Perspectives of neutrino oscillation physics with long baseline ν beams

- **The European Program**
  OPERA
  ICARUS

- **The US Program**
  MINOS

- **The Japanese Program**
  JHF-Kamioka

Lucia Votano L.N.F.

Neutrino Mass &Oscillation

- **$m_n \neq 0$?**
  - **Major consequences both for physics and astrophysics**
  - **New physics beyond S.M.**

- **Three hints of ν nonzero mass:**
  - **Atmospheric neutrinos** (ΔM^2 10^{-3} to 10^{-2})
  - **Solar** (ΔM^2 10^{-10} to 10^{-4}) → **SNO**
  - **LSND** (ΔM^2 10^{-1} to 10^{1})

- **Why m_ν« m $_{leptons}$, m_{quark} ?**
  - **See-saw mechanism**

- **Why mixing in lepton»quark ?**

- ***Neutrino oscillation process can only occur if the neutrino has non vanishing mass***

- ***Only neutrino oscillation can reveal the smallest neutrino masses***

Neutrino mass scenarios

3 ν

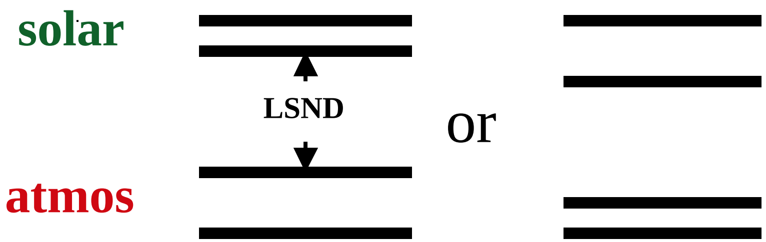
- **3 ν mass eigenstates and ν_e, ν_μ , ν_τ**

Analysis attempted in order to include solar, atmospheric and LSND in this scenario are controversial and somewhat inconsistent with some of the data.
More easy solutions if LSND is set aside

4 ν

- **4 ν mass eigenstates and ν_e, ν_μ , ν_τ, $\nu_{sterile}$**

From the Z boson width, the fourth ν ***must be sterile***



Generates "tension" among data subsets

Note that oscillations determine only mass splitting not actual masses

The 3 ν matrix

Atmospheric, K2K analyses — Terms probed by new experiments — Solar, reactor analyses

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}\\ 0 & 1 & 0\\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & e^{i\delta_{CP}}\cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

Leading oscillations in vacuum

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

$$\mathbf{P(\nu_e \rightarrow \nu_\tau) = \cos^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{23}}$$

$$\mathbf{P(\nu_\mu \rightarrow \nu_\tau) = \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\Delta_{23}}$$

$$\Delta_{23} \equiv 1.27\Delta m^2_{23}\frac{L(km)}{E_\nu}$$

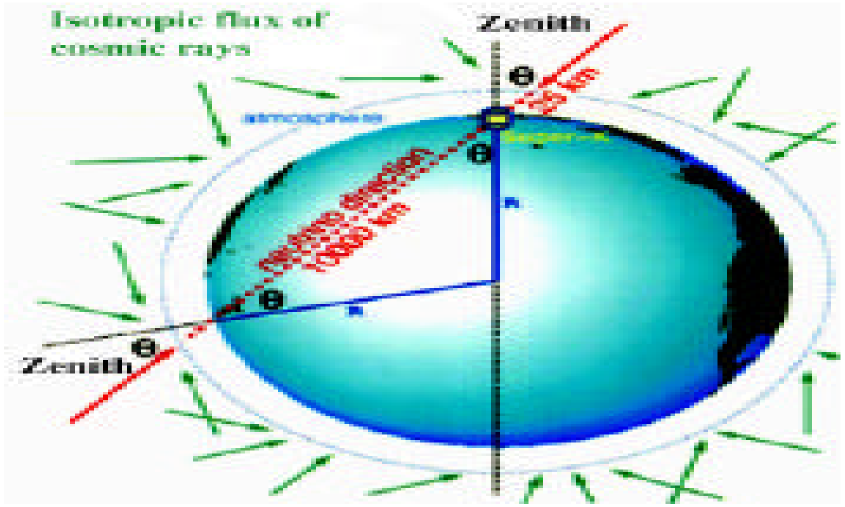
$\nu_e \rightarrow \nu_\mu$ is suppressed due to small Δm_{12}^2

Δm_{23}^2 and θ_{23} dominate

δ_{CP} is the CP violation phase

PRESENT STATUS

EXPERIMENTAL RESULTS:



- **Atmospheric Neutrinos**

  Super-Kamiokande
  Macro
  Soudan II

- **Long Baseline Neutrino Beam**

  From KEK to Super-Kamiokande
  250 Km away,
  below threshold for τ production

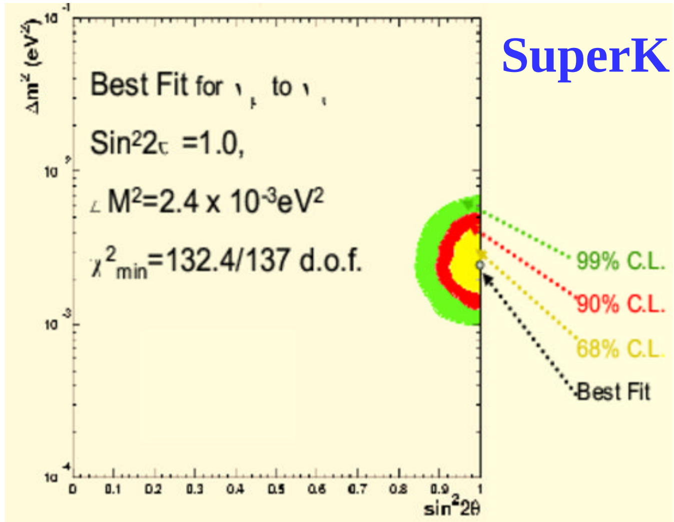
Latest results from Super-Kamiokande and K2K

(Lepton-Photon Conference 2001)

- ν_μ **disappearance in Super-K**

  $\nu_\mu - \nu_\tau$ {
  1.2 < Δm^2 < 5.4 x 10^{-3} eV^2 at 90% CL
  1.0 7.0 99%
  Best fit Δm^2 = 2.4 x 10^{-3} eV^2

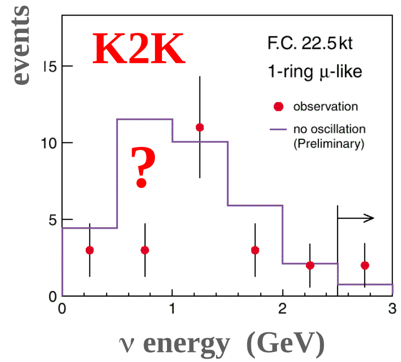
  Sterile ν disfavoured at ~ 99%



- ν_μ **disappearance in K2K**

  Expected (no osc.) 63.9 + 6.1 - 6.6
  Detected 44 (~ 2σ effect)

  Oscillation dip in the E_ν spectrum at $\Delta m^2 \sim 3 \times 10^{-3}$ eV^2 ?



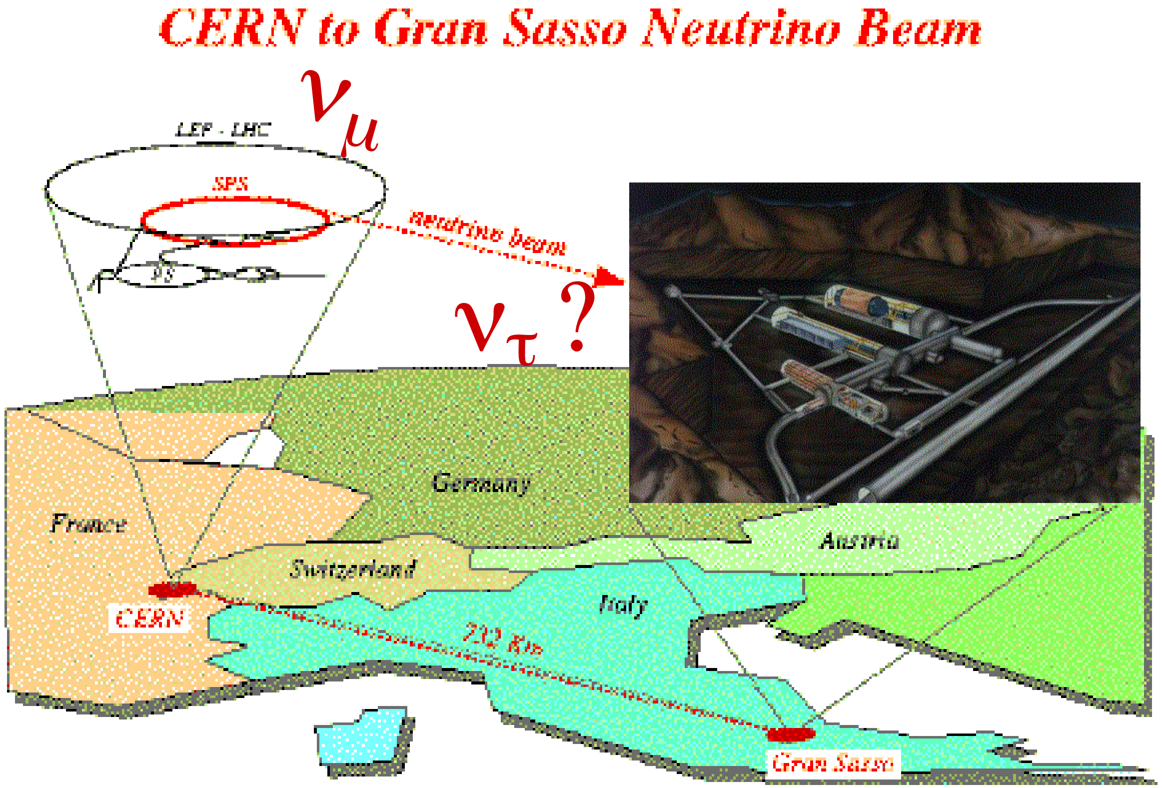
- ν_τ **appearance in Super-K**

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

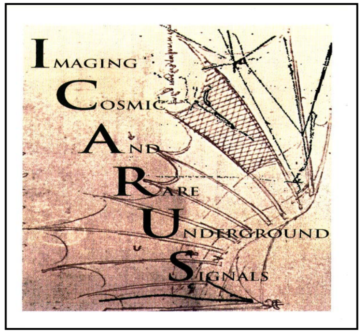
Why long baseline experiments?

- Check atmospheric neutrino results with a controllable beam
- See ν_τ appearance
- Measure the product $|\Delta m^2_{23}| x \theta_{23}$ with ~10% precision
- Measure $\nu_\mu \rightarrow \nu_e$ and θ_{13}
- Constrain or measure $\nu_\mu \rightarrow \nu_s$

The European Long Baseline Program



OPERA



From *disappearance* to *appearance* experiments

"Disappearance"

Statistical deficit of ν_μ

SuperKamiokande, K2K … MINOS at FNAL-Soudan

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

"Statistical appearance"

Apparent excess of ν_μ NC interactions , imputable to ν_τ

… MINOS at FNAL-Soudan

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

"Appearance"

Detection of ν_τ with low background

A new generation of τ detectors and technologies

CHORUS and NOMAD at CERN $\rightarrow$ CNGS detectors

CNGS beam optimised for ν_τ appearance

(400 GeV proton energy)

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

Motivations

- Study neutrino oscillations at $\Delta m^2 > 10^{-3}$ eV^2 in the region indicated by SuperKamiokande
- Establish unambiguously and definitively that the anomaly is due to $\nu_\mu \rightarrow \nu_\tau$ oscillations by observing ν_τ appearance in a beam containing negligible ν_τ at production
- Search for $\nu_\mu \rightarrow \nu_e$ oscillations with higher sensitivity than CHOOZ

➡ **Focussing on ν_τ appearance:**

high energy beam optimized for τ appearance,
clear signature, almost background free experiments,
no need for near detectors,
730 Km baseline from CERN to Gran Sasso

Detection of the $\nu_\mu \rightarrow \nu_\tau \rightarrow \tau^-$ signal and background rejection

ν_μ .... ν_τ $\rightarrow$ τ^- + X

oscillation

CC interaction

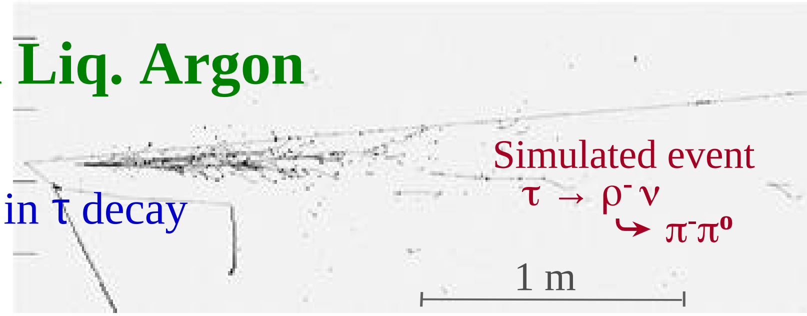
Decay	BR
$\mu^- \; \nu_\tau \; \bar{\nu}_\mu$	BR 18 %
$h^- \; \nu_\tau \; n\pi^o$	50 %
$e^- \; \nu_\tau \; \bar{\nu}_e$	18 %
$\pi^+ \pi^- \pi^- \; \nu_\tau \; n\pi^o$	14 %

ICARUS: Detailed general picture in Liq. Argon

Kinematics ***(à la NOMAD)***

Momentum unbalance from unseen ν_τ in τ decay

Energy measurement

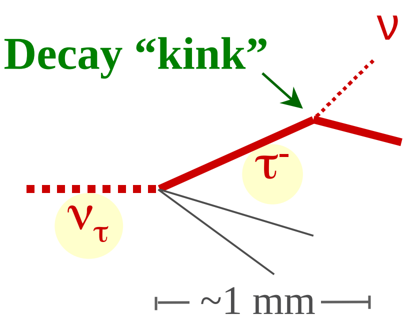


OPERA: Observation of the decay "signature" at microscopic scale ***(à la CHORUS)***

⬇

"nuclear" photographic emulsion

(~ **1μm** granularity)



The Experimental Program

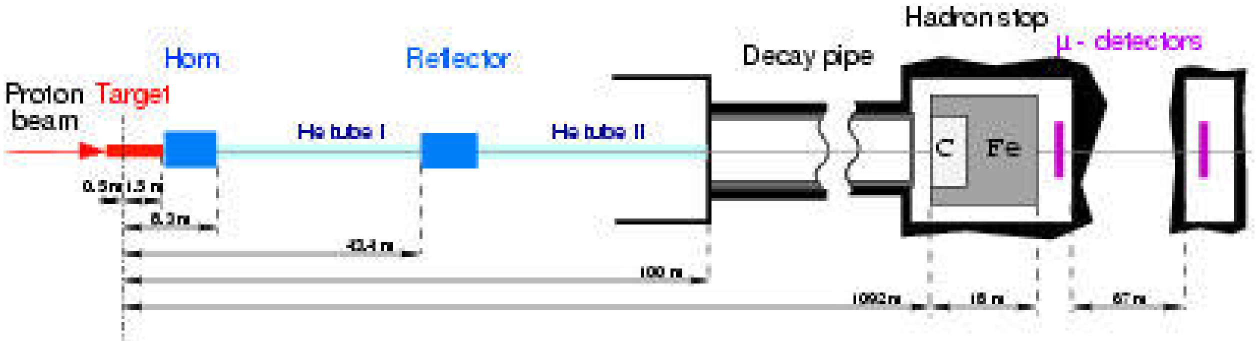
- **CNGS:** Approved at the end of 1999, civil engineering in progress, first neutrinos expected by 2005
- **OPERA:** Approved in February 2001 (CNGS1), observation of the τ^- decay kink in a high resolution detector consisting of emulsion films and lead plates for a mass of 2 Ktons, same technique as the one used by DONUT for the first direct observation of the ν_τ charged current interactions (2000)
- **ICARUS:** Not yet approved. Liquid Argon TPC, kinematic technique a` la NOMAD, total detector mass of about 5 Ktons, 600 Ton demonstration module being completed, first results

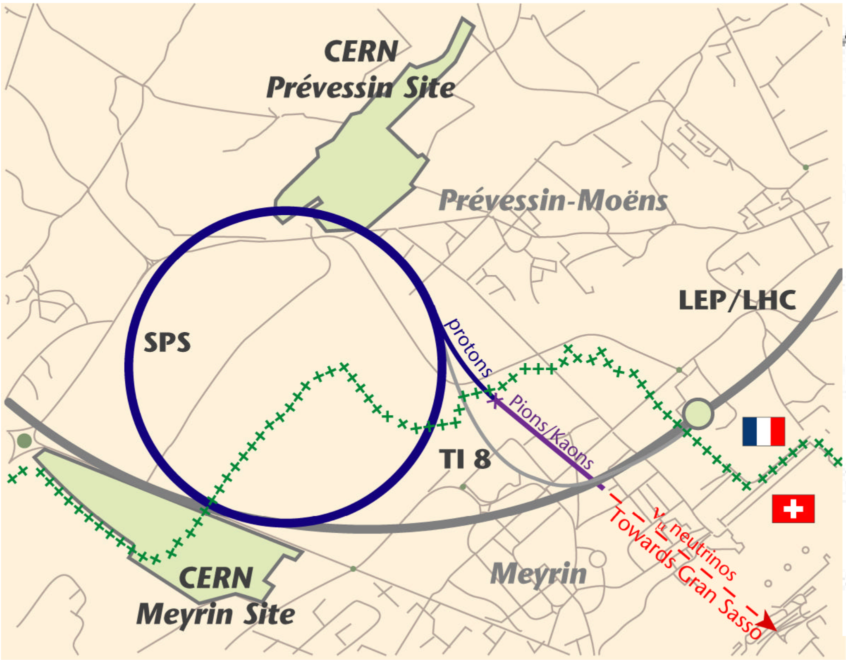
The two experiments are a natural continuation of the CHORUS and NOMAD short baseline experiments at CERN but:

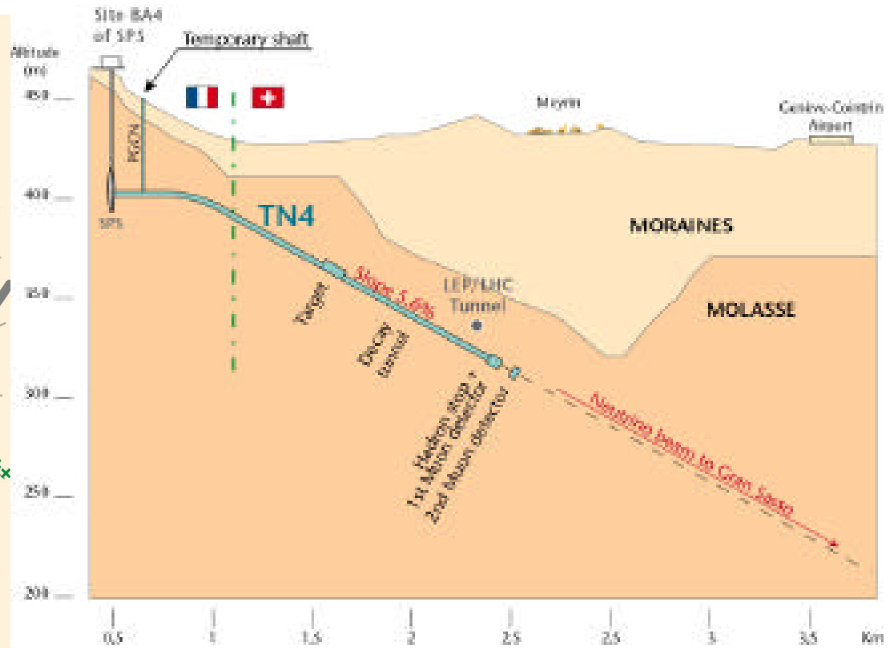
→ **The conflicting requirements of large scale and at the same time very good space/energy resolution represent a big challenge solved by many years of R&D**

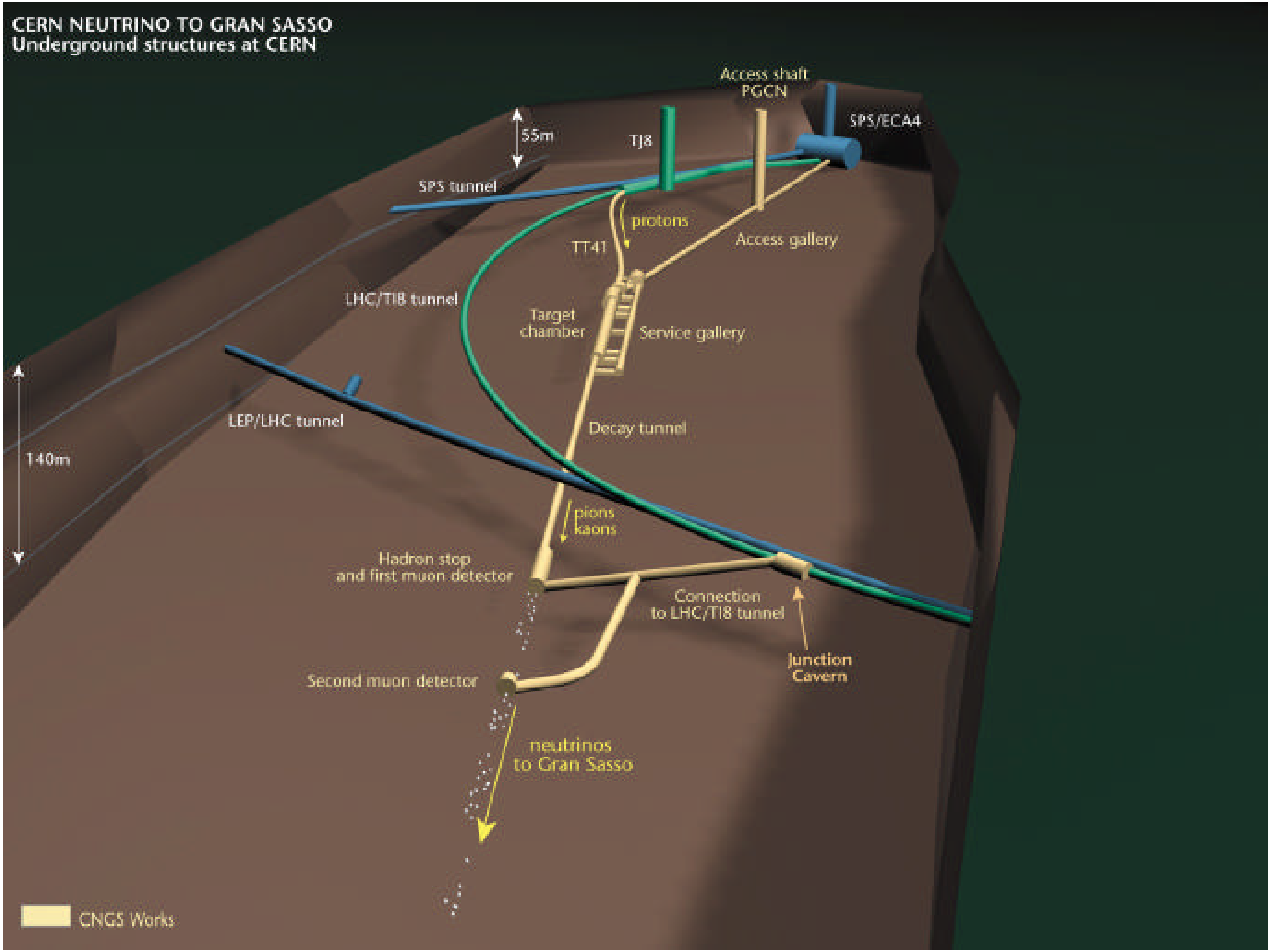
The CERN side

400 GeV/c

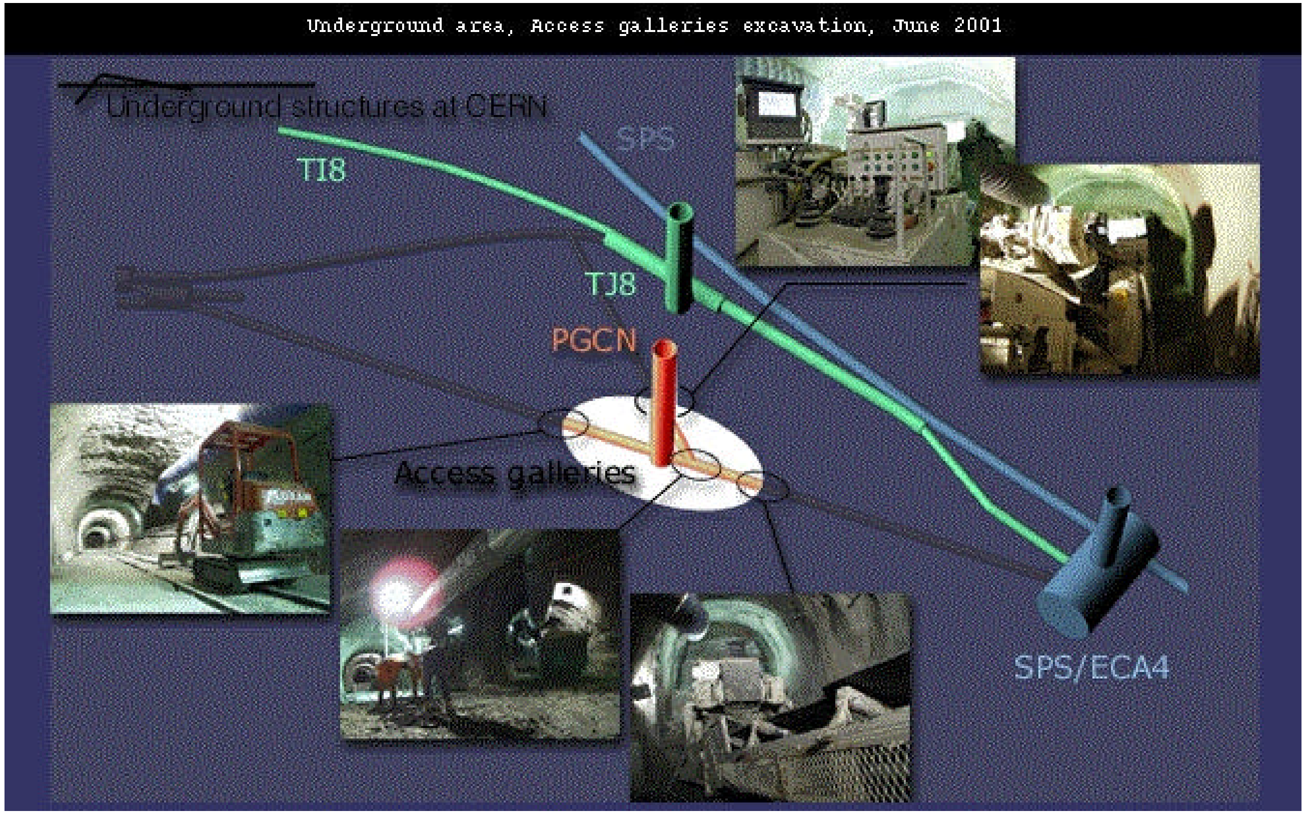







CERN NEUTRINO TO GRAN SASSO
Underground structures at CERN
Access shaft
PGCN
SPS/ECA4
55m
TJ8
SPS tunnel
protons
TT41
Access gallery
LHC/TI8 tunnel
Target
chamber
Service gallery
LEP/LHC tunnel
Decay tunnel
140m
pions
kaons
Hadron stop
and first muon detector
Connection
to LHC/TI8 tunnel
Junction
Cavern
Second muon detector
neutrinos
to Gran Sasso
CNGS Works

Status of the civil engineering work



Excavation is going on smoothly,
very good ground conditions so far ...

