Results on Neutrino Physics at CERN

Francesca Spada

University of Rome “La Sapienza” and INFN

for the NOMAD and CHORUS collaborations

Two ν experiments at CERN:

Early 90's: theoretical indication for neutrino mass differences of a few eV

Two experiments proposed at CERN in 1993:

NOMAD high resolution on momentum reconstruction and pid

→ signal from kinematical criteria

CHORUS high resolution at vertex

→ signal from τ's direct observation

Sensitive to very small mixing angles for $\Delta m^2 \sim 50\ eV^2$

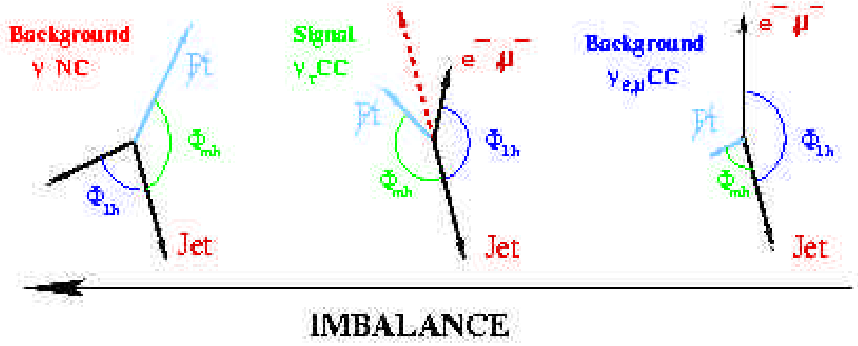
(1993, proposal) ➔ neutrinos of mass in the cosmological region

Today: SK – CMB experiments ➔ $\Sigma m_\nu < 4eV$ ($\Delta m^2 < 16\ eV^2$) at 90%CL

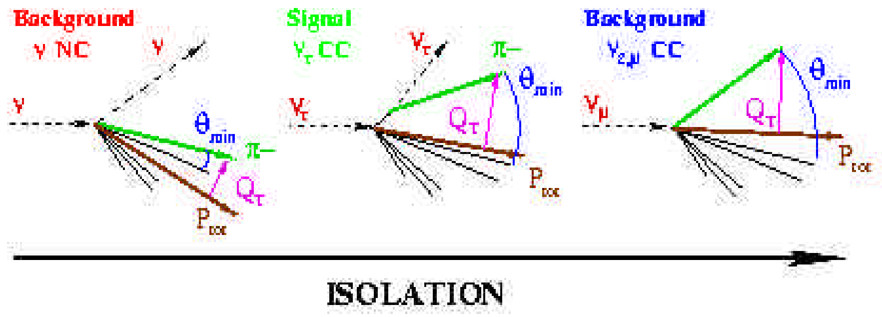
THE NOMAD ν_τ SEARCH

- The signal ν_τ CC has intermediate properties between two background sources:

I CC INTERACTIONS

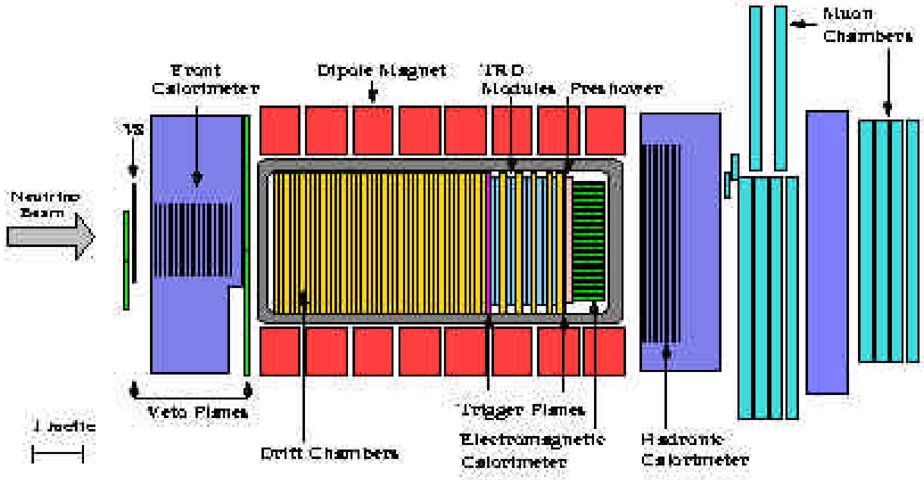


II NC INTERACTIONS



Difficult to reject efficiently both background sources with simple kinematic criteria $\Longrightarrow$ *opposite requirements.*

THE DETECTOR



TRIGGER: $\overline{\mathrm{V}}$ T_1 T_2

- **Drift Chambers (target and momentum measurement)**
  Fiducial mass 2.7 tons with average density $0.1\mathrm{g/cm}^3$
  44 chambers + 5 chambers in TRD region
  Momentum resolution $\sim 3.5\%$ $(p < 10\mathrm{GeV}/c)$

- **Transition Radiator Detector (TRD) for $e^{\pm}$ identification**
  9 modules (315 radiator foils followed by straw tubes plane)
  π *rejection* $\sim 10^3$ *for electron efficiency* $\geq 90\%$

- **Lead glass Electromagnetic Calorimeter (energy measurement)**
  $\sigma(E)/E = 3.2\%/\sqrt{E[\mathrm{GeV}]} \oplus 1\%$

- **Preshower (e and γ detection)**
  Additional π *rejection* $\sim 10^2$ *for electron efficiency* $\geq 90\%$
  Precise γ *position measurement* $\sigma(x), \sigma(y) \sim 1cm$

- **Hadronic Calorimeter (n and K_L^0 veto)**

- **Muon Chambers for $\mu^{\pm}$ identification**
  $\epsilon \sim 97\%$ *for* $p_\mu > 5\mathrm{GeV}/c$

- **Front Hadronic Calorimeter (FCAL)**
  Extra 17.7 tons target.

- *Detailed description in Nucl. Instr. Meth. A404 (1998) 96.*

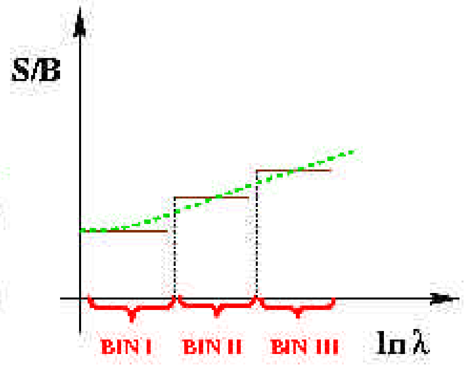
THE ANALYSIS - 1

- *Definition of probability density functions,* **pdf $\mathcal{L}$**, *describing the probability, for an event with the given set of N variables X_i, to be signal ($\mathcal{L}_S$) or background ($\mathcal{L}_B$):*
  - *the global pdf $\mathcal{L}$ is subdivided into n-dimensional partial pdf's with $n < N$ and $n = 1, 2, 3, 4$, chosen among the most discriminating internal correlations of of the set of variables X_i;*
  - *partial pdf's can be included in the set of variables X_i, as well.*

- *Event classification based on* **LIKELIHOOD RATIO** *between the signal S and background(s) B hypotheses:*

$$\ln \lambda \stackrel{\text{def}}{\equiv} \ln \frac{\mathcal{L}_S}{\mathcal{L}_B}$$

