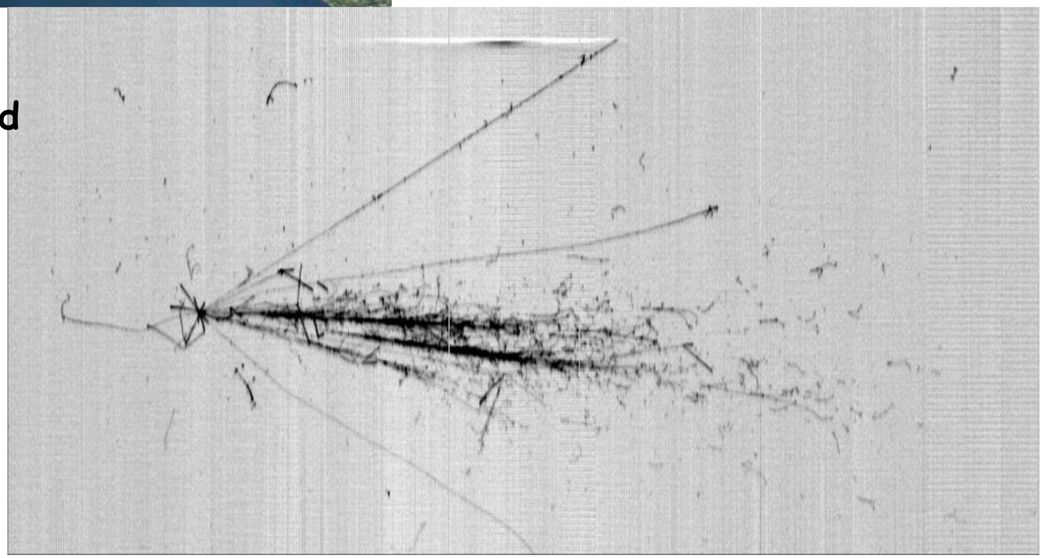
# ICARUS report to the June 2012 SPS-C

Jan Kisiel
Inst. of Physics, Univ. Silesia, Katowice, Poland
For the ICARUS Collaboration

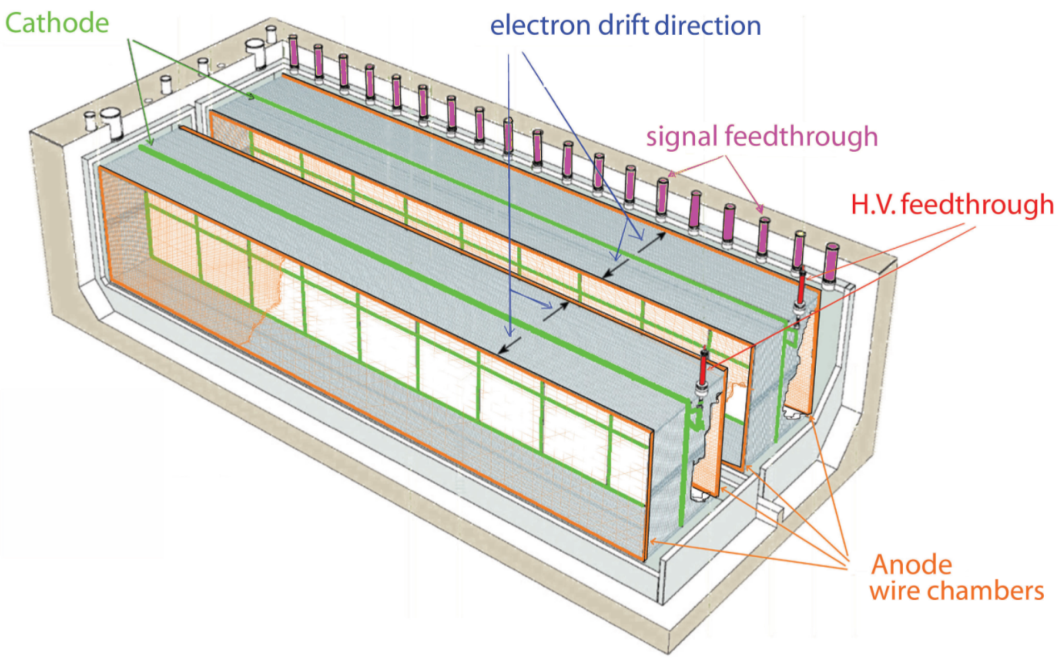



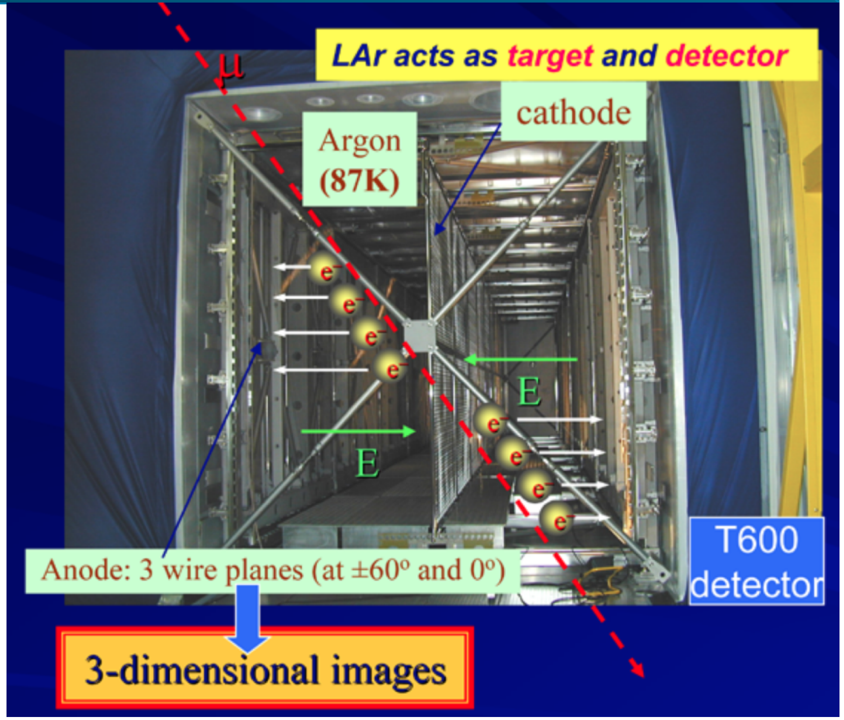
# The ICARUS Collaboration

M. Antonello[a], P. Aprili[a], B. Baibussinov[b], M. Baldo Ceolin[b,†], P. Benetti[c], E. Calligarich[c], N. Canci[a], S. Centro[b], A. Cesana[f], K. Cieslik[g], D. B. Cline[h], A.G. Cocco[d], A. Dabrowska[g], D. Dequal[b], A. Dermenev[i], R. Dolfini[c], C. Farnese[b], A. Fava[b], A. Ferrari[j], G. Fiorillo[d], D. Gibin[b], A. Gigli Berzolari[c,†], S. Gninenko[i], A. Guglielmi[b], M. Haranczyk[g], J. Holeczek[l], A. Ivashkin[i], J. Kisiel[l], I. Kochanek[l], J. Lagoda[m], S. Mania[l], G. Mannocchi[n], A. Menegolli[c], G. Meng[b], C. Montanari[c], S. Otwinowski[h], L. Periale[n], A. Piazzoli[c], P. Picchi[n], F. Pietropaolo[b], P. Plonski[o], A. Rappoldi[c], G.L. Raselli[c], M. Rossella[c], C. Rubbia[a,j], P. Sala[f], E. Scantamburlo[e], A. Scaramelli[f], E. Segreto[a], F. Sergiampietri[p], D. Stefan[a], R. Sulej[m,a], M. Szarska[g], M. Terrani[f], F. Varanini[b], S. Ventura[b], C. Vignoli[a], H. Wang[h], X. Yang[h], A. Zalewska[g], K. Zaremba[o].

a *Laboratori Nazionali del Gran Sasso dell'INFN, Assergi (AQ), Italy*
b *Dipartimento di Fisica e INFN, Università di Padova, Via Marzolo 8, I-35131 Padova, Italy*
c *Dipartimento di Fisica Nucleare e Teorica e INFN, Università di Pavia, Via Bassi 6, I-27100 Pavia, Italy*
d *Dipartimento di Scienze Fisiche, INFN e Università Federico II, Napoli, Italy*
e *Dipartimento di Fisica, Università di L'Aquila, via Vetoio Località Coppito, I-67100 L'Aquila, Italy*
f *INFN, Sezione di Milano e Politecnico, Via Celoria 16, I-20133 Milano, Italy*
g *Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Science, Krakow, Poland*
h *Department of Physics and Astronomy, University of California, Los Angeles, USA*
i *INR RAS, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia*
j *CERN, CH-1211 Geneve 23, Switzerland*
k *Institute of Theoretical Physics, Wroclaw University, Wroclaw, Poland*
l *Institute of Physics, University of Silesia, 4 Uniwersytecka st., 40-007 Katowice, Poland*
m *National Centre for Nuclear Research, A. Soltana 7, 05-400 Otwock/Swierk, Poland*
n *Laboratori Nazionali di Frascati (INFN), Via Fermi 40, I-00044 Frascati, Italy*
o *Institute of Radioelectronics, Warsaw University of Technology, Nowowiejska, 00665 Warsaw, Poland*
p *INFN, Sezione di Pisa. Largo B. Pontecorvo, 3, I-56127 Pisa, Italy*

# The ICARUS T600 detector



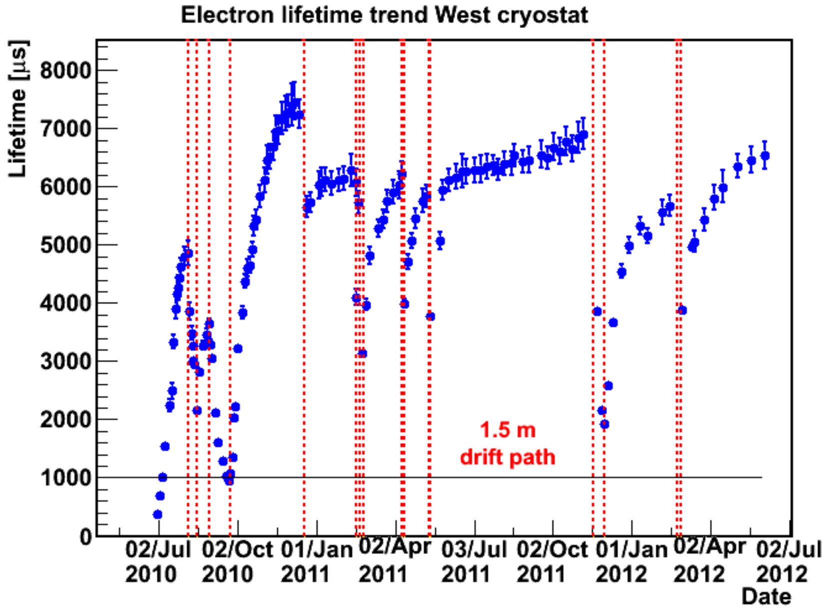



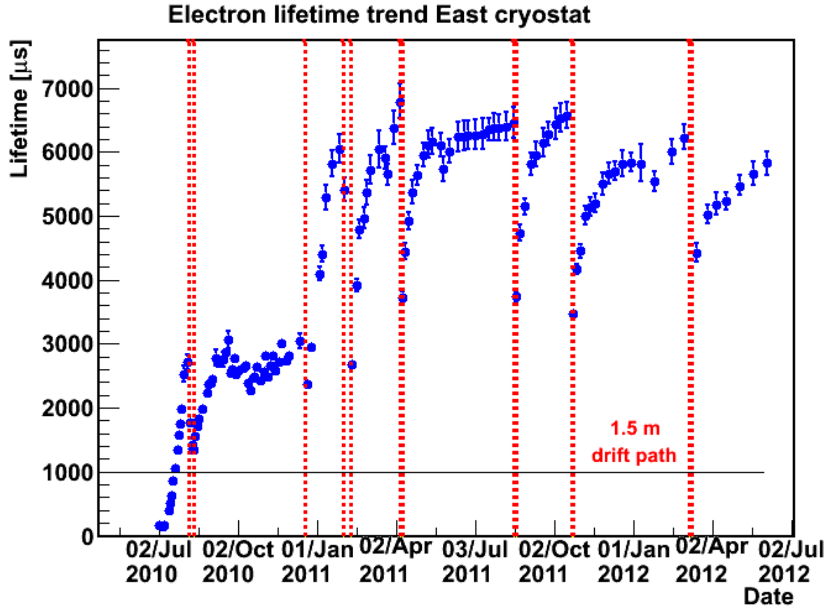

- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 $m^3$ each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV  E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0, ±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- 20+54 PMTs , 8" Ø, for scintillation light:
  - VUV sensitive (128nm) with wave shifter (TPB)

Key feature: LAr purity from electro-negative molecules ($O_2$, $H_2O$,$CO_2$).
Now: 0.06 ppb ($O_2$ equivalent) -> 5 ms lifetime.

# The ICARUS detector in underground Hall B of LNGS

# LAr purification




LAr continuously filtered, $e^-$ life-time measured by charge attenuation study on cosmic $\mu$ tracks.

