The Chorus Search for $\nu_\mu \rightarrow \nu_\tau$ Oscillation

Lucio Ludovici
University of Rome “La Sapienza” and INFN

for the CHORUS collaboration

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Outline

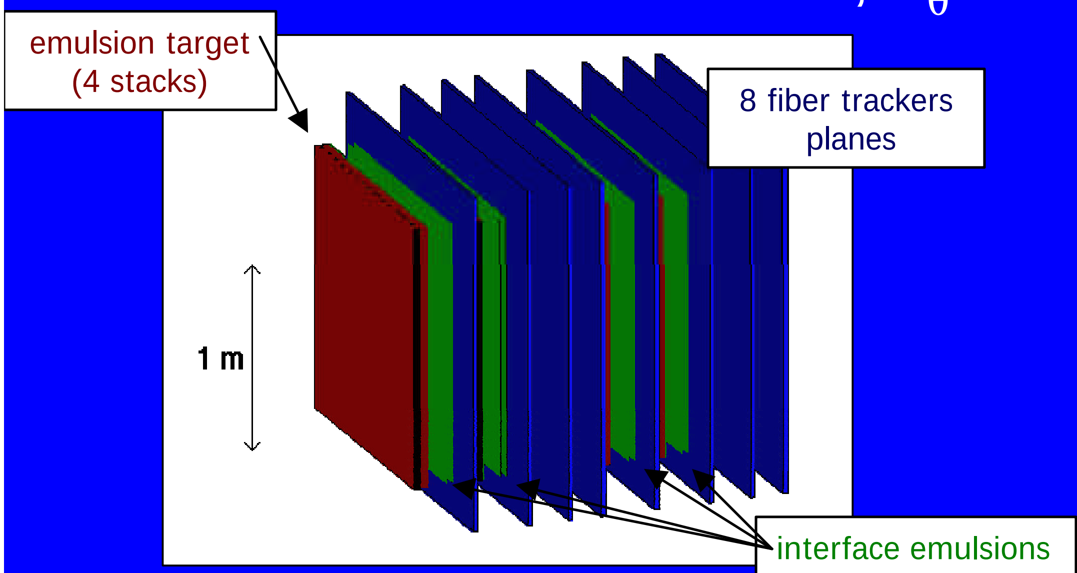
- The Chorus search for Oscillation
- The experimental layout
- The analysis strategy
- Results from the “first round” analysis of the full 1994-97 data sample
- Prospects for the final “second round” analysis result

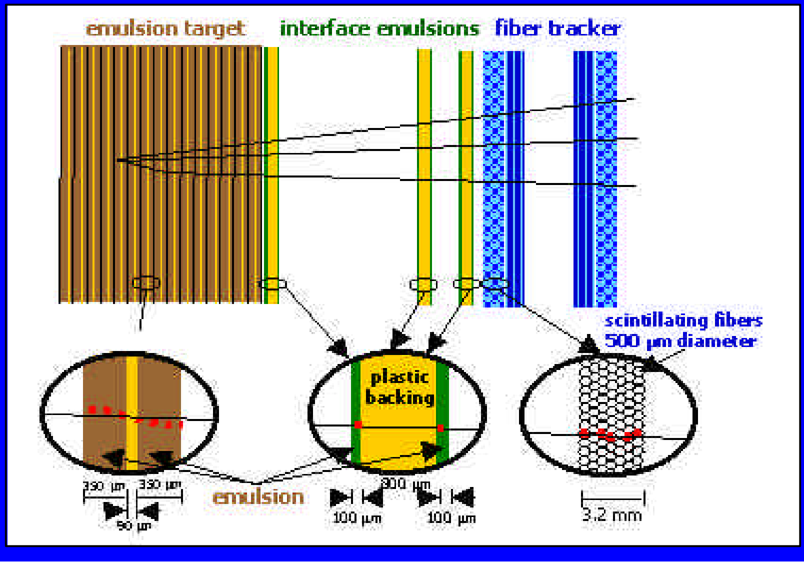
Experimental Principles

- Search for ν_τ appearance on a "pure" ν_μ beam
- 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 high background rejection calls for an unambiguous appearance signature
- A ν_τ is detected observing the τ^- produced in a CC interaction and its subsequent decay vertex in an active nuclear emulsion target

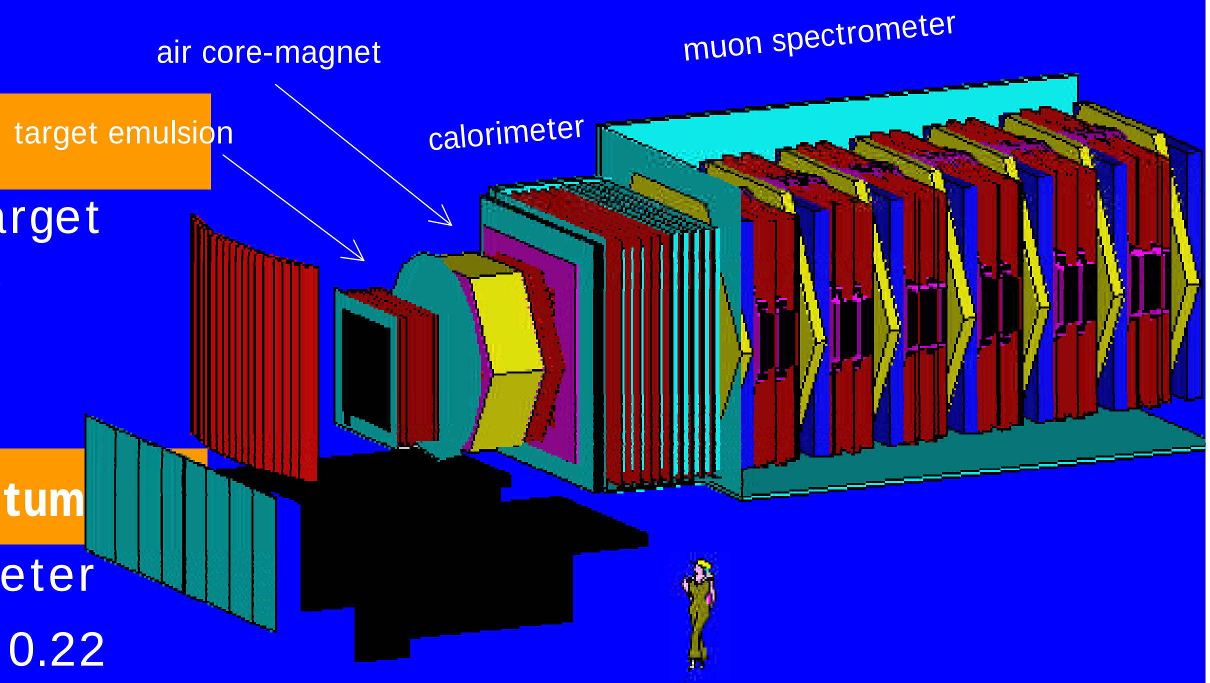
Detection Technique

- 0.8 t emulsion as active neutrino target
  - 4 stacks of 36 plates perpendicular to the beam
  - A μvertex with ~μm resolution, 300 3D hits/mm
- The scintillating fiber tracker
  - reconstructs the primary vertex, tracks leaving the target and extrapolates back to emulsion: 160 mm resolution, s_{θ}=3mrad





Chorus Layout



- **Neutrino target**
- Active nuclear emulsion target
- Scintillating fiber tracker

- **Hadrons Sign and momentum**
- air-core magnet spectrometer

  $\Delta p/p = 0.035 \cdot p(GeV/c) \oplus 0.22$

  1996-97 upgrade: ET, HC

- **Showers energy, missing P_t**
- lead&fibers "spaghetti" calorimeter

  $\Delta E/E = 32\%/\sqrt{E}$ (hadrons)

  $\Delta E/E = 14\%/\sqrt{E}$ (electrons)

  $\Delta\theta_{hadr} \sim 60$ mrad @10 GeV

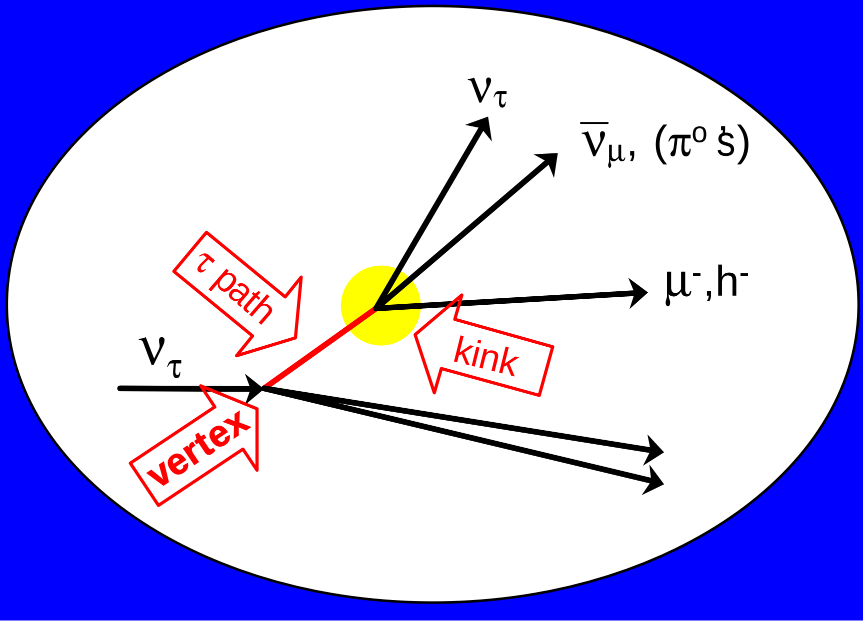
- **Muon ID, sign and momentum**
- iron-core muon spectrometer

