Liquid Argon detectors for Neutrino Factories and Superbeams

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For the ICARUS Collaboration

http://www.cern.ch/icarus/

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Introduction - Disclaimer

- The Liquid Argon TPC on the kton scale is the fruit of a successful R&D program that has lasted many years
- It has recently regained a strong interest in the community, after the
  1. Successful assembly and operation of the **ICARUS T600**
  2. The realization of the **ENORMOUS** physics potential offered by high granularity imaging and extremely high resolution, in the context of
     - **UNDERGROUND PHYSICS** (proton decay, solar, supernova, …)
     - **SHORT-BASELINE** (now called "near detectors") low/medium cross-sections or high-energy precision neutrino physics
     - **LONG-BASELINE** neutrino physics (superbeams and/or NF)
- As a consequence, preprints, proceedings, LOI's, etc… have recently appeared concerning liquid argon detectors, from the smallest (≈10-100 tons) to the biggest (>100 ktons) sizes, with varying level of credibility.
- **I WILL TRY TO CONCENTRATE ON "REAL" RESULTS RELATED TO LIQUID ARGON TPC'S**
  - ➥ These results have (so far) been achieved within the ICARUS Collab.

The ICARUS Collaboration

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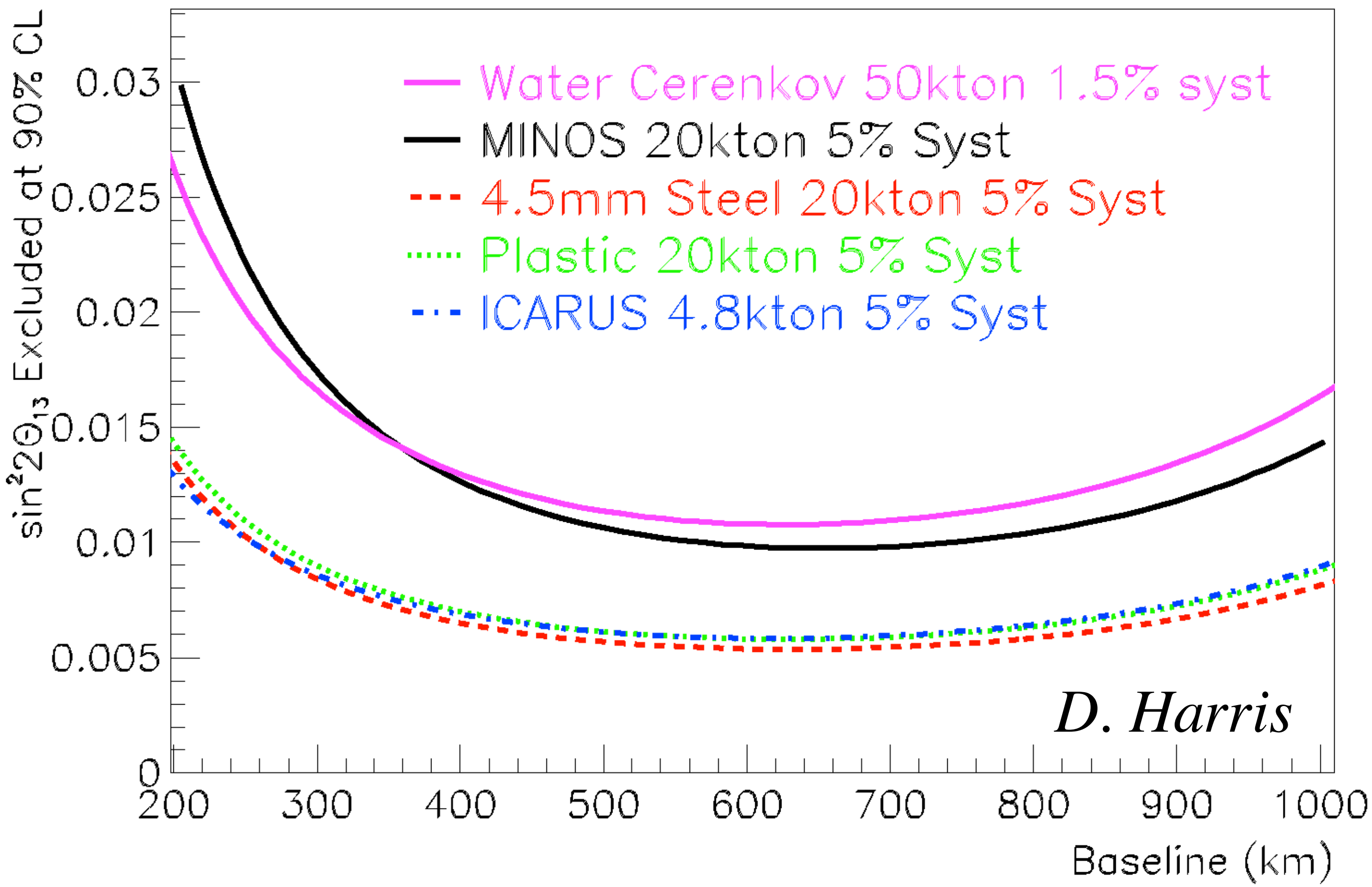
ITALY: L'Aquila, LNF, LNGS, Milano, Napoli, Padova, Pavia, Pisa, CNR Torino, Politec. Milano.
SWITZERLAND: ETH/Zurich.
CHINA: Academia Sinica Beijing.
POLAND: Univ. of Silesia Katowice, Univ. of Mining and Metallurgy Krakow, Inst. of Nucl. Phys. Krakow, Jagellonian Univ. Krakow, Univ. of Technology Krakow,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

The physics program at the Superbeam

SEE D. MICHAEL'S TALK

- Better $\nu_\mu \rightarrow \nu_e$ appearance physics per mass than any other type of technology: *mass is not everything!*

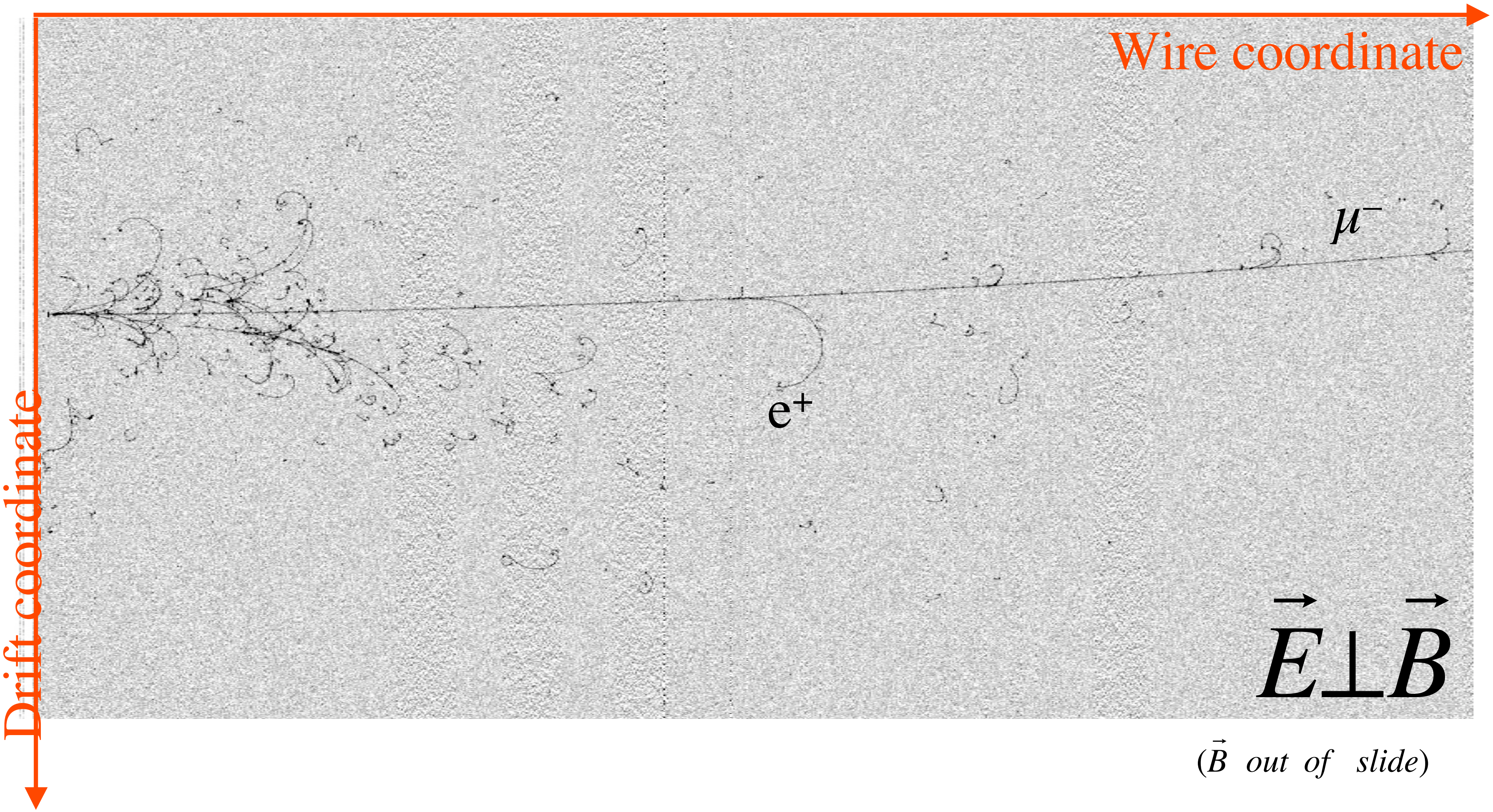


The "ICARUS-like" physics program at the NF

See Nucl.Phys.B589:577-608,2000, Nucl.Phys.B631:239-284,2002

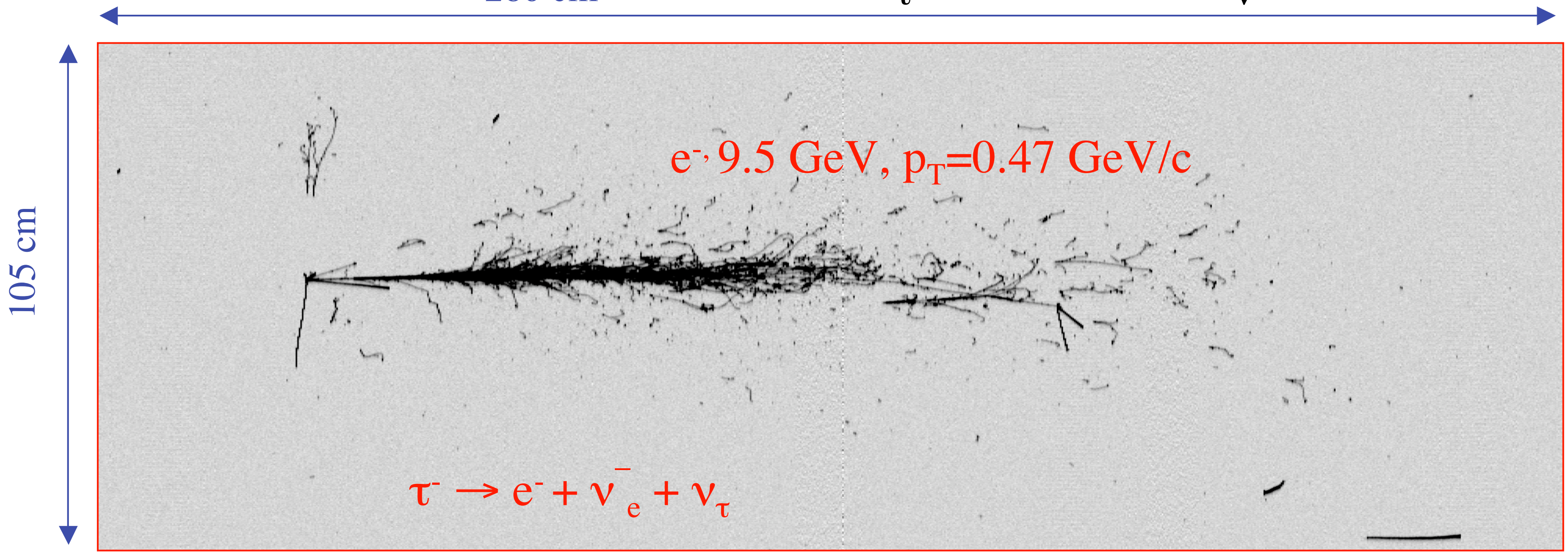
- With a **MAGNETIZED LIQUID ARGON TPC**, we can do the measurements proposed with magnetized Fe calorimeter **(*SEE JJ. GOMEZ "GOLDEN" TALK*)**
  - Since muons are very well measured:
    - Momentum threshold in LAr TPC can be very low (dE/dx ≈ 200 MeV/m)
    - Muon well separated from jet thanks to detailed imaging
- This means
  - Precise determination of Δm^2_{23} and θ_{23}
  - Stringent limit/precise measurement of θ_{13}
  - Determination of Δm^2_{23} sign
  - Study matter effects
  - Search for CP violation
- However, the better granularity & resolution offers in addition new possibilities :
  - **KINEMATICAL DETECTION** of $\nu_e \rightarrow \nu_\tau$ oscillations (**SILVER**)
  - **OVER-CONSTRAIN** the oscillation parameters (matrix unitarity)
  - Study the δ phase by **DIRECT SEARCH OF T VIOLATION**
  - **DISENTANGLE δ vs θ_{13}** thanks to energy dependent studies

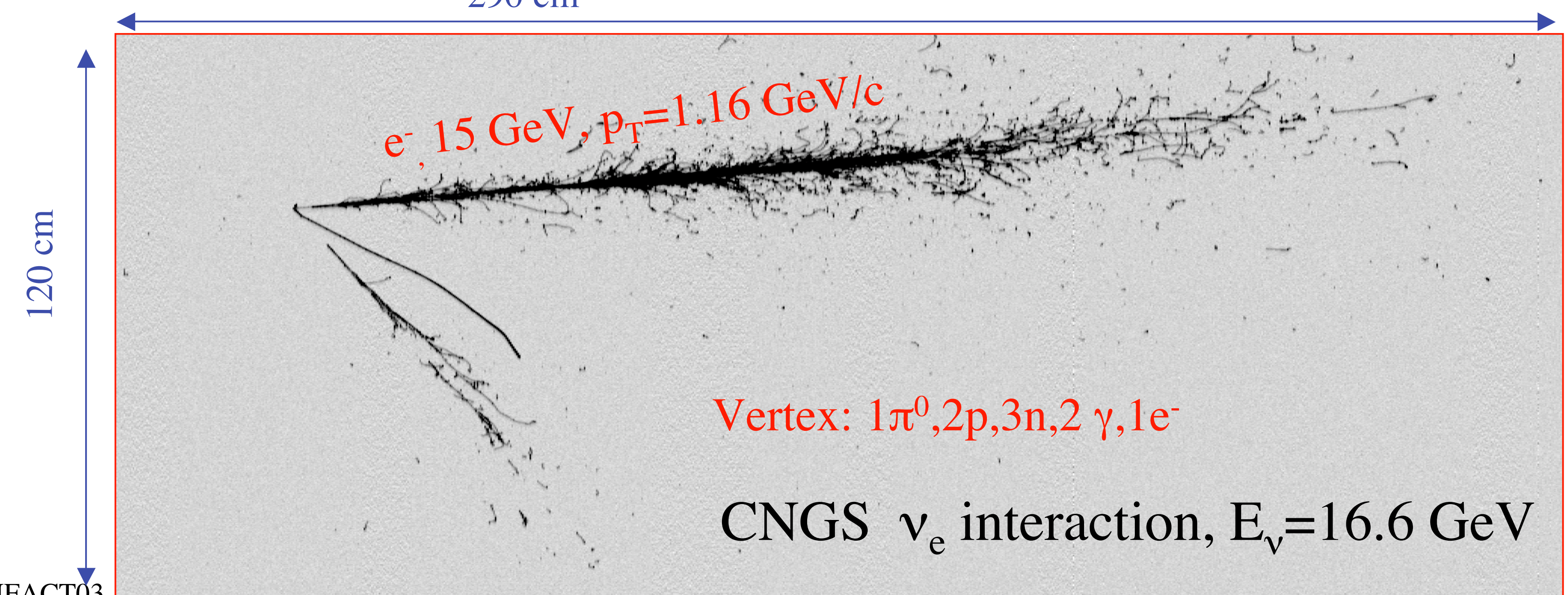
Simulated ν_μ CC event in B=0.2 T



($\vec{B}$ *out of slide*)

CNGS ν_τ interaction, E_ν=18.7 GeV





CNGS ν_e interaction, E_ν=16.6 GeV

The required mass and magnetic field optimizations

- Short-baseline (now called “near detectors”) low/medium cross-sections or high-energy precision neutrino physics
  - ➥ **10–100 TON MAGNETIZED B=0.5–1T**
- Long-baseline neutrino physics
  - ➥ Superbeams
    - ☛ **10 KTON NOT NECESSARILY MAGNETIZED (PHASE I)**
    - ☛ **50–100 KTON NOT NECESSARILY MAGNETIZED (PHASE II)**
  - ➥ NF
    - ☛ **10–20 KTON MAGNETIZED B=1 T**
- Underground physics (proton decay, supernova, atm, solar, …)
  - ➥ **100 KTON NON MAGNETIZED**

DIFFERENT OPTIMIZATIONS FOR DIFFERENT KINDS OF PHYSICS (MINI, MEDIUM, LARGE, XL)

What me worry?

Challenges of the Liquid Argon TPC

- Cost effective implementation
  - Single large cryostat
  - Argon purity in large volumes
  - Long drift distance
  - Very high voltage
- Safety, safety,safety
- Data acquisition

- A case of a dog, which did not bark (Conan Doyle)
  - 50 l prototype exposed to the WANF beam + NOMAD
  - 300 ton prototype exposed to cosmic rays in Pavia
  - No results (QE ν_μ? ν_e? Angular distribution of CR muons? Uniformity of the detector? Long term stability? Other?)

Small LAr TPC in a neutrino beam at KEK or Fermilab ? :

•Proof of principle as a reliable experimental technique

•Rich source of physics information about low E neutrino interactions

ADAM PARA, NUFACT 02 (LONDON)

A dog living in a virtual world…

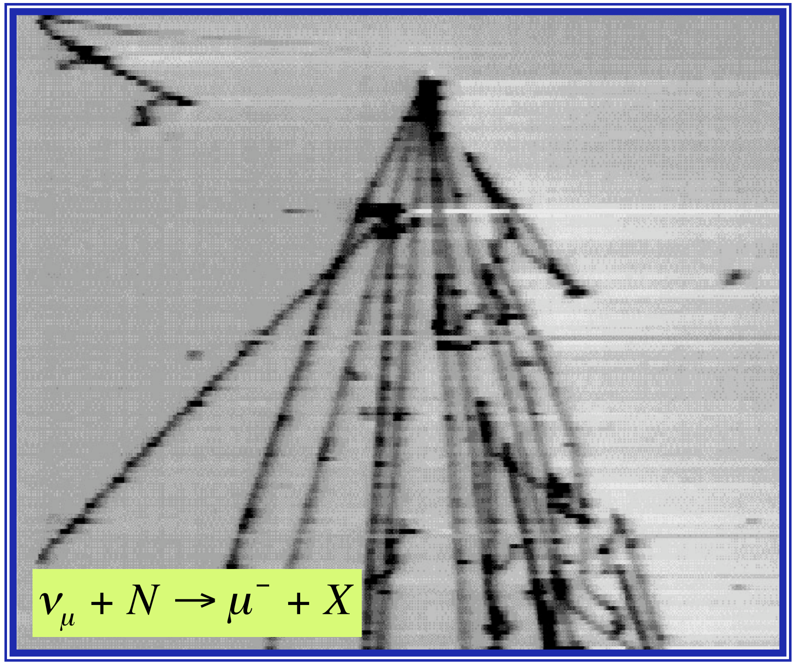
Past experience and results - 50 liter prototype

- 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)

