CHORUS

Accelerator searches for $\nu_\mu \to \nu_\tau$ oscillations

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Legend

- Introduction to neutrino oscillations
- Short baseline accelerator searches for $\nu_\mu \rightarrow \nu_\tau$
  - ***CHORUS***
  - *NOMAD*
- Future long baseline accelerator searches

Neutrino mixing

Associate neutrino flavour with the charged lepton flavour as seen in charged-current interactions:

$$\left(\nu_\ell + A \to \ell + B\right)$$

For massive neutrinos: flavour eigenstate need not be a mass eigenstate but can be a coherent superposition:

Mixing matrix U is unitary

$$\left|\nu_l\right\rangle = \sum_m U_{\ell m}\left|\nu_m\right\rangle$$

The propagation of different mass eigenstates leads to flavour oscillation in vacuum:

$$A\left(\nu_\ell \to \nu_{\ell'}\right) = \sum_m U_{\ell m}\, e^{-i\frac{M_m^2}{2}\frac{L}{E}}\, U^*_{\ell' m}$$

Simplification for 2 mixing flavours with mixing angle θ (phase δ):

$$U = \begin{pmatrix} \cos\theta & e^{i\delta}\sin\theta \\ -e^{-i\delta}\sin\theta & \cos\theta \end{pmatrix}$$

Interactions are now nondiagonal with the mass eigenstates!

Neutrino oscillations

The probability that a neutrino oscillates (changes flavour):

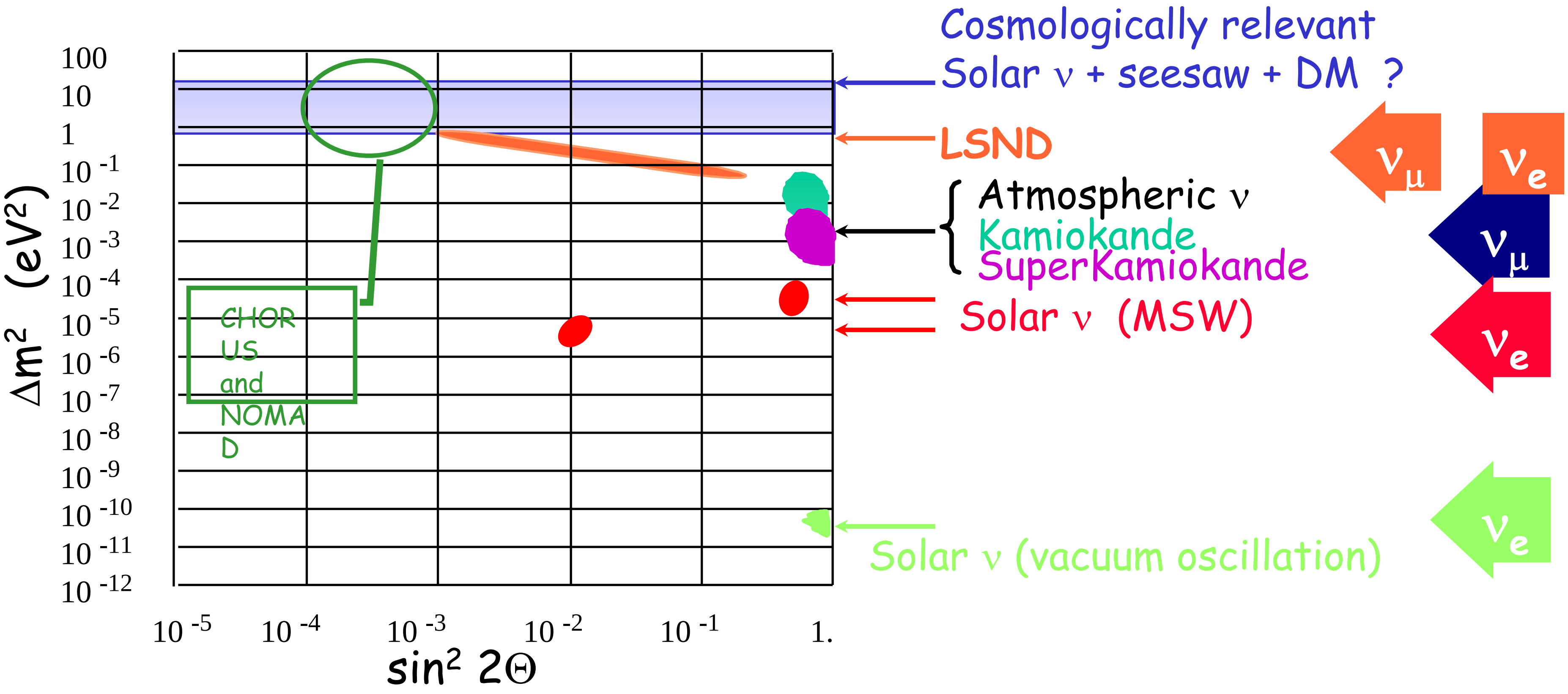
$$P\left(\nu_\ell \to \nu_{\ell'\neq\ell}\right) = \sin^2 2\theta \sin^2\left[1.27\,\delta M^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right]$$

With definition: $\delta M^2 \equiv M_2^2 - M_1^2$

To have a large effect: $\delta M^2\left(eV^2\right) \geq \frac{L(km)}{E(GeV)}^{-1}$

Maximum at 1/4 oscillation length $\left(\frac{L}{E}\right)^{-1} = \frac{2}{\pi} 1.27\,\delta M^2$

Two parametric oscillation plot



CHORUS and NOMAD

Cosmologically relevant
Solar ν + seesaw + DM ?

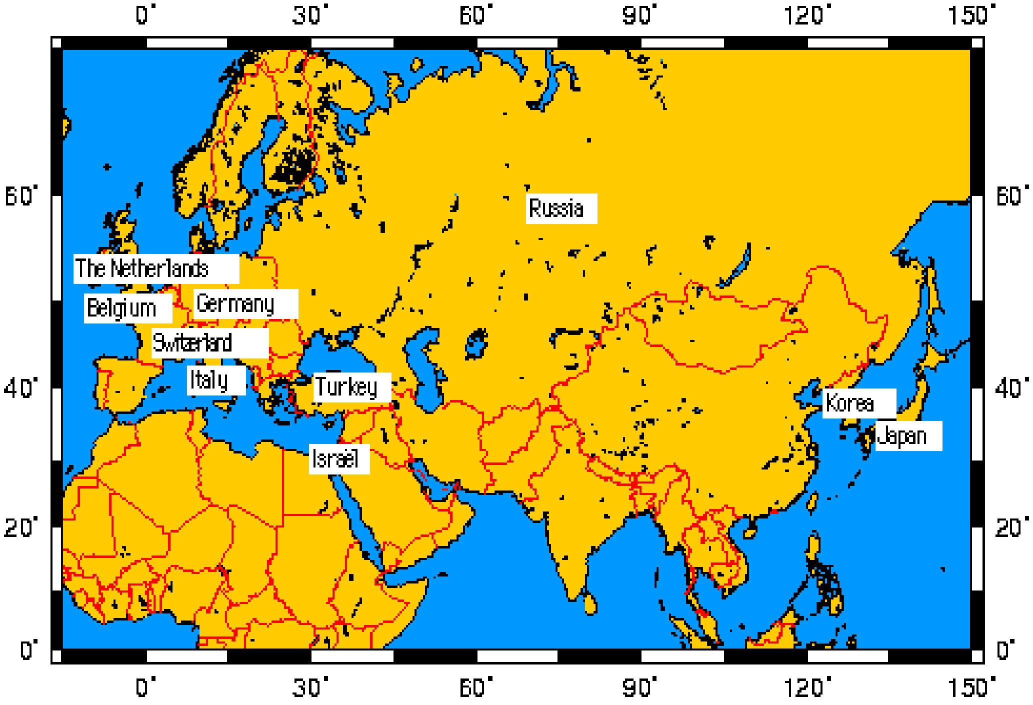
LSND

Atmospheric ν
Kamiokande
SuperKamiokande

Solar ν (MSW)

Solar ν (vacuum oscillation)

The CHORUS Collaboration



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)

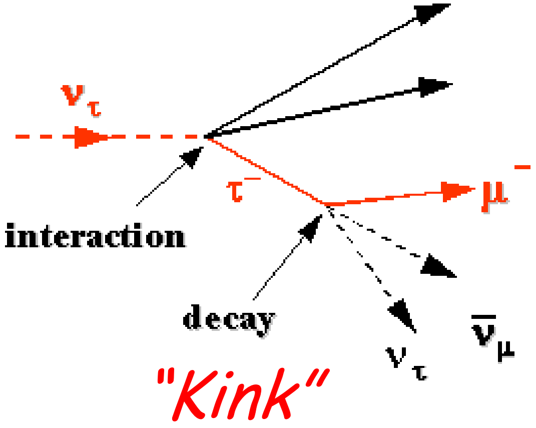
CHORUS Main objective

- 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

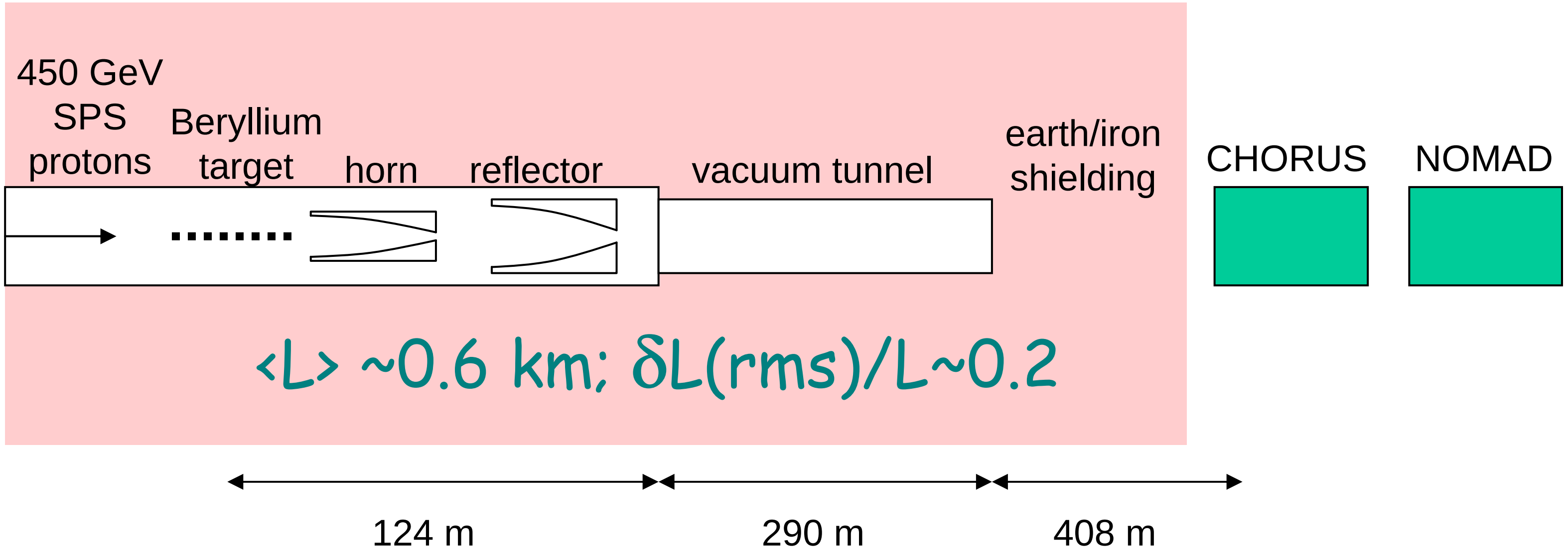
decay of primary τ-lepton

(decay path ~1.5 mm)



$\mu^- \ \nu_\tau \ \bar{\nu}_\mu$	BR 18 %
$h^- \ \nu_\tau \ n\pi^o$	50 %
$e^- \ \nu_\tau \ \bar{\nu}_e$	18 %
$\pi^+ \ \pi^- \ \pi^- \ \nu_\tau \ n\pi^o$	14 %

