Neutrino Physics and oscillation studies at CERN

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Neutrino 2002, Munich, Germany, May 25-30 2002

Outline

- The Cern short baseline program:

  CHORUS and NOMAD experiments

- Search for ν_τ appearance in the SPS ν_μ beam

  Cosmologically relevant region

- The $\nu_\mu \rightarrow \nu_e$ oscillation search

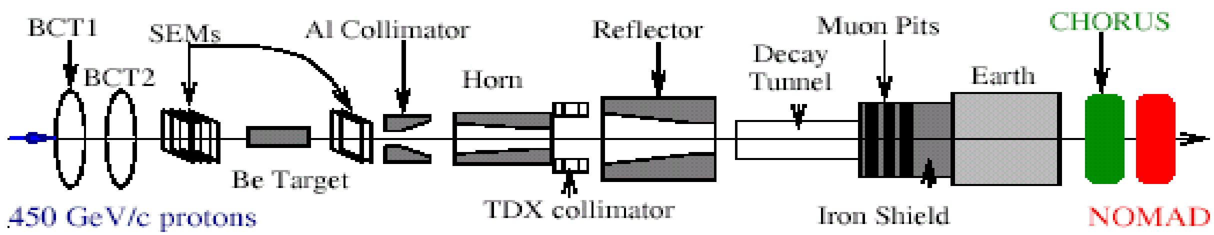
  LSND signal region

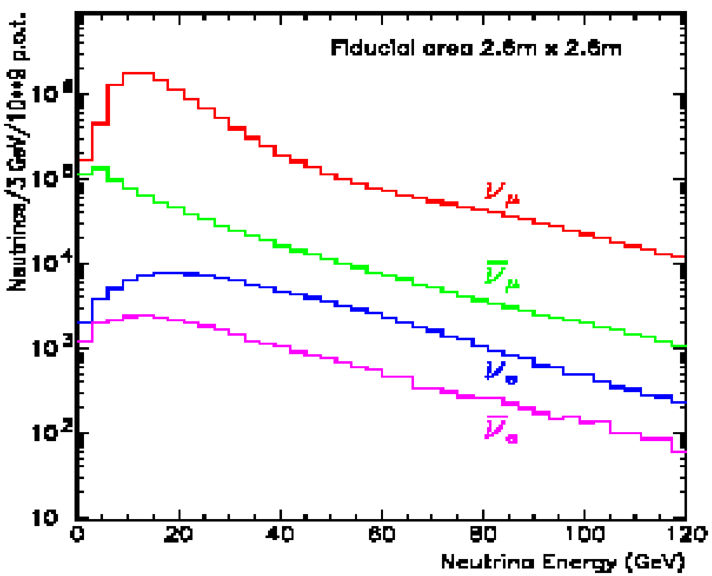
- Study of neutrino interactions

  Charmed and strange particles production

The SPS neutrino beam

- Mean distance from ν source (π, K decays): NOMAD ~ 620m, CHORUS ~ 600m.





- Wide Band Beam: broad energy spectra.
  - Main component average energy ~25 GeV
  - Antineutrino contamination <6%, ν_e ~1%
  - Prompt ν_τ negligible
- Short Baseline Experiments:

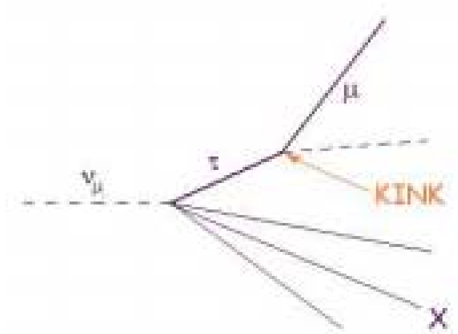
$$\langle L\rangle / \langle E\rangle \approx 2\times10^{-2}\ \mathrm{km/GeV}$$

$$\Rightarrow \Delta m^2 \text{ sensitivity in the range } 1 \le \Delta m^2 \le 100\ \mathrm{eV}^2$$

The $\nu_\mu \rightarrow \nu_\tau$ oscillation search

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

τ identified by its decay properties:



Decay mode	BR
$\mu \bar{\nu}_\mu \nu_\tau$	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%

NOMAD high resolution on momentum reconstruction and pid

Indirect search $\rightarrow$ signal from kinematical criteria

CHORUS very high resolution at vertex

Direct search $\rightarrow$ signal from visual scanning

High design sensitivity $P(\nu_\mu \rightarrow \nu_\tau) = 10^{-4}$ for $\Delta m^2 \approx 1\text{-}10$ 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

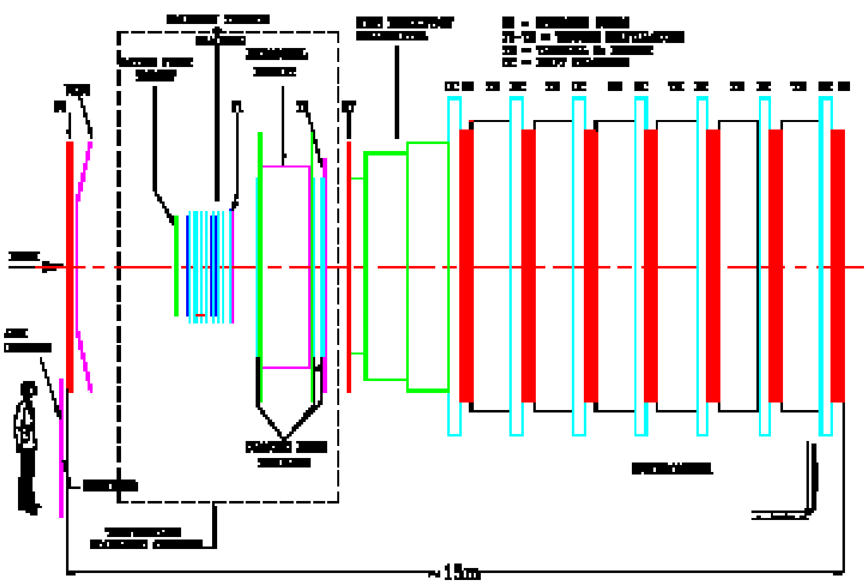
⇒ momentum resolution 3.5% (p<10 GeV)

