ICARUS

A Second-Generation Proton Decay Experiment and Neutrino Observatory at the Gran Sasso Laboratory

and

The CNGS beam from CERN to Gran Sasso

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The ICARUS Collaboration

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CHINA: Academia Sinica Beijing.
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USA: UCLA Los Angeles.
SPAIN: Univ. of Granada.

The ICARUS program: introduction

- **ICARUS was proposed to INFN in 1993**

  Today: *"A Second Generation Proton Decay Experiment And Neutrino Observatory At The Gran Sasso Laboratory",*

  Proposal, LNGS-EXP 13/89 add. 2/01, ICARUS-TM/2001-09, CERN/SPSC 2002-027 SPSC-P-323.

- **The experiment is based on**
  - the novel detection technique of the liquid Argon TPC
  - its extrapolation to large (kton) masses
  - a rich physics program

    proton decay

    atmospheric neutrinos

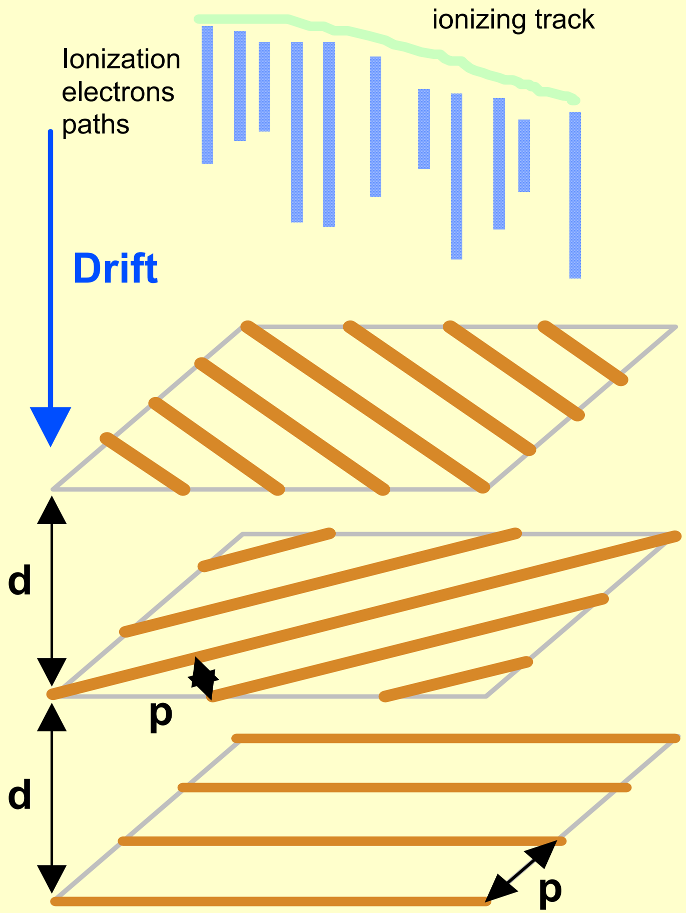
    solar neutrinos

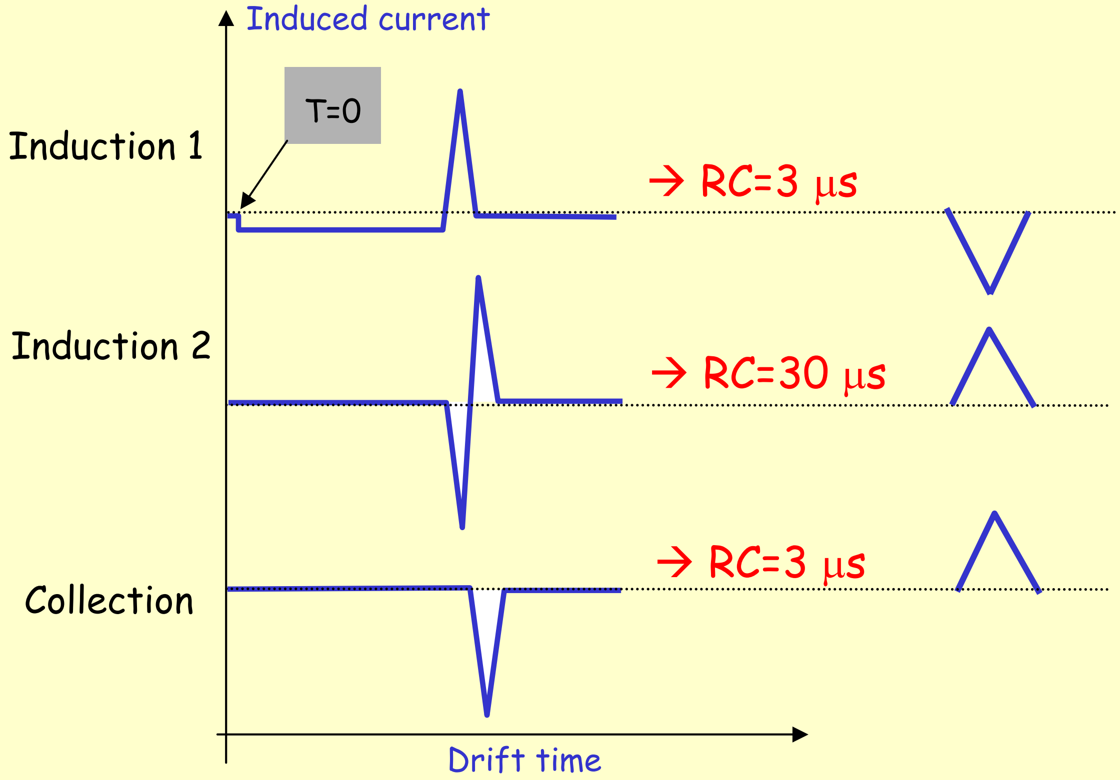
    supernovae neutrinos

    LBL neutrino oscillations (CNGS, future LE beams,…)

Principle and signals

Ionization electrons drift (msec) over large distances (meters) in a volume of highly purified liquid Argon (0.1 ppb of O_2) under the action of an E field. With a set of wire grids (traversed by the electrons in ~ 2-3 μs) one can realize a massive, continuously sensitive electronic "bubble chamber".





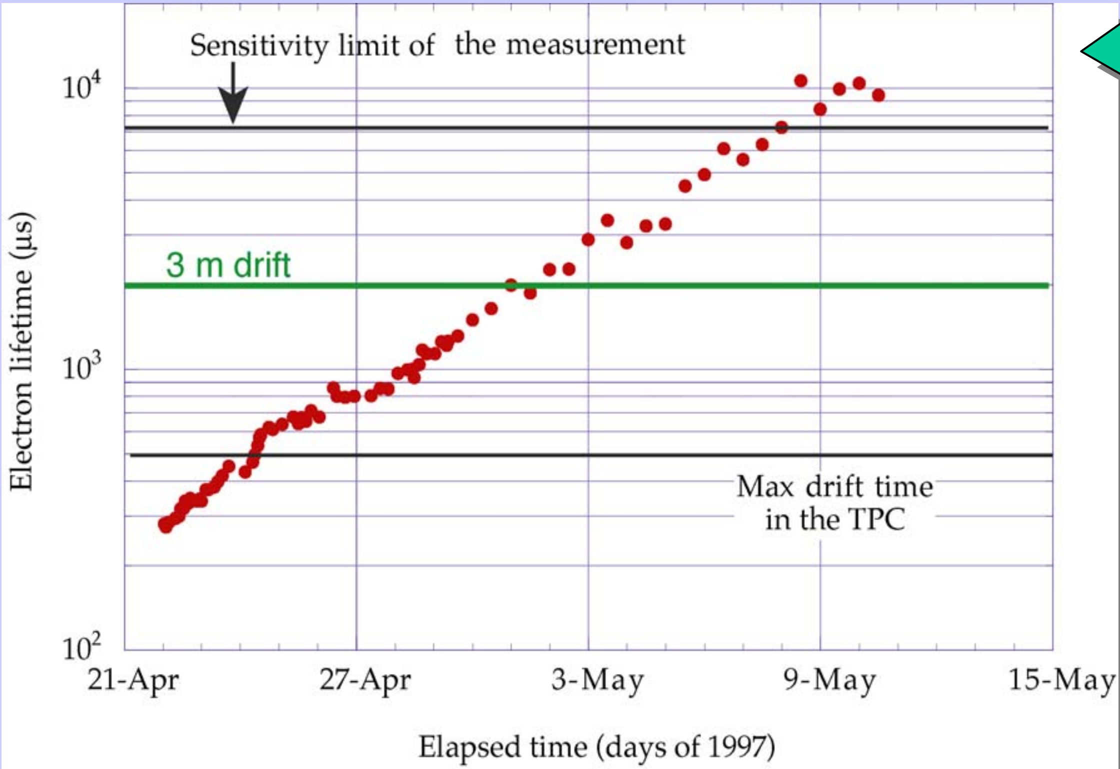
Liquid Argon TPC properties

- High density, heavy ionization medium
  ρ = 1.4 g/cm^3, X_0=14 cm, λ_{int} = 80 cm
- Very high resolution detector
  3D image 3 x 3 x 0.6 mm^3 (400 ns sampling)
- Continuously sensitive
- Self-triggering or through prompt scintillation light
- Stable and safe
  Inert gas/liquid
  High thermal inertia (230 MJ/m^3)
- Relatively cheap detector
  Liquid argon is cheap, it is only "stored" in the experiment
  TPC: # of channels proportional to surface

- Cryogenic temperature ← **Cryogenic plant**
  T = 88 K at 1 bar
- High purity required for long-drift time ← **Argon purification**
  0.1 ppb of O_2 equivalent for 3 ms drift
- No signal amplification in liquid ← **Low noise electronics**
  1 m.i.p. over 3 mm yields 20000 electrons
  equivalent noise charge 1200 electrons

Drift velocity, HV and signal attenuation

- Working drift field
  E = 500 V/cm ⇒ drift velocity v_d=1.6 mm/µs
  For a 3 m drift: HV_{drift}=150 kV, maximum drift time τ_{max}=1.875 ms
- Require high level of purity in order to avoid charge attenuation
- Measured electron lifetime: 50 liter prototype: τ > 10 ms



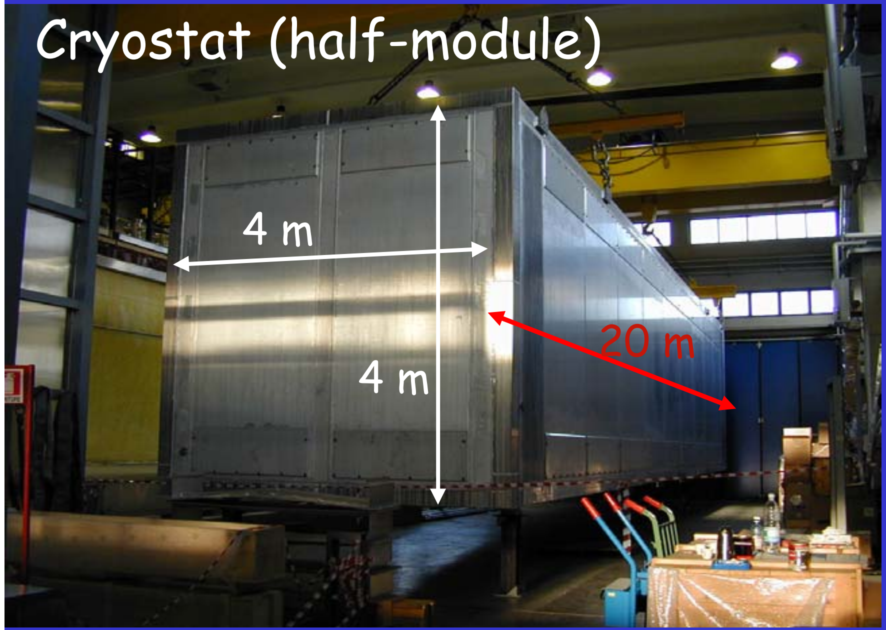
Experience and results: 600 ton detector

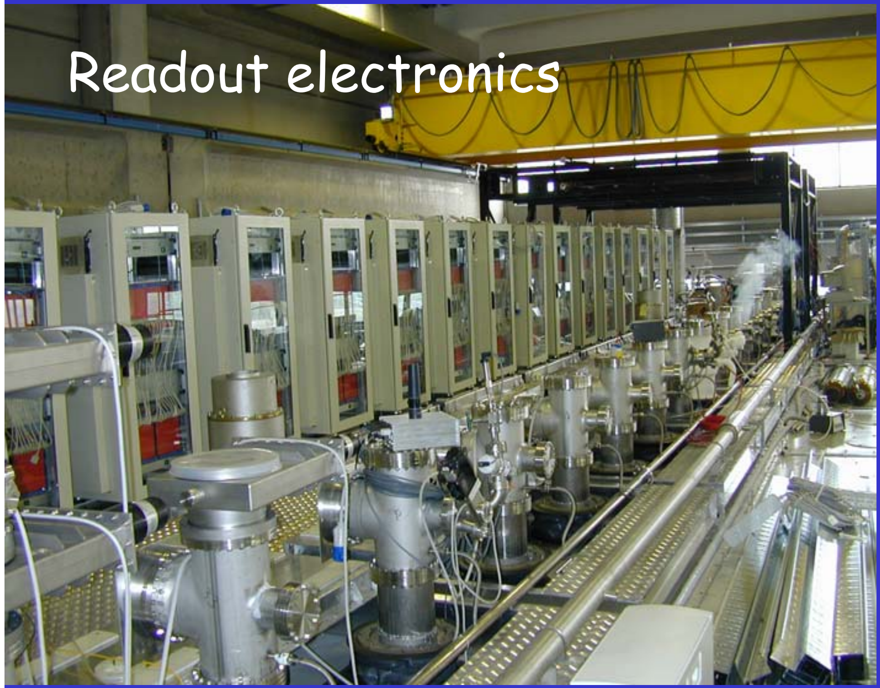
Industrial module made of two independent LAr containers
½ module equipped and filled with LAr (300 ton)
Total volume : 350 m^3
Readout planes: 2 x 3 (–60°,60°,0°), about 54000 wires
Maximum drift distance: 150 cm

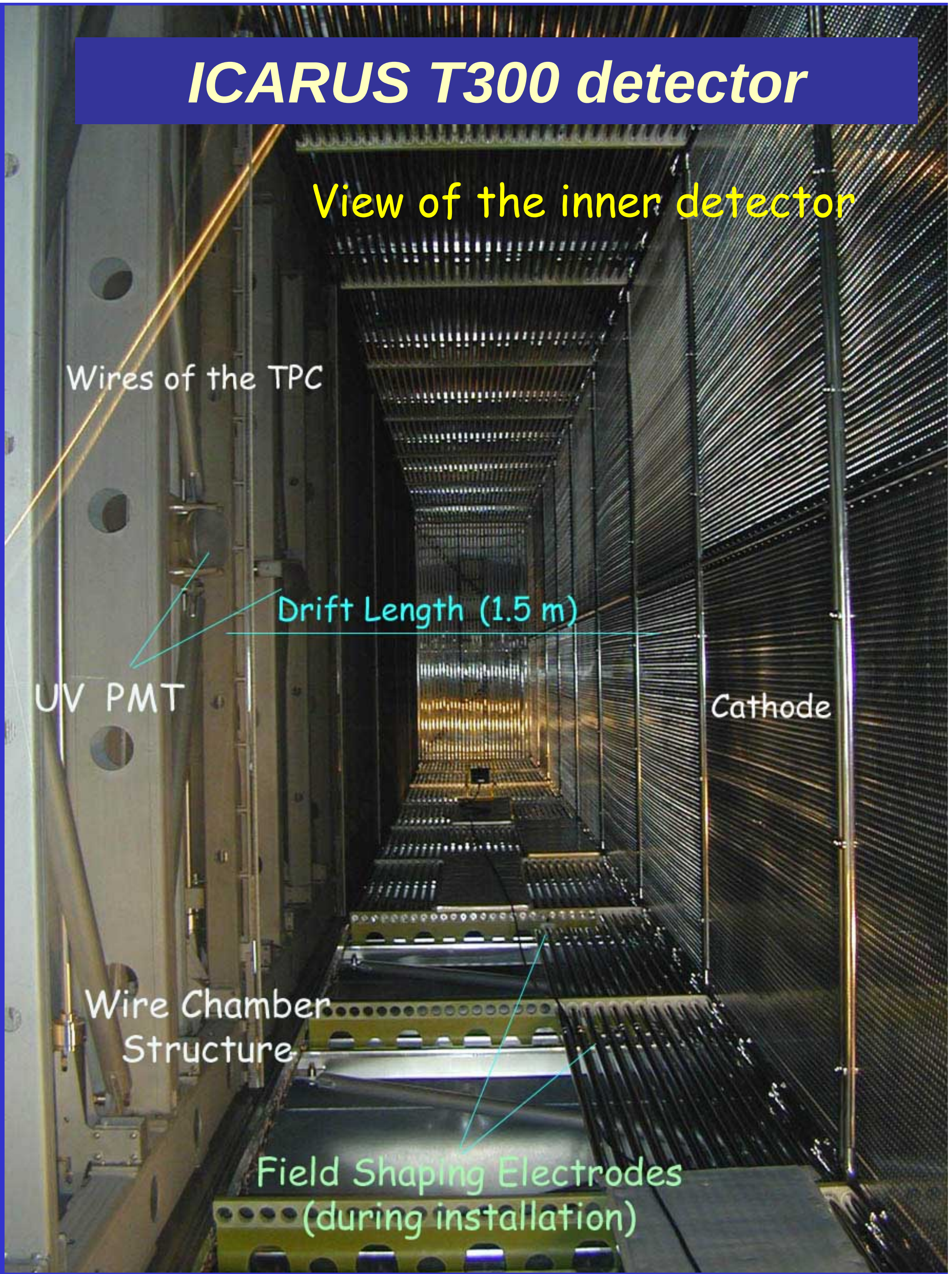
- Full scale technical run of the T300 detector in Pavia (2001)
  - Cryogenics ✓
  - Wire chamber mechanics ✓ ✓
  - Argon purification ✓
  - Electronic noise ✓
  - High voltage for the drift ✓ ✓
  - PMTs for scintillation light collection ✓
  - Readout & DAQ ✓
  - Slow control ✓
- Event reconstruction SW with real events and data analysis (ongoing effort)
  - Imaging ✓ ✓
  - Event reconstruction ✓
  - 3 plane readout ✓
  - Calibration ✓
  - Resolution ✓


ICARUS T600 (1 half-module out of 2)
≈300‘000 kg LAr
= T300

ICARUS T300 detector








Wires
(before tensioning)
sensors
PMT
PMT
Wire Chamber mechanical Structure

...before closing...

T600 detector performance

- Technical run held in Pavia in Summer 2001: ascertain the maturity of large scale liquid Argon imaging TPC. Main phases:

  clean-up (vacuum) 10 days, cool-down 15 days, LAr filling 15 days,
  debug and data-taking 68 days.

