Neutrino factories$^{(*)}$*: Detector concepts*

**we do not consider conventional "superbeams" (see hep-ph/0103052)*

André Rubbia, ETH Zürich
(ICARUS Collaboration)

Special thanks to A. Bueno & M. Campanelli

IX International Workshop on "Neutrino Telescopes"

6th-10th March, 2001

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**

$$\begin{cases} \nu_\ell N \to \ell^- + hadrons \\ \bar{\nu}_\ell N \to \ell^+ + hadrons \end{cases} \qquad \begin{cases} \nu_\ell N \to \nu_\ell + hadrons \\ \bar{\nu}_\ell N \to \bar{\nu}_\ell + hadrons \end{cases}$$

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 Neutrino Factory

$$\boxed{\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \quad or \quad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu}$$

Roughly as many ν_e's as ν_μ's

Flux scales as

E^2_μ/L^2

Total event rate scales as

$\approx E^3_\mu/L^2$

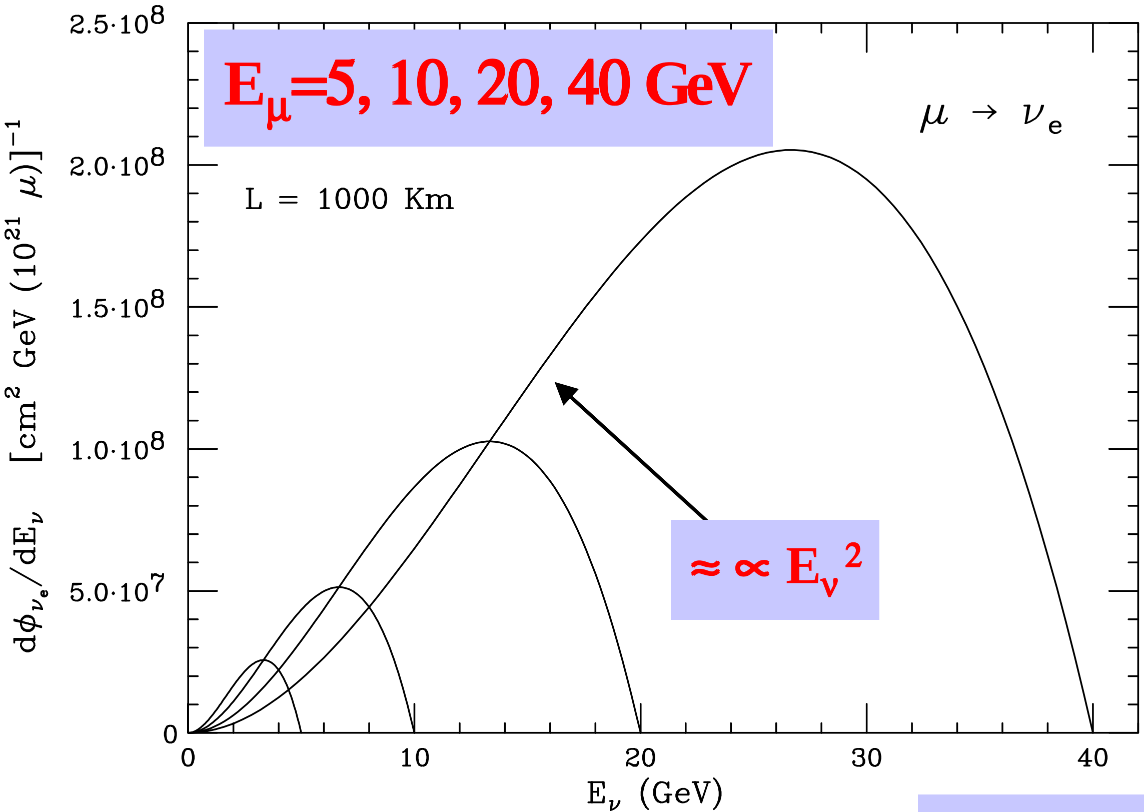
A very important feature!

The generally adopted consensus (see later) ⇒

high energy ν-factory

$E_\mu = O(30\text{GeV})$

P. Lipari, hep-ph/0102046



E_ν (GeV)

$$\frac{dN}{dx} \propto x^2(1-x) \qquad x \equiv E_\nu / E_\mu$$

Predicted event rates at a Neutrino Factory

FNAL-FN-692, Apr 2000

10^{20} μ^- decays

No oscillations assumed

Experiment		Baseline (km)	$\langle E_{\nu_\mu} \rangle$ (GeV)	$\langle E_{\bar{\nu}_e} \rangle$ (GeV)	N(ν_μ CC) (per kt–yr)	N($\bar{\nu}_e$ CC) (per kt–yr)
NuMI	Low energy	732	3	–	458	1.3
	Medium energy	732	6	–	1439	0.9
	High energy	732	12	–	3207	0.9
CNGS		732	17	–	2714	1.4
Muon ring	E_μ (GeV)					
	10	732	7.5	6.6	1400	620
	20	732	15	13	12000	5000
	50	732	38	33	1.8×10^5	7.7×10^4
Muon ring	E_μ (GeV)					
	10	2900	7.6	6.5	91	41
	20	2900	15	13	740	330
	50	2900	38	33	11000	4900
Muon ring	E_μ (GeV)					
	10	7300	7.5	6.4	14	6
	20	7300	15	13	110	51
	50	7300	38	33	1900	770

However, in addition to the increased neutrino flux, ambitious oscillation physics program requires detectors in the ***10's kton*** *range to perform experiment with baselines* ***L≈1000's km***

The goal: detect μ^+, μ^-, e^+, e^-, τ^+, τ^- and NC !

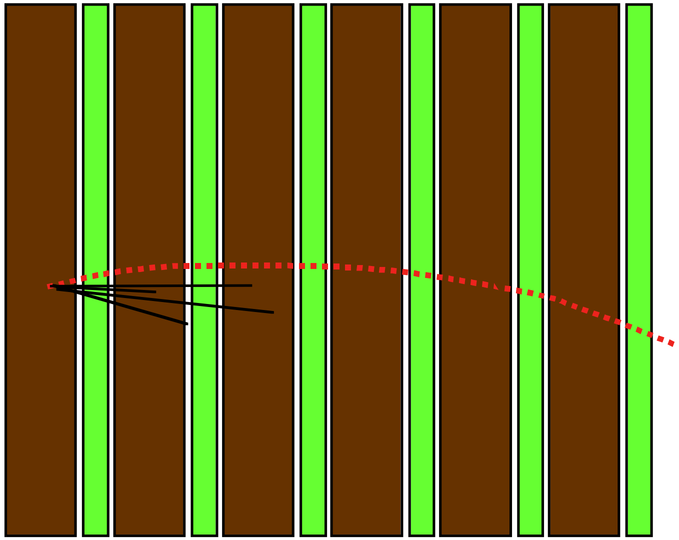
- **Particle ID**: ⇒ *via CC interactions*
  - → **Muons**: ***straight-forward***, look for penetrating particles, but beware $\pi^\pm$,$K^\pm$ and charm decays
  - → **Electrons**: ***harder***, look for large & “short” energy deposition, need good granularity for e/π^0 separation
  - → **Taus**: ***hardest***, “kink” or kinematical methods (statistical separation), $\tau \rightarrow$hadrons$+\nu$ (Br≈60%) look like “NC”
- **Charge ID**: ⇒ *via magnetic analysis*
  - → **Muons**: ***easy***, muon spectrometer downstream or fully magnetized target
  - → **Electrons**: ***hardest***, need to measure significantly precisely the bending in B-field before start of e.m. shower
  - → **Taus**: easy for $\tau \rightarrow \mu\nu\nu$ (Br≈18%), otherwise ***difficult***

This has to be implemented on multi-kton detectors… various choices & optimizations considered.

1a. Magnetized steel-scintillator sandwich

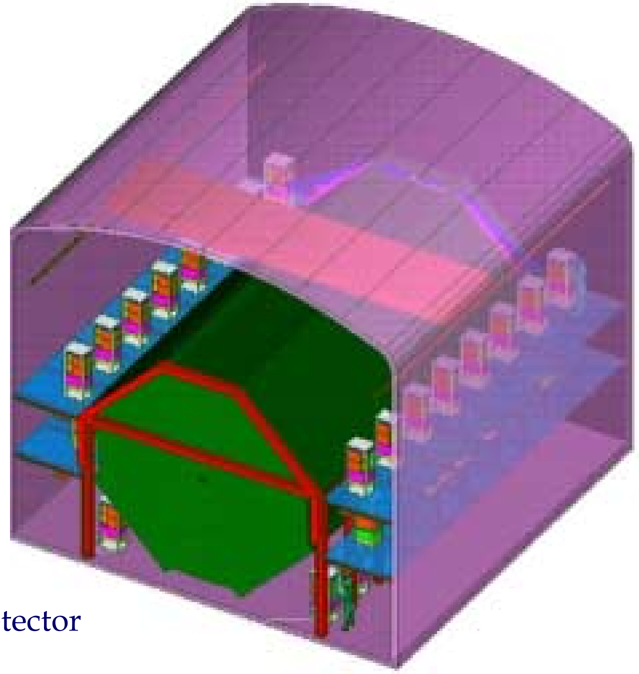
- ***High density***
- ***Magnetizable*** for μ^+/μ^- discrimination
  - → Detects: μ^+, μ^-, [e, NC]
- Good muon and reasonable jet energy resolution $\sigma_{E_h}/E_h \sim 80\%/\sqrt{E_h}$
- ***Lots of experience***: e.g. CCFR/NuTeV, CDHS.
  MINOS will reach 5.4 kton in 2003.
- Disadvantages:
  - → Amount of instrumentation scales with ***volume***
  - → ***Minimum muon energy threshold*** (4-6 GeV) in order to separate it from hadrons and muon isolation from jet difficult to tell. Threshold even higher to have excellent wrong-sign-μ @ 10^{-5}
  - → ***e/h discrimination*** rather poor
  - → Angular resolution determined by transverse readout segmentation, usually rather modest.

The MINOS far detector



- 8m octagonal tracking calorimeter
- 486 layers of 2.45cm 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 <B>=1.3T
- 5.4kton total mass

⇨ *Can it be scaled to 40 kton ?*



Half MINOS detector

MINOS far detector parameters

System	Parameters
MINOS cavern	82.3 m × 13.8 m × 11.6 m (height)
Supermodules	2 supermodules, each 2.7 metric kt, 14.4 m long × 8 m wide
Detector mass	5.14 ktons steel + 261 tons scintillator = 5.4 ktons
Planes/supermodule	***486 steel planes and 485 scintillator planes, 2.54 cm pitch***
Detector units/plane	192 scintillator strips packaged in 8 modules
Readout	2-ended, with 8 × multiplexing
Channel count	484 planes × 192 strips × 2 ÷ 8 = 23,232 channels
Photodetectors	1,452 16-channel PMTs in 484 MUX boxes
Installation rate	1 plane/1.85 shifts or 24 planes/month (maximum)
Installation time	12 months for first supermodule, 22.5 months for two
Magnetic field	1.3 T at 2 m radius in steel octagon planes
Magnet coils	15 kA-turns, water-cooled copper wire, 58 kW total
Total cavern cooling	292 kW maximum (at the end of the installation period)

Table 13: Summary of some of the major parameters of the far detector and its requirements on the infrastructure systems of the MINOS cavern in the Soudan mine.

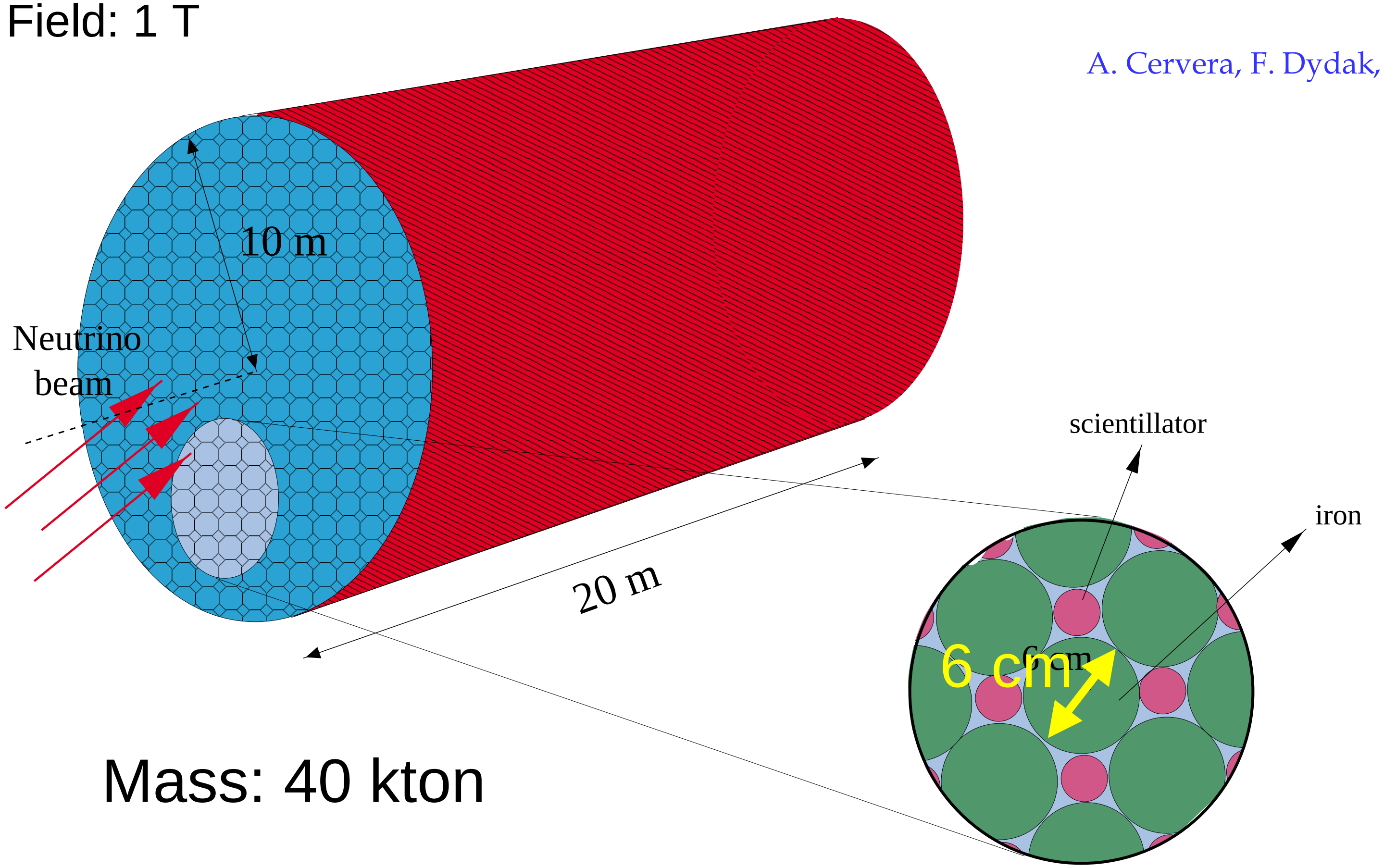
Lifting of an instrumented MINOS plane

From MINOS WWW page

1b. Large Magnetized Detector

Cylindrical symmetry, R=10m,=20m
6 cm thick iron rods interspersed with 2cm thick scintillators “longitudinally segmented”
Field: 1 T

A. Cervera, F. Dydak, J.J. Gomez. , NIM.A451 (2000) 123



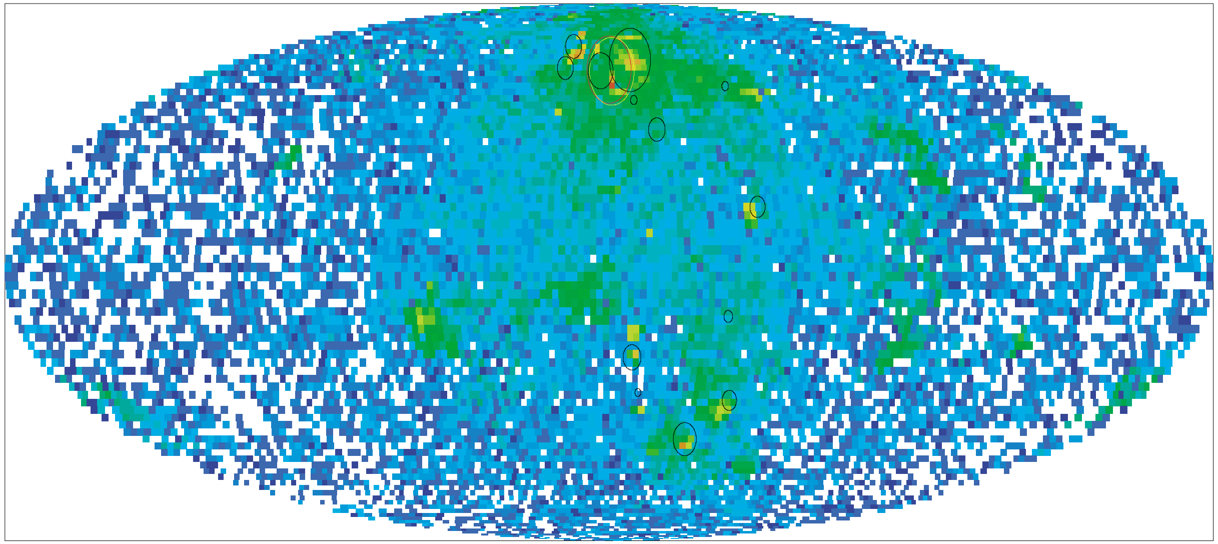
Mass: 40 kton

⇒ Muon performance studied with GEANT and assume MINOS-like performance for E_{had}, θ_{had}…

$$\sigma_{E_h}/E_h \sim 76\%/\sqrt{E_h} \oplus 3\%$$
$$\sigma_{\theta_h}/\theta_h \sim 17/\sqrt{E_h} \oplus 12/E_h$$

2. Large Water Cerenkov

- Well proven technology, e.g. ***Kam***, ***IMB***, ***SuperKamiokande***
  - → Detects: μ, e, [NC]
- low cost target material, only the surface (not volume) needs to be instrumented, but size eventually limited by water properties
- Next generation 1Mton under consideration C.K. Jung, hep-ex/0005046
- Disadvantages:
  - → Reconstructed (pattern) limited to “simple event topologies” (e.g. single-ring)
  - → Not compatible with precise reconstruction of high energy neutrinos (e.g. $E_\nu >\approx 5$ GeV ?)
  - → Muon charge ID