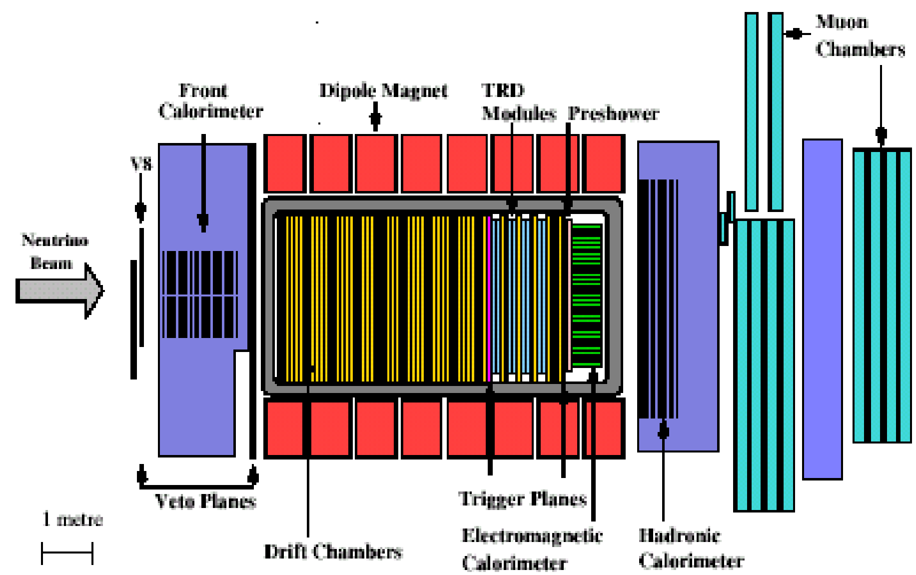
- Fine grained calorimetry

⇒ $\Delta E/E=3.2\%/\sqrt{E} \oplus 1\%$

- Particle id

⇒ pion rej 10^3 with electron eff >90%





Data samples

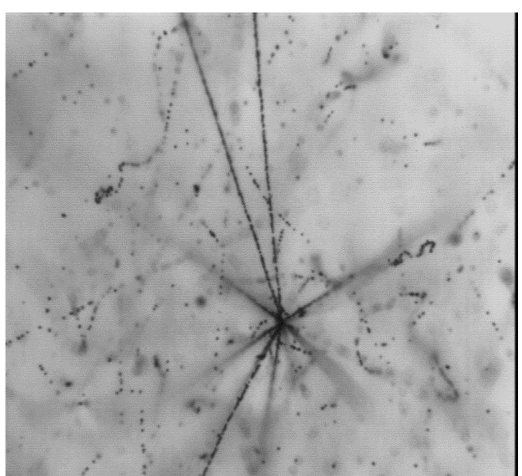
Chorus (94-97)

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



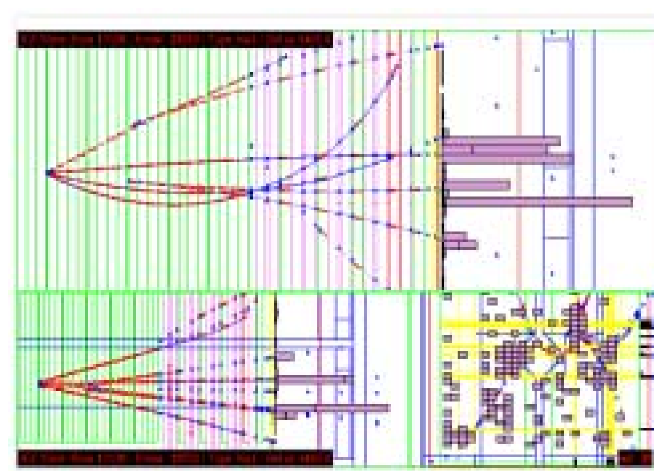
Nomad (95-98)

1,354k ν_μ CC interactions

- 100% of data analysed

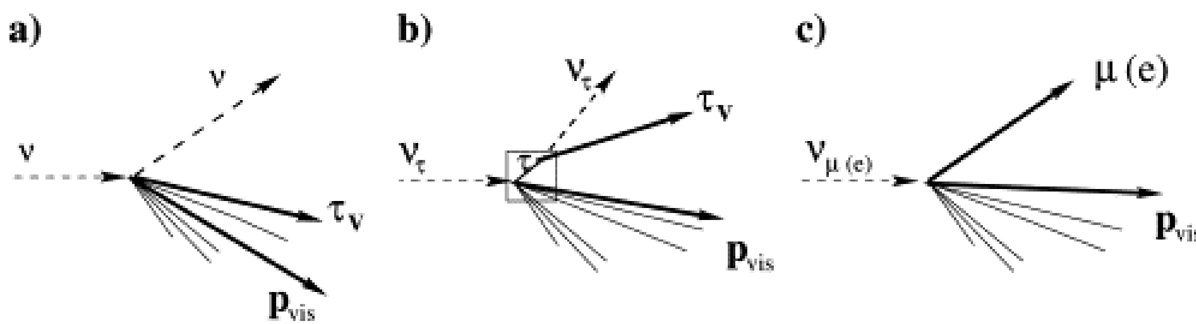
"Bubble chamber" quality

- very high resolution in momentum and energy
- particle Id



The Nomad ν_τ search

The ν_τ CC signal has intermediate properties between two background sources



NC background | Signal | CC background

Hadronic decay

The main source of bkgd are NC

⇒ isolation between the visible τ decay products and the hadronic jet.