CERN West Area Neutrino Facility

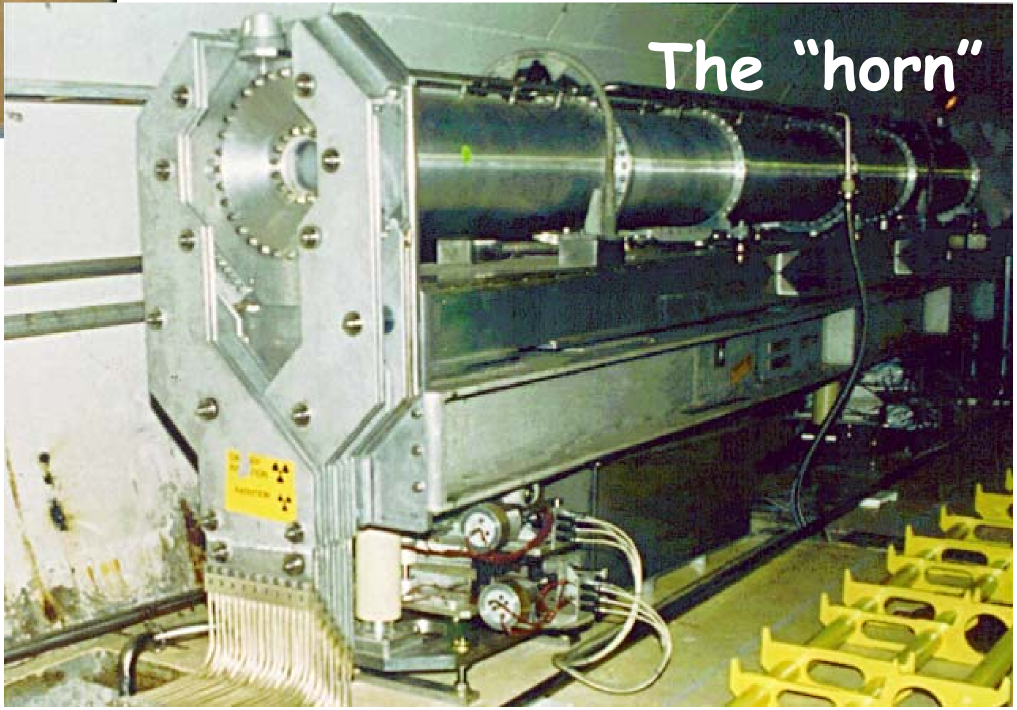


$\langle L\rangle$ ~0.6 km; $\delta L(\mathrm{rms})/L$~0.2

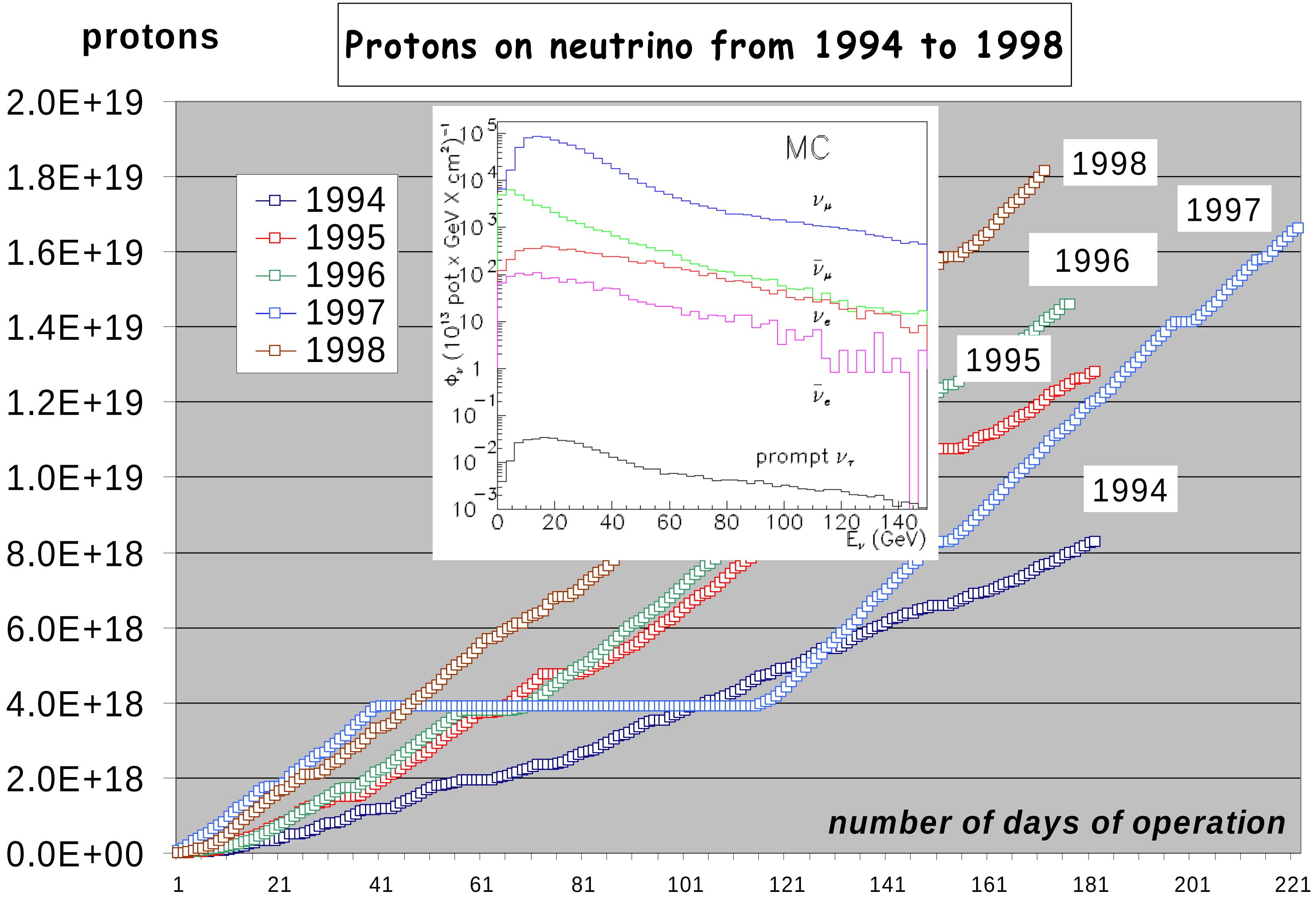
- WBB, $\langle E_{\nu_\mu}\rangle = 26.6$ GeV
- ~$5 \cdot 10^{19}$ protons on target
- ~840K ν_μ CC in CHORUS
- ν_τ CC / ν_μ CC ~ 3.10^{-6}

(~0.1 background event)

West Area Neutrino Facility

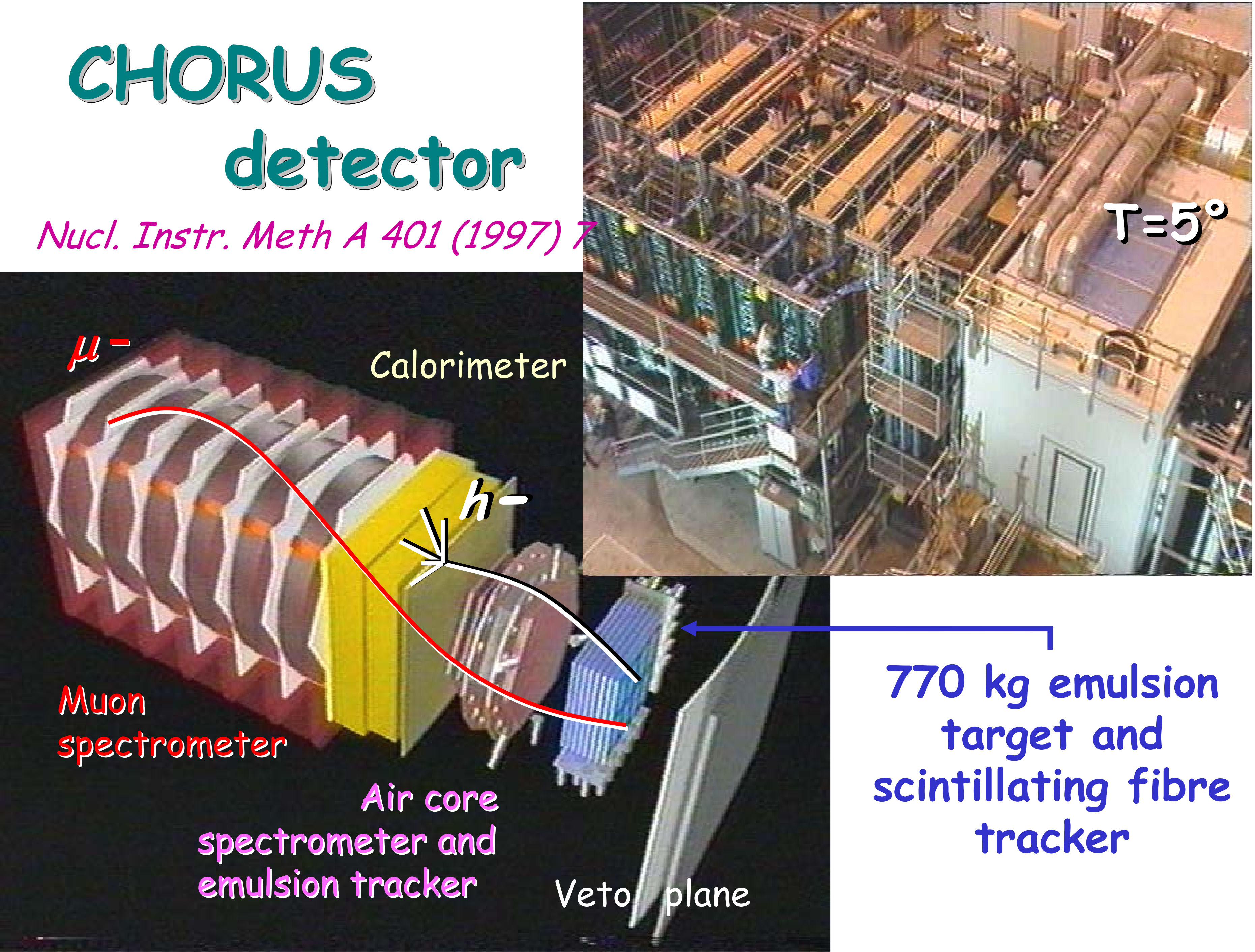


SPS and WANF (ν_μ) neutrino beam



CHORUS detector

Nucl. Instr. Meth A 401 (1997) 7

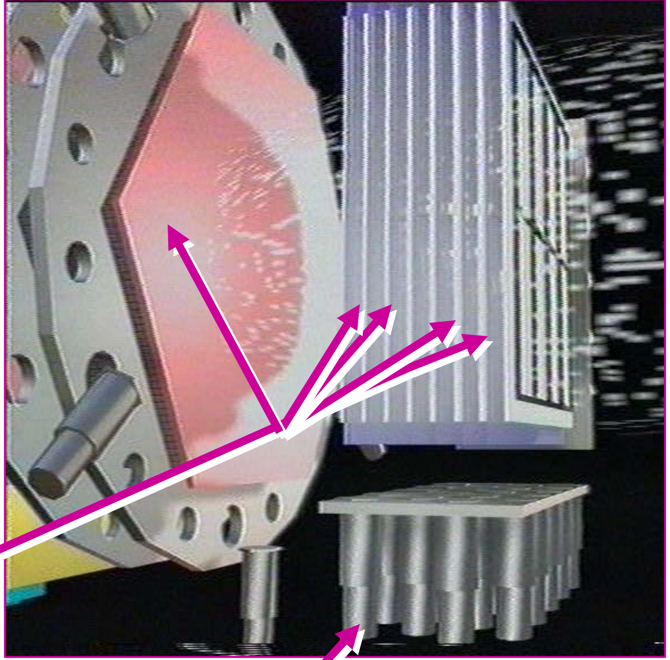


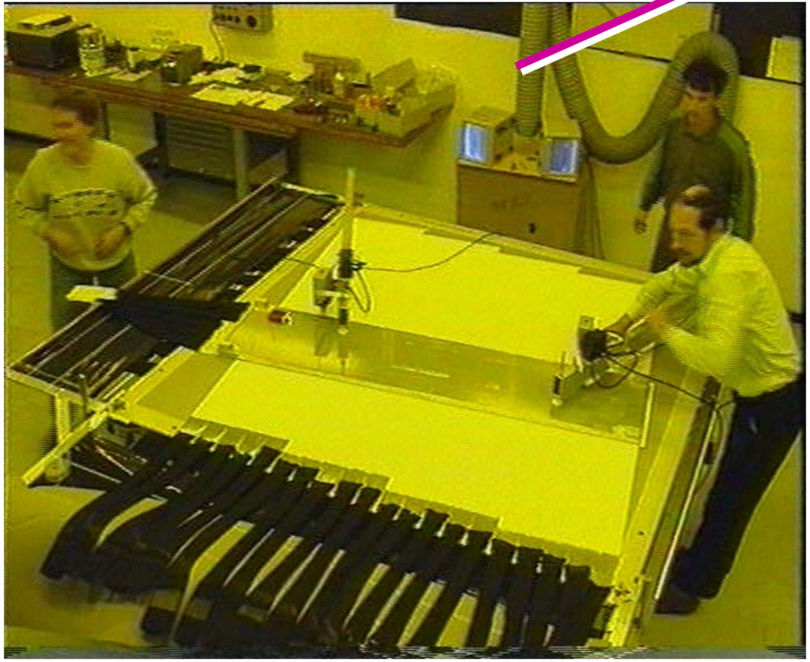
770 kg emulsion target and scintillating fibre tracker

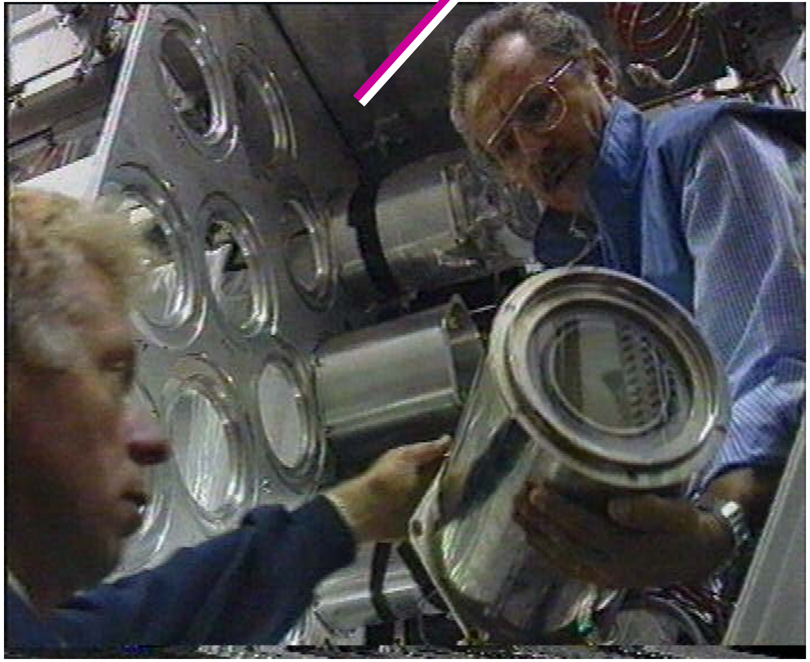
Scintillating fibre trackers

Nucl. Instr. Meth A 412 (1998) 19

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



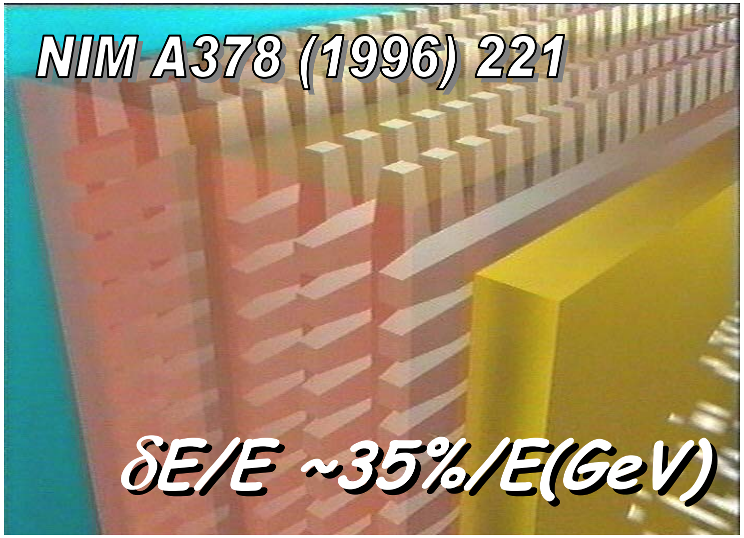




External electronic detectors:

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

Event pre-selection and post-scanning analysis



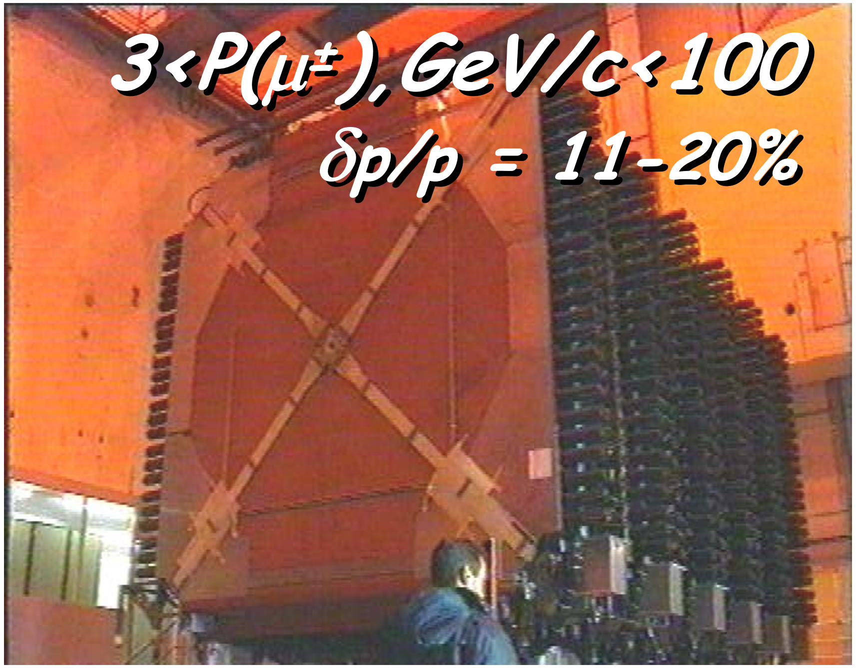
NIM A378 (1996) 221

$\delta E/E \sim 35\%/E(\mathrm{GeV})$

$P(h^{\pm}) < 20$ GeV/c

$\delta p/p \sim 25\%$

NIM A357 (1995)243



$3 < P(\mu^{\pm})$, GeV/c < 100

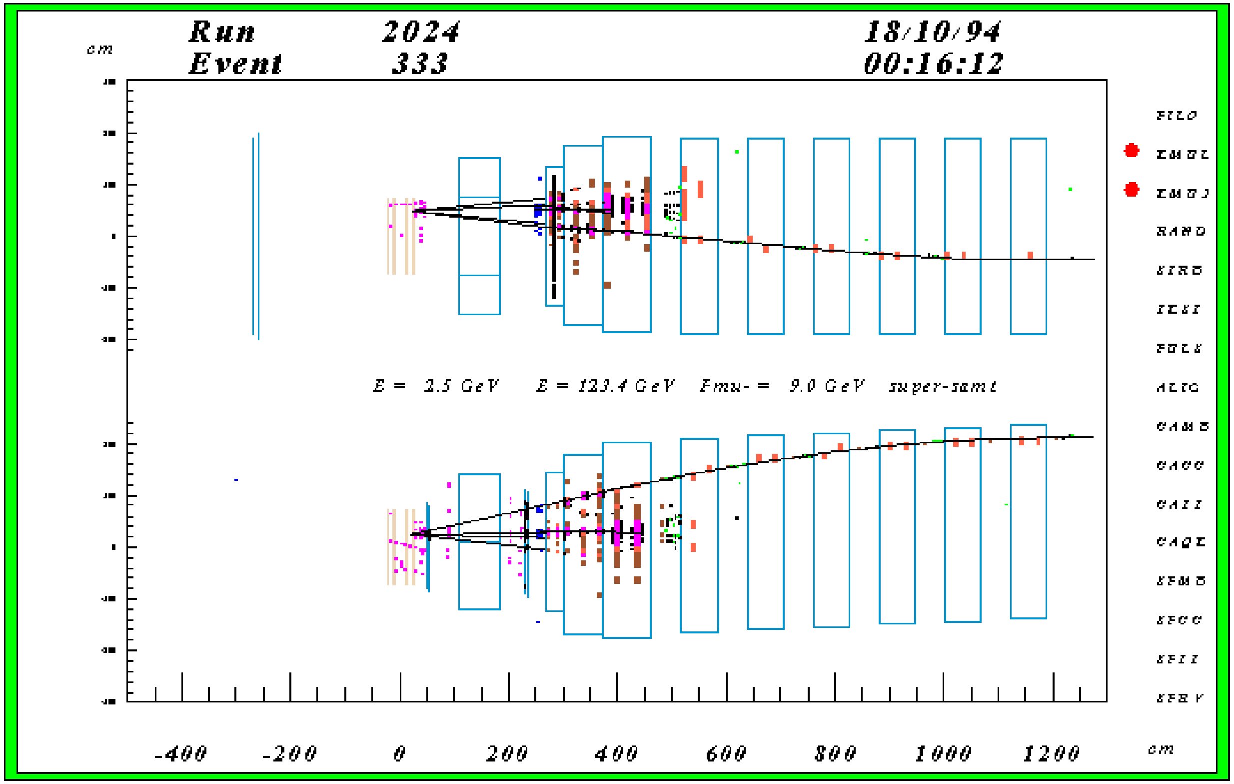
$\delta p/p = 11\text{-}20\%$

Neutrino data-taking collection efficiency 1994-1997

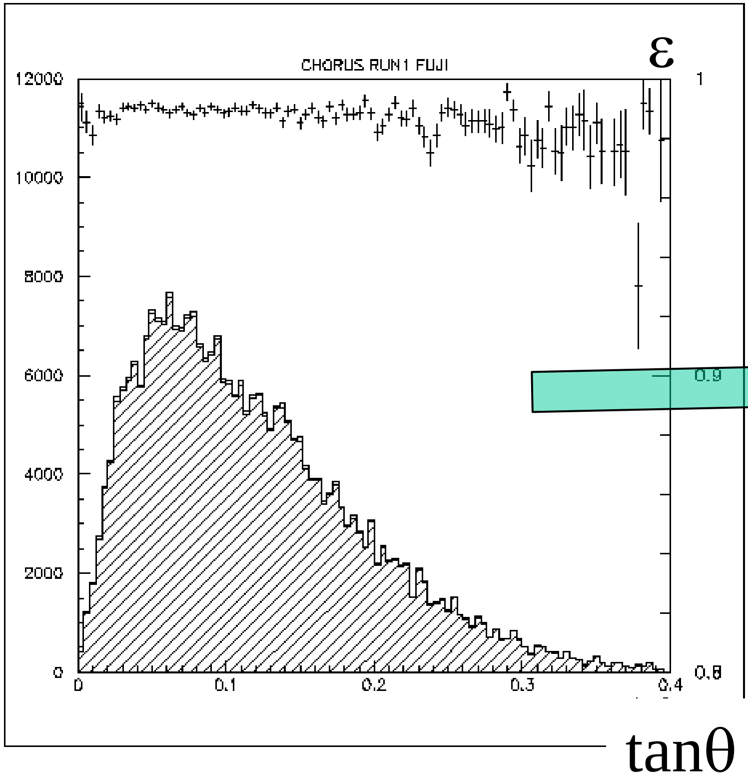
Year of exposure	*1994*	*1995*	*1996*	*1997*	*All*
POT / 10^{19}	**0.81**	**1.20**	**1.38**	**1.67**	**5.06**
Expected Ncc / 10^{3}	**120**	**200**	**230**	**290**	**840**
Chorus efficiency	**0.77**	**0.88**	**0.94**	**0.94**	**0.90**
Deadtime	**0.10**	**0.10**	**0.13**	**0.12**	**0.11**
Good emulsion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

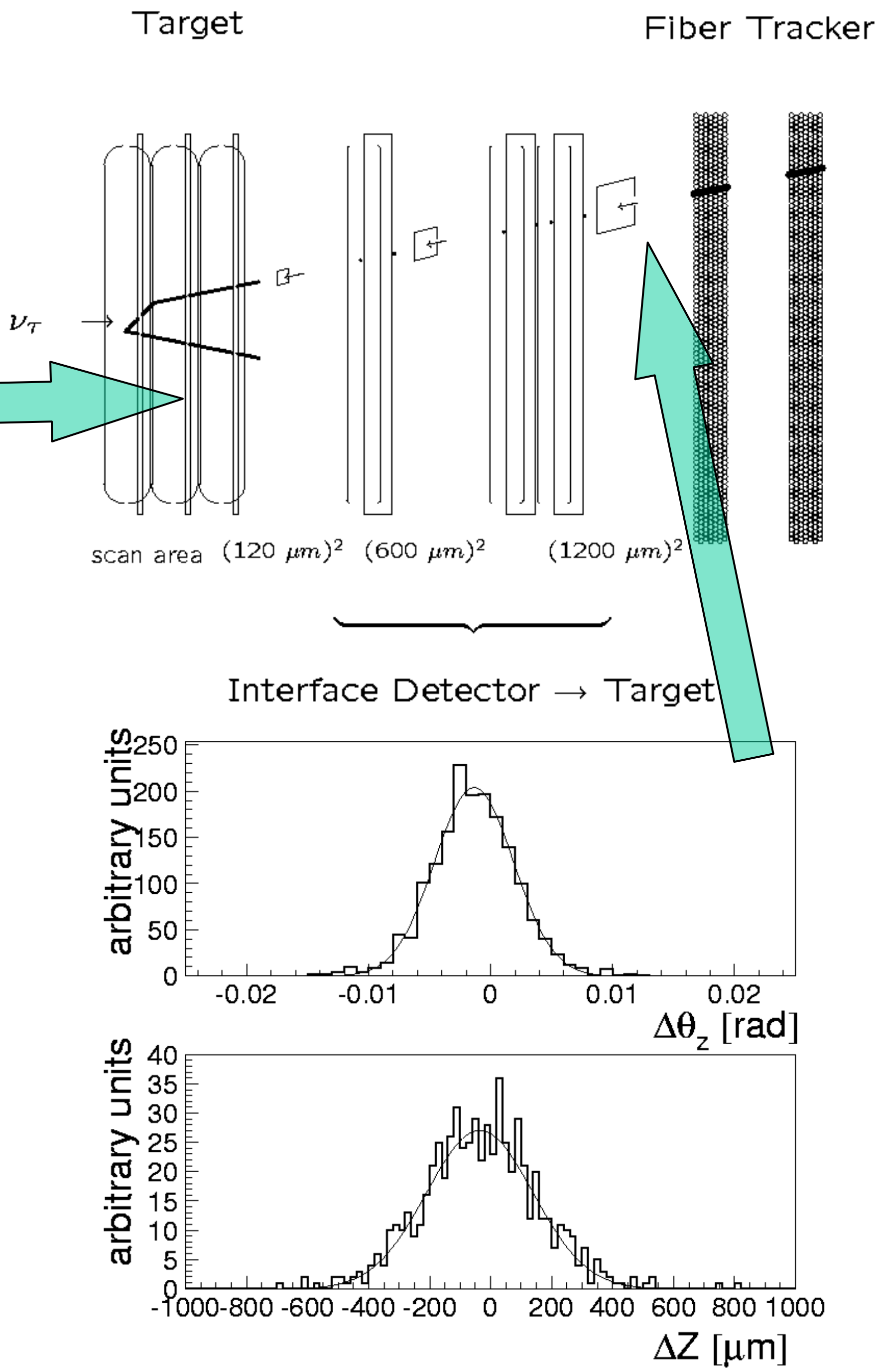
N.B. Longest/Largest emulsion exposure ever done