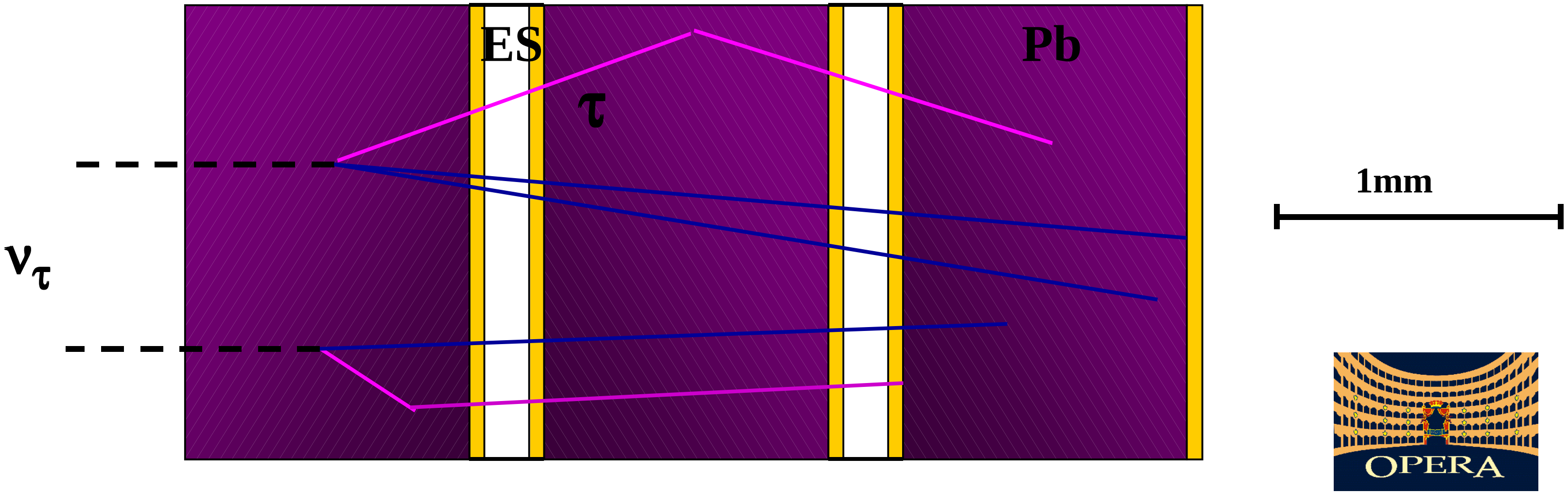


Simulated neutrino event from a 50 GeV storage ring

FNAL-FN-692, Apr 2000

3. Emulsion/target sandwich

- ***OPERA***: Technique on the ≈1 kton scale to be demonstrated by at LNGS in 2005
  - ➜Detects: μ^+, μ^-, τ (“kink”), [e,NC]
  - ➜ Direct search of $\nu_e \rightarrow \nu_\tau$ oscillations, if charge of the tau can be detected to suppress $\nu_\mu \rightarrow \nu_\tau$ “background”
- Disadvantages:
  - ➜ Probably difficult to scale to multi-kton mass
  - ➜ Scanning (e.g. $\nu_e \rightarrow \nu_\tau$ to $\sin^2 2\theta_{13} \approx 10^{-4}$?)
  - ➜ Possibly severe charm background from ν_e interactions



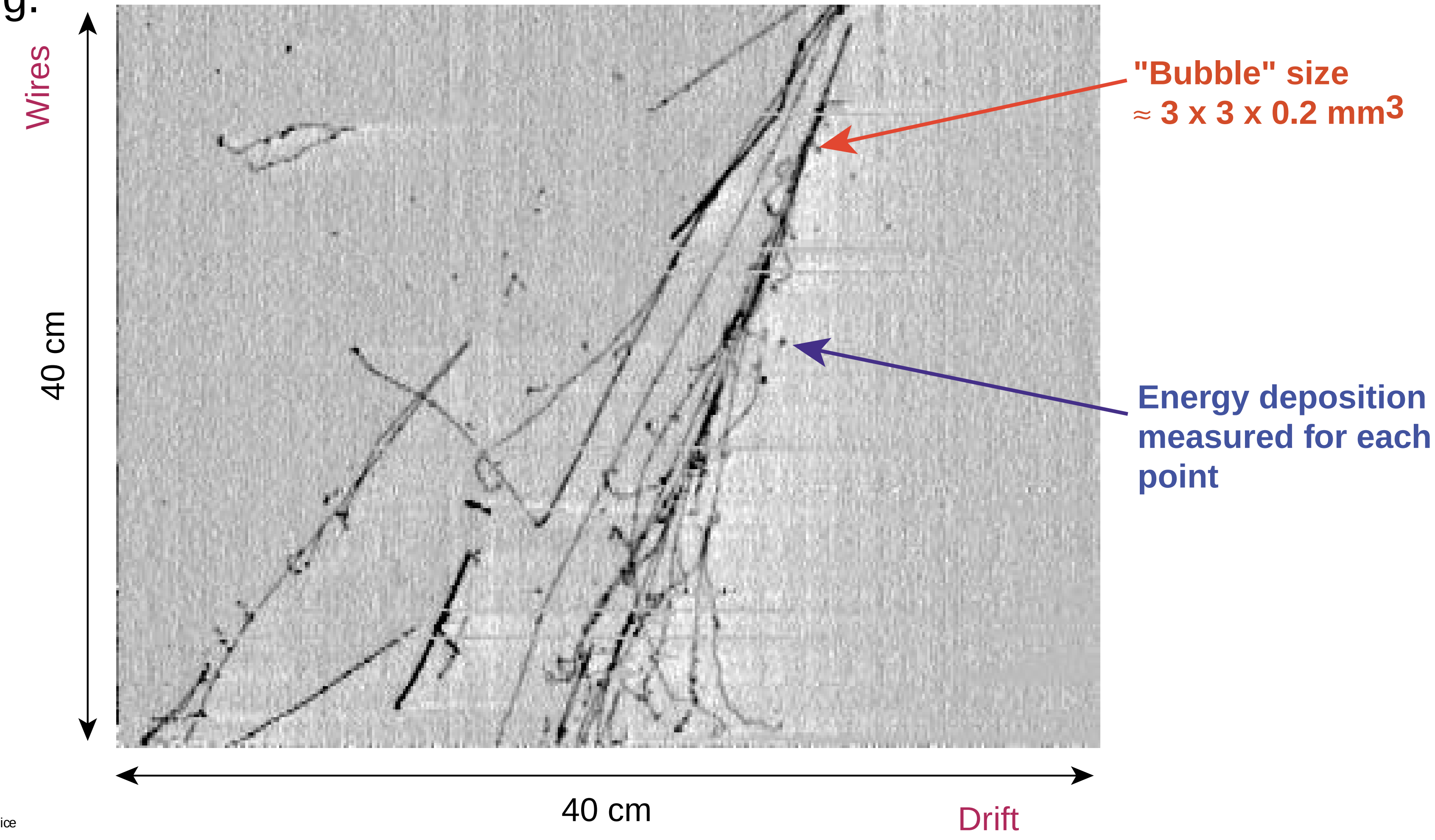
4. Liquid Argon imaging TPC

- ***ICARUS***: mature technique, demonstrated up to 15 ton prototype
- Features provided:
  - Detects: μ^+, μ^-, e, NC, [τ]
  - Fully homogeneous, continuous, precise ***tracking device*** with high resolution dE/dx ***measurement*** and full sampling ***electromagnetic and hadronic calorimetry***
  - Excellent ***e identification/measurement*** and ***e/hadron*** separation
  - Very good hadronic energy resolution
- 600 ton prototype construction ***very advanced***
  - After the foreseen series of technical tests to be performed in Pavia within the summer 2001, ***the T600 module will be ready to be transported into the LNGS tunnel***
- Disadvantages:
  - Muon charge discrimination: target cannot be easily magnetized (but...)
  - Rely on ***down-stream muon spectrometer*** (low threshold since dE/dx ≈ 240 MeV/m)

Idea first implemented in the ICANOE proposal

Liquid Argon technology

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



"Bubble" size ≈ 3 x 3 x 0.2 mm^3

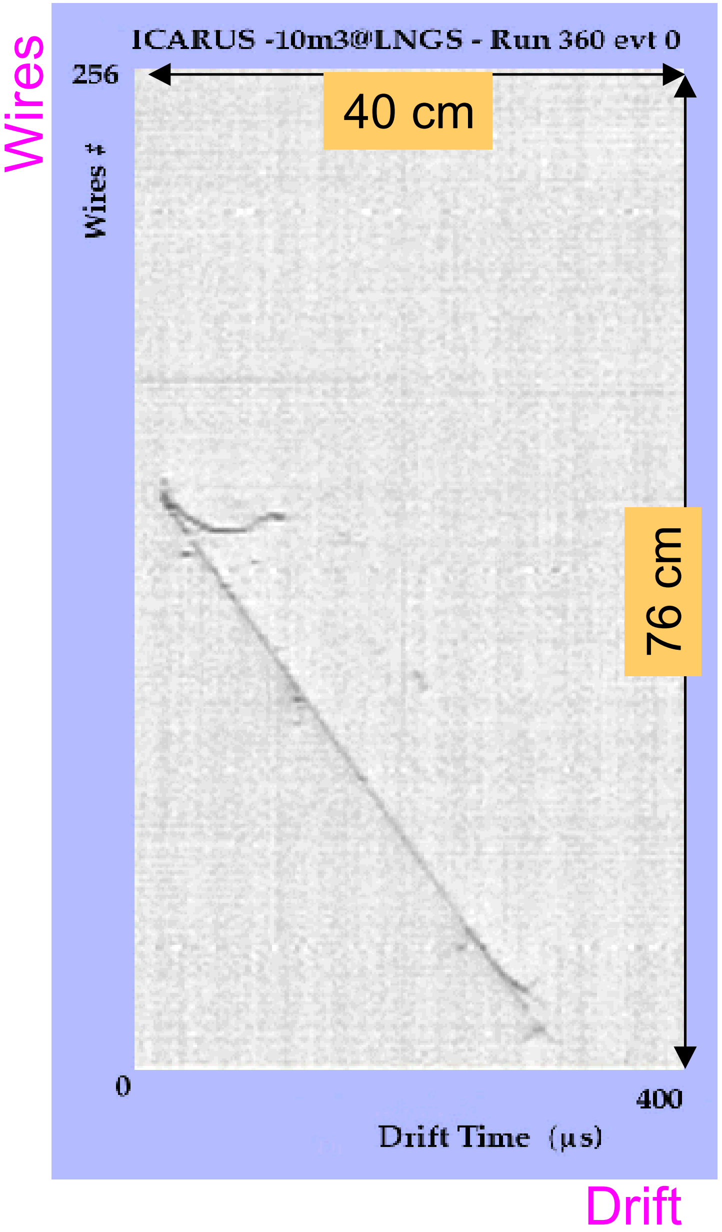
Energy deposition measured for each point

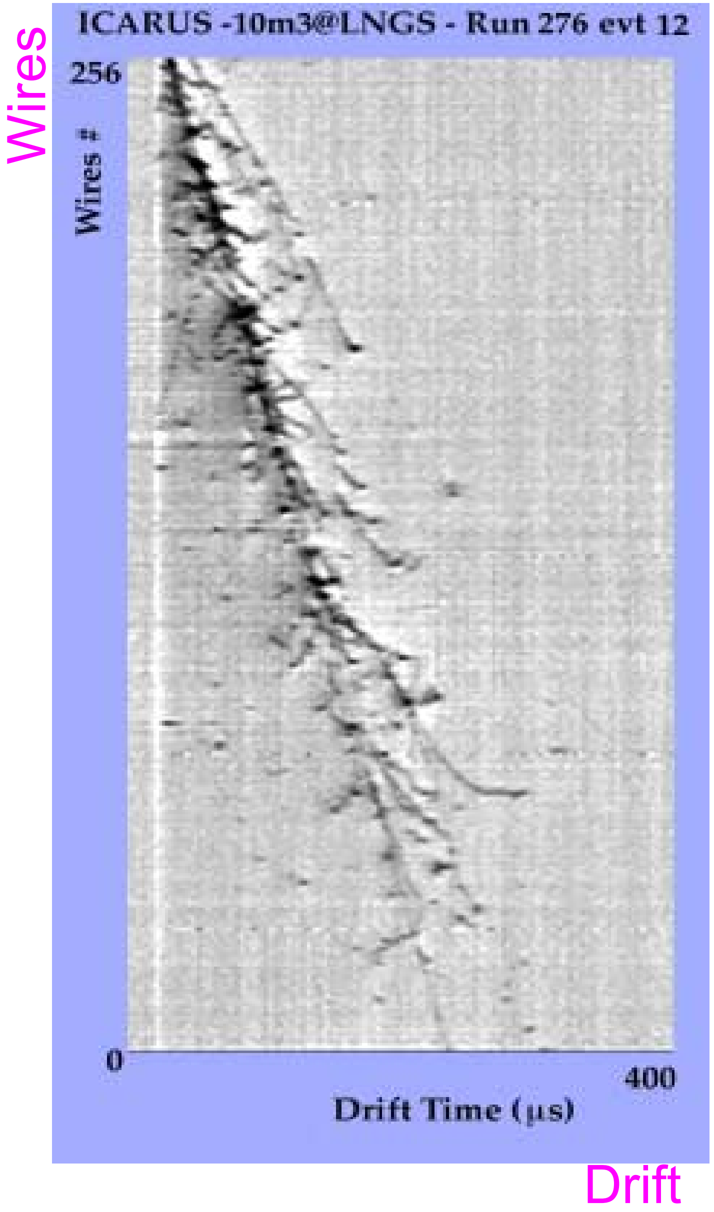
Liquid Argon imaging on large scales

10m^3 Module
at LNGS

Cosmic Ray tracks recorded during the 10 m^3 operation

“Big track” in T600 semimodule expected soon...





T600 assembly schedule

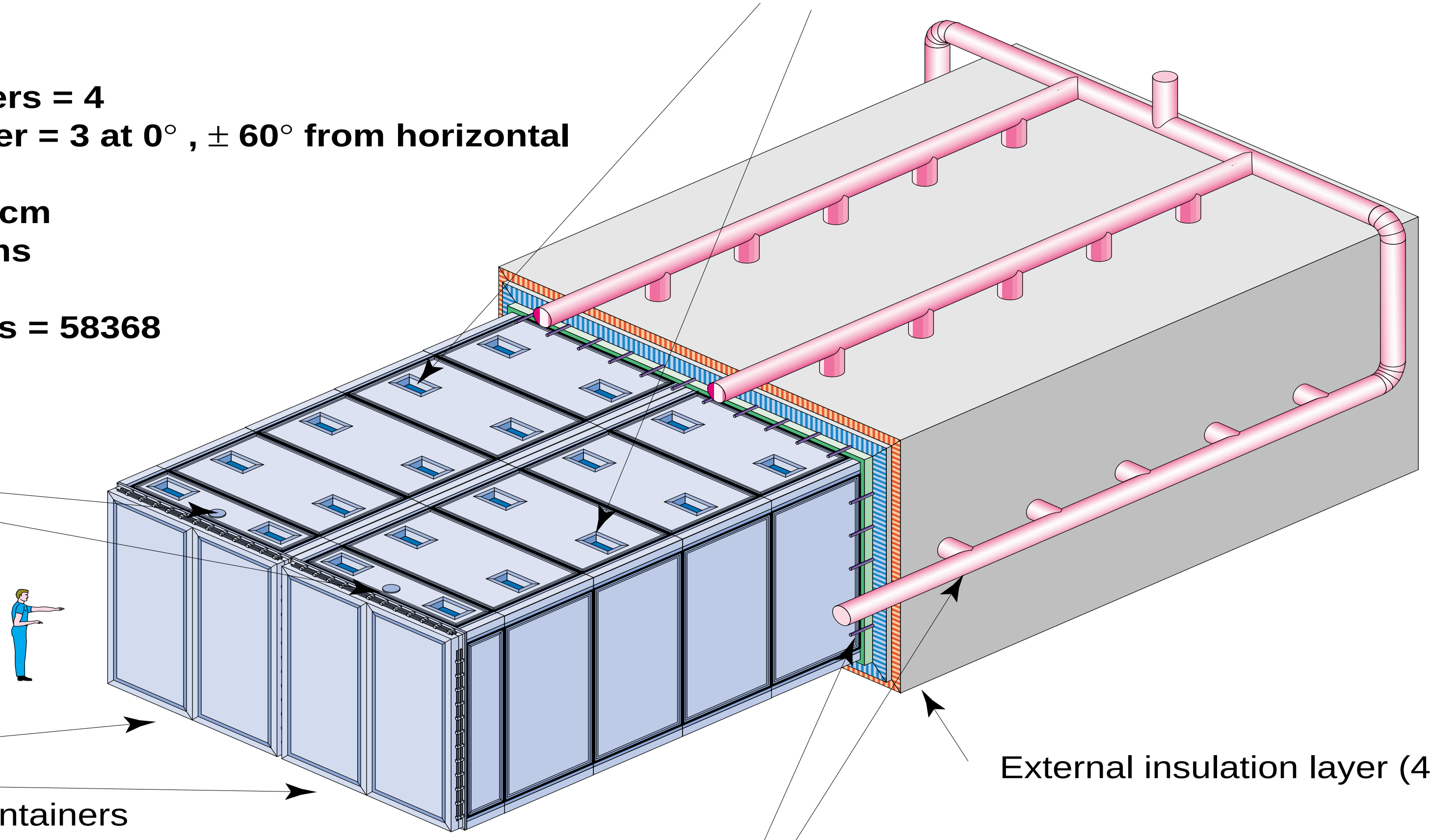
- Completed ***site preparation*** in Pavia for the T600 cryostat (***Nov 1999***)
  - → “clean room”, “assembly island”, floor, ...
- Delivery of the ***1st cryostat*** by AirLiquide (***Feb 2000***)
  - → Successful vacuum tightness and mechanical stress tests
- Beginning of ***assembly of the internal detector mechanics*** (***Mar 2000***)
- Completion of assembly and positioning of inner detector frames (***Jul 2000***)
- Installation of ***30000 wires*** + ***signal cables*** (***Jul 2000-Oct 2000***)
- Delivery of the ***2nd cryostat*** of AirLiquide (***Aug 2000***)
  - → Successful vacuum tightness and mechanical stress tests
- Installation of ***scintillation light*** and all ***slow control devices*** (***Jul 2000-Dec 2000***)
- ***H.V. and field electrodes system*** installation (***Oct 2000- Jan 2001***)
- Installation of the ***48 electronic racks*** on top of dewar (***Dec 2000-ongoing***)
- Installation of ***external heat insulation*** (for both dewars) and ***LAr and*** LN_2 ***cryogenic circuits*** (***Dec 2000-Jan 2001***)
- Semi-module now ready to be sealed.

