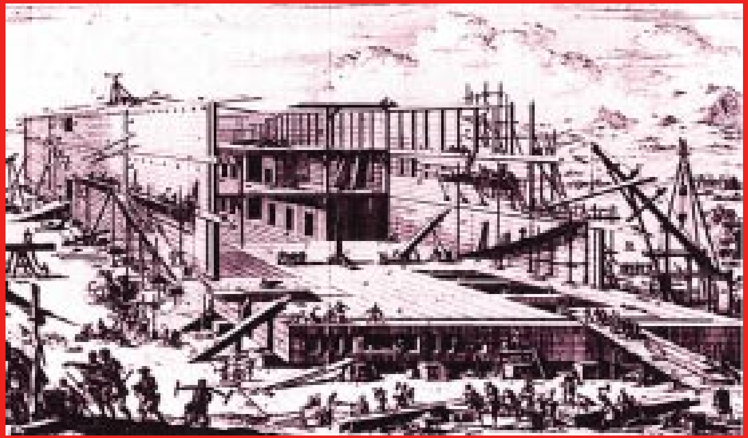
Status of the ICARUS/ICANOE experiment



André Rubbia
ETH Zürich

Particle Physics Seminar
Université de Genève

May 31st, 2000

Weak charged currents

By symmetry arguments, one would expect quark and lepton weak currents to have similar structure:

Quarks charged current:

$$(\bar{u} \quad \bar{c} \quad \bar{t})_L \gamma^\mu U_q \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} \equiv U_q \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak eigenstates **Flavor eigenstates**

Leptons charged current:

$$(\bar{e} \quad \bar{\mu} \quad \bar{\tau})_L \gamma^\mu U_l \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \equiv U_l \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Weak eigenstates **Mass eigenstates**

However, in the Standard Model, neutrinos are massless (degenerate)

$$\Rightarrow U_l \equiv 1$$

$$\Rightarrow \quad (\bar{e} \quad \bar{\mu} \quad \bar{\tau})_L \gamma^\mu \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_L$$

Neutrino flavor oscillations (in vacuum)

In vacuum:

Time evolution of a neutrino mass eigenstate ν_i
(=stationary state of the free Hamiltonian)

$$e^{-iE_i t}$$

$E_i \equiv$ energy of state

Neutrino state produced in weak decay:

$$\left|\nu(t=0)\right\rangle \equiv \left|\nu_\alpha\right\rangle$$

$(\alpha \equiv$ **e,μ,**$\tau)$

$$\left|\nu(t=0)\right\rangle \equiv \left|\nu_\alpha\right\rangle = \sum_j U_{\alpha j}\left|\nu_j\right\rangle \Rightarrow \left|\nu(t)\right\rangle = \sum_j U_{\alpha j}\underbrace{e^{-iE_j t}}\left|\nu_j\right\rangle$$

phase

Neutrino flavor oscillation probability:

$$P_\alpha \equiv \left|\left\langle \nu_\alpha \mid \nu(t)\right\rangle\right|^2$$

Oscillation probability

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

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

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

- The oscillation probability is:

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

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

Neutrino oscillation phenomenology

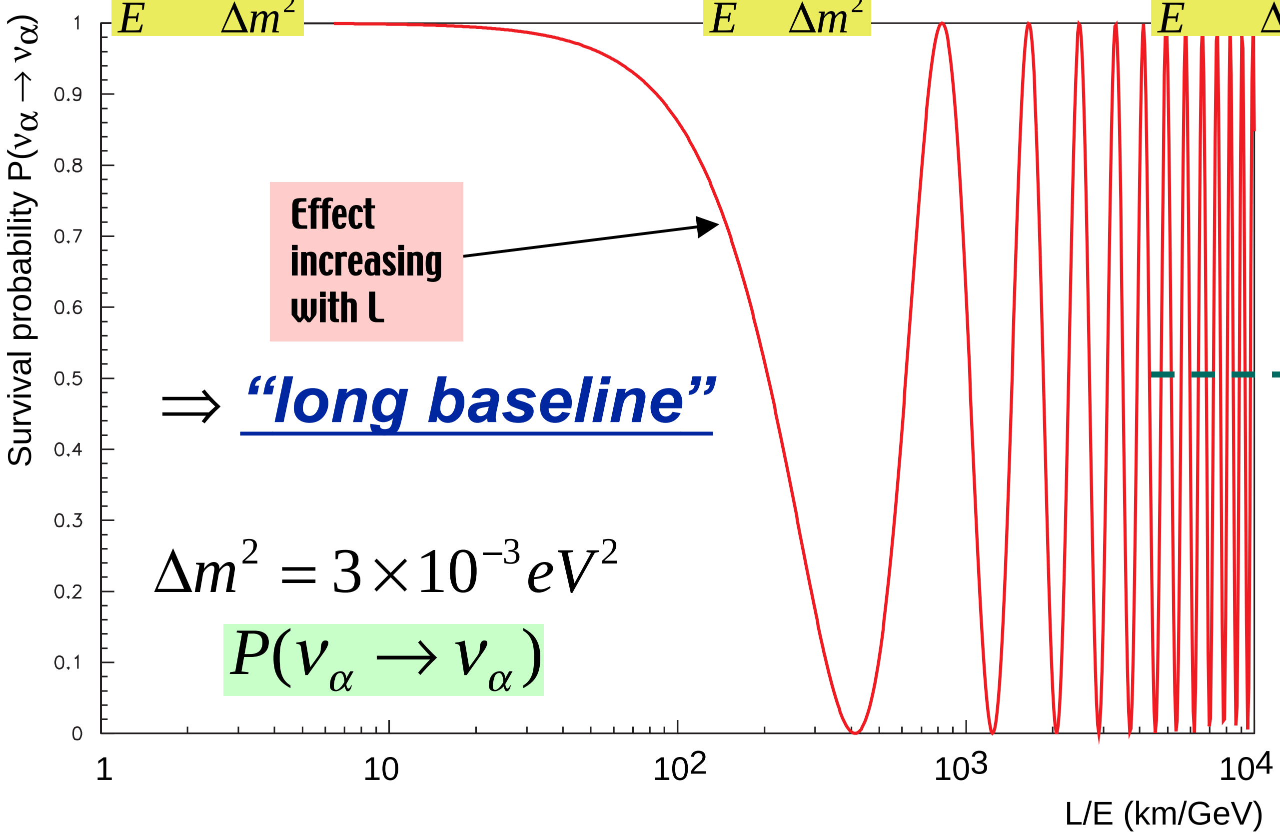
- In interesting cases, the oscillations decouple so that they are approximated by a **two-neutrino oscillation** :

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

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\ \ \Delta m_{12}^2 L}{E}\right)$$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\ \ \Delta m_{12}^2 L}{E}\right)$$

$\frac{L}{E} << \frac{1}{\Delta m^2}$ $\frac{L}{E} \approx \frac{1}{\Delta m^2}$ $\frac{L}{E} >> \frac{1}{\Delta m^2}$



Effect increasing with L

$\Rightarrow$ ***“long baseline”***

$\Delta m^2 = 3 \times 10^{-3} eV^2$

$P(\nu_\alpha \to \nu_\alpha)$

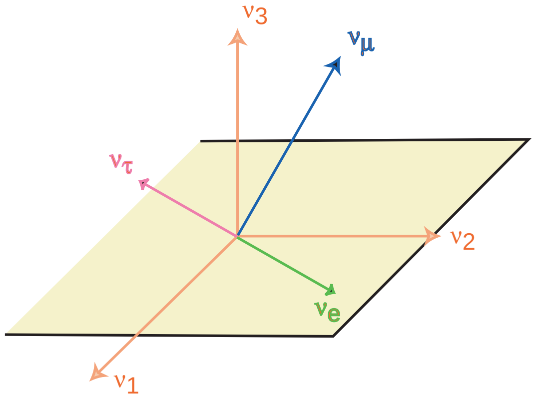
At large distance P ≈ 1/2

Three flavor mixing

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

Mass eigenstates

Weak eigenstates



$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = P_{CP}(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) \pm P_{\not{C}\not{P}}(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta)$$

CP-conserving

CP-violating

$$P_{CP} = \delta_{\alpha\beta} - 4\sum_{j>k} \mathrm{Re}\, J_{\alpha\beta jk} \sin^2 \Delta_{jk}$$

$$P_{\not{C}\not{P}} = 4\sum_{j>k} \mathrm{Im}\, J_{\alpha\beta jk} \sin \Delta_{jk} \cos \Delta_{jk}$$

$$J_{\alpha\beta jk} = U_{\alpha k} U^*_{\beta k} U^*_{\alpha j} U_{\beta j}$$

Mixing strength

$$\Delta_{jk} = \frac{1.27 \;\; \Delta m^2_{jk} L}{E}$$

Oscillatory pattern

Δm^2_{jk} in eV^2, L in km, E in GeV

In general, the oscillation pattern may be complicated and involve **a combination of transitions** to ν_e, ν_μ, ν_τ and by symmetry with quark sector **it is natural to expect CP violation** at some level.

Oscillation map – “allowed regions”

Two-neutrino oscillation

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

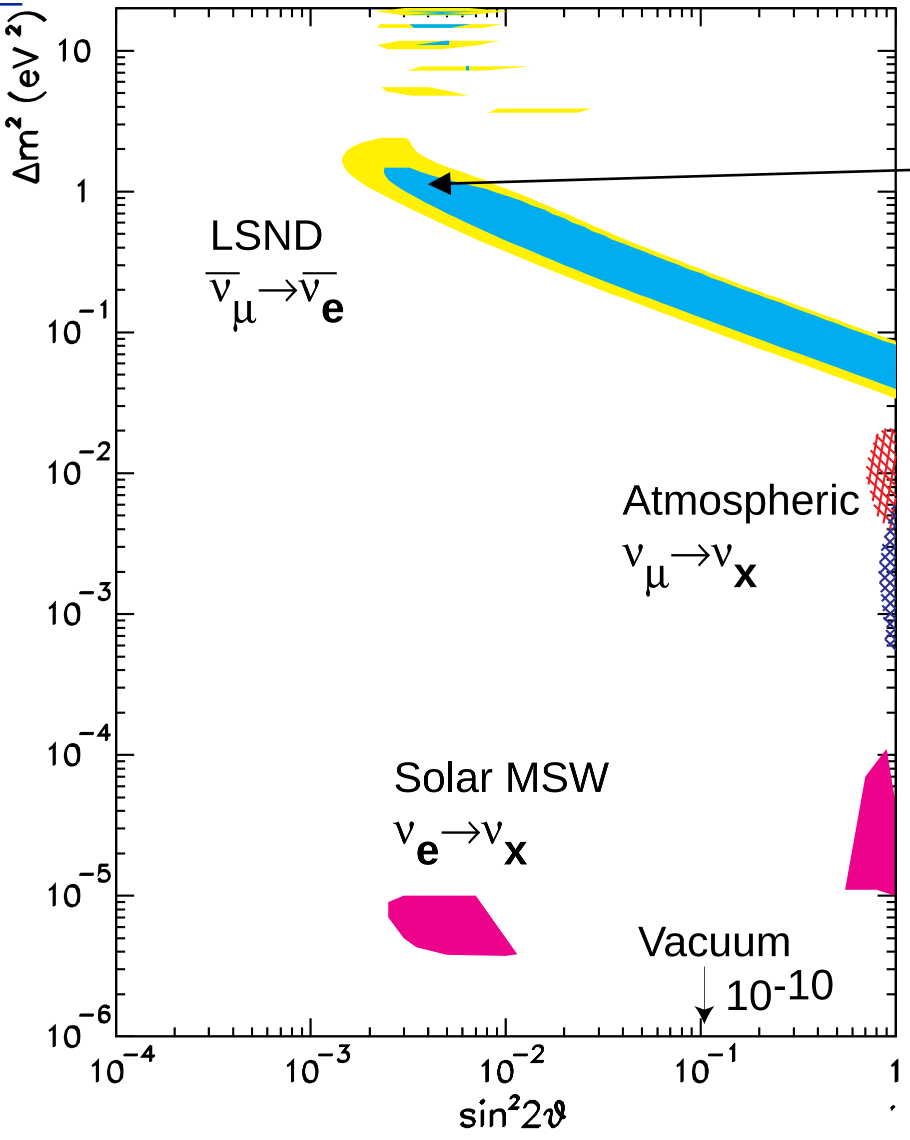
Electron excess

$\nu_\mu \rightarrow \nu_x$

Muon deficit

$\nu_e \rightarrow \nu_x$

Electron deficit



$\Delta m^2_{LSND} \approx 1\ eV^2$
$\sin^2 2\theta \approx 0.003$

$\Delta m^2_{atm} \approx 10^{-3}$–$10^{-2}\ eV^2$
$\sin^2 2\theta \approx 1$

$\Delta m^2_{solar} \approx 10^{-5}\ eV^2$
$\sin^2 2\theta \approx 0.8$ or 0.008

Matter enhanced (MSW effect)

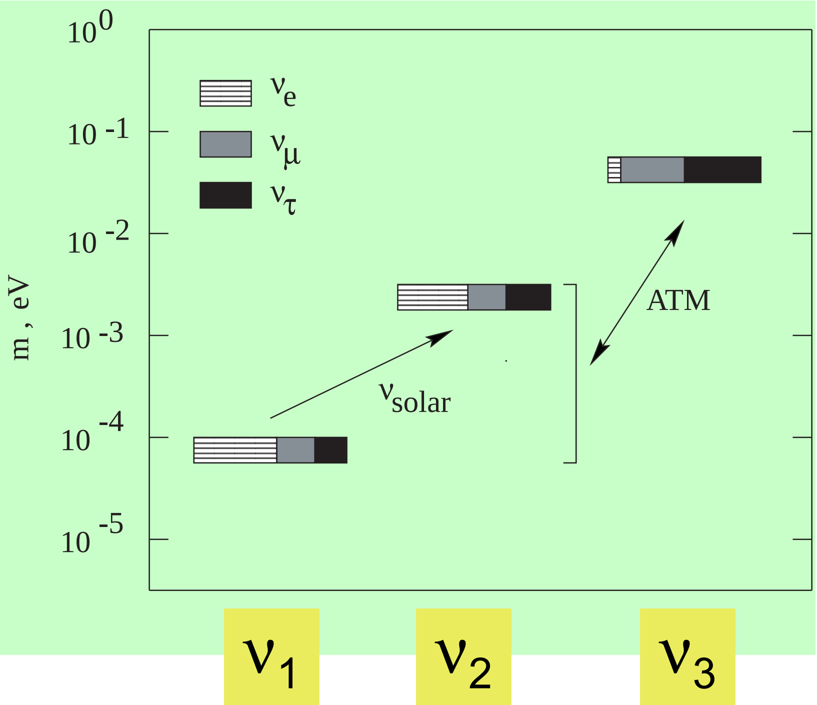
$\Delta m^2_{solar} \approx 10^{-10}\ eV^2$
$\sin^2 2\theta \approx 0.8$

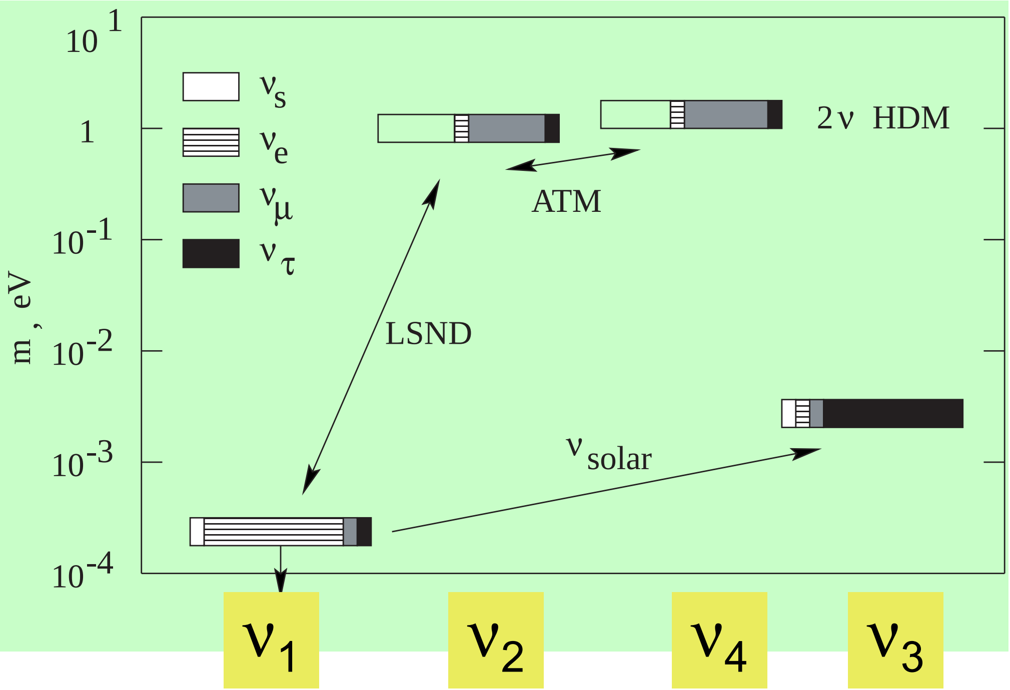
Vacuum oscillation

Where do we stand with the models?

- The three-flavor mixing **cannot accommodate all experiments**
  - ➜ Only two independent Δm^2 with three neutrinos
  - ➜ 3 distinct Δm^2 regions $\Delta m^2_{solar} << \Delta m^2_{atm} << \Delta m^2_{LSND}$ required to accommodate solar, atmospheric and LSND data requires
  - ➜ transitions involving **“sterile” states** could be occurring as well

Smirnov, hep-ph/9907296

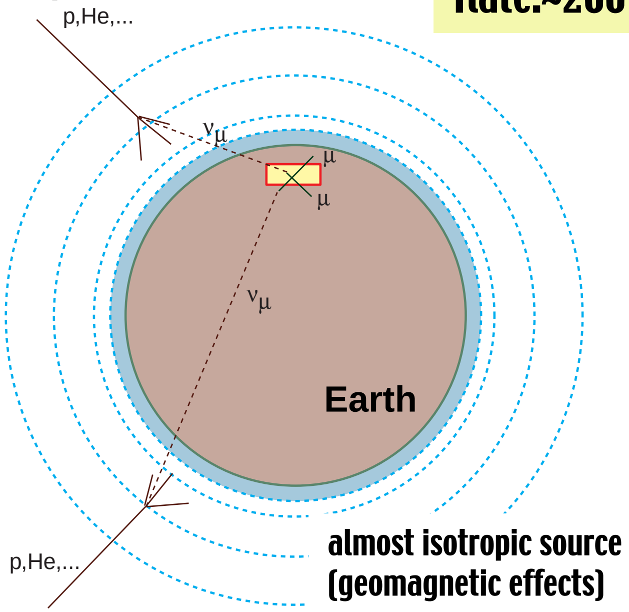




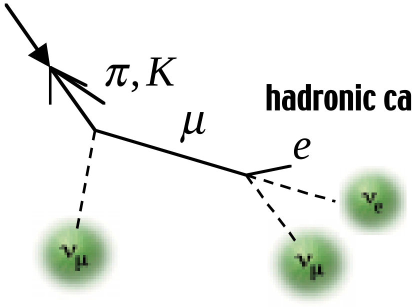
Atmospheric neutrinos

Earth is a splendid neutrino beam line!

Rate:≈200 events/kton/year



almost isotropic source (geomagnetic effects)



hadronic cascade + decays

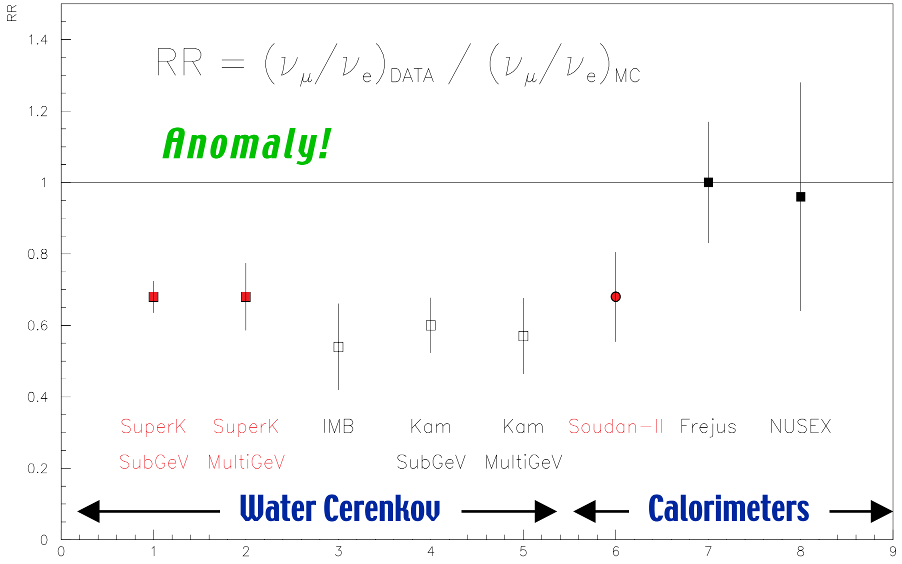
$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

Predicted ratio of muon to electron neutrinos

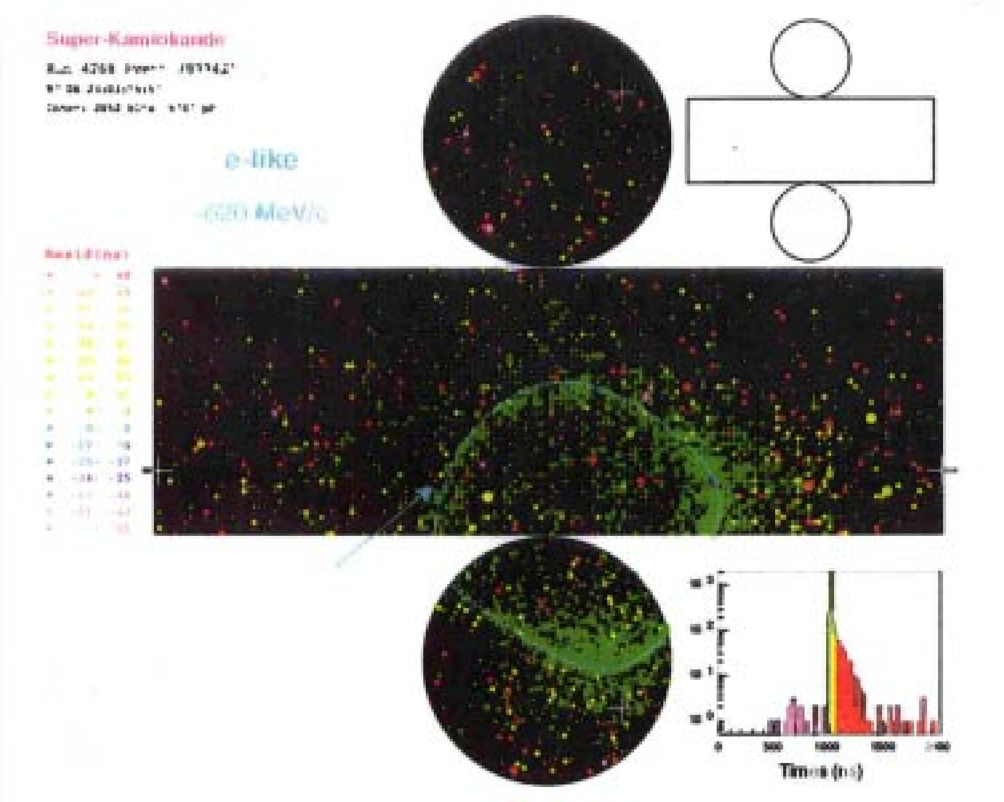
Use "double ratio":

$$RR \equiv \frac{(\mu / e)_{measured}}{(\mu / e)_{predicted}}$$

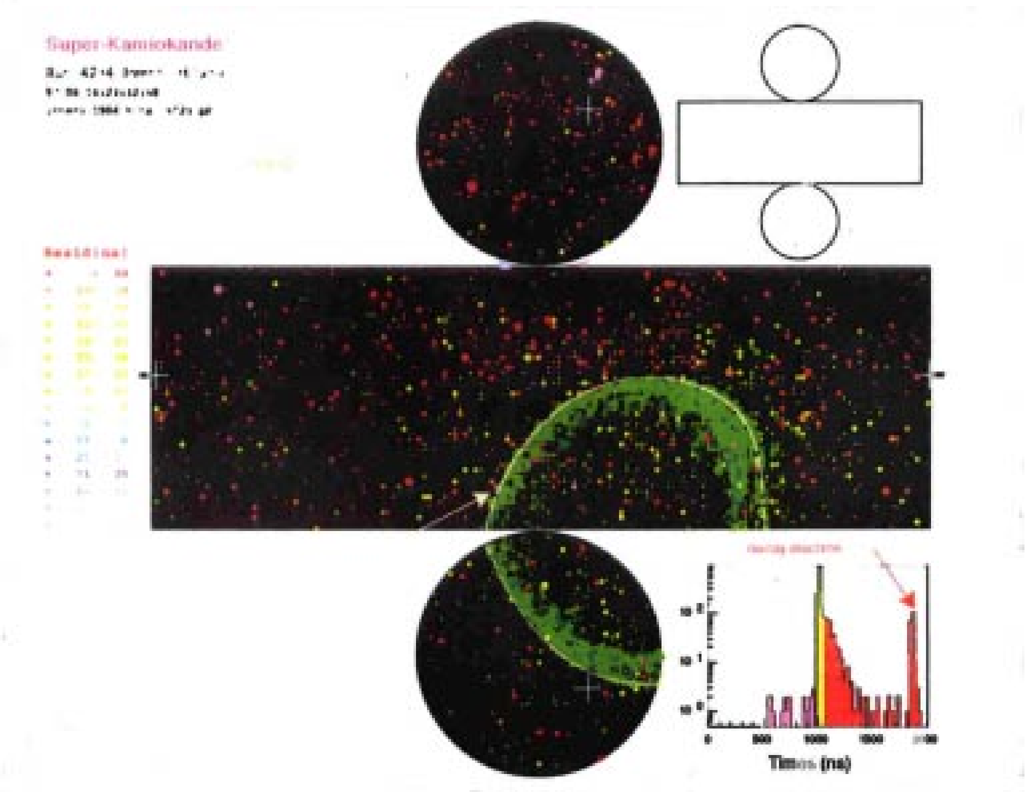
Experiment	Kt.year	RR
SuperK subGeV	**52.0**	**0.68±0.02±0.05**
SuperK multiGeV	**52.0**	**0.68±0.04±0.08**
IMB	7.7	0.54±0.05±0.11
Kam subGeV	6.1	0.60±0.06±0.05
Kam multiGeV	6.1	0.57±0.08±0.07
Soudan-II	**4.6**	**0.68±0.11±0.06**
NUSEX	0.4	0.96+0.32–0.28
Fréjus	2.0	1.00±0.15±0.08



