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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INFN Napoli

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

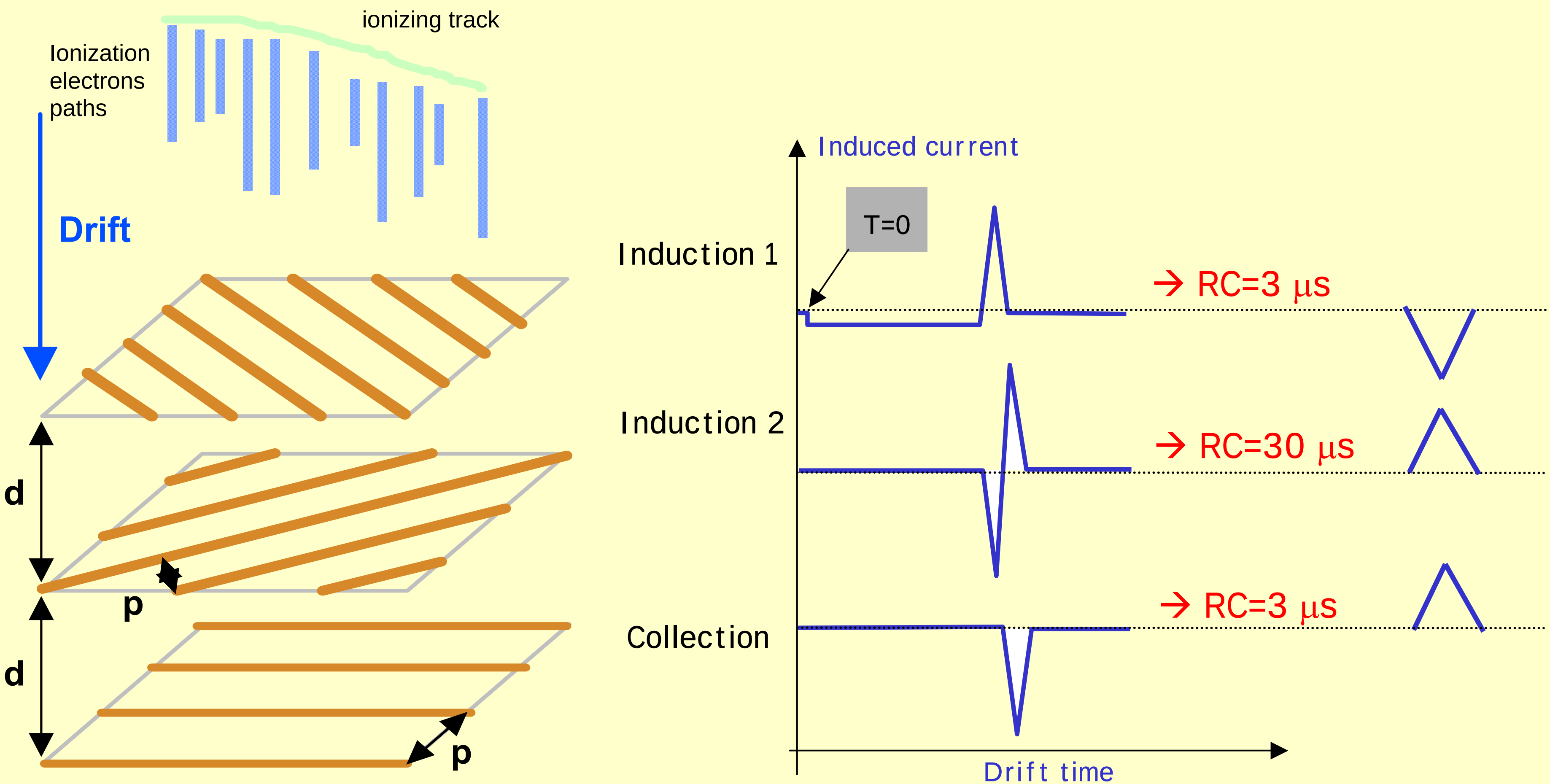
    supernovae neutrinos

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

General features and past experience

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 “stored” not “used” in the experiment
  - TPC: number of channels proportional to surface

- Cryogenic temperature
  - T = 88 K at 1 bar

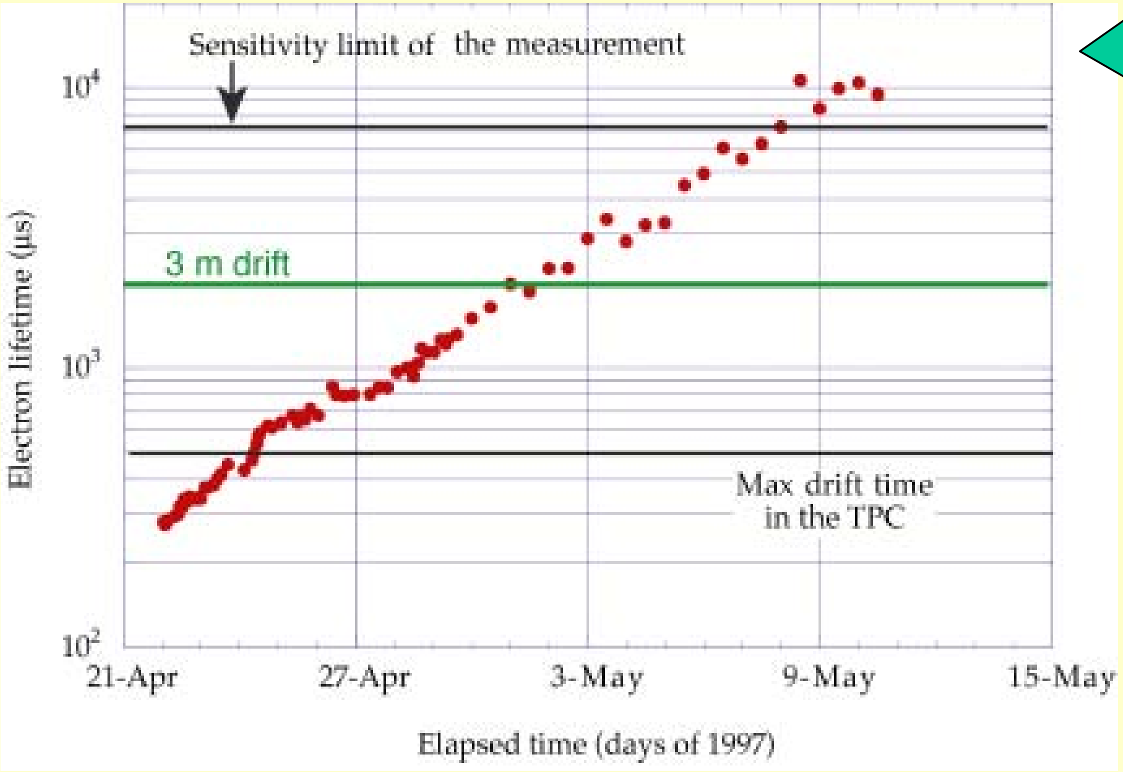
  ⟵ Cryogenic plant
- High purity required for long-drift time
  - 0.1 ppb of O_2 equivalent for 3 ms drift

  ⟵ Argon purification
- No signal amplification in liquid
  - 1 m.i.p. over 3 mm yields 20000 electrons
  - equivalent noise charge 1200 electrons

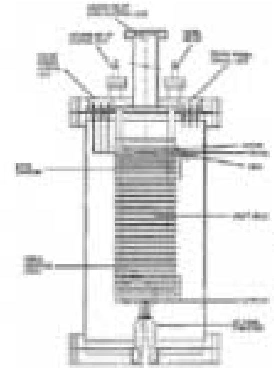
  ⟵ Low noise electronics

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

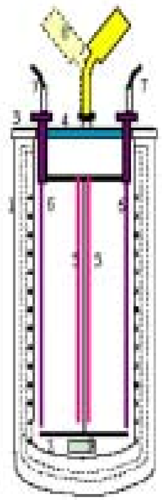


Milestones: LAr Imaging



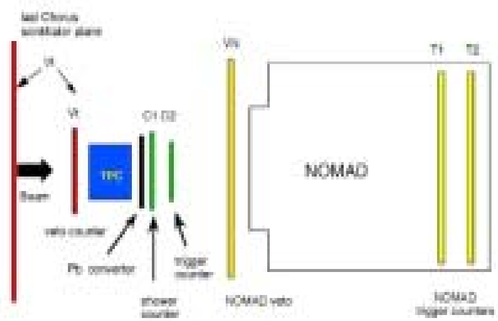
24 cm drift
wires chamber

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.

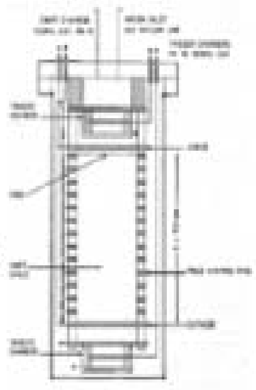
10 m^3 industrial prototype

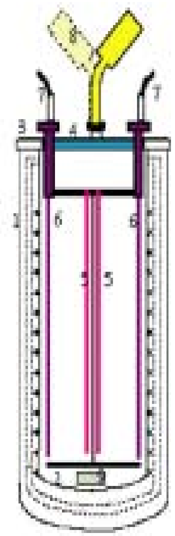
1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

Milestones: LAr purity

First purity monitor chamber

1987: First LAr Ultra-purification.
Measured Lifetime > 10 ms



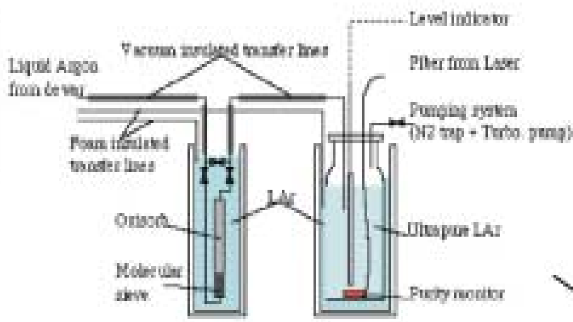


3 ton prototype

1991-1995: First demonstration on large masses. Argon recirculation in gas phase. Long duration test.

Liquid Phase purification

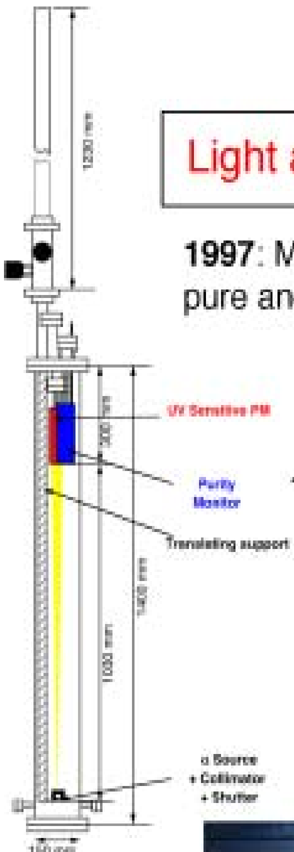
1994



10 m^3 industrial prototype

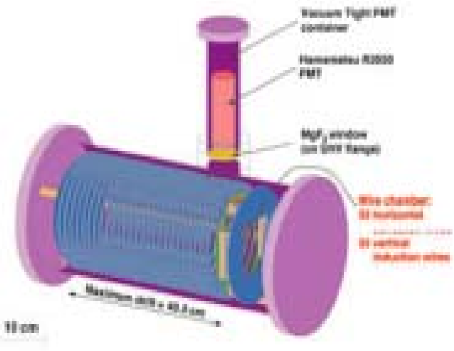
1998-1999: Ultra-pure LAr technique industrialization.
Forced LAr recirculation.

Milestones: LAr Scintillation



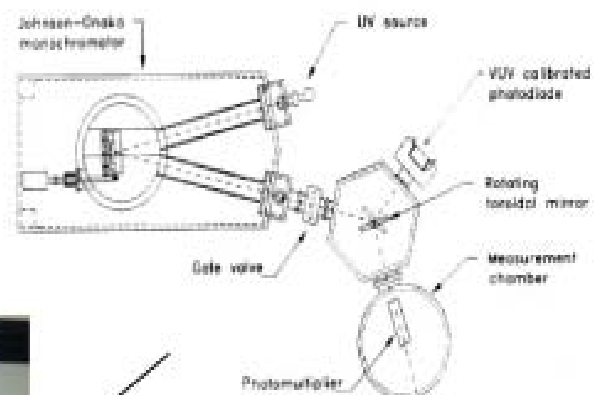
Light attenuation length

1997: Measurements in pure and Xenon doped LAR



30 litres prototype

1996: Scintillation light detection in coicidence with tracks in a LAr TPC. Proof of principle, efficiency measurements.



PMs and WLS

1999-2000: Wavelength shifters test and choice. Design and test of the final system for the T600

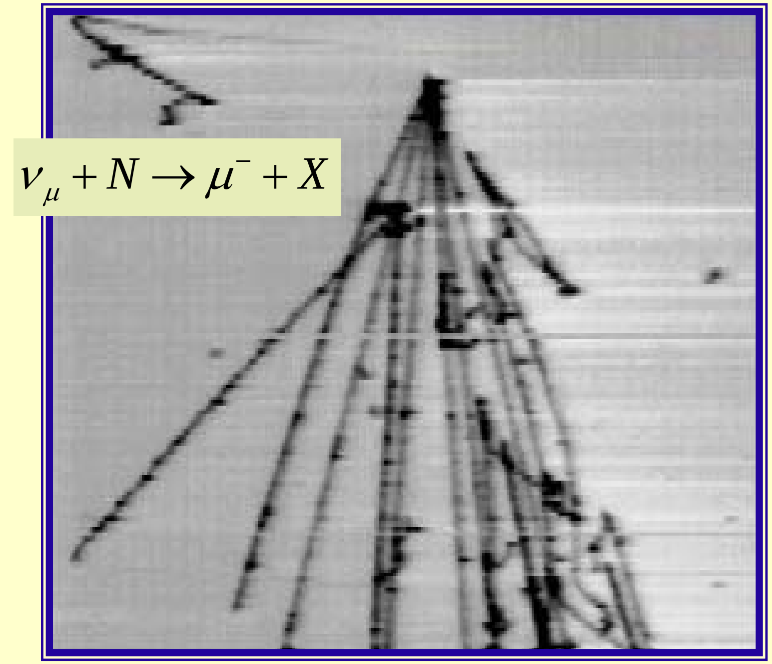
PM Choice and test

2000: Chosen Large size (8") PMs especially designed to work at cryogenic temperature. Performance and reliability tests.

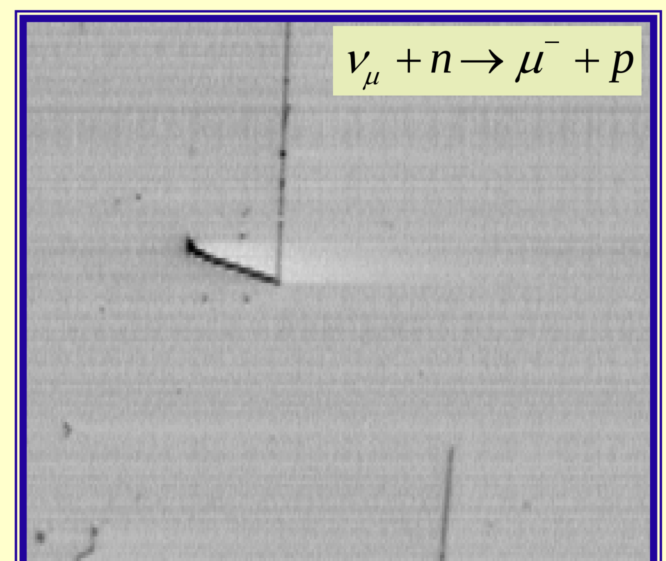
Past experience and results - 50 liter prototype

Active volume: 50 liters
Readout planes: 2
(0°, 90°)
Max. drift distance: 45 cm

- Fermi-motion
- Track direction by δ-rays
- dE/dx versus range for K, π, p discrimination
- Max. electron lifetime > 10 ms



- LAr purification by vapor filtering and recondensation
- LAr purity monitors
- Optimization of FEE for induction and collection
- Warm and cold electronics
- Readout chain calibration studies
- Signal treatment
- Collection of scintillation light
- 1.4 m drift length (special test)
- Test in the CERN neutrino beam (see figures)



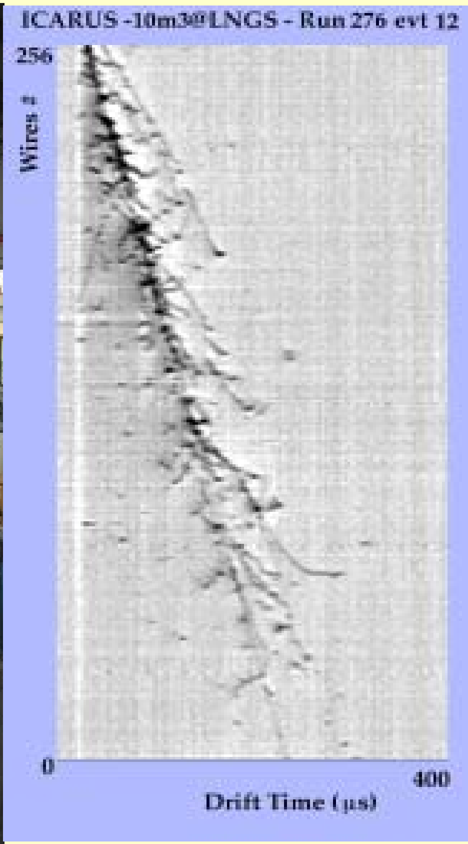
Past experience and results - 15 ton prototype

Total volume : 10 m^3
Readout planes: 2 (–60˚ ,60˚)
Max. drift distance: 35 cm

- Final electronics
- DAQ
- External trigger
- 100 days run at LNGS surface
- Max. electron lifetime ≈ 2 ms

- Purification in liquid phase
- HV feed-through
- Cryogenic technology
- Signal feed-through
- Variable geometry wire chamber


T15 @ LNGS



The T600 module

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

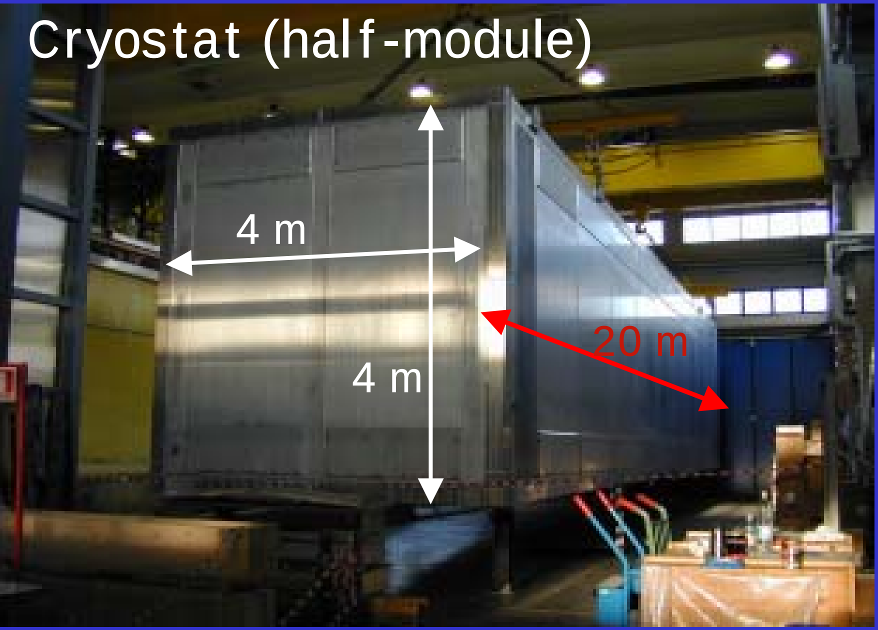
Readout planes: 2 x 3 (–60° ,60° ,0°), about 54000 wires

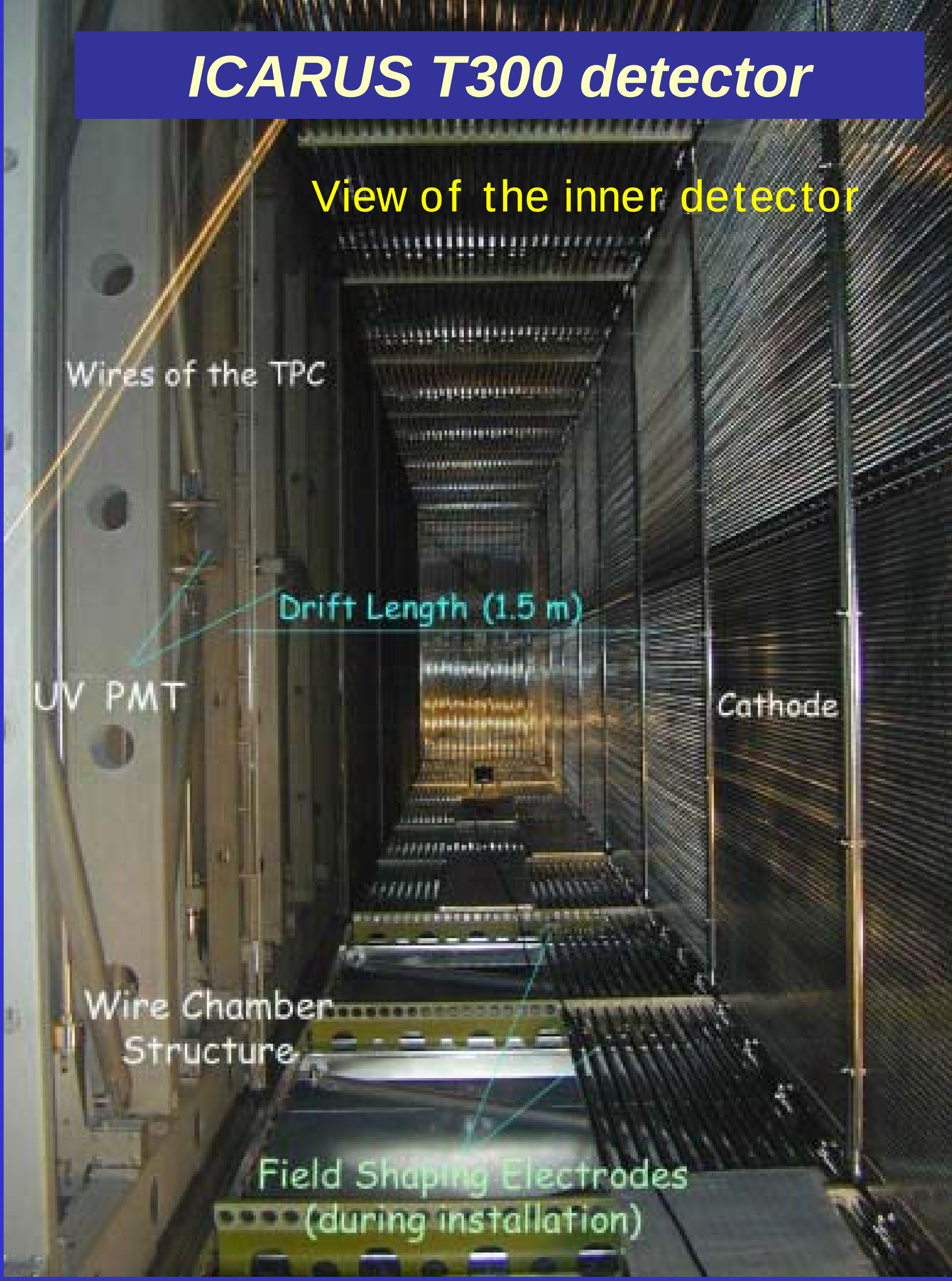
Maximum drift distance: 150 cm

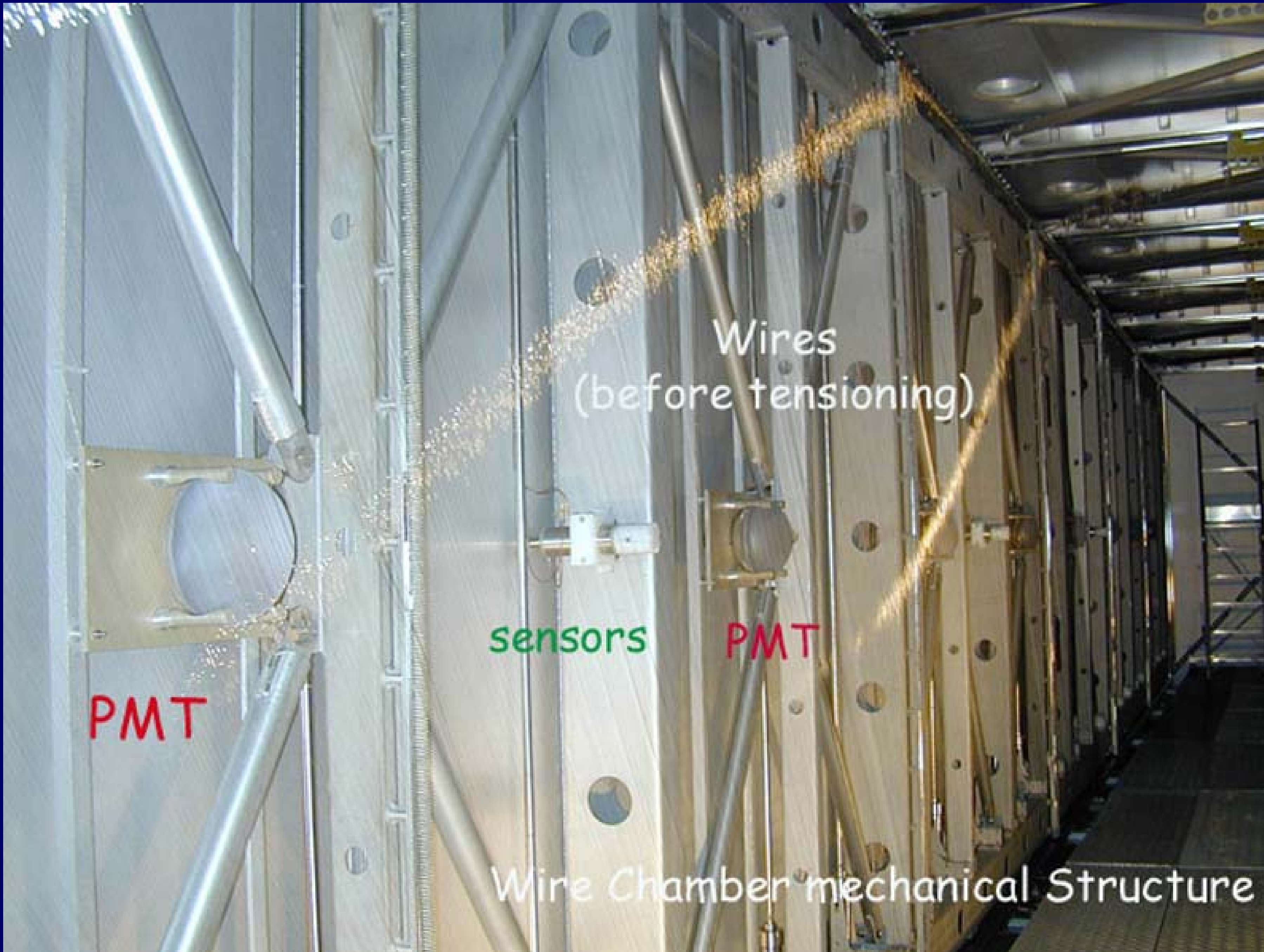
- Full scale technical run of the T300 detector in Pavia (2001)
  - Cryogenics ✓
  - Wire chamber mechanics ✓ ✓
  - Argon purification ✓
  - Electronic noise ✓
  - High voltage for the drift ✓ ✓
  - PMTs for scintillation light collection ✓
  - Readout & DAQ ✓
  - Slow control ✓
- Event reconstruction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

ICARUS T600 cryostat (1 out of 2)

ICARUS T300 detector






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


ICARUS T600 semimodule (front-face), Feb. 7th 2001

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:

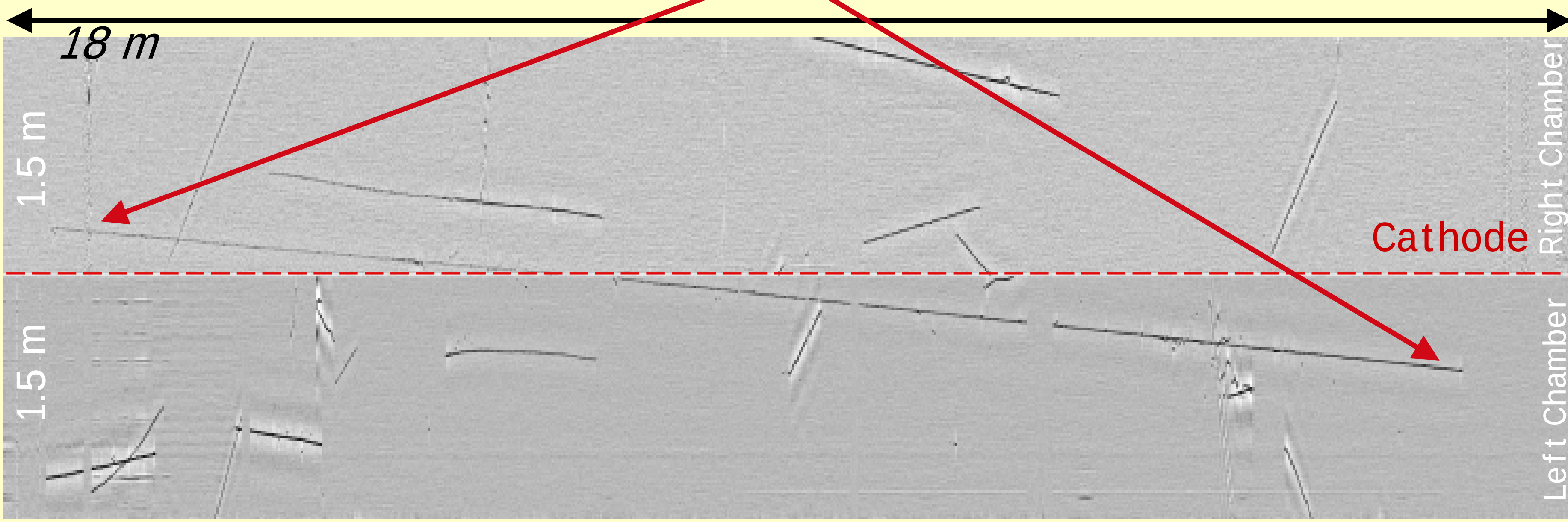
  results of the same quantitative quality as those obtained with small prototypes (e.g. 3 ton, 50 liter, …) are achieved with a 300 ton device.