CNGS beam characteristics

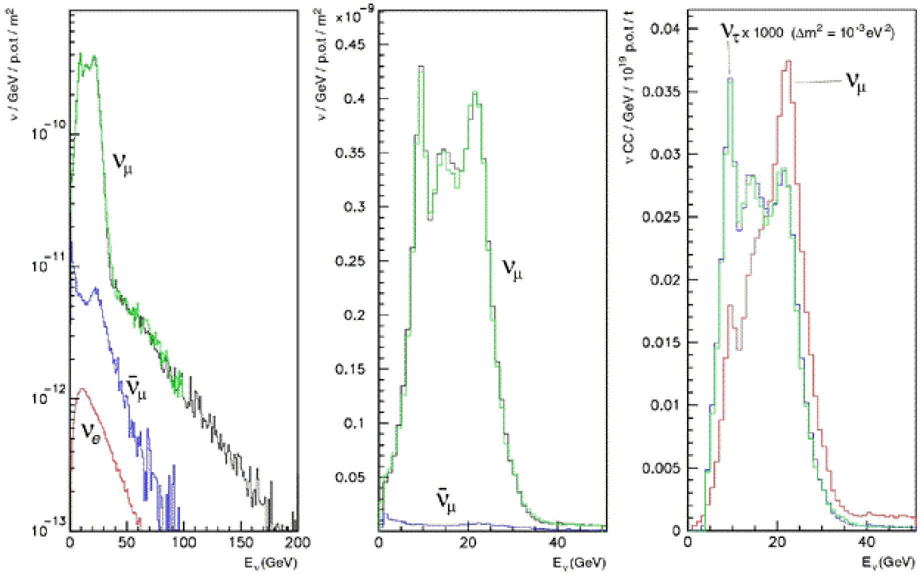
Nominal ν beam

ν_μ (m^{-2} / pot)	7.78×10^{-9}
ν_μ CC / pot / kton	5.85×10^{-17}
$< E >_\nu$ (GeV)	17
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.87 %
$\bar{\nu}_\mu / \nu_\mu$	2.1 %
ν_τ prompt	negligible

$\Rightarrow$ **Interactions with 1.8 kton target x 5 years**

~ 30000 ν NC+CC

~ 140 ν_τ CC (@full mixing, $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2)

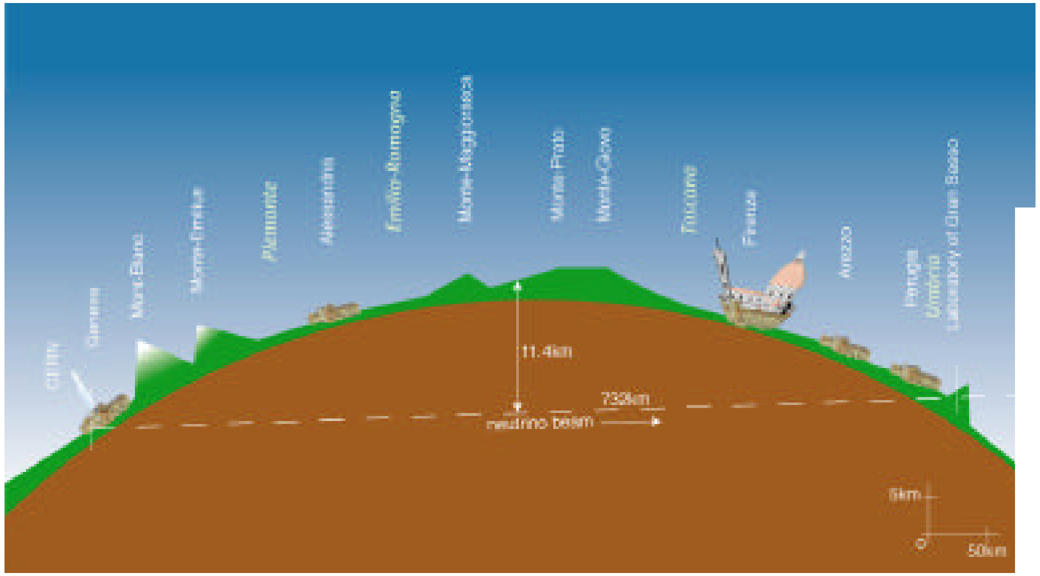


Shared SPS operation

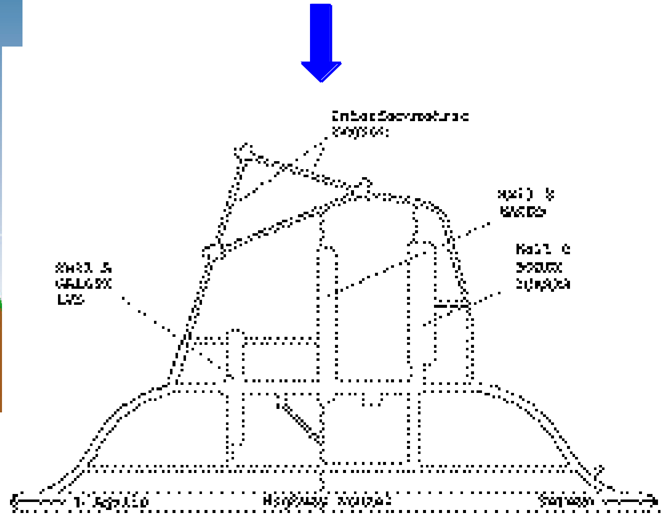
200 days/year

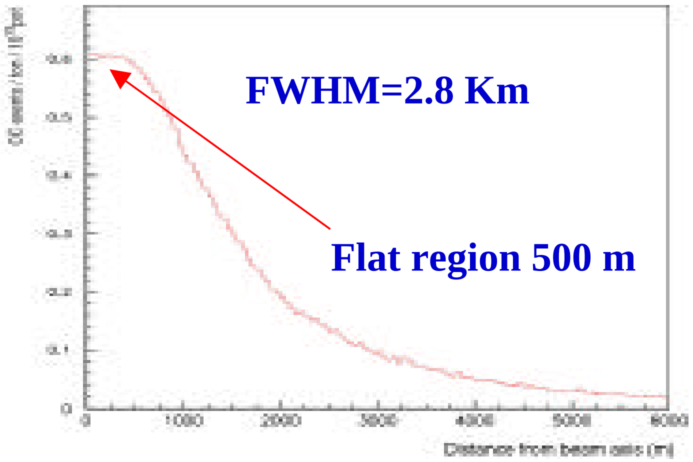
4.5×10^{19} pot / year

The beam at Gran Sasso



CERN



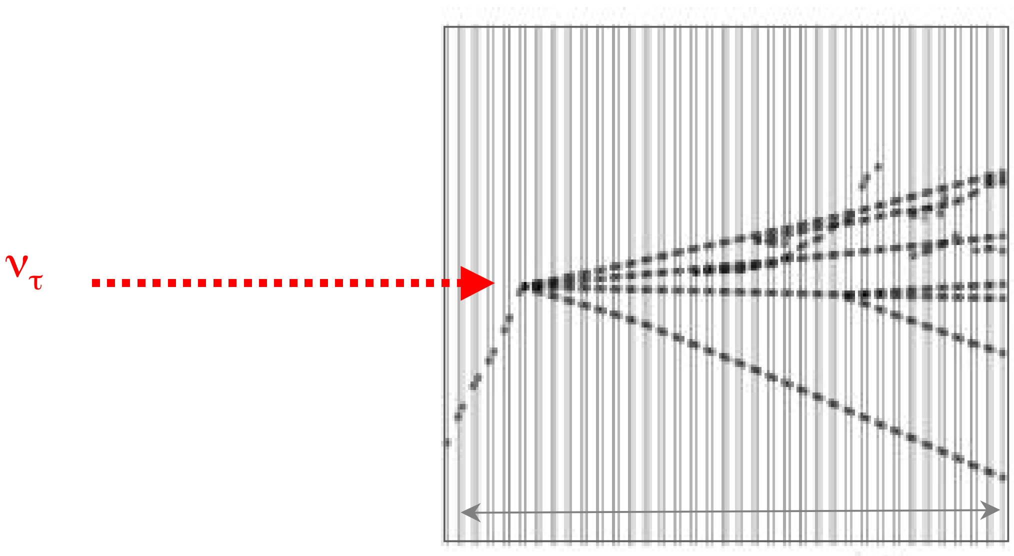


Beam transverse dimensions at Gran Sasso given by $\pi^+ \rightarrow \mu^+ \nu_\mu$ kinematics: max p_T= 30 MeV/c

$\theta_{\nu\mu} = 0.03/E_{\nu\mu}$ (GeV)

The OPERA experiment

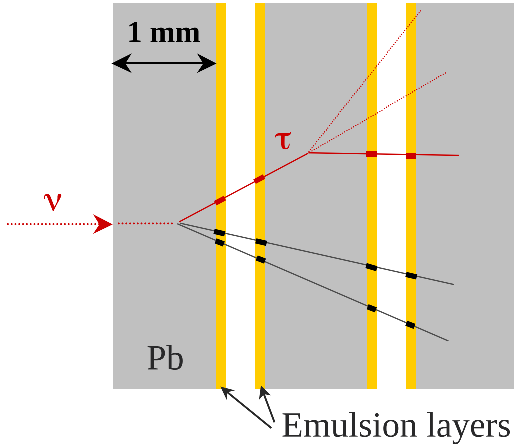
Brick
(56 Pb/Emulsions. “cells”)



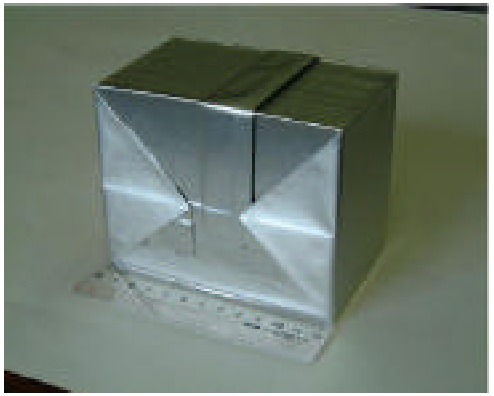
8 cm ($10X_0$)

The experimental technique

- **Emulsion Cloud Chamber (ECC)**
  (emulsions for tracking, passive material as target)
  - Basic technique works
    - charmed "X-particle" first observed in cosmic rays (1971)
    - DONUT/FNAL beam-dump experiment: ν_τ events observed



- **$\Delta m^2 = (1.6 - 4) \times 10^{-3}\ eV^2$** (SuperK) $\rightarrow$ **$M_{target} \sim$ 2 kton** of "compact" ECC (baseline)
  - large detector $\rightarrow$ sensitivity, complexity
  - modular structure ("bricks"): basic performance is preserved



- **Ongoing developments,** required by the large vertex detector mass:
  - industrially produced emulsion films
  - automatic scanning microscopes with ultra high-speed

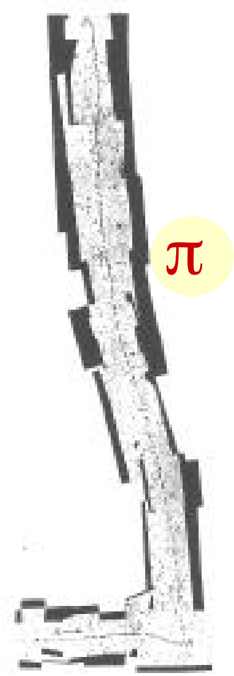
Experience with emulsions and/or ν_τ searches : E531, CHORUS, NOMAD and DONUT

1947 : π discovery

Sensitivity of ***nuclear*** emulsion

↓

π **discovery** with cosmic rays



Nuclear Emulsion: unique to “see” the decay of short-lived particles

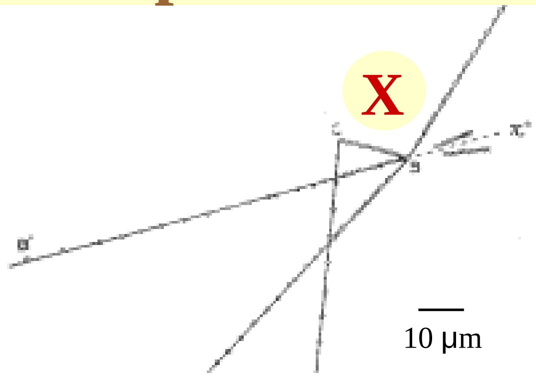
1971 : charm

Emulsion Cloud Chamber

(Pb-emulsion sandwich)

↓

Charm first seen as ***X-particle*** in cosmic ray interactions

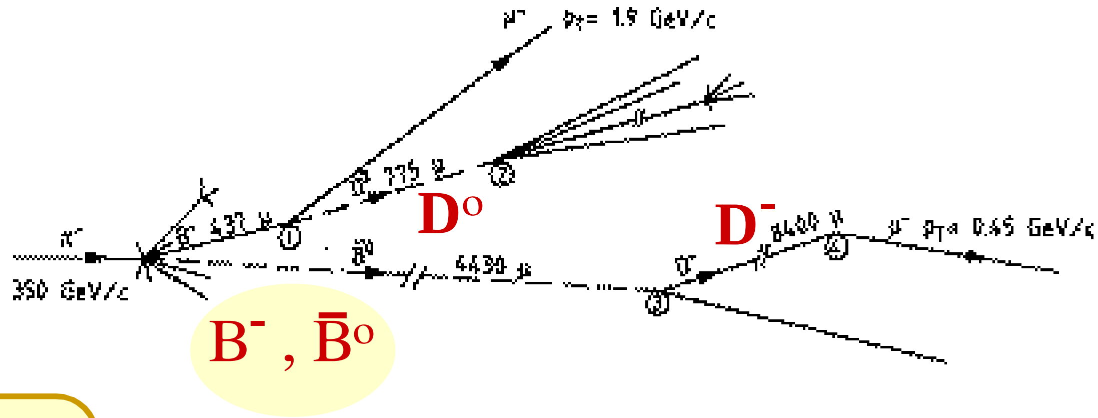


1985 : beauty

WA75 “hybrid” experiment

↓

First observation of beauty production and decay



50 years after π discovery

***Automatic scanning*, massive targets**

↓

Search for τ ***decay*** from ν_τ interactions

If zero background :
1 event gives a result

Material	DONUT Fe →	OPERA Pb **better for physics analysis** (Fe density : too large or too small)

ν_τ detection by Emulsion-Counter Hybrid Experiments

	Emulsion gel	Track density In emulsion	Scan area
CHORUS	400 liter	10^4 /cm^2	6x10^4 cm^2
DONUT	50 liter	10^5 /cm^2	2x10^4 cm^2
OPERA	10^4 liter diluted 5000 liter equivalent	10^2 /cm^2	5x10^6 cm^2

10 x CHORUS

100 x CHORUS

UTS → S-UTS : x 20

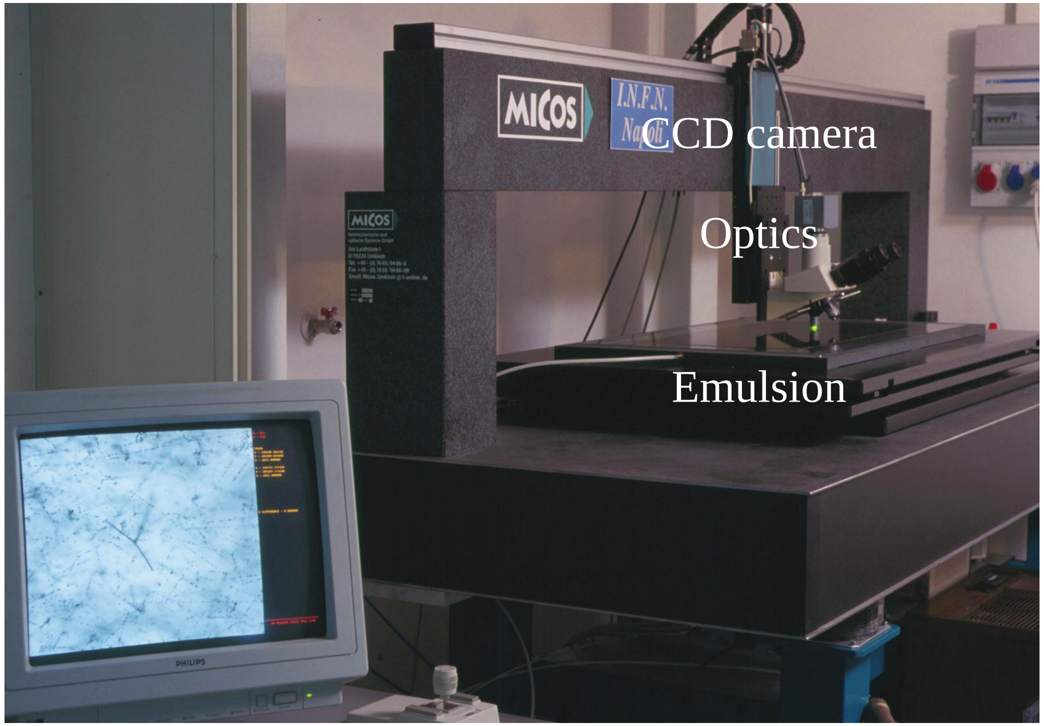
# of S-UTS : x 5

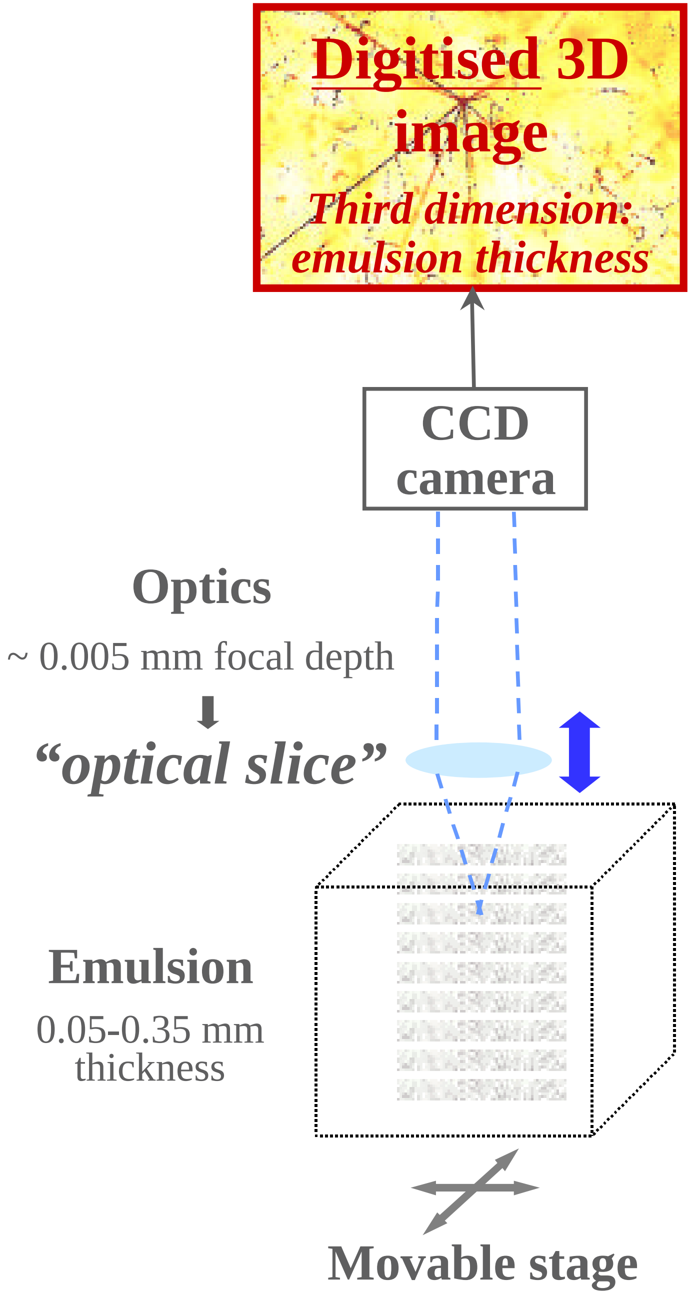
Industrial emulsion films (as for X-rays)

Scanning speed x 10 every few years

Microscope for automatic image analysis

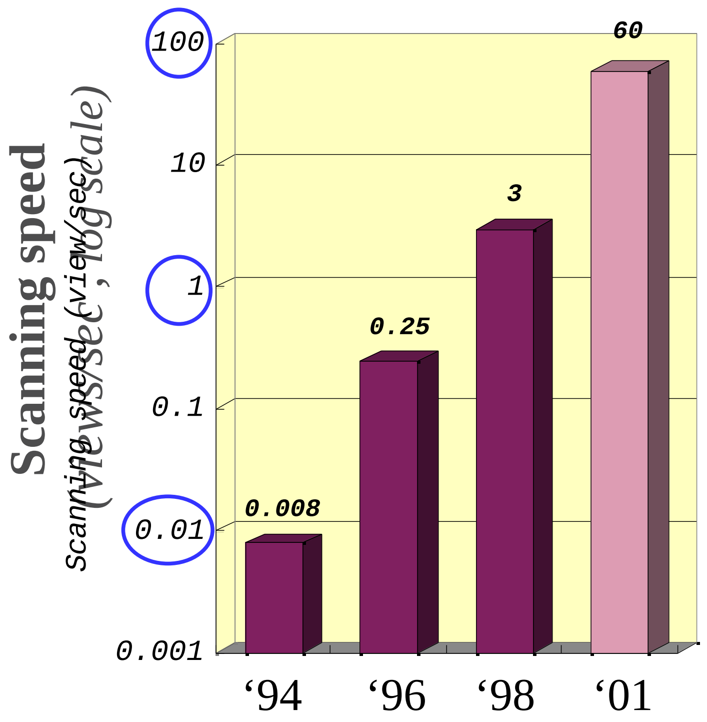
Computer controlled
Multidisciplinary applications: e.g. biophysics





Progress in automatic emulsion scanning

Scanning speed road map
(Nagoya University)



New tools always made a difference !

