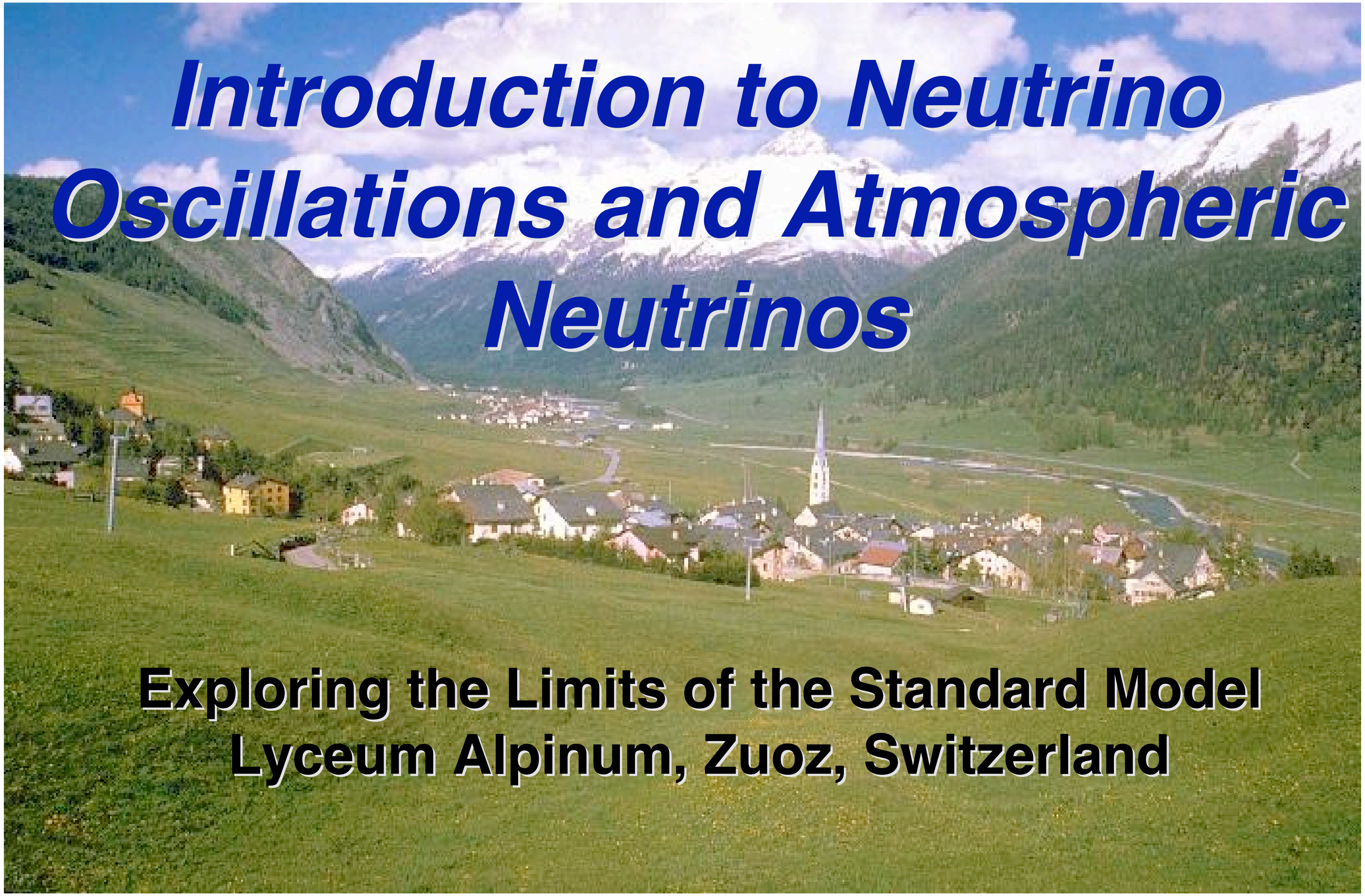
Introduction to Neutrino Oscillations and Atmospheric Neutrinos

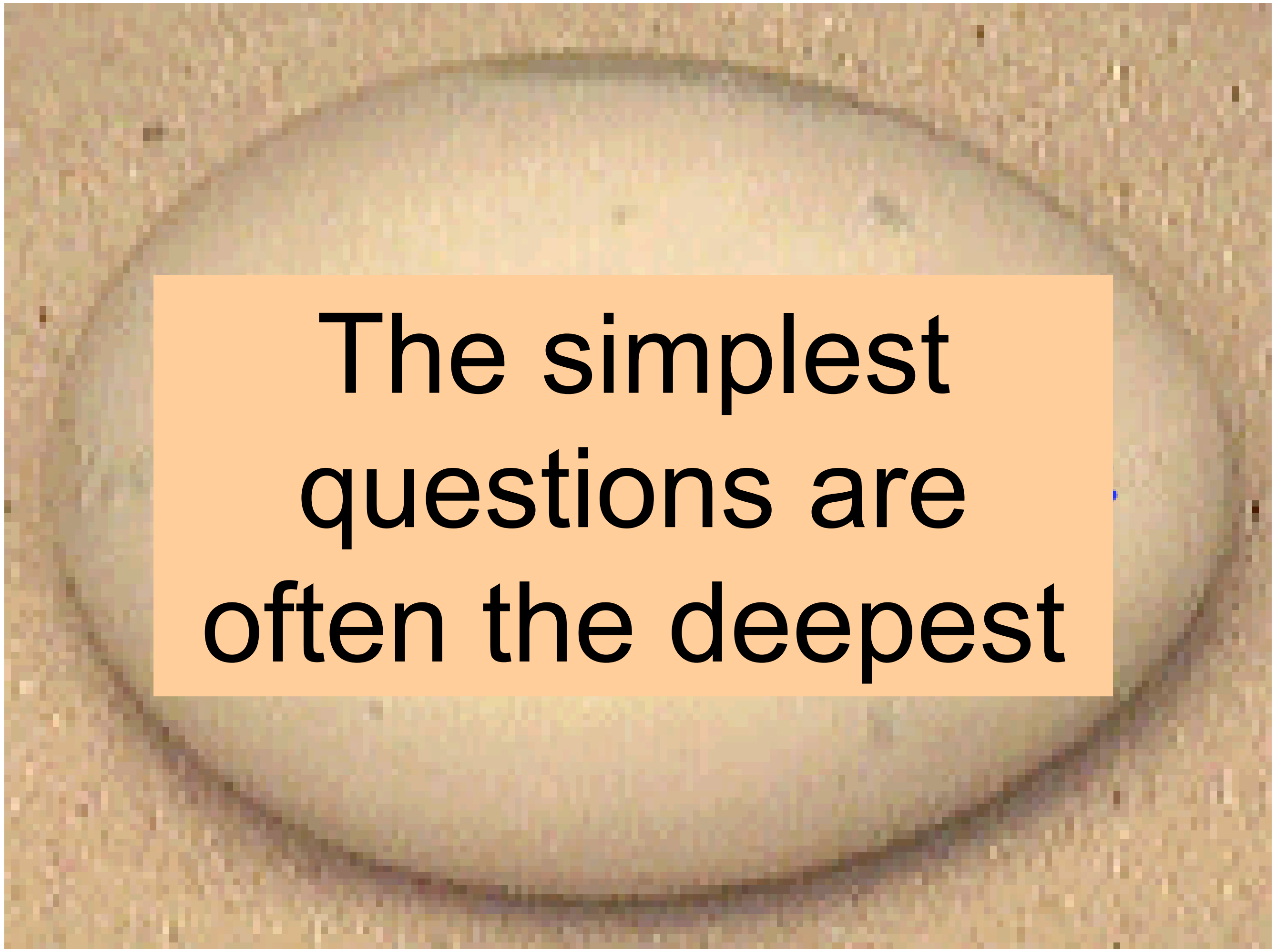


Exploring the Limits of the Standard Model
Lyceum Alpinum, Zuoz, Switzerland

André Rubbia
ETH Zürich

August 18-24, 2002

Why neutrino physics?



Neutrinos might help us answer the philosophical question: WHY ARE WE HERE ?

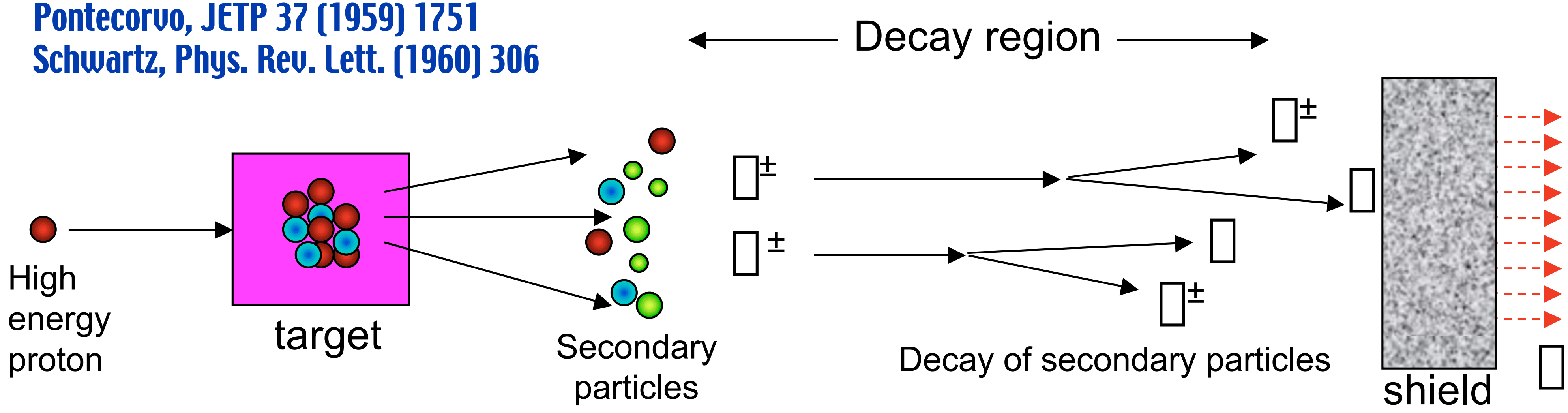
1) The neutrino flavor

$$\nu_\mu \neq \nu_e$$

Intense high energy neutrino sources (≈1960)

It was realized that high energy accelerators could be used to produce intense high-energy neutrino beams!

Pontecorvo, JETP 37 (1959) 1751
Schwartz, Phys. Rev. Lett. (1960) 306



The birth of "accelerator neutrino physics"...

$\pi^\pm \to \mu^\pm + \nu_\mu$?

While the technique has been perfected (in particular with the help of magnetic focalizing systems), the basic principle is still the same used today in modern neutrino accelerator experiments

The first accelerator neutrino beam (1962)

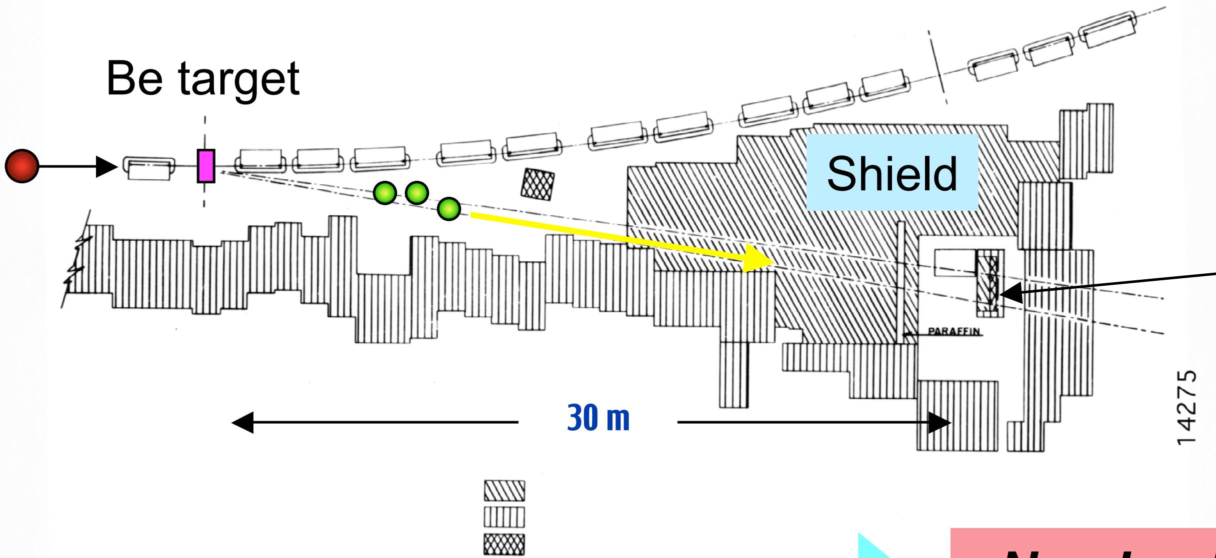
In 1962 at the Brookhaven AGS accelerator

proton energy : 15 GeV

proton intensity: 400’000’000’000 protons/pulse

3000 pulses/day

neutrinos: energy≈1 GeV, mostly ν_{μ} ?



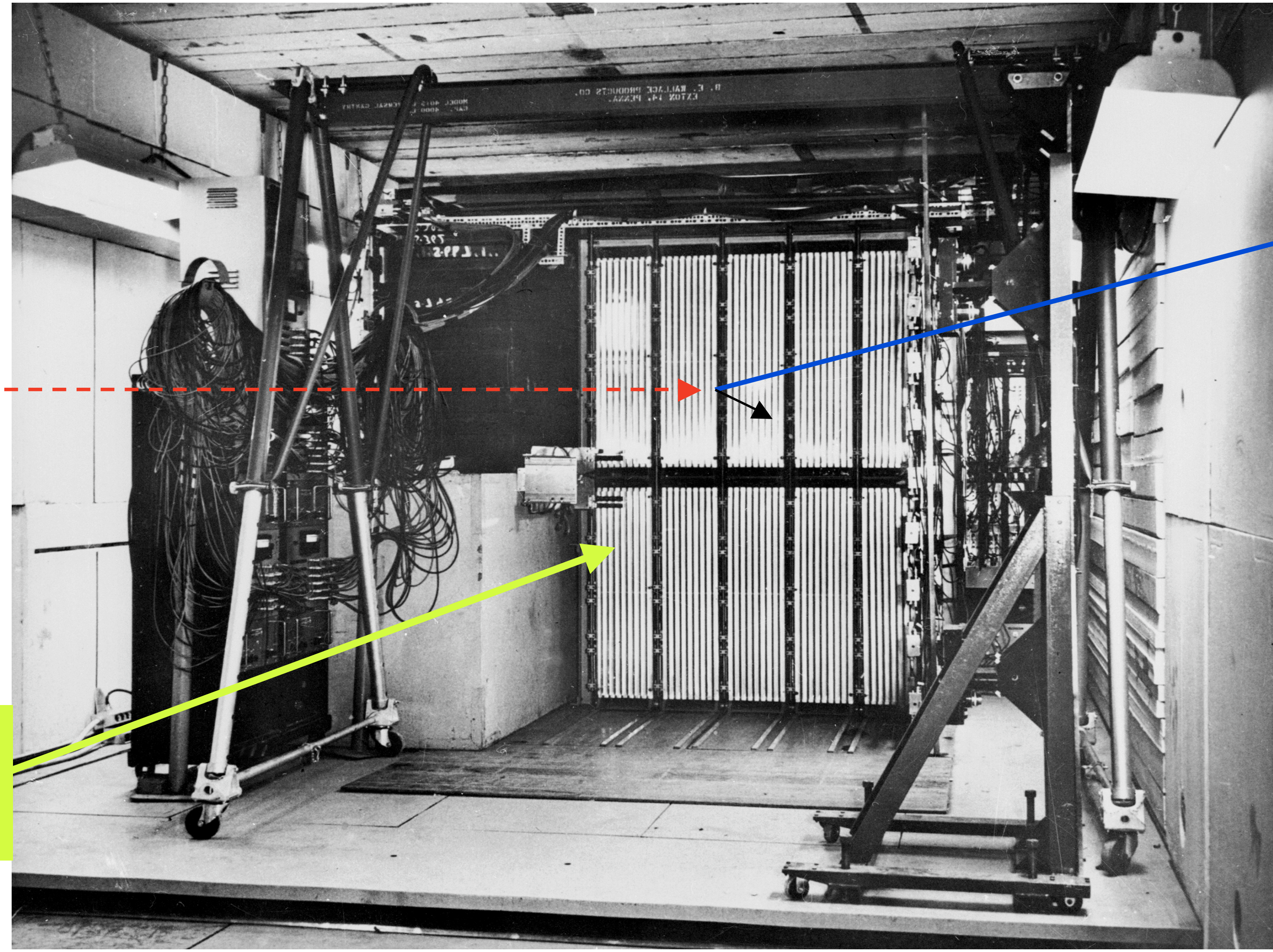
1 neutrino interaction per 1000 kg per day!

Need a detector with large mass able to distinguish electrons from muons !

BNL-Columbia experiment (1962)

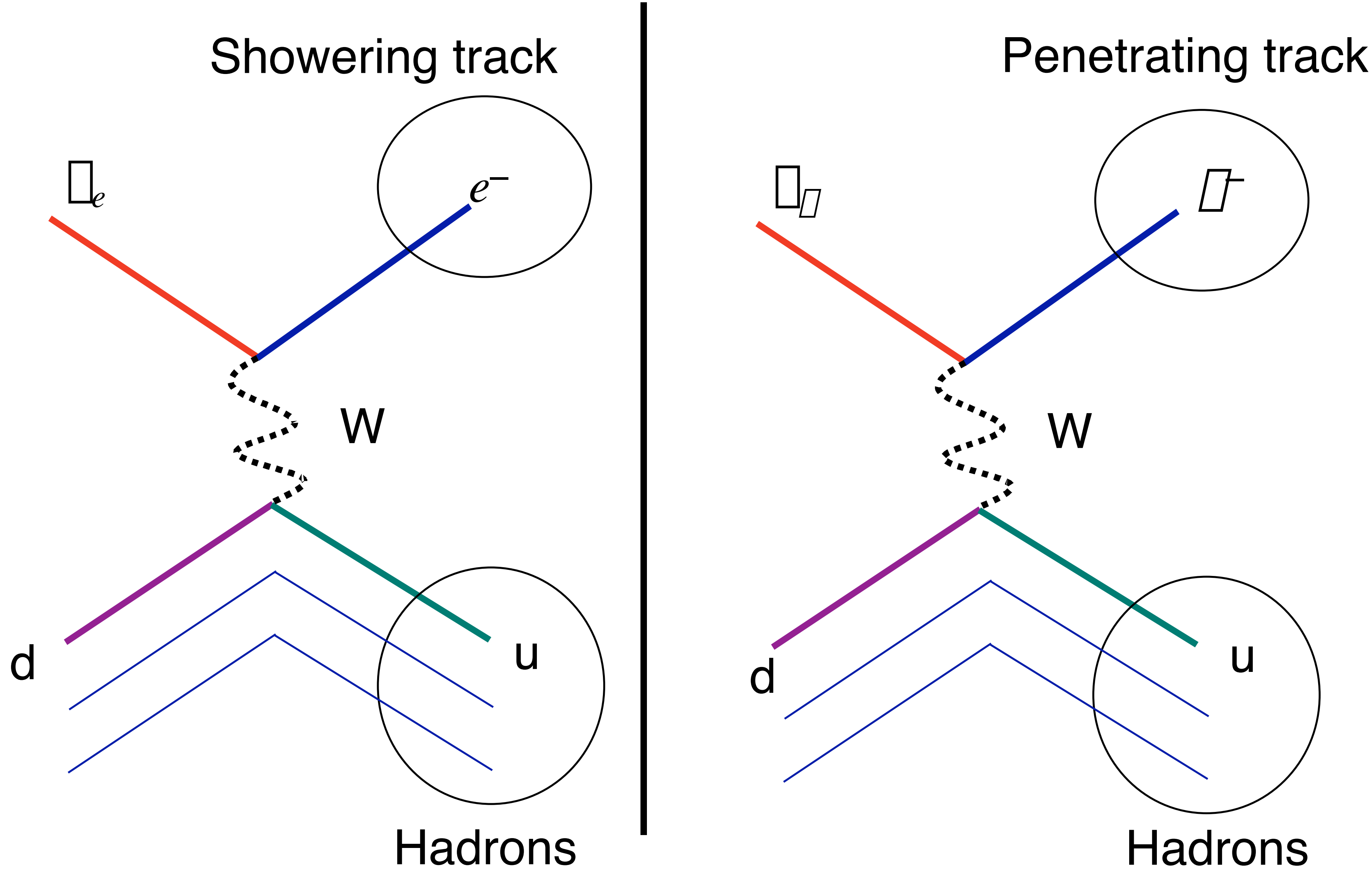
10 ton “spark chamber” detector

Danby, Gaillard, Goulianos, Lederman, Mistry, Steinberger, Schwartz, Phys. Rev. Lett. 9 (1962) 36

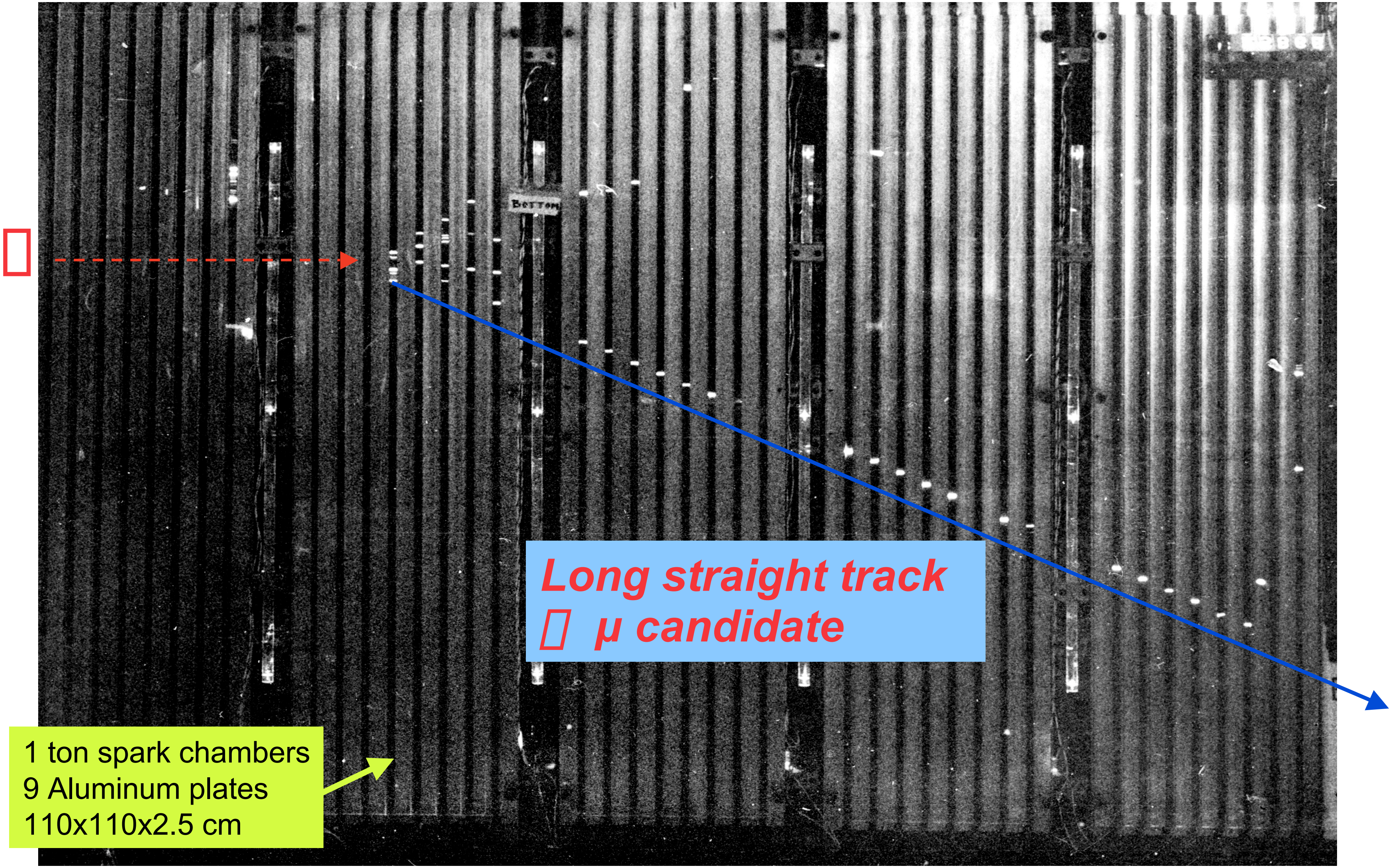


1 ton spark chambers
9 Aluminum plates
110x110x2.5 cm

Neutrino-nucleon charged current interactions

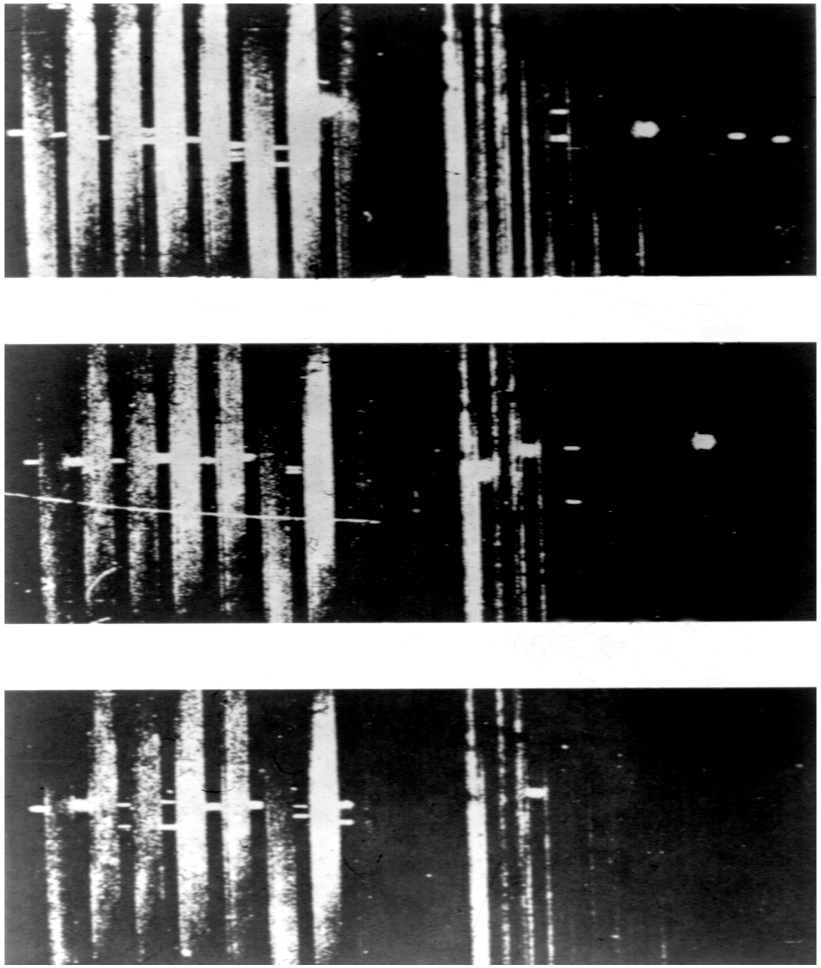


One “muon-like” event in spark chamber



Results from BNL-Columbia experiment

400 MeV electron test beam



	Number of events
Single tracks	34
Multi tracks	22
“Showers”	**8**

Only 2 are compatible with electrons

$$\nu_e \neq \nu_\mu$$

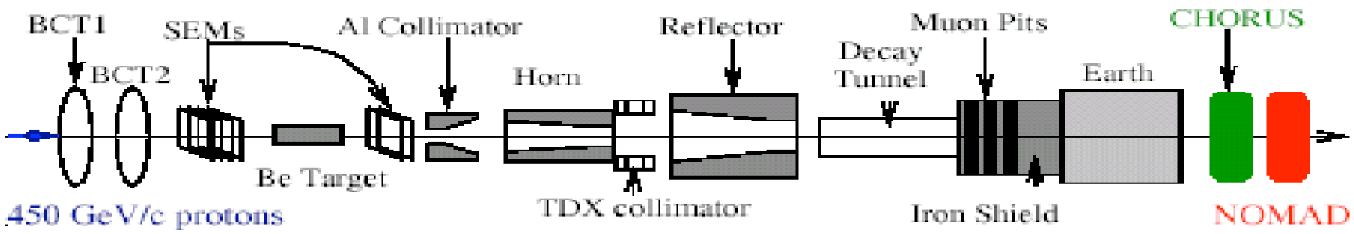
2) Three distinct neutrino flavors

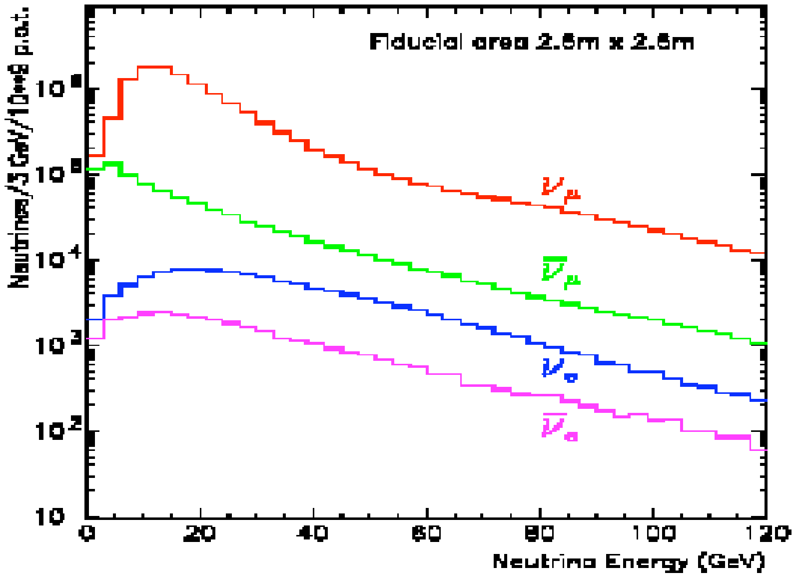
$$\nu_e \neq \nu_\mu \neq \nu_\tau$$

Alias "search for neutrino oscillations at short baseline"
FNAL E531, CHARM-II, CCFR, etc..
Recently CHORUS, NOMAD

The SPS neutrino beam

- Mean distance from ν source (π, K decays): NOMAD ~ 620m, CHORUS ~600m.





- Wide Band Beam: broad energy spectra.
  - Main component average energy ~25 GeV
  - Antineutrino contamination <6%, ν_e ~1%
  - Prompt ν_τ negligible

Assuming individual lepton flavor conservation at production vertex

The detectors

Hybrid detector

- Active emulsion target

⇒ locate interaction and decay vertices

- Electronic detector

⇒ predict tracks in emulsion + kinematics

Electronic detector

- High resolution tracking

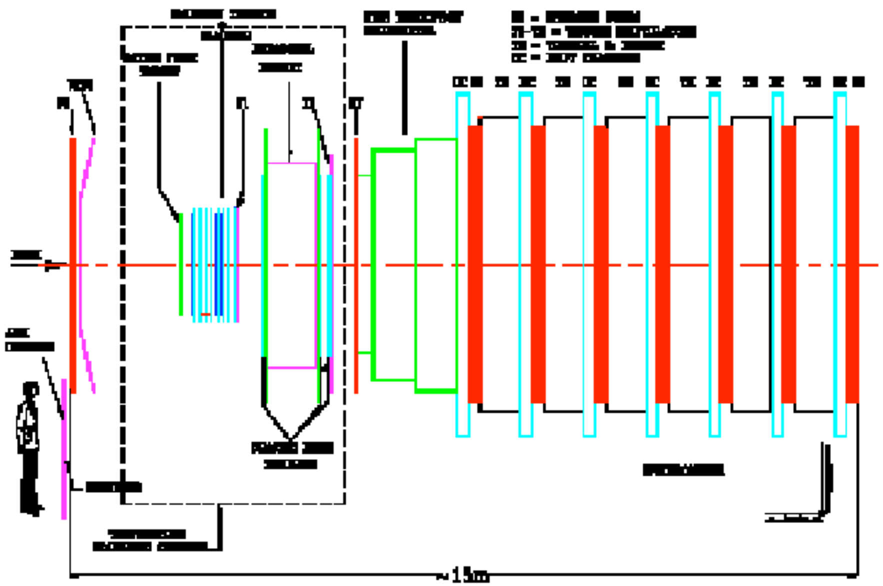
⇒ momentum resolution 3.5% ($p<10$ GeV)

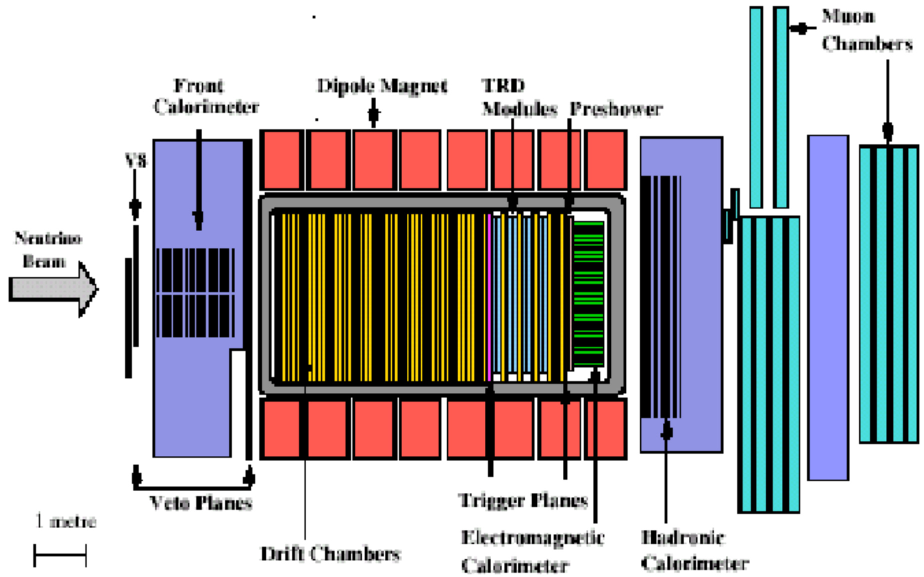
- Fine grained calorimetry

⇒ $\Delta E/E = 3.2\%/\sqrt{E} \oplus 1\%$

- Particle id

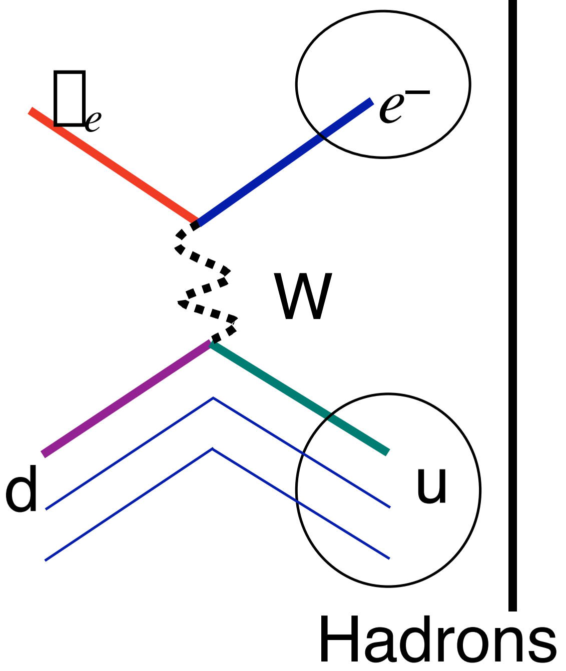
⇒ pion rej 10^3 with electron eff >90%



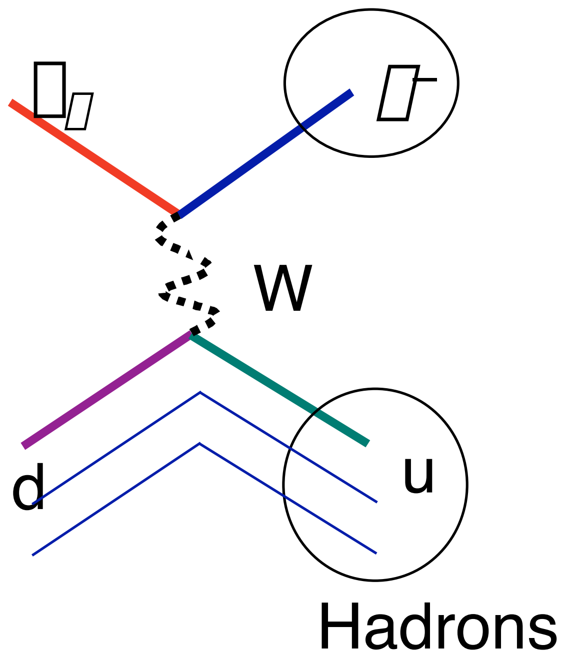


Neutrino-nucleon charged current interactions

Showering track

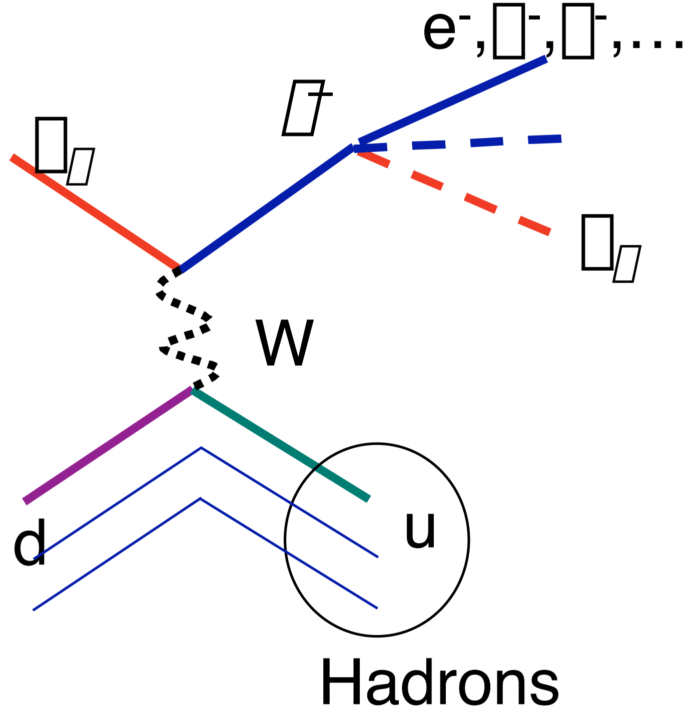


Penetrating track



Short-lived, decaying track

Neutrino(s) in final state



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

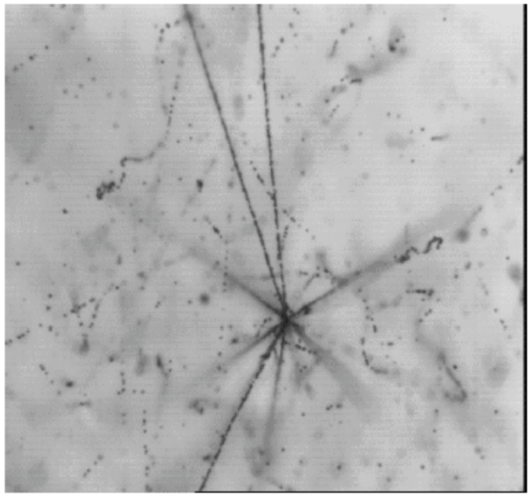
m_e = 0.5 MeV, - m_μ = 106 MeV - m_τ = 1770 MeV

Data samples

Chorus (94-97)

2,305k emulsion triggers
- Phase I: 167k events located in emulsion
- Phase II: ~60k new events located + full event analysis at vertex

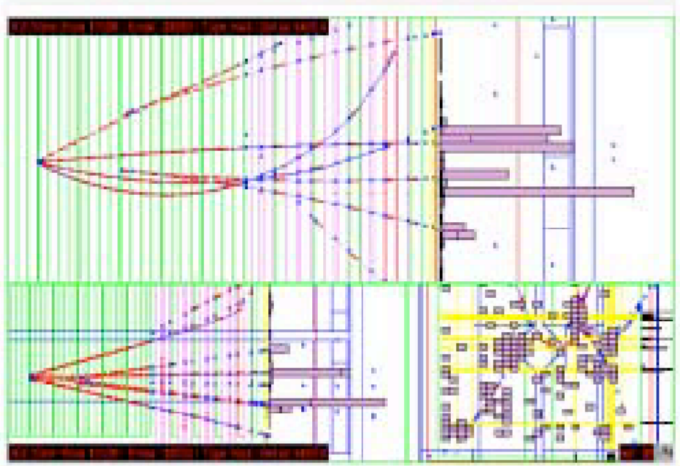
3-dimensional visual reconstruction
- sub-micron resolution at vertex



Nomad (95-98)

1,354k ν_μ CC interactions
- 100% of data analysed

"Bubble chamber" quality
- very high resolution in momentum and energy
- particle Id



Giuliana Fiorillo

Results of the $\nu_\mu \to \nu_\tau$ oscillation search

Total bkgd	N_τ^{max}	Data
1.2	7018	0
(±30% syst)	(±15% syst)	

Total bkgd	N_τ^{max}	Data
50.5	15226	52
(±20% syst)	(±10% syst)	

No excess of τ-like events found !

Unofficial combined CHORUS+NOMAD result (G. Fiorillo, Neutrino 2002) can be reinterpreted as LFV limit:

$$Br\left((\pi/K)^+ \to \mu^+ \nu_\tau\right) < \sim 5 \times 10^{-5} \quad (90\%C.L.)$$

Compare with

$$Br\left(\pi^+ \to \mu^+ \nu_e\right) < 8 \times 10^{-3} \quad LF$$

$$Br\left(\pi^+ \to \mu^+ \bar{\nu}_e\right) < 1.5 \times 10^{-3} \quad L$$

(90%C.L., PDG2000)

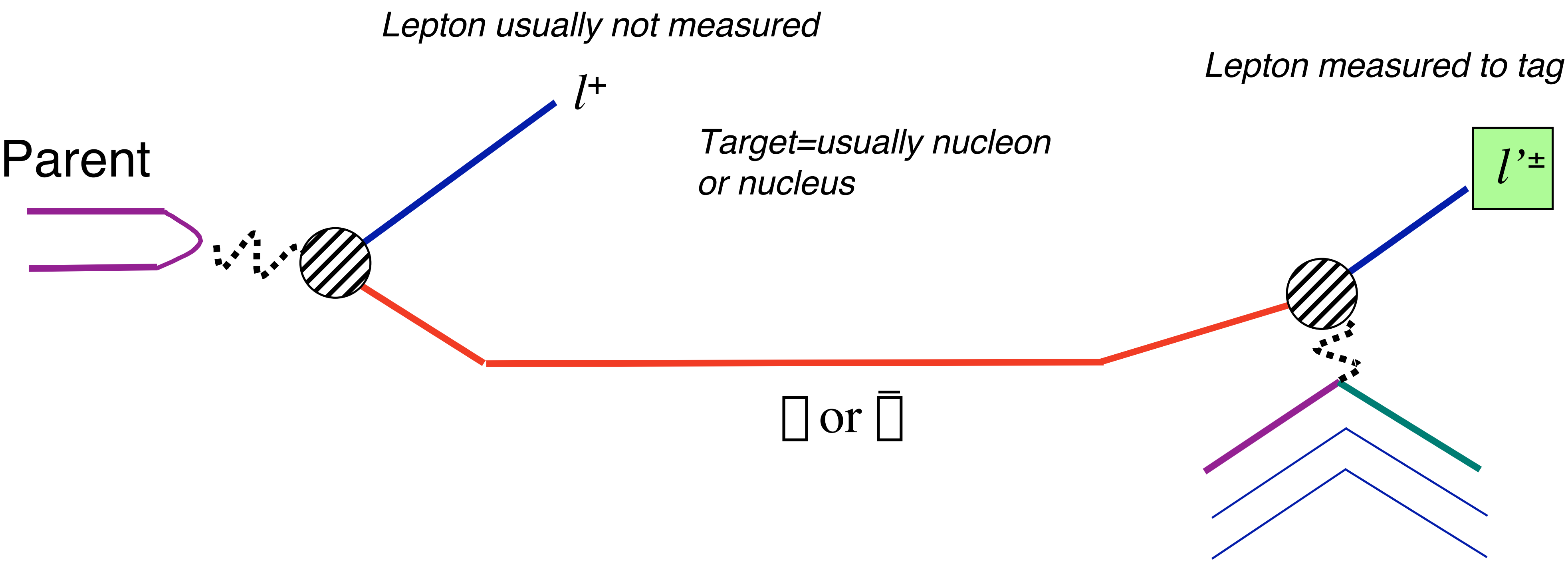
Neutrino properties

	ν_e	ν_μ	ν_τ
Electric charge	0		
Angular momentum ("spin")	1/2		
Chirality	Only left-handed coupling		
Interactions	Only weak		
Rest mass (95%C.L.)	***<≈ 5 eV***	***<160 KeV***	***<18.2 MeV***
Lifetime (90%C.L.)	>300 s/eV	>15.4 s/eV	?
Anomalous magnetic moment (μ/μ_B)	$<1.8\times10^{-10}$	$<7.4\times10^{-10}$	$<5.4\times10^{-7}$
Intrinsic nature	*Dirac particle ? Majorana ?*		

(from PDG98)

LEP electroweak fit: $N_\nu = 2.994 \pm 0.011$

The "generic" neutrino flavor experiment



Production vertex

Propagation in space: distance=L

Detection vertex

In a typical experiment, we can control (or predict) the parent. A decay occurs in which a neutral particle (neutrino or antineutrino) is produced. This particle is detected and tagged via the charged lepton flavor and charge $l'^{\pm}$. ***In general, the charged leptons could have different flavors $l^+ \neq l'^{\pm}$ and their charges could be the same or opposite !***

In the Standard Model

- SM gauge invariance implies an (accidential) global symmetry
  - ➥ $U(1)_B \otimes U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau$
  - ➥ The **total lepton number** and **the individual lepton flavors** are exactly conserved

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

$L_e=$	1	0	0
$L_\mu=$	0	1	0
$L_\tau=$	0	0	1

Lepton-Number conservation:

$$L_e + L_\mu + L_\tau = const.$$

Lepton-Flavors conservation:

$$\begin{cases} L_e = const. \\ L_\mu = const. \\ L_\tau = const. \end{cases}$$

Lepton flavor conservation

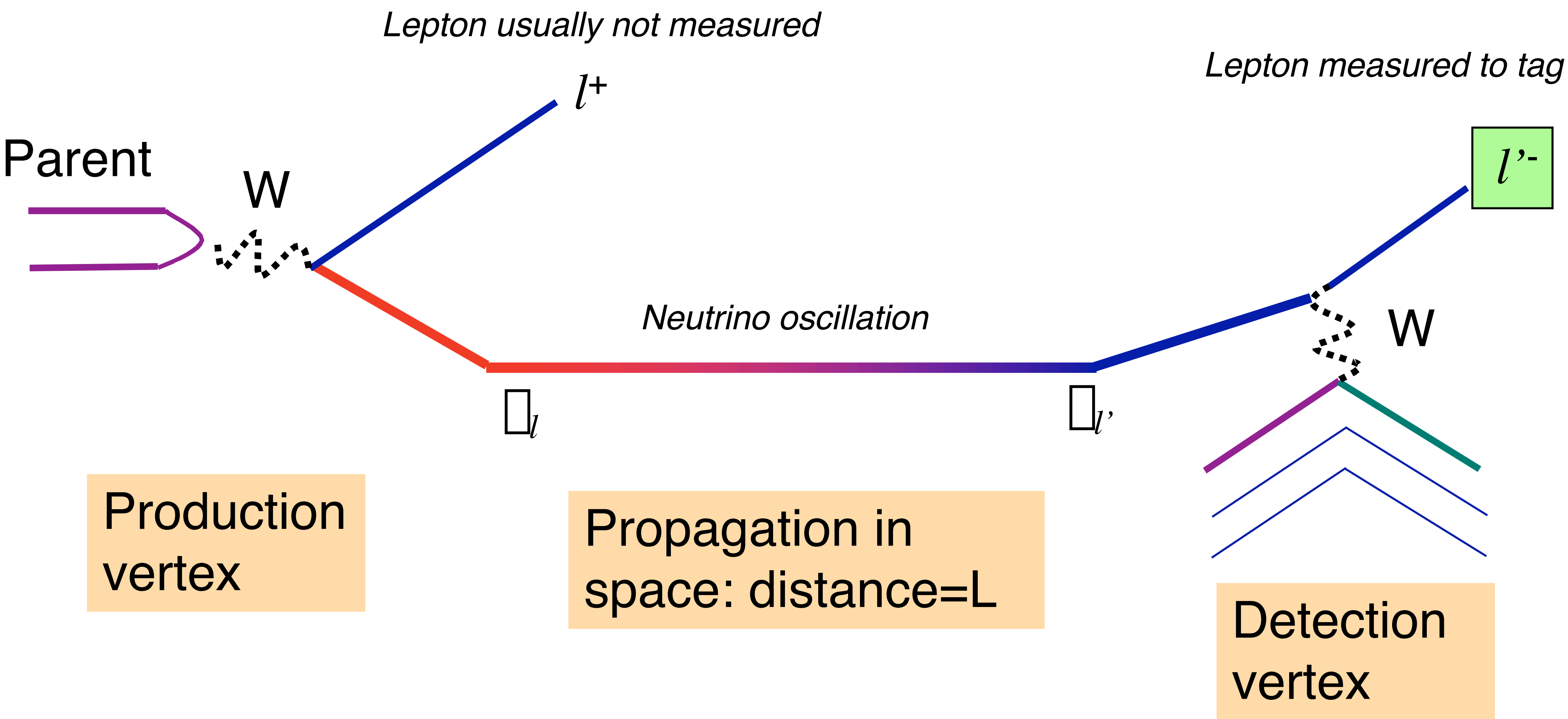
$\Gamma(Z \to e^{\pm}\mu^{\mp})/\Gamma_{total}$	[i]	$<1.7 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to e^{\pm}\tau^{\mp})/\Gamma_{total}$	[i]	$<9.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to \mu^{\pm}\tau^{\mp})/\Gamma_{total}$	[i]	$<1.2 \times 10^{-5}$, CL = 95%
limit on $\mu^- \to e^-$ conversion		
$\sigma(\mu^- {}^{32}S \to e^- {}^{32}S) / \sigma(\mu^- {}^{32}S \to \nu_\mu {}^{32}P*)$		$<7 \times 10^{-11}$, CL = 90%
$\sigma(\mu^- Ti \to e^- Ti) / \sigma(\mu^- Ti \to capture)$		$<4.3 \times 10^{-12}$, CL = 90%
$\sigma(\mu^- Pb \to e^- Pb) / \sigma(\mu^- Pb \to capture)$		$<4.6 \times 10^{-11}$, CL = 90%
$\Gamma(\mu^- \to e^- \nu_e \overline{\nu}_\mu)/\Gamma_{total}$	[j]	$<1.2 \times 10^{-2}$, CL = 90%
$\Gamma(\mu^- \to e^- \gamma)/\Gamma_{total}$		$<1.2 \times 10^{-11}$, CL = 90%
$\Gamma(\mu^- \to e^- e^+ e^-)/\Gamma_{total}$		$<1.0 \times 10^{-12}$, CL = 90%
$\Gamma(\mu^- \to e^- 2\gamma)/\Gamma_{total}$		$<7.2 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^- \gamma)/\Gamma_{total}$		$<2.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \gamma)/\Gamma_{total}$		$<1.1 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^0)/\Gamma_{total}$		$<3.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^0)/\Gamma_{total}$		$<4.0 \times 10^{-6}$, CL = 90%

Total lepton number conservation

$\Gamma(\pi^+ \to \mu^+ \overline{\nu}_e)/\Gamma_{total}$	[k]	$<1.5 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \mu^+ \overline{\nu}_e)/\Gamma_{total}$	[k]	$<3.3 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^0 e^+ \overline{\nu}_e)/\Gamma_{total}$		$<3 \times 10^{-3}$, CL = 90%
$\Gamma(Z \to pe)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to p\mu)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 95%
limit on $\mu^- \to e^+$ conversion		
$\sigma(\mu^- {}^{32}\mathrm{S} \to e^+ {}^{32}\mathrm{Si}^*)$ / $\sigma(\mu^- {}^{32}\mathrm{S} \to \nu_\mu {}^{32}\mathrm{P}^*)$		$<9 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- {}^{127}\mathrm{I} \to e^+ {}^{127}\mathrm{Sb}^*)$ / $\sigma(\mu^- {}^{127}\mathrm{I} \to \text{anything})$		$<3 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- \mathrm{Ti} \to e^+ \mathrm{Ca})$ / $\sigma(\mu^- \mathrm{Ti} \to \text{capture})$		$<3.6 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^+ \pi^- \pi^-)/\Gamma_{total}$		$<1.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^+ \pi^- \pi^-)/\Gamma_{total}$		$<3.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^+ \pi^- K^-)/\Gamma_{total}$		$<2.1 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^+ K^- K^-)/\Gamma_{total}$		$<3.8 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^+ \pi^- K^-)/\Gamma_{total}$		$<7.0 \times 10^{-6}$, CL = 90%

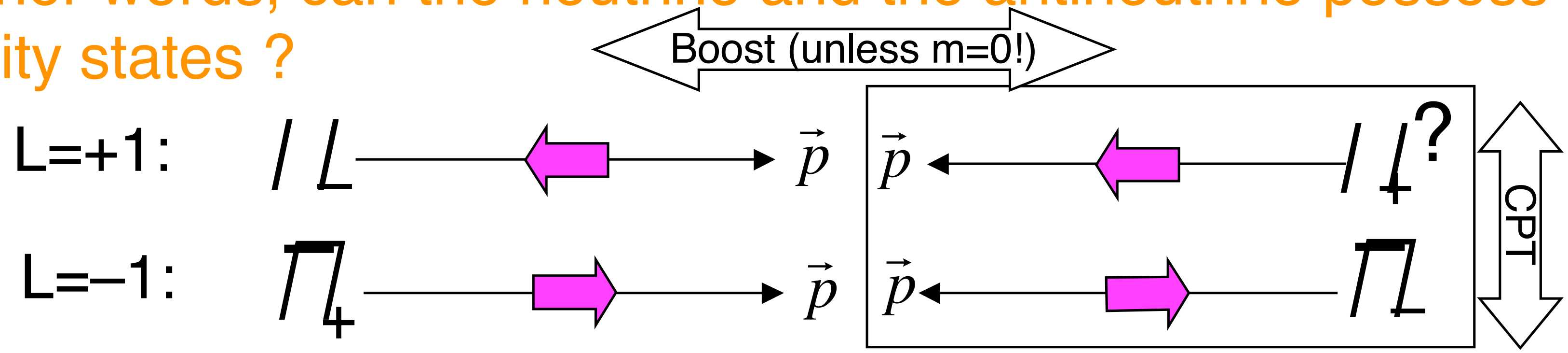
Today's understanding

- Direct lepton flavor or lepton number violation is strongly constrained, mostly in reactions involving charged leptons at the level of 10^{-6} or below.
- Note that experimental limits involving neutrino flavors are at the level of 10^{-3}.
- Lepton flavor violation is believed to occur via mixing in the leptonic sector (neutrino flavor oscillations).



Dirac mass term (I)

- Electron mass: $-\mathcal{L}_e = m_e \bar{e} e = \left(\bar{e}_L e_R + h.c.\right)$ where $e_{R,L} \equiv \frac{1}{2}\left(1 \pm \gamma^5\right) e$
- Natural mass term for neutrino: $-\mathcal{L} = m_D \left(\bar{\nu}_L \nu_R + h.c.\right)$
- All experiments are consistent with (i.e. the *V–A* weak CC couples to these only):
  - ➥ The state of neutrinos is fully ν_L
  - ➥ The state of antineutrinos is fully ν^c_R where C is the charge conjugation
- Do the chiral states ν_R and ν^c_L exist as independent eigenstates ? In other words, can the neutrino and the antineutrino possess two helicity states ?



- A Dirac mass term requires 4 independent helicity states !
- It can be generated by the standard Higgs mechanism.