- In addition to the 18 m long track requested by the Scientific Committees, a large number of cosmic-ray events was collected:

  about 28000 triggers with different topologies

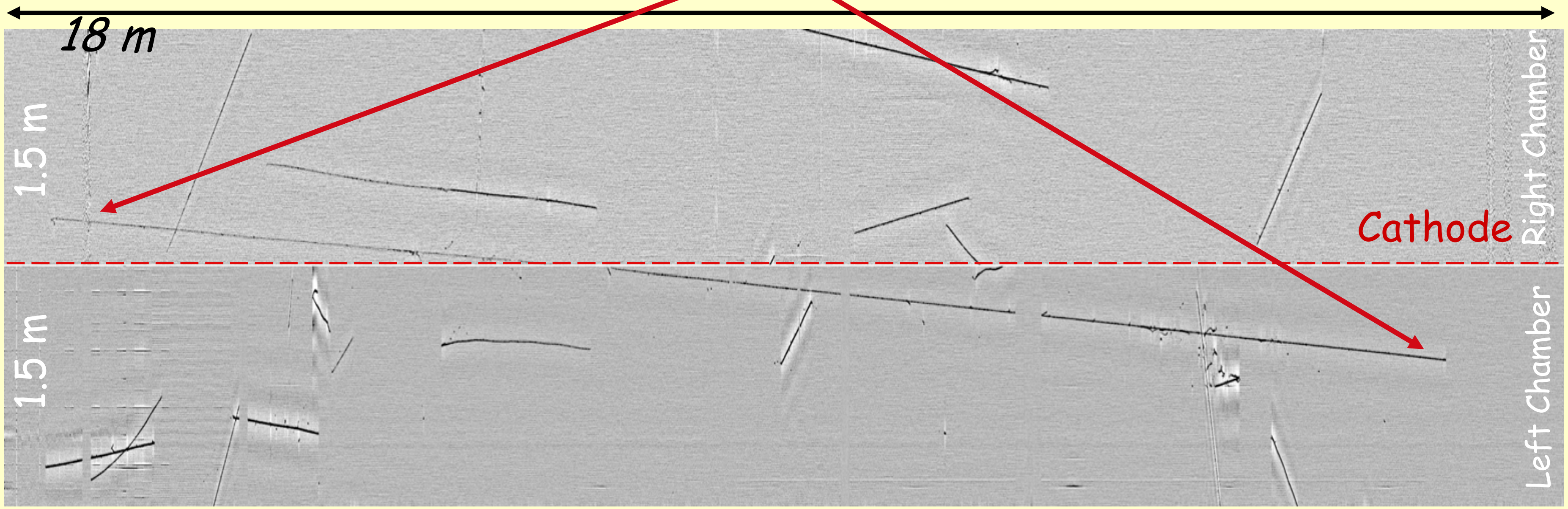
  4.5 TB of data, 200 MB/event.

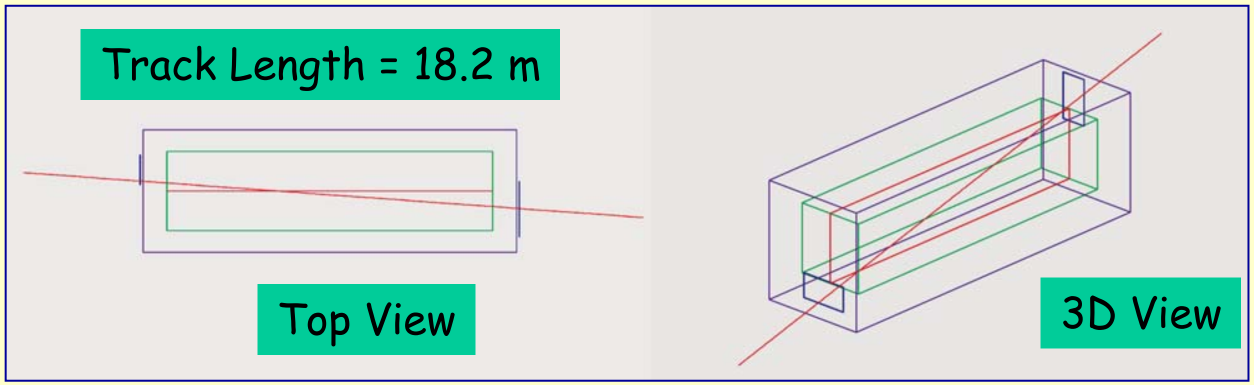
- Valuable data: check performance of a such large scale detector. Found that:

  results of the same quantitative quality as those obtained with small prototypes
  (e.g. 3 ton, 50 liter, …) are achieved with a 300 ton device.

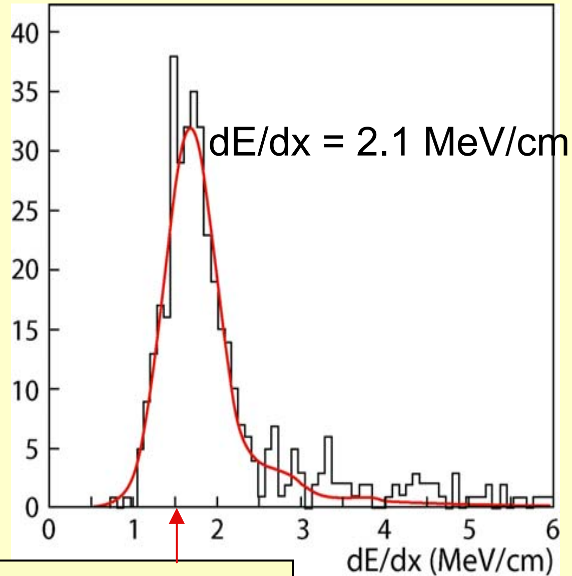
scaling up is successful

Long longitudinal muon track crossing the cathode plane





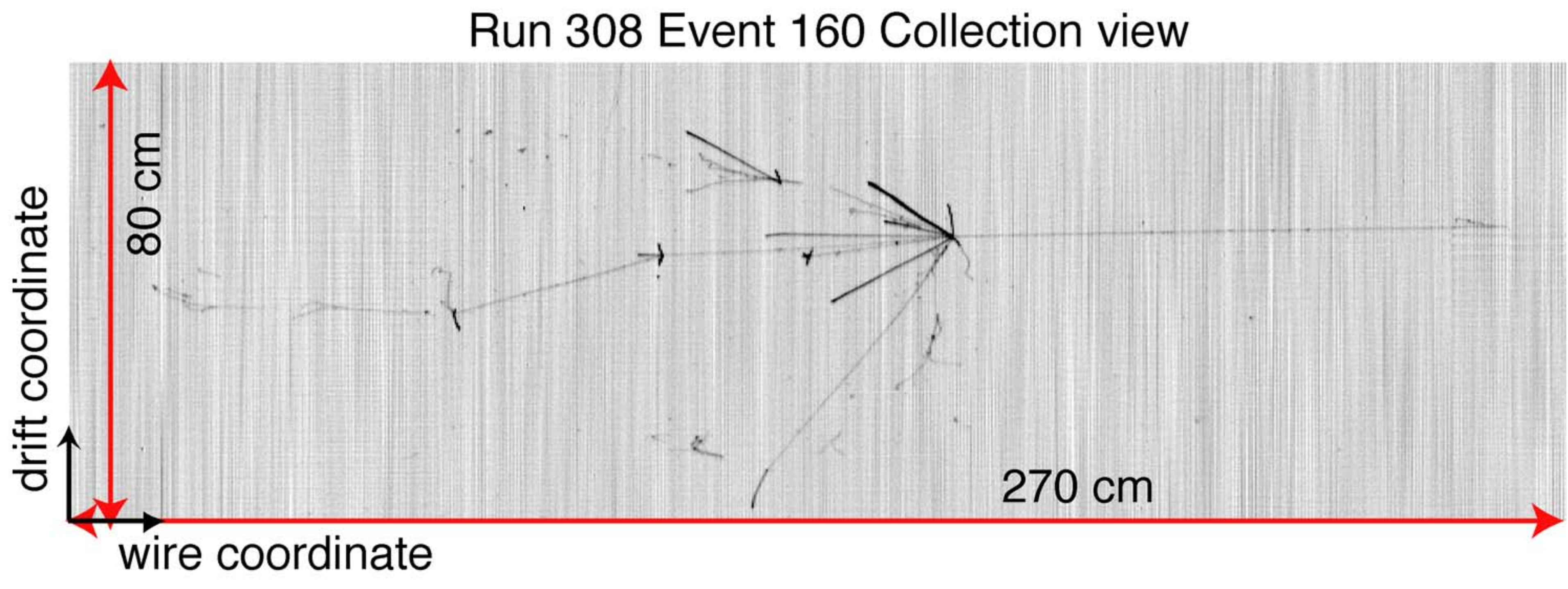
3-D reconstruction of the long track



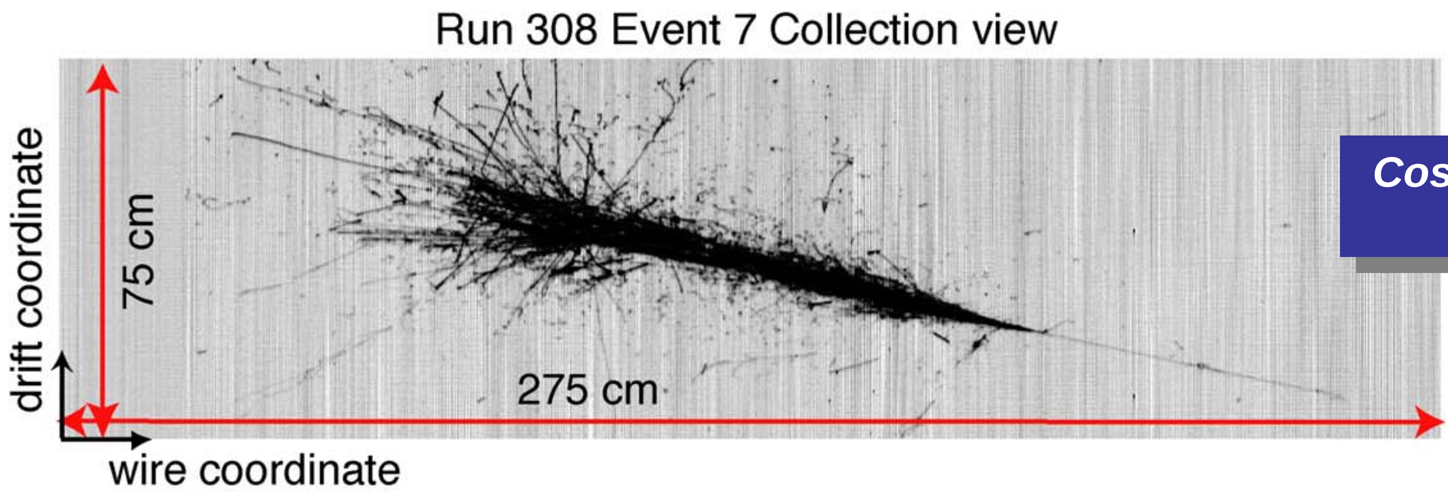
dE/dx distribution along the track

Examples of events: "electronic" bubble chamber (I)

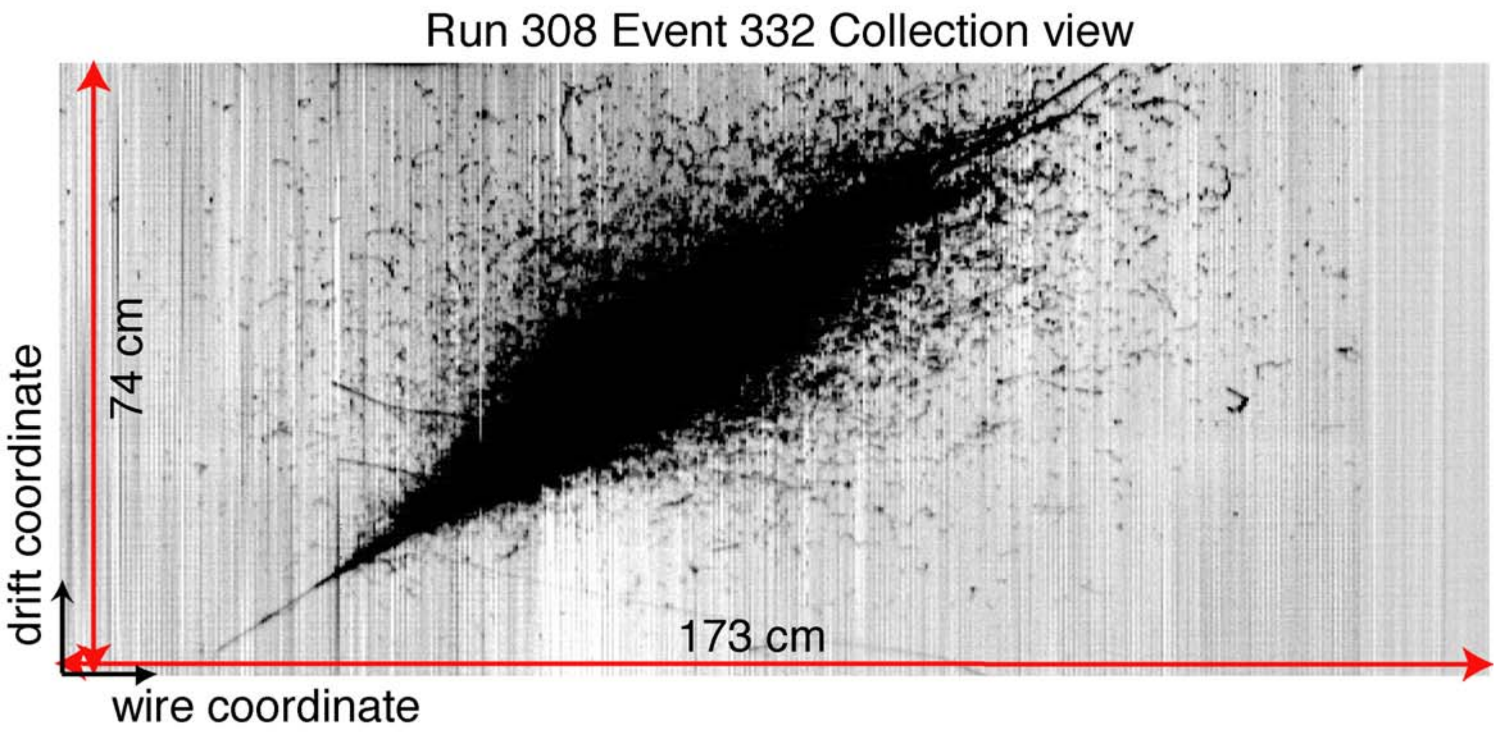
Hadronic interaction (T600)



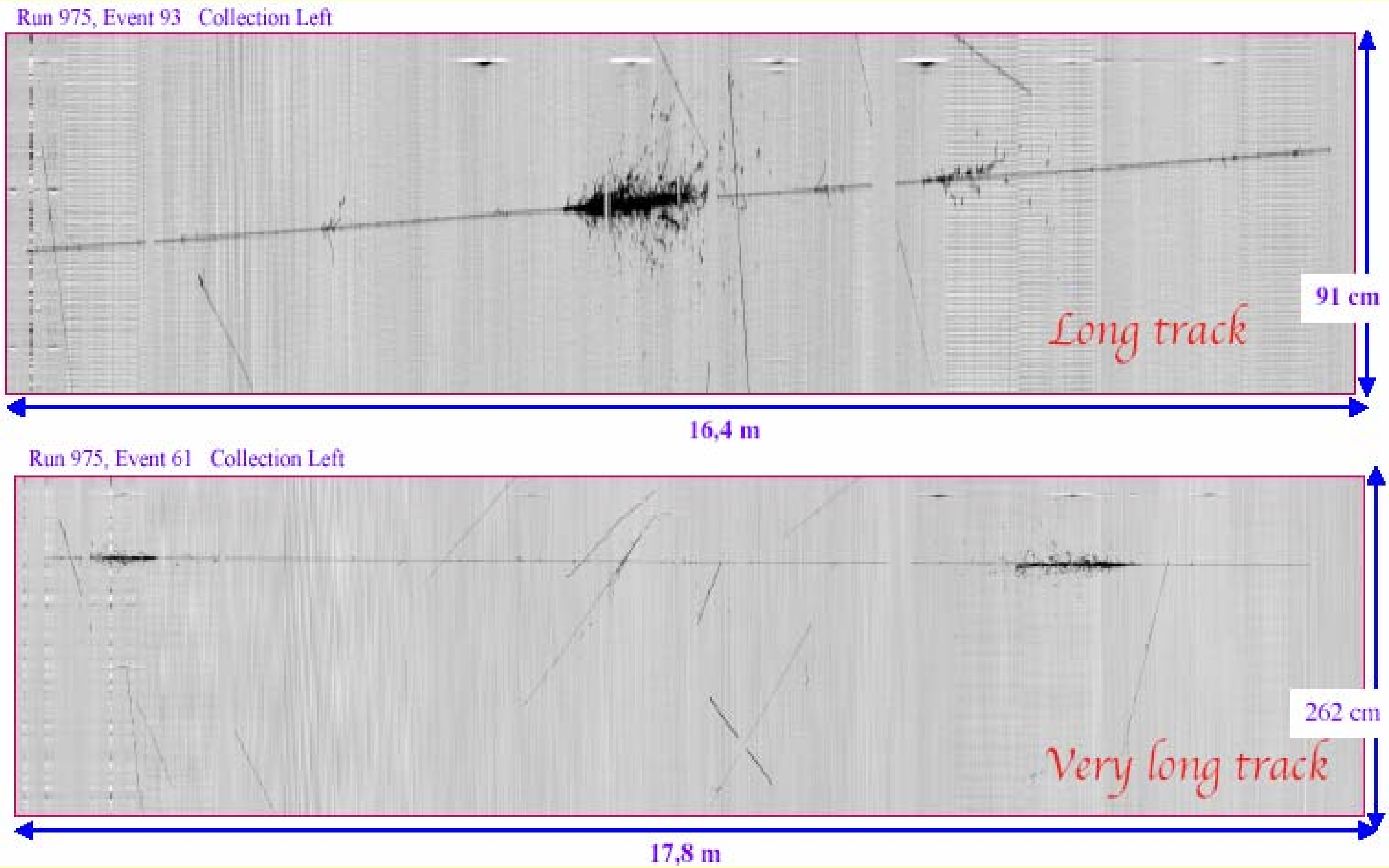
"Electronic" bubble chamber (II)



Cosmic ray showers (T600)

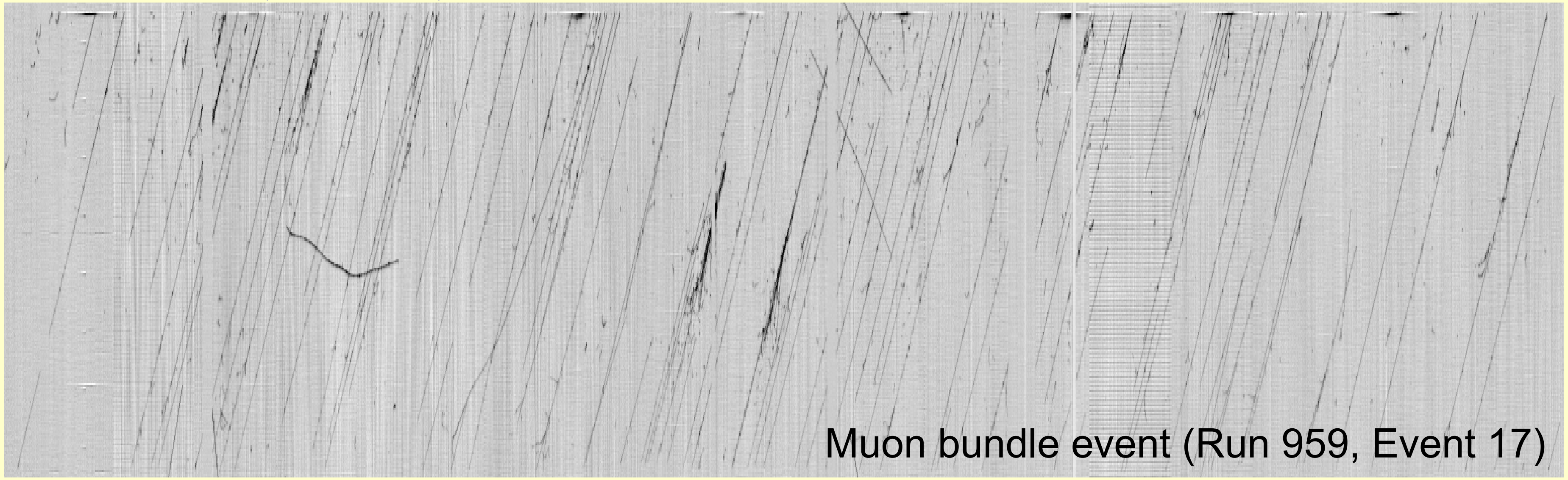


“Electronic” bubble chamber (III)

