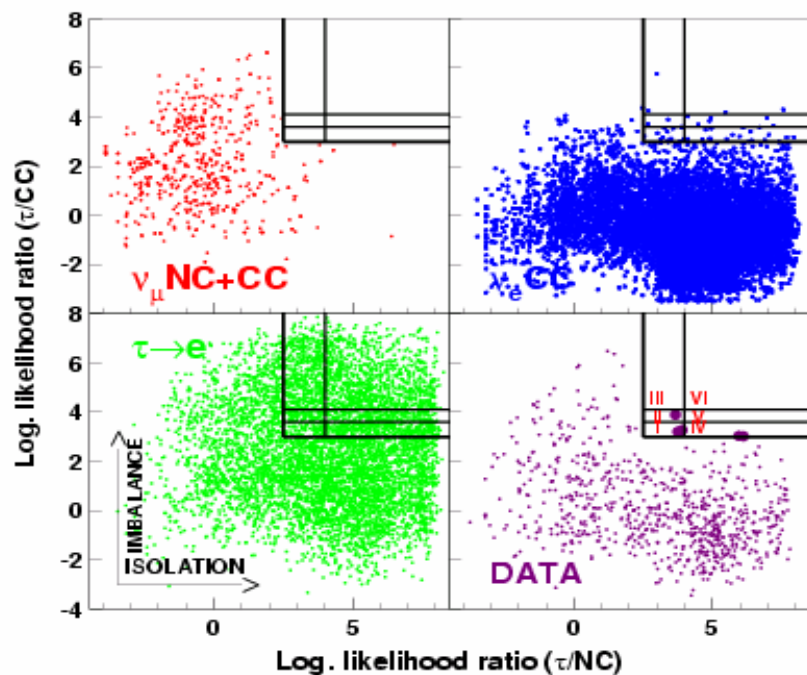
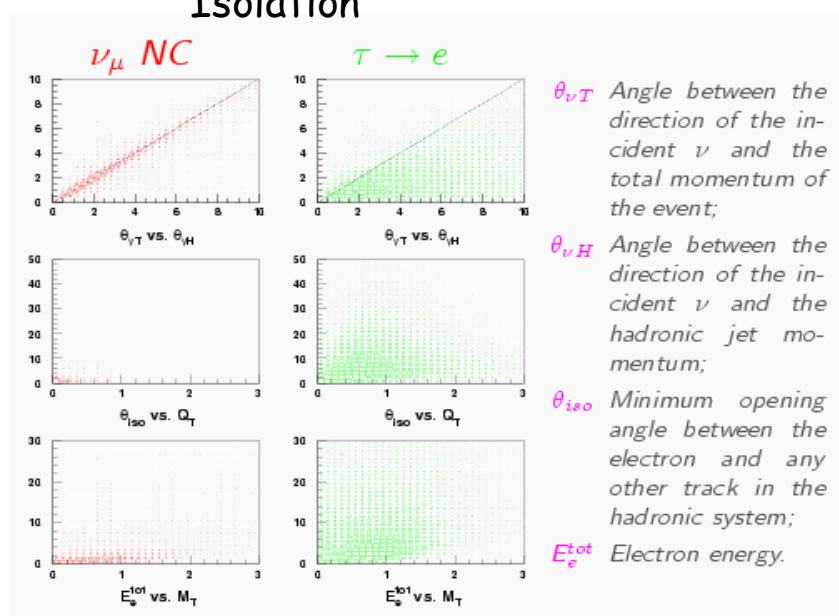
Corrections to the Monte Carlo predictions are evaluated from the data themselves by looking at the differences between data and MC for the  $\nu_\mu$  CC events, the muonic decay channel is sacrificed

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 elsewhere, the search is performed as cross-check also for the  $\tau^+$  (purely background sample)

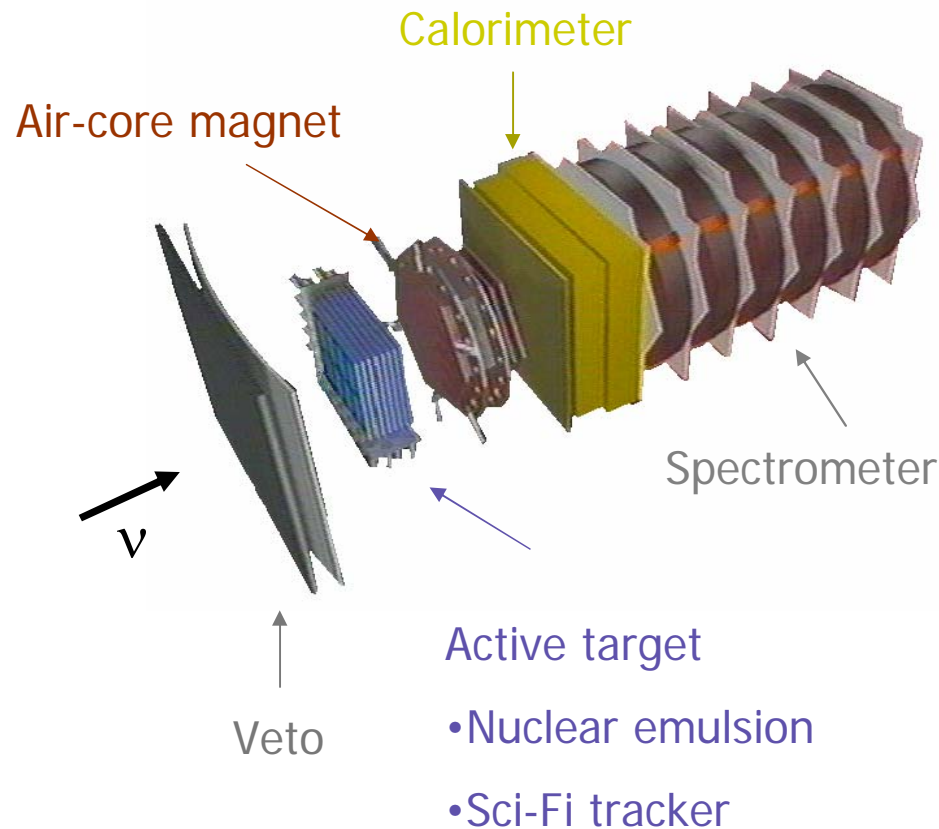
## Imbalance



## Isolation



# CHORUS



Target: 800 kg of nuclear emulsions

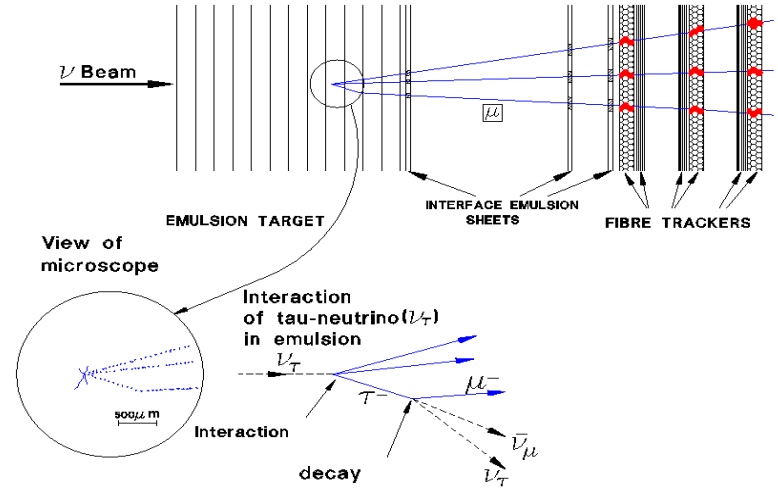
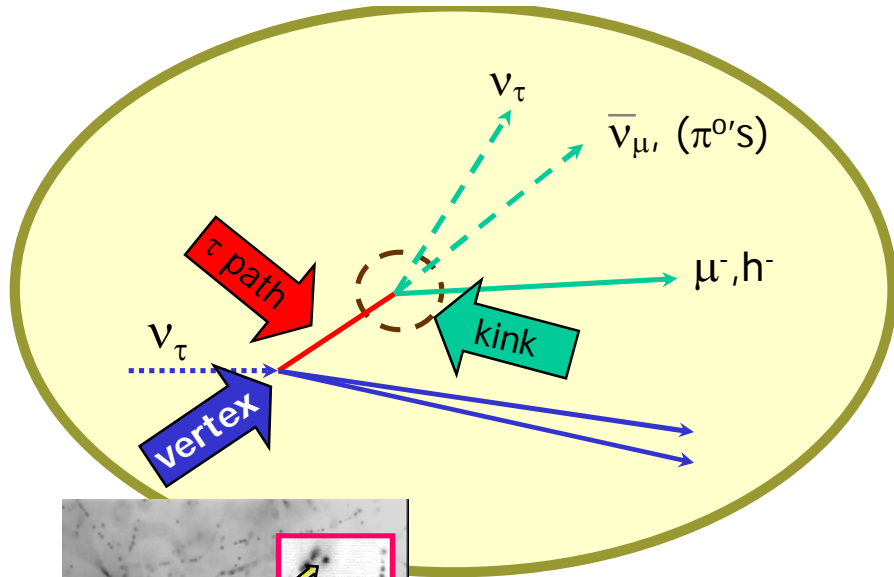
Scintillating fibers tracker: high space resolution for the localization of the neutrino interaction in the emulsions

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

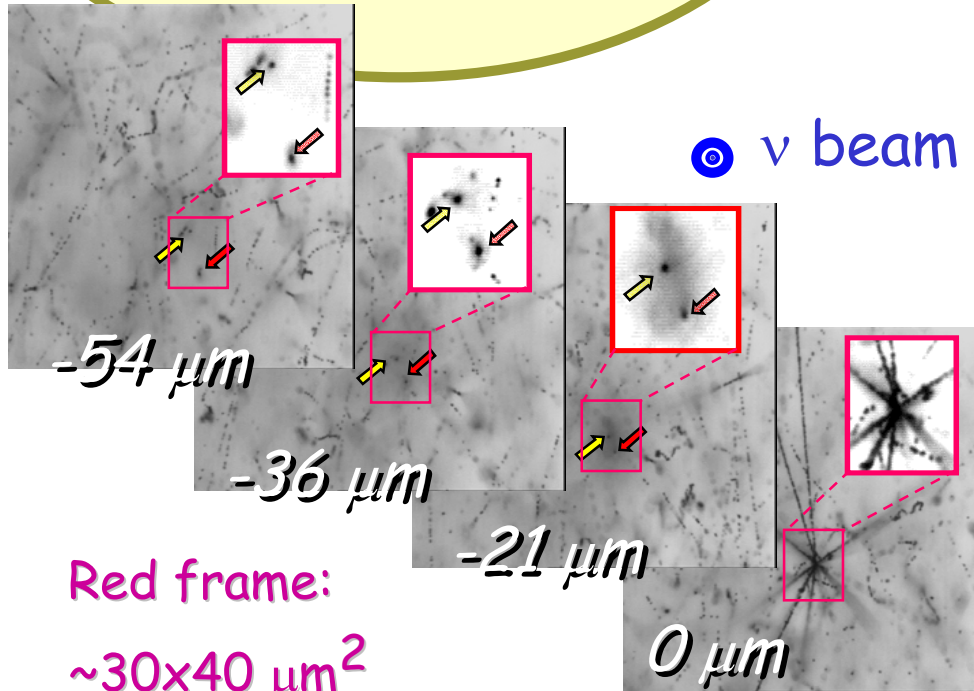


1- $\mu$  vertex predicted in bulk

Electronic detectors

```

    graph TD
      A[Look for muons] --> B[1μ]
      A --> C[0μ]
      B --> D[apply cuts]
      C --> E[apply cuts]
      D --> F[Scan-back]
      E --> F
      F --> G[Kink finding]
      G --> H[apply kinematical cuts]
      H --> I[τ candidates]
  