Event in CHORUS



Predictions and Scanback





Nuclear emulsion yesterday

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

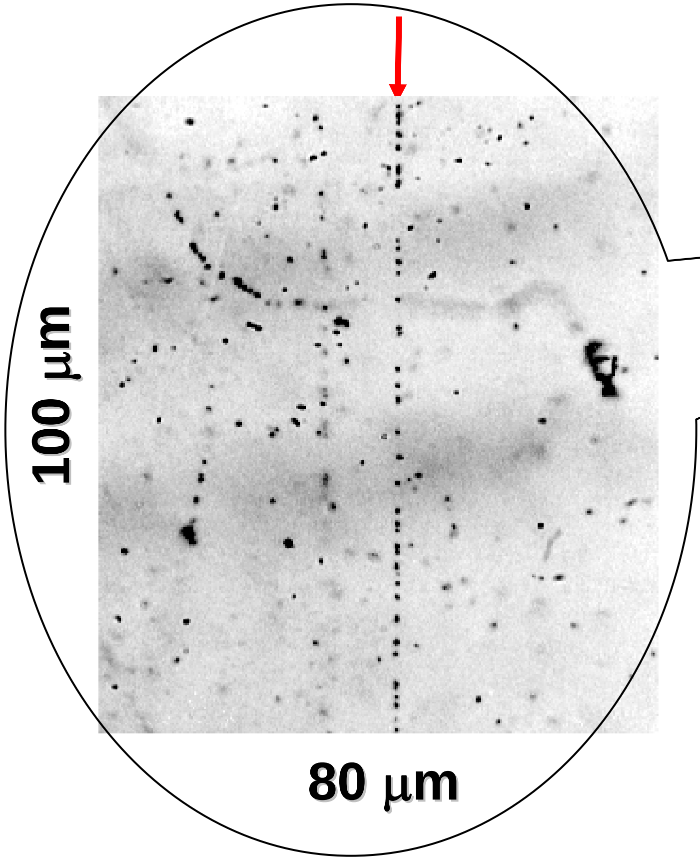
Discovery of $\pi \to \mu \to e$

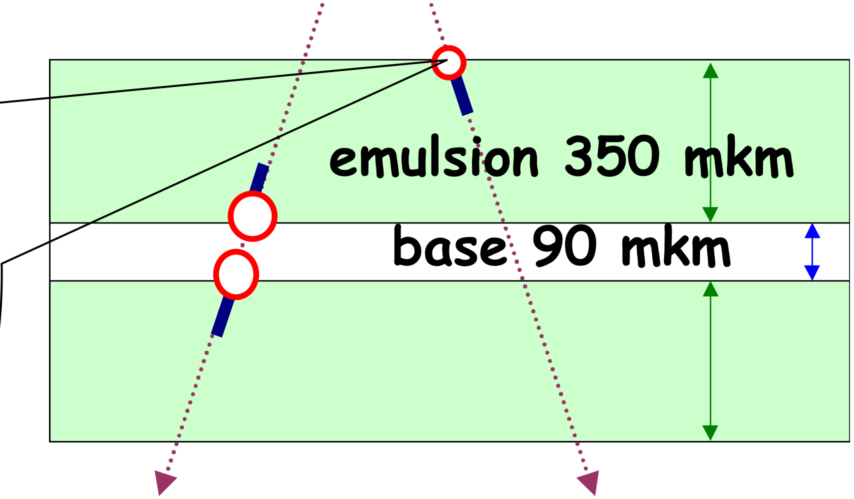
CHORUS emulsion plate

Target = 4 stacks (1.4⑨1.4 m^2)
1 stack = 36 plates

MIP : 30 ~ 40 grains / 100 μm

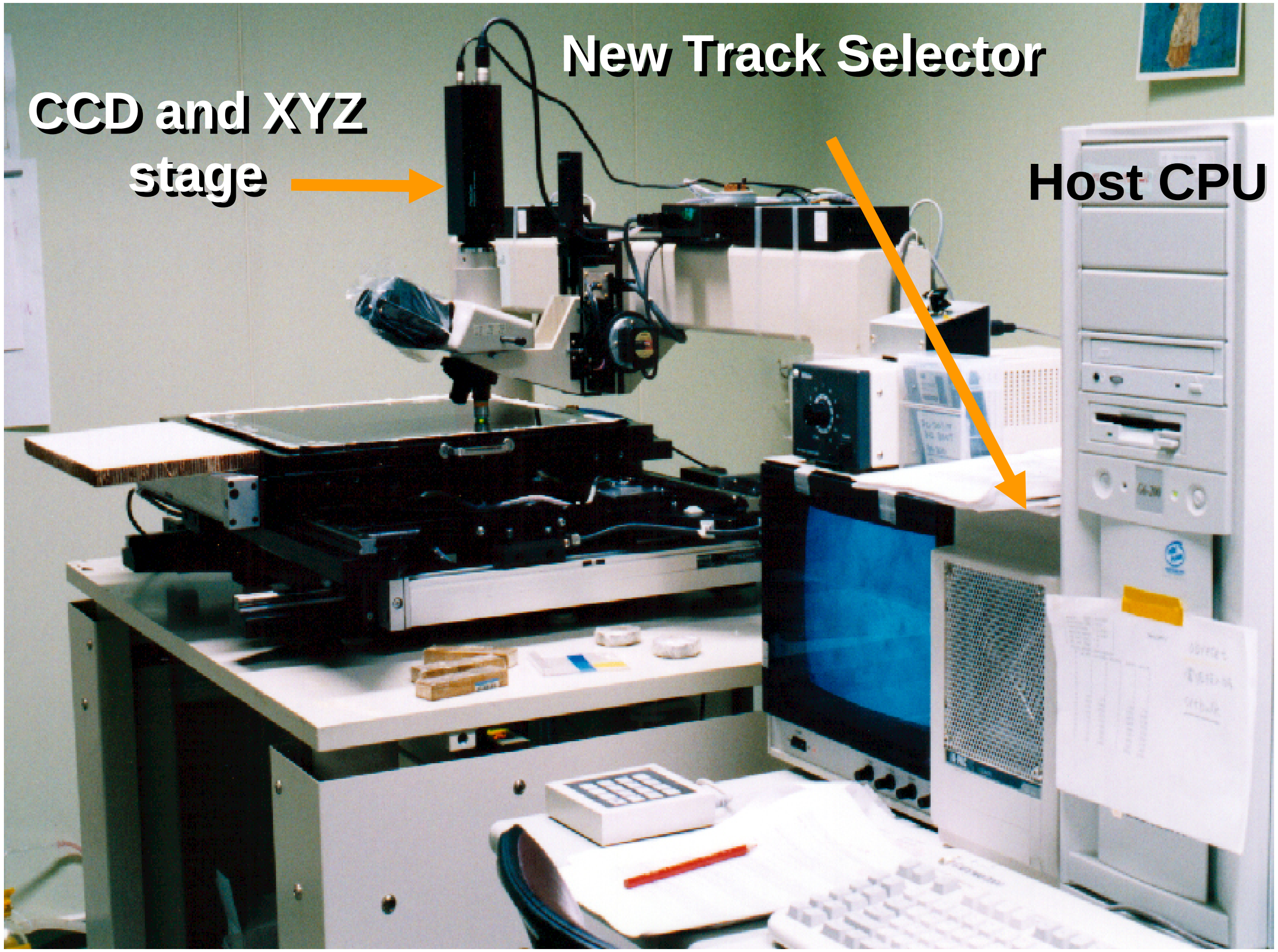
1/4 plate





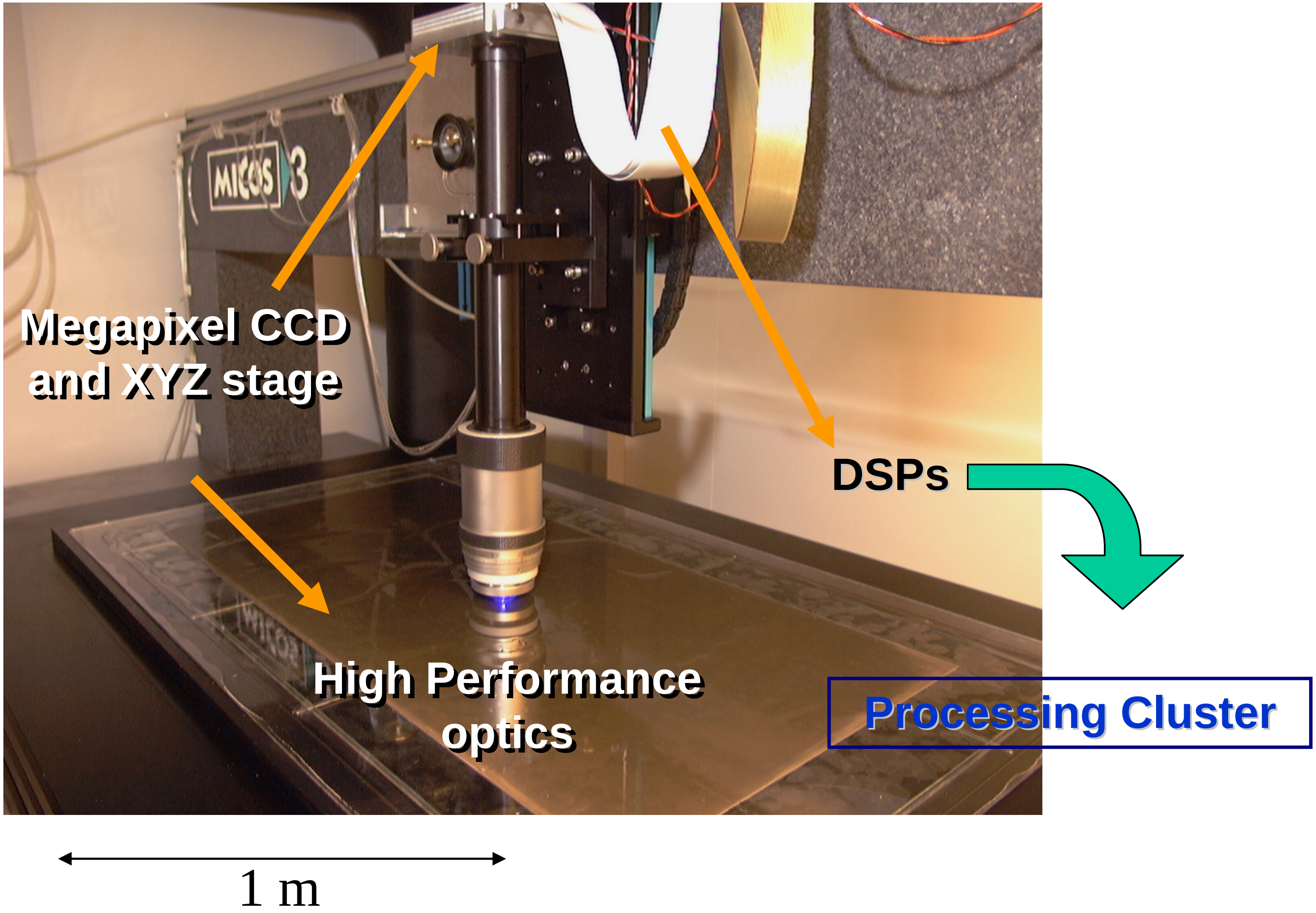
- Grain size ~ 0.3 mm
- Angular resolution ~ 1.5 mrad

CHORUS automatic microscopes



Network data storage

CHORUS automatic microscopes



Megapixel CCD and XYZ stage

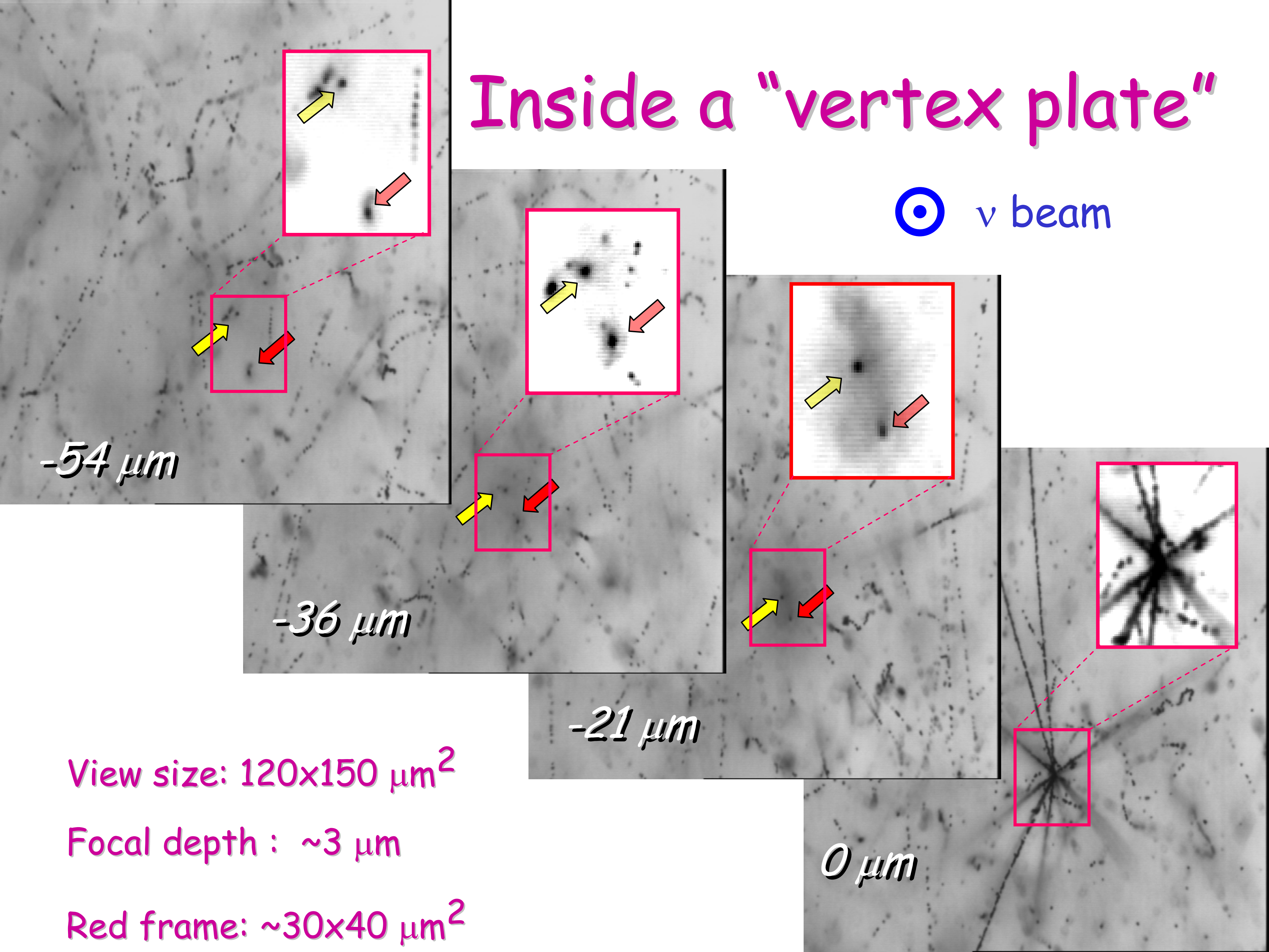
DSPs

High Performance optics

Processing Cluster

1 m

Inside a “vertex plate”



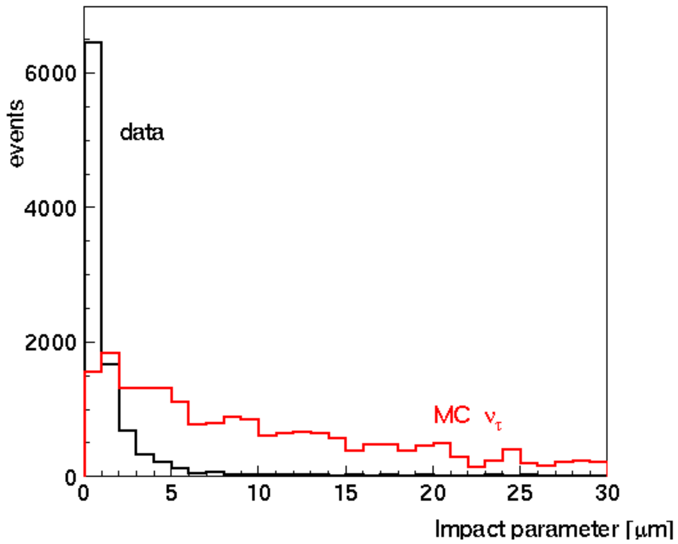
⊙ ν beam

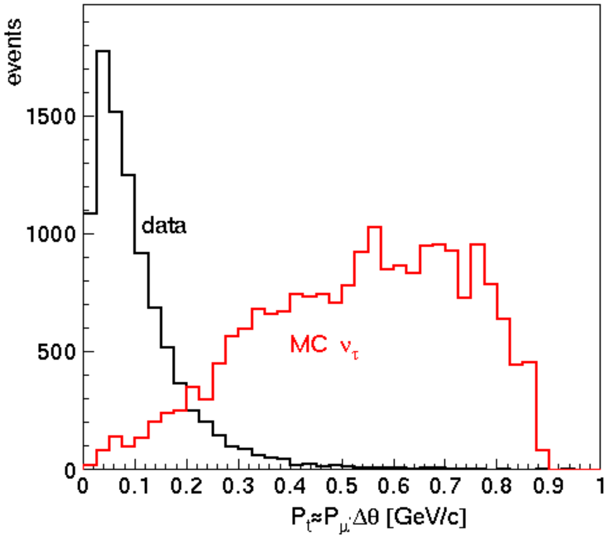
View size: 120x150 μm^2

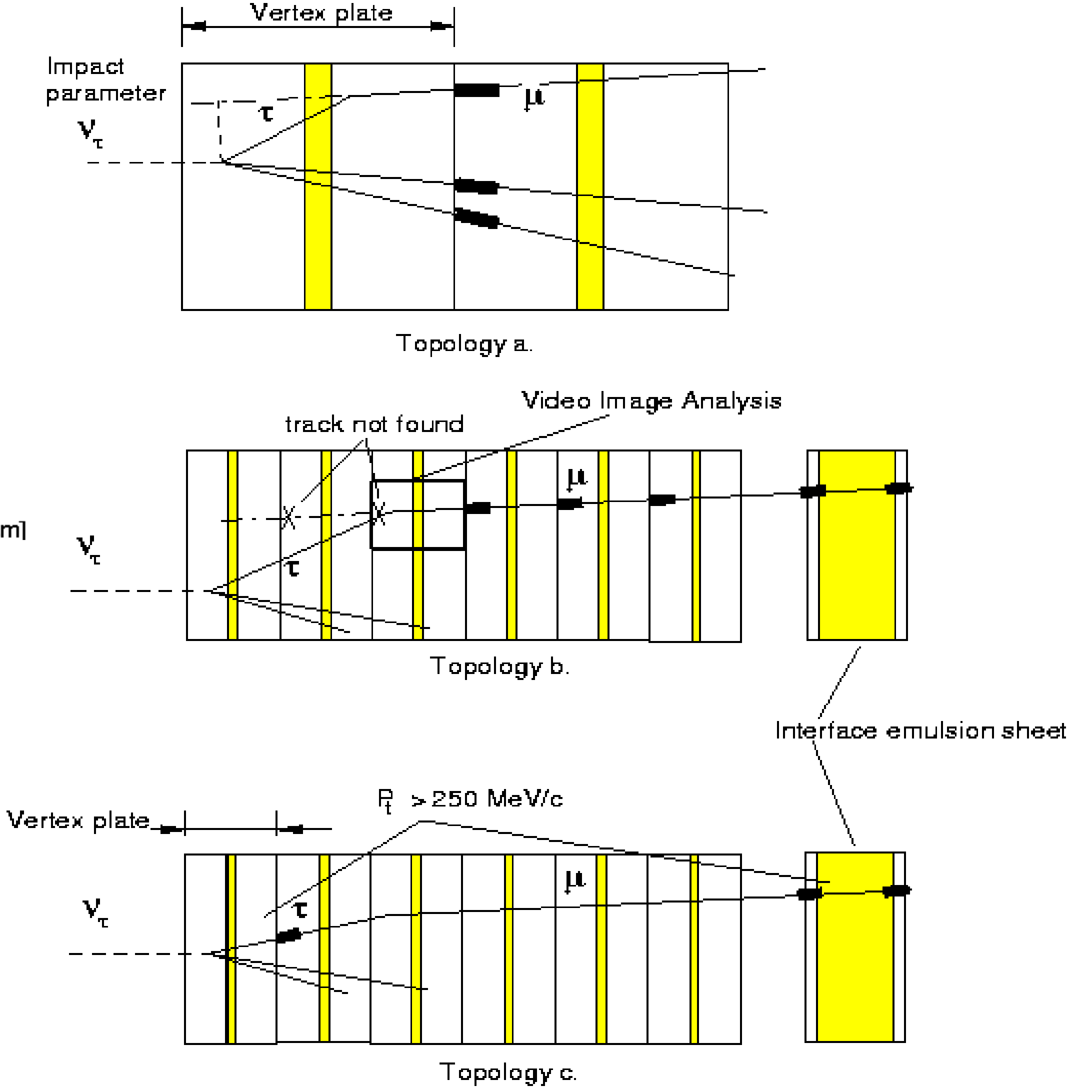
Focal depth : ~3 μm

Red frame: ~30x40 μm^2

Decay search







Topology a.

Topology b.

Topology c.