Dirac mass term (II)

- But adding these neutrino states is NOT trivial !
- Sterile:
  - ➥ The new states are singlet states of the fundamental symmetry $SU(2)_L x U(1)_Y$ of the SM: $I=0, I_3=0, Y=0$
  - ➥ *No interaction with known gauge fields*

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L ; \quad e_R^- ; \quad \nu_{eR}$$

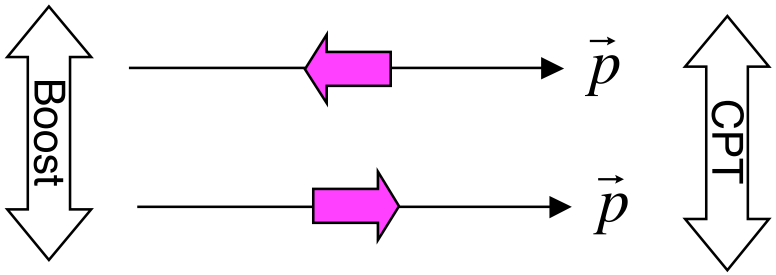
- Lepton number
  - ➥ A term $\bar{\nu}_L^c \nu_R$ is gauge invariant, but violates lepton number by two units !

$$\bar{\nu}_L^c \nu_R$$

L=−1 ↙ ↘ L=+1

Majorana mass

- The neutrinos are electrically neutral, hence they could be invariant under charge conjugation, e.g. $\nu \equiv \nu_L + \nu_R \Rightarrow \nu = (\nu)^c$



- At the cost of lepton number conservation, a mass term (Majorana mass term) can be introduced with these two states only:

$$-\mathcal{L}_{Majorana} = m_L\left(\bar{\nu}_L \nu_R^c + h.c.\right) \qquad |\Delta L| = 2$$

- Majorana mass terms require a new mechanism of mass generation that is beyond the SM.
- They could come from terms of the type $\frac{1}{M}\bar{\nu}_L \Phi \otimes \Phi \nu_R^c$ where Φ is the SM Higgs doublet, suppressed by a cutoff M ($\Rightarrow$ SM is an effective theory)

The scale of New Physics : $\Lambda_{\rm NP}$

If SM is an effective low energy theory, for $E \ll \Lambda_{\rm NP}$

– The same particle content as the SM and same pattern of symmetry breaking

– But there can be non-renormalizable (dim$>$ 4) operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_n \frac{1}{\Lambda_{\rm NP}^{n-4}} \mathcal{O}_n$$

First NP effect $\Rightarrow$ dim=5 operator

There is only one!

$$\mathcal{O}_5 = \frac{Z_{ij}^\nu}{\Lambda_{\rm NP}} \phi\phi L_i L_j$$

which after symmetry breaking

induces a ν Majorana mass

$$(M_\nu)_{ij} = \frac{Z_{ij}^\nu}{2} \frac{v^2}{\Lambda_{\rm NP}}$$

$\mathcal{O}_5$ breaks total lepton and lepton flavour numbers

Implications:

– It is natural that ν mass is the first evidence of NP

– Naturally $m_\nu \ll$ other fermions masses $\sim \lambda^f v$

– $m_\nu > \sqrt{\Delta m^2_{atm}} \sim 0.05$ eV $\Rightarrow \Lambda_{\rm NP} < 10^{15}$ GeV

– If $Z^\nu_{ij} \gtrsim 10^{-4} \Rightarrow 10^{10} < \Lambda_{\rm NP} < 10^{15}$ GeV

– Lepton flavour violation and CP violation expected

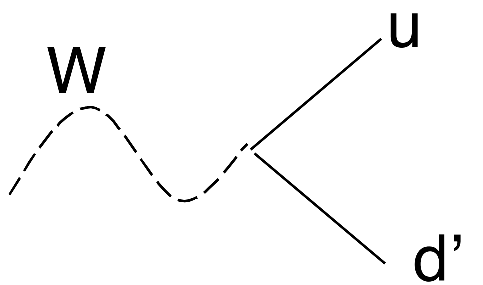
New Physics Scale close to GUT scale

Form of the weak charged current

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

Quarks charged current:

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



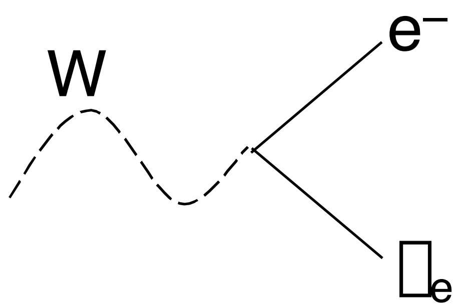
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} \equiv U_q \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

unitary

Weak eigenstates **Flavor eigenstates**

Leptons charged current:

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



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

Weak eigenstates **Mass eigenstates**

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

$\Rightarrow$ ***$U_l \equiv 1$***

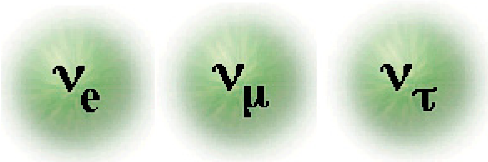
$\Rightarrow$ $$(\bar e \quad \bar \mu \quad \bar \tau)_L \gamma^\mu \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_L$$

Mixing in the lepton sector

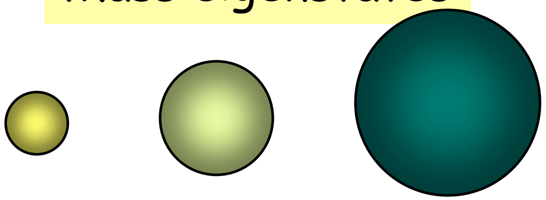
If neutrinos are massive particles, then the ***mass eigenstates*** *and the* ***weak eigenstates*** *do not have to be the same*

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

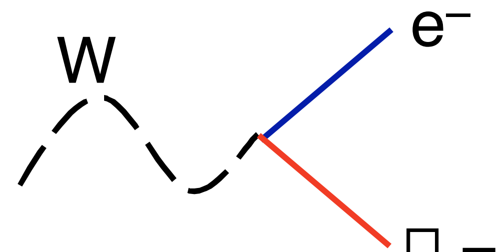
Weak eigenstates
„flavor eigenstates"



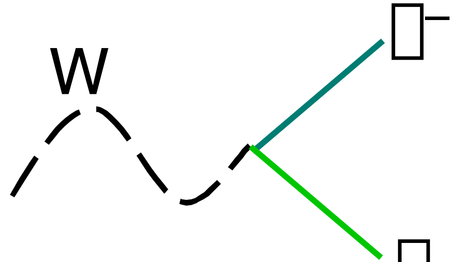
Mass eigenstates



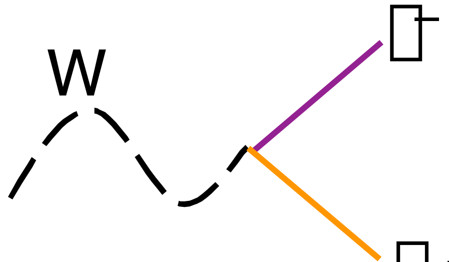
m_1 m_2 m_3



$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$



$\nu_\mu = U_{\mu 1}\nu_1 + U_{\mu 2}\nu_2 + U_{\mu 3}\nu_3$



$\nu_\tau = U_{\tau 1}\nu_1 + U_{\tau 2}\nu_2 + U_{\tau 3}\nu_3$

Useful parameterization of the mixing matrix

Writing unitary mixing matrix U for three families (N=3) as the product of ***three rotations*** *plus* ***one complex phase****:*

N(N–1)/2=3 independent angles θ_{12}, θ_{13}, θ_{23}, (N–1)(N–2)/2=1 complex phase δ

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

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

NB. In the case of Majorana neutrinos there are additional N–1=2 phases that are not observable in neutrino oscillation experiments

NEUTRINO OSCILLATION IN VACUUM

vacuum → time evolution of a neutrino mass eigenstate ν_i
(≡ stationary state of free Hamiltonian)

$$e^{-iE_i t} \qquad E_i \equiv \text{energy of state}$$

ν produced in weak decay : $|\nu(t=0)\rangle = |\nu_\alpha\rangle \quad \alpha = e, \mu, \tau$

weak eigenstate

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = \sum_j U_{\alpha j} |\nu_j\rangle$$

$$\Rightarrow |\nu(t)\rangle = \sum_j U_{\alpha j} \underbrace{e^{-iE_j t}}_{\text{phase}} |\nu_j\rangle$$

neutrino flavor oscillation probability : $P_\alpha \equiv |\langle\nu_\alpha|\nu(t)\rangle|^2$

in matrix notation: $\vec{\nu} \equiv \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$

time evolution equation: $$i\frac{d\vec{\nu}}{dt} = UHU^{+}\vec{\nu}$$ where

week basis

$$H \equiv \begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix}$$

hamiltonian in mass basis

assume relativistic neutrinos $E_i \approx p + \frac{m_i^2}{2p} \approx p + \frac{m_i^2}{2E}$

$$i\frac{d\vec{\nu}}{dt} \approx U\begin{pmatrix} p & & \\ & p & \\ & & p \end{pmatrix}U^{+}\vec{\nu} + \frac{1}{2E}U\begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix}U^{+}\vec{\nu}$$

overall phase

phase evolution

$$i\frac{d\vec{\nu}}{dt} = \frac{1}{2E}U\begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix}U^{+}\vec{\nu}$$

$\Rightarrow$ $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$

<u>time integration</u>

$$i\frac{d\vec{\nu}}{dt} = U H_\Delta U^+ \vec{\nu} \Rightarrow |\vec{\nu}(t)\rangle = U e^{-iH_\Delta t} U^+ |\nu(t=0)\rangle$$

<u>oscillation probability:</u>

$$P(\nu_\alpha \to \nu_\beta; E, t) \equiv |\langle \nu_\beta | S(t) | \nu_\alpha \rangle|^2 \equiv |S_{\beta\alpha}(t)|^2$$

where $S(t) \equiv U e^{-iH_\Delta t} U^+$ time evolution operator

$\Rightarrow$ matrix elements

$$|S_{\beta\alpha}(t)|^2 = \left| \sum_{ij} U_{\beta i} \left(e^{-it\,\mathrm{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})/2E} \right)_{ij} U^*_{\alpha j} \right|^2$$

$$= \left| \sum_j U_{\beta j} e^{-i\Delta m^2_{j1} t/2E} U^*_{\alpha j} \right|^2$$

$$= \sum_{jk} \underbrace{U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}}_{\equiv J_{\alpha\beta jk}} e^{-i\Delta m^2_{jk} t/2E}$$

$|\nu_\alpha\rangle = \sum_j U_{\alpha j} |\nu_j\rangle$ for neutrinos $|\bar{\nu}_\alpha\rangle = \sum_j U^*_{\alpha j} |\bar{\nu}_j\rangle$

$\Rightarrow$ must replace $U \to U^*$ i.e. $J_{\alpha\beta jk} \to J^*_{\alpha\beta jk} = J_{\beta\alpha jk}$

if $\underline{U}$ complex

$$\boxed{S_{\bar{\beta}\bar{\alpha}} \equiv S_{\alpha\beta} \neq S_{\beta\alpha}}$$

$$P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = P(\nu_\beta \to \nu_\alpha) \neq P(\nu_\alpha \to \nu_\beta)$$

"CPT"

CP or T violation

CP invariance $\Rightarrow$ U real

$$S_{\beta\alpha} = \sum_i U_{\alpha i}^2 U_{\beta i}^2 + 2 \sum_{j>i} U_{\alpha i} U_{\alpha j} U_{\beta i} U_{\beta j} \cos\Delta_{ij}$$

$$= \delta_{\alpha\beta} - 4 \sum_{j>i} U_{\alpha i} U_{\alpha j} U_{\beta i} U_{\beta j} \sin^2 \frac{\Delta_{ij}}{2}$$

$$\boxed{\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 t}{2E}}$$

case of two neutrinos $\underline{n=2}$

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}}_{\text{unitarity} \Rightarrow 1 \text{ angle, real}} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\Rightarrow P(\nu_\alpha \to \nu_\alpha) = P(\nu_\beta \to \nu_\beta) = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = P(\bar{\nu}_\beta \to \bar{\nu}_\beta)$$

$$= 1 - 4\cos^2\theta \sin^2\theta \sin^2\frac{\Delta}{2}$$

$$= 1 - \sin^2 2\theta \sin^2\frac{\Delta}{2}$$

$$\Rightarrow P(\nu_\alpha \to \nu_\beta) = P(\nu_\beta \to \nu_\alpha) = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = P(\bar{\nu}_\beta \to \bar{\nu}_\alpha)$$

$$= \sin^2 2\theta \sin^2\frac{\Delta}{2} = 1 - P(\nu_\alpha \to \nu_\alpha)$$

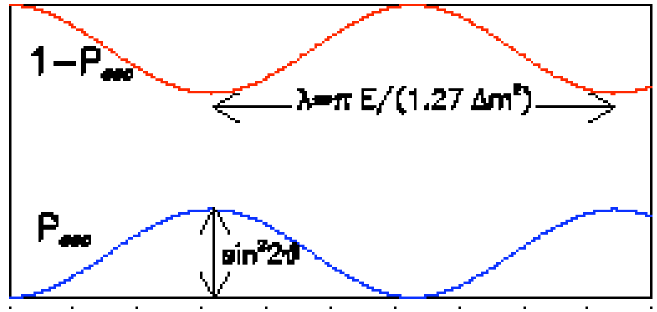
Units: $\Delta \equiv \frac{\Delta m^2 t}{2E}$ neutrino path length $L \simeq t$

$$\Delta \cong 2.53 \frac{\Delta m^2 (eV^2)\, L\,(km)}{E\,(GeV)}$$

• For 2-ν: Convention $\Delta m^2 > 0$, $U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$ with $0 \leq \theta \leq \frac{\pi}{2}$

$P_{osc} = \sin^2(2\theta)\,\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$ Appear

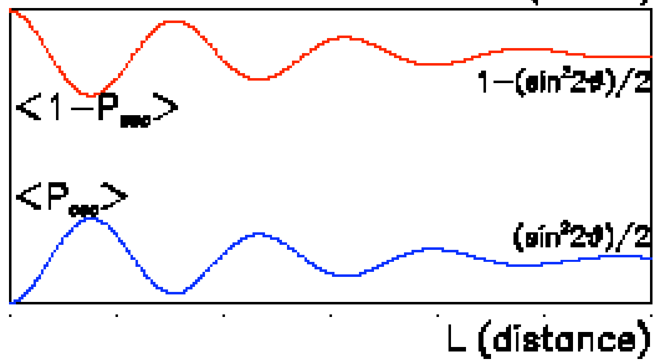
$P_{\alpha\alpha} = 1 - P_{osc}$ Disappear



• In real experiments

neutrinos are not monochromatic

$\Rightarrow \langle P_{\alpha\beta}\rangle = \int dE_\nu \frac{d\Phi}{dE_\nu}\sigma_{CC}(E_\nu) P_{\alpha\beta}(E_\nu)$



• Maximal sensitivity for $\Delta m^2 \sim E/L$

– $\Delta m^2 \ll E/L$ $\Rightarrow$ No time to oscillate

$\langle\sin^2(1.27\Delta m^2 L/E)\rangle \simeq 0 \rightarrow \langle P_{osc}\rangle \simeq 0$

– $\Delta m^2 \gg E/L$ $\Rightarrow$ Averaged oscillations

$\langle\sin^2(1.27\Delta m^2 L/E)\rangle \simeq \frac{1}{2} \rightarrow \langle P_{osc}\rangle \simeq \frac{1}{2}\sin^2(2\theta)$

1) Evidence for atmospheric muon neutrino disappearance

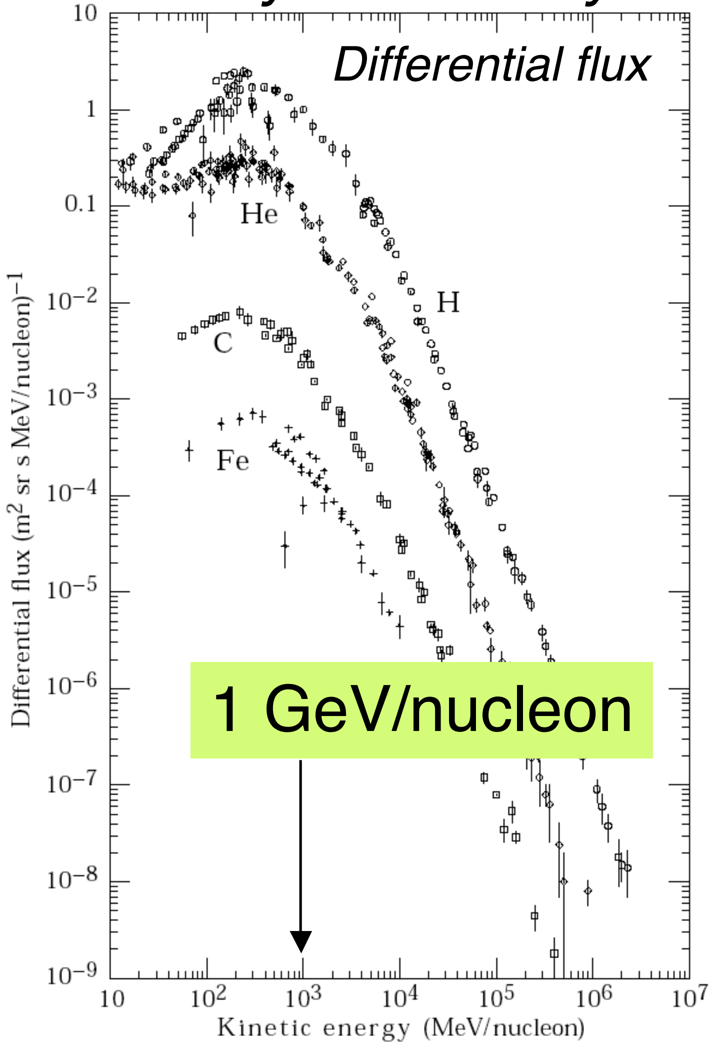
$$\nu_\mu \rightarrow \nu_X$$

with

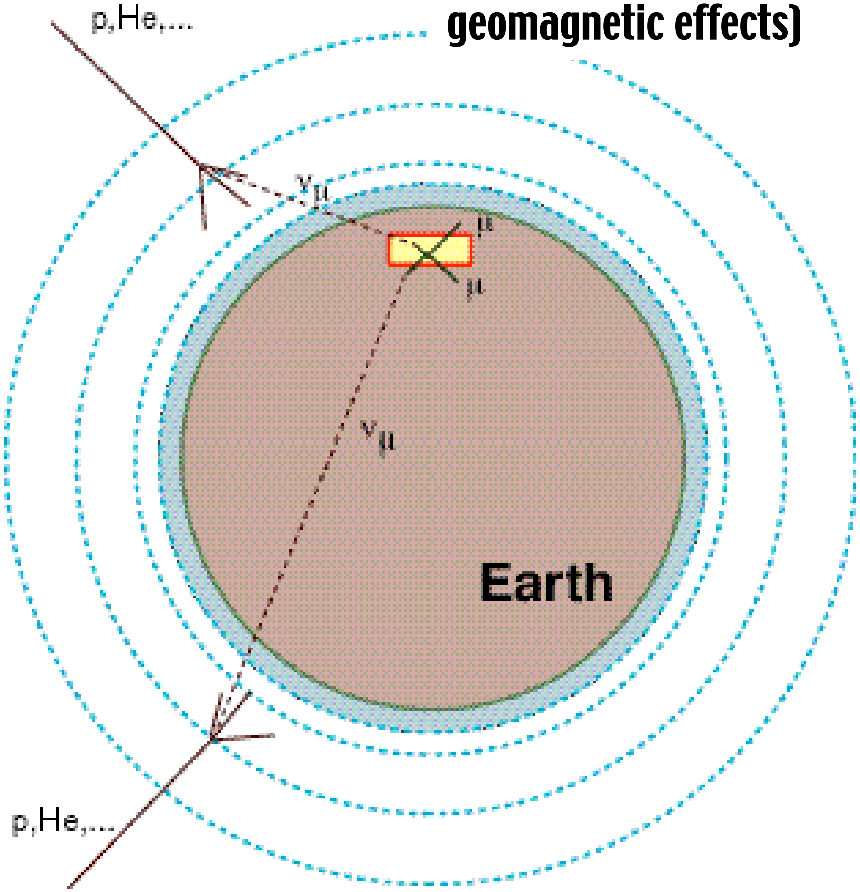
$$\Delta m^2 \approx O(10^{-3} eV^2)$$ and large mixing

Atmospheric neutrinos

Primary cosmic rays



Isotropic source (small anisotropy comes from geomagnetic effects)



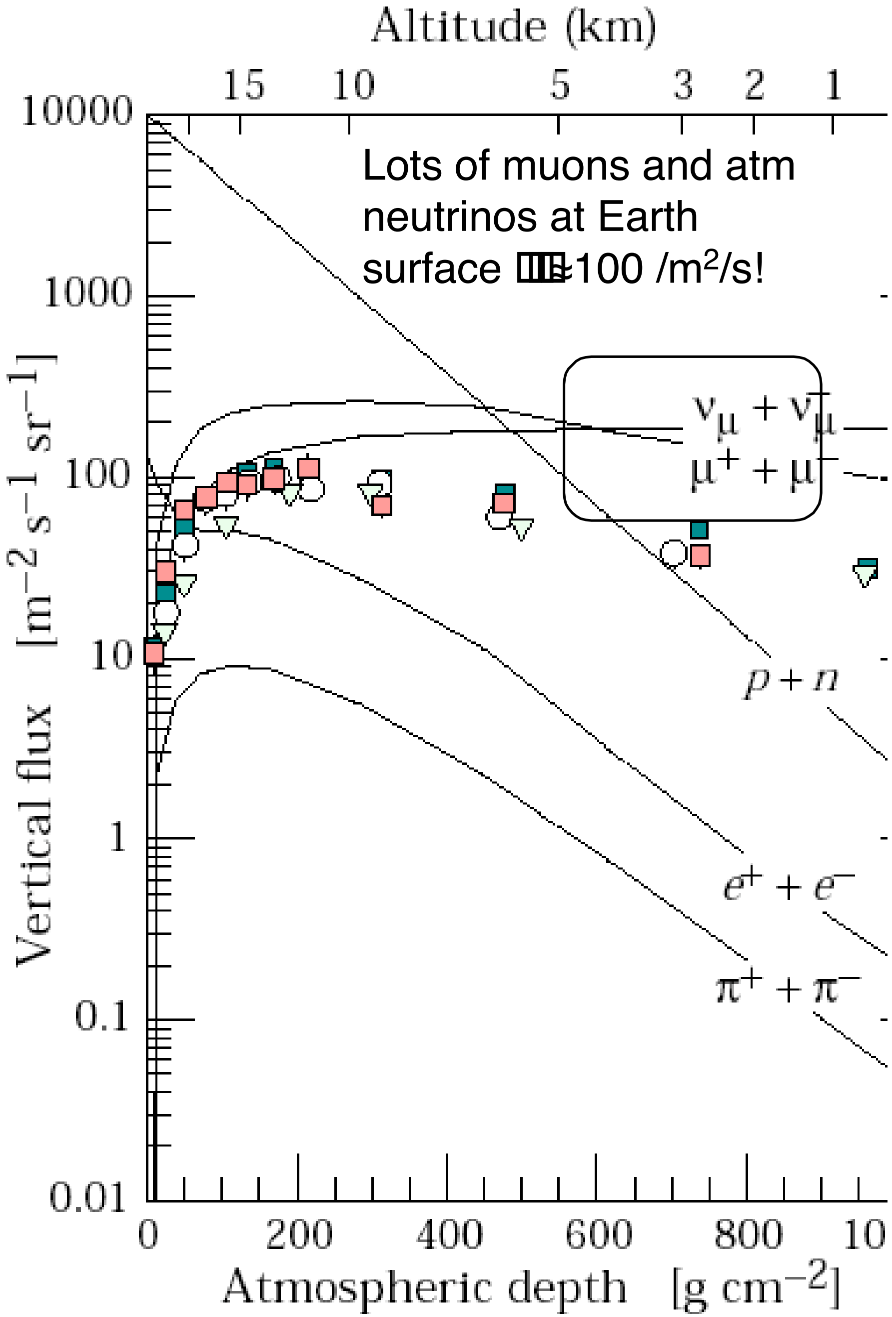
Earth is a splendid neutrino beam line!

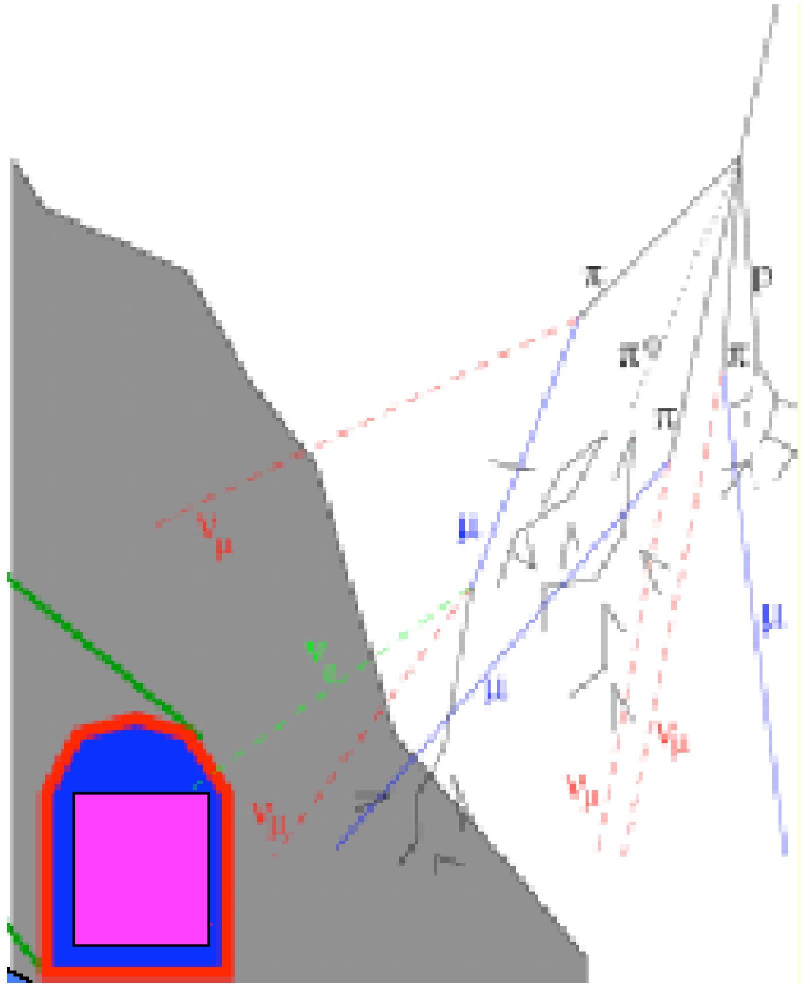
$$I(E(GeV/nucleon)) \approx 1.8\ E^{-2.7}\ nucleons/cm^2/s/sr/GeV$$

$$cosmic\ ray + air \rightarrow \pi^{+-}, K^{+-}, K^{0}, \ldots$$

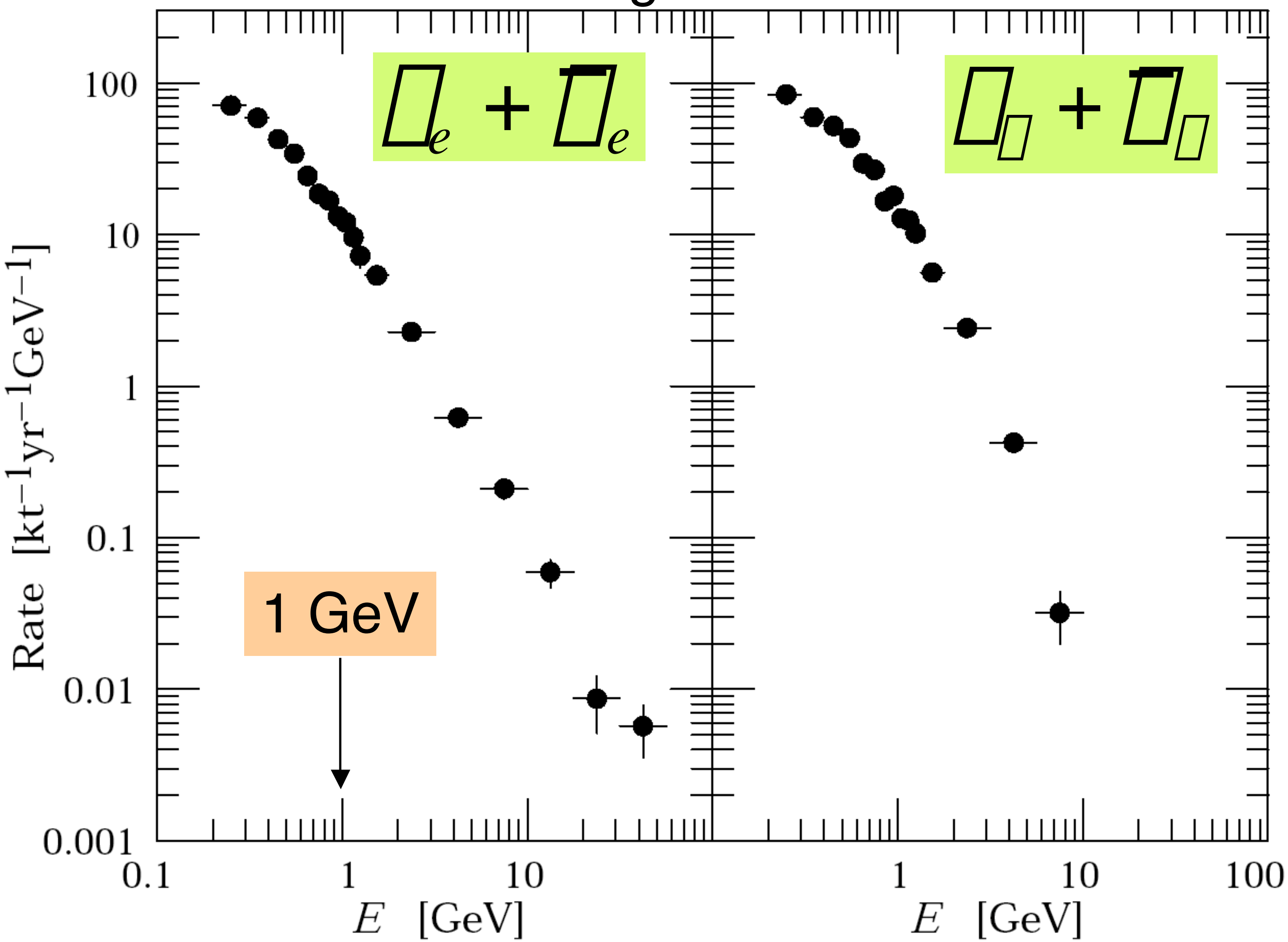
Hadronic shower cascade

Atmosphere depth ≈ 1000 g/cm²





Absolute charged current event rates



Neutrino interaction rate is small: ≈150 CC events/kton/year
Average energy: ≈400 MeV
Spectrum ≈ $E^{-1.7}$ above 1 GeV

KGF– The 1st reported Atmospheric ν

Several detectors in KGF mine at various depths.

3 ν published 15 Aug 65

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

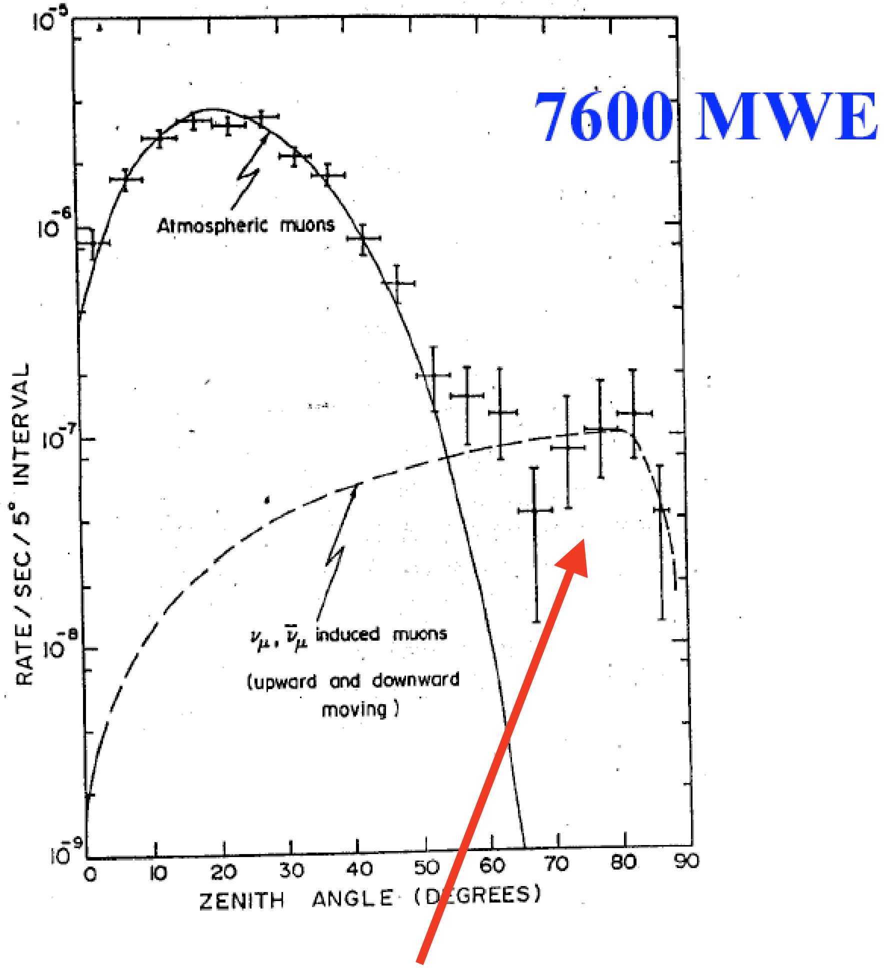
C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

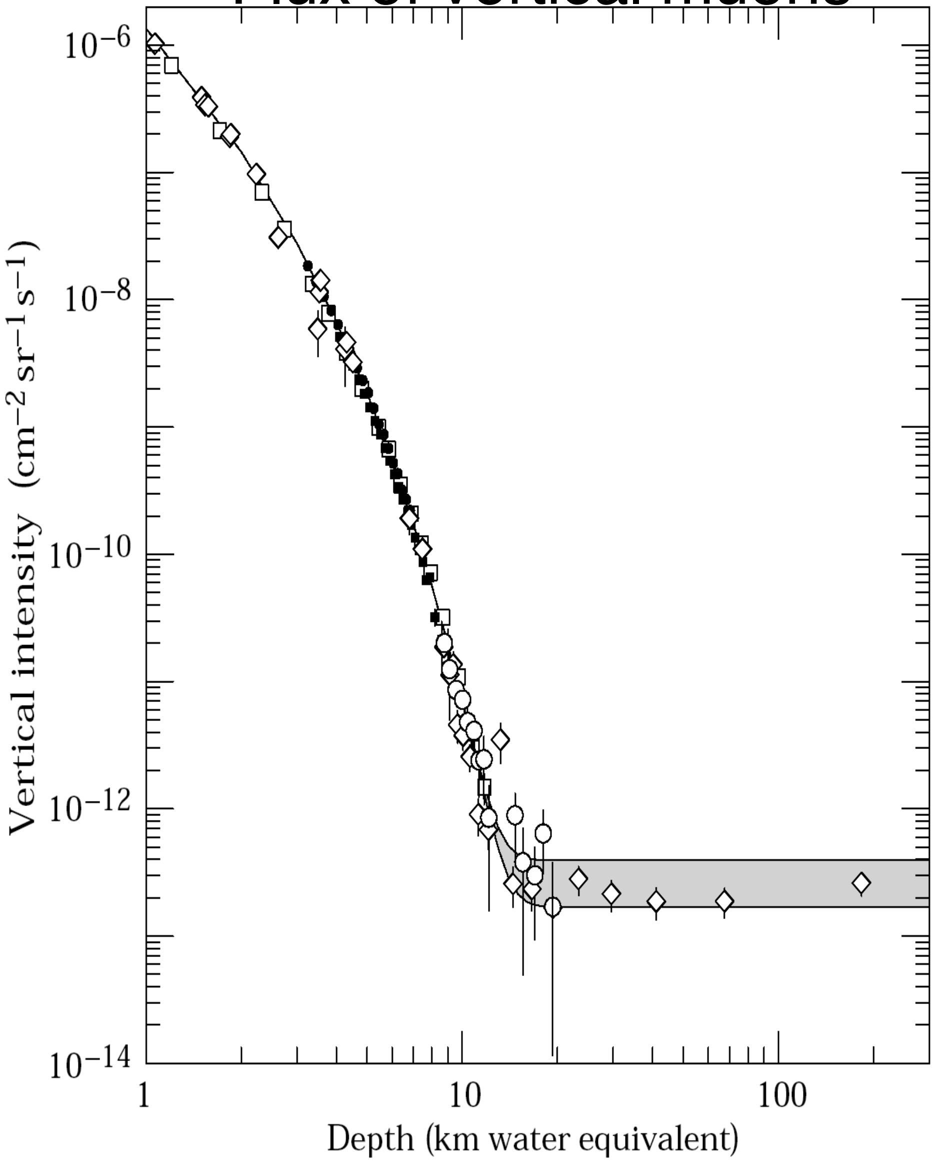
Event number	Type of coincidence	Projected zenith angle	Date	Time
1	TEL. 2 $N_4 + S_4$	37°	30.3	20.04
2	TEL. 1 $N_1 + S_1$	48 ± 1°	27.4	18.26
3	TEL. 2 $N_6 + S_6$	75 ± 10°	25.5	20.03



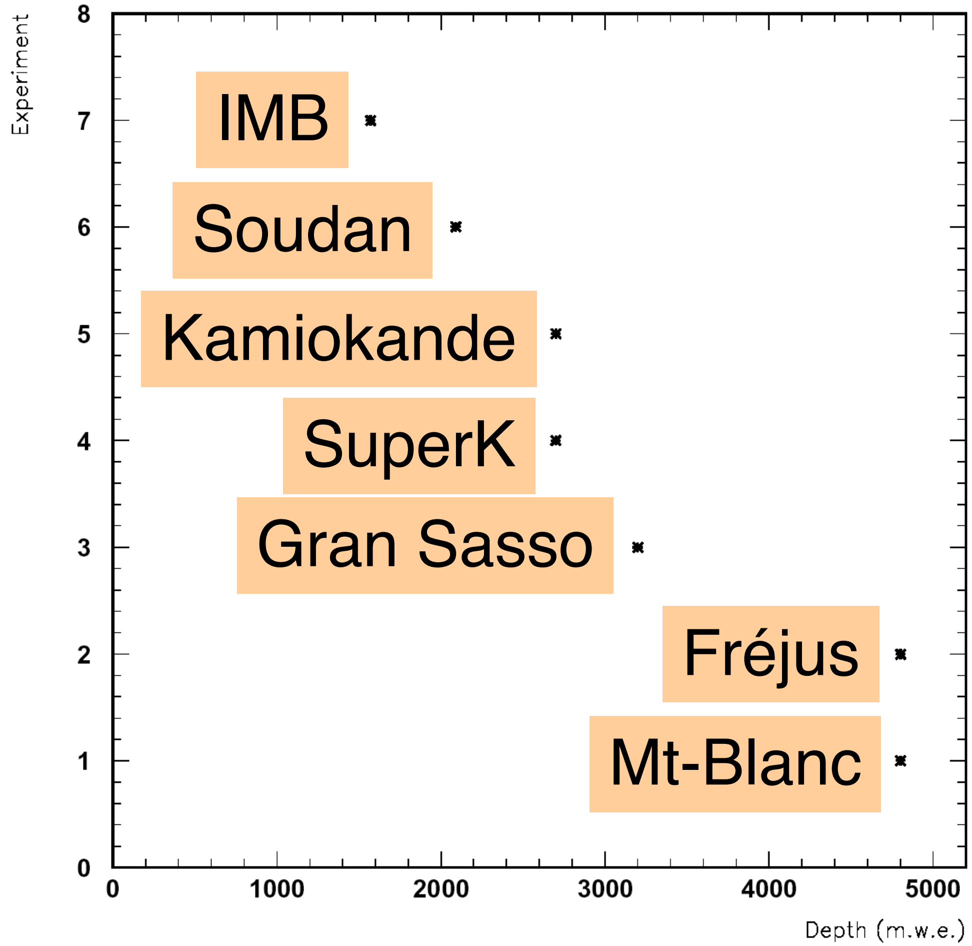
Most neutrinos cross the Earth! Look for upward muons!

Suppressing cosmic muons + backgrounds

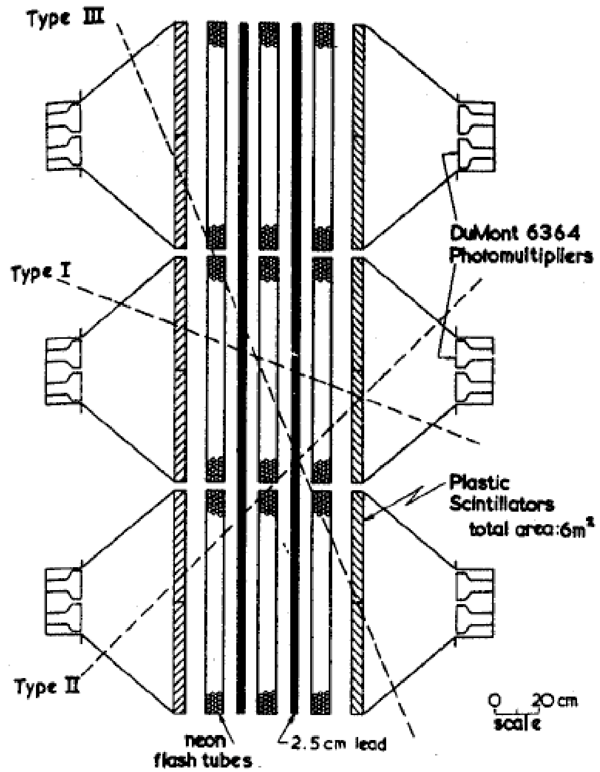
Flux of vertical muons



Depth of underground exps.



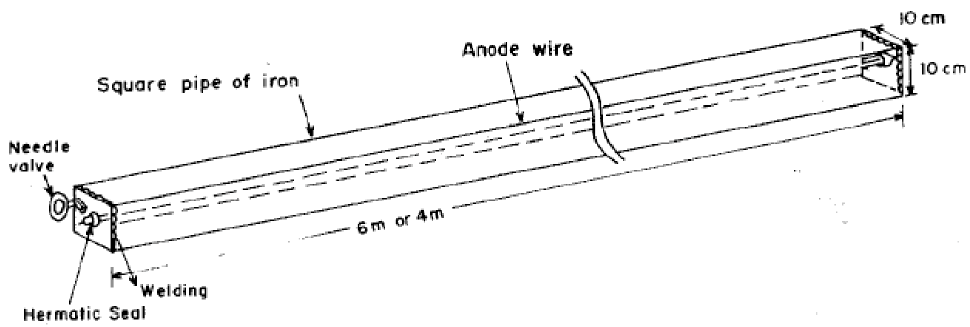
Detectors in KGF mine (1965-1991)



ν Telescope

Iron, flash tubes & scintillator

Proportional Tube element of proton decay detector and Monopole detector



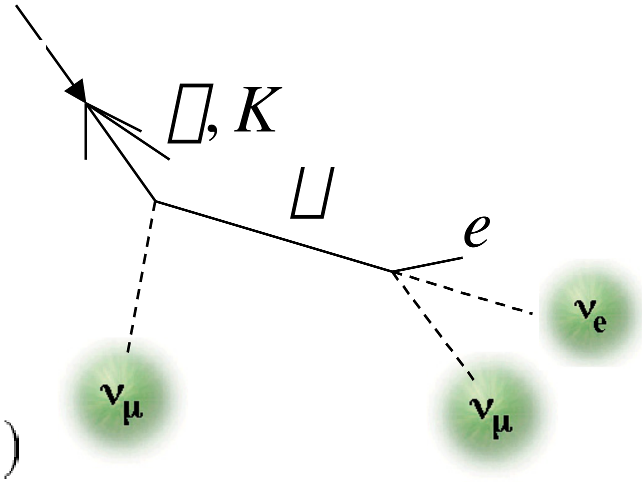
Ratio of muon to electron neutrinos

Dominant decays

$\pi^\pm$	$\rightarrow \mu^\pm \nu_\mu(\bar{\nu}_\mu)$	(100 %)	
$\mu^\pm$	$\rightarrow e^\pm \nu_e(\bar{\nu}_e)\bar{\nu}_\mu(\nu_\mu)$	(100 %)	
$K^\pm$	$\rightarrow \mu^\pm \nu_\mu(\bar{\nu}_\mu)$	(63.5 %)	
	$\rightarrow \pi^\pm \pi^0$	(21.2 %)	
	$\rightarrow \pi^\pm \pi^+ \pi^-$	(5.6 %)	
	$\rightarrow \pi^0 \mu^\pm \nu_\mu(\bar{\nu}_\mu)$	(3.2 %)	$(K_{3\mu\nu})$
	$\rightarrow \pi^0 e^\pm \nu_e(\bar{\nu}_e)$	(4.8 %)	$(K_{3e\nu})$
	$\rightarrow \pi^\pm \pi^0 \pi^0$	(1.73 %)	
K^0_S	$\rightarrow \pi^+ \pi^-$	(68.6 %)	
K^0_L	$\rightarrow \pi^+ \pi^- \pi^0$	(12.37 %)	
	$\rightarrow \pi^\pm \mu^\mp \nu_\mu(\bar{\nu}_\mu)$	(27 %)	$(K_{3\mu\nu})$
	$\rightarrow \pi^\pm e^\mp \nu_e(\bar{\nu}_e)$	(38.6 %)	$(K_{3e\nu})$

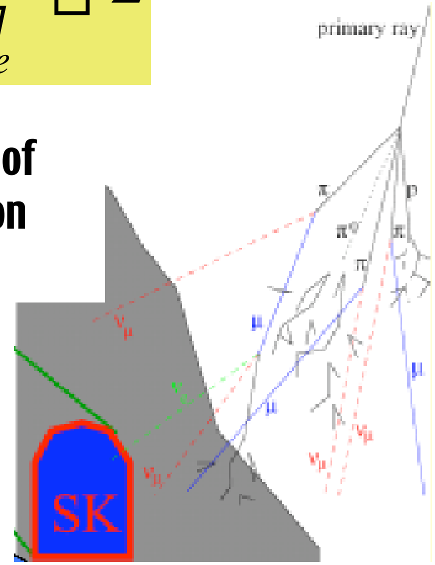
Kaon production kinematically suppressed

hadronic cascade + decays



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

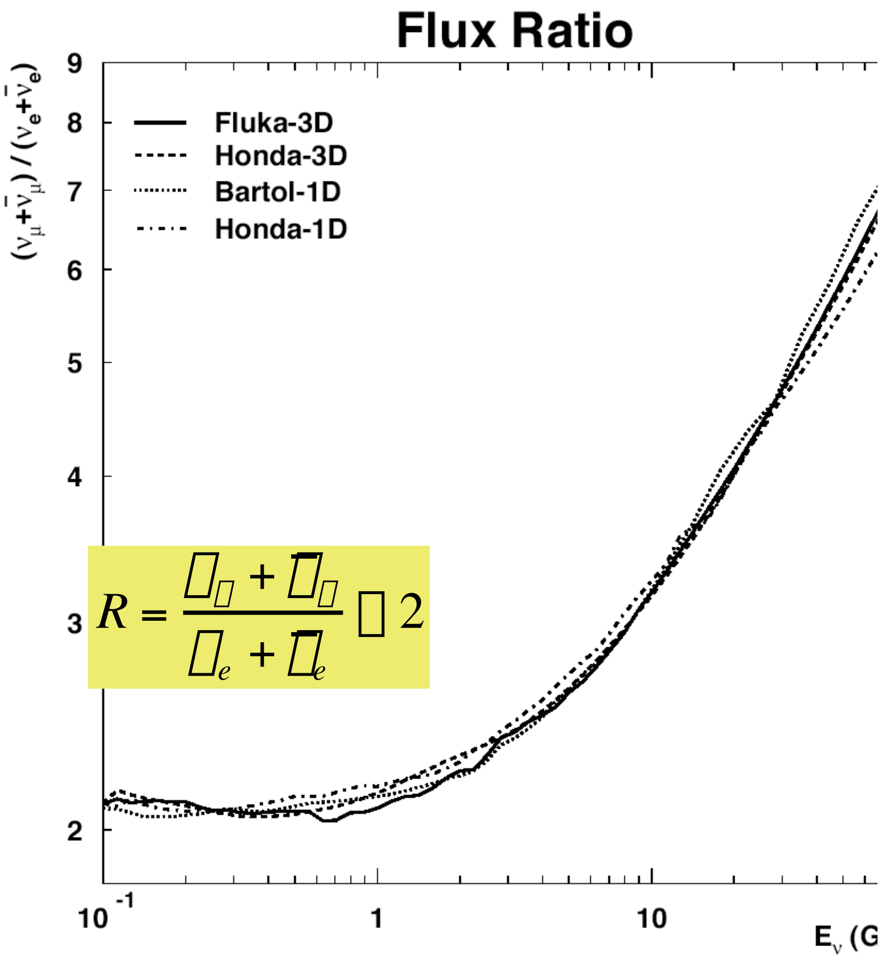
Predicted ratio of muon to electron neutrinos

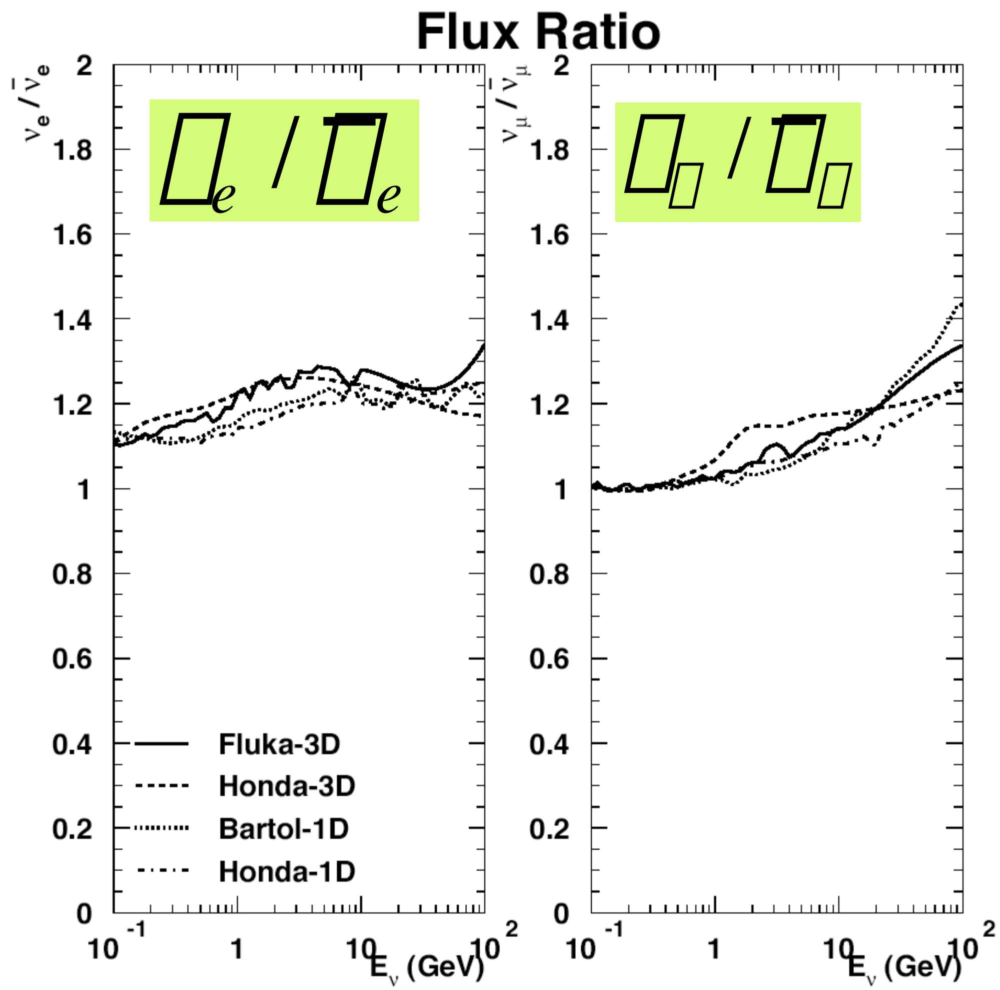


André Rubbia, ETH/Zürich, 9/26/02, ZUOZ

Results from detailed simulations of atmosphere

- Complicated calculations confirm naïve expectations (as usual?)



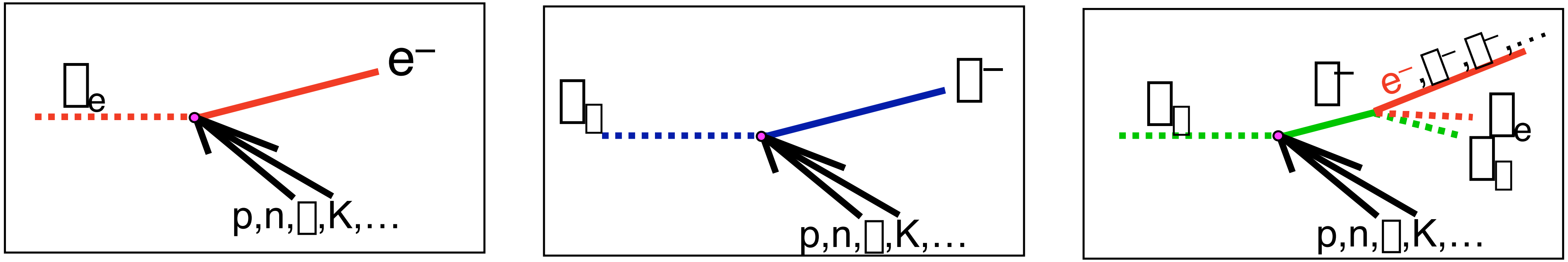


Neutrino energy (GeV)

So far experiments could not distinguish neutrinos from antineutrinos on an event-by-event basis

Atmospheric 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

Past and present atmospheric experiments

Table 1.1: Summary of atmospheric neutrino experiments.

Experiment	Detector	Location	Mass
IMB	Water Cherenkov	Cleveland, Ohio, USA	3.3 kton
Kamiokande	Water Cherenkov	Kamioka, Gifu, Japan	0.88 kton
Super-Kamiokande	Water Cherenkov	Kamioka, Gifu, Japan	22.5 kton
Nusex	Iron Calorimeter	Mont B lanc, France	0.15 kton
Fréjus	Iron Calorimeter	Fréjus, Alps, France	1.56 kton
Soudan 2	Calorimeter	Soudan, Minnesota, USA	3.9 kton
MACRO	streamer tubes	Gran Sasso, Italy	

1. *They all stopped data taking*
2. *SuperK had an accident and is under repair. It is the only experiment that will resume data taking in the future.*
3. *In addition, only one new experiment ICARUS is under construction and will start data taking next year. It is the only approved new experiment.*
4. *Other bigger experiments are being discussed (HyperK, MONOLITH, …)*

Measured double ratio

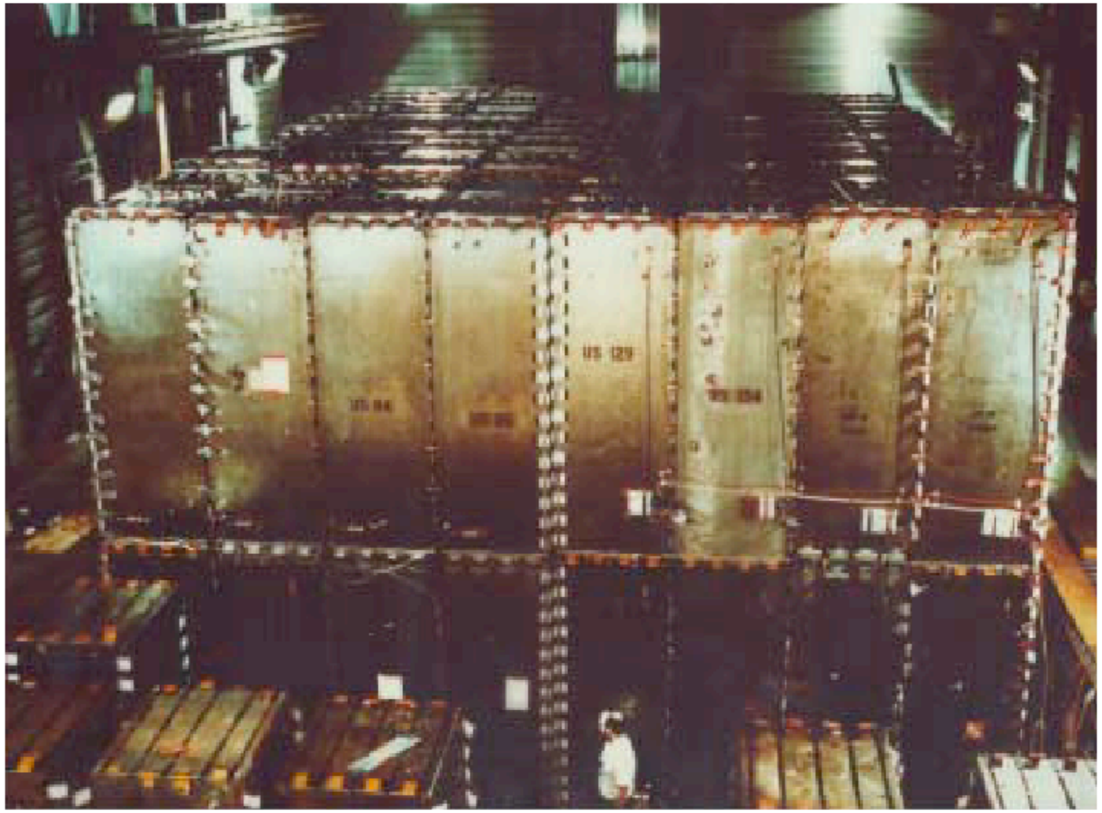
$$R \equiv (\square / e)_{data} / (\square / e)_{MC}$$

Detector		Exposure	Double Ratio	Ref.
IMB	sub-GeV	7.7	$0.54 \pm 0.05 \pm 0.012$	[4]
	multi-GeV	2.1	$1.4^{+0.4}_{-0.3} \pm 0.3$	[10]
Kamiokande	sub-GeV	7.7	$0.60^{+0.06}_{-0.05} \pm 0.05$	[11]
	multi-GeV	8.2 / 6.0	$0.57^{+0.08}_{-0.07} \pm 0.07$	[11]
Super-Kamiokande	sub-GeV	25.5	$0.61 \pm 0.03 \pm 0.05$	[8]
	multi-GeV	25.5	$0.66 \pm 0.06 \pm 0.08$	[9]
Nusex		0.74	$0.96^{+0.32}_{-0.28}$	[12]
Fréjus		1.56	$1.00 \pm 0.15 \pm 0.08$	[13]
Soudan 2		3.9	$0.64 \pm 0.11 \pm 0.06$	[16]
MACRO		1122 evts	$0.72 \pm 0.026 \pm 0.043 \pm 0.12$	[17]

Atmospheric neutrino problem !

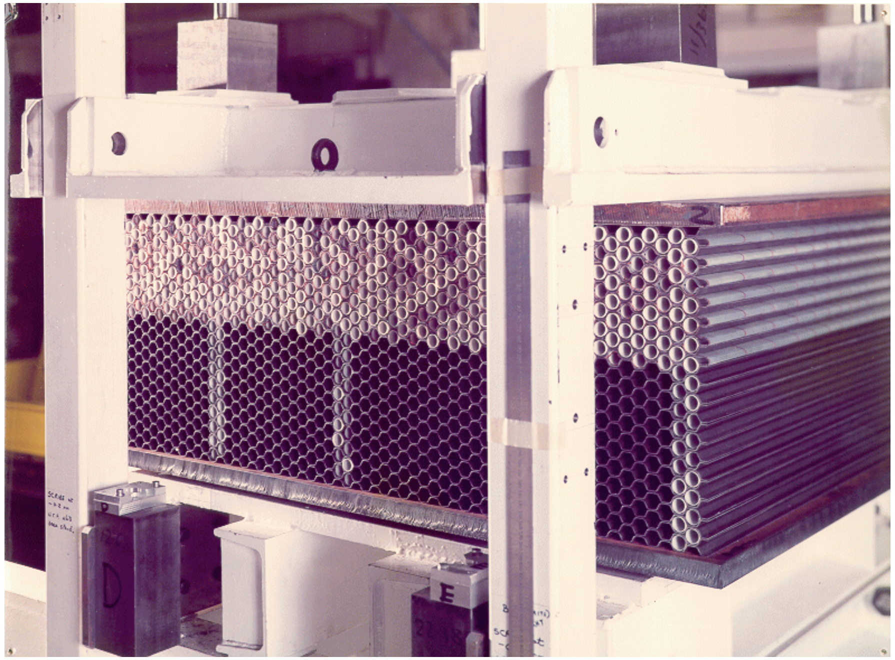
SOUDAN-2 detector (1989-2000)

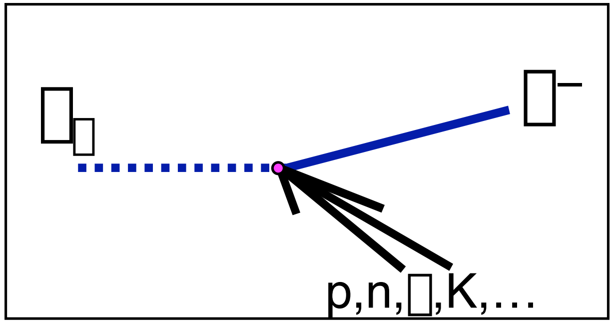
Soudan II detector is located in an underground laboratory in the Tower-Soudan Iron Mine 1/2 mile (2,090 metres of water equivalent) beneath Soudan, Minnesota, USA

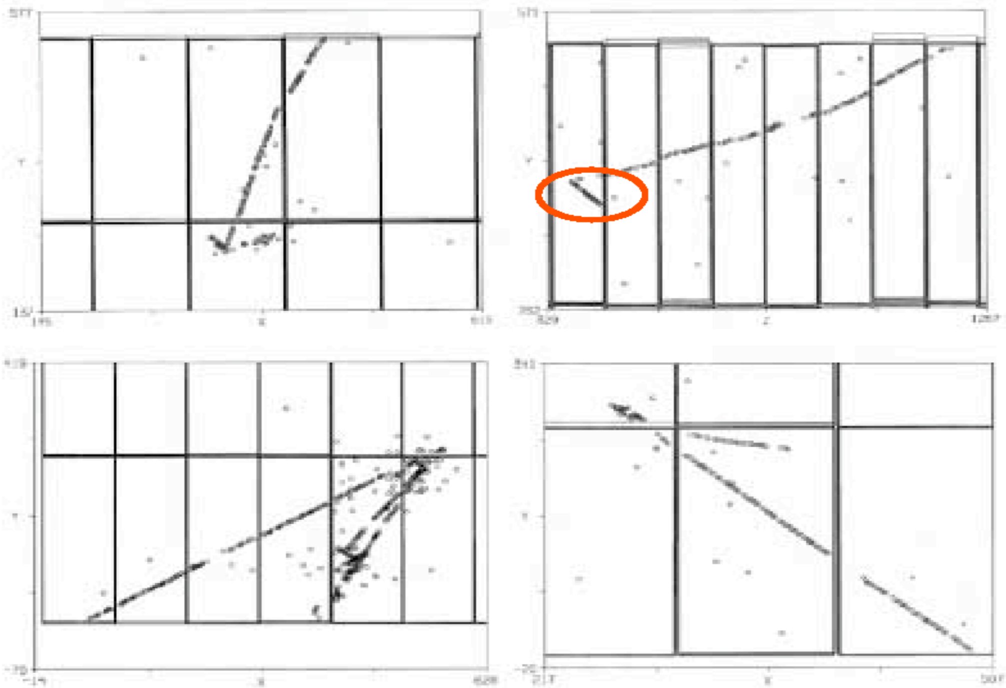


Soudan II detector was **960 ton** tracking calorimeter composed 224 modules of steel sheets shaped as honeycombs to host drift tubes.

Atmospheric neutrino events in SOUDAN





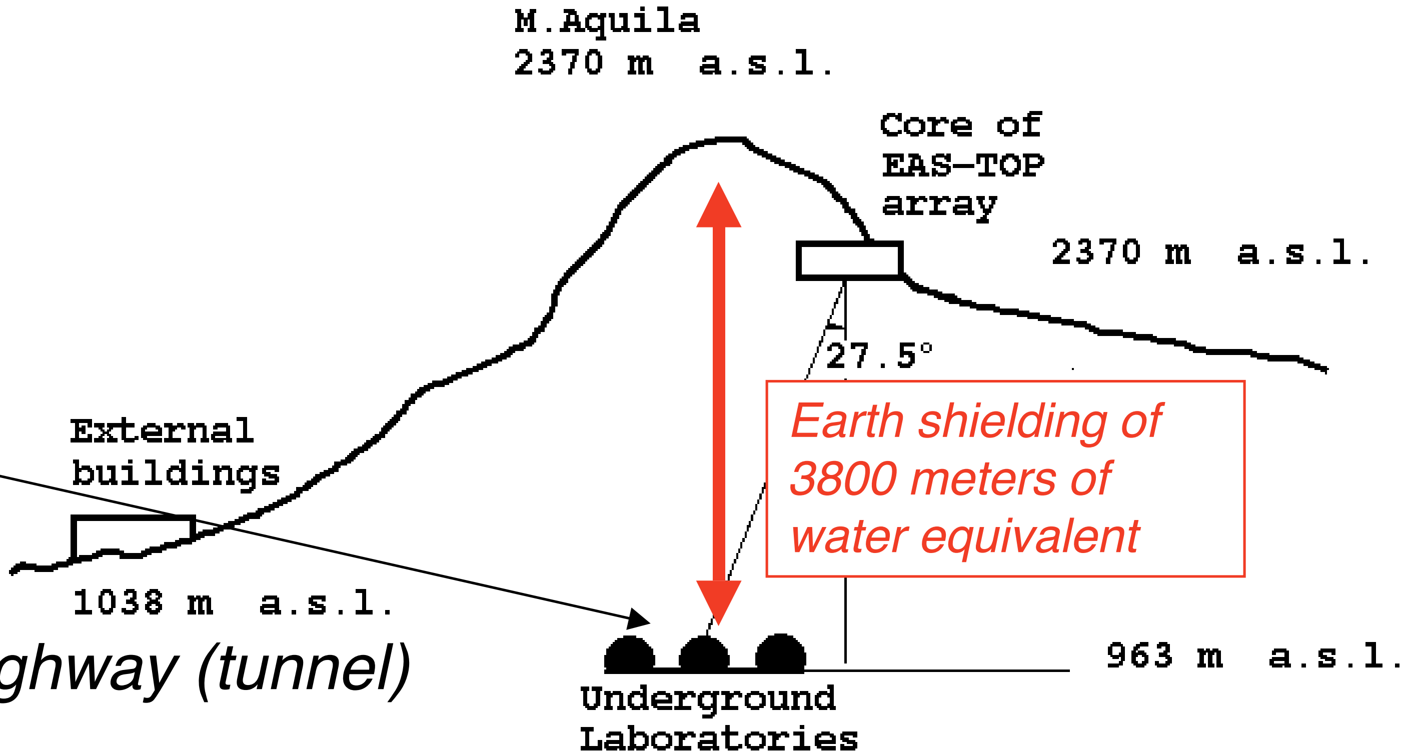


The entire calorimeter is comprised of 224 modules
Each module contained a tightly packed <u>honeycomb array</u> of 15,120 drift tubes
The drift tube array provides 3-dimensional hit reconstruction, with an r.m.s. accuracy of 1.12cm in the drift direction and 3.5mm in the orthogonal plane, together with dE/dX sampling.

