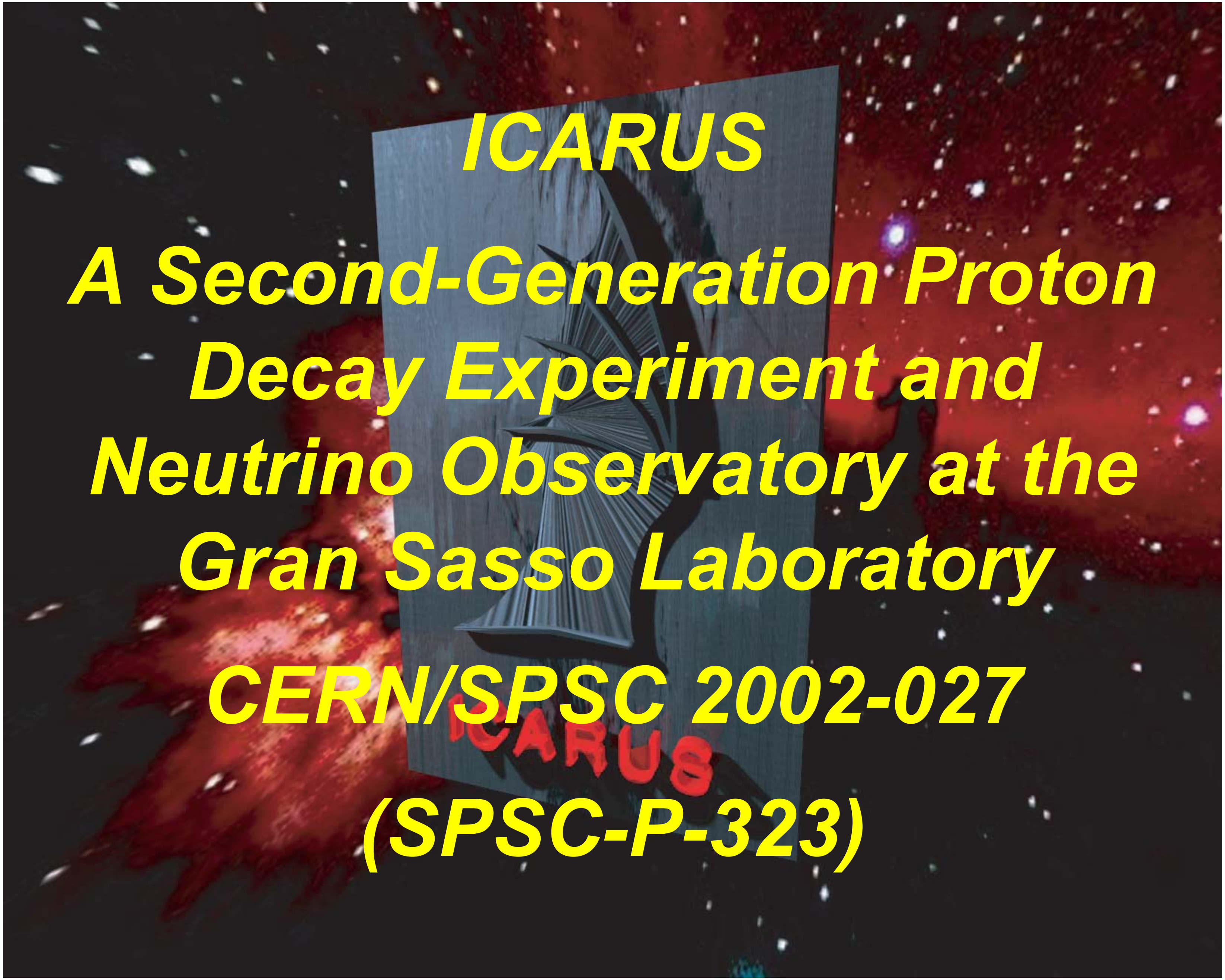


ICARUS

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

CERN/SPSC 2002-027

(SPSC-P-323)

The ICARUS Collaboration

S. Amoruso, P. Aprili, F. Arneodo, B. Babussinov, B. Badelek, A. Badertscher, M. Baldo-Ceolin, G. Battistoni, B. Bekman, P. Benetti, A. Borio di Tigliole, M. Bischofberger, R. Brunetti, R. Bruzzese, A. Bueno, E. Calligarich, D. Cavalli, F. Cavanna, F. Carbonara, P. Cennini, S. Centro, A. Cesana, C. Chen, Y. Chen, D. Cline, P. Crivelli, A. Dabrowska, Z. Dai, M. Daszkiewicz, R. Dolfini, A. Ereditato, M. Felcini, A. Ferrari, F. Ferri, G. Fiorillo, S. Galli, Y. Ge, D. Gibin, A. Gigli Berzolari, I. Gil-Botella, A. Guglielmi, K. Graczyk, L. Grandi, K. He, J. Holeczek, X. Huang, C. Juszczak, D. Kielczewska, J. Kisiel, L. Knecht, T. Kozlowski, H. Kuna-Ciskal, M. Laffranchi, J. Lagoda, Z. Li, B. Lisowski, F. Lu, J. Ma, G. Mangano, G. Mannocchi, M. Markiewicz, F. Mauri, C. Matthey, G. Meng, C. Montanari, S. Muraro, G. Natterer, S. Navas-Concha, M. Nicoletto, S. Otwinowski, O. Palamara D. Pascoli, L. Periale, G. Piano Mortari, A. Piazzoli, P. Picchi, F. Pietropaolo, W. Polchlopek, T. Rancati, A. Rappoldi, G.L. Raselli, J. Rico, E. Rondio, M. Rossella, A. Rubbia, C. Rubbia, P. Sala, D. Scannicchio, E. Segreto, Y. Seo, F. Sergiampietri, J. Sobczyk, N. Spinelli, J. Stepaniak, M. Stodulski, M. Szarska, M. Szeptycka, M. Terrani, R. Velotta, S. Ventura, C. Vignoli, H. Wang, X. Wang, M. Wojcik, G. Xu, X. Yang, A. Zalewska, J. Zalipska, C. Zhang, Q. Zhang, S. Zhen, W. Zipper.

University and INFN of: L'Aquila, LNF, LNGS, Milano, Naples, Padova, Pavia, Pisa - Italy
ETH Hönggerberg, Zürich - Switzerland
IHEP, Academia Sinica, Beijing - China
CNR Istitute of cosmogeophysics, Torino - Italy
Politecnico di Milano - Italy
University of Silesia, Katowice - Poland
University of Mining and Metallurgy, Krakow - Poland
H.Niewodniczanski Inst. of Nucl. Phys., Krakow - Poland
Jagellonian University, Krakow - Poland
Cracow University of Technology, Krakow - Poland
A.Soltan Inst. for Nucl. Studies, Warszawa - Poland
Warsaw University, Warszawa - Poland
Wroclaw University, Wroclaw - Poland
UCLA, Los Angeles - USA
University of Granada - Spain

The ICARUS programme: introduction (I)

- **ICARUS was initially proposed to INFN in 1993**
  - ➥ ICARUS-II. A Second Generation Proton Decay Experiment And Neutrino Observatory At The Gran Sasso Laboratory Proposal, VOL I (1993) & II (1994), LNGS-94/99.
- **The proposal was based on**
  - ➥ *The novel detection technique of the liquid argon TPC*
  - ➥ *Its extrapolation to large (kton) masses*
  - ➥ *To provide a rich physics programme*
    - ☛ Proton decay
    - ☛ Atmospheric neutrinos
    - ☛ Solar neutrinos
    - ☛ Supernovae neutrinos
  - ➥ *In addition, the potentialities for LBL neutrino oscillations from CERN were already covered in such proposal.*

The ICARUS programme:introduction (II)

- The ICARUS detector has been approved in 1997 by the Italian INFN and it is currently financed as an integral part of the LNGS programme.
- In view of the innovative nature of the LAr technology, a graded approach is being followed:
  1. A full scale 600 ton module, "the first in a series", has been constructed in Pavia, in collaboration with industry.
  2. The successful operation of the T600 half-module during the Summer 2001 has demonstrated that the technique has matured.
  3. With a physics program of its own, the installation of the T600 has been recommended by GSSC. It will be placed in Hall B of LNGS during Summer 2003, and commissioned for physics right after.
  4. In order to reach the design mass, the cloning of the T600 for further modules has been recommended by GSSC:
     - ☛ *"(…) urges both the collaboration and the laboratory to work closely together on carrying out a complete risk analysis including all the safety relevant data of the final module (resembling the possible base element of T3000)"*
  5. INFN Comm II has approved the T3000 scientific programme and the design of successive T1200 modules (design is now ongoing in collaboration with industry). The first T1200 module is funded.
  6. The upgrade foresees extending the T600 with two new T1200 modules by early 2006. Total active liquid argon mass: 2003: 476 ton; Q4 2004: 1430 ton; Q4 2005: 2380 ton.

Recent presentations at CERN

- "A proposal for a CERN-GS long baseline and atmospheric neutrino oscillation experiment", SPSC, September 1999
- "A Status Report on the LAr detector construction", SPSC, September 2000
- "Liquid Argon Imaging: a Novel Detection Technology", Carlo Rubbia, CERN Seminar, February 2002

The ICARUS R&D has also been extensively reported in publications (see also http://www.aquila.infn.it/icarus and http://www.cern.ch/icarus and links therein)

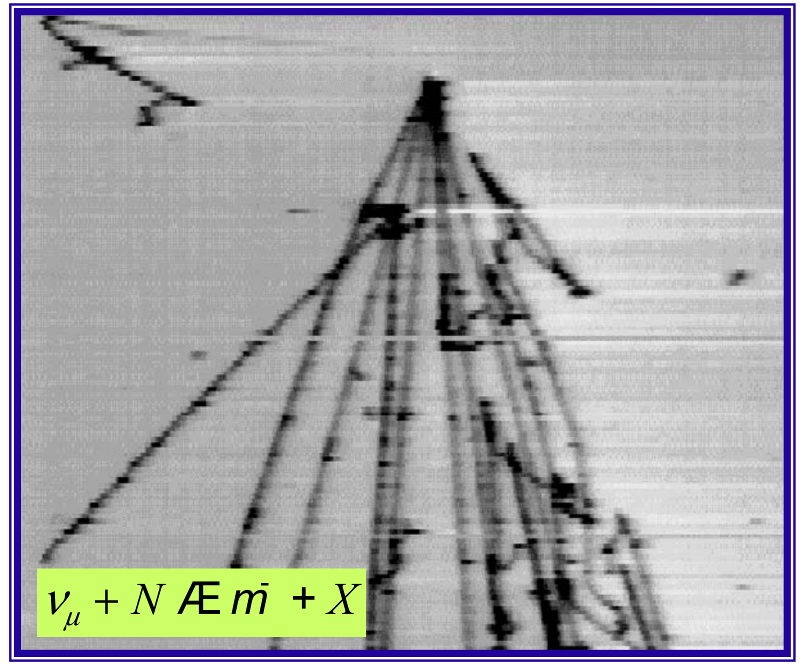
Past experience and results: the scaling up in mass

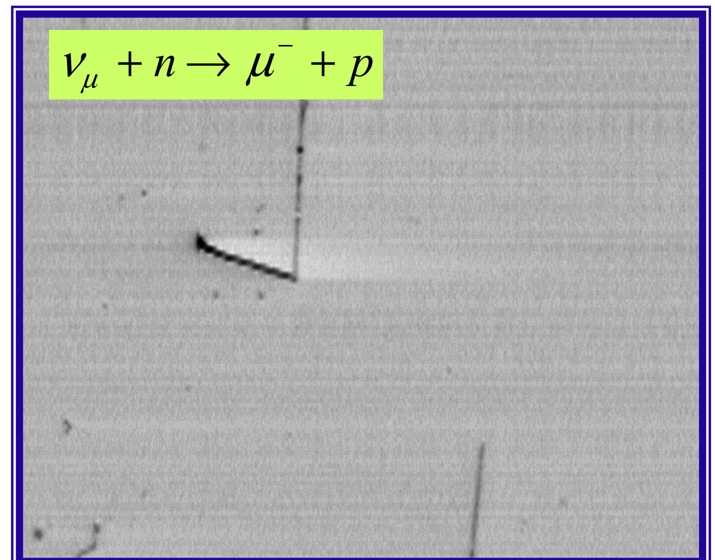
Past experience and results - 50 liter prototype

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

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

- LAr purification by Ar vapour filtering and re-condensation
- LAr purity monitors
- Optimization of front-end electronics for induction and collection planes
- Warm and cold electronics
- Readout chain calibration studies
- Signal treatment
- Collection of scintillation light
- 1.4 m drift length (special test)





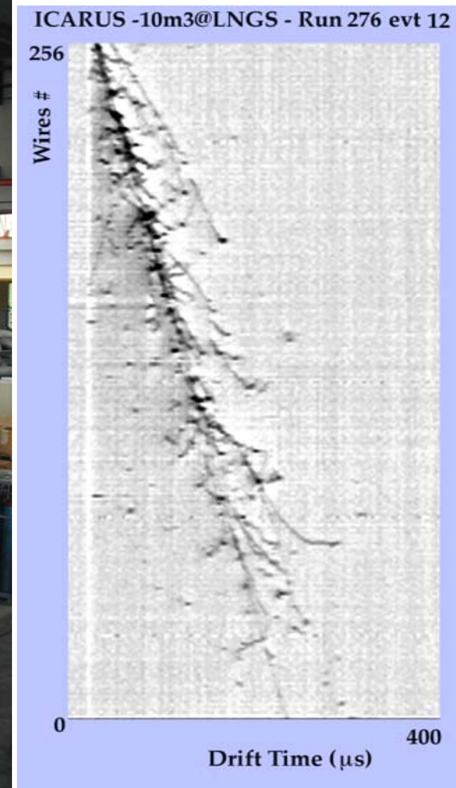
Past experience and results - 15 ton prototype

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

✓Final electronics
✓DAQ
✓External trigger
✓100 days run in LNGS external hall
✓Max. electron lifetime ≈ 2 ms

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

T15 installation @ LNGS (Hall di Montaggio)

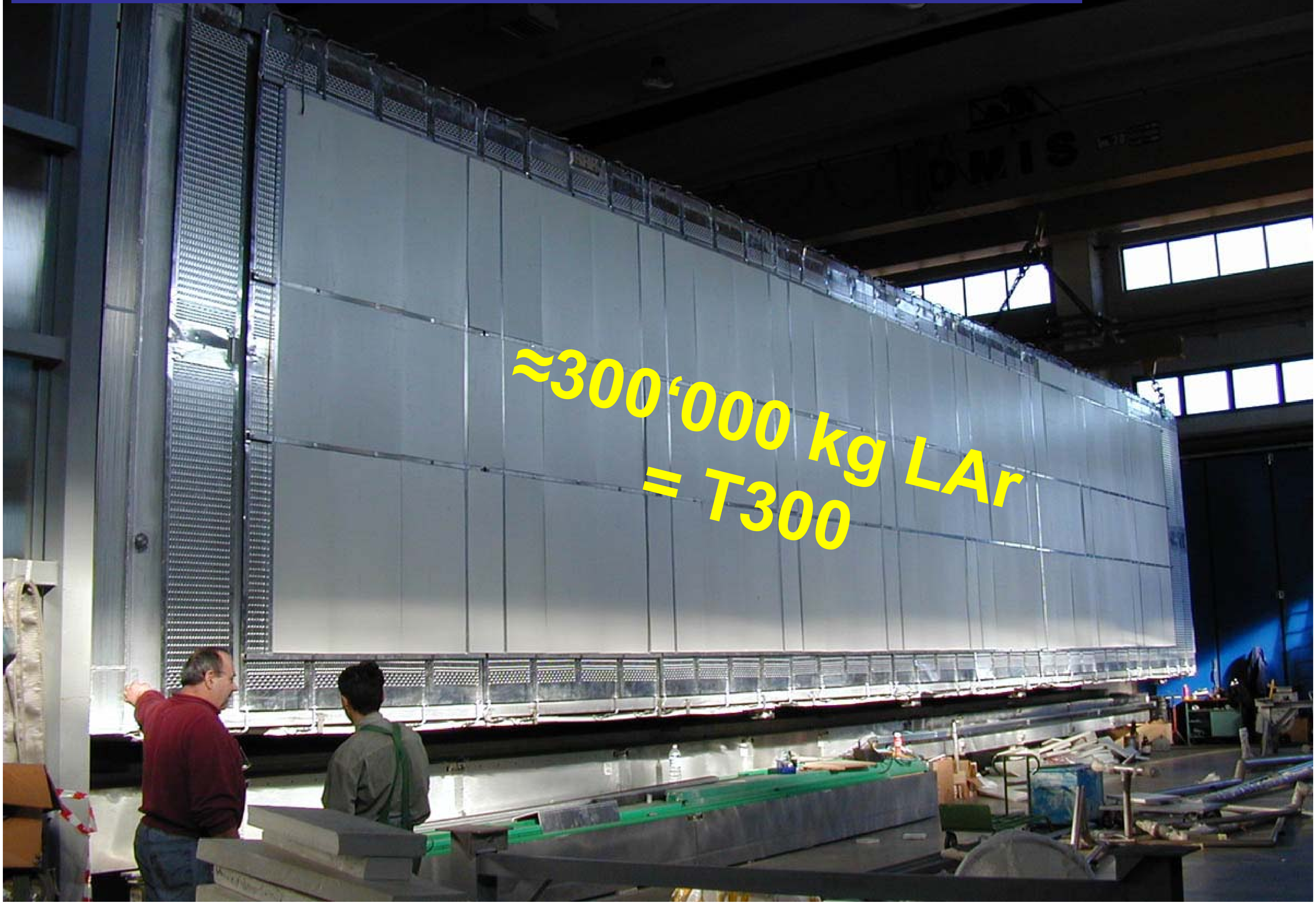


Experience and results - 300 ton detector

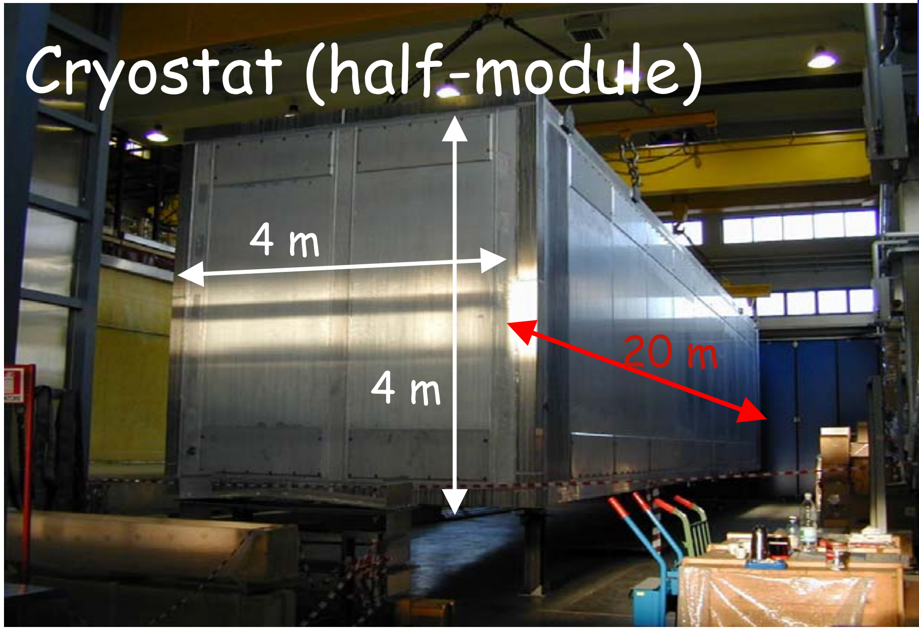
- Total volume : 350 m^3
- Readout planes: 3 (–60°,60°,0°)
- Max drift distance: 150 cm

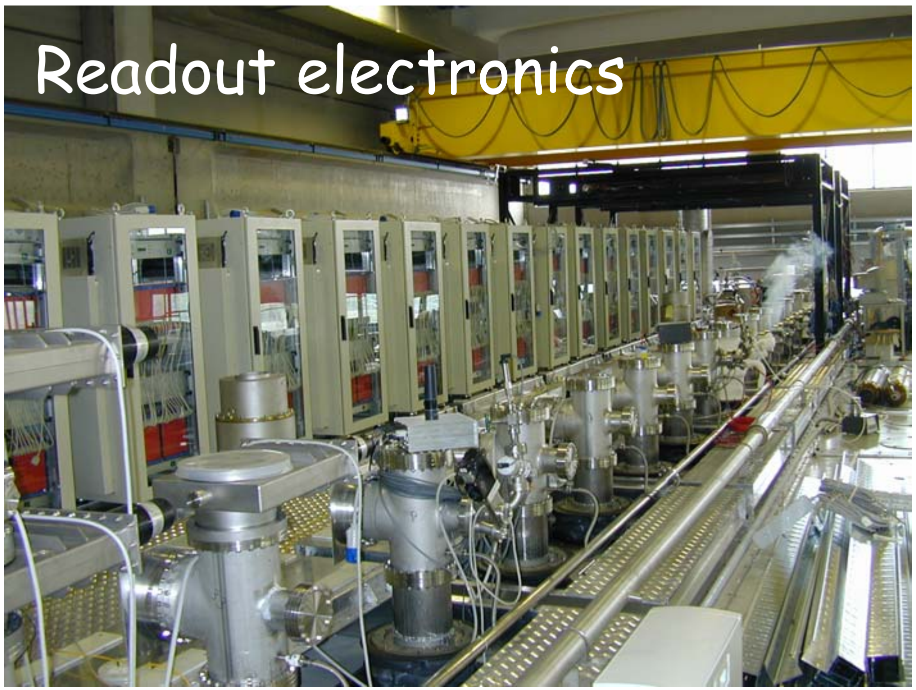
- Full scale technical run of the T300 detector in Pavia:
  - ➥ Cryogenics ✔ (decrease the LN2 consumption)
  - ➥ Wire chamber mechanics ✔✔
  - ➥ Argon purification ✔
  - ➥ Electronic noise ✔
  - ➥ High voltage for the drift ✔✔ (also at 150 KV)
  - ➥ PMTs for scintillation light collection ✔
  - ➥ Readout & DAQ ✔
  - ➥ Slow control ✔
- Development of event reconstruction SW with real events and data analysis (ongoing effort)
  - ➥ Imaging ✔ ✔
  - ➥ Event reconstruction ✔
  - ➥ 3 plane readout ✔
  - ➥ Calibration ✔
  - ➥ Resolution ✔

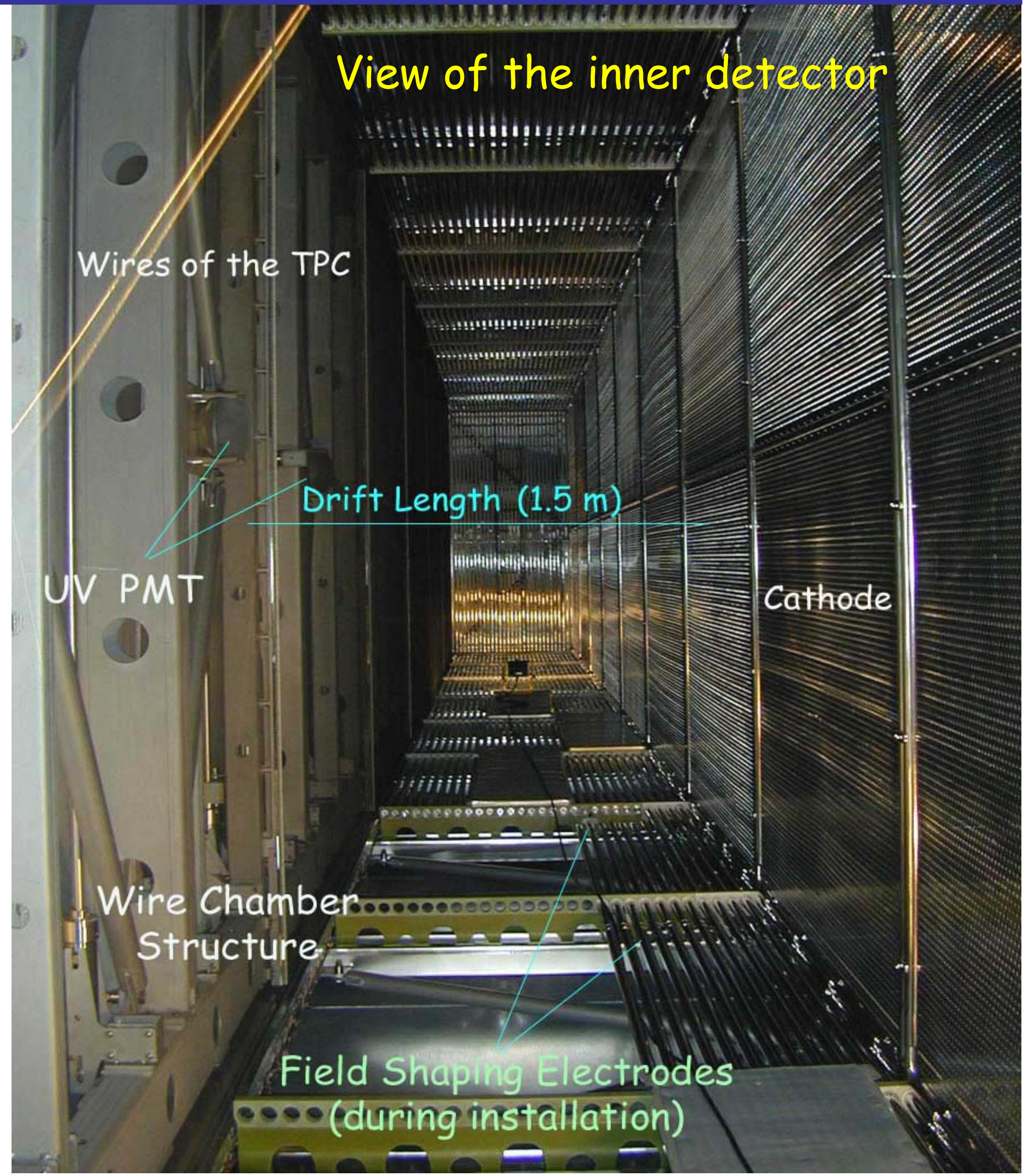
ICARUS T300 cryostat (1 out of 2)