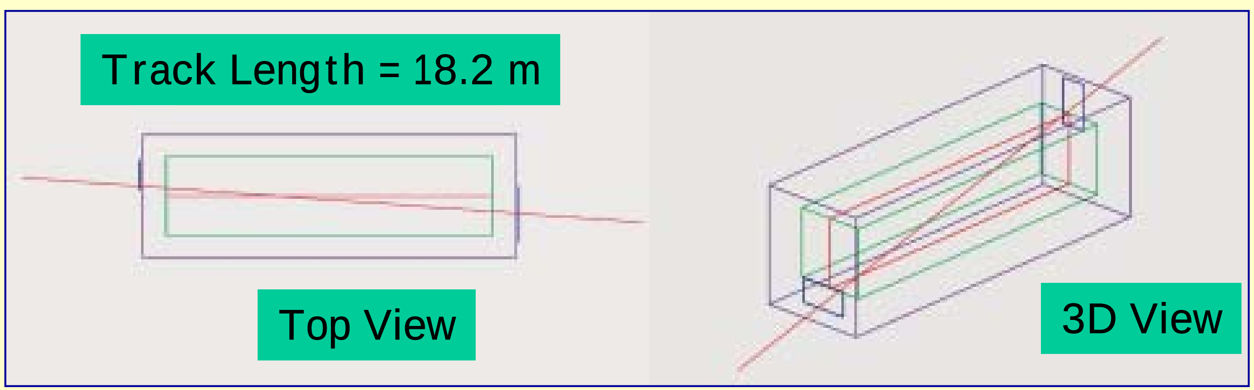
scaling up is successful

Answering the SPSC request: the 18 meter long track…

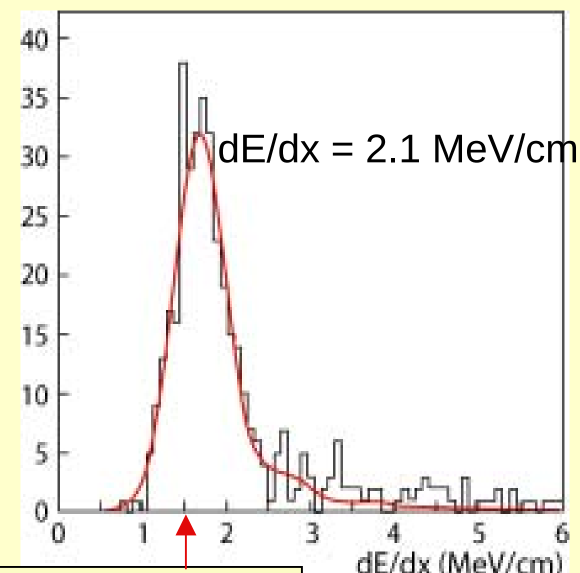
"The Committee congratulates (…) progress (…) in the construction of the T600 module and awaits recording of long tracks in this module.", SPSC September 2000

Longitudinal muon track crossing the cathode plane





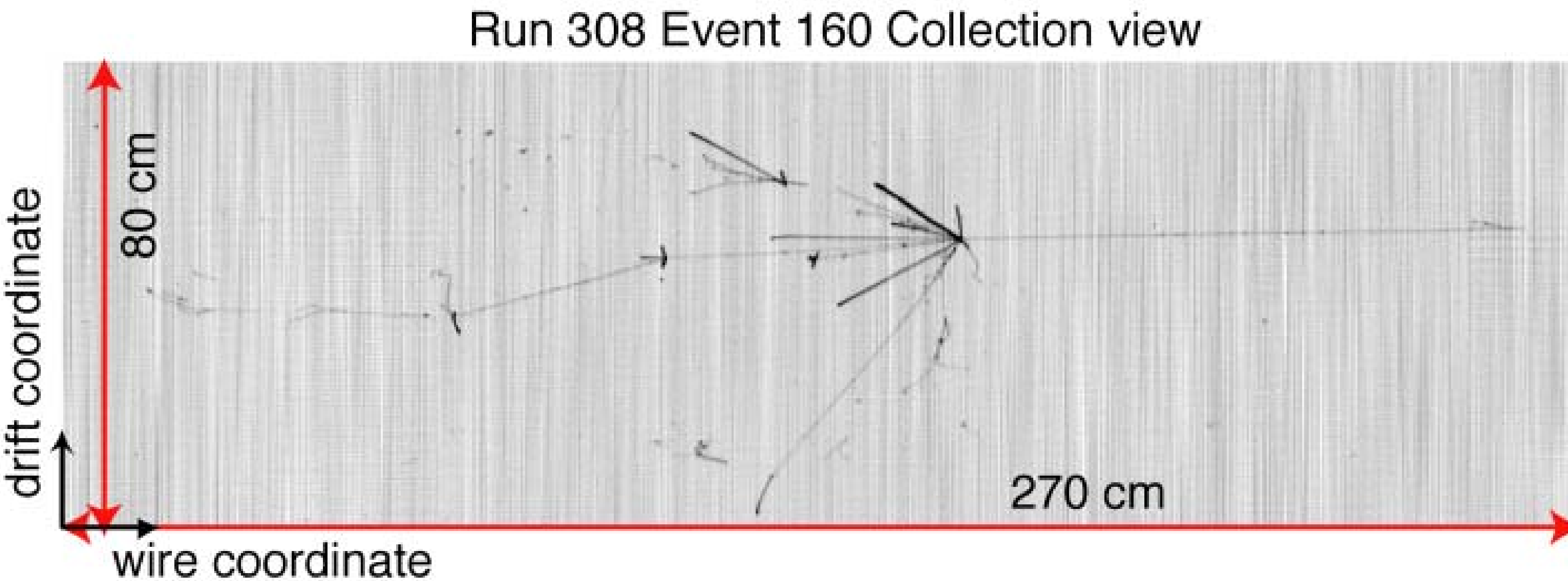
3-D reconstruction of the long track



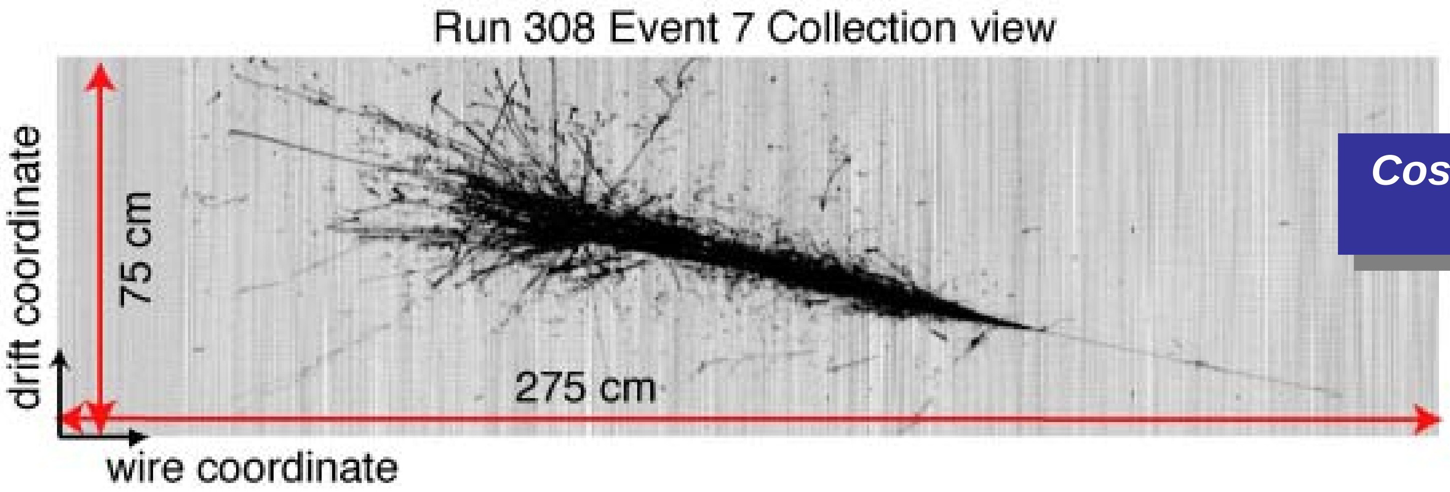
dE/dx distribution along the track

Examples of events: “electronic” bubble chamber (I)

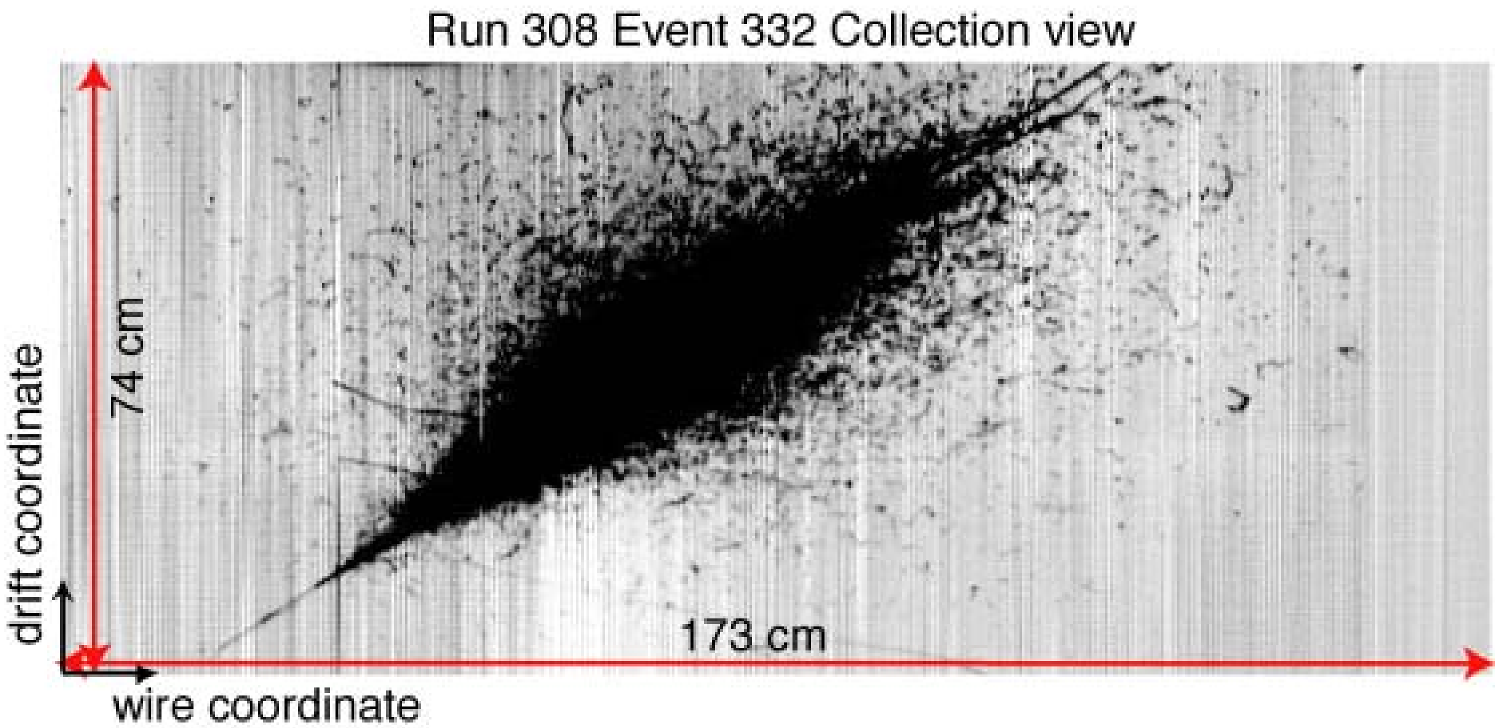
Hadronic interaction
(T600)



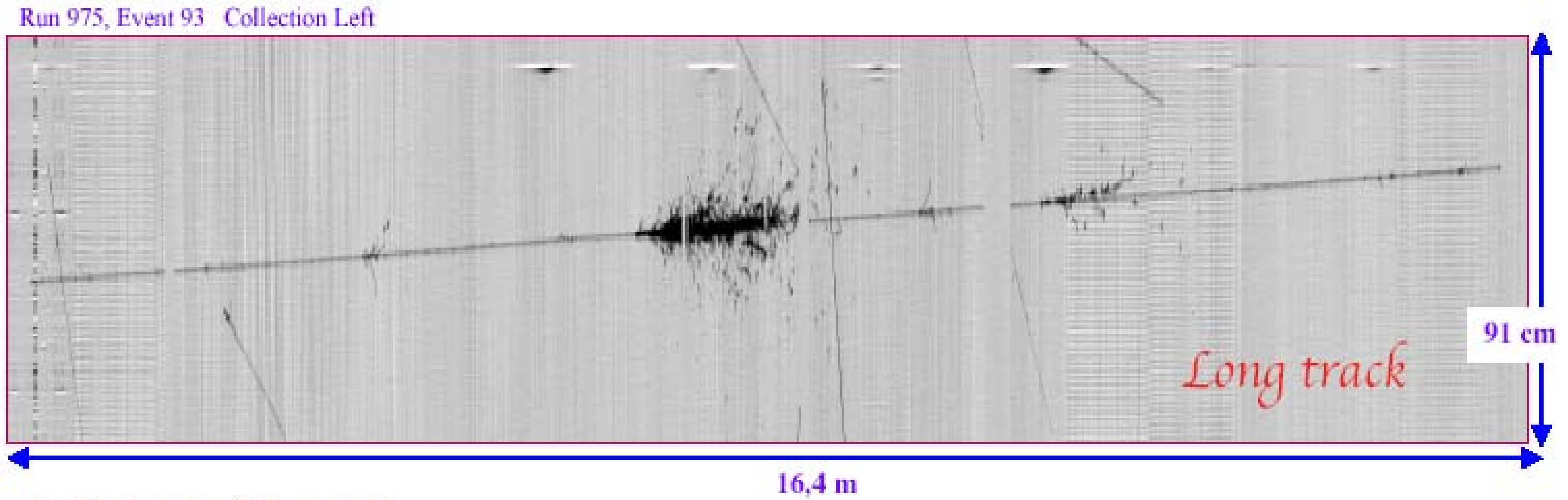
“Electronic” bubble chamber (II)

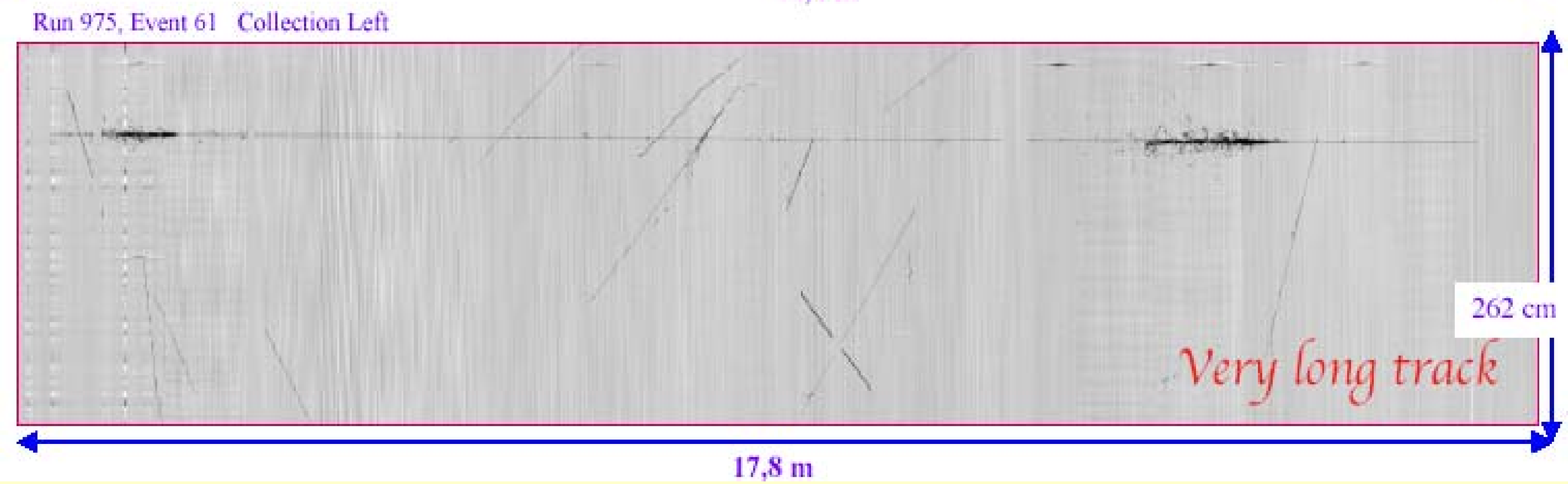


Cosmic ray showers (T600)



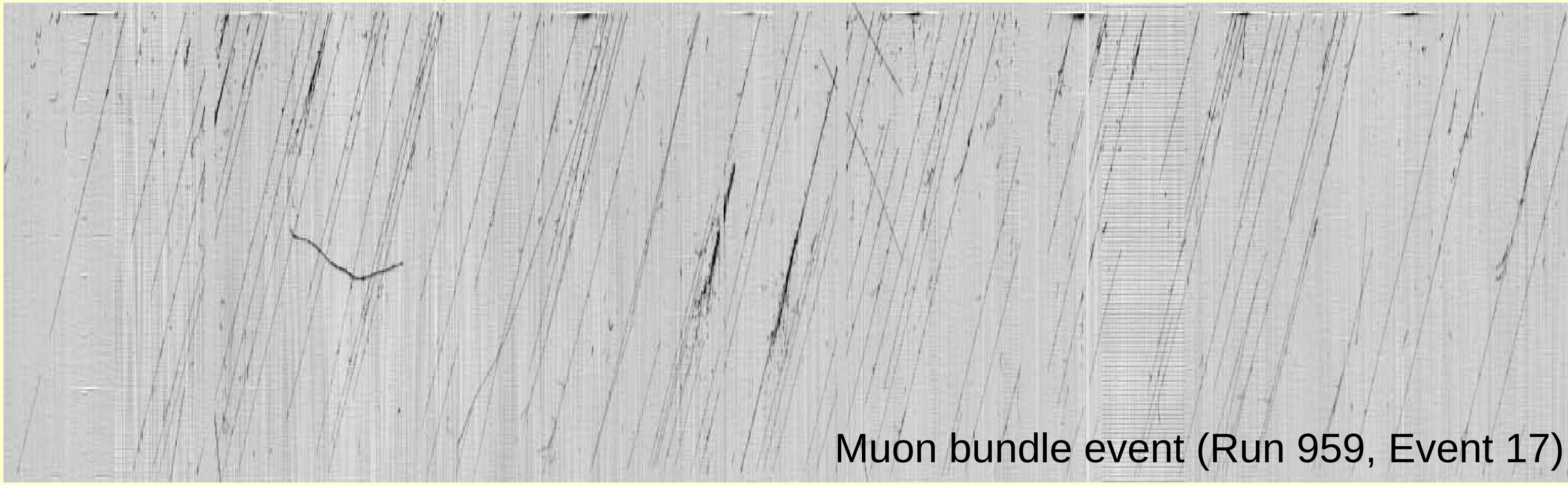
“Electronic” bubble chamber (III)



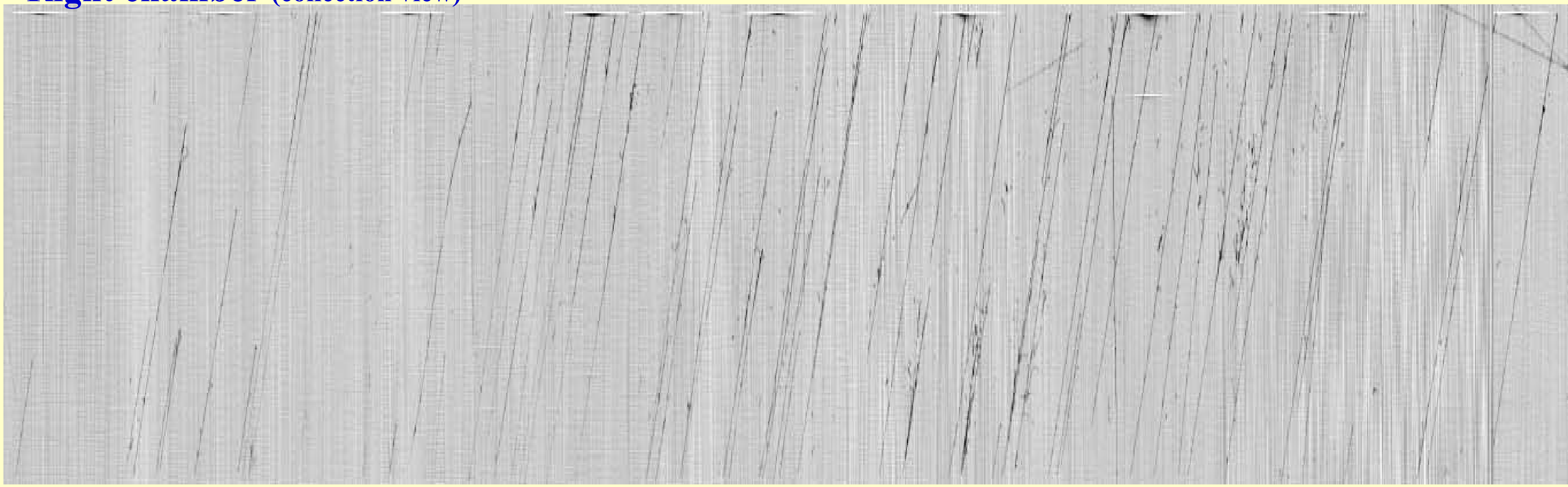


"Electronic" bubble chamber (IV)

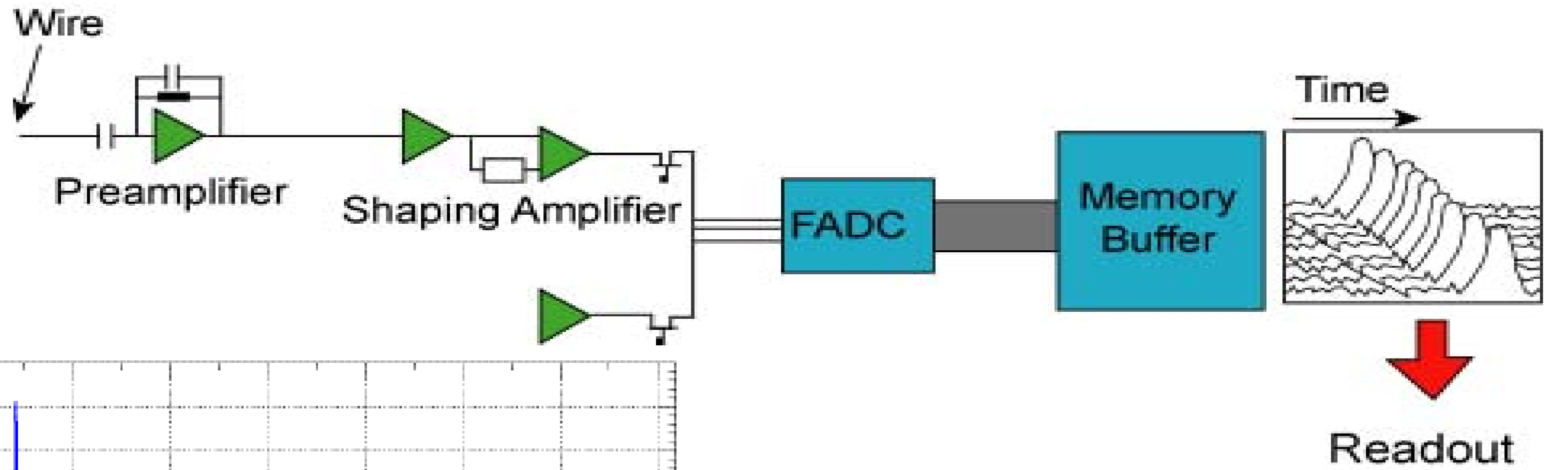
Left chamber **(collection view)**

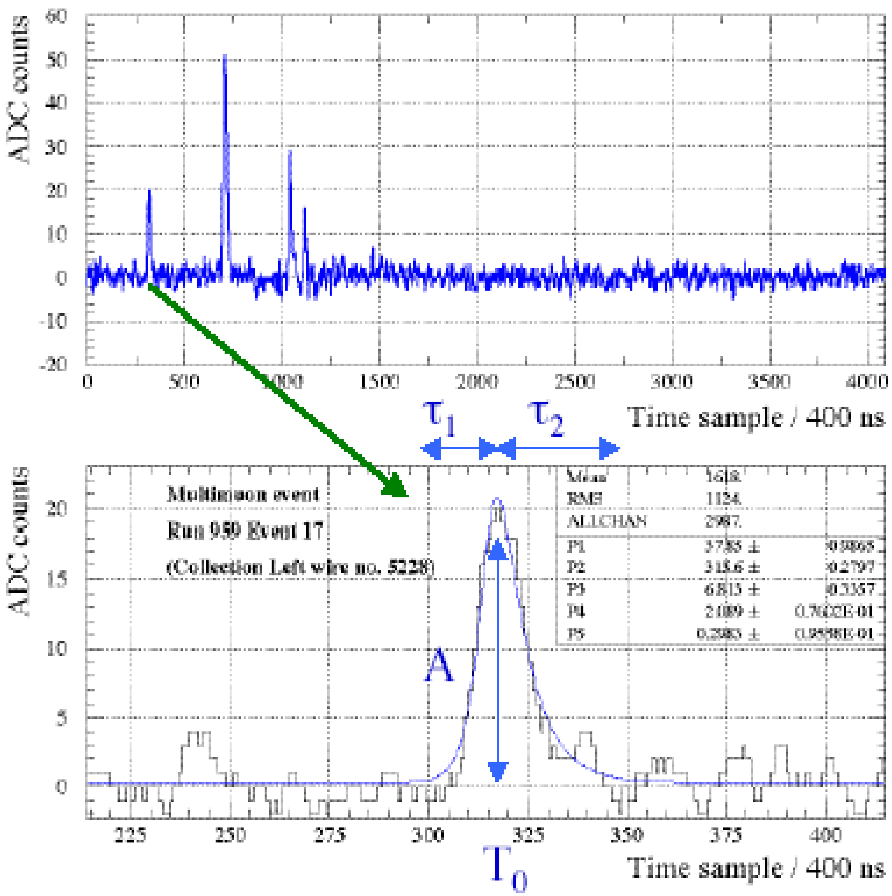


Right chamber **(collection view)**



Signal extraction procedure





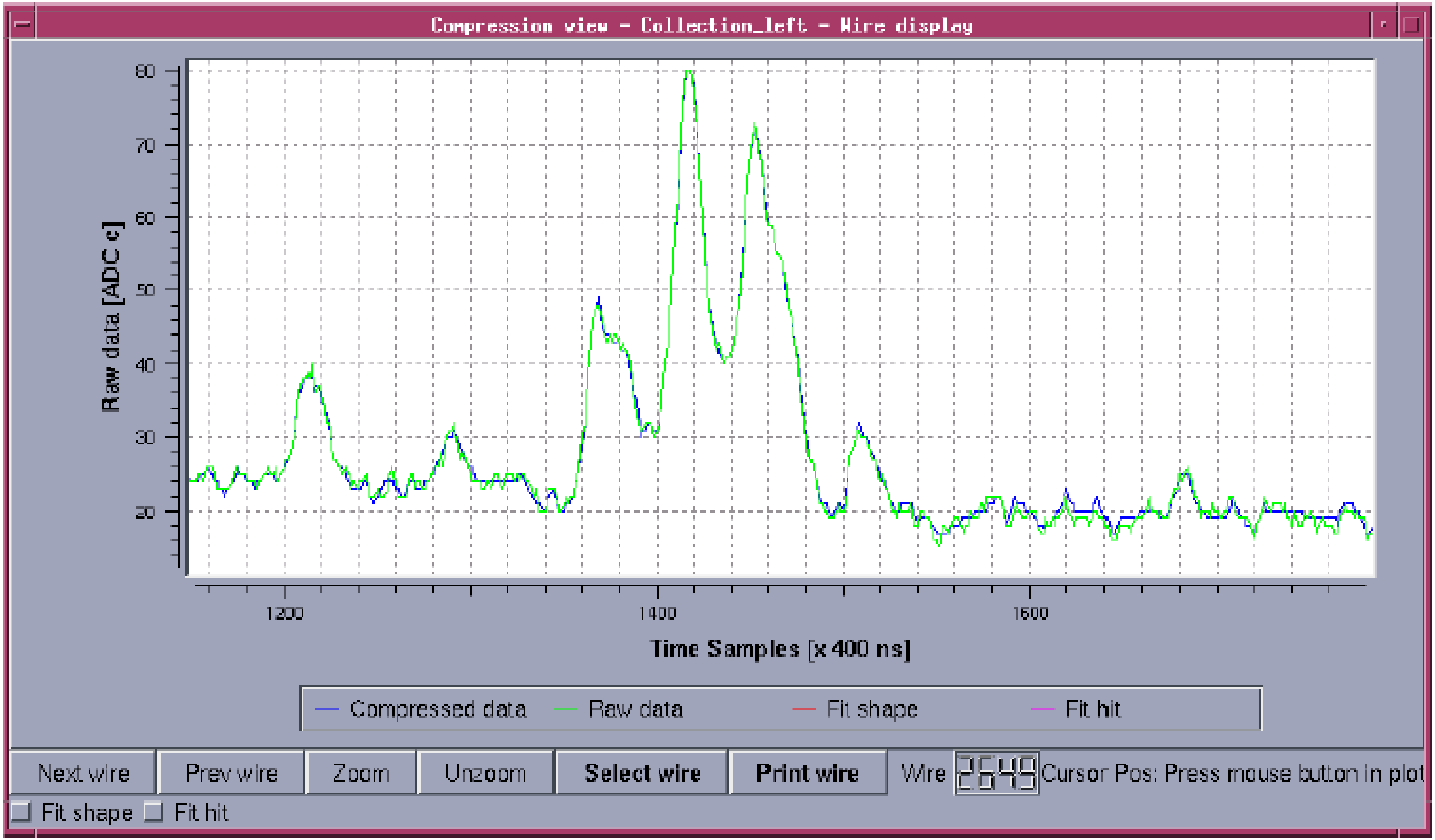
Collection plane wire: charge = signal area

