CHORUS search for $\nu_\mu \rightarrow \nu_\tau$ oscillations

In Memoriam – Engin Arik and her colleagues

Roumen Tsenov

St. Kliment Ohridski University of Sofia

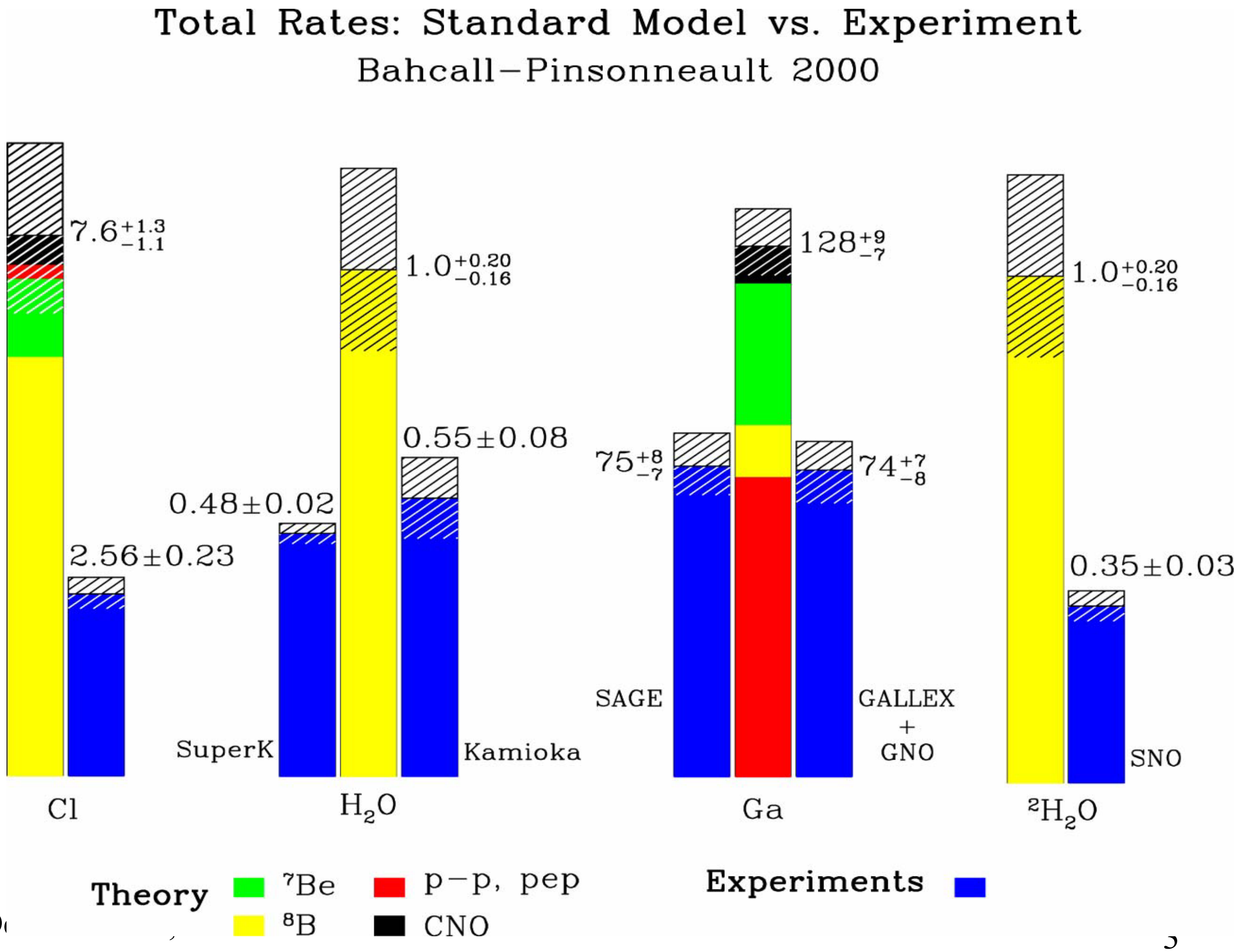
ICPP, Istanbul, 27-31 October 2008

Content

- Introduction to neutrino oscillations
- Motivation of CHORUS short baseline accelerator search for $\nu_\mu \rightarrow \nu_\tau$
- Neutrino beam and CHORUS detector
- Final results

$$\Phi_\nu = \frac{2L_{\rm sun}}{25\,{\rm MeV}}\,\frac{1}{4\pi(1{\rm AU})^2} = 7\cdot 10^{10}\ {\rm sec}^{-1}\ {\rm cm}^{-2}$$

The pioneer:
Ray Davis,
Homestake
since ~1968



Neutrino Oscillations

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source → propagation in vacuum (or matter) → detection

L

weak interaction produces
'flavour' neutrinos
e.g. pion decay $\pi \to \mu\nu$

$$|\nu_\mu\rangle = \alpha\, |\nu_1\rangle + \beta\, |\nu_2\rangle + \gamma\, |\nu_3\rangle$$

Energy (i.e. mass) eigenstates propagate

$$|\nu(t)\rangle = \alpha\, |\nu_1\rangle \exp(i E_1 t) + \beta\, |\nu_2\rangle \exp(i E_2 t) + \gamma\, |\nu_3\rangle \exp(i E_3 t)$$

proper time $\propto$ L/E

weak interaction: (CC)

$$\nu_\mu\, N \to \mu^-\, X$$
$$\nu_e\, N \to e^-\, X$$
$$\nu_\tau\, N \to \tau^-\, X$$

$$P(\mu \to \tau) = |\langle \nu_\tau | \nu(t)\rangle|^2$$

Бруно Понтекорво

The idea raised first by Bruno Pontecorvo in 1957.

Oscillation Probability

- The case with two neutrinos:
  - → A mixing angle: θ
  - → A mass difference:

$$\Delta m^2 = m_2^2 - m_1^2$$

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- The oscillation probability is:

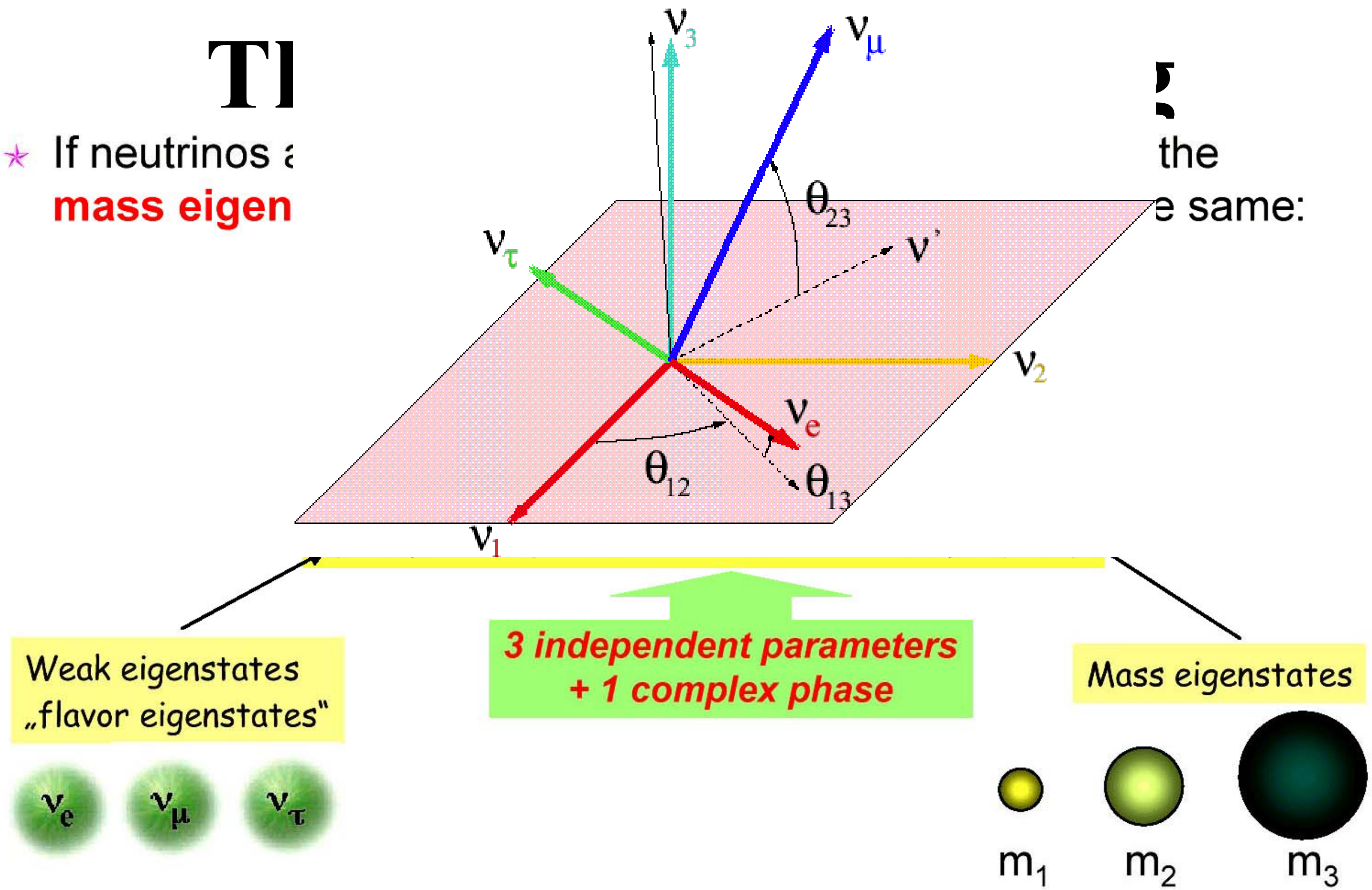
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27 \Delta m^2 \frac{L}{E}\right)$$

Δm^2 in ev^2
L in km
E in GeV

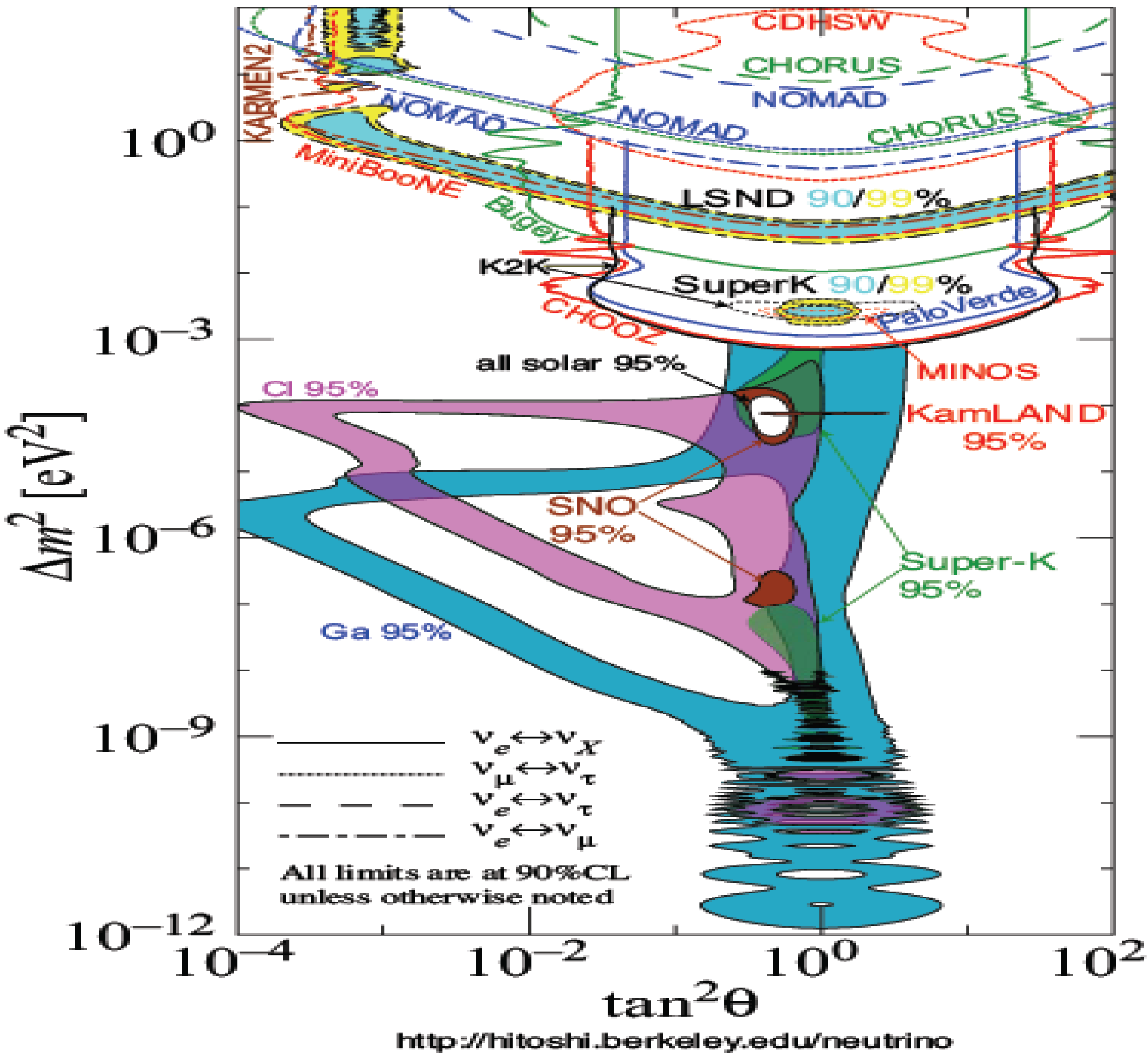
where L = distance between source and detector
E = neutrino energy

Th... g

- If neutrinos a... the **mass eigen...** ...e same:



The global plot



Motivation for short base-line neutrino oscillation search

(year 1993)

The question whether neutrino flavours mix at some level and the related question whether neutrinos have non-zero mass is one of the remaining great challenges of experimental high energy physics. A new search for $\nu_\mu - \nu_\tau$ oscillations has recently received incentives from the solar neutrino experiments. Combining the results of the Davis Chlorine experiment [1], the Kamiokande neutrino-electron scattering experiment [2] and results from GALLEX [4] and SAGE (Soviet-American-Gallium-Experiment) [3], a consistent description by a MSW solution seems to be a possible explanation of the solar neutrino problem [5]. The cosmological connection between neutrino masses and the enigma of dark matter has been invoked by Harari [6]. The COBE-IRAS data seem to prefer a mixed dark matter scenario with $m_{\nu_\tau} \sim 7$ eV. None of these considerations is compelling; however, they suggest that $\nu_\mu - \nu_\tau$ oscillation may be within reach of a new experiment which we will perform at the CERN-SPS [7]. We shall perform the experiment in the wide band neutrino beam facility of the CERN-SPS to explore the domain of small mixing angles down to $\sin^2 2\theta_{\mu\tau} \sim 3 \times 10^{-4}$ for mass parameters $\Delta m^2 > 1$ eV^2. The region of sensitivity of this new experiment and those already explored previously are shown in figure 1. If oscillations would occur at the present limit ($\sin^2 2\theta_{\mu\tau} = 5 \times 10^{-3}$, $\Delta m^2 > 50$ eV^2) we would observe 64 events in the proposed experiment.