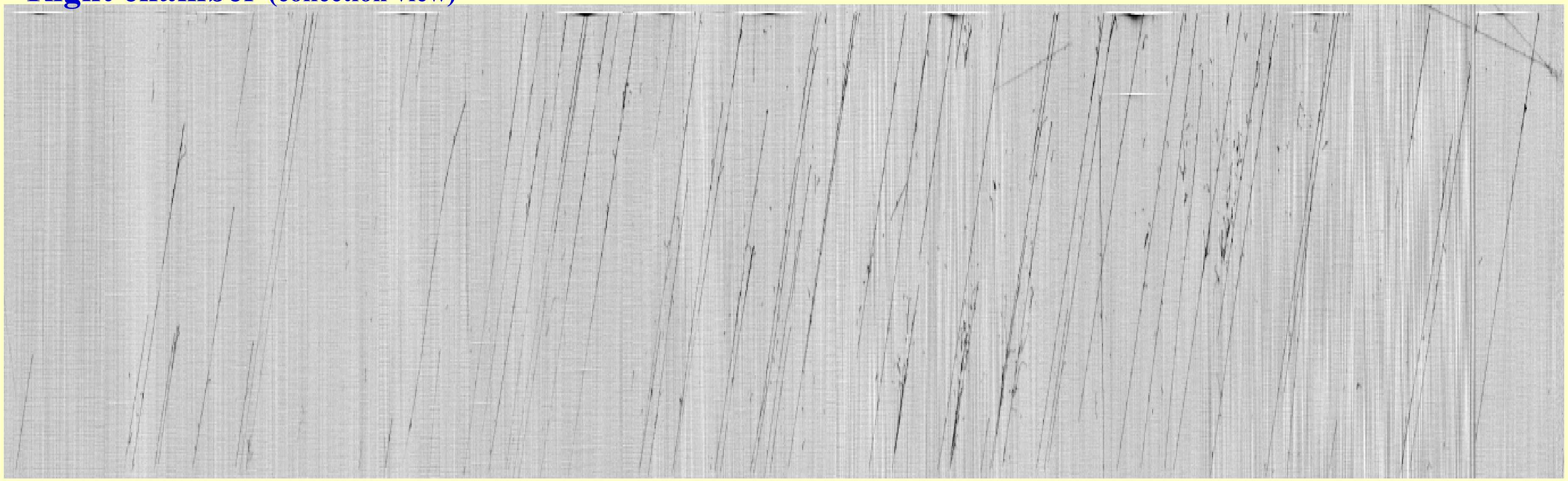


"Electronic" bubble chamber (IV)

Left chamber **(collection view)**

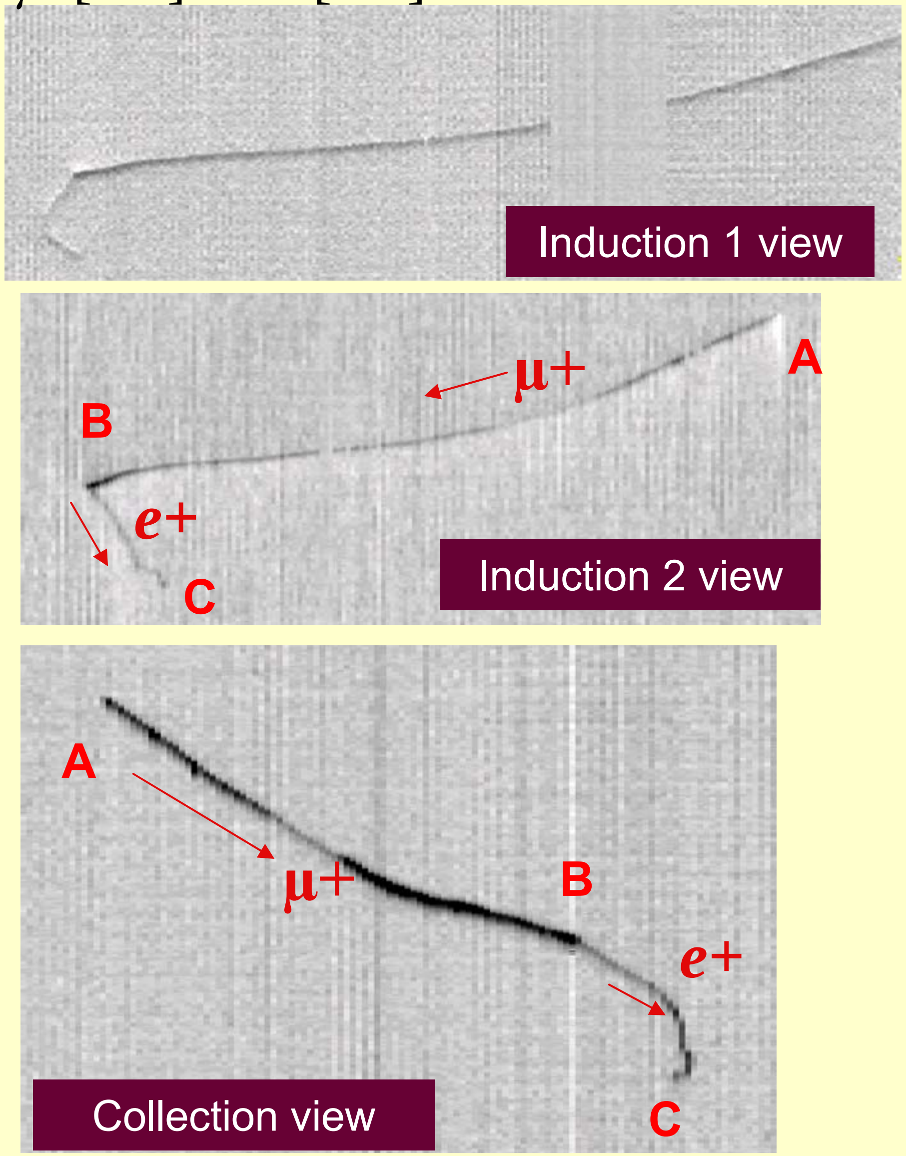


Right chamber **(collection view)**

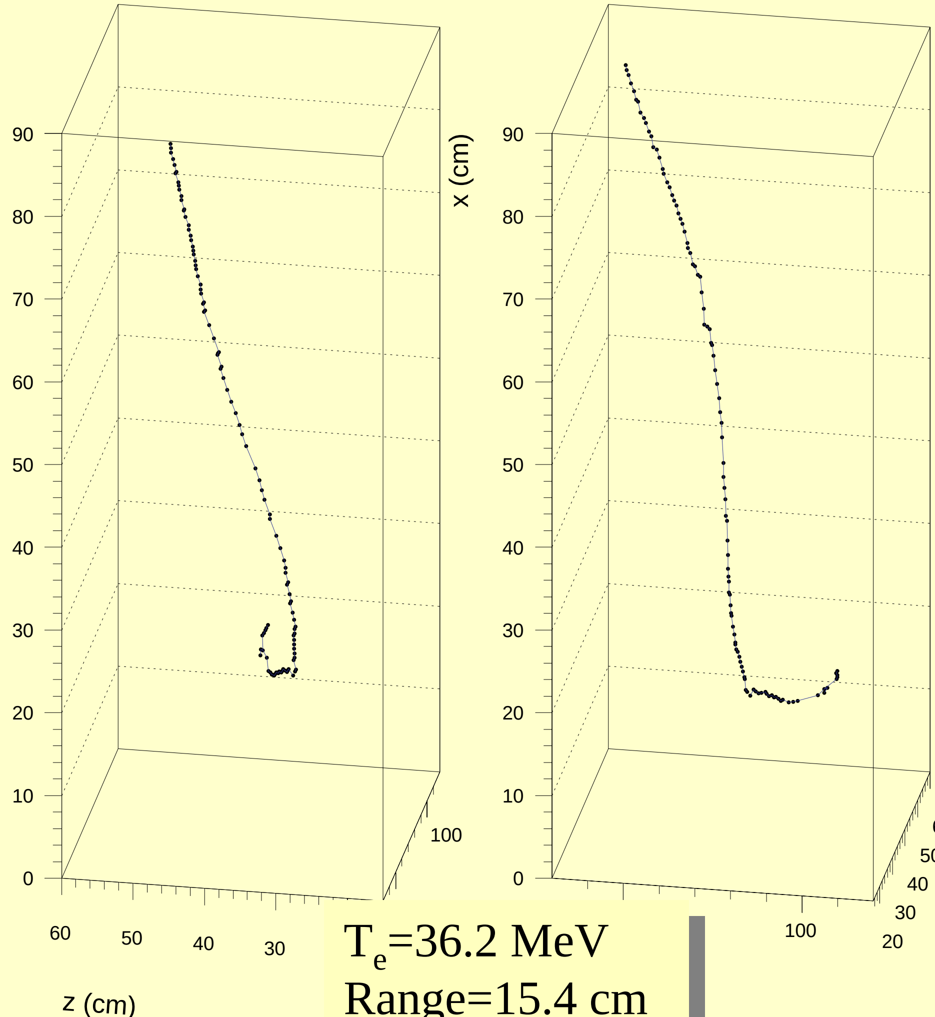


Stopping muon reconstruction example

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

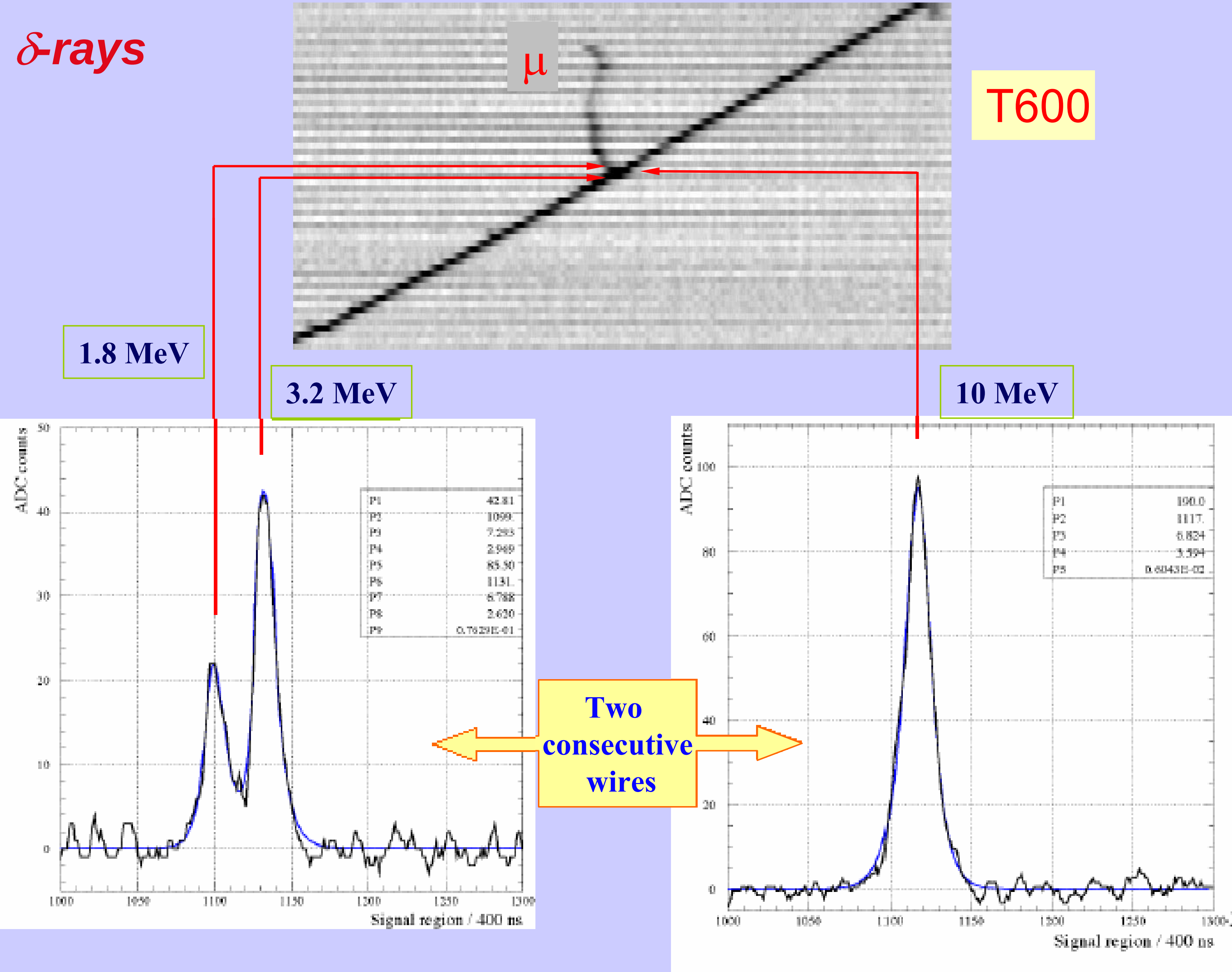


Run 939 Event 95 Right chamber



T_e=36.2 MeV
Range=15.4 cm

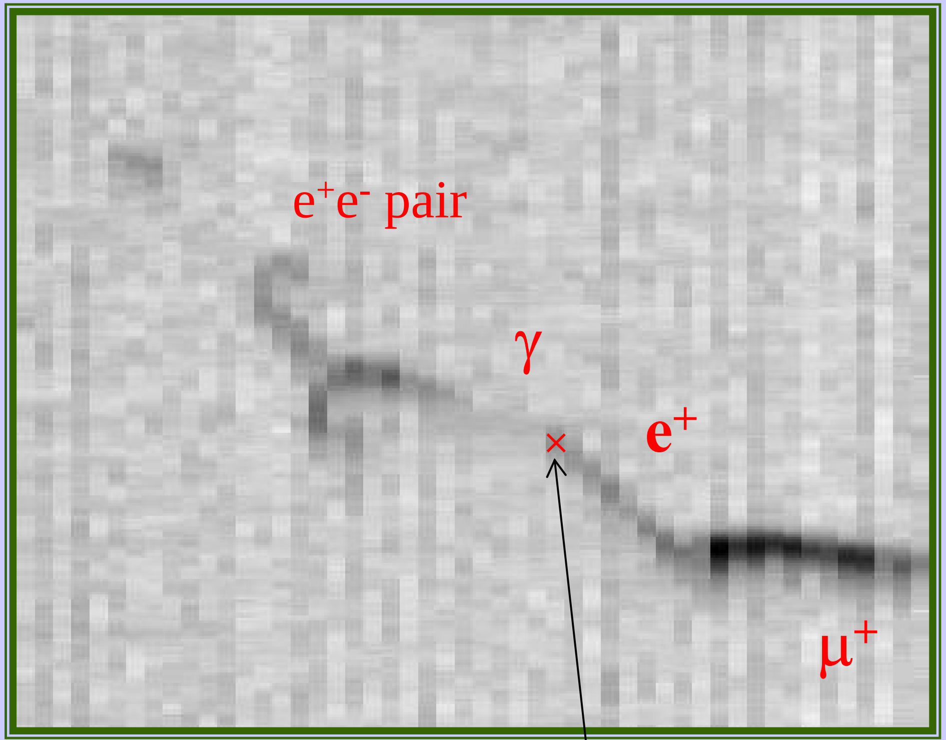
δ-rays



μ
T600
1.8 MeV
3.2 MeV
10 MeV
Two consecutive wires
ADC counts
Signal region / 400 ns
ADC counts
Signal region / 400 ns

