Neutrino Physics and oscillation studies at CERN

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Outline

- The Cern short baseline program: **CHORUS and NOMAD experiments**
- Search for $\nu_\tau$ appearance in the SPS $\nu_\mu$ beam
  - Cosmologically relevant region
- The $\nu_\mu \rightarrow \nu_e$ oscillation search
  - LSND signal region
- Study of neutrino interactions
  - Charmed and strange particles production
The SPS neutrino beam

- Mean distance from $\nu$ source ($\pi$, $K$ decays): NOMAD $\sim 620$ m, CHORUS $\sim 600$ m.

- Wide Band Beam: broad energy spectra.
  - Main component average energy $\sim 25$ GeV
  - Antineutrino contamination $<6\%$, $\nu_e \sim 1\%$
  - Prompt $\nu_{\tau}$ negligible

- Short Baseline Experiments:
  $$\langle L \rangle / \langle E \rangle \approx 2 \times 10^{-2} \text{ km/GeV}$$
  $$\Rightarrow \Delta m^2 \text{ sensitivity in the range } 1 \leq \Delta m^2 \leq 100 \text{ eV}^2$$
The $\nu_\mu \rightarrow \nu_\tau$ oscillation search

**Appearance experiments:** $\nu_\tau + N \rightarrow \tau^- + X$

$\tau$ identified by its decay properties:

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu \bar{V}<em>\mu V</em>\tau$</td>
<td>17.4%</td>
</tr>
<tr>
<td>$e \bar{V}<em>e V</em>\tau$</td>
<td>17.8%</td>
</tr>
<tr>
<td>$h(n\pi^0)V_\tau$</td>
<td>49.8%</td>
</tr>
<tr>
<td>$3h(n\pi^0)V_\tau$</td>
<td>15.2%</td>
</tr>
</tbody>
</table>

- **NOMAD** high resolution on momentum reconstruction and pid
- **Indirect search** → signal from kinematical criteria
- **CHORUS** very high resolution at vertex
- **Direct search** → signal from visual scanning

High design sensitivity $P(\nu_\mu \rightarrow \nu_\tau)=10^{-4}$ for $\Delta m^2 \approx 1-10$ eV$^2$ (relevant for cosmology & DM)
The detectors

Hybrid detector
- Active emulsion target
  ⇒ locate interaction and decay vertices
- Electronic detector
  ⇒ predict tracks in emulsion + kinematics

Electronic detector
- High resolution tracking
  ⇒ momentum resolution 3.5% (p<10 GeV)
- Fine grained calorimetry
  ⇒ ΔE/E=3.2%/√E ± 1%
- Particle id
  ⇒ pion rej 10^3 with electron eff >90%
Data samples

**Chorus (94–97)**
- 2,305k emulsion triggers
  - Phase I: 167k events located in emulsion
  - Phase II: ~60k new events located + full event analysis at vertex
- 3-dimensional visual reconstruction
  - Sub-micron resolution at vertex

**Nomad (95–98)**
- 1,354k $\nu_\mu$ CC interactions
  - 100% of data analysed
- "Bubble chamber" quality
  - Very high resolution in momentum and energy
  - Particle Id
The Nomad $\nu_\tau$ search

The $\nu_\tau$ CC signal has intermediate properties between two background sources

Hadronic decay
The main source of bkgd are NC
$\Rightarrow$ isolation between the visible $\tau$ decay products and the hadronic jet.

Electron decay
The main source of bkgd are $\nu_e$ CC
$\Rightarrow$ kinematics based on the missing momentum and angular relations in the transverse plane.
The Nomad analysis (1): general principles

Maximum rejection power achieved using full topology of the events

• Definition of a pdf $L$, describing the probability for an event to be signal or background

• Event classification based on likelihood ratio between signal and background hypothesis

\[ \ln \lambda = \frac{L_S}{L_B} \]

• $\ln \lambda$ is subdivided into bins characterized by different S/B ratios

• The position of the bins is decided on the basis of the sensitivity of the analysis

Independent measurements from different decay modes & signal bins are combined within the frequentist Unified Approach

