Liquid Argon Imaging Detectors

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SNRI ‘09

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Outline

- The ICARUS Liquid Argon TPC:
  - General principles
  - Technological challenges
  - Detector performance
- The WArP double-phase Ar-TPC
  - Physics motivation
  - Detector technology and performance
- Further developments

The need of visual detectors of high target density

- The success of the bubble chamber as a main tool in high energy fixed target physics is due to two main characteristics:
  - It provides a massive target, of substantial density
  - It provides complete imaging and reconstruction of the events in itself
- This technology has permitted in the past very substantial advances based on :
  - Single events with complete reconstruction (e.g. discovery of Ω^-)
  - Surprise events, i.e. topologies not a priori expected (e.g. Gargamelle neutral currents)
- Technology is costly and complicated
  - It requires high pressures and mechanical expansion
  - Its sensitivity is limited to about a few milliseconds
  - Optics limits viewing of large volumes
- These limitations make the bubble chamber technology ***inapplicable*** to ***modern needs*** (e.g. Neutrino / underground physics)

Liquid noble gasses as detector media: basic properties

- Ideal materials for detection of ionizing radiation:
  - Dense (≈ g/cm^3 ≈ 10^3 x ρ_{gas}), homogeneous, target and detector
  - Do not attach electrons (long drift paths possible in liquid phase)
  - High electron mobility (≈quasi-free drift electrons, not neon)
  - Commercially easy to obtain (in particular, liquid Argon)
  - Can be made very pure and many impurities freeze out at low temperature
  - Inert, not flammable

Type	Density (r/cm^3)	Energy loss dE/dx (MeV/cm)	Radiation length X_0 (cm)	Collision length l (cm)	Boiling point @ 1 bar (K)	Thermal electron mobility (cm^2/Vs)	
Neon	1.2	1.4	24	80	27.1	high&low	
Argon	1.4	2.1	14	80	87.3	500	€
Krypton	2.4	3.0	4.9	29	120	1200	€€
Xenon	3.0	3.8	2.8	34	165	2200	€€€

• A Historical View On the R&D for liquid Rare Gas detectors, T. Doke, NIM A 327 (1993) 113 and references therein.

Liquids vs Solids

- Liquids are particularly interesting when compared to solids, since their uniform properties ensure a very precise movement of the ionization electrons.
- Solids are used to detect ionizing events collecting electronic charges, like in the case of semiconductor detectors. These are very uniform but relatively small, being part of crystals. In order to build large-scale detectors with solids one has to worry about cracks, medium transitions and so forth.
- Some early attempts of using solid noble gasses for particle detection have evidenced a number of serious difficulties of the type just mentioned.
- None of these difficulties are present with liquids, emerging as best candidates for very large scale detectors.

The ICARUS experiment

- A multi-kton detector based on a new powerful detection technique:
  - the Liquid Argon Time Projection Chamber
    - [C. Rubbia: CERN-EP/77-08 (1977)]
  - first proposed to INFN in 1985
    - [ICARUS: Imaging Cosmics And Rare Underground Signals: INFN/AE-85/7]
  - capable of providing a 3D imaging of any ionizing event ("electronic bubble chamber") with in addition:
    - high granularity (~mm)
    - excellent calorimetric properties
    - particle identification (through dE/dx vs range)
    - self triggering
    - continuously sensitive

The ICARUS program

- A rich physics program addressing issues beyond the standard model of elementary particles such as:
  - Matter stability:
    - proton decay (> 10^{34} years)
  - Neutrino physics (masses, flavour mixing, CP violation):
    - atmospheric neutrinos (100 MeV - GeV)
    - solar neutrinos (1 - 10 MeV)
    - supernovae neutrinos (1 -10 MeV)
    - Long-Base-Line “artificial” neutrino beam from CERN (3 - 30 GeV)

Few events/day/kt

  - These extremely rare events, spanning a wide energy range, require:
    - large mass general purpose detectors (several kton)
    - shielding from cosmic radiation (large underground labs: LNGS)

The ICARUS collaboration

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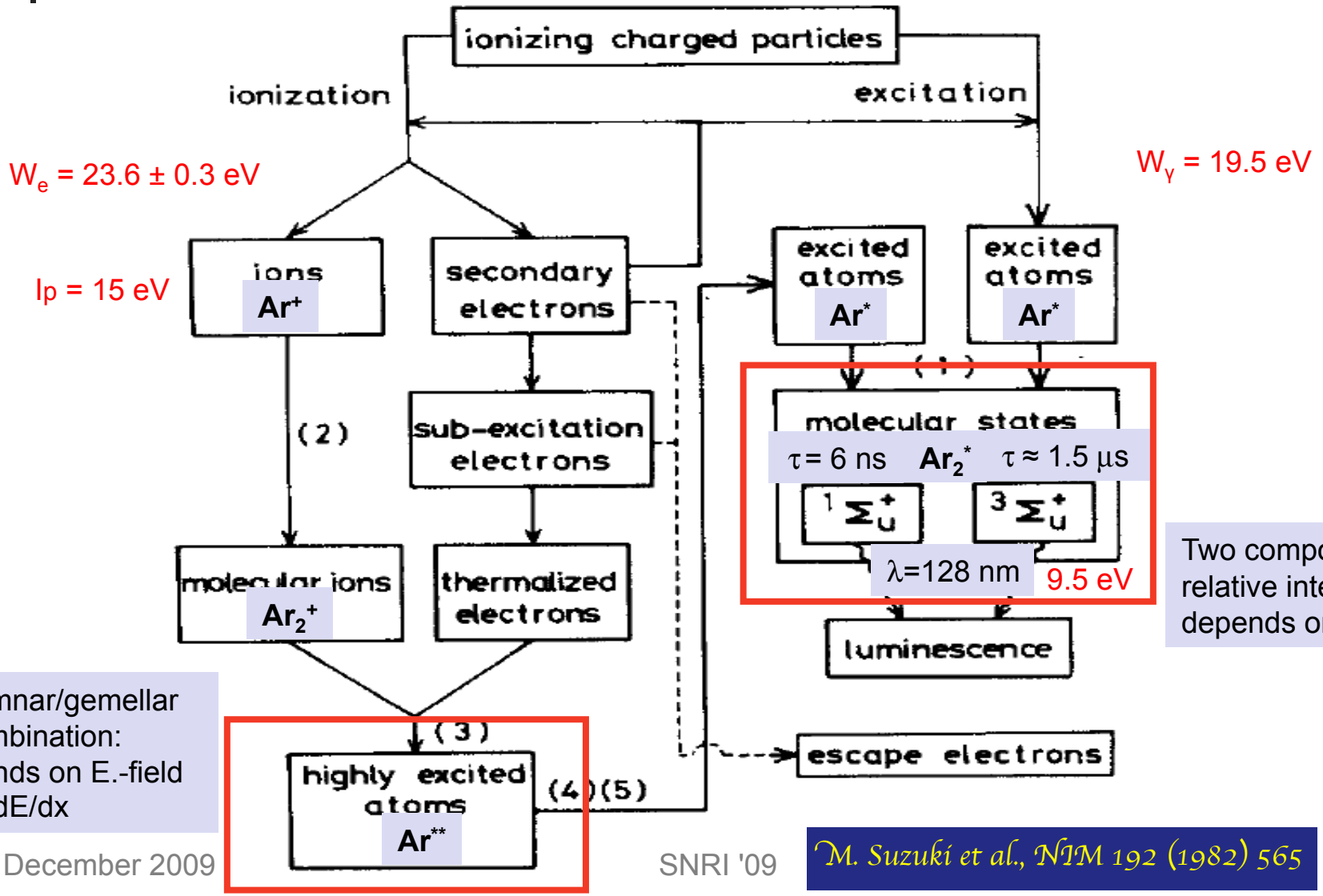
Processes induced by charged particles in Argon



Two components: relative intensity depends on dE/dx

Columnar/gemellar recombination: depends on E.-field and dE/dx

M. Suzuki et al., NIM 192 (1982) 565

LAr detection medium properties

	Water	Liquid Argon
Density (g/cm^3)	1	1.4
Radiation length (cm)	36.1	14.0
Interaction length (cm)	83.6	83.6
dE/dx (MeV/cm)	1.9	2.1
Refractive index (visible)	1.33	1.24
Cerenkov angle	42°	36°
Cerenkov d^{2}N/ dEdx (b=1)	≈ 160 eV^{-1} cm^{-1}	≈ 130 eV^{-1} cm^{-1}
Muon Cerenkov threshold (p in MeV/c)	120	140
Scintillation (E=0 V/cm)	No	Yes (≈ 50000 g/MeV @ l=128nm)
Long electron drift	Not possible	Possible (μ = 500 cm^2/Vs)
Boiling point @ 1 bar	373 K	87 K

When a charged particle traverses LAr:

1) Ionization process

W_e = 23.6 ± 0.3 eV

Fano factor = 0.11 (energy resolution)

2) Scintillation (luminescence)

W_γ = 19.5 eV

UV "line" (λ = 128 nm ➔ 9.7 eV)

No more ionization: Argon is transparent

Only Rayleigh-scattering

3) Cerenkov light (if relativistic particle)

☞ **Charge**

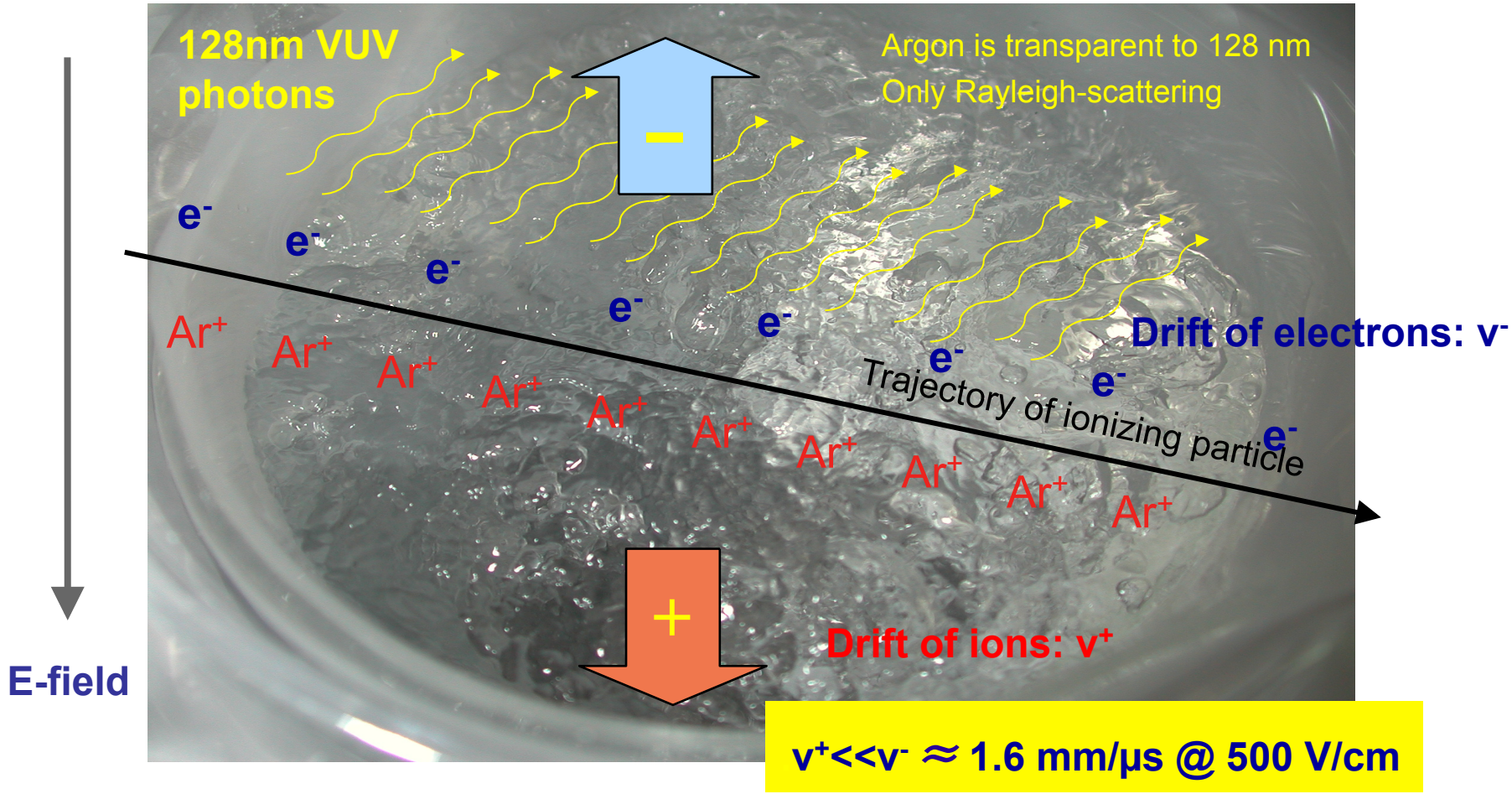
☞ **Scintillation light (VUV)**

☞ **Cerenkov light (if β>1/n)**

Scintillation & Cerenkov light can be detected independently !

Passage of particle in LAr

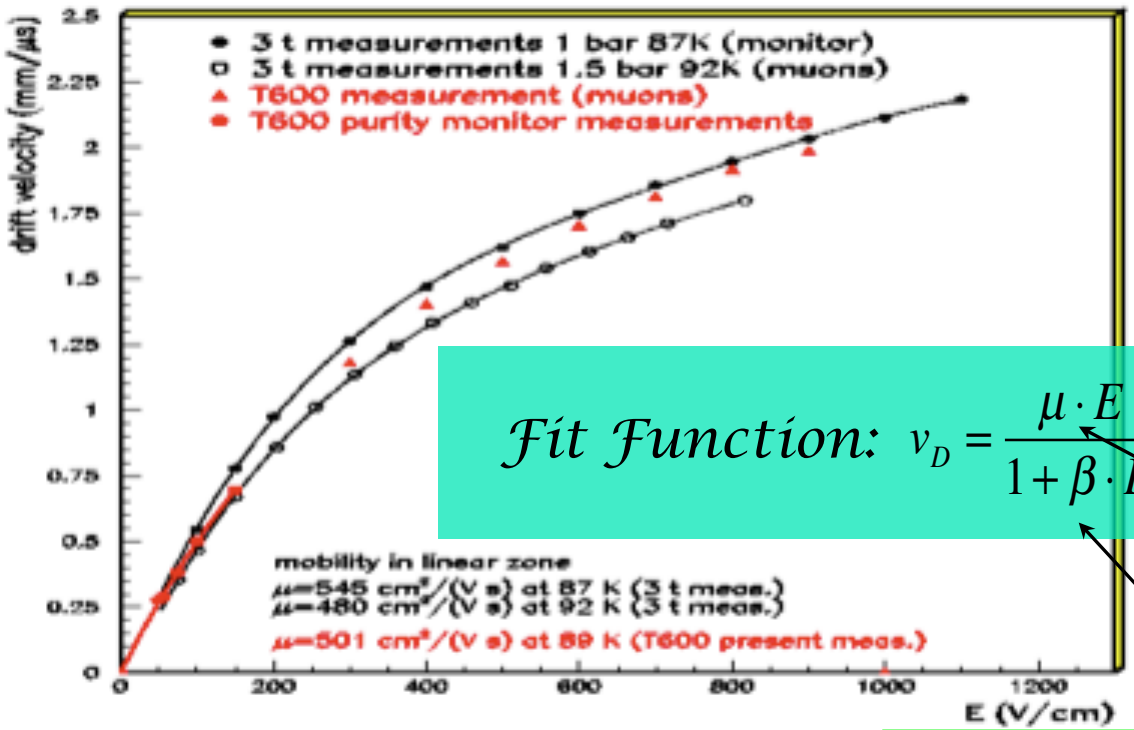
In the presence of electric field

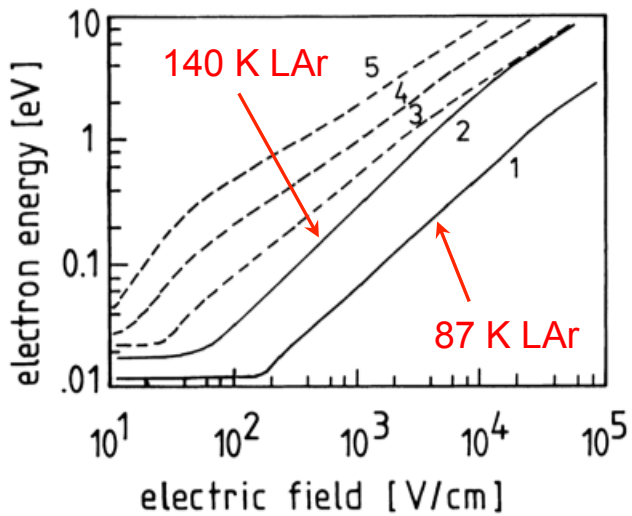


$v^+ << v^- \approx$ 1.6 mm/μs @ 500 V/cm

Free electron drift velocity in LAr

W.F. Schmidt, IEEE Trans. EI-19 No.5 (1984)





$$\textit{Fit Function:}\quad v_D = \frac{\mu \cdot E}{1+\beta \cdot E}$$

Electrons mobility
μ = 542 cm^2/V/s

$\mu \approx T^{-3/2}$

$$v_{DRIFT} \approx \frac{Ee}{m_e} \cdot \frac{\lambda}{v_T}$$

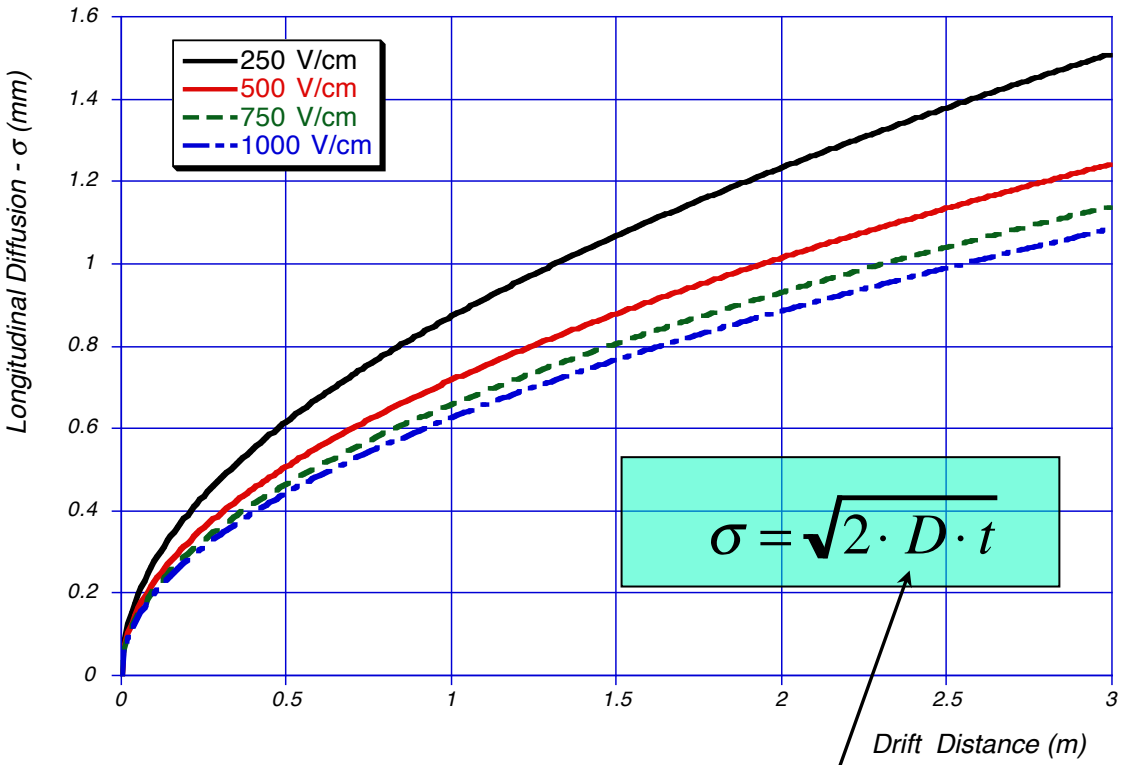
λ → Mean free path

v_T → maxwellian velocity

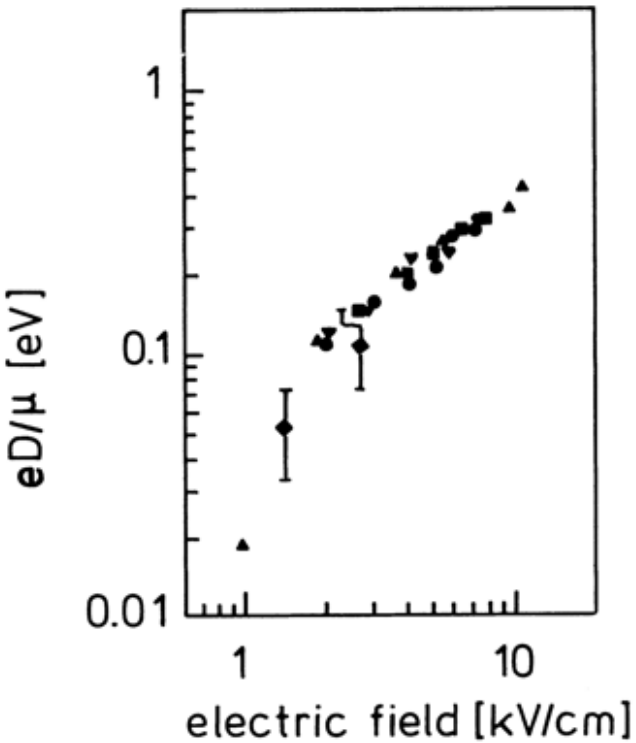
Velocity saturation factor $\beta^{-1} \approx 450$ V/cm
Accounts for loss of linearity when electron is no more thermalized

Free electron diffusion in LAr

W.F. Schmidt, IEEE Trans. EI-19 No.5 (1984)



$$\sigma = \sqrt{2 \cdot D \cdot t}$$

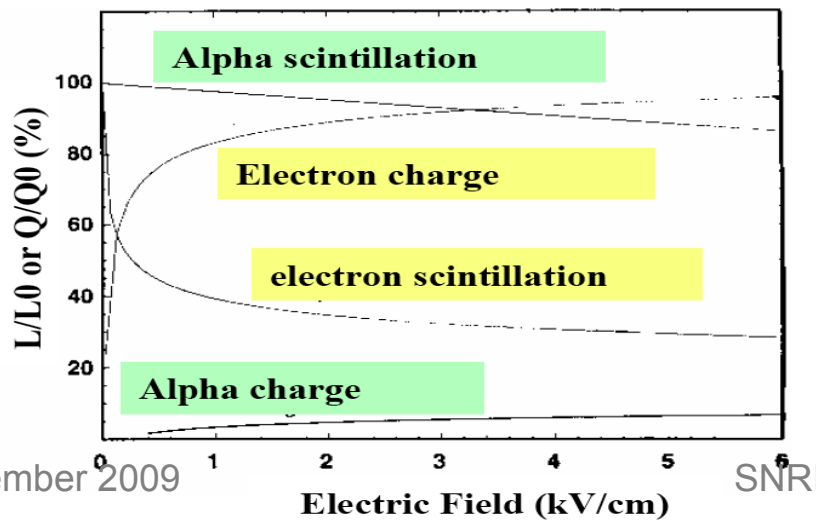


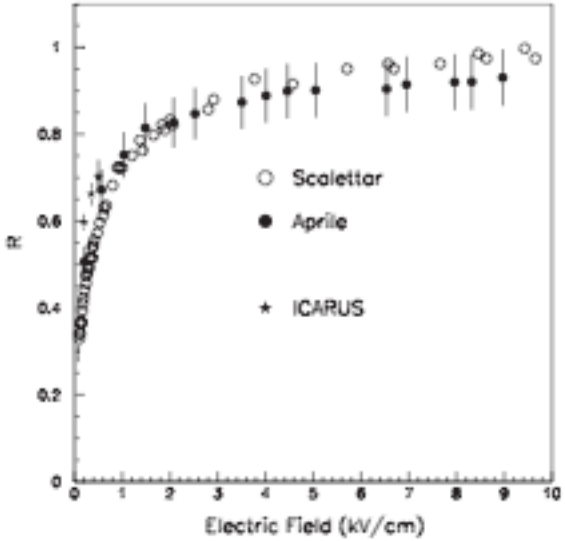
Measured Diffusion Coefficient. D = 4.06 $cm^2\ s^{-1}$
In agreement with Einstein relation with mobility for quasi thermal electrons.