From B.Kurtén, *Our earliest ancestors*
Columbia University Press (1993)

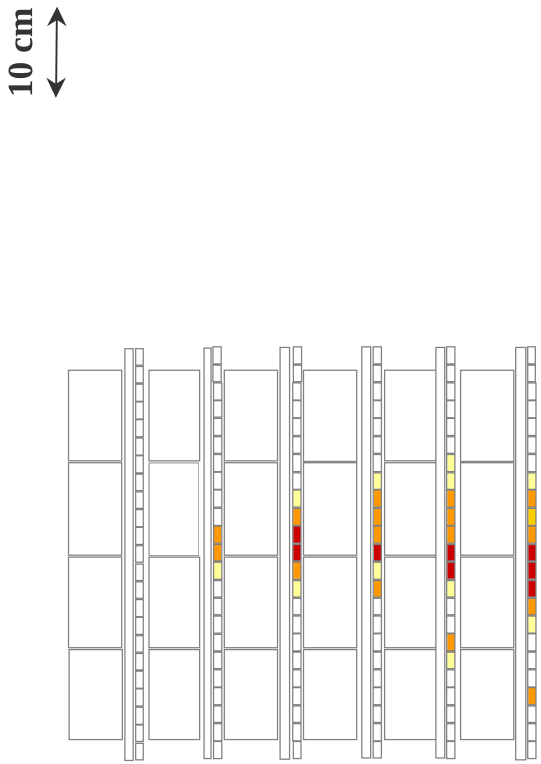
Aim for OPERA

~20 cm^2/hour/system

- Road map : speed x 10 every few years
- At present : Ultra Track Selector ~ 1 cm^2 / h / s

R&D in Japan and in Europe

- **Target Tracker task :**
  - **a) trigger on neutrino interactions**
  - **b) select bricks efficiently**
  - **c) initiate muon tagging**



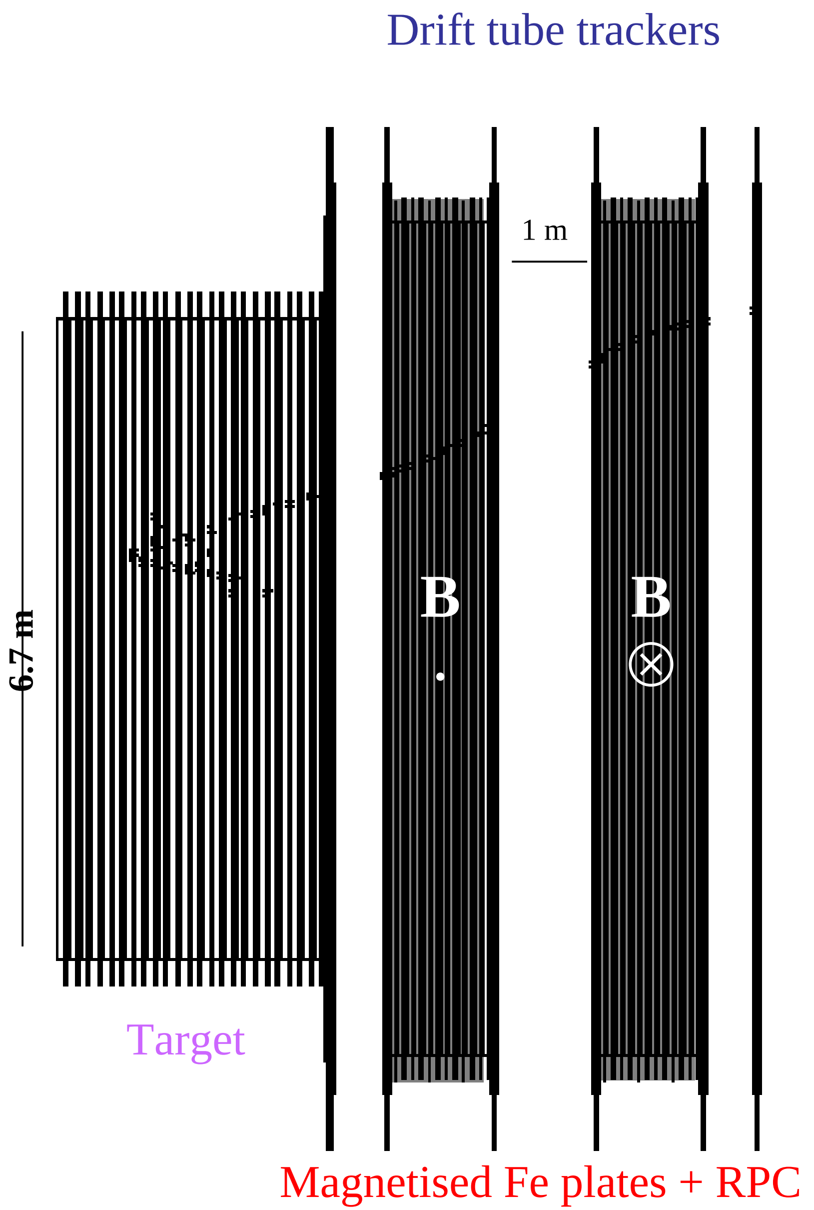
Selected bricks extracted daily using dedicated robot

↑ **Reject charm background**

– **Tag and analyse $\tau^- \rightarrow \mu^-$ candidates**

• **Drift Tube trackers**

muon momentum measurement

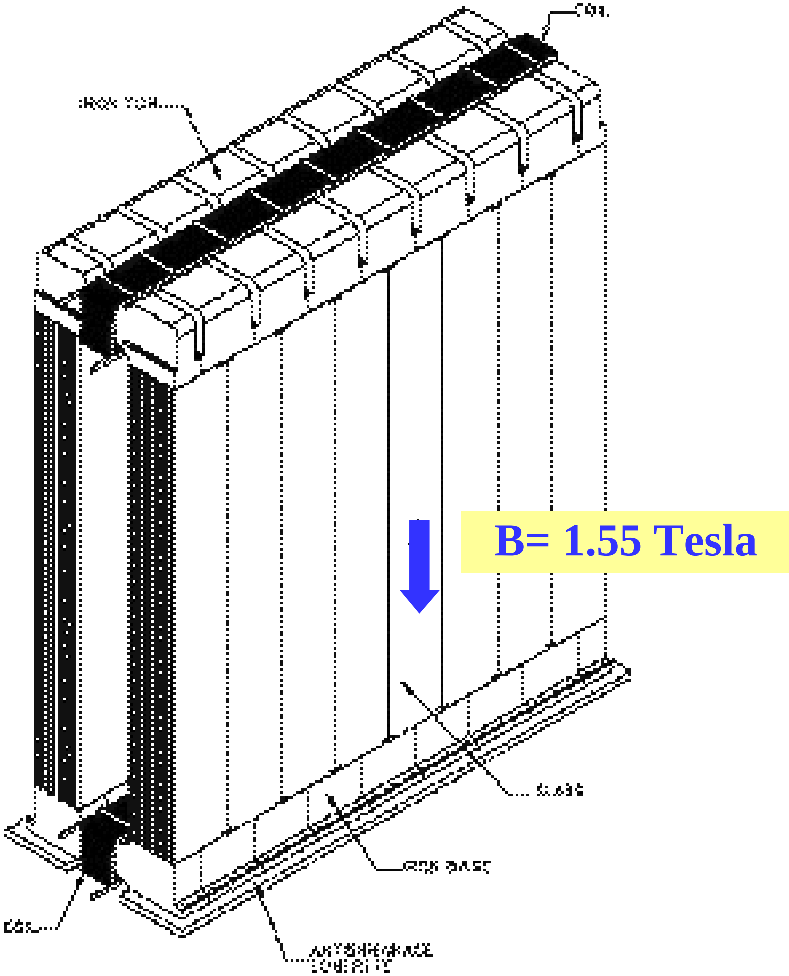


Muon spectrometer

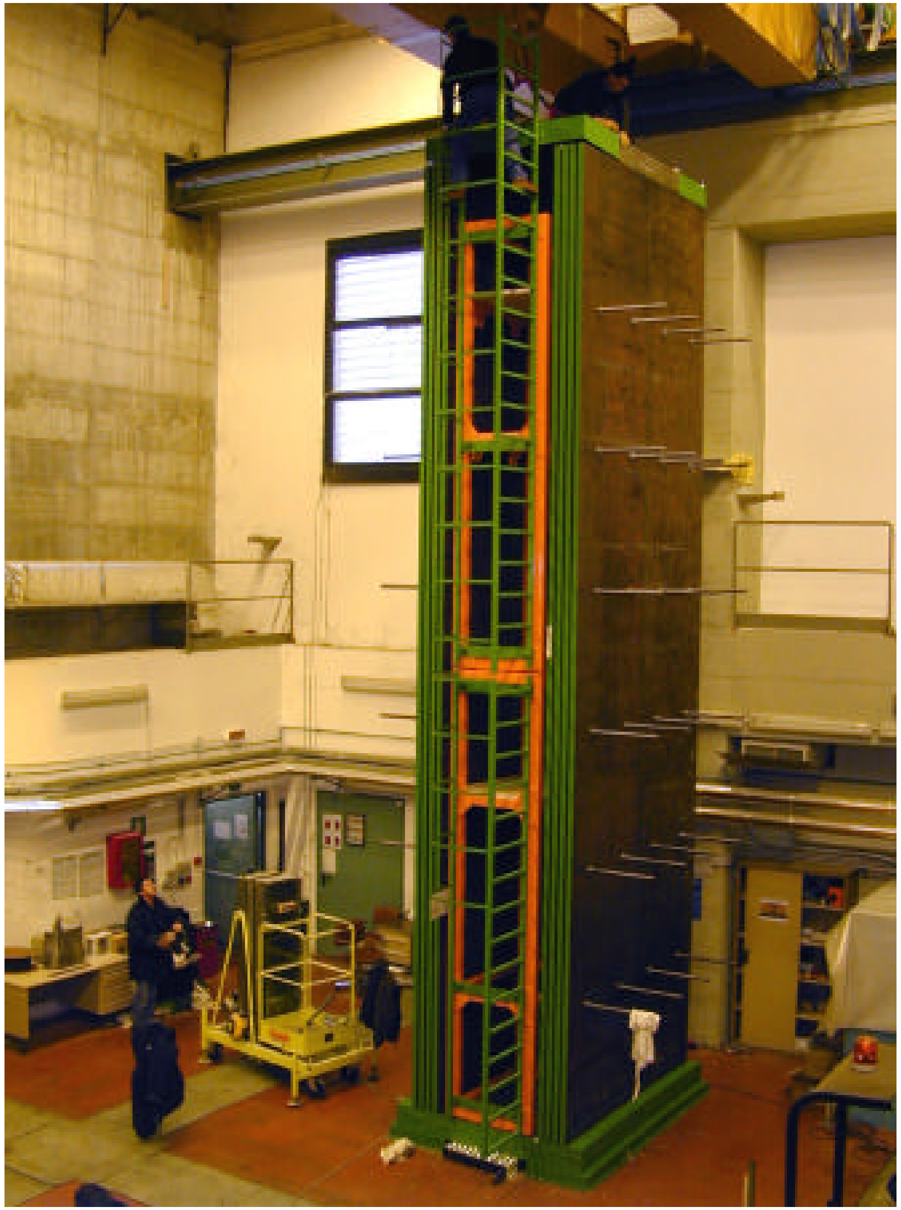
(top view)

Dipolar spectrometer magnet

(weight: ~ 950 ton)

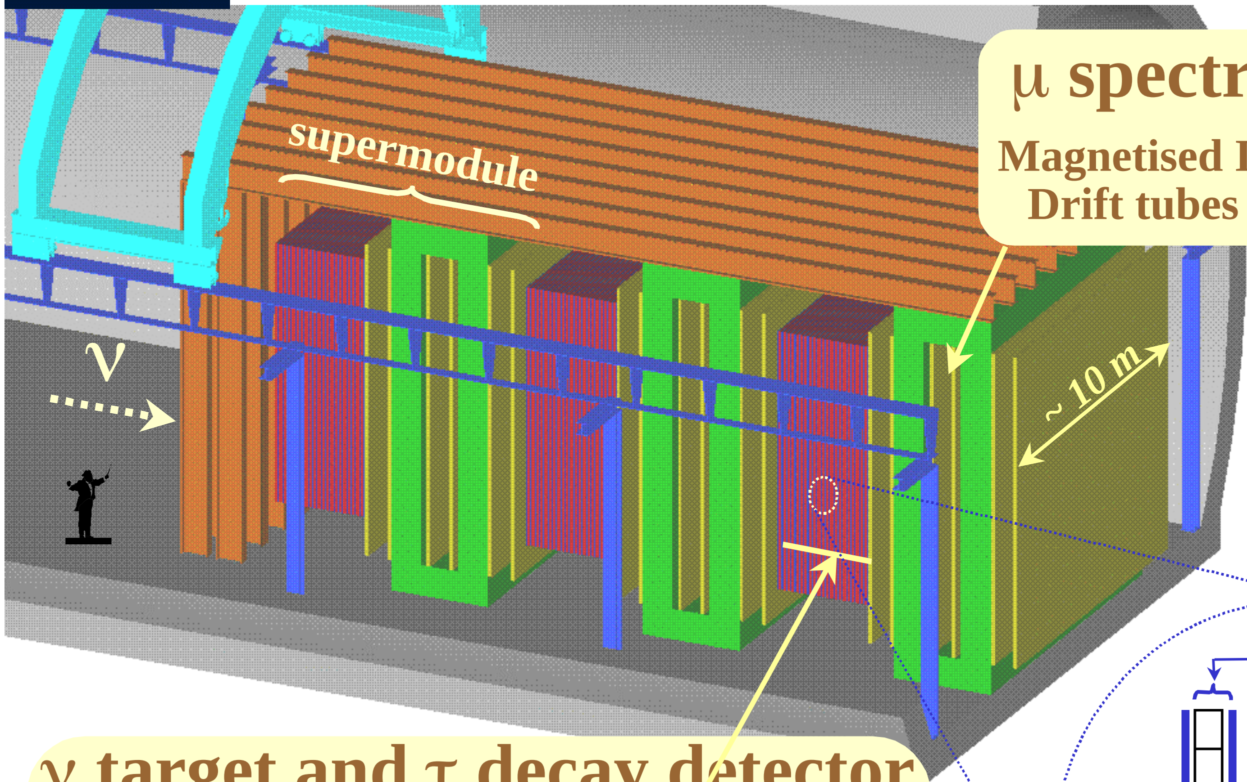


Prototype of magnet section being assembled at Frascati



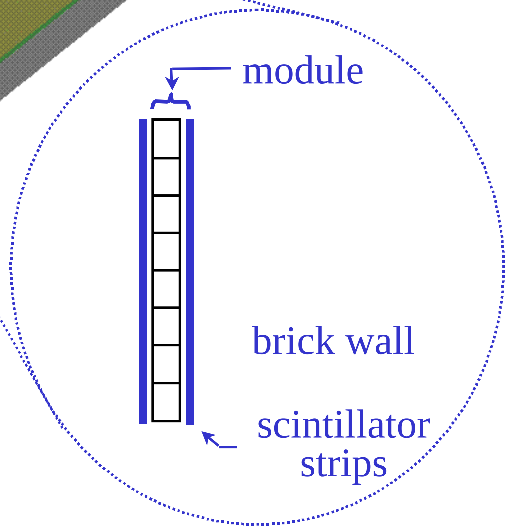
The detector at Gran Sasso

(modular structure, three "supermodules")



μ spectrometer

Magnetised Iron Dipoles
Drift tubes and RPCs

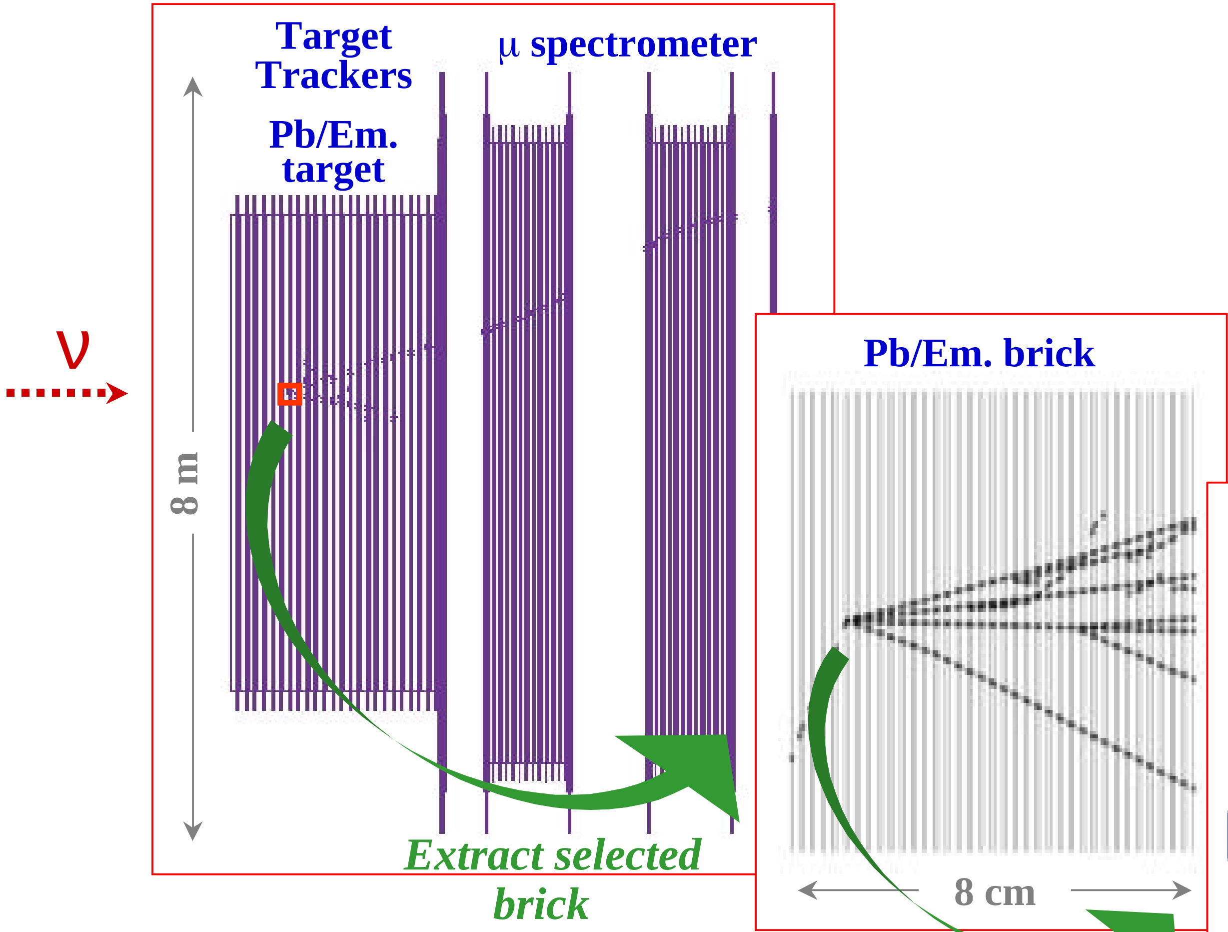


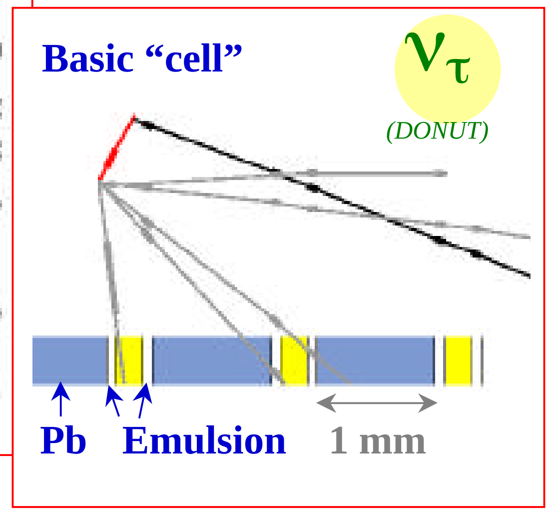
ν target and τ decay detector

Each "supermodule" is
a sequence of 24 "modules" consisting of

- **a "wall" of Pb/emulsion "bricks"**
- **planes of orthogonal scintillator strips**

A “hybrid” experiment at work





<u>Electronic detectors</u>

→ **select ν interaction brick**

→ **μ ID, charge and p**

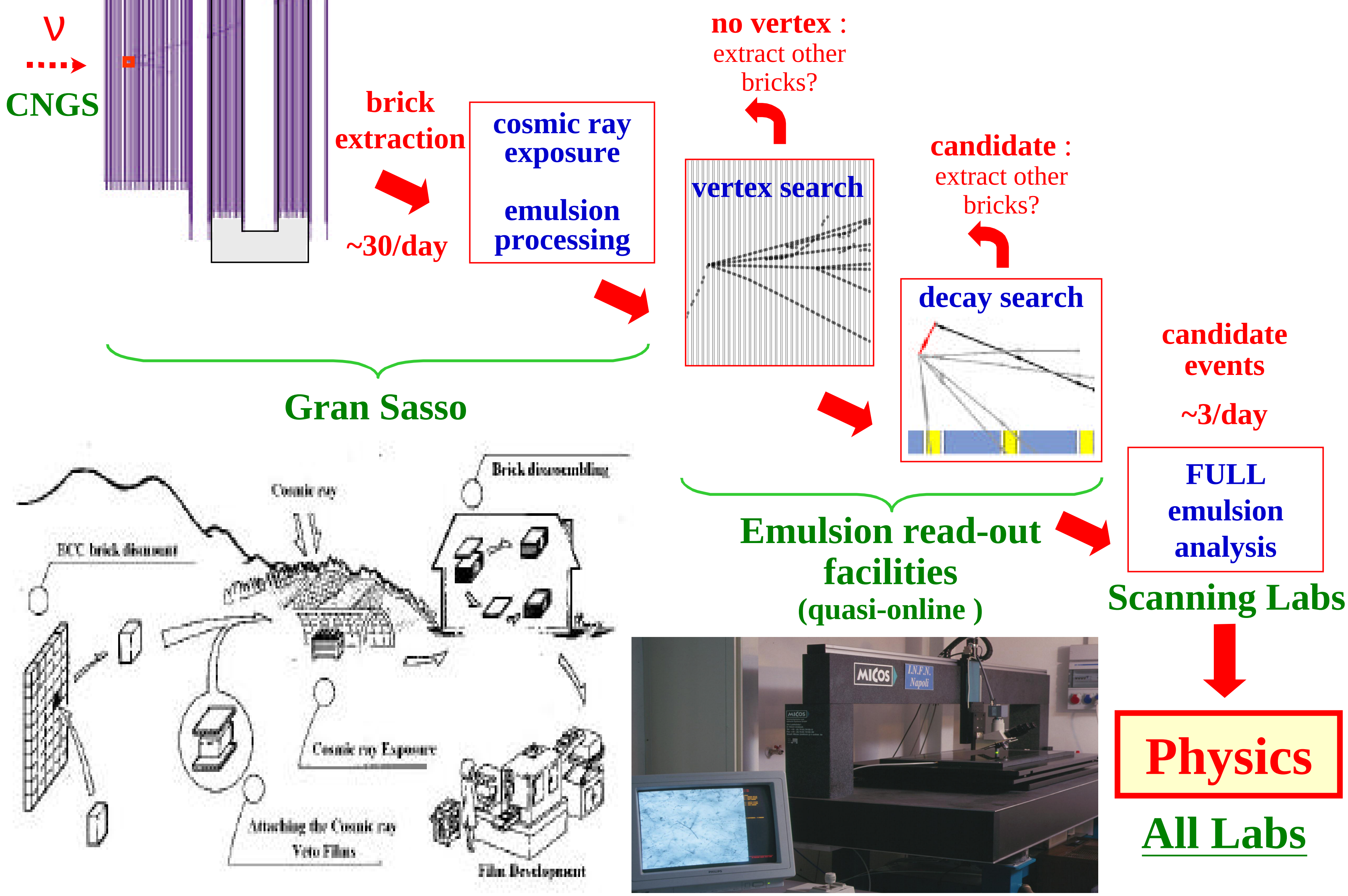
<u>Emulsion analysis</u>

→ **vertex search**

→ **decay search**

→ **e/γ ID, kinematics**

From the CNGS to physics

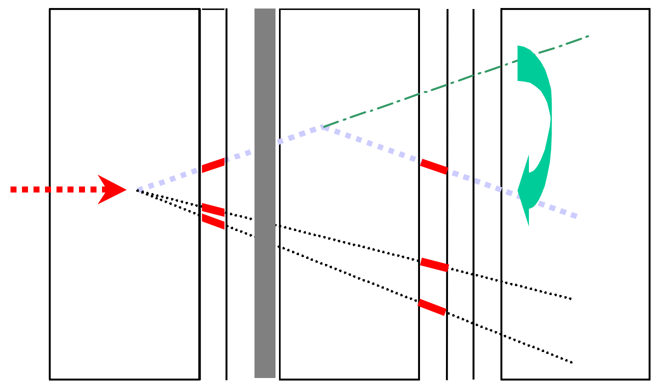


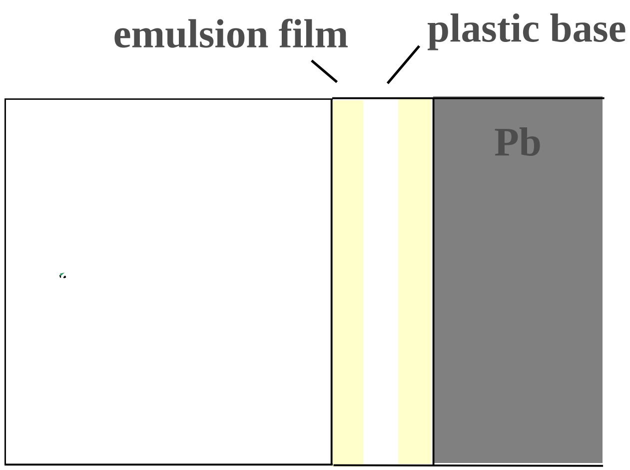
Exploited τ decay channels

- **"Long" decays**
  kink angle θ_{kink} > 20 mrad

τ → **e**	Progr. Rep.	1999
τ → μ	Progr. Rep.	1999
τ → **h ($n\pi^0$)**	Proposal	2000
+ ρ **search**		**2001**