The Nomad analysis (2): selection scheme

Background rejection optimized separately for NC and CC
→ two distinct likelihood functions: $\ln \lambda^{CC}$ and $\ln \lambda^{NC}$

Definition of signal region: “BOX” overall sensitivity to oscillations is optimized
Blind analysis: data events inside the “box” cannot be analysed until background predictions are finalised
The Nomad analysis (3): reliability of background estimate

large kinematical suppression + multidimensional correlations
⇒ knowledge of bkgd $O(10^{-5})$

**Data simulator**

Corrections to $MC$ extracted from data

- Use identified $\nu_\mu$ CC in both Data (DS) and MonteCarlo (MCS) and replace the leading $\mu^-$ by the appropriate MC particle: $\nu$ for NC, $\tau^-$ for signal, $e^-$ for $\nu_e$ CC

- Compute all efficiencies as $\epsilon = \frac{\epsilon_{DS}}{\epsilon_{MCS}}$

**Control samples**

$\tau^+$ search and $\tau^-$ search outside the "box" are used to check final predictions and evaluate systematics
Final result: no evidence for oscillations in Nomad

Blind box is opened:
- Data are consistent with background in each bin
- Integrals and shapes of $\ln\lambda$ distribution agree with background predictions
The Chorus $\nu_\tau$ search

1) Event reconstruction by electronic detectors
   Pre-selection of events and tracks
   ➔ reduce scanning load

2) Event location in emulsion
   Automatic emulsion scanning: location of the selected tracks in the emulsion sheets and follow up to the interaction vertex (Scanback)

3) Decay search
   Automatic scanning and offline selection for decay topology search
   ➔ confirmation by eye-scan
   (Netscan: search for all tracks in $1.5 \times 1.5 \times 6 \text{ mm}^3$)

4) Post-scanning analysis
   Kinematical study, kink $P_\tau$ measurement

1-ry vertex predicted in bulk

Look for muons

1$\mu$

apply cuts

0$\mu$

apply cuts

Scan-back

Kink finding

apply kinematical cuts

$\tau$ candidates
The event location in emulsion

1µ sample: 1 negative muon from the primary interaction vertex with $P < 30$ GeV/c
0µ sample: at least one negative track with $P \in [-1,-20]$ GeV/c

Location efficiency higher for 1µ (40%) than for 0µ (27%) independently from track angle
Kink finding

Decay search
- Segments with small IP wrt the scan-back track are parent candidates
- Large angle – Long path kinks are visible

Candidates are selected for eye-scan
## Data flow in Chorus Phase I

### Emulsion triggers: 2,305K

<table>
<thead>
<tr>
<th></th>
<th>$1\mu$</th>
<th>$0\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial sample</td>
<td>713,000</td>
<td>Initial sample (CC contamination)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>335,000 (140,000)</td>
</tr>
<tr>
<td>Momentum cut +</td>
<td>477,600</td>
<td>≥1 negative tracks + Momentum cut + angle</td>
</tr>
<tr>
<td>angle cut</td>
<td></td>
<td>cut</td>
</tr>
<tr>
<td></td>
<td></td>
<td>122,400</td>
</tr>
<tr>
<td>Events scanned</td>
<td>355,395</td>
<td>Events scanned</td>
</tr>
<tr>
<td></td>
<td></td>
<td>85,211</td>
</tr>
<tr>
<td>Vertex located</td>
<td>143,742</td>
<td>Vertex located</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20,081</td>
</tr>
<tr>
<td>Selected for eye-scan</td>
<td>11,398</td>
<td>Selected for eye-scan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2,282</td>
</tr>
</tbody>
</table>
Manual scanning

Computer-assisted operator measurements of candidate kink topology

- Low momentum BG track (80%)
- Parent = Daughter Distortion (4%)
- Backward going nuclear fragment (12%)
- Hadron secondary interaction (2.5%)
- Decay (1.5%)

Decay topology: no black prongs, no blobs, no recoil, no Auger electrons

\[ P_t > 250 \text{ MeV/c to reject } \pi \text{ and } K \text{ decays} \]
White kink background