  $\Delta p/p \sim 10\%-15\%$ ($p<70$ GeV)

The Chorus τ "signature"

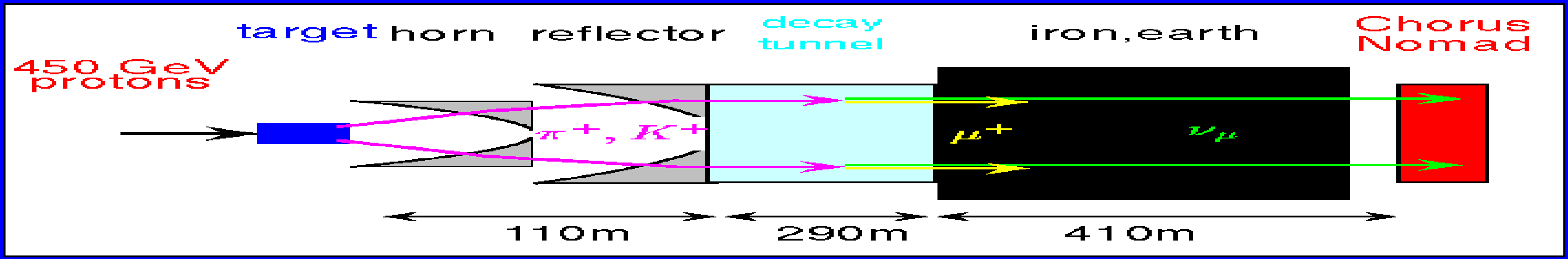
- The τ lepton is identified by the three-fold simultaneous observation of:

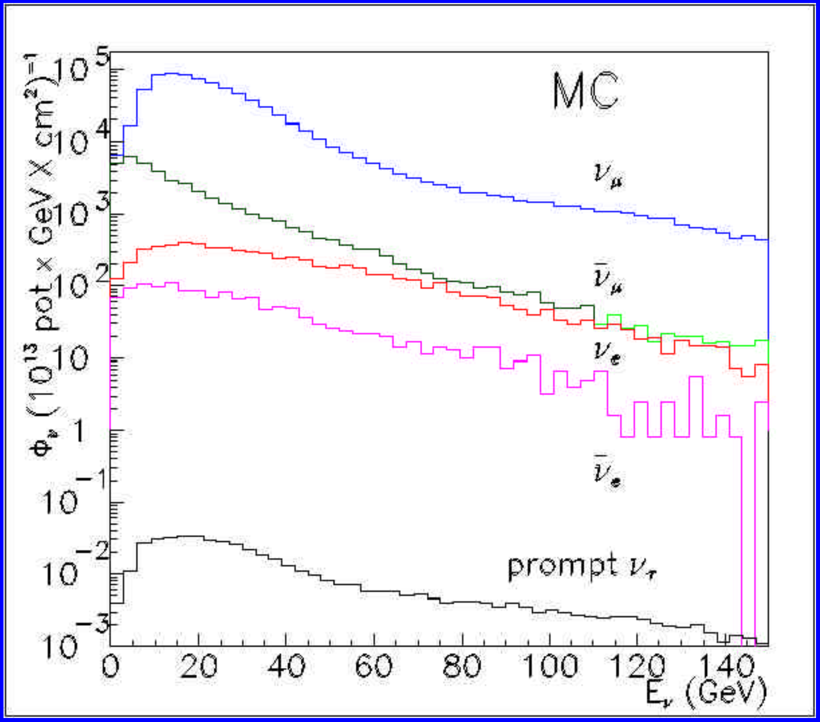
1. the neutrino CC interaction vertex
2. the short τ^- path, $c\tau$=87μm, γ~O(10)
3. the τ^- decay topology: kink



Neutrino Beam

Cern SPS-WANF: $5 \cdot 10^{19}$ PoT $\rightarrow$ 840,000 ν_μ CC





ν_μ : $\bar{\nu}_\mu$: ν_e : $\bar{\nu}_e$

1.00 : 0.05 : 0.017 : 0.007

ν_τ prompt contamination (from Ds decaying in the proton target) well below the Chorus sensitivity:

ν_τ CC ~$3.3 \cdot 10^{-6}$ ν_μ CC

Analysis Strategy

1. Electronic detector reconstruction
   – pre-selection of events and tracks to reduce the scanning load
2. Event location in emulsion
   – location of tracks in the interface emulsion sheets and follow-up to the interaction vertex (Scanback)
3. Kink finding
   – Several “automatic” algorithms $\rightarrow$ confirmation by operator eye-scan
   – (NETscan: search for all tracks in 1.5x1.5x6.3 mm^3)
4. Post-scanning analysis
   – Kinematic study, kink Pt cut, precise momentum measurement with ET

Pre-Selection

(electronic detector only)

$\tau^- \rightarrow \mu^- \ \nu_\tau \bar{\nu}_\mu$	Br=18%	1μ channel

1 negative muon from the primary interaction vertex with P < 30 GeV/c

$\tau^- \rightarrow h^- \ \nu_\tau \ n(\pi^o)$	Br=50%	0μ channel
$\tau^- \rightarrow e^- \ \nu_\tau \bar{\nu}_e$	Br=18%	

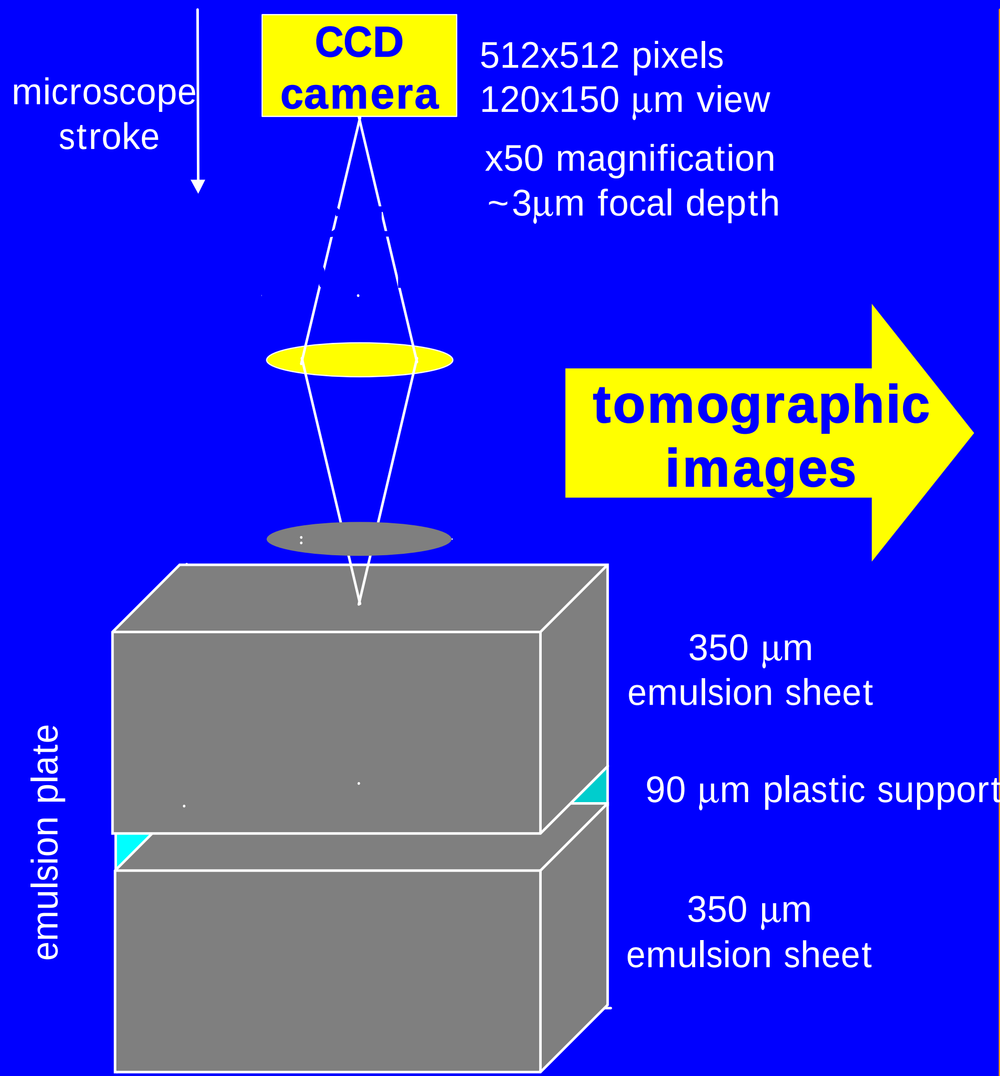
No muons in the primary interaction vertex and at least one negative track with P ∈ [-1,-20] GeV/c

