ICARUS experiment at LNGS

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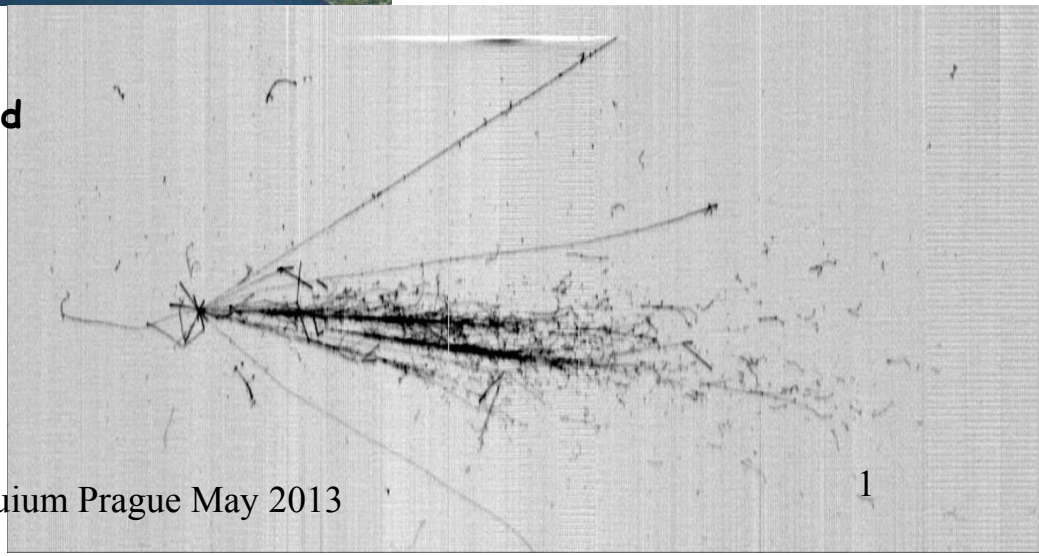
For the ICARUS Collaboration



Outline

- ICARUS LAr TPC – detector description and performance
- Results: superluminal neutrino, search for the LSND anomaly
- An idea for the detector future (decommissioning starts June 2013) – ICARUS-NESSIE experiment at CERN
- Conclusions

The ICARUS Collaboration

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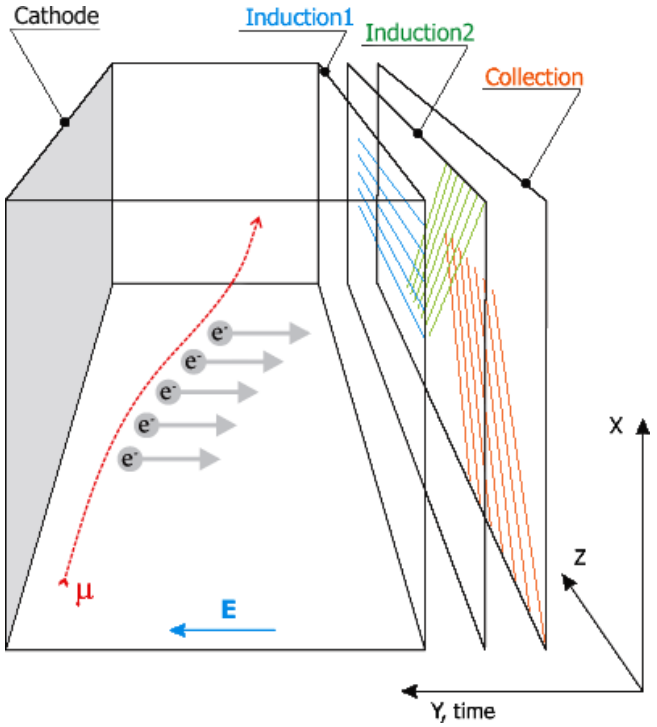
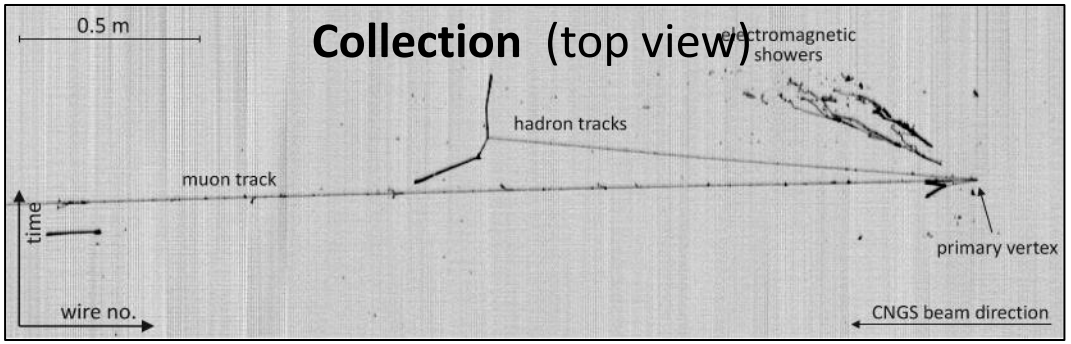
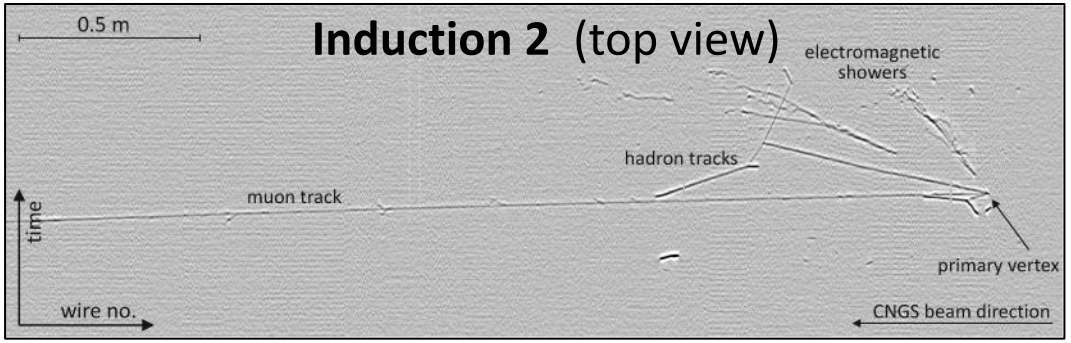
ICARUS LAr-TPC detection technique

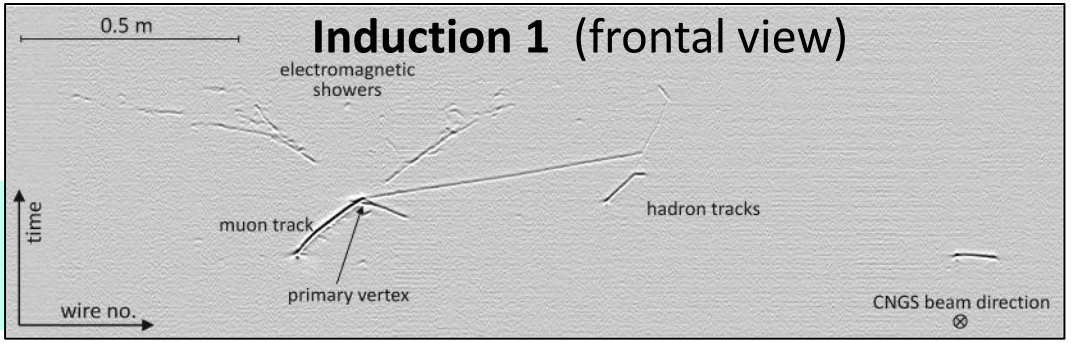
- 2D projection for each of 3 wire planes per TPC
- 3D spatial reconstruction from stereoscopic 2D projections
- charge measurement from Collection plane signals
- Absolute drift time from scintillation light collection



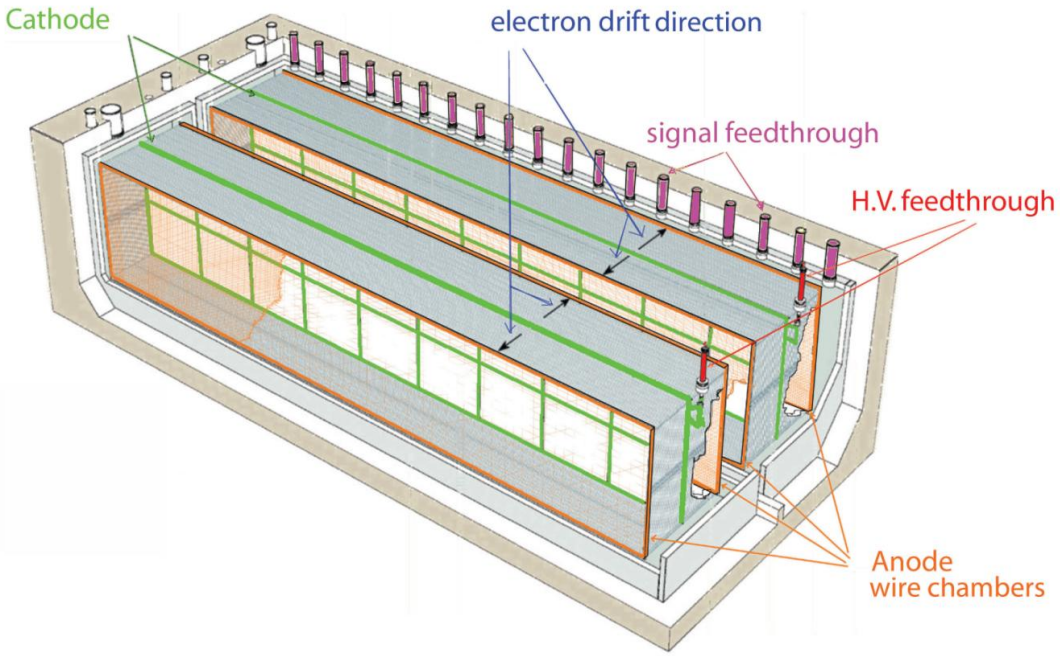
CNGS ν_μ charge current interaction, one of TPC's shown

