Search for $\nu_\mu \rightarrow \nu_e$ Oscillations in the

NOMAD

Neutrino Oscillation MAgnetic Detector

Experiment

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for

The NOMAD Collaboration:

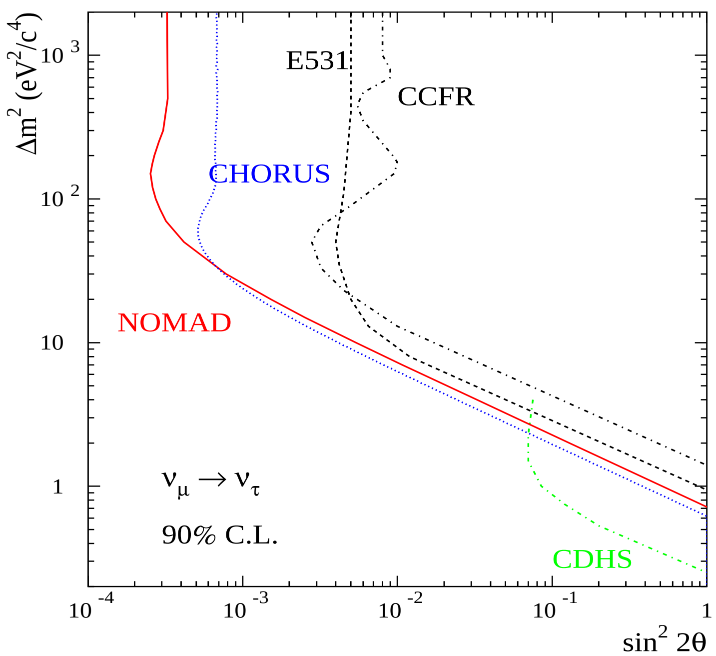
Australia:	*Melbourne, Sydney*
CERN	
Croatia:	*Zagreb*
France:	*LAPP Annecy, Paris VI and VII, Saclay DAPNIA*
Germany:	*Dortmund*
Italy:	*Cosenza, Firenze, Padova, Pavia, Pisa, Roma Tre, Urbino*
Russia:	*INR Moscow, JINR Dubna*
Spain:	*Valencia*
Switzerland:	*Lausanne, ETH Zurich*
USA:	*Harvard, Johns Hopkins, South Carolina, UCLA*

IV INTERNATIONAL CONFERENCE
on NON-ACCELERATOR NEW PHYSICS

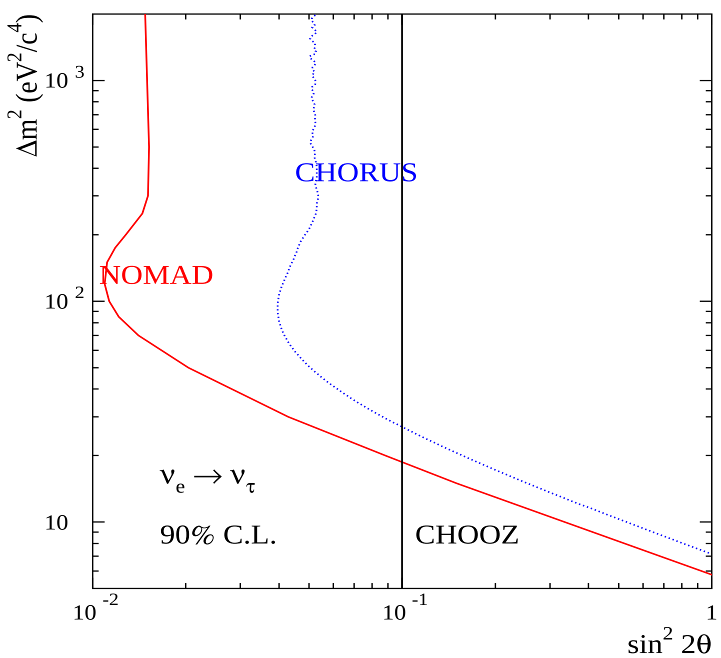
Dubna, June 23–28, 2003

Final Published Results of the ν_τ Search

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



- $\nu_e \to \nu_\tau$

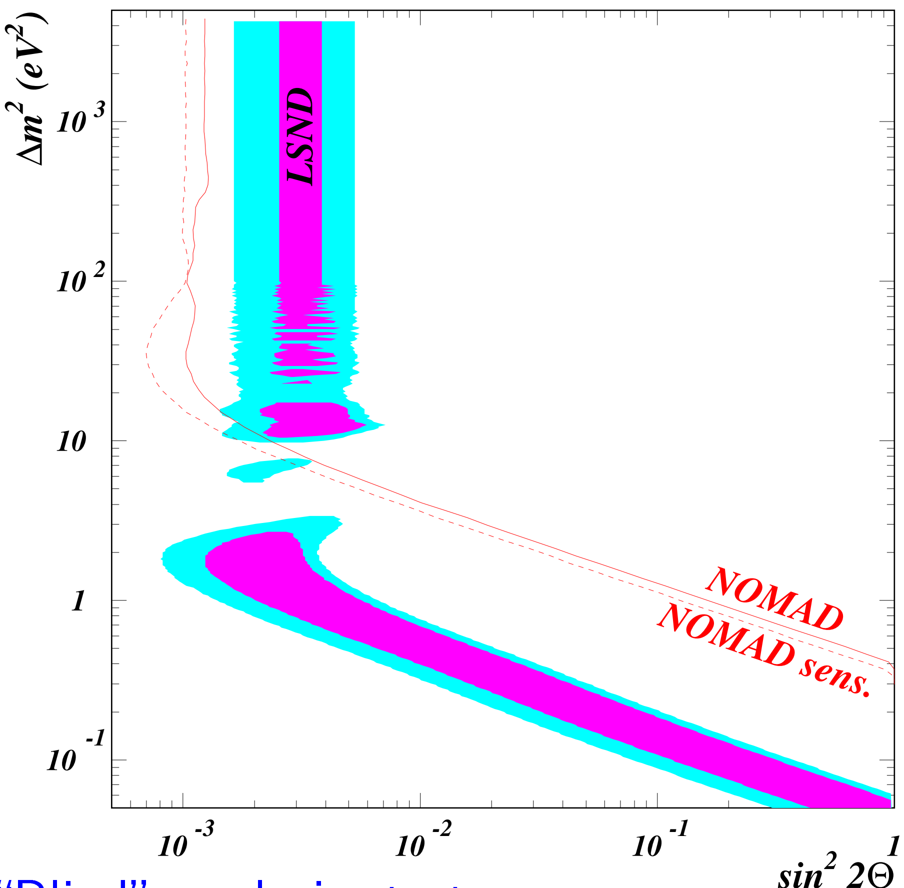


$$\left\{ \begin{array}{lll} \text{At large} & \Delta m^2 : & \\ P_{\nu_\mu \to \nu_\tau} & < & 1.63 \times 10^{-4} \quad (90\%\ \mathrm{C.L.}) \\ \sin^2 2\theta_{\nu_\mu \nu_\tau} & < & 3.3 \times 10^{-4} \end{array} \right.$$

$$\left\{ \begin{array}{lll} \text{At large} & \Delta m^2 : & \\ P_{\nu_e \to \nu_\tau} & < & 0.74 \times 10^{-2} \\ \sin^2 2\theta_{\nu_e \nu_\tau} & < & 1.5 \times 10^{-2} \end{array} \right.$$

