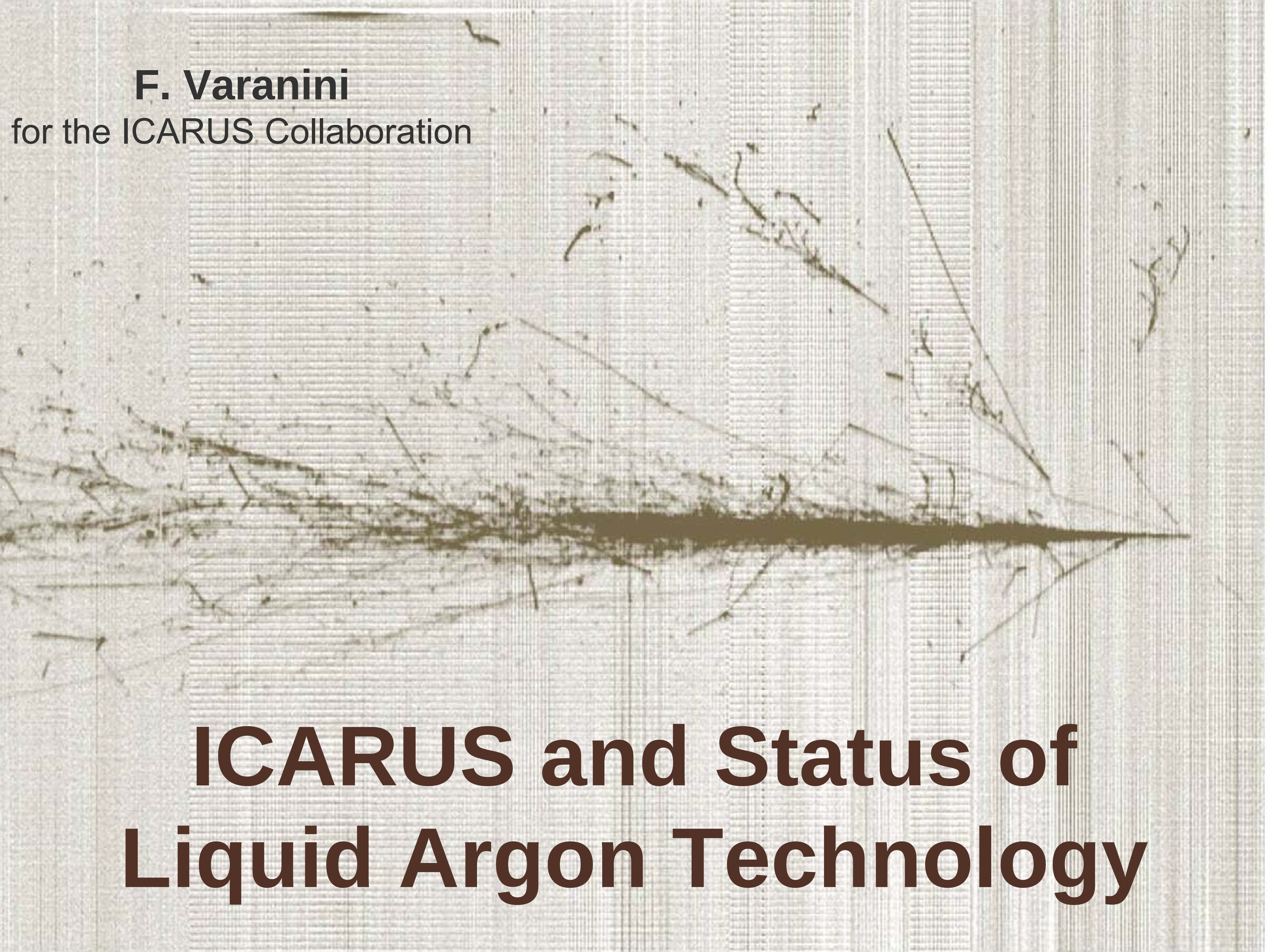

**F. Varanini**
for the ICARUS Collaboration

# ICARUS and Status of Liquid Argon Technology

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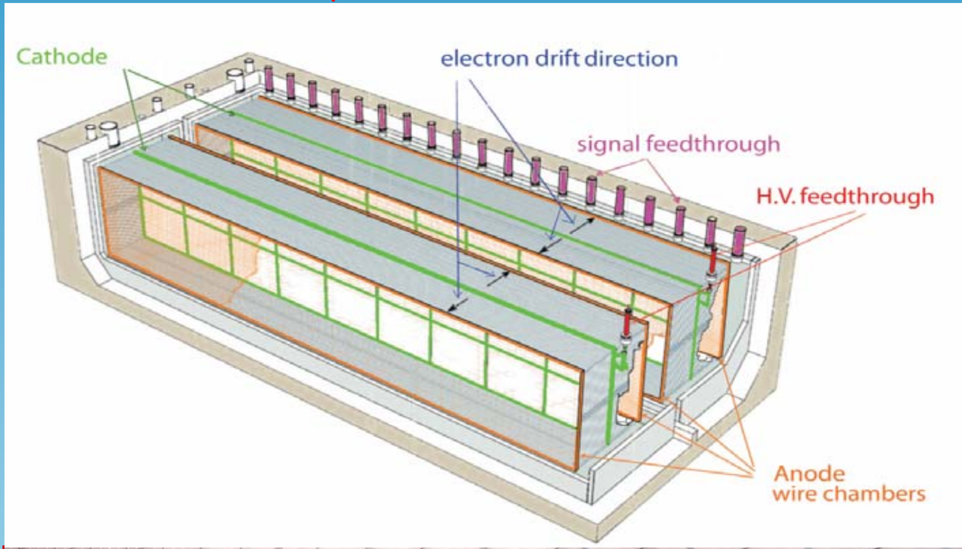
# ICARUS T600@LNGS: A novel instrument for neutrino physics

- Two identical T300 modules (2 chambers for each module)
- LAr active mass 476 t:
  - 3.0 x 3.2 x 18.0 ≈ 173 $m^3$;
  - drift length = 1.5 m;
  - $E_{drift}$=0.5 kV/cm; $v_{drift}$=1.55 mm/μs.
- 3 readout wire planes/chamber at 0°, ±60°, 3 mm plane spacing:
  - ≈ 53000 wires, 3 mm pitch
  - 2 Induction planes, 1 Collection
- PMT for scintillation light (128 nm):
  - 74 PMTs, 8" diameter + TPB

*Electronegative impurities (mainly $O_2$,$H_2O$) can attenuate $e^-$ signal: HIGH PURITY IS CRUCIAL!! (currently ~50 ppt)*

Installed in Hall B, receiving the CNGS $\nu_\mu$ beam from CERN




# ICARUS LAr TPC performance

Ideal detector for neutrino physics and rare events

3D imaging of any ionizing event (''electronic bubble chamber'') scalable to large masses:

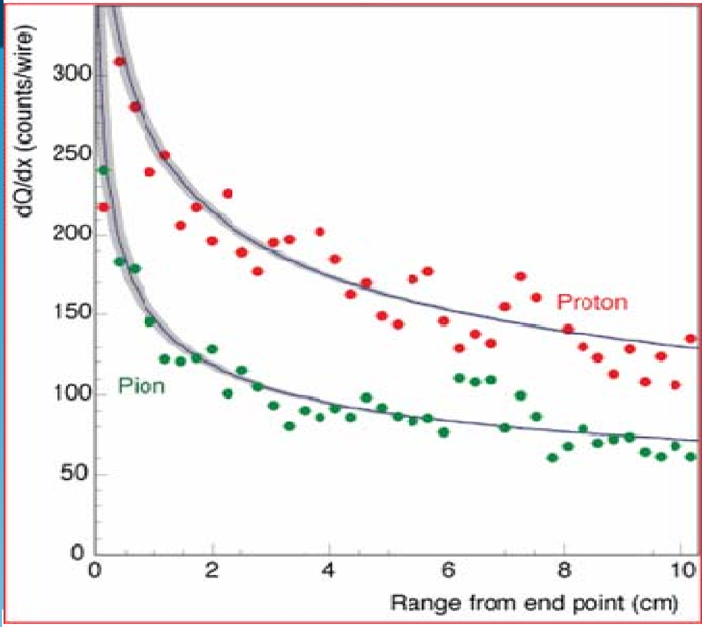
- continuously sensitive, self triggering;
- high granularity;
- excellent calorimetric properties ;
- scintillation light signals for trigger purposes;