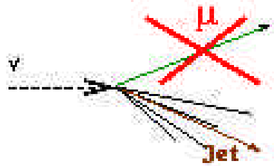
- *The optimal treatement is to compare the* **SHAPE** *of signal & background(s) in a likelihood fit to $\ln \lambda$:*
  - *limited by available statistics;*
  - *the relevant information from a fit is the* **S/B RATIO** *along the $\ln \lambda$ distribution;*
  - *define different SIGNAL BINS in the tail of $\ln \lambda$, characterized by different S/B ratios;*
  - *different bins are considered statistically independent.*

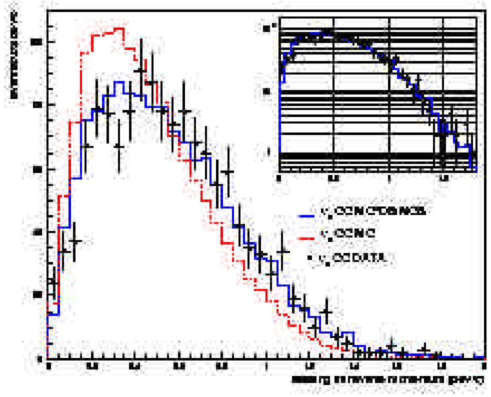


- *Independent measurements from different decay modes & signal bins are combined within the UNIFIED APPROACH,* *(G.F. Feldman & R.D. Cousins, Phys. Rev. D57 (1998) 3873).*

THE ANALYSIS - 2

- The large *kinematical suppression* and the use of *multi-dimensional correlations* require a precise knowledge of *background(s) down to a $\sim 10^{-5}$ level*. The final estimate of backgrounds & efficiencies is obtained from the **DATA SIMULATOR** technique:
  - use **IDENTIFIED ν_μCC** in both *Data (DS)* and *Monte Carlo (MCS)* and replace the μ^- by:
    - ν (i.e. nothing)
    - e^- from MC
    - $\tau^- \rightarrow X$ MC



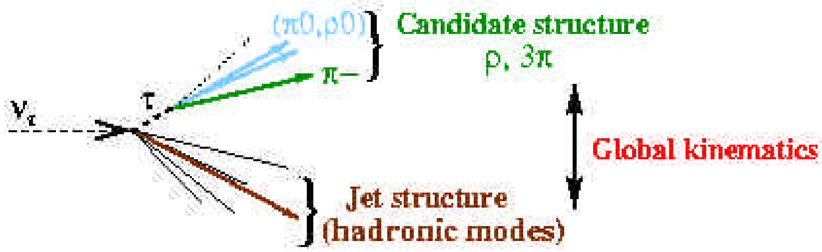


  - compute all efficiencies as $\varepsilon \stackrel{\text{def}}{\equiv} \frac{\varepsilon(MC) \times \varepsilon(DS)}{\varepsilon(MCS)}$

- In order to obtain *reliable background predictions* a **'BLIND ANALYSIS'** is used:
  - define a signal region, **THE "BOX"**, by optimizing the overall sensitivity to oscillations;
  - data events falling *inside the BOX CANNOT be analyzed* until the bkgnd predictions are finalized;
  - *the τ^+ search and the τ^- search outside the "BOX"* are used as control samples for backgrounds.

THE ANALYSIS - 3

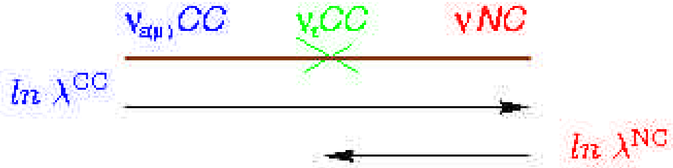
✦ Three types of **TOPOLOGICAL CONSTRAINTS** are used for the kinematic selection of the ν_τ CC signal:



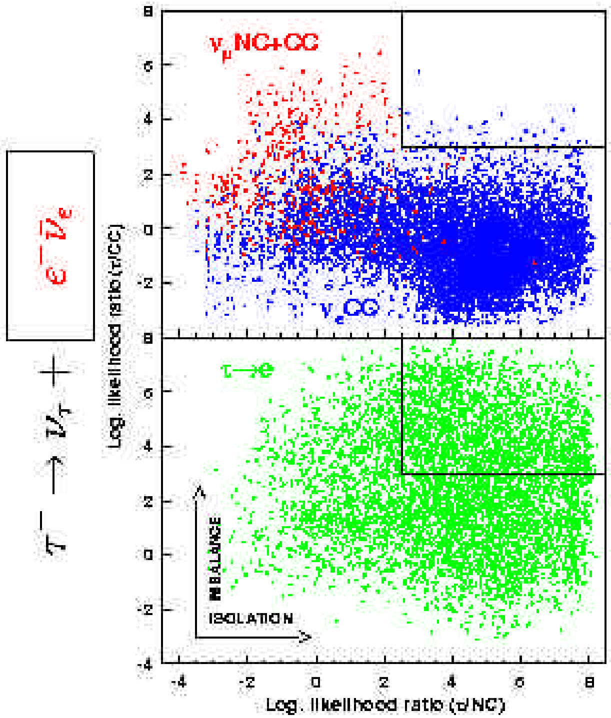
I **Candidate structure**:
The internal structure of the ρ (3π) candidate is exploited both for the selection procedure and for the rejection of the $\nu_\mu + \nu_e$ CC backgrounds through a a likelihood function $\mathcal{L}^{INT}$.

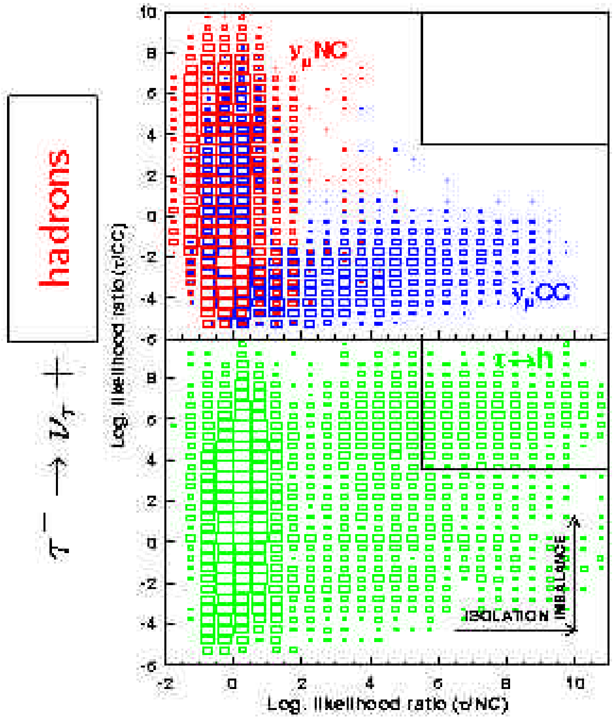
II **Jet structure**:
In the τ hadronic decays a control of the jet structure is needed since for background(s) the candidate is mostly extracted from the jet.

III **Global kinematics**:
The rejection of each of the two main background contributions is achieved by constructing TWO appropriate likelihood ratios λ^{NC} and λ^{CC}, exploiting the full event kinematics.