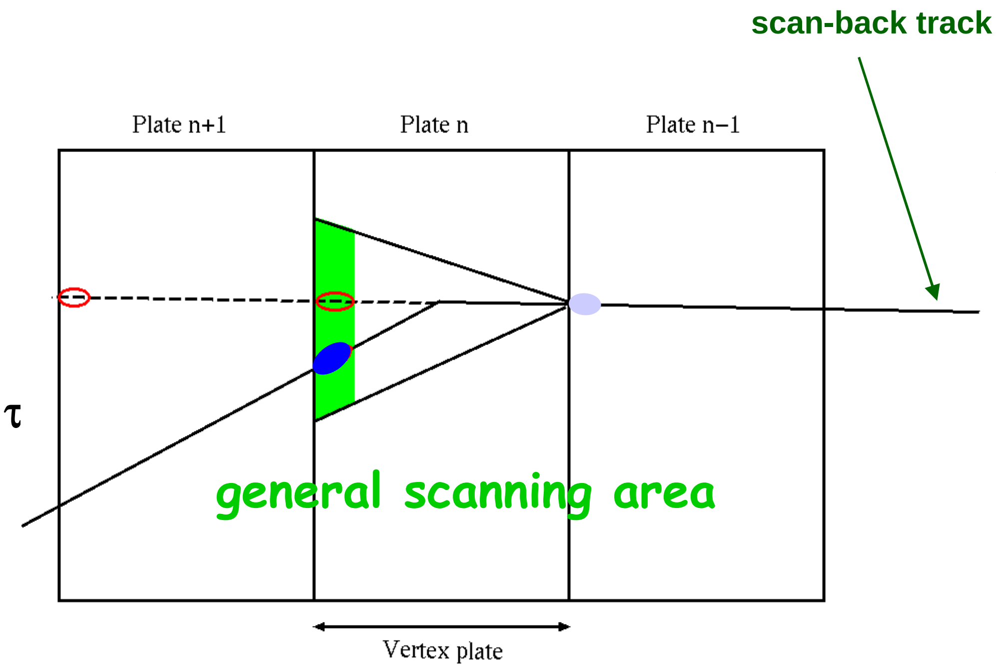
τ- kink detection
(*parent search*)

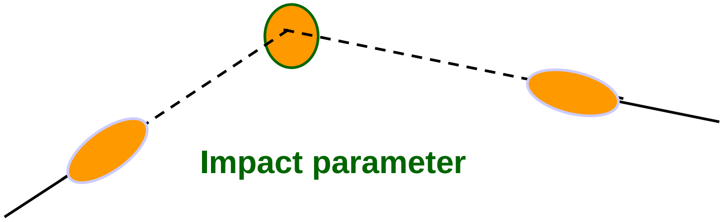
Principle:

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

Offline selection

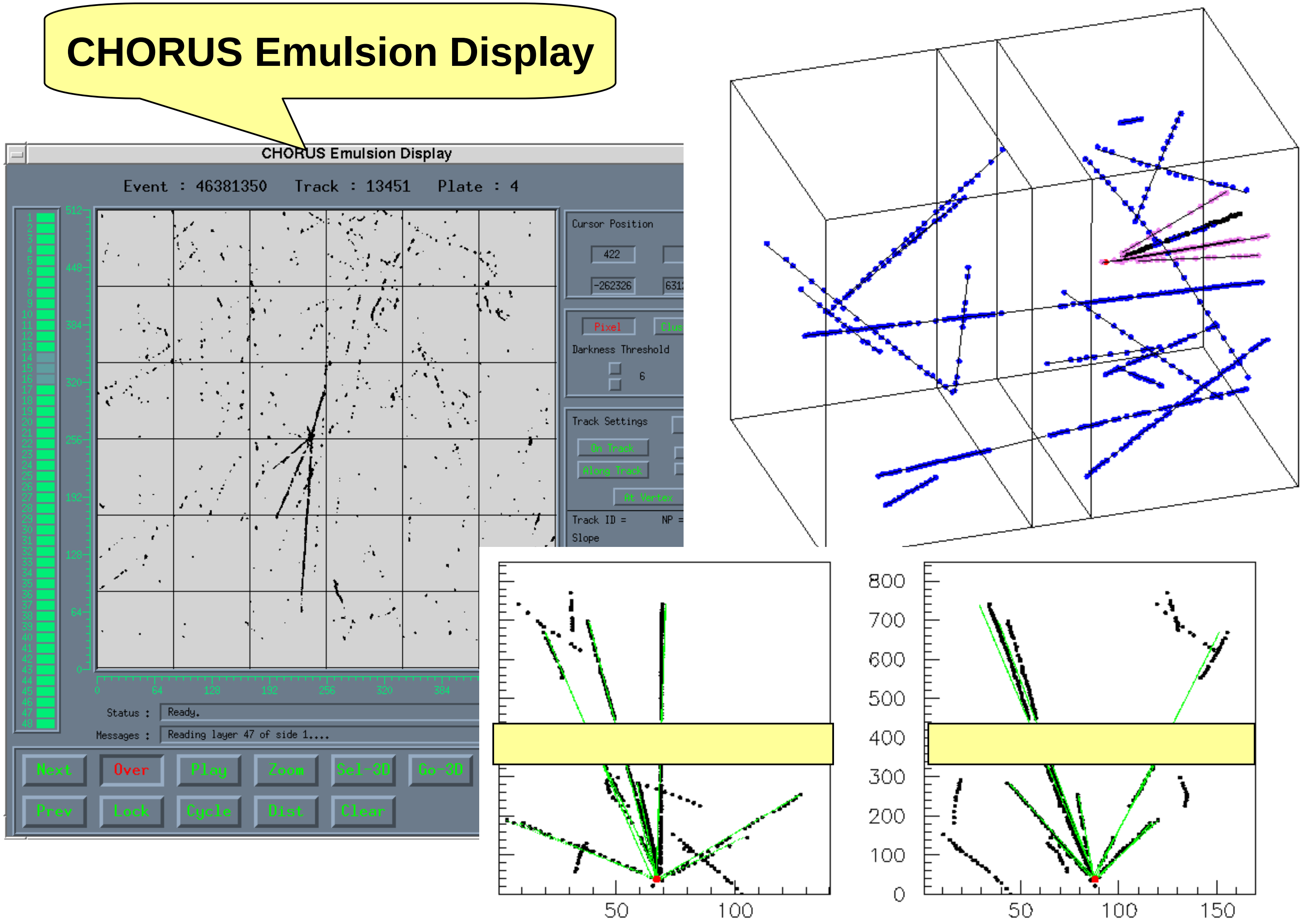
- **small impact parameter between parent and daughter**
- **kink point is in the vertex plate**





Off-line video-image analysis

CHORUS Emulsion Display



CHORUS Emulsion Display

Event : 46381350 Track : 13451 Plate : 4

Cursor Position

422

-262326

Darkness Threshold 6

Track Settings

Track ID =

NP =

Slope

Status : Ready.

Messages : Reading layer 47 of side 1....

Manual scanning on special events:

Diffractive D^*_s production, double leptonic decay

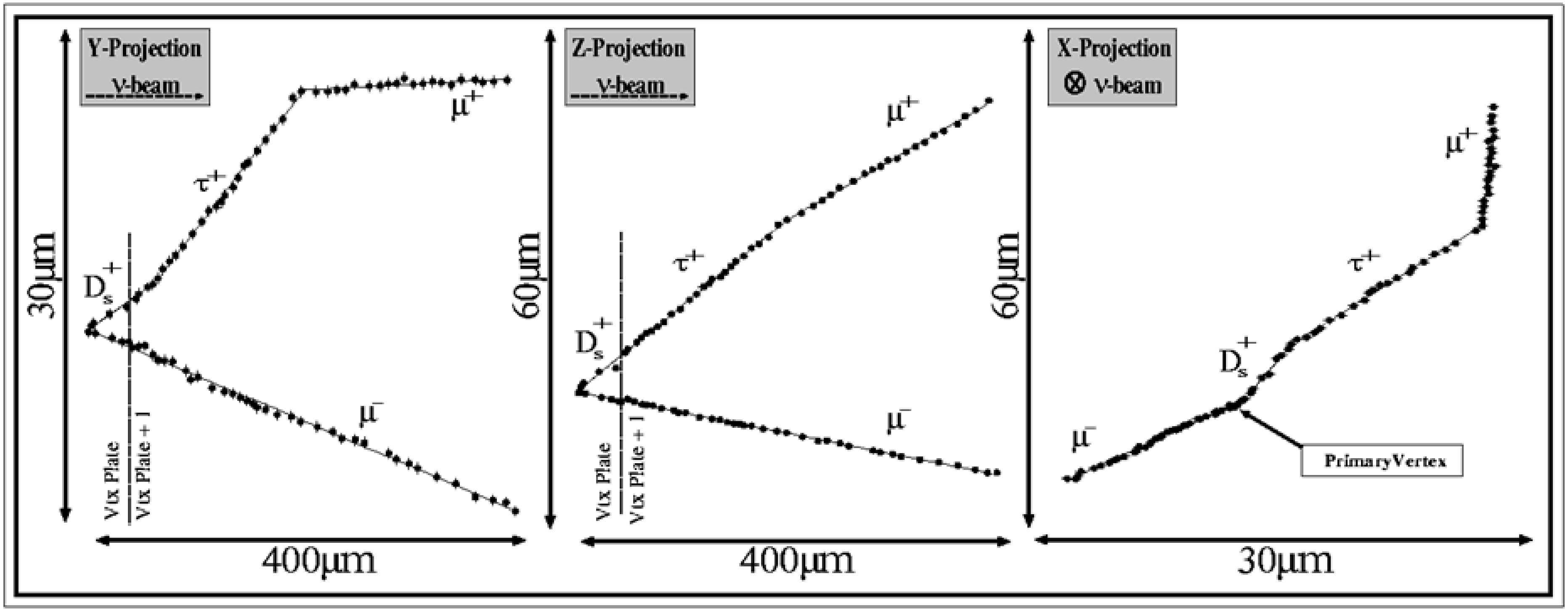
$$\nu_\mu N \to \mu^- \qquad D_s^{*+} N$$

$$\to D_s^+ \gamma$$

$$\to \tau^+ \nu_\tau$$

$$\to \mu^+ \nu_\mu \bar{\nu}_\tau$$

Phys. Lett. B 435(1998) 458-464.



Status of Phase I scanning

Year of exposure	1994	1995	1996	1997	All
Good emulsion	97%	73%	100%	100%	~93%
1μ to be scanned	66911	110916	129669	151105	458601
1μ scanned so far	69%	47%	76%	72%	66%
1μ vertex location and kink search	19581	21809	38919	45920	126229
0μ to be scanned	17731	27841	32548	37929	116049
0μ scanned so far	60%	48%	73%*	51%*	55%*
0μ vertex location and kink search	3491	4023	6758*	5164*	19436*

* *0μ decay search not finished yet (1996-1997), not included in current results*

τ Det efficiency:

Located Vertexes

$$S^{\tau\rightarrow\mu} = \frac{\sigma^{CC}_{\nu_\tau}}{\sigma^{CC}_{\nu_\mu}} \cdot \frac{A^{\tau\rightarrow\mu}}{A^{1\mu}} \cdot N^{1\mu} \cdot Br(\tau \rightarrow \mu) \cdot \eta^{\tau\rightarrow\mu}_{kink}$$

Ratio of Acceptances

	1994	1995	1996	1997
$N_{1\mu}$	19581	21809	38919	45920
r_σ	1.89	1.89	1.89	1.89
r_A	0.93	0.93	0.93	0.93
$\langle A_{\tau\mu}\rangle$	0.39	0.39	0.39	0.39
$\langle A_{\tau h}\rangle$	0.17	0.17	-	-
$\langle A_{\tau e}\rangle$	0.093	0.093	-	-
$\langle A_{\tau\not{\mu}}\rangle$	0.026	0.026	-	-
$\langle \varepsilon_{\tau\mu}\rangle$	0.53	0.35	0.37	0.37
$\langle \varepsilon_{\tau h}\rangle$	0.24	0.25	-	-
$\langle \varepsilon_{\tau e}\rangle$	0.12	0.13	-	-
$\langle \varepsilon_{\tau\not{\mu}}\rangle$	0.22	0.23	-	-
N_μ^{eq}	11987	14769	-	-

$S=N_\tau$ if $P_{\mu\tau}=1$

A=detector acceptance

$N^{1\mu}$=normalization

η=Kink finding efficiency

In the same way,
it is applied to
the 0μ sample

Background

- **1μ sample ($\tau^- \to \mu^-$)**
  - charm production from antineutrino CC (with primary lepton (e^+ or μ^+) unidentified

$$\begin{pmatrix}\bar{\nu}_\mu \\ \bar{\nu}_e\end{pmatrix} + N \to \begin{pmatrix}\mu^+ \\ e^+\end{pmatrix} + D^- + X \qquad \sim 10^{-6} / N^{1\mu}$$

$$\hookrightarrow \mu^- + neutrals$$

  - ν_τ contamination of the beam $\sim 10^{-7} / N^{1\mu}$

- **0 μ sample ($\tau^- \to h^-$)**
  - charm production from antineutrino CC $\sim 2 \cdot 10^{-6} / N^{1\mu}$
  - 1-prong nuclear interaction without visible recoil or nuclear break-up (White kinks) $\sim 2 \cdot 10^{-5} / N^{1\mu}$

Current Result

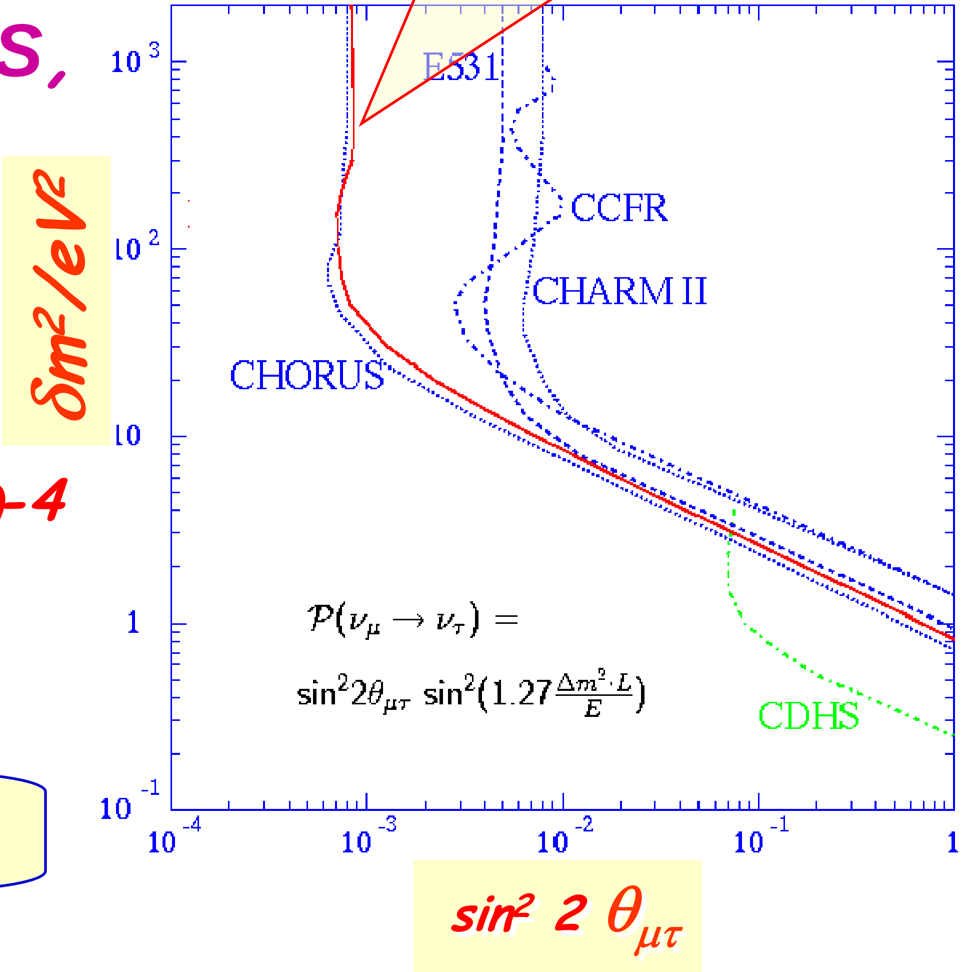
- No ν_τ candidates found
- $n^{\nu_\tau CC}$ (expected) = $P_{\mu\tau} \cdot S$,
- S = 6003 ± 17% (syst)
- $P_{\mu\tau} < 2.38 / 6003 = 4 \cdot 10^{-4}$

(@ 90% C.L.)