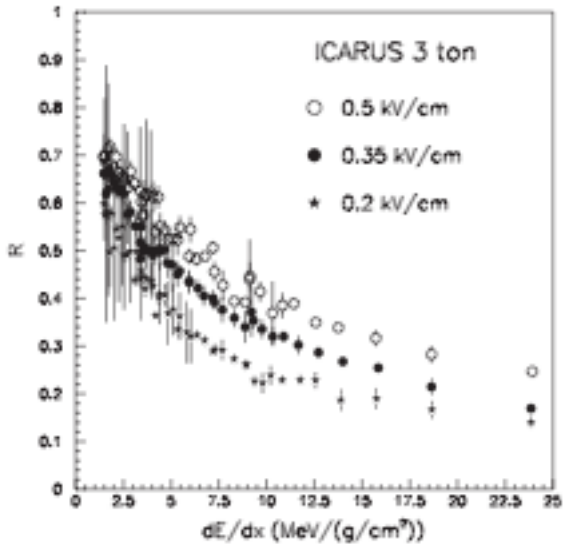
Lateral diff. ~ longitudinal diff.

Free electron yield in LAr

- Strong e^--ion recombination due to comparable thermalization distance (~140 nm) and e^--ion separation.
- Both geminate (Onsager) and columnar (Jaffe) active depending on dE/dx and E.F.
- Decrades dE/dx linearity (particle i.d.) and energy resolution
- Additional scintillation light is generated in the recombination process.







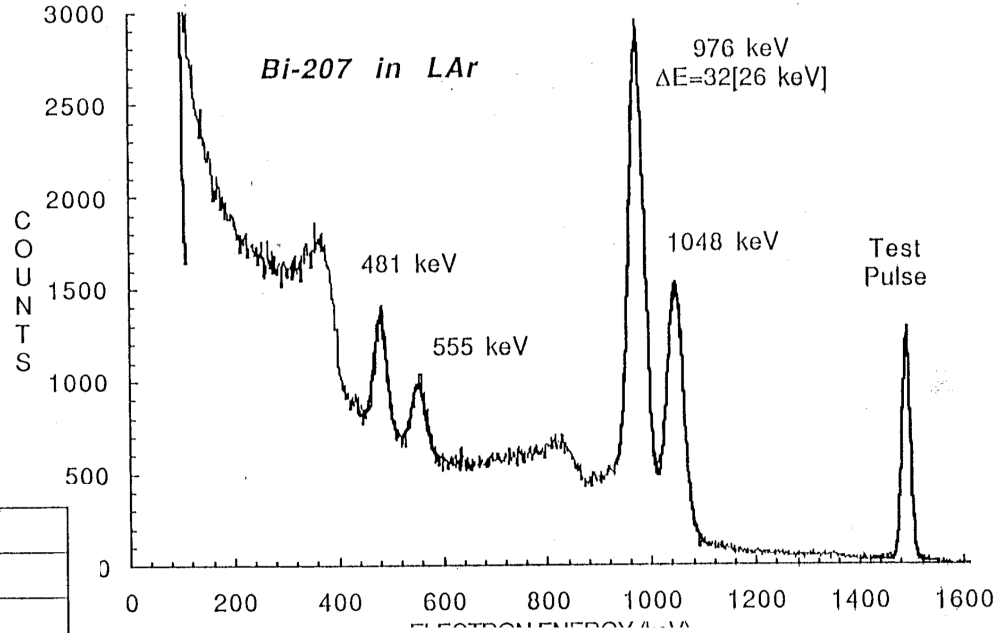
Energy resolution in LAr

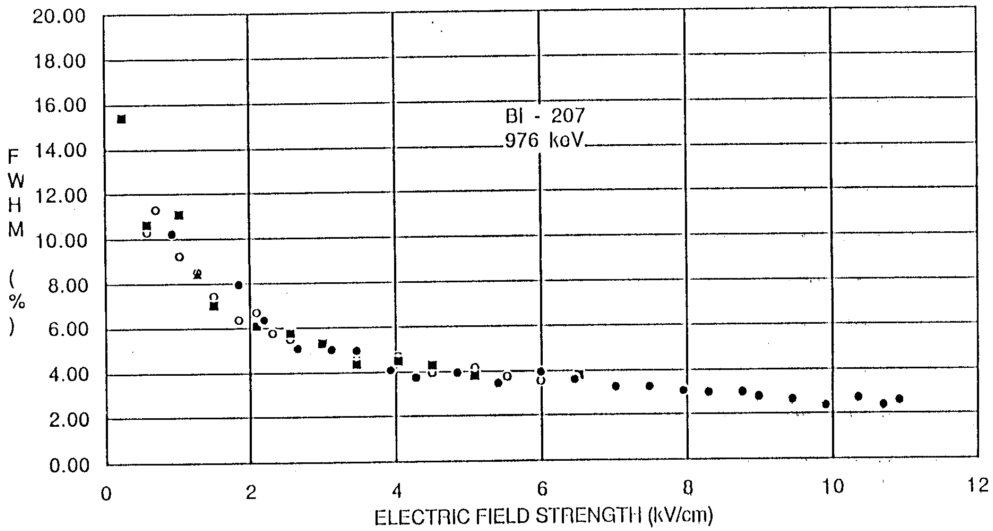
- Intrinsic resolution @ E = 1 MeV

$$\Delta E = \sqrt{FWE} \approx 4keV$$

  - F=0.11 Fano factor
  - W =24.6
- Best result 32 KeV @ 10kV/cm

E. Aprile et al., NIM (1987)

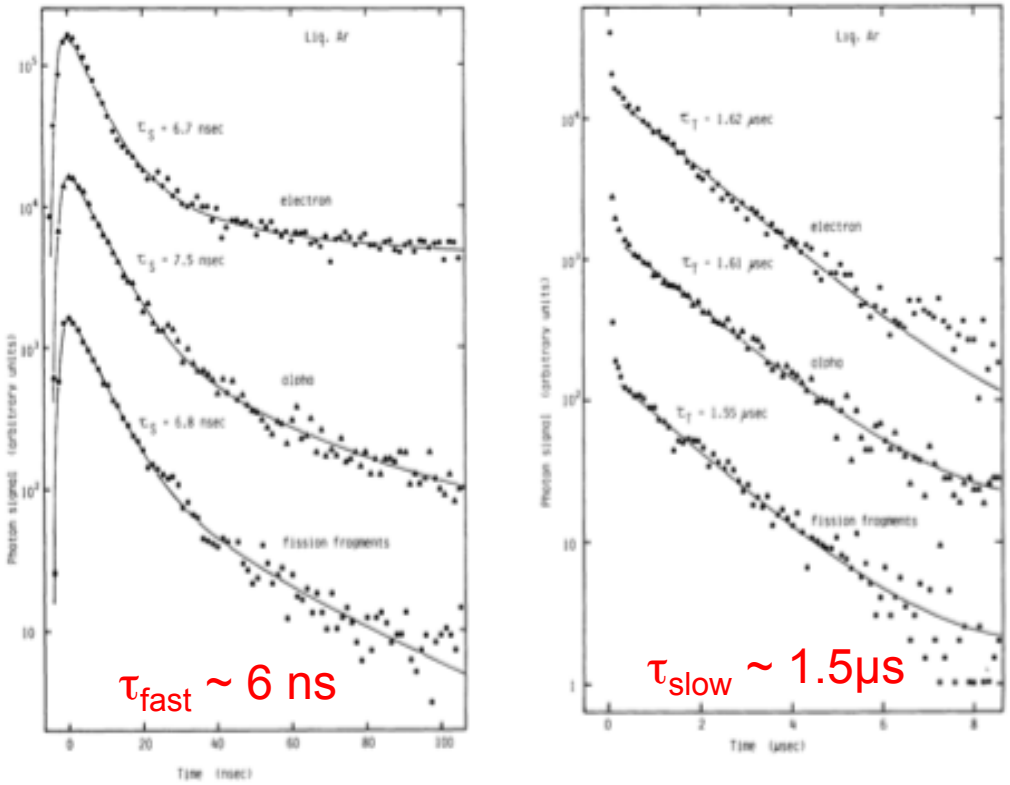




- Degradation possibly due to fluctuation in δ-ray production inducing:
  - Variation in e^--ion recombination at each track end-point (dE/dx)
  - Depends on E-field

Scintillation properties

- Abundant scintillation light @ 128 nm: 40000 photons/MeV @ null E-field
- E.-field dependence also present (related to recombination)
- Fast / Slow component ratio strongly depend on dE/dx:
  - F/S_{mip} ~1/3;
  - F/S_{alpha}~1.3;
  - F/S_{nuc_rec}~3.
- Simultaneous recording of Light and Charge helps improving overall energy resolution
  - Anti-correlation due to electron ion recombination changing 1 free electron into 1 scintillation photon

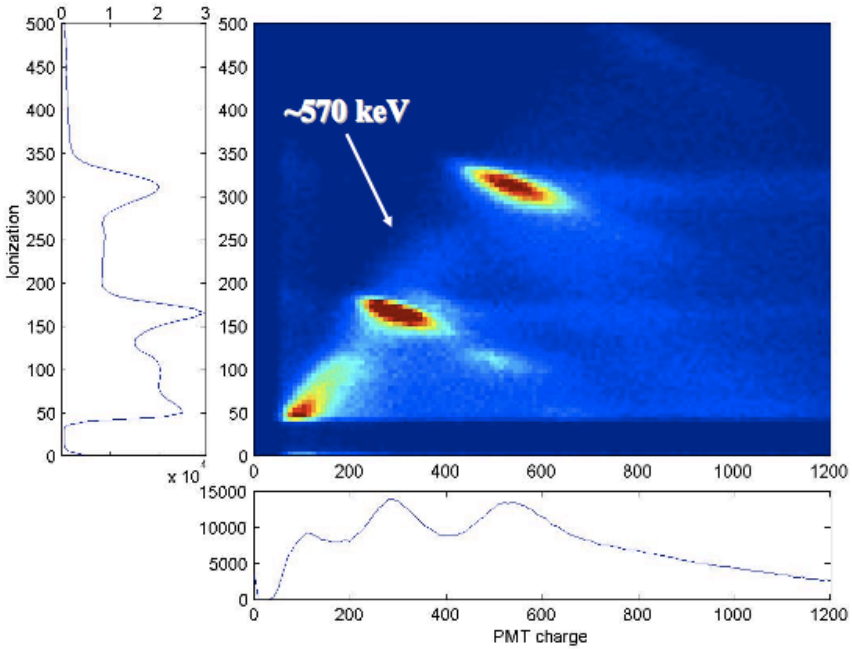


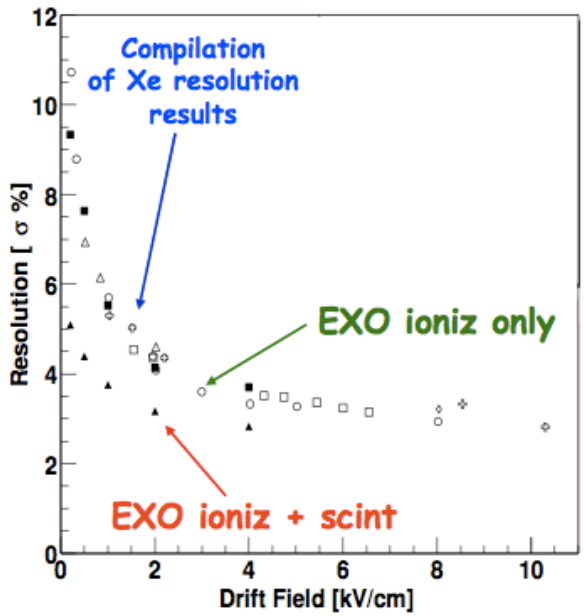
A. Hitachi et al., Phys. Rev. B 27 (1983).

Improved energy resolution

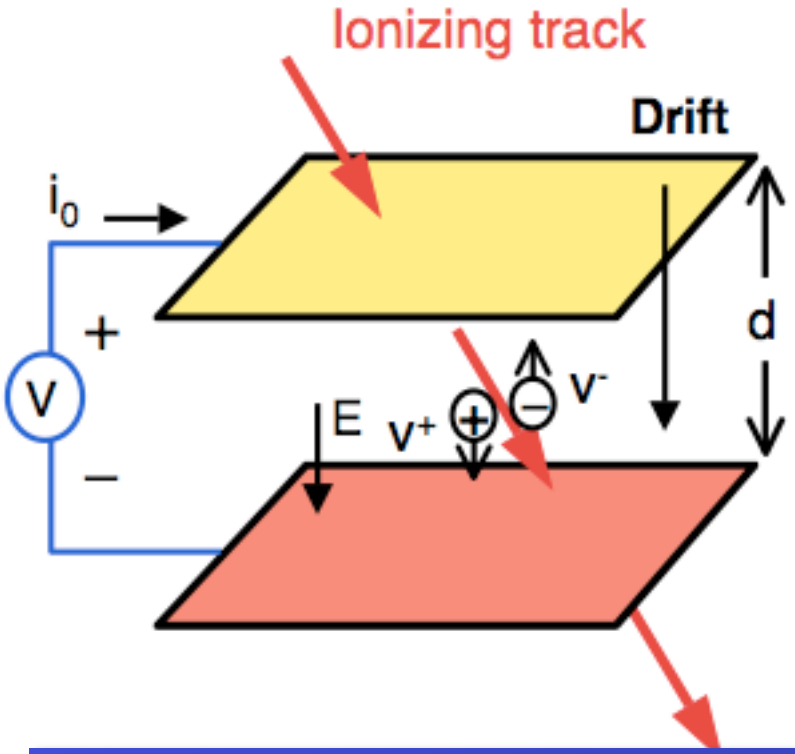
- Anti-correlated ionization and scintillation (in Lxe)
  - Ionization: σ(E)/E = 3.8% @ 570 keV
  - Ionization & Scintillation: σ(E)/E = 3.0% @ 570 keV

E.Conti et al. Phys. Rev. B: 68 054201 (2003)





Signals from dielectric liquids



The "work" performed by the power supply which puts electrons and ions in movement is given by:

$$dW=eE(v^+ + v^-)dt=Vi_0dt$$

from which the current and charge are:

$$i_0=e\,(v^+ + v^-)/d$$

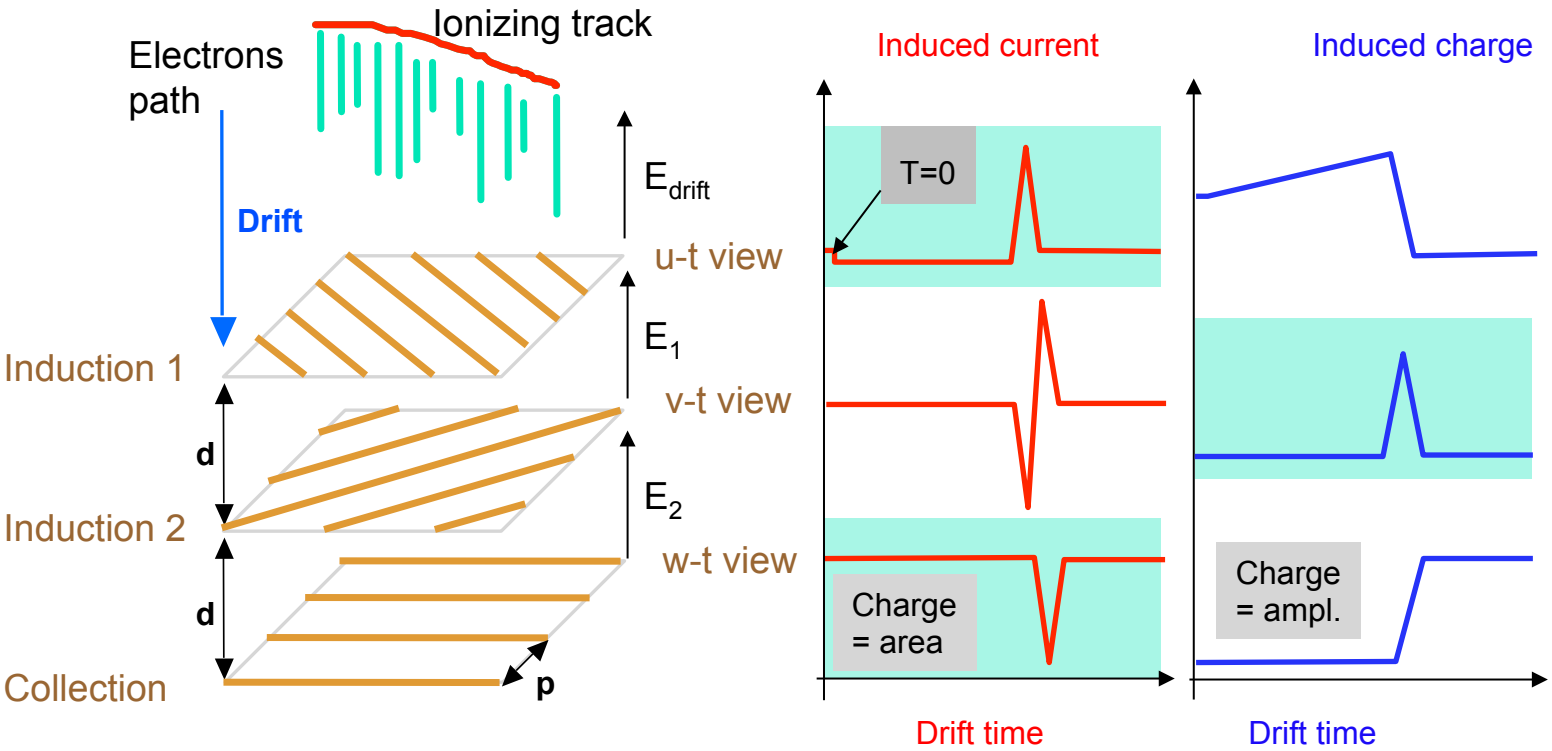
$$Q^{\pm}=e(d-x^{\pm})/d$$

since $v^- / v^+ \approx 10^5$, *electron current is dominant*.

If a *grid* is inserted on the path of the electron, the work changes sign under traversal and so does the current, with a total *charge collected* equal to zero.

In case of multiple electrodes, the contribution to the "work" and therefore to the current is proportional to the fractional field contribution at the point of the electrons.

The induction signals (3D)



The drifting electron is traversing an ***arbitrary number of wire planes*** oriented in the direction of the required view. Each of them provides a *triangular induction signal* of maximum charge, equal to the electron charge. The electron charge in finally *collected* by the ***collection wire plane***.The generated view of the event is the one seen by a camera at infinity with the optical axis in the direction of the wires.

- ICARUS: three wire planes (pitch 3mm, separation 3mm)

Grid shielding and transparency

O. Bunemann, et al., Can. J. Res. 27(1949) 191

- Best signal localization and charge collection is realized if each grid perfectly shields the adjacent electrodes.
  - Shielding inefficiency σ is a pure geometrical effect:

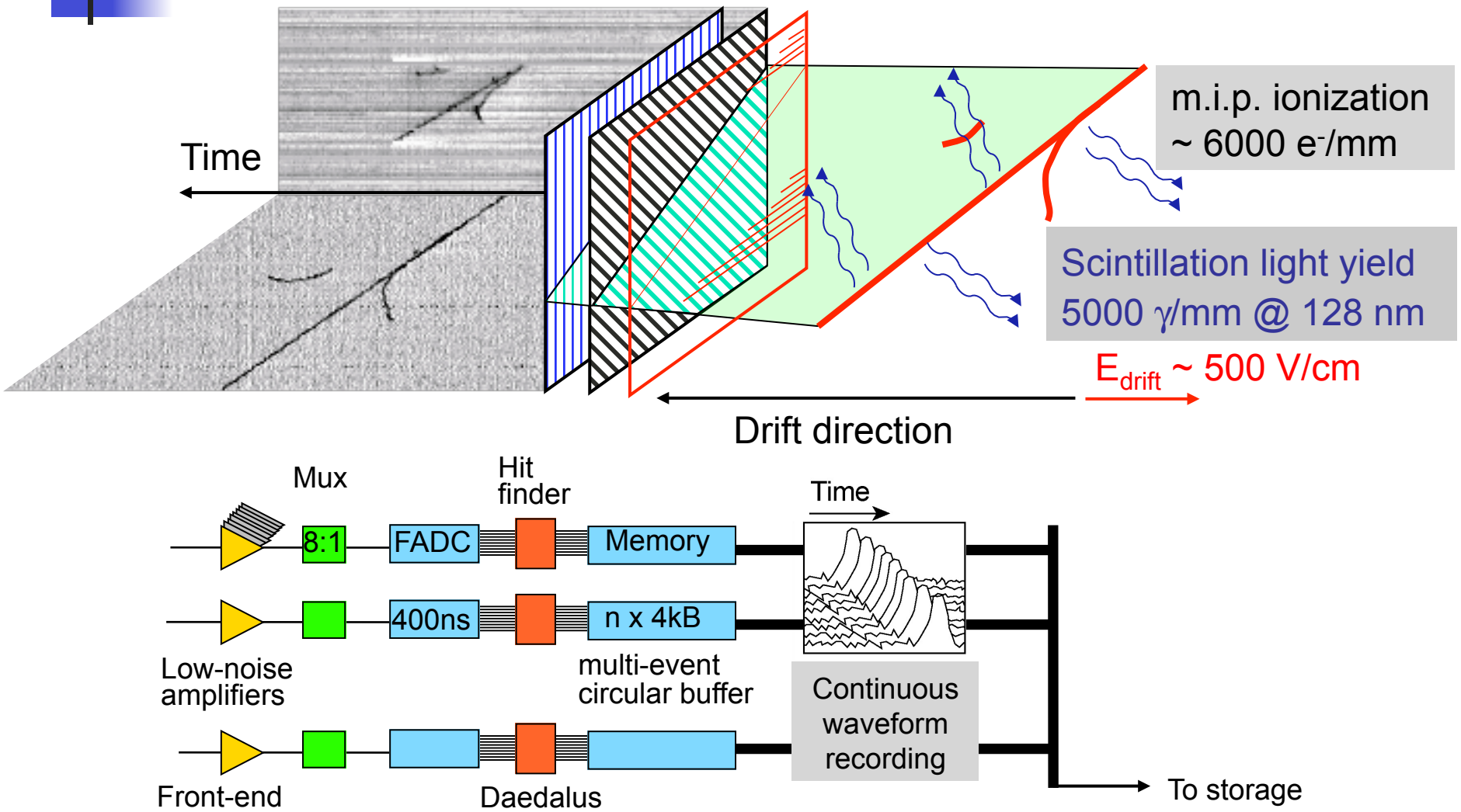
$$\sigma = \frac{p}{2\pi d}\ln\left(\frac{p}{2\pi r}\right) \qquad p = 3mm; d = 3mm; r = 75\mu m \Rightarrow \sigma = 18\%$$

    - Depends on pitch p, wire radius r and distance from other grids d.
  - Full transparency is required not to loose electrons along the path before reaching the collecting grid

$$\frac{E_1}{E_2} > \frac{1+\rho}{1-\rho} \qquad \rho = \frac{2\pi r}{p} \qquad \frac{E_1}{E_2} > 1.4 \Rightarrow$$ Full transparency

    - Depends also on E-field ratio across the grid
    - For equal fields loss is twice the geometrical cross-section.