Electron decay

The main source of bkgd are ν_e CC

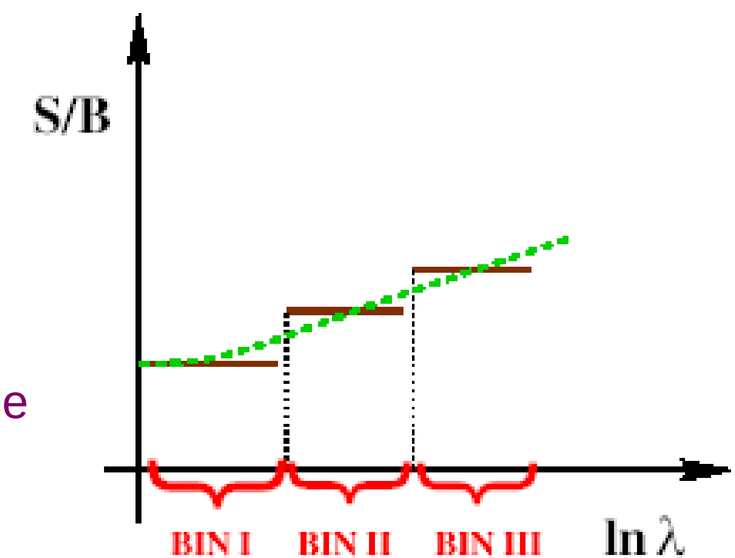
⇒ kinematics based on the missing momentum and angular relations in the transverse plane.

The Nomad analysis (1): general principles

Maximum rejection power achieved using full topology of the events

- Definition of a **pdf** $\mathcal{L}$, describing the probability for an event to be signal or background
- Event classification based on likelihood ratio between signal and background hypothesis

$$\ln\lambda = \mathcal{L}_S / \mathcal{L}_B$$



- $\ln\lambda$ 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

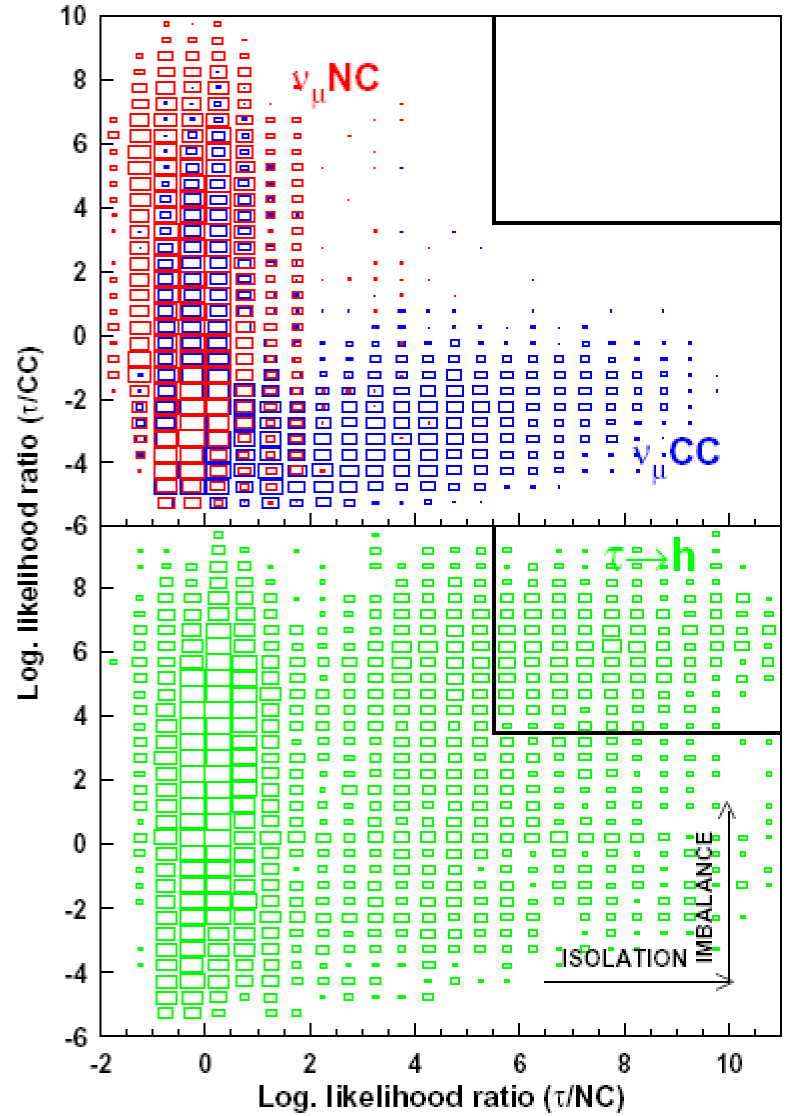
(Feldman & Cousins Phys. Rev. D57(1998)3873)

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

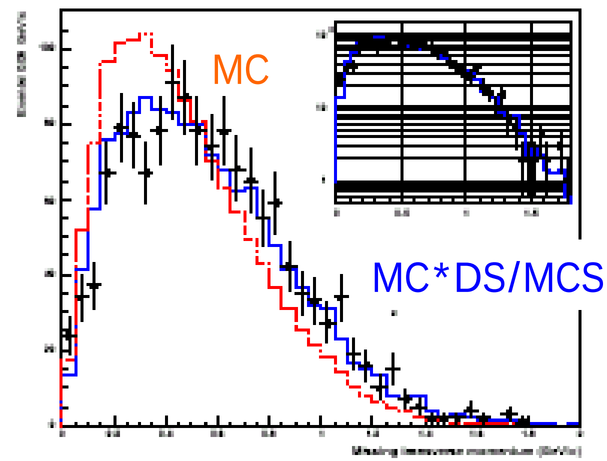
large kinematical suppression + multidimensional correlations
$\Rightarrow$ knowledge of bkgd O(10^{-5})

Data simulator

Corrections to MC extracted from data

- Use identified ν_μ CC in both Data (DS) and MonteCarlo (MCS) and replace the leading μ^- by the appropriate MC particle: ν for NC, τ^- for signal, e^- for ν_e CC
- Compute all efficiencies as $\varepsilon = \varepsilon_{MC} \dfrac{\varepsilon_{DS}}{\varepsilon_{MCS}}$

