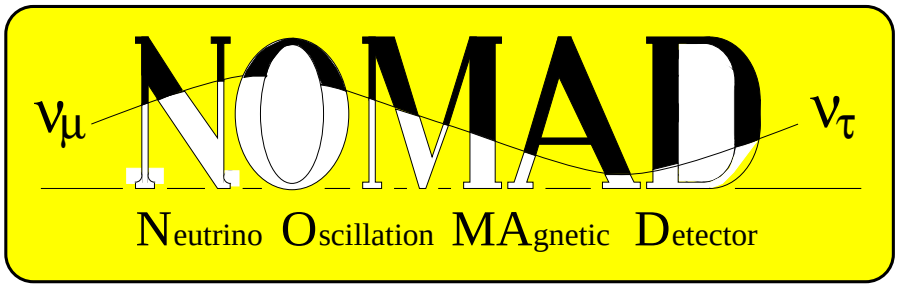
Search for $\nu_\mu \longrightarrow \nu_e$ Oscillations in the



Experiment

Viatcheslav Valuev, UCLA / JINR

for

The NOMAD Collaboration:

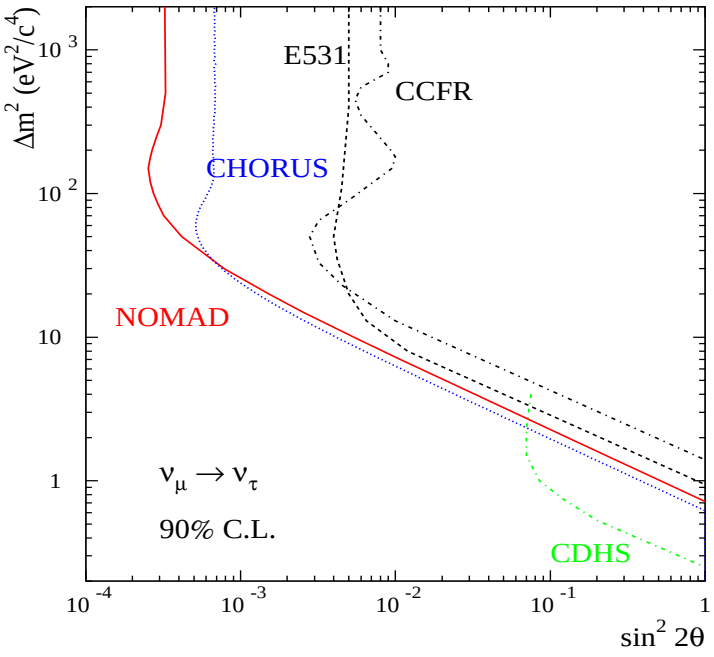
Australia:	*Melbourne, Sydney*
CERN	
Croatia:	*Zagreb*
France:	*LAPP Annecy, Paris VI and VII, Saclay DAPNIA*
Germany:	*Dortmund*
Italy:	*Cosenza, Firenze, Padova, Pavia, Pisa, Roma Tre, Urbino*
Russia:	*INR Moscow, JINR Dubna*
Spain:	*Valencia*
Switzerland:	*Lausanne, ETH Zurich*
USA:	*Harvard, Johns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

