ICANOE and OPERA experiments at the CNGS

Presented by André Rubbia
ETH Zürich, Switzerland

Special thanks to A. Ereditato for providing material about OPERA

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Sudbury, Canada June 16 - 21, 2000

Long-baseline neutrino experiments in Europe

- The ***CNGS beam*** directed towards LNGS (L=730 km) has been ***approved by the CERN council*** in December 1999
- Two experiments have been proposed:

- LNGS-P21/99; CERN /SPSC 99-25; SPSC/P314
- CERN/SPSLC 96-58 SPSC/P 304
- CERN/SPSC 98-33 SPSC/M620

`http://pcnometh4.cern.ch`

- 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

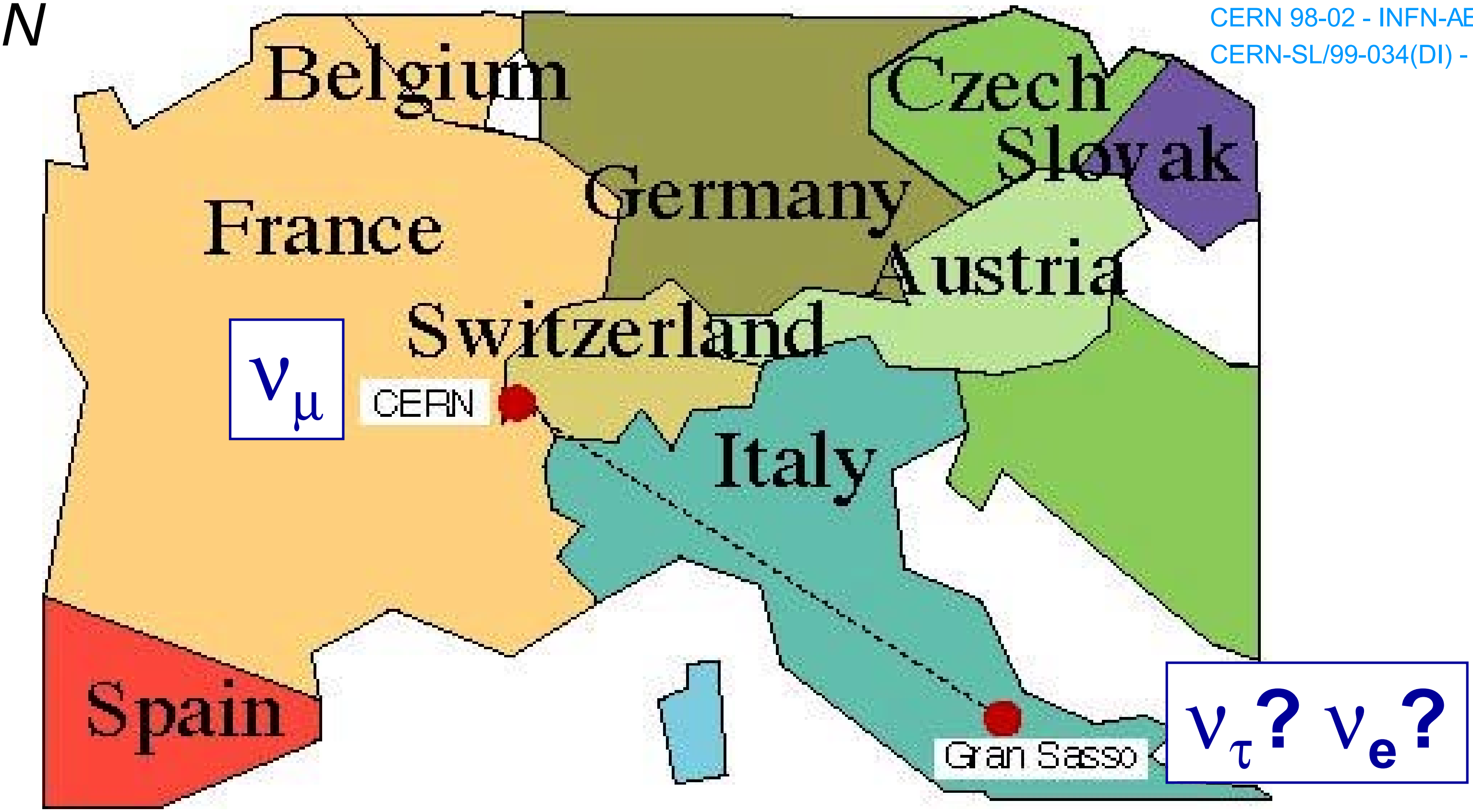
`http://www.cern.ch/opera`

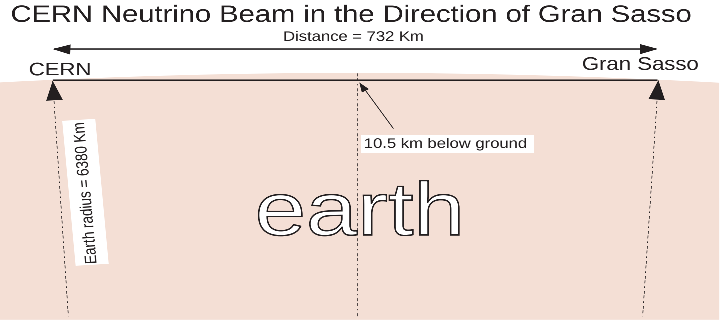
- The two experiments, while ***technologically challenging*** compared to “traditional” massive neutrino detectors, are both based on many years of R&D.
- Natural follow-ups of CHORUS and NOMAD at CERN.

CNGS neutrino beam

The CNGS beam design is the outcome of many years of experience at CERN

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





Planned beam commissioning: May 2005

CNGS event rates

- Primary protons: **400 GeV; 4x2.3x10^{13} p/cycle; 26.4 s/cycle**
- Pots per year: **4.5x10^{19} pots** “shared”; **200x0.75 days/year**

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

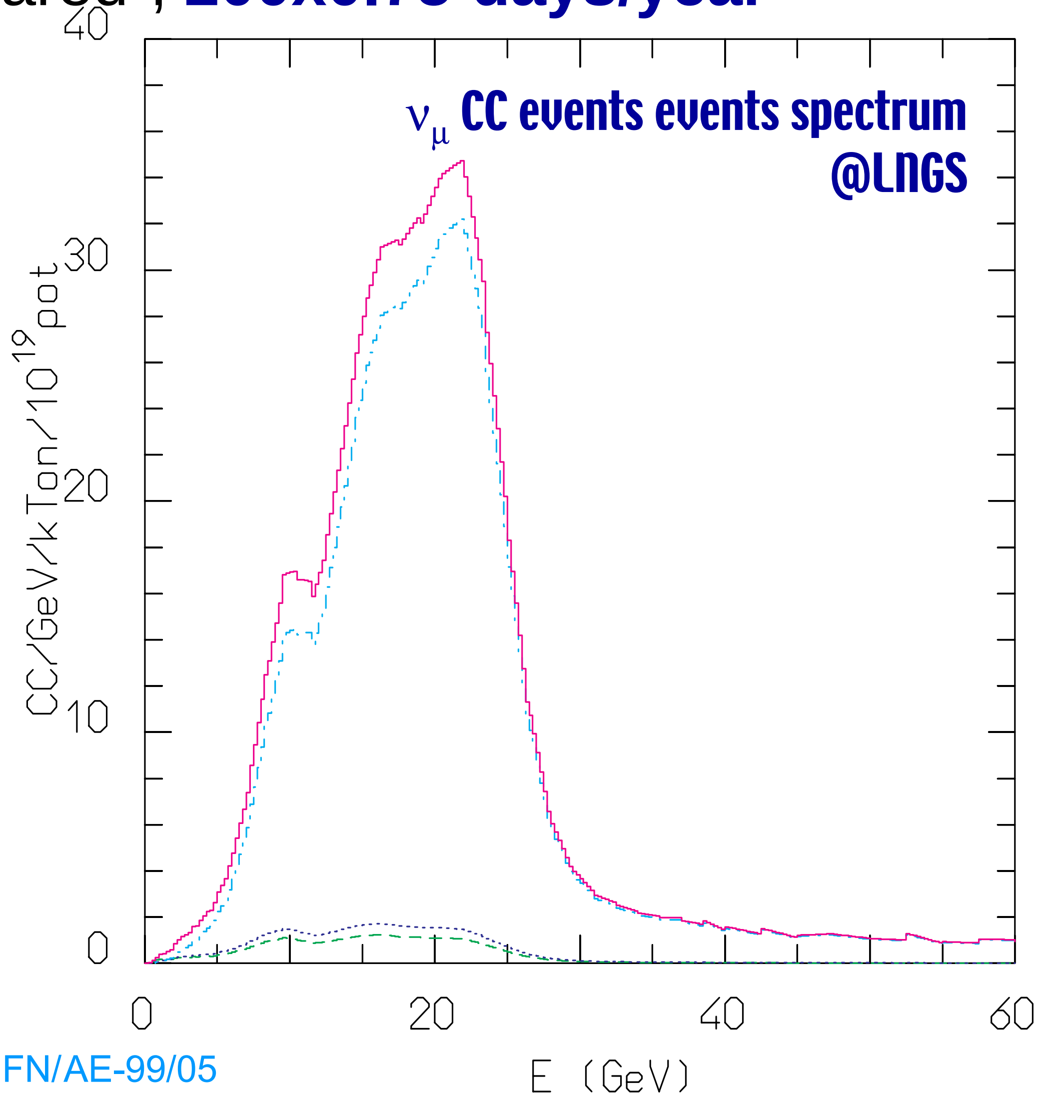
No oscillations

- Optimized for $N_\tau \propto \int \phi_{\nu_\mu}(E)\times\sigma^{CC}_{\nu_\tau}(E)E^{-2}dE$

Δm^2 (eV^2)	**Rates (events/kton/year)**
1×10^{-3}	2.4
2.5×10^{-3}	15.1
3.5×10^{-3}	29.4
5×10^{-3}	58.6
1×10^{-2}	209.0

ν_τ CC event rates

- 7.6x10^{19} pots/yr “dedicated”



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

OPERA

COLLABORATION

29 institutes from Europe and Japan

Belgium
Brussels

CERN

China
Beijing, Shandong

Croatia
Zagreb

France
Annecy, Lyon, Orsay, Starsbourg

Germany
Berlin, Hagen, Hamburg, Münster, Rostock

Israel
Haifa

Italy
Bari, Frascati, Naples, Padova, Rome, Salerno

Japan
Aichi, Toho, Kobe, Nagoya, Utsunomiya

Russia
ITEP Moscow

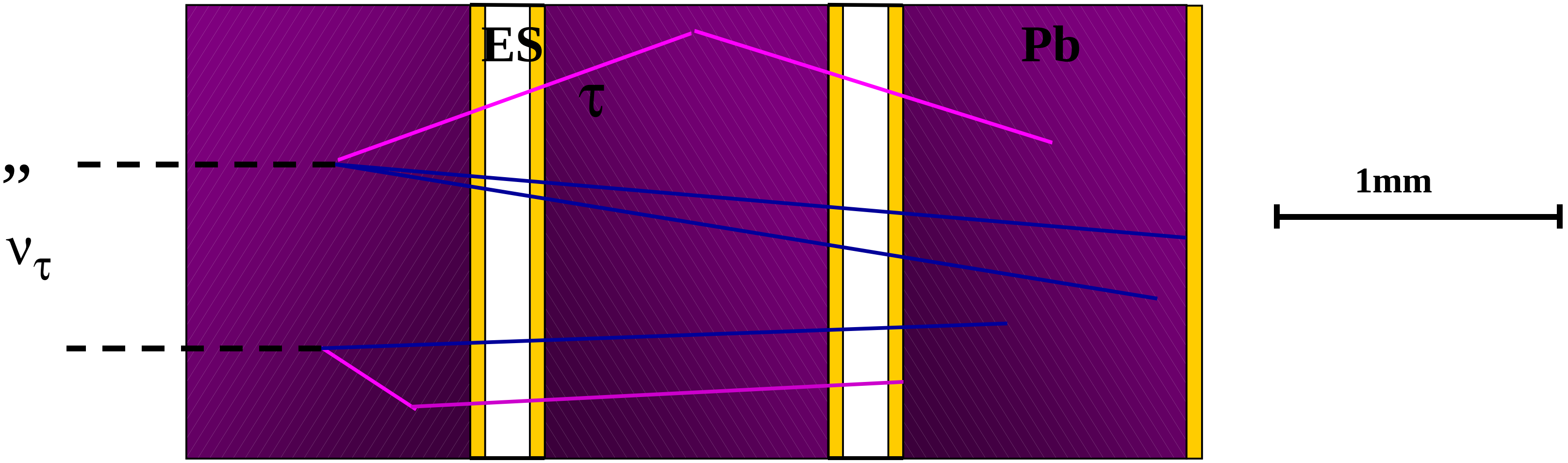
Switzerland
Bern

Turkey
METU Ankara

OPERA ECC elementary cell

***Direct* detection of τs by decay topology (γcτ ~ 1mm)**

Baseline option: “compact”



Basic ECC (Emulsion Cloud Chamber) concept:

Passive target material and emulsion tracking

⇩ large mass

⇩ high space resolution

Prototype: Measured angular and position resolution with 100 μm segments: ~2 mrad in angle and ~0.6 μm in position

OPERA detector

✯ Modular detector structure:

cells → bricks → walls → modules → supermodules

electronic trackers ↑ (walls → modules)

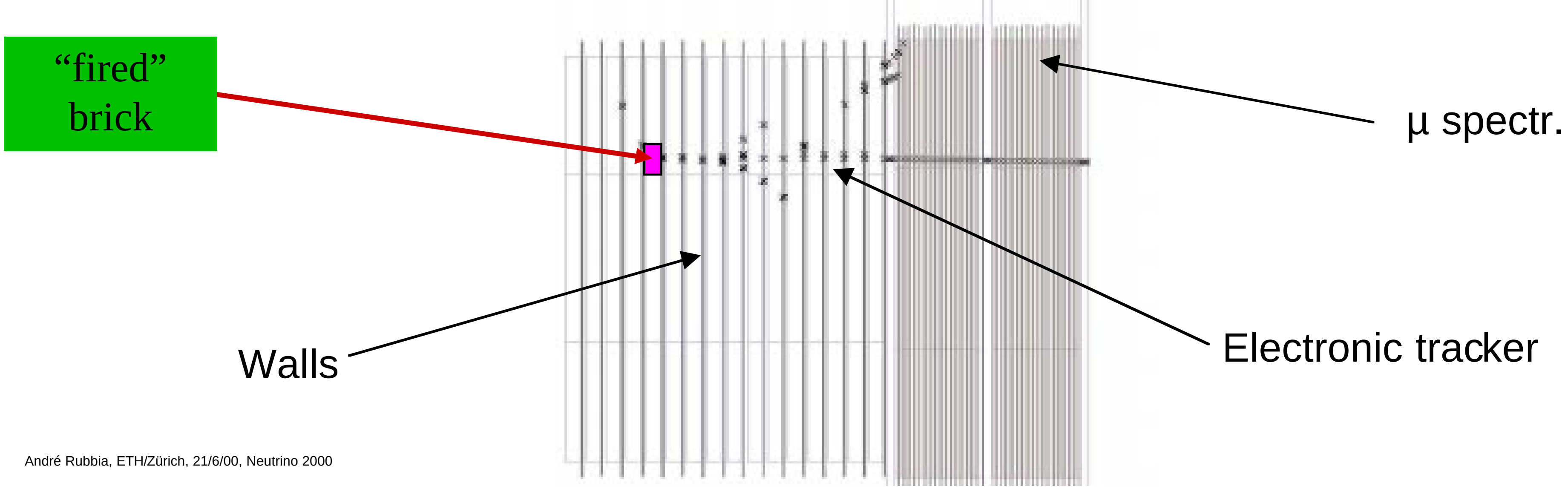
μ spectr. ↑ (modules → supermodules)

Task:
- identify fired brick (shower axis)
- tracking and shower energy

Baseline option:
- scintillator strips (WLS fiber r/o)

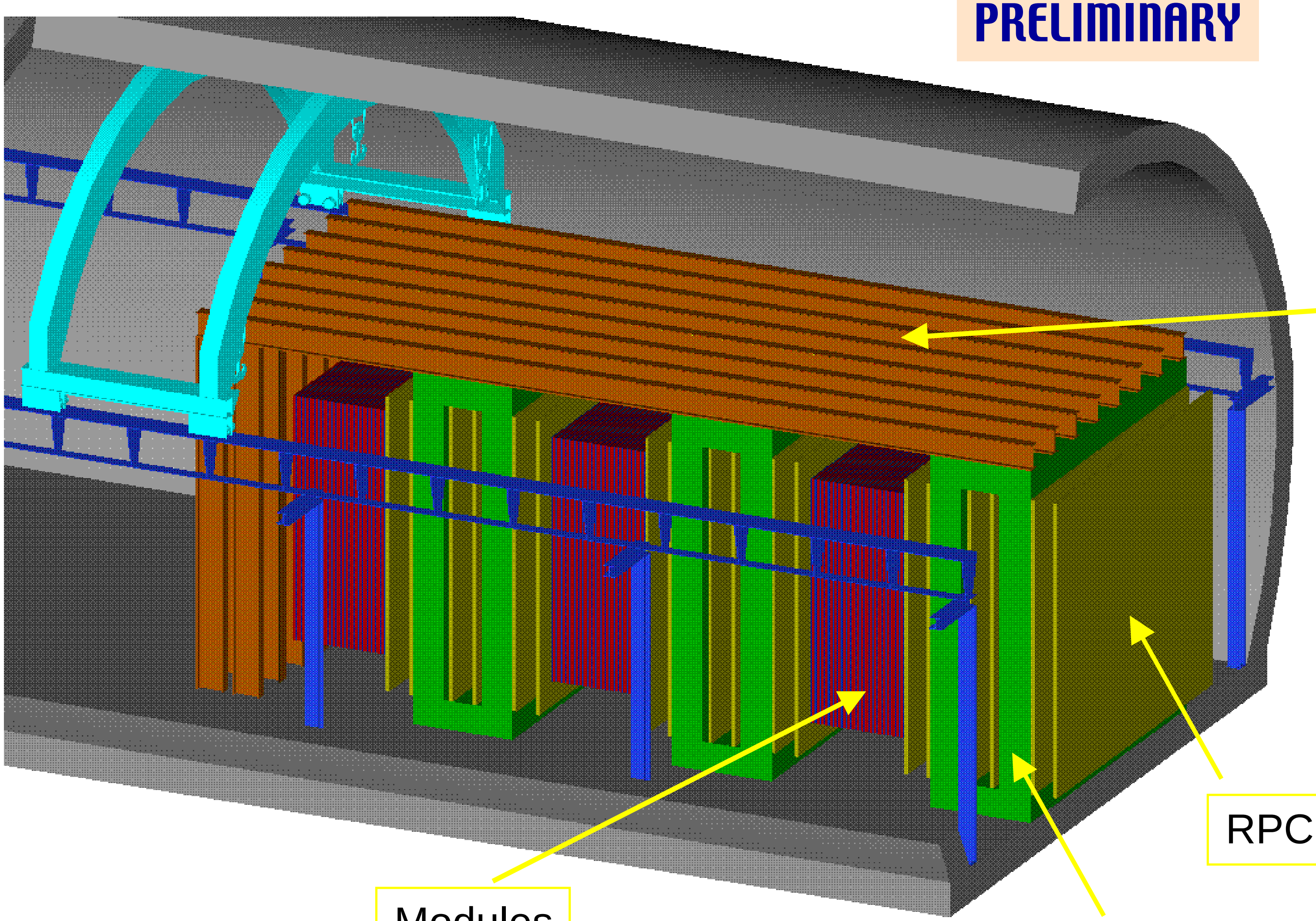
Task:
- identify muons
- measure μ charge (reduce BG for muonic decays, beam knowledge)

Baseline option:
- iron dipoles, RPC (inner tracker), Drift tubes (precision trackers)



OPERA baseline design (July 2000 proposal)

PRELIMINARY



Supporting "roof"

RPC+drift tubes

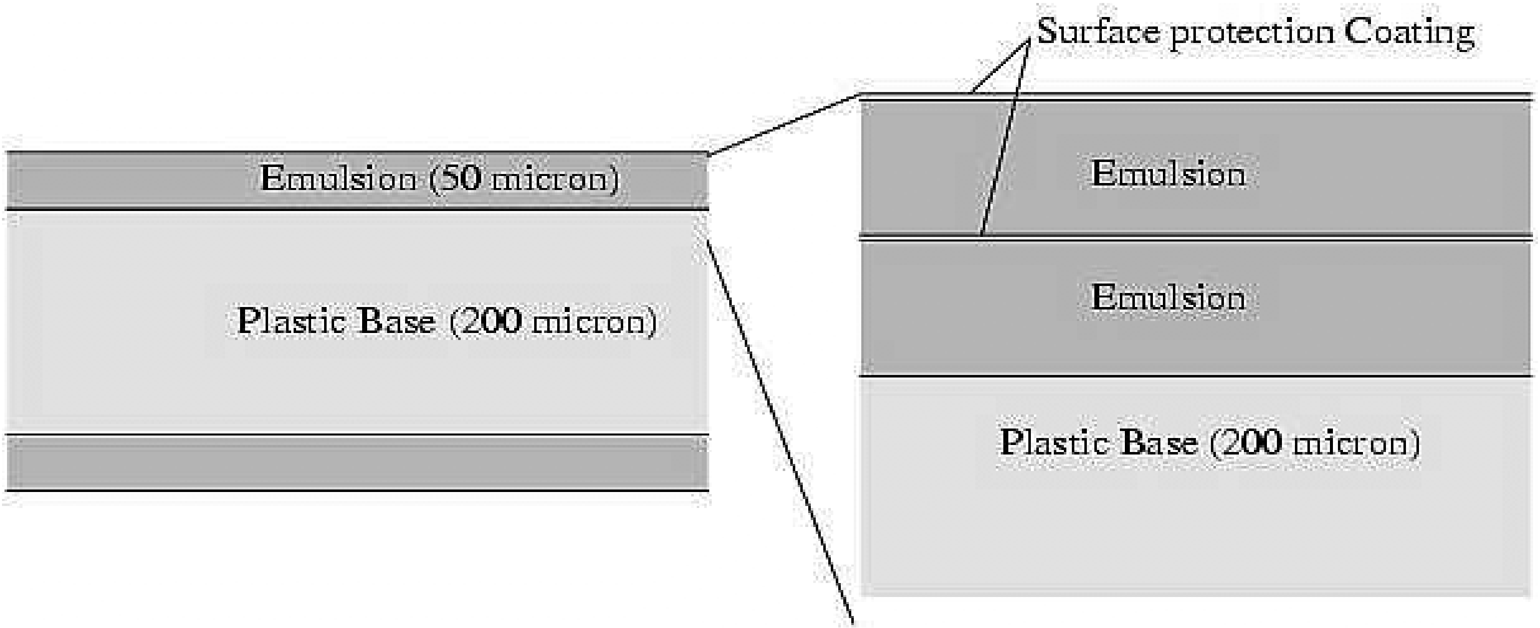
Modules

μ spectrometer dipoles

OPERA design is "LNGS Hall independent"

Industrial Emulsion films: OPERA: ~200000 m^2 ES !