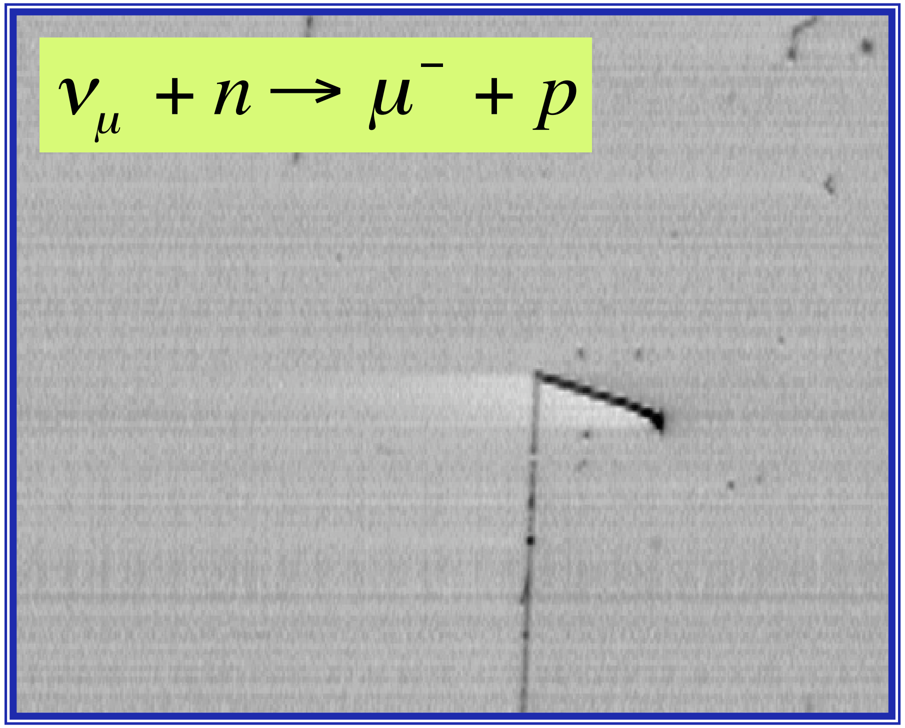
Exposed to CERN WANF

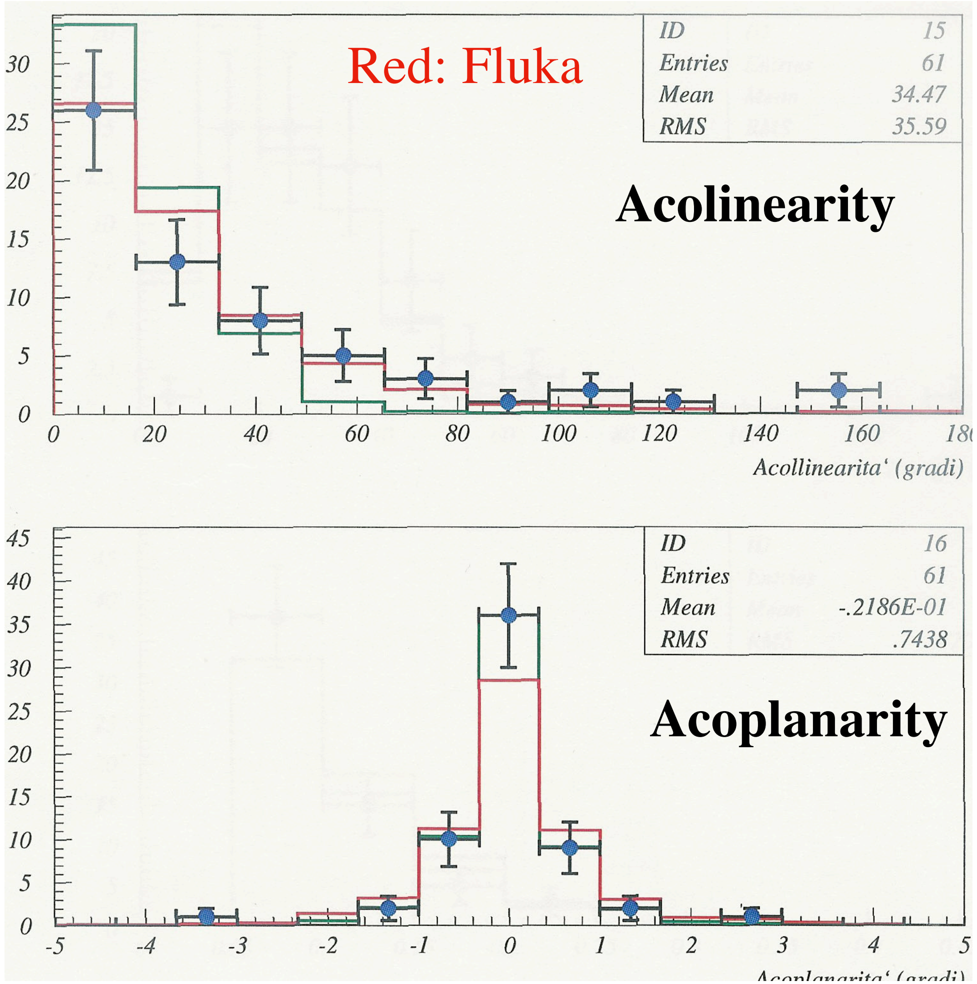


NOMAD experiment provided escaping muon momentum

Quasi-elastic interactions in 50 liter exposed to CERN WANF

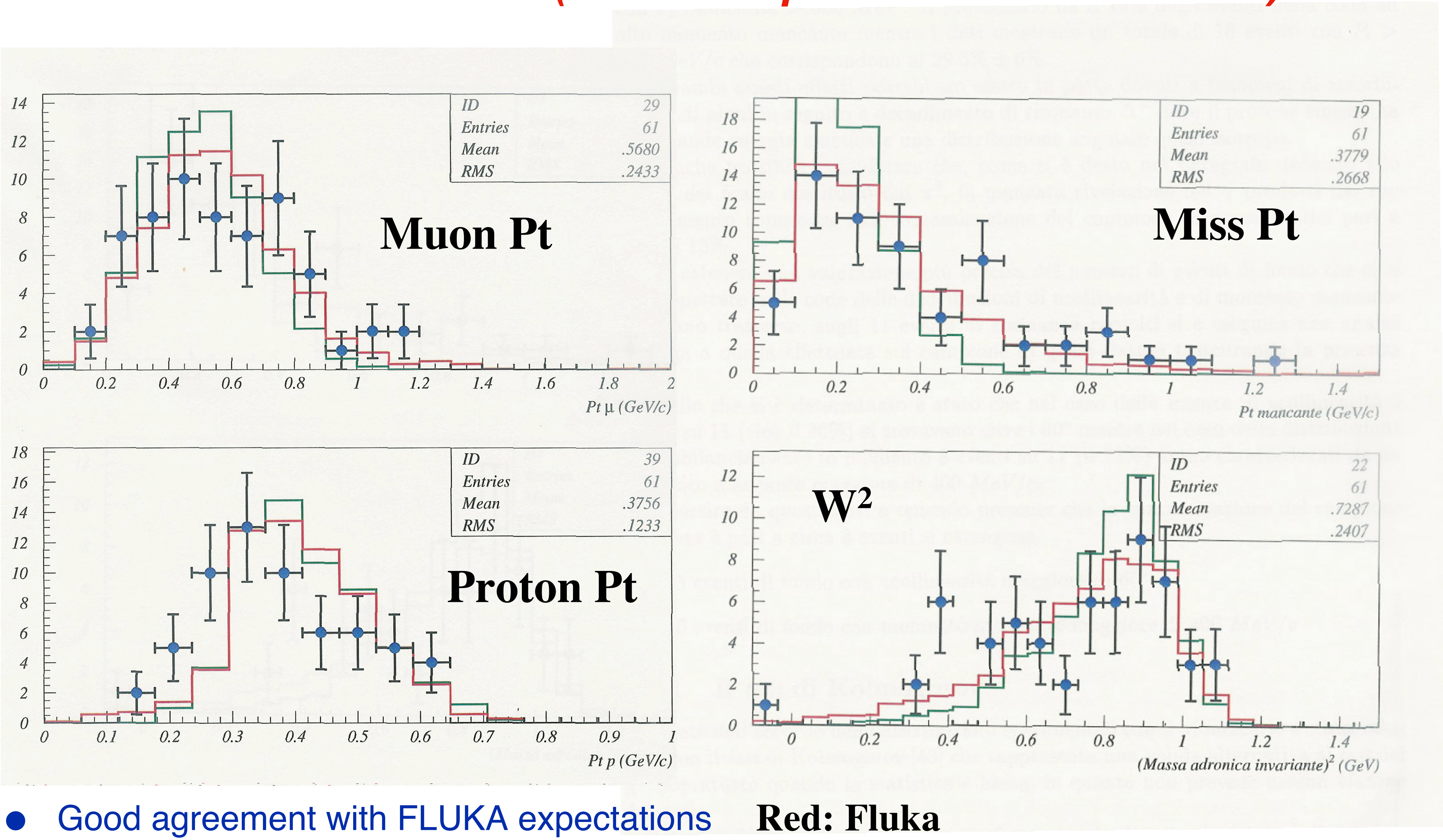
- Selection of pure lepton-proton final state with exactly one proton T_P>50 MeV (range > 2 cm) and any number protons T_P<50 MeV





B. Boschetti's thesis (Milano, 1998)

Quasielastic events (50 liter exposed to CERN WANF)



- Good agreement with FLUKA expectations

Red: Fluka

B. Boschetti's thesis (Milano, 1998)

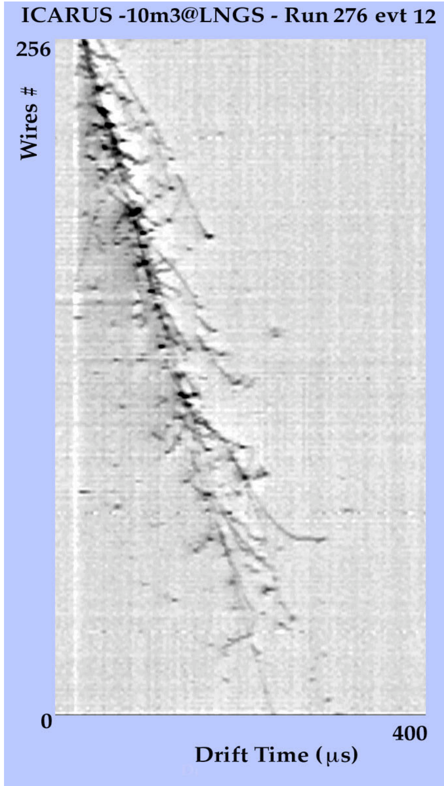
Past experience and results - 15 ton prototype

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

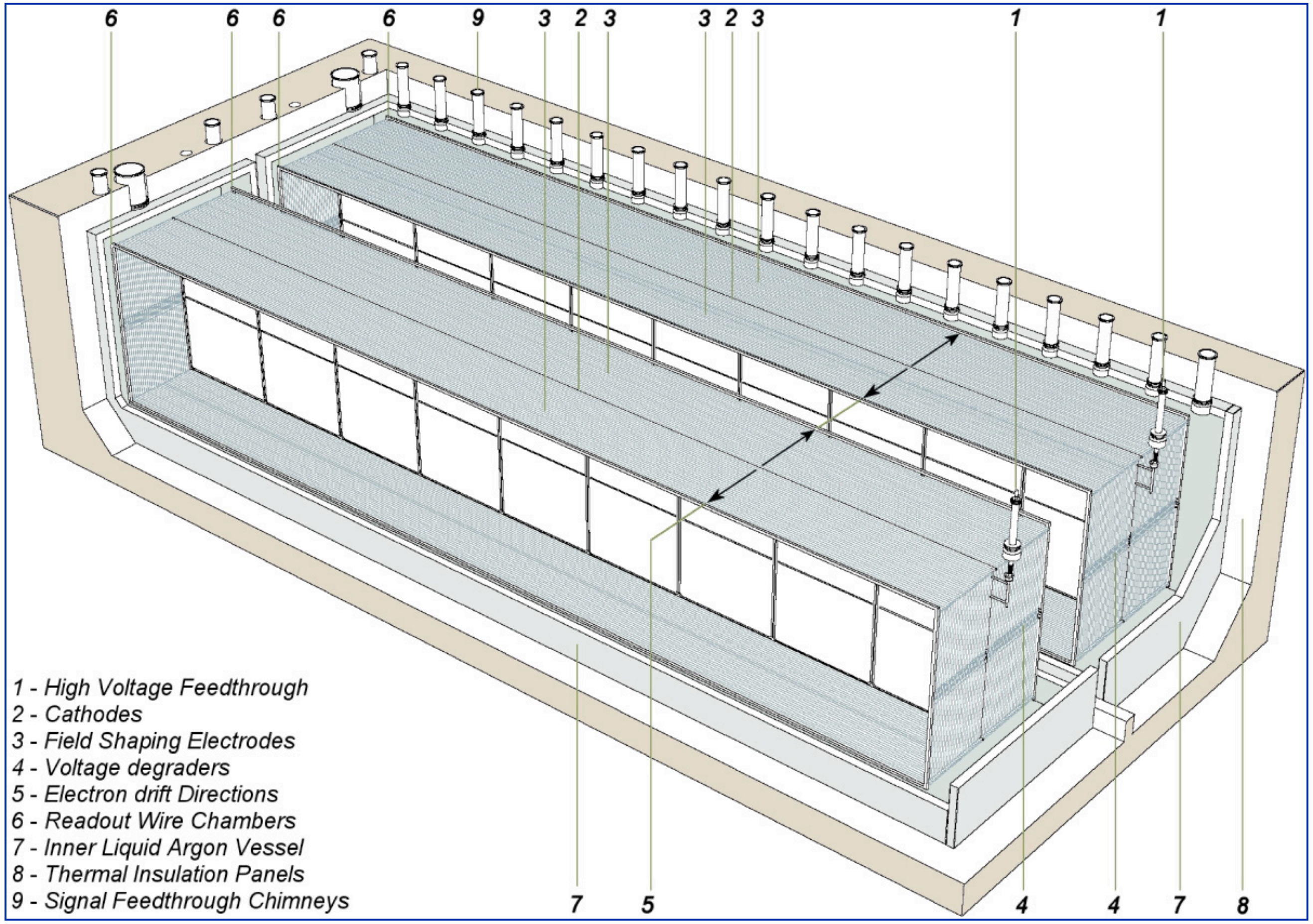
✓Final electronics
✓DAQ
✓External trigger
✓100 days run in LNGS external hall
✓Max. electron lifetime ≈ 2 ms

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

T15 installation @ LNGS (Hall di Montaggio)



The ICARUS T600 Module



- Two separate containers
  - ➥inner volume/cont. = **3.6 x 3.9 x 19.6 m³**
- **SENSITIVE MASS = 476 TON**
- 4 wire chambers with 3 readout planes at 0°, ±60° (two chambers / container)
  - ➥≈ **54000 WIRES**
    None broke during test
- Maximum drift = 1.5 m
  - ➥HV = -75 kV @ 0.5 kV/cm
- **SCINTILLATION LIGHT READOUT** with 8" VUV sensitive PMTs

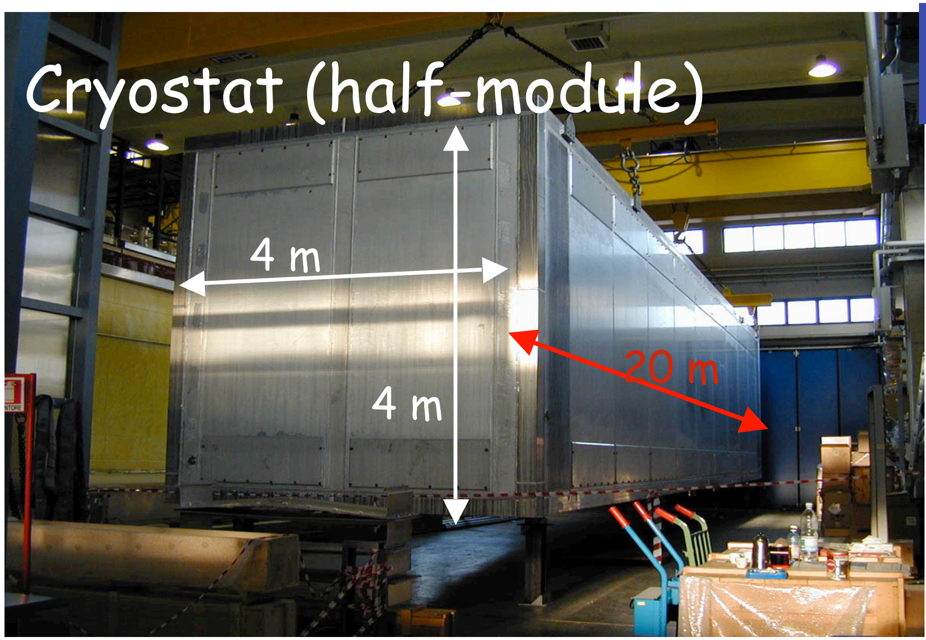
Experience and results - First container of T600 test

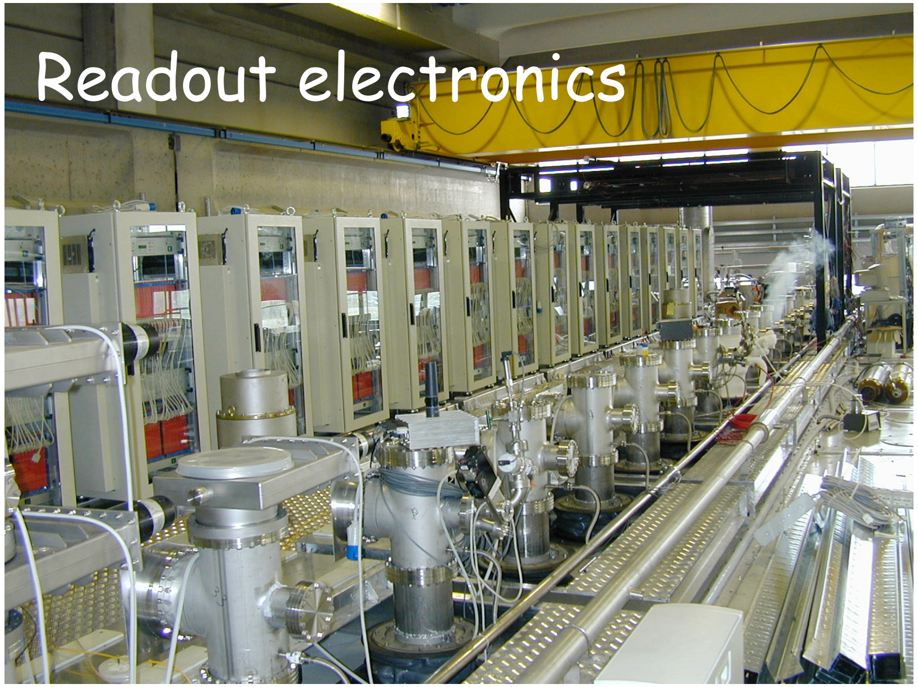
- Total volume of one container: 350 m^3
- Readout planes: 3 (–60°,60°,0°)
- Max drift distance: 150 cm

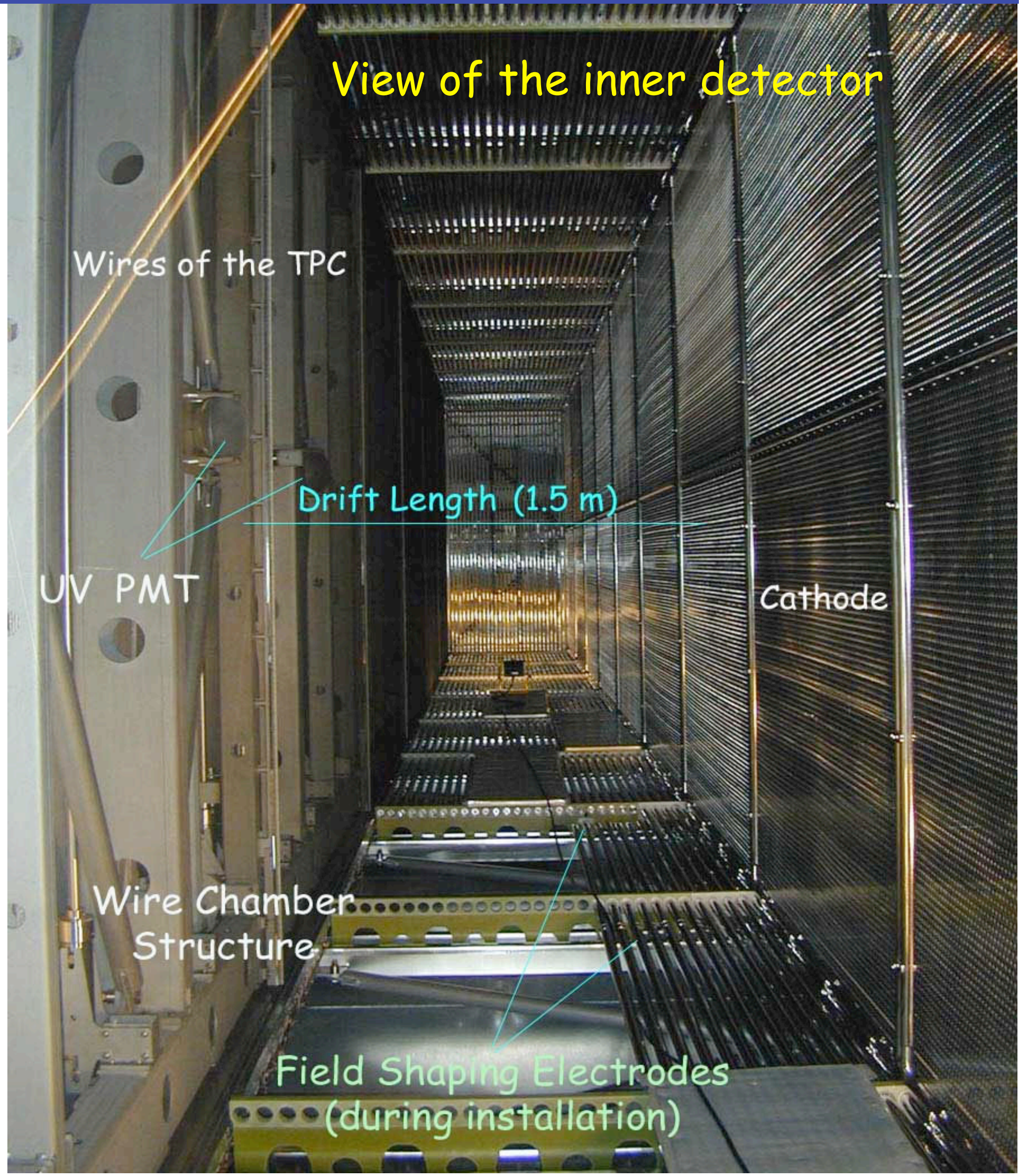
- Full scale technical run of the T300 detector in Pavia:
  - ➥ Cryogenics ✔ (decrease the LN2 consumption)
  - ➥ Wire chamber mechanics ✔✔
  - ➥ Argon purification ✔
  - ➥ Electronic noise ✔
  - ➥ High voltage for the drift ✔✔ (also at 150 KV)
  - ➥ PMTs for scintillation light collection ✔
  - ➥ Readout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

ICARUS T300 cryostat (1 out of 2)