Gran Sasso Underground Laboratory (LNGS)

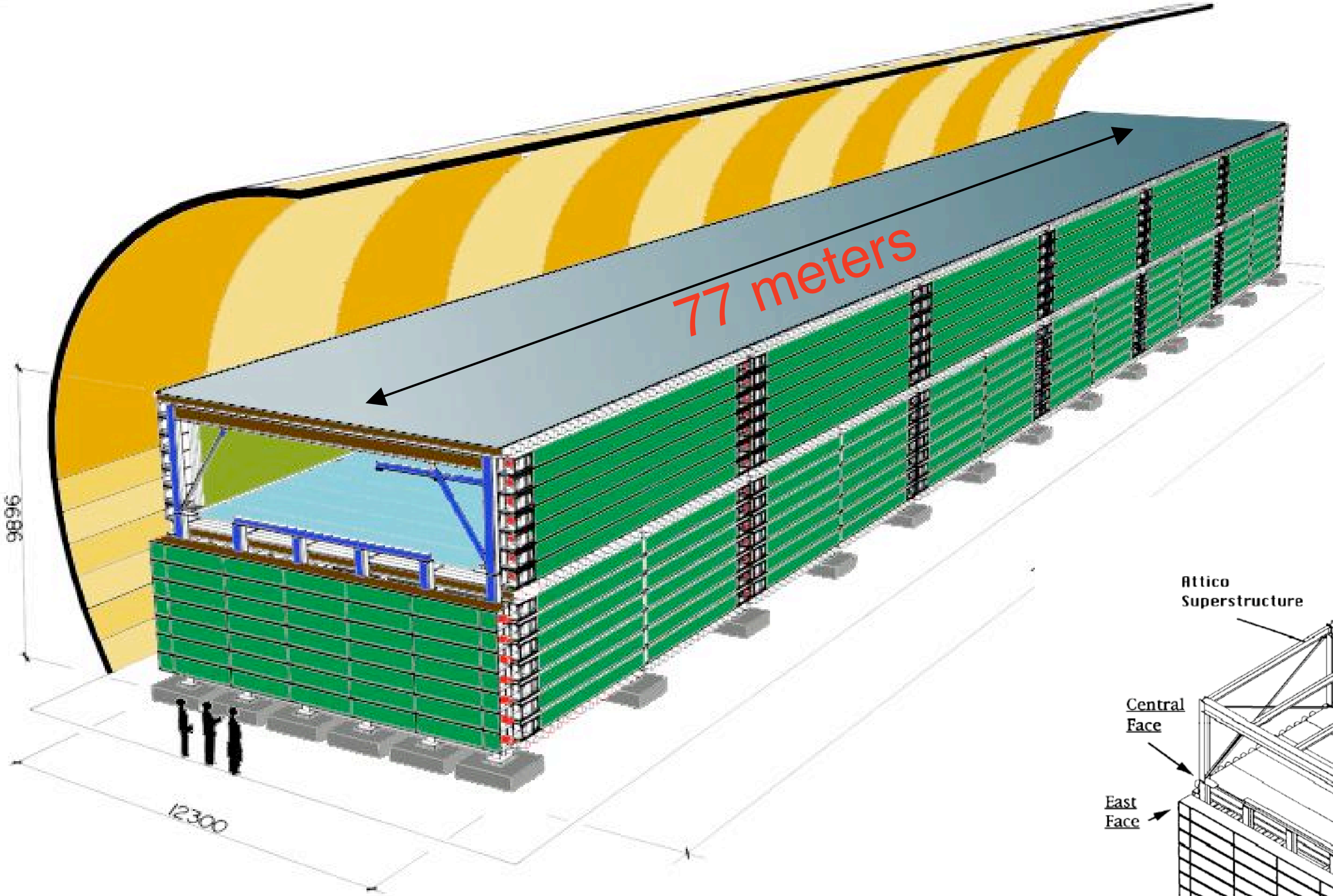
http://www.lngs.infn.it/

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



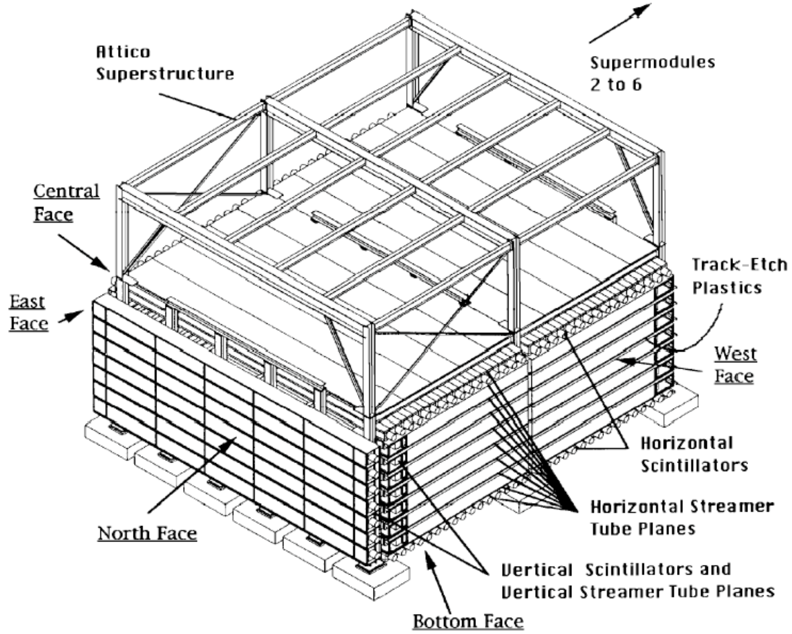
• *Access through highway (tunnel)*

MACRO experiment (until 2001)



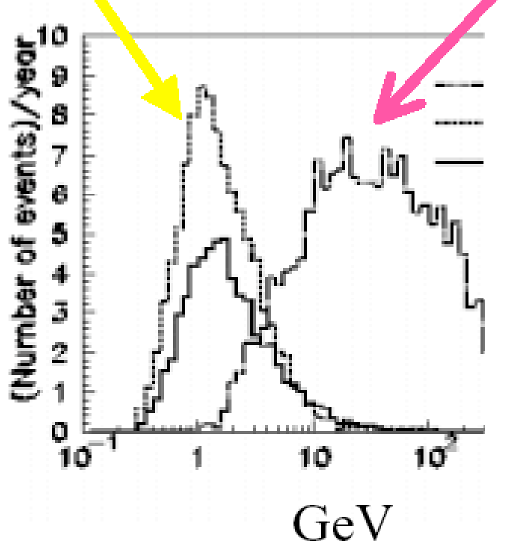
MACRO was built to search for monopoles, but is also sensitive to C.R. muons and atmospheric neutrinos

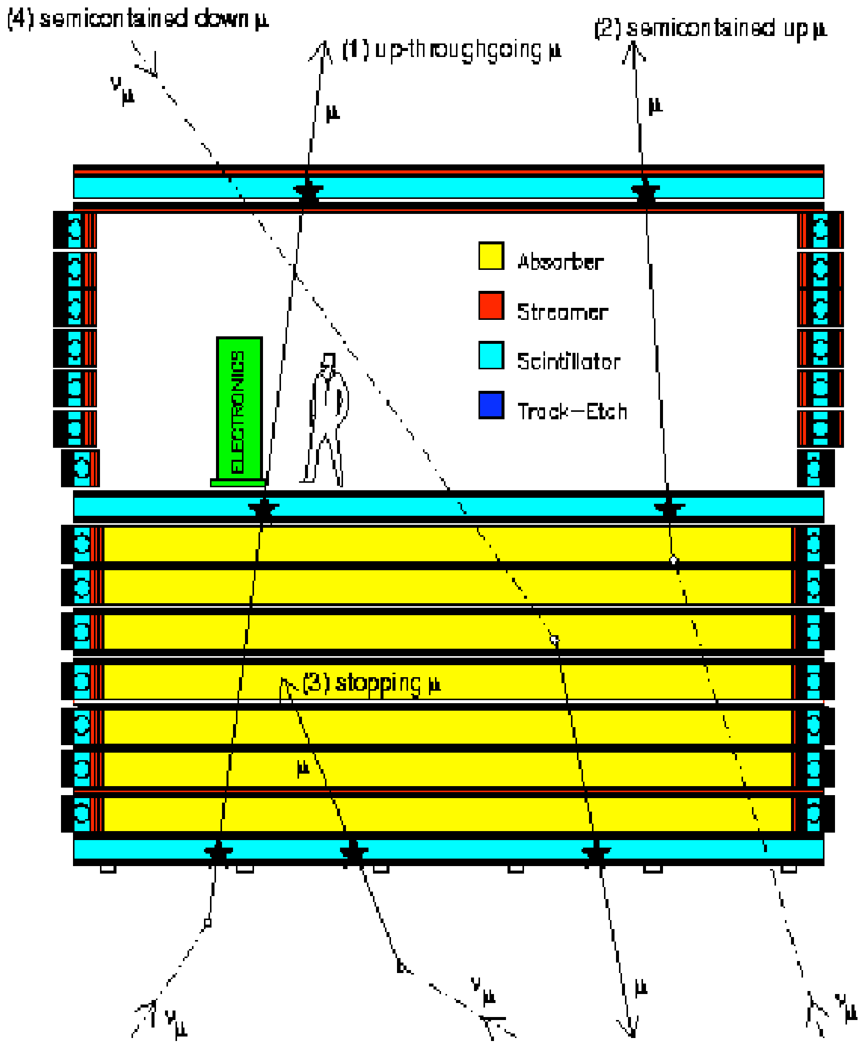
MACRO was composed of 6 supermodules, each consisting of streamer tubes planes and scintillators for precise timing



Detection of Atmospheric ν's **MACRO**

- Interaction in Detector
  - Fully Contained Events
  - Partially Contained Events
- Interaction Outside Detector
  - Throughgoing μ's
  - Up-stopping μ's

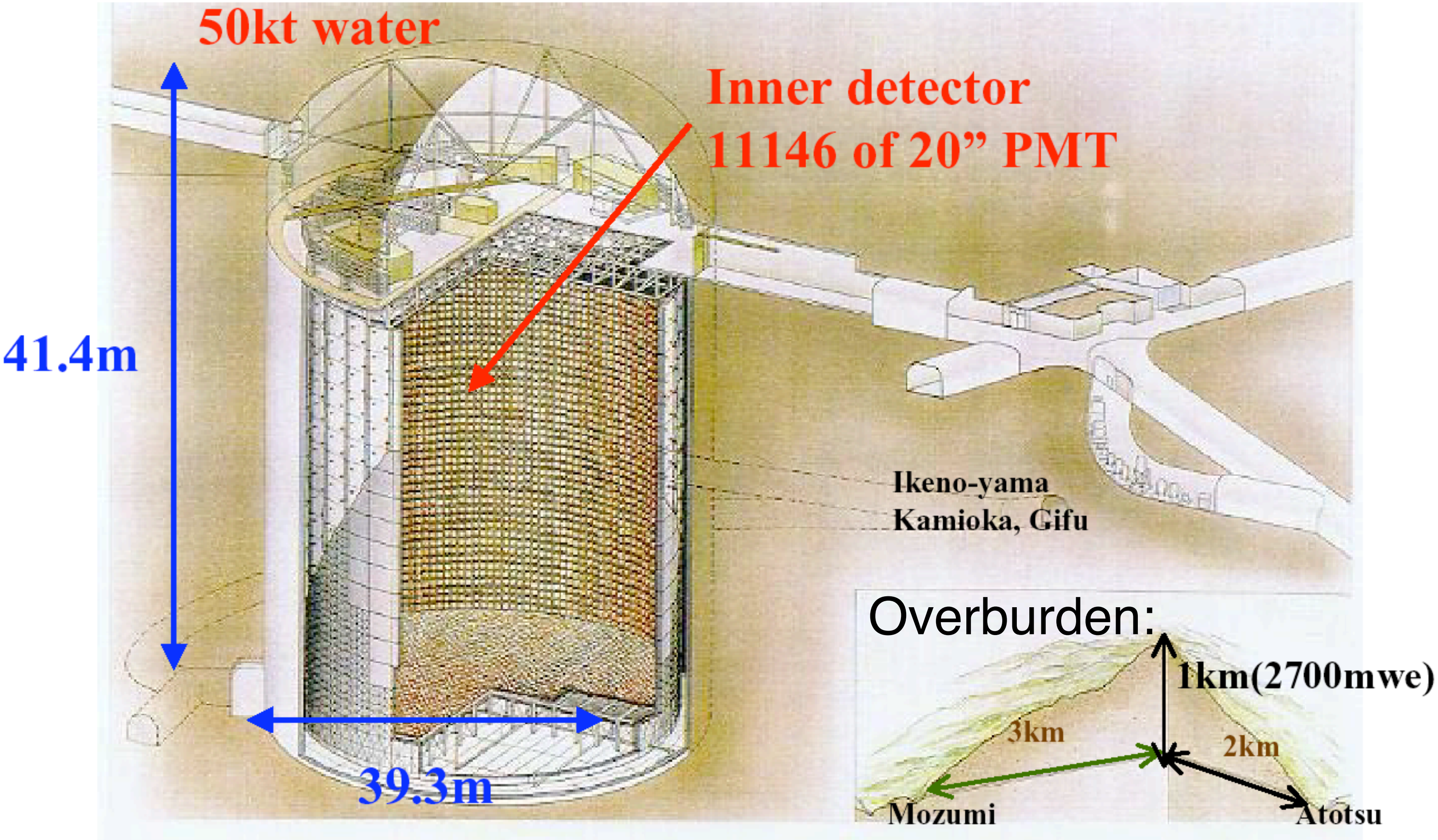




Maury Goodman, Neutrino 2002
"Other Atmospheric ν Experiments"

SuperKamiokande Detector

Very large Water Cerenkov detector: Fiducial mass 22.5 kton

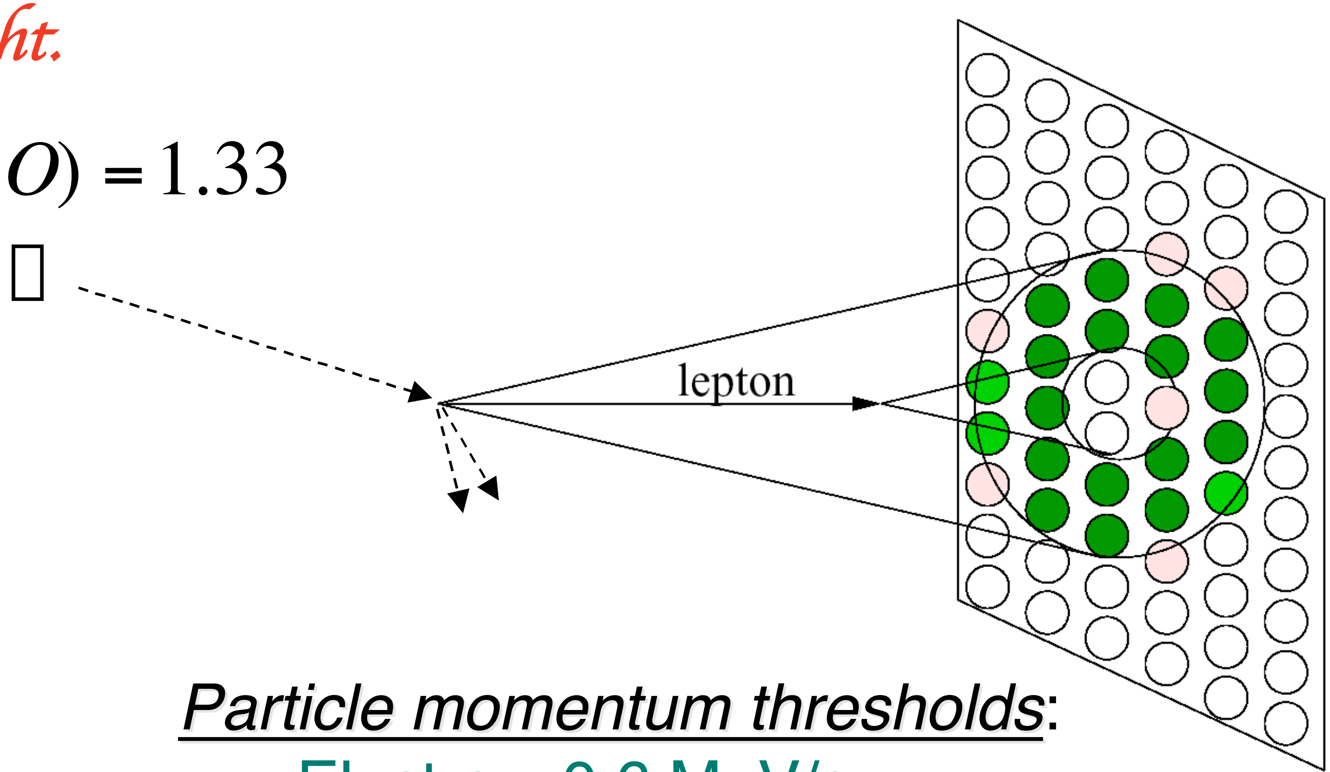


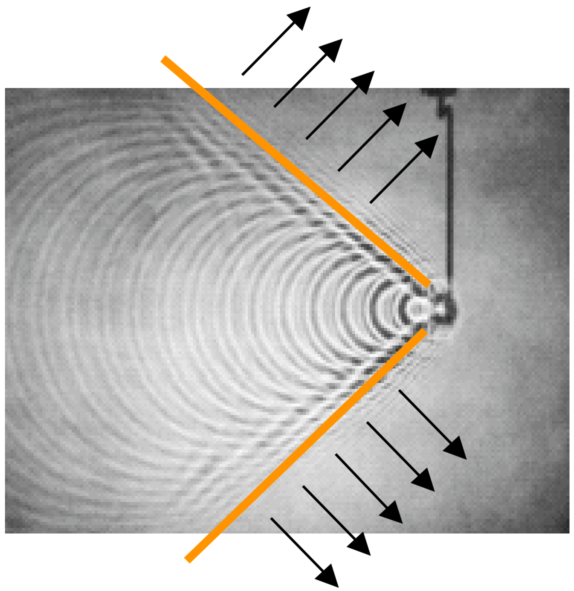
Operation from April 1996 till November 2001 (currently under repair)

Cerenkov rings

Particle traversing medium at speed faster than the speed of light in that medium emits light.

$$\cos\theta = \frac{1}{n\beta} \qquad n(H_2O) = 1.33$$

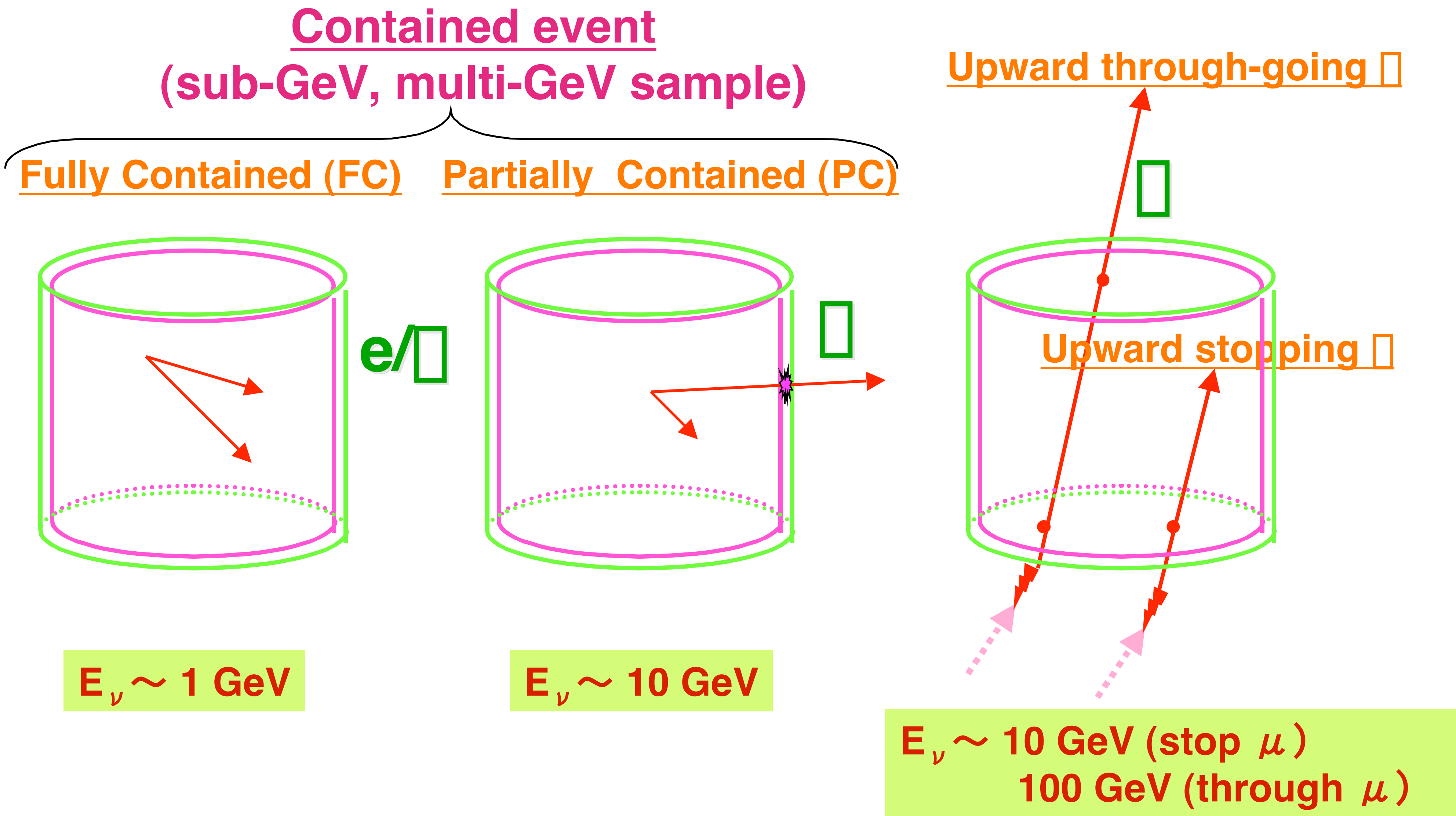




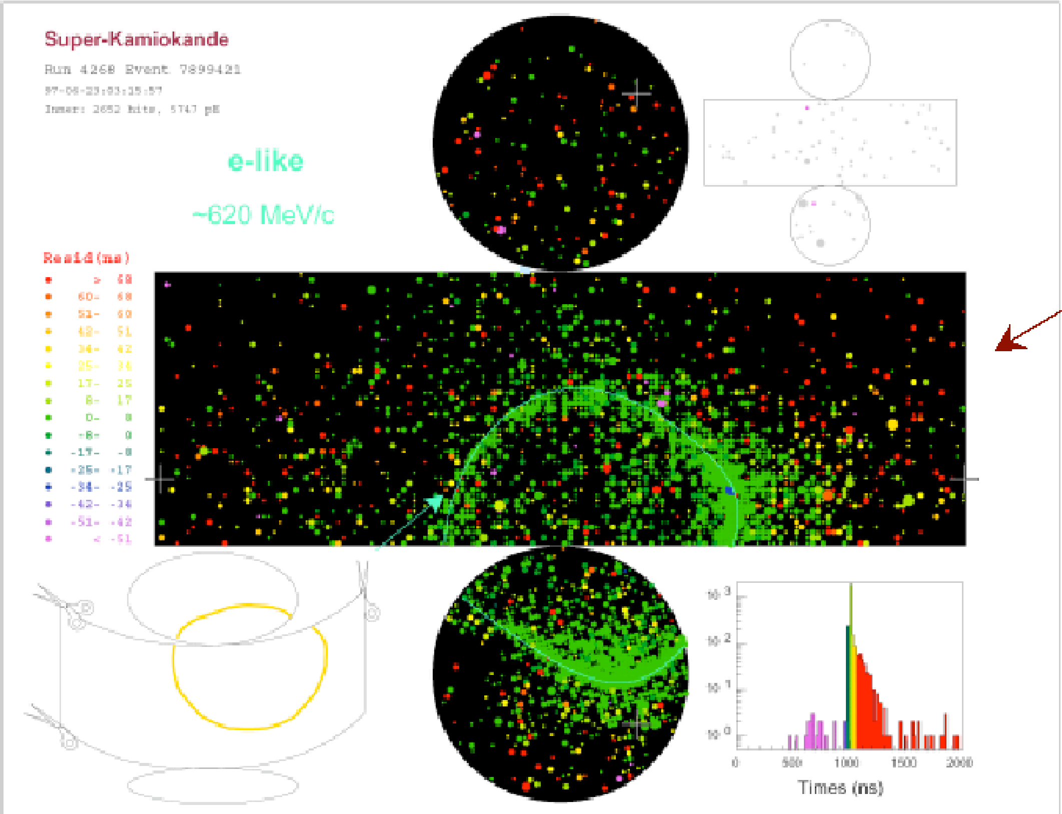
Particle momentum thresholds:

- Electron 0.6 MeV/c
- Muon 120 MeV/c
- Pion 159 MeV/c
- Kaon 568 MeV/c
- Proton 1070 MeV/c

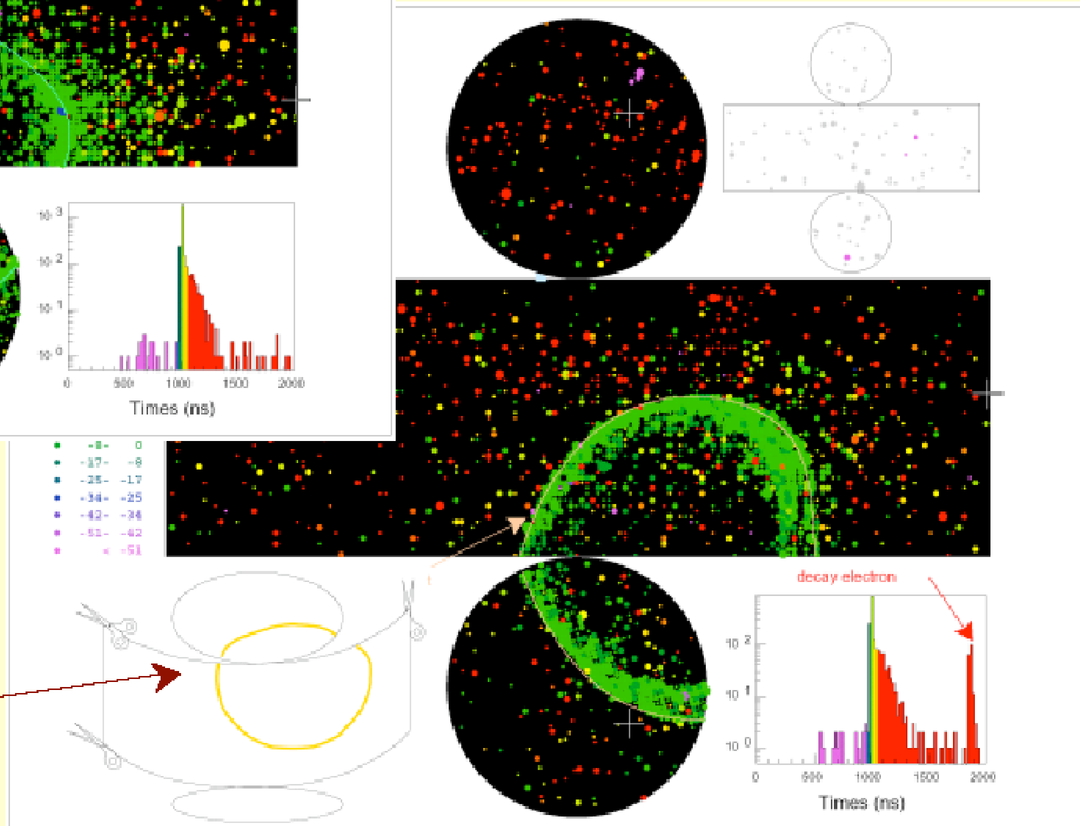
Event classification of atmospheric ν



Electron and muon events in SuperK



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

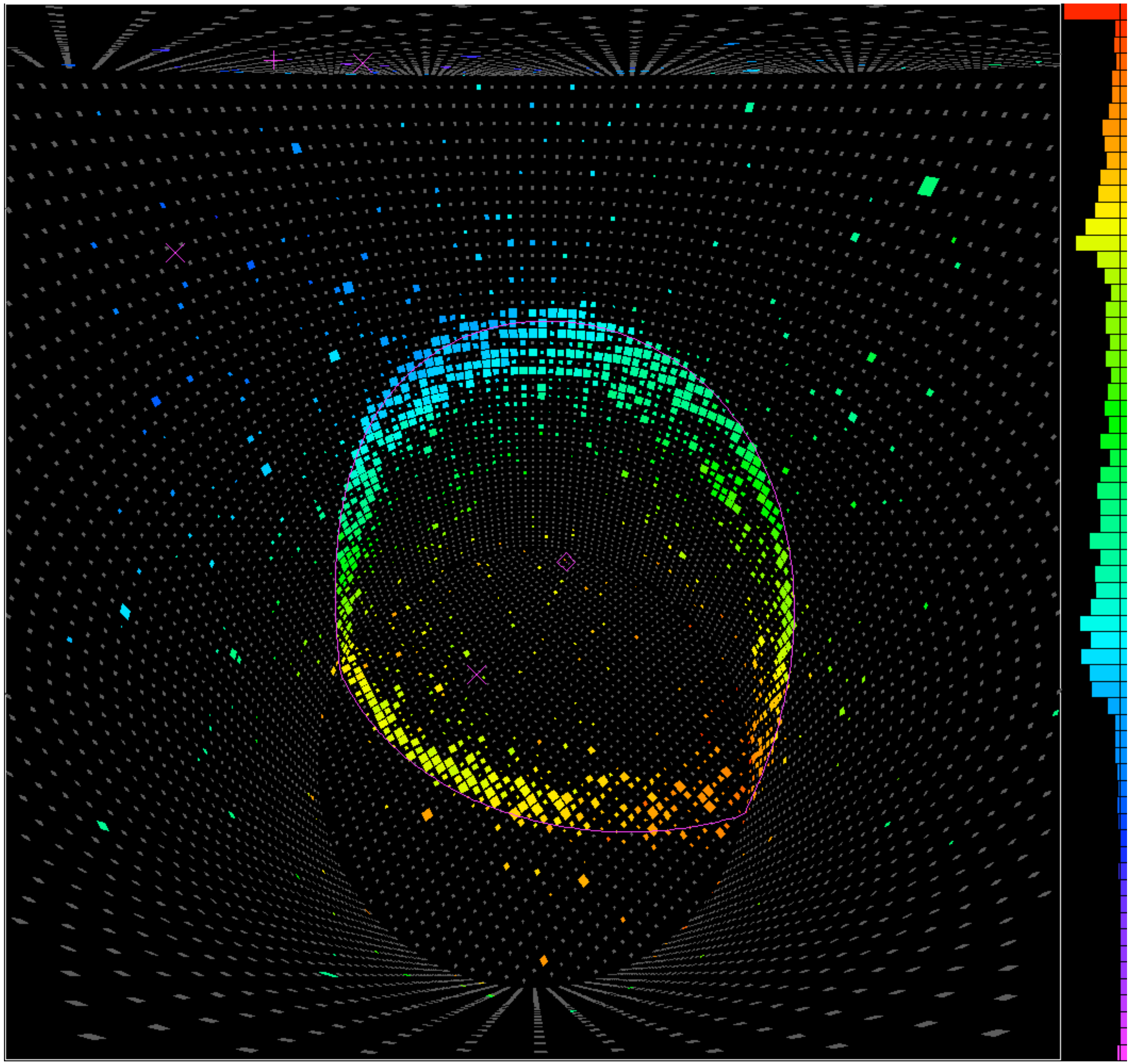


- Non-Showering ring (μ-like)
- Sometimes decay electron

Michael Smy, UC Irvine

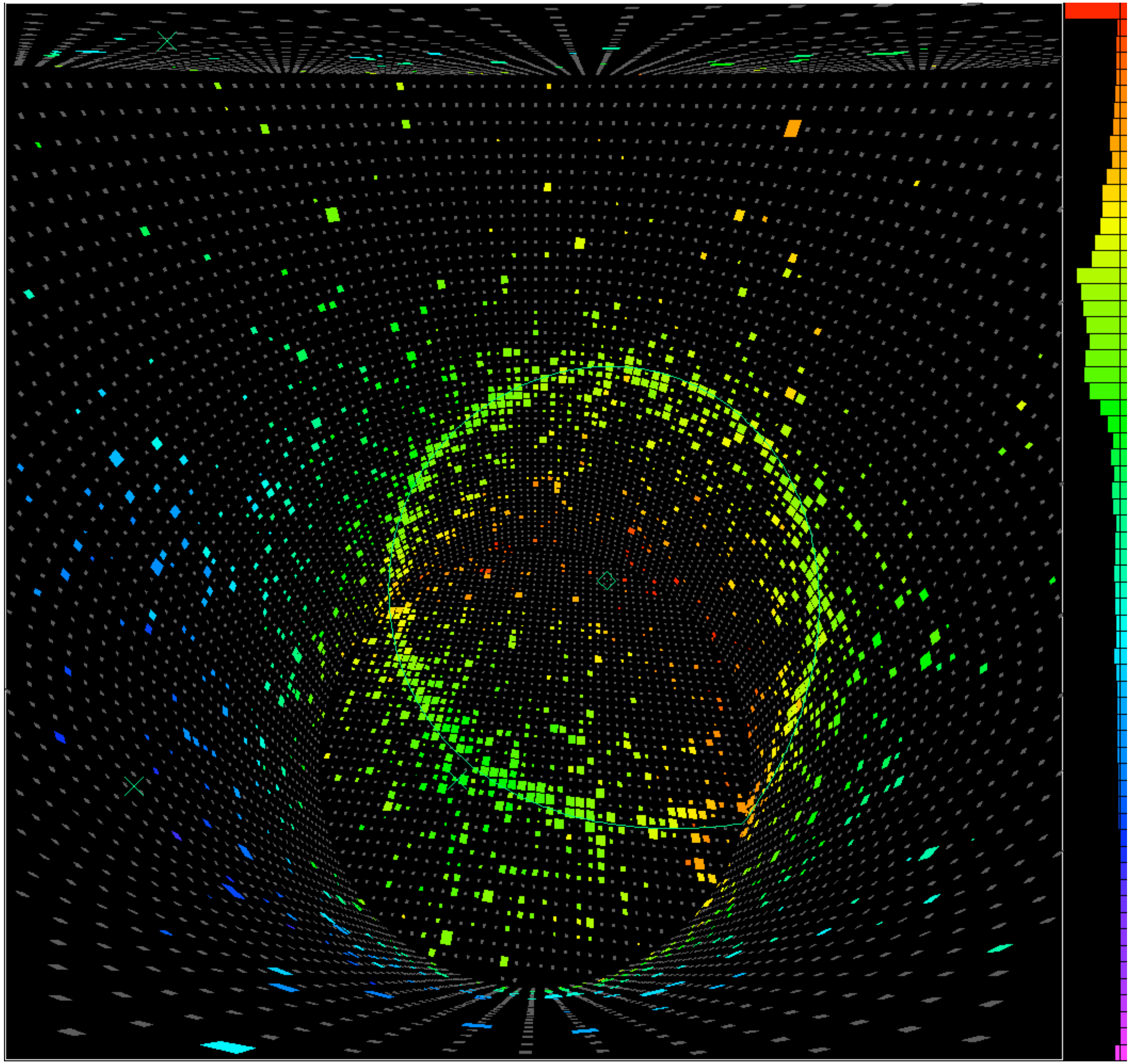
A muon candidate in SuperK

1998-04-04 08:35:22. It was reconstructed as a muon with momentum of 603 MeV



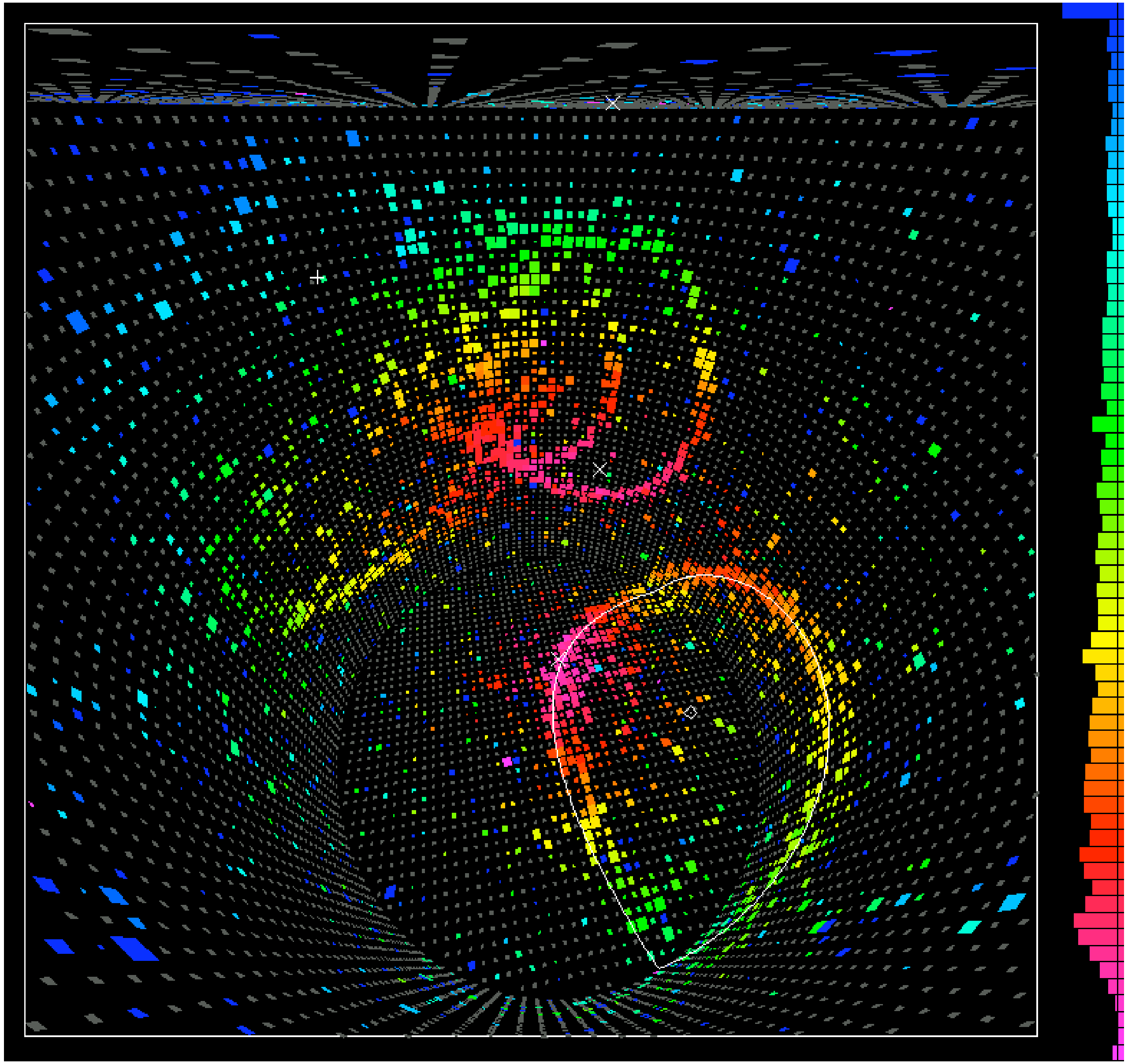
An electron candidate in SuperK

1998-04-04 21:26:08. It was reconstructed as an electron with momentum of 492 MeV



e+π^0 final state candidate

1997-09-24 12:02:48



Sub-GeV, Multi-GeV Event Summary

Sub-GeV event Summary

Evis < 1.33GeV
P_e > 100MeV/c
P_μ > 200MeV/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

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

$$= 0.671 \pm^{0.021}_{0.020\,\text{stat.}} \pm 0.053_{\text{sys.}} \text{ (Bartol)}$$

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

$$= 0.660 \pm^{0.038}_{0.035\,\text{stat.}} \pm 0.078_{\text{sys.}} \text{ (Honda)}$$

$$= 0.664 \pm^{0.038}_{0.036\,\text{stat.}} \pm 0.079_{\text{sys.}} \text{ (Bartol)}$$

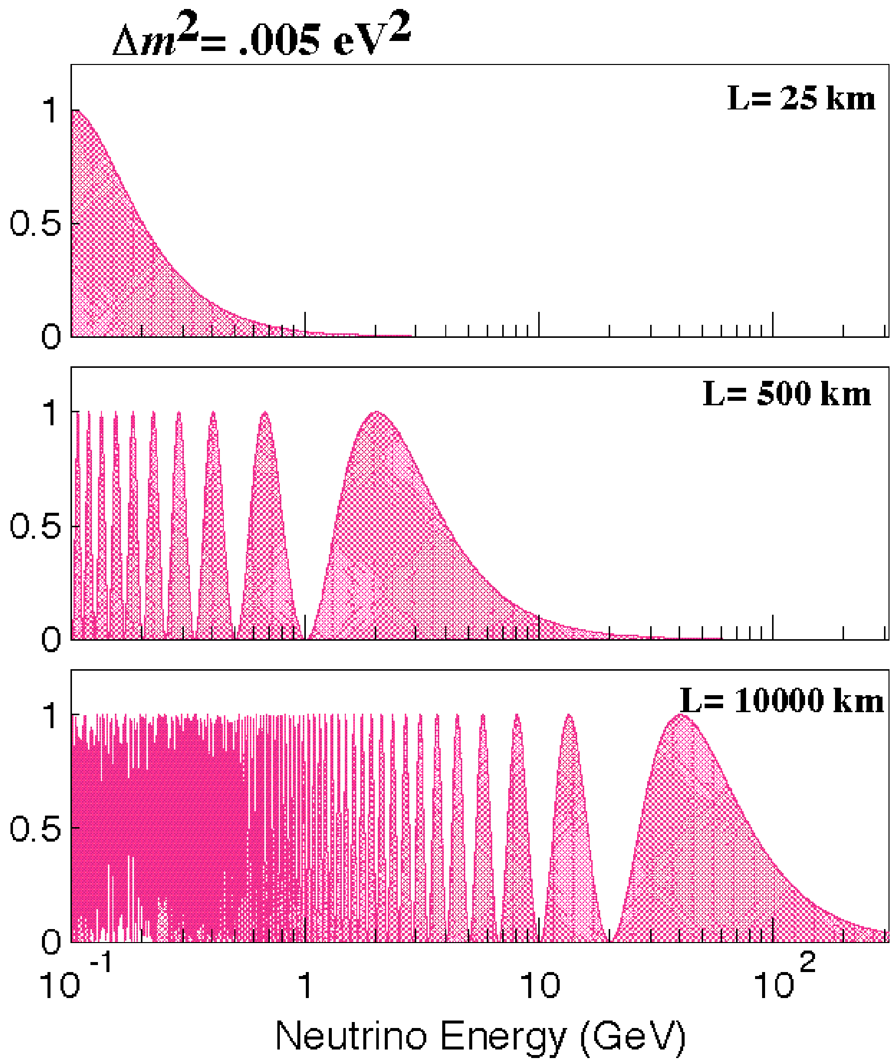
FC only

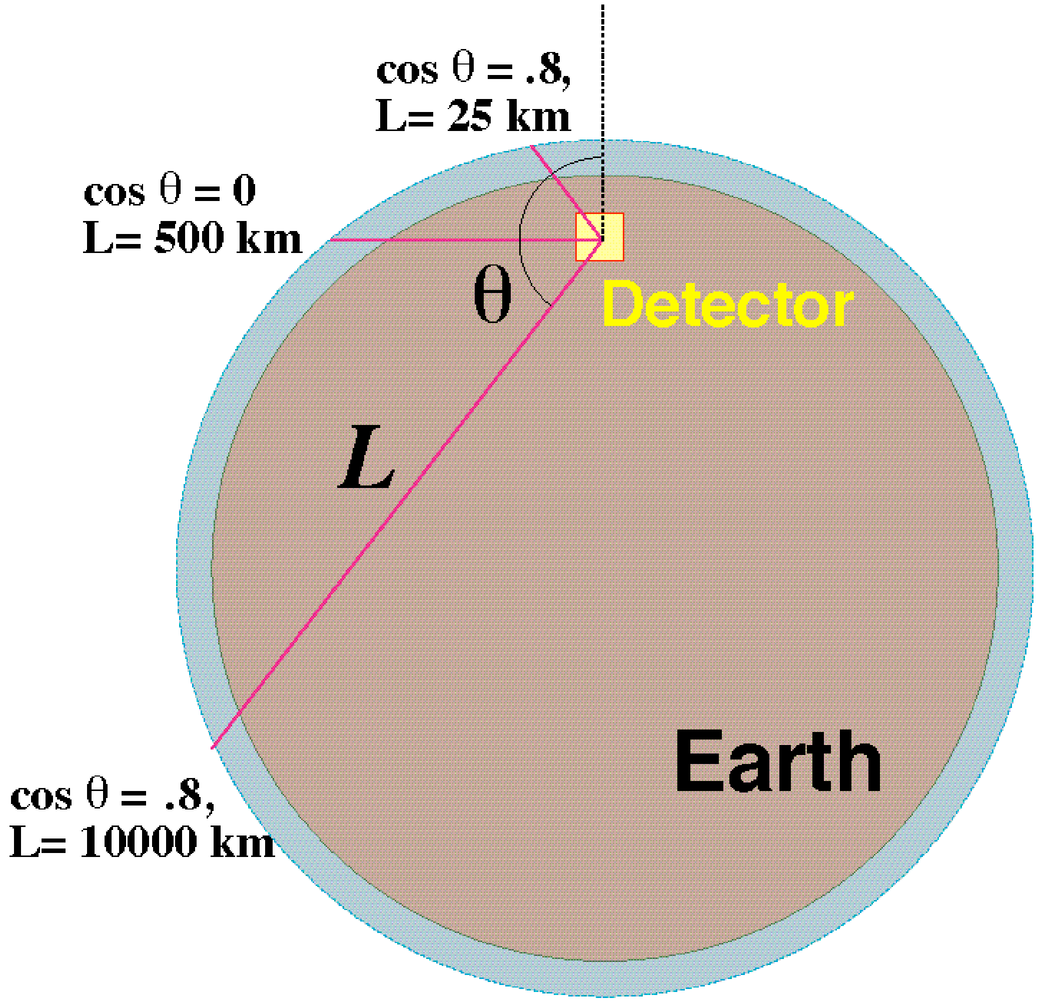
$$= 0.643 \pm^{0.044}_{0.042\,\text{stat.}} \pm 0.094_{\text{sys.}} \text{ (Honda)}$$

$$= 0.667 \pm^{0.046}_{0.043\,\text{stat.}} \pm 0.098_{\text{sys.}} \text{ (Bartol)}$$

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

Zenith angle distribution

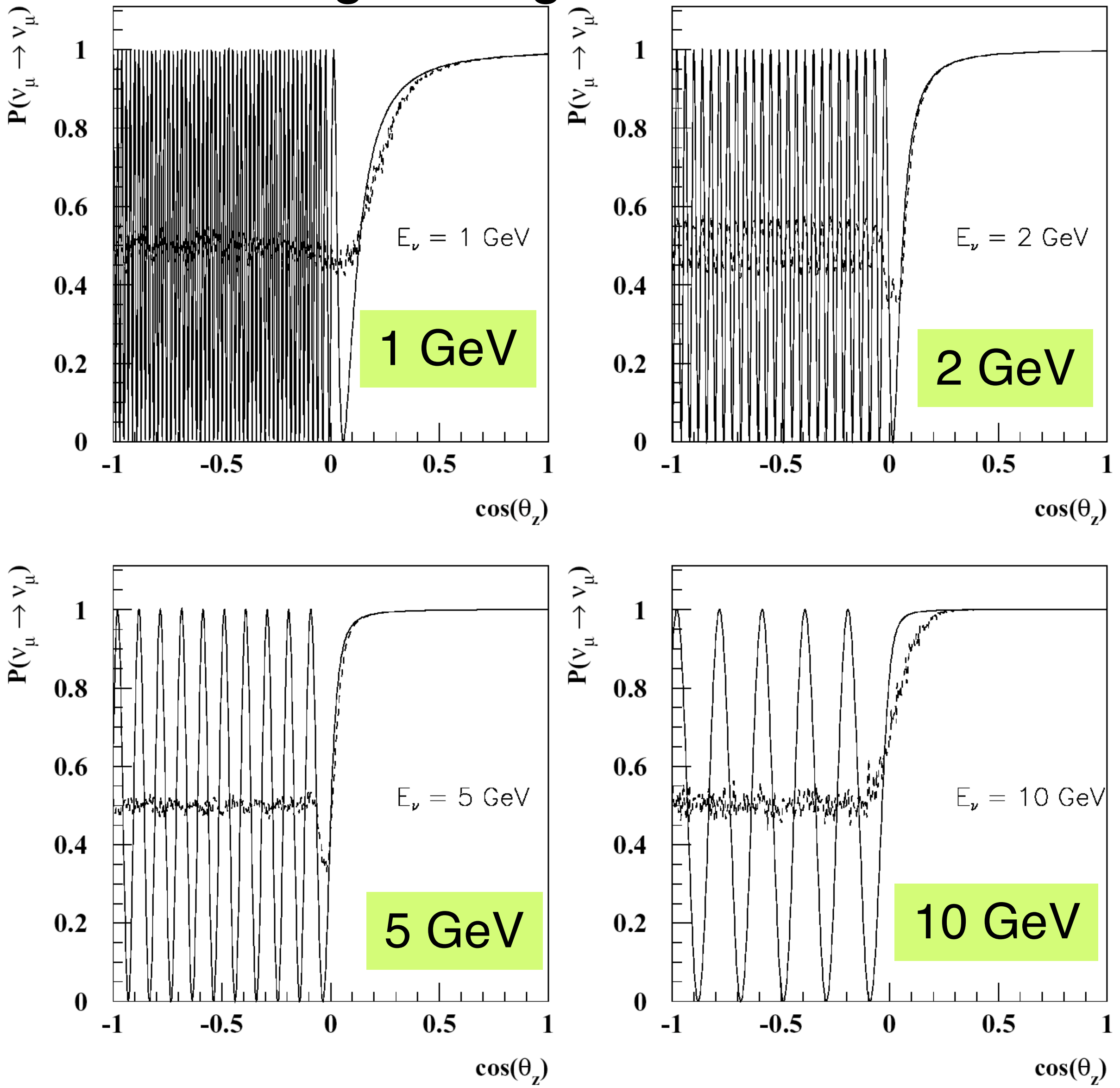




$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

Zenith angle dependence: effect of resolution

Dotted curve: 20% smearing on angle

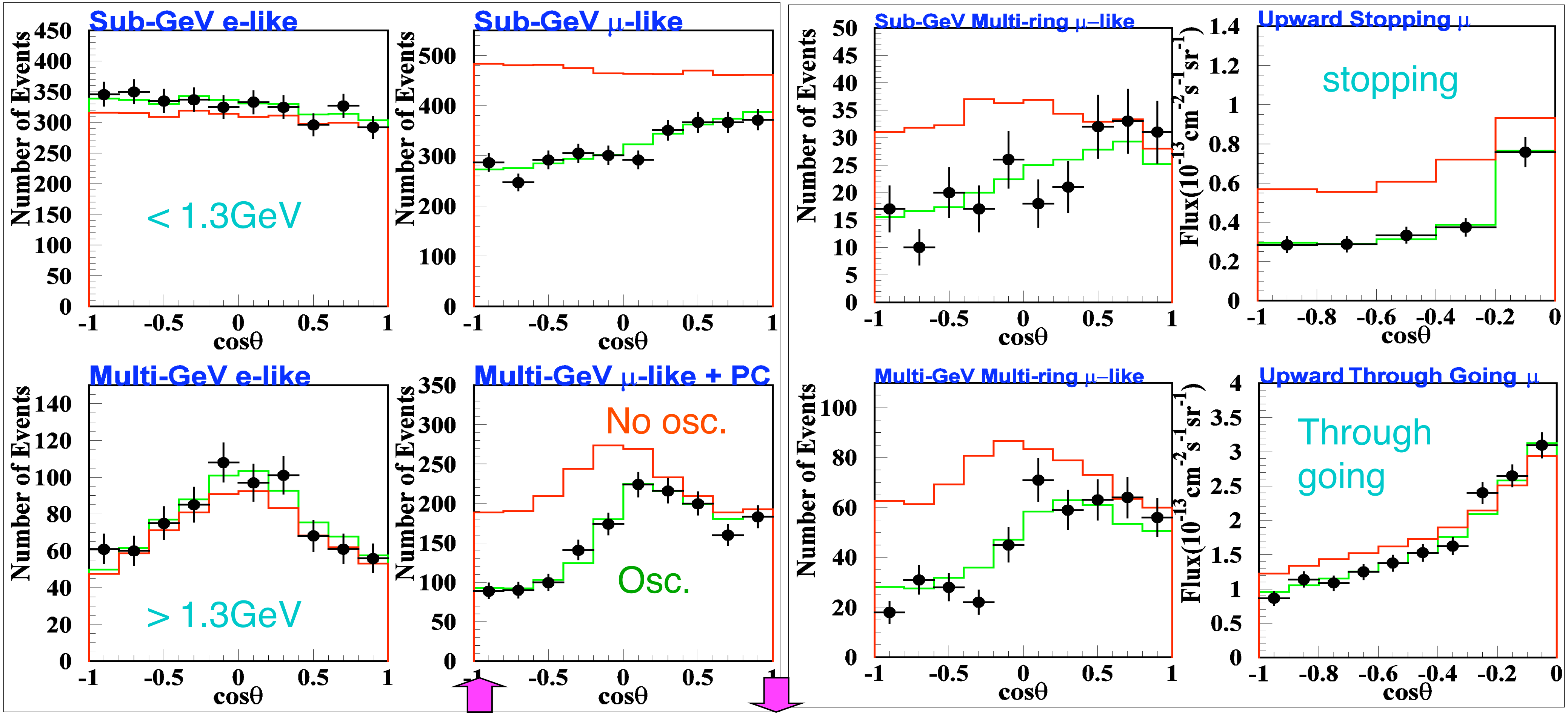


Super-Kamiokande data

1489day FC+PC data + 1678day upward going muon data

- Whole SK-1 data have been analyzed.

1-ring e-like   1-ring μ-like   multi-ring μ-like   up-going μ

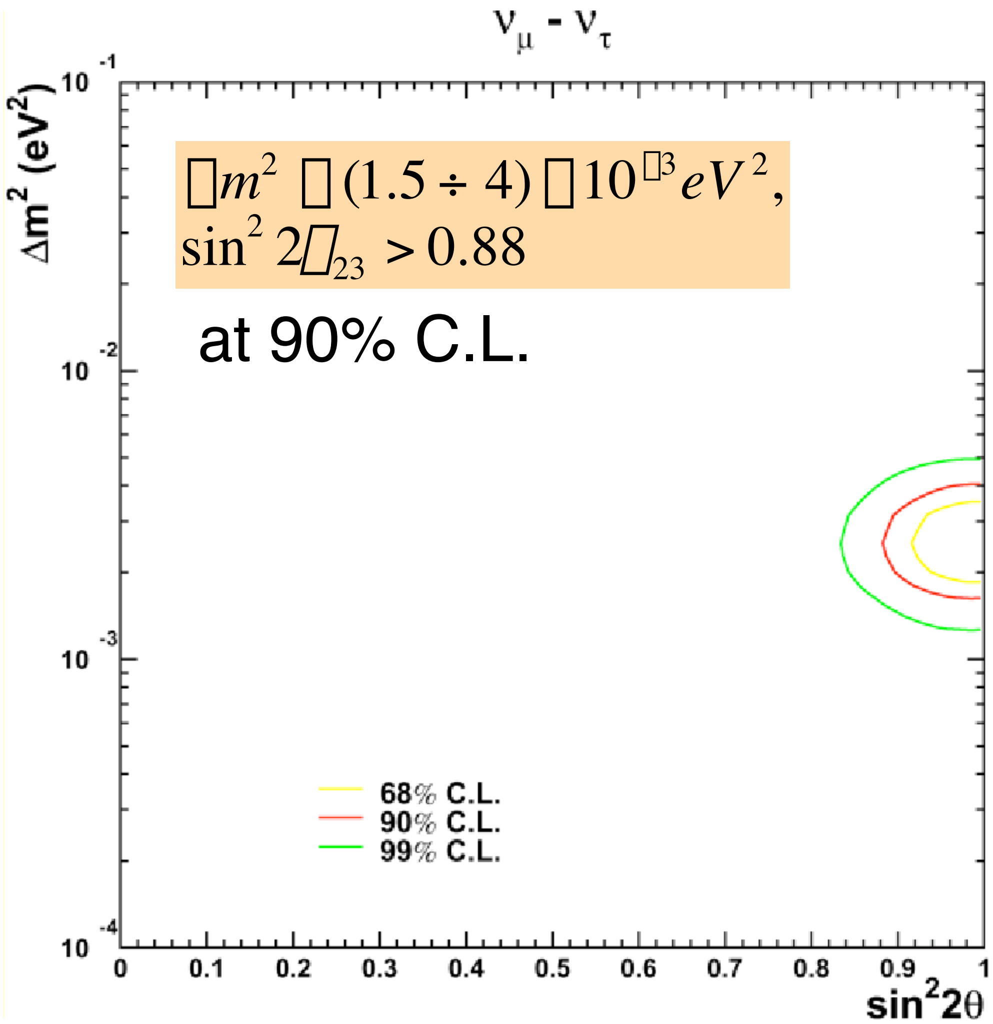


Up-going   Down-going

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°

1290 days data taking



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

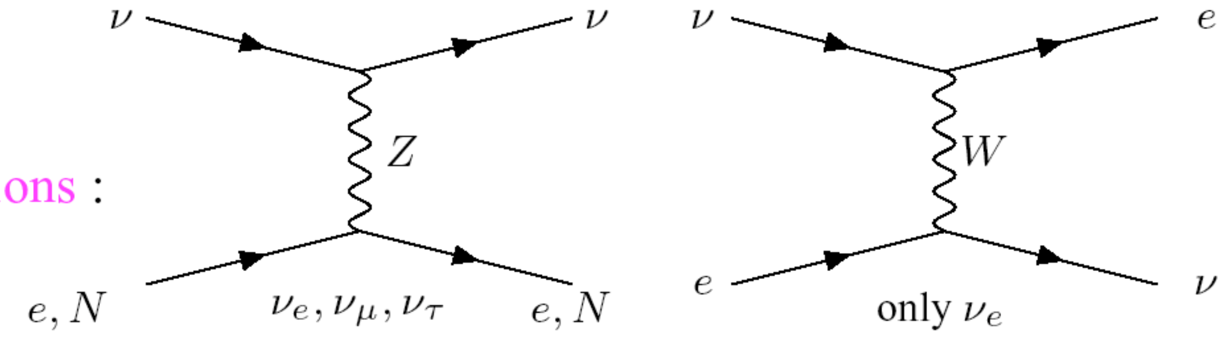
at 90% C.L.

Mode	Best fit	Δχ2	σ
ν_μ-ν_τ	$\sin^2 2\theta$=1.00; Δm^2=2.5x10^{-3}eV^2	0.0	0.0
ν_μ-ν_e	$\sin^2 2\theta$=0.97; Δm^2=5.0x10^{-3}eV^2	79.3	8.9
ν_μ-ν_s	$\sin^2 2\theta$=0.96; Δm^2=3.6x10^{-3}eV^2	19.0	4.4
LxE	$\sin^2 2\theta$=0.90; α=5.3x10^{-4}	67.1	8.2
ν_μ Decay	$\cos^2\theta$=0.47; α=3.0x10^{-3}eV^2	81.1	9.0
ν_μ Decay to ν_s	$\cos^2\theta$=0.33; α=1.1x10^{-2}eV^2	14.1	3.8

$\nu_\mu \rightarrow \nu_\tau$ indirectly favored mode

Neutrino oscillations through matter

- If ν cross matter regions (Sun, Earth...) it interacts *coherently*
  - But Different flavours have different interactions :



$$\sin^2 2\theta_m(D) = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\pm \frac{D}{\Delta m^2} - \cos 2\theta\right)^2}$$

$$\Delta_m = L \cdot \sqrt{\sin^2 2\theta + \left(\pm \frac{D}{\Delta m^2} - \cos 2\theta\right)^2}$$

+ for neutrinos
– for antineutrinos

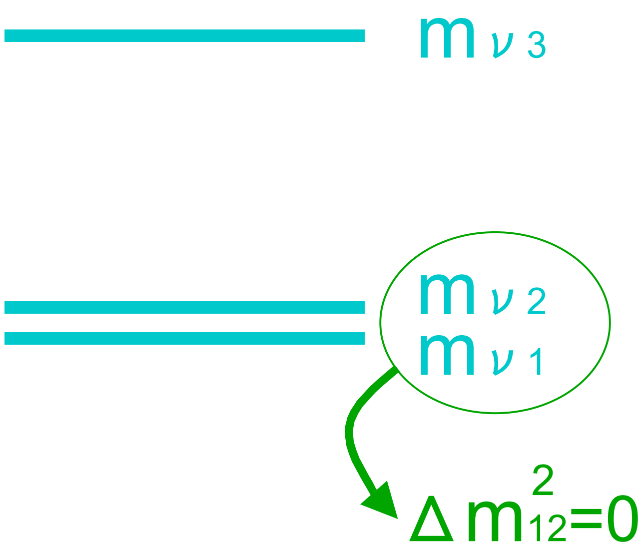
where

$$D(E_\nu) = 2\sqrt{2} G_F n_e E_\nu \approx 7.56 \times 10^{-5} \quad eV^2 \left(\frac{\rho}{g cm^{-3}}\right)\left(\frac{E}{GeV}\right)$$

Resonance: $D \approx \Delta m^2 \cos 2\theta$ ⟹ $\sin^2 2\theta_m(D) \approx 1$

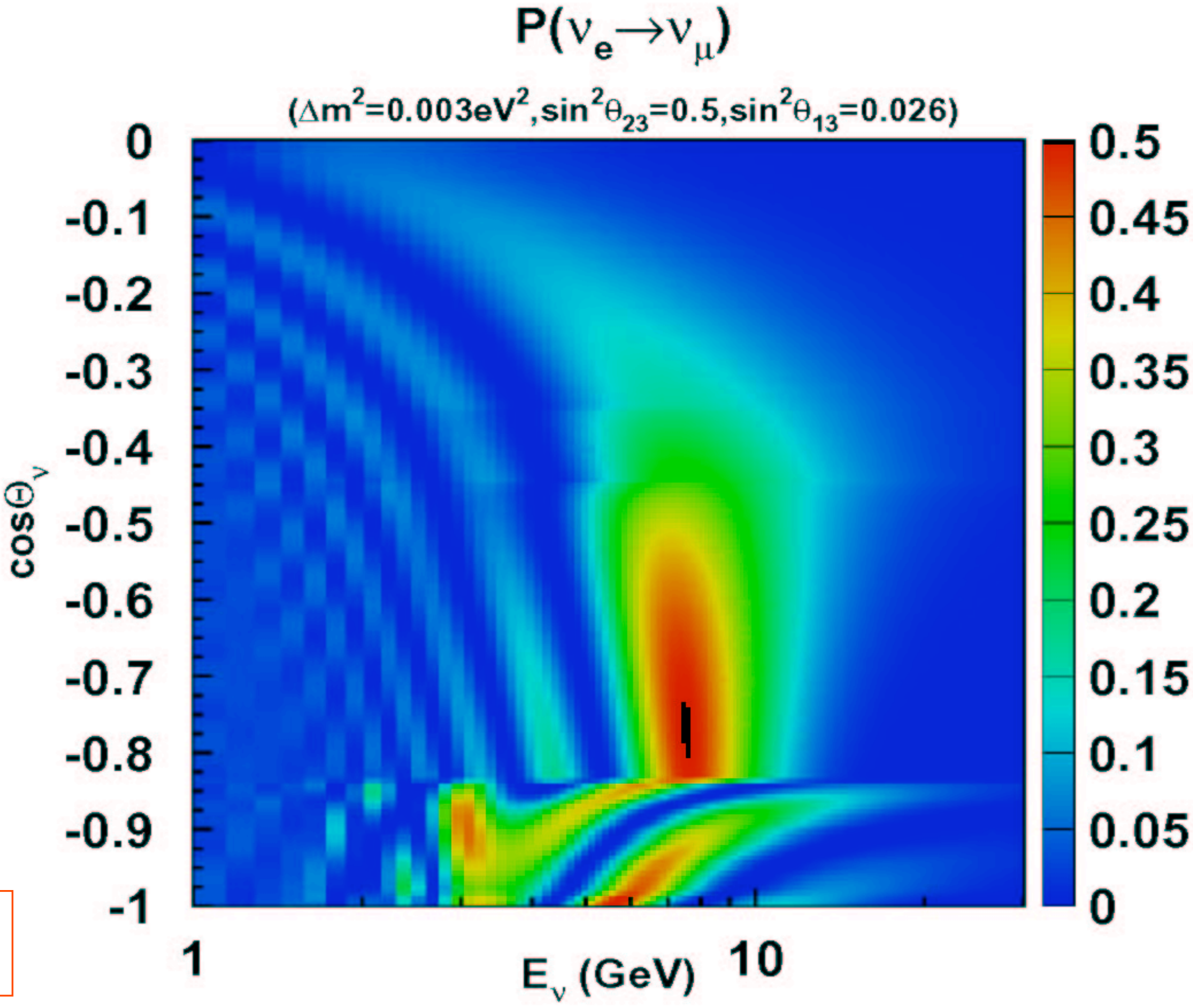
Matter effects in 1-mass approximation

Must consider mixing with electron-neutrino 3 neutrino mixing



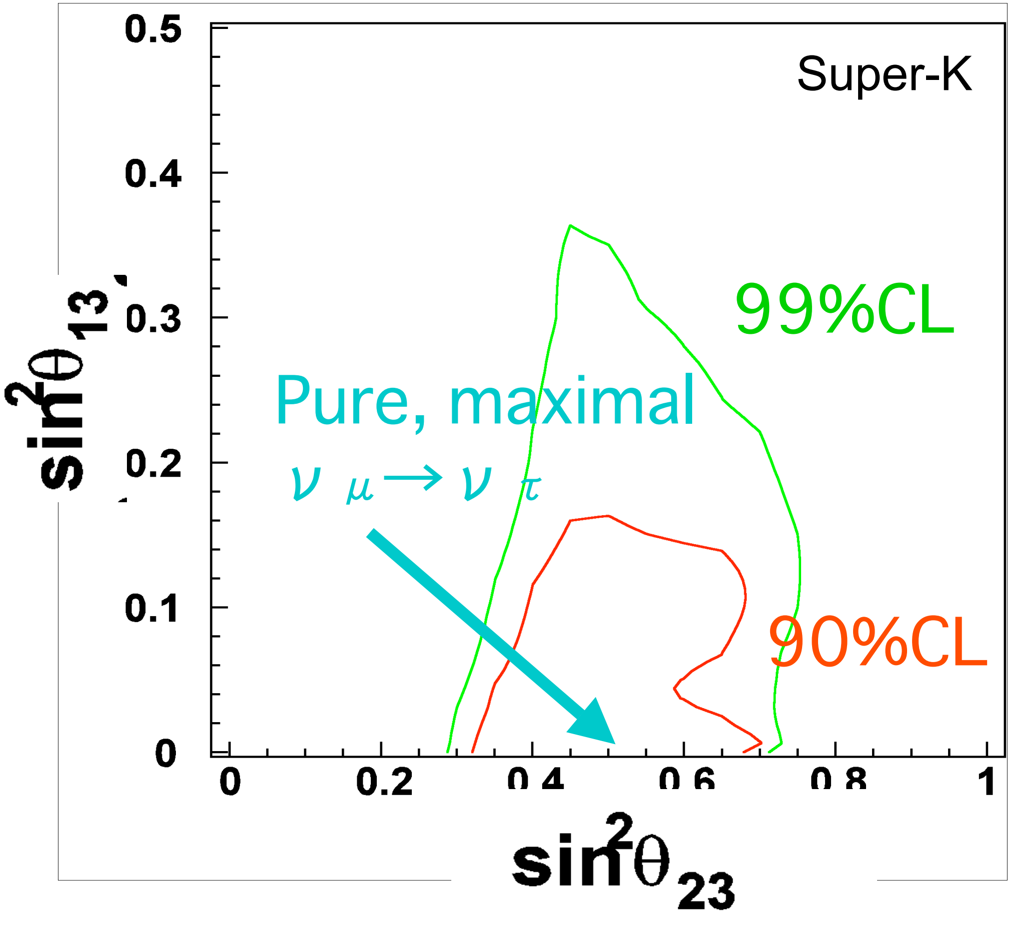
$\Delta m^2_{13} = \Delta m^2_{23} = \Delta m^2$

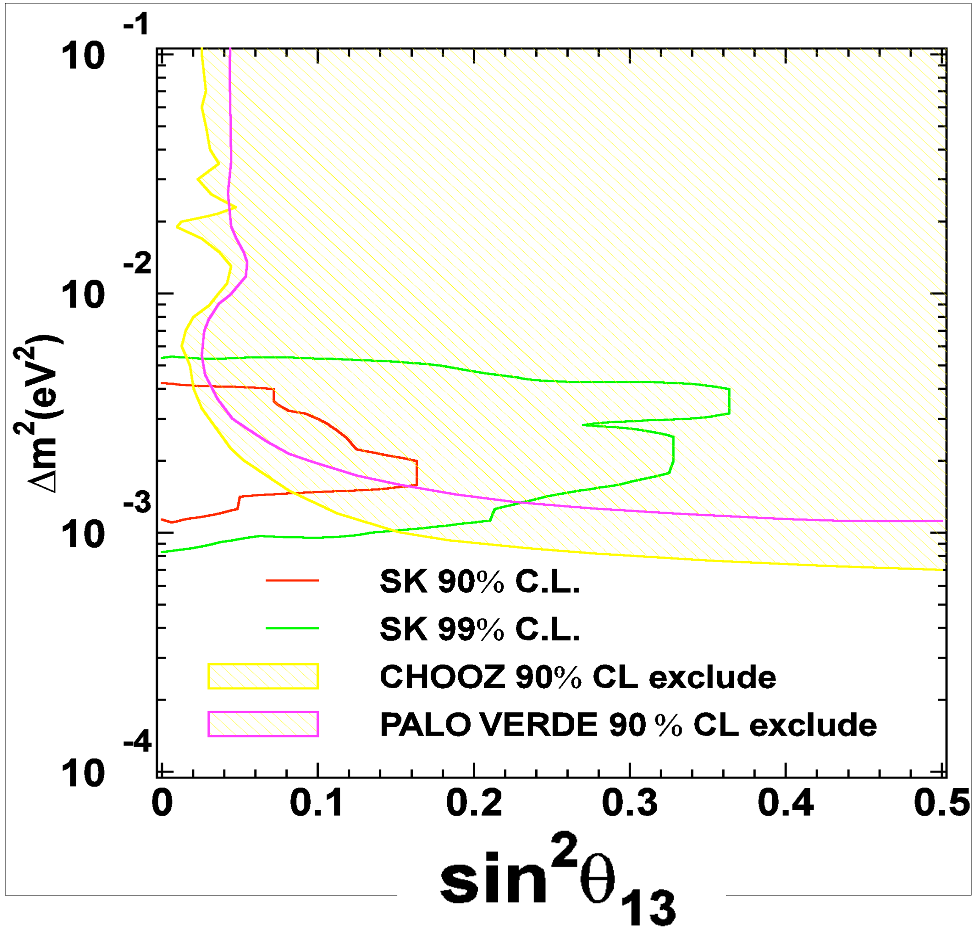
$\Delta m^2, \ \theta_{13}, \ \theta_{23}$



Allowed parameter region

(3 flavor, 1 mass scale dominance, normal mass hierarchy)





No evidence for non-zero θ_{13}. Consistent with reactor exp.