```



Location efficiency 40%  $1\mu$   
27%  $0\mu$



## NOMAD (completed)

Analysis	Bin	Tot. bkg.	$N_{P=1}^T$	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	$0.25 \pm 0.09$	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

Number of signal events expected in case of full mixing

## CHORUS (Phase I)

Analysis	Tot. bkg.	$N_{P=1}^T$	Data
$\nu_\tau \bar{\nu}_\mu \mu$	$0.11 \pm 0.03$	5014	0
$\nu_\tau 0\mu$	$1.10 \pm 0.33$	2004	0

$1.21^{+0.33}_{-0.33}$  7018

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

## Chorus Phase II:

New location method (increase by 60K the sample)

Scan a volume of  $1.5 \times 1.5 \times 6.3 \text{ mm}^3$  around already located events

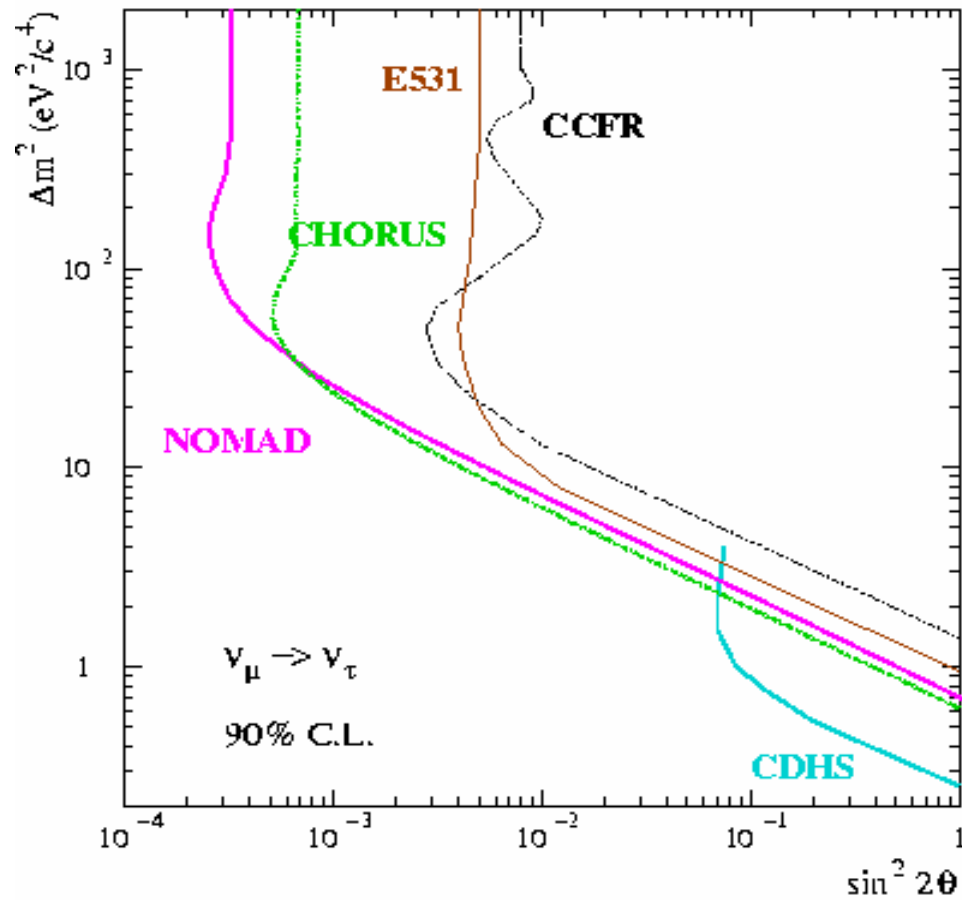
Decay search not limited to just the scan-back track