Search for $\nu_\mu \to \nu_e$ Oscillations in NOMAD

- Motivated, in part, by LSND claim for evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ oscillations
- Only preliminary results were presented before



EPS 2001 plot

- "Blind" analysis strategy:

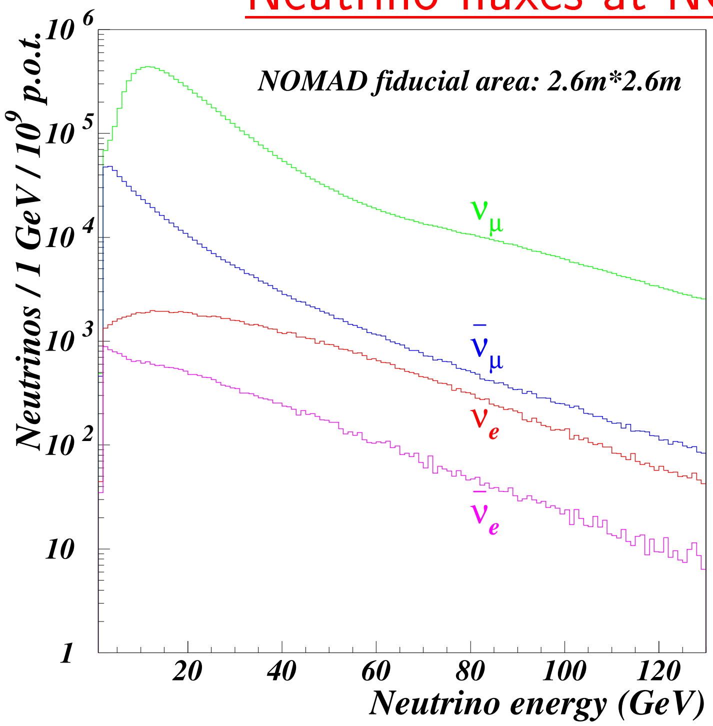
$\Rightarrow$ compare ν_e CC and $R_{e\mu}$ distributions in data and MC only after robust flux predictions and full error analysis

- Careful simulation of the neutrino beam line
- Detailed analysis of systematic uncertainties

Search for $\nu_\mu \to \nu_e$ Oscillations in NOMAD

- Appearance experiment; based on powerful electron identification in the NOMAD detector
- Exploits low ν_e contamination in the CERN wide band neutrino beam

Neutrino fluxes at NOMAD:



ν_x/ν_μ	$\langle E_\nu \rangle$, GeV
1.0	24.3
0.068	17.2
0.010	36.4
0.0027	27.6

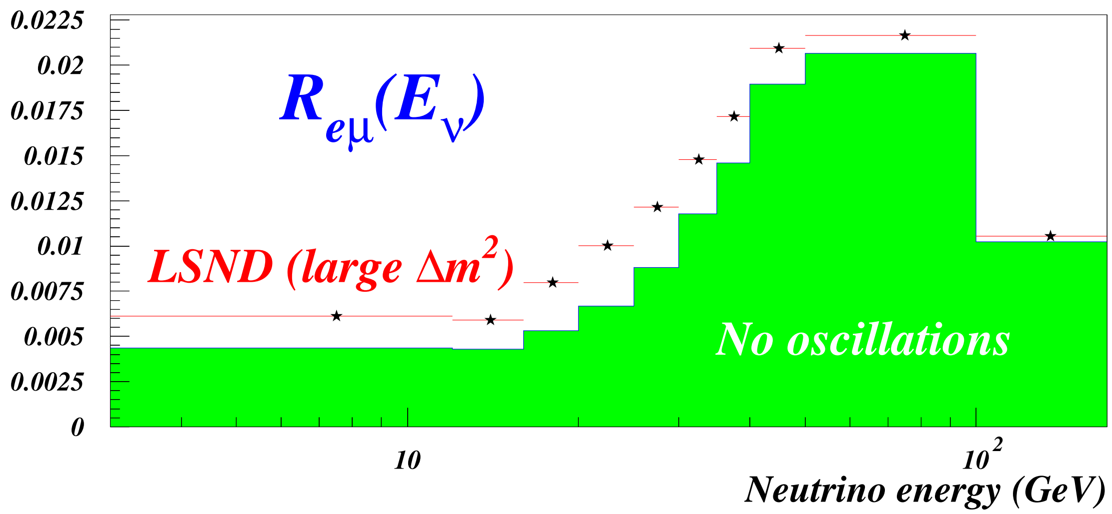
- Relative ν_e/ν_μ abundance in CERN SPS beam $\sim 1\%$
  $\Rightarrow$ $\nu_\mu \to \nu_e$ oscillations at a 10^{-3} level would increase the expected ν_e flux by $\sim 10\%$
- Different energy spectra for ν_e and ν_μ
  $\Rightarrow$ oscillation effect is enhanced at low ν_e energies
- Radial distribution of ν_e is broader than that of ν_μ
  $\Rightarrow$ oscillation effect is enhanced at the center of the detector

The General Analysis Procedure

To reduce systematic uncertainties, we study the ratio $R_{e\mu}$ of the number of charged current interactions (ν_e CC)/(ν_μ CC), as a function of E_ν and r:

$$R_{e\mu} = \frac{\text{“}\nu_e \text{ CC”}}{\text{“}\nu_\mu \text{ CC”}}(E_\nu, r) =$$