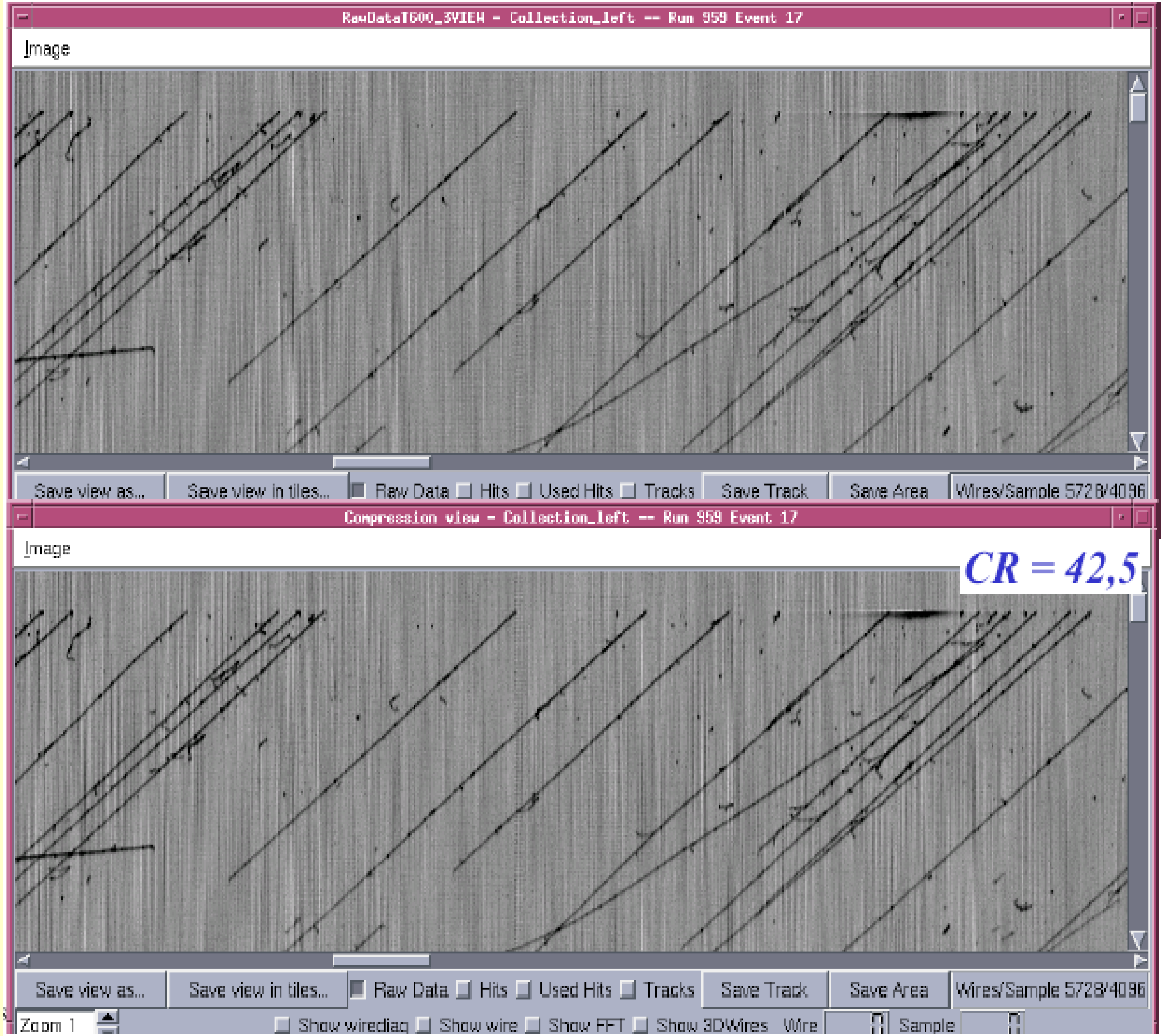
$$f(t) = B + A\,\frac{e^{-\frac{t-T_0}{\tau_2}}}{1 + e^{-\frac{t-T_0}{\tau_1}}}$$

B = baseline, A = amplitude

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

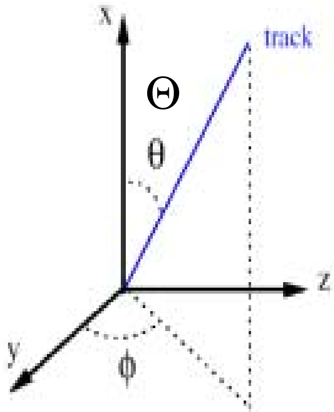
Compression with de-noising: CR =21.4




RawDataT600_3VIEW - Collection_left -- Run 959 Event 17
Image
Save view as...
Save view in tiles...
Raw Data
Hits
Used Hits
Tracks
Save Track
Save Area
Wires/Sample 5728/4096
Compression view - Collection_left -- Run 959 Event 17
Image
CR = 42,5
Save view as...
Save view in tiles...
Raw Data
Hits
Used Hits
Tracks
Save Track
Save Area
Wires/Sample 5728/4096
Zoom 1
Show wirediag
Show wire
Show FFT
Show 3DWires
Wire
Sample

3D reconstruction

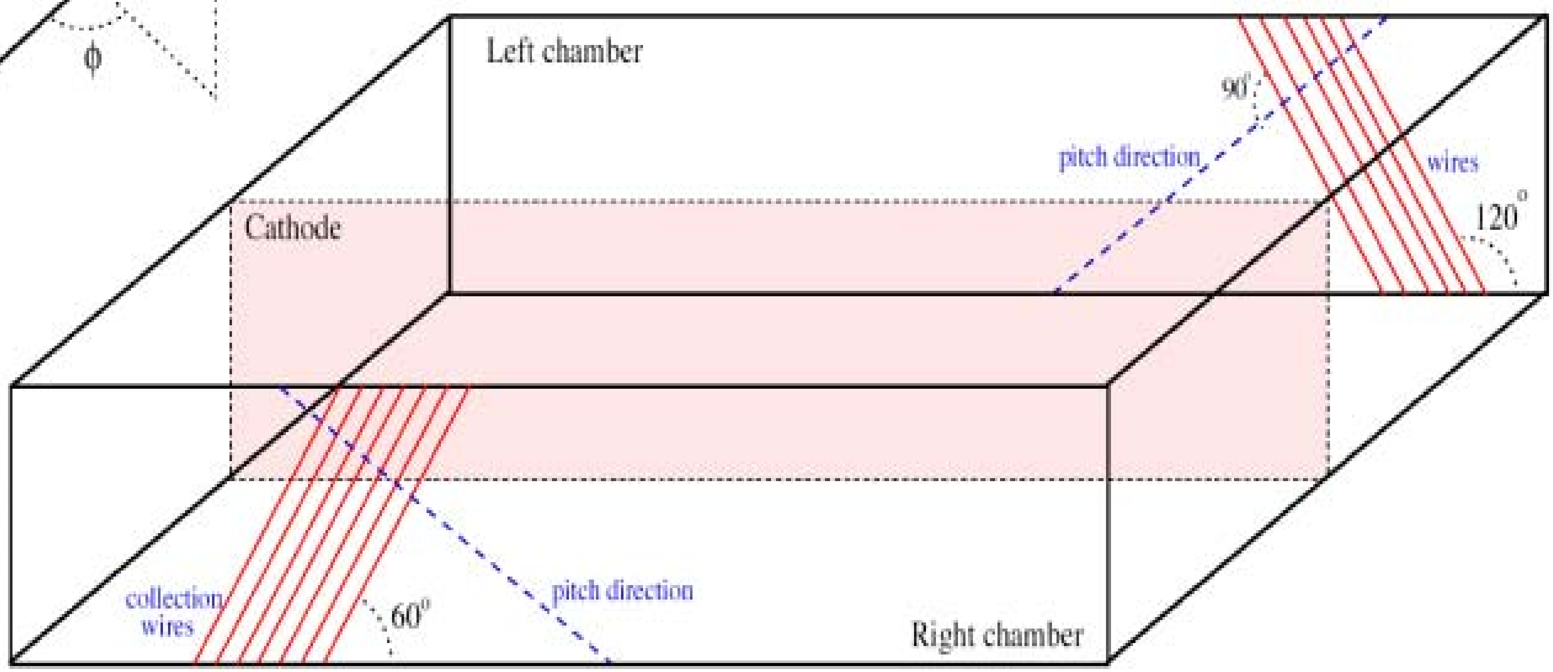
- 3D reconstruction: drift time coordinate (y-coordinate) shared among all three views.
- Matching between the views is redundantly done at the “hit”-level



$$
\begin{aligned}
x_{1,2} &= \frac{p}{2\cos\theta}(w_1 - w_2 + w_0) \\
x_3 &= p\,w_3 \\
y &= \frac{s\,v}{f}
\end{aligned}
$$

$$
\begin{aligned}
z_{1,2} &= \frac{p}{2\sin\theta}(w_1 + w_2 - w_0) \\
z_{2,3} &= \frac{p}{\tan\theta}\left(w_3 + \frac{w_2 - w_0}{\cos\theta}\right) \\
z_{1,3} &= \frac{p}{\tan\theta}\left(\frac{w_1}{\cos\theta} - w_3\right)
\end{aligned}
$$

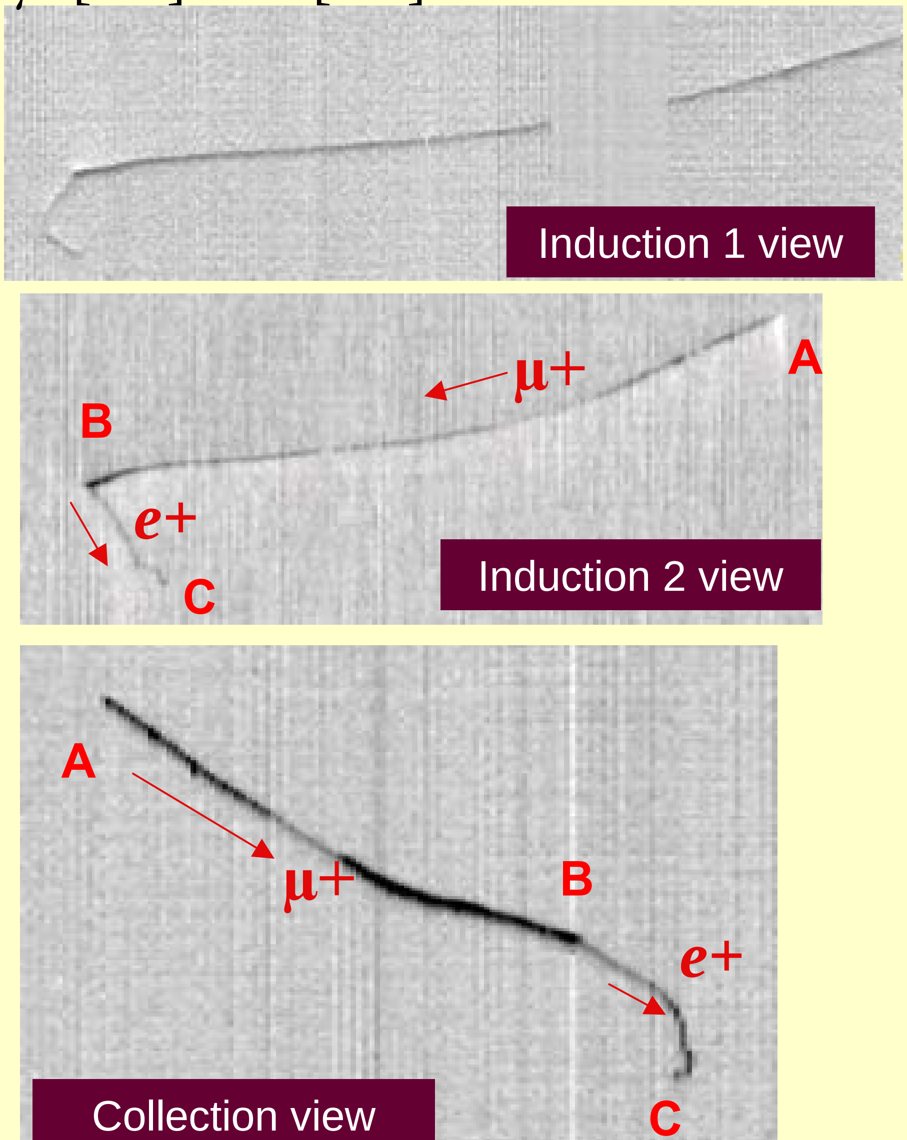
p	= 2.99 mm
θ	= 60º
ω_0	= 528
f	= 2.5 MHz



Stopping muon reconstruction example

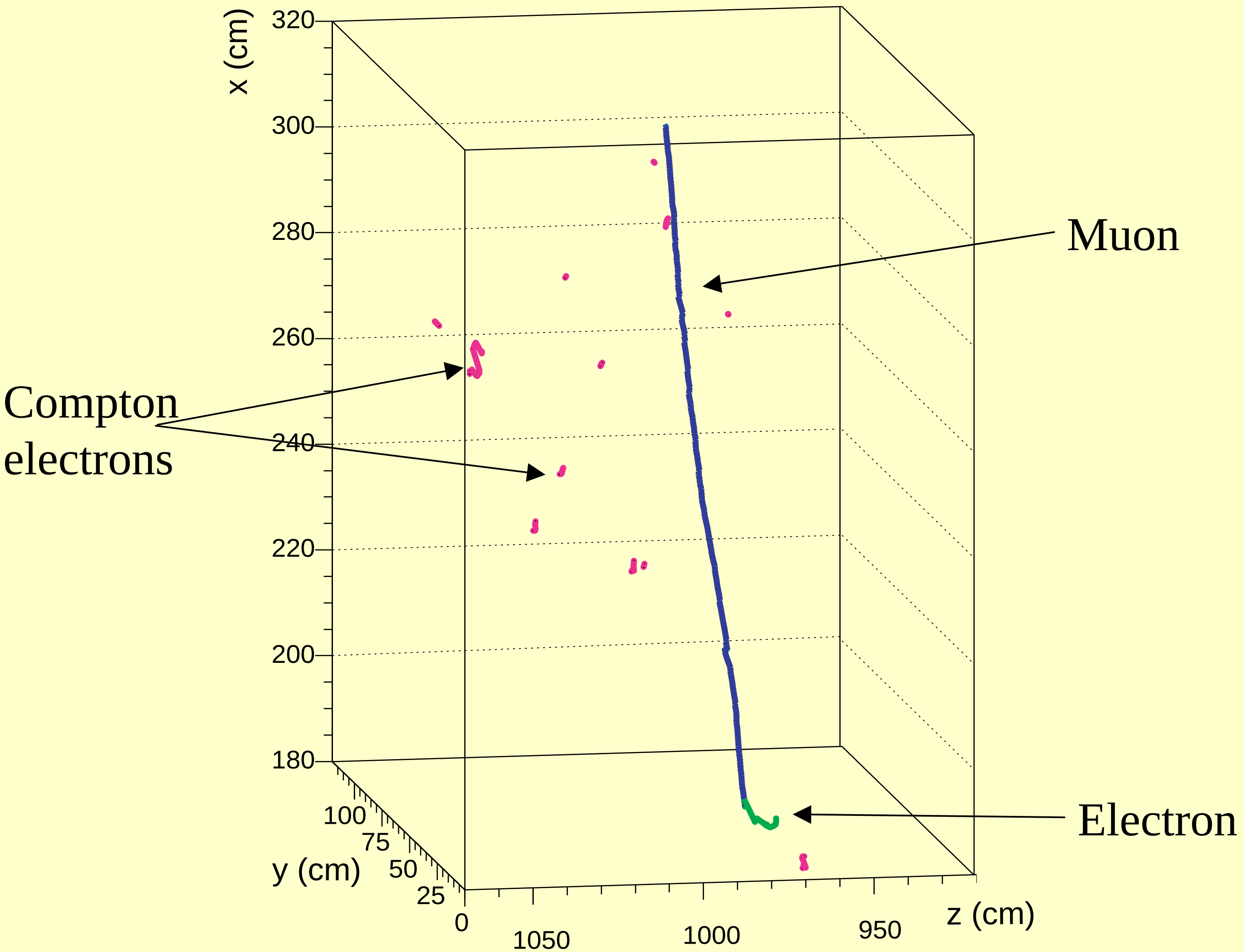
$$\mu^{+}[AB] \rightarrow e^{+}[BC]$$

Run 939 Event 95 Right chamber

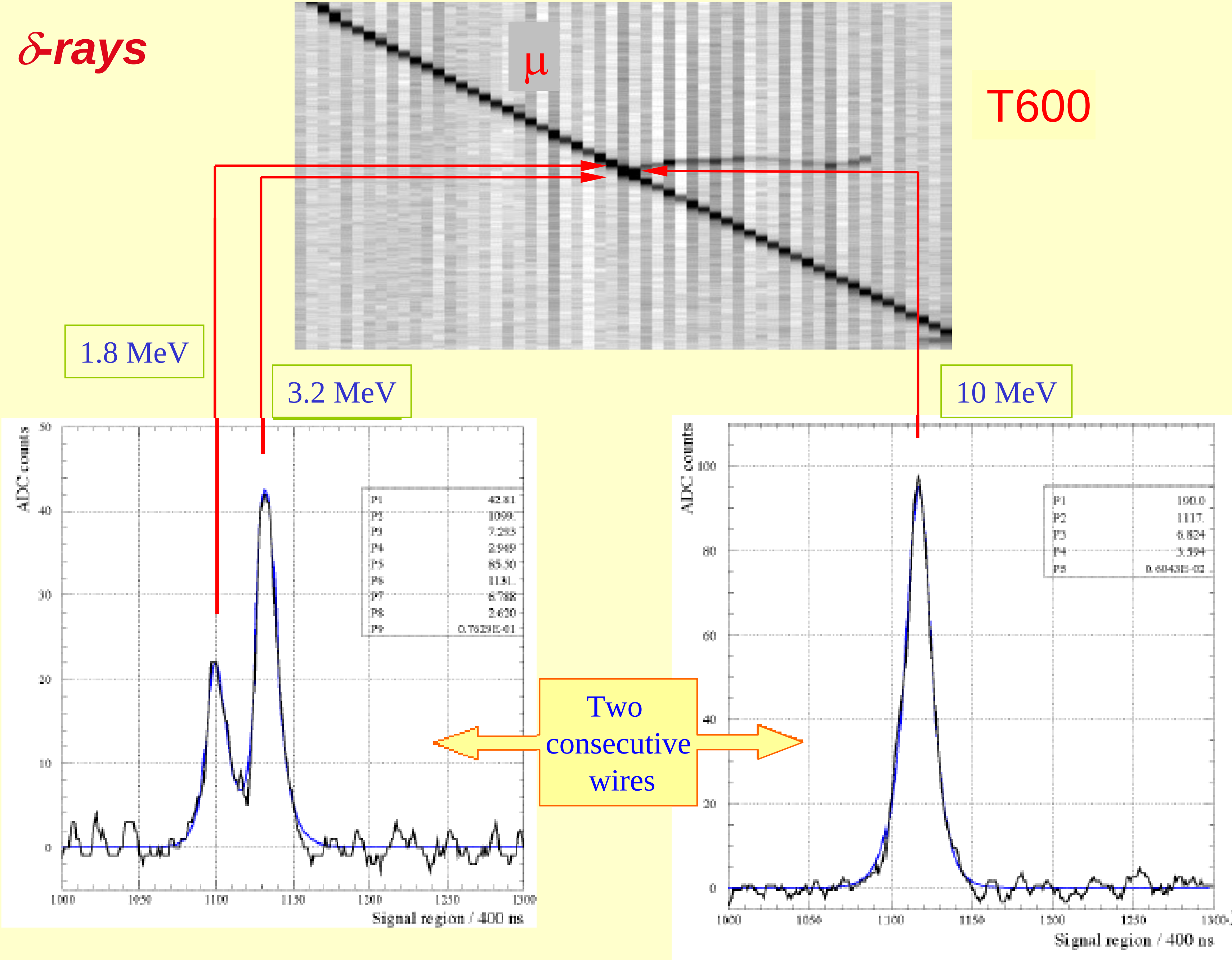


T_e=36.2 MeV
Range=15.4 cm

Stopping muon automatic 3D reconstruction

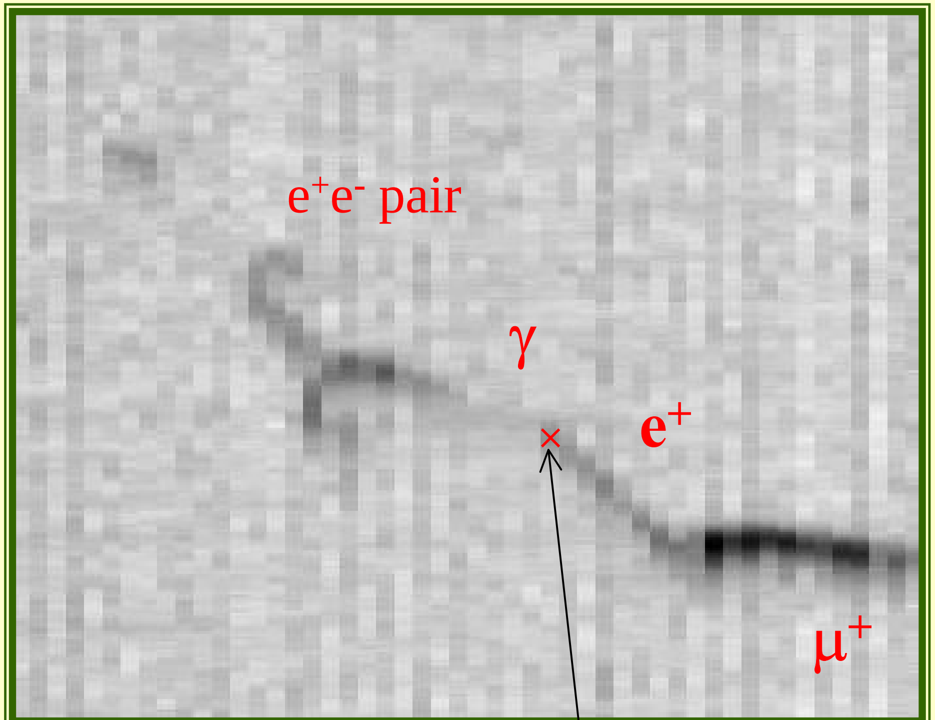


δ-rays


μ
T600
1.8 MeV
3.2 MeV
10 MeV
Two consecutive wires
ADC counts
P1 42.81
P2 1099.
P3 7.283
P4 2.969
P5 85.50
P6 1131.
P7 6.788
P8 2.620
P9 0.7829E-01
Signal region / 400 ns
ADC counts
P1 190.0
P2 1117.
P3 6.824
P4 3.594
P5 0.6043E-02
Signal region / 400 ns