$\tau_{ele}$ > 5ms ( ~60 ppt $[O_2]_{eq}$) corresponding to a maximum charge attenuation of 17% at 1.5m

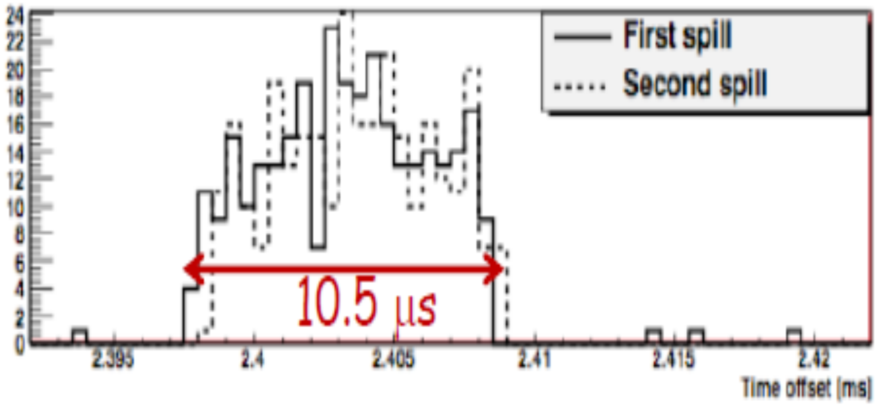
These results allow operation at larger drift distances

**LAr recirculation system upgrade**:

- 11 accidental stops up to now (LAr immersed pumps)
- New pumps with non-immersed motor already ordered – installation 2012. Similar pumps operating since 2010 on the LN2 circulation systems worked without any accidental stop.

# ICARUS T600 trigger system

- CNGS:
  - CNGS "Early Warning" signal sent 80 ms before the SPS p extraction: allows opening a 60 ms wide gate around neutrino arrival time at LNGS.
  - PMT sum signal for each chamber in coincidence with the beam gate.




  - 2.40 ms offset value in agreement with 2.44 ms ν tof (40 μs fiber transit time from external lab to Hall B)
  - Spill duration reproduced (10.5μs), 1 mHz event rate , ≈ 80 events/day

- Cosmic Rays:
  - PMT sum signal: coincidence of two adjacent chambers (50% cathode transparency)
  - Globally 35 mHz trigger rate achieved: ~130 cosmic events/h
- Local trigger based on deposited charge (SuperDaedalus):
  - on-line hit-finding/zero-skipping algorithm implemented in FPGA's, used to improve trigger efficiency at low energy (below 500 MeV)

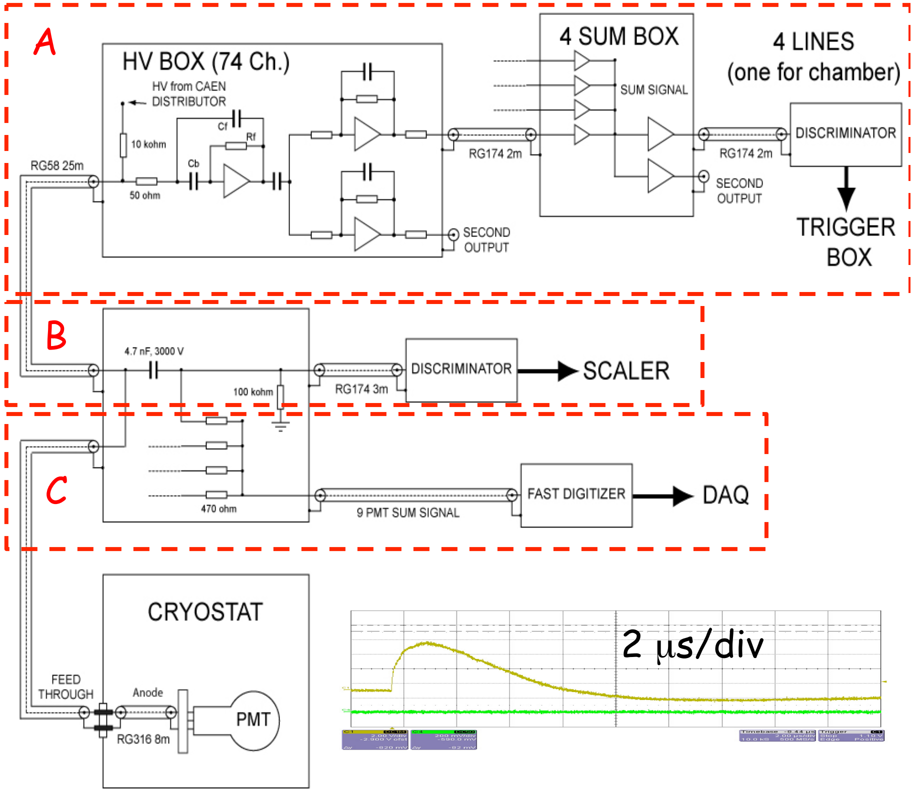
# Light detection system upgrades (1)

- PMTs sum signal used as cosmic trigger during 2011: 28 mHz trigger rate ~ <u>100 cosmic events/hour</u> collected; <u>160 events/hour</u> predicted by Monte Carlo
- Difference due to PMT's HV biasing/signal read-out (impedance termination mismatch). Only prompt photons (30-40% of total) can be exploited.
- The full PMTs read-out system re-designed, tested in 2011 during CNGS beam shutdown and installed after the beam stop

A. PMT signal for trigger: custom low-noise integrating preamplifier for each PMT + external active signal adder → light signal slow component integration (RC = 10 μs), 2x signal amplitude increase (at least). Slow component of the light signal recorded.

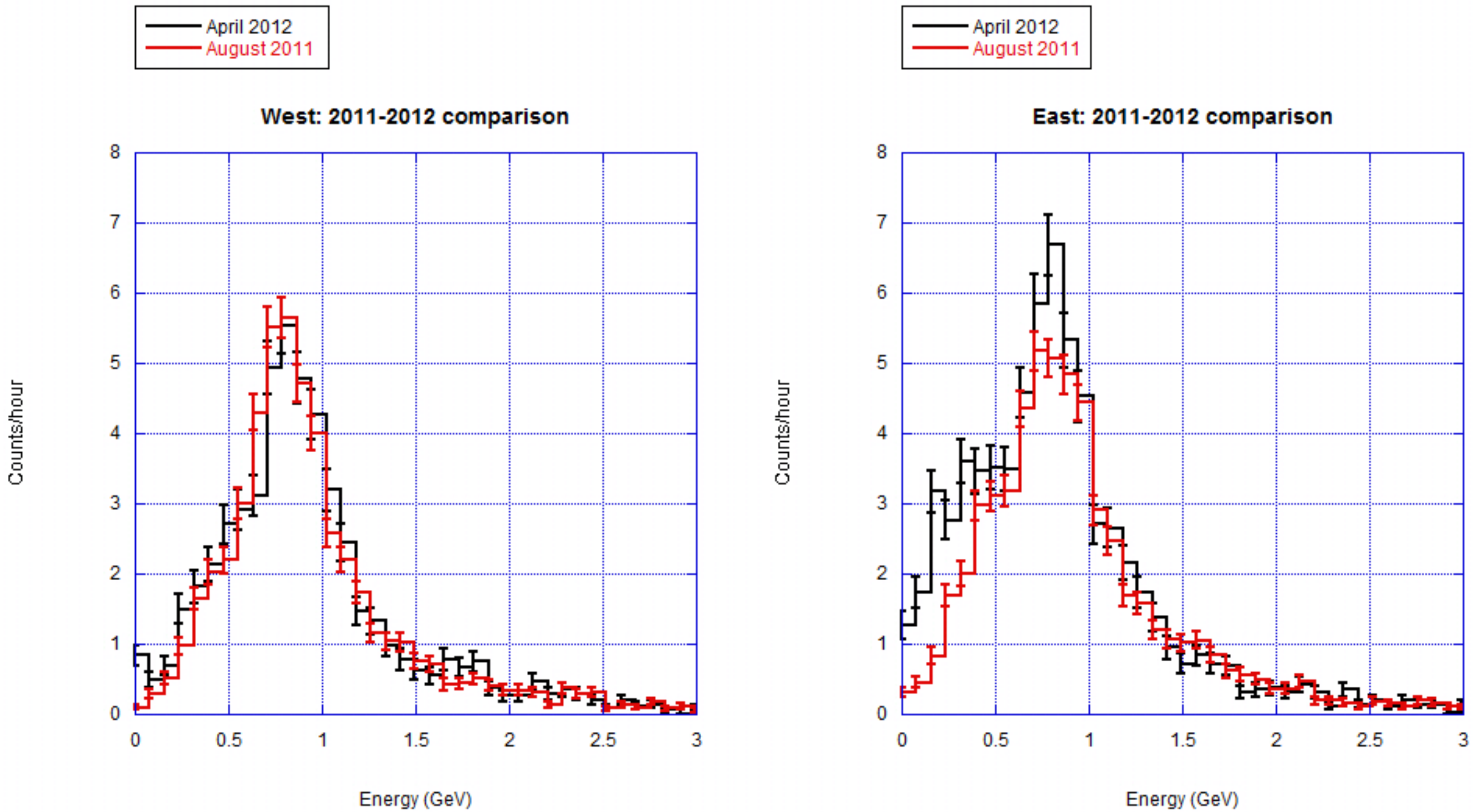
B. Monitoring system of the single PMT rates

C. ν-tof Timing: direct PMT-sum signal recording with higher granularity (x 3)



# Light detection system upgrades (2)

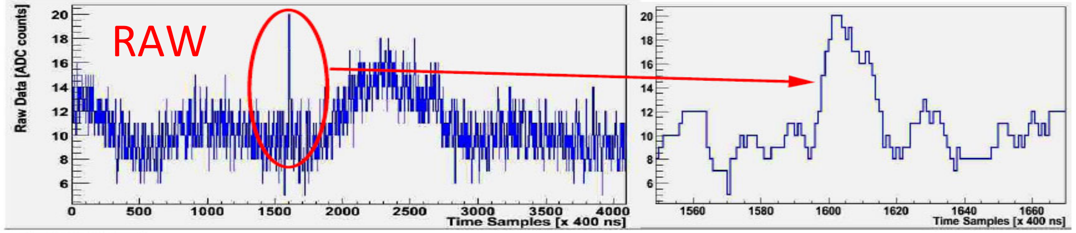
- Tests on PMTs cosmic trigger in December 2011 and March 2012 with threshold of ~ 100 (200) phe West (East) cryostat.
- 35 mHz trigger rate achieved, ~ 130 cosmic events/hour collected.
- Increase of the rates in the East half-module below ~ 1 GeV obtained



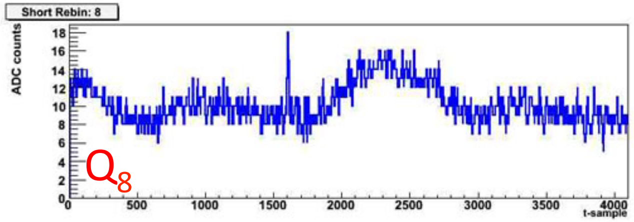
# Triggering on local charge deposition

- New algorithm to detect local Region of Interest (ROI) implemented in a new SuperDaedalus chip (FPGA) to trigger charge deposition on TPC wires.

[B.Baibussinov et al., JInst 5:P12006 (2010)].

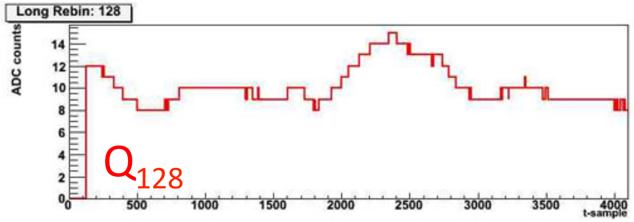



On each channel a "peak signal" is generated when S(t) is over threshold.

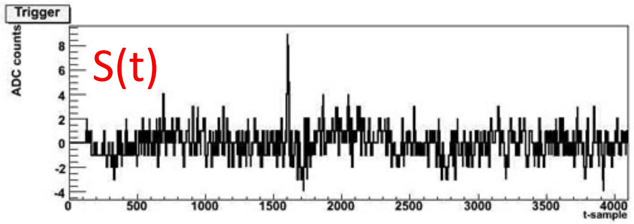



$$Q_8(t) = \frac{1}{8}\sum_{i=0}^{8} Q(t-i)$$

On each 32 wire board a Global-Trigger-Out (GTO) signal is generated if at least one of two 16-channel blocks has reached majority threshold.