In-flight annihilation of positron

≈20% of positrons from μ decays expected to annihilate before stopping



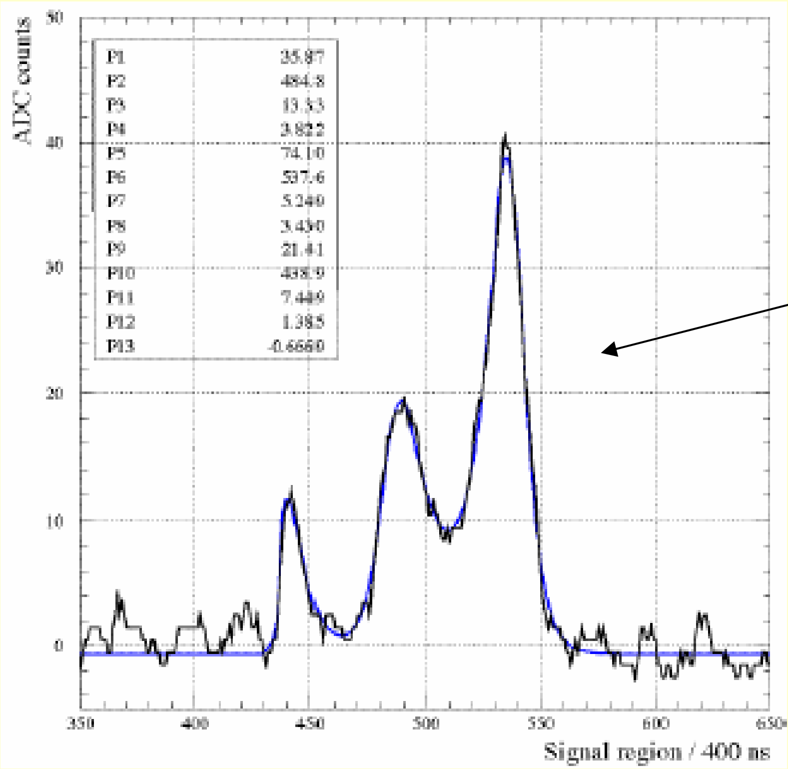
Collection view

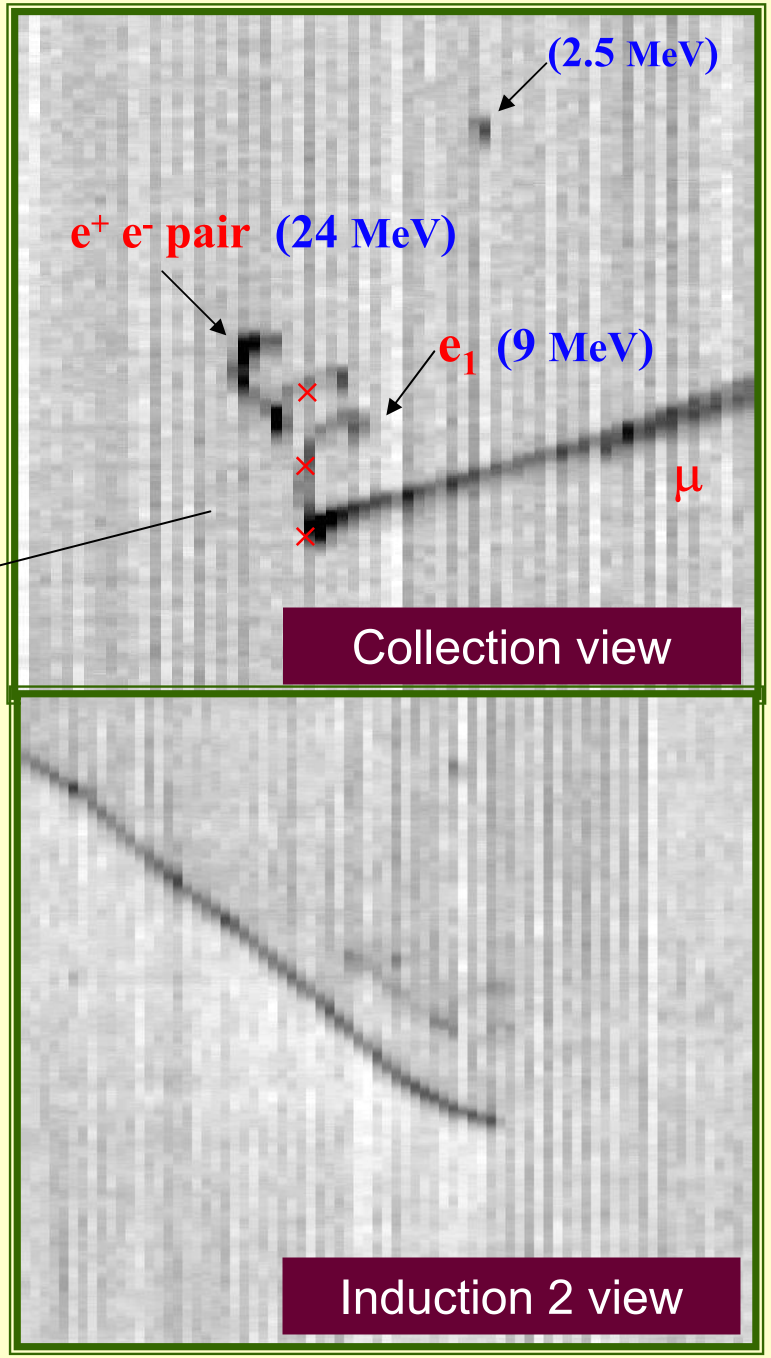
annihilation point

Induction 2 view

Bremsstrahlung + pair-production

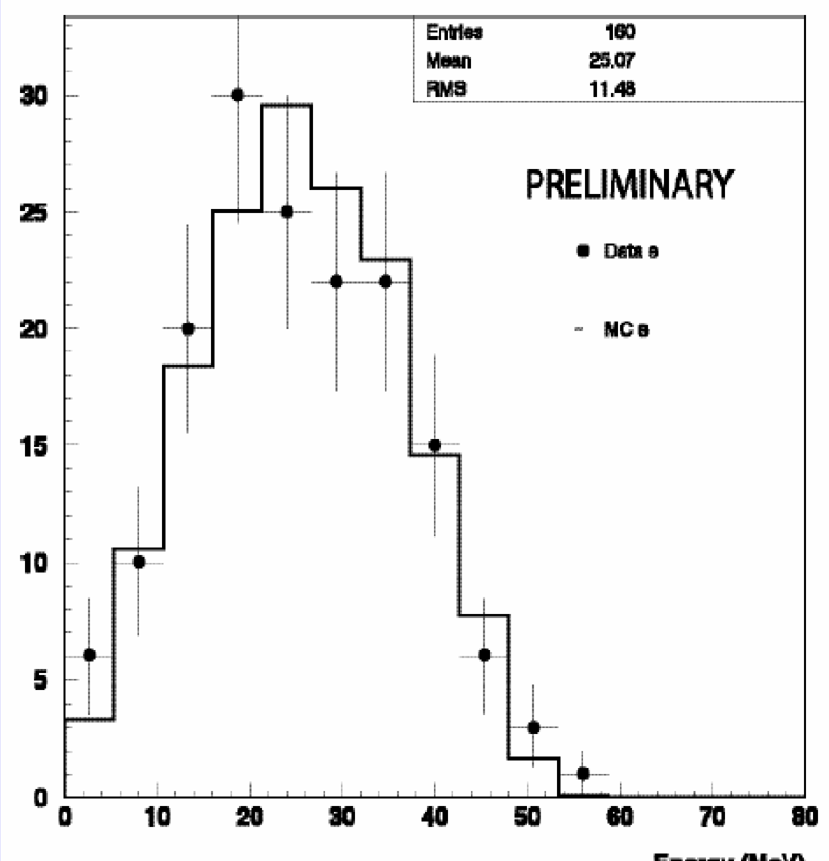
Run 975, Event 163



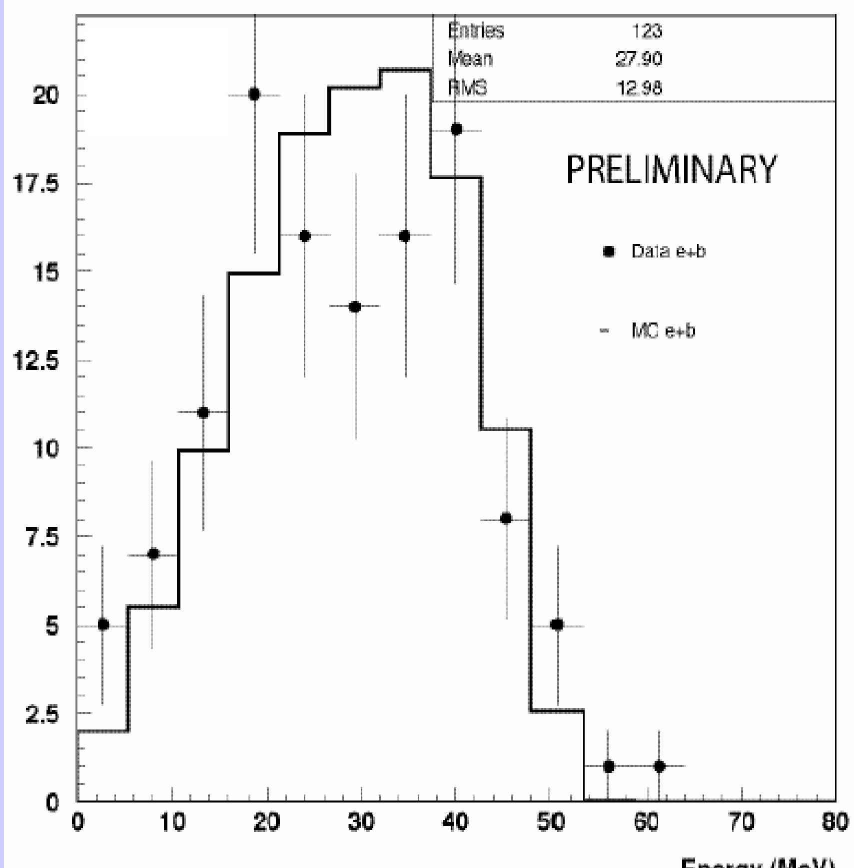


Fitted signal shapes on single wire

Calorimetric reconstruction Michel electrons (T600)



no bremsstrahlung

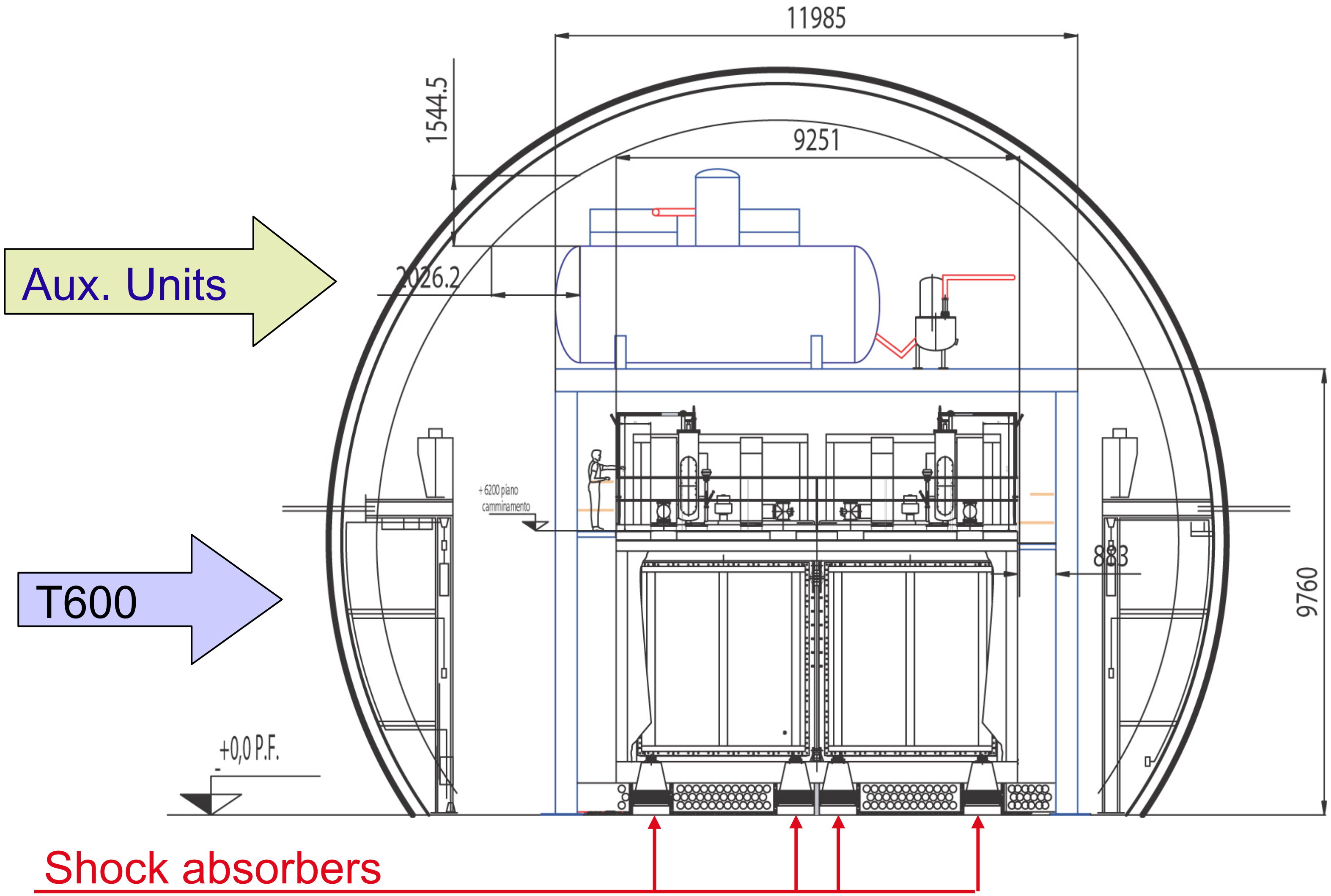


with bremsstrahlung

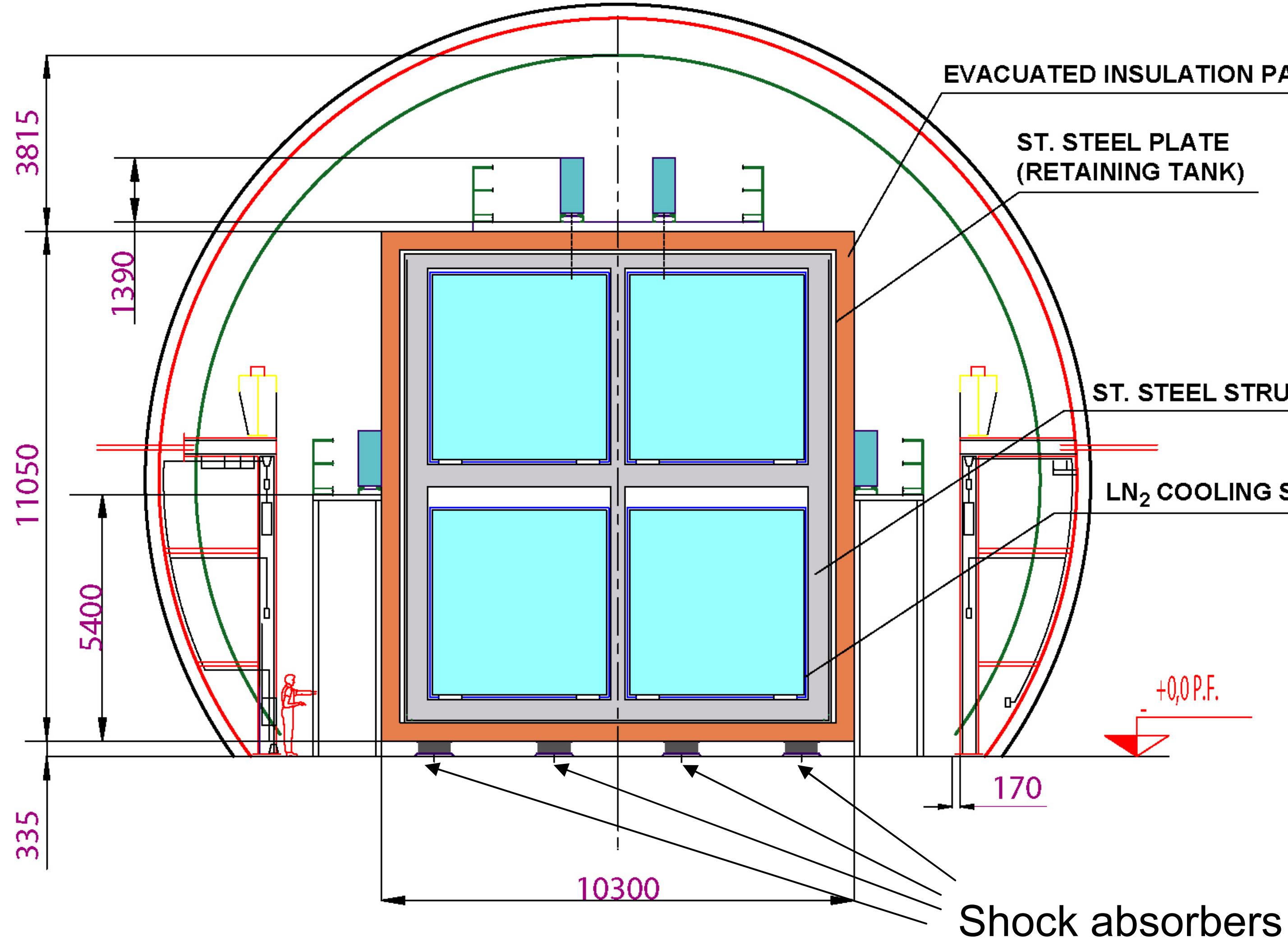
Energy resolution: $\frac{\sigma}{E} = \frac{(13 \pm 2)\%}{\sqrt{E(MeV)}} - (1.8 \pm 0.3)\%$

LNGS Hall B

First step: T600 installation at LNGS



Next: the basic layout of the T1200 unit

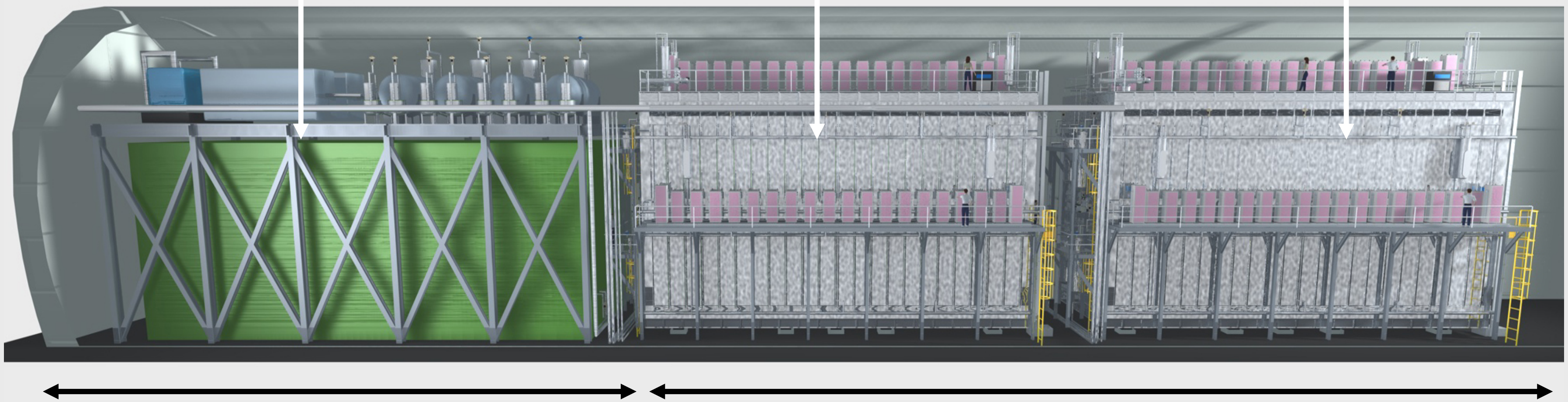


ICARUS detector configuration at LNGS Hall B (T3000)

First Unit T600 + Auxiliary Equipment

T1200 Unit (two T600 superimposed)

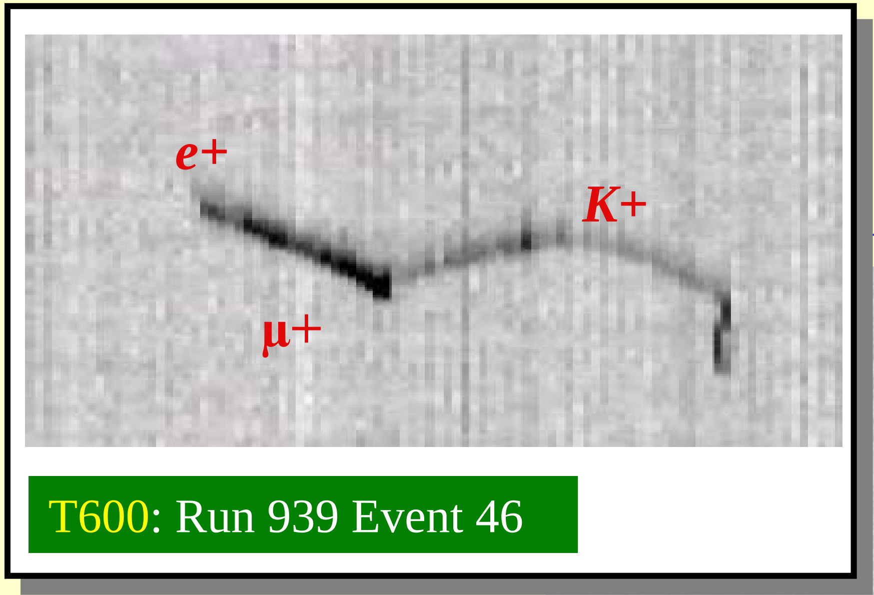
T1200 Unit (two T600 superimposed)

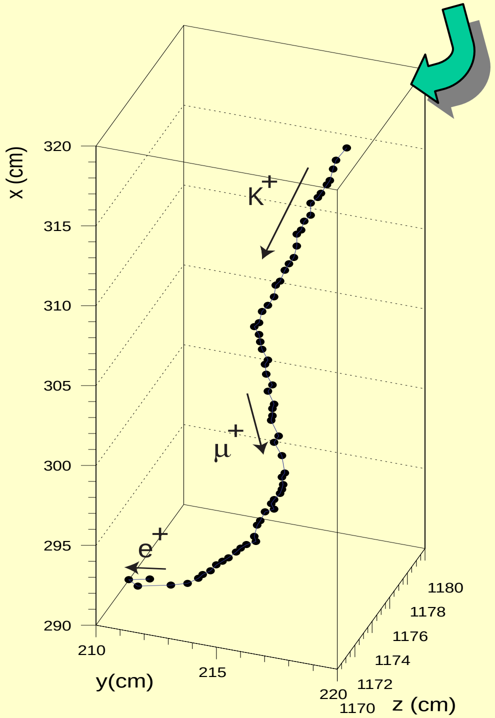


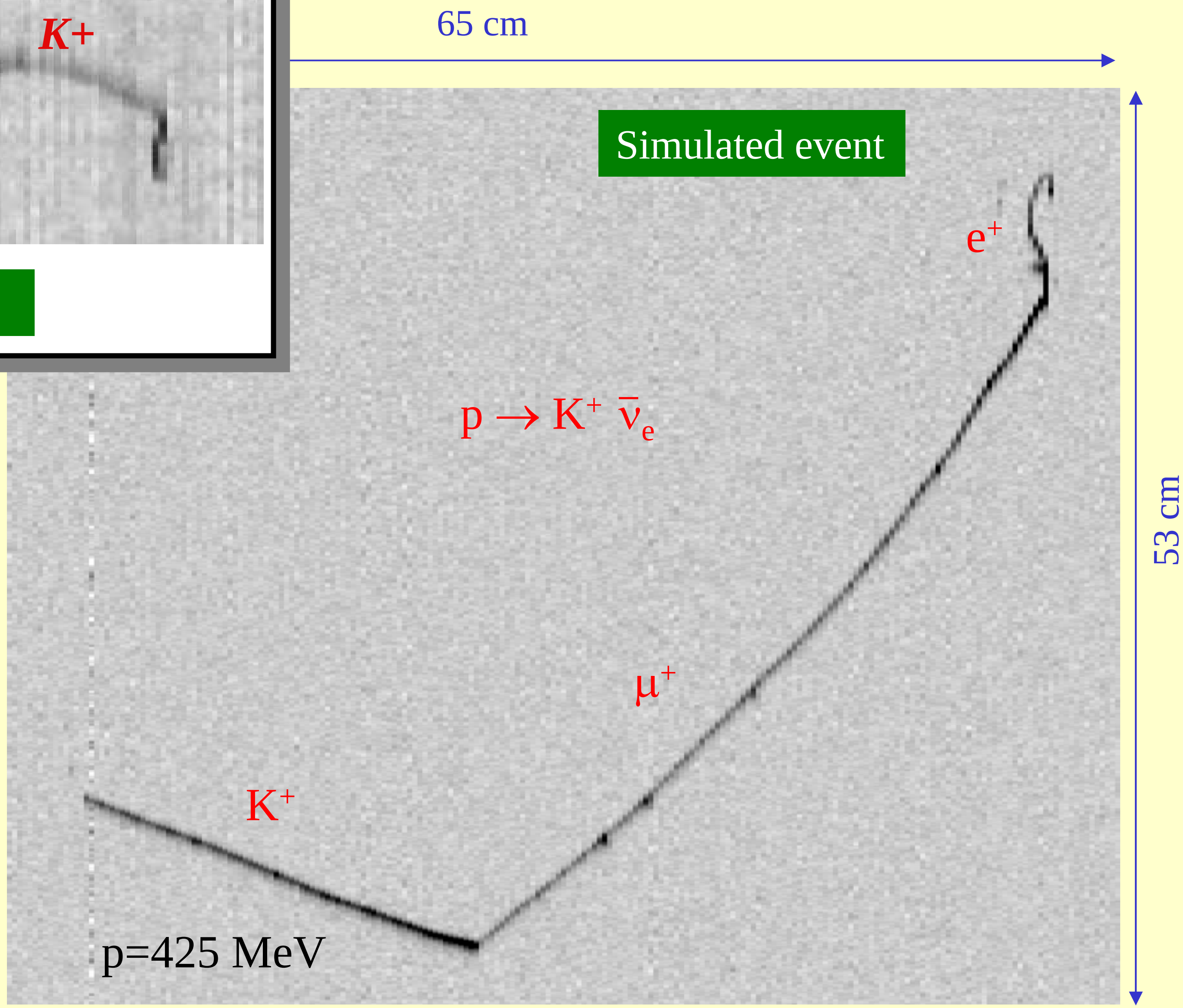
≈ 35 m

≈ 60 m

Proton decay in ICARUS







Proton decay: ICARUS expected sensitivities

Channel		Eff. (%)	Observed (evts.)	Bkg. (evts.)	Exposure (kTon×yr)	τ/B limit (10^{32} yr)	Needed Exposure to reach PDG'02 (kTon×yr)
$p \to \mu^- \pi^+ K^+$	ICARUS	98	–	0.005	5	5.7	2.1
$p \to e^+ \pi^+ \pi^-$	ICARUS	19	–	0.125	5	1.1	3.8
$p \to \pi^+ \bar{\nu}$	ICARUS	42	–	4	5	1.2	0.5
$p \to e^+ \pi^+ (\pi^-)$	ICARUS	30	–	6	5	0.7	
$p \to e^+ (\pi^+ \pi^-)$	ICARUS	16	–	20	5	0.2	
$n \to e^- K^+$	ICARUS	96	–	0.005	5	6.9	0.24
$n \to \mu^- \pi^+$	ICARUS	45	–	0.12	5	3.2	1.6
$n \to e^+ \pi^-$	ICARUS	44	–	0.04	5	3.2	2.5
$n \to \pi^0 \bar{\nu}$	ICARUS	45	–	2.4	5	2	2.4
$n \to \mu^- (\pi^+)$	ICARUS	21	–	15	5	0.4	
$n \to e^+ (\pi^-)$	ICARUS	26	–	27	5	0.4	

