Neutrino Physics
at
CERN and Gran Sasso

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OUTLINE

I *Introduction*

- *Why neutrinos?*
- *Neutrino oscillations*

II *The SBL experiments at CERN*

- *Motivations for SBL*
- *The WANF neutrino beam*
- *Detectors & data samples*
- *The ν_τ search*

III *The LBL program at Gran Sasso*

- *Motivations for LBL*
- *The CNGS neutrino beam*
- *The proposed detectors*
- *The ν_τ search*

IV *Outlook and conclusions*

I

Introduction

WHY NEUTRINOS?

- *Neutrinos have already given foundamental contributions to the assesment of Standard Model (NC discovery, first determination of $\sin^2\theta_W$ etc.).*

- BRIGHT SIDE

  Neutrinos produce very clean interactions, which can be potentially used for precision physics:

  - *switch off all but weak interaction;*
  - *fully polarized;*
  - *sensitivity to GUT and new physics.*

  $\Longrightarrow$ *excellent laboratory probe.*

- DARK SIDE

  Neutrinos are *largely unknown particles:*

  - *mass (if any)?*
  - *properties (Fermi, Majorana etc.)?*
  - *tiny cross-section with matter.*

  $\Longrightarrow$ *still many things to learn.*

EXPERIMENTAL ISSUES

- The main difficulty to overcome for neutrino experiments is STATISTICS, due to the small probability of interaction with matter. Two options are possible:
  - massive detectors
    $\Longrightarrow$ difficult to keep high resolution at reasonable cost.
  - large fluxes
    $\Longrightarrow$ long running time and/or high intensity beams.

Experiment	Target mass	Exposure p.o.t.	Statistics ν_μ CC	Technique
CDHS	750 t	5.2×10^{18}	$\boxed{10^7}$	massive calo
CHARM II	547 t	9.0×10^{18}	$\boxed{10^7}$	massive calo
BBC	various	various	5.7×10^4	bubble ch.
E531	91 kg	2.0×10^{19}	3.8×10^3	emulsions
CCFR	690 t		$\boxed{0.6\times10^6}$	massive calo
NuTeV	690 t	1.3×10^{18}	$\boxed{1.3\times10^6}$	massive calo
Super-K	22.5 kt	–	6.8×10^3	water Ceren.
SNO	1.0 kt	–	1.1×10^3	D_2O

- So far, the word "precision" for neutrinos means the % level, in the best cases.

NEUTRINO OSCILLATIONS

- In general, if $m_\nu \neq 0$, neutrinos can have different weak (ν_e,ν_μ,ν_τ) and mass (ν_1,ν_2,ν_3) eigenstates, which are then related, in analogy to the quarks, by the relationship:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

where U is a unitary matrix: complex phase $\Longrightarrow$ $\not{C}\not{P}$

- The oscillation $\nu_\alpha \longrightarrow \nu_\beta$ has a $\boxed{\text{PROBABILITY}}$:

$$P(\nu_\alpha \to \nu_\beta) \; = \; \delta_{\alpha\beta} - 4 \sum_{i=1}^{3} \sum_{j>i}^{3} U_{\alpha i} U_{\beta i} U^*_{\alpha j} U^*_{\beta j} \sin^2 \left(\pi \frac{L}{\lambda_{osc}} \right)$$

where L is the distance from the neutrino source (Km) and the oscillation length λ_{osc} is defined as:

$$\lambda_{osc} \;\stackrel{\text{def}}{\equiv}\; \frac{2.48 \; E}{\Delta m^2_{ij}}$$

with $\Delta m^2_{ij} \equiv \mid m_i^2 - m_j^2 \mid$ (eV^2) and E ν energy (GeV).

- Only $\boxed{\text{TWO } \Delta m^2_{ij}}$ are independent. Thus if there are three different mass scales from experiments there must be:
  - a massive sterile neutrino;
  - at least one mass scale not correctly determined:
    - superposition of oscillation patterns;
    - wrong interpretation.

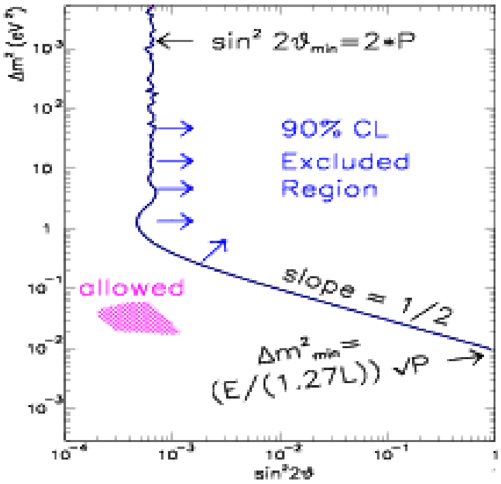
◆ *If different mass scales, oscillations will decouple and can be approximated by a* TWO-NEUTRINO *oscillation:*

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

and the probability of oscillation becomes:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\pi \frac{L}{\lambda_{osc}}\right)$$

◆ *Results are presented in the* PLANE $(\sin^2 2\theta, \Delta m^2)$, *the TWO independent parameters which define the mixing:*



- *Low* Δm^2: *large* λ_{osc}, $P \propto L^2/E^2$;
- *High* Δm^2: *small* λ_{osc}, $P = 1/2 \sin^2 2\theta$.

◆ *The actual oscillation pattern is a function of the two parameters* L *and* E, *which can be adjusted experimentally:*
$\Longrightarrow$ *strongest evidence signal showing* L/E *dependence*

II

The Short Baseline experiments at CERN

MOTIVATIONS FOR WANF

- From a cosmological point of view, massive neutrinos could be one of the contributions to the missing 'DARK MATTER' provided:

$$\sum_{\nu,i} m_{\nu,i} \geq a\ few\ eV$$

- Within the SEE-SAW framework it is possible to obtain an estimate for neutrino masses, based on the MSW solar interpretation:

$$\Delta m^2_{\mu e} = \left(\frac{m^2_{\mu(c)}}{M}\right)^2 - \left(\frac{m^2_{e(u)}}{M}\right)^2 \sim \left(\frac{m^2_{\mu(c)}}{M}\right)^2 \sim 10^{-5}\ eV^2$$

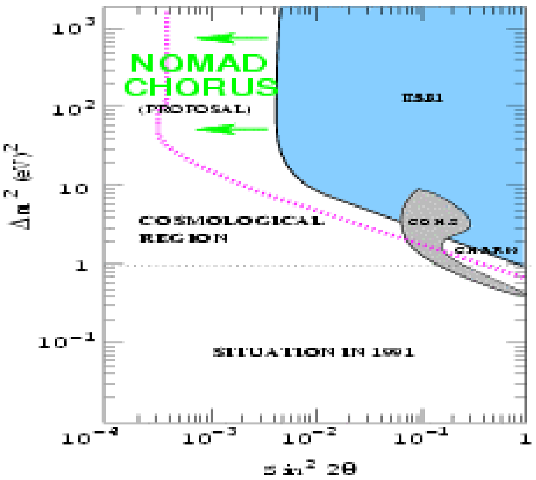
where M is a Majorana mass term $\gg$ standard electroweak scale.
The above expression taking into account flavour hierarchy leads to:

$$\begin{cases} m_{\nu_\mu} \sim 3 \times 10^{-3}\ eV & m_{\nu_\tau} \sim 0.9\ eV \quad \text{(leptons)} \\ m_{\nu_\mu} \sim 3 \times 10^{-3}\ eV & m_{\nu_\tau} \sim 34\ eV \quad \text{(quarks)} \end{cases}$$

- MAXIMAL SENSITIVITY to a possible $\nu_\mu \to \nu_\tau$ oscillation signal from the above m_{ν_τ} values is reached in the range:

$$10^{-3} < \frac{L}{E} < 1\ Km/GeV$$

$$\Downarrow$$



Sept. 1991 Approval

1994-1995 Full detectors

1994-1998 Data taking

- *The ideal evidence for $\nu_\mu \longrightarrow \nu_\tau$ oscillations is the direct appearance of ν_τ's in a pure ν_μ beam.*

  $\Longrightarrow$ *SBL experiments to probe the large Δm^2 region.*

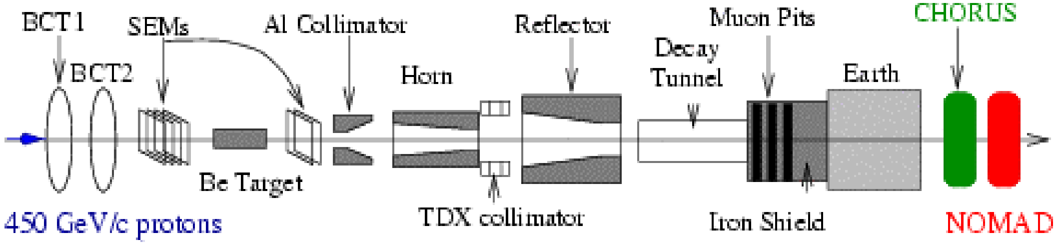
- *Severe constraints are imposed on the experimental program in order to achieve the* $\boxed{\text{DETECTION OF } \tau}$:
  - *high resolution detectors for a precise measurement of ν_τ charged current (CC) interactions;*
  - *large statistics for a sensitivity down to $P_{\mu\tau} \sim 10^{-4}$.*

  $\Longrightarrow$ *optimal compromise for SBL designs with*
  high resolution light (few tons) targets
  & large overall neutrino fluence (p.o.t.).

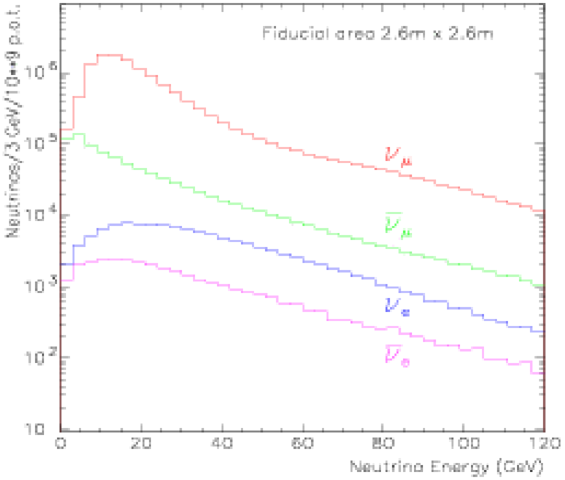
- *The result is an unprecedent neutrino data sample ($\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e$), which can match both the statistics of previous massive calorimeters* **AND** *the precision of previous bubble chamber/emulsion experiments.*

THE WANF NEUTRINO BEAM

- **Mean distance from ν source** (π,K *decay*): *NOMAD* $\sim 620m$, *CHORUS* $\sim 600m$.



- **Wide Band Beam (WBB)**: *broad energy spectra*.



	Flux		*CC interactions*	
Flavour	$\langle E_\nu \rangle [GeV]$	*abund.*	$\langle E_\nu \rangle [GeV]$	*abund.*
ν_μ	23.5	1.0	43.8	1.0
$\bar{\nu}_\mu$	19.2	0.061	42.8	0.025
ν_e	37.1	0.0094	58.3	$\boxed{\mathbf{0.015}}$
$\bar{\nu}_e$	31.3	0.0025	54.5	0.0016
ν_τ	$\sim$35			$\simeq \boxed{\mathbf{5 \times 10^{-6}}}$

- **Short Baseline Experiments (SBL)**: $\langle L \rangle / \langle E \rangle \sim 2 \times 10^{-2}\ Km/GeV$
  $\Longrightarrow \Delta m^2$ *sensitivity in the range* $1 \leq \Delta m^2 \leq 100\ eV^2$

THE ν_τ SEARCH AT CERN

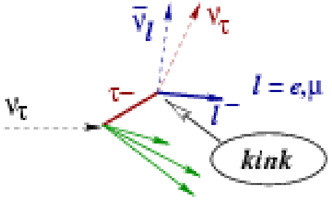
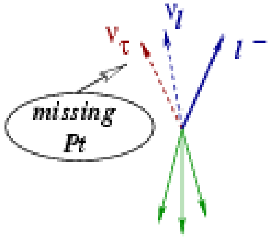
✦ APPEARANCE experiments.

ν_τ is detected by CC interactions:

$$\nu_\tau + N \longrightarrow \tau^- + X$$

$\boxed{\tau}$ identified by its decay properties:

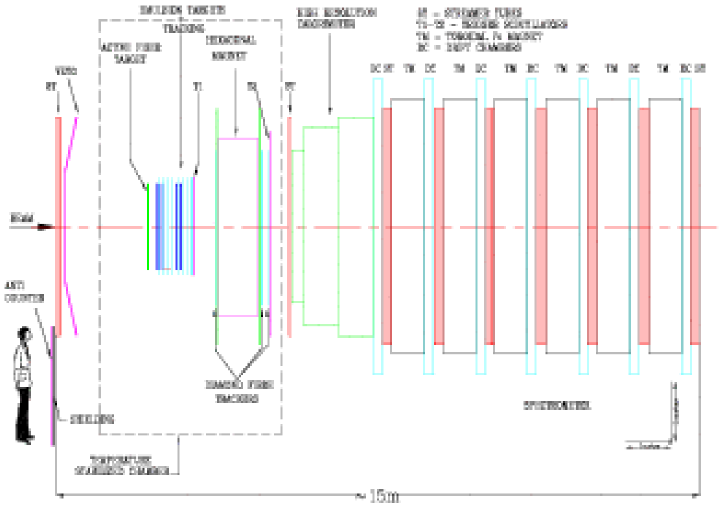
	Decay mode	BR	
CHORUS	$\mu\bar{\nu}_\mu\nu_\tau$	17.4%	
CHORUS	$e\bar{\nu}_e\nu_\tau$	17.8%	NOMAD
CHORUS	$h(n\pi^0)\nu_\tau$	49.5%	NOMAD
	$3h(n\pi^0)\nu_\tau$	15.2%	NOMAD

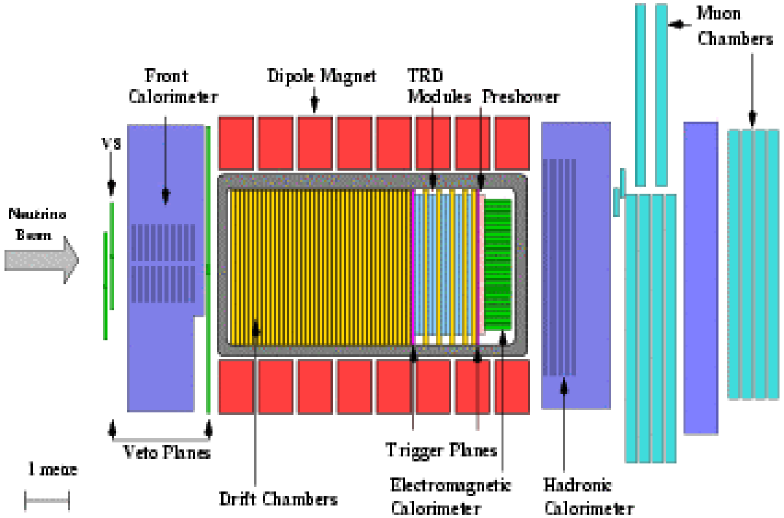
CHORUS	NOMAD
τ lifetime	τ mass & final neutrino(s)
⇓	⇓
kink, secondary vertex	high $P_\perp$ and missing $P_\perp$
	
⇓	⇓
nuclear emulsions	tracking & calorimetry
⇓	⇓
direct τ search	**indirect** τ search
VISUAL SCANNING	KINEMATIC ANALYSIS