Includes also 17% systematic error (NIM A320 (1993) 331)

CHORUS current limit

$\sin^2 2\theta_{\mu\tau} < 8 \cdot 10^{-4}$



Outlook:

- **Phase I** scanning: Going to finish this year

  Expected gain in sensitivity:
  - ~1.2 from 1μ *(short decays, statistics)*
  - ~1.2 from 0 μ *(3prongs, 0 μ 96+97)*
- **Phase II** scanning and analysis: years 2000-2001
  - *New generation of automatic systems*
  - *Upgraded predictions*
  - *3prongs dedicated search*
  - τ → *e ? (electron id by MS in emulsion)*
  - *Full vertex analysis*
    (NETSCAN, General tracking) → *charm physics:* $|V_{cd}|^2$*,cc,D+/D0*

$P_{\mu\tau} < 1.0 \cdot 10^{-4}$ (in absence of τ-candidates)

THE NOMAD EXPERIMENT

◆ *The NOMAD experiment is based on a fine-grained* **ELECTRONIC DETECTOR** *optimized for:*

- *particle identification (e,μ of both signs);*
- *accurate measurement of momenta and energies of particles (charged and neutral) produced in ν interactions.*

$\Longrightarrow$ *good reconstruction of kinematics & event topology.*

◆ *The detector is a* **TRACKING & CALORIMETRY** *device with the following properties:*

- *large mass to maximize neutrino interactions (2.7 tons);*
- *low target density to minimize reinteractions: the average density is $0.1\ g/cm^3$ ($0.07\ g/cm^3$ for liquid hydrogen);*
- *high resolution apparatus allowing fine measurements.*

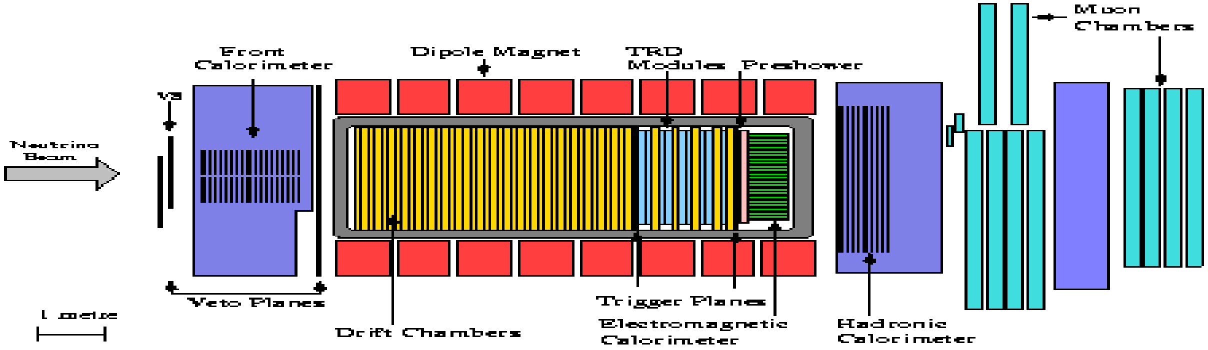
$\Longrightarrow$ *"electronic bubble chamber" with high statistics data.*

◆ *Although originally conceived for the $\nu_\mu \longrightarrow \nu_\tau$ search, NOMAD is suitable for different* **PHYSICS TOPICS***:*

- *ν_τ appearance search;*
- *ν_e appearance search (LSND at large Δm^2);*
- *search for rare phenomena: axion search, new gauge boson search, Karmen anomaly etc.;*
- *study of particle production in ν interactions.*

$\Longrightarrow$ *general purpose detector for neutrino physics.*

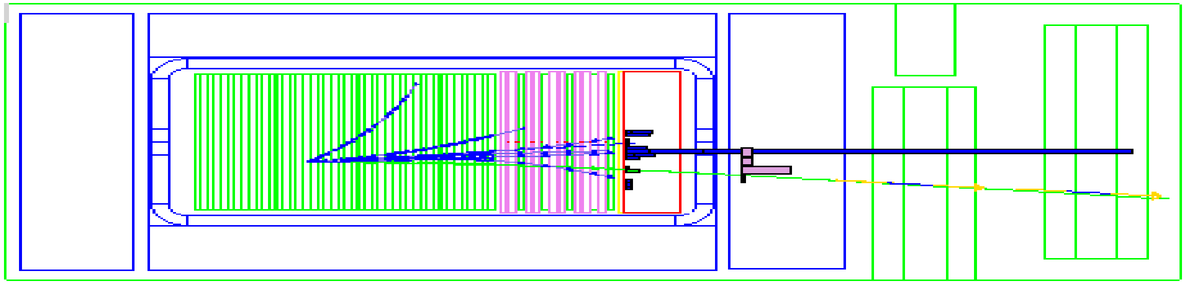
THE DETECTOR



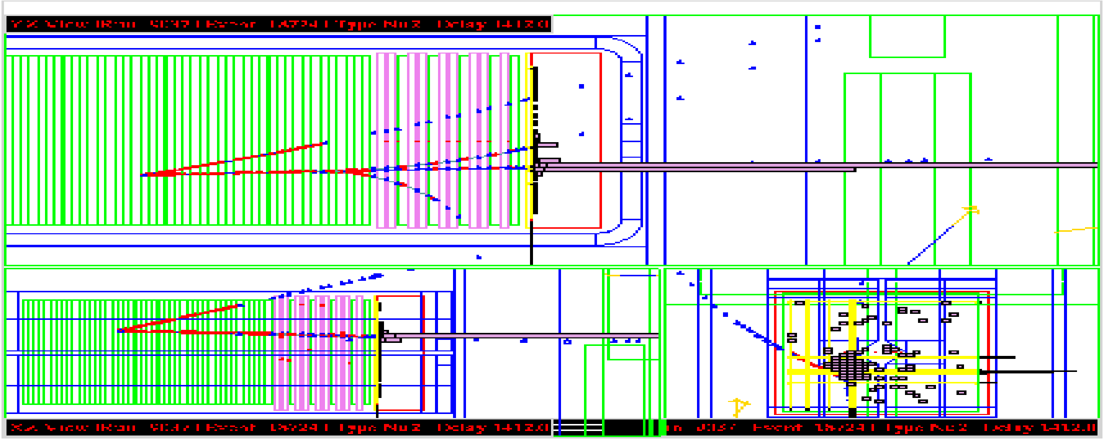
TRIGGER: $\overline{V}$ T_1 T_2

- **Drift Chambers** (target and momentum measurement)
  Fiducial mass 2.7 tons *with average density* $0.1 g/cm^3$
  44 chambers + 5 chambers in TRD region
  Momentum resolution $\sim 3.5\%$ $(p < 10 GeV/c)$
- **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)
  $\sigma(E)/E = 3.2\%/\sqrt{E[GeV]} \oplus 1\%$
- **Preshower** (e and γ detection)
  Additional π *rejection* $\sim 10^2$ *for electron efficiency* $\geq 90\%$
  Precise γ *position measurement* $\sigma(x), \sigma(y) \sim 1 cm$
- **Hadronic Calorimeter** (n and K_L^0 veto)
- **Muon Chambers for** $\mu^\pm$ identification
  $\epsilon \sim 97\%$ *for* $p_\mu > 5 GeV/c$
- **Front Hadronic Calorimeter (FCAL)**
  Extra 17.7 tons *target.*
- *Detailed description in Nucl. Instr. Meth. A404 (1998) 96.*

ν_μ CC candidate (run 8744, event 228)



ν_e CC candidate (run 9037, event 18724)



Data sample	ν_μ CC interactions
1995	190,000
1996	409,000
1997	427,000
1998	328,000
Total 1995-98	1,354,000

THE ν_τ SEARCH

- APPEARANCE experiment.
  ν_τ is detected by CC interactions $\nu_\tau + N \longrightarrow \tau^- + X$

- INDIRECT τ identification through its secondary visible decay products:

$$\tau^- \longrightarrow \begin{cases} e^- \bar{\nu}_e \nu_\tau & 17.8\% \\ h^- (n\pi^0)\,\nu_\tau & 49.8\% \\ \pi^- \pi^- \pi^+ (n\pi^0)\,\nu_\tau & 15.2\% \end{cases}$$

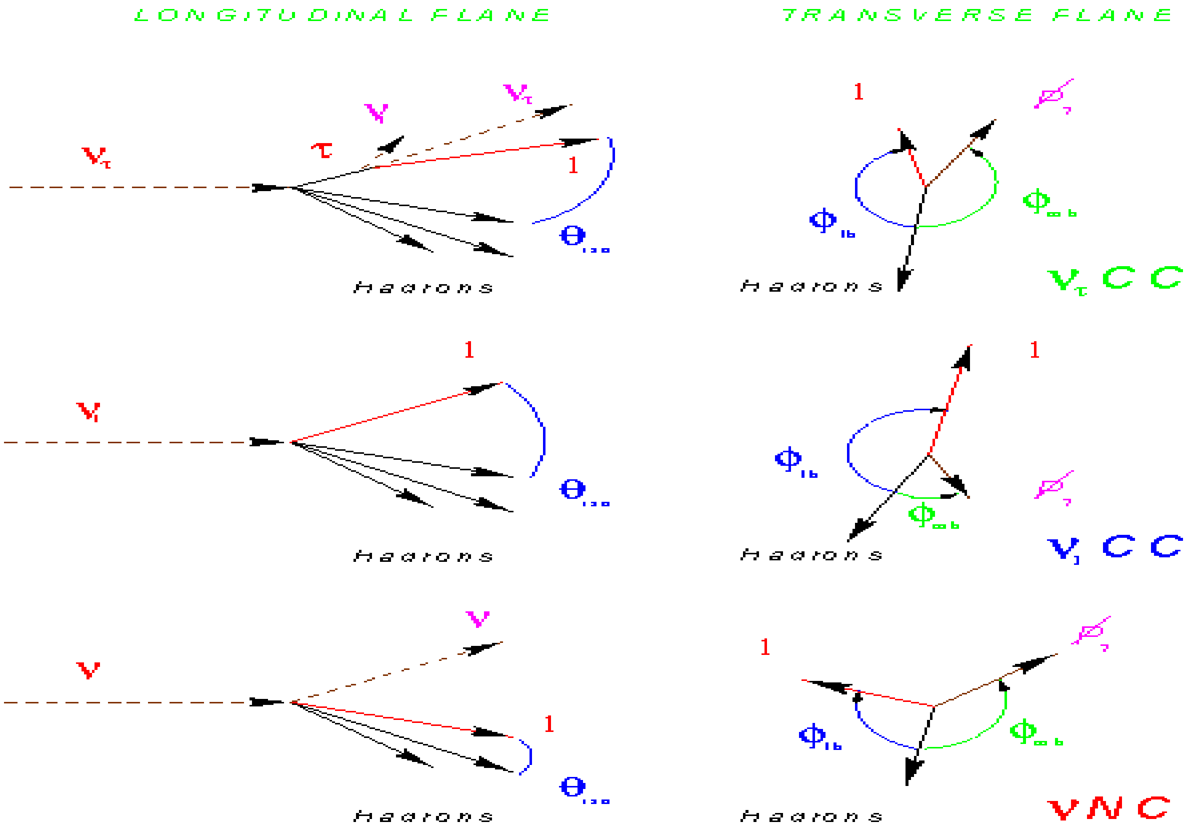
Total 82.8%

- The signal is extracted from the tails of the background distributions by means of KINEMATIC CRITERIA
  $\Longrightarrow$ $\varepsilon_\tau \sim 1 \div 4\%,\ \varepsilon_{BKG} \sim 10^{-4} \div 10^{-6}$.

- A ν_τ signal will appear as a STATISTICAL EXCESS of events in the interesting kinematic regions:
  - background from ordinary ν interactions;
  - ambiguous events;
  - good control on background predictions is required.

  $\Longrightarrow$ relies on BACKGROUND SUBTRACTION.

III The signal ν_τ CC has intermediate properties between the two backgrounds:



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

$\nu_\mu \rightarrow \nu_\tau$ SEARCH

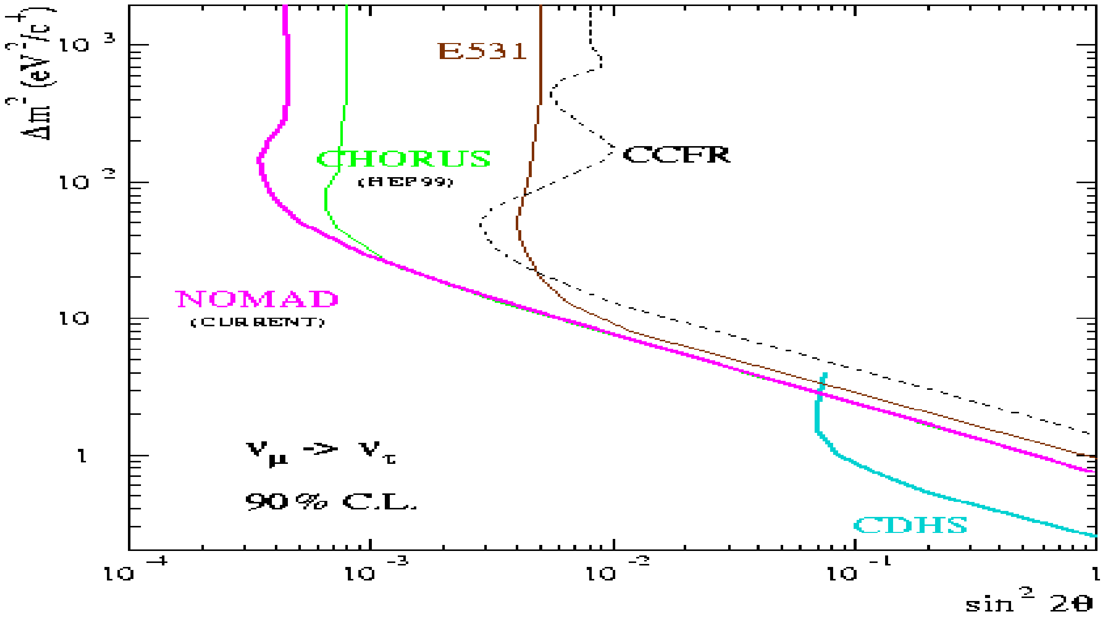
Decay channel			BR(%)	τ^- search Obs.	 Tot. bkg.	τ^+ search Obs.	 Tot. bkg.	ϵ(%)	$N^\tau_{P=1}$
$\nu_\tau \bar{\nu}_e e$		DIS	17.8	5	$5.3^{+0.7}_{-0.5}$	9	8.0 ± 2.4	3.6	4110
$\nu_\tau h(n\pi^0)$	ρ	DIS	49.8	7	9.3 ± 2.5	6	5.6 ± 1.5	1.04	3307
	h	DIS	49.8	5	6.8 ± 2.1	19	16.0 ± 4.0	0.63	2022
	h/ρ	DIS	49.8	1	$0.0^{+0.74}_{-0.0}$			0.07	210
$\nu_\tau 3h(n\pi^0)$		DIS	15.2	9	9.6 ± 2.4	6	6.9 ± 2.5	1.9	1820
$\nu_\tau \bar{\nu}_e e$		LM	17.8	6	5.4 ± 0.9	3	2.2 ± 0.5	6.3	859
$\nu_\tau h(n\pi^0)$	ρ	LM	49.8	7	5.2 ± 1.8	21	22.2 ± 6.6	1.02	458
	h	LM	49.8	5	6.7 ± 2.3	19	21.9 ± 6.4	0.84	357
$\nu_\tau 3h(n\pi^0)$		LM	15.2	5	3.5 ± 1.2	1	2.2 ± 1.1	2.0	288
Total			82.8	50	51.8 ± 5.3	84	85.0 ± 10.7	2.4	13431

- NO EVIDENCE for oscillations since in all available decay modes & signal bins the number of observed events is compatible with background predictions

  $\Longrightarrow$ the final result is obtained by combining directly the individual modes & bins

- The systematic uncertainty is 10 % for the signal and 20 % for the background

- Results 1995-1998 to be submitted for publication (details in Phys. Lett. B453 (1999) 169).