- joint R&D project between Fuji Co. and the Nagoya group
- diluted (x2) emulsion gel, good sensitivity (~30 grains/100 μm)
- excellent mechanical properties and uniformity
- large production capability (photographic films production lines)



Scanning speed is important for **OPERA**:

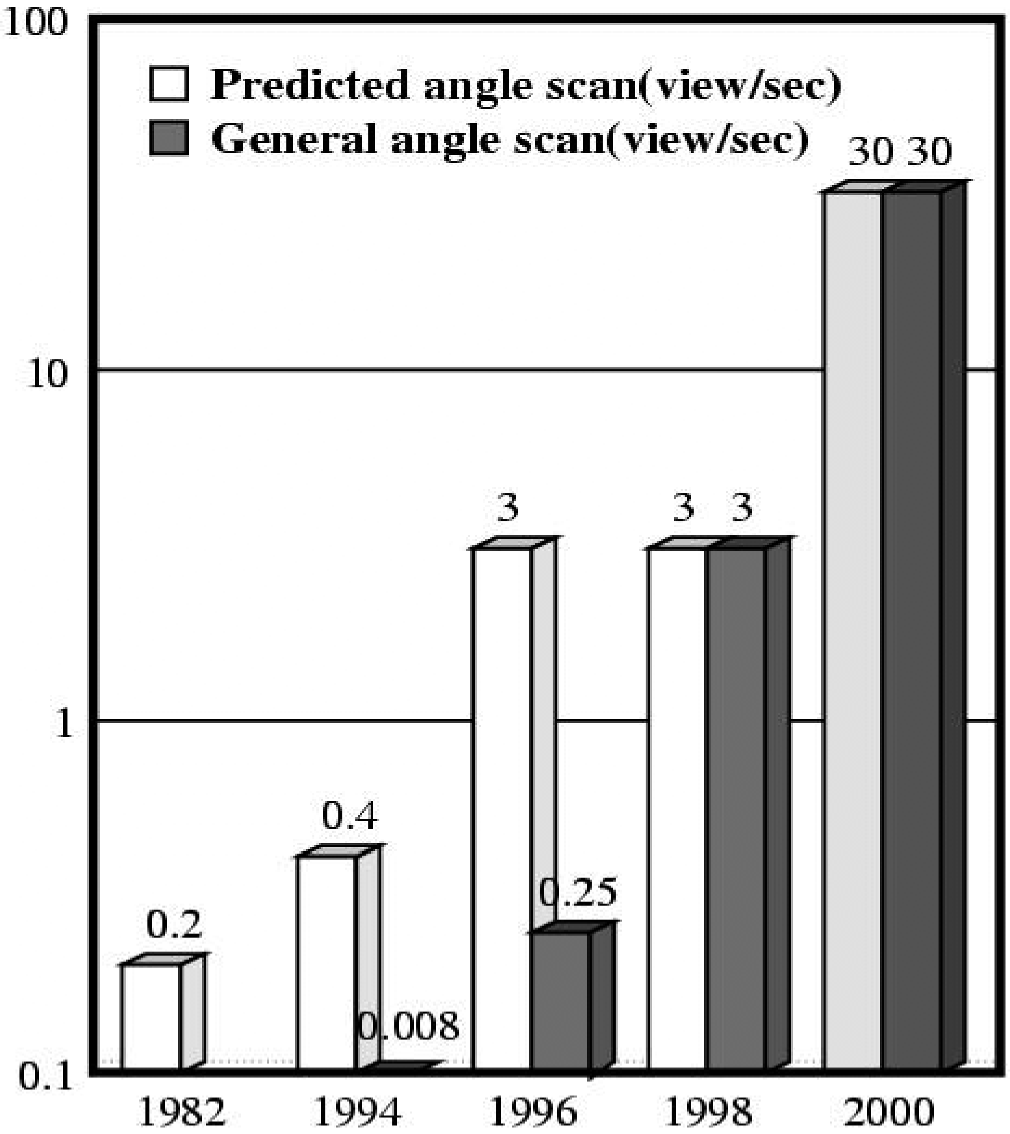
- ~20 bricks/day
- ~50 cm^2 general scanning/brick
- ~1000 cm^2/day

⇩

aim: ~10 cm^2/hour/system
(UTS ~ 1 cm^2/hour)

⇩

R&D efforts underway in Japan and in Europe



Track Selector road-map

OPERA expected signal sensitivity

Test bench for OPERA: present analyses in CHORUS, DONUT

Expected signal (1999 Progr.Report)

~ 6 τ events	**@ 2 x 10^{-3} eV^2 and full mixing**
~ 18	**@ 3.5 x 10^{-3} eV^2**
~ 53	**@ 6 x 10^{-3} eV^2**

OPERA
5 supermodules
5 years

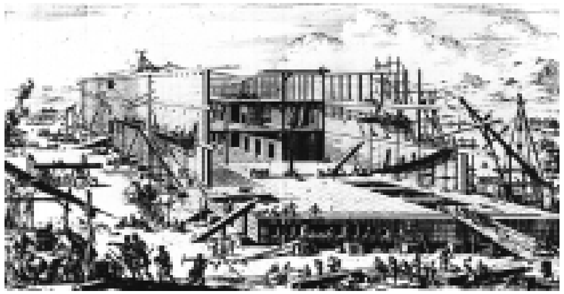
…work is in progress to increase efficiency ⇒ forthcoming Proposal

Background sources:

1) cosmics and radioactivity
2) hadronic decays and re-interactions
3) muon scattering
4) charm decay

other sources expected to be negligible

Background expected: <1 event



ICANOE
PROPOSAL

25 institutes from
Europe, Asia & USA

ICARUS

CERN

China
IHEP

Italy
Aquila, LNGS, Milano, Padova, Pavia, Pisa, Torino

Switzerland
ETH/Zurich

Poland*
Katowice, Krakow, Warszawa
*pending formal approval

USA
UCLA

NOE

Italy
Bari, Calabria, Lecce, LNGS, Napoli

Russia
IHEP, INR, ITEP, Lebedev, MEPI

Armenia
Yerevan

Proposed ICANOE detector

LNGS-P21/99; CERN /SPSC 99-25; SPSC/P314

Physics motivation: ***necessity for an improved observation of atmospheric neutrinos and oscillation searches with long-baseline accelerator beams***

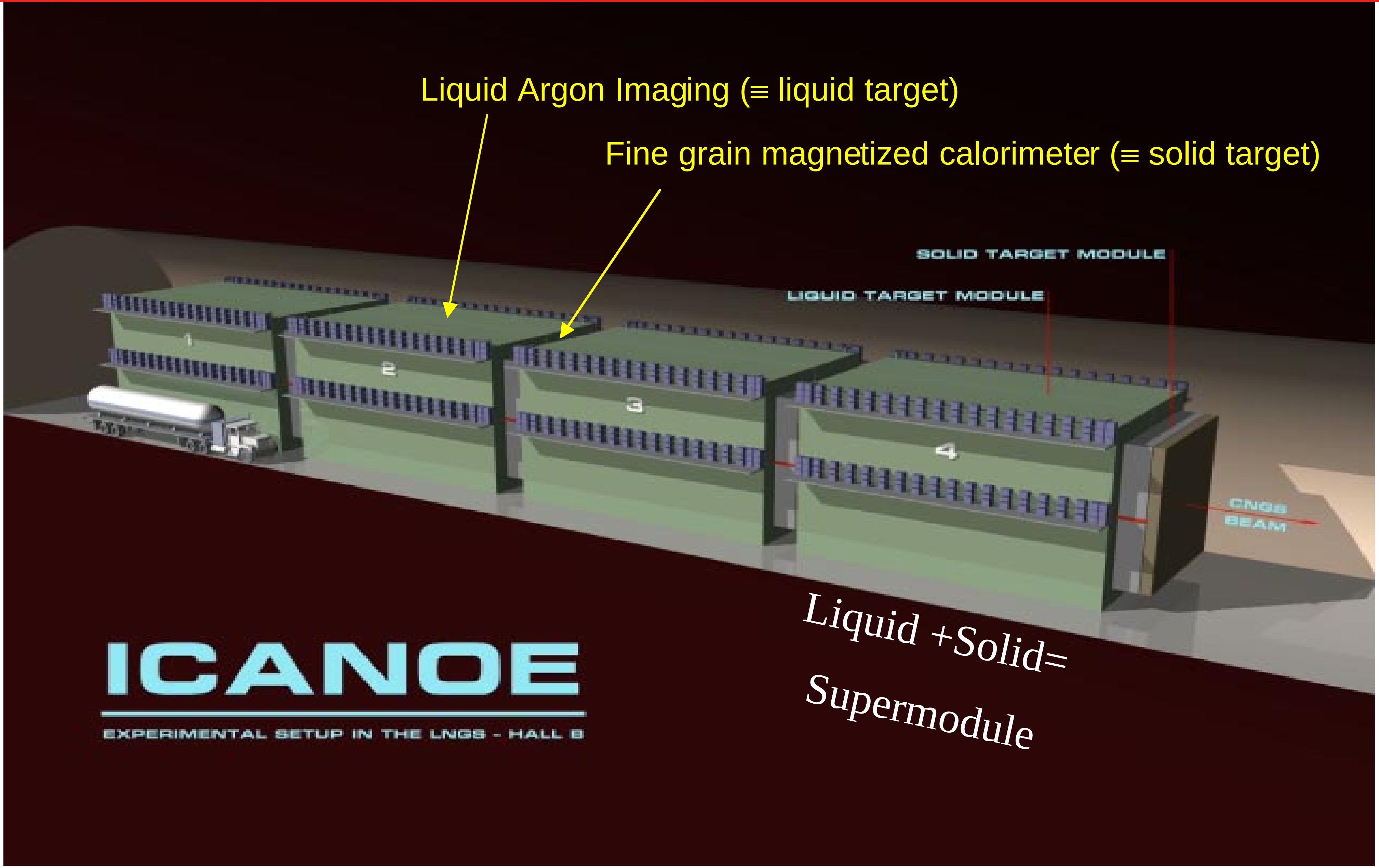
A high-granularity, massive target

- Detect and measure final state ***e,γ,μ*** and ***hadrons***
- Provide μ **charge** discrimination
- **Isotropic** detector

✓CERN neutrino beam
✓atmospheric neutrinos
✓nucleon stability

An appropriate combination of a
liquid argon imaging detector (liquid target)
and of
a fine grain magnetized calorimeter (solid target)

ICANOE proposed layout @ LNGS Hall B


Liquid Argon Imaging (≡ liquid target)

Fine grain magnetized calorimeter (≡ solid target)

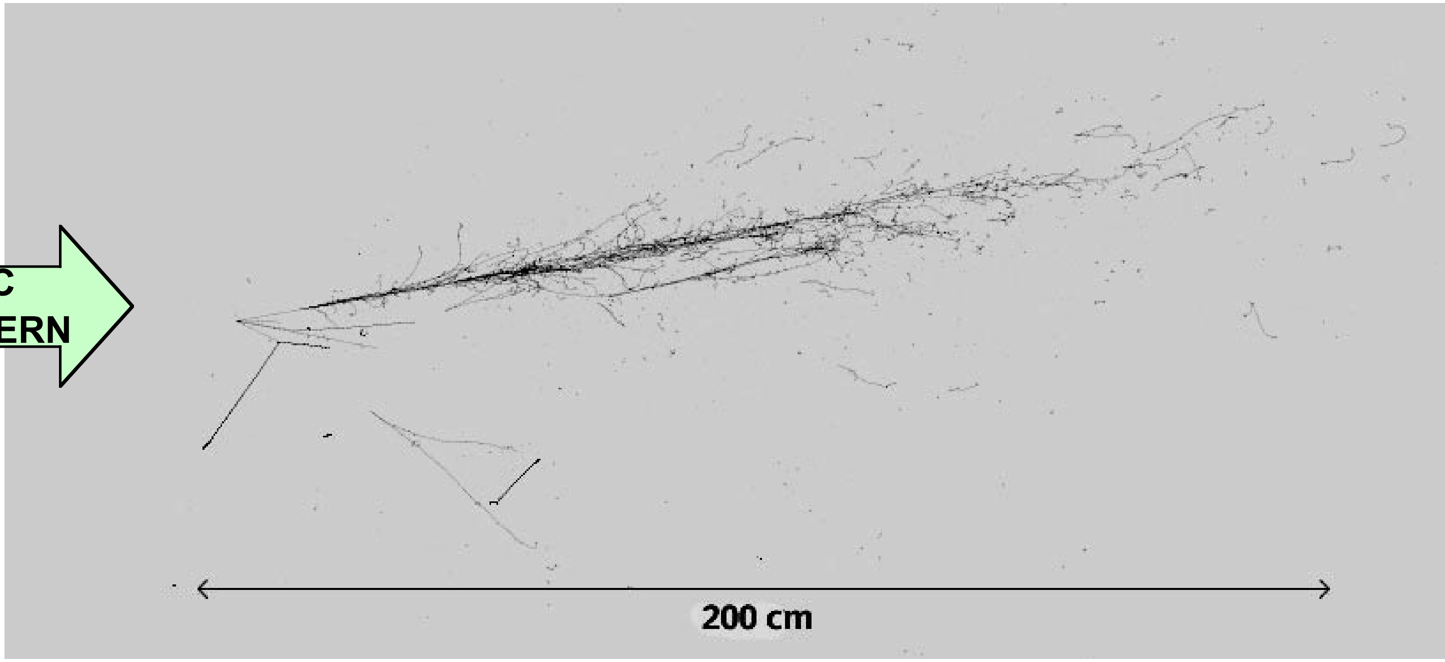
Liquid +Solid=

Supermodule

ICANOE simulated events

A ≈5.6 kton "electronic bubble chamber" complemented by an external ≈3.2 kton calorimeter and μ-spectrometer

ν_e CC from CERN

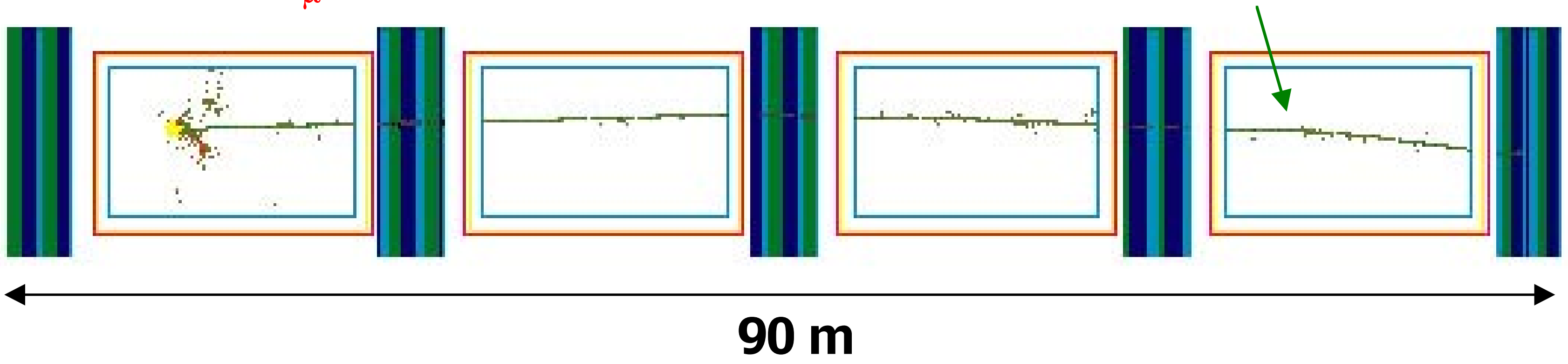


LAr Imaging

Full sized ν_μ event

muon

ν_μ CC from CERN



ICANOE event rates

4 supermodules

- One liquid target module:
  - Total mass: 1900 tons
  - Imaging mass: 1400 tons (8x8x16 m^3)
  - Fiducial mass: **1245 tons** (7.45x7.45x16 m^3)

} ***20 kt year ≈ 4 years "shared"***

- One solid target module:
  - Instrumented mass: **800 tons**

} ***10 kt year ≈ 4 years "shared"***

Process	liquid target	solid
ν_μ CC	54300	27150
$\bar{\nu}_\mu$ CC	1090	545
ν_e CC	437	219
$\bar{\nu}_e$ CC	29	15
ν NC	17750	8875
$\bar{\nu}$ NC	410	205
ν_τ CC, Δm^2 (eV^2)		
1×10^{-3}	52	26
2×10^{-3}	208	104
3.5×10^{-3}	620	310
5×10^{-3}	1250	625
7.5×10^{-3}	2850	1425
1×10^{-2}	4330	2165

No oscillations

Expected rate in four years of running

1.8x10^{20} pots

Features of the ICANOE detector

Liquid target:

- 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)

$$\sigma(E_{em})/E_{em} = 3\%/\sqrt{E_{em}} \oplus 1\% \qquad \sigma(E_{had})/E_{had} \approx 20\%/\sqrt{E_{had}} \oplus 1\%$$

for pure Argon, correction for quenching & compensation

- Excellent **imaging capabilities (**“bubble-chamber-like”)
- Excellent electron id and e/π separation: >1/500 from dE/dx measurement & imaging
- 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 kilotons with high granularity feasible

Solid target:

- 9x9m^2 5mm thick Fe slabs; magnetic field 1(outer)–2(inner) Tesla
- 200 Fe layers/module
- 200 layers of 9m-long fibers, readout both ends, 5x5cm^2 grouped to PMT
- 20 layers of drift tubes (for μ bending measurement)
- Performance matched to catching tail of hadronic shower from LAr events

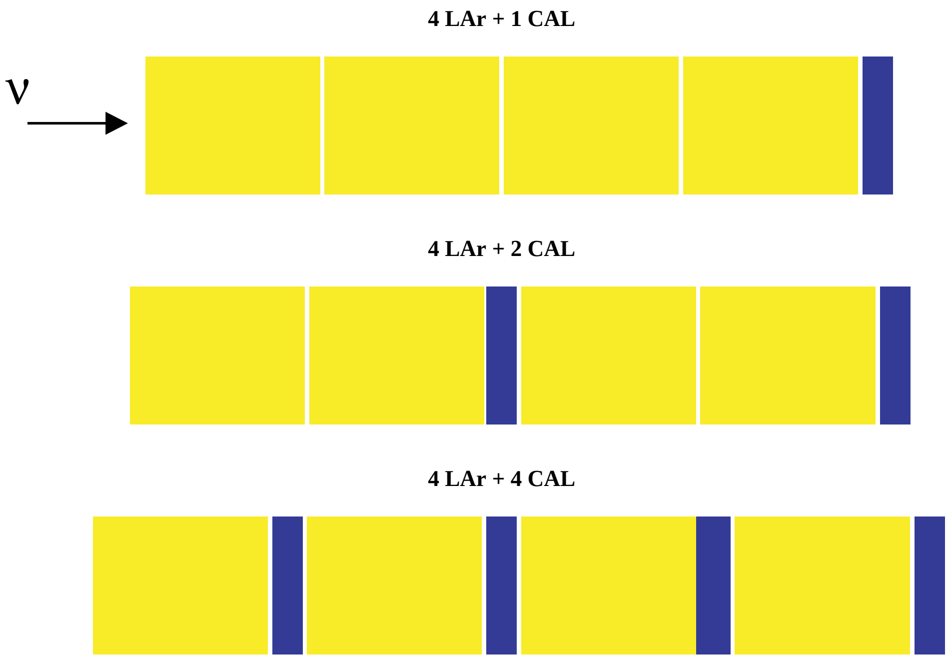
$$\sigma(E_{em})/E_{em} = 20\%/\sqrt{E_{em}} \oplus 1\% \qquad \sigma(E_{had})/E_{had} \approx 45\%/\sqrt{E_{had}} \oplus 1.5\%$$