In-flight annihilation of positron

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



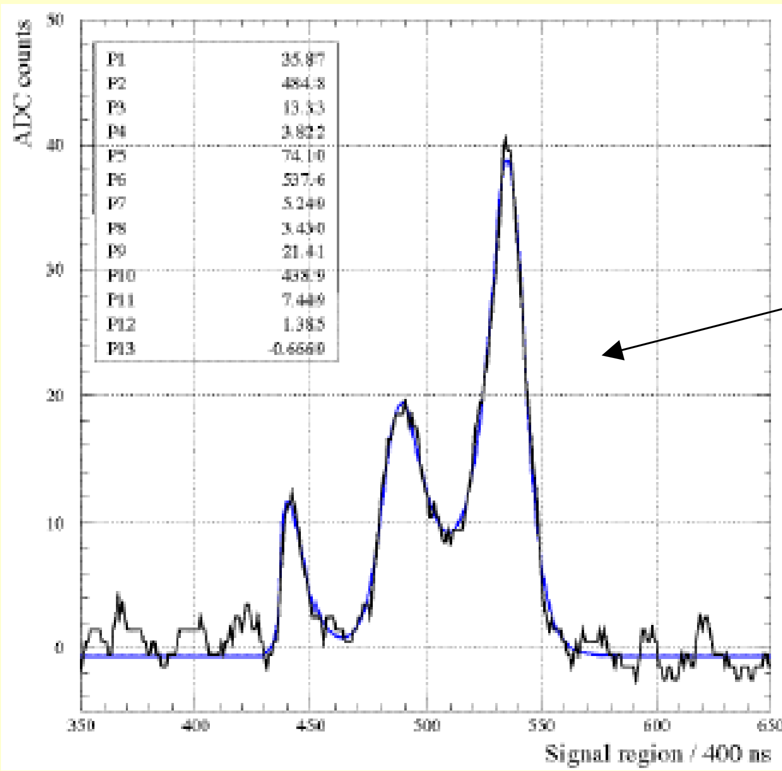
Collection view

Annihilation point

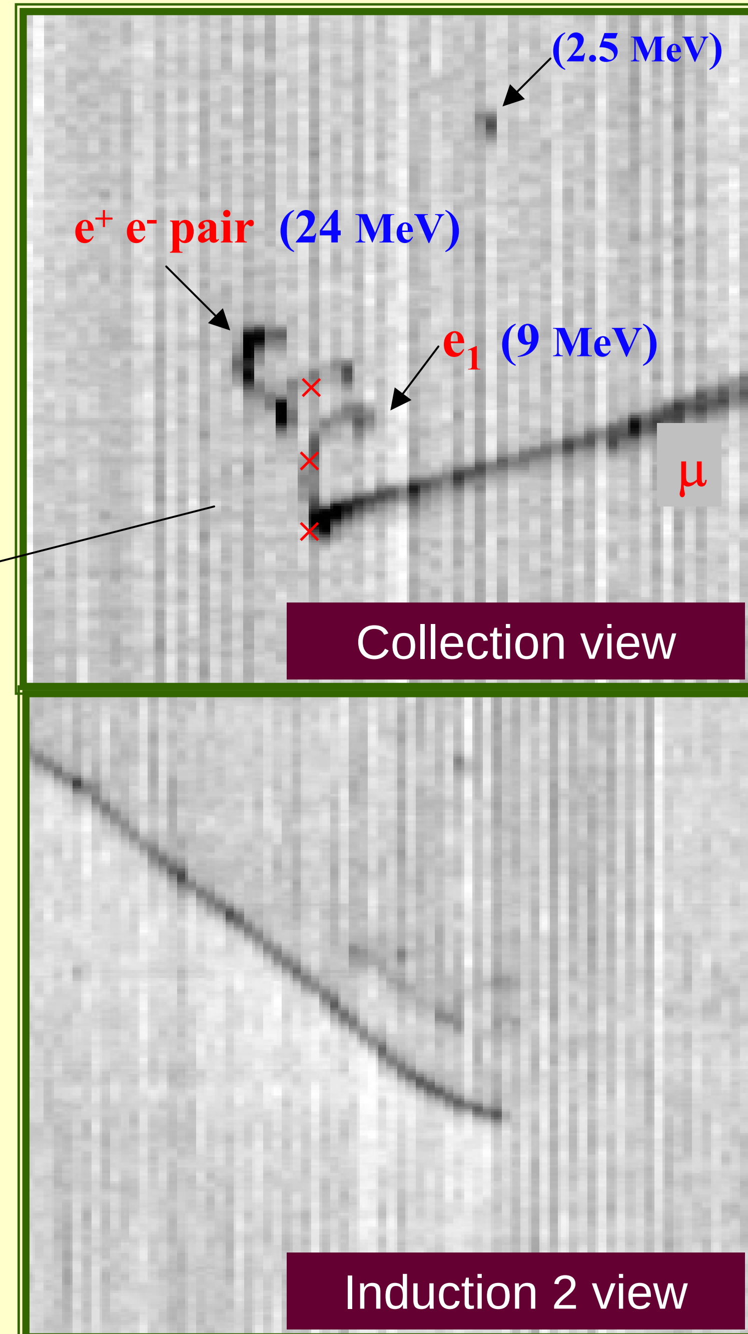
Induction 2 view

Bremsstrahlung + pair-production

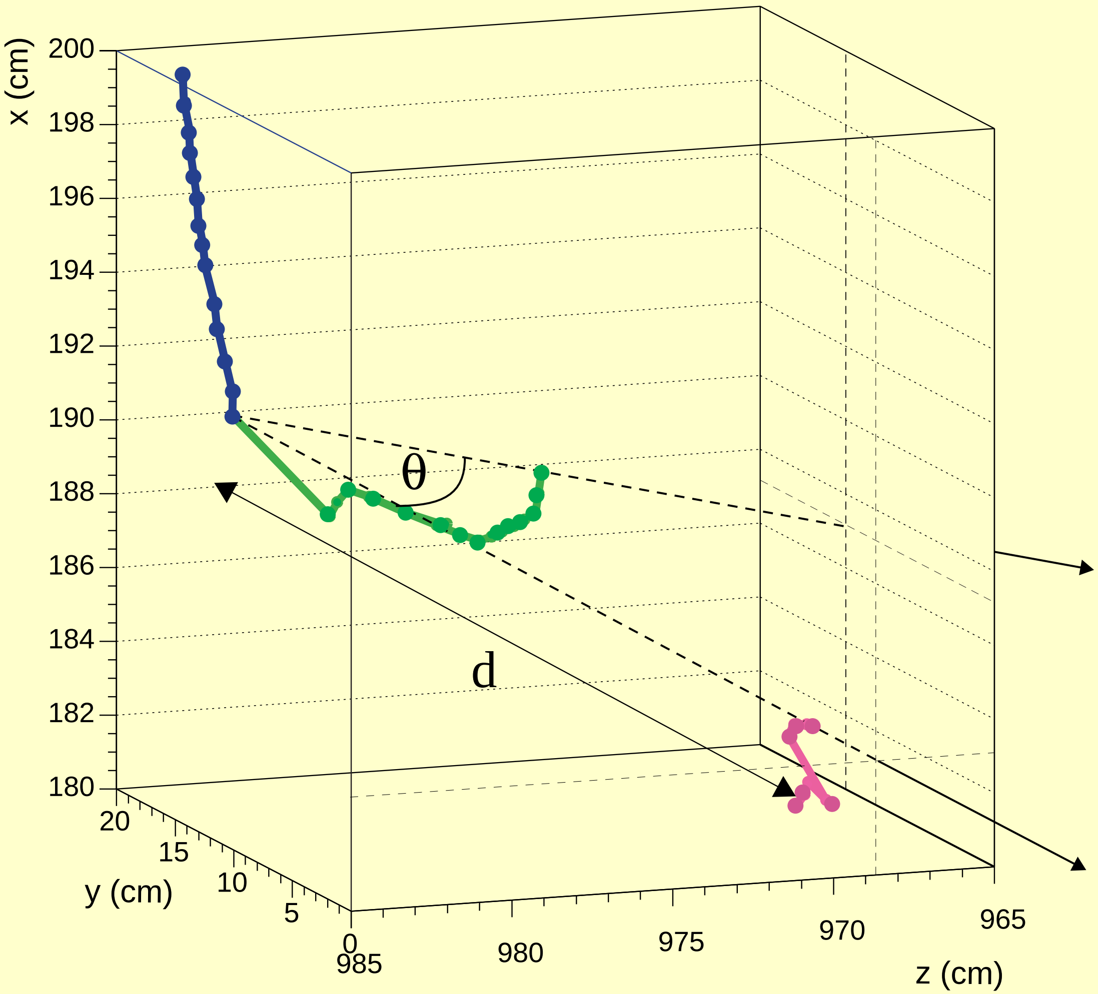
Run 975, Event 163



Fitted signal shapes on single wire



Bremsstrahlung track selection

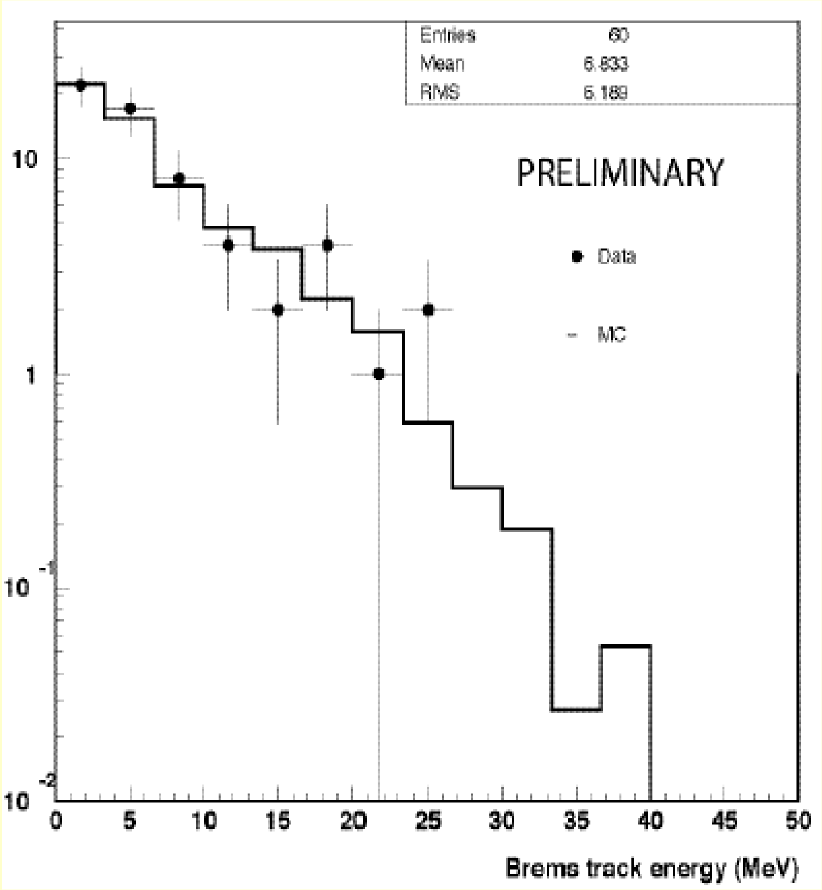


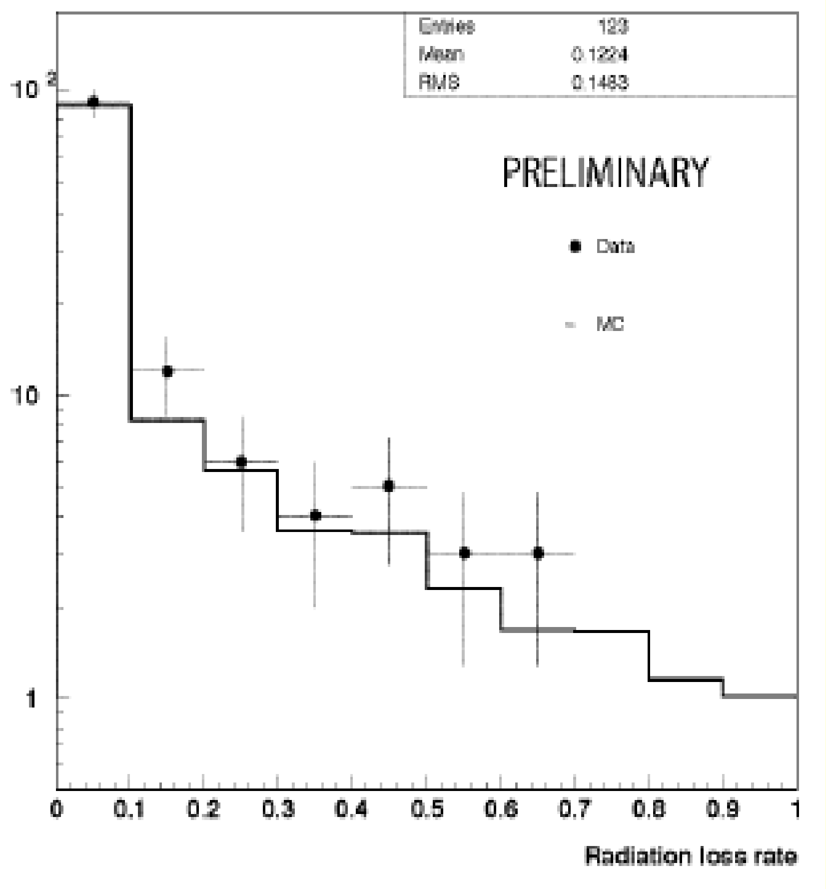
Rejection of noise and out of time tracks:

$\theta < 40^{o}$

$d < 60$ cm

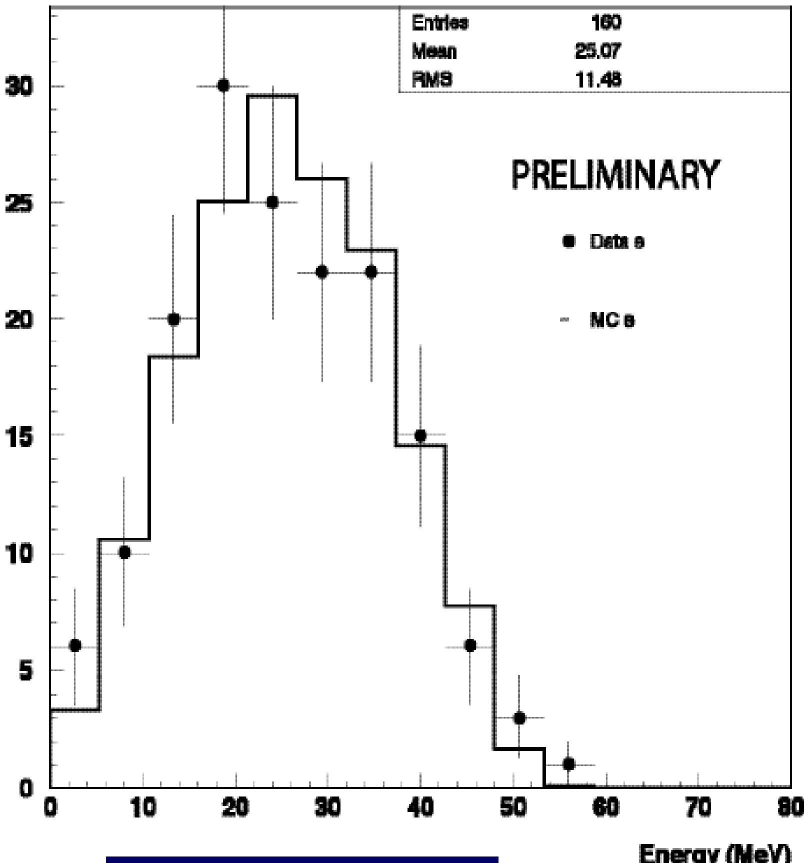
Reconstruction Bremsstrahlung photons (T600)



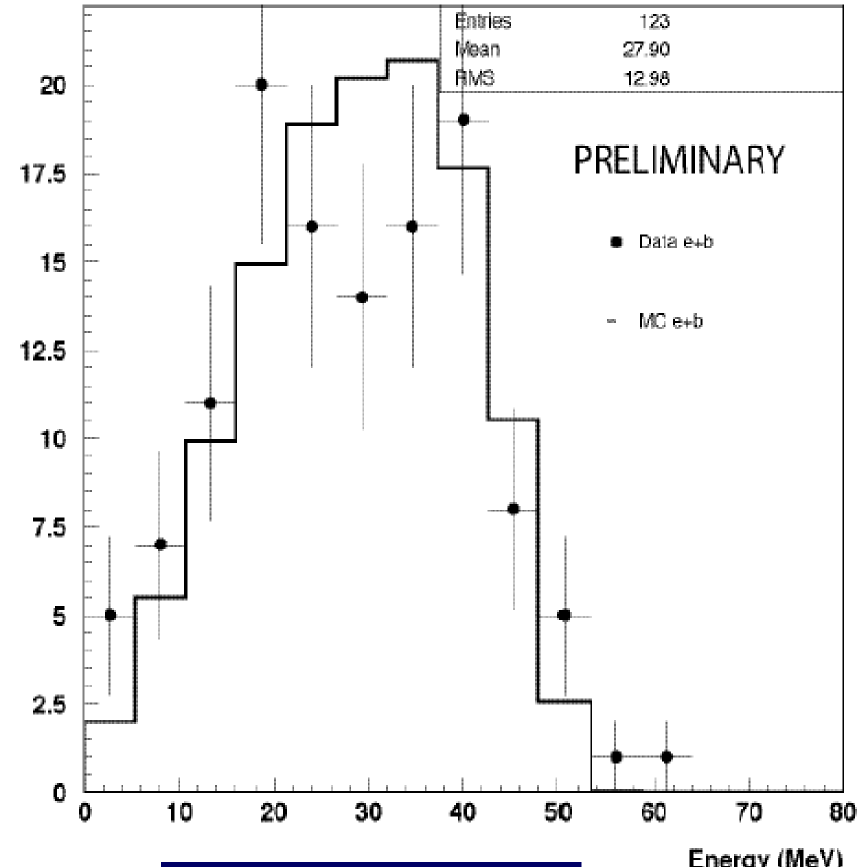


Good agreement between data and MC

Calorimetric reconstruction Michel electrons (T600)



no bremsstrahlung



with bremsstrahlung

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

π_0 candidate (preliminary)