Offline data analysis

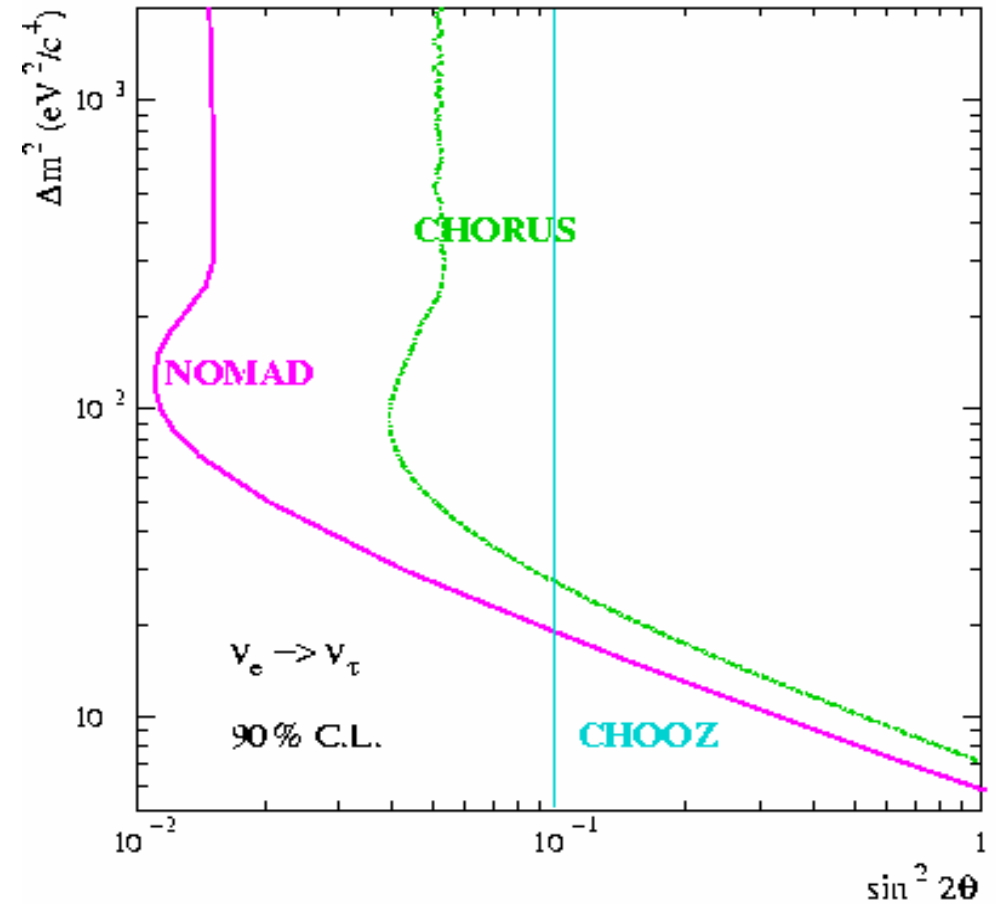
In Progress

# Status of short baseline oscillation searches into $\nu_\tau$

$$\nu_\mu - \nu_\tau$$



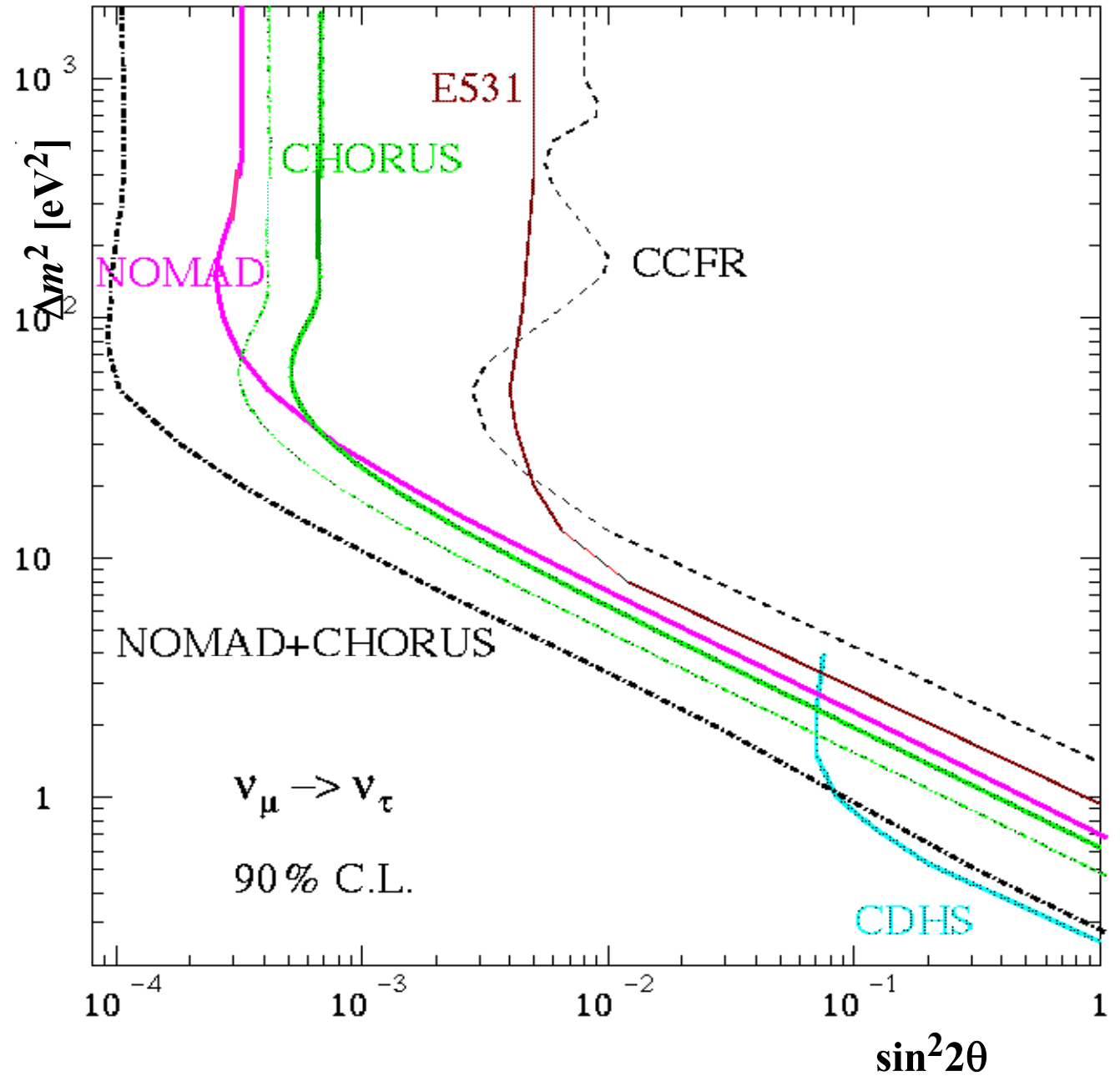
$$\nu_e - \nu_\tau$$



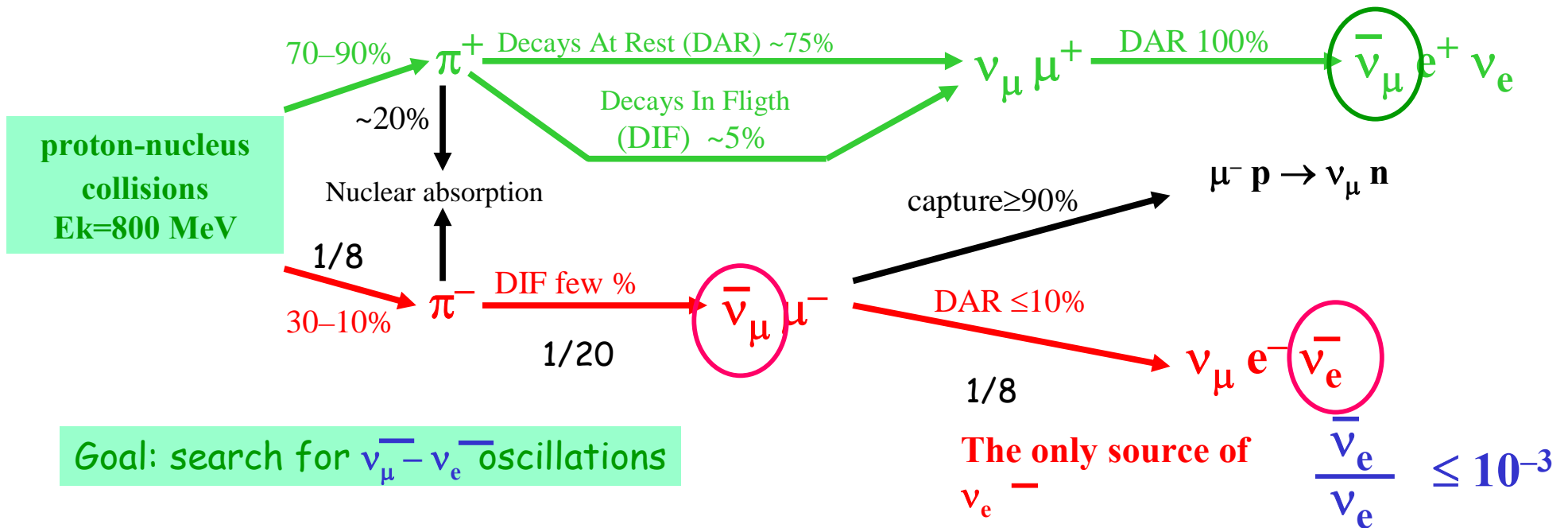
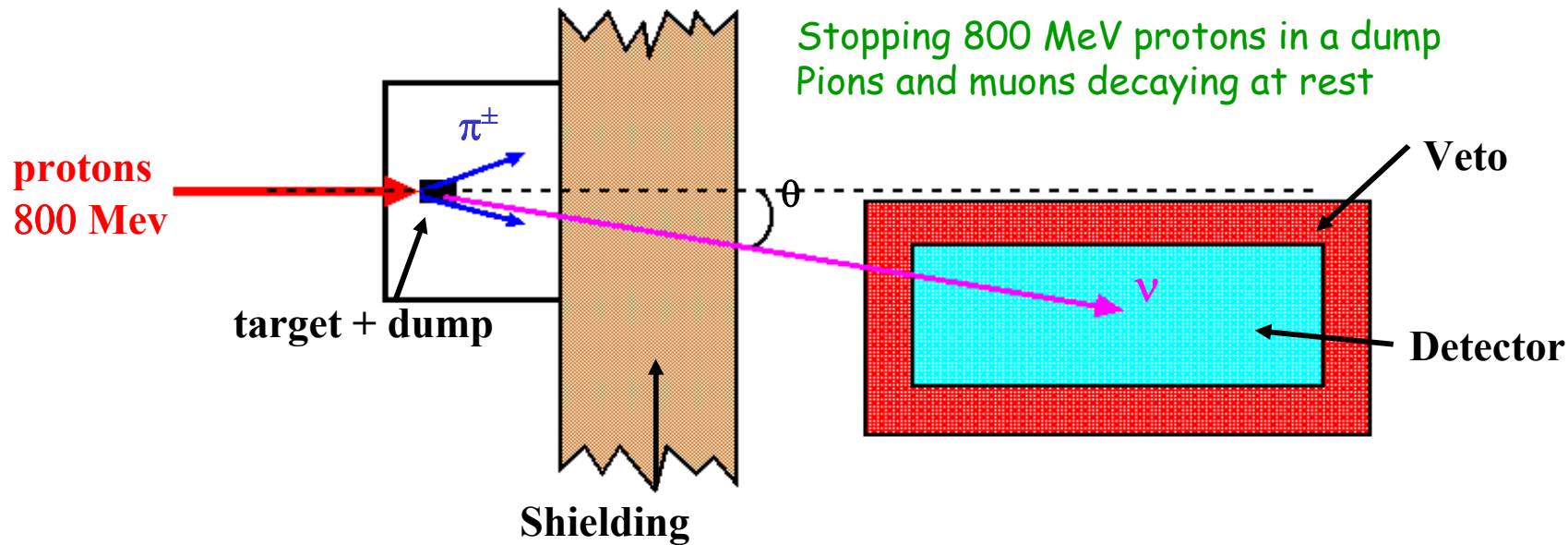
NOMAD data: final - CHORUS phase-II not yet finished

Combined  
NOMAD-CHORUS limit

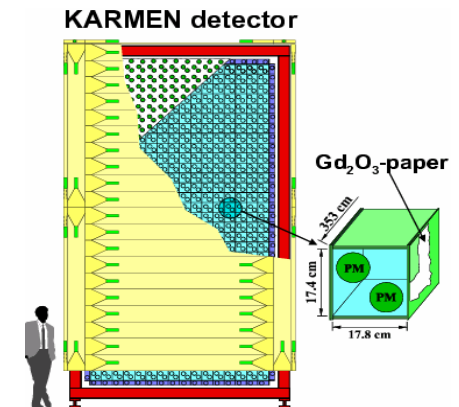
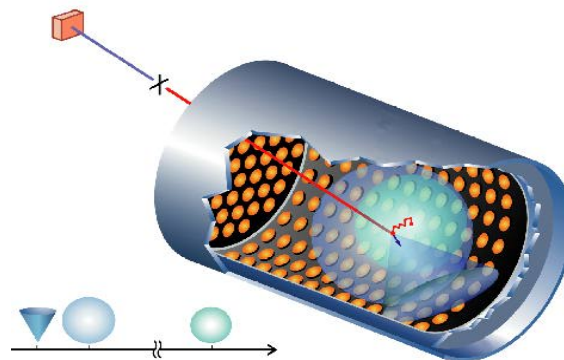
Upper limit on the  
oscillation probability for  
 $\nu_\mu \rightarrow \nu_\tau : 0.5 \cdot 10^{-4}$



# The LSND and Karmen experiments (1993-2001)



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

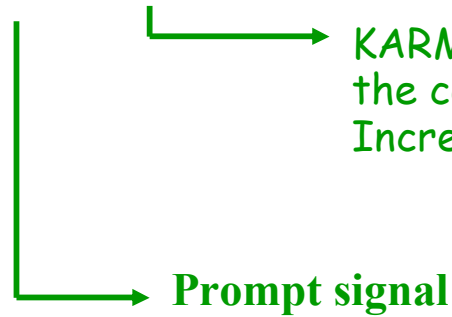


# $\bar{\nu}_e$ detection

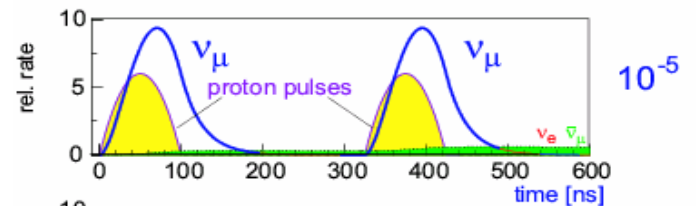
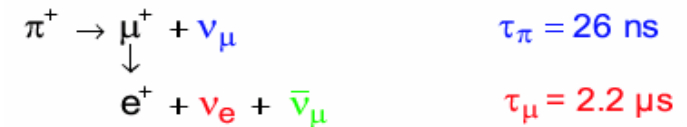


Delayed signal from neutron capture  
 $np \rightarrow \gamma d$  ( $E_\gamma = 2.2$  MeV)

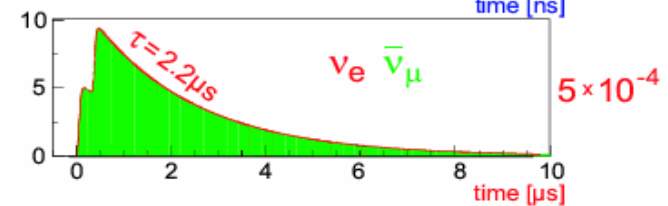
KARMEN: paper sheets doped with Gadolinium in between the cells  
 Increase of neutron capture probability,  $\Sigma E_\gamma = 8.1$  MeV



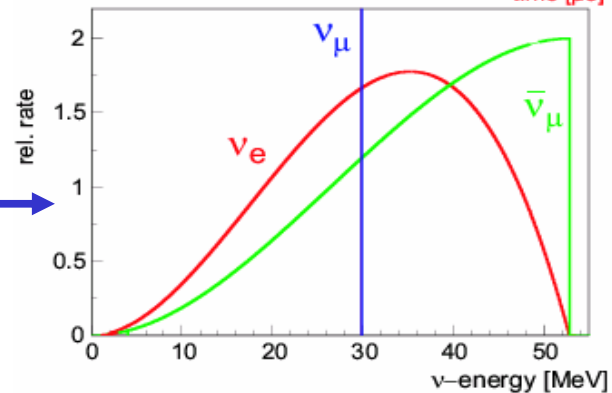
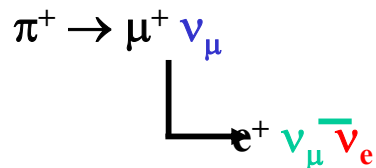
KARMEN: time structure of the beam  
 Repetition rate 50 Hz



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



Neutrino energy spectra from DAR (LSND, KARMEN)



## 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  $\gamma$  rays of 2.2 MeV expected from the neutron capture:

$$N(\text{“beam-on”}) - N(\text{“beam-off”}) = 117.9 \pm 22.4 \text{ events}$$

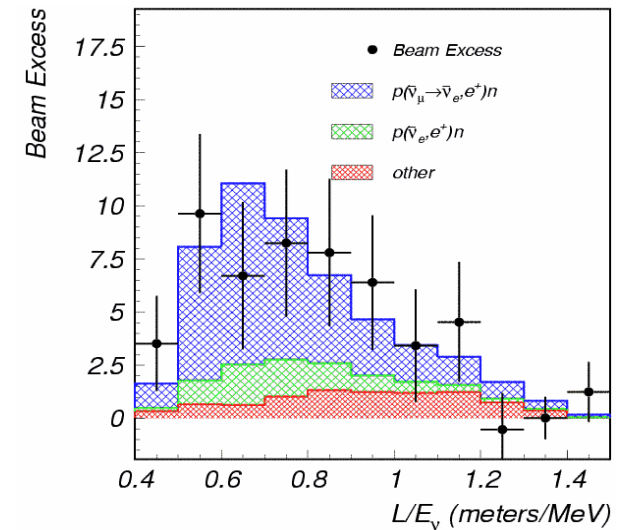
$$\text{Background due to } \mu^- \text{ DAR} = 19.5 \pm 3.9$$

$$\text{Background from } \pi^- \text{ DIF} + (\nu_\mu + \bar{p} \rightarrow \mu^+ + n) = 10.5 \pm 4.6$$

$$\text{Signal } \bar{\nu}_e = 87.9 \pm 22.4 \pm 6.0 \text{ events} \quad 3.8 \sigma \text{ effect}$$

(stat.)      (syst.)

