ICARUS:

analysis of real events, waiting for CNGS neutrino beam

ICARUS at Venice 2001

ICARUS: mature technique, ***demonstrated up to 15 ton prototype***

Electromagnetic and hadronic calorimetry e/hadron separation

600 ton prototype construction very advanced

ICARUS at Venice December 2003

Demonstrated up to 600 ton first module of 3000 ton

Measurement with real data of π^0 (preliminary) , electrons (in publication) and MC simulations (published)

600 ton module constructed and ready for transportation to LNGS

ICARUS at Venice 2001

ICARUS at Venice December 2003

The T600 module will be ready to be transported into the LNGS tunnel

→ ***Safety plan approved (waiting for details), transportation scheduled next year***

Disadvantages: muon charge discrimination:
target cannot be easily magnetized (but...)
rely on ***down-stream muon spectrometer***

→ ***Designed and approved the muon spectrometer (ETH with new collaborators of Spain and Russia)***

Installation project of T600 at LNGS has been APPROVED by the LNGS laboratory February 2003

Long baseline Neutrino beam

<u>History</u>: since 1993 proposal the ICARUS Collaboration has put forward the possibility to use the CERN SPS as a proton driver to create:

<u>a long-baseline neutrino beam</u>

<u>in the direction of the Gran Sasso Laboratory.</u>

Today, the ICARUS T3000 experiment has been approved as an integral part of the

CERN-NGS program. (CNGS02 experiment)

The first two important physics issues to be addressed with the CNGS are the searches for oscillations:

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

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

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

The $\nu_\mu \rightarrow \nu_\tau$ search is based on the discrimination between signal and background through the **kinematical technique**.

It is well known that the **precise kinematical event closure**, which depends on the ***detector performance*** but also from the ***complicated nuclear effects*** at the neutrino vertex, can be precisely monitored by the ν_μ **charged current (CC) interactions**, which provide a **control sample** with very high statistics.

The ***kinematical closure of these events*** requires a precise enough measurement of the leading muon in order to be sensitive to the kinematical feature of the recoiling jet, namely of the order of **$\Delta p/p$ ~16%.**

CNGS02 $\nu_\mu \rightarrow \nu_\tau$ appearance search

1. Assuming T3000 detector (2.35 kton active, 1.5 kton fiducial) 5 years running and
2. integrated pots = 2.25 x10^{20} we expect about **33000 CC neutrino interactions** and
3. **280 CC τ – interactions** for Δm^2_{23}**=3 x 10^{-3} eV^2** and maximum mixing angle.
4. Several decay channels are exploited (**electron = golden channel**)
5. (**Low**) backgrounds measured in situ (control samples)
6. **High sensitivity to signal, and oscillation parameters determination.**

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

Expected events / 5 years

Process	Expected events total LAr	Expected events Active LAr
ν_μ CC	52600	32600
$\bar{\nu}_\mu$ CC	1050	652
ν_e CC	423	262
$\bar{\nu}_e$ CC	27	17
ν NC	17100	10600
$\bar{\nu}$ NC	400	245
ν_τ CC, Δm^2 (eV^2)		
1×10^{-3}	50	31
2×10^{-3}	200	125
3×10^{-3}	450	280
5×10^{-3}	1210	750

Table 2.1: Expected event rates for five years of CNGS running and 5 T600 modules. For standard processes, no oscillations are assumed. For ν_τ CC, we take two neutrino $\nu_\mu \to \nu_\tau$ oscillations with $\sin^2 2\theta = 1$.

$\nu_\mu \rightarrow \nu_e$

The $\nu_\mu \rightarrow \nu_e$ search is based on the **search for an excess of electron neutrino** signal over the intrinsic beam contamination.

It is also well known that the precise prediction of the parent meson yields and hence of the various neutrino flavor components at LNGS can be largely improved by a precise and independent **in-situ measurement of the energy spectrum of the** ν_μ **and** $\bar{\nu}_\mu$ **fluxes** and by a good sensitivity to the high energy tail (typically E > 50 GeV) where muon neutrinos come primarily from kaon decays.

Muon charge discrimination and measurement in the neutrino energy range 50 < E < 100 GeV requires the external magnetic analysis of the leading muons.

Search for sub-leading $\nu_\mu \rightarrow \nu_e$

- **Search for excess of electrons**
- **Takes advantage of unique e/π^0 separation in ICARUS**
- Assume 5 years @ 4.5×10^{19} pots/year, 2.35 kton fiducial
- **Needs more intensity** **(low E)** to increase statistics to exploit ICARUS features

