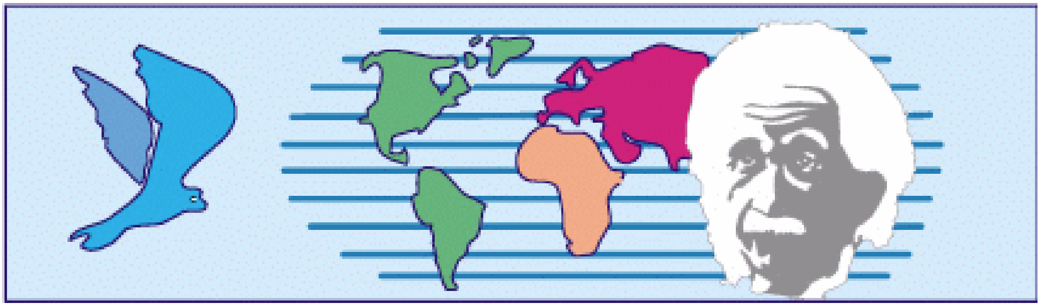
Neutrino oscillations: atmospheric and accelerator experiments

André Rubbia
ETH Zürich



Four Seas Conference, Thessaloniki (Greece)

19. April 2002

The renaissance of neutrinos (I)

- The evidence for **neutrino masses** and **neutrino mixing** (two surprises) has triggered an enormous excitement and activity around the subject
  - ➥ Solar neutrino experiments (see J. Bouchez's talk)
  - ➥ **Atmospheric neutrino experiments**
  - ➥ **Accelerator neutrino experiments**
  - ➥ Double beta decay experiments

In this talk

- It was not obvious ! It came with some reluctance !
  - ➥ Theory:
    - First "breaking" of the Standard Model since it was founded in 1967 (which otherwise dramatically confirmed by all experiments to very high precision) !!
    - Cosmological (HDM) $\square_{\square}$?
    - Large mixing angles?
  - ➥ Experiment:
    - Misunderstood backgrounds? Statistical treatments? etc...
- In fact, the issue is **NOT** solved: neutrino is **hot** topic !
  - ➥ E.g. LSND, double-beta decay signals, etc…

Renaissance of neutrino physics (II)

Some selected top cited papers in the QSPIRES data base

		#citations
1.	**A MODEL OF LEPTONS** By S. Weinberg (MIT, LNS). Phys.Rev.Lett.19:1264-1266,1967	5092
2.	**EVIDENCE FOR OSCILLATION OF ATMOSPHERIC NEUTRINOS.** By Super-Kamiokande Collaboration (Y. Fukuda *et al.*), Jul 1998. 9pp. **Phys.Rev.Lett.81:1562-1567,1998**	1286
3.	**OBSERVATION OF TOP QUARK PRODUCTION IN ANTI-P P COLLISIONS.** By CDF Collaboration (F. Abe *et al.*), Mar 1995. 18pp. **Phys.Rev.Lett.74:2626-2631,1995**	890
4.	**OBSERVATION OF THE TOP QUARK.** By D0 Collaboration (S. Abachi *et al.*), Mar 1995. 12pp. **Phys.Rev.Lett.74:2632-2637,1995**	850
5.	**EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT S**(1/2) = 540-GeV.** By UA1 Collaboration (G. Arnison *et al.*), 1983. 31pp. **Phys.Lett.B122:103-116,1983**	774
6.	**EXPERIMENTAL OBSERVATION OF LEPTON PAIRS OF INVARIANT MASS AROUND 95-GeV/c**2 AT THE CERN SPS COLLIDER.** By UA1 Collaboration, **Phys.Lett.B126:398-410,1983**	747
7.	**EVIDENCE FOR ANTI-MUON-NEUTRINO ---> ANTI-ELECTRON-NEUTRINO OSCILLATIONS FROM THE LSND EXPERIMENT AT LAMPF.** By LSND Collaboration (C. Athanassopoulos *et al.*). May 1996. 4pp. **Phys.Rev.Lett.77:3082-3085,1996**	500
8.	**MEASUREMENT OF THE SOLAR ELECTRON NEUTRINO FLUX WITH THE HOMESTAKE CHLORINE DETECTOR.** By Bruce T. Cleveland, Timothy Daily, Raymond Davis, Jr., James R. Distel, Kenneth Lande, C.K. Lee, Paul S. Wildenhain (Pennsylvania U.), Jack Ullman (City Coll., N.Y.). 1998. **Astrophys.J.496:505-526,1998**	363
9.	**MEASUREMENT OF THE RATE OF NUE+ D --> P + P + E- INTERACTIONS PRODUCED BY B-8 SOLAR NEUTRINOS AT THE SUDBURY NEUTRINO OBSERVATORY.** By SNO Collaboration (Q.R. Ahmad *et al.*), Jun 2001. 6pp., **Phys.Rev.Lett.87:071301,2001**	252
10.	**OBSERVATION OF AN EXCESS IN THE SEARCH FOR THE STANDARD MODEL HIGGS BOSON AT ALEPH.** By ALEPH Collaboration (R. Barate *et al.*), Nov 2000. 20pp. **Phys.Lett.B495:1-17,2000**	108

Neutrino mass is NEW physics...

- From point of view of theory, electrically neutral neutrinos can possess two types of mass terms:

Dirac-Mass term ***Majorana-Mass term***

$$-\mathcal{L} = m_D\left(\bar{\nu}_R \nu_L + h.c.\right) + m_L\left(\bar{\nu}_L \nu_R^c + h.c.\right)$$

- Experimentally it appears that:
  - The state of neutrinos is fully ν_L
  - The state of antineutrinos is fully ν^c_R
- **Dirac mass term**: If ν_R and ν^c_L exist in Nature, new physics beyond SM to describe their interactions (sterile in SM other than due to mass)
- **Majorana mass term**: ν_R and ν^c_L do not need to exist, but then coupling between neutrino and antineutrino: Lepton number L not conserved. Cannot be generated by standard Higgs-mechanism. Dim-5 operator $L_i^T □_{ij} L_j □□/M$ □□(□ SM is an effective theory □ new physics beyond SM).

Neutrino flavor oscillation probability

- The case with three neutrinos: *($c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$)*

$$U=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

- Solar and atmospheric data are compatible with $\theta_{13}\approx 0$ and present limit from CHOOZ is **$\sin^2 2\theta_{13} < 0.1$**:
  - ➥ experimentally decouple two 2x2 mixing matrices $U_1(\theta_{12})$ and $U_2(\theta_{23})$
  - ➥ And $|\Delta m^2_{12}| << |\Delta m^2_{23}|$ *where Δm^2 = mass squared difference*
- The two-flavor oscillation probabilities are then essentially:

$$P(\nu_e \to \nu_{\mu/\tau}) \approx \sin^2 2\theta_{12}\sin^2\left(1.27\,\Delta m^2_{12}(eV^2)\frac{L(km)}{E(GeV)}\right) \quad for \quad solar$$

$$P(\nu_\mu \to \nu_\tau) \approx \sin^2 2\theta_{23}\sin^2\left(1.27\,\Delta m^2_{23}(eV^2)\frac{L(km)}{E(GeV)}\right) \quad for \quad atmospheric$$

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

Two-neutrino oscillation

$\nu_\mu \to \nu_e$

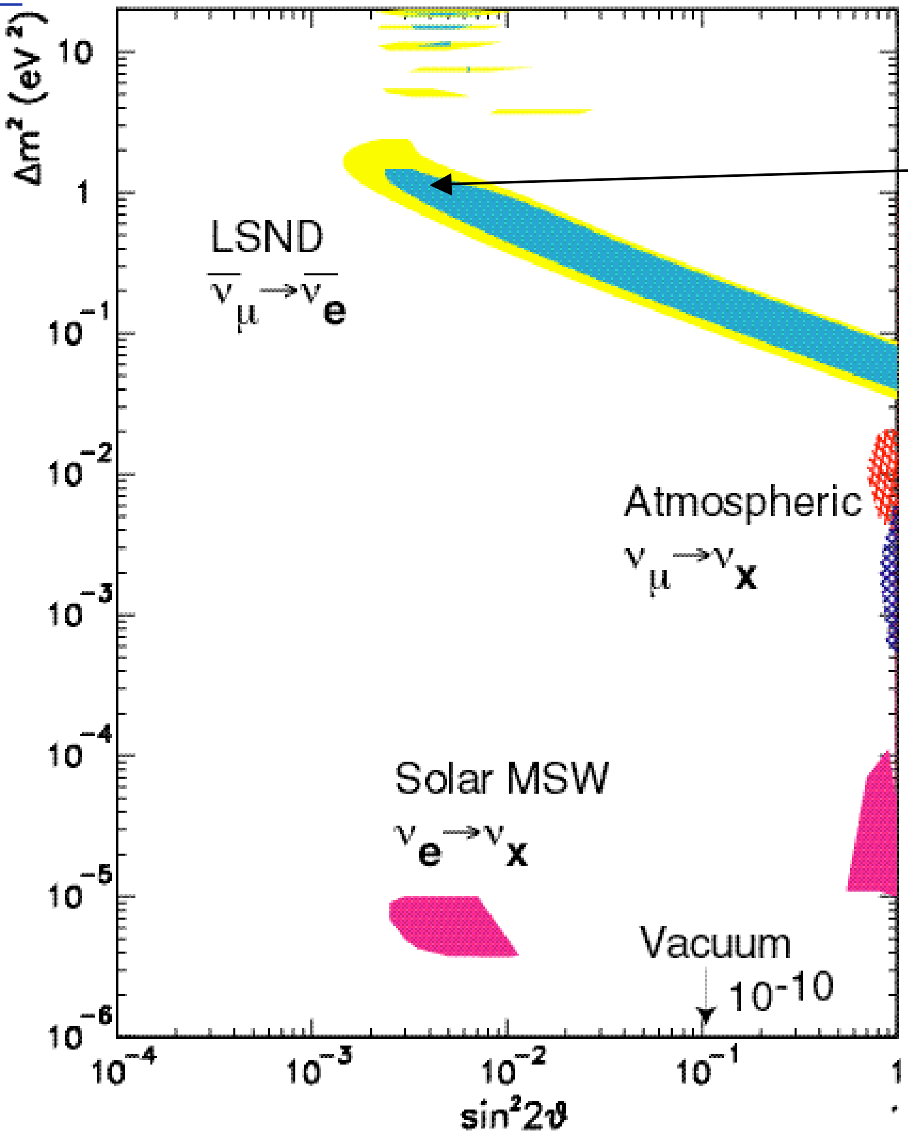
Electron excess

$\nu_\mu \to \nu_x$

Muon deficit

$\nu_e \to \nu_x$

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

1) Evidence for atmospheric muon neutrino disappearance

Phys.Rev.Lett.81:1562-1567,1998

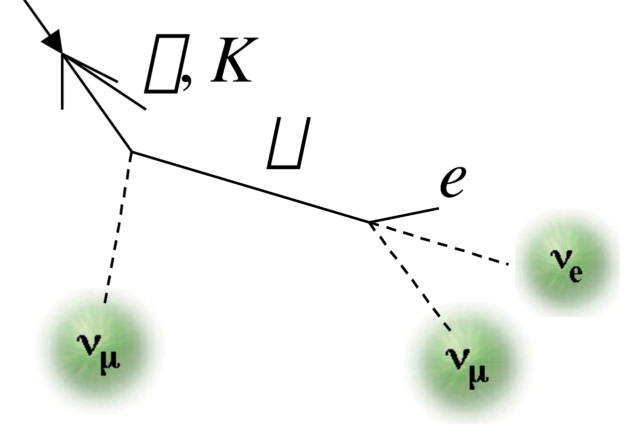
$$\nu_\mu \rightarrow \nu_X$$

with

$\Delta m^2 \approx O(10^{-3} eV^2)$ and large mixing

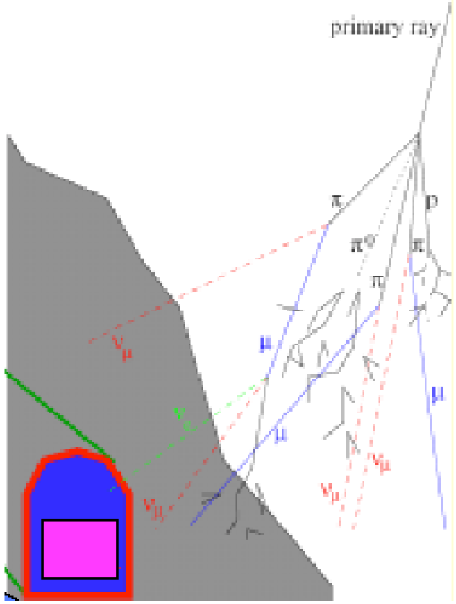
Atmospheric neutrinos

hadronic cascade + decays

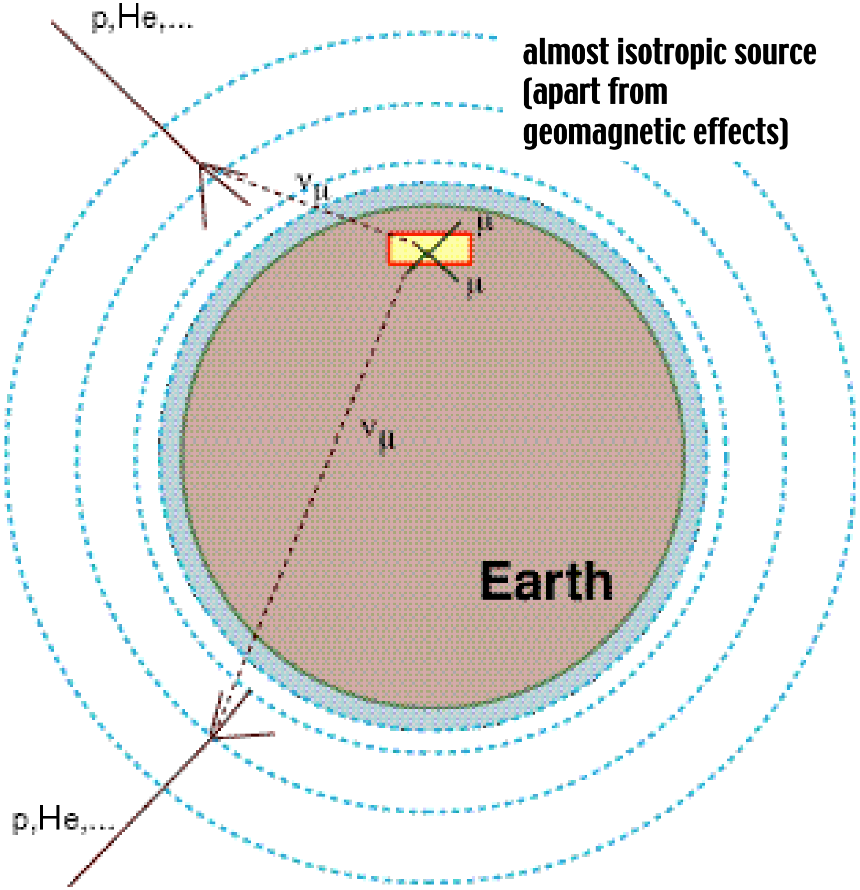


$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

Predicted ratio of muon to electron neutrinos



Interaction rate:
≈150 CC events/kton/year
Average energy:
≈400 MeV

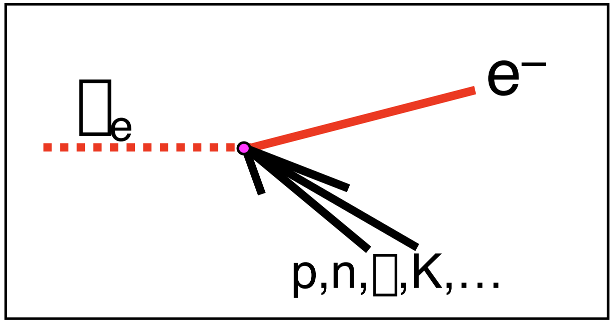


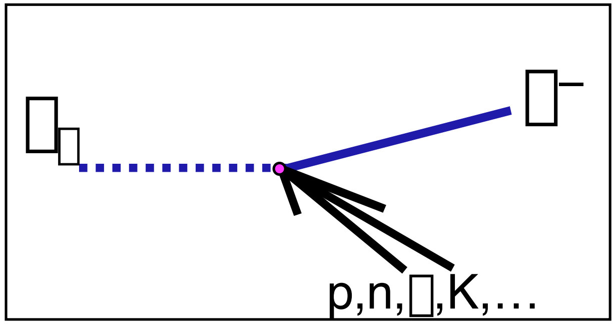
almost isotropic source (apart from geomagnetic effects)

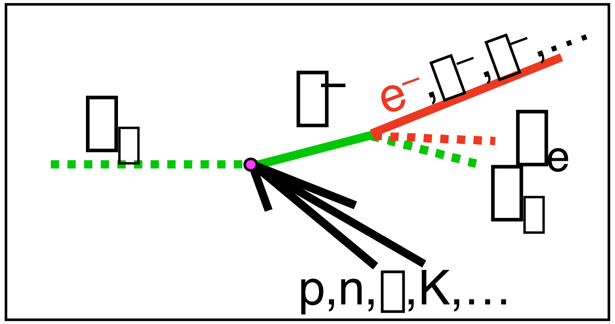
Earth is a splendid neutrino beam line!

Neutrino detection

Neutrinos interact VERY rarely with matter - when they do, they often produce a charged lepton of their "own character":







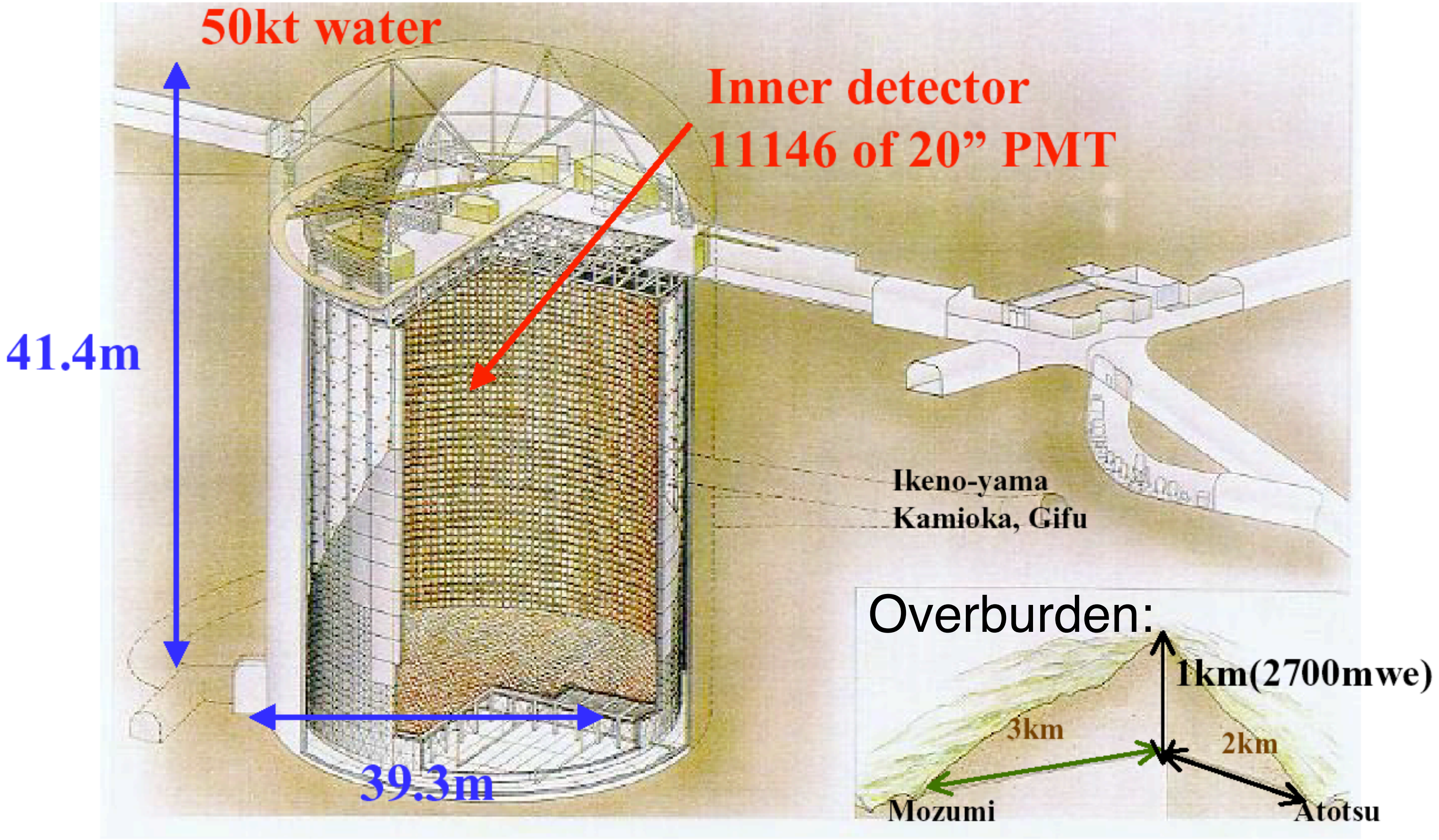
NOTE: a minimum amount of energy is needed (to create the mass of the lepton):

m_e = 0.5 MeV, - m_μ = 106 MeV - m_τ = 1770 MeV

- Tau neutrino not expected in atmospheric flux (if no oscillations)
- In any case, atmospheric tau neutrinos are very difficult to detect because (1) energy threshold (i.e. very low rate) (2) hard to distinguish from ν_e or ν_μ interactions

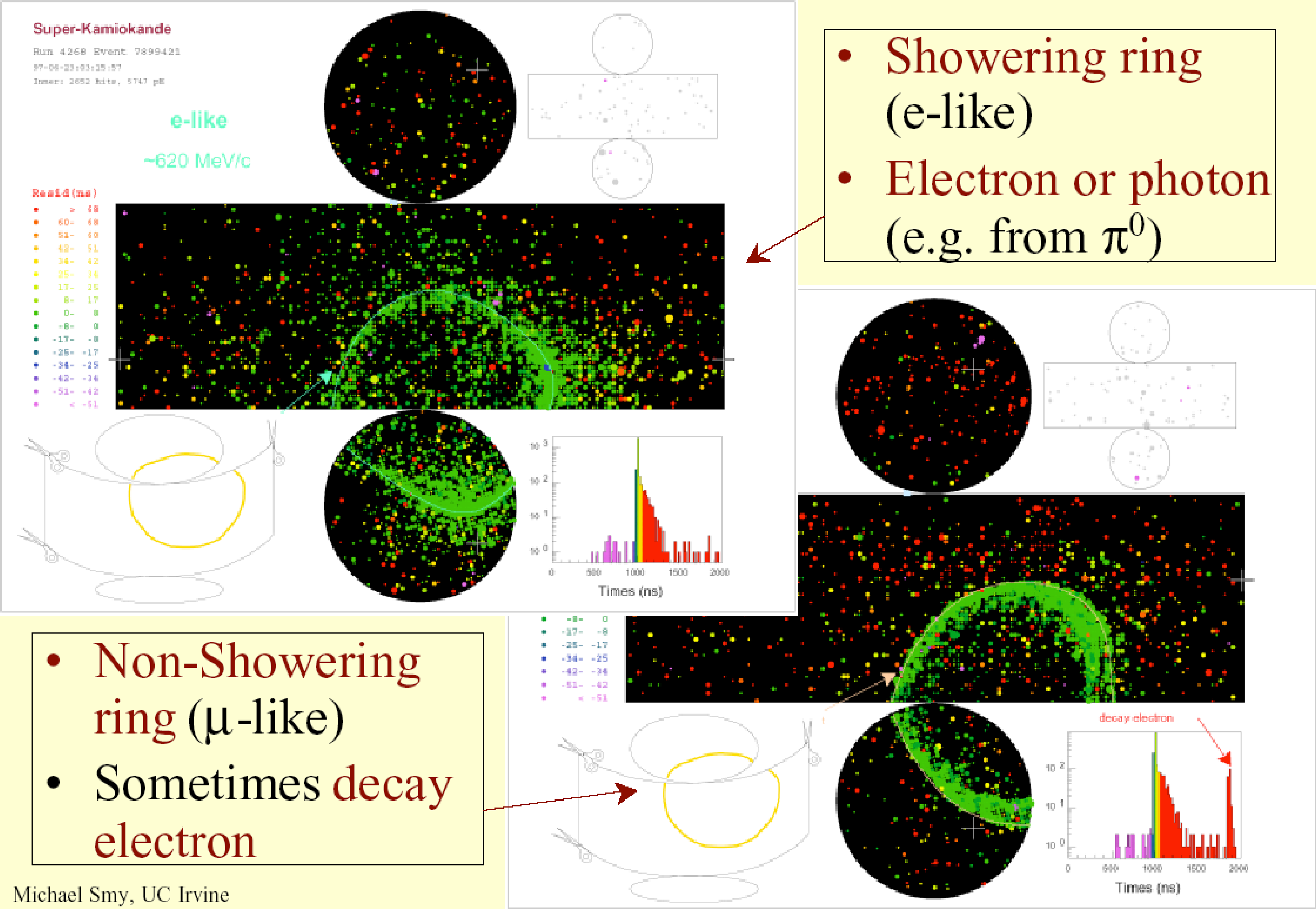
SuperKamiokande Detector

Very large Water Cerenkov detector: Fiducial mass 22.5 kton



Operation from April 1996 till November 2001 (currently under repair)

Electron and muon events in SuperK

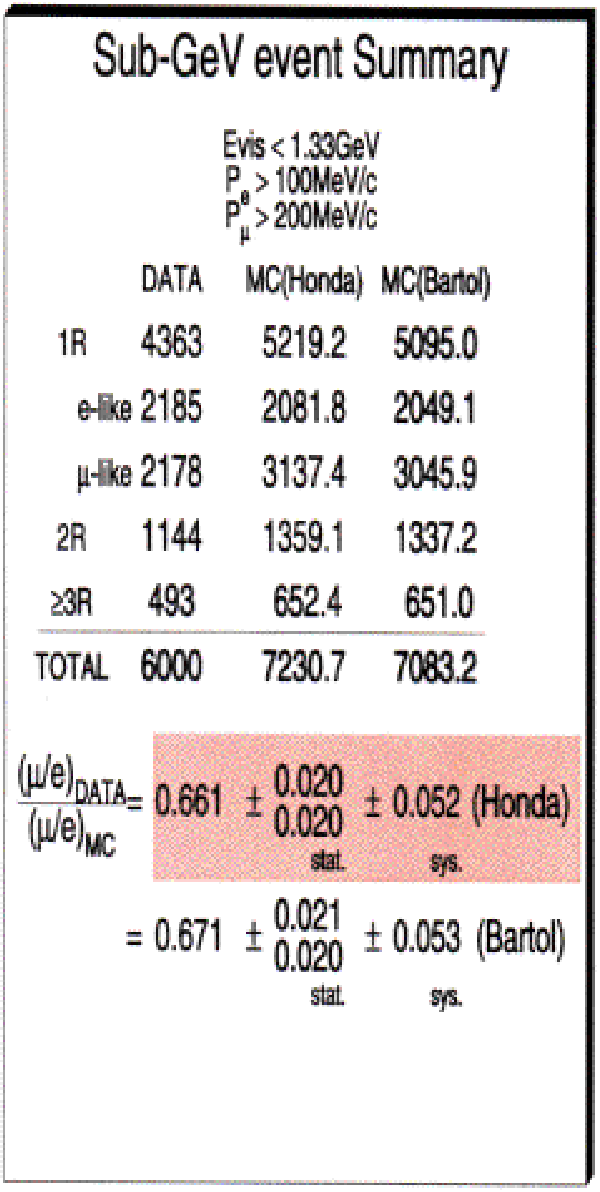


- Showering ring (e-like)
- Electron or photon (e.g. from π^0)

- Non-Showering ring (μ-like)
- Sometimes decay electron

Michael Smy, UC Irvine

Sub-GeV, Multi-GeV Event Summary



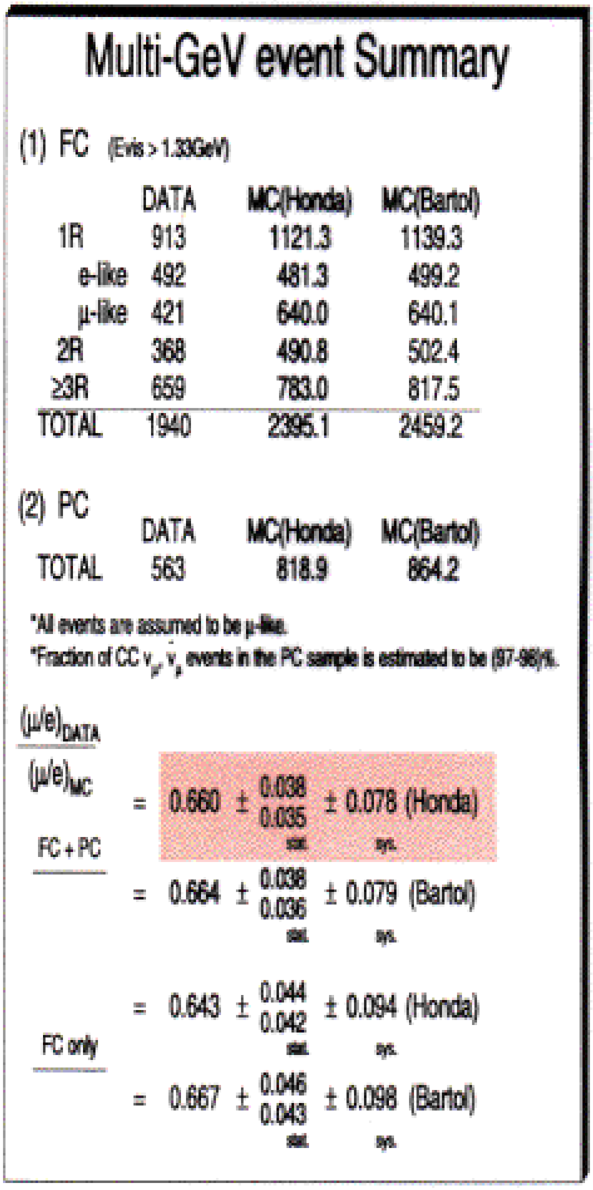
Sub-GeV event Summary

Evis < 1.33GeV
$P_e > 100\text{MeV/c}$
$P_\mu > 200\text{MeV/c}$

	DATA	MC(Honda)	MC(Bartol)
1R	4363	5219.2	5095.0
e-like	2185	2081.8	2049.1
μ-like	2178	3137.4	3045.9
2R	1144	1359.1	1337.2
≥3R	493	652.4	651.0
TOTAL	6000	7230.7	7083.2

$$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.661 \pm \underset{\text{stat.}}{\overset{0.020}{0.020}} \pm \underset{\text{sys.}}{0.052}\ (\text{Honda})$$

$$= 0.671 \pm \underset{\text{stat.}}{\overset{0.021}{0.020}} \pm \underset{\text{sys.}}{0.053}\ (\text{Bartol})$$



Multi-GeV event Summary

(1) FC (Evis > 1.33GeV)

	DATA	MC(Honda)	MC(Bartol)
1R	913	1121.3	1139.3
e-like	492	481.3	499.2
μ-like	421	640.0	640.1
2R	368	490.8	502.4
≥3R	659	783.0	817.5
TOTAL	1940	2395.1	2459.2

(2) PC

	DATA	MC(Honda)	MC(Bartol)
TOTAL	563	818.9	864.2

*All events are assumed to be μ-like.
*Fraction of CC ν_μ, $\bar{\nu}_\mu$ events in the PC sample is estimated to be (97-98)%.