ICARUS T300 prototype

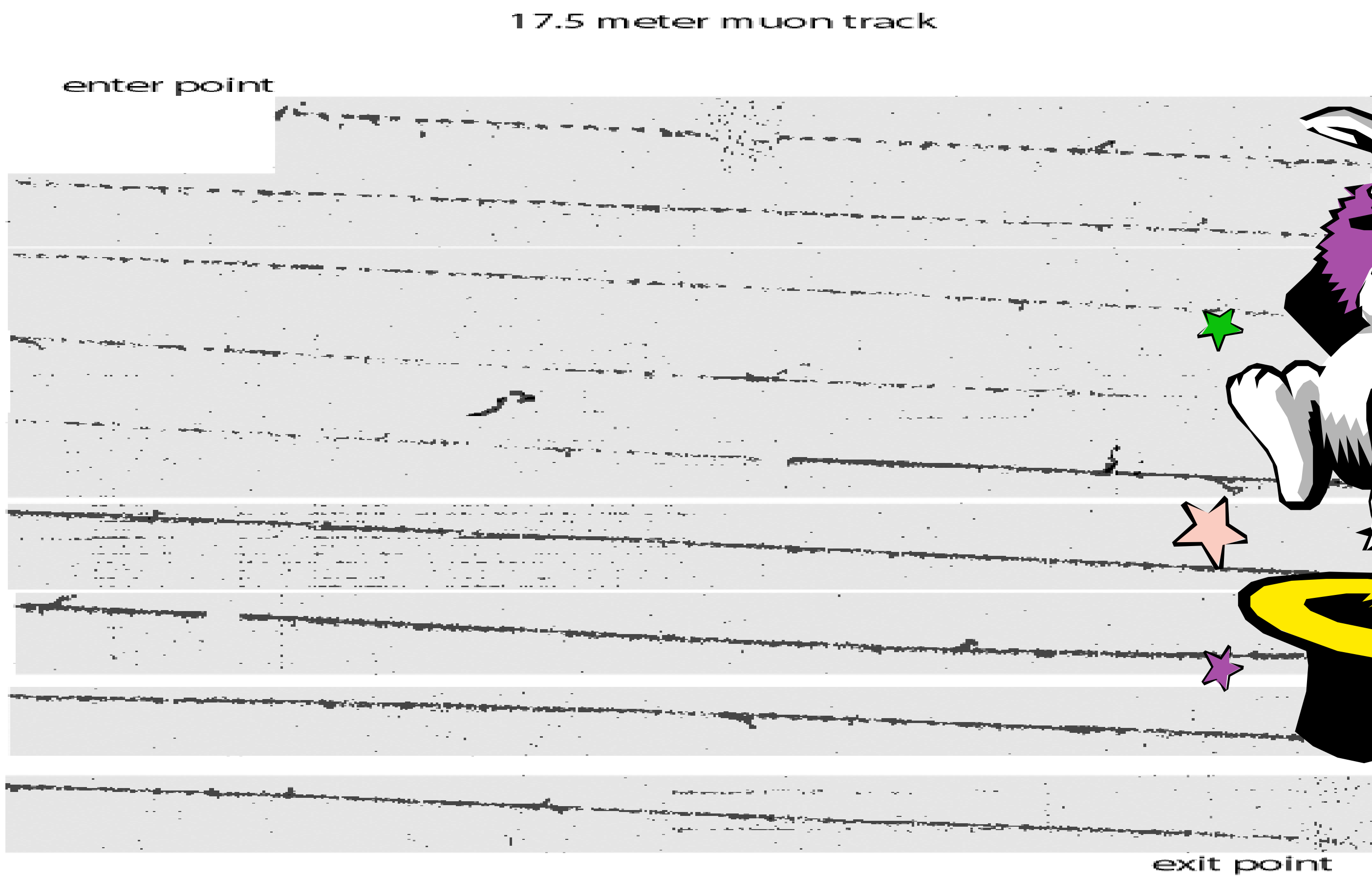


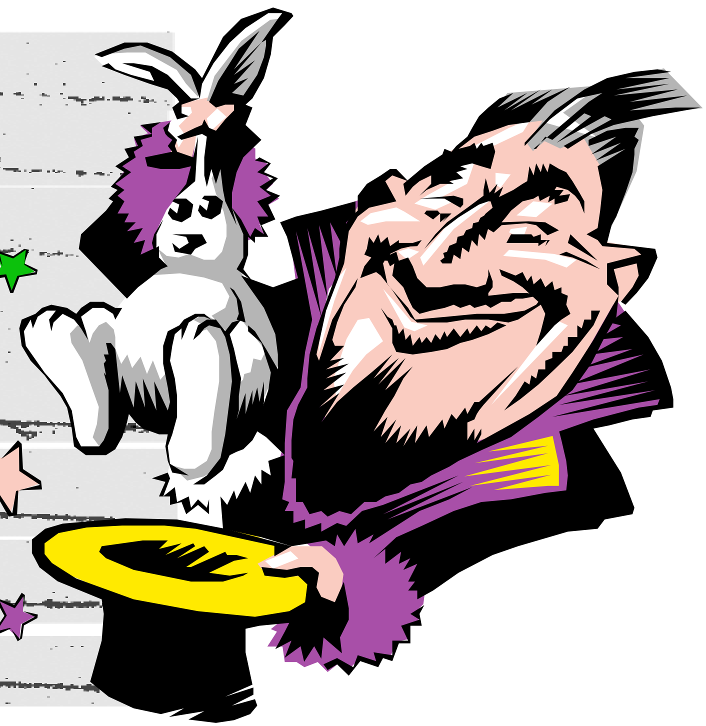




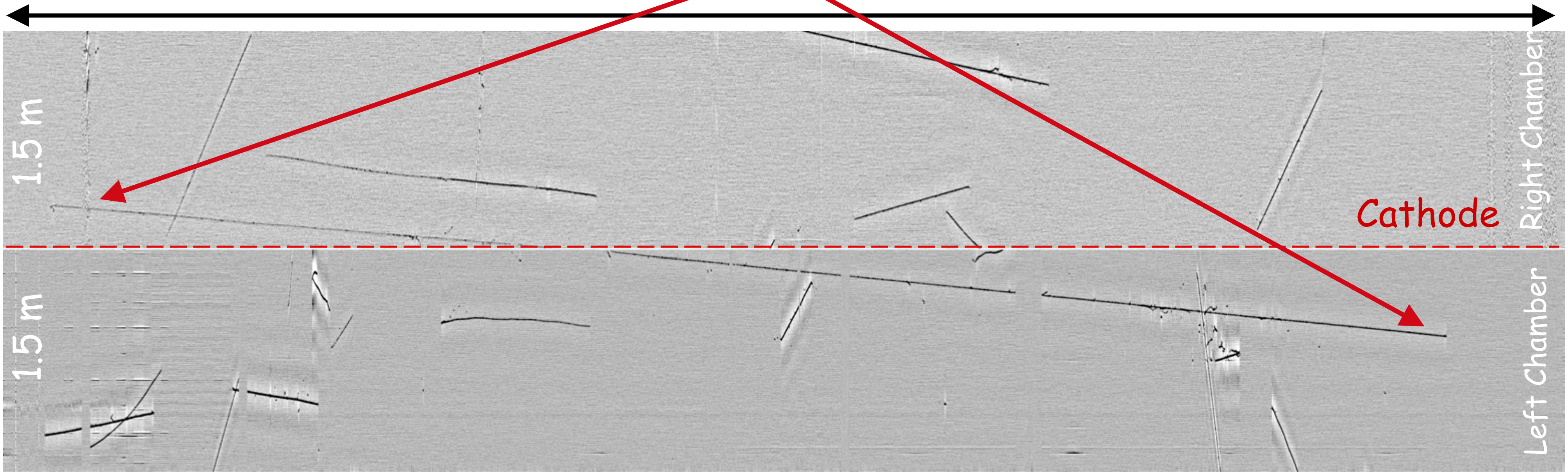
Answering the SPSC request: The 18 meter long track…

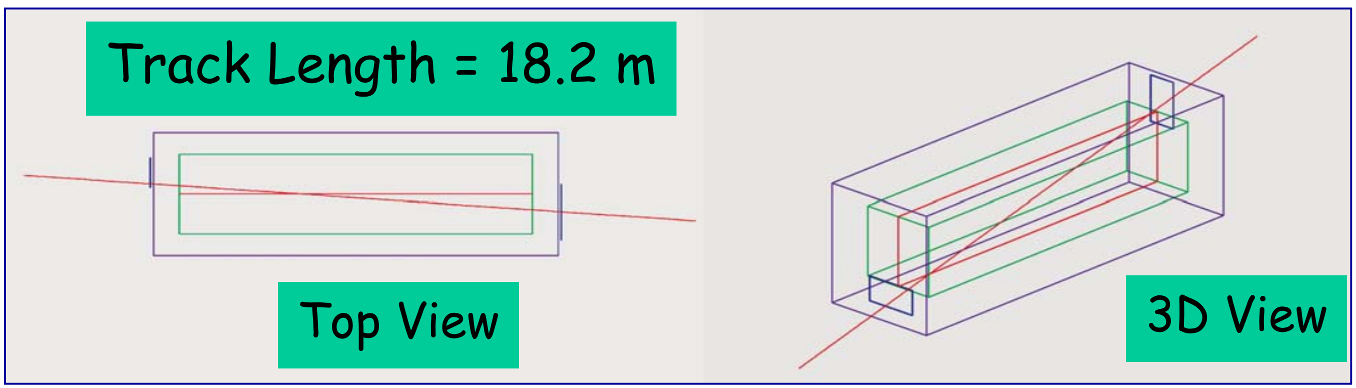
- “The Committee congratulates (…) progress (…) in the construction of the T600 module and **awaits recording of long tracks in this module**.”, SPSC September 2000



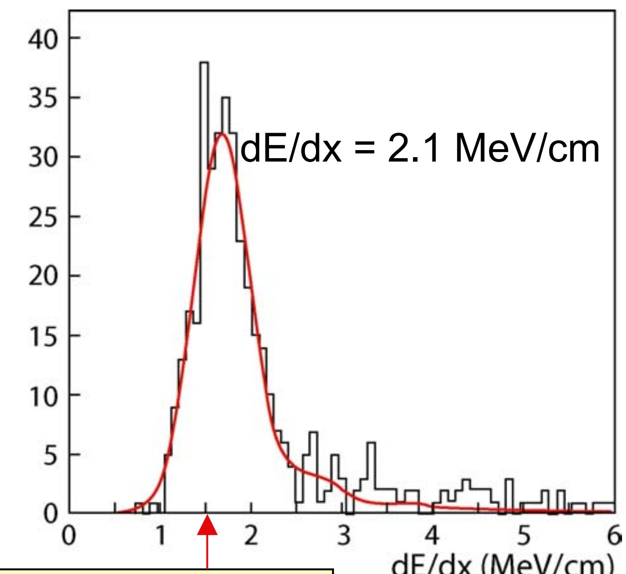


Longitudinal muon track crossing cathode plane





3-D reconstruction of the long track



dE/dx distribution along the track

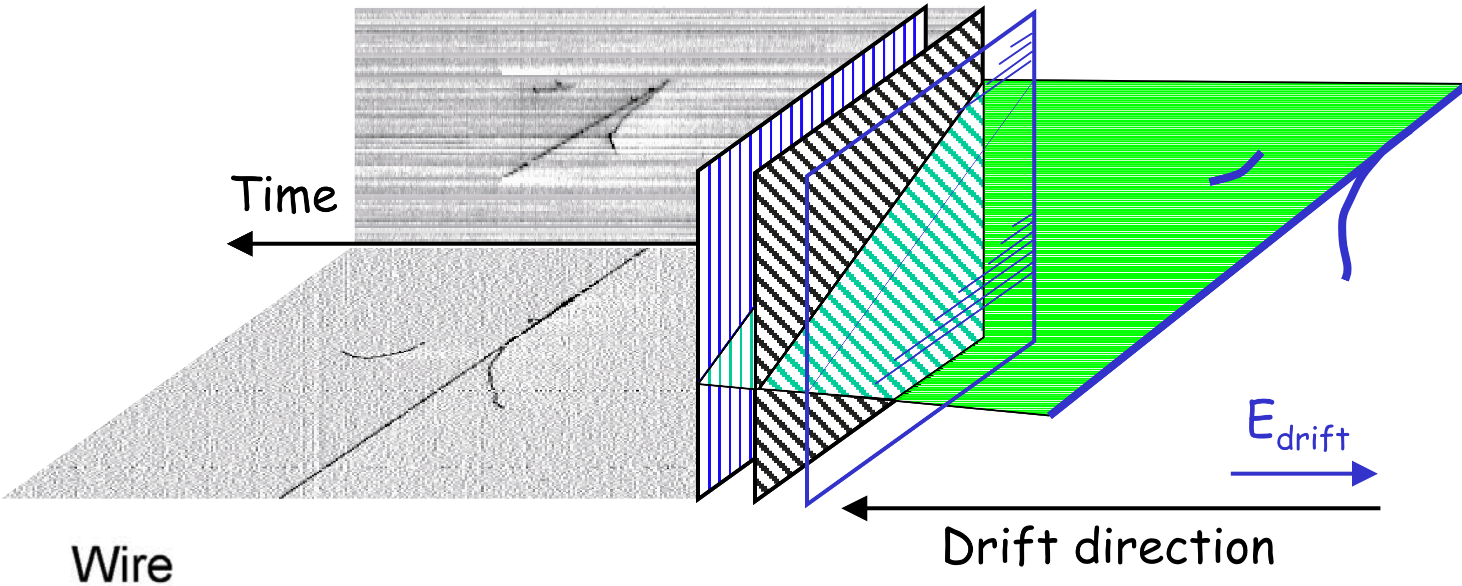
Brief overview of T600 perfomance

T600 prototype performance

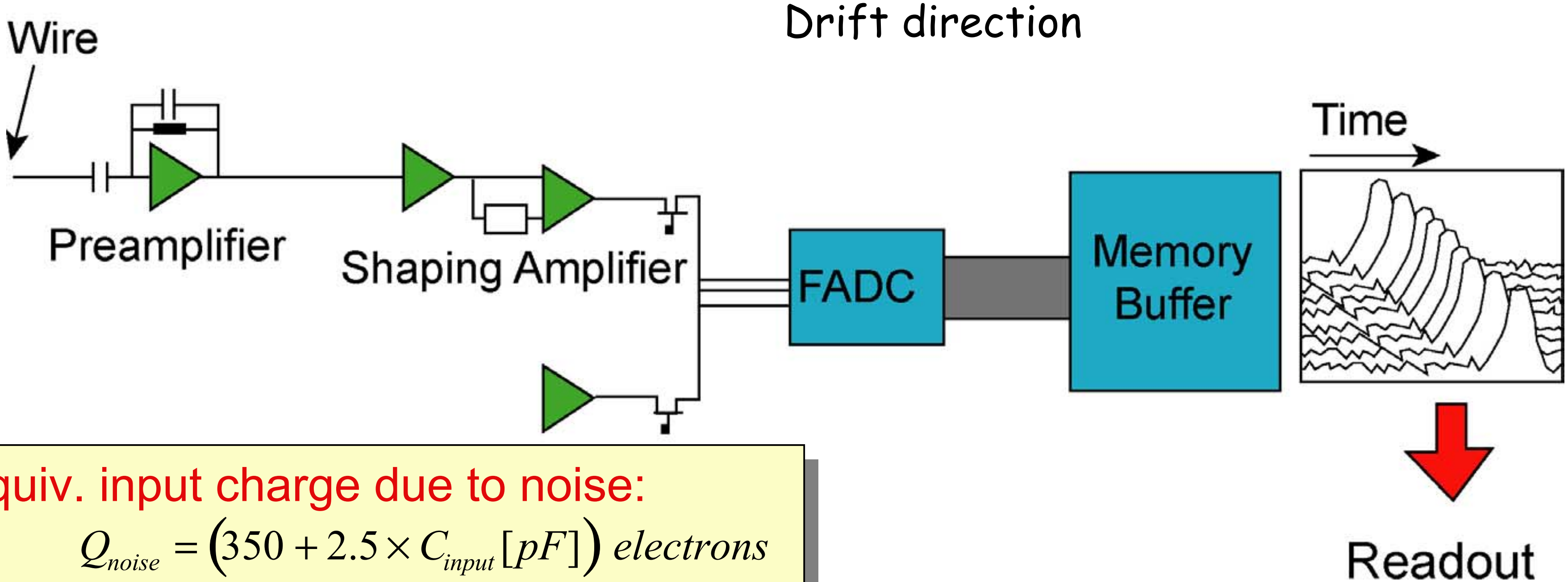
- The technical run in Pavia in summer 2001 has allowed not only to ascertain the maturity of large scale liquid Argon imaging TPC, but has also allowed to collect (in addition of the 18 m long track) a large number of C.R. events
  - ➥About 28000 triggers have been accumulated
- These events provide valuable data to check the performance of a detector of such large scale. We find that:
  results of the same quantitative quality as those obtained with smaller prototypes (e.g. 3 ton, 50 liter, …) have been achieved with a 300 ton device.

  ☛ Scaling up is successful.

Readout principle



- Continuously sensitive
- Self-triggering



Equiv. input charge due to noise:

$$Q_{noise} = \left(350 + 2.5 \times C_{input}[pF]\right)\ electrons$$

Signal extraction procedure

Collection plane wire analysis: charge = signal area

The same empirical function used to fit muon hits and test pulse hits

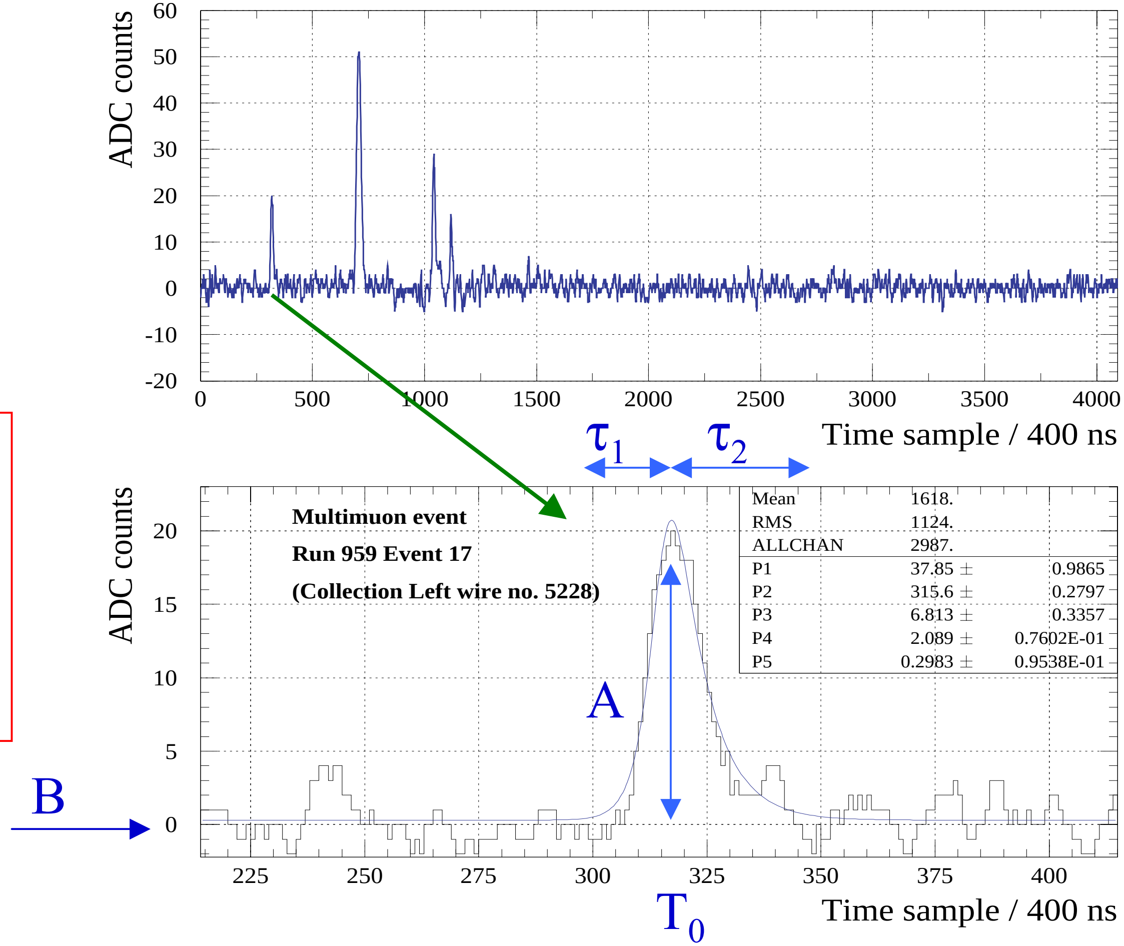
$$f(t) = B + A \frac{e^{-\frac{t - T_0}{\tau_2}}}{1 + e^{-\frac{t - T_0}{\tau_1}}}$$

B = baseline

A = amplitude

τ_1 , τ_2 = rise and fall time

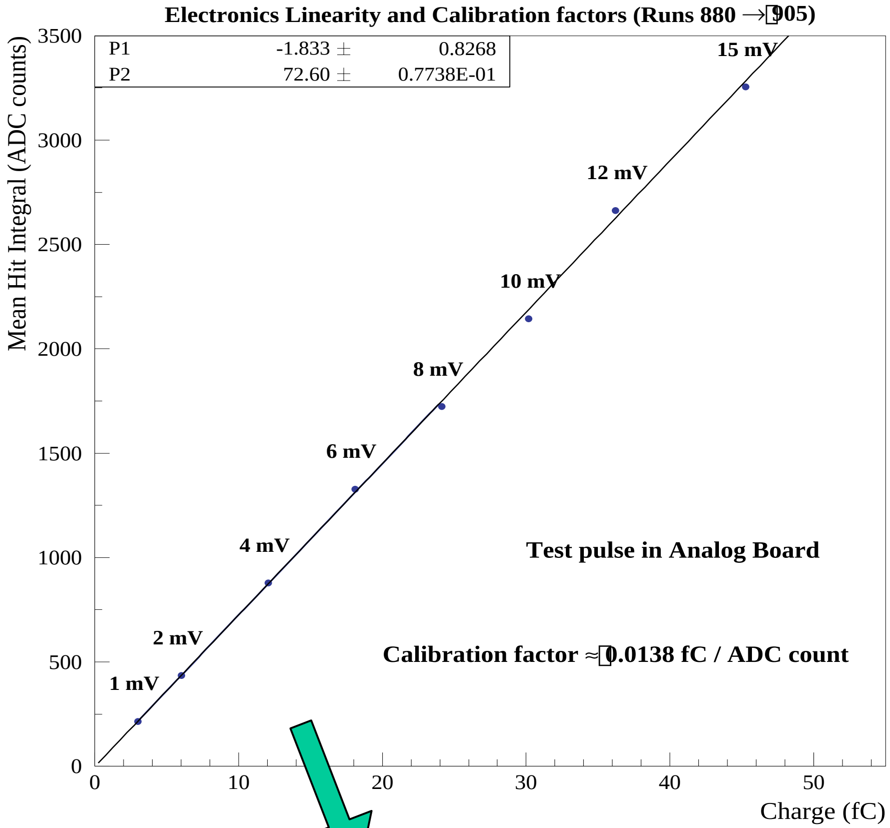
T_0 = peak position



… find the equivalence between charge and ADC counts = CALIBRATION FACTOR

Linearity and calibration

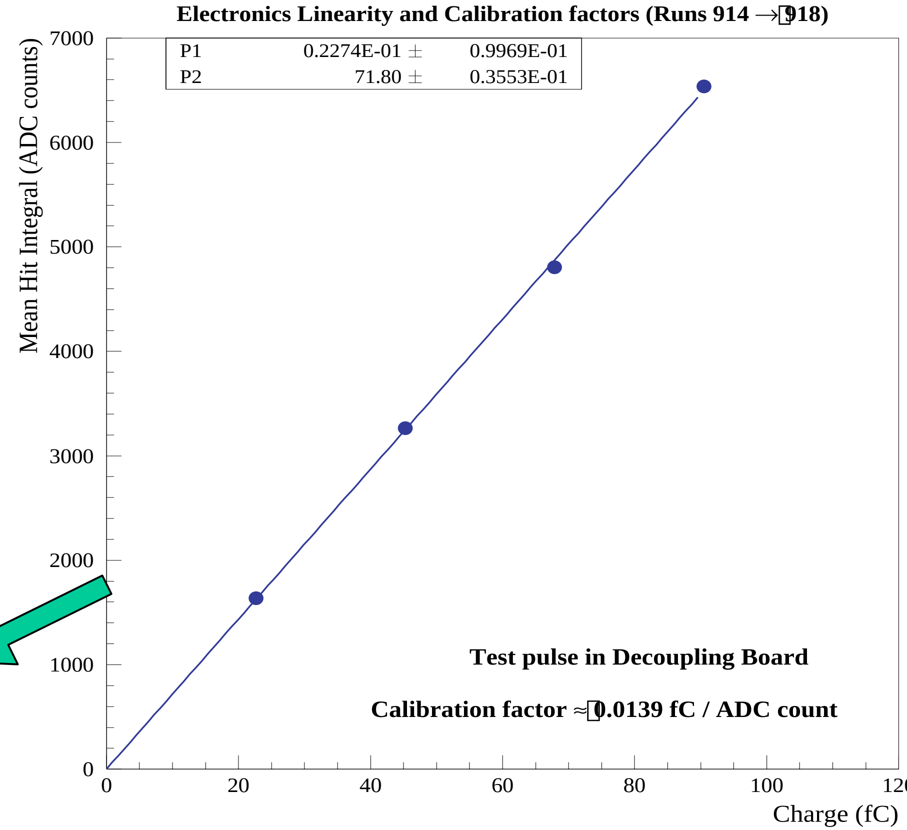
Analog Boards: 0.0138 ± .01% fC / ADC count



For each channel and for each value of the injected charge:

- calculate the hit integral (= charge)
- plot it as a function of the input charge (fC)
- fit the distribution to a straight line (1/slope gives the calibration factor)

Decoupling Boards: 0.0139 ± 0.05% fC/ADC count



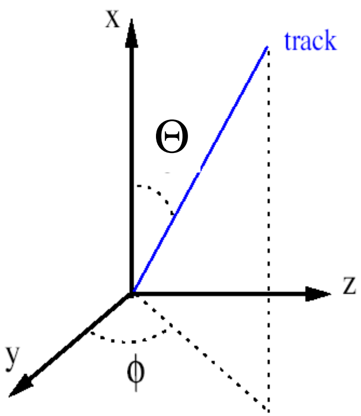
Good agreement Analog ↔ Decoupling boards

0.0138 ± 3% fC / ADC count

(error mainly due to test capacitances nominal accuracy)

3D reconstruction

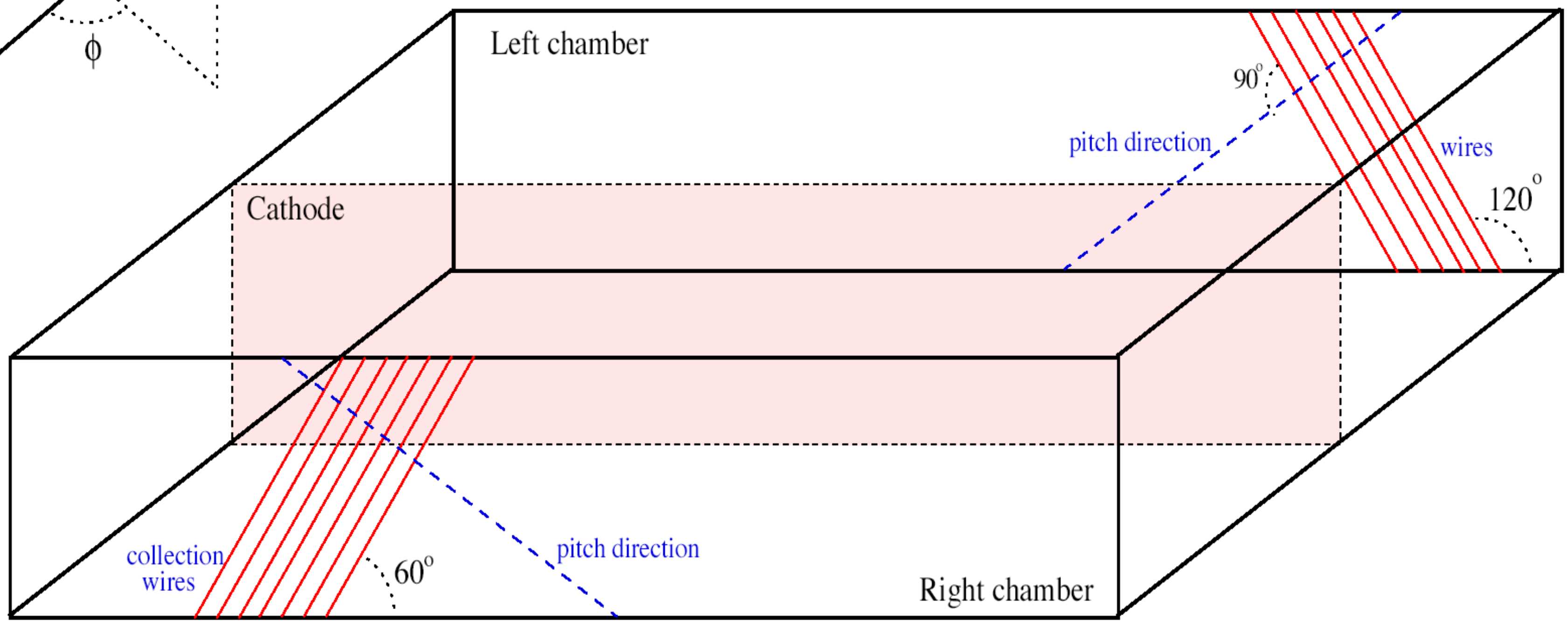
- The 3D reconstruction is based on the fact that the drift time coordinate (y-coordinate) is shared among all three views.
- The matching between the views is redundantly done at the “hit”-level