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

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

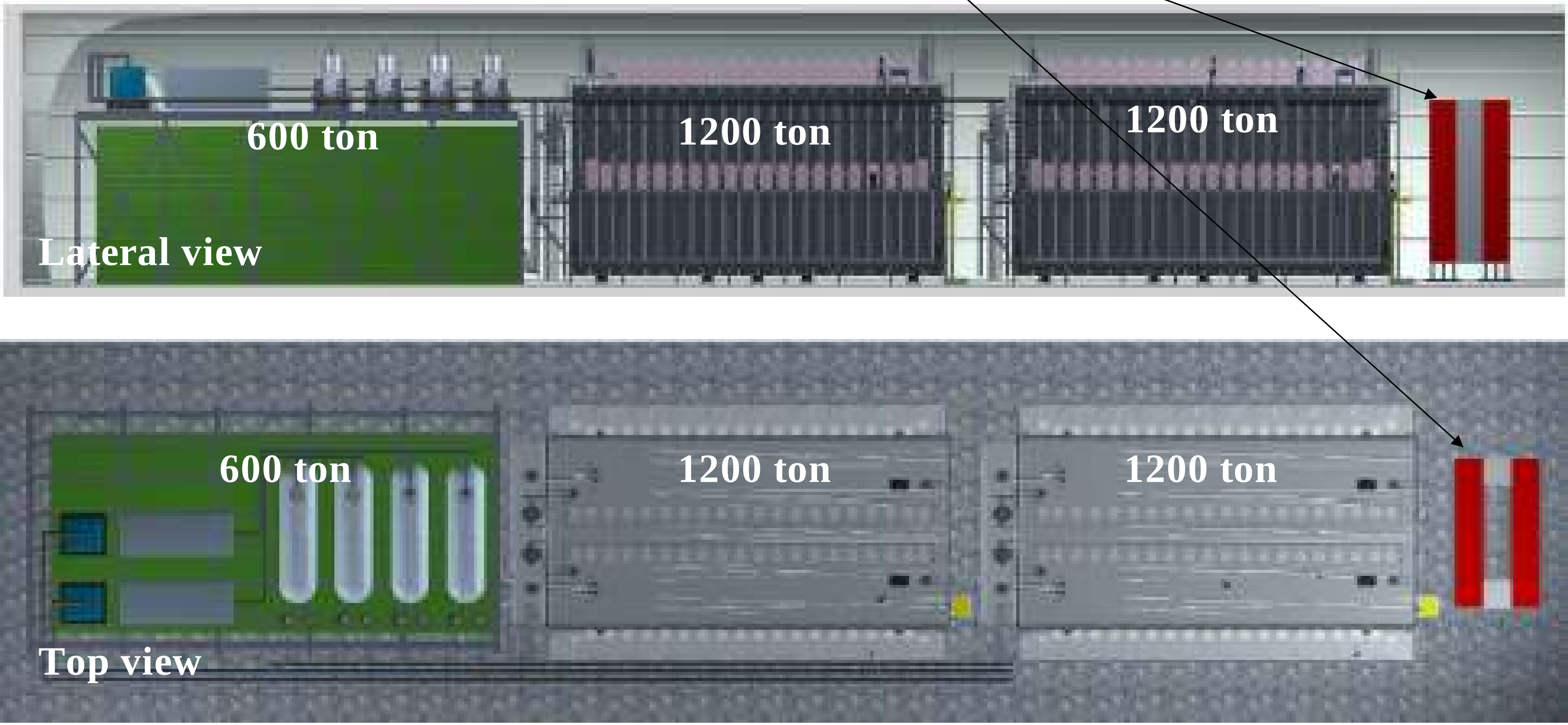
<u>NEW!</u> *muon Spectrometer*

We decided for the above reasons to complement the liquid argon modules by an iron-core magnetic muon spectrometer.

The muon spectrometer is located at the end of the liquid argon modules and acts as a stand-alone detector.

The momentum and charge of the crossing muons is measured through two bending regions, each 1.5 m long, in almost saturated iron at a field of 1.8 T.

Approved design

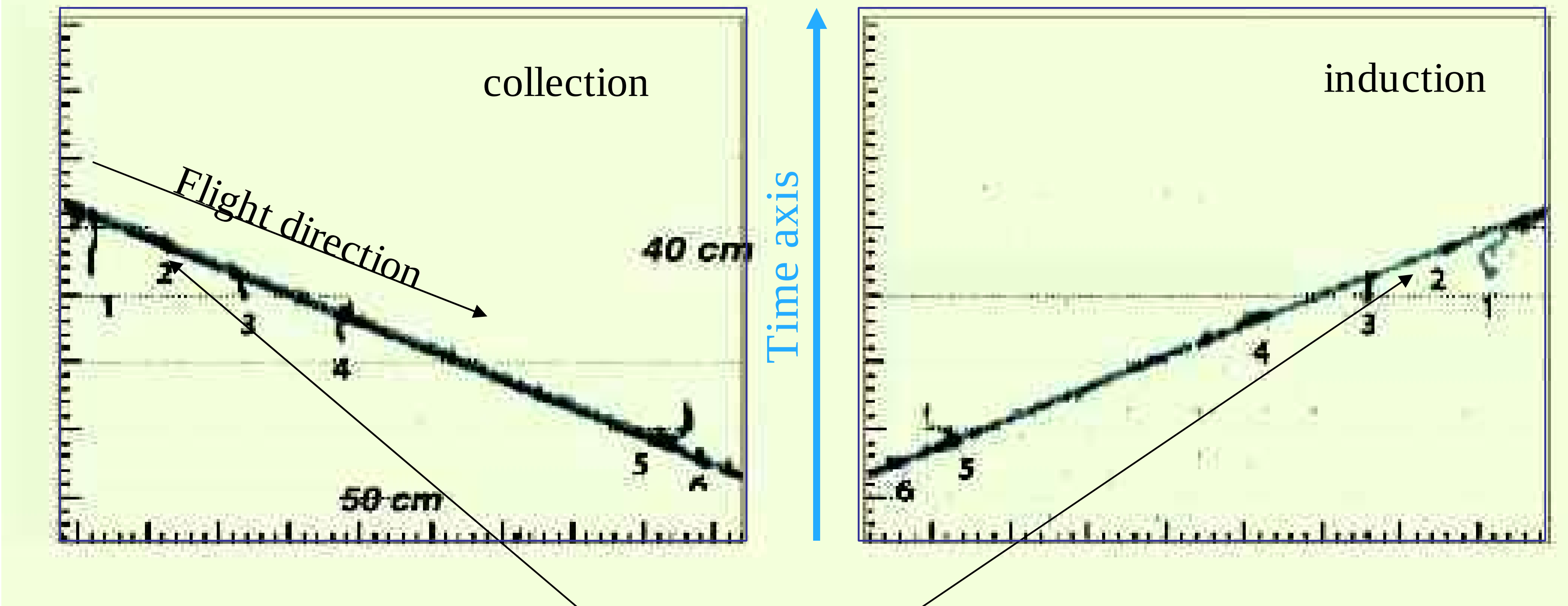


Quality of kinematical reconstruction must be high

ICARUS collaboration is processing 20,000 triggers, recorded in Summer 2001 with 300 ton liquid argon detector, exposed to cosmic rays in Pavia, in order to reach the necessary high quality of kinematical event reconstruction.

Small scale: δ rays

few MeV electrons detected and measured in two views



At **small scale**:

δ ray cutoff energy

1.7 MeV

1.1 ± 0.3 MeV “electron 2”