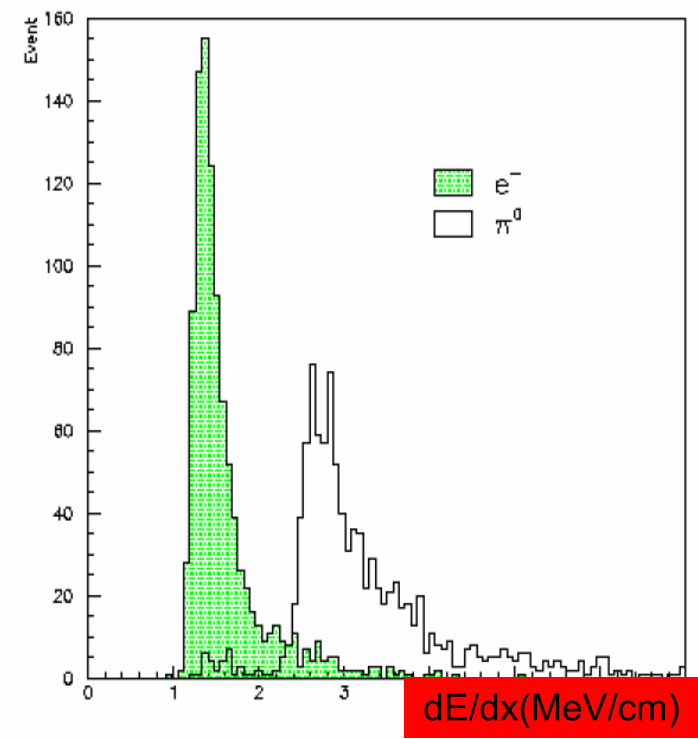
- Spatial resolution ~ mm
- Energy resolution for contained events
  3% / √ E(GeV) (EM showers)
  30% / √ E(GeV) (hadronic showers)
  11% / √ E(MeV) (LE electrons)

- Muon momentum by mult.scattering $\Delta p/p \sim 15\%$
- particle ID (dE/dx vs range + topology)

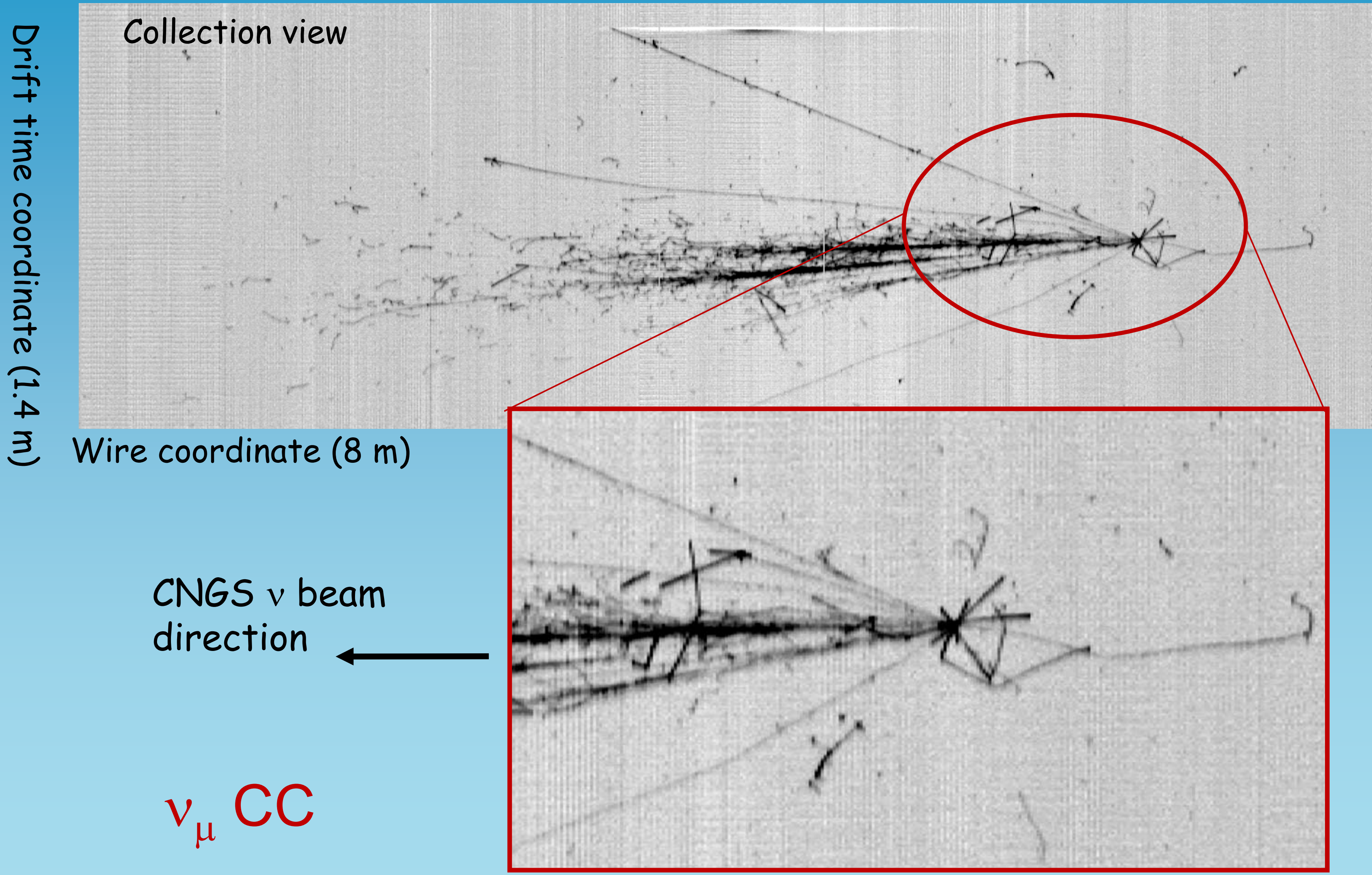
Very good $e/\pi^0$ separation:
$\nu$NC background rejected at <0.1% level while keeping 90% of $\nu_e$CC!!