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



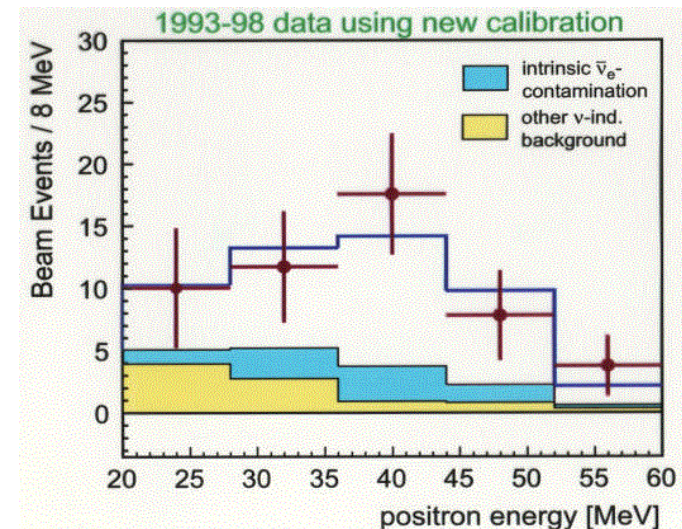
## Sample with reduced background:

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

$$N(\text{beam-on}) - N(\text{beam-off}) = 49.1 \pm 9.4 \text{ events}$$

$$\text{Neutrino background} = 16.9 \pm 2.3 \text{ events}$$

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



# KARMEN final result

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

$$16 < E(e^+) < 50 \text{ MeV}$$

**Data: 15 events after cuts with a total background of  $15.8 \pm 0.5$  events**

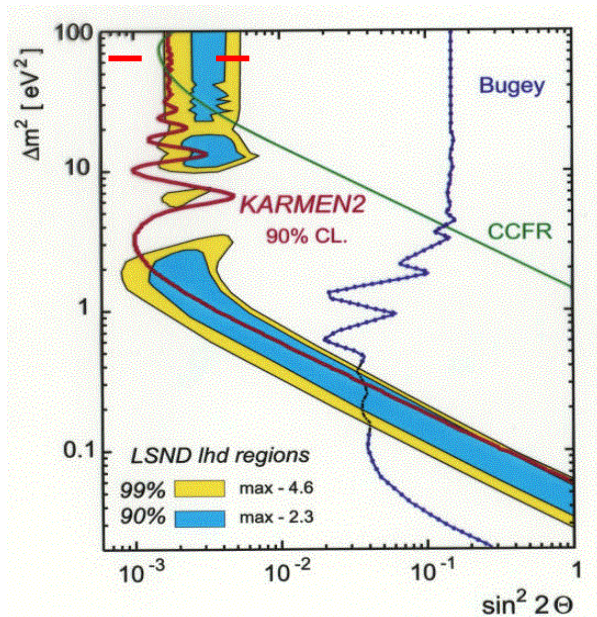
## Backgrounds:

Cosmics:  $3.9 \pm 0.2$  events

Random coincidences  $\nu_e \rightarrow e^-$ :  $5.1 \pm 0.2$

Random coincidences among  $\nu_e \rightarrow e^-$  and uncorrelated  $\gamma$ :  $4.8 \pm 0.3$

Intrinsic contamination of  $\nu_e$  in the beam :  $2.0 \pm 0.2$



No evidence for oscillations:

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

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  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  in LSND complicates the global scenario:  
with 3 neutrinos only two independent  $\Delta m^2$  are possible:

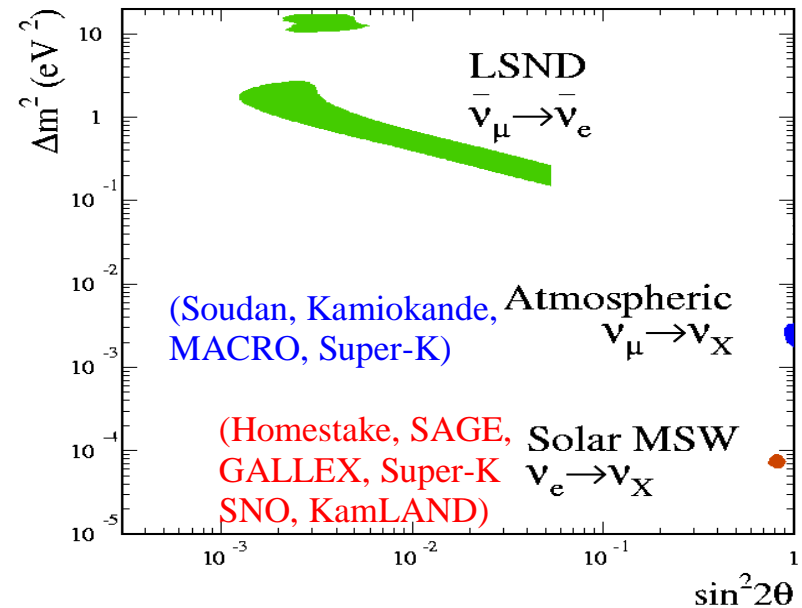
$$\Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 = 0$$

$$\Delta m_{\text{solar}}^2 + \Delta m_{\text{atm}}^2 \neq \Delta m_{\text{LSND}}^2$$

Oscillation signals:

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

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



- 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 sophisticated mechanisms like CPT violation must be advocated

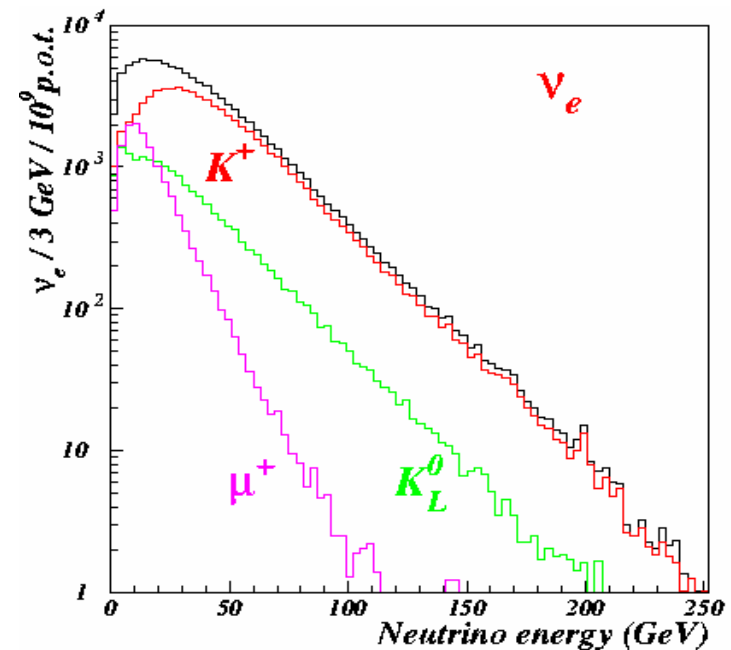
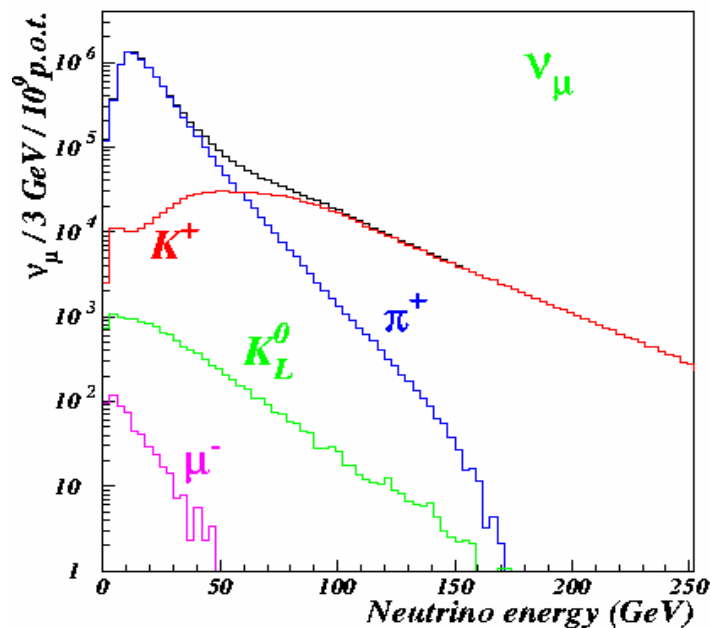
# Search for $\nu_\mu - \nu_e$ oscillations in NOMAD (1995-2002)

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  $\nu_\mu$  and  $\nu_e$  spectra)

Exploit powerful electron identification

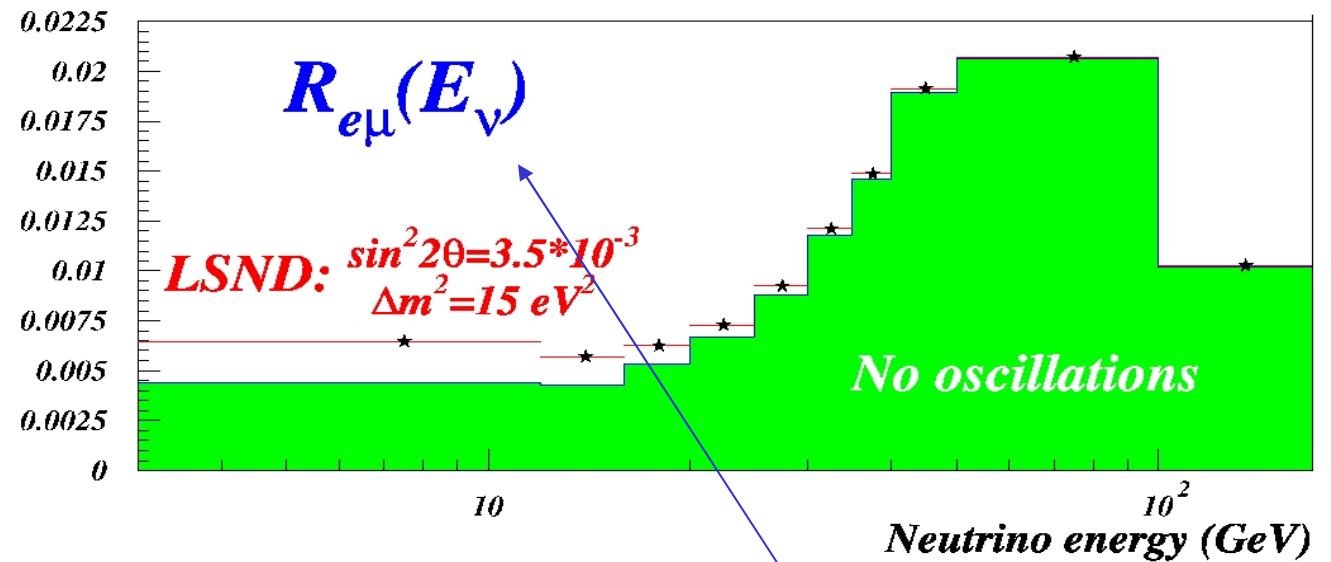
Study energy spectra (enhanced at low energy) and radial distributions (enhanced in the center)



## NOMAD can also study $\nu_\mu \rightarrow \nu_e$ oscillations:

- Good electron ID
- Low  $\nu_e$  contamination in the beam (1%)

→  $\nu_e$  appearance



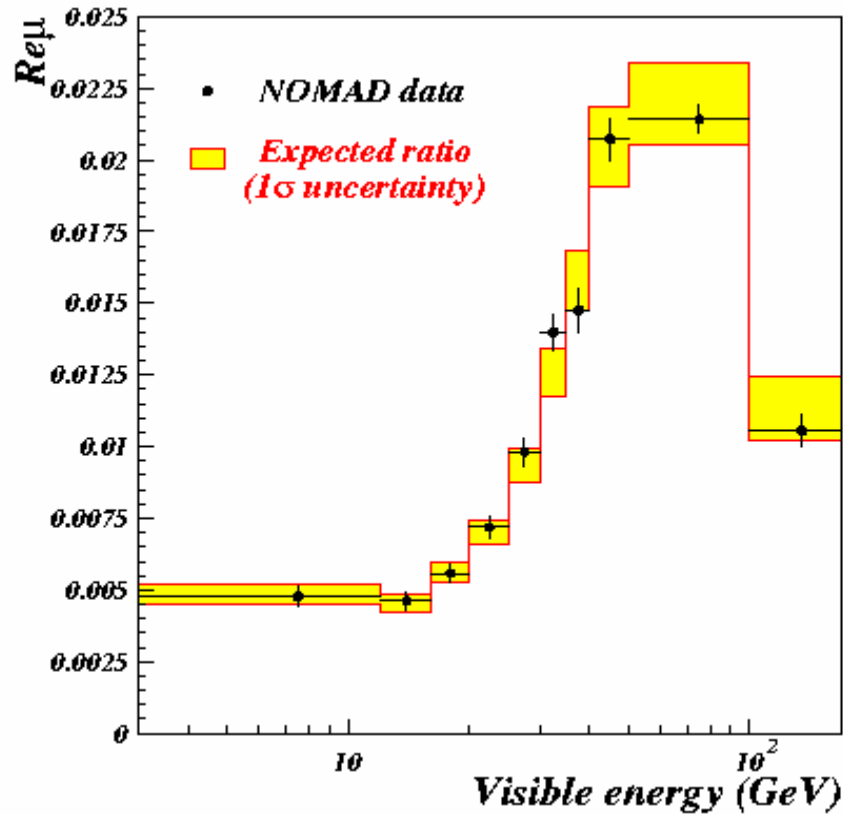
$\nu_\mu \rightarrow \nu_e$  at  $10^{-3}$  results  
in a 10% increase in  $\nu_e$  flux.