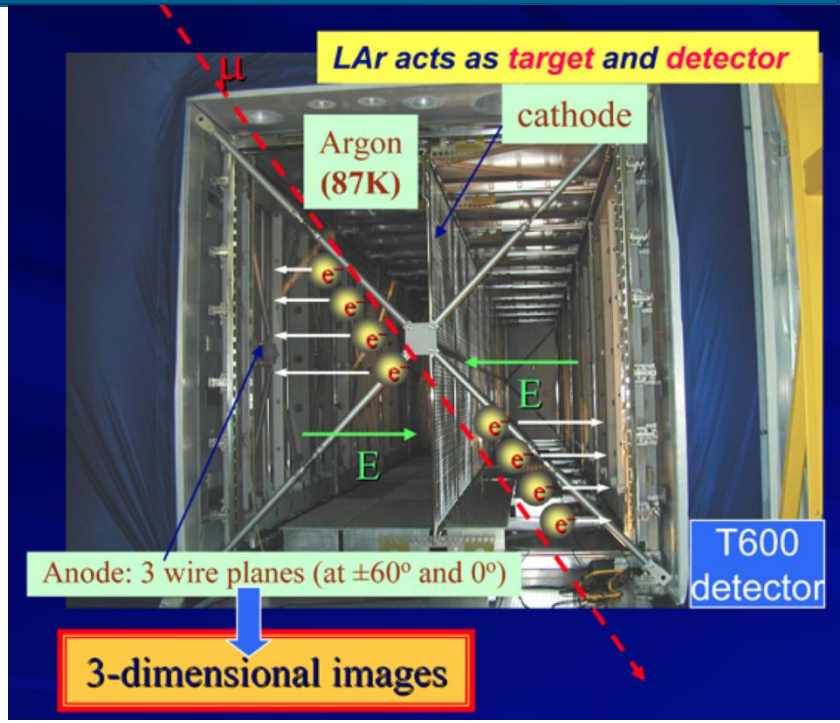






The ICARUS T600 detector



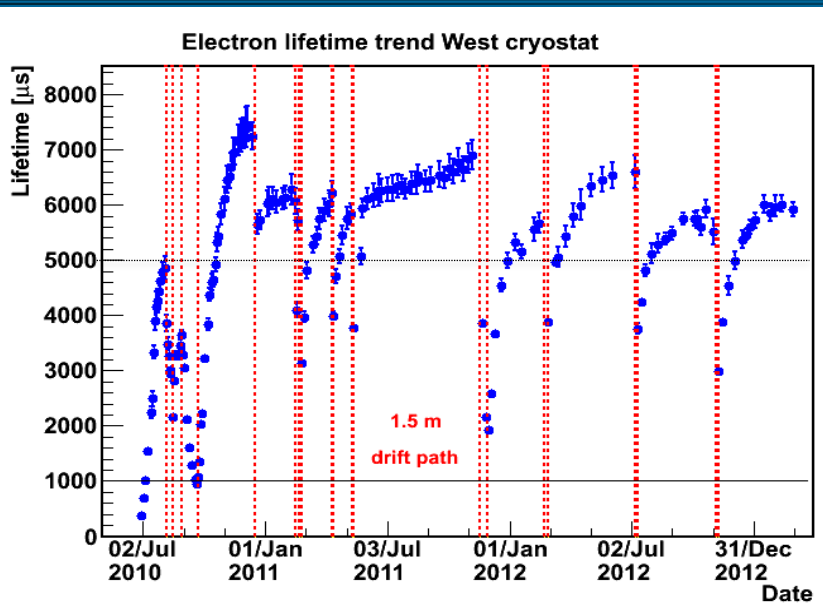


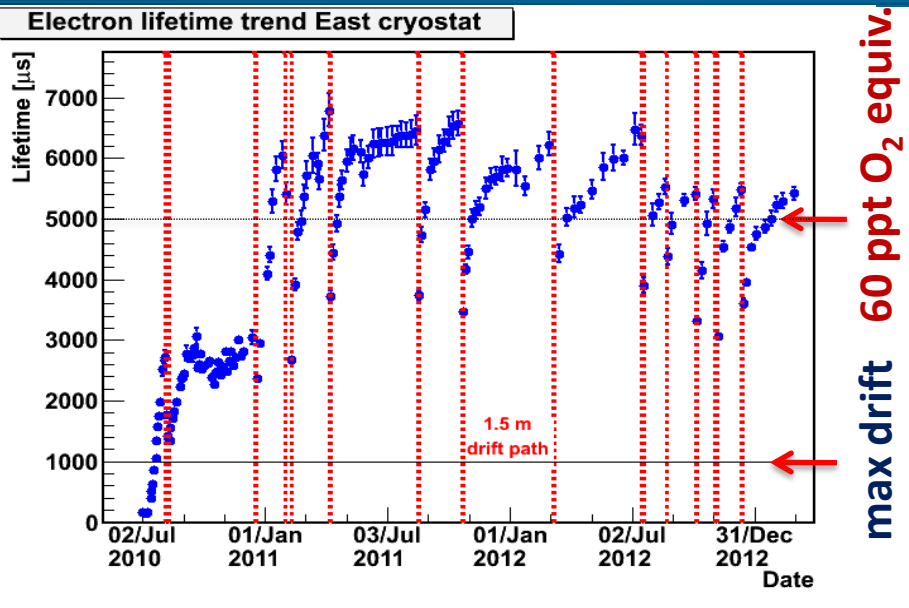
- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0, ±60°
  - ≈ 54000 wires, 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 μ tracks.

τ_{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

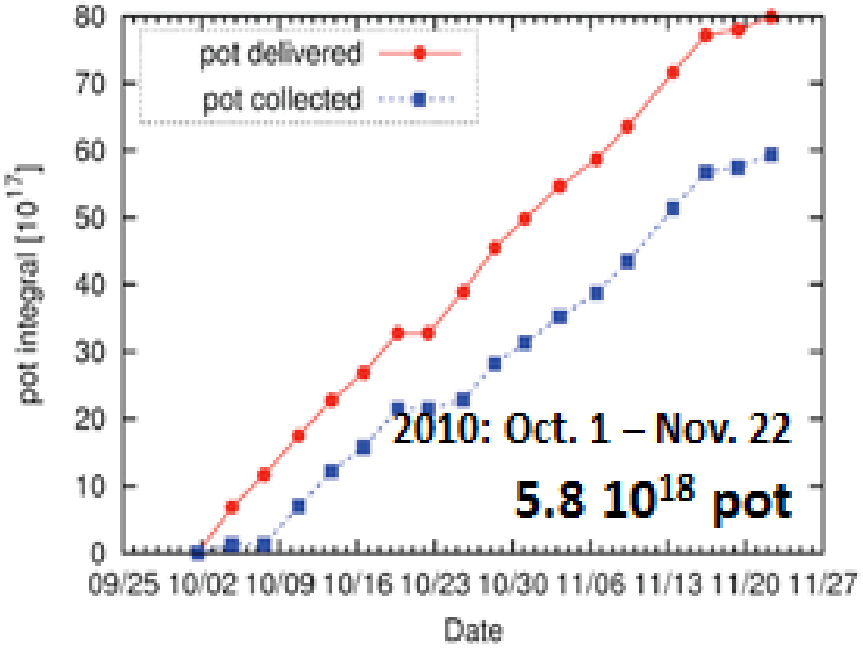
LAr recirculation system upgrade:

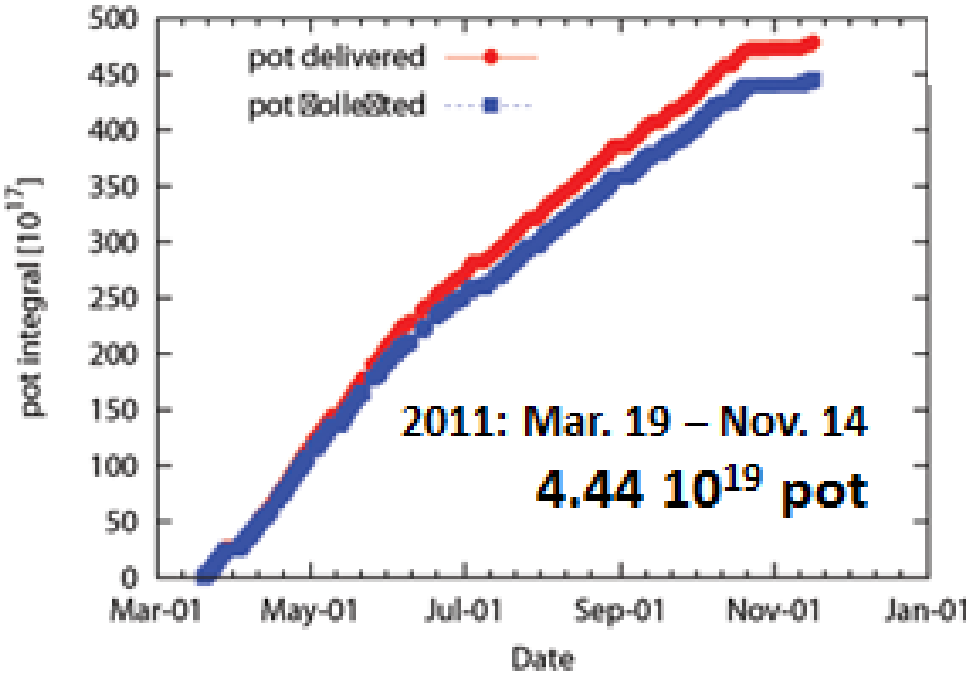
- Several accidental stops with LAr immersed pumps
- New pumps with non-immersed motor installed in 2012. Similar pumps operating since 2010 on the LN2 circulation systems worked without any accidental stop.

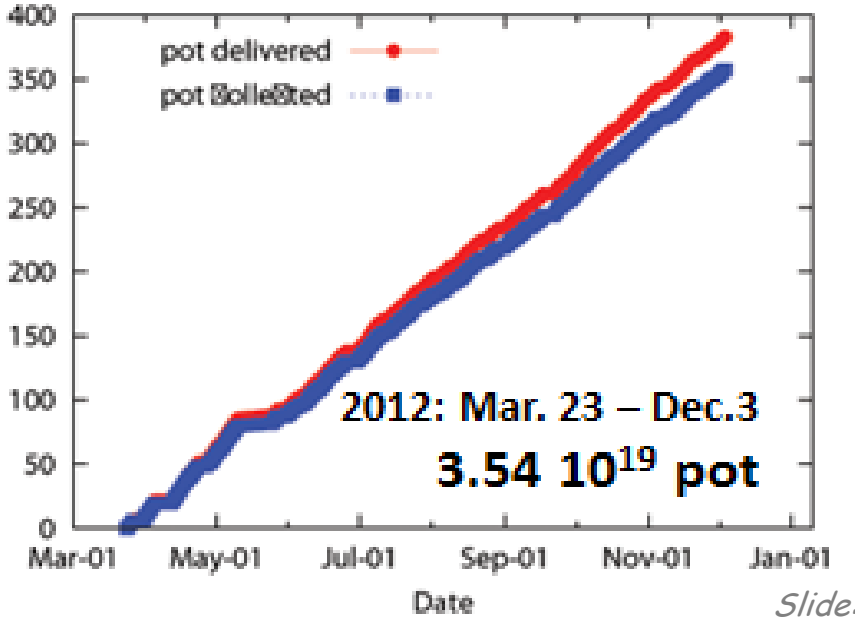
CNGS RUN (Oct 2010 – Dec 2012)

- Detector live-time > 93%
- November 2011 and May 2012: timing measurement with bunched beam.

Collected 8.6 x 10^{19} protons on target (pot)







ICARUS LAr-TPC performance

Total energy reconstr. from charge integration

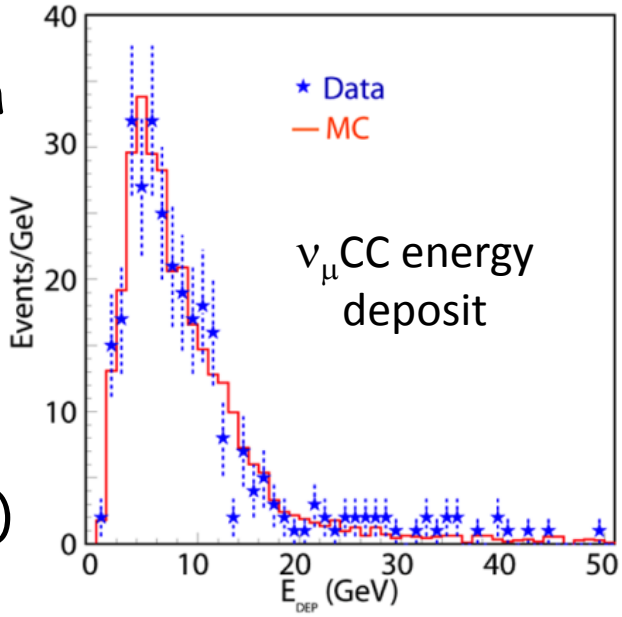
- Full sampling, homogeneous calorimeter with excellent accuracy for contained events

Tracking device

- Precise 3D topology and accurate ionization
- Muon momentum via multiple scattering

Measurement of local energy deposition dE/dx

- e/γ remarkable separation (0.02 X_0 samples)
- Particle identification by dE/dx vs range



Low energy electrons:

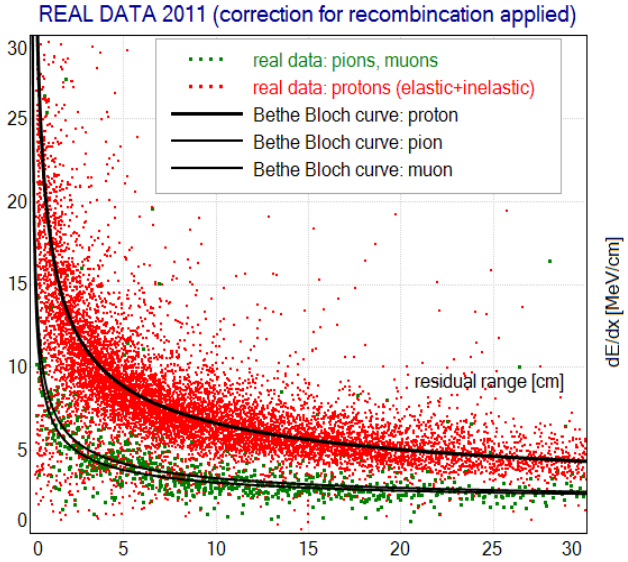
σ(E)/E = 11%/√ E(MeV)+2%

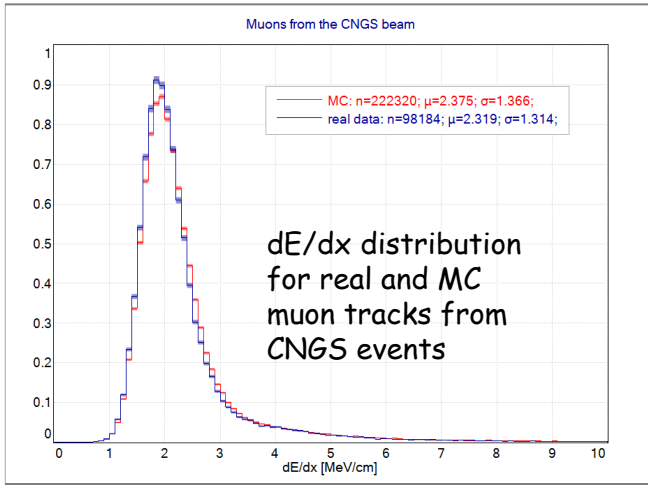
Electromagn. showers:

σ(E)/E = 3%/√ E(GeV)

Hadron showers:

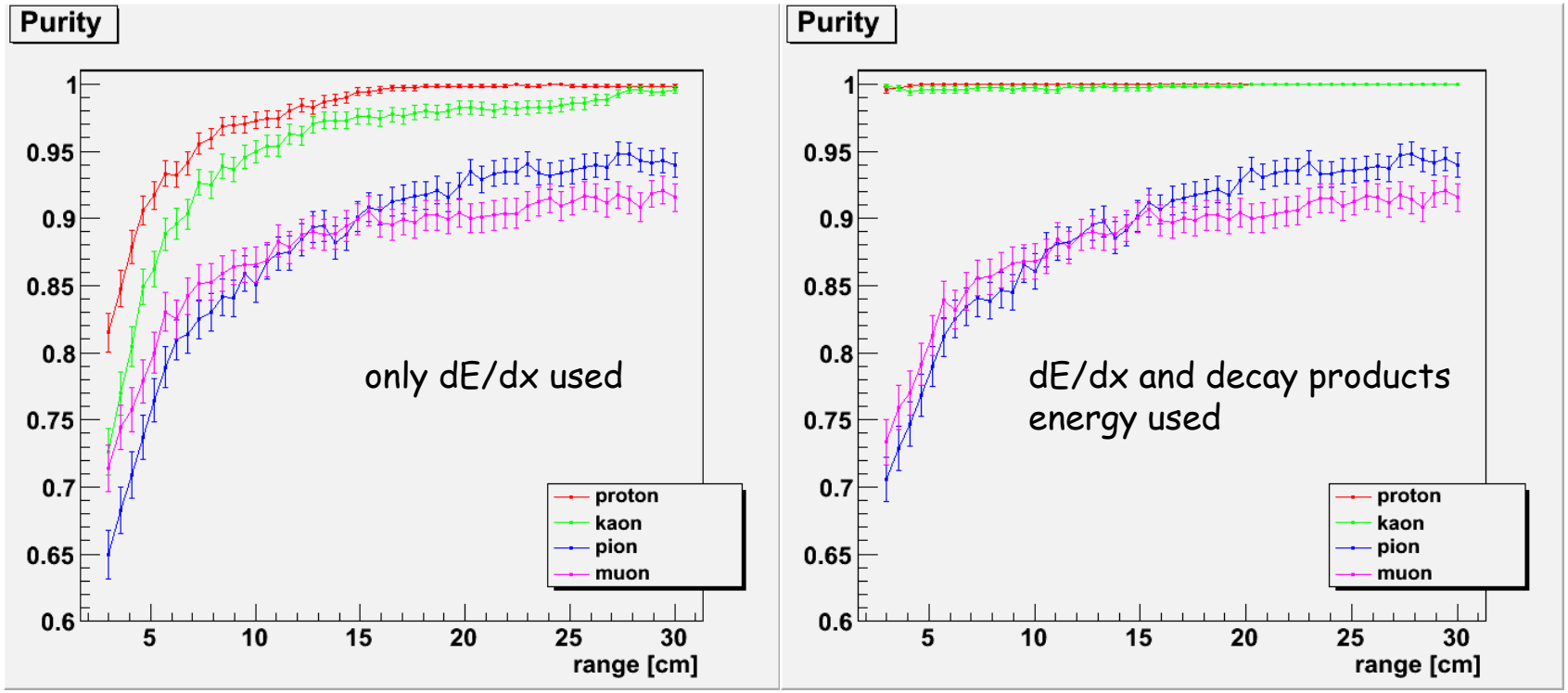
σ(E)/E ≈ 30%/√ E(GeV)





Particle identification: dE/dx + decay products energy deposit

PId algorithm: neural network approach



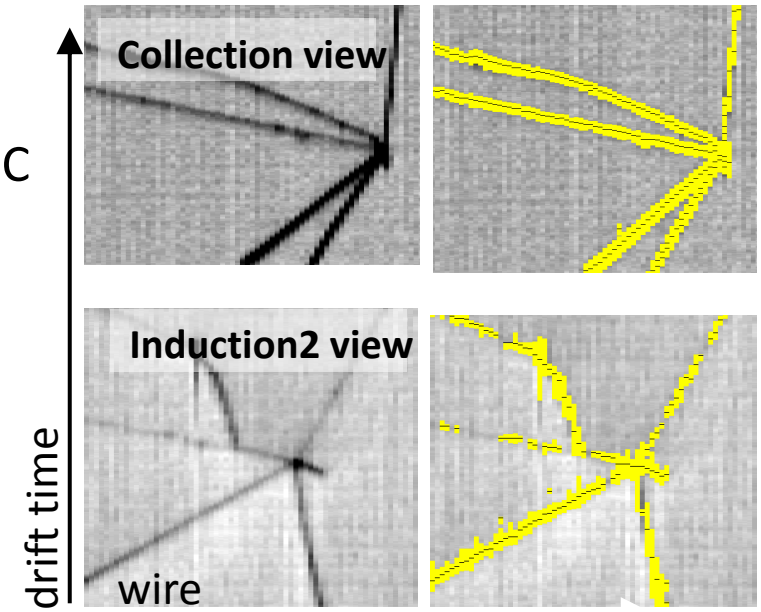
MC test of the particle id algorithm:
purity as a function of the observed track length before complete stop

- 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

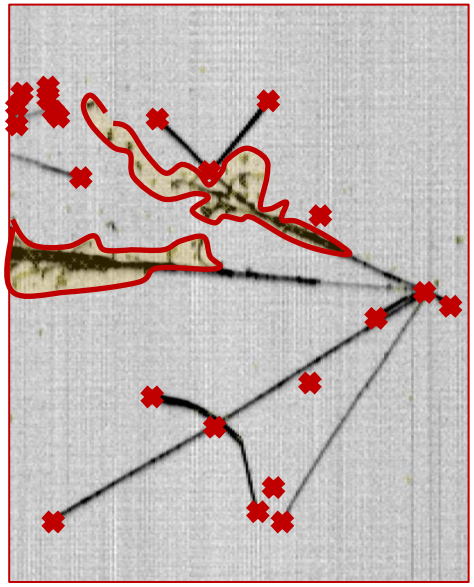
Event reconstruction: from hits to 3D picture – new approach (1)

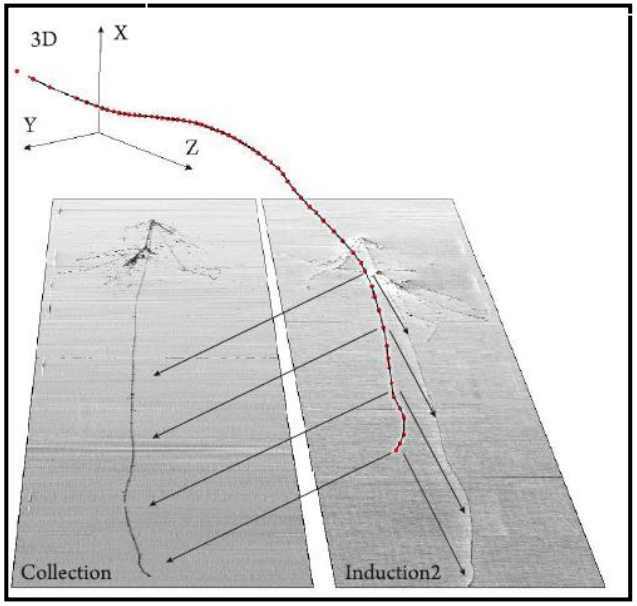
Adv. High Energy Phys. (2013) 260820

- **Hit finding**: wire ADC pulse position (drift time) and charge reconstruction (collection).
- **2D clusters:** 2D objects (tracks, cascades) formed from hits.
- **3D reconstruction:** resulting from combining 2D objects in different views.

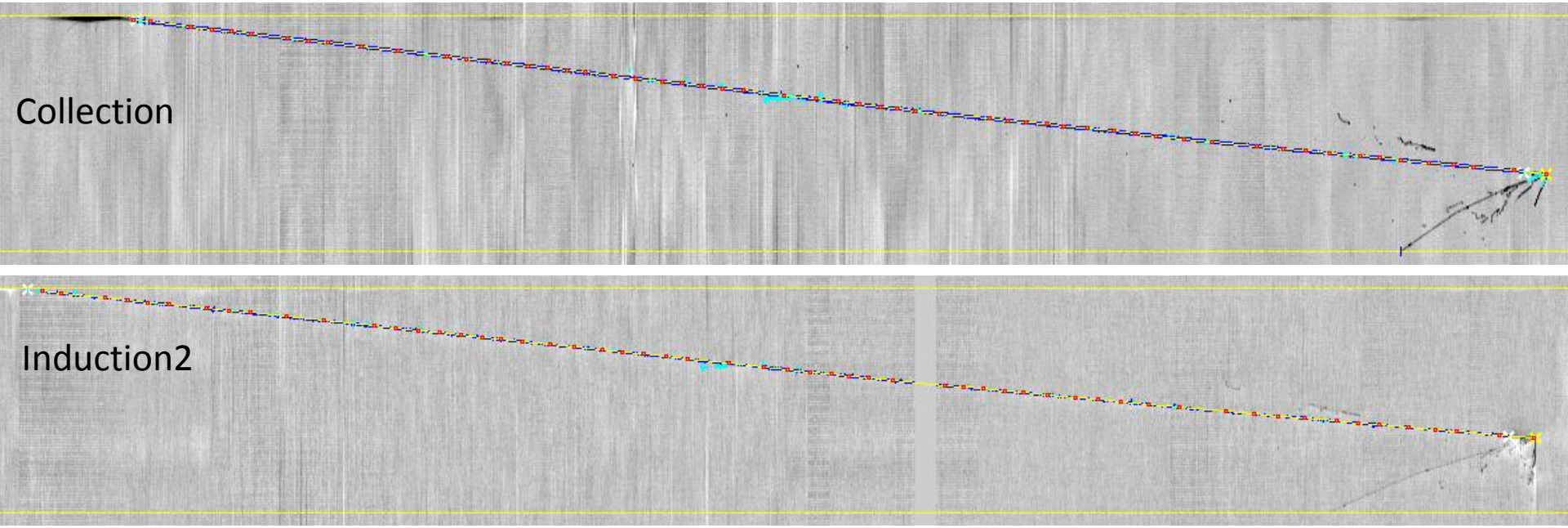


- ✓ Total energy reconstruction of events from charge integration.
- ✓ Tracking device (muon momentum, precise 3D reconstruction)
- ✓ Measurement of local energy deposition dE/dx