DEFINITION OF THE SIGNAL REGION

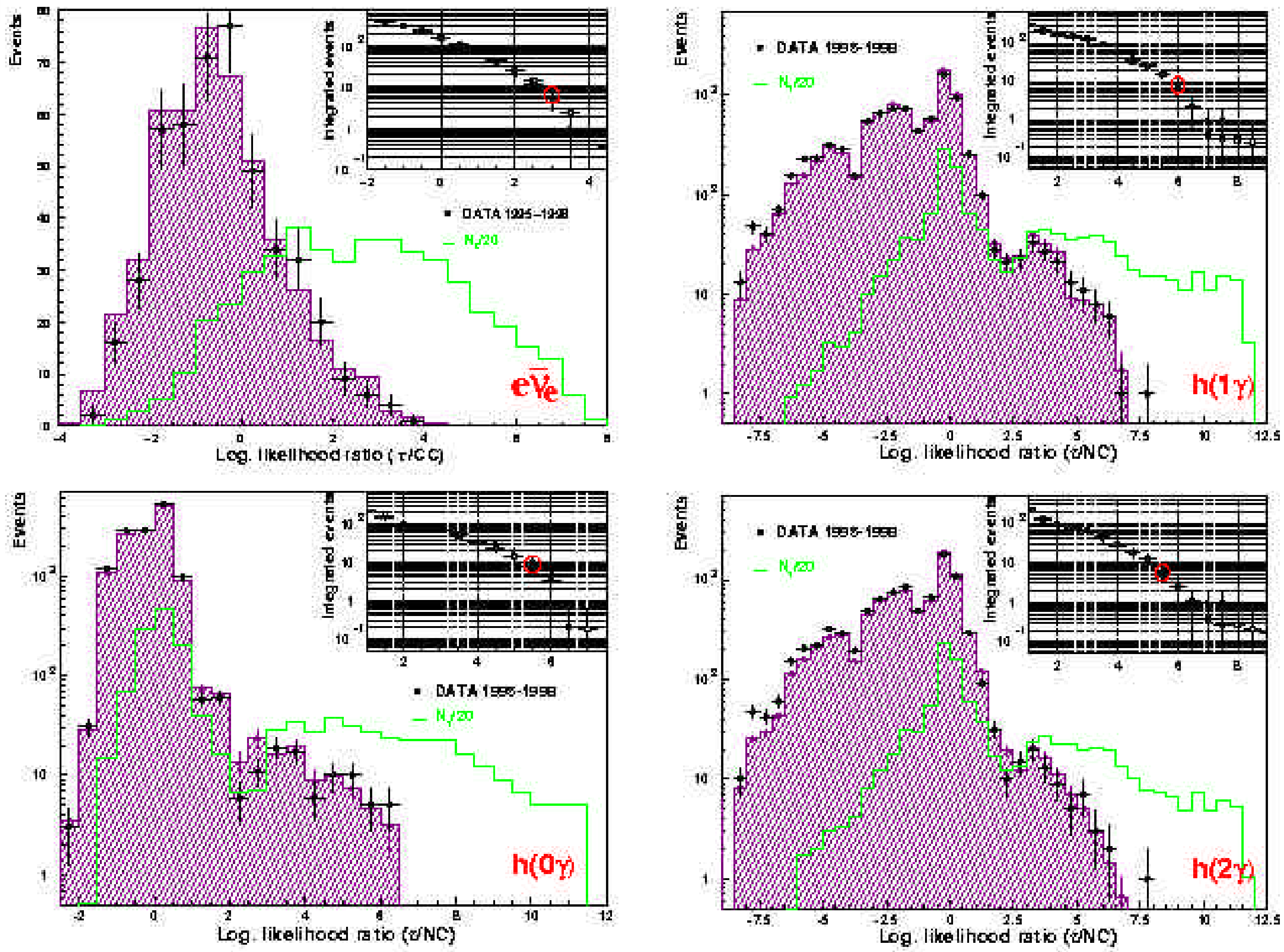




$$\begin{cases} \mathcal{L}_e^{CC} \stackrel{\text{def}}{\equiv} [[\rho_h, \rho_l, Q_{lep}], \not{p}_T, M_T, E_{vis}] \\ \mathcal{L}_e^{NC} \stackrel{\text{def}}{\equiv} [[[\theta_{\nu T}, \theta_{\nu H}], \theta_{\min}, Q_T], M_T, E_e] \end{cases}$$

$$\begin{cases} \mathcal{L}_h^{CC} \stackrel{\text{def}}{\equiv} [[I_G, R_{PT}, \theta_{\nu l}], \not{p}_T, M_T, E_{vis}] \\ \mathcal{L}_h^{NC} \stackrel{\text{def}}{\equiv} [[[\theta_{\nu T}, \theta_{\nu H}], \theta_{\min}, Q_T], \not{p}_T, P_T^H] \end{cases}$$

NO EVIDENCE FOR OSCILLATIONS



FINAL RESULTS OF THE ν_τ SEARCH

- **NO EVIDENCE** for oscillations from the *analysis of data*:
  - *NUMBER & SHAPE* of observed events consistent with background.;
  - **75%** *of the overall sensitivity* comes from regions with only a **SMALL BACKGROUND**.

Tot. bkg.	51.1 ± 5.4
$N^\tau_{P=1}$	14415
Data	*52*
Syst.:	*10% on* $N^\tau_{P=1}$, *20% on bkg.*

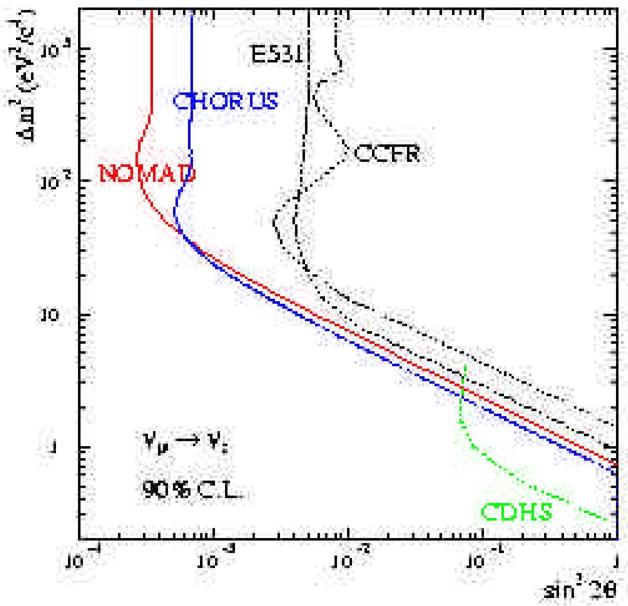
$$\begin{cases} S_{\nu_\mu \to \nu_\tau} = 2.5 \times 10^{-4} \ \ 90\%\mathrm{CL} \\ L_{\nu_\mu \to \nu_\tau} = 1.7 \times 10^{-4} \ \ 90\%\mathrm{CL} \\ P(\leq L) = 39\% \end{cases}$$