$\tau^- \rightarrow \pi^+ \pi^- \pi^- \nu_\tau \ n(\pi^o)$	Br=14%

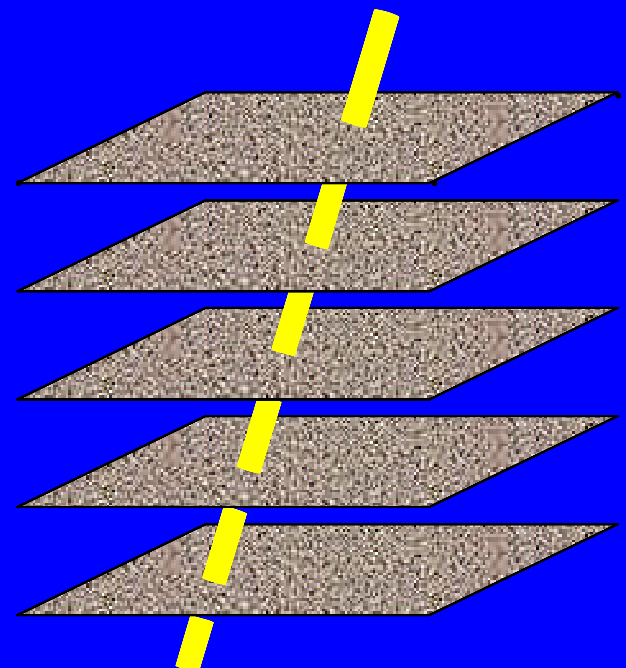
Not yet included in the analysis

Automatic Emulsion Data Taking

(pioneered by the Nagoya Chorus group)

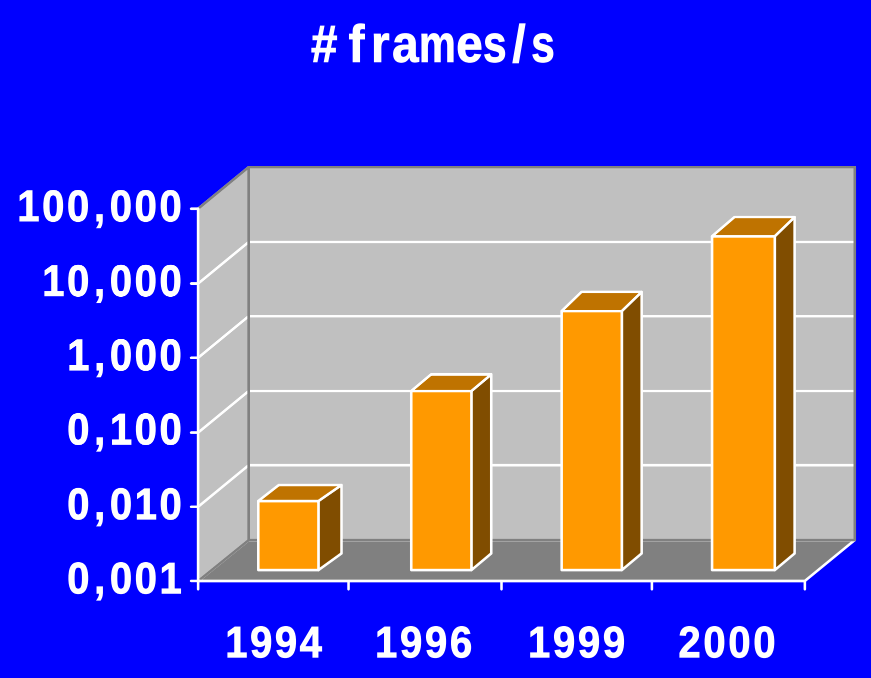


Hardware video processors reconstruct tracks as frame-to-frame emulsion grain coincidence.



Scanning speed

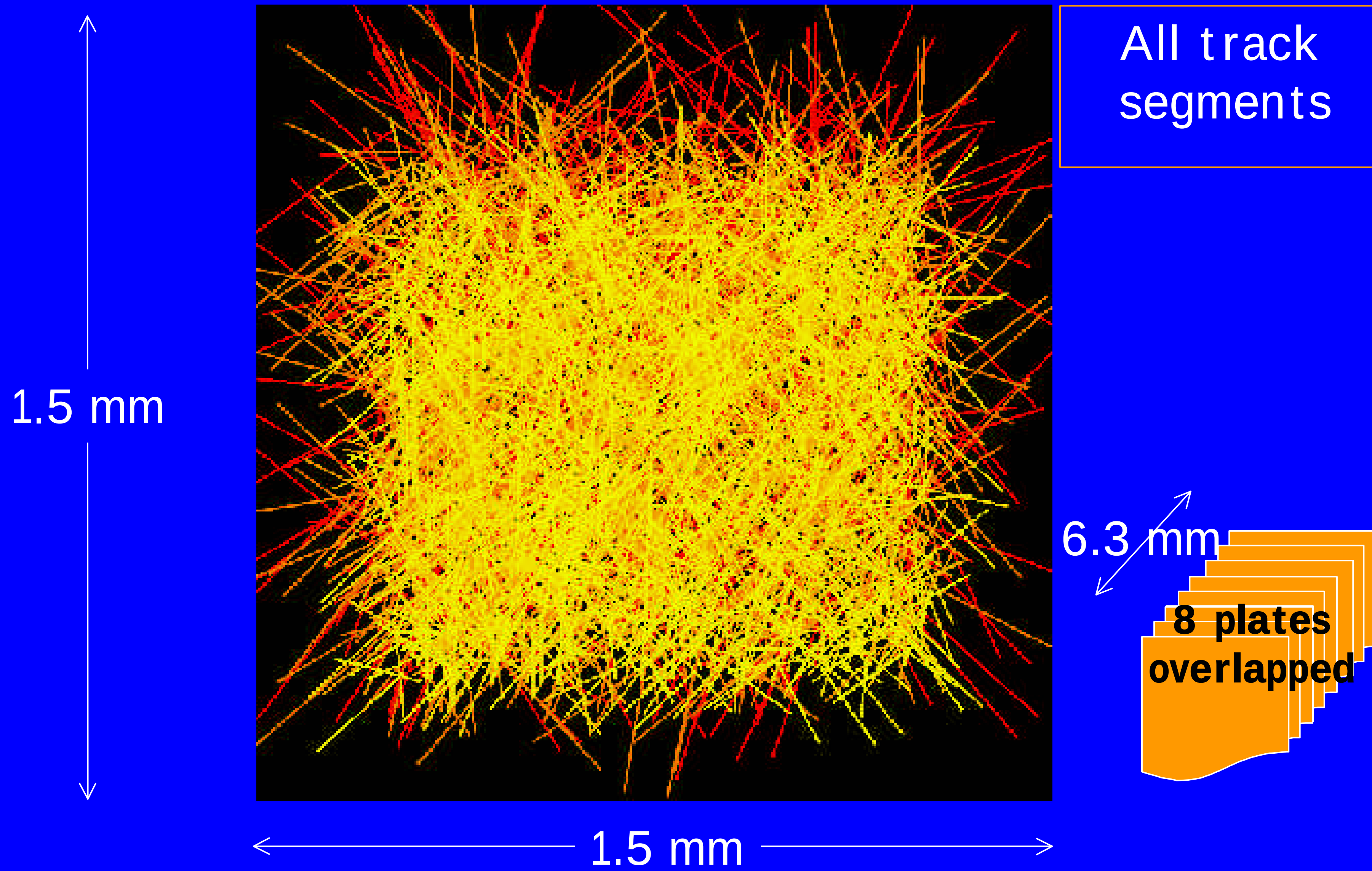
- Impressive progress of the automatic scanning speed since the Chorus start
- Almost one order of magnitude every two years



- Scanning a large emulsion volume with automatic systems is now feasible
- Emulsion data taking → database of measured tracks