dE/dx energy losses

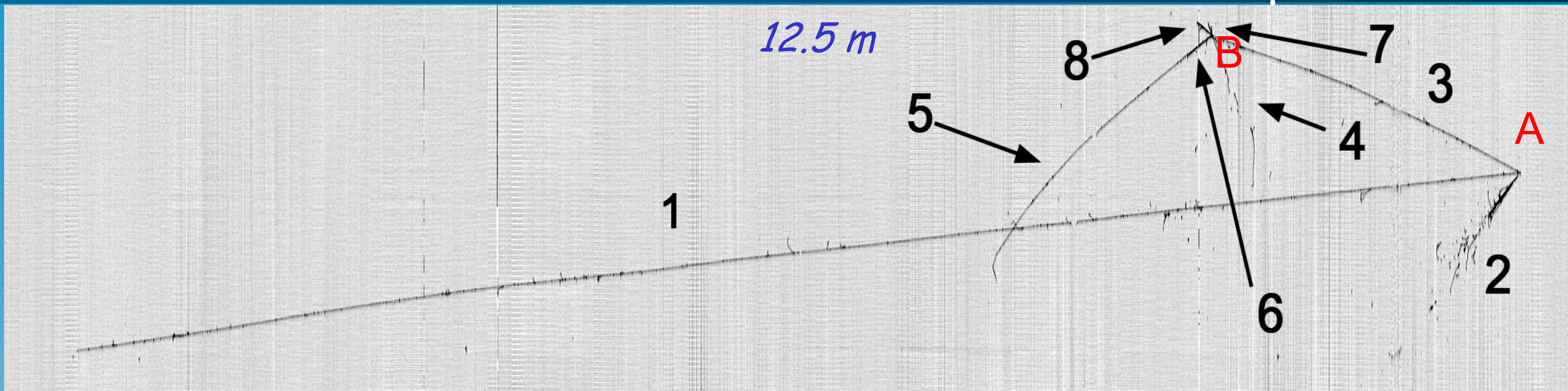


# The first CNGS neutrino interaction in ICARUS T600



# Full reconstruction of typical CNGS $\nu_\mu$CC event



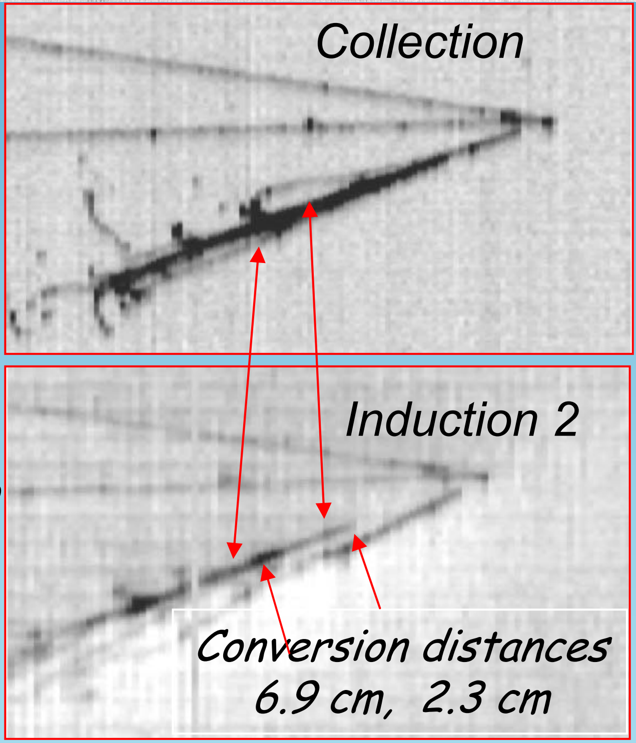

*ALL PARTICLES RECONSTRUCTED in 3D*
*+ DEPOSITED ENERGY MEASUREMENT*

*Primary vertex (A)*

- *Long $\mu$ - not contained(1) – 10.5 GeV from MS*
- *e.m. cascade(2),identified as $\pi^0$*
- *charged pion (3).*

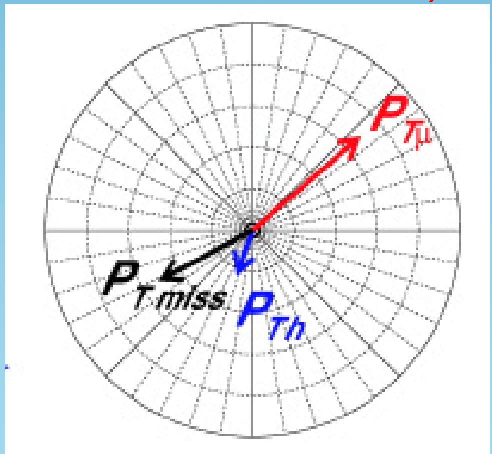
*Secondary vertex (B)*

*The longest track (5) is a $\mu$ coming from stopping K (6).*
*- $\mu$ decay is observed.*



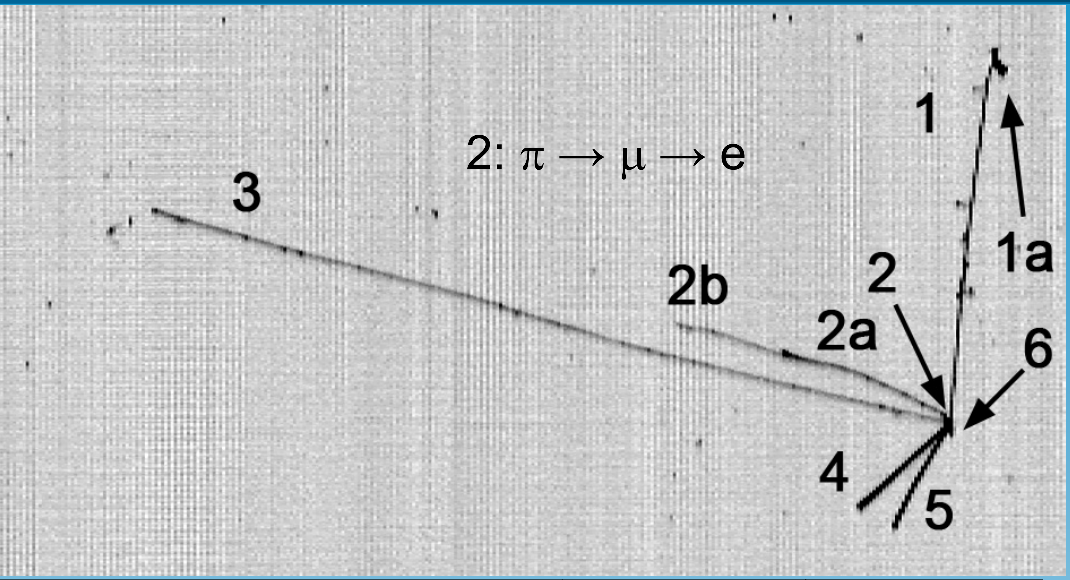

*$M^*_{\gamma\gamma}$ = 125±15 MeV/c²*

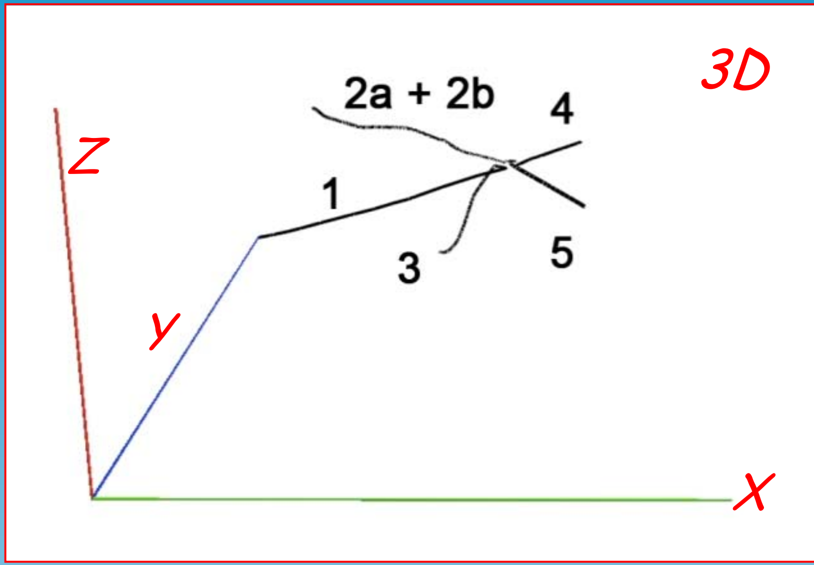
Total transverse Momentum ~ 250 MeV (consistent with Fermi momentum)