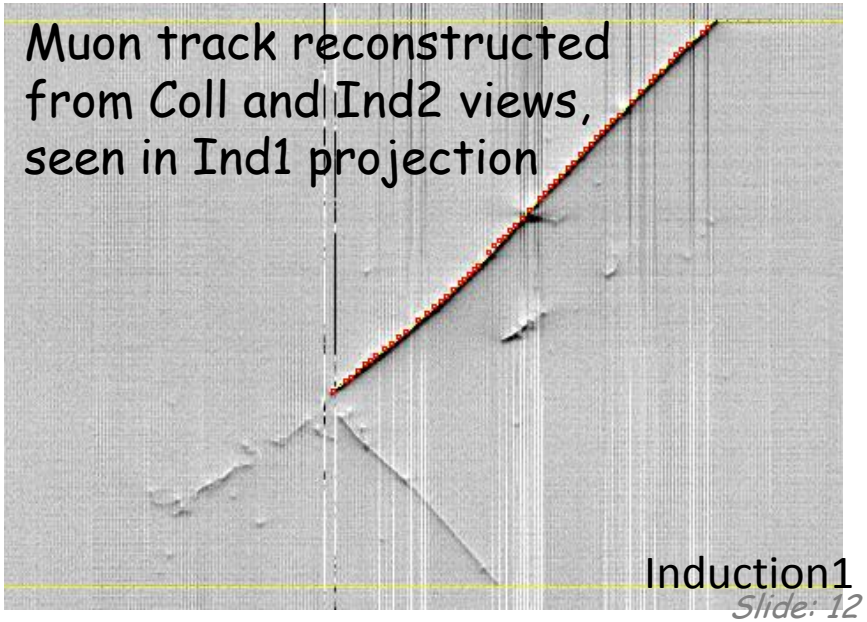




Event reconstruction: from hits to 3D picture – new approach (2)



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



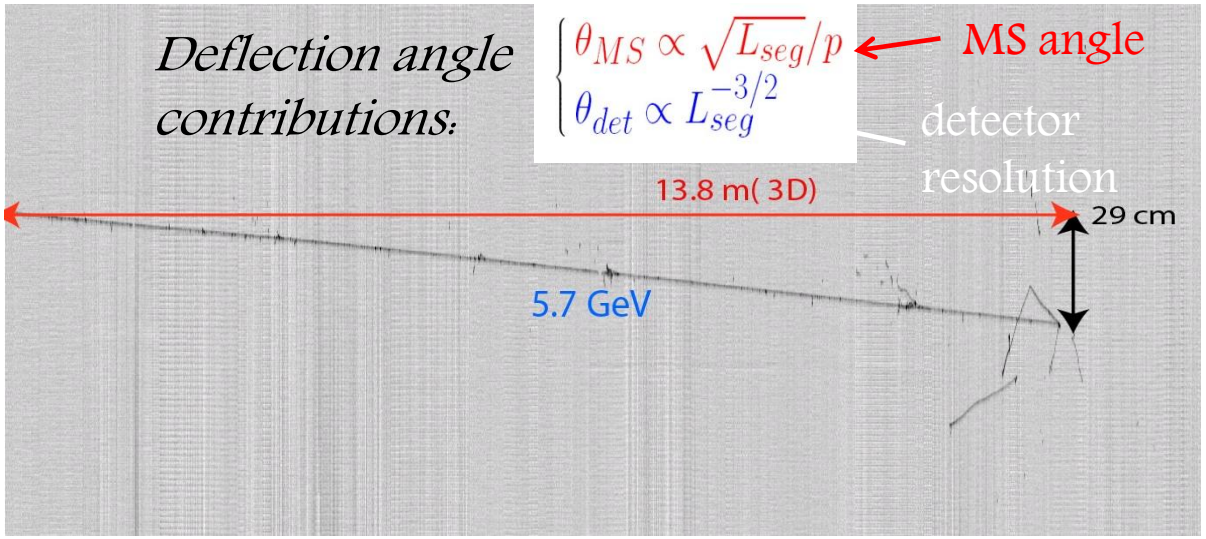
Muon momentum by multiple scattering

- Key tool to measure momentum of non-contained μ's: essential for ν_μ CC event reconstruction.

Two methods under development – results will be published soon:

- 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.



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
  - ~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:

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

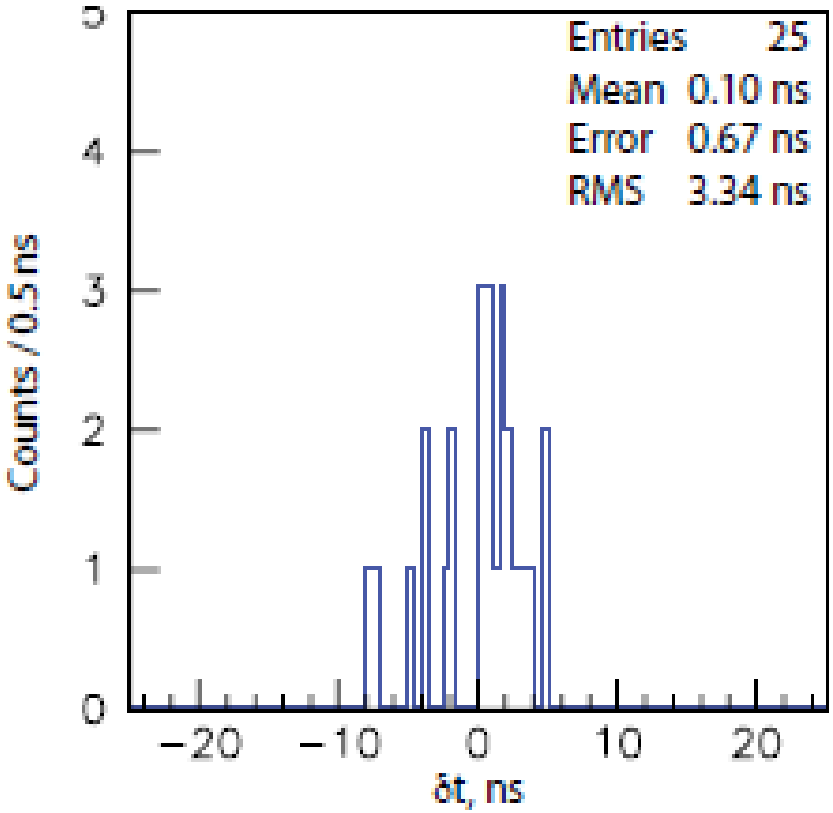
- comparable to the SuperK atm. limit $\delta < 1.4\ 10^{-8}$, somewhat larger than the lower energy velocity constraint $\delta < 4\ 10^{-9}$ from SN1987A.

Neutrino time of flight: 2012 result

JHEP 11 (2012) 049 (Phys. Lett. B 713 (2012) 17-22)

- New beam structure: 64 bunches, 3 ns width, 100 ns spacing.
- Both ICARUS PMT-DAQ and CERN-LNGS timing synchronization improved
- Beam related events observed in ICARUS (for ~1.8 10^{17} pot):
  - 16 crossing μ's (1 stopping) from the upstream rock;
  - 7 CC ν_μ events;
  - 2 NC ν events.

- Results:
  - $\delta t = tof_c - tof_\nu =$ $0.10 \pm 0.67_{stat.} \pm 2.39_{syst.}$
  - compatible with 2011 value, based on 7 events
  - distribution r.m.s: ~ 3.3 ns (10.5 ns in 2011)
  - Improved statistical and systematic accuracy.

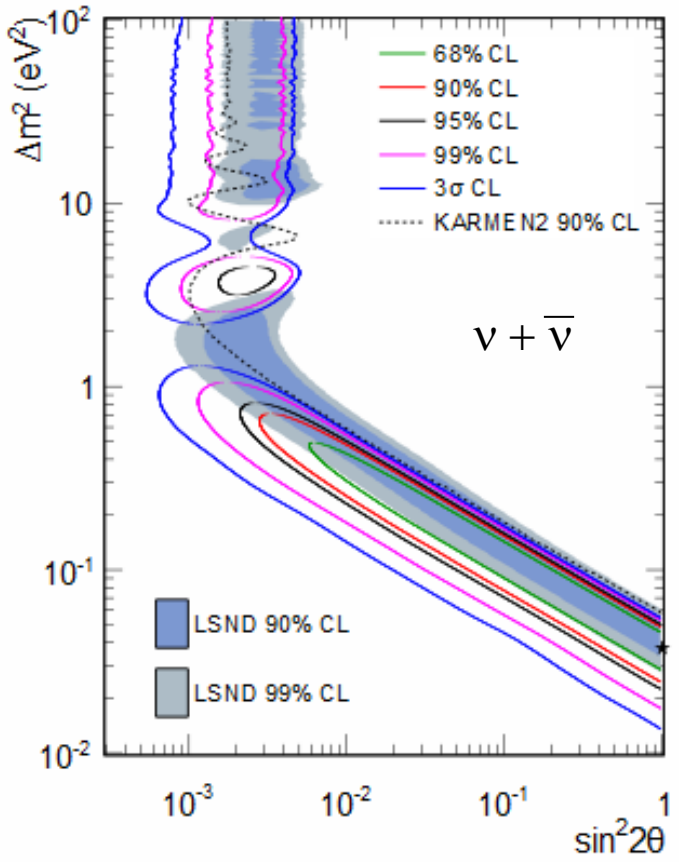


LSND anomaly

The LSND experiment reports on anomalous production signal, later confirmed by MiniBoone and compatible with KARMEN limits.