- Very low backgrounds
- Relevant results for few kton × year exposure already
- Expected range in few 10^{32} years after 5 kton × year exposures.
- Rather complementary to SuperK

Atmospheric neutrinos

Present situation:

- SuperK: resumed with 50% coverage
- ICARUS: look at atmospheric events with a new technique

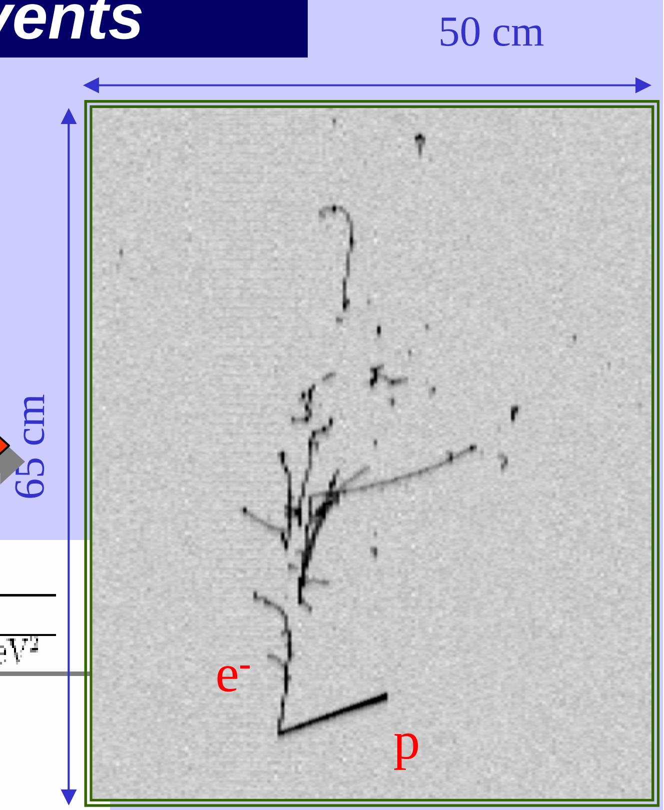
The ICARUS analysis is characterized by

- Unbiased, systematic-free observation. Expect improvement w.r.t. SK which:
  - Focuses to single-ring CC events
  - Relies on MC for other analyses
  - (e.g. "NC enriched sample", τ-appearance neural networks, …)
- Good energy and angular reconstruction
- Advances in MC of the atmospheric ν rates: expertise within the Collaboration.
  Improvements expected in:
  - Low energy events
  - Clean electron sample
  - All final states, and with ν and $\bar{\nu}$ statistical separation
  - Neutral currents

Atmospheric neutrino events

Mass is not the only issue!

In 1 year of T600 running ICARUS will collect about 100 events of this quality (in presence of oscillations)



	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

Sun and Supernovae: low energy reactions in Argon

- Elastic scattering from neutrinos (ES)

  $\phi(\nu_e)+0.15\ \phi(\nu_\mu + \nu_\tau)$

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

- Electron-neutrino absorption (CC)

  $\phi(\nu_e)$

  Q=5.885 MeV

$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

- Elastic scattering from antineutrinos (ES)

  $\phi(\bar{\nu}_e)+0.34\ \phi(\bar{\nu}_\mu + \bar{\nu}_\tau)$

$$\bar{\nu}_x + e^- \rightarrow \bar{\nu}_x + e^-$$

- Electron-antineutrino absorption (CC)

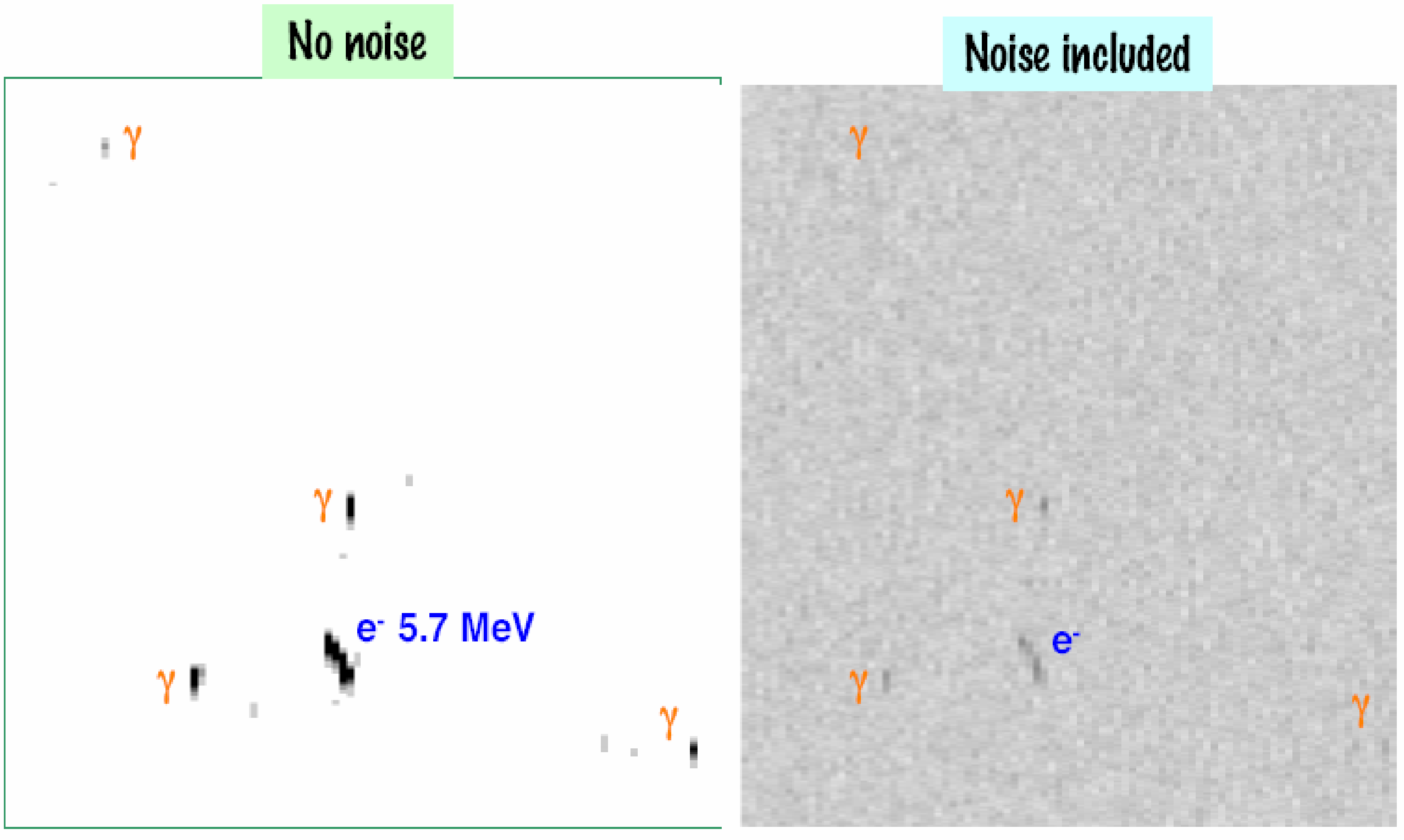
  $\phi(\bar{\nu}_e)$

  Q≈8 MeV

$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$$

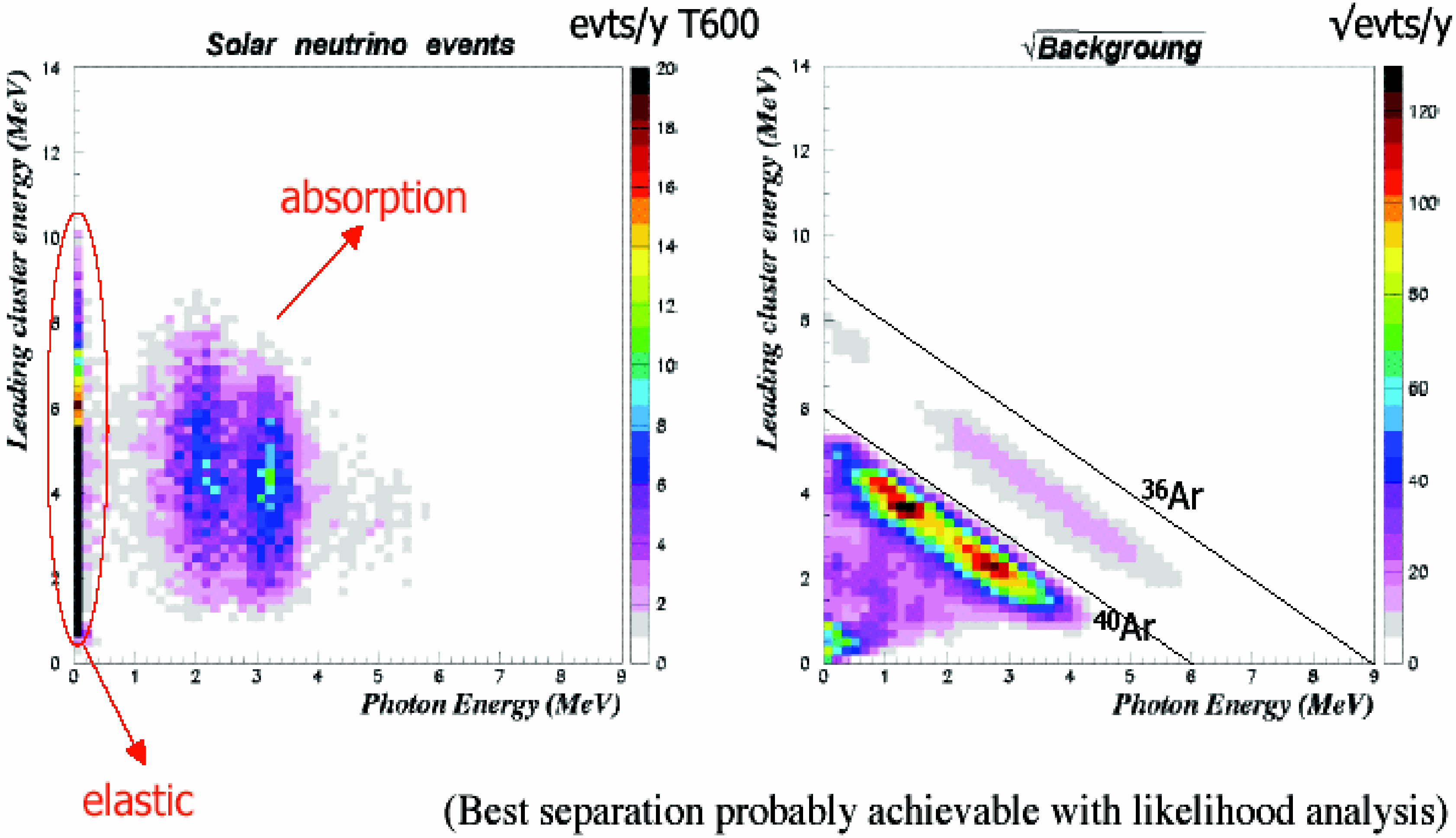
Solar neutrino absorption event

(Simulation using observed correlated noise in T600)



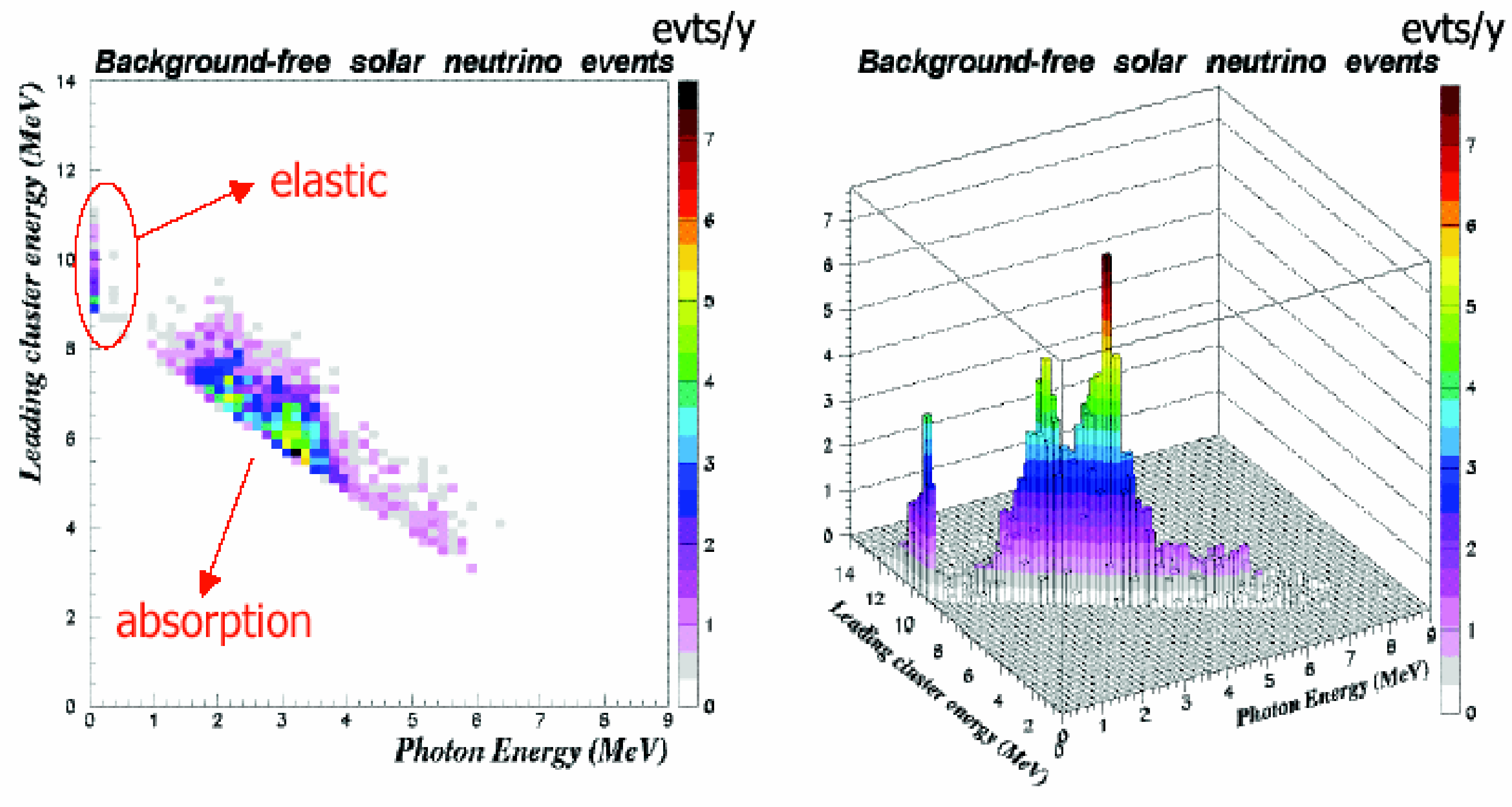
Correlation electron-photon energy

A better separation is achieved if one considers electron and γ correlations



(Best separation probably achievable with likelihood analysis)

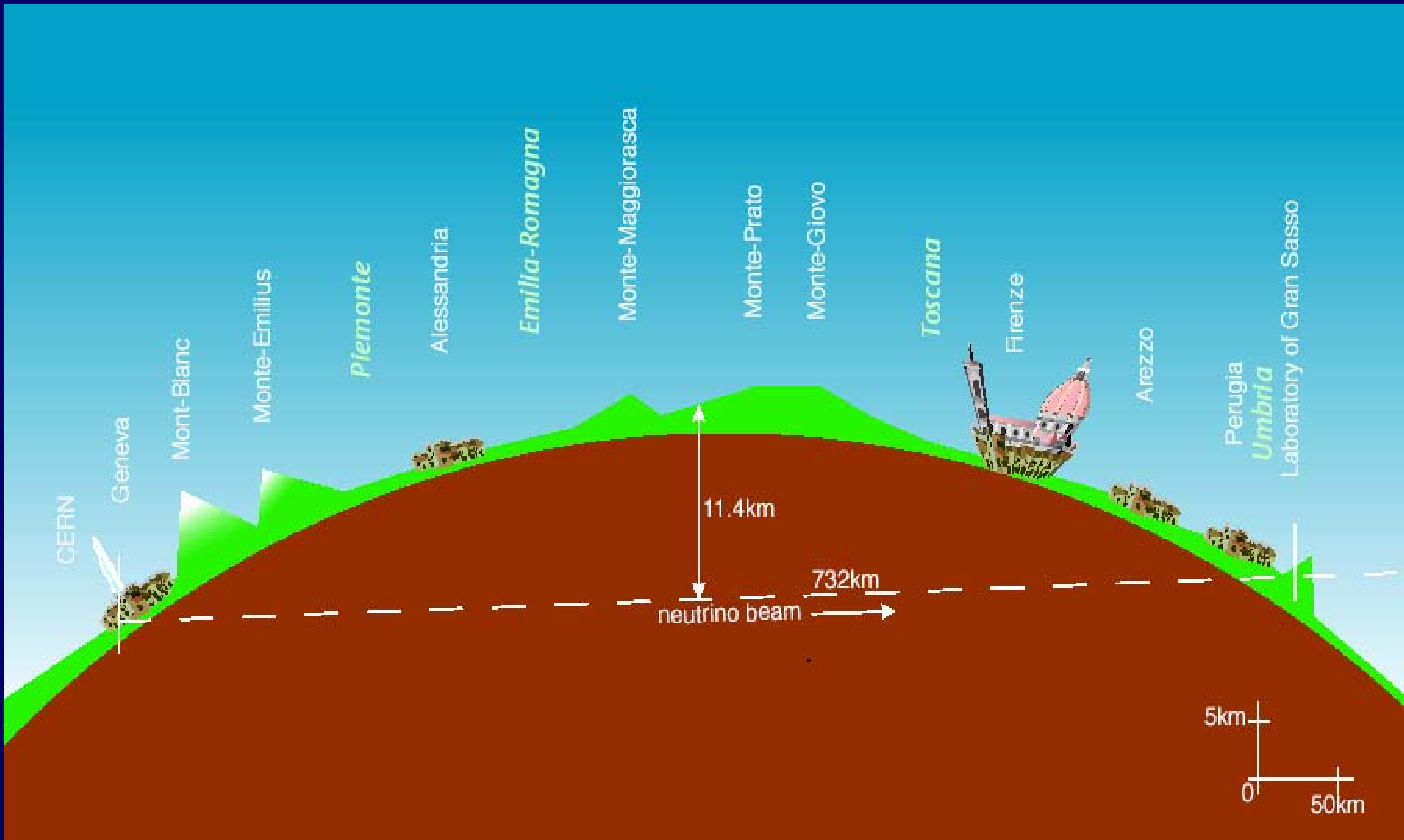
BG free solar events (E > 8 MeV)



