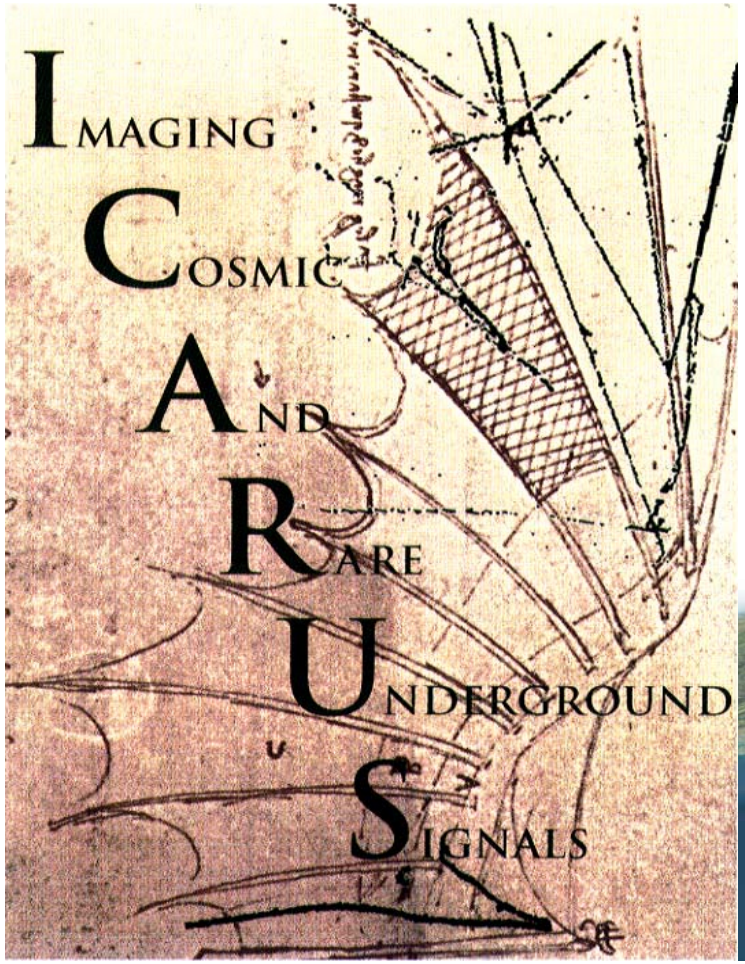
The ICARUS Experiment at LNGS Underground Laboratory



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on behalf of the
ICARUS Collaboration

ICFP 2012
International Conference on New Frontiers in Physics
10-16 June 2012 Kolymbari, Crete, Greece

The ICARUS Collaboration

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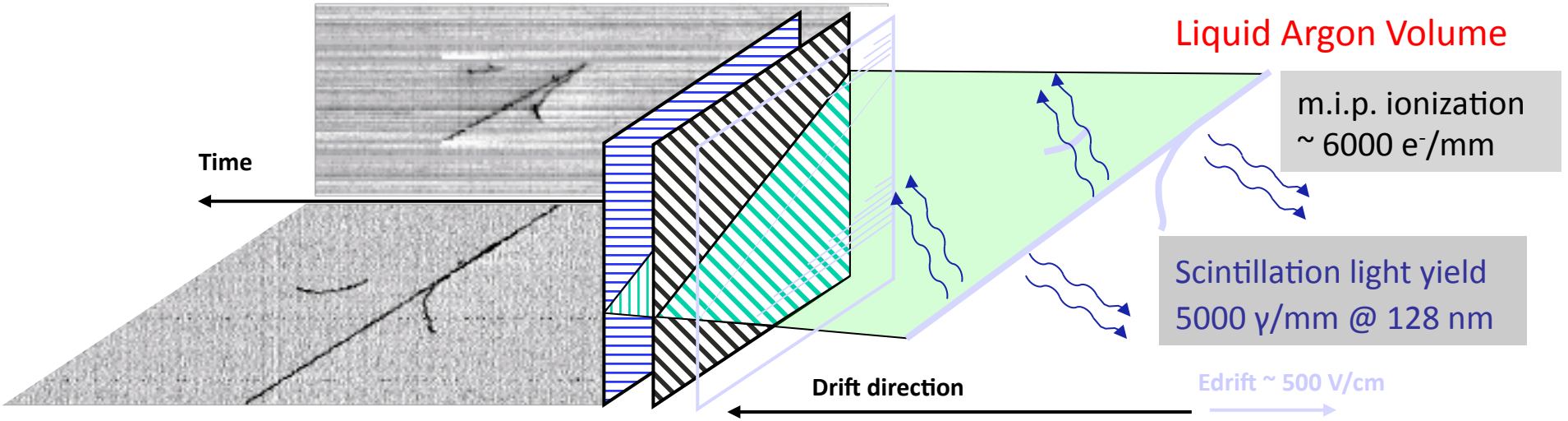
A powerful detection technique

The Liquid Argon Time Projection Chamber [C. Rubbia: CERN-EP/77-08 (1977)] first proposed to INFN in 1985 [ICARUS: INFN/AE-85/7] capable of providing a 3D imaging of any ionizing event ("electronic bubble chamber") with in addition:

- continuously sensitive, self triggering
- high granularity (~ 1 mm^3)
- excellent calorimetric properties
- particle identification (through dE/dx vs range)



Electrons from ionizing track are drifted in LAr by E_{drift}. They traverse transparent wire arrays oriented in different directions where induction signals are recorded. Finally electron charge is collected by collection plane.

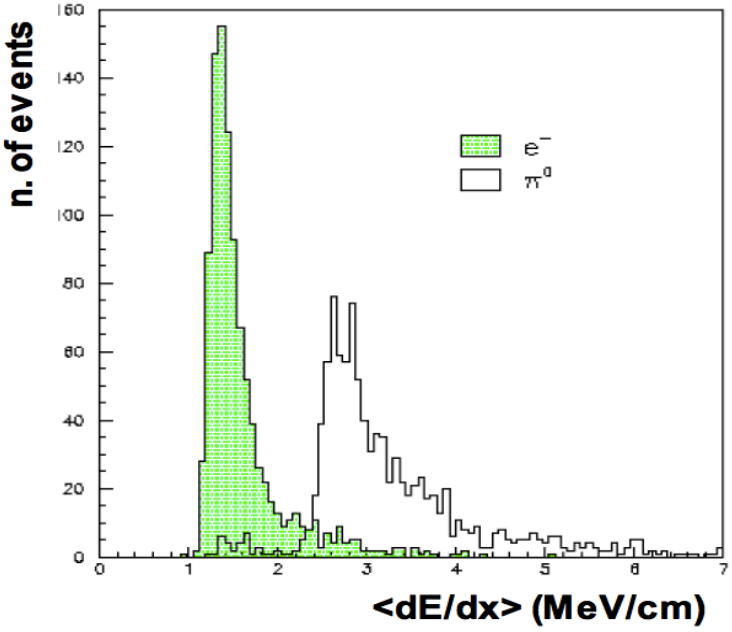
Key feature: LAr purity from electro-negative molecules (O_2, H_2O,CO_2)

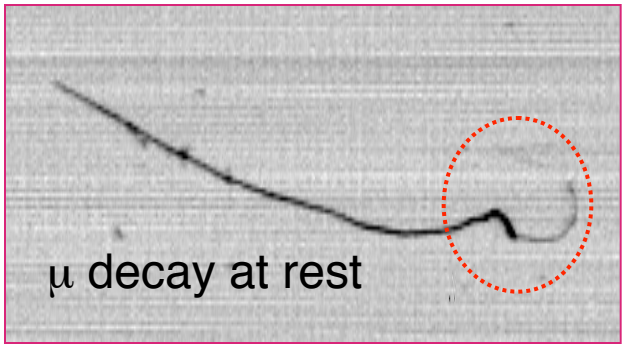
Required purity: ~0.1 ppb O_2 equivalent ≈3 ms lifetime (4.5 m drift @ E_{drift} = 500 V/cm)

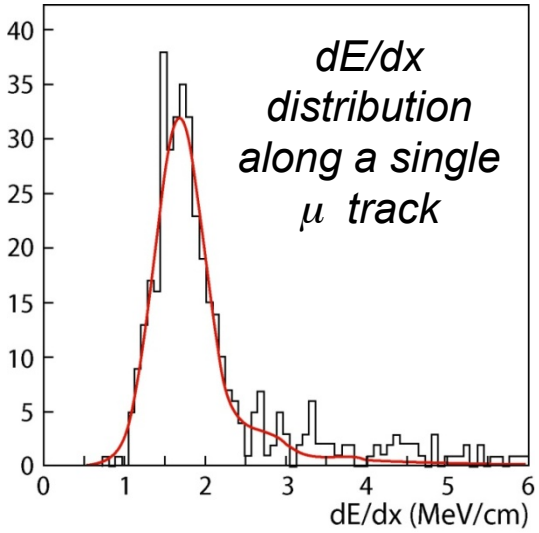
LAr-TPC performance

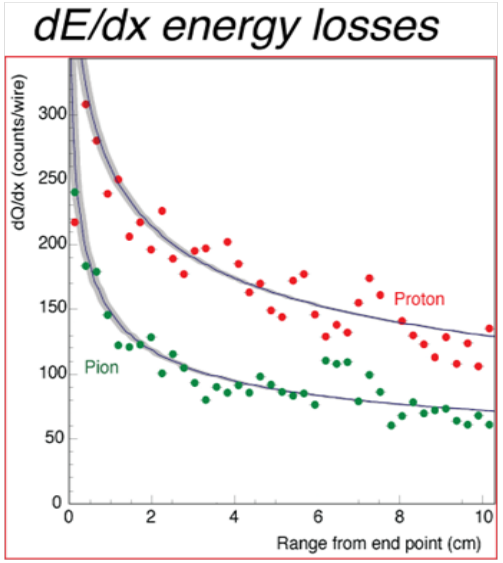
- **Tracking device**:
  - precise event topology ($s_{x,y}$ ~ 1mm, s_z ~ 0.4mm)
  - μ momentum measurement via multiple scattering: Δp/p ~10-15% depending on track length and p
  - Total energy reconstruction by charge integration
- **Measurement of local energy deposition dE/dx**:
  - e/γ separation (2% X_0 sampling);
  - particle ID by means of dE/dx vs range
- **Good e/π^0 separation** (10^{-3})

  by means of dE/dx in the first part of the track after the vertex and π^0 mass measurement