ICARUS T300 prototype



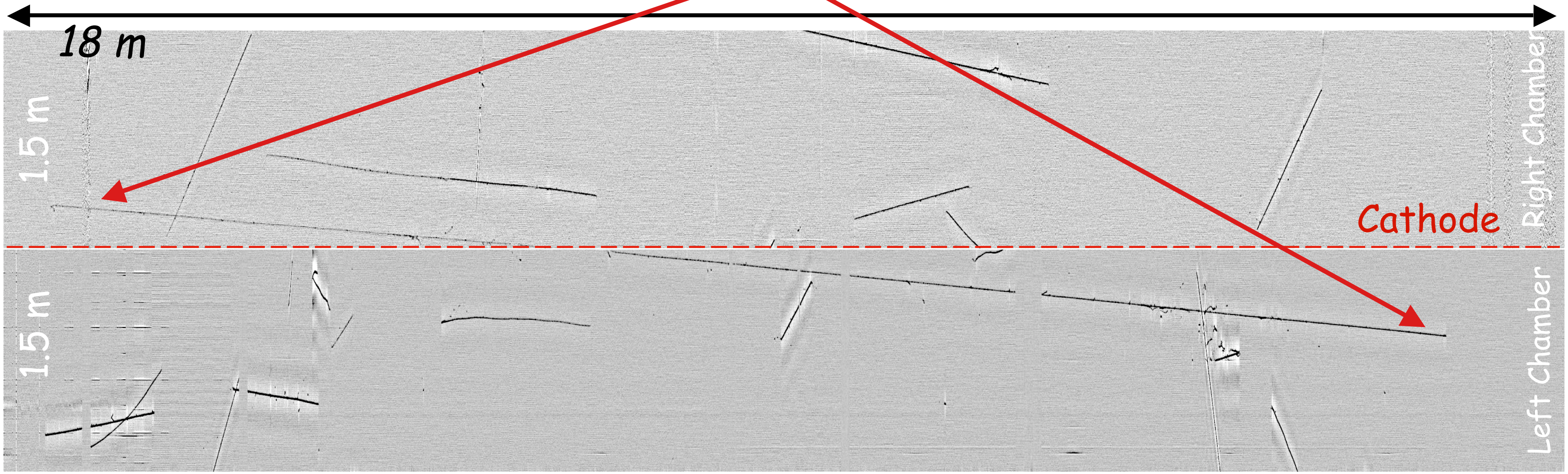


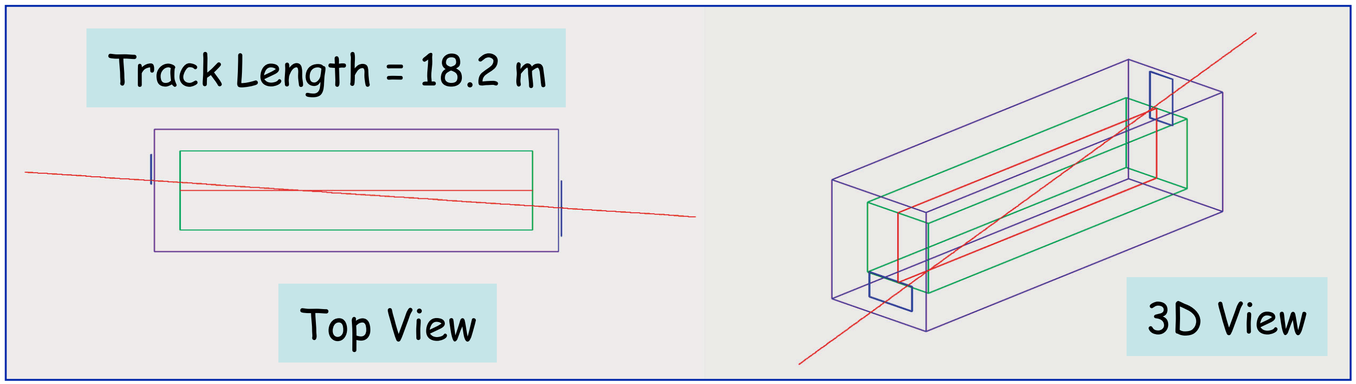


The T600 module

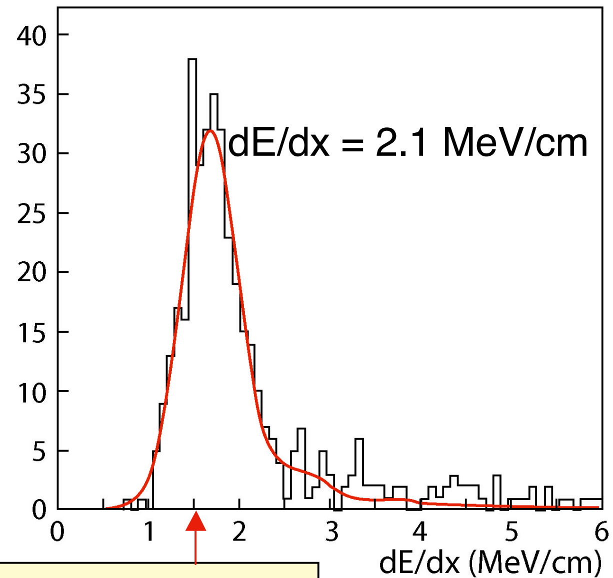
- Approved and funded in 1996
- Built between years 1997 and 2001
- **COMPLETELY ASSEMBLED** in the INFN assembly hall in Pavia
- Demonstration test run during first half 2001
  - ➥Three months duration
  - ➥Completely successful
  - ➥Data taking with cosmic rays
- **INSTALLATION PLAN IN THE GRAN SASSO UNDERGROUND LAB COMPLETED EARLY 2003 (INCLUDING SAFETY RISK ANALYSIS)**
- Transportation and installation in LNGS in 2003-2004

Long longitudinal muon track crossing the cathode plane





3-D reconstruction of the long track

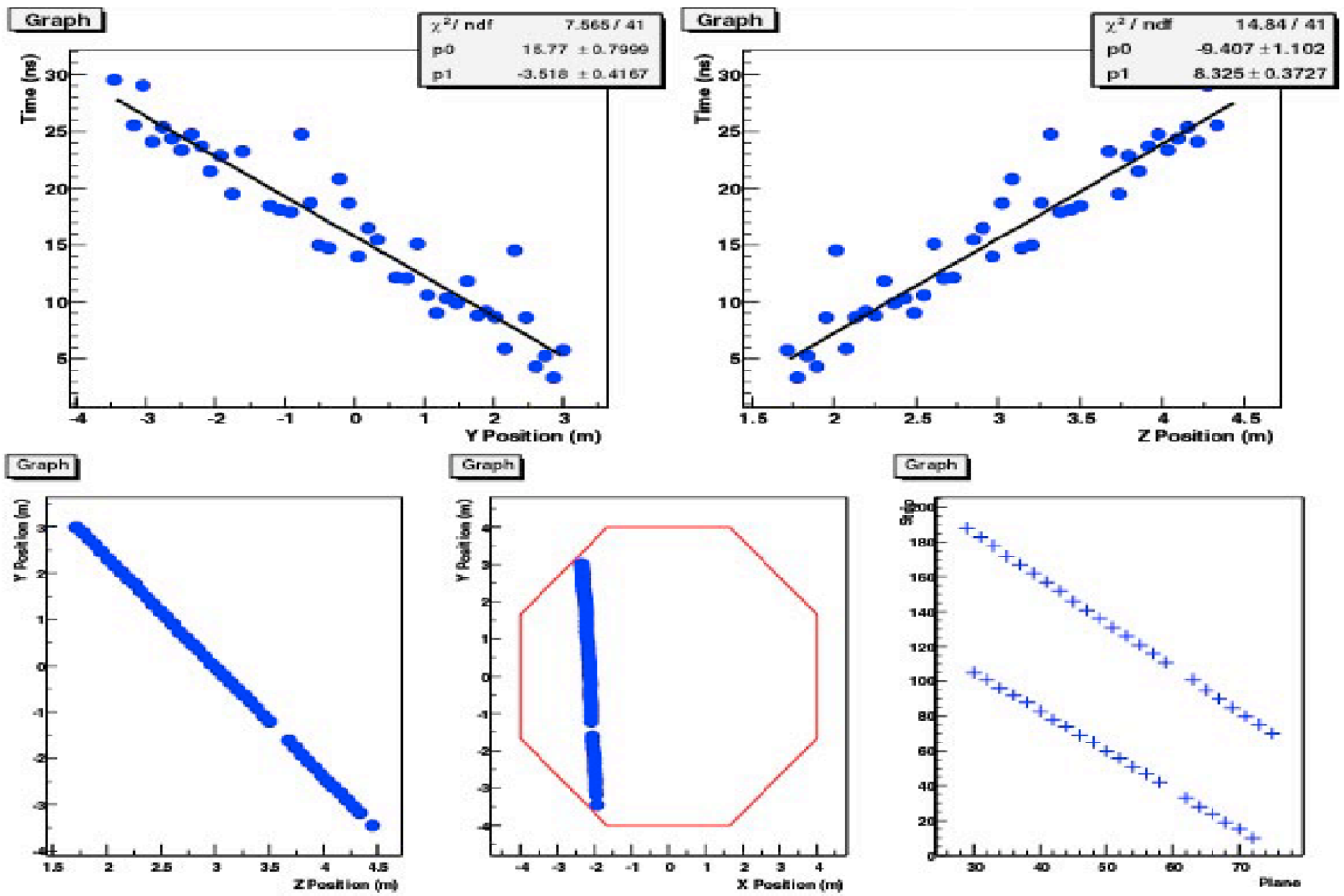


dE/dx distribution along the track

Cosmic Ray Muon in the Far Detector

- Downgoing Cosmic Ray Muon
- Current rate of CR muons ~ 2 Hz
- Magnetic field not yet on (curvature measurable up to ~70 GeV)

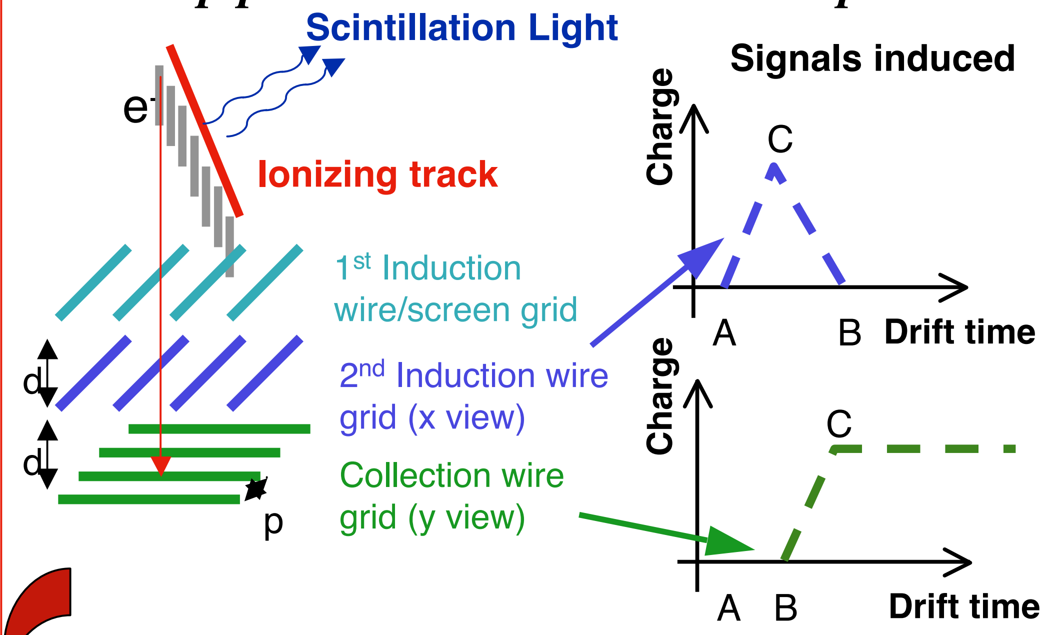
D. Michael or A. Para?



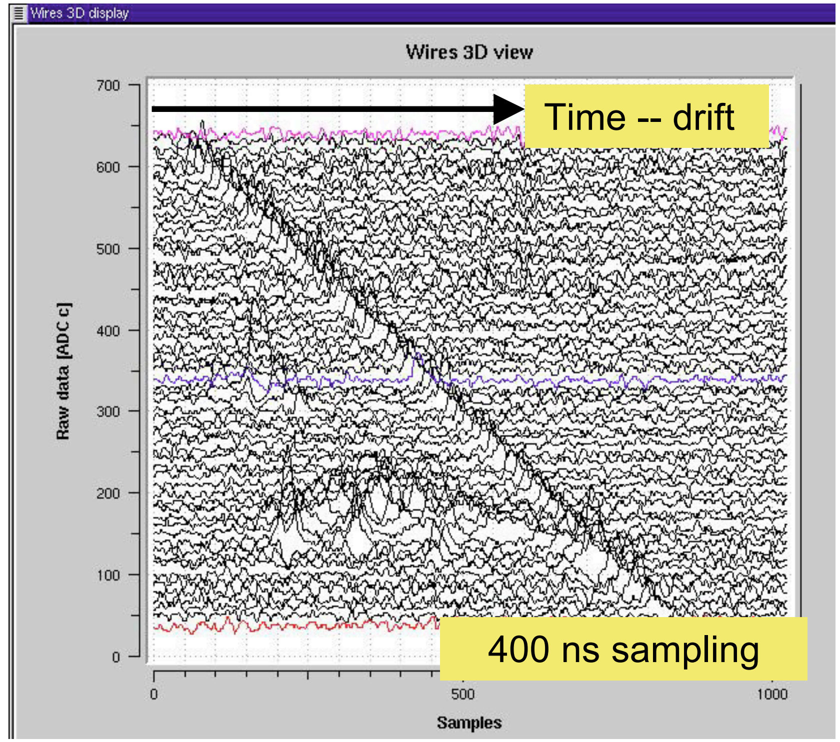
The front-end electronics

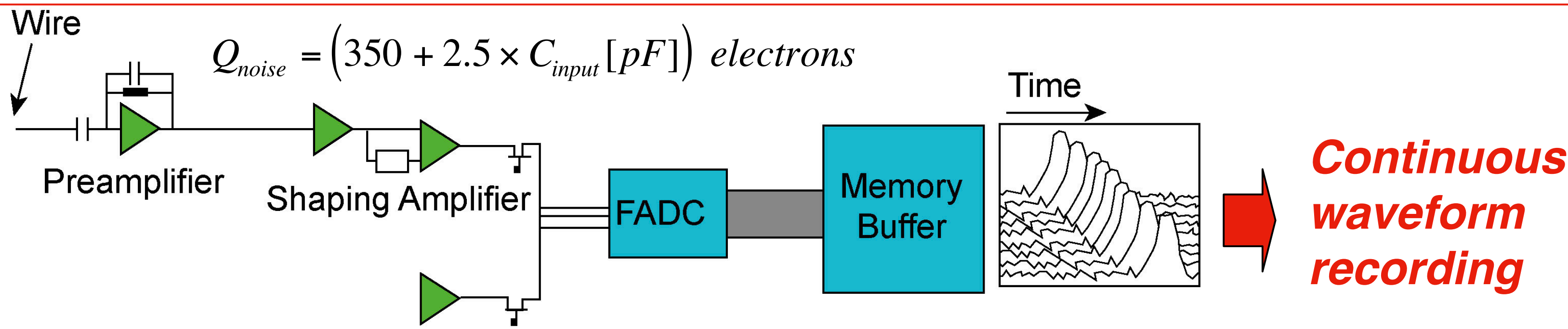
Non-destructive multiple readout

A mip produces ≈20000 electrons per 3mm



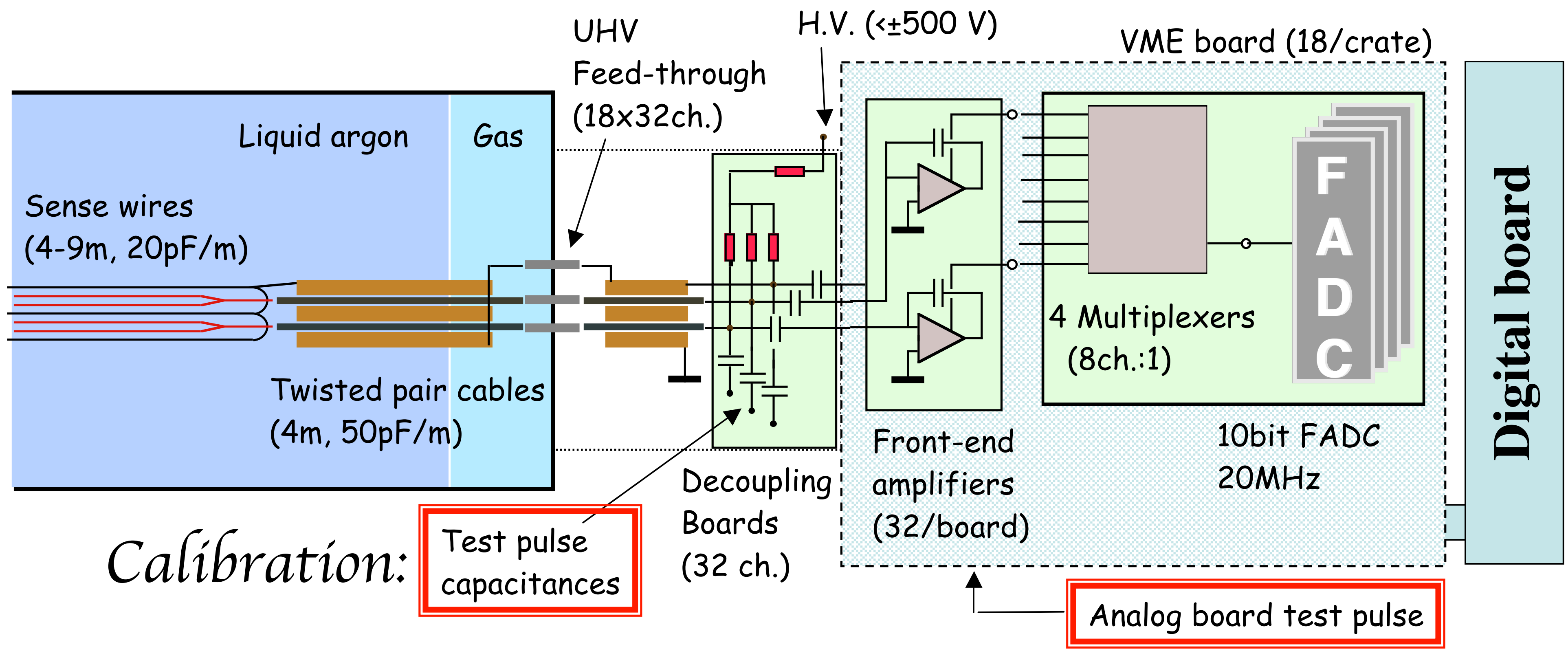
Raw Data from a 10 m³ prototype





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

Layout of front-end electronics

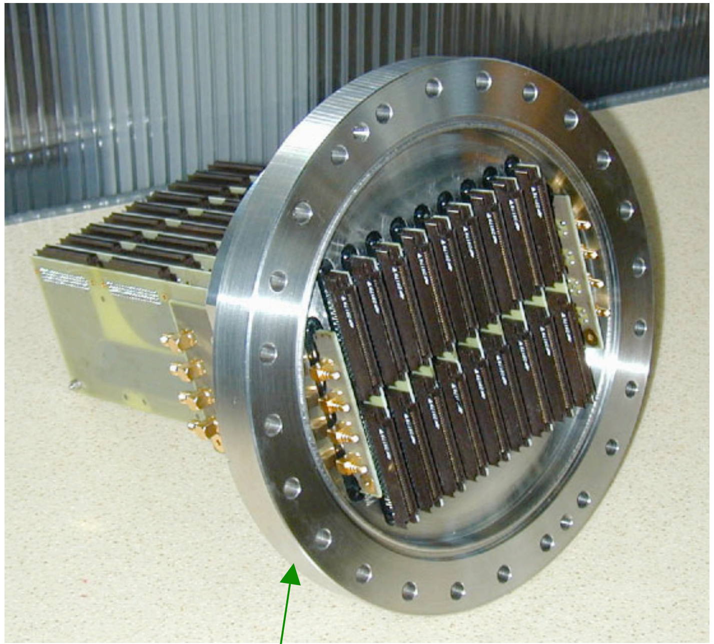


Each T600 half-module:

~ 27000 channels — 860 boards — 48 crates

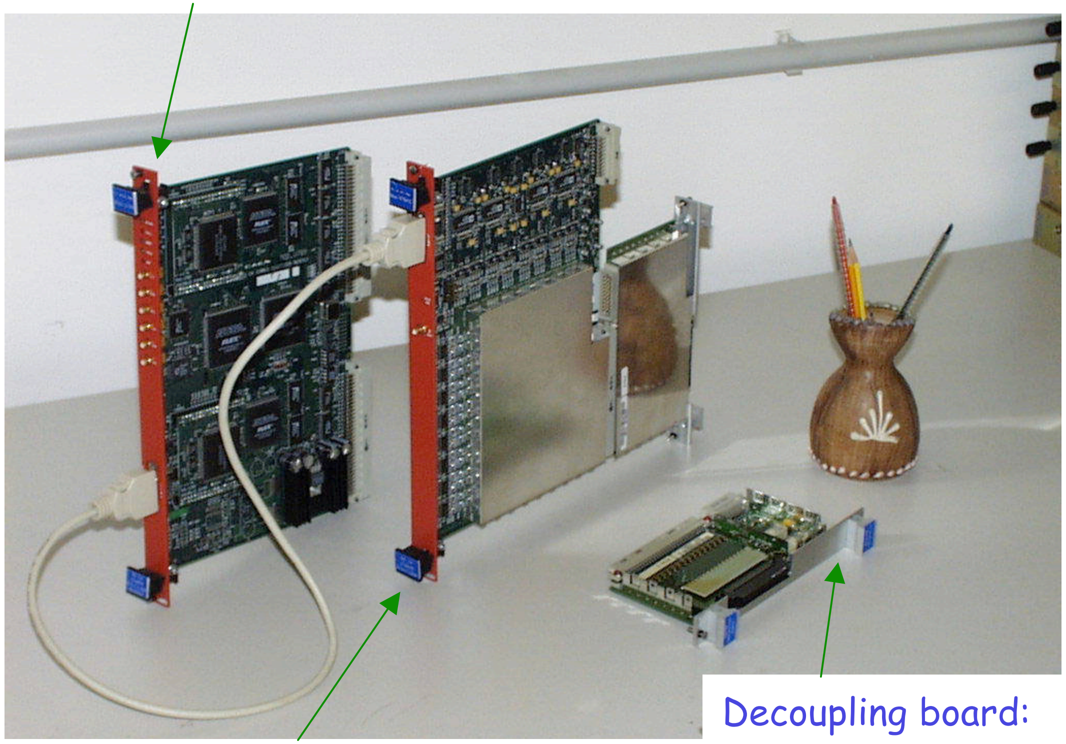
Fully industrialized production, ≈100 CHF/channel