Outer circle=500 MeV

# An atmospheric neutrino candidate

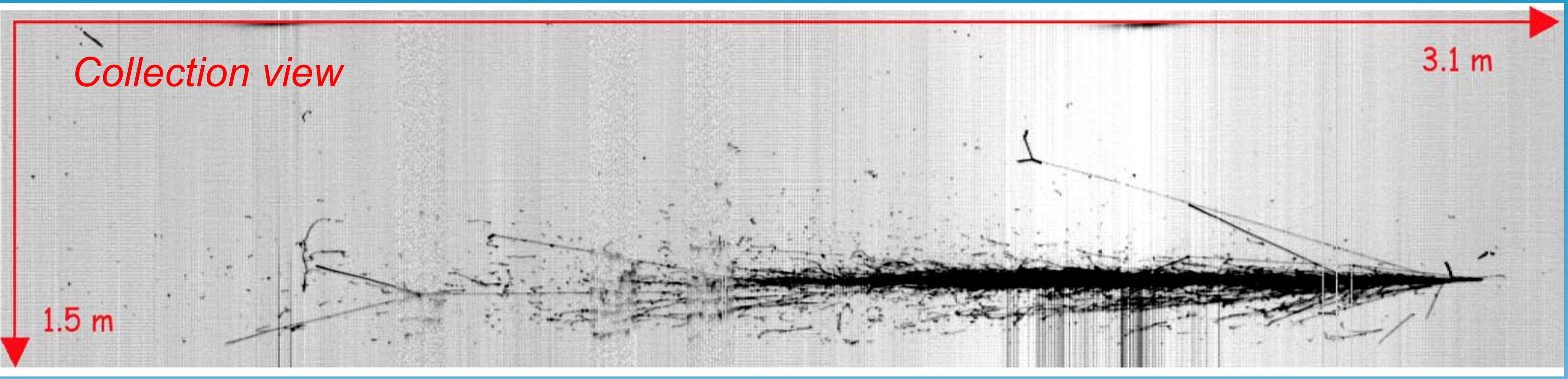


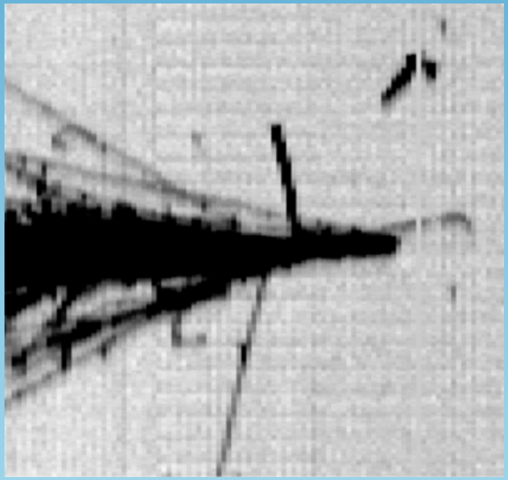

| Track | Ek[MeV] | range[cm] |
|---|---|---|
| 1 (prob. $\pi$, decays in flight) | 136.1 | 55.77 |
| 2 ($\pi$) | 26 | 3.3 |
| 2a ($\mu$) | 79.1 | 17.8 |
| 2b (e) | 24.1 | 10.4 |
| 3 ($\mu$) | 231.6 | 99.1 |
| 4 (p) | 168 | 19.2 |
| 5 (p) | 152 | 16.3 |
| 6 (?) (merged with vtx) | | 2.9 |

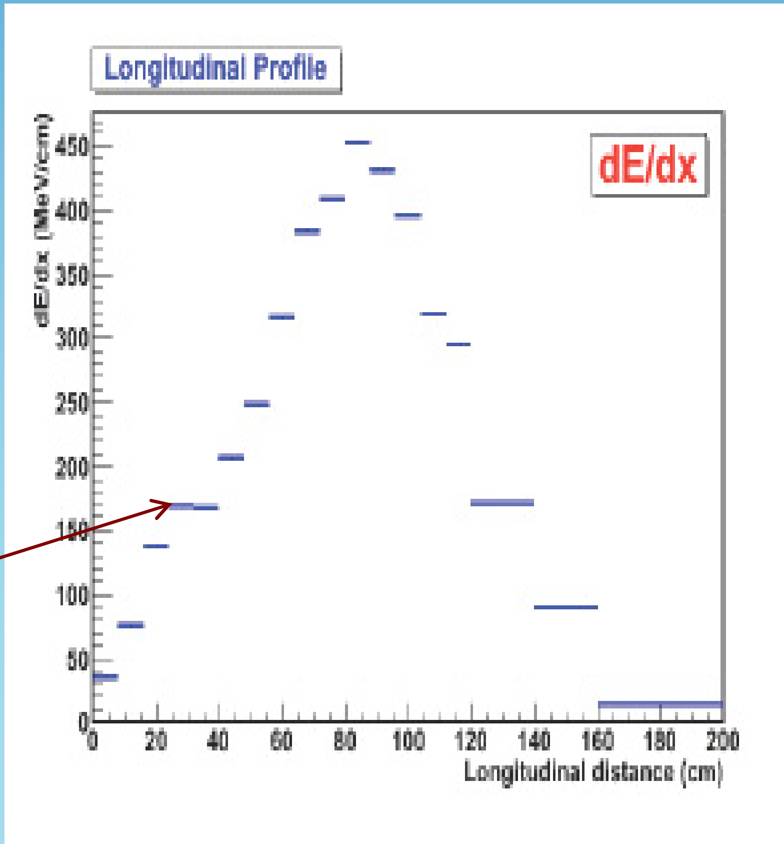
- Total deposited energy: 887 MeV
- Total reconstructed momentum: 929 MeV/c (~35° from beam direction)
- Out of time w.r.t. CNGS spill

# Electron event candidate




- single high energy EM shower (37 GeV) measured by charge integration, partially overlapped to hadronic jet
- Total deposited energy 45 GeV
- EM shower profile peaks at the expected position (~88 cm). Hadronic jet visible





# Preliminary results on event reconstruction

## MUON MOMENTUM BY MULTIPLE SCATTERING:

- Muon tracks are segmented (few cm) to enhance physical deflection (MS) w.r.t. apparent deflection due measurement errors.

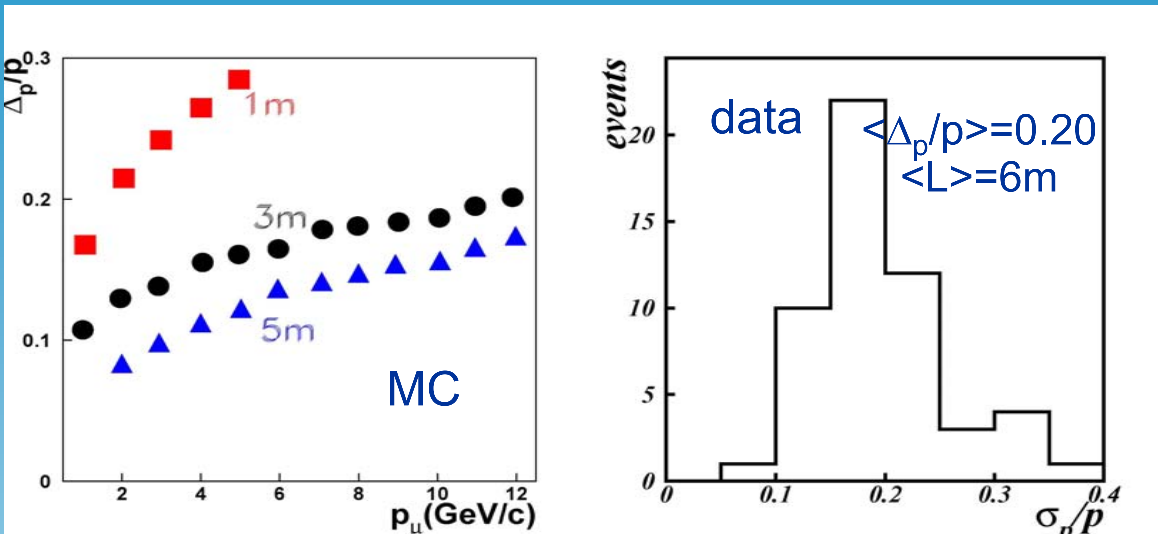
- Multiple 3D Kalman fits are performed, varying assumption on initial muon momentum $p_0$

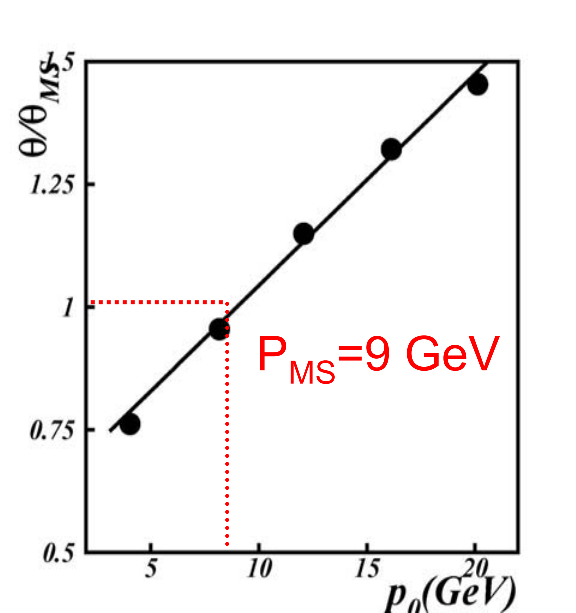
- RMS of scattering angle θ is compared with
 $\theta_{MS} \sim 14MeV/p*(L/X_0)^{1/2}$