Long decays





- **"Short" decays**
  impact parameter I.P. > 5 to 20 μm

τ → **e**	Proposal	2000
τ → μ		**2001**

Summary of τ detection efficiencies

(in % and including BR)

	DIS long	*QE long*	*DIS short*	*Overall**
$\tau \rightarrow e$	2.7	2.3	1.3	3.4
$\tau \rightarrow \mu$	2.4	2.5	0.7	2.8
$\tau \rightarrow h$	2.8	3.5	-	2.9
Total	**8.0**	**8.3**	**1.3**	**9.1 (8.7)**

*** weighted sum of DIS and QE events**

Efficiency given in the Proposal

Expected background

(5 year run with 1.8 kton average target mass)

		$\tau \rightarrow e$	$\tau \rightarrow \mu$	$\tau \rightarrow h$	*Total*
LONG DECAYS	*Charm production*	0.14	0.03	0.14	0.31
	ν_e *CC and* π^0	0.01	-	-	0.01
	Large angle μ *scattering*		0.10	-	0.10
	Hadron reinteractions	-	-	0.10	0.10
	ν_μ CC		0.06		0.06
	ν_μ NC		0.10		0.10
	Total	**0.15**	**0.29**	**0.24**	**0.67**
SHORT DECAYS	*Charm production*	0.03	0.02	-	0.05
	Large angle μ *scattering*	-	0.02	-	0.02
	ν_e *CC and* π^0	« 0.01	-	-	« 0.01
	Total	**0.03**	**0.04**	-	**0.07**
	Total	**0.18**	**0.33**	**0.24**	**0.75**

New estimates

0.57 in the Proposal

Expected number of events

(5 year run with 1.8 kton average target mass)

Full mixing, Super-Kamiokande best fit and 90% CL limits
as presented at the 2001 Lepton Photon Conference
(update with respect to the EPS 2001 results taken for the written Status Report)

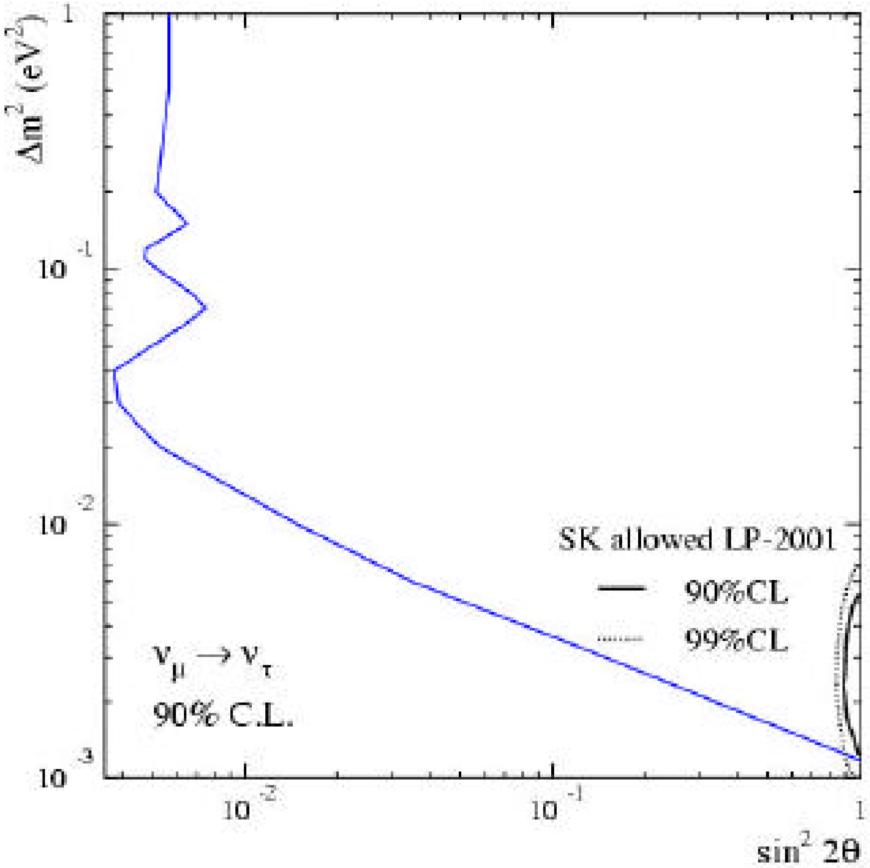
Decay mode	*Signal* 1.2*10–3	*Signal* *2.4*10-3*	*Signal* *5.4*10-3*	*Bkgnd.*
$\tau \to e$ *long*	**0.8**	**3.1**	**15.4**	**0.15**
$\tau \to \mu$ *long*	**0.7**	**2.9**	**14.5**	**0.29**
$\tau \to h$ *long*	**0.9**	**3.4**	**16.8**	**0.24**
$\tau \to e$ *short*	**0.2**	**0.9**	**4.5**	**0.03**
$\tau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

In the Proposal:

Δm^2	**1.5** x 10^{-3}	**3.2** x 10^{-3}	**5.0** x 10^{-3}	
events	**4.1**	**18.3**	**44.1**	**0.57**

Exclusion plot in the absence of a signal

(5 year run with 1.8 kton average target mass)



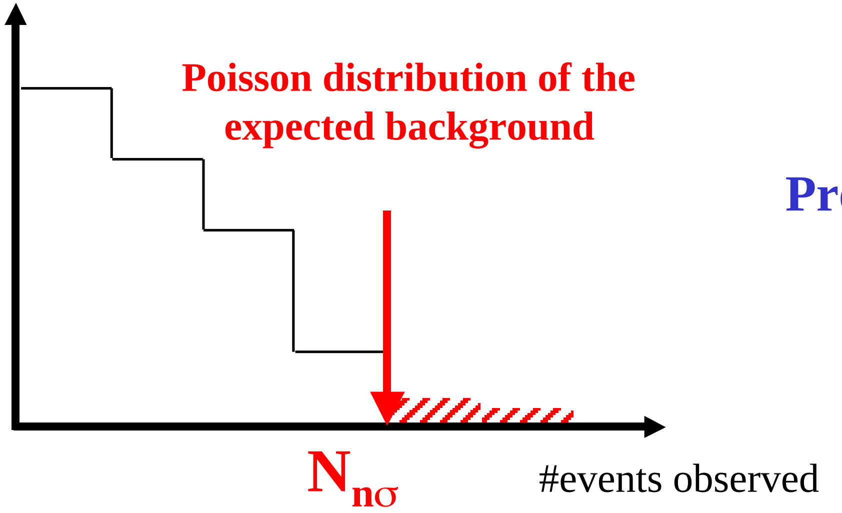
90 % CL upper limit obtained on average by a large ensemble of experiments

Δm^2	$< 1.2 \times 10^{-3}$ eV^2 at full mixing
$\sin^2(2\theta)$	$< 5.7 \times 10^{-3}$ at large Δm^2

Gives an indication of the sensitivity … but of course we expect to see a signal

Uncertainties on background (±33%) and on efficiencies (±15%) accounted for here and in the following

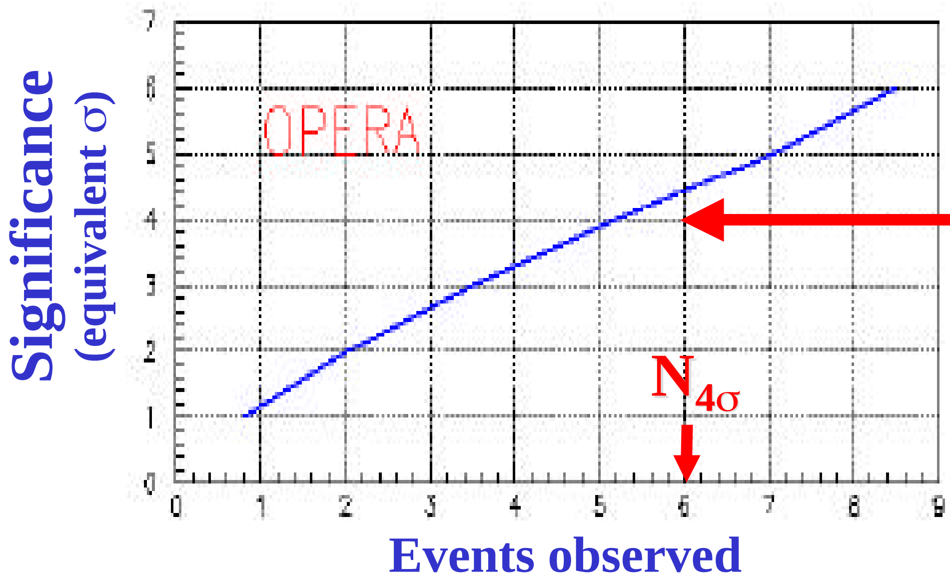
Statistical significance for discovery



Probability that the b.g. fakes the signal:
< $P_{n\sigma}$ if #observed events ≥ $N_{n\sigma}$

$P_{4\sigma} = 6.3 \times 10^{-5}$

$P_{3\sigma} = 2.7 \times 10^{-3}$



≥ 6 events

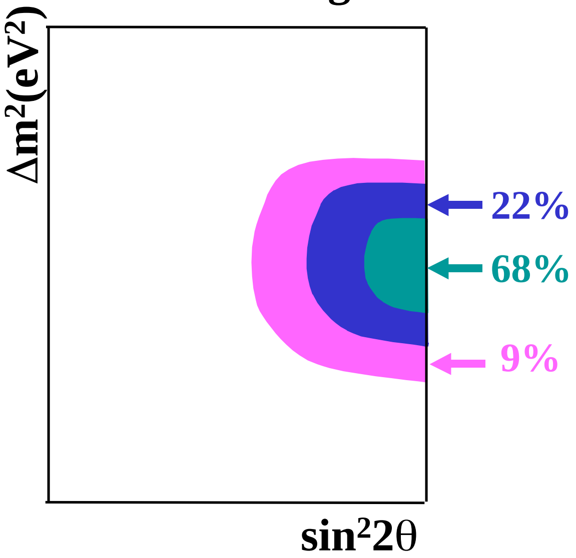
⬇

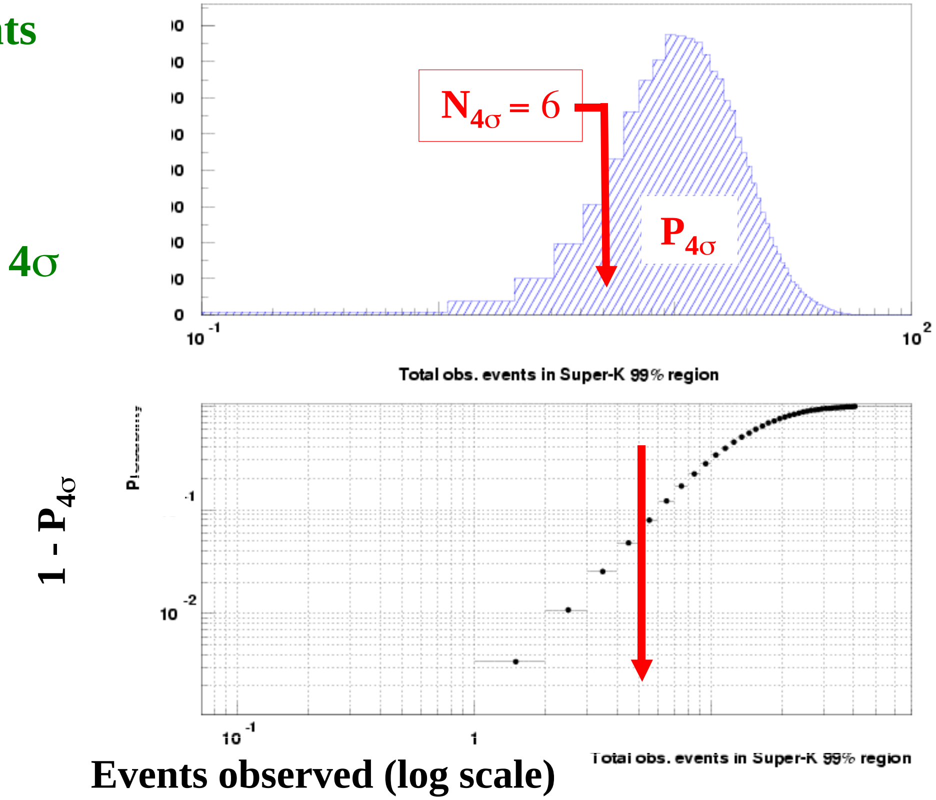
4σ "discovery"

Probability of 4σ significance

- Simulate a large number of experiments with oscillation parameters generated according to the SuperK probability distribution
- $N_{4\sigma}$ events required for a discovery at 4σ
- Evaluate fraction $P_{4\sigma}$ of experiments observing $\int N_{4\sigma}$ events

Schematic view of the SK allowed region





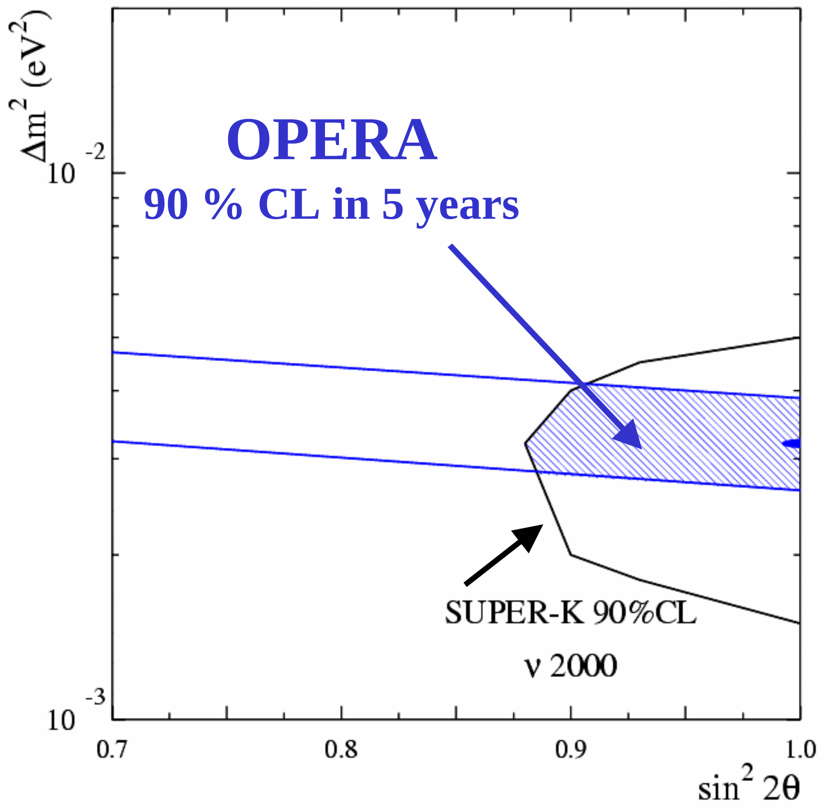
years	$P_{3\sigma}$	$P_{4\sigma}$
3	94%	80%
5	97%	92%

Determination of Δm^2

(mixing constrained by SuperK)

90 % CL limits *	Δm^2 (10^{-3} eV^2)		
	1.5	3.2	5.0
Upper limit	2.1	3.8	5.6
Lower limit	0.8	2.6	4.3
(U - L) / True	41 %	19 %	12 %

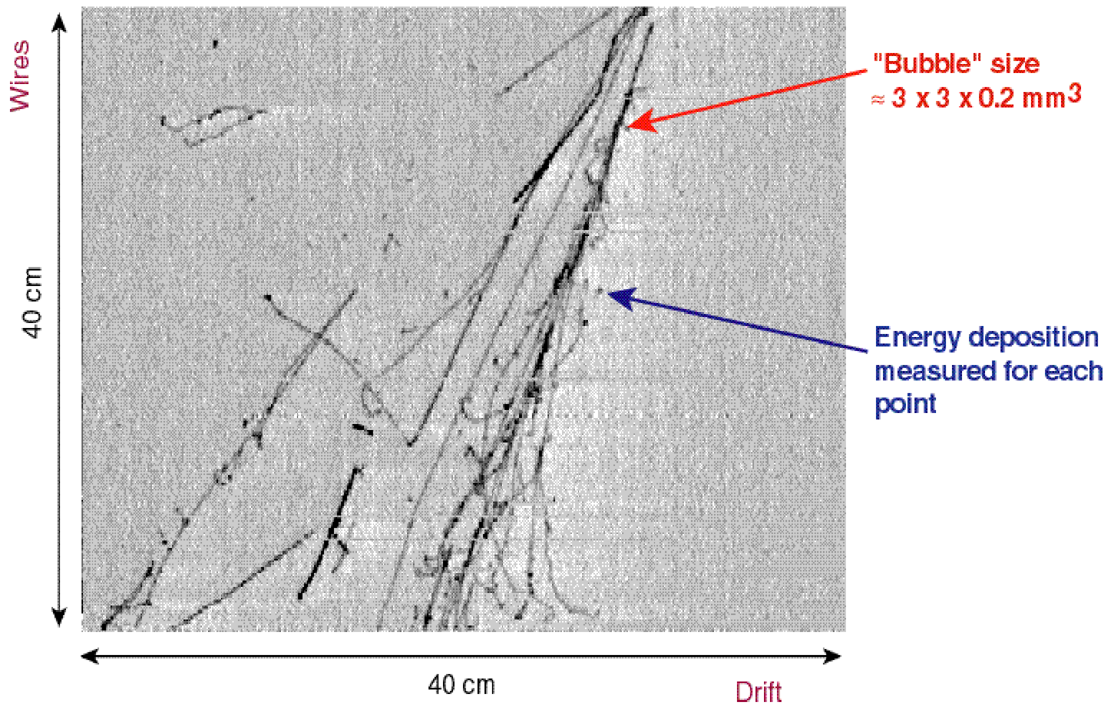
*** assuming the observation of a number of events corresponding to those expected for the given Δm^2**



ICARUS liquid argon imaging

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

C.R. shower from 3 ton prototype



The ICARUS Liquid Ar Time Projection Chamber

- **Event reconstruction in 3D with measurement of the primary ionization**
  1. drift time
  2. induction wires
  3. collection wires

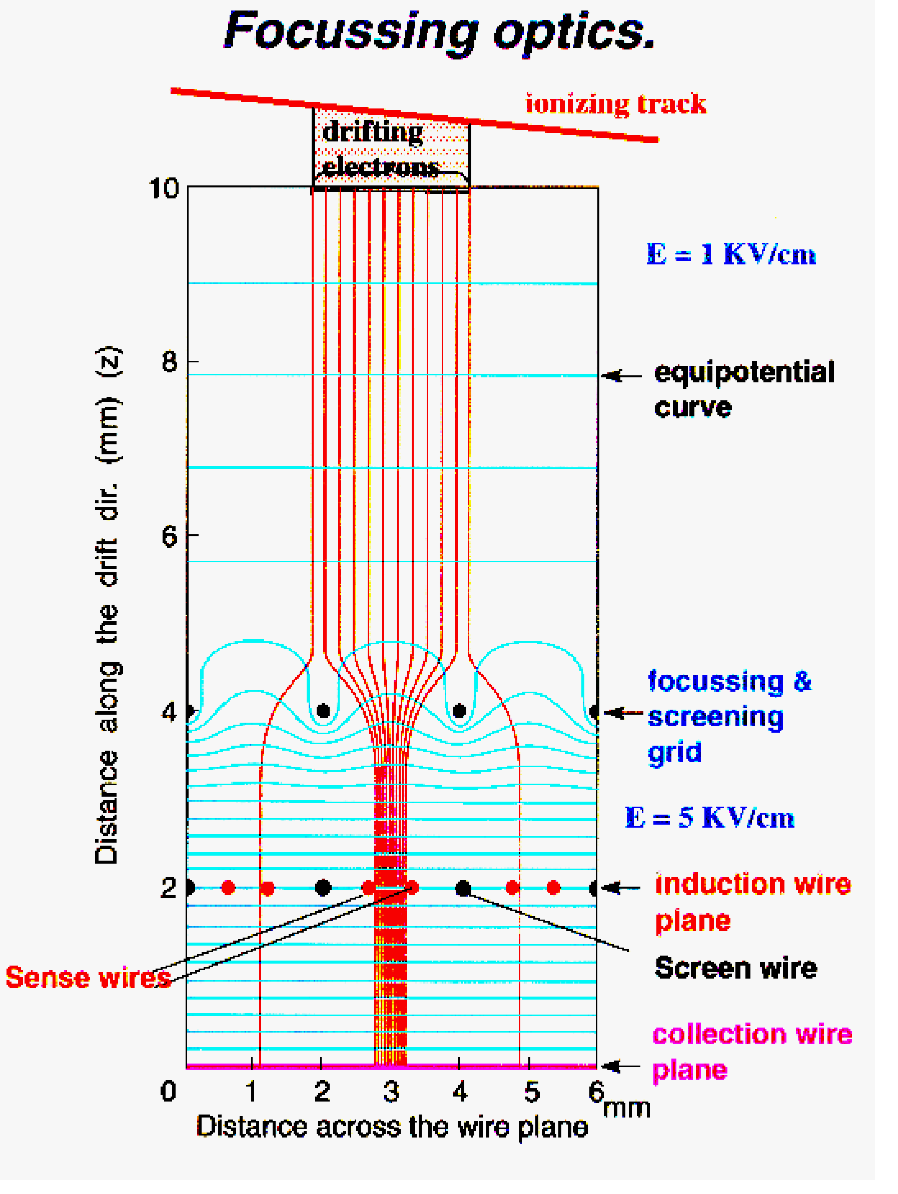
- **Space resolution around 1 mm**

- **Maximum drift length** in the Liq. Ar
  1.5 m in the 600 ton module
  (requiring < 0.1 ppb O_2 equiv. impurities)

- **Calorimetric energy resolution:**

$$\frac{\sigma(E)}{E} \approx \frac{0.03}{\sqrt{E}} (Em.)$$

$$\frac{\sigma(E)}{E} \approx \frac{0.12}{\sqrt{E}} (Hadr.)$$

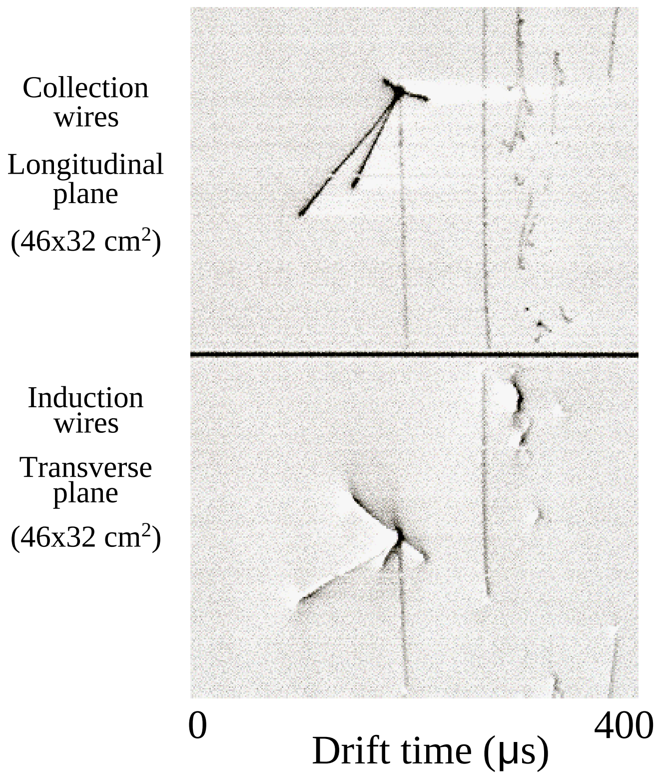


The ICARUS liquid Ar Image TPC

An electronic Bubble Chamber (BC)

• Large sensitive volume	(as BC)
• Detector = Target	(as BC)
• High spatial granularity	(as BC)
• Energy measurement	(as BC)
• High energy resolution	
• Specific ionisation (dE/dx) measurement	
• dE/dx vs. range for particle identification	
• Continuous sensitivity	
• Self triggering capability	

A ν interaction in the 50 liters test TPC



New detector → new physics potentialities

Under construction : 0.6 kton module

For physics : multi kton ➡
proton decay
atmospheric ν
long baseline ν oscillation
solar ν

ICARUS 5kton x year physics reach (I)

- ✓Atmospheric neutrinos
  - ✓Large event statistics with
    - ✓*Detection down to production thresholds*
    - ✓*Complete event final state reconstruction*
    - ✓*Identification all neutrino flavors*
    - ✓*Identification of neutral currents*
  - ✓Excellent resolution on L/E reconstruction
  - ✓Direct τ appearance search

Δm^2_{32}, θ_{23}

Δm^2_{12}

- ✓Neutrinos from CERN
  - ✓Search for $\nu_\mu \rightarrow \nu_\tau$
  - ✓Search for $\nu_\mu \rightarrow \nu_e$

extract ⇒ Δm^2_{32} θ_{23} θ_{13}

- ✓Solar neutrinos
  - ✓Energy threshold: 5 MeV
  - ✓Large statistics, precision measurements
  - ✓“Smoking gun”: CC & NC

Δm^2_{12}, θ_{12}

ICARUS 5kton x year physics reach (II)

✓**Proton decay**

- ✓**Large variety of decay modes accessible**
  - $\Rightarrow$ ***study branching ratios free of systematics***
- ✓**Background free searches**
  - $\Rightarrow$ ***linear gain in sensitivity with exposure***

✓**Neutrino "factory"**

- ✓**Precise measurement oscillation**
- ✓**Matter effects, sign of Δm^2_{23}**
- ✓**First observation of $\nu_e \rightarrow \nu_\tau$**
- ✓**CP violation**

Δm^2_{32} θ_{23} θ_{13}

$\Delta m^2_{32}>0$ or $\Delta m^2_{32}<0$?