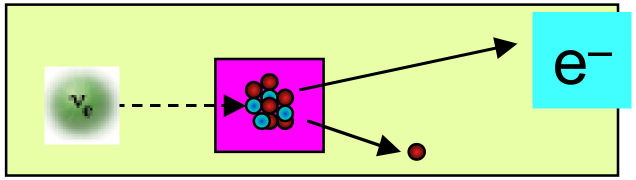
Electron and muon events in Superkamiokande

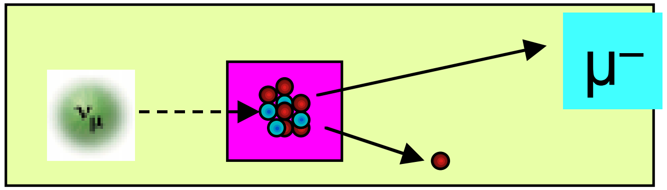


Electron-like event



Muon-like event

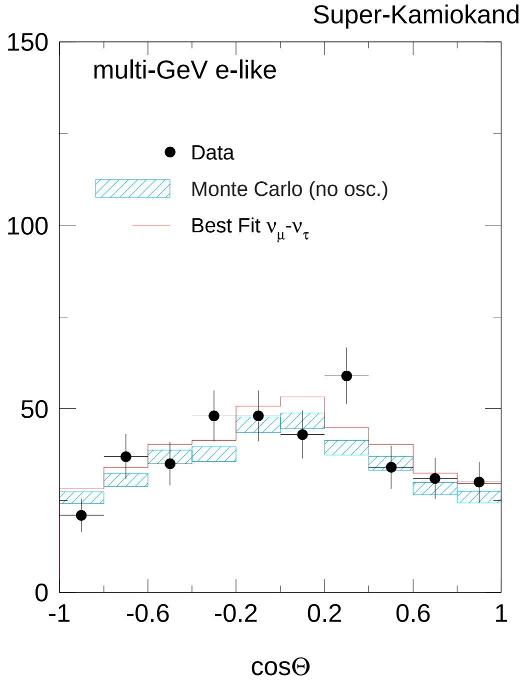


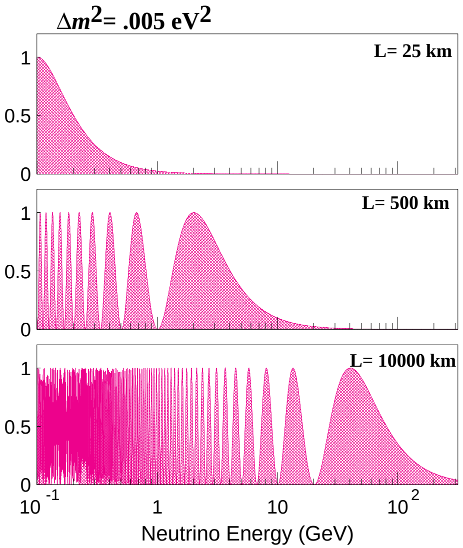


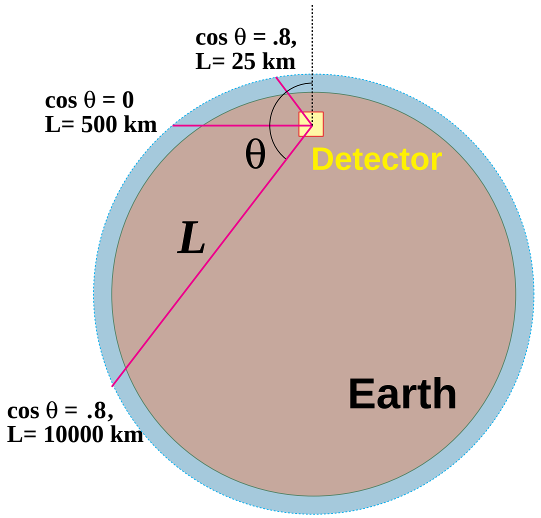
Note: at high energy, the direction & energy of outgoing e/μ is ≈ that of incoming neutrino

Zenith angle distribution

By looking in different zenith angle directions, one can select the neutrino "baseline" L…







$$P\left(\nu_\mu \to \nu_\mu\right) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

(Δm^2 in eV², L in km, E in GeV)

$$\Rightarrow \nu_\mu \to \nu_\tau \text{ oscillations?}$$

- ☛ ***ν_μ deficit increases with L***
- ☛ ***no apparent effect with ν_e***

$$U^2_{\mu 3} = U^2_{\tau 3} \approx \frac{1}{2}$$

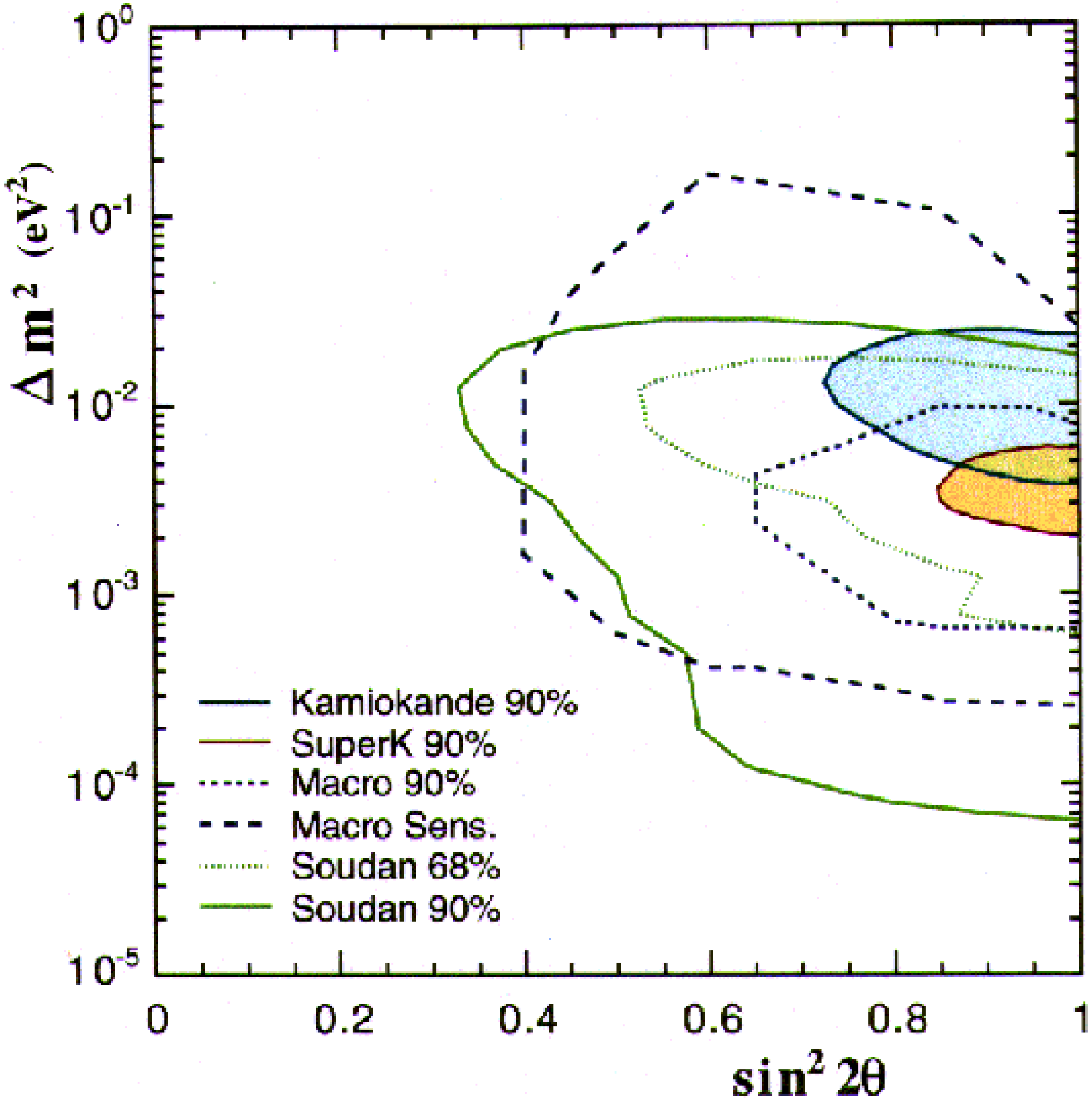
Maximal mixing

$$U^2_{e3} <\approx 0.05$$

Small mixture allowed

Agreement among atmospheric observations

Two-neutrino oscillation

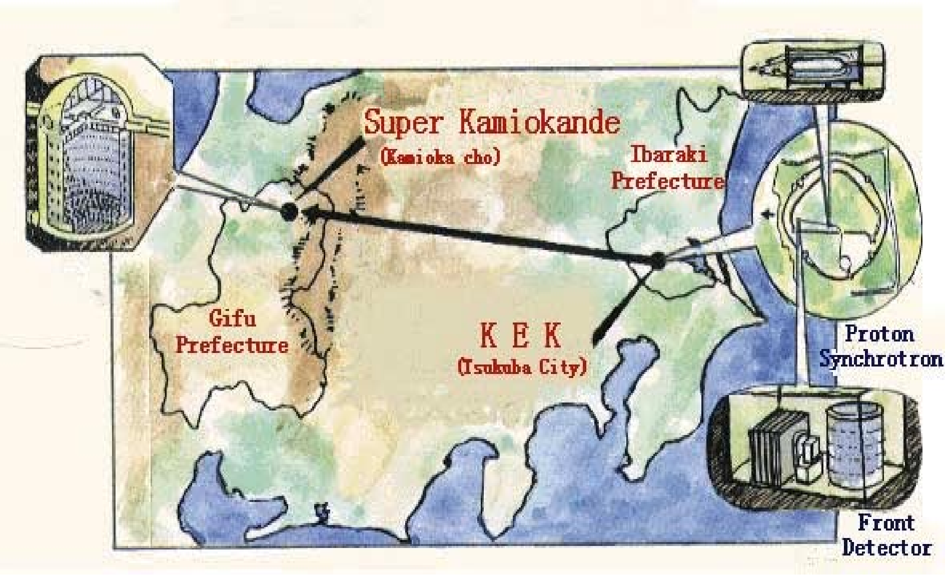


- Effect seen by many experiments in different modes
  - ➜ internal contained, PC events
  - ➜ Stopping/through upward μ
- Consistent with $\nu_\mu \Leftrightarrow \nu_\tau$ maximal mixing with $\Delta m^2 \approx 3\text{x}10^{-3}$ eV^2

Experiment	Analysis	Δm^2 is ...	Δm^2(eV)^2
Kamiokande	R	best fit	1.6×10^{-2}
Kamiokande	up-going μ	best fit	3.2×10^{-2}
Super K	R	best fit	2.2×10^{-3}
Super K	up-going μ	consistent with	2.5×10^{-3}
Soudan II	R	consistent with	$> 10^{-3}$
MACRO	up-going ν	consistent with	5×10^{-3}
MACRO	up-going μ	consistent with	2.5×10^{-3}

K2K experiment

- Experiment started in March 1999
  - Some initial problems with optics system now apparently solved
  - Beam intensity : 5.5 x 10^{12} ppp
  - Total integrated (Apr-Nov 99): **7.2 x 10^{18} pots** (goal: 10^{20} pots)
- ***Beam measured with near detectors*** (FD)
  - 3 different detectors: 1kt H_2O, SCIFI tracker+water, MUC (Fe μ ranger)
  - Event rate & energy spectrum under study
- ***Extrapolation at far detector*** (SK)



L = 250 km

$E_\nu \approx 1$ GeV

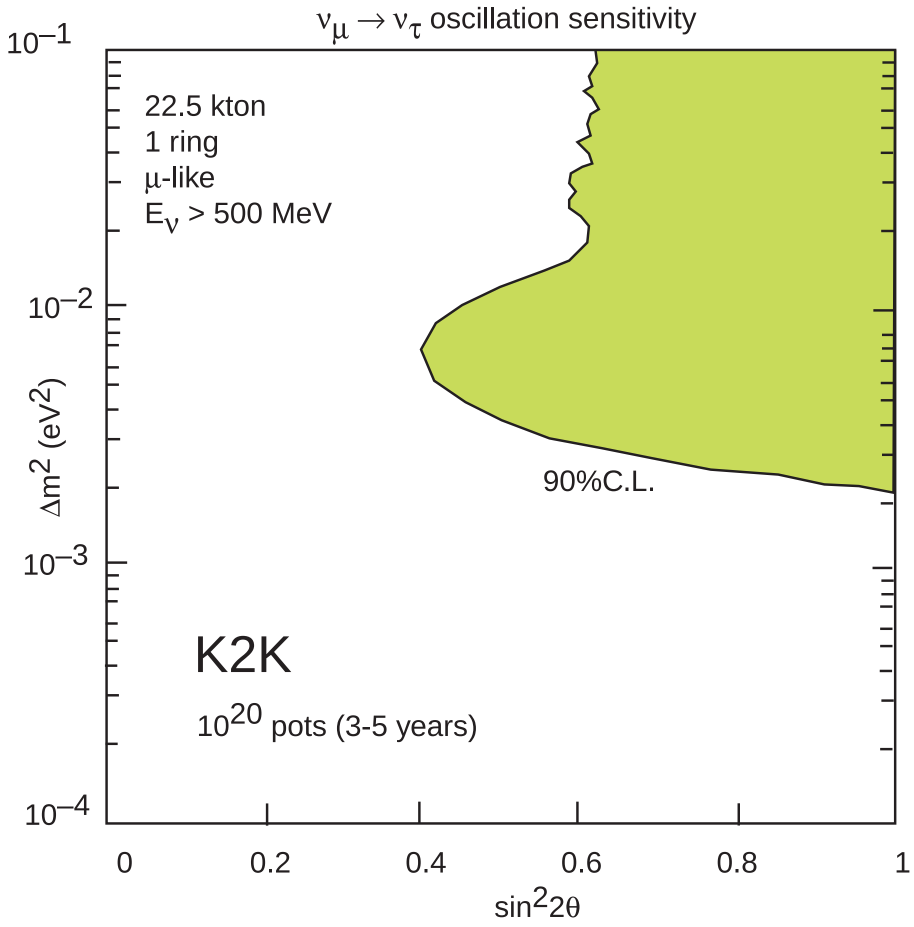
stat syst

Expected@SK: 12.1±0.1±1.8

Events seen: 3 events

⇒Consistent with a muon disappearance effect!

K2K sensitivity



1. *Will provide first confirmation of muon disappearance with artificial beam!*

✓ $$\boxed{\nu_\mu \to \nu_x}$$

2. *Measurement of Δm^2 & $\sin^2 2\theta$*

Limited by statistics

3. *No unambiguous flavor oscillation signature?*

$$\boxed{\nu_\mu \xrightarrow{?} \nu_\tau \cancel{\to} \tau + X}$$

Neutrino energy is below production threshold

4. *Subdominant $\nu_\mu \to \nu_e$ sensitivity?*

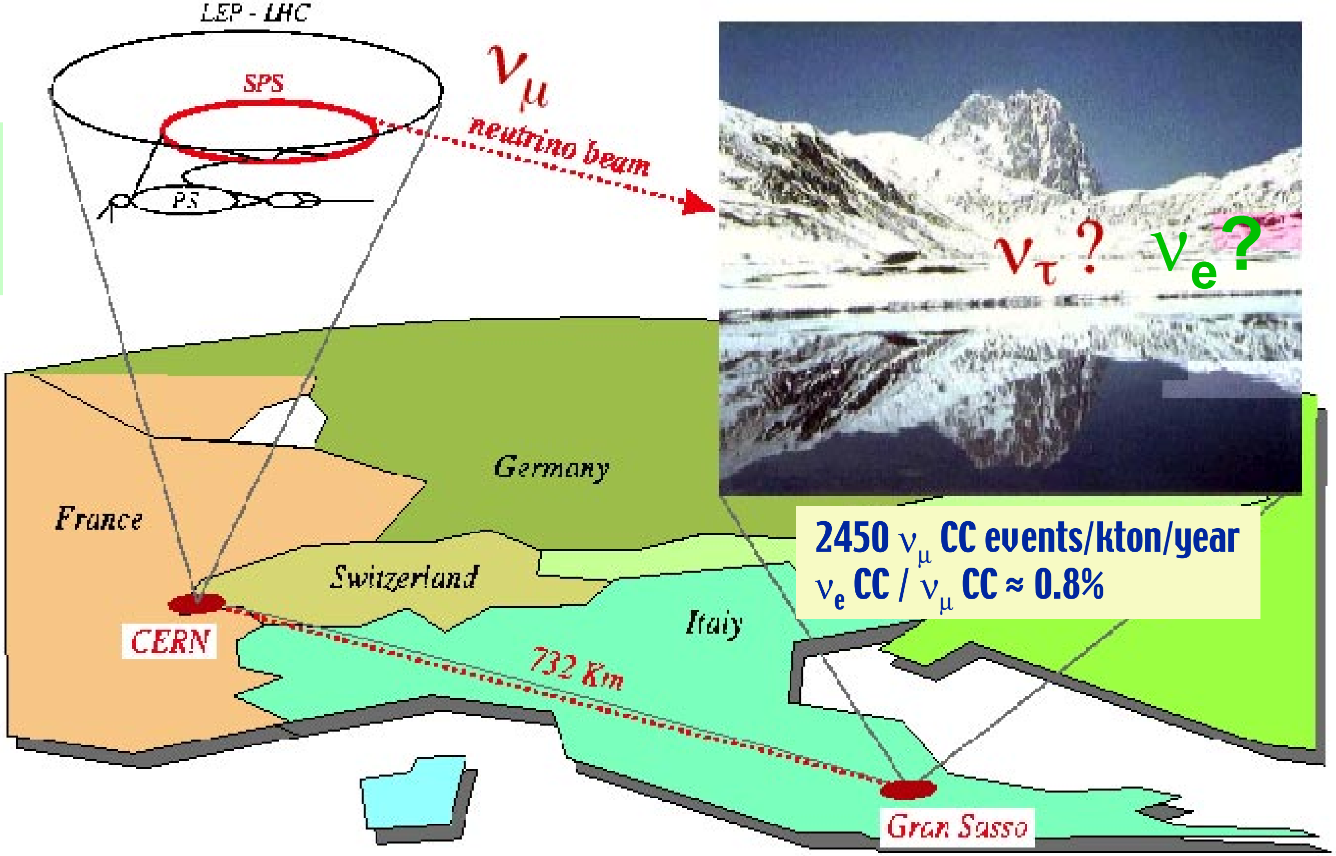
Poor (statistics, π^0 contamination)

CNGS neutrino beam

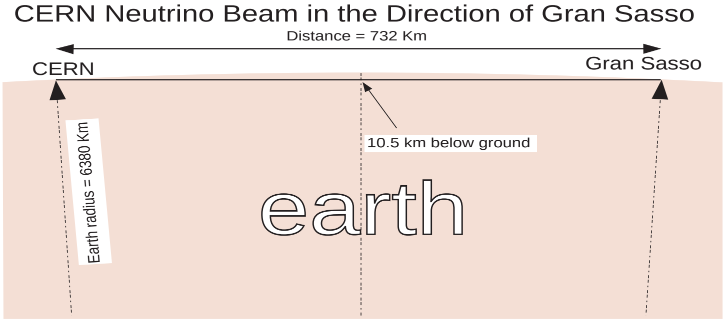
L = 732 km
$E_\nu \approx 17$ GeV

⇒Optimized for tau appearance

400 GeV protons from CERN/SPS (4.5×10^{19} pots /year "shared"; 7.6×10^{19} pots/year "dedicated")



2450 ν_μ CC events/kton/year
ν_e CC / ν_μ CC ≈ 0.8%



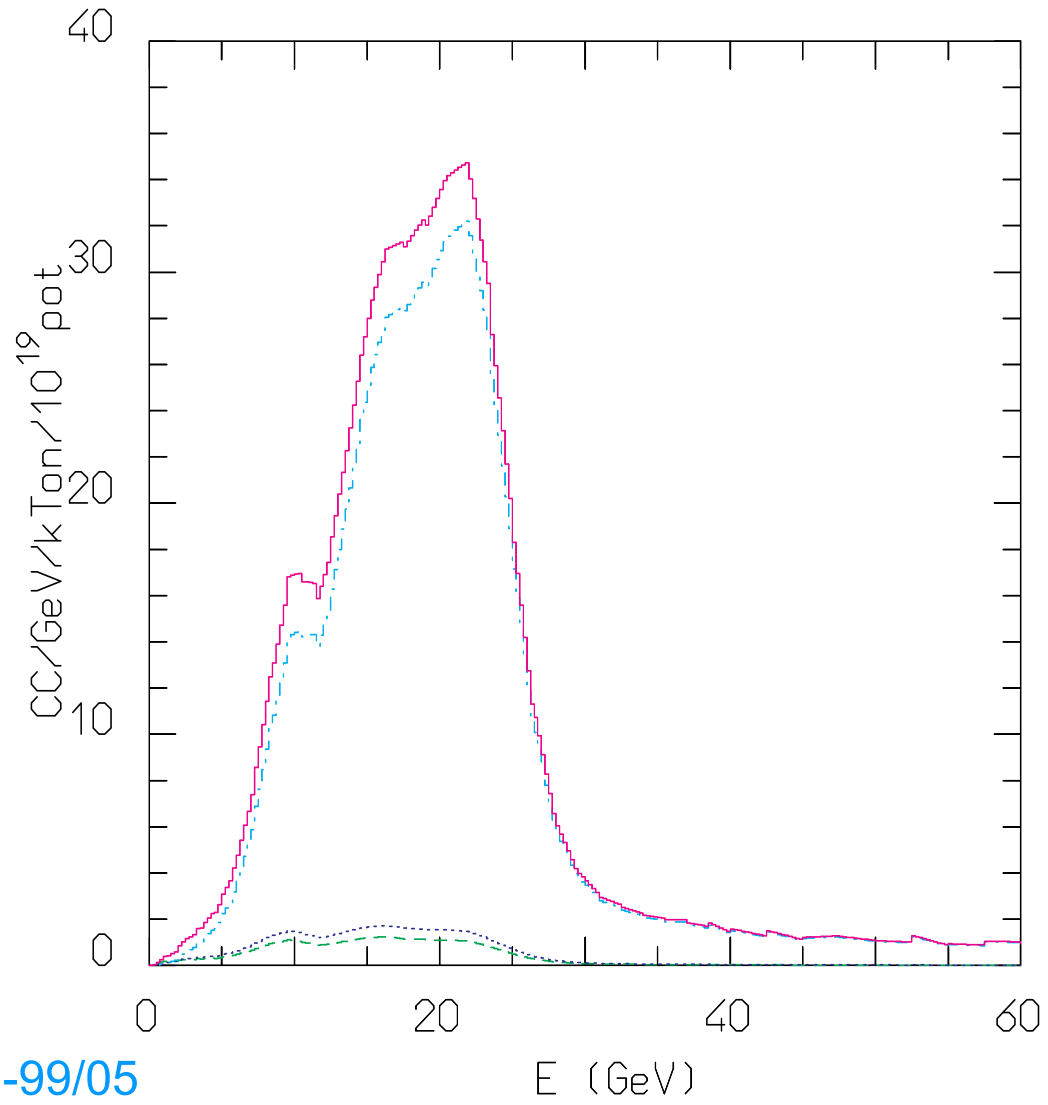
Approved program (Dec 1999)
⇒ beam ready in Spring 2005.

CERN 98-02 - INFN-AE/98-05
CERN-SL/99-034(DI) - INFN/AE-99/05

The CERN NGS event rates

- ✯ High energy p: 400 GeV
- ✯ Pots per year:
  - → **4.5×10^{19} pots** “shared”
  - → 7.6×10^{19} pots “dedicated”

Process	Rates (events/kton/year)
ν_μ CC	2450
$\bar{\nu}_\mu$ CC	49
ν_e CC	20
$\bar{\nu}_e$ CC	1.2
ν NC	823
$\bar{\nu}$ NC	17



CERN 98-02 - INFN-AE/98-05

CERN-SL/99-034(DI) - INFN/AE-99/05

Event rates at Gran Sasso

- No oscillations:

2450 ν_μ CC events/kton/year
ν_e CC / ν_μ CC ≈ 0.8%

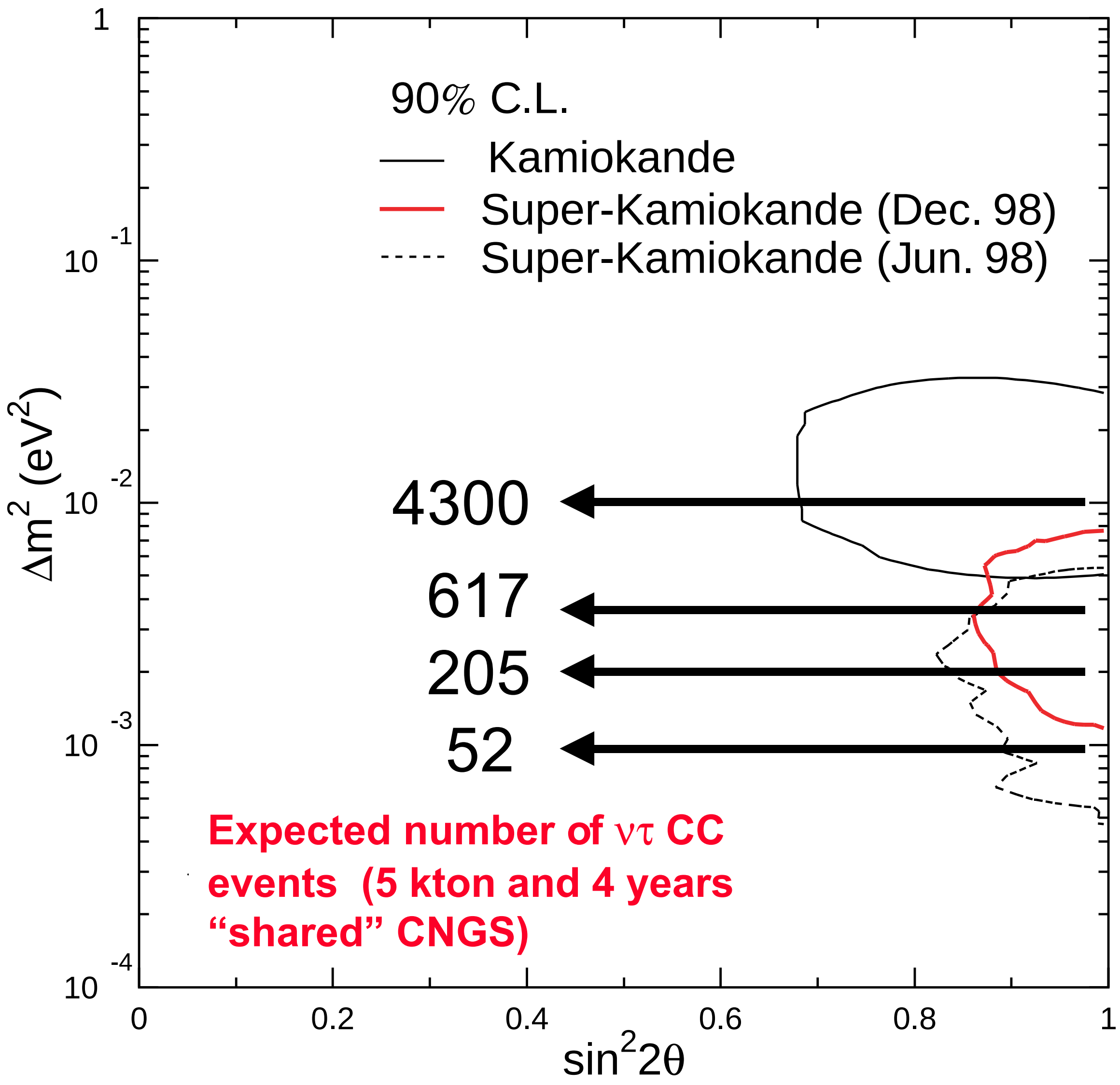
- The exact rate of ν_τ CC events is at the moment not known, since **Δm^2 is not yet precisely determined** by atm neutrinos.