CHORUS Proposal: CERN-PPE-93-131

The CHORUS Collaboration

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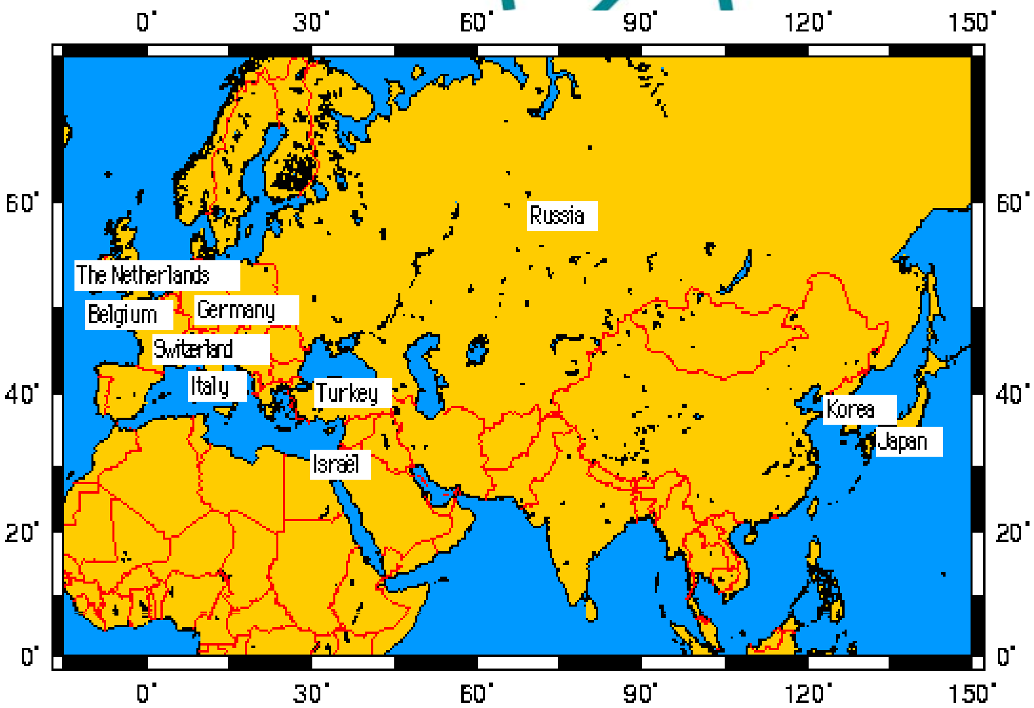


Belgium (Brussels, Louvain-la-Neuve), CERN, Germany (Berlin, Münster), Israel (Haifa), Italy (Bari, Cagliari, Ferrara, Naples, Rome, Salerno), Japan (Toho, Kinki, Aichi, Kobe, Nagoya, Osaka, Utsunomiya), Korea (Gyeongsang), The Netherlands (Amsterdam), Russia (Moscow), Turkey (Adana, Ankara, Istanbul) + more later (…R. Tsenov[17]…)

[17]) On leave of absence from Sofia University, Bulgaria, **with support from the Bogazici University, Centre for Turkish-Balkan Physics Research and Applications. (1994, 1995).**

CHORUS Main objective

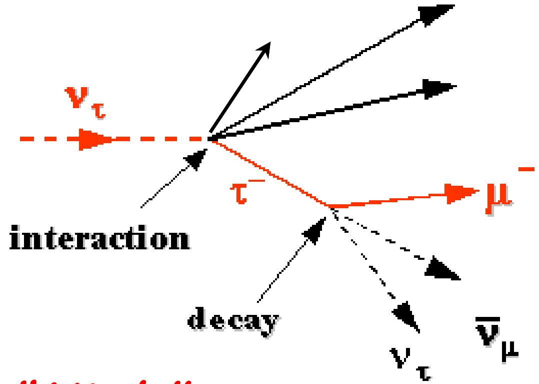
- ν_τ appearance in the SPS WBB ν_μ beam via oscillation
- $P(\nu_\mu \rightarrow \nu_\tau)$ down to $1 \cdot 10^{-4}$ for δm^2 ~10 eV^2
- ν_τ direct detection in 770 kg nuclear emulsion target

Tag: visible 1- and 3- prongs

decay of primary τ-lepton

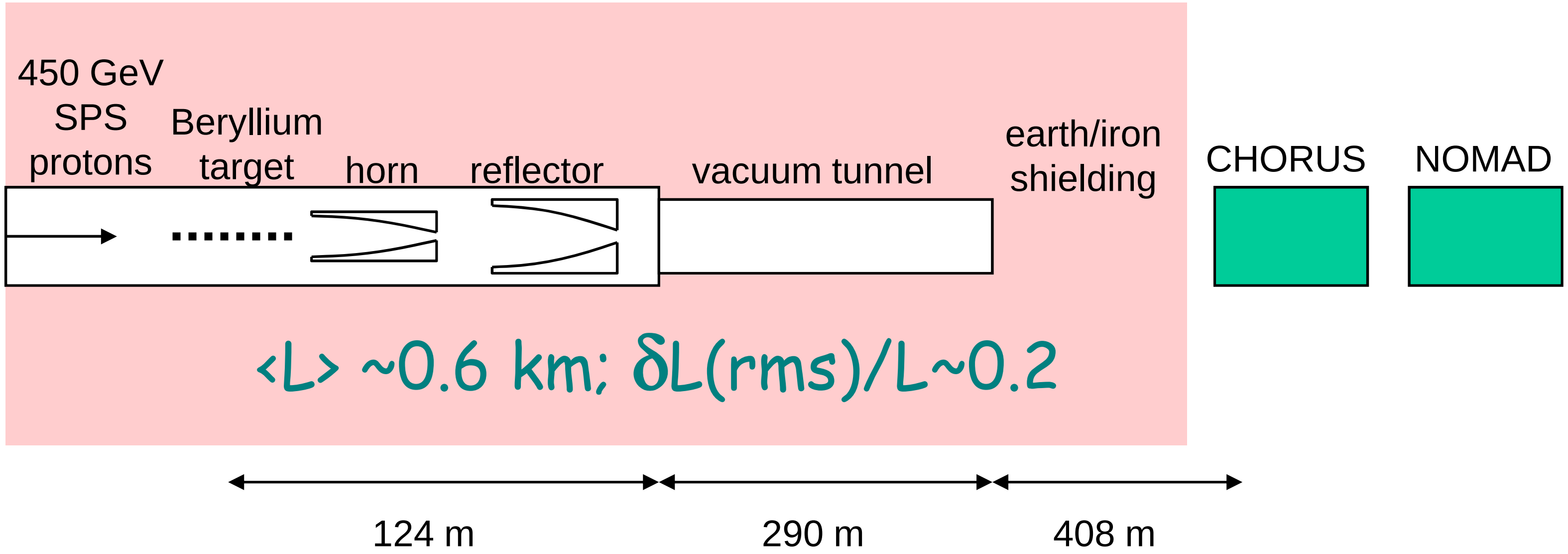
(decay path ~1.5 mm)

$\mu^- \, \nu_\tau \, \bar{\nu}_\mu$	BR 17 %
$h^- \, \nu_\tau \, n\pi^o$	50 %
$e^- \, \nu_\tau \, \bar{\nu}_e$	18 %
$\pi^+ \pi^- \pi^- \, \nu_\tau \, n\pi^o$	15 %



"Kink"

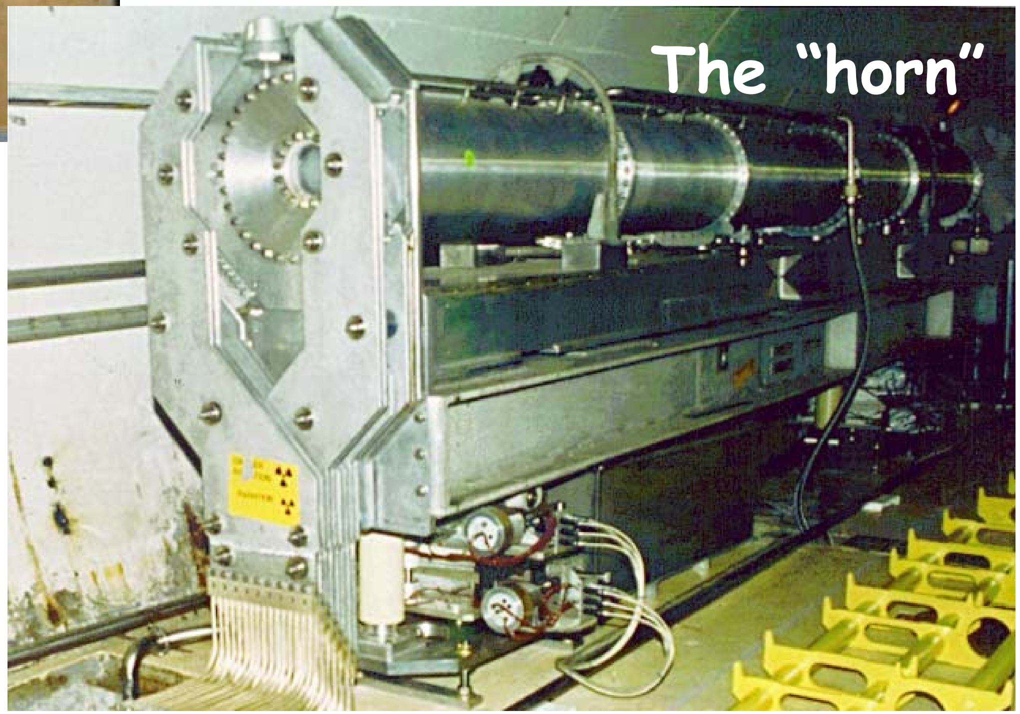
CERN West Area Neutrino Facility



- WBB, $\langle E_{\nu_\mu} \rangle = 26.6$ GeV
- ~$5 \cdot 10^{19}$ protons on target
- ~840K ν_μ CC in CHORUS
- ν_τ CC / ν_μ CC ~ 3.10^{-6}

(~0.1 background event)