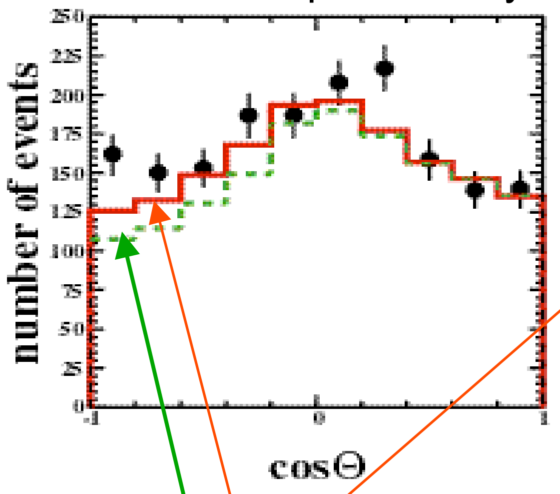
Oscillation to sterile neutrinos?

Pure $\nu_\mu \rightarrow \nu_s$ oscillation: (1) NC deficit & (2) Matter effect

(1) NC deficit

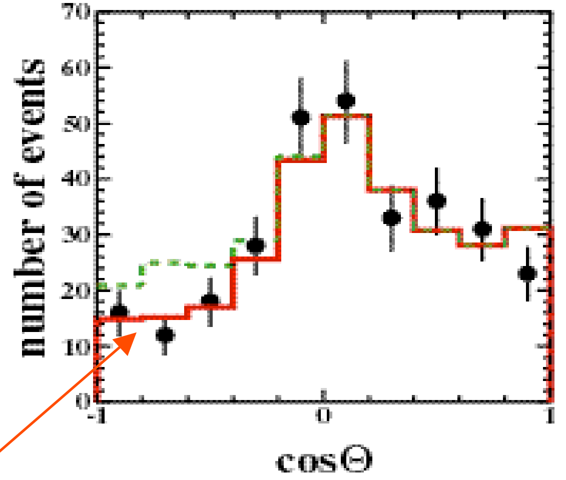
NC enriched multi-ring events

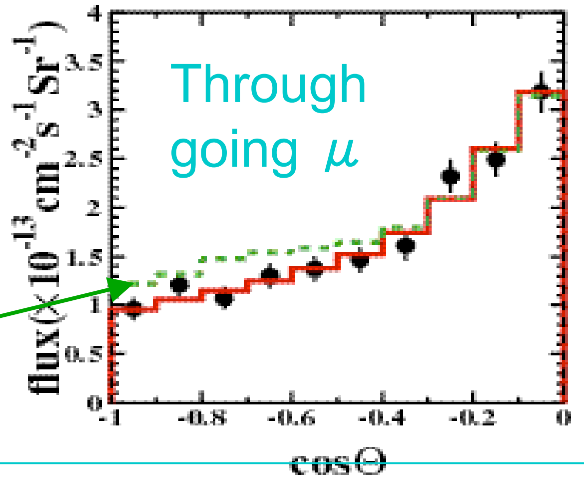
Super-K 79ktyr



High E. PC

Super-K





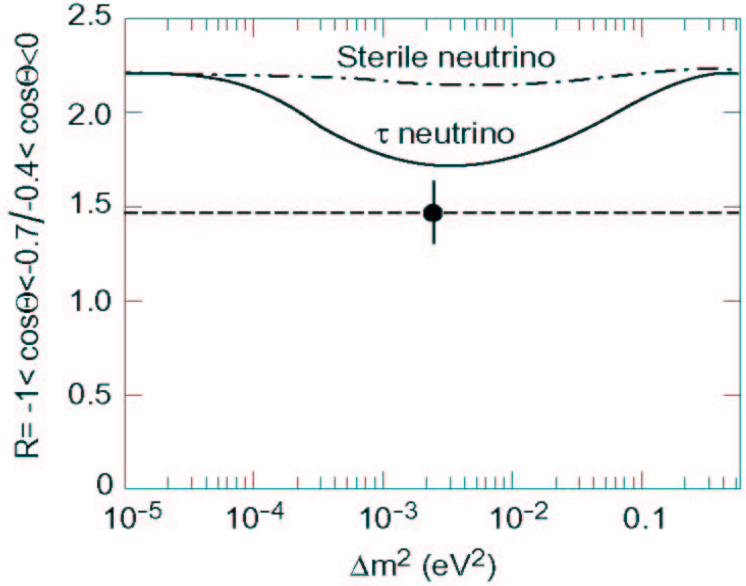
$\nu_\mu \rightarrow \nu_\tau$

$\nu_\mu \rightarrow \nu_s$

(2) Matter effect

Vertical / Horizontal ratio (through going μ)

MACRO

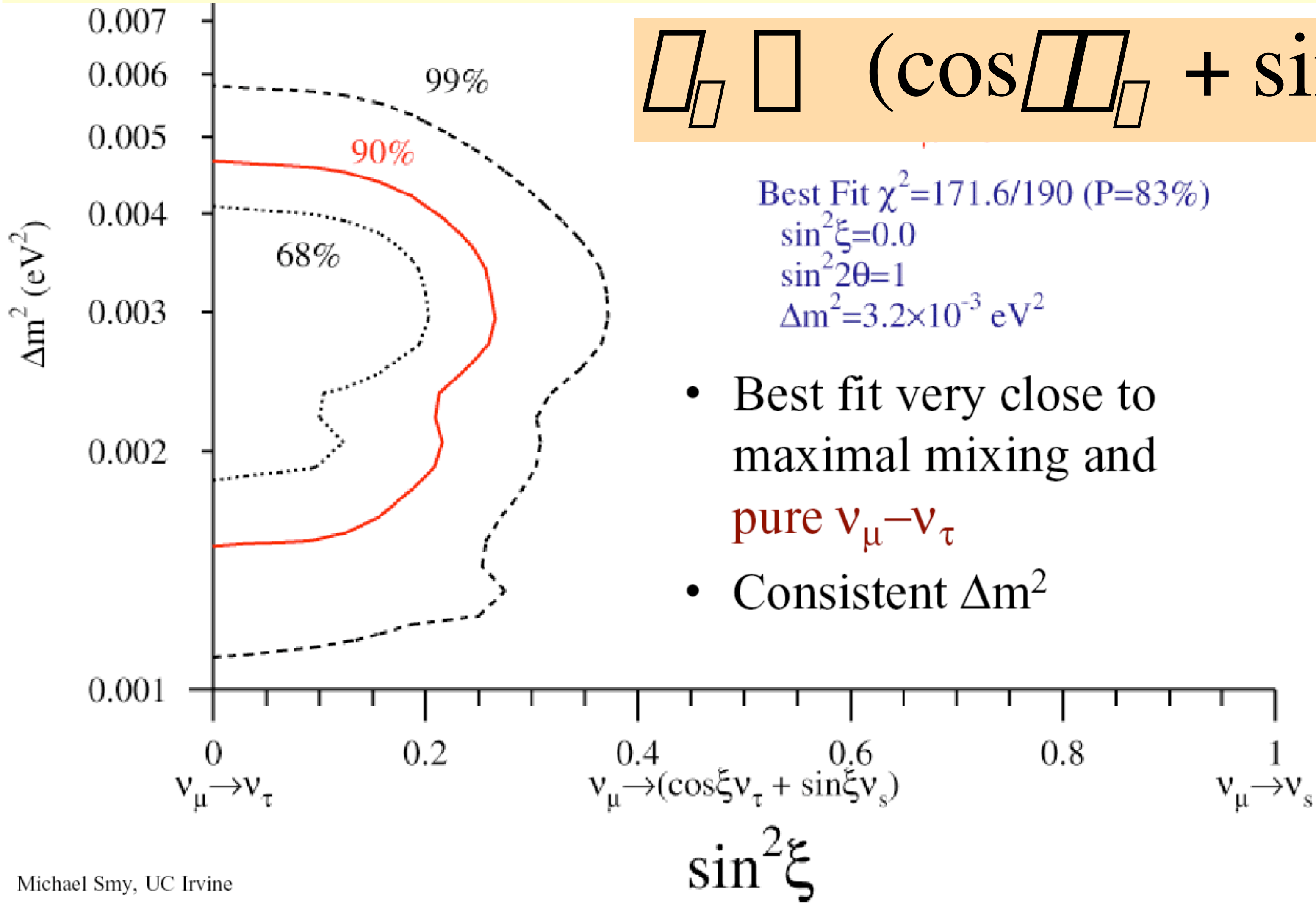


$\nu_\mu \rightarrow \nu_s$ is disfavored > 99%.

Oscillation into something non-interacting?

Limit on Sterile Content

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



- Best fit very close to maximal mixing and pure $\nu_\mu - \nu_\tau$
- Consistent Δm^2

$\sin^2\xi$ 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

2) Confirming the atmospheric neutrinos effect

$$\nu_{\mu} \rightarrow \nu_X$$

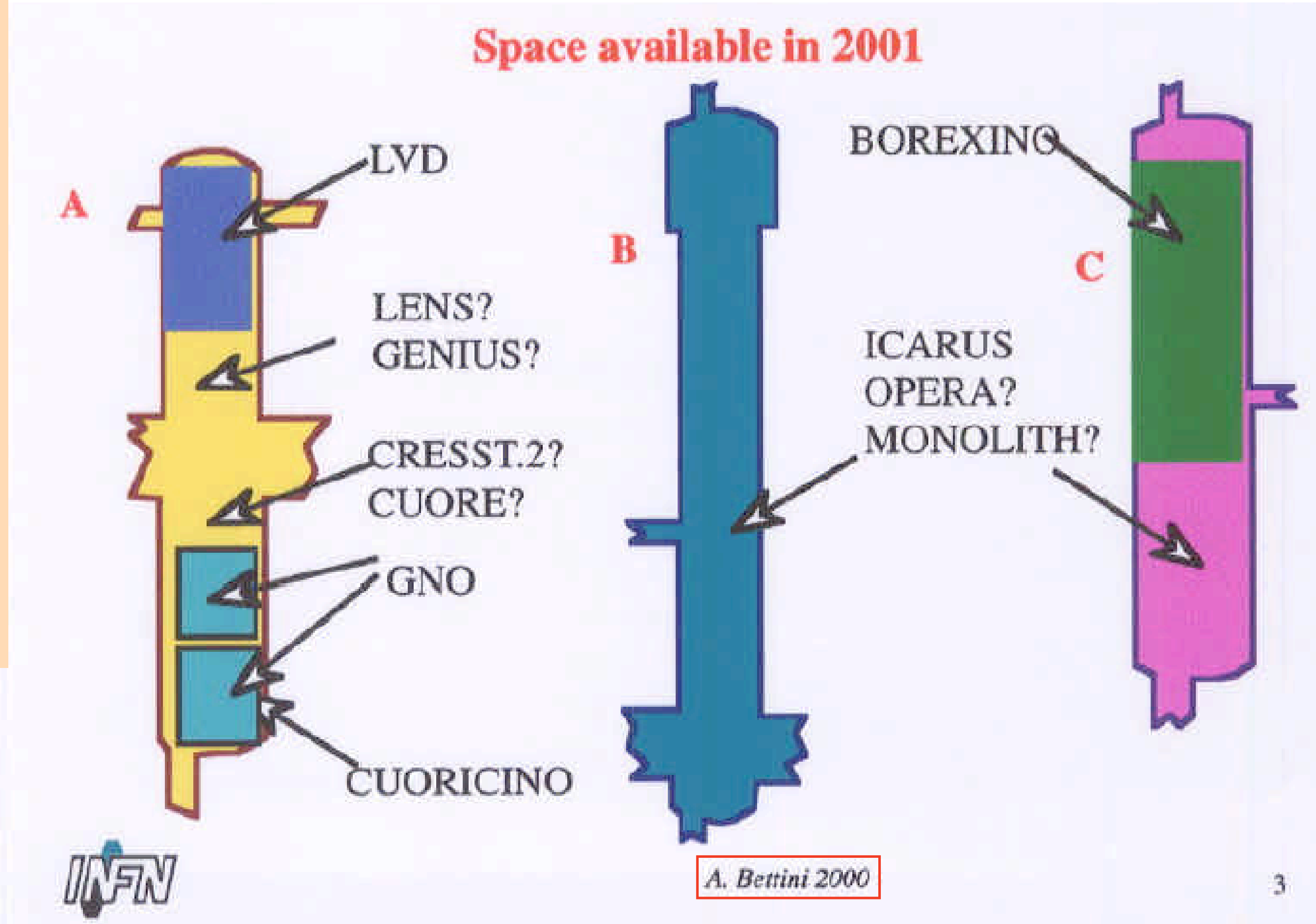
with

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

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

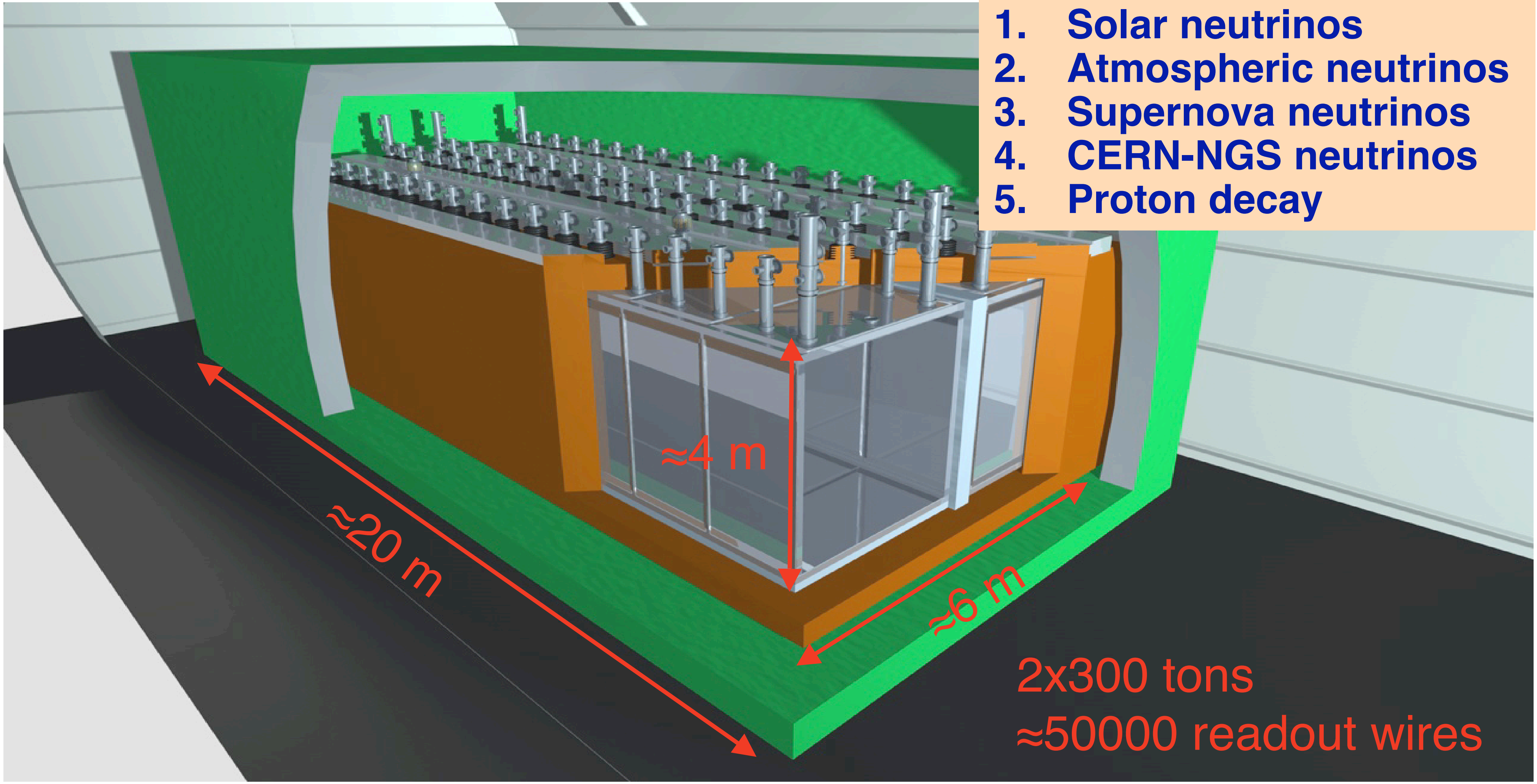
- *1400 m rock overburden*
- *Cosmic ray flux attenuation ≈ 10^{-6}*



ICARUS detector

<u>Novel</u> 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**

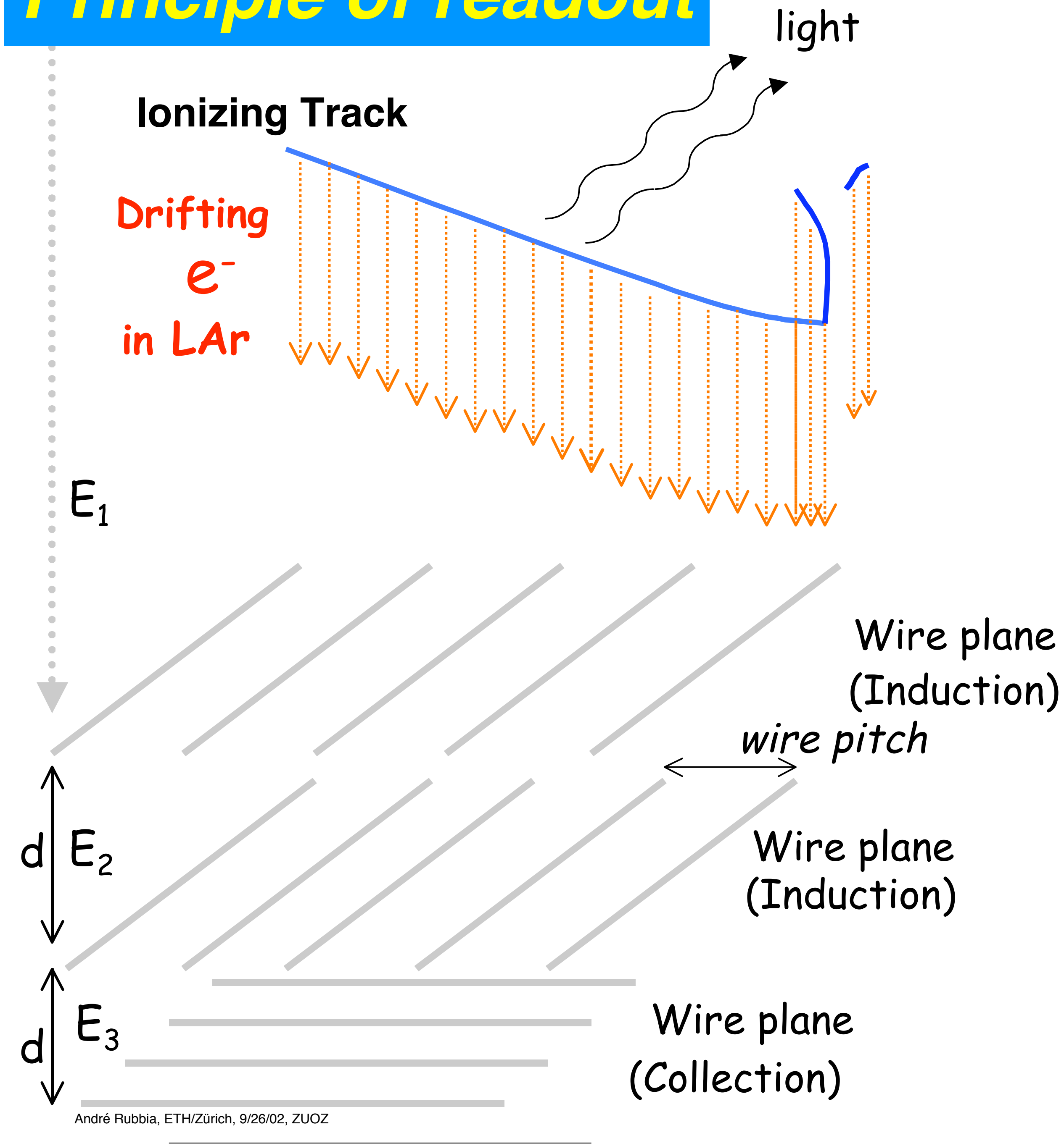


Planned start data taking in 2003

Liquid Argon

Density 1.4 g/cm^3
Radiation length 14 cm
Interaction length 80 cm
dE/dx = 2.1 MeV/cm
T=88K @ 1 bar

Principle of readout



✓When charges drift, they induce a signal on the wires

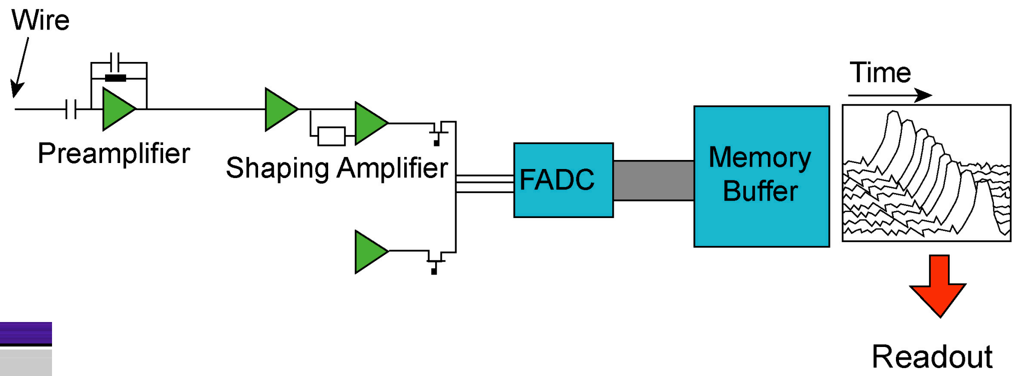
✓Since the mobility of electrons is much higher than that of ions, only electrons contribute to the observed signal.

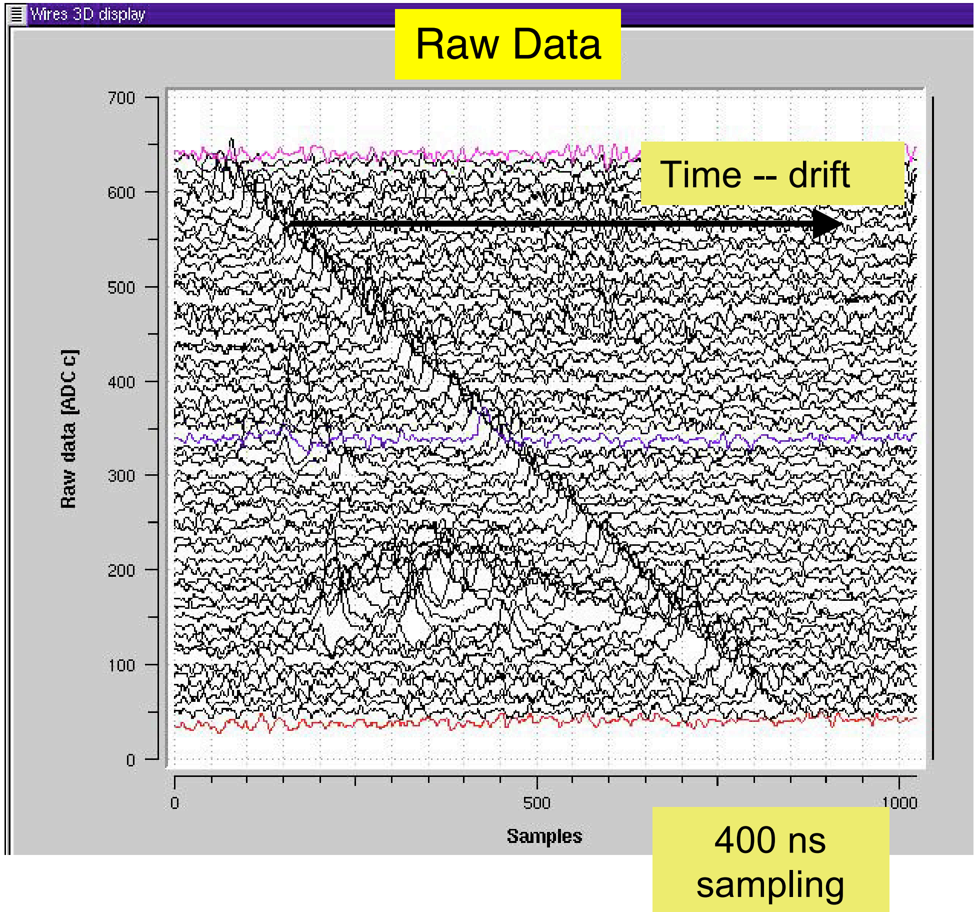
✓Electrons can drift over macroscopic distances if argon very pure (e.g. ≈ meter drift requires purity of <1 in 10^{10} atoms)

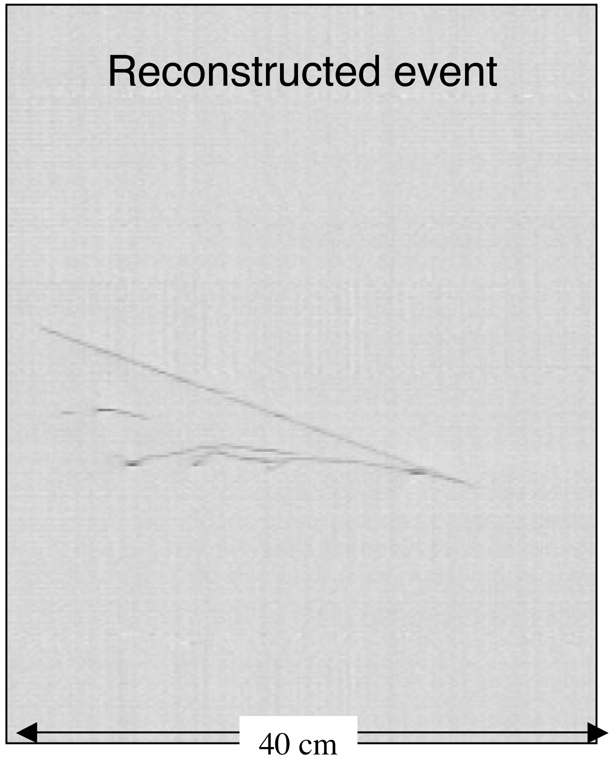
✓Multiple non-destructing readout wire plans can be assembled for multi-views

Principle of signal recording

55000 e⁻/cm and no amplification near wires (liquid)
⇒ low-noise electronics
typ. 1000 e⁻ RMS



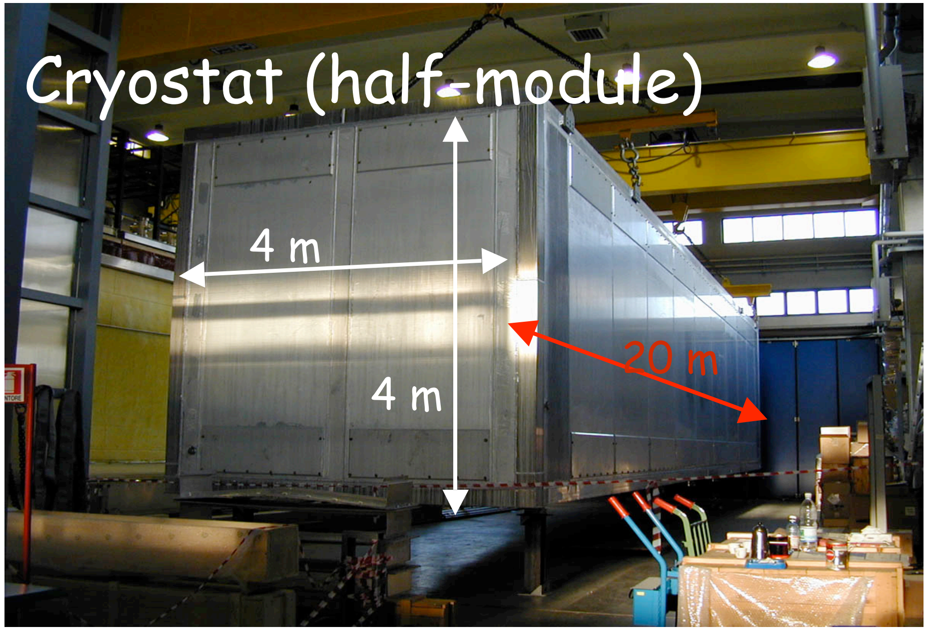


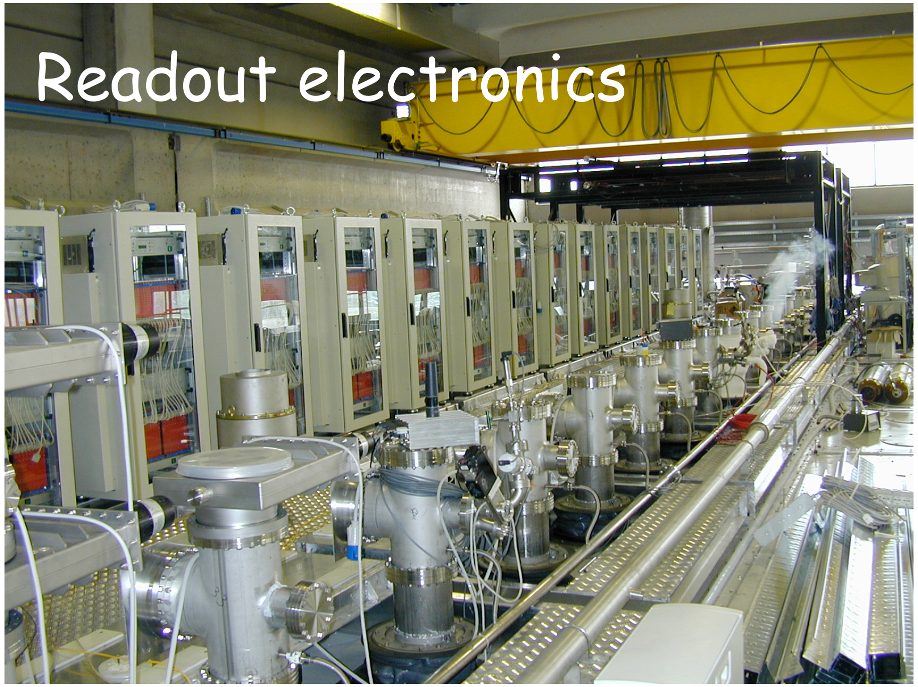


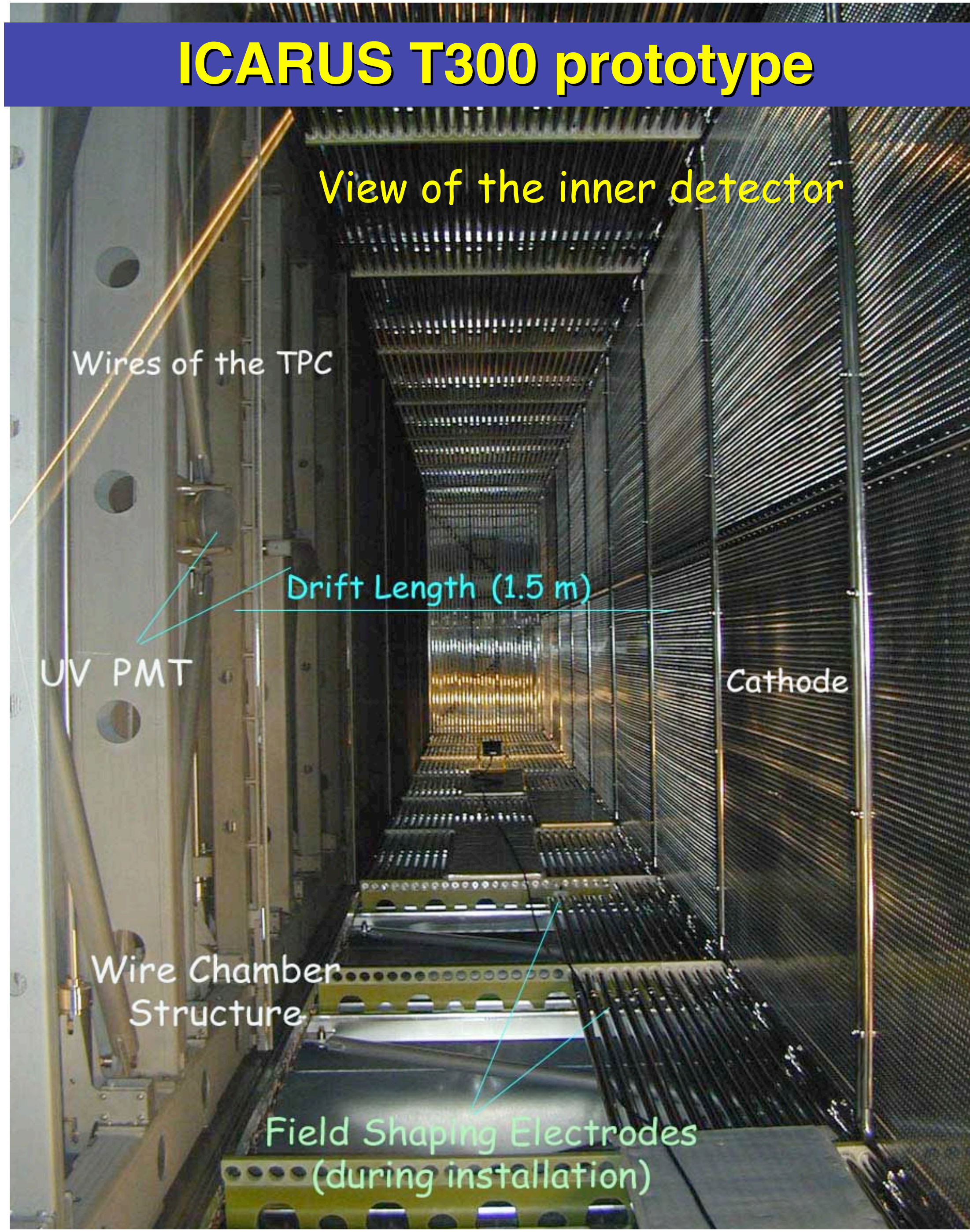
Real Event from a 15 ton LAr Detector

ICARUS T300 cryostat

ICARUS T300 prototype



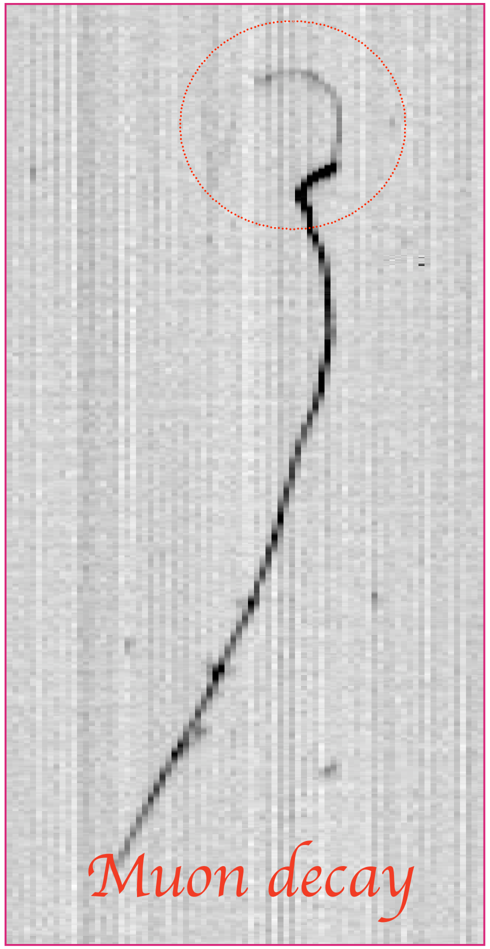




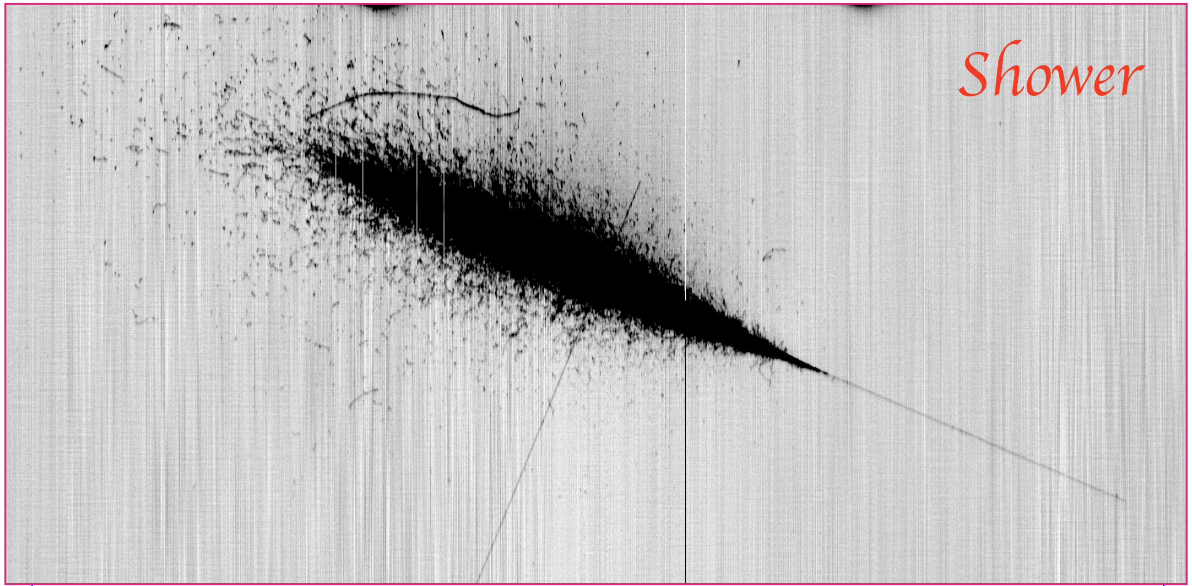
Electronic bubble chamber (I)

25 cm

85 cm



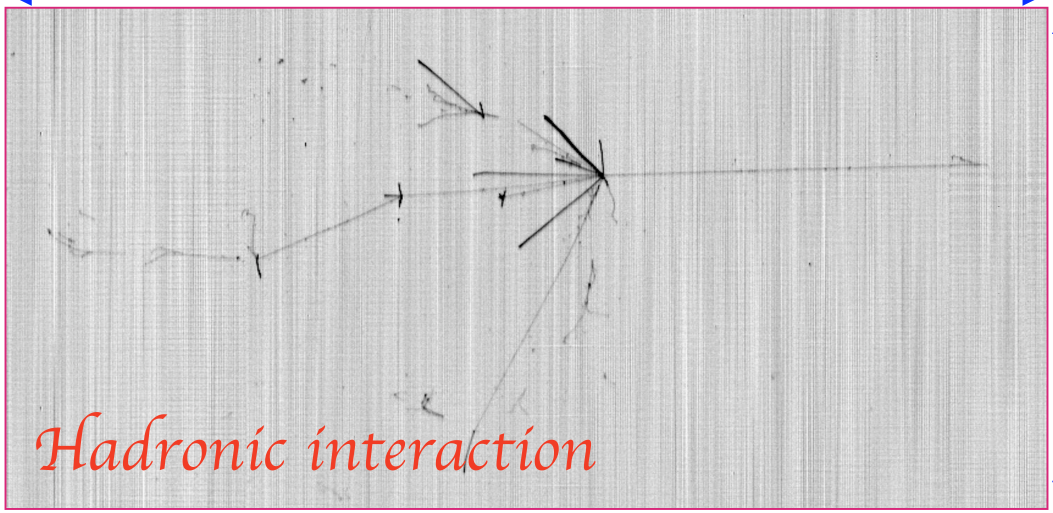
Run 960, Event 4 Collection Left



176 cm

434 cm

265 cm

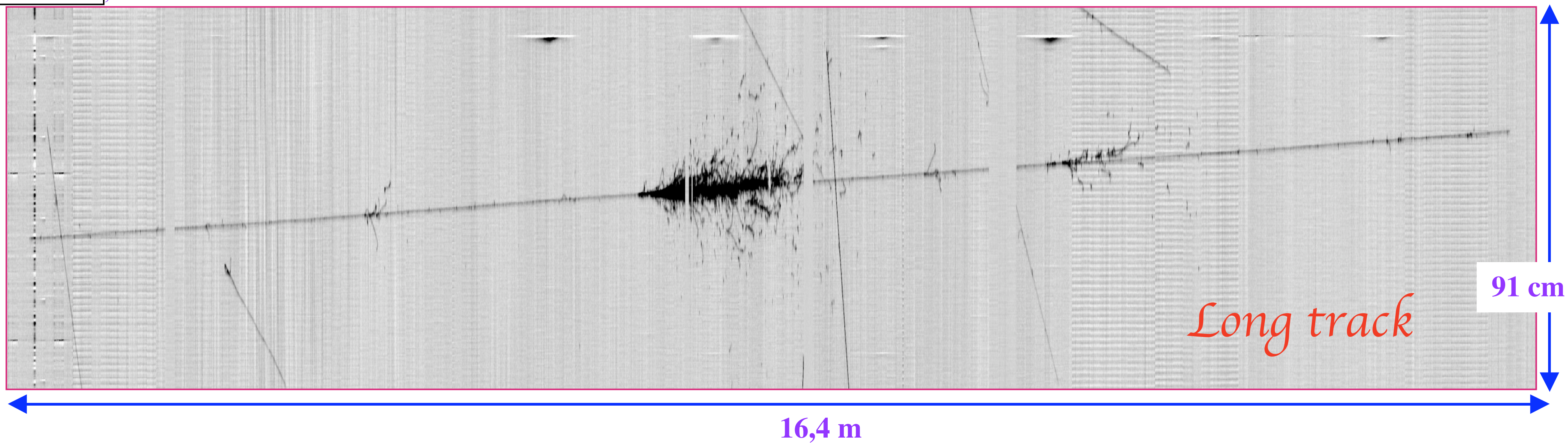


142 cm

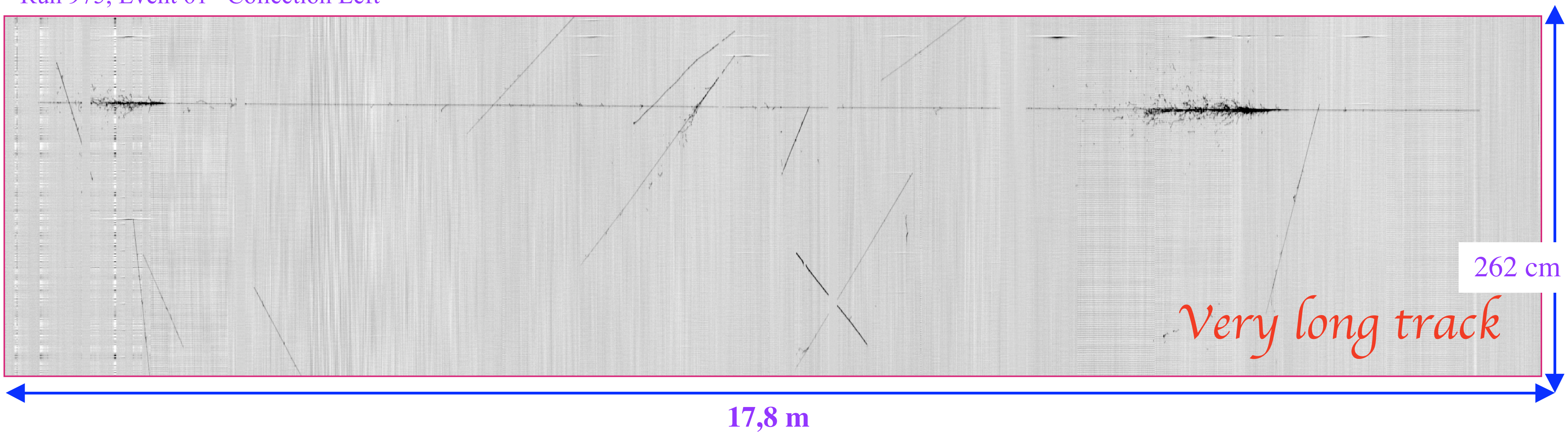
Run 308, Event 160 Collection Left

Electronic bubble chamber (II)

, Event 93 Collection Left

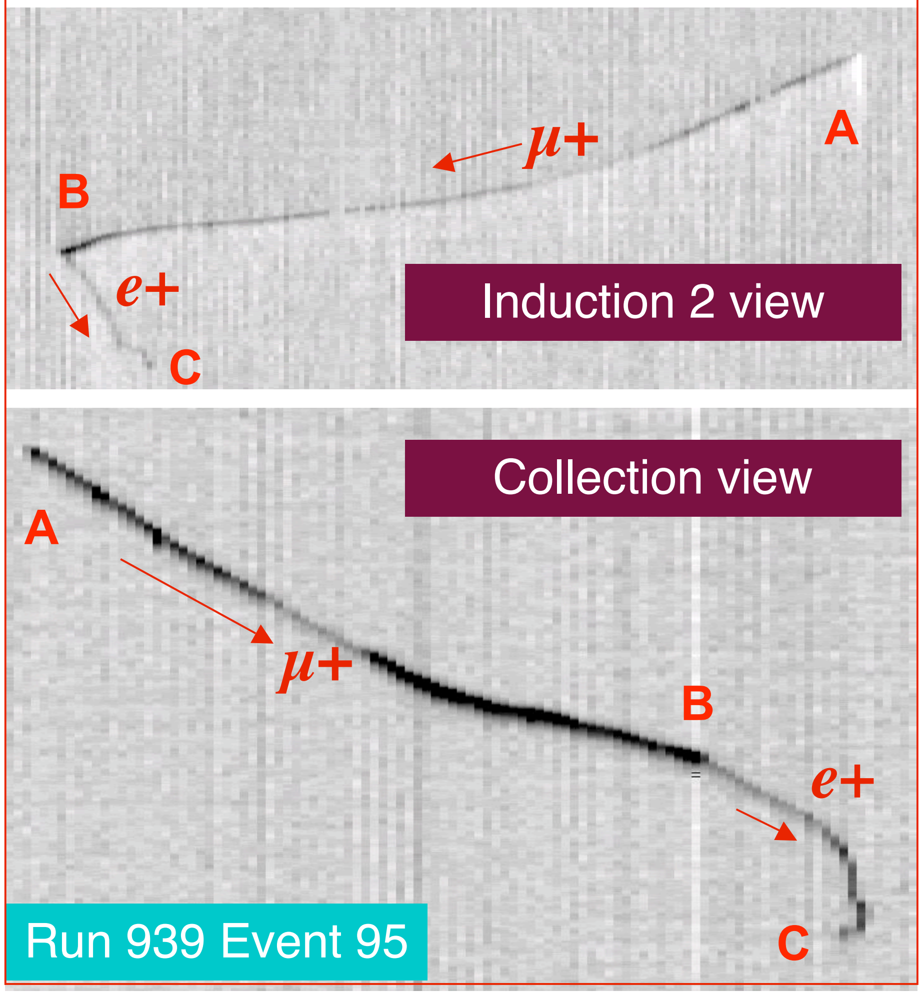


Run 975, Event 61 Collection Left

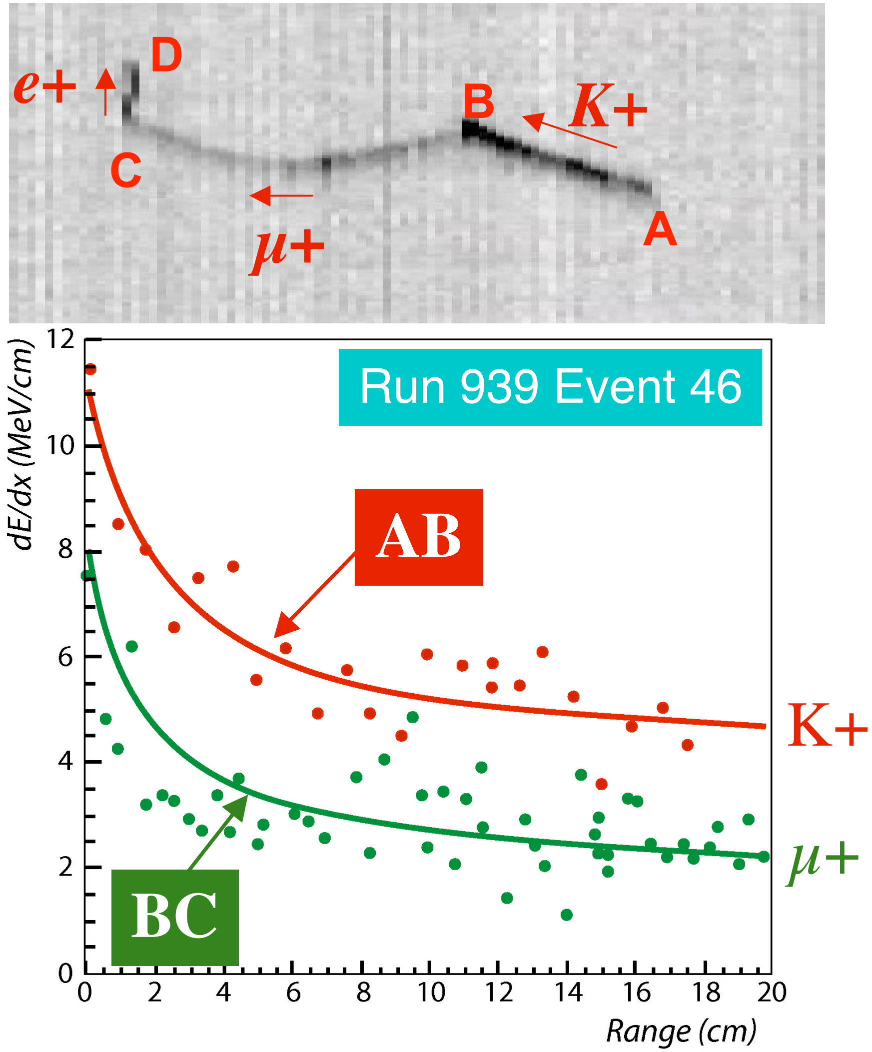


Particle identification

$\square^{+}[AB]\square\ e^{+}[BC]$

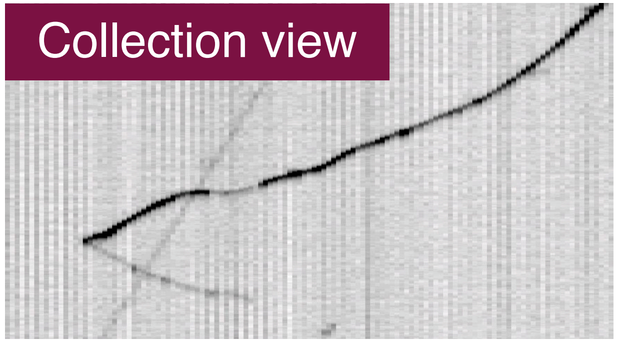


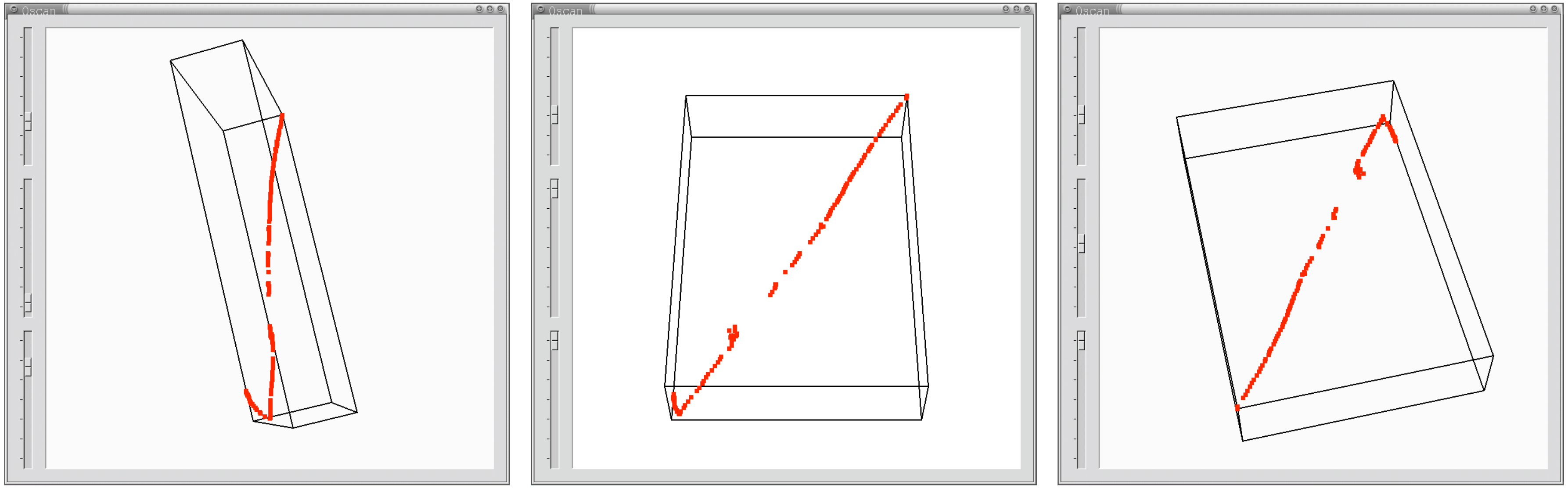
$K^{+}[AB]\square\ \square^{+}[BC]\square\ e^{+}[CD]$



Reconstruction in 3-D

- Since the detector has three views 60° apart, it is possible to reconstruct the events in space, using the redundancy of coordinates





Run 939 Event 51

ICARUS T600 prototype

The developed technology allows (relatively) easy transportability

The *ICARUS T600* module (cryostat & internal detector) can be fully assembled and then shipped to the defined experimental beam site

Ext. insulation, Electronic & DAQ installation

LAr filling, RUN

LNGS Hall B is getting ready to receive ICARUS… (MACRO dismantled)

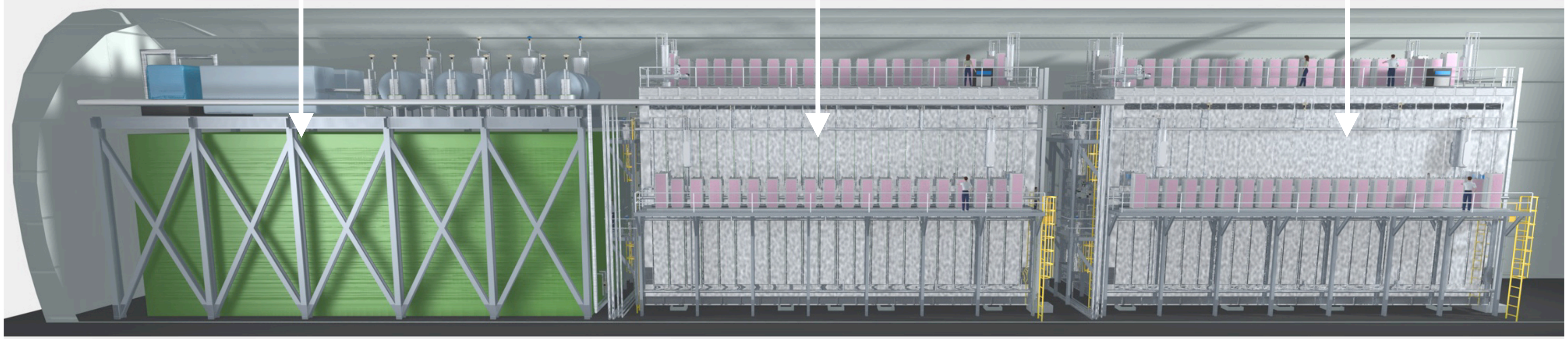
ICARUS T3000

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:

$\approx$ 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

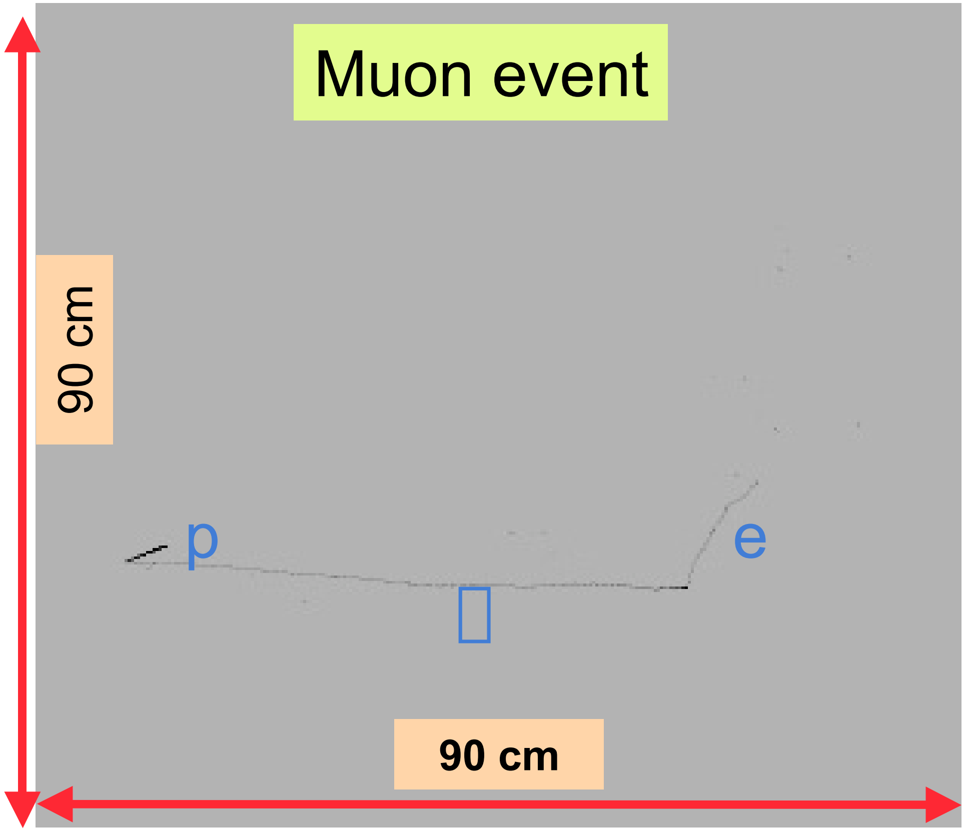
T3000: operational by summer 2006

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

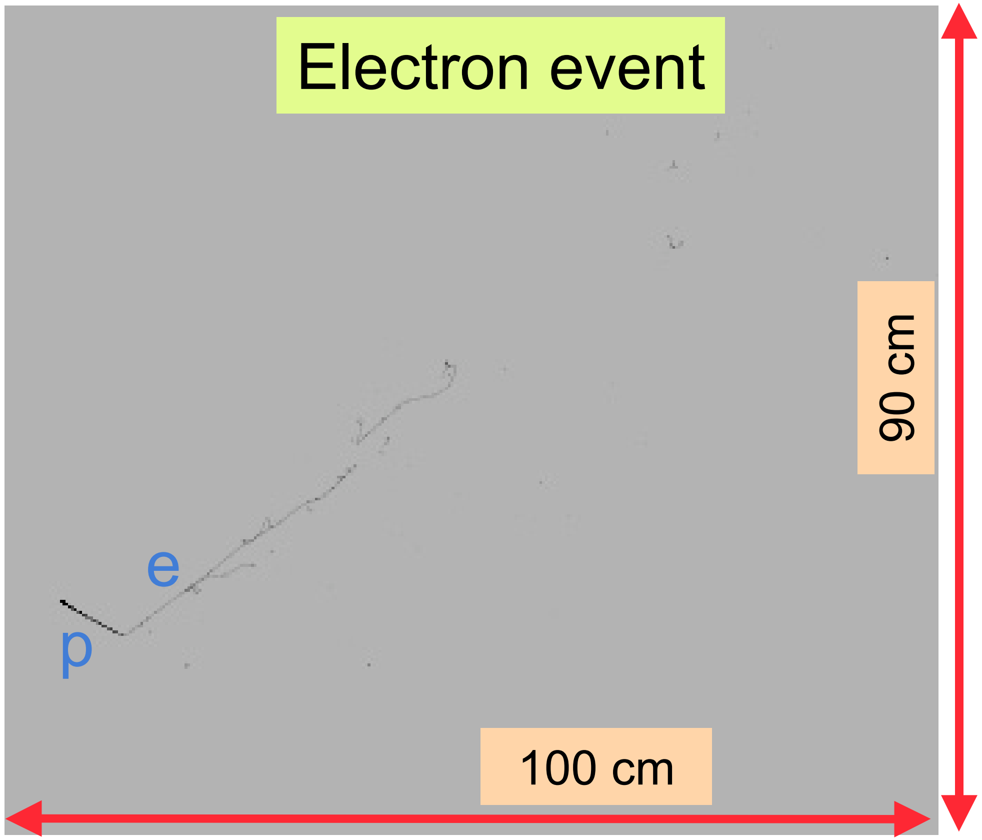
Simulated atmospheric events in ICARUS



ν_μ quasi-elastic interaction

E_ν = 370 MeV

P_μ = 250 MeV **T_p = 90 MeV**

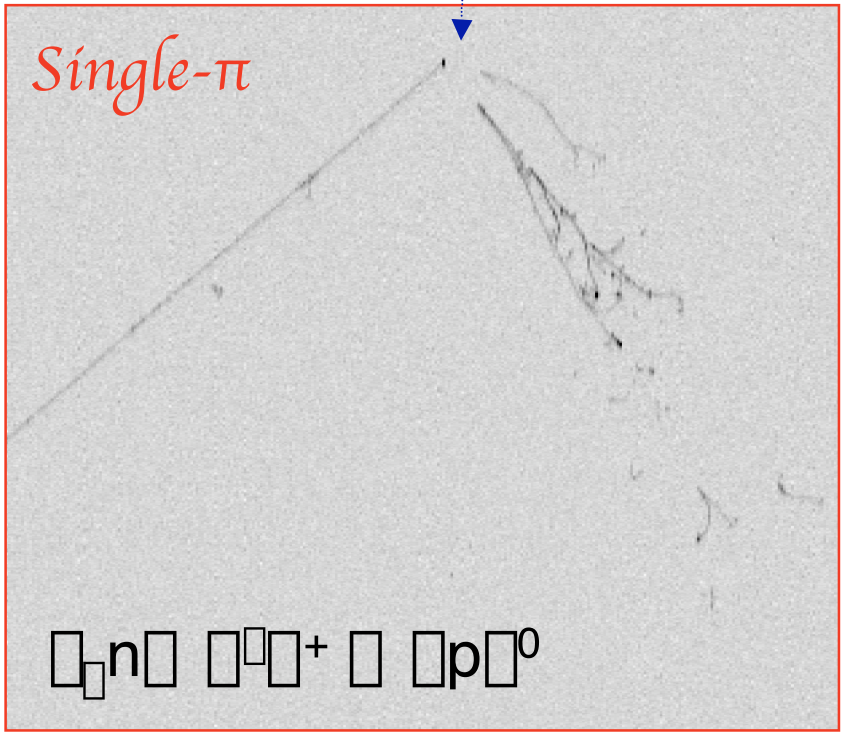


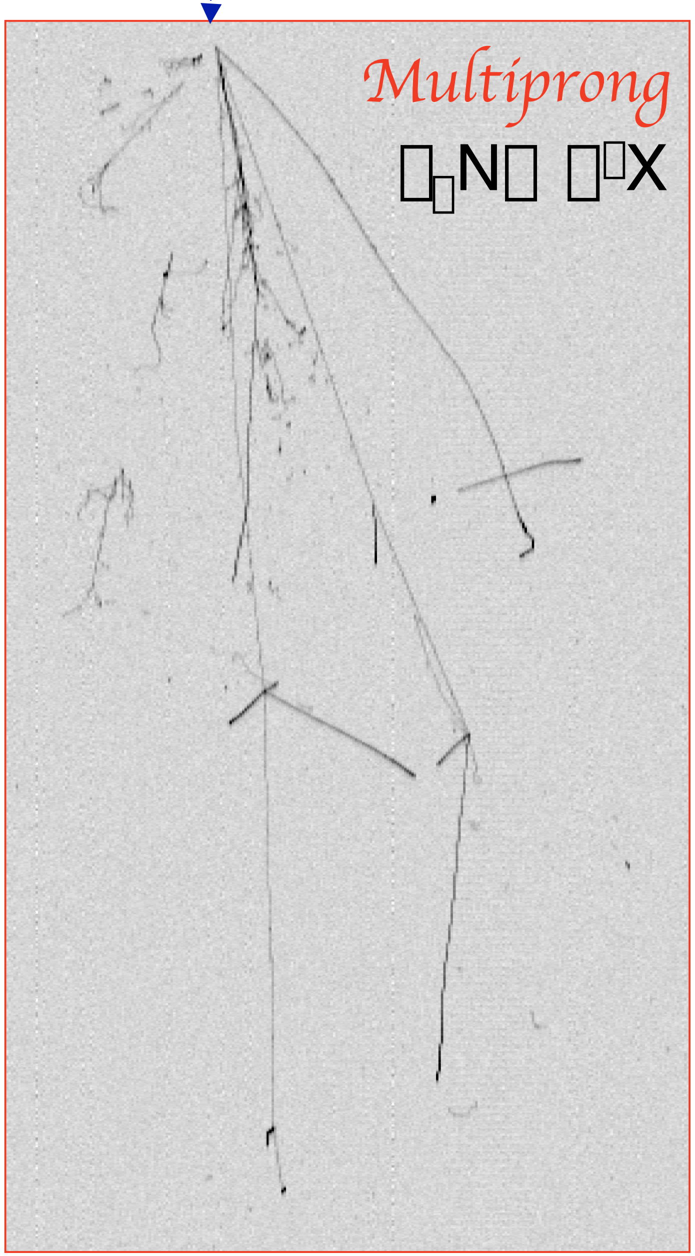
ν_e quasi-elastic interaction

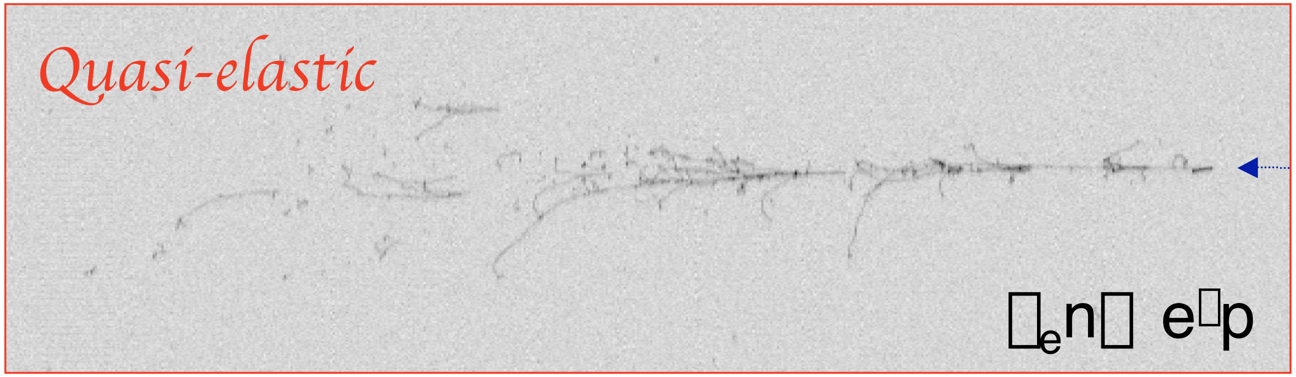
E_ν = 450 MeV

P_e = 200 MeV **T_p = 240 MeV**

Simulated atmospheric events in ICARUS







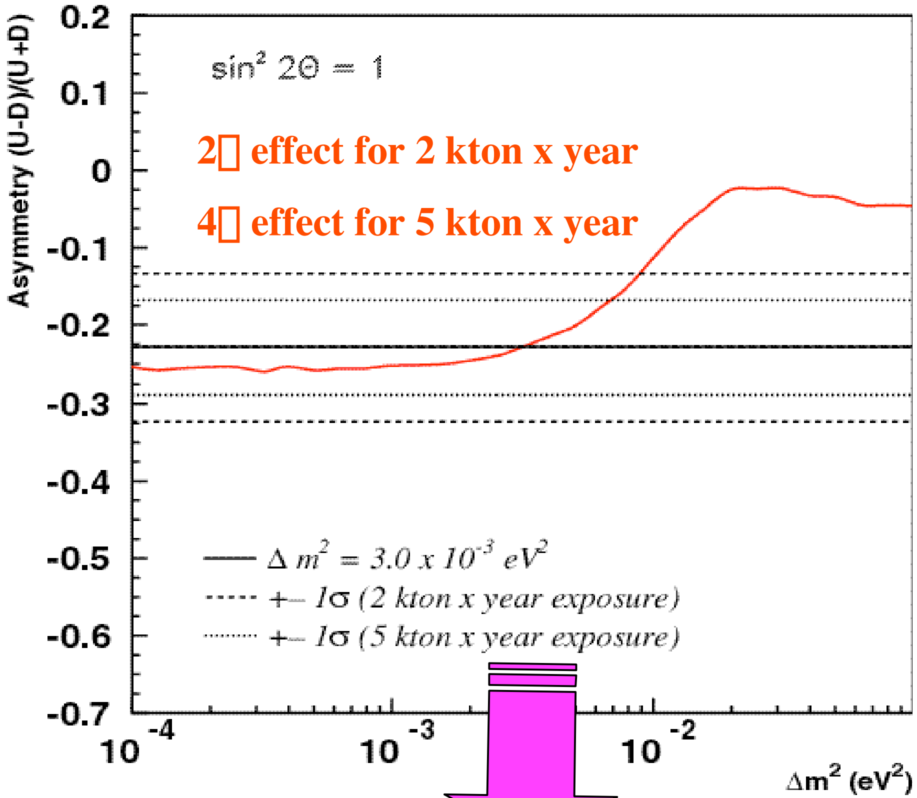
Rates for upward/downward events

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

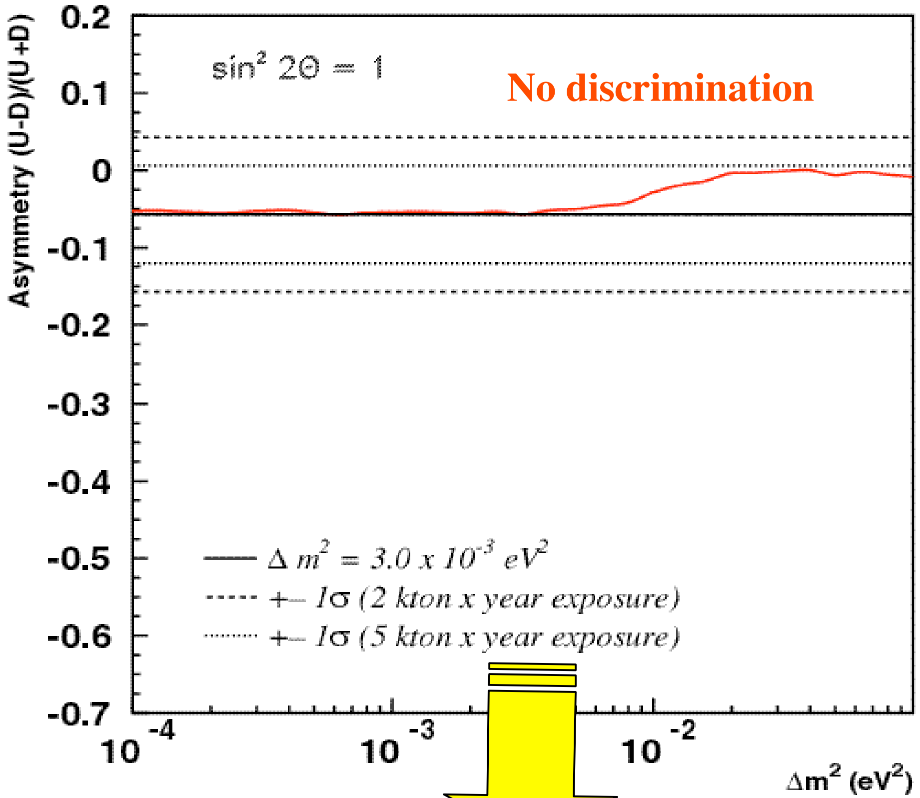
All particles



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

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

Lepton only



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

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

New issues with atmospheric neutrinos

- Explicit observation of the oscillation pattern in ν_μ disappearance
  - Test of the disappearance dynamics (proof of oscillations)
  - Precision measurement of $\Delta m^2_\otimes$ and $\sin^2 2\theta_{23}$
- Search for subdominant effects
  - Matter effects in scenarios with three (or more) neutrinos
    - $\sin^2\theta_{13}$, sign of Δm^2, …
  - Non statndard interactions (FCNC, VLI, VEP, …)
- Explicit detection of ν_τ appearance

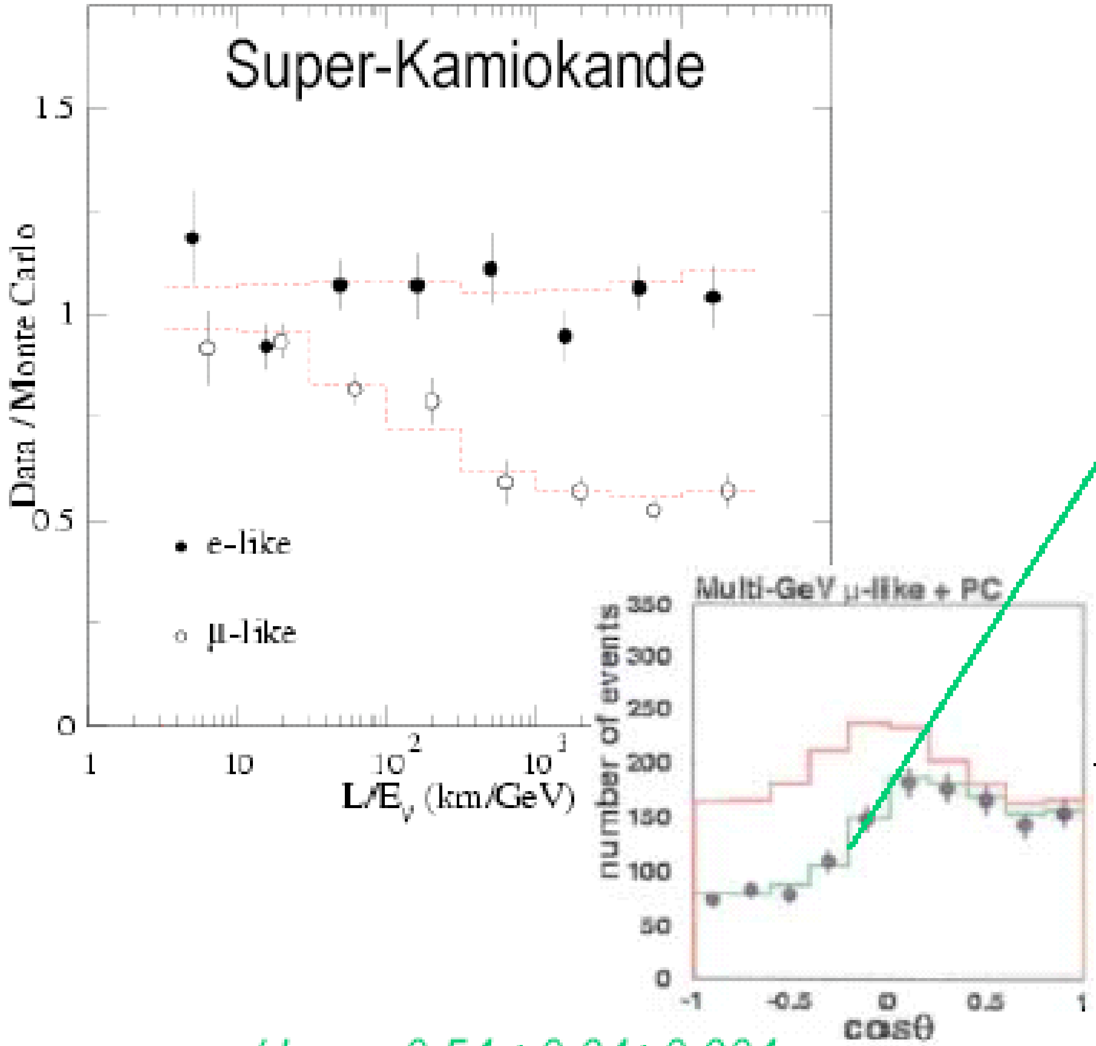
Overview future detectors

	Mass	Status	Physics start
Reference			
Super-K	50/22 kt	idle	*2003 (restart)*
Large Water Cherenkov			
UNO	650/450 kt,	discussed	*201?*
Hyper-K	1.0 Mt	discussed	*201?*
Aqua-RICH	1.0 Mt	R&D	*??*
Magnetised Iron Neutrino Detectors			
Minos	5.4/3.3 kt	construction	*2003*
MONOLITH	34/27 kt	not approved by INFN	*??*
Generic 50 kt	?/50 kt	discussed for ν-factories	*201?*
Liquid Argon TPC			
ICARUS T600	0.6/0.5 kt	approved	*2003*
ICARUS T3000	3.0/2.5 kt	proposed for CNGS	*2006*

Explicit detection of oscillations

Neutrino 2002 Munich

T.T.F



up/down=0.54 ±0.04±0.004

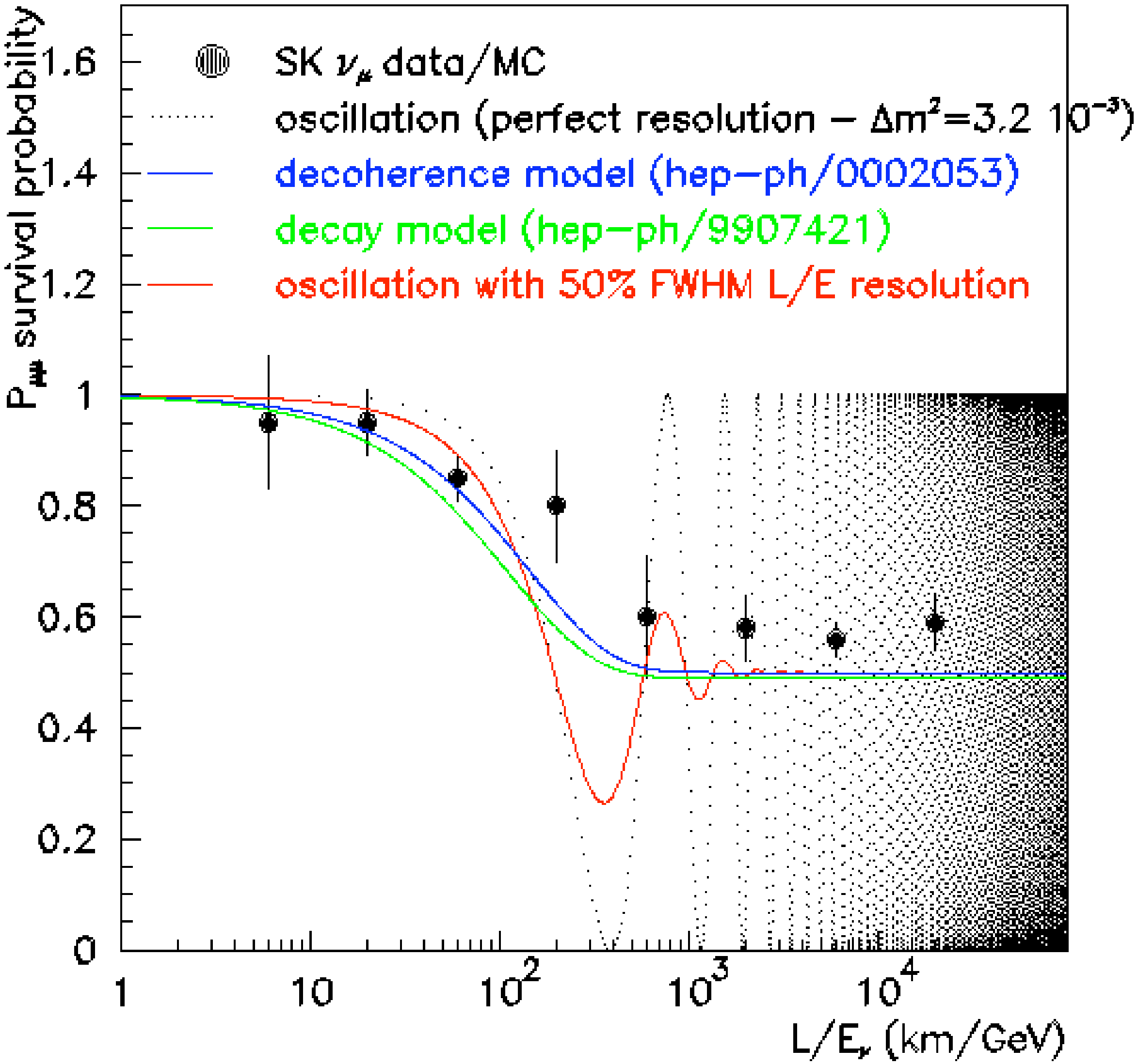
- Poor L/E resolution
  - Limited acceptance to high energy μ's (E_{cont} < 10 GeV)
  - Disappearance occurs about the horizon ($\sigma_L/L \approx \tan\theta\,\sigma_\theta$)
- Limited precision on Δm^2
- Direct proof of oscillation still outstanding

- The up/down asymmetry of multi-GeV muons fixes the mixing with little systematic uncertainty
- Precision on $\sin^2 2\theta_{23}$ ÷ (exposure)^{½}

L/E resolution requirements

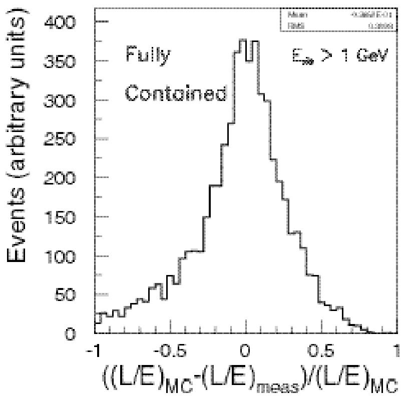
P. Antonioli
Now2000

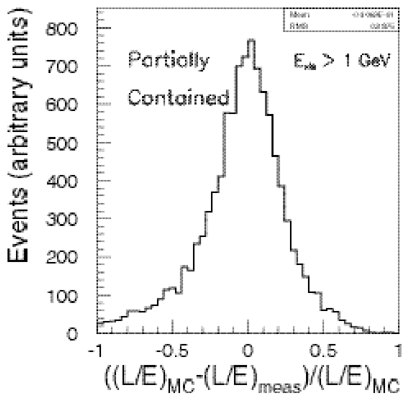
The oscillation pattern is smeared by the finite detector resolution on L/E



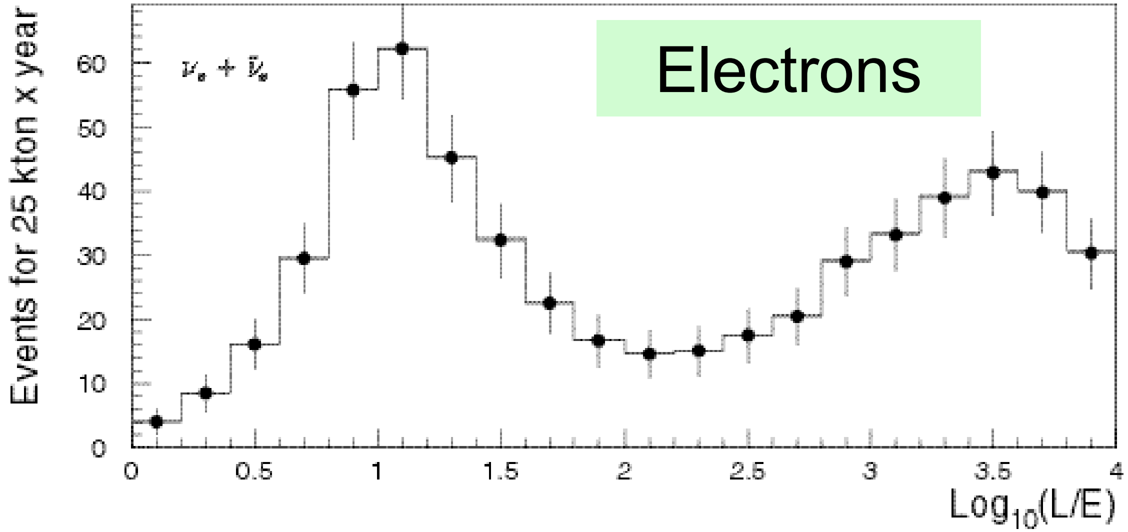
ICARUS L/E distribution (2003)

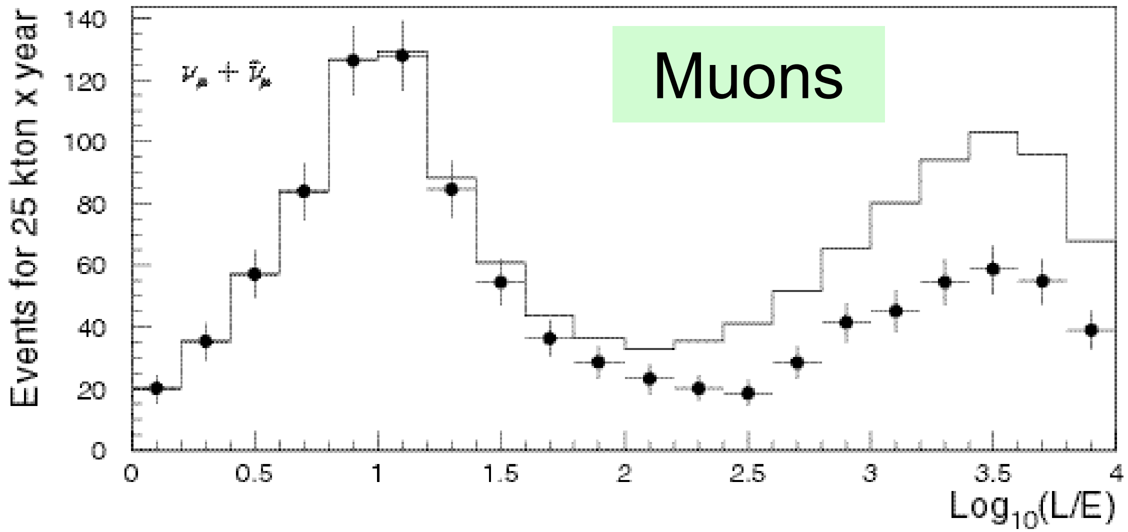
25 kt year





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





- 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***

MONOLITH (>20??)

Large mass ~ 35 kton

Magnetized Fe spectrometer B = 1.3 Tesla

Space resolution ~ 1 cm (rms on X-Y coordinates)

Time resolution ~ 1 ns (for up/down discrimination)

Momentum resolution $\Delta p/p$ ~ 20% from track curvature for outgoing μ

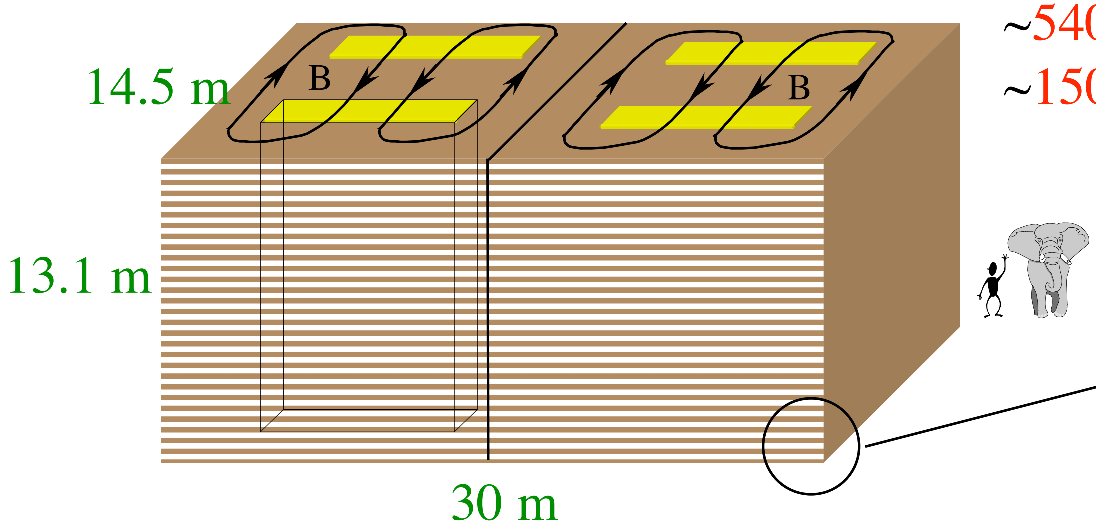
~ 6% from range for stopping muons

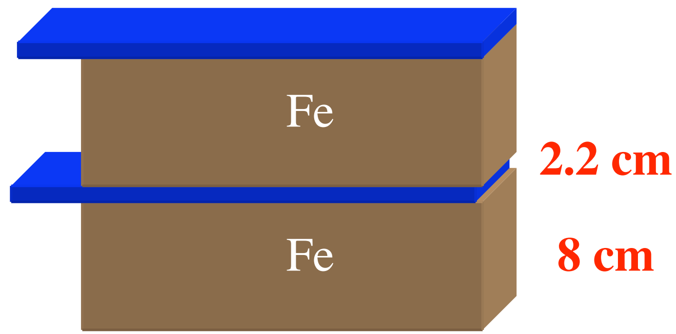
Hadron E resolution $\sigma_{E_h}/E_h \sim 90\%/\sqrt{E_h} \oplus 30\%$

8.0 x 3000 x 1500 cm^3 x 7.87 g/cm^3 = 285 ton/plane 120 planes

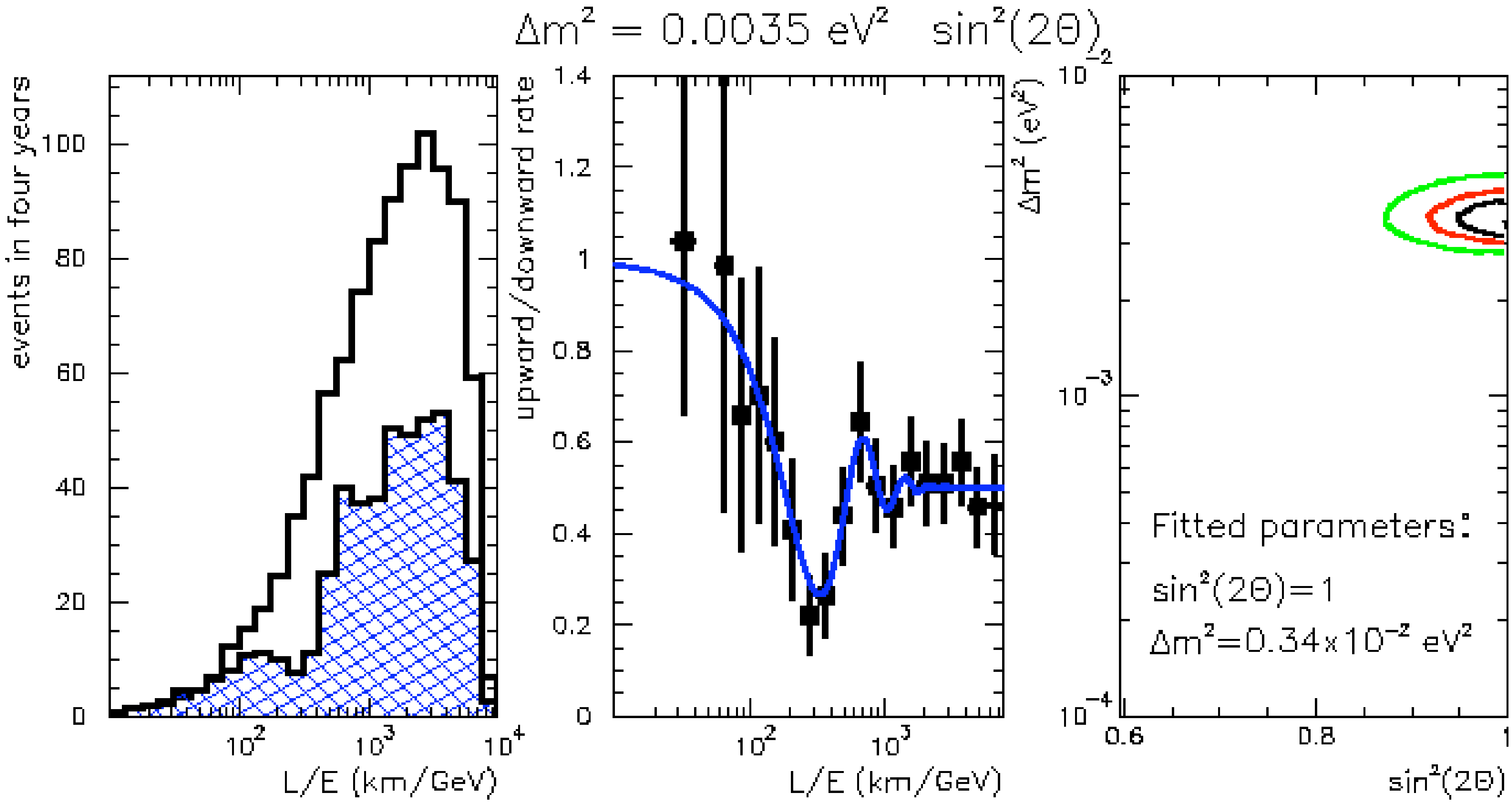
~54000 m^2 of detector : Glass Spark Counters

~1500 m^2 for external veto: Scintillator Counters



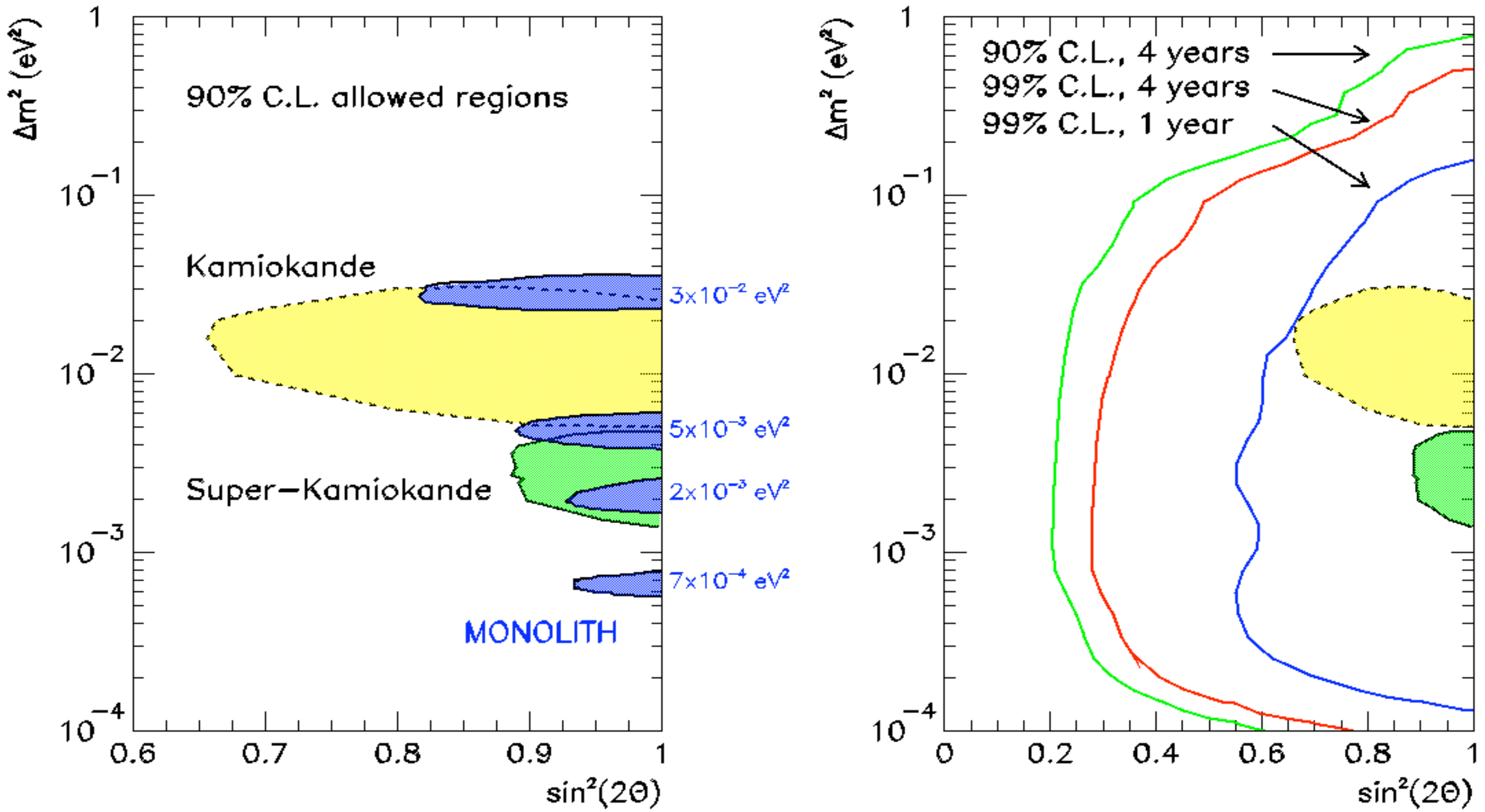


…after four years!



André Rubbia, ETH/Zürich, 9/26/02, ZUOZ

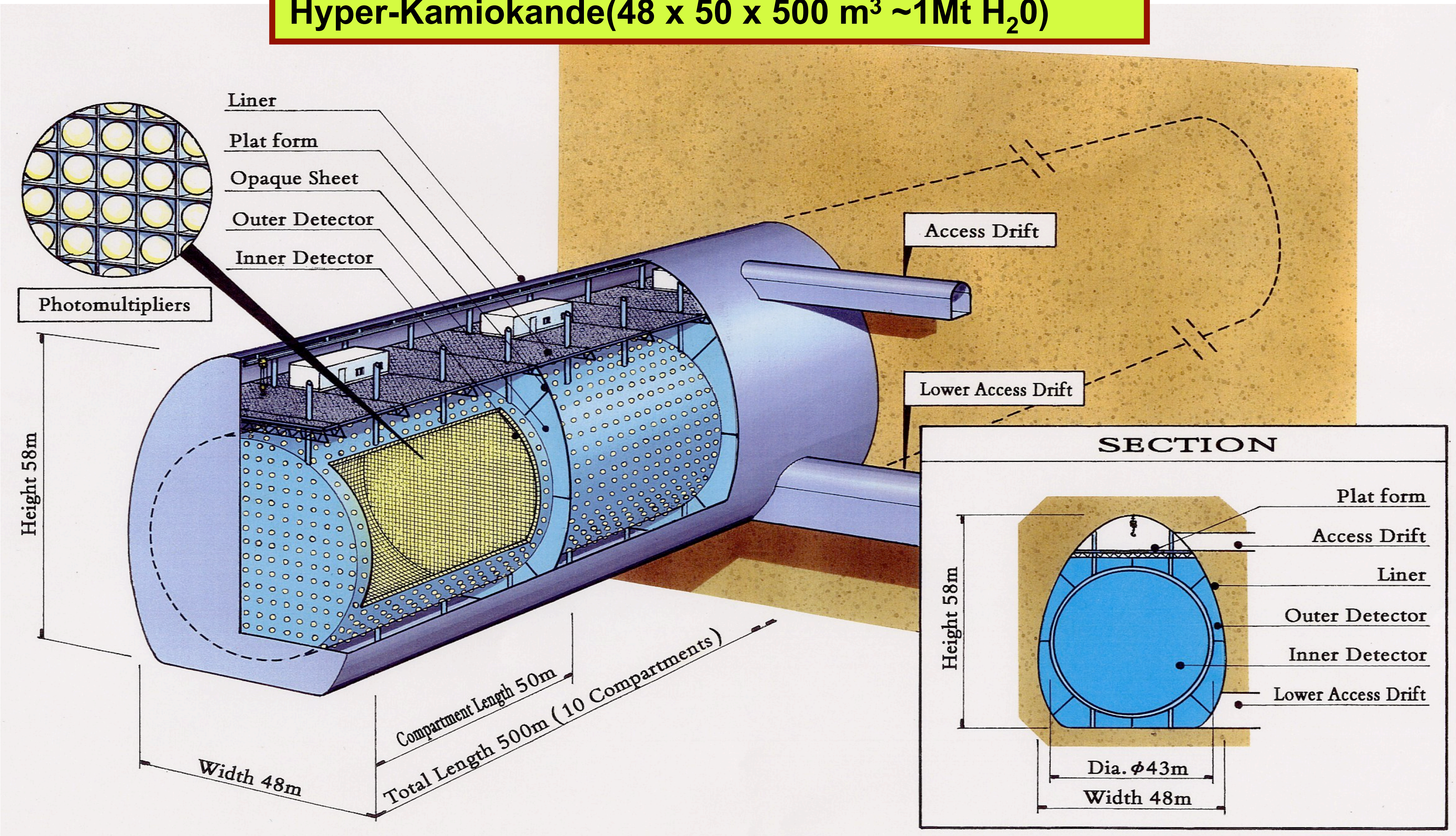
MONOLITH sensitivity – 4 years



- Comparison of MONOLITH sensitivity to oscillations with Kamiokande and SuperKamiokande
- 90% C.L. allowed regions after 4 years for different Δm^2 (left)
- Exclusion regions if no effect is found (right)

Hyperkamiokande (>2010)

Hyper-Kamiokande(48 x 50 x 500 m^3 ~1Mt H_20)



A further extrapolation from Kamiokande, SuperKamiokande

F. Sergiampietri

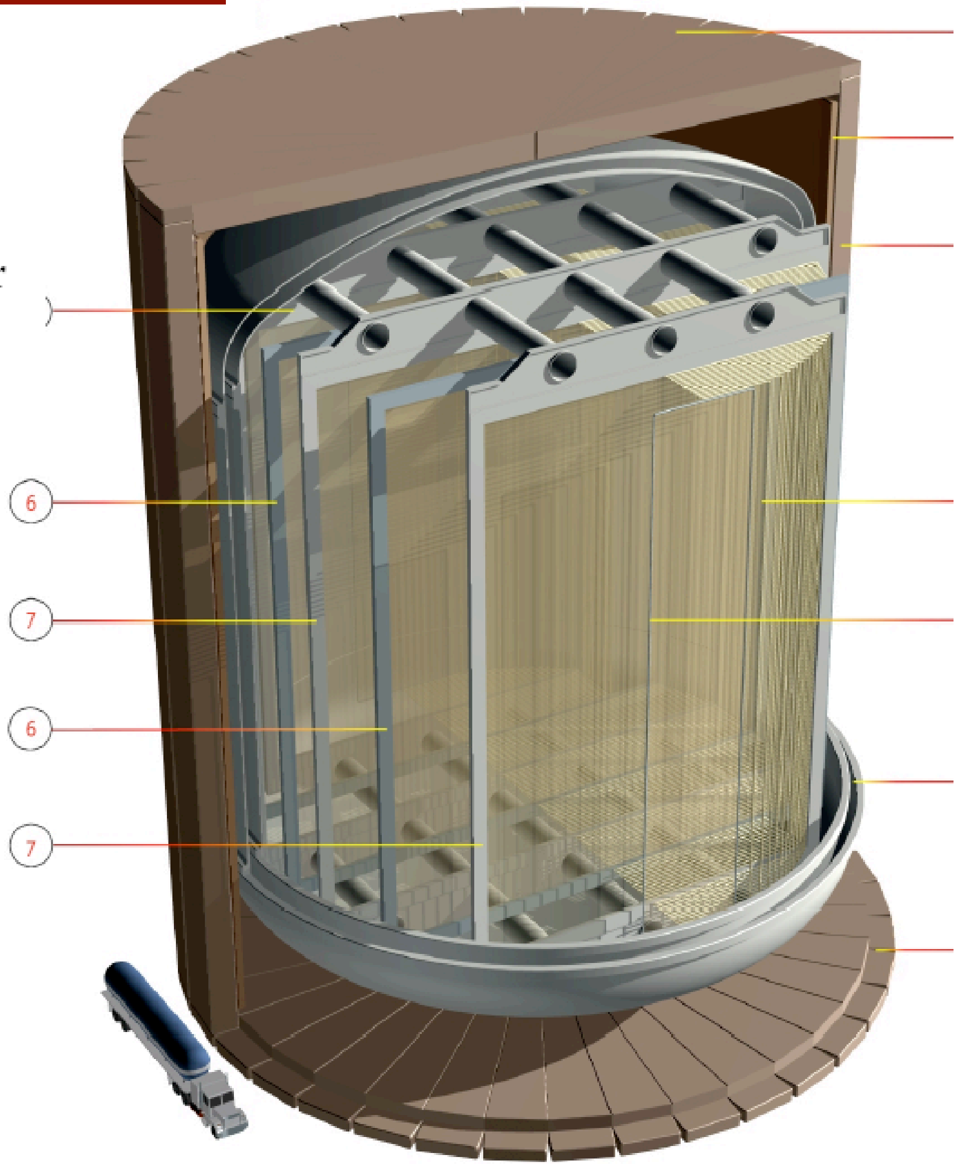
"On the possibility to extrapolate Liquid Argon Technology to a super massive detector for a future Neutrino Factory"

LANNDD

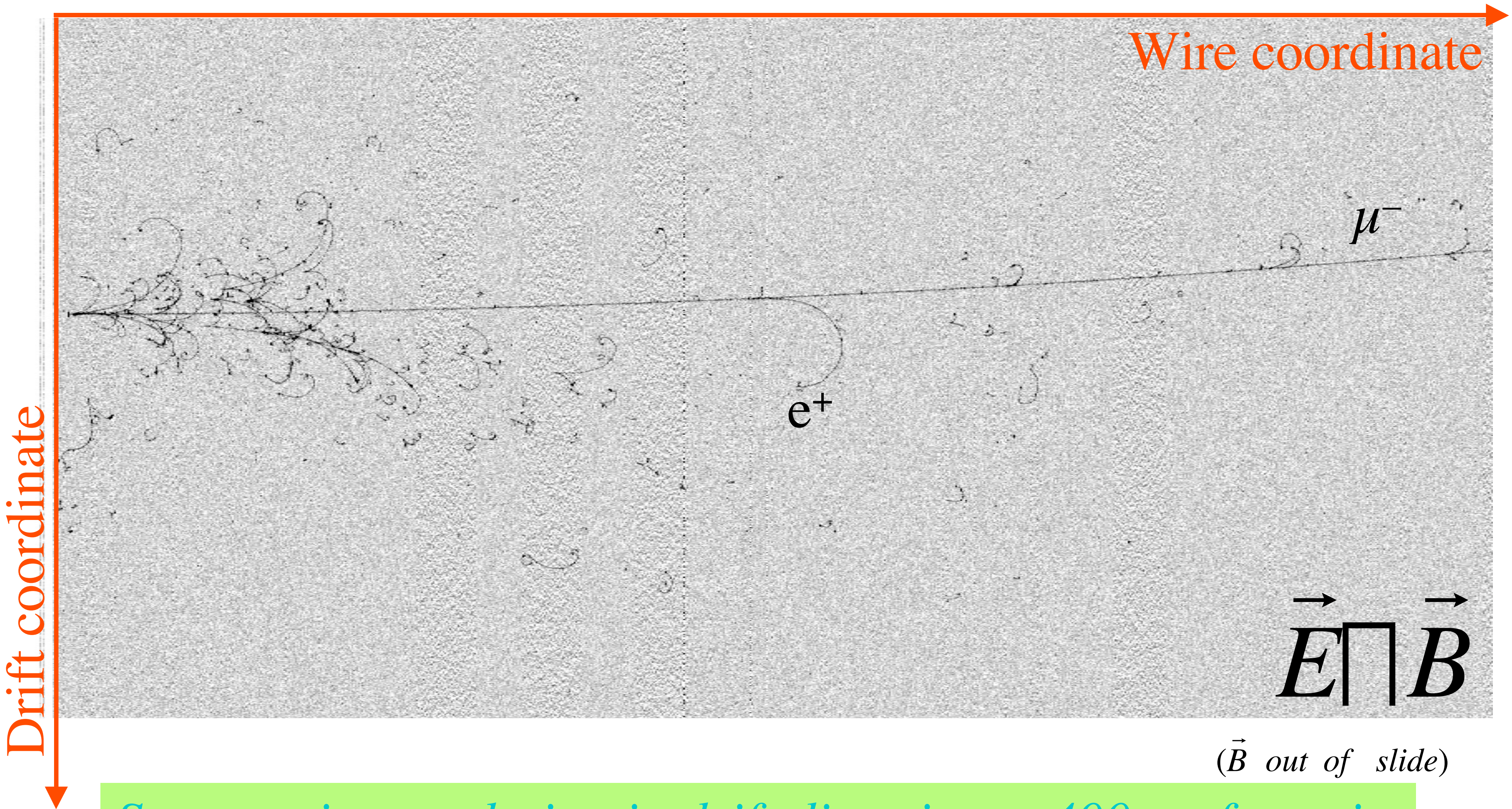
Liquid Argon Neutrino and Nucleon Decay Detector
in Magnetic Field

70 kton LAr

N° OF WIRE CHAMBERS	4
WIRE CHAMBER CH1, CH4	W=26.8 m ...H=40 m
CH2, CH3	W=39.2 m ...H=40 m
READOUT PLANES / CHAMBER [2 at 0°, 2 at 90°]	4
SCREEN-GRID PLANES / CHAMBER	3
TOTAL N° OF WIRES (CHANNELS)	194648
ACTIVE VOLUME	48000 m³
ACTIVE MASS	67 kT
N° OF CATHODE PLANES	5
MAXIMUM DRIFT	5 m
MAXIMUM HIGH VOLTAGE	250 kV
REQUIRED ELECTRON LIFETIME (PURITY)	15 ÷ 20 ms

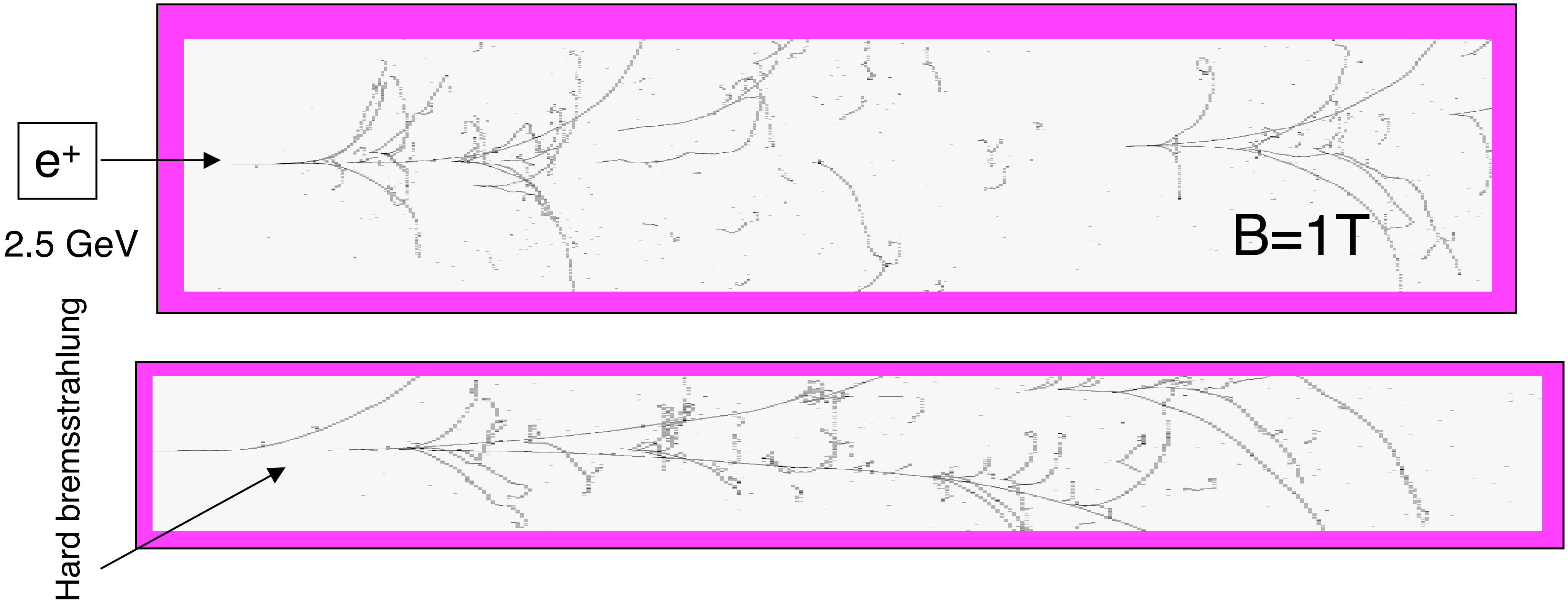


Simulated $\square_{\square}$ CC event in B=0.1 T



Space point resolution in drift direction: ≈400μm for m.i.p

Measuring the electron charge



a) Primary electron momentum … curvature radius obtained by the calorimetric energy measurement

b) Soft bremsstrahlung γ's … the primary electron remembers its original direction → long effective x for bending

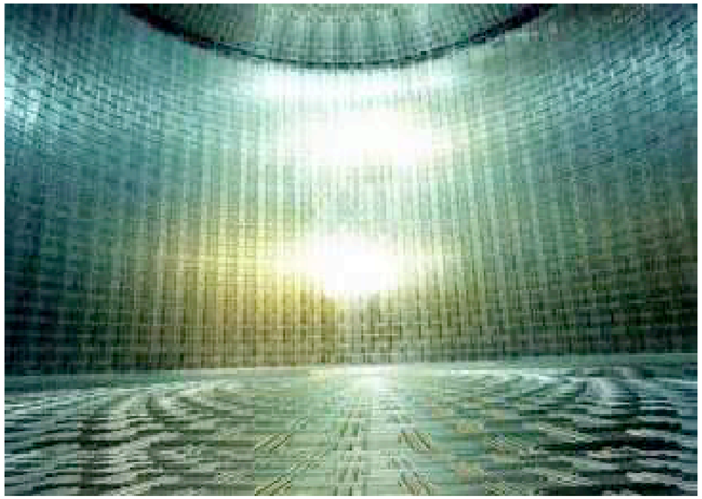
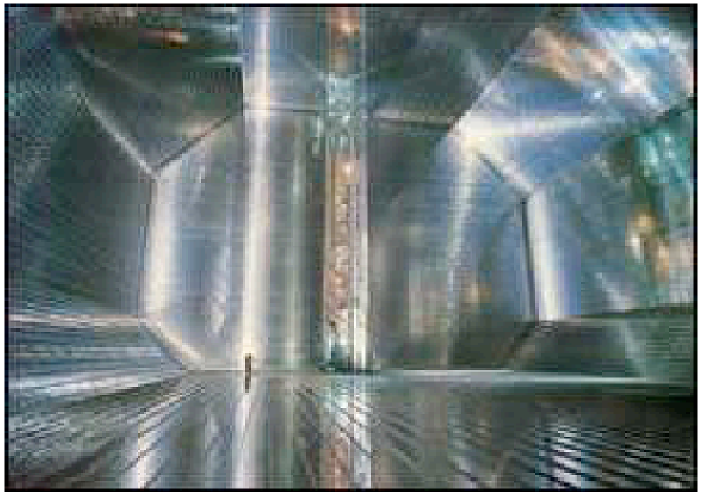
c) Hard initial bremsstrahlung γ's … the energy is reduced → low P → small curvature radius

Cryogenic storage tanks from LNG (USA)

≈200 kton tanks on surface, no magnet

K. McDonald



Very ambitious but conceivable on the timescale >2015

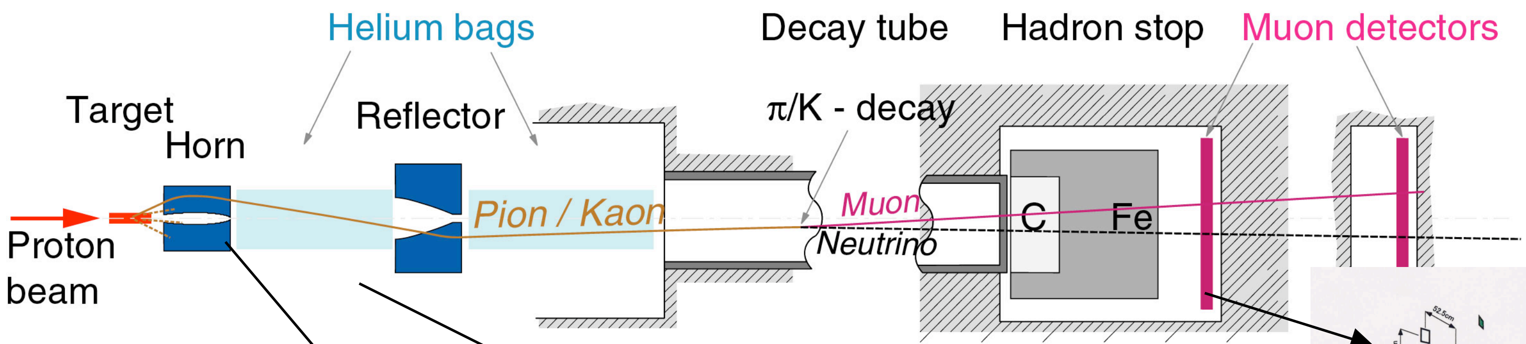
New generation very large detectors

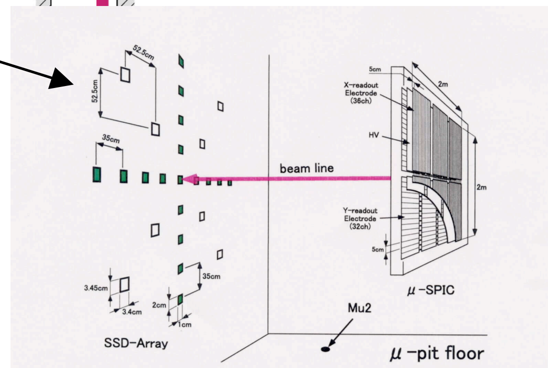
- These very large detectors are conceivable only because they will in fact **provide simultaneously the study of**
  - ➥Atmospheric neutrinos
  - ➥Solar neutrinos
  - ➥Supernova watch
  - ➥Long-baseline neutrinos
  - ➥Proton decay searches!
- The construction and operation of such detectors will be the real challenges of the future underground physics.
- The cost of one of these experiments is at the scale of an LHC detector.

Accelerator neutrinos

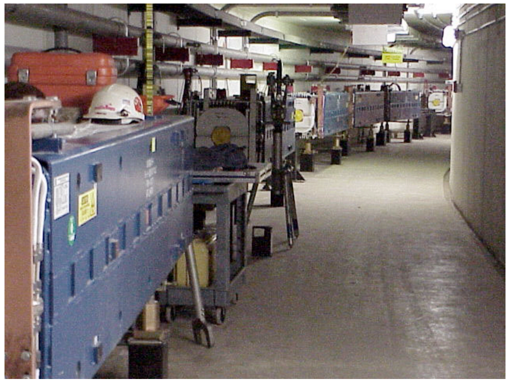
$p + C \rightarrow$ (interactions) $\rightarrow \pi^+, K^+, (\square^+) \rightarrow$ (decay in flight) $\rightarrow \mu^+ + \nu_\mu$

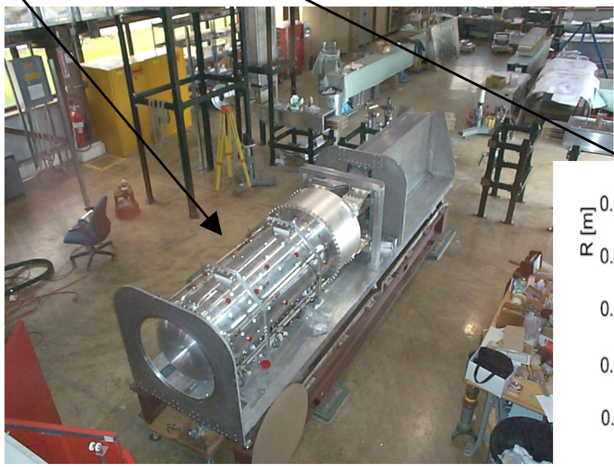
+ few % of ($\bar{\nu}_\mu$, ν_e)



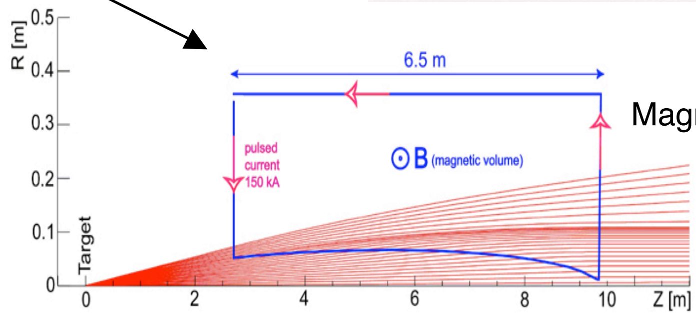


Proton accelerator





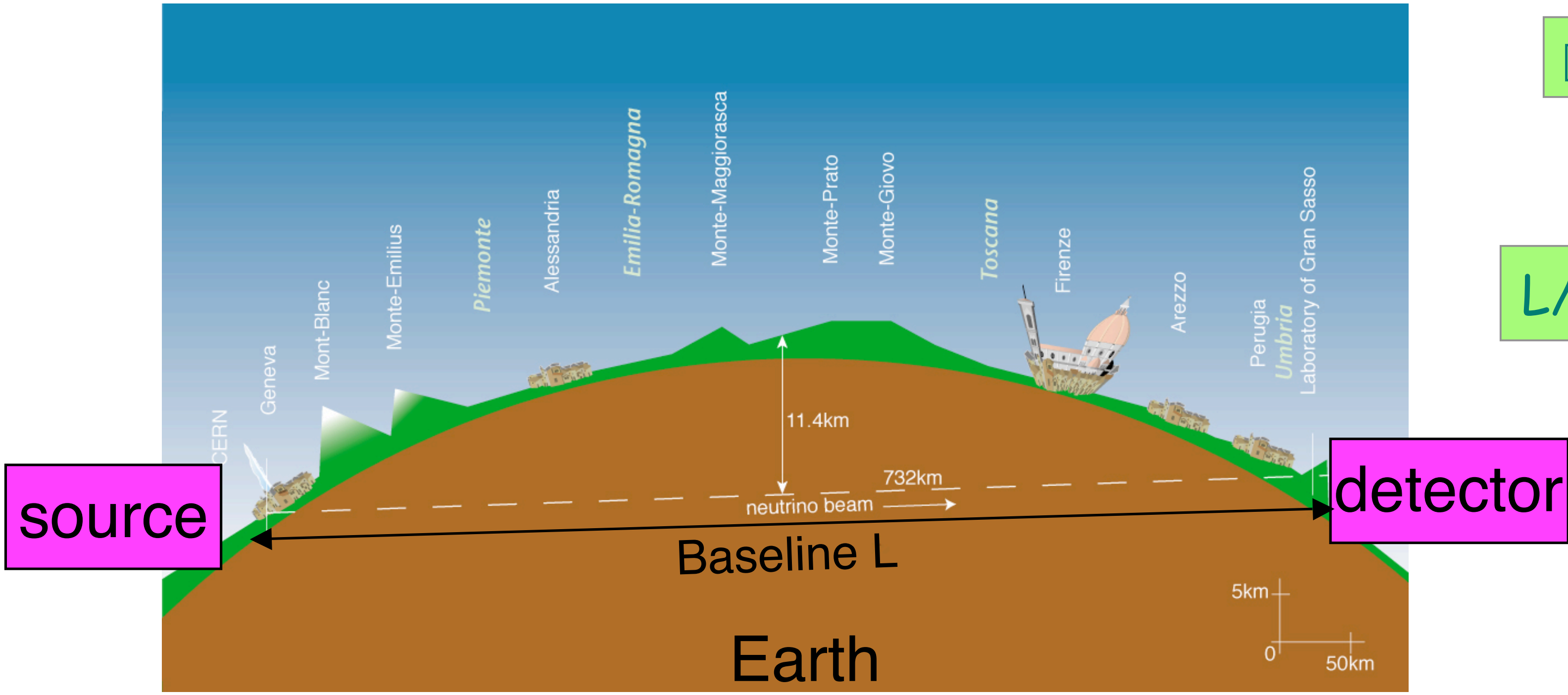
Boone Horn



Magnetic focusing

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 !