The ICARUS T600 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

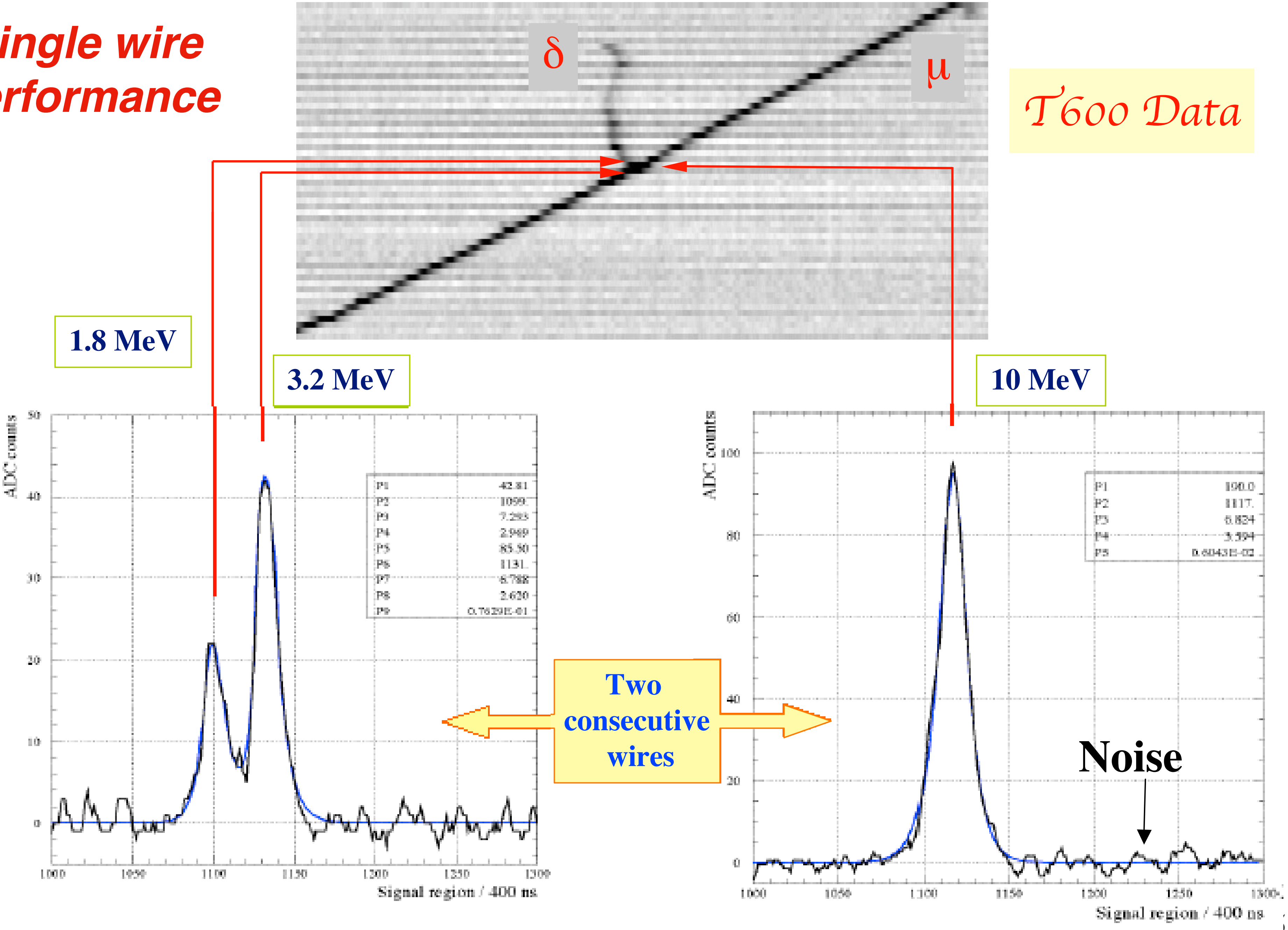


CAEN-V791 board: 32 pre-amplifiers +
4 multiplexers (8:1) + 4 FADC's (10 bits - 20 MHz)

Decoupling board:
HV distribution
and signal input

RESULT OF MANY YEARS OF ICARUS R&D

Single wire performance



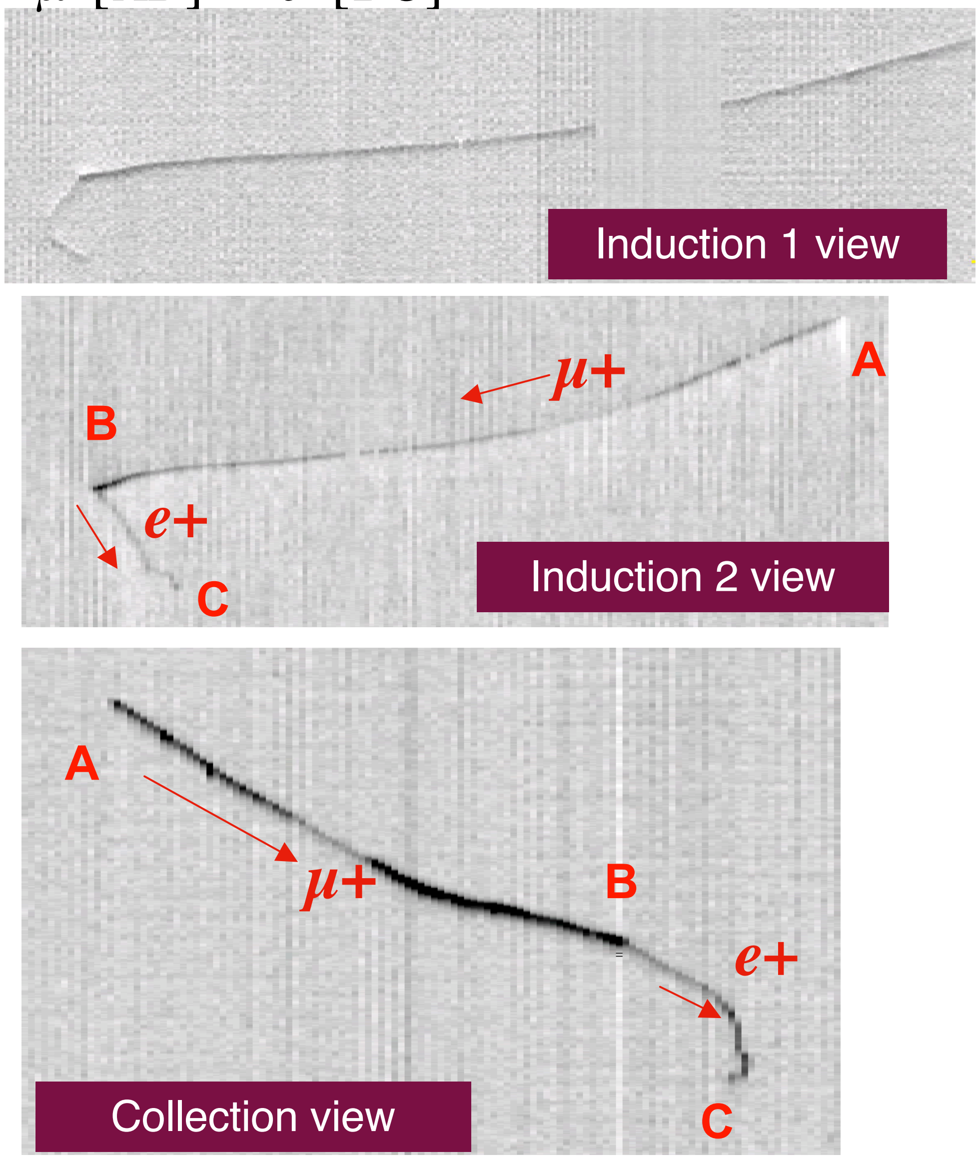
Further progress in analysis of T600 data

- Progress on reconstruction, analysis and detector performance understanding
  - ➥ Big effort on detector response modeling
    - ☛ Full detailed simulation, digitization and noise
  - ➥ Big effort on automatic reconstruction
    - ☛ Hit, clustering, tracking in 2D and 3D, calorimetric reconstruction
- Publications
  - ✓ *Performance of the 10 m^3 ICARUS liquid argon prototype*, NIM A498 (2002) 292-311
  - ✓ *Observation of long ionizing tracks with the ICARUS T600 first half-module* , NIM in press
  - ➥ **IN PHASE OF SUBMISSION**:
    1. Detection of Cerenkov light emission in Liquid Argon
    2. Design, construction and tests of the ICARUS T600 detector (100 pages)
    3. Analysis of the liquid argon purity in the very large ICARUS T600 TPC
    4. Momentum estimation via multiple scattering in the ICARUS T600 TPC
    5. Analysis of of the stopping muon sample in the ICARUS T600 TPC
    6. Study of electron recombination (quenching)
    7. Observation of multi-muon events

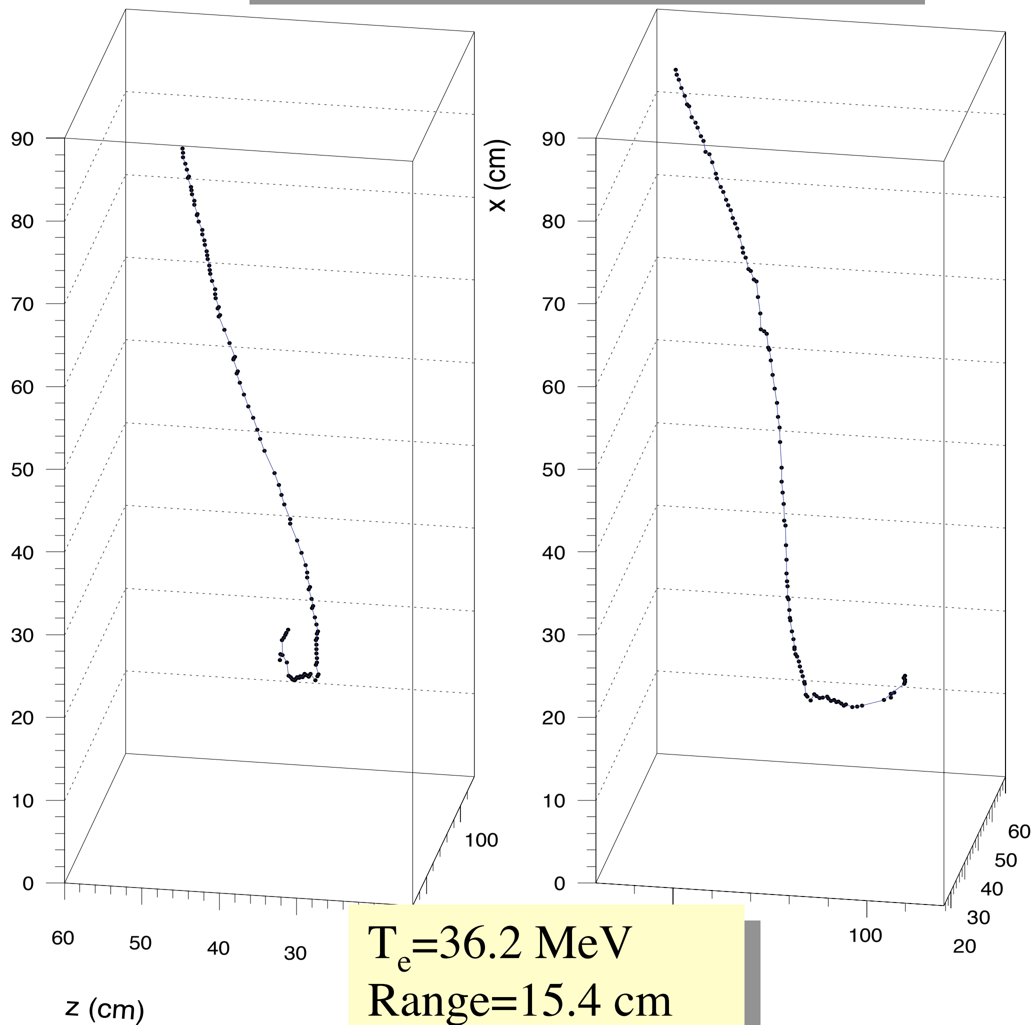
Stopping muon reconstruction example

J. Rico's thesis (ETHZ, 2002)

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

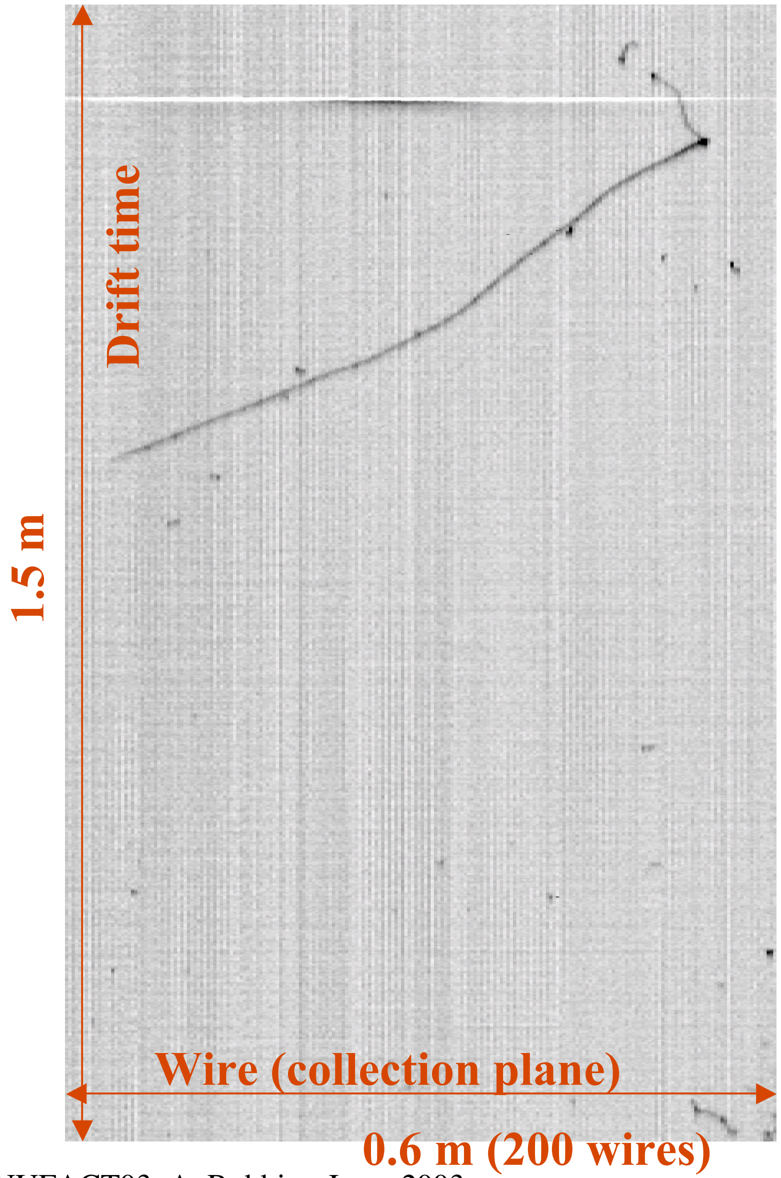


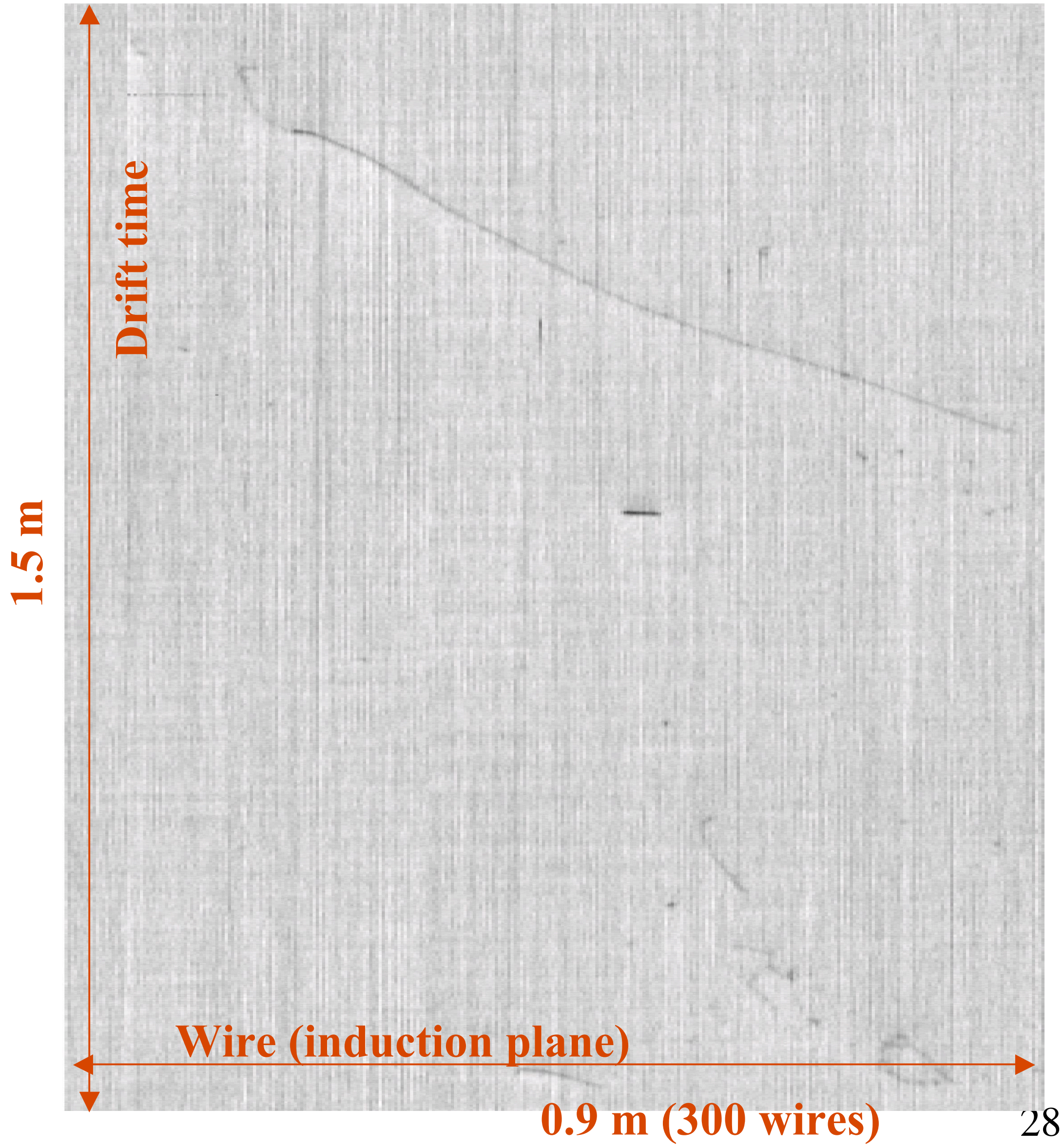
Run 939 Event 95 Right chamber



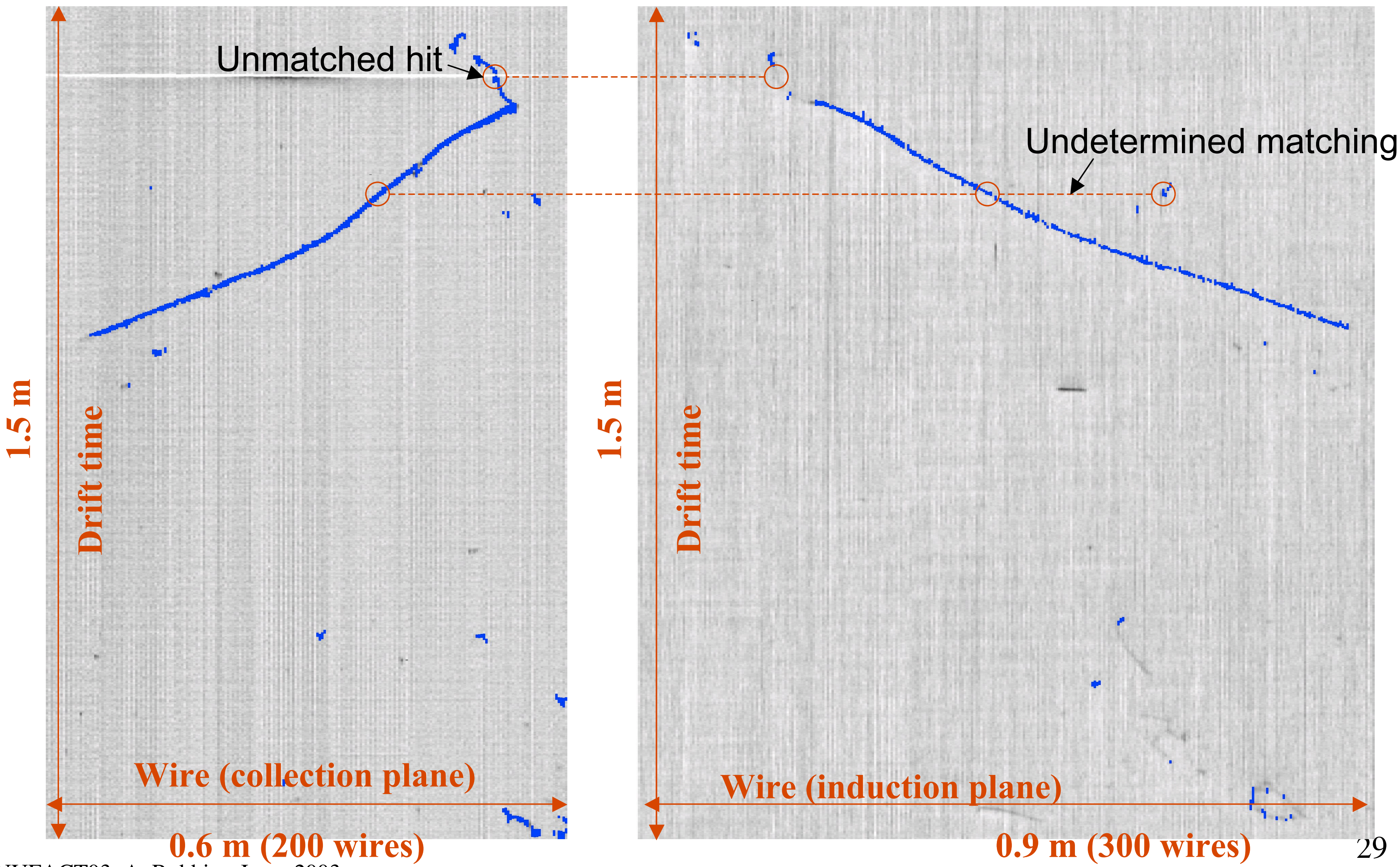
T_e=36.2 MeV
Range=15.4 cm

Stopping muon automatic reconstruction (I)