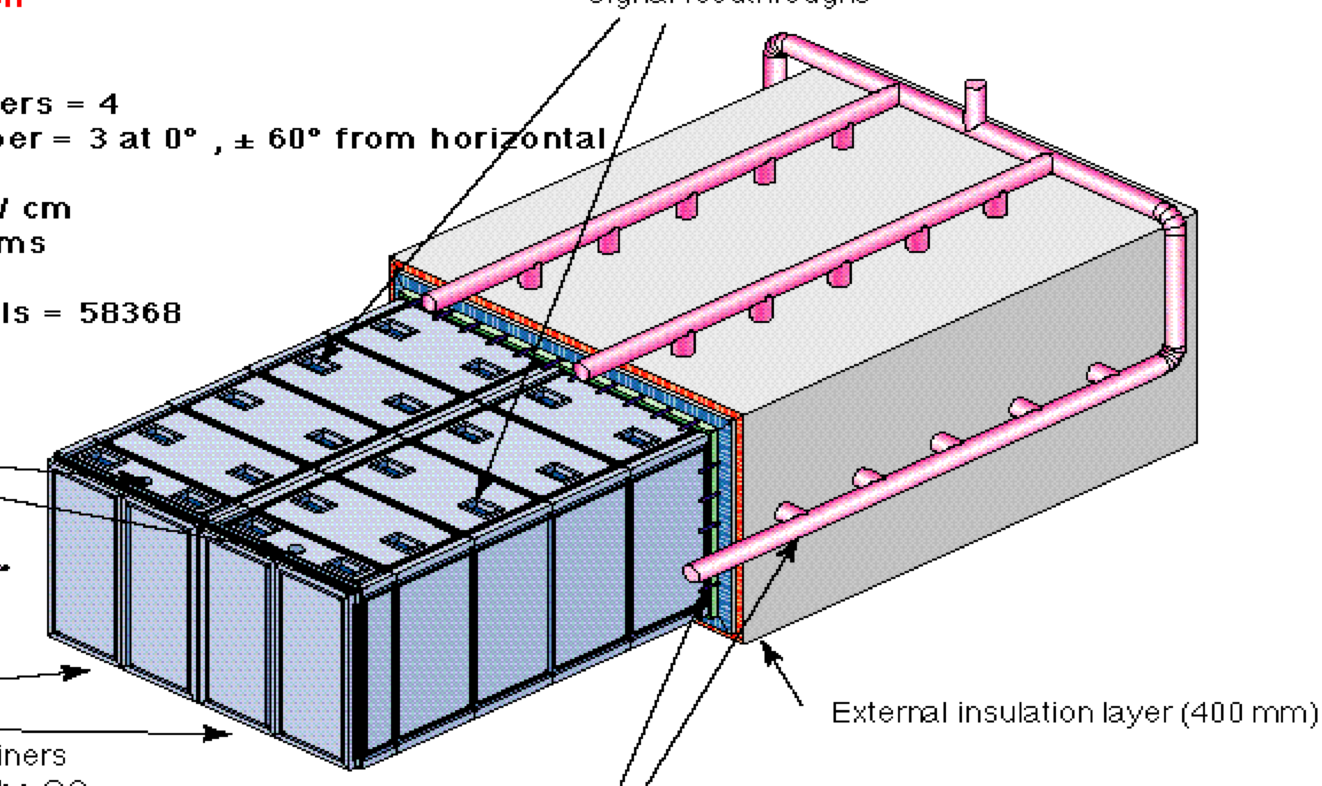
Unitarity of mixing matrix

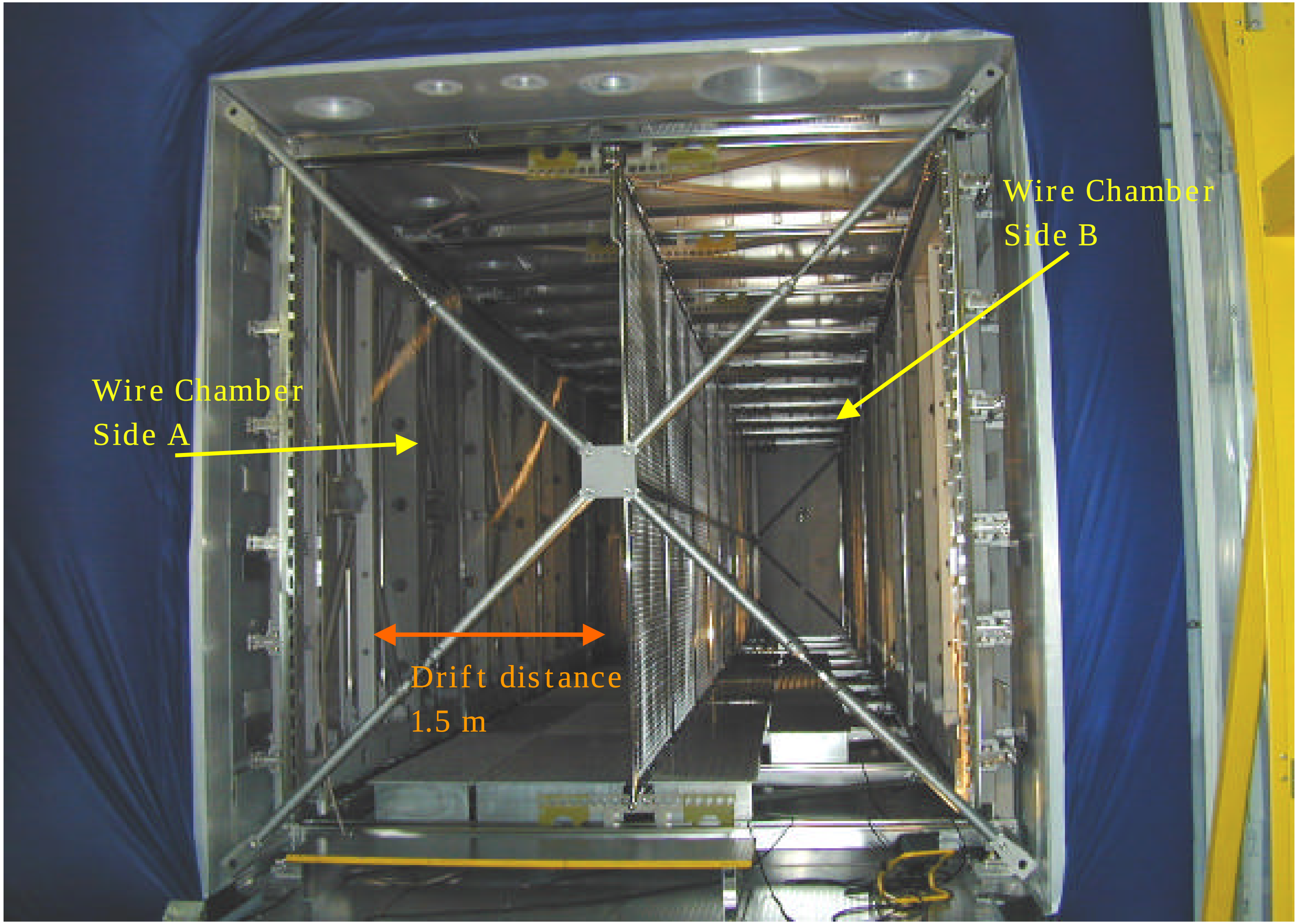
$\delta \neq 0$?

The ICARUS T600 module

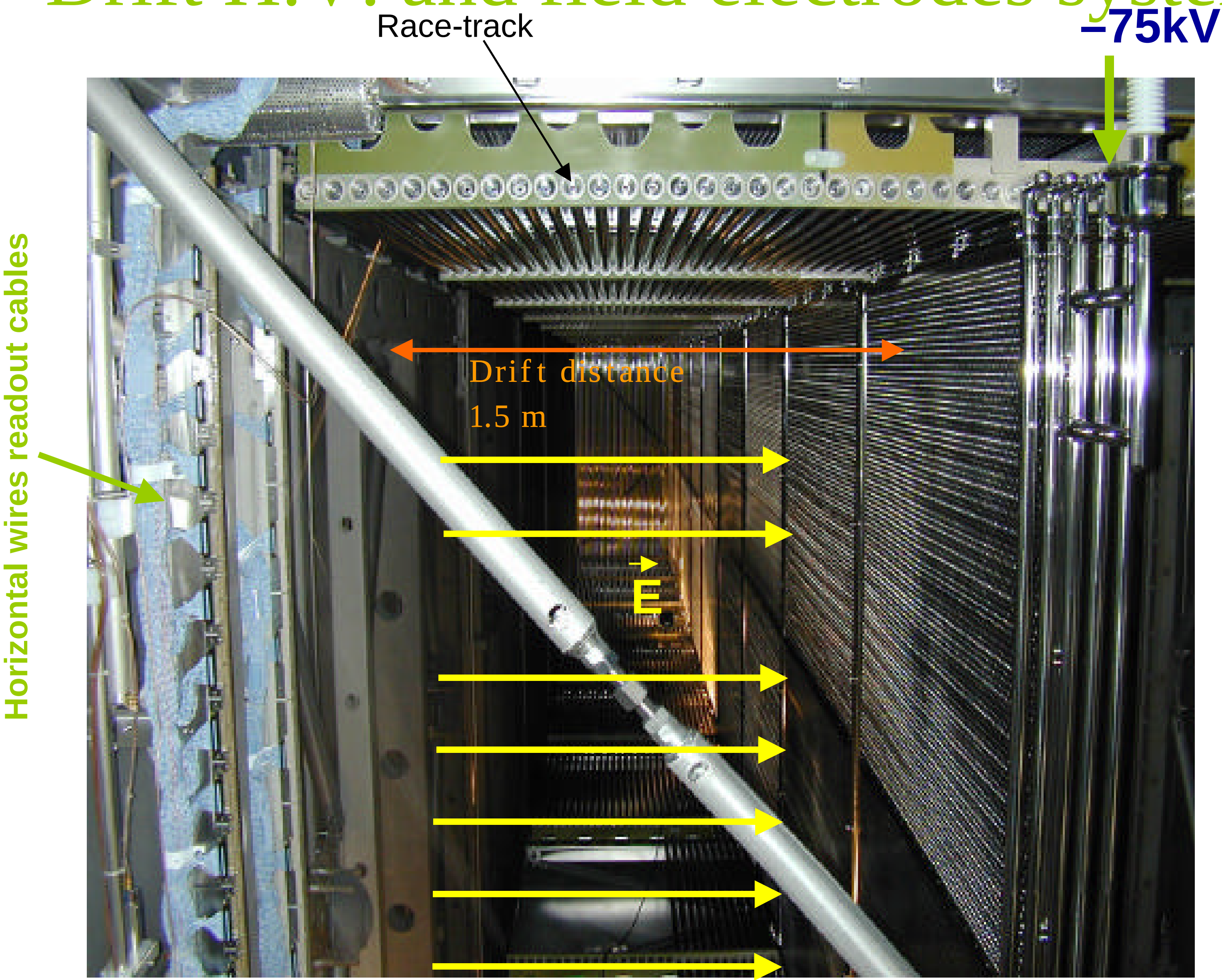
Number of independent containers = 2
Single container Internal Dimensions: Length = 19.6 m , Width = 3.9 m , Height = 4.2 m
Total (cold) Internal Volume = 534 m^3
Sensitive LAr mass = 476 ton

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

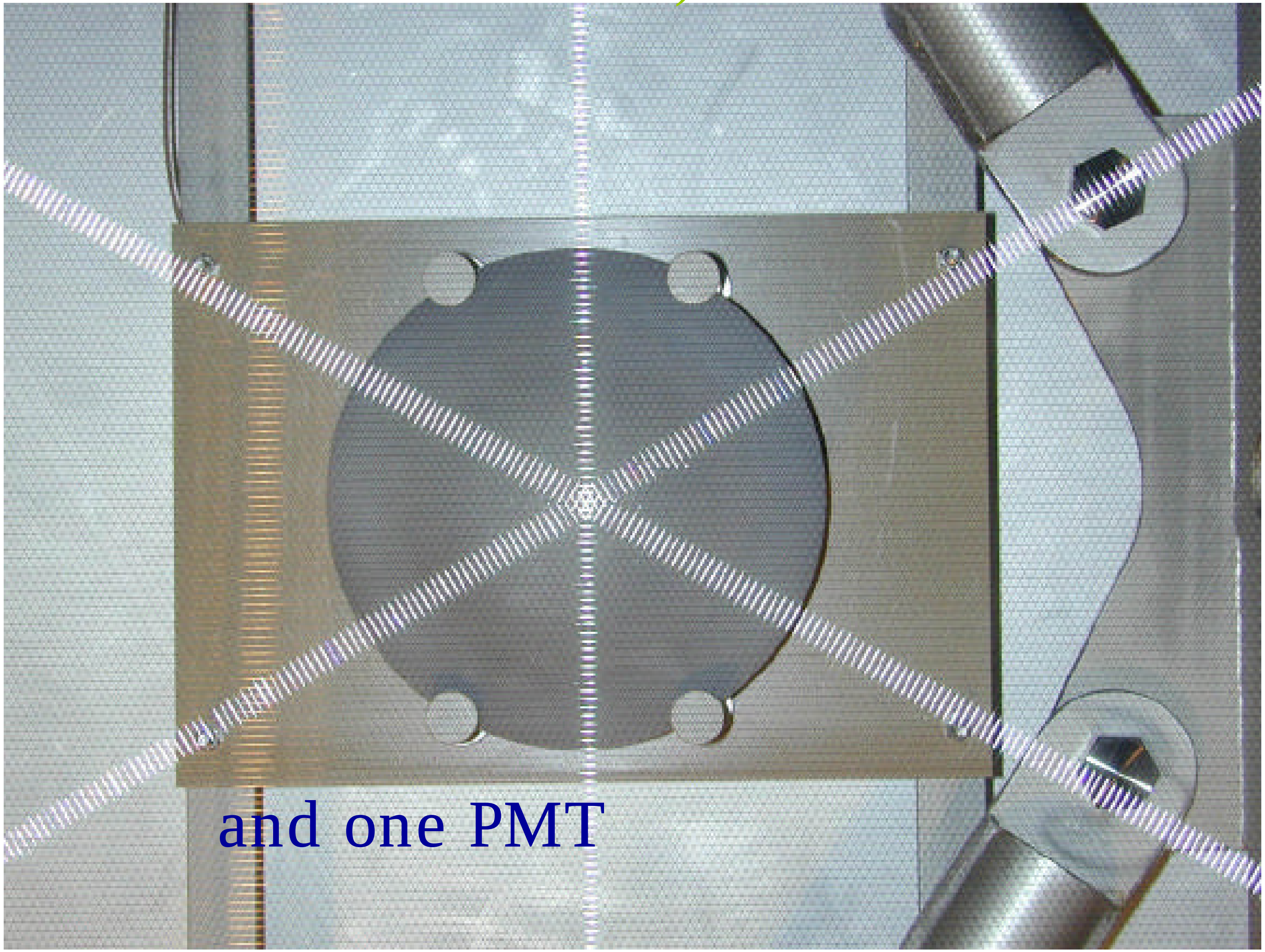



Wire Chamber
Side B
Wire Chamber
Side A
Drift distance
1.5 m

Drift H.V. and field electrodes system



The three wire planes at 0°,±60° (wire pitch = 3mm)



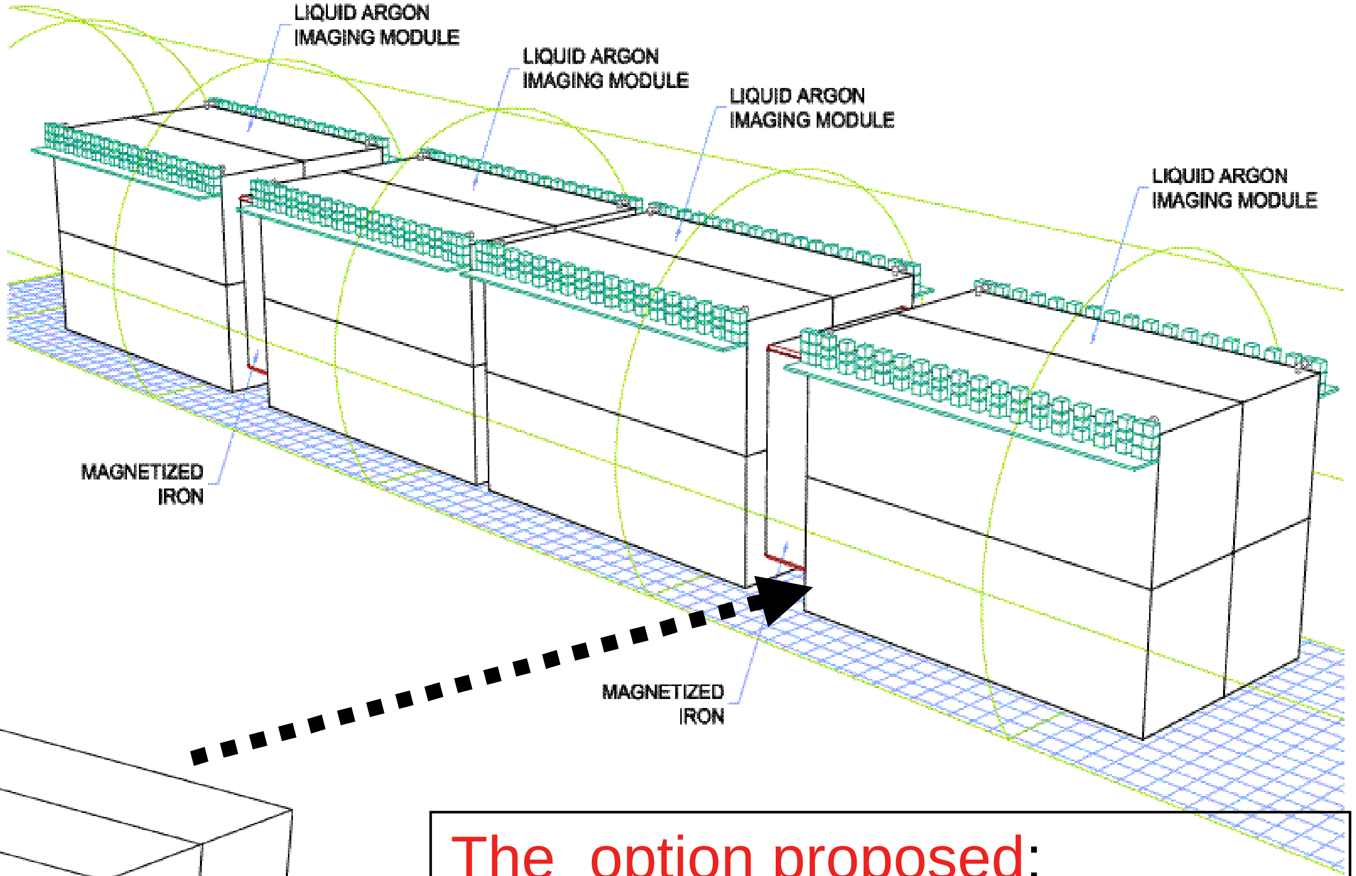
Current T600 status

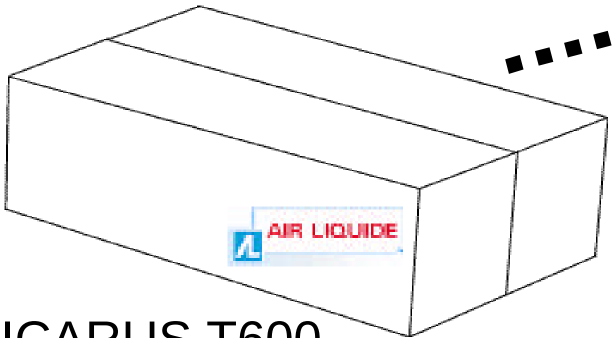
- Total run duration in Pavia ≈ 3 months (100 days)
  - √ Day 1 to 10 — Vacuum (including leak detection)
  - √ Day 11 to 15 — Pre-cooling
  - √ Day 16 to 20 — Cooling
  - √ Day 21 to 30 — Filling
  - √ Day 31 to 45 — Liquid recirculation
  - √ Day 46 to 55 — Complete detector start-up
  - √ Day 56 to 65 — Data taking with horizontal tracks ***"Big Track"***
  - – Day 66 to 70 — Data taking with vertical tracks
  - – Day 71 to 75 — Data taking with internal trigger only
  - – Day 76 to 90 — Data taking with DEDALUS triggers
  - – Day 91 to 93 — Data taking with liquid recirculation on
  - – Day 94 to 100 — Data taking with 1 kV / cm drift field

We are here!

ICARUS

The T600 is a milestone towards future evolutions. In order not be statistically limited a multi-Kton detector is needed for the CNGS. This could come naturally from a cloning strategy of the T600.





ICARUS T600

The option proposed:
2 x T1200 +T600

$\nu_\mu \rightarrow \nu_\tau$ oscillations (I)

- Analysis of the electron sample
  - Exploit the small intrinsic ν_e contamination of the beam (0.8% of ν_μ CC)
  - Exploit the unique e/π^0 separation

8 years of "shared" running

$\nu_\mu \longrightarrow \nu_\tau$

$\nu_\tau + N \longrightarrow \tau + jet; \tau \rightarrow e\nu\nu$

Charged current (CC)

Br ~18%

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

110 *events*

Background: $\nu_e + N \longrightarrow e + jet$

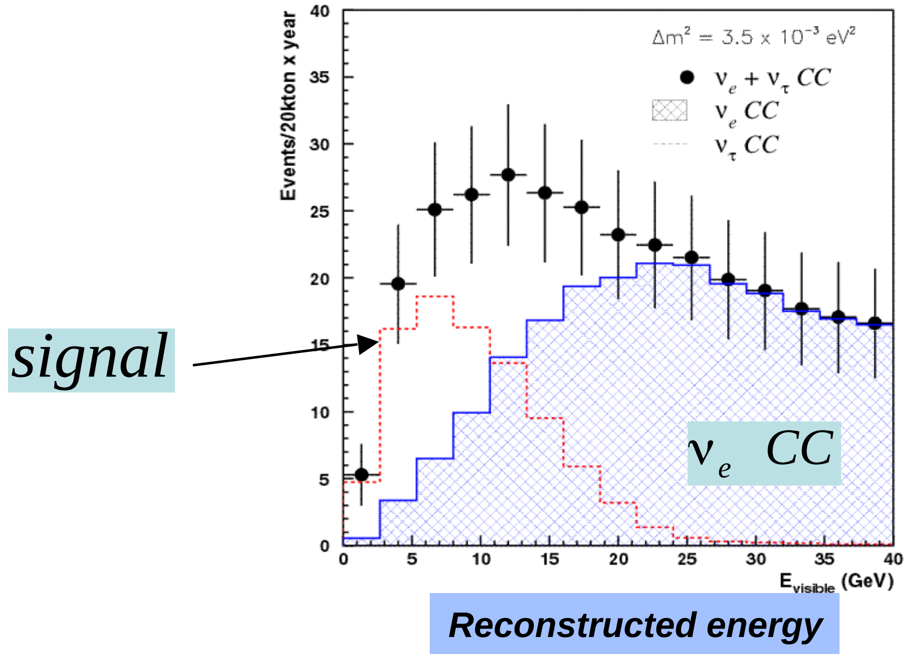
Charged current (CC)

$470 \ \nu_e CC$

Statistical excess visible before cuts ⇒ this is the main reason for performing this experiment at long baseline !