THE DETECTORS AT CERN

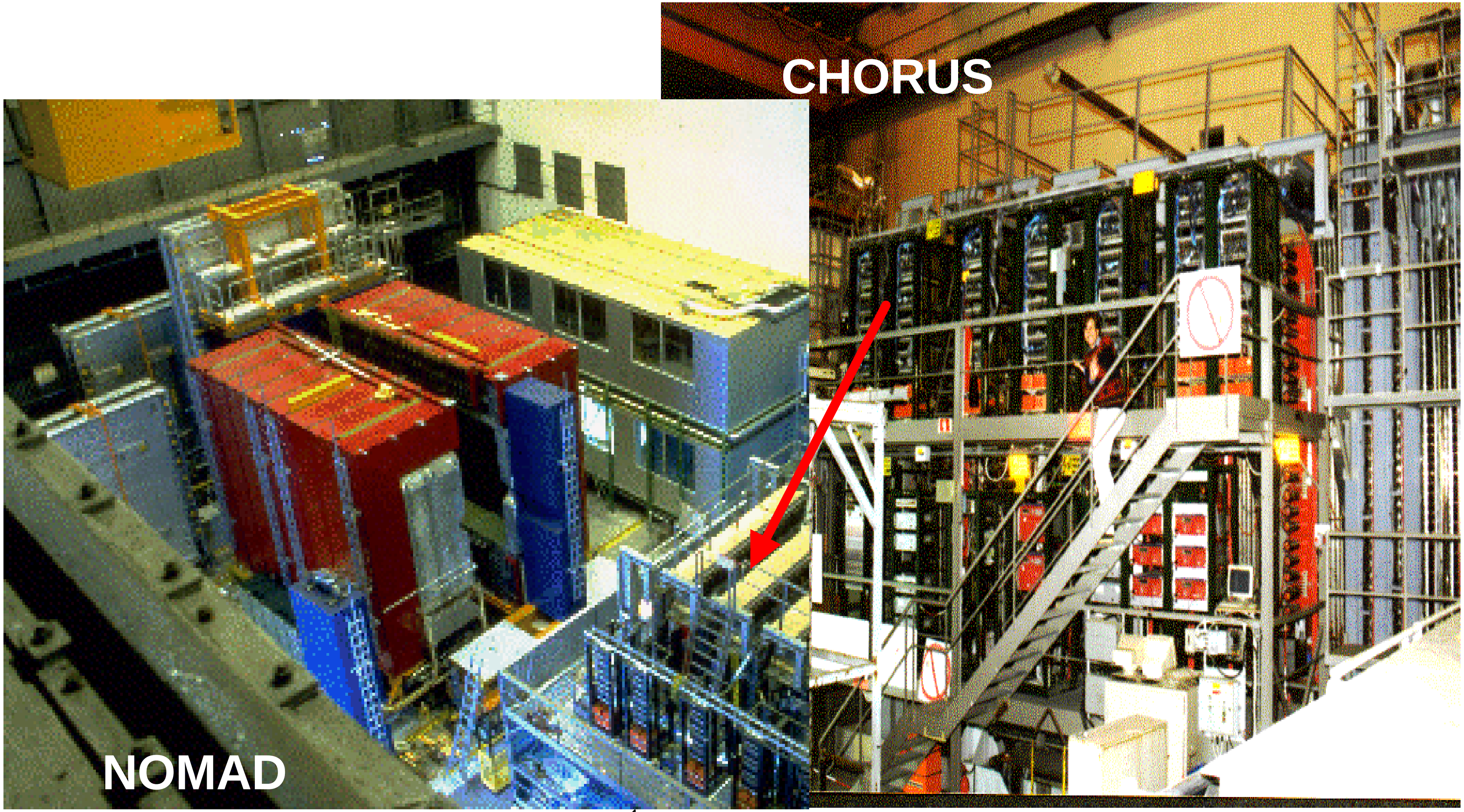
- **Hybrid detector:**
  - I *electronic detector*
    $\Longrightarrow$ *predict tracks BACK into emulsions;*
  - II *active emulsion target*
    $\Longrightarrow$ *LOCALIZE interactions into emulsions.*

- **Electronic detector:**
  - I *high resolution tracking*
    $\Longrightarrow$ *mom. resolution* $\sim 3.5\%$ $(p < 10 \mathrm{GeV}/c)$;
  - II *fine-grained calorimeter*
    $\Longrightarrow$ $\sigma(E)/E = 3.2\%/\sqrt{E[\mathrm{GeV}]} \oplus 1\%$.





Detectors at CERN (1994-1998)



Neutrino beam

DATA SAMPLES COLLECTED

small background

⇓

selection efficiency $\varepsilon_\tau^{\mathrm{Tot}} \sim 1 \div 8\%$

⇓

nominal target mass 0.8*t*

5×10^{19} *p.o.t*

⇓

DATA 94-97 **713k** ν_μ **CC**

Phase I *completed:*

75% *of* 1μ *analyzed*

67% *of* 0μ *analyzed*

Phase II *started*

large background

⇓

selection efficiency $\varepsilon_\tau^{\mathrm{Tot}} \sim 1 \div 4\%$

⇓

nominal target mass 2.7*t*

5×10^{19} *p.o.t*

⇓

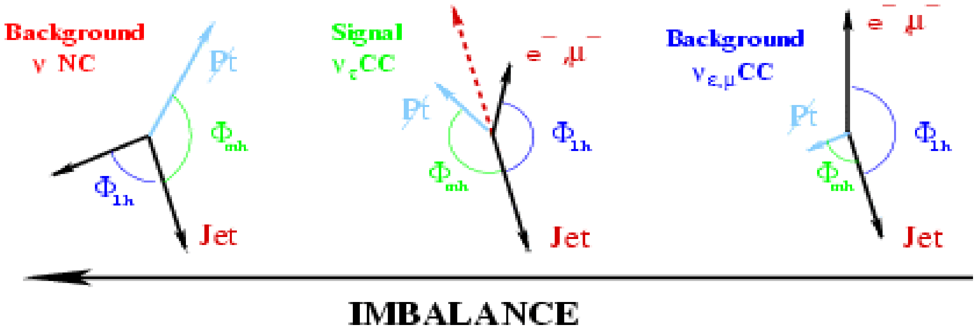
DATA 95-98 **1354k** ν_μ **CC**

100% *of data analyzed*

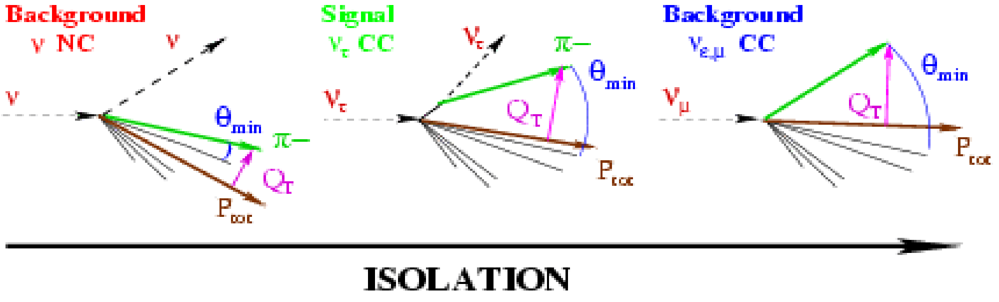
THE NOMAD ν_τ SEARCH

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

I **CC INTERACTIONS** :



II **NC INTERACTIONS** :



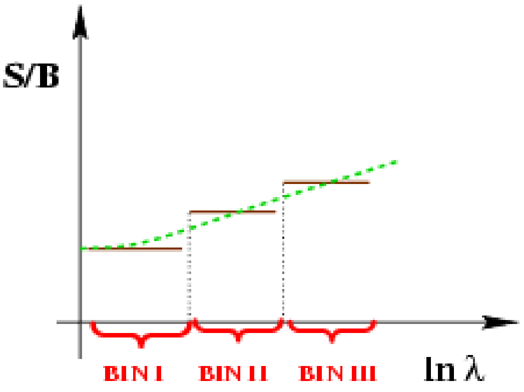
Difficult to reject efficiently both background sources with simple kinematic criteria $\Longrightarrow$ *opposite requirements.*

- *Definition of probability density functions,* $\boxed{\text{pdf } \mathcal{L}}$*, 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* $\boxed{\text{LIKELIHOOD RATIO}}$ *between the signal S and background(s) B hypotheses:*

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

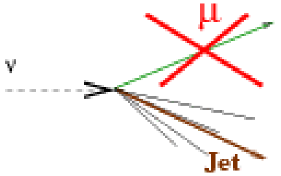
- *The optimal treatement is to compare the* $\boxed{\text{SHAPE}}$ *of signal & background(s) in a likelihood fit to* $\ln\lambda$*:*

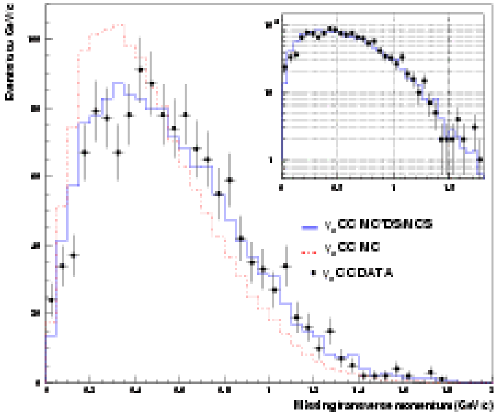


  - *limited by available statistics;*
  - *the relevant information from a fit is the* $\boxed{\text{S/B RATIO}}$ *along the* $\ln\lambda$ *distribution;*
  - *define different SIGNAL BINS in the tail of* $\ln\lambda$*, characterized by different S/B ratios;*
  - *different bins are considered statistically 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 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
    - ○ $\tau^- \to X$ MC



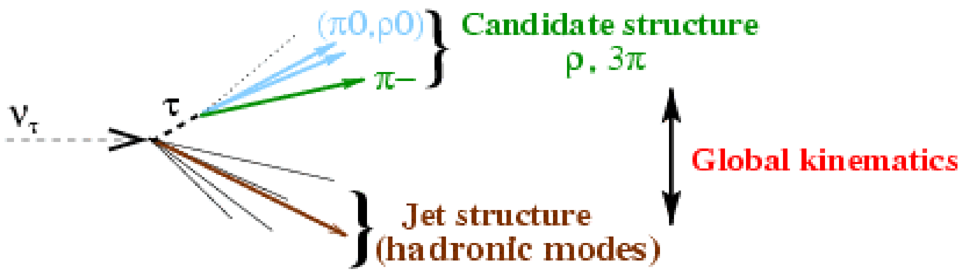


  - compute all efficiencies as $\boxed{\varepsilon \overset{\text{def}}{\equiv} \frac{\varepsilon(MC) \times \varepsilon(DS)}{\varepsilon(MCS)}}$

- 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.

	$\tau^- \to \nu_\tau + \boxed{e^- \bar{\nu}_e}$	$\tau^- \to \nu_\tau + \boxed{\text{hadrons}}$
Candidate selection	ONE *candidate* *defined by particle ID* $\Longrightarrow$ $\sim 100\%$ *purity*	MANY *candidates* *choice based on topology* $\Longrightarrow$ $70 \div 90\%$ *purity*
Rejection of CC	MAINLY ν_e *CC* *kinematics* $\Longrightarrow$ *rejection* $\mathcal{O}(10^4)$	UNIDENTIFIED ν_μ & ν_e *CC* *particle ID* $+$ *kinematics* $\Longrightarrow$ *rejection* $\mathcal{O}(10^6)$
Rejection of NC	$\pi^0 \to \gamma e^+ e^-$, π/K MISID. *particle ID* $+$ *kinematics* $\Longrightarrow$ *rejection* $\mathcal{O}(10^5)$	*hadrons inside jet* *kinematics* $\Longrightarrow$ *rejection* $\mathcal{O}(10^5)$
Selection efficiency	**3.6%**	$\mathbf{1 \div 2\%}$
Sensitivity range	*loose isolation* *small visible energy* (ν_e *CC*) $\Downarrow$ *high & low* Δm^2 (> 0.8 *eV*^{2})	*tight isolation* $\Downarrow$ *high* Δm^2

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



I **Candidate structure**:

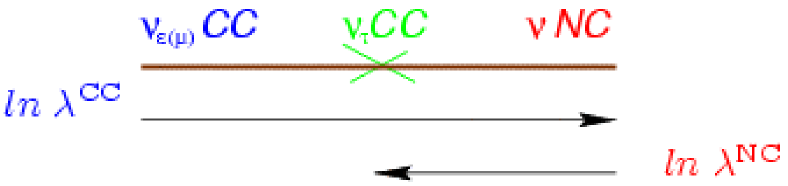
The internal structure of the ρ (3π) candidate is exploited both for the selection procedure and for the rejection of the $\nu_\mu + \nu_e$ CC backgrounds through a a likelihood function $\boxed{\mathcal{L}^{\mathrm{INT}}}$.

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.

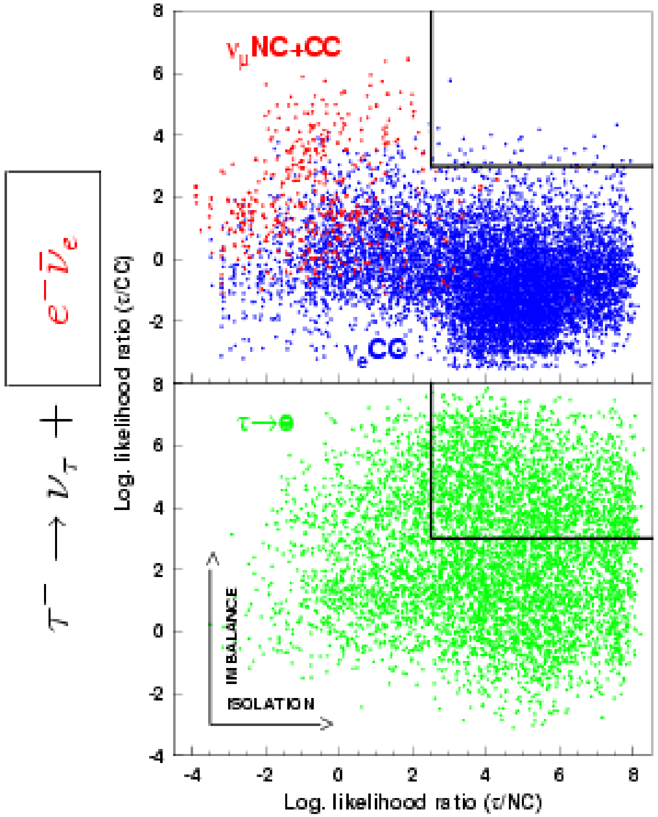
III **Global kinematics**:

The rejection of each of the two main background contributions is achieved by constructing TWO appropriate likelihood ratios $\boxed{\lambda^{\mathrm{NC}}}$ *and* $\boxed{\lambda^{\mathrm{CC}}}$, *exploiting the full event kinematics:*

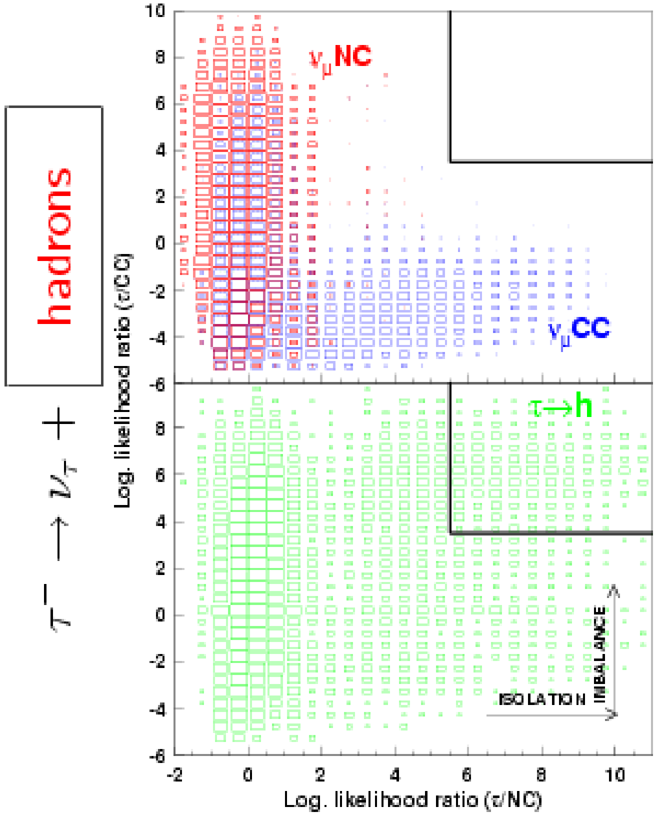


✦ Definition of the signal region:

$\tau^- \longrightarrow \nu_\tau + e^- \bar{\nu}_e$



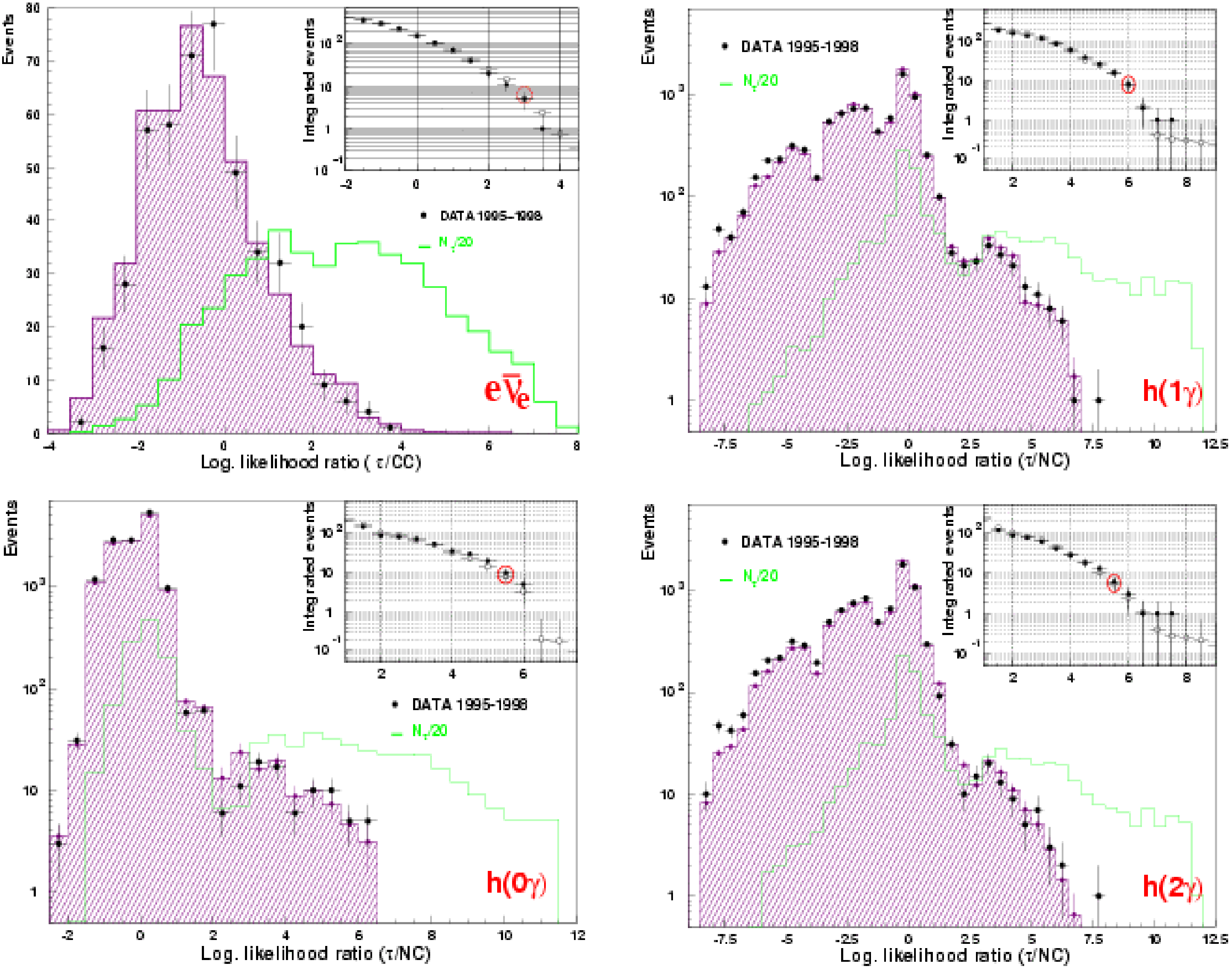
$\tau^- \longrightarrow \nu_\tau +$ hadrons



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

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

✦ Final results: NO EVIDENCE for oscillations



THE CHORUS ν_τ SEARCH

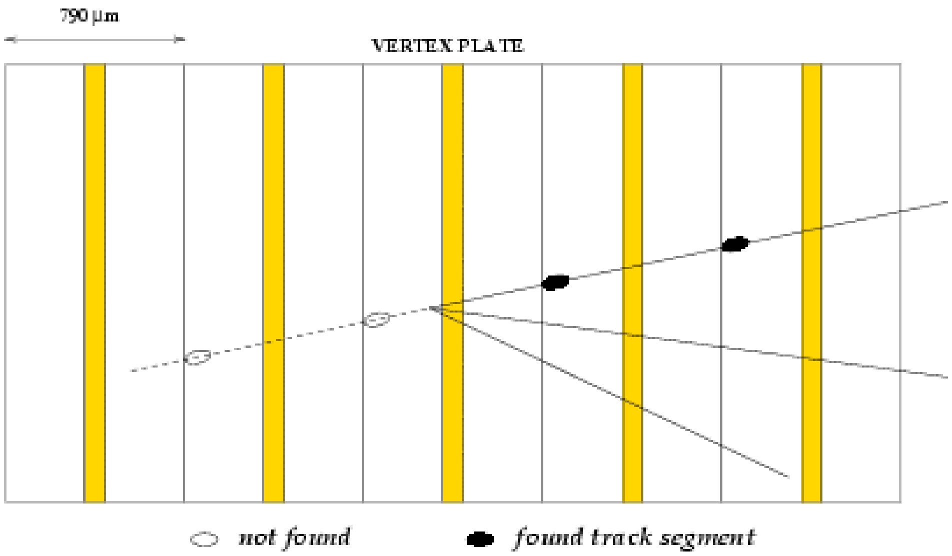
✦ Location of primary vertex (Phase I):

I PREDICTIONS *from the electronic detector & loose preselection to reduce the scanning load:*

- *identification of primary MUONS;*
- *automatic scanning in the interface emulsion sheets & track extrapolation at the emulsion target.*

II BULK EMULSION *automatic scanning procedure:*

- *track disappearance defines the vertex plate;*
- *the vertex location efficiency is evaluated from Monte Carlo simulations and is cross-checked with real data.*



✦ Procedure of τ decay search (Phase I):

I SHORT DECAY *path search*

when the kink is within the vertex plate

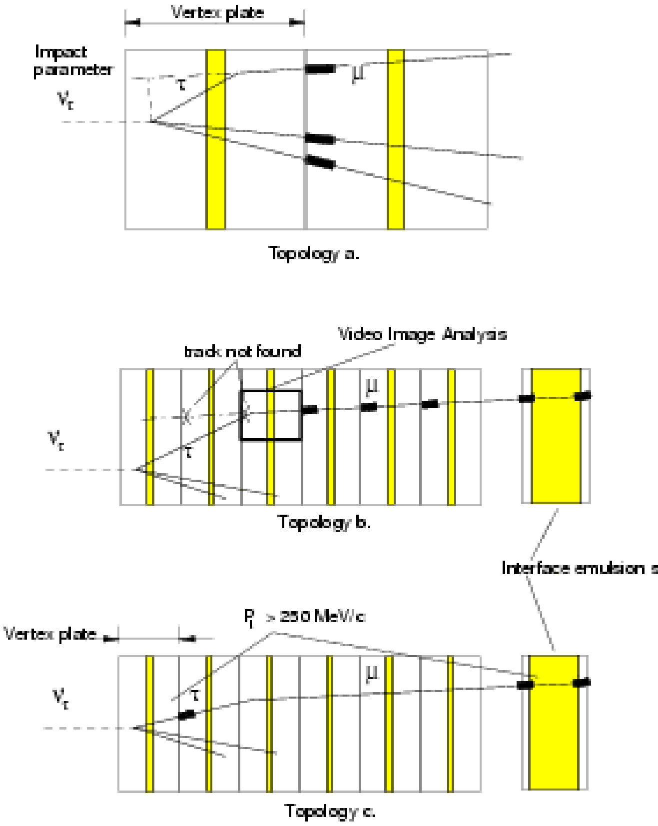
$\Longrightarrow$ *require LARGE impact parameter w.r.t. any track*

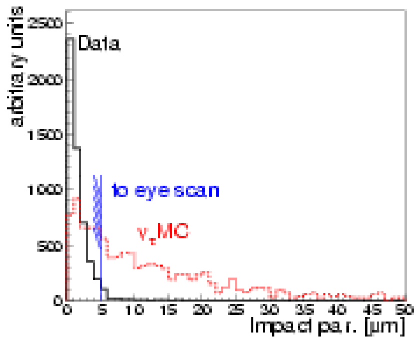
II LONG DECAY *path search*

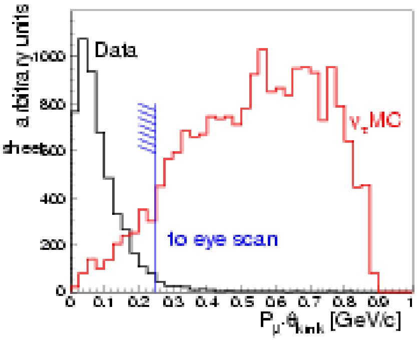
when the kink is downstream of the vertex plate

- ○ *kink angle larger than the scan-back angular tolerance*
- ○ *kink angle smaller than the scan-back angular tolerance*

$\Longrightarrow$ *require a transverse momentum $P_T > 250$ MeV*







$\tau^- \to \nu_\tau + \boxed{\mu^- \bar{\nu}_\mu}$ $\qquad$ $\tau^- \to \nu_\tau + \boxed{0\mu}$

<table>
<tr><td><i>Kink search</i></td><td><i>search along a</i>
<i>SINGLE track (μ)</i></td><td><i>search along</i>
<i>MANY tracks (h's)</i></td></tr>
<tr><td><i>Charm bkgnd.</i></td><td colspan="2">$\bar{\nu}$ <i>CC with missed primary lepton</i>
ν <i>CC with</i> μ^+/h^+ <i>wrong charge assignement</i>
$c\bar{c}$ <i>in NC with</i> D^+/D^0 <i>missed</i></td></tr>
<tr><td></td><td><i>kink constraints</i>

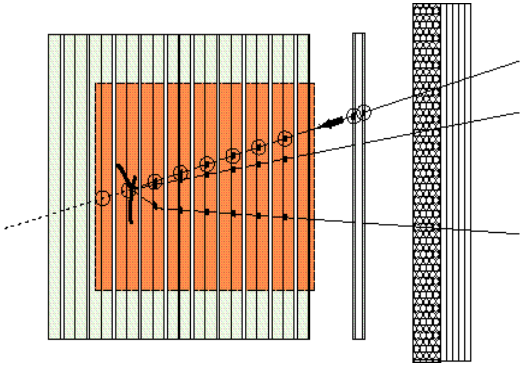
$\Longrightarrow$ <i>rejection</i> $\mathcal{O}(10)$</td><td><i>kink constraints</i>
+
<i>kinematics ($\Phi_{\tau H}$ cut)</i>
$\Longrightarrow$ <i>rejection</i> $\mathcal{O}(10)$</td></tr>
<tr><td><i>"White kink" bkgnd.</i></td><td>–</td><td><i>nuclear 1-prong interactions</i>
<i>without heavily ionizing tracks</i>
<i>kink constraints</i>
+
<i>kinematics ($\Phi_{\tau H}$ cut)</i>
$\Longrightarrow$ <i>rejection</i> $\mathcal{O}(10)$</td></tr>
<tr><td><i>Acceptance (vertex)</i></td><td><i>20%</i></td><td><i>8%</i></td></tr>
<tr><td><i>Kink efficiency</i></td><td><i>38%</i></td><td><i>10%</i></td></tr>
<tr><td><i>Selection efficiency</i></td><td>7.6%</td><td>0.8%</td></tr>
</table>

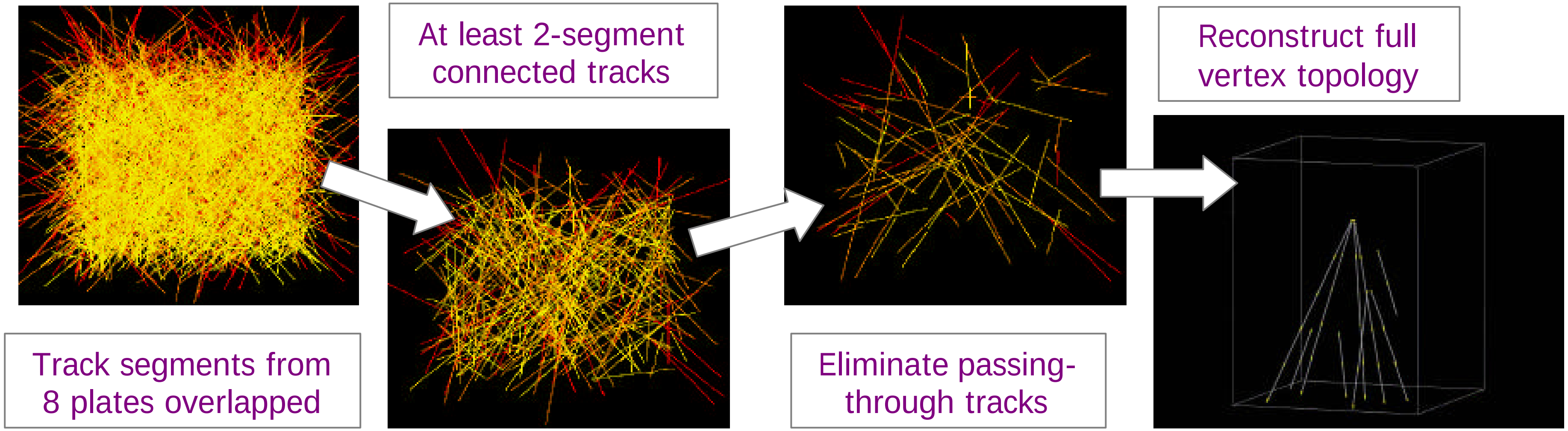
NETSCAN location (Phase II):

- *Pick up **all track segments** (q < 0.4 rad) in the scanning volume*

  (1.5 x 1.5 mm^2 ´ 8 plates)

- ***Offline analysis** of emulsion data*





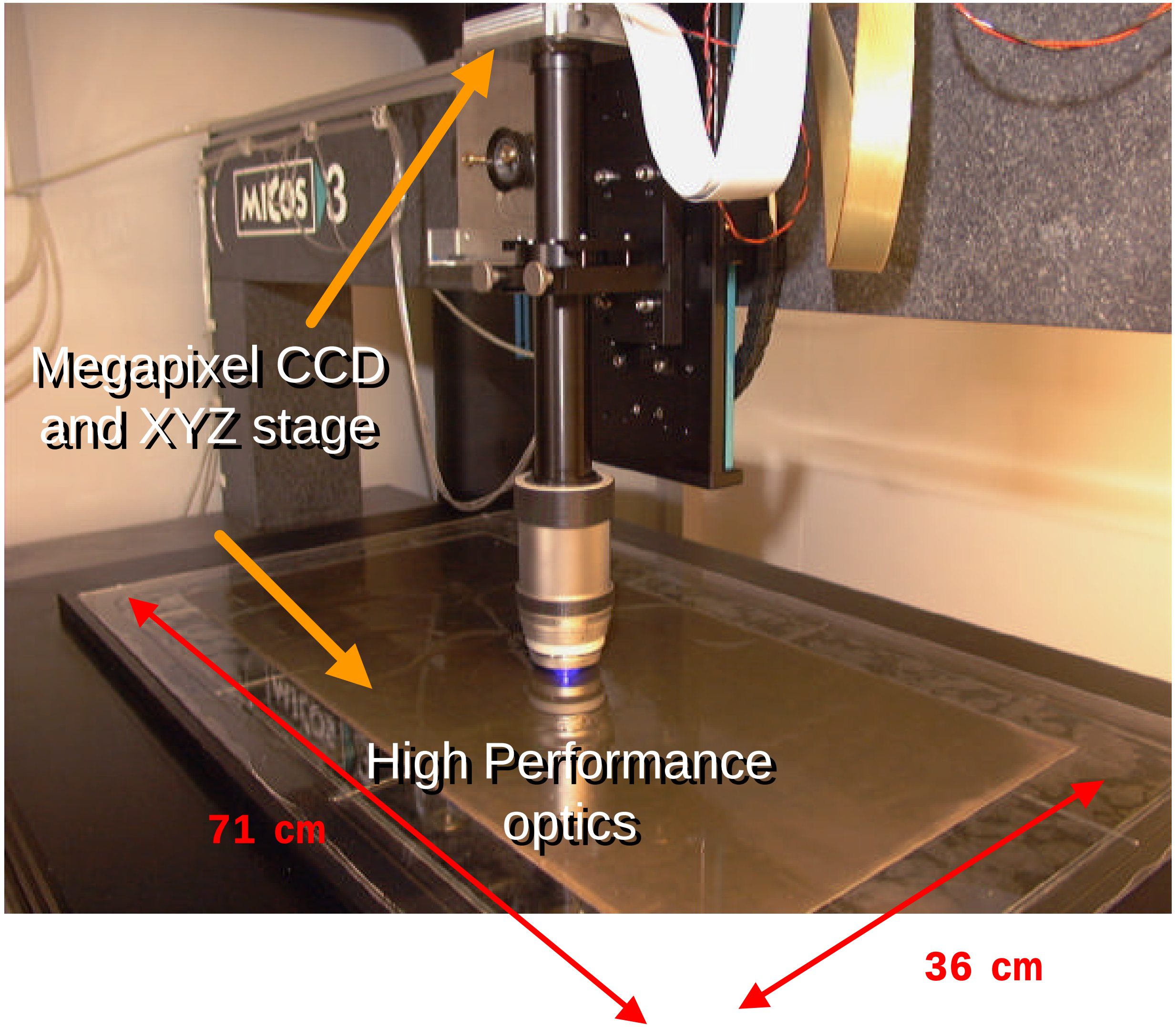
Track segments from 8 plates overlapped

At least 2-segment connected tracks

Eliminate passing-through tracks

Reconstruct full vertex topology

Automatic microscope at CERN:



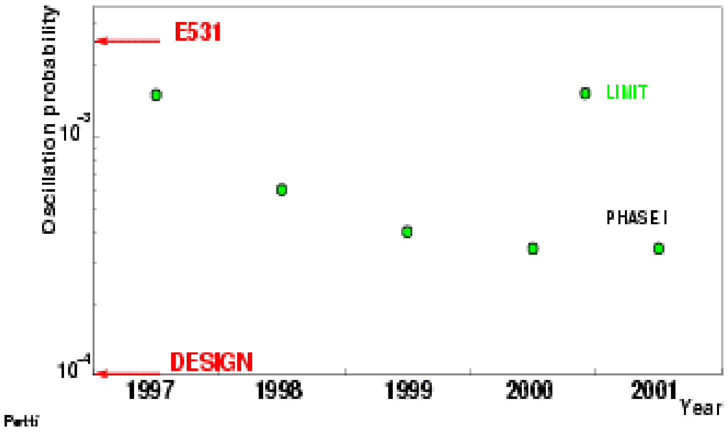
RESULTS OF THE ν_τ SEARCH

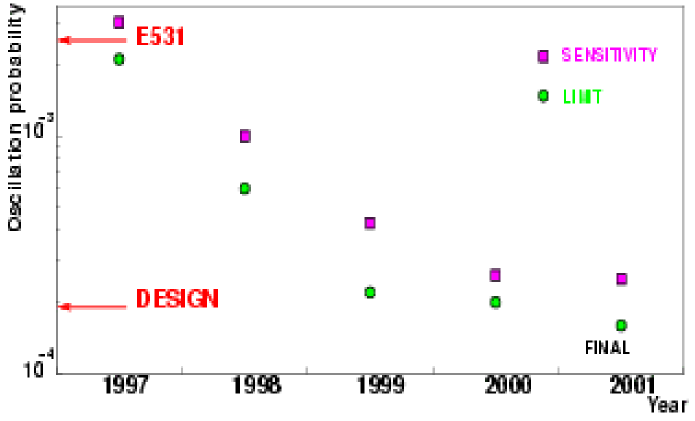
✦ NO EVIDENCE *for oscillations from the analysis of data:*

- *NUMBER of observed events consistent with bkgnd.;*
- *SHAPE of relevant distributions in good agreement with bkgnd.*

Tot. bkg.	1.21 ± 0.33
$N^\tau_{P=1}$	7018
Data	*0*
Syst.:	*17%* $N^\tau_{P=1}$*, 30% bkg.*

Tot. bkg.	50.5 ± 5.1
$N^\tau_{P=1}$	15226
Data	*52*
Syst.:	$5 \div 10\%$ $N^\tau_{P=1}$, $5 \div 20\%$ *bkg.*





- *Both approaches allow the definition of regions with a* SMALL BACKGROUND:

CHORUS

Analysis	*Tot. bkg.*	$N^{\tau}_{P=1}$	*Data*
$\nu_\tau \bar{\nu}_\mu \mu$	0.11 ± 0.03	*5014*	*0*
$\nu_\tau 0\mu$	1.10 ± 0.33	*2004*	*0*
	$\boxed{\mathbf{1.21}^{+0.33}_{-0.33}}$	$\boxed{7018}$	*0*

$$\begin{cases} S_{\nu_\mu \to \nu_\tau} & = & 3.7 \times 10^{-4} \ \ 90\%\mathrm{CL} \\ L_{\nu_\mu \to \nu_\tau} & = & 3.4 \times 10^{-4} \ \ 90\%\mathrm{CL} \\ P(\leq L) & = & 28\% \end{cases}$$

(T. Junk, NIM A434 (1999) 435).

$$\begin{cases} S_{\nu_\mu \to \nu_\tau} & = & 3.4 \times 10^{-4} \ \ 90\%\mathrm{CL} \\ L_{\nu_\mu \to \nu_\tau} & = & 2.1 \times 10^{-4} \ \ 90\%\mathrm{CL} \\ P(\leq L) & = & 29\% \end{cases}$$

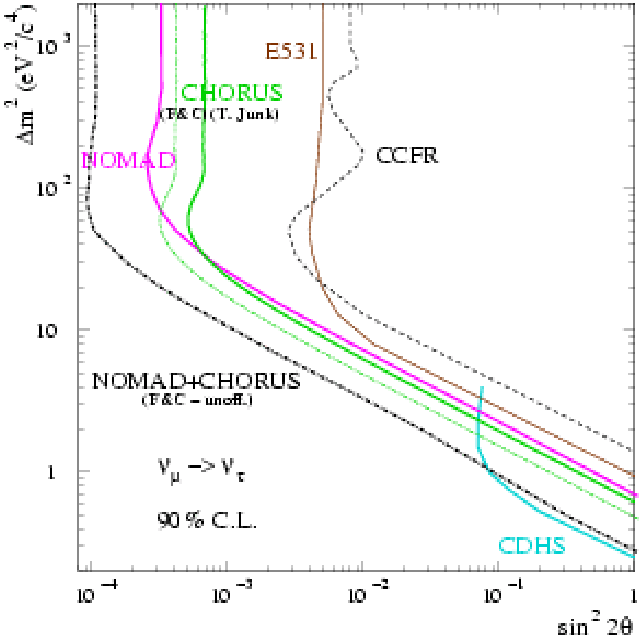
(Feldman & Cousins, Phys. Rev. D57 (1998) 3873).

NOMAD

Analysis		*Bin*	*Tot. bkg.*	$N^{\tau}_{P=1}$	*Data*
$\nu_\tau \bar{\nu}_e e$	*DIS*	*III*	$0.28^{+0.31}_{-0.09}$	*948*	*0*
$\nu_\tau \bar{\nu}_e e$	*DIS*	*VI*	0.25 ± 0.09	*1780*	*0*
$\nu_\tau h(0\gamma)$	*DIS*	*III*	$0.05^{+0.60}_{-0.03}$	*288*	*0*
$\nu_\tau h(0\gamma)$	*DIS*	*IV*	$0.12^{+0.60}_{-0.05}$	*1345*	*0*
$\nu_\tau h(1\gamma)$	*DIS*	*III*	$0.07^{+0.70}_{-0.04}$	*223*	*0*
$\nu_\tau h(1\gamma)$	*DIS*	*IV*	$0.07^{+0.70}_{-0.04}$	*1113*	*0*
$\nu_\tau h(2\gamma)$	*DIS*	*IV*	$0.11^{+0.60}_{-0.06}$	*211*	*0*
$\nu_\tau h(1/2\gamma)$	*DIS*	*III*	$0.20^{+0.70}_{-0.06}$	*707*	*1*
$\nu_\tau h(0/1\gamma)$	*DIS*	*IV*	$0.14^{+0.70}_{-0.06}$	*1456*	*0*
$\nu_\tau 3h$	*DIS*	*V*	$0.32^{+0.57}_{-0.32}$	*675*	*0*
			$\boxed{\mathbf{1.61}^{+1.70}_{-0.37}}$	$\boxed{8746}$	*1*

$$\begin{cases} S^{\mathrm{Total}}_{\nu_\mu \to \nu_\tau} & = & 2.5 \times 10^{-4} \ \ 90\%\mathrm{CL} \\ L^{\mathrm{Total}}_{\nu_\mu \to \nu_\tau} & = & 1.6 \times 10^{-4} \ \ 90\%\mathrm{CL} \\ P(\leq L) & = & 37\% \end{cases}$$

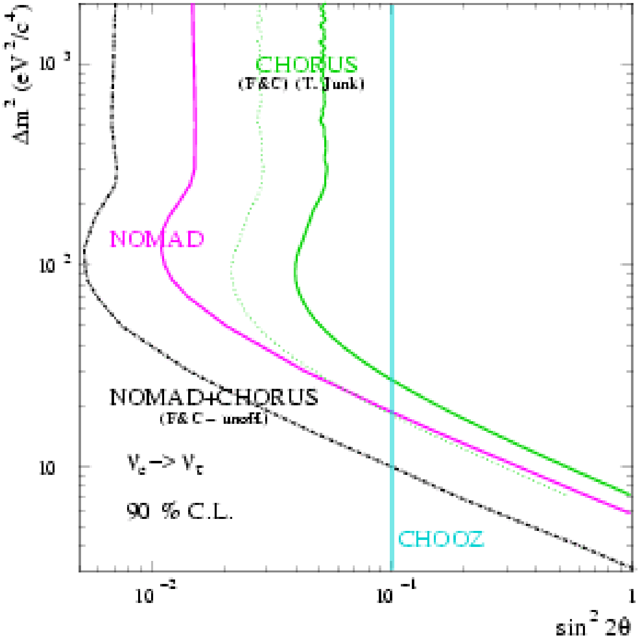
- $\boxed{\nu_\mu \to \nu_\tau}$:



Combined result with F&C (unoff.):

$$\left\{\begin{array}{lcl} S_{\nu_\mu\to\nu_\tau} & = & 1.7\times10^{-4}\ \ 90\%\mathrm{CL} \\ L_{\nu_\mu\to\nu_\tau} & = & 0.5\times10^{-4}\ \ 90\%\mathrm{CL} \\ P(\leq L) & = & 15\% \end{array}\right.$$

- $\boxed{\nu_e \to \nu_\tau}$:



Combined result with F&C (unoff.):

$$\left\{\begin{array}{lcl} S_{\nu_e\to\nu_\tau} & = & 0.9\times10^{-2}\ \ 90\%\mathrm{CL} \\ L_{\nu_e\to\nu_\tau} & = & 0.4\times10^{-2}\ \ 90\%\mathrm{CL} \\ P(\leq L) & = & 25\% \end{array}\right.$$

THE NOMAD $\nu_\mu \rightarrow \nu_e$ SEARCH

Motivated by the LSND result:

◆ *Relative abundance in the beam:*

$$\boxed{\nu_\mu} \; : \; \bar{\nu}_\mu \; : \; \boxed{\nu_e} \; : \; \bar{\nu}_e$$

$$\boxed{1} \; : \; 0.072 \; : \; \boxed{0.010} \; : \; 0.0026$$

different energy spectra & radial profiles for ν_e *and* ν_μ

SEARCH FOR DISTORSIONS IN THE ν_e SPECTRUM

$\Longrightarrow$ *oscillation effect enhanced at low* ν_e *energies.*

◆ *Different approaches to evaluate* π, K *contributions:*

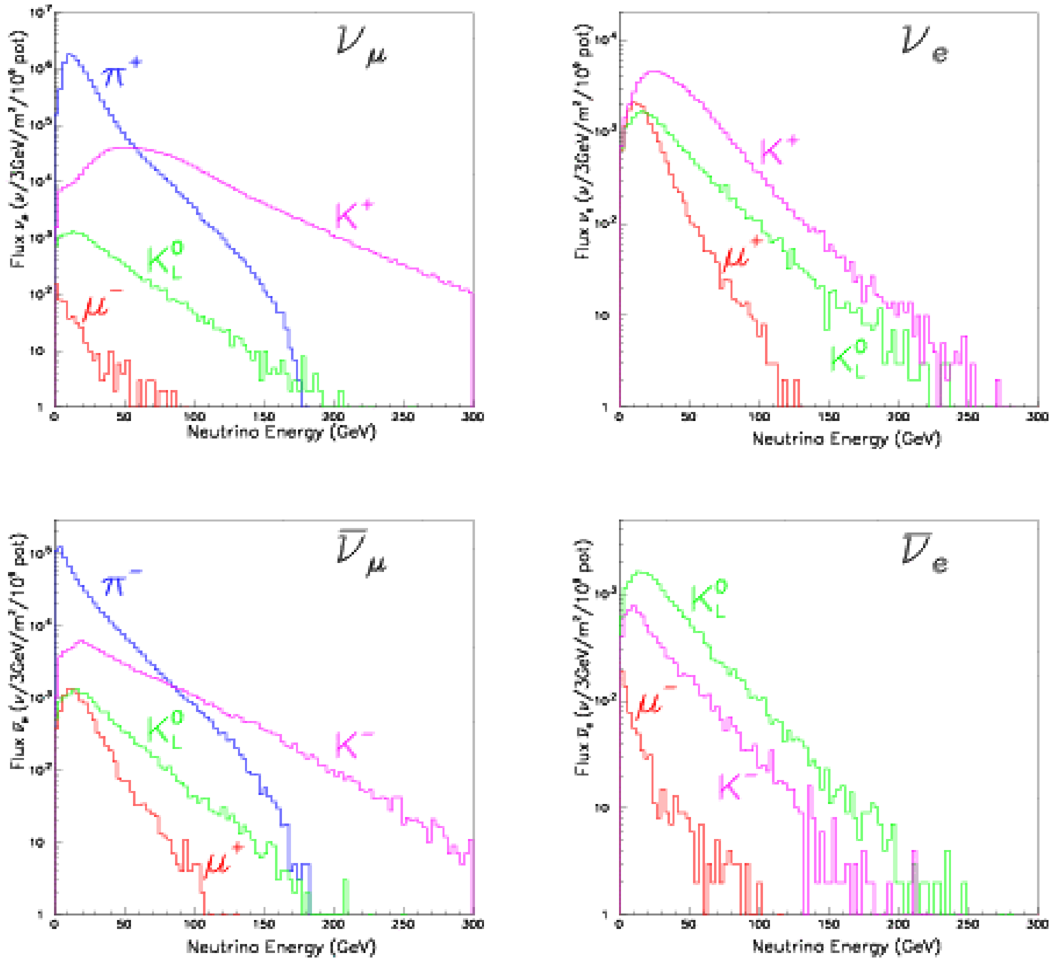
a) MONTE CARLO *simulations (FLUKA+GEANT);*

b) *Measured spectra of* $\nu_\mu, \bar{\nu}_\mu$ & $\bar{\nu}_e$ (not ν_e !) *to extract* $K^{\pm,0}$ *content;*

c) *Cross-check with* NA56-SPY *measurement of* K/π.