Design sensitivity 1.9×10^{-4}

Analysis		*Bin*	*Tot. bkg.*	$N^\tau_{P=1}$	*Data*
$\nu_\tau \bar{\nu}_e e$	DIS	III	$0.28^{+0.31}_{-0.09}$	903	0
$\nu_\tau \bar{\nu}_e e$	DIS	VI	0.25 ± 0.09	1694	0
$\nu_\tau h(0\gamma)$	DIS	III	$0.05^{+0.60}_{-0.03}$	274	0
$\nu_\tau h(0\gamma)$	DIS	IV	$0.12^{+0.60}_{-0.05}$	1246	0
$\nu_\tau h(1\gamma)$	DIS	VII	$0.07^{+0.70}_{-0.04}$	211	0
$\nu_\tau h(1\gamma)$	DIS	VIII	$0.07^{+0.70}_{-0.04}$	1037	0
$\nu_\tau h(2\gamma)$	DIS	XII	$0.11^{+0.60}_{-0.06}$	197	0
$\nu_\tau h(1/2\gamma)$	DIS	XV	$0.20^{+0.70}_{-0.08}$	660	1
$\nu_\tau h(0/1\gamma)$	DIS	XVI	$0.14^{+0.70}_{-0.06}$	1348	0
$\nu_\tau 3h(n\pi^0)$	DIS	IV	$0.33^{+0.65}_{-0.33}$	645	0
			$1.62^{+1.89}_{-0.38}$	8215	1

NOMAD EXCLUSION PLOTS

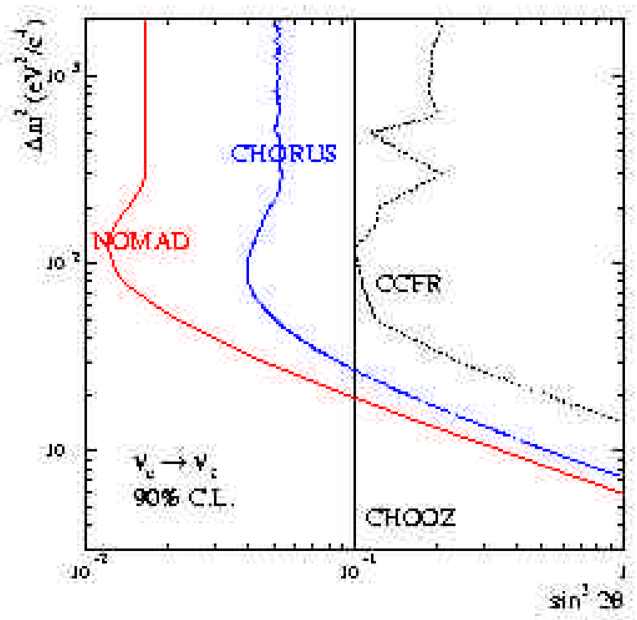
- $\nu_\mu \to \nu_\tau$



Final NOMAD result (data 95-98):

$$\begin{cases} S_{\nu_\mu \to \nu_\tau} & = & 2.5 \times 10^{-4} & 90\%CL \\ L_{\nu_\mu \to \nu_\tau} & = & 1.7 \times 10^{-4} & 90\%CL \\ P(\leq L) & = & 39\% & \end{cases}$$

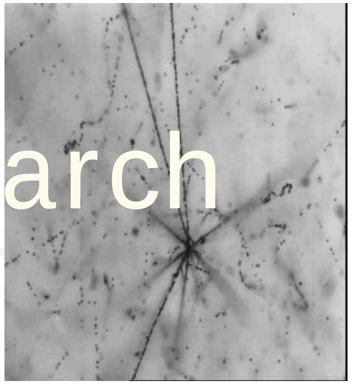
- $\nu_e \to \nu_\tau$



Final NOMAD result (data 95-98):

$$\begin{cases} S_{\nu_e \to \nu_\tau} & = & 1.2 \times 10^{-2} & 90\%CL \\ L_{\nu_e \to \nu_\tau} & = & 0.8 \times 10^{-2} & 90\%CL \\ P(\leq L) & = & 43\% & \end{cases}$$

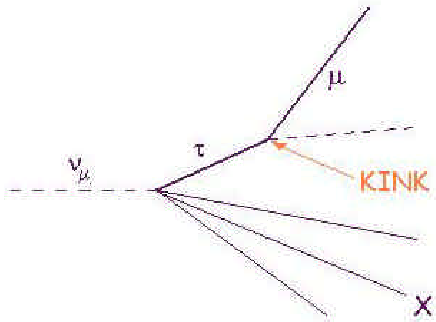
CHORUS Oscillation Search



- ν_τ appearance in a pure ν_μ beam

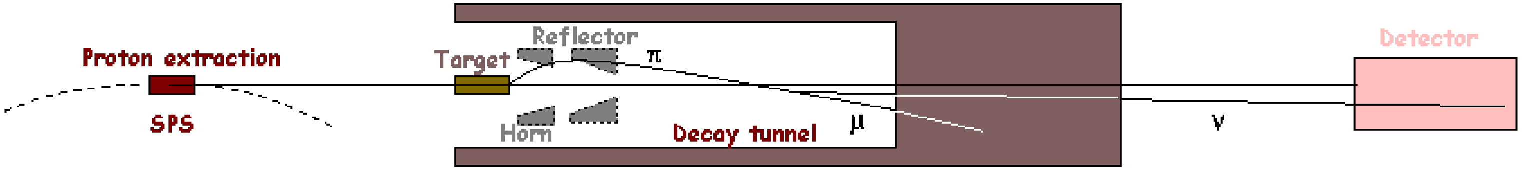
ν_μ energy well above τ production threshold

- A target/detector of nuclear emulsions allows direct observation of τ decay
  - 770 Kg of nuclear emulsions divided in 4 stacks perpendicular to the beam
  - Very high spatial resolution (~1µm) with 300 tridimensional hits/mm
  - Suitable to detect the τ decay signature:
    - Interaction vertex
    - Short τ path ~ 1 mm ($c\tau$ = 87 µm)
    - A *kink* as decay topology