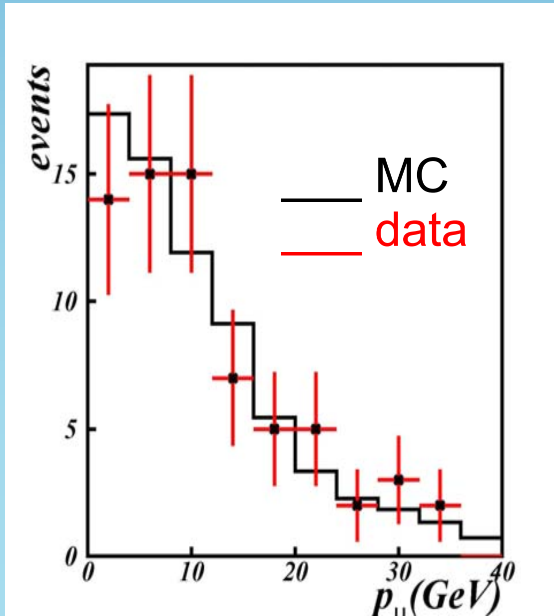
- Dependency of ratio $R=\theta_{RMS}/\theta_{MS}$ on $p_0$ is used to estimate $p$ (similarly for track $\chi^2$)

- Precision on momentum depends on track parameters (mainly length $L$ and drift coordinate resolution)

Δp/p resolution on muons from CNGS ν



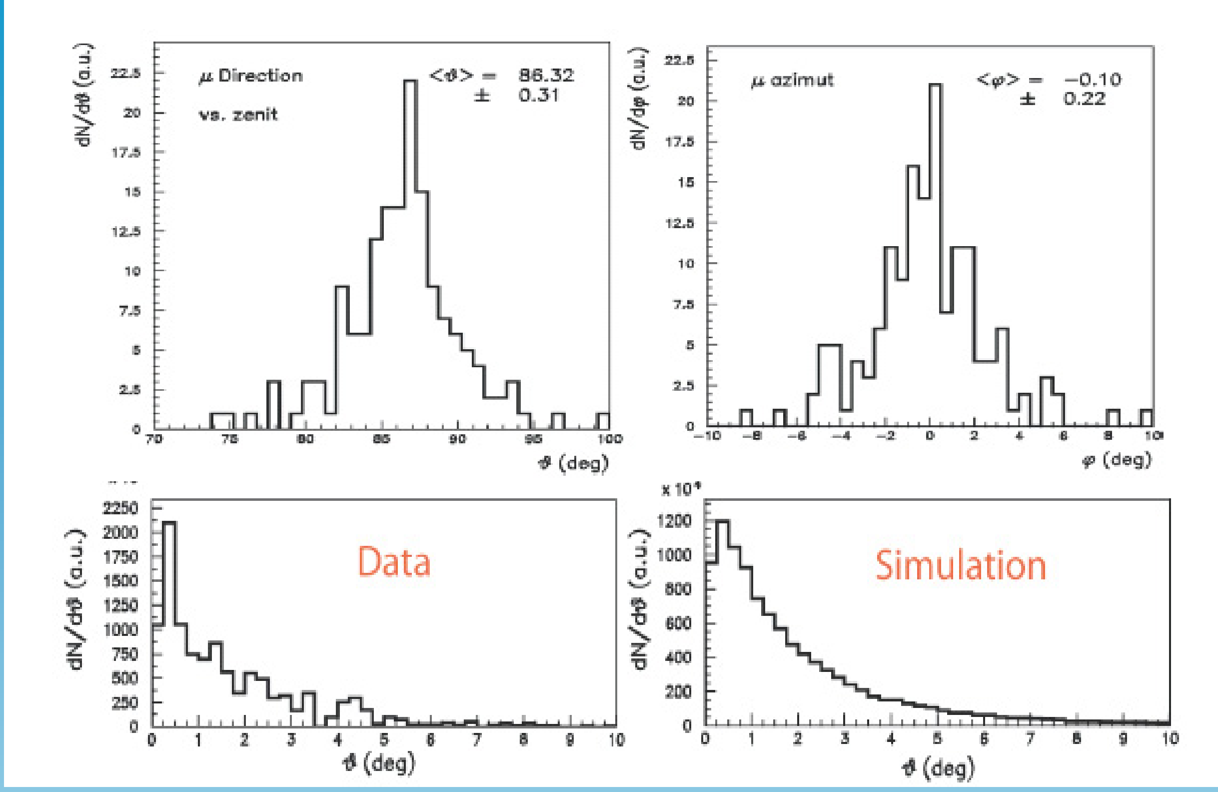




good agreement with MC!

Reconstruction of muon direction (from "rock $\mu$") Agrees with expectations (allowing for Earth curvature) $\theta$=86.7° $\varphi$=0°

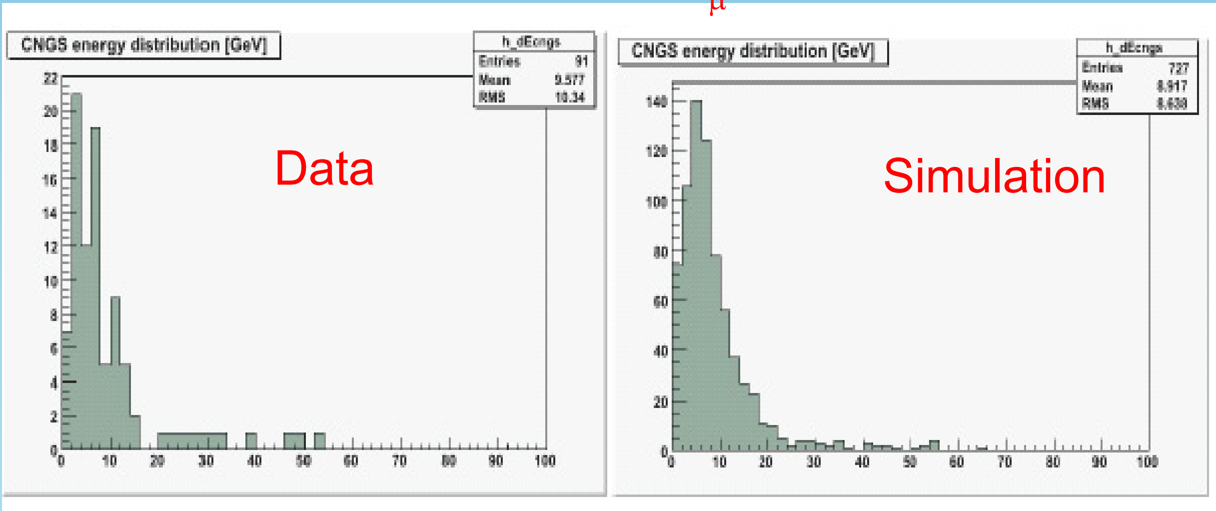
polar angle w.r.t. CNGS beam

"rock muons"




Deposited energy of $\nu_\mu$CC events

muons from $\nu_\mu$CC




Good agreement with MC!
Directional reco,calorimetry, MS measurement seem unbiased and correct

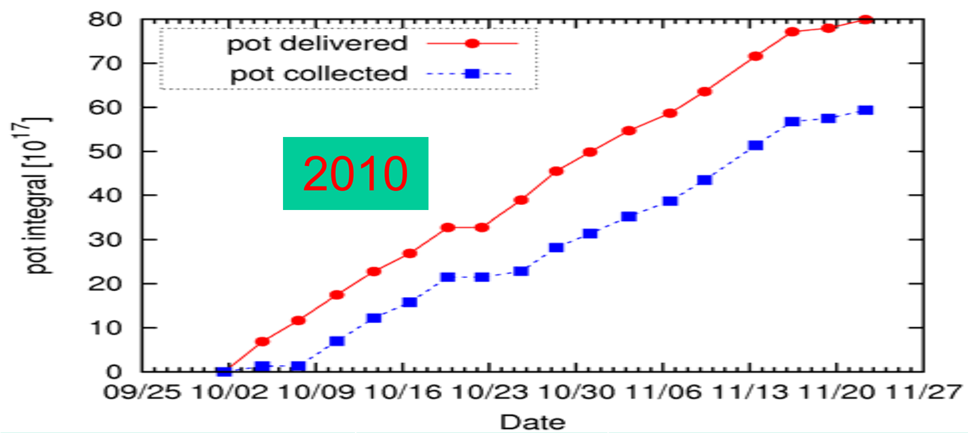
# CNGS runs in 2010 and 2011

- ICARUS fully operational for CNGS events since Oct. 1st 2010.
- 5.8 $10^{18}$ pot collected in 2010. Number of ν interactions agrees with expectations
- Trigger: photomultiplier signals summed for each chamber (100 phe threshold), within 60 μs beam gate.