Solar ν events per year in T600

Elastic	Fermi	Gamow-Teller
38	165	295

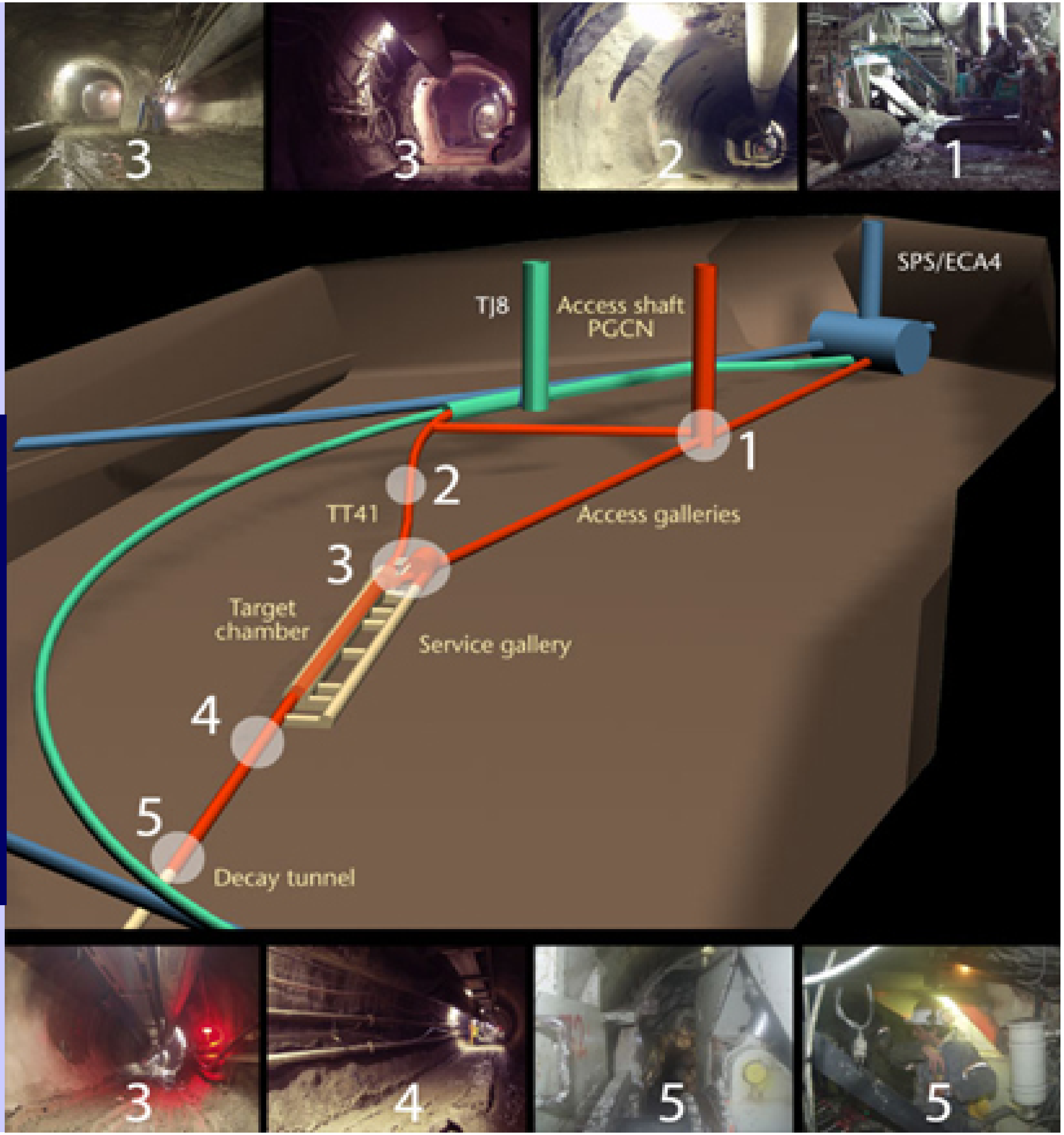
The CNGS neutrino beam



CNGS beam layout at CERN site.

Progress in the civil engineering work:
excavation completed
concreting started

CNGS commissioning:
May 2006



ICARUS and the CNGS beam

- ICARUS as a LBL experiment between CERN and LNGS already discussed in 1993:

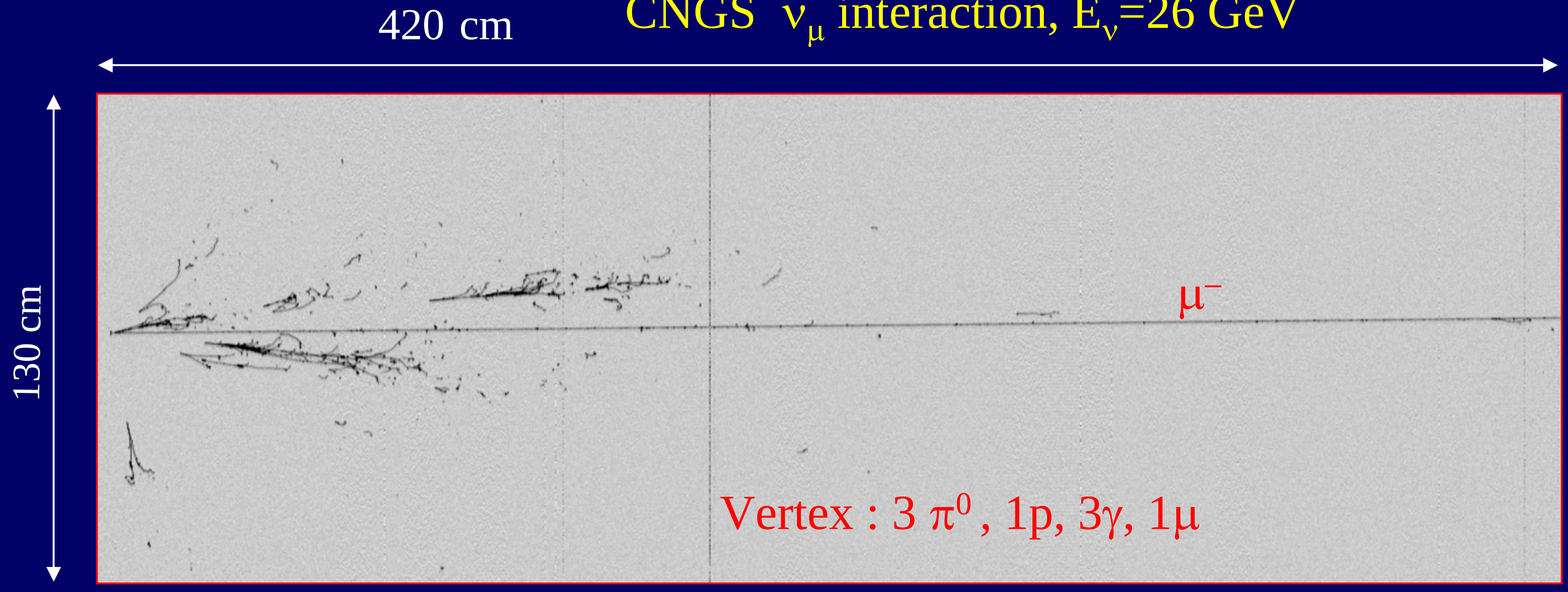
simultaneous study of accelerator and non-accelerator ν is possible due to the nature of the detection technique

- continuously sensitive and isotropic
- CNGS events: separated from other events by timing (SPS spill)

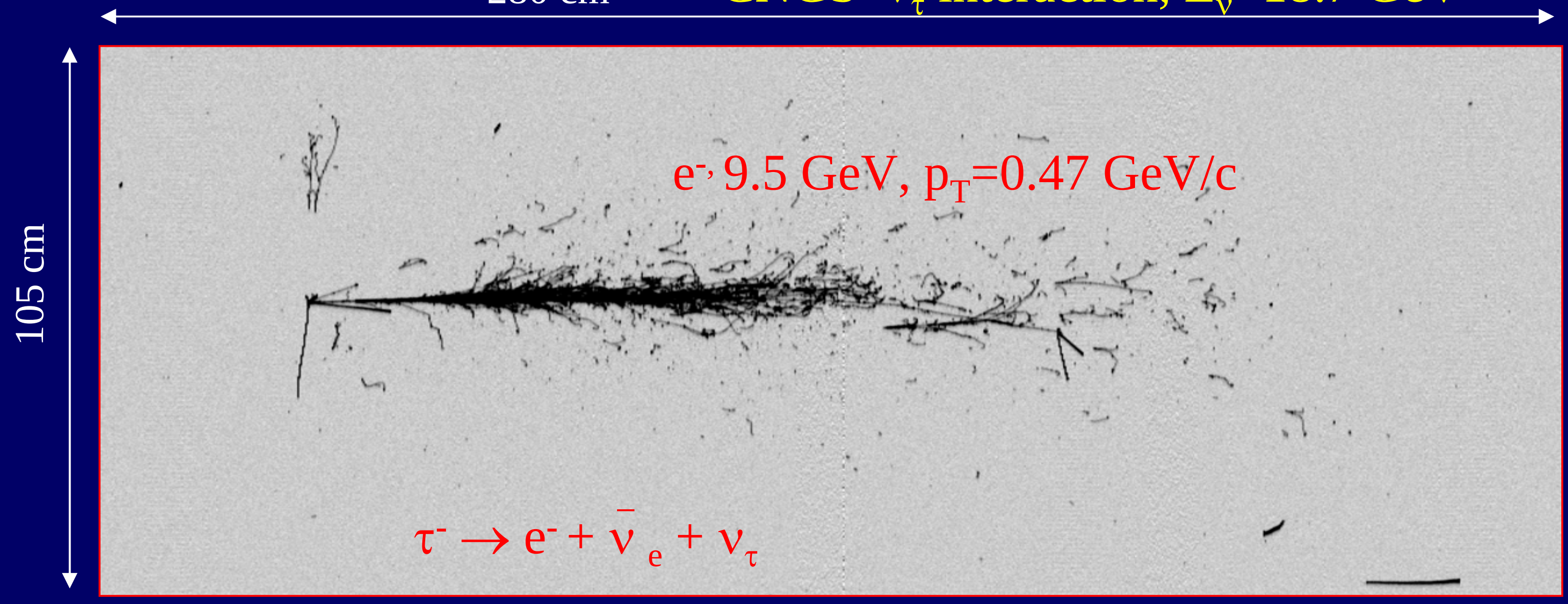
- Real-time detection, excellent granularity and energy resolution of LAr TPC will allow to collect and identify interactions from CNGS neutrinos:

- ν_μ CC: online study of beam profile, steering and normalization
- ν_e CC: search for $\nu_\mu \rightarrow \nu_e$ oscillations: best sensitivity until the JHF-SK
- ν_τ CC: search for $\nu_\mu \rightarrow \nu_\tau$ oscillations with sensitivity similar to OPERA
- NC events: search for $\nu_\mu \rightarrow \nu_s$ oscillations or exotic models.

CNGS ν_μ interaction, E_ν=26 GeV



CNGS ν_τ interaction, E_ν=18.7 GeV



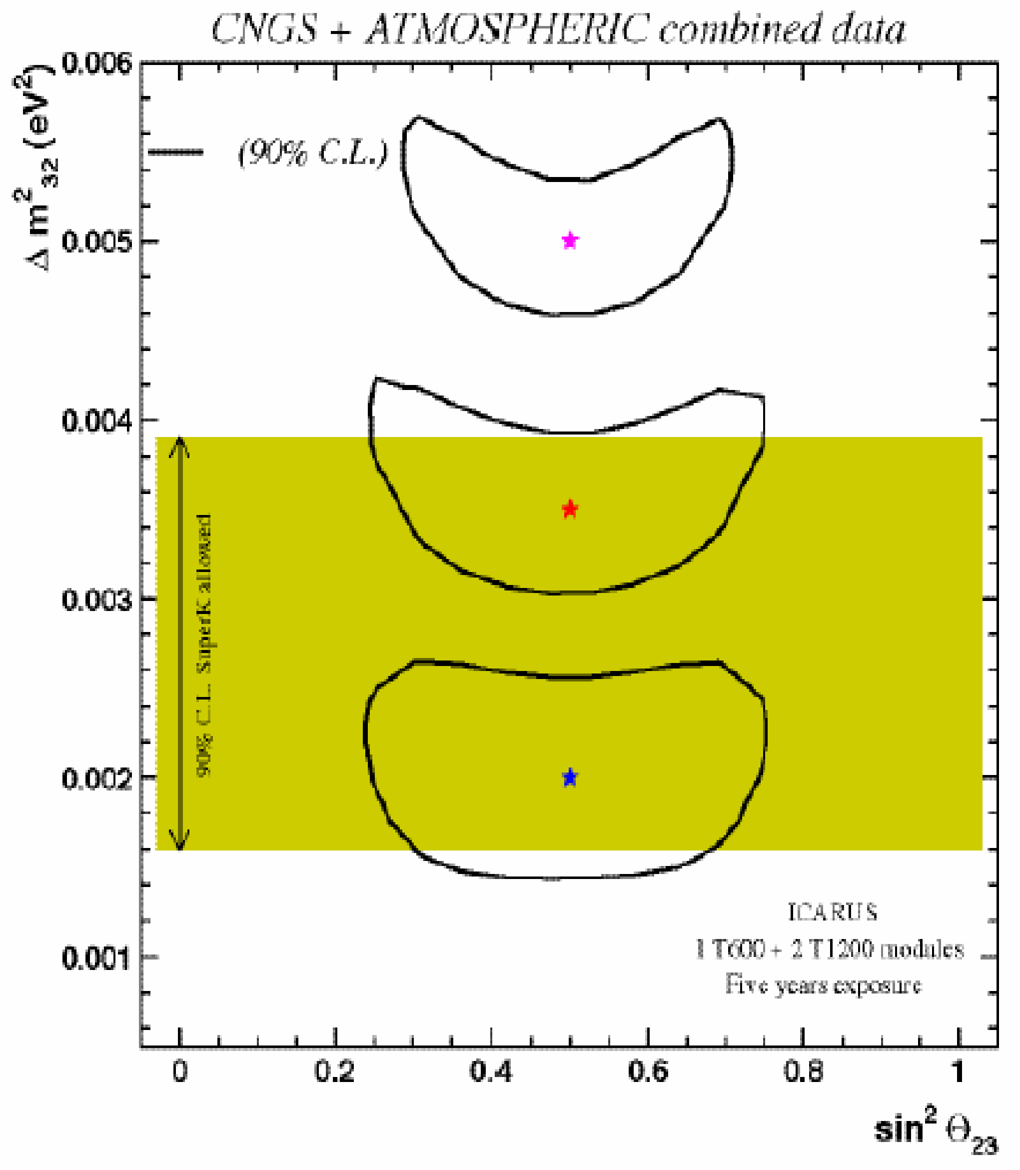
CNGS $\nu_\mu \rightarrow \nu_\tau$ appearance search

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

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

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
$\tau \rightarrow e$	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**

Oscillation parameters determination



5 years exposure combining beam and atmospheric neutrino events (within the same detector)

$$\frac{\delta\left(\Delta m^2\right)}{\Delta m^2} \approx 10\%$$

Search for subleading $\nu_\mu \to \nu_e$

- Search for excess of electrons, on top of τ electronic decays
- Takes advantage of **unique e/π^0 separation in ICARUS**
- Assume 5 years @ 4.5x10^{19} pots/year, 2.35 kton fiducial
- Limited by statistics: needs more intensity (low E) to exploit ICARUS features

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

θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC		$\nu_\mu \to \nu_e$	
		$E_\nu < 4$ 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

Comparison between τ and LE optimizations

The current CNGS optimization for τ appearance is not optimal for the search for subleading $\nu_\mu \to \nu_e$ oscillation. Try to optimize

Maximize flux between 0 and 2.5 GeV

E_p GeV	focus	decay tunnel length (m)	ν_μ flux ν/cm^2	ν_e flux ν/cm^2	10^{19} p.o.t. ν_μ CC ev/kton	10^{19} p.o.t. ν_e CC ev/kton	$< E_\nu >$, CC ν_μ GeV	$< E_\nu >$, CC ν_e GeV	ν_μ/ν_e CC
400	p.f	350	$1.3 \cdot 10^{-13}$	$2.6 \cdot 10^{-15}$	**9.0**	0.12	1.8	1.8	1.3%
400	horn	350	$1.0 \cdot 10^{-15}$	$9.0 \cdot 10^{-16}$	**4.5**	$4.2 \cdot 10^{-2}$	1.8	1.4	0.9%
400	p.f †	CNGS	$1.6 \cdot 10^{-14}$	$3.2 \cdot 10^{-16}$	**1.8**	$2.2 \cdot 10^{-2}$	2.1	1.7	1.2%
400	$\tau^{\dagger}$	CNGS	$1 \cdot 10^{-14}$	$9.4 \cdot 10^{-17}$	**0.9**	$8.7 \cdot 10^{-3}$	1.8	1.8	0.9%

Table 3: Neutrino beam parameters for the CNGS baseline, with $E_\nu < 2.5$ GeV. The † cases correspond to the *present CNGS design* for target, acceptance and focusing system.