International Europhysics Conference
on High Energy Physics

Budapest, July 12–18, 2001

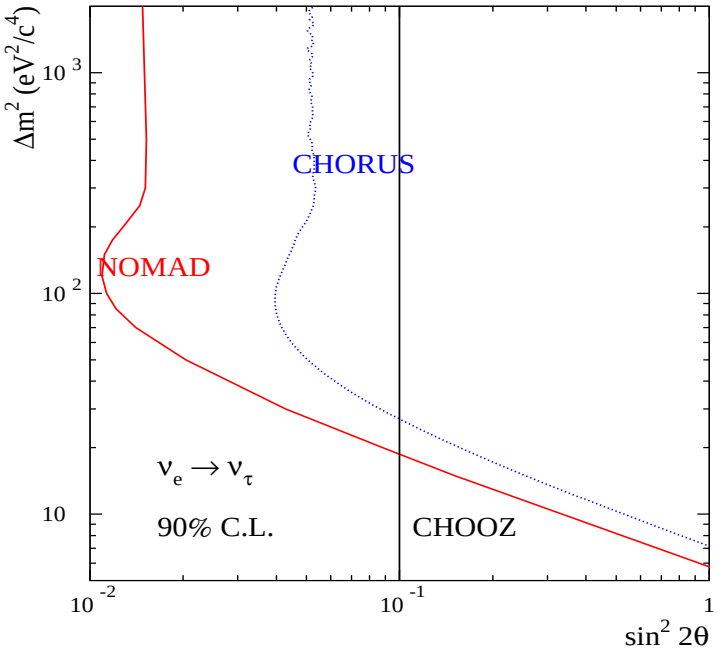
Final Results of the ν_τ Search

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



$$\begin{cases} S_{\nu_\mu \to \nu_\tau} &= 2.50 \times 10^{-4} \\ L_{\nu_\mu \to \nu_\tau} &= 1.63 \times 10^{-4} \\ P(\leq L) &= 37\% \end{cases} \quad (90\%\,\text{C.L.})$$

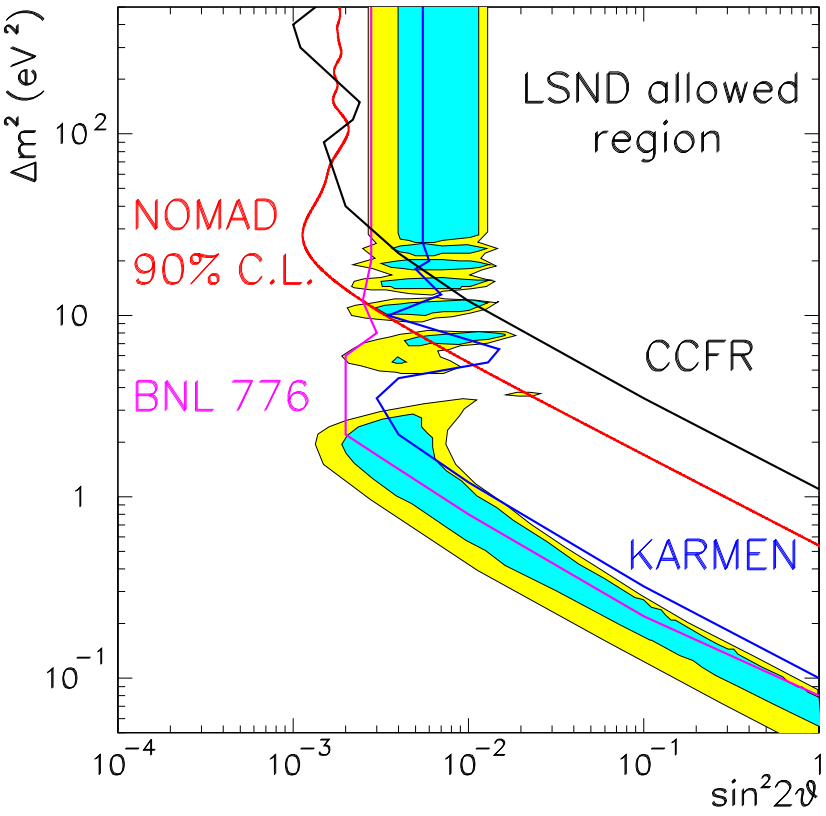
- $\nu_e \rightarrow \nu_\tau$



$$\begin{cases} S_{\nu_e \to \nu_\tau} &= 1.10 \times 10^{-2} \\ L_{\nu_e \to \nu_\tau} &= 0.74 \times 10^{-2} \\ P(\leq L) &= 39\% \end{cases}$$

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

- Motivated, in part, by LSND claim for evidence for $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ and $\nu_\mu \longrightarrow \nu_e$ oscillations
- First results, based on 1995 data ($\sim$ 15% of NOMAD data), were presented in 1997-98:



1997 plot

- Since then, "blind" analysis:

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

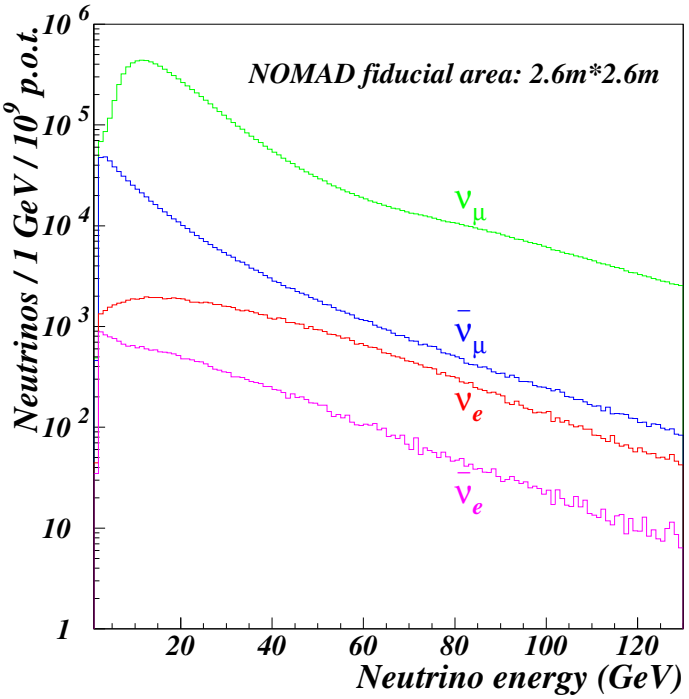
– Full revision of neutrino beam line simulation

– Detailed analysis of systematic uncertainties

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

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

Neutrino fluxes at NOMAD:



ν_x/ν_μ	$\langle E_\nu \rangle$, GeV
1.0	24.2
0.064	18.5
0.010	36.6
0.003	28.7

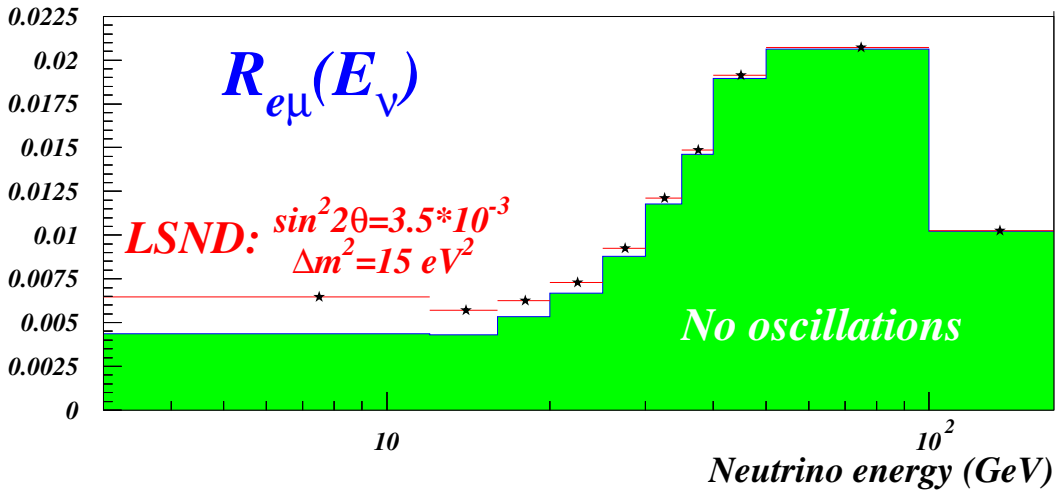
- Relative ν_e/ν_μ abundance in CERN SPS beam $\sim$ 1%
  $\Rightarrow \nu_\mu \longrightarrow \nu_e$ oscillations at a 10^{-3} level would increase the expected ν_e flux by $\sim$ 10%
- Different energy spectra for ν_e and ν_μ
  $\Rightarrow$ oscillation effect is enhanced at low ν_e energies
- Radial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