The ICARUS read-out principle



How far can free electrons drift?

- Detector complexity grows with the number of electron collection wire planes. Therefore the distance over which electrons are made to drift should be as long as possible. Several limitations come into play.
  - The value of a practical high voltage. At the convenient drift field of 500 V/cm, in order to drift over 3 meters, it requires 150 kV. The drift time over this distance is 1.85 ms (v_{drift} ~ 1.56 mm/μs @ 87 K).
  - The diffusion of electrons, which slightly blur the image, transforming a delta function into an approximately gaussian distribution:

$$\sigma(t) = \sqrt{2 \cdot D \cdot t}\ , D = 4.0 \pm 0.2\ cm^2 s^{-1}$$

t = 2 ms, σ = 1.4 mm

  - The electron attachment probability during the drift time. In order to collect a significant electric signal, electrons must not become bound as ions, which have a much smaller v^-. The fraction of surviving free electrons is given by ($k^{(i)}$ = adsorption rate for the i-th impurity of concentration $N^{(i)}$):

$$N(t) = N(0)\exp(-t/\tau) \quad \frac{1}{\tau} = \sum_i N^{(i)} k^{(i)}$$

for O_2, $k \sim 10^{11}$ l mol^{-1} s^{-1}

  - Concentrations < 30 ppt Oxygen equivalent (τ>10 ms) are the state of the art.

LAr TPC: crucial requirements

- Cryogenic temperature
  - T = 88 K at 1 bar
  - high standards of technical reliability, stability and safety, UHV techniques
- High purity required for long-drift time
  - 0.1 ppb of O_2 equivalent for 3 ms drift
- No signal amplification in liquid
  - 1 m.i.p. over 3 mm yields 20000 electrons equivalent noise charge 1200 electrons
- Self triggering
  - Prompt scintillation VUV light (128 nm) abundantly produced by ionizing events

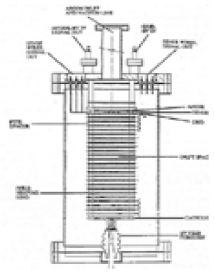
Cryogenic plant

Argon purification

Low noise electronics

PMT's wth wave-shifter

The path to larger LAr detectors



24 cm drift wires chamber

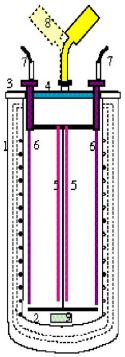
CERN

1

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

2

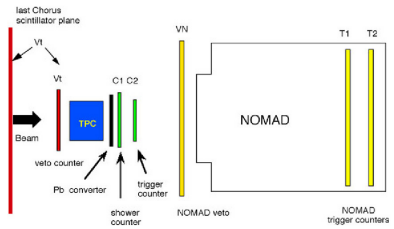
3 ton prototype



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

CERN

Laboratory work



50 litres prototype
1.4 m drift chamber

CERN

3

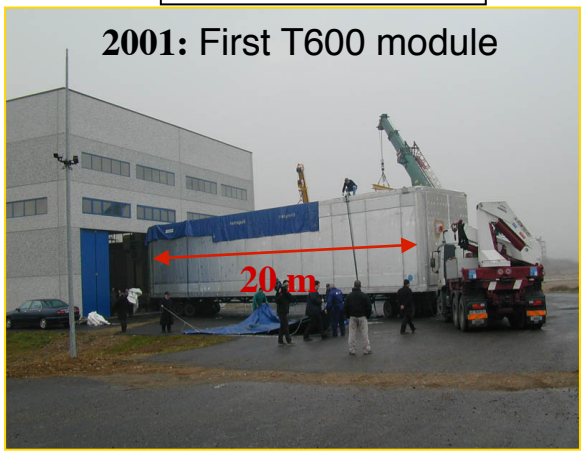
1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

4

10 m3 industrial prototype

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

T600 detector



2001: First T600 module

5

Cooperation with industry
AirLiquide, Breme, Cinel, CAEN

LAr contaminants

- Because of their low temperatures (87 K for LAr), noble liquids can be easily purified, since most of the contaminants freeze out spontaneously.
- Main residual contaminants are O_2, H_2O, CO_2 both for charge and light and N_2 for light.
- O_2 can be efficiently eliminated with oxidation reactions (e.g. Oxisorb)
- H_2O, CO_2 and other polar molecules can be tapped with specific molecular sieves (e.g. Hydrosorb)
- N_2 has to be reduced at production plant (ppm level).

Free electron lifetime in LAr

- By direct injection of given amounts of impurities:

$$\tau \approx 300\mu s \times \frac{1\,ppb}{N(O_2)}$$

- Essentially independent of the electric field for O_2
- Within the ICARUS program, routinely reach LAr purification level of < 0.1 ppb of impurities via liquid recirculation.

A. Bettini et al., NIM A305 (1991) 177

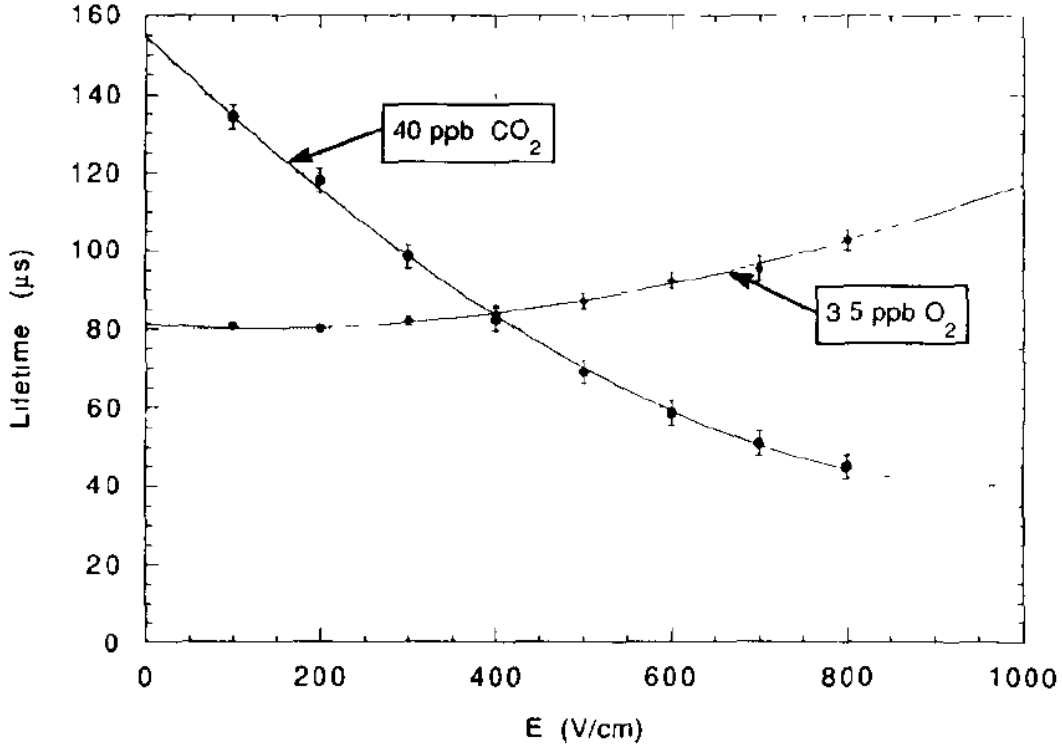
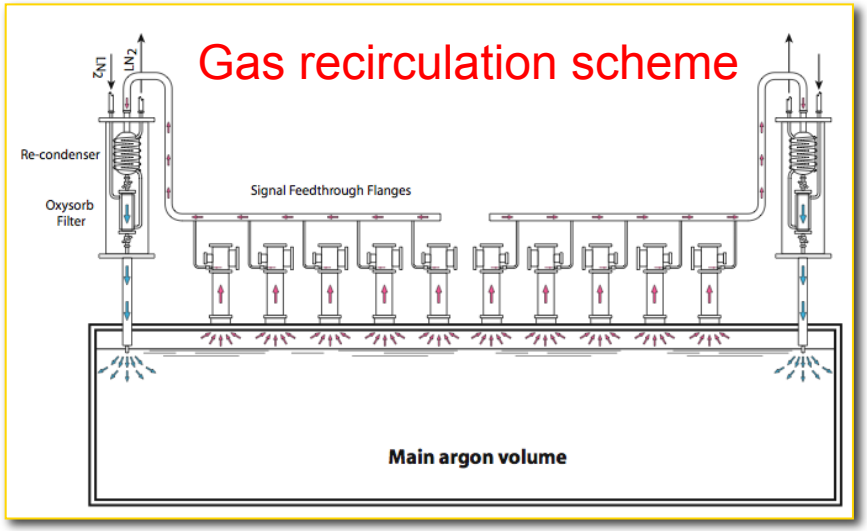
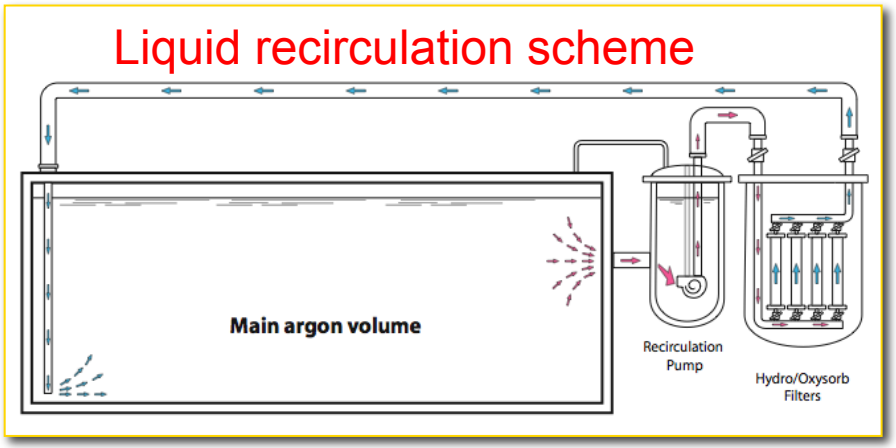


Fig. 12. Electric field dependence of the electron lifetime τ in purified LAr doped with 40 ppb CO_2 and 3.5 ppb O_2. Lines are drawn to guide the eye.

LAr purification

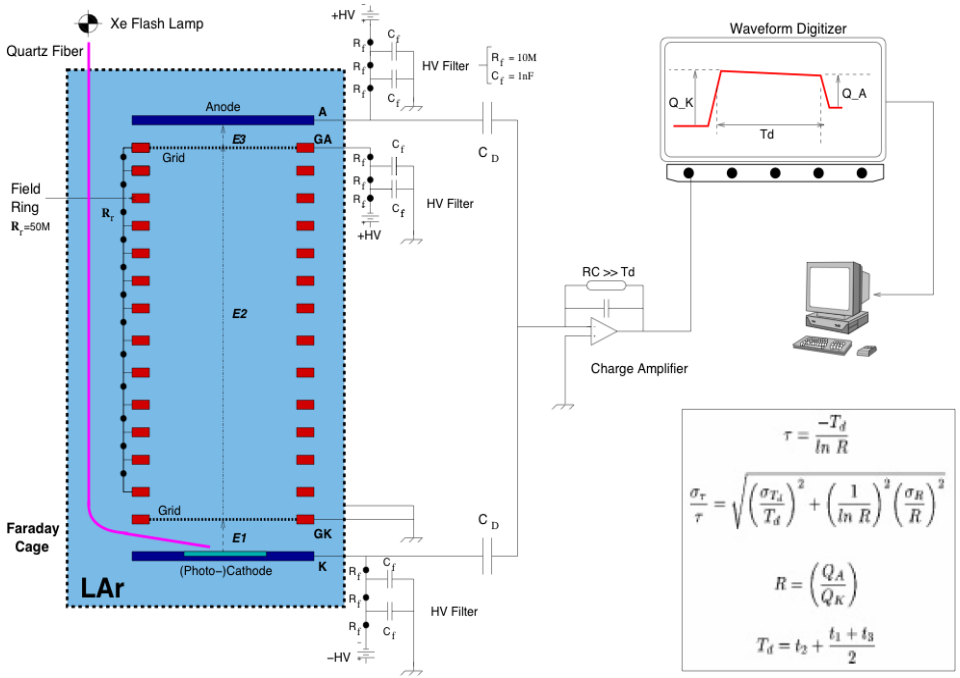
- The “standard” ICARUS:
  1. Use ultra high vacuum standards for detector components design, construction, cleaning and assembly;
  2. Removal of air and outgassing of surfaces by evacuating the argon container volume to the molecular vacuum level (< 10^{-3} mbar);
  3. Fast cooling (to minimize out-gassing) and filling with ultra-purified LAr;
  4. Recirculation/purification of the gas phase to block the diffusion of the impurities from the hot parts of the detector and from micro-leaks on the openings (typically located on the top of the device) in the bulk liquid;
  5. Recirculation/purification of the bulk liquid volume to further reduce the impurities concentration.





Purity monitor

Double gridded ionization chamber



$$\tau = \frac{-T_d}{\ln R}$$

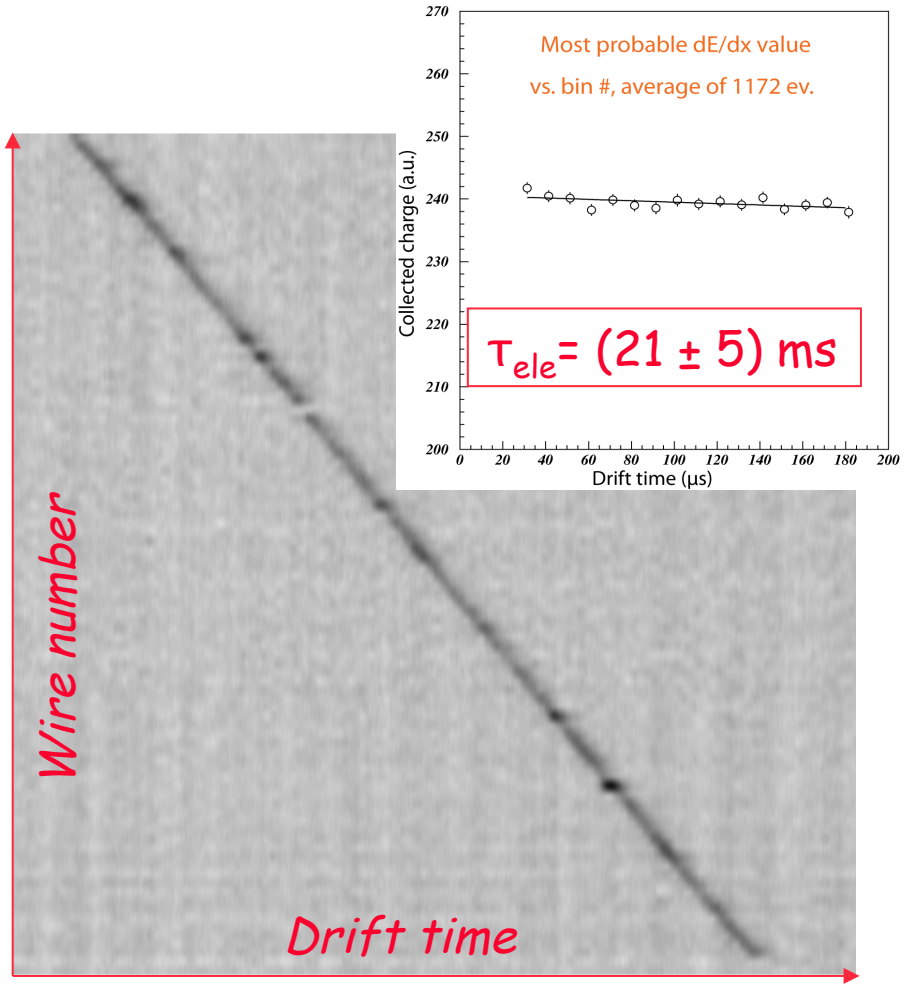
$$\frac{\sigma_\tau}{\tau} = \sqrt{\left(\frac{\sigma_{T_d}}{T_d}\right)^2 + \left(\frac{1}{\ln R}\right)^2 \left(\frac{\sigma_R}{R}\right)^2}$$

$$R = \left(\frac{Q_A}{Q_K}\right)$$

$$T_d = t_2 + \frac{t_1 + t_3}{2}$$

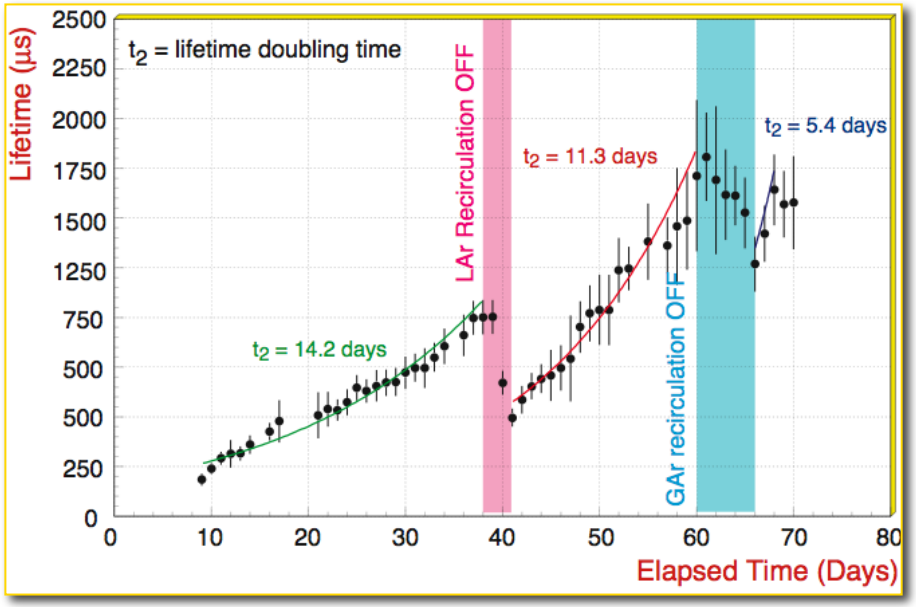
UV laser (266 nm) used to extract electron cloud from gold photocathode

Charge vs drift time along m.i.p tracks

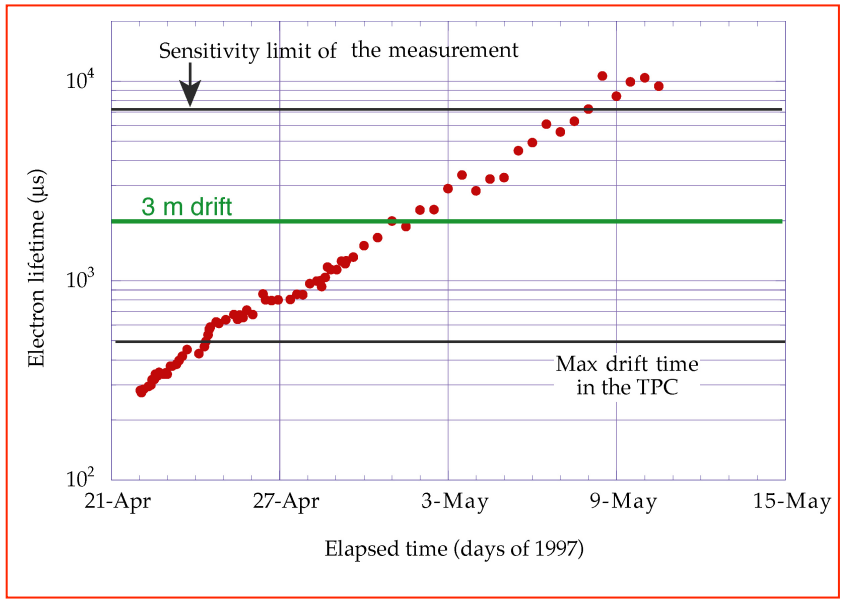


Purity Achievements

In the T300 IN Pavia



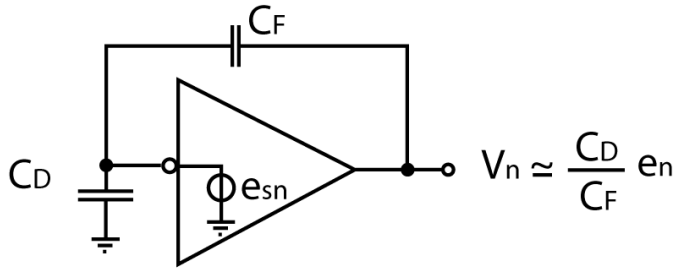
In a small scale protoptype (50 liter LAr-TPC)



Recent result in LNL test facility: $\tau \sim 20$ ms (15 ppt O_2 equivalent) measured with charge attenuation along crossing cosmic muon tracks!!