$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}}$

FC + PC

$$= 0.660 \pm \underset{\text{stat.}}{\overset{0.038}{0.035}} \pm \underset{\text{sys.}}{0.078}\ (\text{Honda})$$

$$= 0.664 \pm \underset{\text{stat.}}{\overset{0.038}{0.036}} \pm \underset{\text{sys.}}{0.079}\ (\text{Bartol})$$

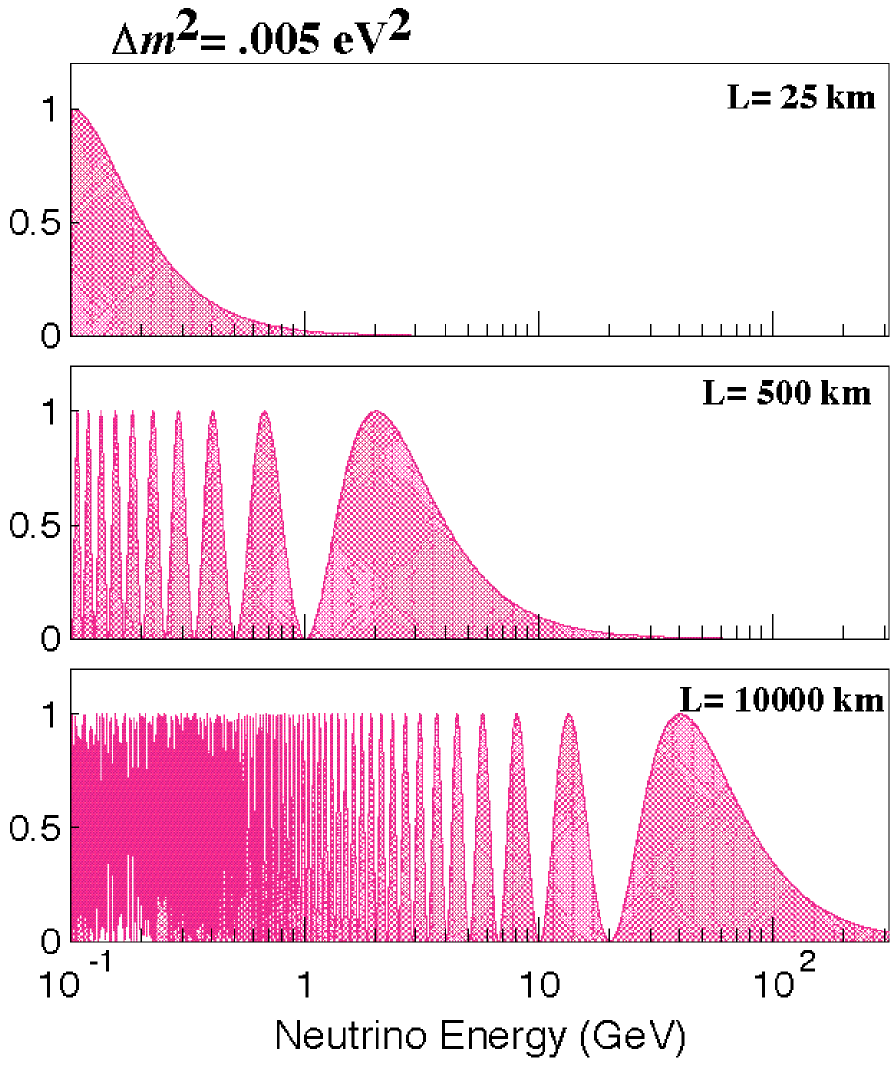
FC only

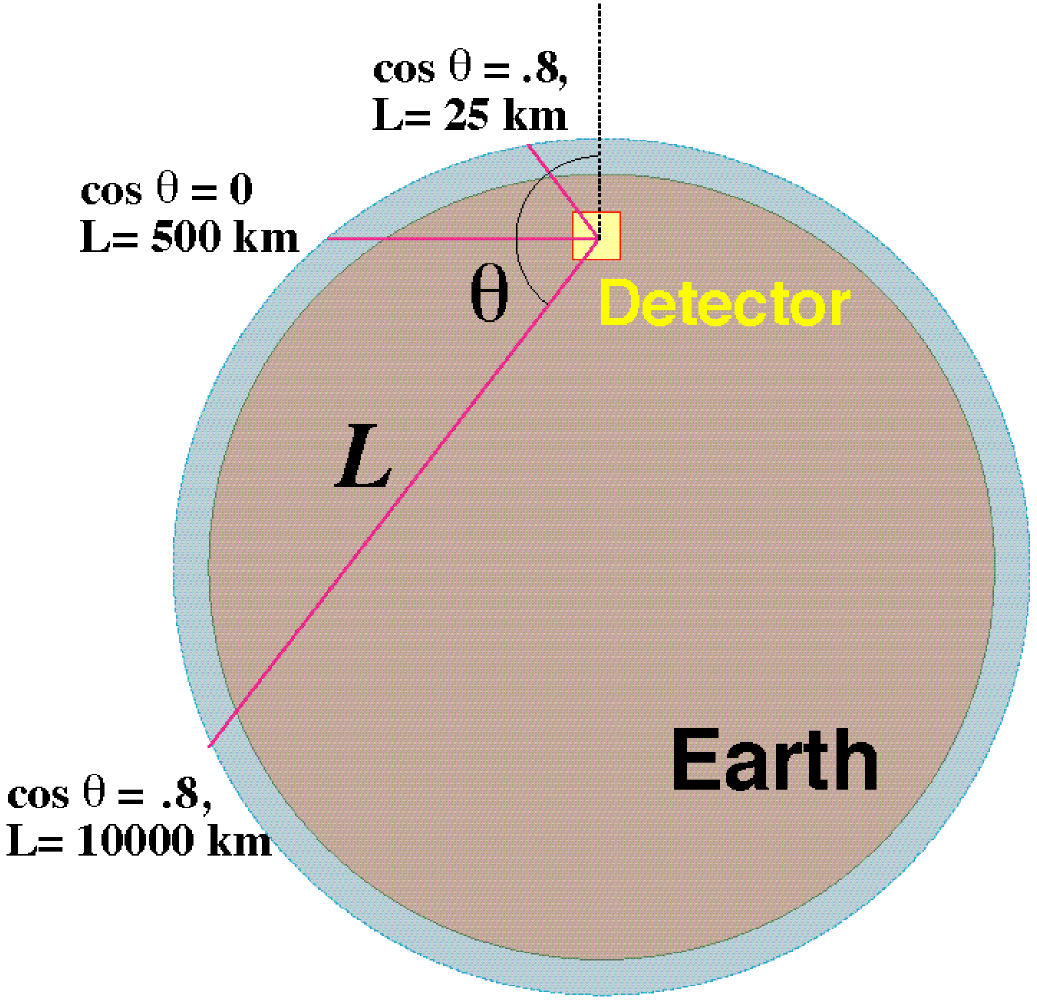
$$= 0.643 \pm \underset{\text{stat.}}{\overset{0.044}{0.042}} \pm \underset{\text{sys.}}{0.094}\ (\text{Honda})$$

$$= 0.667 \pm \underset{\text{stat.}}{\overset{0.046}{0.043}} \pm \underset{\text{sys.}}{0.098}\ (\text{Bartol})$$

K. Nakamura, NUFACT00, Monterey (USA), May 2000

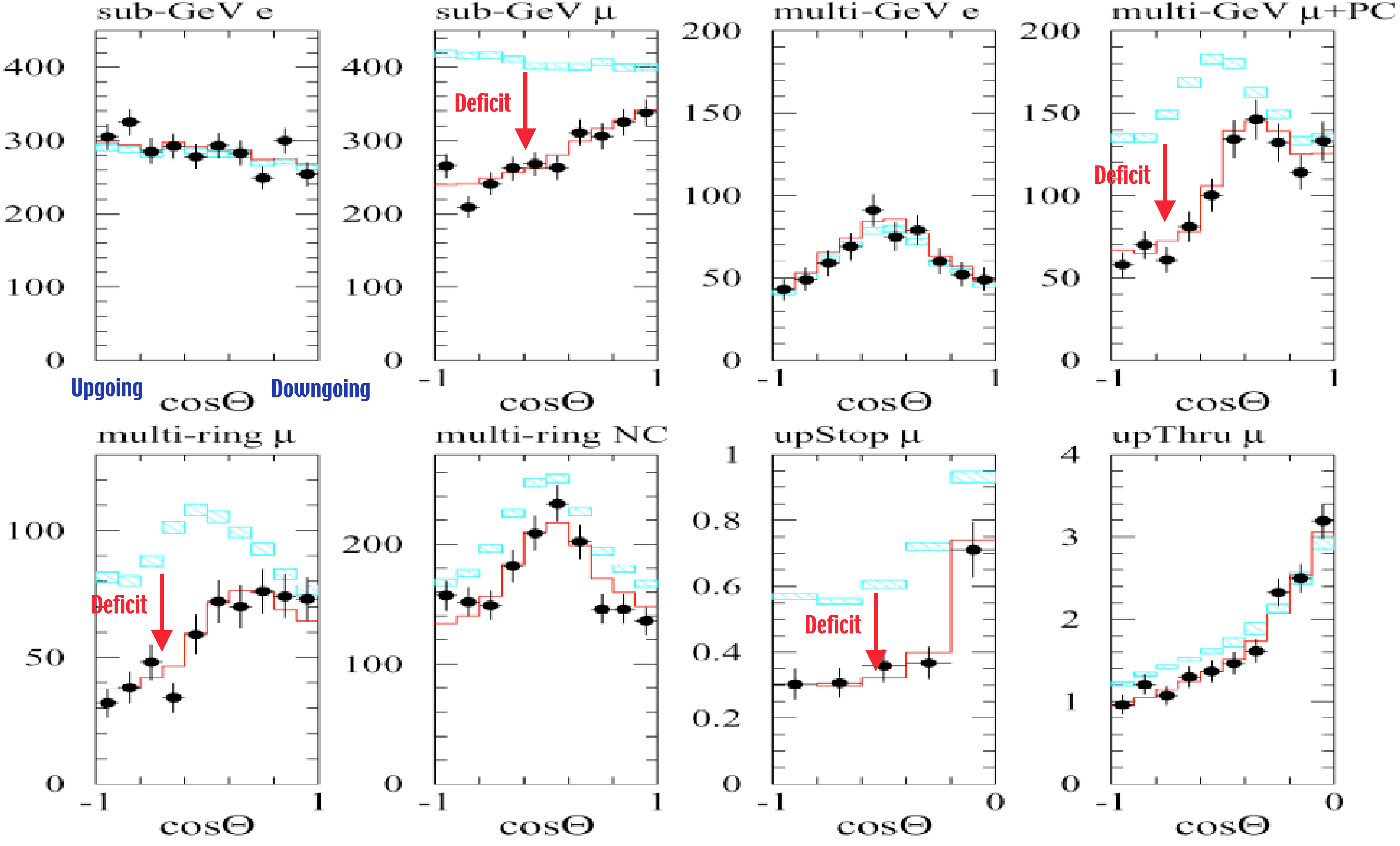
Zenith angle distribution





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

Data and Oscillation Best Fit ($\nu_\mu - \nu_\tau$)

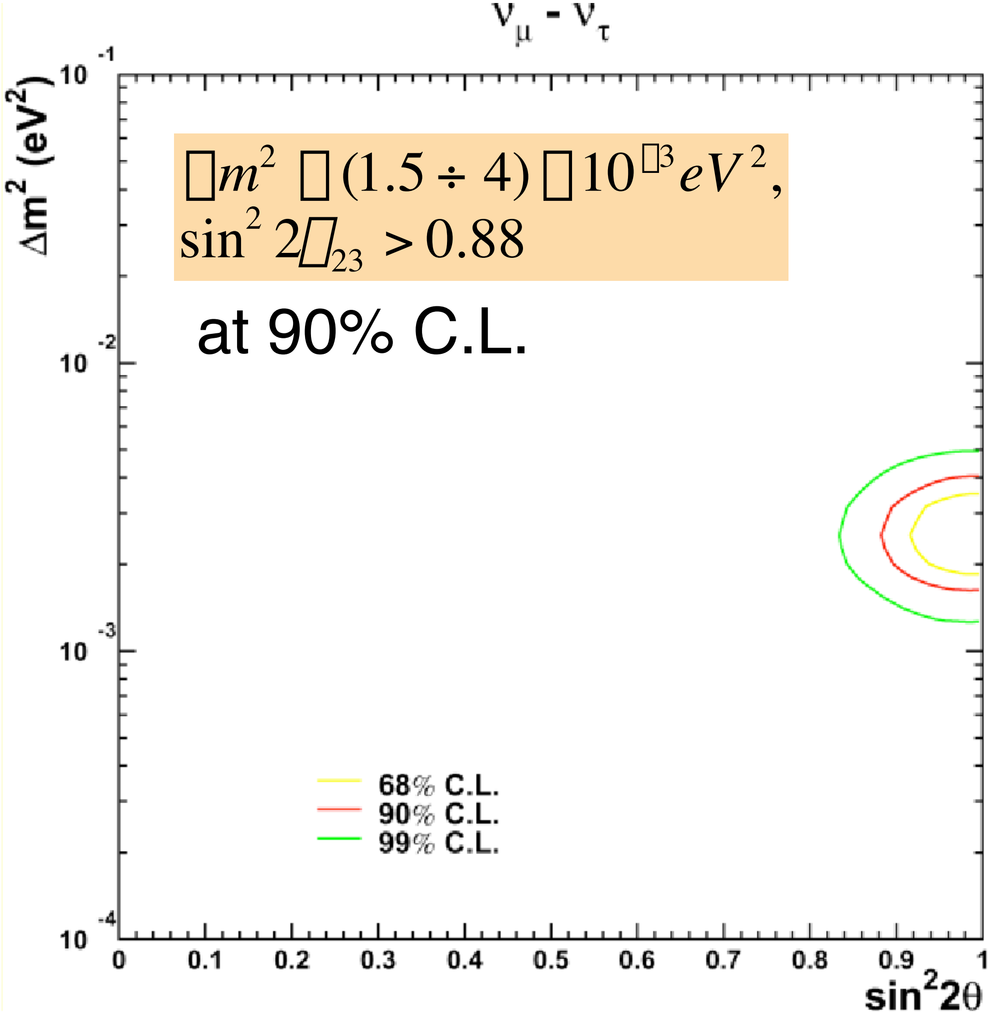


Parameters and mode determination

- Fit of muon disappearance data and no apparent electron appearance
- Uses FC,PC,up mu and multi-ring events
- Very good χ^2 (175.0/190)
- Consistent with maximal mixing θ_{23}=45°

Mode	Best fit	$\Delta\chi2$	σ
ν_μ-ν_τ	$\sin^2 2\theta=1.00$; $\Delta m^2=2.5\times10^{-3}eV^2$	0.0	0.0
ν_μ-ν_e	$\sin^2 2\theta=0.97$; $\Delta m^2=5.0\times10^{-3}eV^2$	79.3	8.9
ν_μ-ν_s	$\sin^2 2\theta=0.96$; $\Delta m^2=3.6\times10^{-3}eV^2$	19.0	4.4
LxE	$\sin^2 2\theta=0.90$; $\alpha=5.3\times10^{-4}$	67.1	8.2
ν_μ Decay	$\cos^2\theta=0.47$; $\alpha=3.0\times10^{-3}eV^2$	81.1	9.0
ν_μ Decay to ν_s	$\cos^2\theta=0.33$; $\alpha=1.1\times10^{-2}eV^2$	14.1	3.8

1290 days data taking



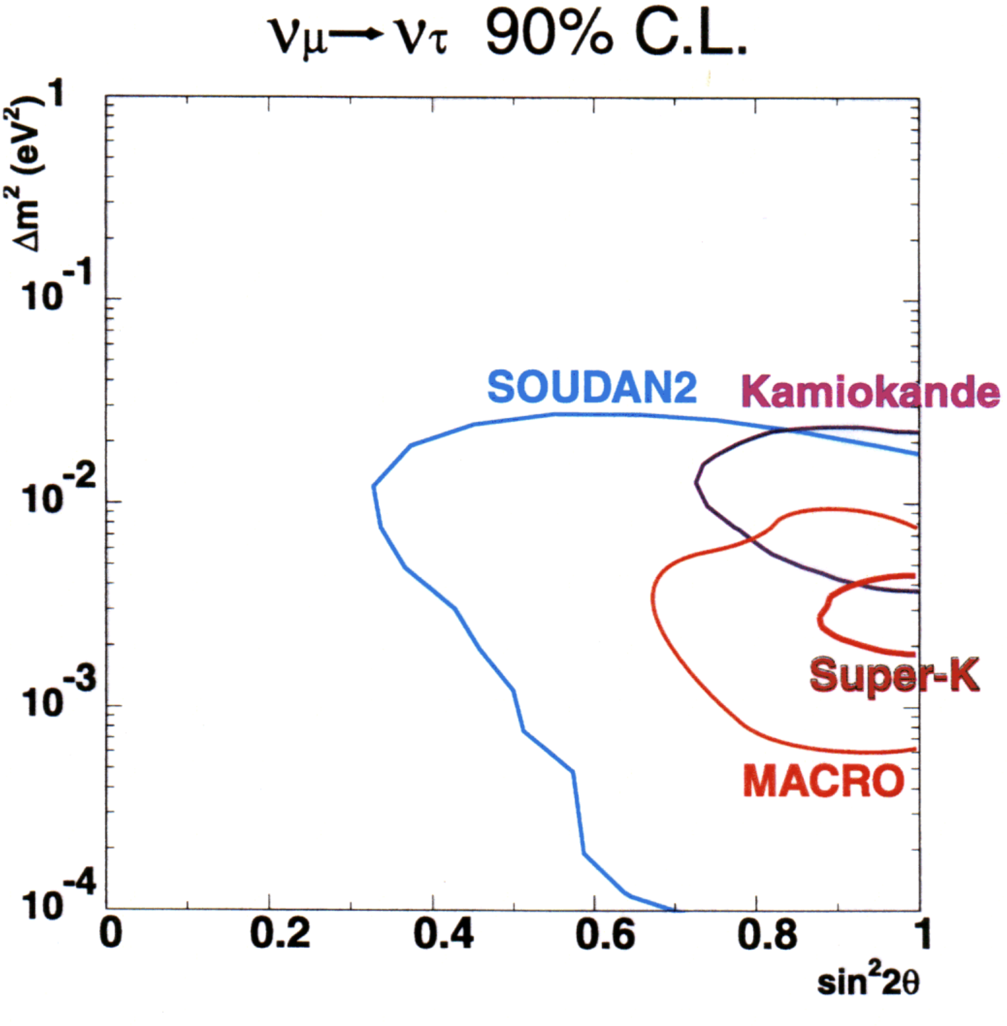
$$\Delta m^2 = (1.5 \div 4) \times 10^{-3} eV^2, \\ \sin^2 2\theta_{23} > 0.88$$

at 90% C.L.

→ $\nu_\mu \to \nu_\tau$ indirectly favored mode

Comparison of allowed regions

Allowed regions

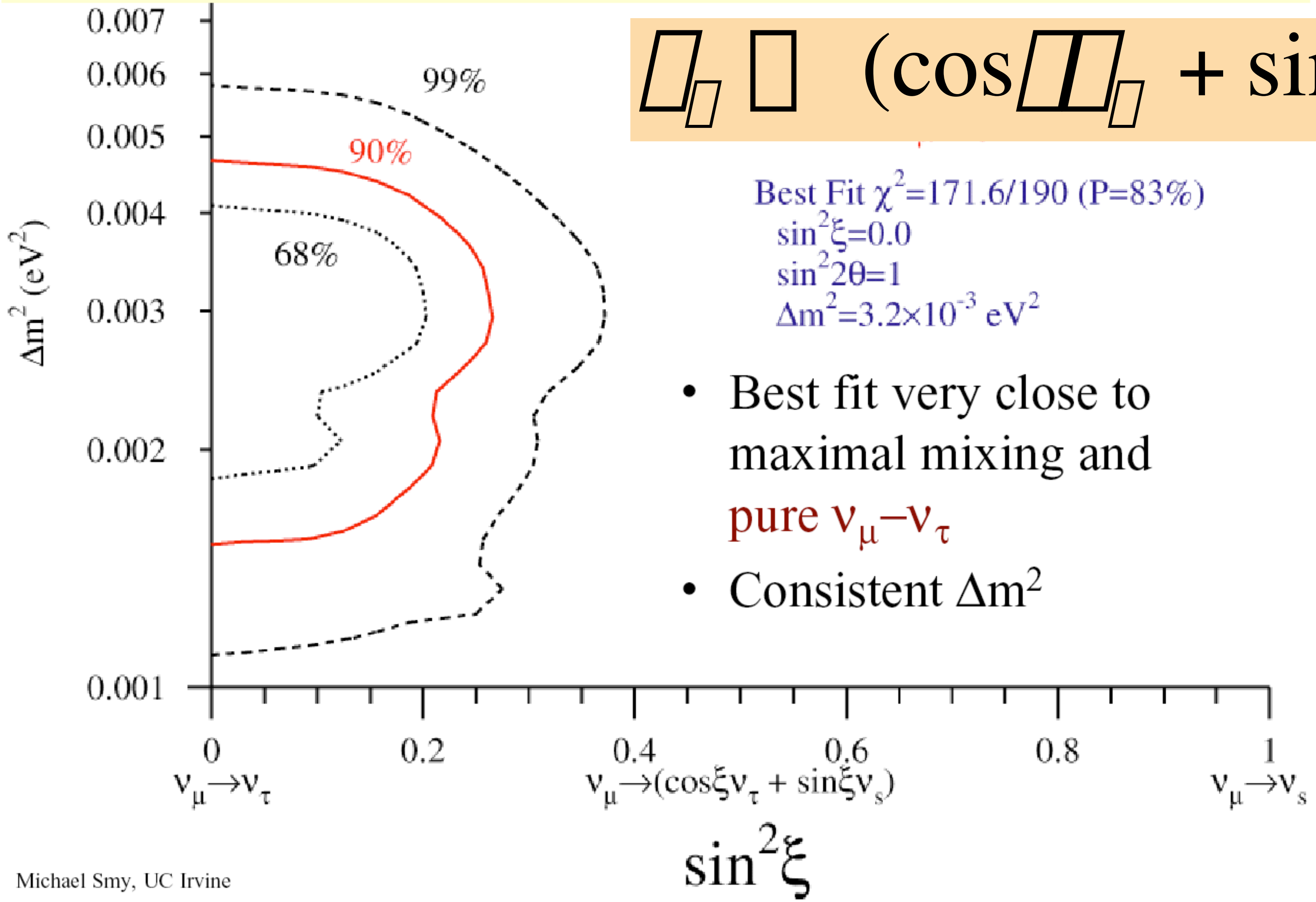


Not so consistent with Kamiokande data (!), but OK with other lower statistics experiments Soudan2 & MACRO

Oscillation into something non-interacting?

Limit on Sterile Content

$$\nu_\mu \to (\cos\xi\,\nu_\tau + \sin\xi\,\nu_s)$$



Best Fit χ^2=171.6/190 (P=83%)
$\sin^2\xi$=0.0
$\sin^2 2\theta$=1
Δm^2=3.2×10^{-3} eV^2

- Best fit very close to maximal mixing and pure ν_μ–ν_τ
- Consistent Δm^2

Michael Smy, UC Irvine

$\sin^2\xi$ controlled by (1) **size of matter effects** (2) **NC disappearance**

Accident on Nov. 12

Broken PMTs

Inner : ～60%

Outer: ～50%

Most possible cause

One PMT broken

and chain reaction occurred

by shock waves.

http://www-sk.icrr.u-tokyo.ac.jp/doc/news/appeal.html

Appeal from Director

Dear colleague,

As a director of the Kamioka Observatory, which owns and is responsible to operate and maintain the Super-Kamiokande detector, it is really sad that I have to announce the severe accident that occurred on November 12 and damaged the significant part of the detector. We would like to express our deep regret to Japanese, US and Korean people who have generously supported the Super-Kamiokande experiment. The cause and how to deal with the loss in future will be discussed by newly founded committees. However, even before discussing with my colleagues of the Super-K and K2K collaborations, I have decided to express my intention on behalf of the staff of the Kamioka Observatory.

We will rebuild the detector. There is no question. The strategy may be the following two steps, which will be proposed and discussed among my colleagues.

1. Quick restart of the K2K experiment.

(1) **We will clear the safety measures which may be suggested by the committees, (2) reduce the number density of the photomultiplier tubes by about a half, (3) use the existing resources, (4) resume the K2K experiment as soon as possible; the goal may be within one year.**

2. Preparation for the JHF-Kamioka experiment.

(1) **Restore the full Super-Kamiokande detector armed with the state-of-the-art techniques. (2) The detector will be ready by the time of the commissioning of the JHF machine.**

Needless to say, we will be able to study atmospheric neutrinos and search for proton decay with the step-1 detector. We will be able to maintain our watch for supernova with a somewhat higher-energy threshold.

To achieve our objective is formidable but we are determined to do so. We certainly need your encouragement, advice and help. I should appreciate it very much if you could support our effort as you have kindly done so before.

Best regards,
Yoji Totsuka
director, Kamioka Observatory
On behalf of the Kamioka Observatory staff

2) Confirming the atmospheric neutrinos effect

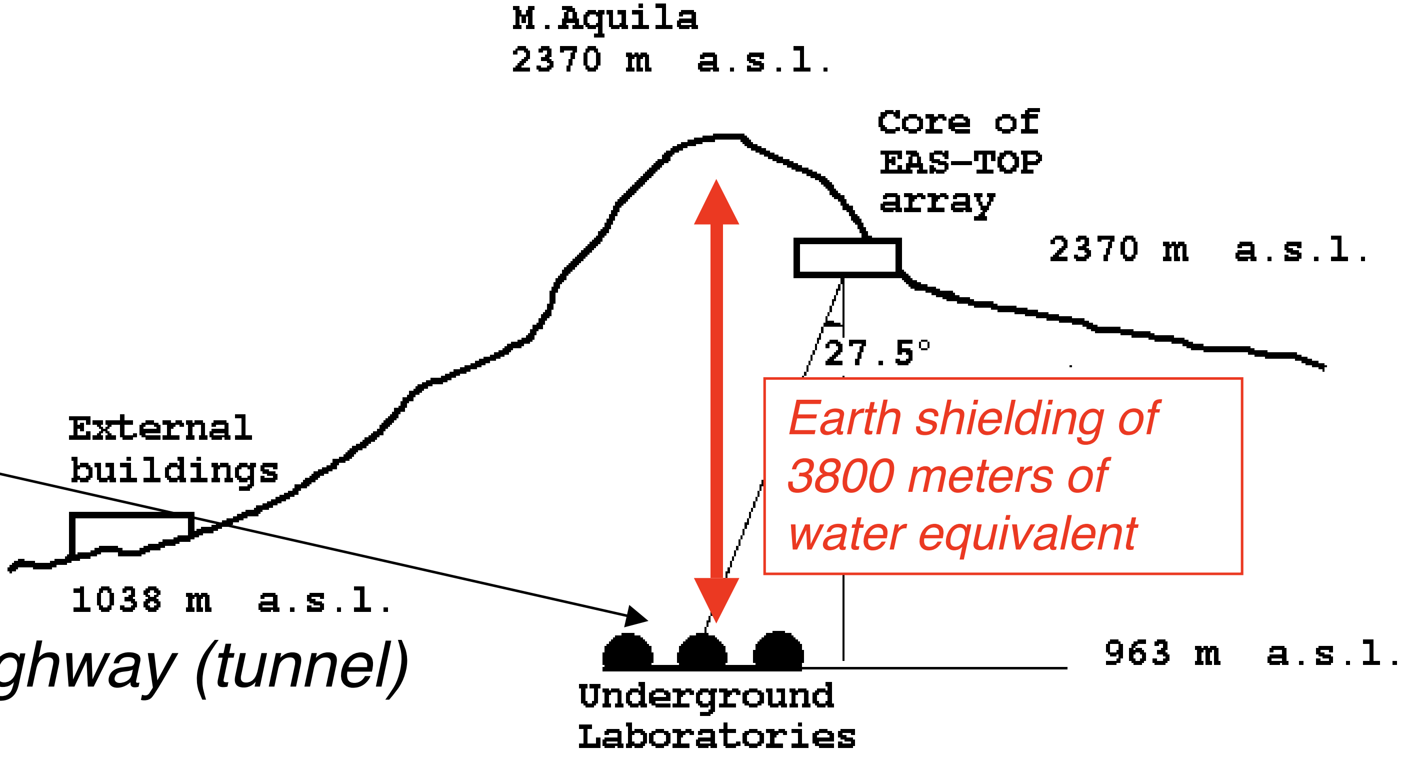
$$□_{□} □ □_X$$

with

an independent, second-generation technique, offering an improved detection of atmospheric events

Gran Sasso Underground Laboratory (LNGS)

http://www.lngs.infn.it/



Earth shielding of 3800 meters of water equivalent

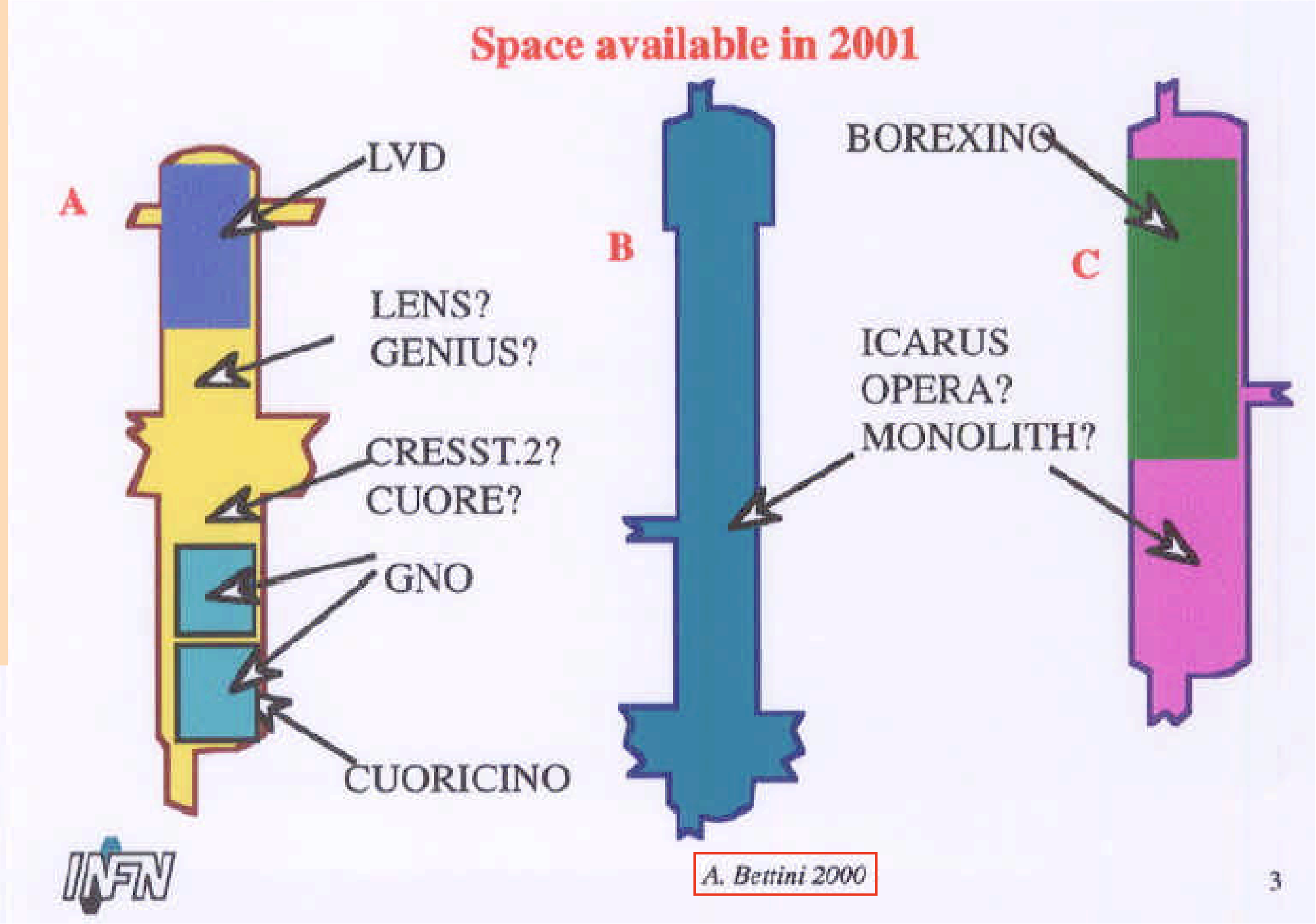
Three experimental halls, each 100m long, 18m height, 18m wide

- *Access through highway (tunnel)*

LNGS physics program

1. Solar neutrinos
2. Atmospheric neutrinos
3. Neutrinos from star collapses (Supernova)
4. Majorana Mass
5. Dark Matter search
6. Nuclear cross section measurements

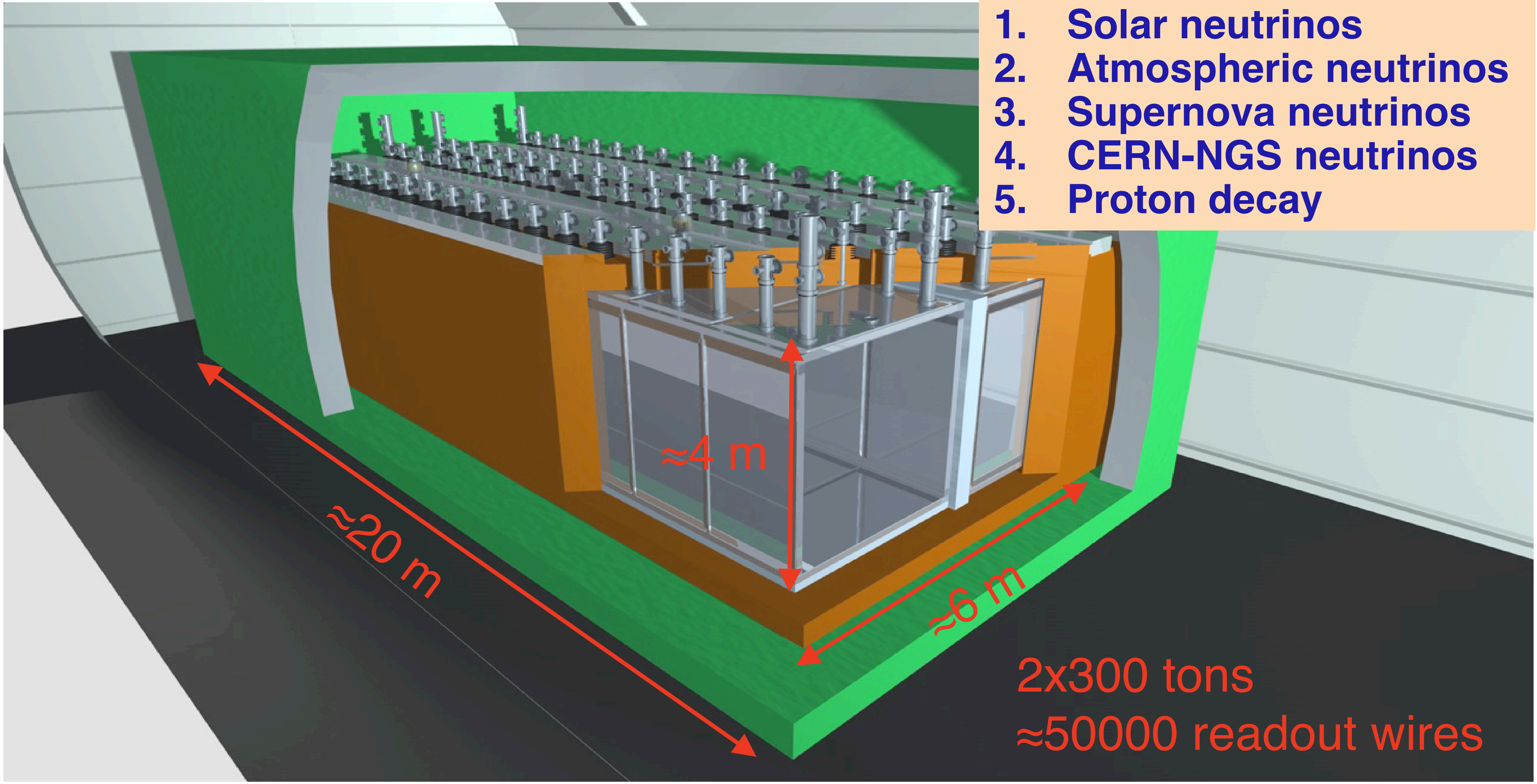
- *1400 m rock overburden*
- *Cosmic ray flux attenuation ≈ 10^{-6}*



A. Bettini 2000

ICARUS detector

Novel liquid Argon imaging TPC technique: Initial mass 0.6 kton

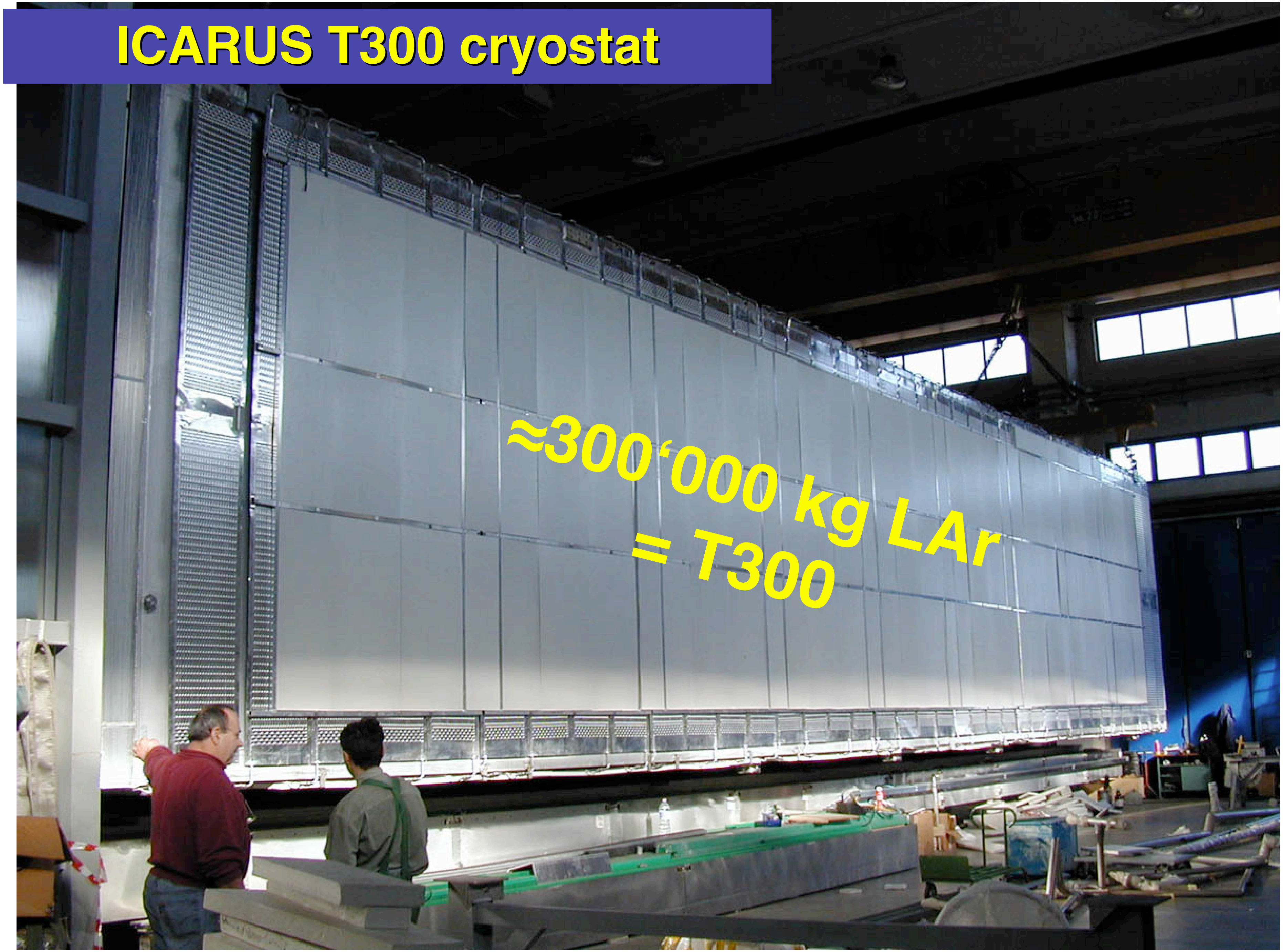


1. **Solar neutrinos**
2. **Atmospheric neutrinos**
3. **Supernova neutrinos**
4. **CERN-NGS neutrinos**
5. **Proton decay**