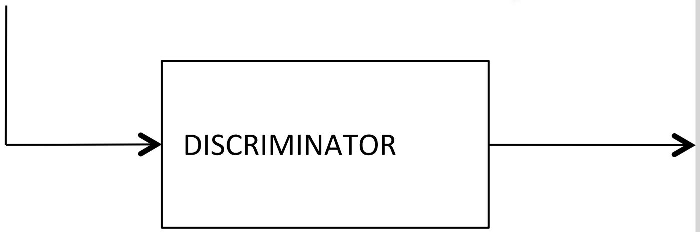


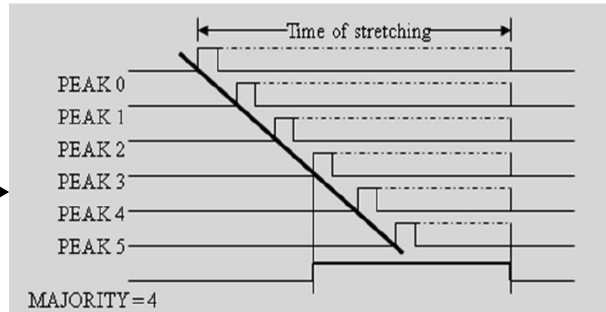

$$Q_{128}(t) = \frac{1}{128}\sum_{i=0}^{128} Q(t-i)$$




$$S(t) = Q_8(t) - Q_{128}(t)$$

Low and high frequency noise washed out



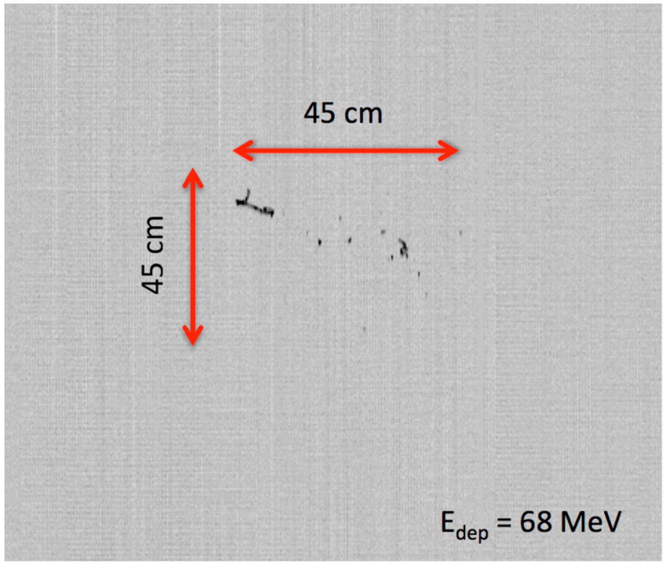




Peak stretching (25÷125 μs) to guarantee high efficiency for inclined tracks

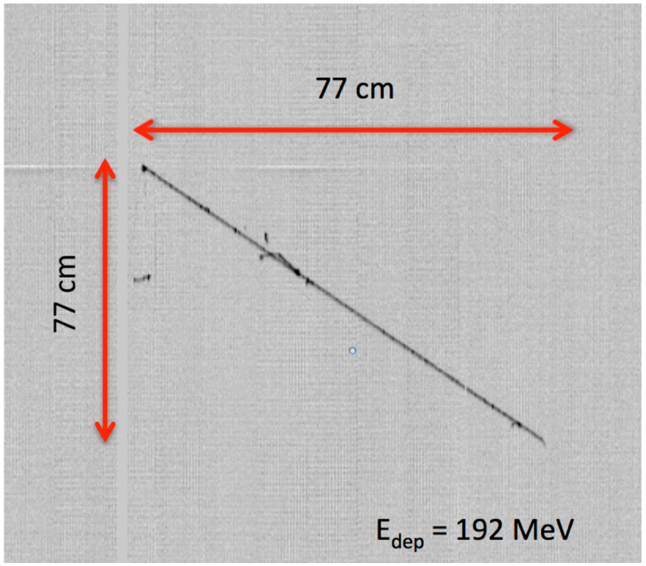
# Equipping T600 with SuperDaedalus

- December 2011: 700 SuperDaedalus chip have been installed in the detector, covering all the Collection views (~ 23000 channels)
- Induction 2 view will be equipped within July 2012 (~ 23000 additional channels).
- It has been possible to trigger on the GTO signals with a trigger rate of ~ 150 mHz, well below the DAQ limit
- Data analysis is in progress.
- Preliminary results indicate a promising improvement of the cosmic event trigger efficiency in the 100÷500 MeV energy range (2 examples below).
- Presently SuperDaedalus are embedded in the CNGS trigger (coincidence of one GTO with the CNGS beam early waring gate).

*Low energy e.m. interaction*



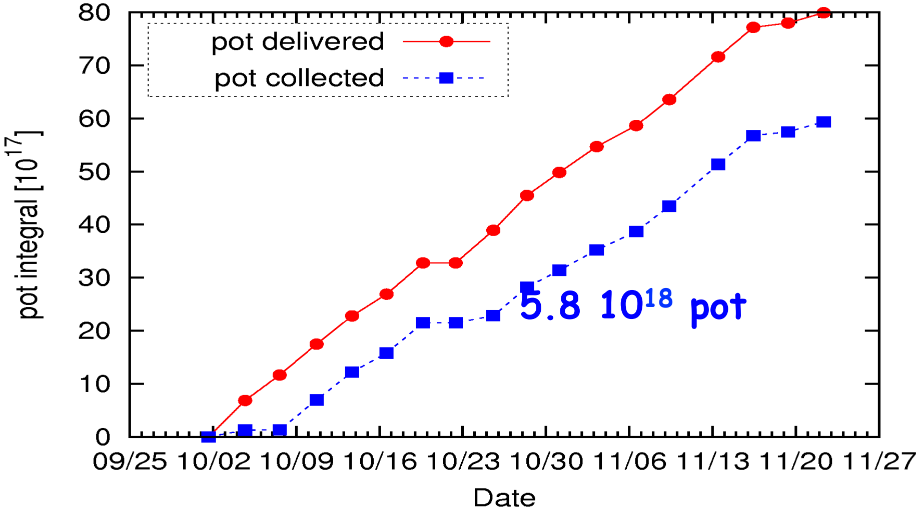

*Atmospheric muon*



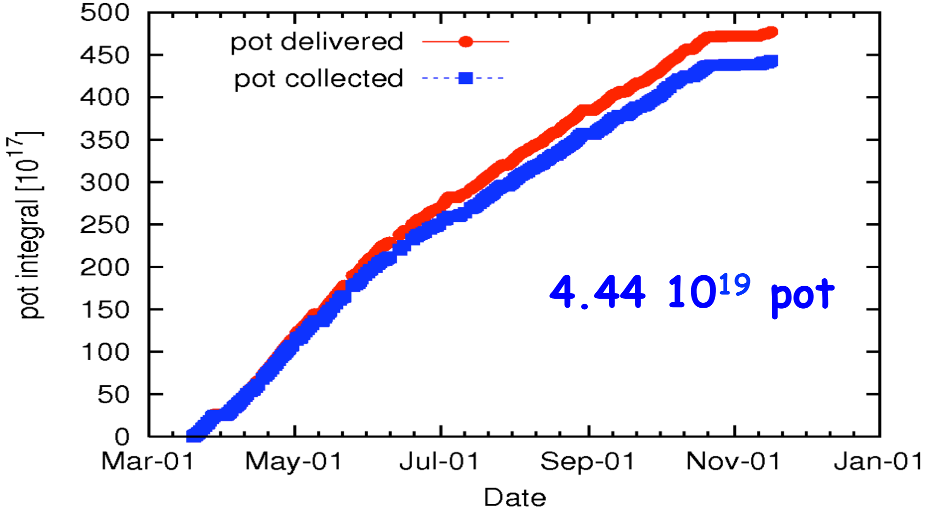
# CNGS neutrino runs – summary

- **ICARUS T600 fully operational since Oct. 1st 2010**

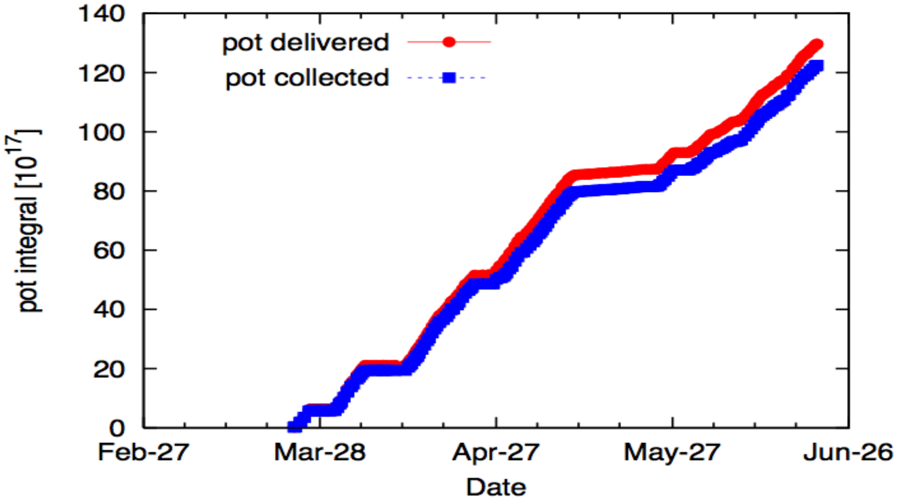
**2010**: Oct. 1st ÷ Nov. 22nd




**2011**: Mar. 19th ÷ Nov. 14th




**2012**: March 23rd ÷ now



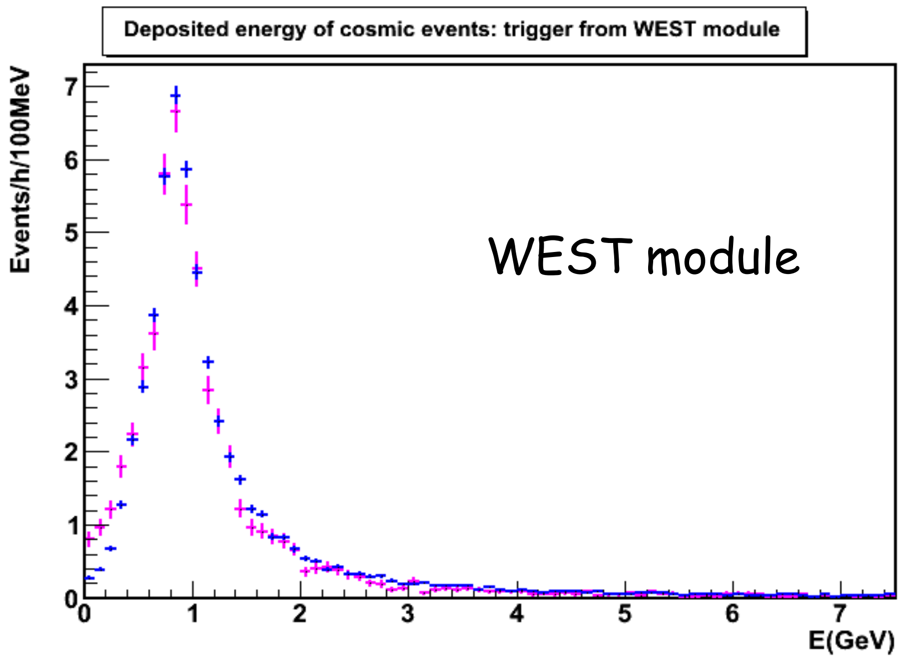

- **Detector live-time > 93%**
- November 2011 and May 2012: timing measurement with bunched beam.
- 2011 run: expected 1200 CC and 390 NC events (so far, for 2.7 $10^{19}$ pot 925 ν interactions in 447 t fiducial volume with ~ 3% detector electronic inefficiency – DAQ crate off; 975 interactions expected from MC assuming full detector efficiency).

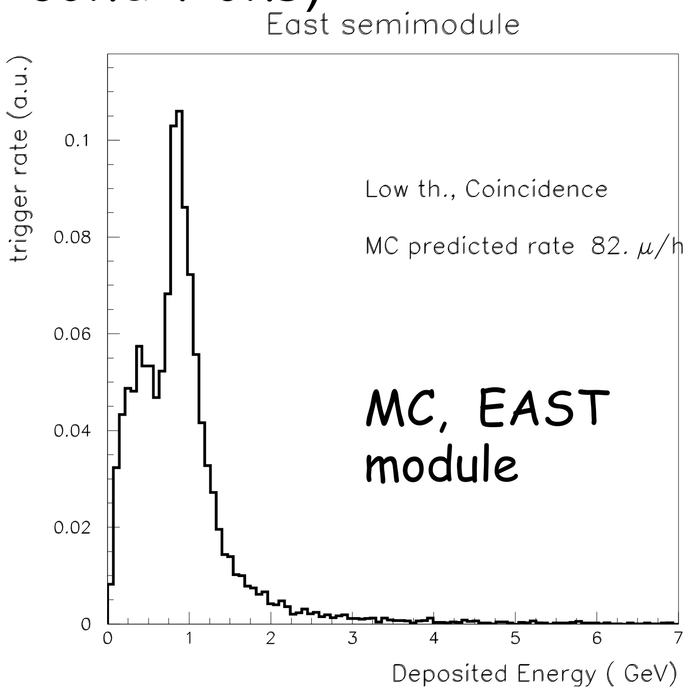
# Progress on data analysis

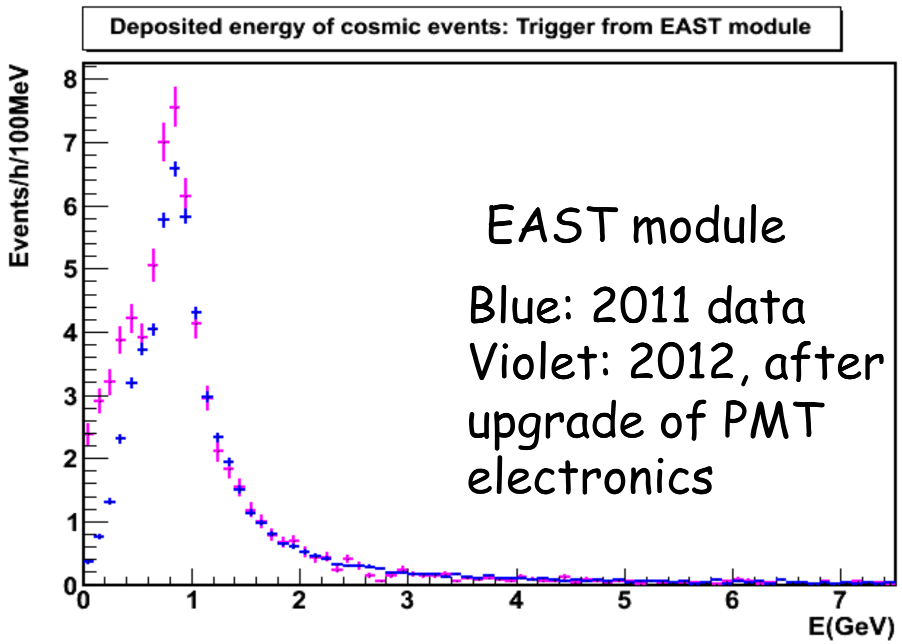
- The analysis of CNGS neutrino events is ongoing. Results will be presented when final.
- First step on cosmic-ray analysis: automatic reconstruction of deposited energy from c-muons in agreement with expectations
- In parallel, optimization of analysis tools in term of performance, calibrations and event reconstruction:
  - Progresses in 3D reconstruction, leading to better performance especially for horizontal tracks
  - Momentum measurement by M.S. for escaping muons, under refinement
  - Progresses in the Particle Identification Algorithm
  - Progresses in automatic reconstruction: vertex finding, clustering, track finding
  - Developments on tools for calorimetric reconstruction