Front-end electronics requirements

- Need of very low noise amplifier:
  - No amplification around sense wires
    - Induced charge ~ 10^4 electrons
  - Large input capacitance (C_D)
    - Wires (20 pF/m) + cables (50 pF/m)
    - In T600 C_D ~ 300-400pF
    - Serial noise (proportional to C_D) dominates over parallel noise (proportional only to signal bandwidth)
  - High trans-conductance (g_m) input device is required to ensure acceptable Signal-to-Noise level (S/N ~ 10) >> jFET



$$A = \frac{Z_{C_D} + Z_{C_F}}{Z_{C_D}} = \frac{C_D + C_F}{C_F} \simeq \frac{C_D}{C_F}$$

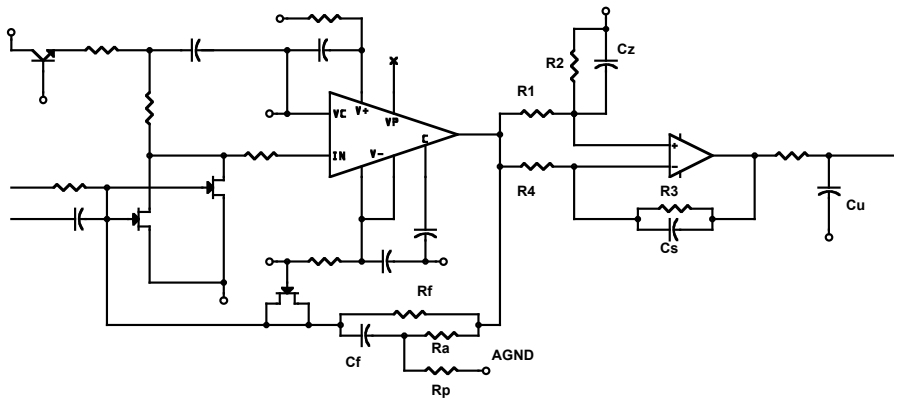
$$e_{sn}^{\ 2} \propto \frac{1}{g_m}$$

$$S/N \propto \frac{q}{C_F} * \frac{C_F}{e_{sn} * C_D} = \frac{q}{e_{sn} * C_D}$$

The ICARUS preamplifier

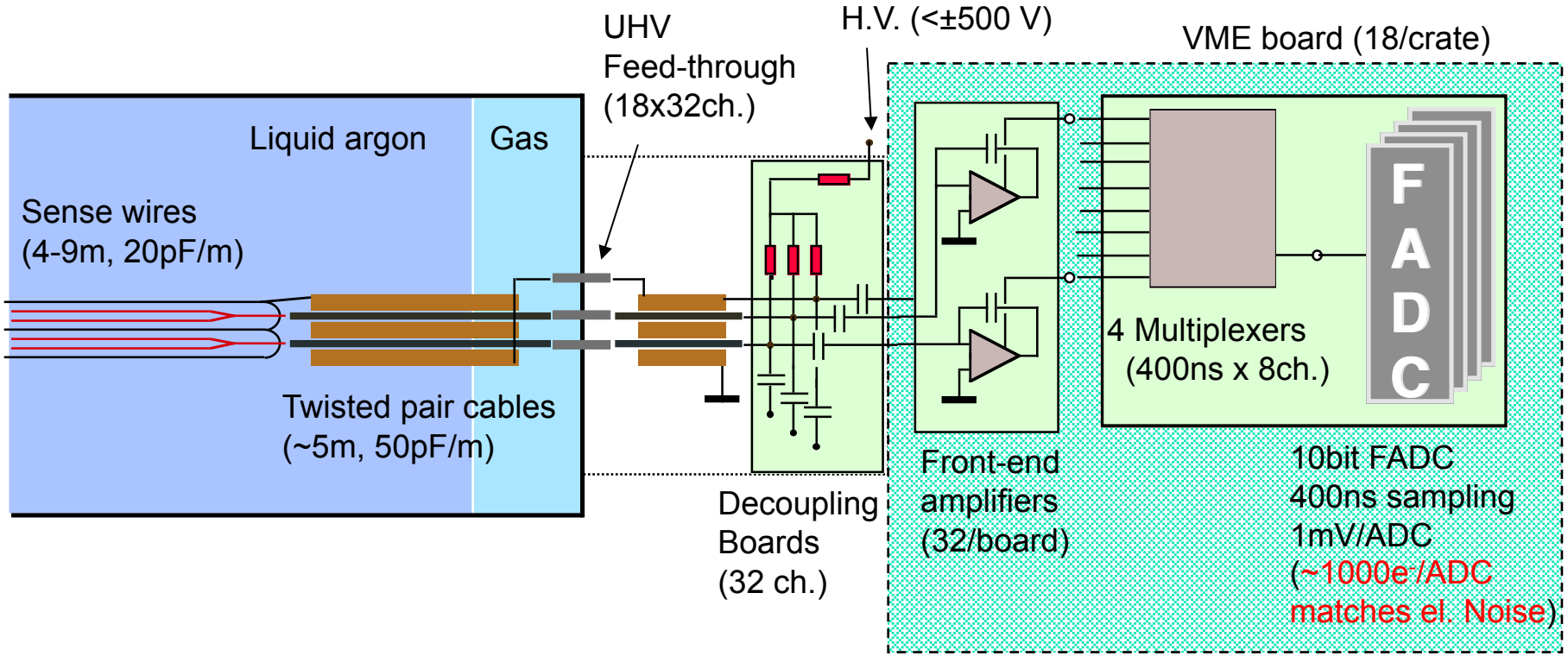
- Custom IC in BiCMOS technology
  - Classical Radeka integrator
  - External input stage jFET's
    - Two IF4500 (Interfet) or BF861/2/3 (Philips) in parallel to increase g_m (50-60 mS)
  - External feed-back network
    - Allow sensitivity and decay time optimization
    - High value f.b. resistor (100MΩ) reduce parallel noise
  - External baseline restorer circuit
    - BW noise reduction
- Two channels per IC
  - Identical symmetrical layout guarantees identical electrical behavior

Two versions:
"quasi-current" mode: $R_fC_f \approx 1.6$ μs (collection + first induction)
"quasi-charge" mode: $R_fC_f \approx 30$ μs (mid induction)



Sensitivity ≈ 6 mV/fC
Dynamic range > 200 fC
Linearity < 0.5% @ full scale
Gain uniformity < 3%
E.N.C. ≈ (350 + 2.5 x C_D) el ≈ 1200 el. @ 350pF
Power consumption ≈ 40 mW

Layout of front-end electronics

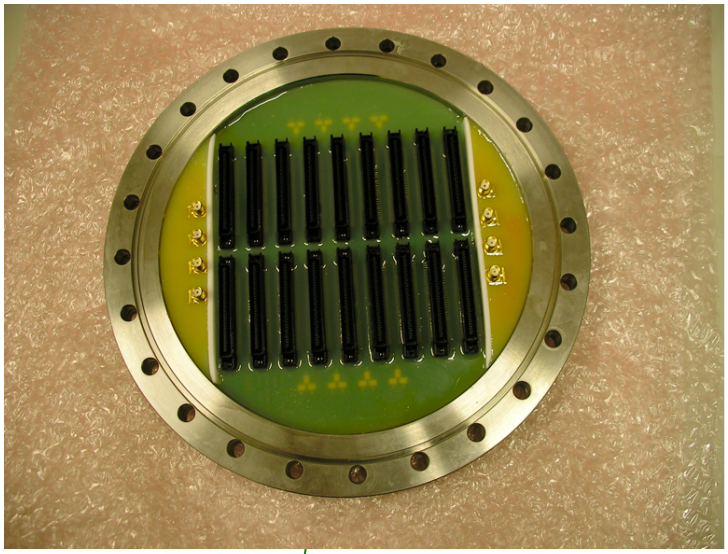


ICARUS T600: ~ 54000 channels — 1720 boards — 96 crates

Cost of the full electronic chain: ~ 60 € / channel

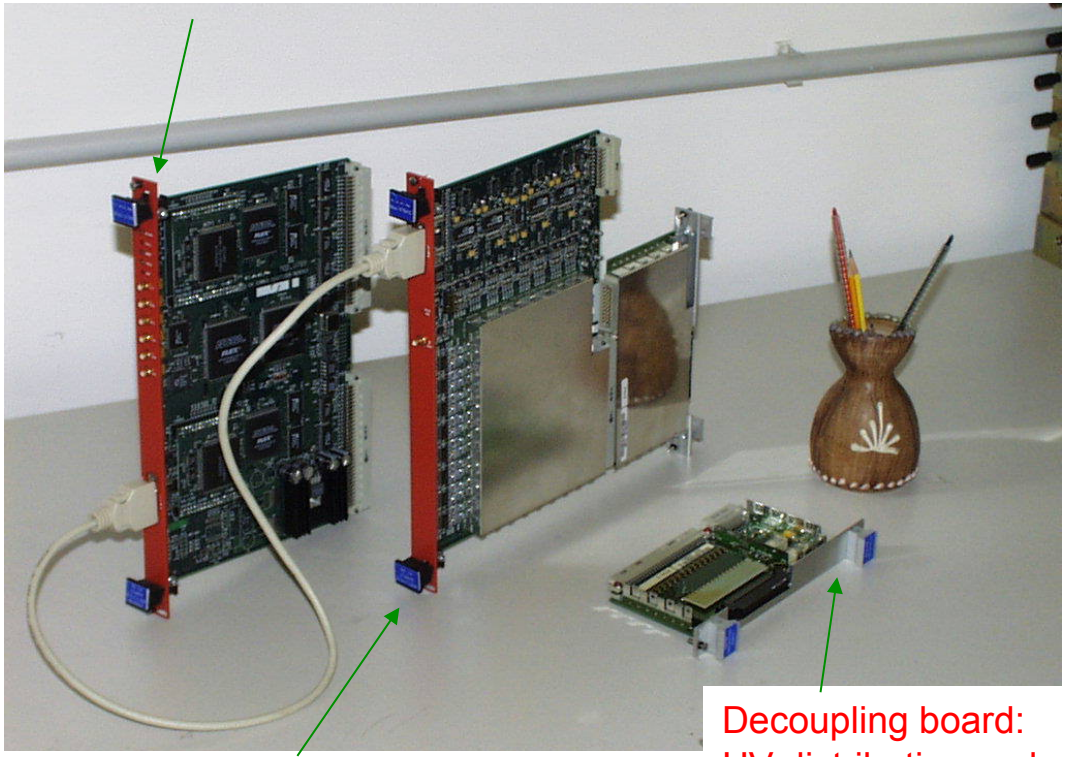
Front-end in LAr also possible, BUT: no major improvents w.r.t inaccessibilty

The ICARUS read-out chain



Signal UHV feed-through:
576 channels (18 connectors x 32)
+ HV wire biasing

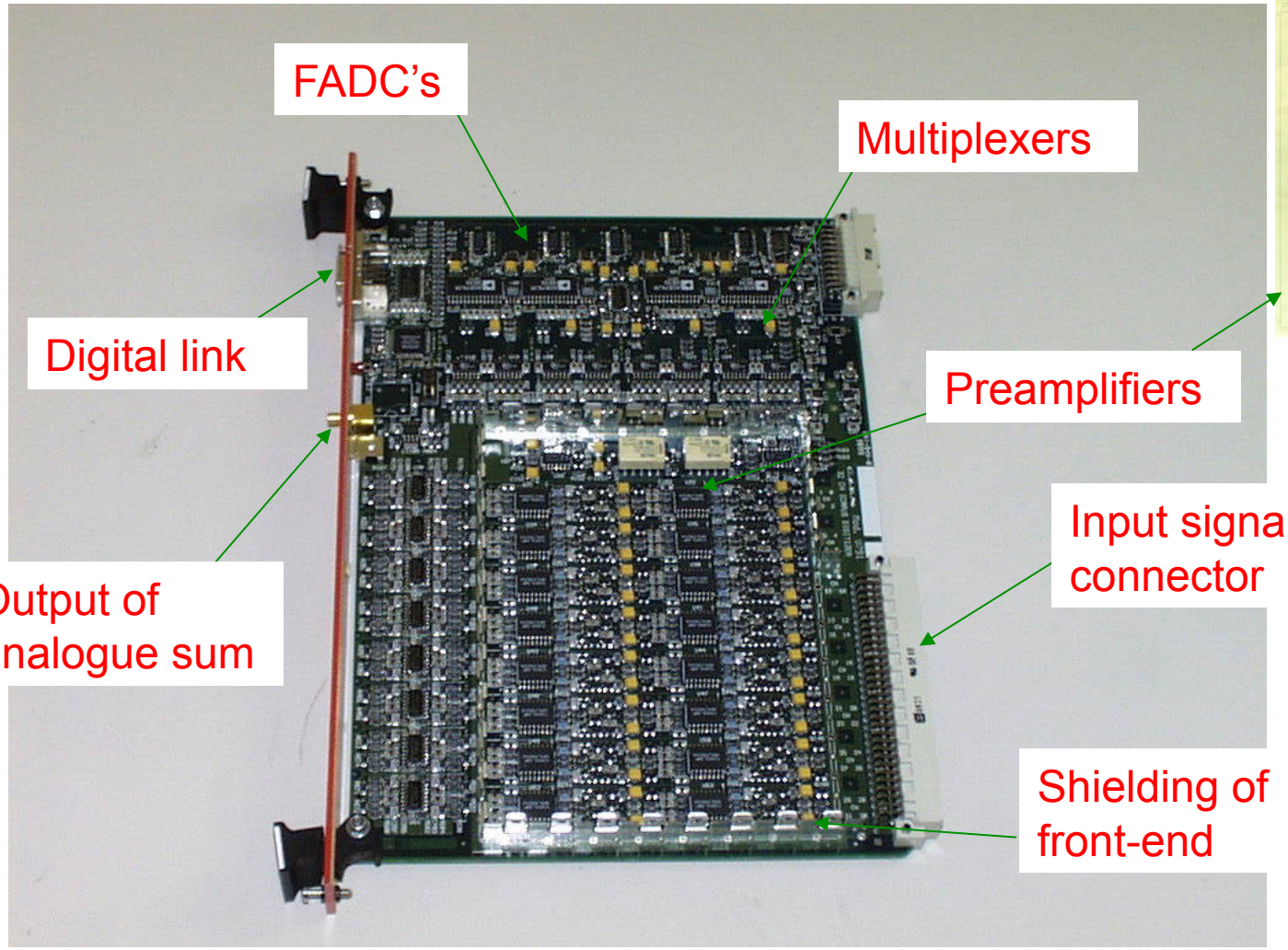
CAEN-V789 board: 2 Daedalus VLSI * 16 input channels (local self-trigger & zero suppression) + memory buffers + data out on VME bus

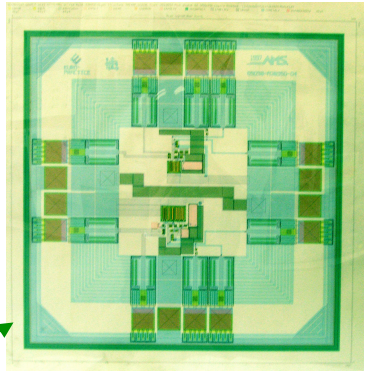


CAEN-V791 board: 32 pre-amplifiers +
4 multiplexers (8:1) + 4 FADC's (10 bits - 20 MHz)

Decoupling board:
HV distribution and
signal input

The analogue board V791

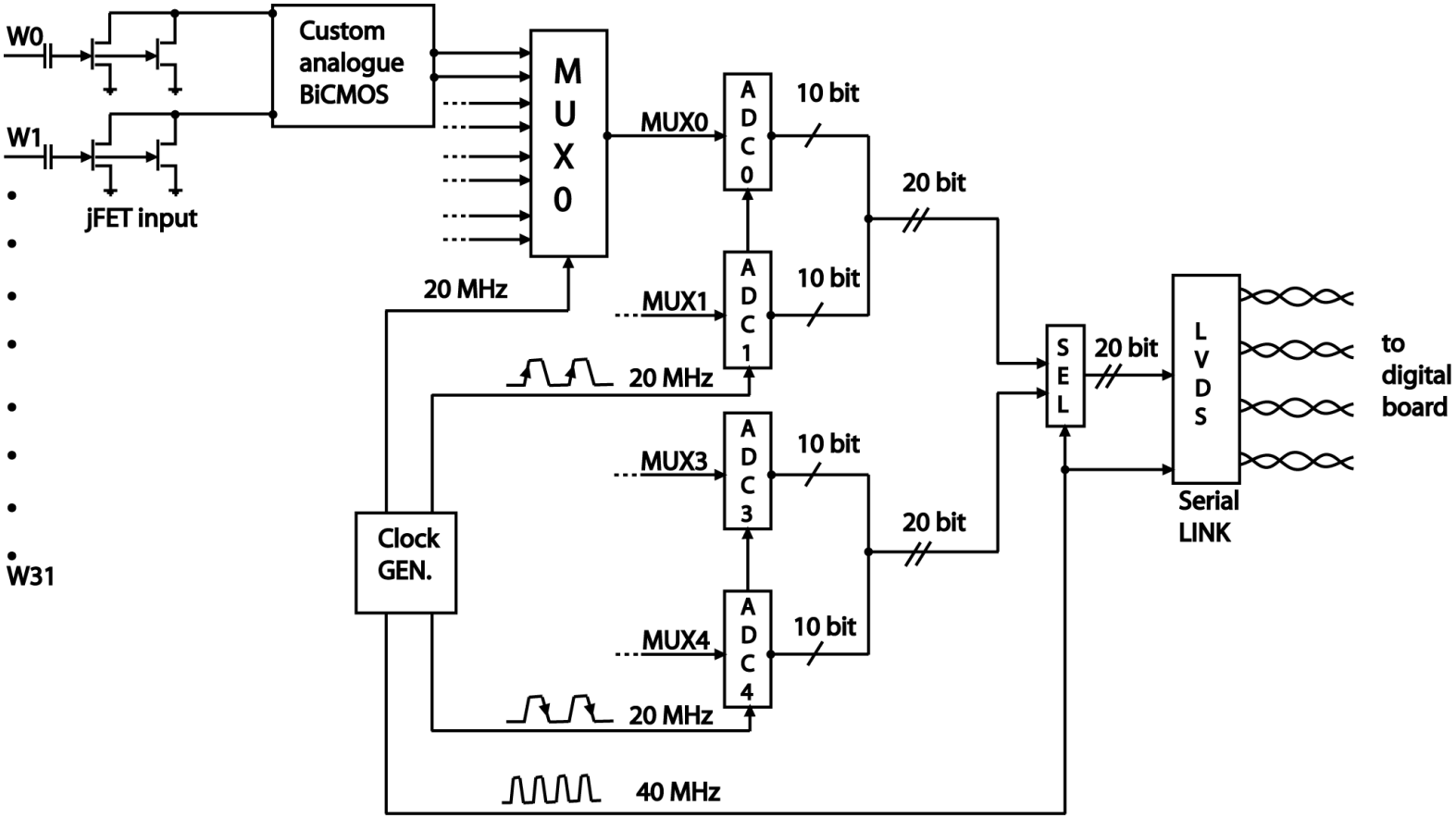




BiCMOS IC layout

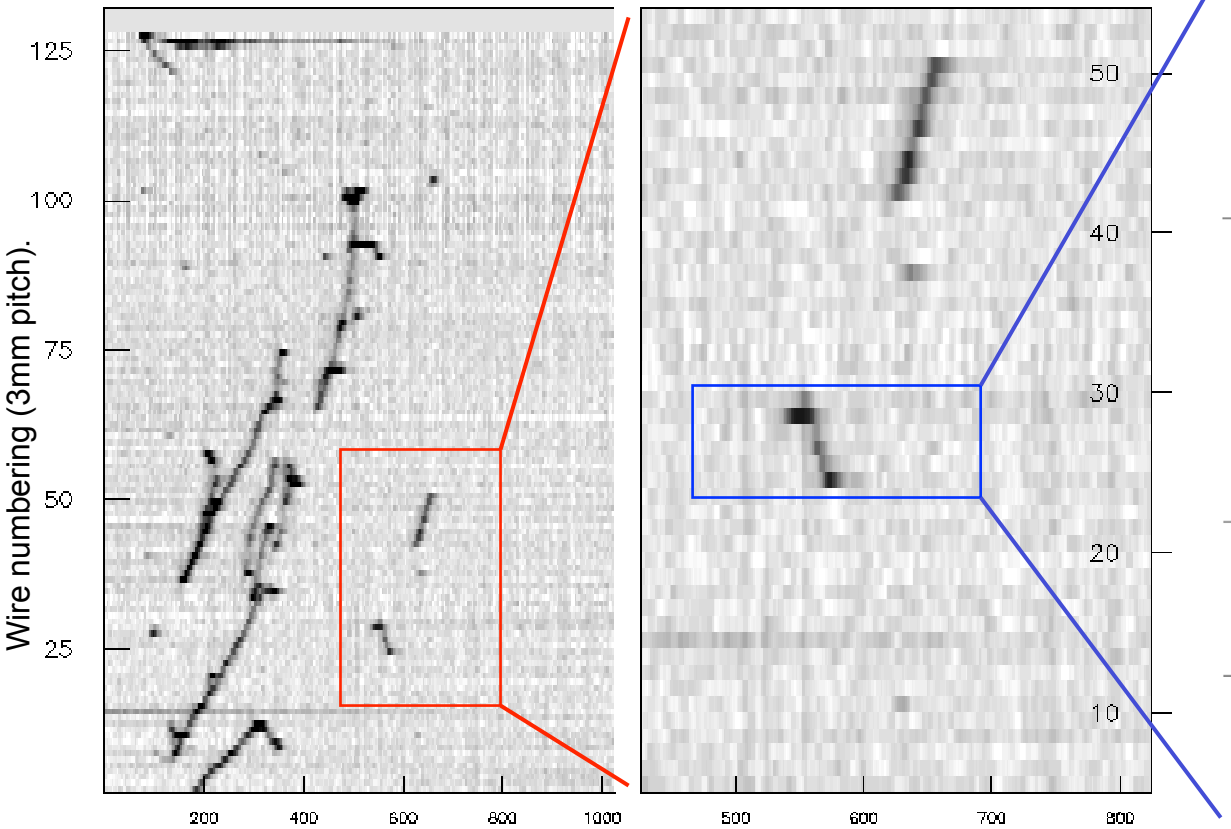
Analogue board block diagram

32 channel module

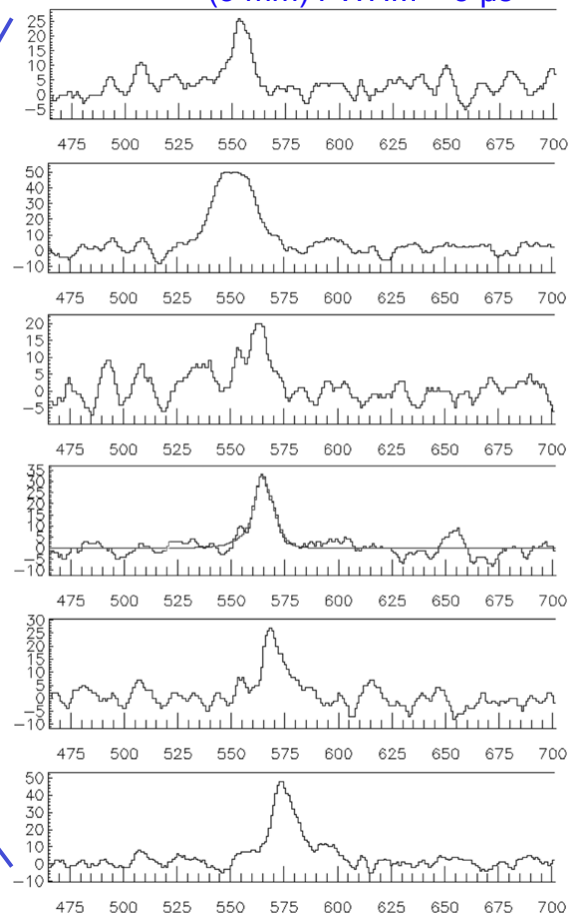


Signals from the LAr-TPC

Image of a low energy electromagnetic shower



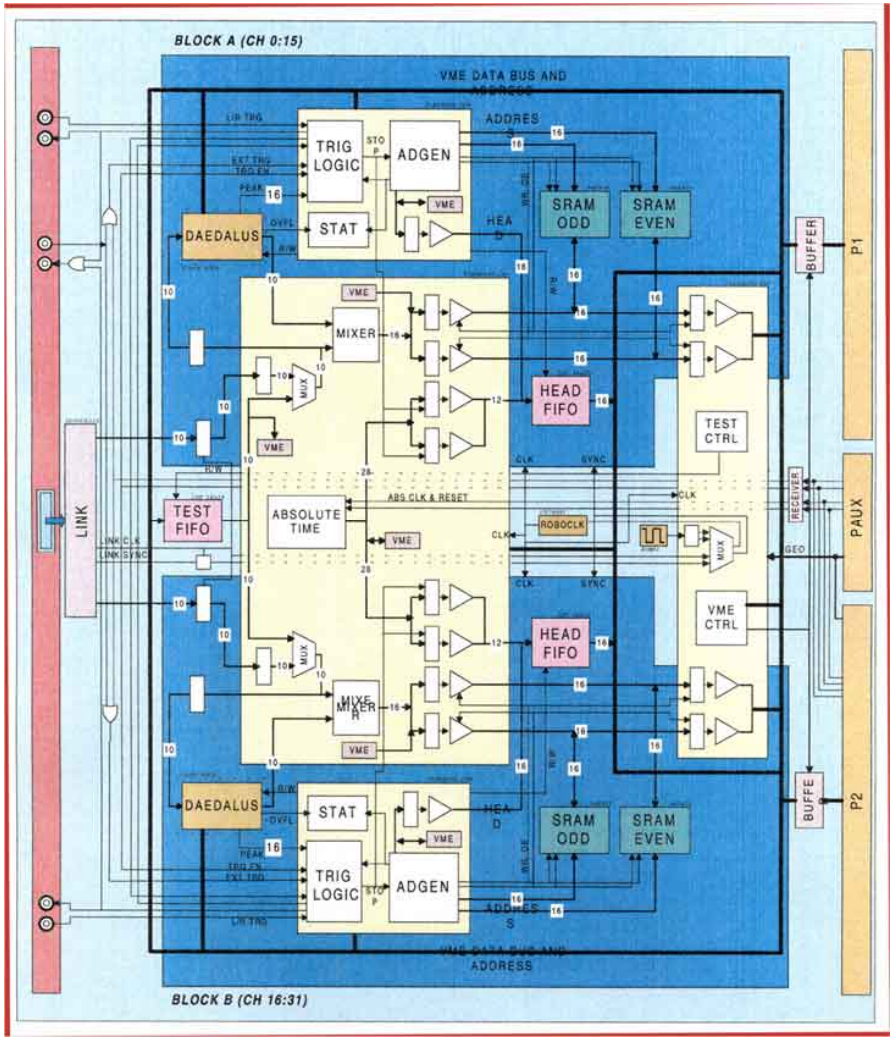
m.i.p. ≈ 12 ADC counts
(3 mm) FWHM ≈ 5 μs