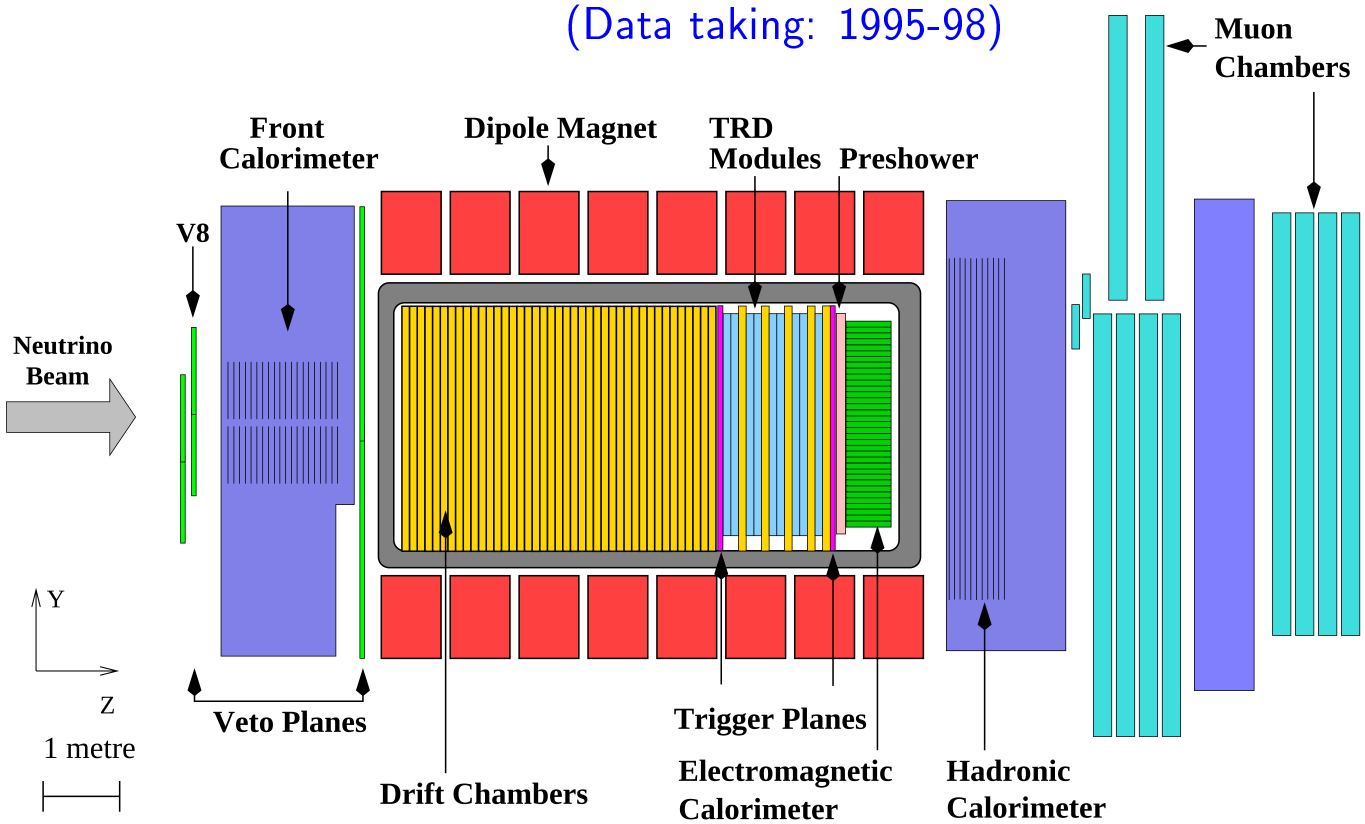
$$= \frac{e^-(\nu_e \text{ CC}) + e^-(bkg) + e^-(\nu_e^{osc} \text{ CC})}{\mu^-(\nu_\mu \text{ CC}) + \mu^-(bkg)}$$



- Select ν_μ CC and ν_e CC interactions (applying lepton ID and kinematic criteria optimised on MC samples).
- Estimate remaining “non-prompt” μ^- and e^- backgrounds.
- Reconstruct neutrino energy E_ν and radial position r on event-by-event basis.
- Estimate systematic uncertainties.
- Compare measured and predicted $R_{e\mu}(E_\nu, r)$.

NOMAD Detector

(Data taking: 1995-98)



Trigger: $\bar{V}$ $T1$ $T2$

- Drift Chambers (target and momentum measurement)
  - Position resolution < 200 μm (small angle tracks)
  - Momentum resolution $\sim 3.5\%$ ($p <$ 10 GeV/c)
- Transition Radiation Detector for $e^{\pm}$ identification
  - π rejection $\sim 10^3$ for electron efficiency $\geq 90\%$
- Lead glass Electromagnetic Calorimeter

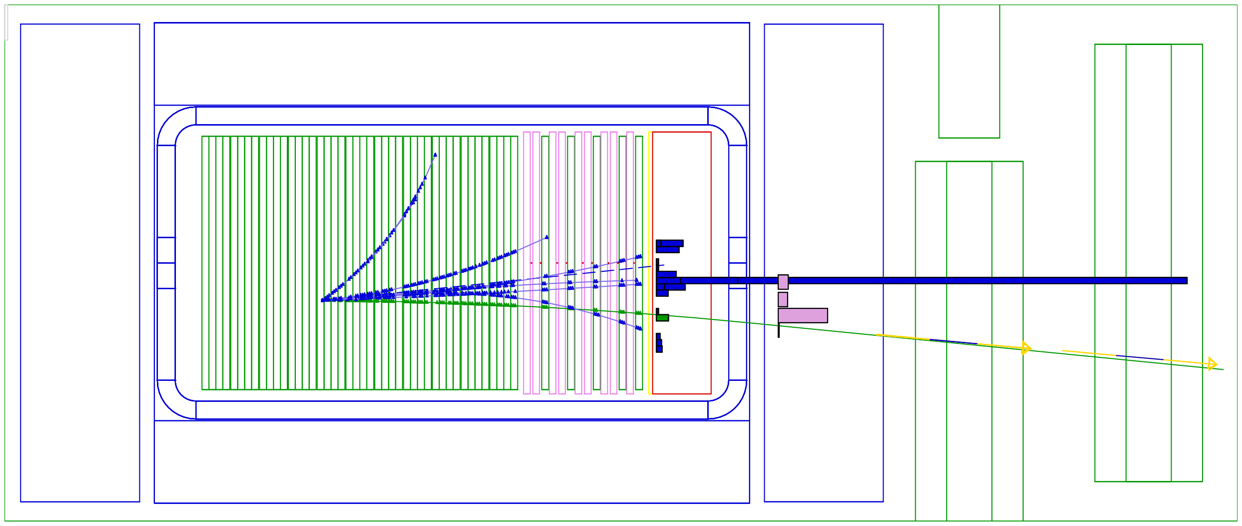
$$\frac{\sigma(E)}{E} = (1.04 \pm 0.01)\% + \frac{(3.22 \pm 0.07)\%}{\sqrt{E(\mathrm{GeV})}}$$

- Muon Chambers for $\mu^{\pm}$ identification
  - Efficiency $\approx 97\%$ ($p_{\mu} > 5$ GeV/c)
- Hadronic Calorimeter for n and K_L^0 veto

Selection of ν_μ CC Interactions

- $\mu^\pm$: track in the drift chambers associated with the segments reconstructed in the muon chambers

  $\Rightarrow$ Clear signature, simple selection



  – Background (mainly ν_μ NC) is small, easy to reject

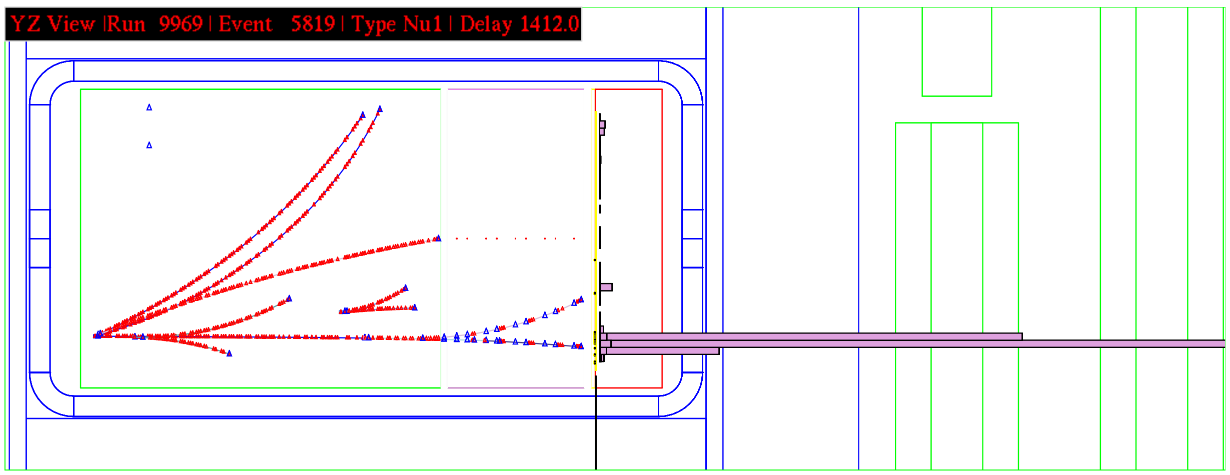
- 1995-98 data sample: 748 000 ν_μ CC candidates ($\varepsilon \sim 60\%$)

after applying selection criteria identical to those used for ν_e CC selection (except particle ID)