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

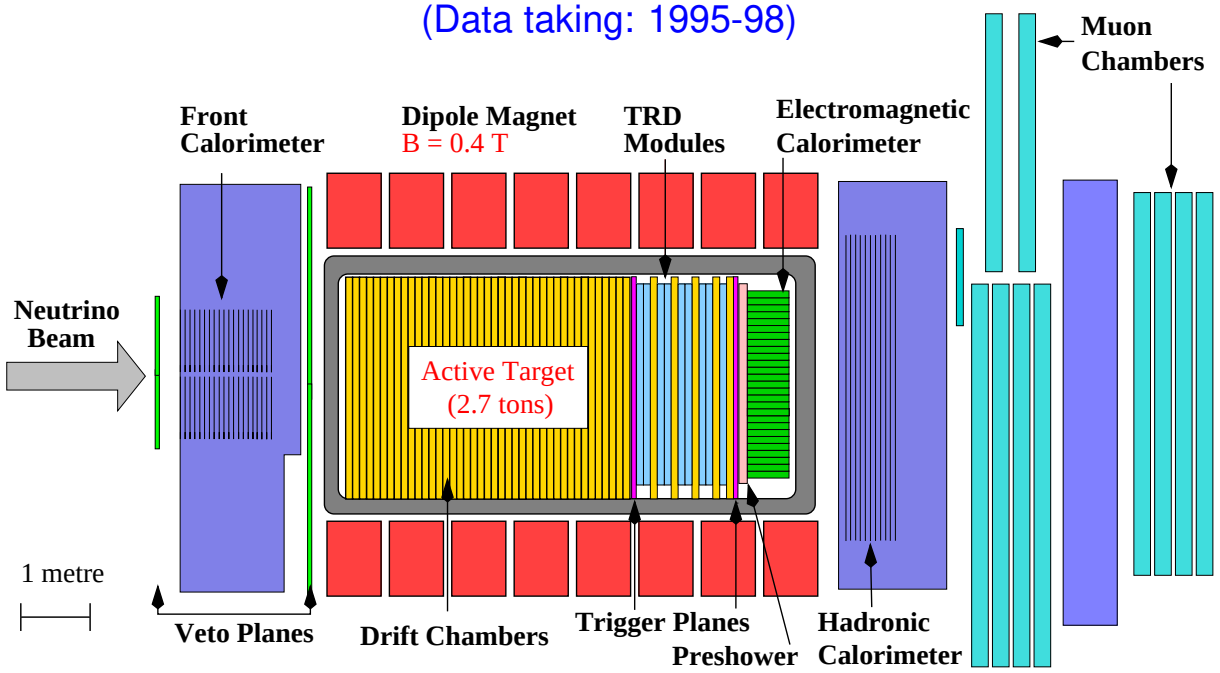
$$= \frac{e^-(\nu_e \text{ CC}) + e^-(bkg) + e^-(\nu_e^{osc} \text{ CC})}{\mu^-(\nu_\mu \text{ CC}) + \mu^-(bkg)}$$



- 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 (TRD) 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

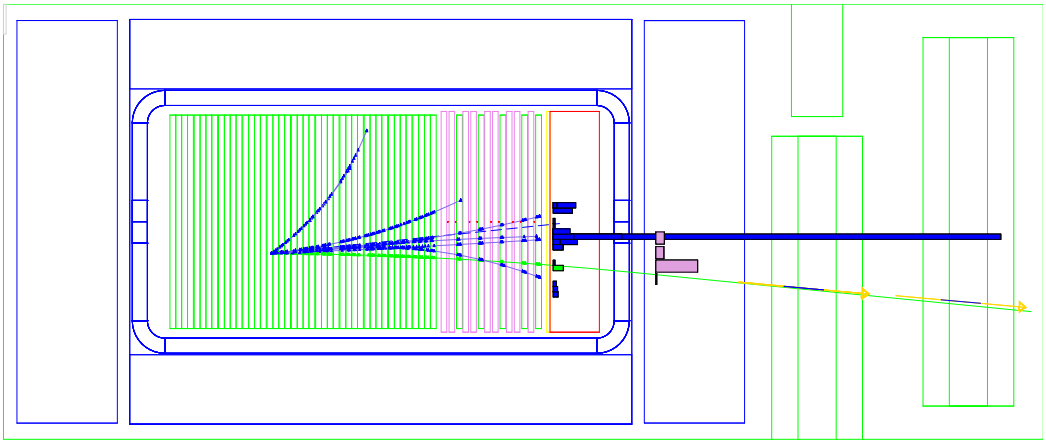
  Efficiency $\approx 97\%$ ($p_\mu > 5$ GeV/c)

- Hadronic Calorimeter for n and K^0_L 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

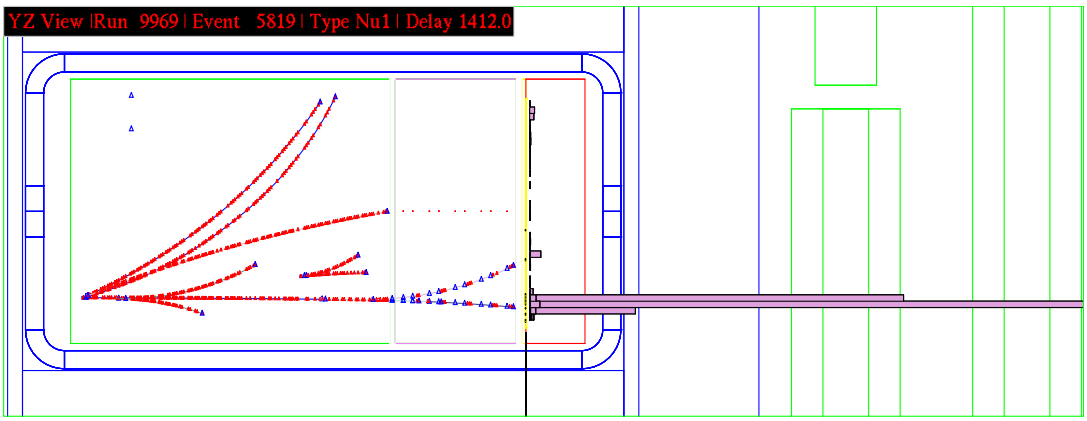
- 1995-98 data sample: 748,000 ν_μ CC candidates ($\varepsilon \sim 60\%$)