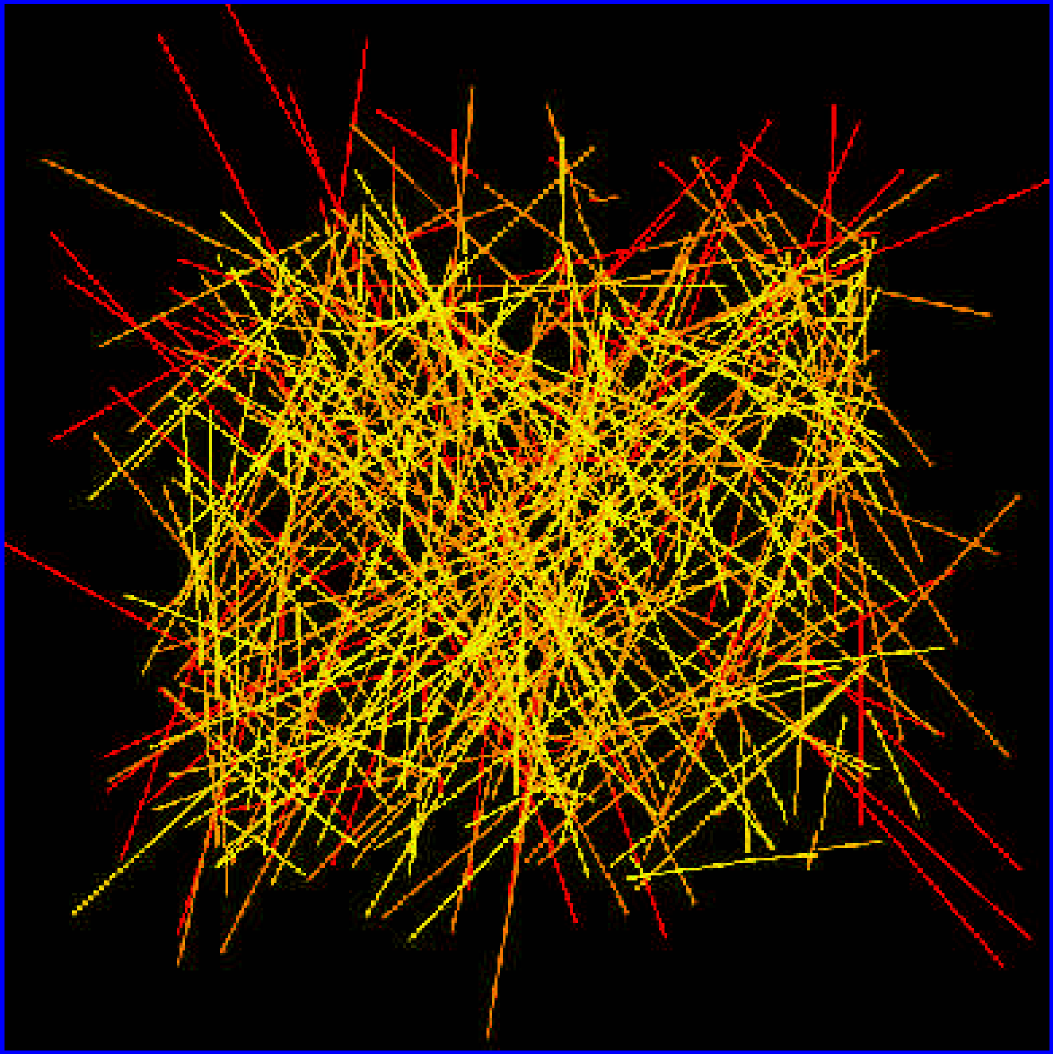
Netscan

(in progress for Chorus phase II)



Netscan

(in progress for Chorus phase I I)



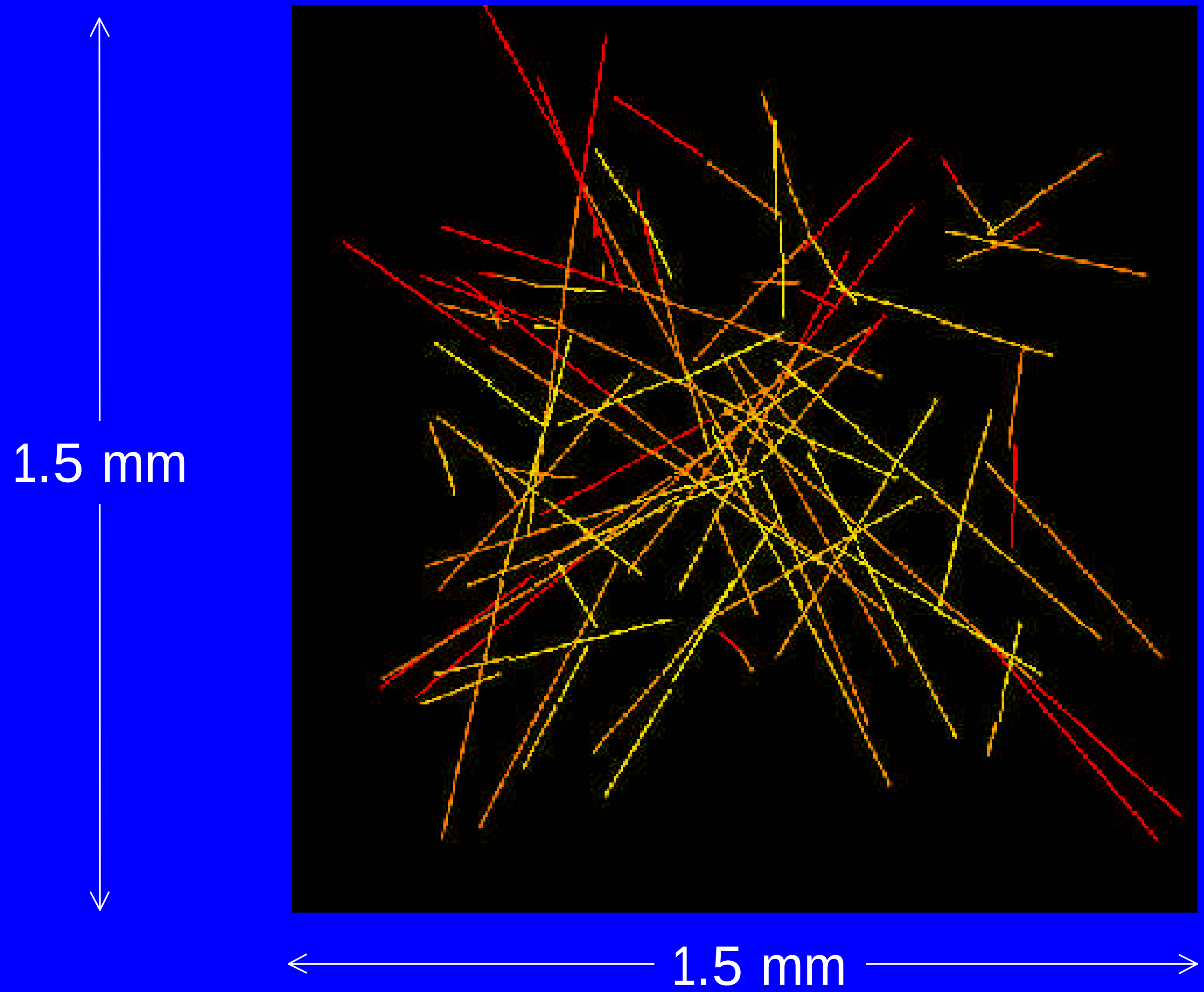
1.5 mm

1.5 mm

≥2 segments connected

Netscan

(in progress for Chorus phase II)

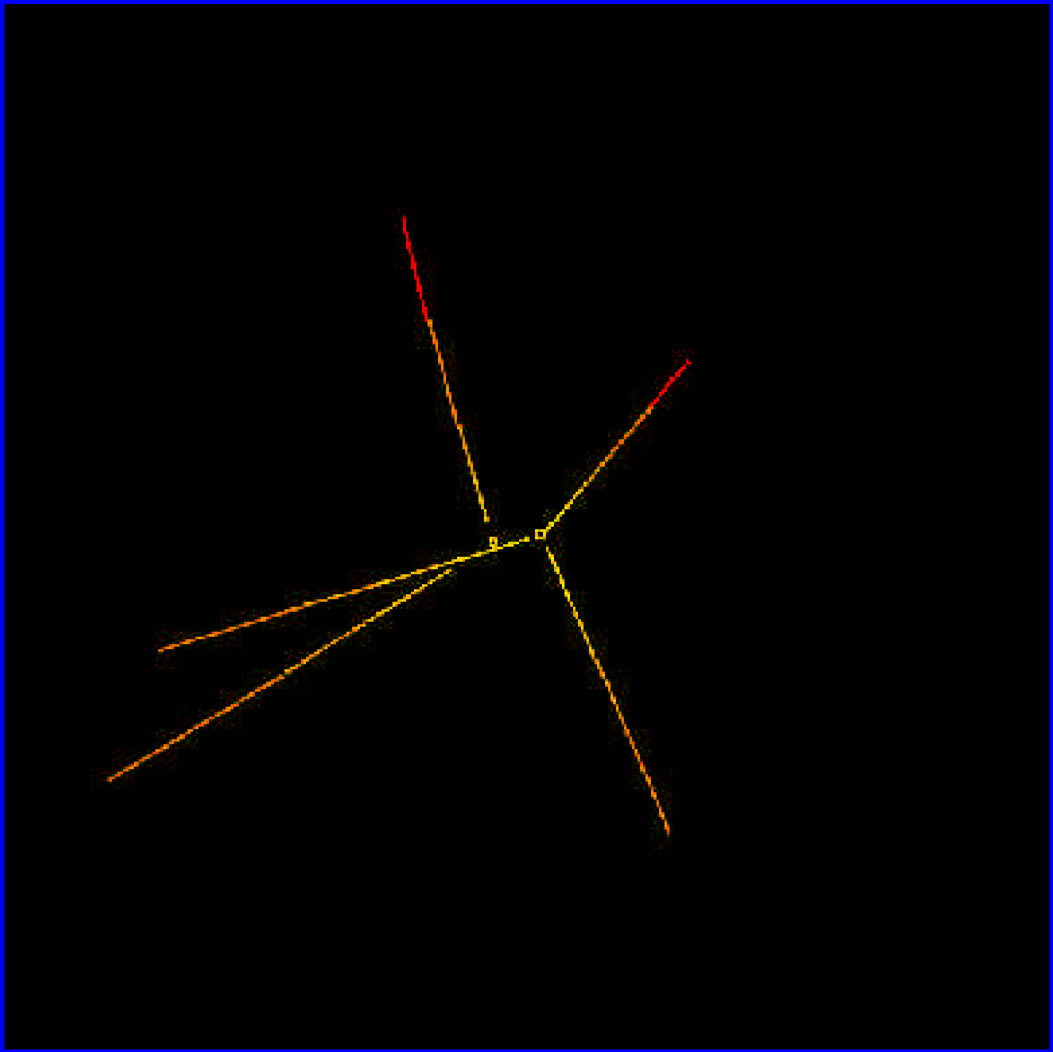


Not passing through

Netscan

(in progress for Chorus phase II)