$$\sigma(p)/p \approx 20\% - 40\%$$

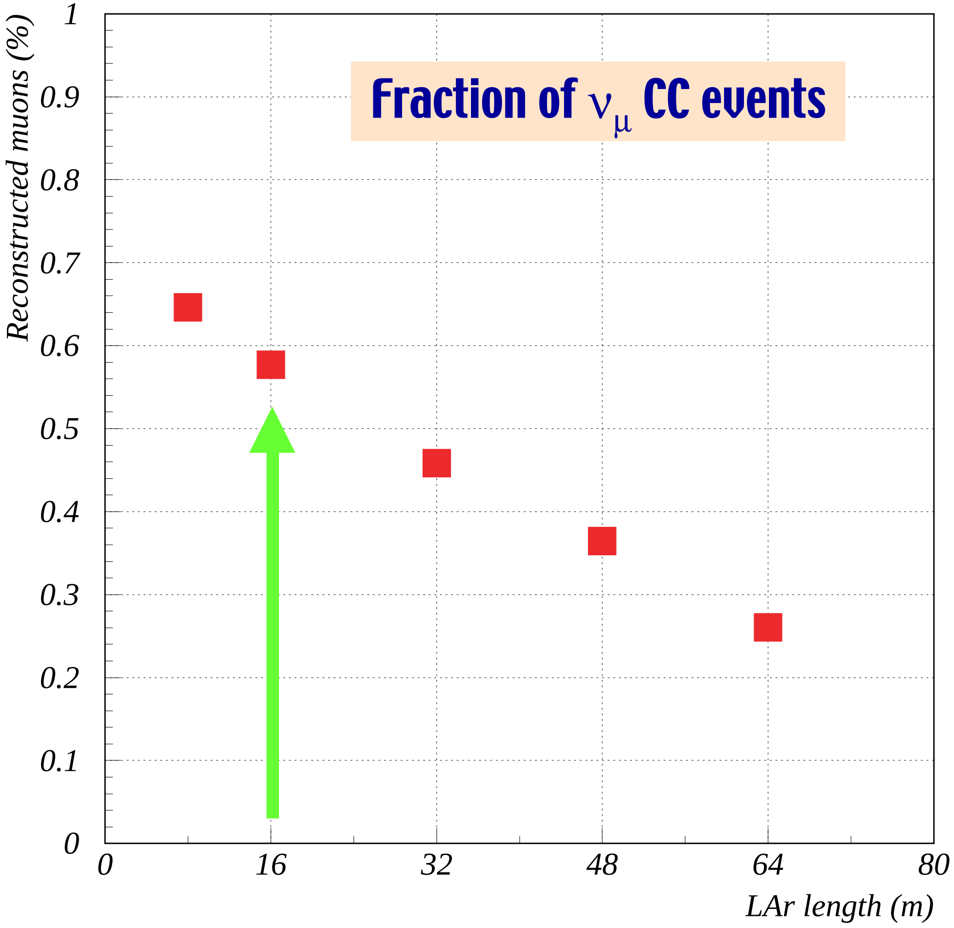
for p<30 GeV

ICANOE muon acceptance

LAr segmentation ⇒ muon acceptance

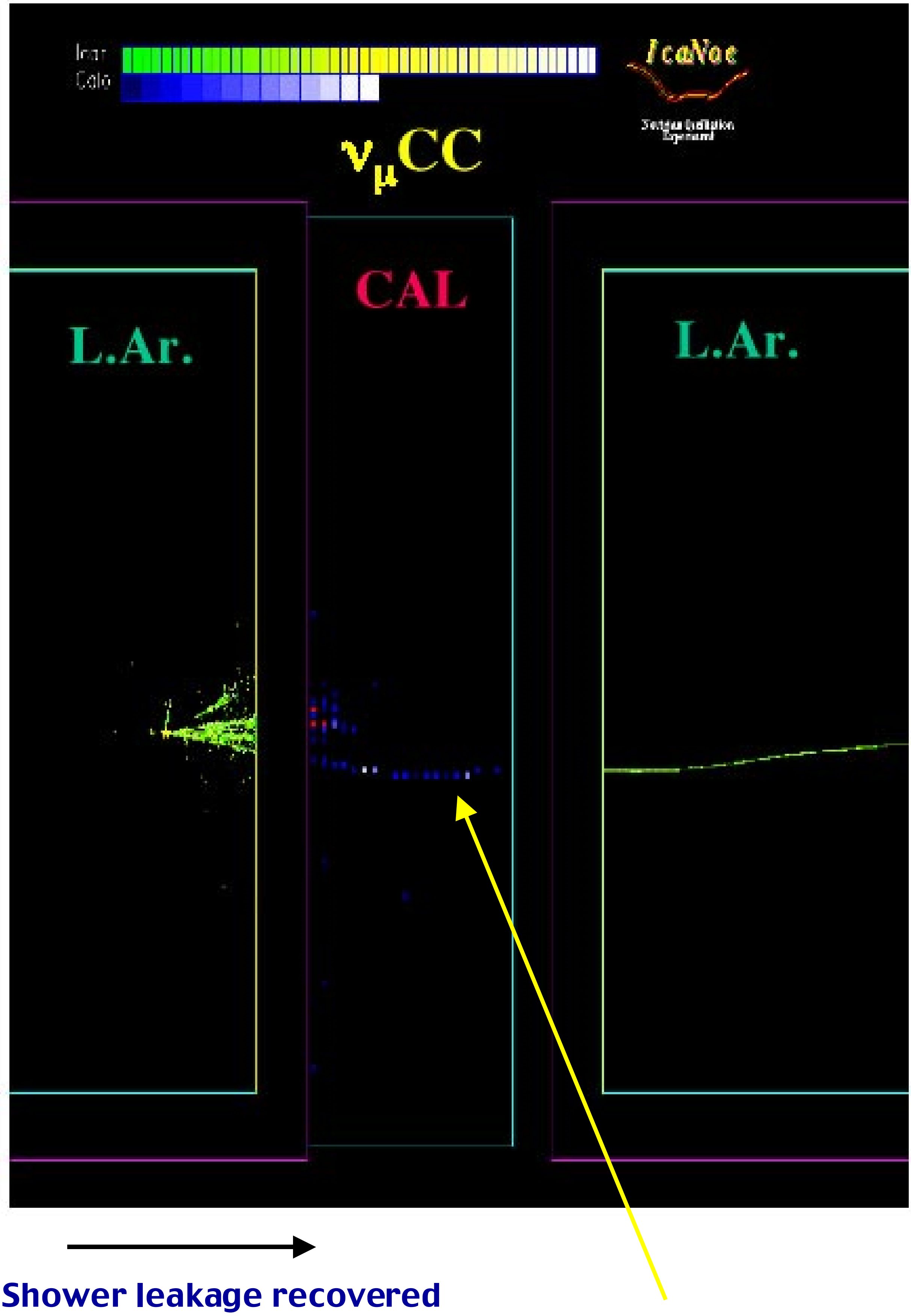


Magnetized μ measurement



The spectrometer is instrumented to allow the hadron energy of showers that leak into the spectrometer to be correctly measured⇒ extend LAr fiducial volume

ICANOE “transition event”

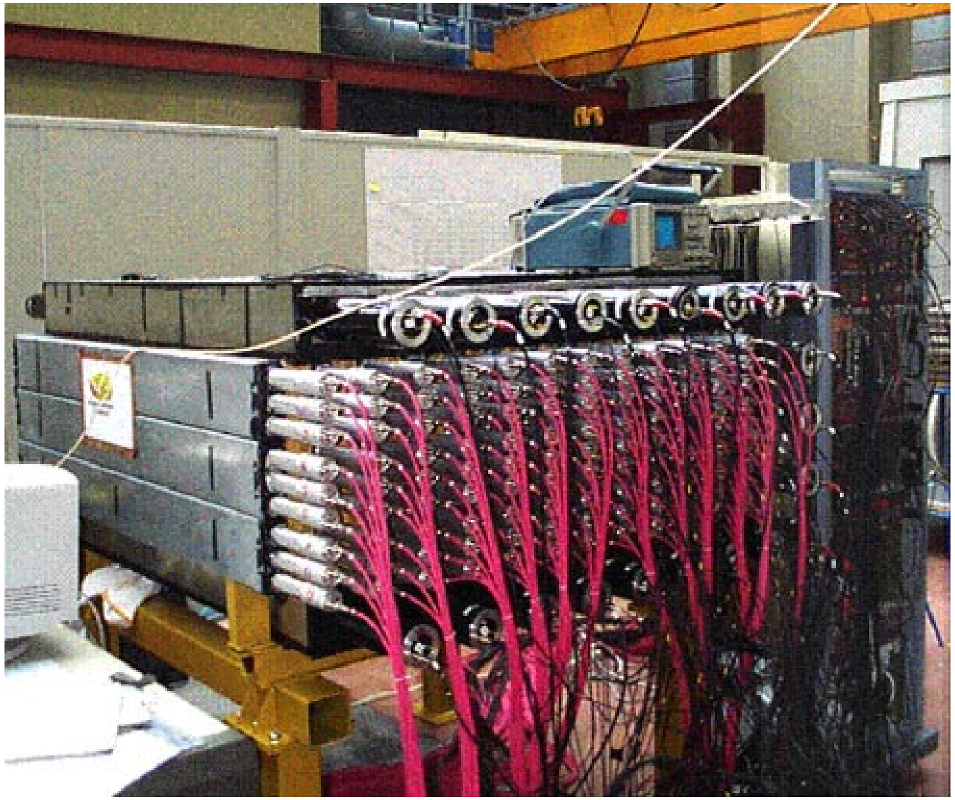


Shower leakage recovered in CAL

μ

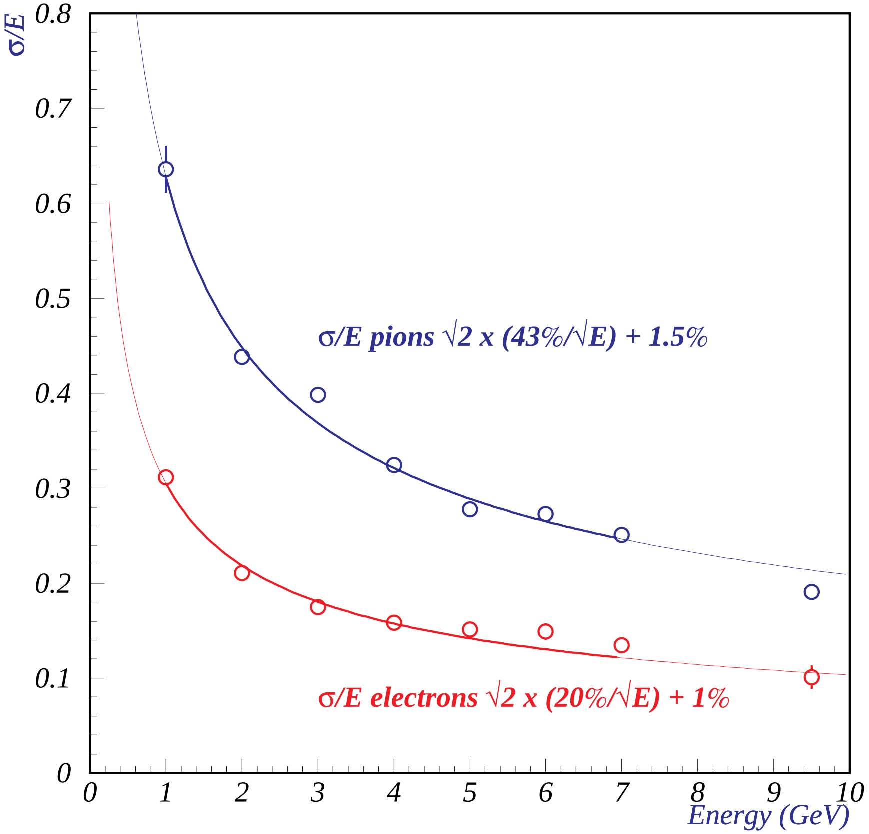
NOE calorimeter prototype

4 years of R&D



NOE calorimeter prototype

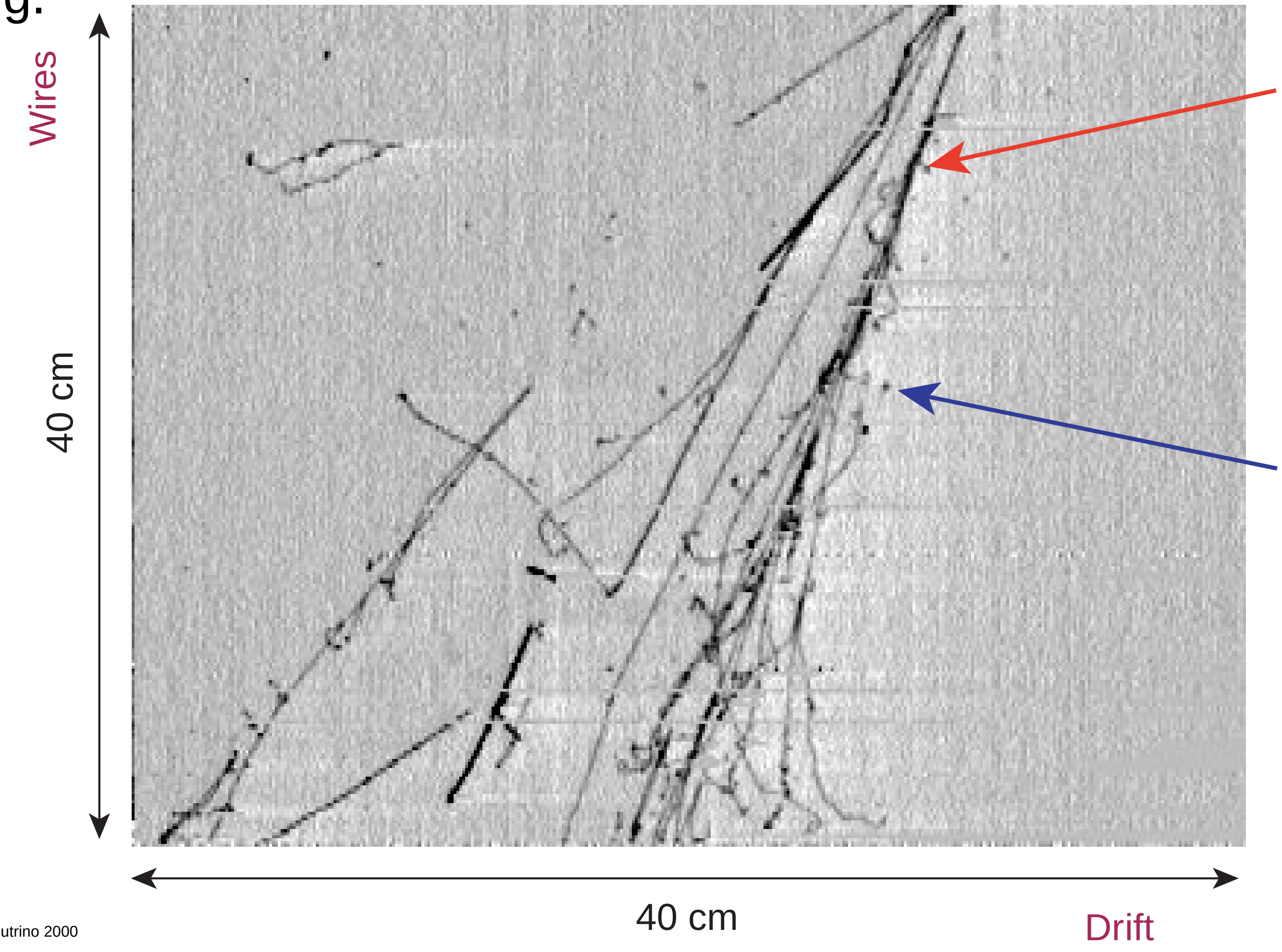
Prototype at CERN/PS beam (Dec 98)



A safe, demonstrated technology

ICARUS liquid argon imaging TPC (I)

- The LAr TPC technique is based on the fact that ionization electrons can drift over large distances (meters) in a volume of purified liquid Argon under a strong electric field. If a proper readout system is realized (i.e. a set of fine pitch wire grids) it is possible to realize a massive "electronic bubble chamber", with superb 3-D imaging.



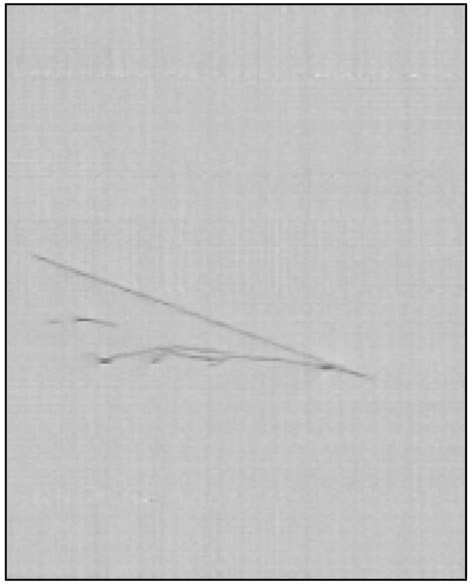
"Bubble" size ≈ $3 \times 3 \times 0.2$ mm^3

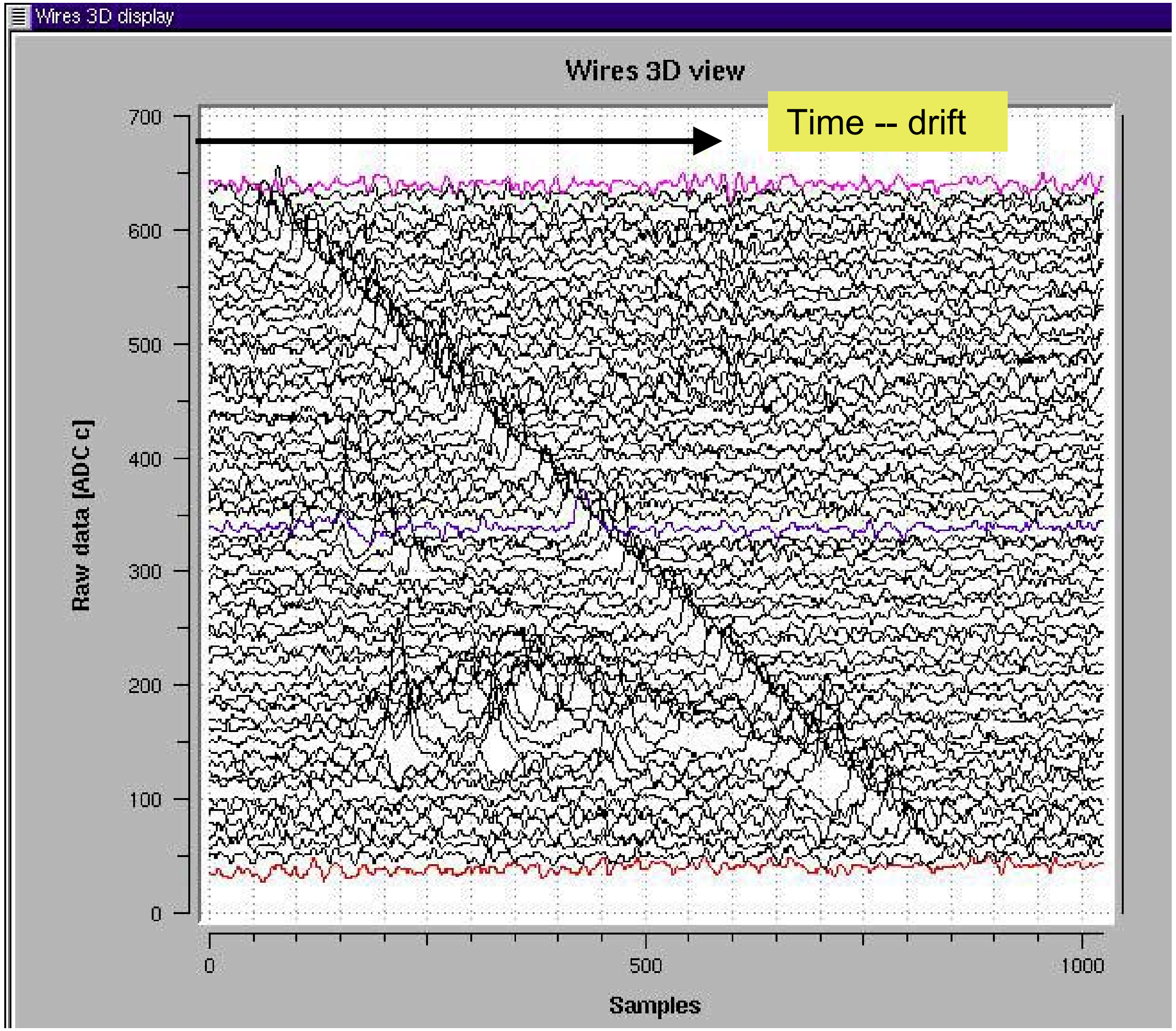
Energy deposition measured for each point

ICARUS liquid argon imaging TPC (II)

Detector is continuously sensitive, thus allowing to easily simultaneously collect atmospheric, CNGS and other rare events…

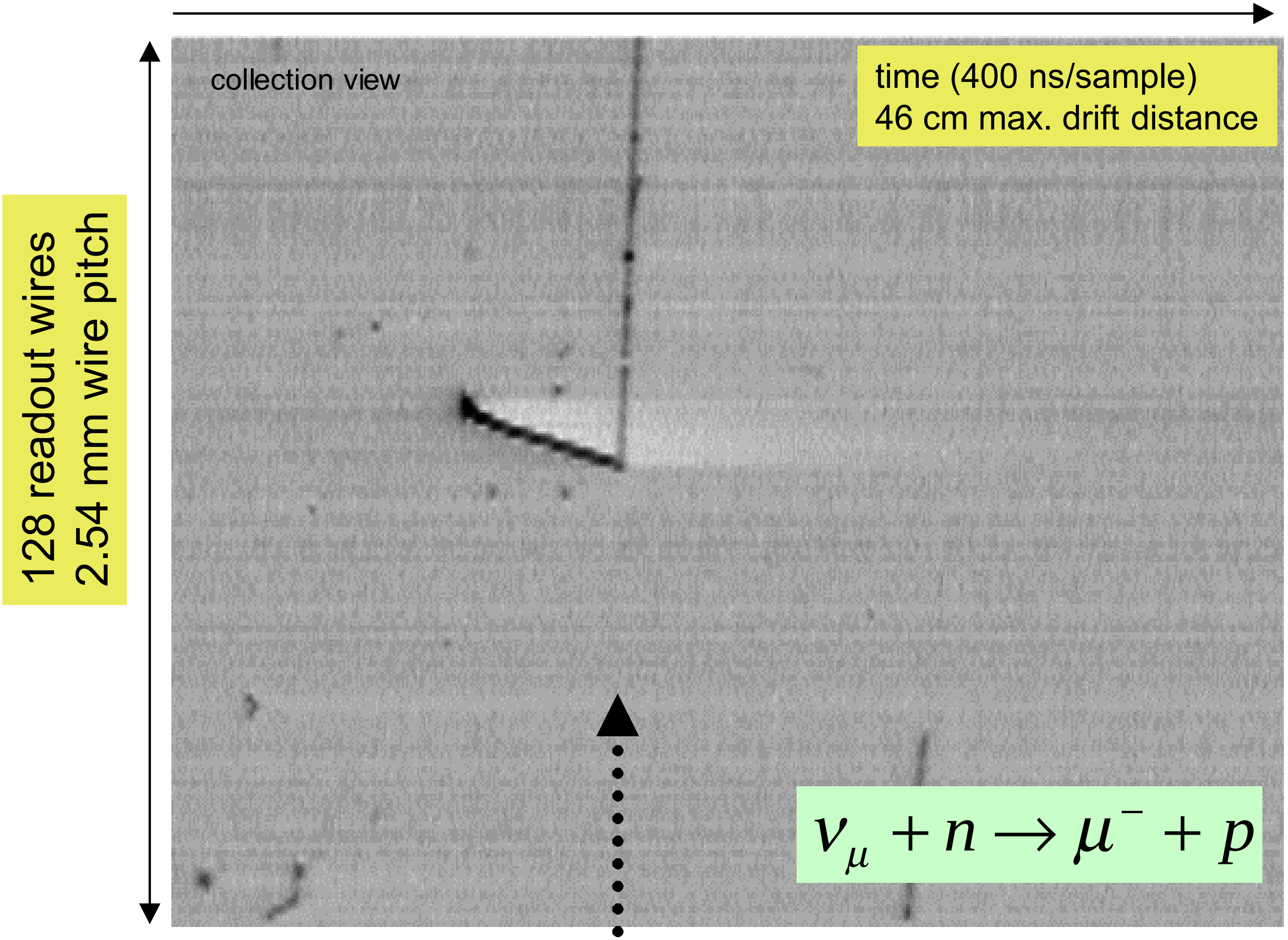
Real event from 15 ton





Neutrino event in 50 liter LAr TPC (1998)

ICARUS-CERN-Milano



collection view

time (400 ns/sample)
46 cm max. drift distance

128 readout wires
2.54 mm wire pitch

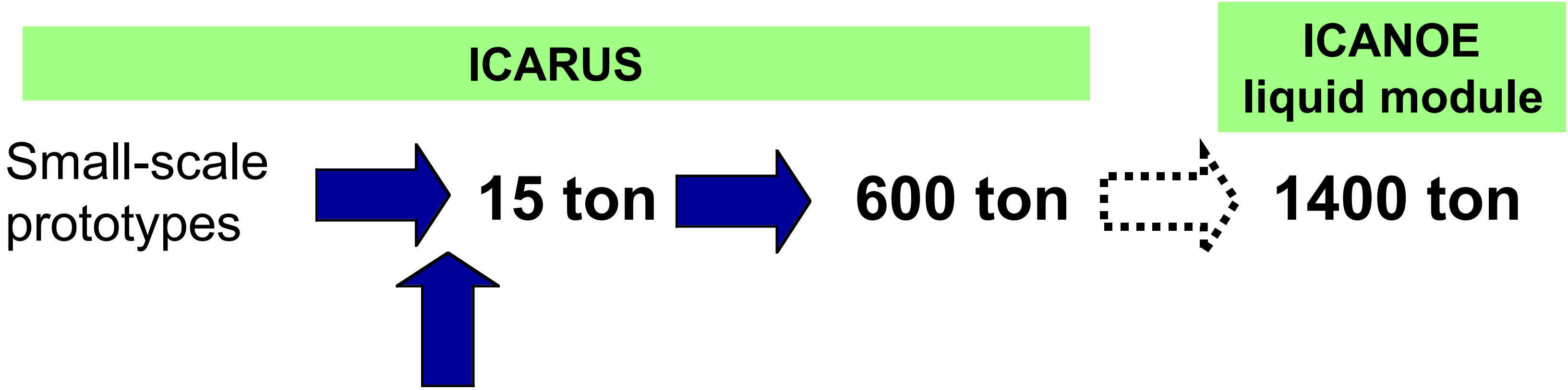
$$\nu_\mu + n \rightarrow \mu^- + p$$

CERN ν-beam

(Chamber located in front of NOMAD detector)

ICARUS state of the art

- After several years of R&D and prototyping, the ICARUS collaboration is now realizing the first **600 ton module**, which will be installed at Gran Sasso in the year 2001.