  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 (photon conversions $\gamma \rightarrow e^+e^-$, $\pi^0 \rightarrow \gamma e^+e^-$, etc.)

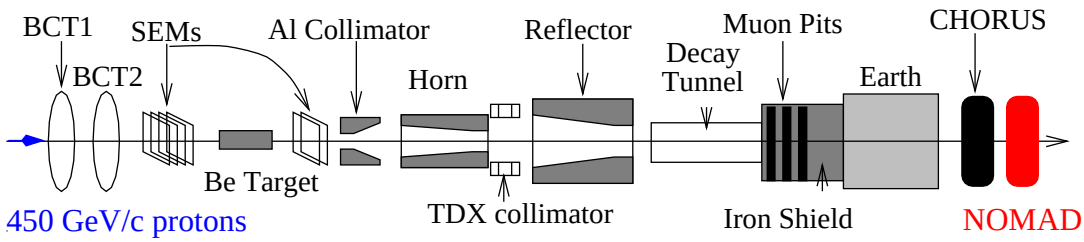
in ν_μ interactions:

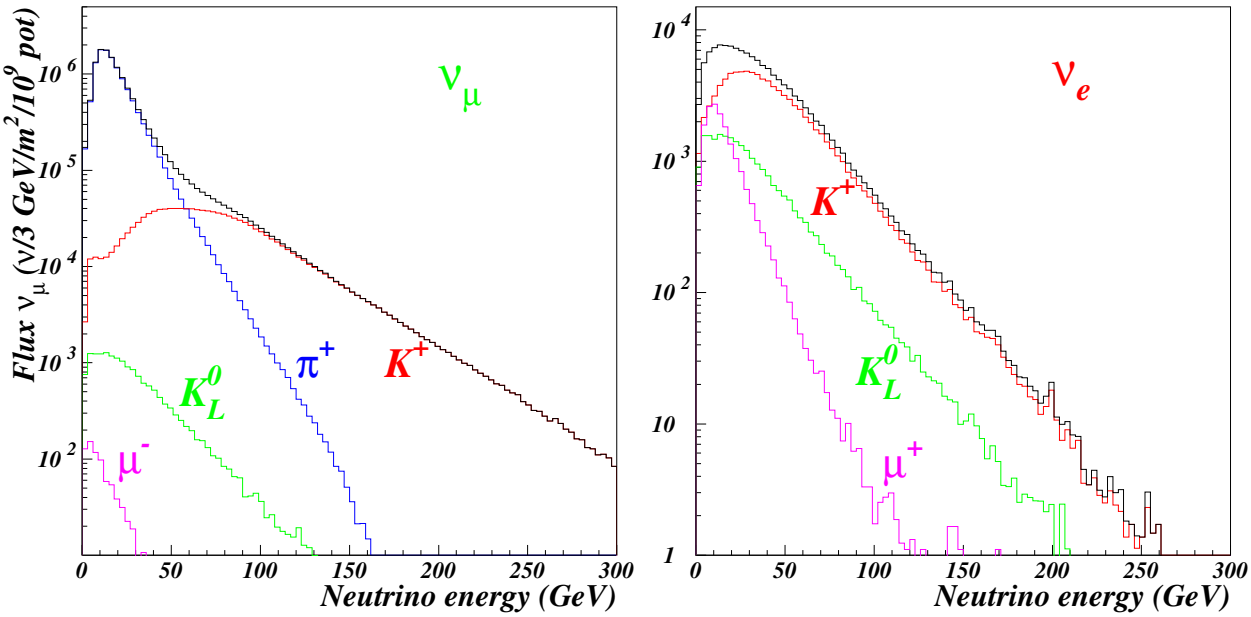
- ν_μ NC: $\nu_\mu\, N \rightarrow \nu_\mu\, X$;
- ν_μ CC: $\nu_\mu\, N \rightarrow \mu^-\, X$ where μ^- was not identified.
  - Background is large, difficult to reject