2x300 tons
≈50000 readout wires

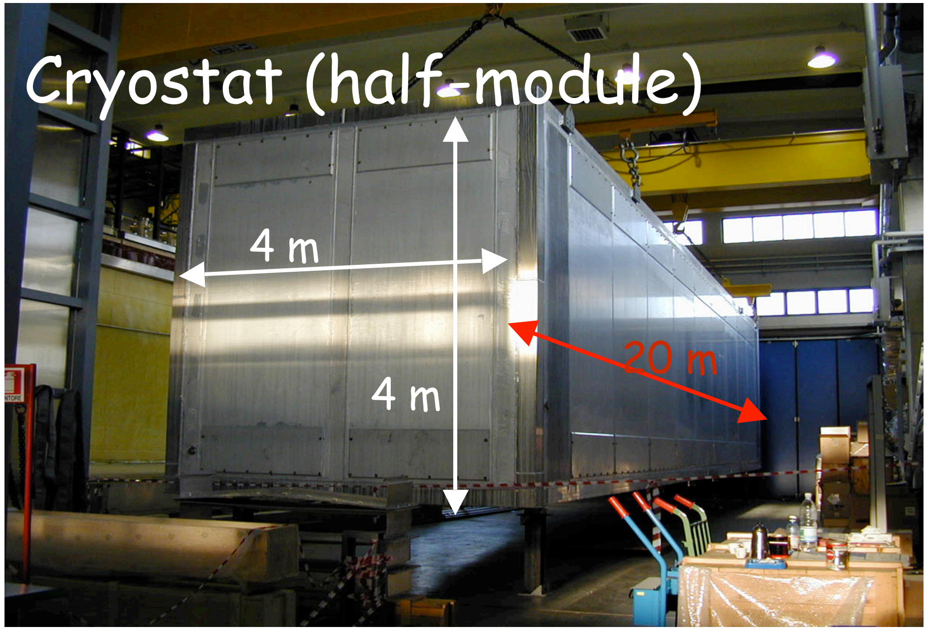
Planned start data taking in 2003

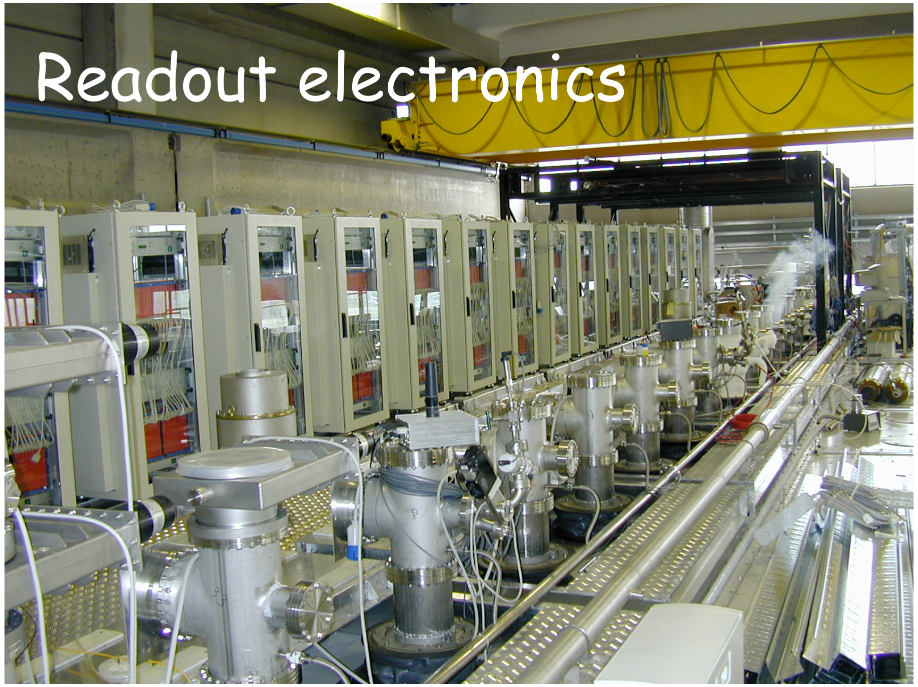
ICARUS T300 cryostat



≈300‘000 kg LAr
= T300

ICARUS T300 prototype





ICARUS T3000 (proposed)

T3000 Detector in Hall B of LNGS (cloning of T600)

First Unit T600 +
Auxiliary
Equipment

T1200 Unit
(two T600
superimposed)

T1200 Unit
(two T600
superimposed)

Improved statistics for:

≈ 70 Metres

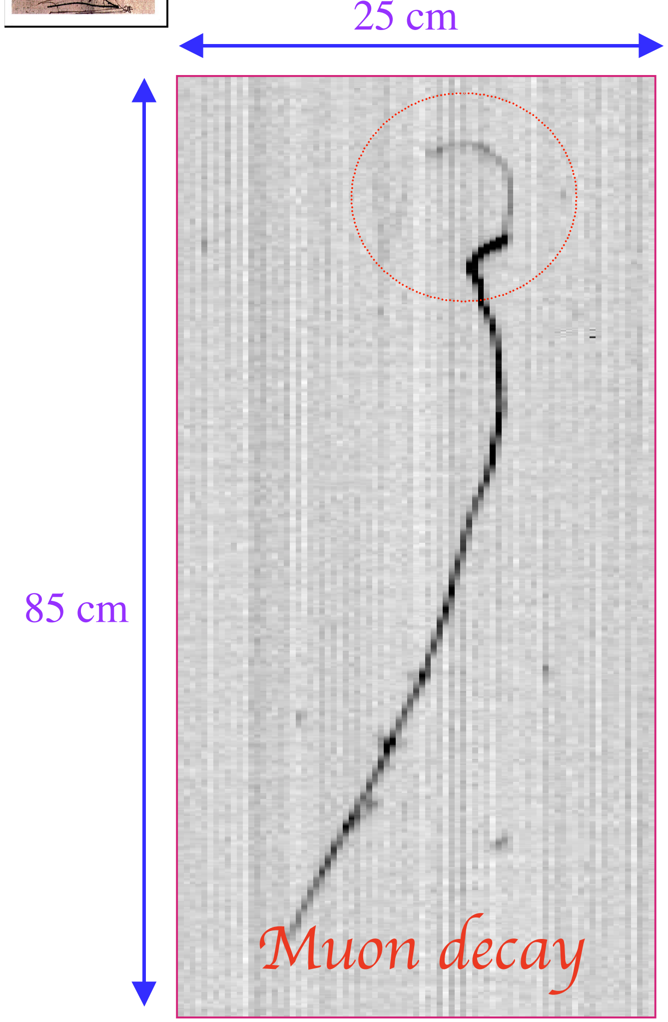
Future extension
to additional modules

1. **Solar neutrinos**
2. **Atmospheric neutrinos**
3. **Supernova neutrinos**
4. **CERN-NGS neutrinos**
5. **Proton decay**

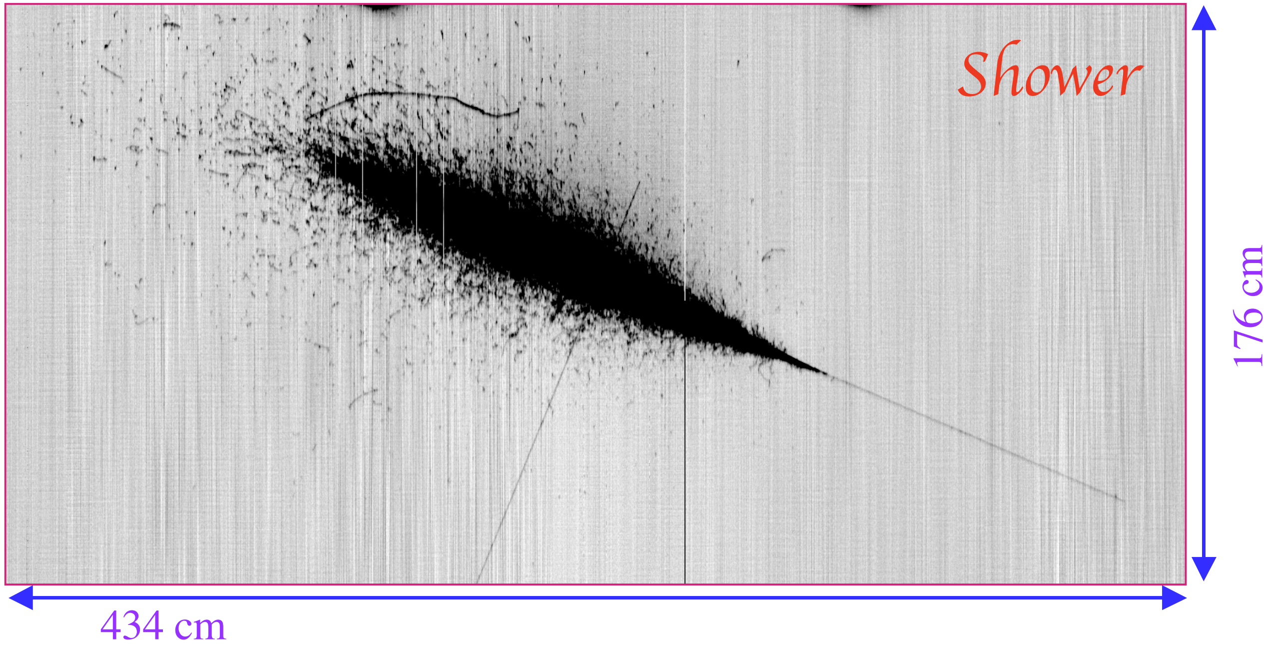
T600: installed in LNGS early 2003

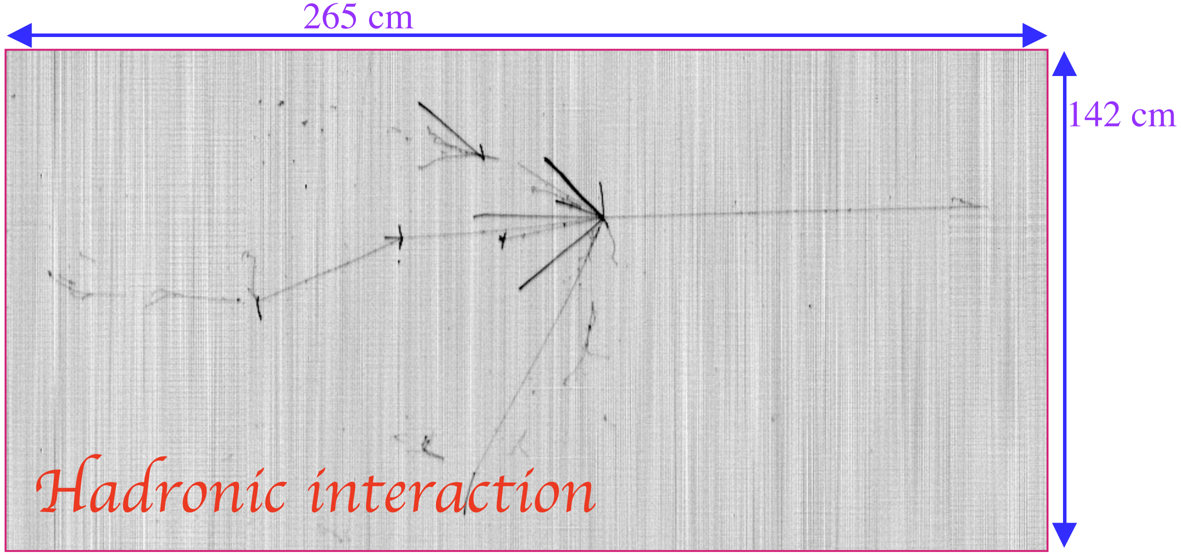
T3000: operational by summer 2006

Electronic bubble chamber (I)



Run 960, Event 4 Collection Left

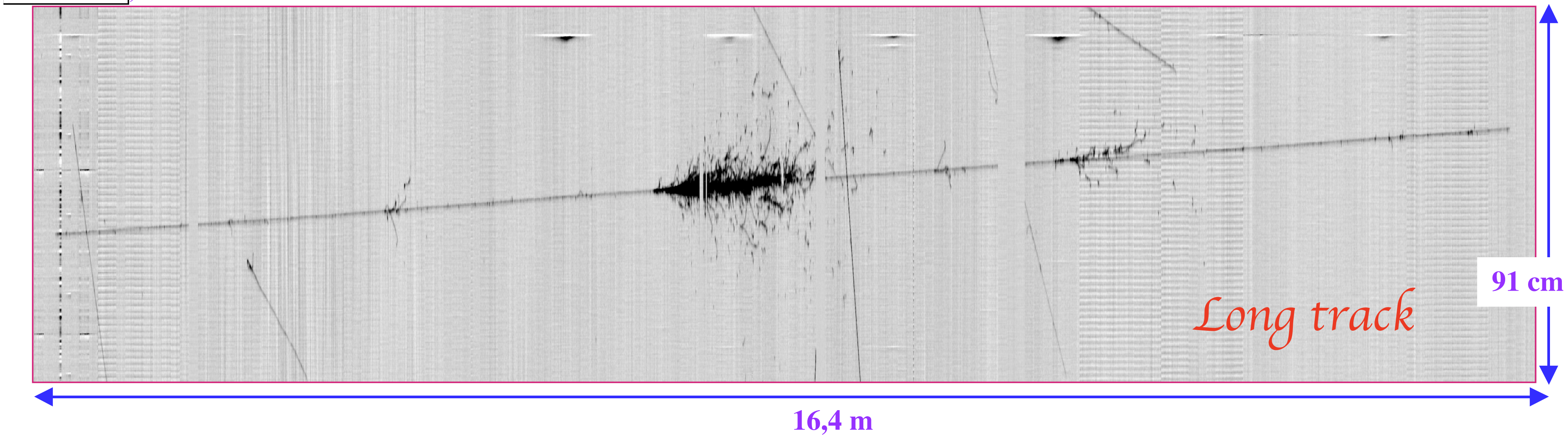




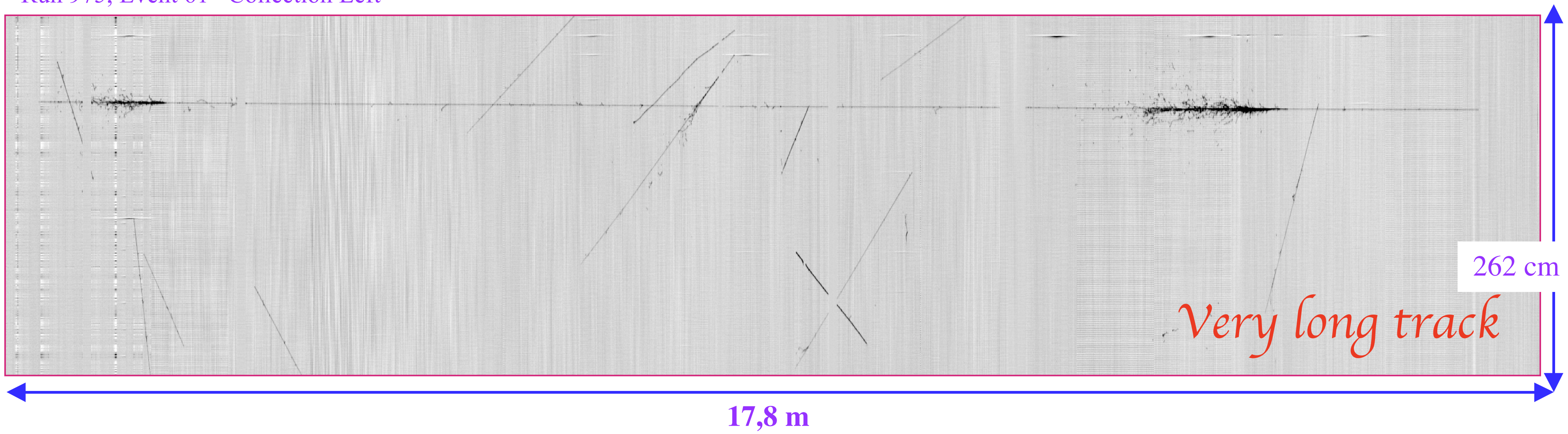
Run 308, Event 160 Collection Left

Electronic bubble chamber (II)

, Event 93 Collection Left

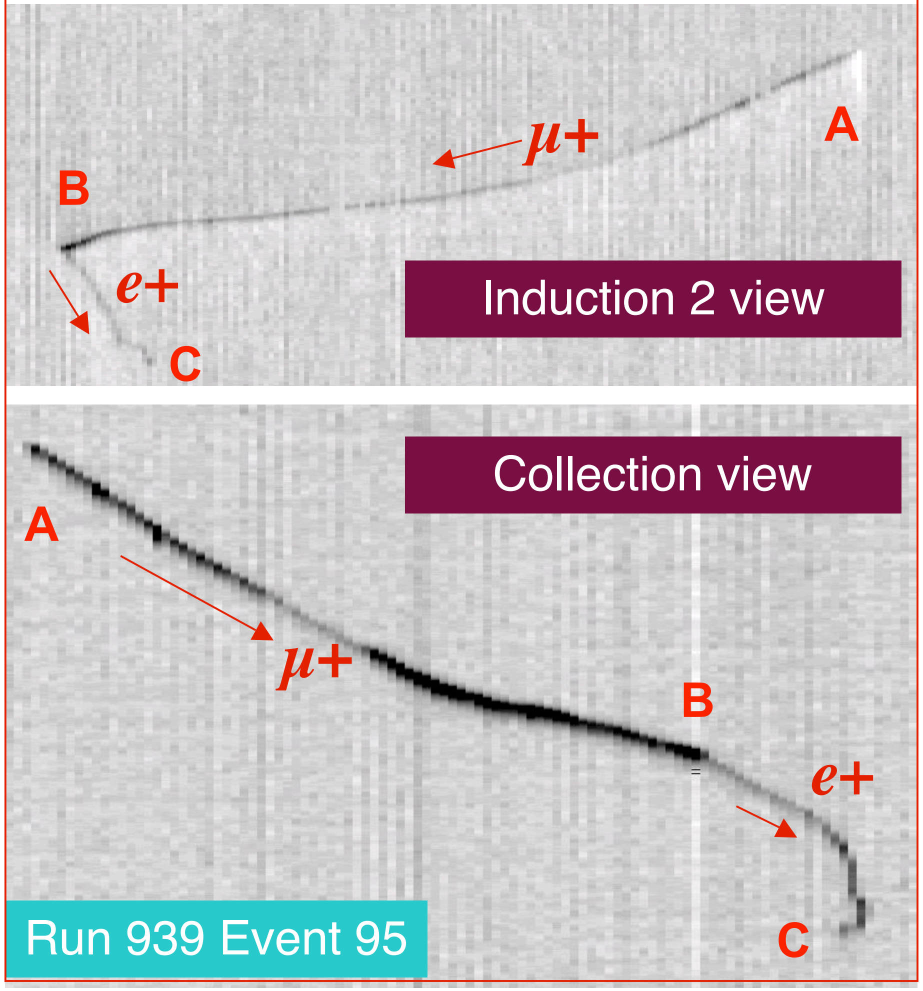


Run 975, Event 61 Collection Left

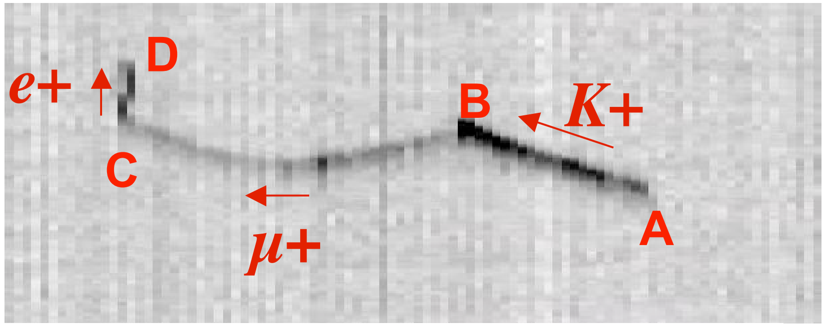


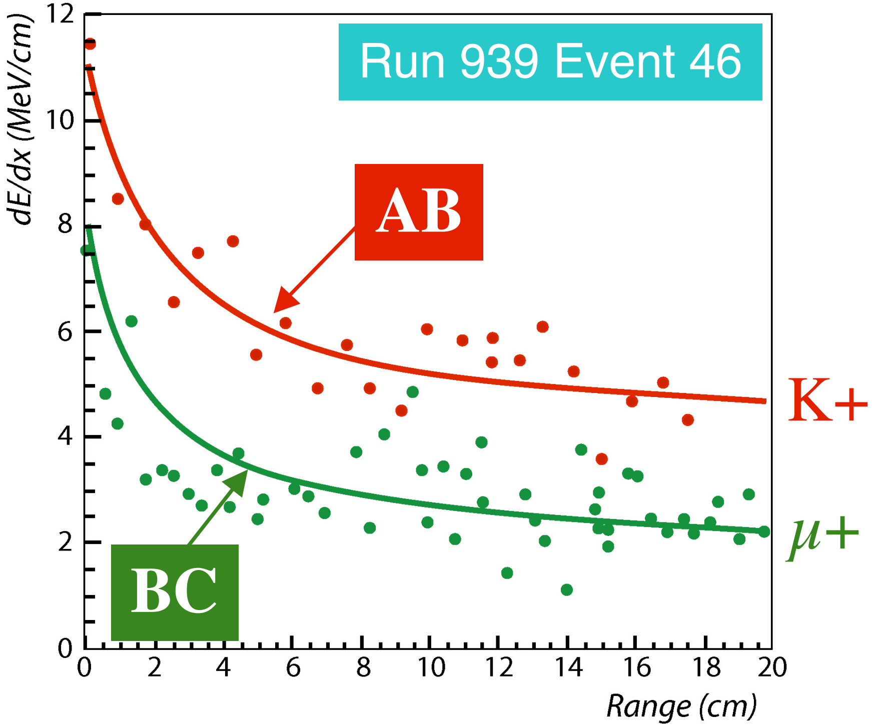
Particle identification

$\mu^+[AB] \to e^+[BC]$



$K^+[AB] \to \mu^+[BC] \to e^+[CD]$



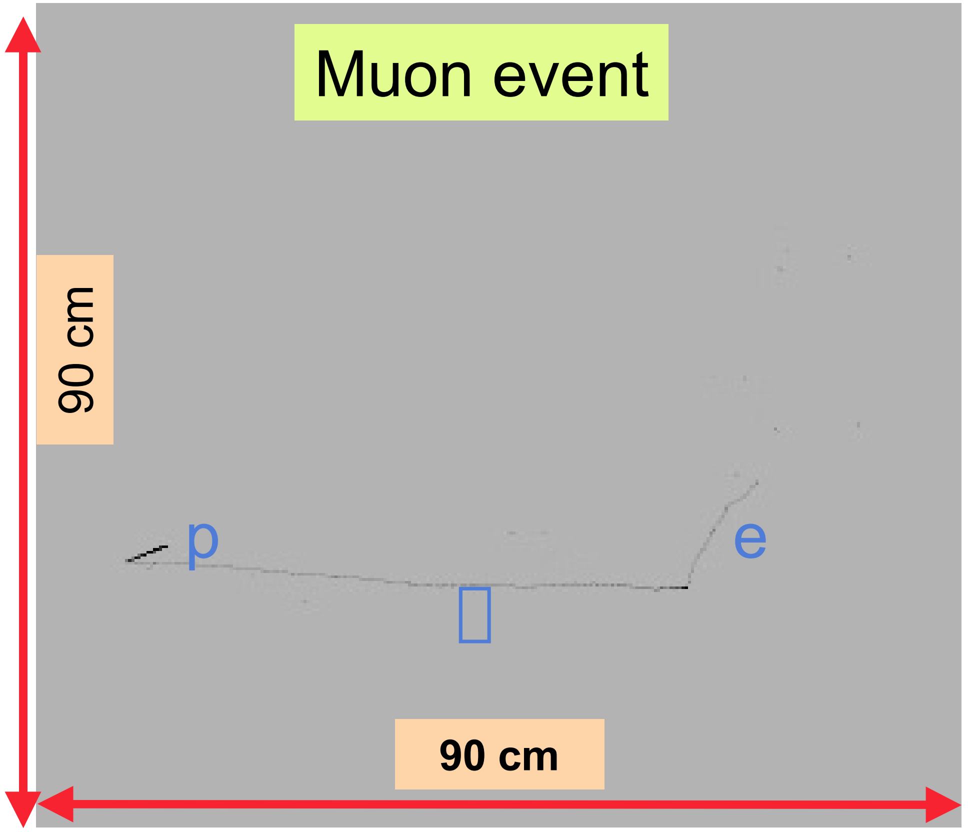


Atmospheric neutrinos in ICARUS

- The atmospheric neutrino analysis will be characterized by
  - Unbiased, systematic-free observation of atmospheric events
  - Precise prediction of neutrino flux (MC developed within the Collab.)

	2 kton×year			
	Solar minimum		Solar maximum	
	No osc.	$\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2	No osc.	$\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2
Muon-like	266 ± 16	182 ± 13	249 ± 16	171 ± 13
$\mu + p$	59 ± 8	39 ± 6	71 ± 8	35 ± 6
$P_{lepton} < 400$ MeV	114 ± 11	69 ± 8	98 ± 10	63 ± 8
$\mu + p$	32 ± 2	20 ± 4	28 ± 5	18 ± 4
Electron-like	150 ± 12	150 ± 12	138 ± 12	138 ± 12
$e + p$	35 ± 6	35 ± 6	40 ± 6	40 ± 6
$P_{lepton} < 400$ MeV	74 ± 9	74 ± 9	66 ± 8	66 ± 8
$e + p$	20 ± 4	20 ± 4	18 ± 4	18 ± 4
NC-like	192 ± 14	192 ± 14	175 ± 13	175 ± 13
TOTAL	608 ± 25	524 ± 23	562 ± 24	484 ± 22

Simulated atmospheric events in ICARUS

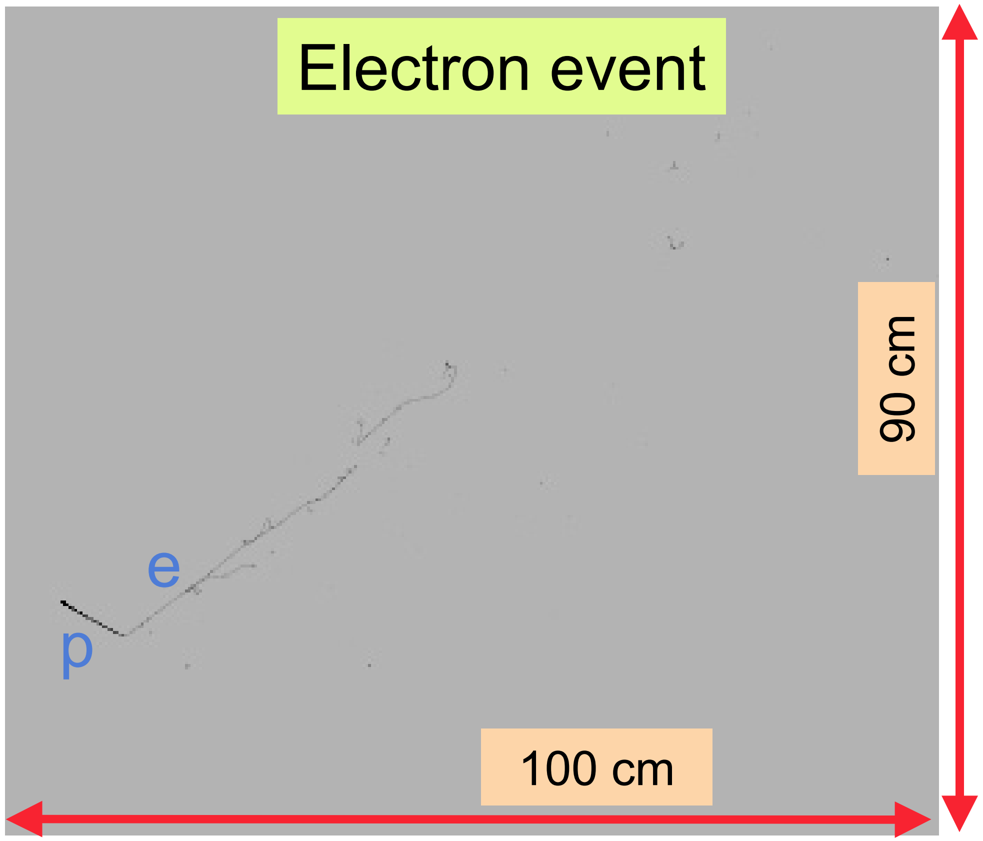


ν_μ quasi-elastic interaction

E_ν = 370 MeV

P_μ = 250 MeV

T_p = 90 MeV



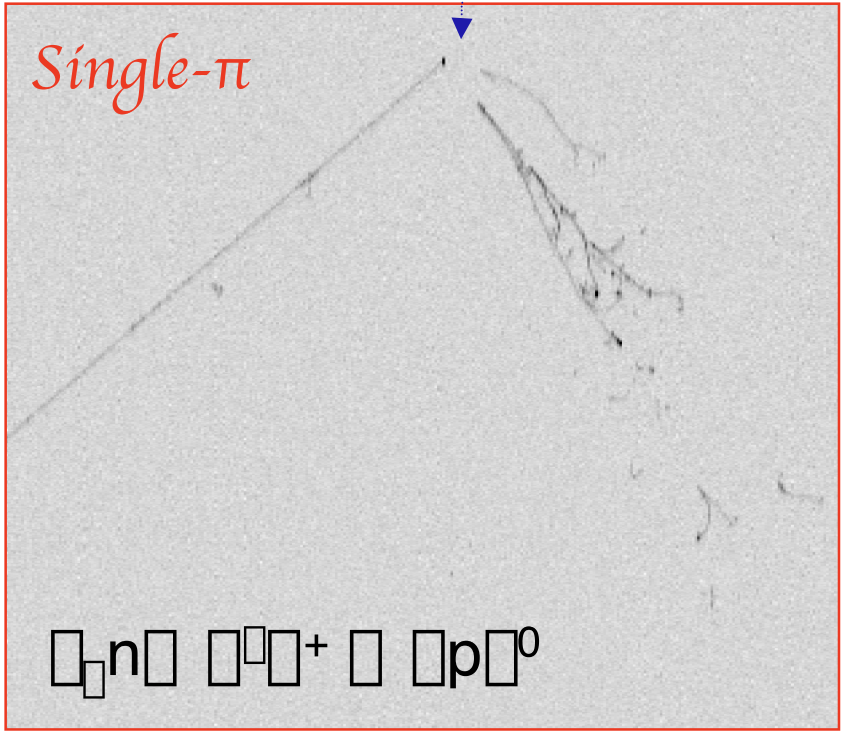
ν_e quasi-elastic interaction

E_ν = 450 MeV

P_e = 200 MeV

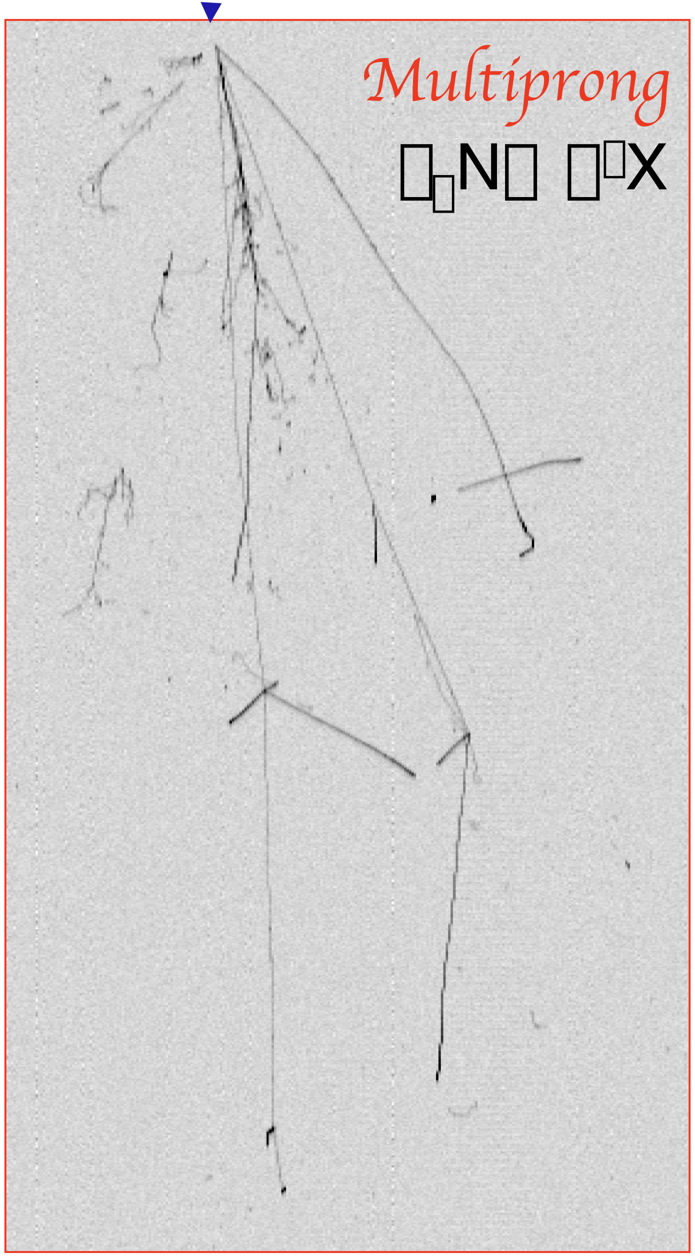
T_p = 240 MeV

Simulated atmospheric events in ICARUS



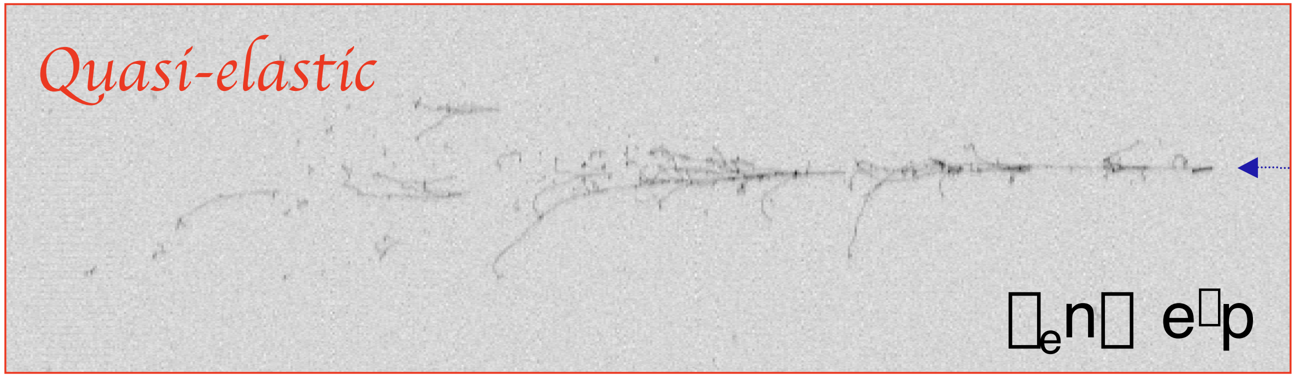
Single-π

□$_□$n□ □$^□$□$^+$ □ □p□^{0}



Multiprong

□$_□$N□ □$^□$X



Quasi-elastic

□$_e$n□ e$^□$p

Rates for upward/downward events

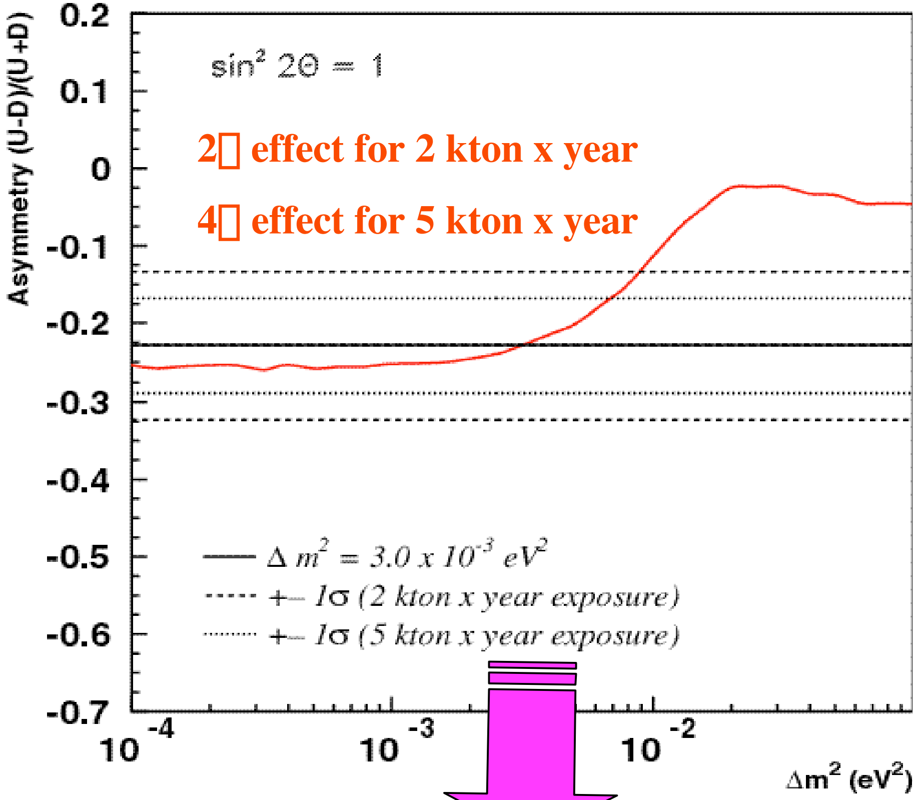
For a 2 kton x year exposure,

significant deficit of upward-going muon-like events

	2 kton×year				
		Δm^2_{23} (eV^2)			
	No osci	5×10^{-4}	1×10^{-3}	3.5×10^{-3}	5×10^{-3}
Muon-like	270 ± 16	206 ± 14	198 ± 14	188 ± 14	182 ± 13
Downward	102 ± 10	102 ± 10	102 ± 10	98 ± 10	95 ± 10
Upward	94 ± 10	46 ± 7	46 ± 7	47 ± 7	49 ± 7
Electron-like	152 ± 12	152 ± 12	152 ± 12	152 ± 12	152 ± 12
Downward	56 ± 7	56 ± 7	56 ± 7	56 ± 7	56 ± 7
Upward	48 ± 7	48 ± 7	48 ± 7	48 ± 7	48 ± 7