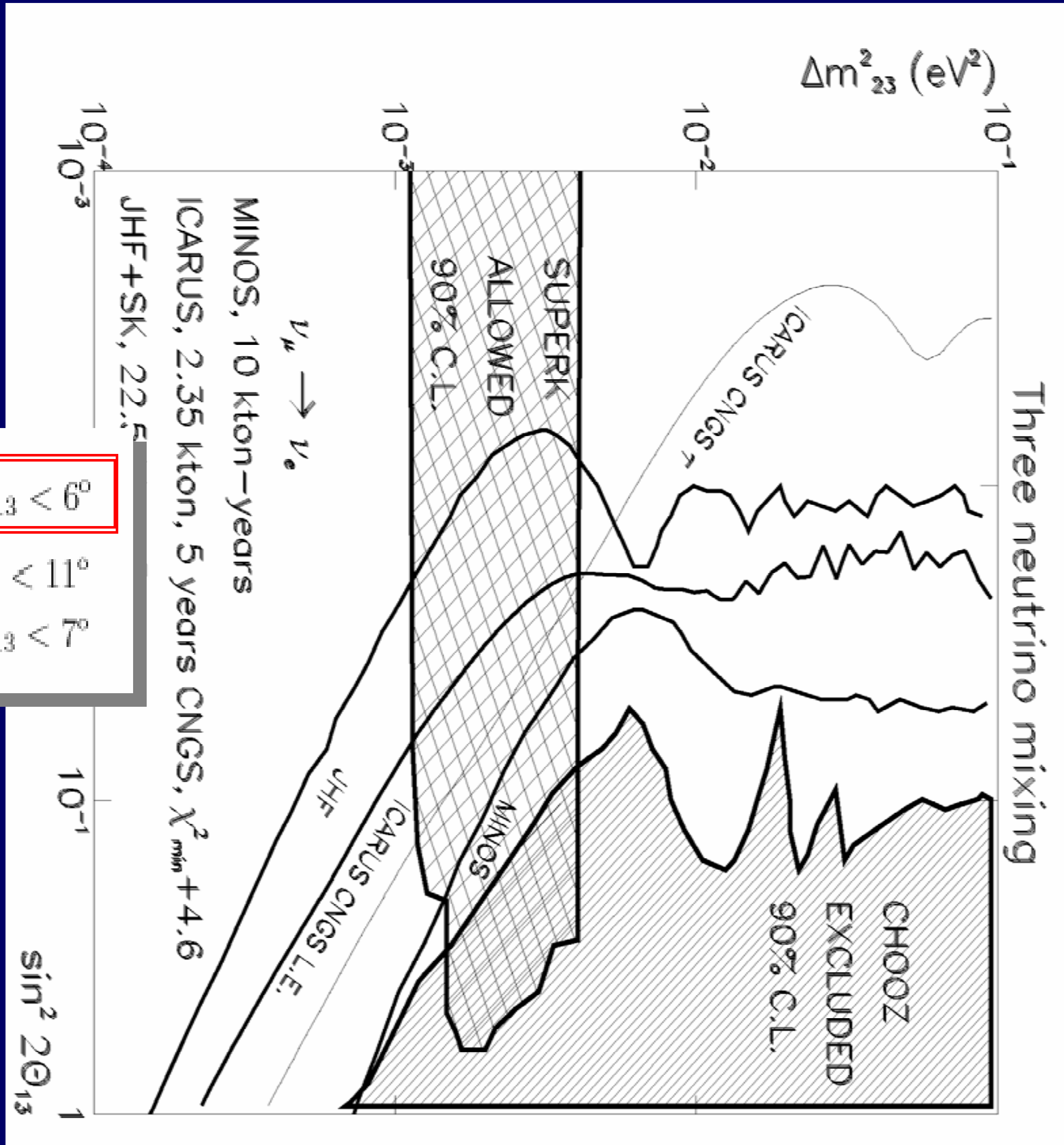
Factor of 5 improvement at low energy

For $\Delta m^2_{23} = 2.5 \times 10^{-3}$

$(\sin^2 2\theta_{13})_{CNGS,\tau} < 0.04 \quad \text{or} \quad \theta_{13} < 6^\circ$

$(\sin^2 2\theta_{13})_{CHOOZ} < 0.14 \quad \text{or} \quad \theta_{13} < 11^\circ$

$(\sin^2 2\theta_{13})_{MINOS} < 0.06 \quad \text{or} \quad \theta_{13} < 7^\circ$



The ICARUS program and plans

The ICARUS detector approved in 1997 by the Italian INFN; currently financed as part of the LNGS program. Innovative nature of the LAr technology
→ graded approach:

1. Full scale 600 ton module constructed in **collaboration with industry**.
2. **Successful operation** of the T300 half-module (Summer 2001) showed that the **technique has matured**.
3. Second T300 half-module **being completed**.
4. Physics program of its own: installation of **T600 recommended** by Gran Sasso Scientific Committee (LNGSSC), **placed in Hall B of LNGS (2003)** and commissioned for physics right after. **Installation program approved by LNGS on February 5th.**
5. Reach the design mass: **cloning the T600** for further modules **recommended by LNGSSC and CERN-SPSC.**
6. INFN approved the T3000 scientific program. The **first T1200 module is funded** and its design ongoing.
7. Extend the T600 with two new T1200 modules **by early 2006** (for CNGS start up).

Conclusions

After many fruitful years of R&D the ICARUS Collaboration has operated at surface a large mass (300 ton) liquid Argon TPC proving that the scaling from prototypes to full scale detectors is successful. The ICARUS agenda now foresees:

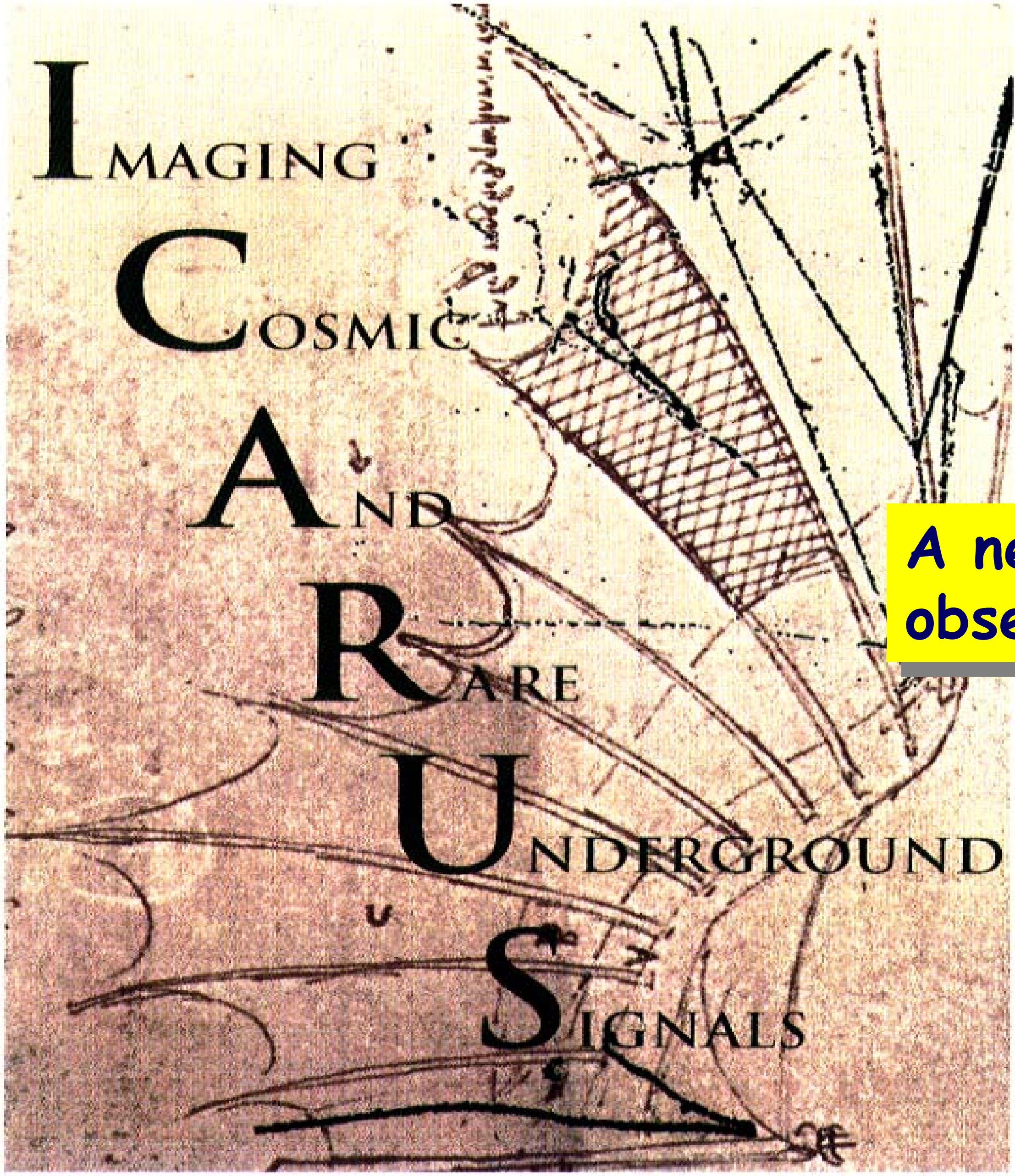
- the completion of the 2^{nd} 300 ton half-module to form the T600 detector
- operation with the T600 at LNGS with data taking of astrophysical events by 2003
- the progressive realisation of two additional T1200 modules, with the T600 as basic cloning unit, to be operational by 2006

Thanks to the potential offered by the LAr technology, ICARUS will be able to perform a vast physics program in the domain of

- nucleon decay
- atmospheric neutrinos
- solar and supernovae neutrinos
- accelerator neutrinos

ICARUS will run with the CNGS beam from 2006 to

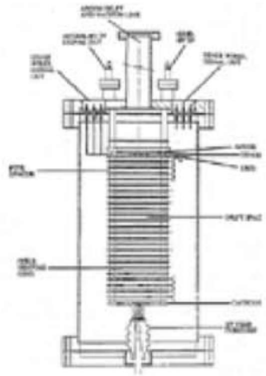
- provide real-time study of the beam properties
- search for $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ flavor appearance
- further future: exploit ICARUS with a LE beam for an improved measurement of the subleading $\nu_\mu \rightarrow \nu_e$ oscillation



A new astroparticle observatory…soon on duty !

Additional transparencies

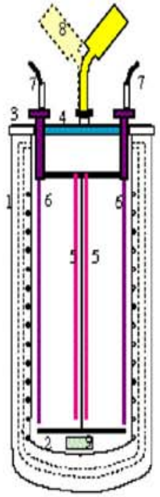
Milestones: LAr Imaging



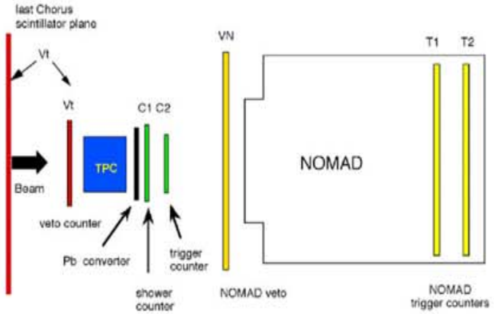
24 cm drift wires chamber

1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

3 ton prototype



1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.



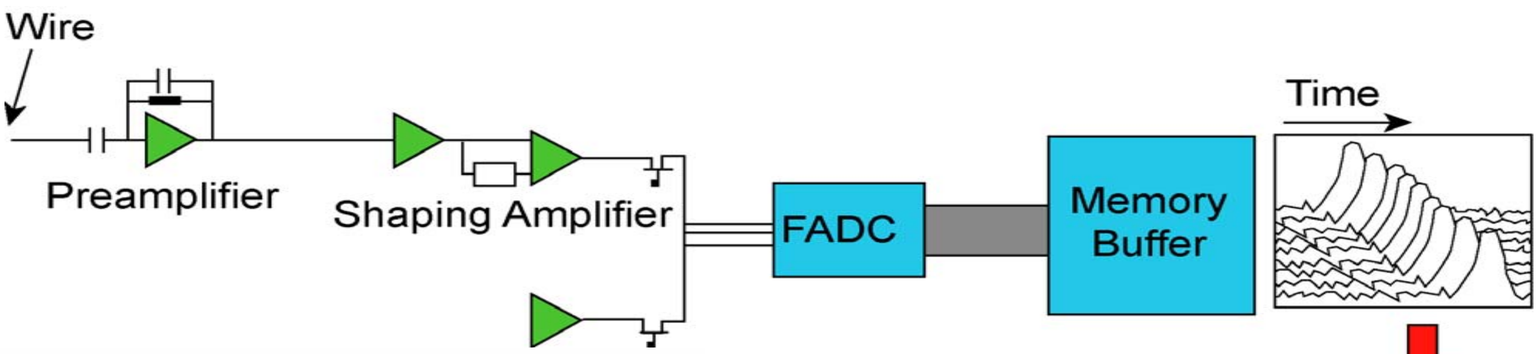
50 litres prototype 1.4 m drift chamber

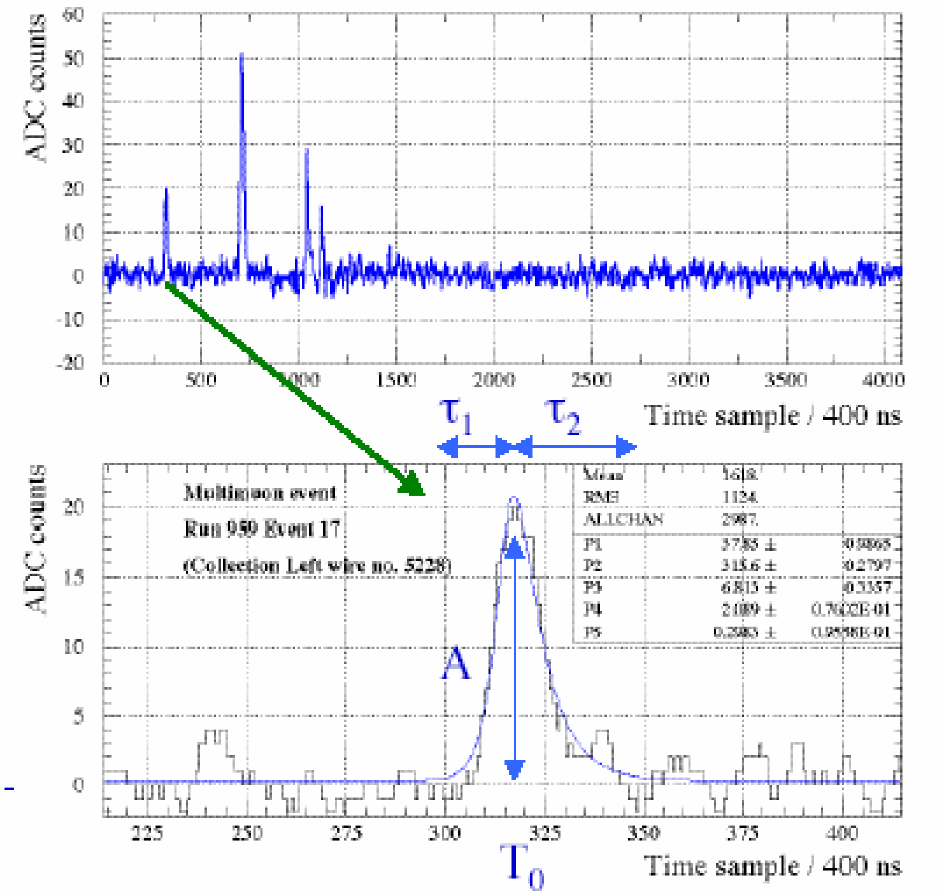
1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

10 m^3 industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

Signal extraction procedure





Collection plane wire: charge = signal area

$$f(t) = B + A \frac{e^{-\frac{t - T_0}{\tau_2}}}{1 + e^{-\frac{t - T_0}{\tau_1}}}$$

B = baseline, A = amplitude

τ_1 , τ_2 = rise and fall time, T_0 = peak position

π_0 candidate (preliminary)