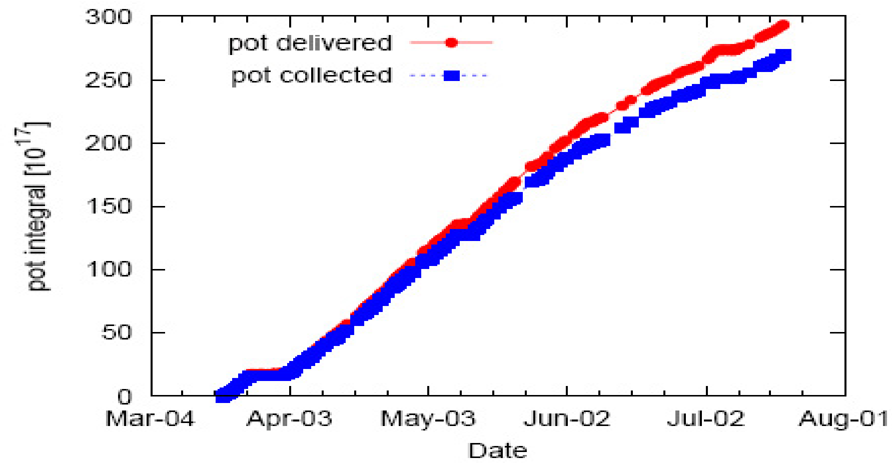
2011 RUN:

- Beam restarted on March 19th.
- 2.8 $10^{19}$ (2.5$10^{19}$) pot delivered (collected) up to July 14th.
- Detector live-time improved (>90%) due to more stable running conditions.

Improvements also in scintillation light collection and DAQ dead-time.




| Event type | Collected | Expected |
|---|---|---|
| νμ CC | 115 | 129 |
| ν NC | 46 | 42 |
| ν XC (further analysis needed) | 7 | - |
| Total | 168 | 171 |



# ICARUS T600 physics potential

- ICARUS T600: **major milestone** towards realization of large scale LAr detector. Now operational underground (LNGS - Hall B). Exposed to CNGS (CERN to Gran Sasso) $\nu_\mu$ beam, $E_\nu$ ~ 17.4 GeV.
- Interesting physics in itself: unique imaging capability, spatial/calorimetric resolutions and e/$\pi^0$ separation → **events "seen" in a new way**.
- "Bubble chamber like" CNGS $\nu$ events detection

  1200 $\nu_\mu$CC events/year; ~7 $\nu_e$CC events/year (4.5 $10^{19}$ pot/year);

  search for $\nu_\tau$ events (electron channel) using kinematical criteria;

  search for sterile $\nu$ in LSND parameter space.
- "Self triggered" events collection:

  ~ 80 ev/y of unbiased atmospheric $\nu$ CC; solar $\nu_e$ rates for $E_\nu$> 8 MeV;

  zero background proton decay with 3 x $10^{32}$ nucleons for "exotic" channels.

# 2011-12 CNGS run: physics perspectives

- 2011-2012 run with dedicated SPS periods @ high intensity: **exp. >$10^{20}$ pot**.
- For 1.1 $10^{20}$ pot ~3000 beam related $\nu_\mu$CC events expected in ICARUS T600.

7 $\nu_e$CC intrinsic beam associated events with visible energy < 20 GeV.

**Background**

- At the effective neutrino energy of 20 GeV and $\Delta m^2 = 2.5\ 10^{-3}\ eV^2$, $P(\nu_\mu \rightarrow \nu_\tau) = 1.4\%$ ~ 17 raw CNGS beam-related $\nu_\tau$CC events expected .
- $P(\tau \rightarrow e\nu\nu)$= 18% ~ 3 electron deep inelastic events with visible energy <20 GeV.

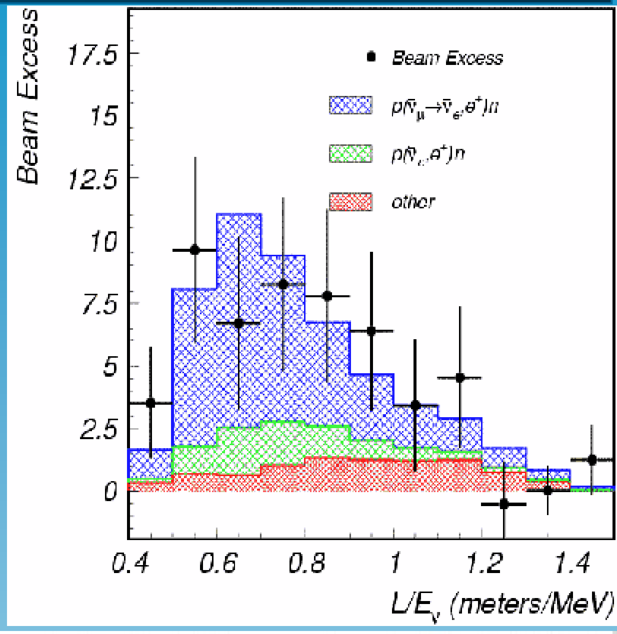
**Signal**

- $\tau \rightarrow e\nu\nu$ events characterized by momentum unbalance (because of 2$\nu$ emission) and relatively low electron momentum.
  Selection criteria suggest a sufficiently clean separation with kinematic cuts and efficiency ~ 50%, allowing to detect 1-2 $\nu_\tau$ CNGS events in ICARUS-T600 in next 2 years.

# Search for sterile neutrinos

Several recent anomalies point out to oscillations with $\Delta m^2$ >~ $eV^2$:

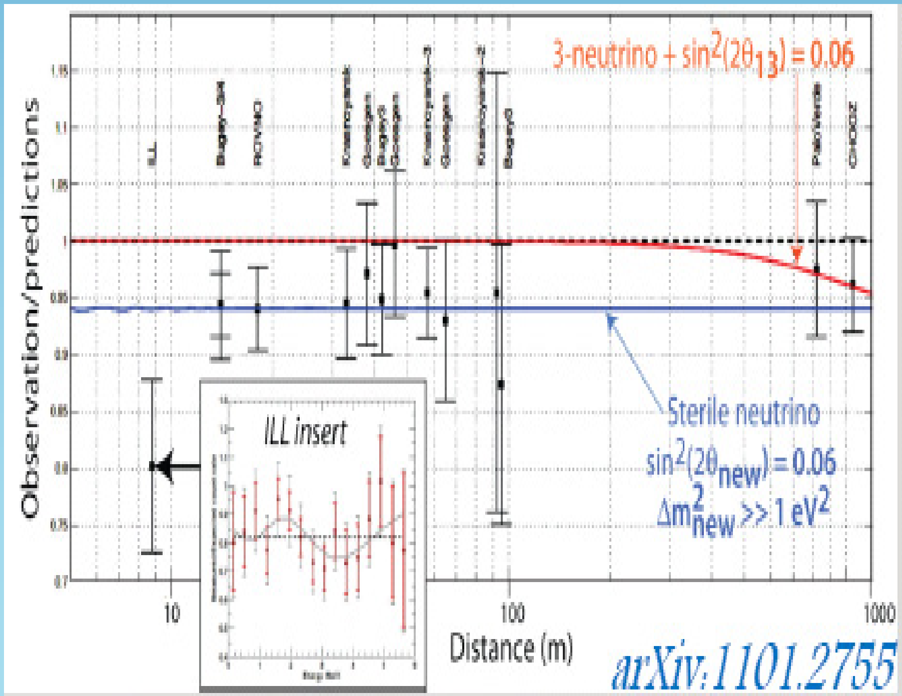
- $\nu_e$ and anti-$\nu_e$ appearance at accelerators (LSND,MiniBoone) *arXiv:1007.1150 etc.*
- Anti-$\nu_e$ disapperance (~6%) at reactors after re-evaluation of reactor fluxes *arXiv:1101.2755*
- Disappearance of $\nu_e$ (~14%) from high-intensity radioactive sources in Gallium solar neutrino experiments (GALLEX, SAGE) *arXiv:1006.3244*




*A sterile neutrino is definitely possible*

*but tension between $\nu$ and anti-$\nu$ results…*

Verification of these hints with a better signal/background separation is definitely needed.