- Estimated background contamination: $\ll 0.1\%$

Selection of ν_e CC Interactions

- $e^{\pm}$: primary isolated track, identified by TRD and ECAL
  - Signature is less obvious, requires sophisticated selection



Main "non-prompt" backgrounds:

- Misidentified hadrons ($\pi^{\pm}$, $K^{\pm}$, etc.)
- Real electrons ($\gamma \to e^+e^-$, $\pi^0 \to \gamma e^+e^-$, etc.)

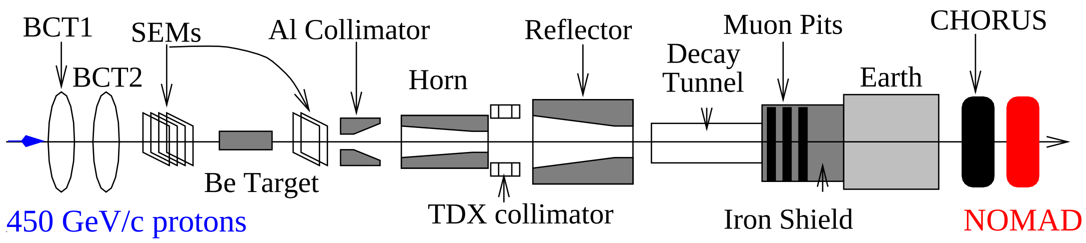
in ν_μ interactions:

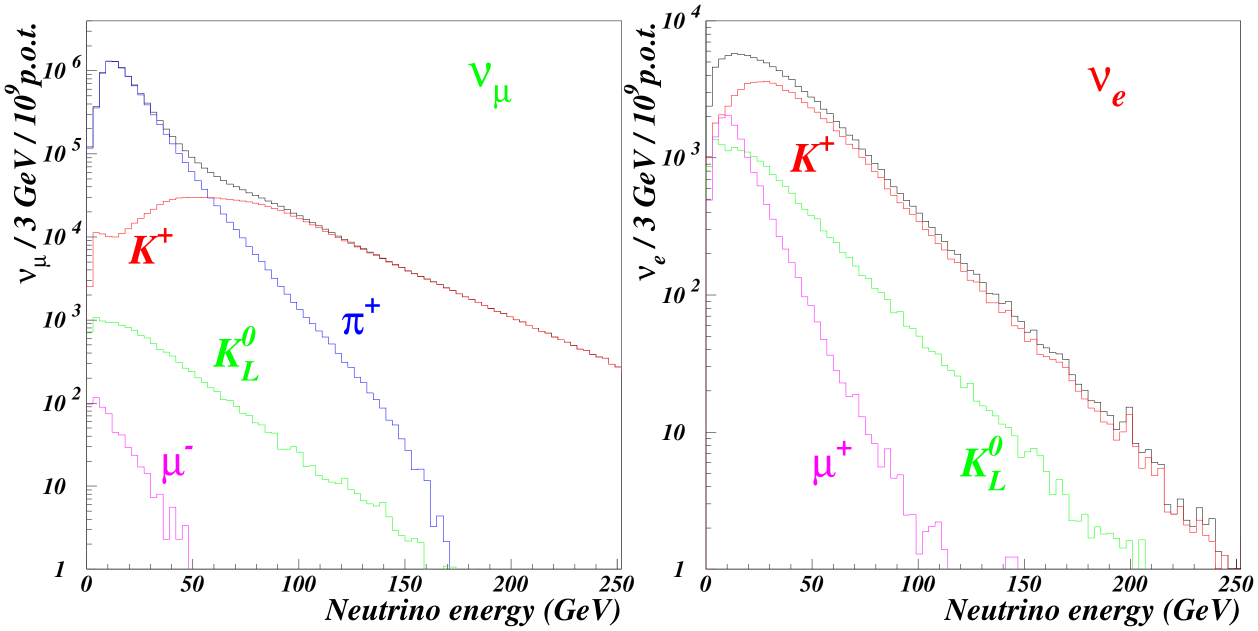
- ν_μ NC: $\nu_\mu\ N \to \nu_\mu\ X$;
- ν_μ CC: $\nu_\mu\ N \to \mu^-\ X$ where μ^- was not identified.
  - Background is large, difficult to reject

- 1995-98 data sample: 8000 ν_e CC candidates (ε ~44%)
- Estimated background contamination: $\sim$ 2.0%

The CERN Neutrino Beam

(not in scale)





An accurate knowledge of the neutrino beam is crucial

- Cross sections of particle production in initial pBe interactions are given by the FLUKA 2000 version modified to take into account the measurements of NA56/SPY and NA20.
- Beam line is described using the GEANT package; secondary interactions ($\sim$ 10% of ν_μ and ν_e fluxes) are simulated by the FLUKA 2000 version.

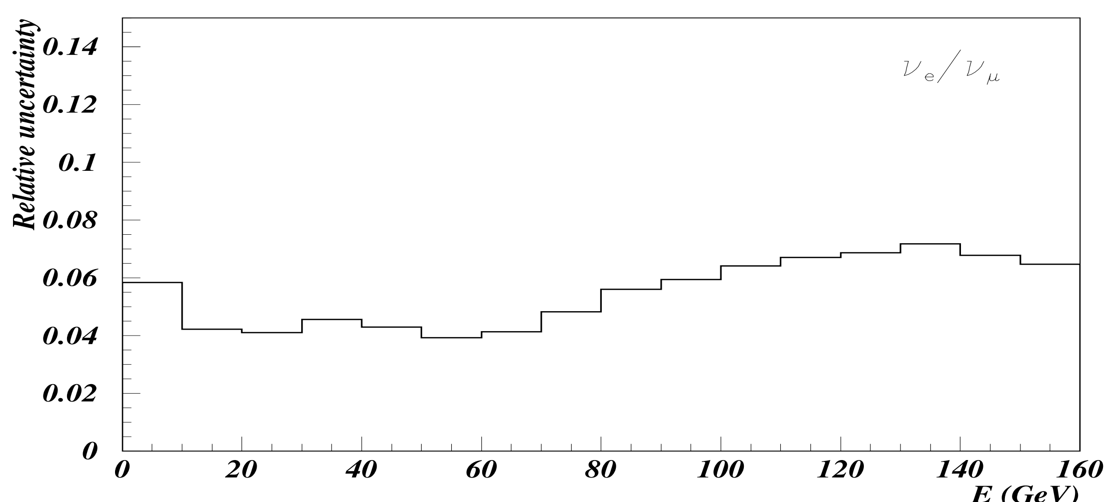
This work is now finalized. The corresponding paper (hep-ex/0306022, CERN–EP/2003–032) is submitted to NIM A