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

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

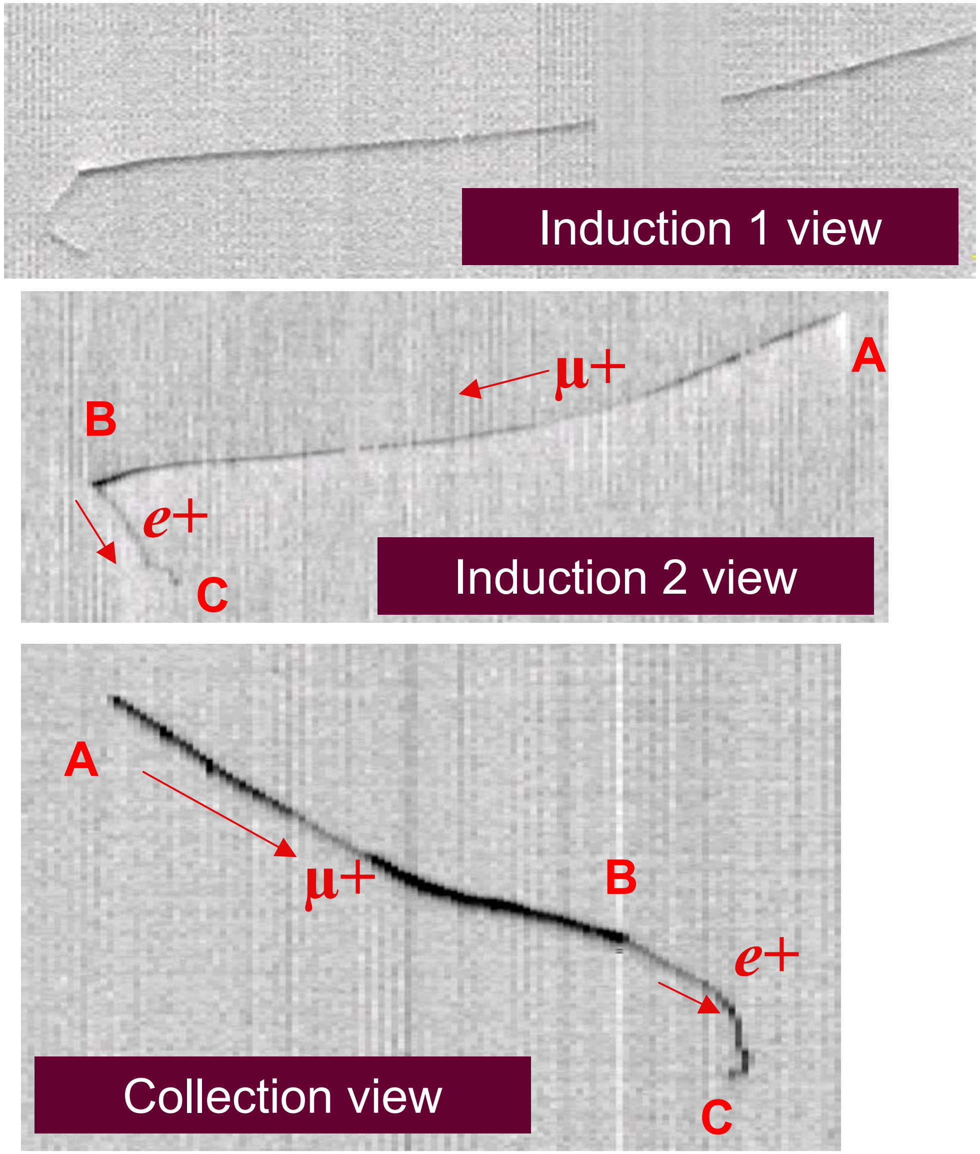
- p = 2.99 mm
- θ = 60°
- ω_0 = 528
- f = 2.5 MHz



Stopping muon reconstruction example

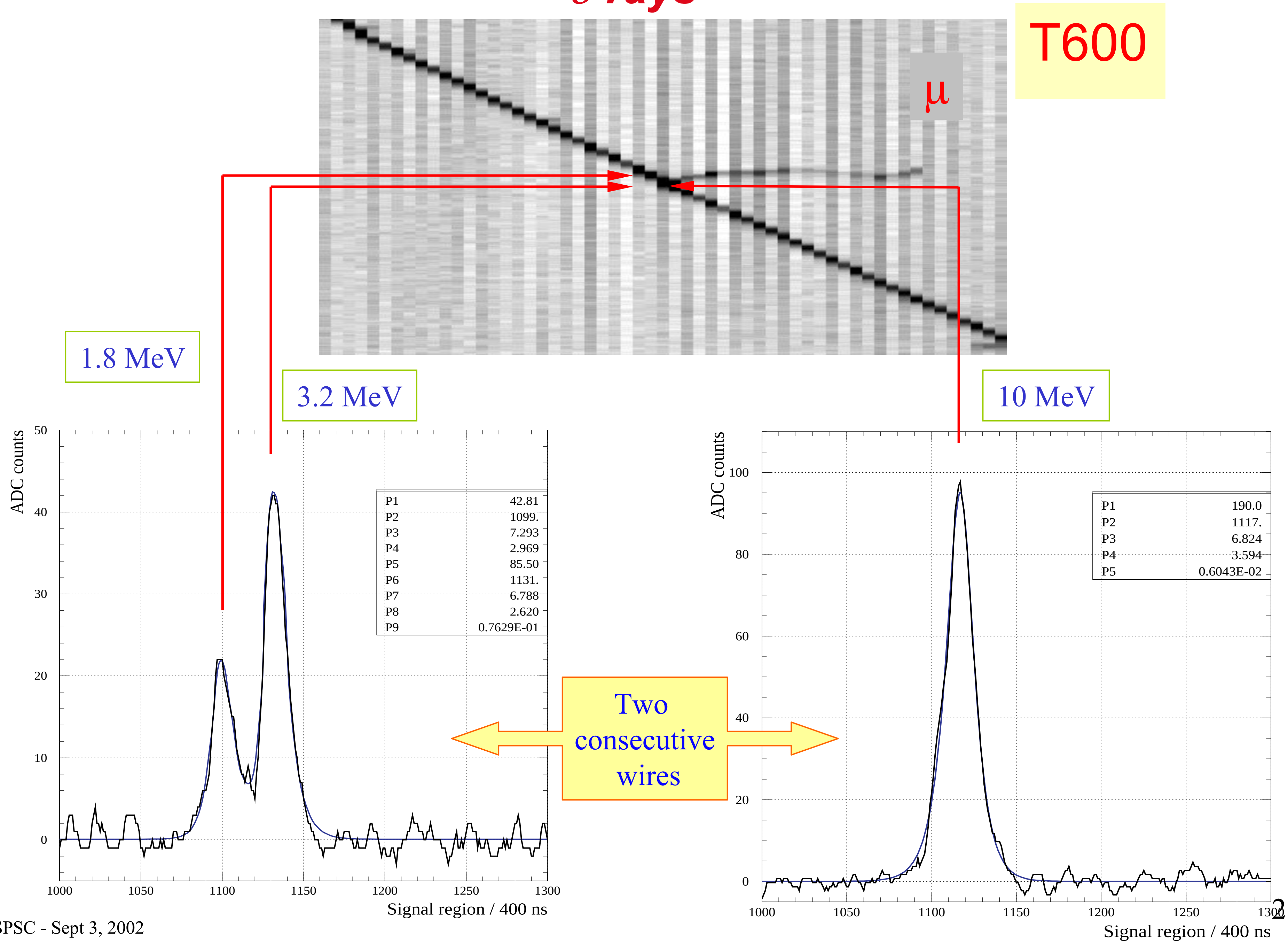
$\mu^{+}[AB] \rightarrow e^{+}[BC]$

Run 939 Event 95 Right chamber



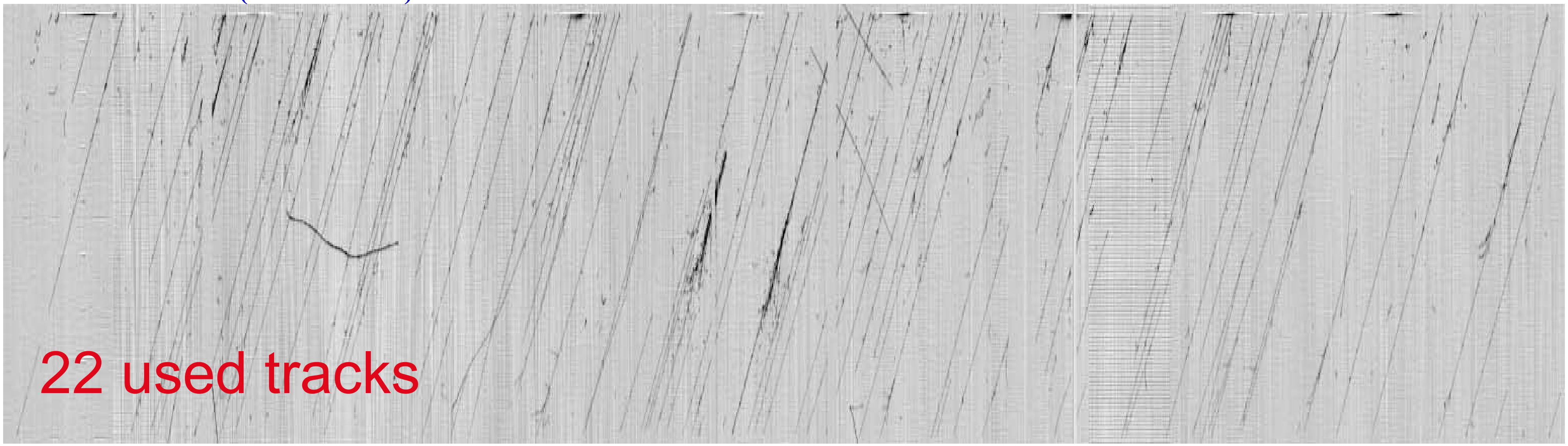
T_e=36.2 MeV
Range=15.4 cm

δ-rays

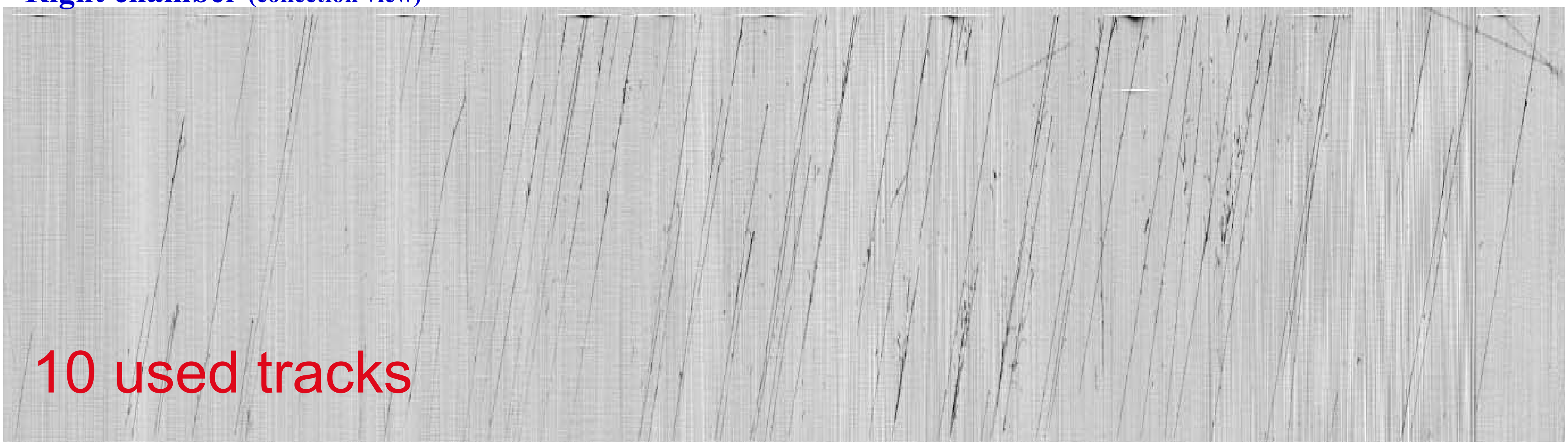

T600
μ
1.8 MeV
3.2 MeV
10 MeV
Two consecutive wires
ADC counts
Signal region / 400 ns
P1 42.81
P2 1099.
P3 7.293
P4 2.969
P5 85.50
P6 1131.
P7 6.788
P8 2.620
P9 0.7629E-01
P1 190.0
P2 1117.
P3 6.824
P4 3.594
P5 0.6043E-02

Muon bundle event (Run 959, Event 17)

Left chamber (collection view)

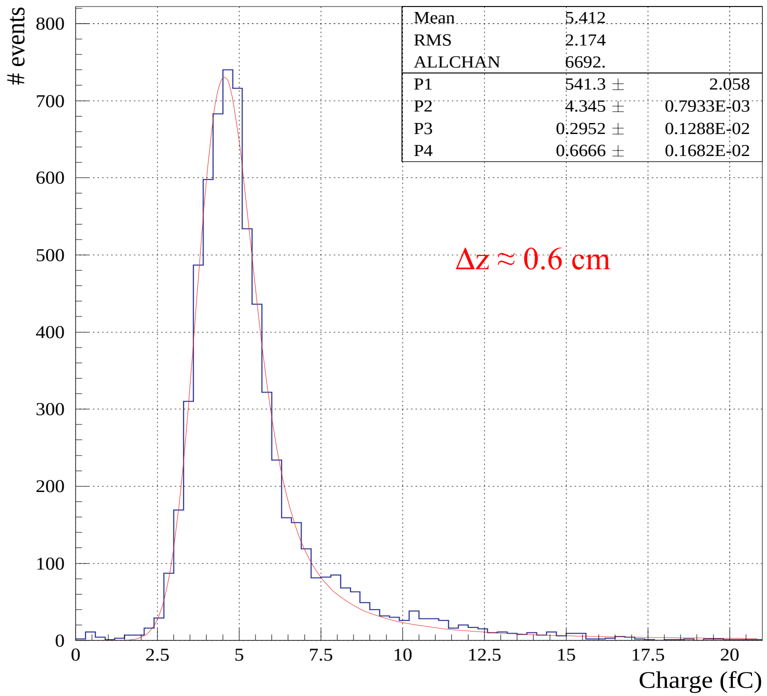


Right chamber (collection view)



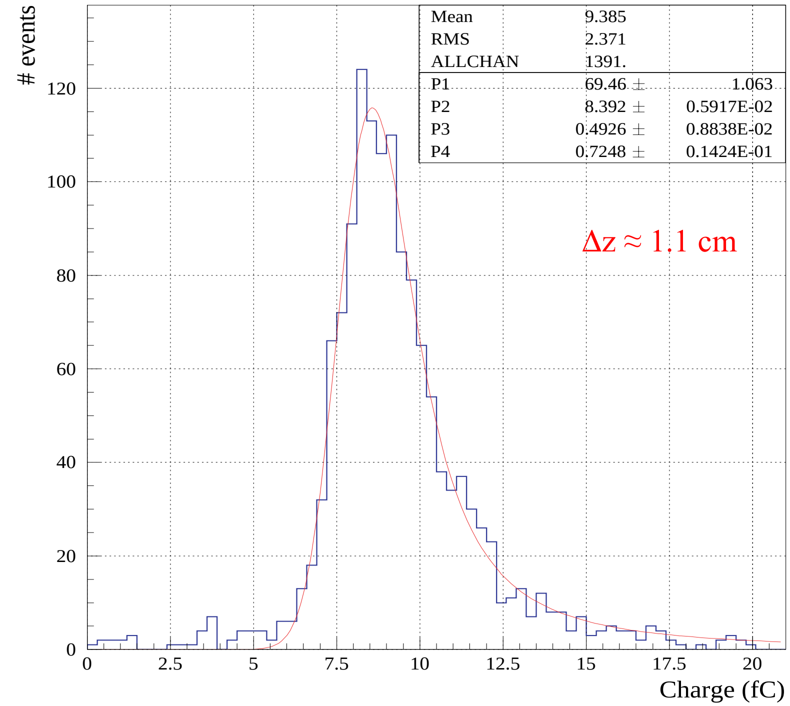
Landau distribution from single event (32 tracks)

Left chamber



6692 entries

Right chamber



1391 entries

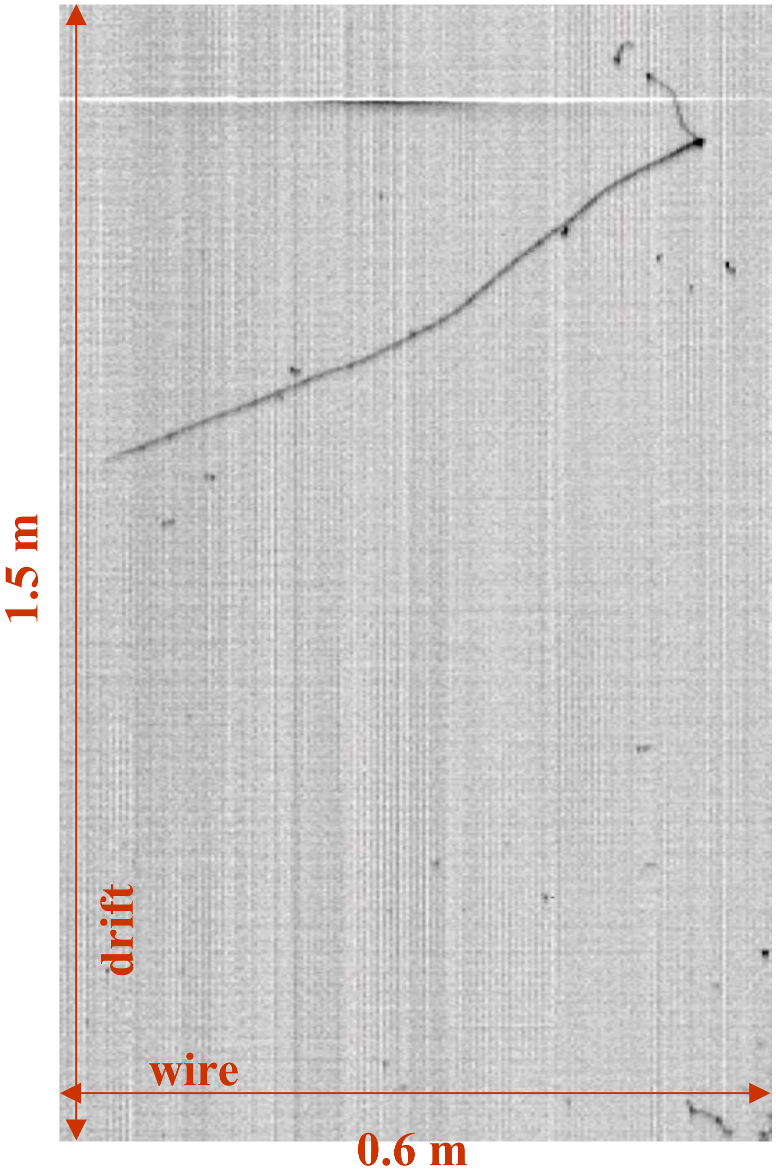
All hits from all tracks
after lifetime correction

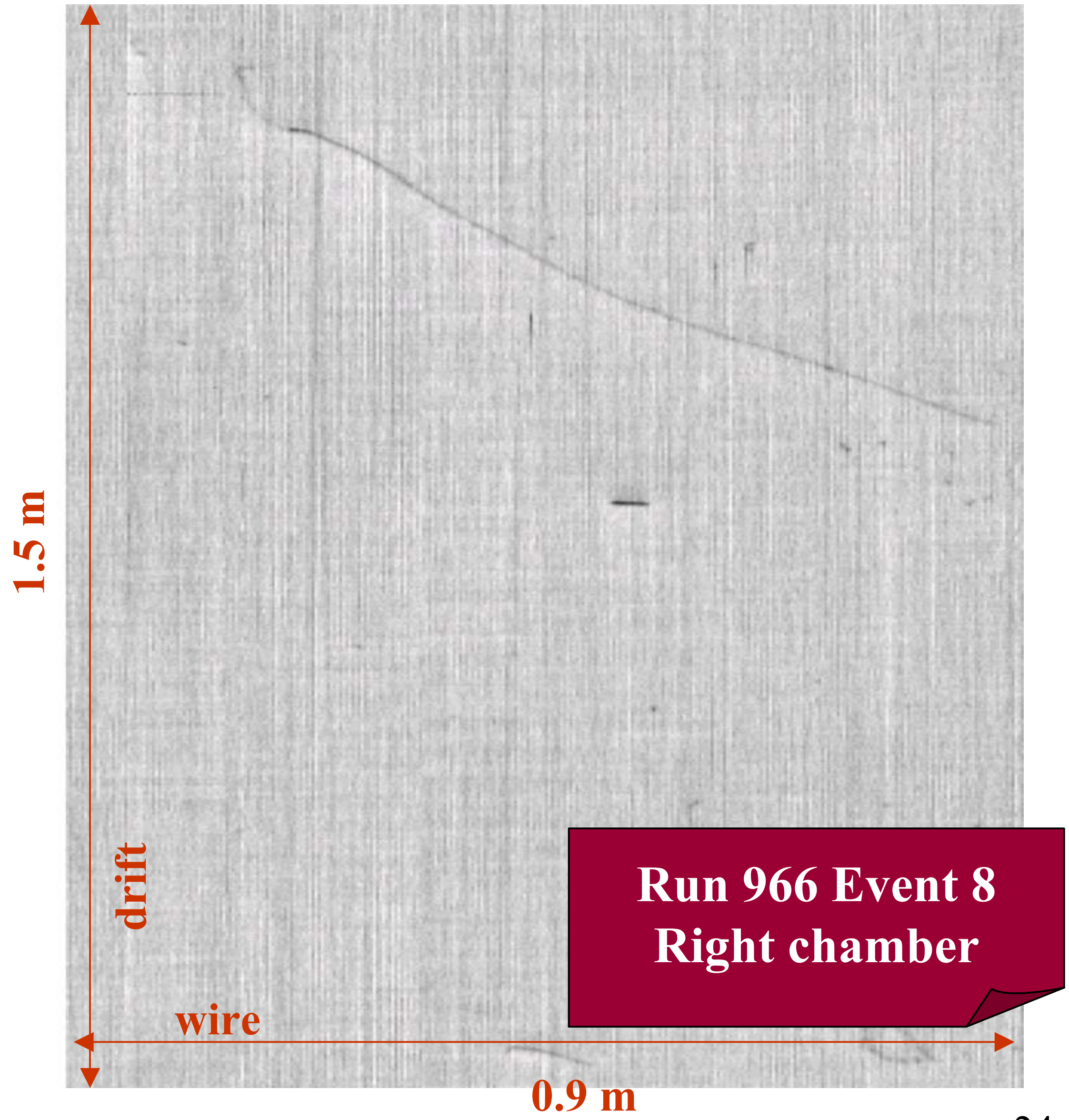
Landau + Gauss fit

$\Delta_{mp} = 4.34 \pm 0.15$ fC

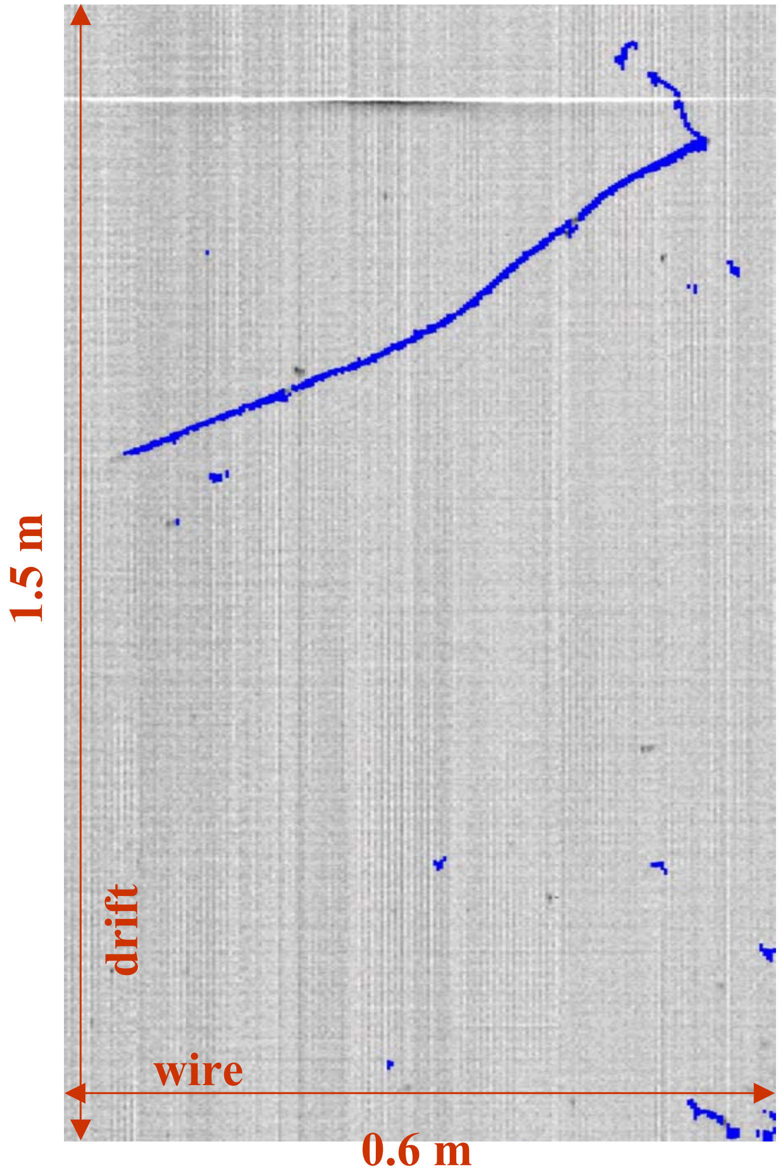
$\Delta_{mp} = 8.39 \pm 0.28$ fC

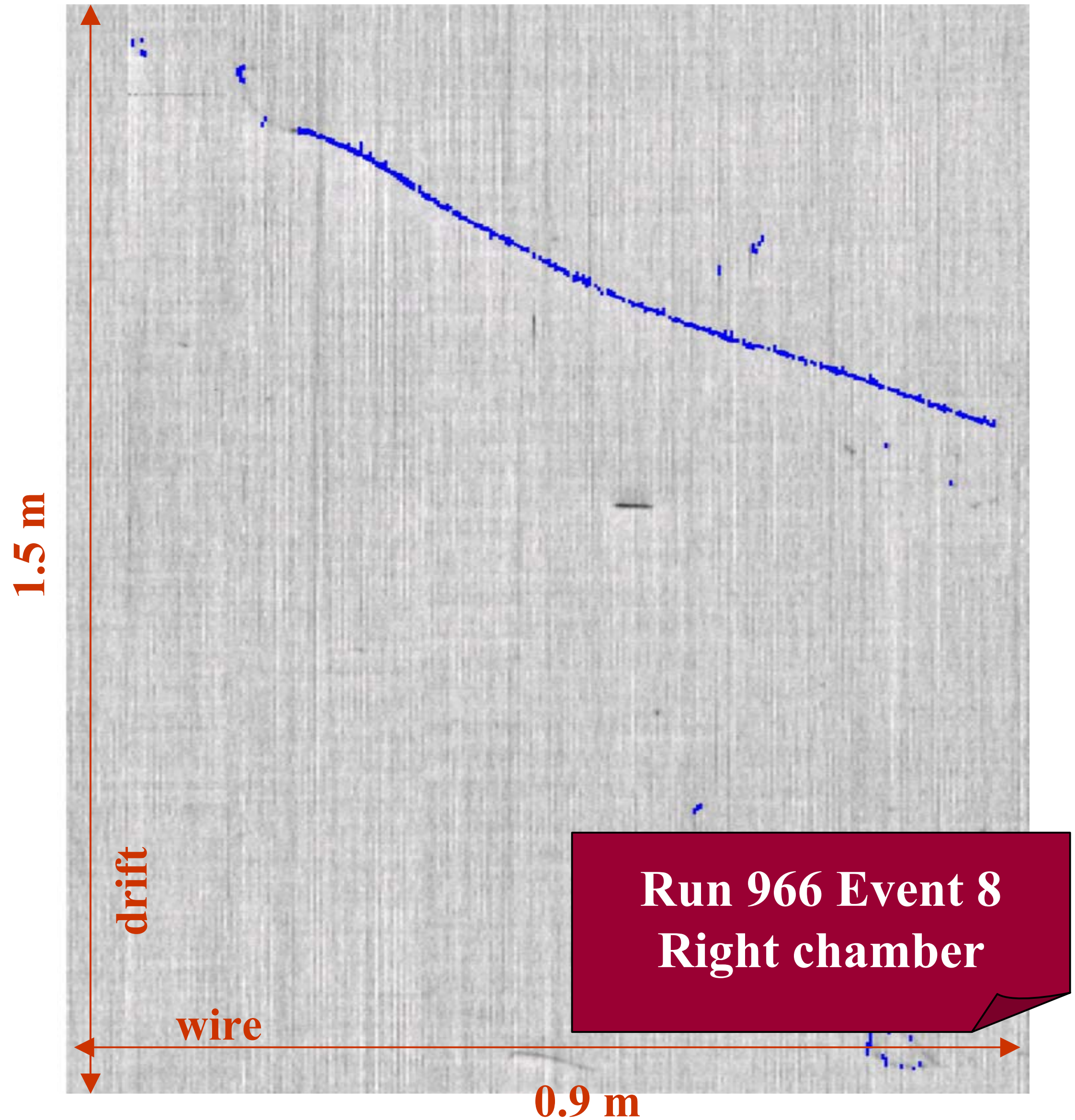
Stopping muon automatic reconstruction (I)