# Cosmic ray muon spectrum

- CR data automatically filtered:
  - Skip fake triggers
  - Find "good" muons for purity
  - First reconstruction
- Good agreement of energy spectrum with MC expectation is found (MC simulation includes light collection and trigger conditions).

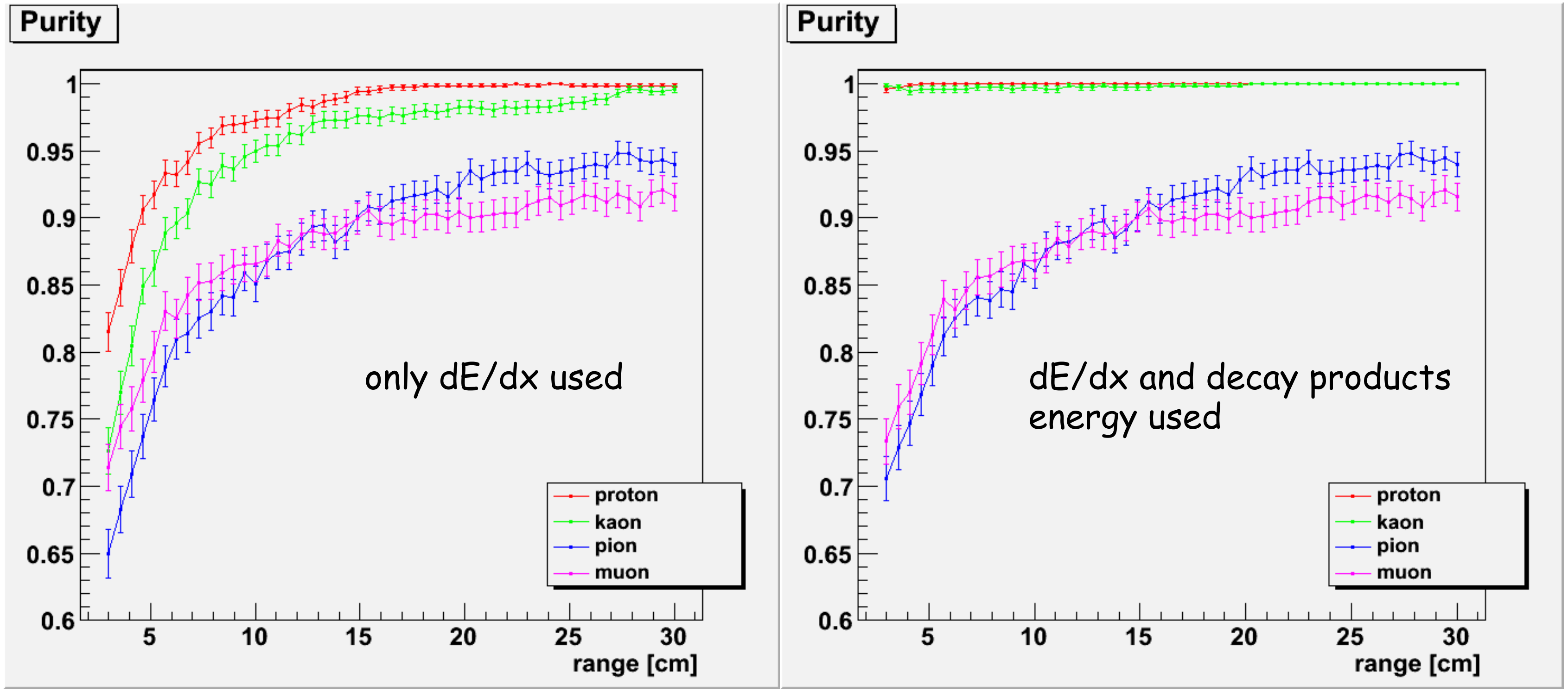


# Particle identification: dE/dx + decay products energy deposit

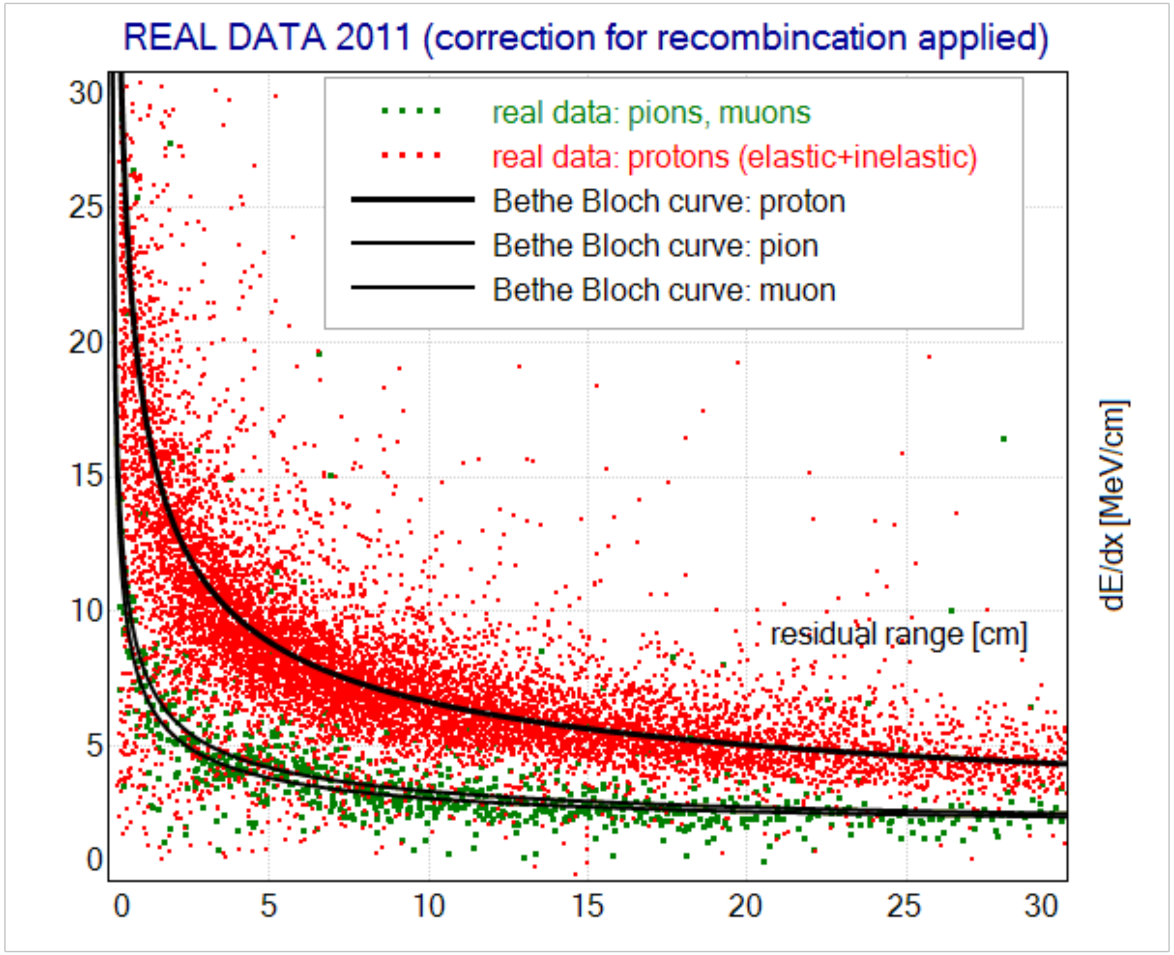
## PId algorithm: neural network approach




**MC test of the particle id algorithm:**
**purity as a function of the observed track length before complete stop**

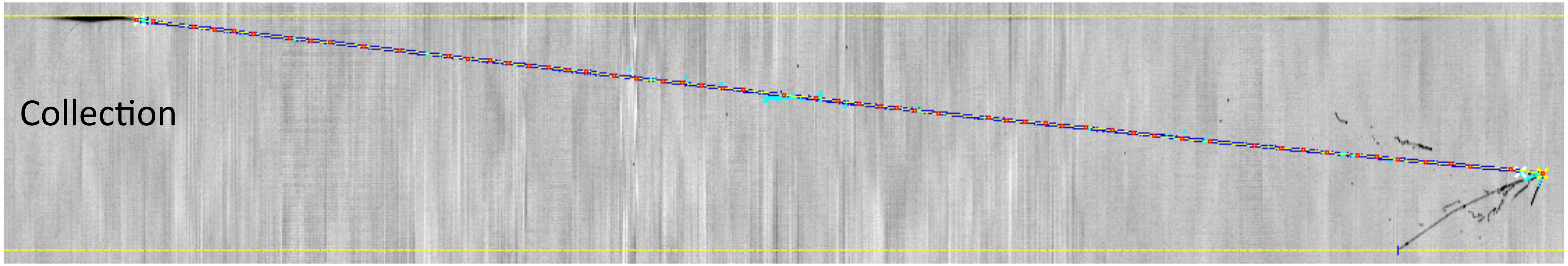
- purity and efficiency is above 80% for tracks longer than 6 cm (p, K, π and μ)
- ~ 100% separation of protons and kaons with the use of decay products

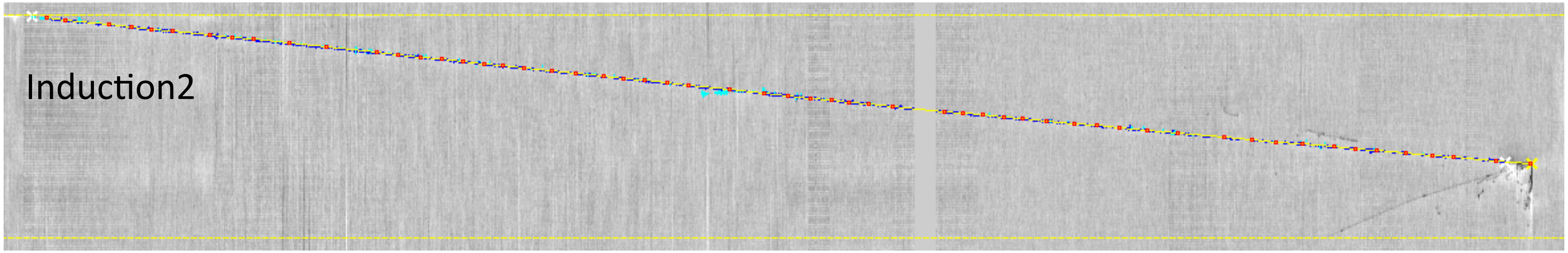
# dE/dx for stopping particles



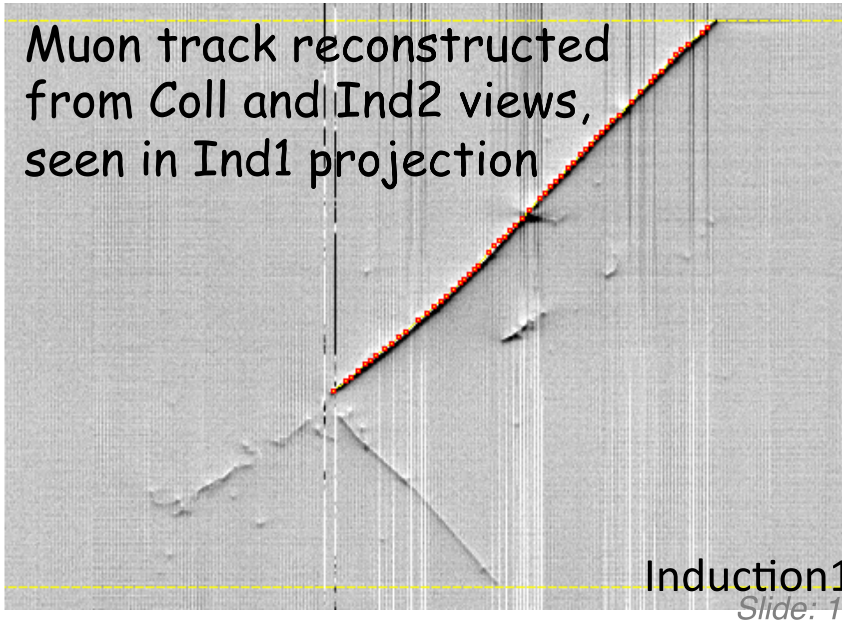

dE/dx as a function of residual range for stopping particles, 2011 data sample, quenching correction applied.