ICARUS

ICANOE liquid module

Small-scale prototypes → **15 ton** → **600 ton** ⇢ **1400 ton**

Cooperation with specialized industries:

- **Air Liquide** for Cryostat and Argon purification
- BREME Tecnica for internal detector mechanics
- CAEN for readout electronics

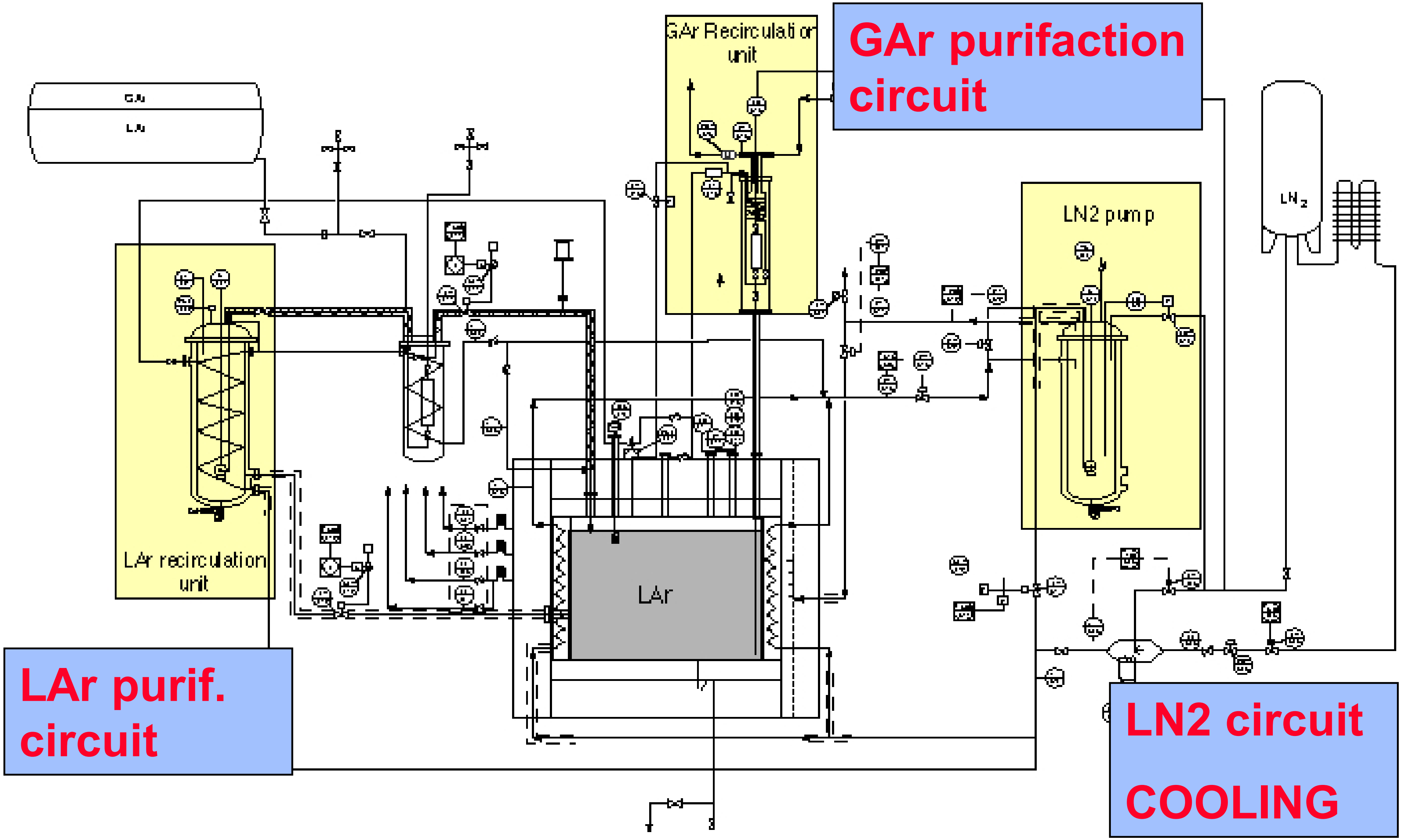
ICARUS 15 ton (10m^3) prototype (1999–2000)

- A recent major step of the R&D program has been the construction and operation of a **10m^3 prototype**
  - ① **Test of the cryostat technology**
  - ② **Test of the “variable-geometry” wire chamber**
  - ③ **Test of the liquid phase purification system**
  - ④ **Test of trigger via scintillation light**
  - ⑤ **Large scale test of final readout electronics**

→ *First operation of a 15 ton LAr mass as an actual “detector”*

T15 installation @ LNGS (Hall di Montaggio)

Cryogenic circuit



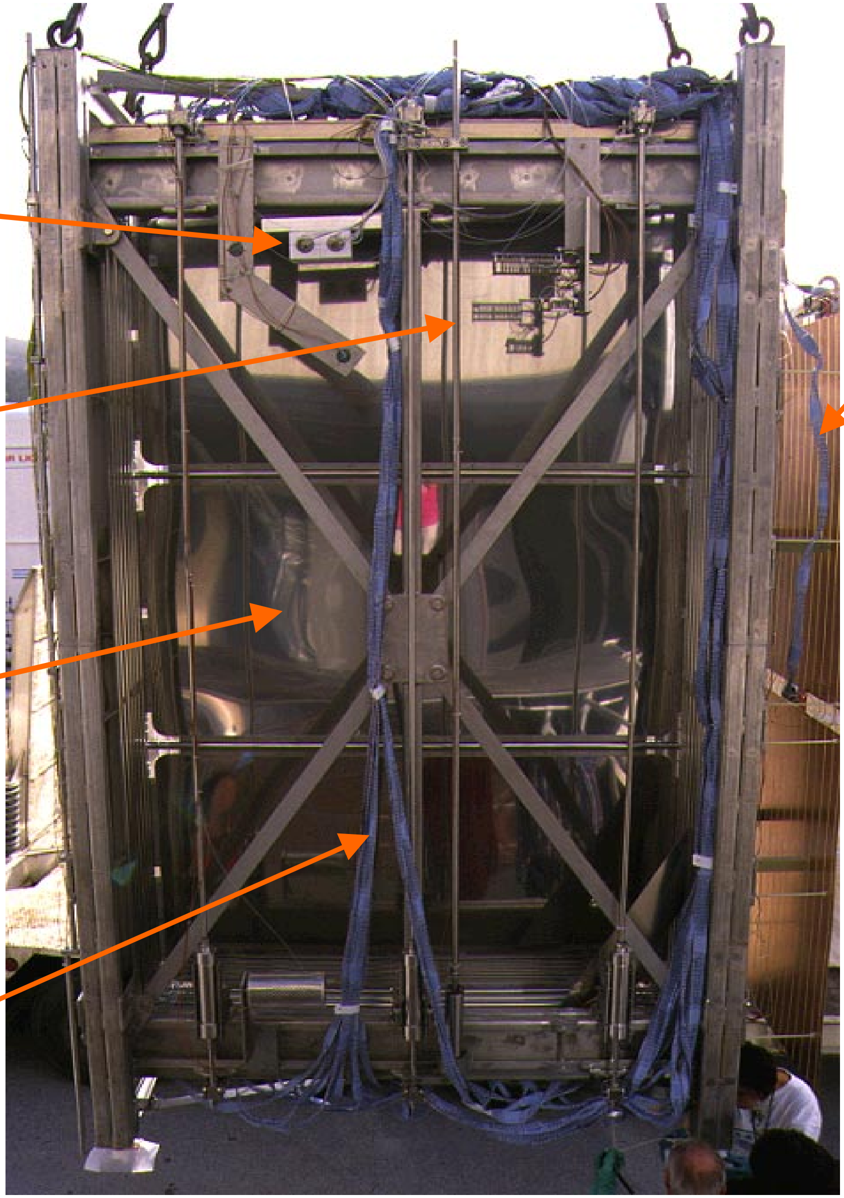
GAr purifaction circuit

LAr purif. circuit

LN2 circuit

COOLING

ICARUS 15 ton prototype – internal detectors



Photomultipliers

Purity Monitors

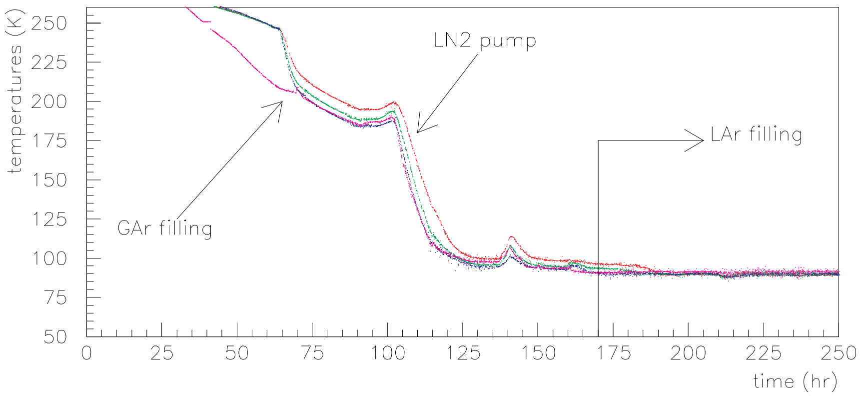
Cathode

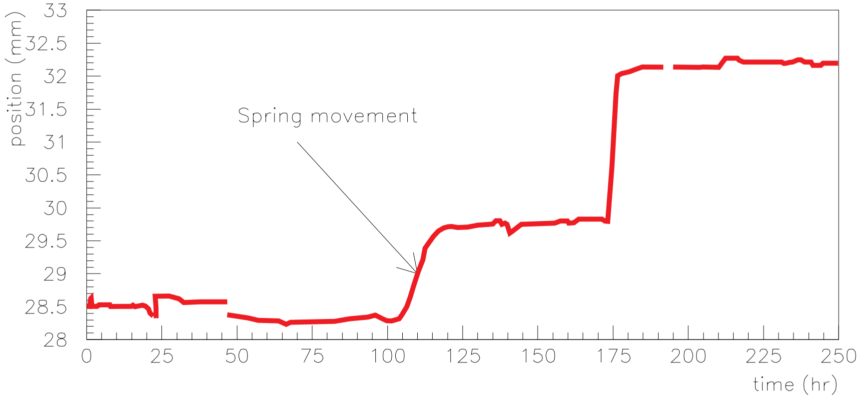
Two wire planes (induction + collection)
928 wires/plane, all connected for readout

Pads

Cooling 15 ton prototype March ‘99

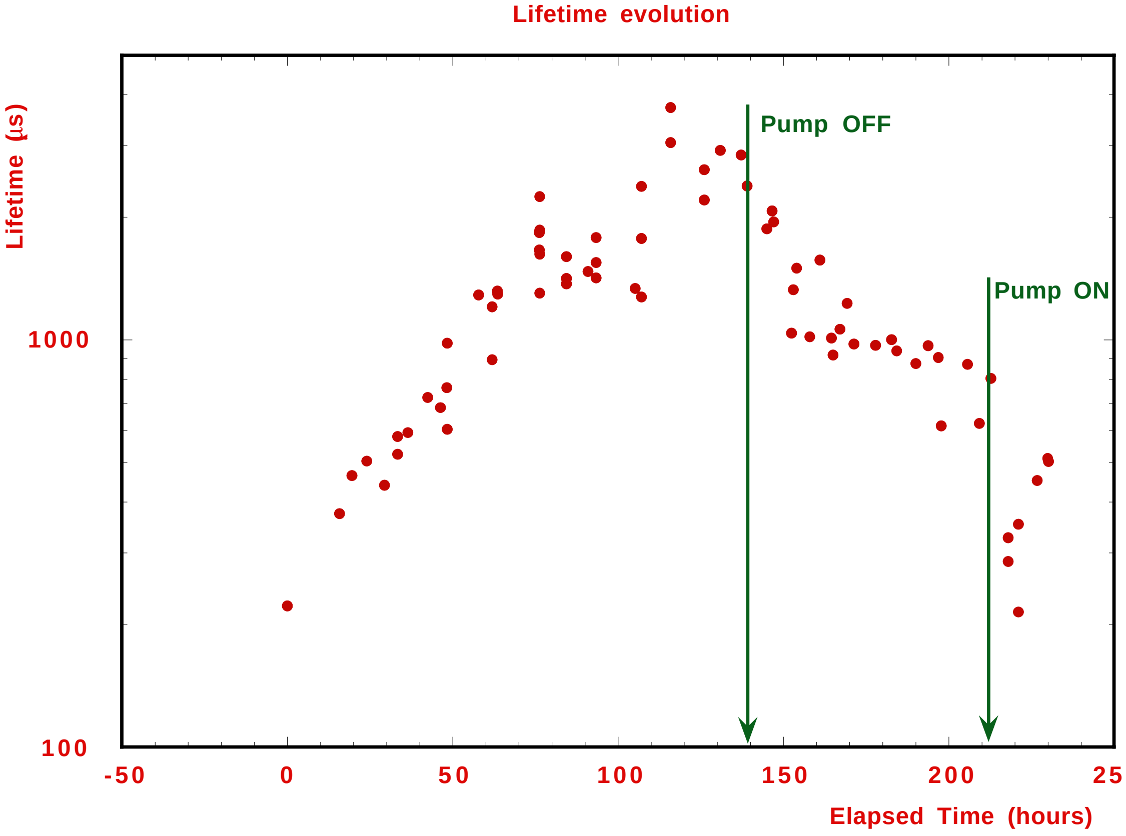
Temperature / Wire stretching





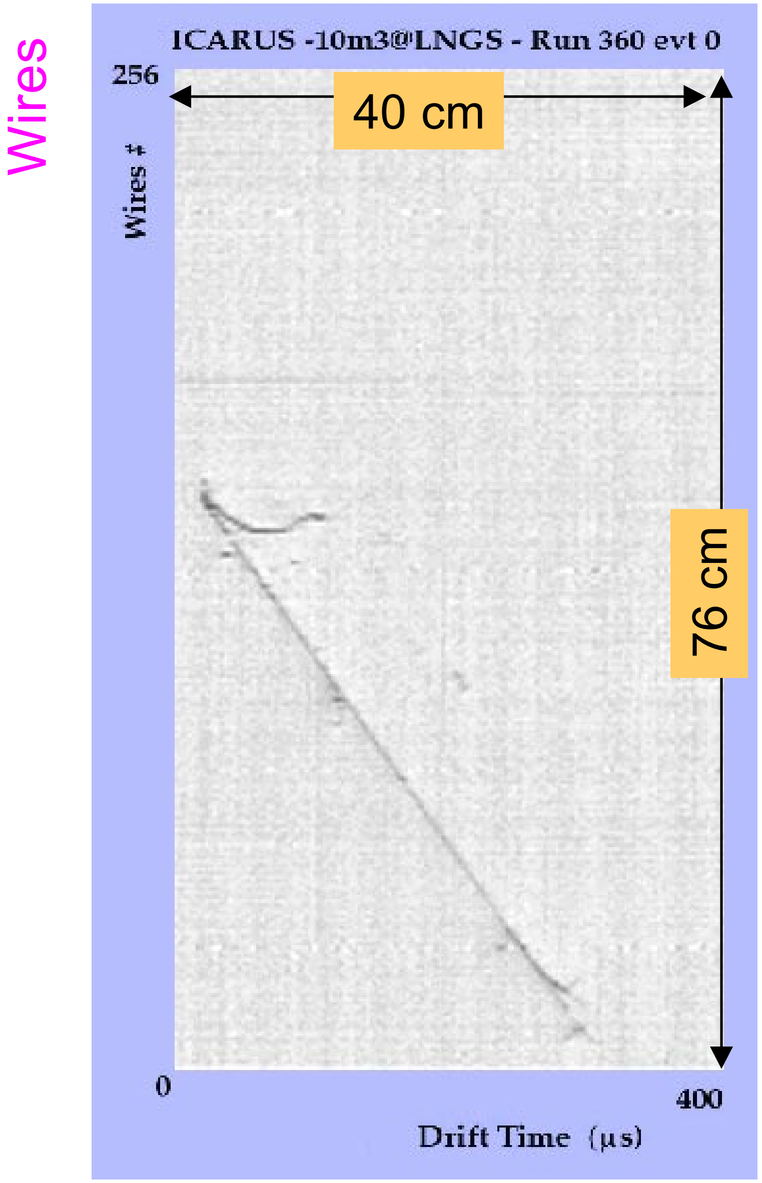
- ✖ Confirmation of the functionality of the *variable geometry* mechanics

LAr purity

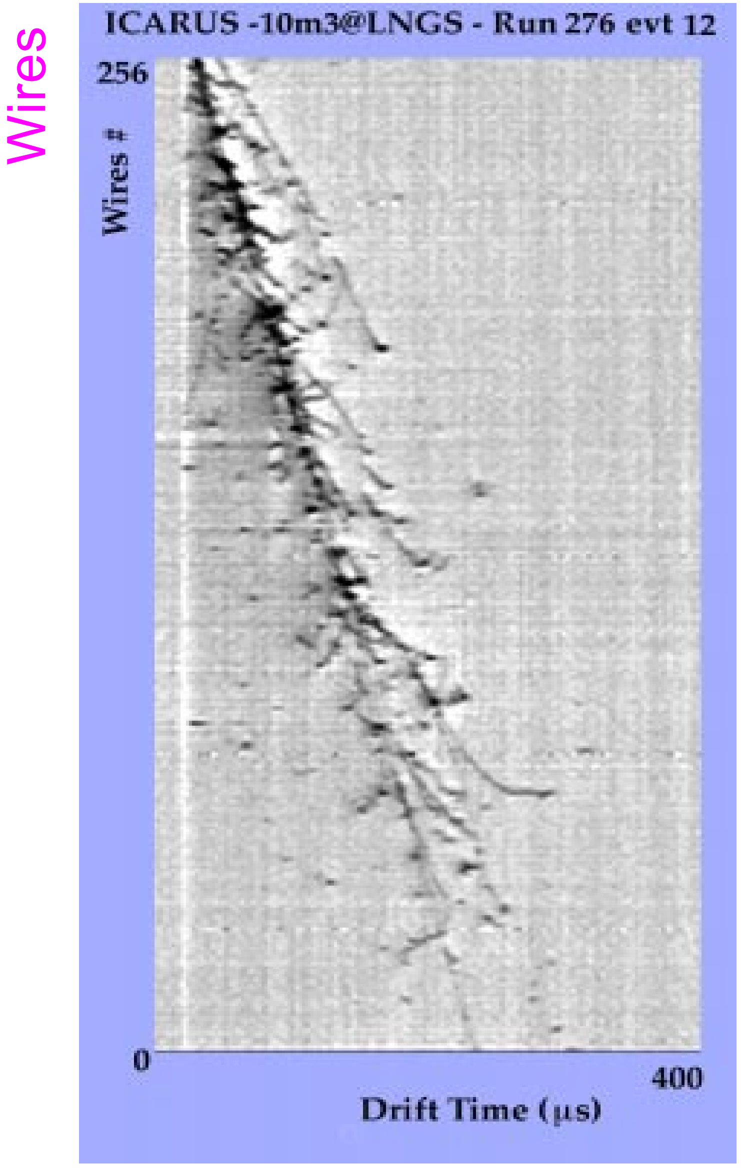


- ✖ **The electrons lifetime, after about 4 days of recirculation, was between 2 ms to 3 ms.**

Tracks in 15 ton prototype (Feb–May 2000)

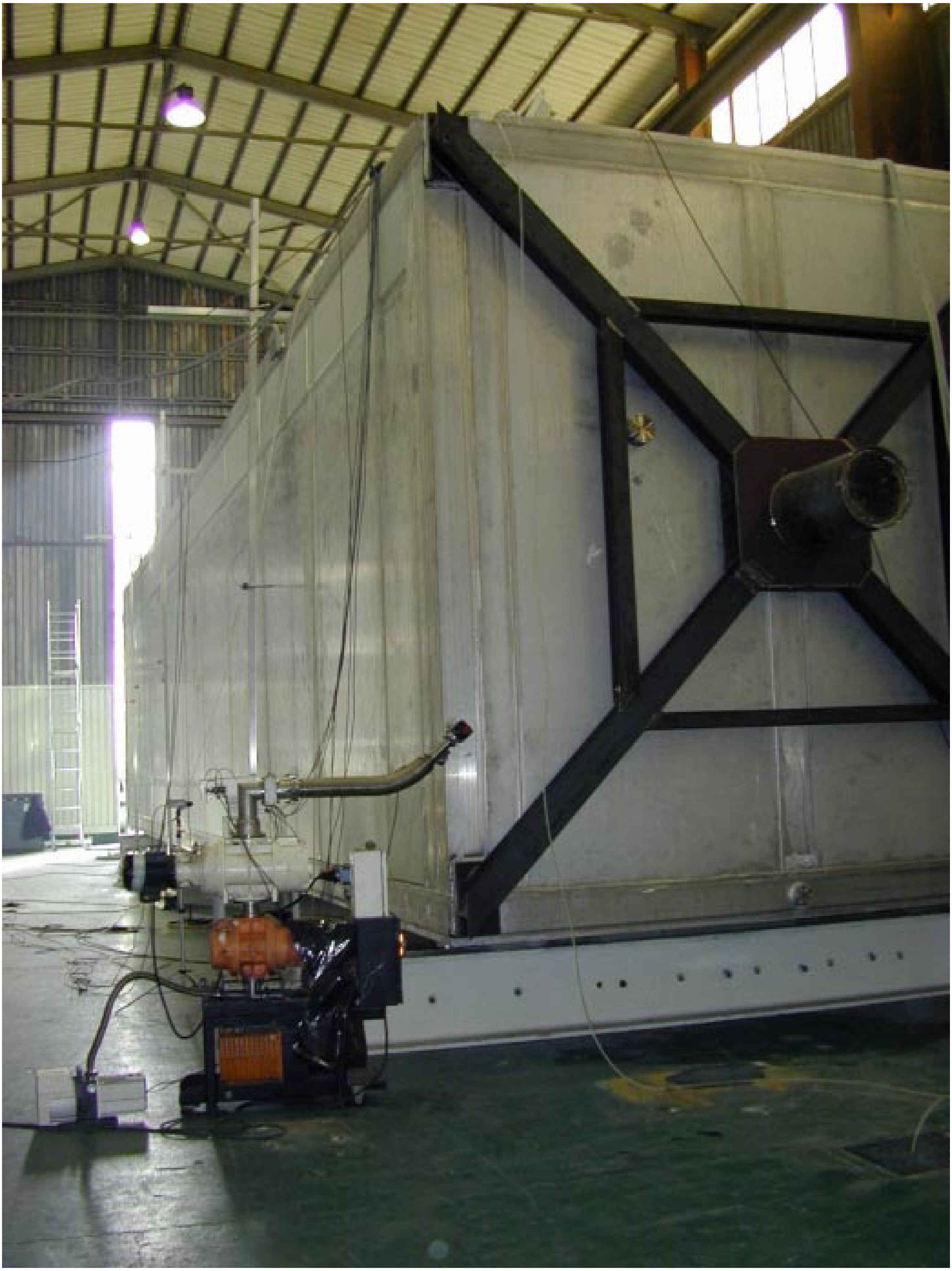


Drift



Drift

External view of the ICARUS T600 half-module



ICARUS T600 assembly progress

2nd half module

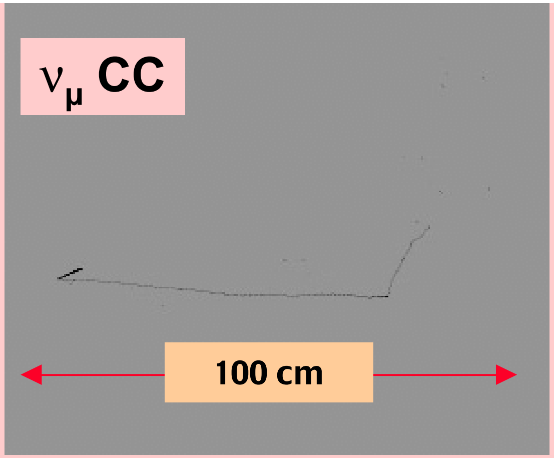
Wire Factory

Wire Chamber Construction

ICANOE physics program

Looking for rare events:

Atmospheric neutrinos

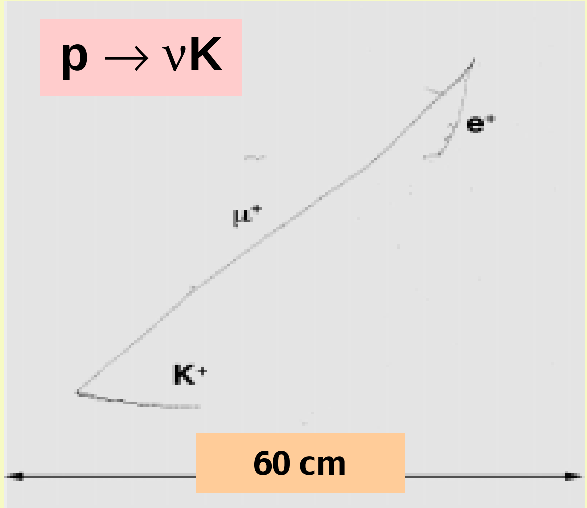


- ✓Detection of all neutrino flavors, CC & NC modes
- ✓Study of L/E distributions for e and μ
- ✓Clean NC/CC
- ✓Direct tau appearance
- ✓Upward going muons
- ✓Very low energy electrons

CERN-NGS

- ✓Direct tau and electron appearance
- ✓Muon disappearance

Nucleon decay



- ✓Background free searches
- ✓Sensitivity >10^{33} years

Two-family $\nu_\mu \to \nu_\tau$ oscillations

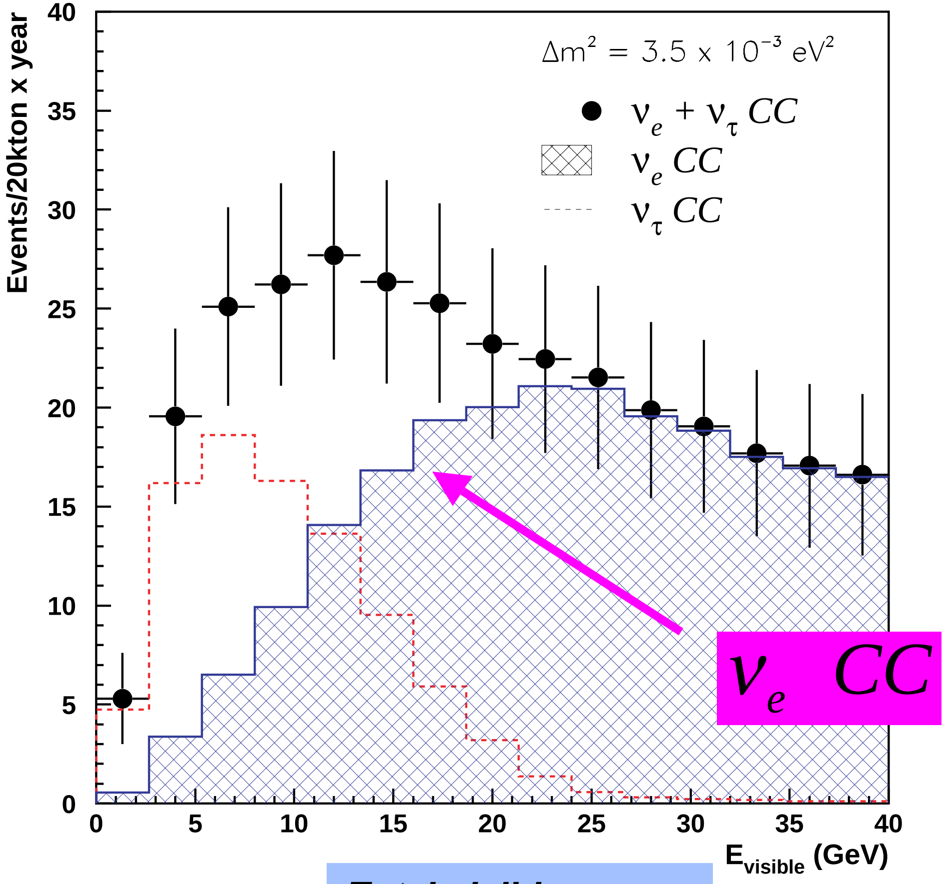
- Search for distortions in the visible energy spectrum of leading electron sample
  - Exploit the small intrinsic ν_e contamination of the beam (0.8% of ν_μ CC)
  - Exploit the unique e/π^0 separation
  - Excess at low energy

$$\approx 470 \;\; \nu_e CC$$

$$\approx 110 \;\; \nu_\tau CC \; + \;\; \tau \to e\nu\nu$$

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

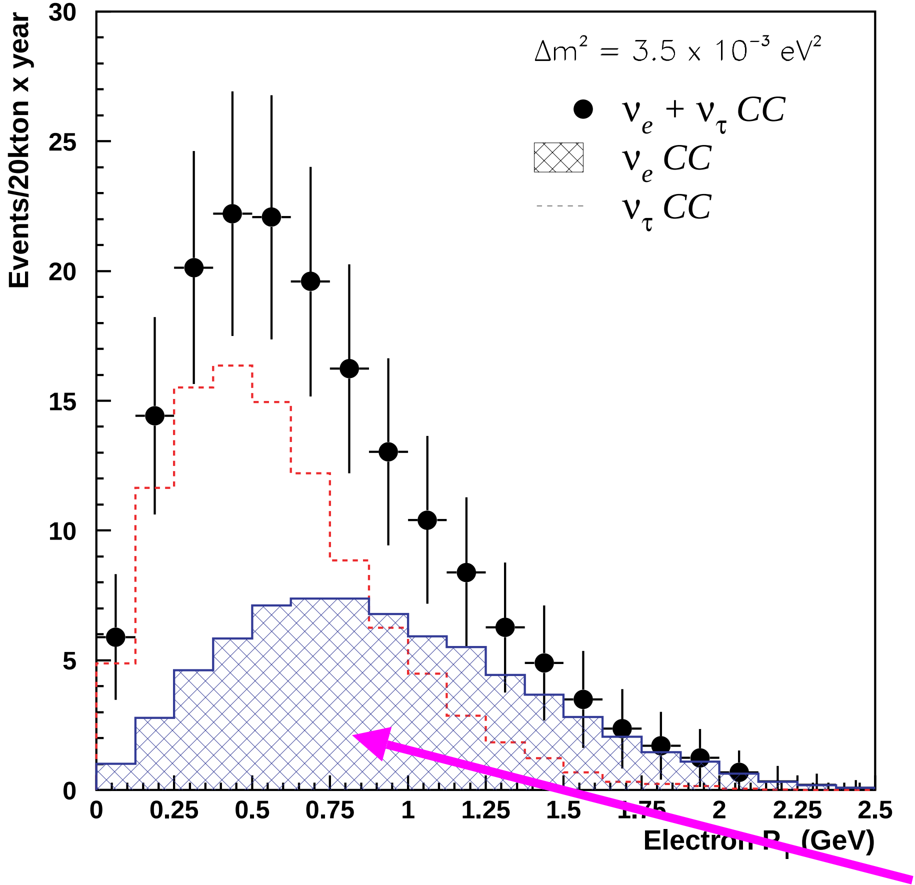
- Excess visible also without cuts
- Kinematical selection in order to enhance S/B ratio
  - Will be tuned “a posteriori” depending on the actual Δm^2



Total visible energy

Tau appearance – kinematic selection

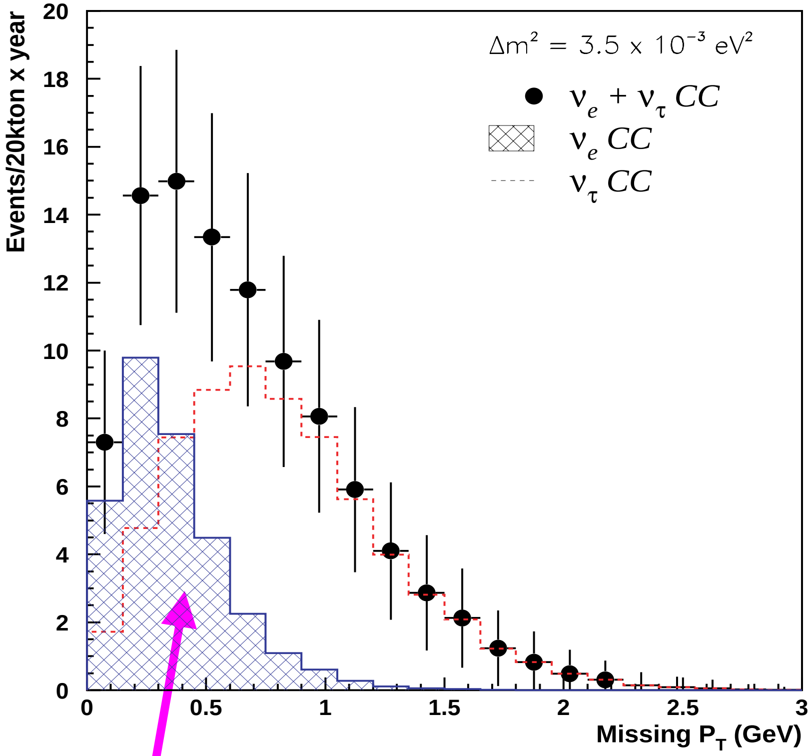
Transverse P electron



$$\varepsilon_{\nu eCC} = 48\%$$

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

Transverse missing P$_T$



ν_e CC

$$P_{T,miss} > 0.6 \ \ GeV: \quad \varepsilon_{\nu eCC} = 14\% \quad \varepsilon_{\nu\tau CC} = 65\%$$

LAr contained

Cuts	ν_τ Eff. (%)	ν_e CC	$\bar{\nu}_e$ CC	ν_τ CC $\Delta m^2 = 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 2.8 \times 10^{-3}$ 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	71	111	779
Fiducial volume	88	383	25	8.2	64	97	686
One candidate with momentum > 1 GeV	72	365	25	6.7	50	80	561
$E_{vis} < 18$ GeV	67	64	5	6.2	46	75	522
$P_T^e < 0.9$ GeV	54	31	3	5.0	38	60	421
$P_T^{lep} > 0.3$ GeV	51	29	2	4.7	35	56	397
$P_T^{miss} > 0.6$ GeV	33	4	0.4	3.1	23	37	257

ICANOE

20kt x year

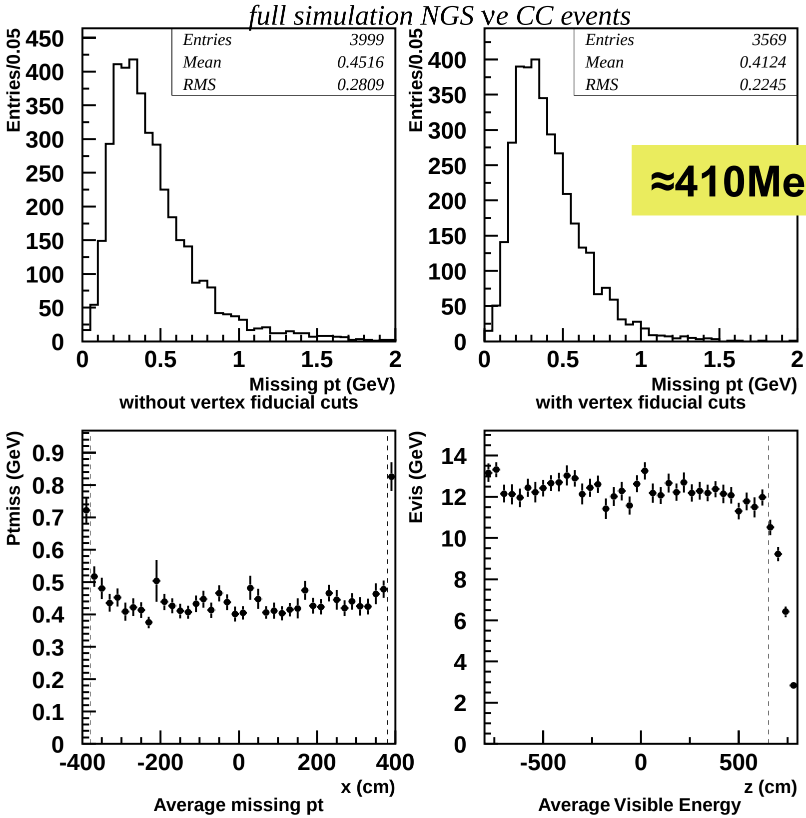
LAr+CAL contained

Cuts	ν_τ Eff. (%)	ν_e CC	ν_τ CC $\Delta m^2 = 3.5 \times 10^{-3} eV^2$
Initial	100	80	21
Fiducial volume	79	62	16
One candidate with momentum > 1 GeV	64	59	13
E$_{vis}$ < 18 GeV	61	11	12
$p_T^e < 0.9$ GeV	49	4.9	10
$p_T^{miss} > 0.6$ GeV	30	1.7	6.3

Kinematics simulation

Liquid target full simulation

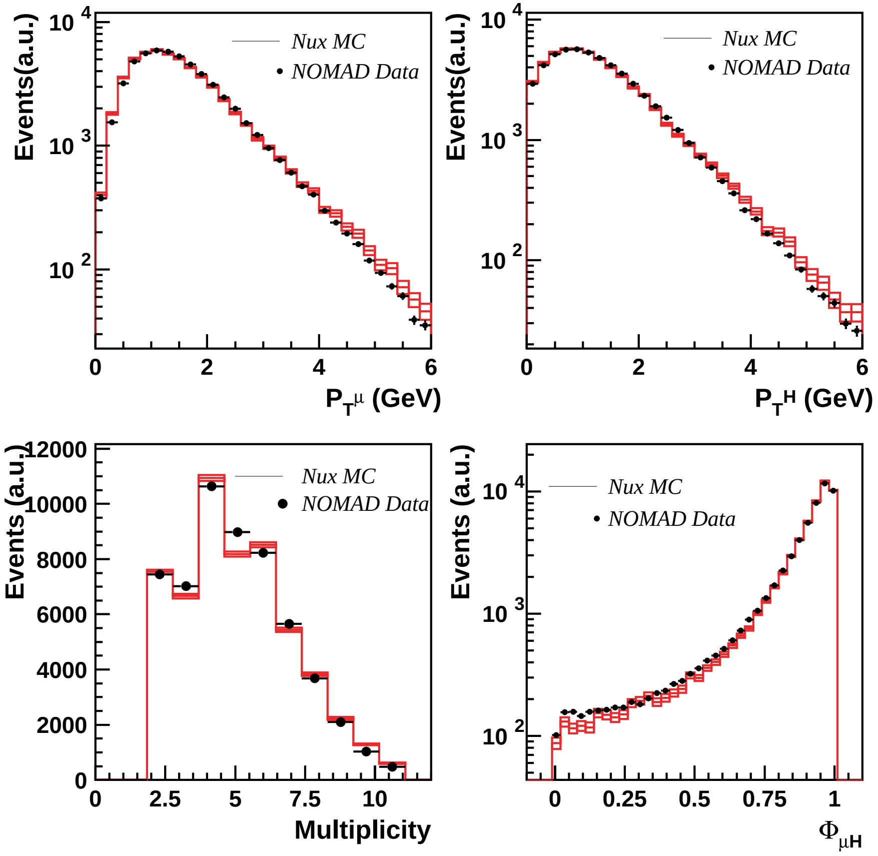
4000 νe CC events



≈410MeV

NUX/FLUKA

Comparison NOMAD data

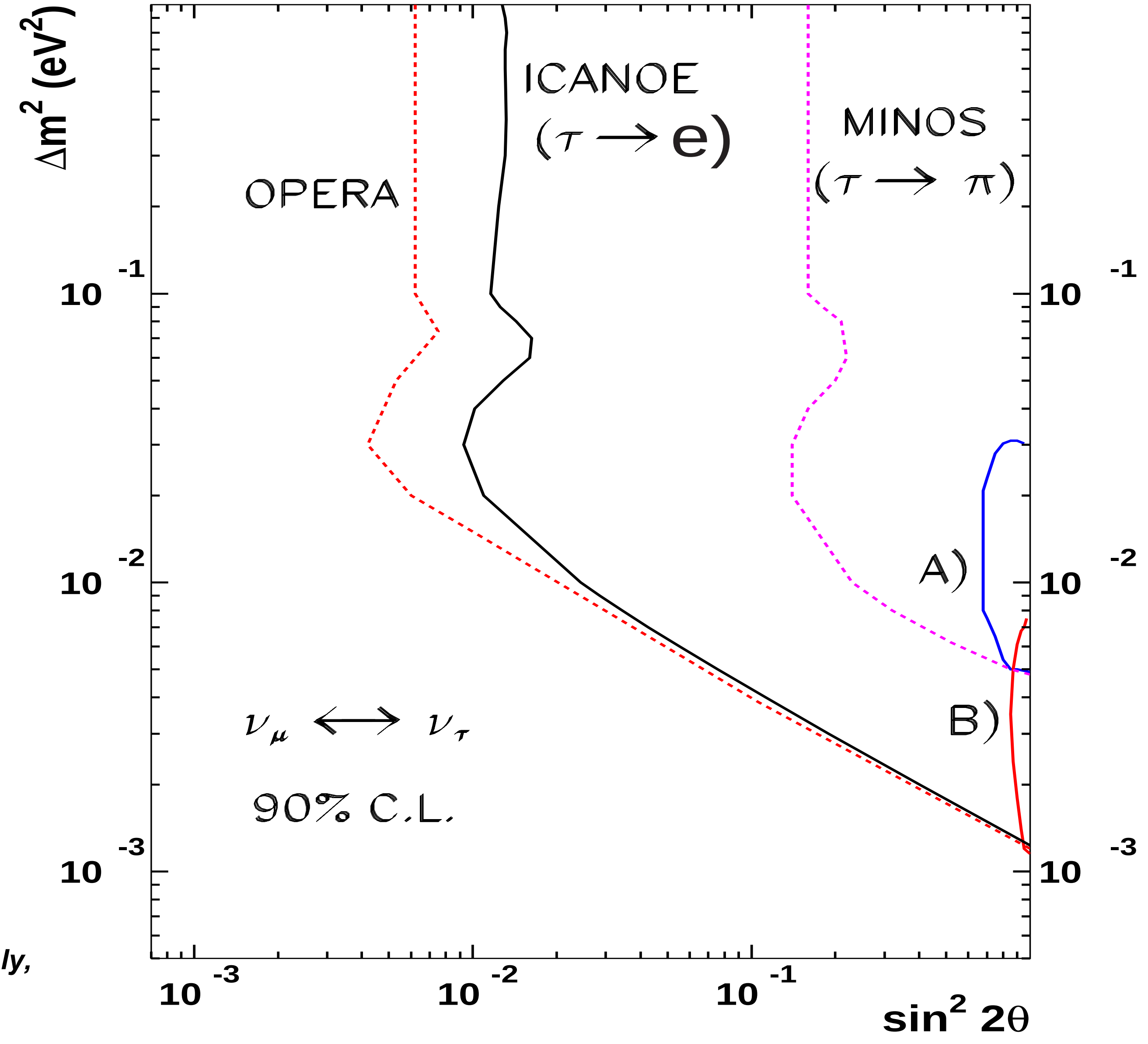


NUX/FLUKA/GENOM

Two–family $\nu_\mu \to \nu_\tau$ oscillations: sensitivity

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

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)

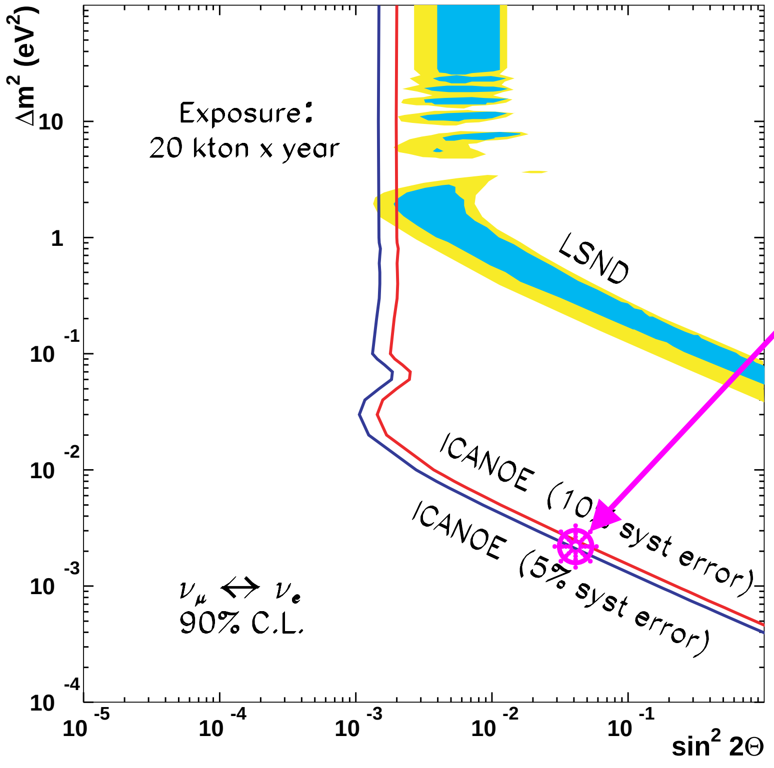
Two-family $\nu_\mu \rightarrow \nu_e$ oscillations