LSND: L/E=1 m/MeV
ICARUS: L=730km, $E_\nu \in [10,30]$ GeV, L/E ≈ 36.5 m/MeV, i.e. fast oscillations as a function of E_ν averaging to ≈ ½

A sterile neutrino signal appear for ICARUS as an access of ν_e events.



ν_e CC event recognition becomes crucial, and possible due to unique Liquid Argon feature and our reconstruction algorithms.

Data sample and cuts

Currently analyzed **1091 ν events** (from 3.3 x 10^{19} pot, 2010-2011 data, half the total statistic) -> compatible with MC expectation within 6%.

CNGS beam ($10 \leq E_n \leq 30$ GeV) is an **almost pure ν_μ beam**: expected ν_e events:

- **3.0 ± 0.4**, due to the **intrinsic ν_e** beam contamination,
- **1.3 ± 0.3**, due to **θ_{13} oscillations**, $\sin^2(\theta_{13}) = 0.0242 \pm 0.0026$,
- **0.7 ± 0.05**, from $\nu_\mu \rightarrow \nu_\tau$ **oscillations** with subsequent electron production, (3ν mixing).

Total: **5.0 ± 0.6 events**.

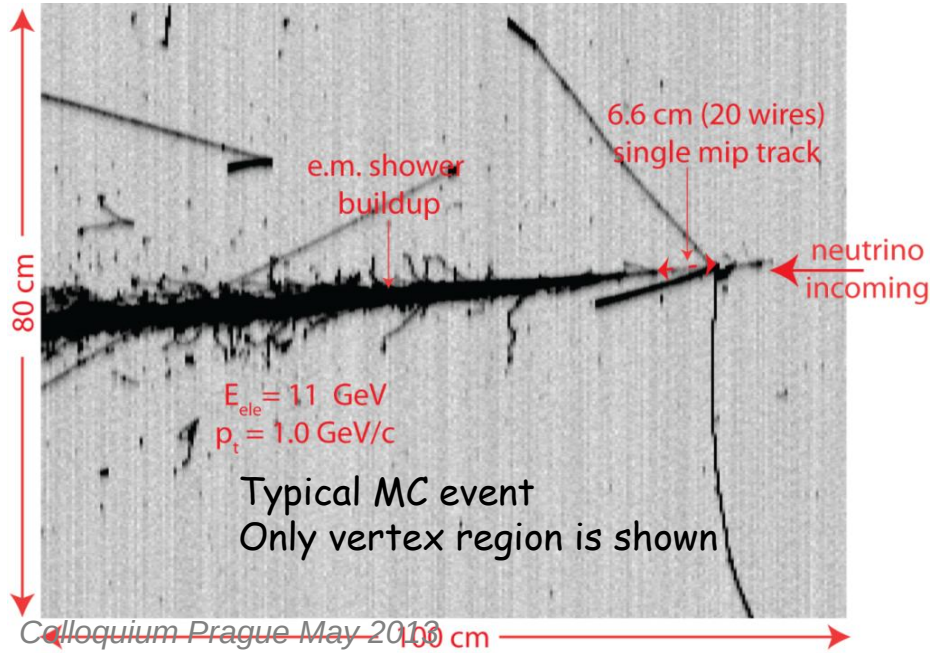
Expected events, weighting for efficiency: **3.7 ± 0.6 events**.

Selections for ν_e during visual scan:

- Single m.i.p. from vertex, al least 8 wires long ($dE/dx \leq 3.1$ MeV/cm, excluding δ-rays), later developing into EM shower.
- Minimum spatial separation (150 mrad) from other tracks coming from vertex, at least in one view between Coll and Ind2.

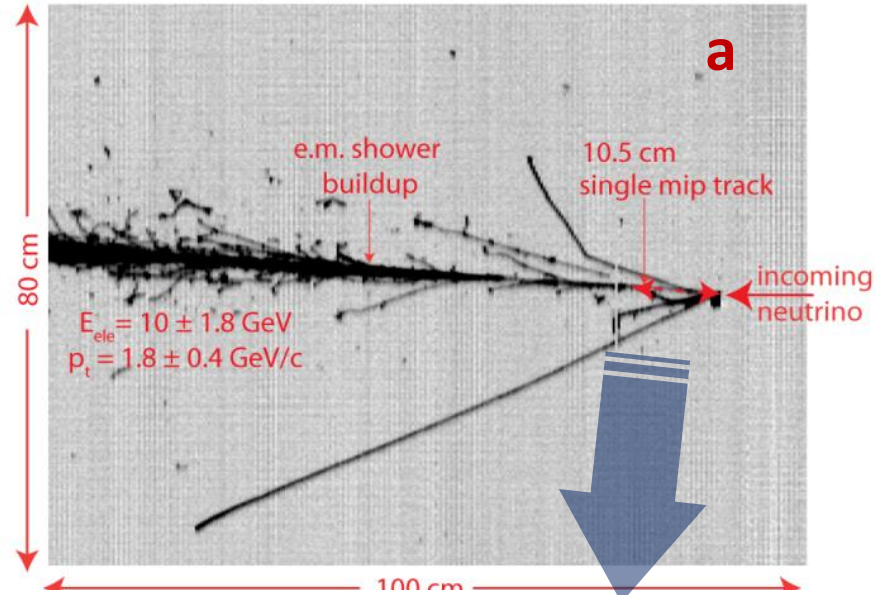
Signal selection efficiency in MC simulation

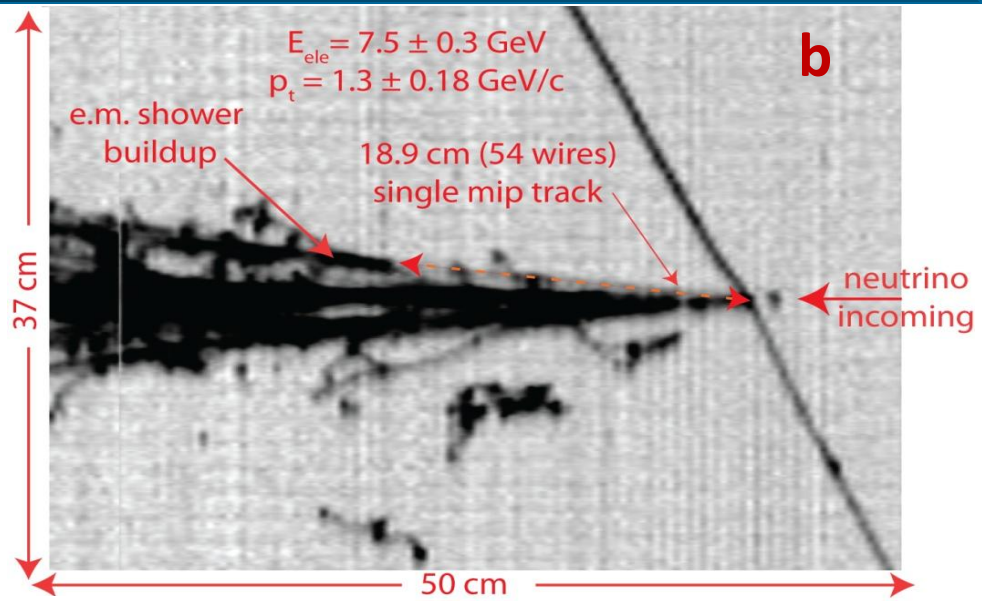
- ν_e events generated according to ν_μ spectrum in order to reproduce oscillation behaviour;
- full physics and detector MC simulation in agreement with data
- 122 events over 171 simulated inside the detector, satisfy fiducial volume and energy cuts;
- visibility cuts: (3 independent scanners), leading to **0.74 ± 0.05 efficiency**;
- < 1% systematic error from dE/dx cut on the initial part of cascade;
- no ν_e-like events selected among NC simulated sample of 800 events.

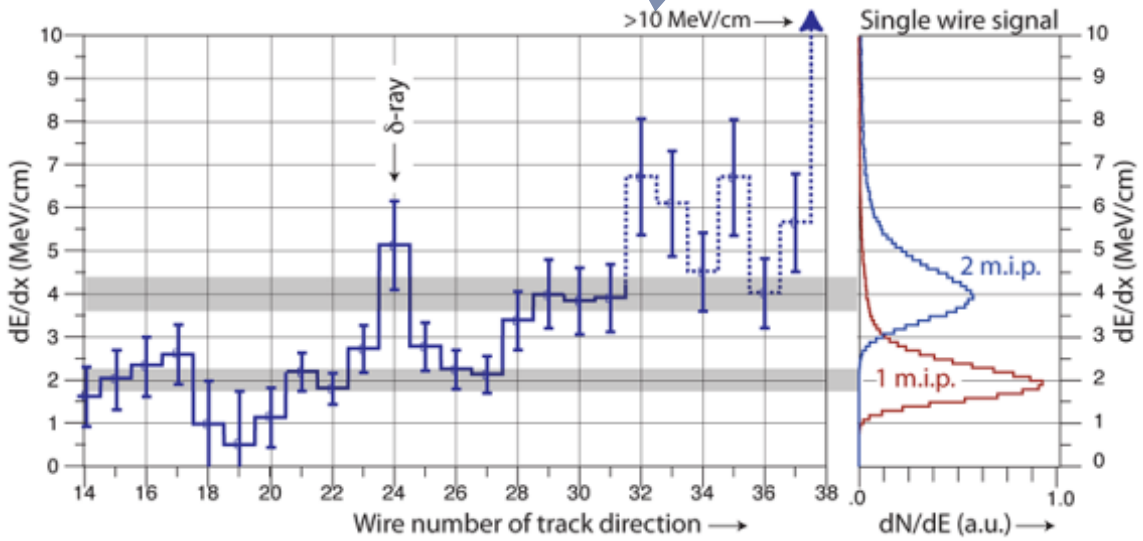


- Automatic data selection, performed on a larger sample of MC events, is consistent with visual scan, returning the same **0.74 efficiency**.