$\Longrightarrow$ *compare flux calculations with data taken with reversed polarity of* ν *beam and with horn/reflector switched off*

Neutrino parent composition:



$$\nu_e \equiv \nu_e(K^+) \oplus \nu_e(K^0_L) \oplus \nu_e(\mu^+)$$

- $K^+ \rightarrow \pi^0 e^+ \nu_e$: constrained by ν_μ at high E_ν
- $K^0_L \longrightarrow \pi^- e^+ \nu_e$: constrained by $\bar{\nu}_e$ and $\bar{\nu}_\mu$ spectra
- $\mu^+ \longrightarrow \bar{\nu}_\mu e^+ \nu_e$: constrained by ν_μ at low E_ν

Systematic uncertainties reduced with ratio:

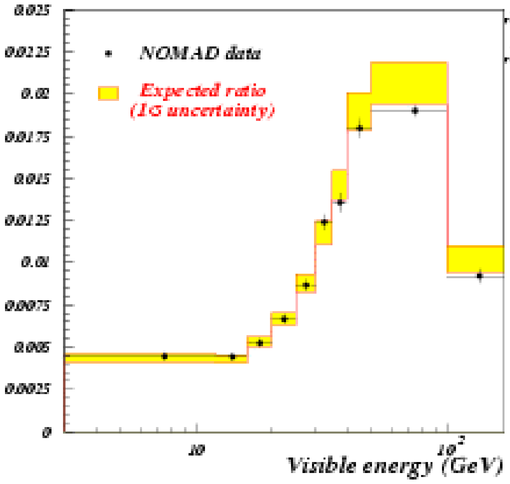
$$\mathcal{R}_{e\mu}(E_\nu) \overset{\text{def}}{\equiv} \left[\frac{\#\ \nu_e\ CC\ \ Events}{\#\ \nu_\mu\ CC\ \ Events}\right](E_\nu)$$

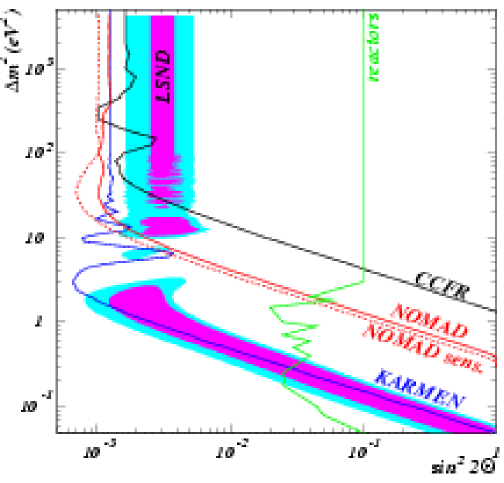
- ✦ The analysis relies upon the excellent electron identification capability of NOMAD. Search for the **APPEARANCE** of ν_e CC events with the energy distribution of ν_μ CC;

- ✦ A **BLIND** oscillation search is performed
  $\Longrightarrow$ compare the $\mathcal{R}_{e\mu}$ distributions in MC and data ONLY after robust beam predictions;

- ✦ Systematics on predictions from the ν_μ, $\bar{\nu}_\mu$ and $\bar{\nu}_e$ CC comparison with beam profiles ($\sim 2\%$ norm., $\sim 5\% shape$);

- ✦ NO EVIDENCE for oscillations from the analysis of the full data set: $\underline{P_{\mu e} < 6.0 \times 10^{-4}}$ at 90%CL (Preliminary)

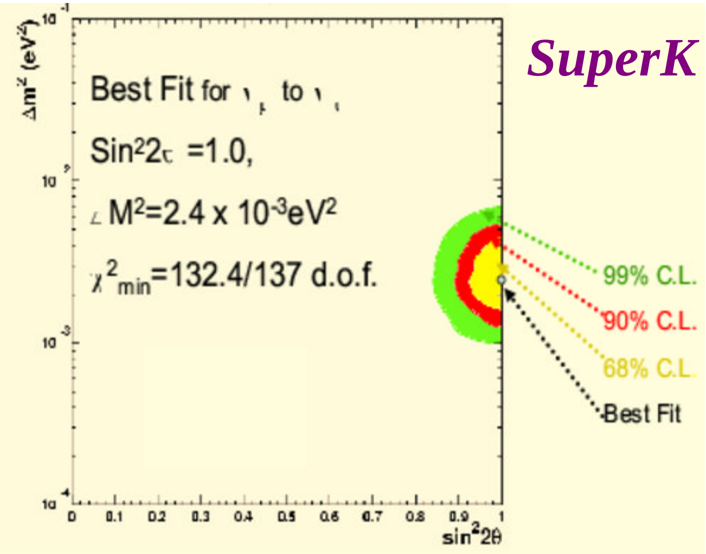




III

The Long Baseline experiments at Gran Sasso

MOTIVATIONS FOR CNGS



- n_m **disappearance in Super-K:**

$n_m - n_t$

$1.2 < Dm^2 < 5.4 \times 10^{-3}$ eV^2 at 90% CL

1.0 7.0 99%

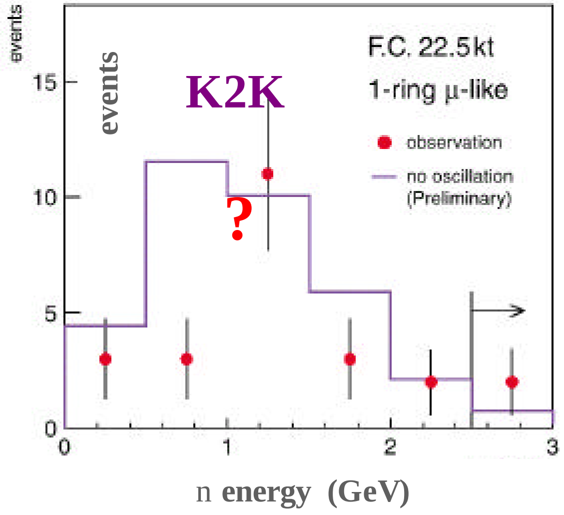
Best fit *$Dm^2 = 2.4 \times 10^{-3}$ eV^2*

Sterile n disfavoured at ~ 99%

- n_m **disappearance in K2K:**

Expected (no osc.)	*80.6 + 7.3 - 8.0*
Detected	*56 (~ 2s effect)*

Oscillation dip in the E_n spectrum at $Dm^2 \sim 3 \times 10^{-3}$ eV^2 ?



- n_t **appearance in Super-K**

Poor S/B ratio ~ 0.7%, statistical significance **~ 2***s*

- A direct detection of the appearance of $\boxed{\nu_\tau \text{ CC}}$ events in the parameter region indicated by the measurements with the atmospheric neutrinos by Super-Kamiokande requires:
  - L/E in the range ≥ 40;
  - energy thresold for τ production $E_\nu > 4$ GeV.

  $\Longrightarrow$ artificial ν_μ beam from CERN to Gran Sasso with $L = 732$ km and $\langle E_\nu \rangle \sim 17$ GeV.

- The resulting Long Baseline design is very challenging for **ANY** ν_τ CC appearance experiment:
  - high resolution for τ detection;
  - limited fluence available at large distance from the neutrino source ($\sim 1/L^2$).

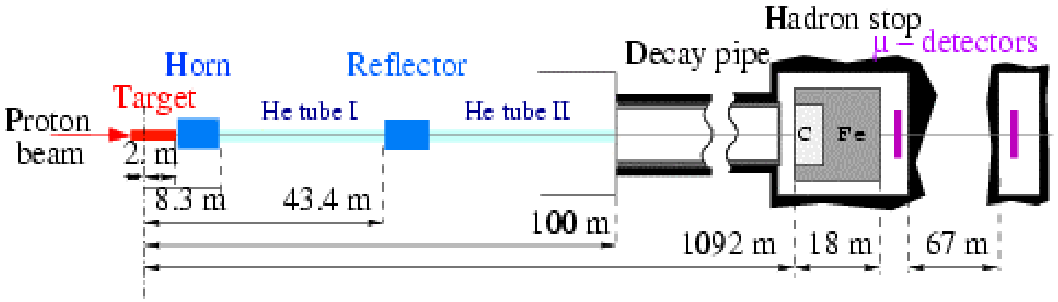
  $\Longrightarrow$ need unprecedent high resolution massive detectors of kton scale ($SBL \times 10^3$).

- Practical construction and costs require the use of different technologies to fulfill the τ detection principles developed in the SBL experiments.

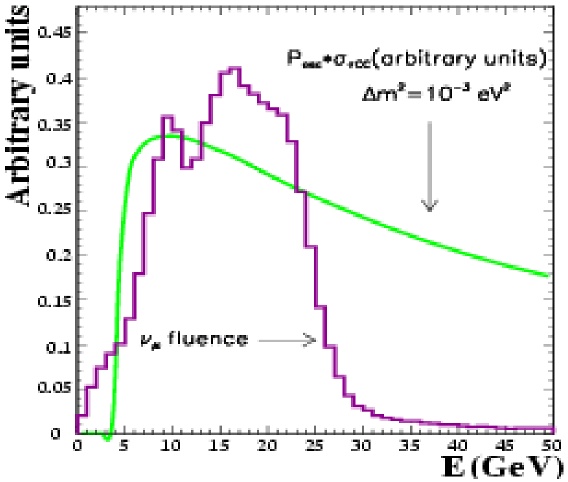
  Note: S/B increases with L since the background is reduced at large distances ($\sim 1/L^2$), whereas the signal rate from oscillations is approximately independent from L for $\frac{L/km}{E/GeV} \frac{\Delta m^2}{eV^2} \ll 1$.

THE CNGS NEUTRINO BEAM

- **Mean distance from ν source** (π,K *decay*): *OPERA, ICARUS* $\sim$ *732km.*



- **Wide Band Beam (WBB)**: *spectra optimized to maximize* $\boxed{\nu_\tau \textbf{ CC rate from oscillations}}$.



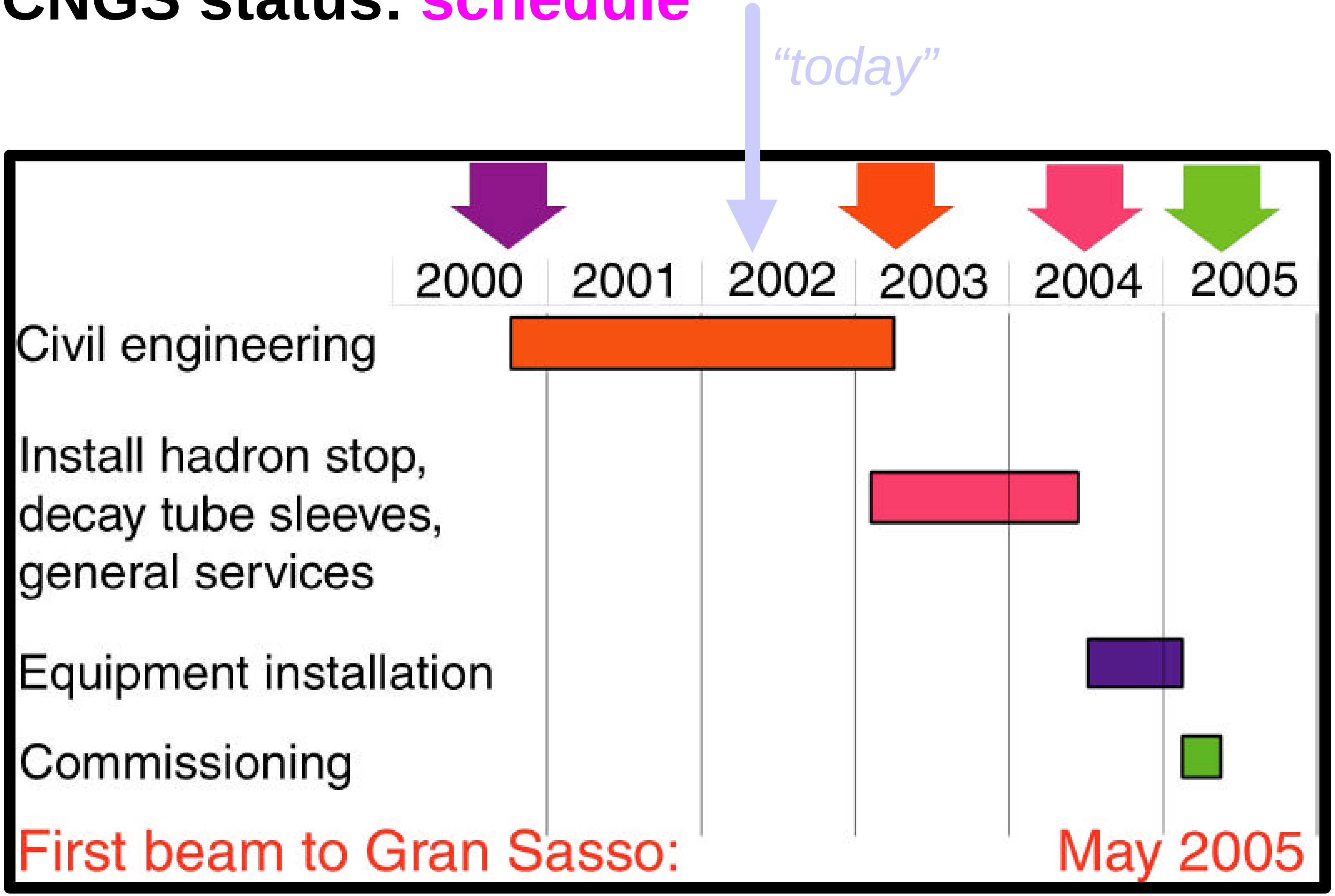
$\nu_\mu (m^{-2}/pot)$	7.45×10^{-9}
ν_μ *CC events/pot/kton*	5.44×10^{-17}
$\langle E \rangle_{\nu_\mu}$ *(GeV)*	**17**
$\bar{\nu}_\mu / \nu_\mu$	*2.1 %*
ν_e / ν_μ	**0.8 %**
$\bar{\nu}_e / \nu_\mu$	*0.07 %*
ν_τ *prompt*	*negligible*

- **Long Baseline Experiments (LBL)**: $\langle L \rangle / \langle E \rangle \sim 40\ Km/GeV$

$\Longrightarrow$ Δm^2 *sensitivity in the range* $\Delta m^2 \geq 10^{-3}$

CNGS status: civil engineering

CNGS status: schedule



First beam to Gran Sasso: May 2005

THE ν_τ SEARCH AT GRAN SASSO

✦ APPEARANCE *experiments.*

ν_τ is detected by CC interactions:

$$\nu_\tau + N \longrightarrow \tau^- + X$$

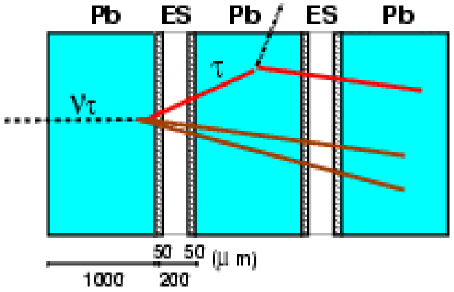
$\boxed{\tau}$ *identified by its decay properties:*

	Decay mode	BR	
	$\mu\bar{\nu}_\mu\nu_\tau$	17.4%	
	$e\bar{\nu}_e\nu_\tau$	17.8%	
	$h(n\pi^0)\nu_\tau$	49.5%	