Run 975, Event 151

Reconstruction of γ-showers

158 MeV

752 MeV

140 MeV

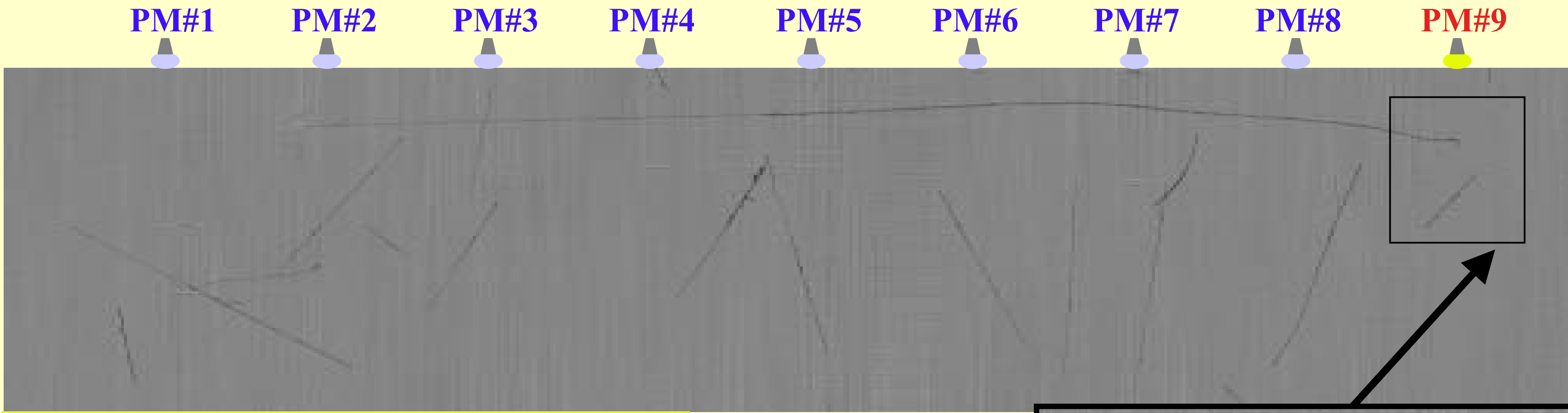
$\theta = 141^o$

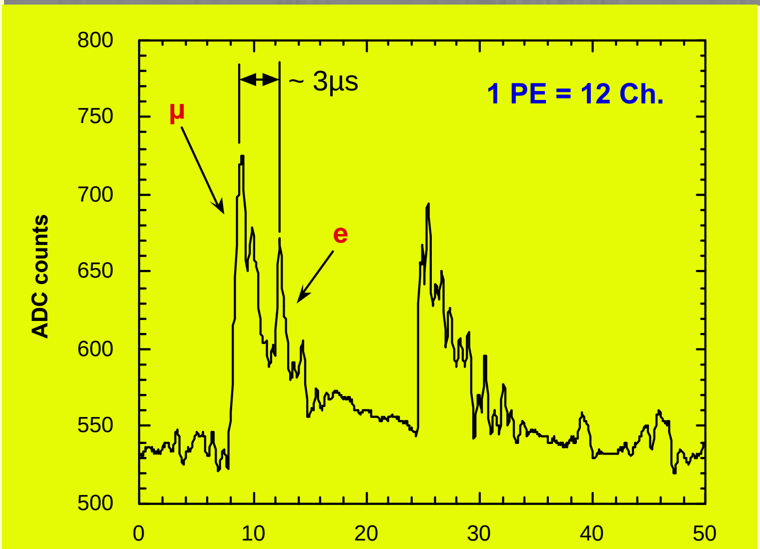
$M_{inv} = 650$ MeV

$\theta = 25^o$

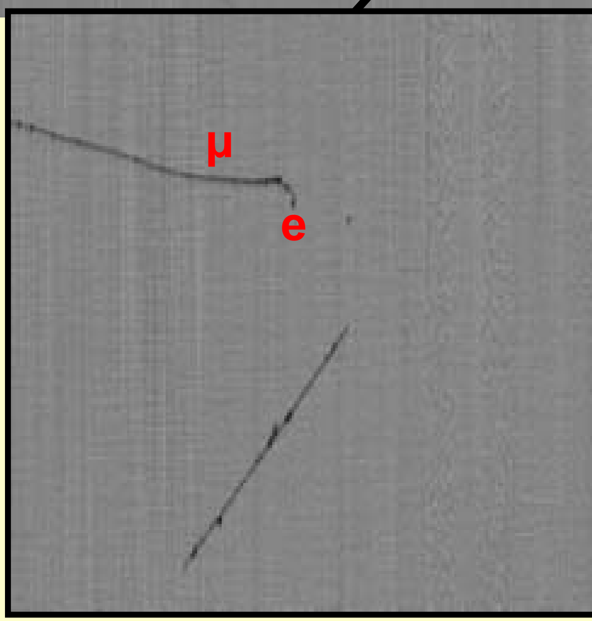
$M_{inv} = 140$ MeV

ICARUS T600: absolute time reconstruction





PM#9 signal



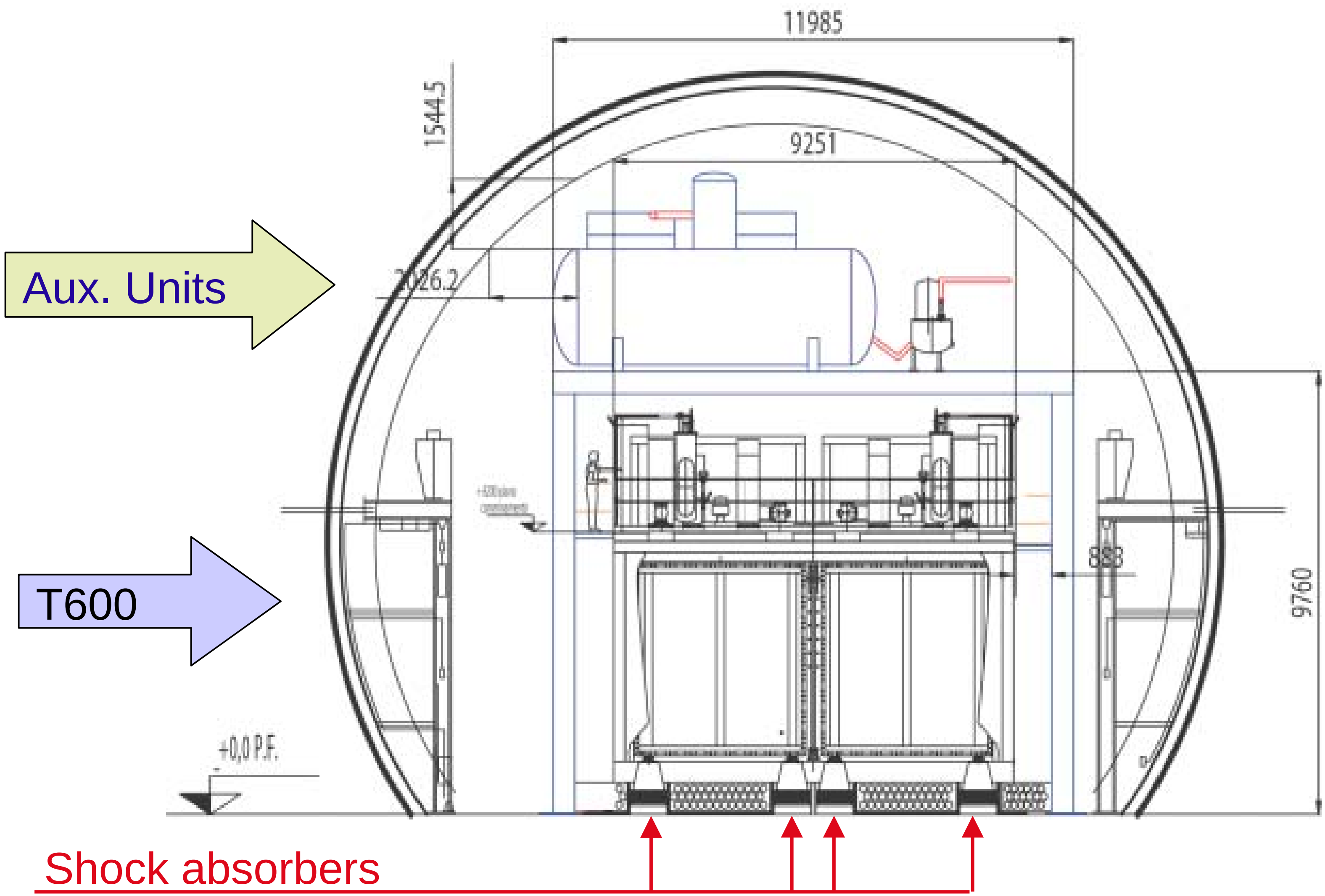
VUV light: 128 nm, 10000 γ/MeV

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

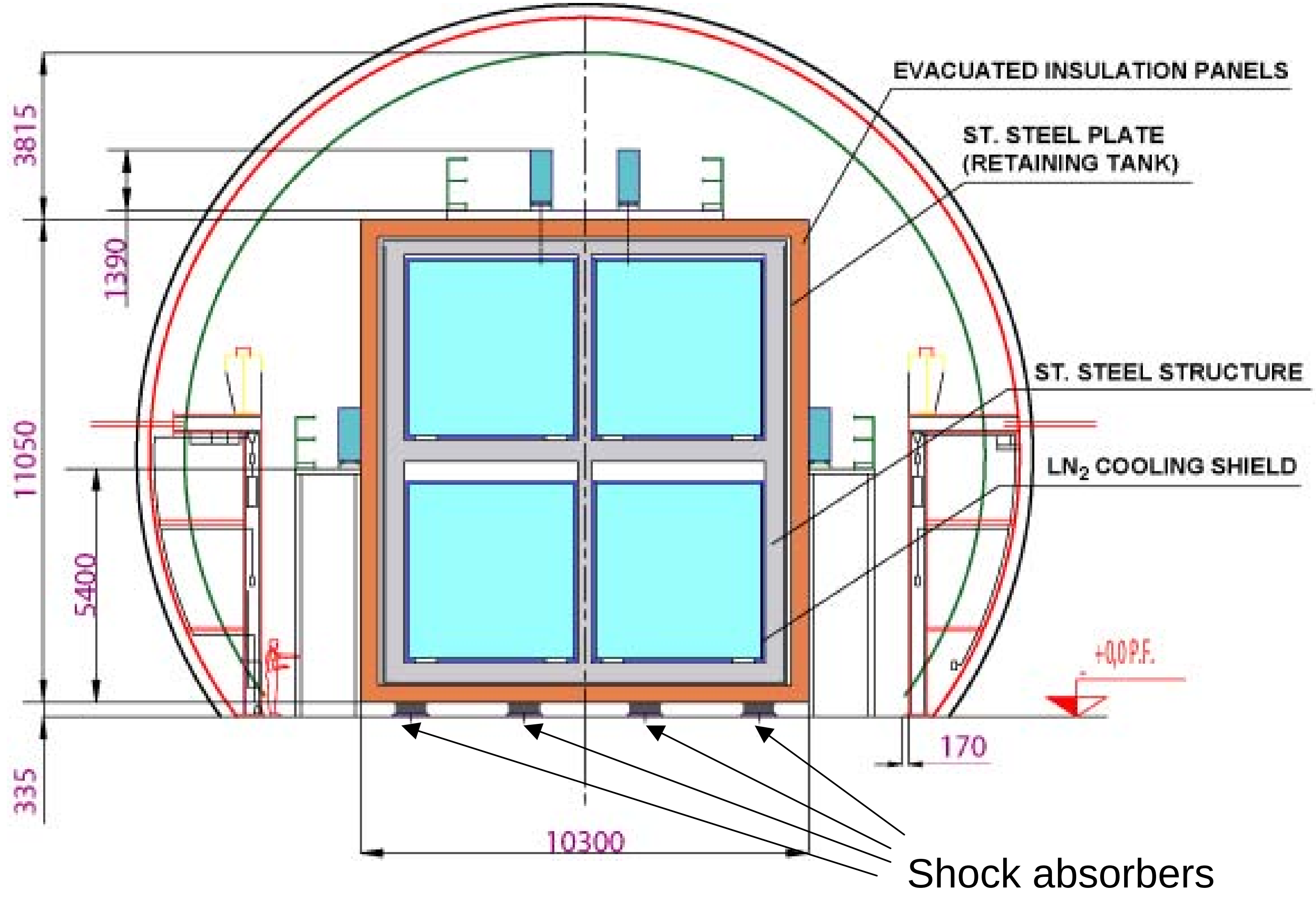
The full detector: T3000

LNGS Hall B

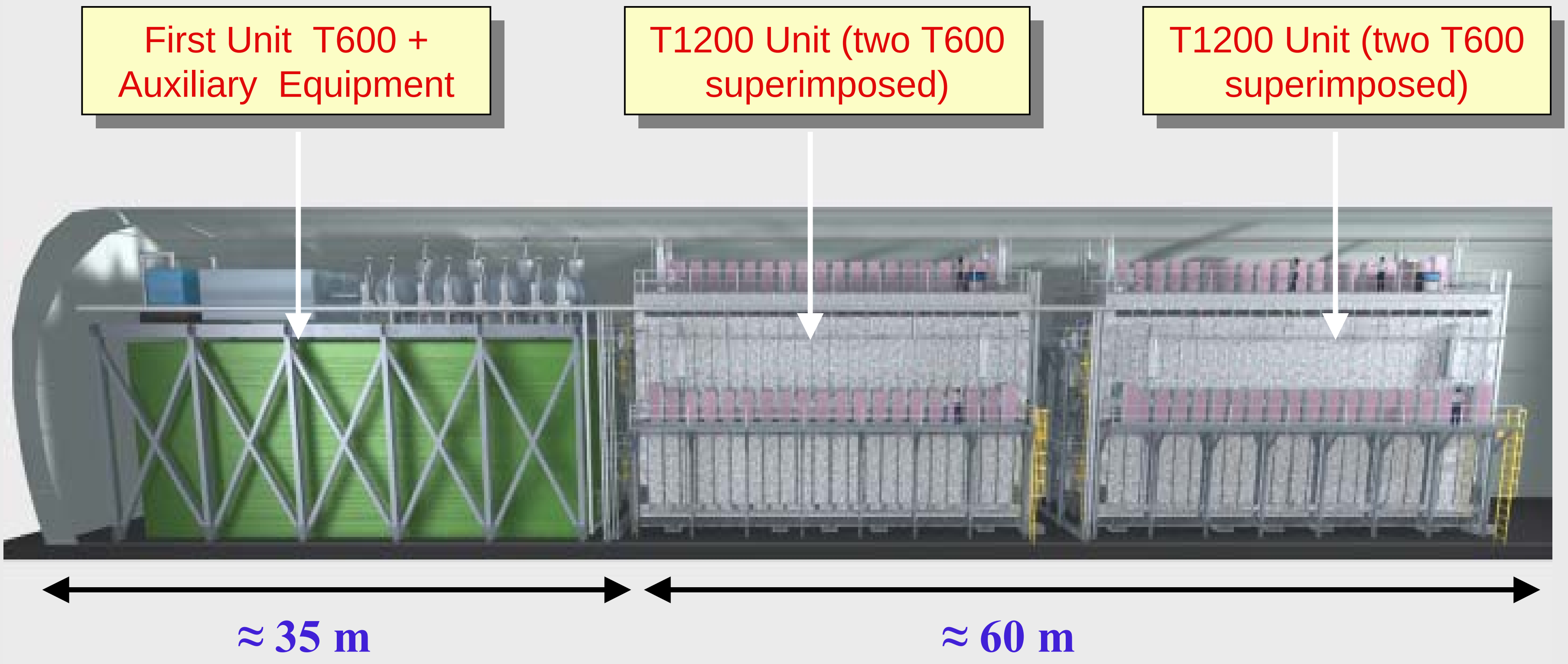
First step: T600 installation at LNGS



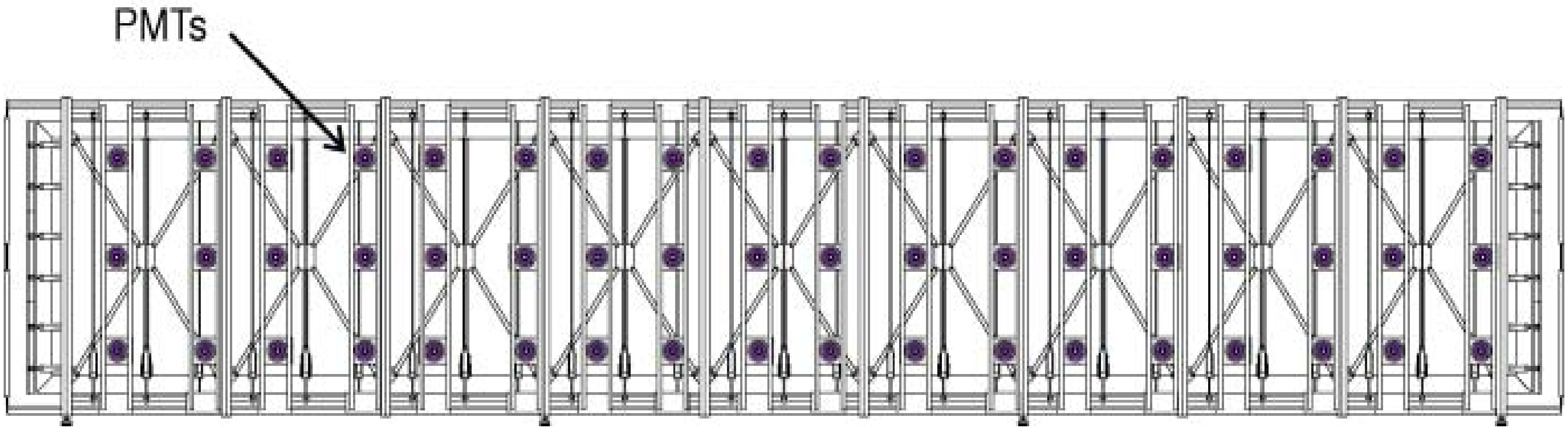
Next: the basic layout of the T1200 unit



ICARUS detector configuration at LNGS Hall B (T3000)

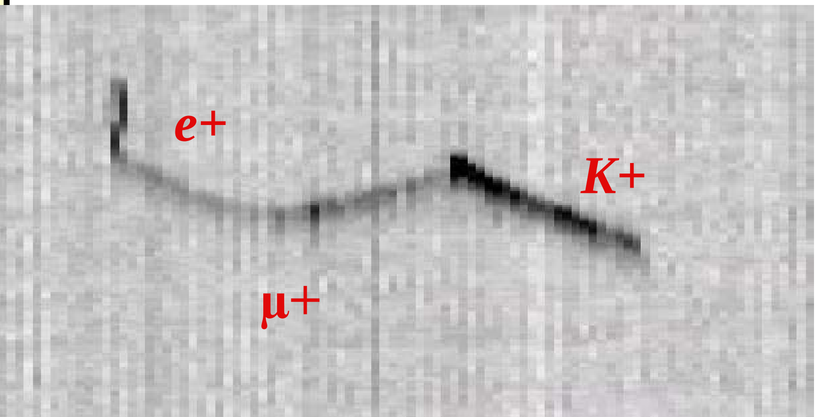


PMTs installation for the T1200

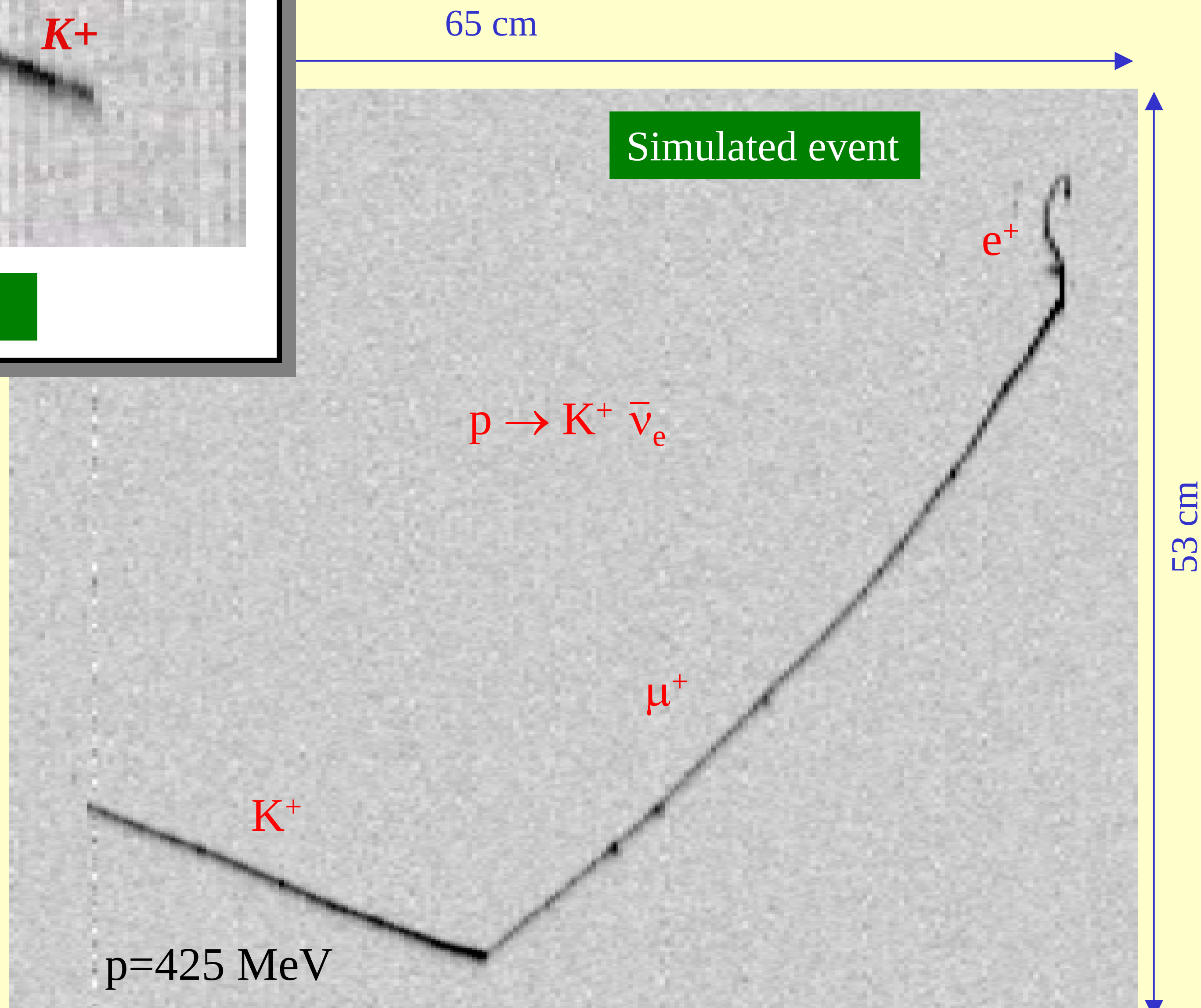


T3000 physics program

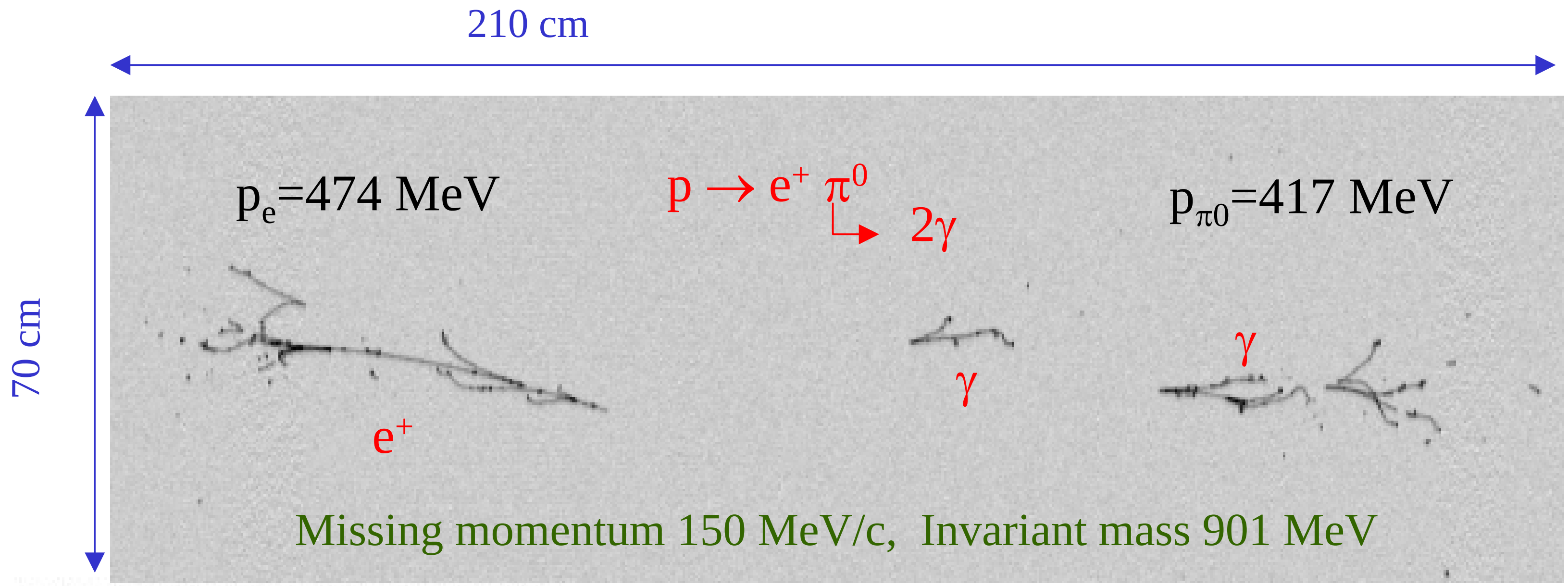
Proton decay in ICARUS (I)

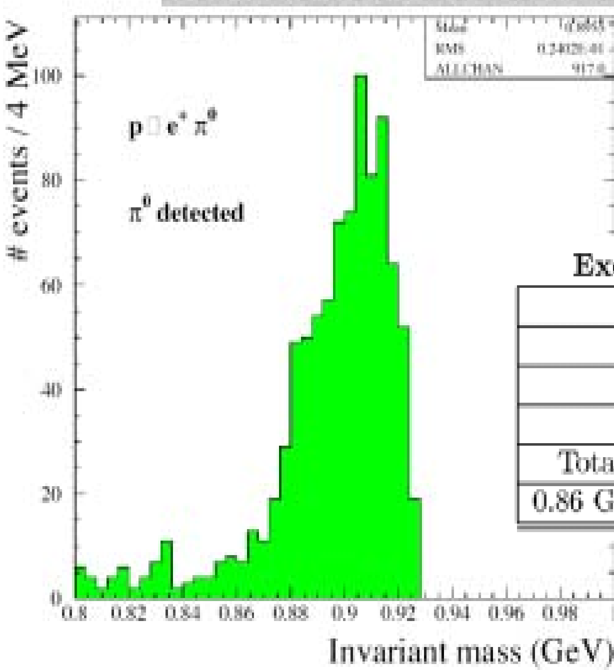


T600: Run 939 Event 46



Proton decay in ICARUS (II)

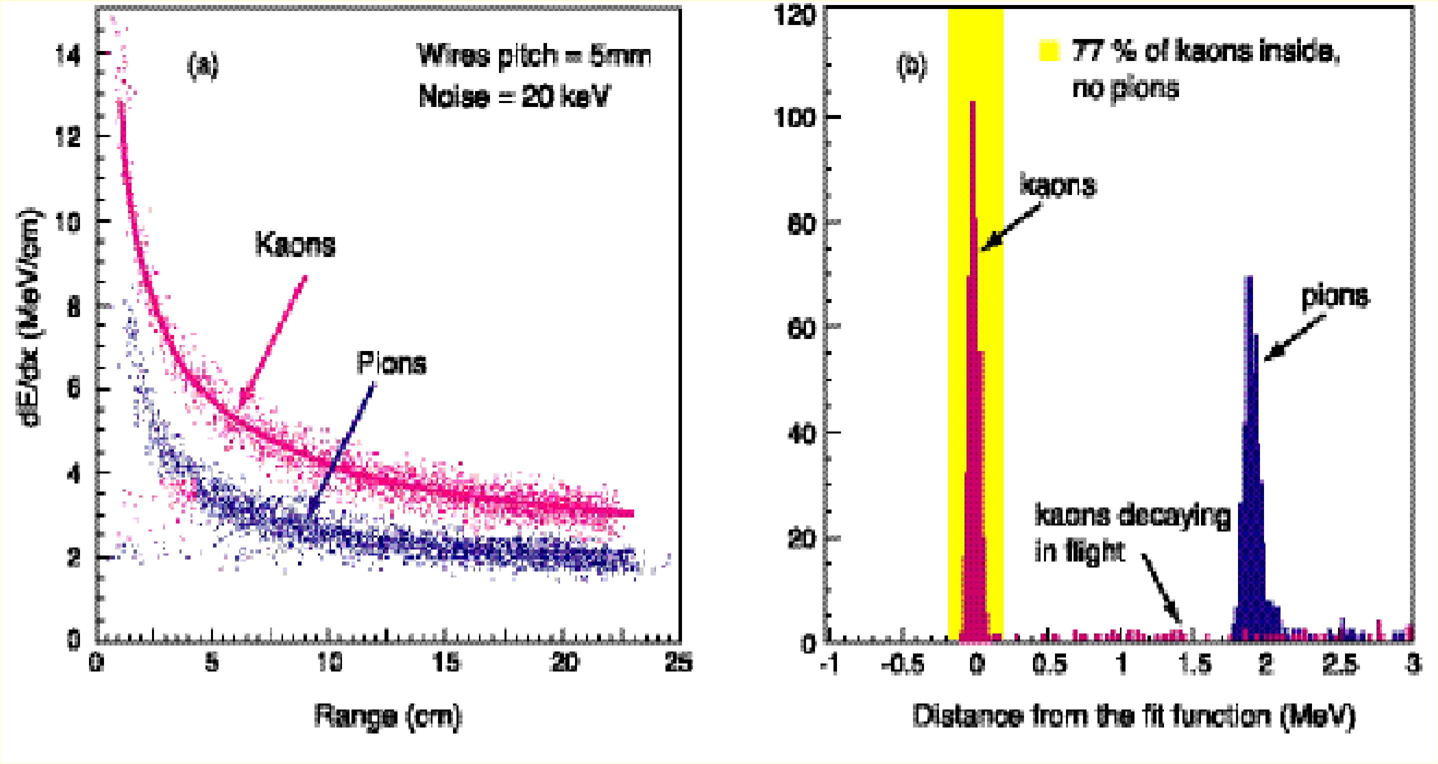




Exclusive Channel Cuts	$p \to e^+ \pi^0$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One π^0	54.00%	6604	2135	15259	5794	8095	3103
One positron	54.00%	6572	2125	20	0	0	0
No charged pions	53.90%	3605	847	5	0	0	0
No protons	50.85%	1188	656	1	0	0	0
Total Momentum < 0.4 GeV	46.70%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

Particle identification (I)

dE/dx in the 3 ton prototype

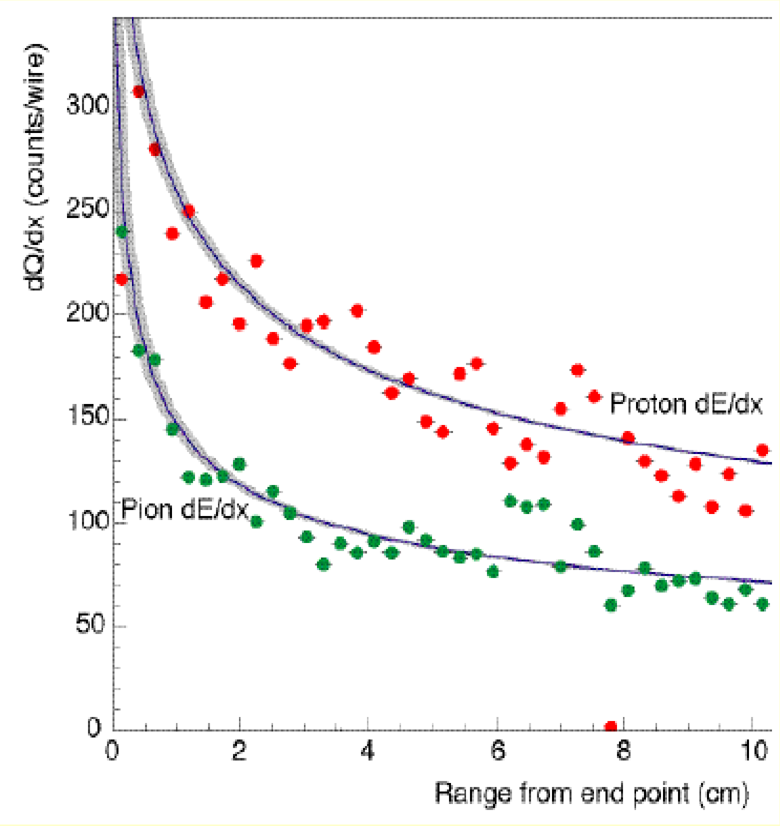


energy loss profile along K and π tracks

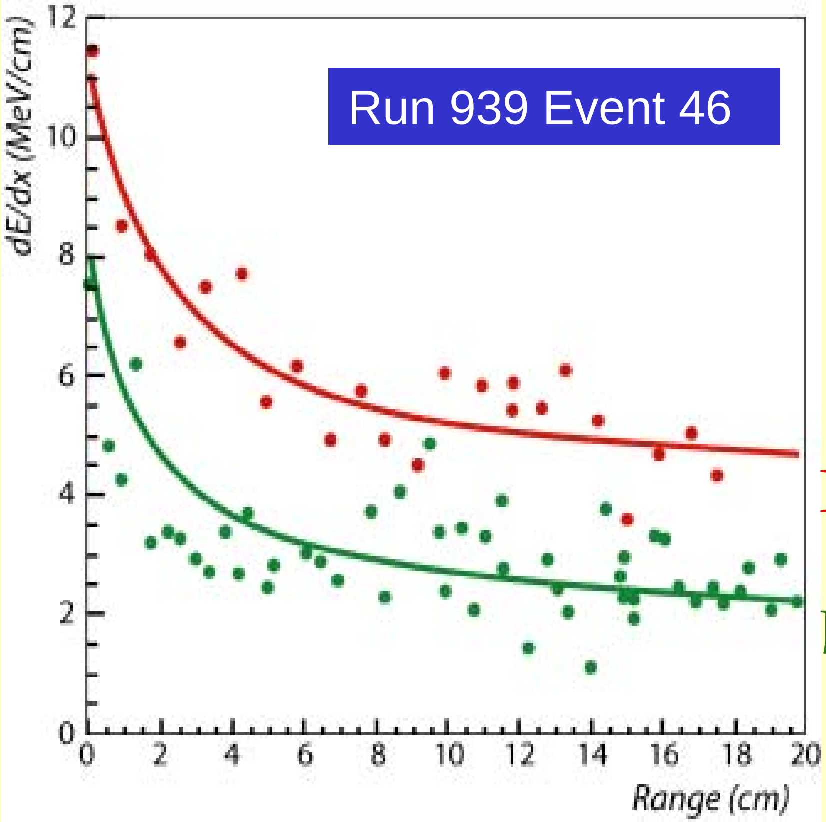
distribution of the distance from the K fit function along π and K tracks

Particle identification (II)

dE/dx in 50 liter



dE/dx in T600



K+

μ+

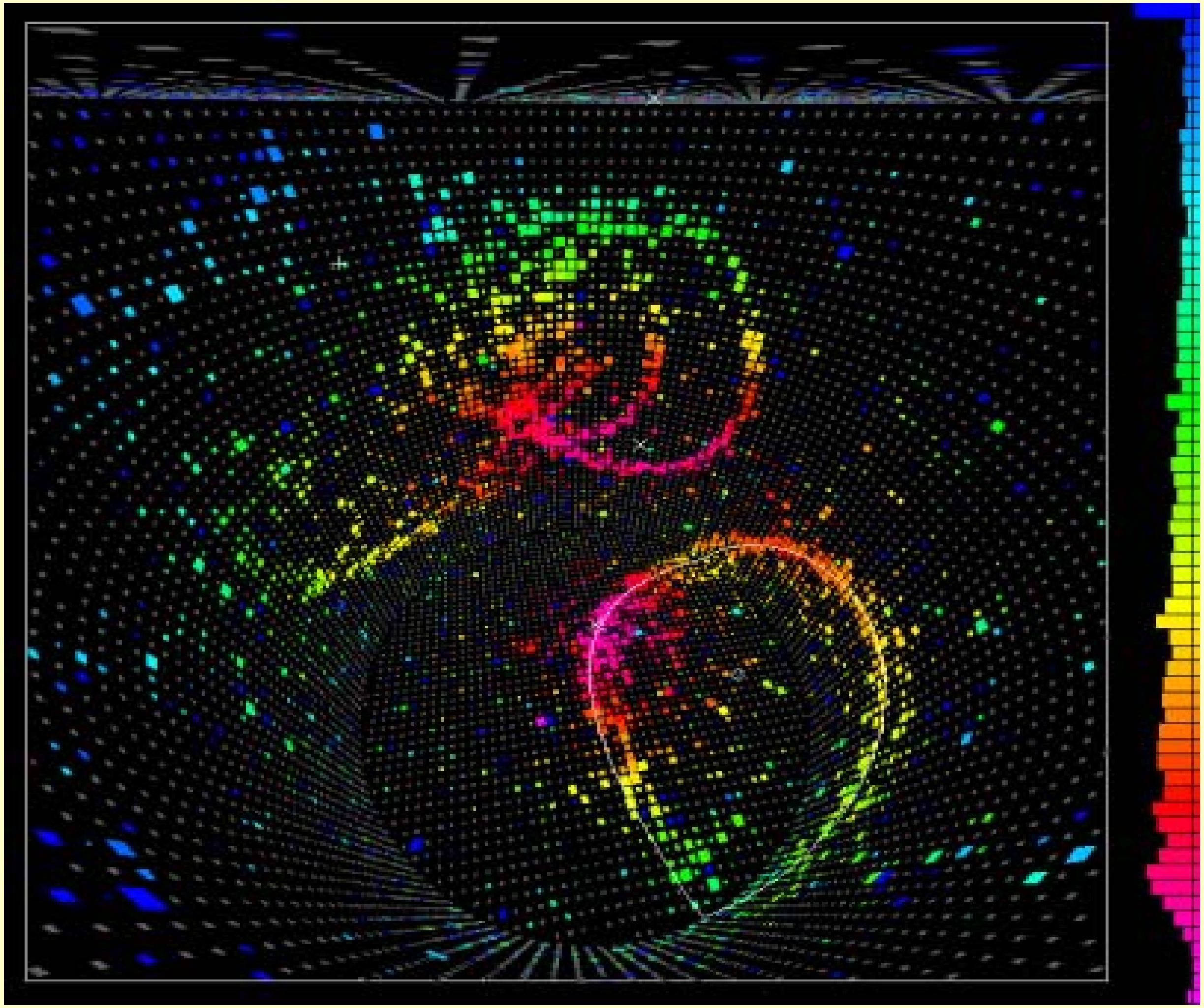
Proton decay: ICARUS expected sensitivities

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
- Inclusive analyses accessible
- Relevant results for few kton × year exposure already
- Expected range in few 10^{32} years after 5 kton × year exposures.