Missing p_t in ν_e CC



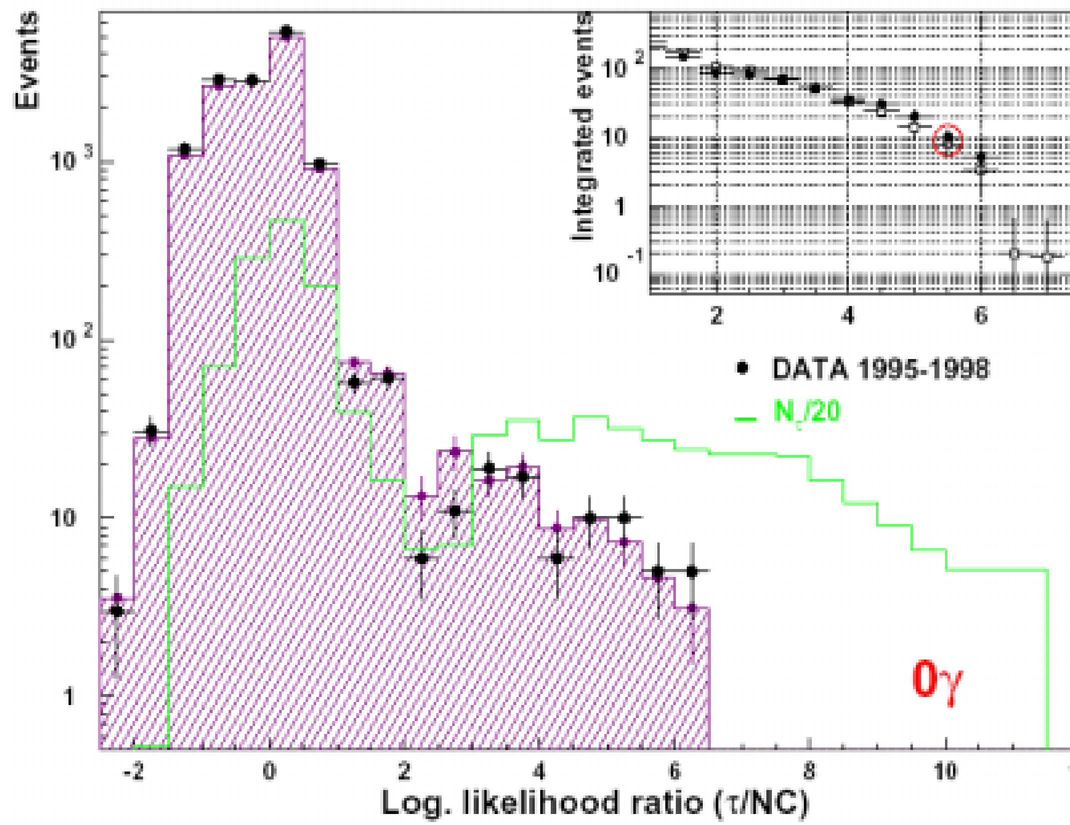
Control samples

τ^+ search and τ^- search outside the "box" are used to check final predictions and evaluate systematics

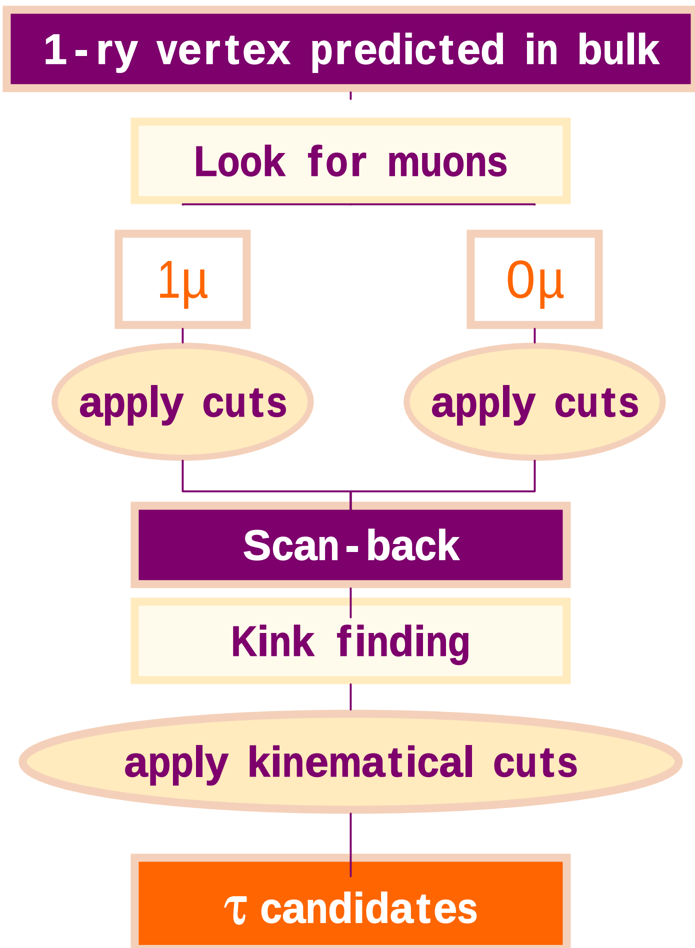
Final result: no evidence for oscillations in Nomad

Blind box is opened:

- Data are consistent with background in each bin
- Integrals and shapes of lnλ distribution agree with background predictions



The Chorus ν_τ 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 $1.5 \times 1.5 \times 6$ mm^3)