2) Independent test of muon neutrino disappearance

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

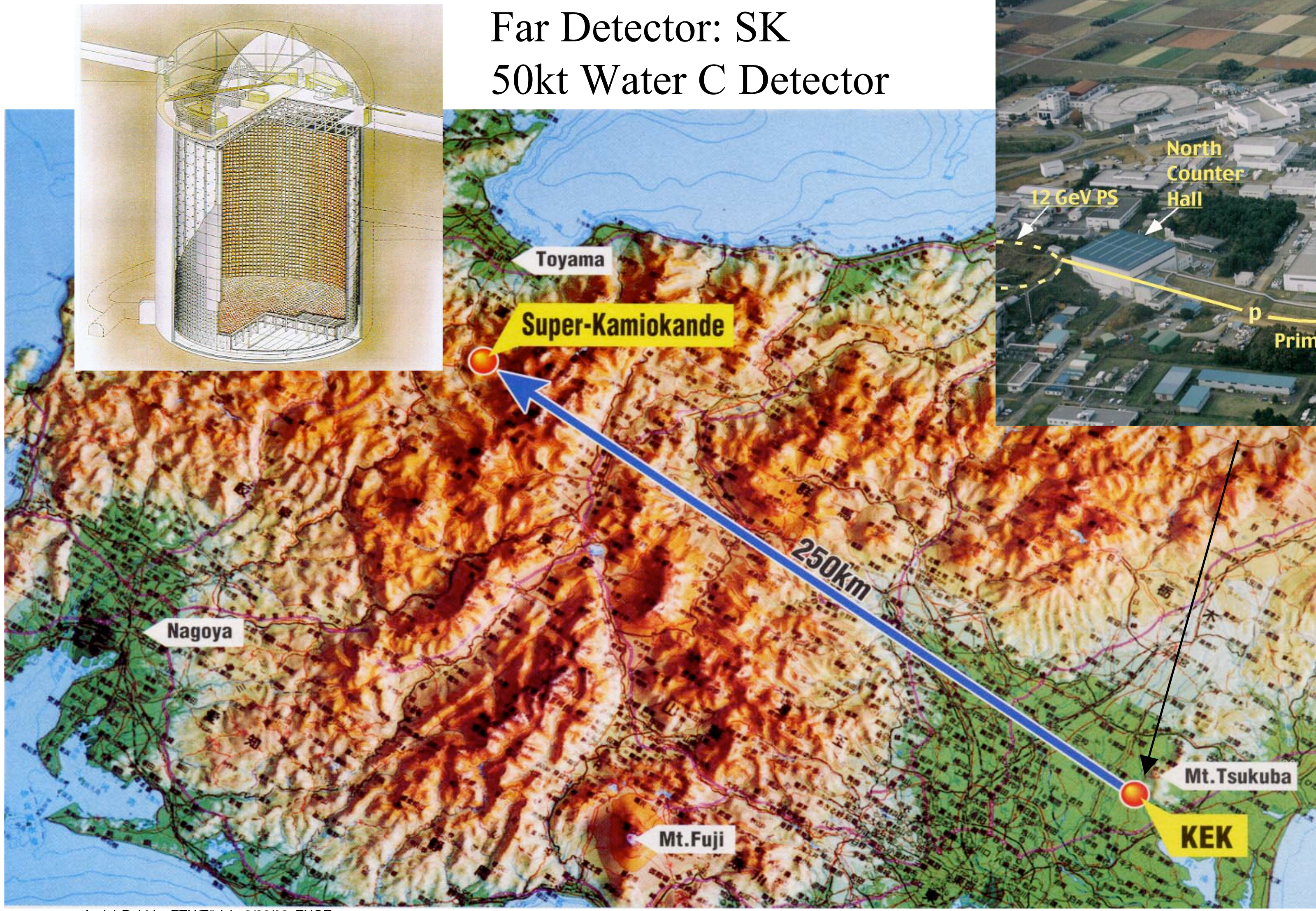
with

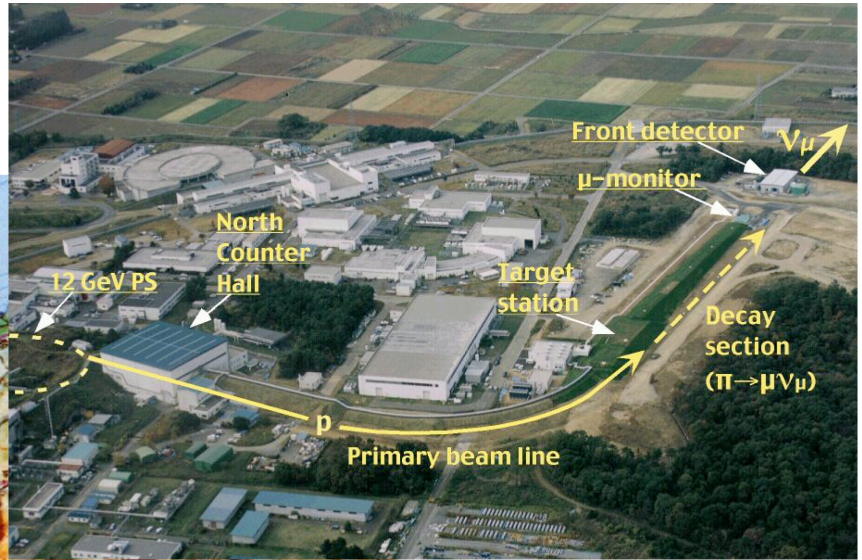
$$\Delta m^2 \approx (1-4)\times 10^{-3} eV^2 \qquad \sin^2 2\theta \approx 1$$

K2K Experiment

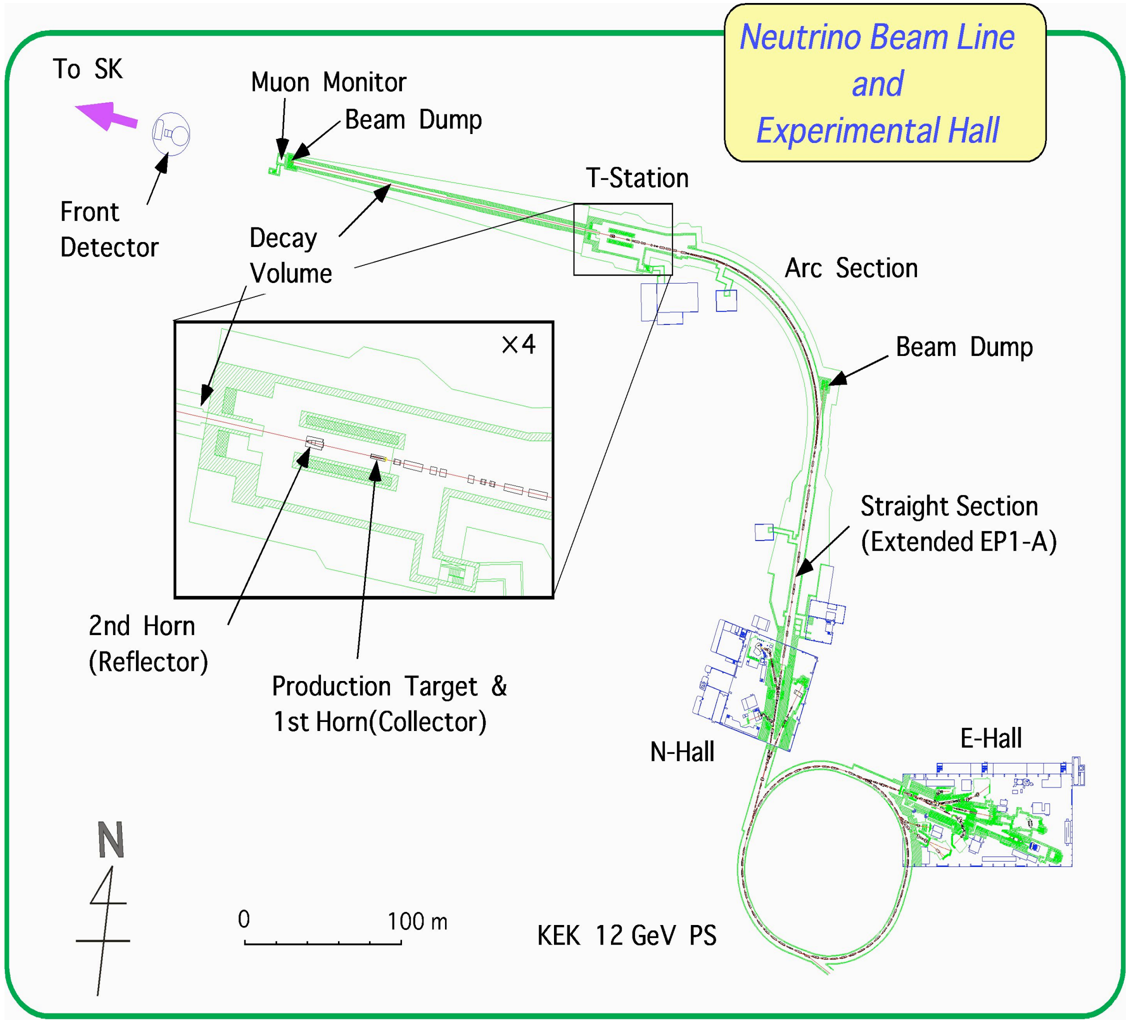
The First Long Baseline (250km)
Neutrino Oscillation Experiment

Far Detector: SK
50kt Water C Detector





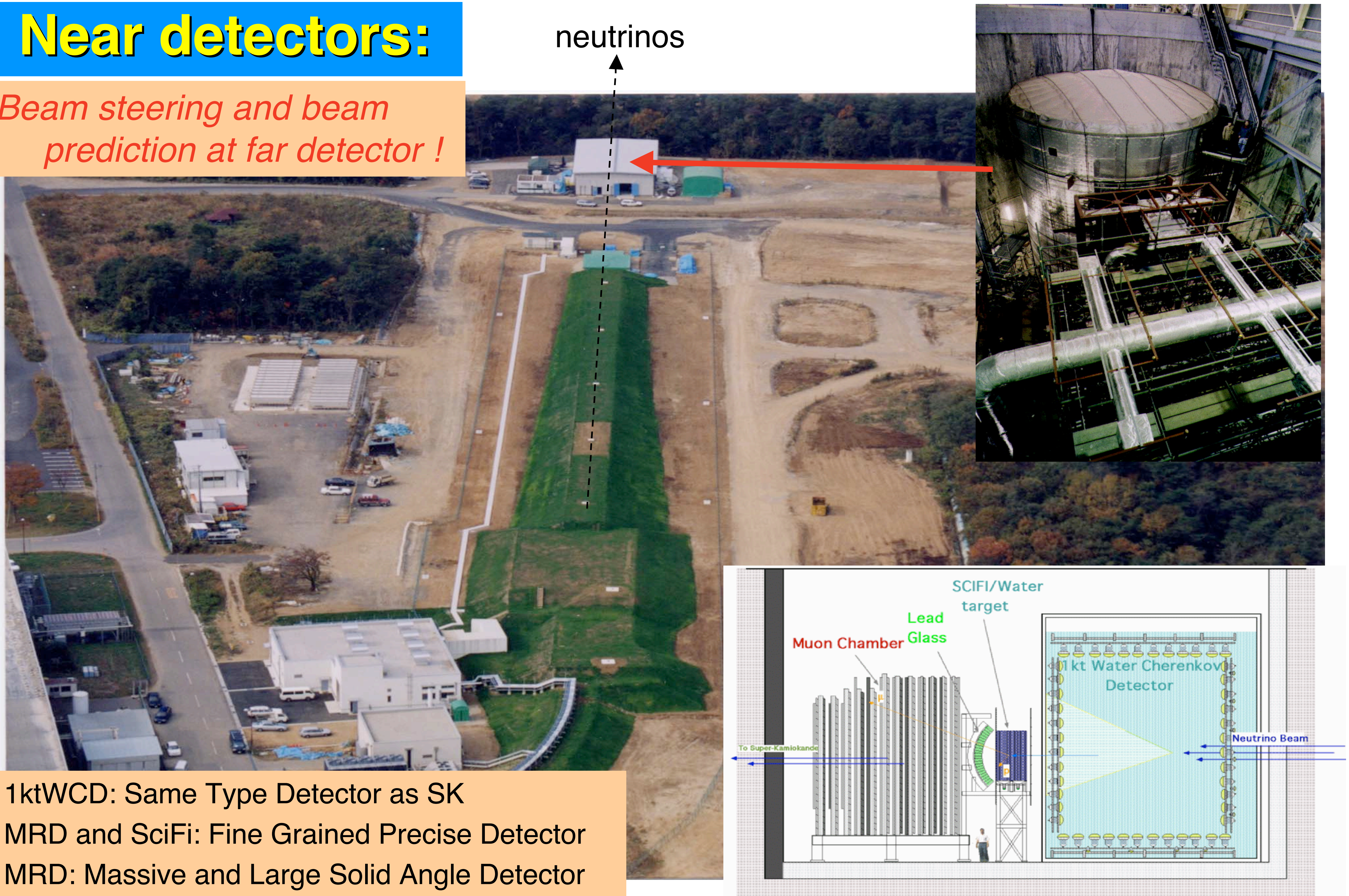
K2K (KEK-to-Kamioka)



- Accelerator: 12 GeV proton synchrotron
  - Intensity 6×10^{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 !

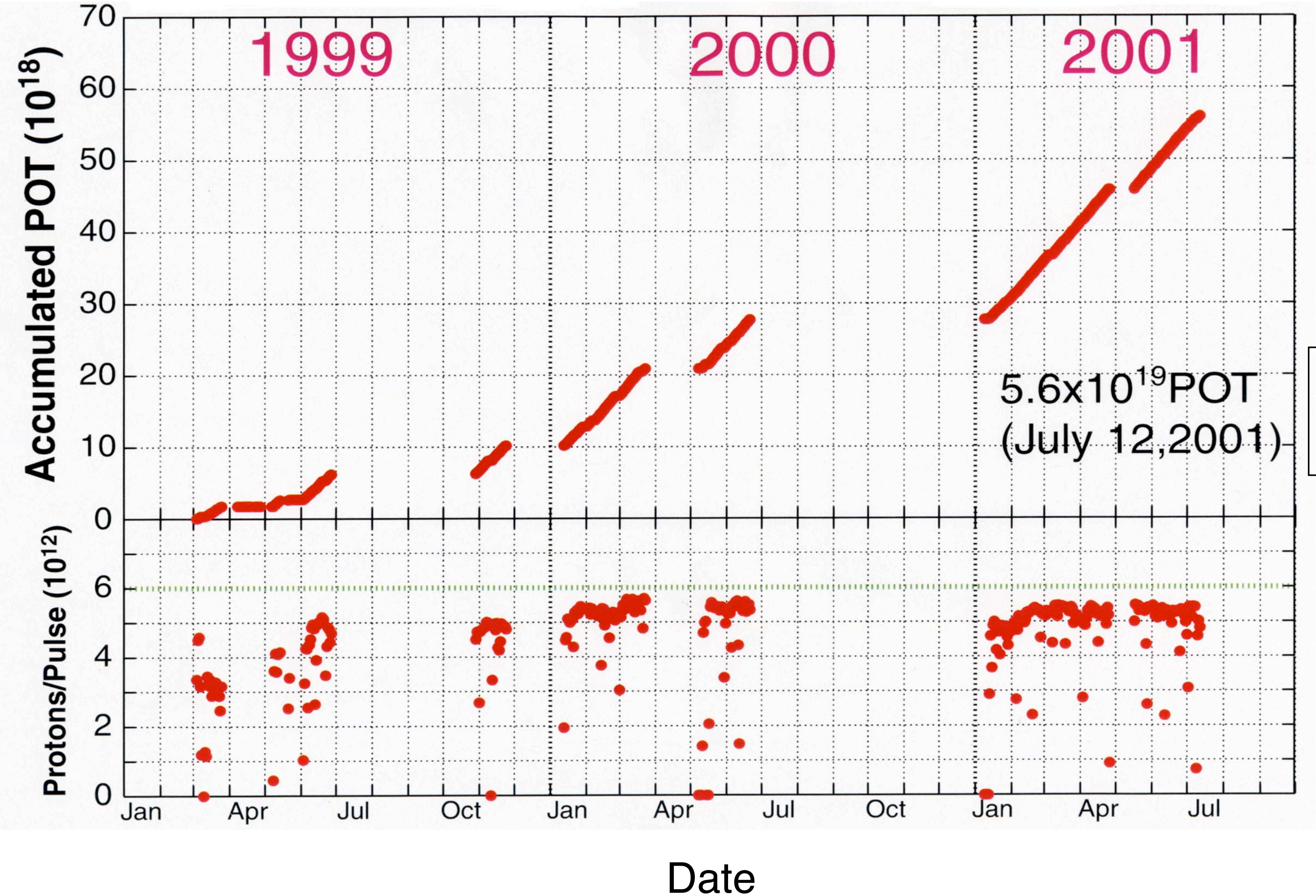


1ktWCD: Same Type Detector as SK

MRD and SciFi: Fine Grained Precise Detector

MRD: Massive and Large Solid Angle Detector

Delivered Protons on Target (POT)

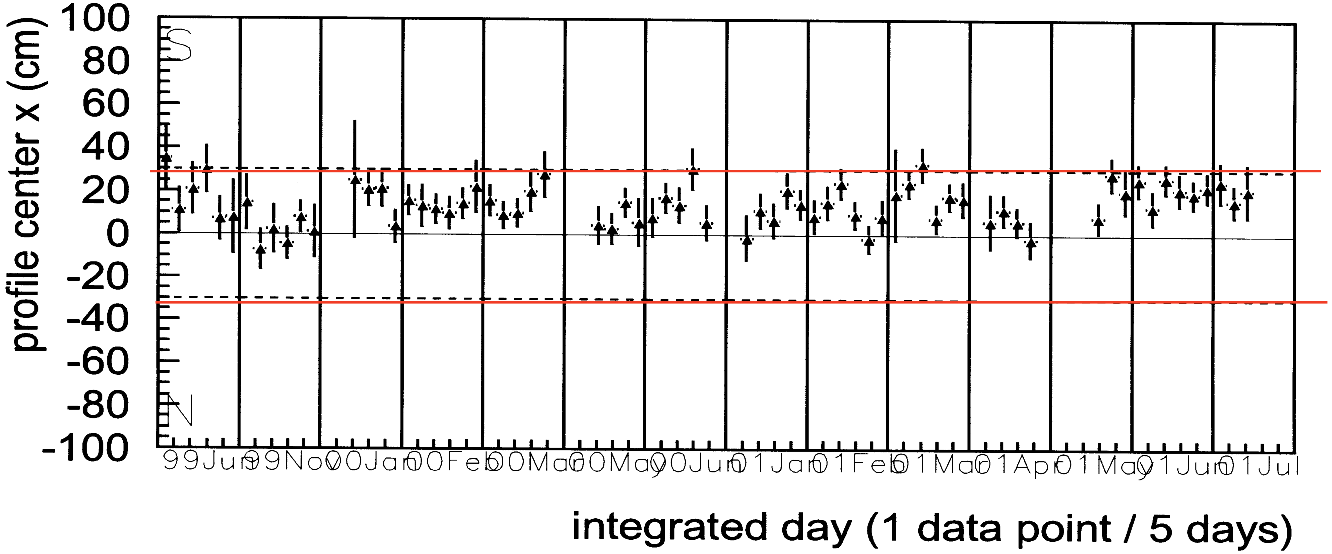


4.8x10^{19} POT for Analysis

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

Neutrino Profile: Centroid Stability

(Muon Range Detector)

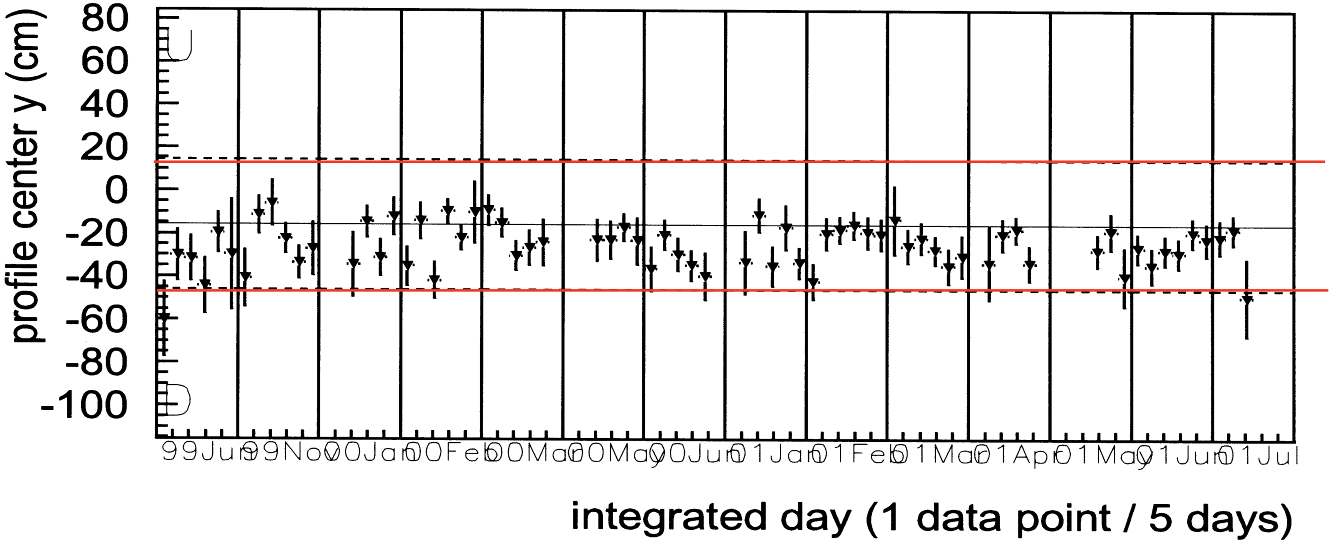


Horizontal

←+1 mrad

← -1 mrad

Beam centered to ±1 mrad

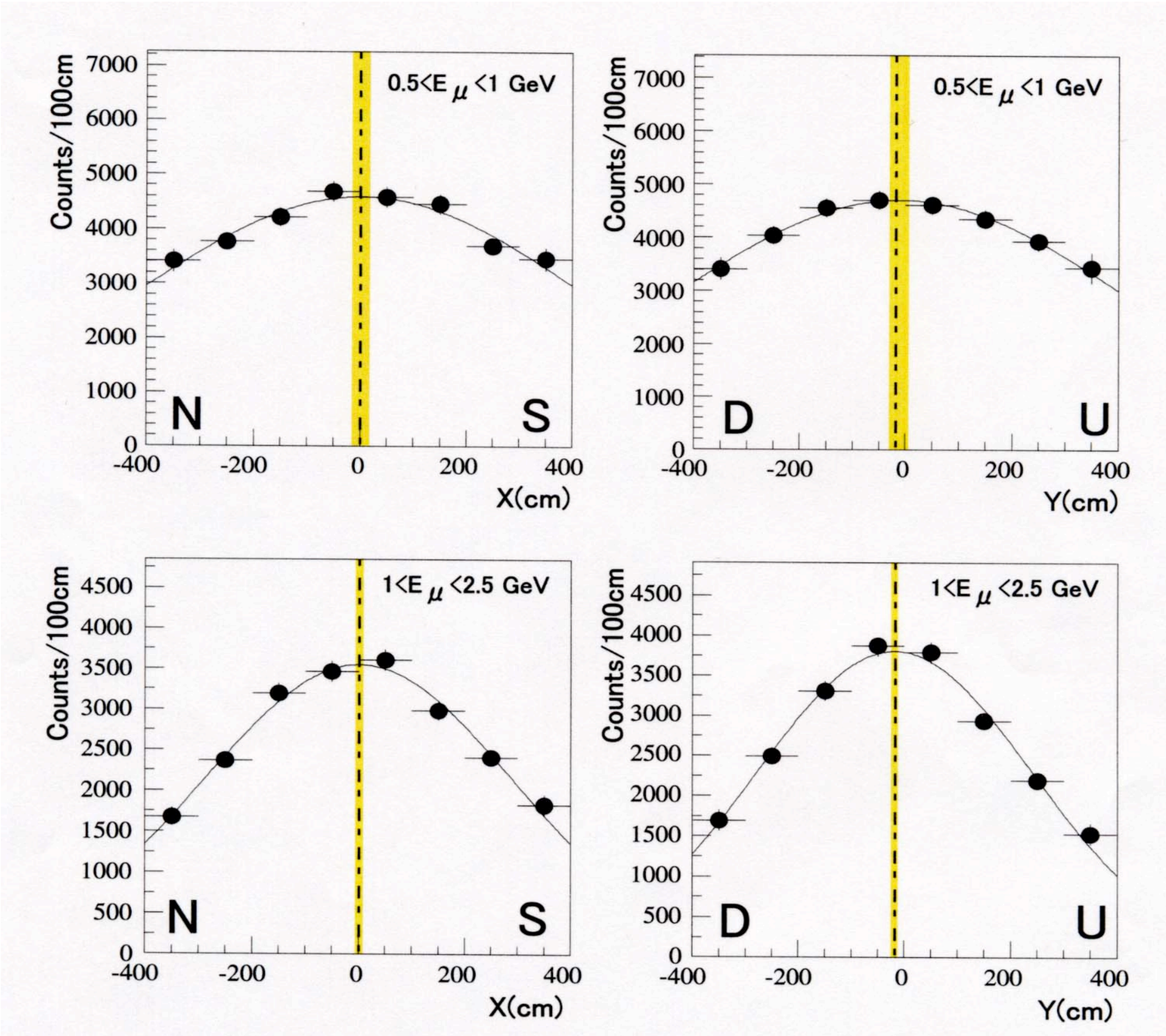


Vertical

←+1 mrad

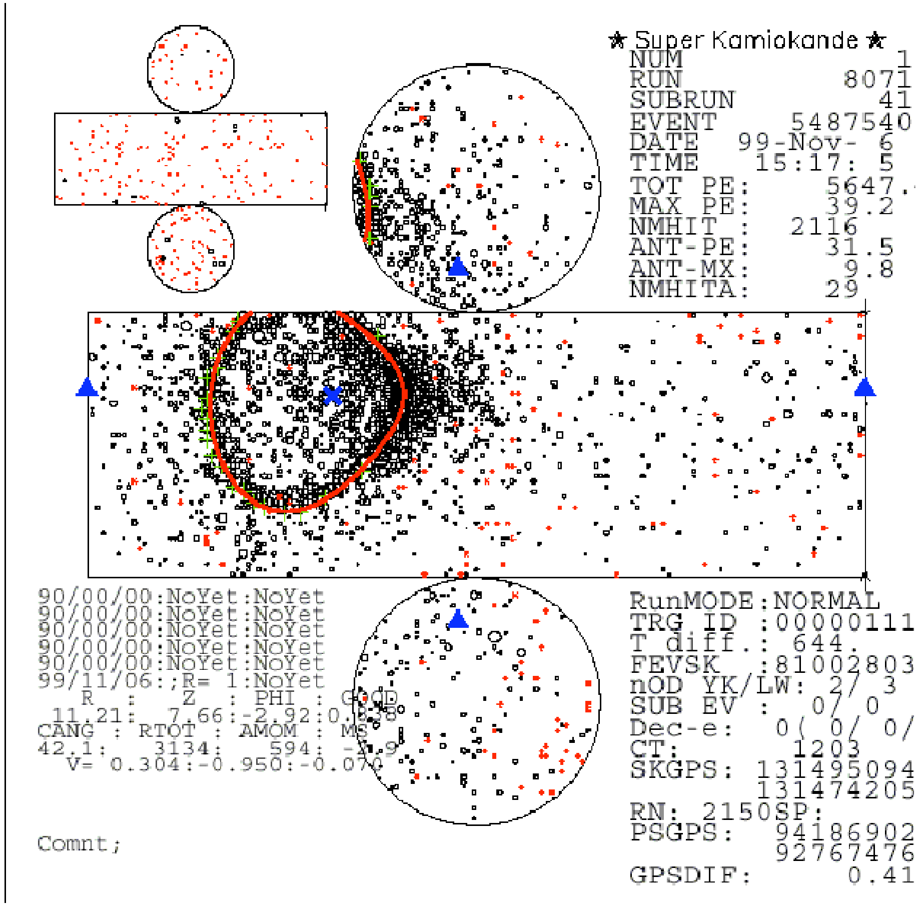
← -1 mrad

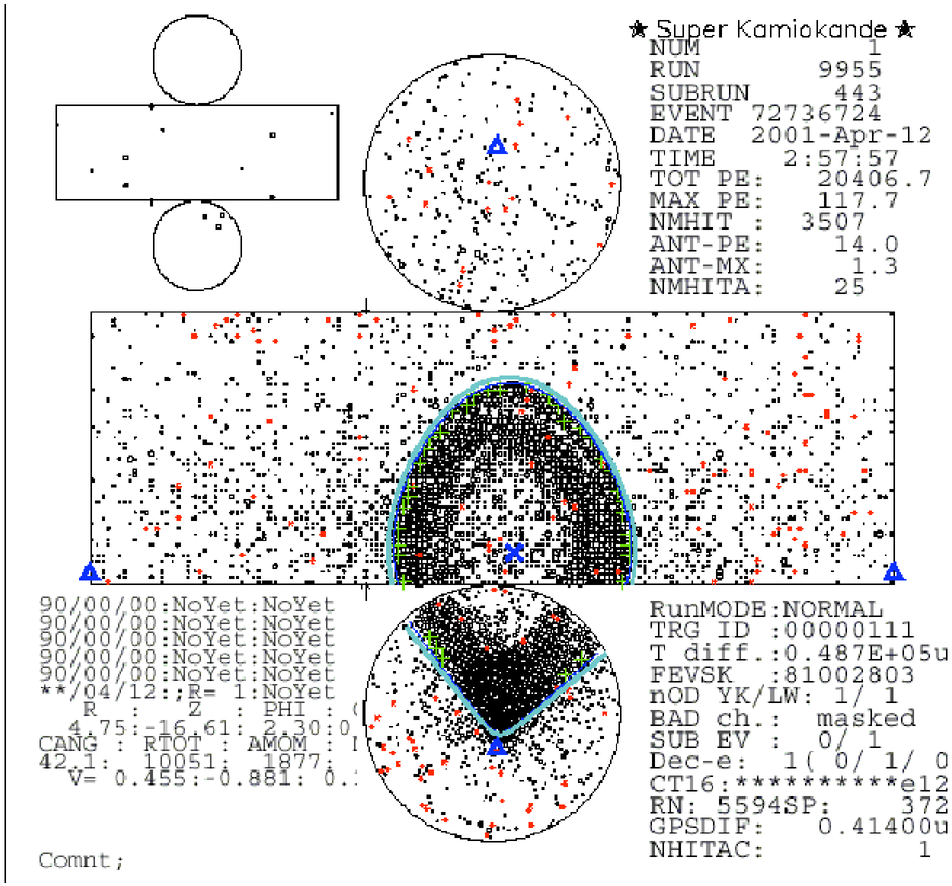
Neutrino Beam Profile (MRD)



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

e-like and μ-like events in Super-Kamiokande

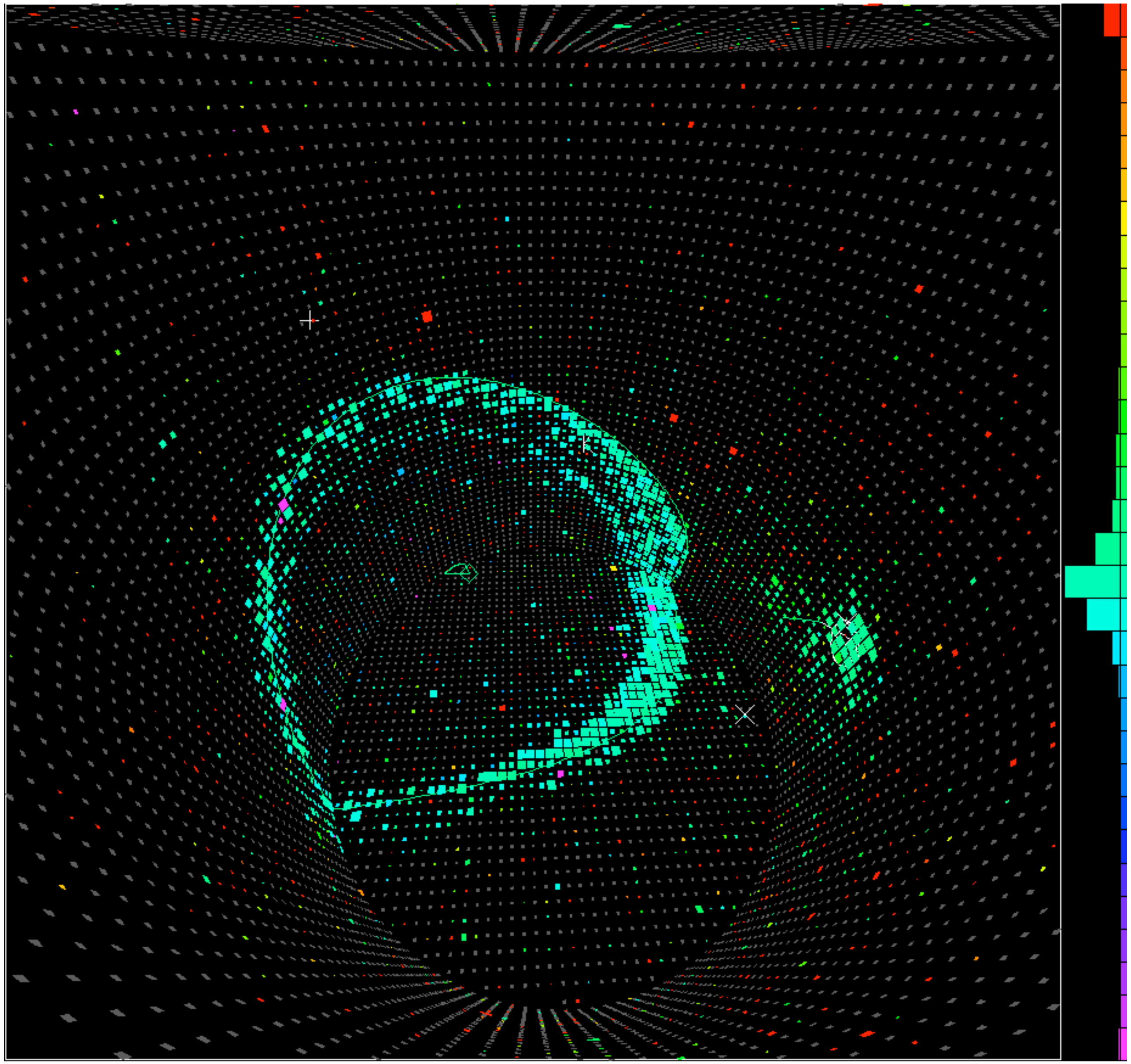


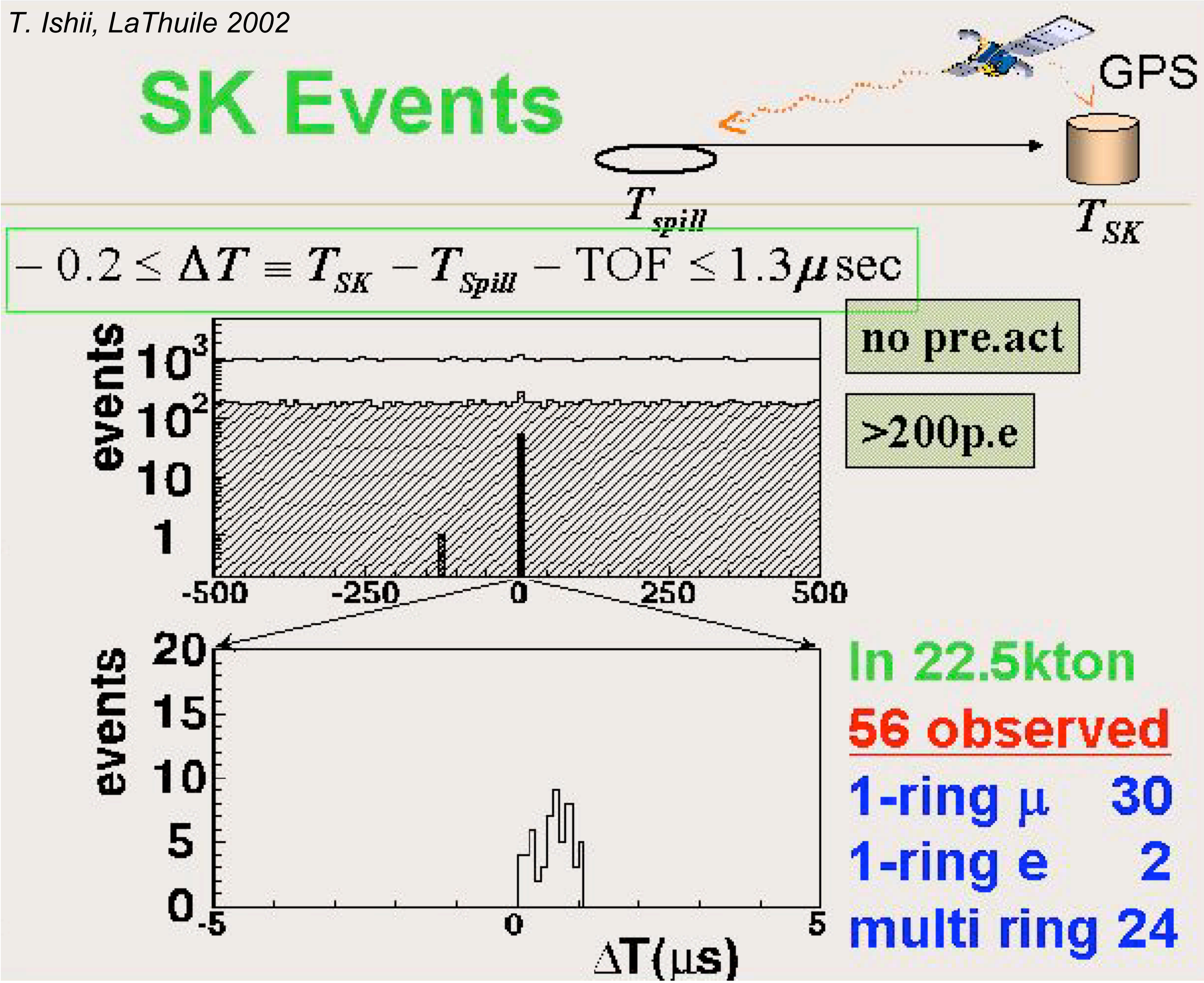


Total rate with low threshold (>30MeV) ~100% efficient for CC
Identification of μ (1Rμ) , e (1Re)

K. Nishikawa, Neutrino 2002

K2K event





Atmospheric neutrino background reduced by 10^6 by precise timing

Observed SK events

4.8×10^{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

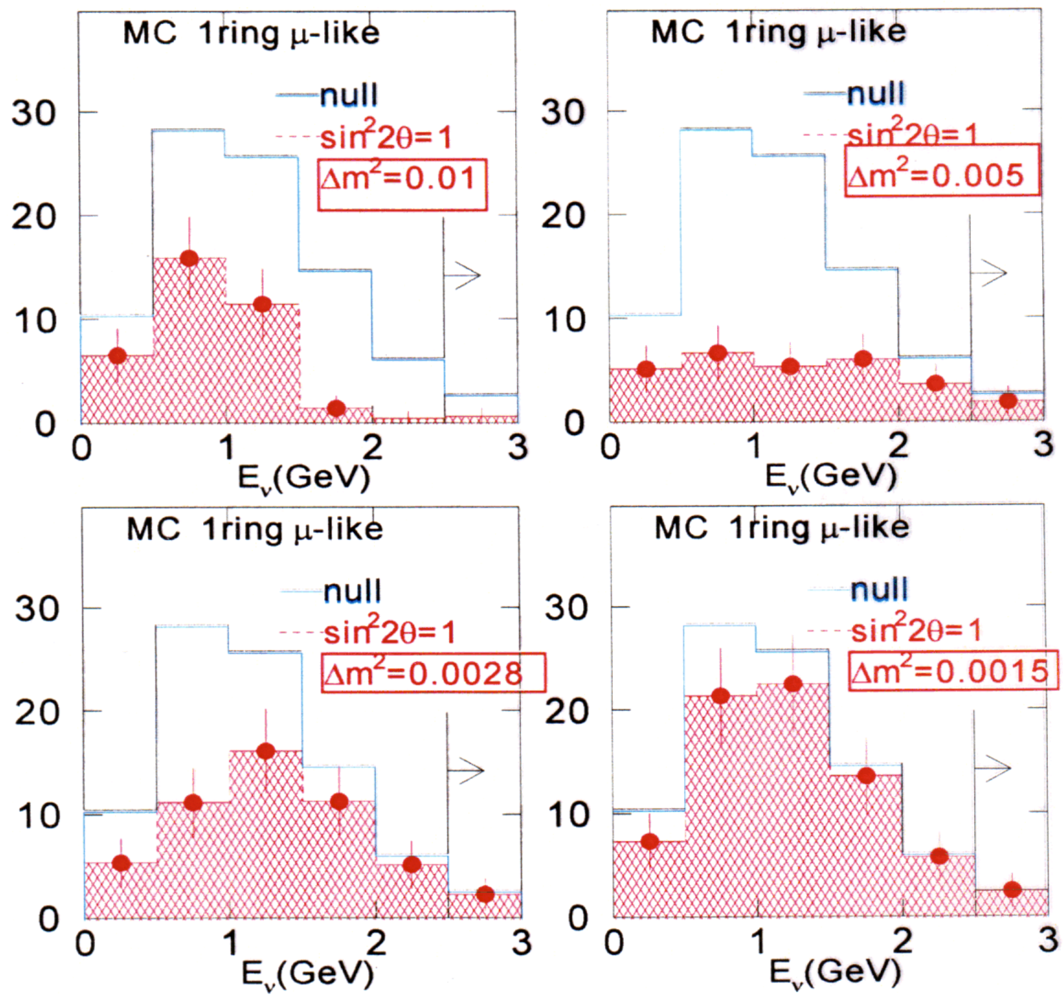
Cf. MRD: $87.4^{+12.7}_{-13.9}$ SciFi : $87.3^{+11.9}_{-11.9}$

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)

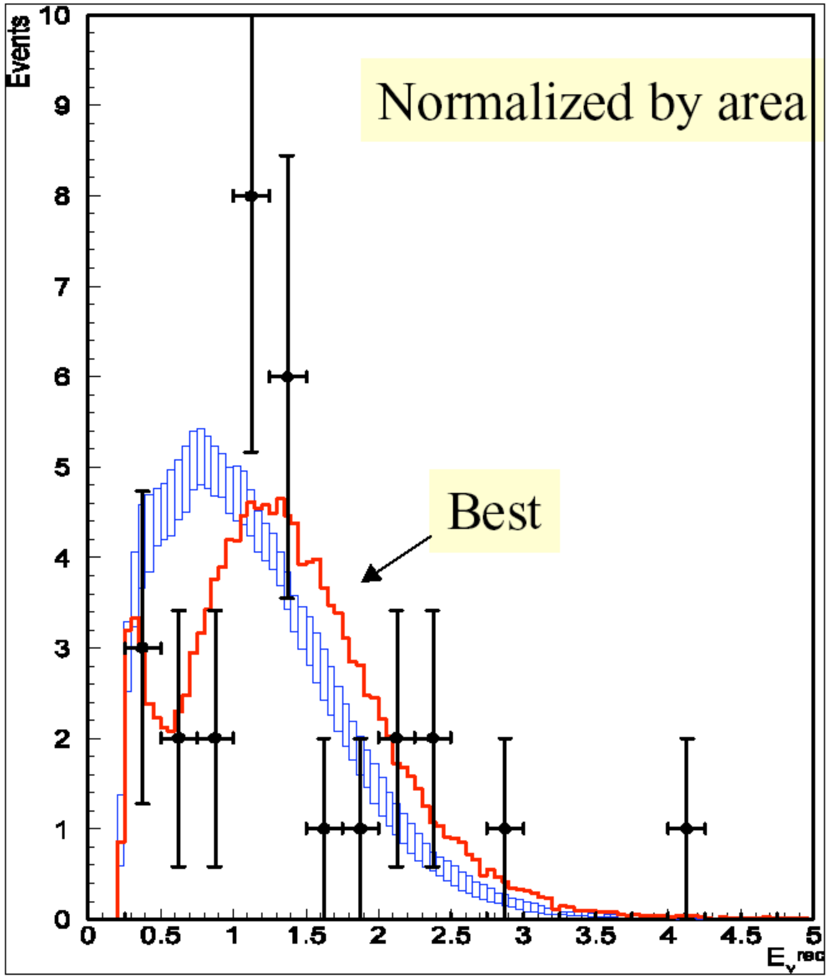


With sufficient statistics and a good reconstruction of the event energy, the disappearance as a function of Evis will be studied (so far not too convincing)

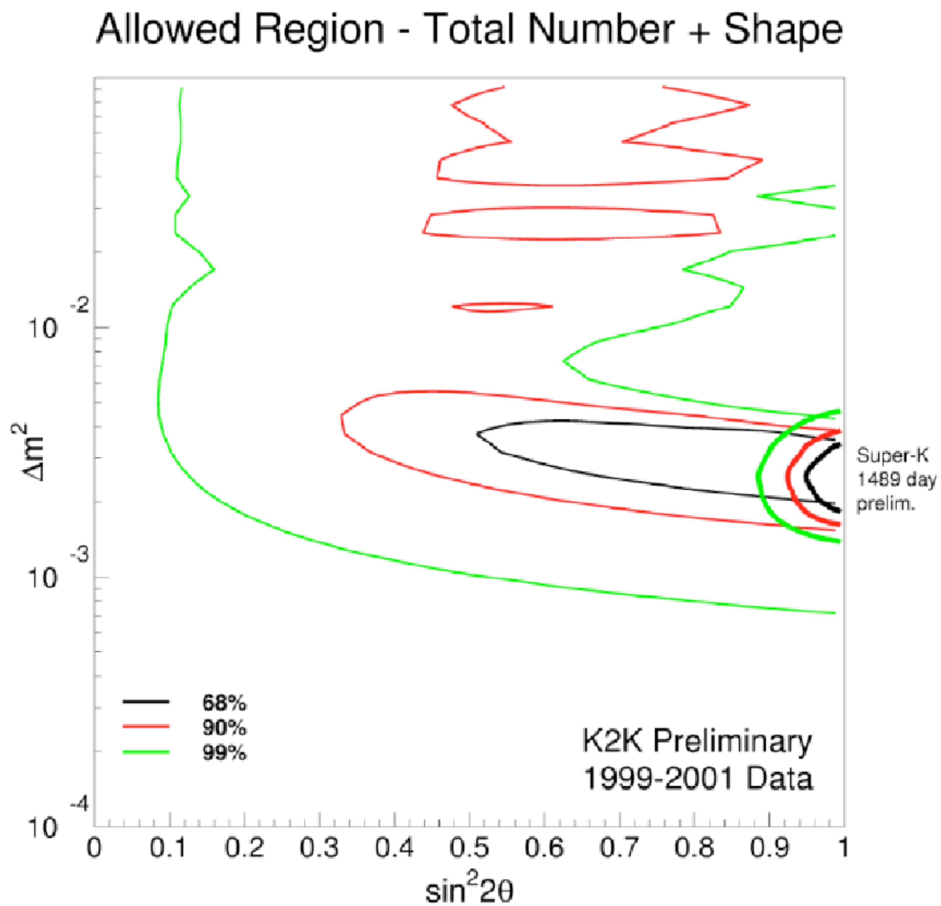
K. Nakamura, NUFACT00, Monterey (USA), May 2000

K2K preliminary shape result

K. Nishikawa, Neutrino 2002



Comparison with SK atm ν observation

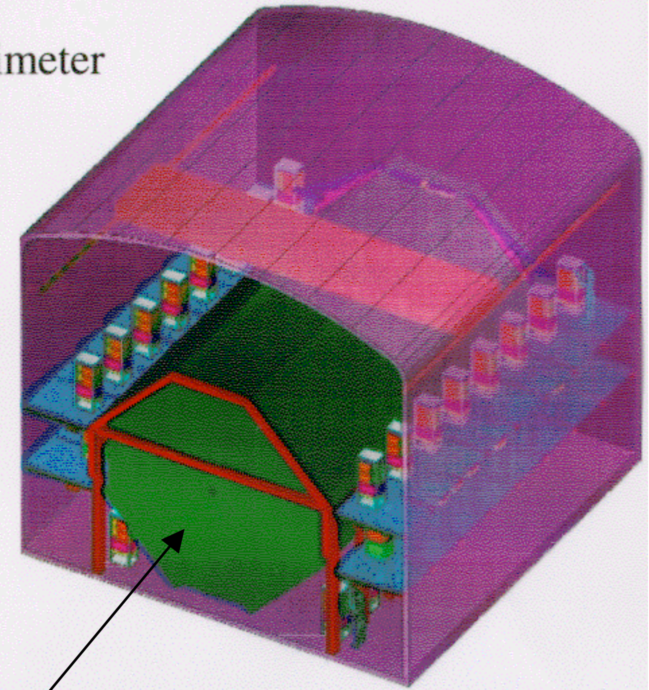


- Consistent values between SK atmospheric and K2K results

NUMI-MINOS program

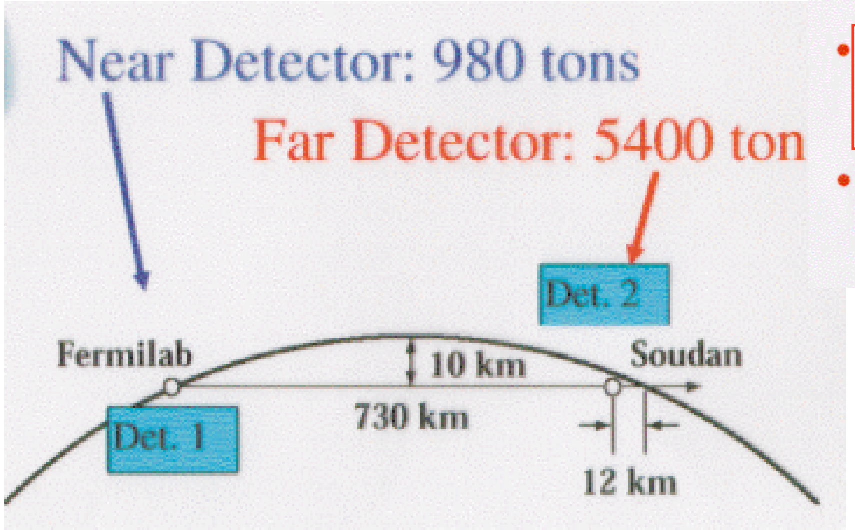
Two detector Neutrino Oscillation Experiment (Start 2004)

- 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 <B> ≈ 1.3T
- 5.4kt total mass



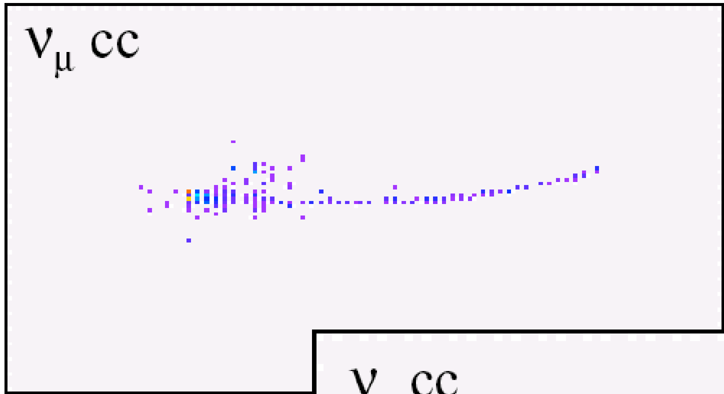
Half of the MINOS Far Detector

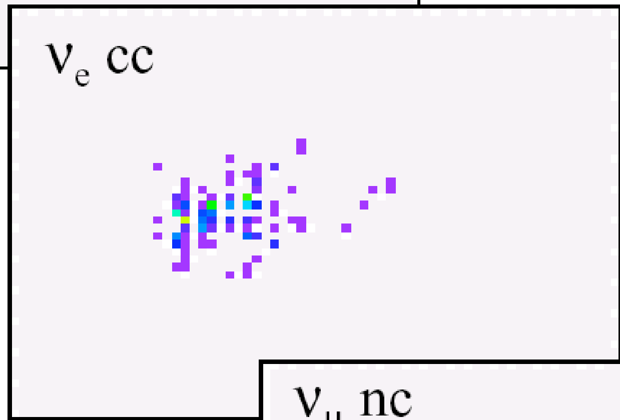
beam



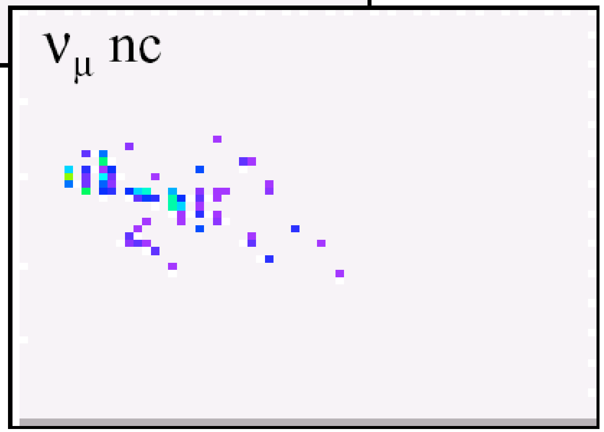
Topology of Neutrino Events

Identified by a relatively long track in an event. At very low energies, there can be some BG from NC π^-.





Identified by lack of a long track and a relatively concentrated EM shower in the core. Main BG comes from NC π^0 events From higher energy ν's.

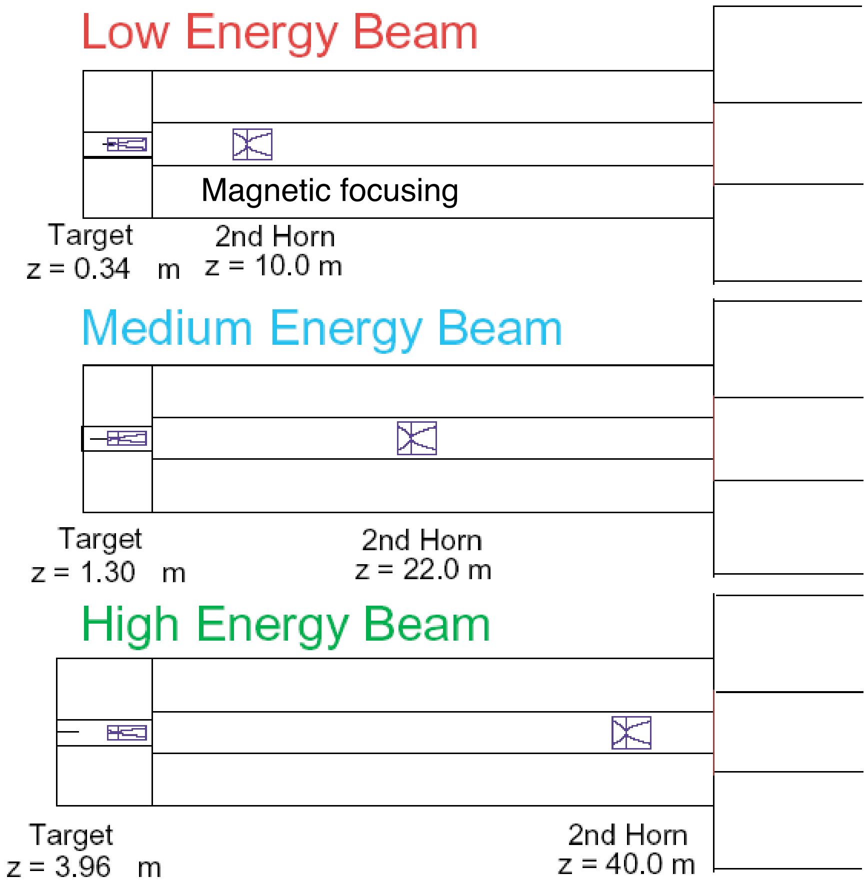


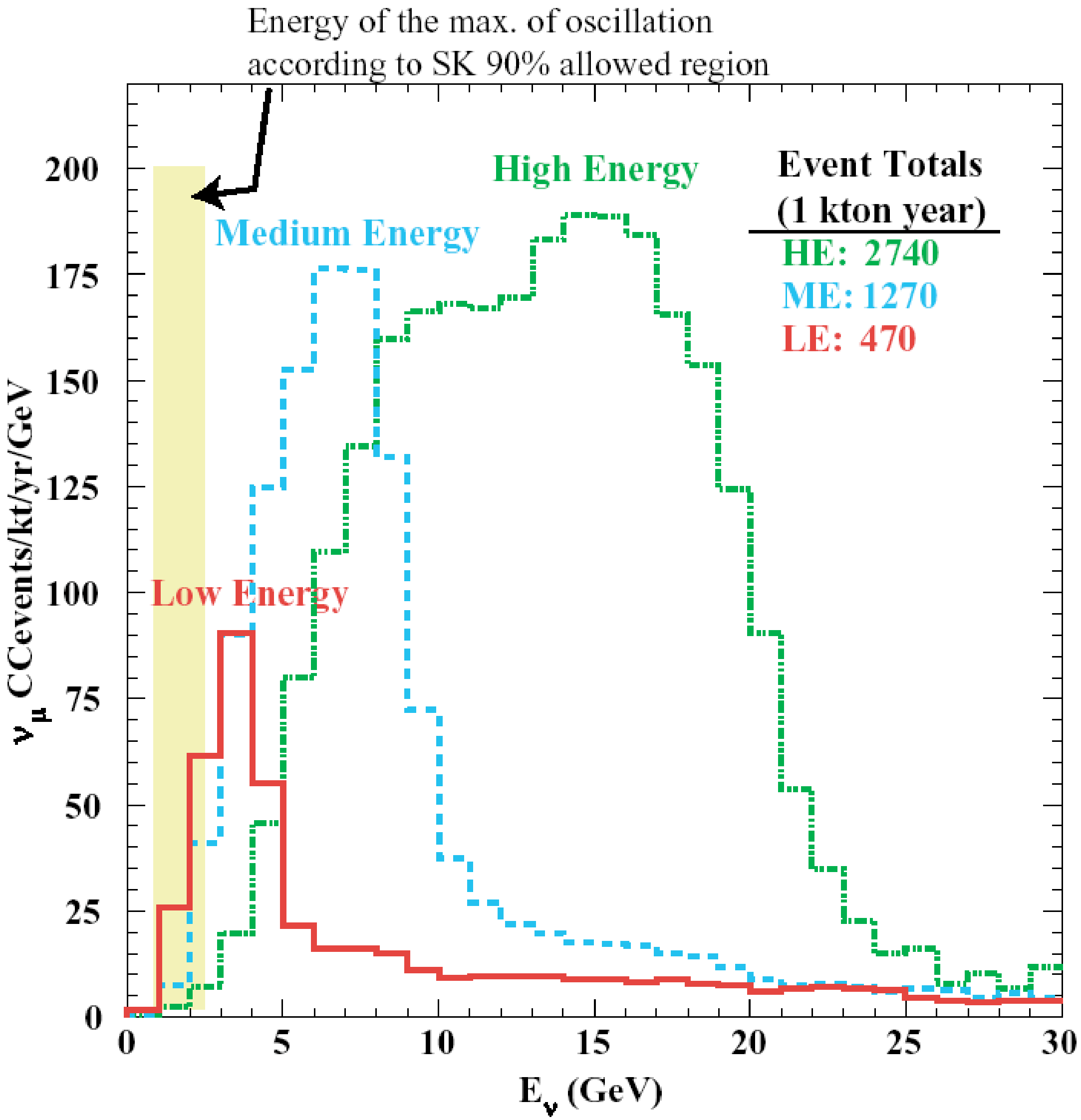
Identified by lack of a long track and lack of strong EM core. Some high y CC events are BG.