dE/dx energy measurement

6 mm long δ -ray

With 1.1 ± 0.3 MeV Energy

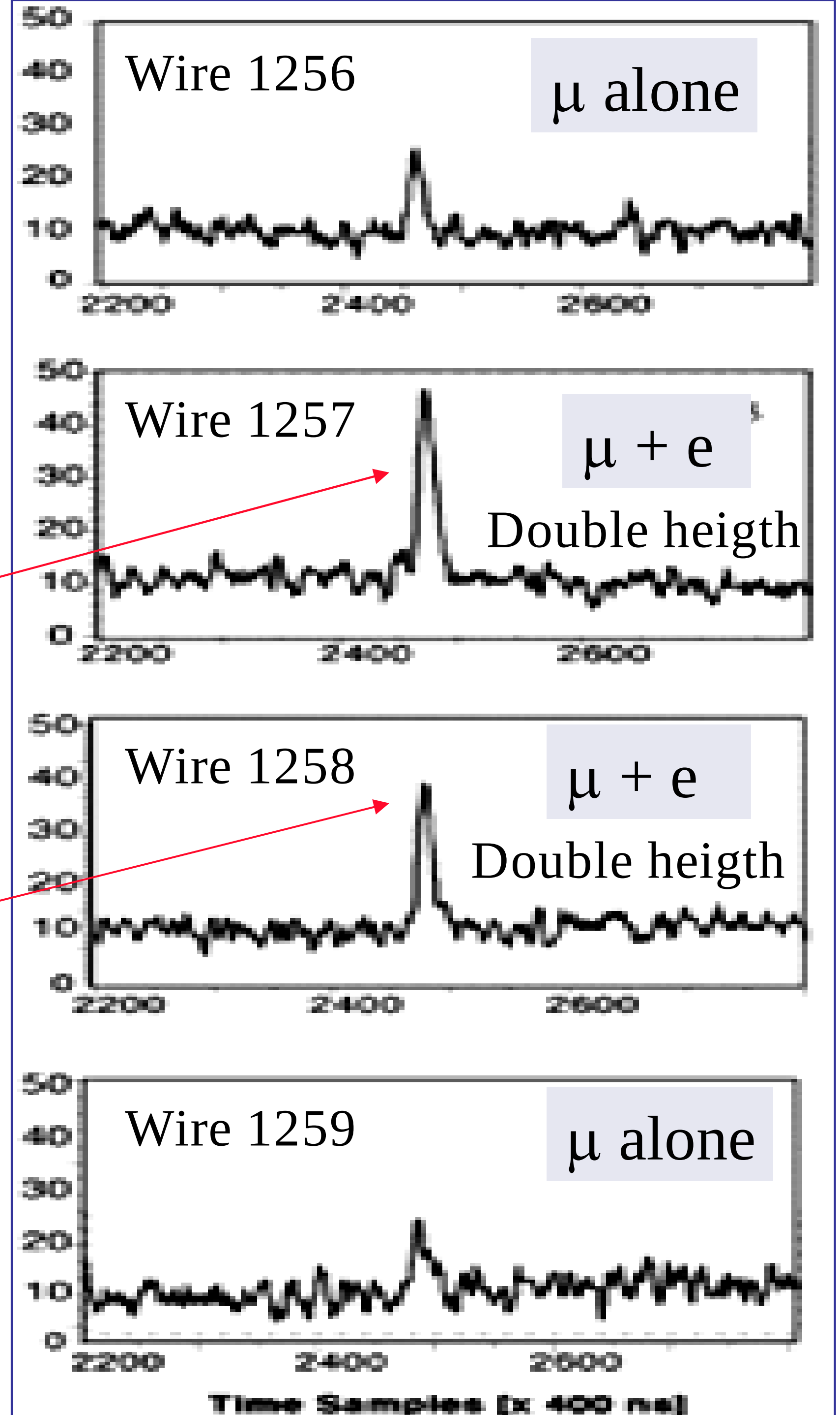
measured with Calorimetric technique by **dE/dx**.

600 ± 200 keV

δ-ray overlapped to m.i.p. muon track

500 ± 200 keV

The energy of electron is obtained subtracting the μ contribution



Intermediate scale:
electrons from decaying muons

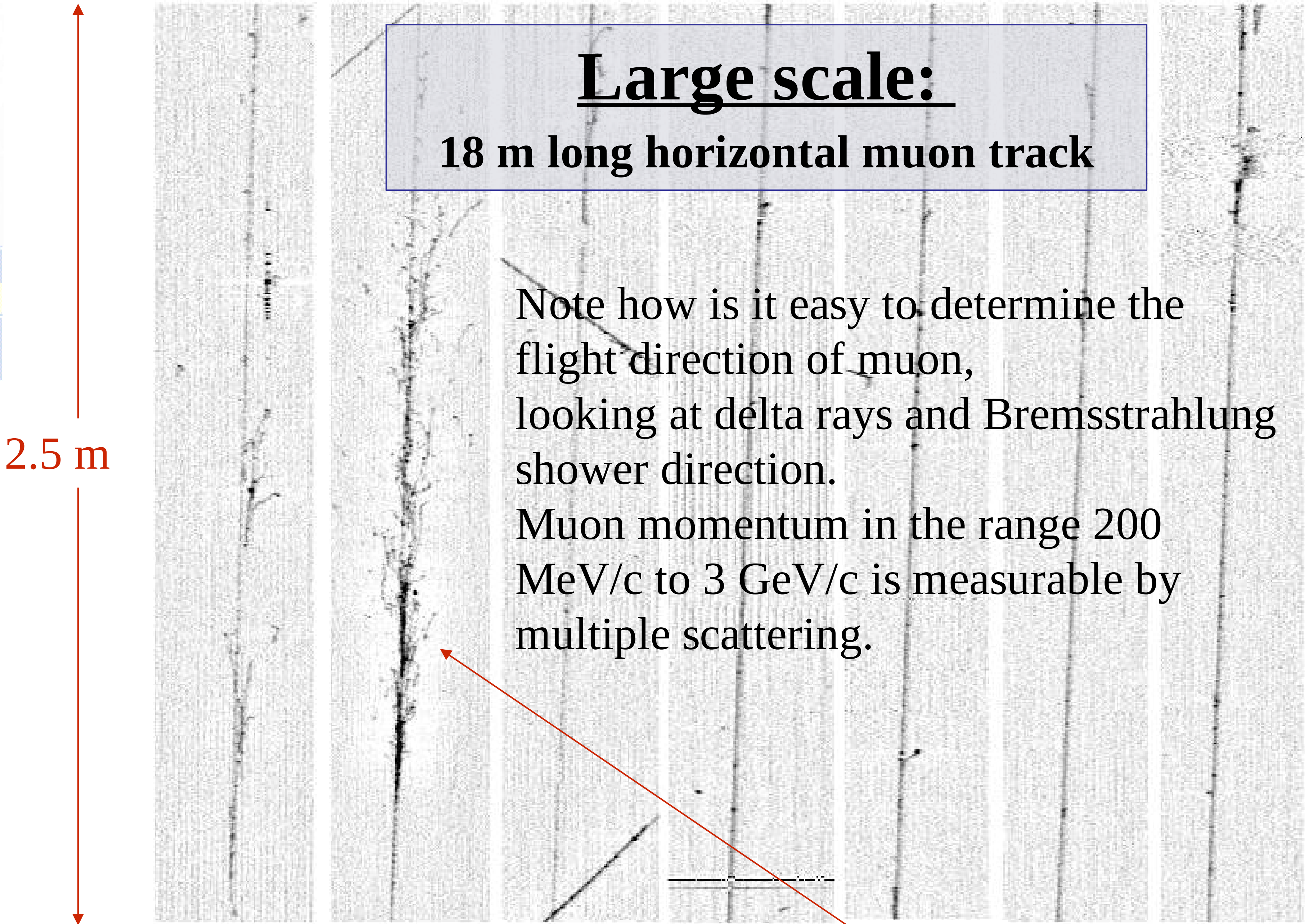
		...ion
Peoples	0.750 ± 0.003	$\eta \equiv 0$
Sherwood	0.760 ± 0.009	$\eta \equiv 0$
Fryberger	0.762 ± 0.008	$\eta \equiv 0$
Derenzo	0.7[illegible] ± 0.003	$-0.13 < \eta < 0.07$
...D	$0.72 \pm$ [illegible] ± 0.03	lepton univers.
...O	$0.747 \pm 0.010 \pm 0.006$	lepton univers.
...US	0.731 ± 0.031	lepton univers.
...3	$0.72 \pm 0.04 \pm 0.02$	lepton univers.
...AL	$0.78 \pm 0.03 \pm 0.02$	lepton univers.
DELPHI	$0.78 \pm 0.02 \pm 0.02$	lepton univers.
ALEPH	0.742 ± 0.016	lepton univers.
This analysis	$0.72 \pm 0.06 \pm 0.08$	$-0.020 < \eta < 0.006$