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

The CERN Neutrino Beam

(not in scale)





An accurate knowledge of the neutrino beam is crucial

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

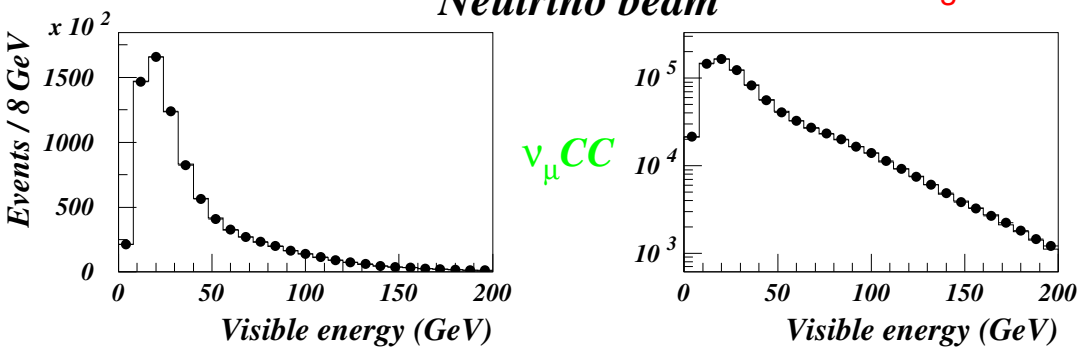
Control Samples: Data vs Monte Carlo

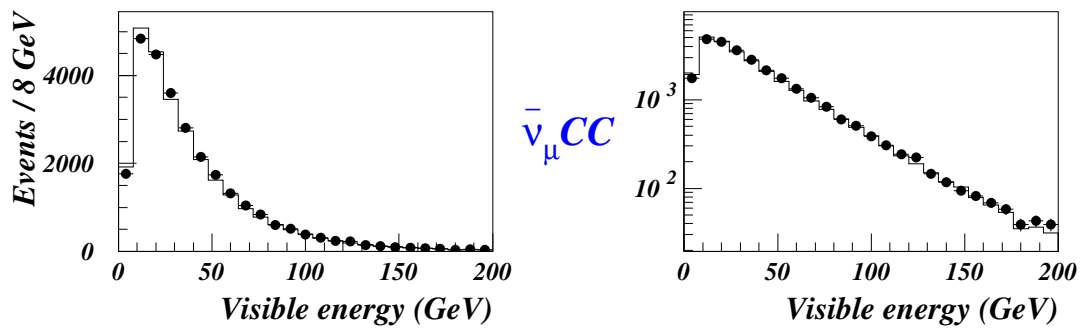
Neutrino energy is approximated by a visible energy:

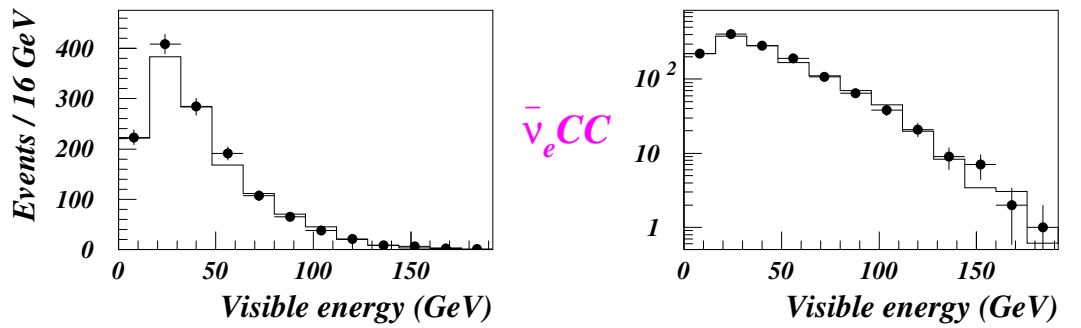
$$E^{vis} = E^{lepton} + \sum E^{prim.trks} + \sum E^{neutrals} + \sum E^{V_0}$$