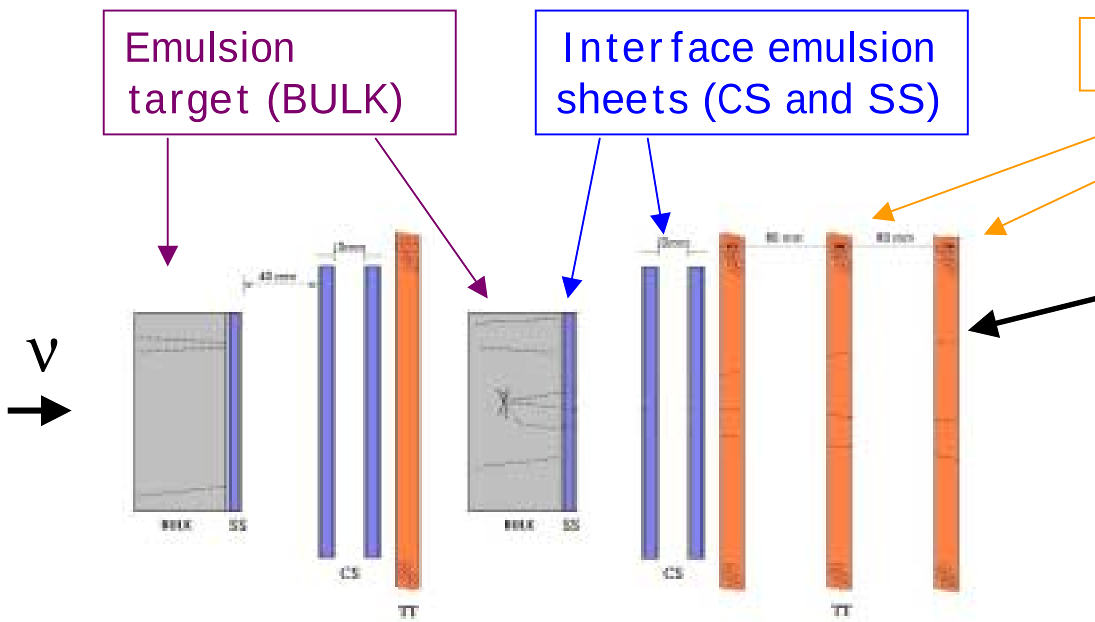
4) Post-scanning analysis

Kinematical study, kink P_t measurement

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 ∈ [-1,-20] GeV/c



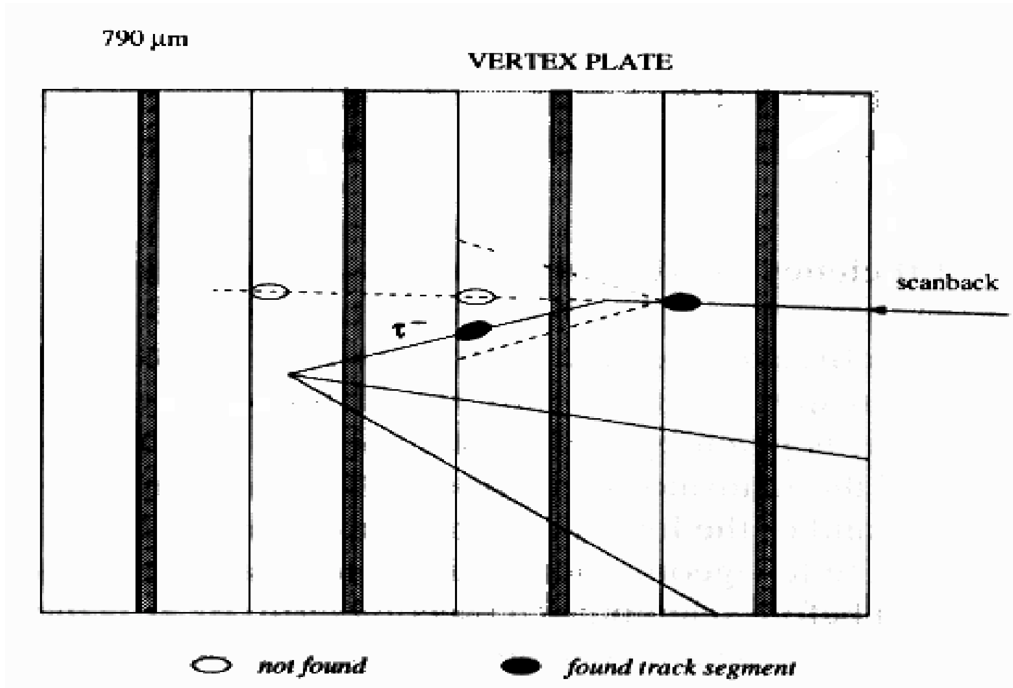
Tracks are predicted by the fiber target tracker

Searched for in the interface emulsion sheets CS and SS

Followed back into the bulk up to the vertex

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

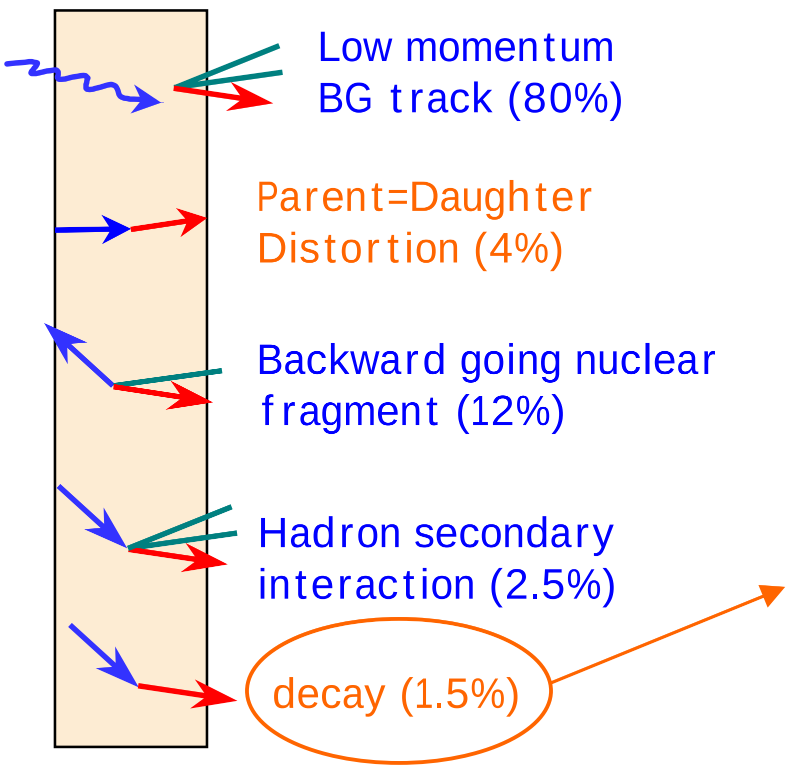
Data flow in Chorus Phase I

Emulsion triggers: 2,305K

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

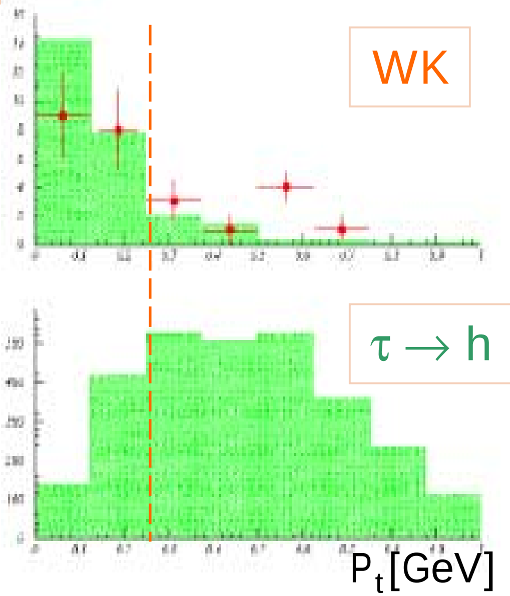
Computer-assisted operator measurements of candidate kink topology