SuperK e+π^0 final state candidate

1997-09-24 12:02:48 : rejected because compatible with background



Particle momentum thresholds in water:

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

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	$50 \to 30$ [1 evt]	
	ICARUS	45	–	0.005	5	2.7	94
$p \to K^+ \bar{\nu}$	SuperK				79	$19 \to 13$ [1 evt]	
prompt $\gamma\ \mu^+$	SuperK	$\boxed{8.7}$	0	$\boxed{0.3}$		$10 \to 7$	
$K^+ \to \pi^+ \pi^0$	SuperK	$\boxed{6.5}$	0	$\boxed{0.8}$		$7.5 \to 5$	
	ICARUS	$\boxed{97}$	–	$\boxed{0.005}$	5	5.7	17
$p \to \mu^+ \pi^0$	SuperK	32	0	0.4	79	$37 \to 24$ [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-rings events, hence in $e\pi^0$ and $\mu\pi^0$ channels channels. SuperK gains on the mass.

- In the favoured $p \to \nu K$ 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

Atmospheric neutrinos

Present situation:

- SuperK: resuming with 50% coverage
- ICARUS: look with a new technique at such astrophysical source

Atmospheric neutrino analysis in ICARUS characterized by

- Unbiased, systematic-free observation whereas:

  SuperK focuses to single-ring CC events

  Other analyses rely on MC

  (e.g. “NC enriched sample”, τ-appearance neural networks, …)

- Excellent energy and angular reconstruction
- Advances in MC of the atmospheric ν rates: match improved measurements possible with ICARUS

  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 rates

Mass is not the only issue!

	2 kton×year			
	Solar minimum		Solar maximum	
	No osc.	$\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2	No osc.	$\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2
Muon-like	266 ± 16	182 ± 13	249 ± 16	171 ± 13
$\mu + p$	59 ± 8	39 ± 6	71 ± 8	35 ± 6
$P_{lepton} < 400$ MeV	114 ± 11	69 ± 8	98 ± 10	63 ± 8
$\mu + p$	32 ± 2	20 ± 4	28 ± 5	18 ± 4
Electron-like	150 ± 12	150 ± 12	138 ± 12	138 ± 12
$e + p$	35 ± 6	35 ± 6	40 ± 6	40 ± 6
$P_{lepton} < 400$ MeV	74 ± 9	74 ± 9	66 ± 8	66 ± 8
$e + p$	20 ± 4	20 ± 4	18 ± 4	18 ± 4
NC-like	192 ± 14	192 ± 14	175 ± 13	175 ± 13
TOTAL	608 ± 25	524 ± 23	562 ± 24	484 ± 22

Simulated atmospheric neutrino events in ICARUS

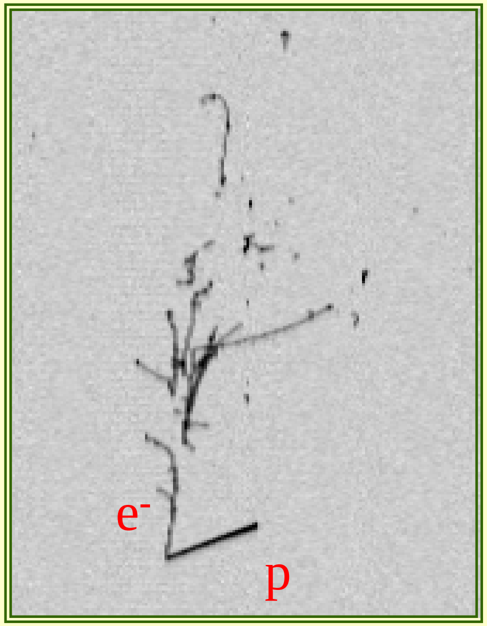
Atmospheric ν_μ interaction, $E_\nu = 1.73$ GeV

240 cm

90 cm

50 cm

65 cm



Atmospheric ν_e interaction, $E_\nu = 0.730$ GeV

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

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

Reconstruction of atmospheric neutrinos

Containment

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

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

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

  3%/$\sqrt{E(\mathrm{GeV})}$ 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

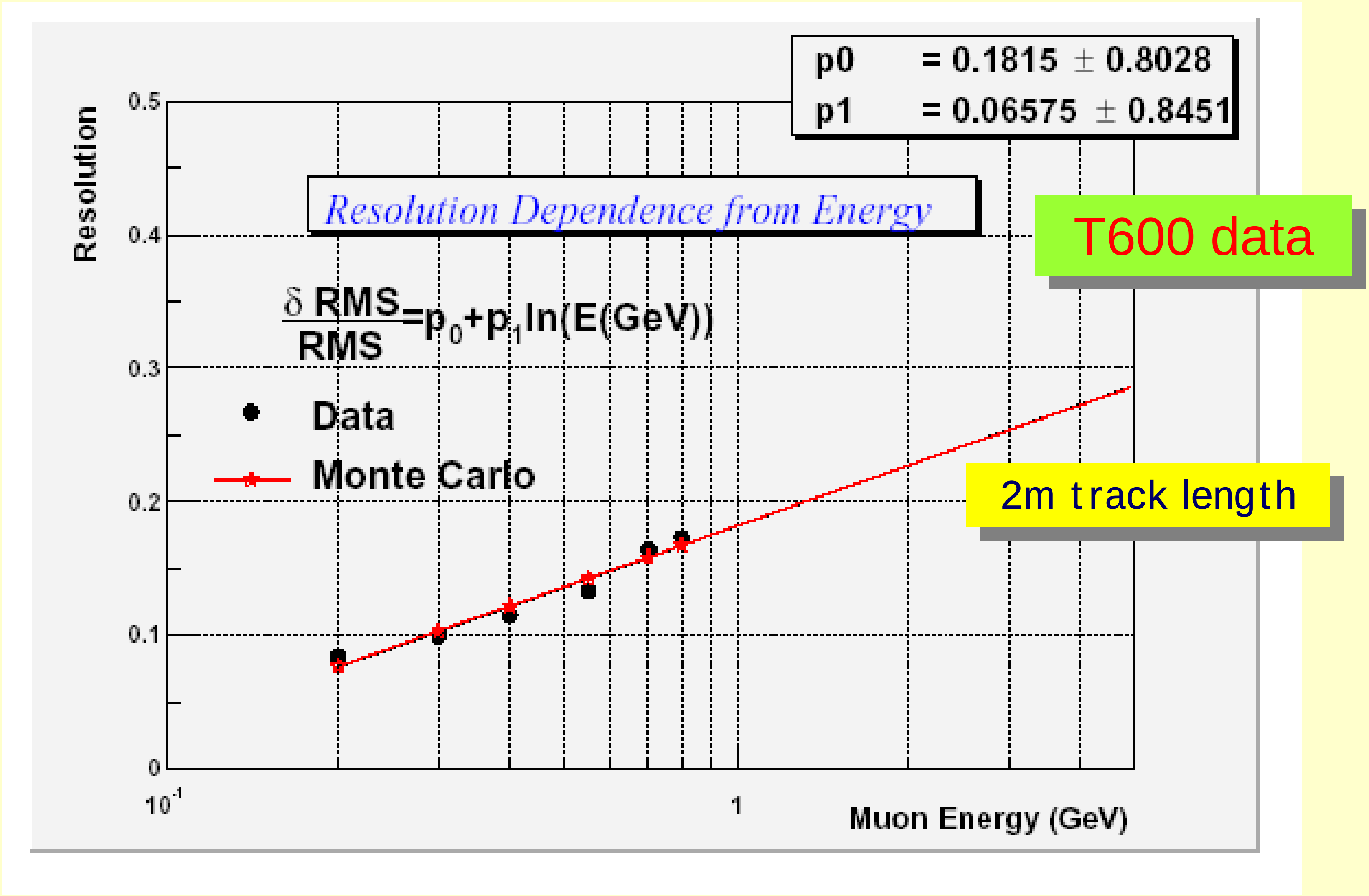
  ($\sigma_p/p \approx 0.10 + 0.048 \ln(p[\mathrm{GeV}])$ for 5 m long track)

- 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 %)

Muon momentum reconstruction by multiple scattering



Reconstructed L/E distribution

After 10 years…

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

Electrons

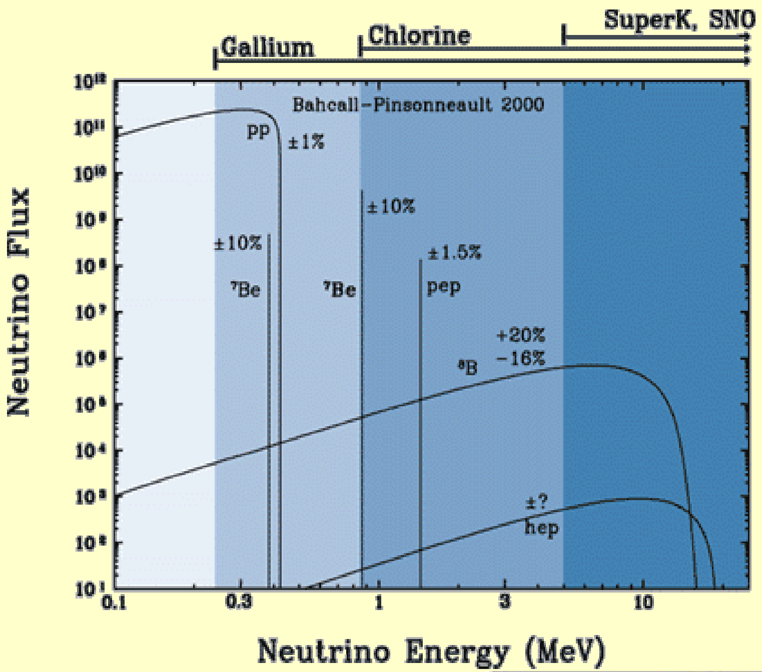
$$\Delta(L/E)_{RMS} \approx 30\%$$

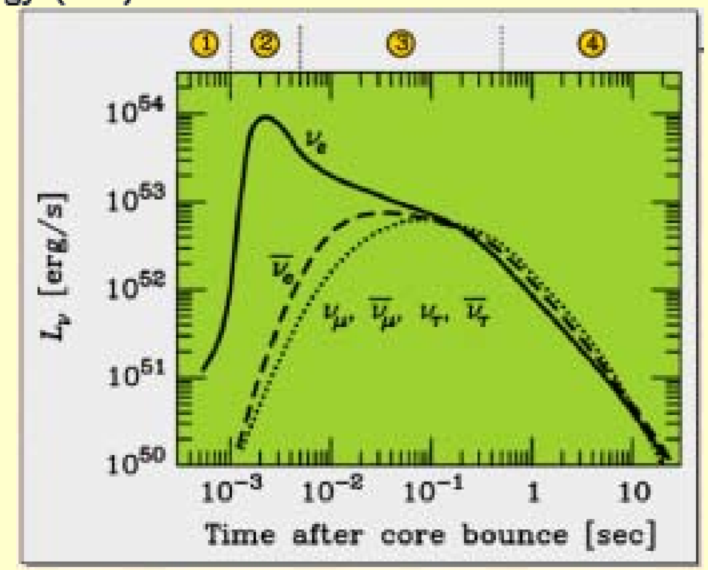
- ***Oscillation parameters:***
  Δm^2_{32} = 3.5 x 10^{-3} eV^2
  $\sin^2 2\Theta_{23}$ = 0.9
  $\sin^2 2\Theta_{13}$ = 0.1

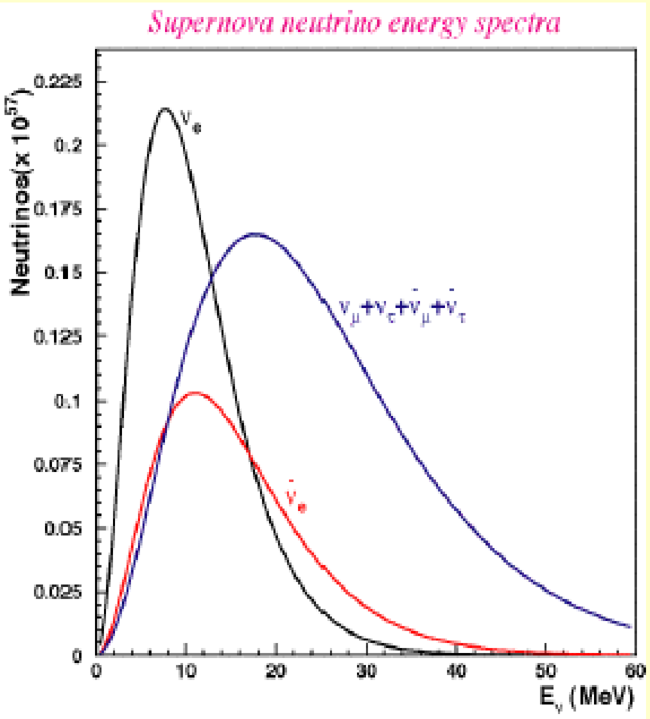
Muons

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

Astrophysical low energy neutrinos: from 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)

  $\phi(\nu_e)$
  Q≈8 MeV

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

Expected solar neutrino rates in T600

Full FLUKA simulation with T600 geometry

BP2000 SSM used

(no oscillation hypothesis)

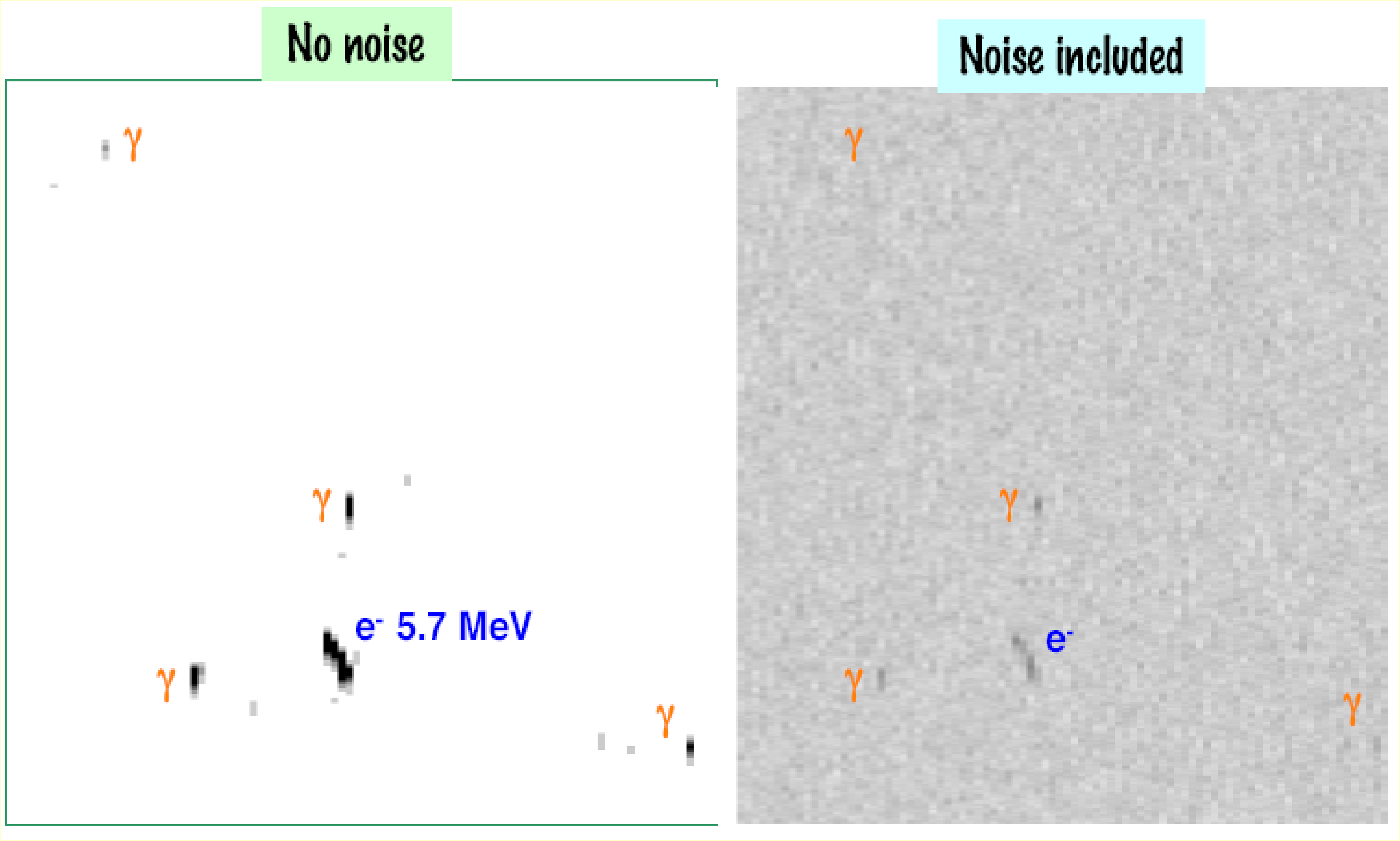
SOLAR ν EVENTS/YEAR in T600 (470 ton LAr)

Electron kinetic energy threshold (MeV)	BP2000 SSM		
	Elastic	Fermi	Gamow-Teller
0.0	367919	945	2134
1.0	2143	930	1545
2.0	872	869	1462
3.0	689	746	1298
4.0	524	570	1058
5.0	380	368	773
5.5	318	272	628
6.0	262	186	490
6.5	212	116	364
7.0	168	64	254
7.5	131	30	164
8.0	99	12	96
8.5	74	5	50
9.0	53	2	23
9.5	36	2	9
10.0	24	1	4
10.5	15	1	2
11.0	9	0	1

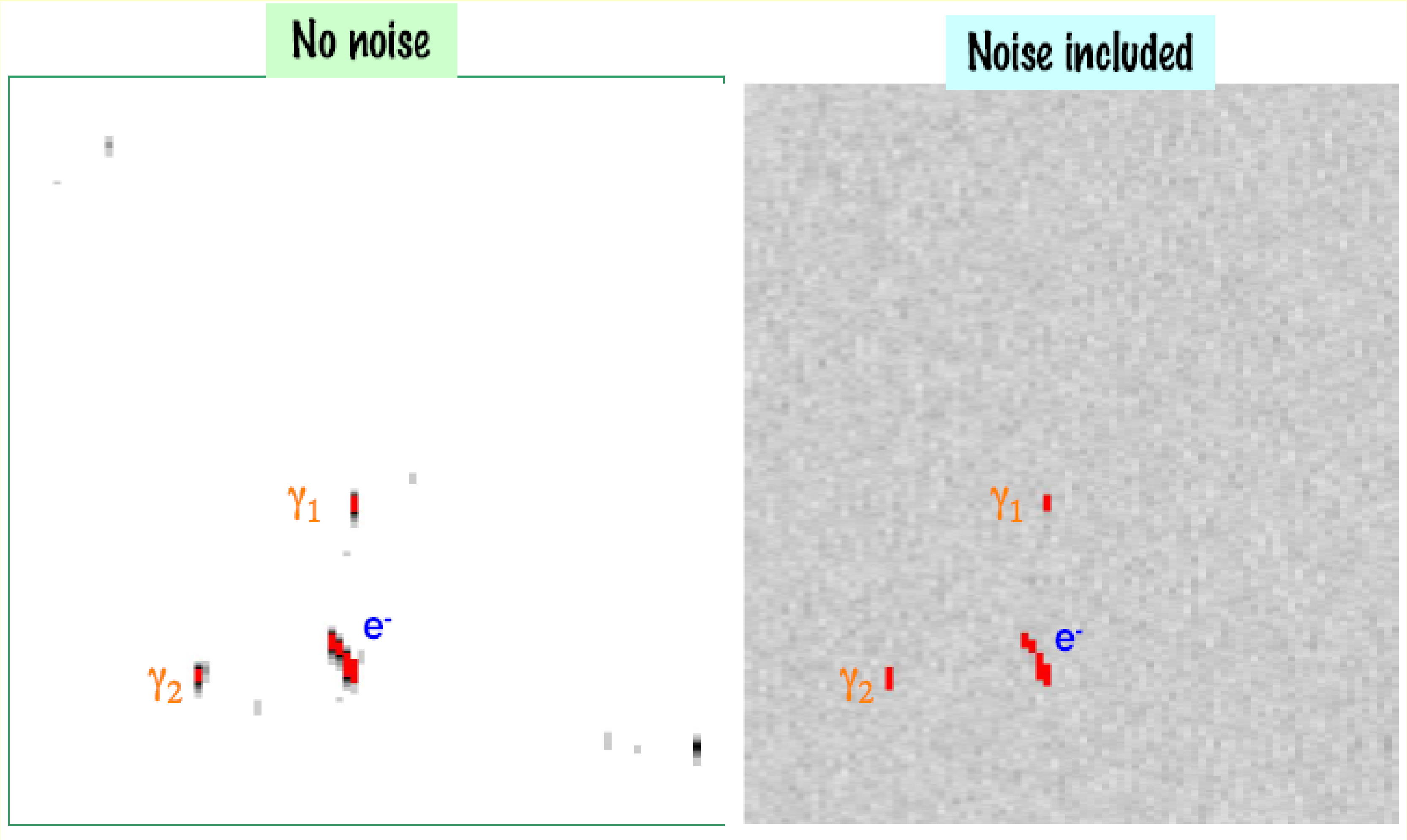
1521 evt/year

Solar neutrino absorption event

(Simulation using observed correlated noise in T600)



Hit reconstruction (200 keV threshold)



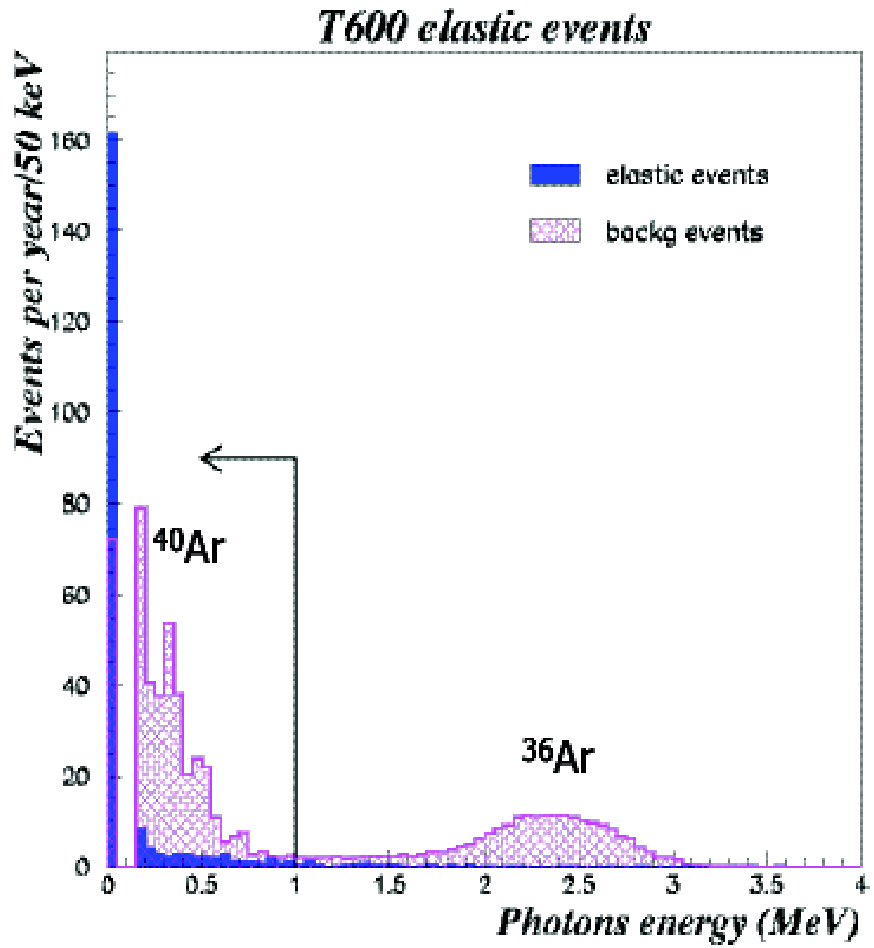
Elastic event analysis (I)

Events per year in T600

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

Statistical significance:

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



Elastic event analysis (II)

Events per year in T600

CUT	Signal	Backg	S/√B
$E_{detec} > 150$ keV	2142	1080000	2.1
$E_{\gamma\text{'s}} < 1$ MeV	2102	260200	4.1
$\cos(\theta_{sun}) > 0.9$ + $E_{clus} > 5$ MeV	202	432	9.7
$E_{clus} > 6$ MeV	137	74	15.9
$E_{clus} > 7$ MeV	82	63	10.3
$E_{clus} > 8$ MeV	45	6	18.4
$E_{clus} > 9$ MeV	21	0	–

Angular cut with Sun efficiency:

72%

77%

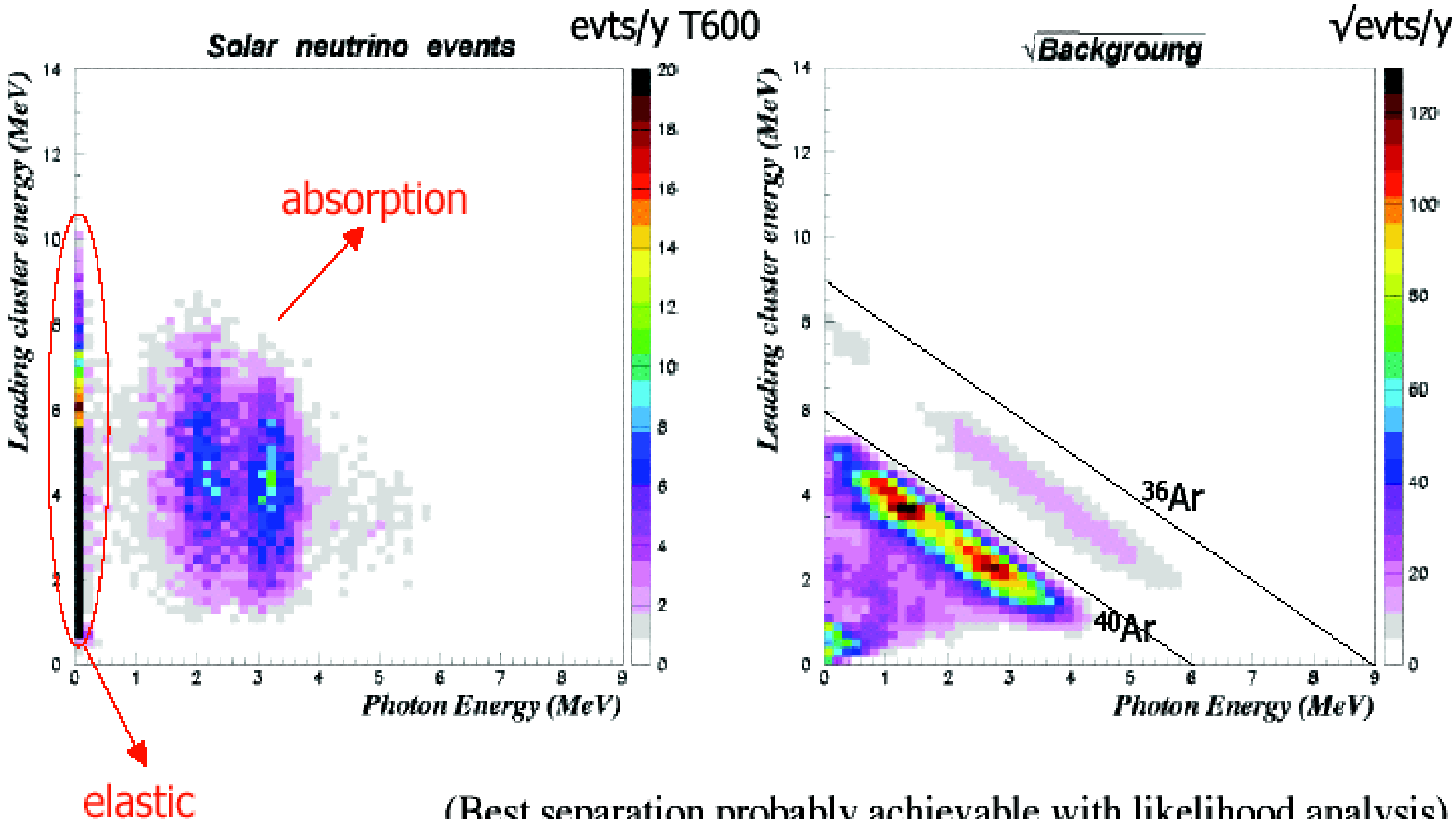
81%

84%

86%

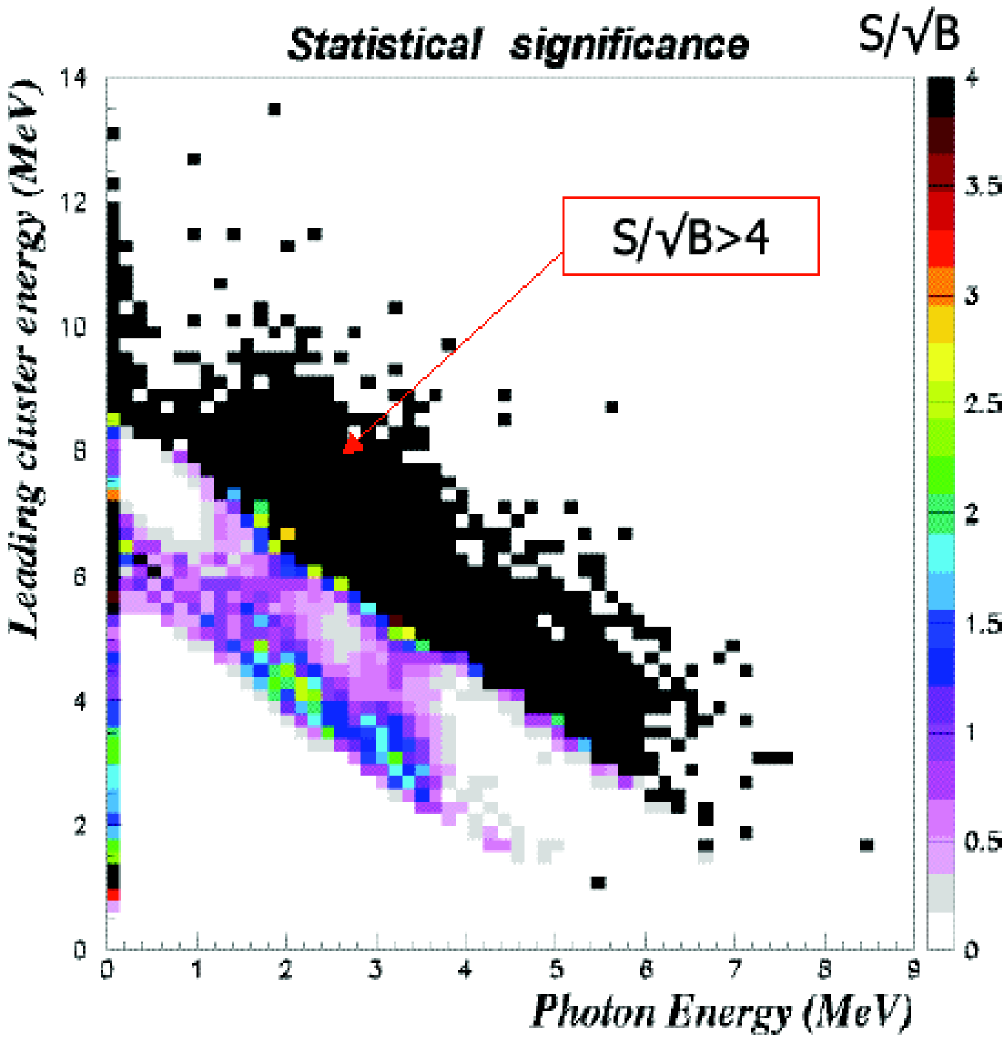
Correlation electron-photon energy

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



(Best separation probably achievable with likelihood analysis)