West Area Neutrino Facility



SPS and WANF (ν_μ) neutrino beam

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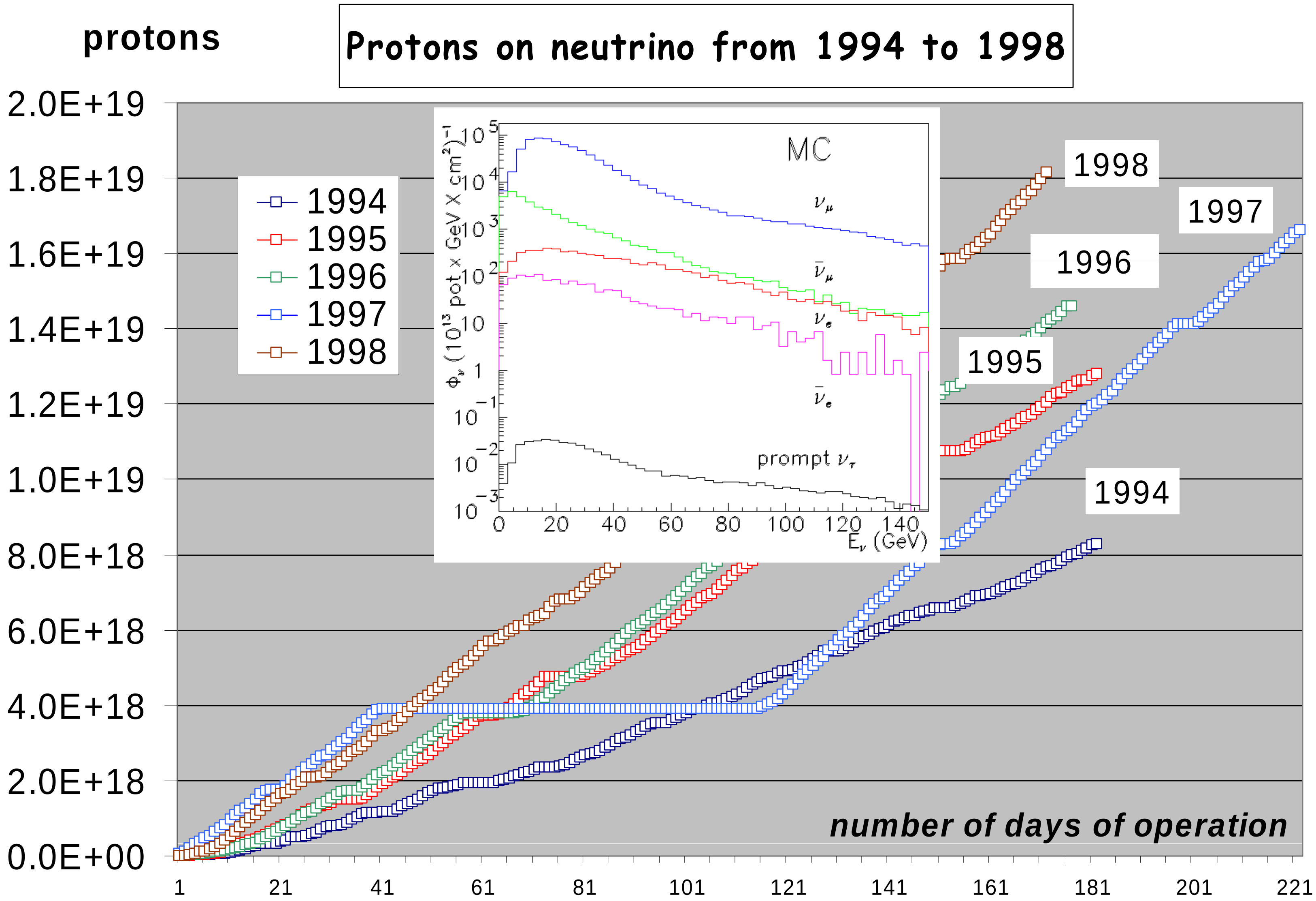
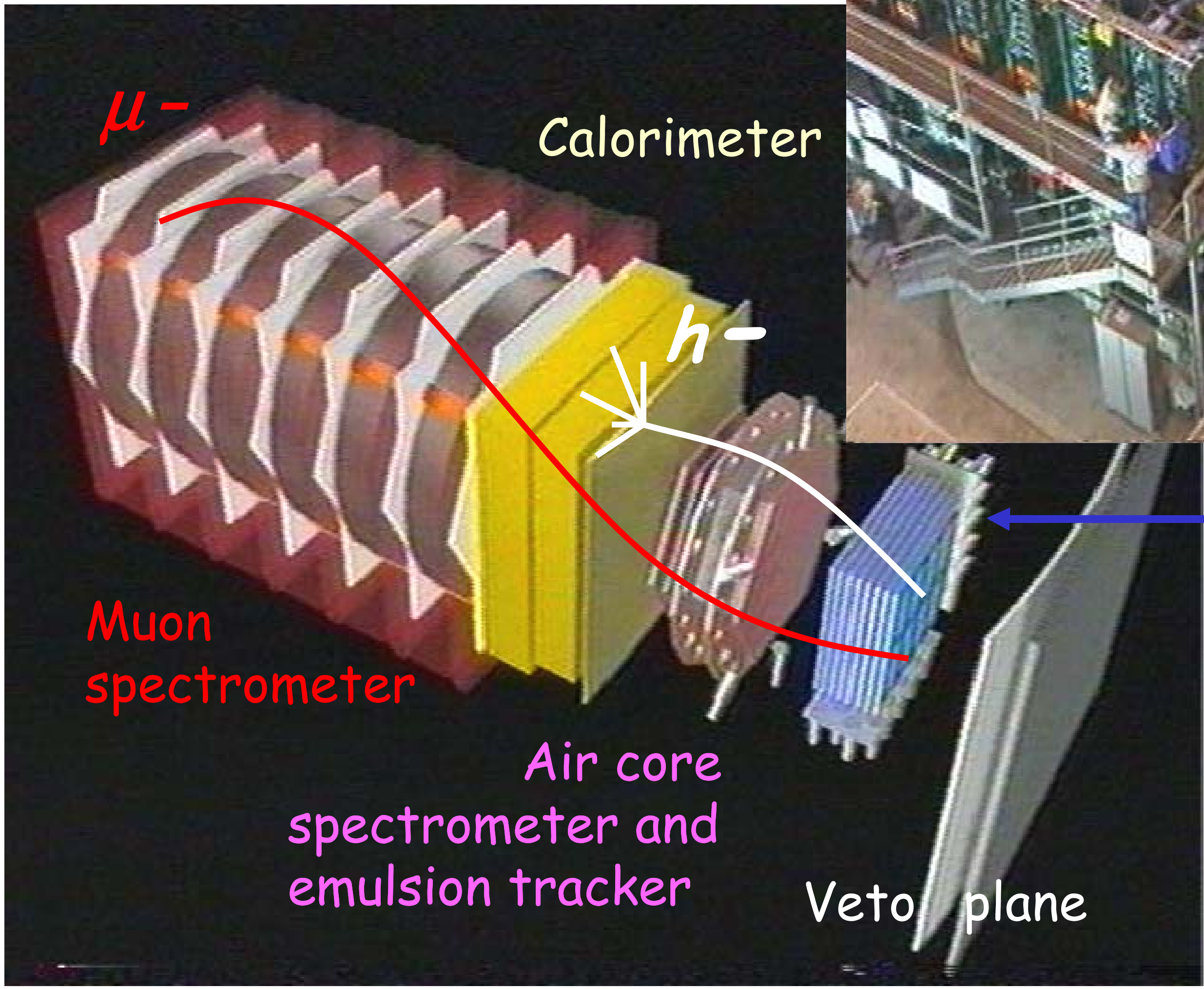
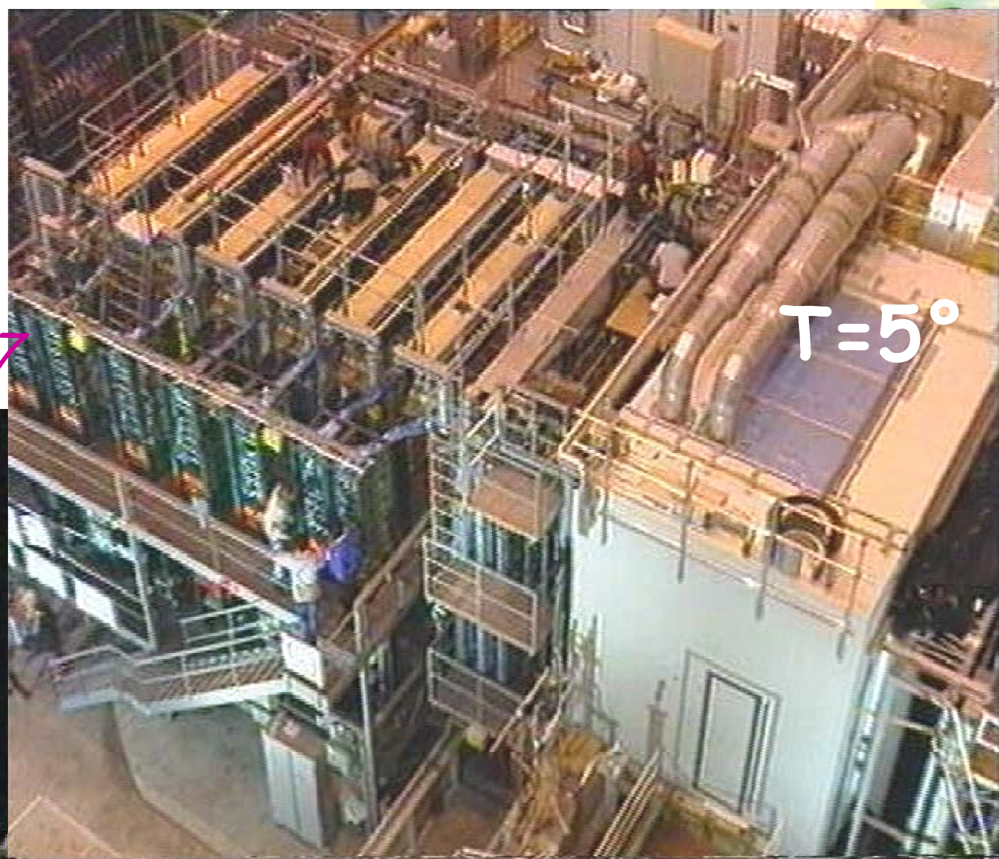


CHORUS detector

Nucl. Instr. Meth A 401 (1997) 7



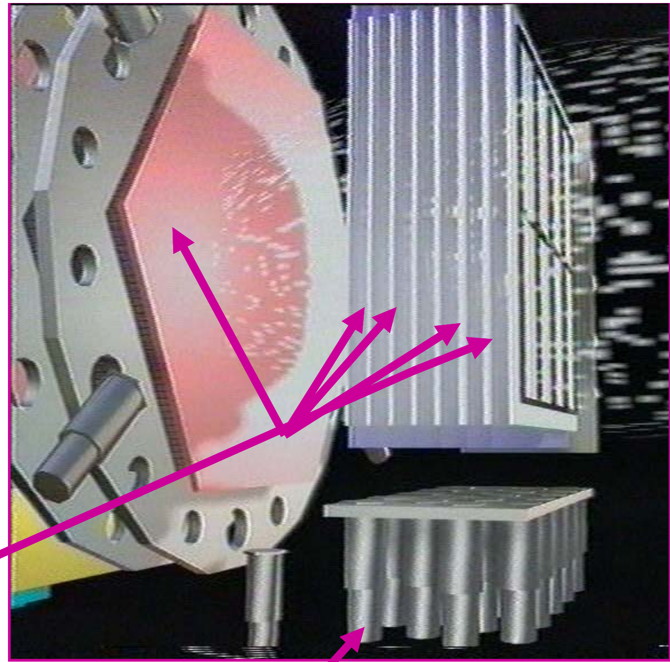


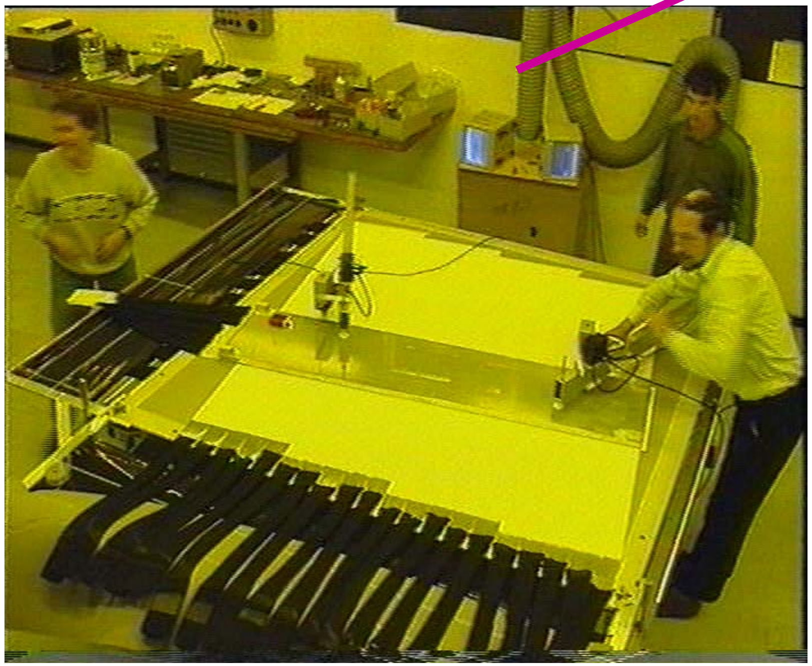
770 kg emulsion target and scintillating fibre tracker