1.5 mm

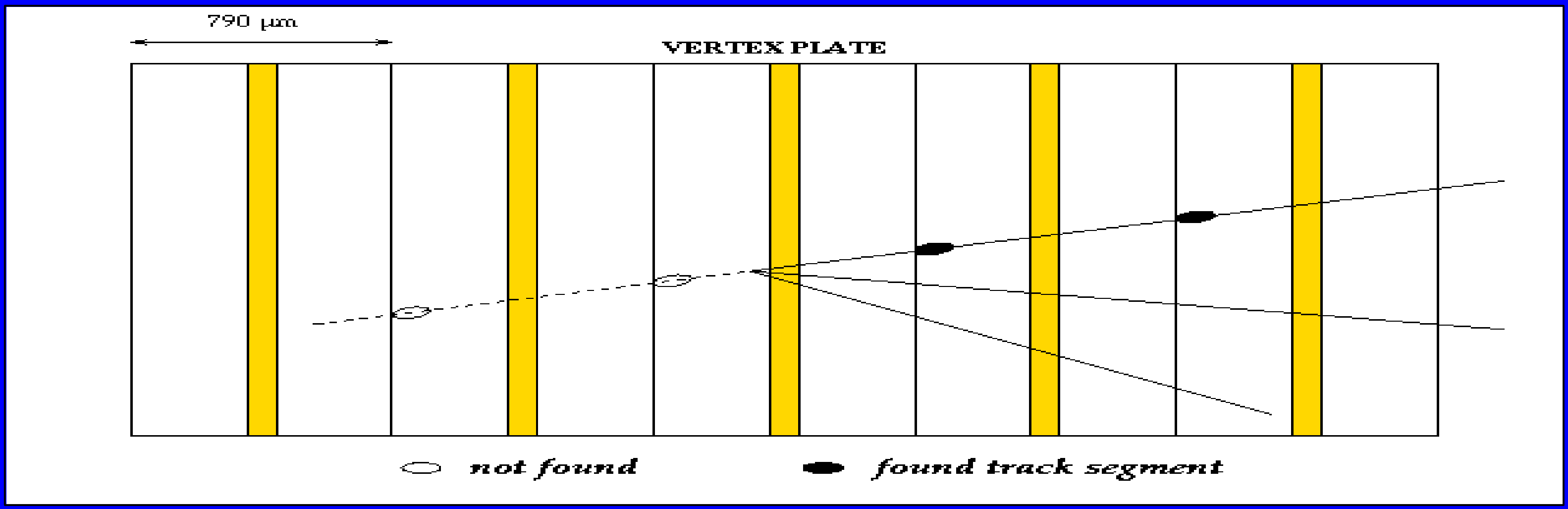


1.5 mm

Small impact parameter

Automatic Vertex Location

- Fiber Tracker → Interface emulsion → Target emulsion
- 100 μm most upstream of each target plate are scanned

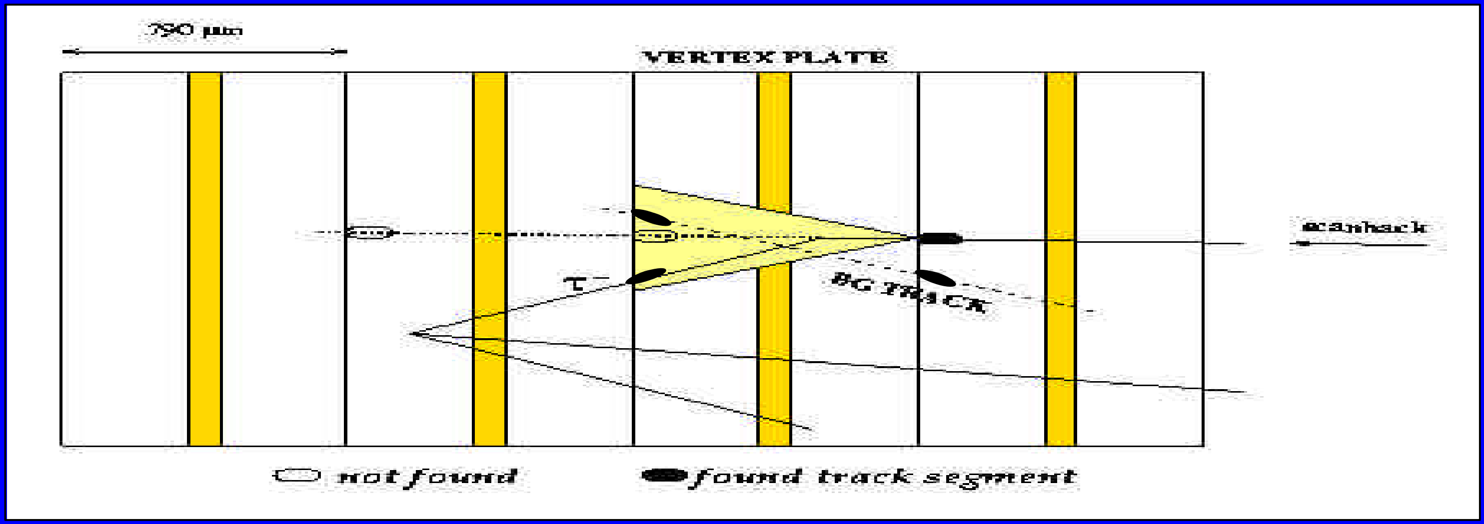


- Follow-up track, plate by plate to the vertex
- Define the vertex plate as the first plate out of two consecutive plates were a track segment is not found

Kink Finding (Parent Search)

(Large Angle-Long Path kinks)

- 100 μm most upstream of the vertex plate are searched for all track segments in a cone of width = 1/P(GeV/c)



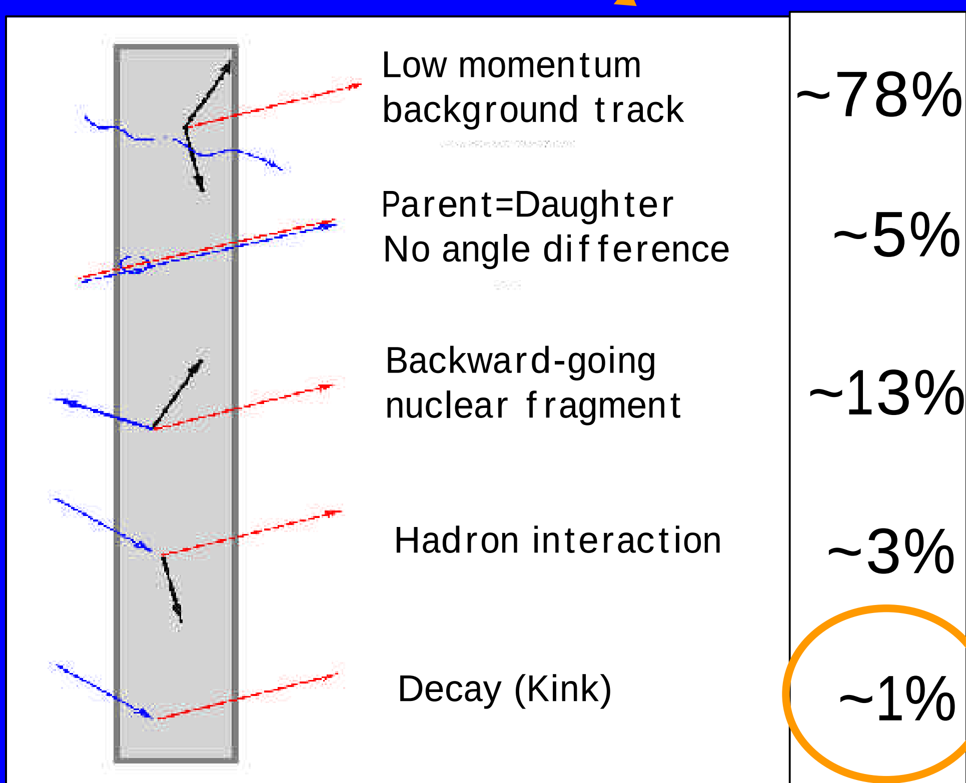
- Segments with small impact parameters w.r.t. the follow-up track are candidates track parent