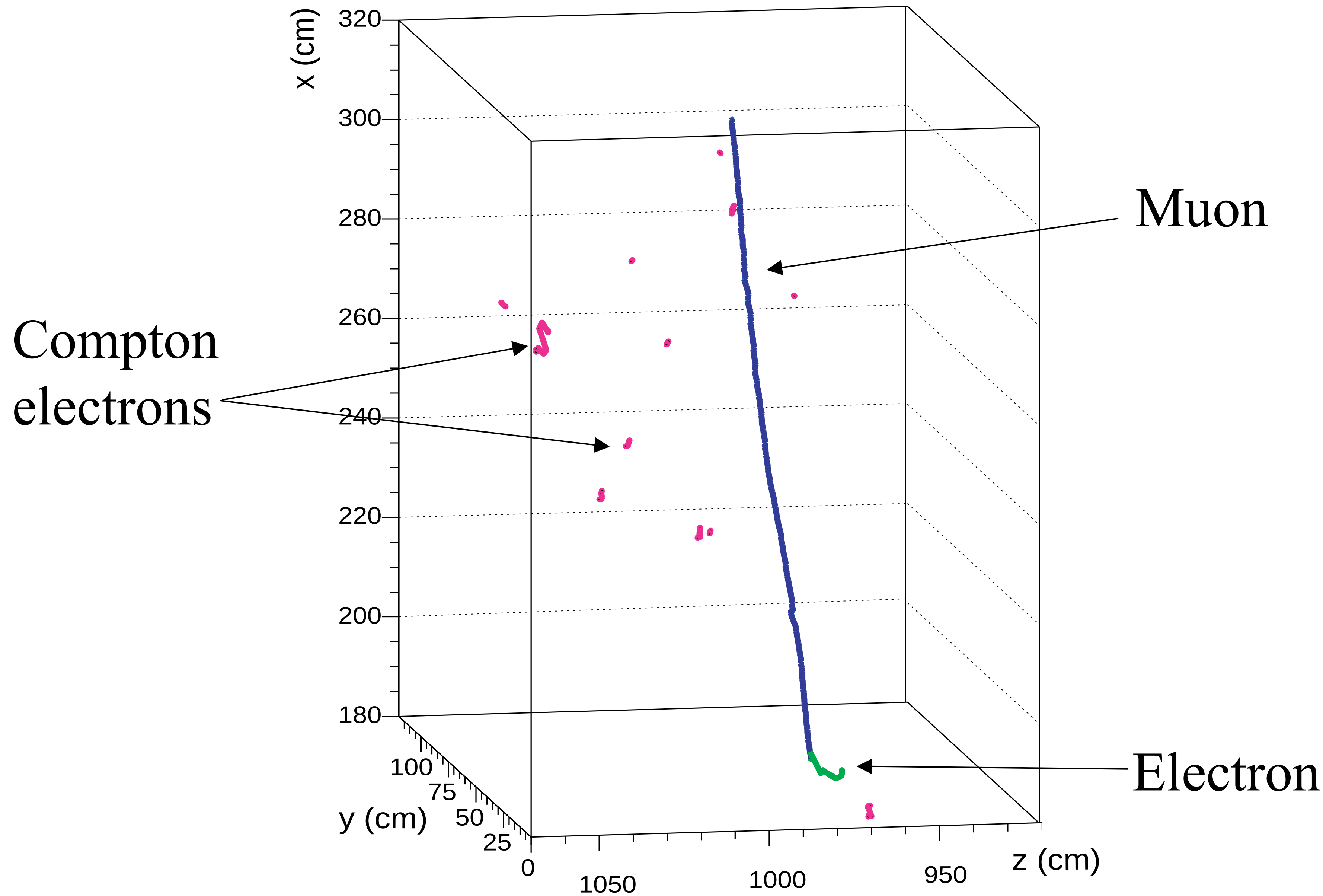


Stopping muon automatic 2D reconstruction (II)





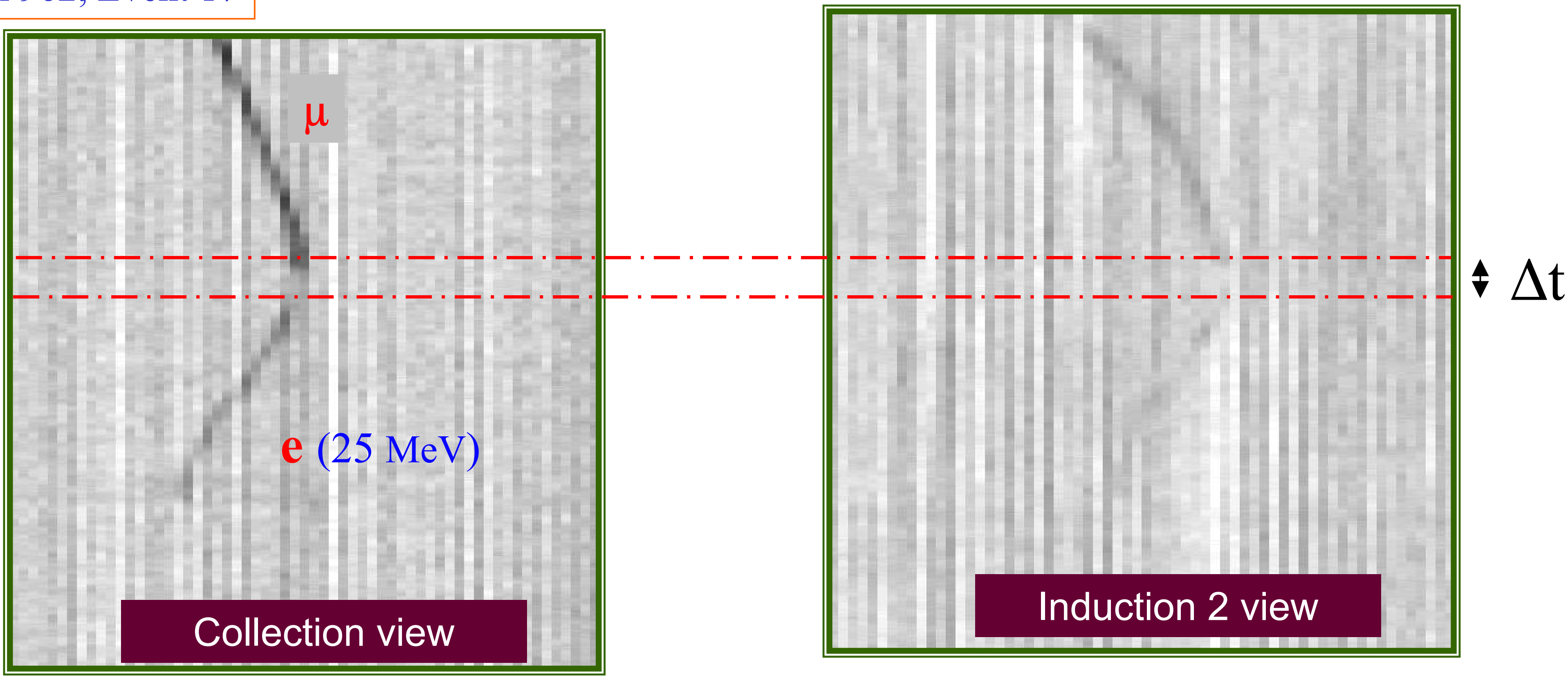
Stopping muon automatic 3D reconstruction (III)



Displaced electron from muon decay lifetime

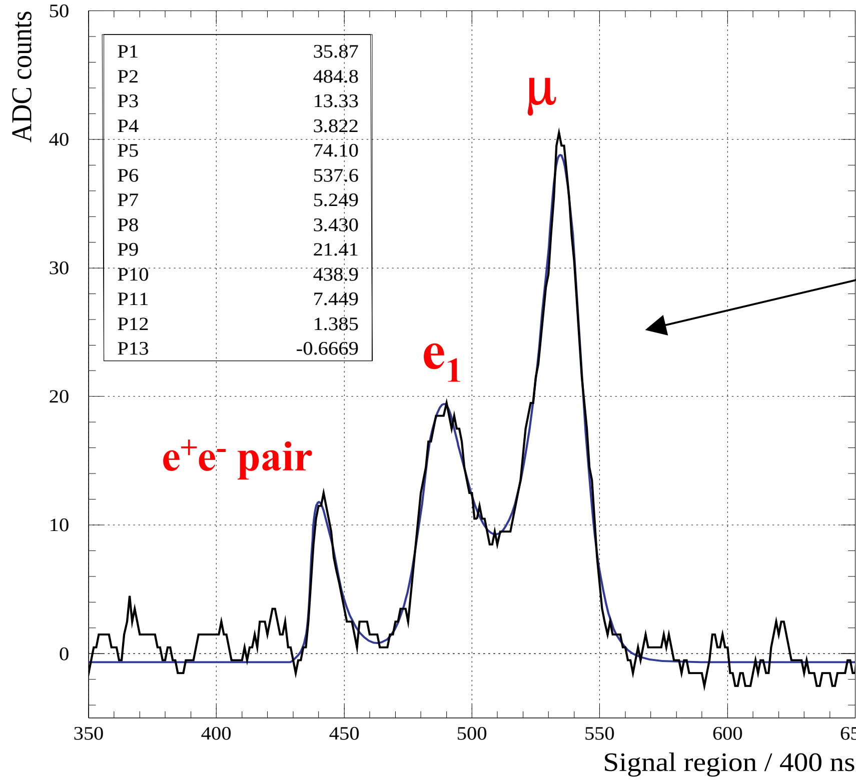
$\Delta t \approx 8\ \mu s$

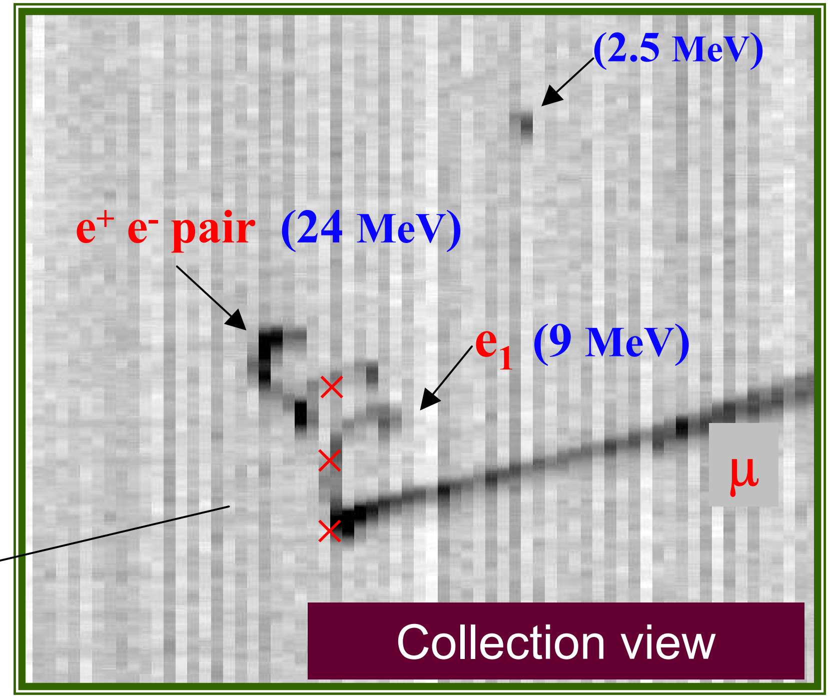
Run 962, Event 17

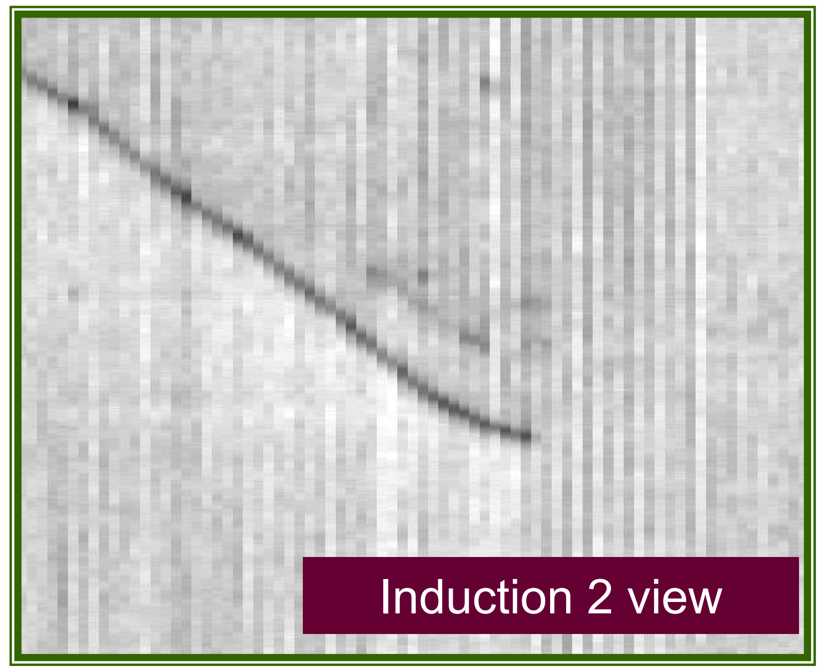


Bremsstrahlung + Pair-production

Run 975, Event 163





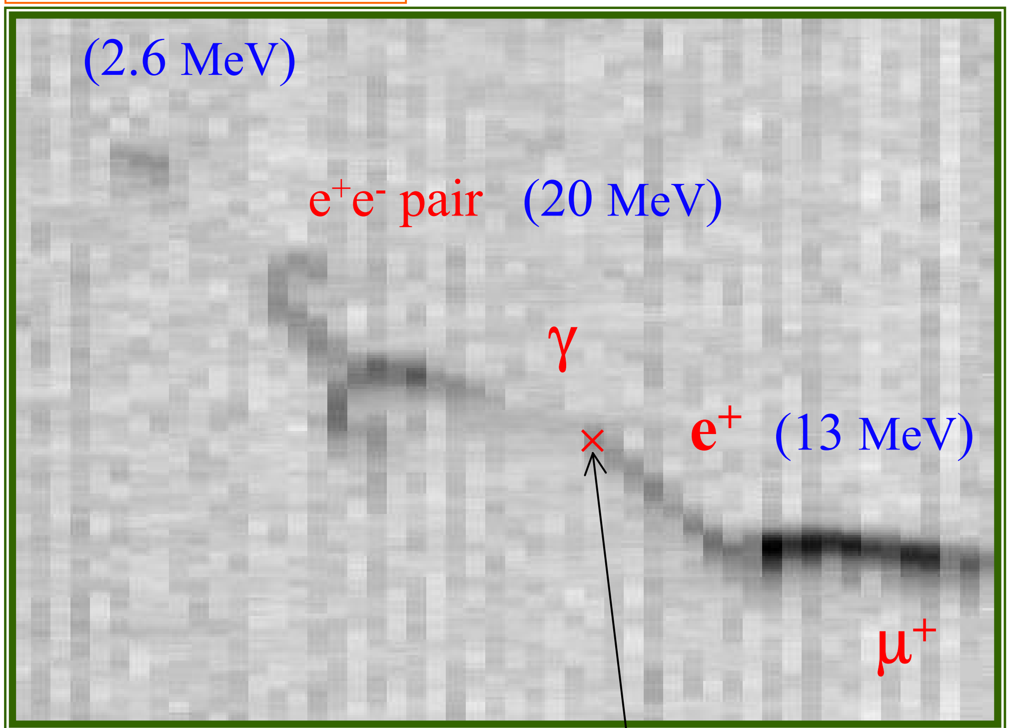


Fitted signal shapes on single wire

In-flight annihilation of positron

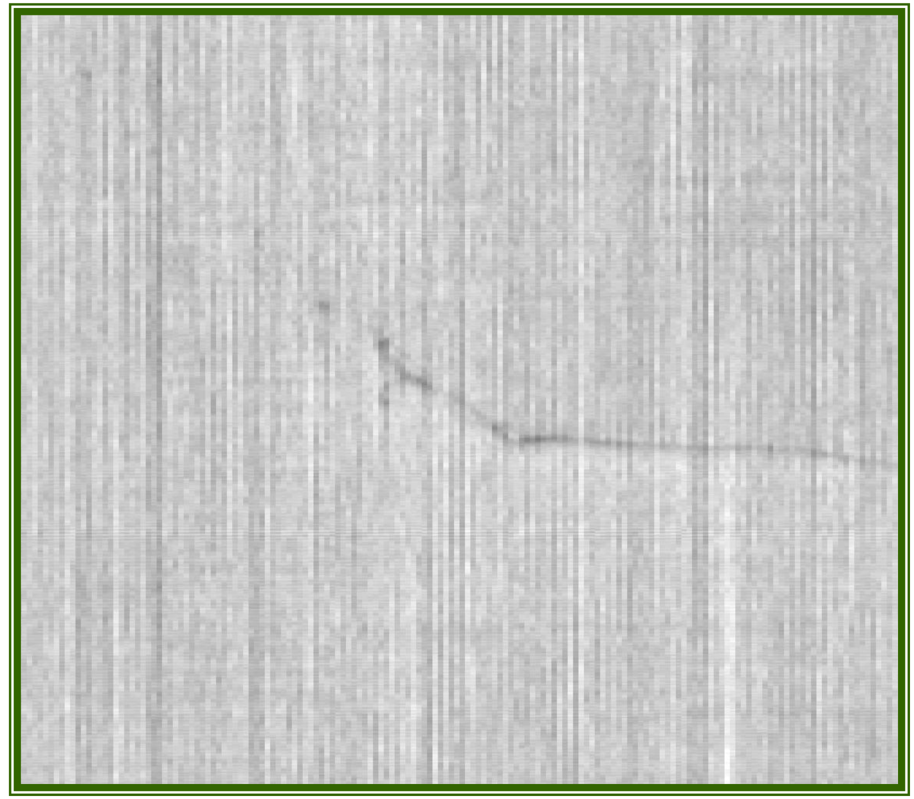
≈20% of positron from μ decays expected to annihilate before stopping

Run 844, Event 24



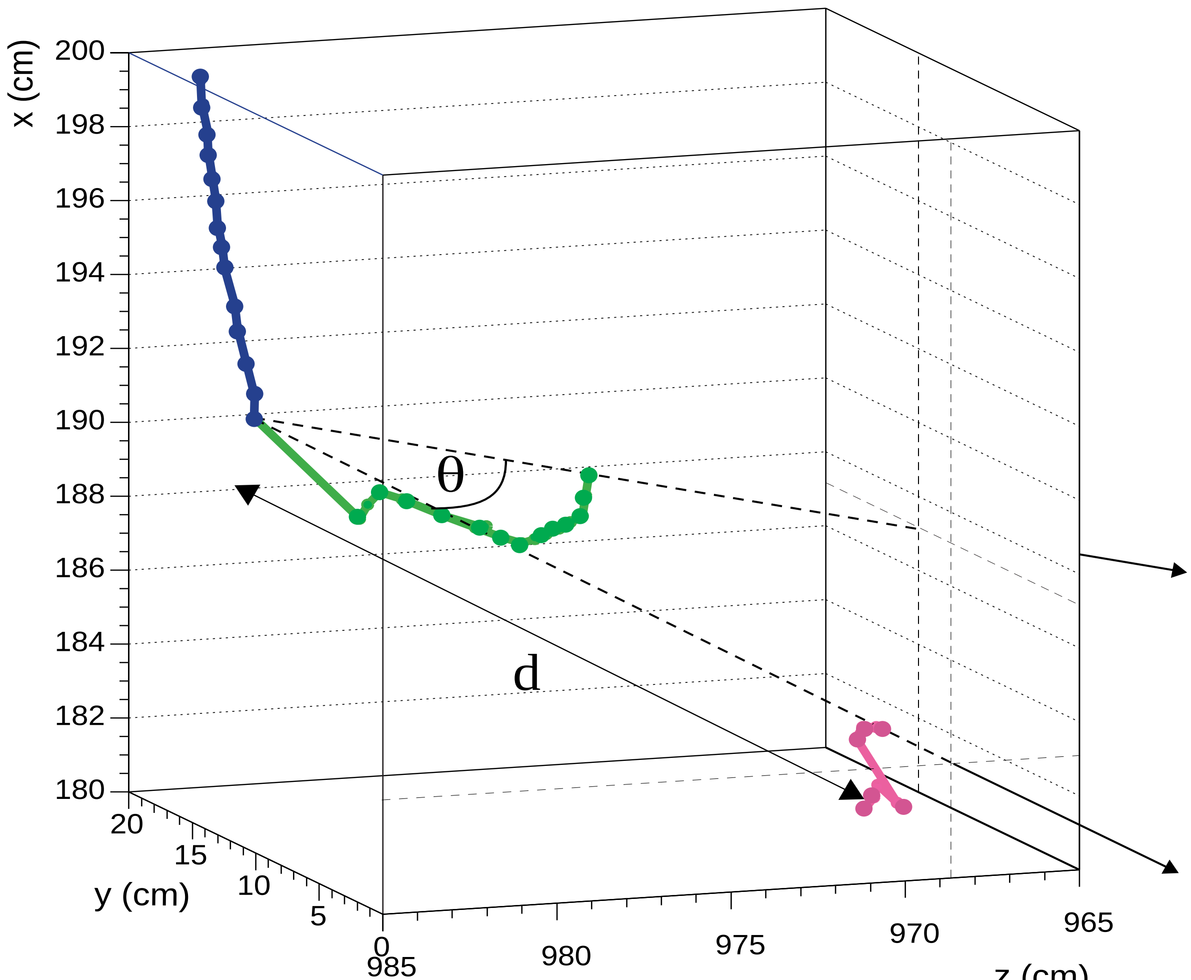
Collection view

Annihilation point



Induction 2 view

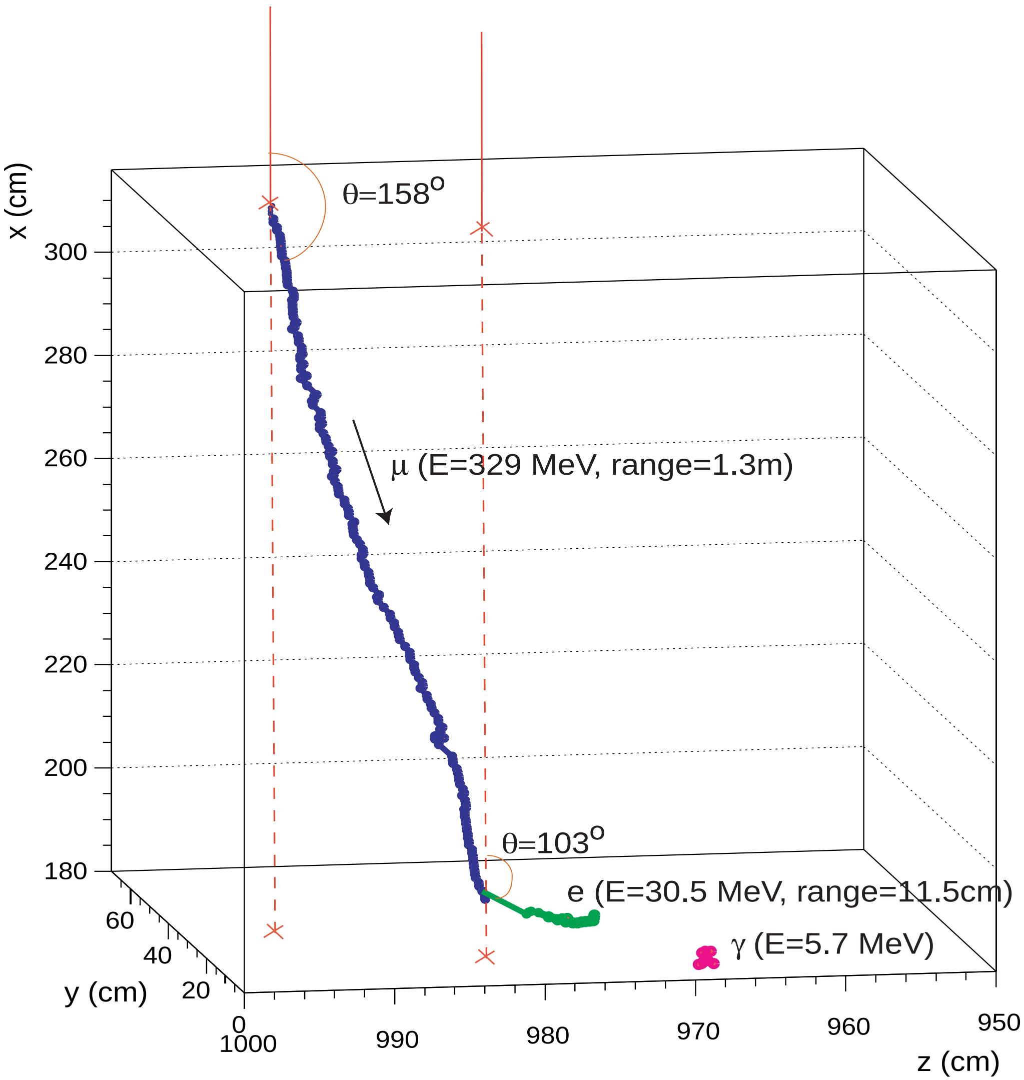
Bremsstrahlung track selection



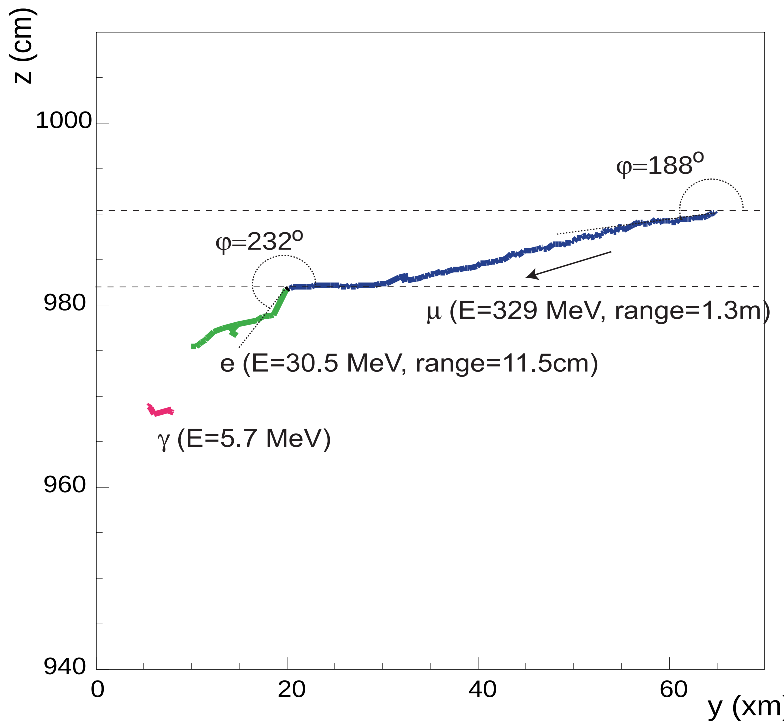
Rejection of noise and out of time tracks:

- θ < 40º
- d < 60cm

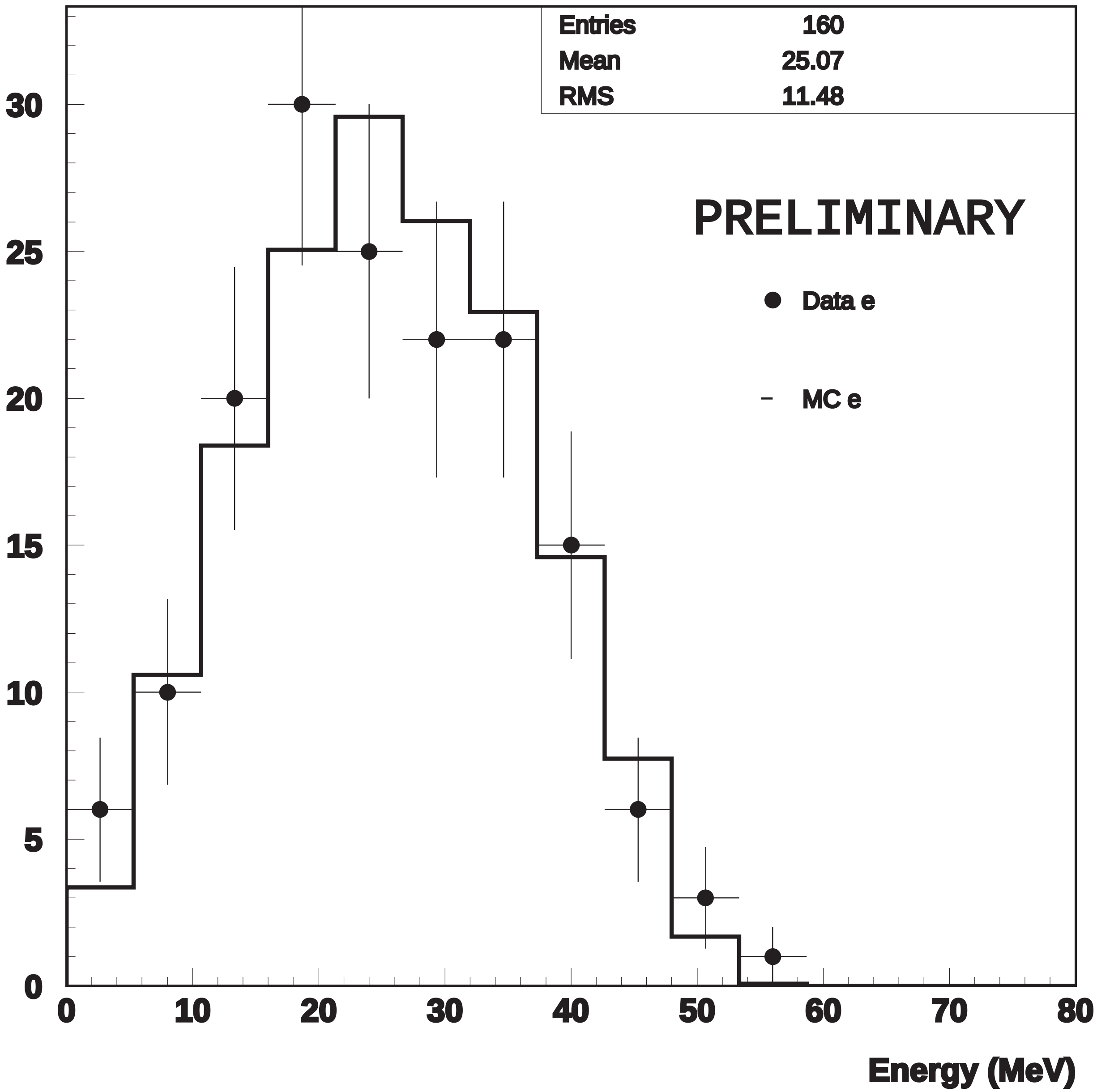
Fully reconstructed stopping muon event



Y-Z plane projection (longitudinal cut)



Calorimetric reconstruction Michel electrons

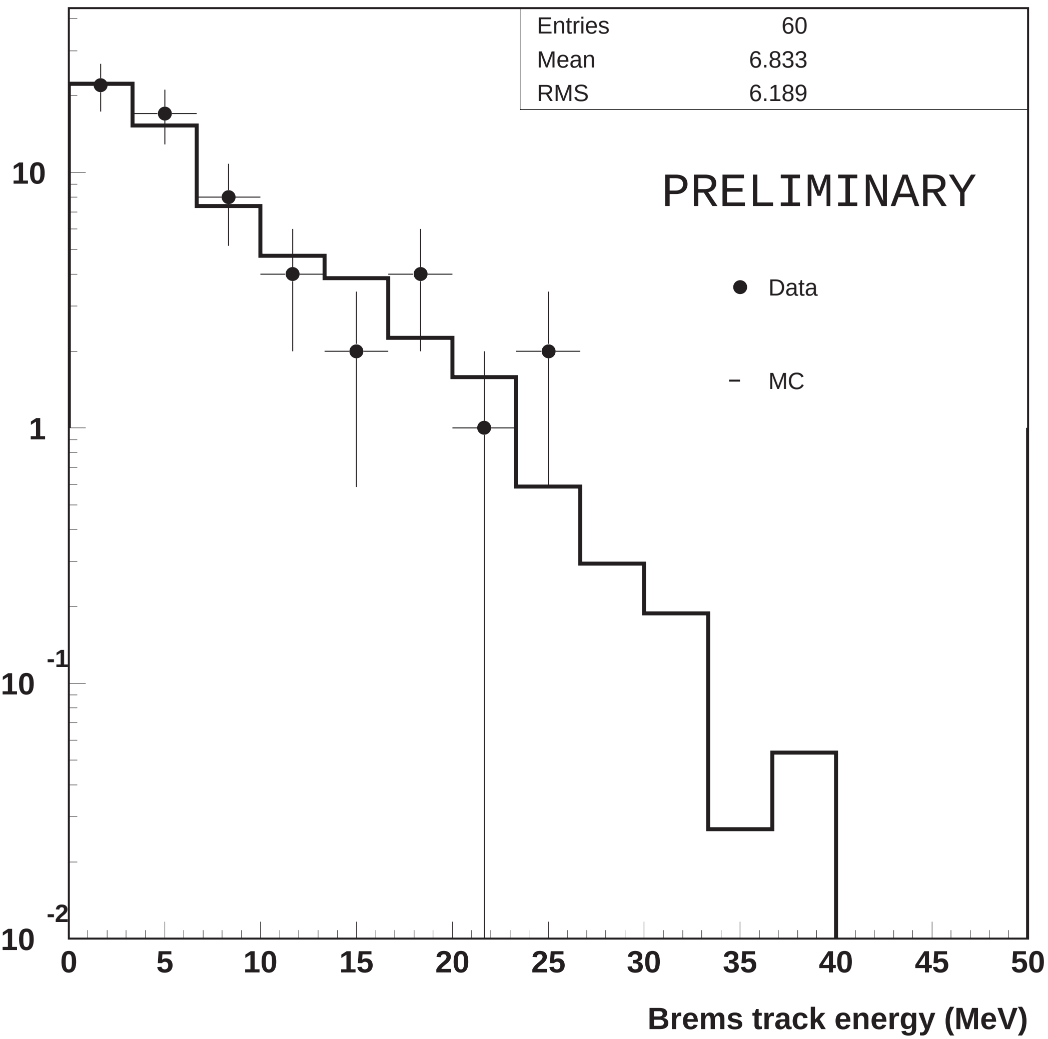


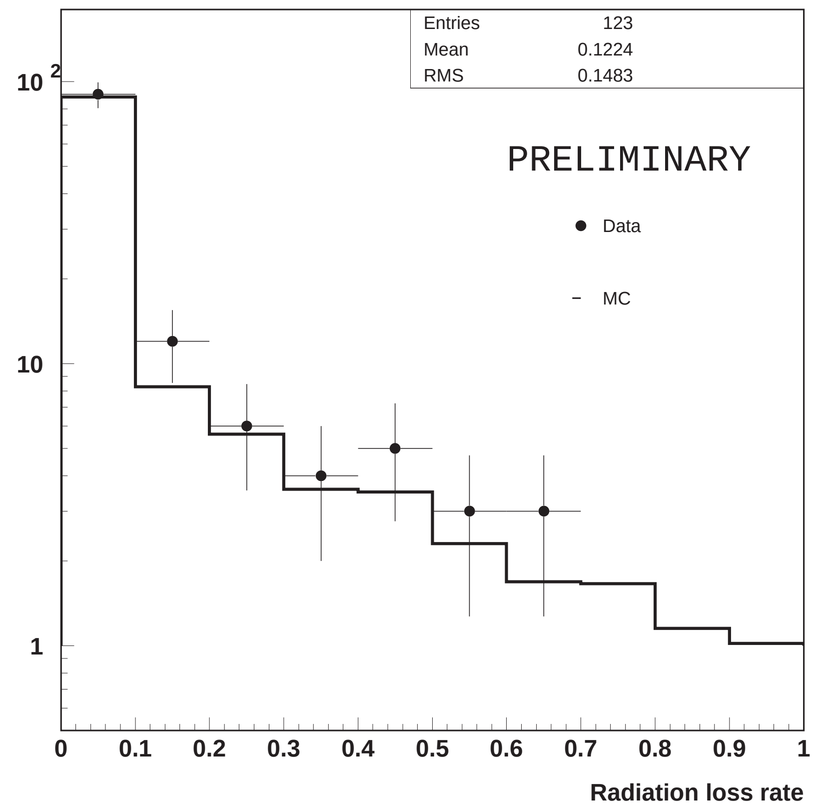
T600

Good agreement between data and MC

Reconstruction Bremsstrahlung photons

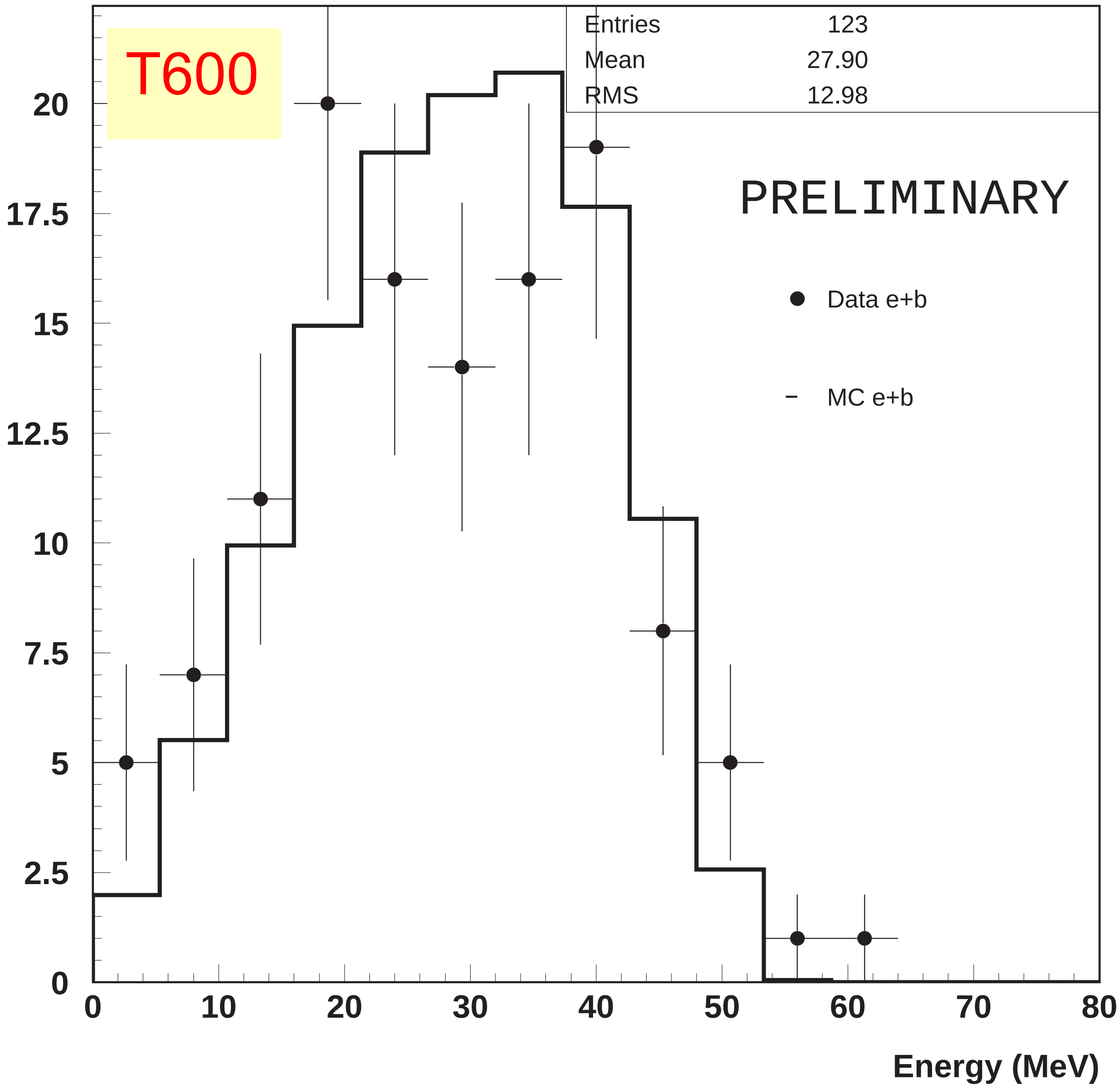
T600





Good agreement between data and MC

Final electron spectrum with Bremsstrahlung photons



Good agreement between data and MC

Preliminary resolution:

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

Low energy electrons

Pi zero candidate (preliminary)

Run 975, Event 151

- Reconstruction of γ-showers

158 MeV

752 MeV

140 MeV

$\theta = 141^{o}$

$M_{inv} = 650$ MeV

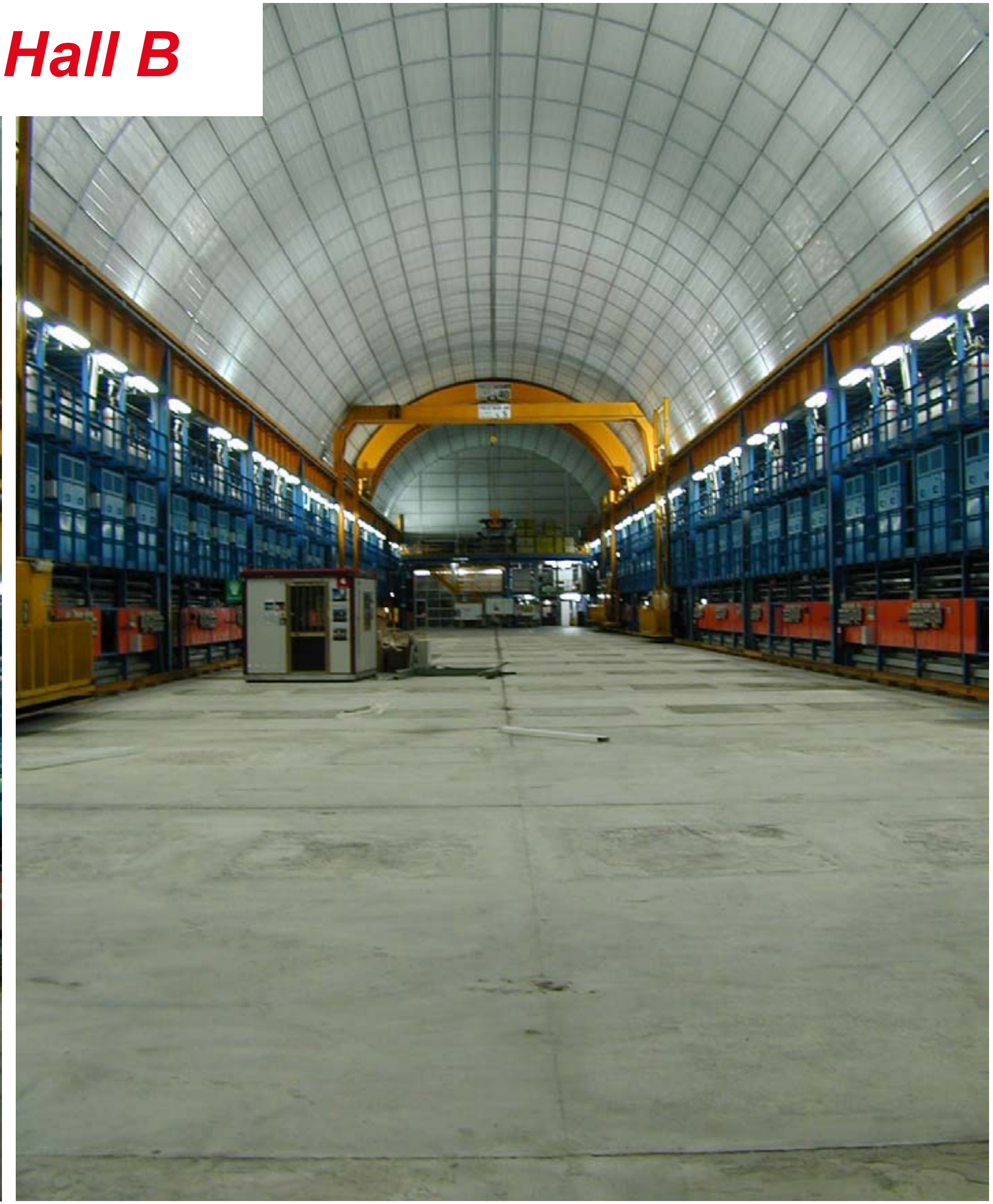
$\theta = 25^{o}$

$M_{inv} = 140$ MeV

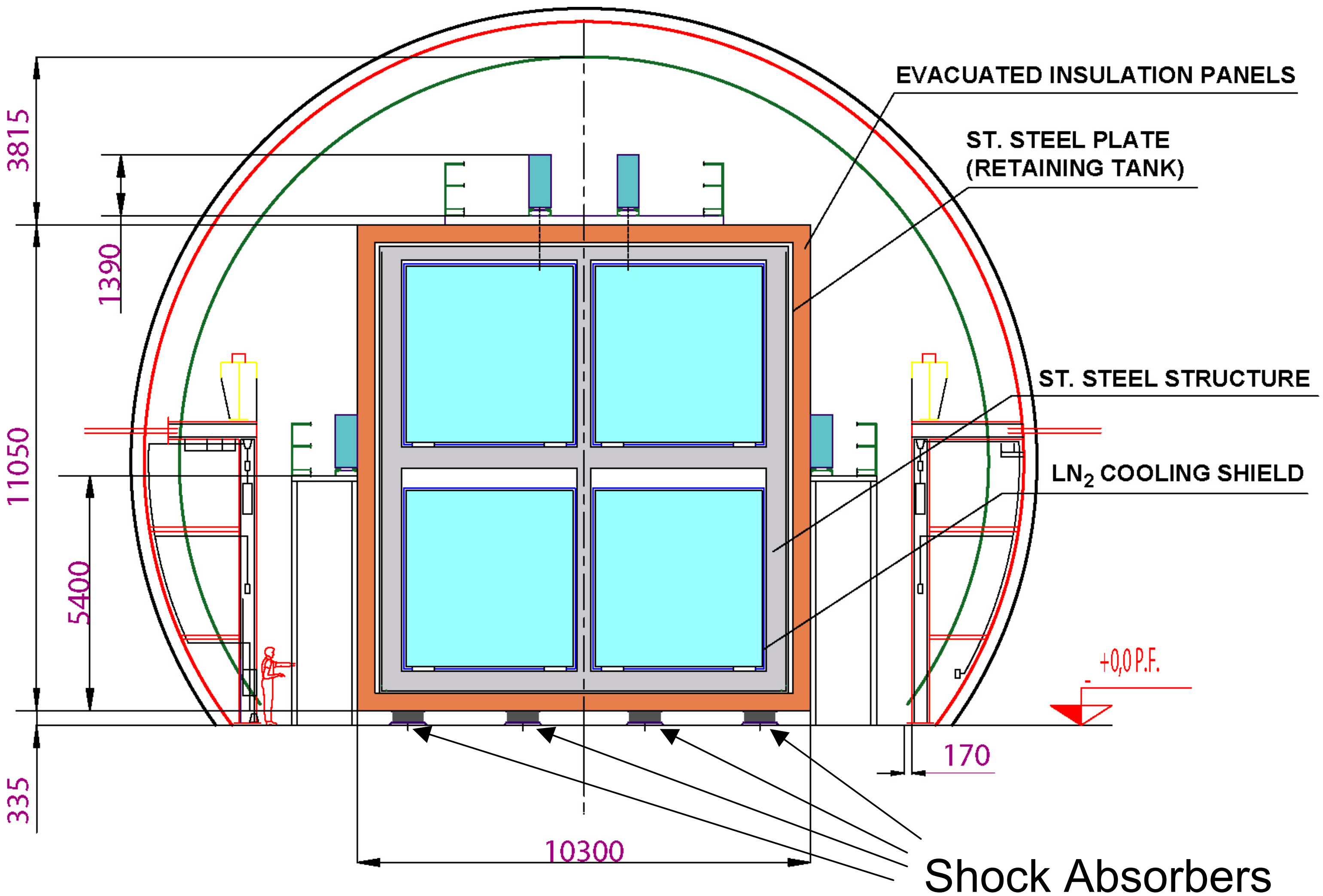
ICARUS T3000

An undeground observatory for rare processes

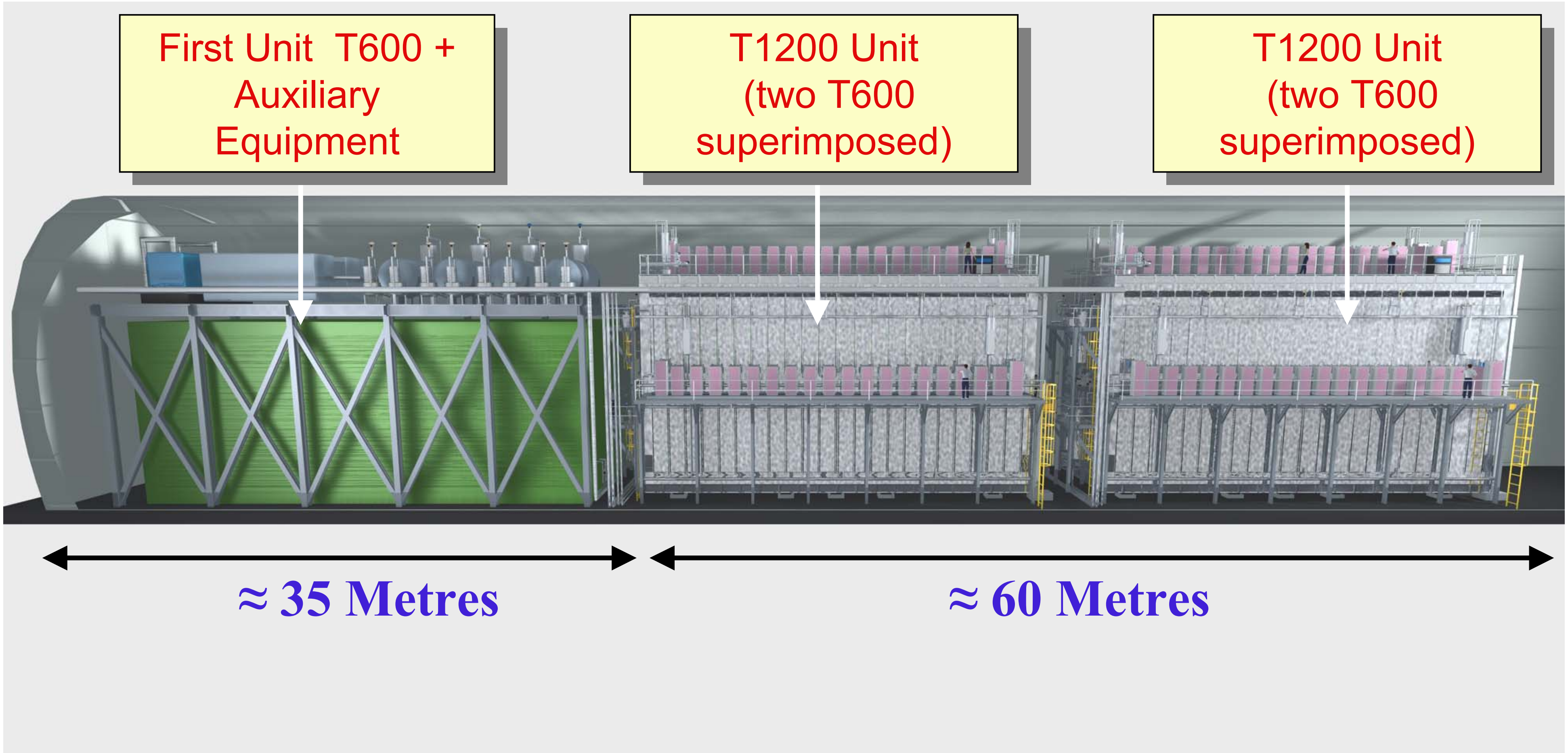
LNGS Hall B



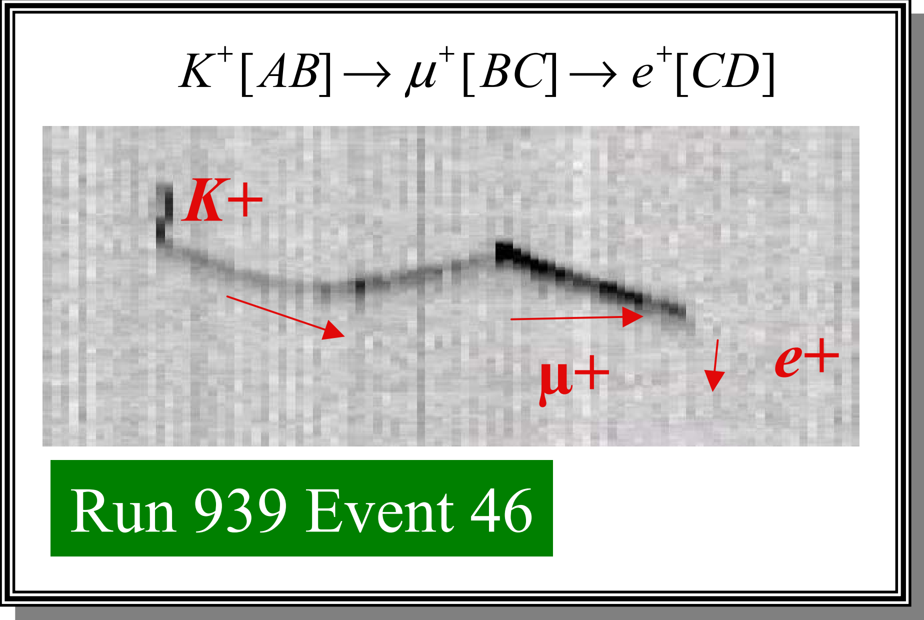
The Basic Layout of the T1200 unit

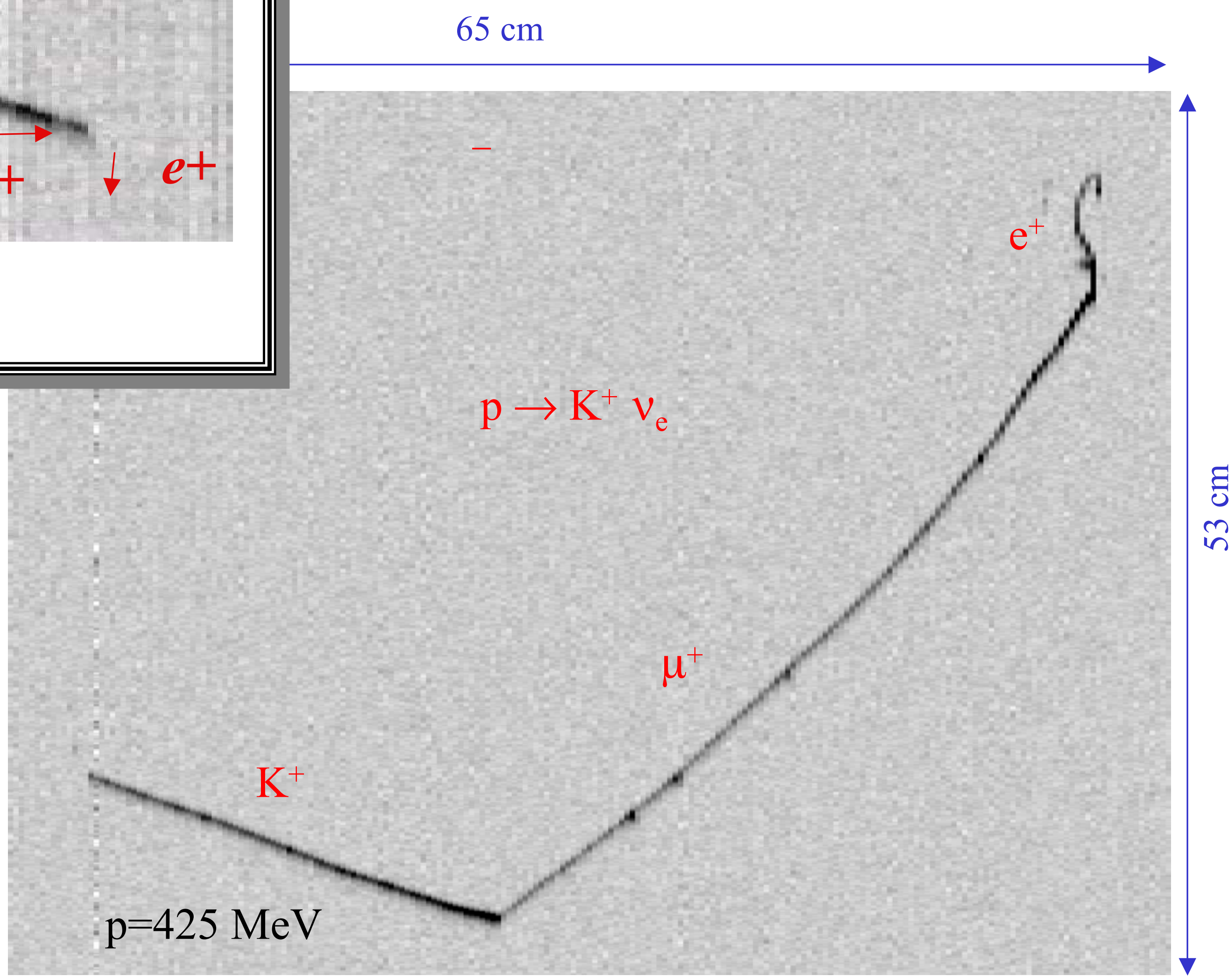


ICARUS detector configuration in LNGS Hall B (T3000)