Noise ≈ 1.3 - 1.7 ADC counts rms

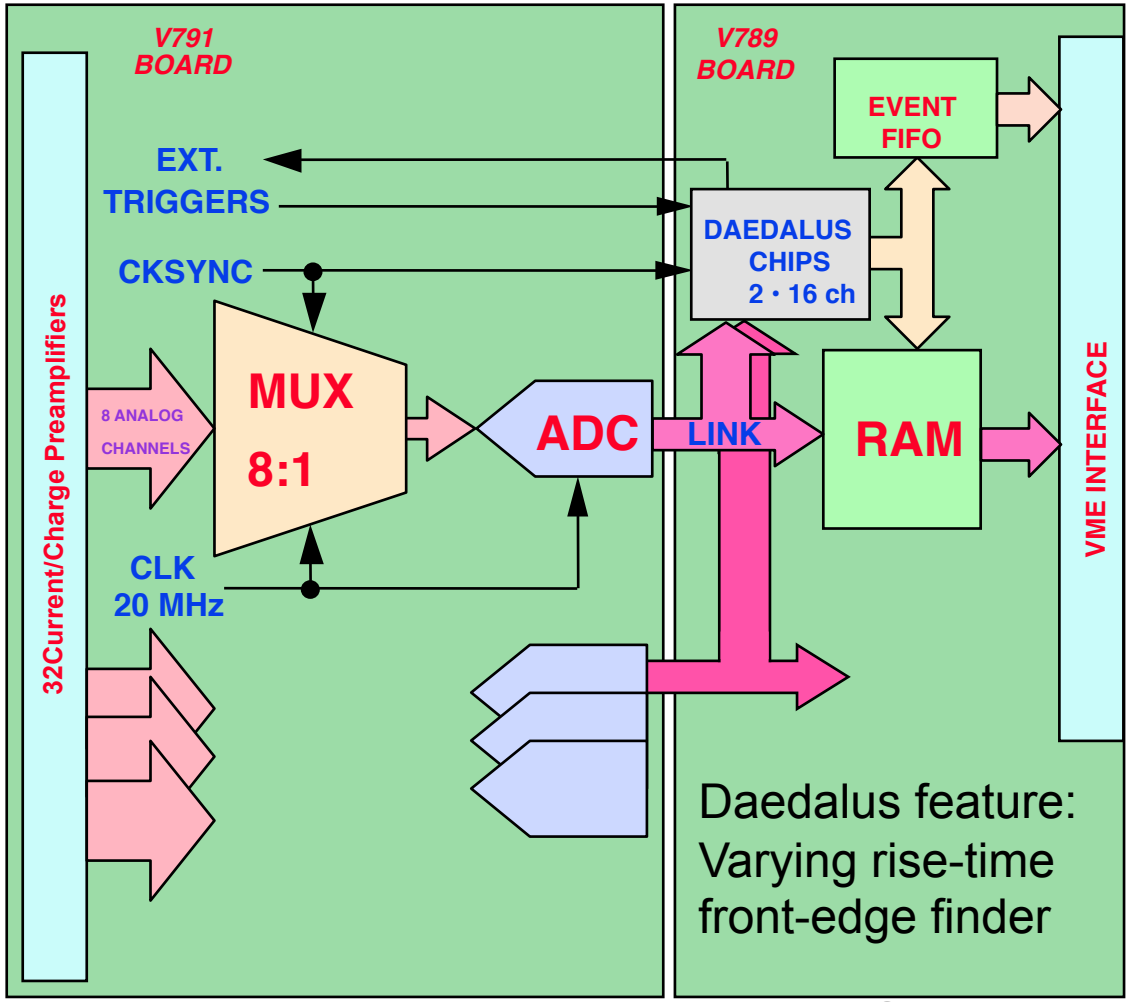
The digital board (ARIANNA)

- Receives 32 channels data stream through the serial link
- Hosts two custom made feature extraction ASIC chips (DAEDALUS) for hit finding, zero skipping and self triggering
- Complies with VME standards
- Each DAEDALUS operates on 16 channel data stream and controls the circular memory multi-buffers. It includes a median filter to reduce high freq. noise
- A 28 bit absolute time register is associated to each buffer in memory to allow alignment of data in event reconstruction

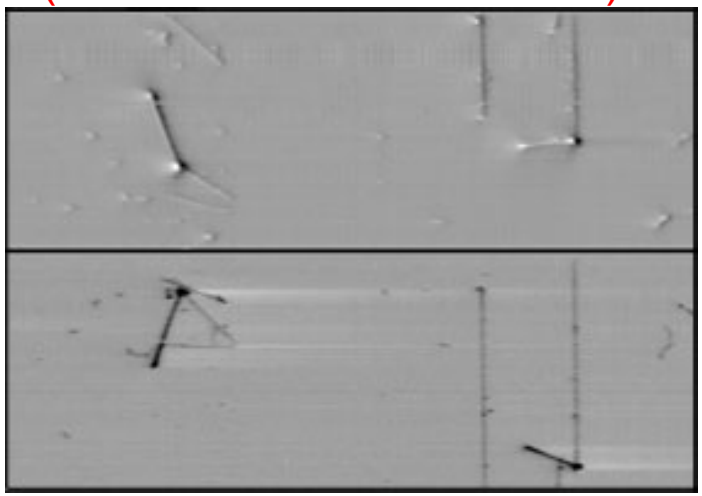


On-line data reduction

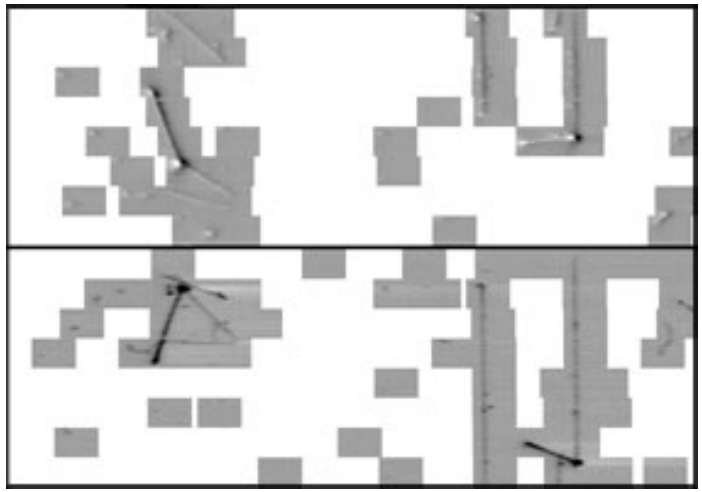
DAEDALUS chip



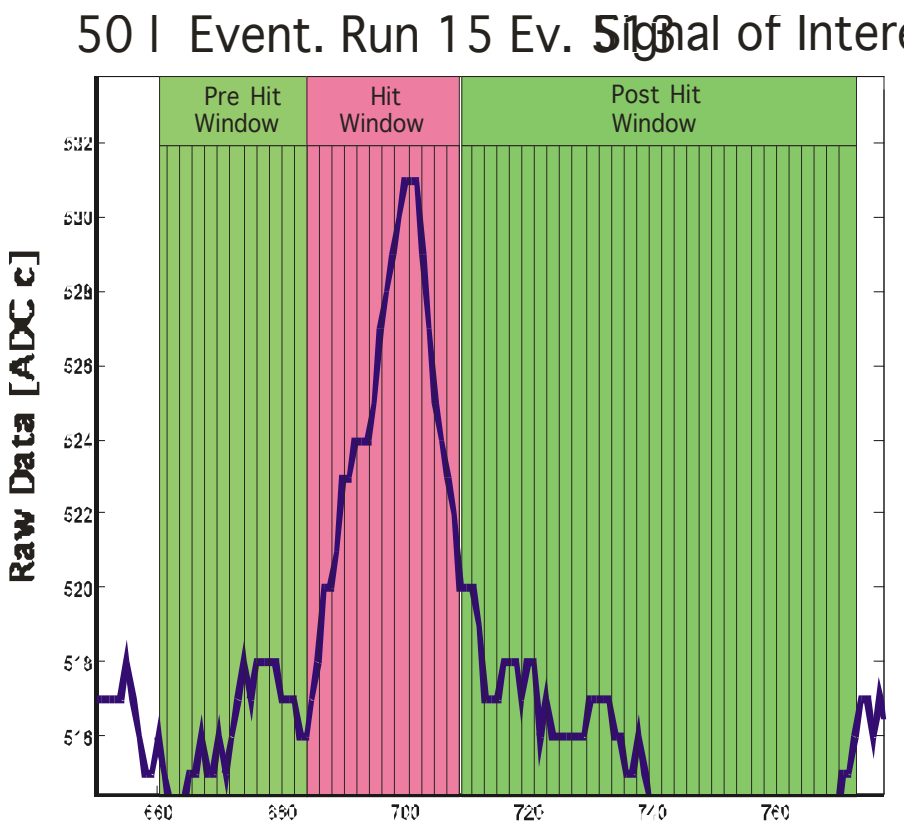
Raw data
(one T600 event = 200 Mb)



Reduced data



Zero-Suppression Algorithm Hit-finder + Tile-Building



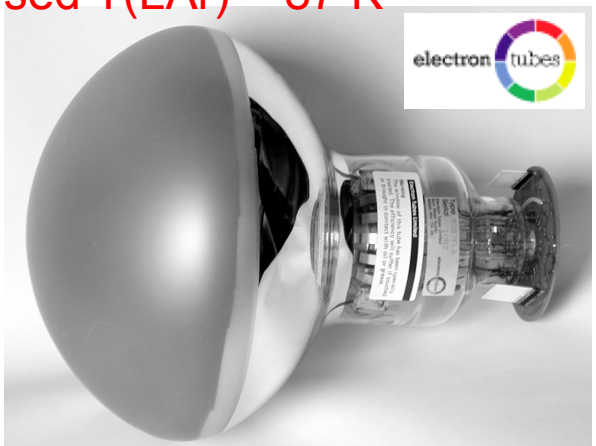
- Daedalus:
  - detects signal Rising-Edge,
  - Falling-Edge, Width…
  - and generates a hitfound signal
- Trigger Logic:
  - handles a 16 channels group
  - and builds a data tile around the hit
- Present Performance
- on T300 RawData:
  - Efficiency = 97% Collection
  - 90% Induction 1 & 2
  - False Detections= 20%
- Studies underway for improvement of algorithm (promising…)

Trigger and T=0 mark

- The abundant prompt scintillation light in LAr can be exploited as global trigger and to determine the event depth along the drift path.
- VUV light detection (more details on WArP):
  - Specially developed photomultipliers directly immersed in LAr
    - Bialkali photocatode + Platinum underlayer to reduce cathode resistivity at low temperature
      - ETL 9357FLA 8" PMs with > 10 % Q.E at 87 K
      - Hamamatsu and ETLrecent achievments: Q.E > 20 %
    - Borosilicate glass window with wavelength shifter coating
      - thin layer of Tetra Phenyl-Butadiene >100% conversion 128 nm -> 420 nm (blue region)
    - High detection coverage

VUV light read-out in ICARUS

- Commercial PMT with large area
  - ➥Glass-window
- For scintillation VUV λ = 128 nm
  - ➥Wavelength-shifter: Tetra-Phenyl-Butadiene
- Immersed T(LAr) = 87 K



Electron Tubes 9357FLA

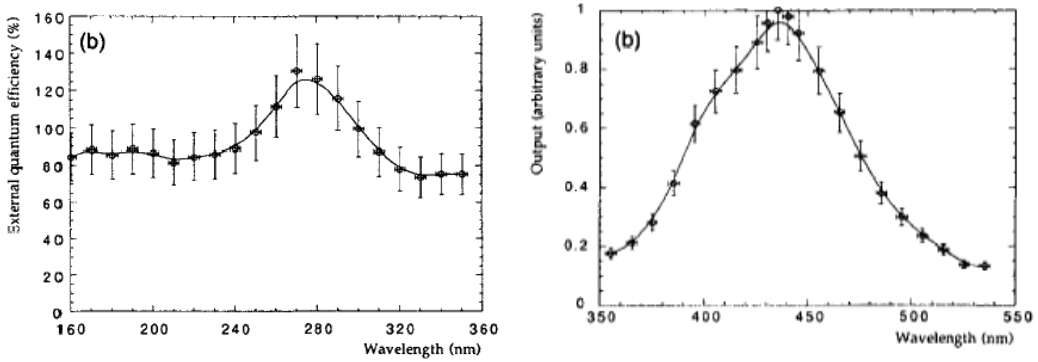
8" PMT (bialkali with Pt deposit)

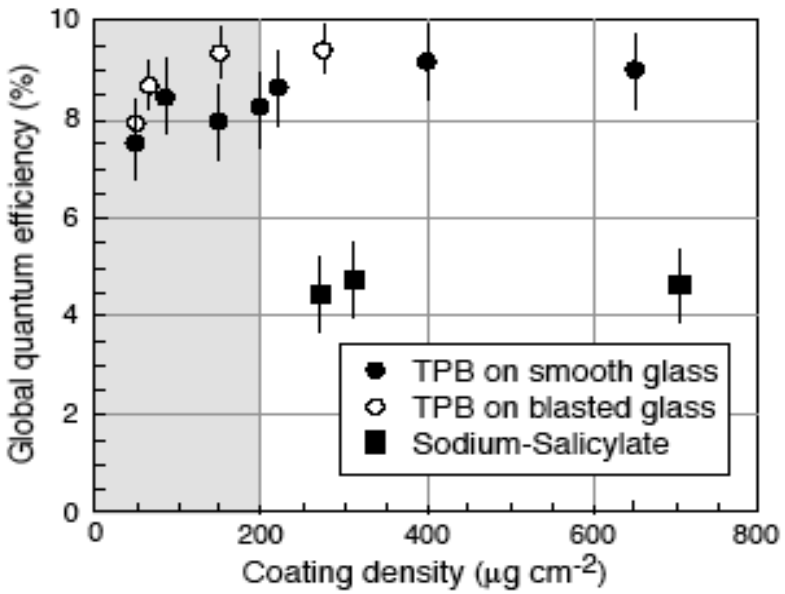
G = 1 x 10^7 @ ~1400 V (12 dynodes)

peak Q.E. (400-420 nm) ~ 18 % (≈10% cold)

T_{rise} ~ 5 ns, FWHM ~ 8 ns

TPB as WLS: Lally et al., NIM-B 117 (1996) 421

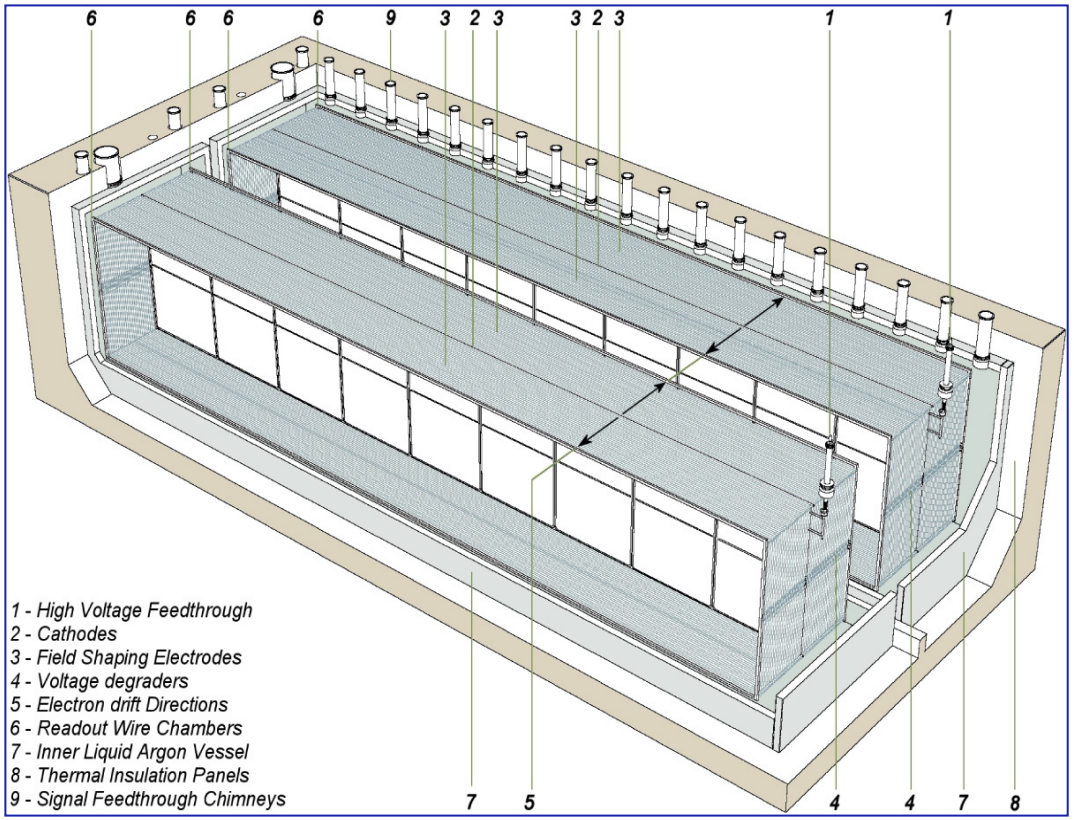




The T600 module

- Approved and funded in 1996
- Built between years 1997 and 2002 (including prototyping, industrialization and testing)
- **COMPLETELY ASSEMBLED** in the INFN assembly hall in Pavia
- **FULL SCALE DEMONSTRATION TEST RUN OF HALF-UNIT** during first half 2001
  - Three months duration
  - Completely successful
  - Data taking with cosmic rays
  - Detector performance
  - Full scale analyses
- **FULL UNIT ASSEMBLY TERMINATED IN 2002**
- **NOW UNDER FILLING WITH LAR AT LNGS**

The T600 detector

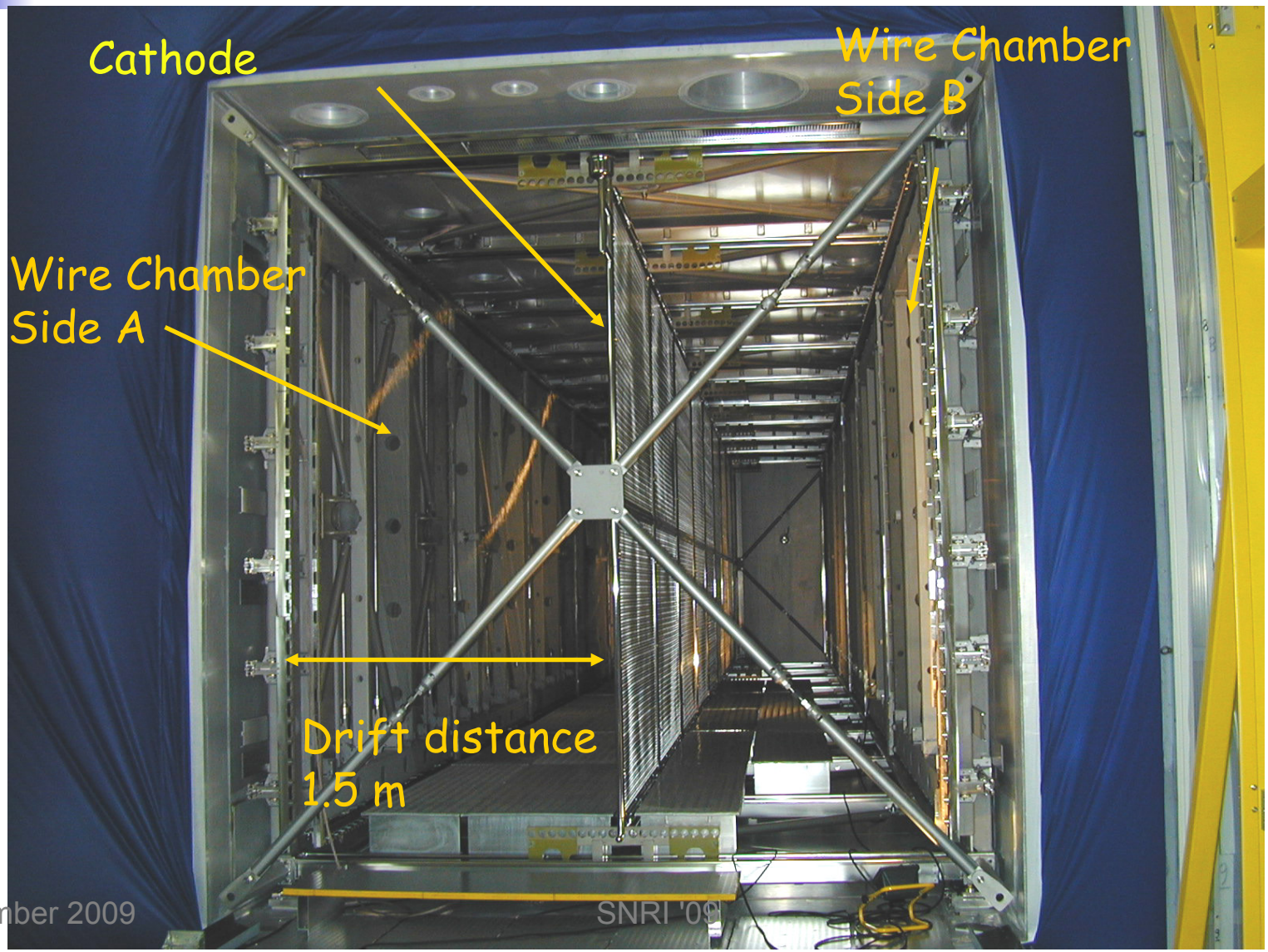


- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar fiducial mass: ≈ 476 t
  - Drift length = 1.5 m
  - HV = -75 kV E= 0.5 kV/cm
- 4 wire chambers:
  - 2 chambers / module
  - 3 readout planes / chamber: at 0°, +60°, -60°
  - ≈ 54000 wires
- PMT for scintillation light:
  - (20+54) PMTs, 8" Ø
  - VUV sensitive (128nm) with wave shifter (TPB)

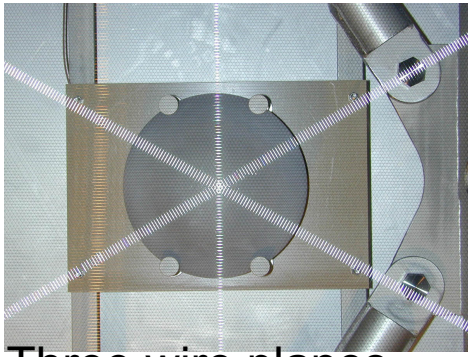
Mechanics & Cryogenics

- High performance of the wire chamber mechanics at cryogenic temperature and during the transient phases (cooling, warming)
  - None of the wires has to break ➔ variable geometry mechanics (springs + rocking frames)
  - High spatial resolution
- Slow control devices
  - to work in cryogenic and high purity environment
- Signal feed-throughs ➔ vacuum-tight DN200CF flanges 576
- HV system ➔stable and uniform electric field all over the LAr volume
  - Development of a HV feed-through ➔ stable up to -150 kV without discharges and leakage currents, vacuum tightness
  - Field shaping electrodes connected by a voltage divider.