linear scale — log scale

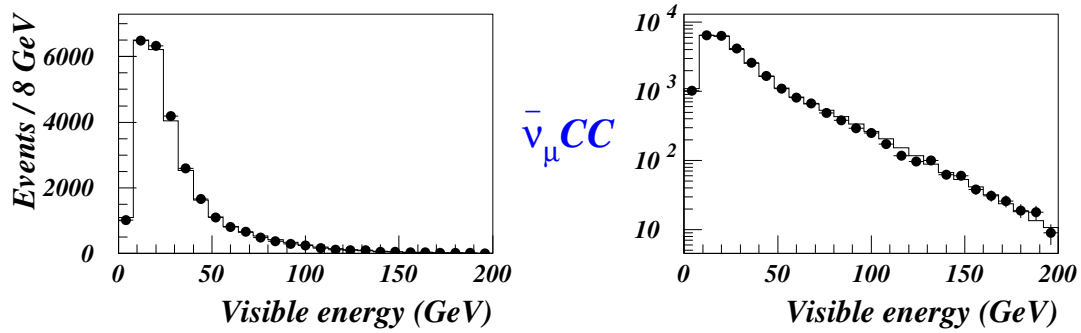
Neutrino beam







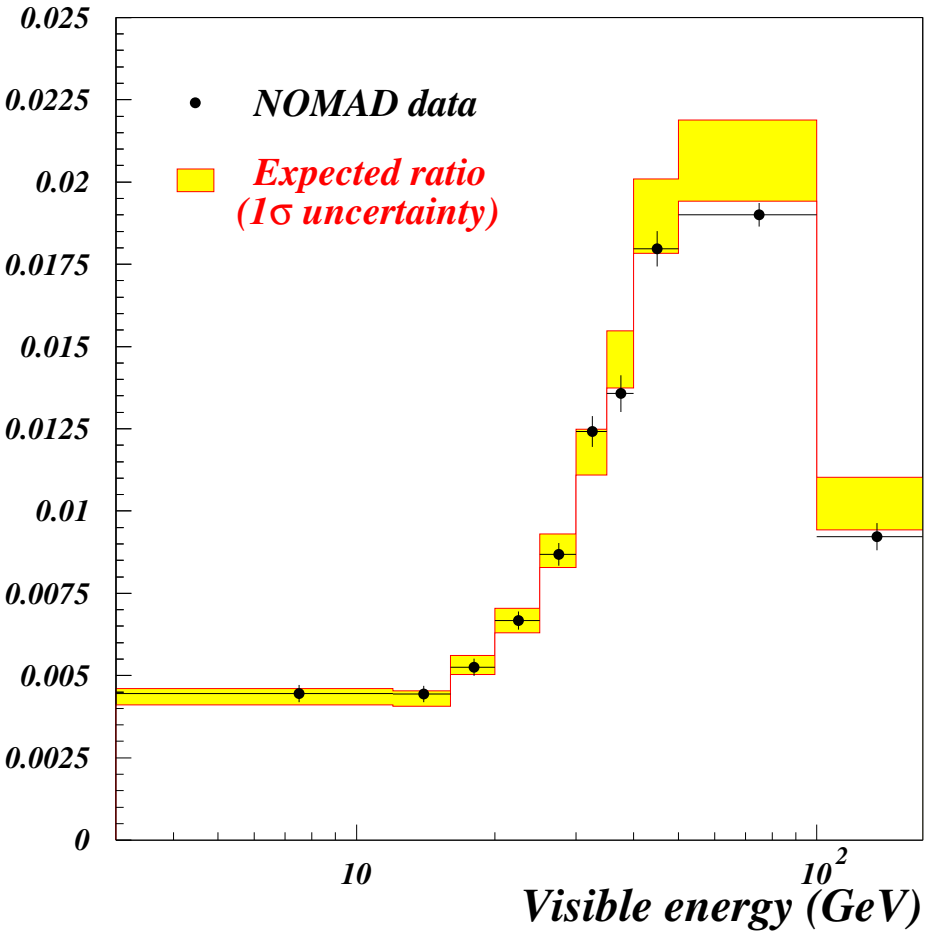
Antineutrino beam



Preliminary Results

- Bin-to-bin systematic errors: 5-8%
  (mainly due to uncertainties in π^+, K^+ and K^0_L yields)
- Overall (normalization) uncertainty: 2%