The ICARUS T600 module

Under construction

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



Signal feedthroughs

HV feedthroughs

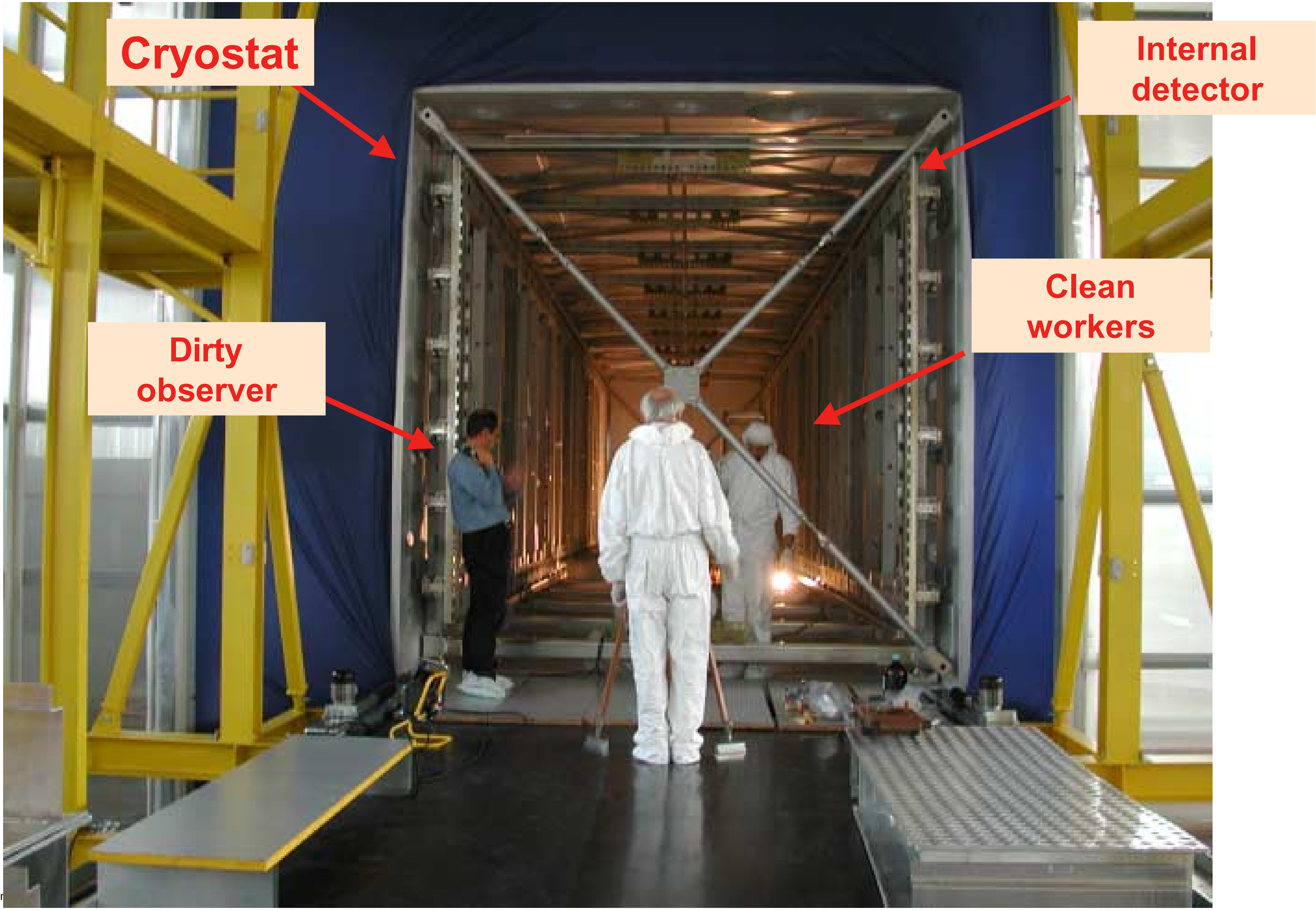
External insulation layer (400 mm)

2 independent aluminum containers
each one transportable inside the GS
Laboratory

LN2 cooling circuit

First half-module delivery in Pavia (Feb 29, 2000)

Assembly of the T600 internal detector (Mar-Jul 2000)



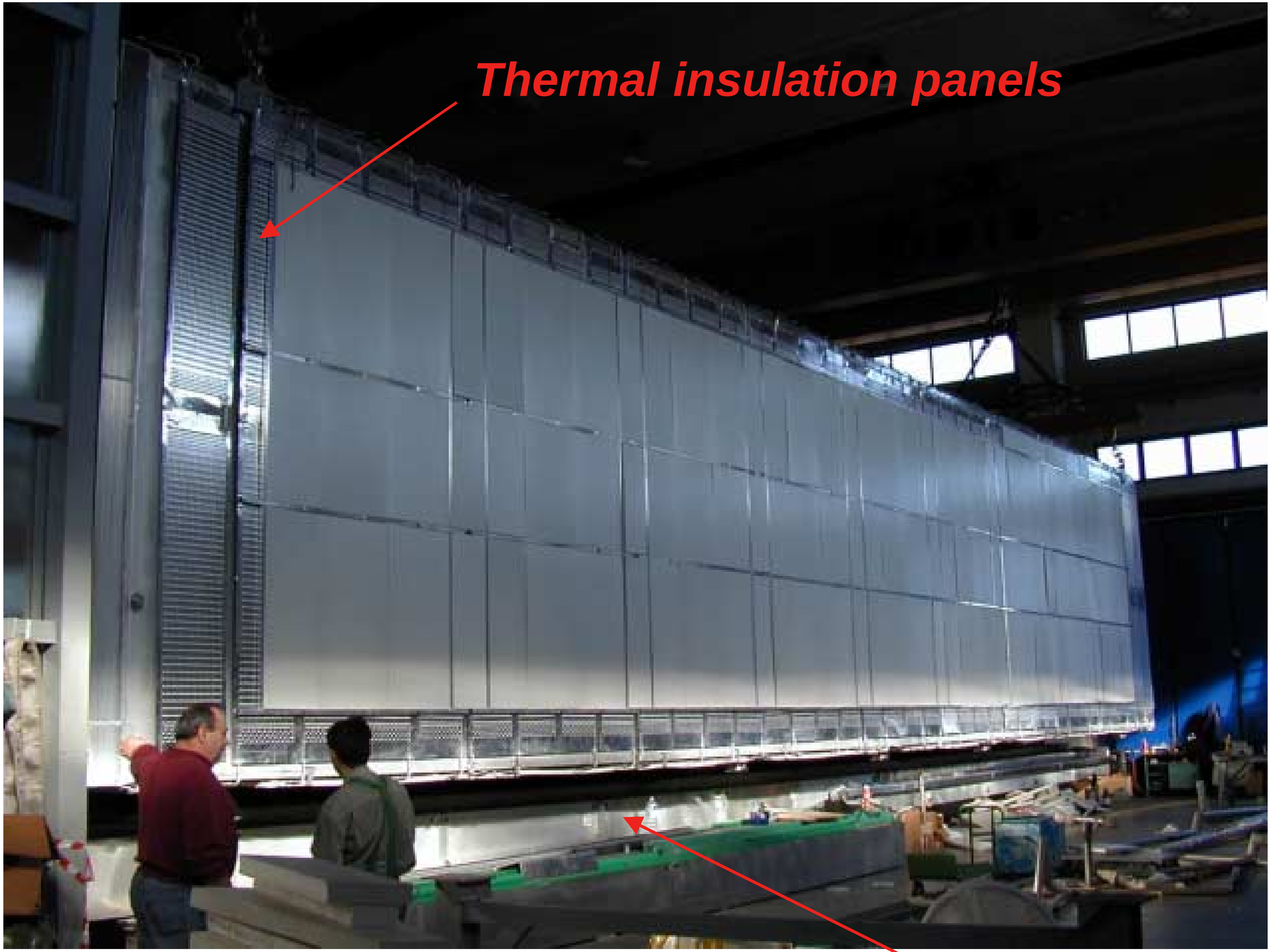
Cryostat

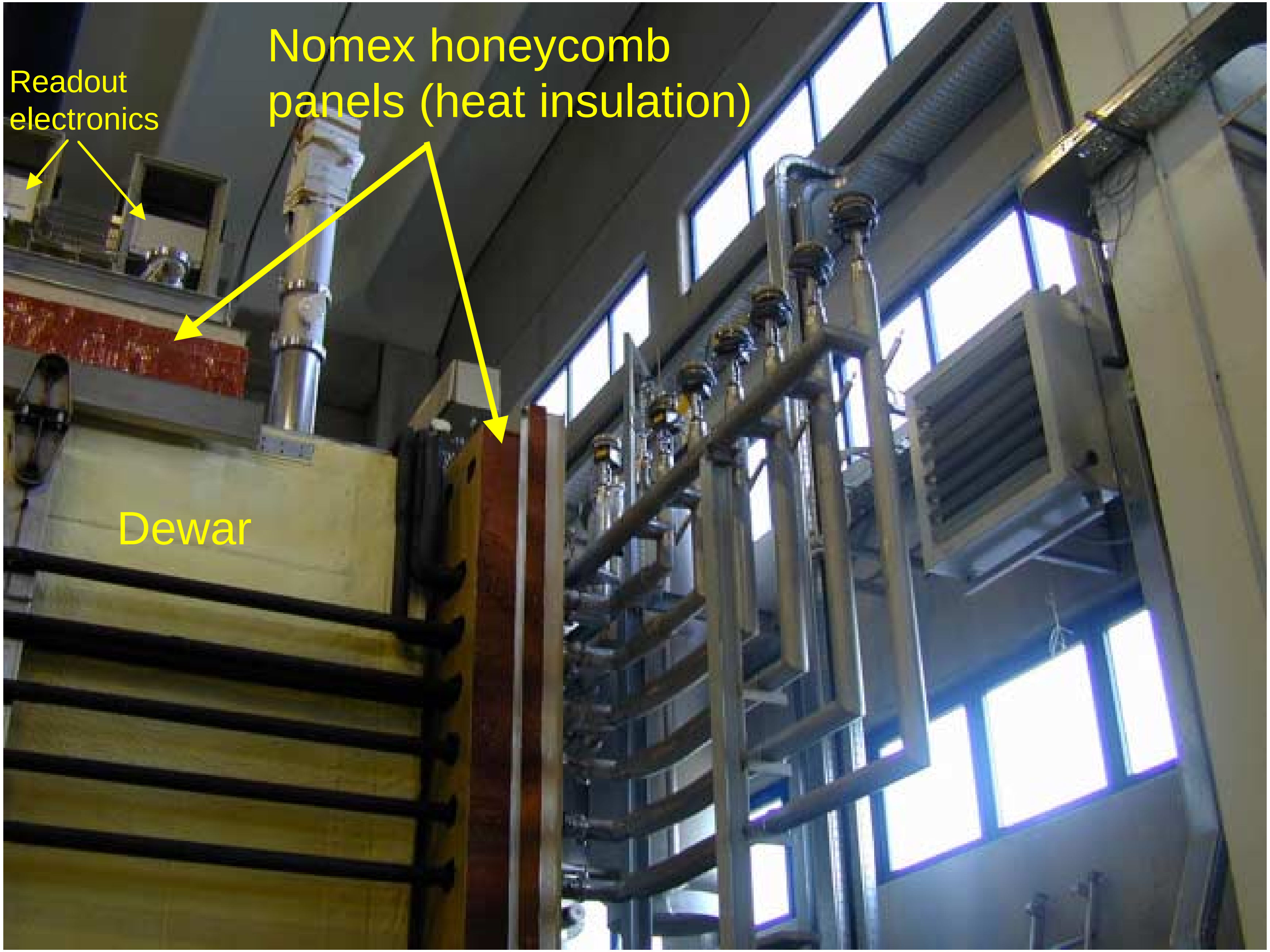
Internal detector

Clean workers

Dirty observer

Second half-module (delivered Aug 2000)



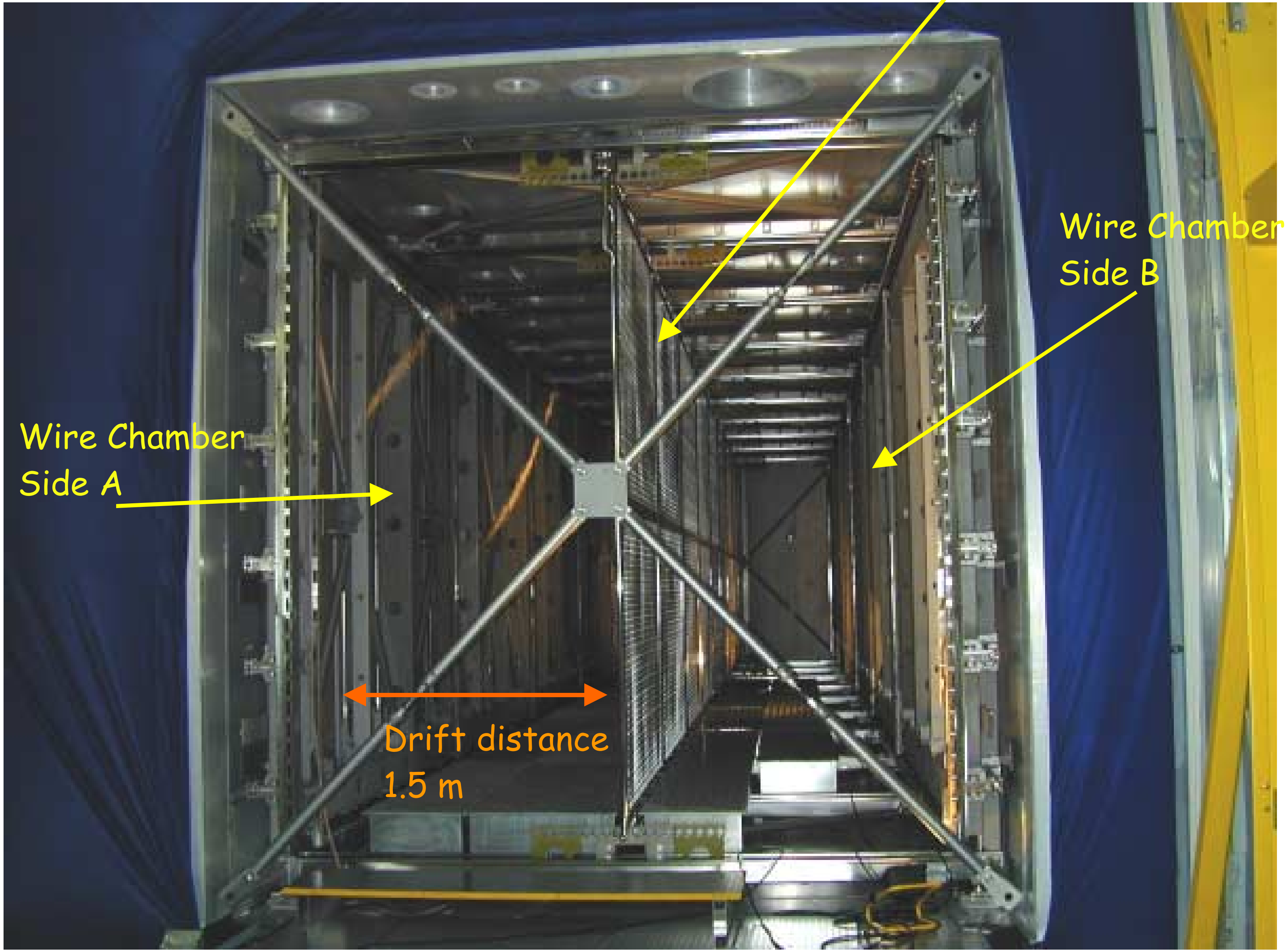

Readout electronics
Nomex honeycomb panels (heat insulation)
Dewar

Wire installation in T600 internal detector (Jul-Oct 2000)

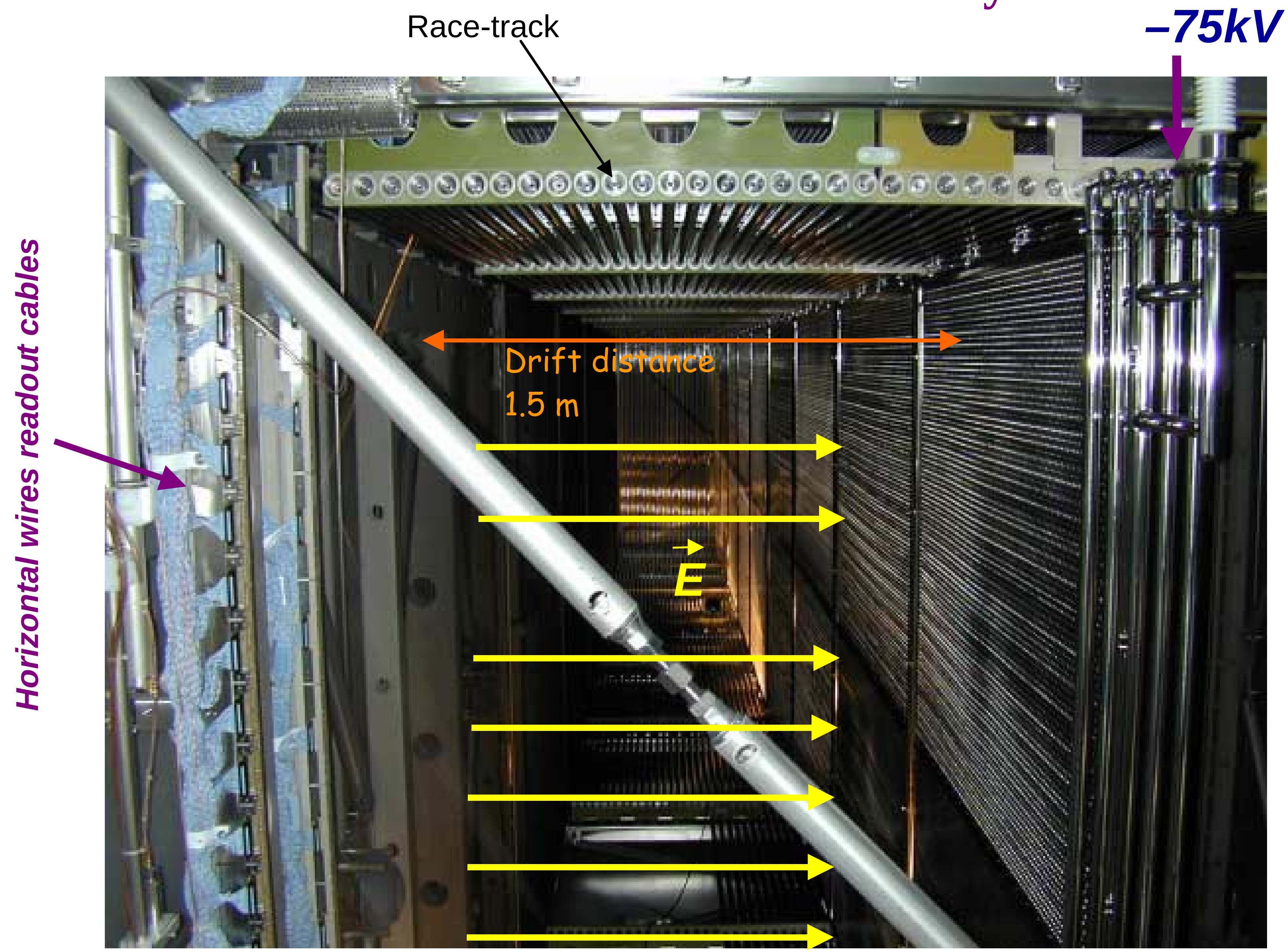
The three wire planes at 0°,±60° (wire pitch = 3mm)