Michel electrons

Comparison between ICARUS 300 ton and world measurements of the Michel ρ parameter.
(submitted for publication)

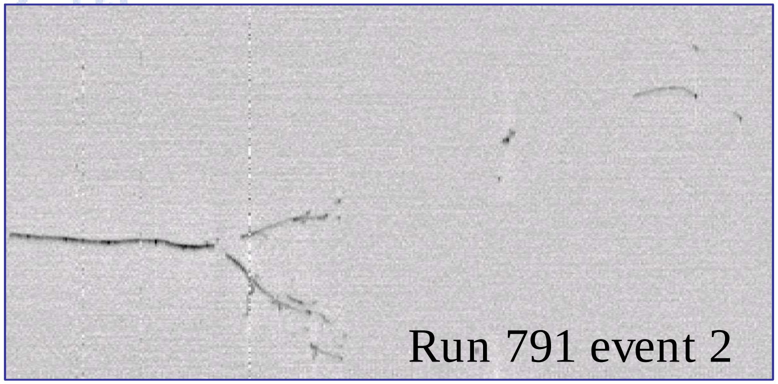
Large scale:

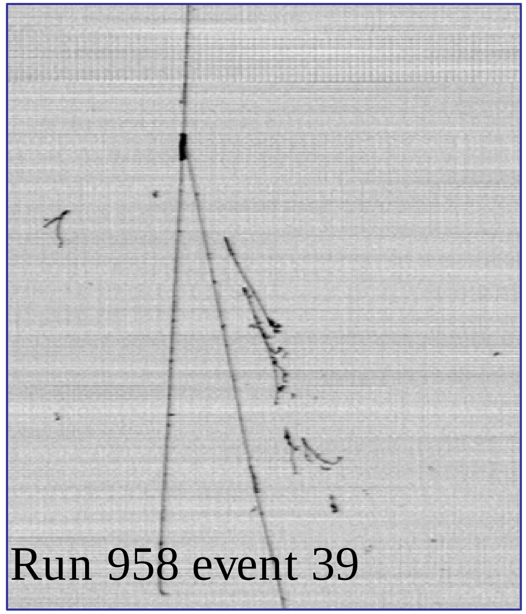
18 m long horizontal muon track

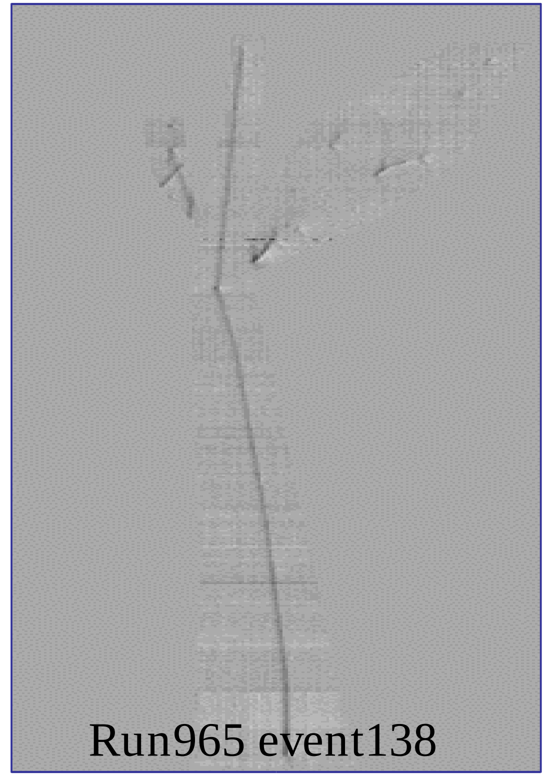


Note how is it easy to determine the flight direction of muon,
looking at delta rays and Bremsstrahlung shower direction.
Muon momentum in the range 200 MeV/c to 3 GeV/c is measurable by multiple scattering.

π^0 measurement (preliminary)







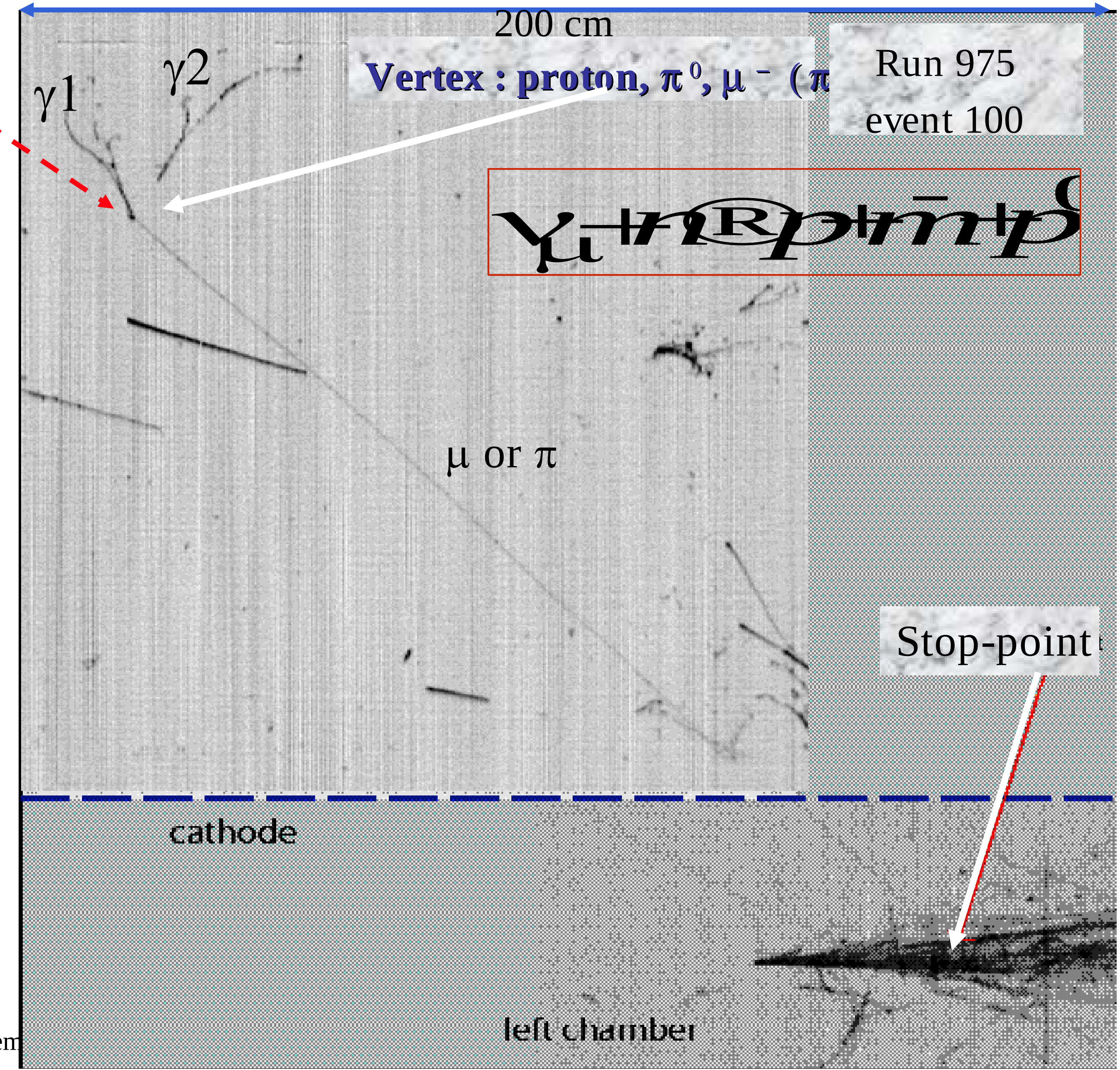
$m(\gamma,\gamma) = (148.5 \pm 10.1)\ \mathrm{MeV}/c^2$