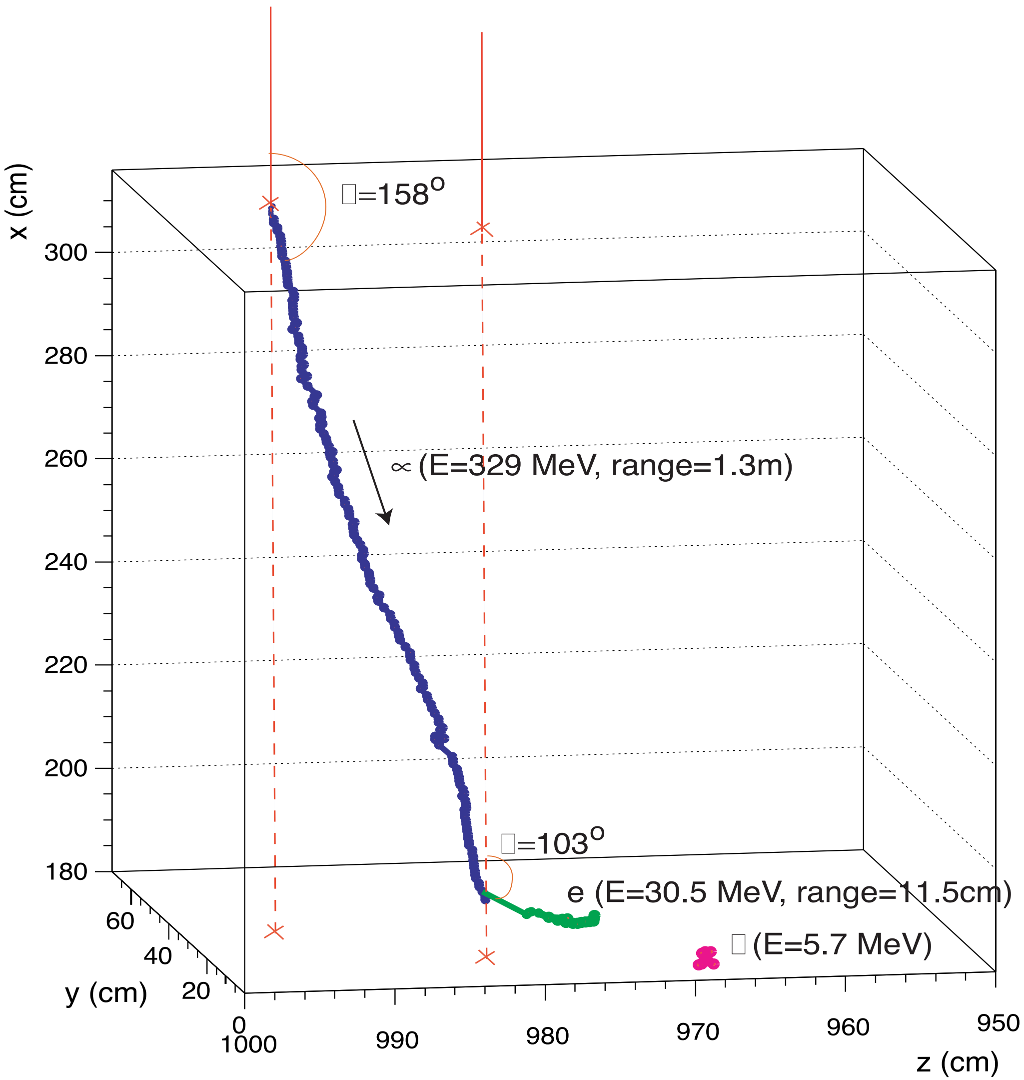




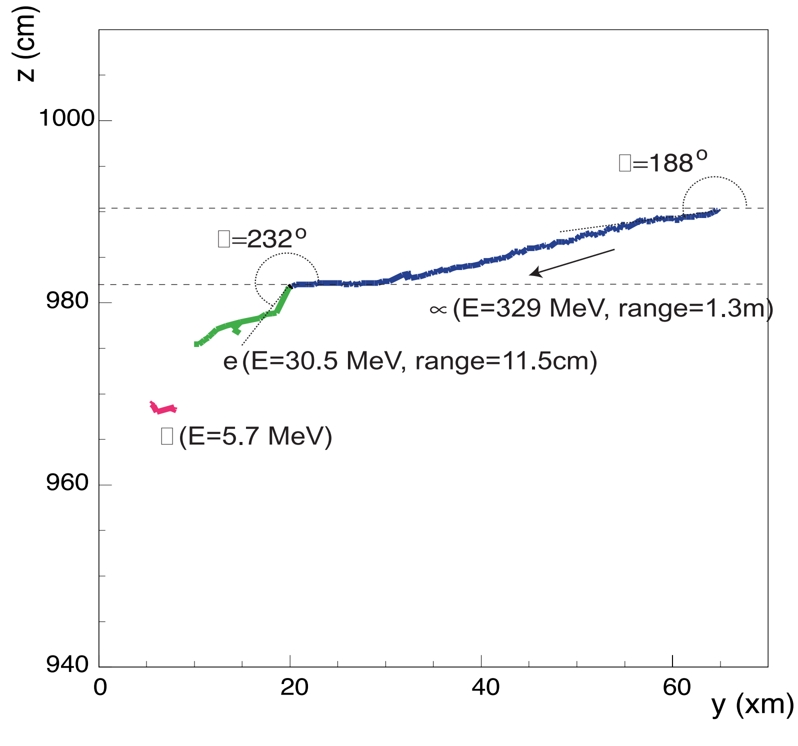
Stopping muon automatic reconstruction (II)



Fully reconstructed stopping muon event

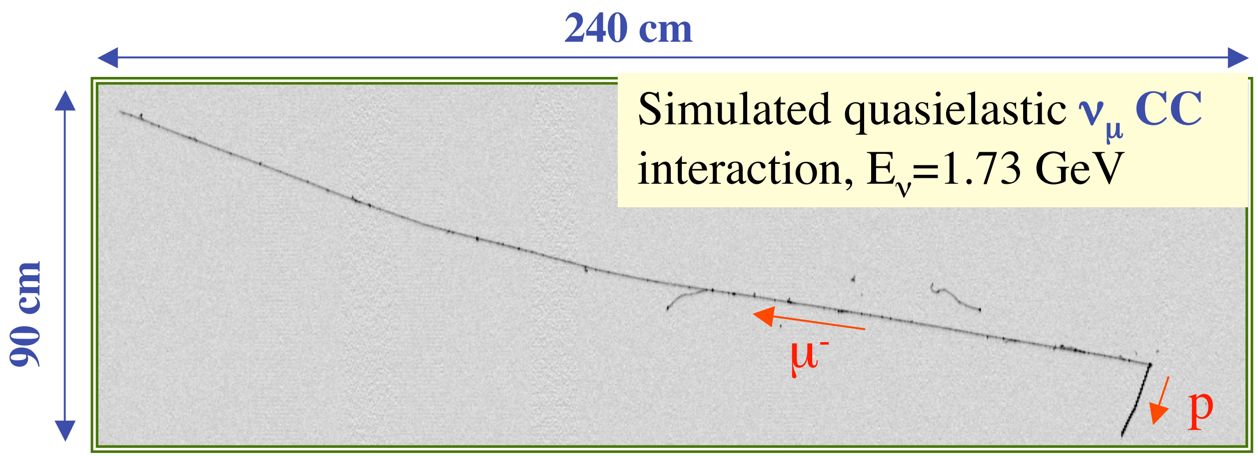


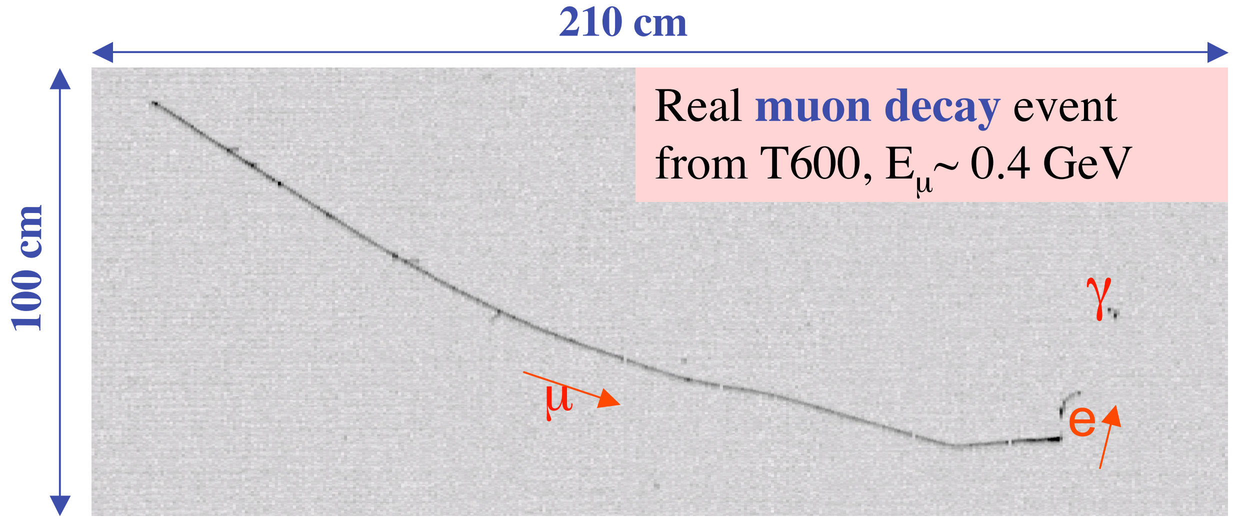
Y-Z plane projection (longitudinal cut)

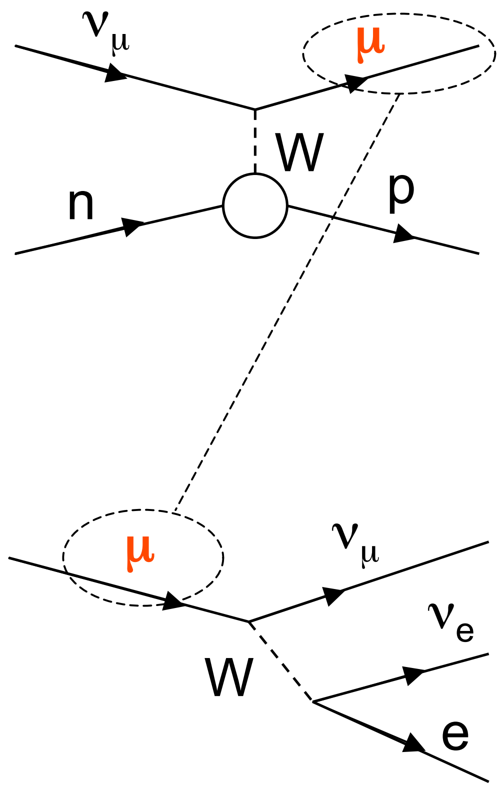


Analysis of the stopping muon sample

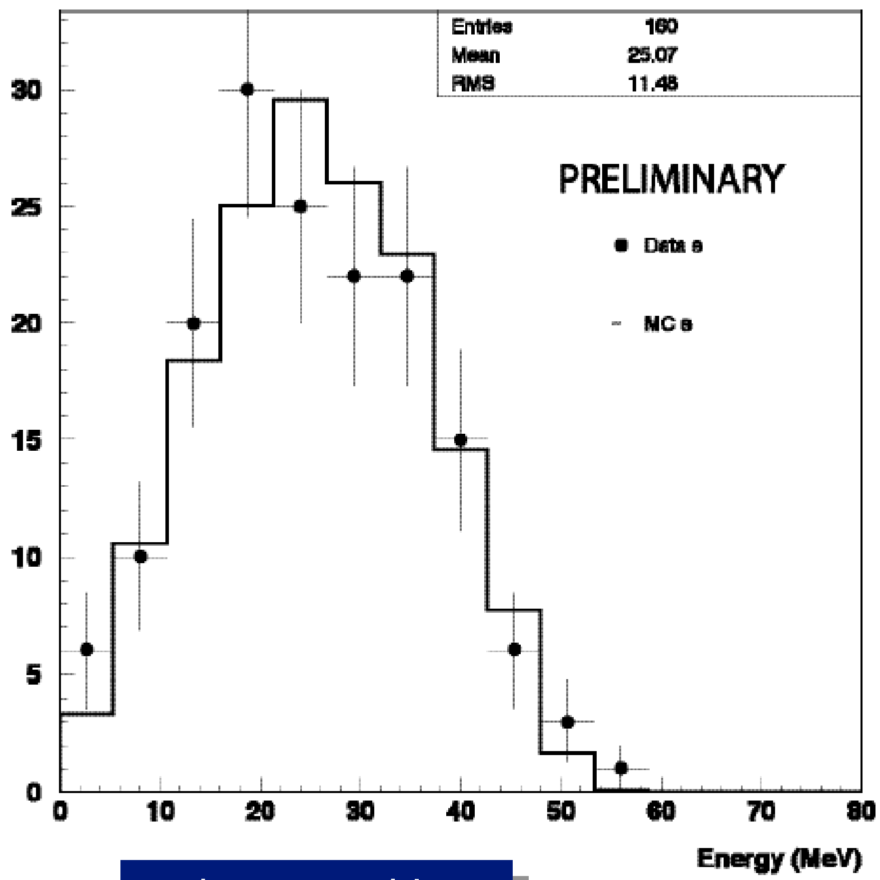
- Preliminary analysis based on ≈200 events
- Being now extended to full statistics (3000 events)



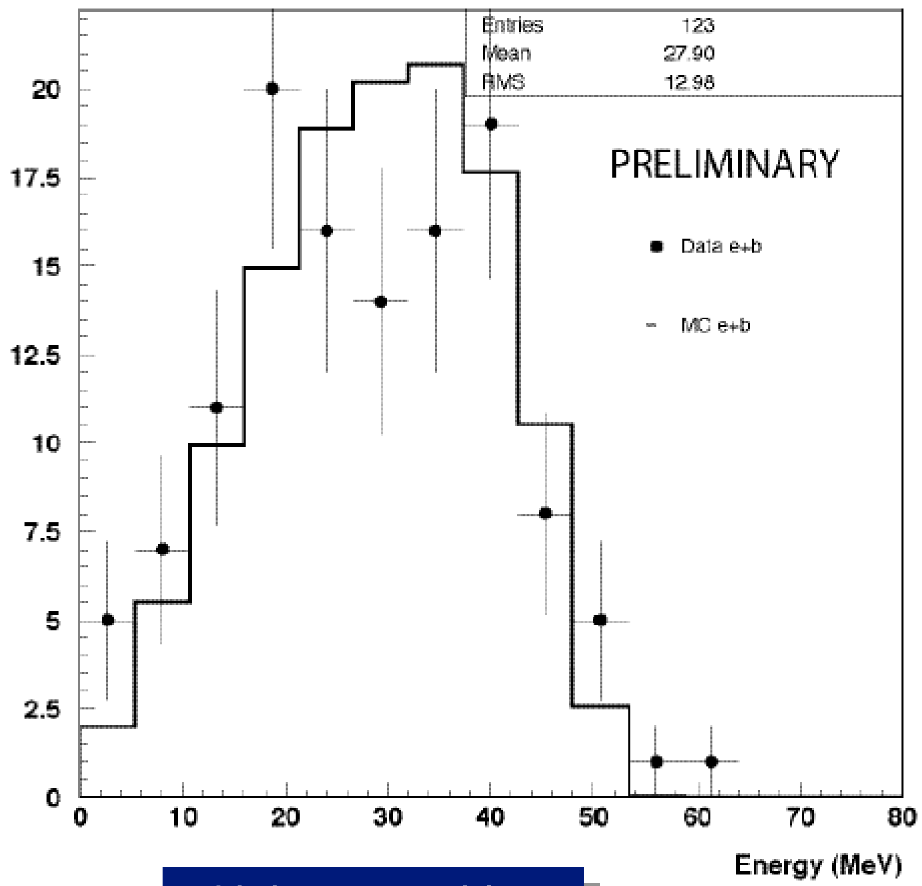




Calorimetric reconstruction Michel electrons (T600)



no bremsstrahlung

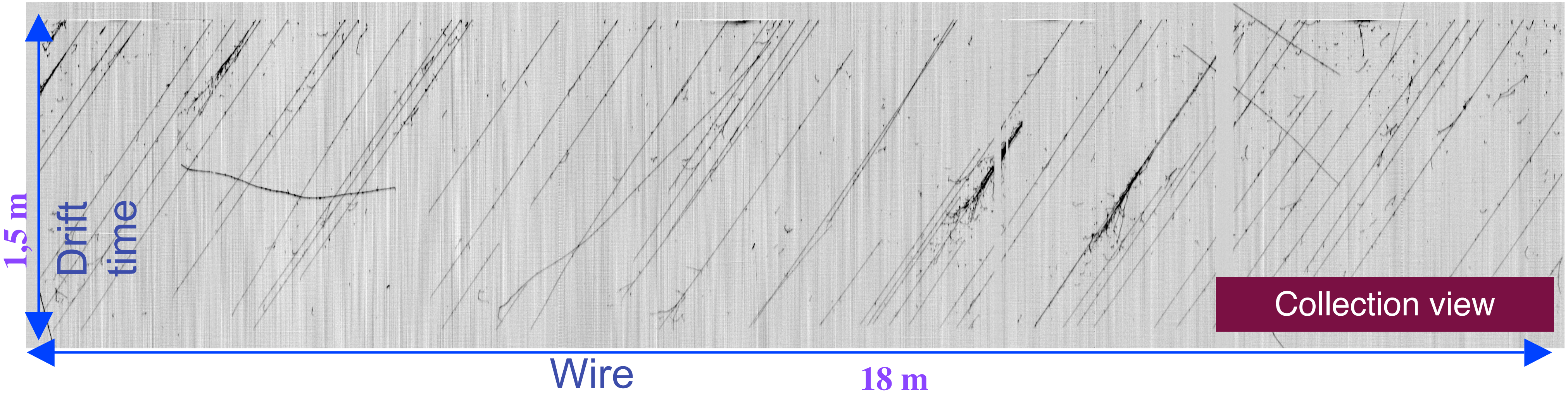


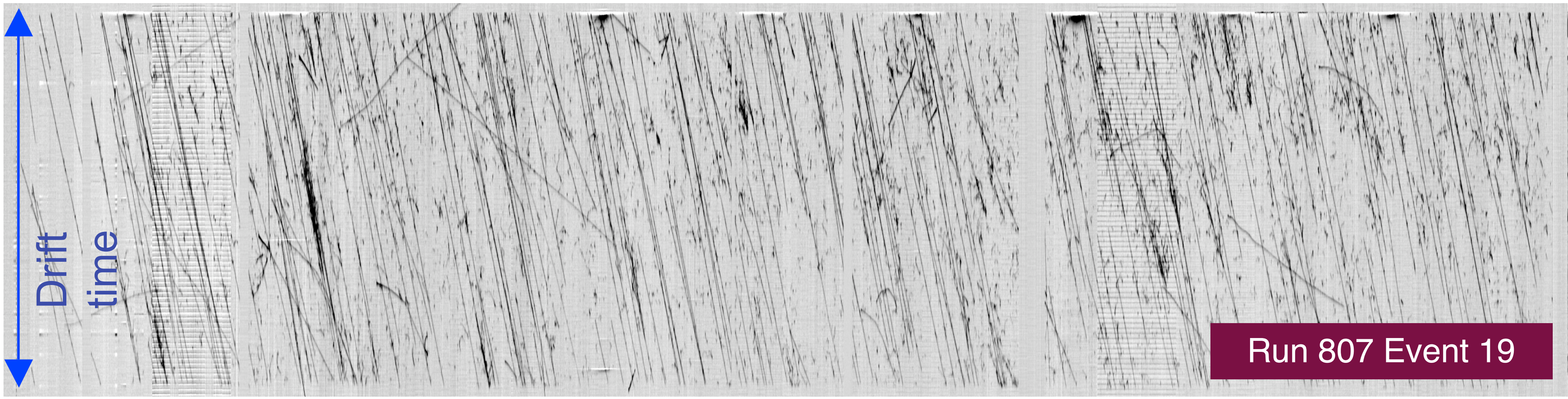
with bremsstrahlung

Energy resolution:

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

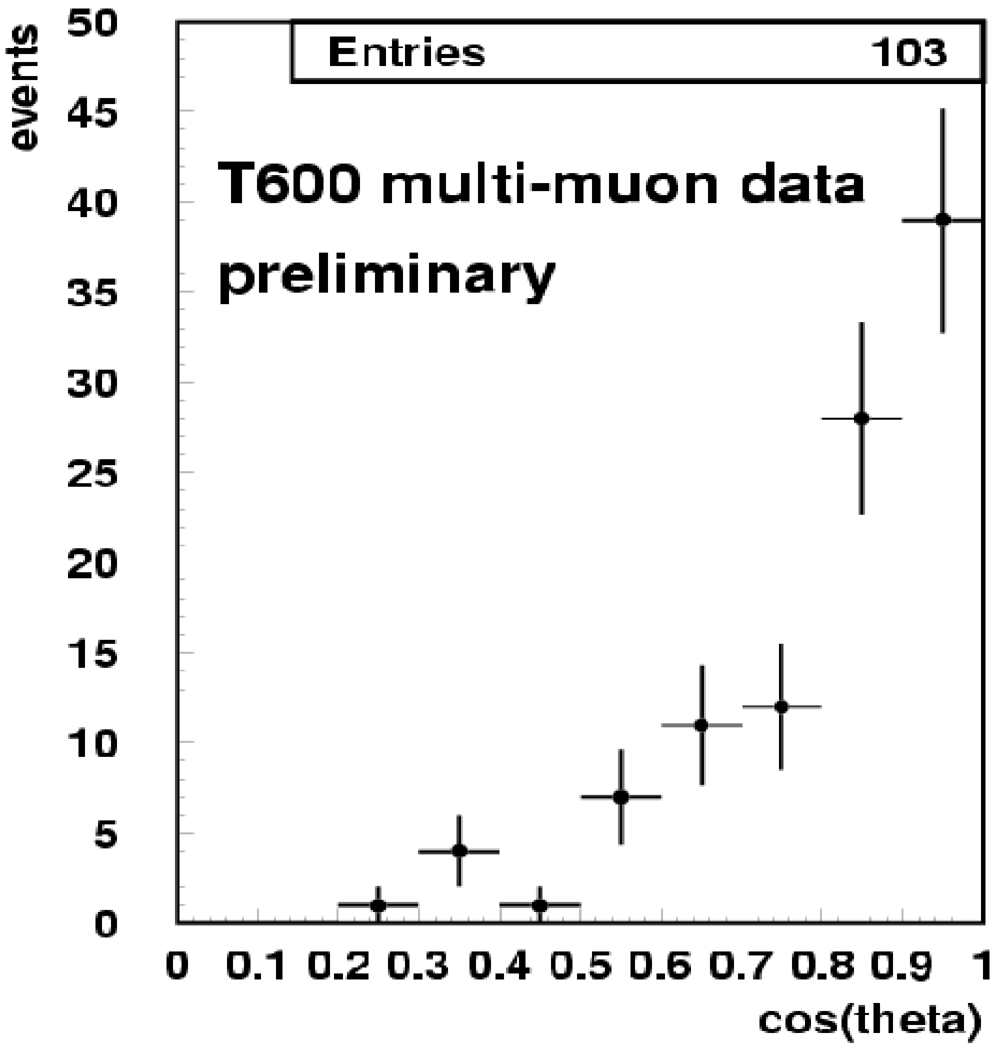
High multiplicity events





Muon bundle analysis

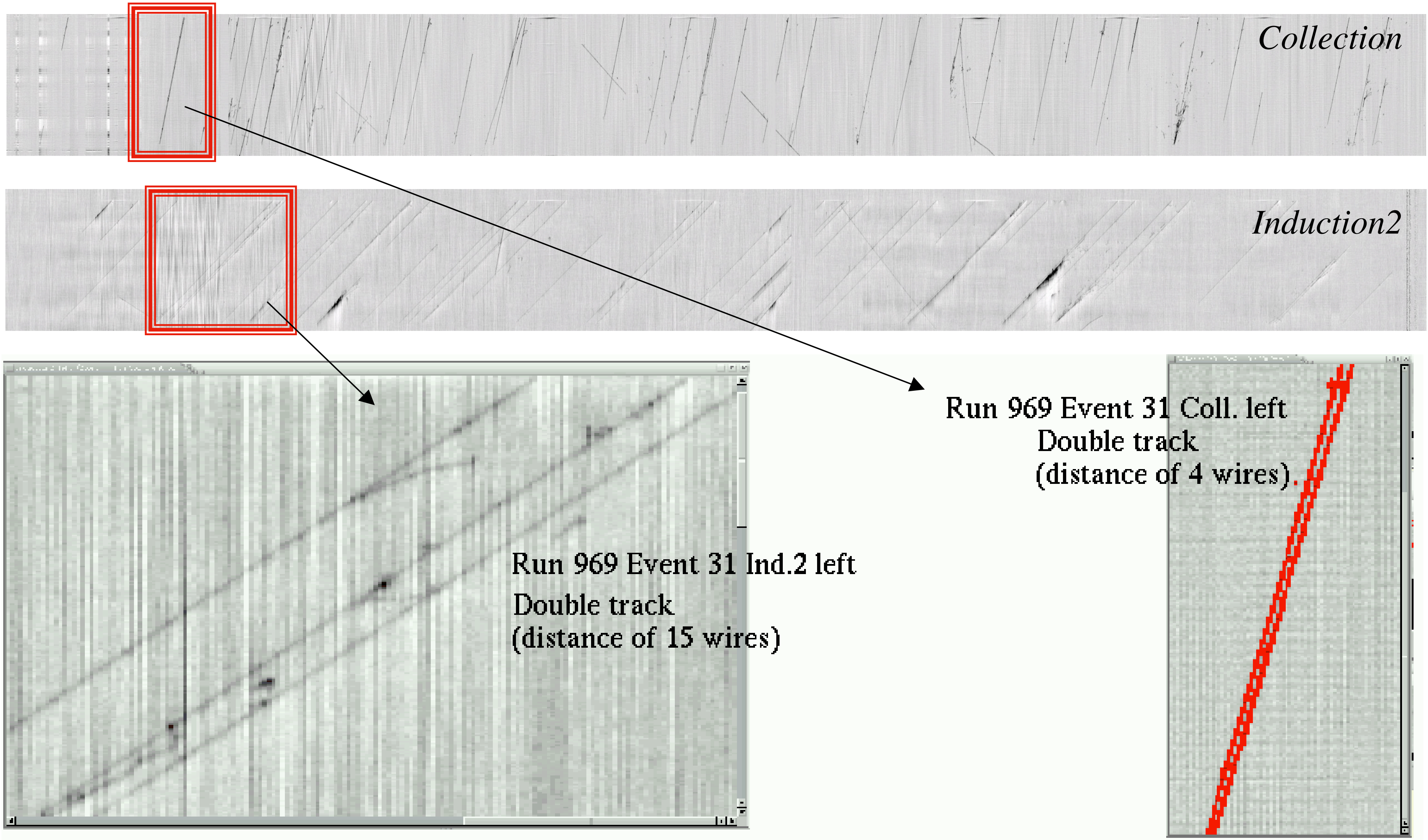
Zenith angle distribution of the muon bundle for the selected (103) multi–muon events



Assuming parallel muons in the bundle

goes like $\cos(\theta)^n$, n ~ 3 to 4

Run 969 Event 31 : double track

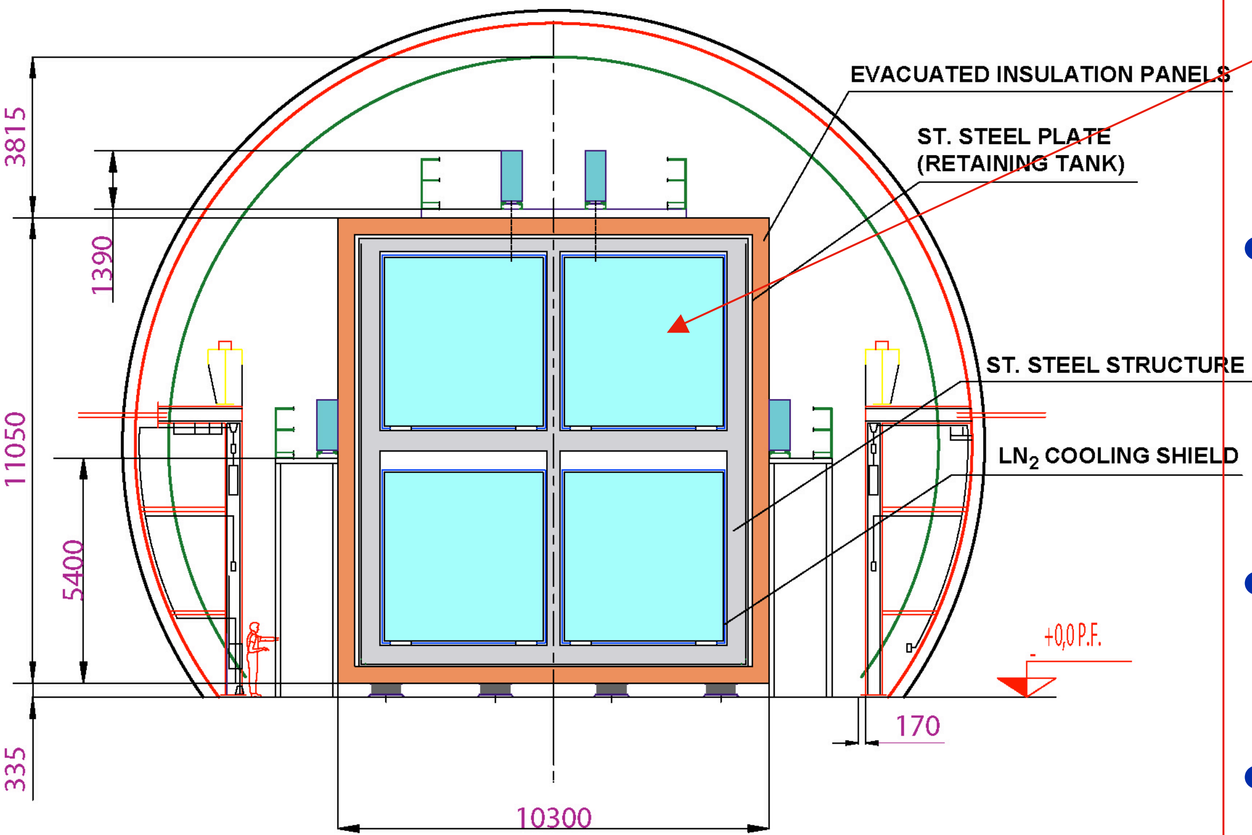


Extrapolation to underground kton liquid Argon TPCs: general considerations

- The ICARUS collaboration has proposed an underground modular T3000 detector for LNGS based on the cloning of the T600
  - ➥ T3000 = T600 + T1200 + T1200
  - ➥ **Design fully proven by T600 technical run**
  - ➥ **Ready to be built by industry**
- The cost can be precisely estimated on the basis of the T600 prototype already built and is supported by actual offers
  - ➥ ≈20M$ per kton
- **A 10 kton modular liquid Argon detector could be ordered *TODAY* and would cost ≈200 M$ (conservative)**
  - ➥ **This would be OK for superbeams (e.g. offaxis)**
- Following a successful scaling up strategy, one could optimize costs and envision building bigger supermodules by increasing the dimensions of the current T1200 by a factor two in each directions:

$$\left(2^3\right) \times T1200 \approx T10K$$

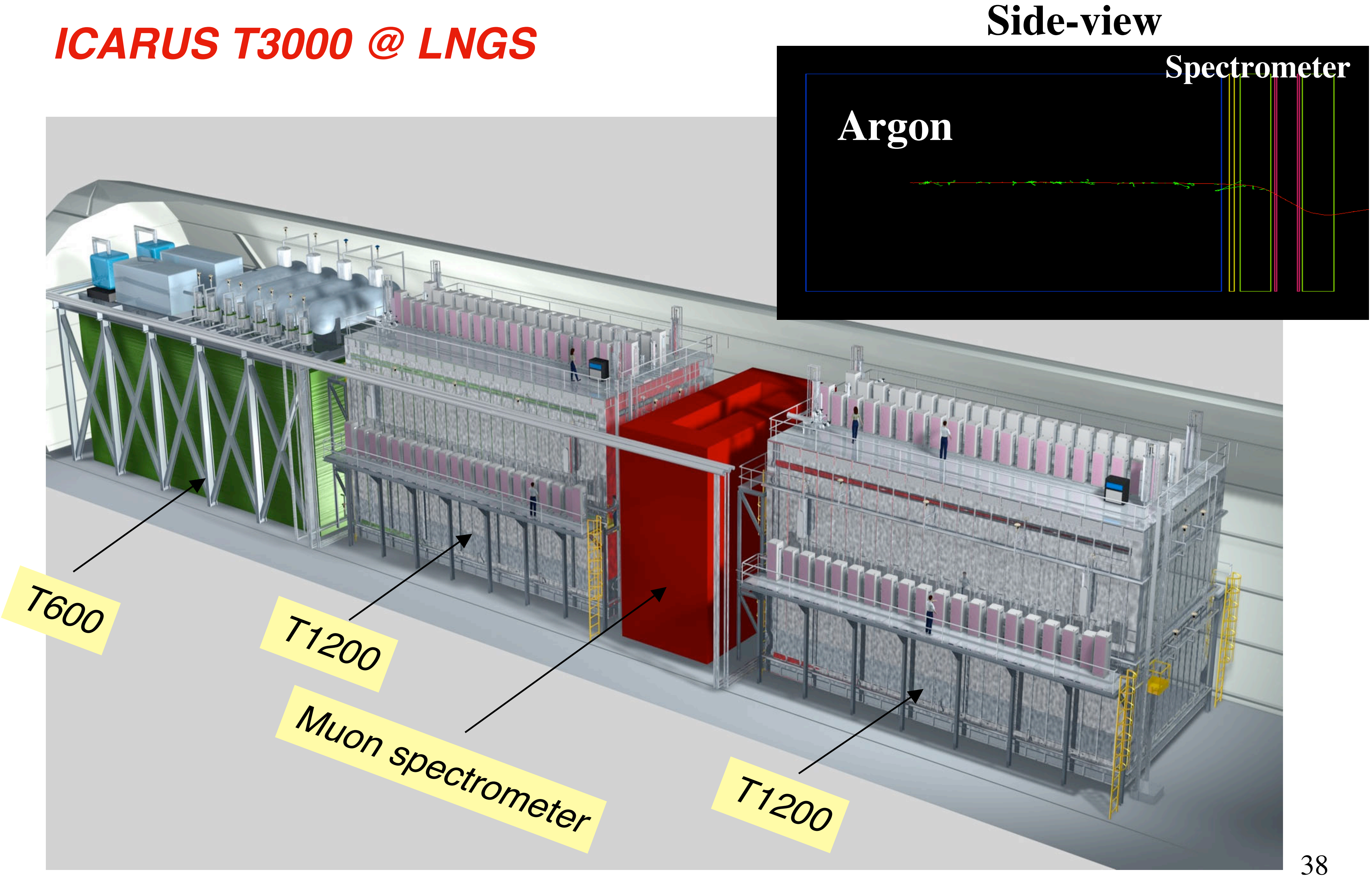
The ICARUS T1200 Detector



- Based on cloning the present T600 containers
  - ➥ **A COST-EFFECTIVE SOLUTION GIVEN TUNNEL ACCESS CONDITIONS**
- Preassembled modules outside tunnel are arranged in supermodules of about 1200 ton each (4 containers)
  - ➥ **TIME EFFECTIVE SOLUTION (PARALLELIZABLE)**
- Drift doubled 1.5 m → 3 m
  - ➥ **SENSIBLE SOLUTION GIVEN PAST EXPERIENCE**
- LAr target to be complemented by a muon spectrometer (for CNGS beam operation)
- First supermodule already funded
- Goal
  - ➥ **T3000 READY BY 2006**

Detailed engineering project was produced by Air Liquide (June 2003) T1200 cryostat ready for tendering

ICARUS T3000 @ LNGS



Safety, safety, safety

- Safety is a critical issue that needs to be handled by real professional experts (typically not a job for physicists)
  - ➥ The problem is to understand the risks of something that has never been done before
  - ➥ It takes time to learn, understand and predict
- Mostly due to the necessity to run underground (not so difficult on surface!)
  - ➥ Flammable gases, (leaking) toxic materials are all absent in liquid argon TPCs
  - ➥ Argon is a non-toxic, inert noble gas
  - ➥ Major problems related to possible spills (earthquake) and cooling (access to bring cold or dissipate heat to outside cavern, shortage of electrical power, etc…)
- It *is* possible, see ICARUS @ LNGS, even though it takes time to design in concordance with safety
  - ➥ Iterations needed, close cooperation between safety experts, risk analysts and engineers
  - ➥ **The "definitive project" of the ICARUS T600 installation at LNGS has been approved in March, 2003**
  - ➥ **The results of the safety risk analysis strongly support the possibility to guarantee the safety inside the underground Labs with the T600 plant installed in Hall B**

INFN Istituto Nazionale di Fisica Nucleare
Laboratorio Nazionale del Gran Sasso
Il Direttore

17 MAR 2003

Prof. Carlo Rubbia
Spokesperson dellEsperimento ICARUS

Prof. Elio Calligarich
Technical coordinator dell'Esperimento ICRUS

LORO SEDI

Oggetto. Analisi del rischio ICARUS 600 T

Cari Colleghi,

facendo seguito alla riunione del 5 marzo scorso, avente per oggetto la ve[…] da parte dei LNGS della documentazione relativa alla Safety Risk Analy[…] esperimento ICARUS T600 – predisposta dalla Società NIER Ingegneria e trasm[…] in data 04/02/2003 prot. n. 0402, è emerso – come già discusso nel corso […] riunione – quanto segue:

- i Laboratori prendono atto con soddisfazione che i risultati dell'analisi di rischio sinora eseguita (Revisione 0) indicano concretamente la possibilità di garantire la sicurezza all'interno dei laboratori sotterranei per ICARUS T600.

Appare peraltro necessario apportare al progetto definitivo in corso di stesura alcune integrazioni – oltre ovviamente a quelle proposte nel documento citato – legate essenzialmente ad una ulteriore verifica degli scenari di incidente ipotizzati, riscontrati nel corso della riunione e come meglio specificati nel seguito.

i Laboratori prendono atto con soddisfazione che i risultati dell'analisi di rischio sinora eseguita (Revisione 0) indicano concretamente la possibilità di garantire la sicurezza all'interno dei laboratori sotterranei per ICARUS T600.

Letter from LNGS director:
March 17, 2003

The laboratories take act with satisfaction that the results of the risk analysis (version 0) concretely indicate the possibility to guarantee the safety inside the underground laboratories for the ICARUS T600.