- Within the currently allowed parameters of SuperK, it can vary in the range:

$50 < \nu_\tau$ CC events < 4000

(for 5kton and 4 years „shared“ mode @ CNGS)

Super-Kamiokande Preliminary: 736 days FC + 685 day



Expected number of ντ CC events (5 kton and 4 years "shared" CNGS)

Detecting flavor oscillations by "appearance"

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

$$\nu_\tau + \mathrm{N} \rightarrow \tau + \mathrm{jet}; \quad \tau \rightarrow \begin{cases} e\nu\nu & 18\% \\ \mu\nu\nu & 18\% \\ h^- n h^0 \nu & 50\% \\ h^- h^+ h^- n h^0 \nu & 14\% \end{cases}$$

Charged current (CC)

1. ***High energy neutrinos***

   ⇒ Sufficient energy to produce heavy tau (m_τ = 1777 MeV)
2. ***Detector capable of identifying tau lepton***

   ⇒ Detect the decay products and missing momentum from neutrinos

   ⇒ or look for tau track (≈1 mm length) to see "kink"

$\nu_\mu \rightarrow \nu_e$

$$\nu_e + \mathrm{N} \rightarrow e + \mathrm{jet}$$

Charged current (CC)

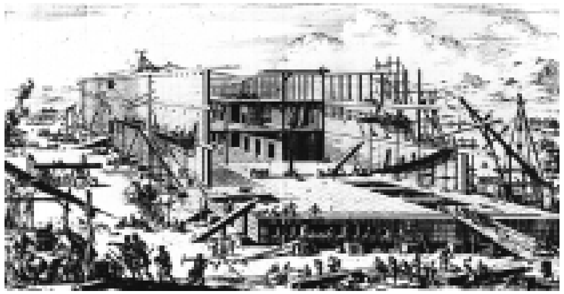
1. ***Excellent electron identification***

   ⇒ high granularity for e/π separation

⇒ ***in general, difficult tasks for large detectors!***

Experiments proposed at CNGS

ICANOE



Instrumented mass ≈9 kt

Homogeneous LAr TPC + Magnetized calorimeter/spectrometer

ν_e appearance
ν_τ appearance
Atmospheric neutrinos
Proton decay

- INFN/AE-99-17; CERN /SPSC 99-25; SPSC/P314
- CERN/SPSLC 96-58 SPSC/P 304
- CERN/SPSC 98-33 SPSC/M620

OPERA

Target mass ≈ 0.8-1.5 kt

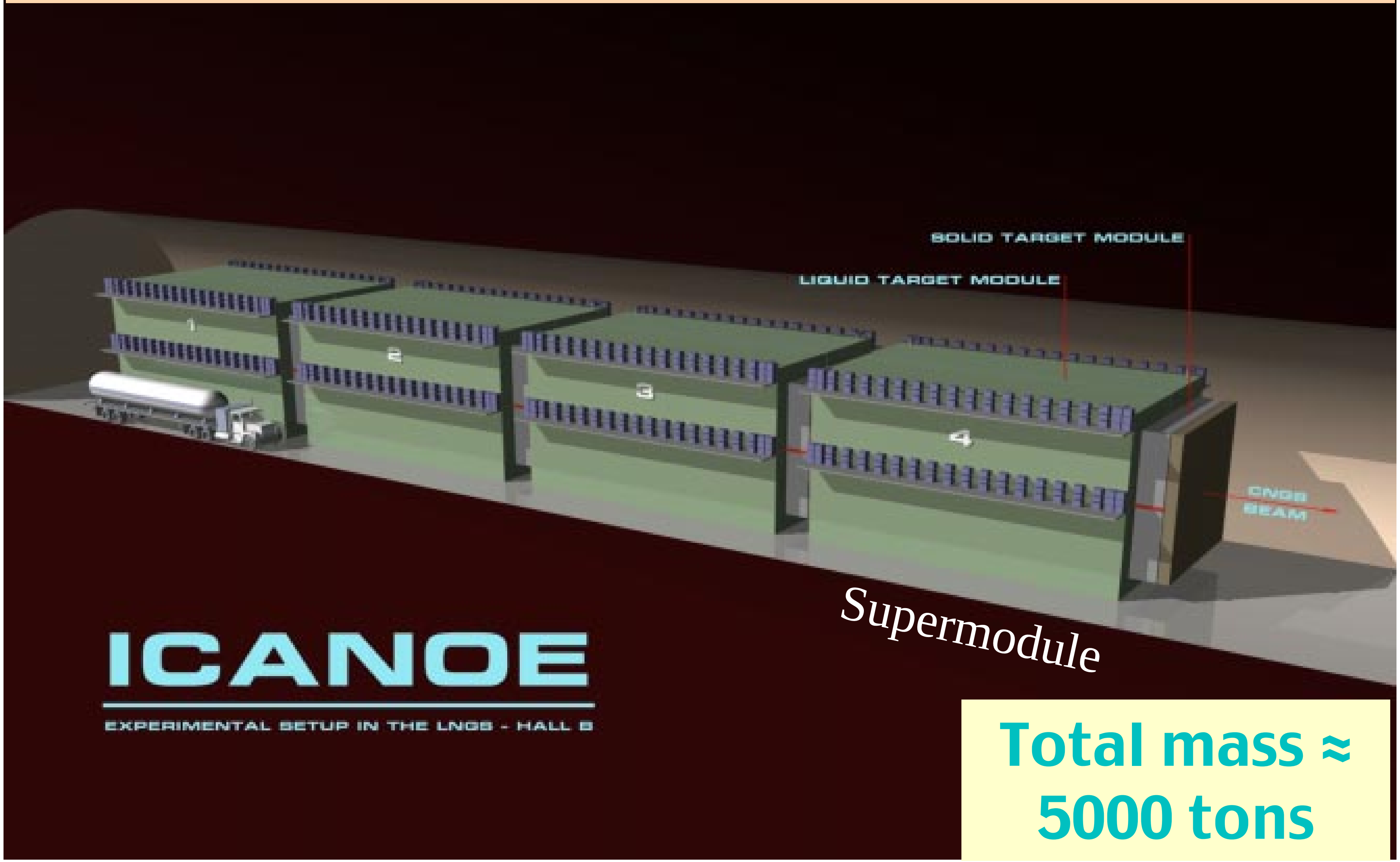
Pb target+emulsion tracking

ν_τ appearance

- LNGS-LOI 8/97
- CERN /SPSC 98-25 SPSC/M612; LNGS-LOI 8/97 Addendum 1
- CERN/SPSC 99-20 SPSC/M635; LNGS-LOI 19/99

Planned ICANOE experiment at LNGS

An "electronic bubble chamber" complemented by an external μ-identifier



Supermodule

Total mass ≈ 5000 tons

The ICANOE detector

A ≈5 kton "electronic bubble chamber" complemented by an external calorimeter μ-identifier

- ***Merging of two technologies***:
  - →*Low density* **liquid target**: ICARUS liquid argon imaging (≈5kton bubble chamber)
  - →*High density* **solid target**: magnetized fine grained NOE ≈3kton calorimeter
- Capable of detecting and measure final state e,γ,μ and *hadrons*, also provides μ charge discrimination
- Isotropic detector suitable to study atmospheric as well as ν beam from accelerators

Proposed experiment at CNGS

LNGS-P21/99 CERN/SPSC 99-40 SPSC/P314

ICARUS+NOE collaborations

The ICARUS Collaboration

F. Arneodo, E. Bernardini, O. Palamara.
Laboratori Nazionali di Gran Sasso, INFN, s.s. 17bis, km 18+910, Assergi (AQ), Italy

B. Babussinov, S. Centro, G. Meng, D. Pascoli, F. Pietropaolo, S. Ventura.
Dipartimento di Fisica e INFN, Università di Padova, via Marzolo 8, Padova, Italy

A. Badertscher, A. Bueno, M. Campanelli, C. Carpanese, J. Rico, A. Rubbia, N. Sinanis.
Institute for Particle Physics, ETH Honggerberg, Zurich, Switzerland\label

G. Battistoni, D. Cavalli, P. Sala, T. Rancati.
Dipartimento di Fisica e INFN, Università di Milano, via Celoria 16, Milano, Italy

P. Benetti, R. Brunetti,E. Calligarich, R. Dolfini, A. Gigli Berzolari, F. Mauri, L. Mazzone, C. Montanari, A. Piazzoli, A. Rappoldi, G.L. Raselli, M. Rossella, C. Rubbia, D. Scannicchio, P. Torre, C. Vignoli, Z. Xu.
Dipartimento di Fisica e INFN, Università di Pavia, via Bassi 6, Pavia, Italy

A. Borio di Tigliole, A. Cesana, M. Terrani.
Politecnico di Milano (CESENF), Università di Milano, via Ponzio 34/3, Milano, Italy

F. Cavanna, D. Mazza, G. Nurzia, S. Petrera, G. Piano Mortari, C. Rossi.
Dipartimento d Fisica e INFN, Università dell'Aquila, via Vetoio, L'Aquila, Italy

P. Cennini, A. Ferrari[1].
CERN, CH 1211 Geneva 23, Switzerland

C. Chen, Y. Chen, K. He, X. Huang, Z. Li, F. Lu, J. Ma, G. Xu, C. Zhang, Q. Zhang, S. Zhen
IHEP -- Academia Sinica, 19 Yuqnan Road, Beijing, People's Republic of China

D. Cline, C. Matthey, S. Otwinowski, H. Wang, J. Woo.
Department of Physics, UCLA, Los Angeles, CA 90024, USA

P. Picchi[2]
University of Torino, Torino, Italy

F. Sergiampietri
INFN Pisa, via Livornese 1291, San Piero a Grado (PI), Italy

≈200 Physicists
27 Institutions

The NOE Collaboration

M.Ambrosio, C.Aramo, G.C.Barbarino, D.Campana, F.Guarino, A.Lauro, A.Ordine, G.Osteria, V.Palladino.
Dip.di Scienze Fisiche dell' Università di Napoli and INFN Sez.di Napoli-Italy

K.V.Alexandrov, V.A.Chechin, A.P. Chubenko, A.D.Erlykin, F.F.Kayumov, S.K.Kotel'nikov, E.P.Kuznetsov, B.N.Lomonosov, G.I.Merzon, V.A.Ryabov, V.O.Tikhomirov, V.A.Tsarev.
P.N.Lebedev Physical Institute, Moscow, Russia

A.M.Baranov, E.T.Gushchin, V.A.Kantserov, A.A.Semak, S.V.Somov.
Moscow Engineering Physical Institute, Moscow, Russia

P.Bernardini, I.De Mitri, G.Mancarella, D.Martello, A.Surdo.
Dip. di Fisica dell'Università di Lecce and INFN Sez. di Lecce – Italy

A.Di Credico, A.Grillo, S.Mikheyev, E.Scapparone.
Laboratori Nazionali di Gran Sasso, INFN, s.s. 17bis, km 18+910, Assergi (AQ), Italy

C.Favuzzi, P.Fusco, N.Giglietto, F.Loparco, A.Rainò, M.N.Mazziotta, I.Panunzio, P.Spinelli.
Dip. di Fisica dell'Università di Bari and INFN Sez. di Bari - Italy

R. Fiore, E.Lamanna, A. Papa, G.Russo.
Università della Calabria and INFN Laboratori Nazionali di Frascati-Italy

G.V.Gavalian, R.L.Kavalov, M.P.Lorikian.
Yerevan Physical Institute, Yerevan, Armenia

S.V.Golovkine, A.M.Gorine.
Institute for High Energy Physics, Moscow, Russia

R.A.Mukhamedshin, G.T.Zatsepin.
Institute of Nuclear Research, Moscow, Russia

V.A.Smotryaev, I.S.Trostin.
Institute of Theoretical and Experimental Physics, Moscow, Russia

This is an open Collaboration and other Participants are being invited to join

Institutes that have already expressed their interest

P. Assimakopoulos, I. Papadopoulos, P. Pavlopoulos, V. Vlachoudis.
University of Ioannina, Greece

G. Fanourakis, S. Tzamarias.
Institute of Nuclear Physics, "Democritos", Greece

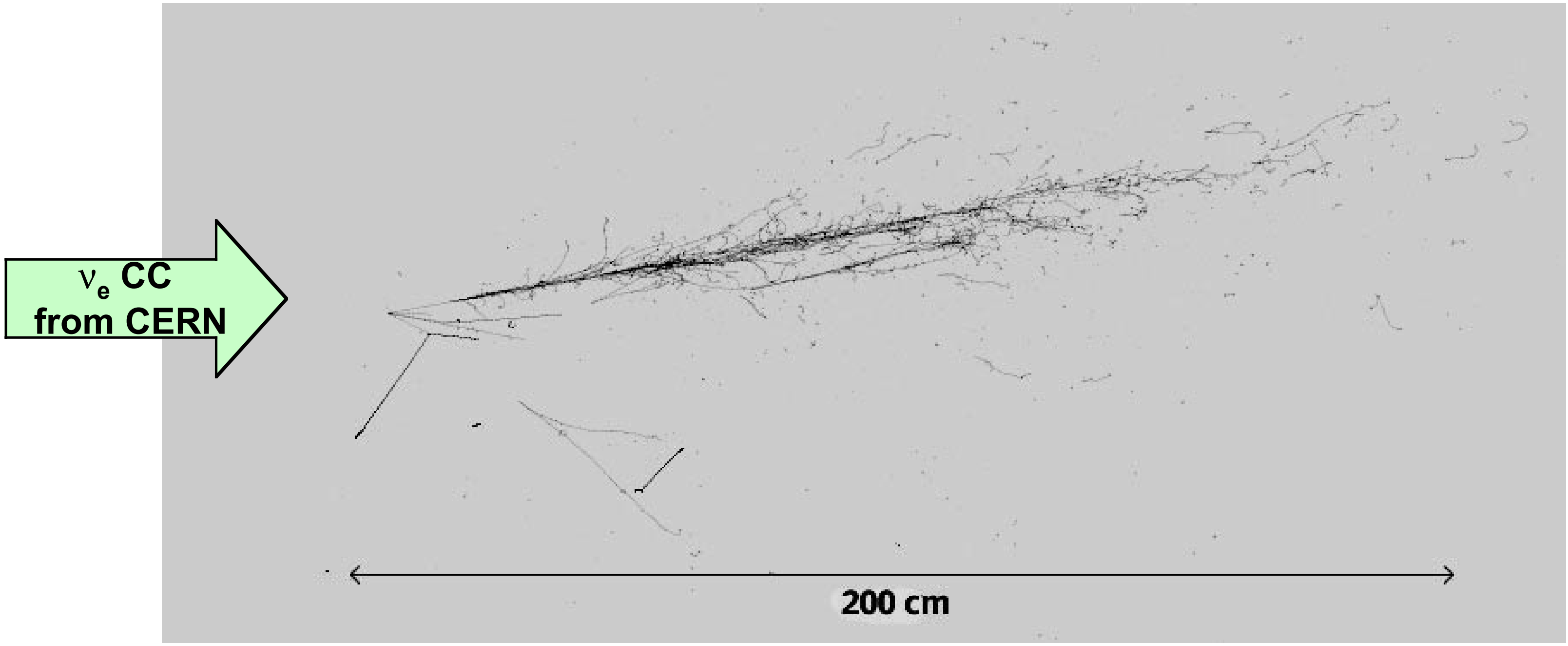
V.A. Matveev, E.N. Goloubeva, A.V. Kovzelev, O.V. Kazachenko, A.V. Polarush, V.E. Postoev, I.N. Semeniouk, A.N. Toropin.
Institute of Nuclear Research, Moscow, Russia}

P. Razis, A. Vorvolakos.

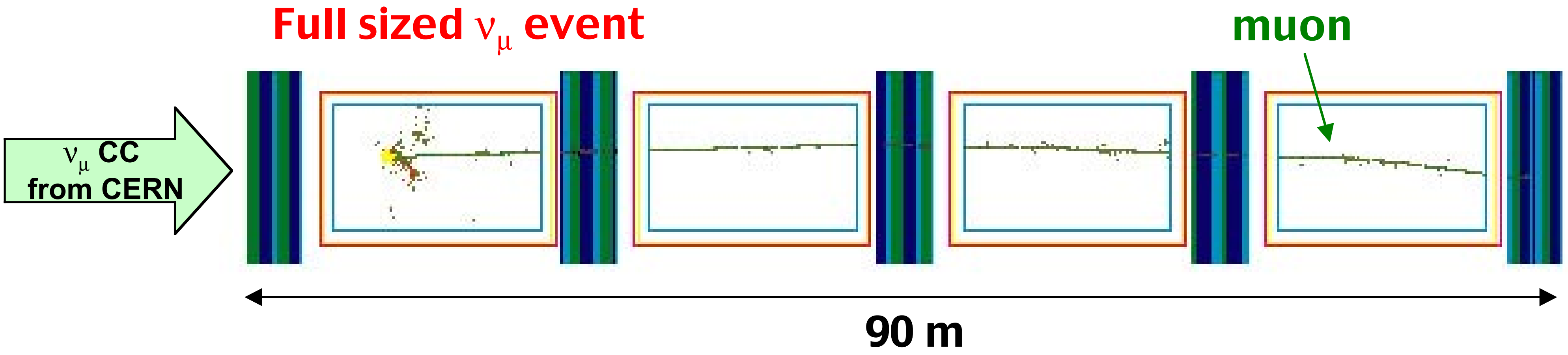
---

[1] Also at Dipartimento di Fisica e INFN, Università di Milano, via Celoria 16, Milano, Italy
[2] Also at Laboratori Nazionali di Frascati, INFN, Frascati, Italy and Istituto di Cosmogeofisica, CNR, Torino, Italy

ICANOE Sample Events

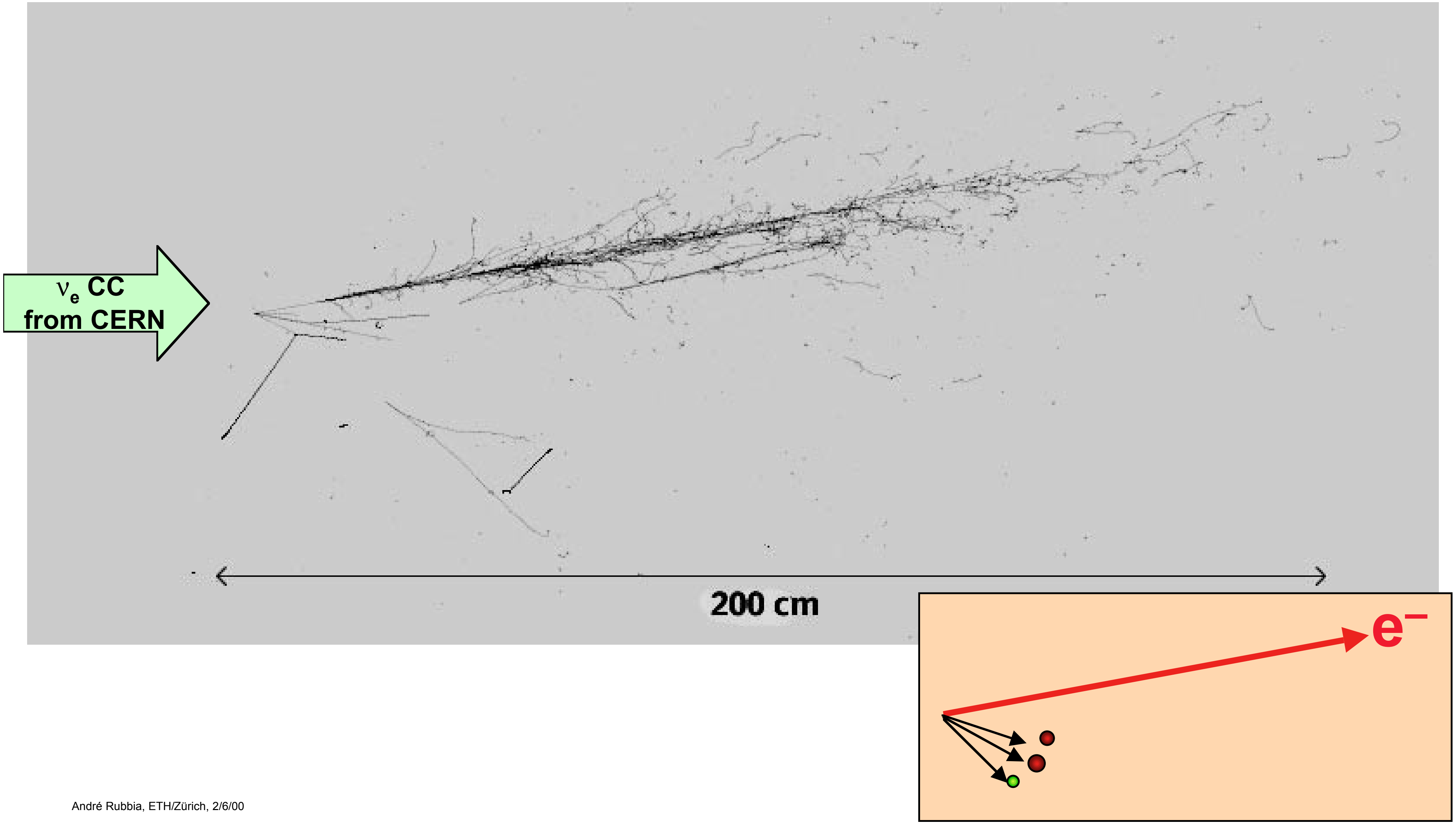


LAr Imaging



Example of neutrino event (simulated)

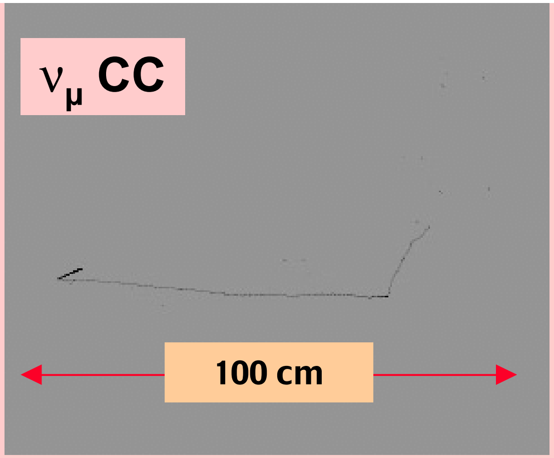
The granularity of a bubble-chamber, with electronic-readout and very large mass



ICANOE physics program

Looking for rare events:

Atmospheric neutrinos



✓Detection of **all neutrino flavors, CC & NC** modes

✓Study of **L/E** distributions for e and μ

✓Clean **NC/CC**

✓Direct **tau appearance**

✓**Upward going muons**

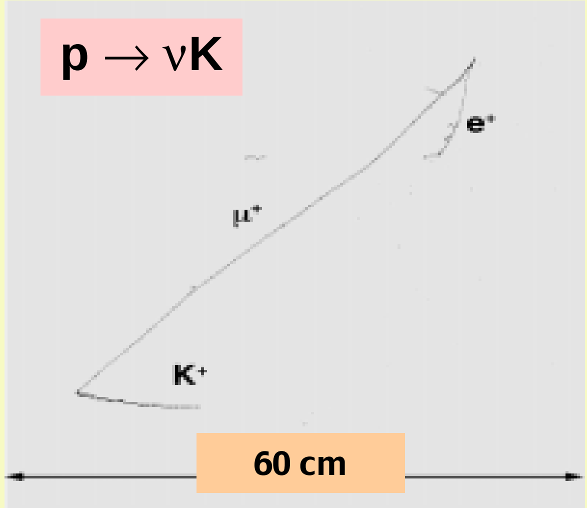
✓**Very low energy electrons**

CERN-NGS

✓**Direct tau and electron appearance**

✓Muon disappearance

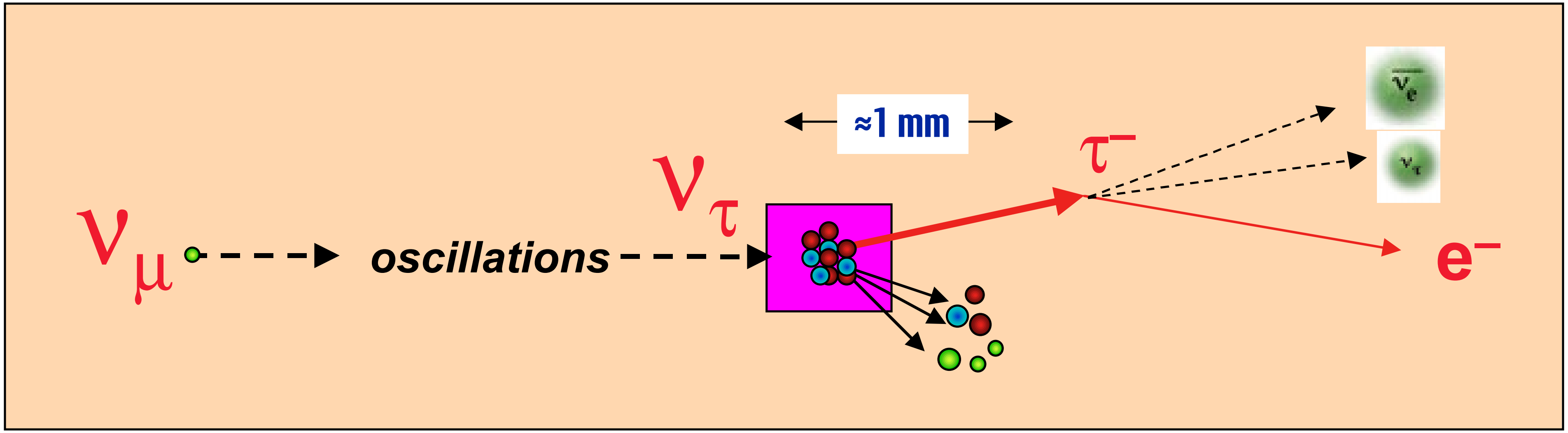
Nucleon decay

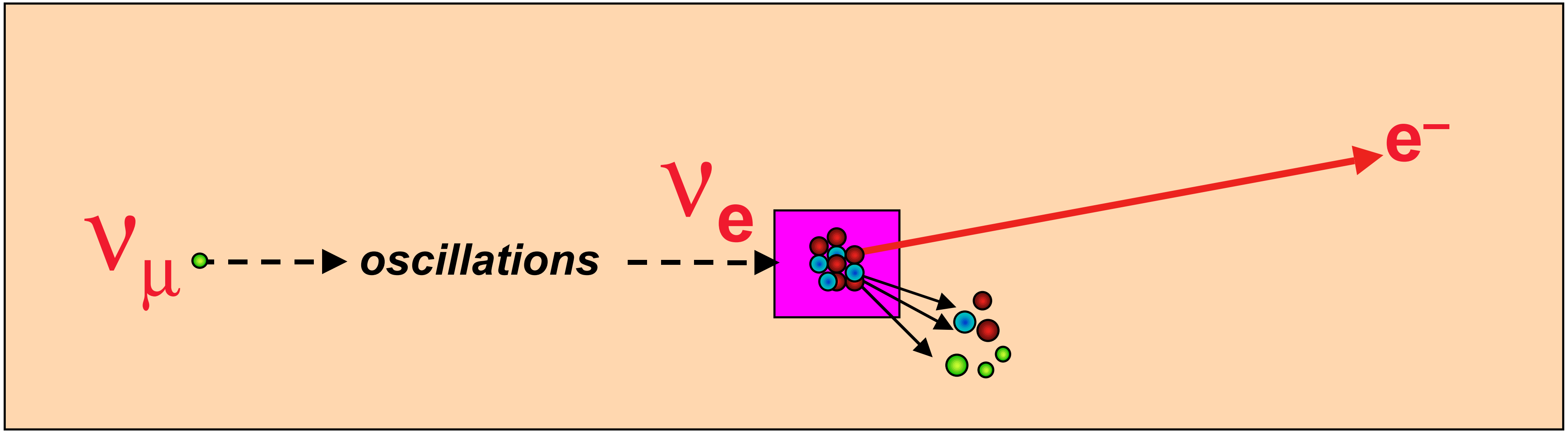


✓**Background free searches**

✓Sensitivity $10^{33} \div 10^{34}$ years

Detecting neutrino oscillations





Tau appearance – Electron channel

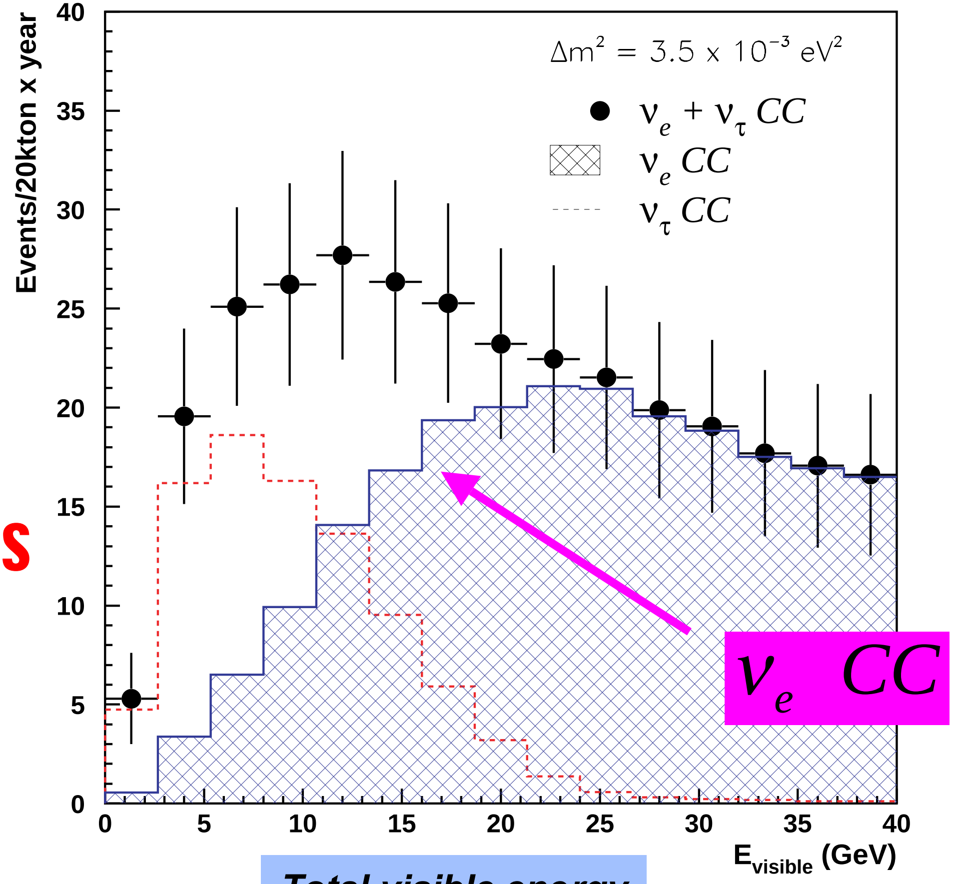
- Search for **distortions in the visible energy spectrum of leading electron sample**
  - → Exploit the **small intrinsic ν_e contamination** of the beam (0.8% of ν_μ CC)
  - → Exploit the unique e/π^0 separation
  - → Excess at low energy

$$\approx 470 \quad \nu_e CC$$

$$\approx 110 \quad \nu_\tau CC \; + \; \tau \rightarrow e\nu\nu$$

$$\Delta m^2 = 3.5 \times 10^{-3} eV^2$$

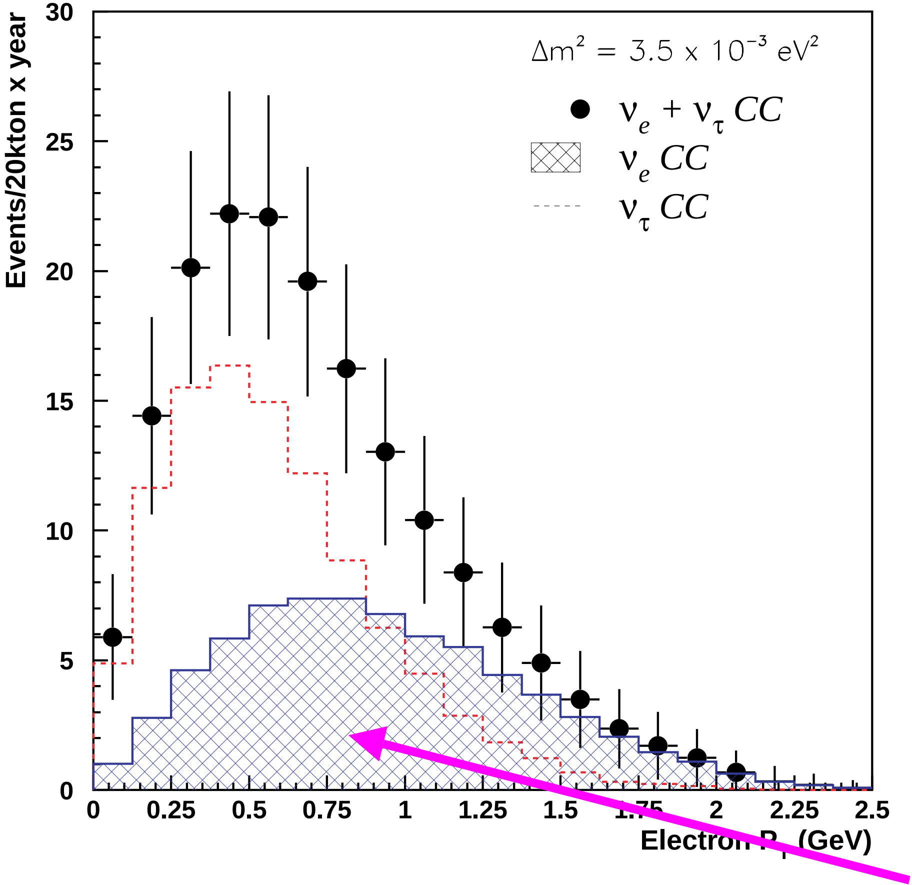
- **Excess visible also without cuts**
- Kinematical selection in order to enhance S/B ratio
  - → Will be tuned "a posteriori" depending on the actual Δm^2



Total visible energy

Tau appearance – kinematic selection

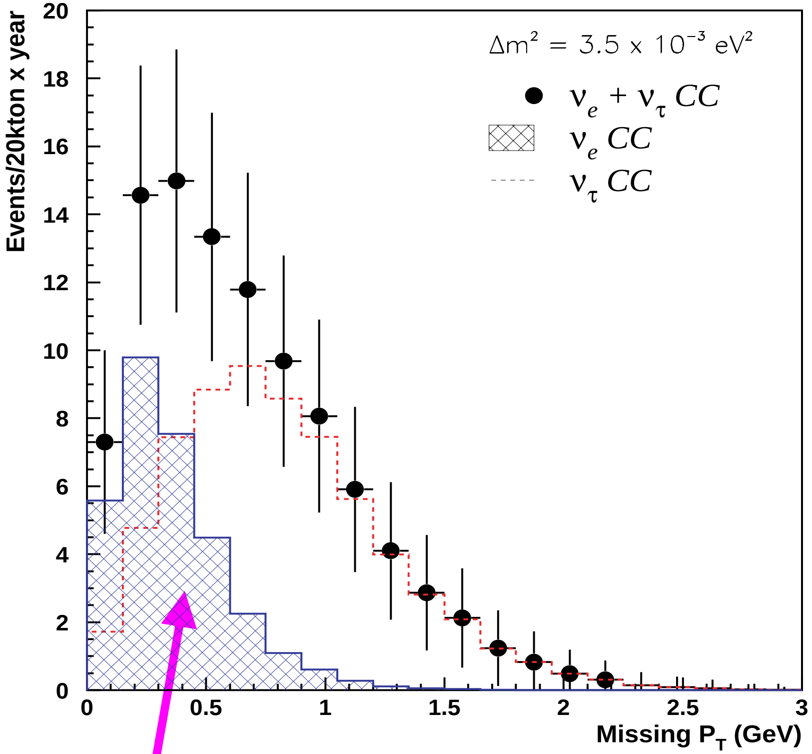
Transverse P electron



$$\varepsilon_{\nu e CC} = 48\%$$

$$\varepsilon_{\nu\tau CC} = 81\%$$

Transverse missing P_T



ν_e CC

$$P_{T,miss} > 0.6\ \ GeV:$$

$$\varepsilon_{\nu e CC} = 14\%$$

$$\varepsilon_{\nu\tau CC} = 65\%$$

Tau appearance – kinematical selection

- ✯ **Kinematical selection in order to enhance S/B ratio**
  - ➜ Will be tuned “a posteriori” depending on the actual Δm^2
- ✯ Intrinsic beam ν_e **CC component**
  - ➜ Event kinematics simulated with nuclear model (initial state fermion+final state tracking of hadrons) → “tuned” to reproduce NOMAD data
  - ➜ Kinematical reconstruction will be studied *in situ* with ν_μ CC events

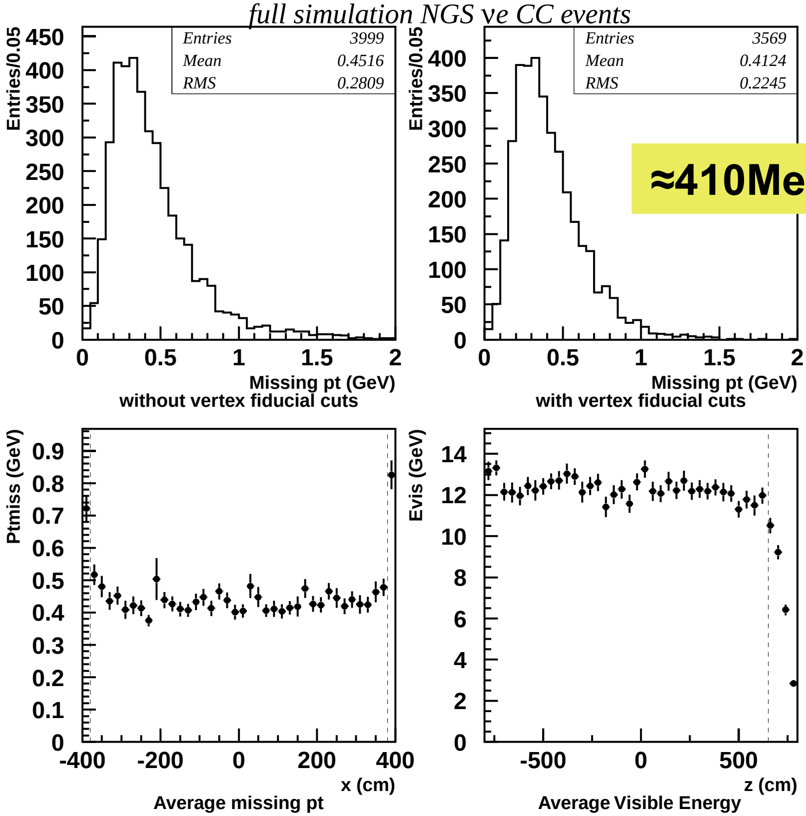
Kinematical selection

Cuts	ν_τ Eff. (%)	ν_e CC	$\bar{\nu}_e$ CC	ν_τ CC $\Delta m^2 = 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 10^{-2}$ eV^2
Initial	100	437	29	9.3	111	779
Fiducial volume	88	383	25	8.2	97	686
One candidate with momentum > 1 GeV	72	365	25	6.7	80	561
$E_{vis} < 18$ GeV	67	64	5	6.2	75	522
$P_T^e < 0.9$ GeV	54	31	3	5.0	60	421
$P_T^{lep} > 0.3$ GeV	51	29	2	4.7	56	397
$P_T^{miss} > 0.6$ GeV	33	4	0.4	3.1	37	257

Kinematics simulation

Liquid target full simulation

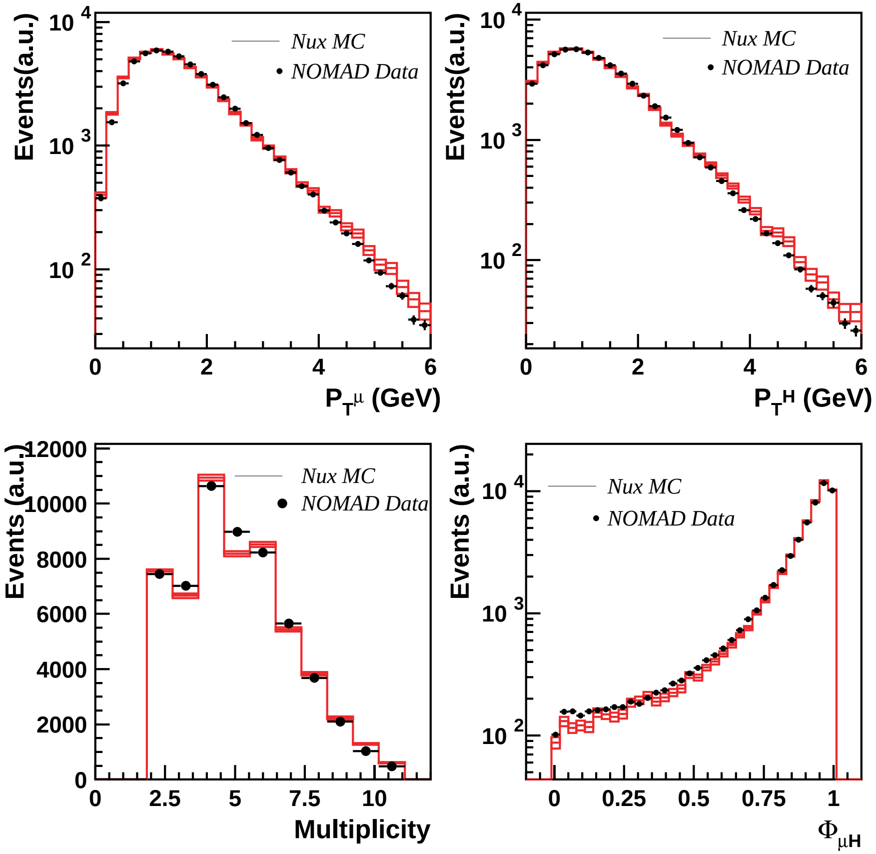
4000 νe CC events



≈410MeV

NUX/FLUKA

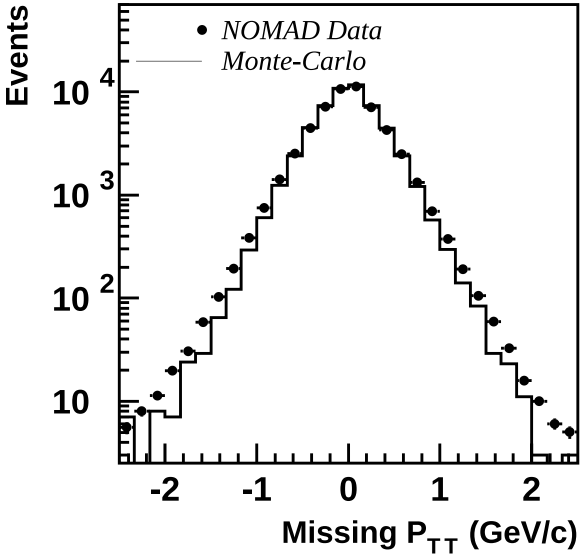
Comparison NOMAD data

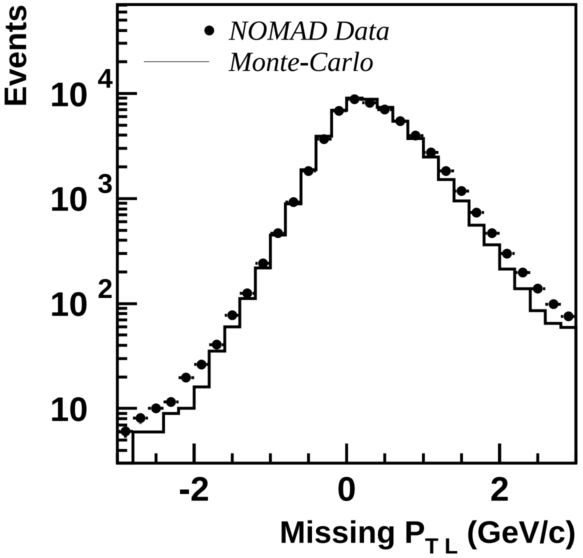


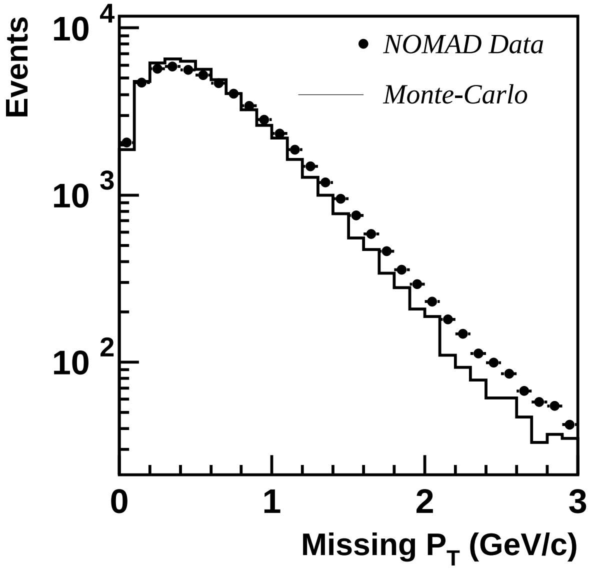
NUX/FLUKA/GENOM

Kinematics simulation (II)

Comparison with NOMAD Data







NOMAD Data $\langle \text{Missing } P_T \rangle = 693$ MeV/c

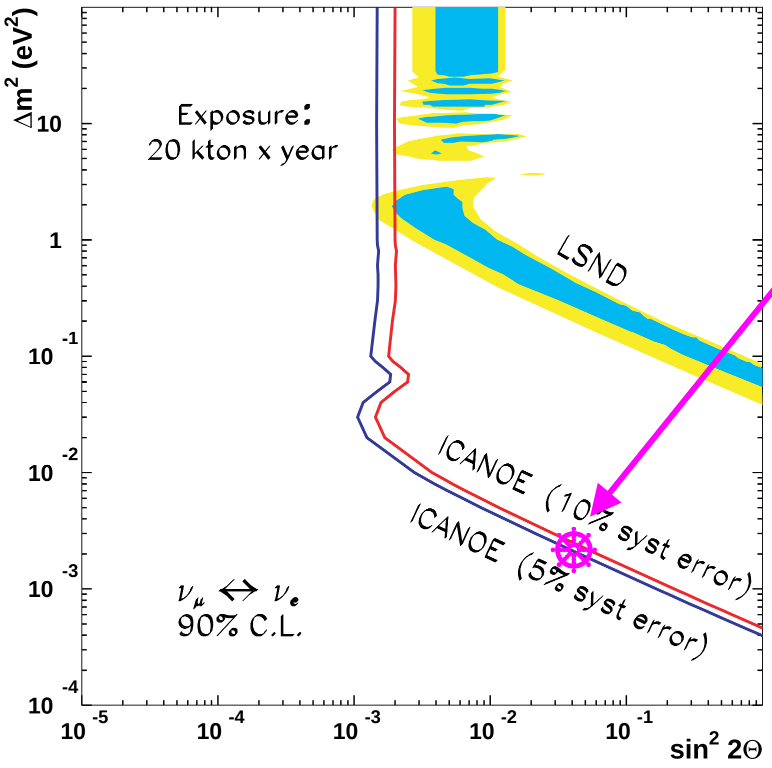
Monte-Carlo $\langle \text{Missing } P_T \rangle = 643$ MeV/c

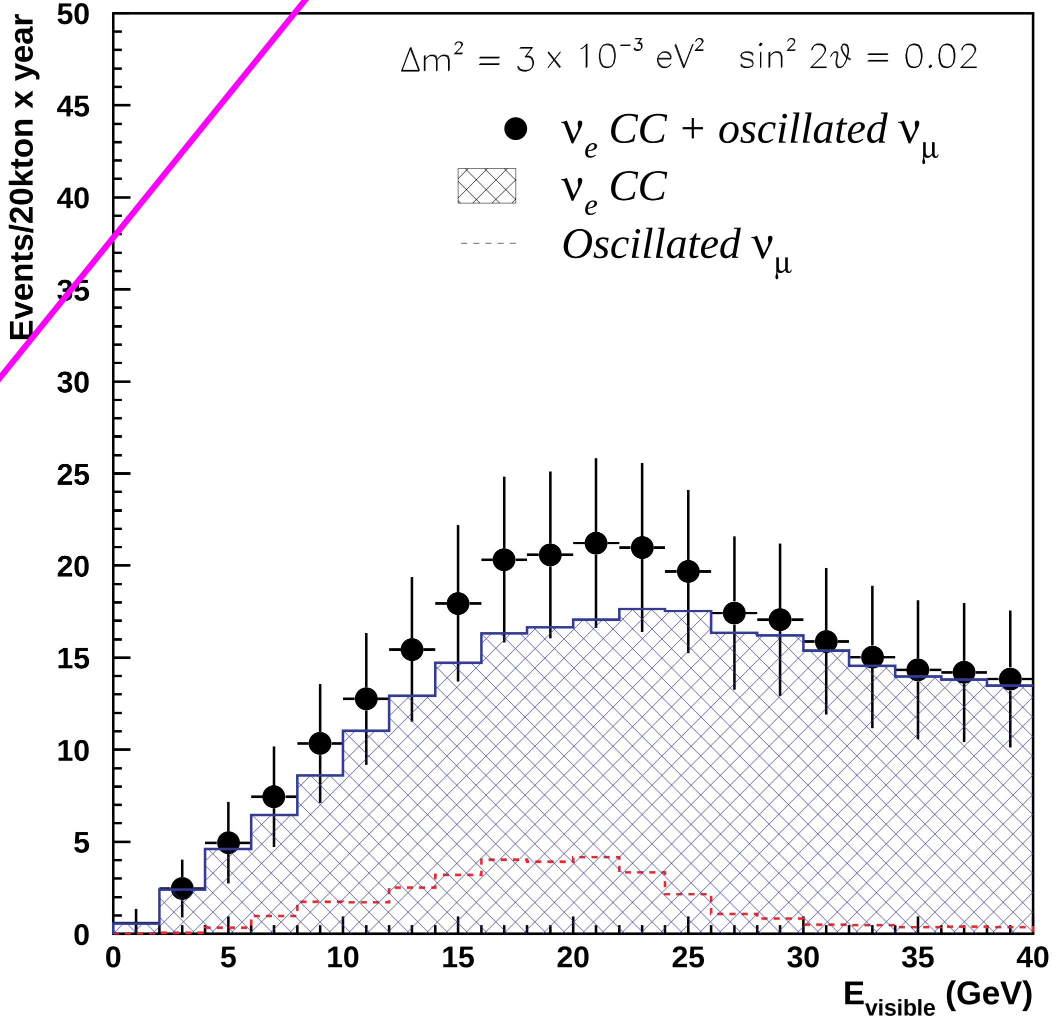
NUX/FLUKA/GENOM

Electron appearance

- Sensitivity at low Δm^2
  - Limited by knowledge of the beam

$$\Delta m^2 = 3\times10^{-3} eV^2;\ \sin^2 2\theta = 0.02$$

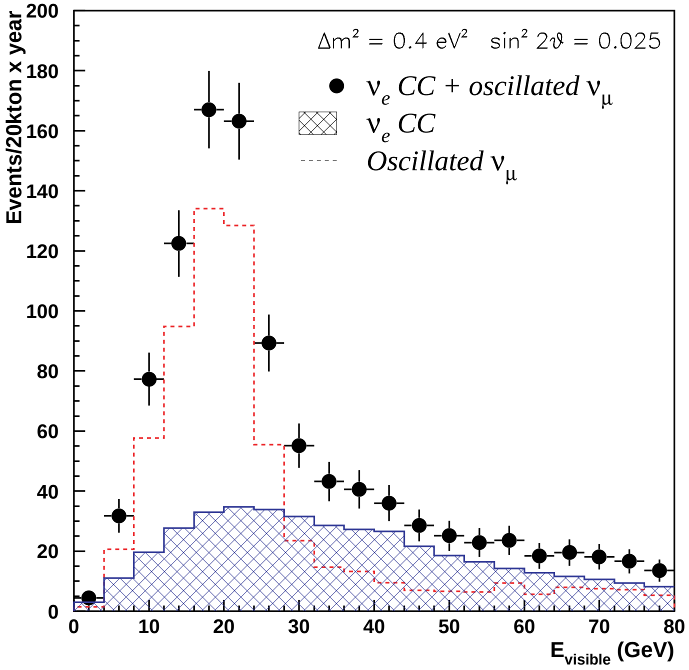


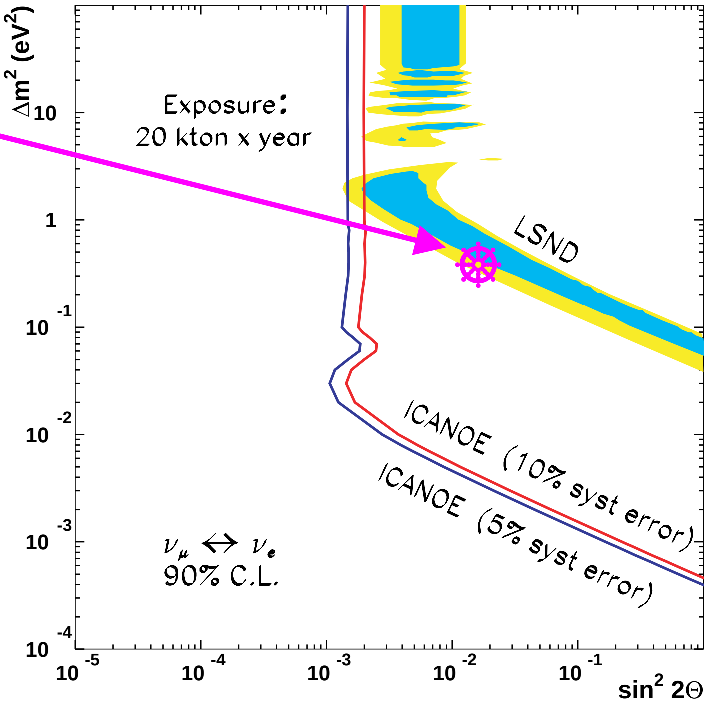


Electron appearance

- ✯ Relevant for testing LSND signal and possible muon-electron mixing at low Δm2