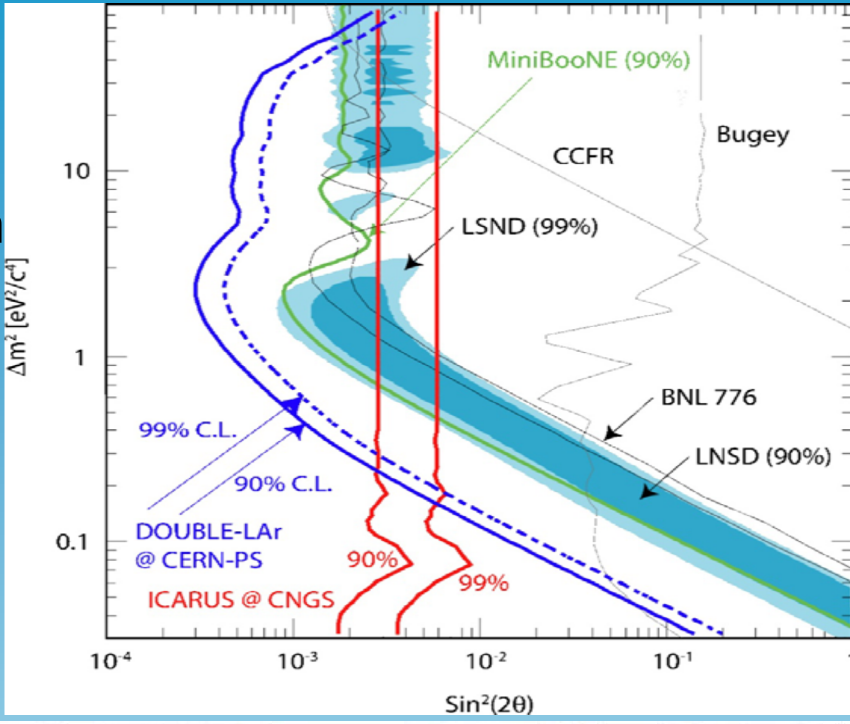


# Sterile neutrinos with ICARUS

ICARUS@LNGS can search for sterile neutrinos through $\nu_\mu$-> $\nu_e$ appearance in the 10<$E_\nu$<30 GeV window:

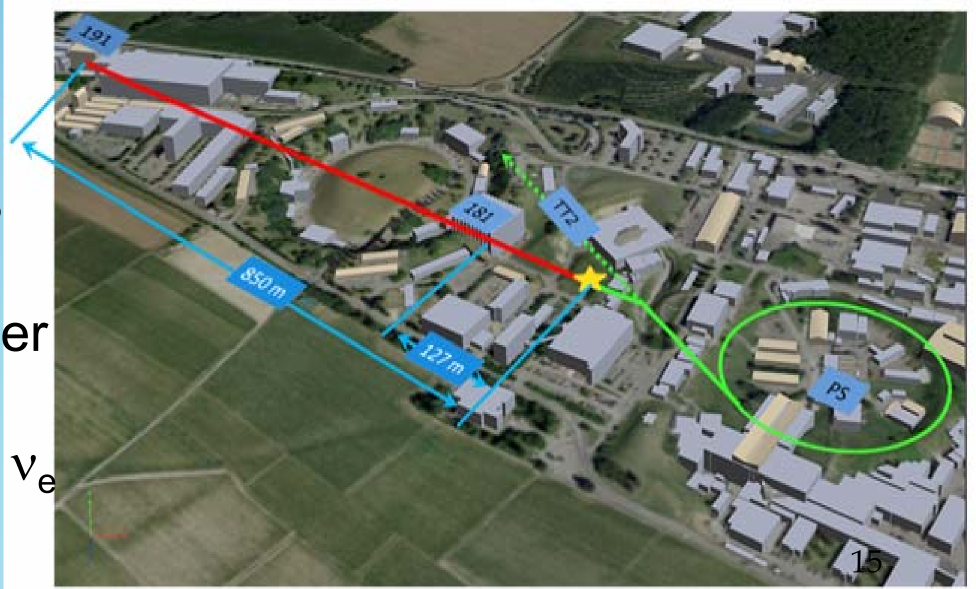
- Signal well above intrinsic $\nu_e$ contamination
- No effect from $\nu_\mu$–>$\nu_\tau$–> e and NC in this energy region
- For $\Delta m^2$=0.4 eV$^2$ and $\sin^2 2\theta$=0.02 signal ~ 30 events, bkg ~ 12

A significant fraction of LSND parameter space can be covered.




*DEDICATED EXPERIMENT PROPOSED AT CERN-PS:*

- From 2013, after CNGS shutdown
- Identical near(T150) and far(ICARUS T600) LAr TPCs
- Capability to cover all LSND parameter space with $\nu$ and anti-$\nu$
- Disappearance measurements using $\nu_e$ contamination



# Conclusions

- ICARUS T600 @ LNGS is taking data with CNGS beam since October 2010
- The unique imaging capability of ICARUS, its spatial/calorimetric resolutions, and $e/\pi^0$ separation allow to reconstruct and identify events in a new way w.r.t. previous/current experiments.
- The successful assembly and operation of this LAr-TPC is the experimental proof that this technique is well-suited for large scale experiments.
- The 2011-2012 run with CNGS $\nu_\mu$ beam will allow to possibly detect few $\nu_\tau$ appearance events. Interesting physics perspectives also for solar and atmospheric neutrinos, nucleon decay search, sterile neutrinos
- **The ICARUS experiment at the Gran Sasso Laboratory is so far the major milestone towards the realization of a much more massive LAr detector.**
- A novel search for sterile neutrinos with a refurbished $\nu$ beam at the CERN-PS is proposed after the ICARUS T600 exploitation at LNGS.

# Thank you

# Backup

# LAr purification and measurement in T600

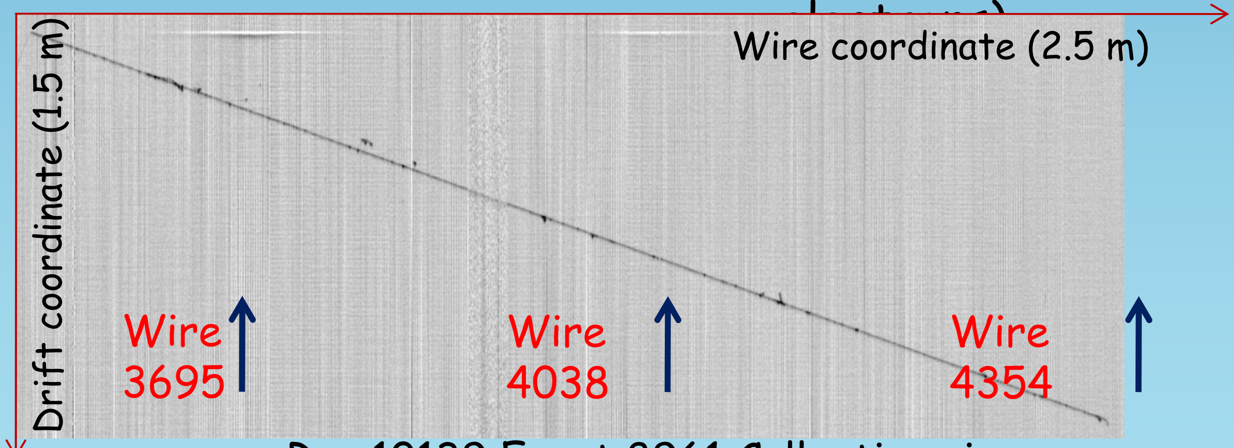
The presence of electron trapping polar impurities attenuates the electron signal as $\exp(-t_D/\tau_{ele})$ [$\tau_{ele}$ ~ 300 μs / ppb ($O_2$ equivalent)].

Most of the contaminants freeze out spontaneously (87 K) . Residuals: $O_2$, $H_2O$, $CO_2$.