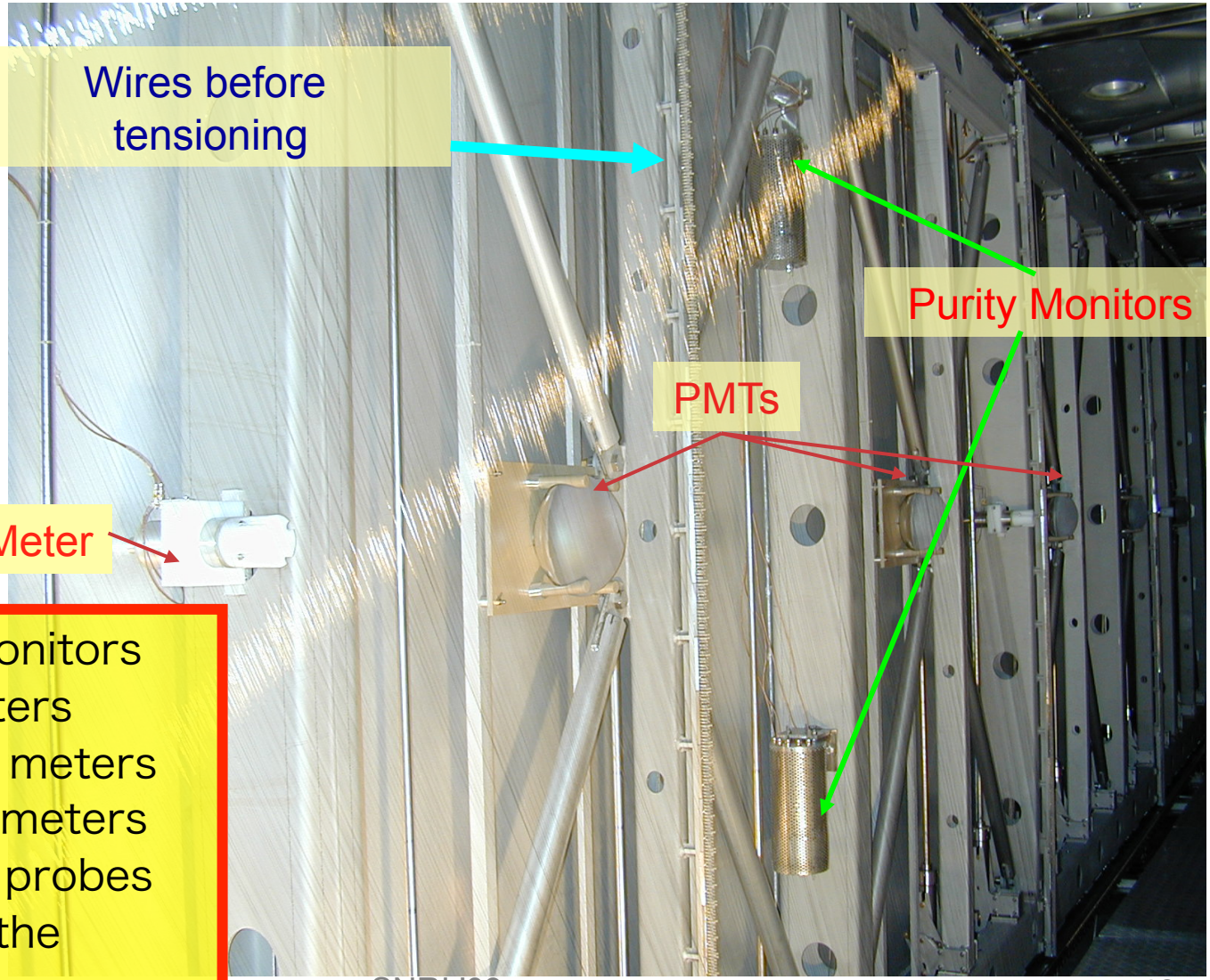
T600 internal detector



Charge and light readout system



Three wire planes and a PMT



6	LAr purity monitors
16	LAr level meters
7	wire position meters
8	wall position meters
30	temperature probes
20	PMTs (54 in the second)

Electronic racks (54000 ch.)

T600 rate and throughput

Event rate in LNGS Hall B

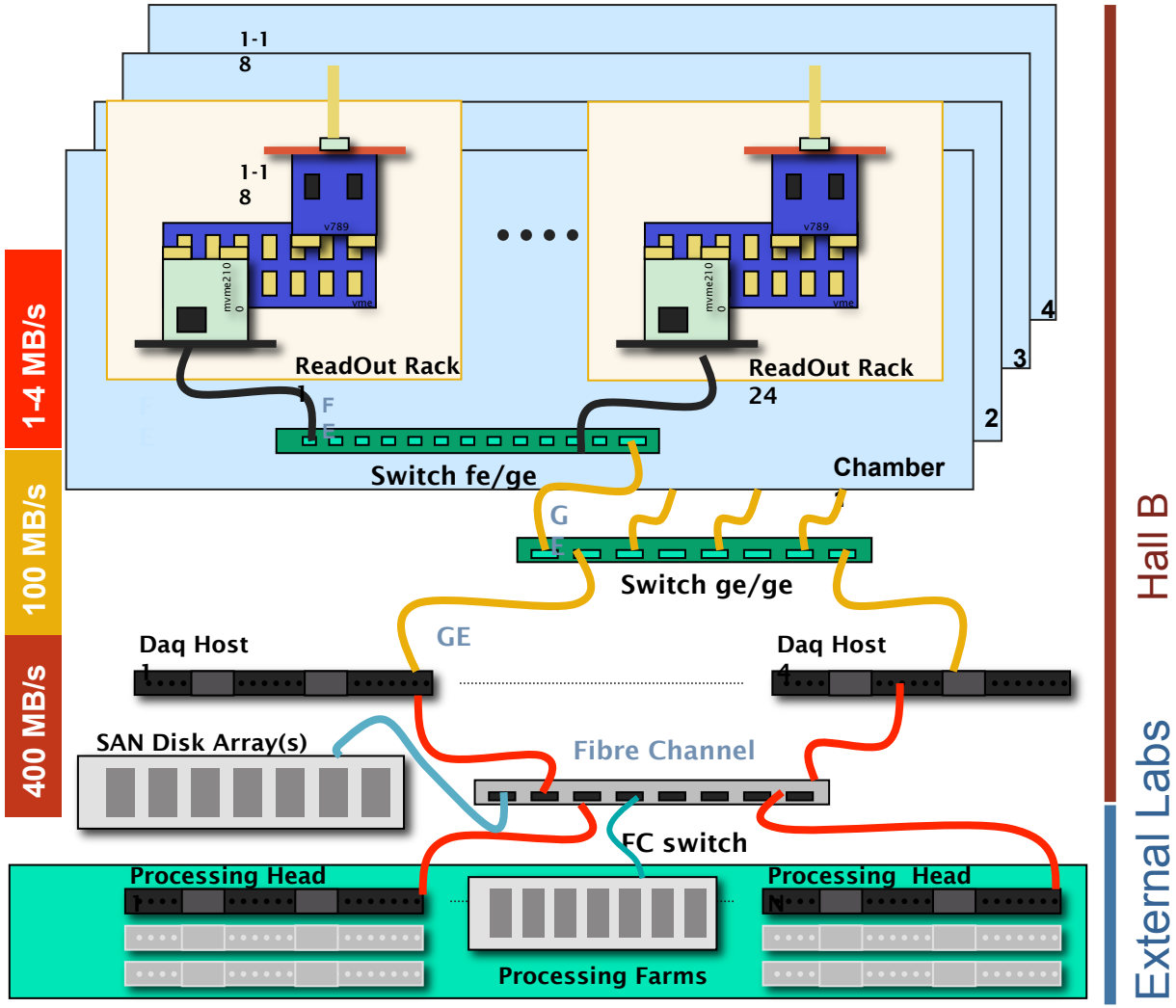
- High energy cosmic rays:
  - ~150 through-going muons/hour,
  - ~0.3/day atmospheric neutrinos
  - ~200 GB/day
- CNGS events:
  - ~10 ν interactions in the T600 per day
  - ~20 μ/day from int. in surrounding rock
  - ~1.5 GBytes/day
- Calibration:
  - ~100 GBytes live storage
- Low energy events (including solar and supernovae neutrinos):
  - ~1-2 ev/day from solar ν
  - ~2 Hz (>5 MeV) from natural radioactivity
  - up to 2.0 TBytes/day: data reduction mandatory!

- Full drift event size:
  - 54000 wires x 2500 T-samples x 2 bytes = 270 MB
- Proprietary online lossless compression
  - ¼ ~ 70 MB/event ~ 1MB/crate
- The T600 DAQ is based on VME standard for Digital boards
  - Best choice at time of design in term of throughput (~40 MB/s).
  - Custom backplane to connect the inputs from wires and distribute common signals (ADC baseline bias, enable signals, test pulses).
- Each VME crate serves a total of 576 channels (18 boards).
  - Configuration and control of the boards relies on a dedicated VME CPU, which also handles the data transfers from board buffers to the Ethernet event builder network.
- Performance of the DAQ system is bounded by the VME interface throughput (4-5 MB/s) equivalent to few Hz full drift collection.

T600 DAQ architecture

Event Builder:
4 independent DAQ hosts
4 Disk Arrays (> 30 TB) as short term storage (~400K full drift events).

Switches and long haul Tranceivers for dedicated Giga-Ethernet/FiberChannel networks to transfer data from the Hall B to the external laboratories (7km) at 2Gbit/s.



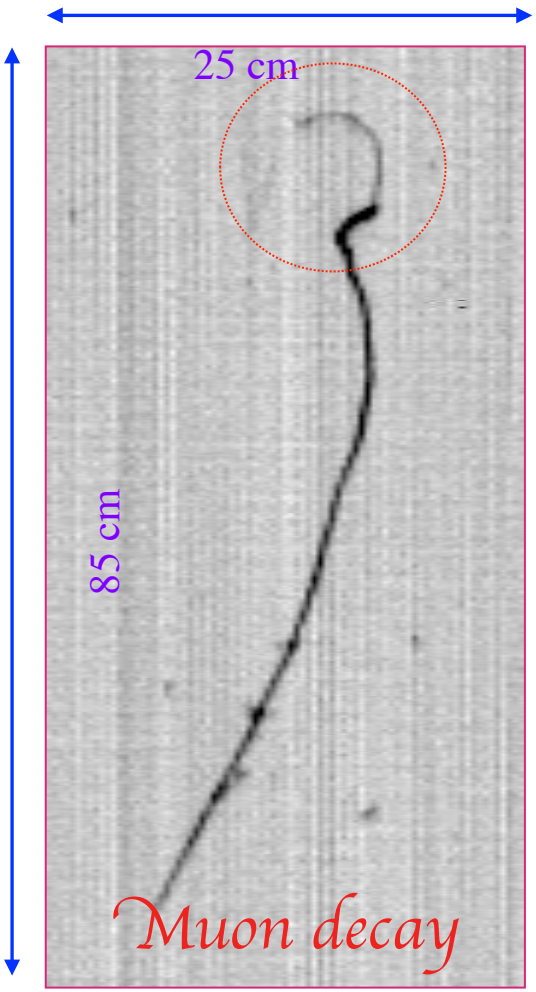
Technical run in Pavia

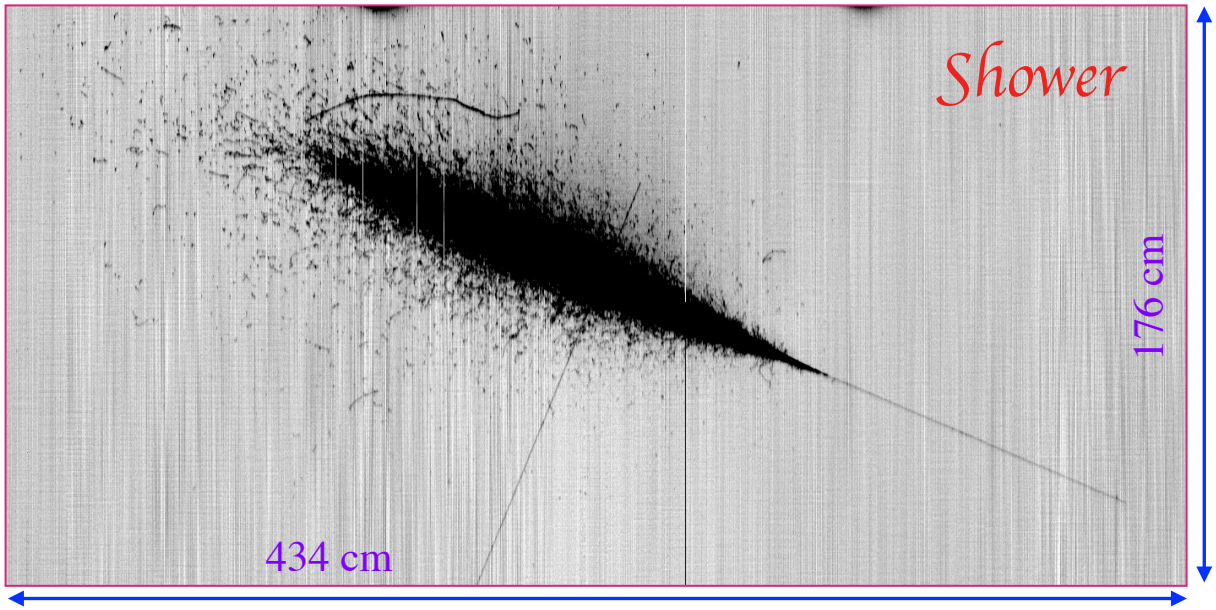
Walking on the detector…

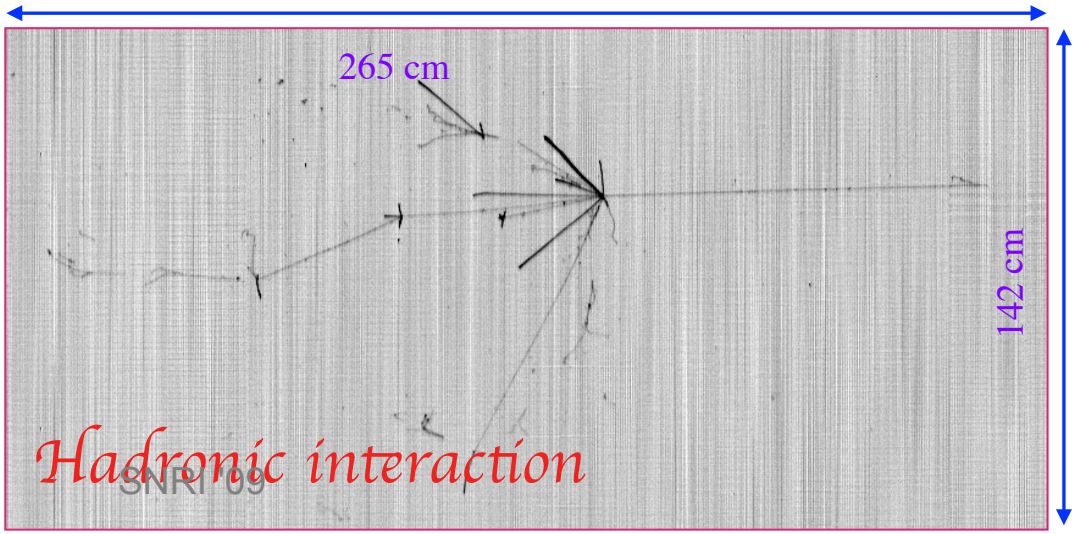
August 2001

…and observing cosmic ray events

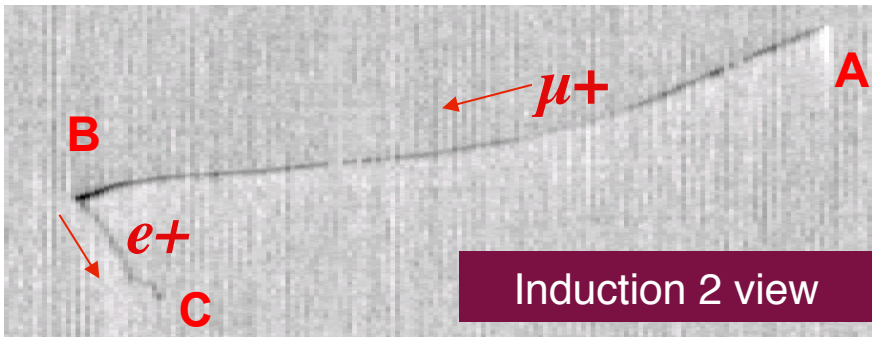
Electronic bubble chamber

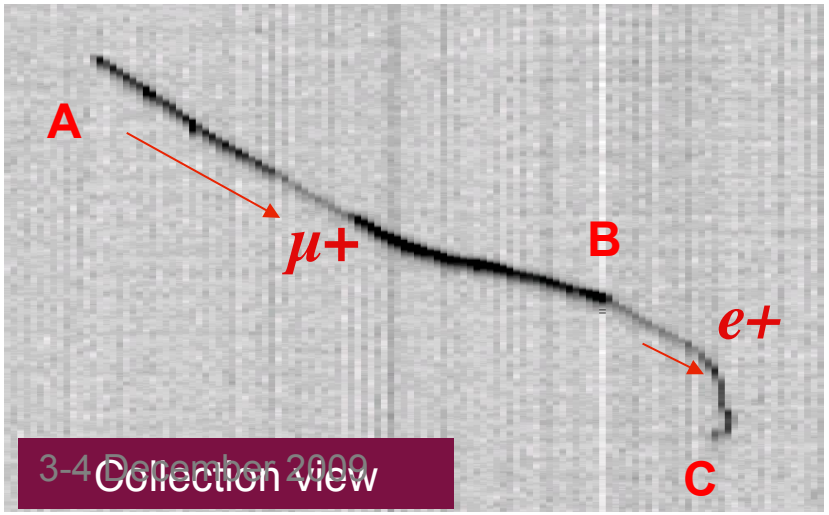


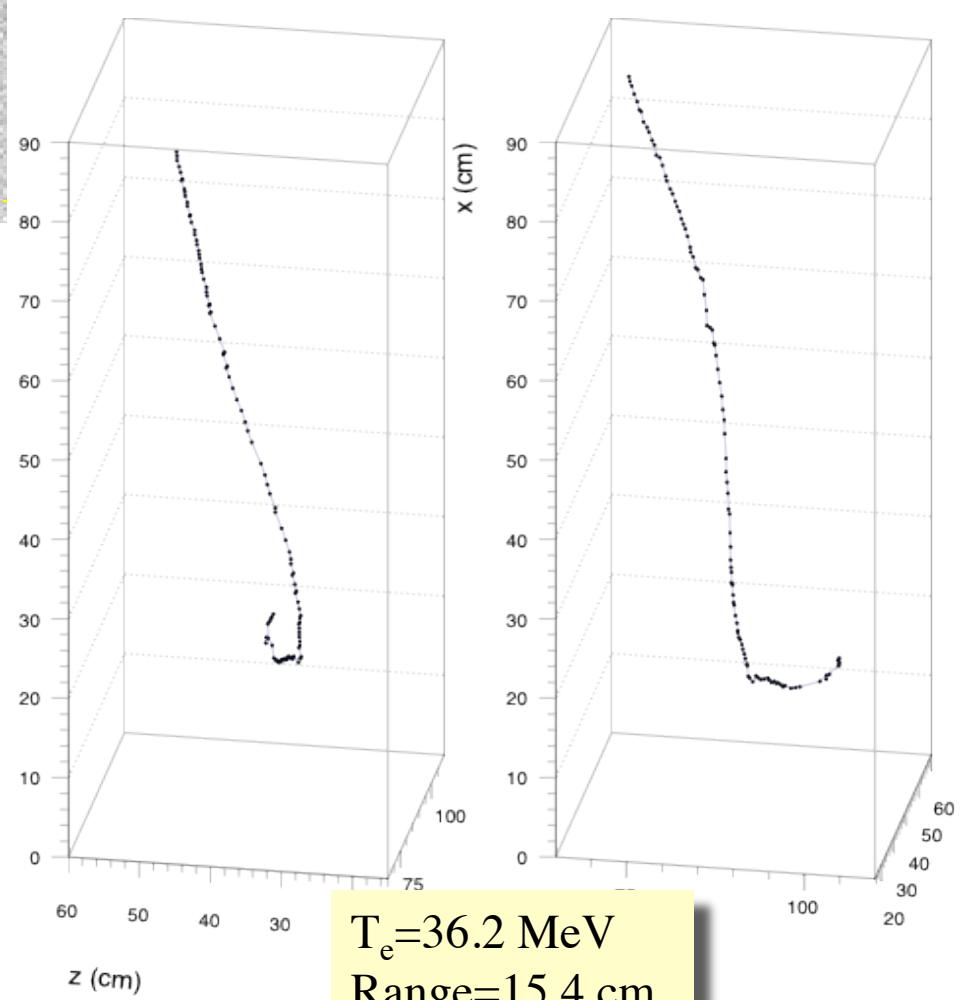




3D reconstruction (stopping μ)