- *The* $\boxed{\text{UPPER LIMIT}}$ *at 90% C.L. obtained on the corresponding $\nu_\mu \to \nu_\tau$ oscillation probability is:*

$$P_{\mu\tau} \leq 2.2 \times 10^{-4} \qquad \sin^2 2\theta_{\mu\tau} \leq 4.4 \times 10^{-4}$$

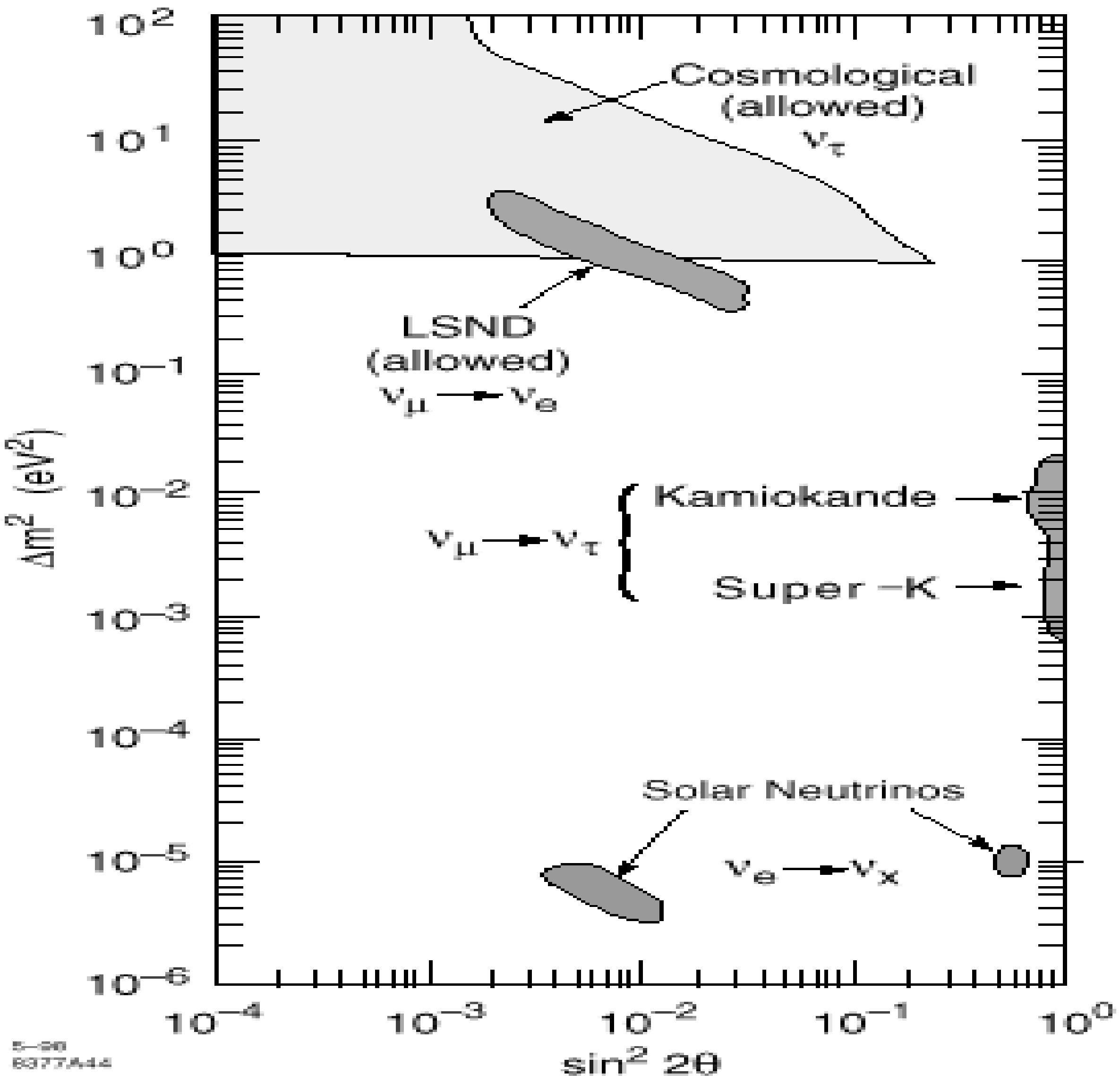
at large Δm^2 and the confidence region includes:

$$\Delta m^2_{\mu\tau} \leq 0.8 \;\; eV^2/c^4$$

- *The probability of obtaining the actual NOMAD limit or a lower one, given the sensitivity $S = 4.3 \times 10^{-4}$, is:*

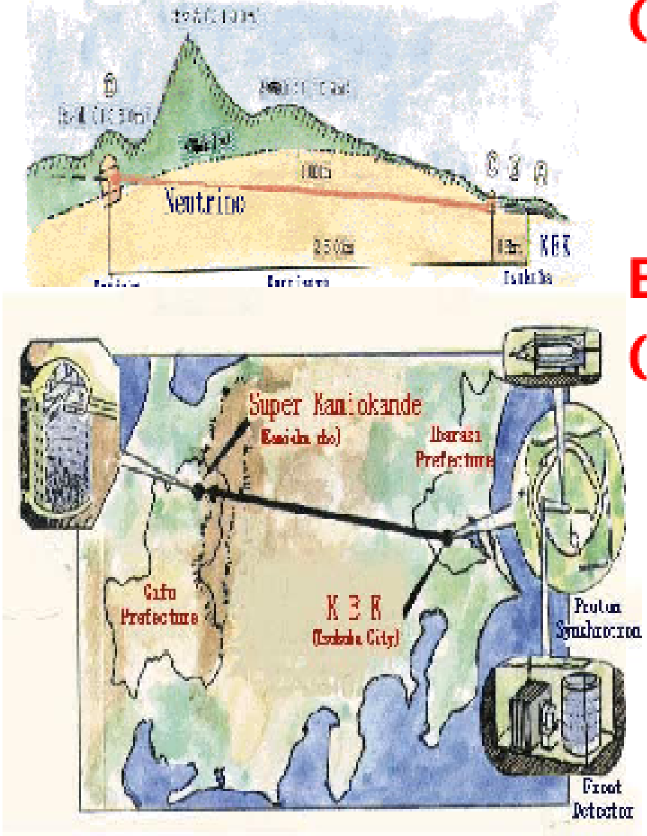
$$P(\leq 2.2 \times 10^{-4}) \;\; = \;\; 27 \pm 2\%$$

What to dofurther with accelerator beams?

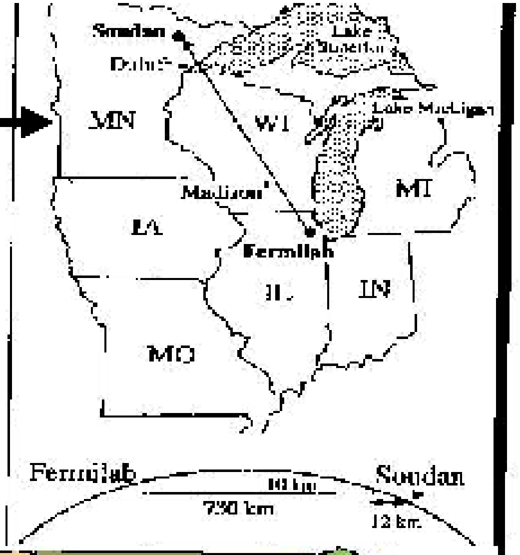


Long baseline experiments

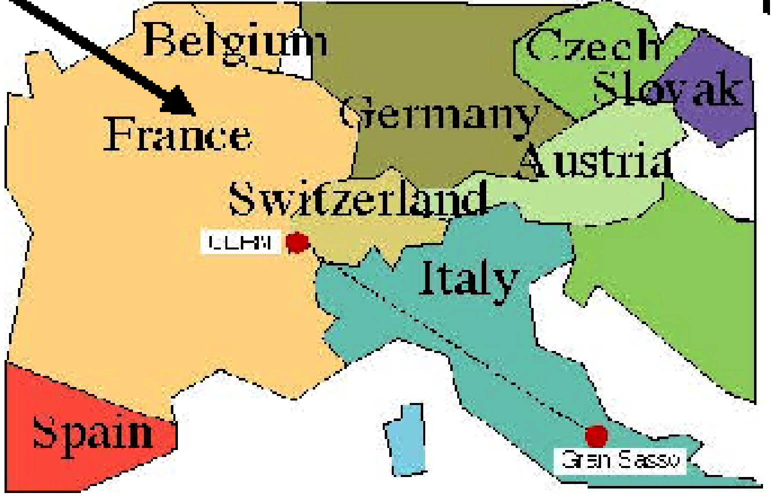
Japan: K2K
(250 km)



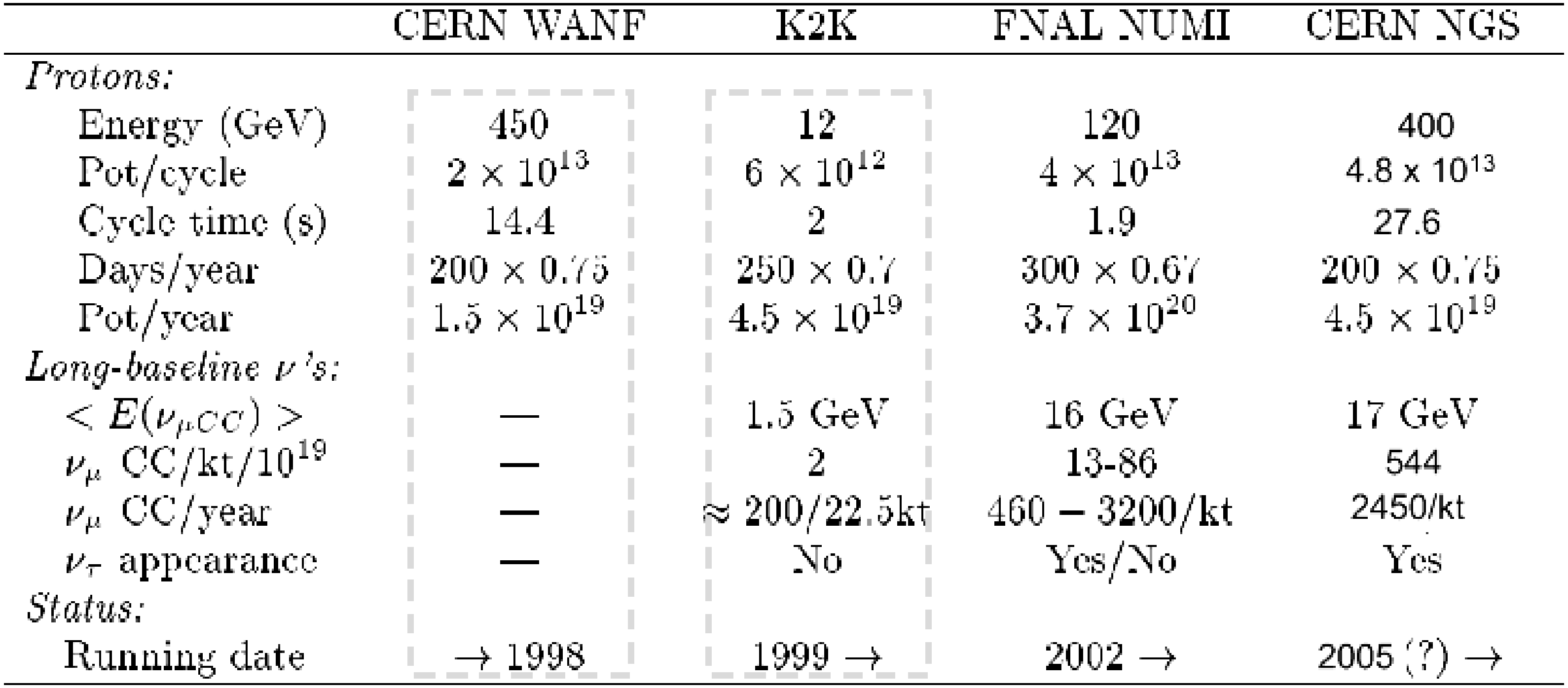
USA: NUMI
(732 km)



Europe: NGS
(732 km)

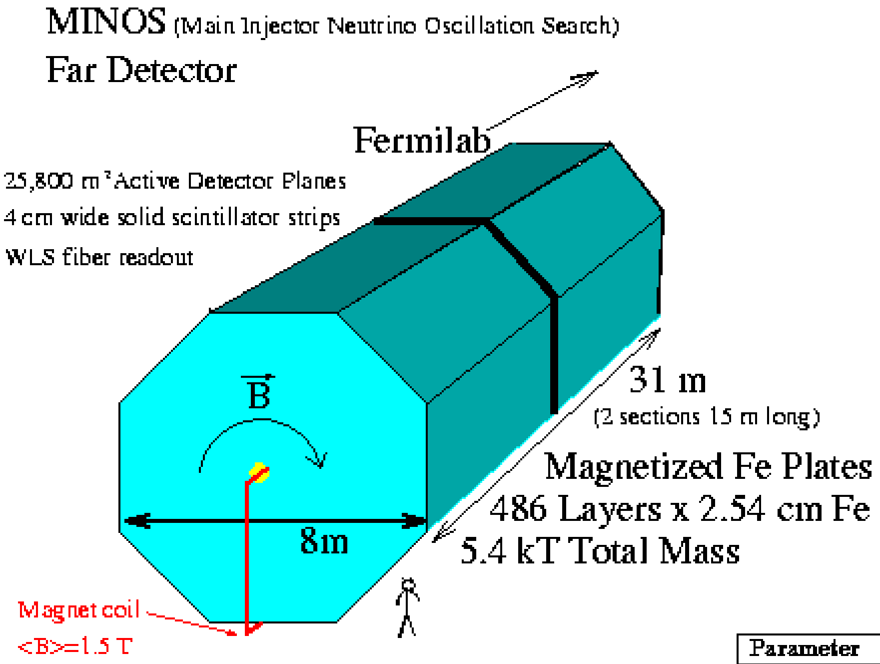


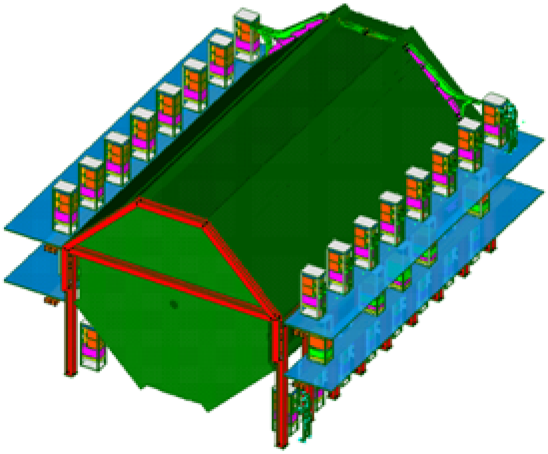
Long base line beams compared to WANF



	CERN WANF	K2K	FNAL NUMI	CERN NGS
Protons:				
Energy (GeV)	450	12	120	400
Pot/cycle	2×10^{13}	6×10^{12}	4×10^{13}	4.8×10^{13}
Cycle time (s)	14.4	2	1.9	27.6
Days/year	200×0.75	250×0.7	300×0.67	200×0.75
Pot/year	1.5×10^{19}	4.5×10^{19}	3.7×10^{20}	4.5×10^{19}
Long-baseline ν's:				
$< E(\nu_{\mu CC}) >$	—	1.5 GeV	16 GeV	17 GeV
ν_μ CC/kt/10^{19}	—	2	13-86	544
ν_μ CC/year	—	$\approx 200/22.5$kt	$460 - 3200$/kt	2450/kt
ν_τ appearance	—	No	Yes/No	Yes
Status:				
Running date	→ 1998	1999 →	2002 →	2005 (?) →