Statistical significance

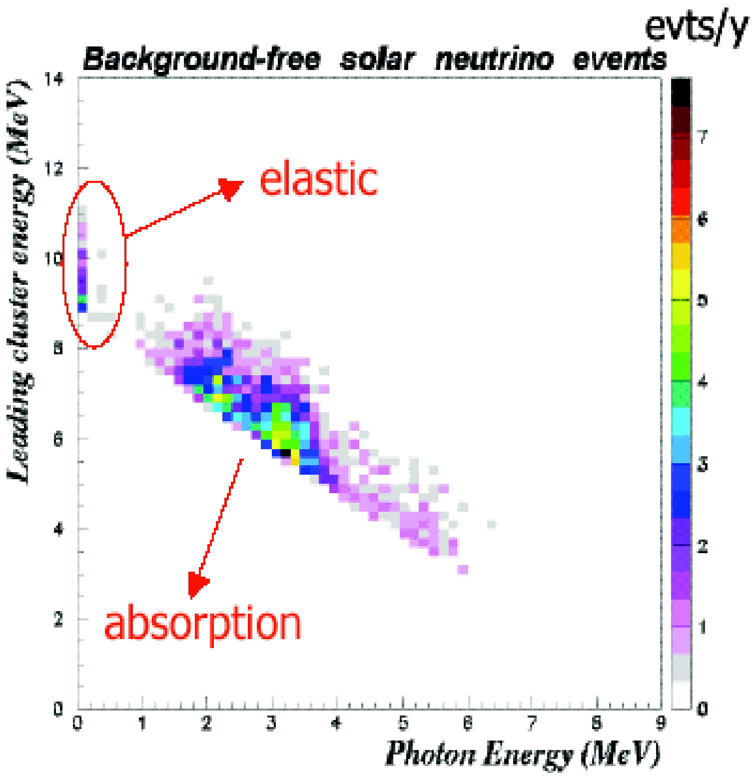


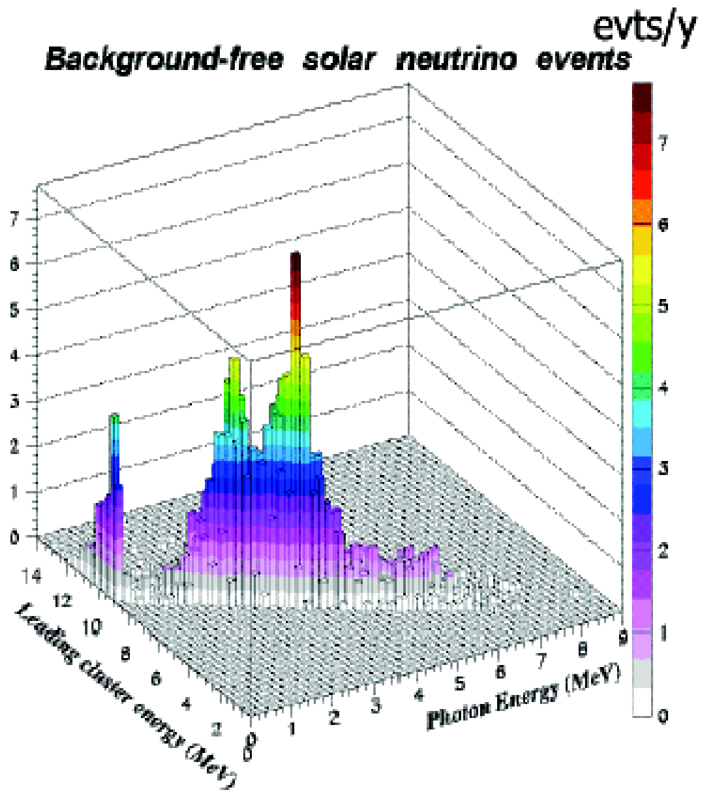
Normalized 1 year T600

For E_{vis} > 8.8 MeV

Background-free events

BG free solar events (E > 8 MeV)

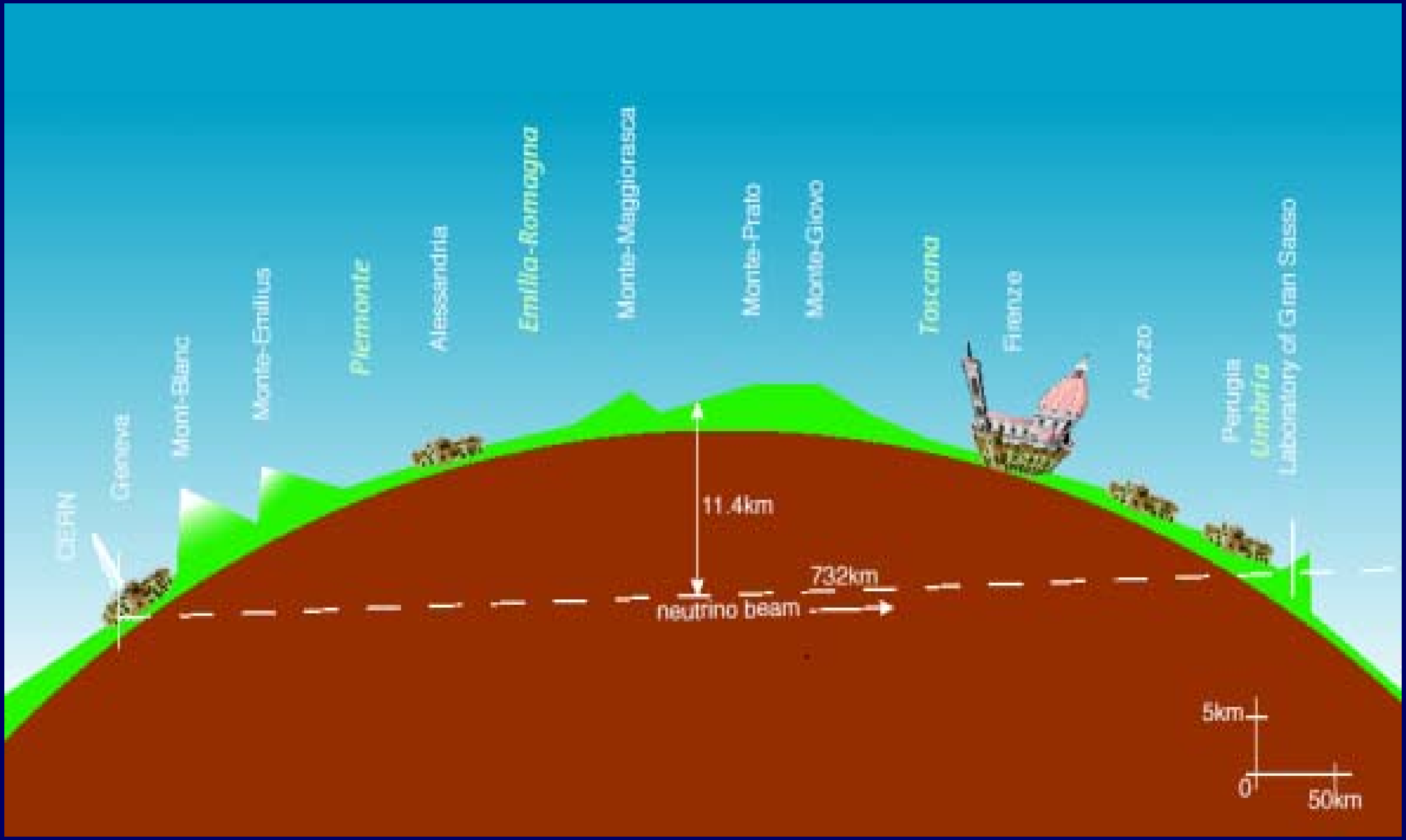




Solar ν events per year in T600

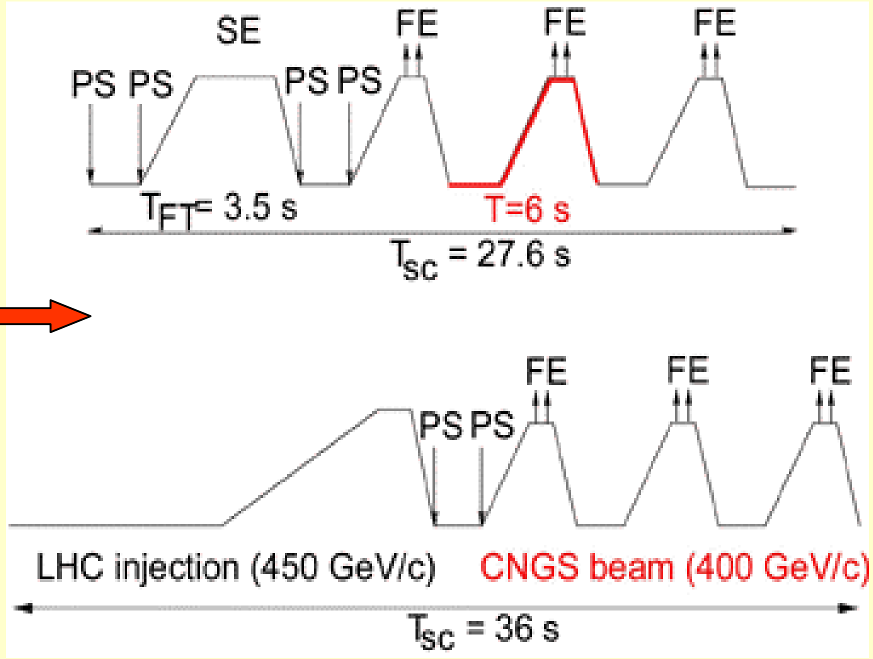
Elastic	Fermi	Gamow-Teller
38	165	295

The CNGS neutrino beam



Proton beam 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.

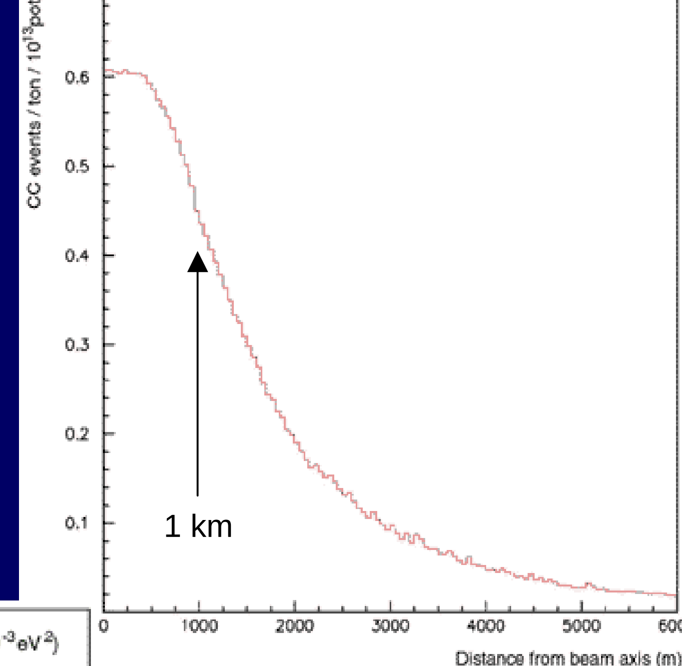


Protons are extracted from the SPS with a fast kicker in two batches (FE = fast extraction) of 10.5 ms each, with 50 ms between the two extractions. The microstructure of the beam reflects the 200 MHz radiofrequency of the SPS. Each batch consists of a train of bunches interspaced by 5 ns, the length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

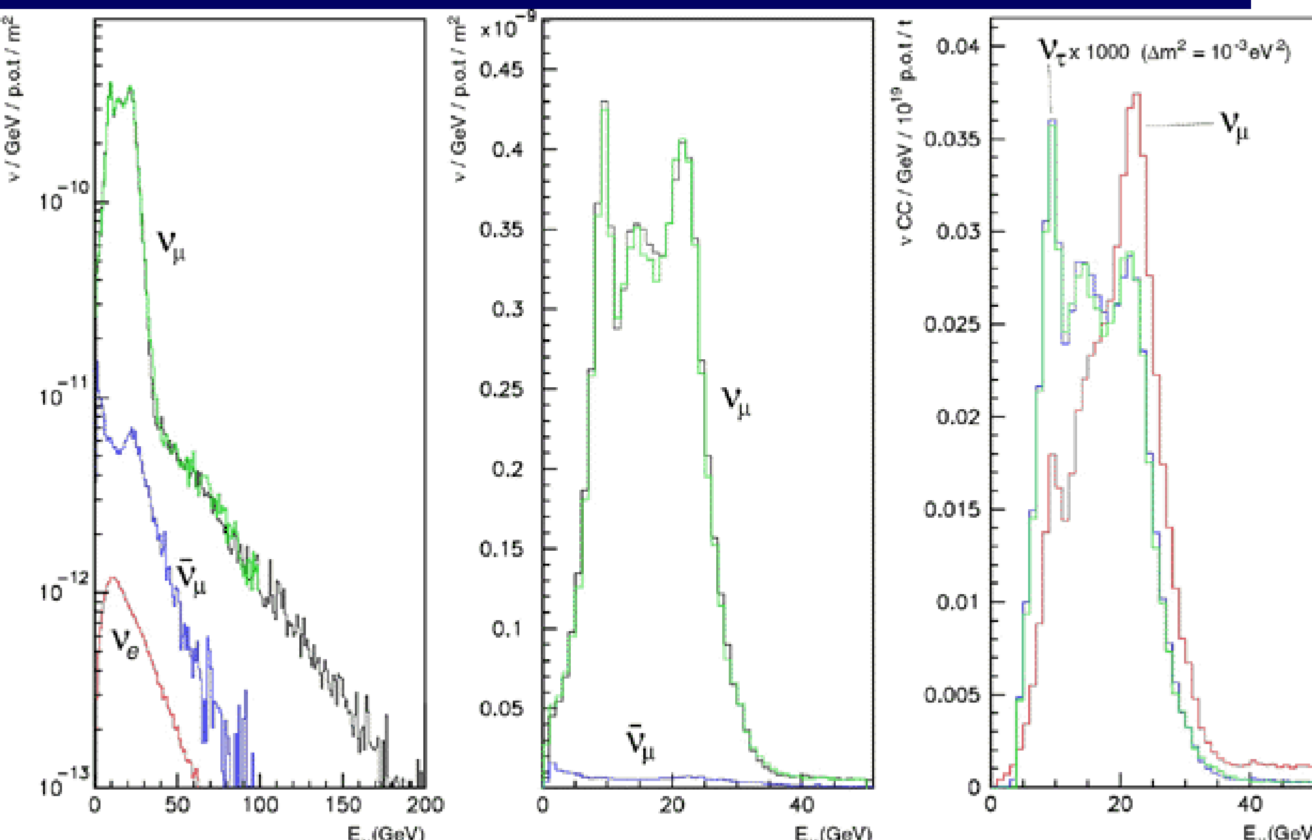
The intensity in the SPS per cycle can reach 4.8×10^{13} protons, thus about 2.4×10^{13} protons per fast extraction. Assuming an overall efficiency of 55% and a running time of 200 days per year in a shared mode (filling LHC, etc.), **4.5×10^{19} protons can be delivered to the CNGS target per year.**

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 $\Delta m^2=3\times10^{-3}$ eV^2:
22 ν_τ charged current **events per kton** of detector mass **per year**



Radial distribution at LNGS



…News from the CNGS

Schedule: start-up in May 2006 (depending on details of the SPS schedule 2006, not yet made).

Possible delays: none (one year more time to build CNGS than what was originally planned).

Civil engineering: all but the last 160 m of galleries are excavated (connection muon detectors to TI8 is missing); excavation should be complete mid-January 2003. Concreting of the target chamber: completed last week (concreting of the proton beam tunnel attacked now).

Decay tunnel: adjudication made in September 2002; price well within the cost estimate.

Activities in 2003:

- finish civil engineering works (June 2003)
- installation of hadron stop (iron from WANF, graphite and cooling plates in production)
- start installation of decay tube (Oct 2003). In parallel: equip muon detector regions and their access galleries with light, ventilation, GSM, emergency services, etc.

Horn and Reflector: first final horn inner conductor arriving now. First complete horn: May 2003.

Target: design advancing well; 5 target units in one target magazine (i.e. 4 spare targets available at start-up).

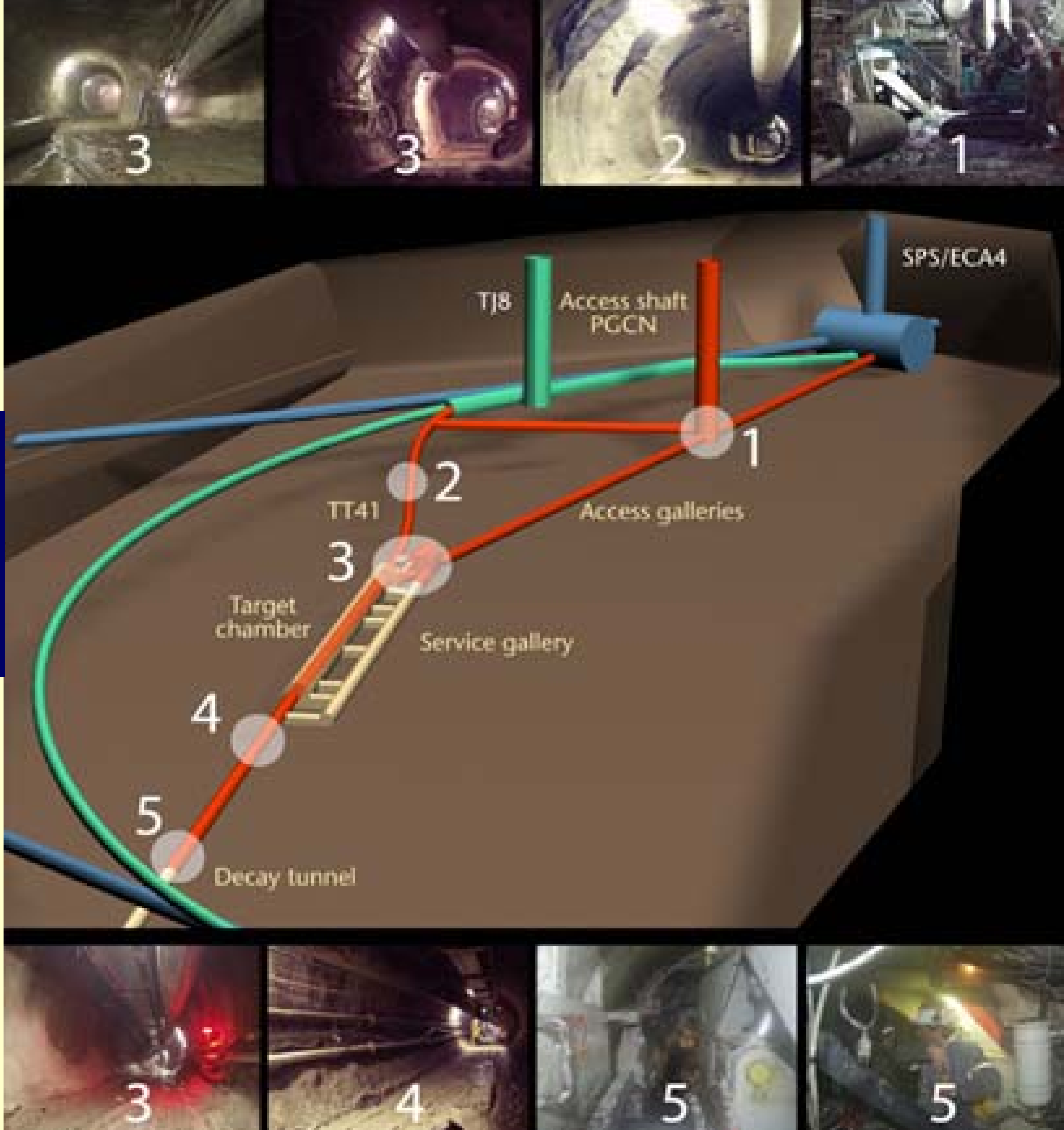
Protons per cycle: progress at the PS, good chance to have 7x10**13 per 6 s cycle already in 2006 (up from 4.8).

Problems under study: vacuum windows SEM monitors around target: standard titanium windows will melt at the high intensities now expected; other options under study, e.g. beryllium window for vacuum system, etc.

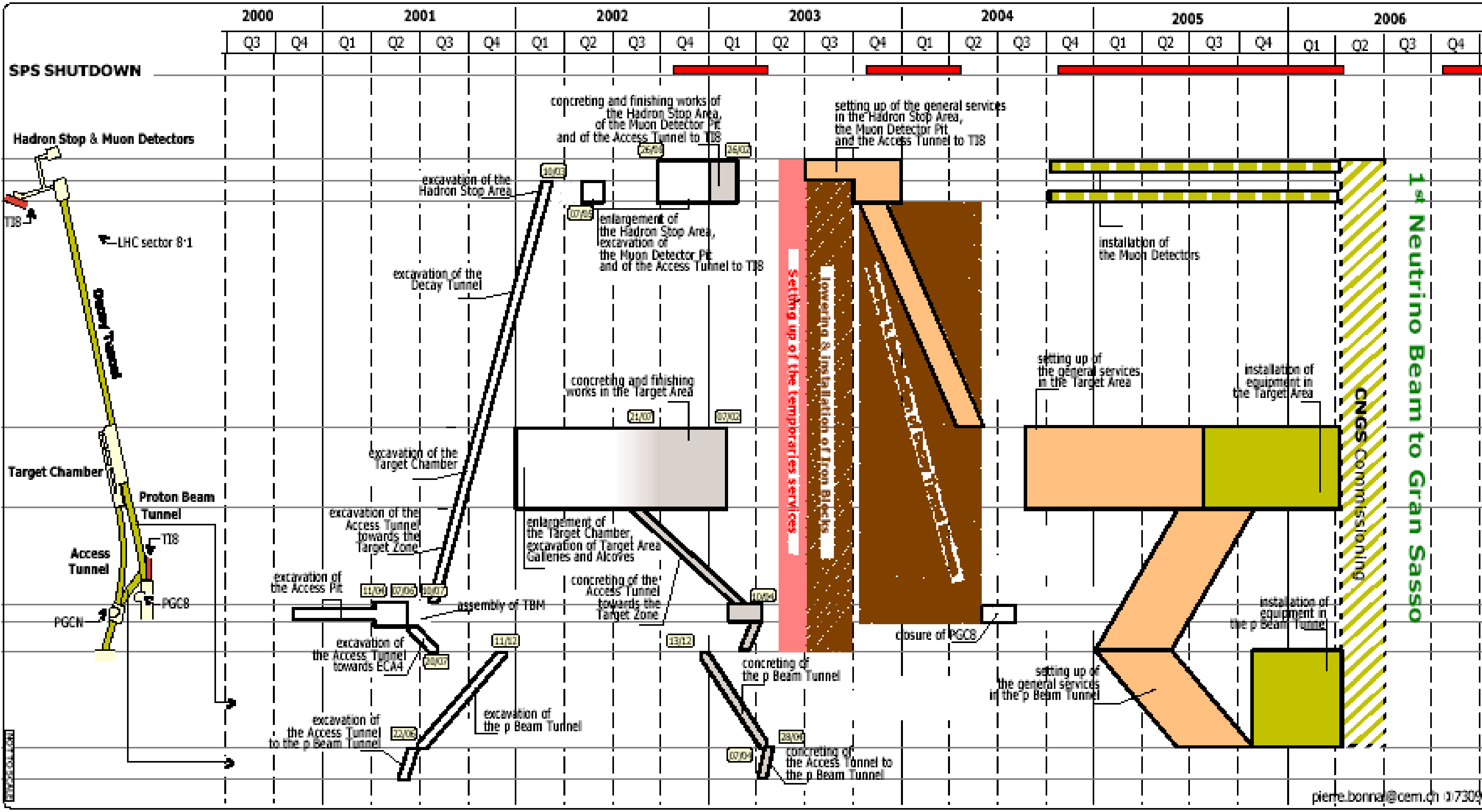
Overall budget: contingency still small; a review to be held (likely) end of April 2003 should provide the full picture. No huge cost overrun for the moment.

CNGS beam layout at CERN site.

Progress in the civil engineering work (excavation)



CNGS schedule: commissioning by Q2 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)
- ICARUS physics program enriched by CNGS oscillation searches.
- ICARUS contributed to design and optimization of the CNGS beam for τ appearance.
- 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.