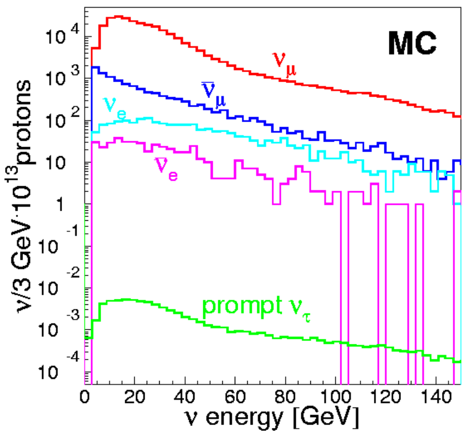


- An electronic detector reconstructs the kinematics

The ν beam

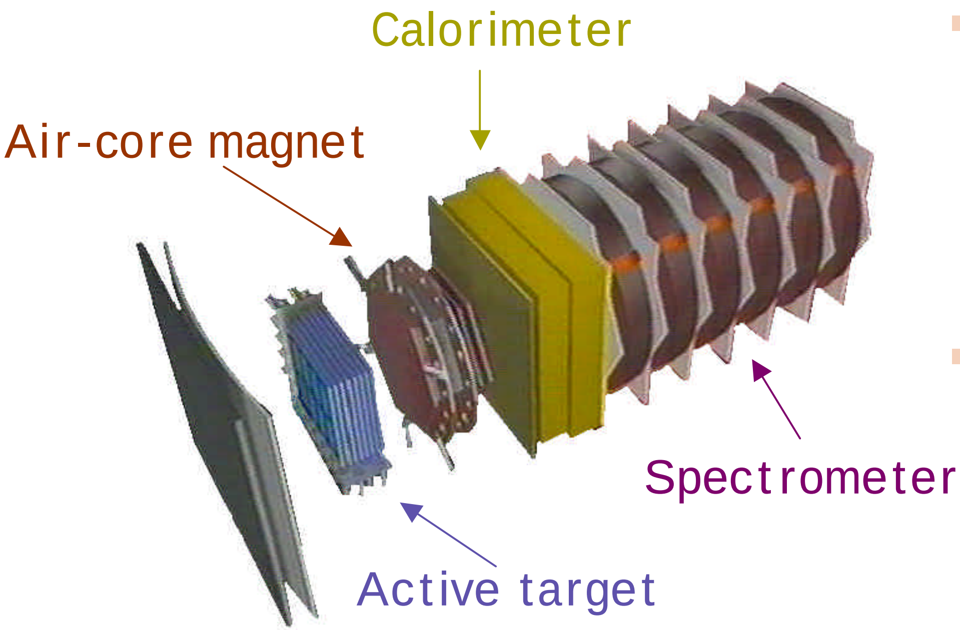


- 4-years exposure to the WBB from SPS at CERN
  - $5 \cdot 10^{19}$ POTs leading to 840,000 ν_μ CC in CHORUS
  - $E_{protons}$ = 450 GeV
- Intense ν_μ beam with $E_\nu \sim 27$ GeV
- Prompt ν_τ negligible (~0.1 bg events)



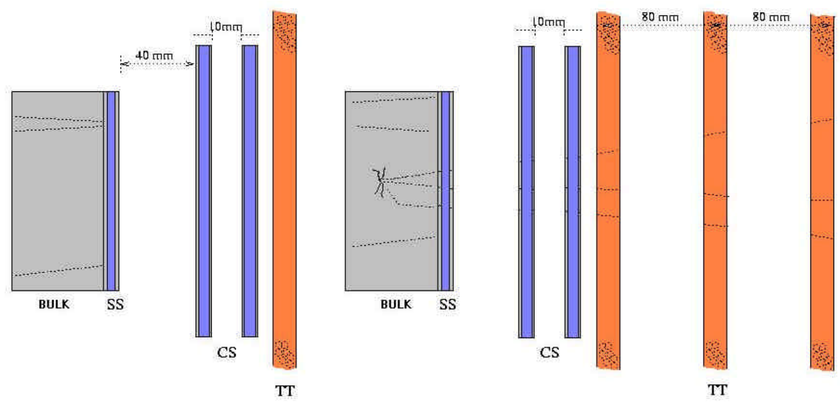
Detector layout

- Active target:
  - nuclear emulsion target
  - scintillating fibre tracker
- Air-core magnet + tracker:
  - Hadron momentum (up to 20 GeV)
  - $\Delta p/p = 0.035\, p\ (\text{GeV}) \oplus 0.22$



- Lead and fibre Calorimeter:
  - $\Delta E/E = 32\%/\sqrt{E}$ (hadrons)
    $= 14\%/\sqrt{E}$ (electrons)
  - $\Delta\theta_{hadrons} = 60$ mrad @ 10 GeV
- Muon spectrometer:
  - $\Delta p/p = 10 – 15\%$ up to 70 GeV

Target region



- 8 modules of scintillating fibre trackers:
  - resolution on extrapolation to CS is 150 mm in position and 2 mrad in angle

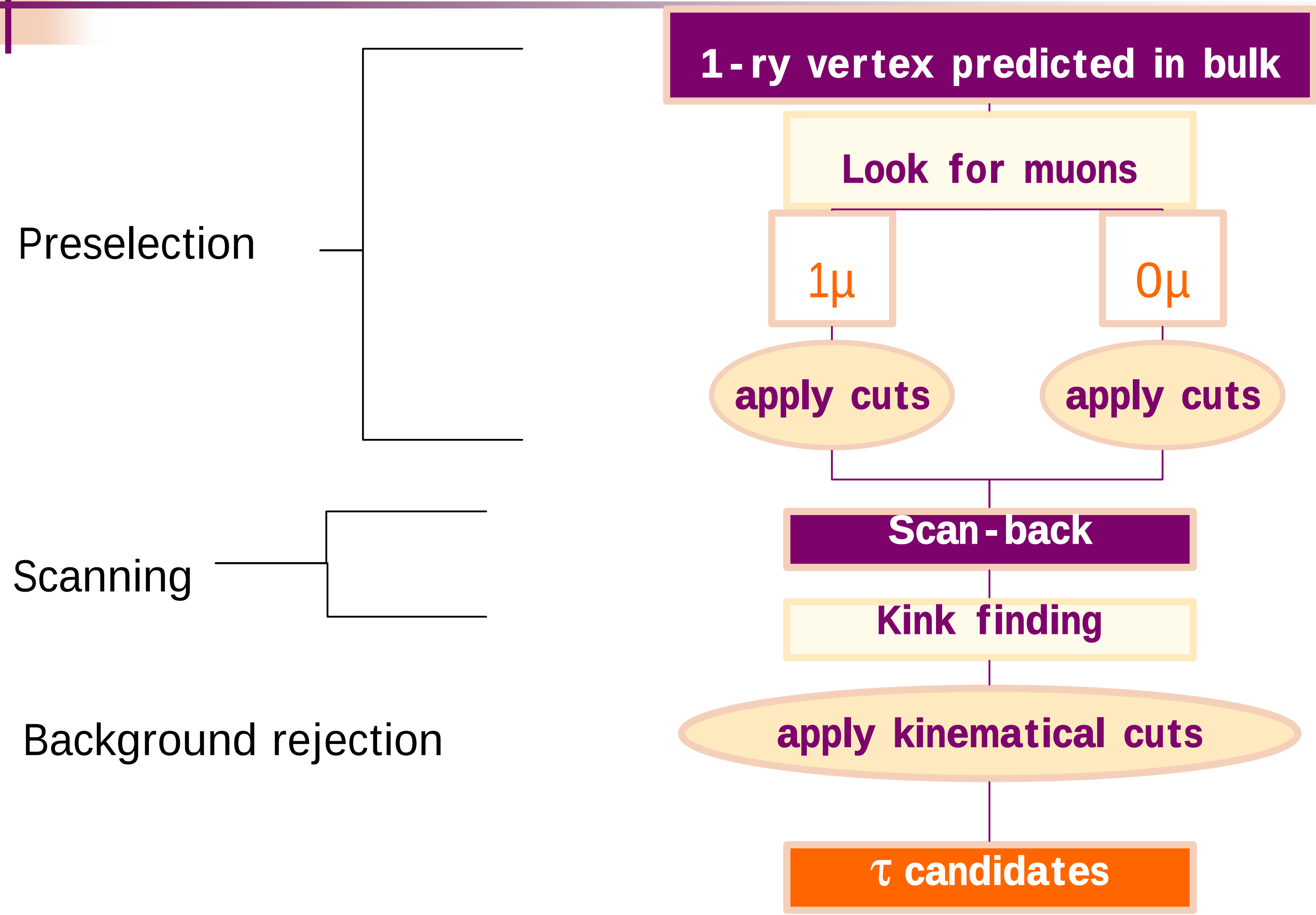
- 8 changeable sheets +
  4 special sheets:
  - Refine the predictions to search for a track in emulsion
- Bulk: 4 emulsion stacks (1.4×1.4 m^2)
  - Each stack is subdivided in 36 plates
  - Plate: 90 µm transparent plastic film + 350 µm emulsion sheets on both sides