and one PMT

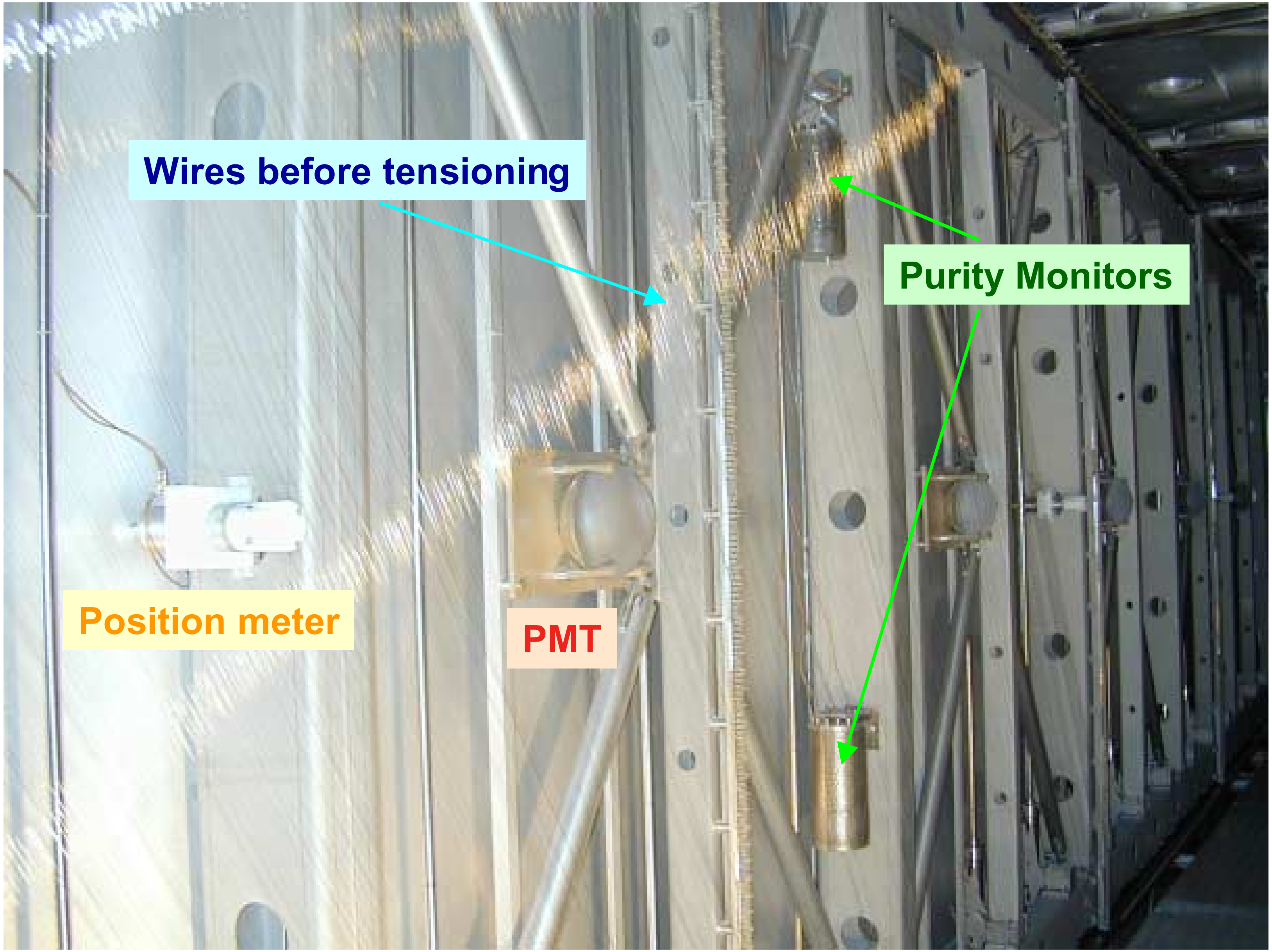
T600 - Completed Internal Detector view



Drift H.V. and field electrodes system



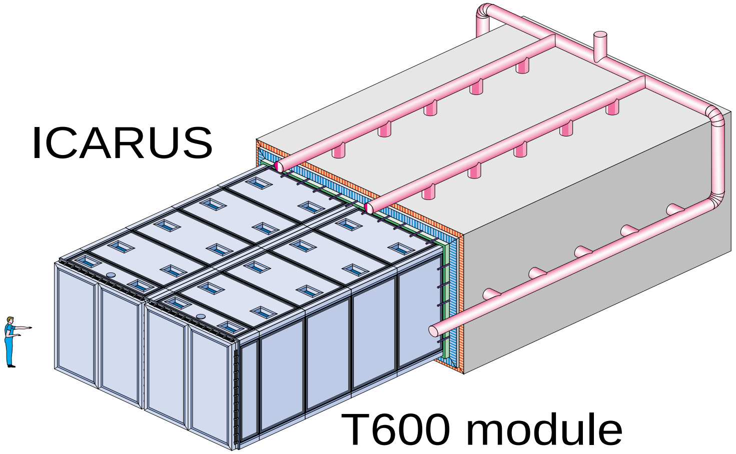
Slow control sensor (behind wire planes)



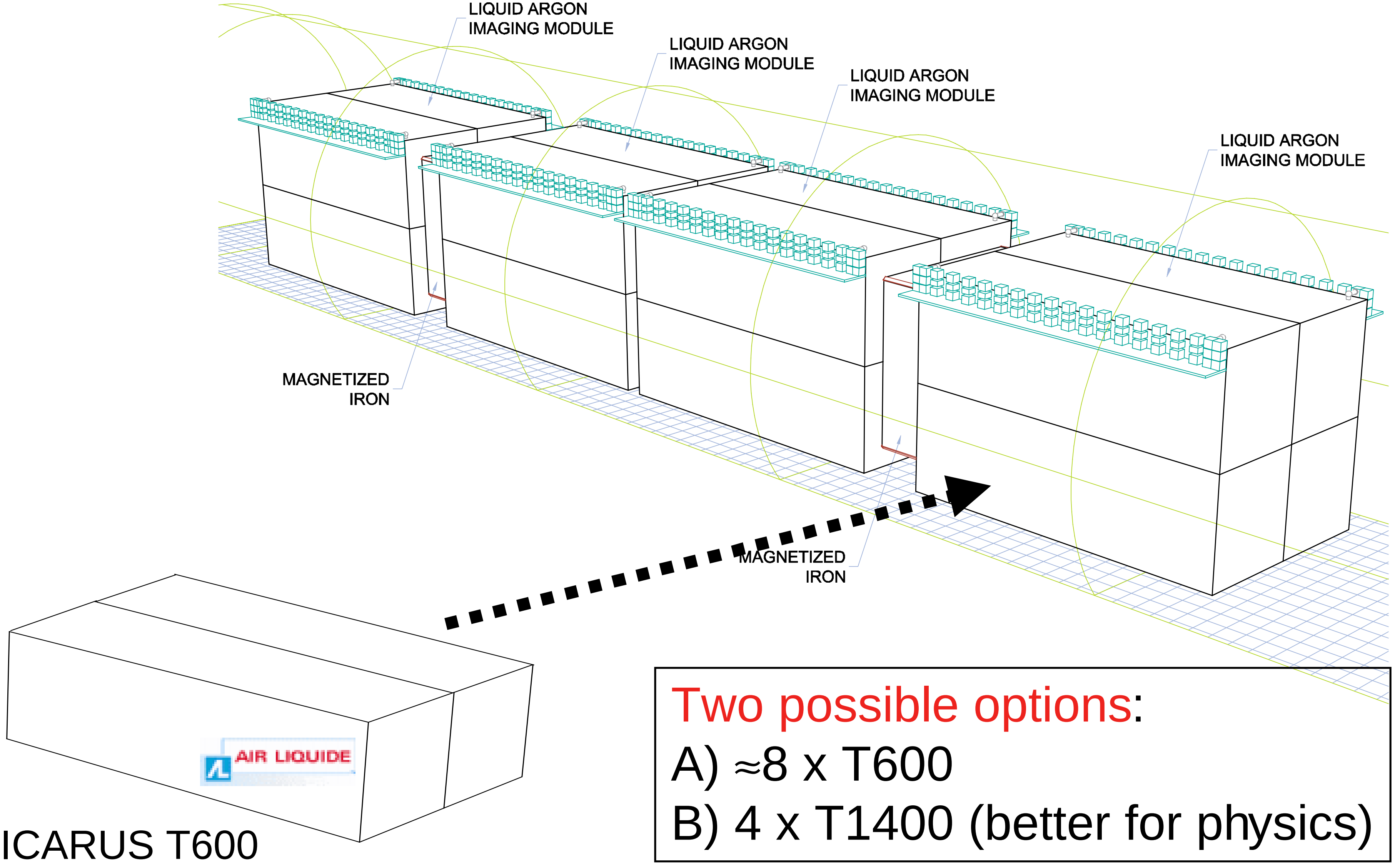
Man-hole (after sealing, the only way to get inside!)

The first ICARUS T600 prototype

- ✯ The T600 module is to be considered as a fundamental milestone on the road towards a total sensitive mass in the multi-kton range
  - ➜First piece of the detector to be complemented by further modules of appropriate size and dimension ⇒ *Goal is* ***to reach a multikton mass in LNGS tunnel in a most efficient and rapid way***
- ✯ It has a physics program of its own, immediately relevant to neutrino physics, though limited by statistics (see hep-ex/0103008)



Proposed setup ICARUS 5kt in LNGS Hall B



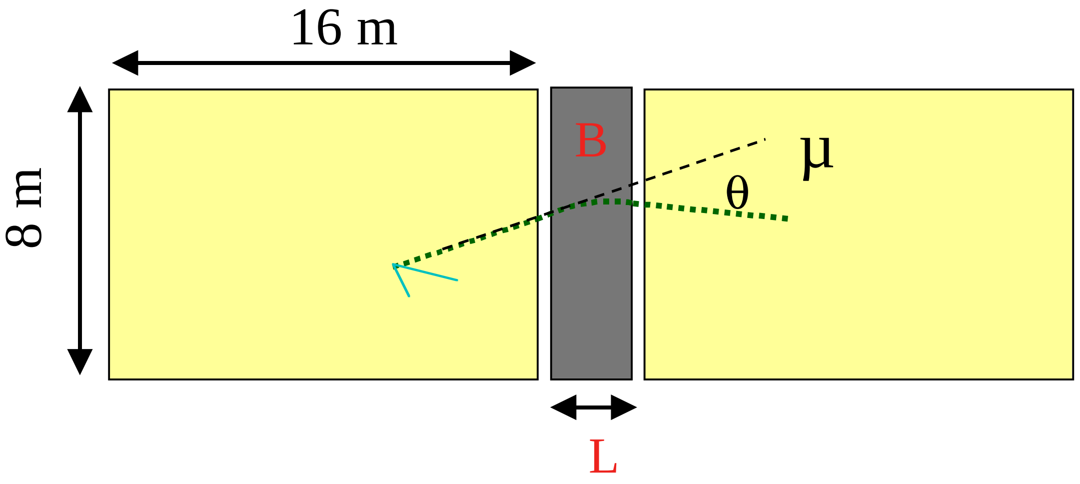
Two possible options:

A) ≈8 x T600

B) 4 x T1400 (better for physics)

Muon bending measurement

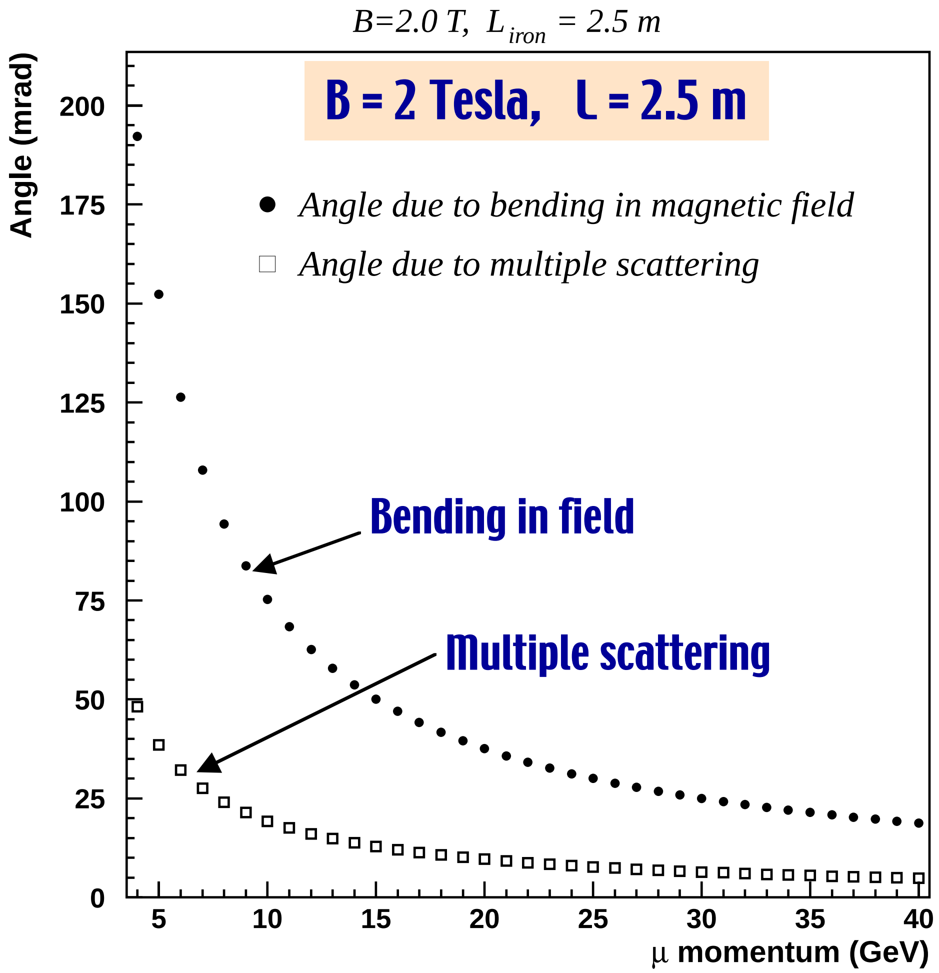
- ✮ We consider a design in which the muon escaping the liquid Argon is bent by a magnetized piece of iron



The bending angle θ is measured with the tracks observed in two subsequent liquid argon module

$\Delta p/p \approx 25\%$

Charge confusion: ~10^{-4}

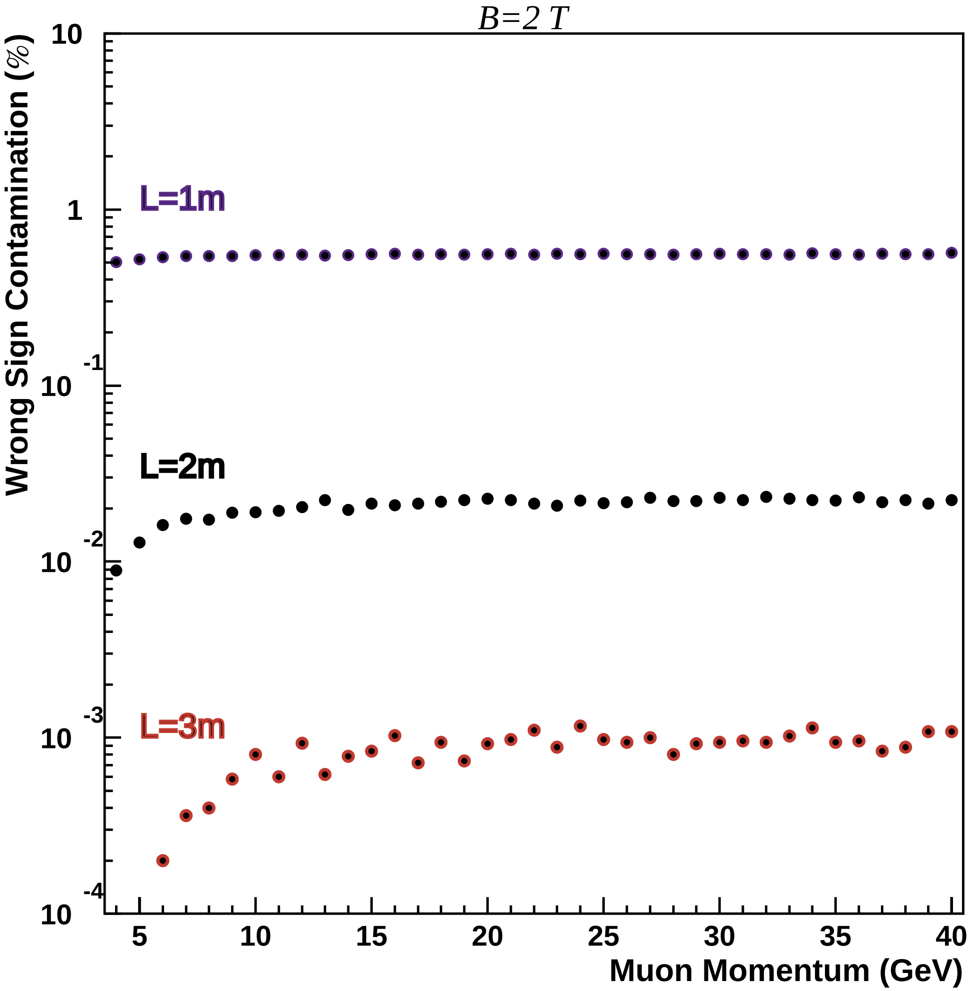


A simpler solution than in the ICANOE proposal

Muon charge misidentification

- ✯ **μ *momentum resolution:***
  - ➜ 25% for a 2.5m long Fe spectrometer with B=2T
- ✯ ***Wrong sign contamination***
  - ➜ Charge confusion: ~10^{-4}
- ✯ ***Large detection efficiency for low energy beam***
  - ⇐ μ detection threshold (dE/dx = 240 MeV/m)

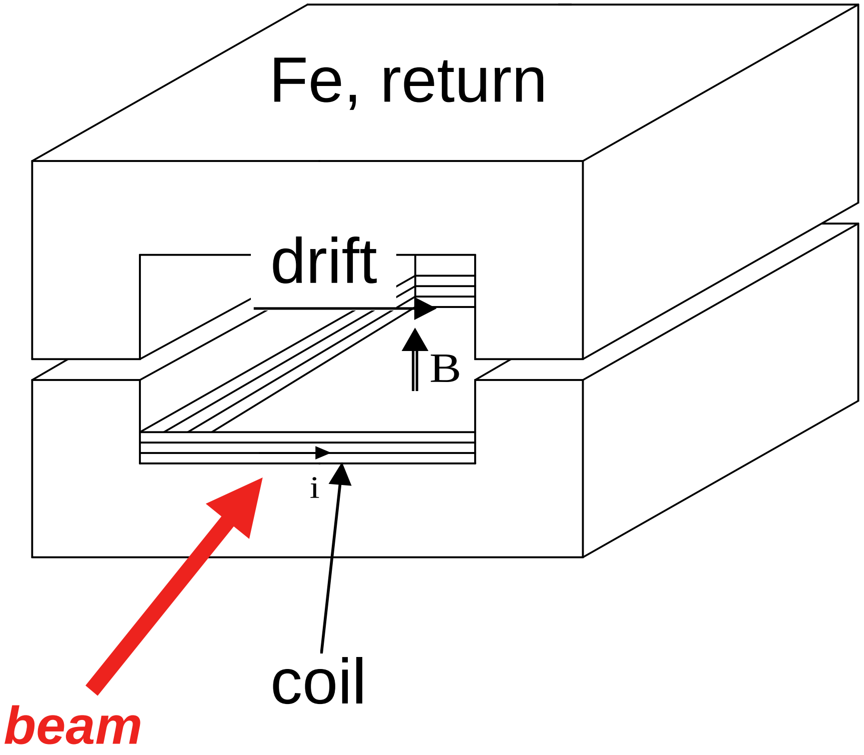
Fraction (%) of misidentified charge



A large magnet ?