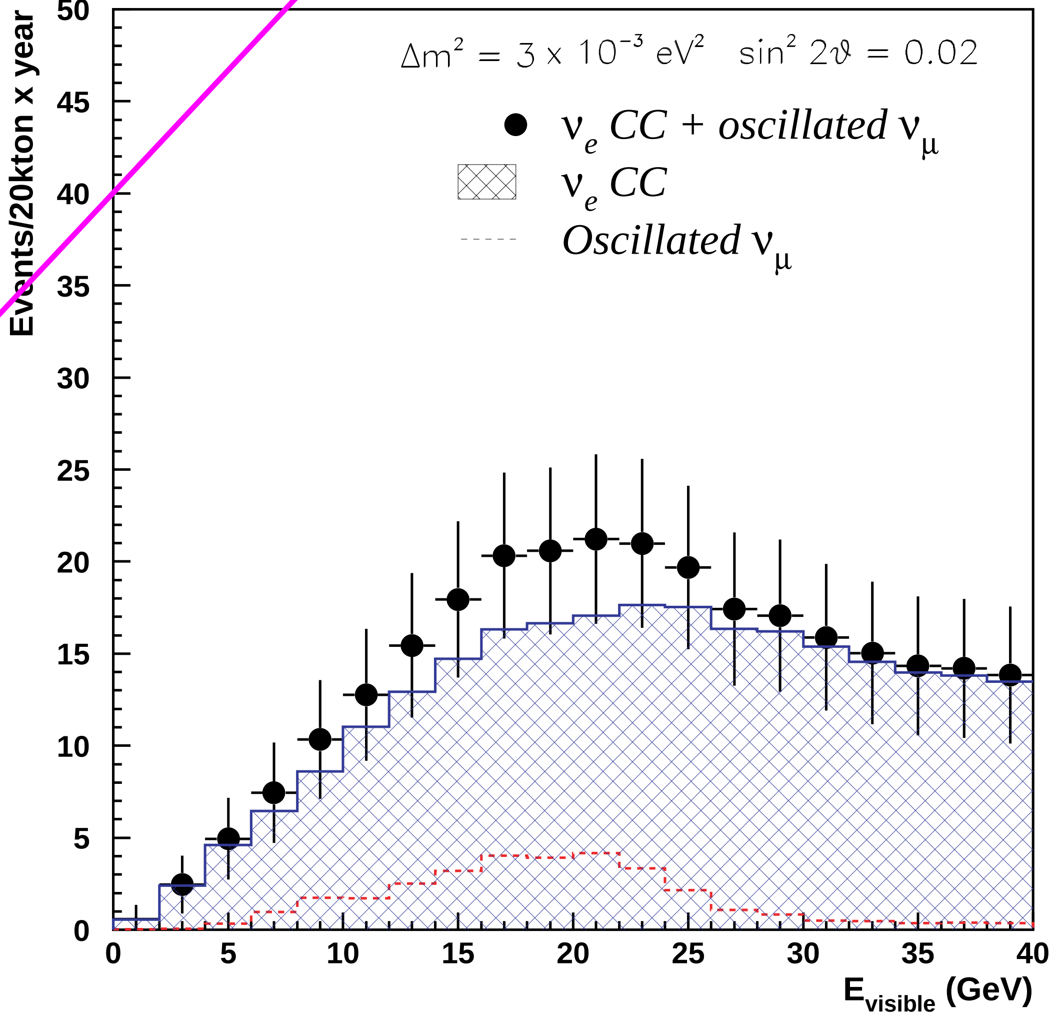
Exploit the small intrinsic ν_e contamination of the beam (0.8% of ν_μ CC)

Exploit the unique e/π^0 separation

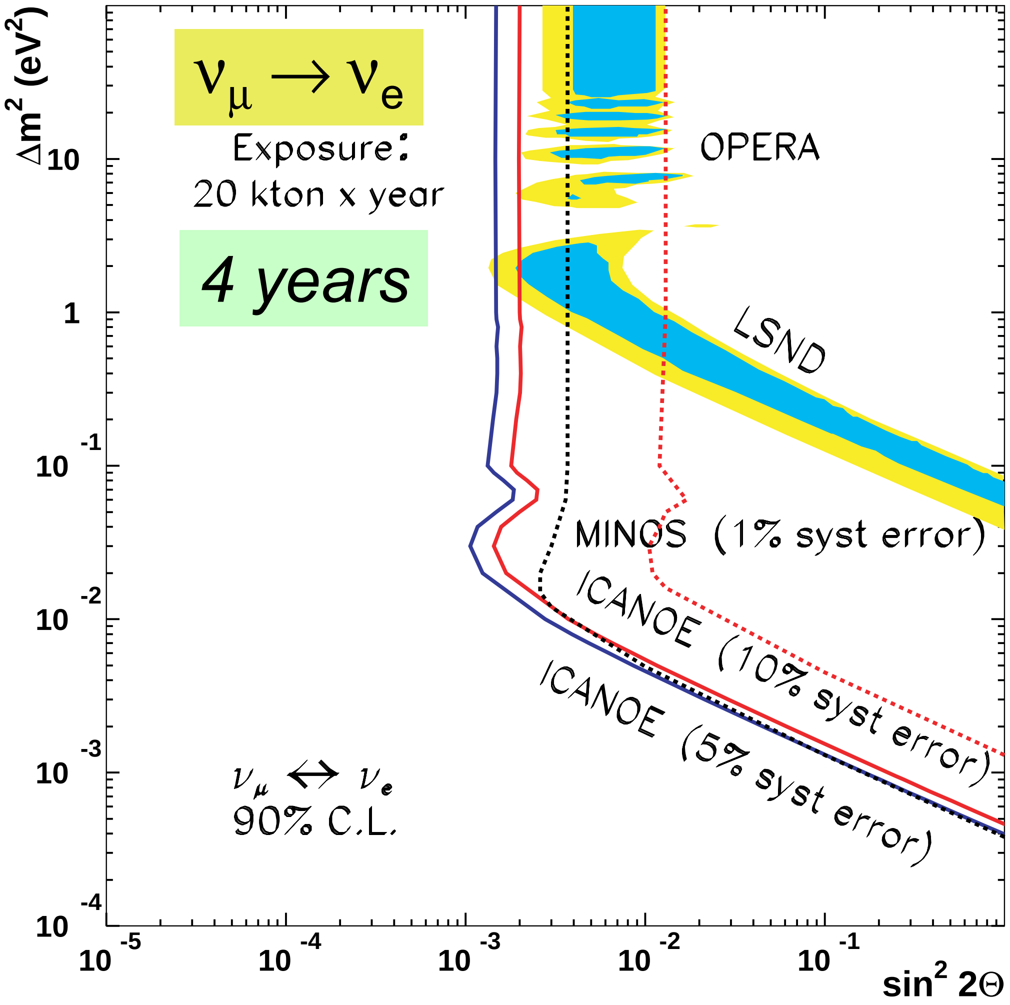
Excess at low energy

$$\Delta m^2 = 3\times 10^{-3}\, eV^2;\ \sin^2 2\theta = 0.02$$

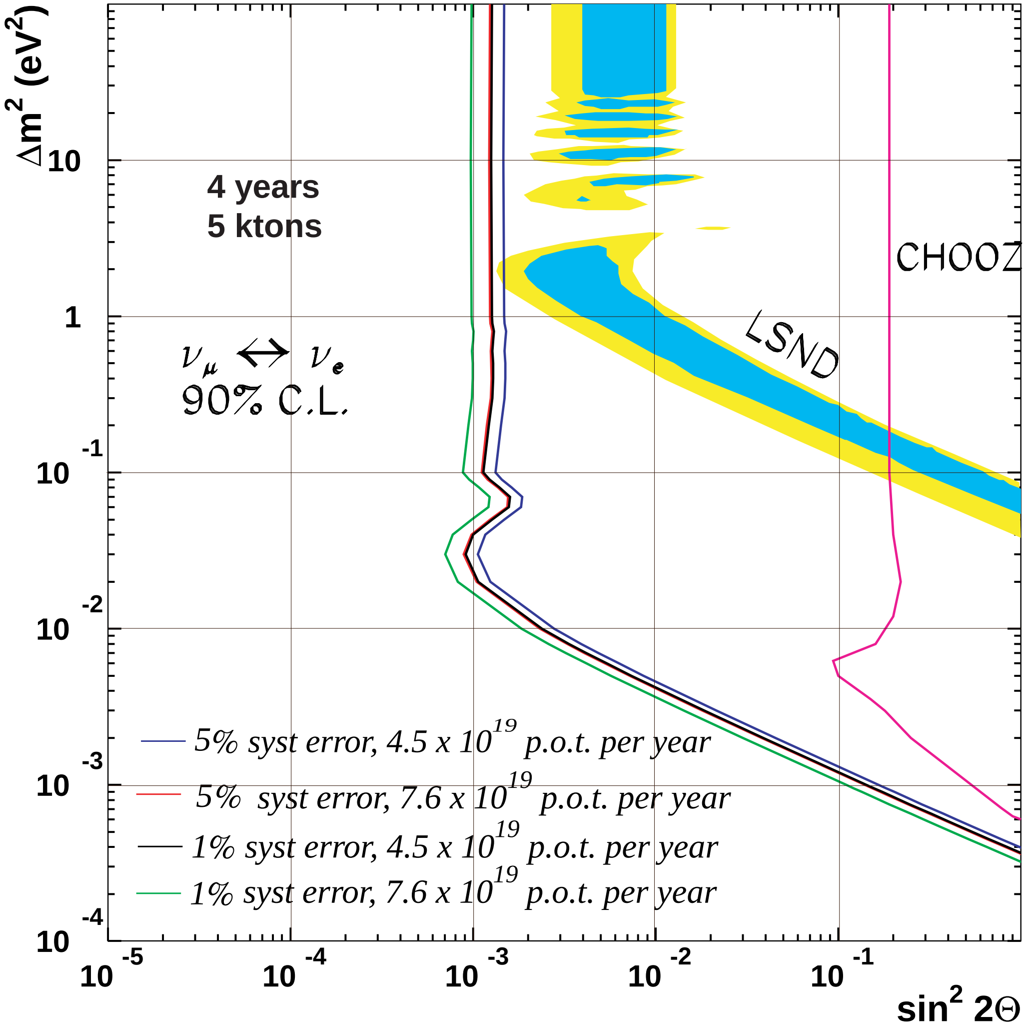




Two-family $\nu_\mu \to \nu_e$ mixing



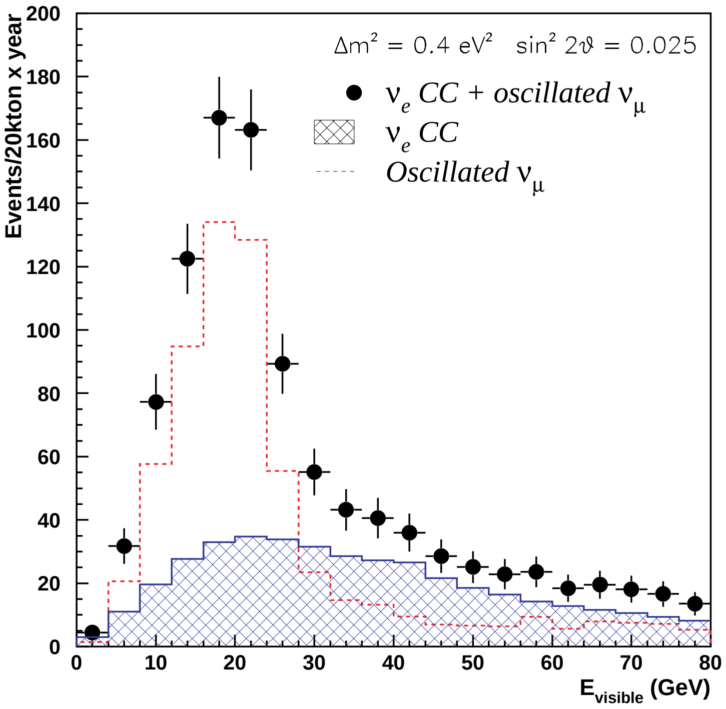
Effect of beam systematics

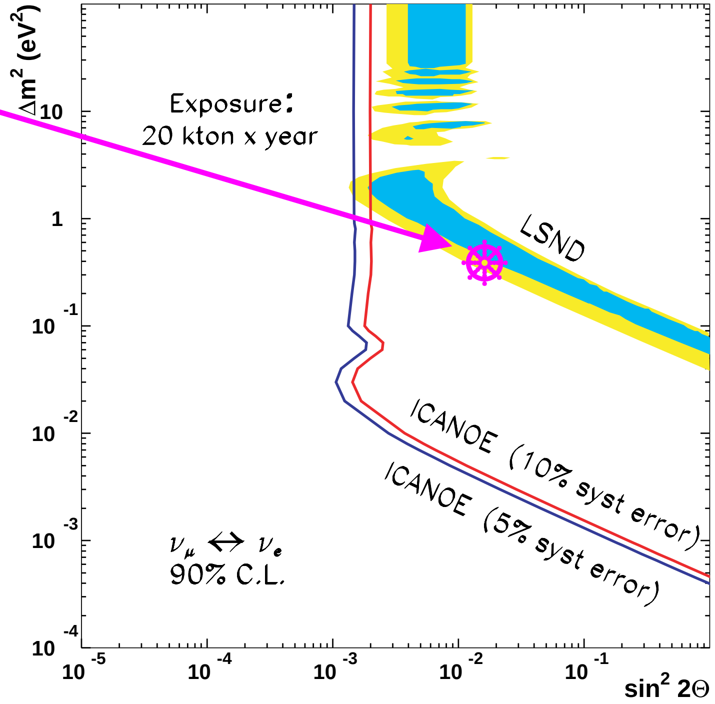


(MINOS high energy beam (PH2high) configuration, NUMI-L228 & TDR)
(OPERA, CERN/SPSC 99-20)

LSND signal

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





	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

Three family oscillations

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

$$P_{\cancel{CP}} = 4\sum_{j>k} \mathrm{Im}\, J_{\alpha\beta jk} \sin \Delta_{jk} \cos \Delta_{jk}$$

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

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

Δm^2_{jk} in eV^2, L in km, E in GeV

3 angles
+ 1 complex phase

$$\boxed{U_{e3}}$$

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

Assuming
$\Delta m^2_{21} = 0$

One mass scale approximation

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

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

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

$$with \quad \Delta_{32}{}^2 = \sin^2(1.27 \Delta m_{32}{}^2 L / E)$$

Search for $\theta_{13} \neq 0$

$\Delta m^2_{32} = 3.5\mathrm{x}10^{-3}$ eV^2; $\sin^2 2\theta_{23} = 1$

ICANOE
4 years

Cuts: Fiducial, $E_e > 1$ GeV, $E_{vis} < 20$ GeV

$\Delta m^2_{23} = 3.5 \times 10^{-3}$ eV^2, $\theta_{23} = 45^o$

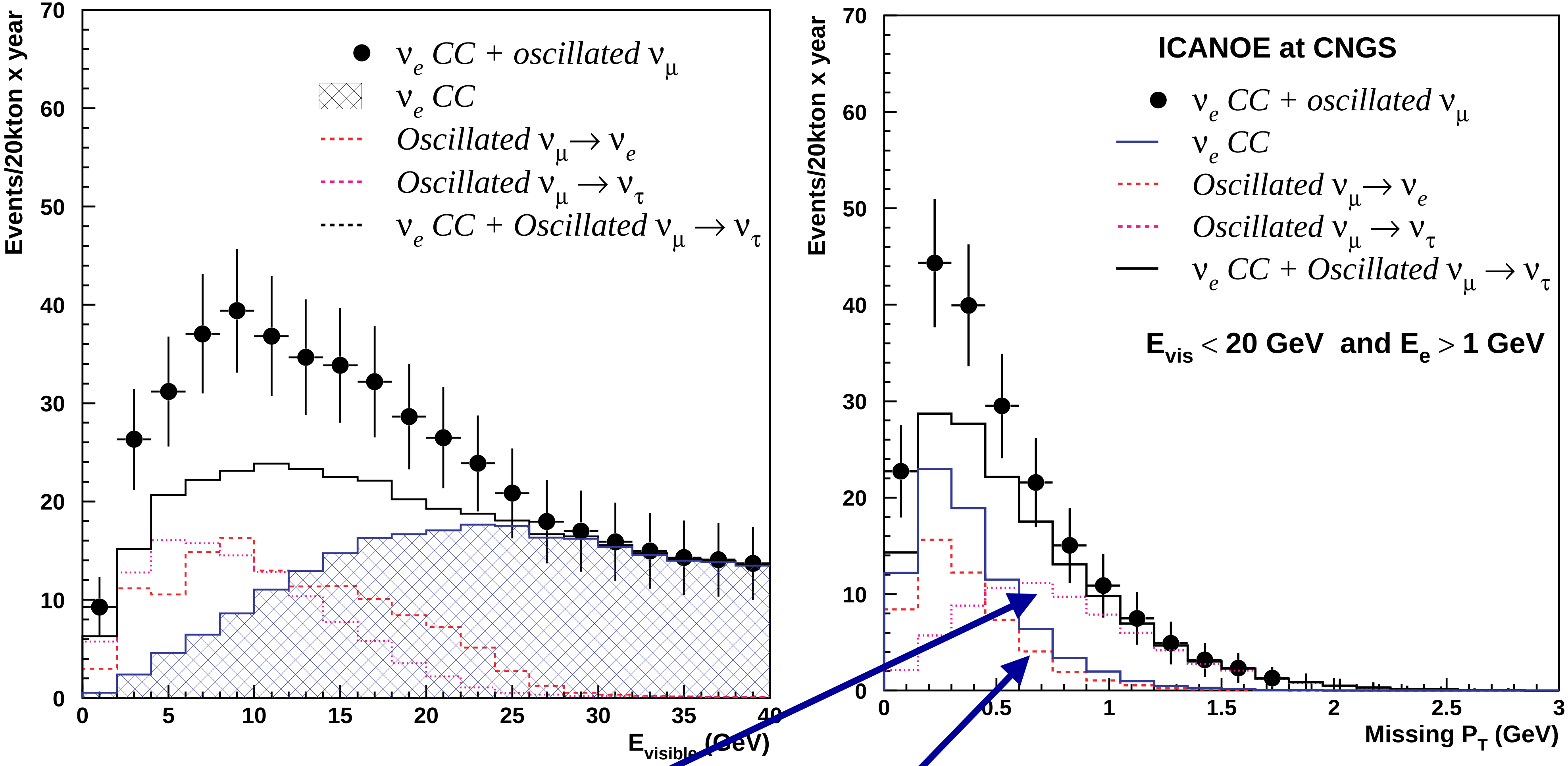
θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC	$\nu_\mu \to \nu_\tau$ $\tau \to e$	$\nu_\mu \to \nu_e$	Total	Statistical significance
9	0.095	79	74	84	237	6.8σ
8	0.076	79	75	67	221	5.4σ
7	0.058	79	76	51	206	4.1σ
5	0.030	79	77	26	182	2.1σ
3	0.011	79	77	10	166	0.8σ

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

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

Δm^2_{32}=3.5x10^{-3} eV^2; sin$^2 2\theta_{23}$ = 1 ; sin$^2 2\theta_{13}$ = 0.05

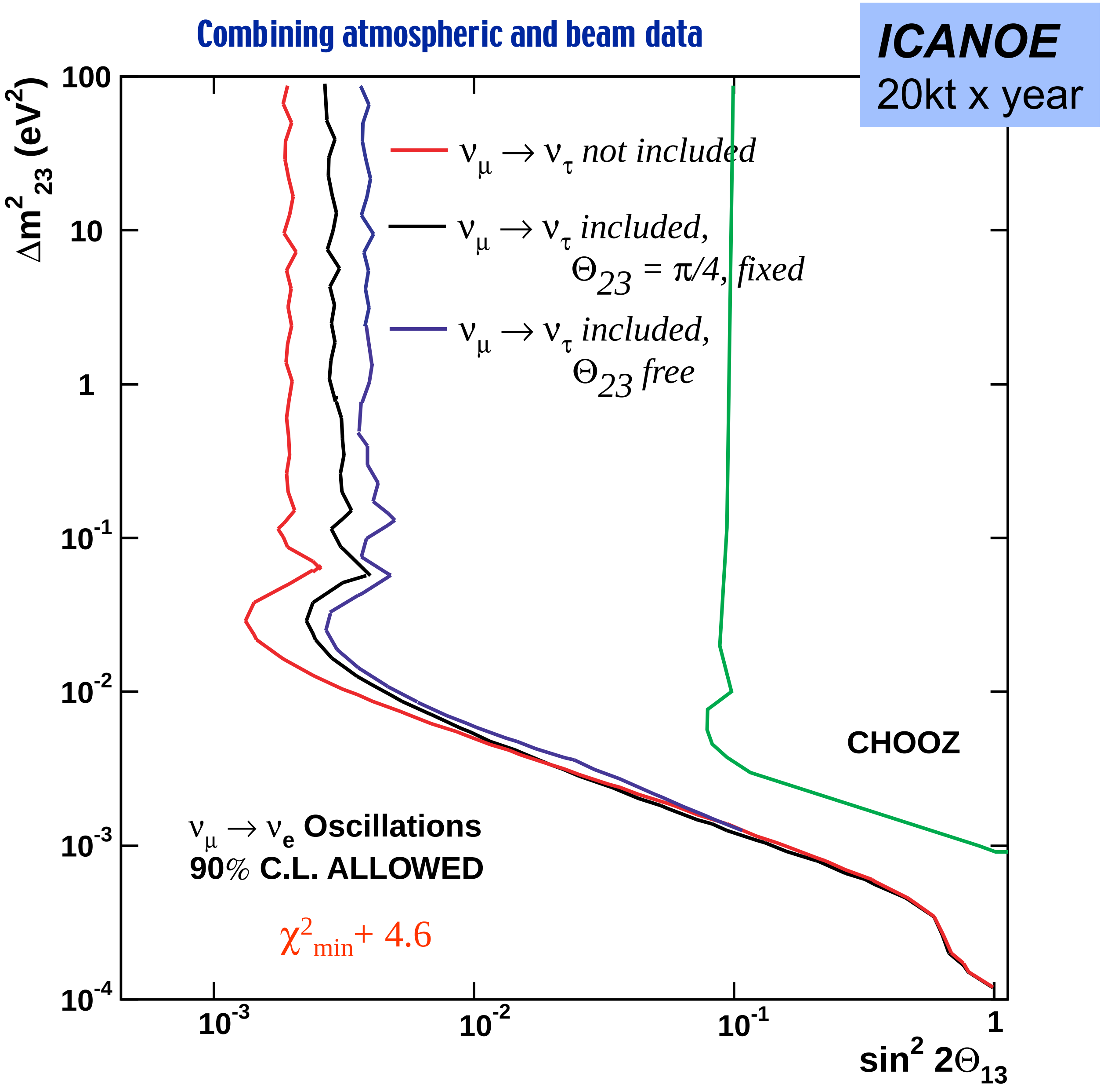
Total visible energy **Transverse missing P_T**