D. Michael, Neutrino 2002

NUMI neutrino beam

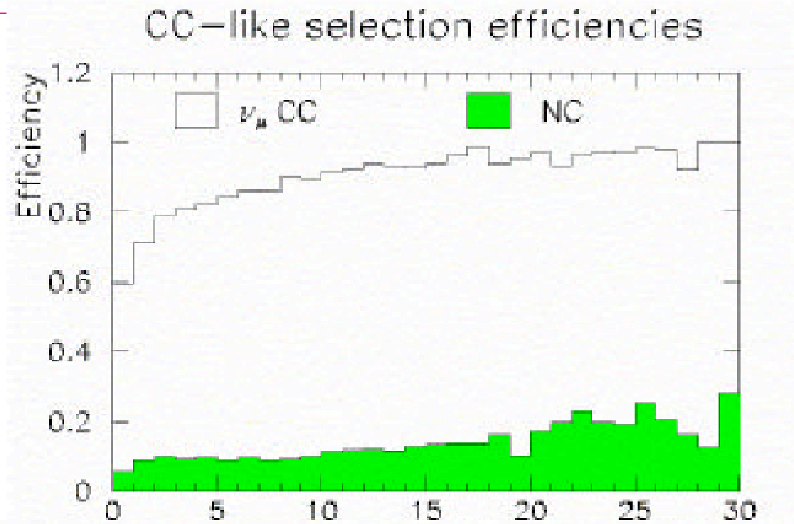
"Sacrifice neutrino flux to fit the expected energy of oscillated events"

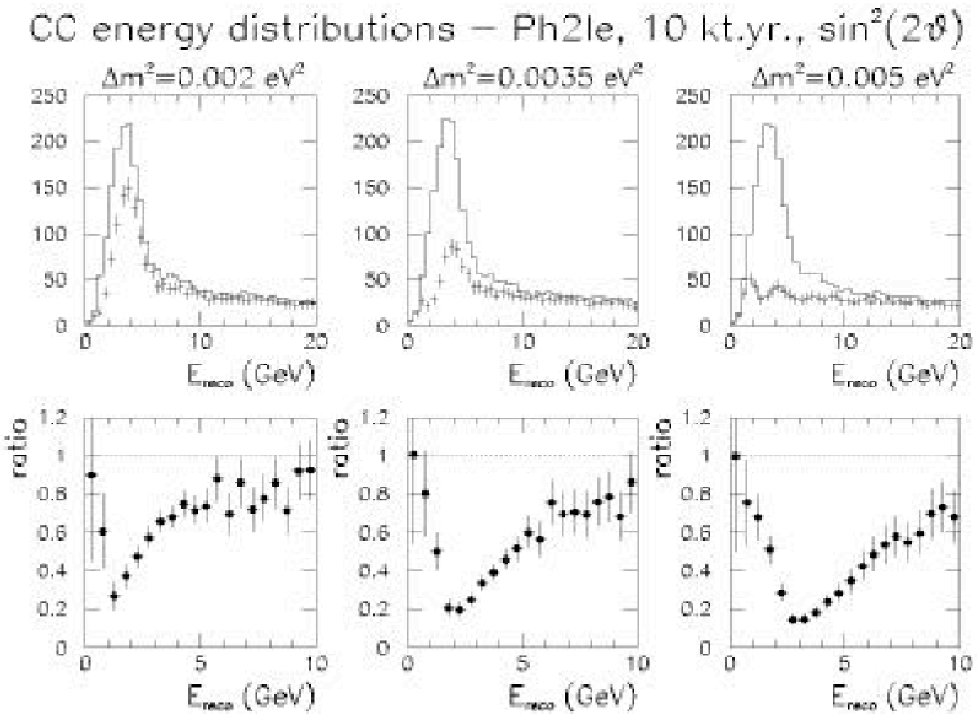


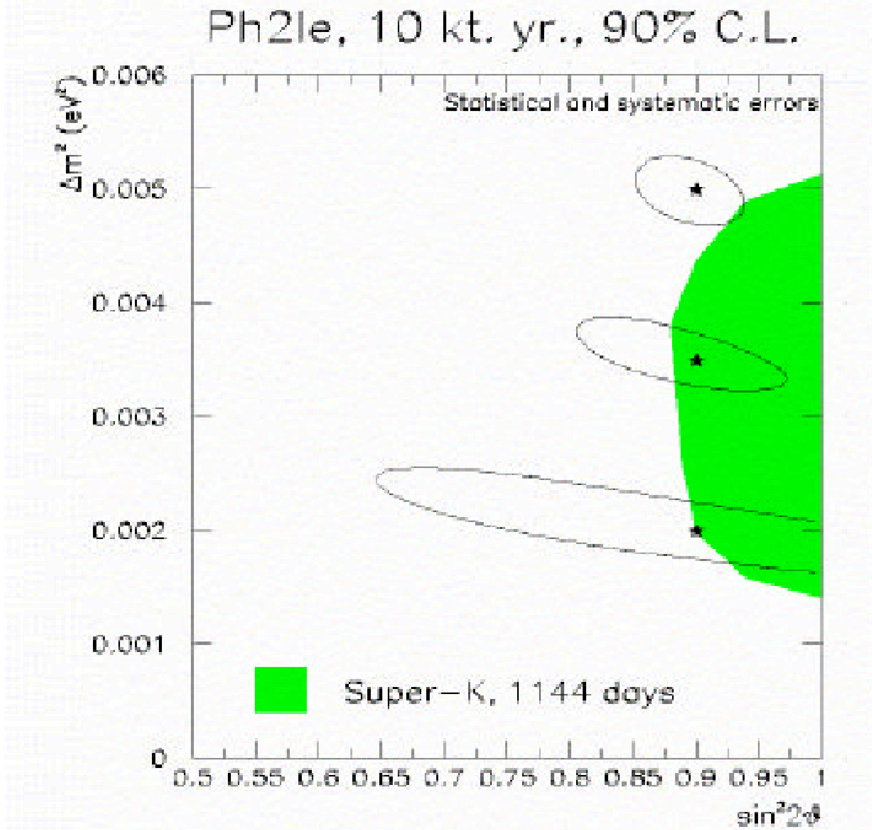


M. Mezzetto, NBI 2002

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

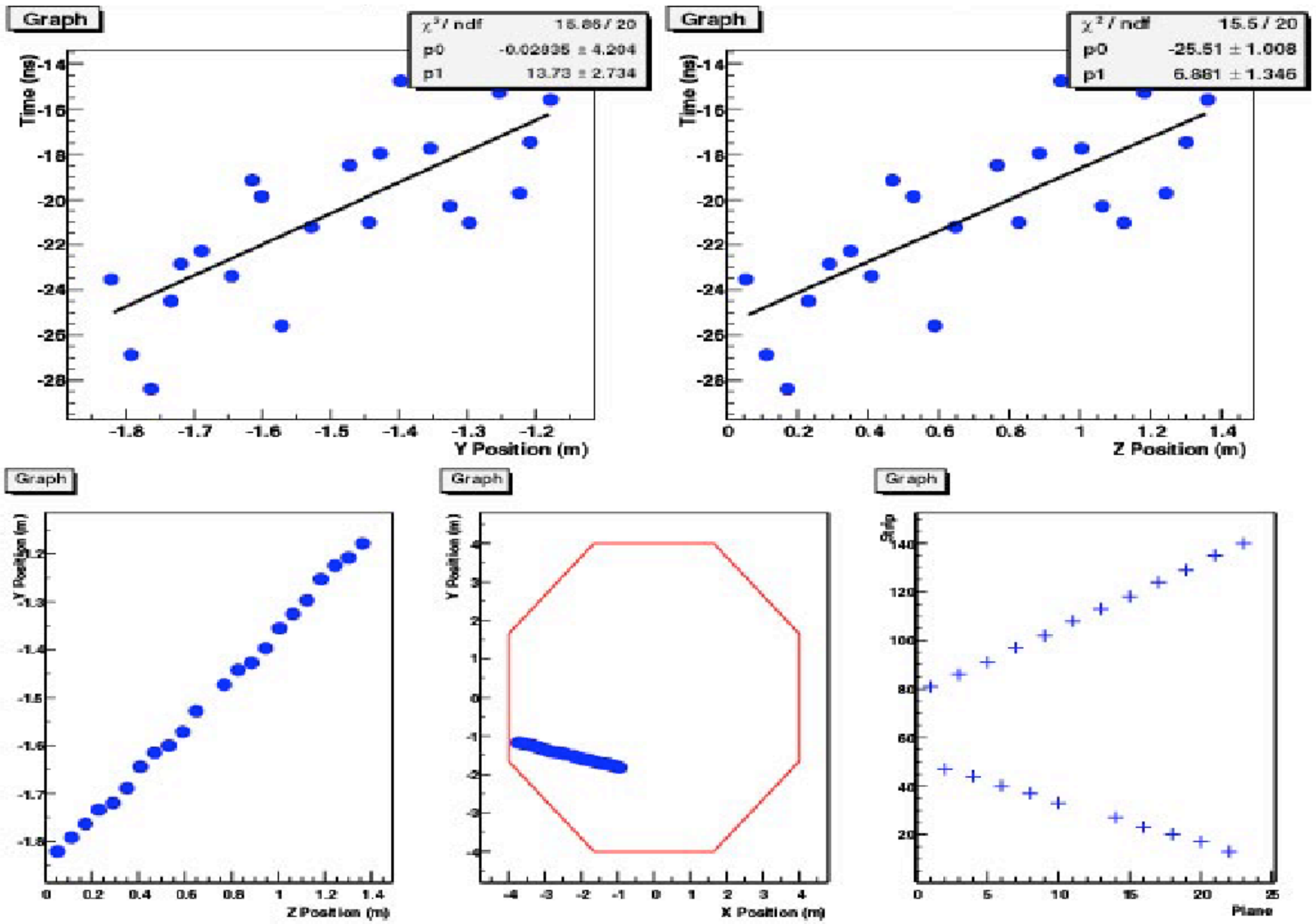
- 146 planes mounted as of 1 March 2002 (1.6 kt mass)
  - ➥ 2% of detector per day at present rate of assembly
- Finish installation of far detector (2001-2003)
- Near detector assembly (2001-2003)
- Beam line commissioning (2004-2005)
- Plan to start with cosmic ray data-taking with half detector and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

Far detector at SOUDAN

R.C. Webb, LaThuile 2002

The First MINOS Neutrino Event!

- The first neutrino-induced event has recently been observed!
- Upgoing muon passing through about 3.5 m of the detector. ($p_{\mu} > 1.9$ GeV/c)
- Magnetic field not on yet so no measurement of the momentum.



D. Michael, Neutrino 2002

3) Search for tau neutrino appearance

$$\nu_\mu \to \nu_X \equiv \nu_\mu \to \nu_\tau \ ?$$

with

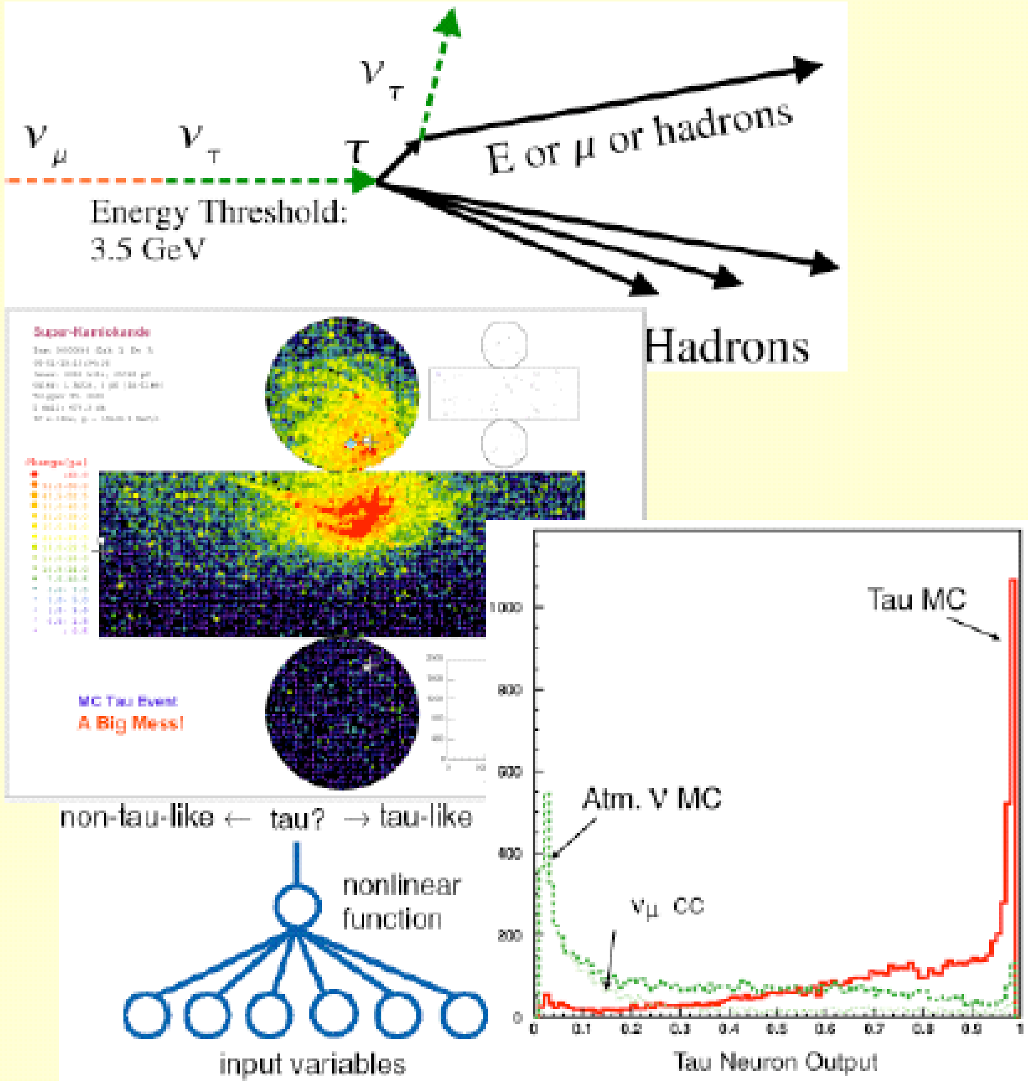
$$\Delta m^2 \approx (1-4)\times 10^{-3} eV^2 \qquad \sin^2 2\theta \approx 1$$

Atmospheric tau appearance in SuperK (I)

M. Smy, Moriond 2002

Three Different Analyses

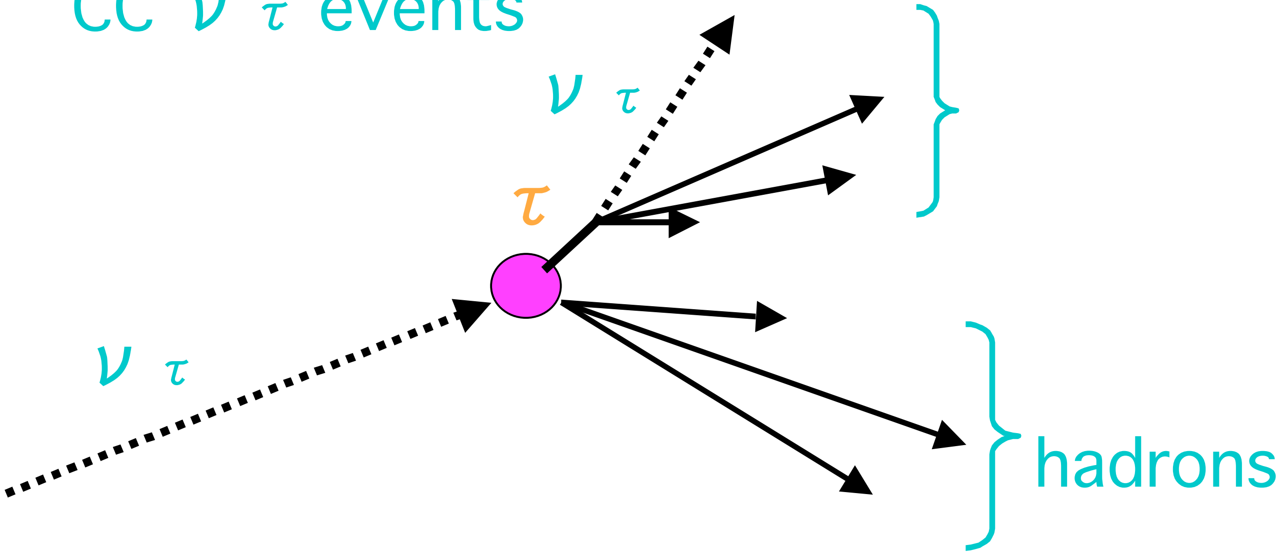
- Different event reconstruction (energy flow, jet variables), Likelihood-function
- Standard ring reconstruction, Likelihood-function
- Standard ring reconstruction, Neural Net



Michael Smy, UC Irvine

Search for CC ν_τ events

CC ν_τ events



Only ~ 1.0 CC ν_τ FC events/kton・yr

(BG (other ν events) ~ 130 ev./kton・yr)

- Many hadrons . . . (But no big difference with other events .)

  → τ - likelihood analysis

- Upward going only

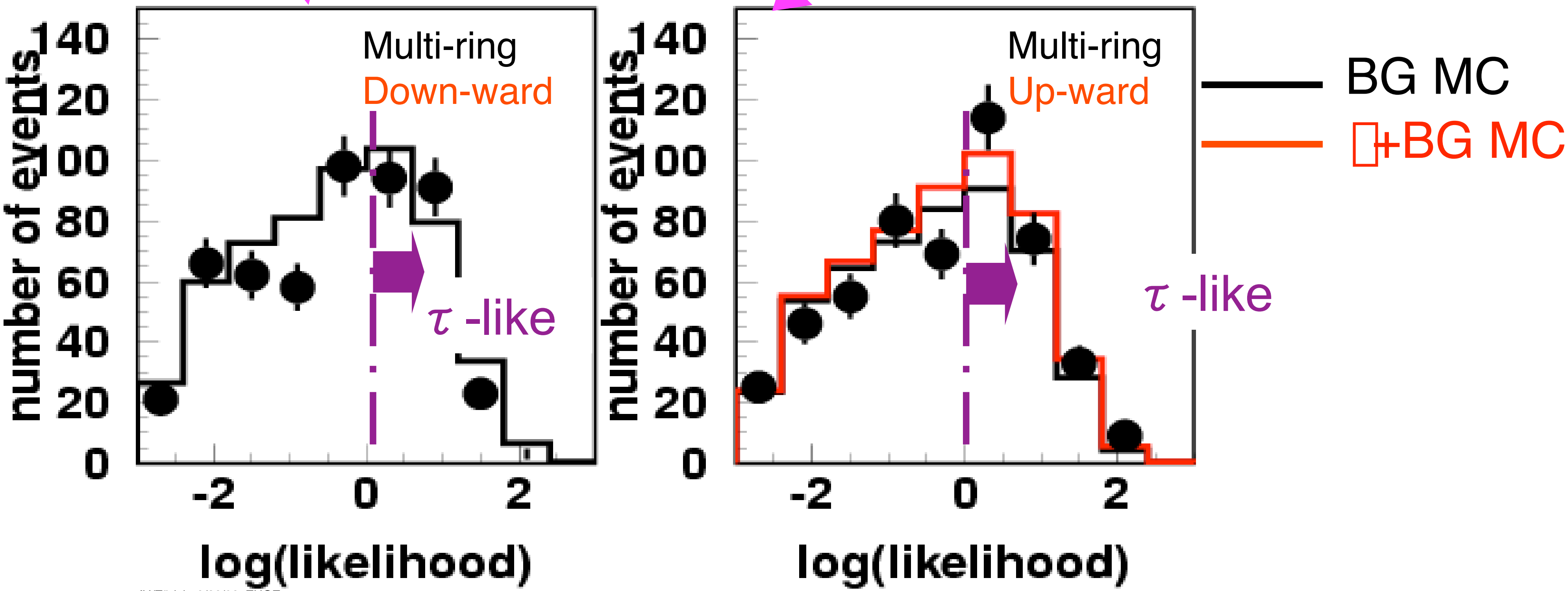
  → Zenith angle

Tau likelihood analysis

Selection Criteria

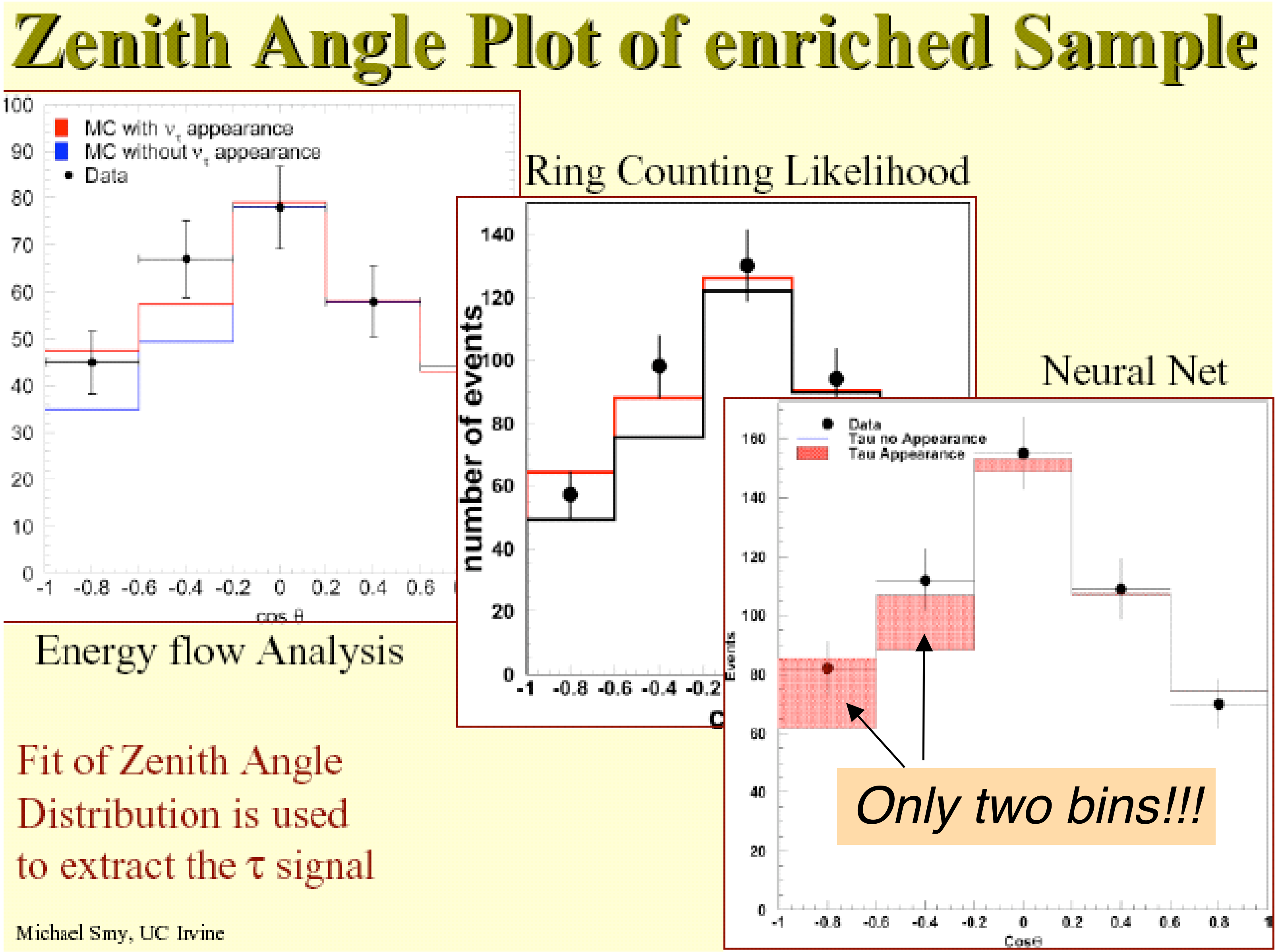
- multi-GeV, multi-ring
- most energetic ring is e-like
- log(likelihood) > 0 (multi-ring)
  > 1 (single-ring)

- total energy
- number of rings
- number of decay electrons
- max(Ei)/Σ Ei
- distance between □ interaction point and decay-e point
- max($P_{□}$)
- $Pt/Evis^{3/4}$
- PID likelihood of most energetic ring



Atmospheric tau appearance in SuperK (II)

M. Smy, Moriond 2002



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

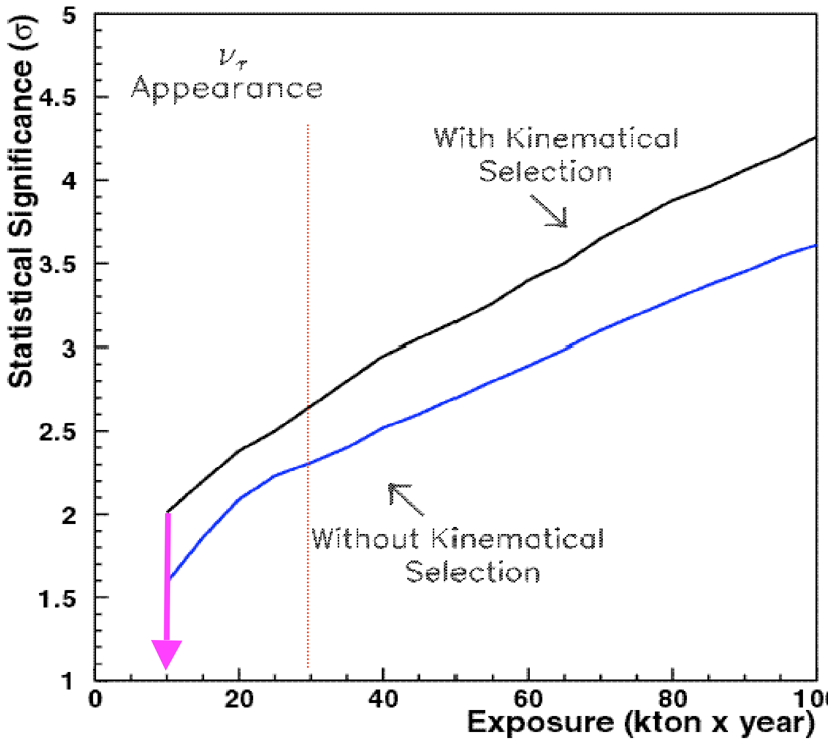
≈80 kt·yr exposure → *A very tough job !*

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**

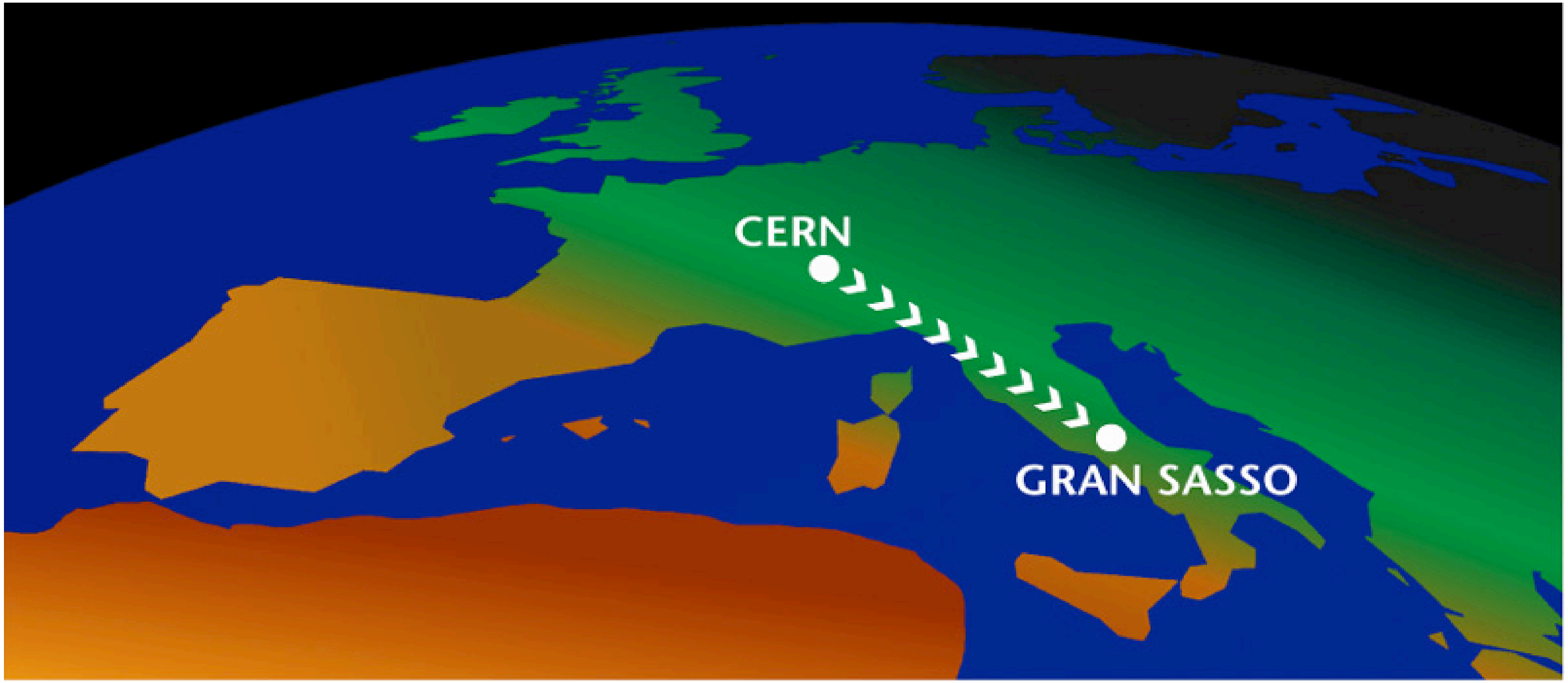
  ⇒Improved discrimination by a study of the event kinematical properties

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



⇨ Still a tough job !

Goal of the CNGS project



"Long Base-Line" $\nu_\mu \to \nu_\tau$ oscillation experiments

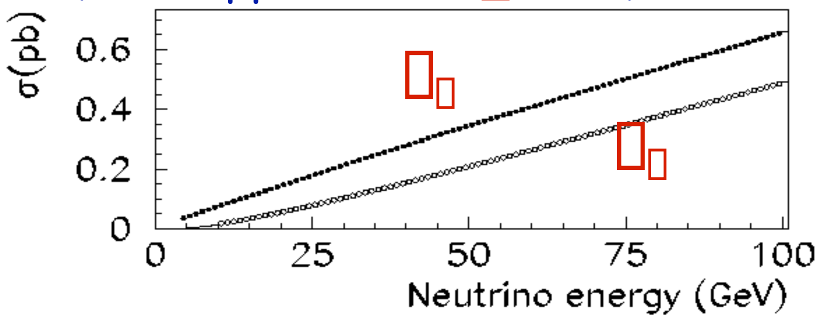
- build an intense high energy ν_μ beam at CERN-SPS
- optimized for ν_τ appearance search at Gran Sasso laboratory (730 km from CERN)

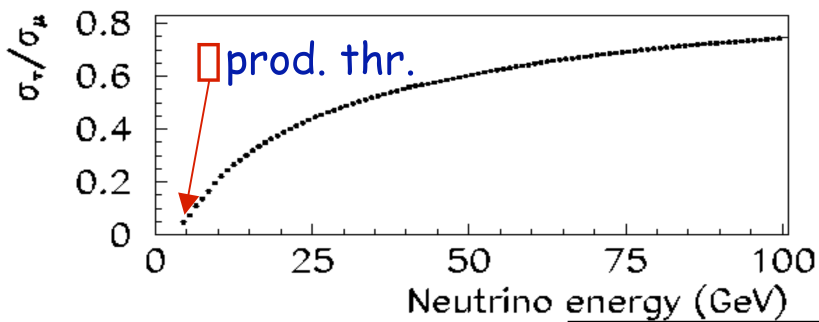
CNGS Optimization for ν_τ Appearance

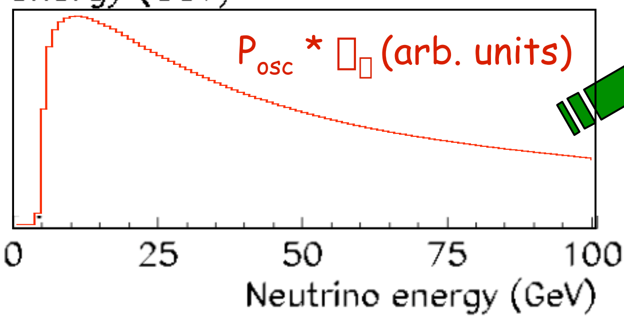
$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(1.27\,\Delta m^2 \frac{L}{E}\right)$$

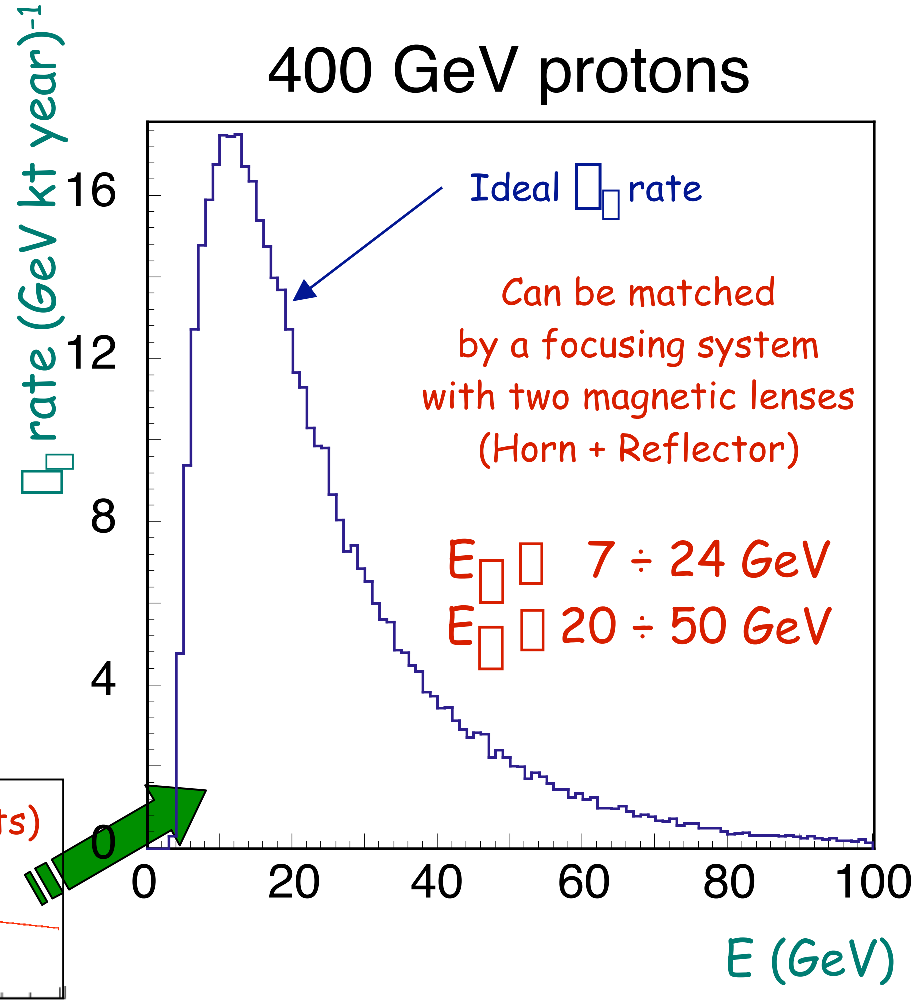
⇒ P_{osc} ↓ E_ν ↑

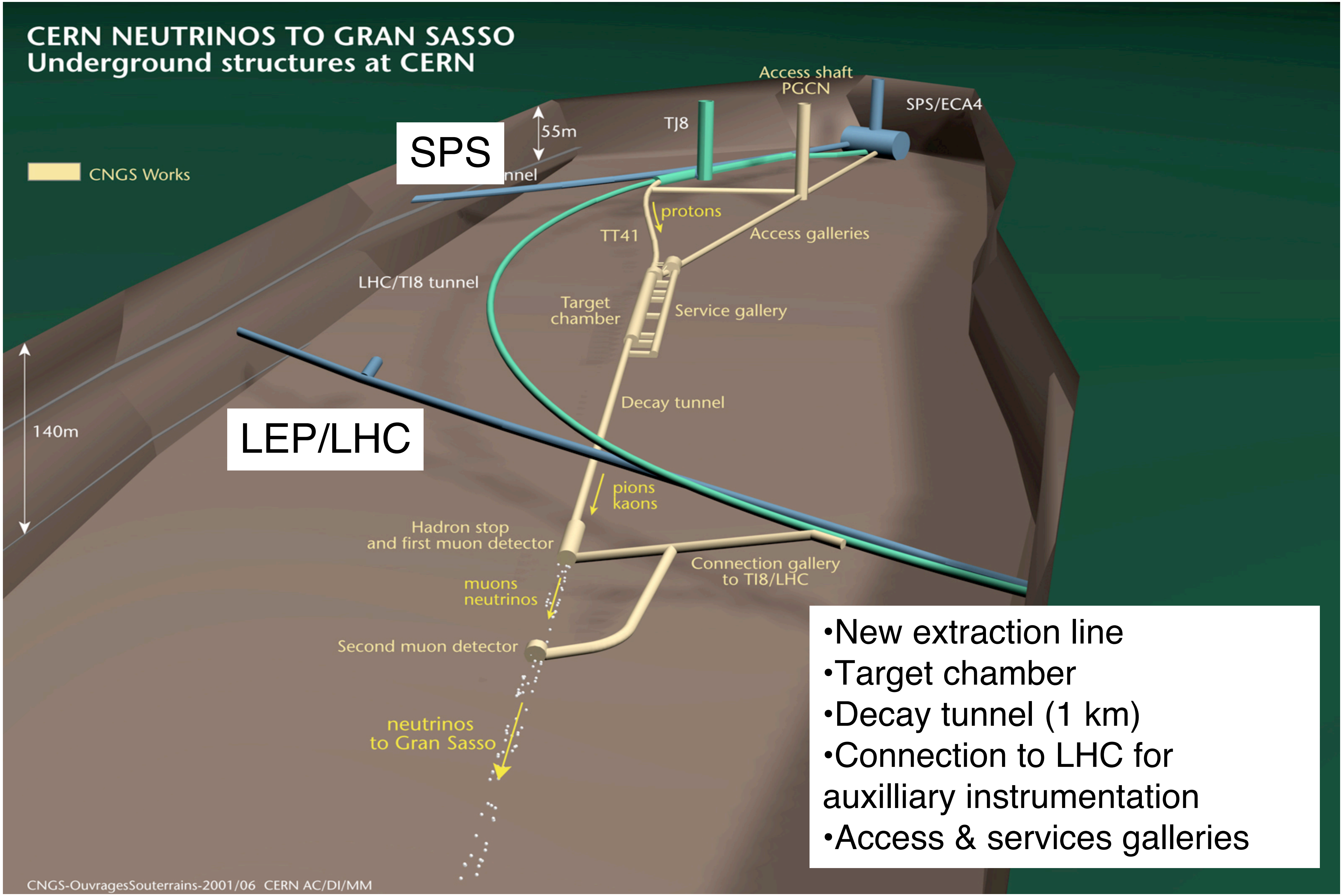
ν_τ/ν_μ CC increases with energy
(kin. suppr. due to τ mass)







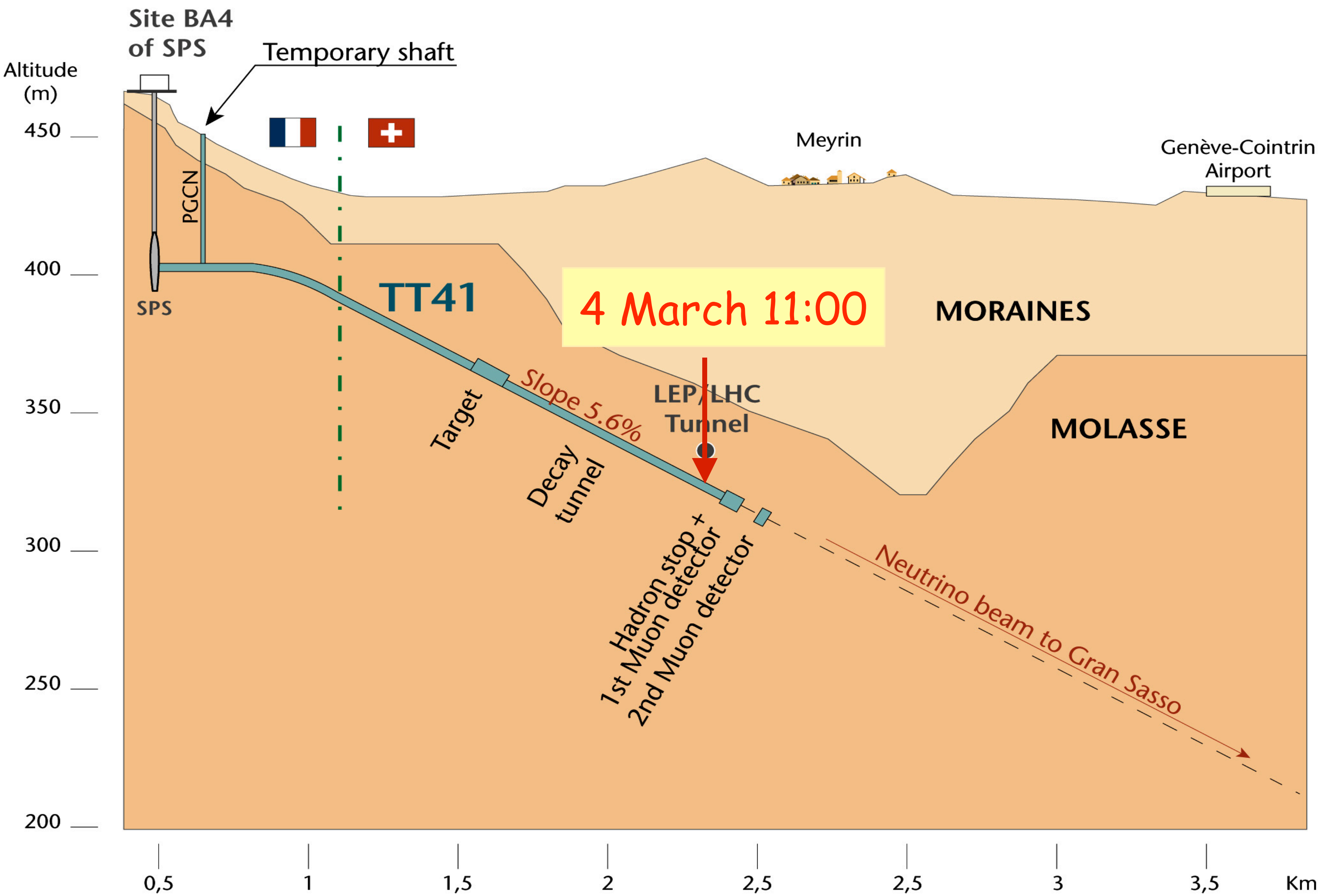




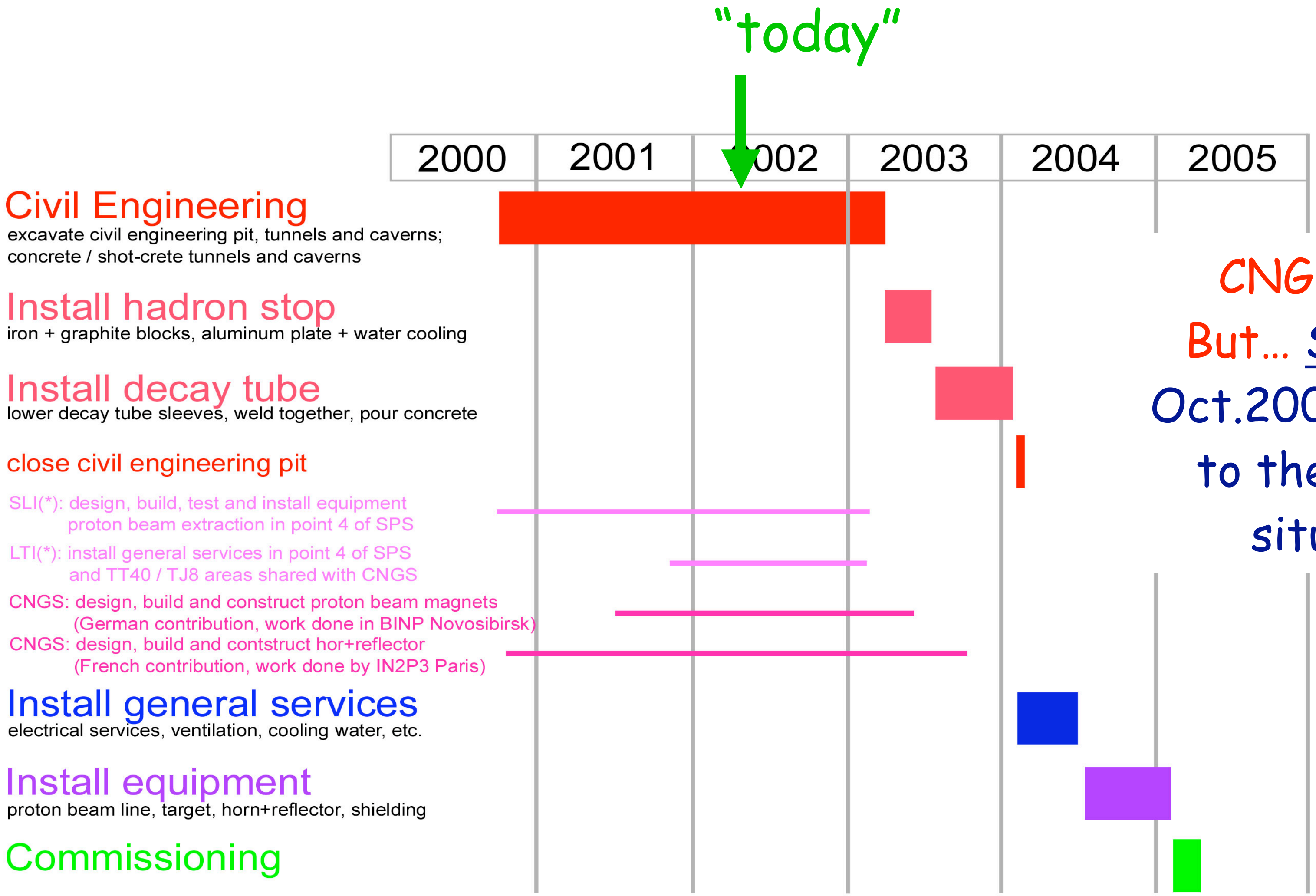
- New extraction line
- Target chamber
- Decay tunnel (1 km)
- Connection to LHC for auxilliary instrumentation
- Access & services galleries


IMER
2594

Aiming at LNGS...



Present CNGS Schedule



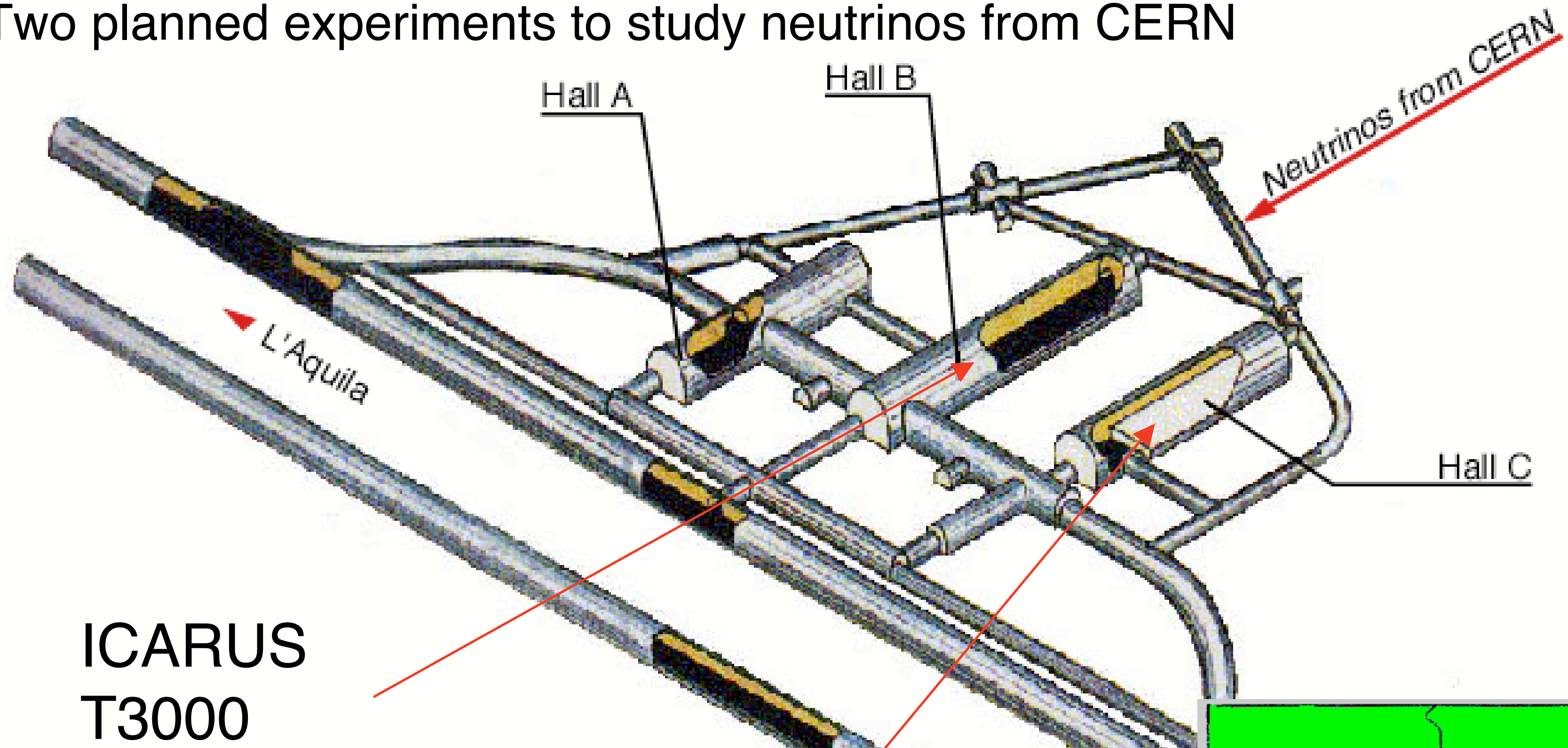
CNGS is on schedule!

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

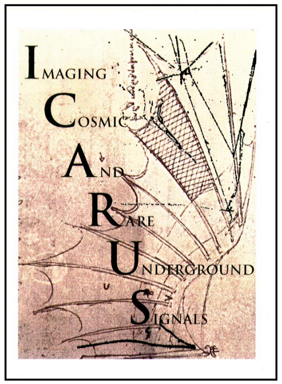
First beam to Gran Sasso: May 2005

LNGS Laboratory and the CNGS beam

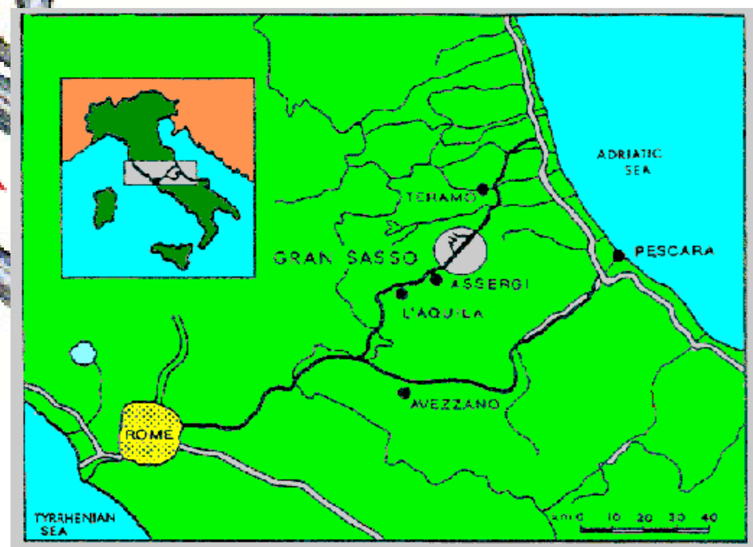
Two planned experiments to study neutrinos from CERN



ICARUS
T3000

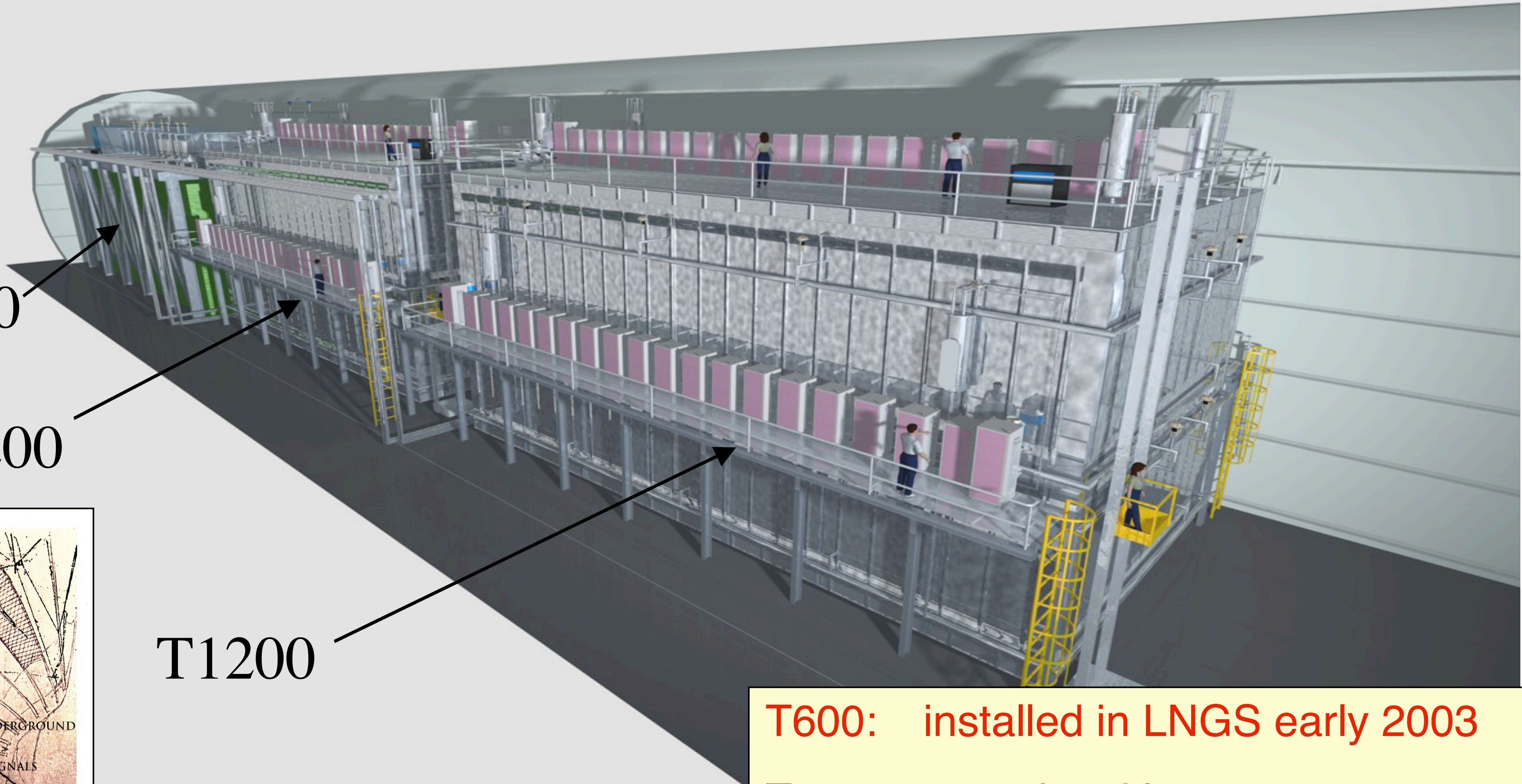


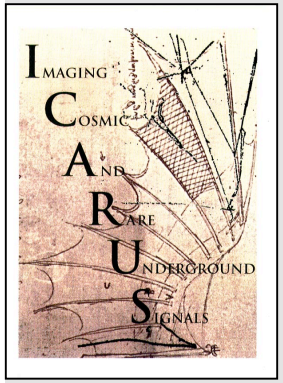
OPERA



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. »





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

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

Golden channel

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

Charged current (CC)

$\nu_\mu \rightarrow \nu_e$

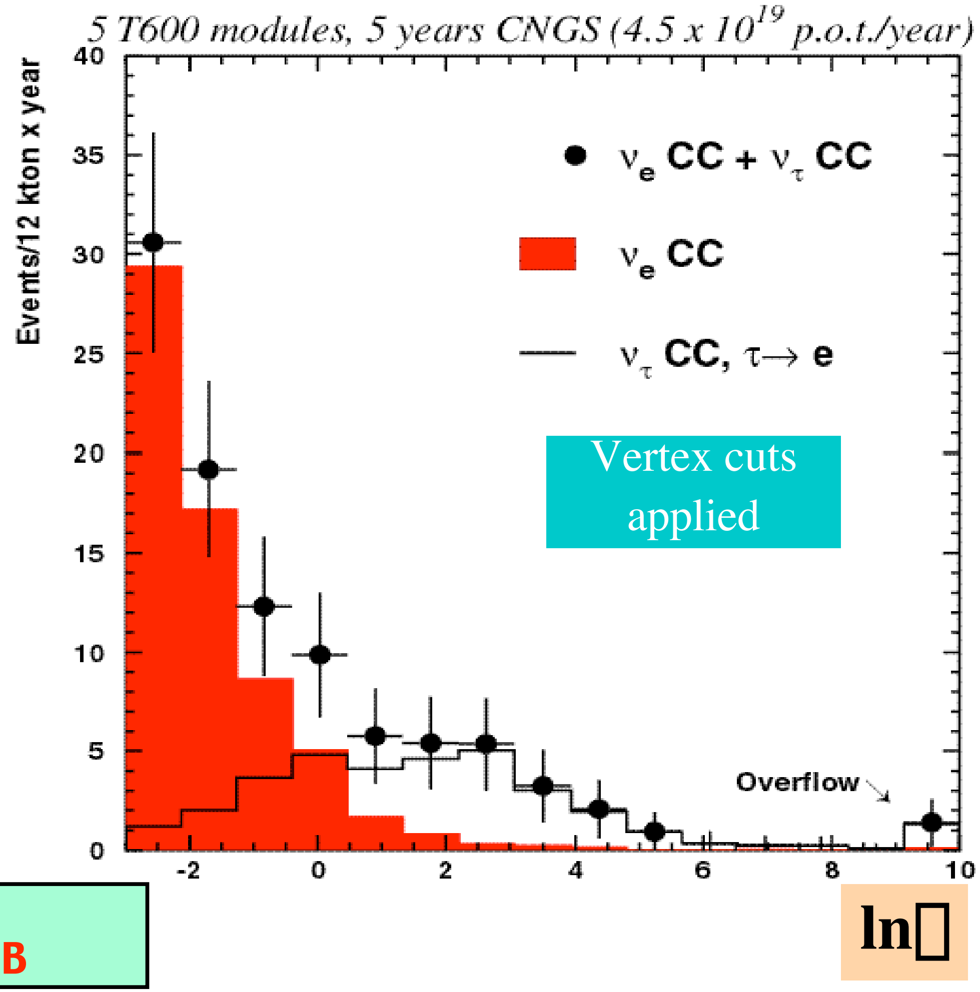
$$\nu_e + Ar \rightarrow e + jet$$

Charged current (CC)

□□ e search: 3D likelihood

- Analysis based on 3 dimensional likelihood
  - ➥ $E_{visible}$, P_T^{miss}, □$_l$≡$P_T^{lep}/(P_T^{lep}+P_T^{had}+P_T^{miss})$
  - ➥ **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□ ≡L([Evisible, P_T^{miss}, □$_l$]) = L_S / L_B



□□□ □□ appearance search summary

ICARUS T3000 detector

(2.35 kton active LAr)

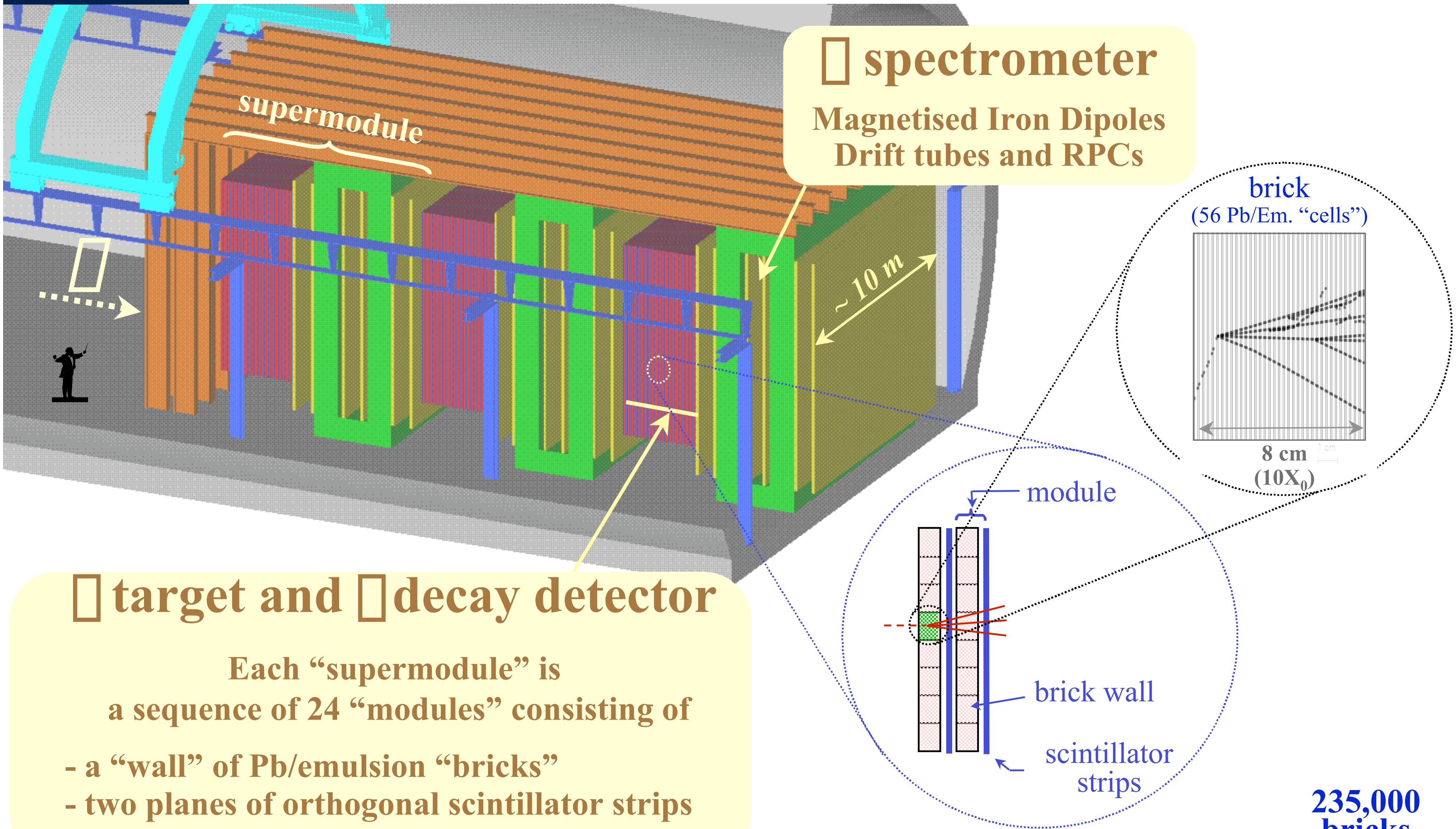
5 year CNGS "shared" running

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

τ decay mode	Signal $\Delta m^2 = 1.6 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 3.0 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 4.0 \times 10^{-3}$ 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 < □m² < 4.0 at 90% C.L.