$$\Delta m^2 = 0.4eV^2;\ \sin^2 2\theta = 0.025$$



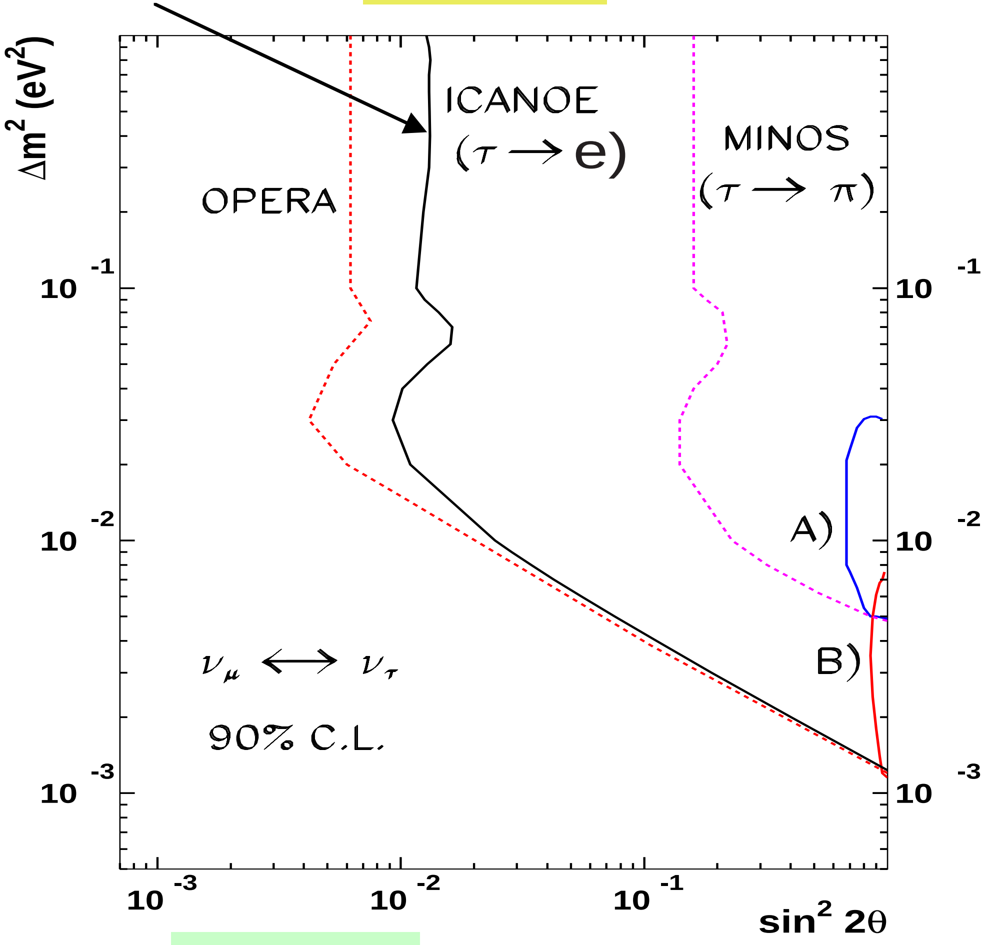


	20 kton × year exposure				
	$\nu_e + \bar{\nu}_e$ CC	Oscillated ν_μ $\Delta m^2 = 0.8$ eV^2 $\sin^2 2\theta = 0.007$	Total ν_e events $\Delta m^2 = 0.8$ eV^2 $\sin^2 2\theta = 0.007$	Oscillated ν_μ $\Delta m^2 = 0.4$ eV^2 $\sin^2 2\theta = 0.025$	Total ν_e events $\Delta m^2 = 0.4$ eV^2 $\sin^2 2\theta = 0.025$
No cut	466±22±23	188±14±9	654±26±33	681±26±34	1146±34±57
$E_{visible} < 20$ GeV	94±10±5	85±9±4	179±13±9	309±17±15	403±20±20

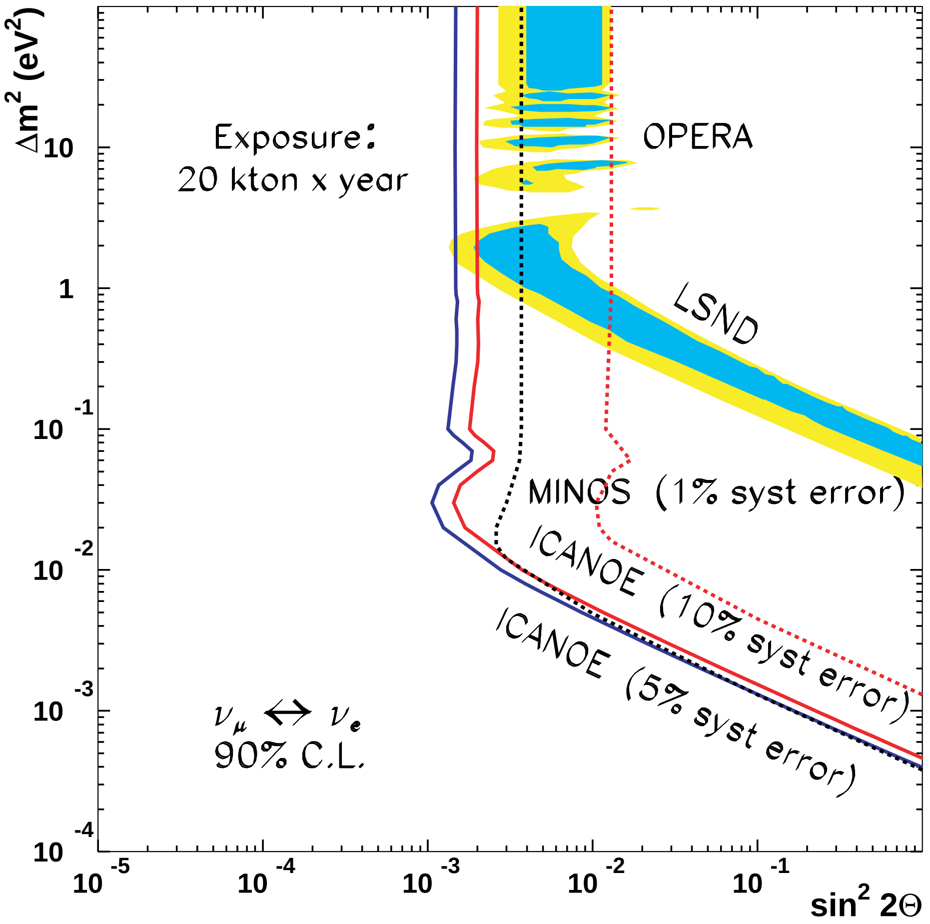
Comparison of sensitivities (CNGS)

High Δm^2 further improved by inclusion of hadronic channels

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



$\nu_\mu \rightarrow \nu_e$



4 years

(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)

Mixing matrix determination

3 angles
+ 1 complex phase

$U_{e3}^2 < 0.05$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Assuming
$\Delta m^2_{21} \ll \Delta m^2_{32}$

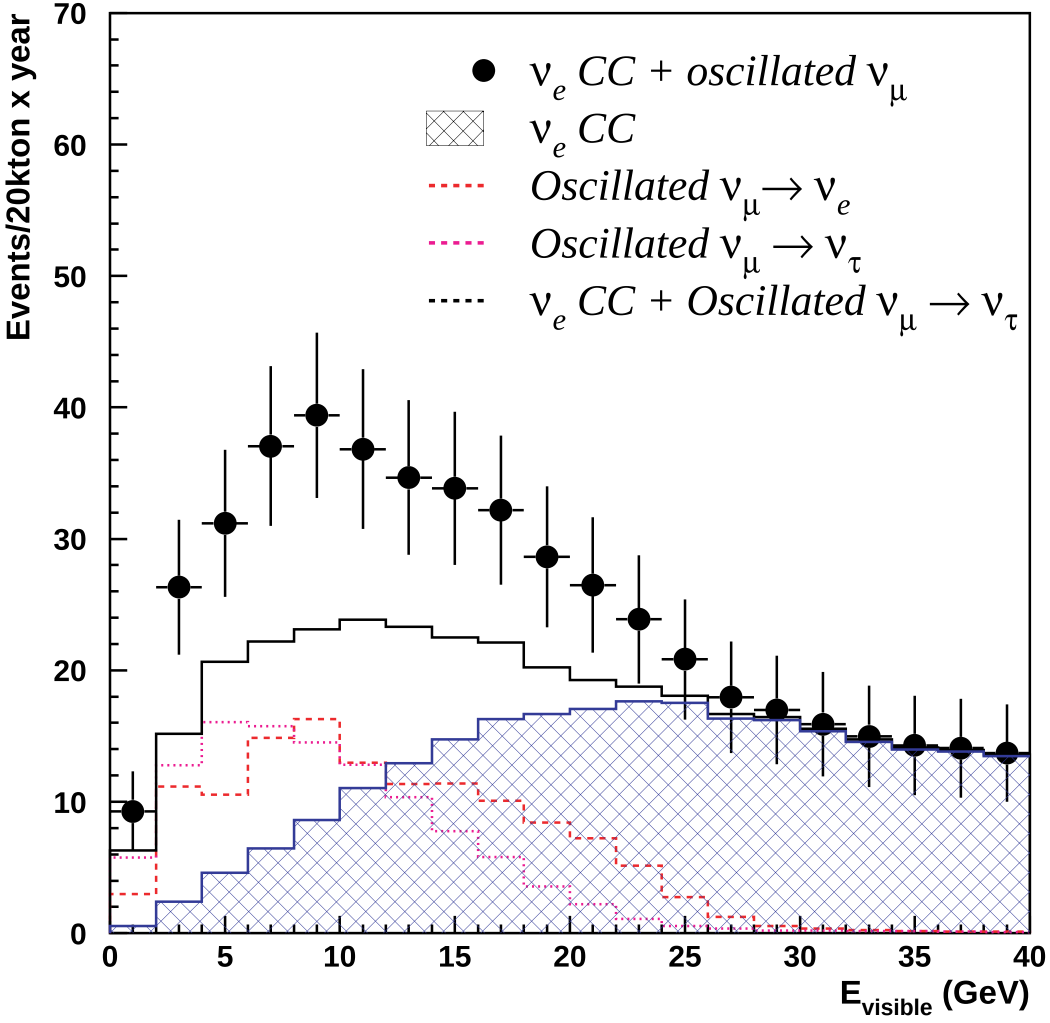
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{32}$$

$$P(\nu_\mu \to \nu_\tau) = \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 \Delta_{32}$$

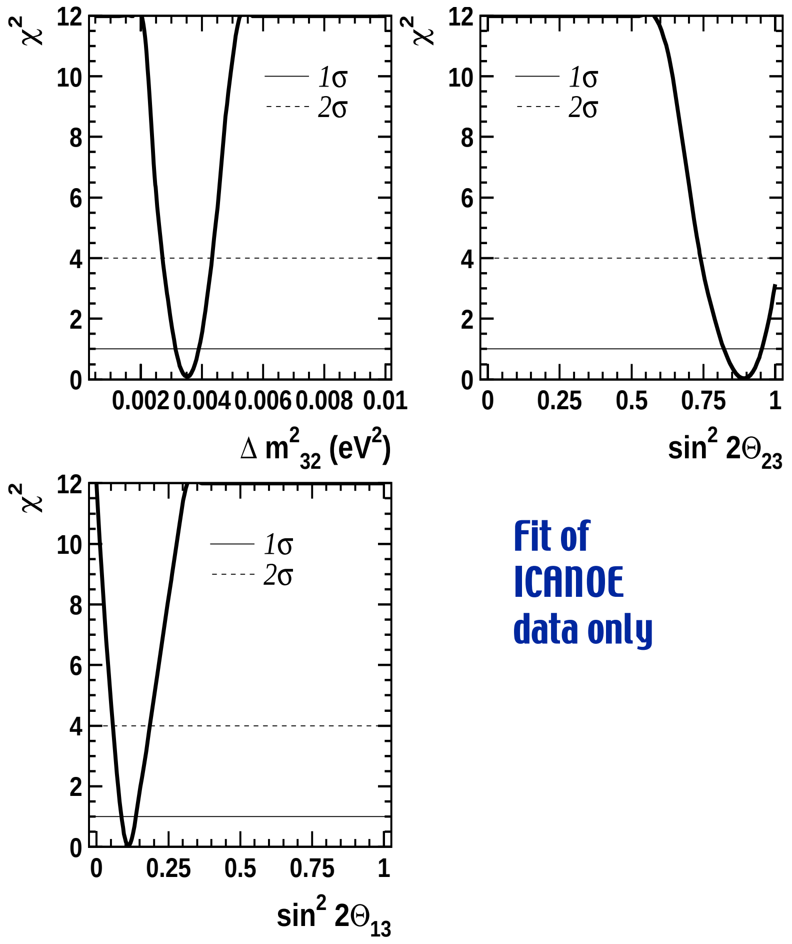
$$\approx \sin^2 2\theta_{23} \sin^2 \Delta_{32} \qquad for \;\; \theta_{13} << 1$$

$$\Delta_{32} = 1.27 \Delta m_{32}{}^2 L / E$$

Mixing matrix determination



Combining atmospheric and beam data

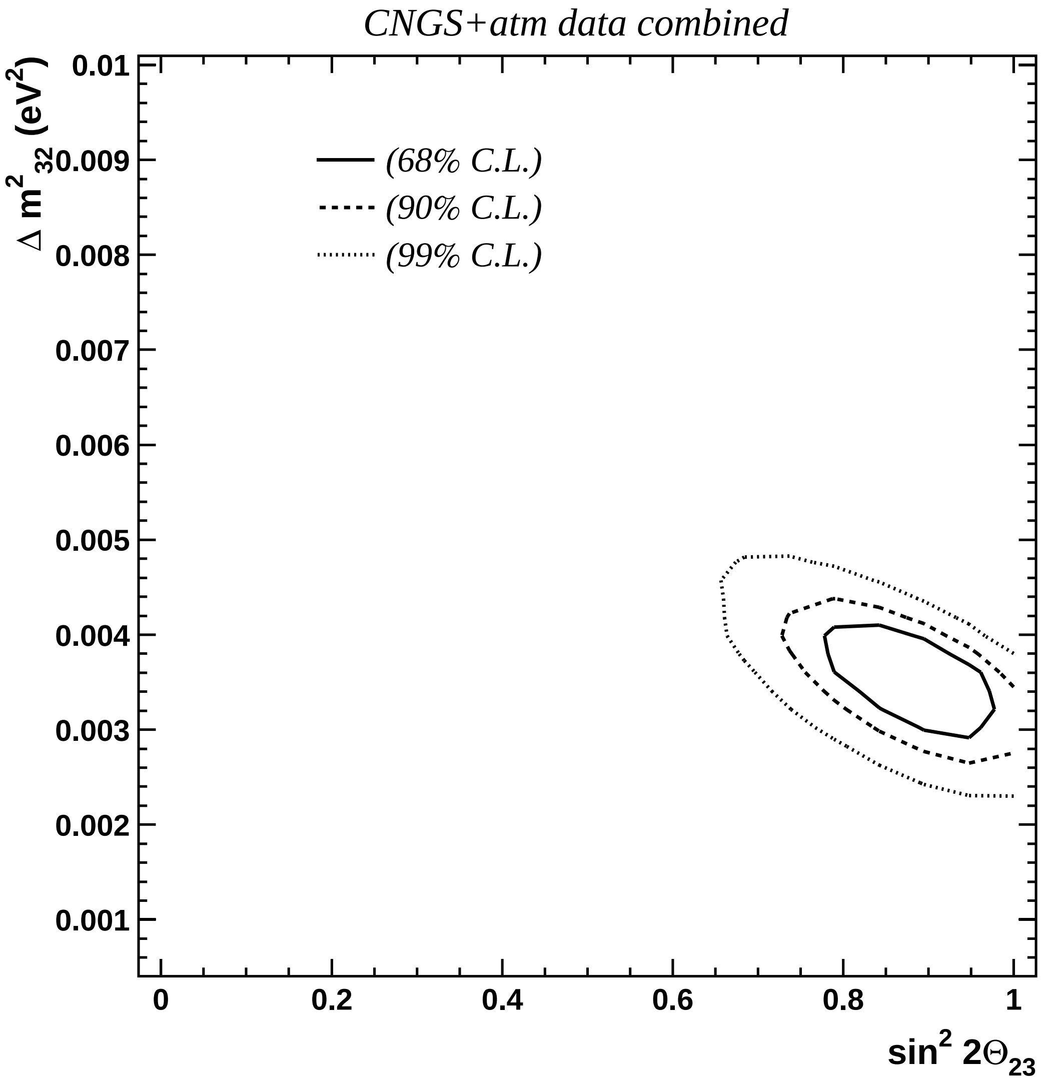


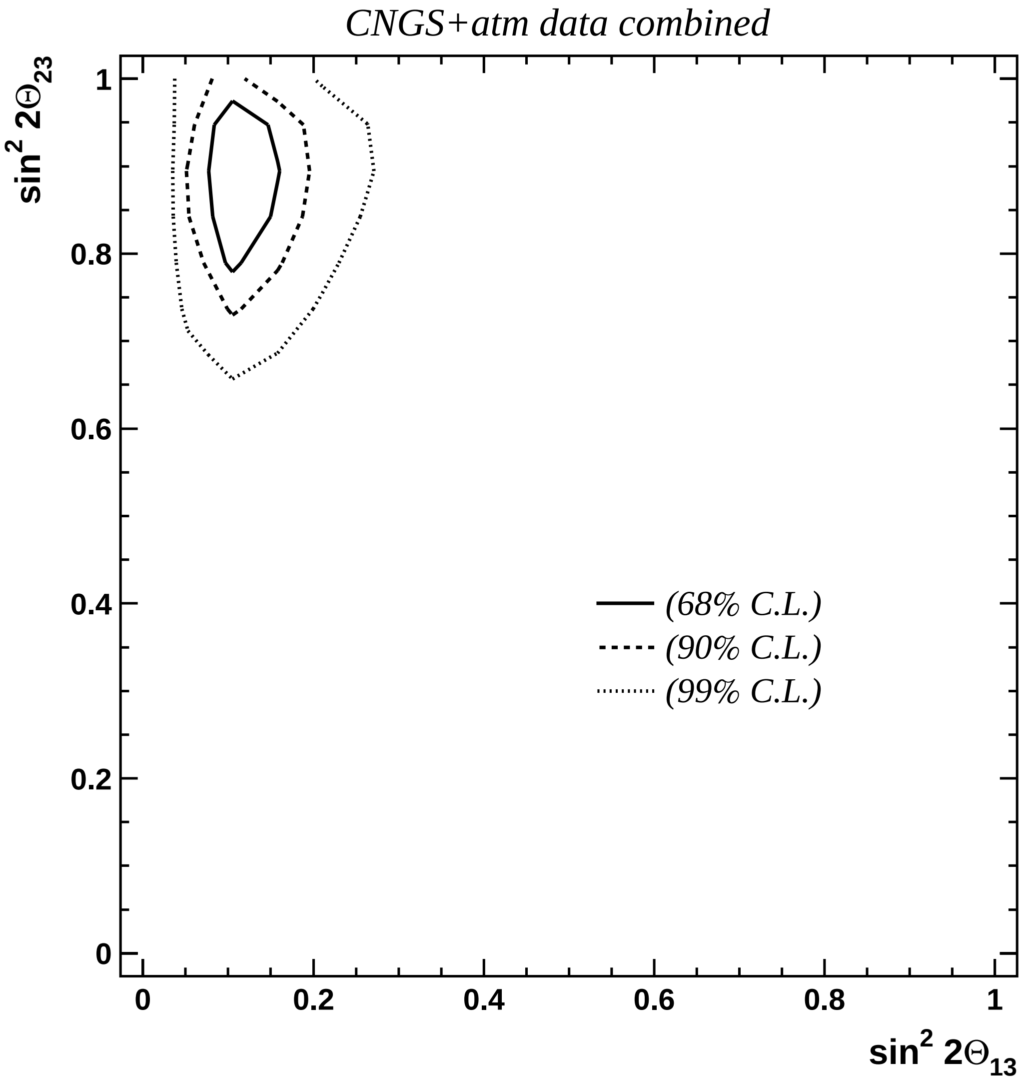
Fit of ICANOE data only

Precision of O(10%) on the oscillation parameters

$\sin^2 2\theta_{13} = 0.10 \pm 0.04$
$\sin^2 2\theta_{23} = 0.90 \pm 0.12$
$\Delta m^2_{32} = (3.5 \pm 0.4) \times 10^{-3}$ eV^2

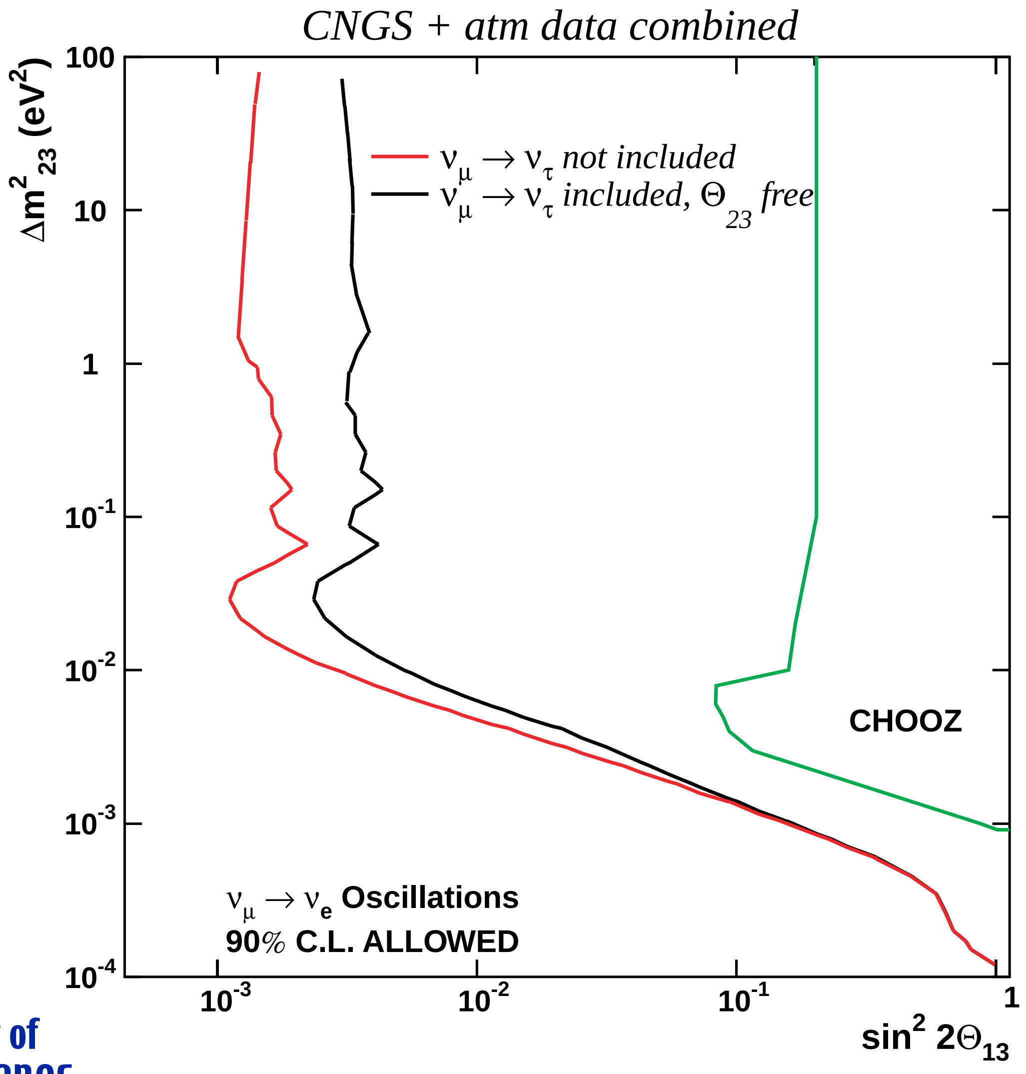
All data combined





Sensitivity to θ_{13}

Combining atmospheric and beam data



Fit of ICANOE data only

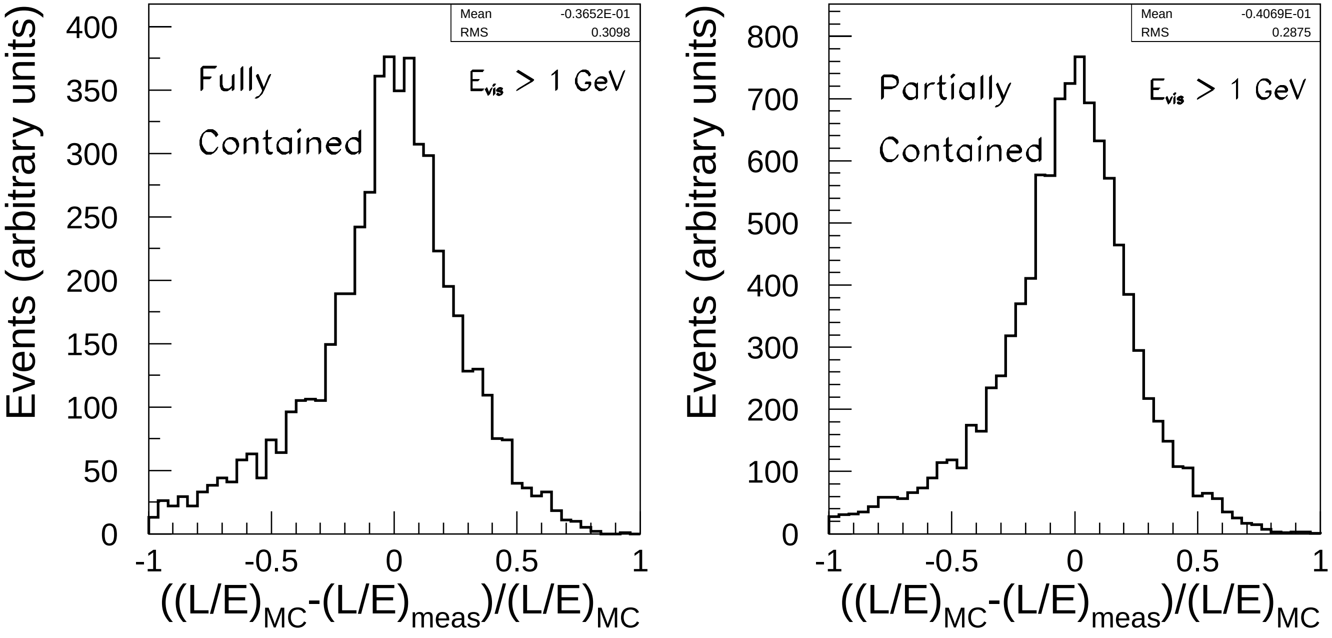
- Limit slightly degraded by inclusion of tau events and leaving contribution as free parameter
- Can be improved if θ_{23} fixed (e.g. to 45° or from other experiments)
- Almost two-orders of magnitude improvement over existing limit