Atmospheric up-down asymmetry

All particles



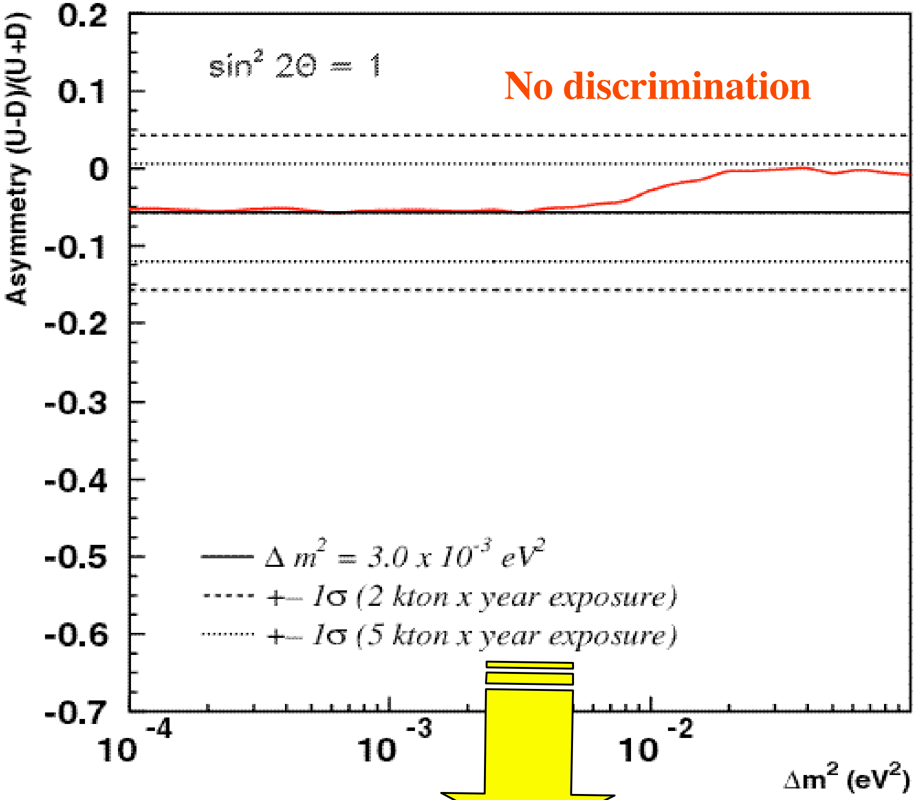
2σ effect for 2 kton x year

4σ effect for 5 kton x year

$$\frac{U-D}{U+D} = -0.228 \pm 0.100\ (2\,kton\ x\ year)$$

$$\frac{U-D}{U+D} = -0.228 \pm 0.060\ (5\,kton\ x\ year)$$

Lepton only



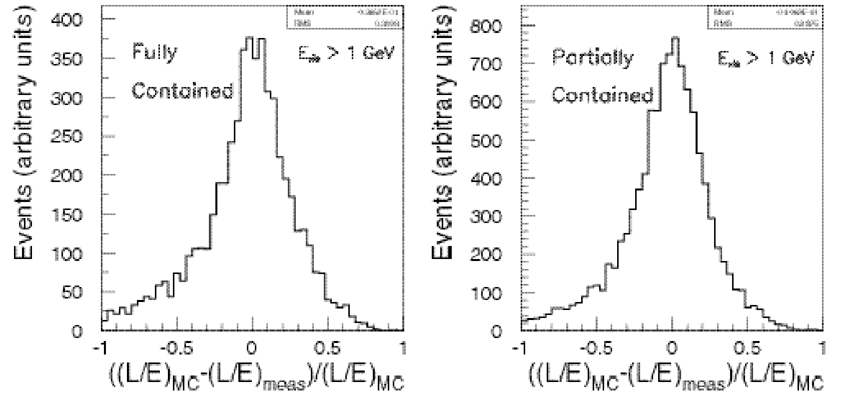
No discrimination

$$\frac{U-D}{U+D} = -0.057 \pm 0.100\ (2\,kton\ x\ year)$$

$$\frac{U-D}{U+D} = -0.057 \pm 0.060\ (5\,kton\ x\ year)$$

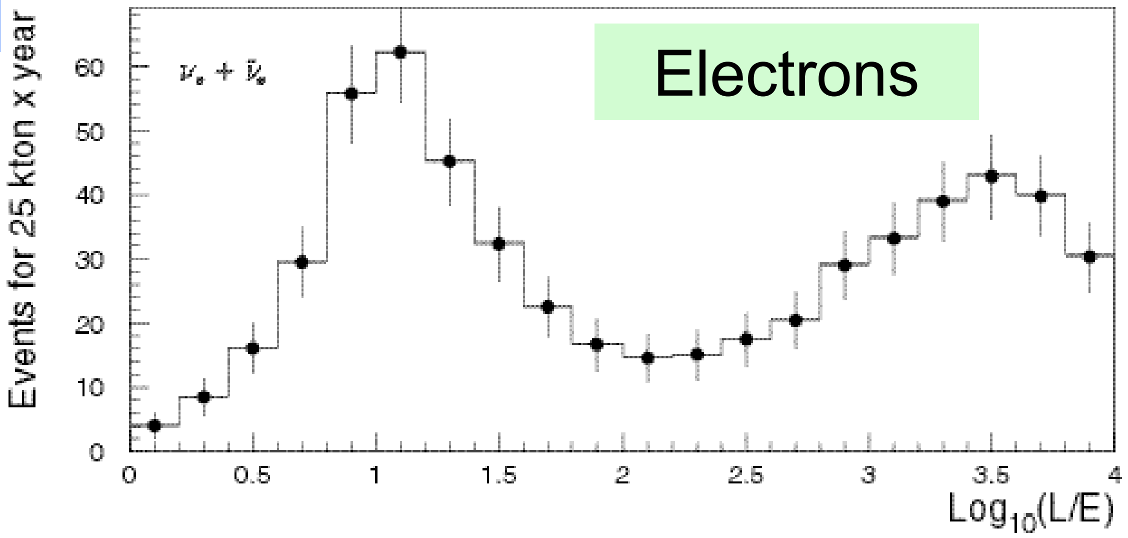
Reconstructed L/E distribution

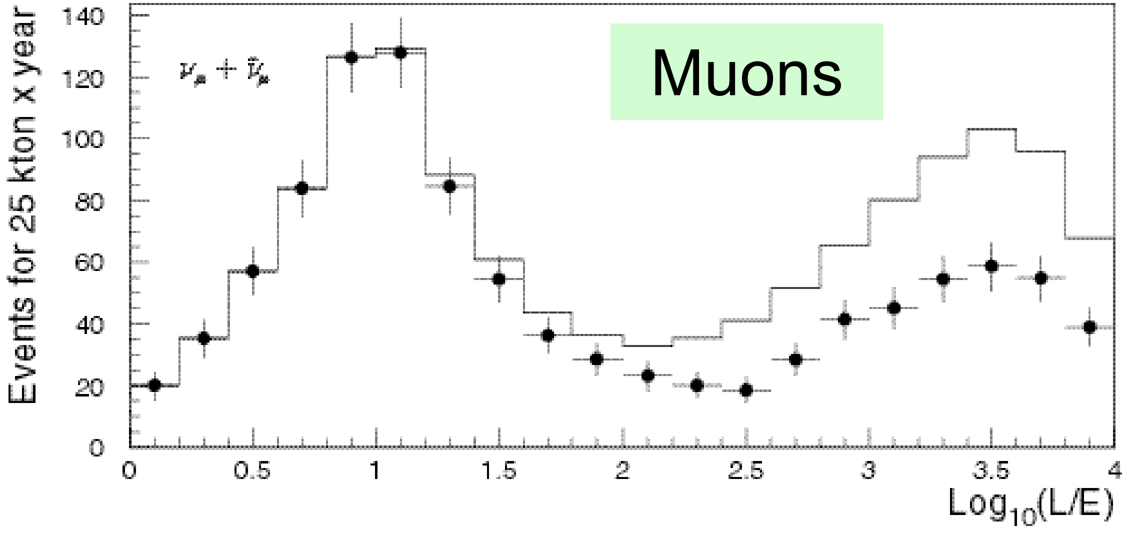
$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(1.27\,\Delta m^2 \frac{L}{E}\right)$$



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

25 kt year





- 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***

2) Independent test of muon neutrino disappearance

$$\nu_\mu \rightarrow \nu_x$$

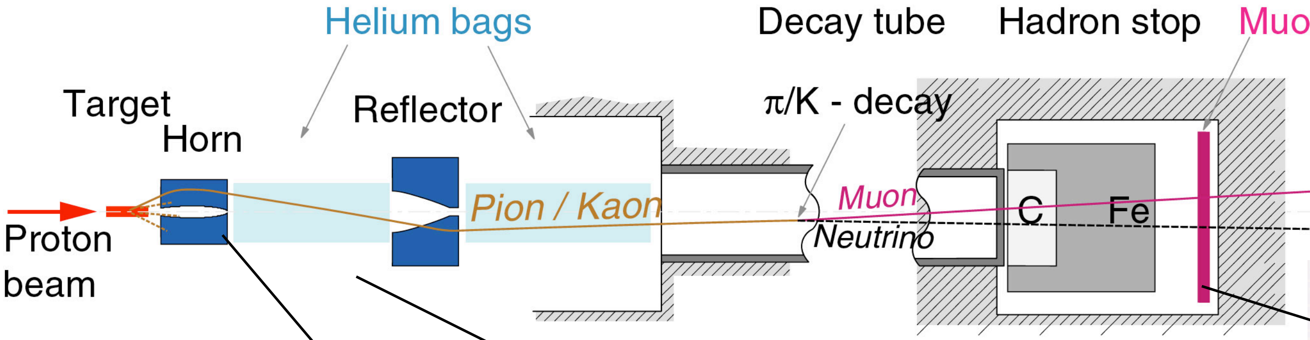
with

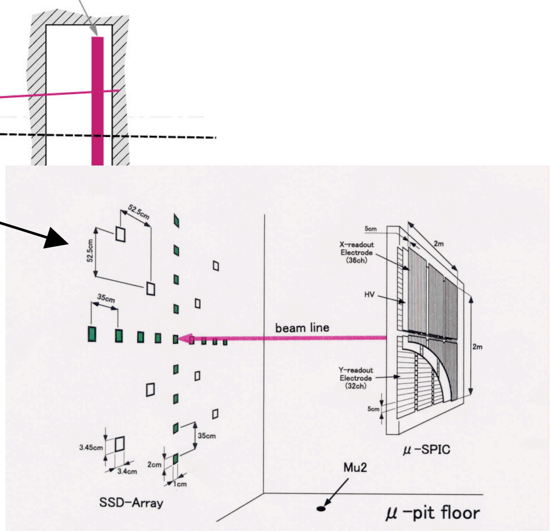
$$\Delta m^2 \approx (1 \div 4) \times 10^{-3}\, eV^2 \qquad \sin^2 2\theta \approx 1$$

Accelerator neutrinos

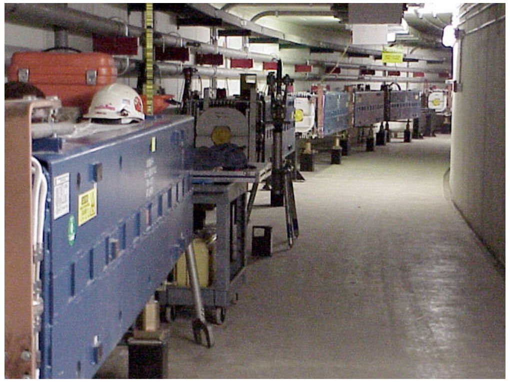
p + C □ (interactions) □ $□^+$, K^+, ($□^+$) □ (decay in flight) □ $□^+ + □_□$

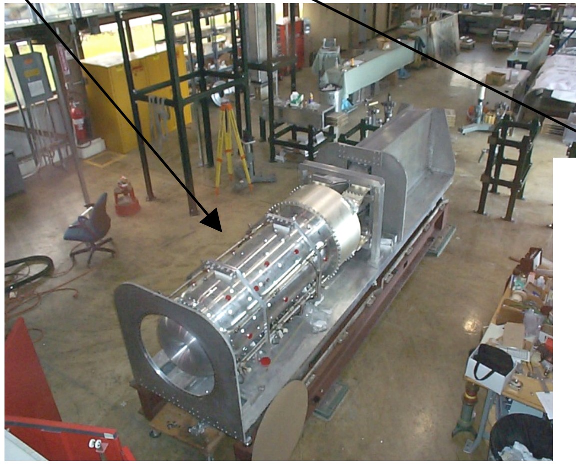
+ few % of ($□_□$, $□_e$)



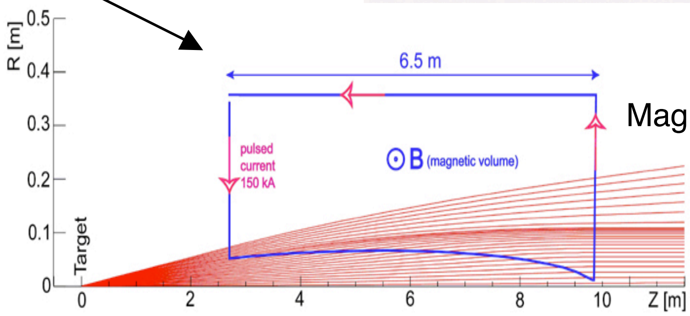


Proton accelerator





Boone Horn

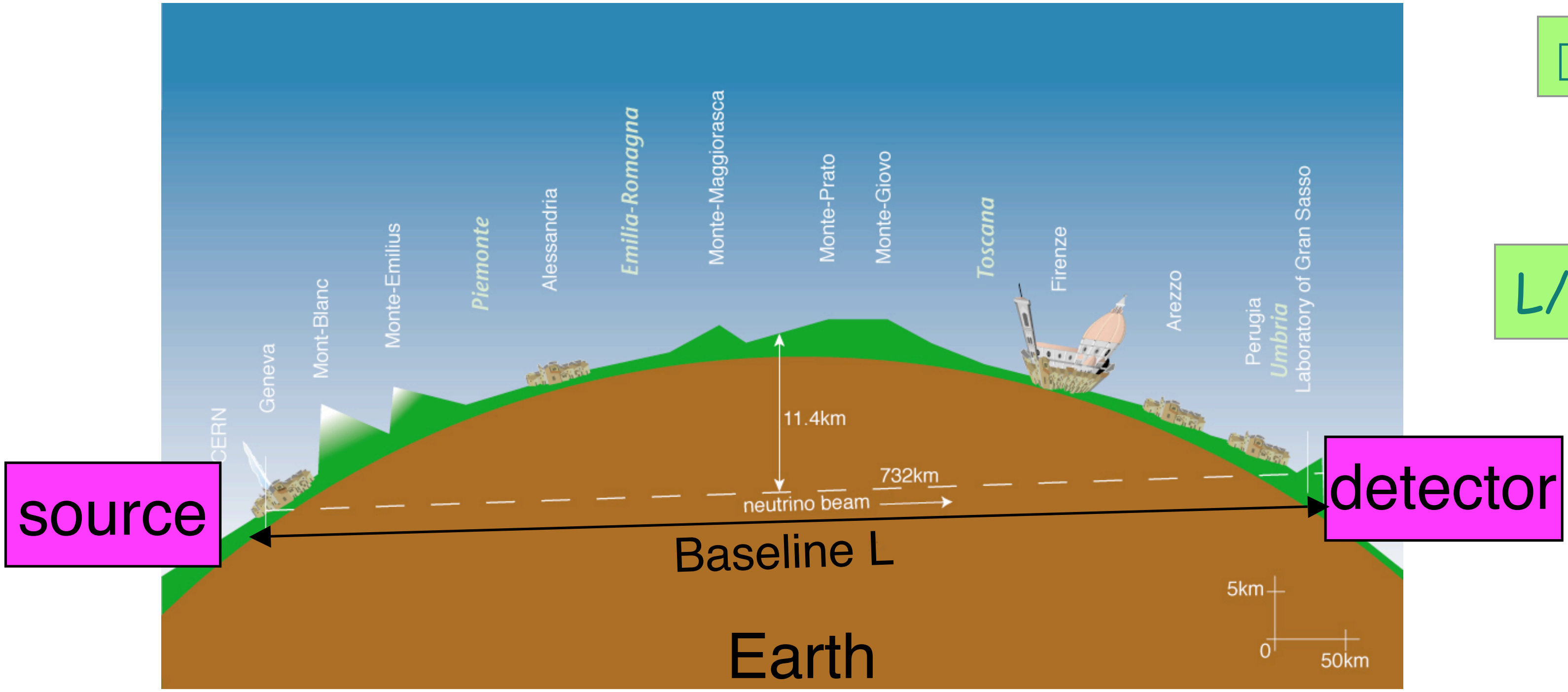


Magnetic focusing

André Rubbia, ETH/Zürich, 4/18/02, Four Seas Conference

Motivation

- Long-baseline neutrino experiment with accelerators aim to establish the neutrino oscillation in
  - **A well defined neutrino flight path length (L)**
  - **A well understood flux of pure (mainly ν_μ) beam**
  - **An priori “tunable” neutrino energy spectrum (E_ν)**



$\Delta m^2 \approx 2.5\ 10^{-3}\ eV^2$

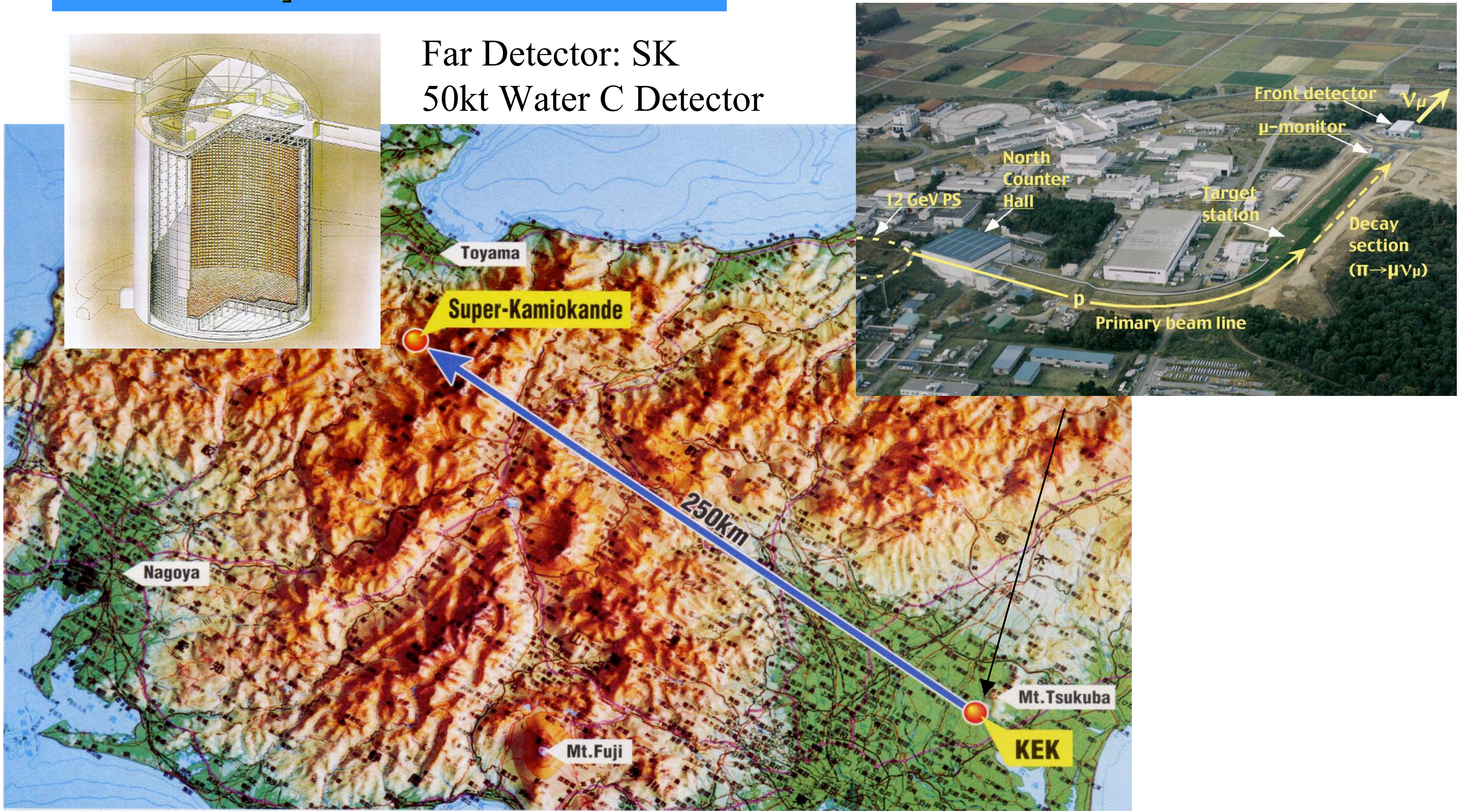
$L/E_\nu \approx 500\ km/GeV$

to maximize oscillation probability !

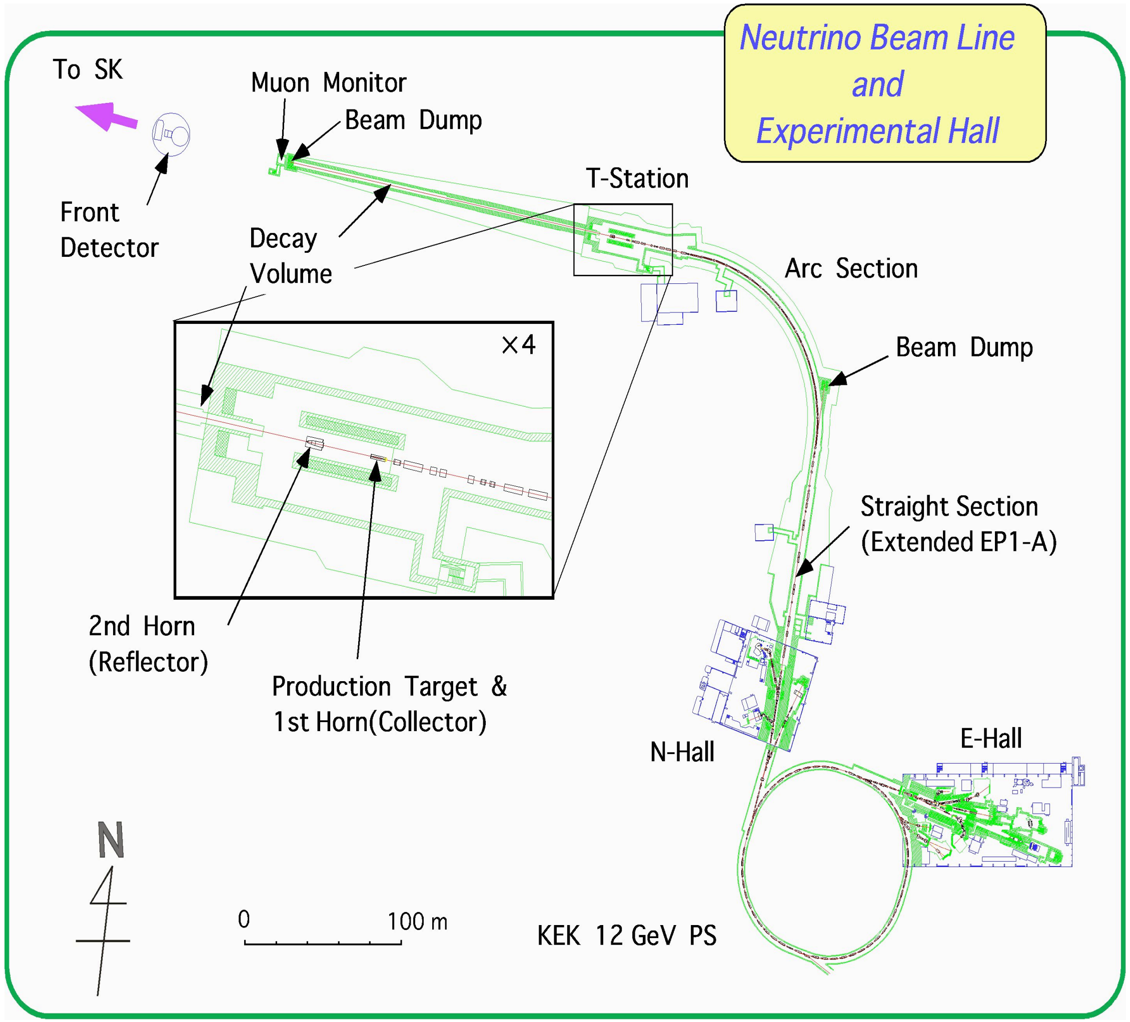
K2K Experiment

The First Long Baseline (250km)
Neutrino Oscillation Experiment

Far Detector: SK
50kt Water C Detector



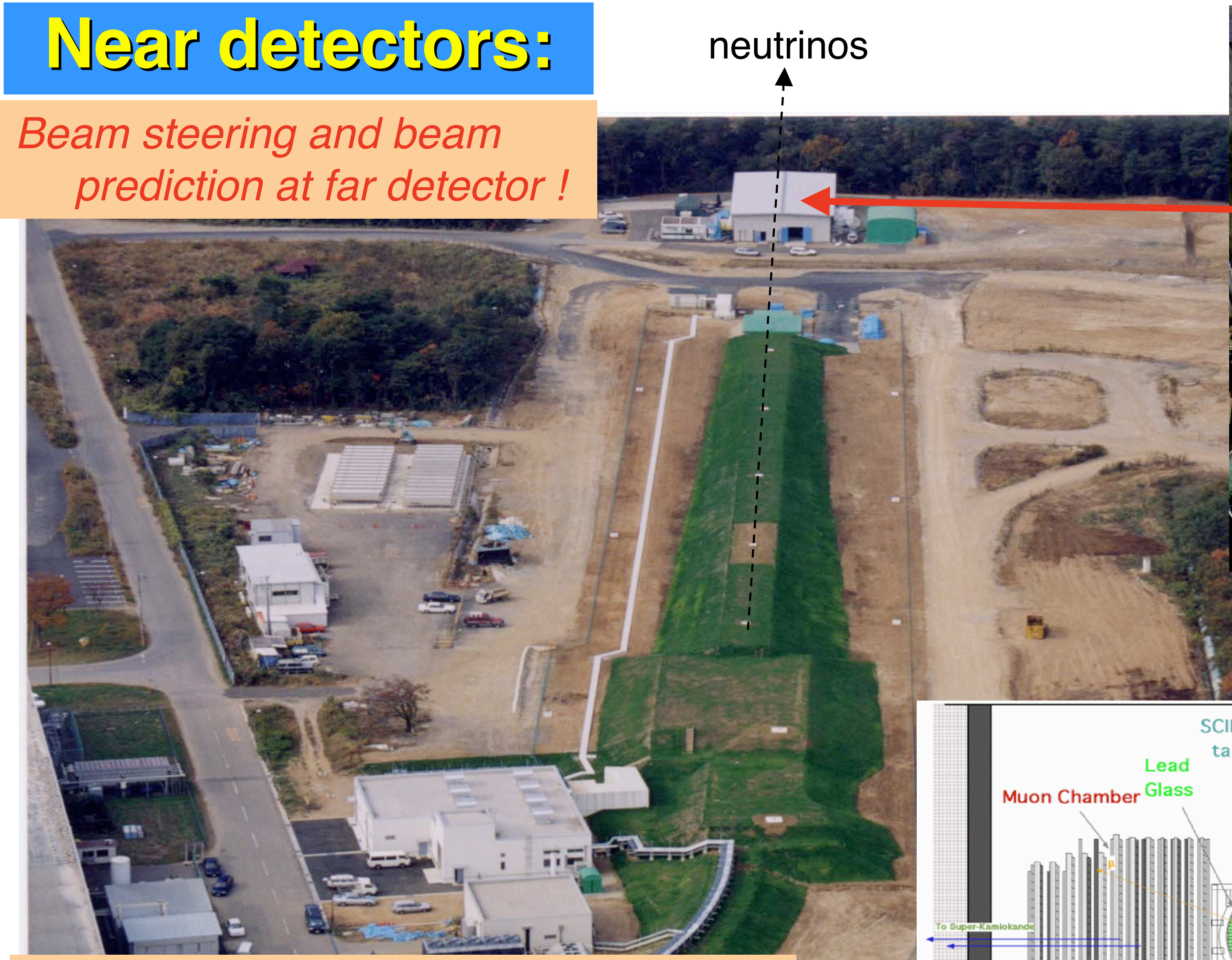
K2K (KEK-to-Kamioka)

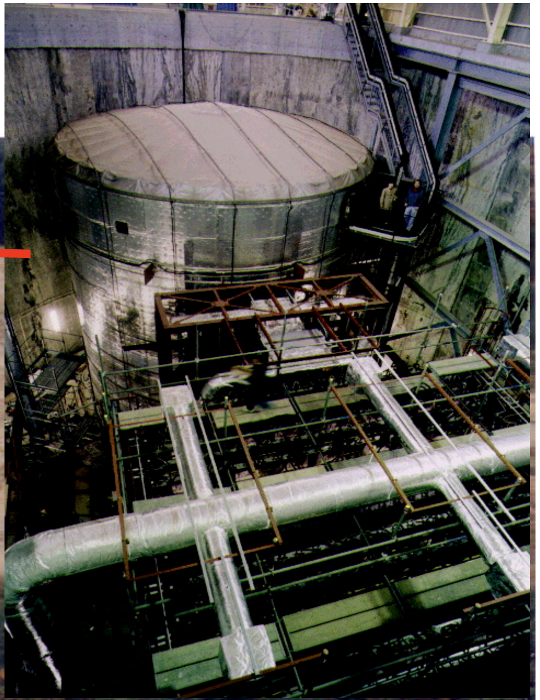


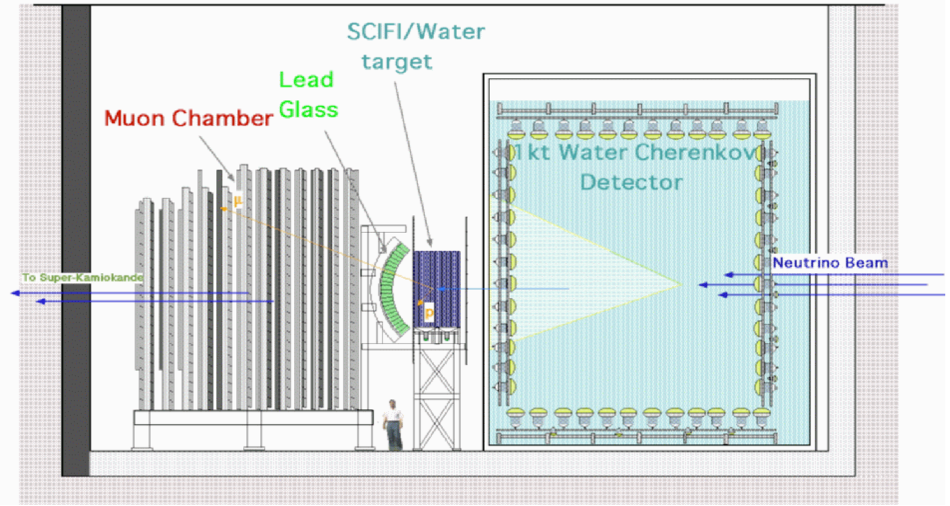
- Accelerator: 12 GeV proton synchrotron
  - Intensity 6x10^{12} protons/pulse
  - Repetition rate: 1 pulse/ 2.2 sec
  - Pulse width: 1.1 μs
- Horn-focused wide-band beam
  - **Average neutrino energy: 1.4 GeV □ below □-threshold**
- Near detector: 300 m from target
- Far detector: SuperK@ 250km from the target
  - **L/E ≈ 180 km/GeV**
- Goal: 10^{20} protons on target

Near detectors:

Beam steering and beam prediction at far detector !