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

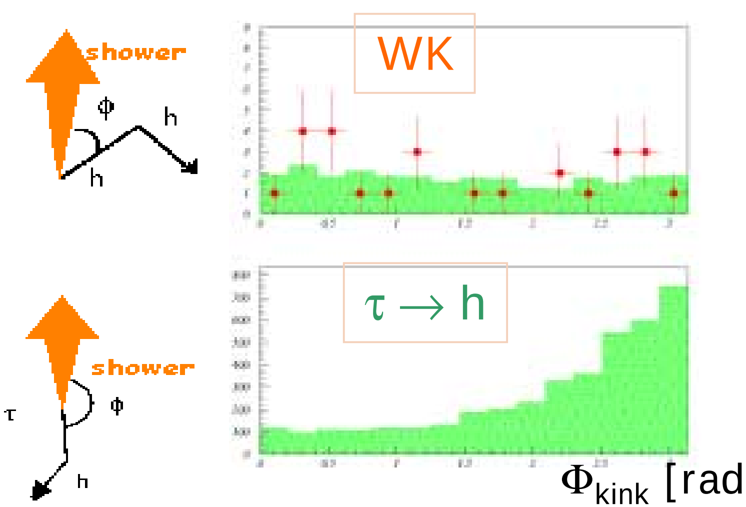
P_t>250 MeV/c to reject π and K decays

White kink background



- 1-prong nuclear interaction with no ionizing activity at interaction point
- CHORUS measured $\lambda_{WK}(P_t > 250 MeV/c) = 24.0 \pm 8.5$ m

$\Rightarrow$ 2.6 ± 0.8 WK expected in the signal region



Post scanning WK rejection

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

Cuts optimisation by the a-priori criterium of maximising the exclusion power, independently from data.

Chorus and Nomad as small background experiments

$N_\tau^{max} = N^{obs} \times (\sigma_\tau/\sigma_\mu) \times (\varepsilon_\tau/\varepsilon_\mu) \times Br$

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

channel	Total bkgd	N_τ^{max}	Data
1μ	0.1	5014	0
0μ	1.1	2004	0
	1.2	7018	0

channel	Total bkgd	N_τ^{max}	Data
e	0.61	2826	0
h	0.76	5343	1
3h	0.32	675	0
	1.69	8844	1

NO EVIDENCE FOR OSCILLATIONS

Results of the $\nu_\mu \rightarrow \nu_\tau$ oscillation search

Total bkgd	N_τ^{max}	Data
1.2	7018	0
(±30% syst)	(±15% syst)	

Total bkgd	N_τ^{max}	Data
50.5	15226	52
(±20% syst)	(±10% syst)	

Calculation of Limit @ 90% CL

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

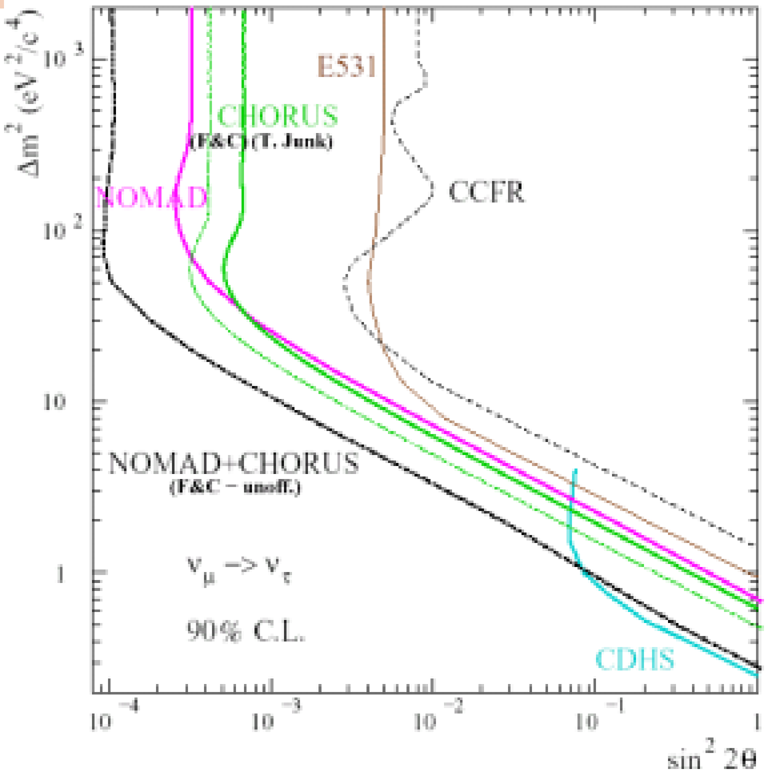
$L_{osc}(\nu_\mu \rightarrow \nu_\tau) = 1.63 \times 10^{-4}$
$S_{osc}(\nu_\mu \rightarrow \nu_\tau) = 2.5 \times 10^{-4}$
$P(\leq L_{osc}) = 37\%$