$\rightarrow$ Kink signature

$\rightarrow$ Manual scanning measurements

Manual Scanning

Operator computer-assisted measurements for about 3% of located vertices which are kink candidates after automatic scanning processing → detailed study of the kink topology



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

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

Data Flow

Protons on target		$5.06 \cdot 10^{19}$
Good emulsion		~93%
Emulsion triggers		2,305 K
1m	Events with 1 negative muon and vertex predicted in emulsion	713,351
	P_{muon} < 30 GeV/c and angular cuts	477,625
	Events scanned	359,506
	Vertices located and kink search	136,357
0m	Event with vertex predicted in emulsion	335,398
	1 negative track with P[-20,-1] GeV/c and angular cuts	122,412
	Events scanned	82,551
	Vertices located and kink search	20,081

Expected Background Events

	1μ	0μ
Charm from $\bar{\nu}$ CC with missed primary lepton $\bar{\nu}_{\mu/e} N \rightarrow D^- X \mu^+/e^+$ └→ μ^-/h^- + neutrals	0.11	0.03
Charm from ν CC with μ^+/h^+ wrong charge	< 0.03	0.69
Associated charm production in NC D^+/D^o missed, associated to $D^- \rightarrow \mu^-/h^-$ + neutrals	< 0.05	
Hadronic "White kinks elastic scattering with no recoil or nuclear breakup	---	2.8
Prompt beam ν_τ	< 0.1	

No kine cuts, only P_t>250MeV/c, L_{decay}<5plates(1μ), 3plates(0μ)

White Kinks Evaluation

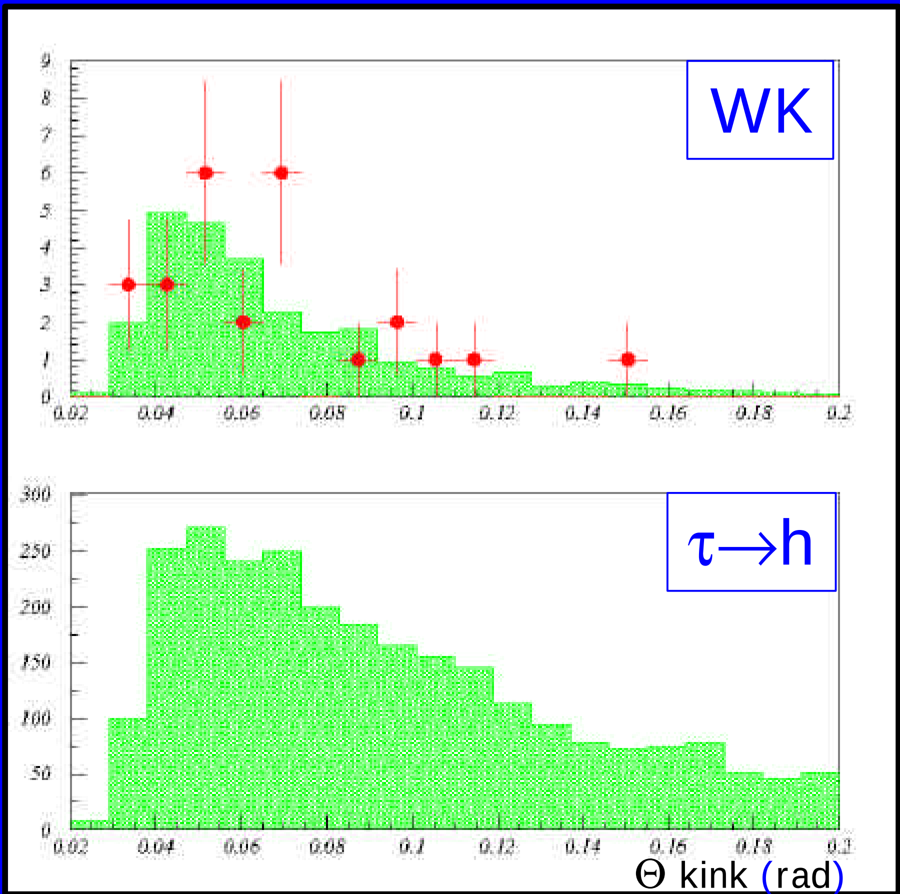
- Poor previous knowledge of $\lambda_{WK}(P,P_t)$. Difficult to extrapolate (sensitive to the operative definition of "whitness")

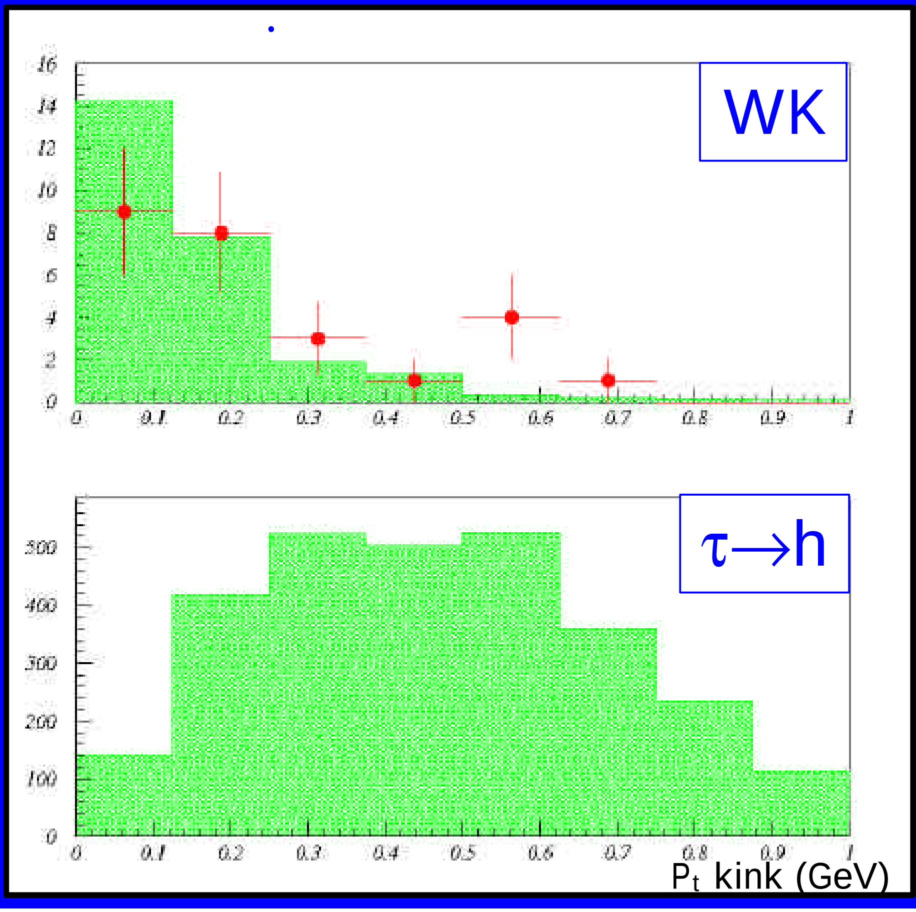
- Direct background evaluation from the 26 WK found in 243m of hadron tracks measured in Chorus $\rightarrow$ WK measurement in the signal-free "side-band" L_{decay} > 3 plates (2.8mm)

- MC development to tune the cuts against the WK background
  - Fluka to model the hadron interactions in emulsion
  - Cuts to reproduce the minimum observable activity (the white-gray transition) in the Chorus emulsions

White Kinks Data vs MC

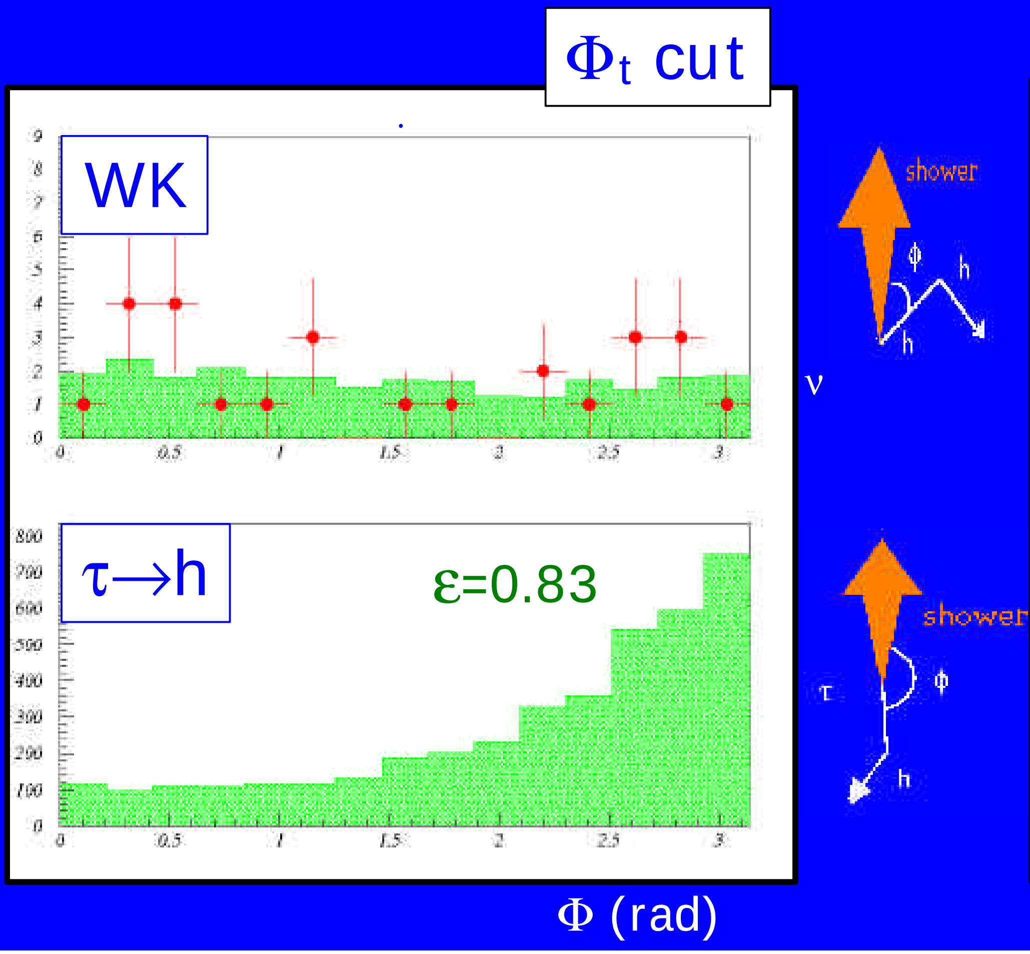
We measured $\lambda_{WK}(P_t > 250 MeV/c) = 21.3 \pm 7$ m
This corresponds to 2.8 ± 0.8 WK expected with a distance from the vertex L<3plates (2.8 mm)