Phase I

- CHORUS was the first emulsion experiment which applied automatic scanning procedures
- History:

94-97	Neutrino data taking	2+2 years of emulsion target exposure
95-98	Predictions	Data processing for electronic detector Kinematical selection
96-99	scan-back + Vertex location	Follow-up of scan-back track in emulsion to reach the vertex
96-99	Kink search	Search of decay topologies on the scan-back track
99-00	Post scanning	Manual check + background rejection

Data analysis



Kinematical preselection

- Decay modes considered:
  - $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ (BR = 18%)
  - $\tau^- \to h^- \left(n\pi^0\right) \nu_\tau$ (BR = 50%)
- Common to both samples:
  - Primary vertex reconstructed by Target Tracker
  - Vertex predicted in target emulsion
  - The event contains at least one negative track (τ daughter?)
- Some kinematical cut sample-dependent are applied to reduce scanning load

1μ sample

- One and only one μ with negative charge
  - Based on spectrometer response
  - Recovery of short muons by calorimeter measurement
- Selection efficiency: 80%
  - Includes vertex reconstruction, μ identification and μ matching efficiencies
- Momentum cut: $p_\mu < 30$ GeV
  - Scanning load reduced by 29%
  - Would reject 15% of ν_τ interactions if ν_τ's have the same energy spectrum of ν_μ's

0μ sample

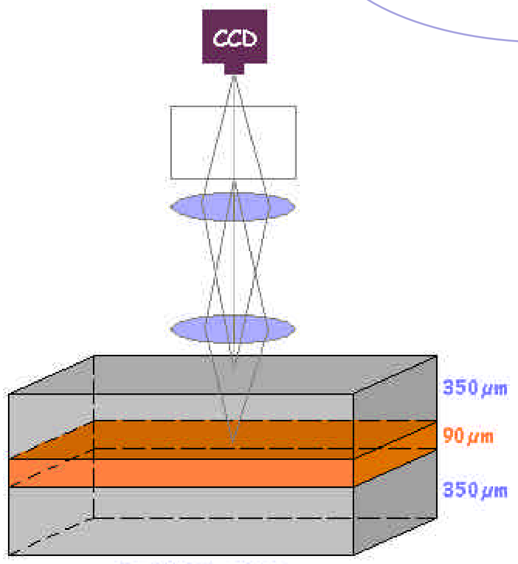
- No muon identified in the detector
- ≥1 negative tracks reconstructed by the fiber trackers
- Contaminations:
  - ~ 40% of events with a misidentified muon
  - ~ 6% of events from neutrinos other than ν_μ's
- Momentum cut: $1 \leq p_\mu \leq 20$ GeV

Rejection of products of γ conversions and secondary interactions

Bad momentum resolution at higher energies

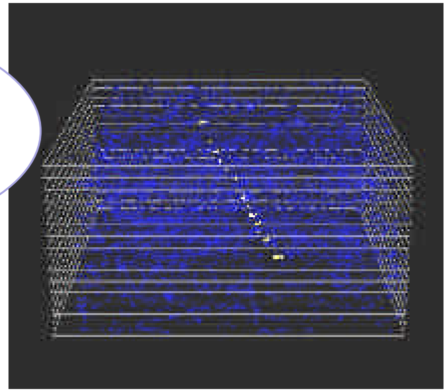
  - No spoke of the magnet crossed
- More than one track can be selected per event

Emulsion data acquisition

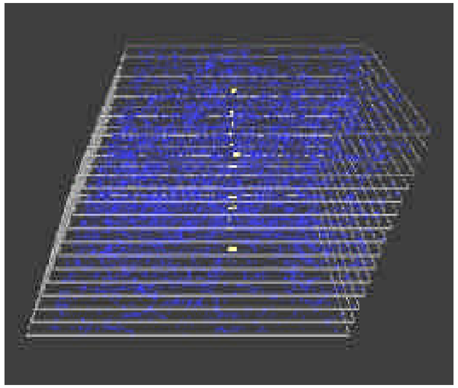


CCD image: 120×150 µm
Focal depth: 3 µm

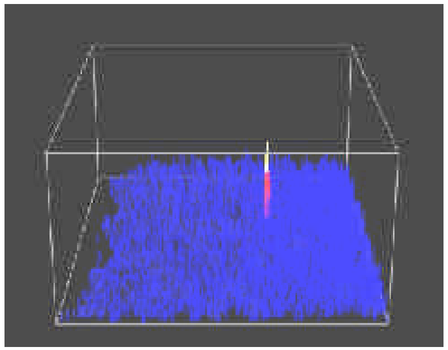
Track selector:
Take 16 tomographic
images per plate



Shift each plane
by the angle given
in predictions



The most upstream 100 µm
of each plate are scanned

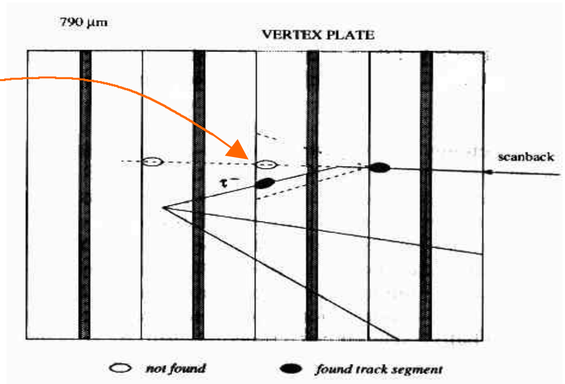


Sum up the ph
A track is recognized
as a peak

Scanning procedure

- Scan-back: Fibre tracker → Interface emulsion → Bulk emulsion

When the scan-back track disappears → that is the vertex plate



  - Location efficiency higher for 1μ (40%) than for 0μ (27%) independently from track angle
- Parent search: look for track segments around the scan-back position
  - Segments at small distance from the scan-back track are parent candidates
  - Large angle – Long path kinks are visible