1-prong nuclear interaction with no ionizing activity at interaction point

\[ \lambda_{WK}(P_t > 250\,\text{MeV}/c) = 24.0 \pm 8.5\,\text{m} \]

\[ \Rightarrow 2.6 \pm 0.8\,\text{WK expected in the signal region} \]

Post scanning WK rejection

- \( \Phi_{\text{kink}} \) cut: \( \tau \) opposite to the shower in the transverse plane
- \( L_{\text{decay}} \) cut: \( \tau \) flight length shorter and correlated with \( p_{\text{had}} \)

Cuts optimisation by the a-priori criterium of maximising the exclusion power, independently from data.
Chorus and Nomad as small background experiments

\[ N_{\tau}^{\text{max}} = N_{\text{obs}} \times \left( \frac{\sigma_{\tau}}{\sigma_{\mu}} \right) \times \left( \frac{\epsilon_{\tau}}{\epsilon_{\mu}} \right) \times \text{Br} \]

75% of the final NOMAD sensitivity comes from low bkgd bins

<table>
<thead>
<tr>
<th>channel</th>
<th>Total bkgd</th>
<th>( N_{\tau}^{\text{max}} )</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1( \mu )</td>
<td>0.1</td>
<td>5014</td>
<td>0</td>
</tr>
<tr>
<td>0( \mu )</td>
<td>1.1</td>
<td>2004</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td><strong>1.2</strong></td>
<td><strong>7018</strong></td>
<td><strong>0</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>channel</th>
<th>Total bkgd</th>
<th>( N_{\tau}^{\text{max}} )</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>0.61</td>
<td>2826</td>
<td>0</td>
</tr>
<tr>
<td>h</td>
<td>0.76</td>
<td>5343</td>
<td>1</td>
</tr>
<tr>
<td>3h</td>
<td>0.32</td>
<td>675</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td><strong>1.69</strong></td>
<td><strong>8844</strong></td>
<td><strong>1</strong></td>
</tr>
</tbody>
</table>

NO EVIDENCE FOR OSCILLATIONS
Results of the $\nu_\mu \rightarrow \nu_\tau$ oscillation search

<table>
<thead>
<tr>
<th>Total bkgd</th>
<th>$N_\tau^{\text{max}}$</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>7018</td>
<td>0</td>
</tr>
<tr>
<td>($\pm30%$ syst)</td>
<td>($\pm15%$ syst)</td>
<td></td>
</tr>
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Calculation of Limit @ 90% CL

$\mathcal{L}_{\text{osc}}(\nu_\mu \rightarrow \nu_\tau) = 3.4 \times 10^{-4}$
$S_{\text{osc}}(\nu_\mu \rightarrow \nu_\tau) = 3.7 \times 10^{-4}$
$P(\leq \mathcal{L}_{\text{osc}}) = 28\%$

$\mathcal{L}_{\text{osc}}(\nu_\mu \rightarrow \nu_\tau) = 1.63 \times 10^{-4}$
$S_{\text{osc}}(\nu_\mu \rightarrow \nu_\tau) = 2.5 \times 10^{-4}$
$P(\leq \mathcal{L}_{\text{osc}}) = 37\%$

Total bkgd | $N_\tau^{\text{max}}$ | Data |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>50.5</td>
<td>15226</td>
<td>52</td>
</tr>
<tr>
<td>($\pm20%$ syst)</td>
<td>($\pm10%$ syst)</td>
<td></td>
</tr>
</tbody>
</table>

T.J. Junk, NIM A434 (1999) 435
G.J. Feldman & R.D. Cousins,
Exclusion plots

Combined result with F&C (*):

\[ L_{\text{osc}}(\nu_\mu \to \nu_\tau) = 0.5 \times 10^{-4} \]
\[ S_{\text{osc}}(\nu_\mu \to \nu_\tau) = 1.7 \times 10^{-4} \]
\[ P(\leq L_{\text{osc}}) = 15\% \]

\[ L_{\text{osc}}(\nu_e \to \nu_\tau) = 0.4 \times 10^{-2} \]
\[ S_{\text{osc}}(\nu_e \to \nu_\tau) = 0.9 \times 10^{-2} \]
\[ P(\leq L_{\text{osc}}) = 25\% \]