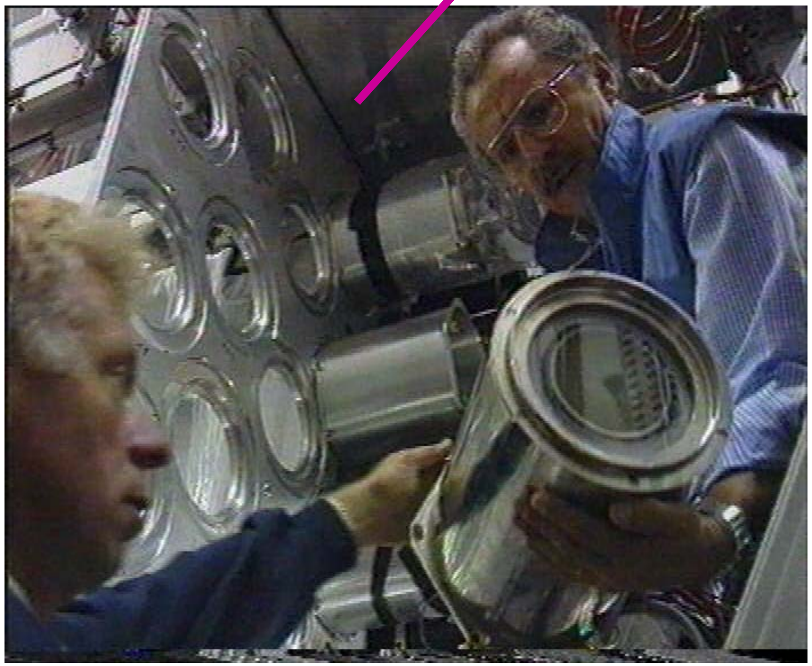
Scintillating fibre trackers

Nucl. Instr. Meth A 412 (1998) 19

$\delta\theta \sim 2$ mrad, $\delta_{xy} \sim 150\ \mu m$



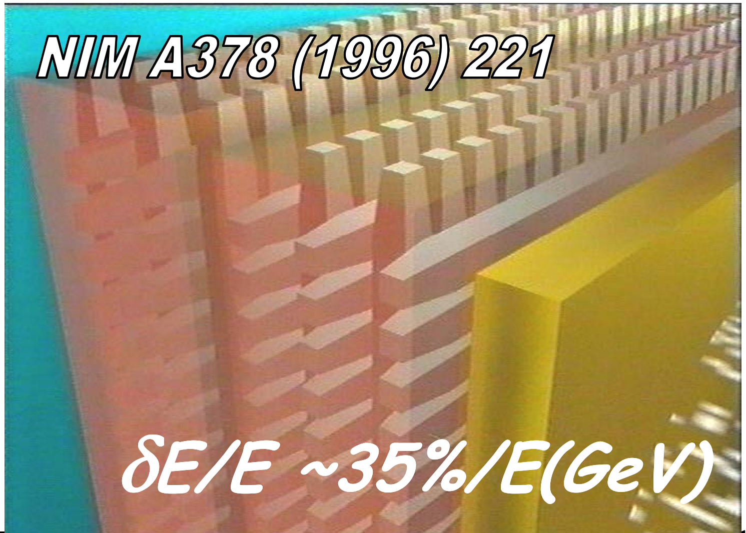


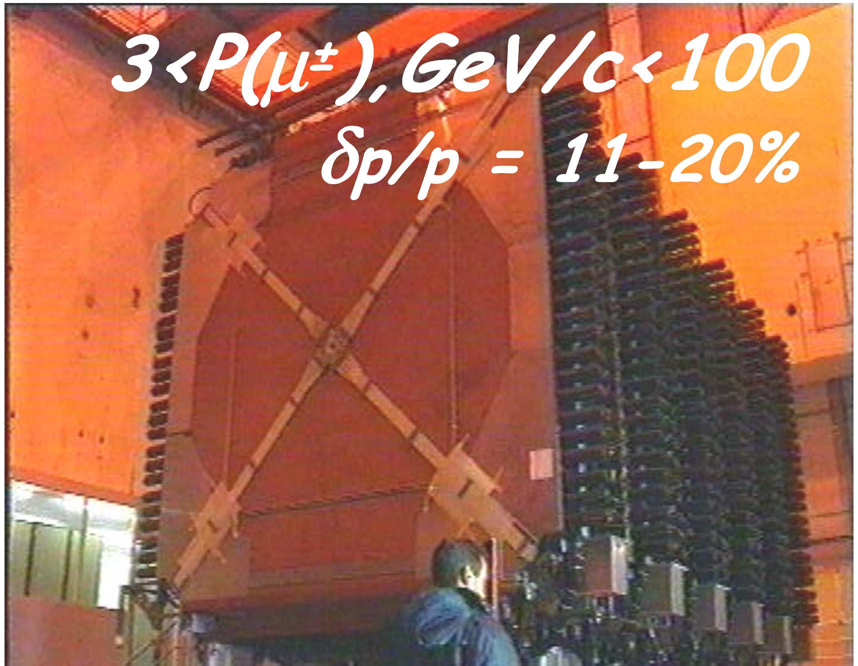


External electronic detectors:

- sign and momentum of pions
- Hadronic and e-m shower energy and direction
- Muon momentum and id

Event pre-selection and post-scanning analysis





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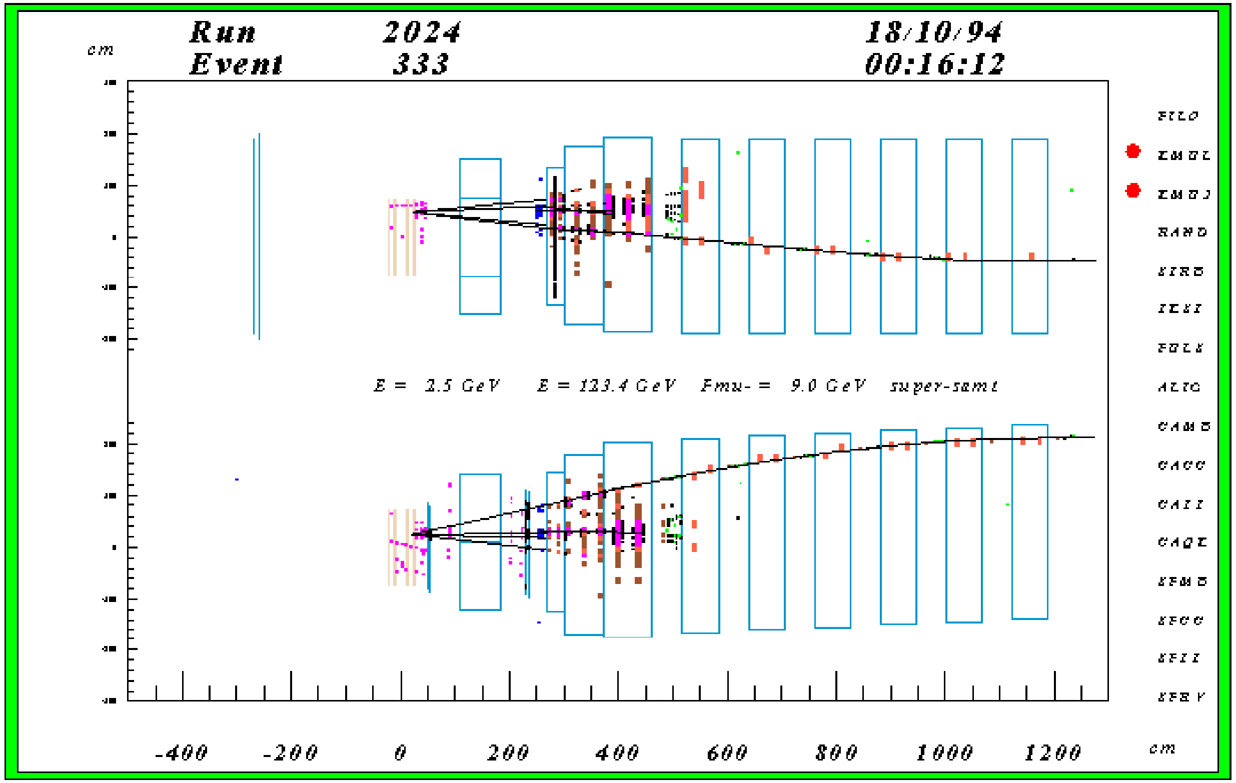
Neutrino data-taking collection efficiency 1994-1997

Year of exposure	*1994*	*1995*	*1996*	*1997*	*All*
POT / 10^{19}	0.81	1.20	1.38	1.67	5.06
Expected Ncc / 10^{3}	120	200	230	290	840
Chorus efficiency	0.77	0.88	0.94	0.94	0.90
Deadtime	0.10	0.10	0.13	0.12	0.11
Good emulsion	0.97	0.73	1.00	1.00	0.93

N.B. Longest/Largest emulsion exposure ever done

Event in CHORUS



Nuclear emulsion yesterday

- 1947, first nuclear emulsions. Lattes *et al.*, Brown *et al.*:

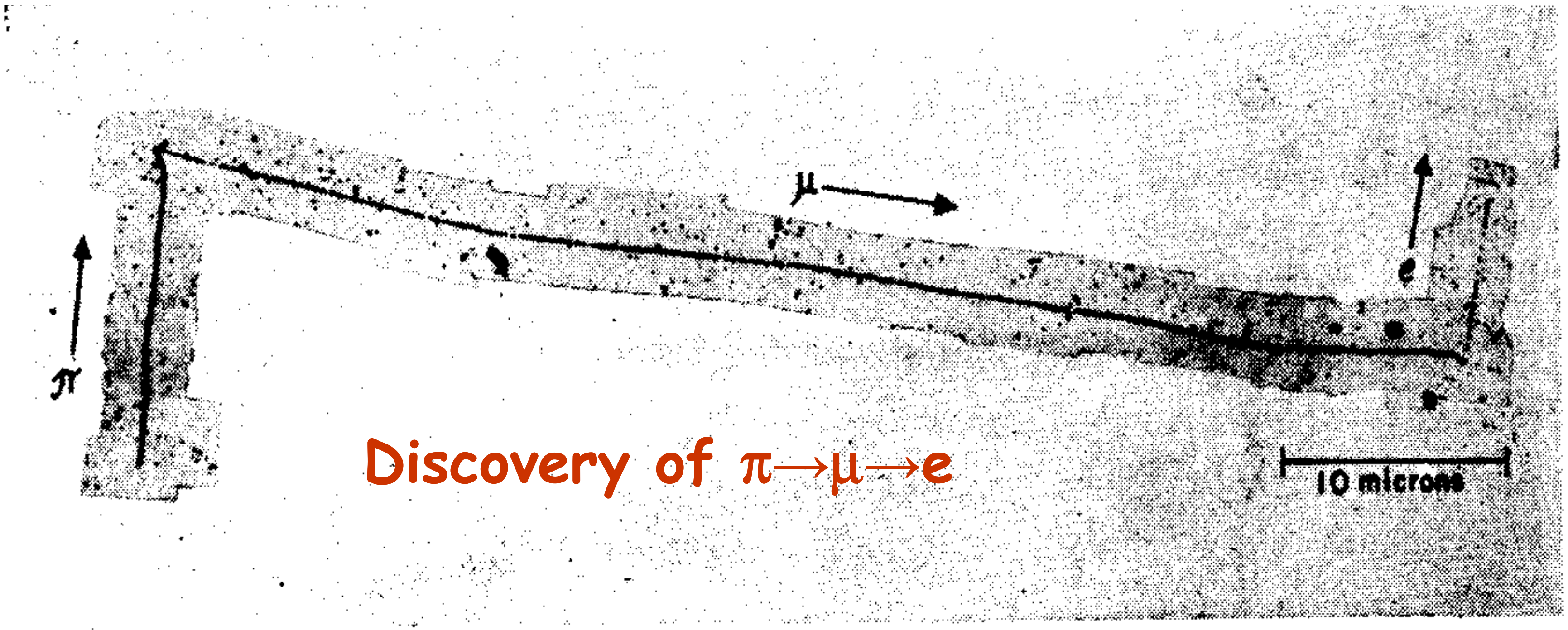


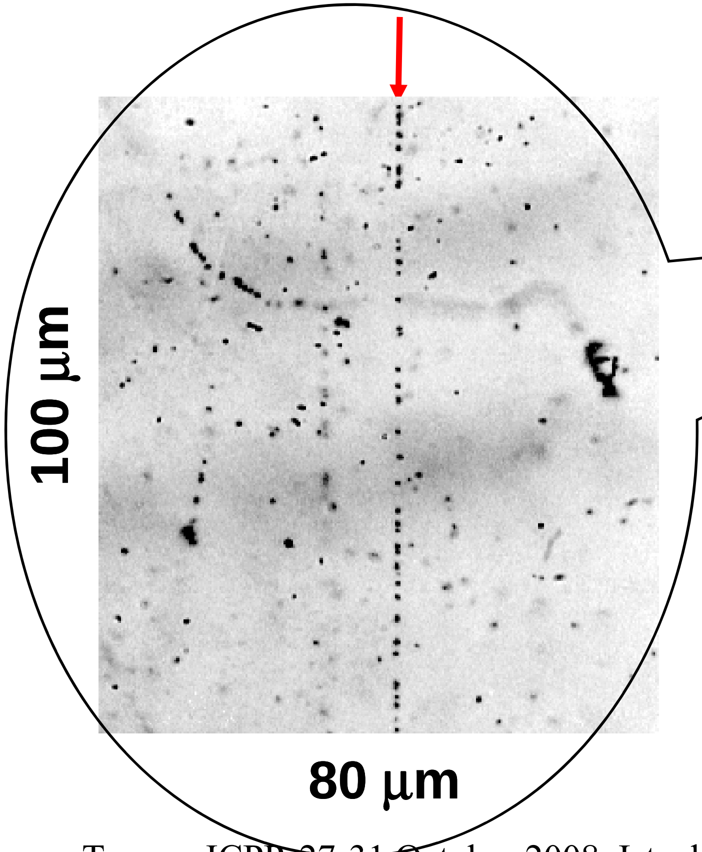
Fig. 4.8.2. Mosaic of microphotographs showing a $\pi \to \mu \to e$ decay. Kodak NT4 electron-sensitive emulsion. From Brown *et al.* (BRH49.2).