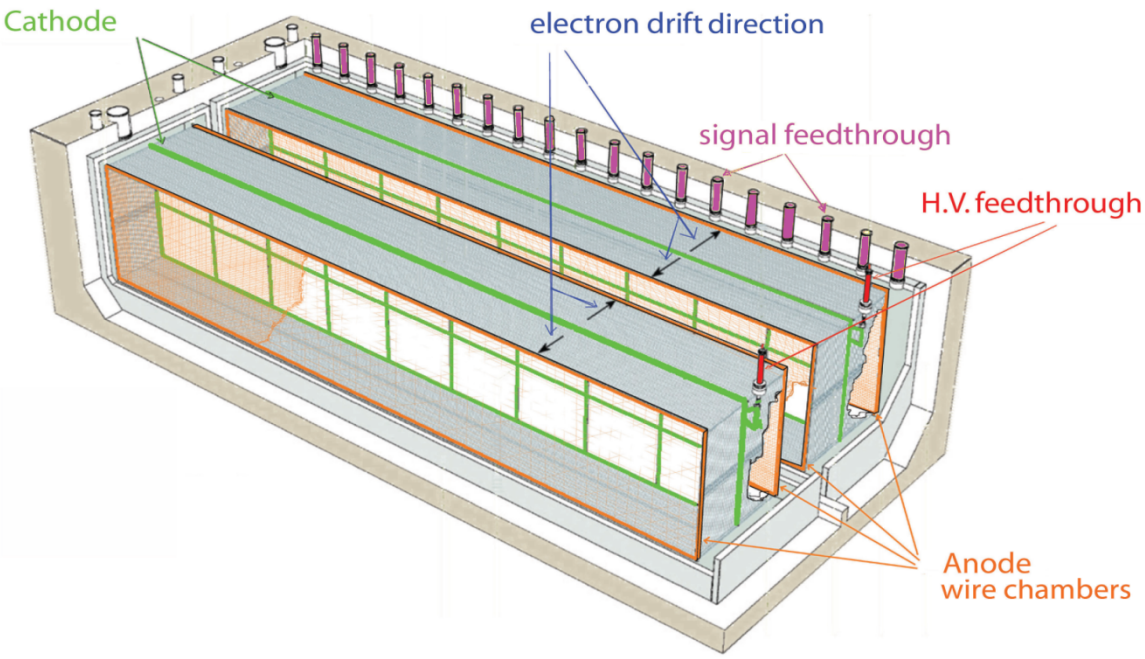
RESOLUTIONS

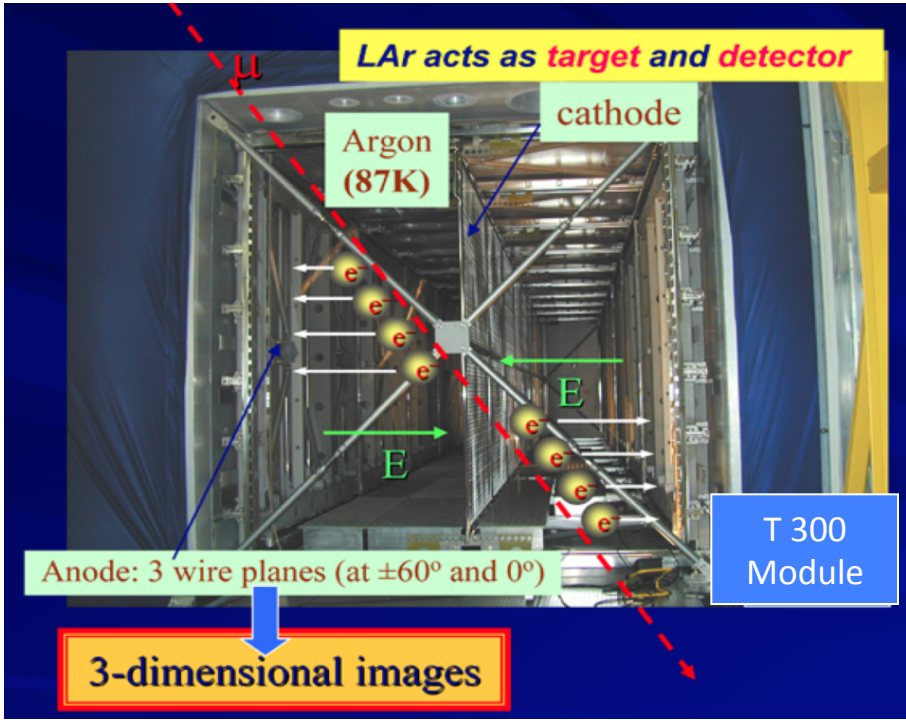
Low energy electrons: $\sigma(E)/E = 11\% / \sqrt{E(MeV)} + 2\%$

Electromagnetic showers: $\sigma(E)/E = 3\% / \sqrt{E(GeV)}$

Hadron shower (pure LAr): $\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$

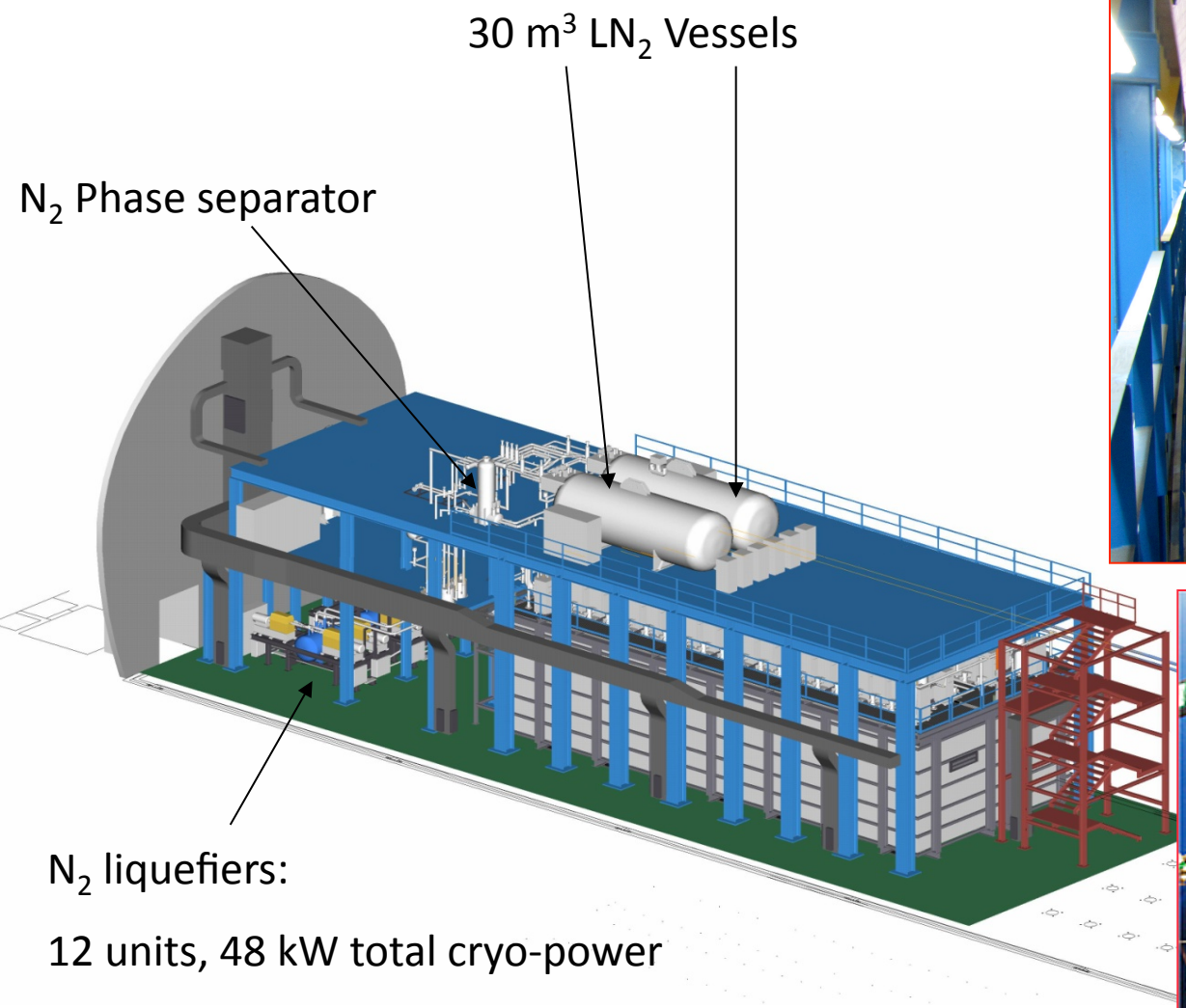
The ICARUS T600 detector

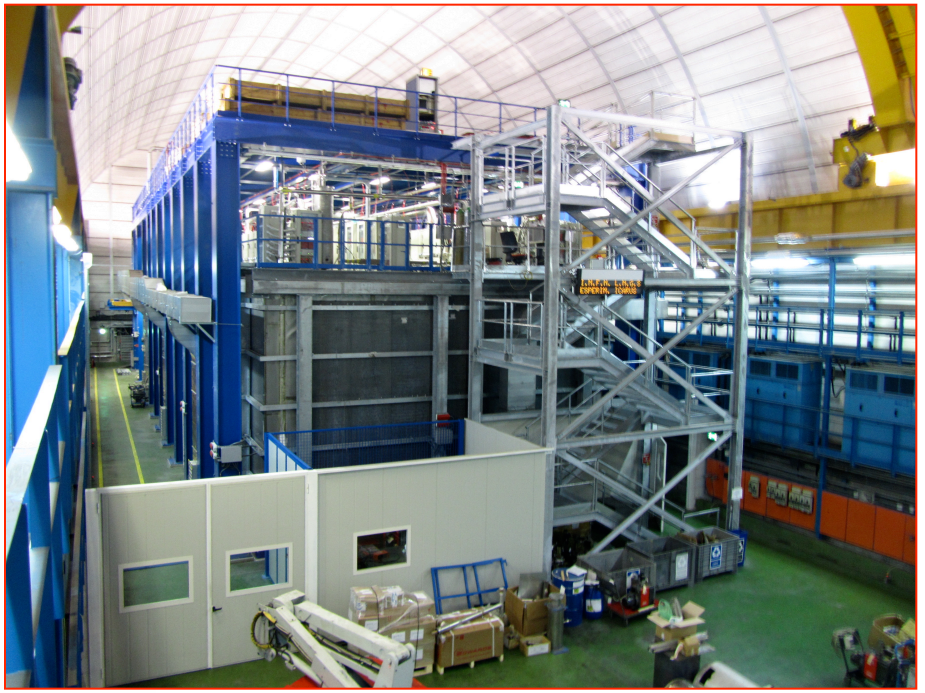




- Two "T300" identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m
  - HV = -75 kV E = 0.5 kV/cm
  - v_{drift} = 1.55 mm/μs
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0°, ±60°
  - ≈ 53000 wires, 3 mm pitch, 3 mm plane spacing
- PMT for scintillation light:
  - (20+54) PMTs, 8" Ø
  - VUV sensitive (128nm) with wave shifter (TPB)