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



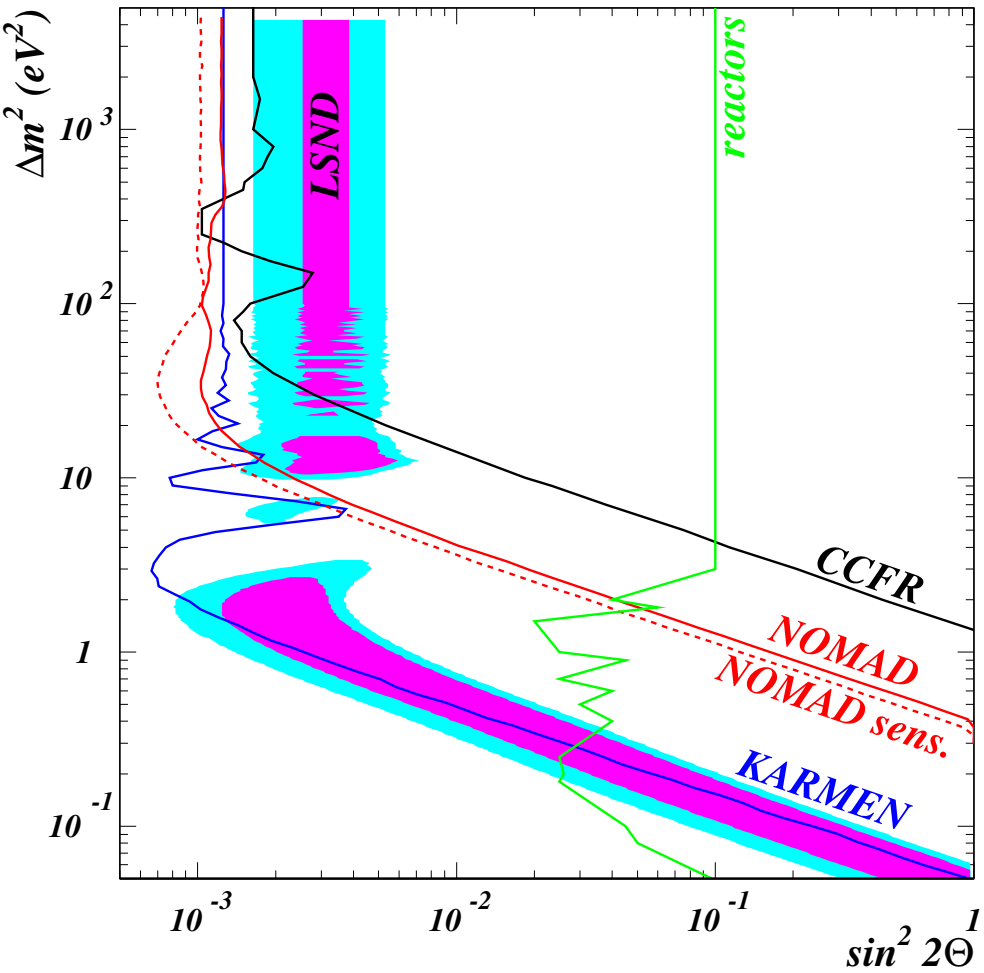
Data are analysed in 10 energy and 3 radial bins:

- χ^2 in the absence of oscillations: 19.7 / 29 d.o.f.
- $\chi^2_{\rm min}$ with oscillation hypothesis: 18.6 / 27 d.o.f.

No evidence for oscillations

Exclusion Region (Preliminary)

(full NOMAD data sample)



At large Δm^2: $\sin^2 2\theta < 1.2 \times 10^{-3}$ @ 90% $C.L.$

(Feldman-Cousins method)

- Exclude high Δm^2 region of oscillation parameters from LSND down to $\sim$ 10 eV^2
- NOMAD is not sensitive to low Δm^2 LSND solutions (limited by beam energy and source–detector distance)

Conclusions and Outlook

- No evidence for $\nu_\mu \longrightarrow \nu_e$ oscillations has been found

  $\Rightarrow$ Independently rule out large Δm^2 interpretation of LSND results

- Our sensitivity is limited by uncertainties in neutrino flux predictions

  – Alternative Empirical Parameterisation method uses

  1. Measured spectra of ν_μ, $\bar{\nu}_\mu$ and $\bar{\nu}_e$ obtained from low hadronic energy charged current events in NOMAD;
  2. Measurements of SPY ($K^\pm$, $\pi^\pm$) and Skubic et al. (K^0_L)

  to parameterise π and K production cross sections at the beryllium target.

  – Gives more accurate flux predictions; being finalised

- Experience gained with WANF neutrino beam and NOMAD data should help to accurately describe CNGS neutrino fluxes