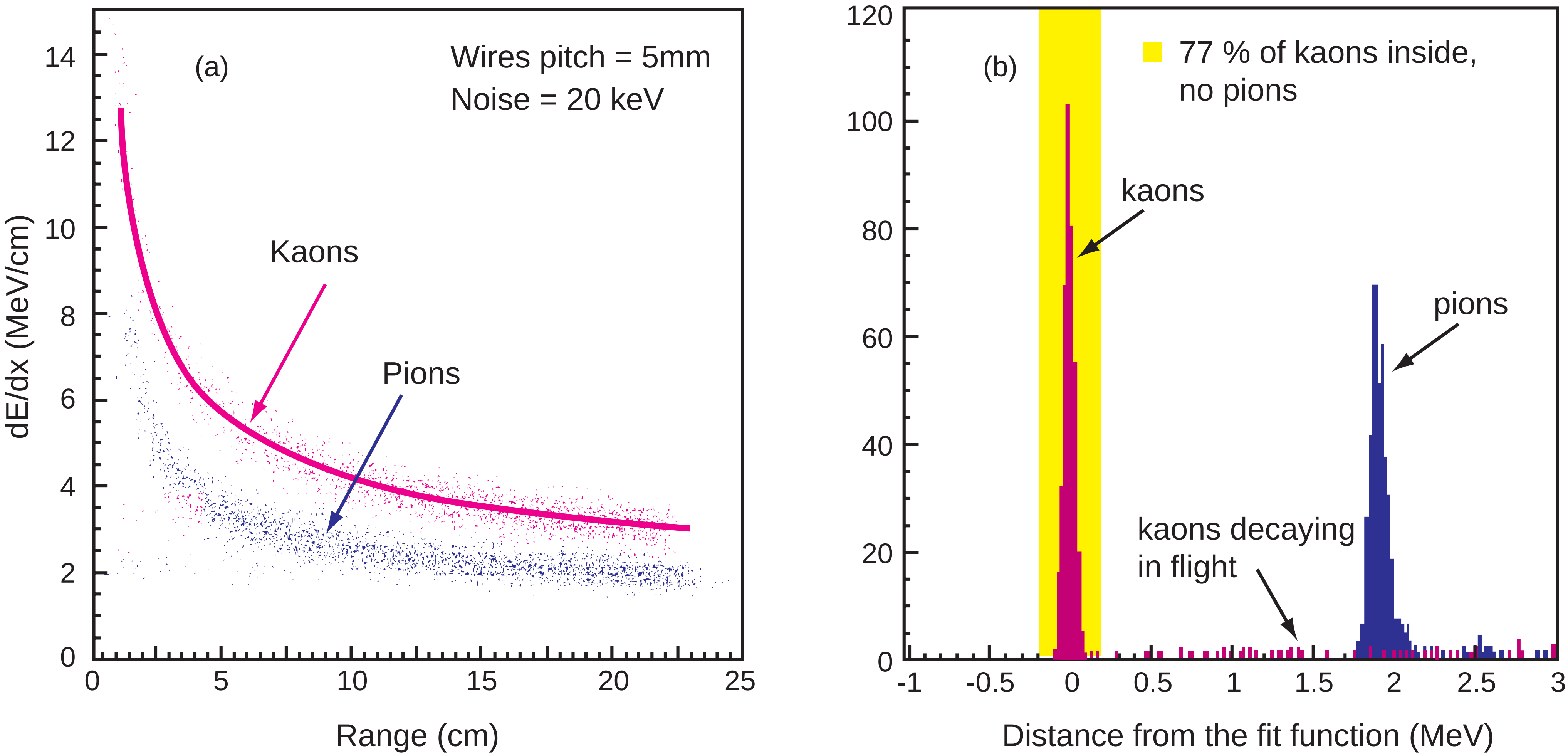
Proton decay





dE/dx in 3 ton

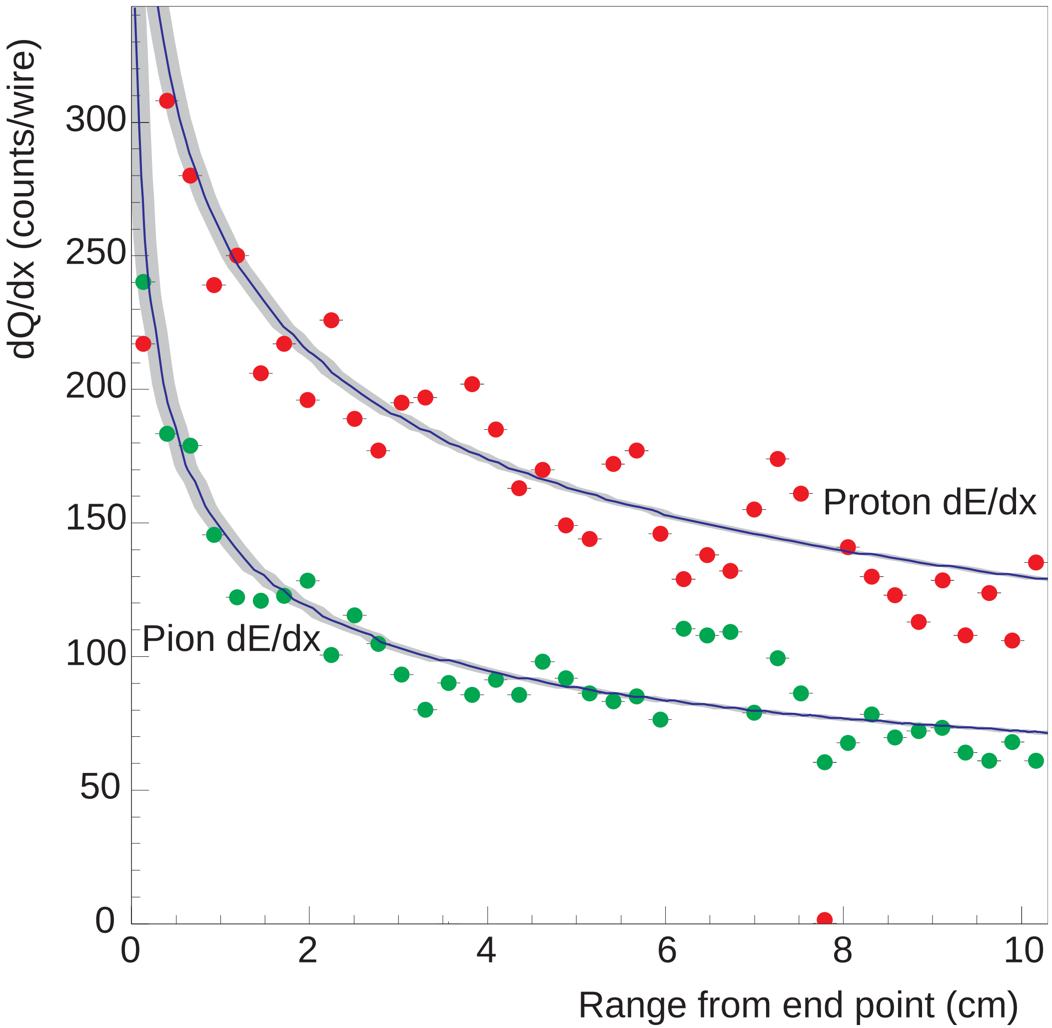
Particle identification (I)



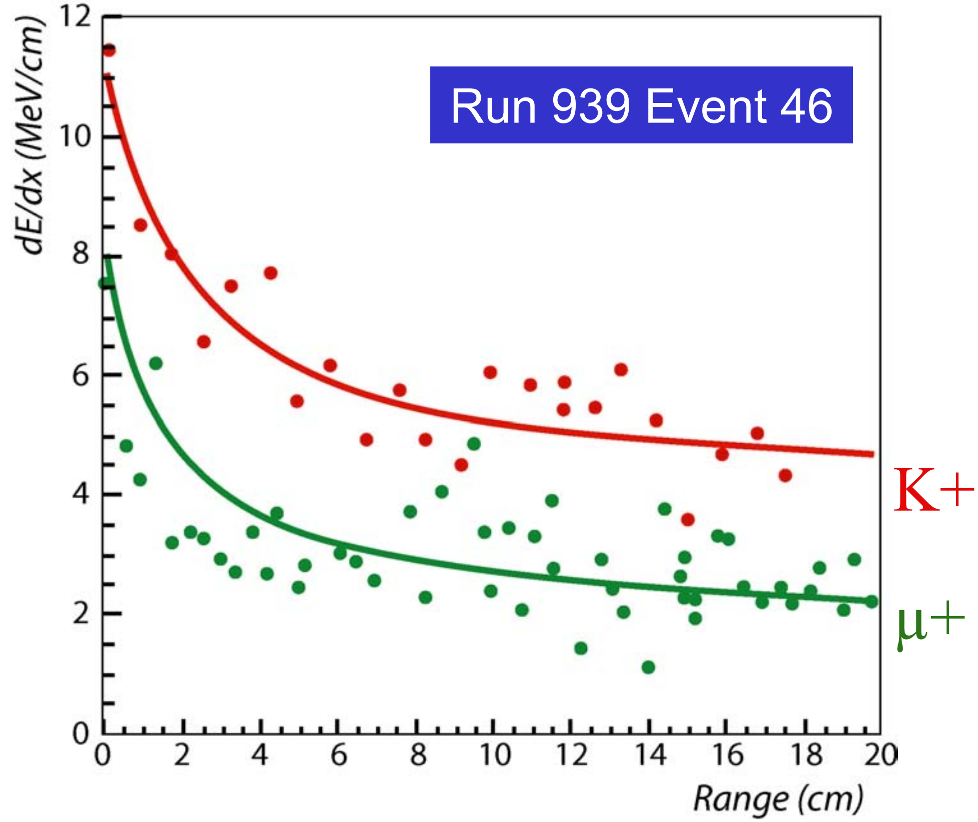
Energy loss profile along kaon and pion tracks and distribution of the distance from the kaon fit function along pion and kaon tracks.

Particle identification (II)

dE/dx in 50 liter



dE/dx in T600



Proton decay: direct comparison with SuperK

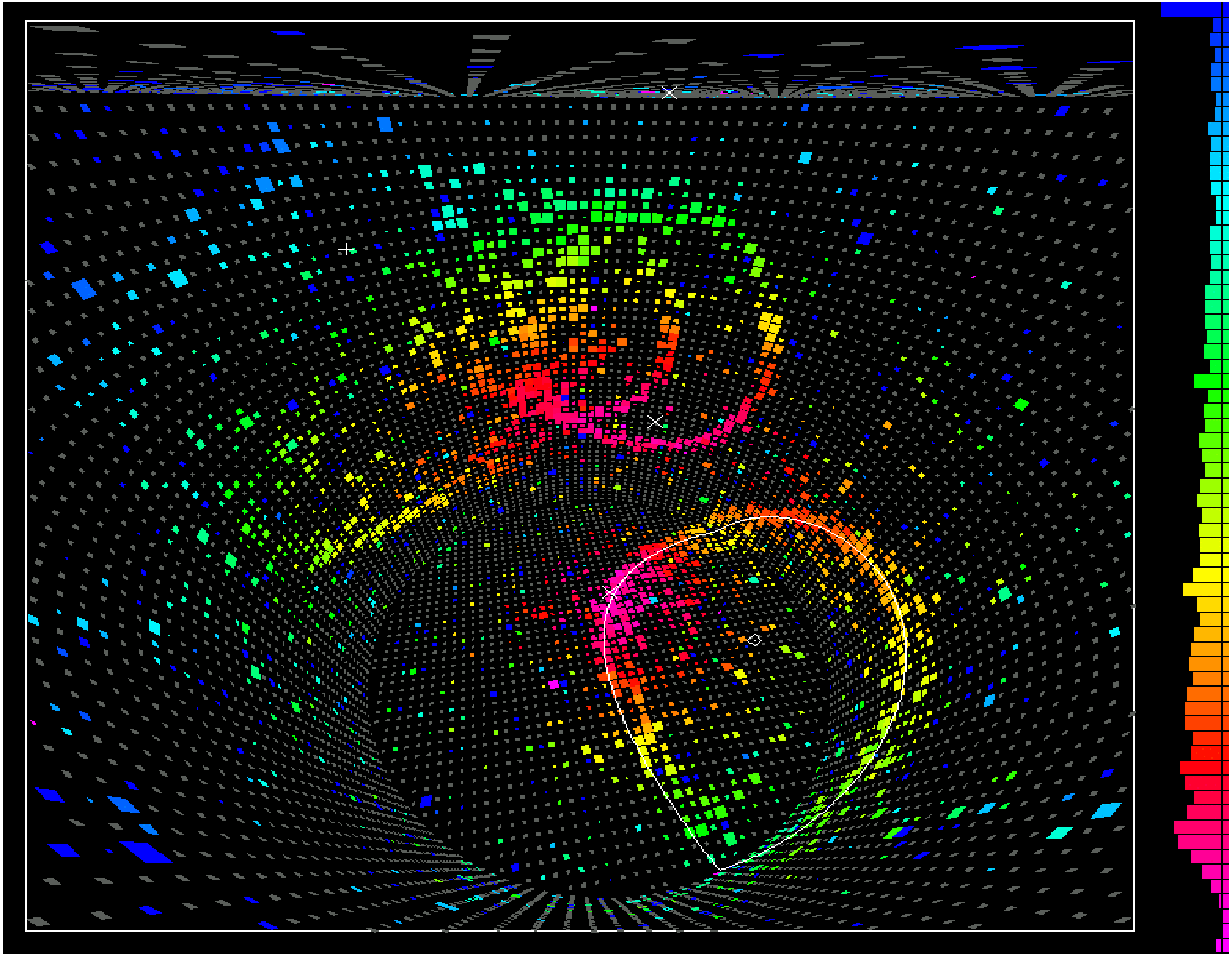
Channel		Eff. (%)	Observed (evts.)	Bkg. (evts.)	Exposure (kTon×yr)	τ/B limit (10^{32} yr)	Needed Exp. to reach SK (kTon×yr)
$p \to e^+ \pi^0$	SuperK	43	0	0.2	79	$50 \to 30$ [1 evt]	
	ICARUS	45	–	0.005	5	2.7	94
$p \to K^+ \bar{\nu}$	SuperK				79	$19 \to 13$ [1 evt]	
prompt $\gamma\ \mu^+$	SuperK	8.7	0	0.3		$10 \to 7$	
$K^+ \to \pi^+ \pi^0$	SuperK	6.5	0	0.8		$7.5 \to 5$	
	ICARUS	97	–	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 notoriously good at back-to-back three-rings events hence in $e\pi^0$ and $\mu\pi^0$ channels channels SuperK gains on the mass, even though backgrounds are round the corner
- In the favoured $p \to \nu K$ channel, the efficiency is 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

SuperK e+π^0 final state candidate

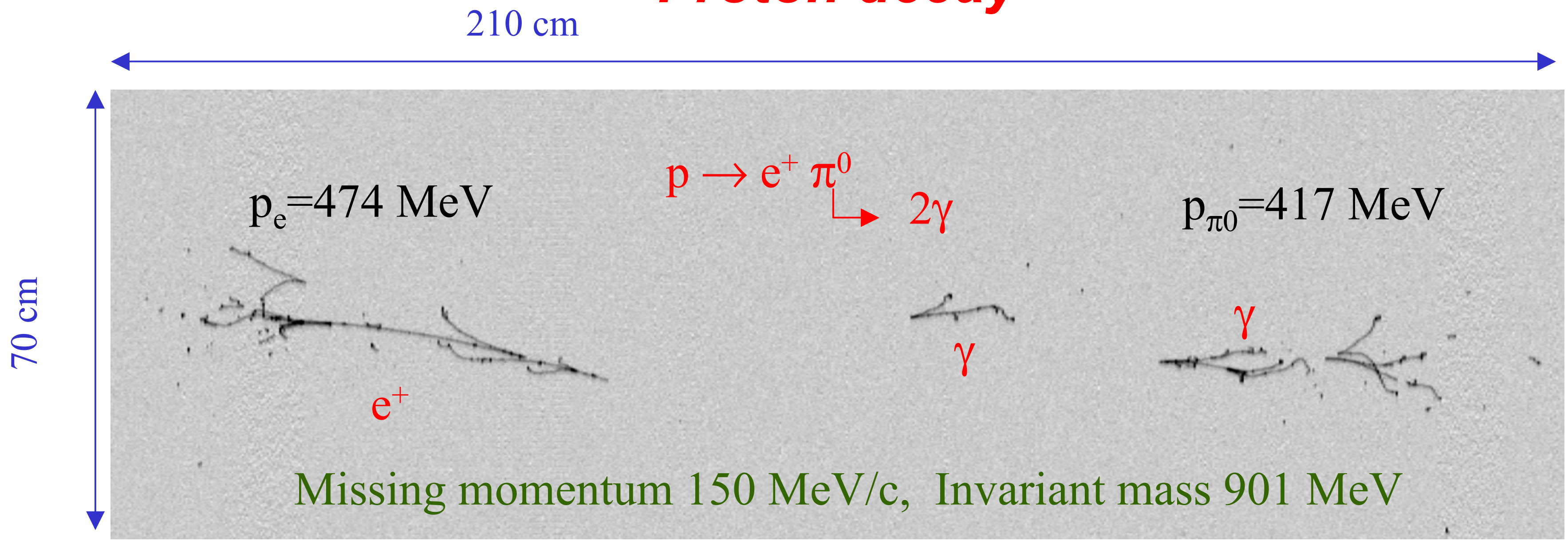
1997-09-24 12:02:48 : cut by SuperK because compatible with background

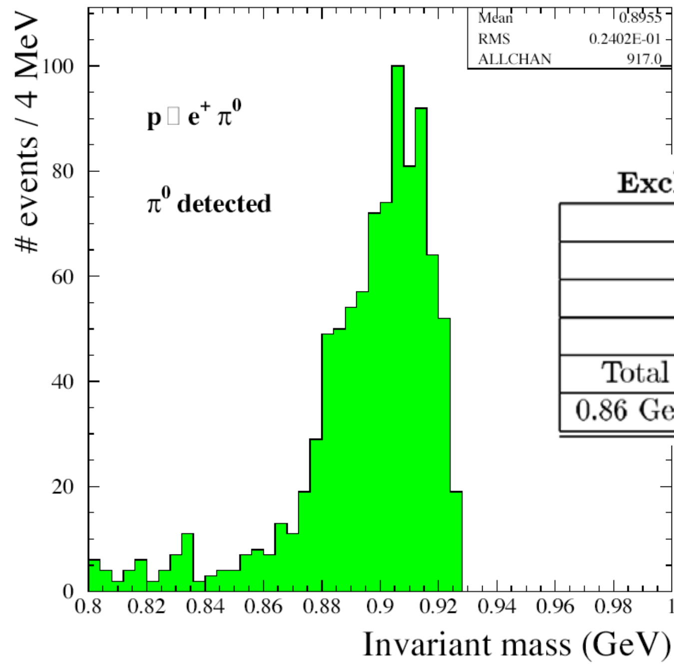


Particle momentum thresholds in Water:

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

Proton decay





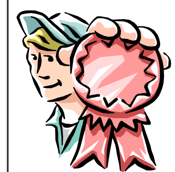
Exclusive Channel Cuts	$p \to e^+ \pi^0$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One π^0	54.00%	6604	2135	15259	5794	8095	3103
One positron	54.00%	6572	2125	20	0	0	0
No charged pions	53.90%	3605	847	5	0	0	0
No protons	50.85%	1188	656	1	0	0	0
Total Momentum < 0.4 GeV	46.70%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

Not cut by ICARUS because of no background !

Proton decay (II): existing SuperK results

Channel		Eff. (%)	Observed (evts.)	Bkg. (evts.)	Exposure (kTon×yr)	τ/B limit (10^{32} yr)
$p \to e^+ \eta$	SuperK	17	0	0.3	45	11
$p \to e^+ \rho$	SuperK	6.8	0	0.6	61	6.1
$p \to e^+ \omega$	SuperK	3.3	0	0.3	61	2.9
$p \to e^+ K^0$	SuperK				70	
$K^0 \to \pi^0\pi^0$		11.8	1	1.4		8.8
$K^0 \to \pi^+\pi^-$		6.2	6	1		1.5
$p \to \mu^+ \eta$	SuperK	12	0	0	45	7.8
$p \to \mu^+ K^0$	SuperK				70	
$K^0 \to \pi^0\pi^0$		6.1	0	1.1		6.2
$K^0 \to \pi^+\pi^-$		5.3	0	1.5		5.4
$n \to \bar{\nu} \eta$	SuperK	21	5	9	45	5.6
$n \to \bar{\nu} K^0$	SuperK				79	
$K^0 \to \pi^0\pi^0$		9.6	25	33.8		3.2
$K^0 \to \pi^+\pi^-$		4.6	10	6.7		1.1

?



>4σ

Table presented by M. Goodman @ NNN02, January 2002

- Note that many are preliminary.
- Many in the range of a few 10^{32} years
- Backgrounds are round the corner and not well understood !
  - $p \to eK^0$ with $K^0 \to \pi\pi$ has excess of 6 vs 1 expected
  - Taking sum of all other proton channels one gets 1 seen for 5.2 expected !
  - Backgrounds for neutron decays unsatisfactory

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	

- Extremely 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.