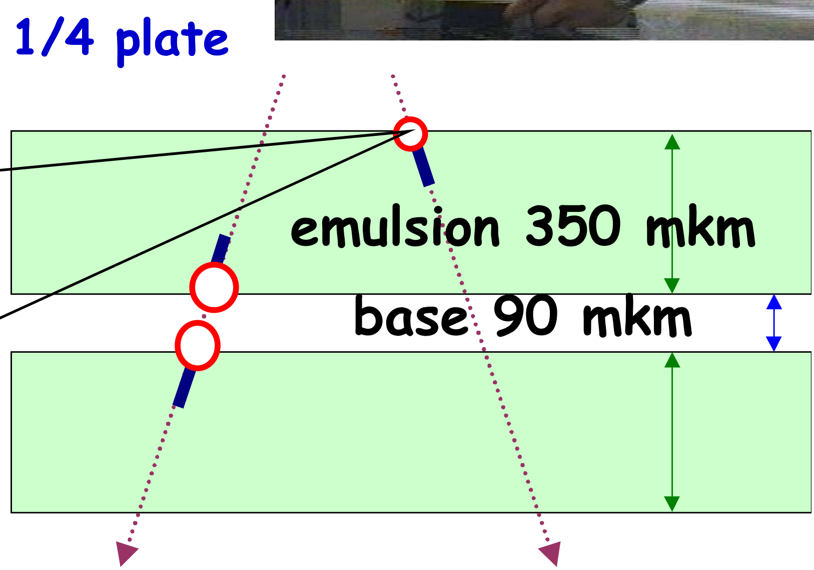
CHORUS emulsion plate

Target = 4 stacks (1.4⑨1.4 m^2)

1 stack = 36 plates

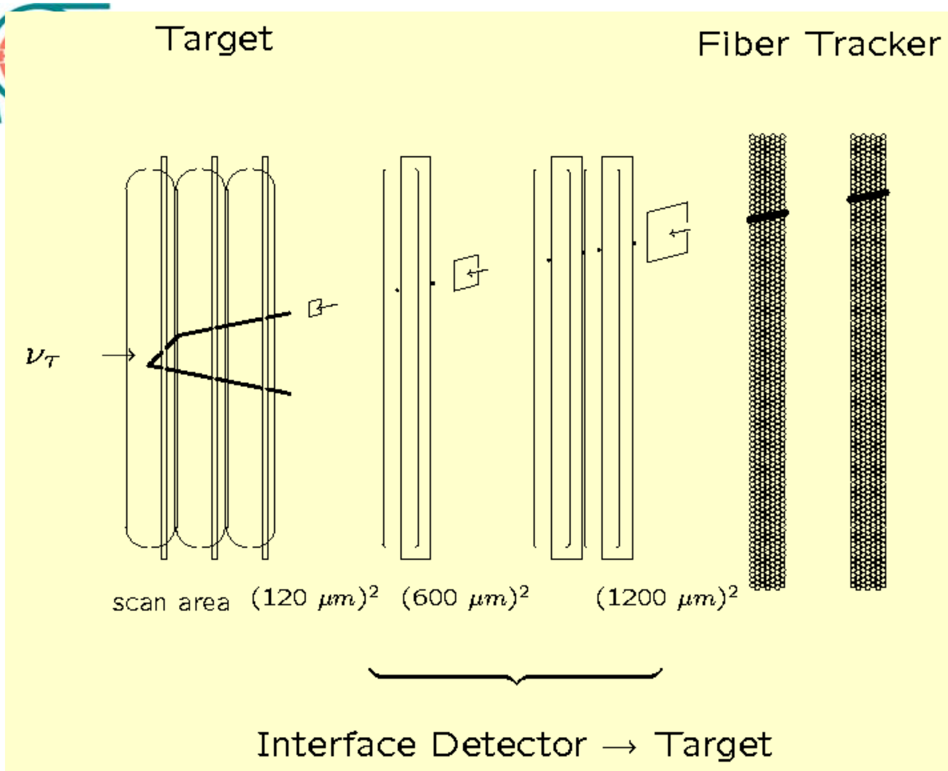
MIP : 30 ~ 40 grains / 100 μm



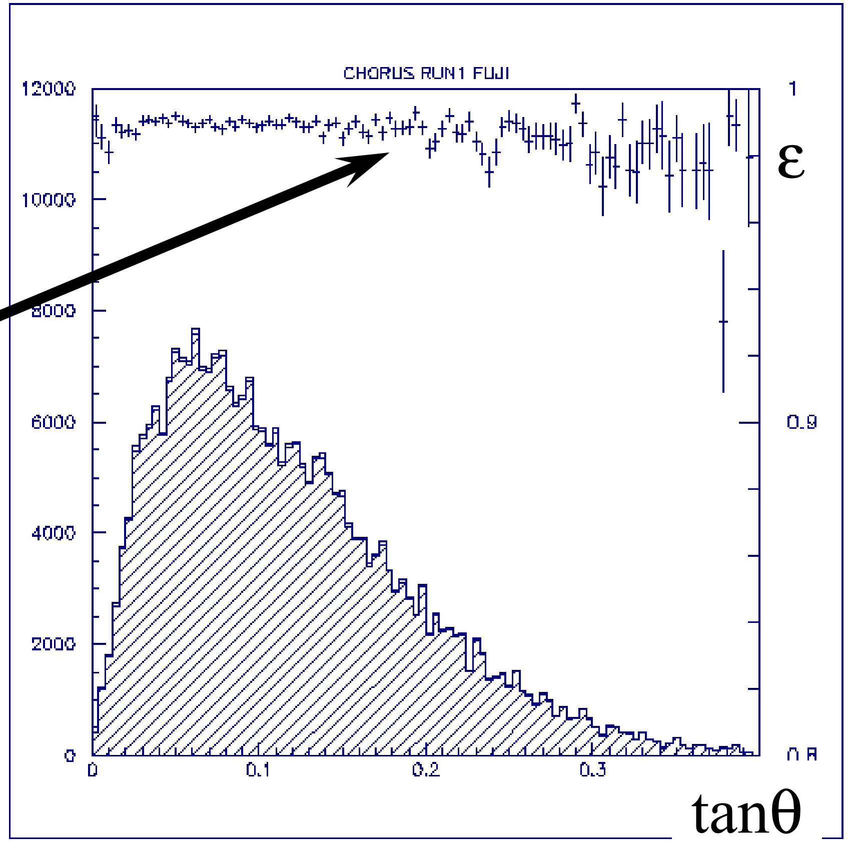


- Grain size ~ 0.3 μm
- Angular resolution ~ 1.5 mrad

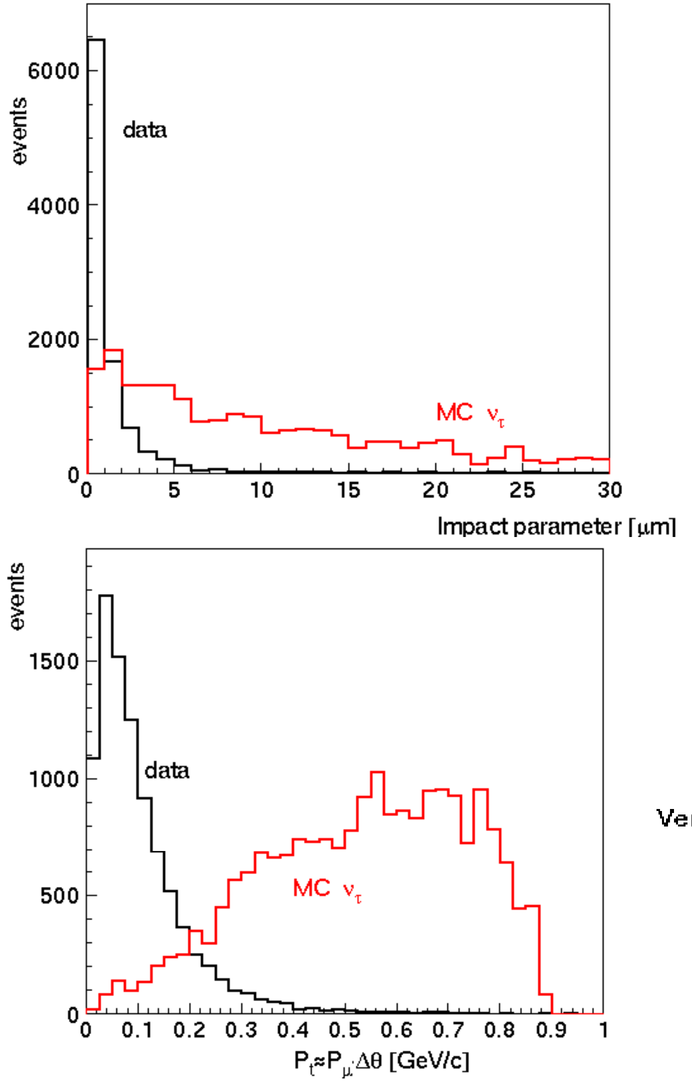
Predictions, Scanback and Vertex location

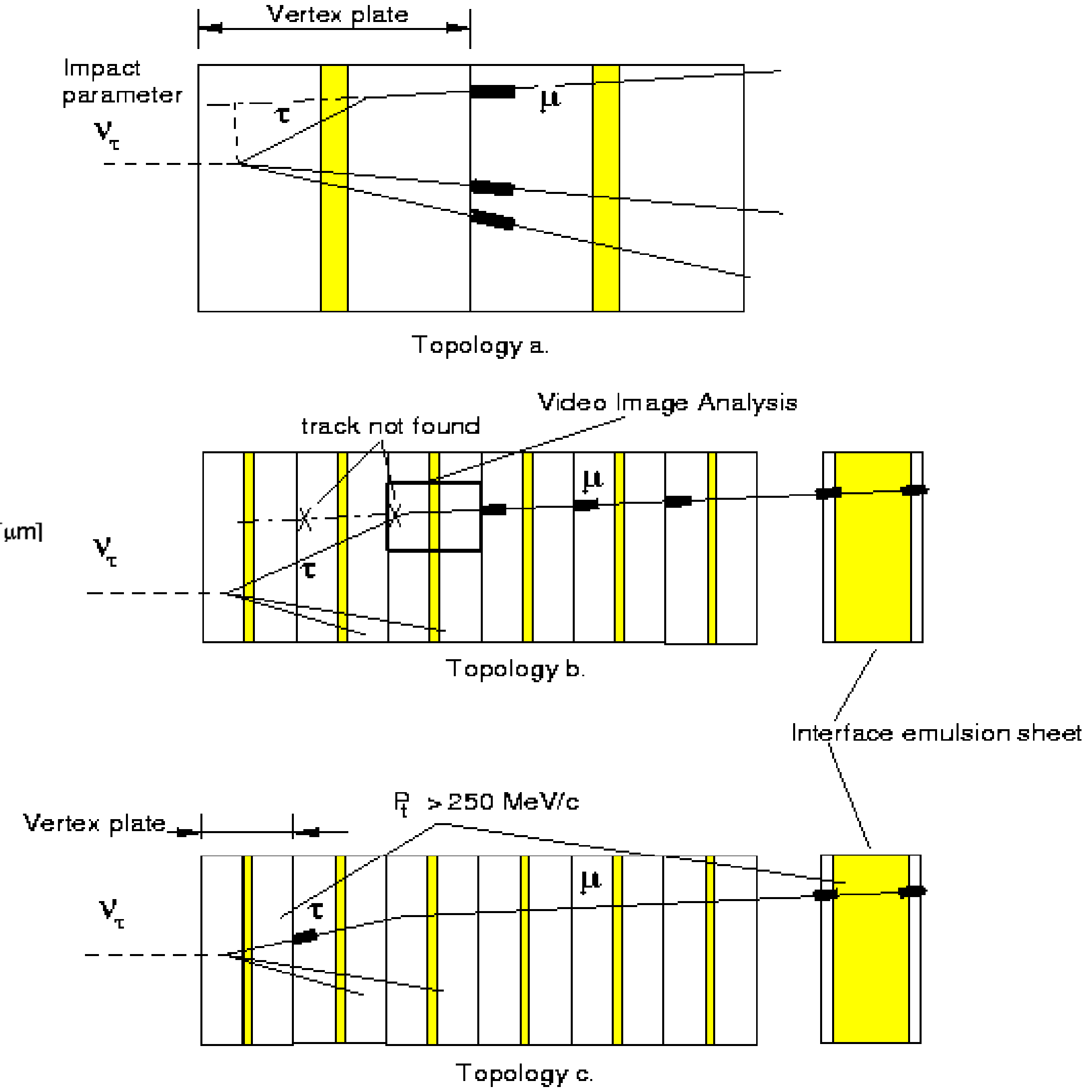


Once the track is found inside the target, <u>large</u> plate-to-plate scanback efficiency; it allows vertex location by disappearance of the scanback track in two consecutive plates.

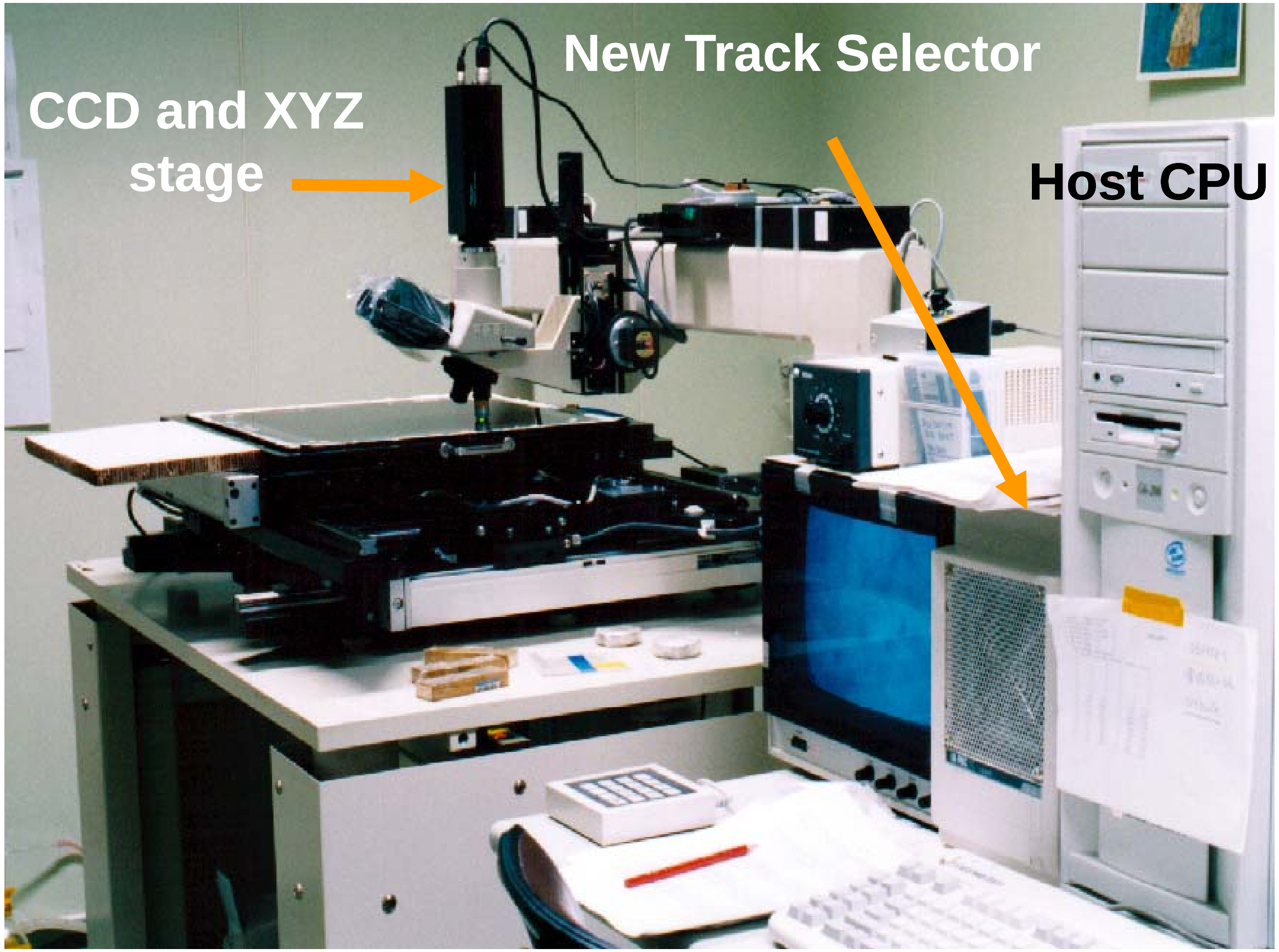


Decay search





CHORUS automatic microscopes



Network data storage

Automatic scanning: Track Selector

(developed in Nagoya)