# 3D reconstruction



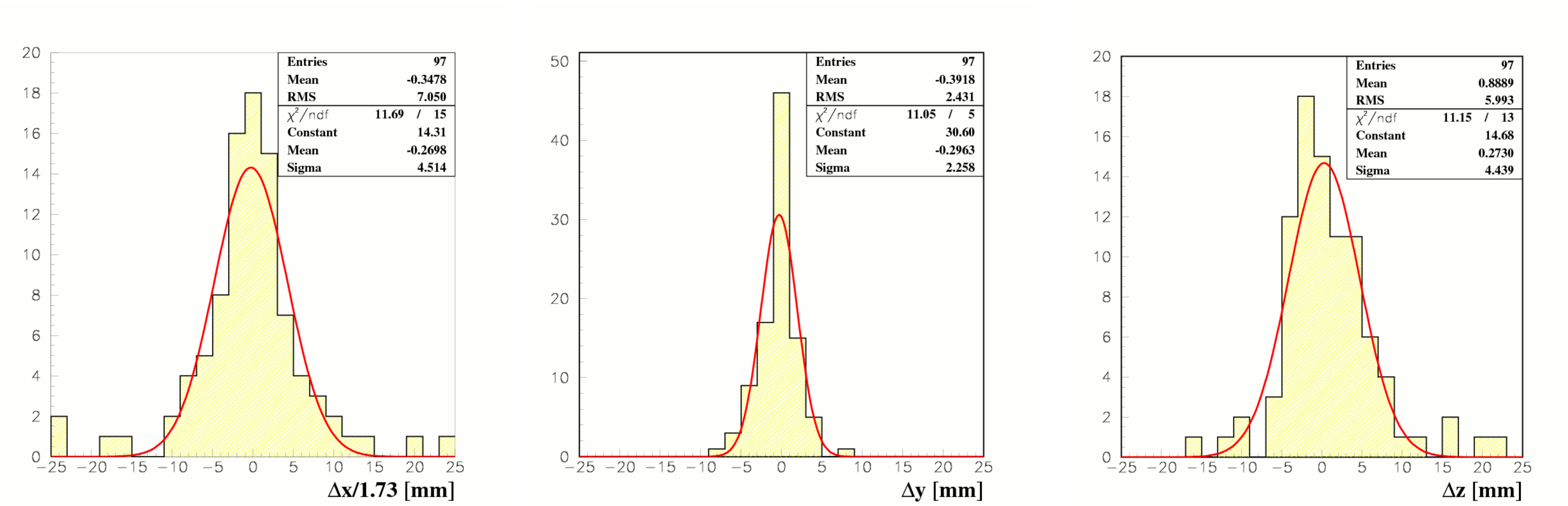




**NEW**: Single **3D** PLA-fit optimized to all available hits in the **2D** wire planes and all identified **3D** reference points (vertices, delta rays). **2D** hit-to-hit associations are not longer needed -> missing parts in a single view and horizontal tracks are now accepted.



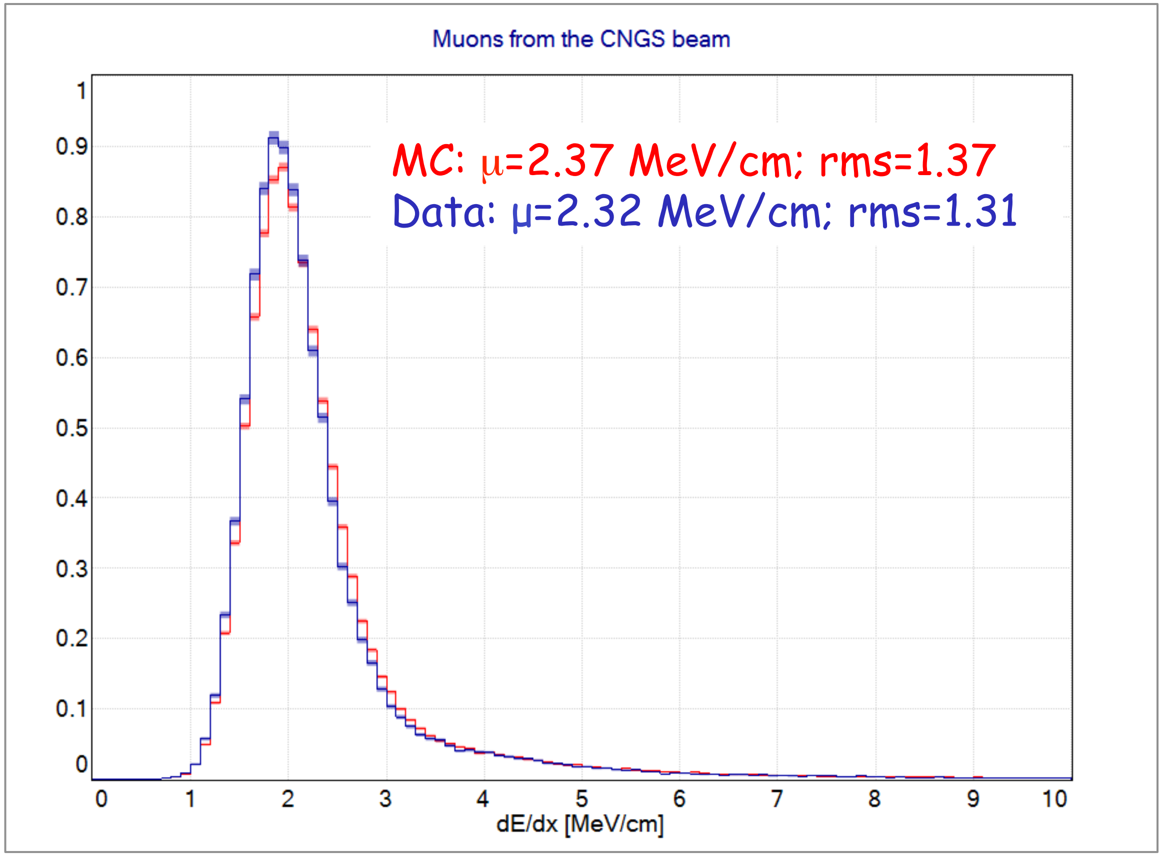
# Automation of the event reconstruction

- A challenging task due to the complexity of high energy CNGS events.
- Algorithm for identification and reconstruction of the promary vertex exploits relative angular distribution of hit positions. Identified 2D vertices are merged together to recontruct 3D vertex.
- Validation with visually identified CNGS vertices. Distributions of the distance between reconstructed and visually identified vertex position.




**Obtained, with real CNGS data, algorithm efficiency ~ 97%.**

# m.i.p. calibration with CNGS muons




dE/dx distribution for real and MC muon tracks from CNGS events

- Tracks reconstructed in 3D. δ rays and showers rejected. Same reconstruction on MC muons with CNGS spectrum.
- Very good agreement (~ 2-3%) - residual small difference due to noise patterns and their effects on δ ray.

# Calibration with stopping particles: data sample

Data : 320 stopping particle tracks visually selected :

- no decay products
- increasing ionization density at the end
- at least 5 hits in Collection
- clean view in Collection

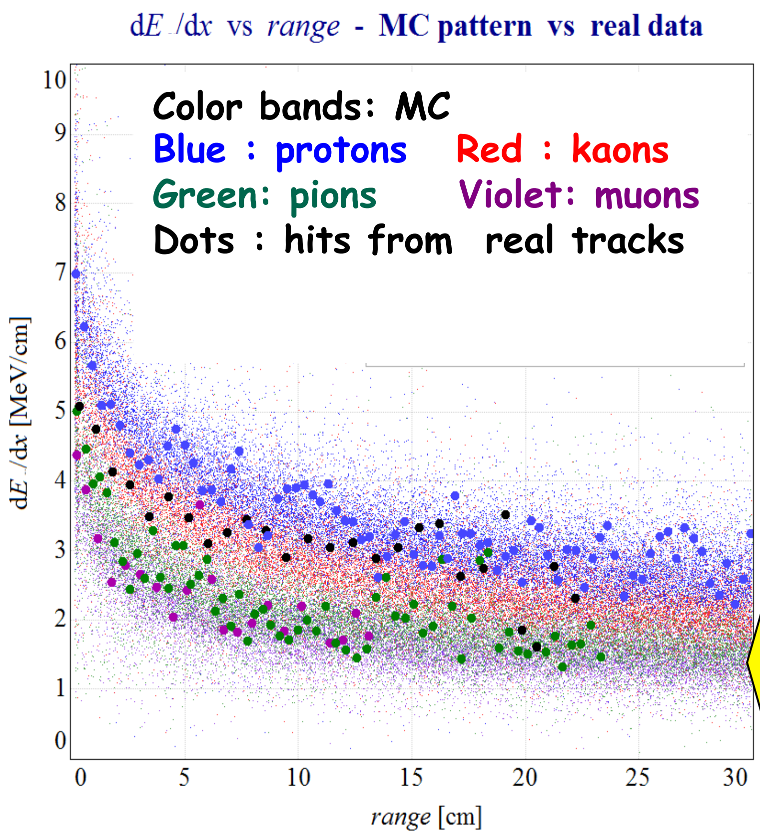
This sample contains both protons and pions (or even muons): stopping $\pi^-$ and $\mu^-$ can be absorbed by Ar nuclei, with sizeable probability of emitting only photons and neutrons.

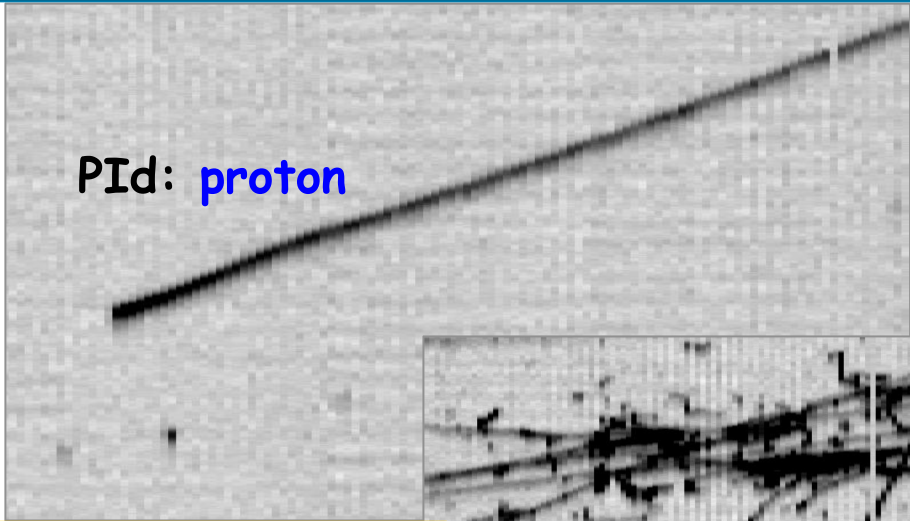
The PID: works on the behavior of dE/dx versus residual range

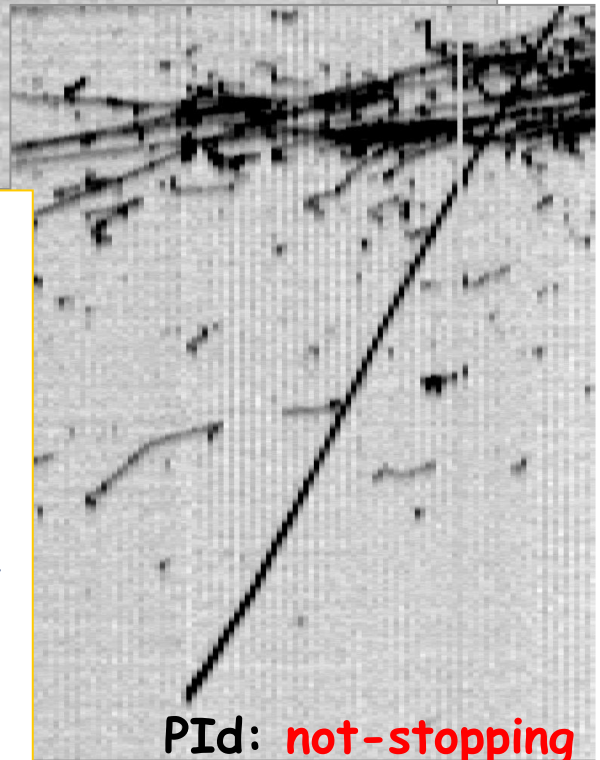
- segment length obtained from 3D track reconstruction
- deposited charge evaluated from collection wire signals without corrections for quenching effects