heavy passive material (Pb) interleaved with emulsions

⇓

target mass ~ 1800 t



⇓

high space resolution

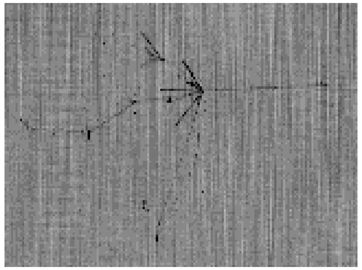
$\sigma < 1\mu m$

VISUAL SCANNING

large sensitive TPC filled with liquid Argon

⇓

target mass ~ 3000 t



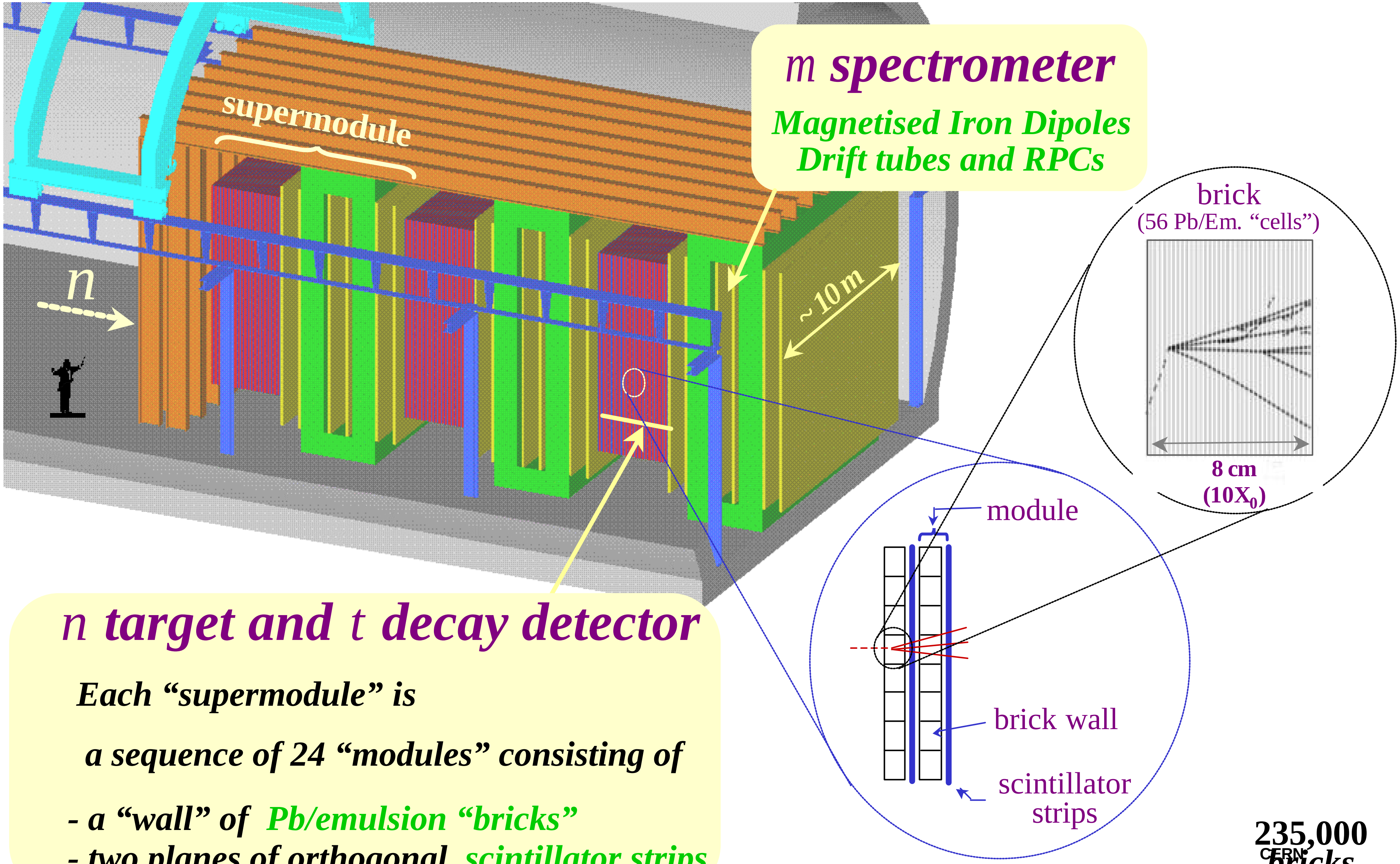
⇓

precision calorimetry

$\sigma_E/E \sim 3\%(12\%)/\sqrt{E}$ *e.m.(had.)*

KINEMATIC ANALYSIS

THE OPERA DETECTOR



μ spectrometer

Magnetised Iron Dipoles
Drift tubes and RPCs

ν target and τ decay detector

Each “supermodule” is

a sequence of 24 “modules” consisting of

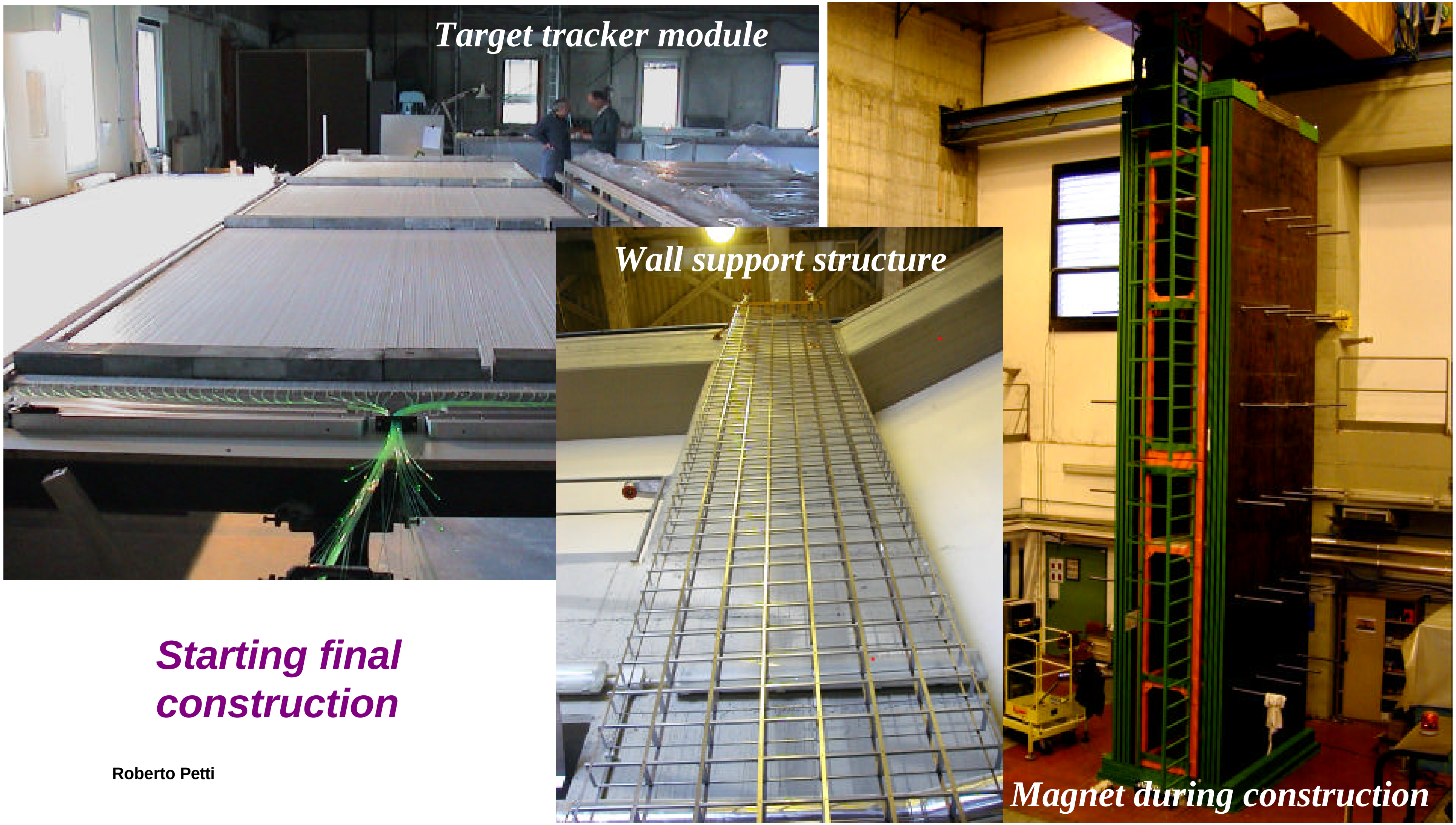
- ***a “wall” of** Pb/emulsion “bricks”*
- ***two planes of orthogonal** scintillator strips*

235,000
bricks

CERN

✦ Status of the experiment

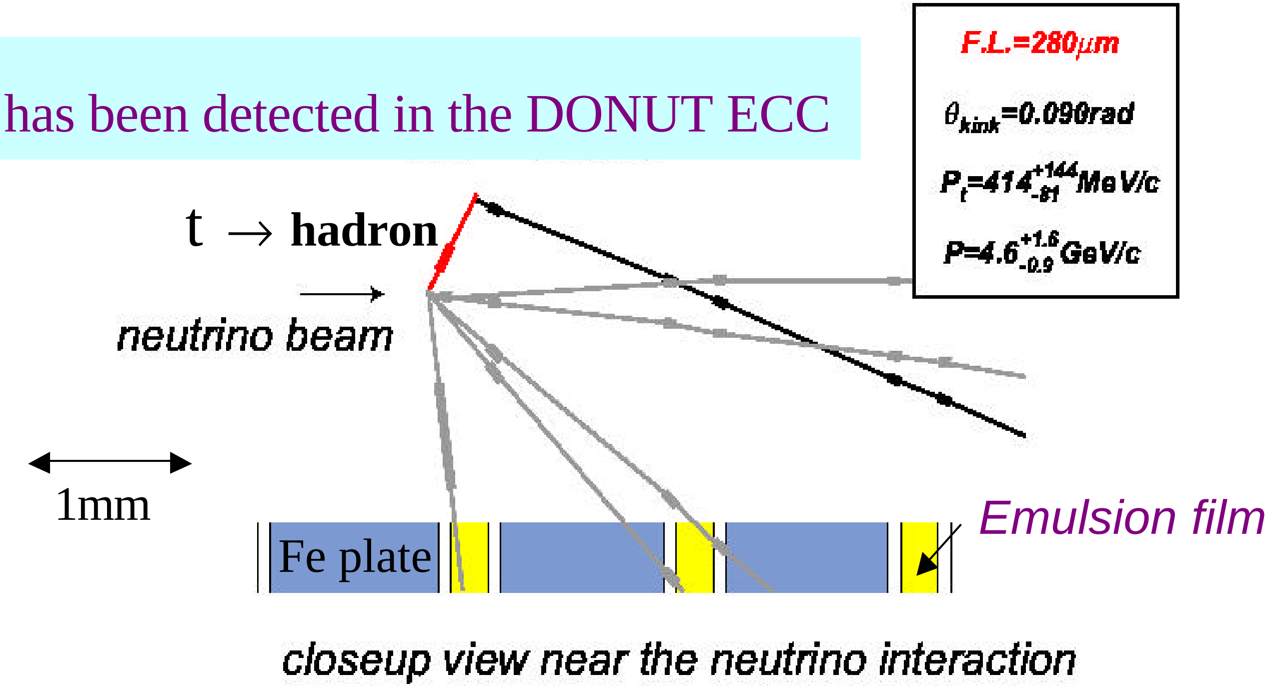
- *Approved as* ***CNGS1*** *in 2000*
- *Construction & test of* ***full-scale prototypes*** *completed*



Starting final construction

THE DONUT BENCHMARK

ν_τ has been detected in the DONUT ECC



Structure: OPERA ECC = DONUT ECC

Material : Lead ≠ Iron

Better performance for physics analysis

Test for the OPERA technology

THE OPERA ν_τ SEARCH

◆ *The electronic detector is used to find the* **BRICK** *where the neutrino interaction occurred.*

$\Longrightarrow$ *the brick is extracted and developed for scanning.*

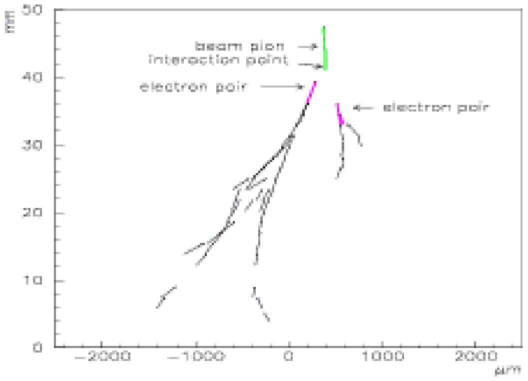
◆ *Tracks are followed back in the brick to locate the primary* **VERTEX** *with a NETSCAN procedure (global scan) already used by DONUT & CHORUS Phase II.*

◆ *The* **DECAY** *search is performed in two topologies:*

- *long decay topology* $\Longrightarrow$ *kink*
- *short decay topology* $\Longrightarrow$ *impact parameter*

◆ *The full event is reconstructed in order to perform a* **KINEMATIC ANALYSIS** *of the selected events:*

- *track momenta by Multiple Coulomb Scattering (MS);*
- *e. m. shower energy from total track length;*
- *specific* π^0 *reconstruction for* $\tau \longrightarrow \rho$ *search.*

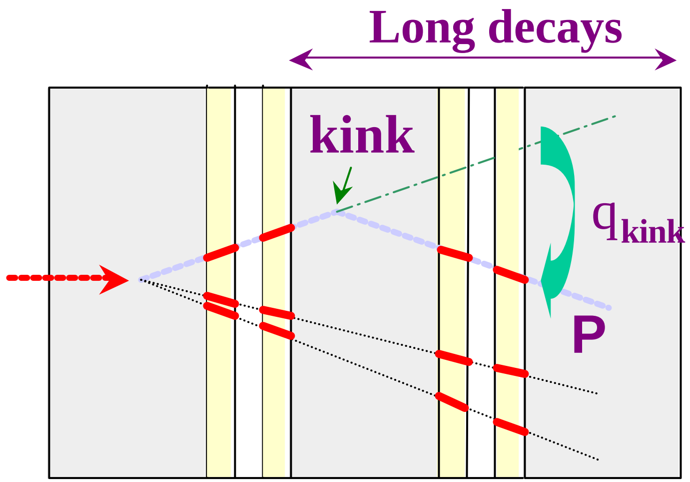


Long decay topology:

- **Search for a kink with an angle q$_{kink}$ > 20 mrad**

leptonic channels t ® **e,** m

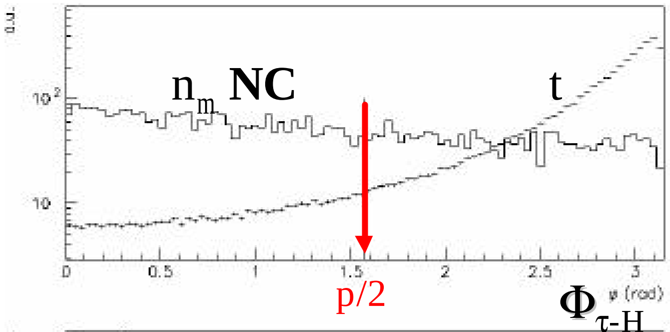
hadronic channels t ® **h,** r



- **Require large P$_T$ = P*q$_{kink}$ at 2ry vtx.**

leptonic channels > **100, 250 Mev/c**

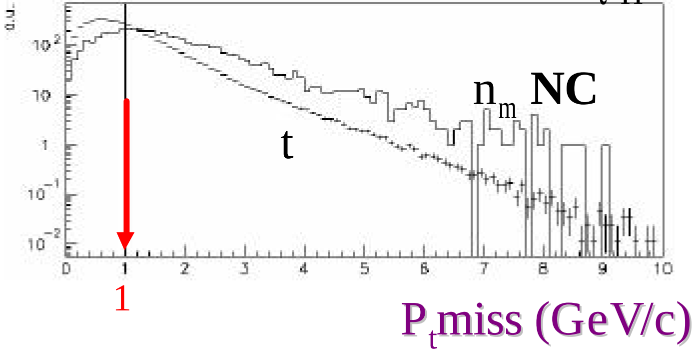
hadronic channels > **600, 300 Mev/c**



- **Additional kinematic cuts at 1ry vtx. for the hadronic channels**

F$_{t\text{-}H}$ > p/2

P$_t$miss < 1 GeV/c



Short decay topology:

- **At least two additional 1ry tracks for vertex reconstruction**

  P > 1.0 GeV/c

- **Require a large impact parameter**

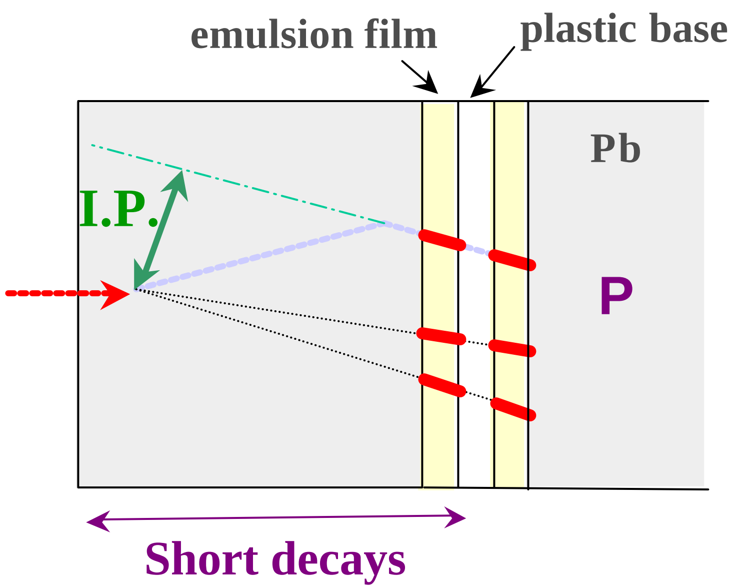
  I.P. > 5 to 20 mm

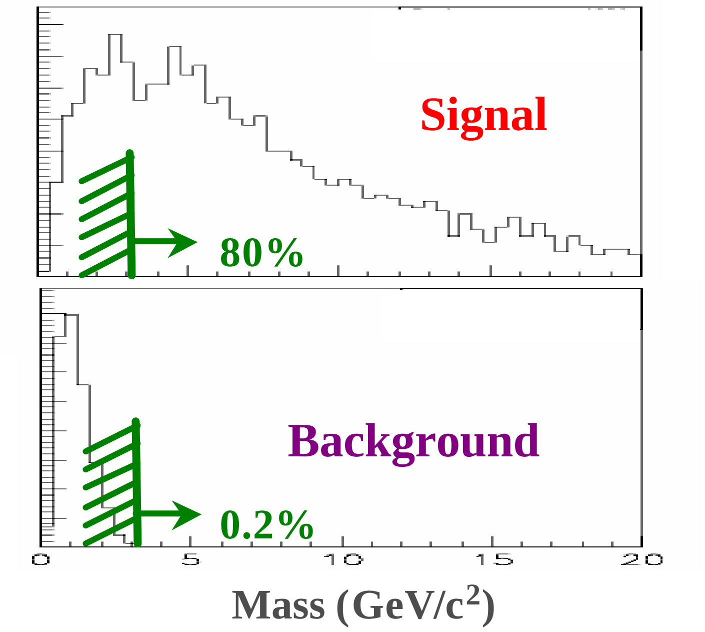
  leptonic channels t ® **e,** m

- **Additional kinematic cuts on minimal mass/P_T for n_eCC/charm rejection**

  $(P_T)_{min}$ > 50 **Mev/c** t ® **e**

  $(M_{inv})_{min}$ **> 3 GeV/c** t ® m



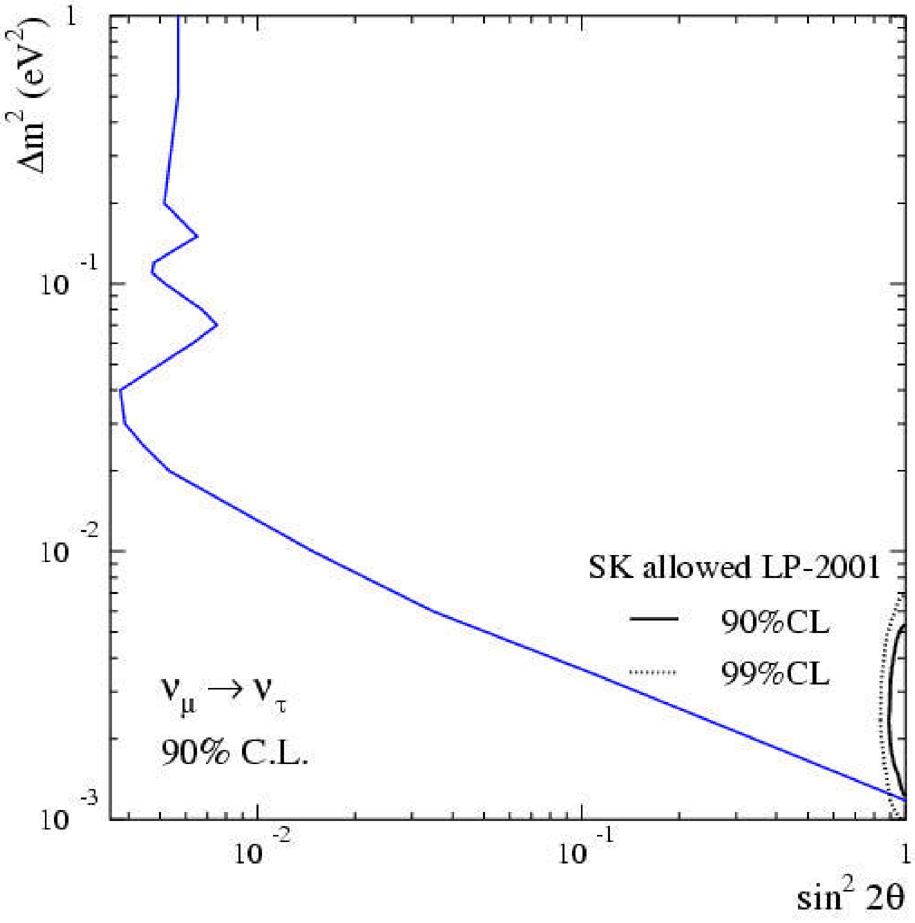


- **Number of signal and background events expected within the 90% CL Super-K allowed region (5 year run, 1800 t):**

Decay mode	*Signal* $1.6 \times 10^{-3}\ eV^2$	*Signal* $2.5 \times 10^{-3}\ eV^2$	*Signal* $4.0 \times 10^{-3}\ eV^2$	*Bkgnd*
$\tau \to e$ *long*	*1.4*	*3.4*	*8.6*	*0.15*
$\tau \to \mu$ *long*	*1.3*	*3.2*	*8.1*	*0.29*
$\tau \to h$ *long*	*1.6*	*3.7*	*9.4*	*0.23*
$\tau \to e$ *short*	*0.4*	*1.0*	*2.5*	*0.03*
$\tau \to \mu$ *short*	*0.2*	*0.5*	*1.3*	*0.04*
Total	$\boxed{\mathbf{4.9}}$	$\boxed{\mathbf{11.8}}$	$\boxed{\mathbf{30.0}}$	$\boxed{\mathbf{0.74}}$

- *Lead/emulsion sandwitch* $\Longrightarrow$ *better momentum measurement (MS) than CHORUS*
  Passive material (Pb) $\Longrightarrow$ *lower overall efficiency (short/long)*

Experimental **sensitivity** (5 years, 1.8kt):



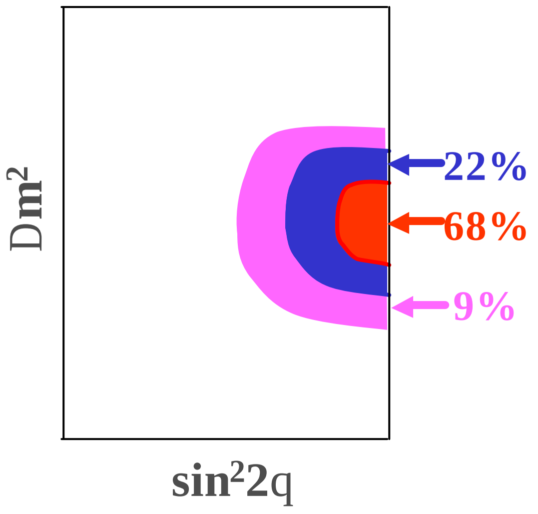
90 % CL upper limit obtained ***on average*** *by a large* ***ensemble of experiments****,* *in the absence of signal events*

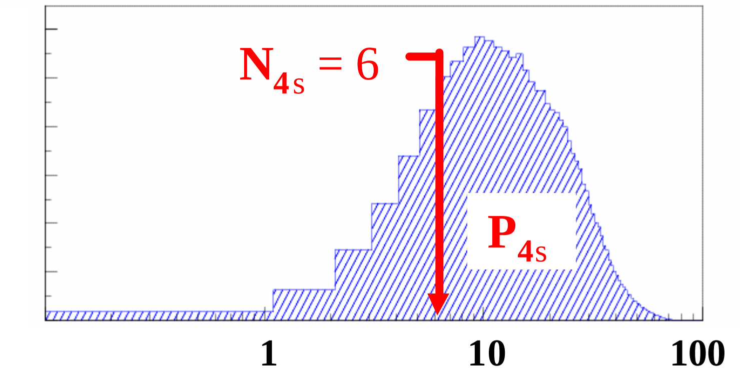
Δm^2	**$< 1.2\times10^{-3}$ eV^2 at full mixing**
$\sin^2(2\theta)$	**$< 5.7\times10^{-3}$ at large Δm^2**

Uncertainties on background (±33%) and on efficiencies (±15%) included

Probability of ^{3} ns significance:

Schematic view of the Super-K allowed region





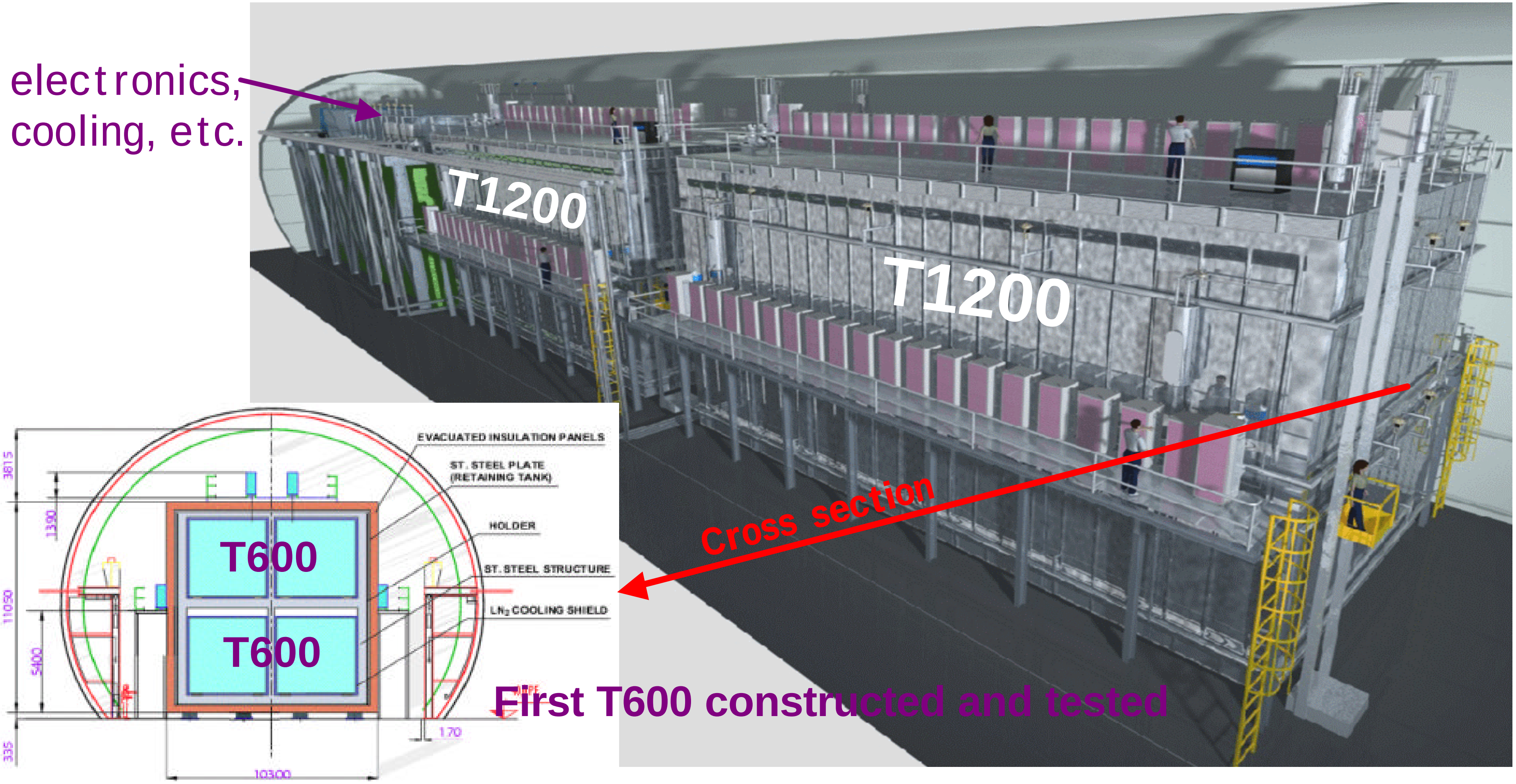
Distribution of events observed

- Simulate a **large number of experiments** with oscillation parameters generated according to the Super-K probability distribution
- **N_{ns} events are required for a ns significance**
- **Evaluate the fraction P_{ns} of experiments observing ^{3} N_{ns} events**

Run	P_{3s} (%)	P_{4s} (%)
3 y	88	82
5 y	96	90

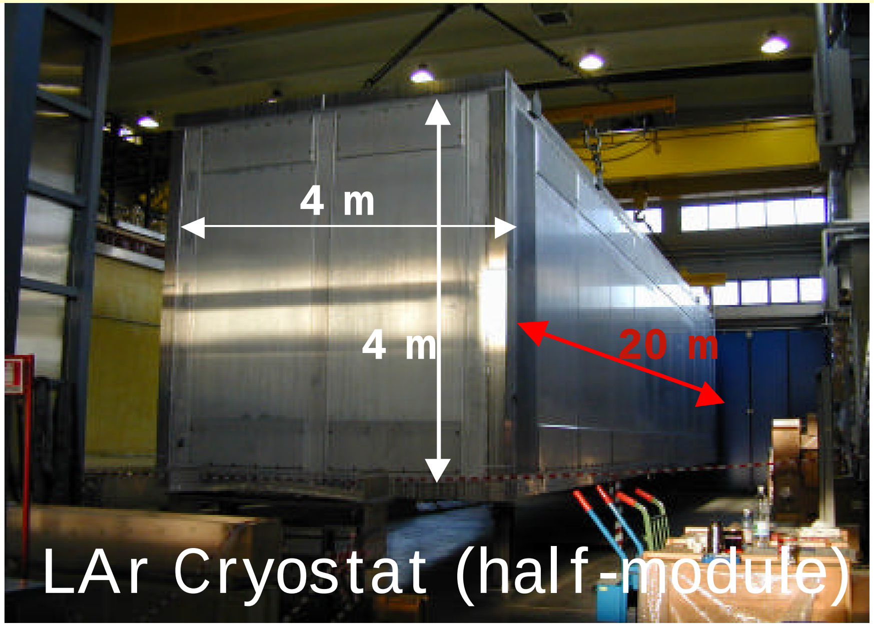
THE ICARUS DETECTOR

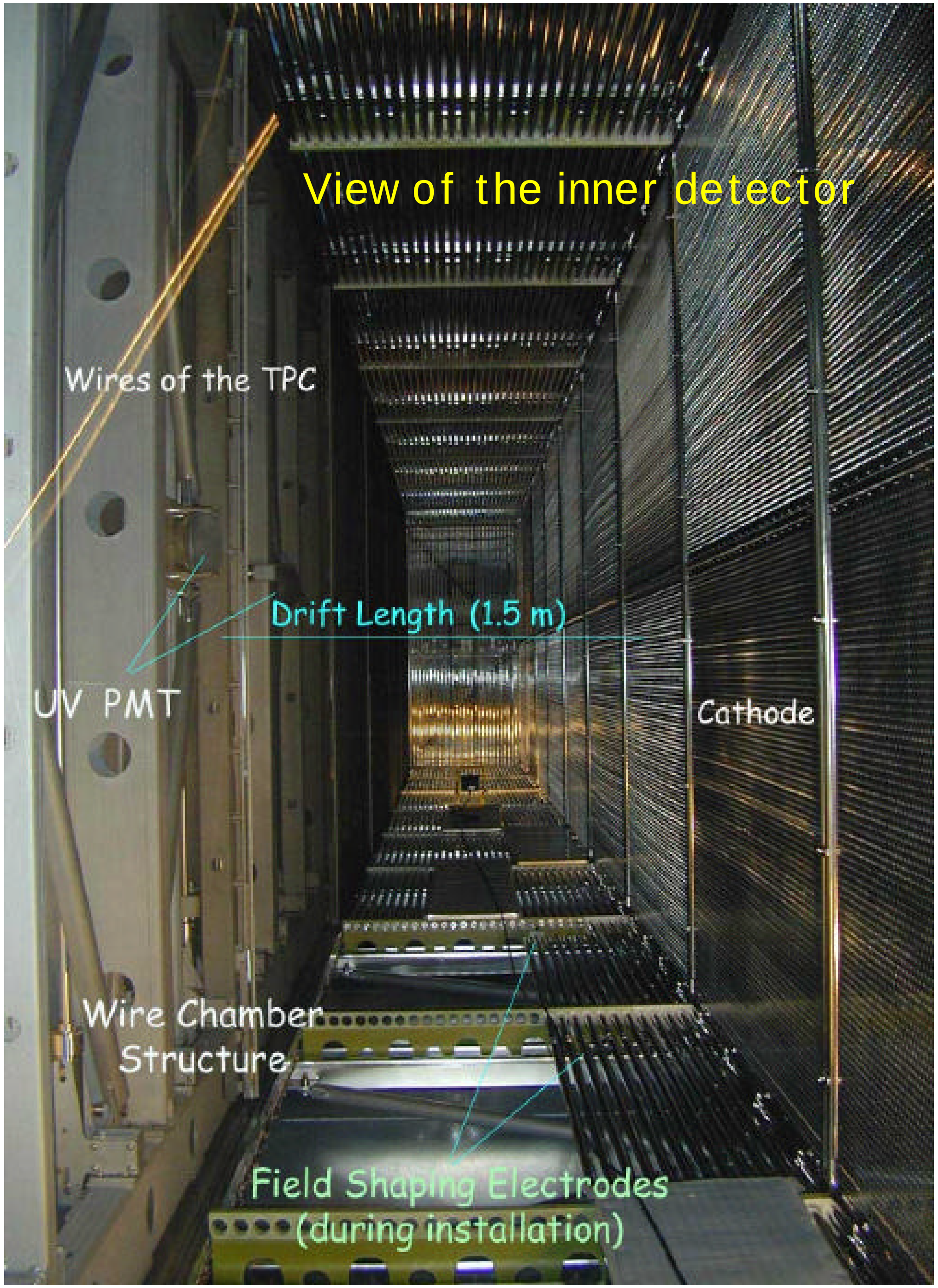
- *Basic element T600 LAr modules (TPC)*
- *Proposed baseline **T600 + 2 * T1200** (3000 t)*