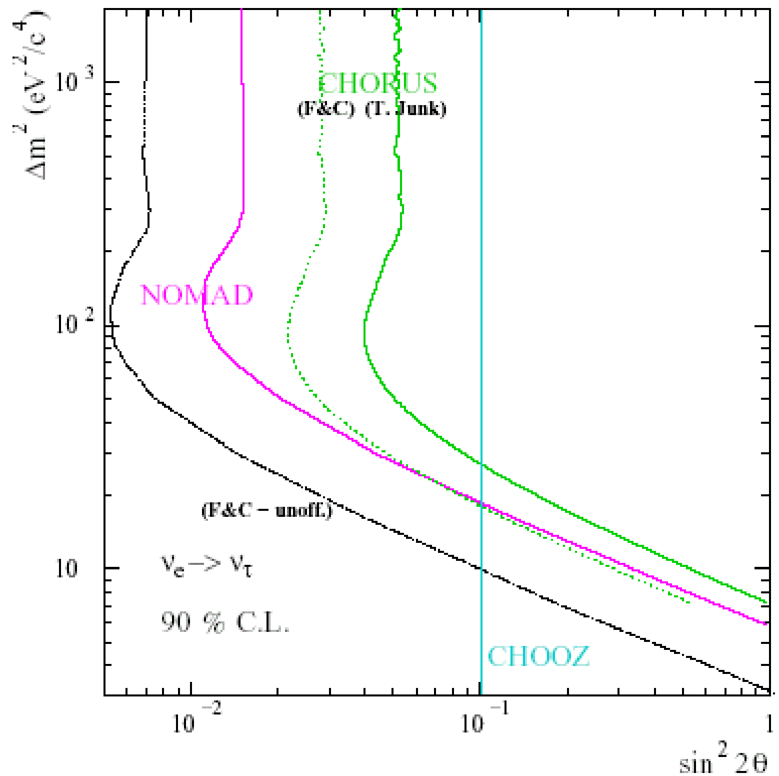
$L_{osc}(\nu_\mu \rightarrow \nu_\tau) = 2.1 \times 10^{-4}$
$S_{osc}(\nu_\mu \rightarrow \nu_\tau) = 3.4 \times 10^{-4}$
$P(\leq L_{osc}) = 29\%$

T.Junk, NIM A434 (1999) 435

G.J.Feldman & R.D.Cousins,
Phys.Rev. D57 (1998) 3873

Exclusion plots





Combined result with F&C (*)

$L_{osc}(\nu_\mu \rightarrow \nu_\tau) = 0.5 \times 10^{-4}$
$S_{osc}(\nu_\mu \rightarrow \nu_\tau) = 1.7 \times 10^{-4}$
$P(\leq L_{osc}) = 15\%$

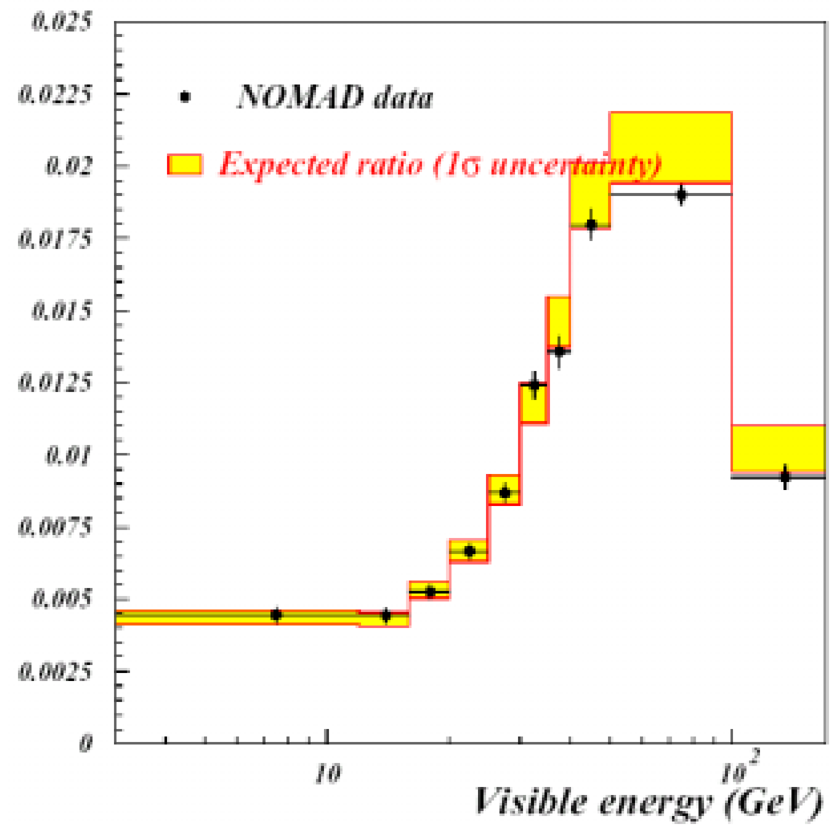
$L_{osc}(\nu_e \rightarrow \nu_\tau) = 0.4 \times 10^{-2}$
$S_{osc}(\nu_e \rightarrow \nu_\tau) = 0.9 \times 10^{-2}$
$P(\leq L_{osc}) = 25\%$

(*) by courtesy of R. Petti

Nomad $\nu_\mu \rightarrow \nu_e$ oscillation search

- Appearance experiment based on powerful electron id in NOMAD
- ν_e in the beam ~ 1%
- Different energy spectra and radial distribution for ν_e and ν_μ