$m(\gamma,\gamma) = (133.7 \pm 9.8)\ \mathrm{MeV}/c^2$

$m(\gamma,\gamma) = (\ 147.1 \pm 9.4\ )\ \mathrm{MeV}/c^2$

T300: atmospheric neutrino-like event (preliminary)

Neutrino direction

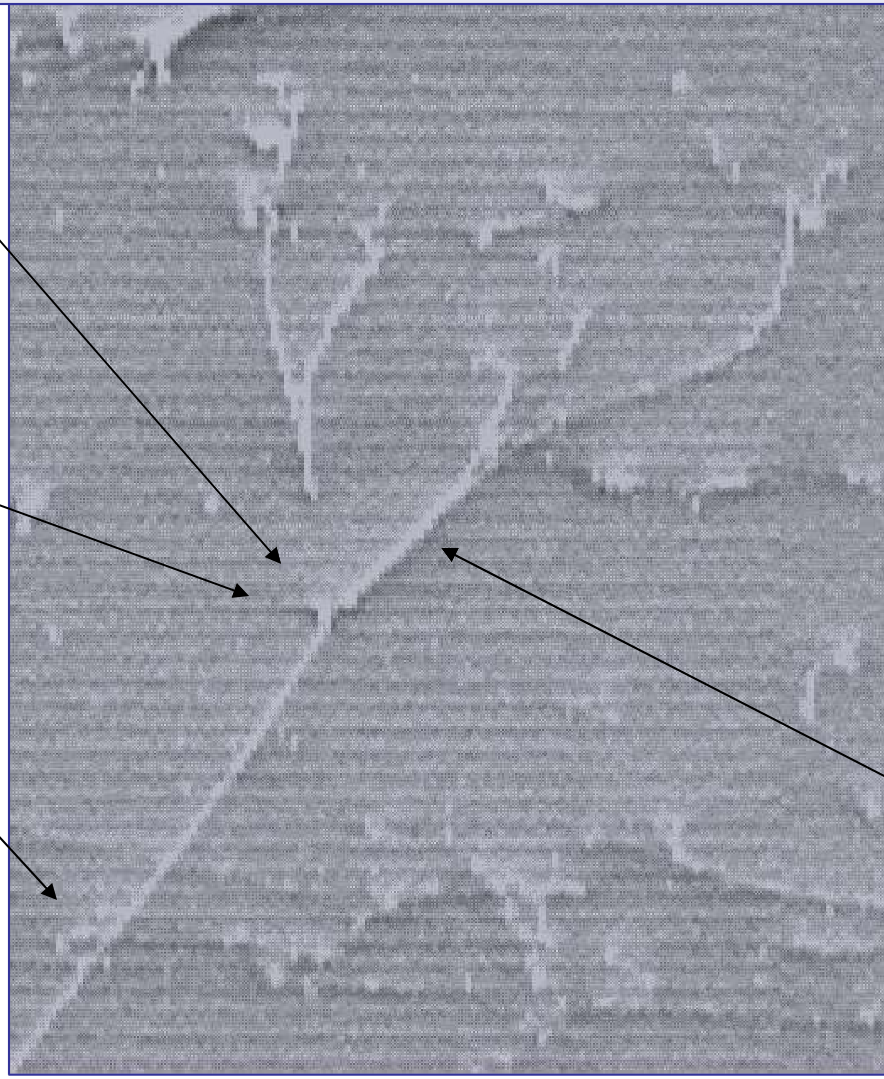


The long track is produced in the vertex and is going down

The vertex is contained

Proton-like 1.7 cm

δ-ray points down-ward

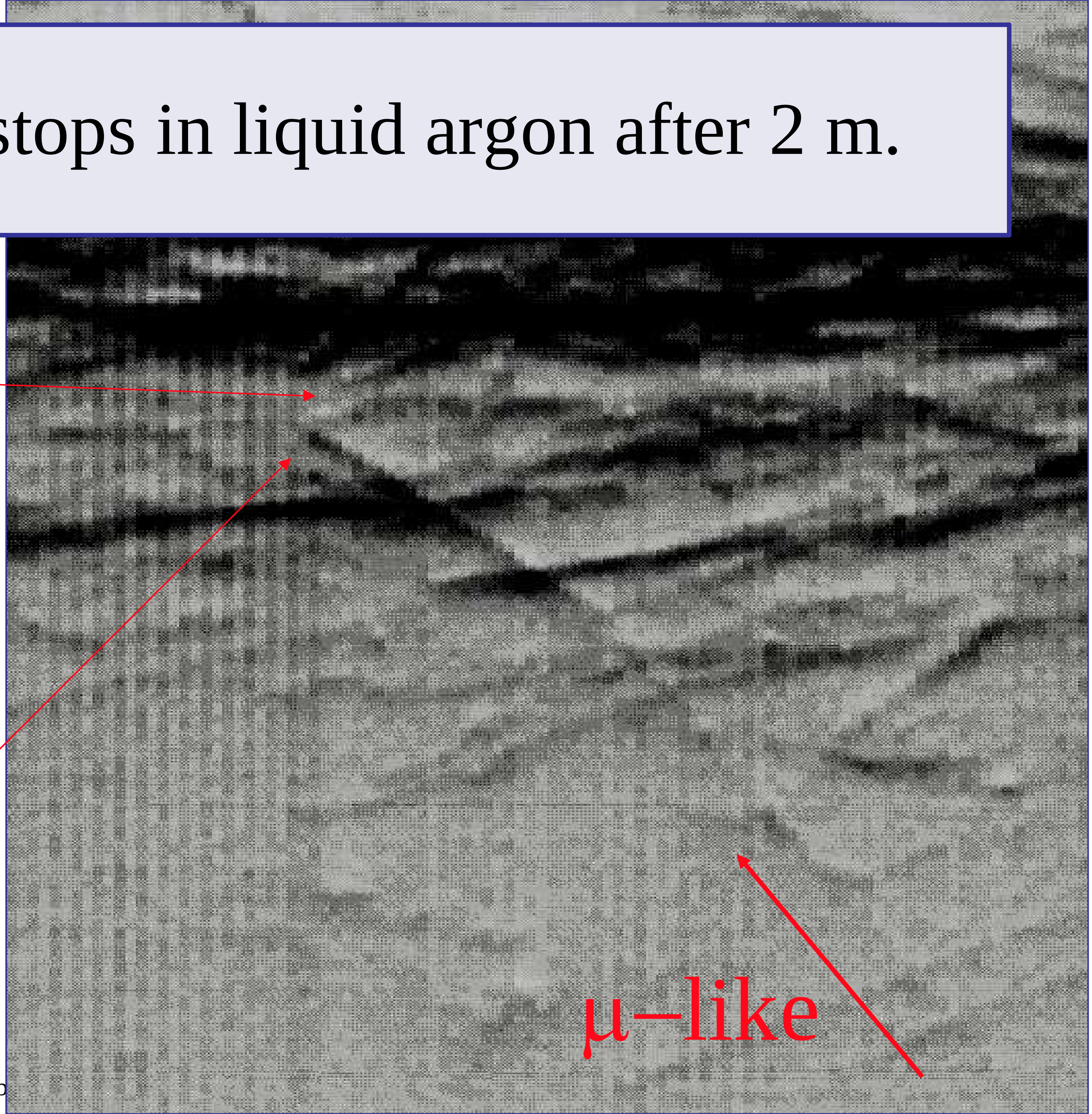


This shower is 1cm far away from the vertex

…and stops in liquid argon after 2 m.

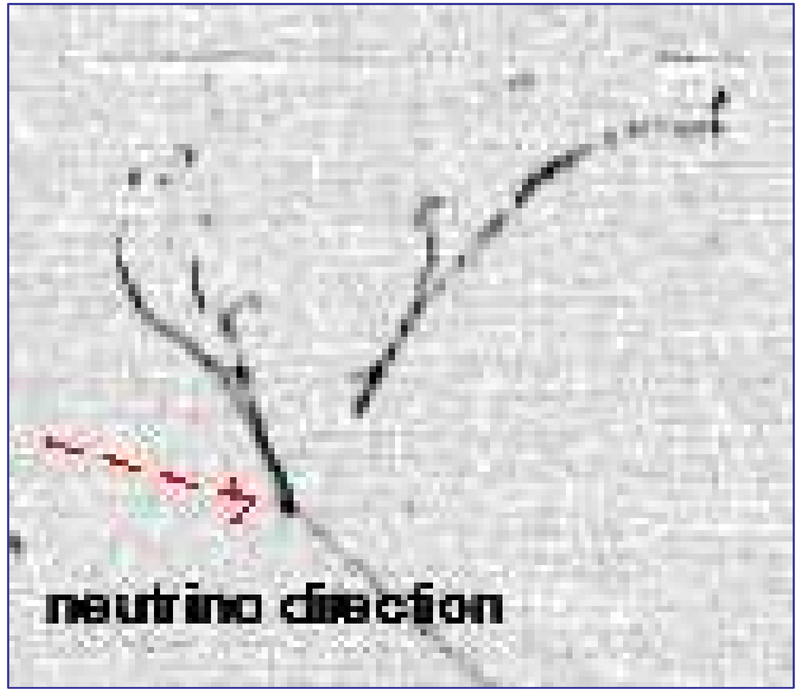
There is a faint indication of decay electron

The stopping point is clearly measurable in this view



(γ,γ) system