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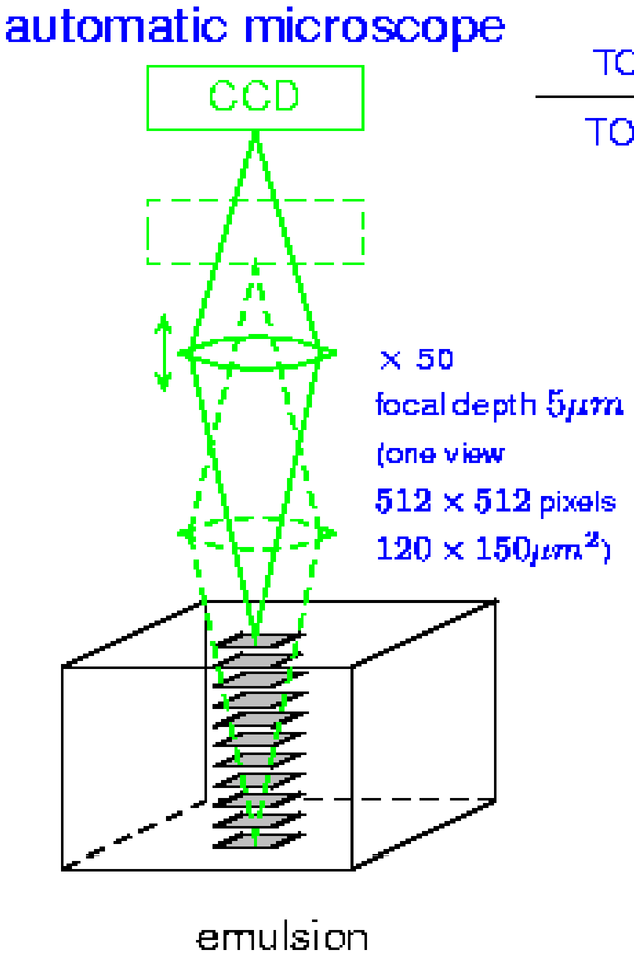
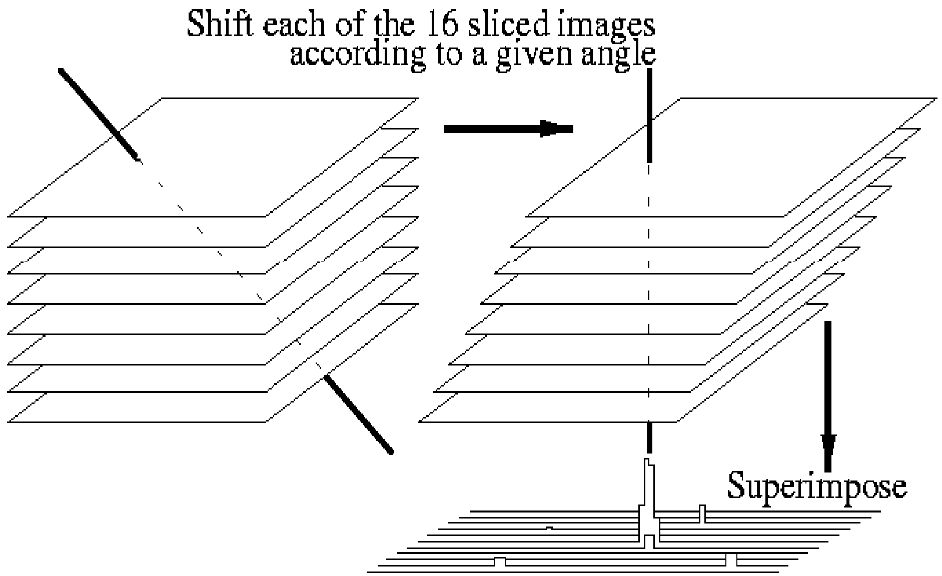
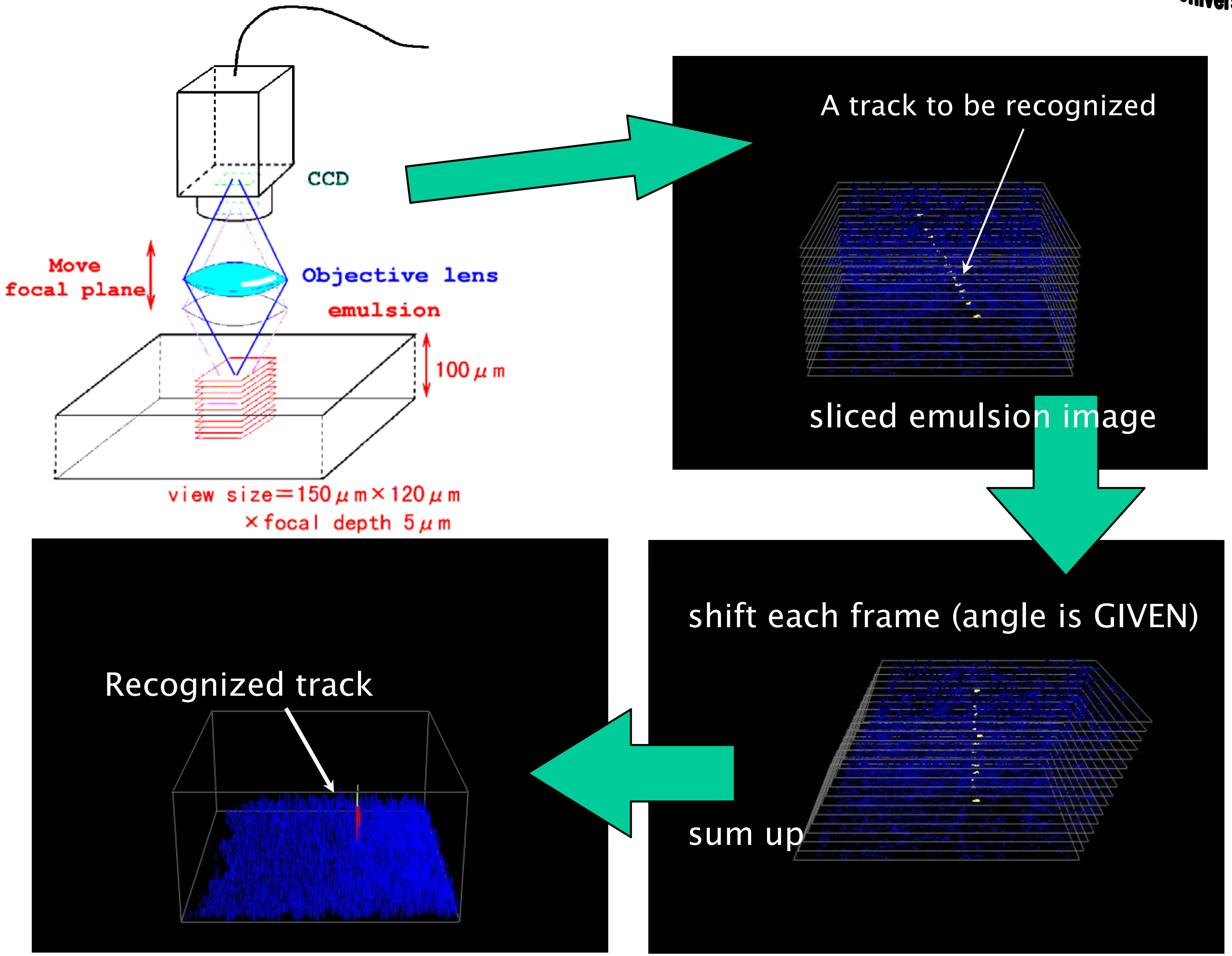
year	views/s
~ 1994	0.008
94 ~ 96	0.25
96 ~ 99	3
2000 ~	~30





AUTOMATIC SCANNING: The Track Selector (TS)



Inside a "vertex plate"

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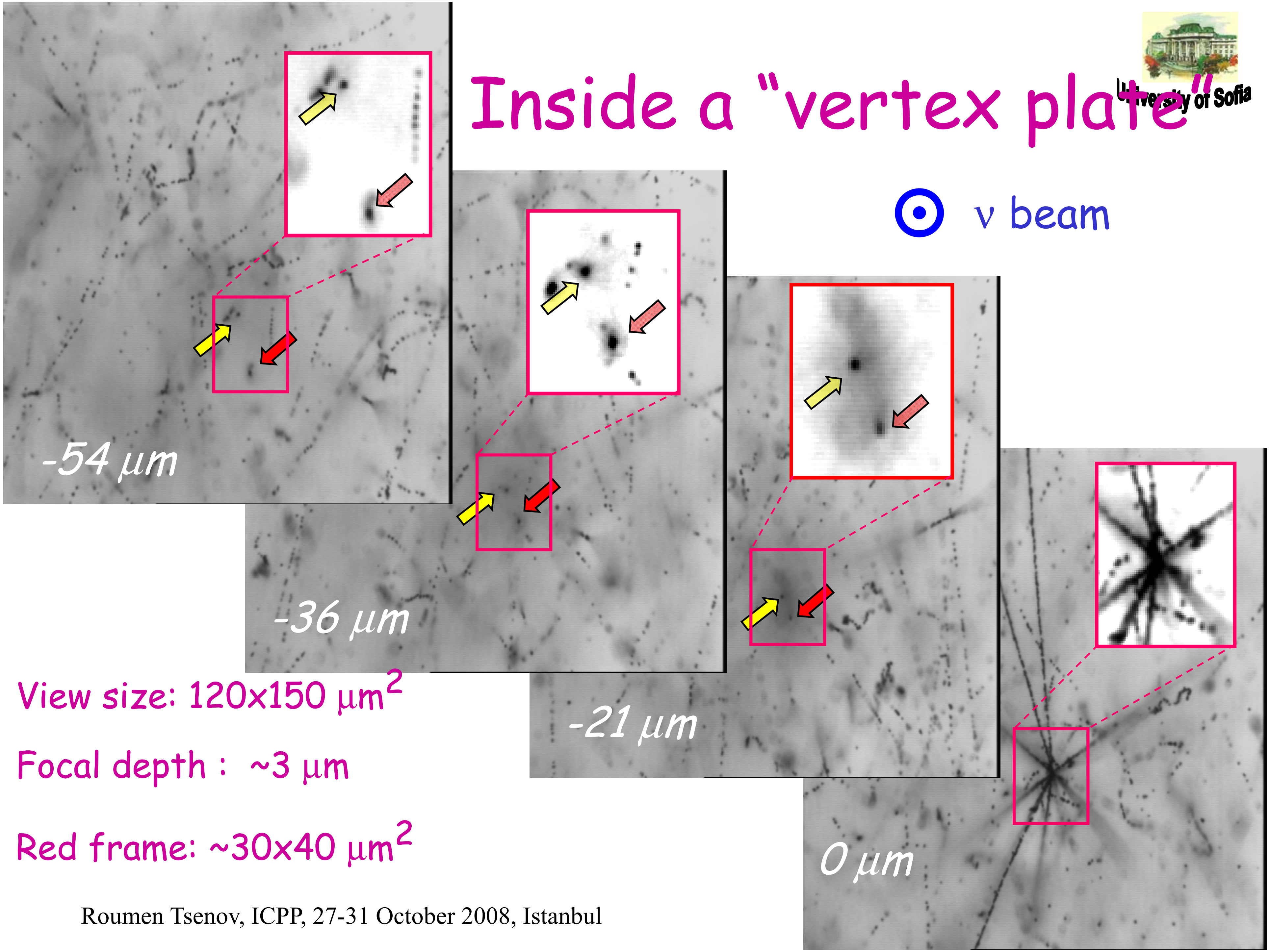