Atmospheric neutrinos

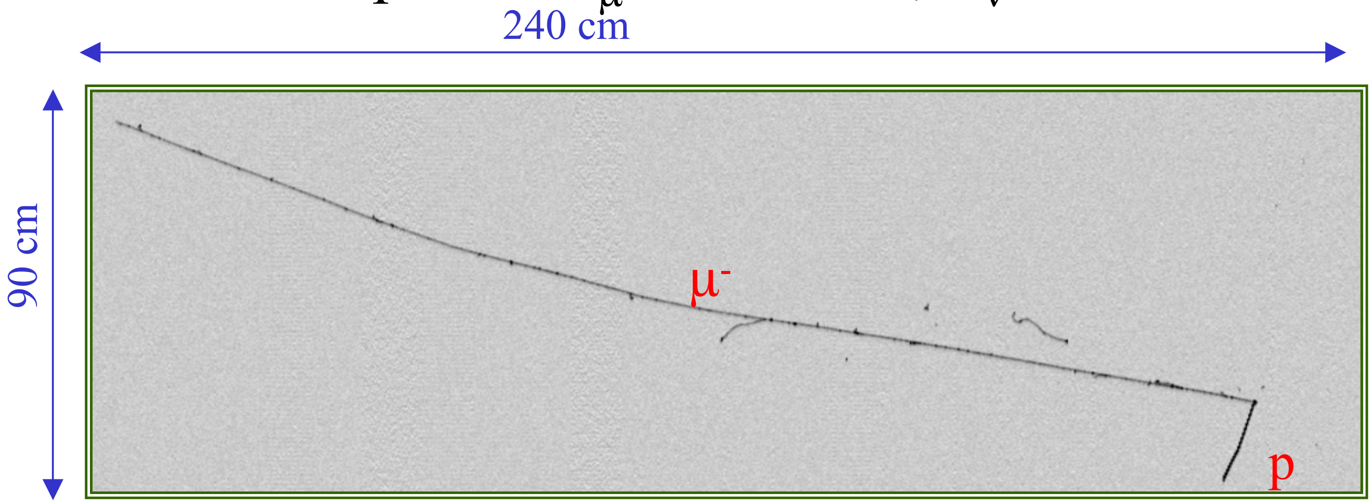
- Present situation:
  - SuperK will resume this year with 50% coverage
  - ICARUS will look with a completely new technique to such astrophysical source
- The atmospheric neutrino analysis in ICARUS will be characterized by
  - An unbiased, systematic-free observation whereas
    - SuperK is in practice limited to single-ring CC events
    - All other analyses rely on MC to extract signals (e.g. “NC enriched sample”, τ-appearance neural net based, …)
  - An excellent energy and angular reconstruction
  - Experimental and theoretical advances in prediction of the atmospheric neutrino rates which will match the improved measurements possible with ICARUS
    - Expertise within the Collaboration
    - Expect improvements in:
      - Low energy events
      - Clean electron sample
      - All final states, and with neutrino and antineutrino statistical separation
      - Neutral currents

Atmospheric rates

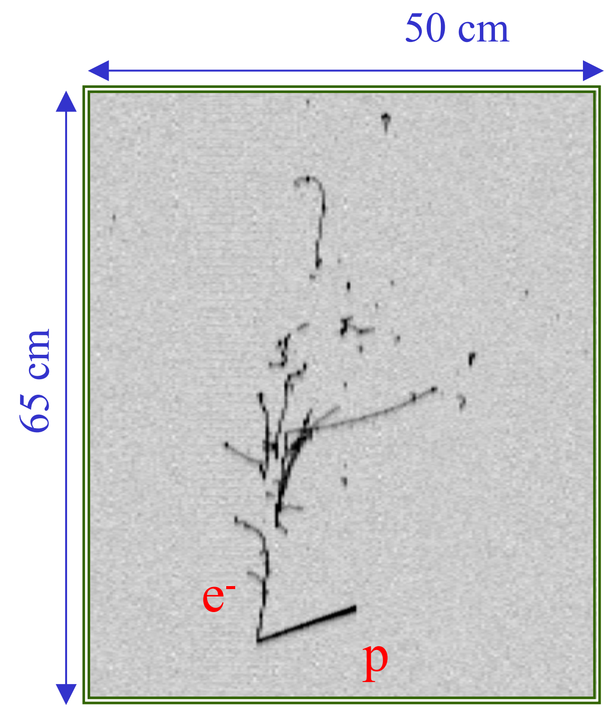
- **Mass is not the only issue!**

	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

Atmospheric ν_μ interaction, E_ν=1.73 GeV



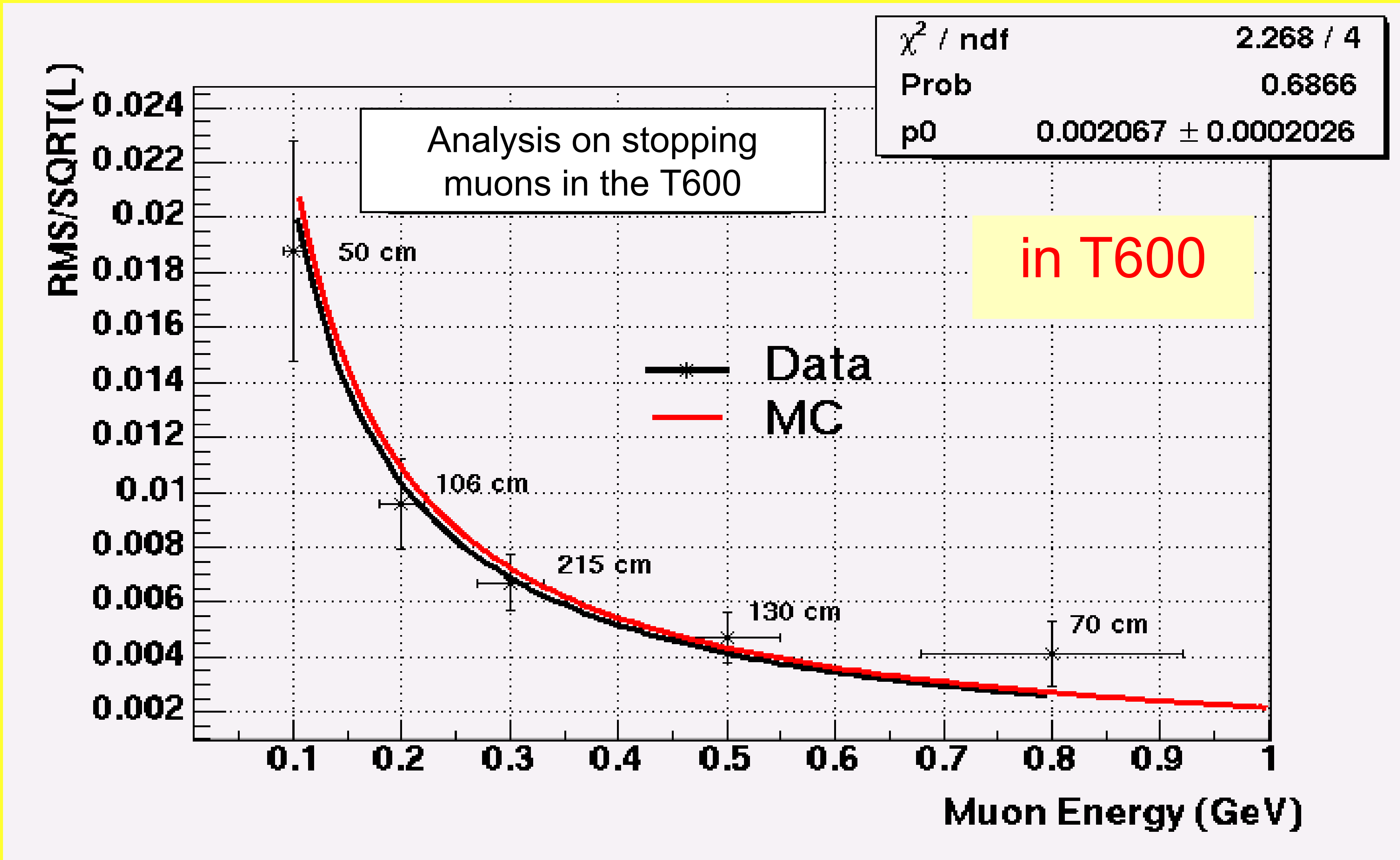
Atmospheric ν_e interaction, E_ν=0.730 GeV



Reconstruction of atmospheric neutrinos

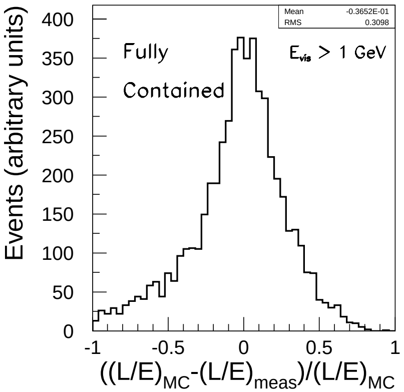
- Containment
  - ≈60% of ν_μ CC events are fully contained
  - Contained tracks will be measured by range and calorimetrically (integration of dE/dx)
    - ≈7%/√E(MeV) for stopping tracks
    - ≈12%/√E(MeV) for soft electrons due to Bremsstrahlung
    - ≈3% %/√E(GeV) for electromagnetic showers
  - Range vs dE/dx provides particle identification
- Measurement of escaping tracks (mostly muons) can be performed in different ways
  - By multiple scattering
    - Exploit the momentum dependence of the scattering
    - $\sigma_p/p \approx 0.10 + 0.048\ln(p[GeV])$ for 5 meters long tracks
  - By precise measurement of the energy loss rate
    - Exploit the relativistic rise of dE/dx precisely determined by combining successive samples
    - $\sigma_p/p \approx$ 20-30 %

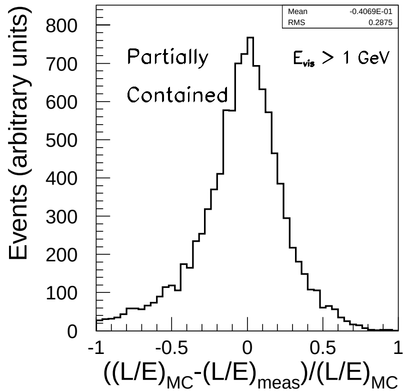
Muon momentum reconstruction by multiple scattering



Reconstructed L/E distribution

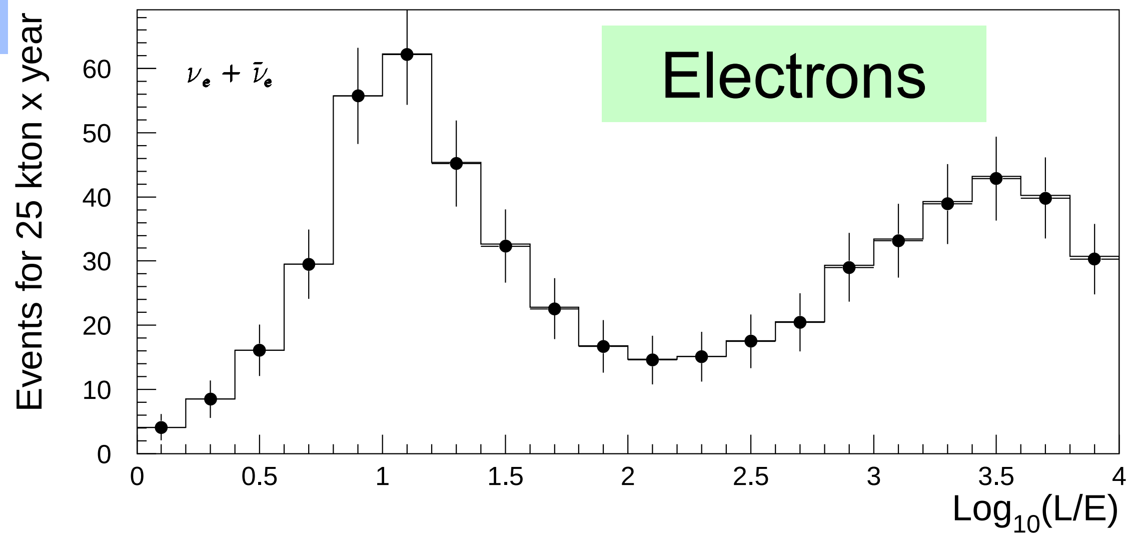
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\,\Delta m^2 \frac{L}{E}\right)$$

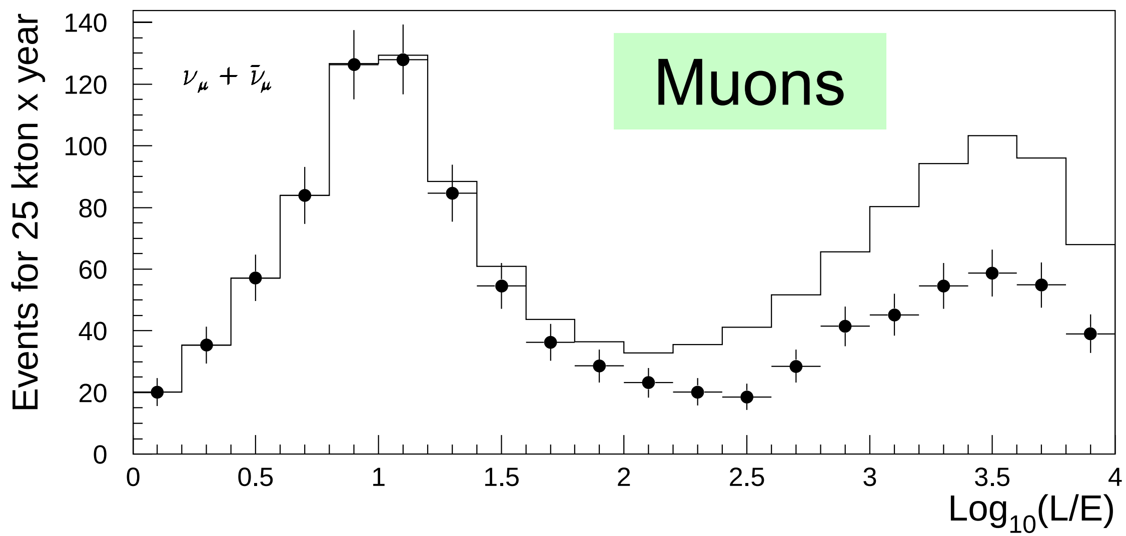




$$\Delta(L/E)_{RMS} \approx 30\%$$

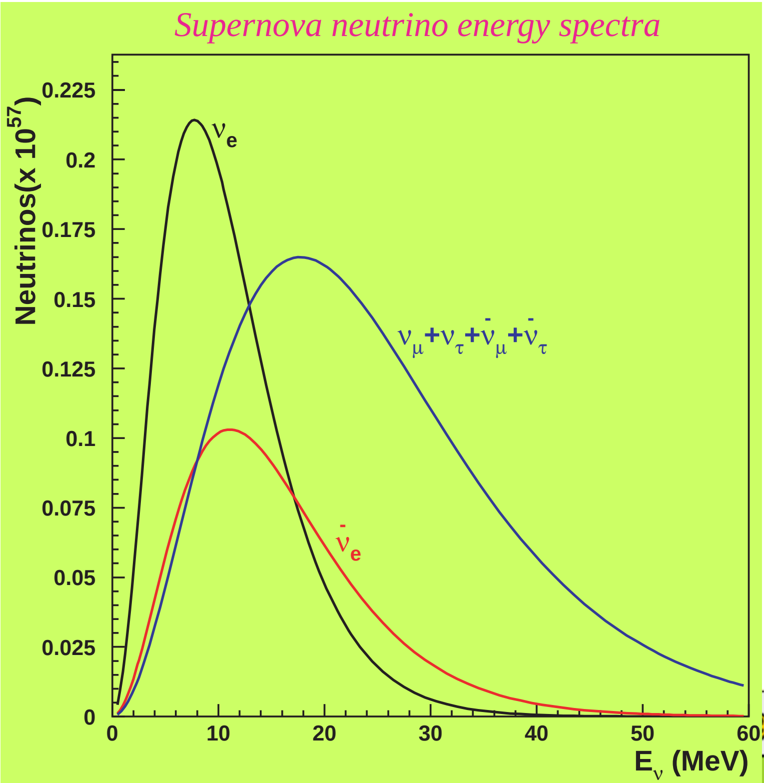
After 10 years…

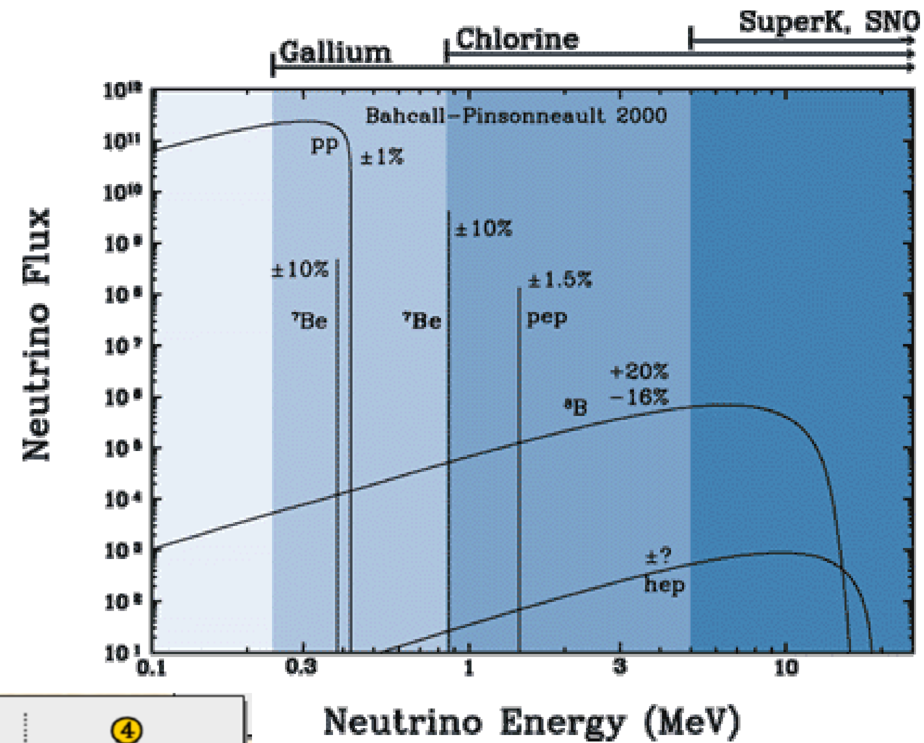




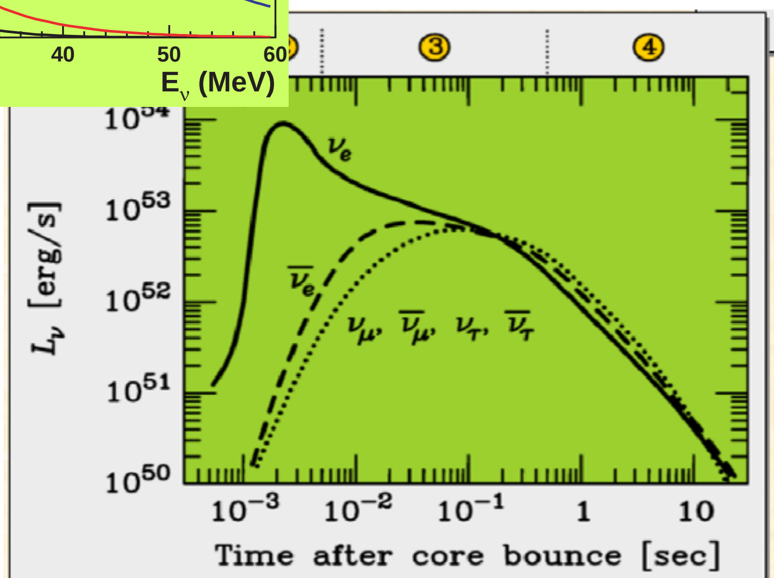
- Oscillation parameters:
  - $\Delta m^2_{32} = 3.5 \times 10^{-3}\ \mathrm{eV}^2$
  - $\sin^2 2\Theta_{23} = 0.9$
  - $\sin^2 2\Theta_{13} = 0.1$
- ***Electron sample can be used as a reference for no oscillation case***

Astrophysical low energy neutrinos: solar and supernovae





Bahcall, http::/www.sns.ias.edu/~jnb



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

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

ICARUS and the CNGS beam (I)

- ICARUS as a LBL neutrino oscillations experiment between CERN and LNGS was already discussed in the 1993 proposal
  - ➥ The simultaneous study of accelerator and non-accelerator sources is possible due to the nature of the detection technique
    - ☛ Continuously sensitive and isotropic
    - ☛ The CNGS events will be separated from other events by timing requirement on the CERN SPS spill
- The ICARUS physics program will be enriched by CNGS oscillation searches.
- The ICARUS collaboration has already contributed to the design and optimization of the CNGS beam.

ICARUS and the CNGS beam (II)

- The real-time detection, the excellent granularity and energy resolution of the liquid argon TPC allows to collect and identify interactions from CNGS neutrinos
  - ➥ ν_μ CC: study online the beam profile, steering and normalization;
  - ➥ ν_e CC: search for $\nu_\mu \rightarrow \nu_e$ oscillations with the best sensitivity until the JHF-SK program turns on;
  - ➥ ν_τ CC: search for $\nu_\mu \rightarrow \nu_\tau$ oscillations with a sensitivity at least similar to that of the OPERA experiment;
  - ➥ NC events: search for $\nu_\mu \rightarrow \nu_s$ oscillations or exotic models.

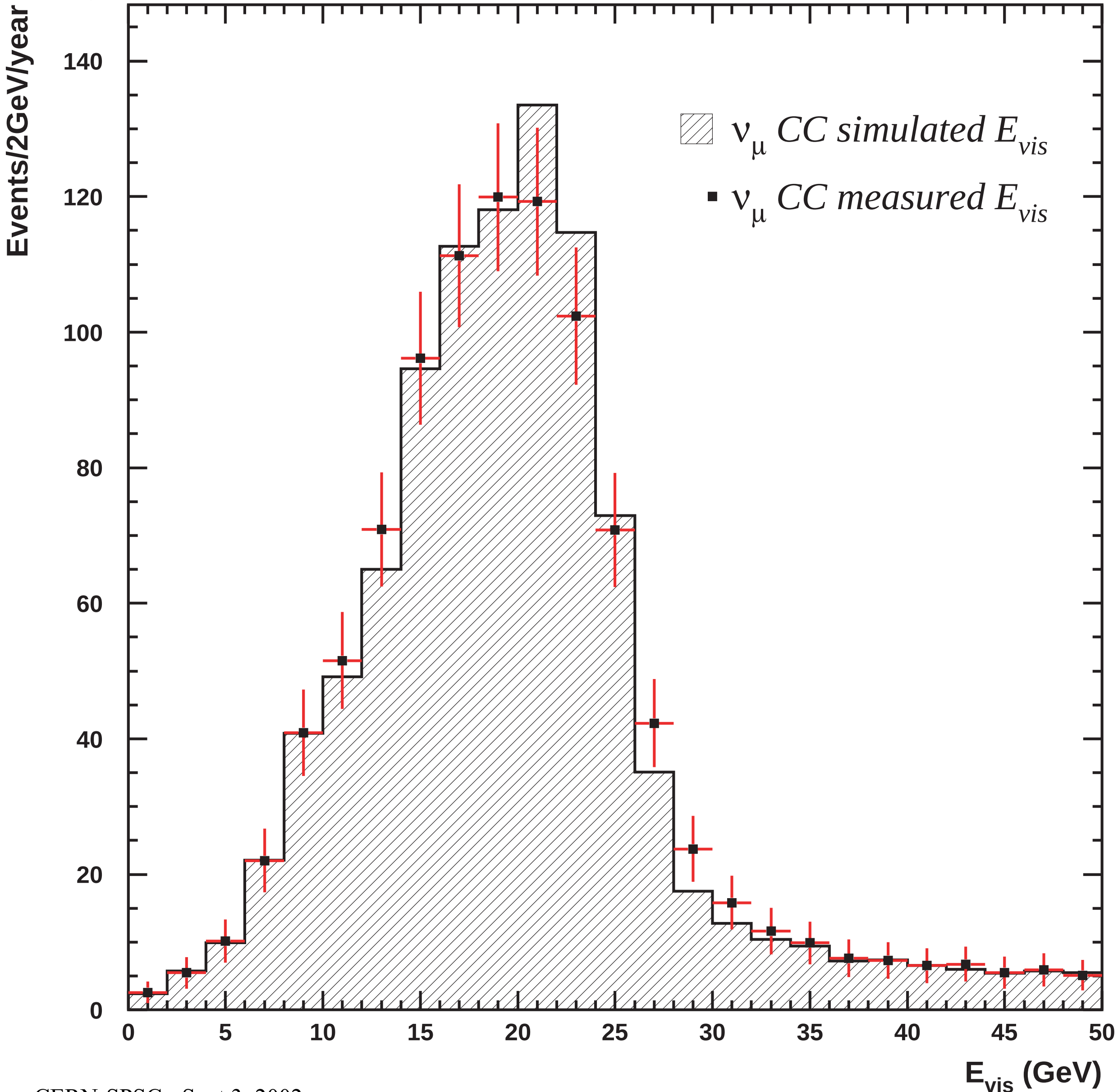
ICARUS-CNGS experiment

- Detector configuration
  - ➥ T3000
  - ➥ Active LAr: 2.35 ktons
- 5 years of CNGS running
  - ➥ Shared mode
  - ➥ 4.5×10^{19} p.o.t./year
- 280 ν_τ CC expected for $\Delta m^2_{23}=3 \times 10^{-3}$ eV^2 and maximal mixing

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

CNGS Beam Profile Measurement

ν_μ *energy beam profile for a T600 + T1200 detector configuration*



2400 events/year

1 year = 4.5×10^{19} pots

(CNGS official "shared" mode)

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

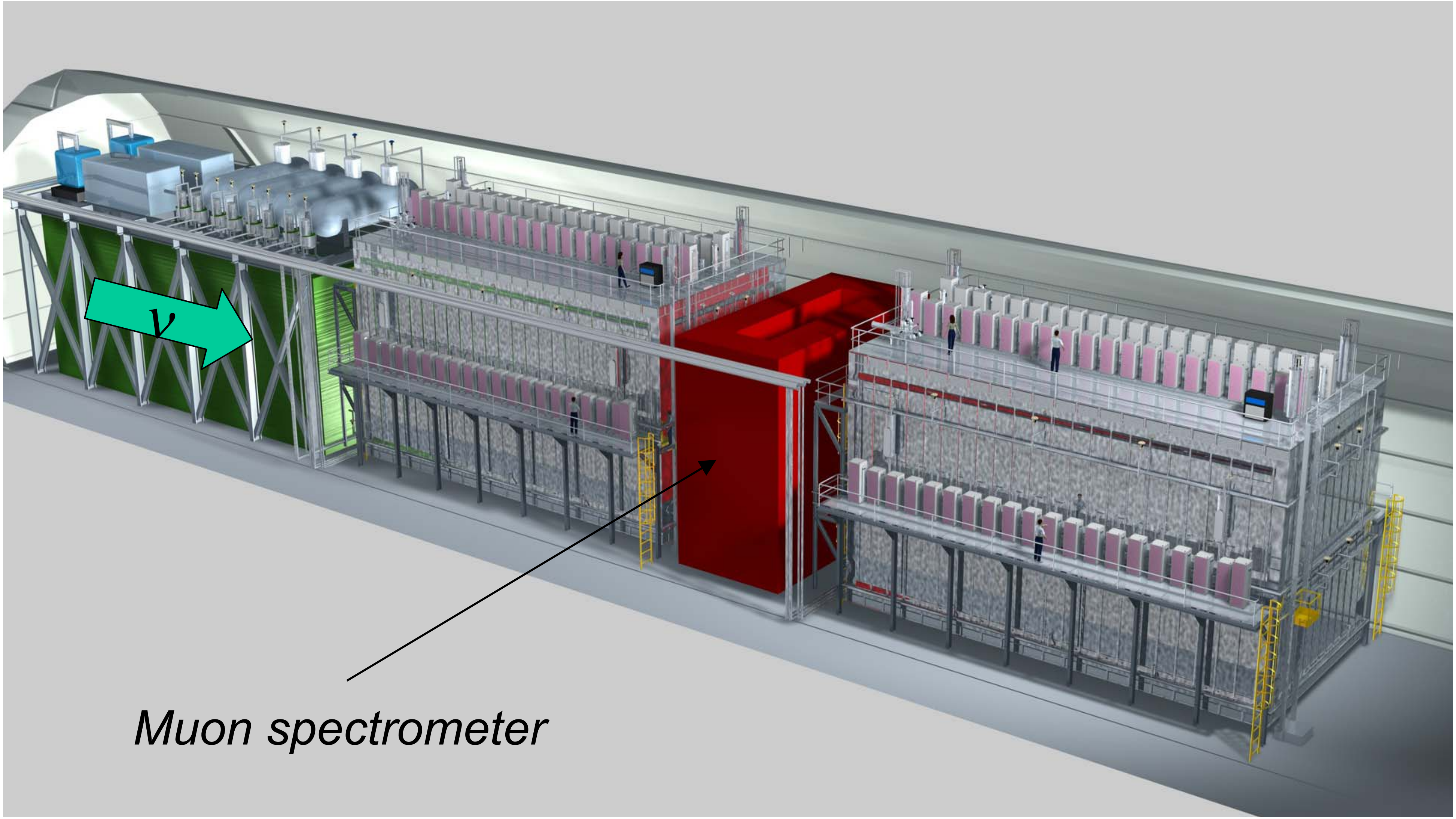
A. External muon spectrometer

- Already in 1999, the Collaboration had put forward the possibility to complement the liquid Argon imaging by an external device capable of magnetic analysis of escaping muons.
- Physics motivation:
  - **Measure the muon charge via magnetic analysis**
  - **Online beam energy spectrum monitoring**
  - **Kinematical properties of closed ν_μ CC events**
    - Direct measurement of background for τ searches
  - **Improve momentum resolution of muons by combining multiple scattering and magnetic bending analysis**
- Magnet design:
  - Strategy: simple design, compatible with the large 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