*An interesting possibility, **to be further understood**, is the creation of the B-field over the large volume encompassing the LAr with the help of a very large solenoid*

$$\vec{B} \perp \vec{v}_{drift} \perp \vec{p}$$



Joule Power (non-superconducting):

$$P = \rho \frac{2(a+b)hB^2}{md\mu_0^{\;2}}$$

d=coil thickness, m=#windings, h=height, a=width, b=length

Parameter	
Argon volume	$8 \times 8 \times 16 m^3$
Argon mass	1.4 kton
Magnetic field	1.0 T
Current	2000 A
Conductor length	150 km
Resistance	1 Ω
Dissipated power	4 MW
Iron mass	5 kton

Neutrino Factory wish list

- ***Precise determination of Δm^2_{23} and Θ_{23}***
- ***Stringent limit/precise measurement of Θ_{13}***
- ***Determination of Δm^2_{23} sign***
- ***Study matter effects***
- ***First detection of $\nu_e \to \nu_\tau$ oscillations***
- ***Over-constrain the oscillation parameters***
- ***Study CP violation in the leptonic sector***

Try to show three concrete examples where detector considerations could be relevant...

Looking at the θ_{13} term

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

a realistic assumption at the NF ⇒ *for* $\Delta m^2_{21}(L/4E) << 1$

$$\approx \sin^2 2\theta_{13} \sin^2\theta_{23} (\Delta m^2_{32})^2 (L/4E)^2$$

Not always a correct assumption at the NF ⇒ *for* $\Delta m^2_{21}(L/4E) << \Delta m^2_{32}(L/4E) << 1$

Similarly,

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

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

In contrast,

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

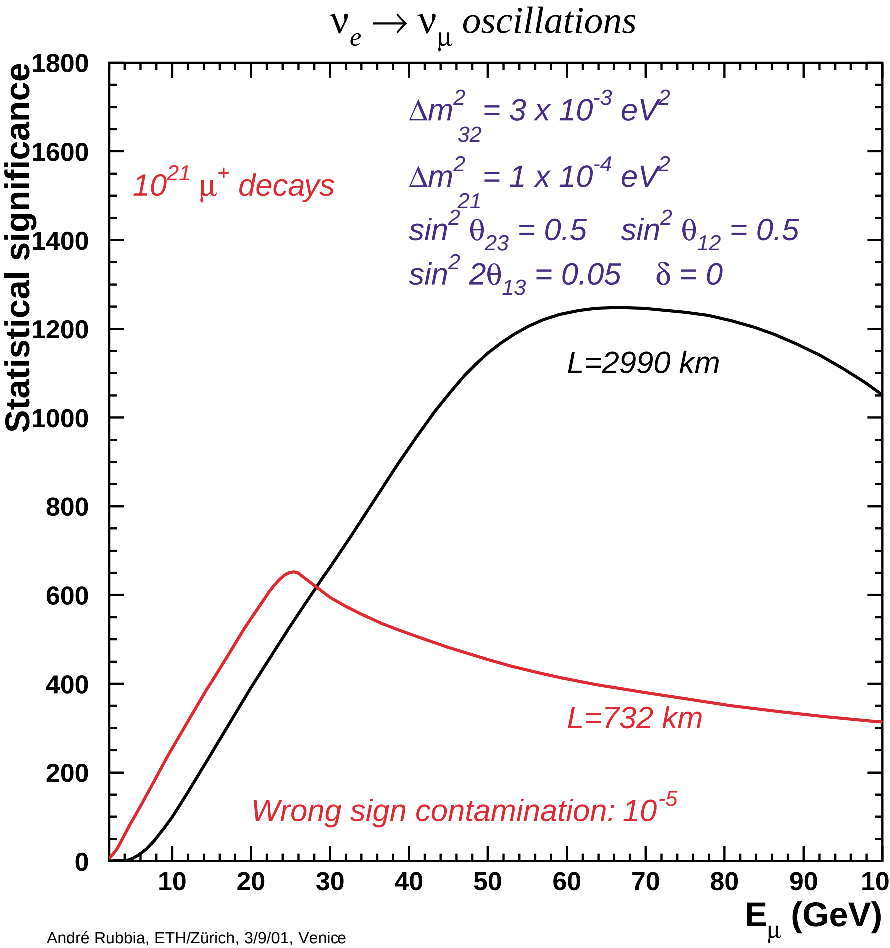
Wrong-sign muon optimization

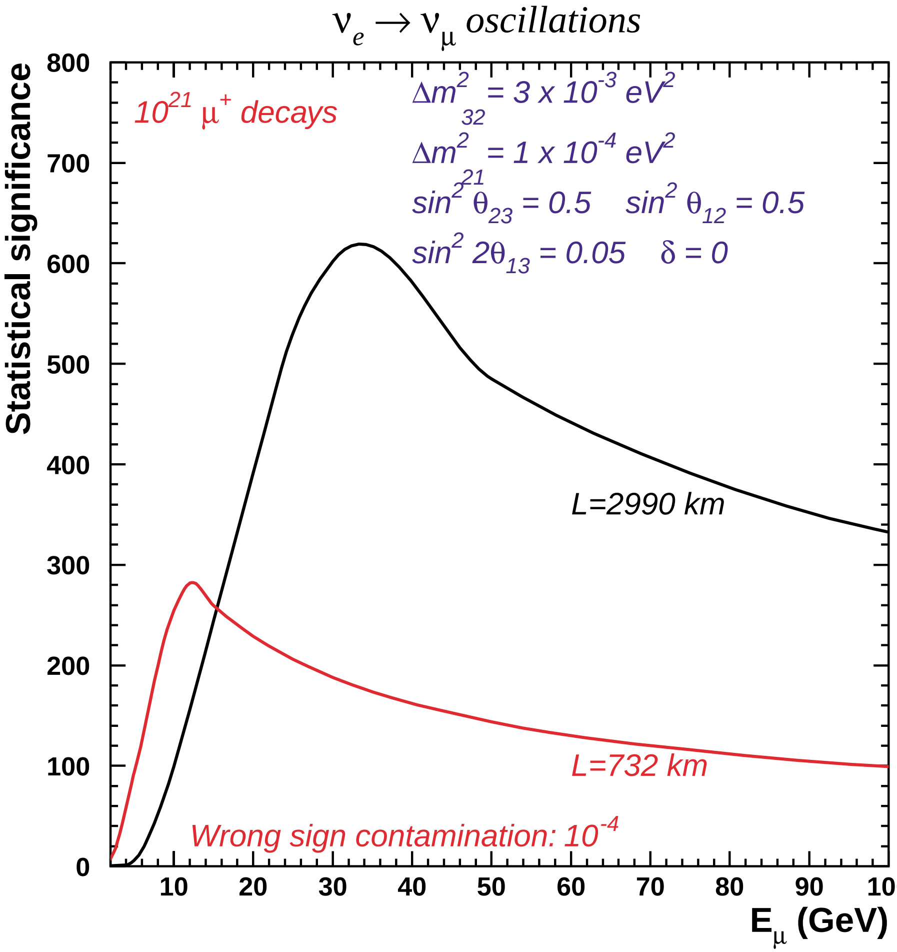
Optimization of E_μ and L depends on detector background considerations

$\Rightarrow$ gain with E_μ, since rate increases like E_μ^3 until background becomes relevant

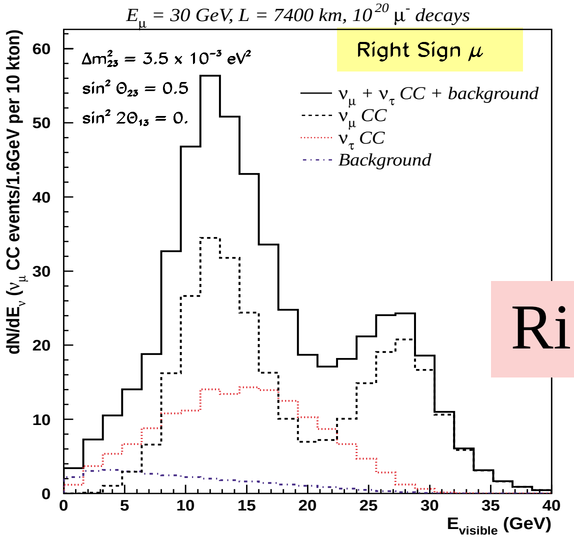
$$S = \frac{Nws\mu}{B}$$

$$B = \begin{cases} \sqrt{Nrs\mu \times \varepsilon_{BKG}} & \text{if} \quad Nrs\mu \times \varepsilon_{BKG} > 10 \\ Poisson & \text{otherwise} \end{cases}$$

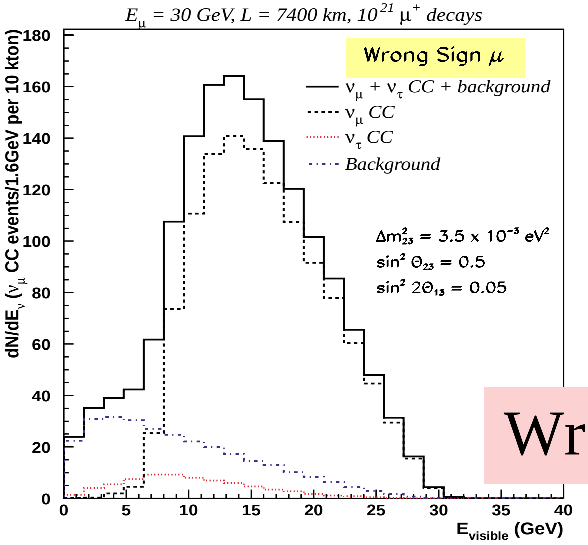




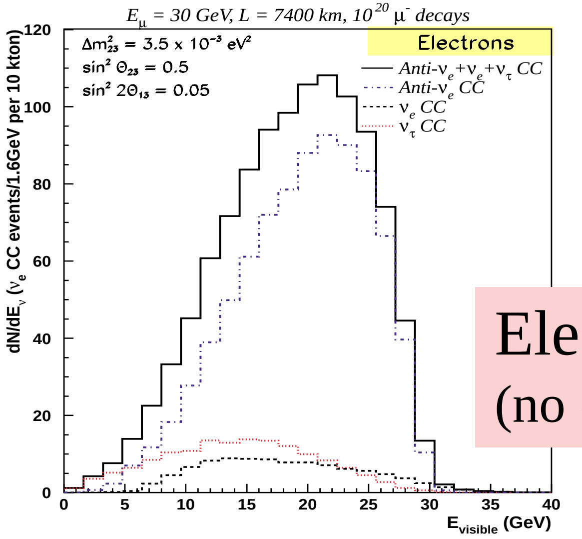
Over-constraining the parameters (I)



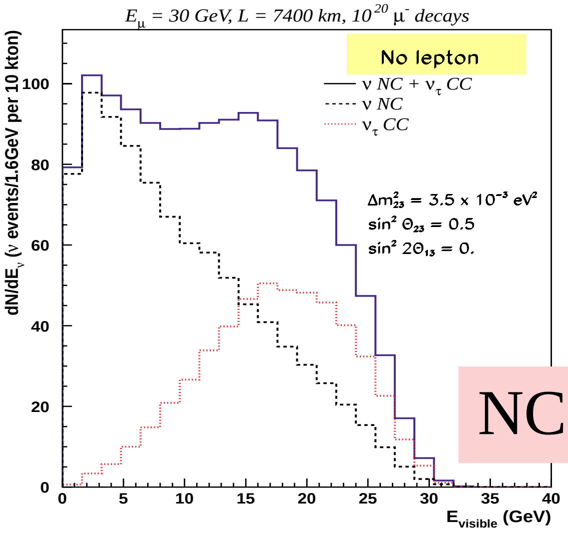
Right sign μ



Wrong sign μ



Electrons
(no charge info)



NC-like

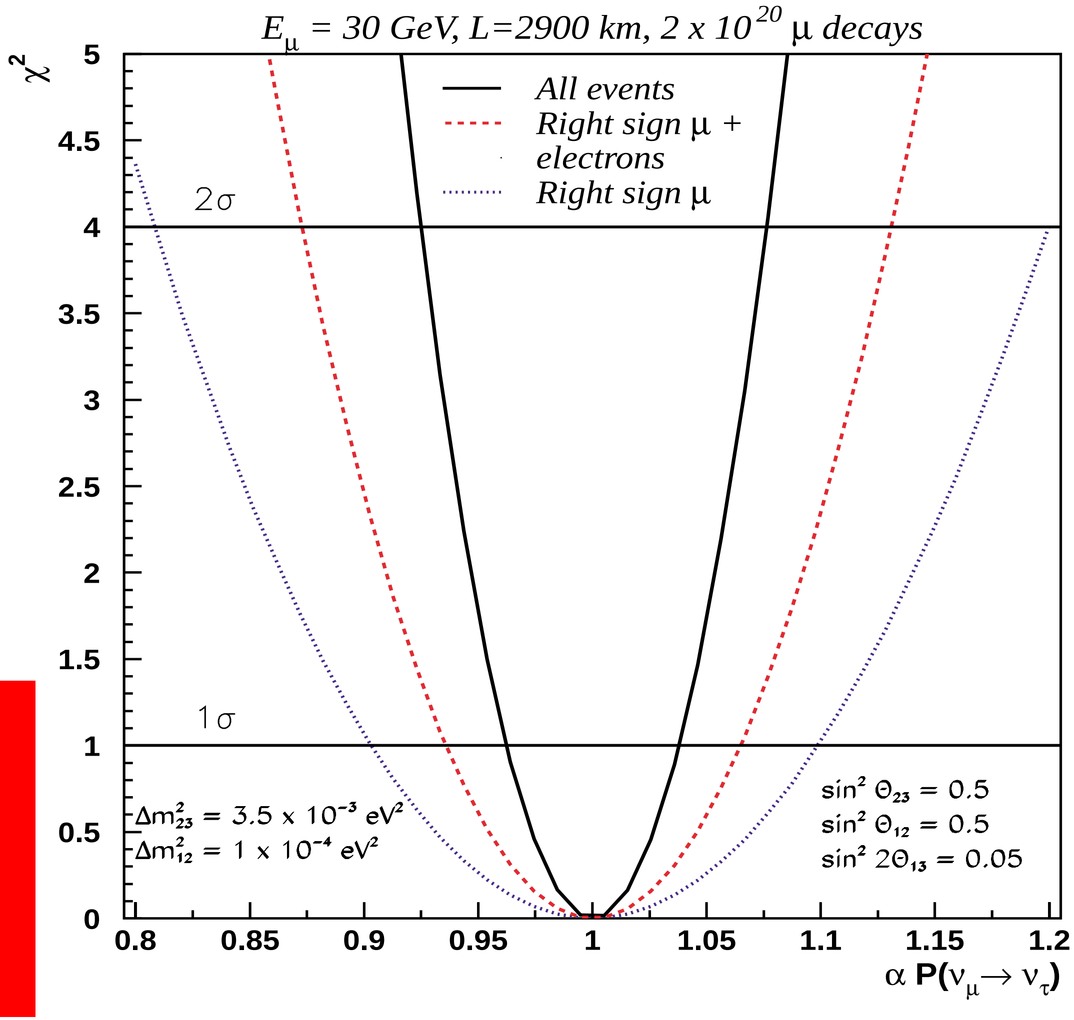
Combining all classes$\Rightarrow$ (over-constrained) sensitivity to all oscillations!

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

Over-constraining the parameters (II)

- Check consistency between different observed oscillation processes
- Proof/rule out the existence of sterile neutrinos
- **First observation of $\nu_e \rightarrow \nu_\tau$**

Ability to detect
τ appearance is crucial



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

A way to rescale probabilities...