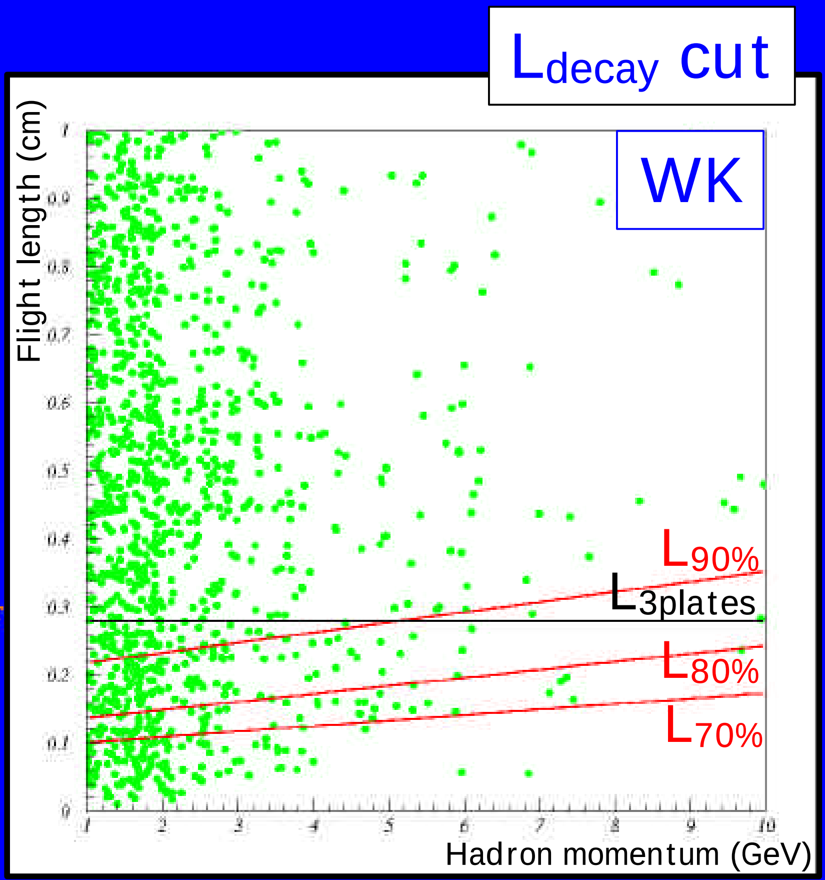




Further WK Reduction

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





Cuts Optimisation

$L_{3plates}$ →

L_{decay} effic	WK	Charm neutrino	Charm antineut	BG_{tot}	N_{observ}	Φ_t cut		Exclusion Power x 10^4
						BG_{tot}	N_{observ}	
0.87	2.82	0.69	0.03	3.54	4	1.57	2	3.80
0.90	2.56	0.69	0.04	3.29	6	1.46	2	3.78
0.80	1.89	0.52	0.03	2.44	1	1.08	0	3.72
0.70	0.96	0.52	0.02	1.50	1	0.66	0	3.75
0.60	0.90	0.46	0.01	1.37	0	0.60	0	3.85
0.50	0.65	0.23	0.01	0.88	0	0.39	0	3.92

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

Limit Evaluation

$$P_{mt} = \sin^2 2q_{mt} \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2_{mt} \cdot L}{E}\right)$$

$$P_{\mu t} = \frac{N_t}{\sum_{i=\{1\mu,0\mu\}} BR_i \cdot N_i \left\langle \frac{s_t^{CC}}{s_\mu^{CC}} \cdot \frac{A_i^t}{A_i^m} \cdot e_i^{\text{kink}} \right\rangle}$$

s_t^{CC} / s_m^{CC}	$N_{1\mu}$	$\left\langle A^t_{1\mu} / A^m_{1\mu} \right\rangle$	$e^{\text{kink}}_{1\mu}$	$N_{0\mu}$	$\left\langle A^t_{0\mu} / A^m_{0\mu} \right\rangle$	$e^{\text{kink}}_{0\mu}$
0.53	143,742	0.97	0.39	20,081	2.3	0.13

Systematics

- Dominant sources are:

  1 - Reconstruction and location efficiency

  2 - Kink detection efficiency

  – - largely cancels in the ratios

  – - From MC, with cross-check on charm events and hadron interactions (80 founds, 84.4 expected)

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

Systematics

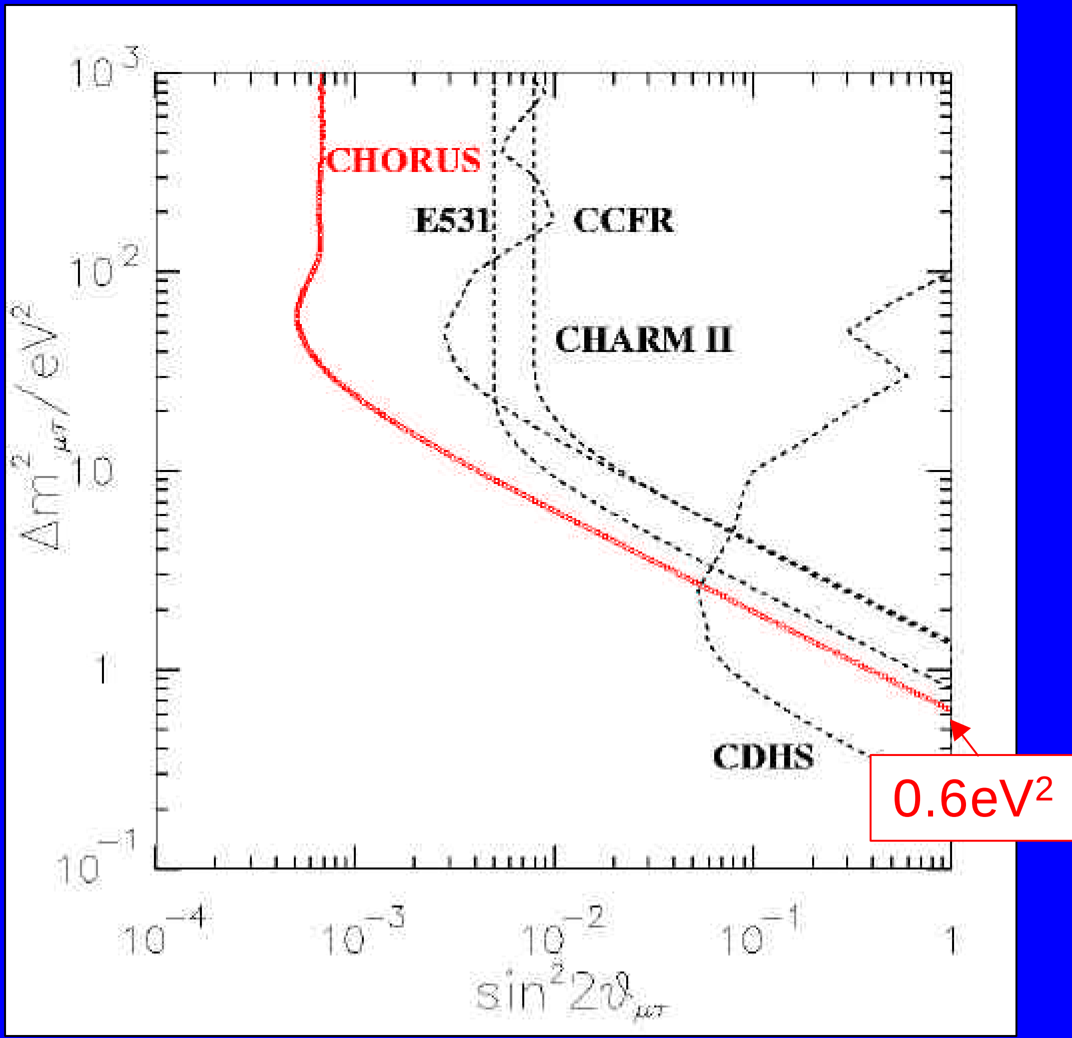
$\Delta\sigma_{CC}$ = 10 %

$\Delta\varepsilon_{kink}$ = 15 % for 1μ, 20% for 0μ

ΔN_{WK} = 30%

ΔN_{charm} = 30%

Exclusion Plot



at 90% CL [1]