Artist view spectrometer

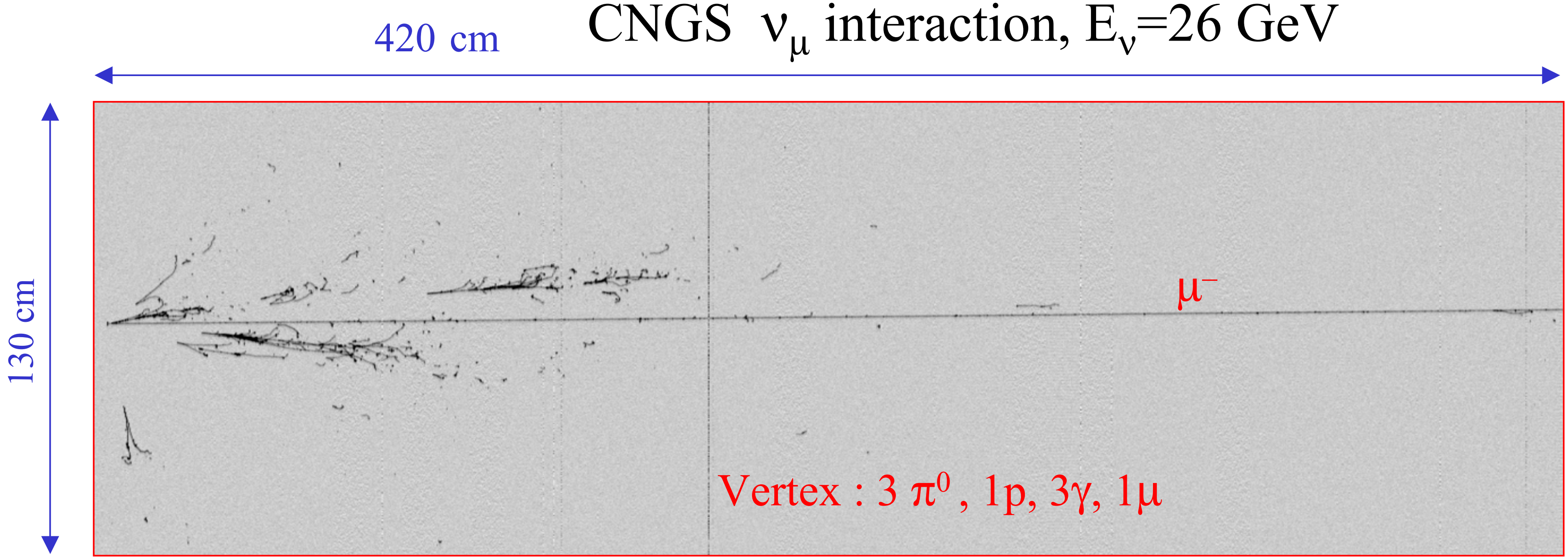


Basic Magnet Parameters

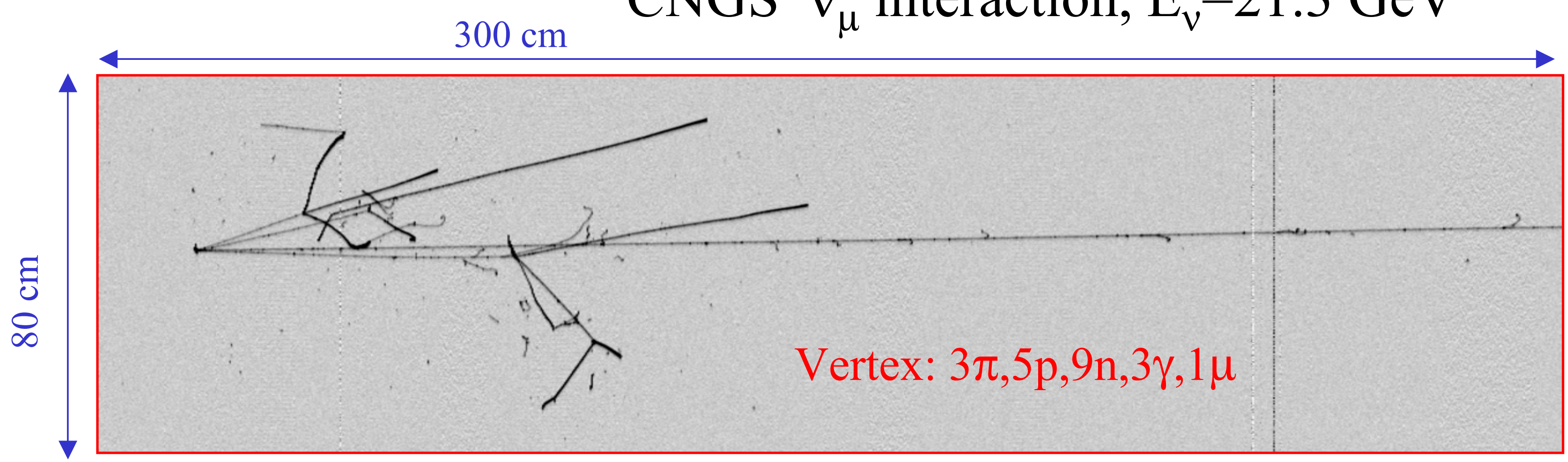
External dimensions	
Width	850 cm
Height	950 cm
Magnetic bending regions	
Number of regions	2
Length of each bending region	150 cm
Fe Plates	
Total number of plates	96
Approximate dimensions	
Width	850 cm
Length	150
Thickness	20 cm
Approximate weight of single plate	20 tons
Preparation	
Number of plates Type EP:200	70
Number of plates Type EP:200 with extra cutting	24
Number of plates Type EP:100	2
Magnetization	
Number of coils	2
Fe blocks within coil	
Number of blocks	12
Width	150 cm
Length	150 cm
Total Height	950 cm
Total Fe weight	2223 tons

Magnetic field	
Field strength	1.8 T
Corresponding Fe magnetization	$100\ A \cdot turns/cm$
Total Fe magnetization	$220000\ A \cdot turns$
Air gap	
Magnetization	$14000\ A \cdot turns$
20% safety margin	$47000\ A \cdot turns$
Total	
Magnetization	$281000\ A \cdot turns$
Total number of conductor loops	48
Current in conductor	5850 A
Resistance	
Al resistivity at 20^o C	$0.03\ \Omega mm^2/m$
Al resistivity at 50^o C	$0.035\ \Omega mm^2/m$
Total resistance of coil	$8 \times 10^{-3} \Omega$
Total electrical power (at 6000 A)	275 kW
Voltage drop	46 V

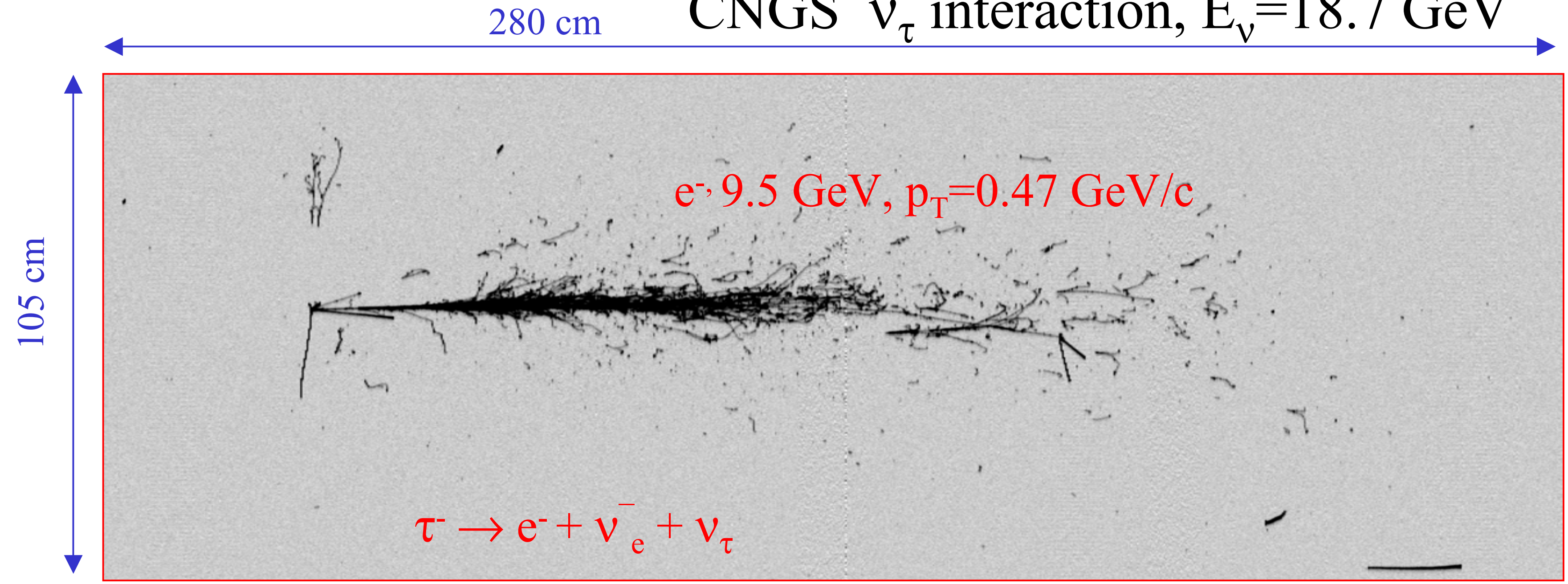
CNGS ν_μ interaction, E_ν=26 GeV

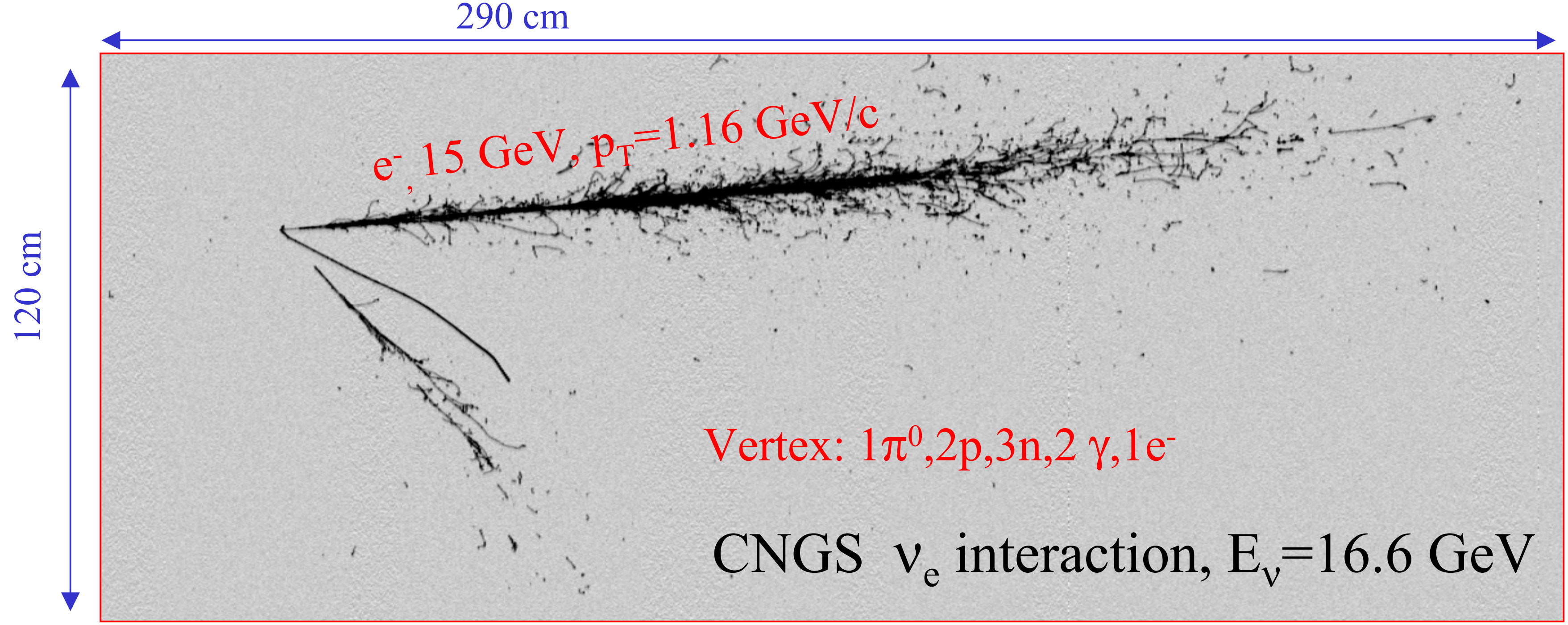


CNGS ν_μ interaction, E_ν=21.3 GeV

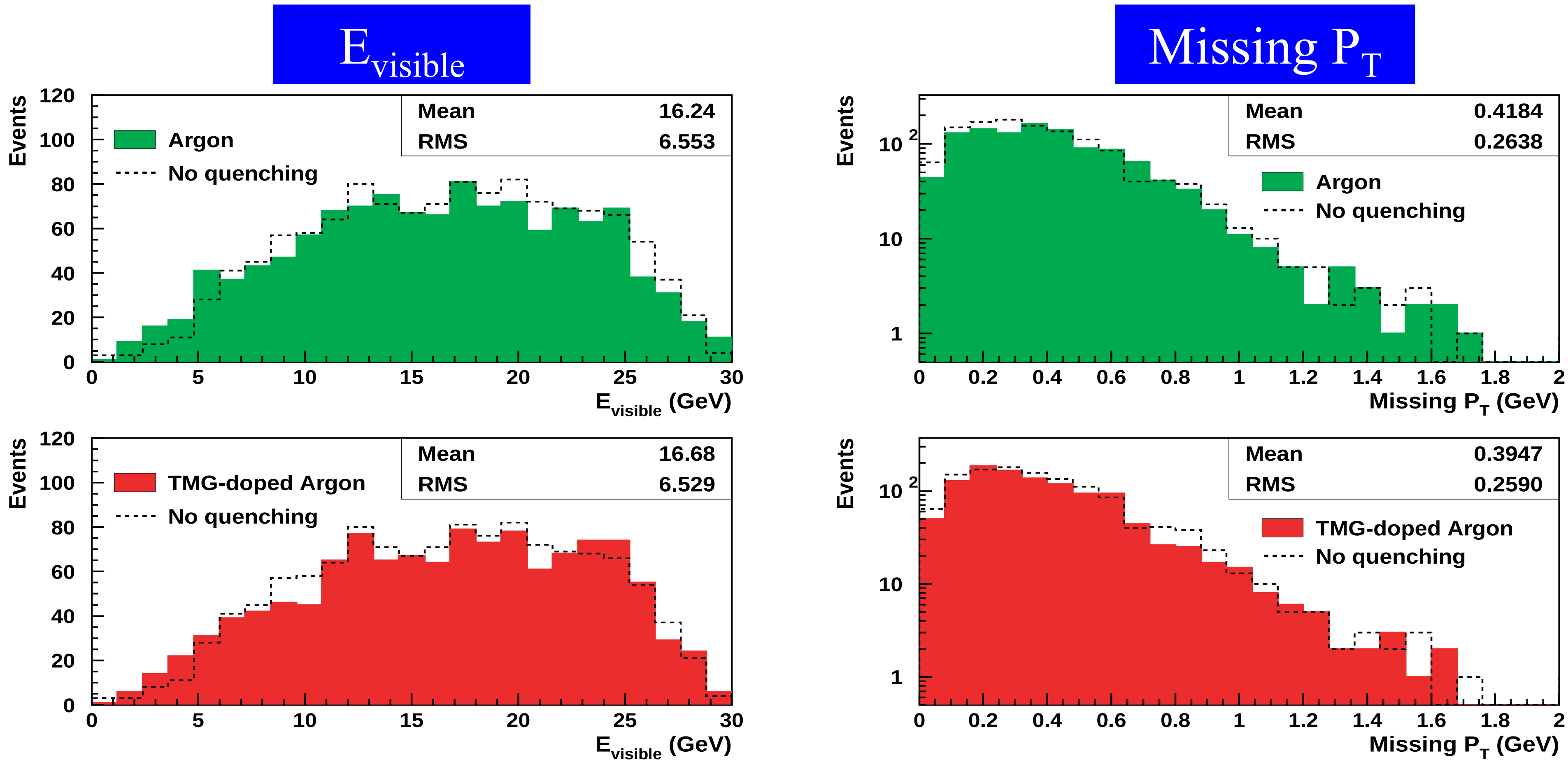


CNGS ν_τ interaction, E_ν=18.7 GeV





Event kinematics reconstruction



<Missing P_T> ≈ 410 MeV

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

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

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

Charged current (CC)

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

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

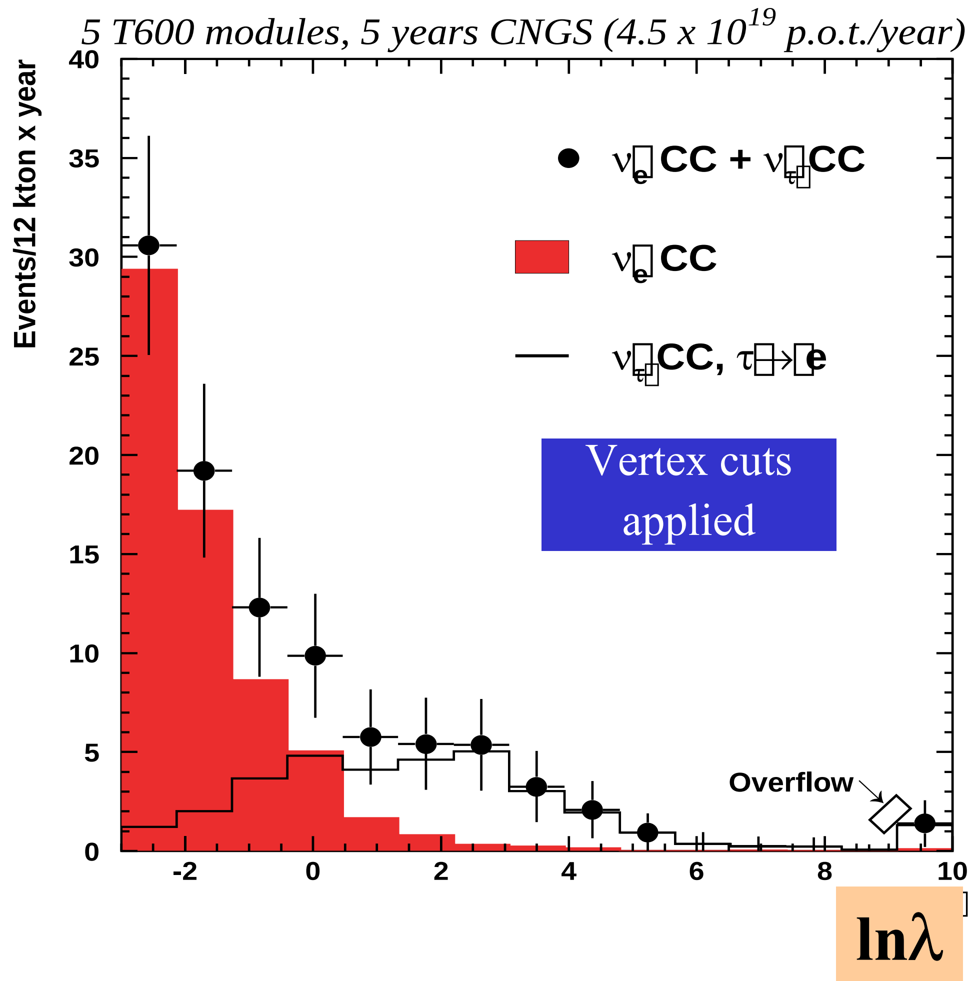
Charged current (CC)

$\tau \rightarrow e$ 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 ([Evisible, P_T^{miss}, ρ_l]) (signal)
  - L_B ([Evisible, P_T^{miss}, ρ_l]) (ν_e CC background)
  - Discrimination given by

$$\ln\lambda \equiv L([\text{Evisible}, P_T^{miss}, \rho_l]) = L_S / L_B$$



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	5.4	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 → ($\ln \lambda > 2.0$)

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

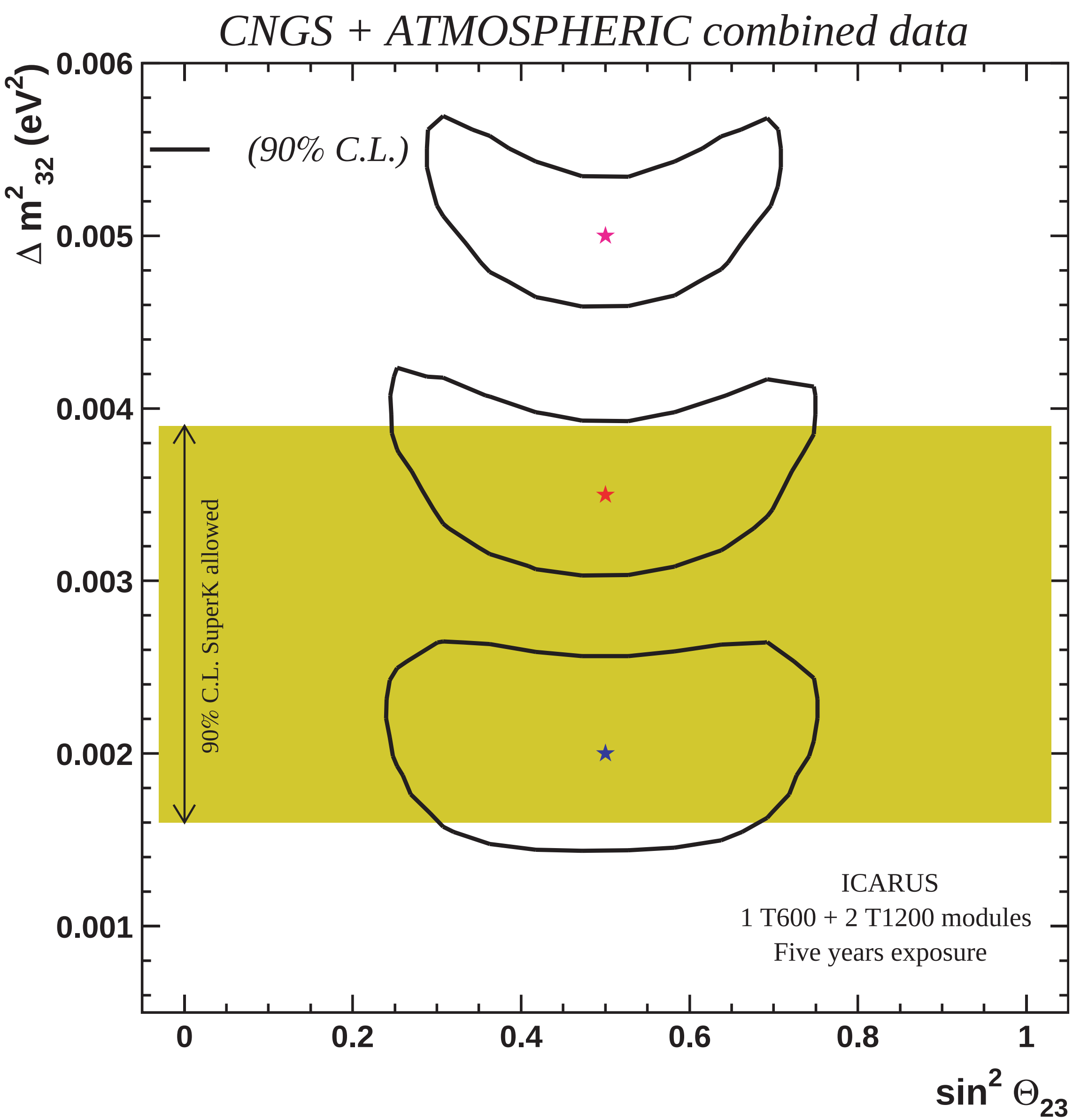
- T3000 detector (2.35 kton active, **1.5 kton fiducial**)
- Integrated pots = $2.25\ \text{x}10^{20}$

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**

- Several decay channels are exploited (golden channel = electron)
- (Low) backgrounds measured in situ (control samples)
- High sensitivity to signal, and oscillation parameters determination

Oscillation parameters determination



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

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

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

- The emerging scenario:
  - ➥ $|\Delta m^2_{21}| = (4 \div 12) \times 10^{-5}$ eV²
  - ➥ $\tan^2\theta_{12} = 0.32 \div 0.51 \Rightarrow 30° < \theta_{12} < 36°$
  - ➥ $|\Delta m^2_{32}| = (1.6 \div 3.9) \times 10^{-3}$ eV²
  - ➥ $\sin^2 2\theta_{23} > 0.92 \Rightarrow 37° < \theta_{23} < 45°$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atm ??? solar

- The confirmation that $\nu_\mu \to \nu_\tau$ 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 search for CP-violation searches in the leptonic sector !

    (note that CP-violation effects will only be visible for relatively large θ_{13})

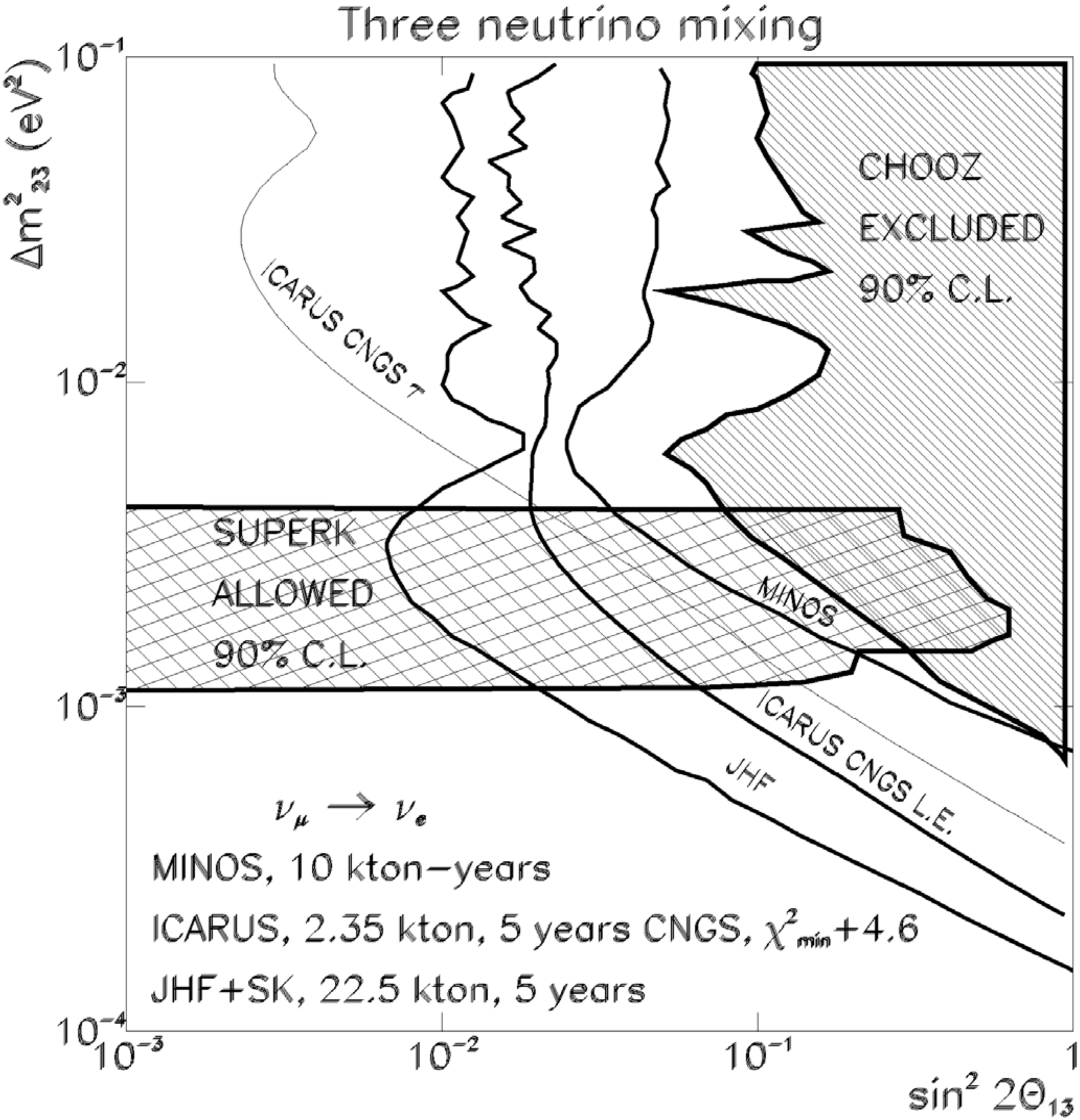
Search for subleading $\nu_\mu \rightarrow \nu_e$ (II)

- Search for excess of electrons, on top of electronic decays of tau
- Takes advantage of **unique e/π^0 separation in ICARUS**
- Assume 5 years @ 4.5×10^{19} pots, 2.35 kton fiducial
- Limited by statistics, needs more intensity at low energy to fully exploit capabilities of ICARUS

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

For $\Delta m^2 = 2.5\times10^{-3}$ eV^2:



Conclusion

- The ICARUS agenda foresees:
  - ➥ Initial operation with the T600 at LNGS, with data taking of astrophysical events in 2003;
  - ➥ the progressive realisation of two additional T1200 modules —starting from the T600 as basic cloning unit — to be operational around 2006.
- In this mass configuration, because of the unique potentials offered by the LAr technology, ICARUS will be able to perform a vast physics program in the domain of
  - ✓ Proton decay
  - ✓ Atmospheric neutrinos
  - ✓ Solar and supernovae neutrinos
- Within this context, it would be very valuable to take advantage of the realization of the CNGS beam in order to:
  - Provide real-time study of the beam properties
  - Search for $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ flavor appearance
- Because of the continuous nature of the detector, both original ICARUS programmes and its extension to CNGS could be performed simultaneously (and at a small added cost).