MINOS detector

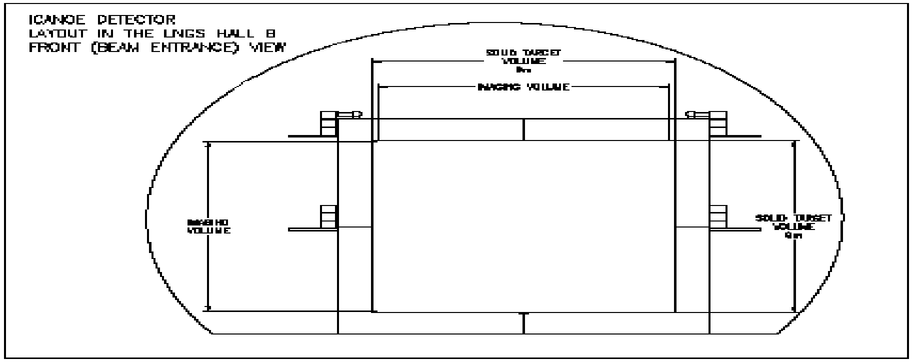


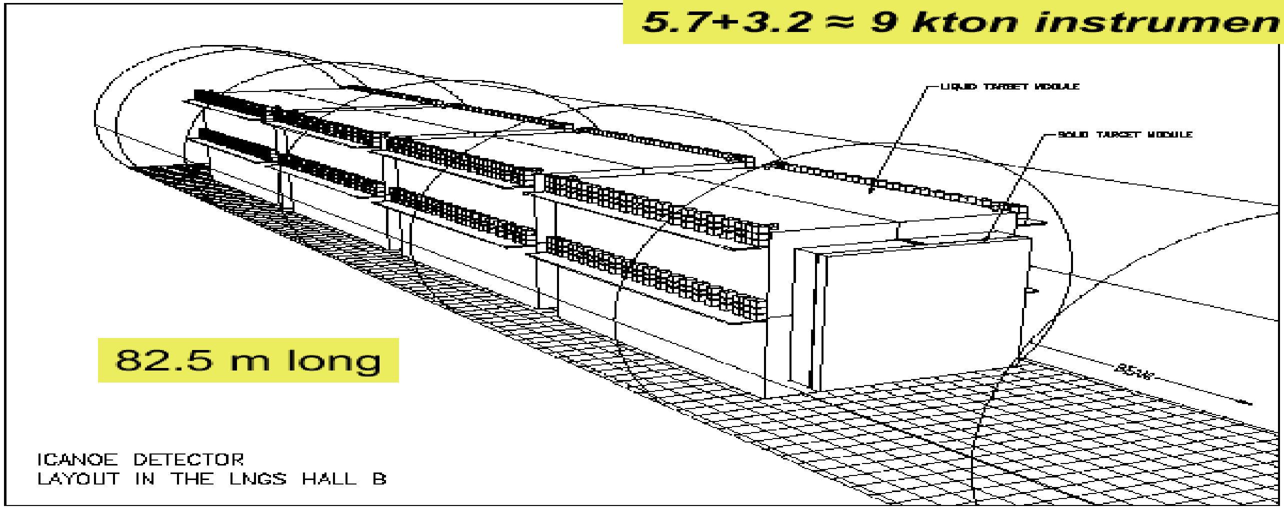


Parameter	Value
Near detector mass	0.98 (metric) kt total, 0.1 kt fiducial
Far detector mass (2 supermodules)	5.4 (metric) kt total, 3.3 kt fiducial
Steel planes (far detector)	8-m wide, 2.54-cm thick octagons
Magnetic field (far detector)	Toroidal, 1.5 T at 2 m radius
Active detector planes	Extruded polystyrene scintillator strips
Active detector strips	4.1-cm wide, 1-cm thick, ~8-m long
Near detector distance from decay pipe	290 m
Far detector distance from decay pipe	730 km
Cosmic ray rates	270 Hz in near det., 1 Hz in far det.
Neutrino energy range (3 configurations)	1 to 25 GeV
Detector energy scale calibration	5% absolute, 2% near-far
Detector EM energy resolution	$23\%/\sqrt{E}$ (<5% constant term)
Detector hadron energy resolution	$60\%/\sqrt{E}$ (<7% constant term)
Detector muon energy resolution	<12% (from curvature or range)
NC-CC event separation	Efficiency >90%, correctable to 99.5%
Electron/π separation	Hadron rejection $\sim 10^2$ for $\epsilon_e \sim$20%
Far det. ν event rate (high-energy beam)	3000 ν_μ CC events/kt/yr (no oscillations)
Near det. ν event rate (high-energy beam)	20 events/spill in target region
Near-far relative rate uncertainty	2%

ICANOE detector

- **Liquid target:**
  - → 1.4(1.9)kton active (total) mass
  - →external dimensions 11.3x11.3x18.0 m^3
- **Solid target:**
  - →Magnetized calorimeter module, 9x9x2.6 m^3 (2 meter of Fe)
  - →0.8 kton mass
- **Supermodule:**
  - →Joining 1 liquid + 1 solid target, i.e. 2.6kton
  - →***"Expandable"***

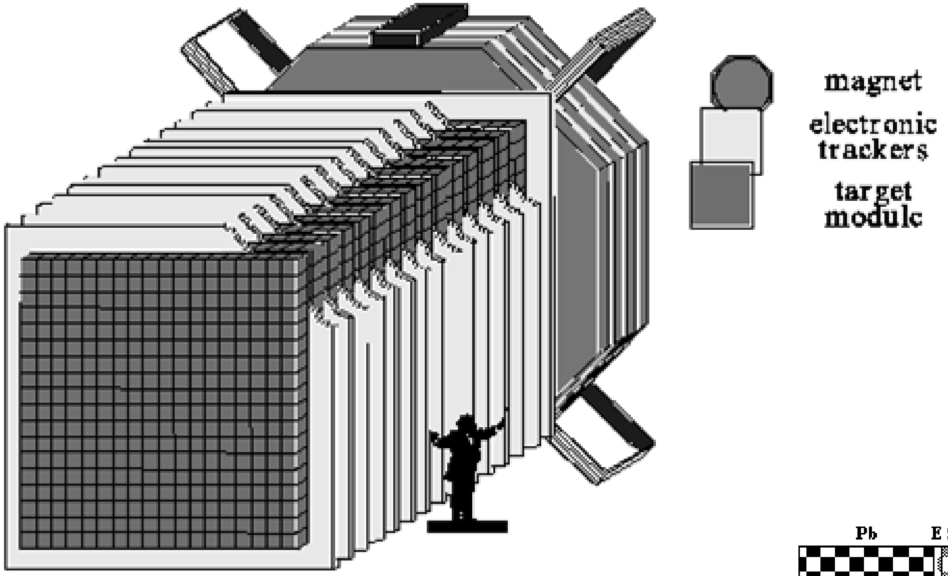




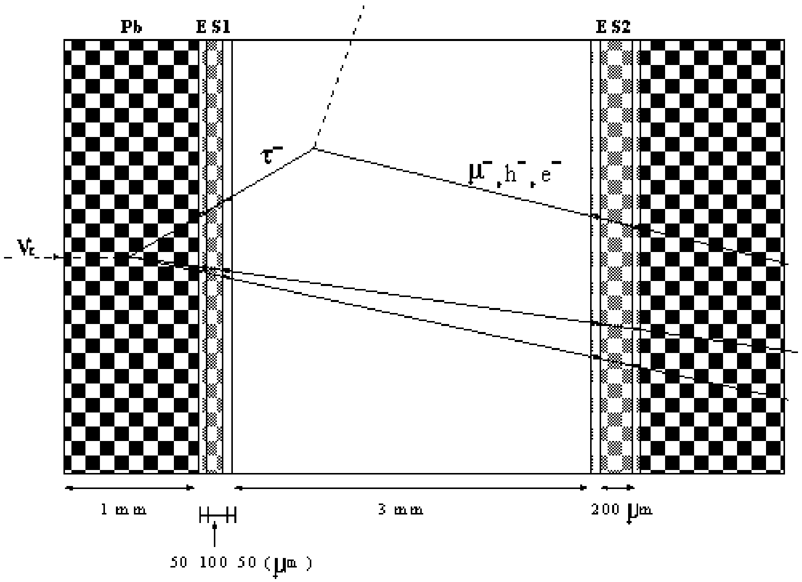
5.7+3.2 ≈ 9 kton instrumented

82.5 m long

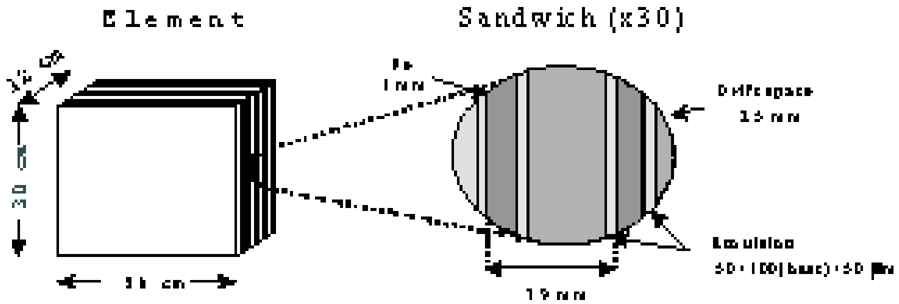
OPERA detector

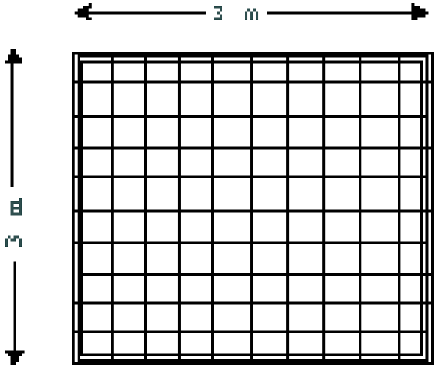


200 ton iron/emulsion sandwiches + muon identificator



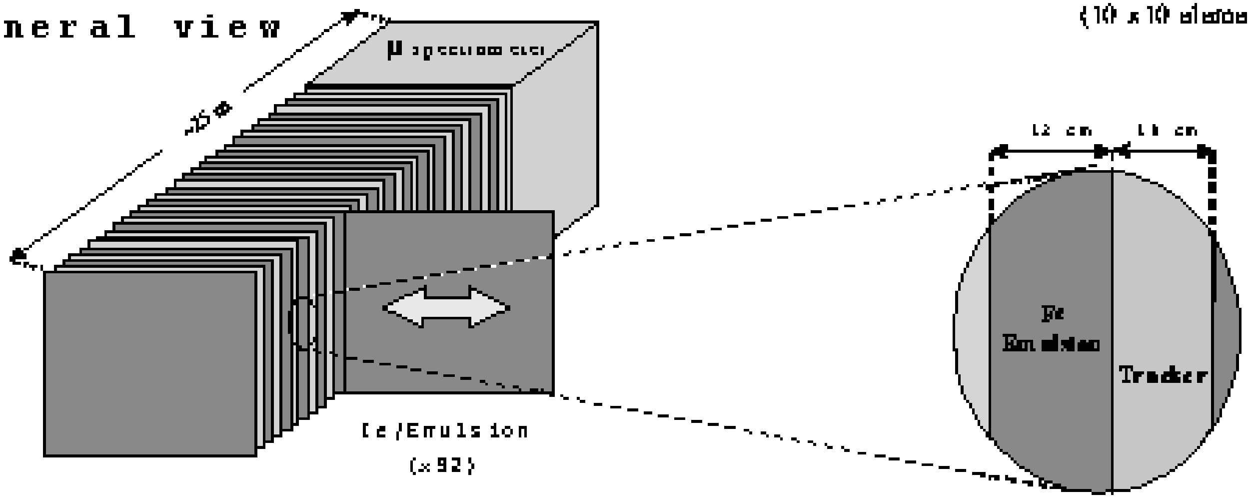
OPERA module





Fe / Emulsion Module
(10 x 10 elements)

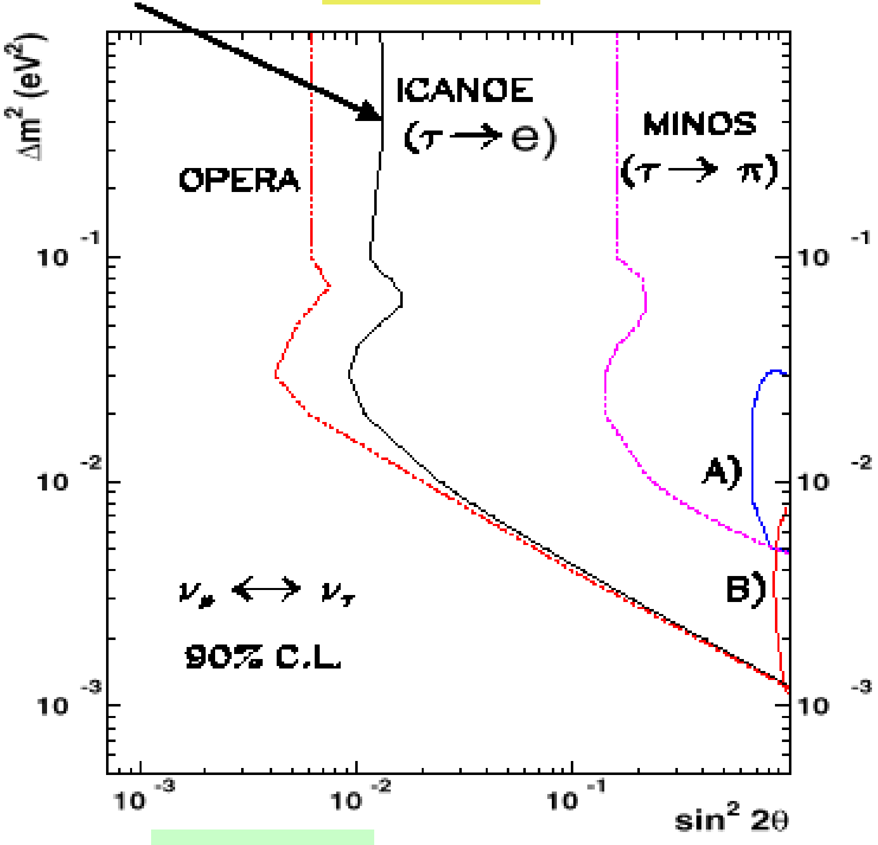
General view



Long baseline experiments' claims ...

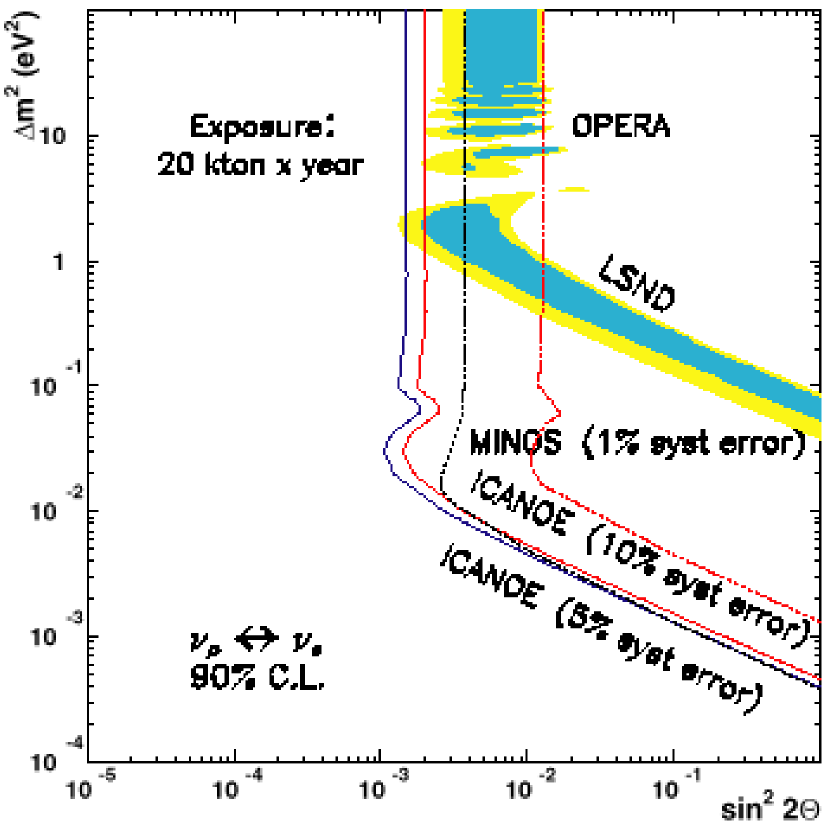
High Δm^2 further improved by inclusion of hadronic channels

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



4 years

$\nu_\mu \to \nu_e$



(MINOS high energy beam (PH2high) configuration, NUMI-L228 & TDR)
(OPERA, CERN/SPSC 99-20)
(ICANOE, tau appearance, electron channel only, optimized for low Δm^2)

Conclusion

- Current short baseline accelerator searches for $\nu_\mu \rightarrow \nu_\tau$ oscillations have almost done their job;
- No oscillations seen (so far) for large δm^2 and small mixing angles;
- Atmospheric neutrino data suggest, on the opposite, small mass difference and large mixing angle;
- Several long baseline accelerator experiments are on the start scratch to clarify the issue...