ICARUS T600 in LNGS Hall B

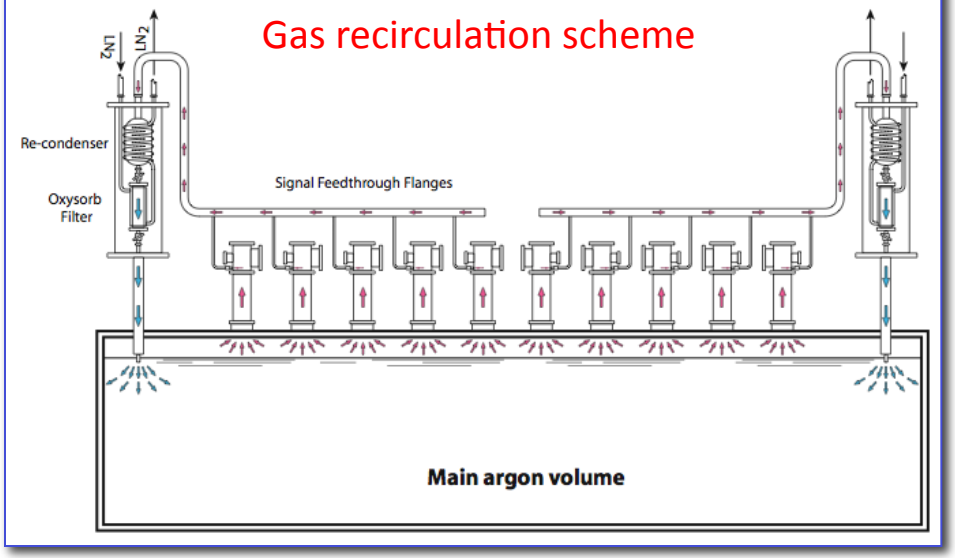




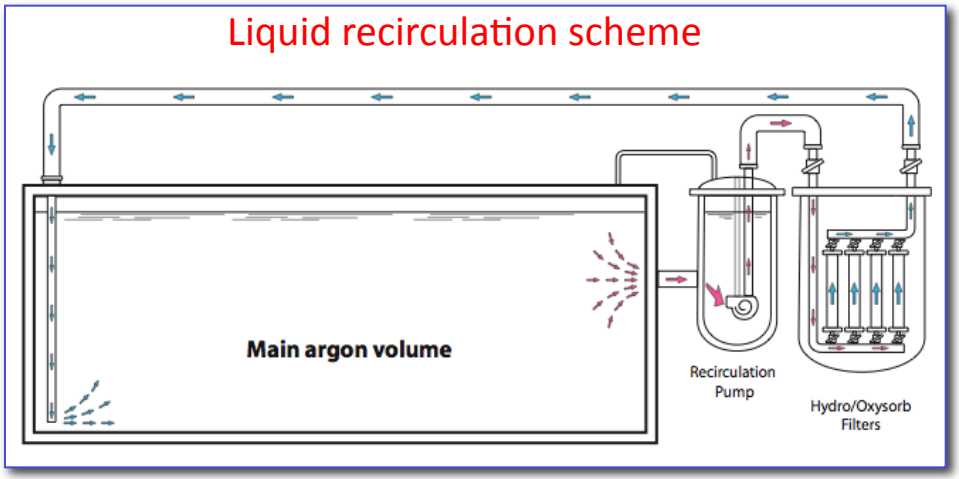
LAr Purification in T600

- The presence of electron trapping polar impurities attenuates the electron signal as $\exp(-t_D/\tau_{ele})$
- τ_{ele} ~ 300 µs / ppb (O_2 equivalent)
- Because of temperature (87 K) most of the contaminants freeze out spontaneously. Main residuals: O_2, H_2O, CO_2
- Recirculation/purification (100 Nm^3/h) of the gas phase (~40 Nm^3) 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) into the bulk liquid
- Recirculation/purification (4 m^3/h) of the bulk liquid volume (~550 m^3) to efficiently reduce the initial impurities concentration (can be switched on/off)

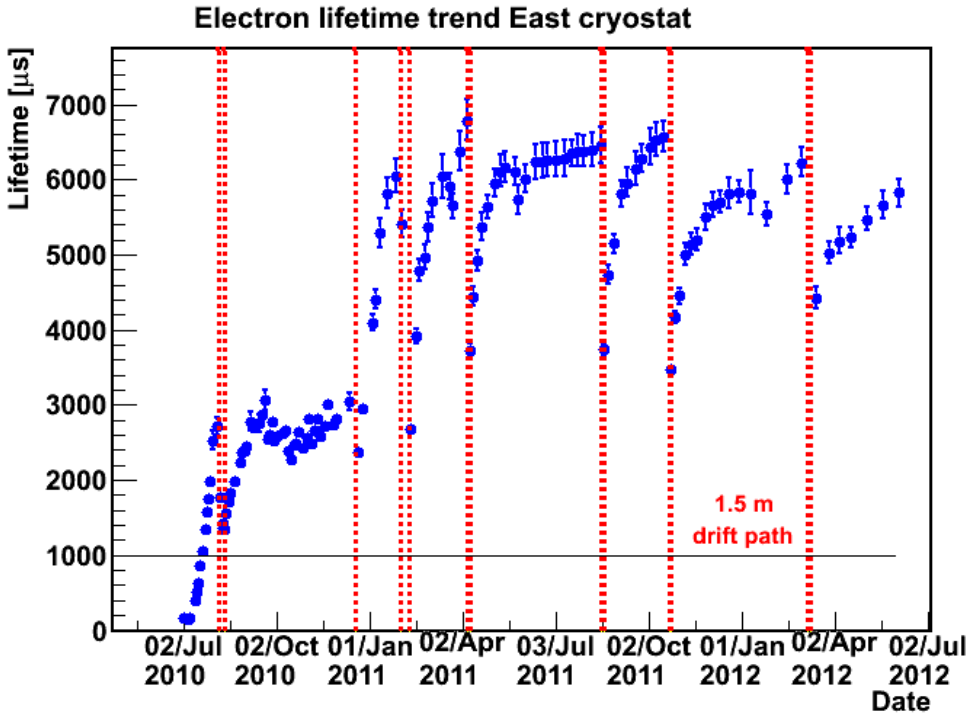
Gas recirculation scheme

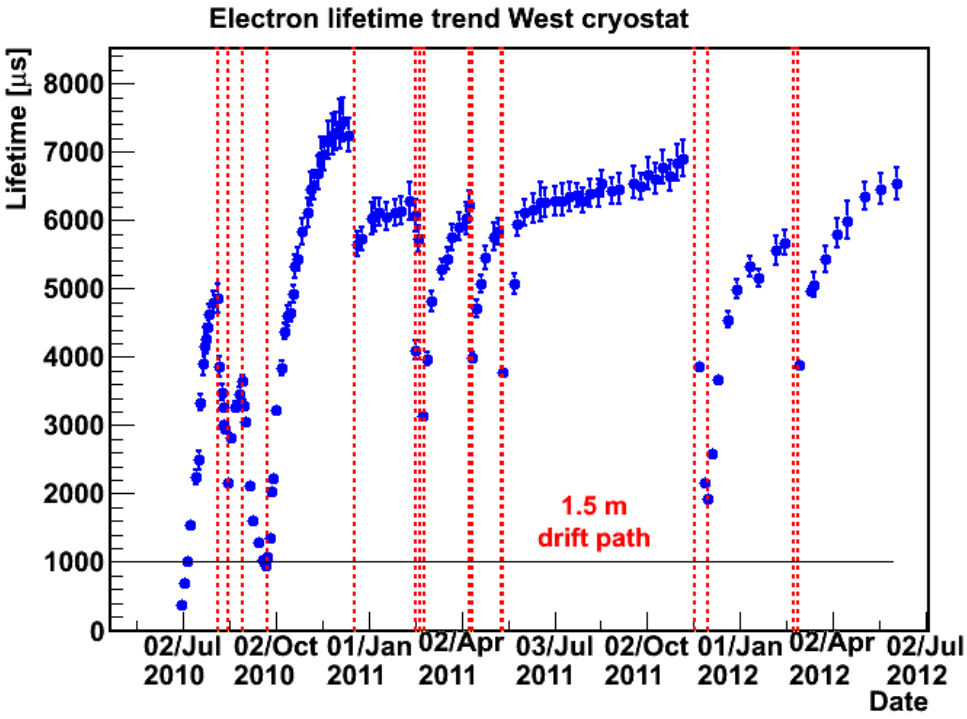


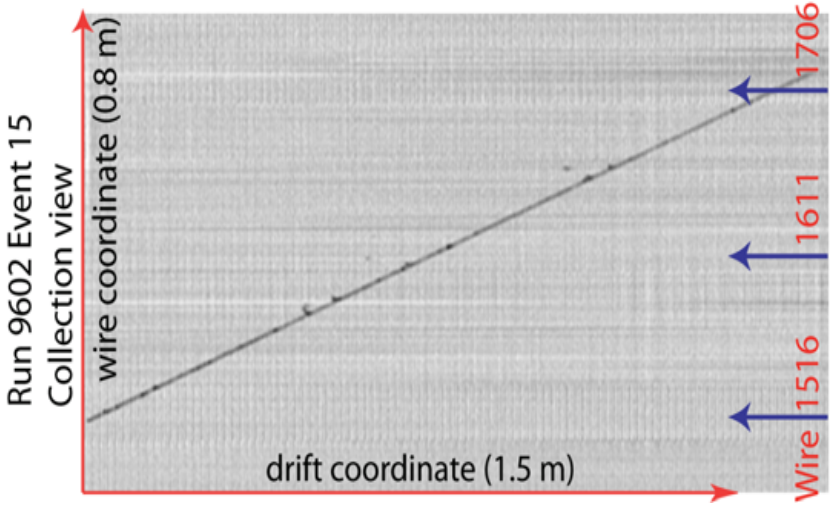
Liquid recirculation scheme



LAr purity measurement







- Key feature: LAr purity from electro-negative molecules (O_2, H_2O, CO_2)
- Electron life-time measured by charge attenuation study on cosmic μ tracks
- τ_{ele}>5ms (~60 ppt $[O_2]_{eq}$) corresponding to 17% max. charge attenuation at 1.5 m
- These results would allows operation at larger drift distances

ICARUS T600 physics potential

- T600 is a major milestone towards the realization of a much more massive multikton LAr detector, but it offers also some interesting physics in itself. The unique imaging capability of ICARUS, its spatial/calorimetric resolutions, and e/π^0 separation allow to observe events in a new way
- The detector is collecting "bubble chamber like" CNGS events: for 10^{20} pot
  - CC event expected ≈ 2800 evts
  - NC event expected ≈ 900 evts
  - Muons from upstream GS rock ≈ 12000 evts (≈ 8200 on TPC front face)
  - Intrinsic beam ν_e CC ≈ 26 evts
  - $\nu_\mu \Rightarrow \nu_\tau$ detecting τ decay with kinematical criteria (~2 event τ->e)
  - $\nu_\mu \Rightarrow \nu_e$ (θ_{13}) from e-like CC events excess at E < 20 GeV (~5 events CC)
  - Search for sterile neutrinos in LSND parameter space, with e-like CC events excess at E > 10 GeV
- The T600 is also collecting simultaneously "self triggered" events:
  - ≈ 100 evts/year of atmospheric ν CC interactions
  - Proton decay with 3×10^{32} nucleons , zero bckg. in some of the channels

ICARUS T600 data taking

- CNGS:
  - CNGS "Early Warning" signal sent 80 ms before the SPS proton extraction: allows opening a 60 ms wide gate around neutrino arrival time at LNGS
  - PMTs 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 (10.5 μs), 1 mHz event rate, ≈ 80 events/day

- Cosmic Rays:
  - PMTs sum signal: coincidence of two adjacent chambers (50% cathode transparency)
  - Globally 36 mHz trigger rate achieved: ~130 cosmic events/h