The oscillated  $\nu_e$  have also a lower energy,  
narrower radial distribution than the  
original  $\nu_e$

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

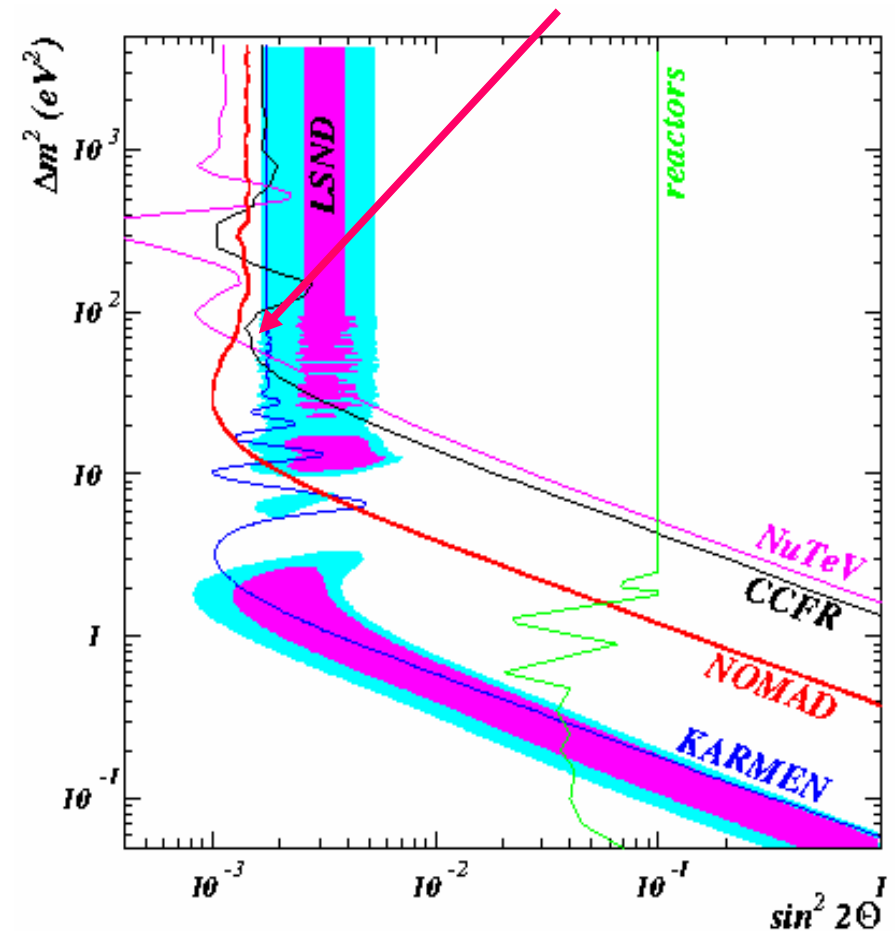
$$R_{e\mu} = \frac{\nu_e CC}{\nu_\mu CC}(E, r)$$

# Final results



Data are compatible with known sources, No evidence for oscillations

NOMAD result rules out the LSND allowed region with  $\Delta m^2$  above  $10 \text{ eV}^2$

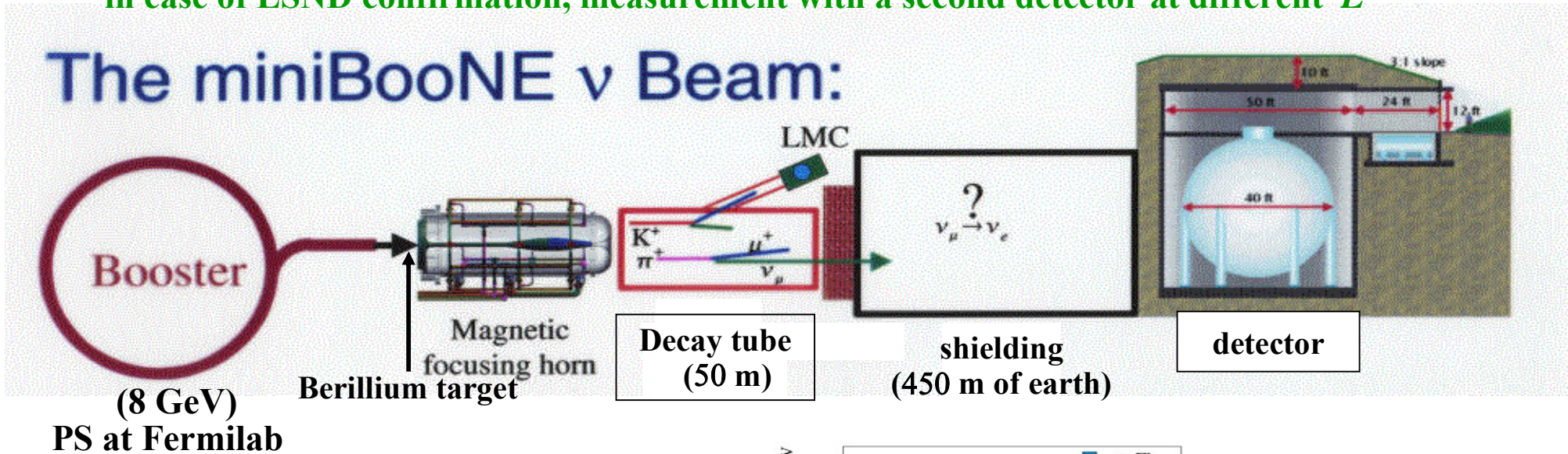


# MiniBooNE (Booster Neutrino Experiment at Fermilab)

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

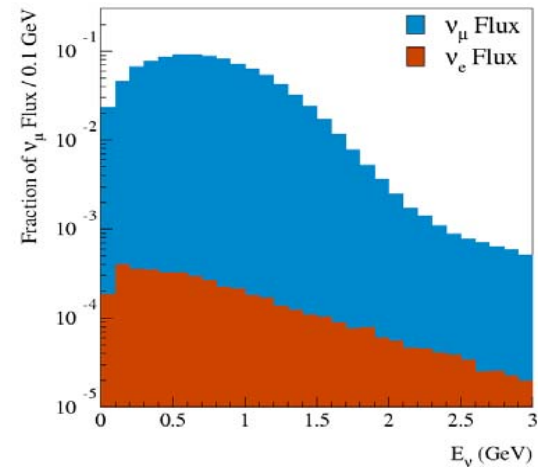
- first phase: search for  $\nu_\mu - \nu_e$  oscillation;
- second phase: search for  $\bar{\nu}_\mu - \bar{\nu}_e$  oscillations;
- in case of LSND confirmation, measurement with a second detector at different  $L$

## The miniBooNE $\nu$ Beam:



-L=540 m ~10x LSND

-E~500 MeV ~10x LSND

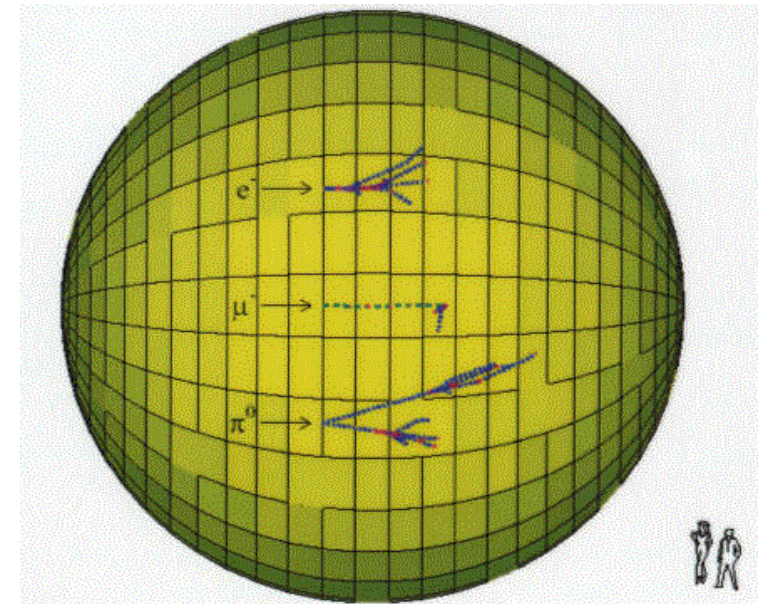
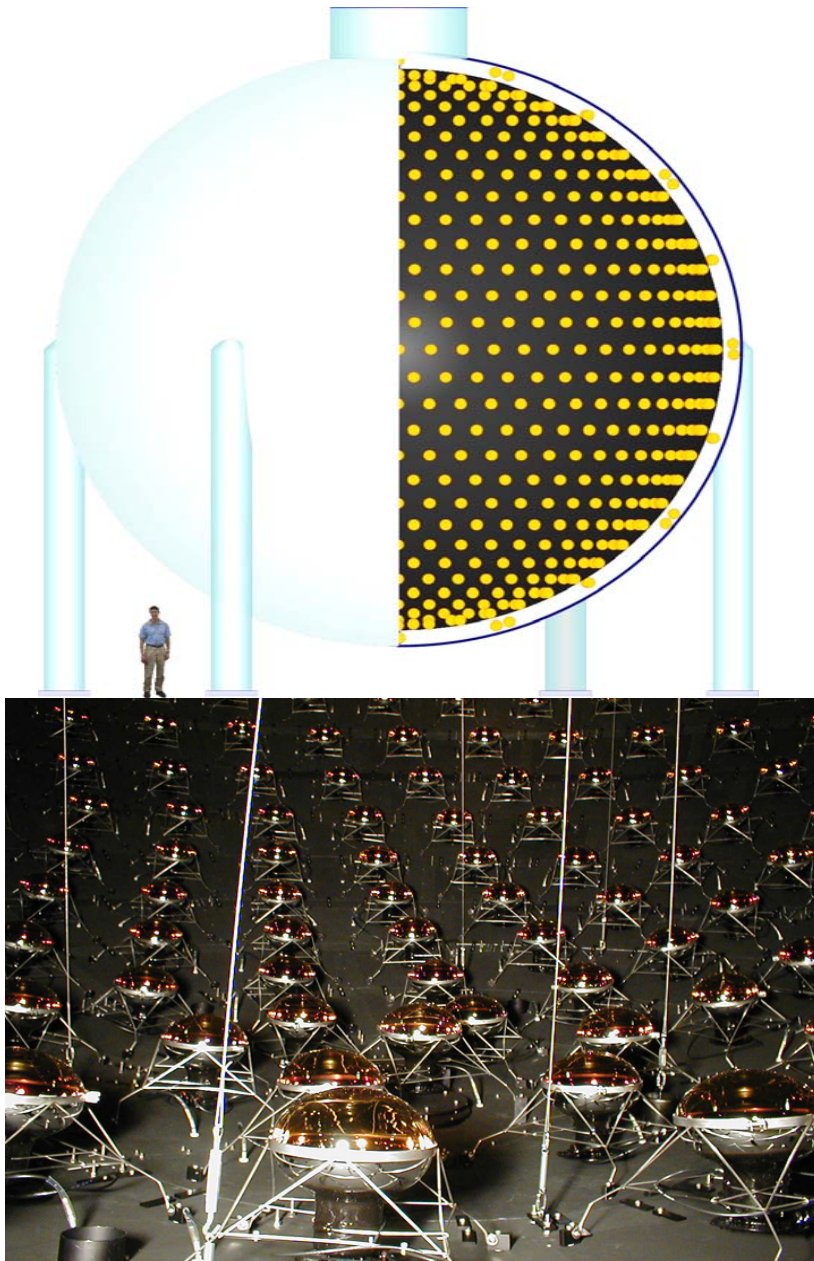