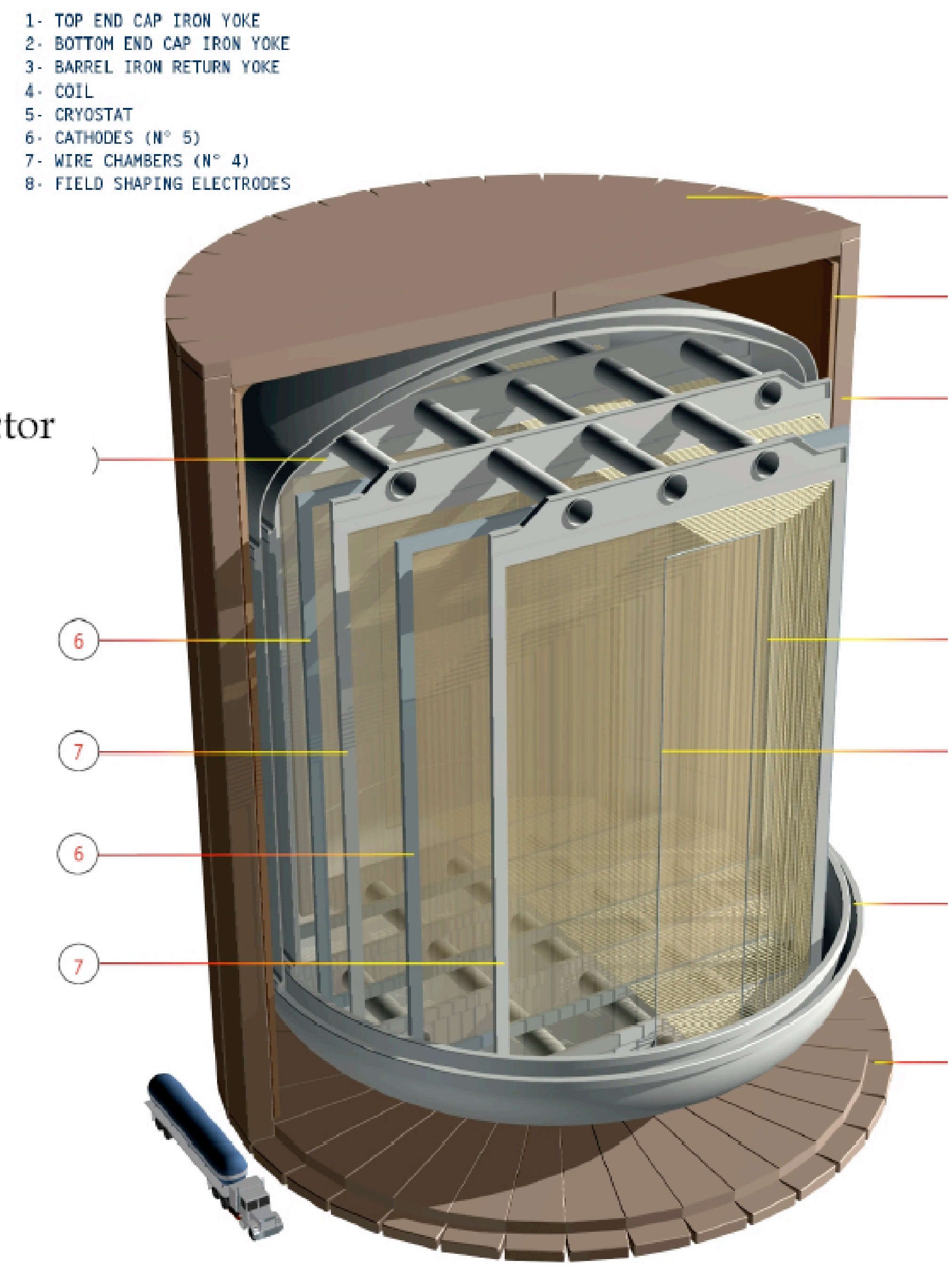
F. SERGIAMPIETRI, NUFACT 01 (TSUKUBA)

LANNDD

Liquid Argon Neutrino and Nucleon Decay Detector
in Magnetic Field

70 kton LAr

N° OF WIRE CHAMBERS	4
WIRE CHAMBER CH1, CH4	W=26.8 m ...H=40 m
CH2, CH3	W=39.2 m ...H=40 m
READOUT PLANES / CHAMBER [2 at 0°, 2 at 90°]	4
SCREEN-GRID PLANES / CHAMBER	3
TOTAL N° OF WIRES (CHANNELS)	194648
ACTIVE VOLUME	48000 m^3
ACTIVE MASS	67 kT
N° OF CATHODE PLANES	5
MAXIMUM DRIFT	5 m
MAXIMUM HIGH VOLTAGE	250 kV
REQUIRED ELECTRON LIFETIME (PURITY)	15 ÷ 20 ms



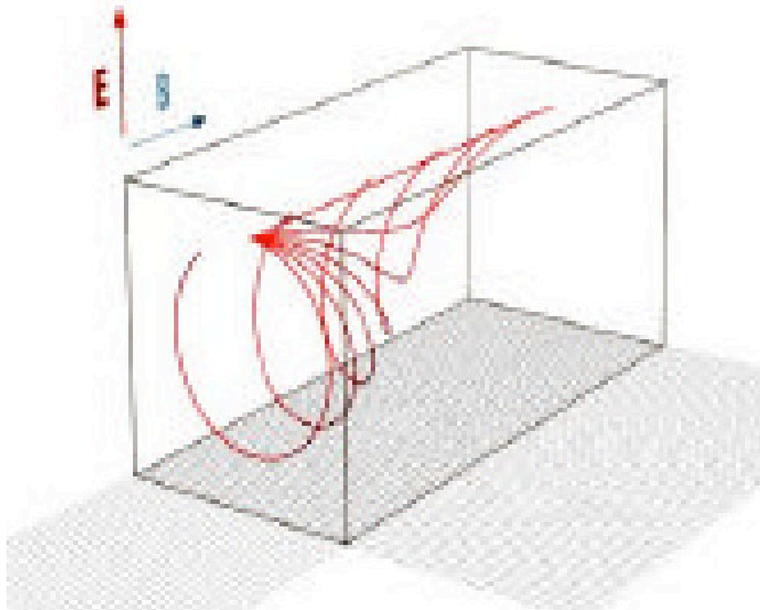
Extrapolation to underground kton liquid Argon TPCs: modular vs single volume

- Single volume appears to be the most attractive solution
  - ➥ A strong R&D program is required to extrapolate the liquid argon TPC to such scale (in a single step?)
- On the other hand, there are counter-indications to a non-modular design (the facts of life!)
  - ➥ Underground installation (access)
  - ➥ Operation
  - ➥ Safety requirements
- Location:
  - ➥ A mine seems to be most adequate solution
    - ☛ USA: WIPP @ Carlsbad (Cline, Learned, Mcdonald, Sergiampetri)
    - ☛ Europe: Pyhäsalmi (Finland)
    - ☛ …

Extrapolation to underground kton liquid Argon TPCs: necessary R&D

- Long drift distances
  - ➥ ICARUS achieved 1.5m and adopts 3m for new T1200 modules
  - ➥ Requires drift electron lifetimes τ in excess of ms ($v_D \approx 1.5 mm/\mu s$ @ E=500 V/cm)
  - ➥ Requires high purity (ICARUS R&D: relation between electron lifetime and purity vs E-field well understood, e.g. 1 ms ⇔ 0.3 ppb(O_2) @ 500 V/cm) and high voltage
  - ➥ **R&D NEEDED TO PROVE >3M DRIFT POSSIBLE**
- Argon purification in large quantities
  - ➥ ICARUS experience: to *maintain* high purity requires liquid recirculation (i.e. continuous purification). This has a cooling cost (pump moving liquid)
  - ➥ Currently based on Oxysorb+Hydrosorb cartridges (typ. 1000 liter/h/cartridge)
  - ➥ **FURTHER R&D NEEDED FOR LOW IMPEDANCE, LOW COOLING CONSUMPTION, FAST RECIRCULATION**
- Very high voltage
  - ➥ ICARUS experience: reached 150 KV, design 300 KV for new T1200
  - ➥ **FURTHER R&D NEEDED FOR HIGHER VOLTAGES**
- Electronic noise
  - ➥ Driven by preamplifier noise with capacitance
  - ➥ **R&D NEEDED TO PROVE LONG WIRES ARE READABLE WITH GOOD S/N**
  - ➥ Environmental noise on big detectors is more difficult (ground loops, …)
- Hydrostatic pressure
  - ➥ **R&D NEEDED TO UNDERSTAND LIQUID ARGON AND DRIFT PROPERTIES AT HIGH P**

R&D for liquid argon in magnetic field



- Opens new possibility
  - ➥ Charge discrimination
  - ➥ Momentum measurement of particles escaping detector (e.g. muons)
  - ➥ MS dominated (Δp/p≈4% at L=12m, B=1T)
- Orientation of the field
  - ➥ Bending in the direction of the drift where resolution is the best
    - ☛ Achieved point resolution in T600 : 400 μm
  - ➥ B-field perpendicular to E-field
  - ➥ Lorentz angle small in liquids α≈30mrad @ E=500 V/cm, B=0.5 T
- Required magnetic field strength for charge discrimination (*x=path in LAr*)

$$b \approx \frac{l^2}{2R} = \frac{0.3B[T](x[m])^2}{2p[GeV]}$$

$$MS \approx \frac{0.02(x[m])^{3/2}}{p[GeV]}$$

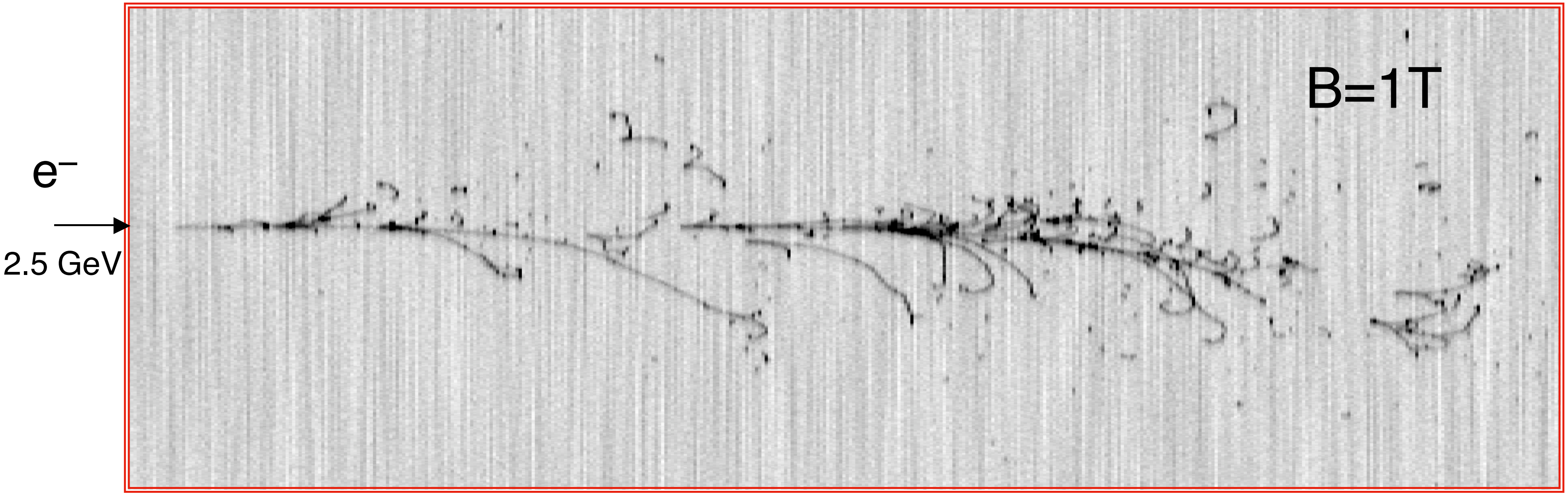
3 sigmas discrimination:

$$b^+ - b^- = 2b > 3MS \quad \Rightarrow \quad B \geq \frac{0.2[T]}{\sqrt{x[m]}}$$

Discrimination of the electron charge

hep-ph/0106088

$$B \geq \frac{0.2[T]}{\sqrt{x[m]}} \Rightarrow \begin{array}{l} x=1X_0 \Rightarrow B>0,5T \\ x=2X_0 \Rightarrow B>0,4T \\ x=3X_0 \Rightarrow B>0,3T \end{array}$$



MC STUDY: CHARGE CONFUSION<10^{-3} @ B=1 T, E<5 GeV

a) Primary electron momentum … curvature radius obtained by the calorimetric energy measurement

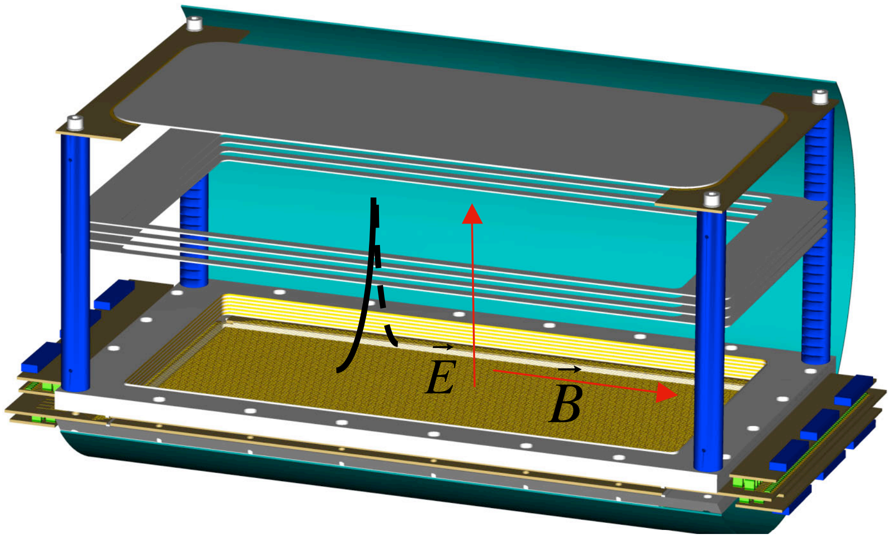
b) Soft bremsstrahlung γ 's … the primary electron remembers its original direction → long effective x for bending

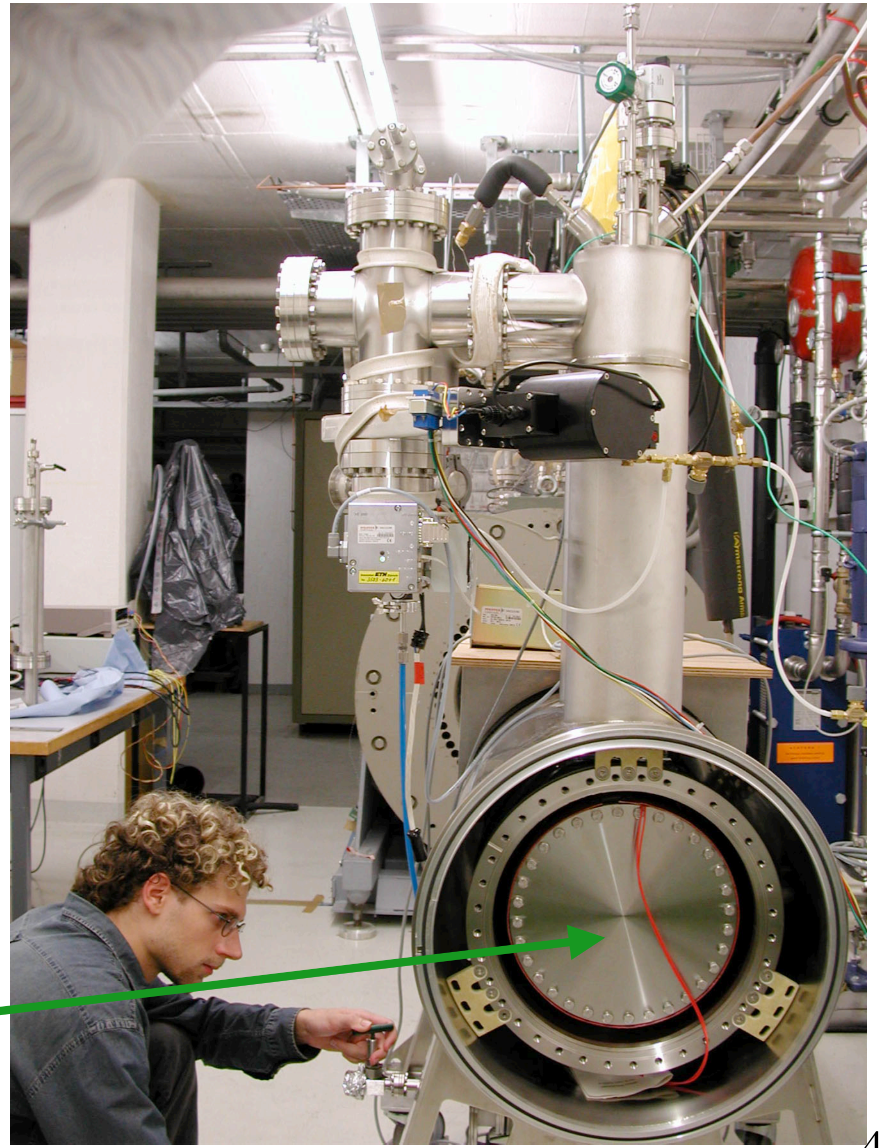
c) Hard initial bremsstrahlung γ 's … the energy is reduced → low P → small curvature radius

Ongoing R&D: Test of liquid Argon imaging in B-field

- Small chamber in SINDRUM-I recycled magnet up to B=0.5T (230KW) given by PSI, Villigen
- Test program:
  - ➥ Check basic imaging in B-field
  - ➥ Measure traversing and stopping muons bending
  - ➥ Charge discrimination
  - ➥ Check Lorentz angle ($\alpha \approx 30$mrad @ E=500 V/cm, B=0.5T)
- Results expected end of 2003

Width 300mm, height 150mm, drift length 150mm

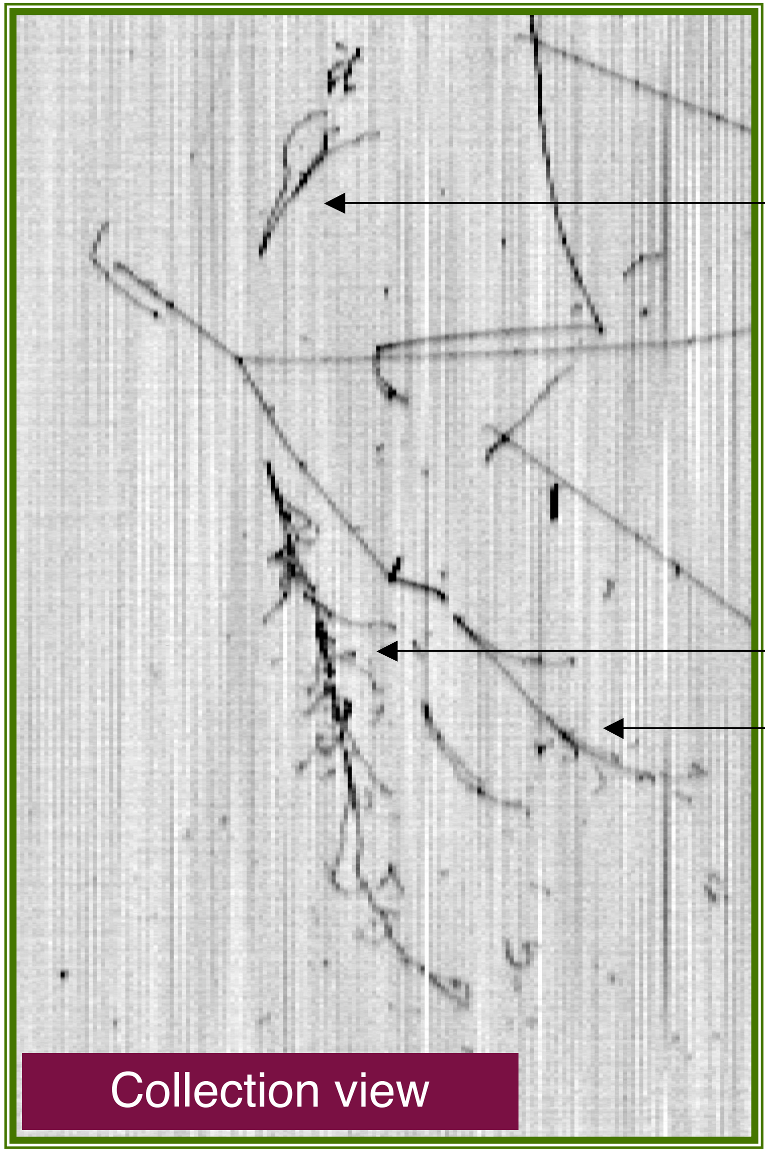




Pi zero candidate (preliminary)

- Reconstruction of γ-showers

T600



Run 975, Event 151

158 MeV

752 MeV

140 MeV

$\theta = 141^{o}$

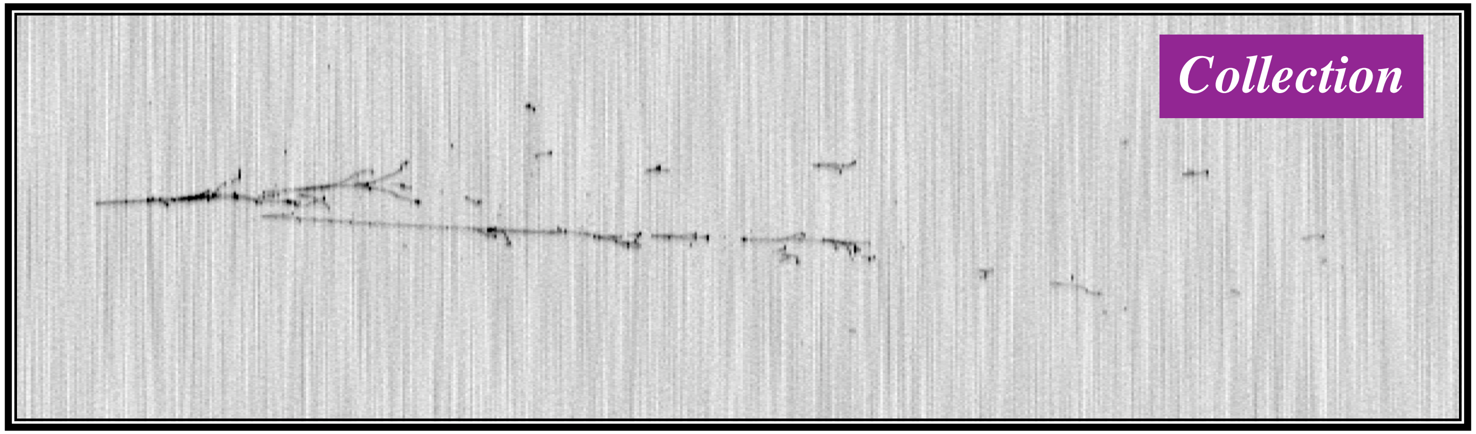
$M_{inv} = 650$ MeV

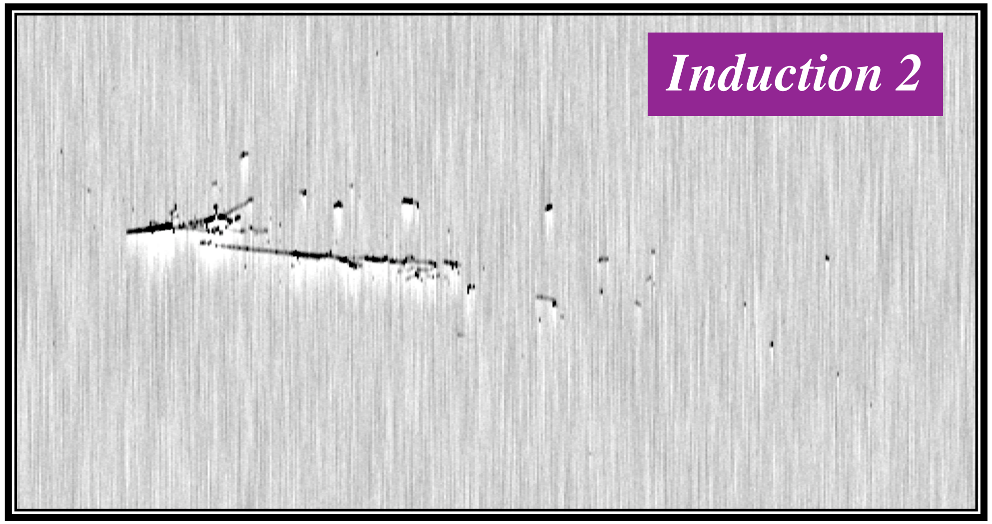
$\theta = 25^{o}$

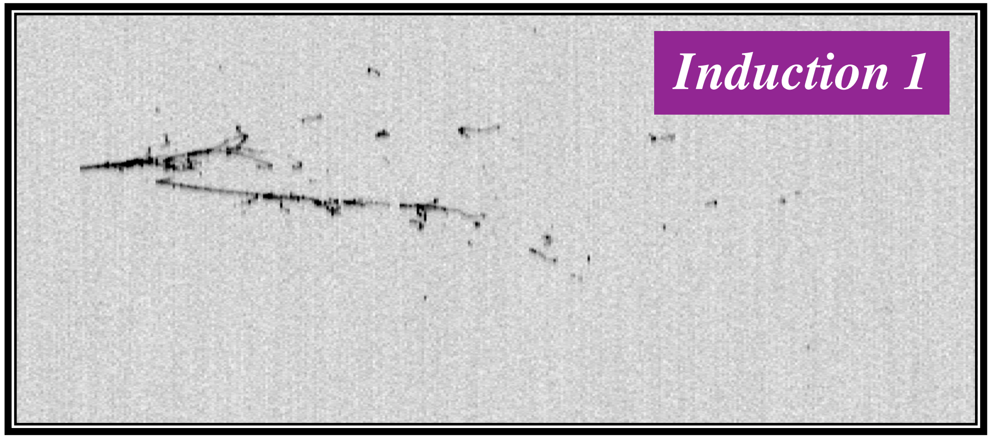
$M_{inv} = 140$ MeV

(error evalulation in progress)