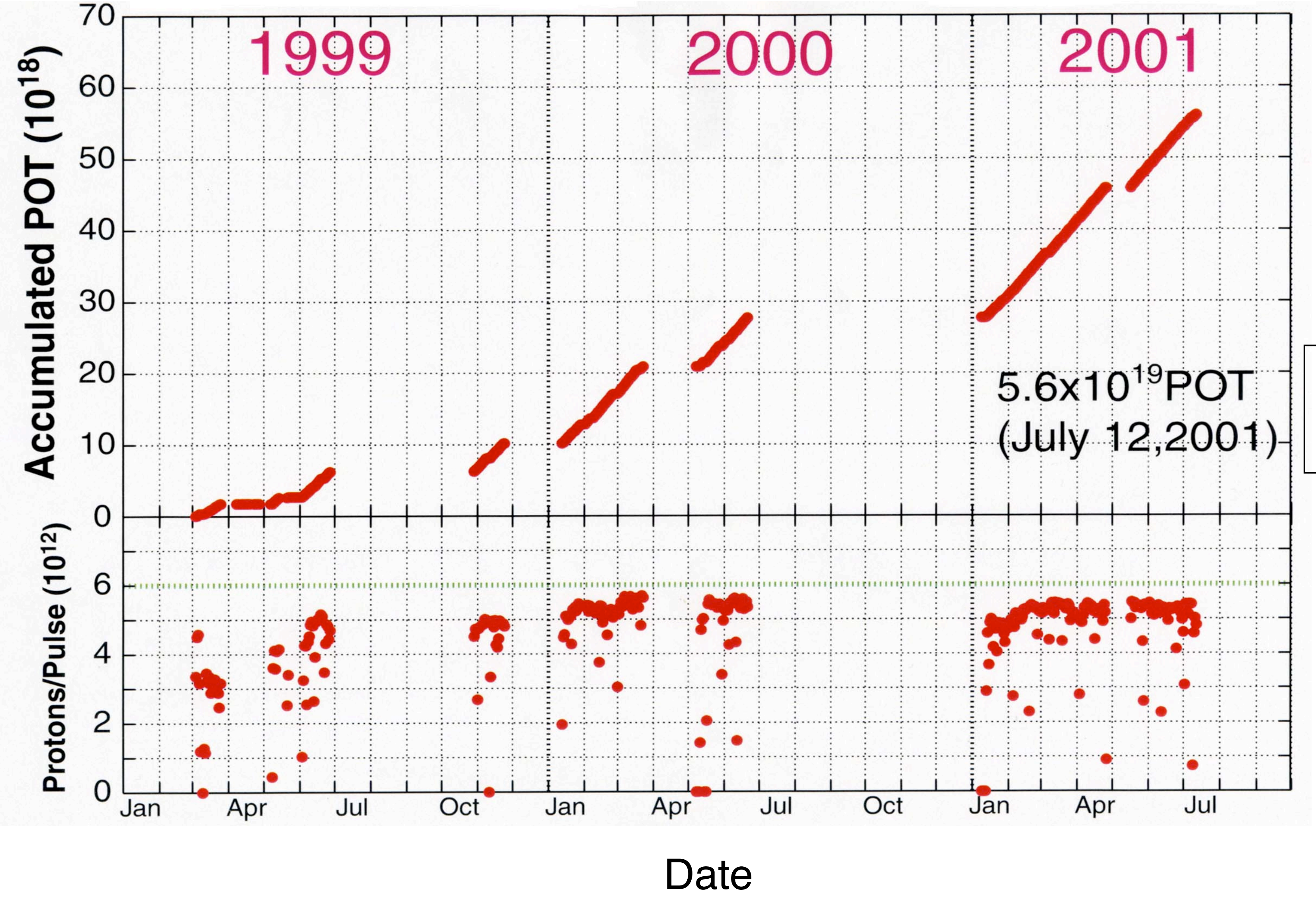


1ktWCD: Same Type Detector as SK

MRD and SciFi: Fine Grained Precise Detector

MRD: Massive and Large Solid Angle Detector

Delivered Protons on Target (POT)

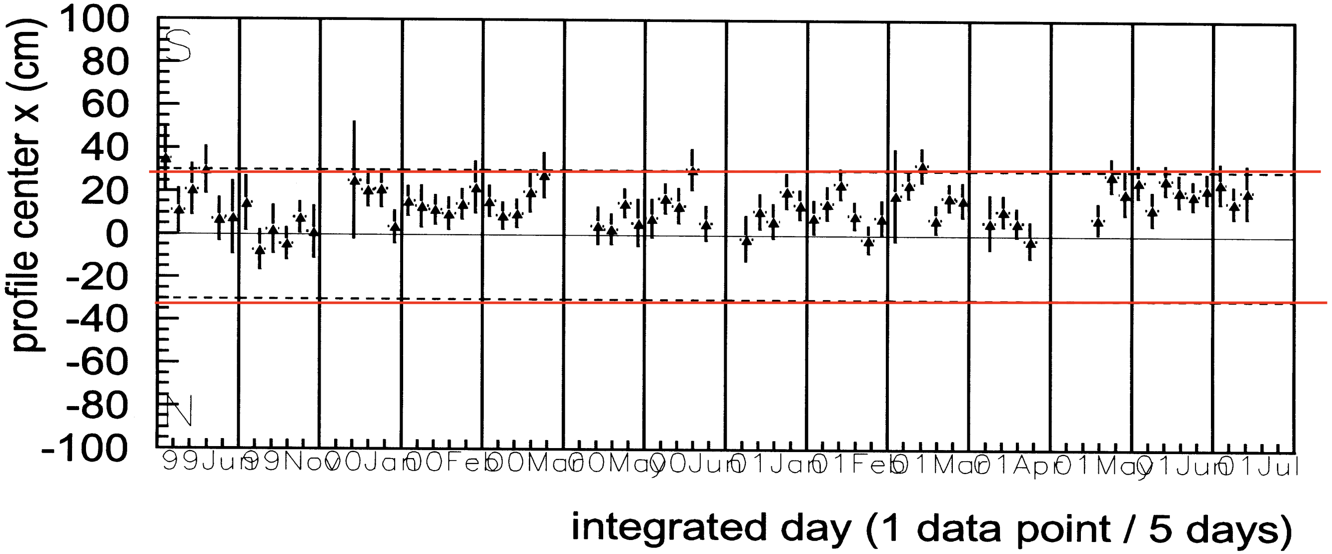


4.8x10^{19} POT
for Analysis

Goal:10^{20} POT (for Analysis)

Neutrino Profile: Centroid Stability

(Muon Range Detector)

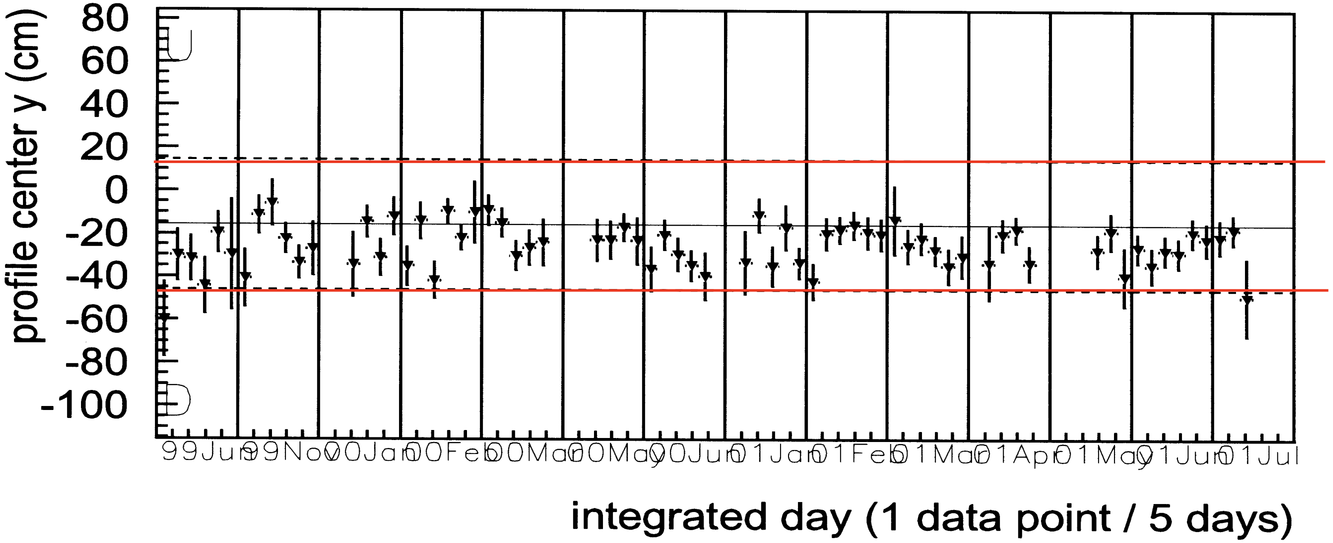


Horizontal

←+1 mrad

← -1 mrad

Beam centered to ±1 mrad

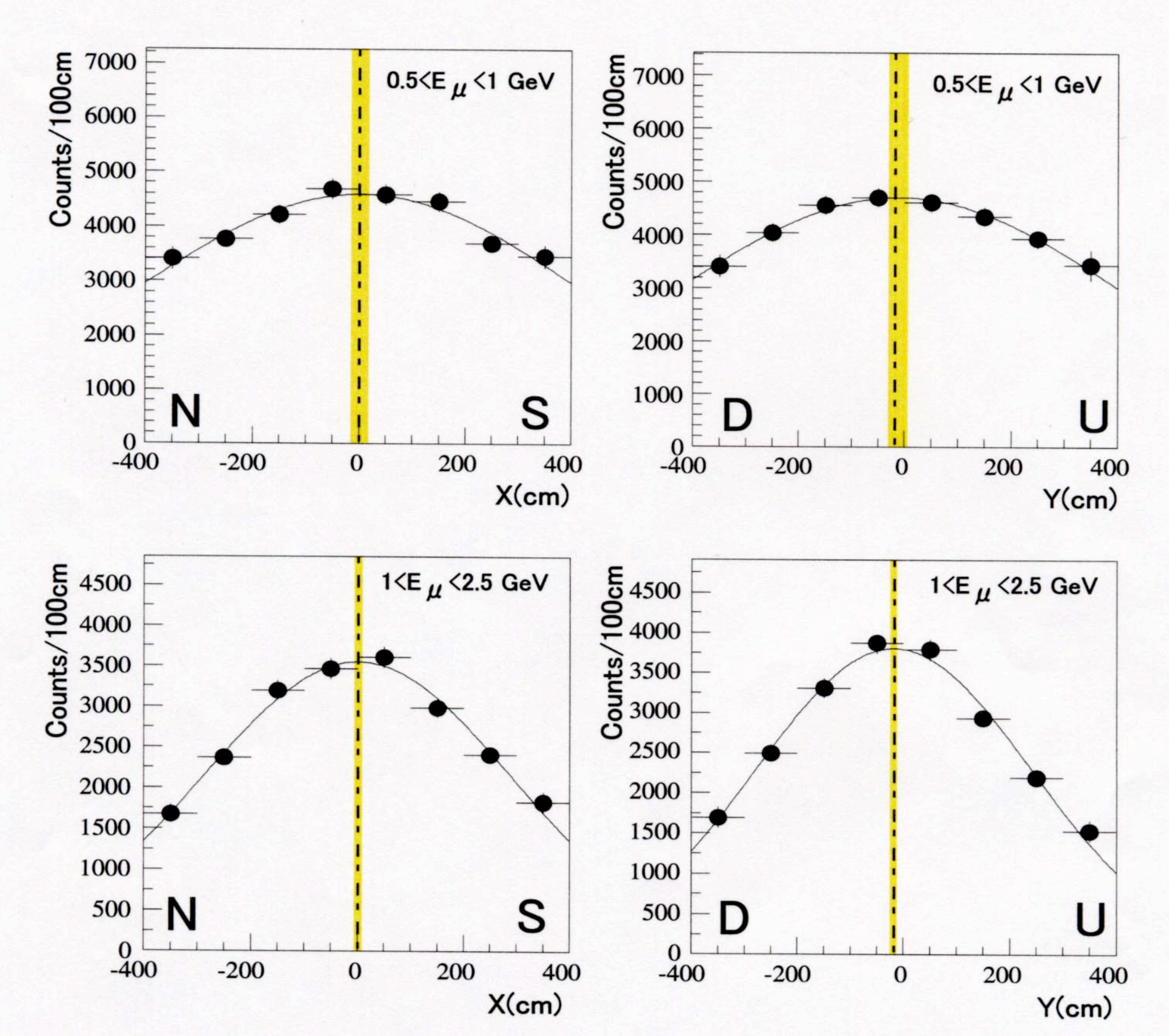


Vertical

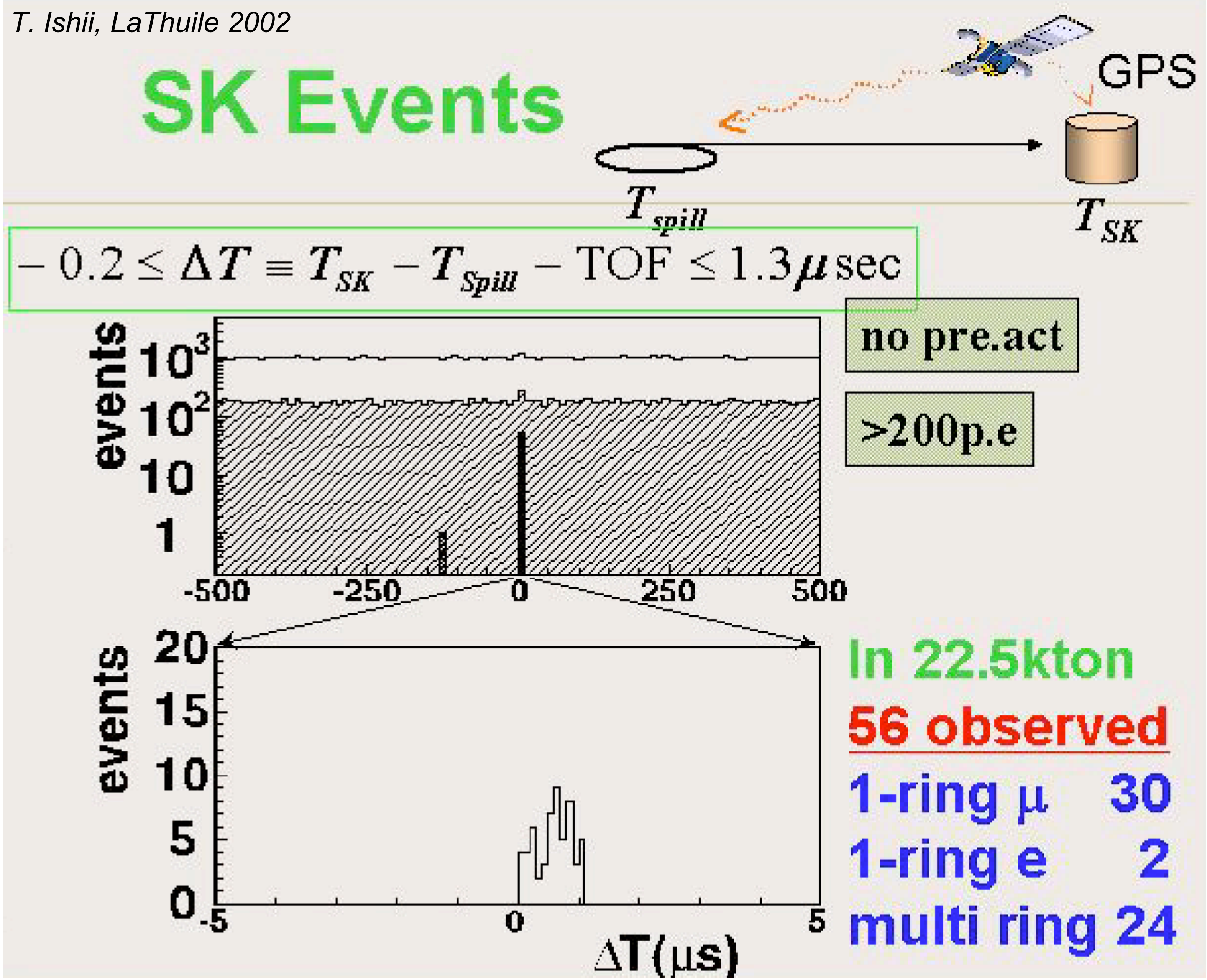
←+1 mrad

← -1 mrad

Neutrino Beam Profile (MRD)



- One Month Data
- Yellow belt: Fitting Error
- Dot-dashed line: Center from GPS survey



T. Ishii, LaThuile 2002

SK Events

$$-0.2 \le \Delta T \equiv T_{SK} - T_{Spill} - \text{TOF} \le 1.3\mu\,\text{sec}$$

no pre.act

>200p.e

In 22.5kton

56 observed

1-ring μ 30
1-ring e 2
multi ring 24

Atmospheric neutrino background reduced by 10^6 by precise timing

Observed SK events

4.8x10^{19}pot (Jun99-Jul01)

# of observed events and expected events
1999/06-2001/07

Observe muon disappearance !

	Obs.	No Ocsi.	$\Delta m^2 (\times 10^{-3} eV^2)$		
			3	5	7
FC 22.5kt	56	$80.6^{+7.3}_{-8.0}$	52.4	34.6	29.2
1-ring	32	48.4±6.7	28.1	17.8	16.6
μ-like	30	44.0±6.8	24.4	14.6	13.5
e-like	2	4.4±1.7	3.7	3.2	3.0
multi ring	24	32.2±5.3	24.3	16.8	12.6

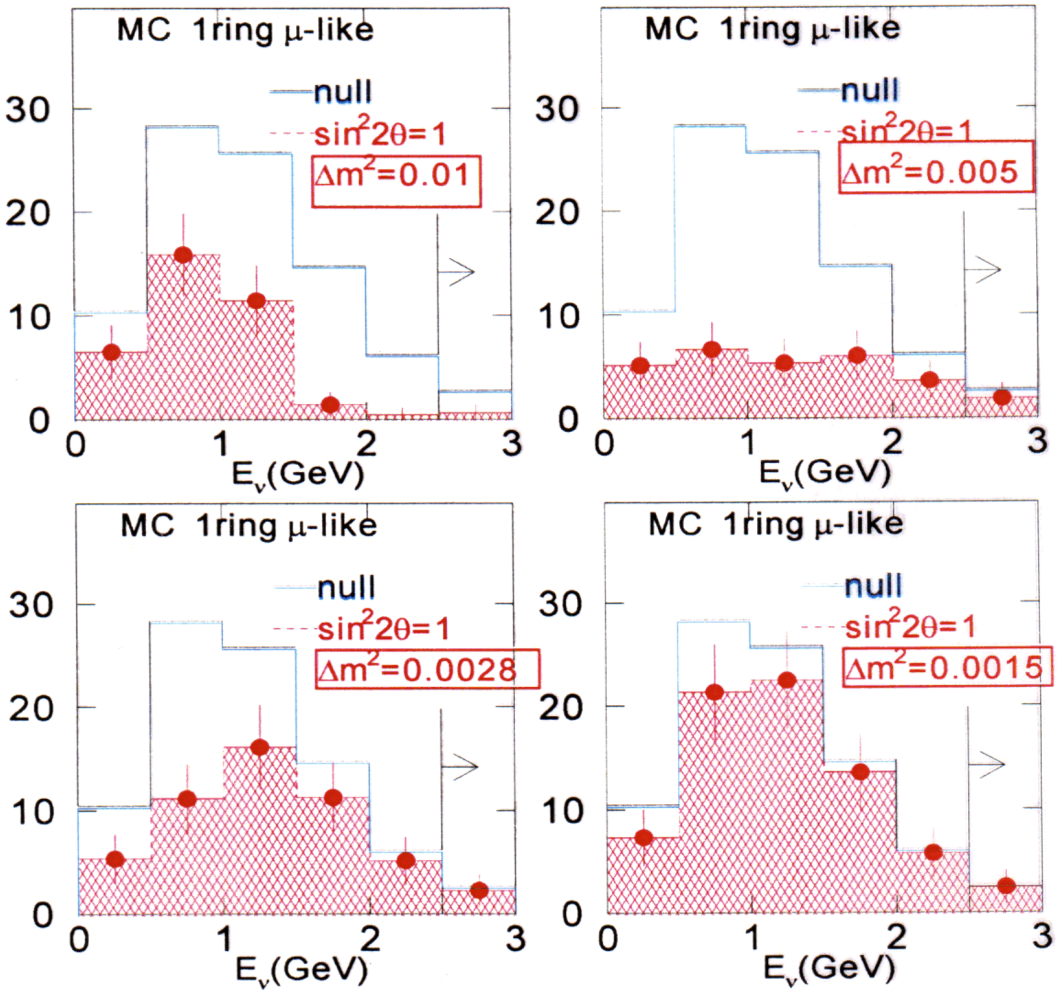
Cf. MRD: $87.4^{+12.7}_{-13.9}$ SciFi : $87.3^{+11.9}_{-11.9}$

No disappearance hypothesis is disfavoured at 97% CL.

Expected SK events at 10^{20} POT

172 interactions in 22.5ktons
88 μ candidates

Reconstructed Neutrino Energy (MC)



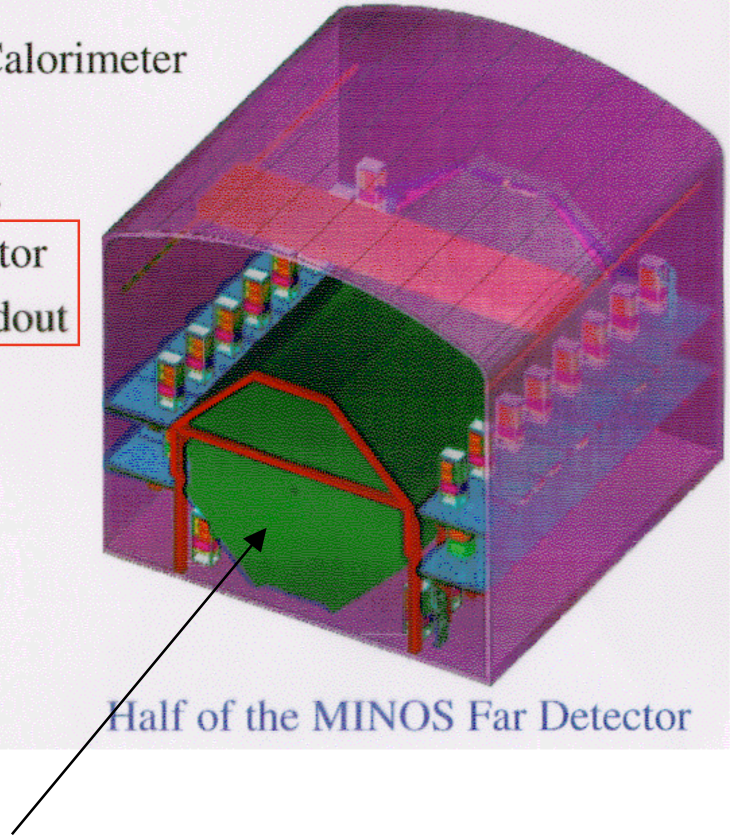
With sufficient statistics and a good reconstruction of the event energy, the disappearance as a function of Evis will be studied (so far not too convincing)

K. Nakamura, NUFACT00, Monterey (USA), May 2000

NUMI-MINOS program

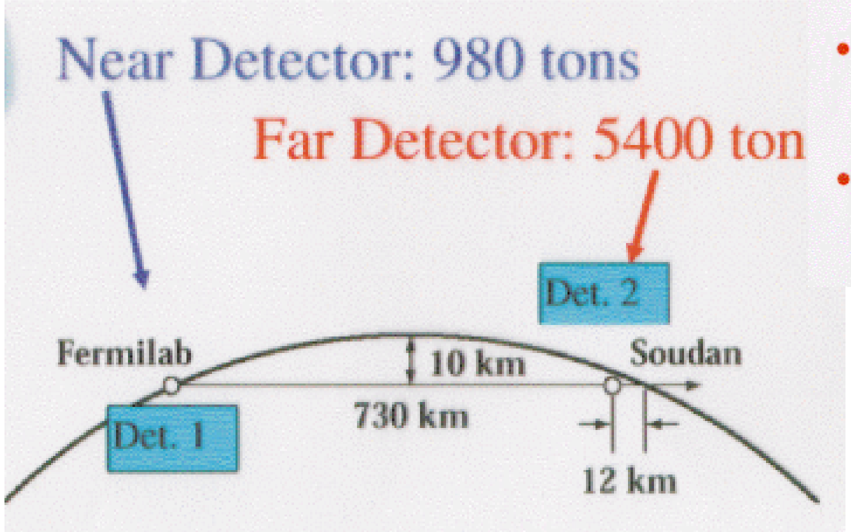
Two detector Neutrino Oscillation Experiment (Start 2004)

- 8m Octagonal Tracking Calorimeter
- 486 layers of 2.54cm Fe
- 2 sections, each 15m long
- 4.1cm wide solid scintillator strips with WLS fiber readout
- 25,800 m^2 active detector planes
- Magnet coil provides $\langle B \rangle \approx 1.3T$
- 5.4kt total mass



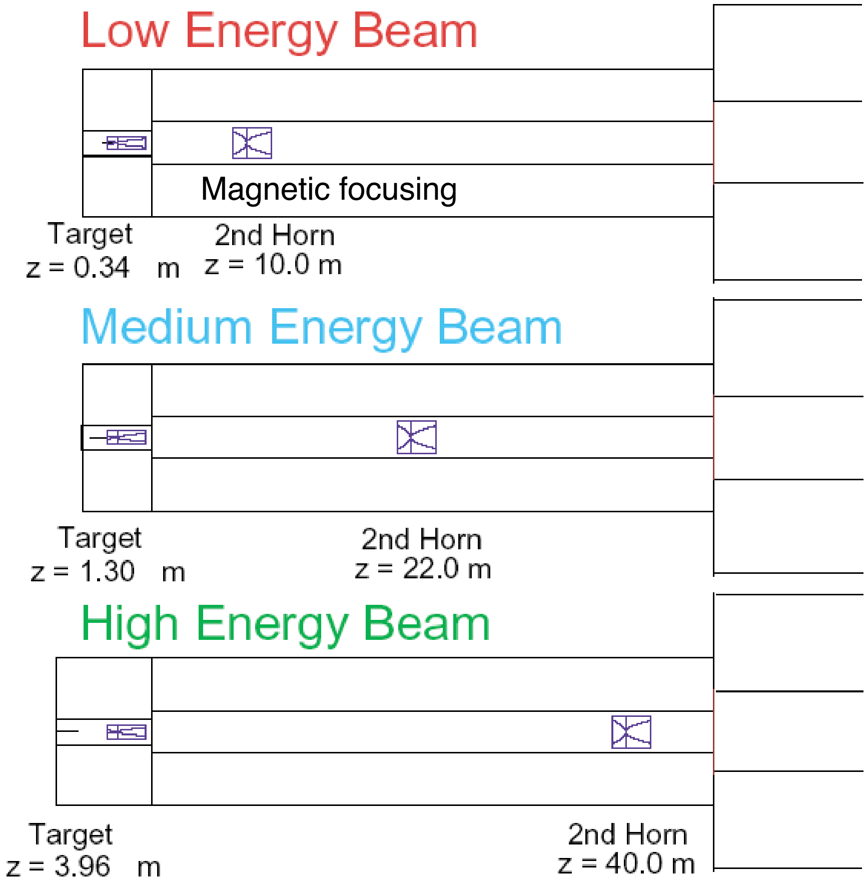
Half of the MINOS Far Detector

beam



NUMI neutrino beam

"Sacrifice neutrino flux to fit the expected energy of oscillated events"



Low Energy Beam

Magnetic focusing

Target
z = 0.34 m

2nd Horn
z = 10.0 m

Medium Energy Beam

Target
z = 1.30 m

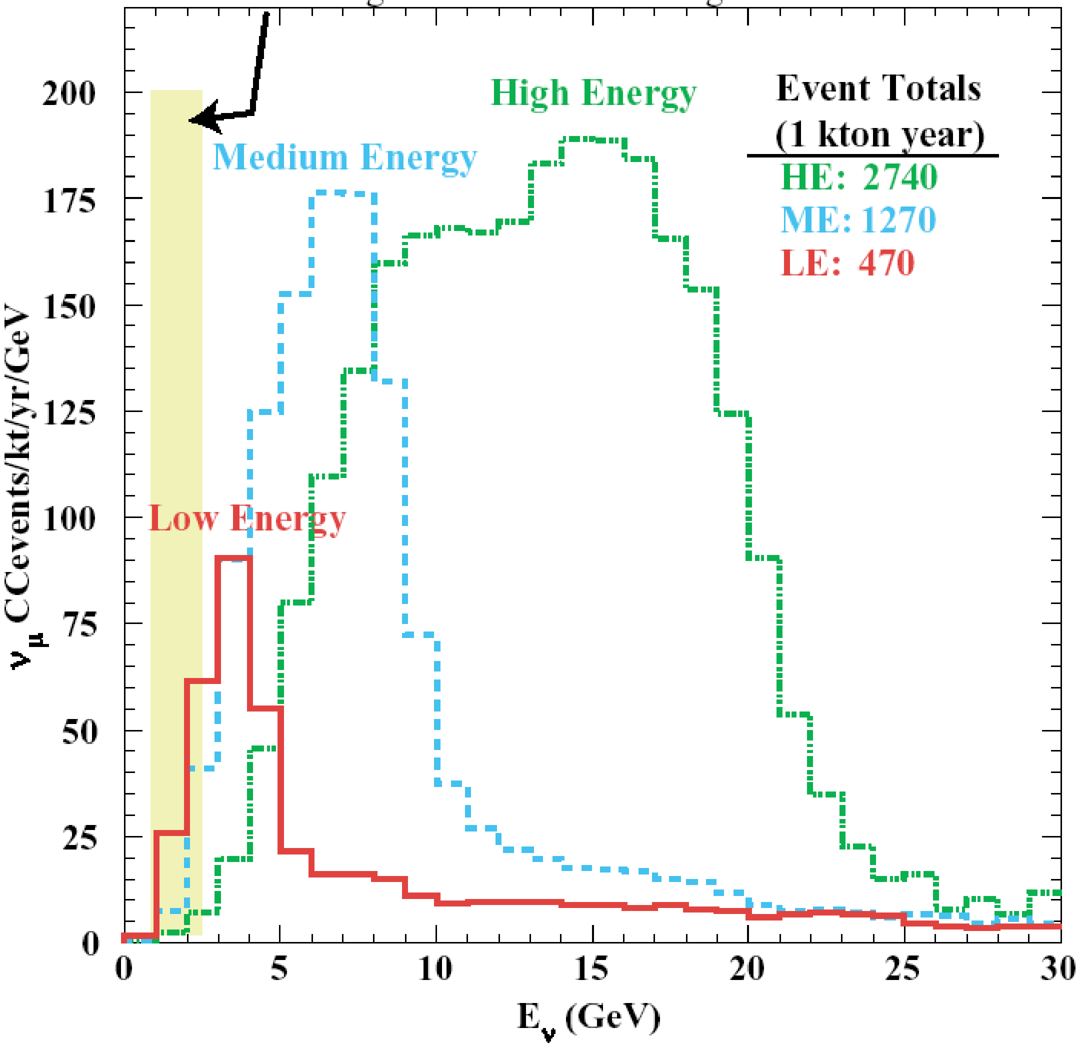
2nd Horn
z = 22.0 m

High Energy Beam

Target
z = 3.96 m

2nd Horn
z = 40.0 m

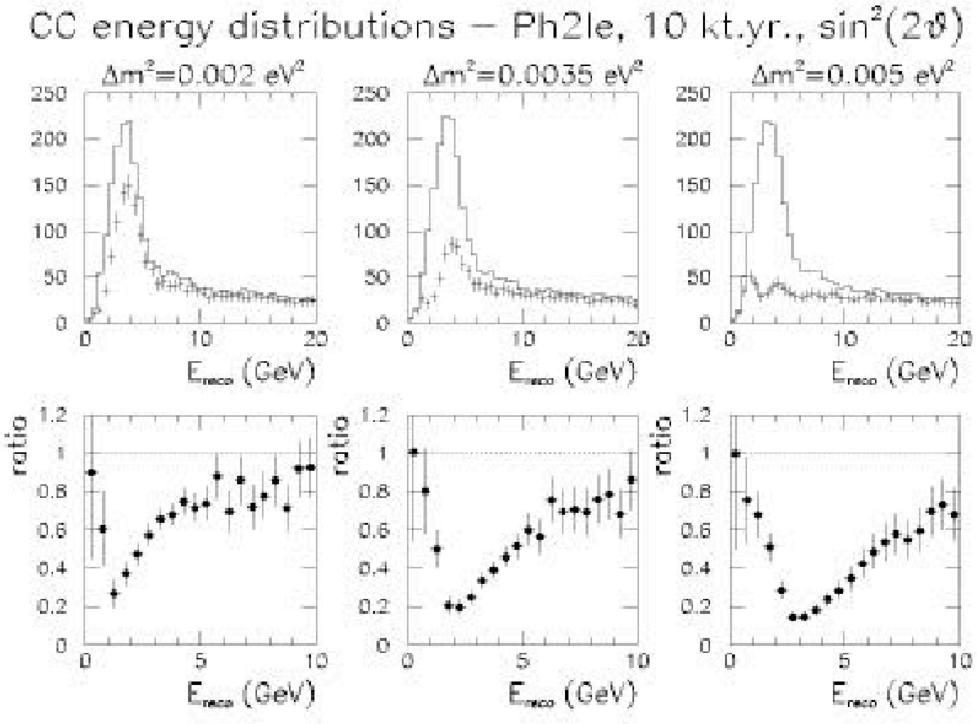
Energy of the max. of oscillation
according to SK 90% allowed region

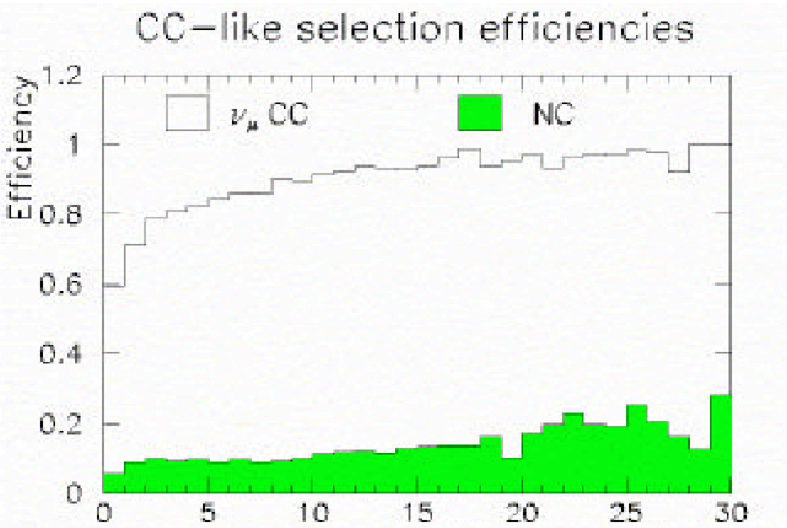


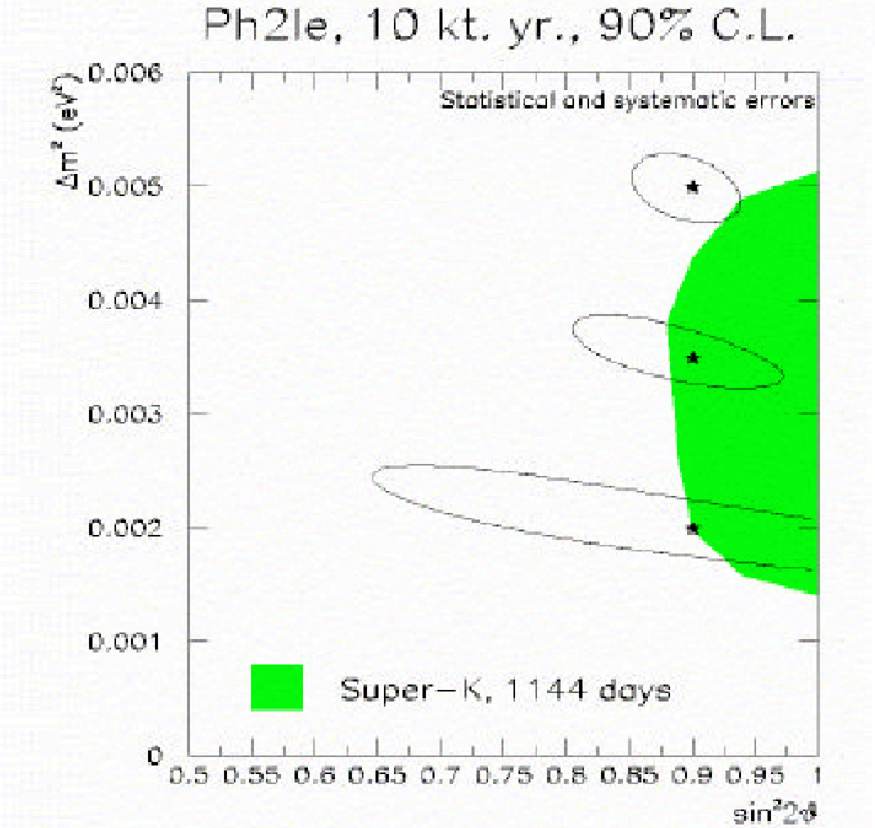
Event Totals
(1 kton year)
HE: 2740
ME: 1270
LE: 470

M. Mezzetto, NBI 2002

With high statistics and good event efficiencies in the energy region of interest MINOS will give substantially improved oscillation parameter measurements in a 2-year run







R.C. Webb, LaThuile 2002

MINOS schedule

- 146 planes mounted as of 1 March 2002 (1.6 kt mass)
  - ➥ 2% of detector per day at present rate of assembly
- Finish installation of far detector (2001-2003)
- Near detector assembly (2001-2003)
- Beam line commissioning (2004-2005)
- Plan to start with cosmic ray data-taking with half detector and B-field in summer 2002

Far detector at SOUDAN

R.C. Webb, LaThuile 2002

3) Search for tau neutrino appearance

$$\square_{\square} \ \square \ \square_{X} \ \square \ \square_{\square} \ \square \ \square_{\square} \ ?$$

with

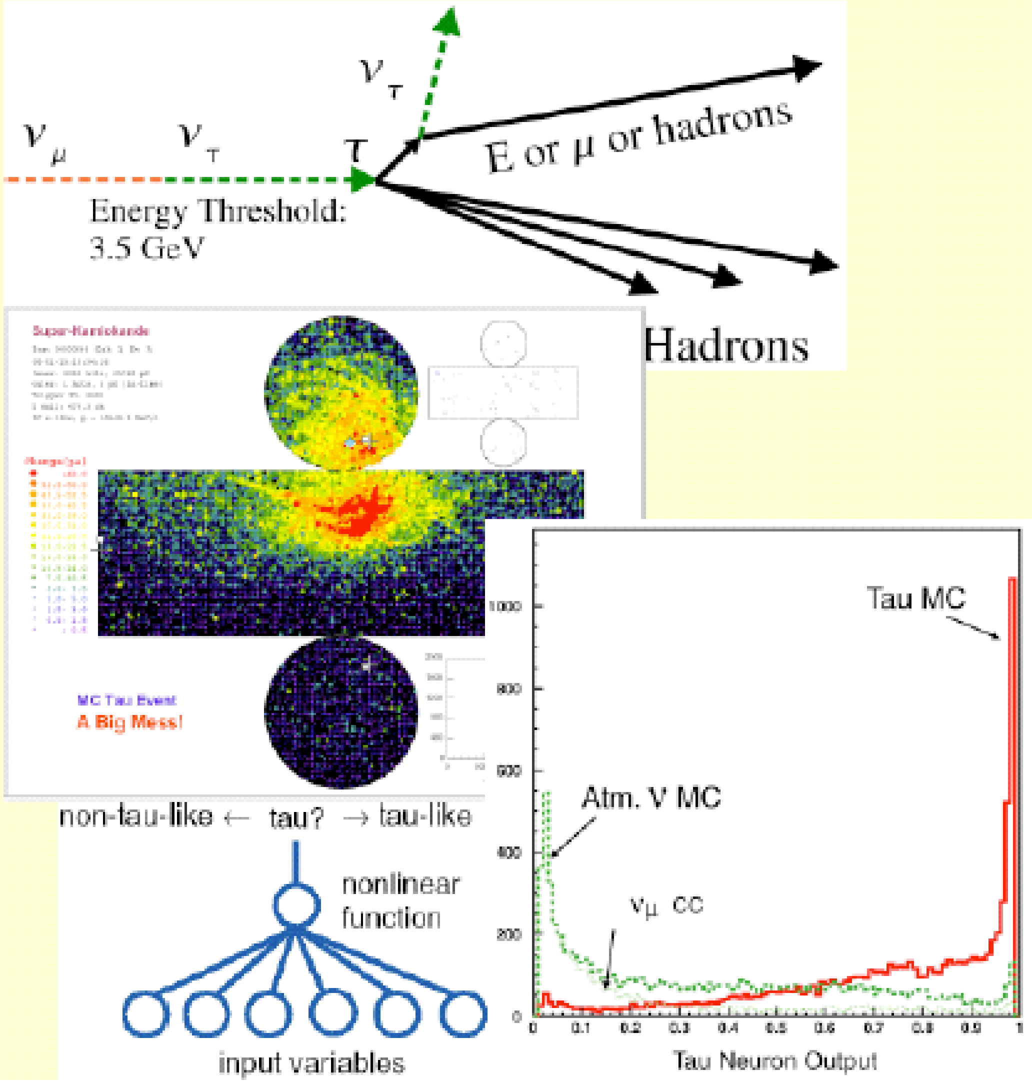
$$\square m^{2} \ \square (1 \square 4) \square 10^{\square 3} eV^{2} \qquad \sin^{2} 2\square \ \square 1$$

Atmospheric tau appearance in SuperK (I)

M. Smy, Moriond 2002

Three Different Analyses

- Different event reconstruction (energy flow, jet variables), Likelihood-function
- Standard ring reconstruction, Likelihood-function
- Standard ring reconstruction, Neural Net