The OPERA detector structure



□ spectrometer

Magnetised Iron Dipoles
Drift tubes and RPCs

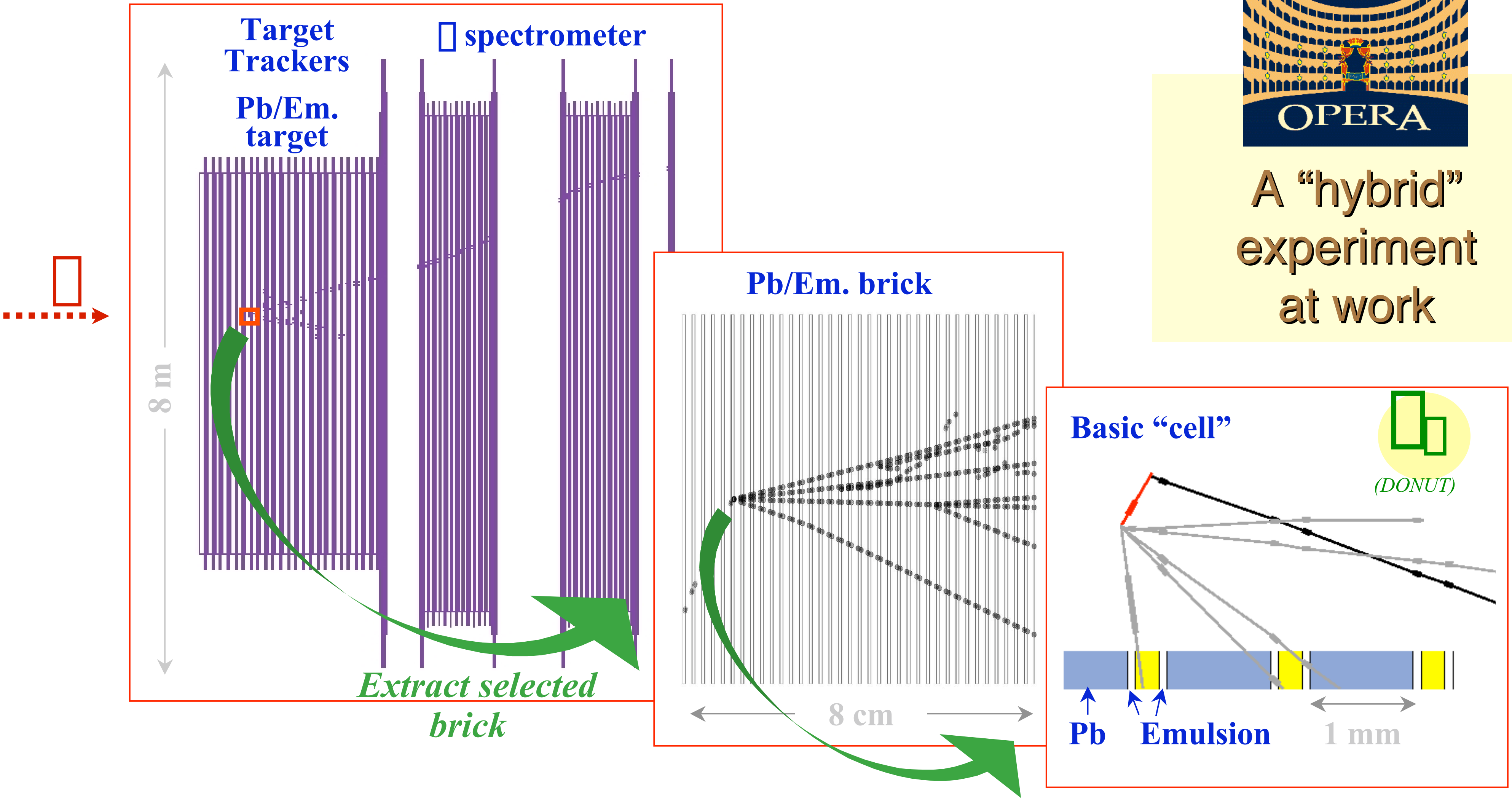
□ target and □ decay detector

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

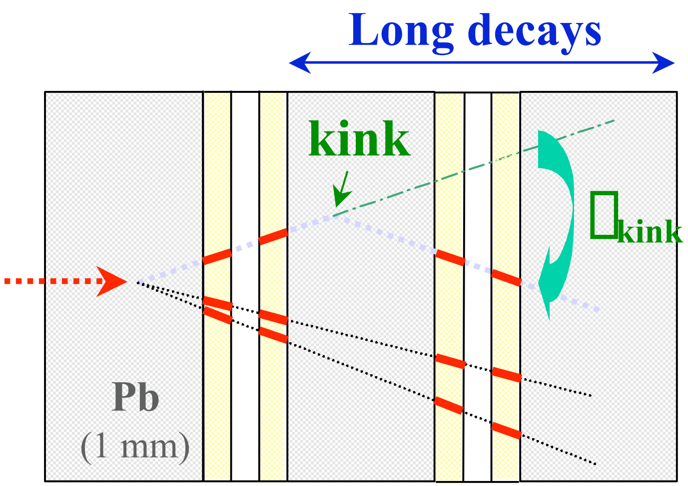
Emulsion analysis

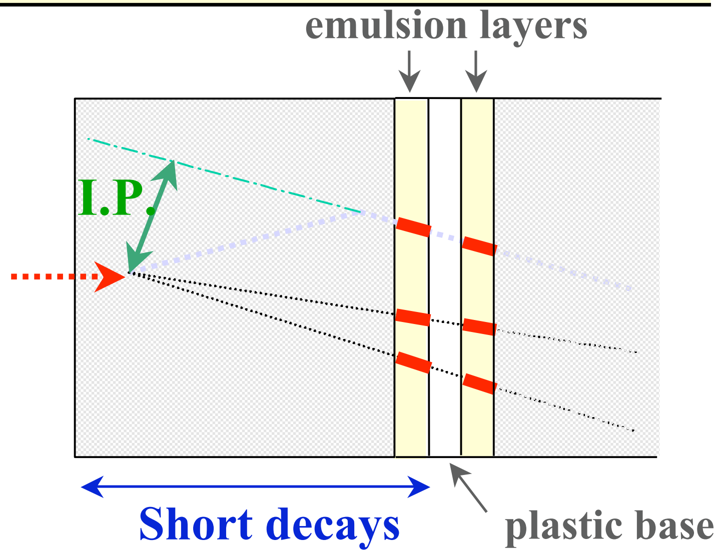
- □ vertex search
- □ decay search
- □ e/□ ID, kinematics

Expected number of events

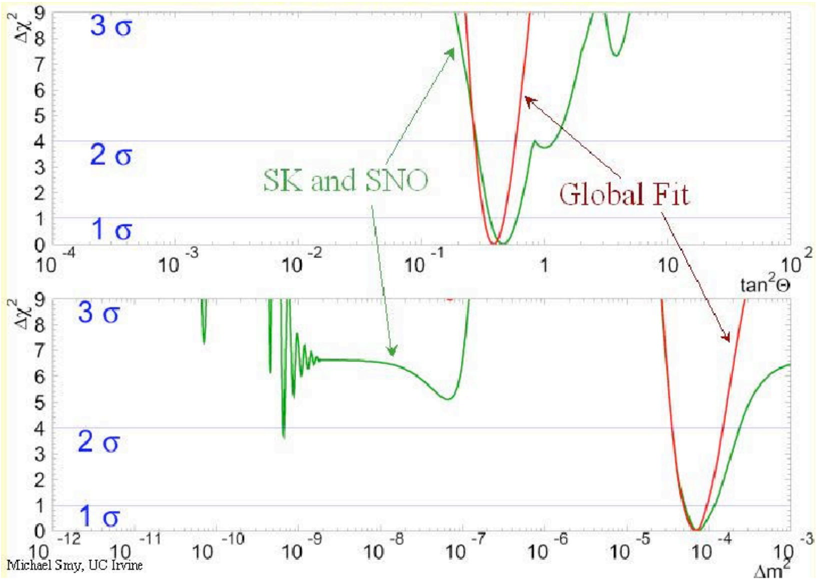
5 year run with 1.8 kton average target mass, nominal □ flux
Full mixing, Super-Kamiokande best fit and 90% CL limits
as presented at the 2001 Lepton Photon Conference

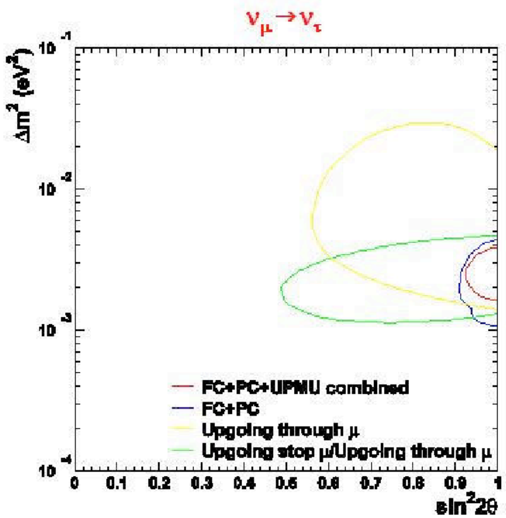
Decay mode	*Signal 1.2□10□3*	*Signal 2.4*10-3*	*Signal 5.4*10-3*	*Bkgnd.*
□□ e long	0.8	3.1	15.4	0.15
□□ □ long	0.7	2.9	14.5	0.29
□□ h long	0.9	3.4	16.8	0.24
□□ e short	0.2	0.9	4.5	0.03
□□ □ short	0.1	0.5	2.3	0.04
Total	2.7	10.8	53.5	0.75





Neutrino oscillation parameters





$\nu_\mu \leftrightarrow \nu_\tau$ oscillations

Best fit($\Delta m^2=2.5\times10^{-3}$, $\sin^2 2\theta=1.0$

$\chi^2_{min}=163.2/170$ d.o.f)

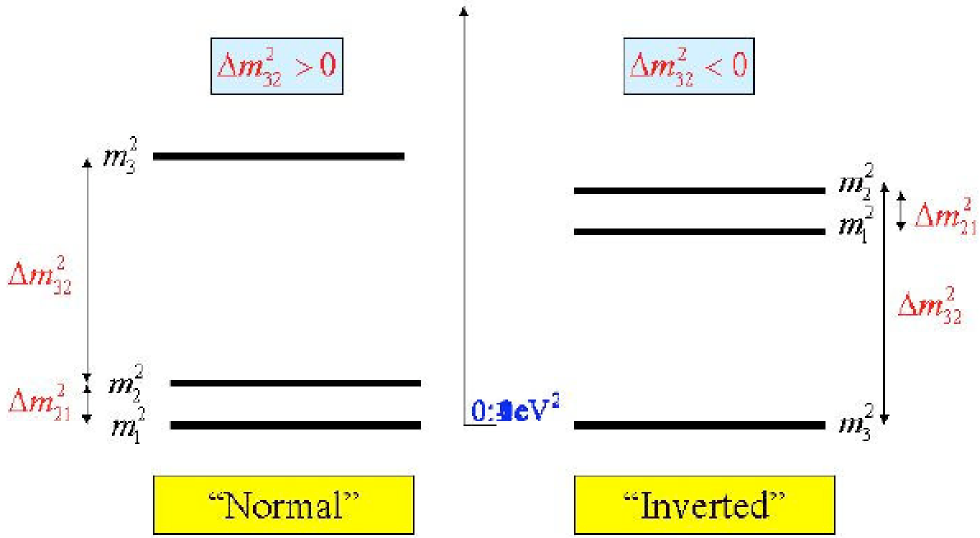
No oscillation

(χ^2 =456.5/172 d.o.f)

$\Delta m^2 = (1.6\sim3.9)\times10^{-3}\,\mathrm{eV}^2$

$\sin^2 2\theta > 0.92$ @ 90%CL

- Solar parameters (1σ interval)
  - $|\Delta m^2_{21}| = (4\div12)\times10^{-5}$ eV^2
  - $\tan^2\theta_{12} = 0.32\div0.51$ ⇒ $30° < \theta_{12} < 36°$
- Atmospheric parameters (90% C.L.)
  - $|\Delta m^2_{32}| = (1.6\div3.9)\times10^{-3}$ eV^2
  - $\sin^2 2\theta_{23} > 0.92$ ⇒ $37° < \theta_{23} < 45°$



So what's next ?

- Solving the solar neutrino problem
  - Assume KAMLAND confirms LMA
- Solving the atmospheric neutrino anomaly
  - Assume LBL experiments MINOS, ICARUS, OPERA, …confirm oscillation into tau neutrino
- Solving the LSND excess
  - Assume MiniBOONE refutes LSND excess
- Simple 3 neutrino emerging scenario:
  - $|\Delta m^2_{21}| = (4 \div 12) \times 10^{-5}$ eV^2
  - $\tan^2\theta_{12} = 0.32 \div 0.51 \Rightarrow 30° < \theta_{12} < 36°$
  - $|\Delta m^2_{32}| = (1.6 \div 3.9) \times 10^{-3}$ eV^2
  - $\sin^2 2\theta_{23} > 0.92 \Rightarrow 37° < \theta_{23} < 45°$
- Is this all ? Absolutely not ! At least three things: **θ_{13}, δ and sign Δm^2_{32}**

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

atm solar

Solar + Atmospheric 3ν Oscillations

The emerging: $$|U_{\rm LEP}| = \begin{pmatrix} 0.73-0.89 & 0.44-0.66 & <0.24 \\ 0.23-0.66 & 0.24-0.75 & 0.51-0.87 \\ 0.06-0.57 & 0.40-0.82 & 0.48-0.85 \end{pmatrix}.$$

with structure $$|U_{\rm LEP}| \simeq \begin{pmatrix} \frac{1}{\sqrt{2}}(1+\mathcal{O}(\lambda)) & \frac{1}{\sqrt{2}}(1-\mathcal{O}(\lambda)) & \epsilon \\ -\frac{1}{2}(1-\mathcal{O}(\lambda)+\epsilon) & \frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \\ \frac{1}{2}(1-\mathcal{O}(\lambda)-\epsilon) & -\frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \end{pmatrix}$$ $\lambda \sim 0.2$ $\epsilon < 0.25$

very different from quark's $$|U_{\rm CKM}| \simeq \begin{pmatrix} 1 & \mathcal{O}(\lambda) & \mathcal{O}(\lambda^3) \\ \mathcal{O}(\lambda) & 1 & \mathcal{O}(\lambda^2) \\ \mathcal{O}(\lambda^3) & \mathcal{O}(\lambda^2) & 1 \end{pmatrix}$$ $\lambda \sim 0.2$

Still open questions:

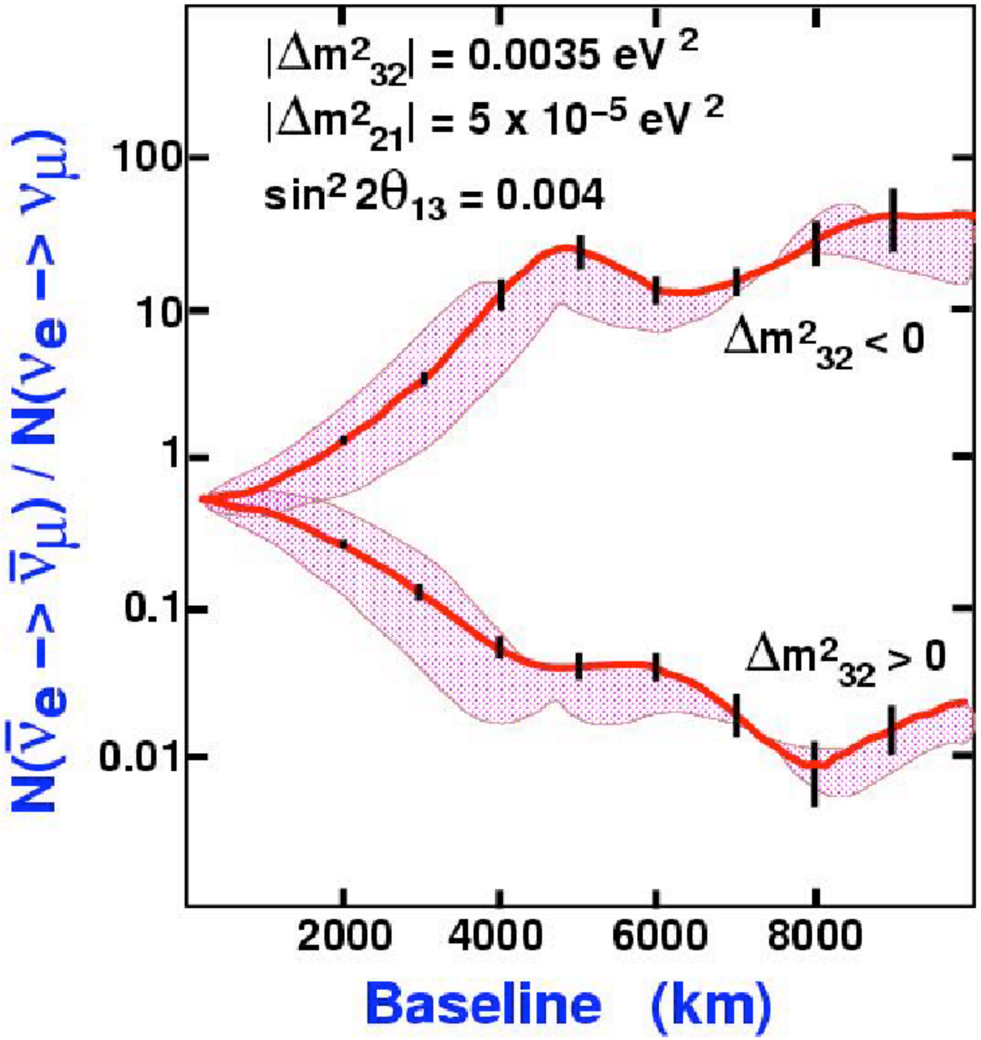
- Is $\theta_{13} \neq 0$?
- Is there CP violation in the leptons (is $\delta \neq 0, \pi$)?
- Are neutrino masses:
  - hierarchical: $m_i - m_j \sim m_i + m_j$?
  - degenerated: $m_i - m_j \ll m_i + m_j$?
- Dirac or Majorana? what about the Majorana Phases?

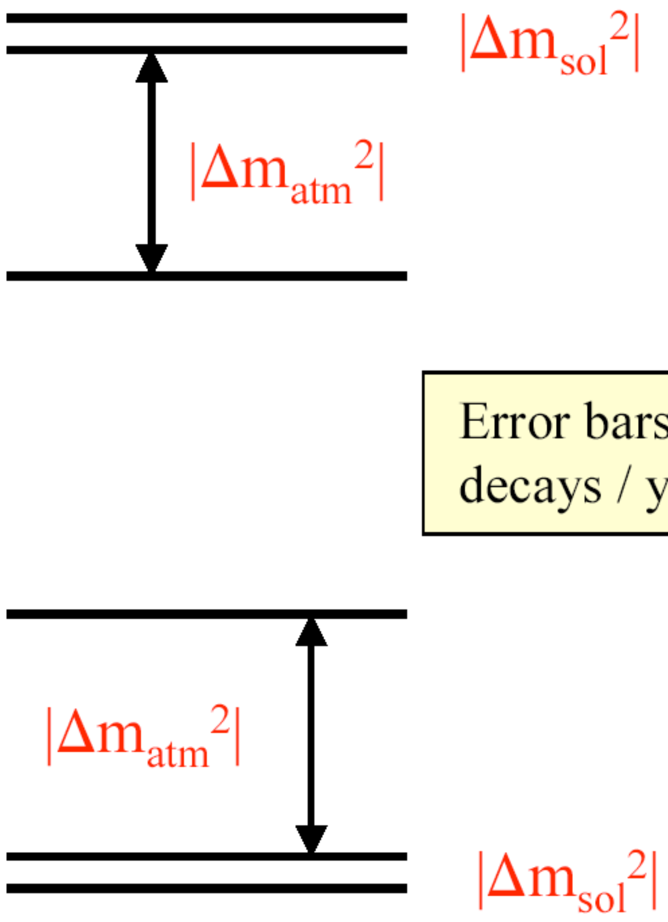
Future experimental program

- **Mass scheme**
  - ➥Normal or inverted?
  - ➥Test via matter effects at very long baselines
- **Value of θ_{13} angle**
  - ➥ICARUS will reach $\sin^2 2\theta_{13} < 0.04$ (limited by statistics)
  - ➥Need new very intense ν_μ beams with low backgrounds
    - – Superbeams: JHF, …
- **CP&T violation**
  - ➥Need solar LMA solution and θ_{13} not too small
  - ➥Most likely need a neutrino factory (neutrinos from decays of muons in storage rings)

Mass hierarchy determination

Barger, Geer, Raja, Whisnant, PRD 62, 073002
S. Geer, hep-ph/0008155





Error bars → 2×10^{20} decays / yr for 5 years

Looking at the θ_{13} term

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

for Δm^2_{21} *(L/4E$_\nu$)<<1, e.g. LBL experiment neglecting solar*

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

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

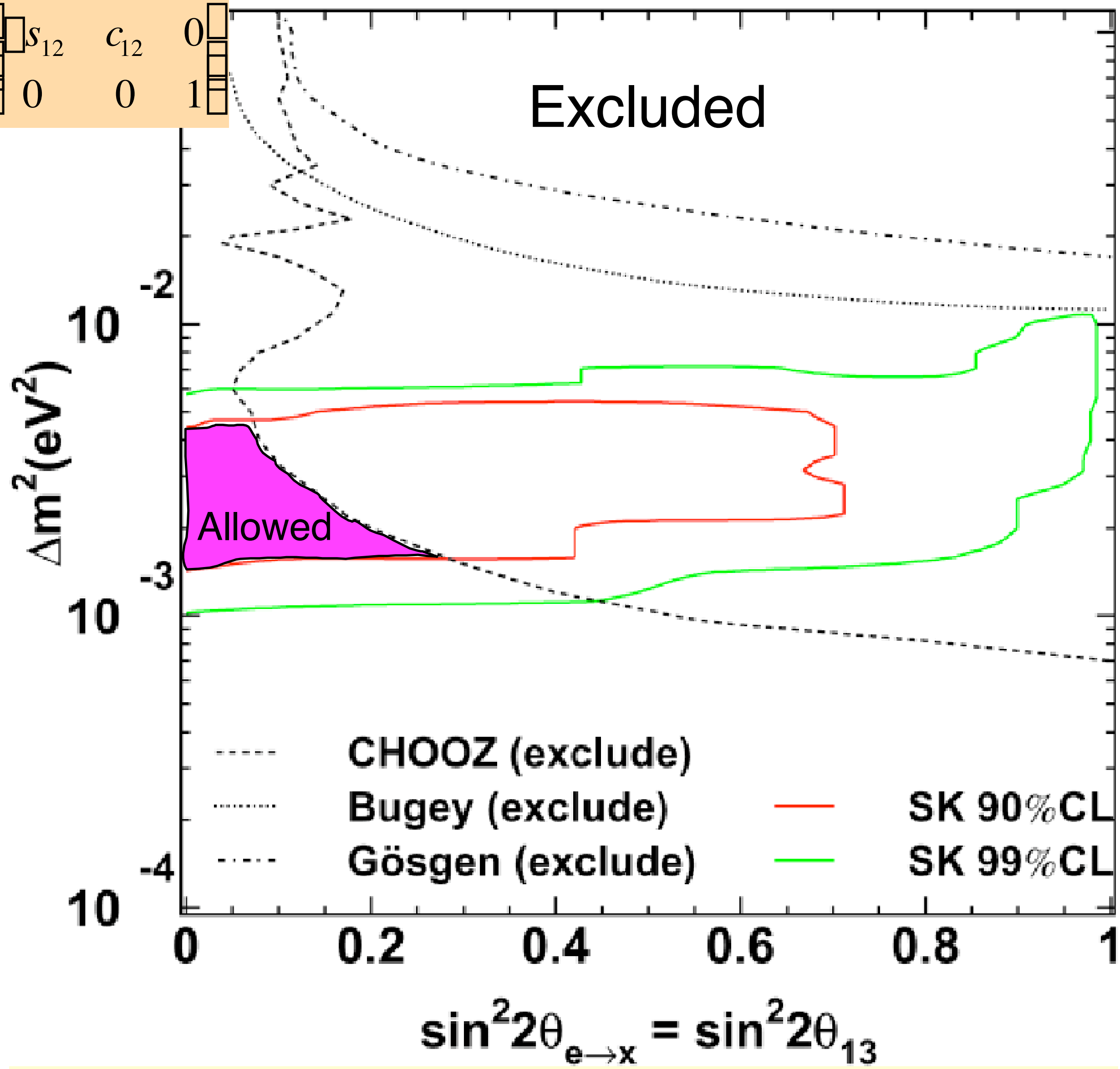
In contrast,

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

Limits on θ_{13}

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

- 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 !!!



5) Search for

subleading electron neutrino appearance

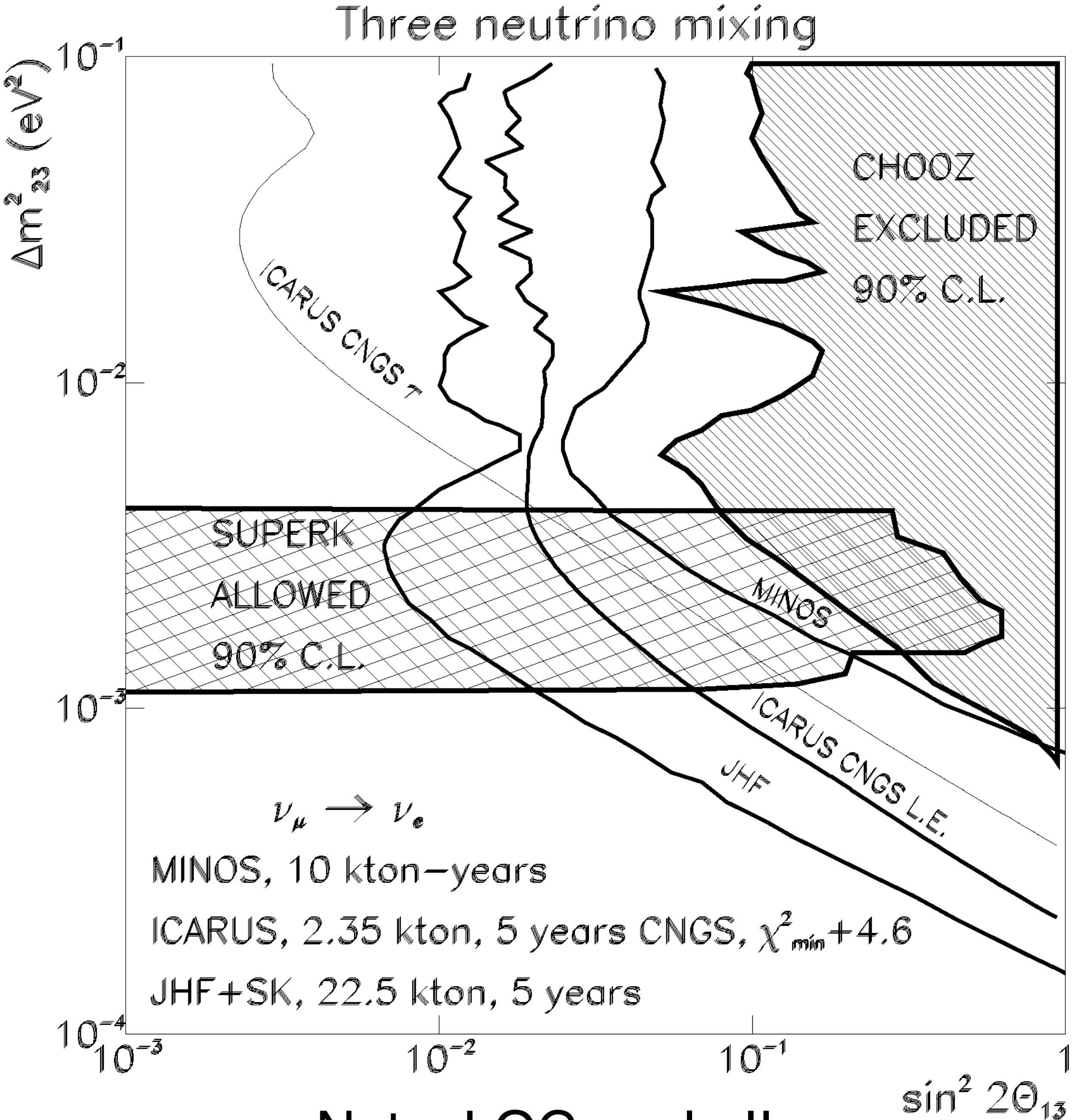
$$\nu_\mu \rightarrow \nu_e$$

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



Note: LOG-scale !!

ICARUS
5 years running
2.35 kton fid. mass

Two beam focusing optimizations

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

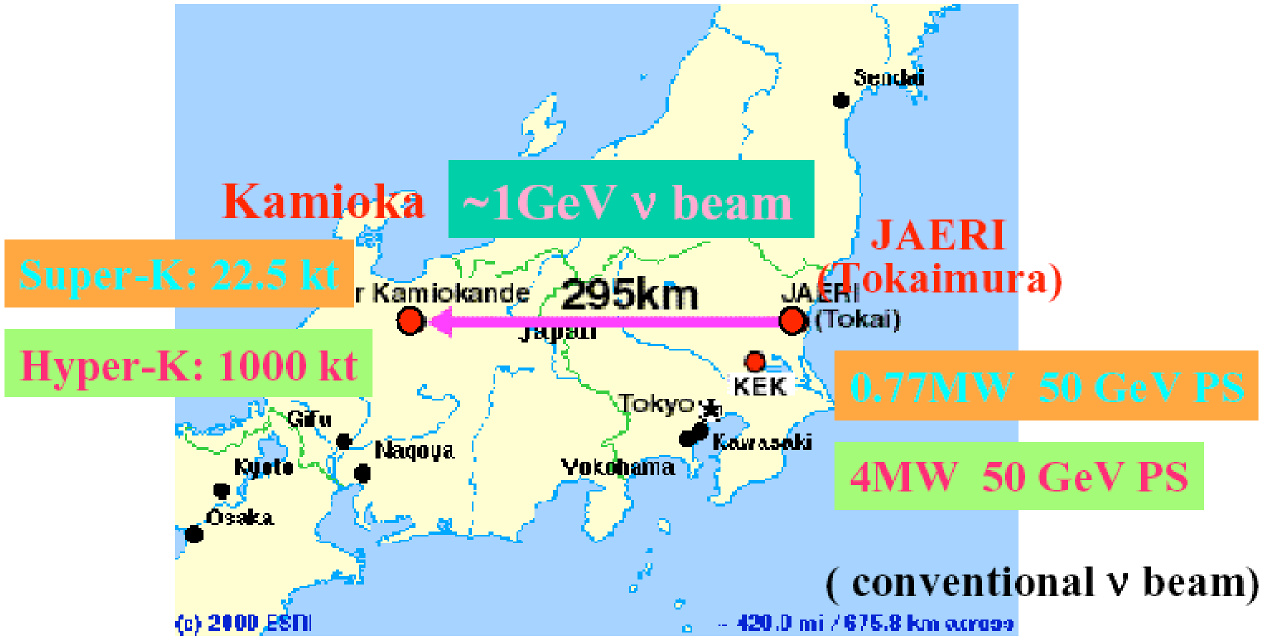
□optimized beam:

θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC		$\nu_\mu \rightarrow \nu_e$	
		$E_\nu < 4$ GeV	$E_\nu < 50$ GeV	$E_\nu < 4$ GeV	$E_\nu < 50$ GeV
9	0.095	1.5	150	4	42
8	0.076	1.5	150	3.1	34
7	0.059	1.5	150	2.4	26
5	0.030	1.5	150	1.2	14
3	0.011	1.5	150	0.4	5
2	0.005	1.5	150	0.2	2.2
1	0.001	1.5	150	0.1	0.5

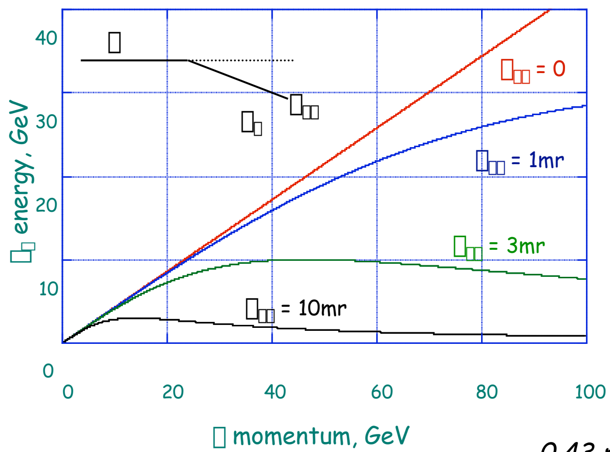
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \Delta^2_{32}$$

Superbeam neutrinos and Neutrino factories

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



Off-axis beams



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

Phase-I (0.77MW + Super-K)

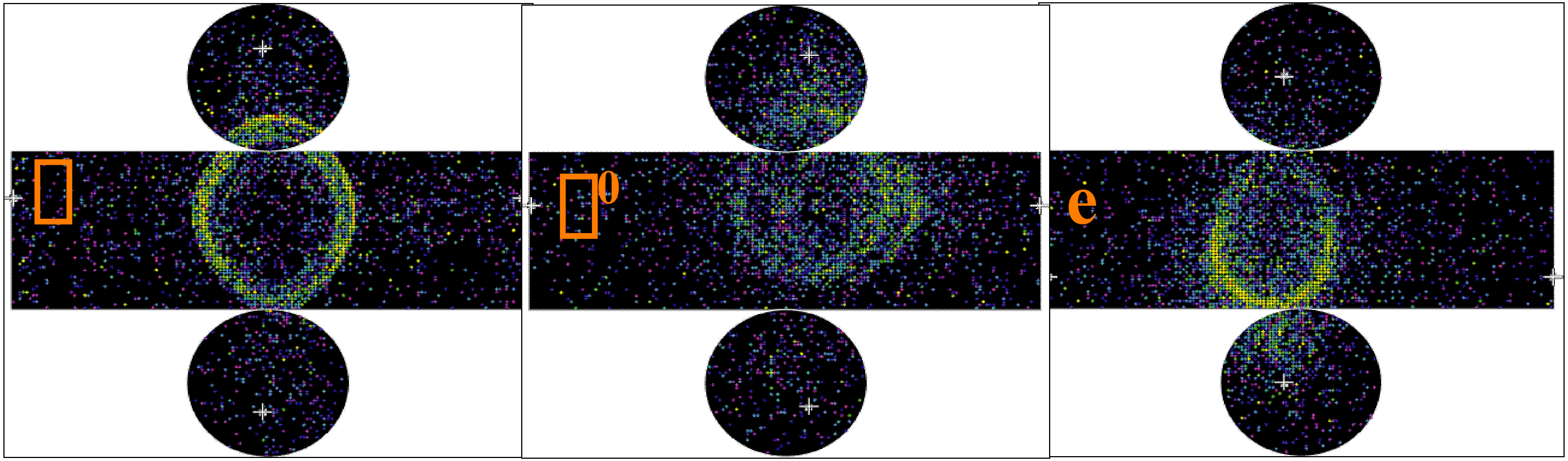
Phase-II (4MW+Hyper-K) ~ Phase-I × 200

("Super-beam") LBL experiments

	E_p (GeV)	Power (MW)	Beam	$\langle E_\nu \rangle$ (GeV)	L (km)	M_{det} (kt)	ν_μCC (/yr)	ν_e @peak
K2K	12	0.005	WB	1.3	250	22.5	~50	~1%
MINOS(LE)	120	0.41	WB	3.5	730	5.4	~2,500	1.2%
CNGS	400	0.3	WB	18	732	~2	~5,000	0.8%
JHF-SK	**50**	**0.75**	**OA**	**0.7**	**295**	**22.5**	**~3,000**	**0.2%**
JHF-HK	50	4	OA	0.7	295	1,000	~600,000	0.2%
OA-NuMI	120	0.3	OA	~2	730?	20kt?	~1,000?	0.5%
OA-NuMI2	120	1.2	OA	~2	730?	20kt?	~4,000?	0.5%
AGS→??	28	1.3	WB/OA	~1	2,500?	1,000?	~1,000?	
SPL-Frejus	2.2	4	WB	0.26	130	40(400)	650(0)	0.4%
OA-CNGS	400	0.3	OA	0.8	~1200	1,000?	~400	0.2%

The plans are in very different phases. Most are in optimization phase.
JHF-SK most advanced.

ν_e appearance in JHF-Kamioka (phase 1)



Backgrounds

1.8 events	9.3 events	11.1 events

Signal

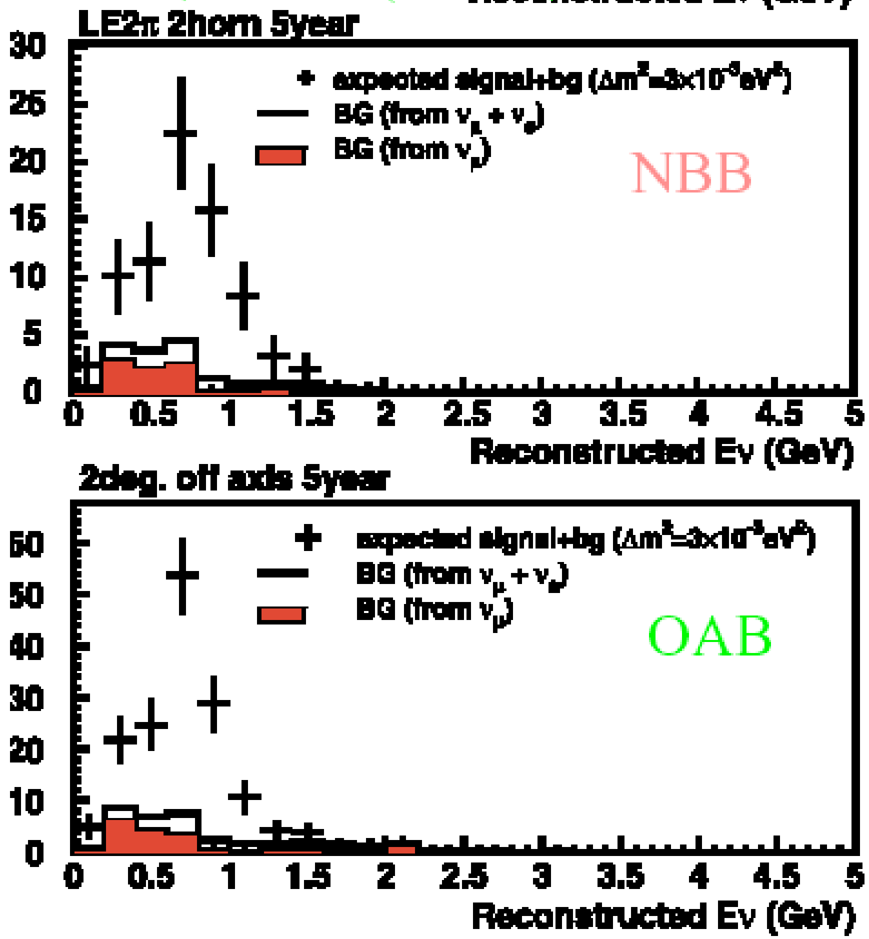
123.2 events @ $\sin^2 2\theta_{13}=0.1$, $\Delta m^2=3\times10^{-3} eV^2$

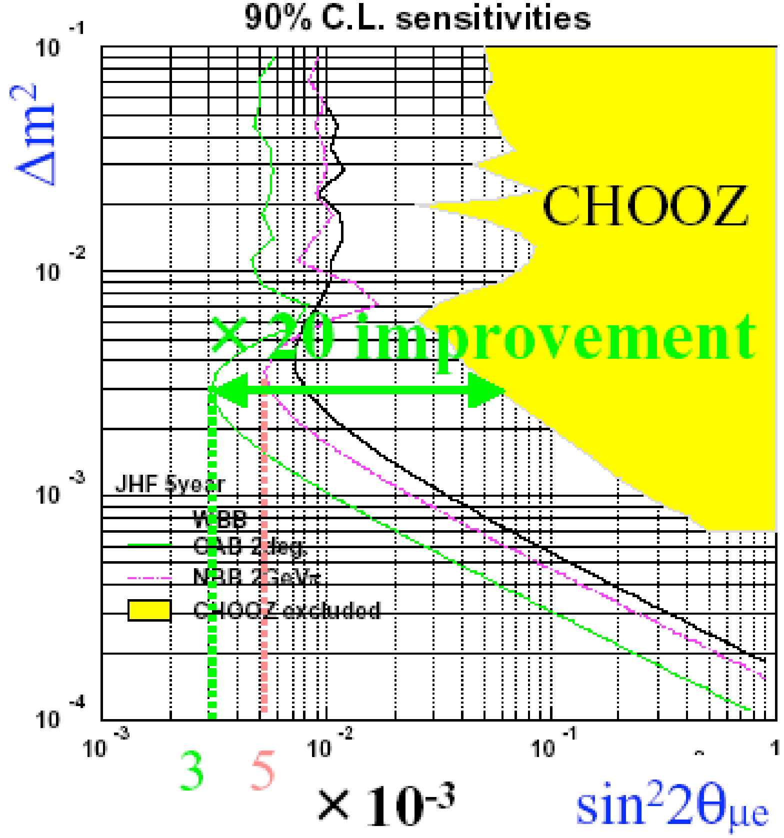
(5 years running)

ν_e appearance

Background rejection against NC π^0 is improved.

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





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

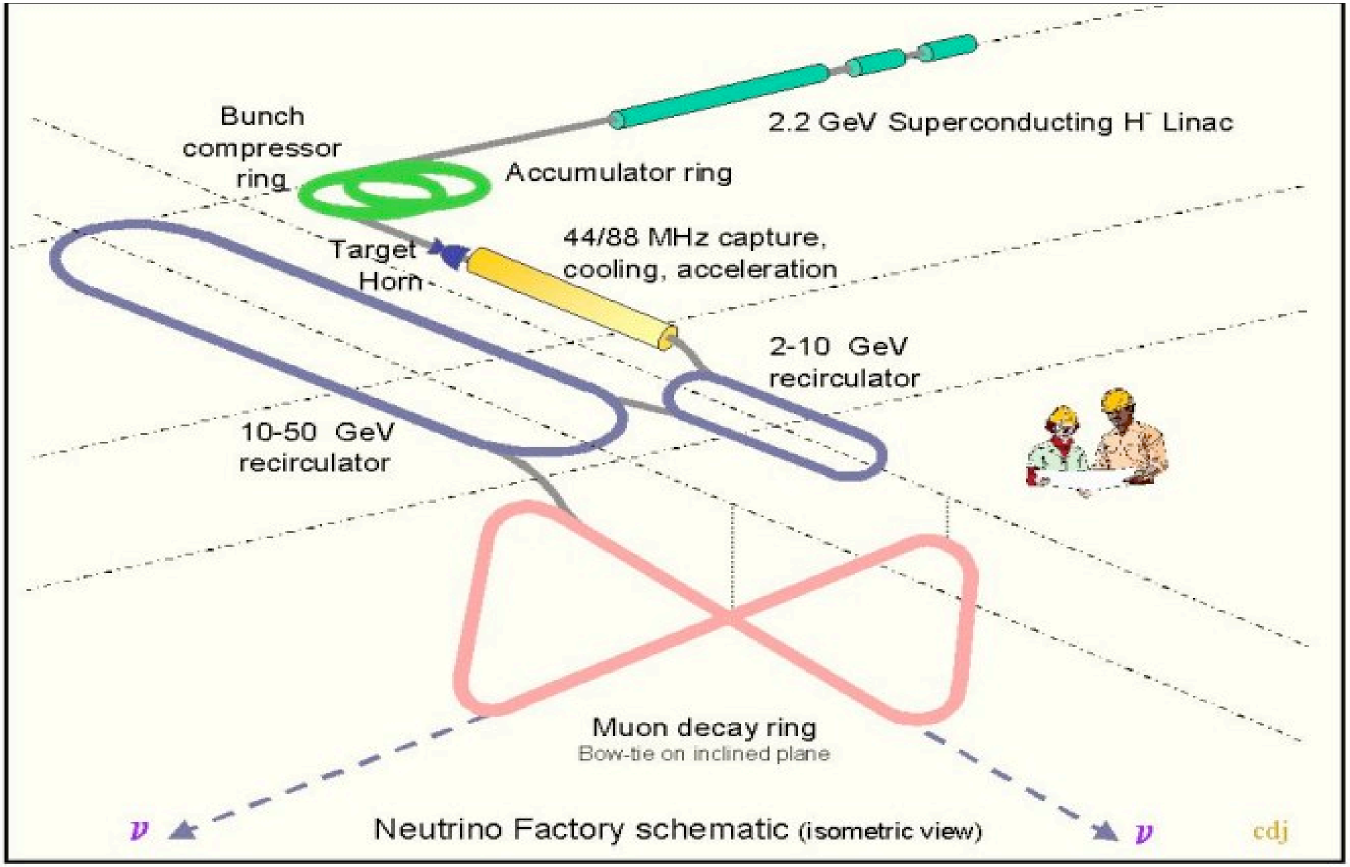
Ph2me, Ph2he from right
A.Para, hep-ph/0005012)

Nakaya, NUFACT01

Neutrino factory (>2015)

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \rightarrow 50\%\ \nu_e\ ,\ 50\%\ \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \rightarrow 50\%\ \bar{\nu}_e\ ,\ 50\%\ \nu_\mu$$



The oscillation physics program at the NF

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

$\nu_\mu \to \nu_e$	appearance
ν_μ	disappearance
$\nu_\mu \to \nu_\tau$	appearance
$\bar{\nu}_e$	disappearance
$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance
$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance

Plus their charge conjugates with μ^+ beam

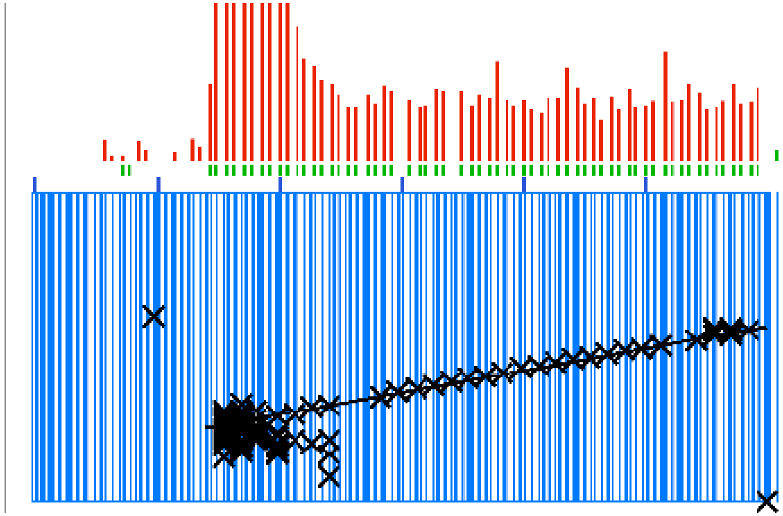
Ideal detector should be able to measure **12 different processes as a function of L and E_ν**

$$\nu_\ell N \to \ell^- + hadrons \qquad \nu_\ell N \to \nu_\ell + hadrons$$

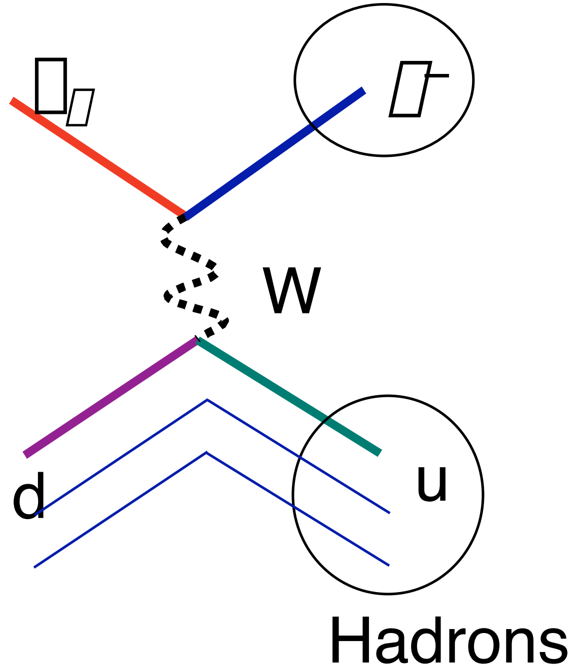
$$\bar{\nu}_\ell N \to \ell^+ + hadrons \qquad \bar{\nu}_\ell N \to \bar{\nu}_\ell + hadrons$$

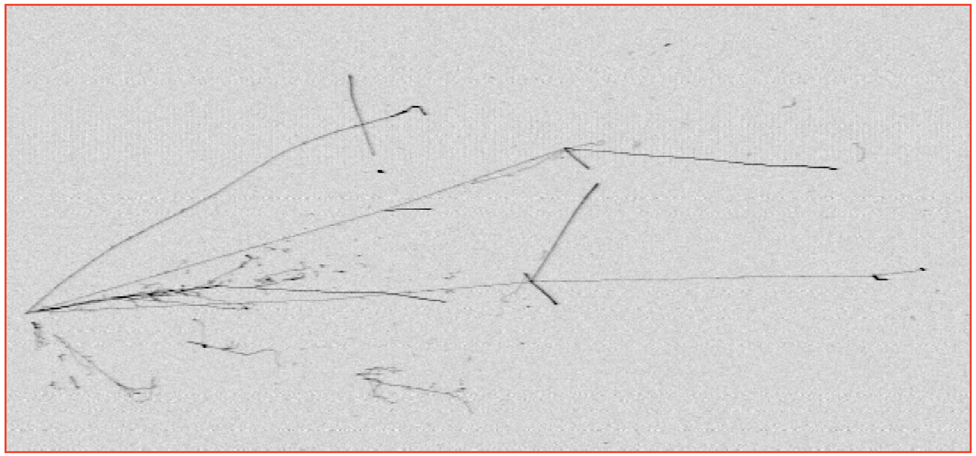
1. ***Particle ID***: *charged lepton tags* ***incoming neutrino flavor***
2. ***Charge ID***: *sign of lepton charge tags* ***helicity*** *of incoming neutrino*
3. ***Energy resolution***: *Reconstructed event energy is* $E_\nu = E_l + E_{had}$
4. ***Various baselines L*** *could help for detector systematics*

The same interaction three different ways…

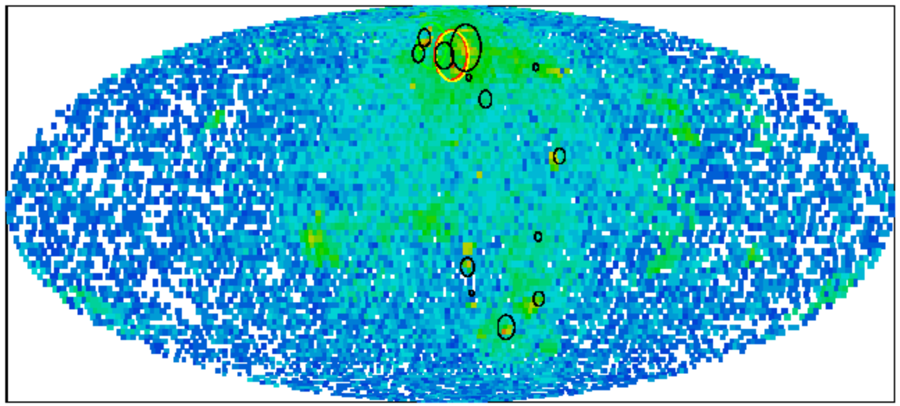


Calorimeter



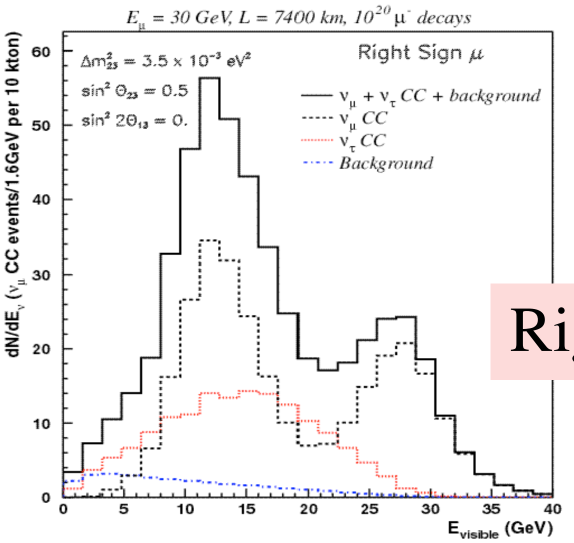


Liquid argon Imaging

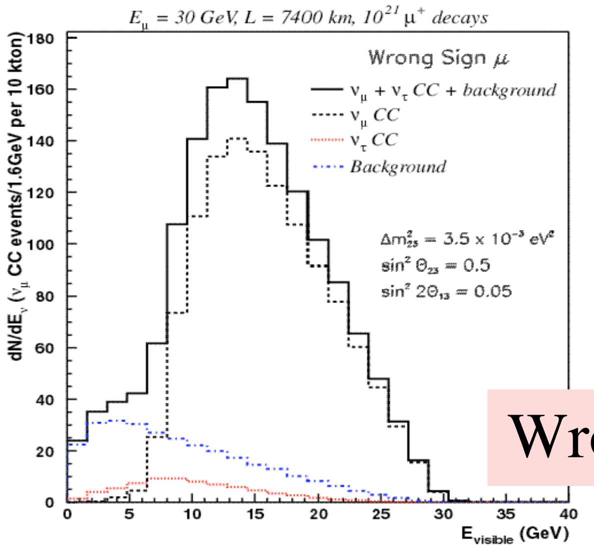


Water Cerenkov

Over-constraining the parameters (I)

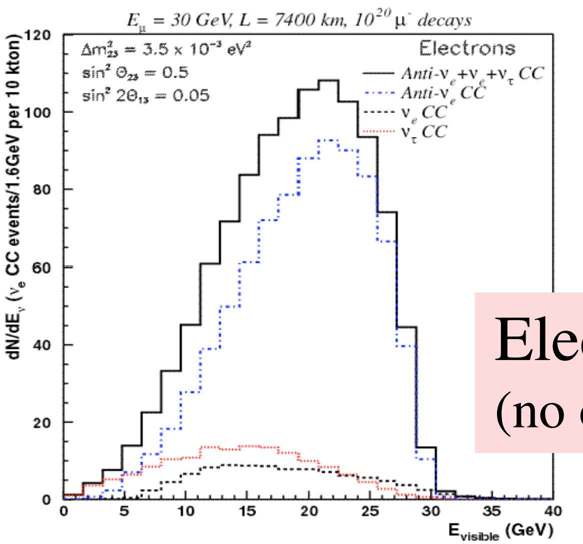


Right sign μ

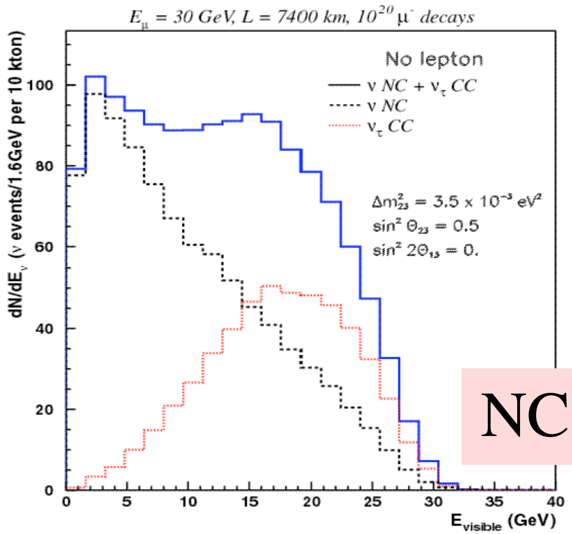


ICARUS-like 10kton

Wrong sign μ



Electrons
(no charge info)



NC-like

Combining all classes (over-constrained) sensitivity to all oscillations!

A. Bueno et.al. , Nucl.Phys.B589 (2000) 577

$\nu_e \to \nu_\mu$ oscillation probability

Following the conventional formalism for leptonic mixing, CP-/T-violating effects are observed in ***appearance transitions involving the first family***. Therefore, transitions between electron and muon flavors are clearly favored.

These probabilities are composed of three terms:

Independent of δ

$$P(\nu_e \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$

$$4c^2_{13}[\sin^2 \Delta_{23} s^2_{12} s^2_{13} + c^2_{12}(\sin^2\Delta_{13} s^2_{13} s^2_{23} + \sin^2\Delta_{12} s^2_{12}(1-(1+s^2_{13})s^2_{23}))]$$

$$-1/2 c^2_{13} \sin^2\theta_{12} s_{13} \sin^2\theta_{23} \cos\delta [\cos^2\Delta_{13} - \cos^2\Delta_{23} - 2\cos^2\theta_{12} \sin^2\Delta_{12}]$$

$$+1/2 c^2_{13} \sin\delta \sin 2\theta_{12} s_{13} \sin^2\theta_{23} [\sin^2\Delta_{12} - \sin^2\Delta_{13} + \sin^2\Delta_{23}]$$

CP-odd

Beat of frequencies

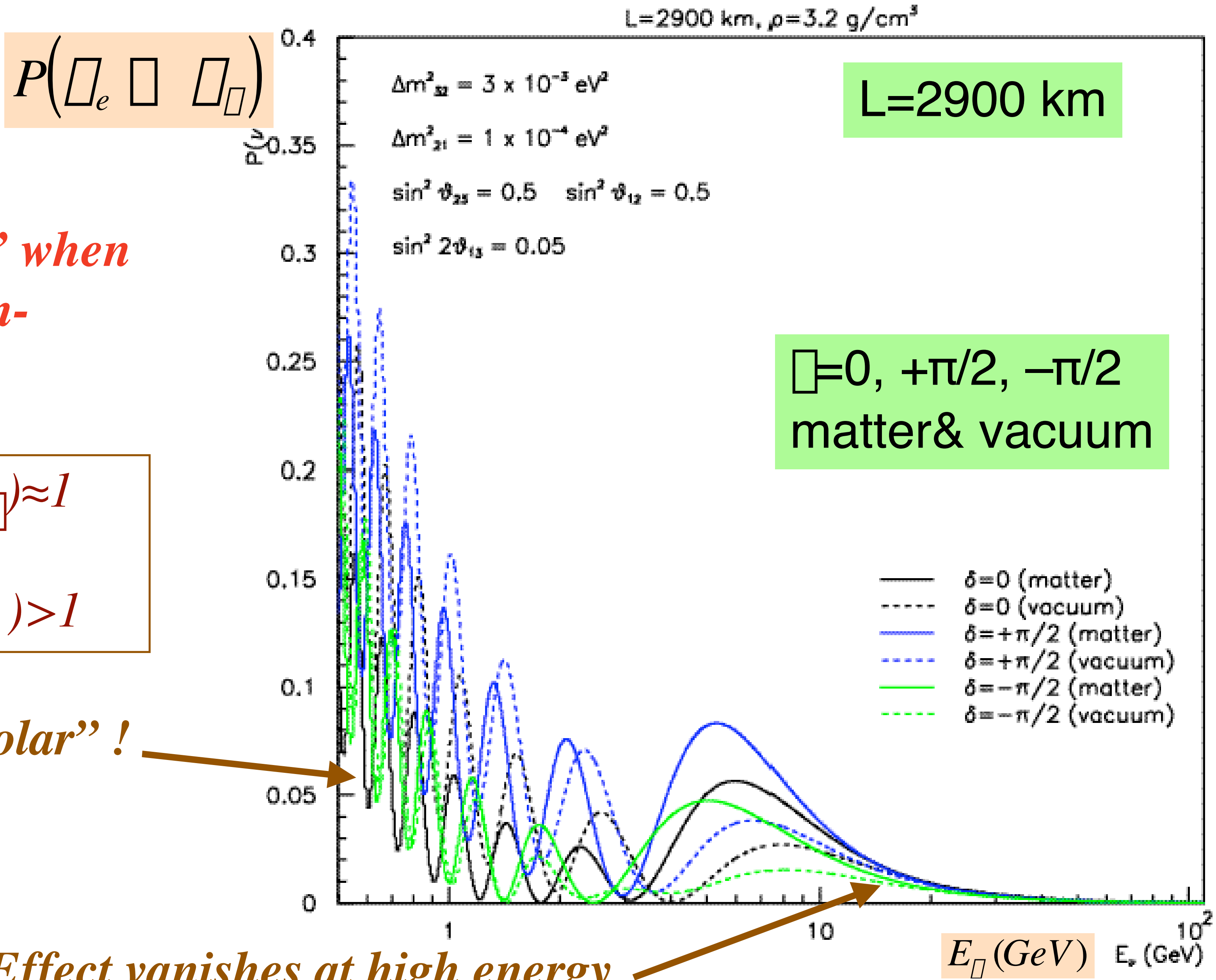
CP-even

Looking for effects of δ !

Effect "largest" when beat of three sin-functions:

$\Delta m^2_{21}(L/4E_\nu)\approx 1$
&
$\Delta m^2_{32}(L/4E_\nu)>1$

⇒ L/E of "solar" !



Effect vanishes at high energy

How to experimentally observe the δ-phase?

- $\Delta\delta \equiv P(\nu_e \rightarrow \nu_\mu; \delta=\pi/2) - P(\nu_e \rightarrow \nu_\mu; \delta=0)$

Compares oscillation probabilities as a function of E_ν measured with wrong-sign muon event spectra, to MonteCarlo predictions of the spectrum in absence of CP violation

- $\Delta CP(\delta) \equiv P(\nu_e \rightarrow \nu_\mu; \delta) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu; \delta)$

Compares oscillation probabilities measured using the appearance of ν_μ and $\bar{\nu}_\mu$, running the storage ring with a beam of stored μ^+ and μ^-, respectively. Matter effects are dominant at large distances

- $\Delta T(\delta) \equiv P(\nu_e \rightarrow \nu_\mu; \delta) - P(\nu_\mu \rightarrow \nu_e; \delta)$

Compares the appearance of ν_μ and ν_e in a beam of stored μ^+ and μ^-. As opposite to the previous case, matter effects are the same, thus cancel out in the difference

- $\Delta \bar{T}(\delta) \equiv P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu; \delta) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e; \delta)$

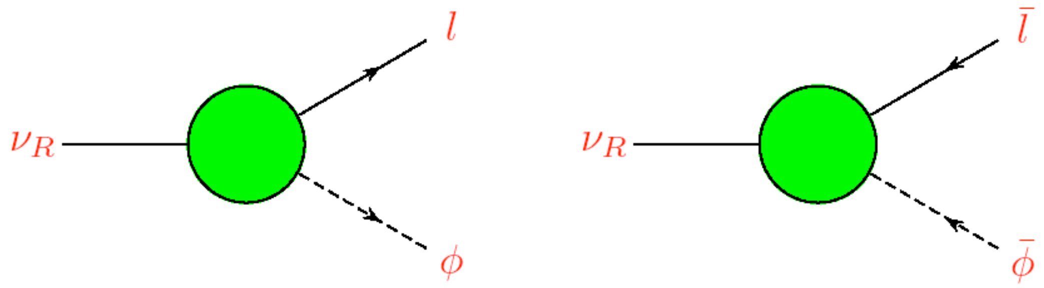
Same as previous case, but with antineutrinos. This effect is usually matter-suppressed with respect to the neutrino case.

Leptogenesis

– Majorana $m_\nu \Rightarrow \not{L} \Rightarrow$ Baryon asymmetry can be generated

– How? In the Early Universe via decay of heavy ν_R

Fukugita and Yanagida



If $\not{C}$P : $\Gamma(\nu_R \to \phi\, l_L) \neq \Gamma(\nu_R \to \overline{\phi}\,\overline{l_L})$

And decay is out of equilibrium:

($\Gamma_{\nu_R} \ll$ Universe expansion rate)

} Δ L is generated

At the electroweak transition sphaleron processes

$\Rightarrow \Delta$ L is transformed in $\Delta B \simeq -\frac{\Delta \mathrm{L}}{2}$

– Details are model dependent (Buchmüler, Plümacher... / Talk by Zing) but

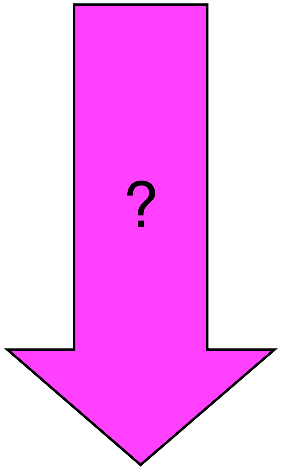
$M_R \sim 10^{10}$ GeV $\Rightarrow$ OK to explain observed η_B/η_γ

So finally, Why neutrino physics?

If we take

1. **neutrino masses** for an indication that new physics at a large energy scale exists and
2. **neutrino oscillations** for a hint that CP-violation is occurring in the lepton sector (hope that □≠0)

then this could have implications for ***the observed matter-antimatter asymmetry in the Universe*** !



WE ARE HERE !