A fully simulated and digitized π^0 event



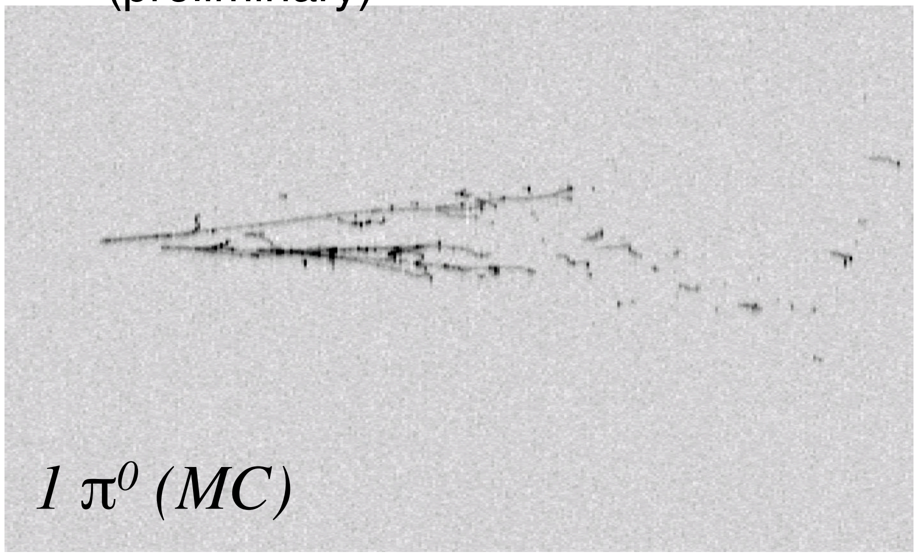


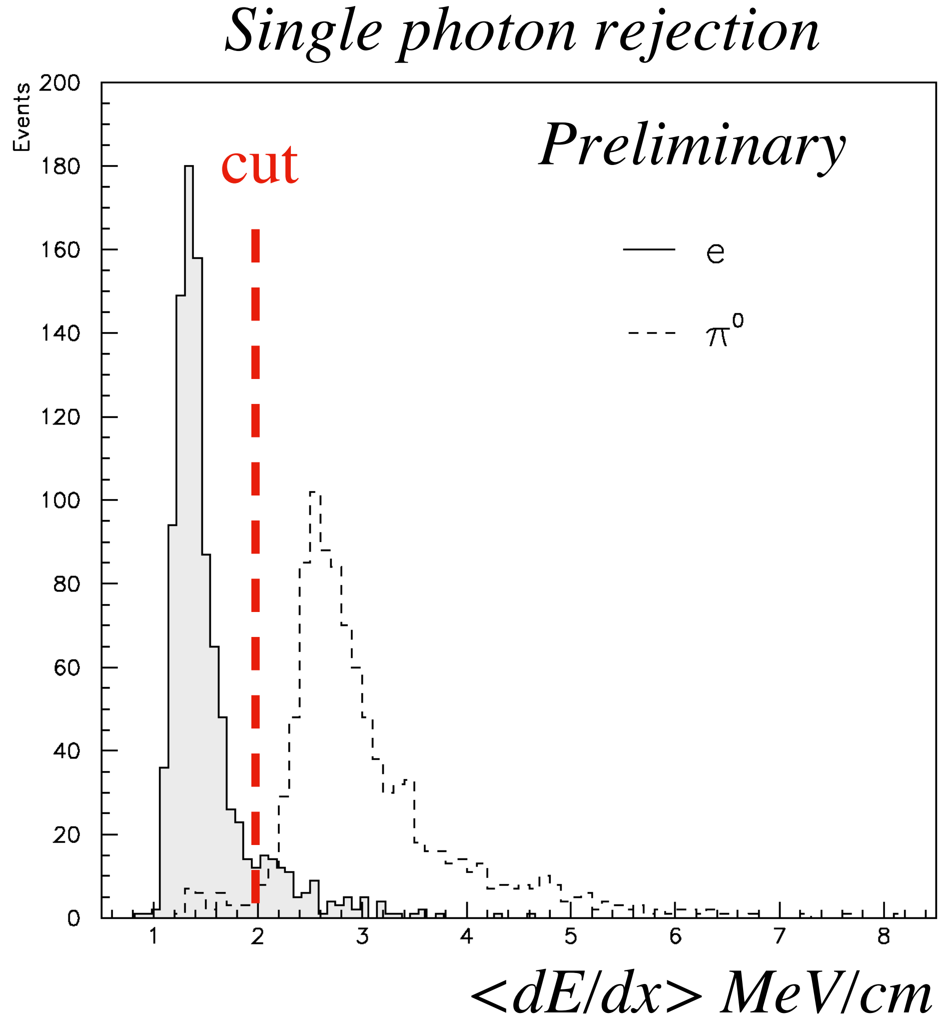


full simulation,digitization, and noise inclusion

Rejection π_0 based on imaging

- Based on full simulation, digitization, noise and automatic reconstruction of events
- Algorithm: cut for 90% eff. electrons
  1. Events with vertex: conversion within 1cm (3 wires) of vertex $R_1 \approx 19$
  2. Single/double mip $R_2 \approx 30$ (preliminary)

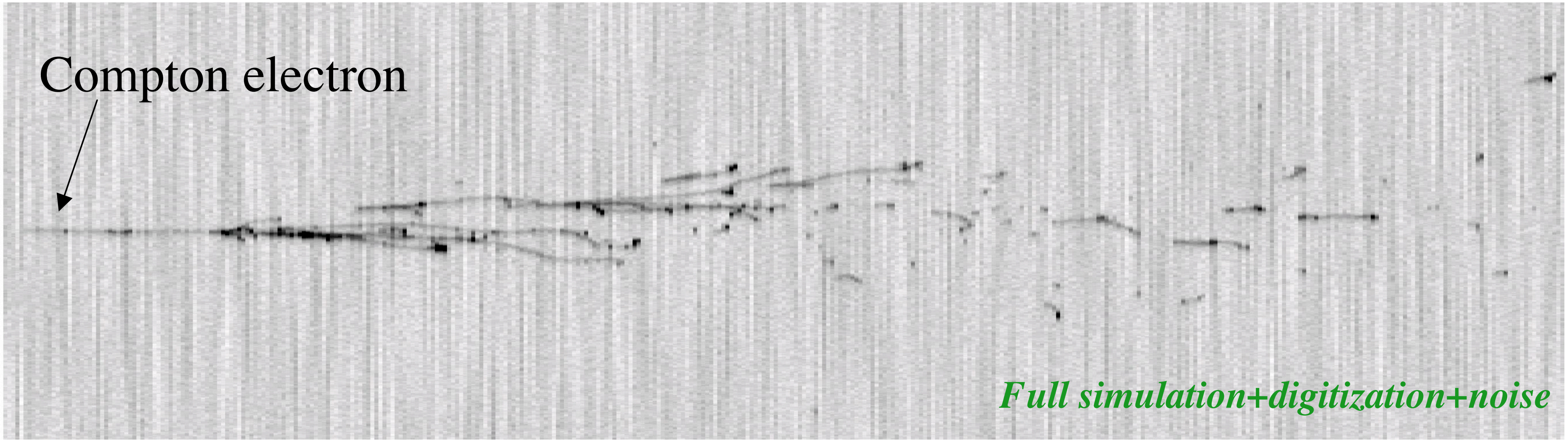




IMAGING PROVIDES $\approx 2\times10^{-3}$ EFFICIENCY FOR SINGLE π_0

Rejection π_0 based on imaging

- π^0 surviving dE/dx separation cut (total 31 events out of 1000 1GeV π^0)
  - ➥ 21 events: Compton scattering
  - ➥ 5 events: Asymmetric decays (partners have less than 4 MeV)
  - ➥ 2 events: positron annihilation immediately
  - ➥ 1 event: positron make immediate Bremsstrahlung taking >90% of energy
- π^0 rejection improves with energy: 5% @ 0.25 GeV, 4% @ 0.5 GeV, 3% @ 1 GeV, 2% @ 2 GeV



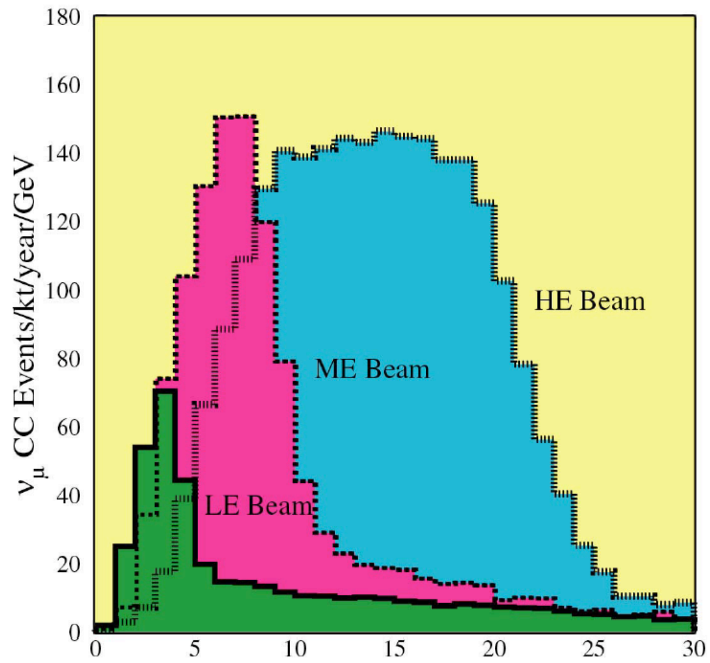
- Further rejection by kinematical cuts (depends on actual beam energy profile)
  - ➥ E.g. $\nu n \rightarrow \nu \pi^0 n$: precise mass reconstruction

FINALLY: NC EVENT REJECTION: F(NC) $<\approx 1\times10^{-3}$

Near future, near beams

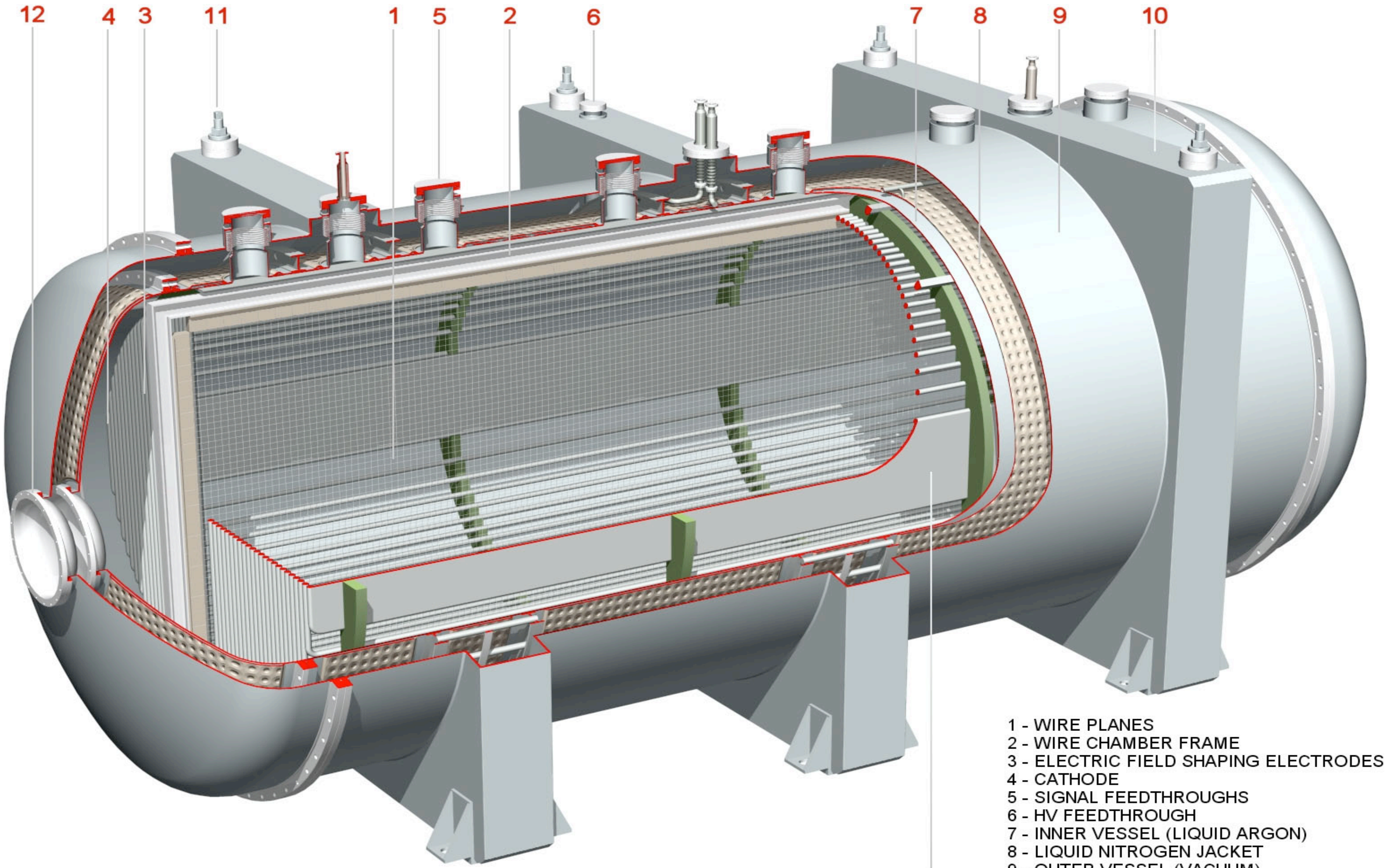
- Low/medium energy (<10 GeV):
  - DIS+resonances modeling
  - QE modeling
  - Binding, Fermi-motion, Pauli-exclusion, NN-correlations, PDF modifications, other nuclear effects, form factors
- High energy (>10 GeV)
  - pQCD, non-pQCD (PDFs), sum rules
  - fundamental constants: α_s , $\sin^2\theta_W$ **(NuTeV anomaly?)**
  - nuclear structure functions (shadowing, Fermi, EMC)
  - Low Q^2 (higher twist corr.)

Beam	Intensity p.o.t / y	Statistics ν_μ CC / t / y
K2K	3.5×10^{19}	4.5×10^3
NUMI Low E	3.8×10^{20}	2.5×10^5
NUMI Medium E	3.8×10^{20}	6.8×10^5
NUMI High E	3.8×10^{20}	1.5×10^6
MiniBoone	5.0×10^{20}	2.6×10^3



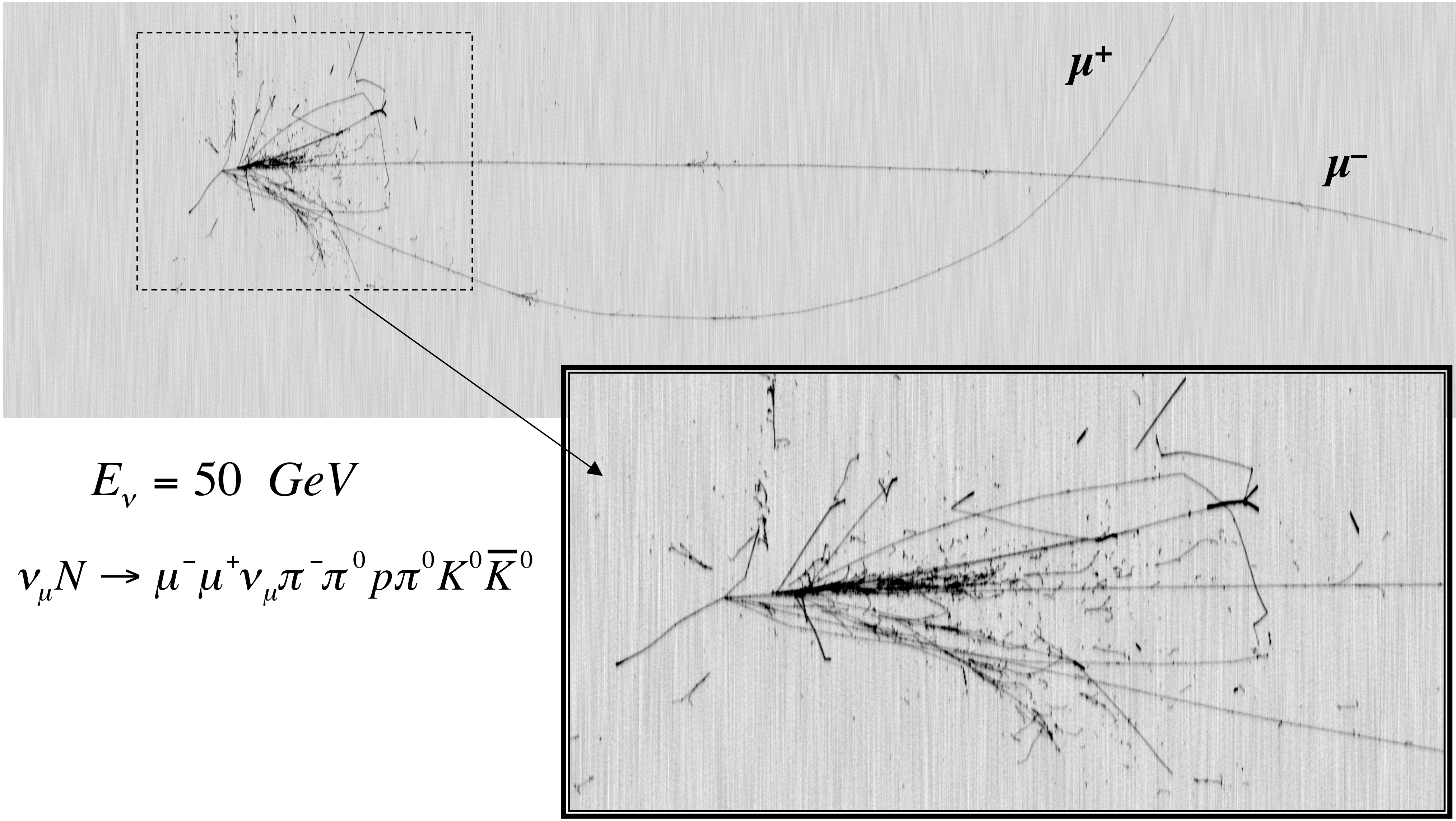
PHYSICS POTENTIALS SHOULD BE STUDIED IN DETAIL

40 ton Liquid Argon detector



See Sergiampetri's talk

Simulated dimuon (charm) event, B=0.2 T



$$E_\nu = 50\ GeV$$

$$\nu_\mu N \rightarrow \mu^- \mu^+ \nu_\mu \pi^- \pi^0 p \pi^0 K^0 \overline{K}^0$$

Conclusions

- **The liquid argon TPC offers unprecedented potentialities in particle physics**
  - ➥ ICARUS has shown that it is **a reliable experimental technique**
- **Recent strong regain in interest in the technology**
  - ➥ What is virtual? What is real?
  - ➥ ICARUS Collaboration has operated at surface a large mass liquid Argon TPC (600 ton module) proving that the **scaling from prototypes to kton scale detectors is possible**.
- **A 10 kton modular detector could be readily envisaged**
- **Strong R&D program needed to extrapolate technology to 100 kton detectors**
  - ➥ Internal issues: Purification, long drift paths, magnetic field,…
  - ➥ External issues: safety, modularity (installation, access, operation, …)
- **Mid-sized (10-100 ton) detector at near site is an important experiment**
  - ➥ Neutrino physics potential of mid-sized detectors are enormous