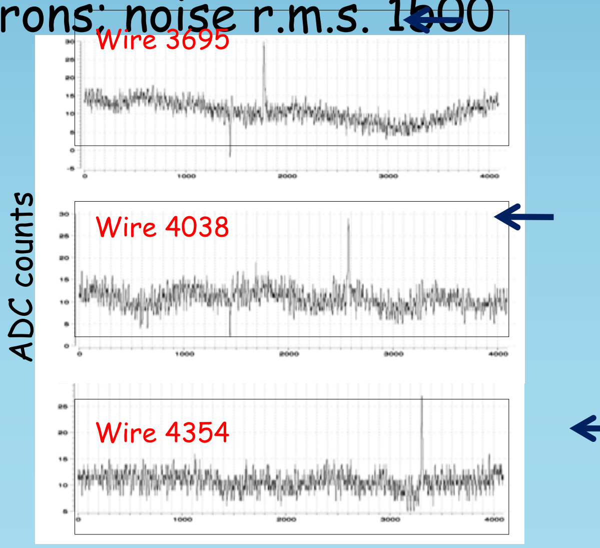
Recirculation/purification (100 $Nm^3/h$) of the gas phase to block the diffusion of the impurities from the hot parts of the detector and from micro-leaks; Recirculation/purification (4 $m^3/h$) of the bulk liquid volume to efficiently reduce the initial impurities concentration.

Charge attenuation along track allows event-by-event measurement of LAr purity

(Pulse height for 3 mm m.i.p. ~ 15 ADC # (15000 electrons; noise r.m.s. 1500 electrons)

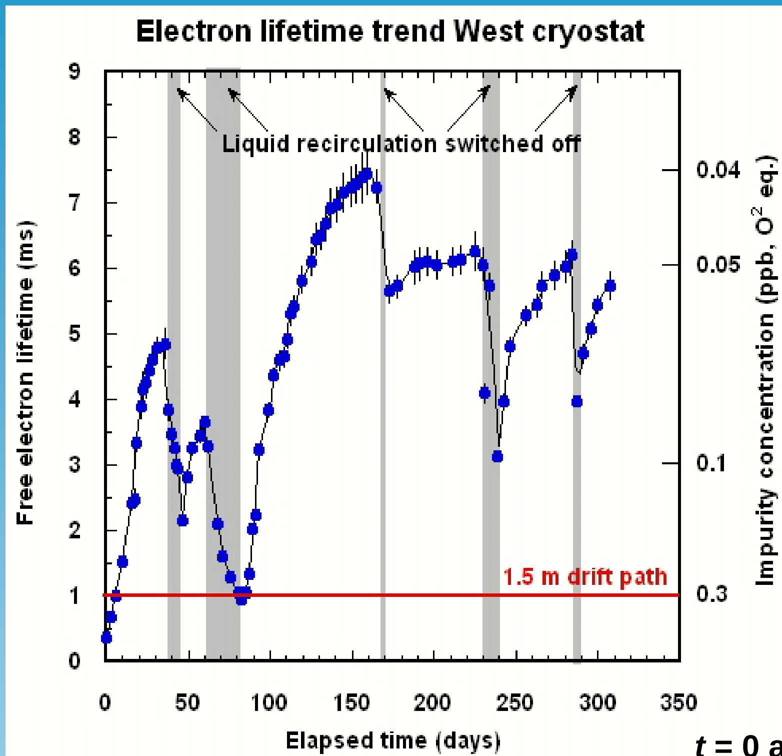


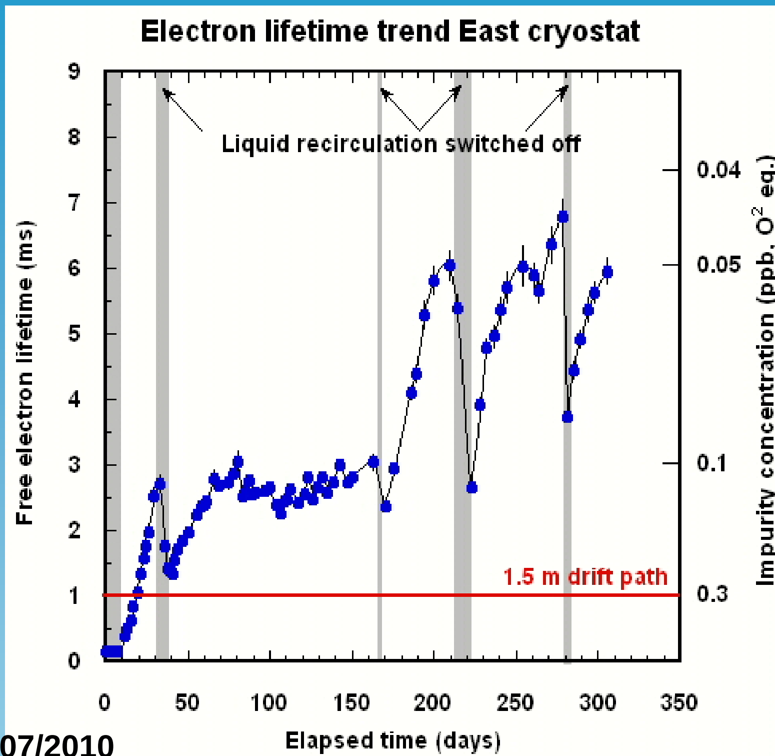
Run 10139 Event 8961 Collection view



Drift time (sampling = 0.4 ms)

# LAr purity time evolution




***t* = 0 at 01/07/2010**

Simple model: uniform distribution of the impurities, including internal degassing, decreasing in time, constant external leak and liquid purification by recirculation.

$$dN/dt = -N/\tau_R + k_L + k_D \exp(-t/\tau_D)$$

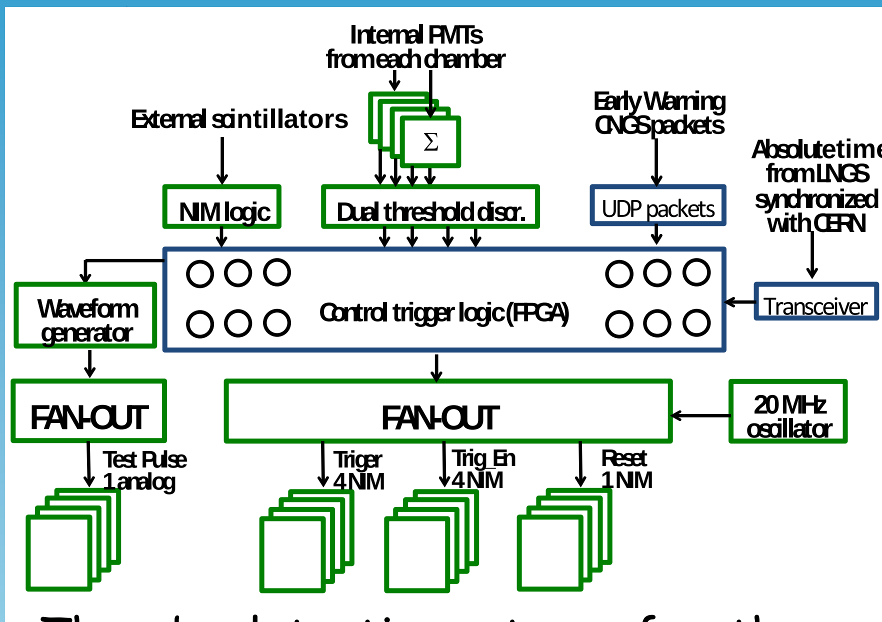
$\tau_{ele}$ [ms] = 0.3 / N[ppb $O_2$ equivalent]

*$\tau_R$: 2 $m^3$/h (per cryostat) corresponding to ≈ 6 day cycle time*

*$\tau_R$: recirculation time for a full detector volume*
*$k_L$ : total impurity leak rate and degassing rate*
*$k_D$: internal residual degassing rate assumed to vanish with a time constant $\tau_D$*

# Trigger System

The trigger set-up is based on a controller crate, hosting a FPGA-board for signals processing, interfaced to a PC for data communication and parameter




Different trigger sources:

- CNGS proton extraction time from "Early Warning" signal (80ms before spills)
- PMTs "Low Threshold" signal (~100phe)
- PMTs "High Threshold" signal (~1000phe)
- Test pulses for calibration
- Trigger on the charge (under test)

The absolute time stamp for the recorded events and the opening of the CNGS proton spill gate are evaluated by means of the signal from LNGS atomic clock.

Reconstruction of CNGS arrival time distribution in agreement with the spill time duration (10.5 μs).