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

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13}\sin^2\theta_{23}\Delta^2{}_{32}$$

Sensitivity to θ_{13} in three family–mixing

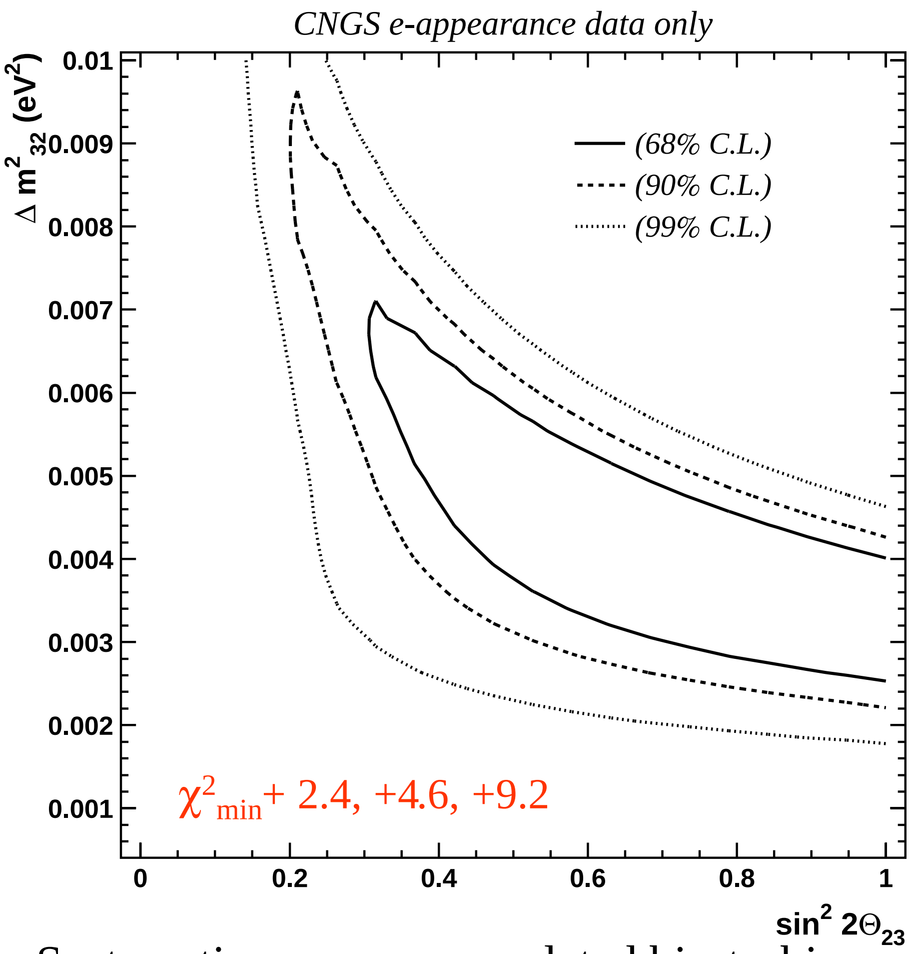


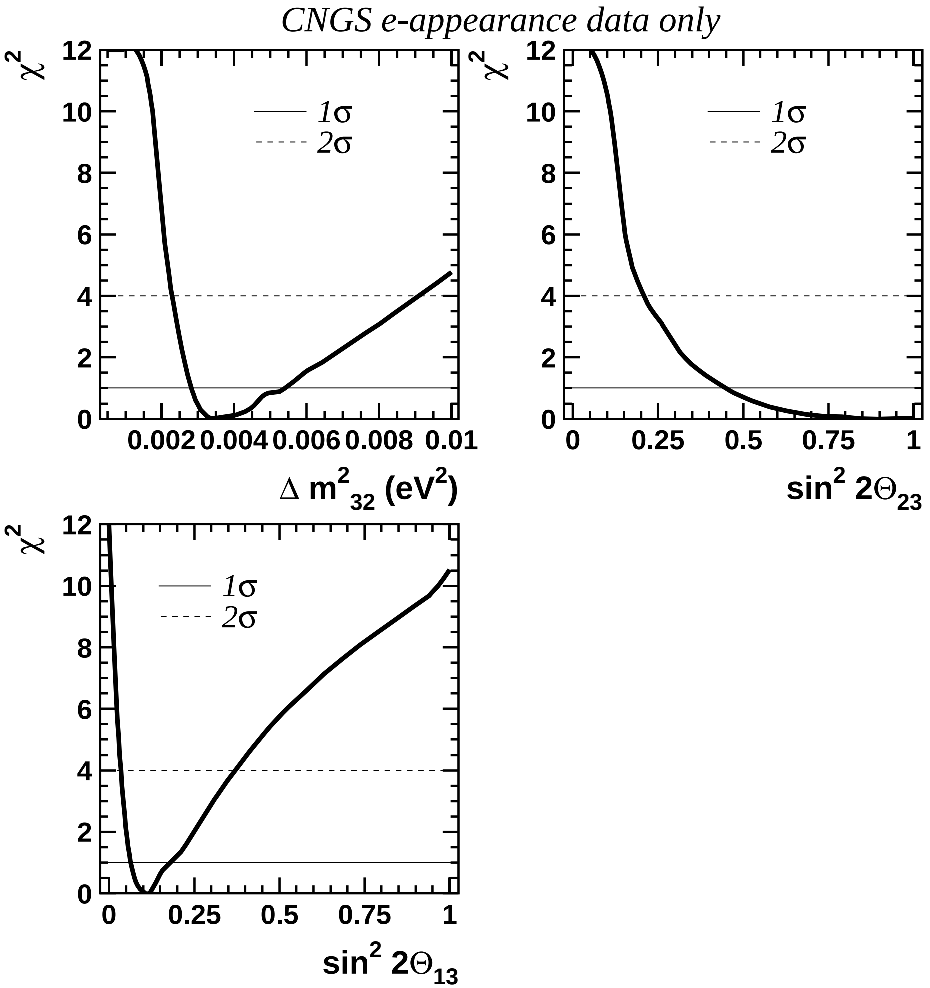
- Limit slightly degraded by inclusion of tau events and leaving contribution as free parameter
- Improved if θ_{23} fixed (e.g. to 45° or from other experiments)
- Almost two-orders of magnitude improvement over existing limit

Parameter determination from beam only

Using electron appearance CNGS beam data only !

ICANOE
20kt x year





Systematic errors: uncorrelated bin-to-bin:

±10% ν_eCC, ±10% ν_τ CC

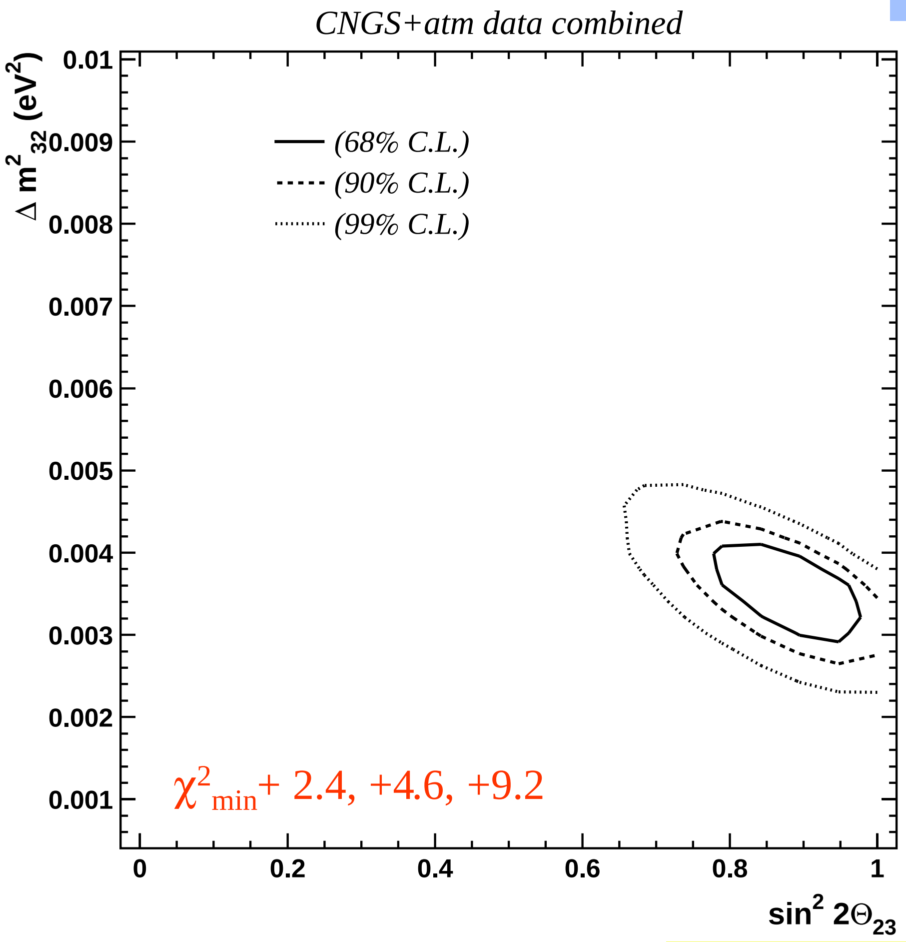
But θ_{23} constrained by atmospheric data !

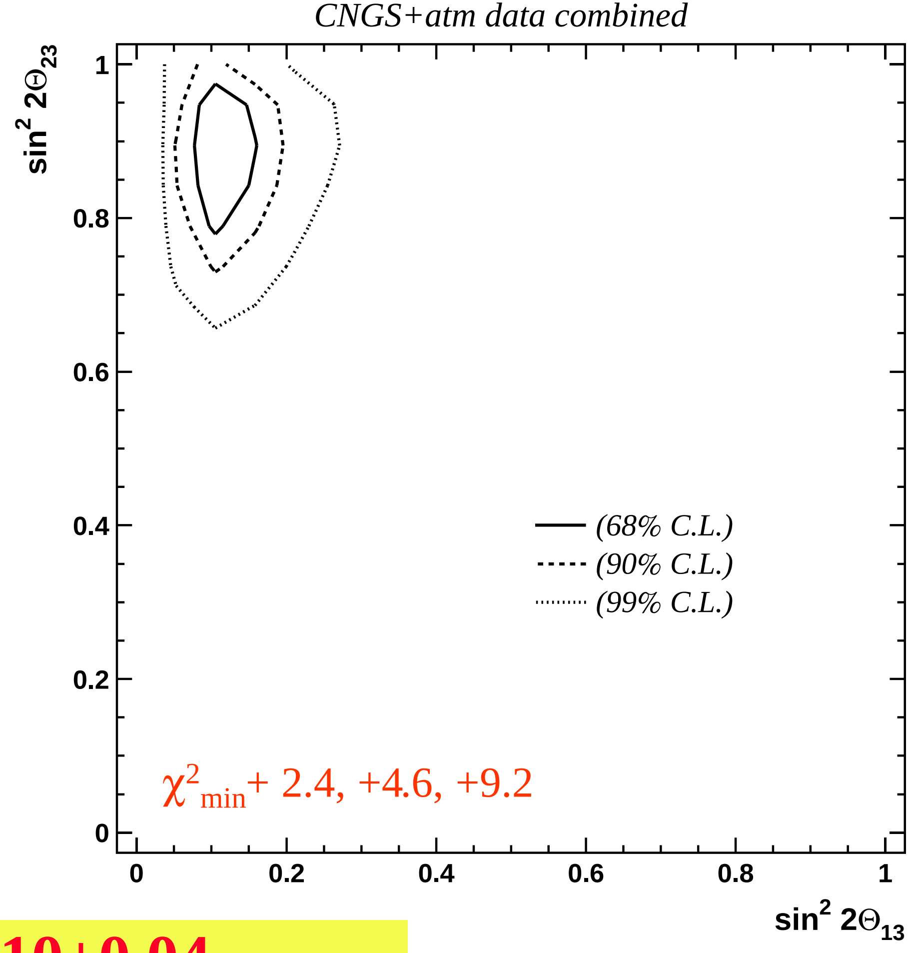
Determination parameters

Combining atmospheric and beam data !

ICANOE
20kt x year

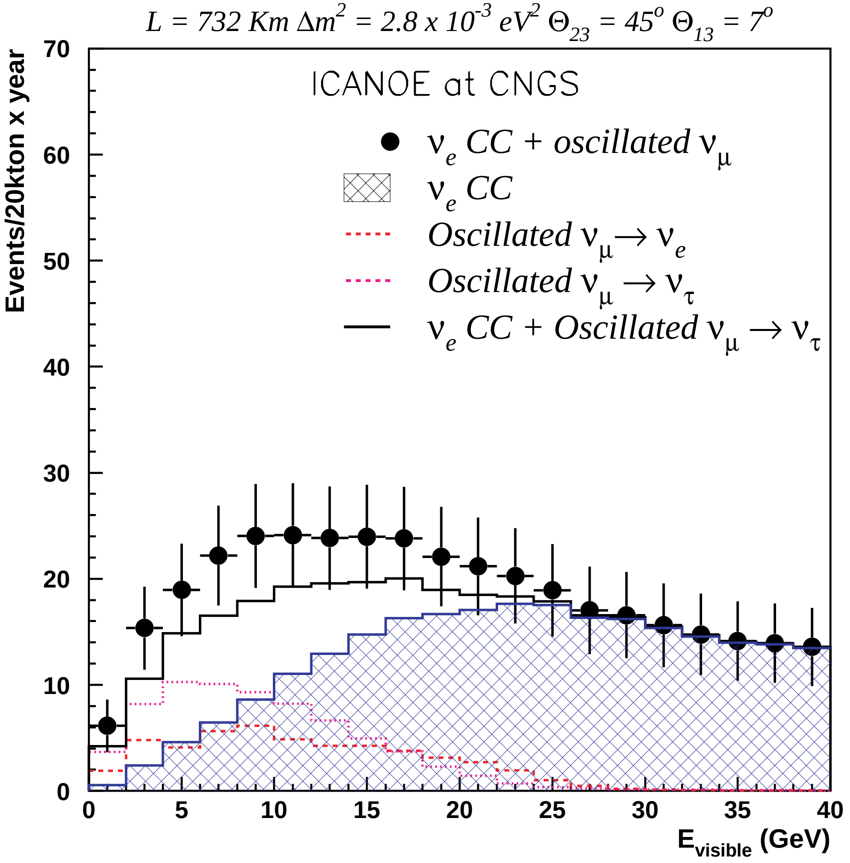
Fit of simulated ICANOE data only





Fitted values:

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



ICANOE

20kt x year

Cuts: Fiducial, $E_e > 1$ GeV, $E_{vis} < 20$ GeV

$\Delta m^2_{23} = 2.8 \times 10^{-3}$ eV^2, $\theta_{23} = 45^o$

θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC	$\nu_\mu \rightarrow \nu_\tau$ $\tau \rightarrow e$	$\nu_\mu \rightarrow \nu_e$	Total	Statistical significance
9	0.095	79	45	55	176	5σ
8	0.076	79	46	44	169	4σ
7	0.058	79	46	34	159	3σ
5	0.030	79	47	17	143	1.5σ
3	0.011	79	47	6	132	0.5σ

ICANOE atmospheric event rates

☆ Complete data set:

	Events/year	
→ **5.6 kton LAr sensitive mass**	1150	1650
→ **3.2 kton calorimeter mass**	500	

Process	Exposure		
	5 kton× year	20 kton×year	50 kton× year
ν_μ CC	535	2140	5350
$\bar{\nu}_\mu$ CC	135	545	1350
ν_e CC	300	1200	3000
$\bar{\nu}_e$ CC	59	235	585
ν NC	325	1300	3250
$\bar{\nu}$ NC	150	590	1500

Flux: 3D calculation, Battistoni et.al., hep-ph/9907408

Data for L/E analysis:

Events/year	**ICANOE liquid** Evisible > 1 GeV	**ICANOE solid** Evisible > 1 GeV
ν_μ CC	380	260
ν_e CC	160	
ν NC	400	

Reconstructed L/E resolution

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

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

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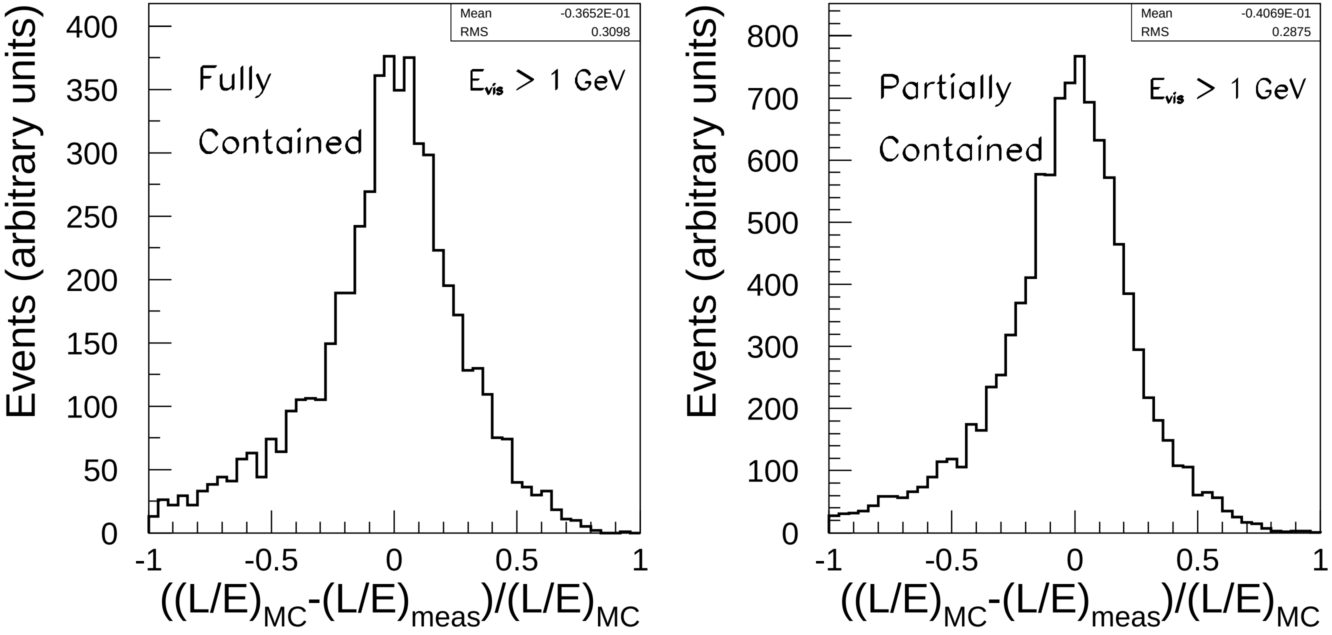
Full simulation



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

L/E distribution: electrons and muons

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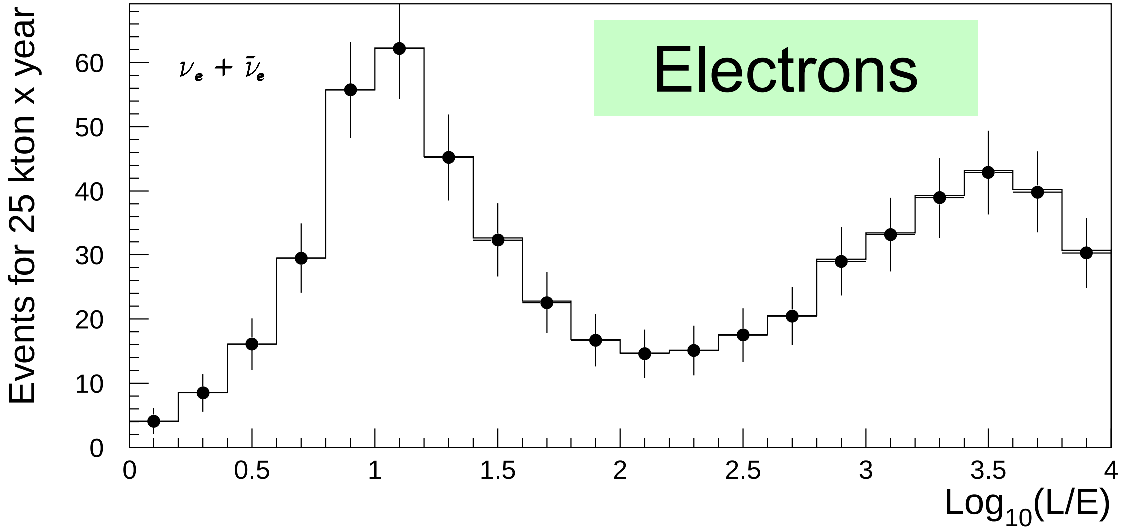
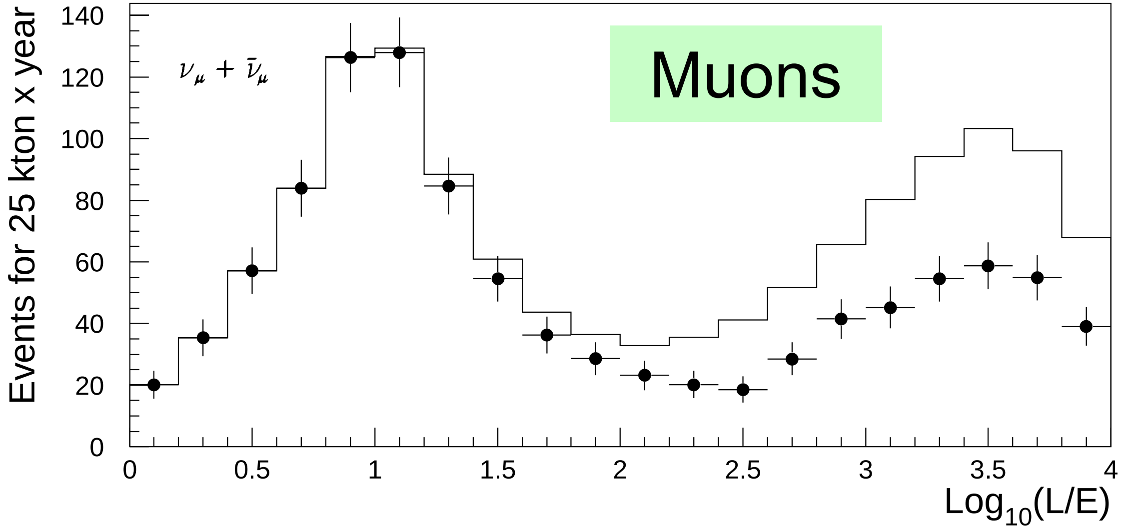
- Oscillation parameters:
  - → $\Delta m^2_{32} = 3.5 \times 10^{-3}$ eV^2
  - → $\sin^2 2\Theta_{23} = 0.9$
  - → $\sin^2 2\Theta_{13} = 0.1$