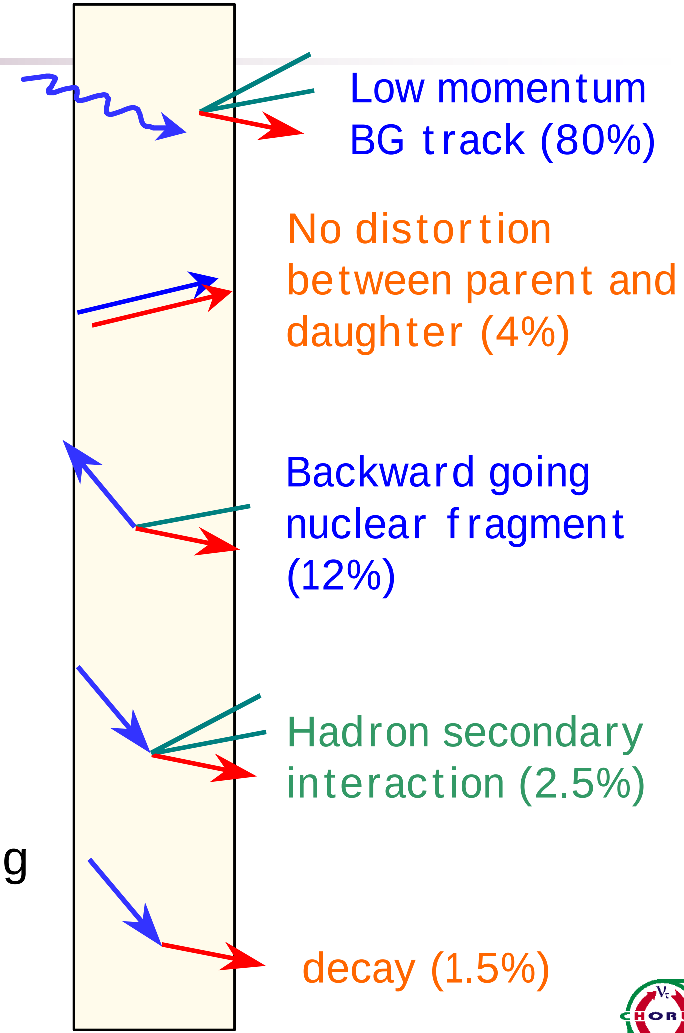
The final sample

Emulsion triggers: 2,305K

1μ		0μ	
Initial sample	713,000	Initial sample (CC contamination)	335,000 (140,000)
Momentum cut + angle cut	477,600	≥1 negative tracks + Momentum cut + angle cut	122,400
Events scanned	355,395	Events scanned	85,211
Vertex located	143,742	Vertex located	20,081
Selected for eye-scan	11,398	Selected for eye-scan	2,282

Manual scanning

- Operator detailed computer-assisted measurement of:
  - ✓ Scan-back track
  - ✓ Parent track
  - ✓ Other tracks from primary
- To be a decay topology:
  - ✓ No black prongs or blobs
  - ✓ No recoil
  - ✓ No Auger electrons
- Selected events after automatic scanning are 5% of located events



Expected background

Cuts applied:

L_{kink} < 3 plates for 0μ

L_{kink} < 5 plates for 1μ

p_t > 250MeV

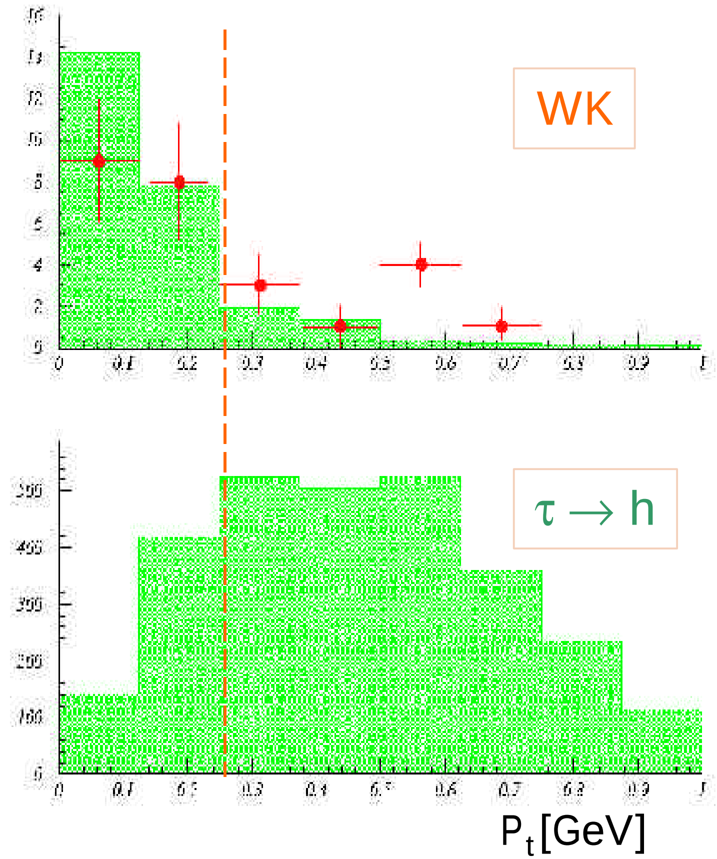
	1μ	0μ
Charm from n CC with missed primary lepton $\nu_{\mu/e}$ N → D^- X μ^+/e^+ └→ μ^-/h^- + neutrals	0.11	0.03
Charm from ν CC with μ^+/h^+ wrong sign	< 0.03	0.69
Associated charm production in NC D^+/D^0 missed, associated to D μ^-/h^- + neutrals	< 0.05	
Prompt ν_τ	< 0.1	
Hadronic white kinks	---	2.8

⇒ Less than 1 bg event from channels other than white kink

White kink background

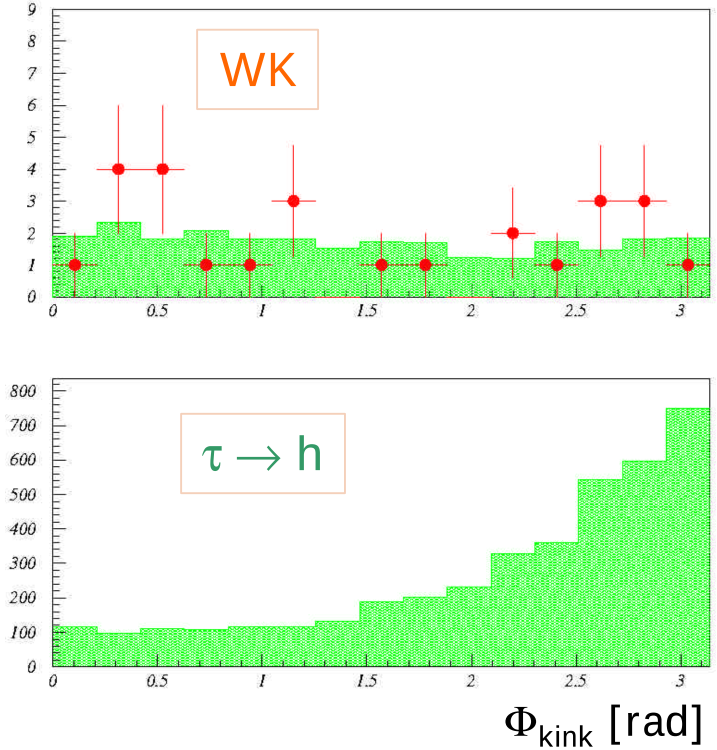
- Poor previous knowledge of $\lambda_{WK}(p_t, p)$
- CHORUS measured $\lambda_{WK}(P_t > 250\text{MeV/c}) = 21.3 \pm 7$ m

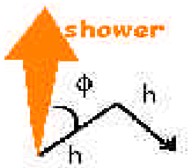
  $\Rightarrow$ 2.8 ± 0.8 WK expected in the signal region (< 3 plates from the vertex position)



Post-scanning WK rejection

- Φ_t cut: τ opposite to the shower in the transverse plane
- L_{decay} cut: τ flight length shorter and correlated with p_{had}





Limit evaluation

- Cut combination was optimized to maximize the sensitivity to oscillation:
  - Retain 80% of τ signal
  - $\Phi_{kink} > 90^o$
- Oscillation probability: $P_{\mu\tau} = \sin^2 2\theta_{\mu\tau} \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2_{\mu\tau} \cdot L}{E}\right)$
- For large Δm^2:

$$P_{\mu\tau} = \frac{N_\tau}{\sum_{i=\{1\mu,0\mu\}} BR_i \cdot N_i^{loc} \left\langle \frac{\sigma_\tau^{CC}}{\sigma_\mu^{CC}} \cdot \frac{A_i^\tau}{A_i^\mu} \cdot \varepsilon_i^{kink} \right\rangle}$$