One shower is close to the interaction vertex (1 cm).
The measured energies of two showers are:
(118.9 ± 8.0) MeV and
(113.7 ± 7.5) MeV .
The angle in space between two gammas is $(56.5 \pm 0.2)^{\circ}$.



The resulting invariant mass of (γ, γ) system is:

(110.1 ± 21.1) MeV/c^2.

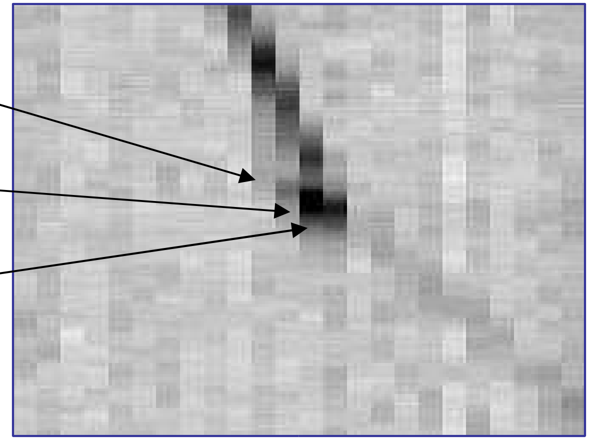
The resulting momentum of π^0 candidate is 445 MeV/c with an angle respect to the vertical axis of 69.6°

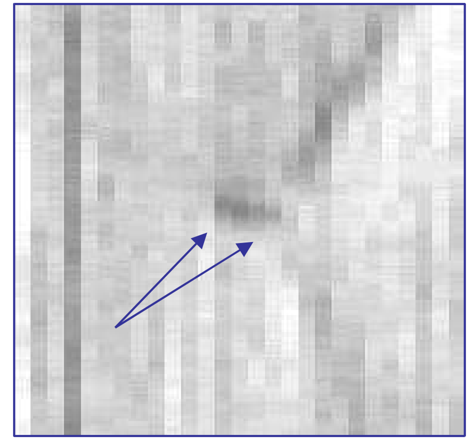
Proton in the interaction vertex

1.3 x m.i.p.

4.1 x m.i.p.

3.3 x m.i.p.





The <u>measured length in space</u> is 1.7 cm. The kinetic energy from range is

(42 ± 12) MeV.