$\nu_\mu \rightarrow \nu_\tau$ oscillations (II)

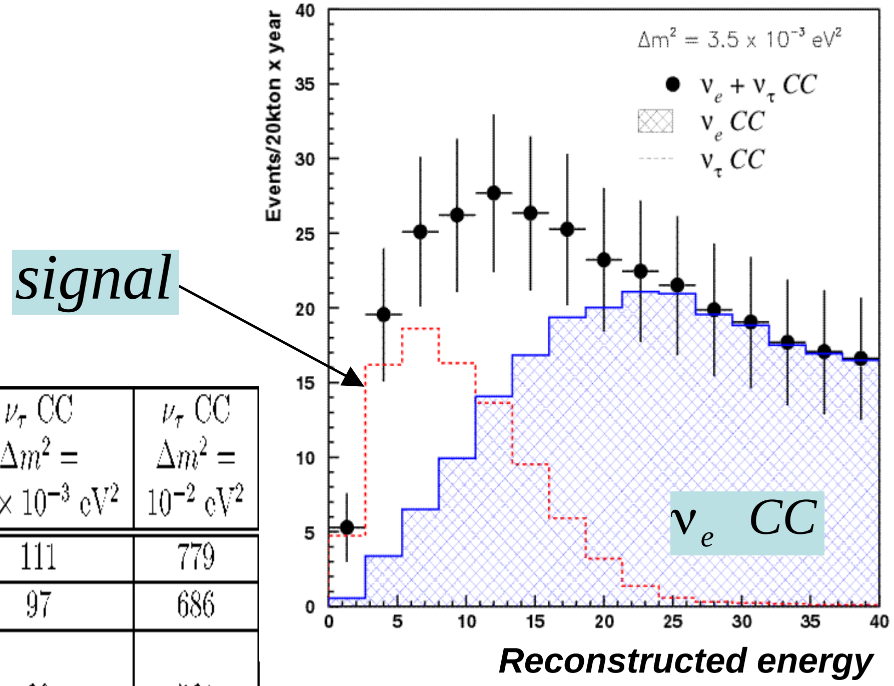
- Reconstructed visible energy spectrum of electron events clearly evidences excess from oscillations into tau neutrino



Cuts	ν_τ Eff. (%)	ν_e CC	$\bar{\nu}_e$ CC	ν_τ CC $\Delta m^2 = 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 10^{-2}$ eV^2
Initial	100	437	29	9.3	71	111	779
Fiducial volume	88	383	25	8.2	64	97	686
One candidate with momentum > 1 GeV	72	365	25	6.7	50	80	561
$E_{vis} < 18$ GeV	67	64	5	6.2	46	75	522

$\nu_\mu \rightarrow \nu_\tau$ oscillations (II)

Reconstructed visible energy spectrum of electron events clearly evidences excess from oscillations into tau neutrino



Cuts	ν_τ Eff. (%)	ν_e CC	$\bar{\nu}_e$ CC	ν_τ CC $\Delta m^2 = 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 10^{-2}$ eV^2
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$E_{vis} < 18$ GeV	67	64	5	6.2	46	75	522
$P_T^e < 0.9$ GeV	54	31	3	5.0	38	60	421
$P_T^{lep} > 0.3$ GeV	51	29	2	4.7	35	56	397
$P_T^{miss} > 0.6$ GeV	33	4	0.4	3.1	23	37	257

$\nu_\mu \rightarrow \nu_\tau$ oscillations (III)

- Kinematical selection in order to enhance S/B ratio
- Can be tuned “a posteriori” depending on the actual Δm^2
- For example, with cuts listed below, reduction of background by factor 100 for a signal efficiency 33%

Cuts	ν_τ Eff. (%)	ν_e CC	$\bar{\nu}_e$ CC	ν_τ CC $\Delta m^2 = 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 10^{-2}$ eV^2
Initial	100	437	29	9.3	71	111	779
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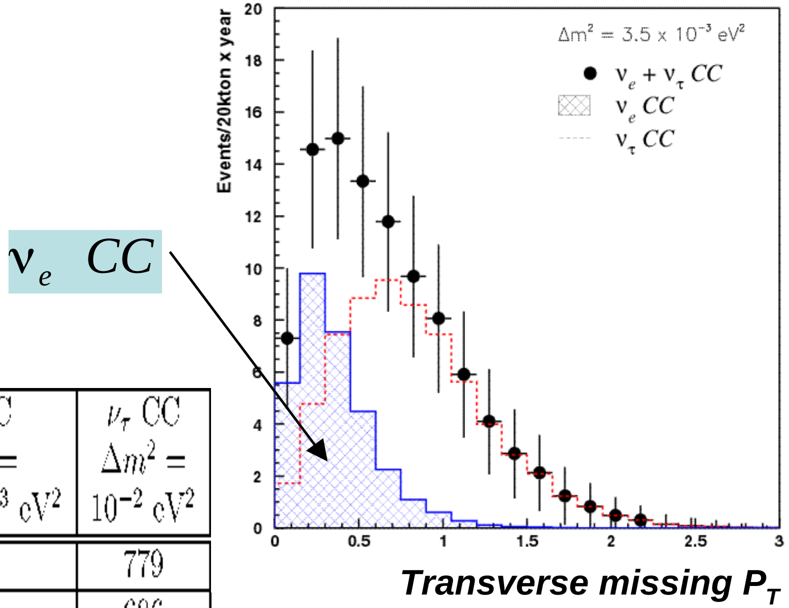
$P_T^{miss} > 0.6$ GeV	33	4	0.4	3.1	23	37	257



Search for $\theta_{13} \neq 0$ (I)

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

8 years @ CNGS

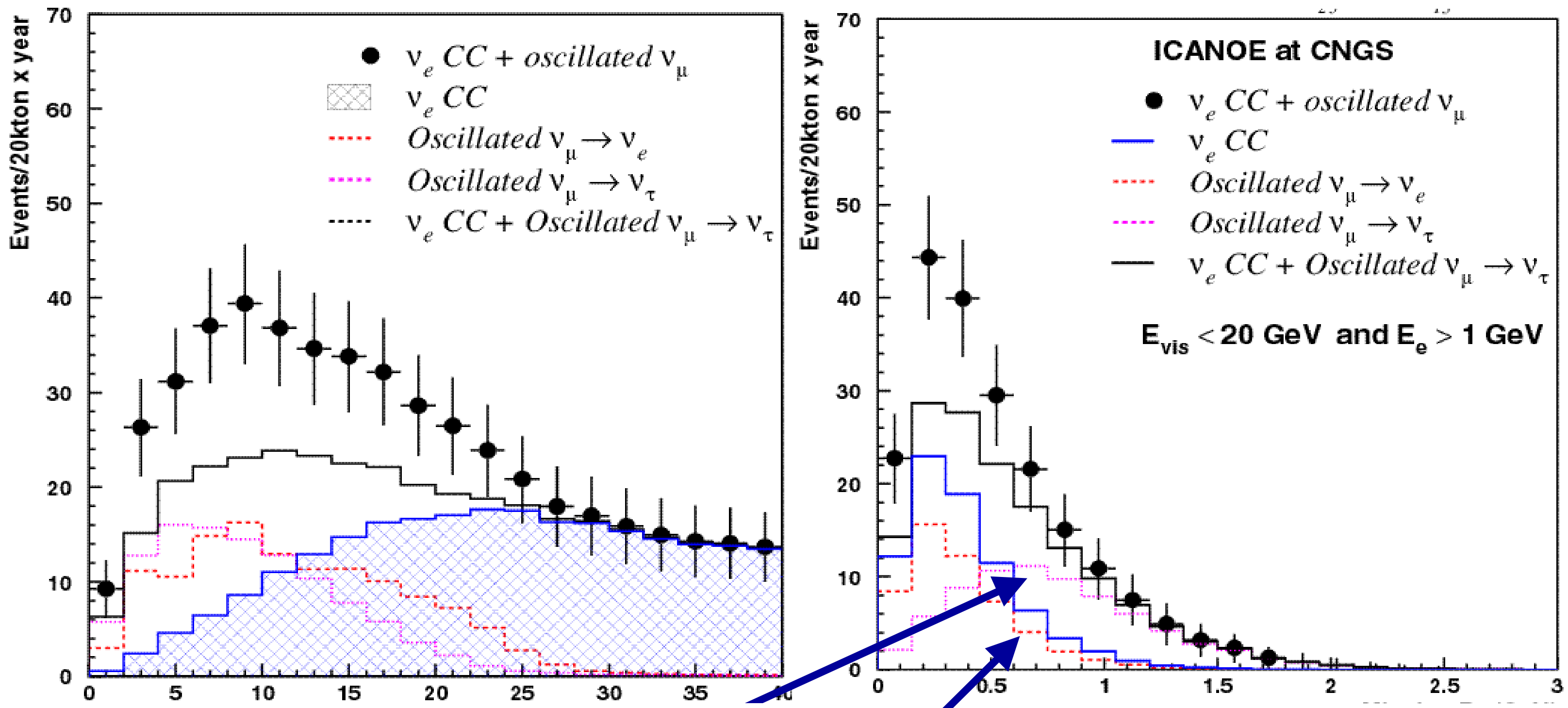
Cuts: Fiducial, $E_e > 1$ GeV, $E_{vis} < 20$ GeV						
$\Delta m^2_{23} = 3.5\times10^{-3}$ eV^2, $\theta_{23} = 45^o$						
θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC	$\nu_\mu \to \nu_\tau$ $\tau \to e$	$\nu_\mu \to \nu_e$	Total	Statistical significance
9	0.095	79	74	84	237	6.8σ
8	0.076	79	75	67	221	5.4σ
7	0.058	79	76	51	206	4.1σ
5	0.030	79	77	26	182	2.1σ
3	0.011	79	77	10	166	0.8σ

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

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

Search for $\theta_{13} \neq 0$ (II)

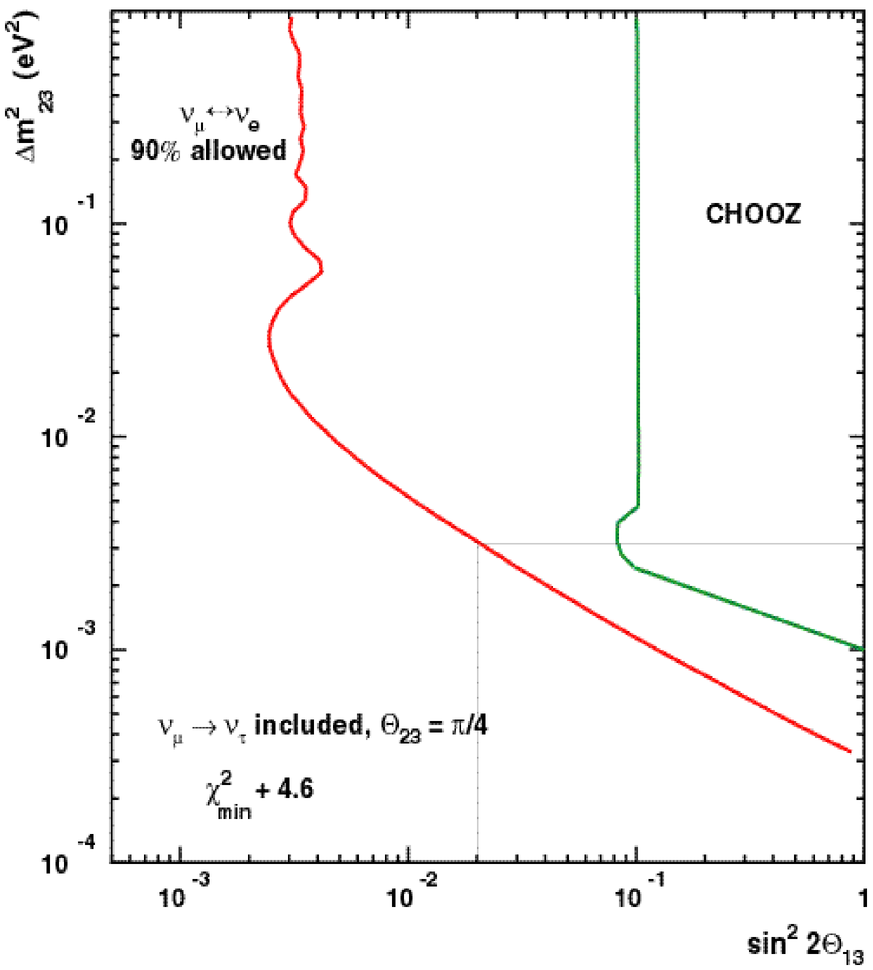
Δm^2_{32}=3.5x10^{-3} eV^2; $\sin^2 2\theta_{23}$ = 1 ; $\sin^2 2\theta_{13}$ = 0.05



Total visible energy ***Transverse missing P_T***

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

Sensitivity to θ_{13} in three family-mixing

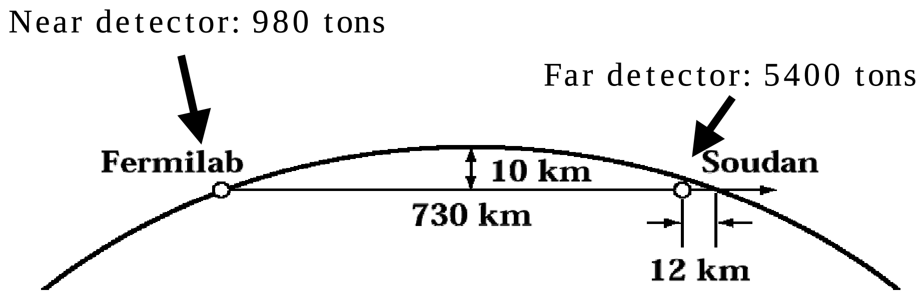


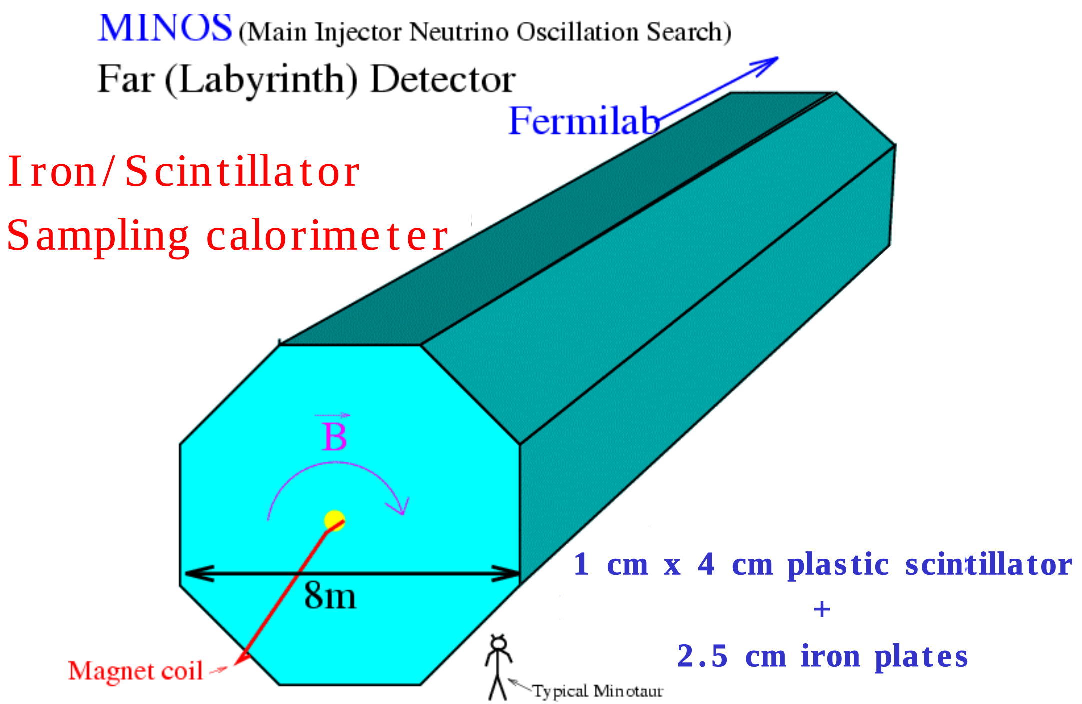
8 years @ CNGS

- Estimated sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillations in presence of $\nu_\mu \rightarrow \nu_\tau$ (three family mixing)
- Factor 5 improvement on $\sin^2 2\theta_{13}$ at $\Delta m^2 = 3\text{x}10^{-3}$ eV^2
- Almost two-orders of magnitude improvement over existing limit at high Δm^2

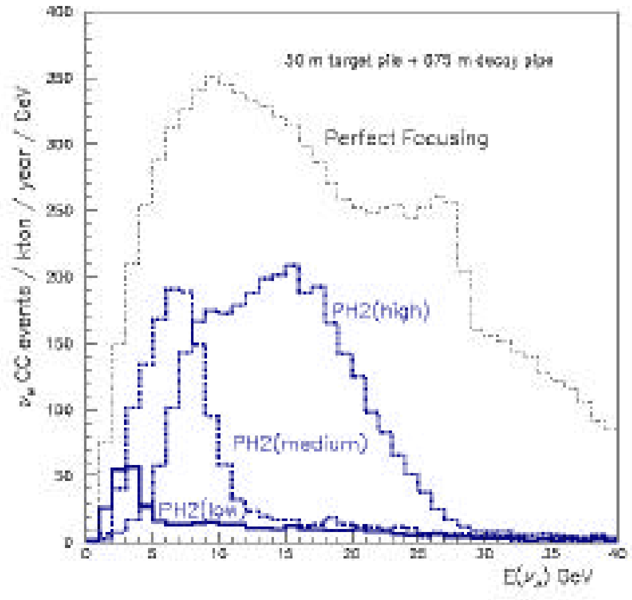
The MINOS Experiment

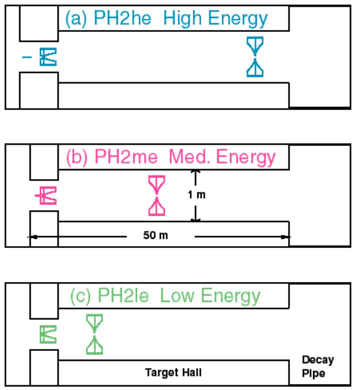
Two Detector Neutrino Oscillation Experiment (Start 2004)





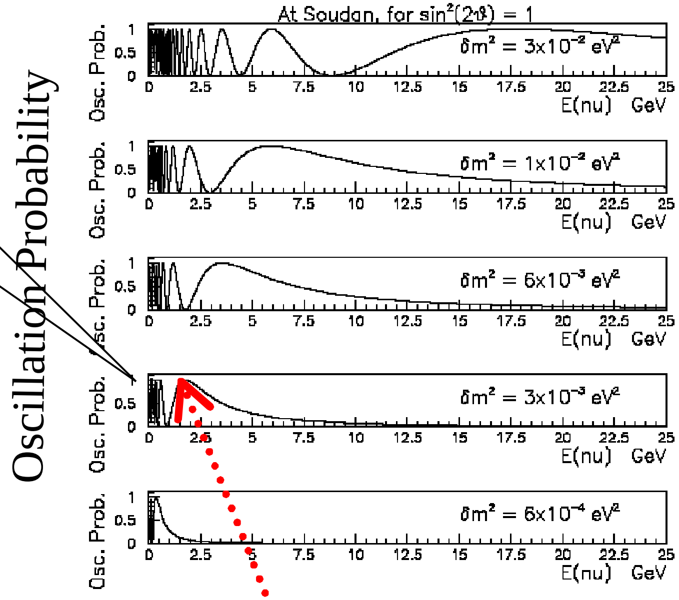
The neutrino beam





Target and horn 2 are moveable
the beam energy can be changed

SK best fit

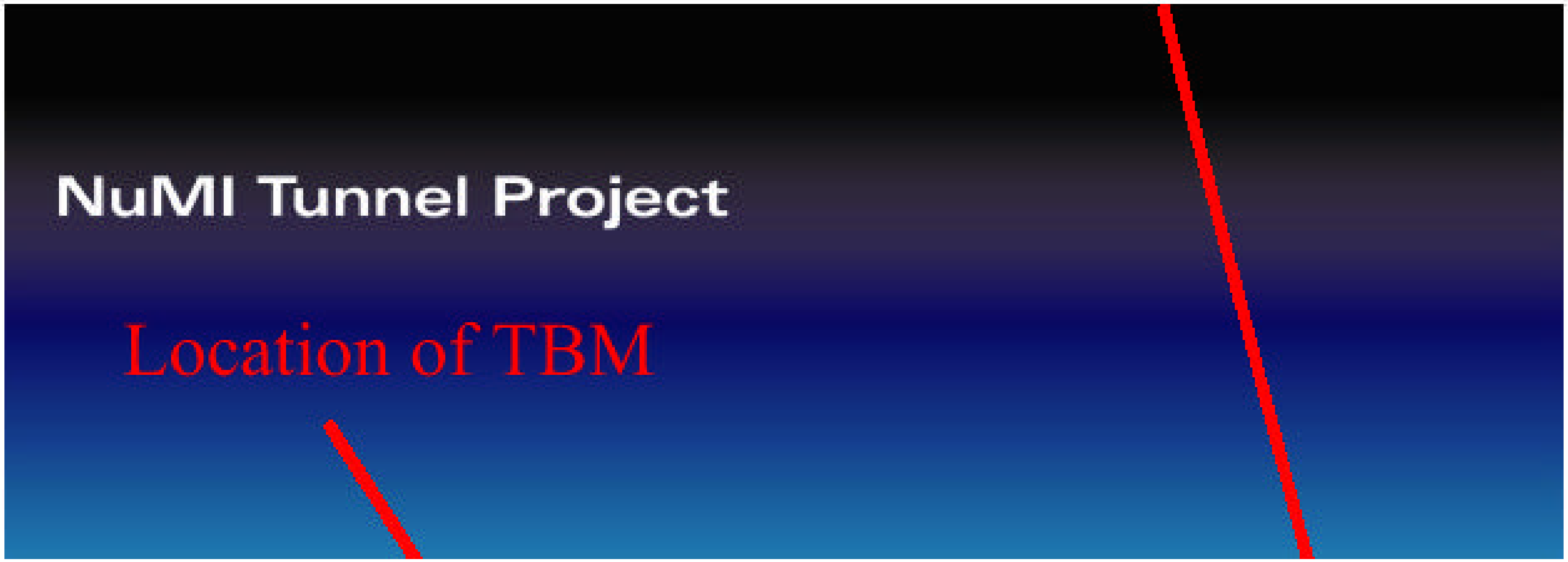


1st oscillation maximum

Need the low energy beam with $\langle E_\nu \rangle$ = 7.6 GeV to see 1st oscillation maximum which occurs at 2 GeV

Beamline from side

Detector shaft
about 3/4
complete

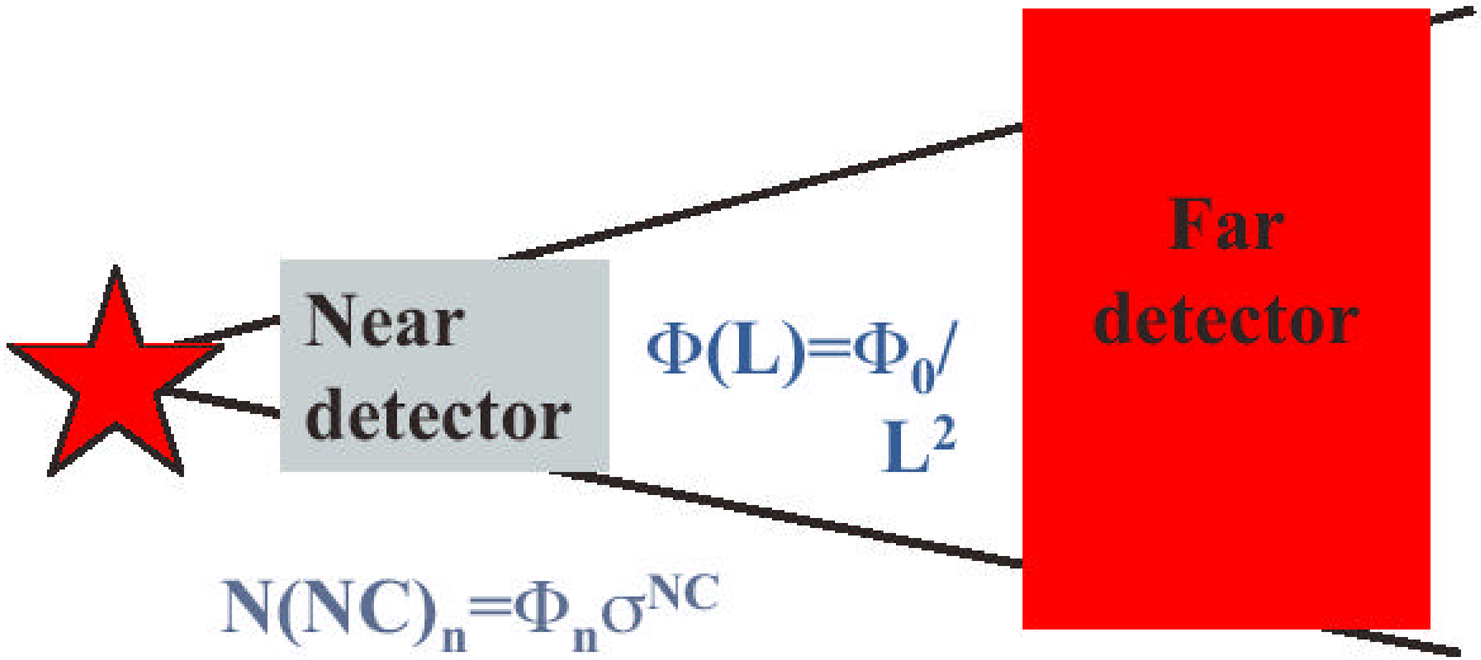


Civil Construction at Soudan

Physics Measurements

- **Obtain firm evidence for oscillations**
  - ✓ Charge current (CC) interaction rate and energy distribution
  - ✓ NC/(CC+NC) ratio (T-test)
- **Measurement of oscillation parameters, Δm^2, $\sin^2 2\theta$**
  - ✓ CC energy distribution
- **Determination of the oscillation mode(s)**
  - ✓ ν_τ or ν_s from NC and CC energy distributions
  - ✓ $\nu_\mu \rightarrow \nu_e$ limits or observation by identification of electrons