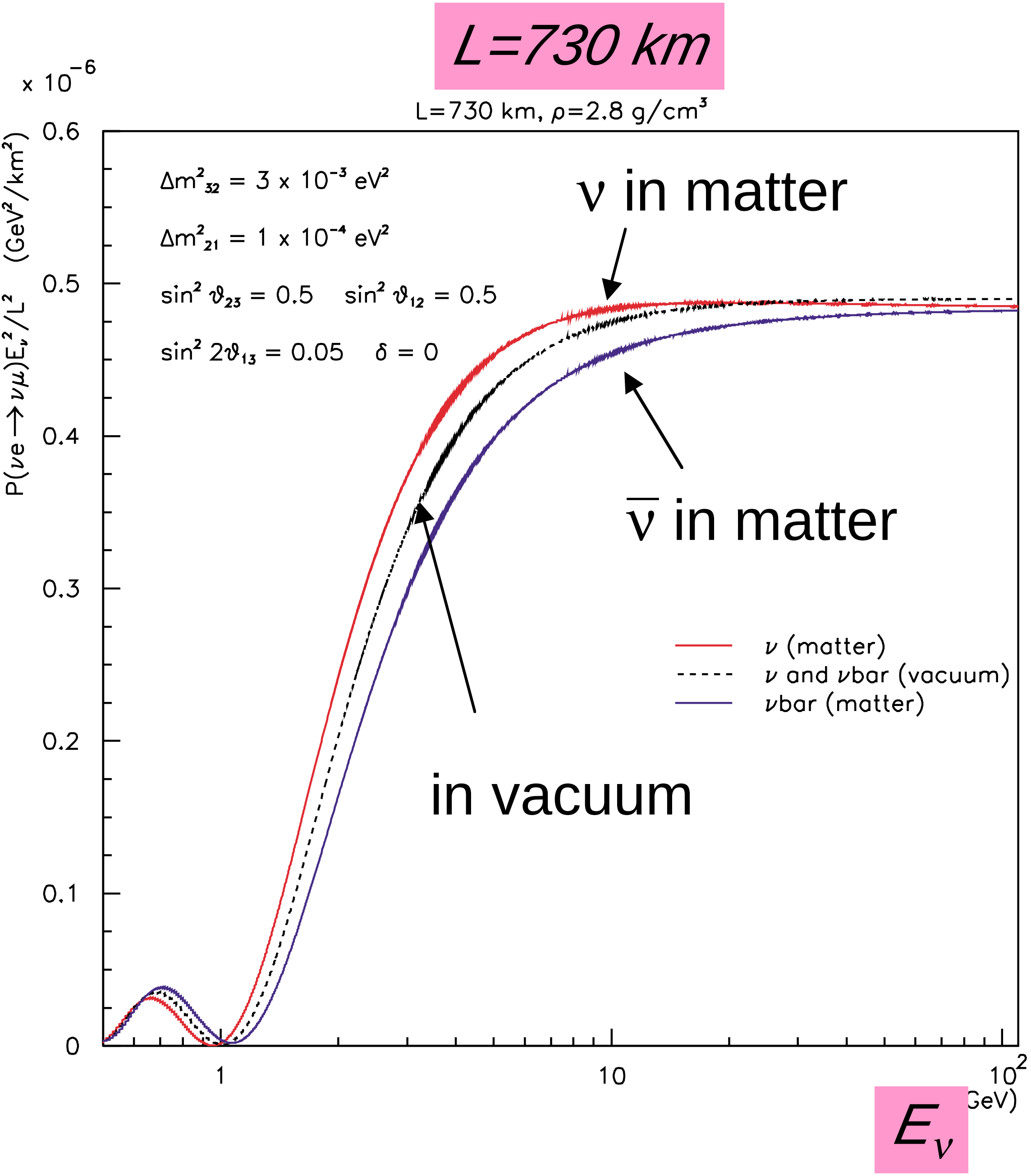
$$p \equiv P(\nu_e \rightarrow \nu_\mu) \times E_\nu^2 / L^2$$

probability

Approximate E_ν-dependence of NF ν-spectrum

Flux attentuation with distance

1. *p→const when E_ν →∞*
2. *It **correctly "weighs" the probabilities with the E_ν dependence of the NF ν spectrum***
3. *p can be **directly compared at different baselines***



Matter effects

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

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

+ for neutrinos
– for antineutrinos

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

For example, for neutrinos:

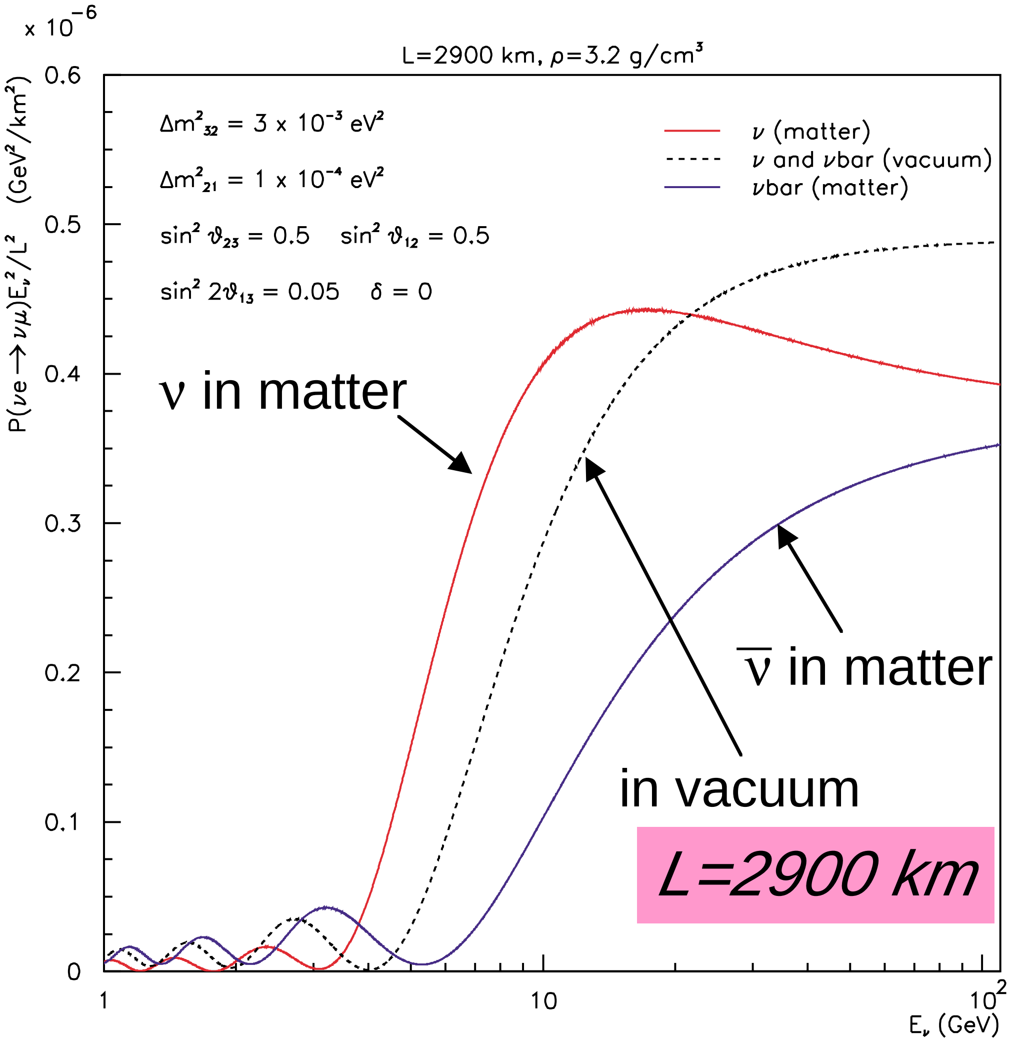
Resonance: $$D \approx \Delta m^2 \cos 2\theta \quad \Longrightarrow \quad \sin^2 2\theta_m(D) \approx 1$$

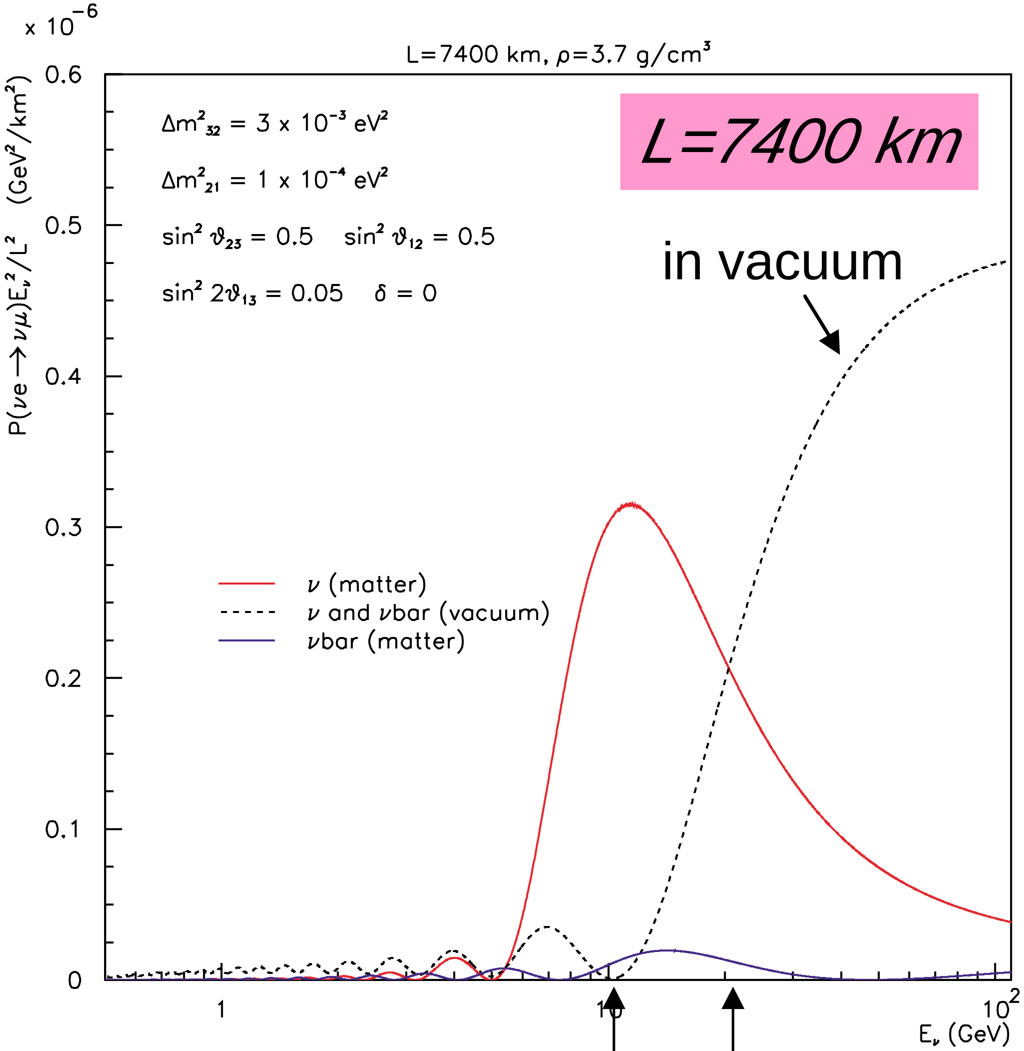
Suppression: $$D > 2\Delta m^2 \cos 2\theta \quad \Longrightarrow \quad \sin^2 2\theta_m(D) < \sin^2 2\theta$$

Mixing in matter smaller than in vacuum

Effect tends to become “visible” for L > ≈1000 km

Behaviour at larger distances...





$D \approx 2\Delta m^2 \cos 2\theta$

$D \approx \Delta m^2 \cos 2\theta$

At large distances, matter effect suppresses oscillations!

Looking for effects of δ!

$P(\nu_e \to \nu_\mu)$

One of the main motivations of NF is to try to look for effects induced by the phase δ

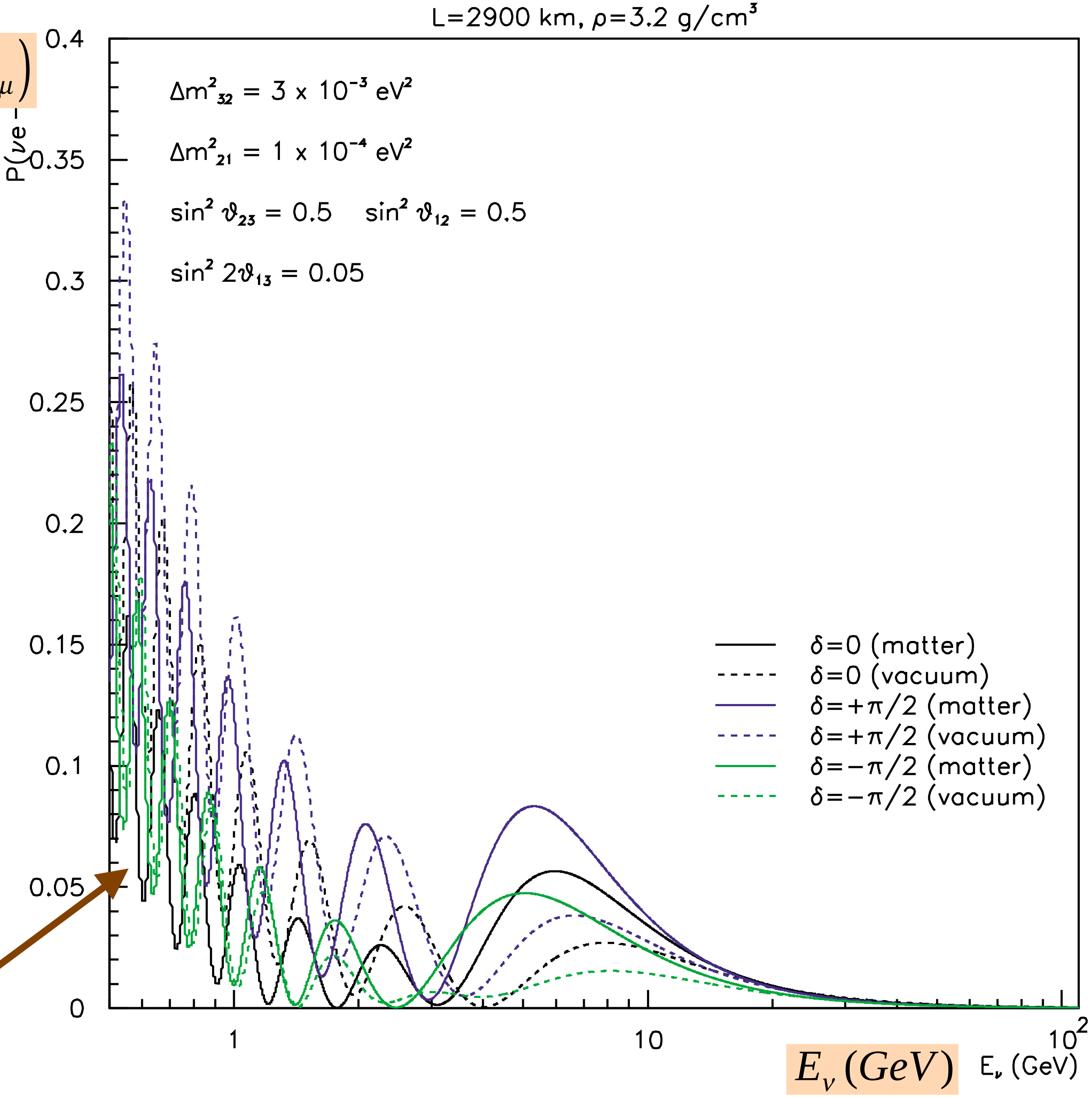
Effect "largest" when beat of three sin-functions:

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

&

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

⇒L/E of "solar" !



The “CP-odd” term

$$\Delta CP = \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{2} =$$

~1

Complex term in matrix

Need LA MSW

Oscillation P goes like $\sin^2\theta_{13}$
hence, $\Delta CP/\sqrt{P}$ independent of θ_{13}

$$\propto \cos\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times$$
$$\sin(\Delta m^2_{12} L/4E_\nu) \sin(\Delta m^2_{13} L/4E_\nu) \sin(\Delta m^2_{23} L/4E_\nu)$$

$$\approx f \times \Delta m^2_{12} (L/4E_\nu) \times \sin^2(\Delta m^2_{23} L/4E_\nu)$$

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

$$\approx f \times \Delta m^2_{12} (\Delta m^2_{23})^2 (L/4E_\nu)^3$$

for $\Delta m^2_{21} (L/4E_\nu) << \Delta m^2_{32} (L/4E_\nu) << 1$

So what to do at high energy?

See also P. Lipari, hep-ph/0102046

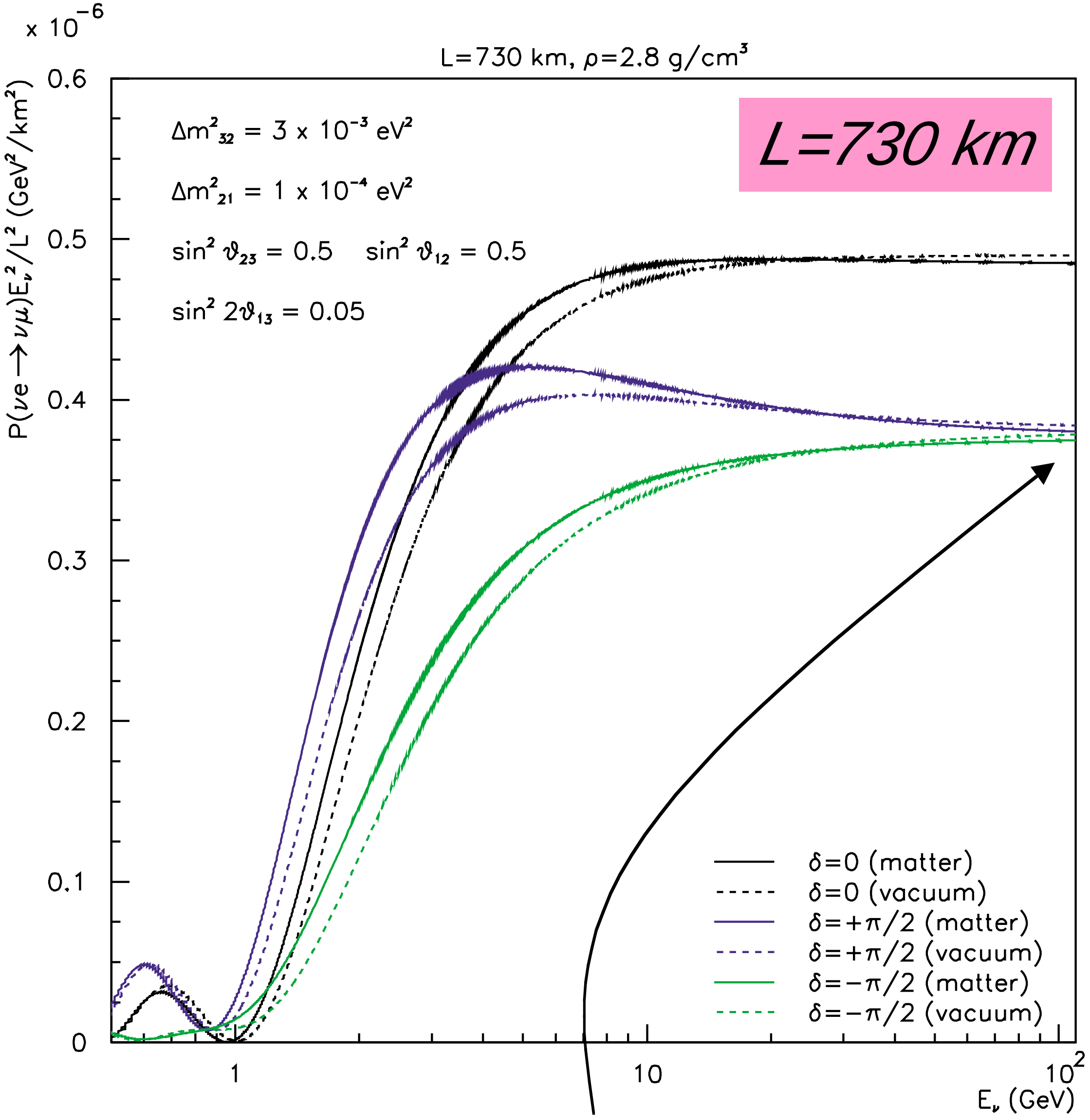
$$P\left(\nu_e \to \nu_\mu\right) \times E_\nu^2 / L^2$$

1. The E_ν^2 term takes into account that the NF likes to go to high energy $\Rightarrow$ damps the part $\Delta m^2_{21}\,(L/4E_\nu) \approx 1$

2. At "high energy", i.e. $\Delta m^2_{21}\,(L/4E_\nu) << 1$ & $\Delta m^2_{32}\,(L/4E_\nu) << 1$, there is no more oscillation

$\Rightarrow$ change of δ = change of θ_{13} !!!

3. At "high energy", the CP-effect goes like $\cos\delta$, as pointed out by Lipari $\Rightarrow$ cannot measure sign of δ



$$P\left(\nu_e \to \nu_\mu, \delta = \frac{\pi}{2}\right) - P\left(\nu_e \to \nu_\mu, \delta = 0\right) \propto \cos\delta$$

So where is the compromise in L/E?