The error on the "proton" direction is big, resulting in a big error on the <u>invariant mass of the (p,γ,γ) system</u>

$$m(p, \gamma, \gamma) = (1152 \pm 172)\ \mathrm{MeV}/c^2.$$

This value suggests the presence of $\Delta^+(1232)$ resonance.

long track kinematics

The **angle with vertical axis** is:

109.6 º,

the **calorimetric measurement** (dE/dx) of the stopping power is compatible with both μ **and π hypotheses**, and gives the following momentum

527.8 ± 105.1 MeV/c

The momentum estimated by multiple scattering in μ hypothesis is:

(670.8 ± 134.0) MeV/c

compatible with the range estimation.

Conclusion (preliminary)

The described event "mimics" atmospheric ν_μ CC interaction on neutron:

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

The reconstructed ν_μ energy in this hypothesis is

1046 ± 180 MeV

The angle with the vertical axis is:

110.9^o

The results of this analysis must be considered almost preliminary,

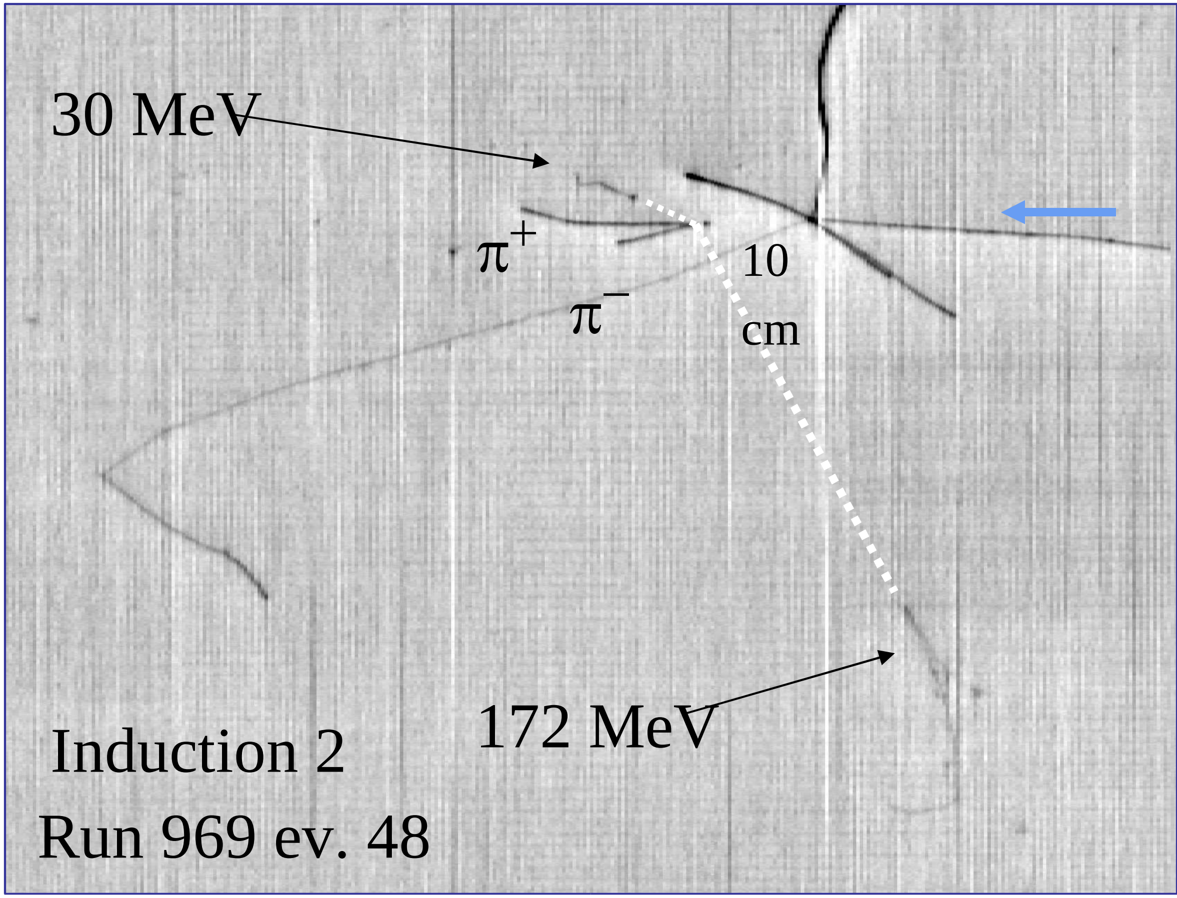
but it demonstrates the high capability of big liquid argon TPC's in detecting and precisely measuring neutrino events in a wide energy range.

No background measurement of K^0 decay

$K^0 \to \pi^+ + \pi^- + \pi^0$

At a distance of 10 cm from the main interaction vertex there is a V of two charged particles, that stop inside the liquid argon.

Two electromagnetic showers point to the charged V vertex. This is clearly the signature of a decaying neutral particle generated in the main vertex.