Two detector experiment

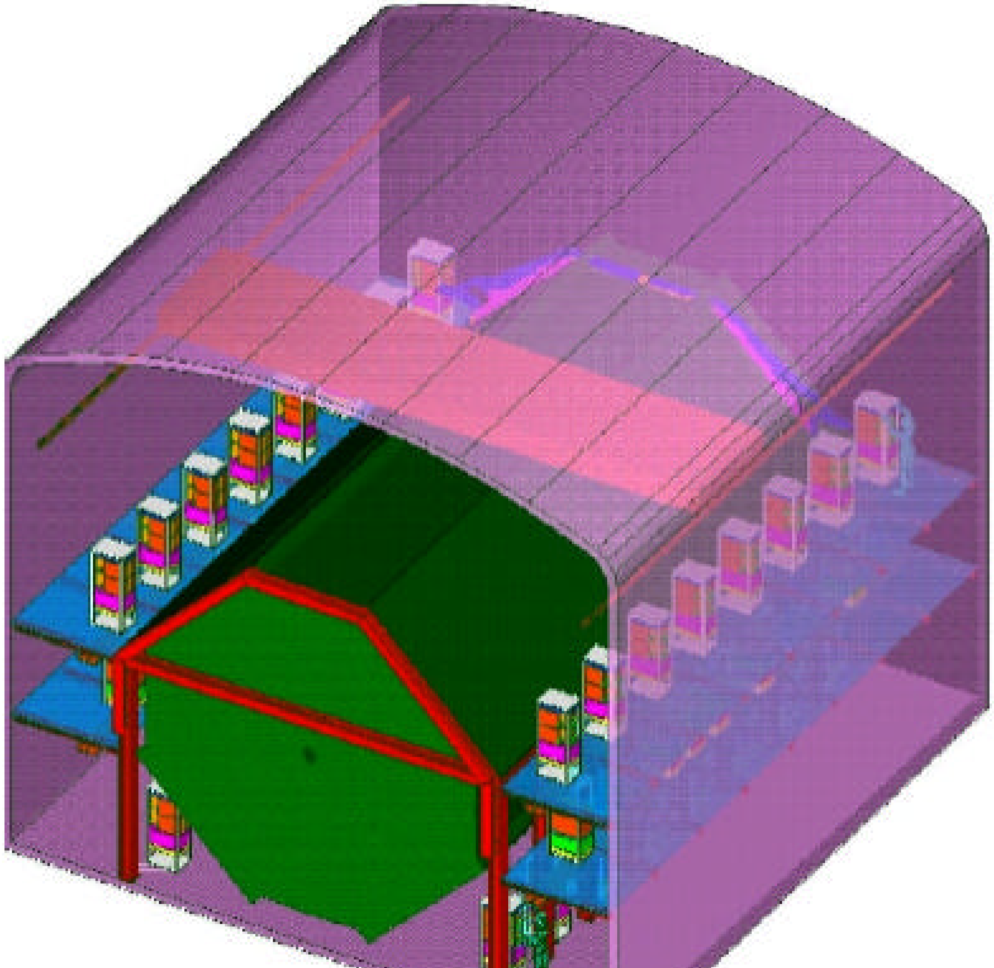


$N(NC)_n=\Phi_n\sigma^{NC}$

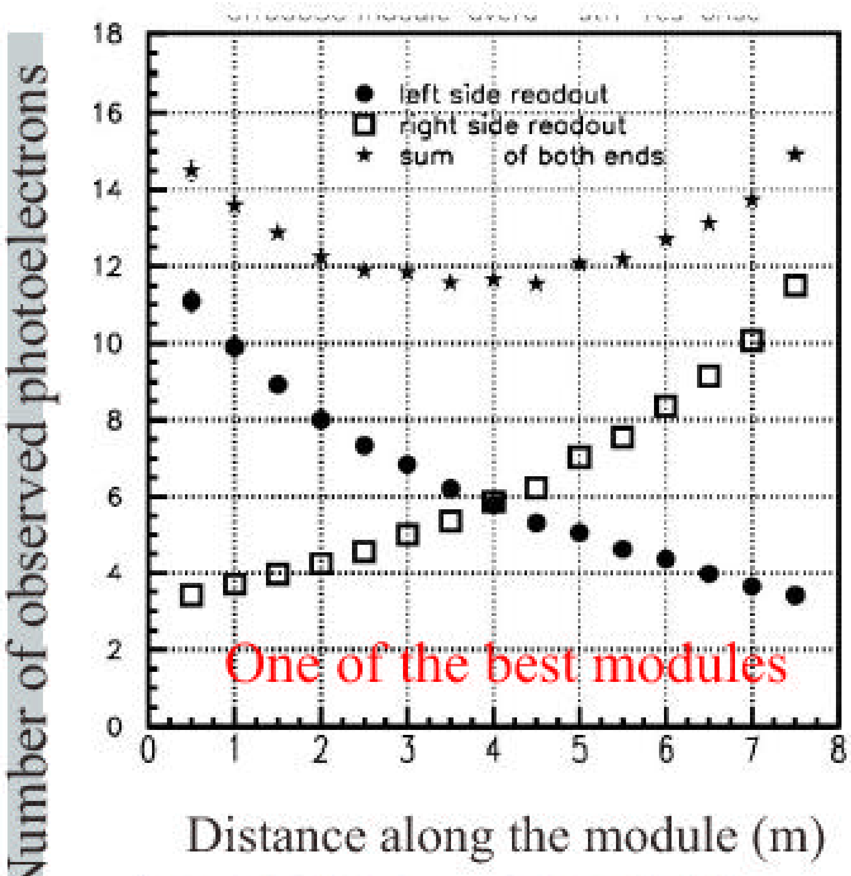
$N(CC)_n=\Phi_n\sigma^{CC}$

$N(NC)_f=\Phi_f\sigma^{NC}$

MINOS Far Detector



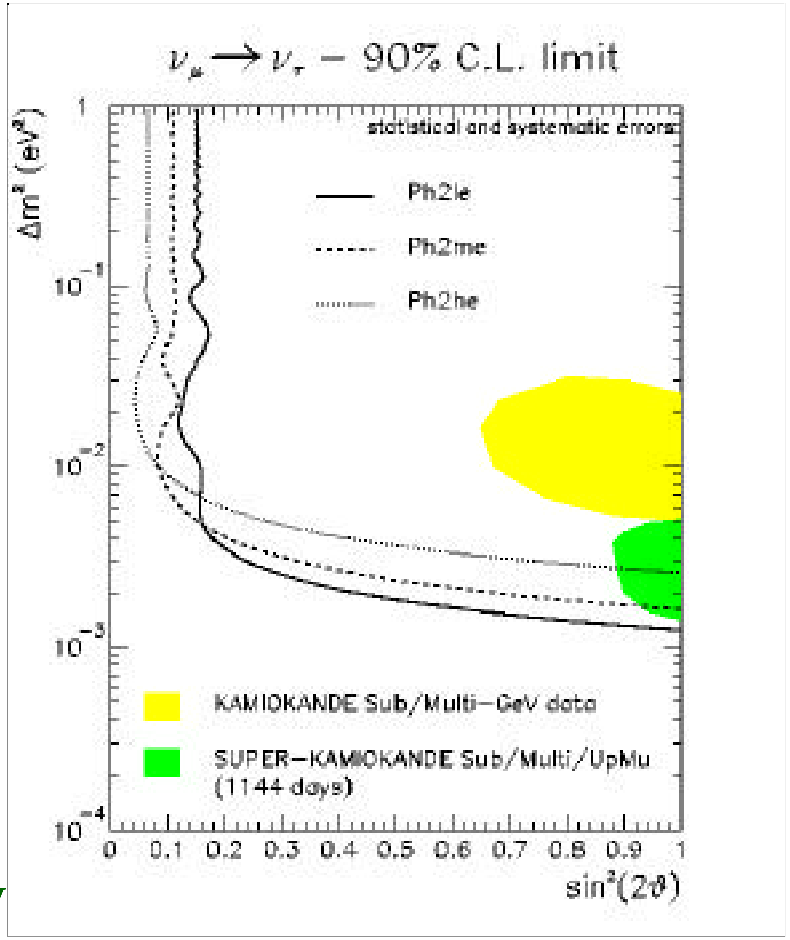
Light Output Measurements



light output measured
Using full MINOS readout chain (connectors, clear fibers, PMTs…).
Light to phototubes improving from initial design (2.2 to 4.7!)

Limit from the T-test

$$T = \frac{N_{CC-like}}{N_{CC-like} + N_{NC-like}}$$



$N_{CC\text{-like}}$ ≡ events with identified muon

$N_{NC\text{-like}}$ ≡ events with no muon

10 kton-yr exposure

2% overall flux uncertainty

2% CC efficiency uncertainty

2% NC trigger efficiency uncertainty

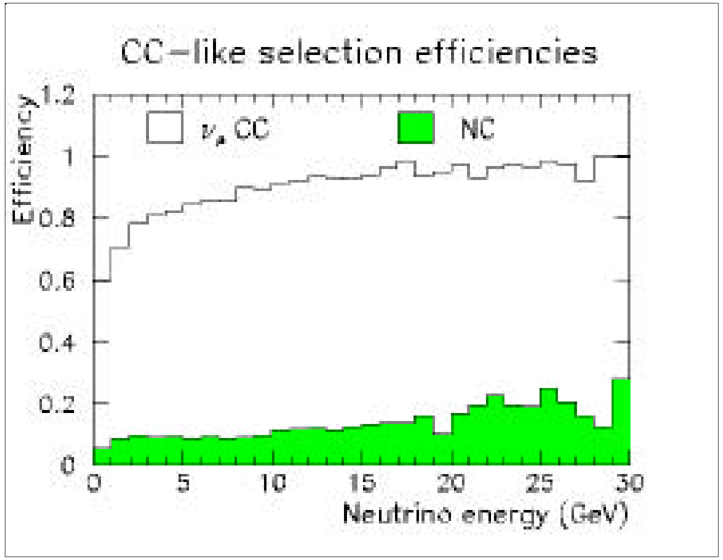
Limit from the CC Energy Spectrum

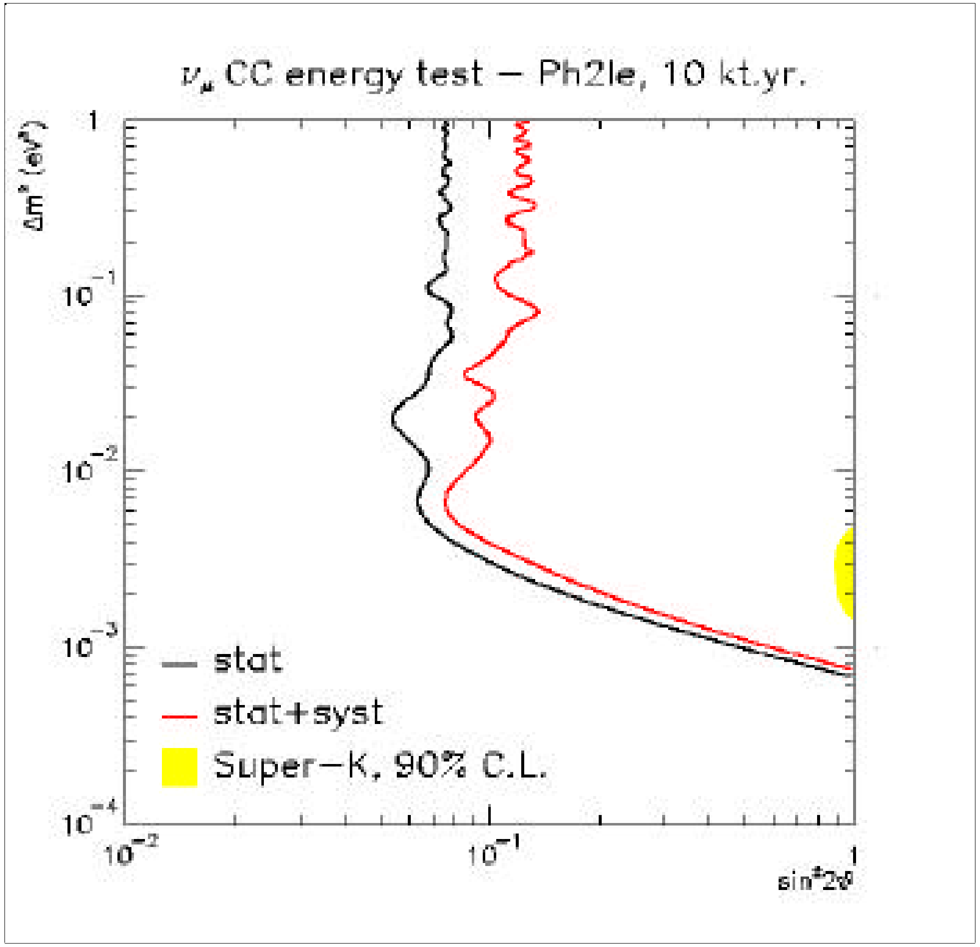
10 kton-yr exposure

2% overall flux uncertainty

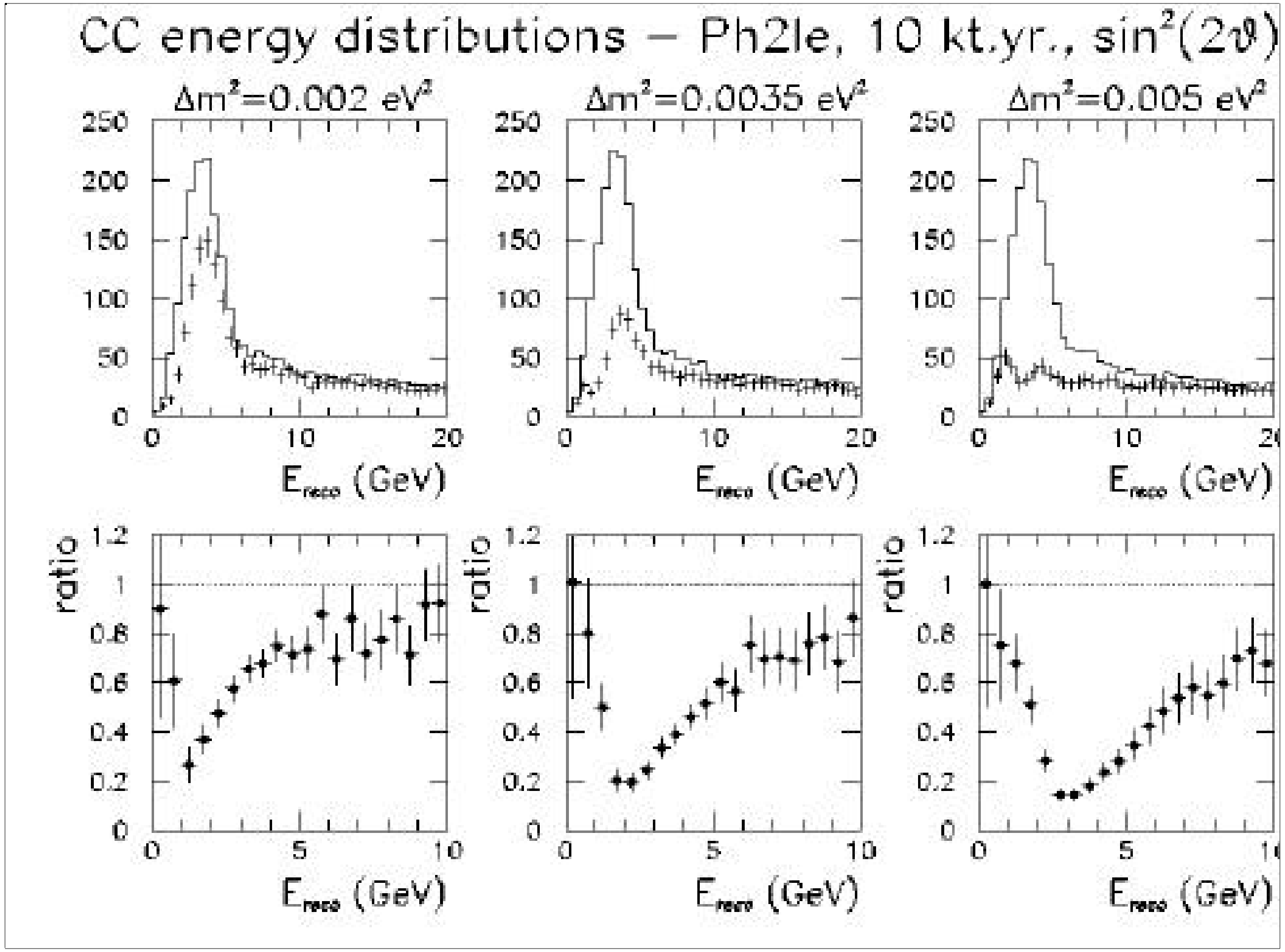
2% bin-to-bin flux uncertainty

2% CC efficiency uncertainty





CC Energy Spectrum for various Δm^2



Δm^2, $\sin^2 2\theta$ sensitivity

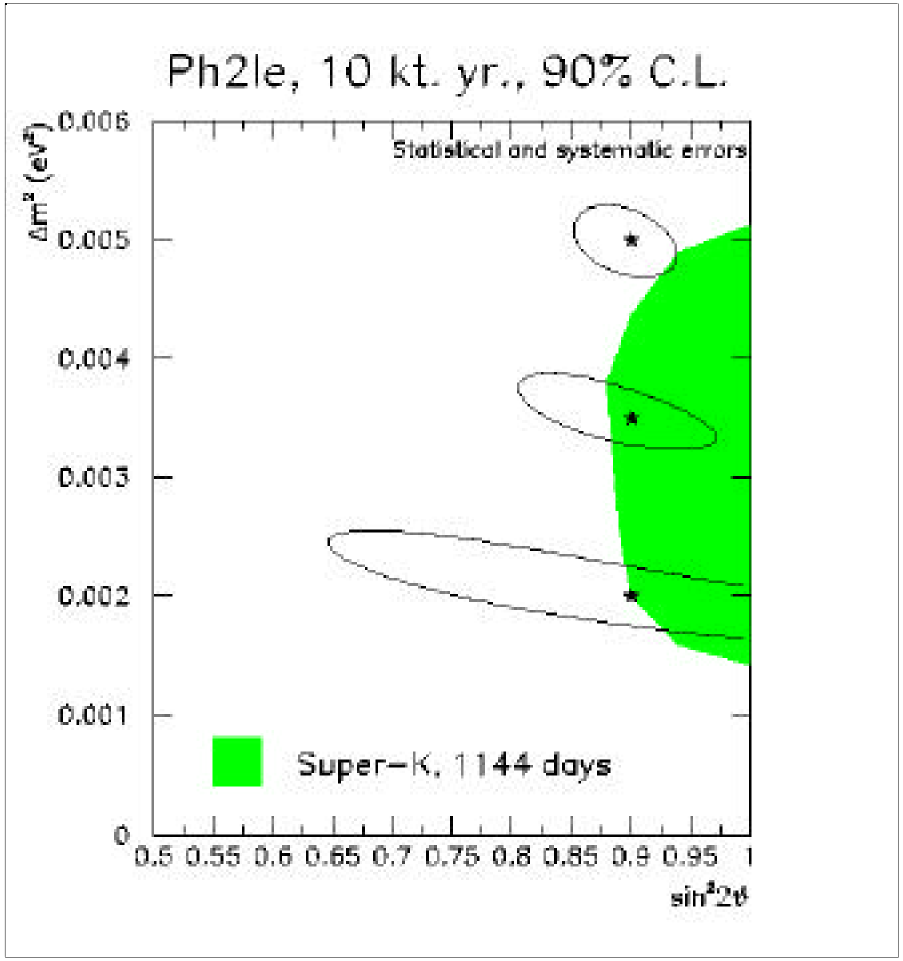
10 kton-yr exposure

2% overall flux uncertainty

2% bin-to-bin flux uncertainty

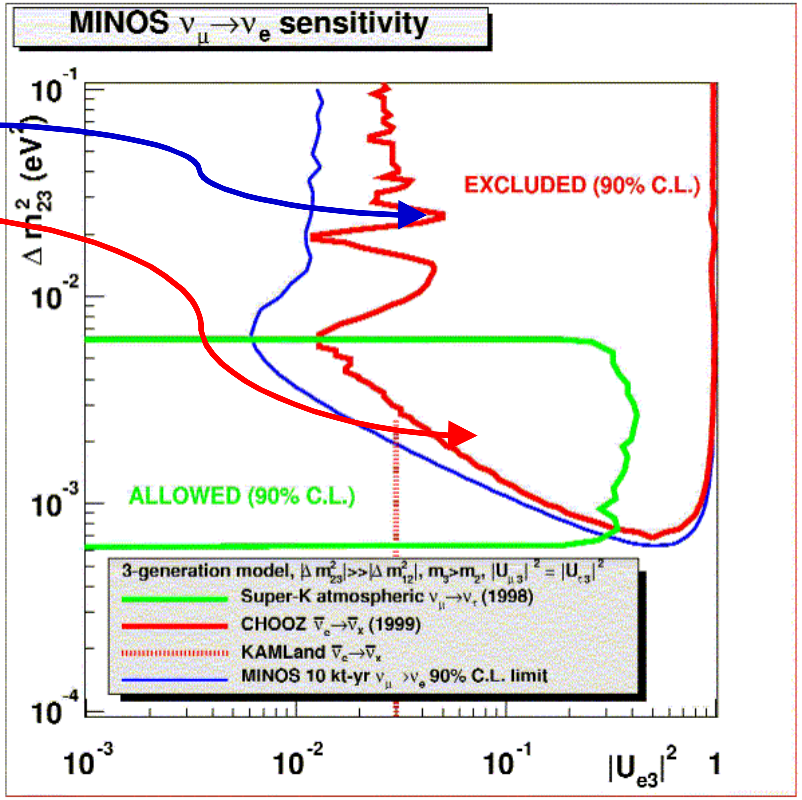
2% CC efficiency uncertainty

For $\Delta m^2 = 0.0035\ eV^2$ should be able to achieve better than 10% error at 68% C.L on both Δm^2 and $\sin^2 2\theta$



Limit on $\nu_\mu \rightarrow \nu_e$

MINOS 10 kt-yr
90% C.L. limit
Chooz 1999

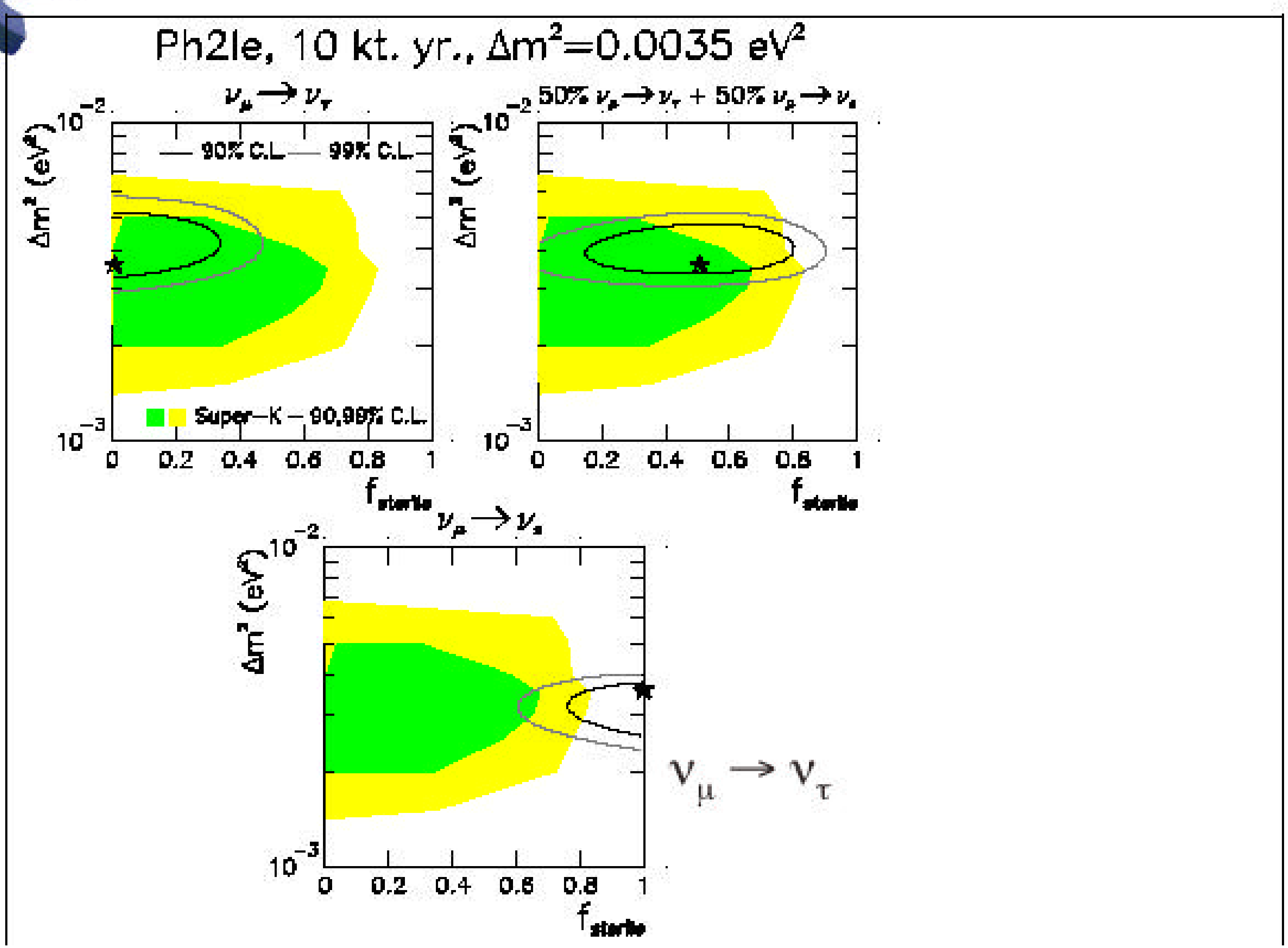


$m_3 > m_2$
Matter effects included
$\Delta m^2_{solar} = 3 \times 10^{-5}$ eV^2
$\theta_{12} = \theta_{23} = 45$ degrees
$\delta = 0$
10% systematic error on background