Systematic Uncertainties

- Many of them are reduced using $R_{e\mu}$ ratio
- Dominant errors are due to uncertainties in π^+, K^+ and K^0_L yields

Source of systematic error	Error on $R_{e\mu}$
Particle production	$\sim 5\%$
Beam transport	$\sim 3\%$
Electron efficiency (identification and reconstruction)	1.0%
Fragmentation and reinteraction model	up to 2%
Electron energy scale	$< 1.0\%$
Relative efficiency of kinematic selection	negligible between 10 and 80 GeV
"Non-prompt" background (amount and shape)	negligible
Mix of QEL, RES and DIS events	negligible

- Beam-related energy-dependent uncertainty on $R_{e\mu}$:



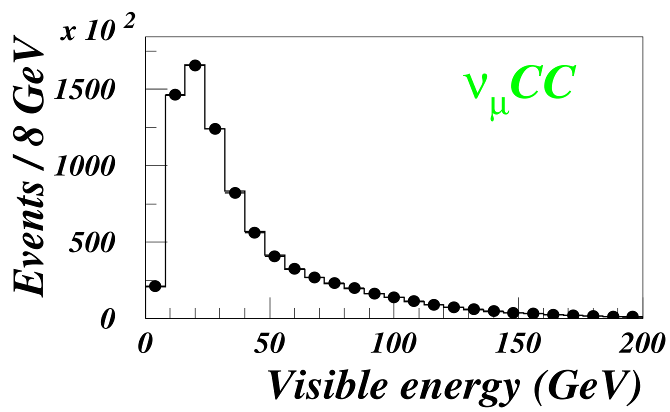
- Beam normalization uncertainty: 4.2%

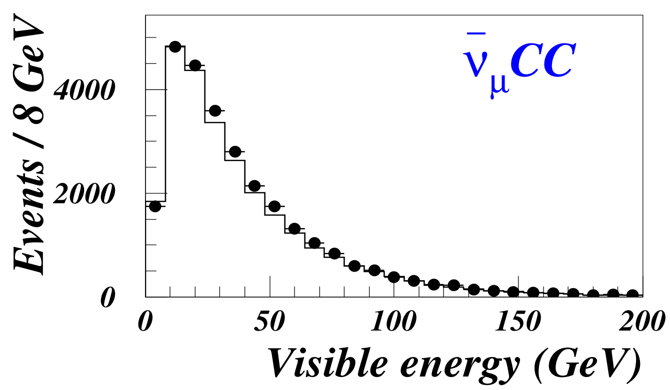
Control Samples: Data vs Monte Carlo

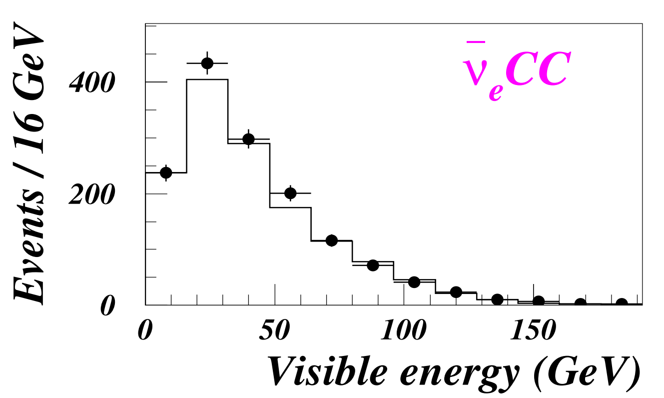
Neutrino energy is approximated by a visible energy:

$$E^{vis} = E^{lepton} + \sum E^{prim.trks} + \sum E^{neutrals} + \sum E^{V_0}$$

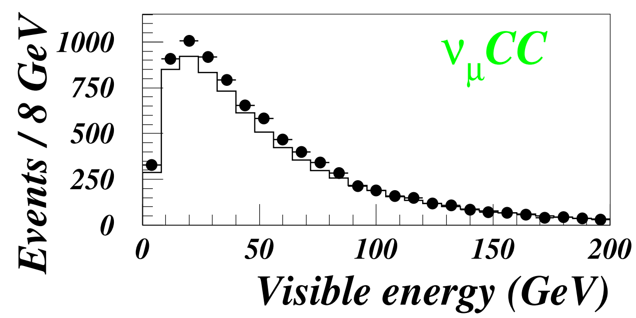
Neutrino beam

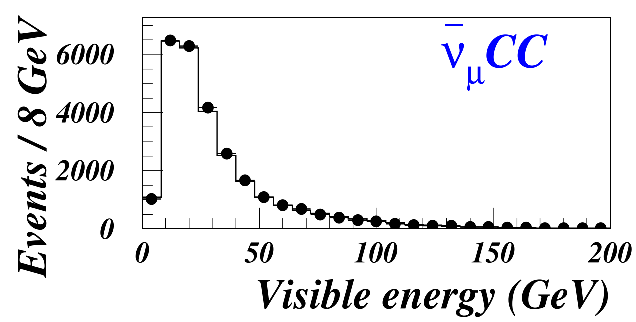


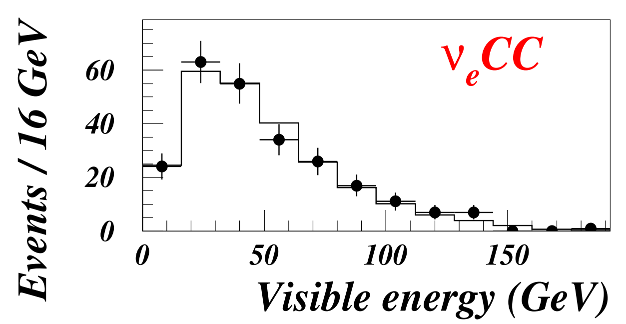


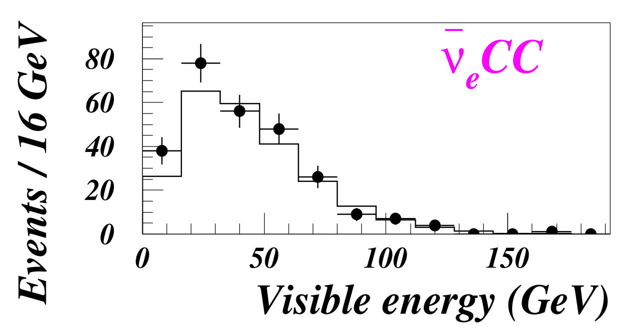


Antineutrino beam

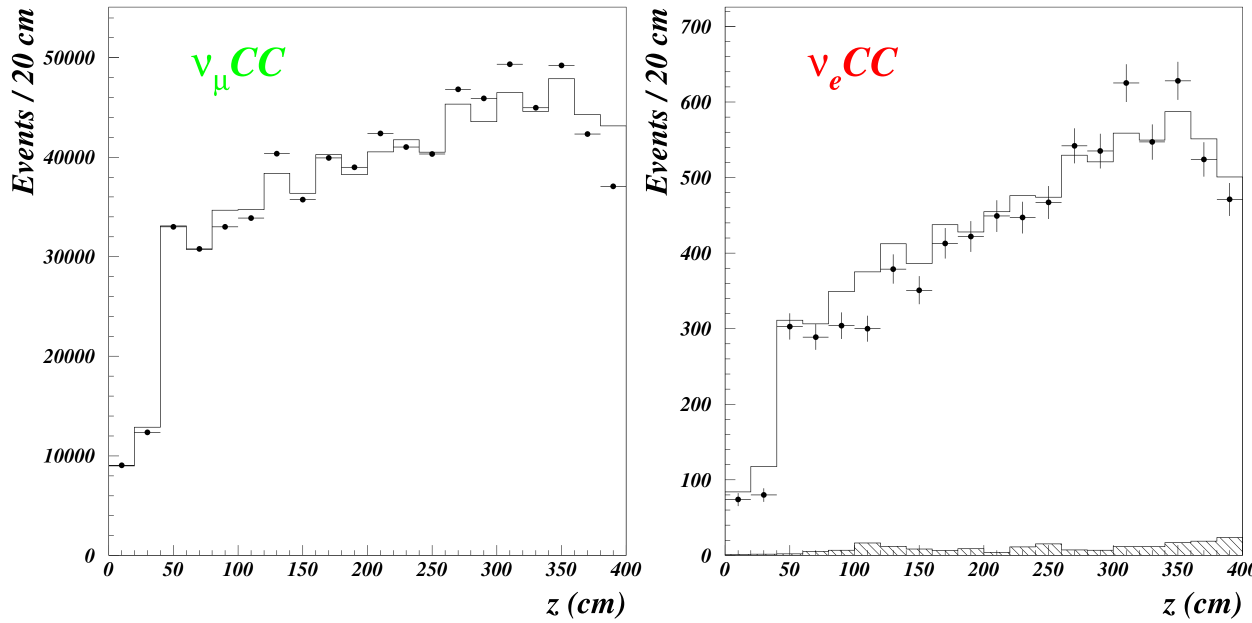








Selection of ν_μ CC and ν_e CC Events



- Additional fiducial cuts to improve the DATA–MC consistency.

$\Rightarrow$ Differences are related to a cut - "density cut" - inctroduced during the reconstruction of events: events with a very high density of hits in the DC were not reconstructed due to a prohibitive reconstruction time. The effect of this cut is different on the two samples

$\Rightarrow$ We put a requirement on the z position of the primary vertex

$$z > 184 \text{ cm}$$

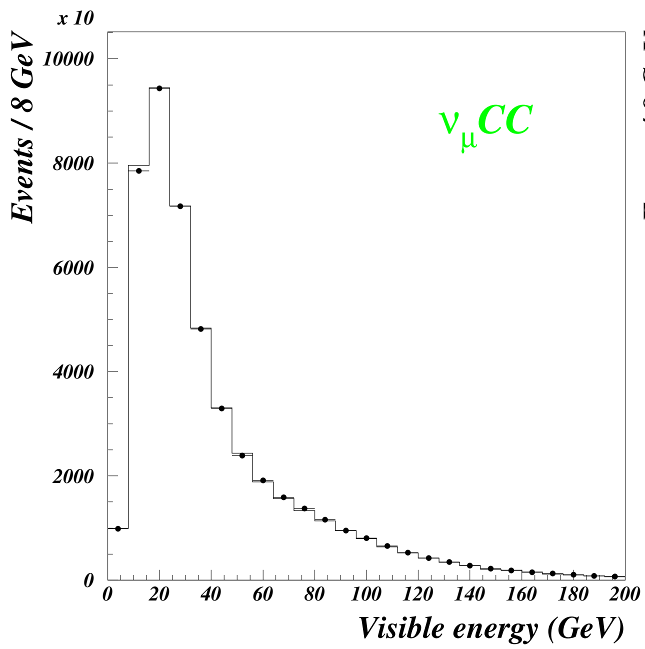
$\Rightarrow$ It should be noted that oscillation effects could not manifest themselves over this short distance in the detector since the point of origin of the neutrinos is spread over more than 300 m

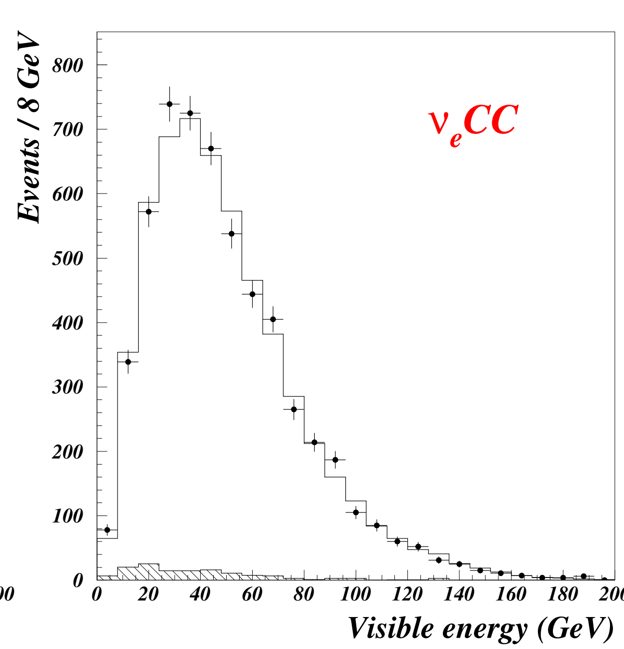
- Finally: 5600 ν_e CC and 470 000 ν_μ CC events were retained

Event Selection: Data vs Monte Carlo

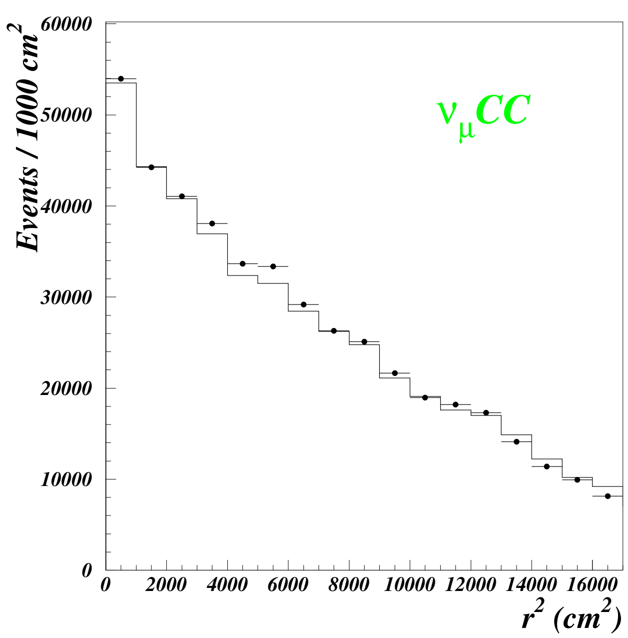
Neutrino energy is approximated by a visible energy:

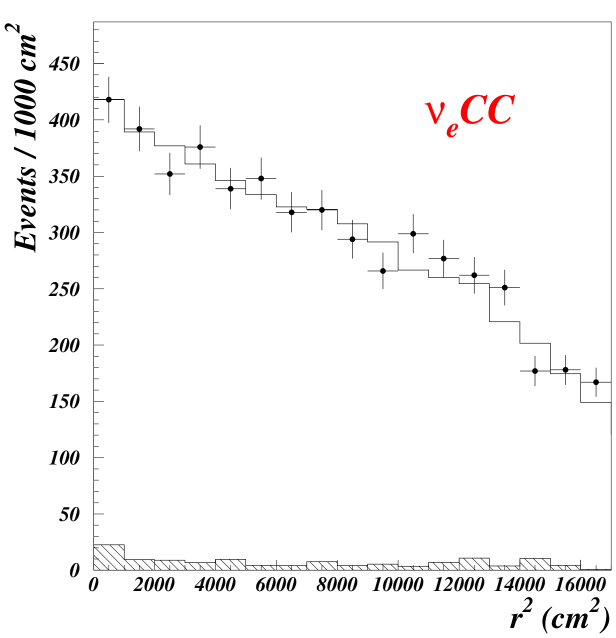
$$E^{vis} = E^{lepton} + \sum E^{prim.trks} + \sum E^{neutrals} + \sum E^{V_0}$$





r^2 - the square of the radial position of the neutrino interaction vertex with respect to the beam axis

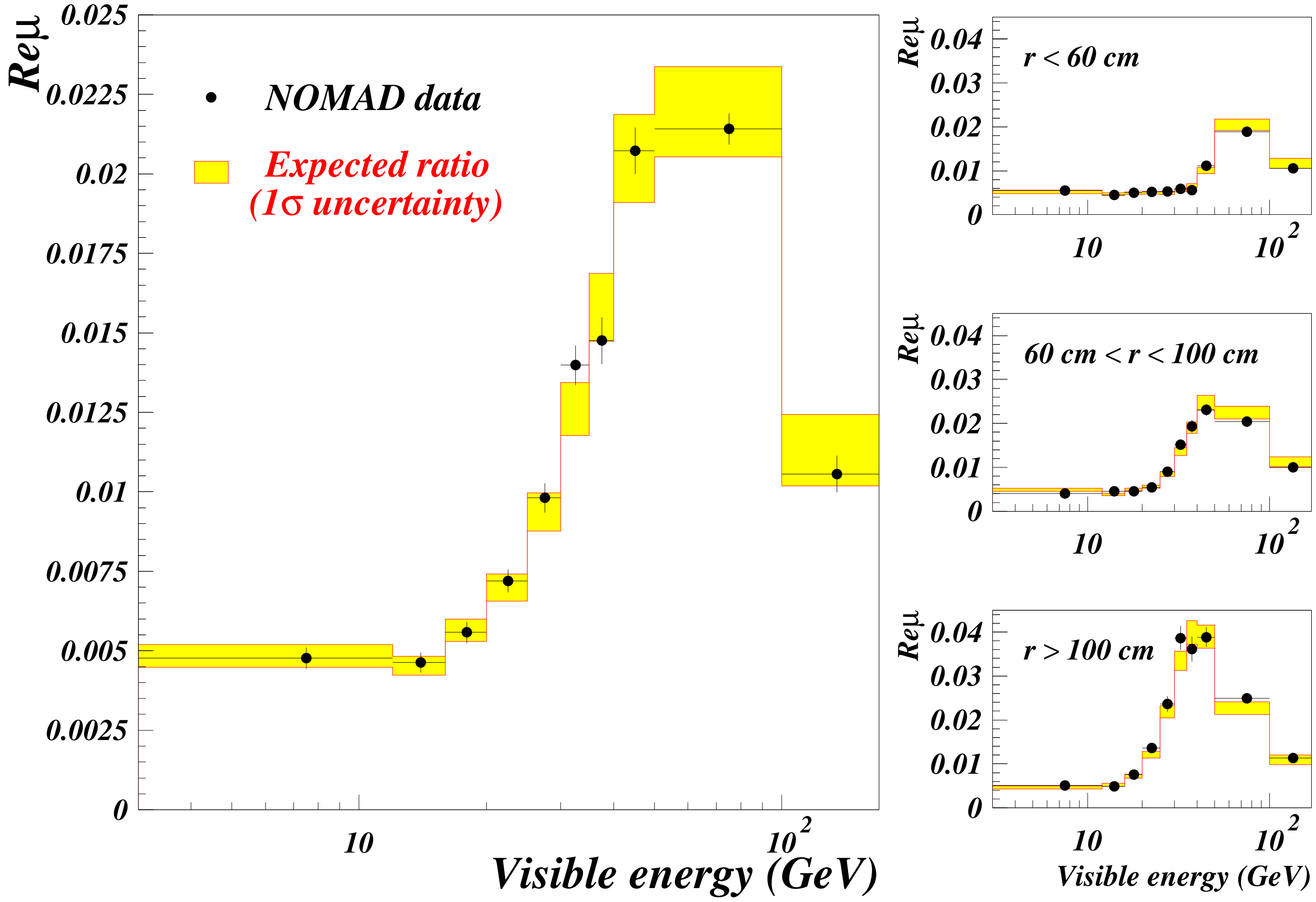




Final Results

- Beam bin-to-bin systematic errors: from 4 to 7%
  (mainly uncertainties in π^+, K^+ and K^0_L yields)
- Beam overall (normalization) uncertainty: 4.2%

$R_{e\mu}$ ratio as a function of neutrino energy:



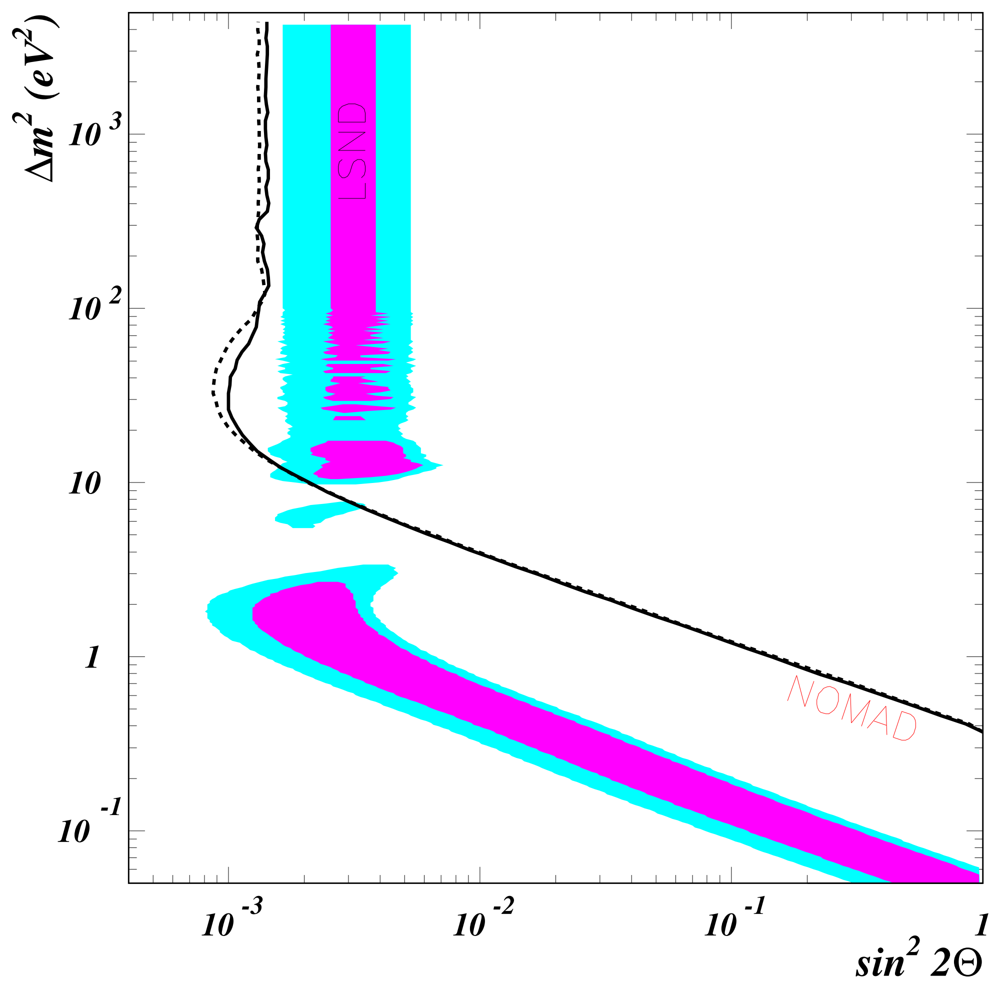
Data are analysed in 10 energy and 3 radial bins:

- χ^2 in the absence of oscillations: 37.1 / 30 d.o.f.
- χ^2_{min} with oscillation hypothesis: 37.0 / 28 d.o.f.

No evidence for oscillations

Final Exclusion Region

($\nu_\mu \to \nu_e$ oscillations)



At large Δm^2: $\sin^2 2\theta_{\nu_\mu \nu_e} < 1.4 \times 10^{-3}$ @ 90% $C.L.$
(Feldman-Cousins method)

Sensitivity (dashed) : $\sin^2 2\theta_{\nu_\mu \nu_e} < 1.3 \times 10^{-3}$ @ 90% $C.L.$

- Exclude the LSND allowed region of oscillation parameters with $\Delta m^2 \geq 10\ eV^2$
- NOMAD is not sensitive to low Δm^2 LSND solutions (limited by beam energy and source–detector distance)

Conclusions and Outlook

- Final results on the $\nu_\mu \to \nu_e$ search in NOMAD are presented
- No evidence for $\nu_\mu \to \nu_e$ oscillations has been found

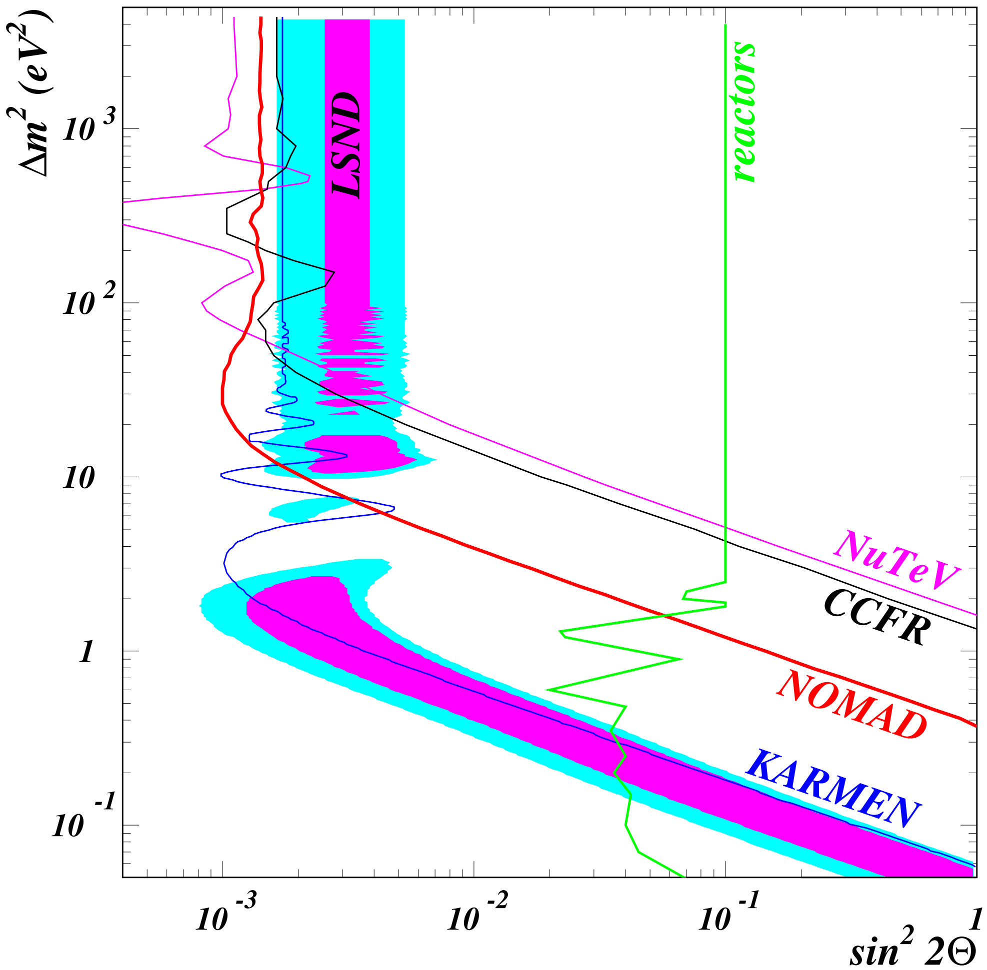
$\Rightarrow$ Limits obtained @ 90% $C.L.$:
$\Delta m^2 < 0.4$ eV^2 for maximal mixing.
At large Δm^2: $\sin^2 2\theta_{\nu_\mu \nu_e} < 1.4 \times 10^{-3}$

$\Rightarrow$ Independently rule out LSND allowed region of oscillation parameters with $\Delta m^2 \geq 10\ eV^2$

- A paper with the results on the $\nu_\mu \to \nu_e$ search in NOMAD (hep-ex/0306037) is submitted to Phys. Lett. B
- Uncertainties in the WANF neutrino flux predictions have been carefully studied and are documented in "Prediction of neutrino fluxes in the NOMAD experiment" (hep-ex/0306022, CERN–EP/2003–032)
- Experience gained with WANF neutrino beam and NOMAD data should help to accurately describe the CNGS neutrino fluxes for the future LBL experiments

Exclusion Region (Compilation)

The resulting NOMAD exclusion region is shown with results of other accelerator experiments, LSND, KARMEN, CCFR and NuTeV, and the combined limit of Bugey and Chooz reactor experiments



At large Δm^2:

$$\sin^2 2\theta_{\nu_\mu \nu_e} \; < \; 1.4 \times 10^{-3} \quad @ \;\; 90\% \;\; C.L.$$

(Feldman-Cousins method)