Run 975, Event 151

Reconstruction of γ-showers

158 MeV

752 MeV

140 MeV

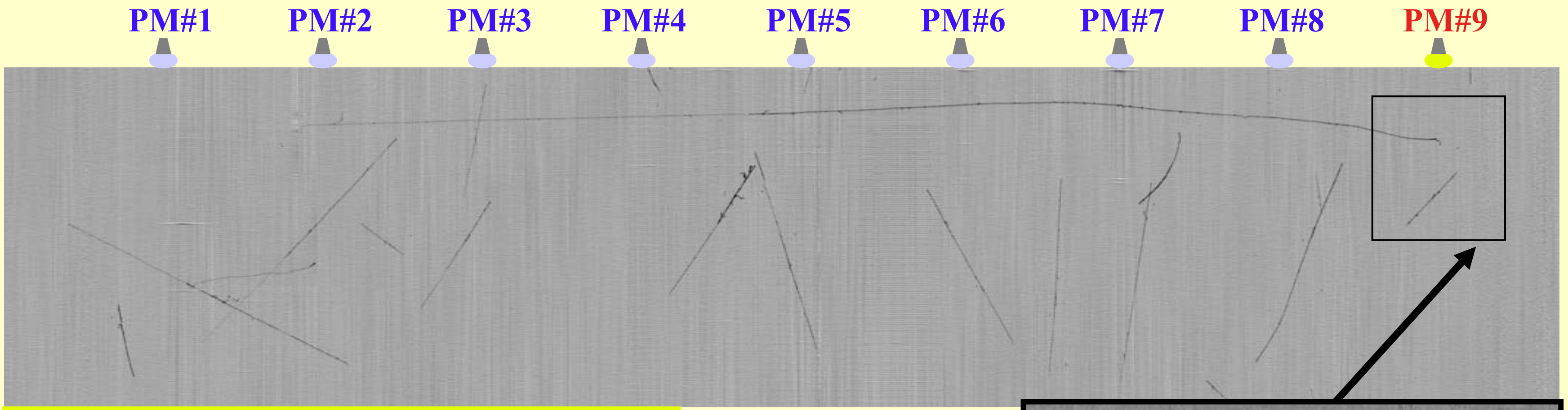
$\theta = 141^o$

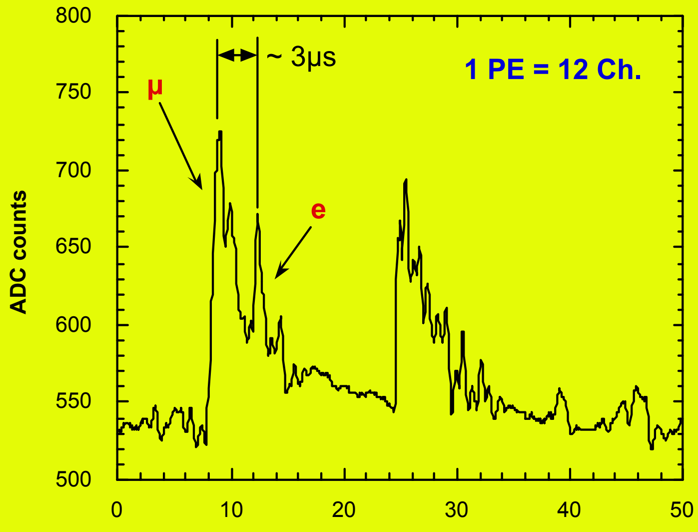
$M_{inv} = 650$ MeV

$\theta = 25^o$

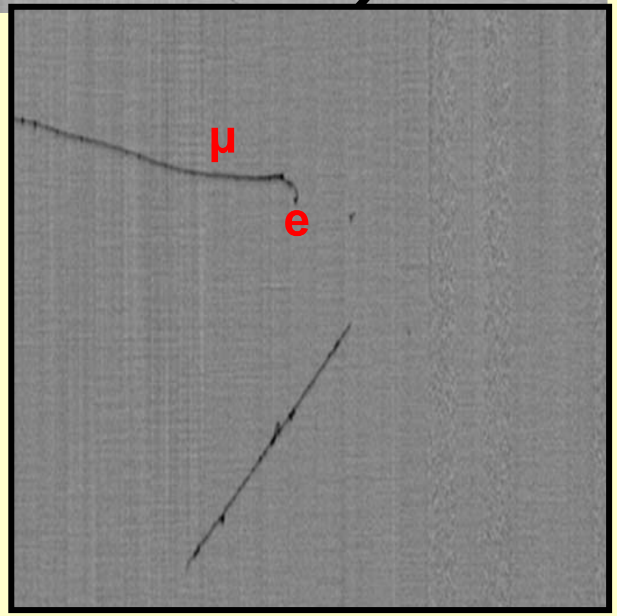
$M_{inv} = 140$ MeV

ICARUS T600: absolute time reconstruction





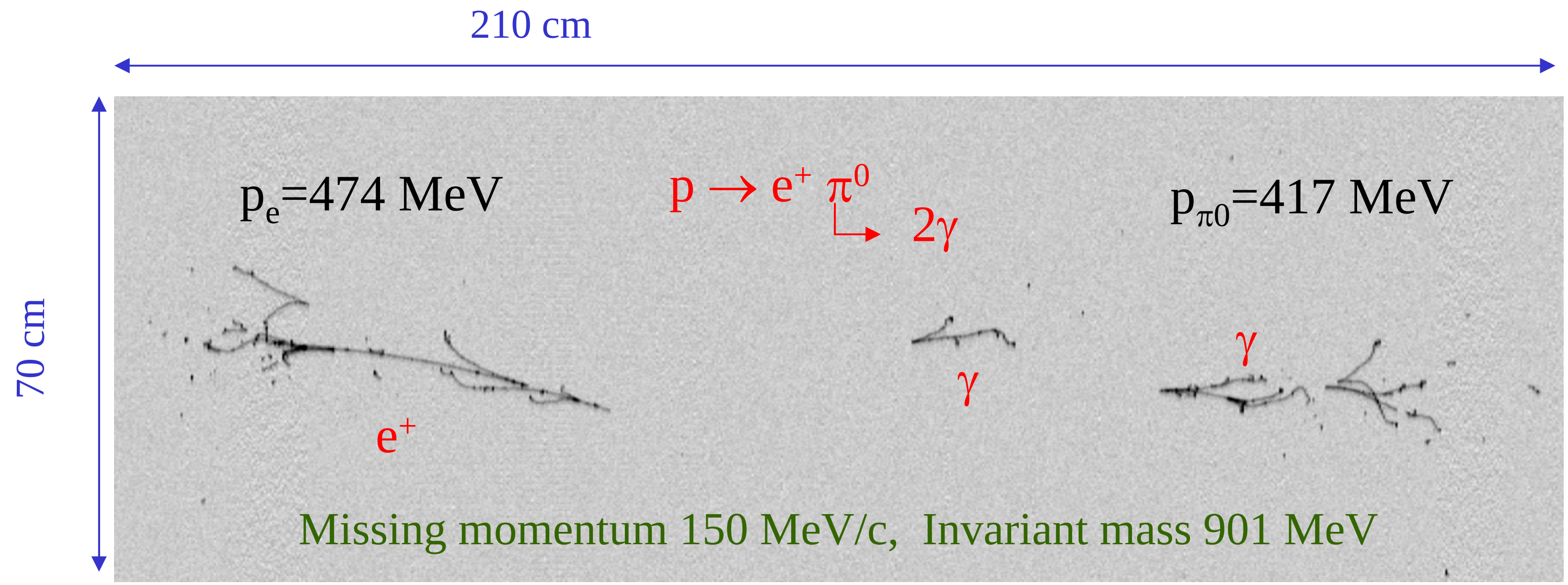
PM#9 signal

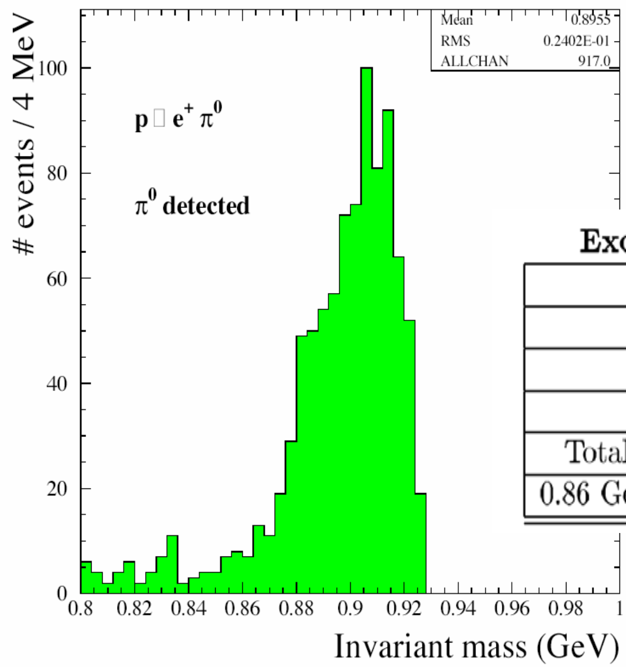


VUV light: 128 nm, 10000 γ/MeV

PMT: 8" FLA - Elect. Tubes Ltd, coated with Tetra-Phenil-Butadiene

Proton decay in ICARUS





Exclusive Channel Cuts	$p \rightarrow e^+ \pi^0$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One π^0	54.00%	6604	2135	15259	5794	8095	3103
One positron	54.00%	6572	2125	20	0	0	0
No charged pions	53.90%	3605	847	5	0	0	0
No protons	50.85%	1188	656	1	0	0	0
Total Momentum < 0.4 GeV	46.70%	454	127	0	0	0	0
0.86 GeV < Total E < 0.95 GeV	45.30%	1	0	0	0	0	0

Proton decay: comparison with SuperK

Channel		Eff. (%)	Observed (evts.)	Bkg. (evts.)	Exposure (kTon×yr)	τ/B limit (10^{32} yr)	Needed Exp. to reach SK (kTon×yr)
$p \to e^+ \pi^0$	SuperK	43	0	0.2	79	50 → 30 [1 evt]	
	ICARUS	45	–	0.005	5	2.7	94
$p \to K^+ \bar{\nu}$	SuperK				79	19 → 13 [1 evt]	
prompt $\gamma\ \mu^+$	SuperK	8.7	0	0.3		10 → 7	
$K^+ \to \pi^+ \pi^0$	SuperK	6.5	0	0.8		7.5 → 5	
	ICARUS	97	–	0.005	5	5.7	17
$p \to \mu^+ \pi^0$	SuperK	32	0	0.4	79	37 → 24 [1 evt]	
	ICARUS	45	–	0.04	5	2.6	102

SuperK results compiled by M. Goodman for NNN02, January 2002

- Water Cerenkov are good at back-to-back three-ring events, hence in $e\pi^0$ and $\mu\pi^0$ channels channels. SuperK gains on the mass.

- In the $p \to \nu$ K channel the efficiency in LAr is ≈10 times better than the channels investigated

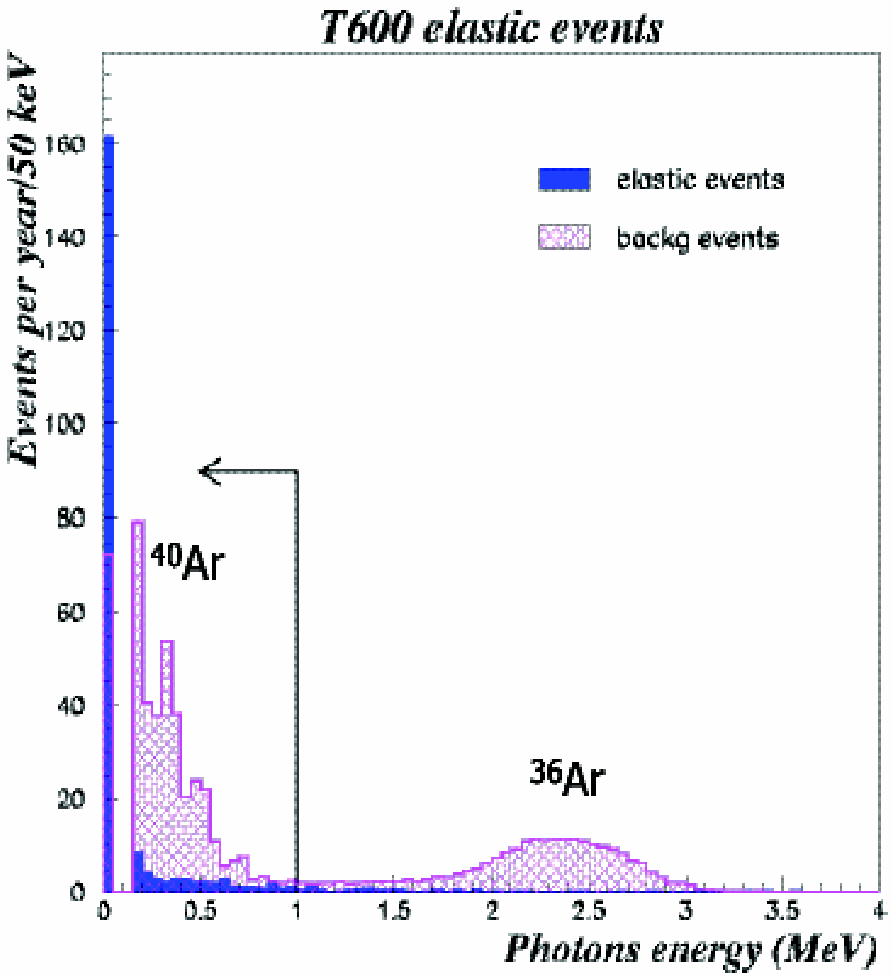
- ICARUS T3000 fiducial is equivalent to 23.5 kton H_2O to be compared to SuperK 22.5 kton

- Rather complementary approaches/abilities

Elastic event analysis

Events per year in T600

CUT	Signal	Background
E_{detec} > 150 keV and E_{clus} > 5 MeV	296	13100
Angular cut at cos (θ_{sun}) = 0.9	213	655
$E\gamma$'s < 1 MeV	202	432



Statistical significance:

$S / \sqrt{B} \approx 10$

Reconstruction of atmospheric neutrinos

Containment

- ≈ 60% of ν_μ CC events fully contained
- Contained tracks measured by range and calorimetrically (dE/dx)

  7%/$\sqrt{}$E(MeV) for stopping tracks

  12%/$\sqrt{}$E(MeV) for soft e- from Bremsstrahlung

  3%/$\sqrt{}$E(GeV) for EM showers
- Range vs dE/dx provides particle ID

Measurement of escaping muons performed in different ways

- By multiple scattering

  Exploit the momentum dependence of scattering

  ($\sigma_p/p \approx 0.10 + 0.048 \ln(p[\mathrm{GeV}])$ for 5 m long track)
- By precise measurement of the energy loss rate

  Use relativistic rise of dE/dx measured by combining successive samples

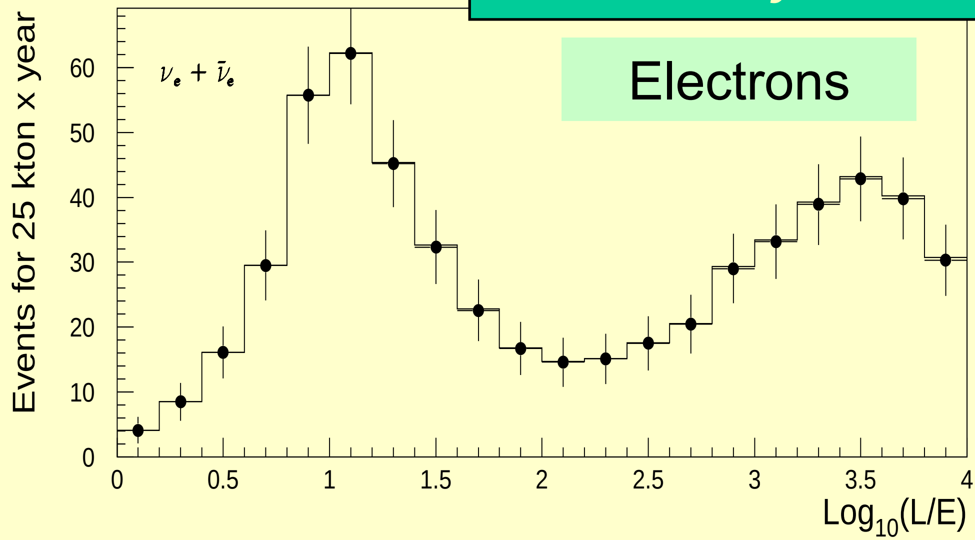
  ($\sigma_p/p \approx$ 20-30 %)

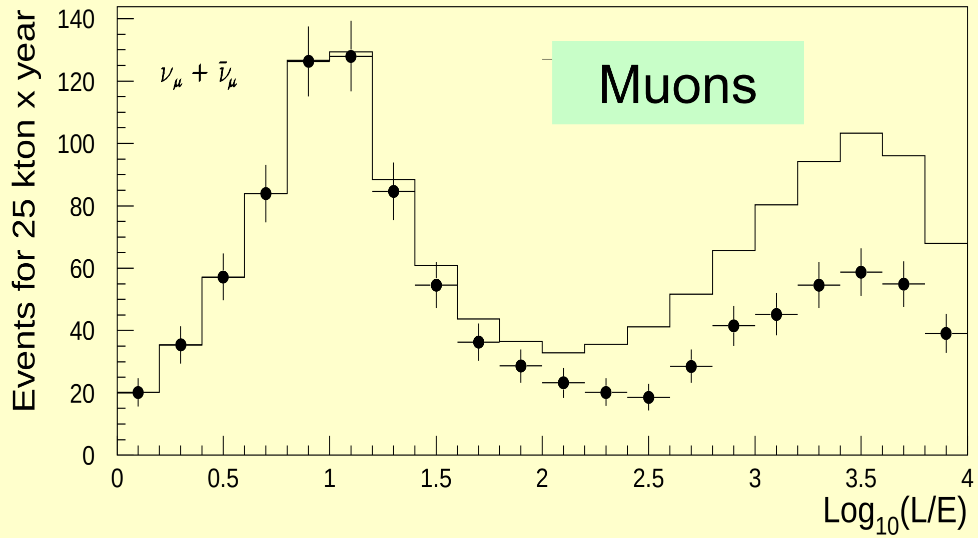
Reconstructed L/E distribution

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

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

After 10 years…



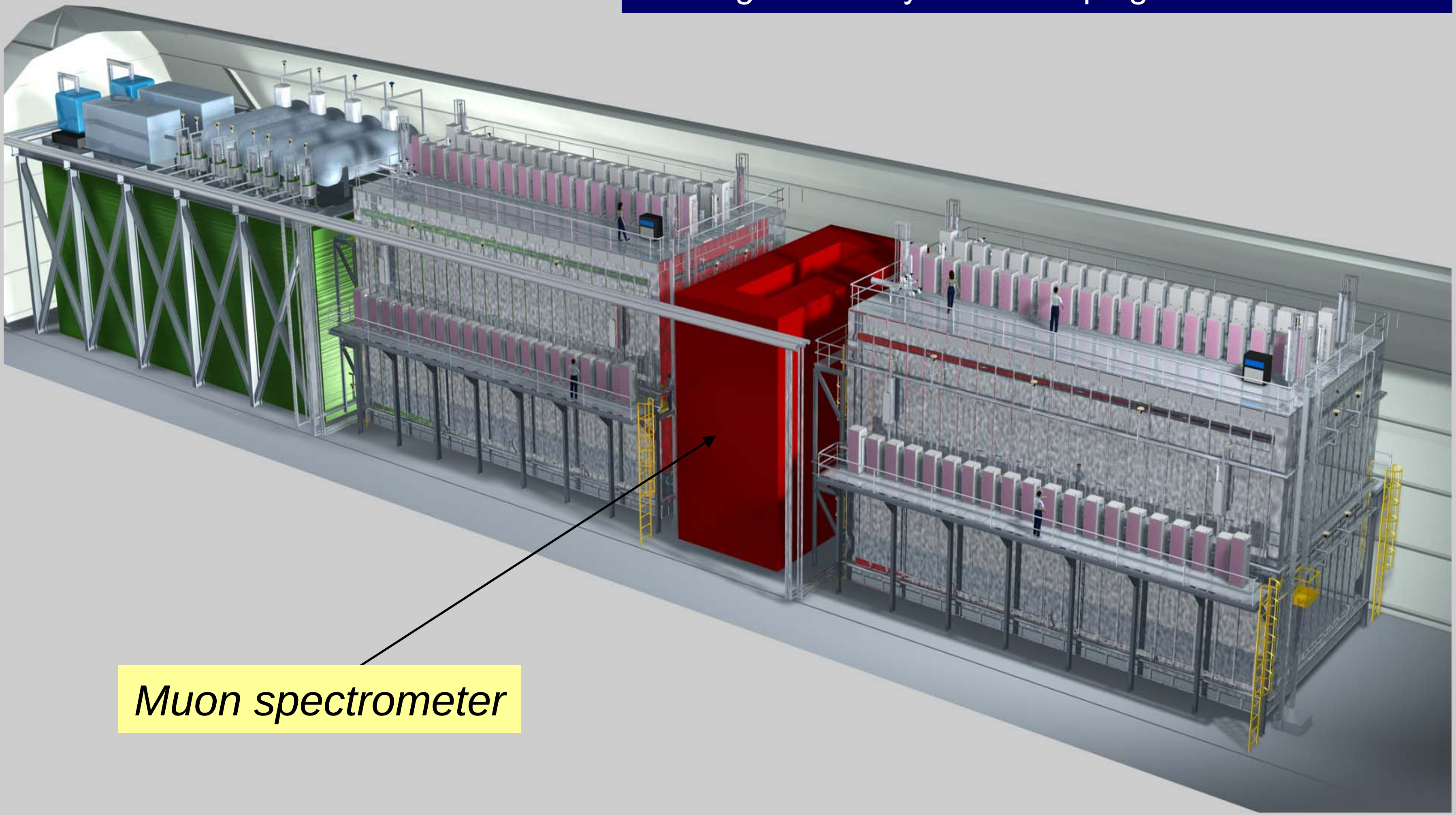


- ***Oscillation parameters:***
  $\Delta m^2_{32} = 3.5 \times 10^{-3}$ eV^2
  $\sin^2 2\Theta_{23} = 0.9$
  $\sin^2 2\Theta_{13} = 0.1$

- ***Electron sample can be used as a reference for no oscillation case***

Spectrometer

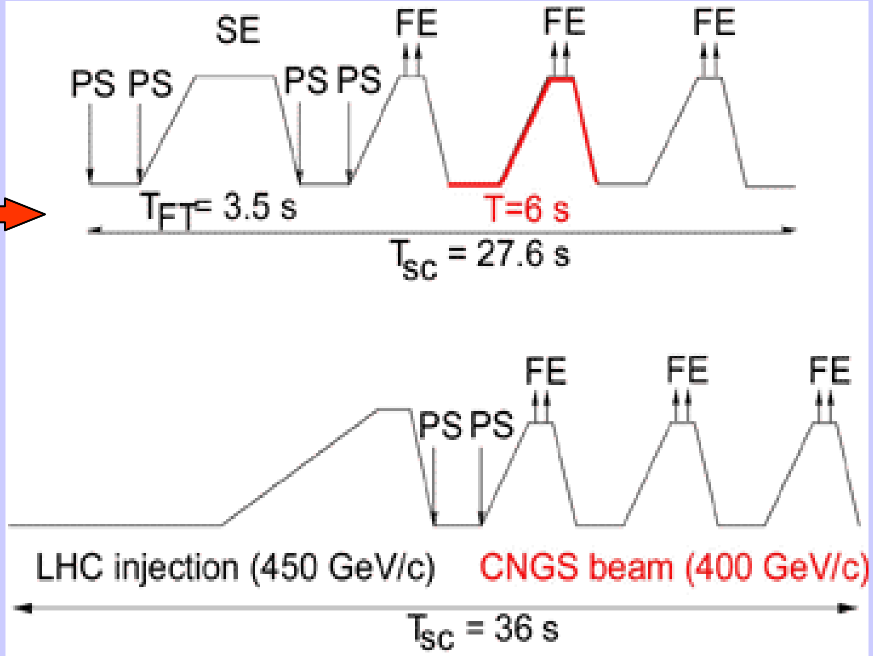
In 1999 the Collaboration put forward the possibility to complement LAr imaging by an external device for magnetic analysis of escaping muons



Muon spectrometer

CNGS features

Protons are accelerated through the existing CERN chain of Linac, Booster, Proton Synchrotron and Super-Synchrotron (SPS). The proton energy at extraction from the SPS to CNGS is 400 GeV. Examples of SPS supercycles during CNGS operation with other users.



Protons are extracted from the SPS with a fast kicker in two batches (FE = fast extraction) of 10.5 ms each, with 50 ms between the two extractions. The microstructure of the beam reflects the 200 MHz radiofrequency of the SPS. Each batch consists of a train of bunches interspaced by 5 ns, the length of a single bunch is 2-3 ns.

The intensity in the SPS per cycle can reach 4.8×10^{13} protons, thus about 2.4×10^{13} protons per fast extraction. Assuming an overall efficiency of 55% and a running time of 200 days per year in a shared mode (filling LHC, etc.), **4.5×10^{19} protons can be delivered to the CNGS target per year.**

In the hypothesis of no oscillation:

2600 ν_μ charged current events **per kton** detector mass **per year**

Assuming ν_μ - ν_τ oscillation, with the parameters **$\sin^2 2\theta = 1$** and **$\Delta m^2 = 3 \times 10^{-3}$ eV^2**:

22 ν_τ charged current **events per kton** of detector mass **per year**

Cost of a single T1200 Super Module