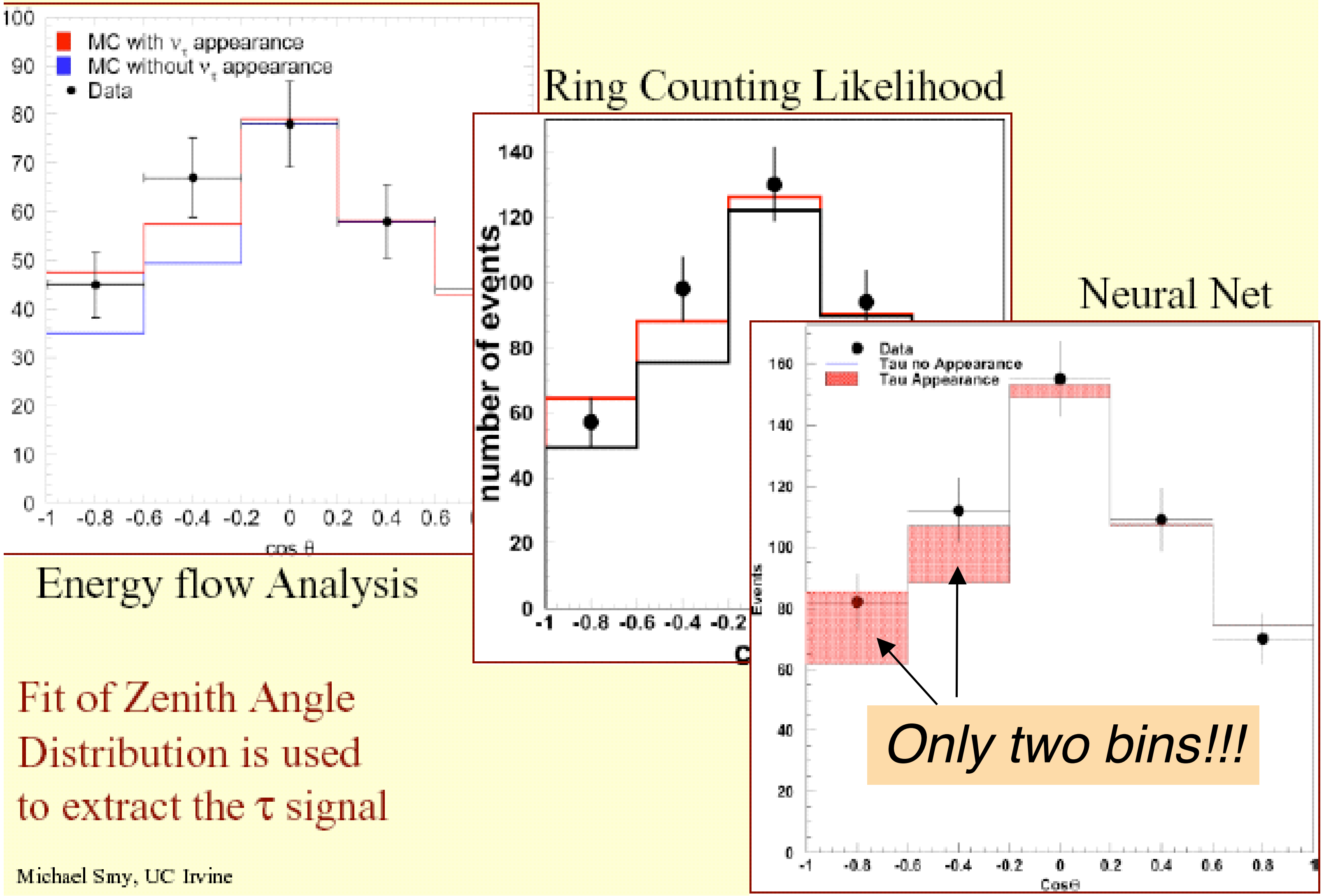


Michael Smy, UC Irvine

Atmospheric tau appearance in SuperK (II)

M. Smy, Moriond 2002

Zenith Angle Plot of enriched Sample



Ring Counting Likelihood

Energy flow Analysis

Neural Net

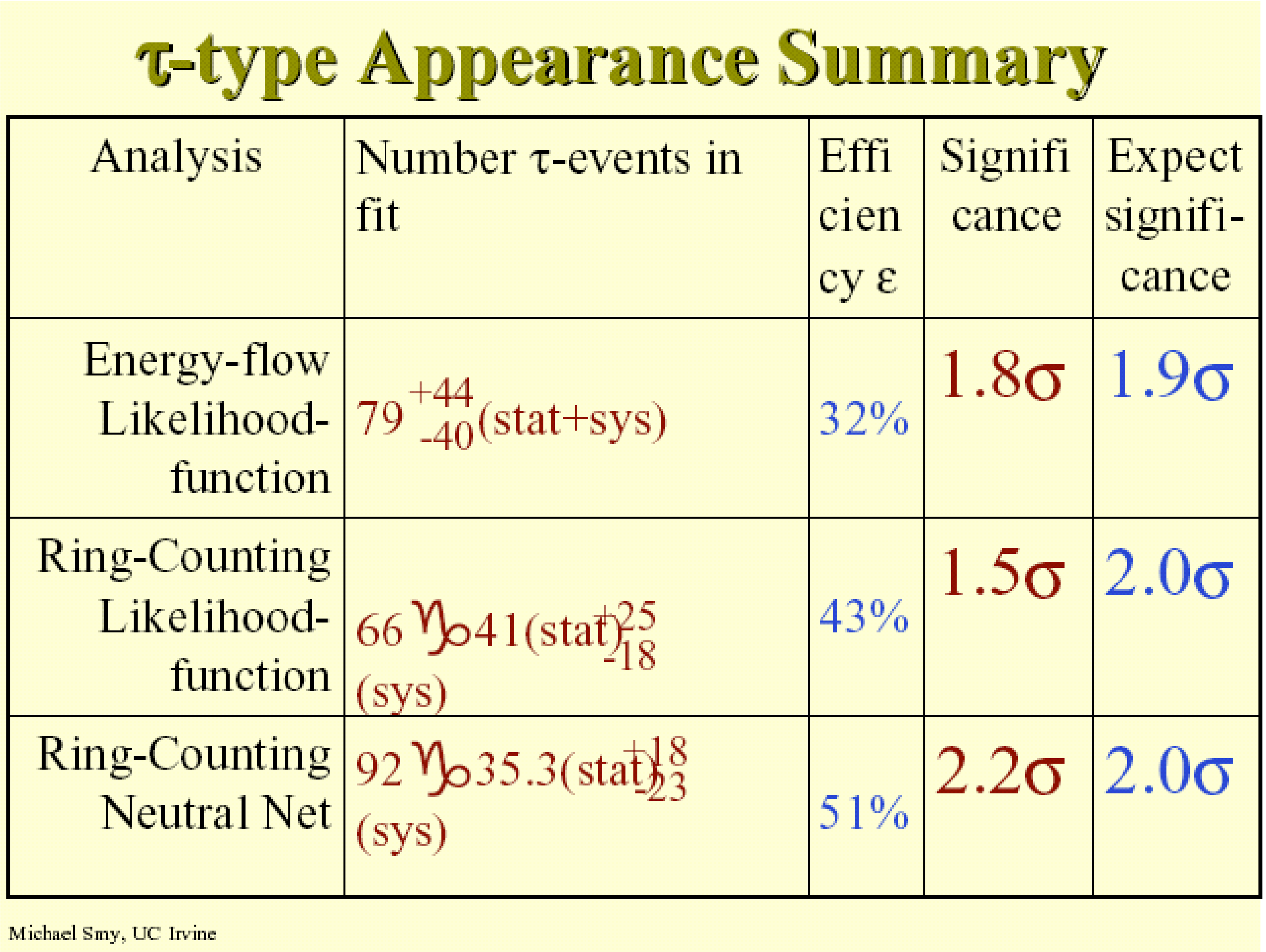
Only two bins!!!

Fit of Zenith Angle Distribution is used to extract the τ signal

Michael Smy, UC Irvine

Atmospheric tau appearance in SuperK (III)

M. Smy, Moriond 2002



τ-type Appearance Summary

Analysis	Number τ-events in fit	Efficiency ε	Significance	Expect significance
Energy-flow Likelihood-function	79^{+44}_{-40}(stat+sys)	32%	1.8σ	1.9σ
Ring-Counting Likelihood-function	66 ± 41(stat)$^{+25}_{-18}$(sys)	43%	1.5σ	2.0σ
Ring-Counting Neutral Net	92 ± 35.3(stat)$^{+18}_{-23}$(sys)	51%	2.2σ	2.0σ

Michael Smy, UC Irvine

≈80 kt□yr exposure ⇒ *A very tough job !*

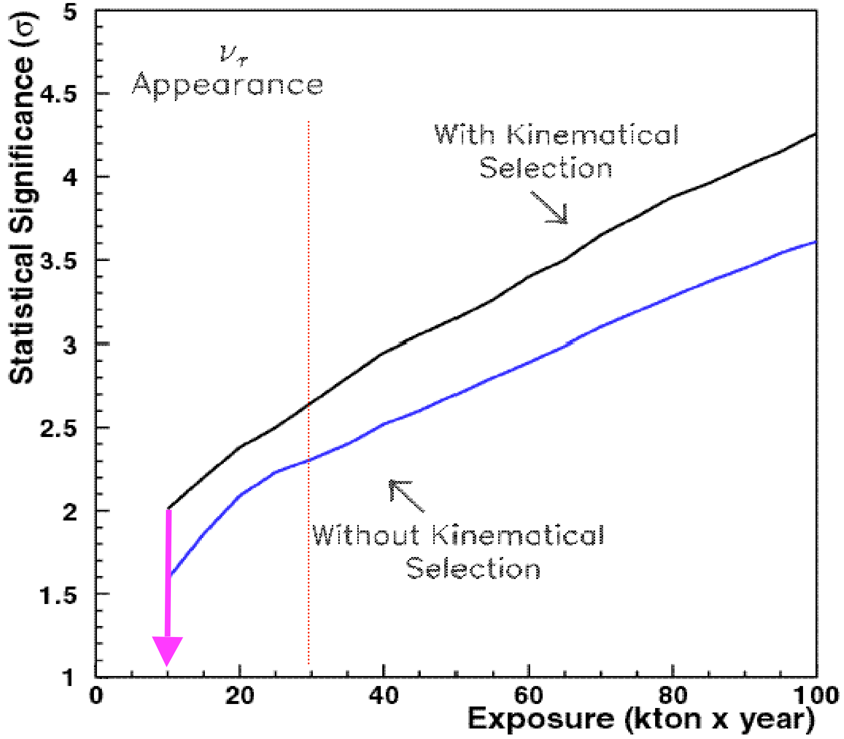
Simulated atmospheric ν_τ appearance in ICARUS

- Compare NC(top) to NC(bottom) at high energy
- **Exploit precise kinematical measurement of all final state particles provided by ICARUS imaging**

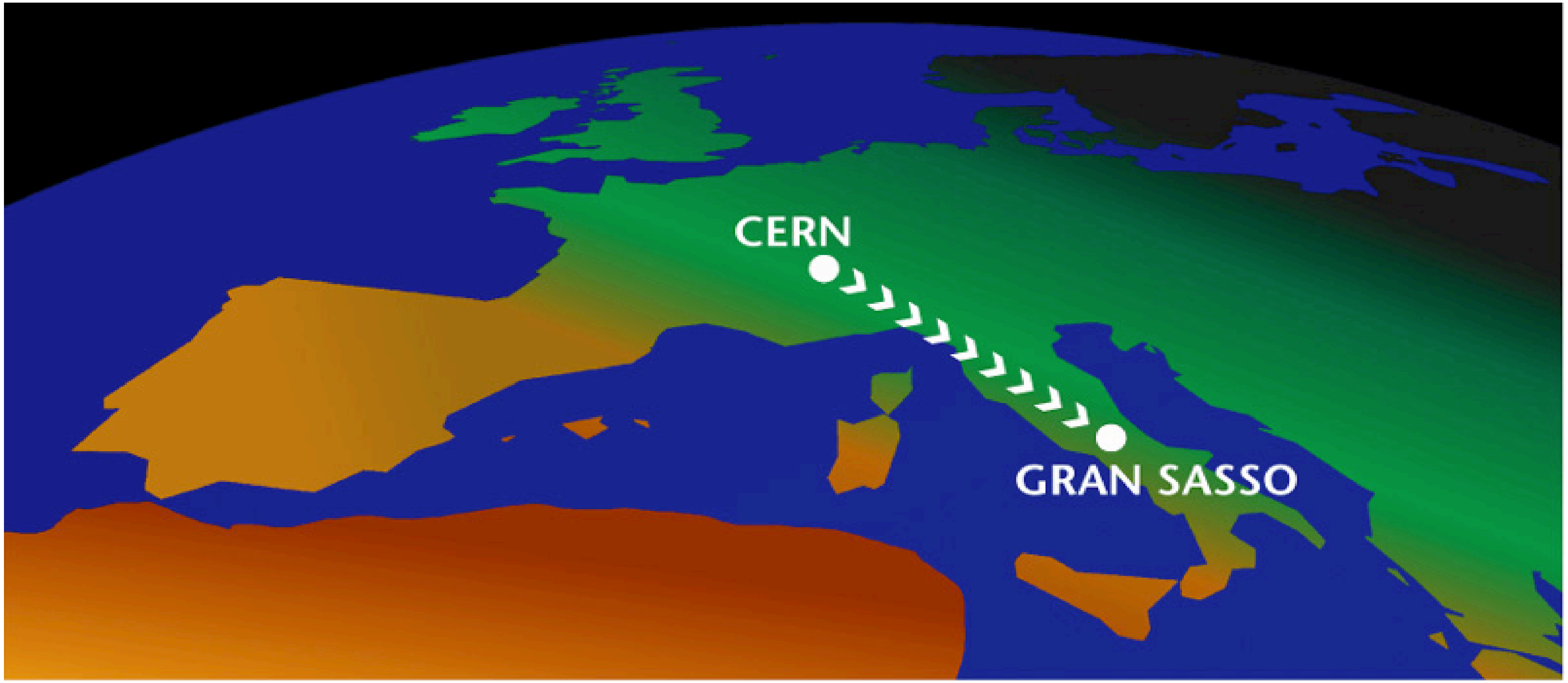
  ⇒Improved discrimination by a study of the event kinematical properties

⇒ Still a tough job !

>3σ **effect**
after **40 kt x year exposure**



Goal of the CNGS project



“Long Base-Line” $\square_{\square}\,\square\;\square_{\square}$ oscillation experiments

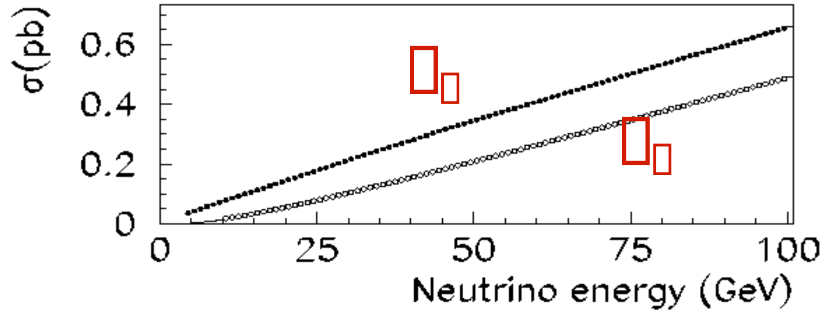
- build an intense high energy $\square_{\square}$ beam at CERN-SPS
- optimized for $\square_{\square}$ appearance search at Gran Sasso laboratory (730 km from CERN)

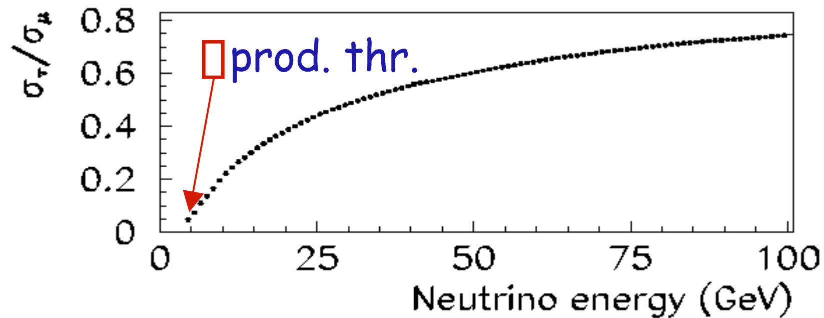
CNGS Optimization for ν_τ Appearance

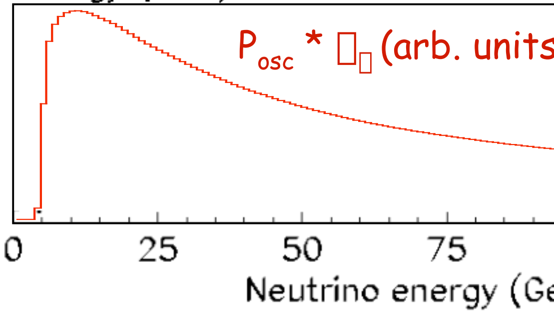
$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

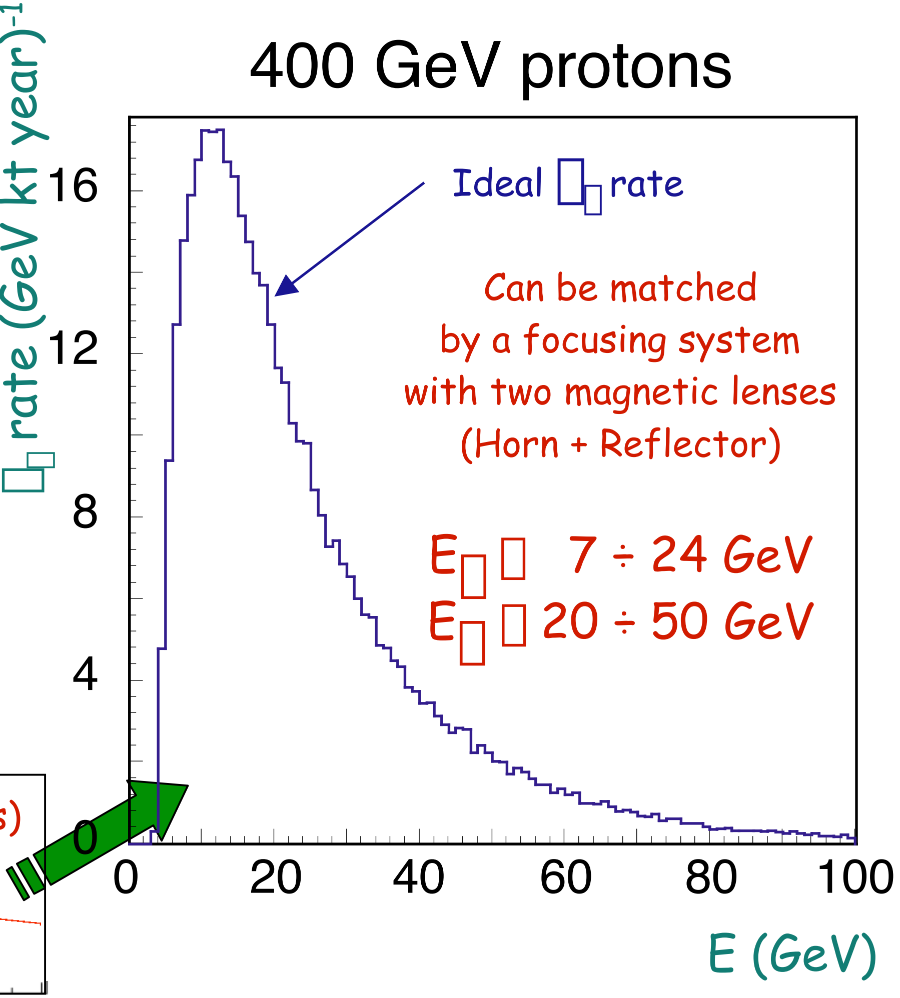
→ P_{osc} ↓ E_ν ↑

σ_τ/σ_μ CC increases with energy
(kin. suppr. due to τ mass)





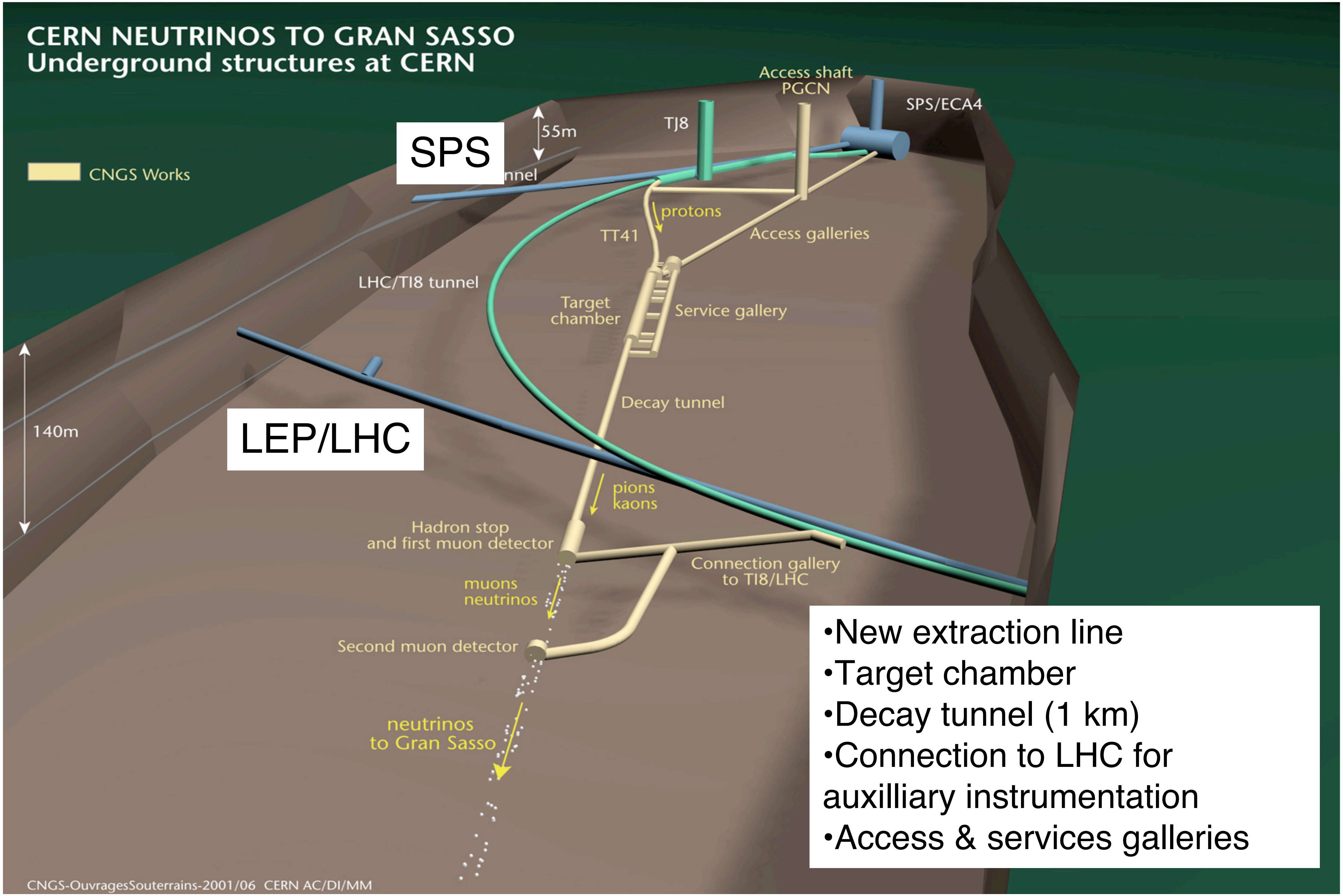




Can be matched by a focusing system with two magnetic lenses (Horn + Reflector)

$E_\nu \approx$ 7 ÷ 24 GeV
$E_\pi \approx$ 20 ÷ 50 GeV

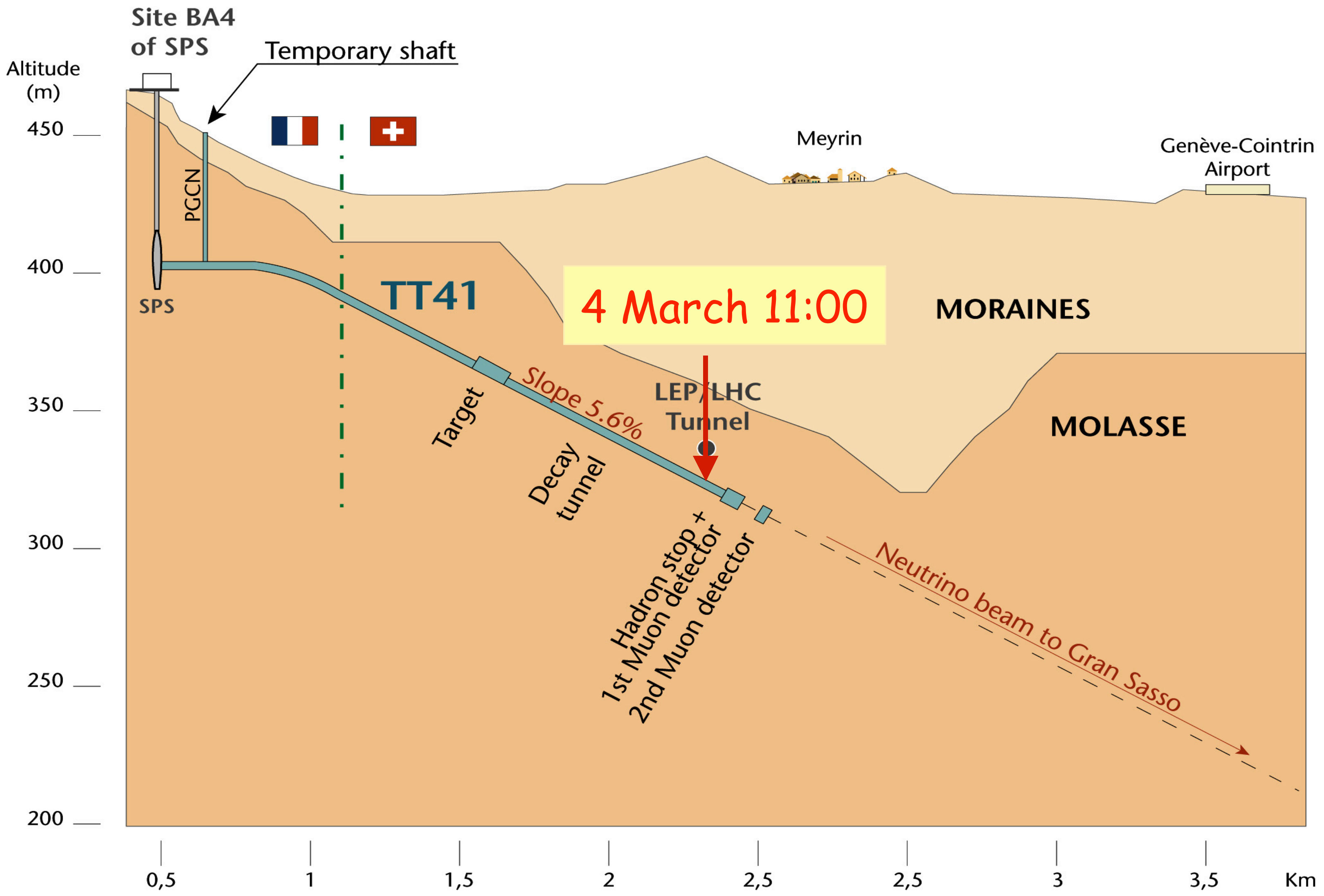
CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN



- New extraction line
- Target chamber
- Decay tunnel (1 km)
- Connection to LHC for auxilliary instrumentation
- Access & services galleries

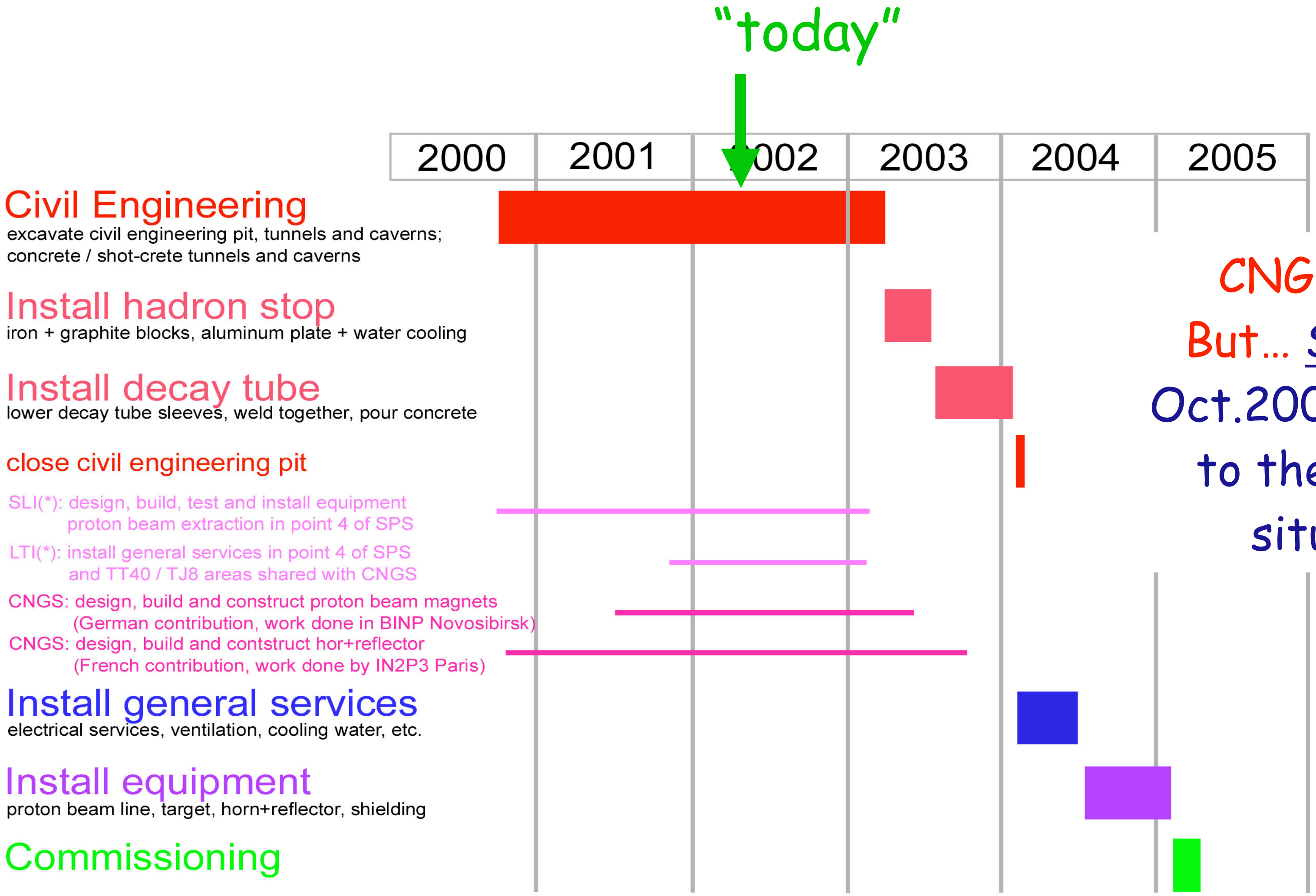

IHI
IMER
25
IMER
2594

Aiming at LNGS…



4 March 11:00

Present CNGS Schedule



Civil Engineering
excavate civil engineering pit, tunnels and caverns;
concrete / shot-crete tunnels and caverns

Install hadron stop
iron + graphite blocks, aluminum plate + water cooling

Install decay tube
lower decay tube sleeves, weld together, pour concrete

close civil engineering pit

SLI(*): design, build, test and install equipment
proton beam extraction in point 4 of SPS

LTI(*): install general services in point 4 of SPS
and TT40 / TJ8 areas shared with CNGS

CNGS: design, build and construct proton beam magnets
(German contribution, work done in BINP Novosibirsk)

CNGS: design, build and contstruct hor+reflector
(French contribution, work done by IN2P3 Paris)

Install general services
electrical services, ventilation, cooling water, etc.