2 ν_e CC events observed in data







(a) vis E_{tot} = 11.5 ± 1.8 GeV,
p_t = 1.8 ± 0.4 GeV/c

(b) vis E_{tot} = 17 GeV,
p_t = 1.3 ±0.18 GeV/c

In both events: single electron shower in the transverse plane clearly opposite to hadronic component

Search for an LSND-like effect with ICARUS at LNGS

Within the present observation, our results is consistent with the **absence of the LSND anomaly**.

Moreover the long baseline should enhance the oscillation probability:

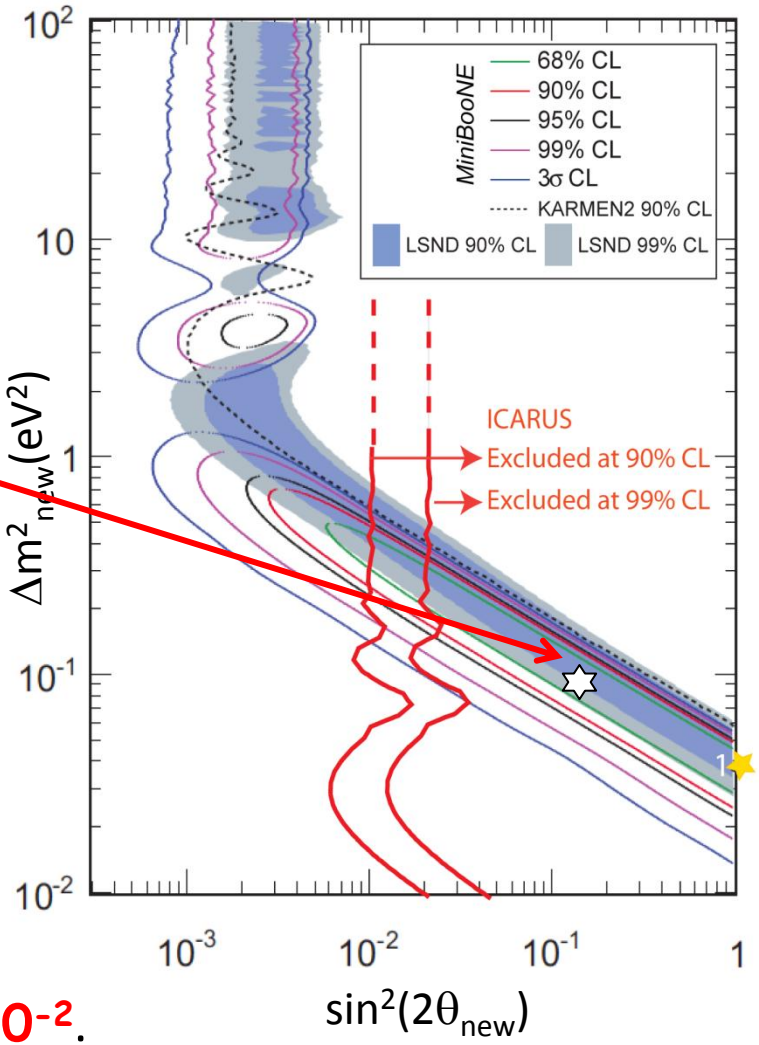
Expected 30 events with E ≤ 30 GeV for $(\Delta m^2_{new}, \sin^2(2\theta_{new})) = (0.11\ eV^2, 0.10)$.

Weighting for efficiency, our limits on the number of events due to LSND anomaly are:

3.4 (90% CL) and **7.1 (99% CL)**,

which give the oscillation probabilities:

$P(\nu_\mu \rightarrow \nu_e) = 5.4 \times 10^{-3}$; $P(\nu_\mu \rightarrow \nu_e) = 1.1 \times 10^{-2}$.



Search for an LSND-like effect with ICARUS at LNGS

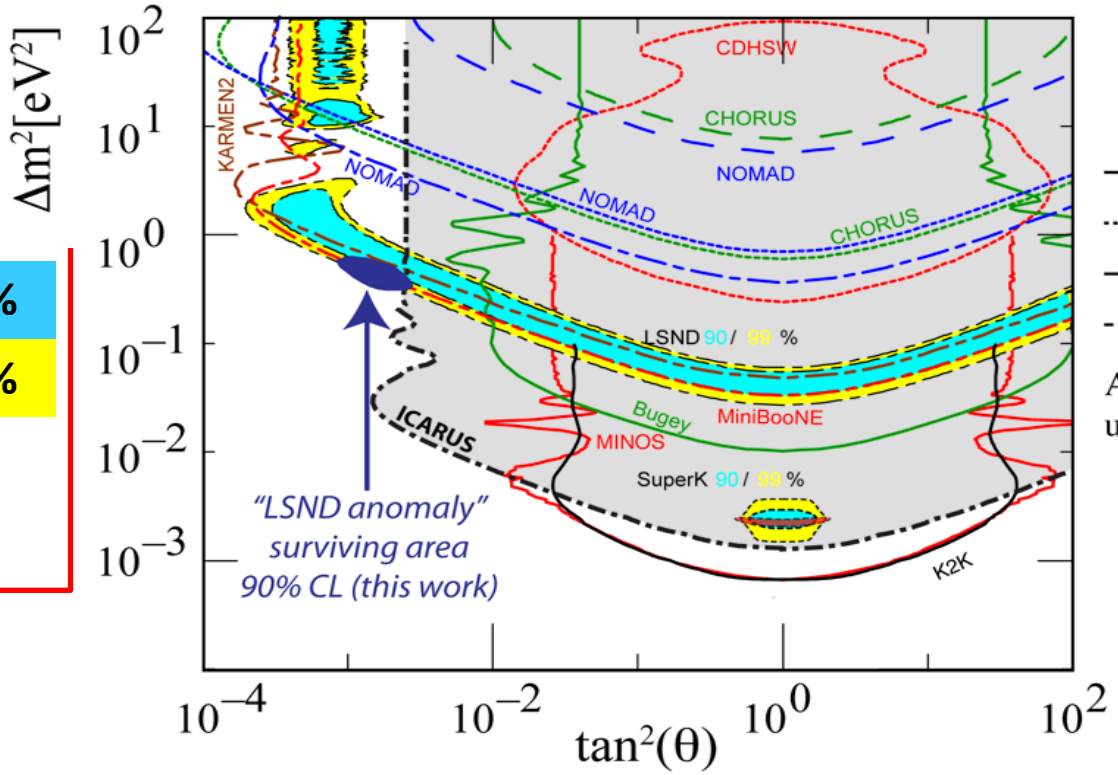
Eur. Phys. J. C73 (2013) 2345

Allowed LSND 90%

Allowed LSND 90%

MiniBoone limit

KARMEN limit



ICARUS excluded region

ICARUS results strongly limit the allowed parameters values for LSND anomaly indicating a narrow region **(Δm^2, $\sin^2 2\theta$) = (0.5 eV^2, 0.005)** where there is overall agreement (90% CL) among:

- **the present ICARUS limit**
- **the limits of KARMEN**
- **the positive signals of LSND and MiniBooNE Collaborations**

The ICARUS-NESSiE experiment at the CERN-SPS
(Idea for the detector future)

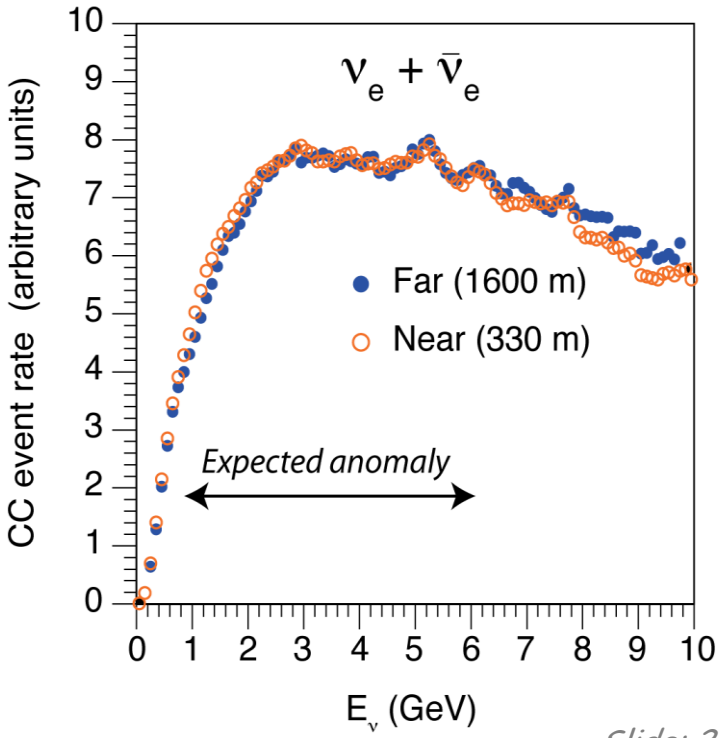
The proposed P-347 exp. At CERN-SPS introduces important new features:

- **simultaneous ν observations at different distances** from ν source: the Δm^2_{new} and $\sin^2(2\theta_{new})$ values can be separately identified;
- **"imaging" detectors** capable of detecting unambiguously <u>all</u> reaction channels with "Gargamelle"-class LAr-TPC's.;
- **very high rates**, due to detectors vicinity and large masses, to be able to detect relevant effects at the percent level (>10^6 ν_μ ≈ 10^4 ν_e);
- interchangeable ν and $\bar{\nu}$ focused beams.