Points from real tracks are compared to the MC predictions for different particle species

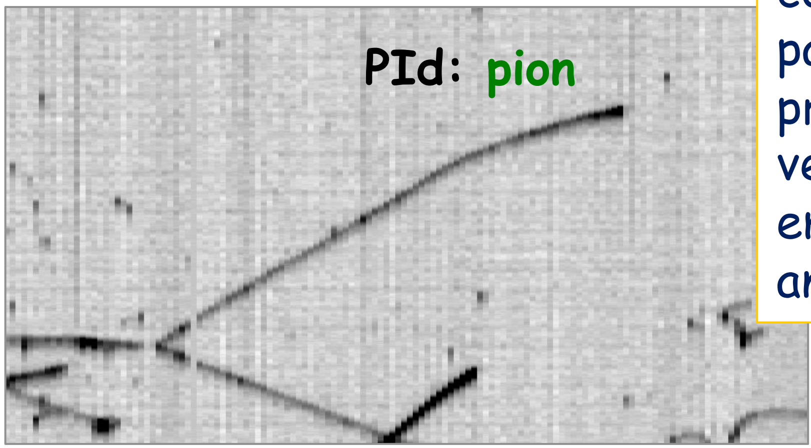
# Calibration with stopping particles: examples




- Deposited dE/dx vs residual range
- No quenching correction
- Black dots: not consistent with any pattern, most probably protons interacting at very low energy with emission of neutrons and photons




Methods for identification of non-stopping particles are under development (including quenching correction)

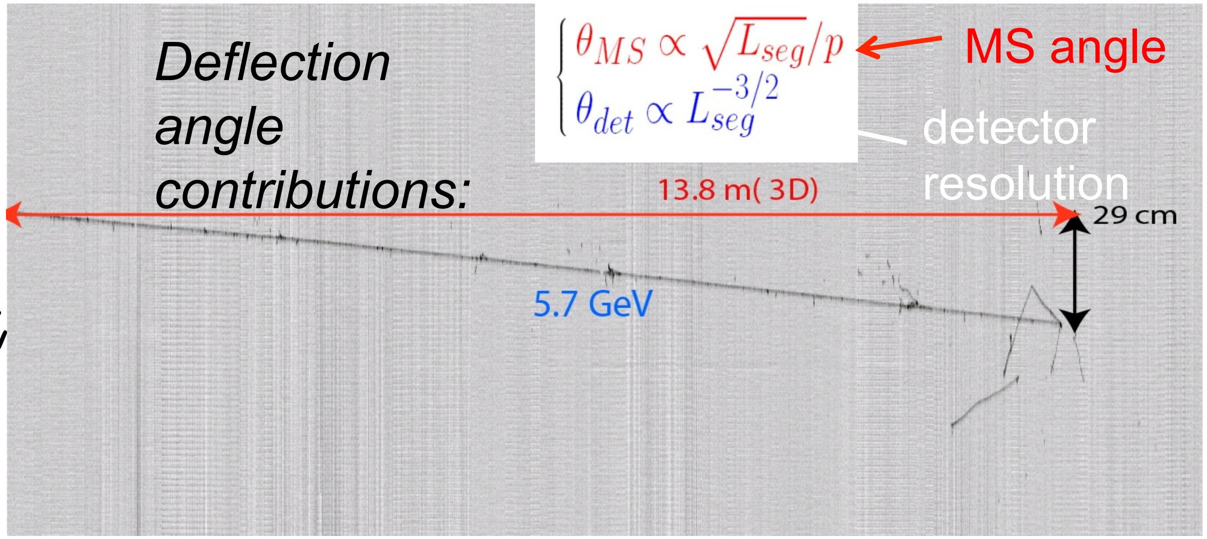
# Muon momentum by multiple scattering

- Key tool to measure momentum of non-contained μ's: essential for $\nu_\mu$ CC event reconstruction.

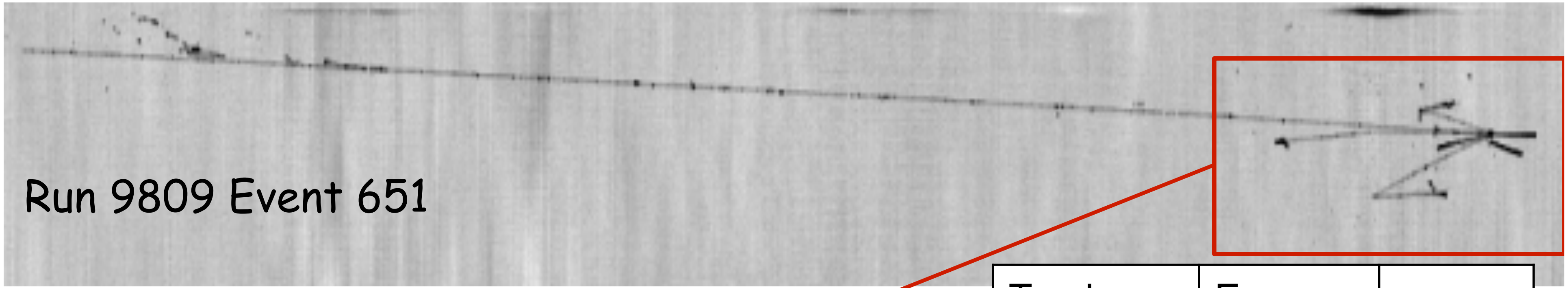
Two methods under development:

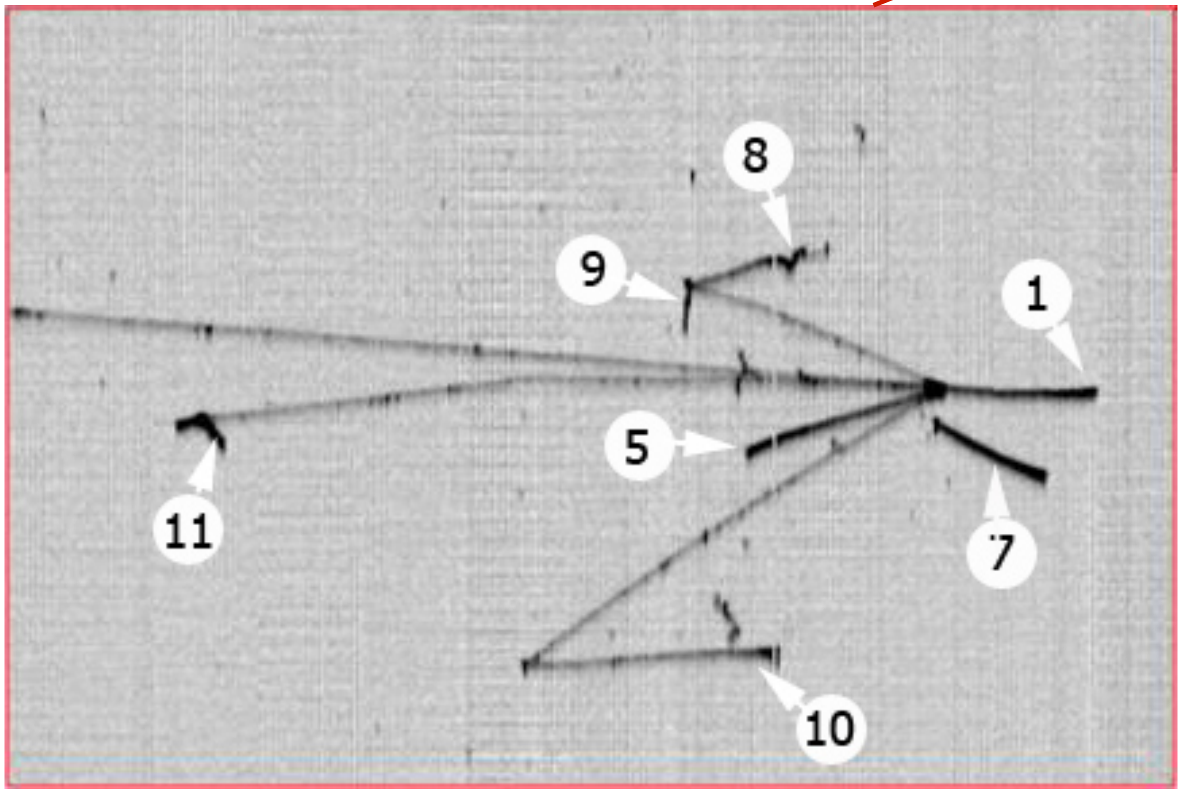
- 2D track projection in Coll. view is repeatedly segmented at various segment lengths ($L_{seg}$); deflection angles θ along the track are extracted by linear fit; to estimate muon momentum the distribution of $\theta(L_{seg})$ is fitted – the opimization of the track segmentation not needed. *(A.Ferrari, C.Rubbia – ICARUS TN 99)*
- Kalman fit of the segmented track; muon momentum p extracted from deflection angle θ. *(ICARUS Coll. - Eur. Phys. J C48 (2006) 667)*

- Both methods under validation on stopping μ's and extended to higher energy.
- Δp/p depends mainly on the track length: for CNGS Δp/p < 20% expected on average.



# $\nu_\mu$ CC CNGS event: reconstruction of stopping tracks

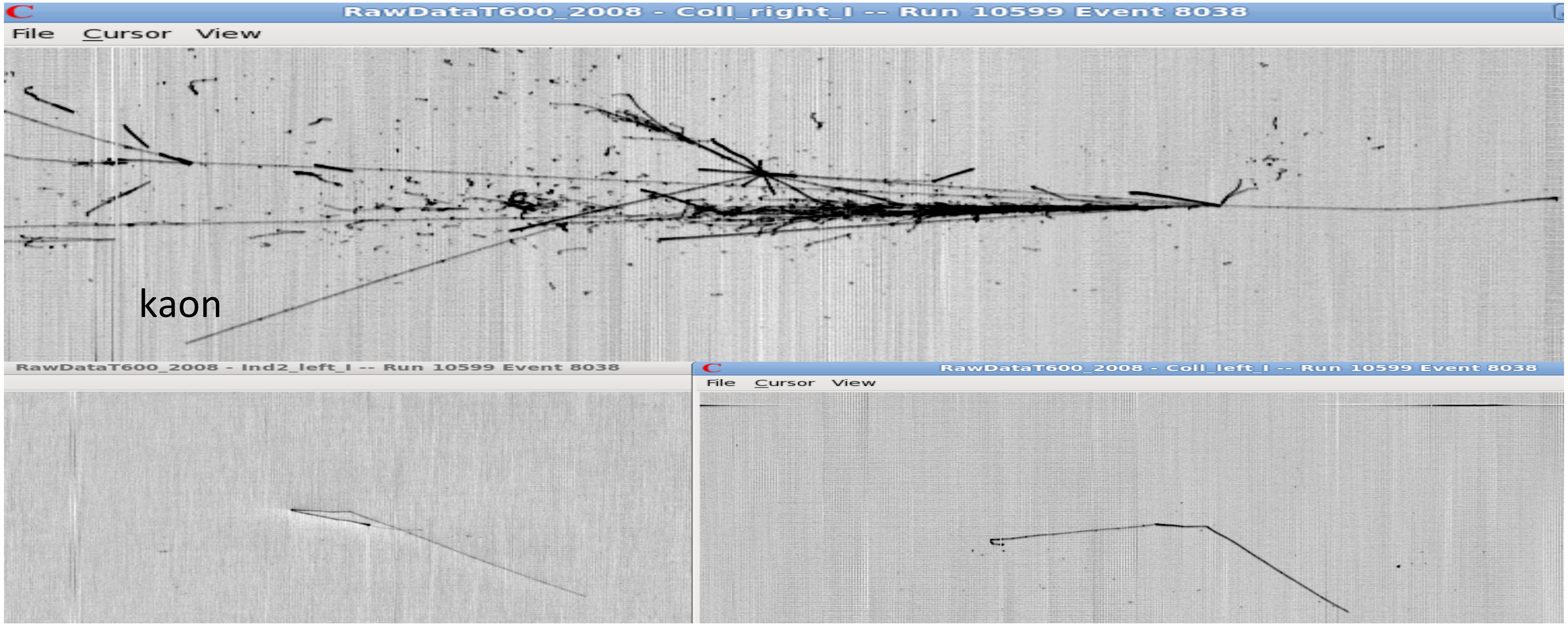


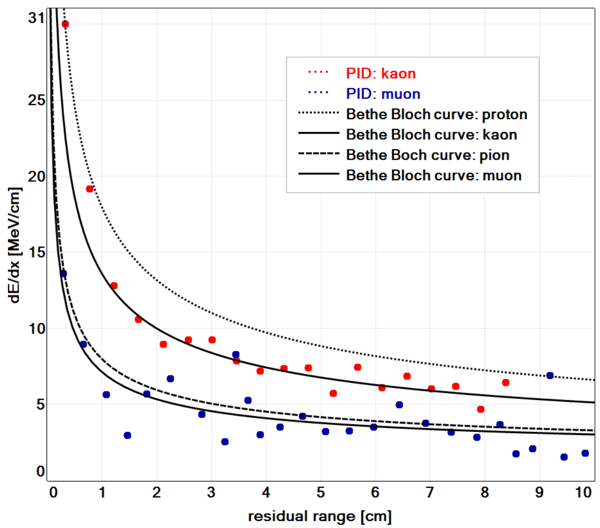




| Track | $E_{dep}$ [MeV] | range [cm] |
|---|---|---|
| 1(p) | 185±16 | 15 |
| 5(p) | 192±16 | 20 |
| 7(p) | 142±12 | 17 |
| 8(π) | 94±8 | 12 |
| 9(p) | 26±2 | 4 |
| 10(p) | 141±12 | 23 |
| 11(p) | 123±10 | 6 |