ICARUS-CNGS experiment

- Detector configuration
  T3000 (Active LAr: 2.35 ktons)

- 5 years of CNGS running
  Shared mode (4.5 x 10^{19} pot/year)

- 280 ν_τ CC expected for
  Δm^2_{23}=3 x 10^{-3} eV^2 and max. mixing

Average resolution on total visible energy: **≈10%**

Process	Expected Rates
ν_μ CC	32600
$\bar{\nu}_\mu$ CC	652
ν_e CC	262
$\bar{\nu}_e$ CC	17
ν NC	10600
ν NC	243
ν_τ CC, Δm^2 (eV^2)	
1 x 10^{-3}	31
2 x 10^{-3}	125
3 x 10^{-3}	280
5 x 10^{-3}	750

A. External muon spectrometer

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

Physics motivation:

- measure muon charge via magnetic analysis
- online monitoring of beam energy spectrum
- kinematical properties of closed ν_μ CC events
- direct measurement of background for τ searches
- improve μ momentum resolution by combining MS and magnetic analysis

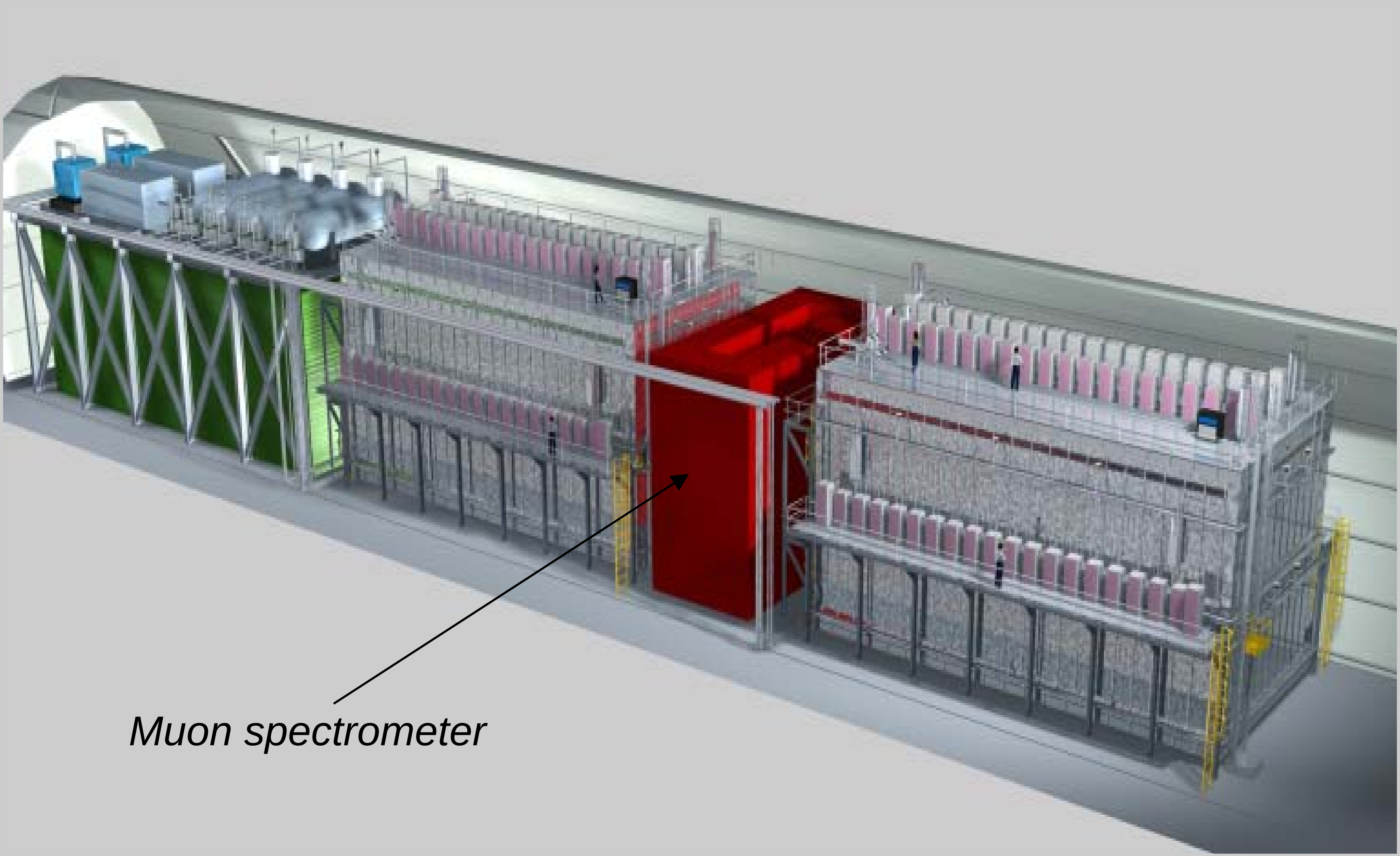
Magnet design:

- simple geometry, compatible with transverse dimensions of the T1200 module
- detection technique: drift tubes + fast trigger devices

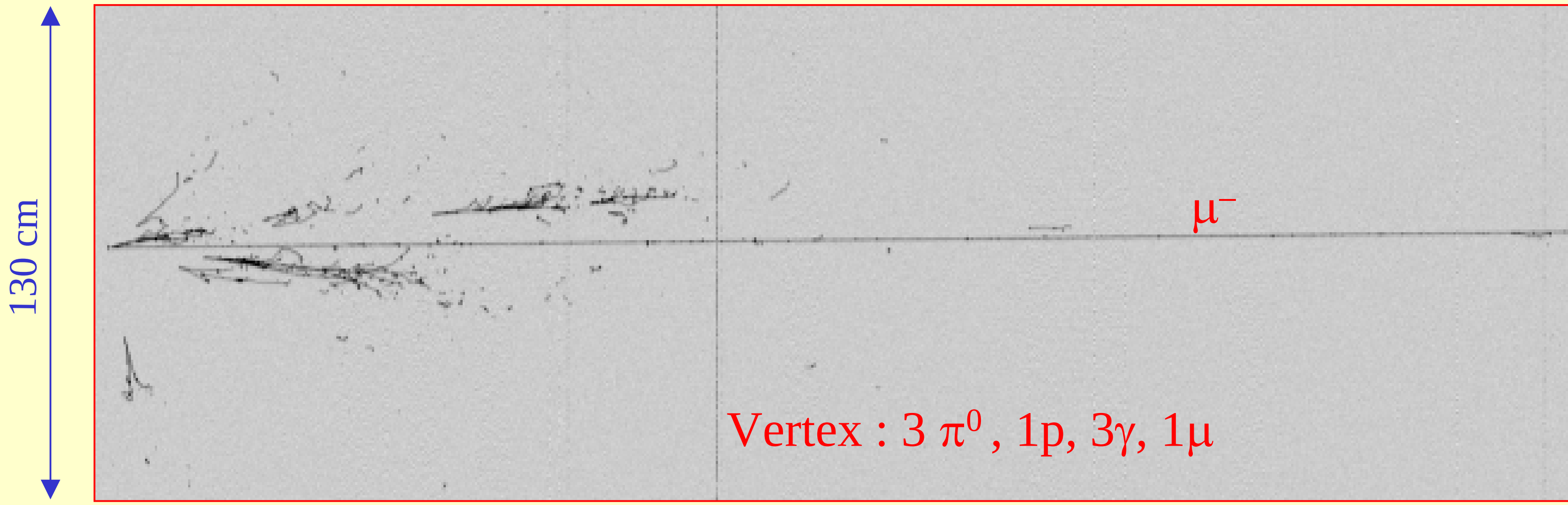
B. Front muon "veto"

Muon detection walls: beam monitoring & tagging of rock interactions

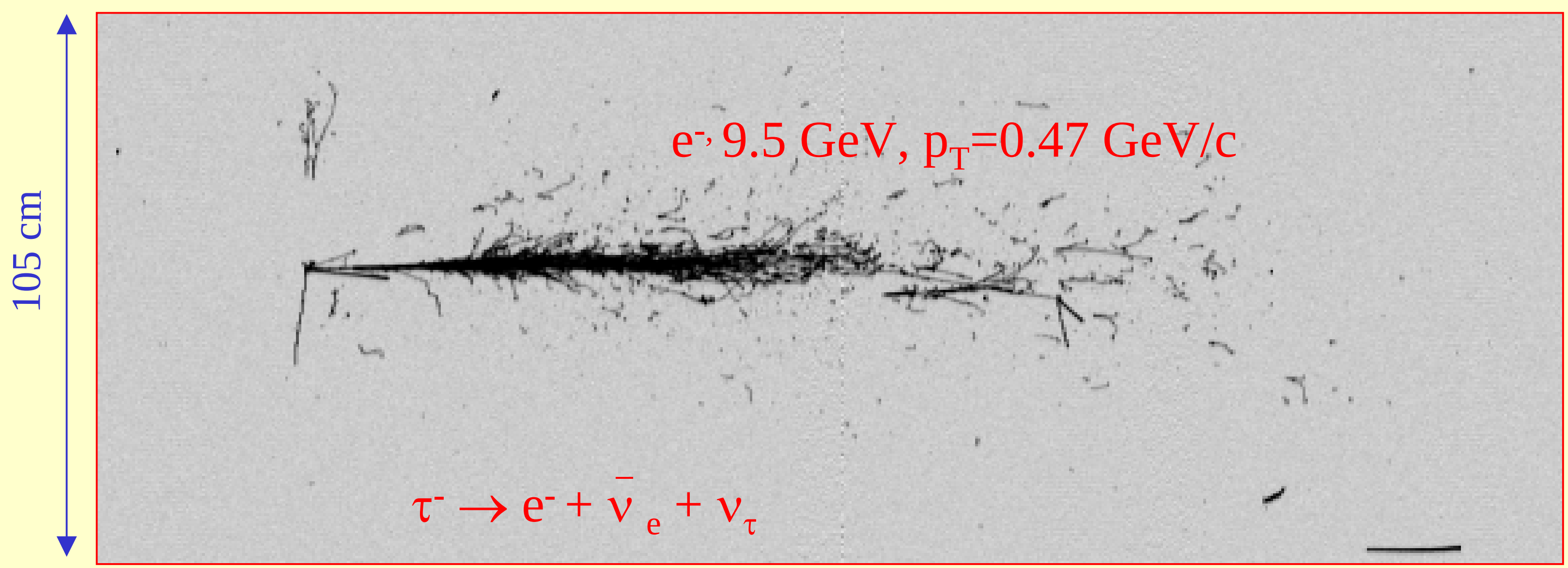
Spectrometer artist view



420 cm   CNGS ν_μ interaction, E_ν=26 GeV



280 cm   CNGS ν_τ interaction, E_ν=18.7 GeV



Direct detection of flavor oscillation

Expected ν_e and ν_τ contamination (in absence of oscillations) is of the order of 10^{-2} and 10^{-7} relative to the main ν_μ component

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

$$\nu_\tau + \mathbf{Ar} \rightarrow \tau + \mathbf{jet}$$

Charged current (CC)

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

$\nu_\mu \rightarrow \nu_e$

$$\nu_e + \mathbf{Ar} \rightarrow \mathbf{e} + \mathbf{jet}$$

$\tau \rightarrow$ *e search: 3D likelihood*

A simple analysis approach: a likelihood method based on 3 variables

3 variables

$E_{visible}$, P_T^{miss}, $\rho_l \equiv P_T^{lep}/(P_T^{lep+} P_T^{had}+P_T^{miss})$

Exploit correlation between them

L_S ([Evis, P_T^{miss}, ρ_l]) (signal)

L_B ([Evis, P_T^{miss}, ρ_l]) (ν_e CC BG)

Discrimination given by

$\ln\lambda \equiv L([\mathrm{Evis}, P_T^{miss}, \rho_l]) = L_s / L_B$

lnλ

More sophisticated approaches (e.g. neural net,…) under study.

$\tau \to e$ search: 3D likelihood summary

5 year "shared" CNGS running

T3000 configuration

Cuts	ν_τ Eff. (%)	ν_e CC	ν_τ CC $\Delta m^2 = 3 \times 10^{-3}$ eV^2
Initial	100	262	49
Fiducial volume	63	169	31
One candidate with momentum > 0.5 GeV	57	165	28
$\ln\lambda > 0$	45	3.4	22
$\ln\lambda > 0.5$	39	2.8	19
$\ln\lambda > 1.0$	33	1.6	16
$\ln\lambda > 1.5$	31	1.2	15
$\ln\lambda > 2.0$	**26**	**0.7**	**13**
$\ln\lambda > 2.5$	18	0.6	9
$\ln\lambda > 3.0$	14	0.4	7
$\ln\lambda > 3.5$	10	0.3	5
$\ln\lambda > 4.0$	8	0.2	4

Maximum sensitivity

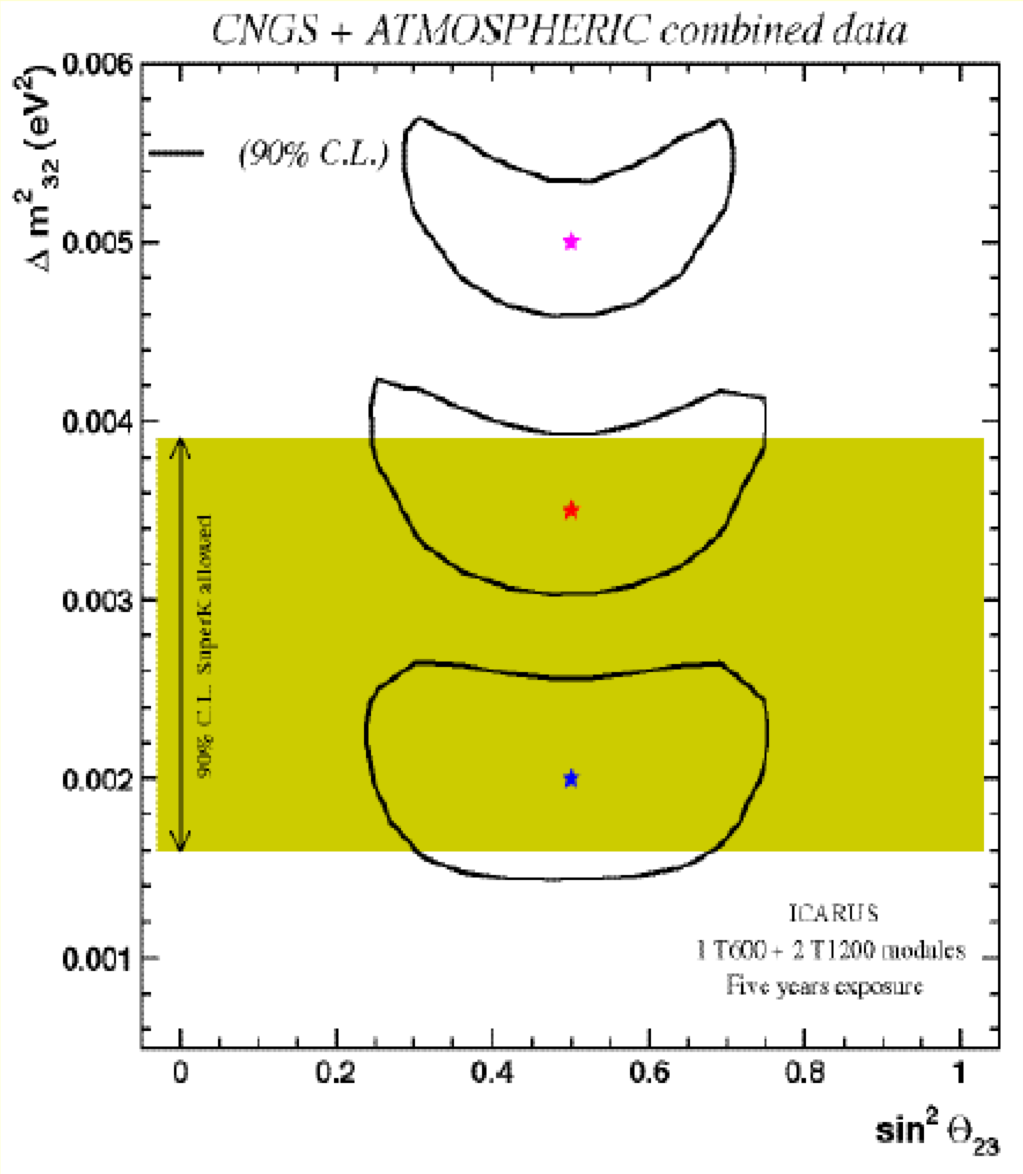
$\nu_\mu \rightarrow \nu_\tau$ appearance search summary

- T3000 detector (2.35 kton active, **1.5 kton fiducial**)
- Integrated pots = 2.25 x10^{20}
- 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: $1.6 < \Delta m^2 < 4.0$ 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 $\nu_\mu \rightarrow \nu_e$ (I)

The emerging scenario:

$|\Delta m^2_{21}| = (4 \div 12) \times 10^{-5}$ eV^2

$\tan^2\theta_{12} = 0.32 \div 0.51 \Rightarrow 30^\circ < \theta_{12} < 36^\circ$

$|\Delta m^2_{32}| = (1.6 \div 3.9) \times 10^{-3}$ eV^2

$\sin^2 2\theta_{23} > 0.92 \Rightarrow 37^\circ < \theta_{23} < 45^\circ$

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atm}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}}_{???} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}}$$

- The confirmation that $\nu_\mu \rightarrow \nu_\tau$ oscillations will be an important milestone
- The measurement of a non-vanishing θ_{13} would

be an important discovery, proving that the mixing matrix is 3x3 and opening the door to CP-violation searches in the leptonic sector (CP-violation effects will only be visible for relatively large θ_{13})

Search for subleading $\nu_\mu \to \nu_e$ (II)

- Search for excess of electrons, on top of τ electronic decays
- Takes advantage of **unique e/π^0 separation in ICARUS**
- Assume 5 years @ $4.5\mathrm{x}10^{19}$ pots, 2.35 kton fiducial
- Limited by statistics: needs more intensity (low E) to exploit ICARUS features

$\Delta m^2_{32} = 3\mathrm{x}10^{-3}$ 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

Example: low energy CNGS optimization

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

	$\Delta m^2 (eV^2)$							
L (km)	1×10^{-3}		2×10^{-3}		3×10^{-3}		4×10^{-3}	
	E_{max} MeV	E_{min} MeV	E_{max} MeV	E_{min} MeV	E_{max} MeV	E_{min} MeV	E_{max} MeV	E_{min} MeV
730	590	295	1180	590	1771	885	2361	1180

Maximize flux between 0 and 2.5 GeV

Comparison between τ and LE optimizations

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

Expected number of events

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	5	44	16	22.
8	0.076	5	44	13	18.
7	0.059	5	44	10	13
5	0.030	5	44	5	7
3	0.011	5	44	1.8	2.5
2	0.005	5	44	0.8	1.1
1	0.001	5	44	0.2	0.3

CNGS L.E.

Table 4: Events from the CNGS L.E. beam, assuming $\Delta m^2_{23} = 3 \times 10^{-3} eV^2$, $\theta_{23} = 45°$, 5 years of operation and 2.35 kton fiducial mass.

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

CNGS τ

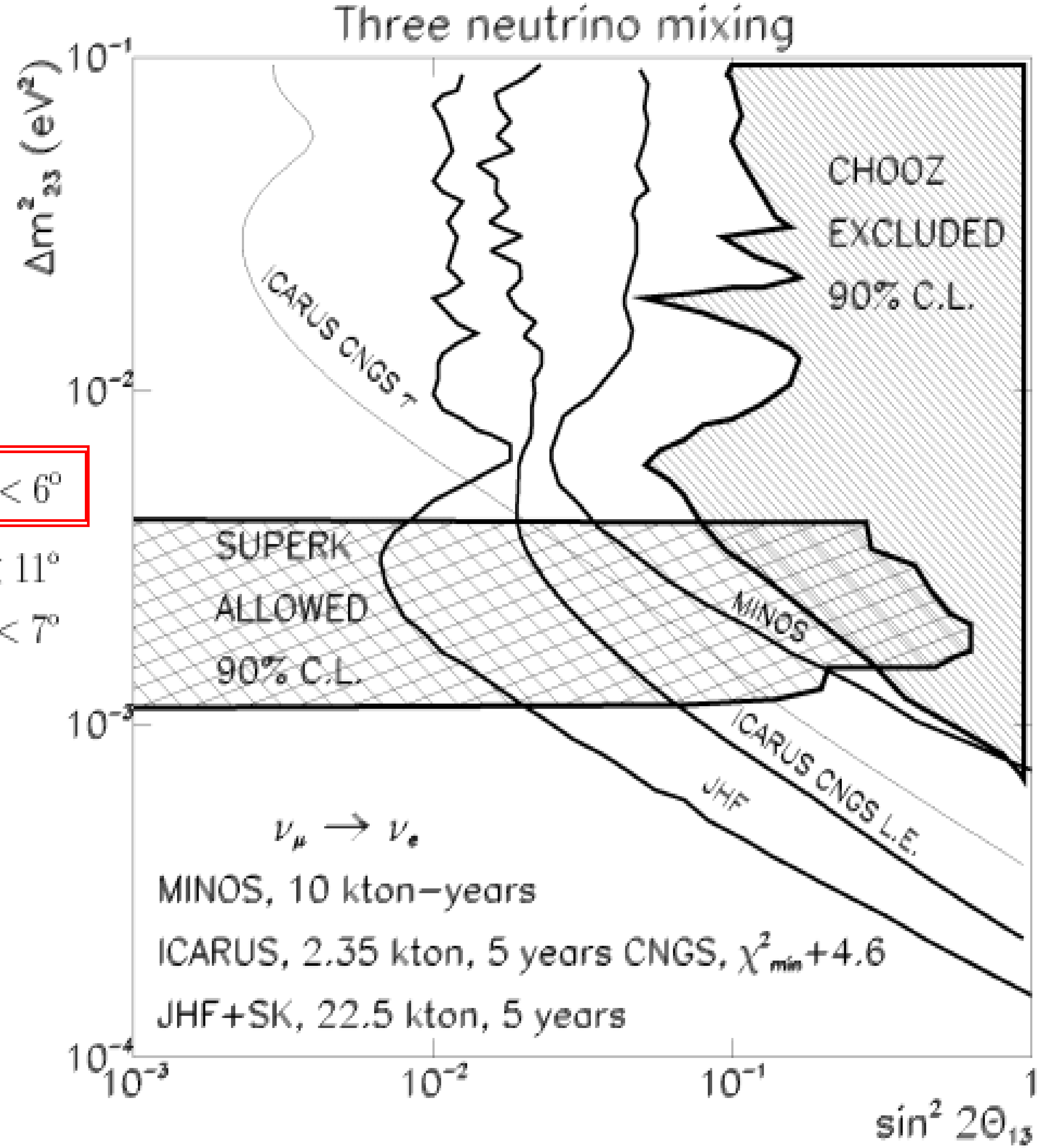
Table 5: Events from the CNGS τ beam, assuming $\Delta m^2_{23} = 3 \times 10^{-3} eV^2$, $\theta_{23} = 45°$, 5 years of operation and 2.35 kton fiducial mass.

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

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

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

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



Status, organization, outlook

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 Pavia 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.
5. Reach the design mass: cloning the T600 for further modules recommended by LNGSSC and CERN-SPSC.
6. INFN approved the T3000 scientific program and the design of successive T1200 modules. 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).

The ICARUS Collaboration

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ITALY: L'Aquila, LNF, LNGS, Milano, Napoli, Padova, Pavia, Pisa, CNR Torino, Politec. Milano.
SWITZERLAND: ETHZ Zürich.
CHINA: Academia Sinica Beijing.
POLAND: Univ. of Silesia Katowice, Univ. of Mining and Metallurgy Krakow, Inst. of Nucl. Phys. Krakow, Jagellonian Univ. Krakow, Univ. of Technology Krakow, A.Soltan Inst. for Nucl. Studies Warszawa, Warsaw Univ., Wroclaw Univ.
USA: UCLA Los Angeles.
SPAIN: Univ. of Granada.

Present institute responsibilities

- Pavia
  cryostat, inner chamber, PMT, pad electrodes, software
- Aquila/LNGS
  installation at LNGS, purity monitors, software
- Padova
  electronics + DAQ, online software
- Pisa/UCLA
  H.V.
- Frascati
  R&D, tracking detectors
- Milano
  software and simulations
- Napoli
  laser calibration, trigger electronics, installation at LNGS, beam monitoring
- ETH/Zurich
  slow control, pad electrodes, magnet (spectrometer), software
- Polish Groups
  wiring
- Granada
  drift tubes (spectrometer), software

All groups involved in data analysis

COSTS & TIMETABLE

- **Costs and time schedule estimates**: based on experience gained with R&D and with the realization of the T600.

- **Contingency** is therefore reduced (5% for costs).

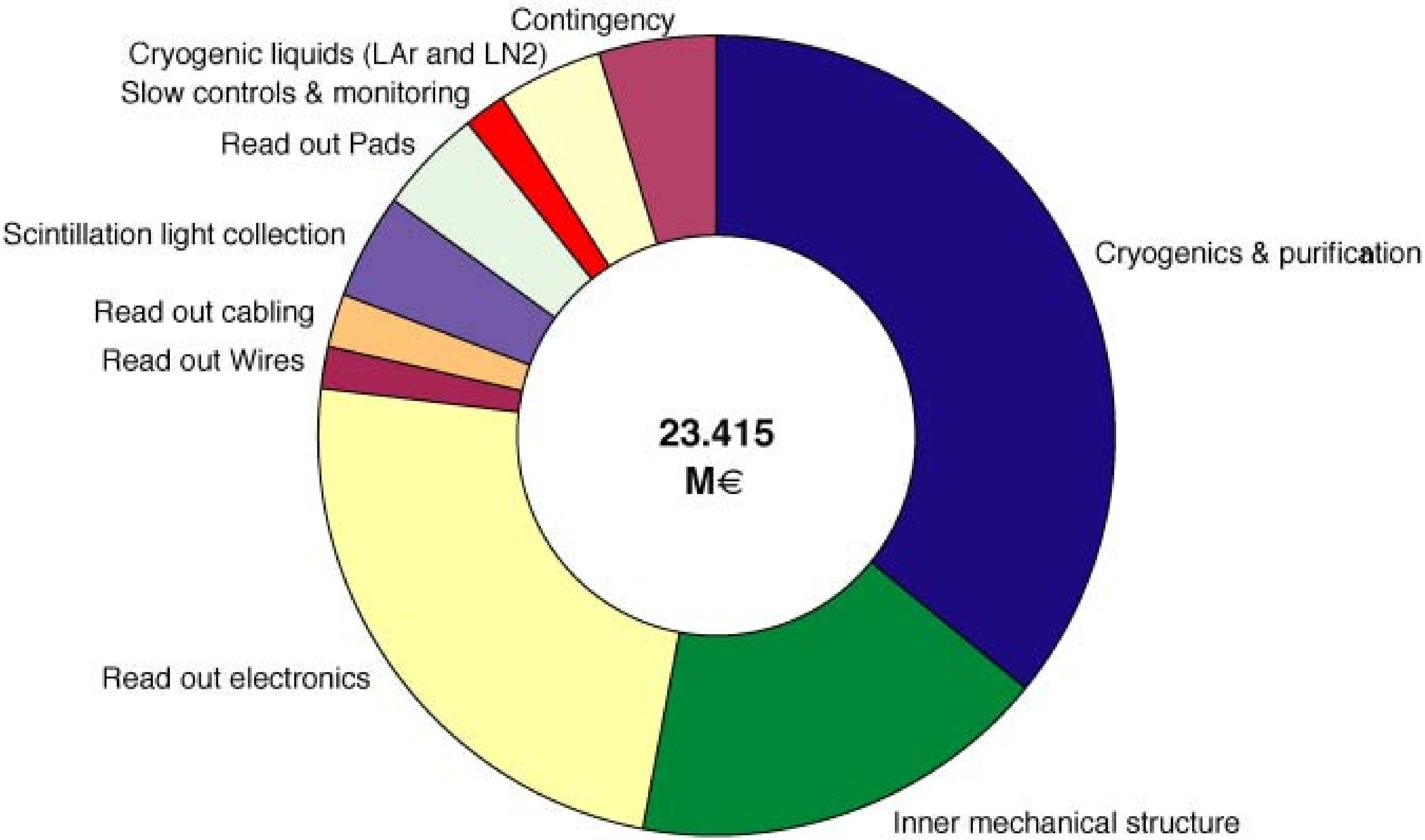
- **The T600 experience**: evaluate the time needed for different construction phases except for the cryostats build-up inside the underground Hall. However, also this last phase should not take a large amount of time.

- **Present cost estimate**: based on offers for the first T600. New bidding to other suppliers may bring to reductions.

- **Large savings** for the T1200 layout:

  - reduction of electronics chann. and mech. components (from drift length doubling);
  - re-utilization of tooling and services used for assembly, installation and run of T600.

Cost for a single T1200 Super Module



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 in 2003
- the progressive realisation of two additional T1200 modules, with the T600 as basic cloning unit, to be operational by 2006

In this configuration, due to the unique 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
- CNGS 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 !