$U_{e3}^2 < 0.013$ @ $\Delta m^2 > 3 \times 10^{-3}$ eV^2
$\sin^2 2\theta_{13} < 0.05$ @ $\Delta m^2 > 3 \times 10^{-3}$ eV^2

Already close to systematics limited with 10% error on background

$\nu_\mu \rightarrow \nu_s$ or $\nu_\mu \rightarrow \nu_\tau$



JHF-Kamioka neutrino experiment

- ✓50 GeV PS machine
- ✓Super-Kamiokande as a far detector
- ✓Baseline 295 km
- ✓Low energy neutrino beam tuned at the oscillation maximum

Approved in December 2000

Construction 2001-2006

Physics measurements

- Factor 10 improvement in ν_μ disappearance

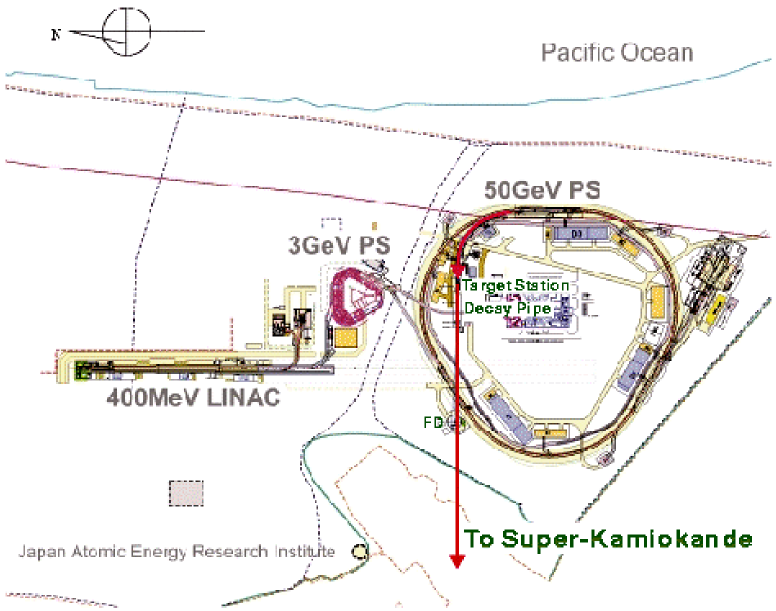
  $\delta(\sin^2 2\theta_{23}) \sim 0.01$ $\delta(\Delta m^2_{23}) \sim 2\text{x}10^{-4}\ \text{eV}^2$

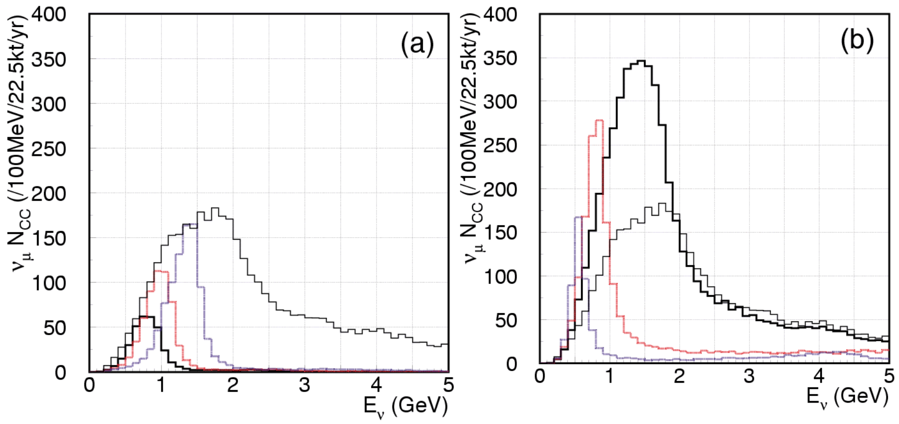
- Search for $\nu_\mu \rightarrow \nu_e$ appearance with a sensitivity 20 times better than CHOOZ limit

  $\sin^2 2\theta\mu e$ $0.5 \text{ x } \sin^2 2\theta_{13} > 0.003$

- Search for a small admixture of sterile neutrinos

Layout of JHF and the ν beam



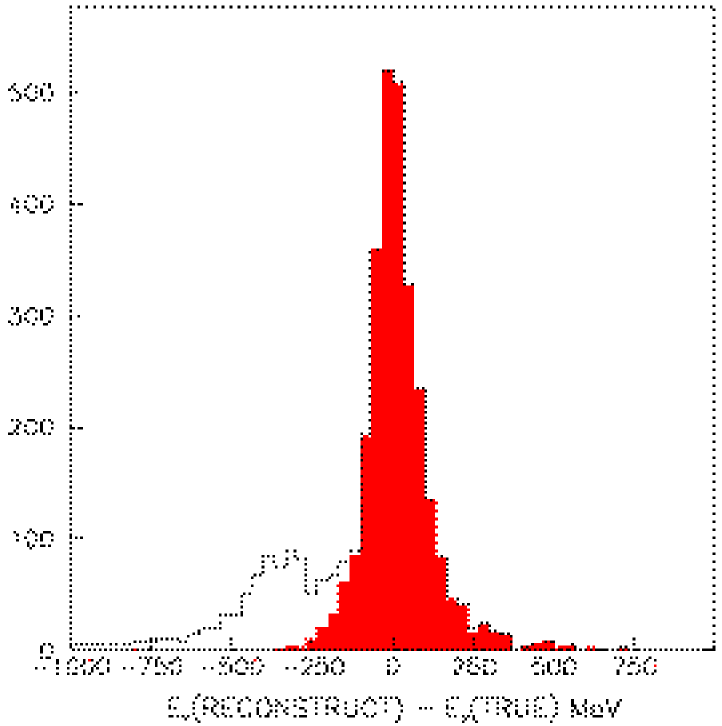


Narrow Band Beam Off Axis beams

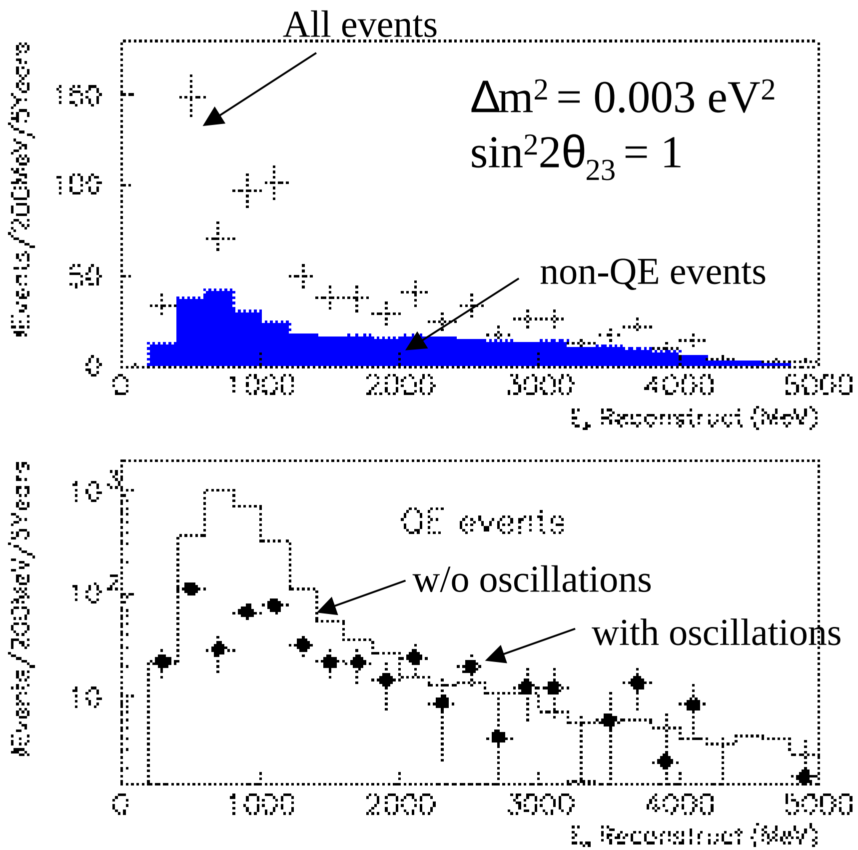
Thin solid line shows the WBB

- A large variety of ν beams is available to tune the energy at the oscillation maximum
- Neutrino beam energy scan possible
- Energy peak around 1 GeV
- Electron neutrino contamination well below 1%

ν_μ disappearance



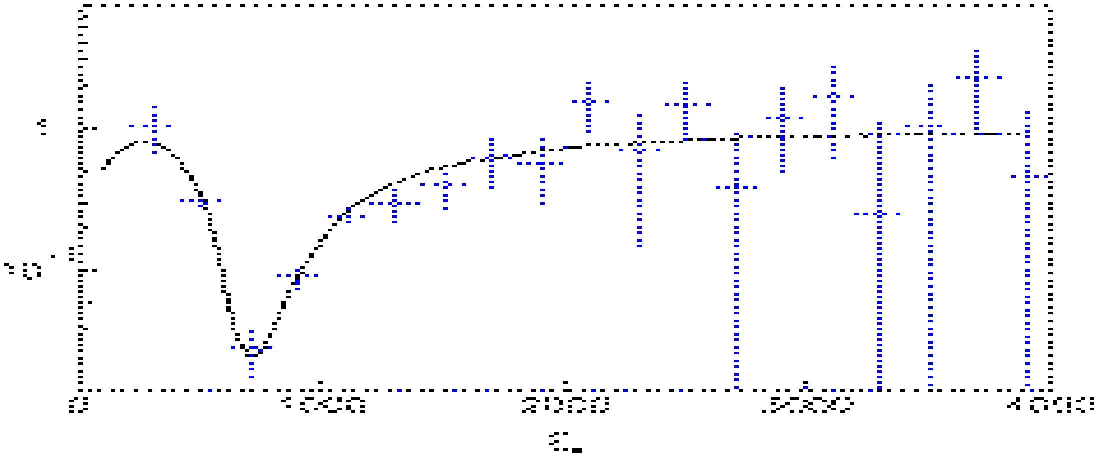
ν energy reconstruction for QE (red) and non-QE interactions



The error bar is from the statistics of 5 years

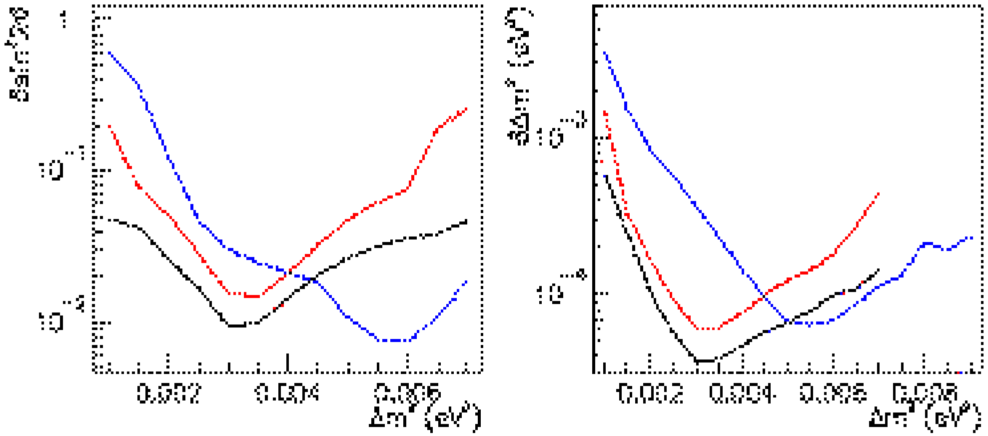
ν_μ disappearance sensitivity

Ratio of measured spectrum with oscillations to the expected one after subtraction of non-QE events



Final sensitivity to oscillation parameters:

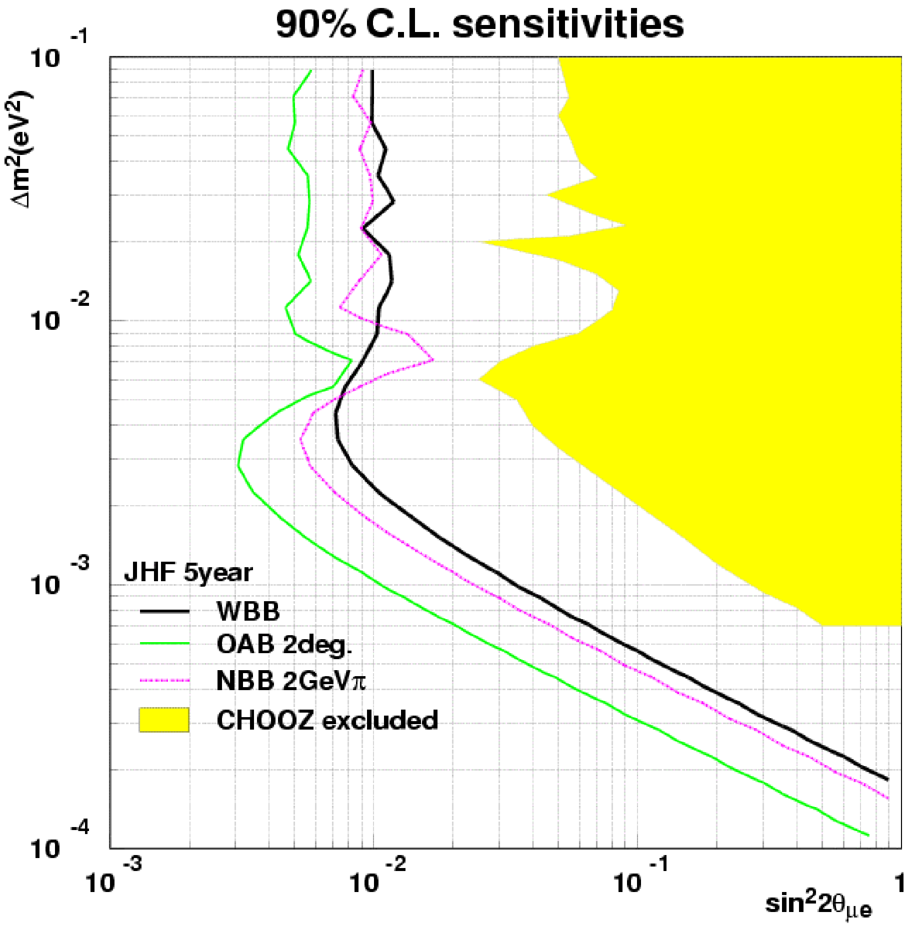
- Off Axis 2° beam
- NBB 1.5 GeV π
- NBB 3 GeV π



$\nu_\mu \rightarrow \nu_e$ appearance search

- Signal: ν_e(Far)/ν_μ(Near) expected to appear at the ν_μ disappearance dip
- Backgrounds
  - ν_μ misidentification: negligible
  - ν_e contamination ~0.2-03%
  - π^0 (neutral current) background ~0.3%

Sensitivity to $\sin^2 2\theta_{\mu e} > 0.003$
A factor 20 better than the CHOOZ limit

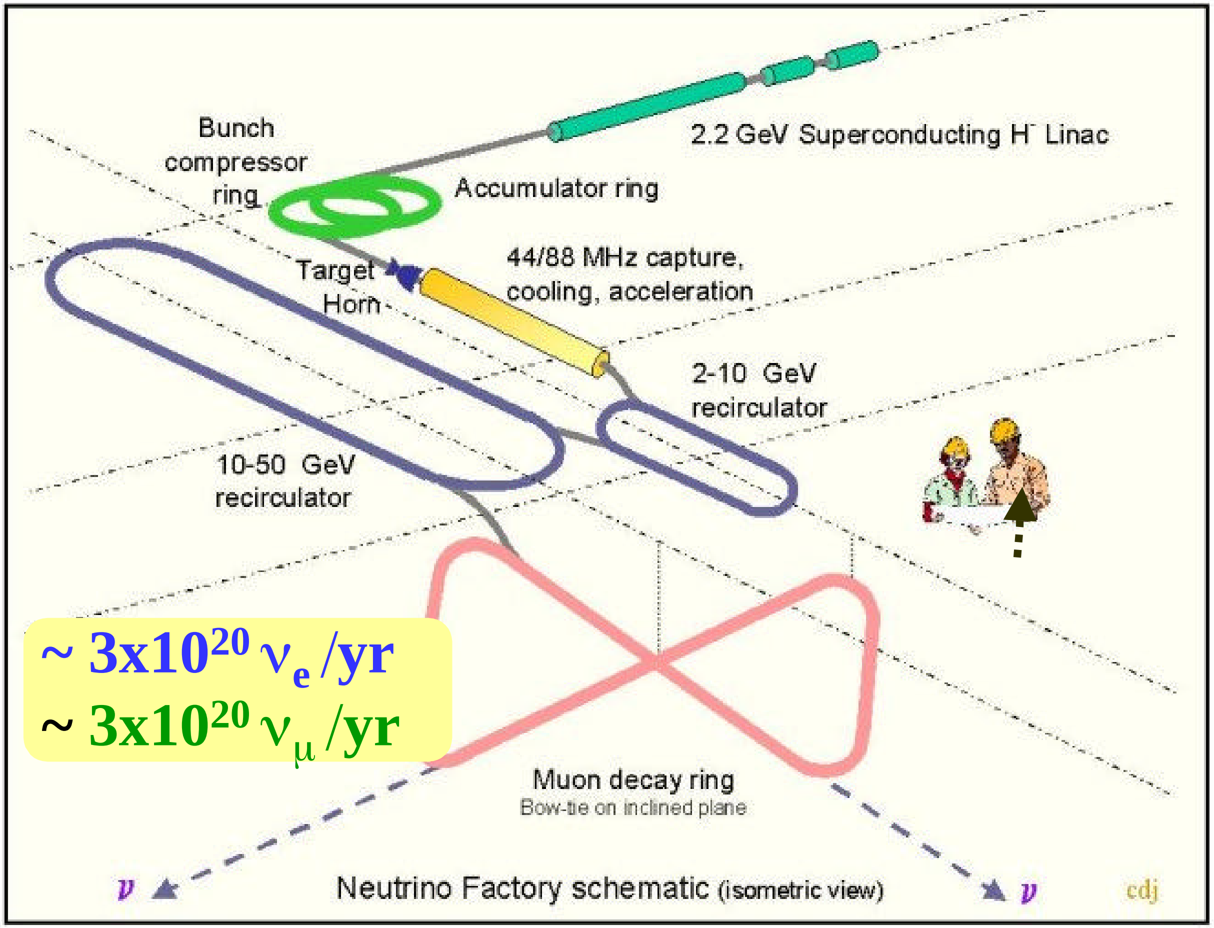


Schedule (assuming full funding in 2002 and 2003)

- October, 2000 – Start of Scintillator Module Production
- December, 2000 – Soudan Cavern Excavation Complete
- August, 2001 - Start of Far Detector Installation
- May, 2002 –Beamline Excavation Complete
- September, 2002 – Completion of 1st MINOS SuperModule

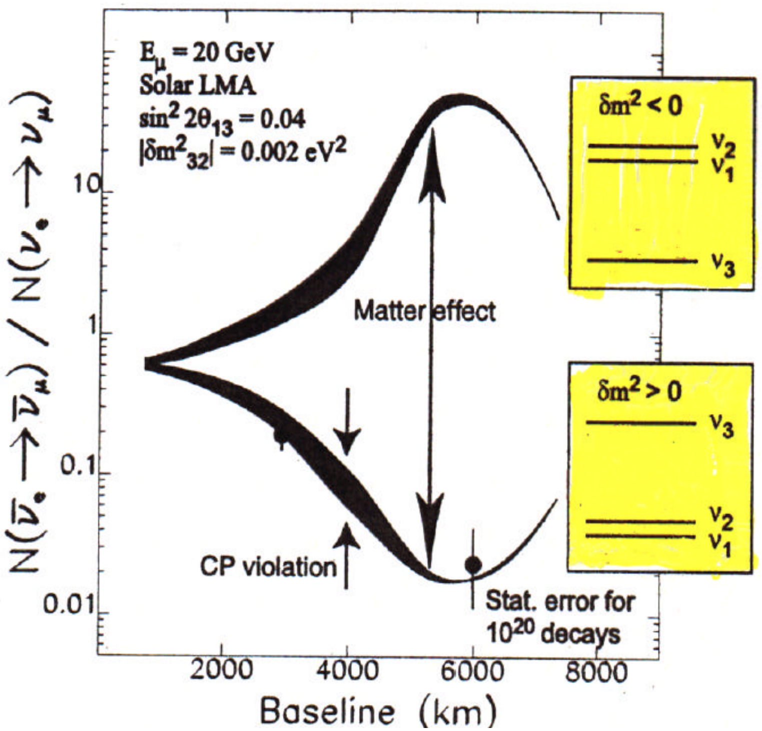
Neutrinos from a muon storage ring

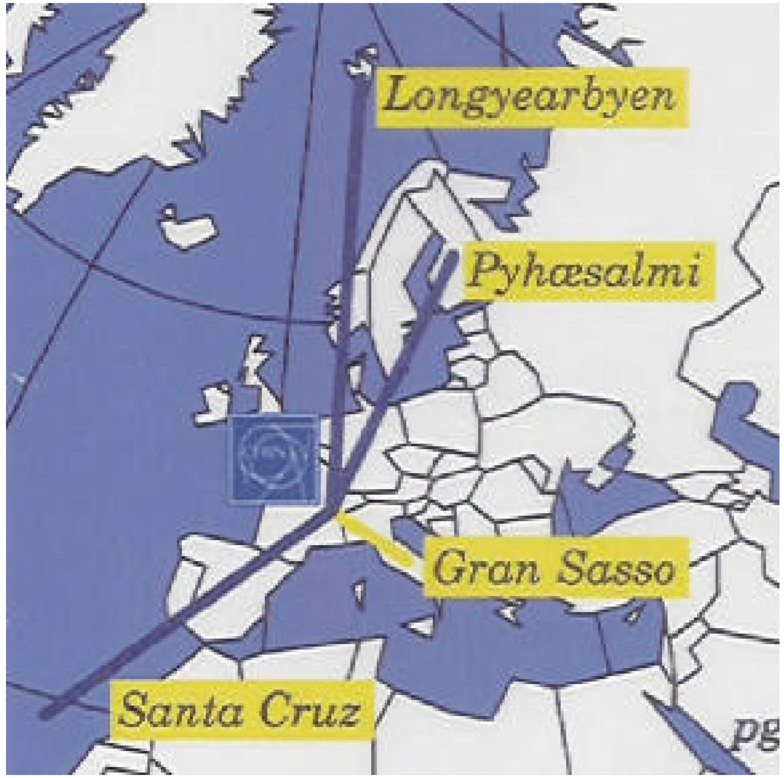
A very complex acceleration and storage system



The CERN present scenario

Search for long-baseline detector laboratories





Optimal baseline is around 3000 km for CP violation + matter effects.

Physics from $\mu \rightarrow e\, \nu_e\, \nu_\mu$ with a long baseline program at a Neutrino Factory

ν_μ disappearance

$\delta(\Delta m^2) \sim 5 \times 10^{-5}$ $\delta(\sin^2 2\theta_{23}) \sim 5 \times 10^{-3}$

$\nu_\mu - \nu_e$ appearance $\rightarrow$ sensitivity down to $\sin^2 2\theta_{\mu e} \sim 10^{-3} - 10^{-4}$

Matter effects $\rightarrow$ sign of Δm_{13}

CP violation

High energy ν_e essential and unique

Neutrino interaction rates x 10 or more w/r to present beams

Very large detectors needed