First T600 constructed and tested

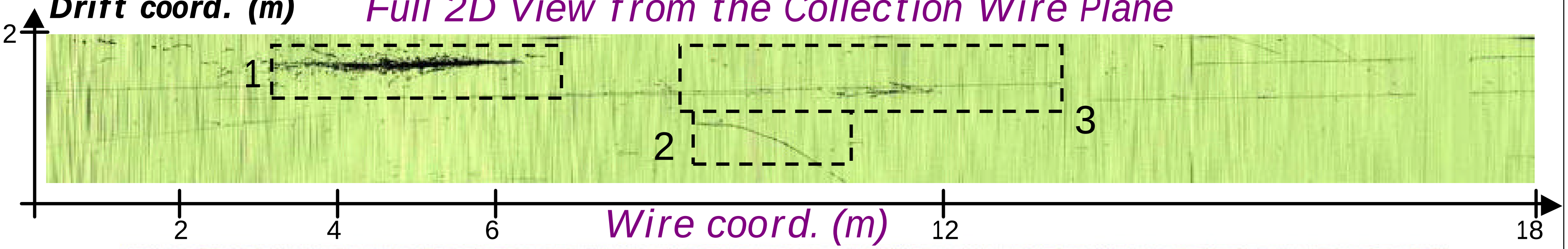
THE T600 DETECTOR





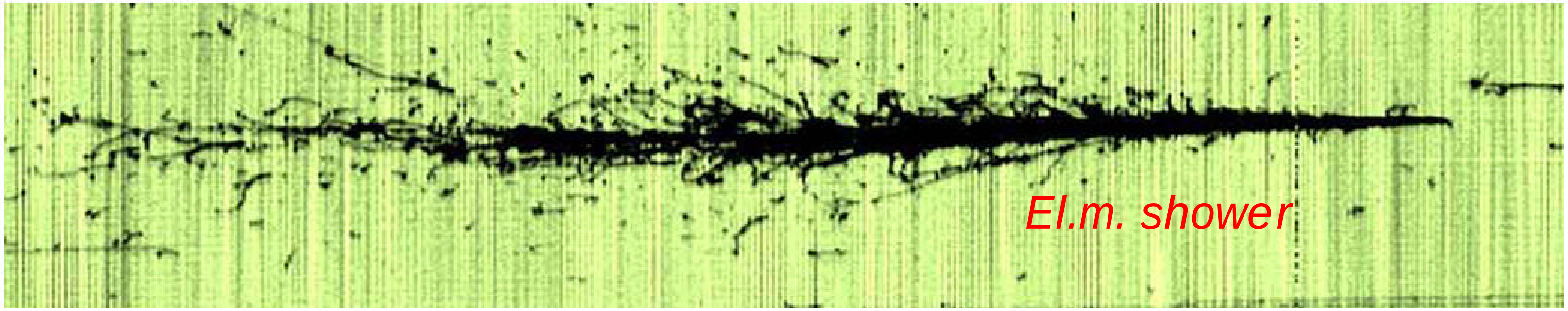
Data from T600

Full 2D View from the Collection Wire Plane

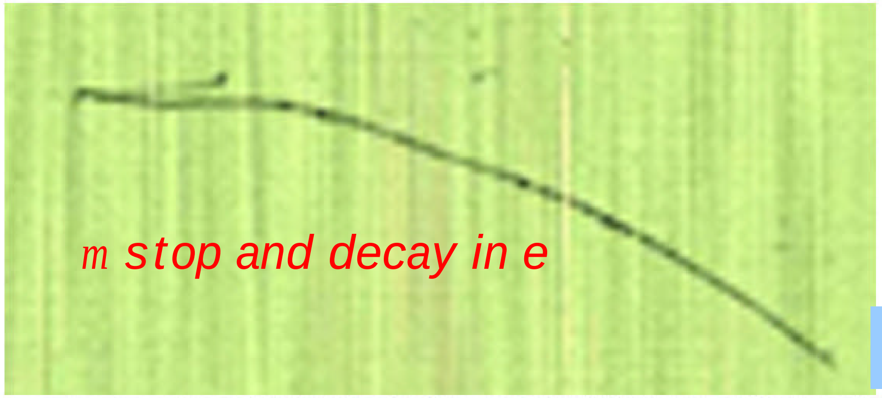


Zoom views

1

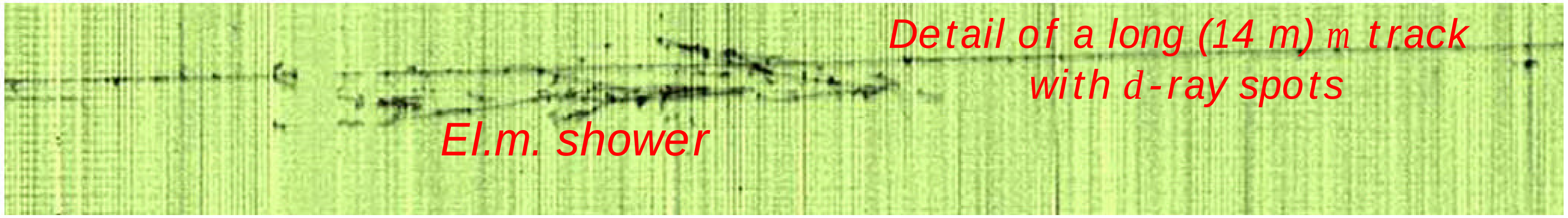


2

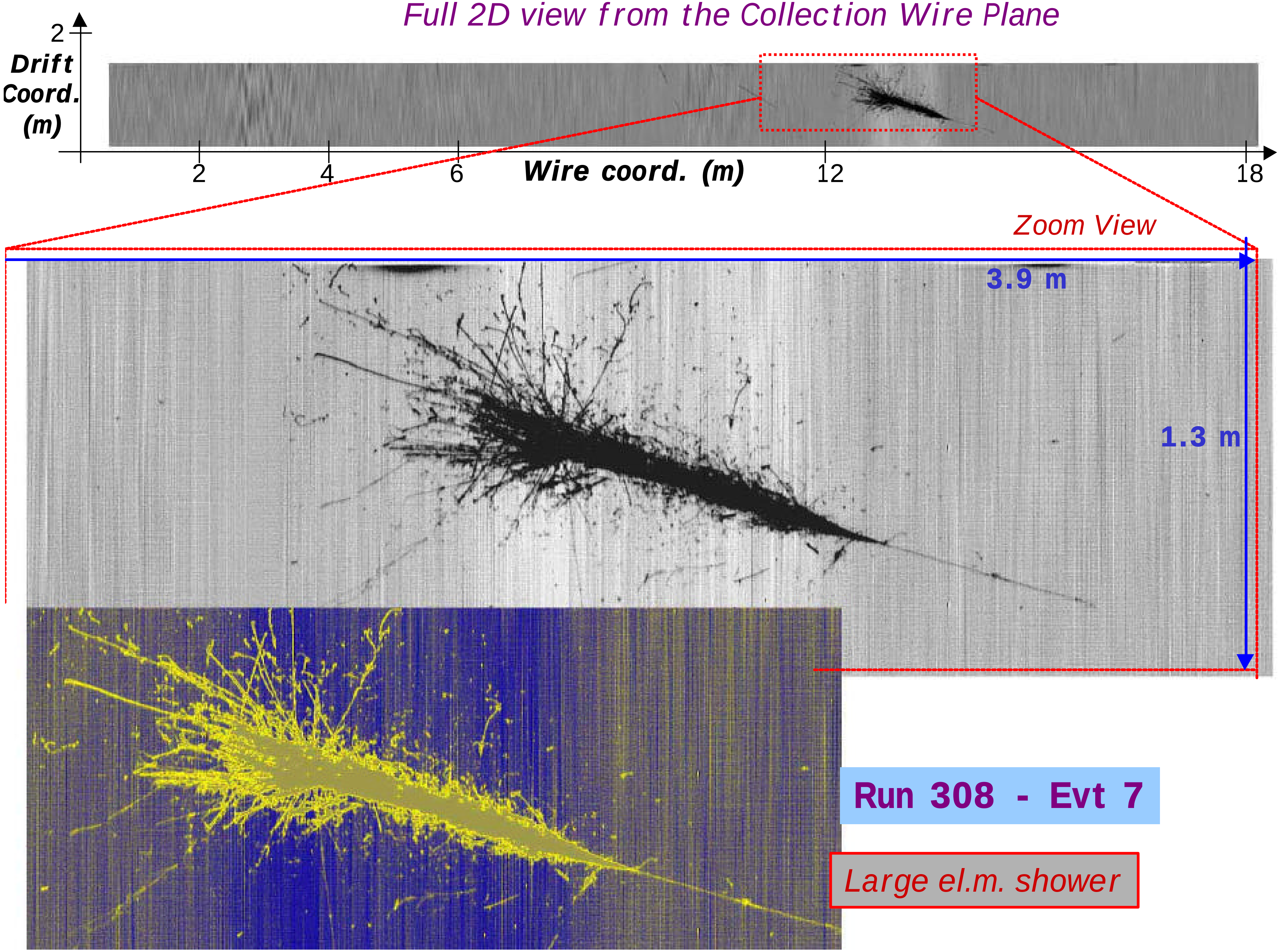


Run 201 - Evt 12

3



Full 2D view from the Collection Wire Plane



Run 308 - Evt 7

Large el.m. shower

THE ICARUS ν_τ SEARCH

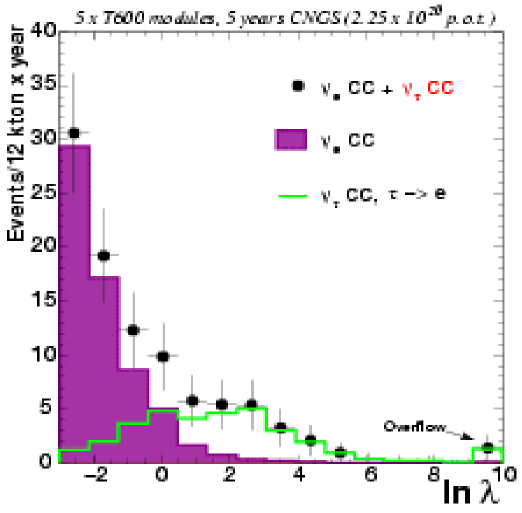
✦ **Signal/background discrimination based upon kinematic criteria similar to NOMAD:**

I ELECTRON CHANNEL :

- *Electron candidate with $P > 0.5$ GeV/c*
- *Main bkgnd from ν_e CC rejected with a multi-dimensional likelihood function:*

$$\mathcal{L}_e^{CC} \stackrel{\text{def}}{\equiv} [\rho_l, \not{P}_T, E_{\text{vis}}]$$

- *Residual ν_μ CC bkgnd rejected by muon ID in LAr (muon veto)*



II HADRONIC CHANNELS :

The $\tau \to \rho$ channel is exploited in the two independent Deep-inelastic (DIS) and Quasi-elastic (QE) samples.

- *Momentum $P_\rho > 5.0$ GeV/c*
- *Invariant mass constraints*
- *Largest bkgnd from NC rejected by isolation (Q_T) in DIS*
- *Residual ν_μ CC bkgnd rejected by muon veto.*

- **Number of signal and background events expected within the 90% CL Super-K allowed region (5 year run, 3000 t):**

Decay mode	*Signal* $1.6 \times 10^{-3}\ eV^2$	*Signal* $2.5 \times 10^{-3}\ eV^2$	*Signal* $4.0 \times 10^{-3}\ eV^2$	*Bkgnd*
$\tau \rightarrow e$	*3.7*	*9.0*	*23.0*	*0.7*
$\tau \rightarrow \rho$ *DIS*	*0.6*	*1.5*	*3.9*	< 0.1
$\tau \rightarrow \rho$ *QE*	*0.6*	*1.4*	*3.6*	< 0.1
Total	**4.9**	**11.9**	**30.5**	**0.7**

$\Longrightarrow$ *sensitivity to* $\nu_\mu \rightarrow \nu_\tau$ *oscillations similar to the OPERA experiment.*

- *Lower background & fully sensitive detector* $\Longrightarrow$ *larger efficiencies than NOMAD*
  No charge measurement $\Longrightarrow$ *the* τ^+ *control sample is not available*

THE ICARUS $\nu_\mu \to \nu_e$ SEARCH

Exploit the good electron identification

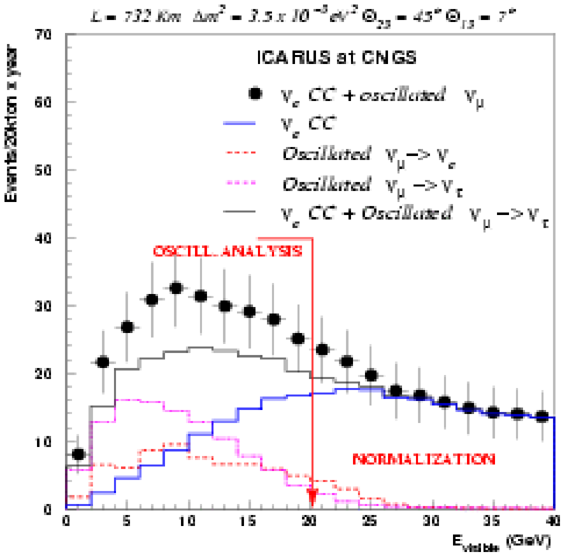
◆ *Main goal to constrain the mixing* $\boxed{\text{ANGLE } \theta_{13}}$, *accessible via a sub-leading oscillation (three-ν mixing):*

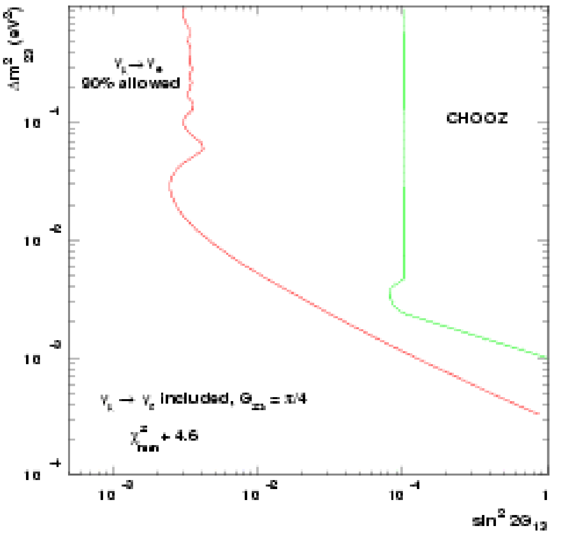
$$
\begin{aligned}
P(\nu_e \to \nu_\mu) &\sim \sin^2\theta_{23} \boxed{\sin^2\theta_{13}} \sin^2\left(\frac{1.27\Delta m^2_{23}L}{E_\nu}\right) \\
P(\nu_\mu \to \nu_\tau) &\sim \cos^4\theta_{13}\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{23}L}{E_\nu}\right) \quad \mid \Delta m^2_{12} \mid \ll \mid \Delta m^2_{23} \mid
\end{aligned}
$$

◆ $\boxed{\text{APPEARANCE}}$ *of ν_e CC events, with $\nu_\mu \to \nu_\tau$ followed by the decay $\tau \to e$ as a background.*

$\Longrightarrow$ *disentangle $\nu_\mu \to \nu_e$, $\nu_\mu \to \nu_\tau$ and intrinsic ν_e CC with kinematic distributions (E_{vis}, $\not{p}_T$).*

◆ *Simultaneous fit to extract $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ rates in the region $E_e > 1$ GeV and $E_{\text{vis}} < 20$ GeV.*





CONCLUSIONS

✦ The short baseline program recently completed at CERN produced an unprecedent neutrino data sample, allowing at the same time large statistics ($> 10^6$) and high resolution measurements.

⟹ large potential for neutrino physics.

✦ The short baseline neutrino experiments at CERN have demonstrated that two different approaches are possible for a ν_τ appearance search:

- The automatic emulsion scanning (CHORUS) is efficient thanks to the continuous advancements in the microscope technology;
- The kinematic method (NOMAD) is reliable and can be controlled up to the extreme tails of the distributions.

⟹ valid techniques for LBL experiments

✦ The long baseline neutrino beam from CERN to Gran Sasso is currently under construction (to be completed by 2005). Two different detectors are foreseen at Gran Sasso for the detection of the appearance of ν_τ CC events:

- OPERA is a hybrid emulsion-based experiment, approved as CNGS1 in 2000 (in preparation).
- ICARUS is an electronic detector based upon a LAr TPC (proposal).