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

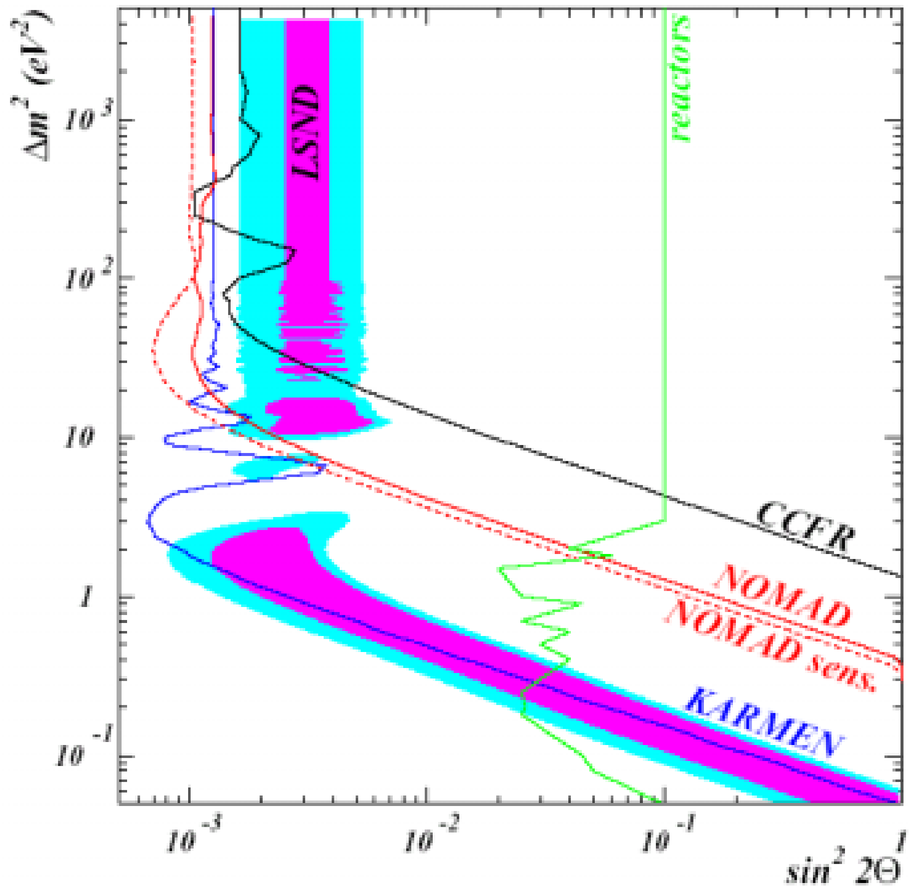


748k ν_μCC and 8k ν_eCC candidates

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

NO EVIDENCE FOR OSCILLATIONS

Nomad $\nu_\mu \to \nu_e$ exclusion region (Preliminary)



At large $\Delta m^2 \to \sin^2(2\Theta) < 1.2 \times 10^{-3}$ @ 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)

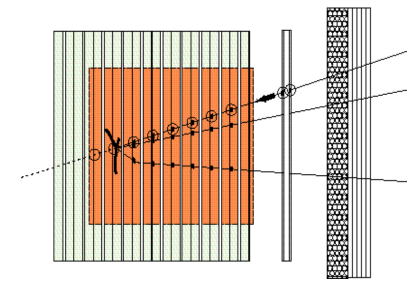
➔ Improvement of oscillation search to reach the proposal sensitivity

- 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

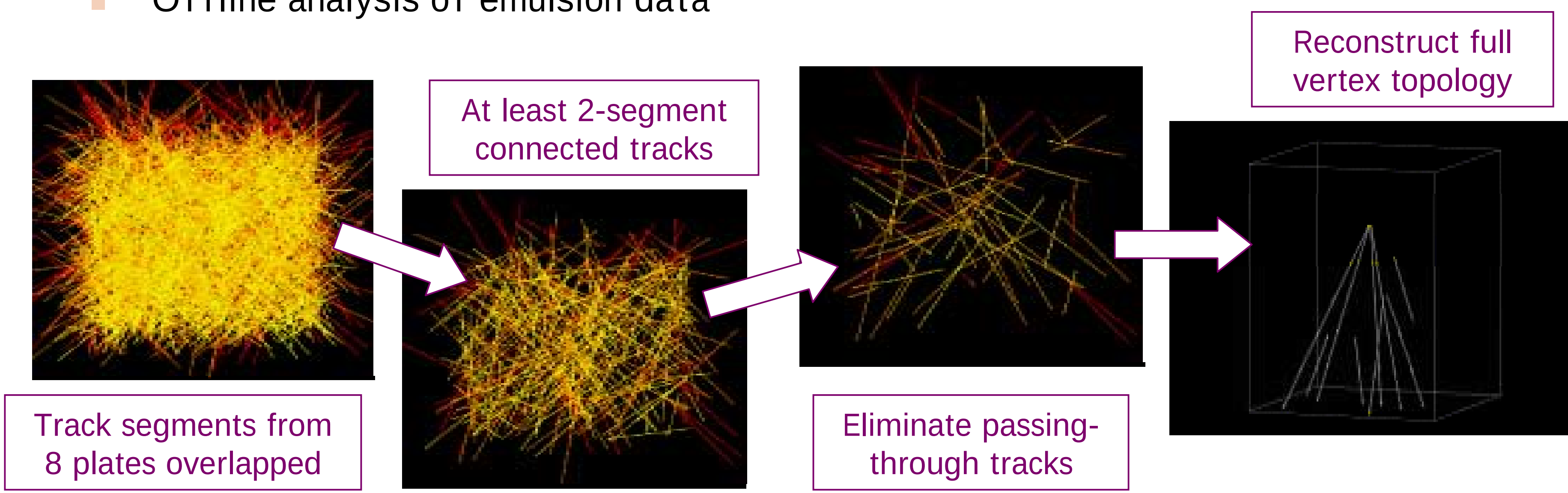


A new scanning technique!

- Use already located events
- Pick up <u>all track segments</u> in 1.5 × 1.5 × 6.3 mm^3 fidvol around scan-back track

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

- Offline analysis of emulsion data



Charm Physics with Chorus

- D^0 production Phys. Lett. B527(2002)173

Data taking ongoing : 25k CC $\rightarrow$ 150k CC
Improved selection : purity 65% $\rightarrow$ 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% $\rightarrow$ 25%

- Exclusive channels

Proton identification
MCS momentum measurement
$\Sigma^{\pm}$ detection

Λ_c absolute BR,QE Λ_c production

Further studies in Nomad

- D^* production Phys. Lett. B526(2002)278

High purity sample of D^{*+} events → study of fragmentation process

Inclusive neutrino charm production by dimuons

currently being updated

- Strange particles and resonances production Nucl. Phys. B621(2001)3

V^0 sample (K^0_s, Λ, anti-Λ) → an order of magnitude increase in statistics with respect to bubble chamber experiments

- (anti-)Lambda polarization Nucl. Phys. B605(2001)3
- Backward going protons and pions in CC reactions Nucl. Phys. B609(2001)255

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 $\sin^2(2\Theta)$ $O(10^{-4})$

NO EVIDENCE FOR OSCILLATIONS IN THE EXPLORED REGION

- The two CERN neutrino experiments have demonstrated that a sensitive search for ν_τ appearance can be achieved with two different approaches: the kinematical analysis and the automatic emulsion scanning $\rightarrow$ valid techniques for planned and future experiments
- Highly valuable data samples have been collected $\rightarrow$ further studies for neutrino physics, more results to come