We must compromise at "medium" energy to

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

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

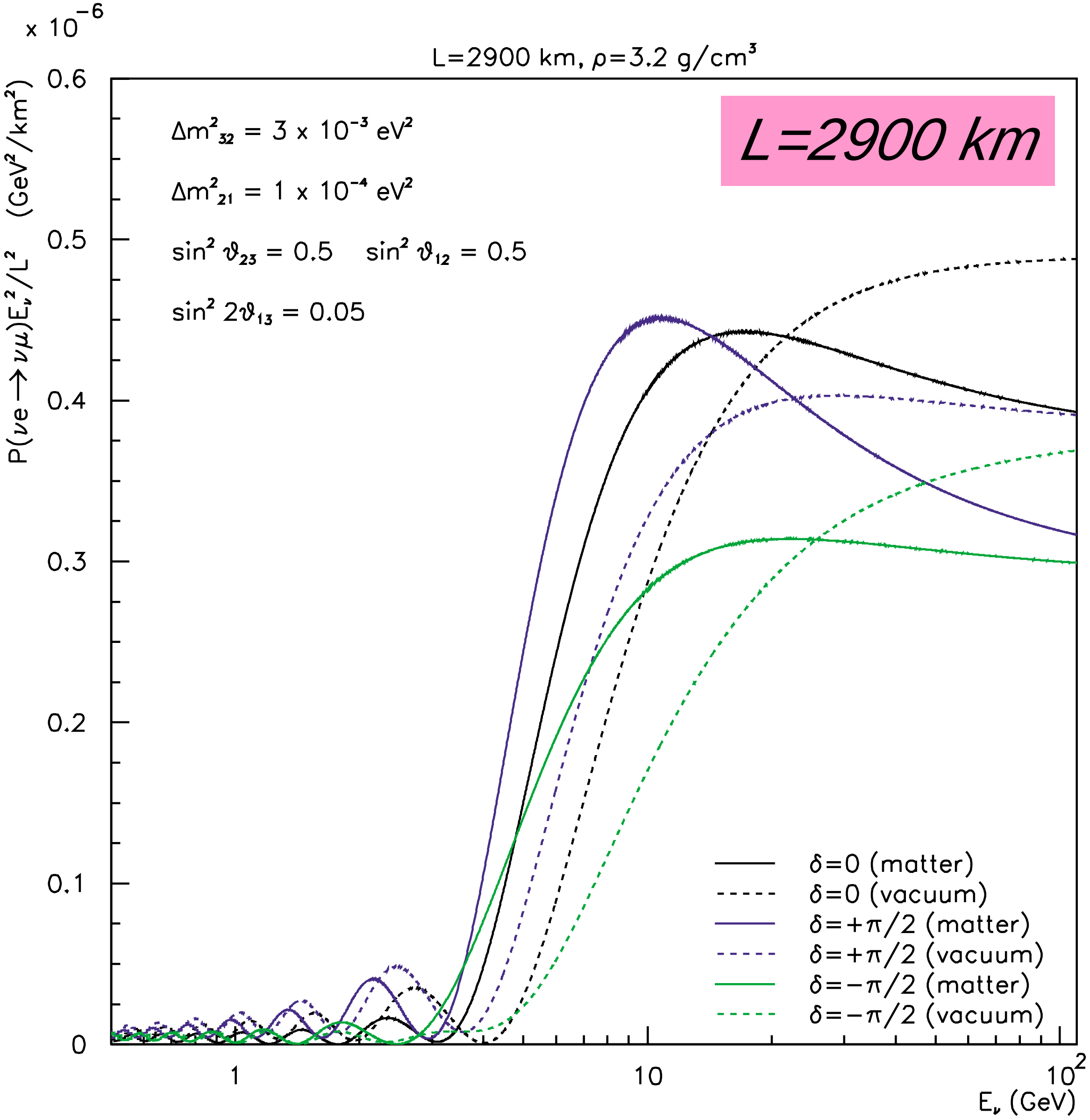
2. To gain from the E_μ^3 *behavior of the NF*

3. To guarantee the possibility to disentangle δ *from* θ_{13}

$$\frac{L}{E_\nu} \approx \frac{4\pi}{2\Delta m^2_{32}}$$

¥$E_{\nu,MAX}$ ˉ 2 GeV for L=732 km

¥$E_{\nu,MAX}$ ˉ 8 GeV for L=2900 km



If L/E$_\nu$ is fixed, what should be L and E$_\nu$?

The magnitude of the CP effect (given by J) is known to be unaffected by matter

$J = \cos\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}/8$

Our "choice-point" for CP is at the fixed L/E$_{\nu,\max}$ given by: $E_{\nu,\max} = \frac{2\times 1.27\times \Delta m^2 L}{\pi}$

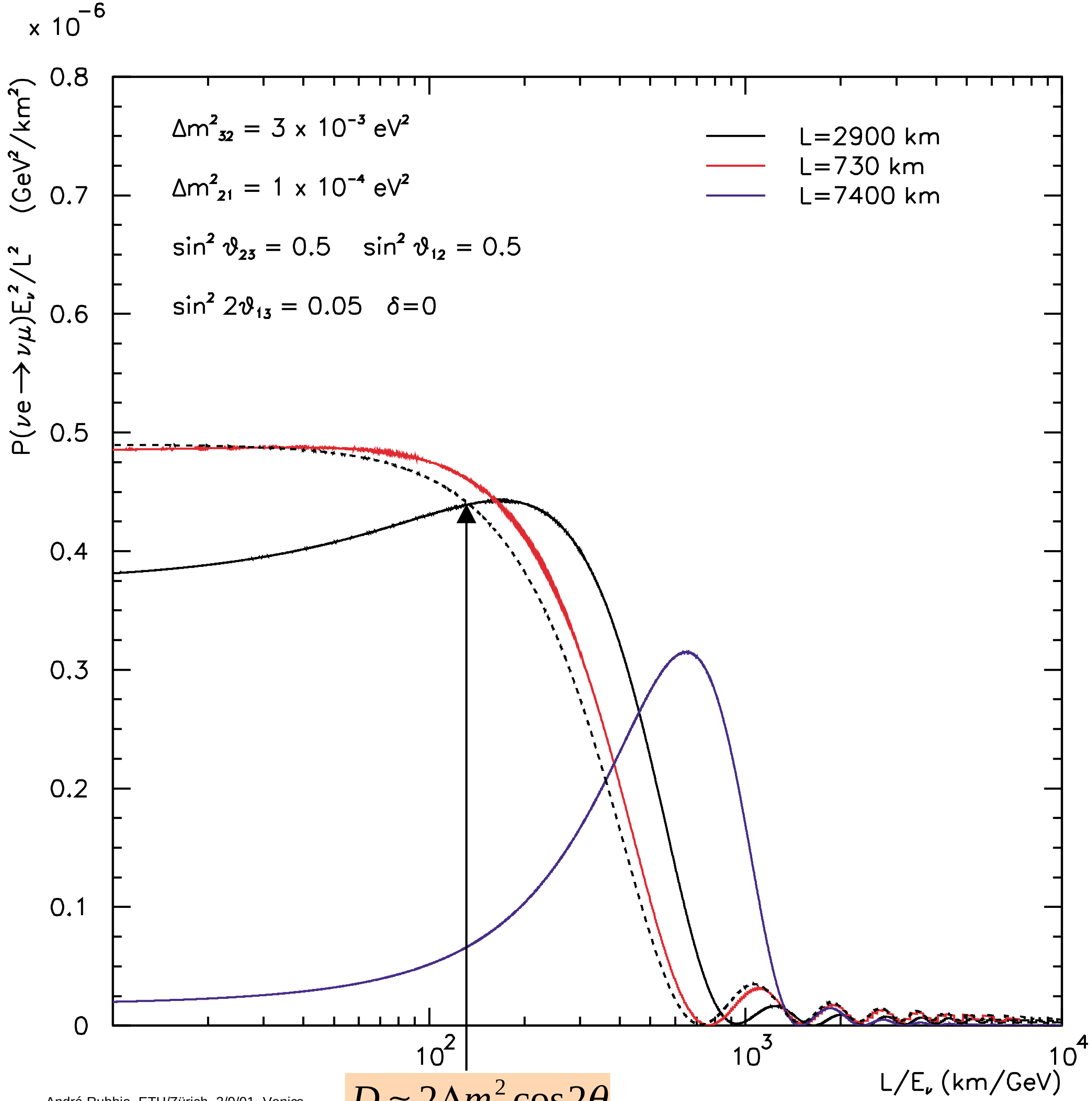
When the neutrino energy becomes close to the MSW resonance, the effective oscillation wavelength increases, hence the CP effect at a fixed distance L becomes less visible.

Hence, we gain until the MSW resonance region and then loose

$$2\sqrt{2}G_F n_e E_\nu < \Delta m^2 \cos 2\theta \quad \Rightarrow \quad 2\sqrt{2}G_F n_e \frac{2\times 1.27 \Delta m^2 L}{\pi} < \Delta m^2 \cos 2\theta$$

$$L < \frac{\pi \cos 2\theta}{2\times 1.27\times 7.56\times 10^{-5} \quad eV^2 \left(\frac{\rho}{gcm^{-3}}\right)} \approx \frac{1.5\times 10^4\, km}{\left(\frac{\rho}{gcm^{-3}}\right)} \approx 5000 km$$

Dependence of probability on L/E_ν

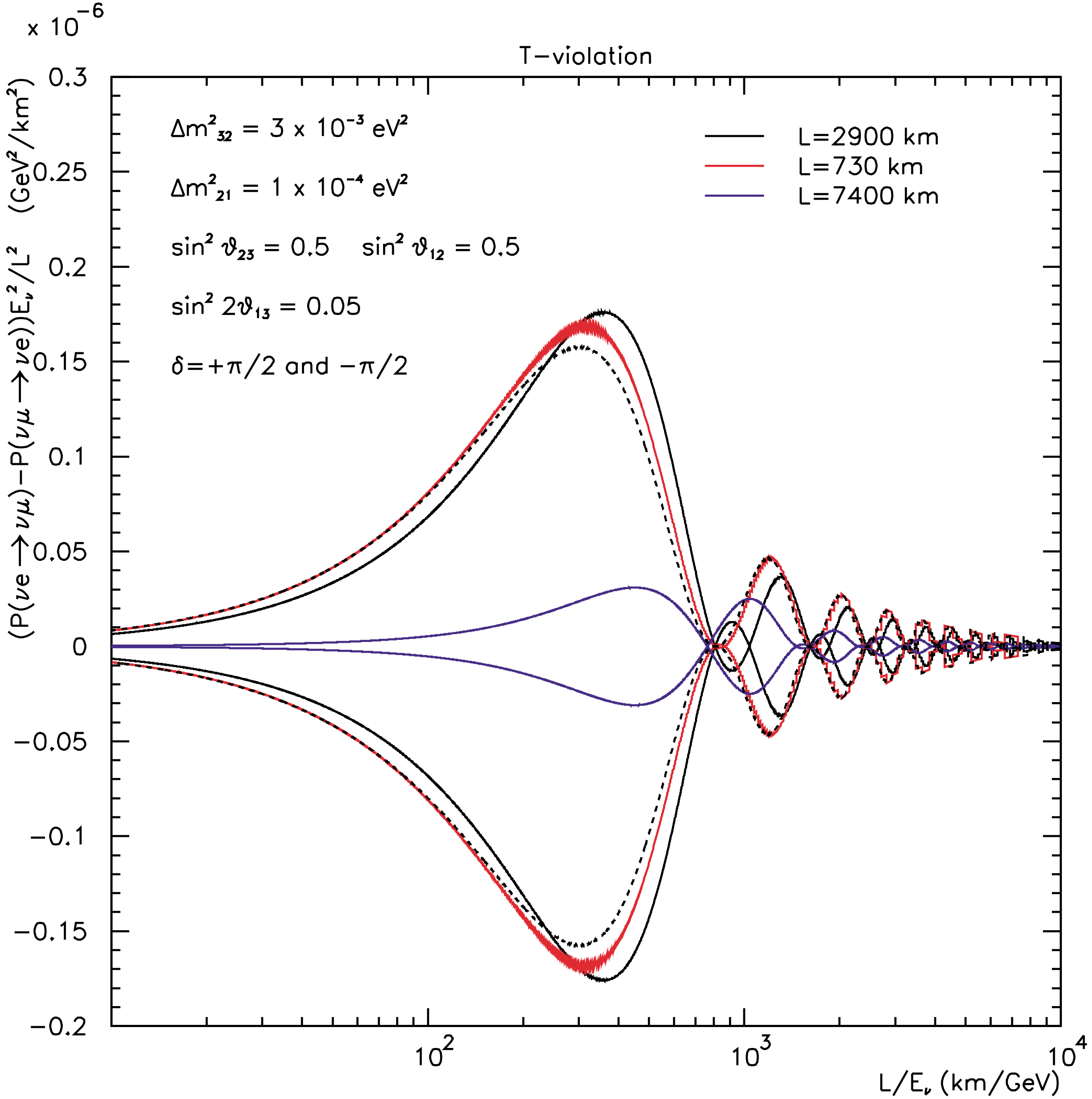


$D \approx 2\Delta m^2 \cos 2\theta$

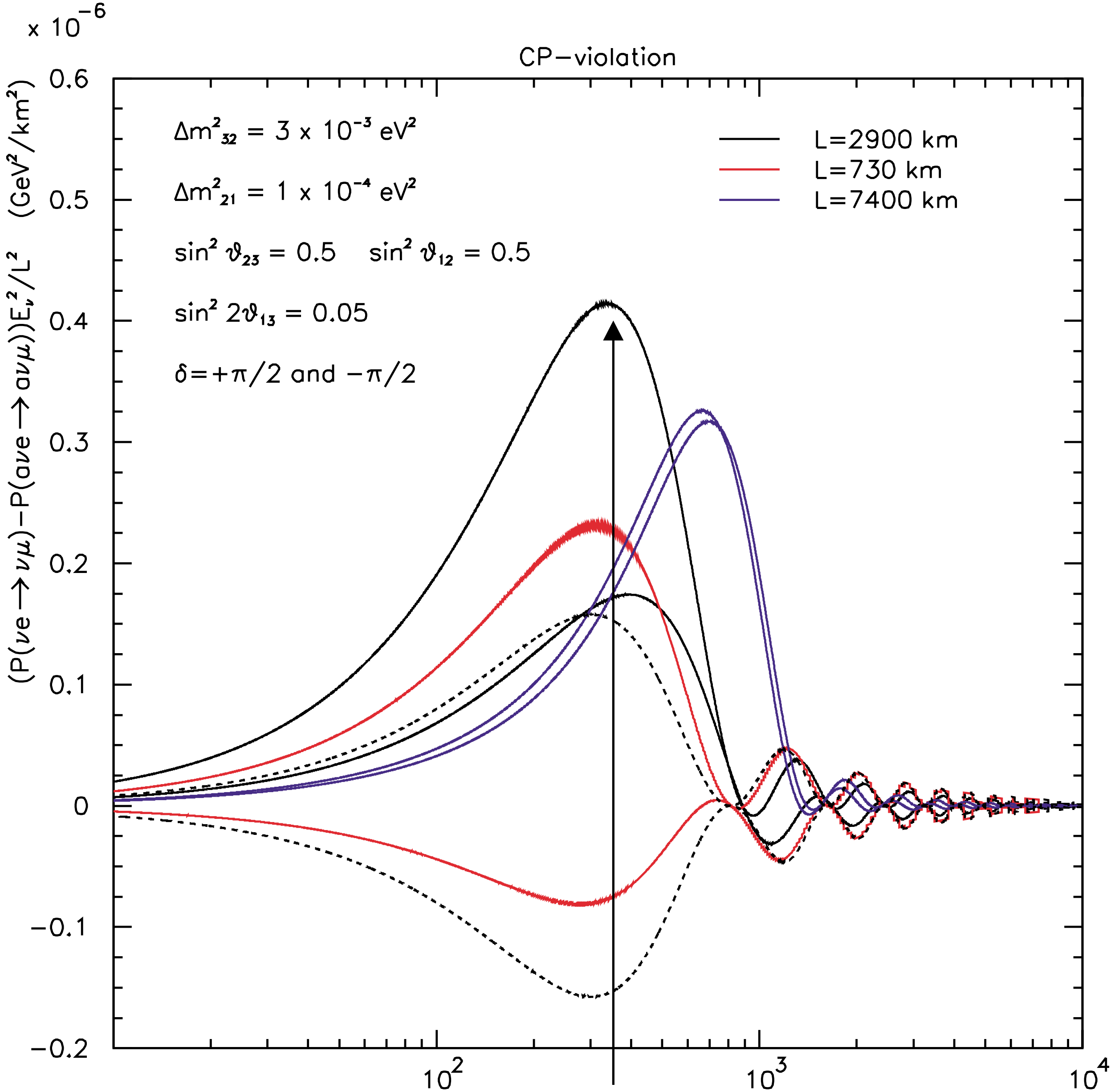
The "scaling" with L/E_ν of the probabilities is destroyed when $E_{\nu,max} > E_{\nu,\, resonance}$, due to matter effects.