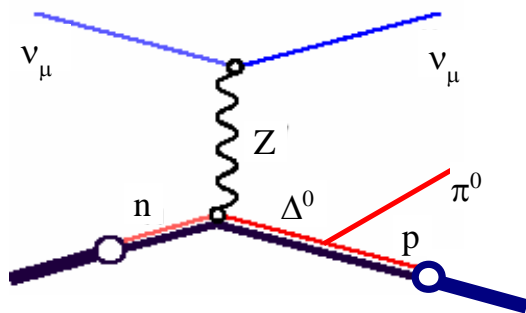
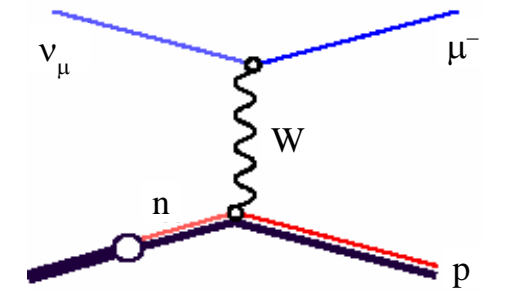
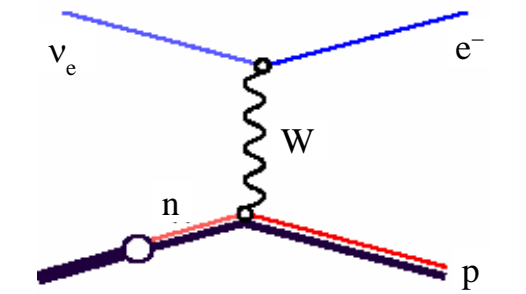
Expected  $\nu$  fluxes

# The MiniBooNE detector

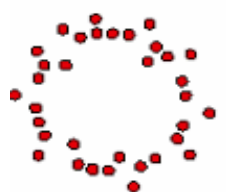
- Sphere 12 m diameter
- 807 ton mineral oil. Čerenkov lighth + delayed scintillation lighth.
- Fiducial mass 445 ton
- Internal volume optically insulated (1280 PM, diam. 20 cm)
- External veto volume (240 PM)

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

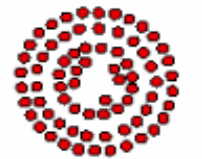




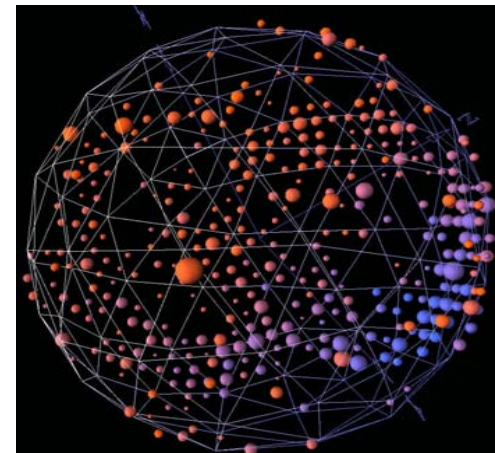
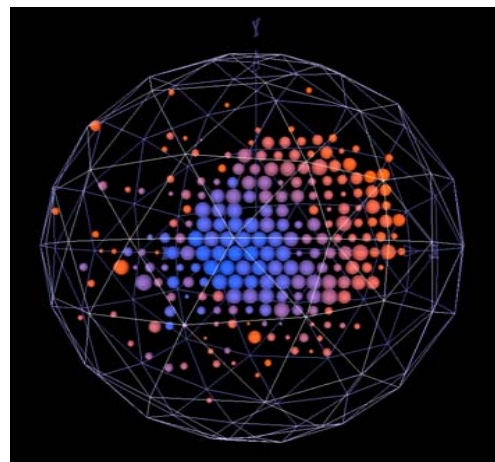
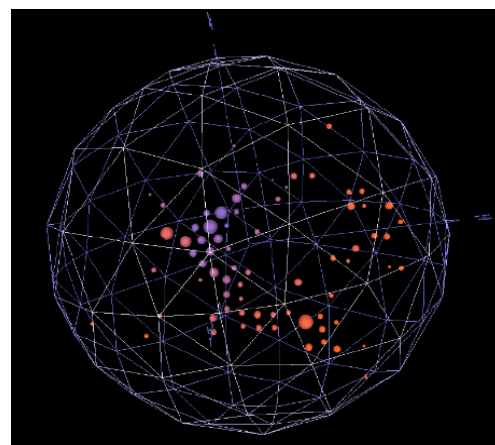
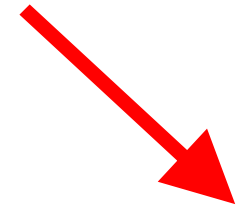
Michel e  
from  $\mu$  decay  
candidate



Beam  $\mu$   
candidate



Beam  $\pi^0$   
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

( $\nu_e$  contamination in the beam)

500 events  $\mu^-$  identified as electrons

500 events  $\pi^0$  identified as electrons

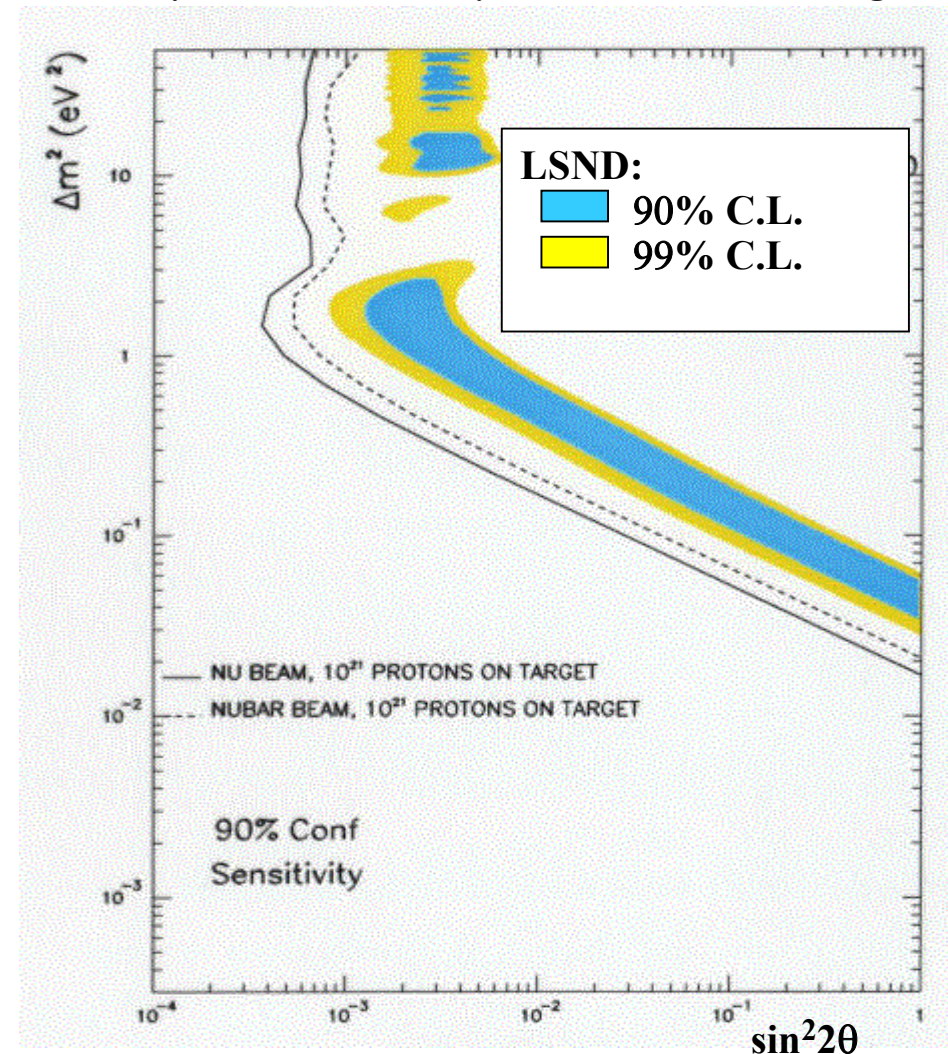
+ 1000 signal events  $\nu_e C \rightarrow e^- X$

if the LSND result is correct

The  $\nu_\mu$  and the  $\nu_e$  contamination in the beam have different energy spectra allowing to better separate the oscillated events from the background

$\nu_e$  are coming from muon decays, the muons have the same origin (pion decays) as the  $\nu_\mu$