Install equipment
proton beam line, target, horn+reflector, shielding

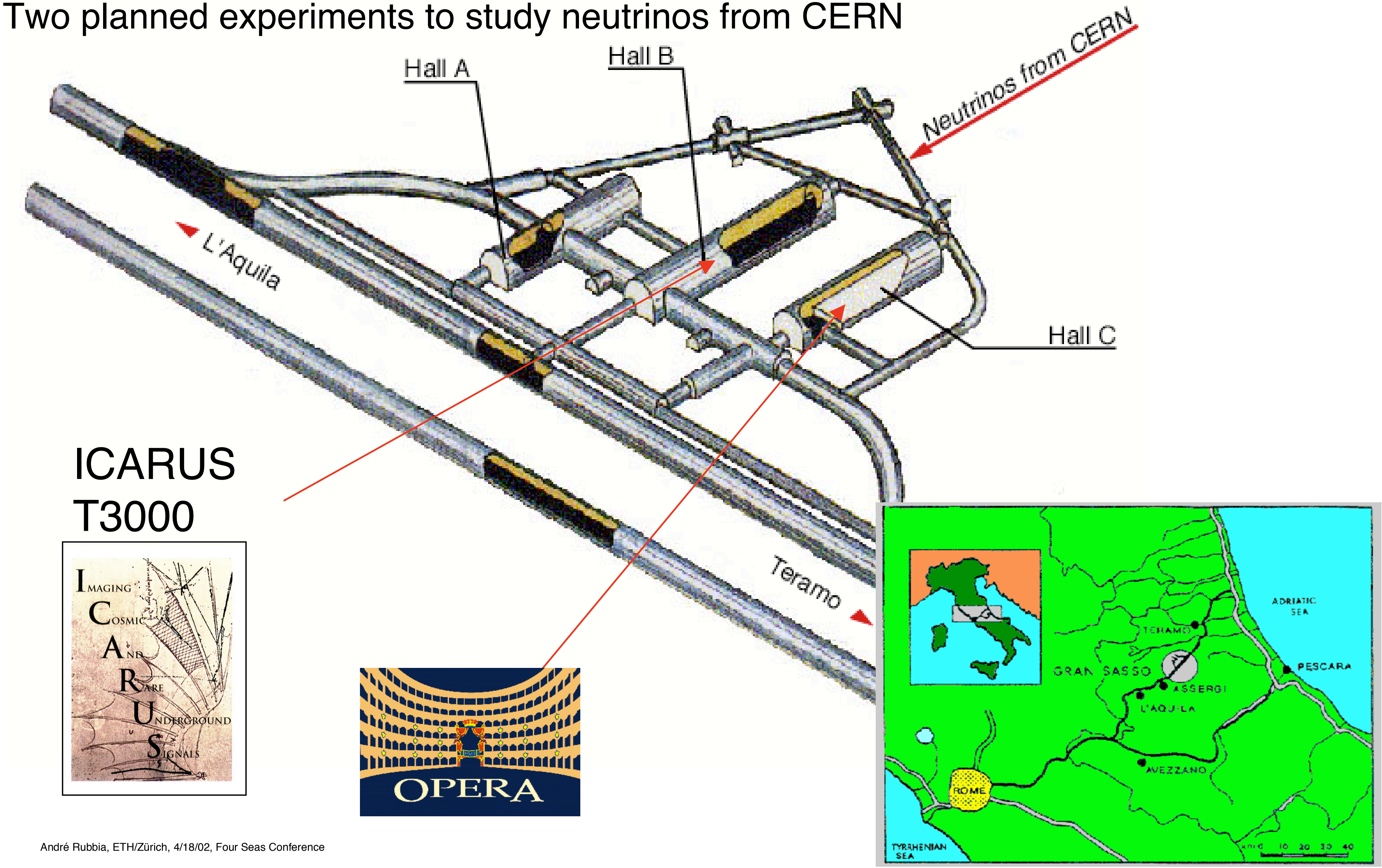
Commissioning

CNGS is on schedule!
But… <u>SPS will stop</u> from
Oct.2004 to Apr.2006, due
to the critical financial
situation of CERN

First beam to Gran Sasso: May 2005

LNGS Laboratory and the CNGS beam

Two planned experiments to study neutrinos from CERN



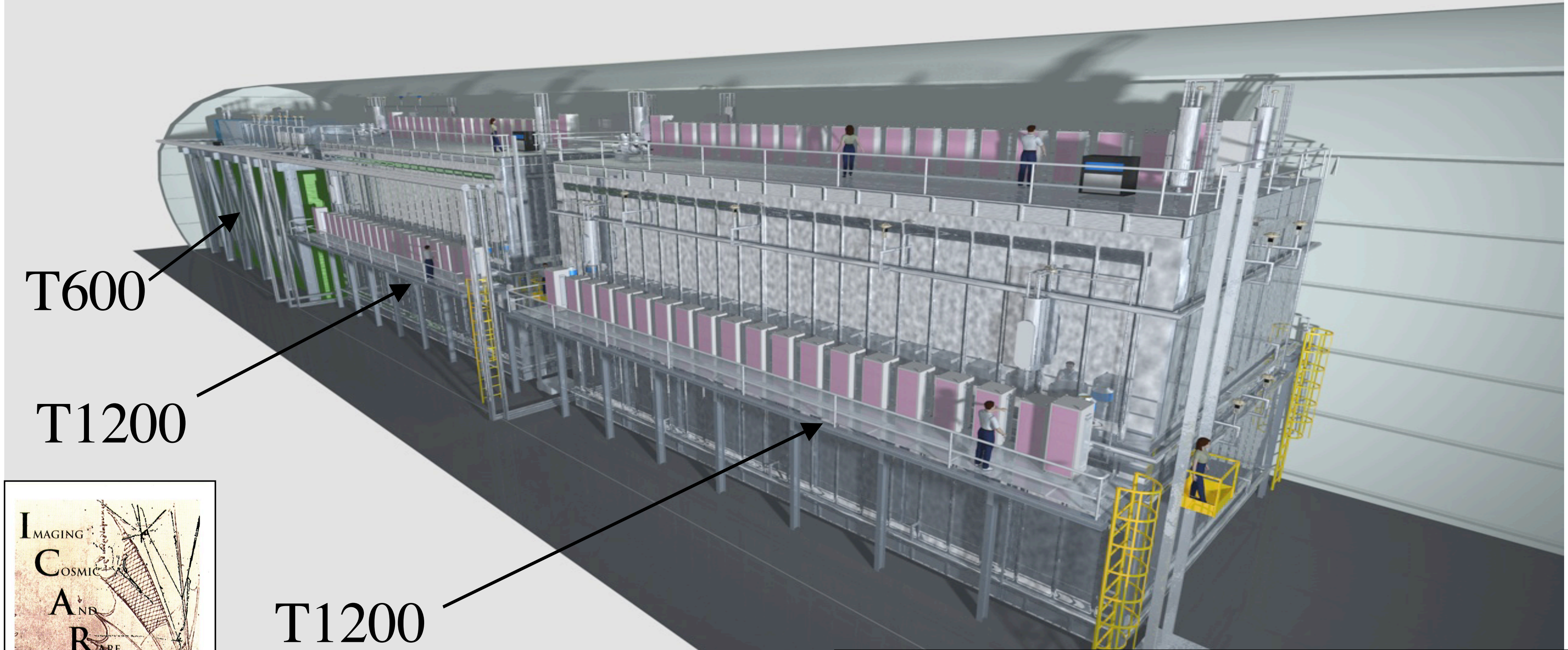
ICARUS
T3000

Imaging Cosmic And Rare Underground Signals

OPERA

ICARUS T3000 proposal

GSSC March 2002: « (…) the proposed experiment is to be considered only if the detector volume is not reduced and the starting time is around 2006. »



Imaging
Cosmic
And
Rare
Underground
Signals

T600: installed in LNGS early 2003

T3000: operational by summer 2006

Direct detection of flavor oscillation

The expected ν_e and ν_τ contamination of the CNGS neutrino beam in absence of oscillations is in the order of 10^{-2} and 10^{-7} relative to the main ν_μ component

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

$\nu_\tau + \mathrm{Ar} \to \tau + \mathrm{jet};\ \tau \to$

Charged current (CC)

Golden channel

$e\nu\nu$	18%
$\mu\nu\nu$	18%
$h^- nh^0 \nu$	50%
$h^- h^+ h^- nh^0 \nu$	14%

$\nu_\mu \to \nu_e$

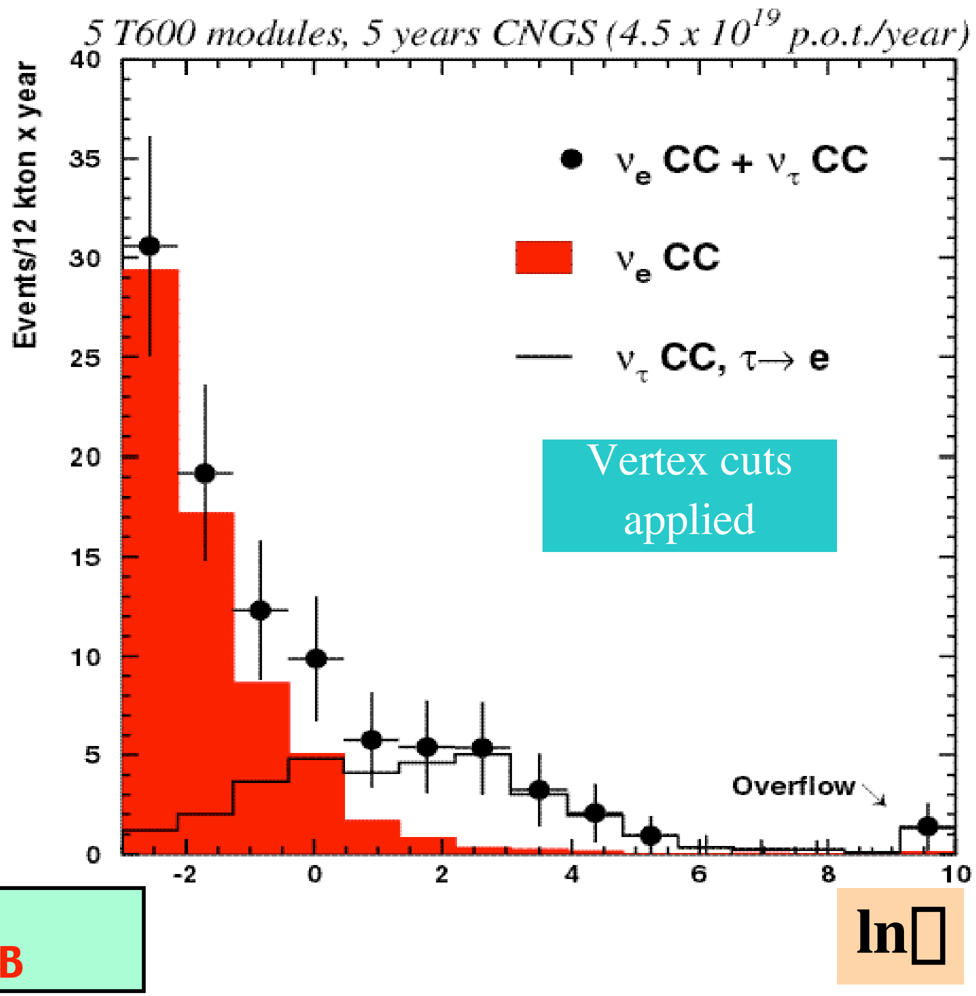
$\nu_e + \mathrm{Ar} \to e + \mathrm{jet}$

Charged current (CC)

□□ e search: 3D likelihood

- Analysis based on 3 dimensional likelihood
  - ➥ $E_{visible}$, P_T^{miss}, $□_l \equiv P_T^{lep}/(P_T^{lep}+P_T^{had}+P_T^{miss})$
  - ➥ **Exploit correlation between variables**
  - ➥ Two functions built:
    - L_S ([Evisible, P_T^{miss}, $□_l$]) (signal)
    - L_B ([Evisible, P_T^{miss}, $□_l$]) ($□_e$ CC background)
  - ➥ Discrimination given by

$$\ln □ \equiv L([\text{Evisible}, P_T^{miss}, □_l]) = L_S / L_B$$



□□□ □□ appearance search summary

ICARUS T3000 detector

(2.35 kton active LAr)

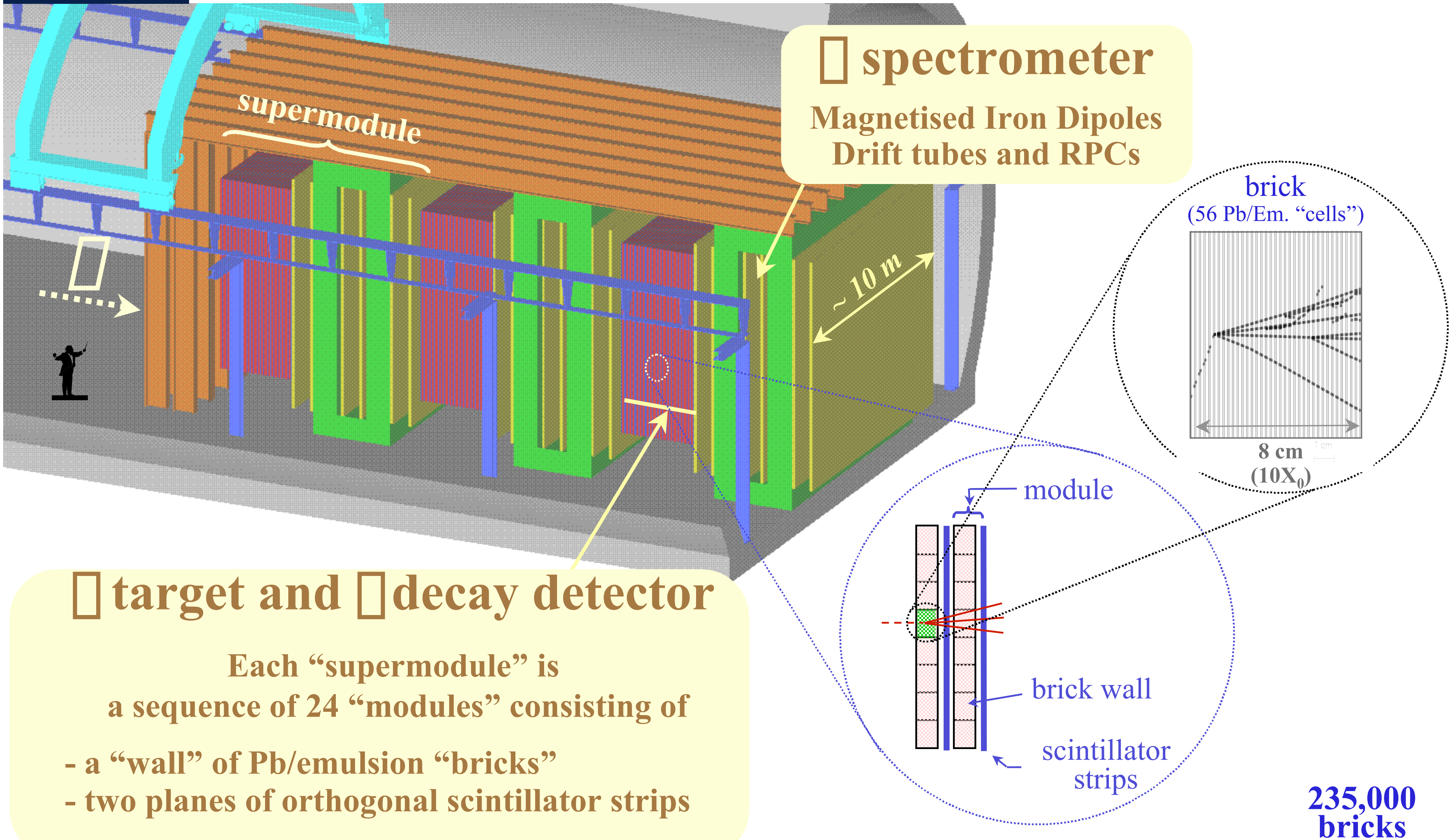
5 year CNGS “shared” running

(2.25 x 10^{20} p.o.t.)

τ decay mode	Signal $\Delta m^2 =$ 1.6×10^{-3} eV^2	Signal $\Delta m^2 =$ 2.5×10^{-3} eV^2	Signal $\Delta m^2 =$ 3.0×10^{-3} eV^2	Signal $\Delta m^2 =$ 4.0×10^{-3} eV^2	BG
$\tau \to e$	3.7	9	13	23	0.7
$\tau \to \rho$ DIS	0.6	1.5	2.2	3.9	< 0.1
$\tau \to \rho$ QE	0.6	1.4	2.0	3.6	< 0.1
Total	**4.9**	**11.9**	**17.2**	**30.5**	**0.7**

Super-Kamiokande: 1.6 < □m^2 < 4.0 at 90% C.L.

The OPERA detector structure



▯ spectrometer

Magnetised Iron Dipoles
Drift tubes and RPCs

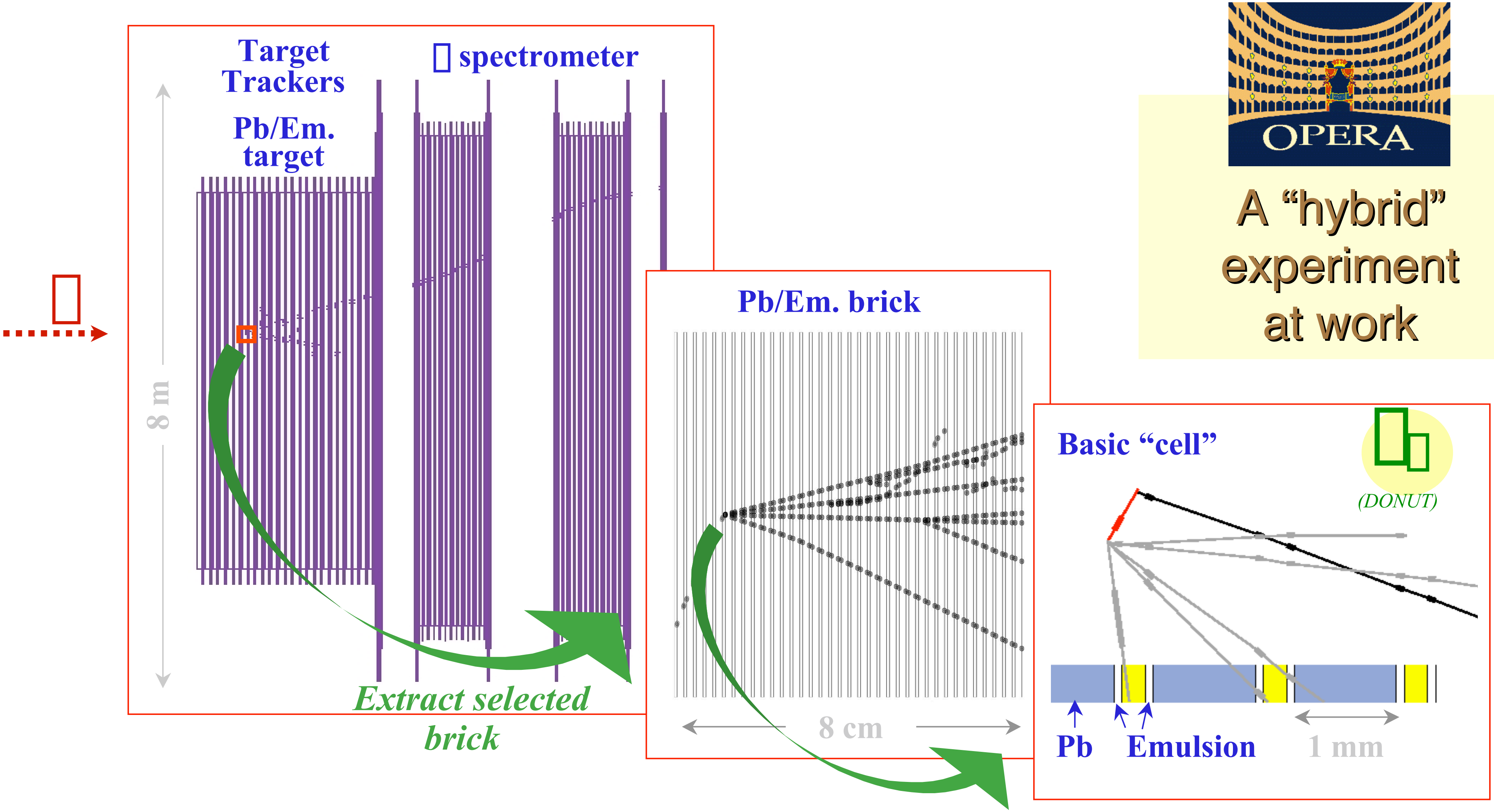
▯ target and ▯ decay detector

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

A “hybrid” experiment at work



Electronic detectors

- □ select □ interaction brick
- □ □ ID, charge and p

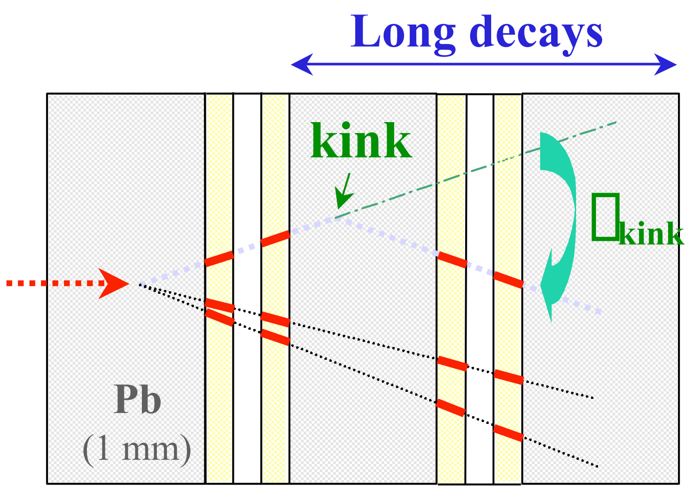
Emulsion analysis

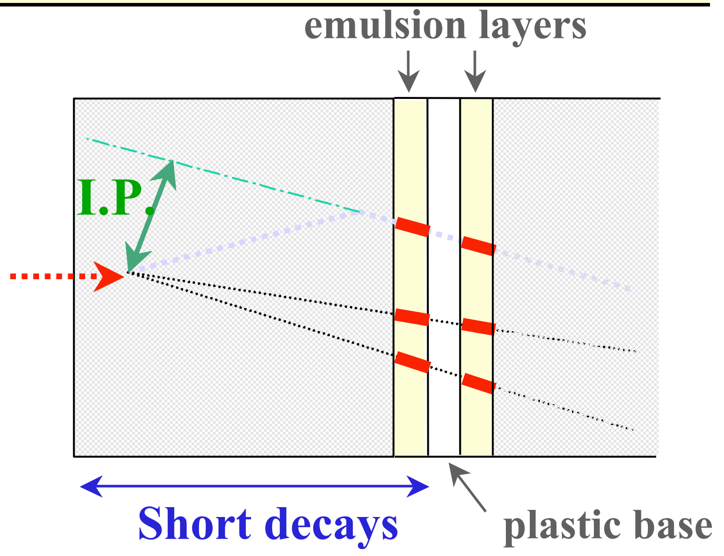
- □ vertex search
- □ decay search
- □ e/□ ID, kinematics

Expected number of events

5 year run with 1.8 kton average target mass, nominal □ flux
Full mixing, Super-Kamiokande best fit and 90% CL limits
as presented at the 2001 Lepton Photon Conference

Decay mode	***Signal*** *1.2□10□3*	***Signal*** *2.4*10-3*	***Signal*** *5.4*10-3*	***Bkgnd.***
□□ *e long*	**0.8**	**3.1**	**15.4**	**0.15**
□□ □ *long*	**0.7**	**2.9**	**14.5**	**0.29**
□□ *h long*	**0.9**	**3.4**	**16.8**	**0.24**
□□ *e short*	**0.2**	**0.9**	**4.5**	**0.03**
□□ □ *short*	**0.1**	**0.5**	**2.3**	**0.04**
Total	**2.7**	**10.8**	**53.5**	**0.75**





OPERA Status

➢ Achieved

- Studies, construction of full scale prototypes
- Detector design finalised
- Construction started, but “moratorium” following the CERN crisis
- Progress in automatic scanning in Europe and Japan
- □detection efficiency improved since CNGS approval
- Collaboration funded and organised for construction

➢ Detector construction and installation

- Large and complex detector, with a “challenging” schedule
- Prompt reaction to overcome problems arising from CERN crisis
- Aim: detector ready at beam start-up in 2006

4) Evidence for electron neutrino appearance

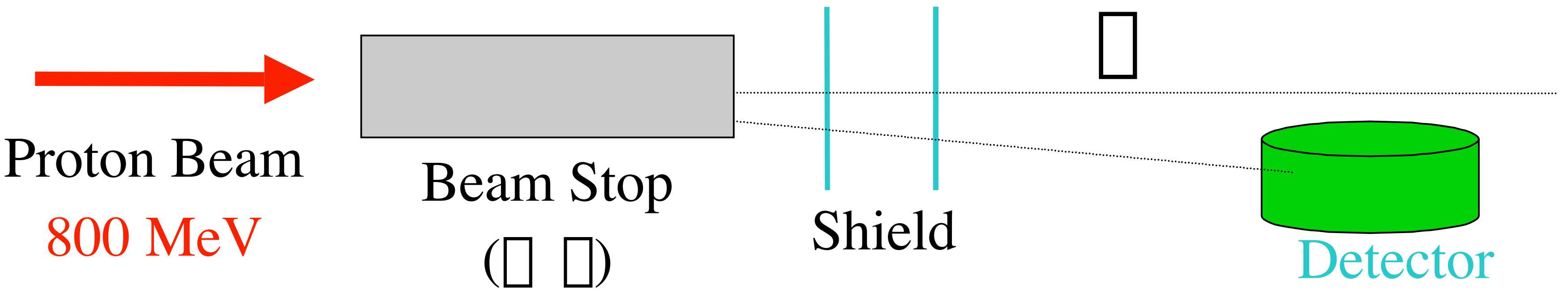
Phys.Rev.Lett.77:3082-3085,1996

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

with

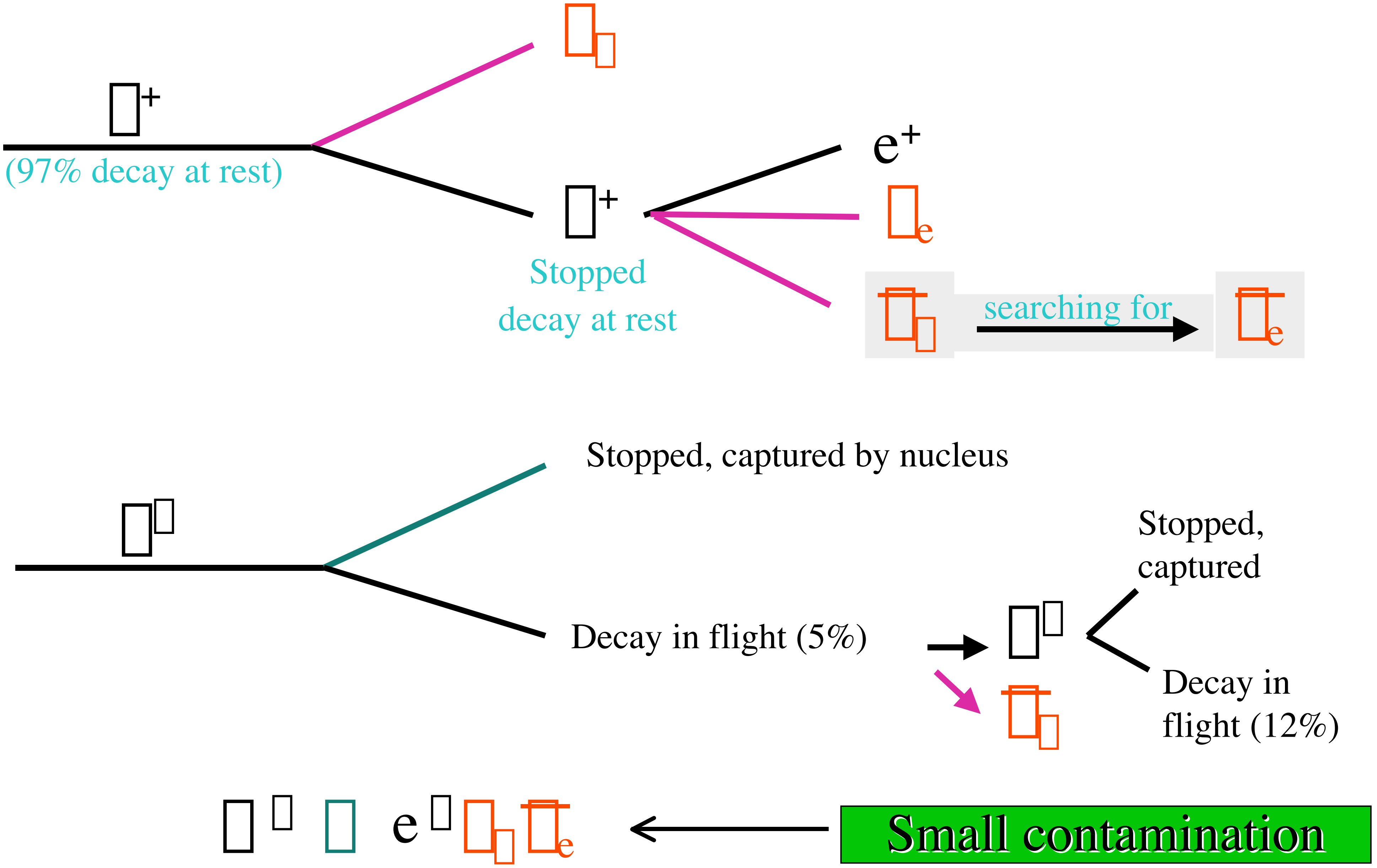
$\Delta m^{2} \approx O(1eV^{2})$ and small mixing

Medium Energy Accelerator



Detector	LSND (U.S.A.)	KARMEN (U.K.)
Accelerator	LAMPF	ISIS
Proton Current	1 mA	0.2 mA
Beam Pulse	500 □s 8.3 ms pause	2 x 100□s 20 ms pause
Mass	180 tons	56 tons
Distance	17 m	30 m
Angle with beam	17^0	90^0

Neutrinos produced from □ and □ decays



□+

(97% decay at rest)

□□

□+

Stopped
decay at rest

e+

□e

□□

searching for

□e

□□

Stopped, captured by nucleus

Decay in flight (5%)

□□

□□

Stopped,
captured

Decay in
flight (12%)

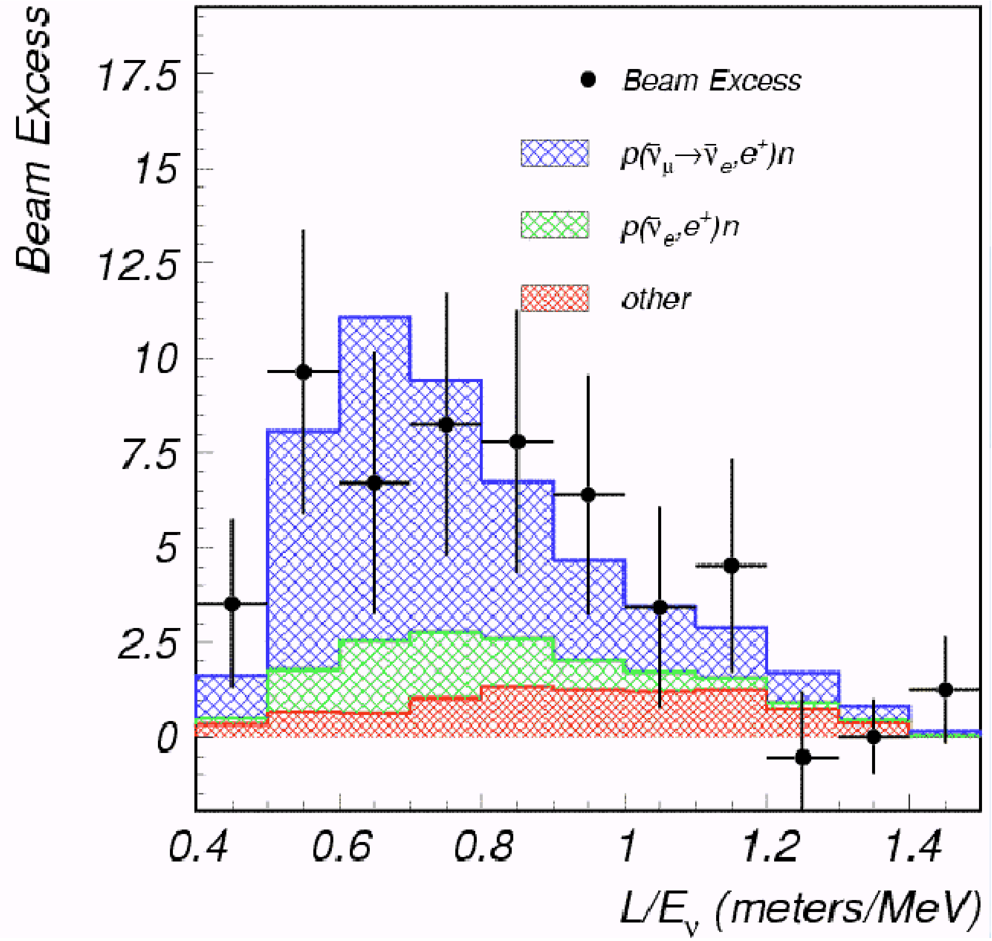
□□ □ e□□□□e

Small contamination

André Rubbia, ETH/Zürich, 4/18/02, Four Seas Conference

LSND DAR Oscillation Result

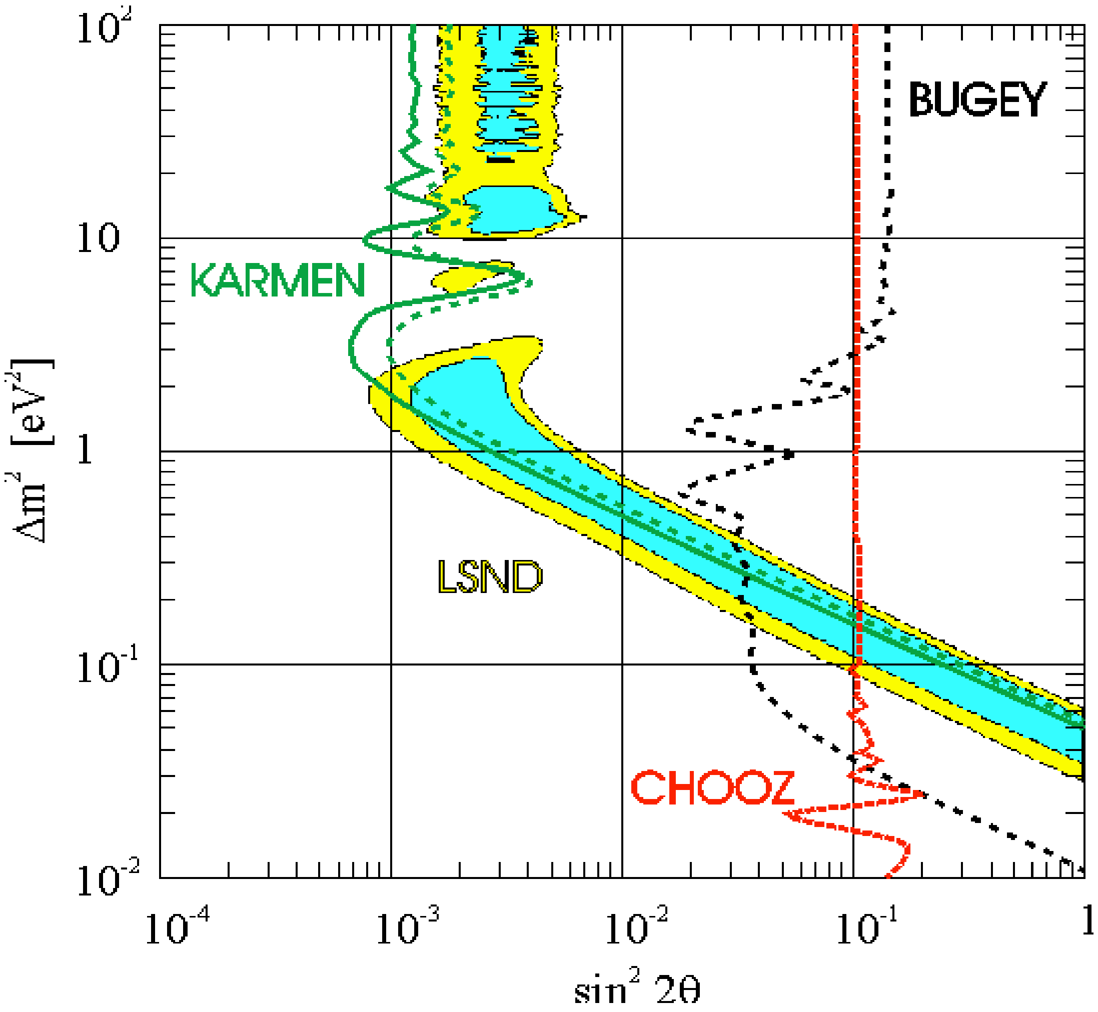
- Data collected at Los Alamos 800 MeV proton accelerator
- Data collected 1993-1998
- Signal reaction (DAR):
  - $\nu_e p \to e^+ n$ followed by n-capture on protons $np \to d+\gamma(2.2MeV)$
- Observed excess:
  - 87.9±22.4±6 events
  - 3.6σ statistical significance
  - **4 times the expected rate from beam anti-ν_e**
- Could be explained in terms of neutrino flavor oscillation
  - Probability: (0.264±0.067±0.045)%
  - Apparently in contrast with solar and atmospheric data which favor large mixing angles!