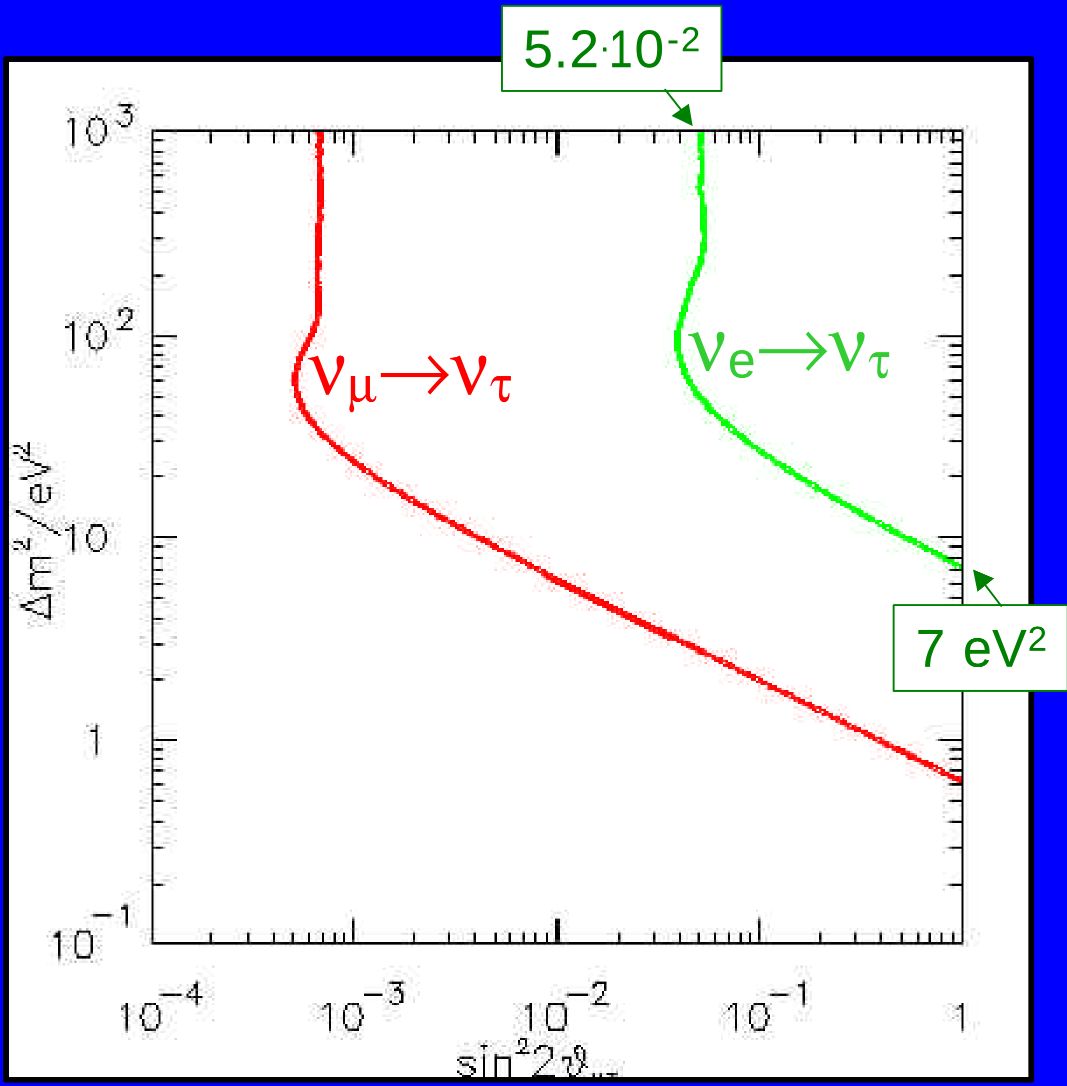
$P_{\mu\tau} < 3.4 \cdot 10^{-4}$
Or, for large Δm^2
$\sin^2 2\theta_{\mu\tau} < 6.8 \cdot 10^{-4}$

Our exclusion power (sensitivity) is:
$P_{\mu\tau} = 3.7 \cdot 10^{-4}$

Using a different approach[2] to CL intervals we could have quoted
$P_{\mu\tau} = 2.2 \cdot 10^{-4}$

[1] T.Junk, NIM A434 (1999) 435
[1] G.J.Feldman and R.D. Cousins, Phys.Rev. D57 (1998) 3873

$\nu_e \rightarrow \nu_\tau$ Exclusion Plot



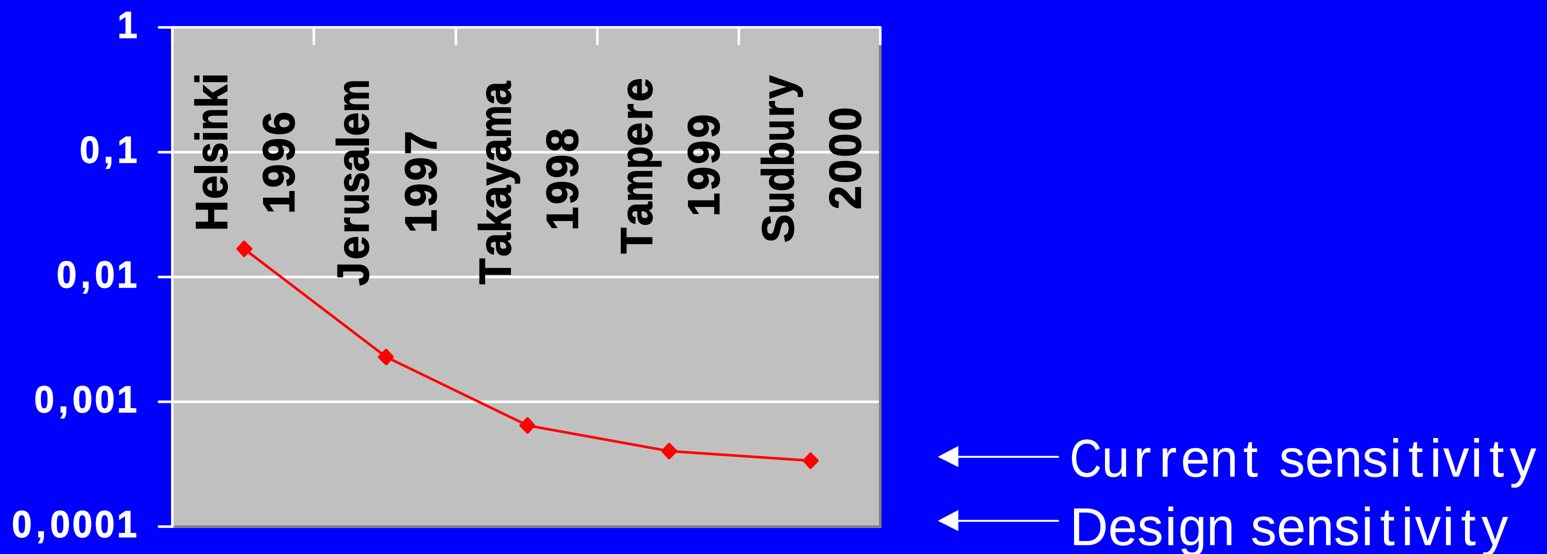
$P_{e\tau} < 2.6 \cdot 10^{-2}$ at 90% CL
Or, for large Δm^2
$\sin^2 2\theta_{\tau\mu} < 5.2 \cdot 10^{-2}$

Maximum mixing is excluded at 90% CL for $\Delta m^2 > 7$ eV^2

Including an additional systematic of 25% on $\Phi\nu_e / \Phi\nu_\mu$

Chorus Phase II Analyis

- New scanning methods (Netscan,...) with higher kink finding efficiency (also charm physics)
- Improved reconstruction (tracking, vertex finding, muon ID,momentum)
- Additional vertices located



Conclusions

- We have completed our first run of data analysis (phase I)
- We expected 0.11 background events in the 1μ channel and 1.08 in the 0μ channel with an exclusion power (sensitivity) of $P_{\mu\tau}=3.7 \cdot 10^{-4}$ (including systematic)
- We observed no candidates, and we interpreted this in an excluded CR at 90%CL for $\nu_\mu \rightarrow \nu_\tau$ and for $\nu_e \rightarrow \nu_\tau$ oscillation.
- We have started our phase II analysis with the aim of reaching our design sensitivity of $P_{\mu\tau} = 10^{-4}$