Reconstructed L/E resolution

- Smearing in L/E is introduced by finite resolution
  - Fermi motion: we apply a cut on **$E_{visible}$ > 1 GeV (40% of all events!)**
  - Measurement resolution

$$\Delta(L/E)_{RMS} \approx 30\%$$

Full simulation

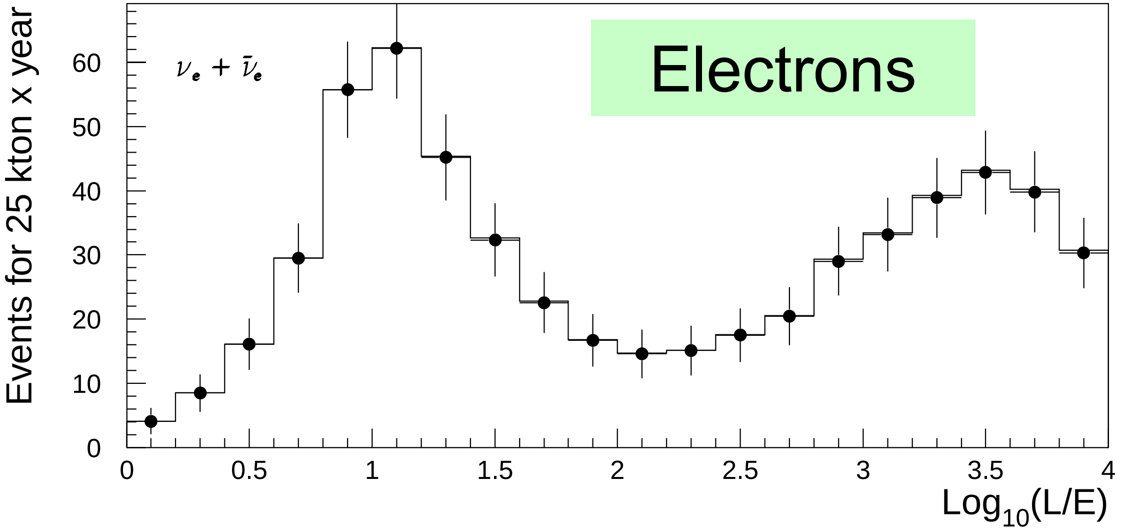


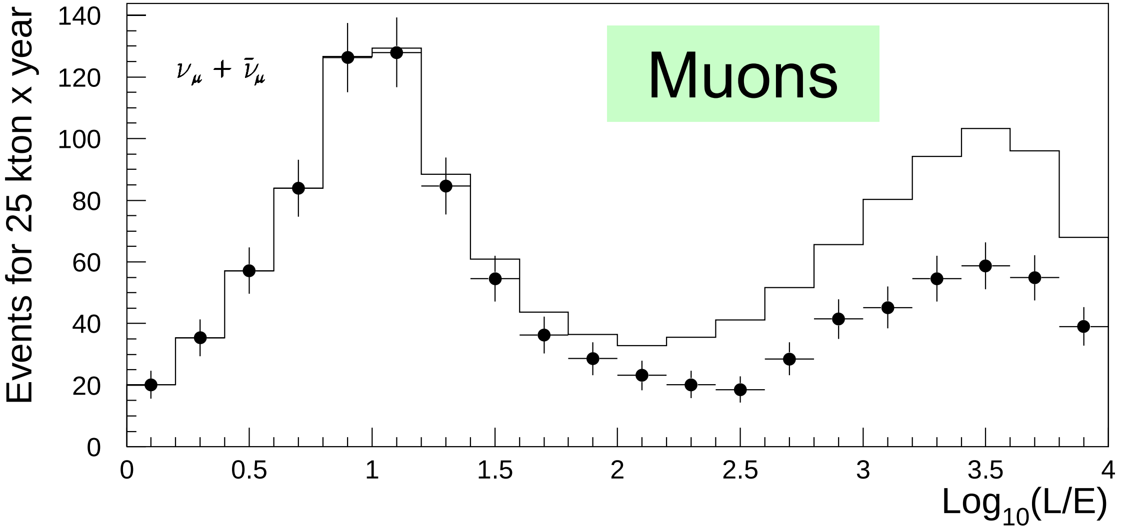
$$\nu_\mu + \bar{\nu}_\mu \quad CC$$

L/E distribution: electrons and muons

- Oscillation parameters:
  - → **$\Delta m^2_{32} = 3.5 \times 10^{-3}\ \mathrm{eV}^2$**
  - → **$\sin^2 2\Theta_{23} = 0.9$**
  - → **$\sin^2 2\Theta_{13} = 0.1$**
- ***Electron sample can be used as a reference for no oscillation case***

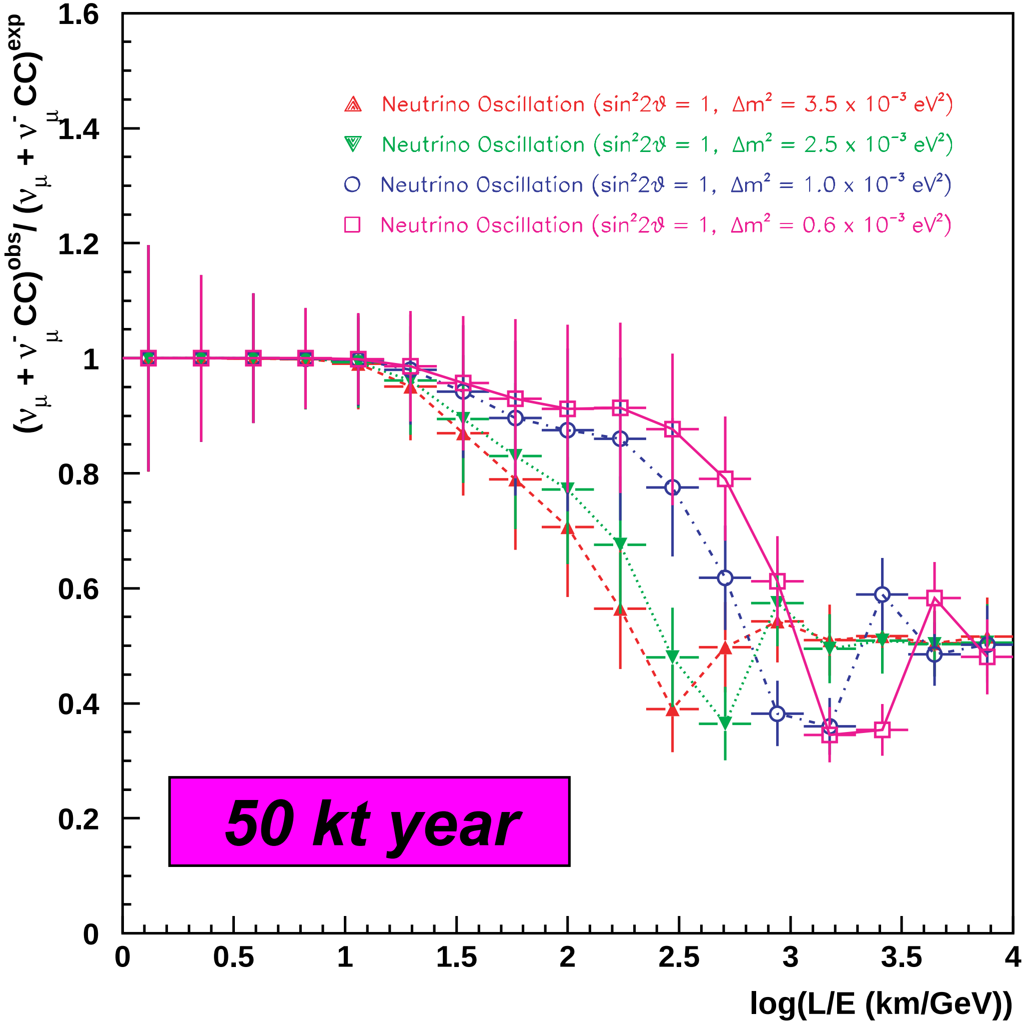
25 kt year





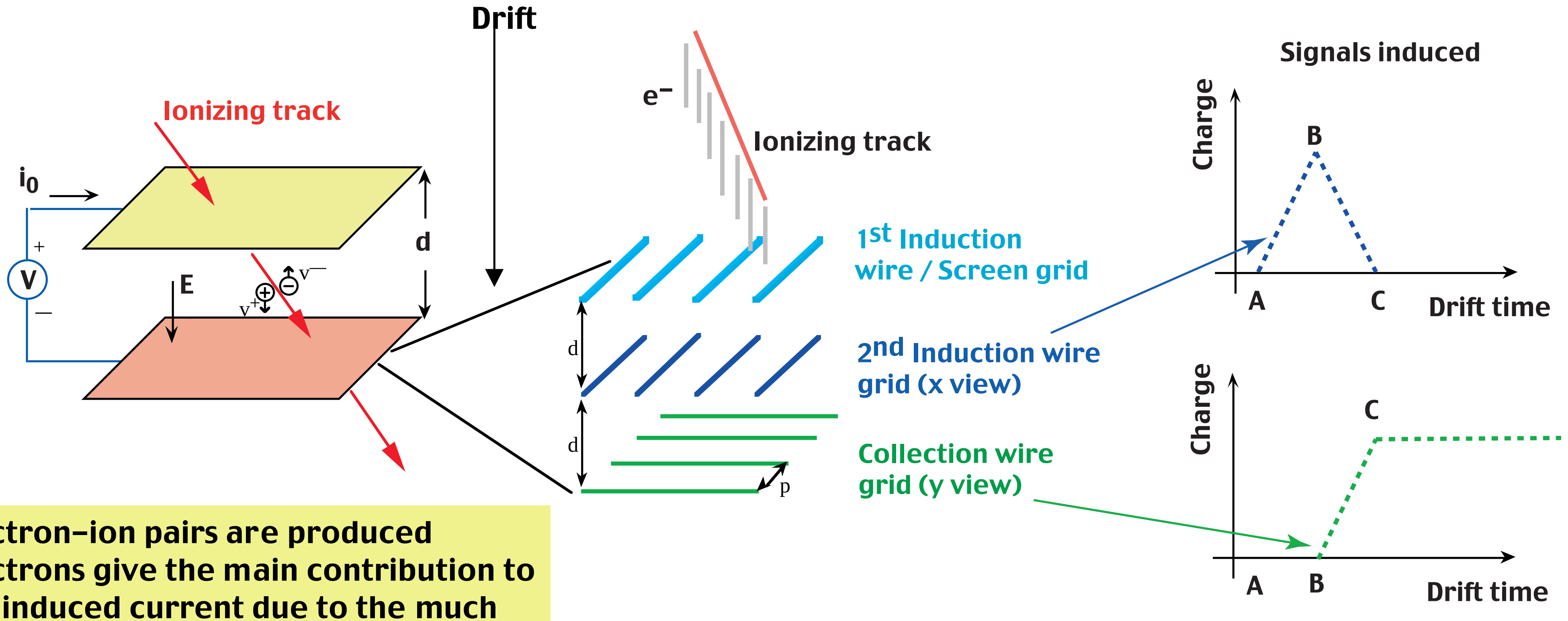
ν_μ disappearance – L/E distribution

- Compare **expected** distribution with **observed**
- Extremely simple selection:
  - → ***Keep all events with $E_{visible}$>1 GeV : $\varepsilon \approx$ 40% of all events!***
- The **characteristic modulation of a given Δm^2** is clearly visible.
- "DIP" visible
- Can precisely measure the oscillation parameter and resolution can be improved (items under study)



Event Imaging in Liquid Argon

- Detect electrons produced by ionizing tracks crossing the LAr

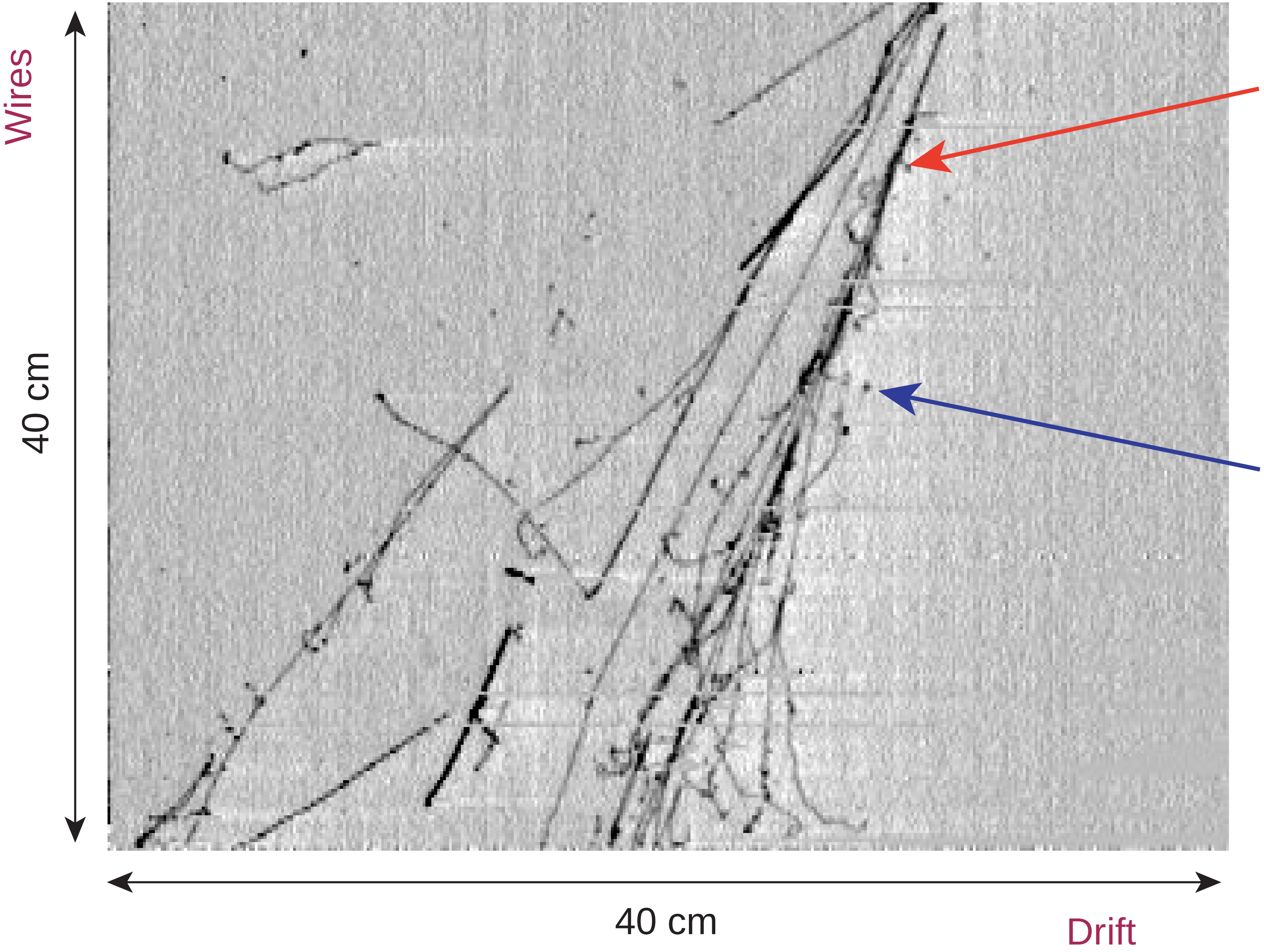


Electron-ion pairs are produced
Electrons give the main contribution to the induced current due to the much larger mobility

$$I_0 = e(v^+ + v^-)/d$$

A set of wires at the end of the drift give a sampling of the track
No charge multiplication occurs near the wires ➨ electrons can be used to induce signals on subsequent wires planes with different orientations ➨ ➨ **3D imaging**

Cosmic Ray Shower Recorded in the 3 ton Prototype



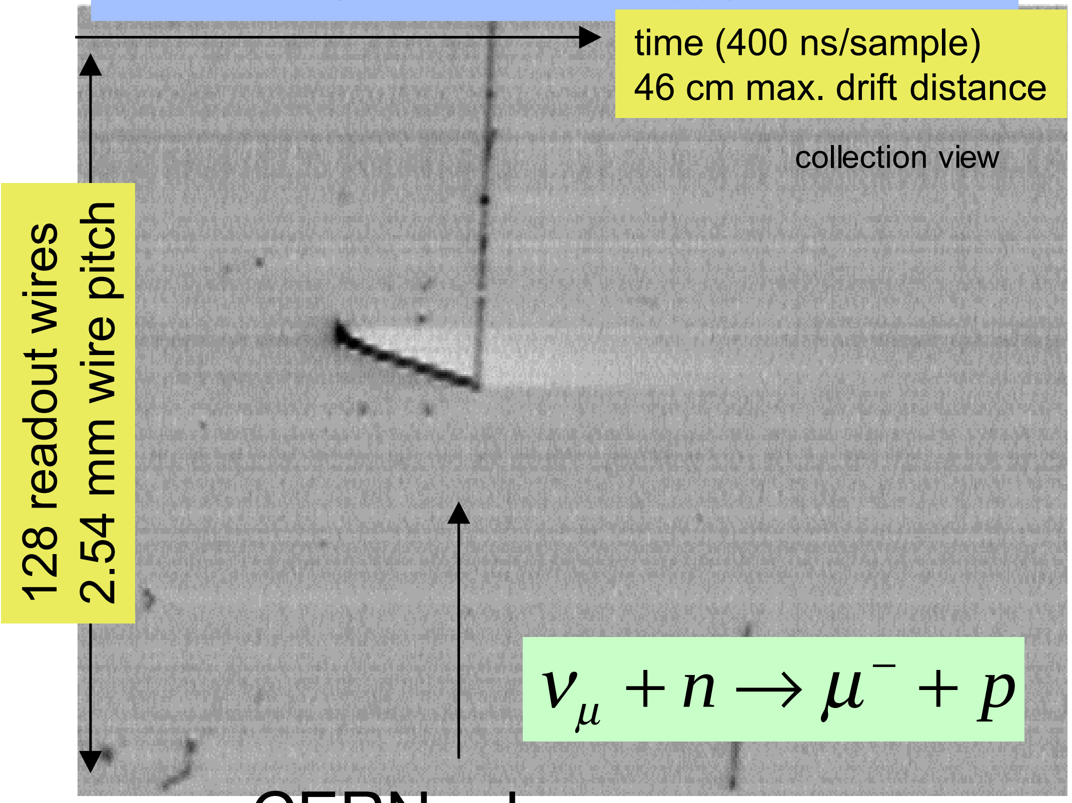
"Bubble" size
≈ 3 x 3 x 0.2 mm^3

Energy deposition measured for each point

Liquid Argon TPC (ICARUS)

- Fully homogeneous, continuous, precise **tracking device** with high resolution dE/dx **measurement** and full sampling **electromagnetic and hadronic calorimetry** (X_0=14cm, λ_{int}=84cm)
- Excellent **imaging capabilities** “bubble-chamber-like” device
- Excellent electron id and e-π^0 separation
- Calorimetry allows full kinematics reconstruction of “contained” events
- dE/dx provides particle id (with range) and precise momentum measurement for soft particles; rejection of conversions and Dalitz decays
- Large detectors (kilotons) with high granularity feasible (600 ton approved)
- LAr TPC is the **outcome of many years of R&D** by the ICARUS Collab.

Real ν event
in the 50 liter LAr TPC in
CERN WANF beam



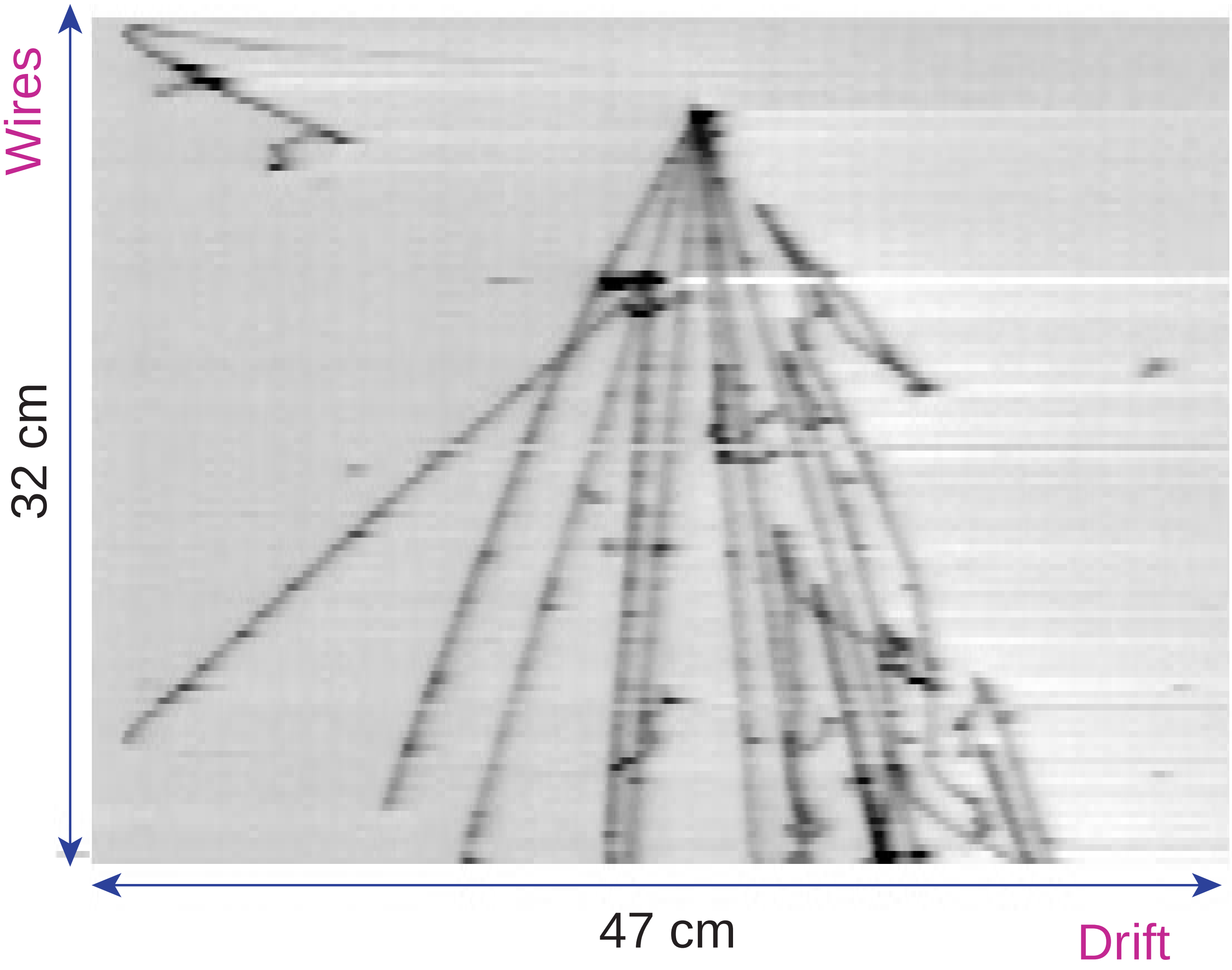
$$\nu_\mu + n \rightarrow \mu^- + p$$

CERN ν-beam

ICARUS-CERN-Milano Collab.