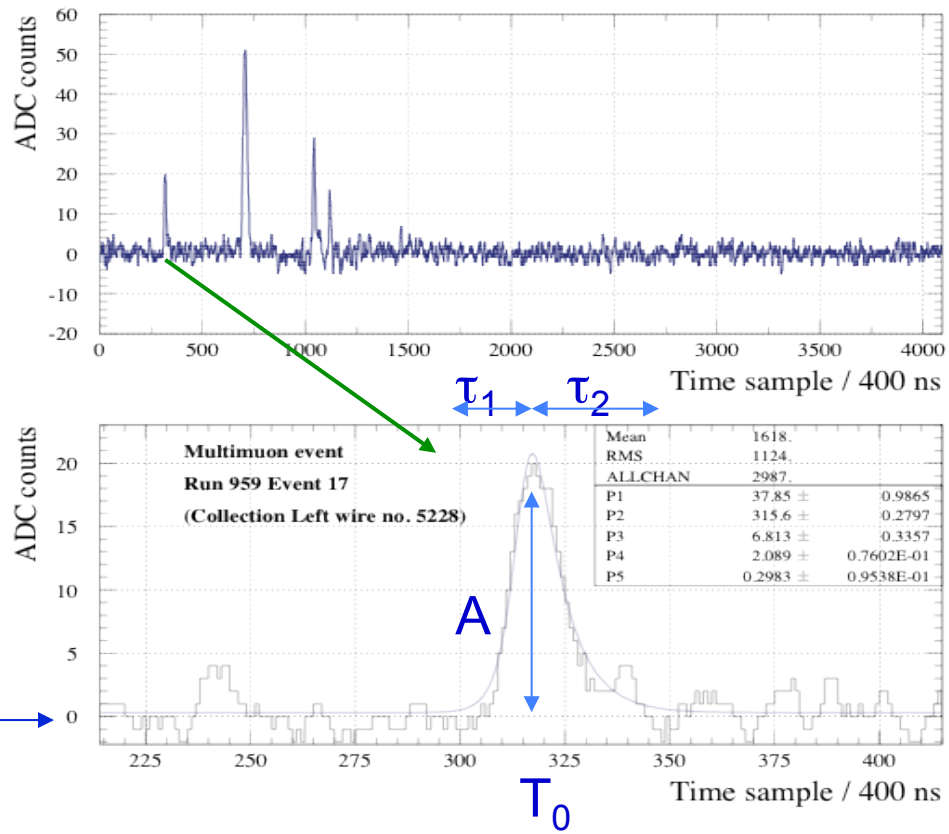
T_e=36.2 MeV
Range=15.4 cm

Signal extraction procedure

Collection plane wire analysis:
charge = signal area

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

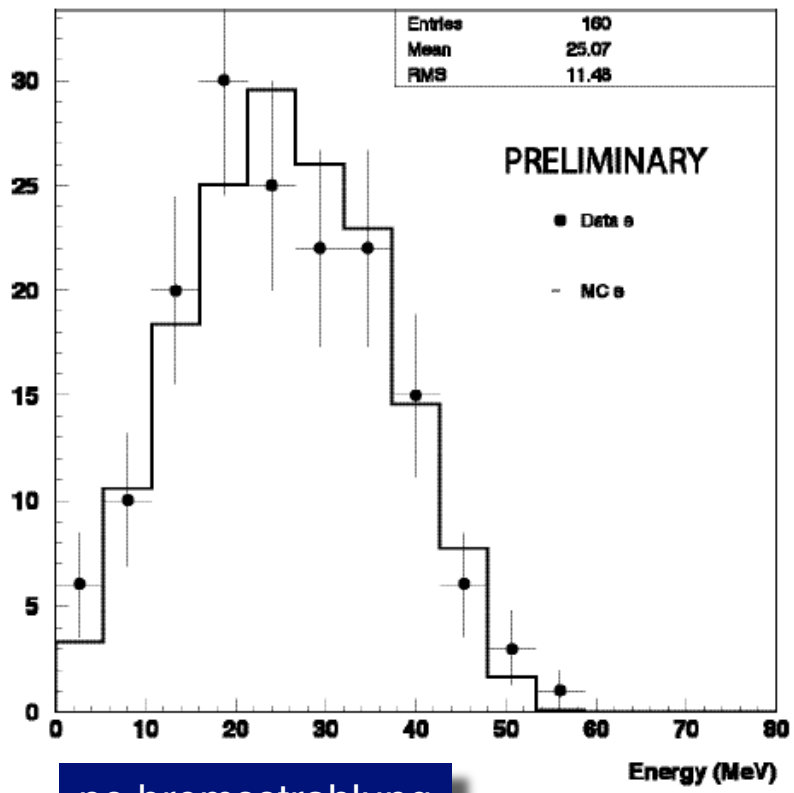
B = baseline
A = amplitude
τ_1 , τ_2 = rise and fall time
T_0 = peak position



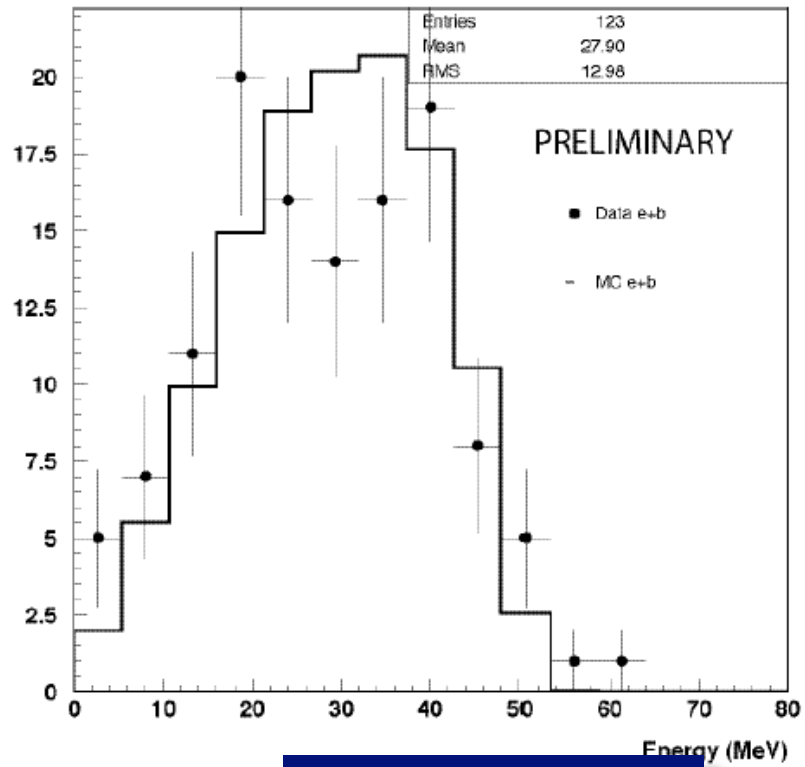
The same empirical function used to fit Ionization hits and test pulse hits (calibration)

Calorimetric reconstruction

Michel electrons (μ decays)



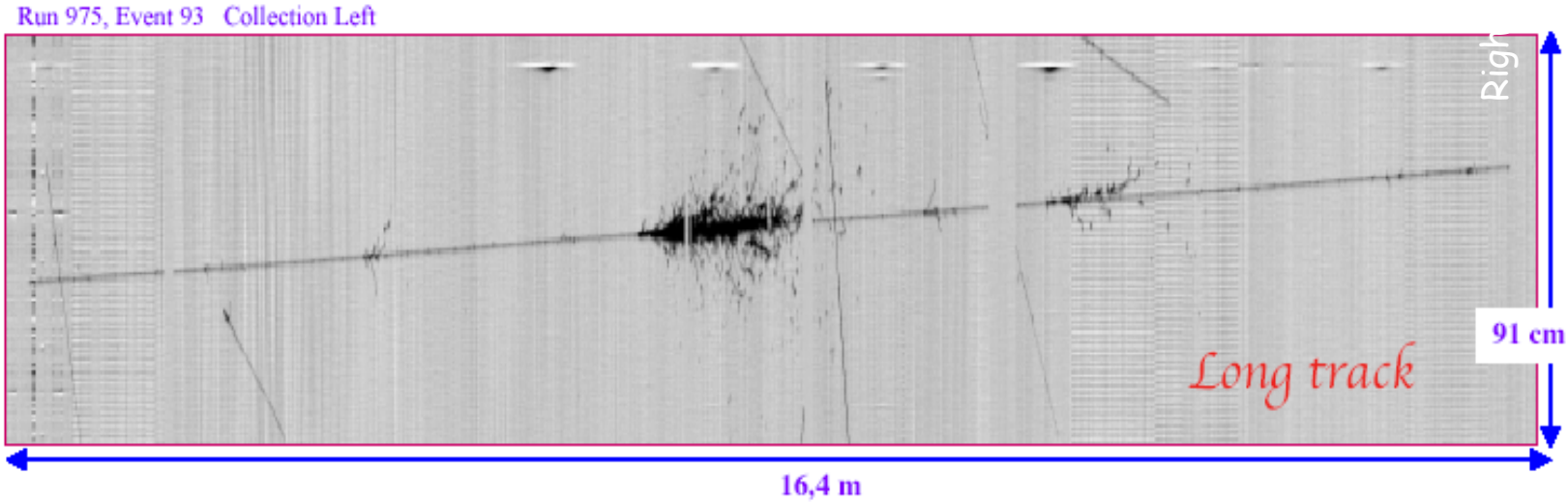
no bremsstrahlung

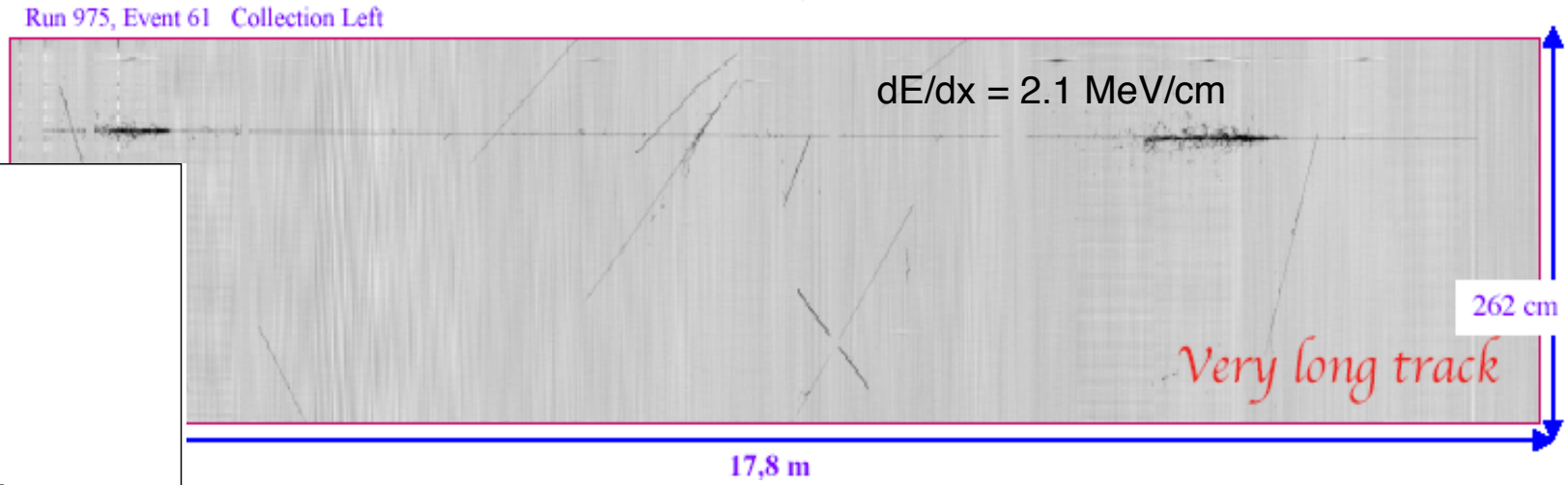


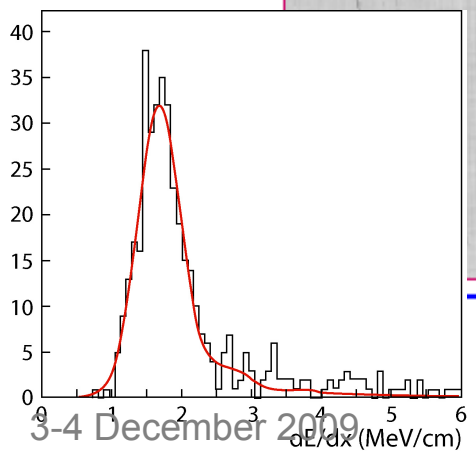
with bremsstrahlung

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

Long muon tracks



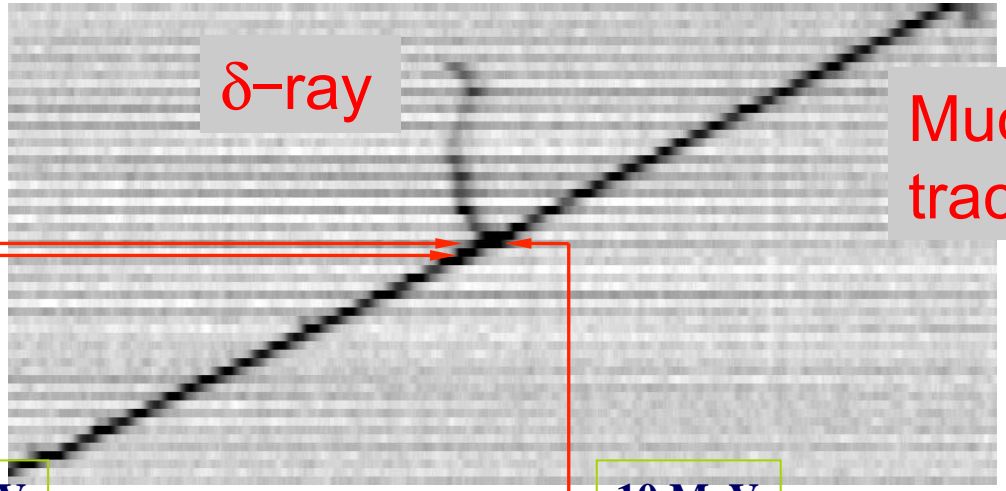


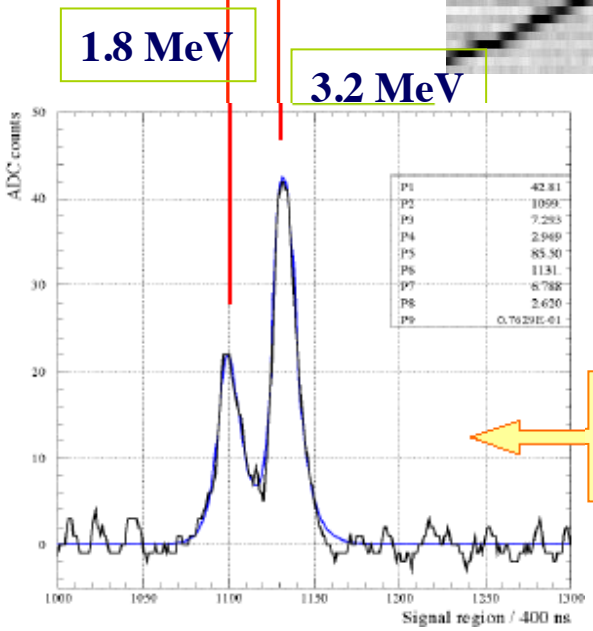


dE/dx distribution along the track

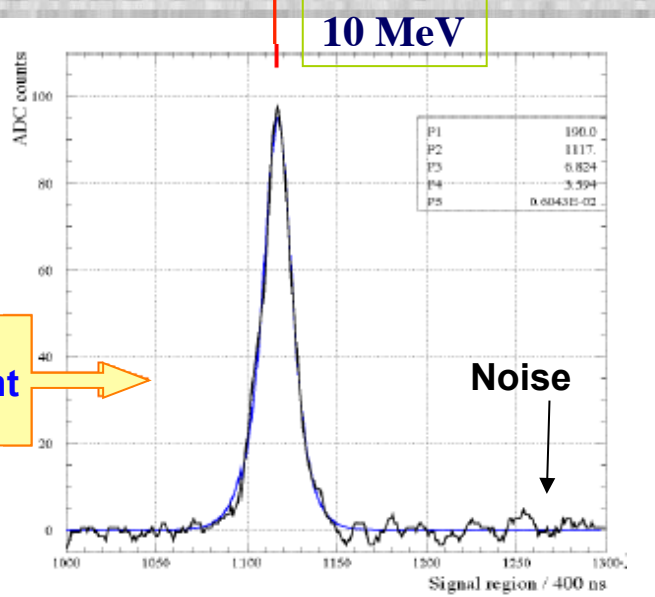
Low energy detail

Single wire performance





Two adjacent wires

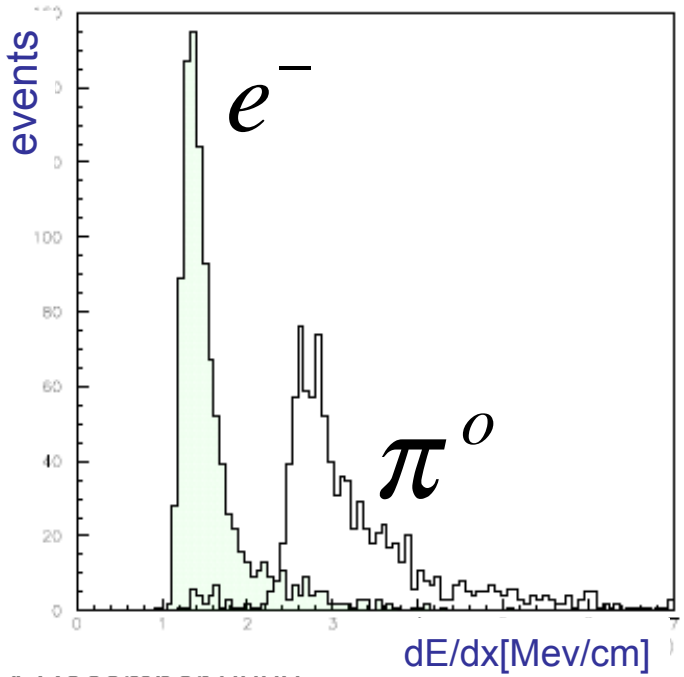


Events with leading electron signature

- The CNGS ν_μ spectrum has a most probable energy of about 25 GeV.

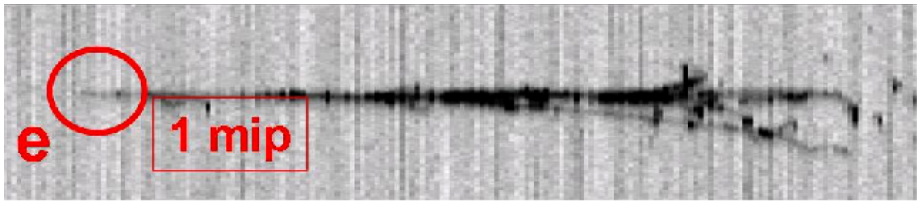
.

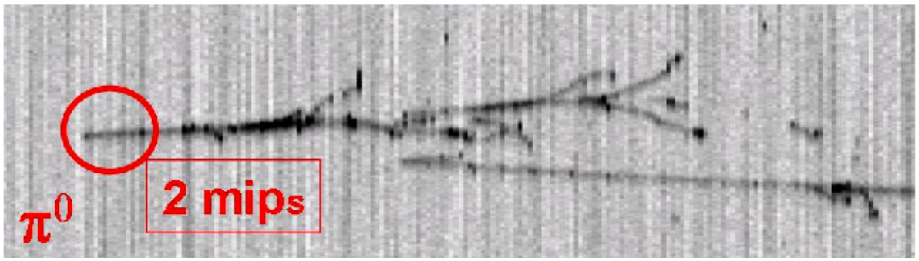
- Electron shower events are extremely well identified experimentally, because of the ionization behaviour in the first cells after the vertex.