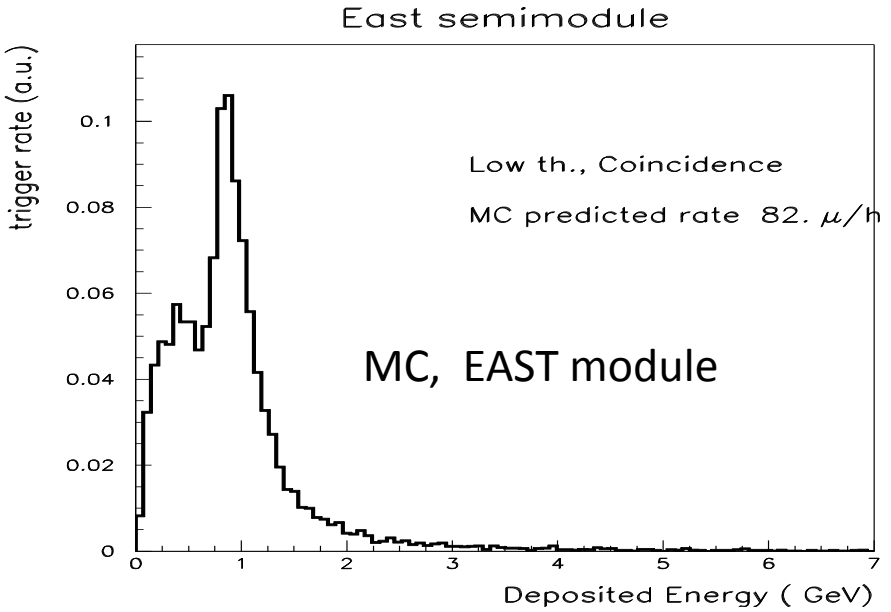
- Local trigger based on deposited charge:
  - On-line hit-finding/zero-skipping algorithm implemented in FPGA's, used to improve trigger efficiency at low energy (below 500 MeV)

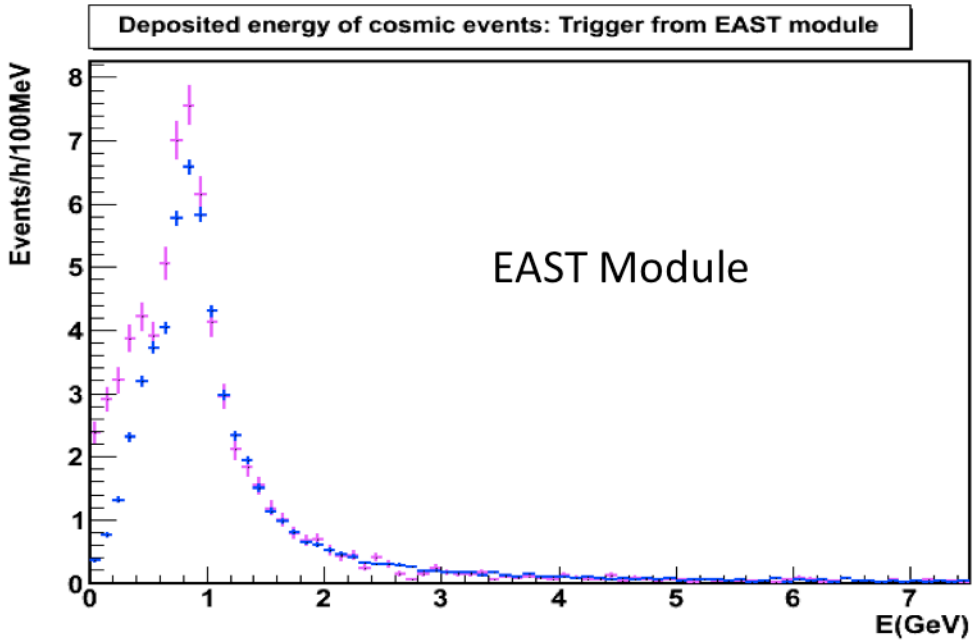
Cosmic ray muon spectrum

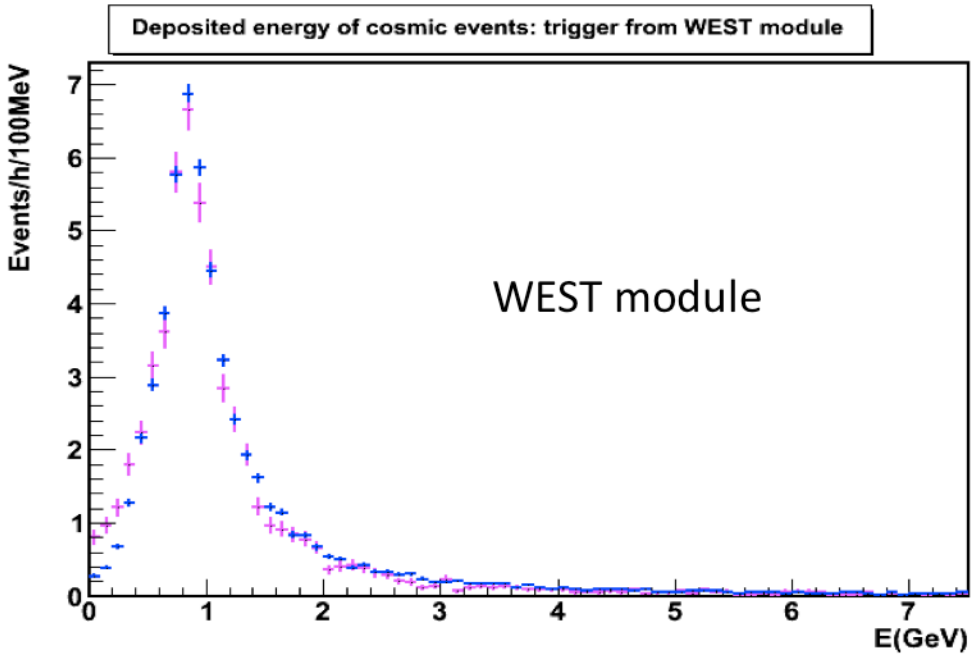
- CR data automatically filtered:
  - Skip fake triggers
  - Find "good" muons for purity

- Good agreement of energy spectrum with MC expectation is found (MC simulation includes light collection and trigger conditions)