(* by courtesy of R. Petti)
Nomad $\nu_\mu \rightarrow \nu_e$ oscillation search

- Appearance experiment based on powerful electron id in NOMAD
- $\nu_e$ in the beam $\sim 1\%$
- Different energy spectra and radial distribution for $\nu_e$ and $\nu_\mu$

$\Rightarrow$ Study $R_{e\mu} = (\nu_e CC)/(\nu_\mu CC)$ as a function of $E_\nu$ and $r$

748k $\nu_\mu CC$ and 8k $\nu_e CC$ candidates

compare $R_{e\mu}$ distribution in data and MC with a Blind Analysis

NO EVIDENCE FOR OSCILLATIONS
Nomad $\nu_\mu \rightarrow \nu_e$ exclusion region (Preliminary)

At large $\Delta m^2 \rightarrow \sin^2(2\Theta) < 1.2 \times 10^{-3} @ 90\%$ CL
CHORUS Phase II

- Scanning speed increased by three orders of magnitude since the start of data taking
  - Automatic scanning of a large emulsion volume is now feasible
    - New predictions/locations (mainly 0μ) to increase by >60k the current sample of ~167k located events (scan-back almost completed)
    - On all located event → NETSCAN analysis at vertex (data-taking is on-going, current speed is ~10k events/month)
  - Improvement of oscillation search to reach the proposal sensitivity
  - Collection of $O(10^5)$ sample of events fully analyzed at vertex
  - Unbiased study of charm production in neutrino interactions
    - About 4000 charm events inclusively selected
Netscan

A new scanning technique!
- Use already located events
- Pick up all track segments in $1.5 \times 1.5 \times 6.3$ mm$^3$ fidvol around scan-back track
- Decay search is not limited to the scan-back track
- Offline analysis of emulsion data

Track segments from 8 plates overlapped

At least 2-segment connected tracks

Eliminate passing-through tracks

Reconstruct full vertex topology
Charm Physics with Chorus

- **D⁰ production**  
  Data taking ongoing: 25k CC → 150k CC  
  Improved selection: purity 65% → 90%  
  
  No need for manual?

- **Inclusive charm**  
  ~ 4,000 neutrino-induced charm events (E531 had 122)  
  Fragmentation fractions $D^0 : D^+ : D_s^+ : \Lambda_c^+$  
  $B(c \rightarrow \mu), V_{cd}, s(x), ...$

- **Associated charm production**  
  Background evaluation based on CHORUS data and FLUKA  
  Improved selection: efficiency 1% → 25%

- **Exclusive channels**  
  Proton identification  
  MCS momentum measurement  
  $\Sigma^\pm$ detection  
  $\Lambda_c$ absolute $BR, QE \Lambda_c$ production
Further studies in Nomad

- **D* production**  
  High purity sample of D*+ events → study of fragmentation process  
  Inclusive neutrino charm production by dimuons currently being updated

- **Strange particles and resonances production**  
  $V^0$ sample ($K^0_s, \Lambda, \text{anti-}\Lambda$) → an order of magnitude increase in statistics with respect to bubble chamber experiments

- **(anti-)Lambda polarization**  

- **Backward going protons and pions in CC reactions**  
  Study of nuclear effects in neutrino interactions. Test of Fermi motion models
Conclusions

The CERN short baseline program explored $\nu_\tau \rightarrow \nu_\tau$ oscillations within the cosmologically relevant region down to $\sin^2(2\Theta) \sim O(10^{-4})$.

**NO EVIDENCE FOR OSCILLATIONS IN THE EXPLORED REGION**

The two CERN neutrino experiments have demonstrated that a sensitive search for $\nu_\tau$ appearance can be achieved with two different approaches: the kinematical analysis and the automatic emulsion scanning → valid techniques for planned and future experiments.

Highly valuable data samples have been collected → further studies for neutrino physics, more results to come.