André Rubbia, ETH/Zürich, 3/9/01, Venice

The T-violation term dependence on L/E$_\nu$



The CP-violation term dependence on L/E_ν



$D \approx \Delta m^2 \cos 2\theta$

Fit with constant L/E

As long as L < ≈5000 km, the effects scale with L/E_ν

However, keeping L/E_μ *constant, we gain linearly with* E_μ *because of the NF flux dependence* $E_\mu{}^3/L^2$

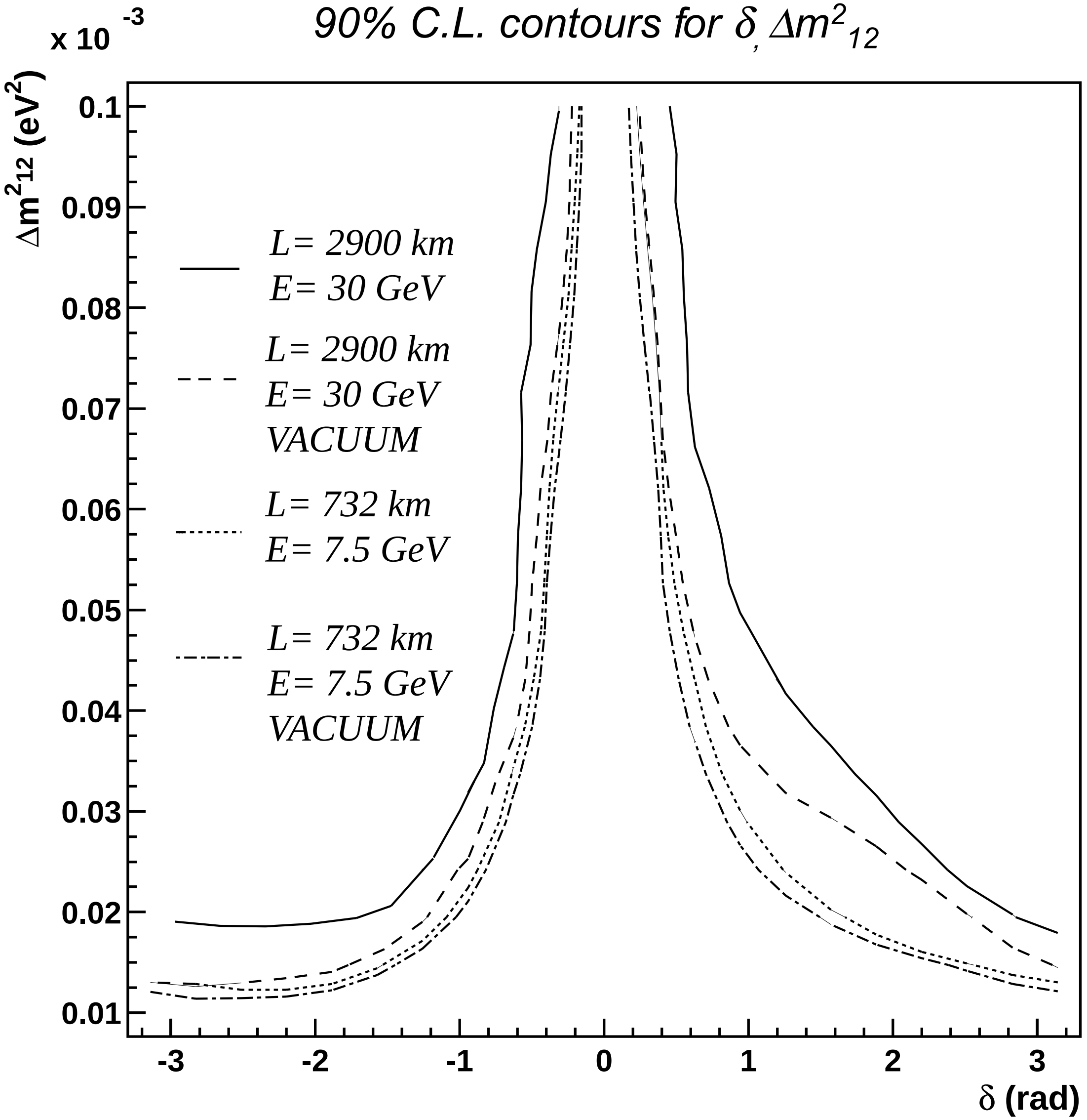
⇒ *At lower* E_μ *must compensate with higher muon intensities*

E_μ=30 GeV & L=2900 km

→ 2.5×10^{20} decays

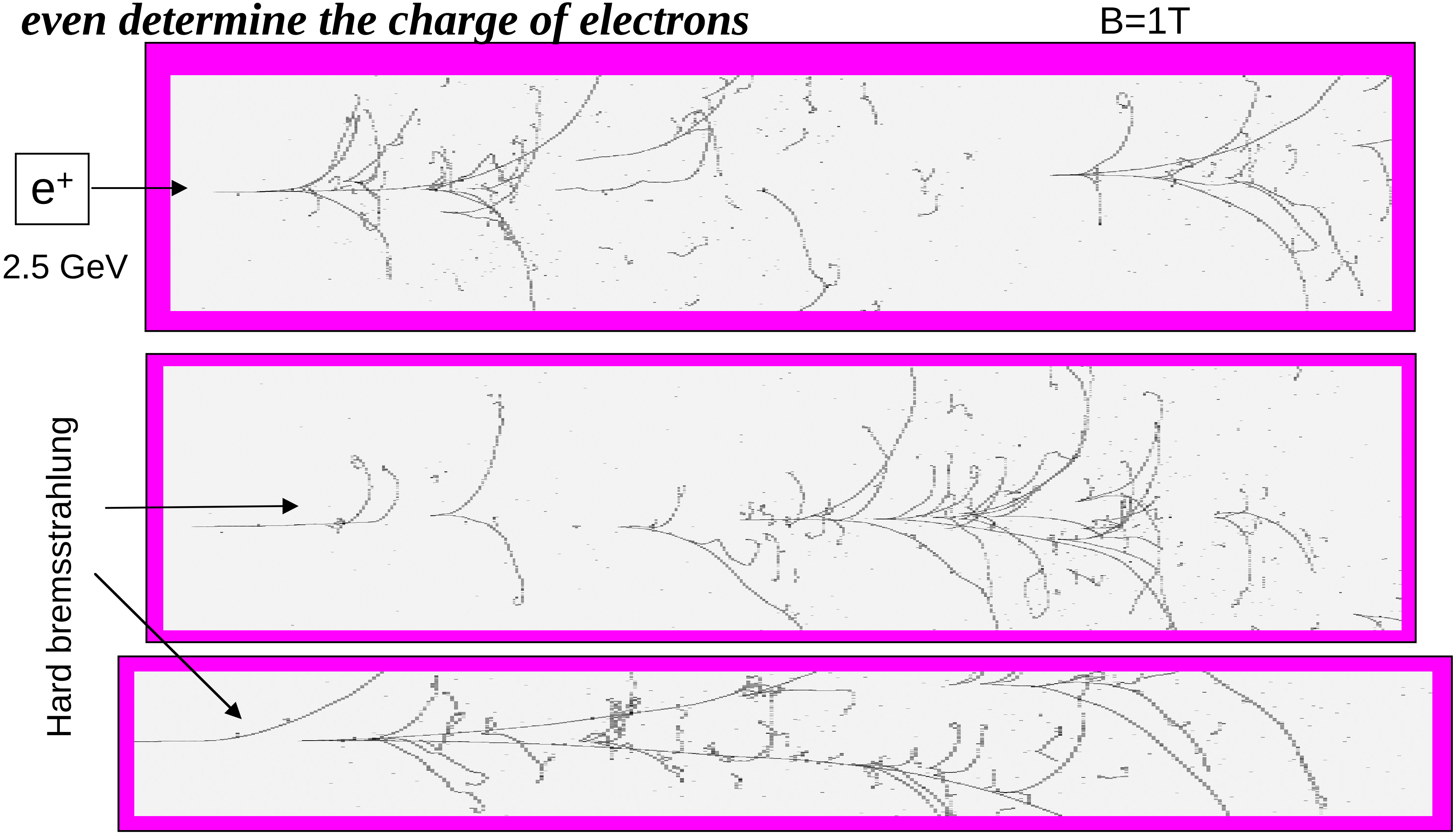
E_μ=7.5 GeV & L=732km

→ 10^{21} decays

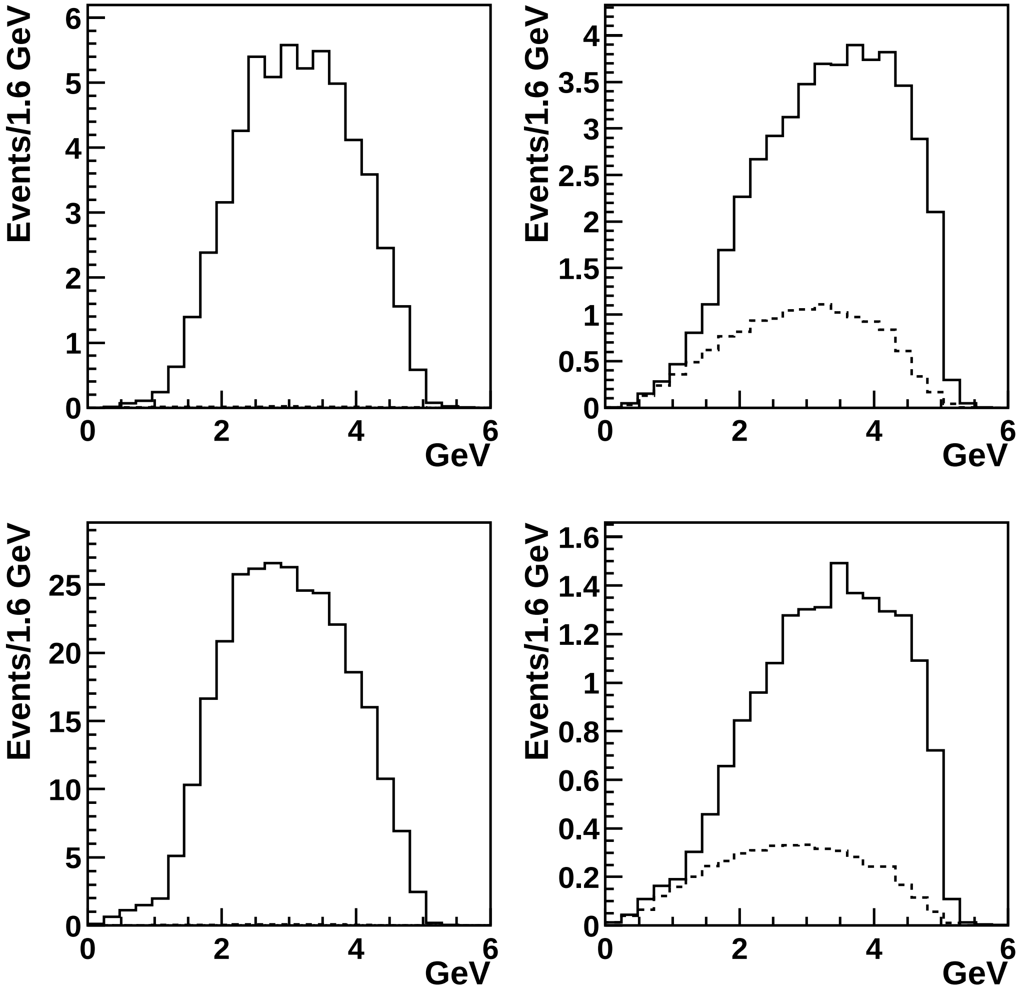


On the possibility to measure the electron charge

The presence of a magnetic field surrounding the LAr should allow to even determine the charge of electrons



Wrong-sign lepton spectra



μ^{-} decays

μ^{+} decays

WS ν_μ CC

WS ν_e CC

- ✭ Main background for WSE:
- o $\mu^{-} \to \nu_\mu \Rightarrow \nu_\tau \to \tau^{-} \to e^{-}$
- o Wrong-sign electrons from τ decays not suppressed as in the WSM case:
- o $\mu^{-} \to \bar{\nu}_e \Rightarrow \bar{\nu}_\tau \to \tau^{+} \to \mu^{+}$

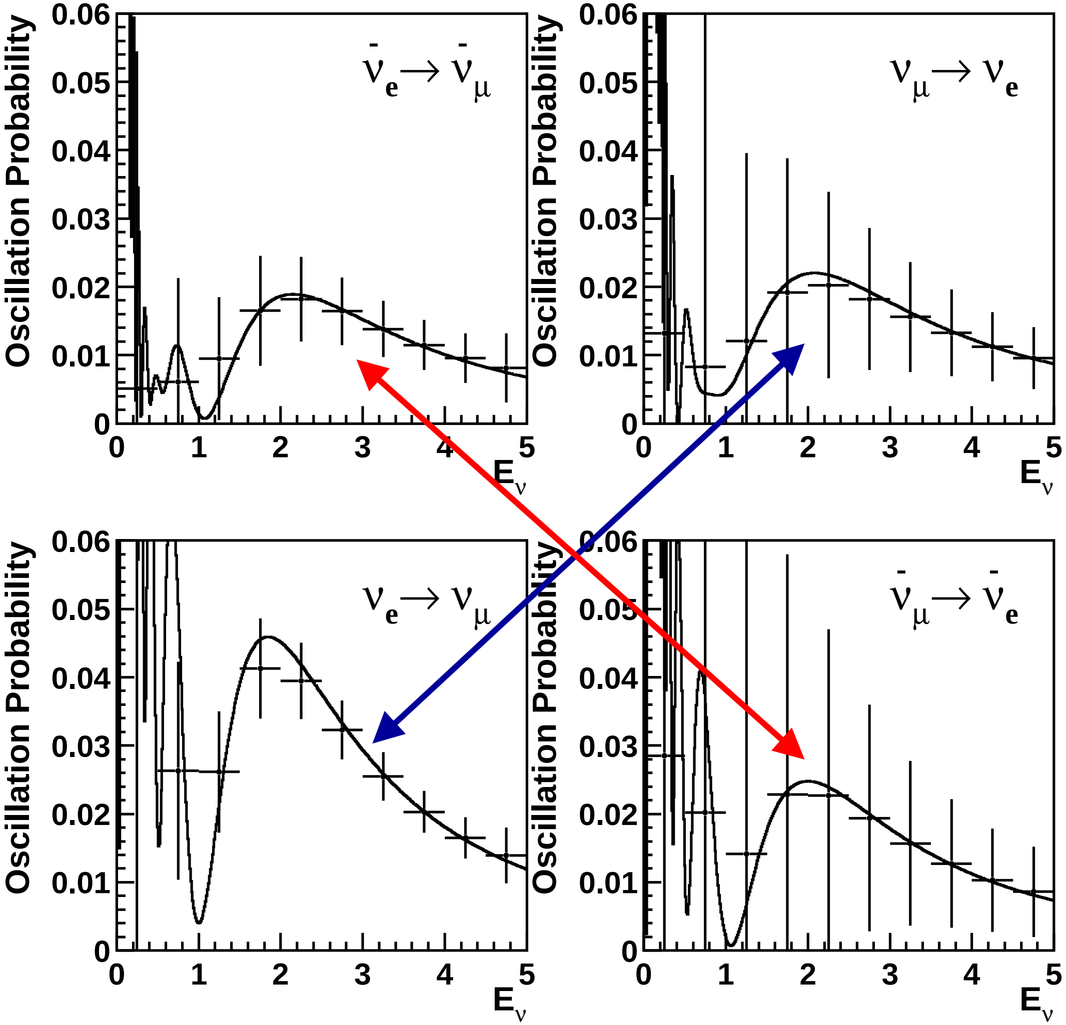
$\propto \sin^2 2\theta_{13}$

One more reason to go to lower energies where τ production is suppressed

Measured oscillation probabilities

- $\Delta m^2_{23}=3.5\times10^{-3}$ eV^2
- $\Delta m^2_{12}=1.\times10^{-4}$ eV^2
- $\sin^2 2\theta_{13}=0.05$
- $\sin^2 2\theta_{23}=1.$
- $\sin^2 2\theta_{12}=1.$
- $\delta_{13}=\pi/2$
- 10^{21} μ decays $E_\mu=5$ GeV
- 10 kton detector

ε=20%, w.s. background 10^{-3}



Direct comparison of oscillation probabilities for neutrinos and antineutrinos

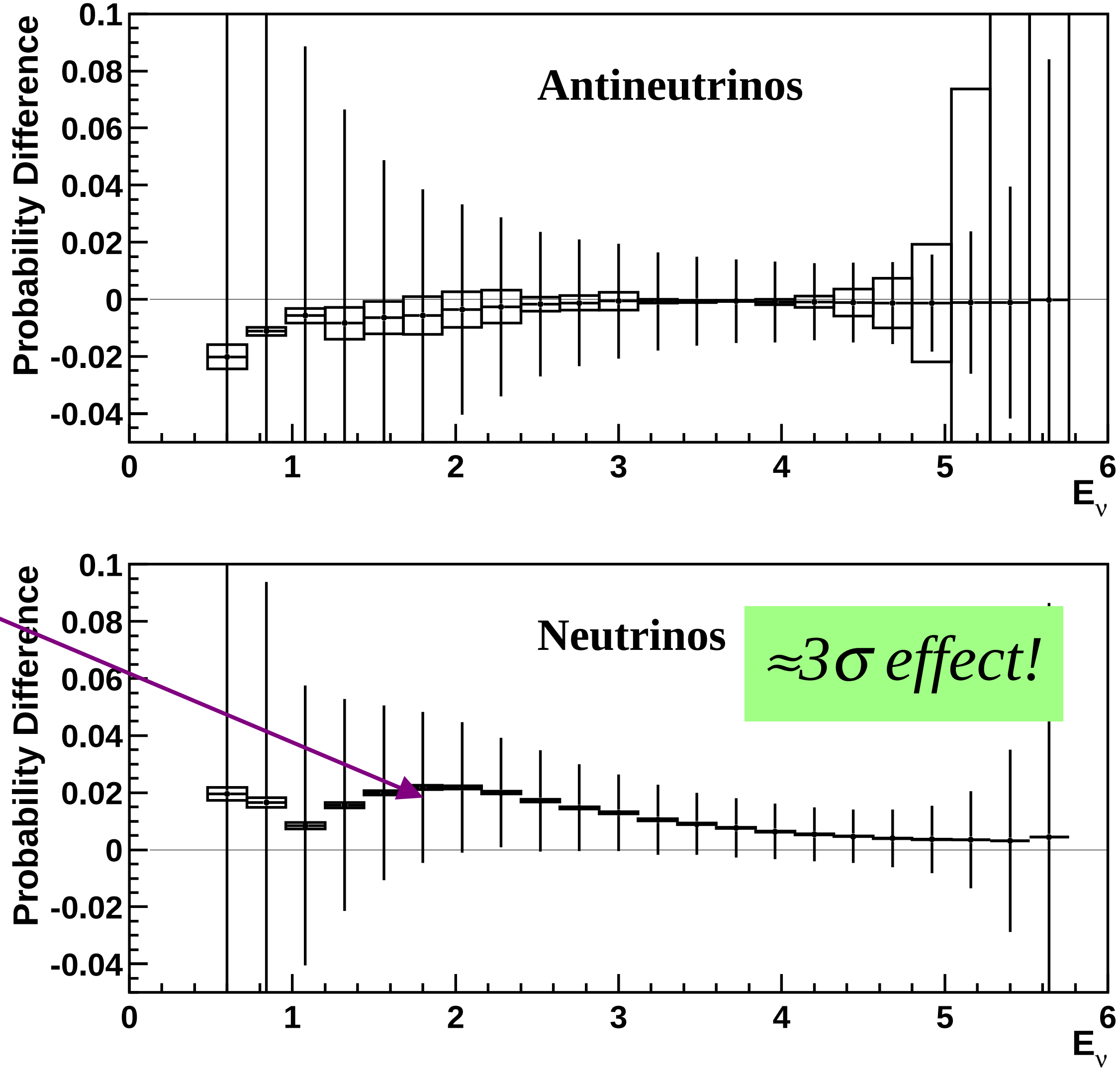
Probability difference

Difference is significant for neutrinos (antineutrinos are matter-suppressed) after evaluation of statistical and systematic errors (5% variation in τ contribution)

$$P\left(\bar{\nu}_e \rightarrow \bar{\nu}_\mu\right) - P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)$$

- ✭ Direct measurement of the CP-odd component.

$$P\left(\nu_e \rightarrow \nu_\mu\right) - P\left(\nu_\mu \rightarrow \nu_e\right)$$



≈3σ effect!

Conclusion

- The richness of the NF oscillation physics calls for ***multikton detectors capable of measuring all leptons and their charges***!
- ***A difficult task***, leading to ***different optimizations***, but
  - → ***MINOS***-like (20kt?) & ***ICARUS***-like (10kt?) (they would cost ≈ the same!) are more than just detector concepts
  - → They could be envisaged, but they will be expensive and to build either of them will be a great enterprise !
- The physics output will depend on the detector, ***different optimizations***? e.g.
  - → For the ***best θ_{13} sensitivity*** (10^{-5} ? the small mixing angle syndrome) it would suffice to have large mass (statistics!) and good muon capabilities at the highest energies
  - → For more subtle effects like ***the study of δ-phase***, a detector with more redundancy and excellent detection in the range 1–15 GeV is favored
  - → If ***energy cannot be afforded***, must go closer, keeping L/E constant (at the price of increasing the muon intensity!)
  - → Charge discrimination for electrons could provide ***a "direct" proof*** of T-violation !