2011 data
2012 data, after upgrade of PMT electronics



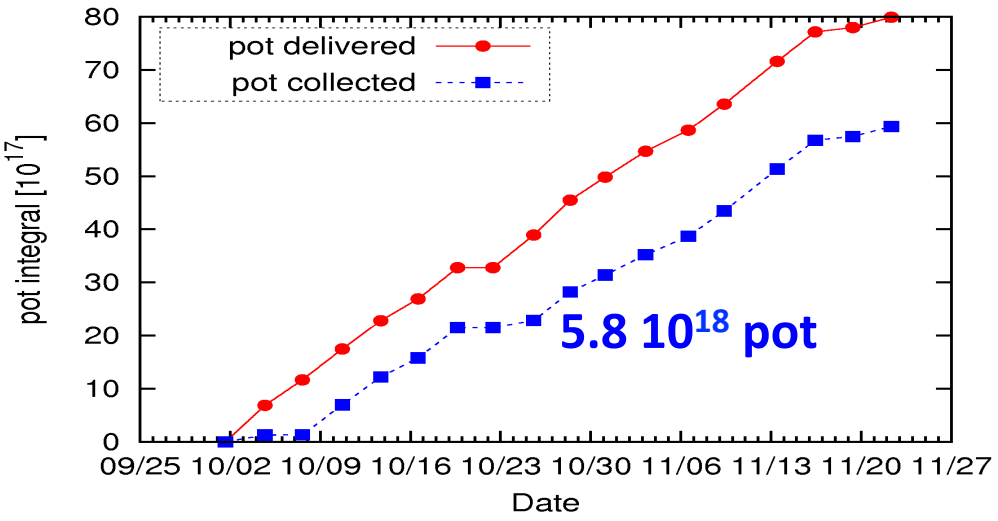




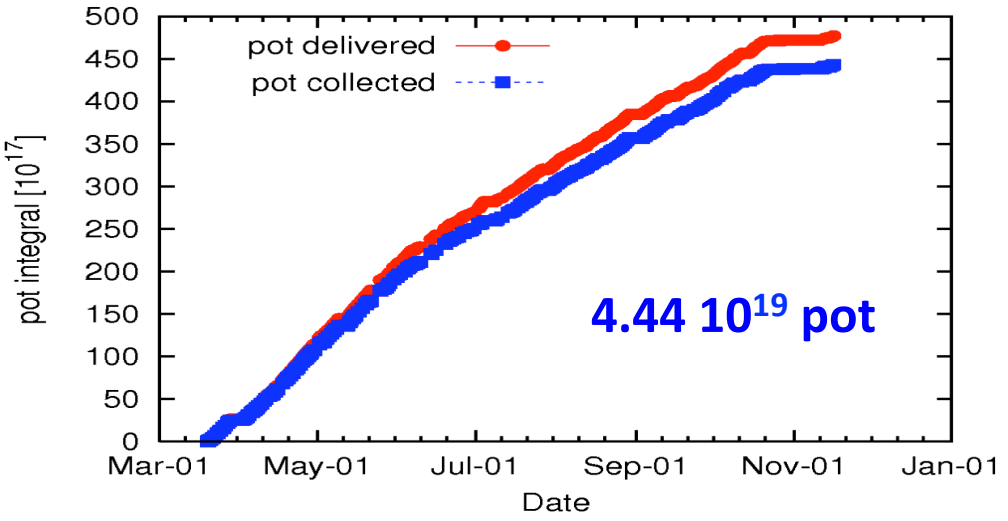
CNGS neutrino runs

ICARUS T600 fully operational since Oct. 1st 2010

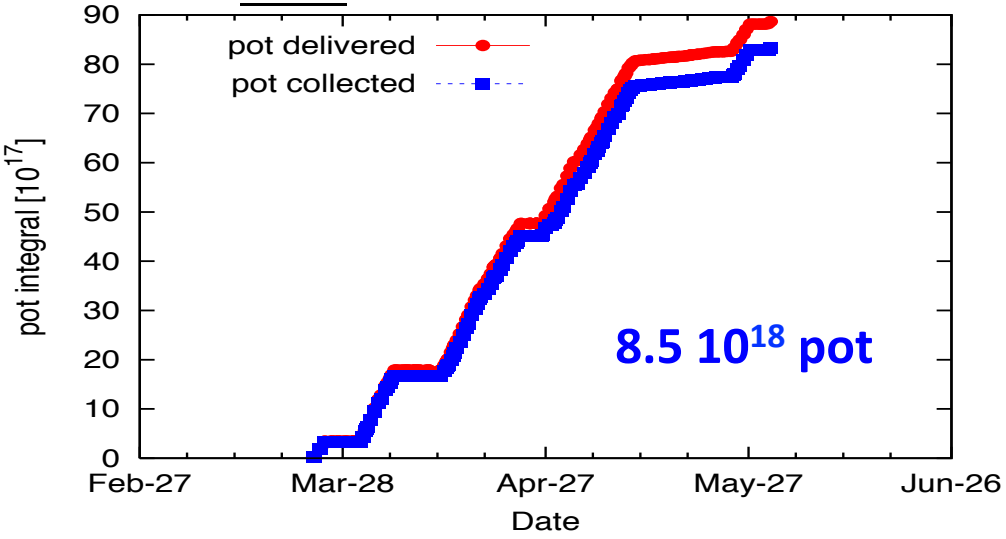
2010: Oct. 1st ÷ Nov. 22nd



2011: Mar. 19th ÷ Nov. 14th

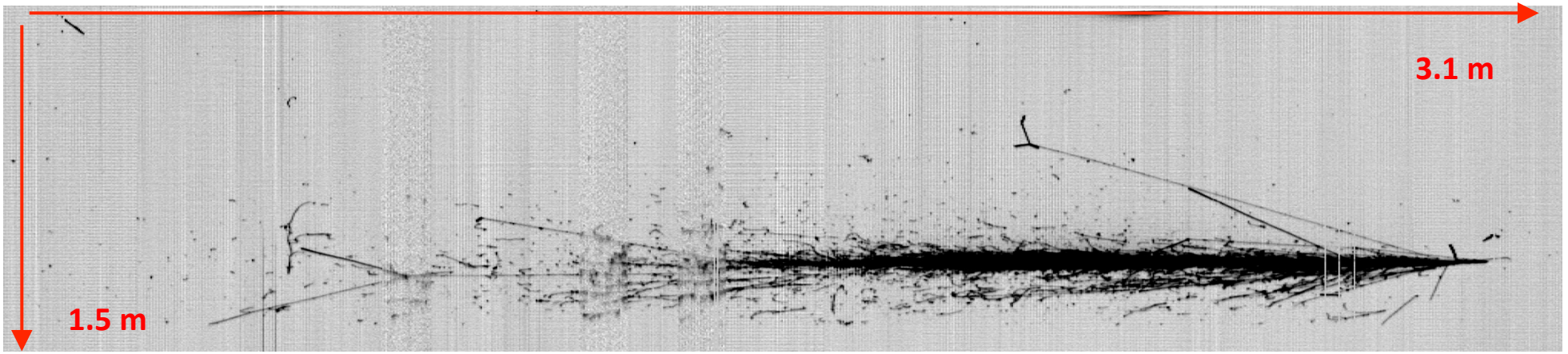


2012: March 23rd ÷ now

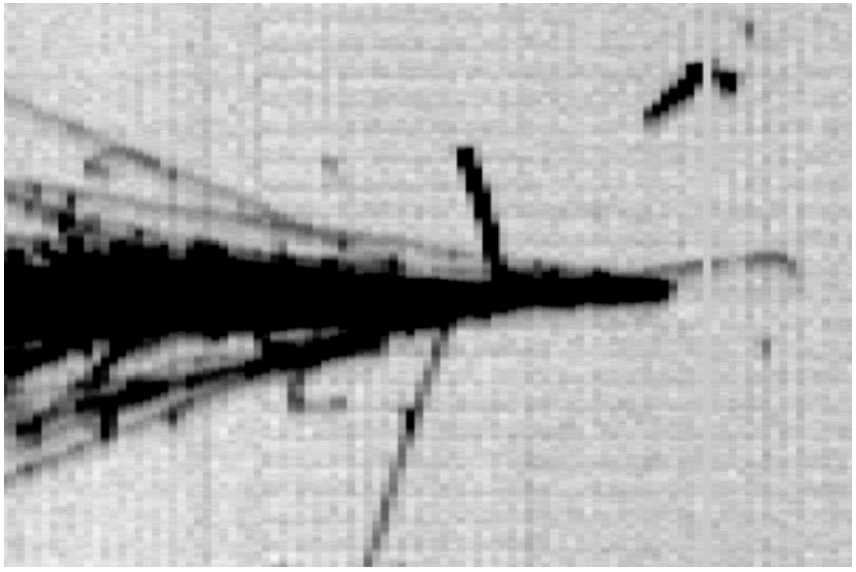


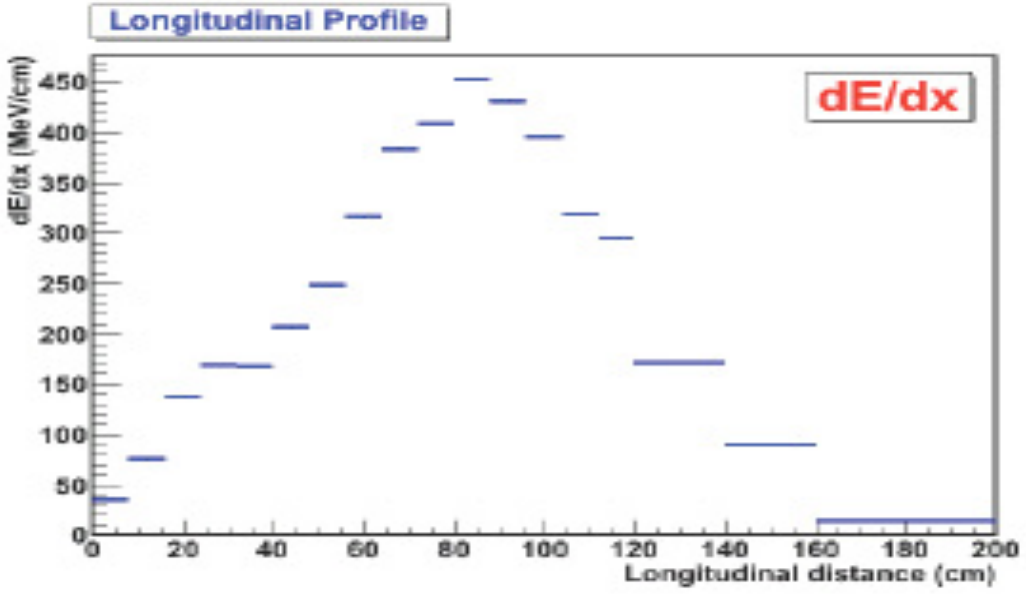
- **Detector live-time > 93%**
- November 2011 and May 2012: timing measurement with bunched beam
- 2010 data used as a training/control sample for reconstruction/analysis software

CNGS CC ν_e event candidate



A ν_e CC candidate from 2010 run. Total energy is 45 GeV with a single energetic 37 GeV e.m. shower at the vertex with a longitudinal profile peaking at the expected position (~88 cm)





CNGS CC ν_μ events reconstruction

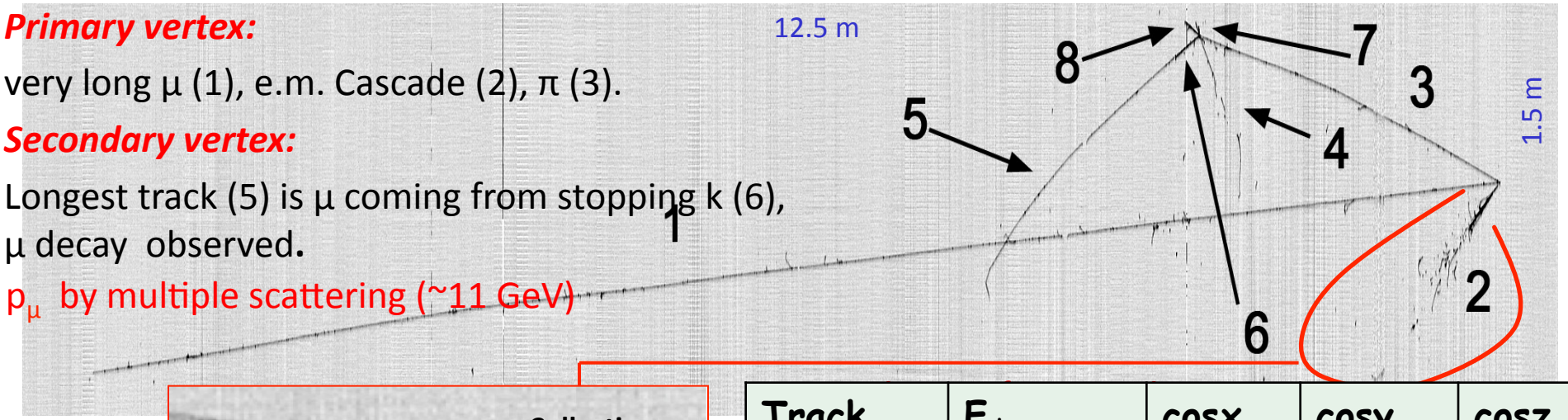
Primary vertex:

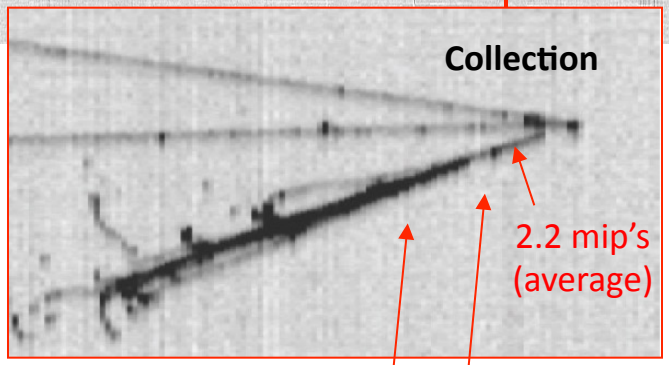
very long μ (1), e.m. Cascade (2), π (3).

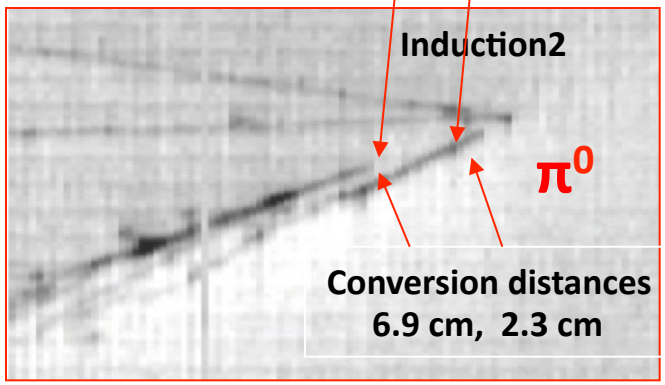
Secondary vertex:

Longest track (5) is μ coming from stopping k (6), μ decay observed.

p_μ by multiple scattering (~11 GeV)