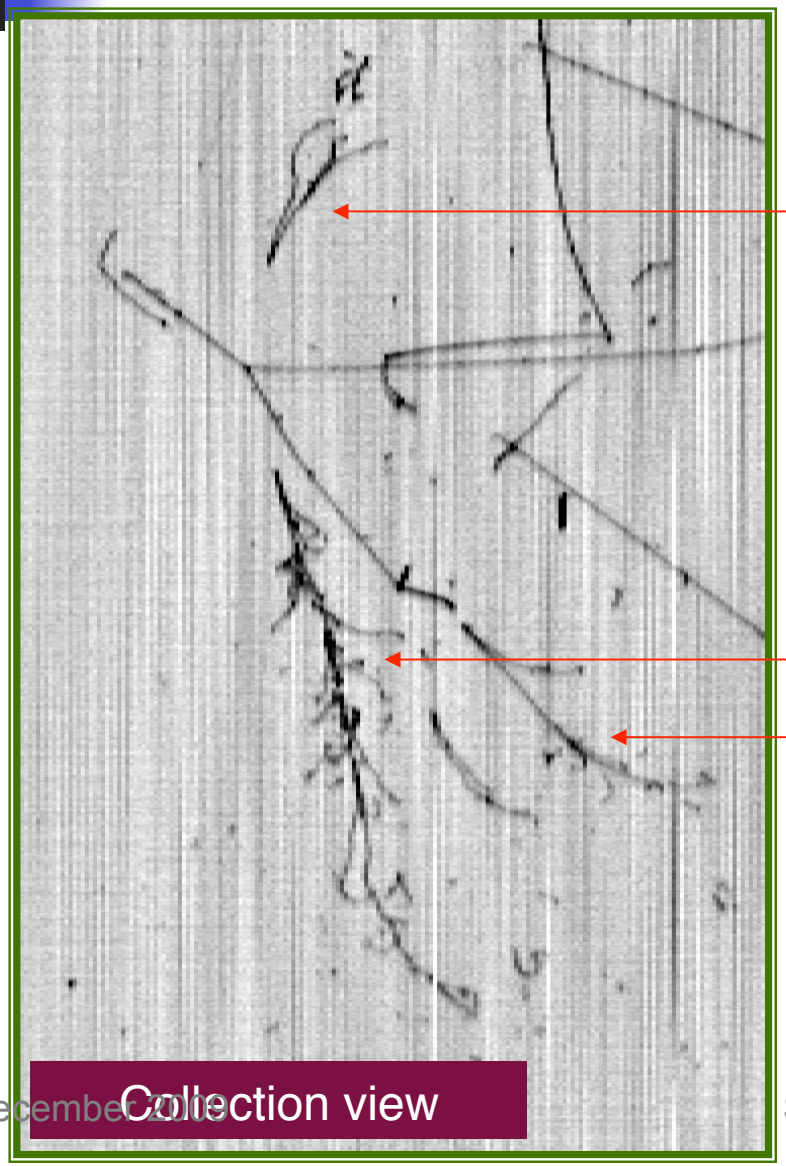
Neural Currents background rejected thanks to:

- Vertex reconstruction
- Pion mass reconstruction
- dE/dx analysis of electron/photon tracks





Pi-zero identification



- Reconstruction of π^0-showers

$$M_{inv} = \sqrt{2E_1E_2\cos(\theta_{12})}$$

158 MeV

$\theta = 141^o$

M_{inv} = 650 MeV

752 MeV

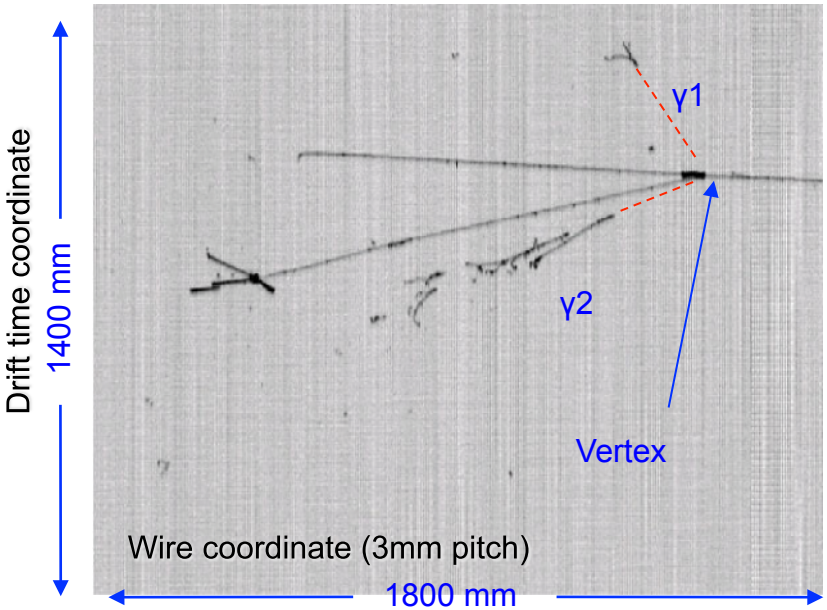
140 MeV

$\theta = 25^o$

M_{inv} =140 MeV

π^0 reconstruction

230 hadronic interactions with π^0 -> γγ candidates have been selected from ICARUS T300 Pavia run



The average (γ,γ) invariant mass is in agreement with the π^0 mass hypothesis (m_{p0} = 135 MeV/c^2);

$$m_{\gamma\gamma} = 133.4 \pm 3.0(stat) \pm 4.0(sys)\mathrm{MeV/c^2}$$

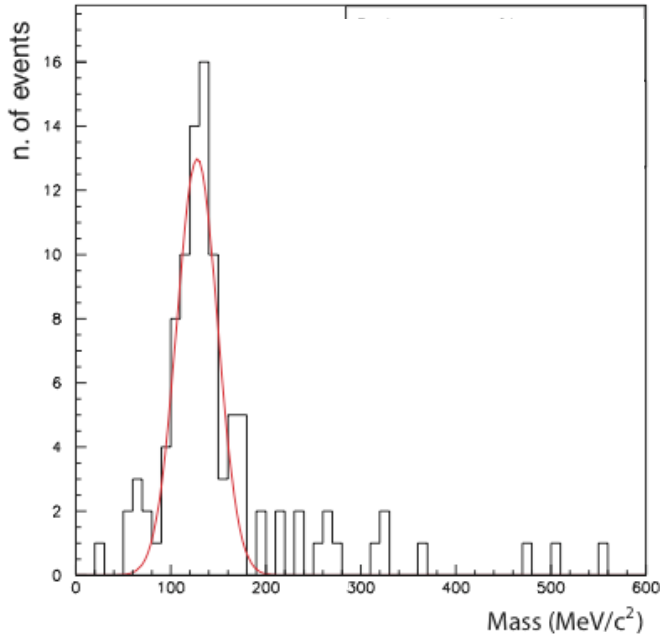
The systematic error is mostly due to the calibration

The measured photon radiation length is

$$X_{\gamma,meas} = (17.4 \pm 0.8)\mathrm{cm}$$

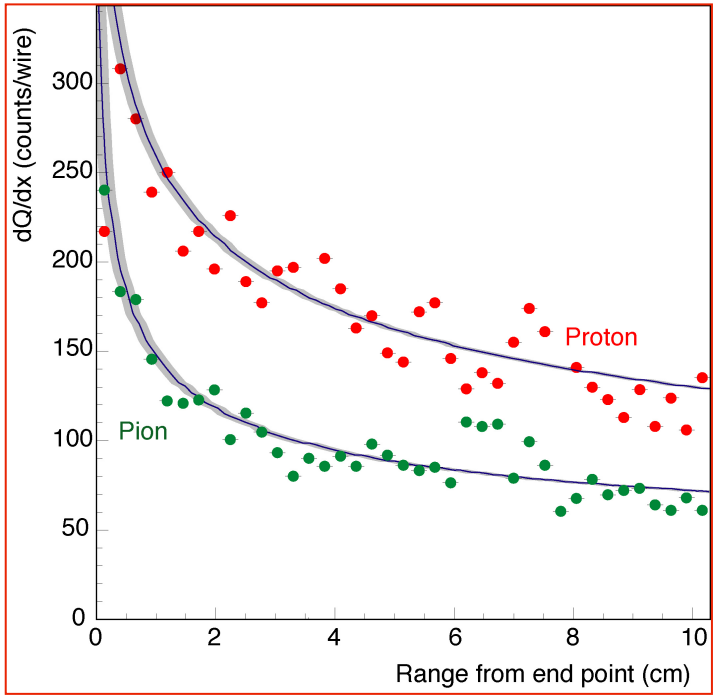
in agreement with expectation:

$$X_{\gamma,\exp} = \frac{9}{7} \cdot 14\mathrm{cm} = 18\mathrm{cm}$$



Detector performance

- Tracking device
  - High granularity event topology (3mm “bubble”, space resolution ~150μm)
  - Momentum measurement via multiple scattering
- Measurement of local energy deposition dE/dx:
  - e / π^0 separation (2% X_0 sampling)
  - Particle ID by means of dE/dx vs range measurement
- Total energy reconstruction of the events from charge integration:
  - Full sampling, homogeneous calorimeter with excellent accuracy for contained events

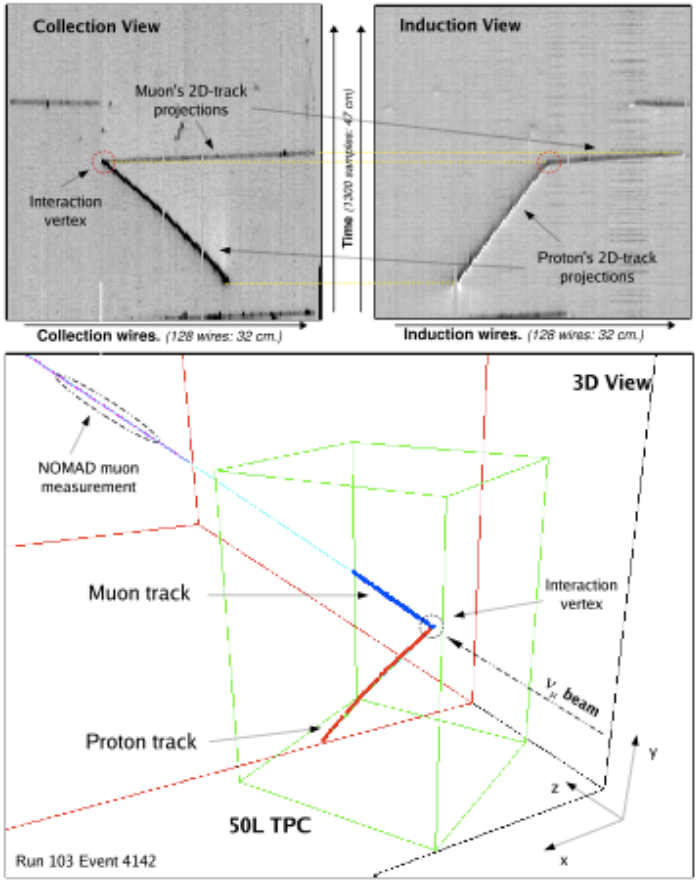


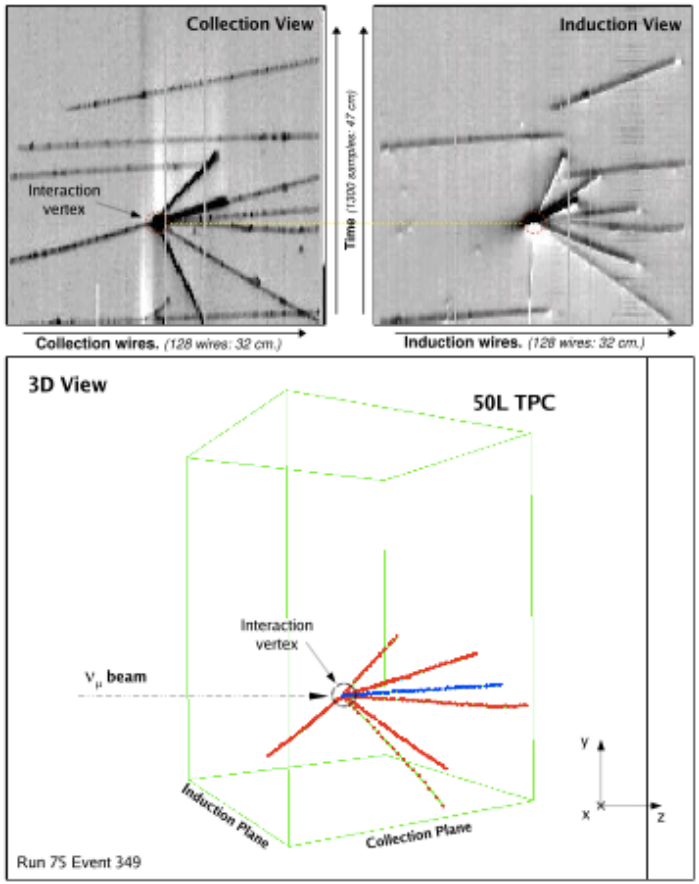
RESOLUTIONS

Low energy electrons:	$\sigma(E)/E = 11\% / \sqrt{E(MeV)} + 2\%$
Electromagn. showers:	$\sigma(E)/E = 3\% / \sqrt{E(GeV)}$
Hadron shower (pure LAr):	$\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$
Hadron shower (+TMG):	$\sigma(E)/E \approx 17\% / \sqrt{E(GeV)}$

Quasi-elastic neutrino interaction

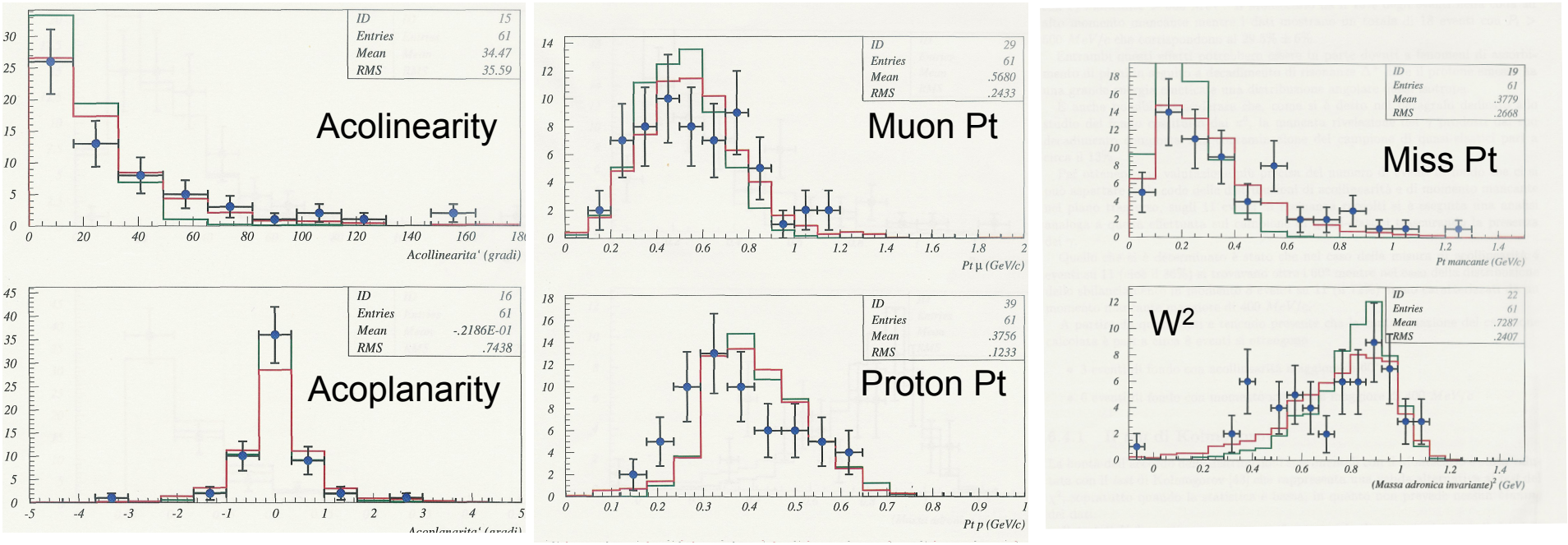
- 50 liter LAr-TPC exposed to CERN WANF (NOMAD as muon spectrometer)
  - Full 3D event kinematics reconstruction, particle id, momentum balance, π^0 rejection





Quasielastic event reconstruction

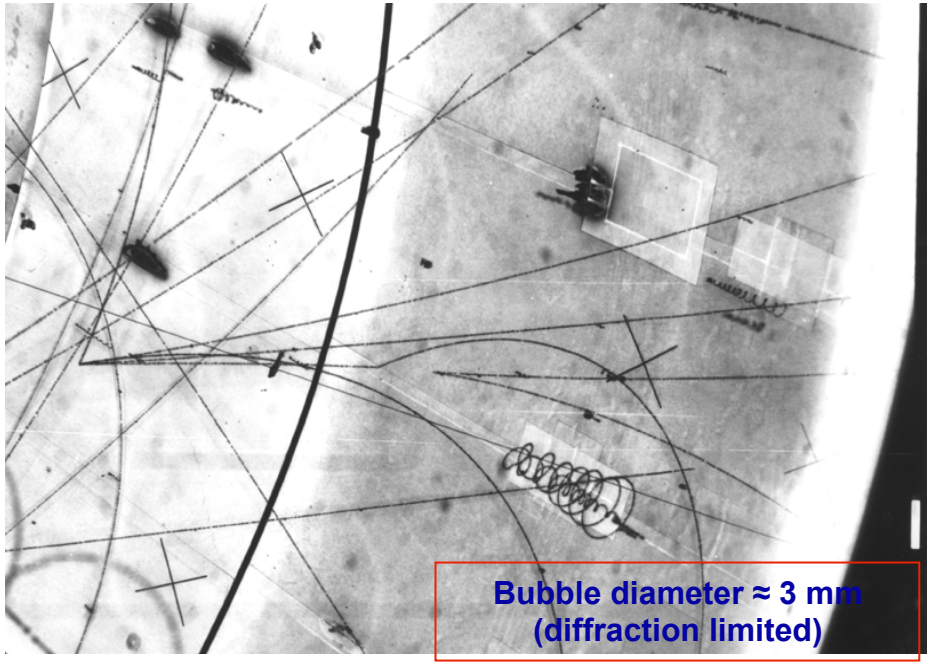
Selection of ~ 200 pure lepton-proton final state with exactly one proton T_P>50 MeV (range > 2 cm) and any number protons T_P<50 MeV



Good agreement with FLUKA expectations (Red line), accunting for Nuclear Fermi motion and re-interactions in nuclei.

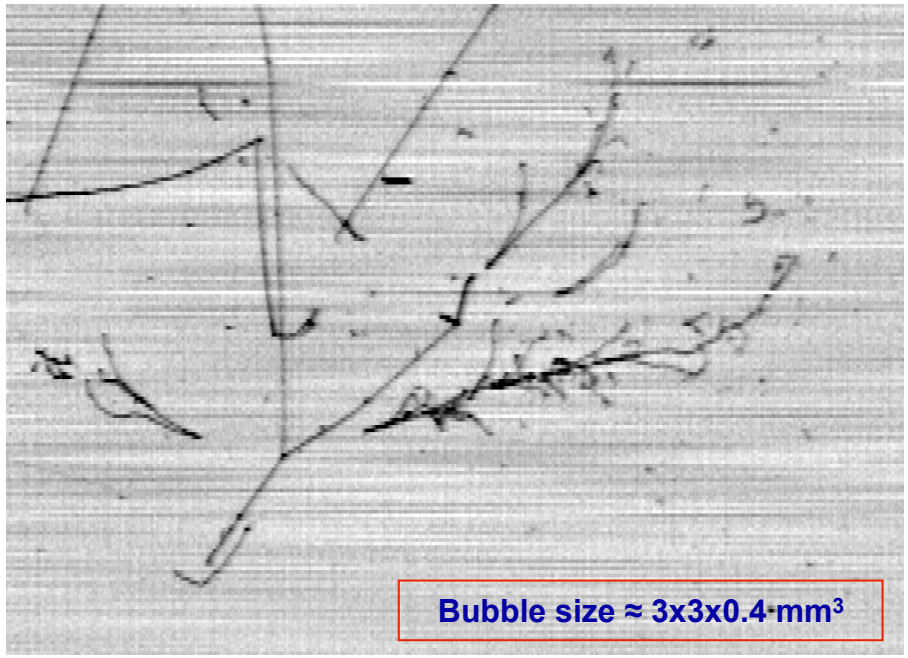
The “electronic bubble chamber”

BEBC - Bubble Chamber - 30 t - CERN 1976



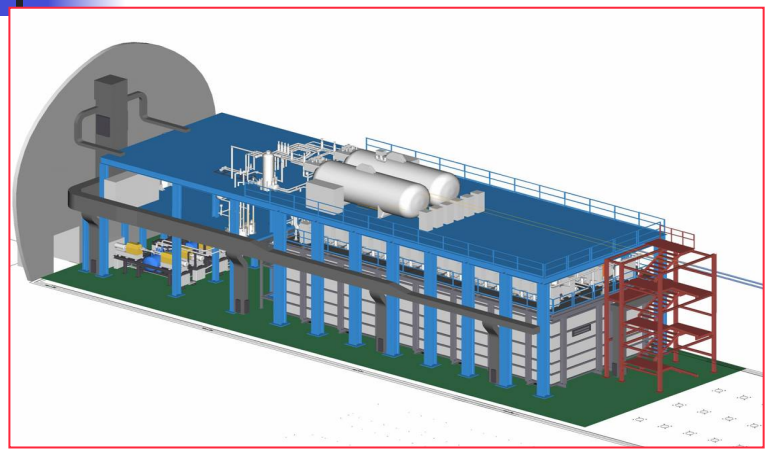
Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

ICARUS - T600 - PAVIA 2001



Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

ICARUS T600 in hall B (11-2009)

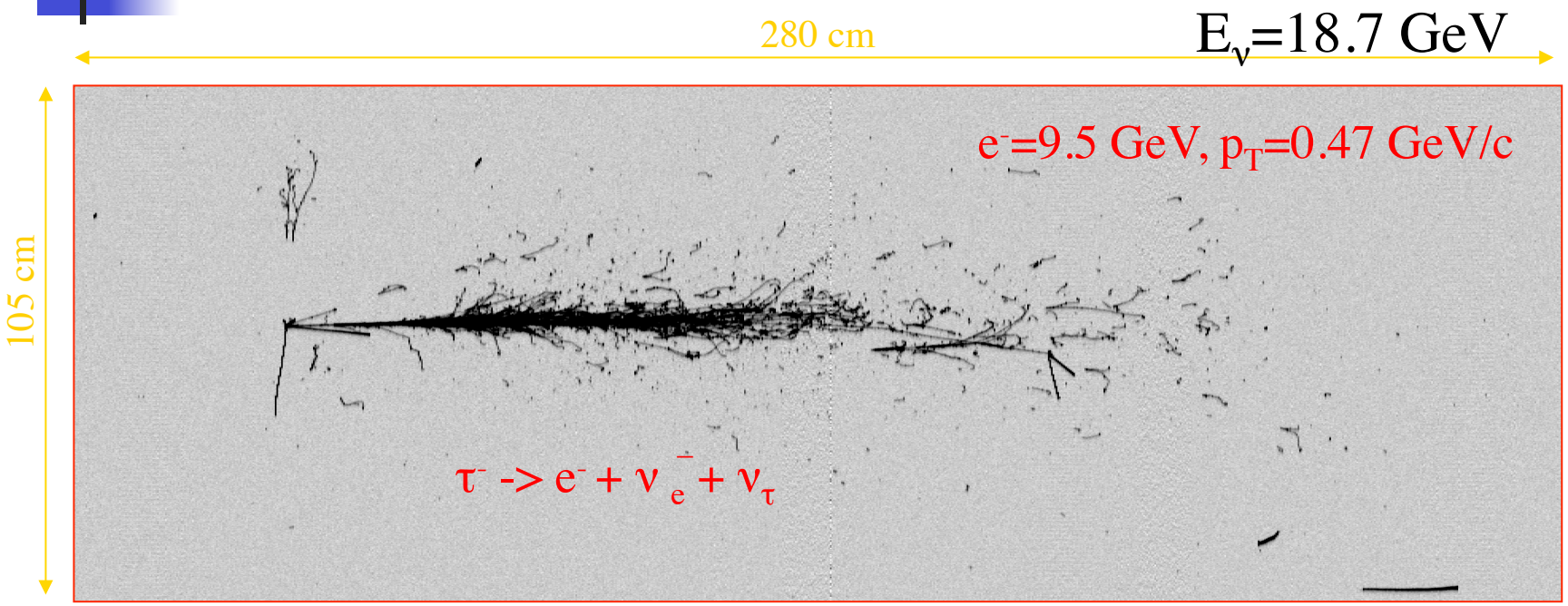


"Power on" by beginning 2010

Physics with the T600

- The T600 is a necessary intermediate technical step towards a much more massive LAr detector (multi-kton LAr detector), now being actively studied by INFN and other institutions, but it offers also some physics issues in itself.
- Two main topics are particularly interesting and imply the exposure of the T600 at the CNGS beam starting from 2008 for few years (up to five):
  - **Searching for sterile neutrinos in T600** with deep e-like inelastic CC events, complementary to MiniBoone
  - **The proof of existence of $\nu_\mu <-> \nu_\tau$ oscillation with T600**, the actual value of Δm^2 being already measured elsewhere by SuperKamiokande, K2K and MiNOS and in the future by OPERA at LNGS.

ν_τ interaction in ICARUS



A multi kton ICARUS detector is needed to ensured a number of events adequate to cover the ν_τ signature with a sensitivity comparable to the one OPERA.

The electron decay channel is however a significant goal, also for the presently reduced T600 mass, uniquely characterized by a large transverse momentum unbalance due to the emission of the two neutrinos.

The Future

- The successful operation of the T600 module will hopefully open the way to the next generation of multi-kton Liquid Argon TPC's
  - Addressing important issues of the physics beyond the standard model
    - Proton decay
    - Neutrino mixing
    - CP violation the lepton sector
- INFN, as well as other international institution, is actively involved in the studies of
  - The detector feasibility
  - The best location (LNGS)
  - The neutrino beam improvements
- The new program would start at the end of the present CNGS campain (~2012).