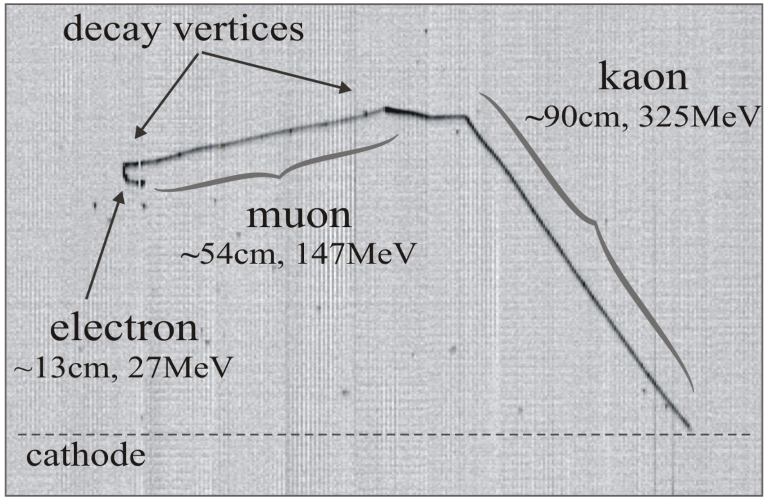
6 protons, 1 pion decays at rest

# Example of data: kaon decay in a CNGS event

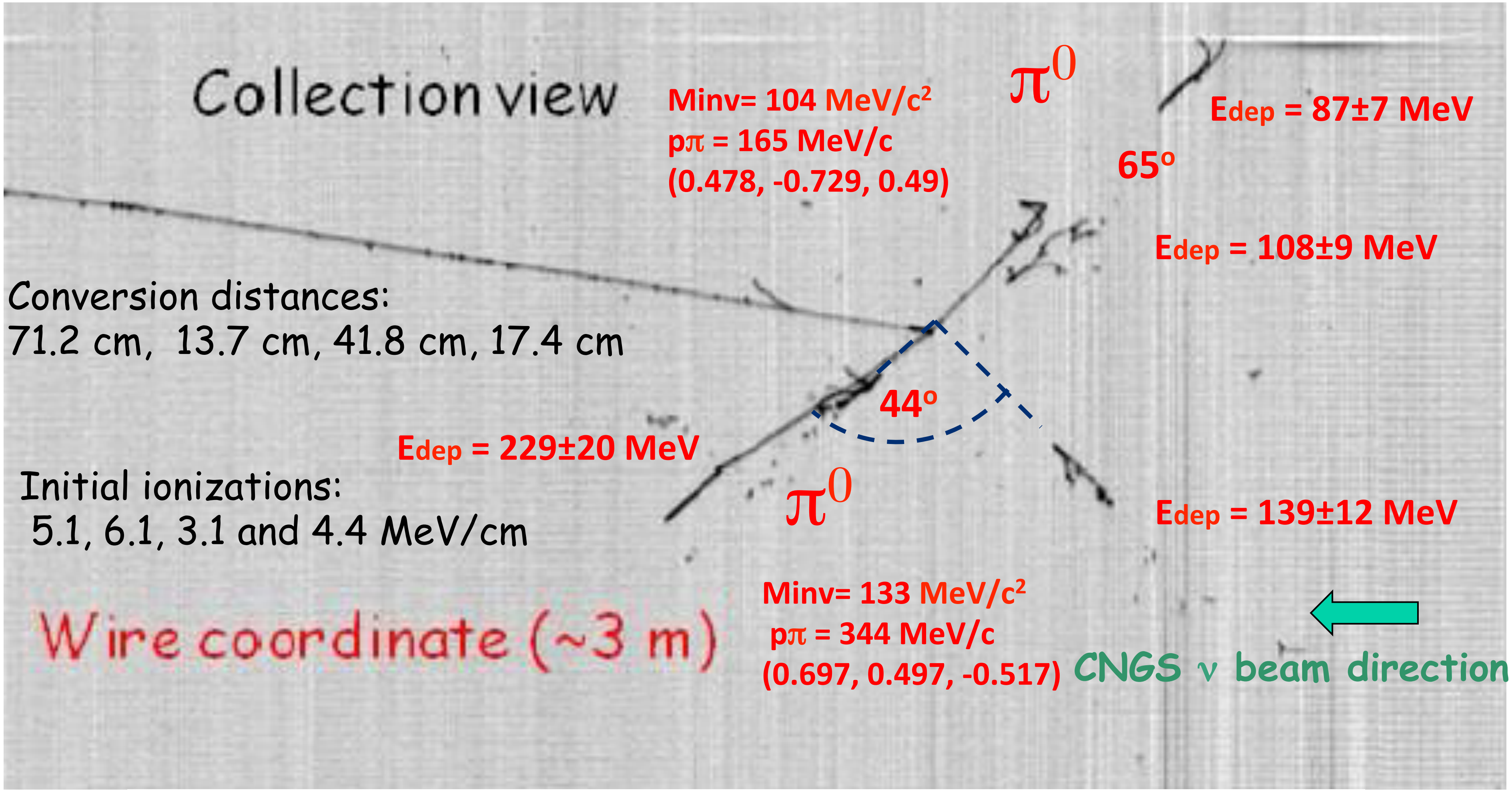



Corresponding PId patterns



# $\pi^0$ identification / reconstruction in CNGS events (1)

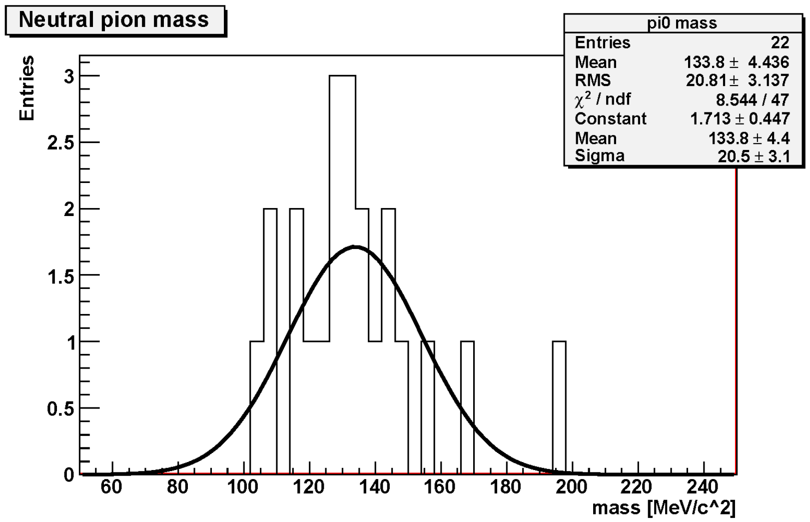



$\pi^0$ showers identified by:

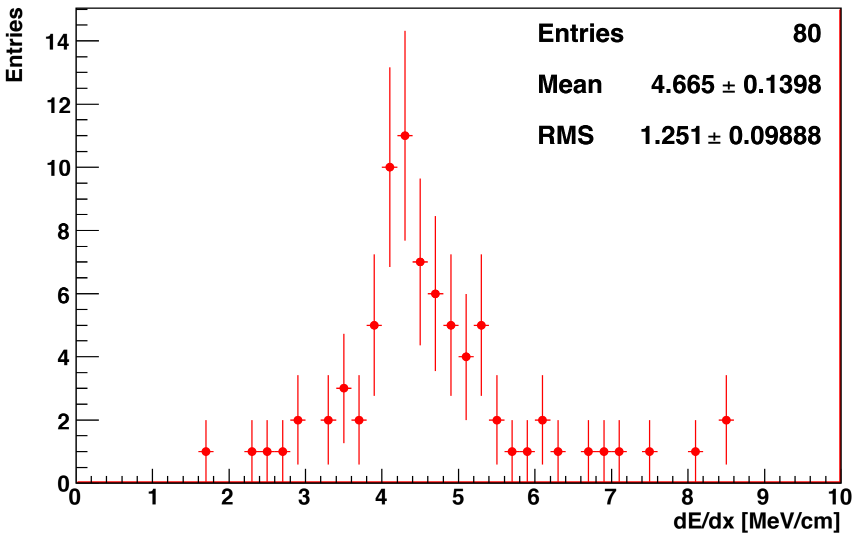
- $2\gamma$ conversion separated from primary vertex
- Reconstruction of $\gamma\gamma$ invariant mass
- Ionization in the first segment of showers (1 or 2 mips)

# $\pi^0$ identification / reconstruction in CNGS events (2)

Preliminary

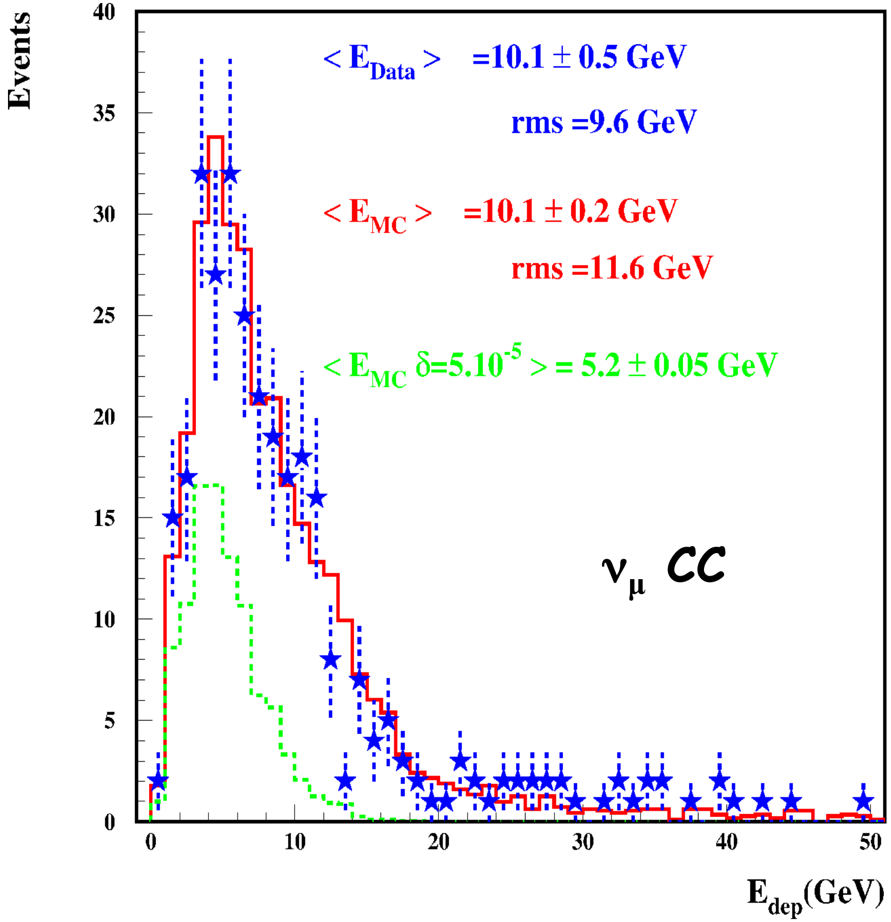


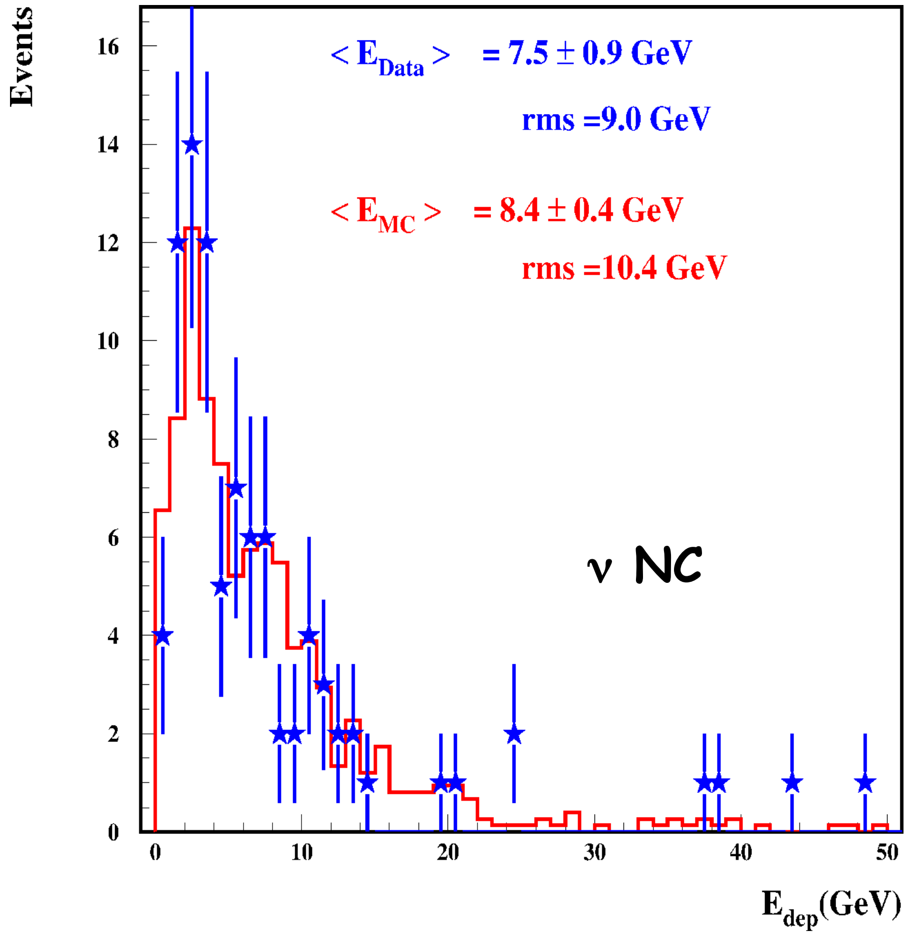

Mean: 133.8 ± 4.4(stat) ± 4 (syst) MeV/$c^2$
$\sigma$ = 20.5 MeV




dE/dx in the first 2.5 cm of candidate photon shower

# Total energy deposition in CNGS n events




- Comparison of the predicted ( full MC) and detected deposited energy spectrum from NC and CC events on 2010 statistics and a subset of the 2011 statistics
- Used for the “superluminal” neutrino searches