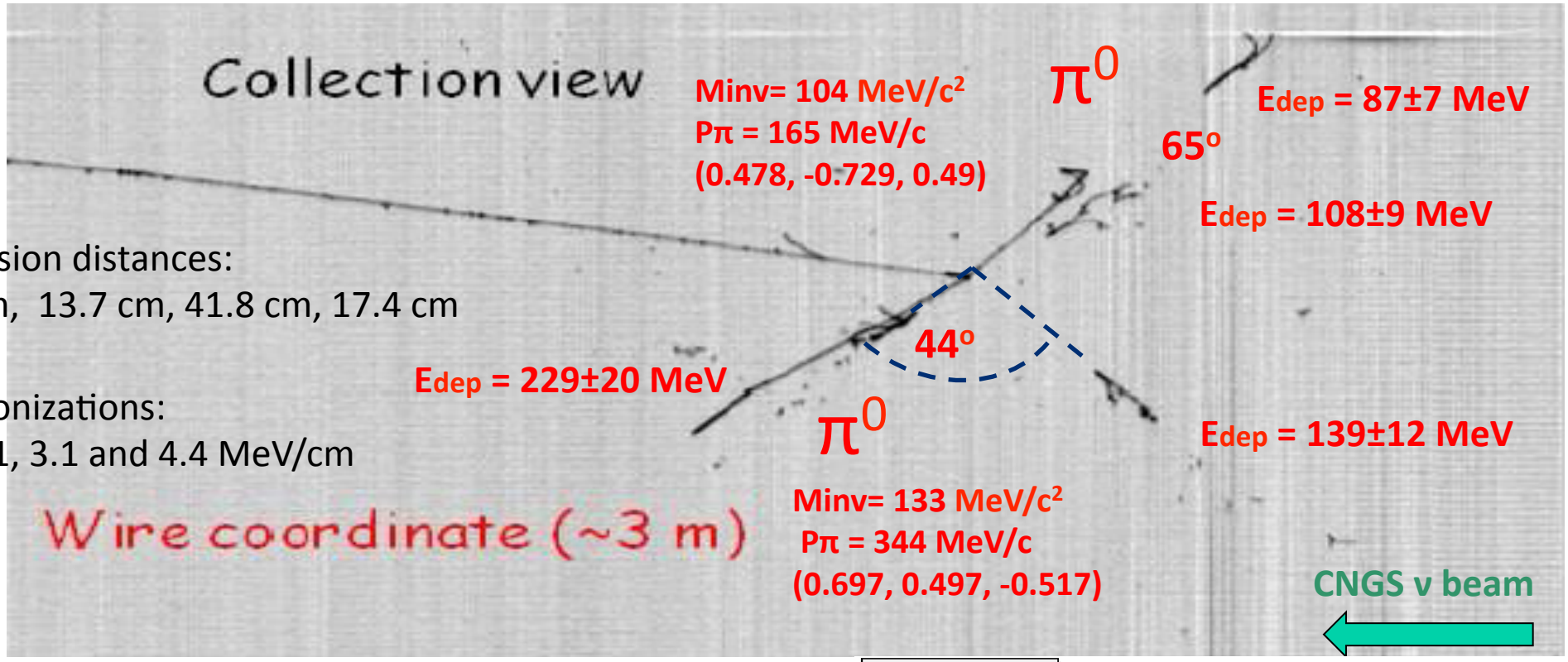




$M^* = 125 \pm 15$ MeV/c^2

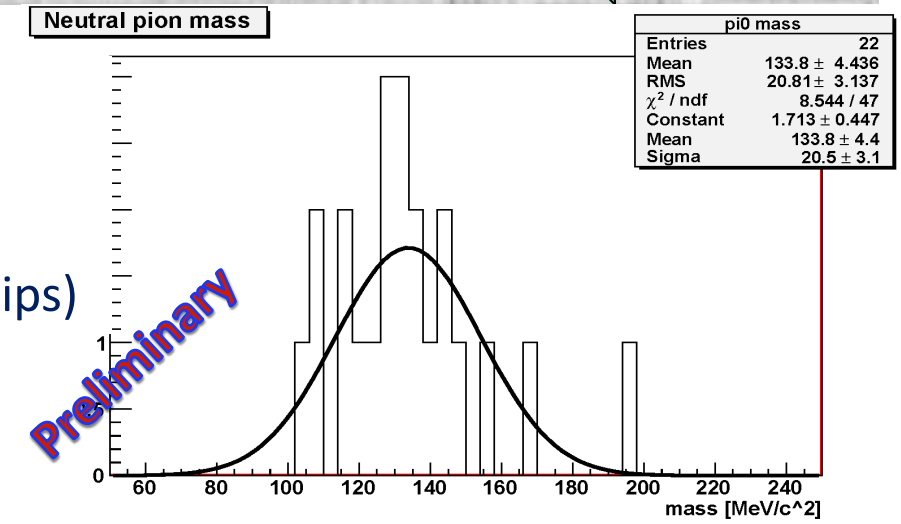
Track	E_{dep} [MeV]	cosx	cosy	cosz
1 (μ)	2702	0.069	-0.040	-0.997
2	521	0.054	-0.420	-0.906
3 (π)	514	-0.001	0.137	-0.991
Sec. vtx.	797			
4	77	0.009	-0.649	0.761
5 (μ)	314			
6 (K)	87	0.000	-0.239	-0.971
7	36	0.414	0.793	-0.446
8	283	-0.613	0.150	-0.776
	4.5 GeV			

π^0 identification/reconstruction in CNGS events



Conversion distances:
71.2 cm, 13.7 cm, 41.8 cm, 17.4 cm

Initial ionizations:
5.1, 6.1, 3.1 and 4.4 MeV/cm



π^0-showers identified by

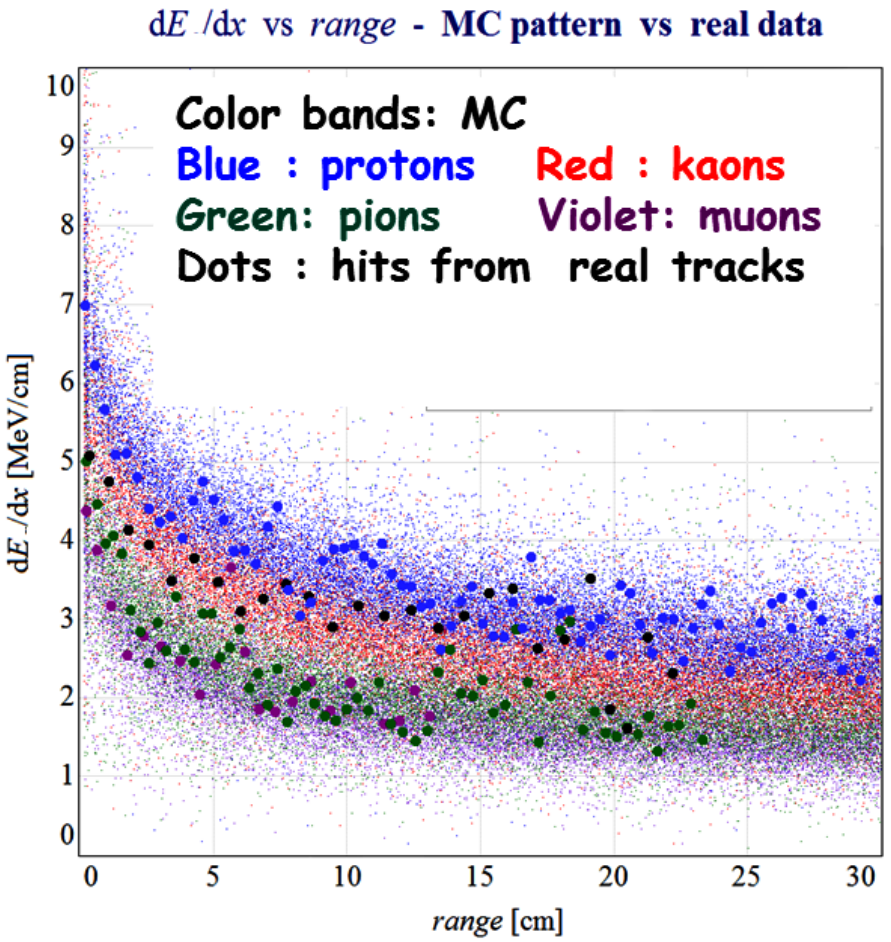
- 2γ conversion separated from primary vertex
- Reconstruction of γγ invariant mass
- Ionization in the first segment of showers (1 or 2 mips)

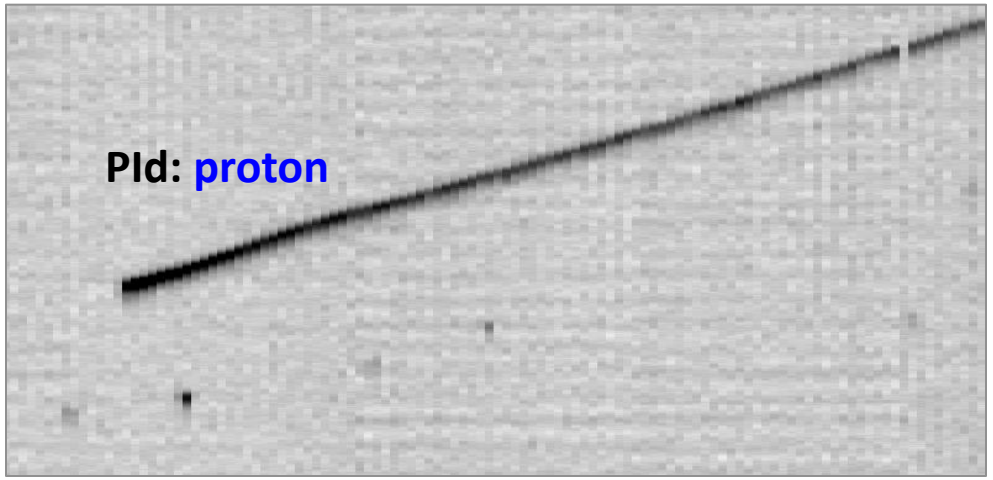
Mean: 133.8 ± 4.4(stat) ± 4 (syst) MeV/c²
σ = 20.5 MeV

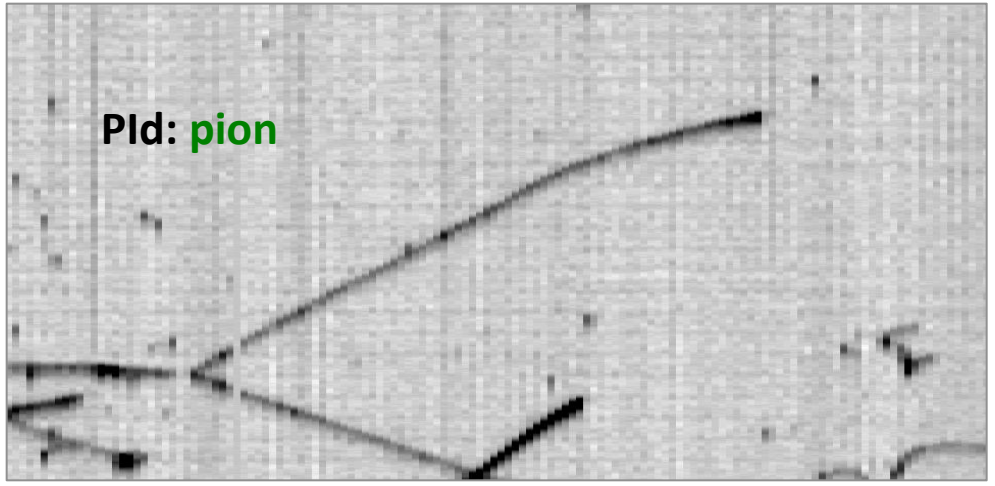
Stopping particles identification

Stopping particle tracks visually selected: no decay products, increasing ionization density at the end, at least 5 hits in Collection, clean view in Collection