Kinematics

$E\gamma_1 = (172.5 \pm 15.4)$ MeV

$E\gamma_2 = (29.7 \pm 2.4)$ MeV

$\theta = (131.5 \pm 4.0)$ degree

$$m(\gamma, \gamma) = (129 \pm 11)\ \mathrm{MeV}/c^2$$

Compatible with π^0 mass

$$m(\pi^+, \pi^-, \gamma_1, \gamma_2) = (528 \pm 37)\ \mathrm{MeV}/c^2$$

Compatible with K^0 mass

"K^0" momentum = 333.7 MeV/c

"K^0" measured decay length = 10 cm

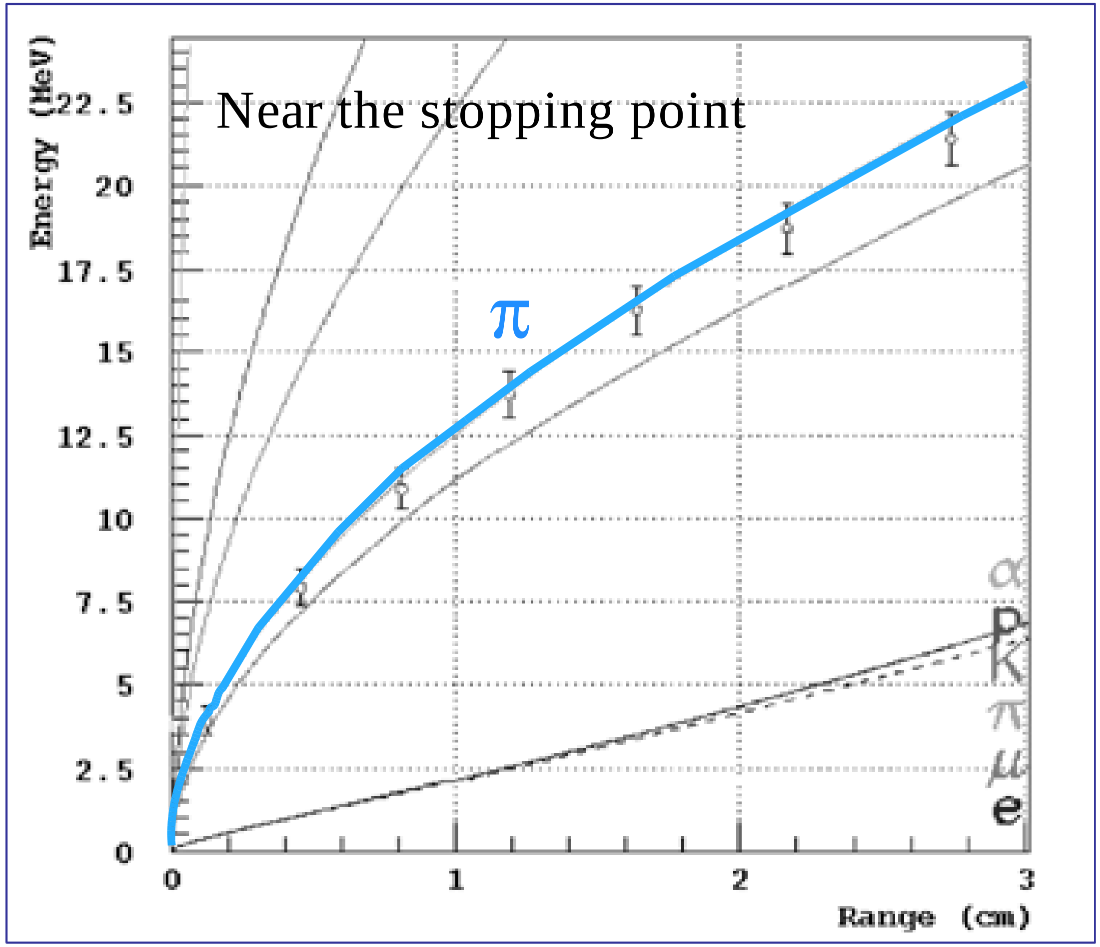
$P(\pi^+) = (187.9 \pm 7.3)$ MeV/c

$P(\pi^-) = (126.5 \pm 5.2)$ MeV/c

dE/dx kinematics

π^- candidate

Measured range-energy



Range: 10.5 cm

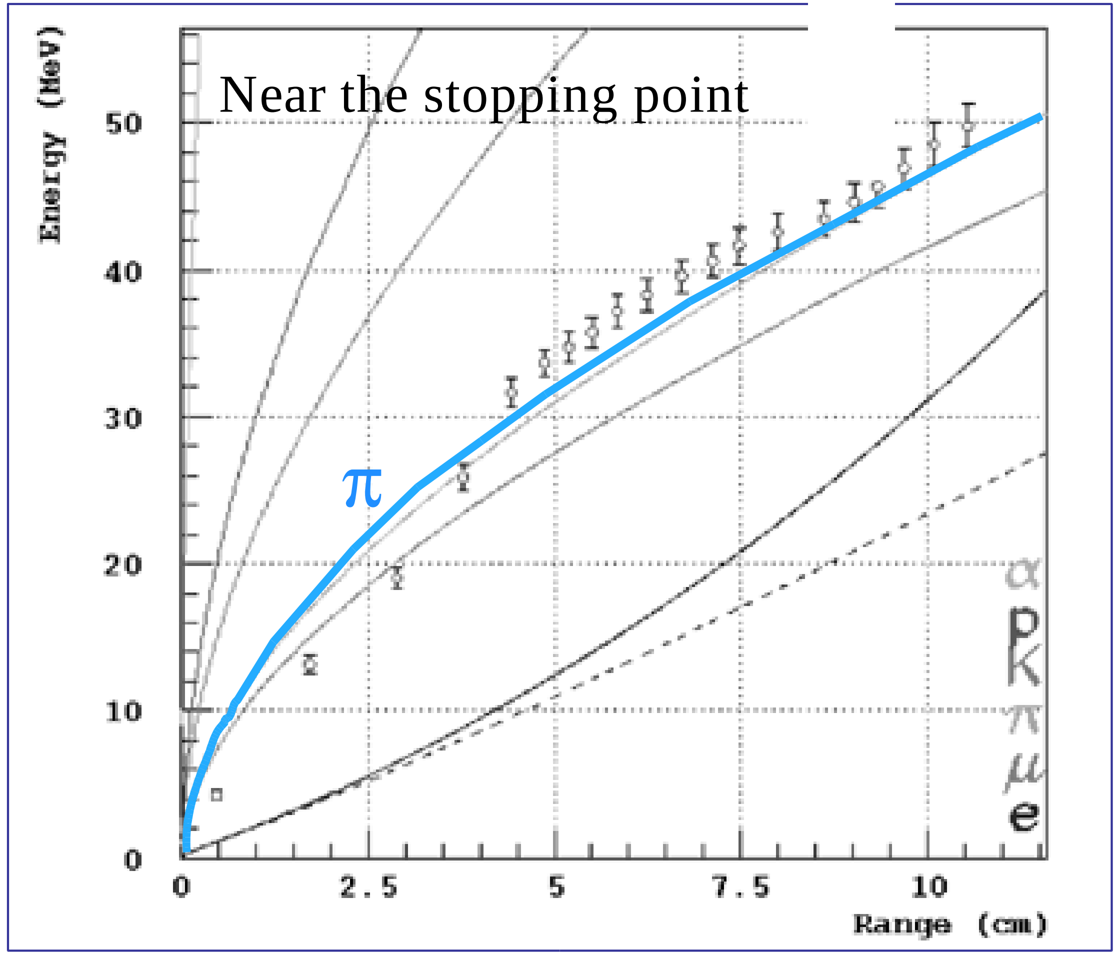
Measured kinetic energy:

(48.8 ± 5.2) MeV from calorimetry

dE/dx kinematics

π^+ candidate

Measured range-energy



Range: 27.5 cm

Measured kinetic energy:

(94.5 ± 7.3) MeV

from calorimetry

Some final considerations

We are very confident that this event can be interpreted as a neutral kaon associated to the interaction vertex at 10 cm distance:

The two charged tracks are definitively not electrons or muons,

The dE/dx measurement exclude the presence of a proton,

The invariant mass of the three pions is compatible with K^0 mass.

Kinematical reconstruction gives a momentum of 334 MeV/c for the kaon. The resulting probabilities are:

0.997 * BR = $\mathbf{4.9 \cdot 10^{-5}}$ ***in K^0_S hypothesis***

0.010 * BR = $\mathbf{1.2 \cdot 10^{-3}}$ ***in K^0_L hypothesis***

Final Considerations

After a long time work, with tenacity of purpose, beyond all hope and applying a big training with the playground of " test-run data" ,

ICARUS is walking over the course.

We are confident that ICARUS, the first liquid argon TPC observatory of neutrinos, will be able to catch new possible physics