# Search for superluminal ν's radiative processes in ICARUS Phys. Lett. B-711 (2012) 270-275

- Cohen and Glashow [Phys. Rev. Lett., 107 (2011) 181803] argued that superluminal ν should loose energy mainly via $e^+e^-$ bremsstrahlung, on average $0.78 \cdot E_\nu$ energy loss/emission
- Full FLUKA simulation of the process kinematics, folded in the CNGS beam, studied as a function of $\delta = (v_\nu^2 - c^2)/c^2$

  For $\delta = 5\ 10^{-5}$ (OPERA first claim):

  - full ν event suppression for E > 30 GeV
  - $\sim 10^7$ $e^+e^-$ pairs $/10^{19}$ pot/kt

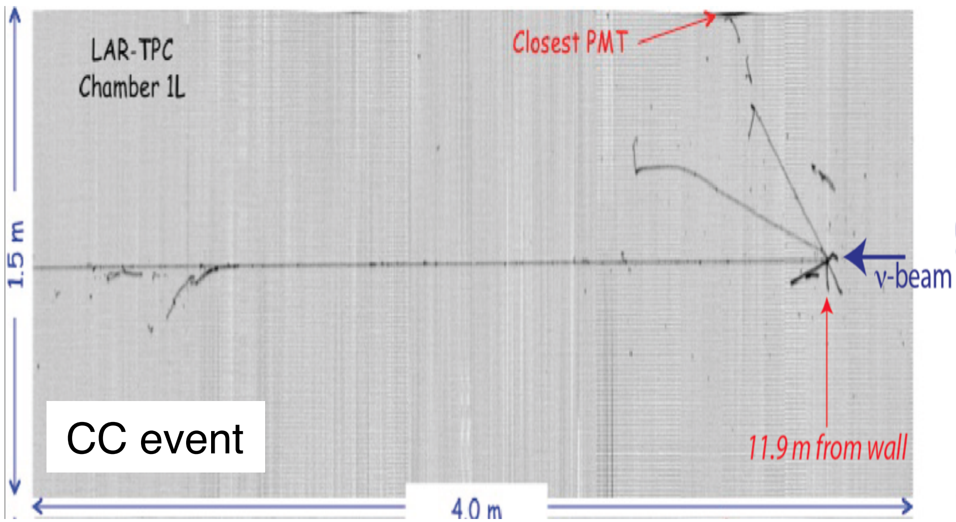
- Effects searched in $6.7\ 10^{18}$ pot·kt ICARUS exposure (2010/11) to CNGS
  - No spectrum suppression found in both NC , CC data (~ 400 events)
  - No $e^+e^-$ pair bremsstrahlung event candidate found
- The lack of pair in CNGS ICARUS 2010/2011 data, sets the limit:

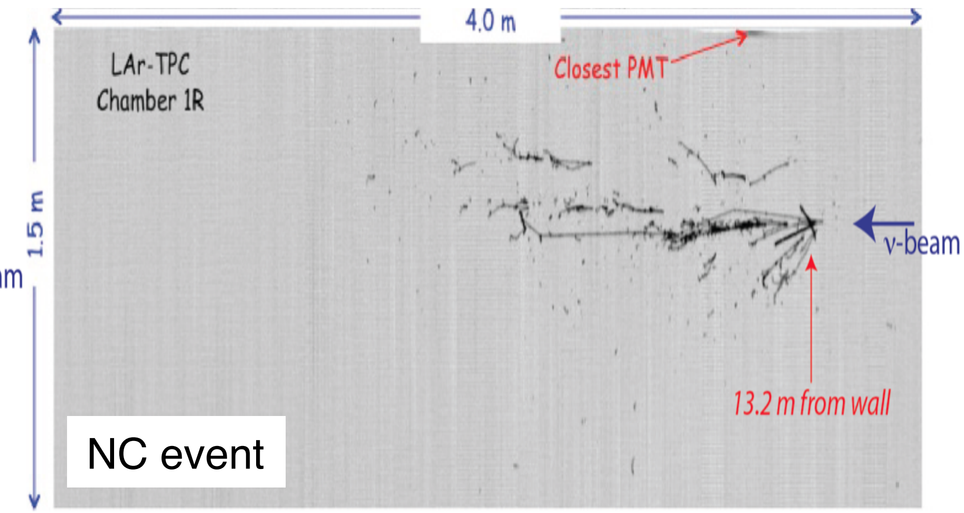
$$\delta = (v_\nu^2 - c^2)/c^2 < 2.5\ 10^{-8}\ 90\%\ CL$$

- comparable to the SuperK atm. limit $\delta < 1.4\ 10^{-8}$, somewhat larger than the lower energy velocity constraint $\delta < 4\ 10^{-9}$ from SN1987A.

# Neutrino time of flight with CNGS bunched beam

- 2011 low intensity bunched beam: 4 bunches/spill, 3 ns FWHM, 524 ns separation.
- ICARUS observed 7 beam-associated events, (~2.2 $10^{16}$ pot collected): 2 CC $\nu_\mu$ events, 1 NC $\nu$ event, 1 stopping + 3 crossing $\mu$'s from $\nu$ interaction in upstream rock.
- Arrival time determined using the prompt scintillation light signals (~ns resolution) and the accurate localization of each event w.r.t. PMT position.



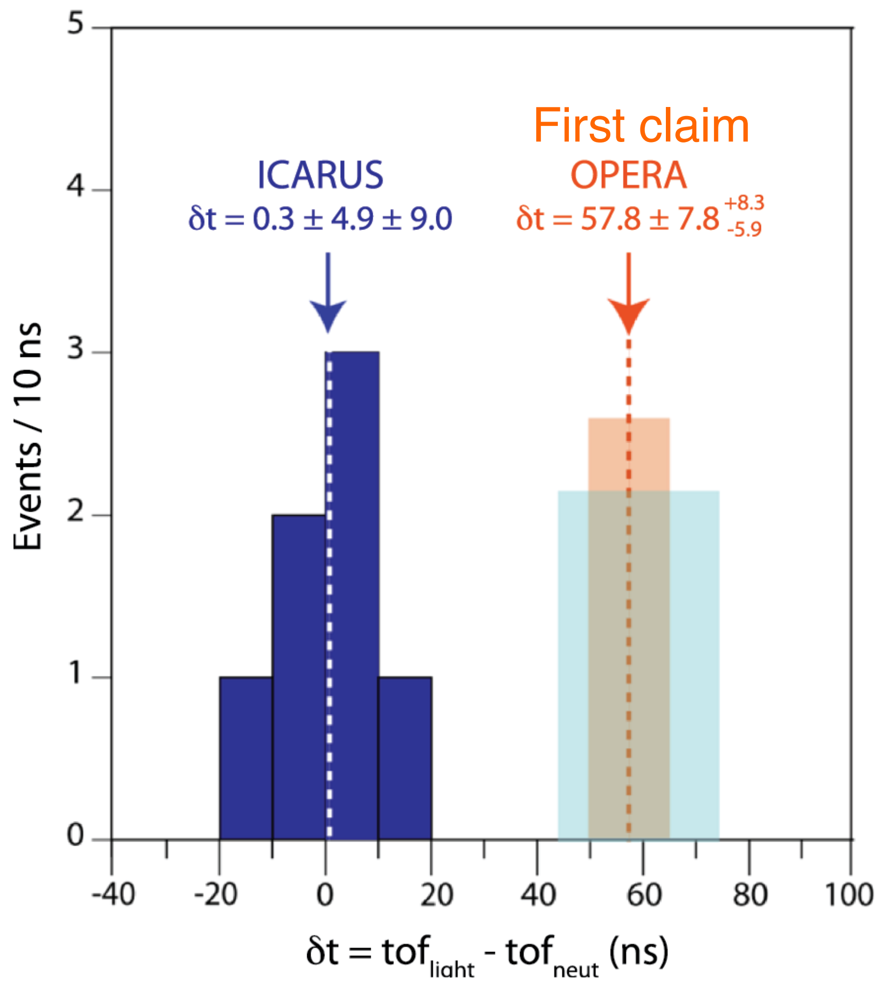



# Neutrino time of flight: 2011 result

Phys. Lett. B 713 (2012) 17-22

- All fixed delays/propagation times calibrated (thanks also to LNGS and CERN)
- Baseline estimation relies on existing available geodesy data (OPERA/LNGS)
- Variable corrections to GPS from OPERA/CERN recipe

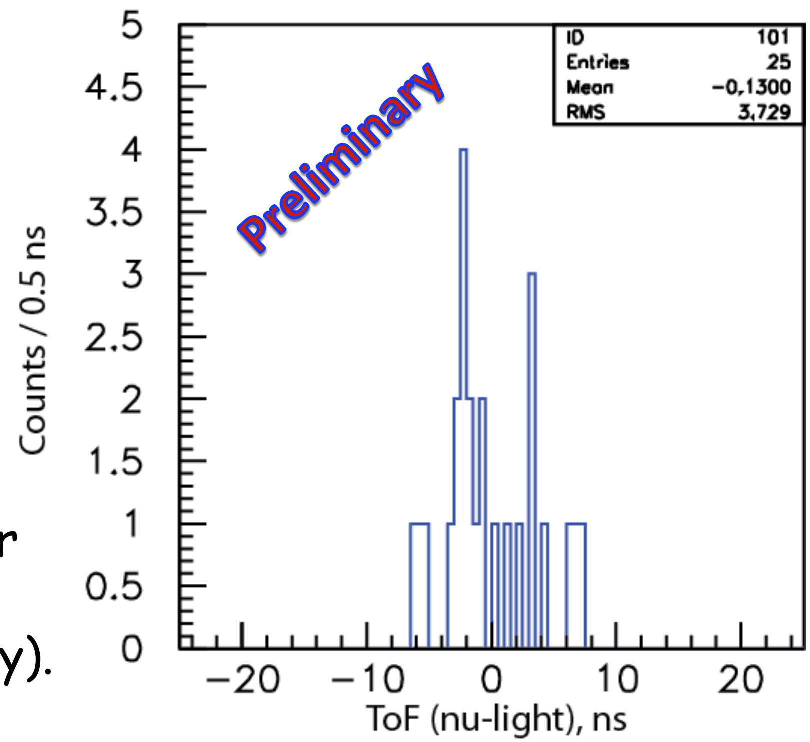
- The average $\delta t = tof_c - tof_\nu$ of the 7 events is + 0.3 ns with an r.m.s. of 10.5 ns; statistical error on the average = 4.9 ns; systematic error ~ 9 ns



# Data taking/analysis with 2012 bunched CNGS

- New beam structure: 64 bunches, 3 ns width, 100 ns spacing.
- Beam related events observed in ICARUS (for ~1.8 $10^{17}$ pot):
  - 16 crossing μ's (1 stopping) from the upstream rock;
  - 7 CC $\nu_\mu$ events;
  - 2 NC ν event.

- Analysis in progress:
  - **PRELIMINARY** results compatible with 2011 value: 0 to 3 ns depending on timing synchronization path;
  - distribution r.m.s: ~ 3.7 ns (10.5 in 2011)
  - Systematics corrections and offset under final evaluation (PMT-DAQ propagation chain, topological corrections, timing delay).



# Conclusions

- ICARUS T600 is the first large LAr TPC operated underground.
- The T600 is acquiring data without interruption since mid-2010 @ LNGS with CNGS beam, searching for $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillations as well as for athmospheric $\nu$'s and proton decay.
- High detection efficiency reached for CNGS events.
- Quality of data as expected.
- Data analysis in progress, results expected on:
  - Search for $\nu_\mu \rightarrow \nu_e$ oscillations and LNSD effect
  - Search for $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Contributions to the "superluminal" neutrino problem (published).


Thank
you !