- Deposited dE/dx vs residual range
- No quenching corrections



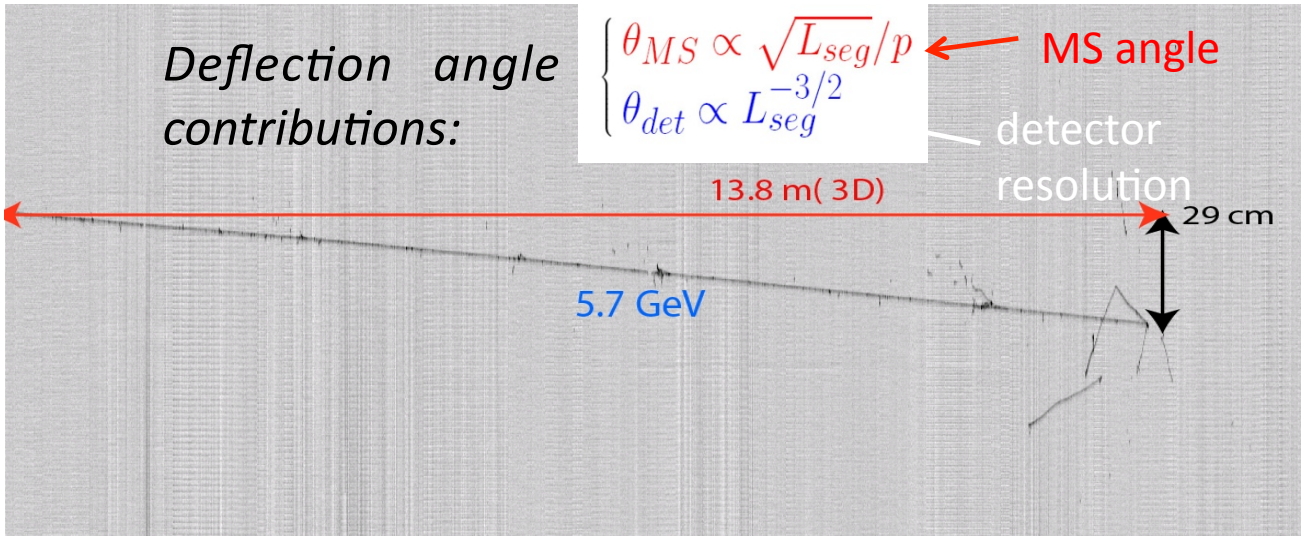




Muon momentum by multiple scattering

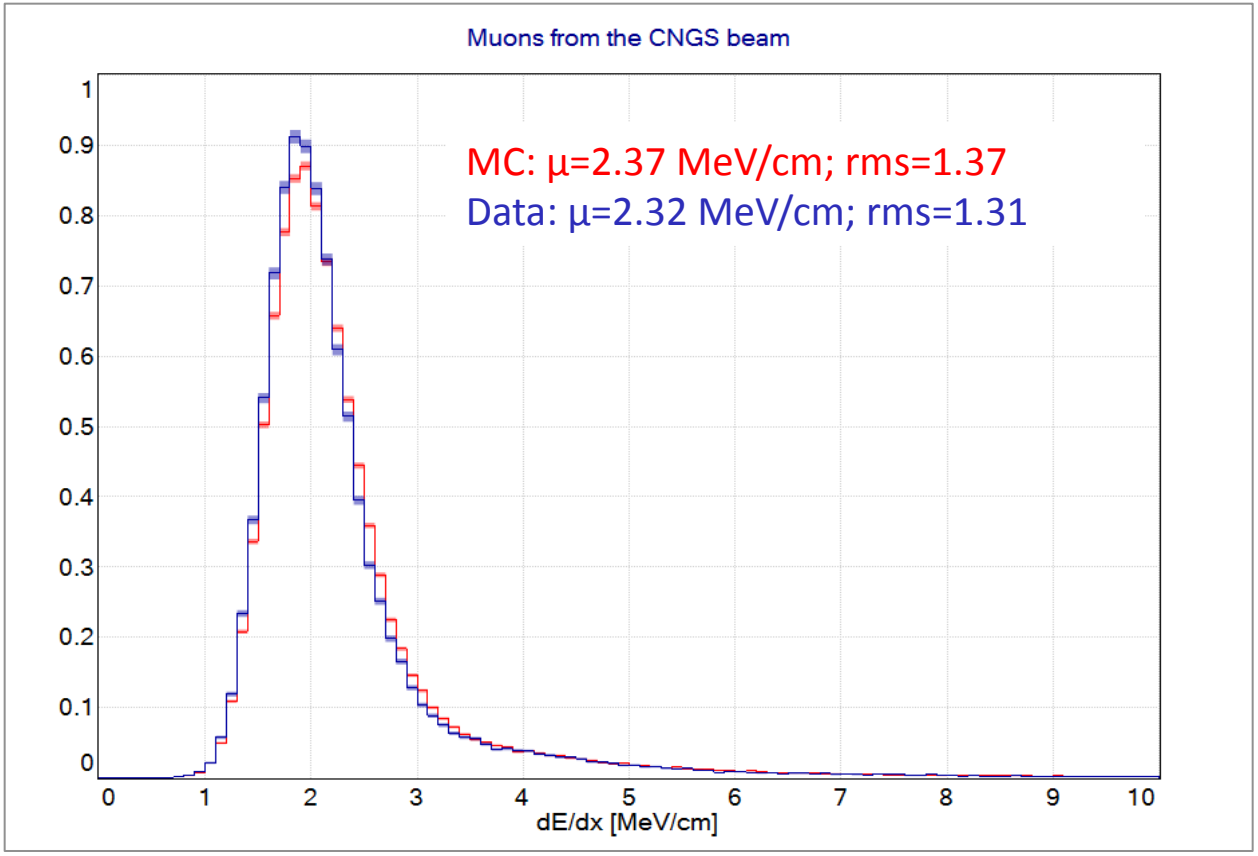
- Key tool to measure momentum of non-contained μ's: essential for atmospheric / CNGS ν's

- Kalman fit of the segmented μ track (segment length L_{seg})
- Momentum p extracted from deflection angle θ, χ^2 of fit



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

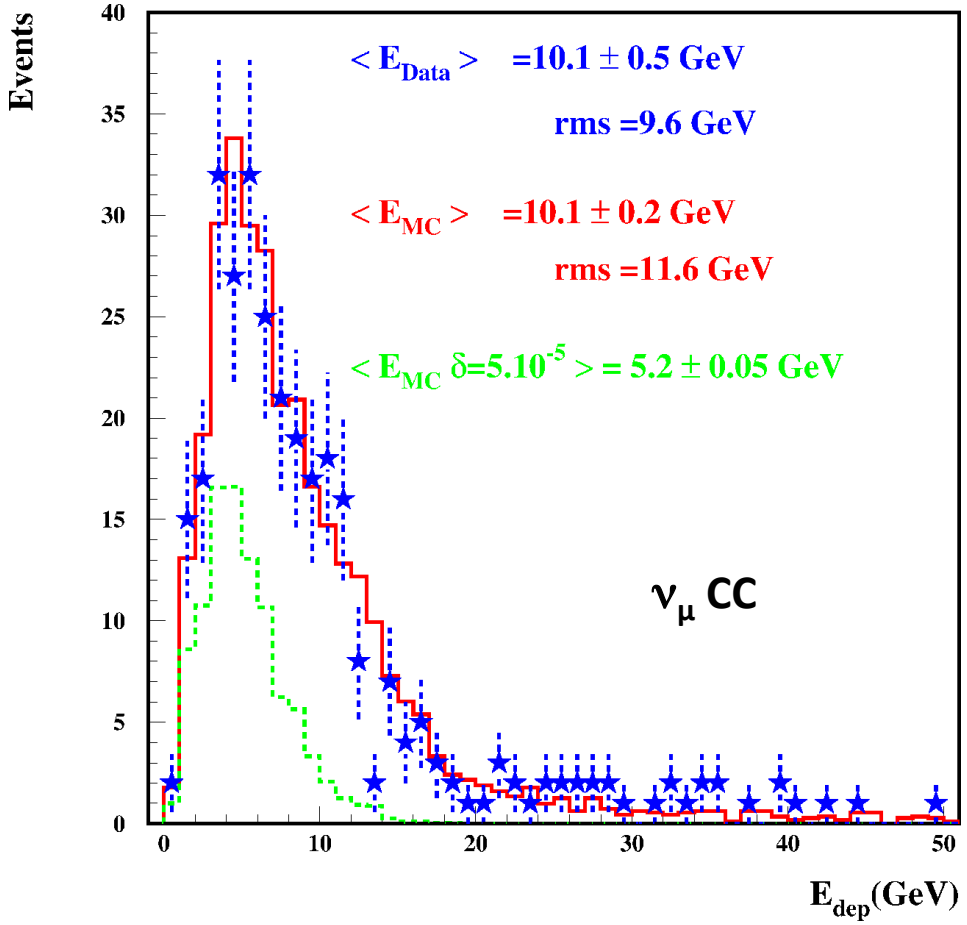
m.i.p. calibration with CNGS muons

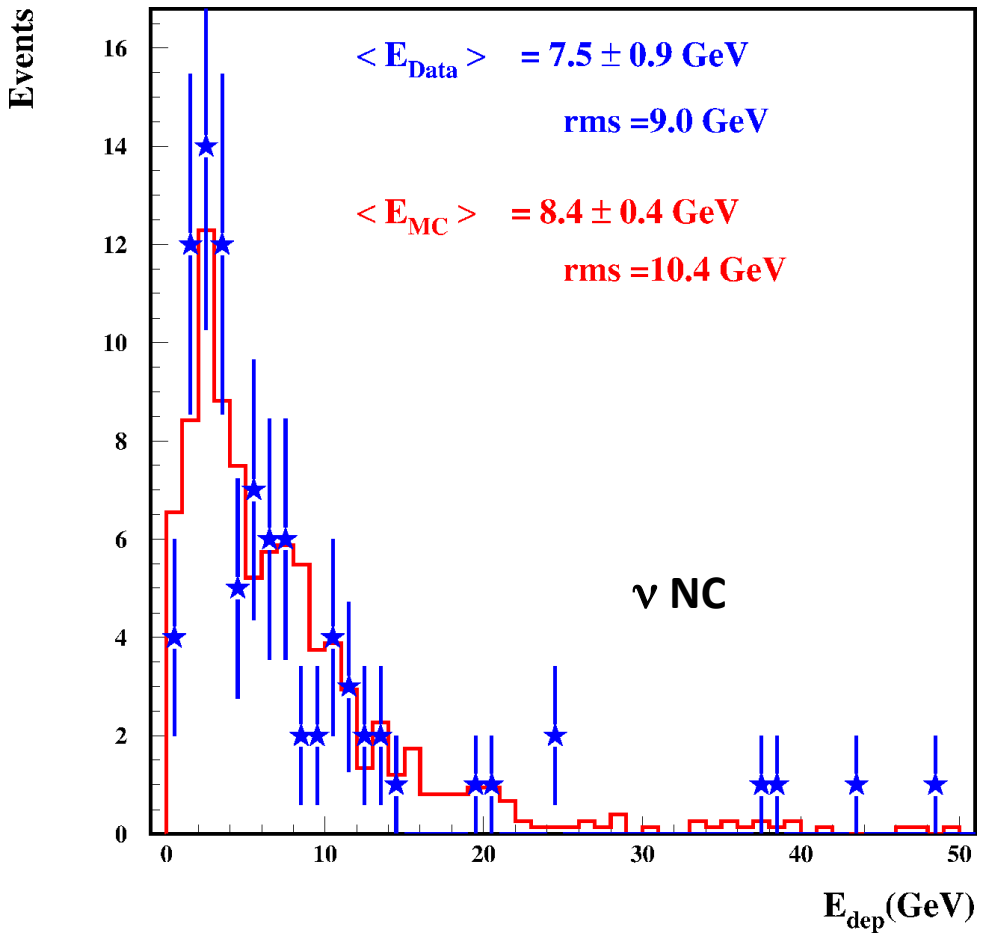


dE/dx distribution for real and MC muon tracks from CNGS events

- 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

Total energy deposition in CNGS ν 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 the ICARUS T600 detector *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 $0.78 \times E_\nu$ 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 $\delta = 5 \times 10^{-5}$ (OPERA first claim):
  - full ν event suppression for E > 30 GeV
  - ~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:

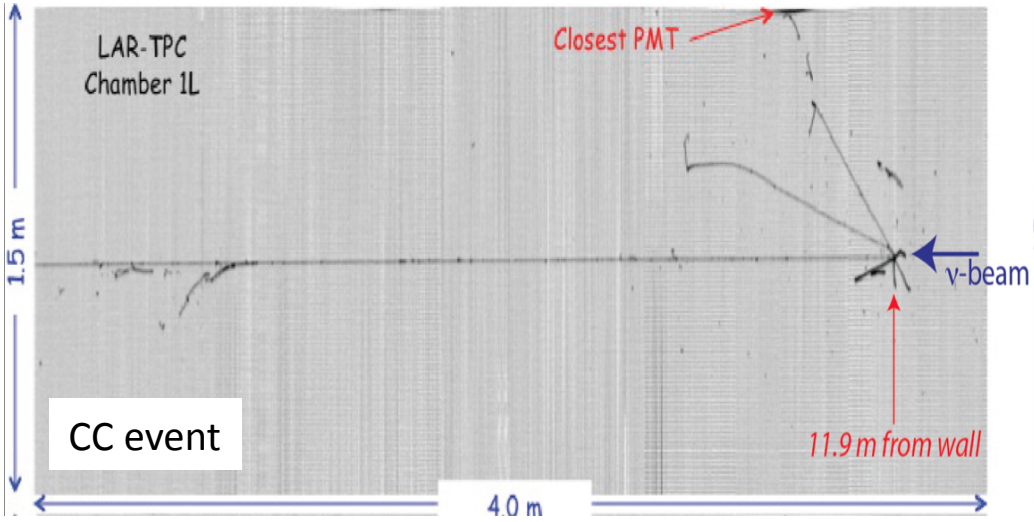
$$\delta = (v_\nu^2 - c^2)/c^2 < 2.5 \times 10^{-8} \text{ 90\% CL}$$

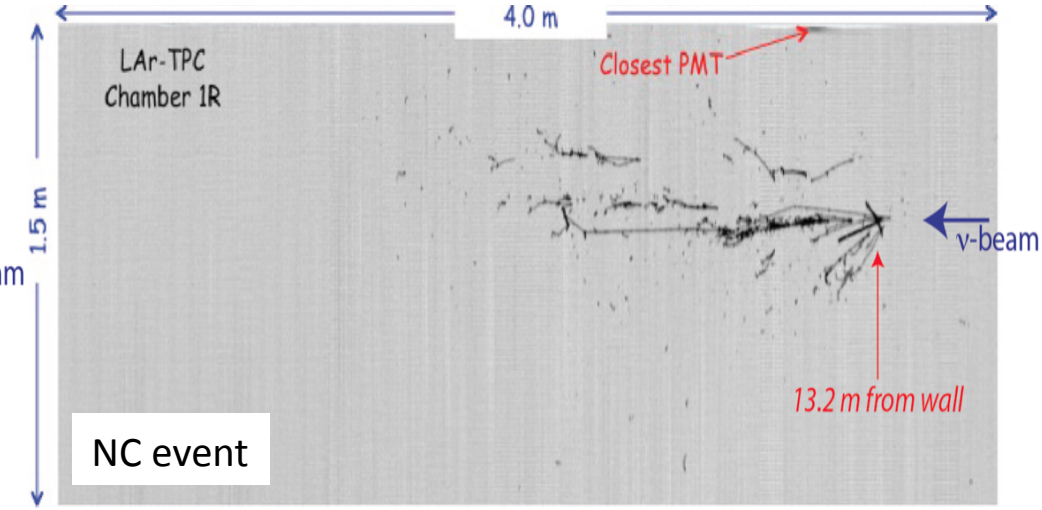
Comparable to the SuperK atm. limit $\delta < 1.4 \times 10^{-8}$, somewhat larger than the lower energy velocity constraint $\delta < 4 \times 10^{-9}$ from SN1987A

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 ν_μ events, 1 NC ν event, 1 stopping + 3 crossing μ's from ν 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



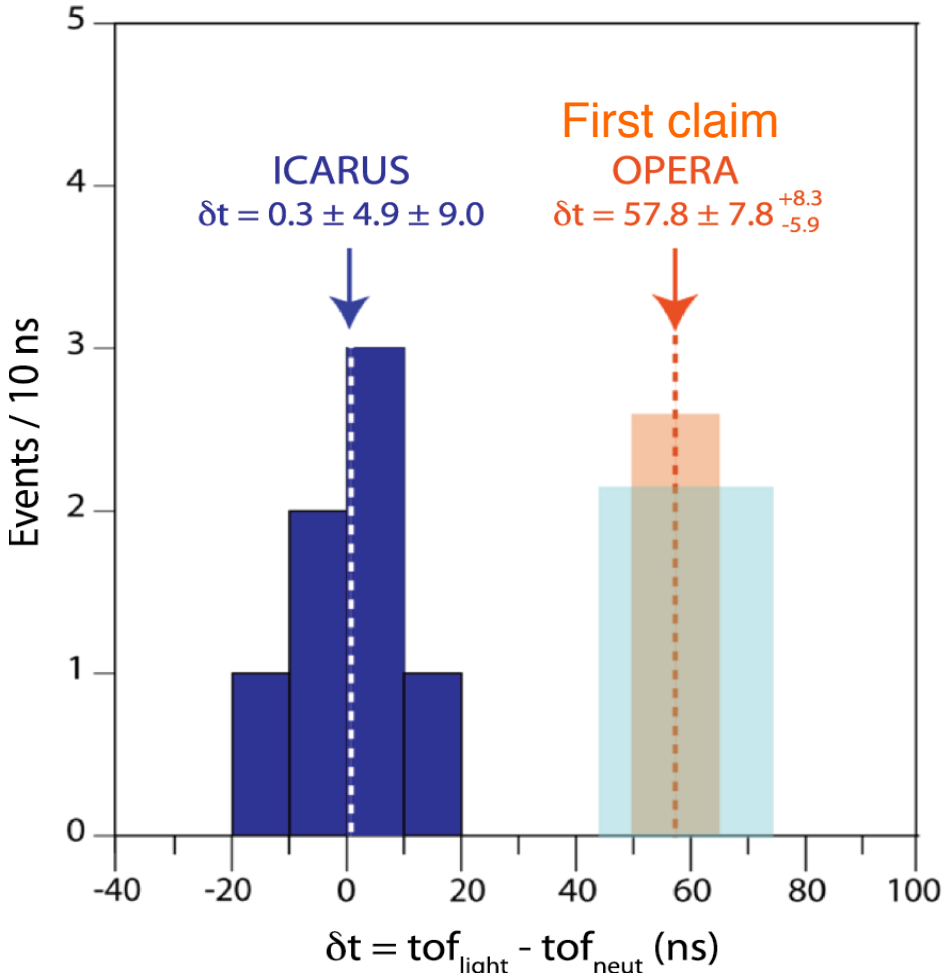


Neutrino time of flight: 2011 results

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

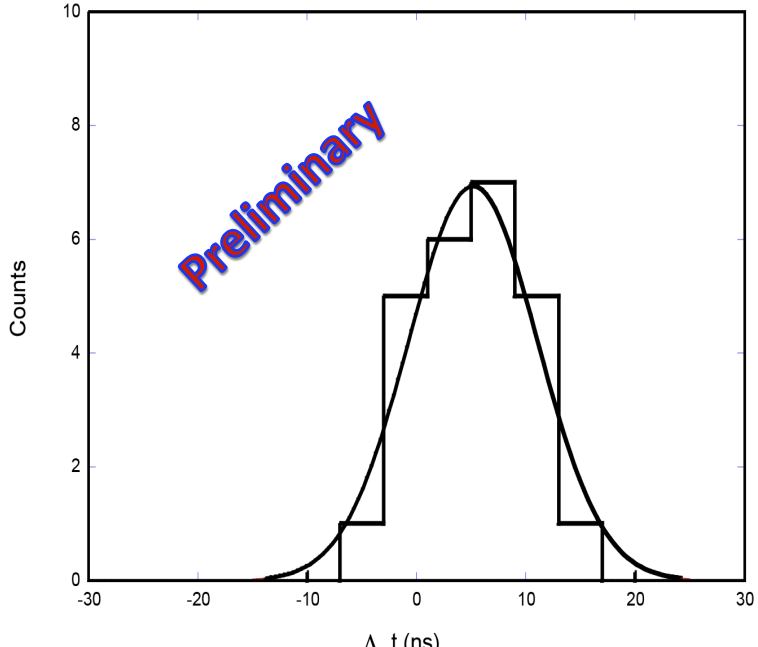
- All fixed delays/propagation times calibrated (thanks also to LNGS and CERN)
- Baseline estimation relies on existing available geodesy data (OPERA/LNGS)
- Variable corrections to GPS from OPERA/CERN recipe

- 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



Neutrino time of flight: 2012 bunched CNGS

- 2012 bunched beam:
  - 4 batches per extraction, ~300 ns batch separation, 1 extraction per CNGS cycle
  - 16 bunches per batch, ~100 ns bunch separation, 3 ns FWHM
- Beam related events observed in ICARUS:
  - 16 crossing μ's (1 stopping) from the upstream rock
  - 7 CC ν_μ events
  - 2 NC ν event
- In agreement with expectation for the integrated ~1.8×10^{17} pot
- Analysis in progress
  - **PRELIMINARY** results compatible with 2011 value: 5.1±1.1 (stat.)±5.5 (syst.); distribution r.m.s: ~ 5.7 ns (10.5 in 2011)
  - Systematics corrections and offset under final evaluation (PMT-DAQ propagation chain, topological delays)
  - Additional informations from other 2 timing systems are under study for cross-check



Conclusions

- ICARUS T600 is the first large Liquid Argon Time Projection Chamber (~600 tons of LAr) operated underground at INFN-LNGS laboratory and addressed to the study of "rare events" and, among these, neutrino interactions
- 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 ν's and proton decay
- Its unique imaging capability, spatial/calorimetric resolutions and e/π^0 separation allow to reconstruct/identify events in a new way, w.r.t. previous/current experiments
- The ICARUS technology can be considered as a major milestone towards the realization of next generation of more massive LAr detectors (~tens of ktons) for neutrino and rare event physics
- High detection efficiency reached for CNGS events
- Contributions to the "superluminal" neutrino problem
- Data analysis of CNGS neutrino events is ongoing. Results expected on neutrino oscillation will be presented when final