Upper limit on the number of τ candicates in absence of signal

Number of ν_τ events observed if all incident ν_μ convert into ν_τ

- Overall systematic error on $\sum_i \left(N^\tau_{max}\right)_i$ estimated to be 17% and included in the upper limit

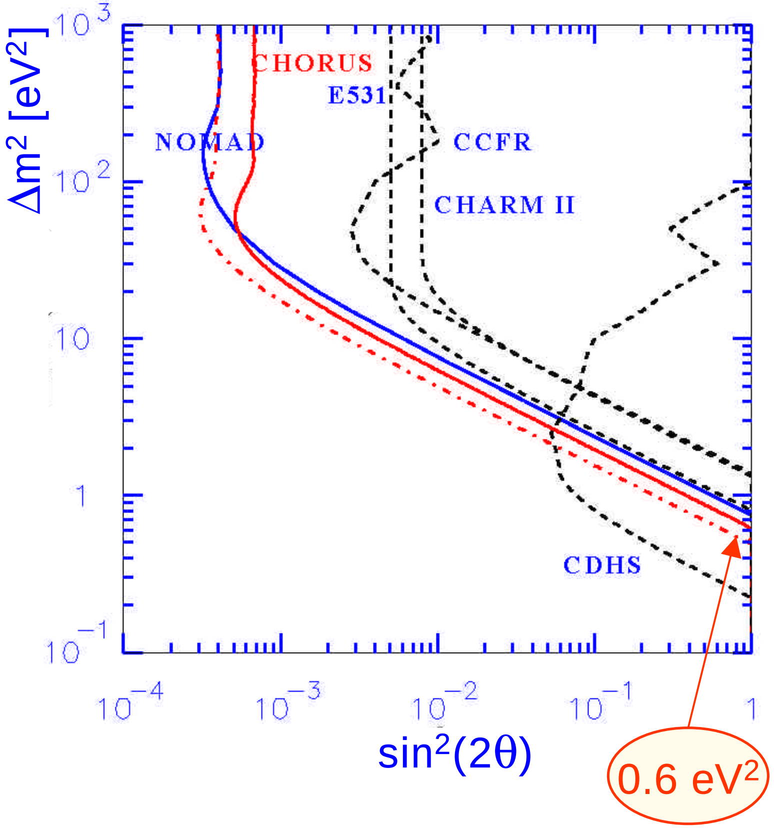
Result of Phase I

$P_{\mu\tau} < 3.4\ 10^{-4}$
@90% CL[1]

Or for large $\Delta m^2 \rightarrow \sin^2 2\theta_{\mu\tau} < 6.8\ 10^{-4}$

Using a different approach[2] to CL intervals we can quote

$P_{\mu\tau} < 2.2\ 10^{-4}$



[1] T.Junk, NIM A434 (1999) 435

[2] G.J.Feldman and R.D.Cousins, Phys.Rev. D57 (1998) 3873

CHORUS Phase I I

- Scanning speed increased from 0.01 frames/sec in 1994 to 10,000 in 2000

➔ Automatic scanning of a large emulsion volume is now feasible

  - New predictions/locations (mainly 0μ) to increase by >80 Kevents the current sample of ~164 Kevents (scan-back started)
  - For each (old and new) located event $\rightarrow$ full event analysis in the vertex region (data-taking started, current speed is ~10 Kevents/month)

➔ Improvement of oscillation search to reach the proposal sensitivity

- We will have a big sample of events fully analyzed in the vertex region

➔ Unbiased study of charm production in neutrino interactions

  - About 300 charm events already identified

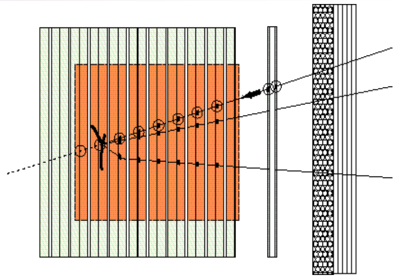
Netscan

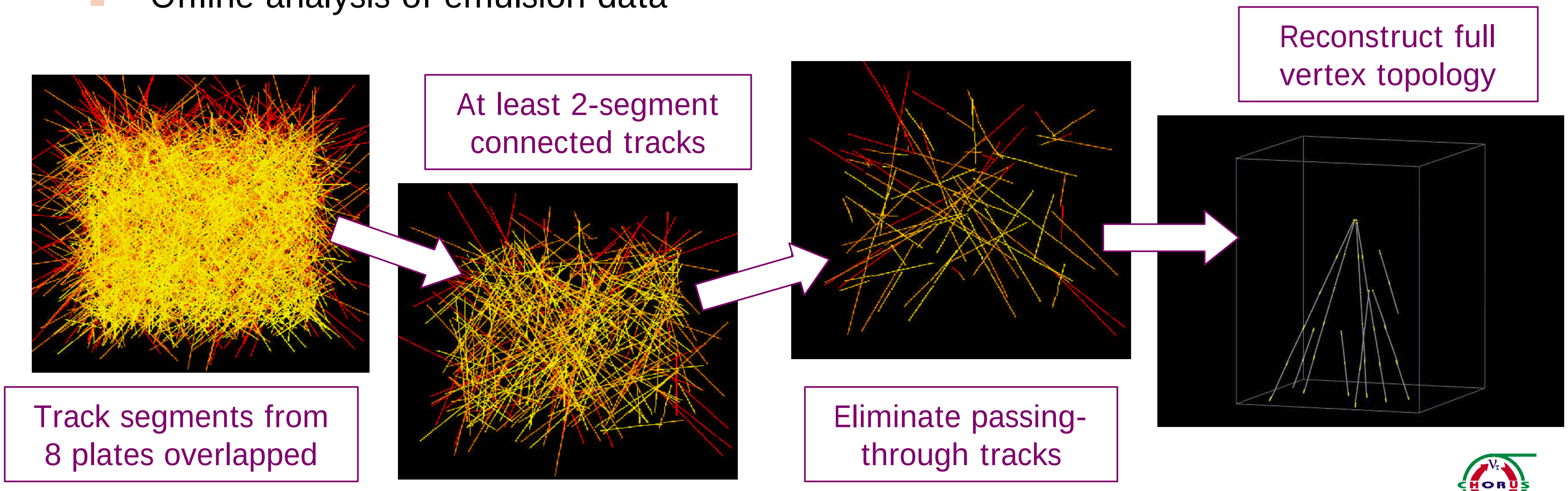
A new scanning technique!

- Use already located events
- Pick up <u>all track segments</u> in an 8-plates deep fiducial volume around scan-back track

➔ Decay search is not limited to the scan-back track

- Offline analysis of emulsion data





Conclusions

- The two CERN neutrino high sensitivity experiments have successfully ended their data taking
- NOMAD has published its final results on oscillations
- CHORUS has published its phase I results and started its phase II analysis

NO EVIDENCE FOR OSCILLATION IN THE EXPLORED REGION

- New techniques have been developed which will be largely applied in future experiments (e.g. Opera)