View size: 120x150 μm^2

Focal depth : ~3 μm

Red frame: ~30x40 μm^2

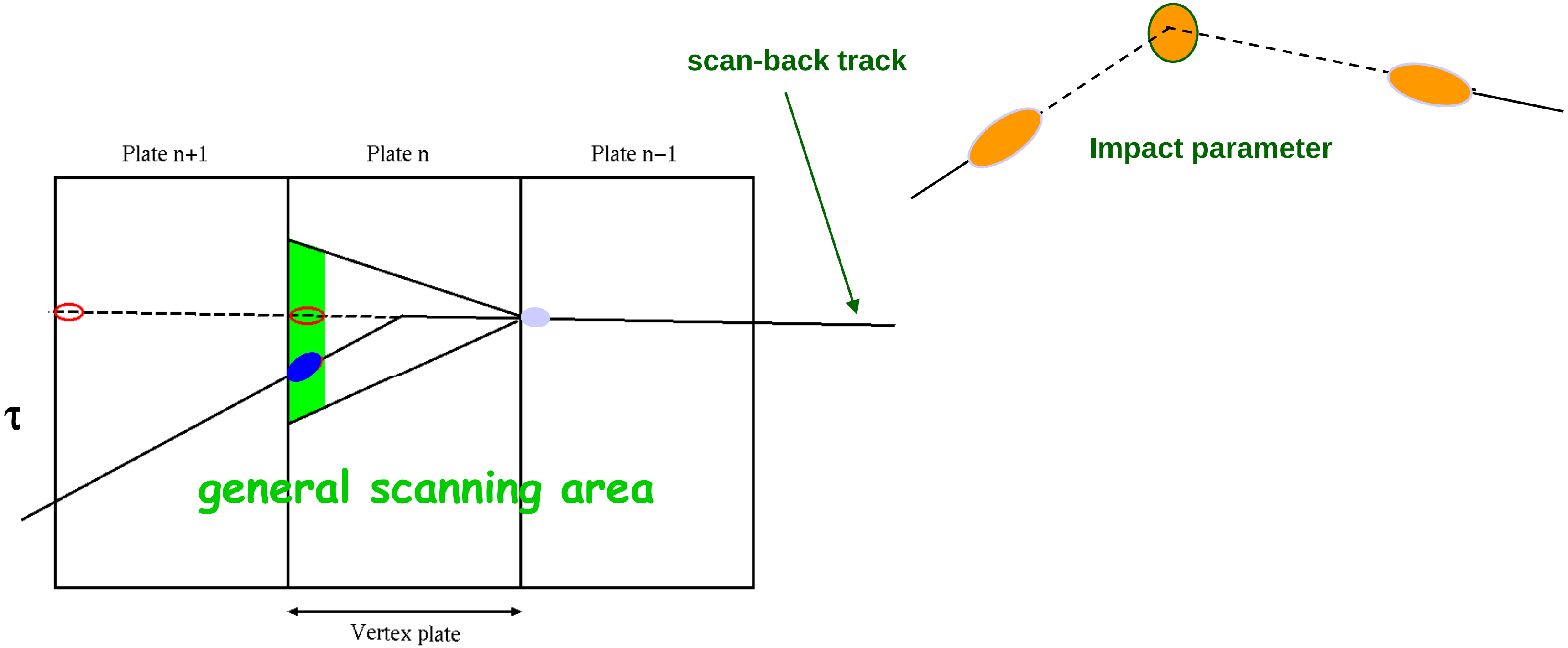
τ- kink detection (*parent search*)

Principle:

Parent track (τ) can be detected by wider view and general angle scanning at the vertex plate

Offline selection

- **small impact parameter between parent and daughter**
- **kink point is in the vertex plate**



Backgrounds

- $\tau^- \rightarrow h^- n(\pi^0)\nu_\tau$

$\bar{\nu}N \rightarrow \mu^+ D^- X$, $\;\hookrightarrow h^-$ neutrals

$\nu N \rightarrow \mu^- D^+ X$, $\;\hookrightarrow h^+$ neutrals

Charm production and missed μ — $\approx 10^{-6}\, N_{1\mu}$

$\nu N \rightarrow \nu\, h^- X$, $\;\hookrightarrow h^- N \rightarrow h^- N$

h scattering without visible recoil or nuclear break-up (***white kink***) — $\approx 10^{-5}\, N_{1\mu}$

- $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$

$\bar{\nu}N \rightarrow \mu^+ D^- X$, $\;\hookrightarrow \mu^-$ neutrals

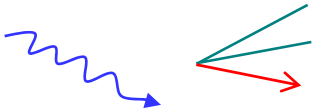
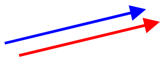
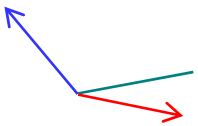
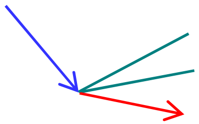
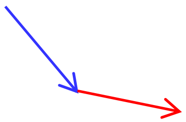
Charm production and missed μ — $\approx 10^{-6}\, N_{1\mu}$

$\nu N \rightarrow \nu\, h^- X$, $\;\hookrightarrow h^- N \rightarrow h^- N$

white kink and wrong μ id — $\approx 10^{-6}\, N_{1\mu}$

Computer assisted eye-scan

to confirm the presence of a secondary vertex

	Low momentum *BG track*	80.0%
	Parent = daughter *no angle difference (distortion)*	4.0%
	Backward going track: *nuclear fragment*	12.0%
	Hadron 2ry interaction	2.5%
	Decay (kink)	1.5%

5% of located events

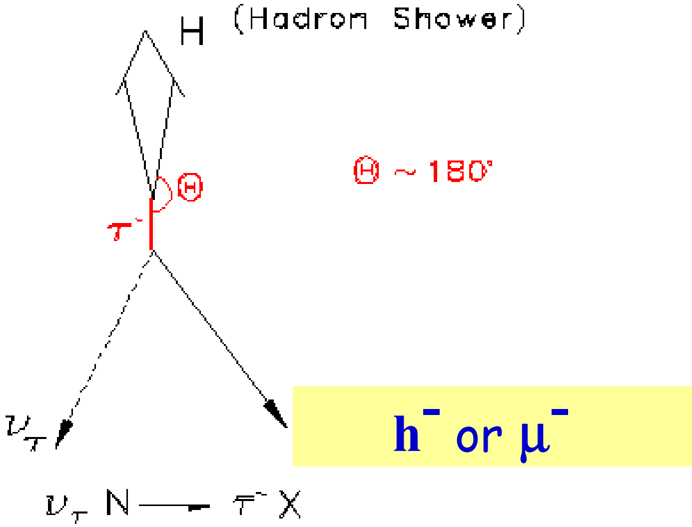
PHASE I data flow chart

Protons on target	5.06×10^{19}
1μ: events with 1 negative muon and vertex predicted in emulsion	713,000
1μ: $p_\mu < 30$ GeV and angular selections	477,600
1μ: events scanned	355,395
1μ: vertex located	143,742
1μ: events selected for eye-scan	11,398
0μ with vertex predicted in emulsion (CC contamination)	335,000 (140,000)
0μ with 1 negative track (p = 1-20 GeV and angular selections)	122,400
0μ: events scanned	85,211
0μ: vertex located (corrected number after reprocessing)	23,206 (20,081)
0μ: events selected for eye-scan	2,282

How to reduce the background or confirm a candidate

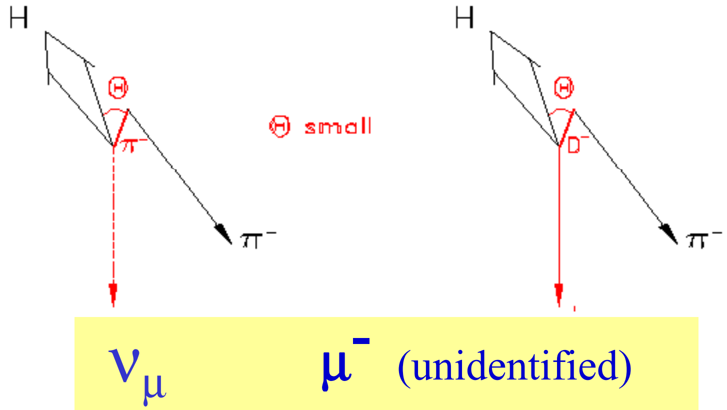
A unique feature of emulsion: kink parent direction

<u>Signal:</u> τ^-



<u>Backgrounds</u>

"White kink" Charm (D^-) decays



⊙ ν beam

Limit Computation

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

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

$$P_{\mu\tau} \leq \frac{N_\tau}{(N_\tau^{max})_{1\mu} + (N_\tau^{max})_{0\mu}}$$

2.4

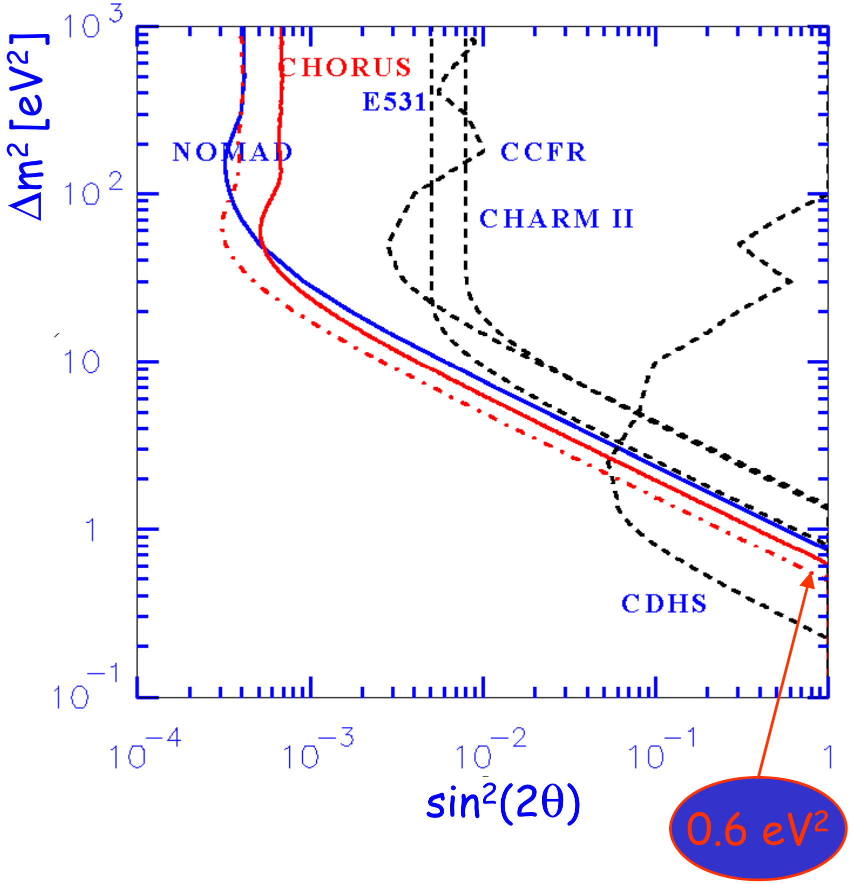
$\sigma_\tau^{CC}/\sigma_\mu^{CC}$	$N_{1\mu}$	$\langle A_{1\mu}^\tau / A_{1\mu}^\mu \rangle$	$e_{1\mu}^{\text{kink}}$	$N_{0\mu}$	$\langle A_{0\mu}^\tau / A_{0\mu}^\mu \rangle$	$e_{0\mu}^{\text{kink}}$
0.53	143,742	0.97	0.39	20,081	2.3	0.13

		charm($\nu + \bar{\nu}$)	WK	Total	Observed	N_τ^{max}
1μ	$L_k < 5$ plates	0.1	-	0.1	0	5,014
0μ	$L_k < 3$ plates	0.7	2.6	3.3	4	2,791
	$(L_k(p_h))_{80\%}$	0.5	1.7	2.2	1	2,537
	$(L_k(p_h))_{80\%}$ and $\Phi_{(\tau-H)} > 90^o$	0.3	0.8	1.1	0	2,004

Result of Phase I

Phys.Lett. B 497 (2001) 8

- $P_{\mu\tau} < 3.4\ 10^{-4}$
- @90% CL[1]
- For for large $\Delta m^2 \rightarrow$ $\sin^2 2\theta_{\mu\tau} < 6.8\ 10^{-4}$



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

CHORUS Phase II : Netscan

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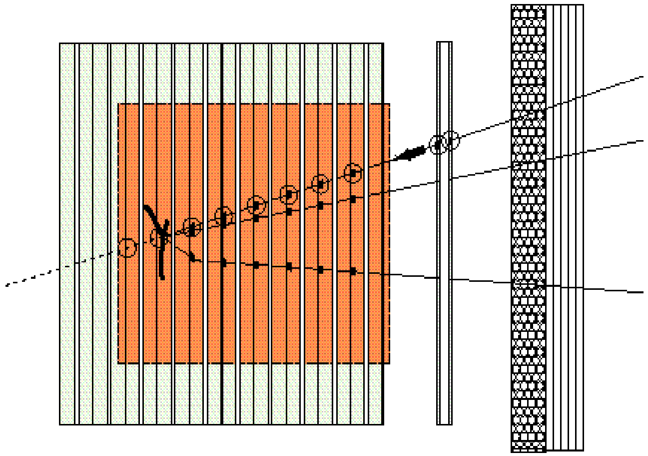
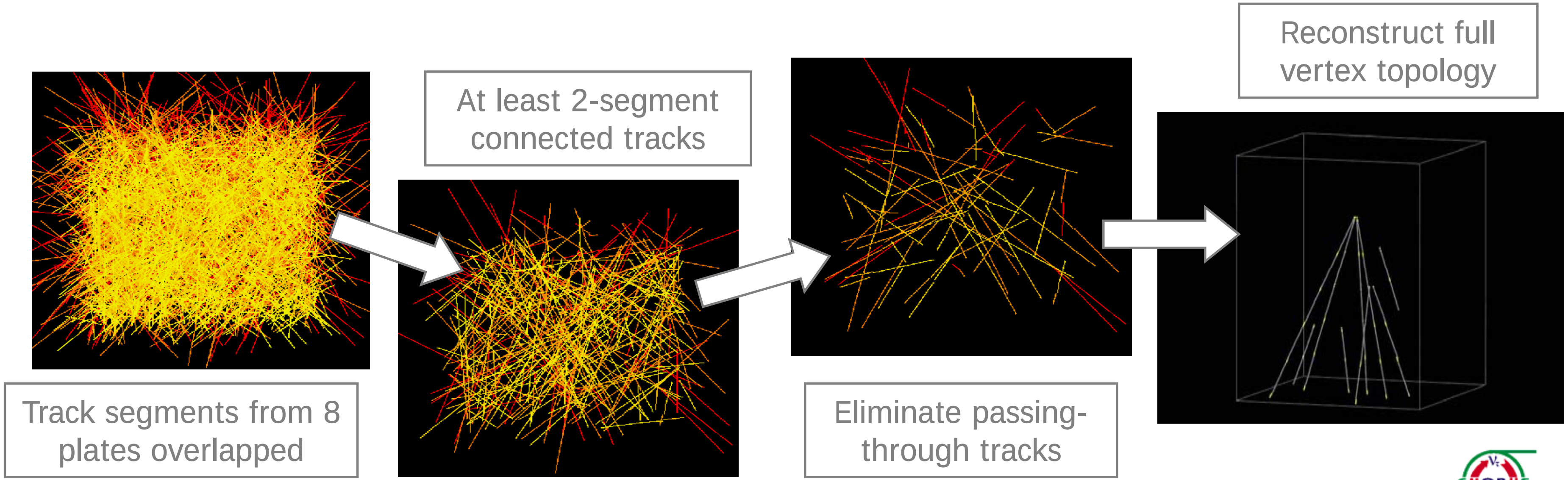
A new scanning technique : scanning speed increased from 0.01 frames/sec in **1994** to 10,000 in **2000**