Exclusion plot after two years of data-taking

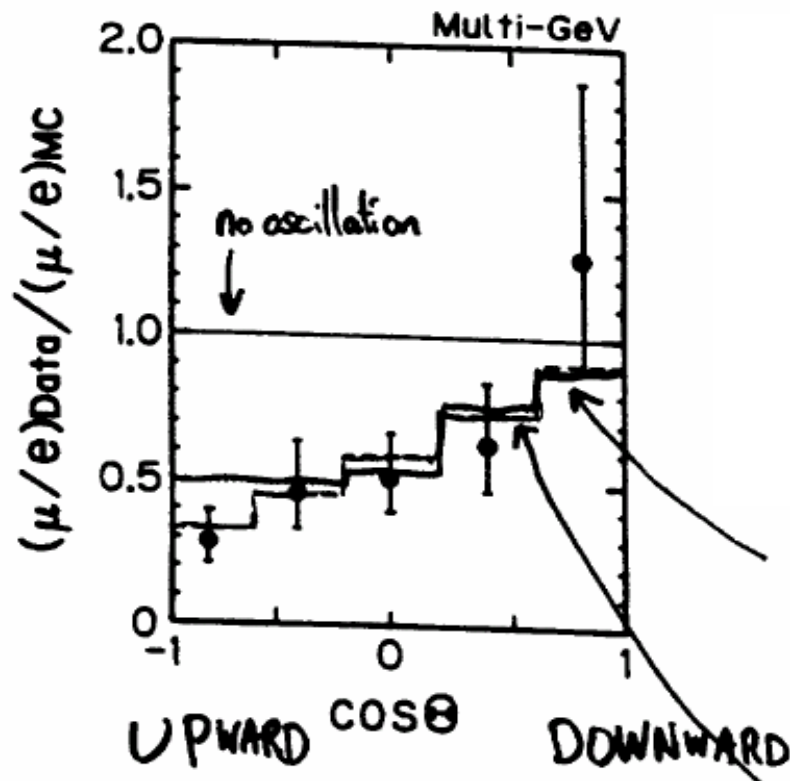




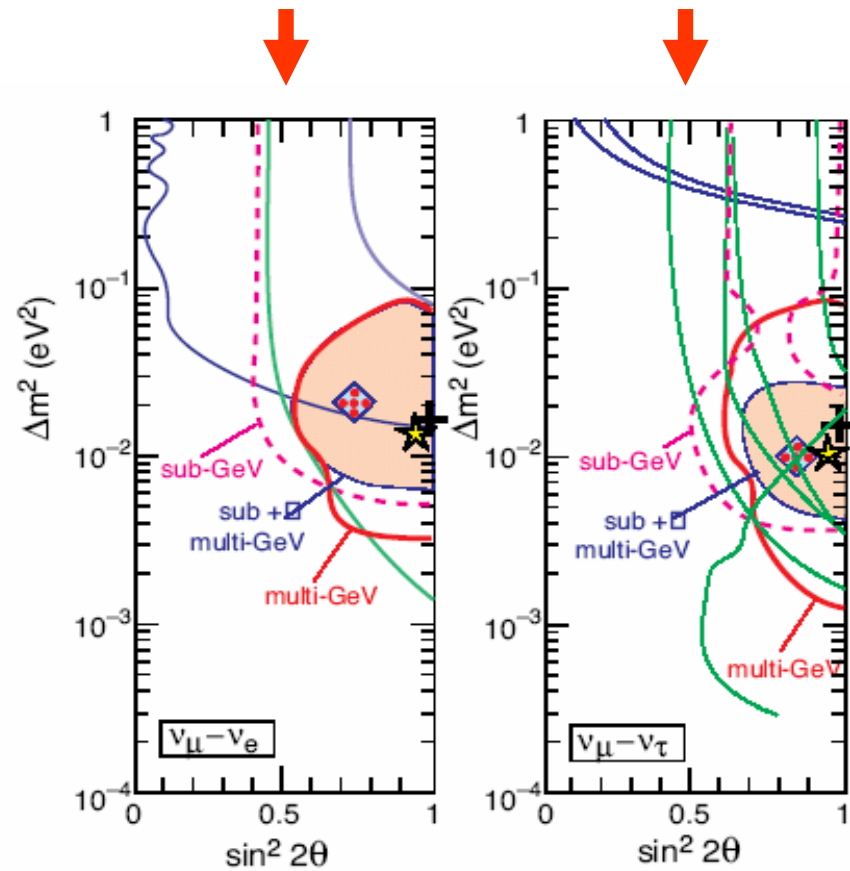
# Kamiokande atmospheric neutrinos anomaly 1994 -1997:

$$R = \frac{(v_{\mu}/v_e)_{\text{measured}}}{(v_{\mu}/v_e)_{\text{expected}}} \sim 0.6$$

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



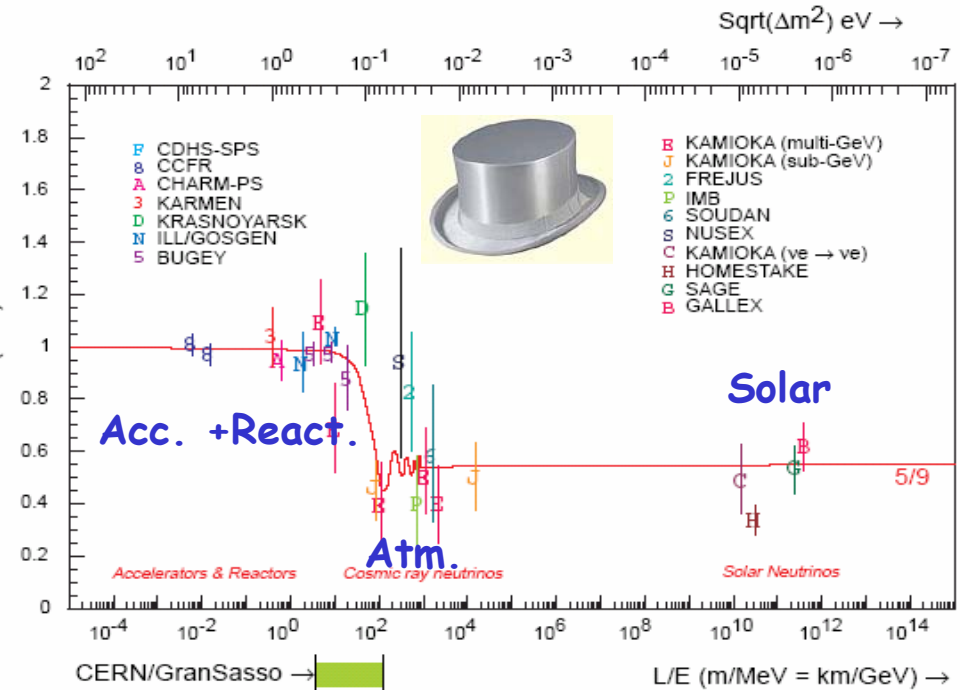
Some first zenith angle dependence



# The Perkins plot (PLB 349 1995)

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

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

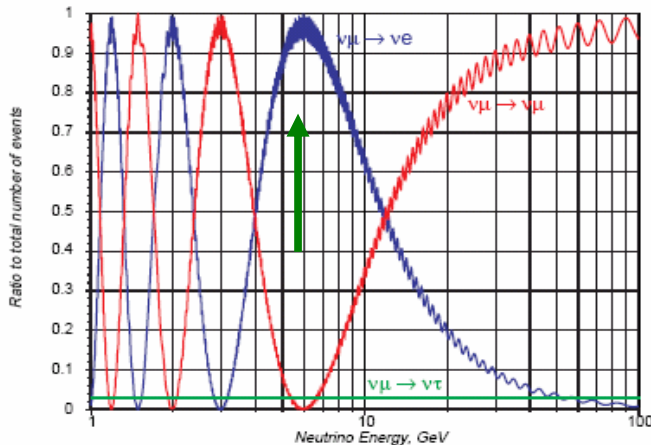


(C) Gran Sasso (735 km)

Icarus SPSLC 96/58 P304 19/12/1996

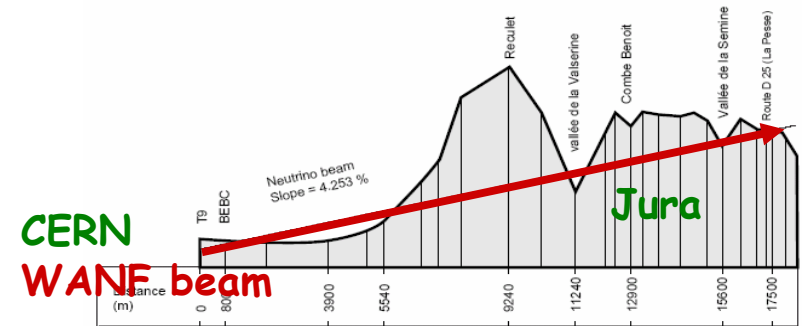
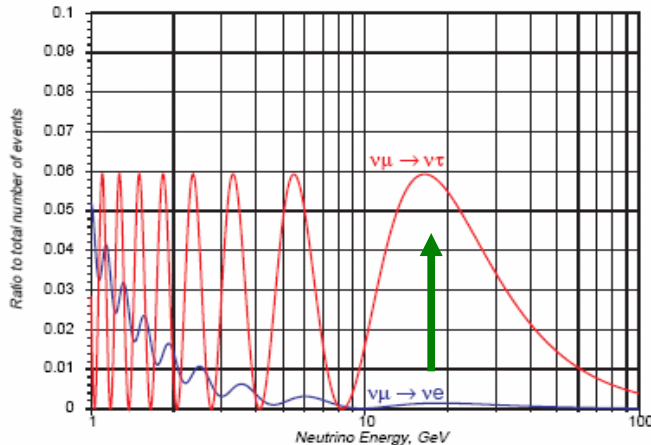
## 6. Conclusion

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.

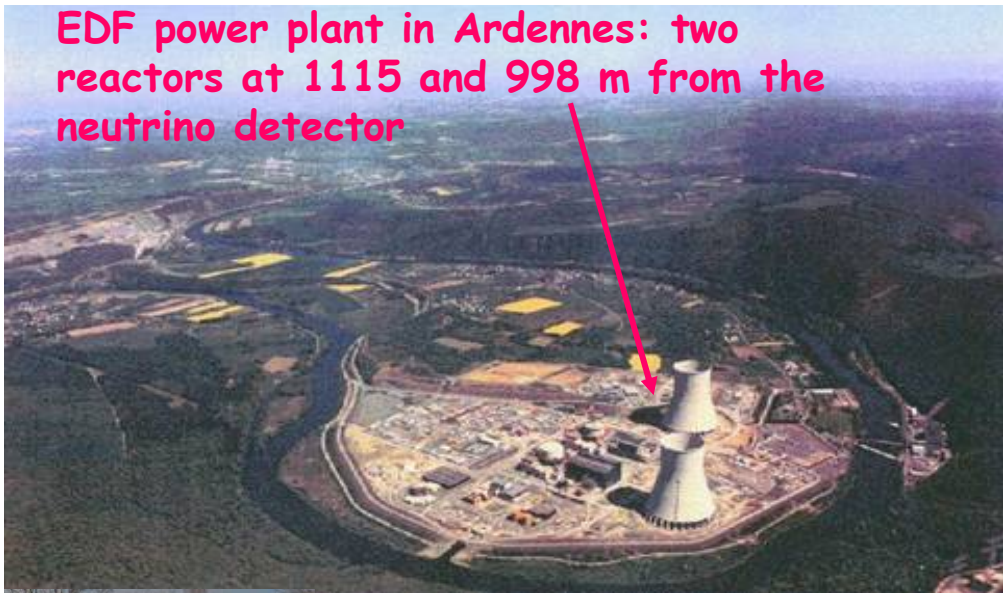


(B) Behind Jura (17 km)

Medium-baseline L/E ~ 1 Km/GeV



# CHOOZ (the first long baseline experiment) 1997-1998

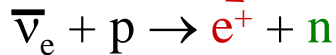


EDF power plant in Ardennes: two reactors at 1115 and 998 m from the neutrino detector



Target: 5 ton liquid scintillator with 0.09% Gadolinium

Prompt annihilation signal ( $\gamma$  rays)



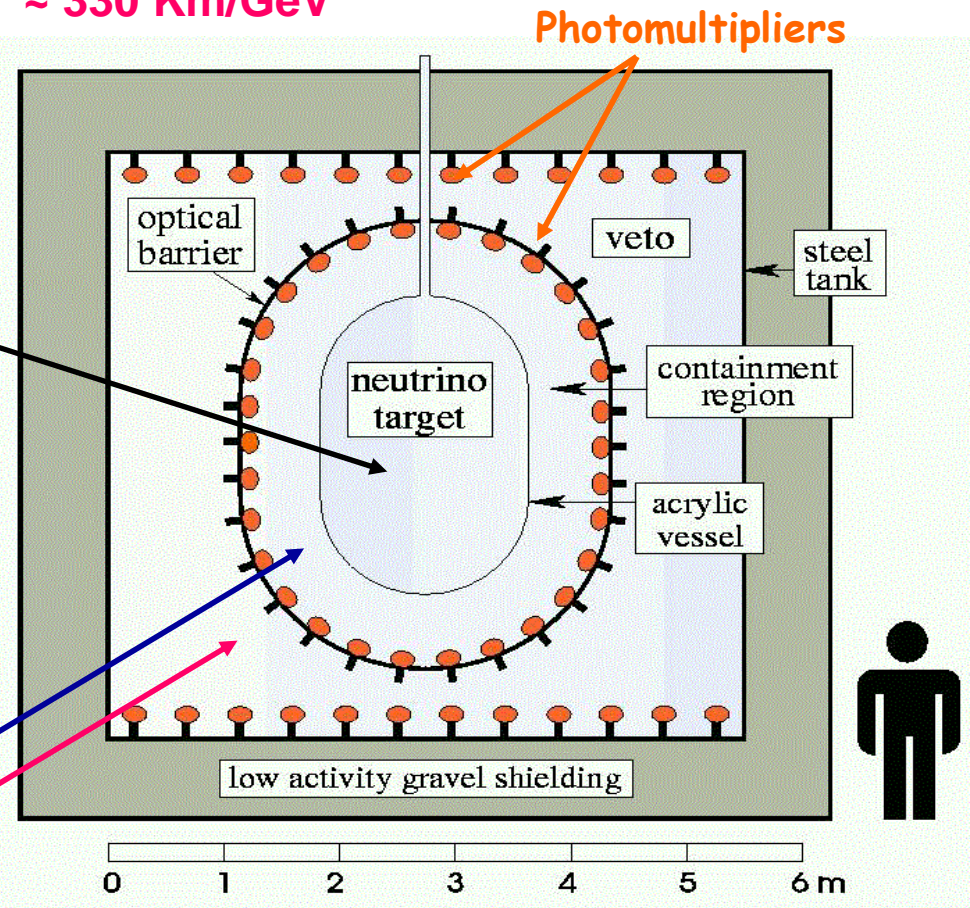
$n$  capture on Gd after thermalization  $\sim 30\mu\text{s}$