(Chamber located in front of NOMAD detector)

Neutrino Event in the 50 lt Prototype



The ICARUS technique – challenges

- ***Liquid Argon environment in big volumes:***
  - → Cool and maintain the temperature of the detector at T=90K with T uniformity of ±1K (uniform drift velocity)
  - → Temperature gradient during cooling phase implies mechanical stress ⇒ e.g. chamber wires contraction
- ***Long drift path ⇒ drift electron lifetime > 1 ms:***
  - → Ultra high vacuum (UHV) requirements
  - → “Clean” elements (chamber structure, cryogenic instrumentation, …) and limited degassing (cables, …)
  - → Reach a purity of LAr at the level of <0.1 ppm O_2 equivalent

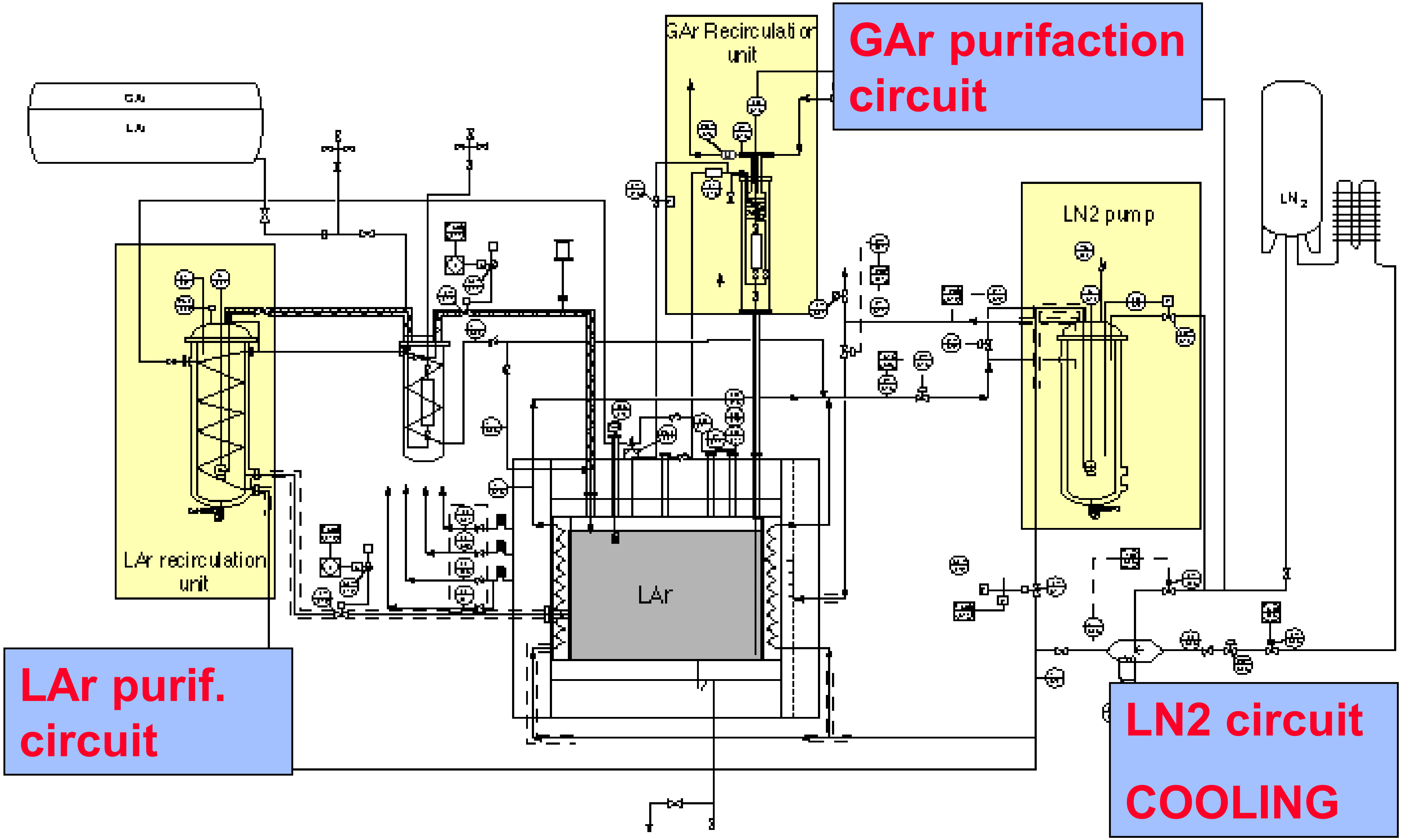
While these goals have been reached in laboratory environment, they have now to be reached at the industrial scale for the T600 detector! ⇒ **15 ton prototype**

The 15 ton ICARUS prototype

15 ton cryostat

Chamber structure

Cryogenic circuit



GAr purifaction circuit

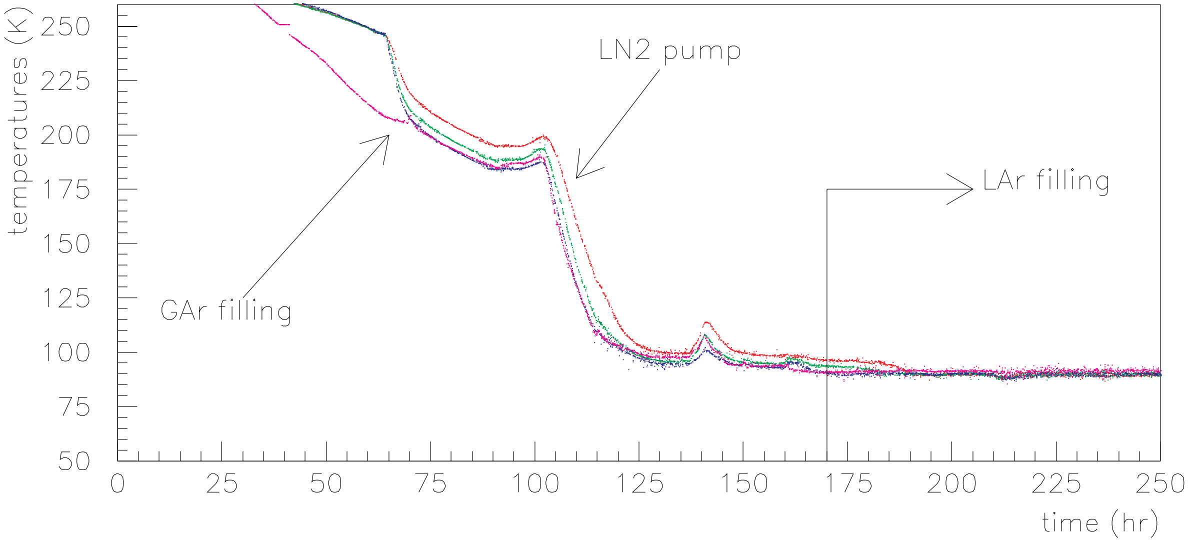
LAr purif. circuit

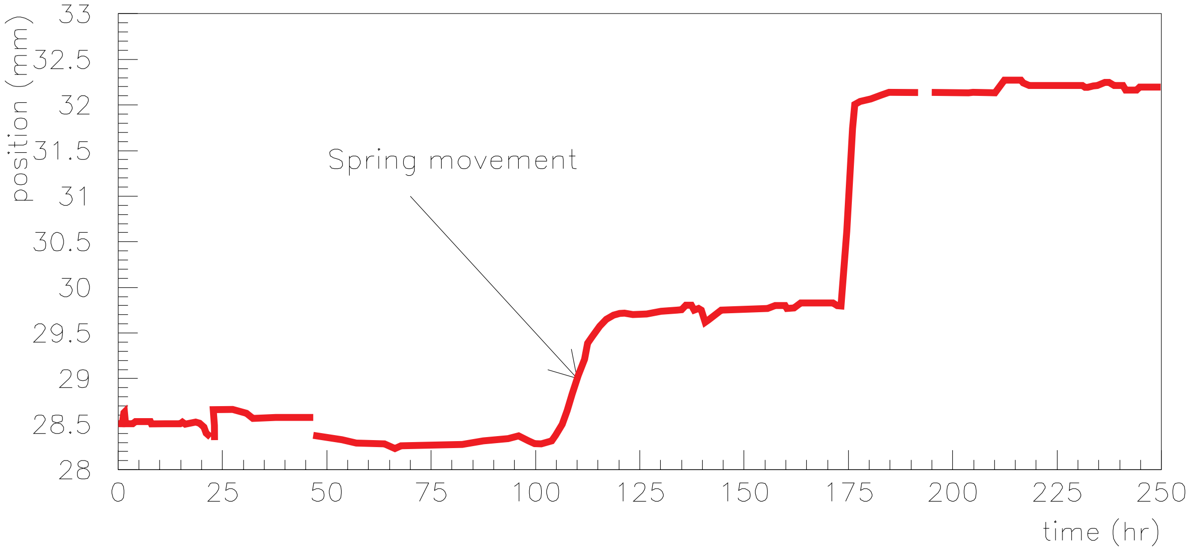
LN2 circuit

COOLING

Cooling 15 ton prototype March '99

- ✖ To avoid large thermal stresses, first part of the cooling, down to about -30 °C made using a dedicated device. Cooling is performed under vacuum.
- ✖ Then filled the cryostat with purified gas argon (GAr).
- ✖ After 2.5 days, when all the temperatures were below –150°C started filling the cryostat with purified LAr.
- ✖ The position meter installed on one of the three tensioning devices of the chambers module, measured a total elongation of the spring of about 1.2 mm ⇒ confirms the functionality of the *variable geometry* mechanics





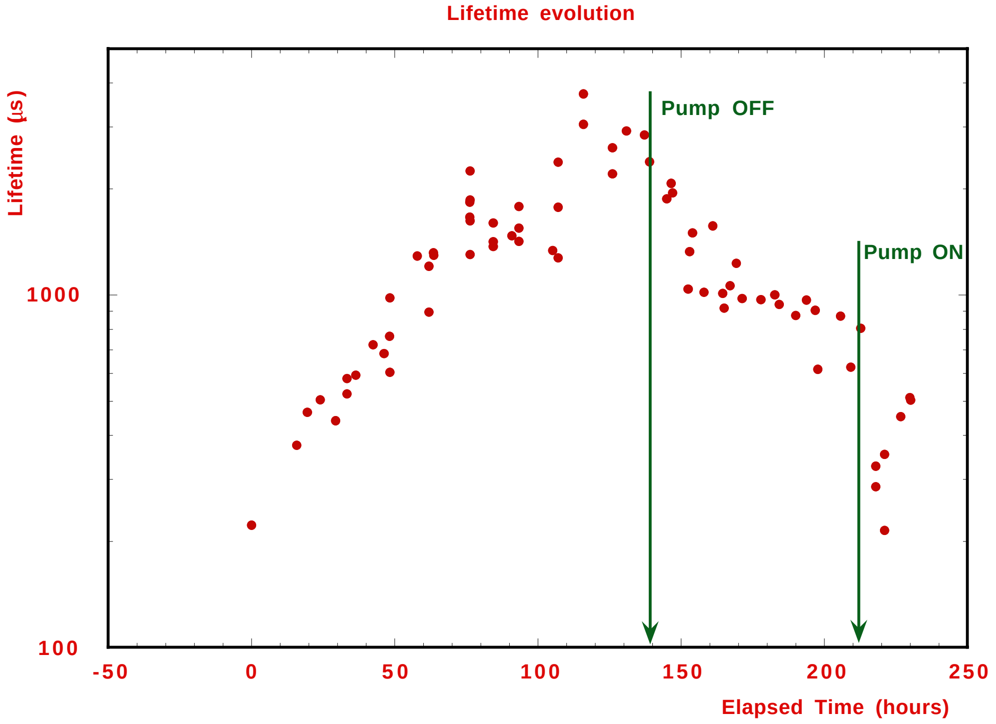
André Rubbia, ETH/Zürich, 2/6/00

Electron lifetime in 15 ton prototype

✖ **The free electrons lifetime (i.e. LAr purity), measured just after the filling, was between 200 μs to 300 μs**.

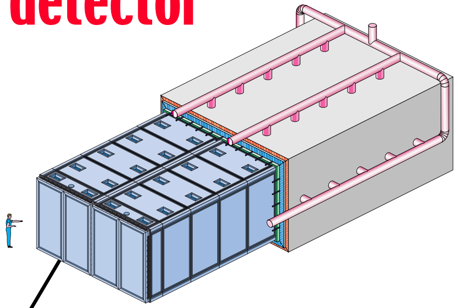
✖ After start of LAr recirculation/purification with the immersed pump, the free electrons lifetime rapidly increased with a slope consistent with a one volume recirculation time of about 40 hours. **The final electrons lifetime, after about 4 days of recirculation, was between 2 ms to 3 ms.**

Taking into account that the maximum drift time in the T600 will be about 1 ms, the goal for purity is reached.



The ICARUS programme

600 ton detector

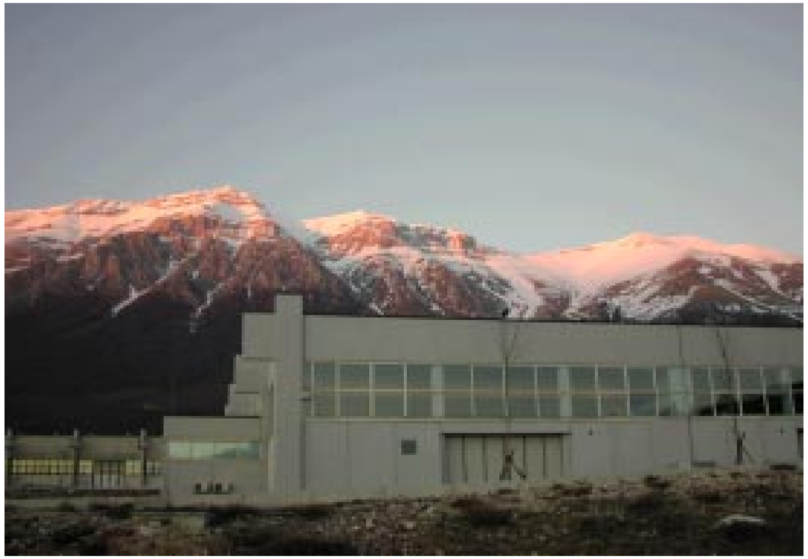


- ✔currently under construction / assembly in strong cooperation with industry
- ✔will be ready for the first test during summer 2000
- ✔Important milestone for the approval of the ICANOE experiment

15 ton prototype

- ✔Cryogenic test
- ✔LAr purification test
- ✔H.V. & readout test

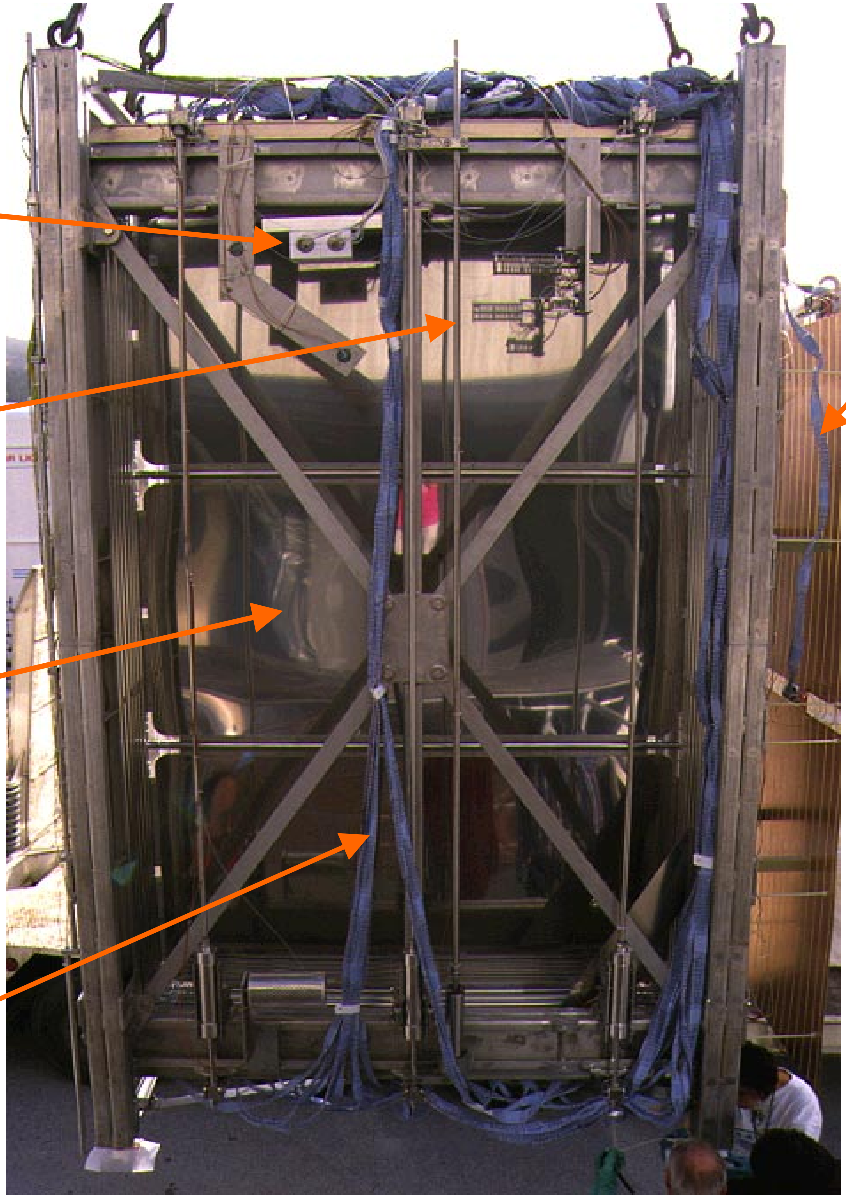
T15 installation @ LNGS (Hall di Montaggio)



Ext. Trigger

N_2 Pump

T15 internal detectors



Photomultipliers

Pads

Purity Monitors

Cathode

Two wire planes (induction + collection)
928 wires/plane, all connected for readout

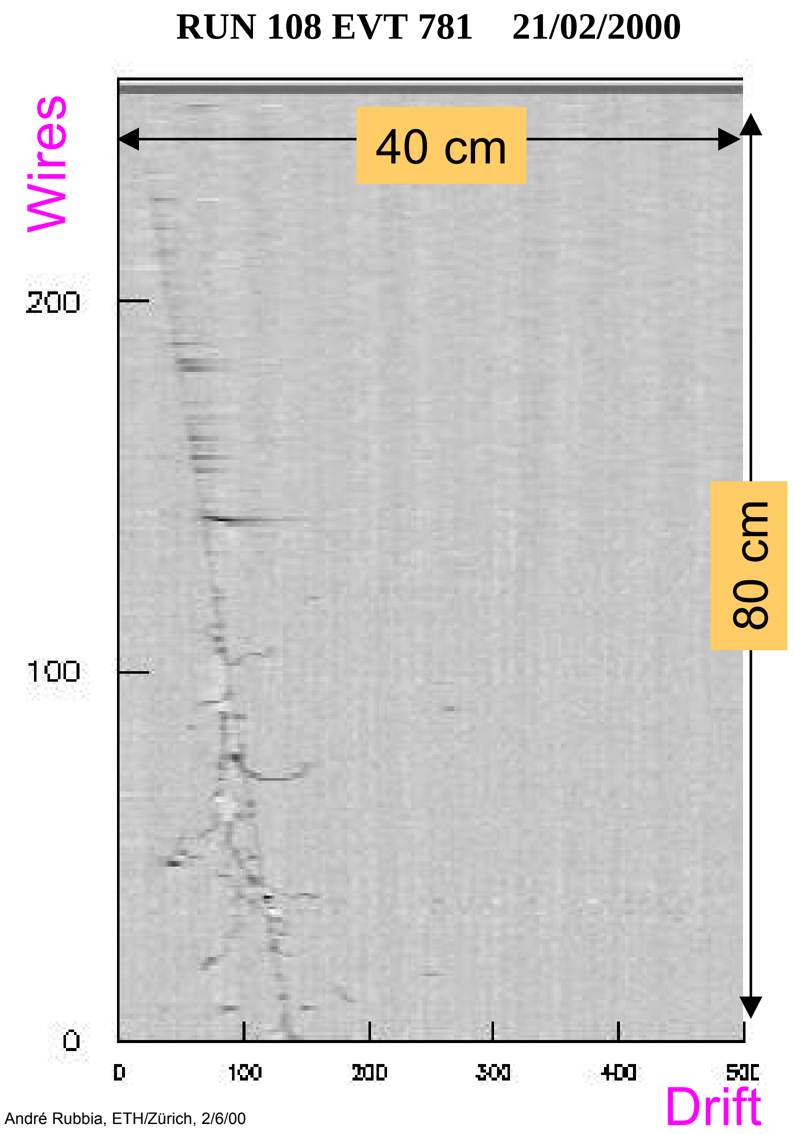
Tracks in 15 ton prototype at LNGS

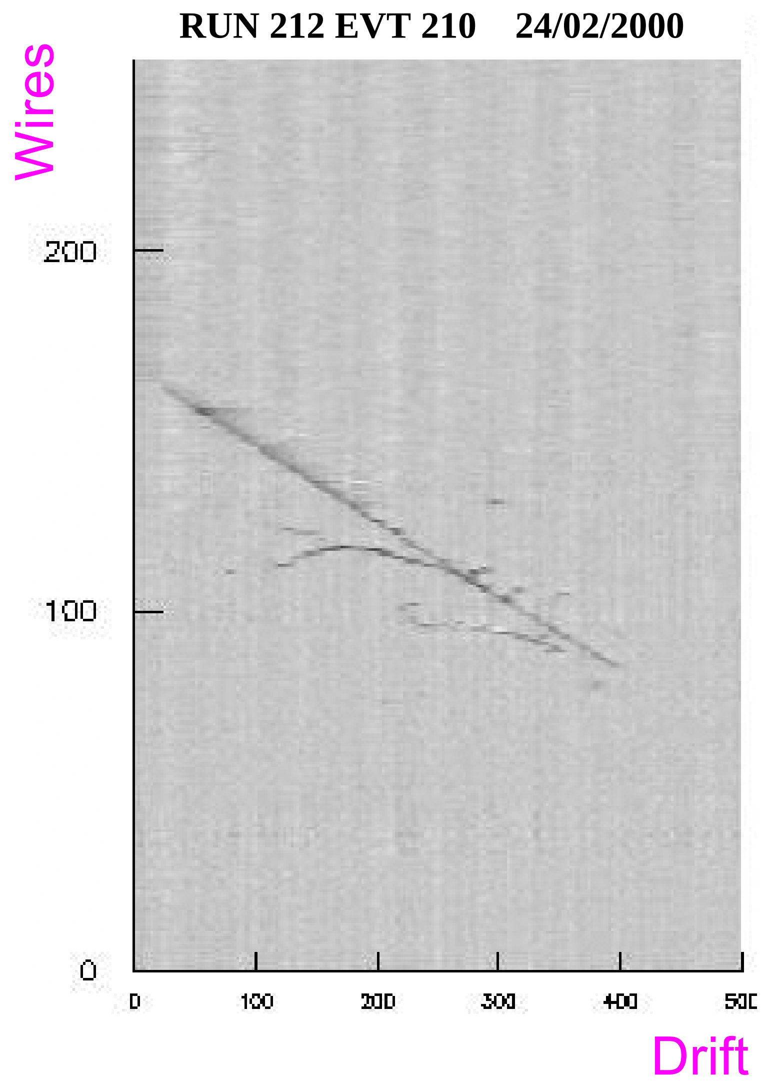
X-ing muon with δ-ray production:

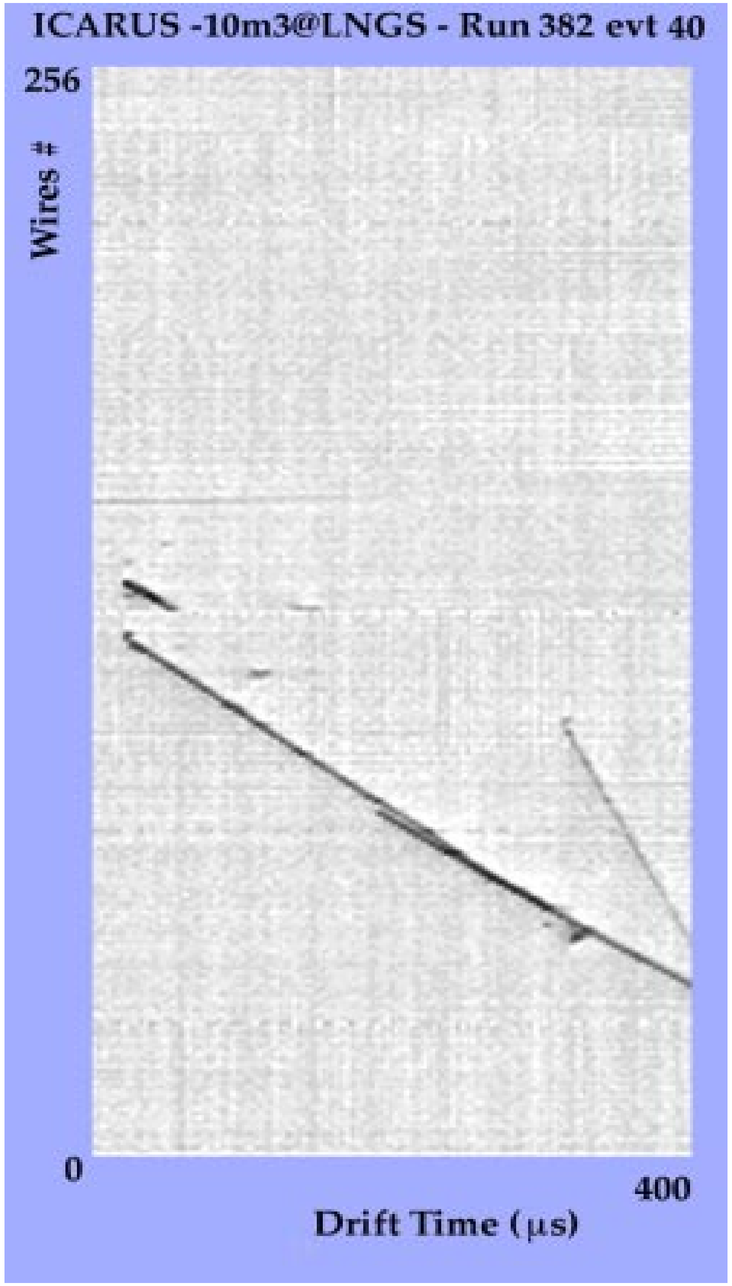
E-field: 300 V/cm

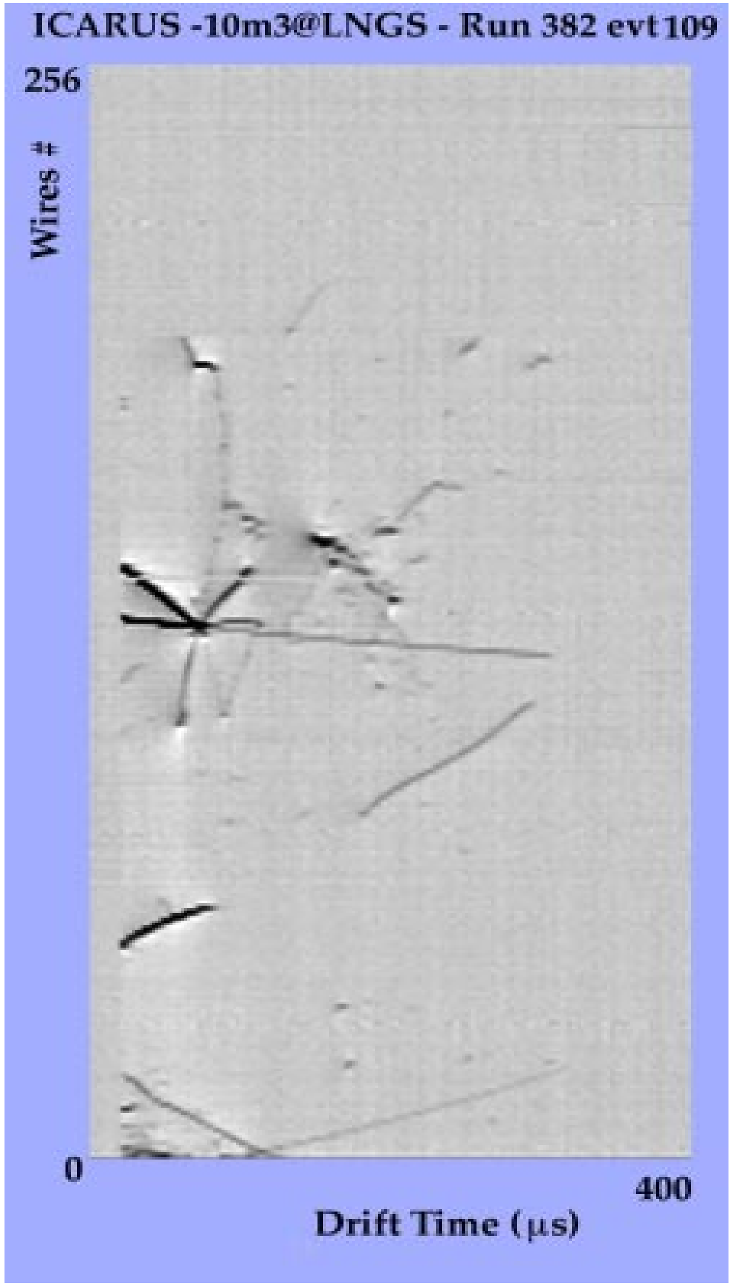
Argon purity: electron lifetime

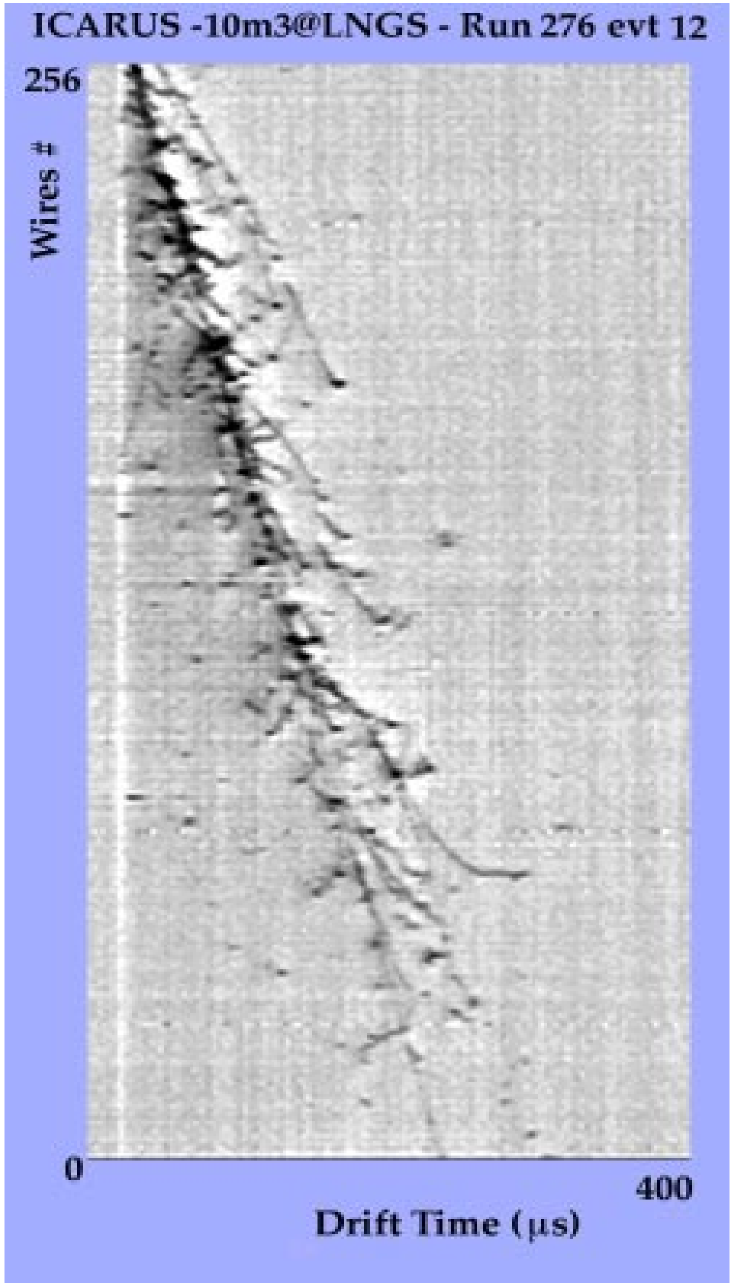
$\langle \tau_{el} \rangle$ = 1.05 ± 0.30 ms

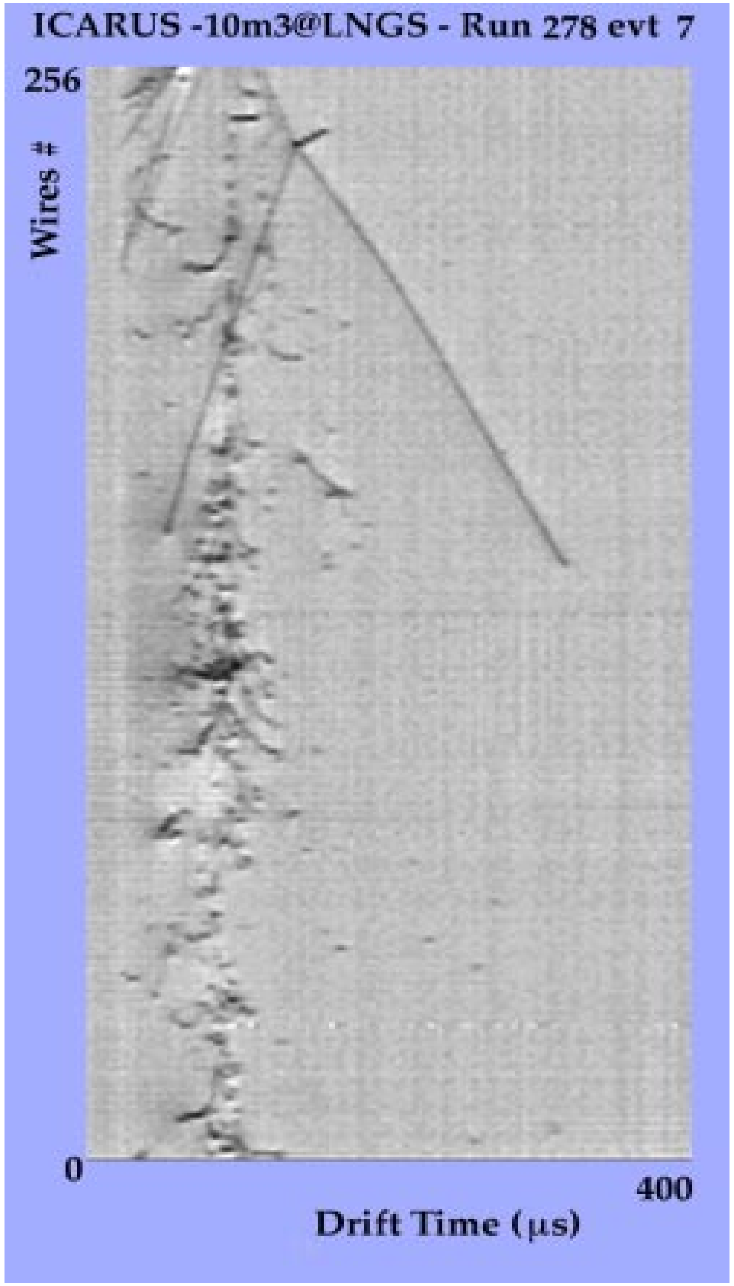





ICARUS -10m3@LNGS - Run 382 evt 40
256
Wires #
0
400
Drift Time (μs)


ICARUS -10m3@LNGS - Run 382 evt 109
256
Wires #
0
400
Drift Time (μs)

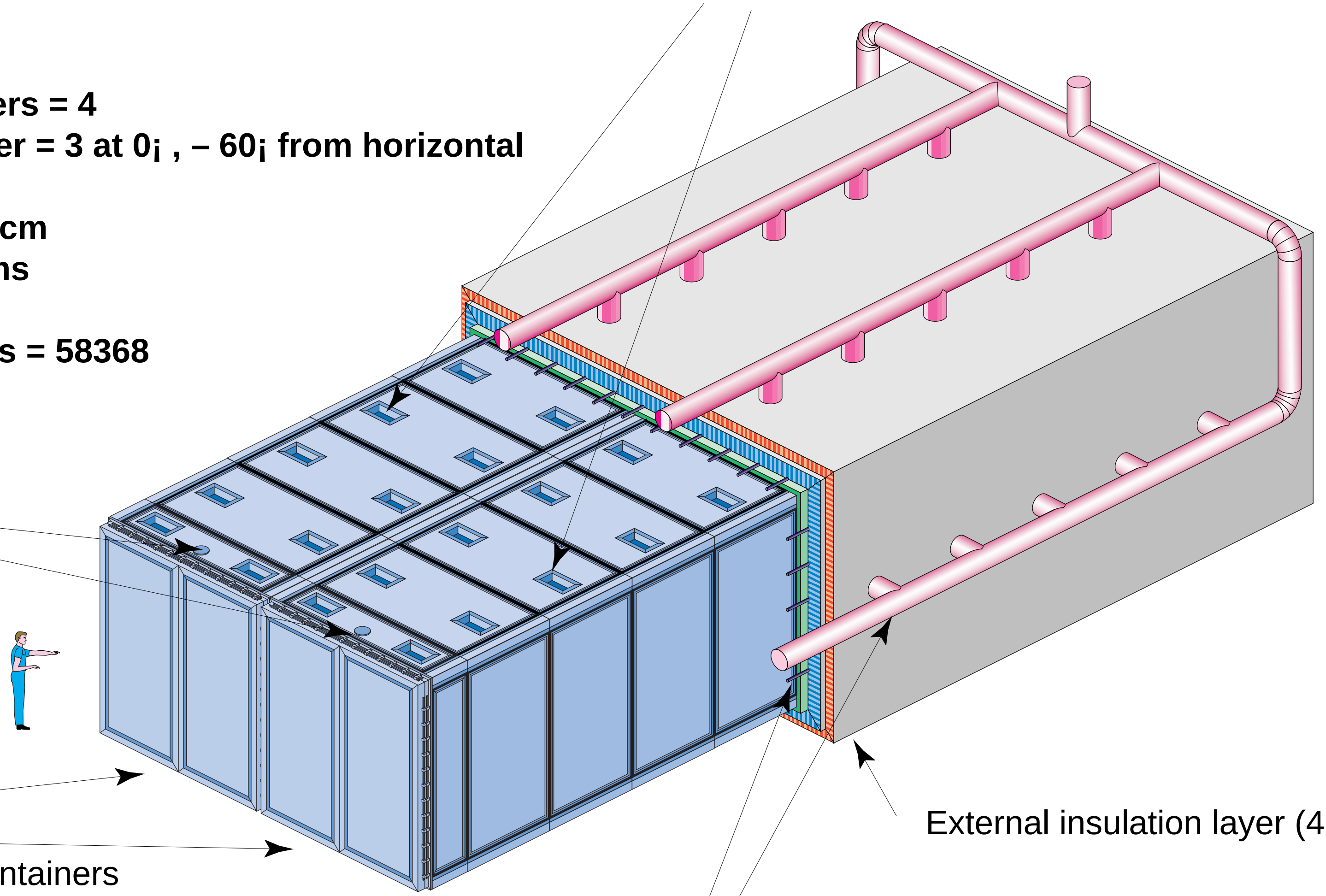

ICARUS -10m3@LNGS - Run 276 evt 12
256
Wires #
0
400
Drift Time (μs)


ICARUS -10m3@LNGS - Run 278 evt 7
256
Wires #
0
400
Drift Time (μs)

The T600 Module

Number of independent containers = 2
Single container Internal Dimensions: Length = 19.6 m , Width = 3.9 m , Height = 4.2 m
Total (cold) Internal Volume = 534 m
Sensitive LAr mass = 476 ton

Number of wires chambers = 4
Readout planes / chamber = 3 at 0¡ , – 60¡ from horizontal
Maximum drift = 1.5 m
Operating field = 500 V / cm
Maximum drift time ¯ 1 ms
Wires pitch = 3 mm
Total number of channels = 58368



Signal feedthroughs

HV feedthroughs

External insulation layer (400 mm)

2 independent aluminum containers
each one transportable inside the GS
Laboratory

LN2 cooling circuit

André Rubbia, ETH/Zürich, 2/6/00

T600 assembly status

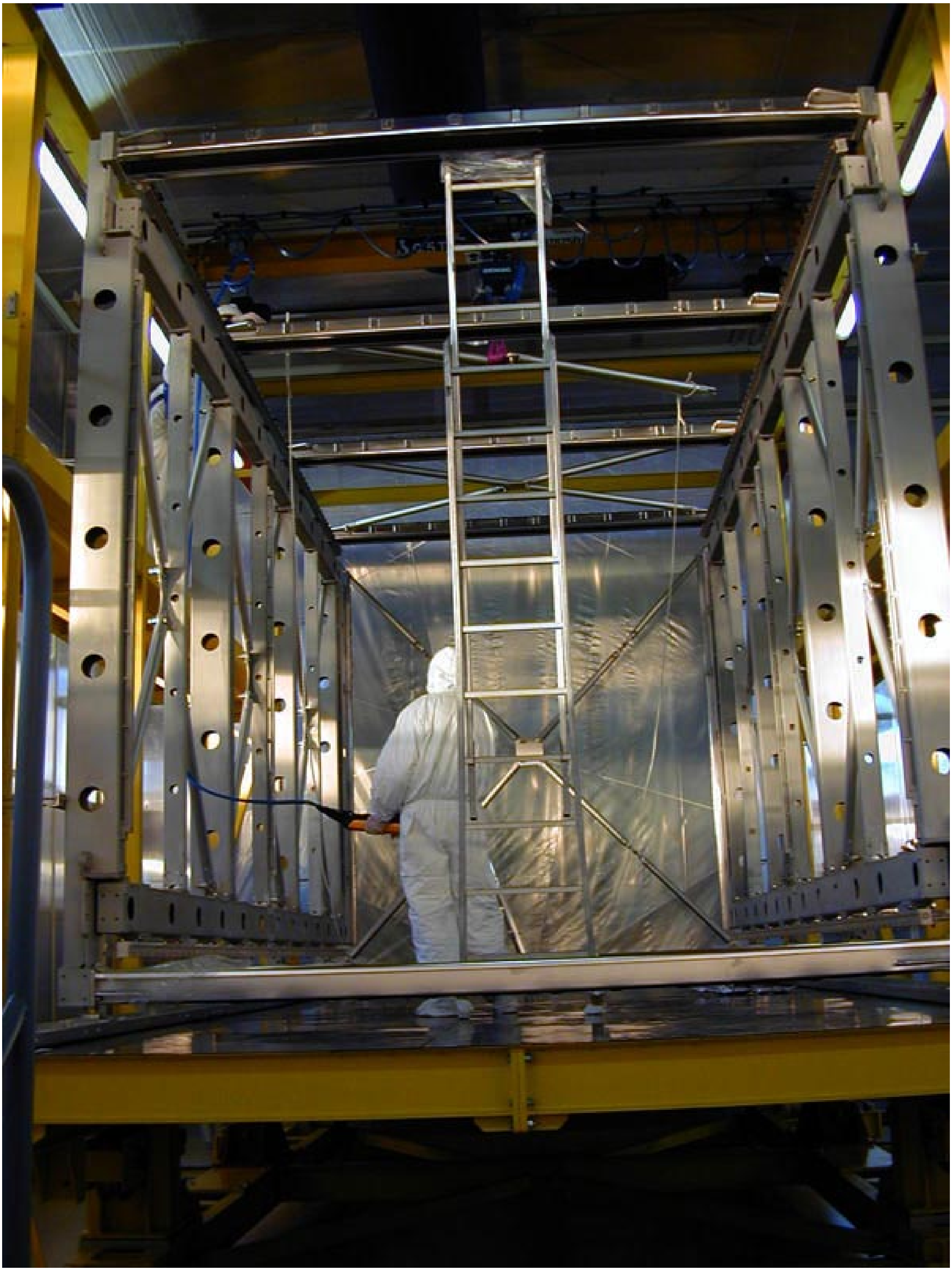
1st Half Module

Cryostat interior

Wire Chamber Construction

External view of the T600 half-module

Clean room – mounting of the wire chamber mechanical structure



André Rubbia, ETH/Zürich, 2/6/00

T600 assembly status (II)

Wire Factory

2nd half Module Construction

Tentative timescale for ICANOE

- 2000:
  - →Operation of the T600 ICARUS module
  - →Decision for approval of ICANOE by CERN & LNGS
  - →Funding for ≈2 supermodule pre-allocated by INFN
  - →Other sources of funding still to be found
- 2001:
  - →Final engineered design
- 2002:
  - →Beginning construction
- 2003:
  - →First supermodule in operation
- 2005:
  - →two (or three?) supermodules

Long and Very Long Baseline Experiments

NuFact location	Distance to Gran Sasso	Mean density
CERN	732 km	2.8 g/cm^3
Canary Islands	2900 km	3.2 g/cm^3
FNAL	7400 km	3.7 g/cm^3
KEK	8815 km	4.0 g/cm^3

$R > 3500$ km & $R < 4500$ km

➜ $\rho\ (g/cm^3) = 7.25 - 5 \times 10^{-4} \times R$

$R > 4500$ km & $R < 6360$ km

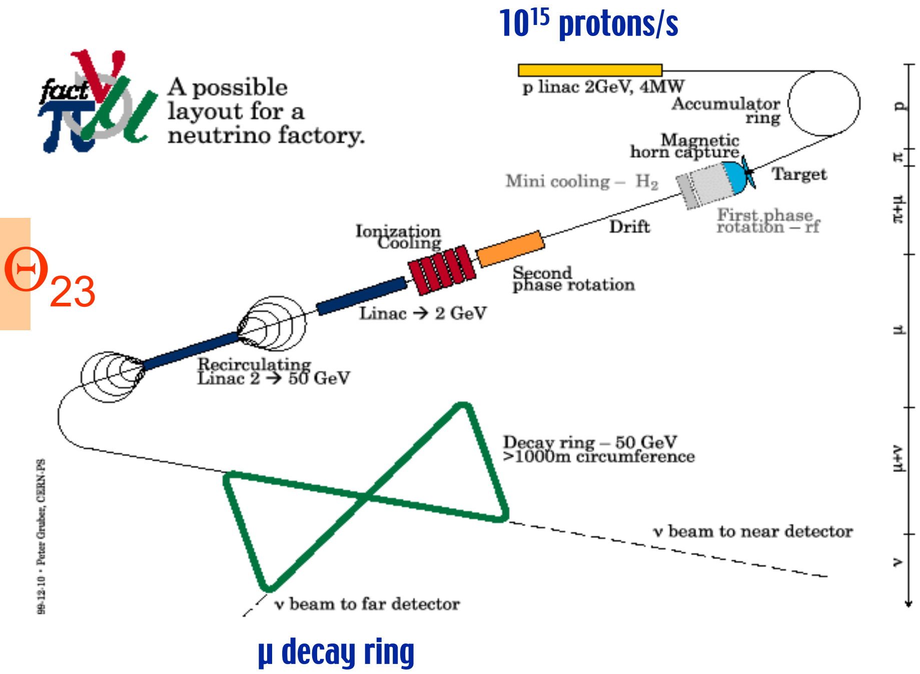
➜ $\rho\ (g/cm^3) = 7.74 - 7 \times 10^{-4} \times R$

$R > 6360$ km

➜ $\rho = 2.8\ g/cm^3$

Second generation LBL experiments: the NuFact

- By the time the **neutrino factory** becomes operational we presume that ν oscillations experimentally established beyond any doubt
- Main goals:
  - → Accurate determination of Δm^2_{23} , Θ_{23}
  - → Improve sensitivity to Θ_{13} by factor ≈100 compared to CNGS
  - → Matter effects
  - → CP violation



E_μ = 20-50 GeV

> 10^{20} μ decays/year!

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

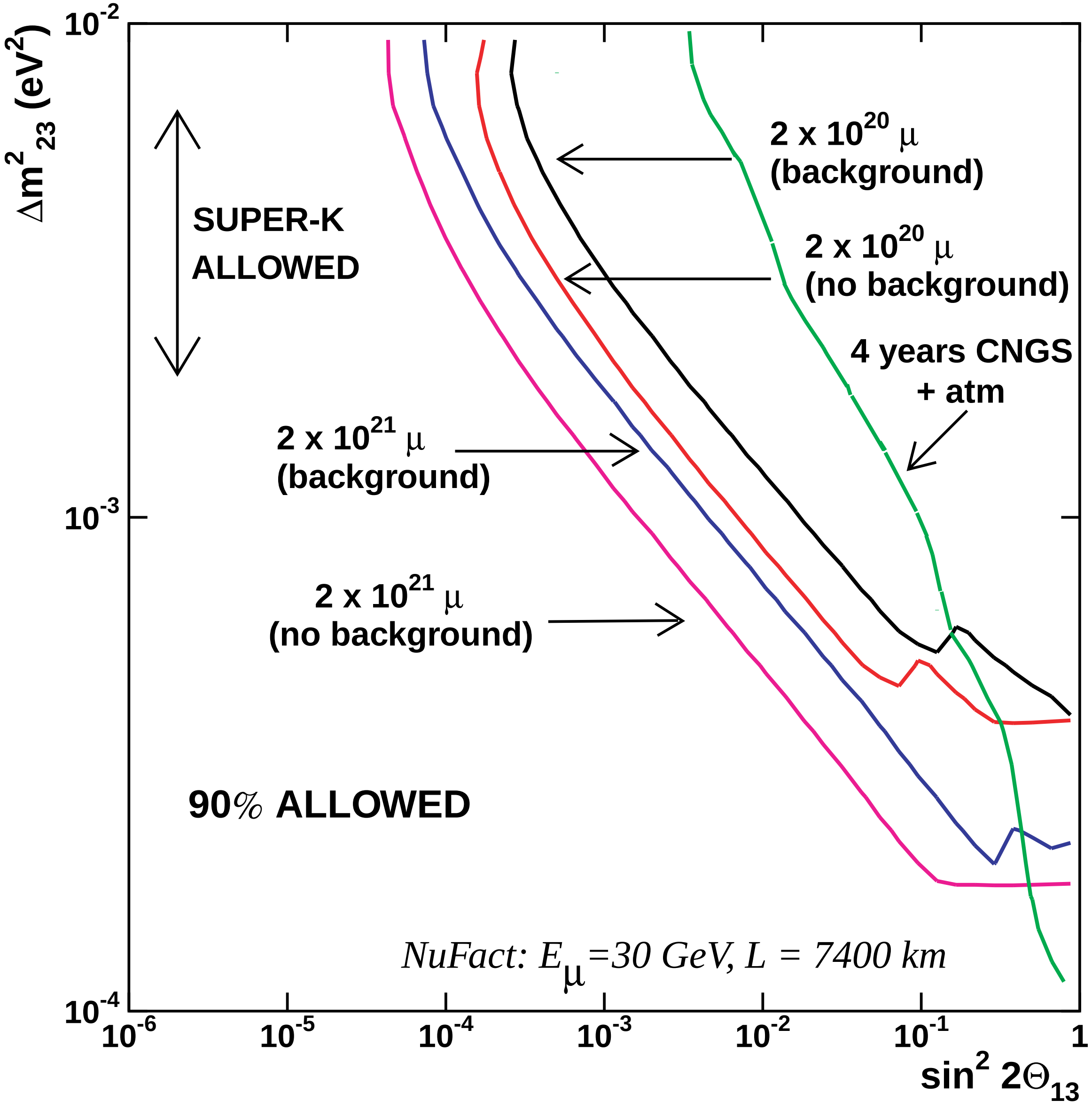
Neutrino Event Rates

- Assume for this study:
  - → **10 kton detector** (fiducial)
  - → **E_μ = 30 GeV**
  - → No polarization
  - → No beam divergence

Rates (no oscillations)

		L=732 km	L=2900 km	L=7400 km
μ^- 10^{20} decays	ν_μ CC	226000	14400	2270
	ν_μ NC	67300	4120	680
	$\bar{\nu}_e$ CC	87100	5530	875
	$\bar{\nu}_e$ NC	30200	1990	300
μ^+ 10^{20} decays	$\bar{\nu}_\mu$ CC	101000	6380	1000
	$\bar{\nu}_\mu$ NC	35300	2240	350
	ν_e CC	197000	12900	1980
	ν_e NC	57900	3670	580

Expected sensitivity to θ_{13} at a neutrino factory



- Very long baseline: L=7400 km
- Search for wrong-sign muons
- Strongly depends on background level for wrong-sign muons
- Almost two-orders of magnitude improvement

Conclusion

- ✯ ***ICANOE detector*** *will provide unique "bubble-chamber" like imaging with multi-kton mass*
  - →help elucidate in a comprehensive way the neutrino mixing pattern with a simultaneous observation of beam and atmospheric events
- ✯ ***ICARUS T600*** *is an* ***important milestone*** *for ICANOE approval*
- ✯ *Time scale (pending approval)*
  - →New atmospheric neutrino experiment that competes with SuperKamiokande measurement starting in ≈2003
    - – Better resolution, better imaging, lower energy threshold ⇒ a new look at atmospheric events
  - →CNGS beam scheduled for May 2005
    - – ν_e and ν_τ appearance ⇒ unambiguous signature for flavor oscillations
- ✯ ***Beyond 2010:*** new physics opportunities may be provided by "neutrino factories"