- 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





Ultra Track Selector (HW based)

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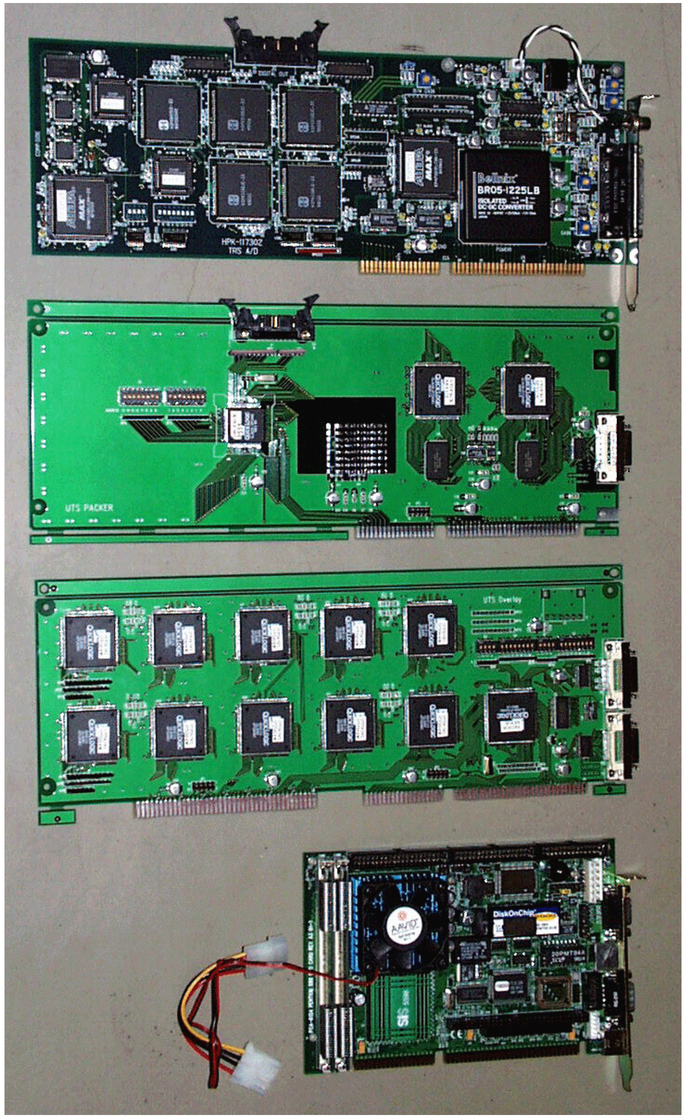
Faster Hardware processing of images:
- from digitization to
- grain finding and data storage

After 16 images are stored:
- PARALLEL angular scan
- for every possible angle:
  - HW summation by FPGA technology (Field programmable Gated Arrays)
  - to find tracks while the microscope moves to the next position



Performance:

3 Hz *(for all tracks with $\theta_z < 400$ mrad)*

OFFLINE Emulsion Analysis

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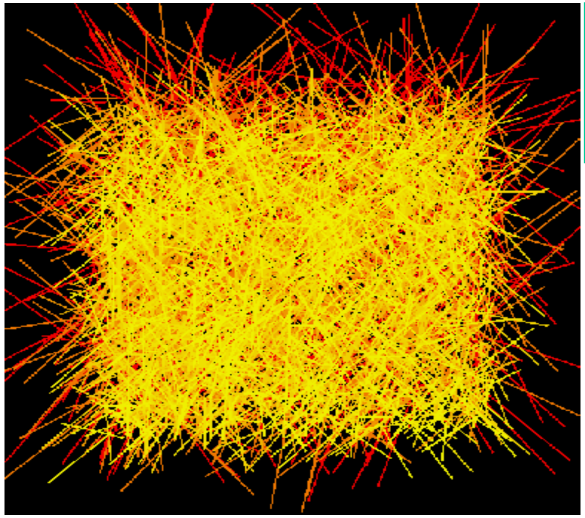
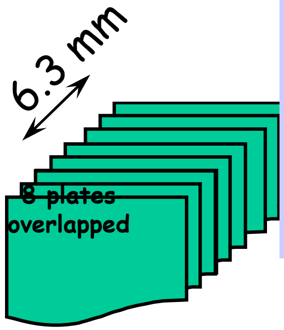
1.5 mm



1.5 mm

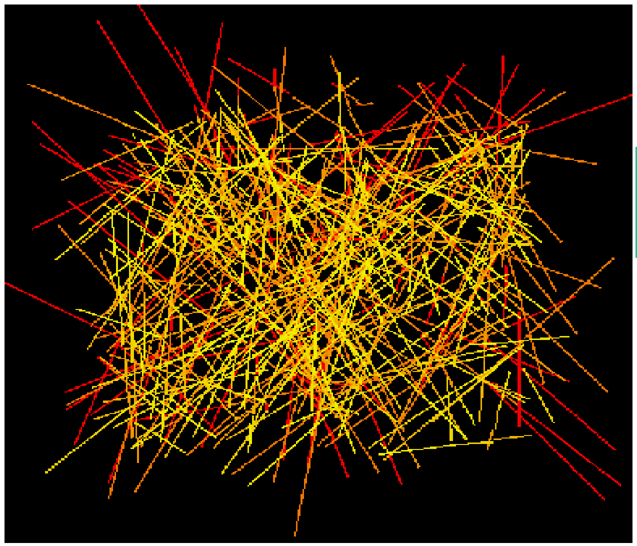
All track segments



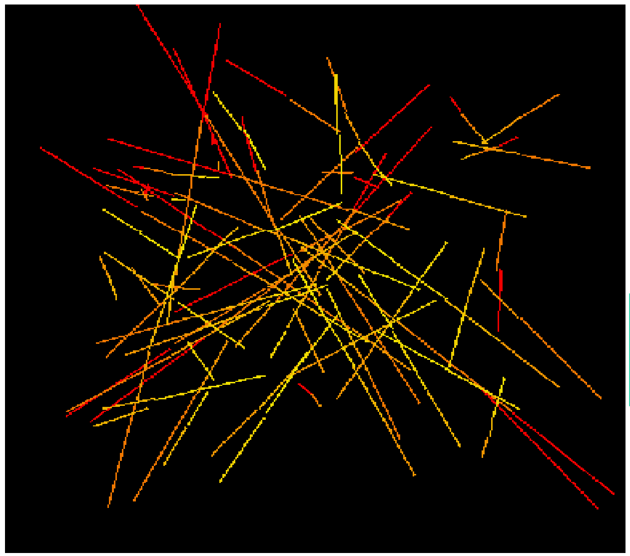
1) Reduction of ~ 10K track segments (each event, a “two-years” history!) by use of emulsion+electronic data

AND

2) Subsequent Physics analysis



≥2 segments connected



Not passing through

PHASE II data flow chart

Results of the reconstruction of the 0μ sample

Stage of reconstruction	Number of events
Interface emulsion scanned	102544
Vertex plate found	35039
NetScan acquisition accepted	29404
Vertex reconstructed	22661

Final Results

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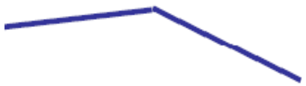
Category	$\Delta\phi$ (rad)	Background	$N_\tau^{\mu\tau}$	$N_\tau^{e\tau}$	Data
$\tau \to 1\mu$ [1994–1997 data taking]		0.100 ± 0.025	5014	55.8	0
$\tau \to 0\mu$ C1 [1994–1995 data taking]		0.300 ± 0.075	526	5.85	0
$\tau \to 0\mu$ C1 [1996–1997 data taking]		53.2 ± 9.0	9621	76.9	59
$\tau \to 0\mu$ C3 [1996–1997 data taking]		47 ± 11	4443	35.5	48

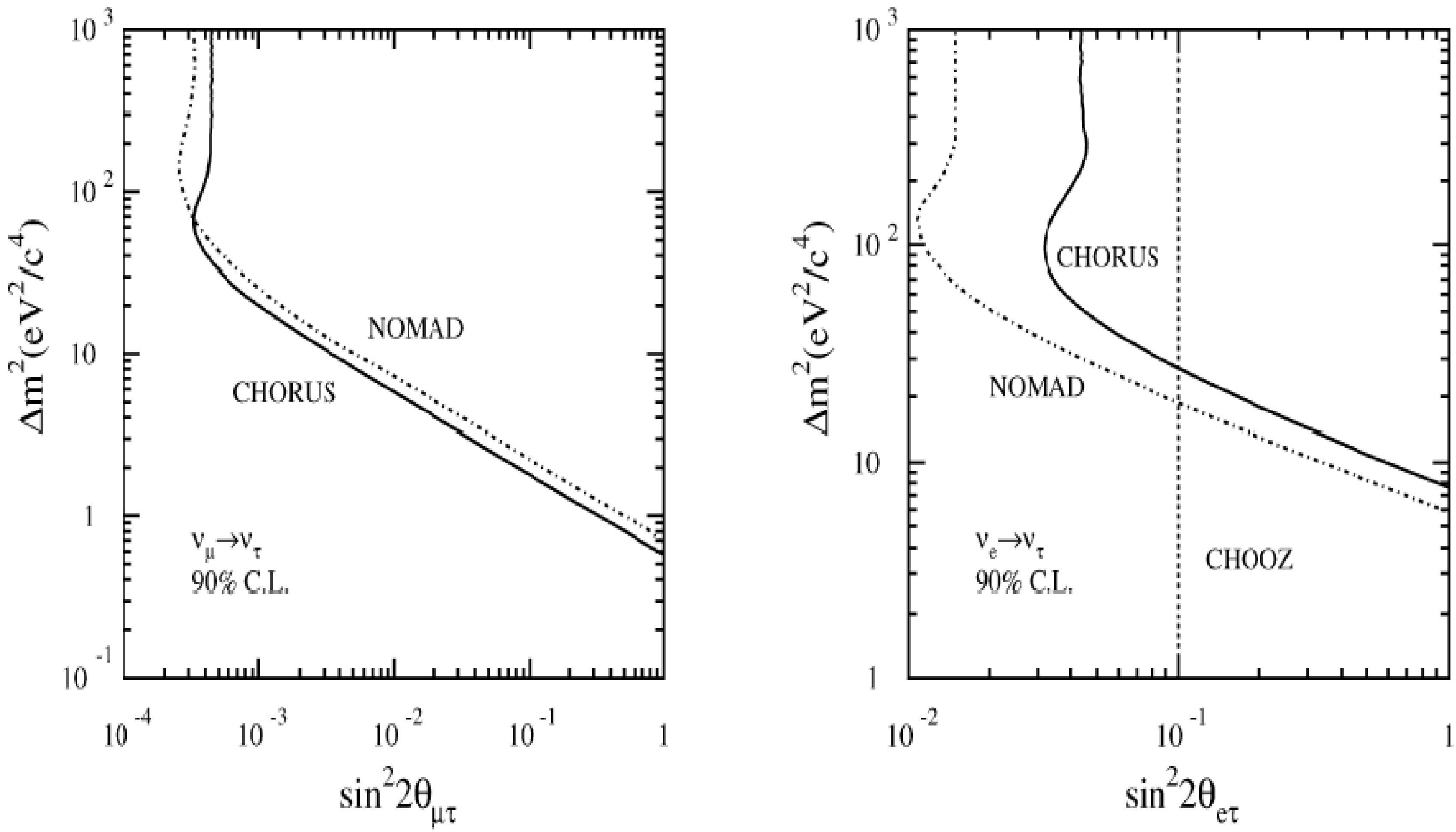
C1



C3

- the same $\tau \to 1\mu$ "would be seen" number of events
- 7 times more $\tau \to 0\mu$ "would be seen" number of events

$P_{\mu\tau} < 2.2\text{x}10^{-4}$ @90% CL $P_{e\tau} < 2.2\text{x}10^{-2}$



Conclusions

- CHORUS has reached its design sensitivity on $P_{\mu\tau}$ ~10^{-4};
- Rich capabilities of a hybrid emulsion experiment for study of short lived particles, e.g. neutrino induced charm production have been demonstrated;
- Successor long base-line τ appearance experiment exploiting similar technique, OPERA, is running.