- ***Electron sample can be used as a reference for no oscillation case***

25 kt year

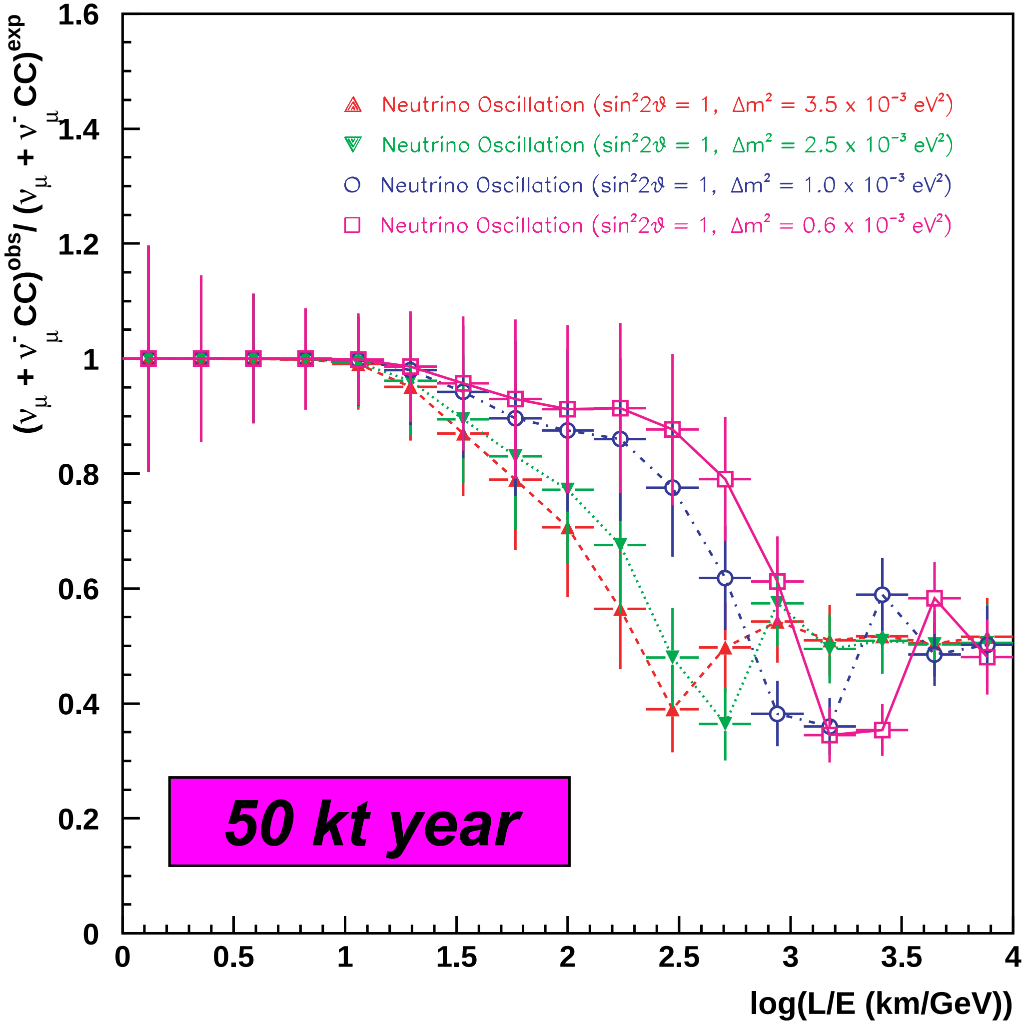




ν_μ disappearance – L/E distribution

ICANOE

- 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 Δm²** is clearly visible.
- "DIP" visible
- Can precisely measure the oscillation parameter and resolution can be improved (items under study)

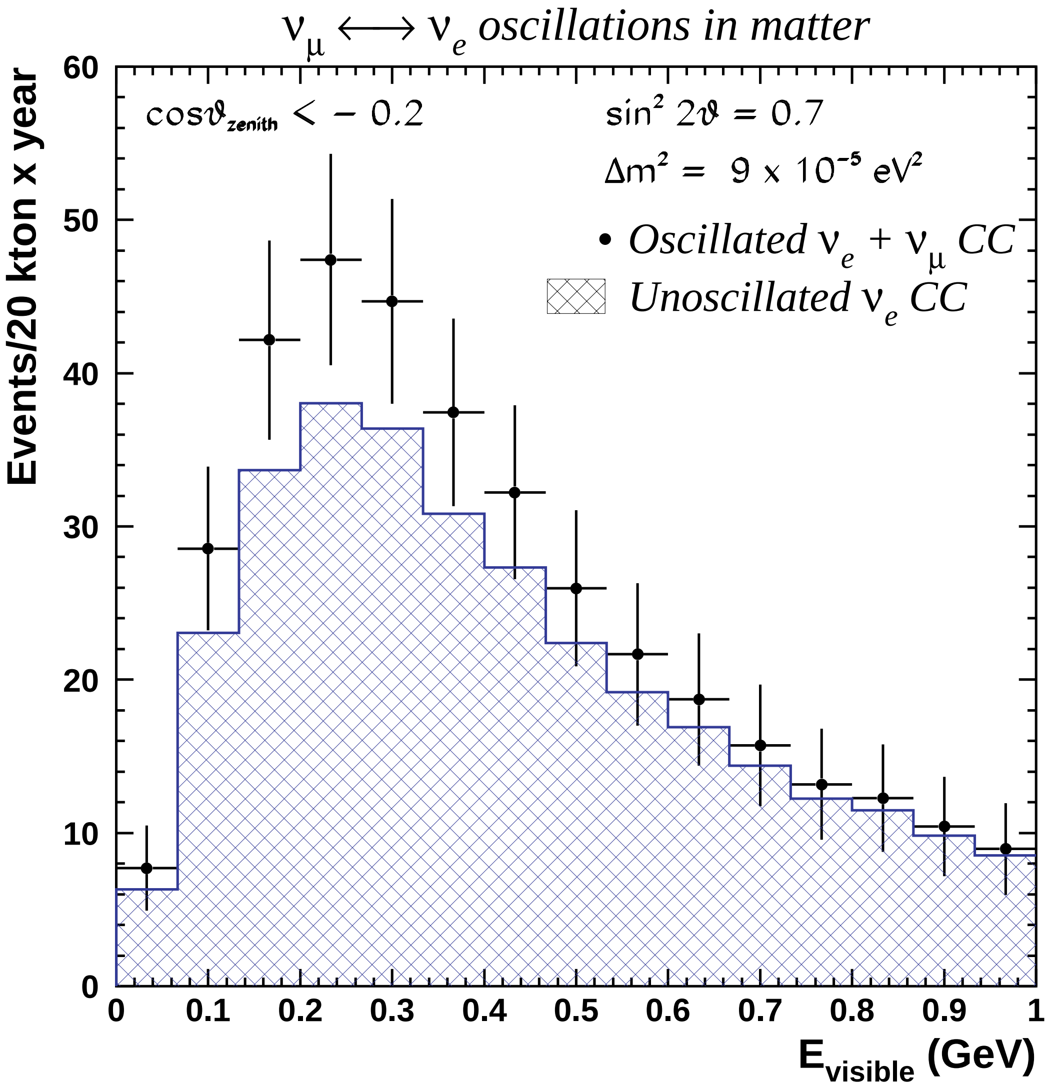


ICANOE low energy electron events

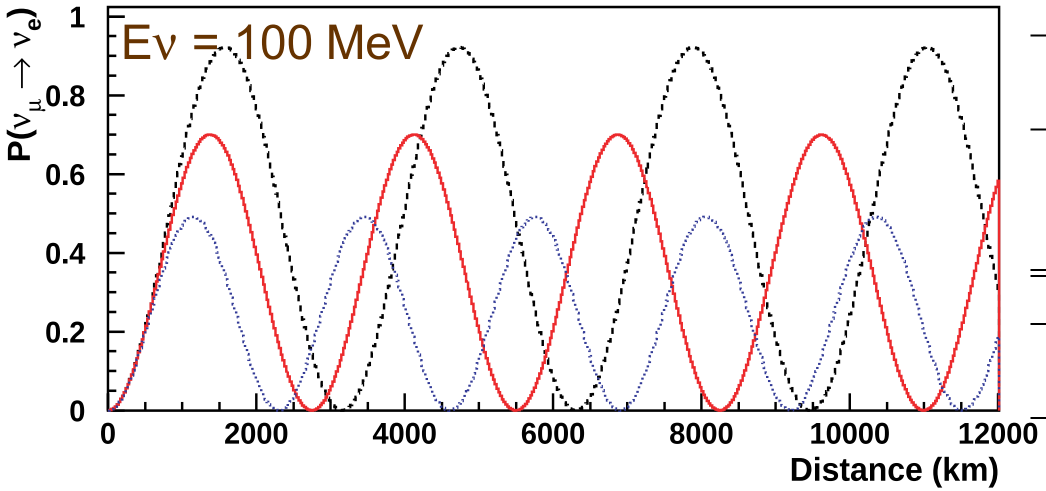
- Study **low energy region** (below 1 GeV) of electron CC sample

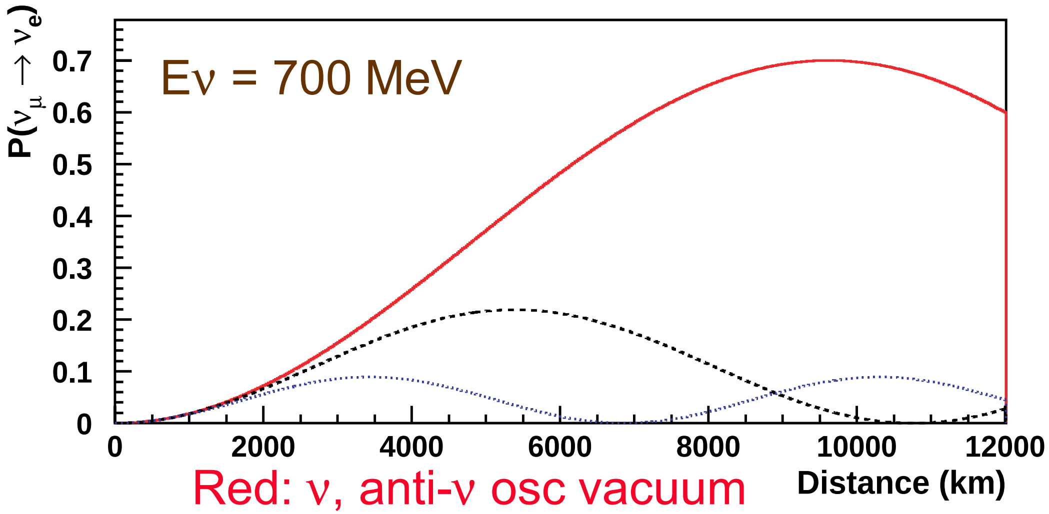
- Assume electron-muon oscillation at Δm^2 relevant for **LMA solar neutrino deficit**

- **Test matter affected oscillations** in neutrinos coming from below.



Oscillations in matter





Red: ν, anti-ν osc vacuum

Black: ν osc matter

Blue: anti-ν osc matter

$\nu_\mu \leftrightarrow \nu_e$ oscillations in matter

Exposure ($kton \times year$)	ν_e CC no oscillations	ν_e CC oscillations	ν_e CC excess (%)
5	111	131	18 ± 10
20	442	523	18 ± 5
50	1104	1308	18 ± 3

$\nu_\mu \leftrightarrow \nu_e$ oscillations in vacuum

Exposure ($kton \times year$)	ν_e CC no oscillations	ν_e CC oscillations	ν_e CC excess (%)
5	111	134	21 ± 10
20	442	535	21 ± 5
50	1104	1338	21 ± 3

$\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations in matter

Exposure ($kton \times year$)	$\bar{\nu}_e$ CC no oscillations	$\bar{\nu}_e$ CC oscillations	$\bar{\nu}_e$ CC excess (%)
5	14	15	7 ± 20
20	58	62	7 ± 13
50	145	155	7 ± 9

$\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations in vacuum

Exposure ($kton \times year$)	$\bar{\nu}_e$ CC no oscillations	$\bar{\nu}_e$ CC oscillations	$\bar{\nu}_e$ CC excess (%)
5	14	19	34 ± 30
20	58	78	34 ± 15
50	145	195	34 ± 10

Cuts: $E_{vis} < 1$ GeV, $\cos\theta_{zenith} < -0.2$

Oscillation parameters: $\Delta m^2 = 9 \times 10^{-5}$ eV^2, $\sin^2 2\theta = 0.7$

ICANOE Nucleon Decay Sensitivities

Example: p → νK

Exposure: 1000 kton x year !

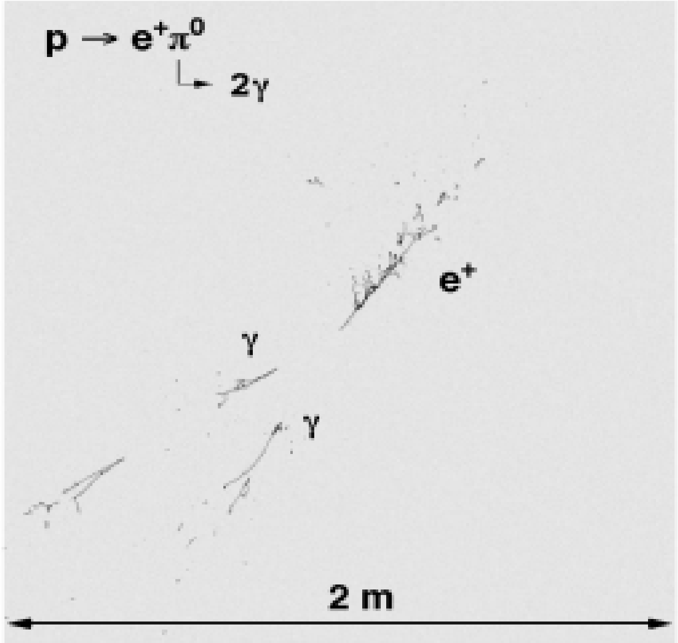
Background free searches

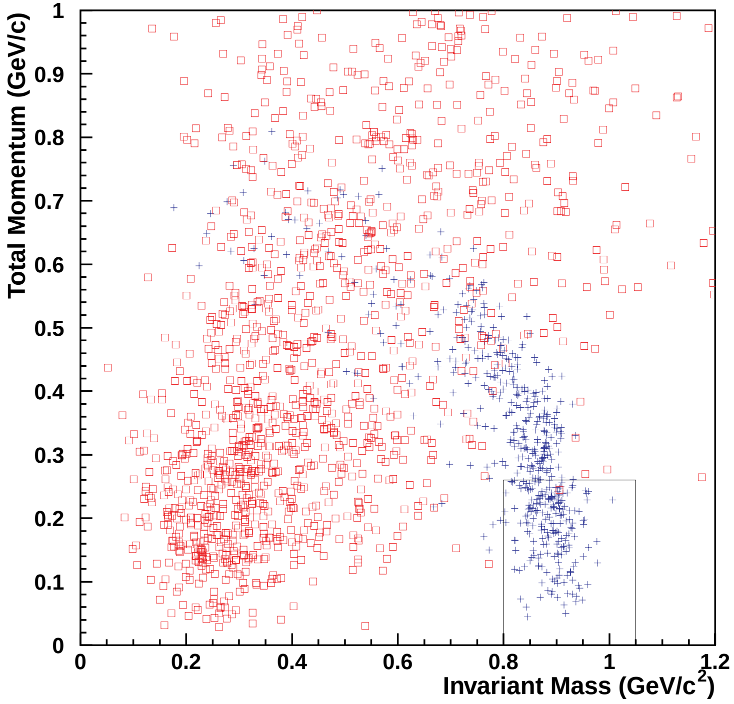
Cuts	$K+\bar{\nu}$	ν NC	$\bar{\nu}$ NC
Initial	100%	64705	29612
No primary $\pi^{\pm}$	99.4%	55481	26033
No primary π^{0}	98.7%	48397	23265
Only one kaon	98.5%	108	22
Total Energy < 0.65 GeV	85%	< 1	< 1

Mode	SuperK	PDG 1998	$5\ kt \times year$	$20\ kt \times year$	$50\ kt \times year$
$p \to e^+\pi^0$	29	5.5	2.5	10	25
$p \to \mu^+\pi^0$	23	2.7	2.25	9	22.5
$p \to \bar{\nu}K^+$	6.8	1.0	4.1	16.3	40.8
$p \to \nu\pi^+$	–	0.25	2.5	10	25
$p \to e^+\pi^+\pi^-$	–	0.21	0.75	3	7.5
$p \to e^+\rho^0$	–	0.75	0.5	2	5
$p \to e^+e^+e^-$	–	5.1	5.9	23.5	58.8
$n \to e^+\pi^-$	–	1.3	2.9	11.5	28.8
$n \to \mu^+\pi^-$	–	1.0	2.6	10.5	26.3
$n \to \nu\pi^0$	–	1.0	3	12	30
$n \to e^-K^+$	–	0.032	6.1	24.5	61.3
$n \to e^+\rho^-$	–	0.58	0.62	2.5	6.3
$n \to e^+\pi^-\pi^0$	–	0.32	0.88	3.5	8.8
$n \to e^+e^-\nu$	–	0.74	7.1	28.5	71.3
$n \to \bar{\nu}K^0$	–	0.86	4.6	18.5	46.2

In 10^{32} years

$p \to e^+ \pi^0$ decay

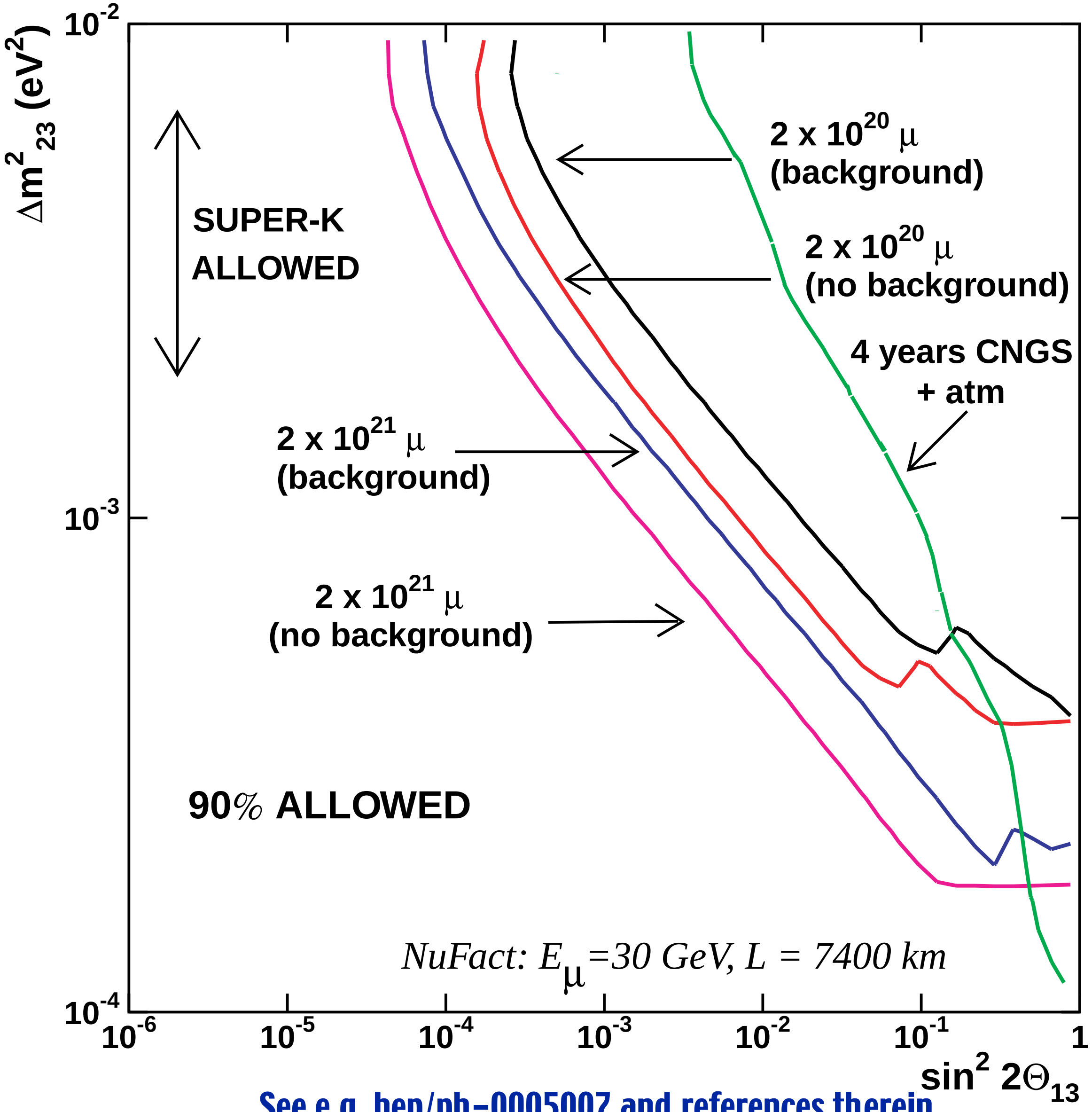




Cuts	$e+\ \pi^0$ Argon	$e+\ \pi^0$ Oxygen	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
Initial	100%	100%	59861	11707	106884	27273	64705	29612
One π^0	54%	70%	5277	1696	11160	4388	6223	2278
One e	54%	70%	5277	1696	7	<1	<1	<1
$T_p < 100$ MeV	53%	68%	2505	1256	<1	<1	<1	<1
$0.8 <$ Inv Mass < 1.05 GeV	38%	53%	306	204	<1	<1	<1	<1
Total Momentum < 0.25 GeV	19%	24%	1	<1	<1	<1	<1	<1

Exposure: 1000 kton x year

Expected sensitivity to θ_{13} at a neutrino factory



See e.g. hep/ph–0005007 and references therein

- 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

- The ***combined ICANOE & OPERA program*** coupled to the ***CNGS beam*** will **provide unique opportunities** to further detect and study the atmospheric neutrino oscillation phenomenon.
  - → Sensitive $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ appearance at accelerator
  - → Continued observation of atmospheric neutrinos
- The ***complementarity of this program*** relative to the disappearance LBL programs (K2K & MINOS) is obvious.
- After many years of R&D and gained experience, ICANOE and OPERA are ready to enter into a phase of realization.
- ***The CNGS program will hopefully contribute to the comprehensive elucidation of neutrino masses and mixings.***

Elucidation of neutrino mass and mixing

→

A fundamental milestone in particle physics, astrophysics and cosmology