LSND and KARMEN Results

A small window of opportunity …

- **KARMEN limits**
  - Solid curve calculated with the Feldman & Cousins approach
  - Dashed curve is experiment's sensitivity
- **LSND signal region**
  - + 90% Lmax - L < 2.3
  - + 99% Lmax - L < 4.6



LSND Implications

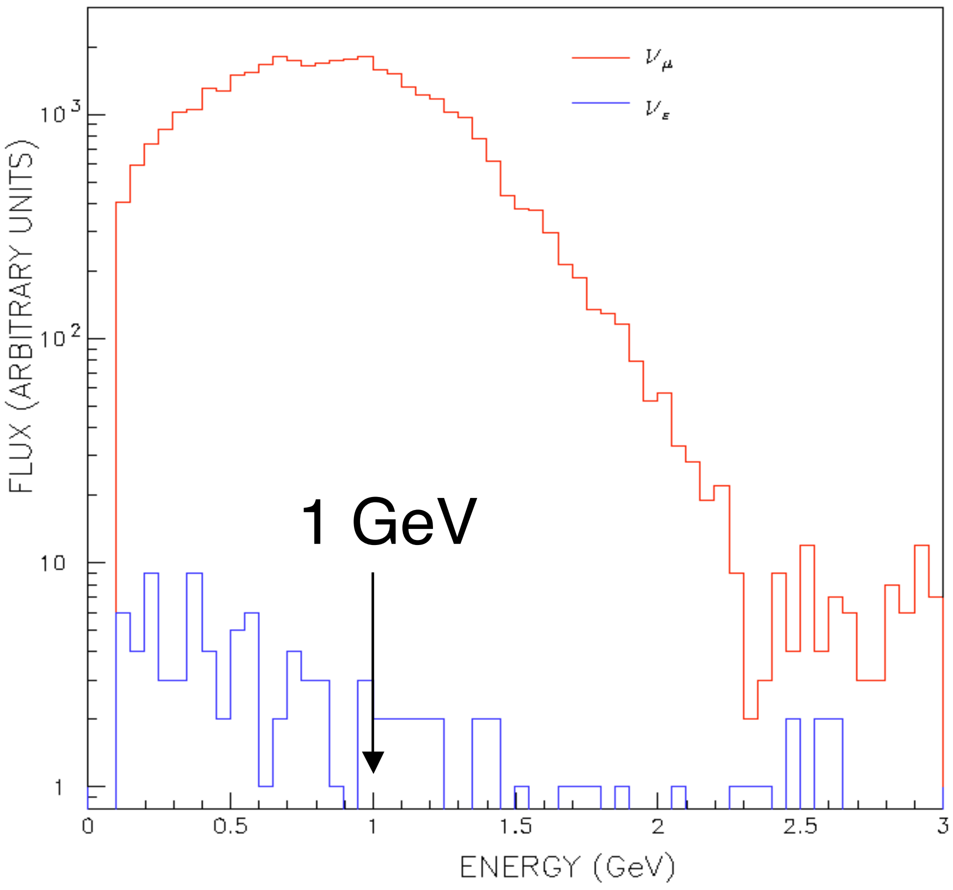
1. **If we believe all experimental results are due to neutrino flavor oscillations**
   - What we know from other experiments
     - Atmospheric ν_μ's oscillate at $\Delta m^2 \sim 10^{-3}$ eV^2 with maximal mixing: $\nu_\mu \to \nu_\tau$ favored
     - Solar ν_e's oscillate at $\Delta m^2 < 10^{-4}$ eV^2 (see J. Bouchez's talk): $\nu_e \to \nu_{\mu/\tau}$ favored
   - LSND results has $\Delta m^2 \sim 1$ eV^2 for $\bar{\nu}_\mu \to \bar{\nu}_e$
     - hence require ≥ 4 neutrino mass states
   - Only 3 active flavors (LEP precision data)
     - hence sterile ν's are required

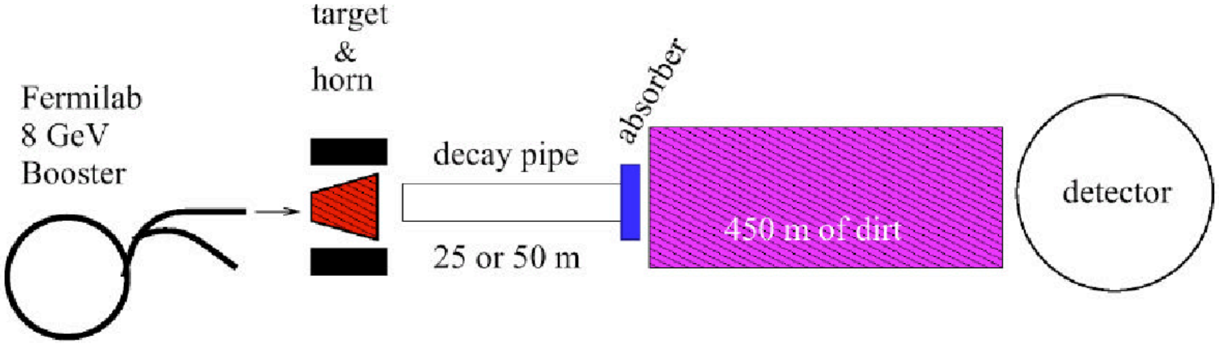
       OR

     - neutrino ≠ antineutrino
2. **Or we believe all experiments but not all effects are due to neutrino flavor oscillations** (new LFV contact interaction, exotic decays, …)
3. **Or we do not believe some experiments…**

The MiniBoone Neutrino Beam

- **8 GeV proton from FNAL Booster**
- Repetition rate: 5 Hz
- Average neutrino energy 1 GeV
  - ➥ $L/E_{boone} \approx L/E_{LSND} \approx 1$ km/GeV
- Intrinsic ν_e contamination can be ..
  - ➥ Inferred from ν_μ events
  - ➥ Simulated using hadroproduction measurements
  - ➥ Measured using muon counters in and around the decay pipe
  - ➥ Checked by comparing 50m and 25m absorber results



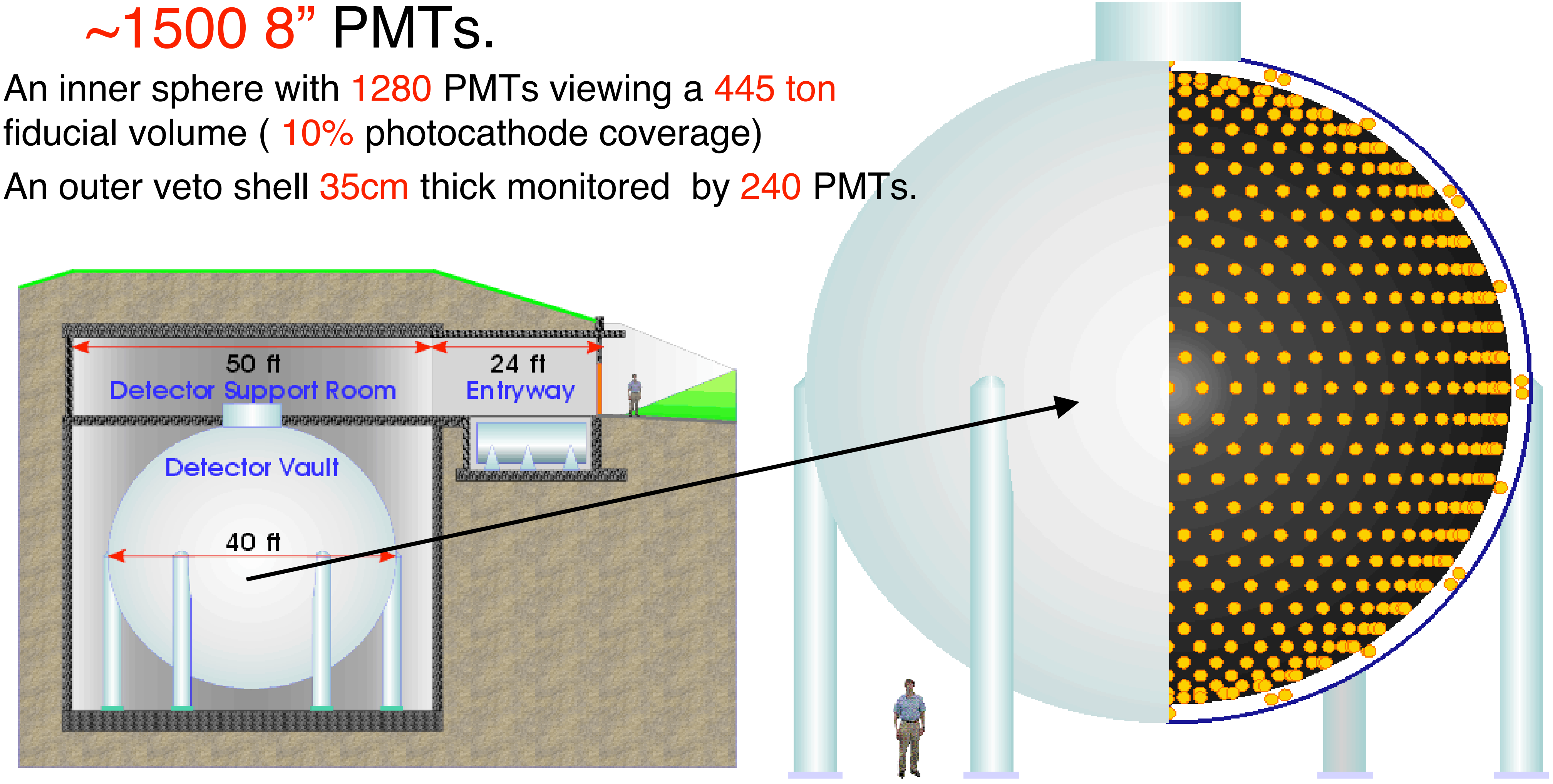


The MiniBoone Detector

- The detector is a 40ft (12.2m) diameter sphere filled with 800 tons of pure mineral oil and instrumented with ~1500 8” PMTs.

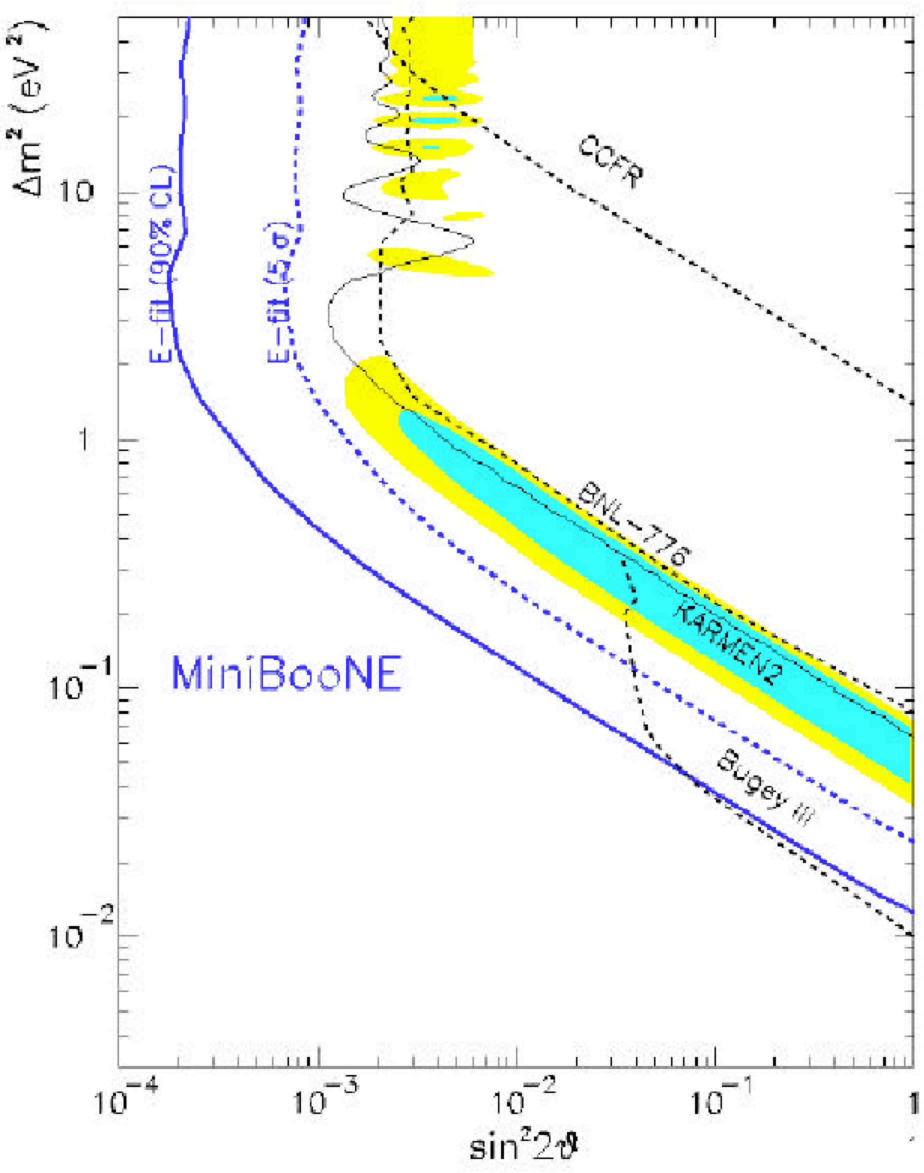
An inner sphere with 1280 PMTs viewing a 445 ton fiducial volume (10% photocathode coverage)

An outer veto shell 35cm thick monitored by 240 PMTs.



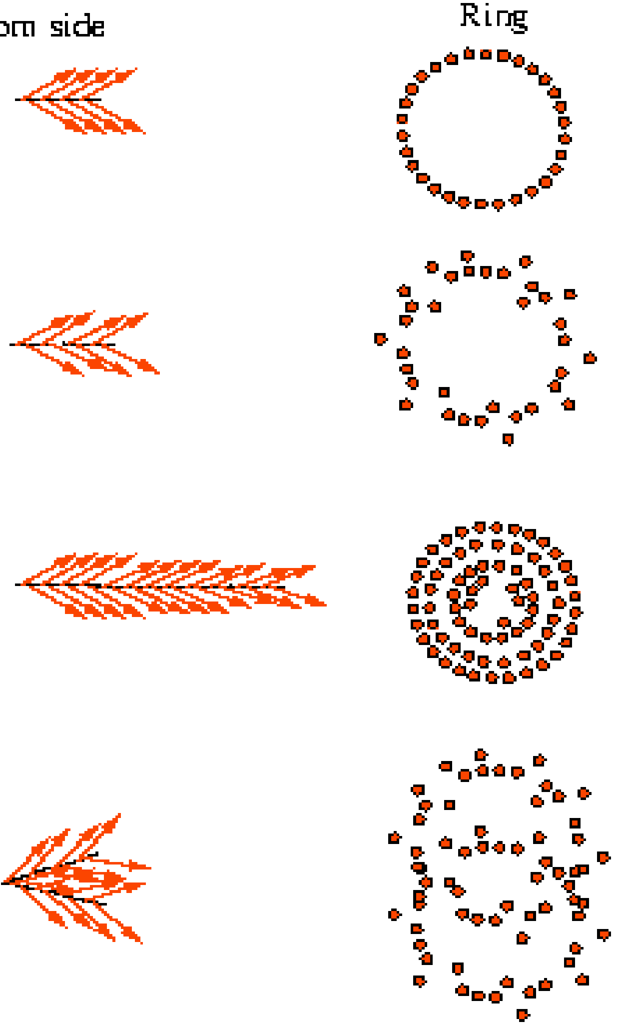
MiniBoone at FNAL

- Within two years of running, should
  - **confirm or refute whether LSND excess is due to neutrino flavor oscillations** (if it refutes LSND, it will still not explain the LSND excess !)
- Start physics data taking in June 2002:
  - All civil construction projects for MiniBooNE are essentially complete.
  - The detector instrumentation is complete and the oil fill is well under way.
  - MiniBooNE is on schedule for taking first data later this summer.
- A fundamental result for the overall understanding of the neutrino data in terms of neutrino oscillations !!!
- In case of positive result from MiniBOONE the roadmap for the future neutrino physics would have to be re-thought !

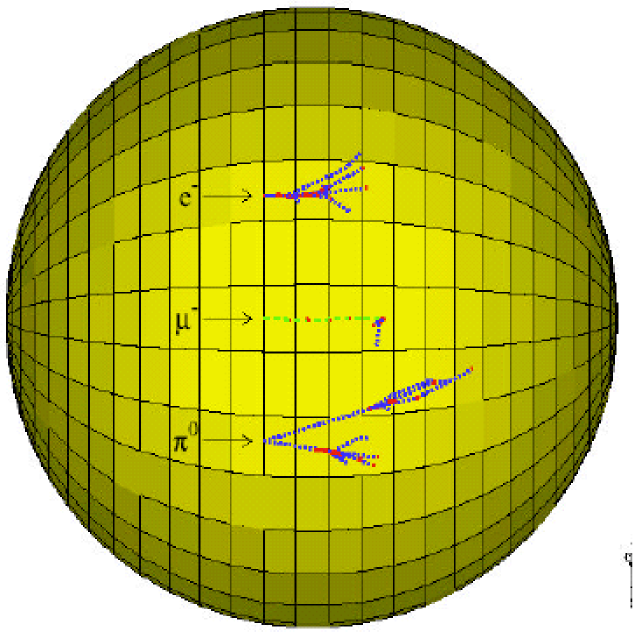


Event Reconstruction

- MiniBooNE will reconstruct quasi-elastic ν_e interactions by identifying the characteristic Cerenkov rings produced by the electrons ...



Pions,…	short track, no multiple scattering	Sharp Ring
Electrons:	electrons: short track, mult. scat., brems.	Fuzzy Ring
Muons:	muons: long track, slows down	Sharp Outer Ring with Fuzzy Inner Region
π^0:	neutral pions: 2 electron-like tracks	Two Fuzzy Rings



Approximate # of Events after 2 Years

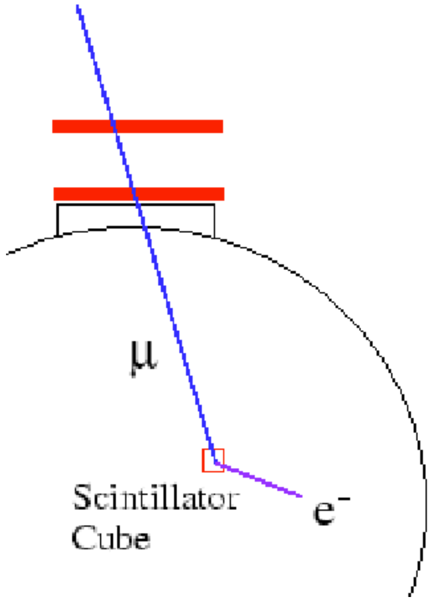
Reaction	# of Events	
ν_μ C –> μ^- N*	500,000	
ν_μ C –> ν_μ π^0 N*	50,000	
ν_μ e –> ν_μ e	100	
ν_e C –> e^- N*		
LSND–based ν_μ–>ν_e	1,000	Signal!
*Intrinsic ν_e background	1,500	
*μ^- mis–ID background	500	Backgrounds!
*π^0 mis–ID background	500	

* we will measure the backgrounds!

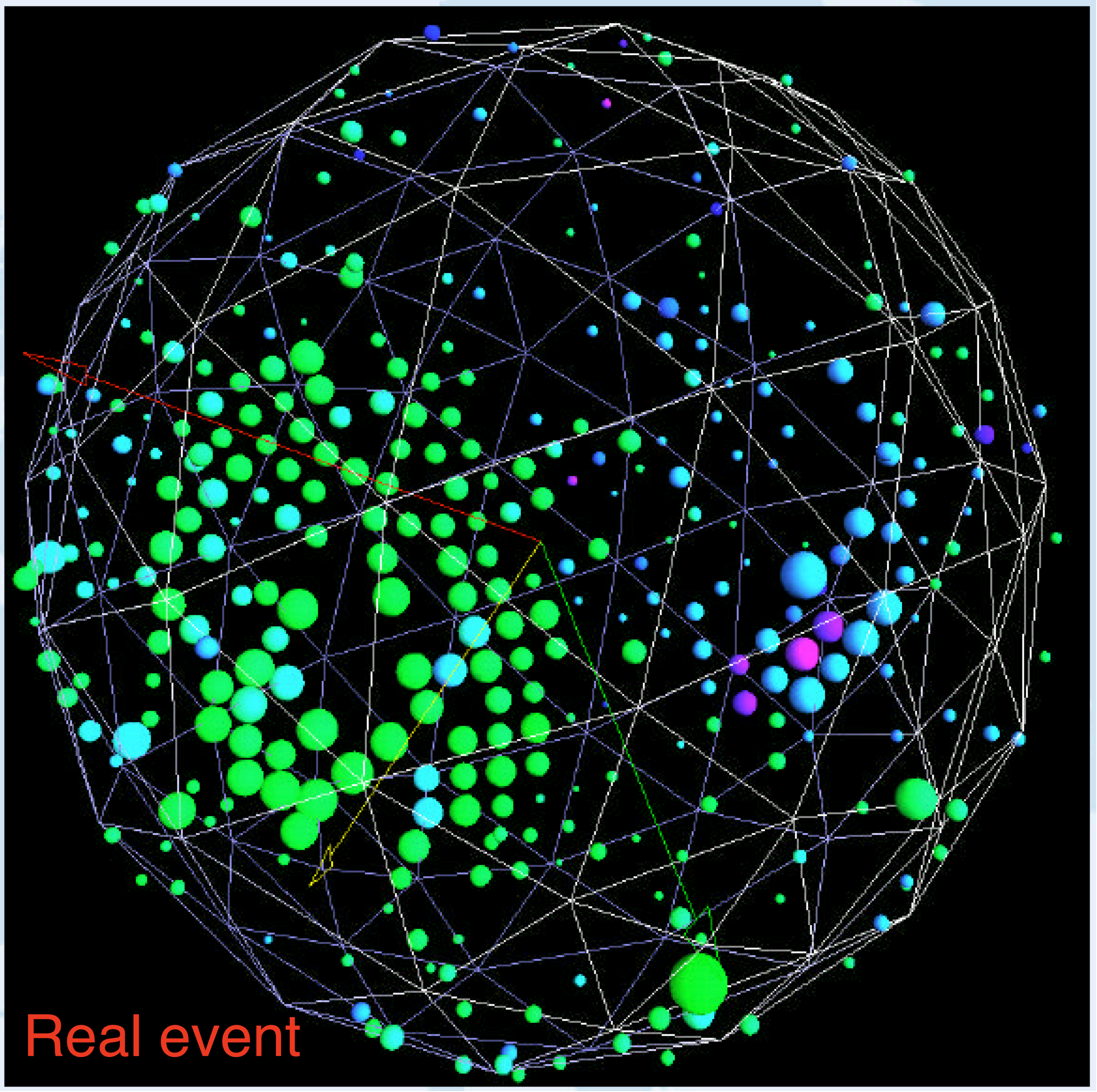
P. Kasper, NBI 2002

MiniBoone “calibration μ tracker”

Scintillator strips to tag cosmic muons



Study stopping muons and Michel electrons



5) Search for

subleading electron neutrino appearance

$$\nu_\mu \rightarrow \nu_e$$

with

$$\Delta m^2 \approx (1 - 4) \times 10^{-3} eV^2 \qquad \sin^2 2\theta_{13} \neq 0$$

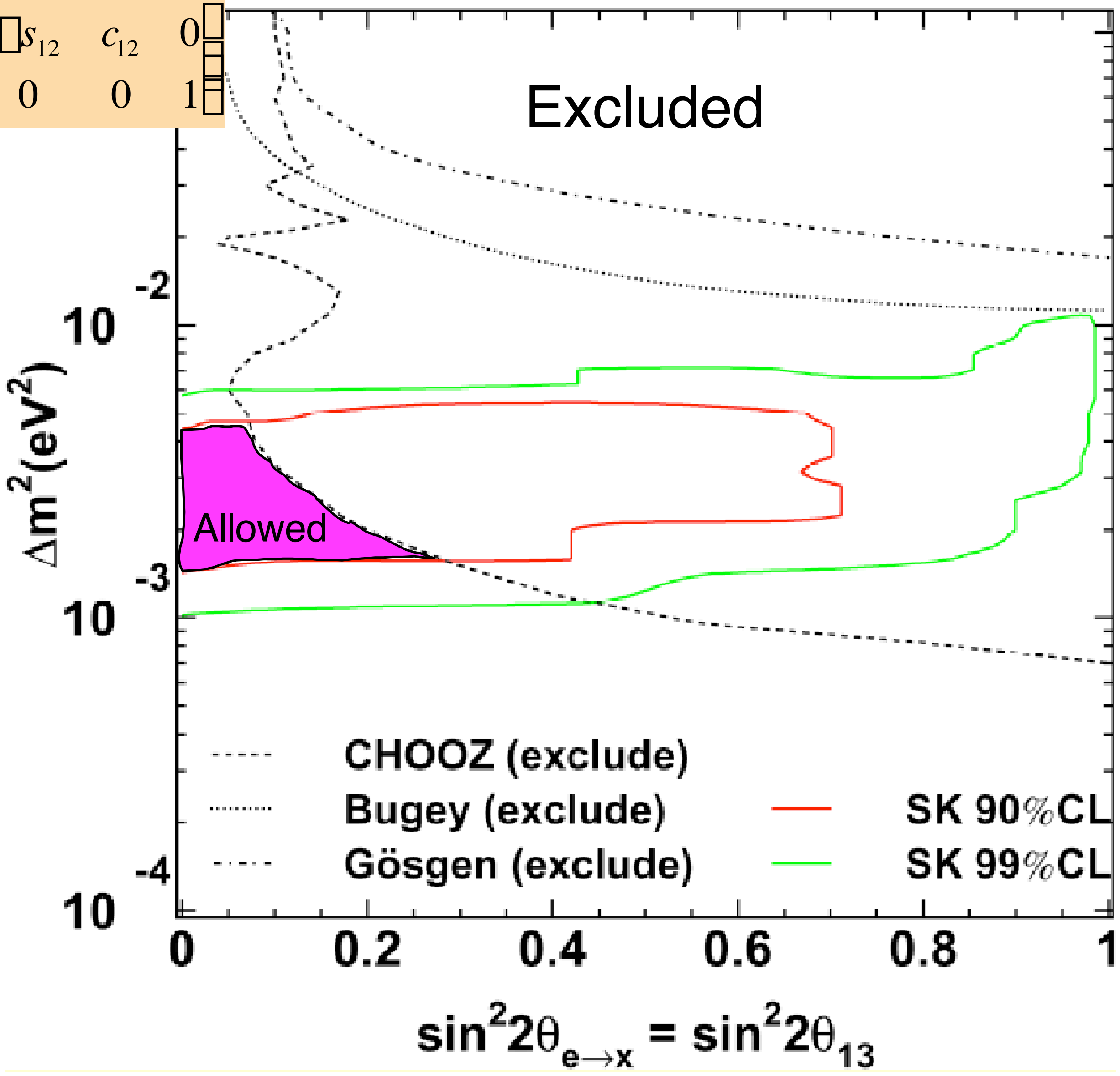
$$P(\nu_e \rightarrow \nu_\mu) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{32} L/4E_\nu)$$

for $\Delta m^2_{21} (L/4E_\nu) << 1$

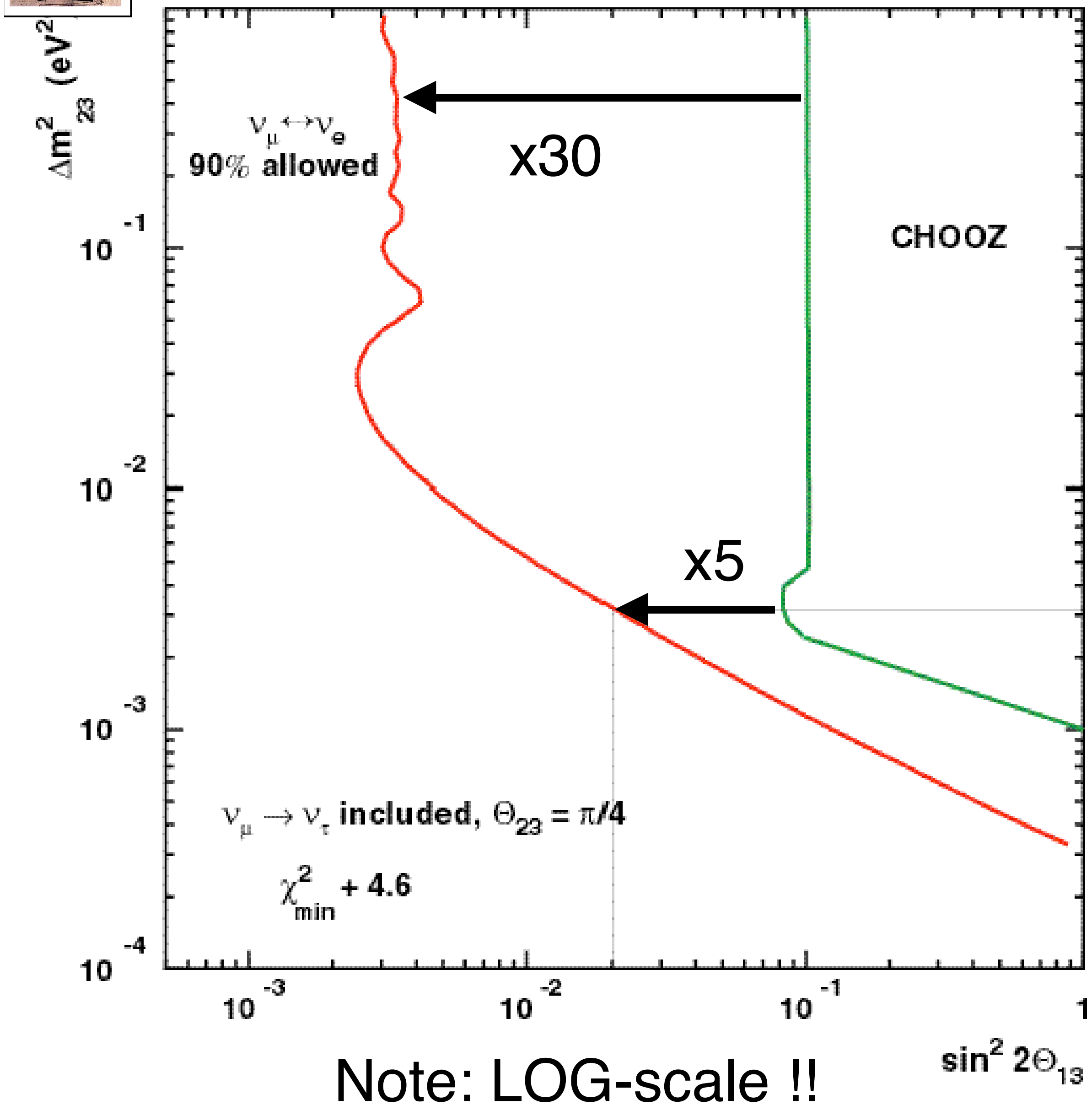
Limits on θ_{13}

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \boxed{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Knowledge dominated by CHOOZ reactor disappearance experiment
- Knowledge from atmospheric neutrinos limited due to accidental cancellation (flux muon ≈ 2x flux electron)
- θ_{13} is crucial to prove the existence of the 3x3 mixing matrix !!!



Expected sensitivity to θ_{13}



Note: LOG-scale !!

ICARUS
5 years dedicated SPS
2.35 kton fid. mass

Sensitivity assuming both $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_e$ at the same Δm^2 (three family mixing)

$$\sin^2 2\theta_{13} > 2 \times 10^{-2}$$
$$for \;\; \Delta m^2_{32} = 3 \times 10^{-3} eV^2$$

Search for $\theta_{13}>0$

$\Delta m^2_{32}=3.5\times10^{-3}$ eV^2; $\sin^2 2\theta_{23}=1$

5 years dedicated SPS
2.35 kton fid. mass

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

$\Delta m^2_{23} = 3.5\times10^{-3}$ eV^2, $\theta_{23} = 45^o$

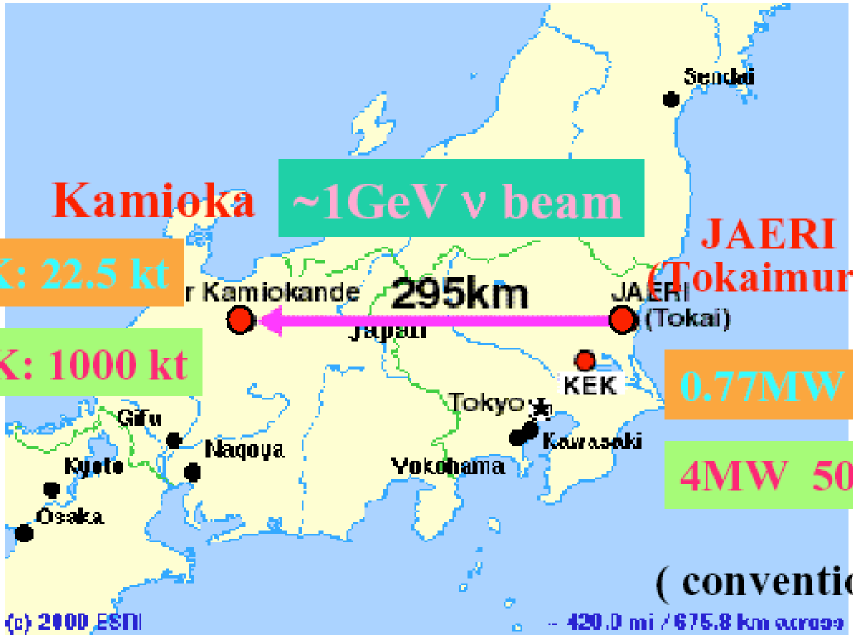
θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC	$\nu_\mu\to\nu_\tau$ $\tau\to e$	$\nu_\mu\to\nu_e$	Total	Statistical significance
9	0.095	79	74	84	237	6.8σ
8	0.076	79	75	67	221	5.4σ
7	0.058	79	76	51	206	4.1σ
5	0.030	79	77	26	182	2.1σ
3	0.011	79	77	10	166	0.8σ

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

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

Superbeam neutrinos and Neutrino factories

The knowledge of θ_{13} is crucial to know if the δ phase (CP/T violation) could be observable !



Kamioka

~1GeV ν beam

Super-K: 22.5 kt

Hyper-K: 1000 kt

JAERI (Tokaimura)

0.77MW 50 GeV PS

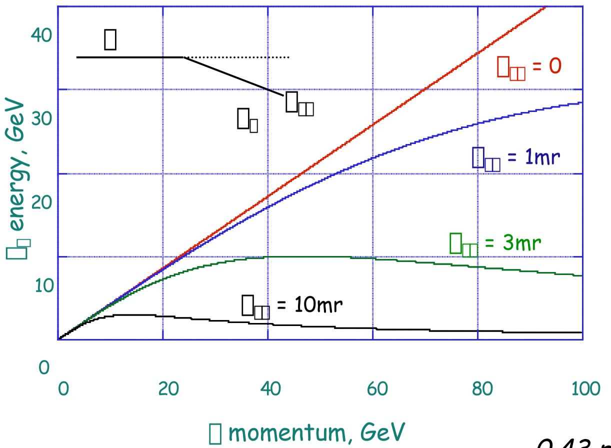
4MW 50 GeV PS

(conventional ν beam)

Phase-I (0.77MW + Super-K)

Phase-II (4MW+Hyper-K) ~ Phase-I × 200

Off-axis beams

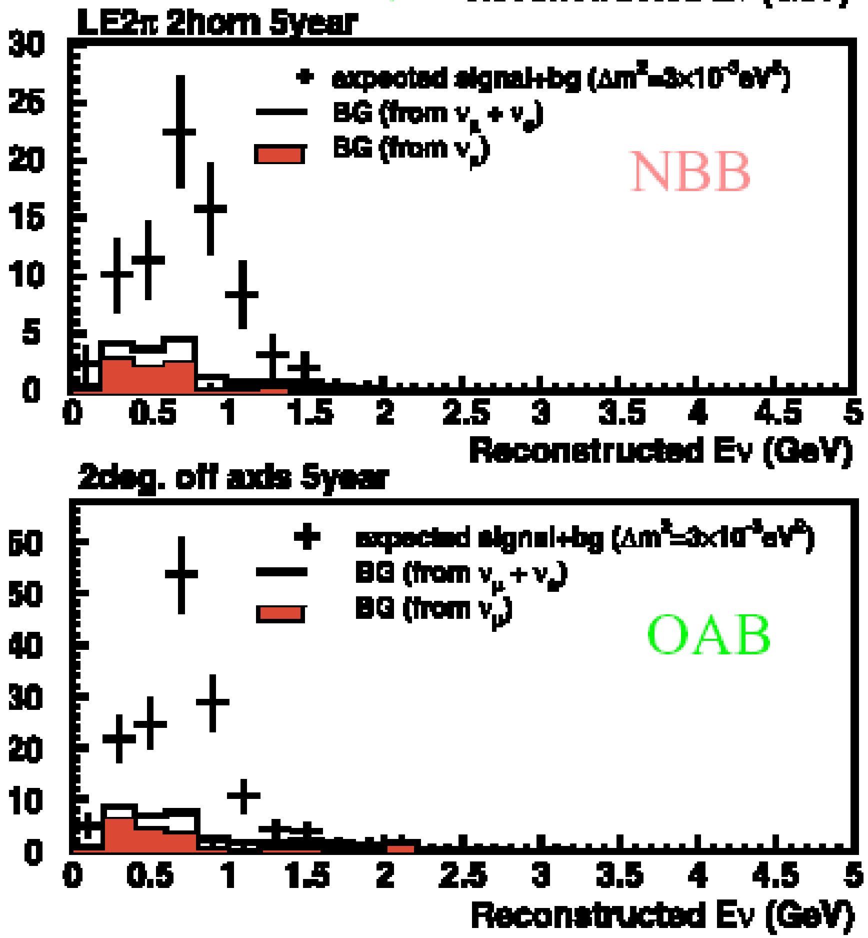


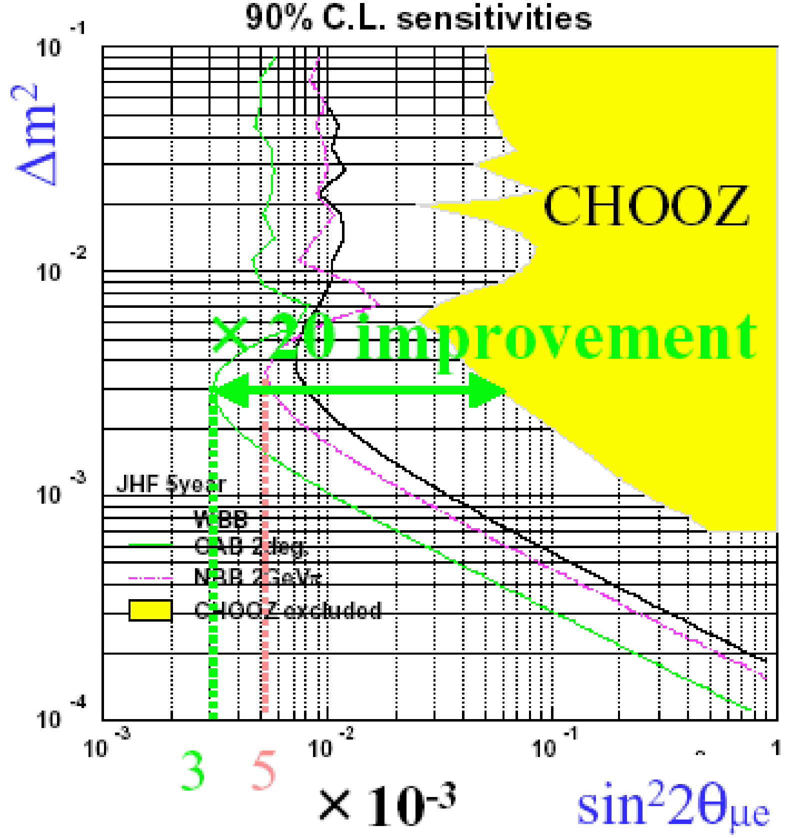
$$E_\nu = \frac{0.43\, p_\pi}{1+(\gamma\theta_{\pi\nu})^2}$$

ν_e appearance

Background rejection against NC π^0 is improved.

$\sin^2 2\theta_{\mu e}=0.05$ ($\sin^2 2\theta_{\mu e} \equiv 0.5\sin^2 2\theta_{13}$)





$$\sin^2 2\theta_{13} > 6 \times 10^{-3}$$

Ph2me, Ph2he from right[17]
A.Para, hep-ph/0005012)

Nakaya, NUFACT01

Conclusions: The roadmap

- The 80-90’s have seen a renaissance of neutrino physics.
  - Two surprises: neutrino masses and neutrino mixing
  - This *is* “new physics beyond the SM”
- A broad experimental has been triggered by those hints in order to
  - Cross-check the evidences, certify the neutrino flavor patterns and to measure the oscillation parameters more precisely
- After the current round of running or planned experiments, two very important parameters of the neutrino mixing will still have to be measured !
  - θ_{13} and the δ-phase
  - A program for >2010’s and beyond
- In case of positive result from MiniBOONE the roadmap for the future would have to be re-thought !