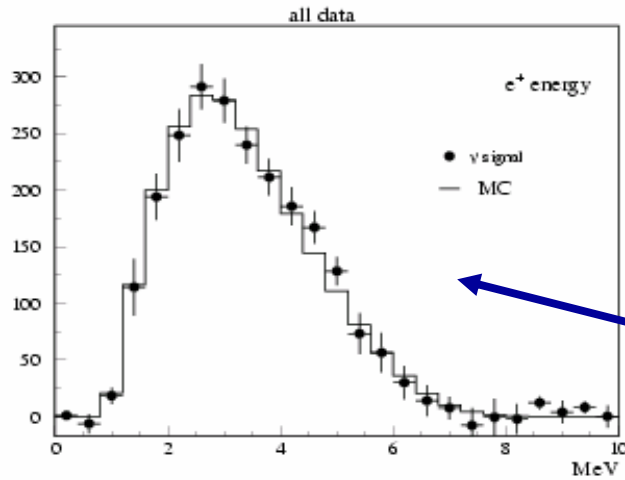
17 ton liquid scint. without Gd (containment of  $\gamma$  rays)

90 ton liquid scint. cosmic rays  $\nu_e$

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

$P_{\text{th}} = 8.5 \text{ GW}_{\text{th}}$ , 1 detector at  $L \sim 1 \text{ km}$ , overburden equivalent to 300 m  $\text{H}_2\text{O}$ , Reactor neutrino flux known at 2.7 %,  $L/E \sim 330 \text{ Km/GeV}$



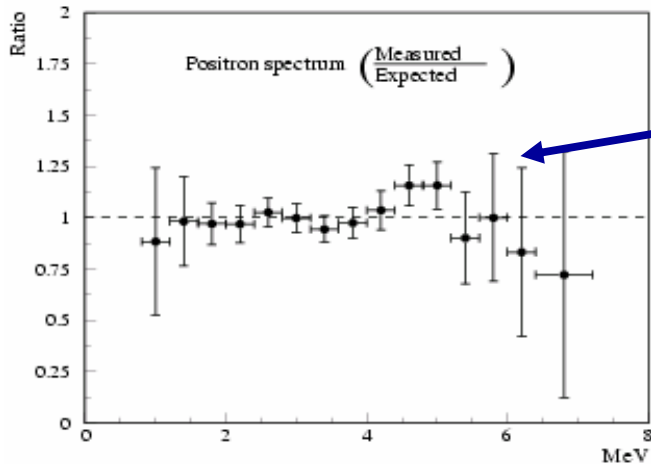


$$N(\bar{\nu}_e) \sim 2 \cdot 10^{20} \text{ s}^{-1} / \text{GW}_{\text{th}}$$

Signal  $\sim 25$  events/day,  
background (reactors off)  
 $\sim 1.2$  events/day

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

$$E(\bar{\nu}_e) = E(e^+) + 1.8 \text{ MeV}$$

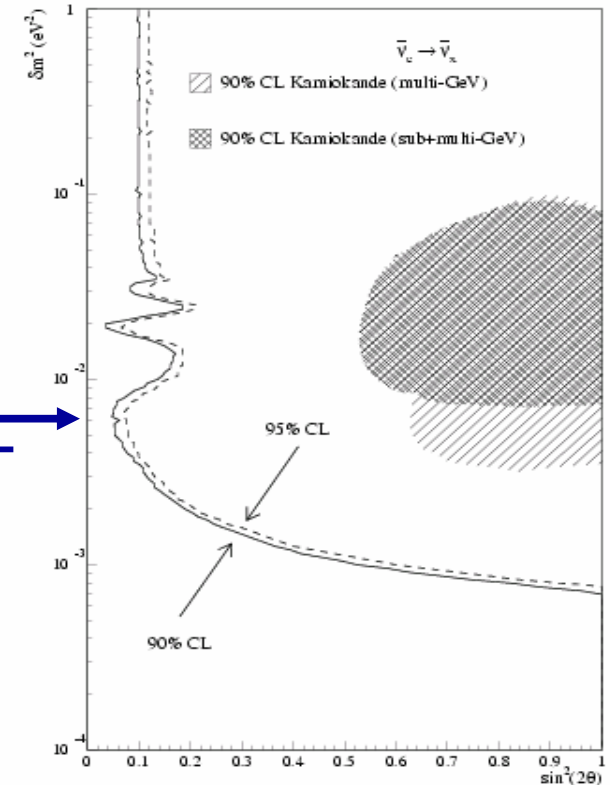
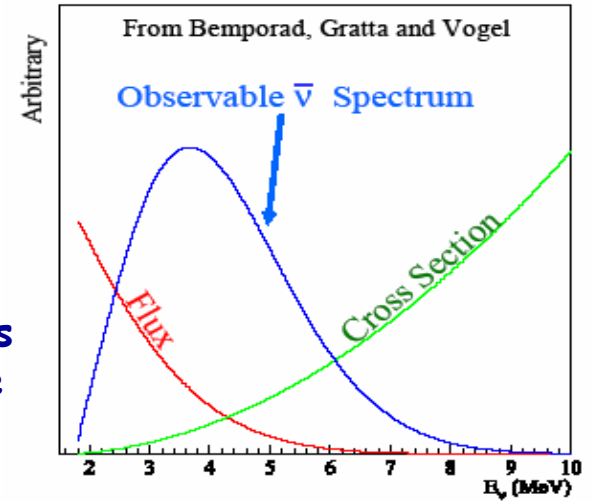


Ratio measured/expected

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

CHOOZ did not observe a significant deficit of  $\bar{\nu}_e$

NO « monumental »  $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$  conversion

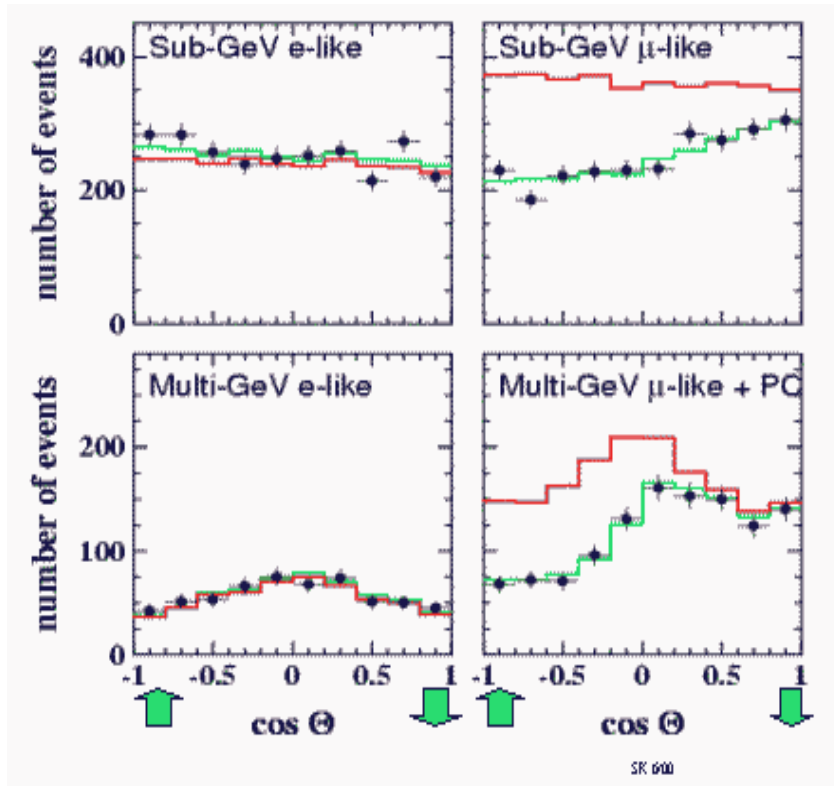


This result was published in 1998 before the Super-Kamiokande results and excluded the atmospheric neutrino anomaly interpretation in terms of  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations

# Neutrino 98 Conference in Takayama (June 1998)

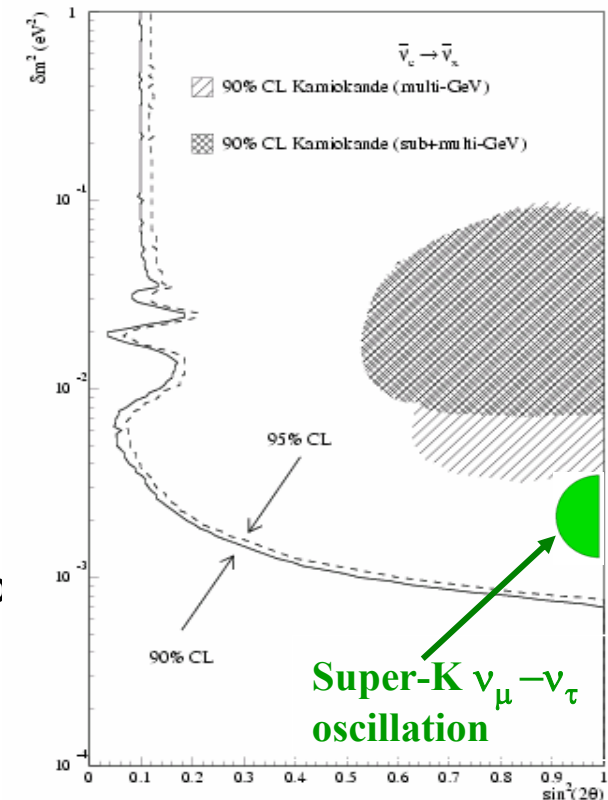
(see G. Giacomelli Lectures)

First results from Super-Kamiokande on atmospheric neutrinos, evidence of a zenith angle dependence of  $\nu_\mu$  disappearance,  $\nu_e$  in agreement with expectations



SK: Atmospheric neutrinos anomaly  
 interpretable in terms of  $\nu_\mu \rightarrow \nu_\tau$  oscillations  
 with a  $\Delta m^2 \sim$  a few  $10^{-3} \text{ eV}^2$

CHOOZ: no  $\nu_\mu \rightarrow \nu_e$  oscillations,  $\Theta_{13} < 11^\circ$



Neutrino oscillations start to be taken seriously as explanatory of the atmospheric neutrinos anomaly  
 Opens a campaign for a new generation of long baseline experiments to provide a final proof

2<sup>nd</sup> Lecture