This will allow:

- definitive clarification of LSND/reactors anomalies;
- Comparison of differences in ν/$\bar{\nu}$ anomalies, maybe due to CPT violations.

In absence of oscillations the two spectra should be **IDENTICAL**, without even need of a Monte Carlo comparison.



SPS 2 GeV neutrino facility in CERN North Area

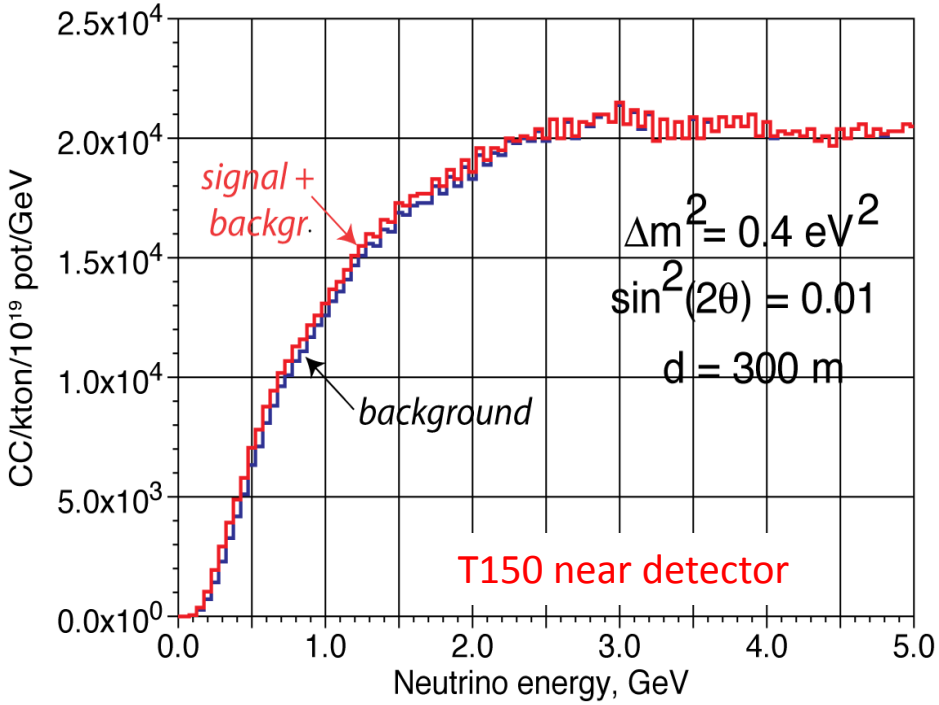
100 GeV primary proton beam fast extracted from SPS, ~ 110 m decay pipe, beam dump followed by μ stations. Interchangeable ν and $\bar{\nu}$ focusing.
Near detector (T150 – to be built) at 460 m, far detector (ICARUS-T600 – to be moved to CERN) at 1600 m, both coupled to magnetic spectrometers.

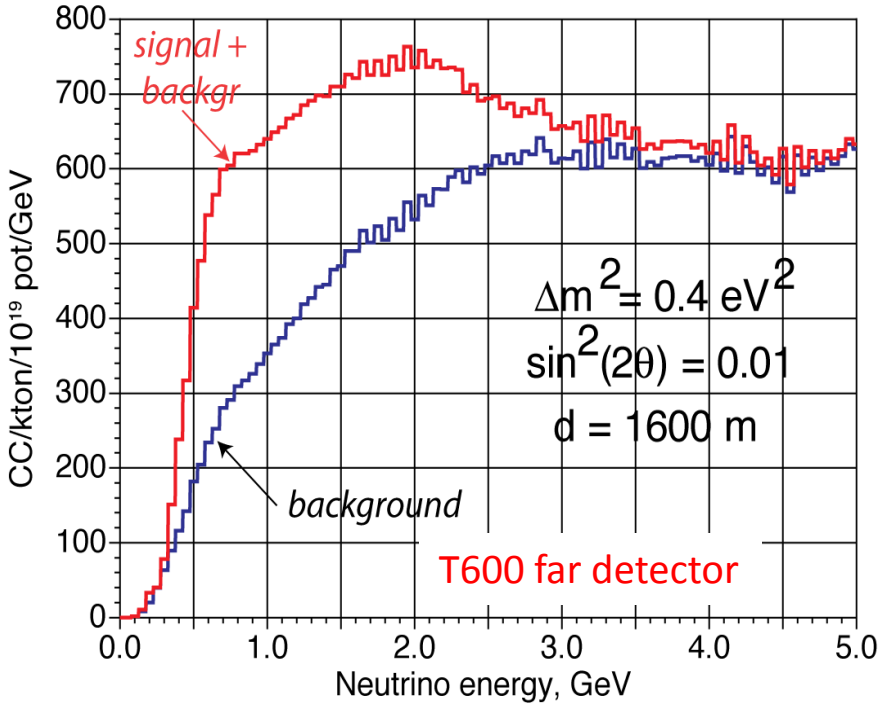
Possible expectation for LSND mass and mixing angle

- 90% **e** detection probability (0.1% NC π^0 misinterpretation prob.)
- Oscillation signals expected to be clustered below 6 GeV.

Expected signal/background rates for 4.5 x 10^{19} pot (1 year data taking), from the optimal prediction by ICARUS et al.: Δm^2_{new} = 0.4 eV2, $\sin^2(2\theta_{new})$ = 0.01.

~1200 ν_e oscillation signals over 5000 background events.

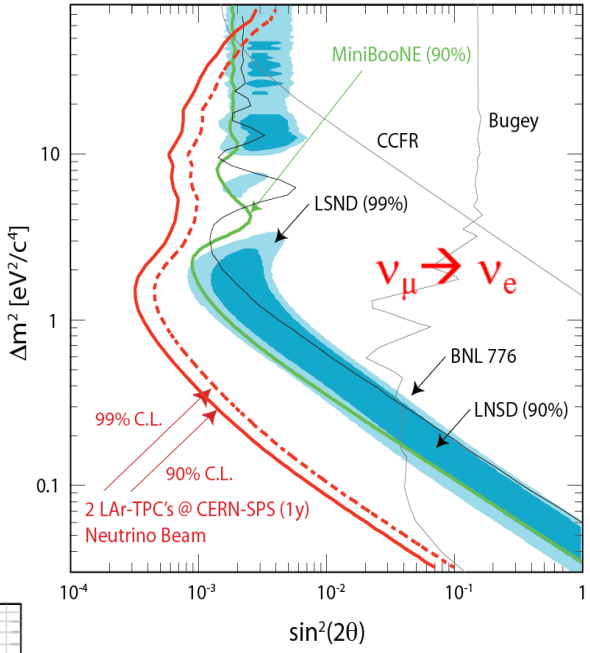


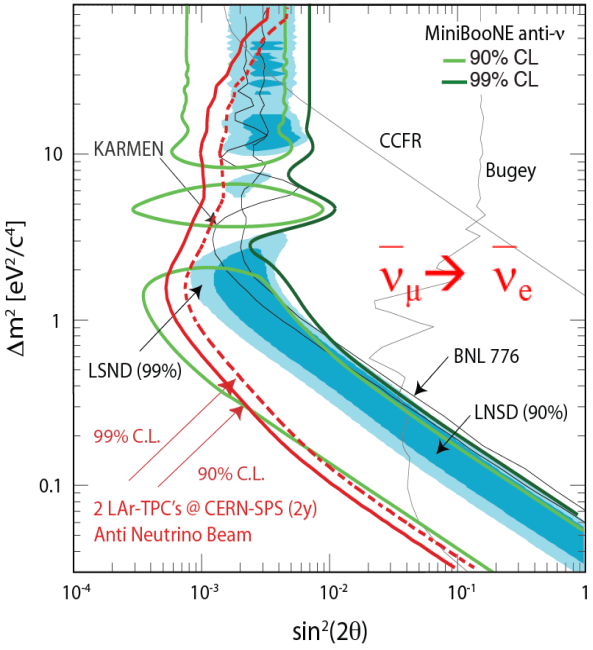


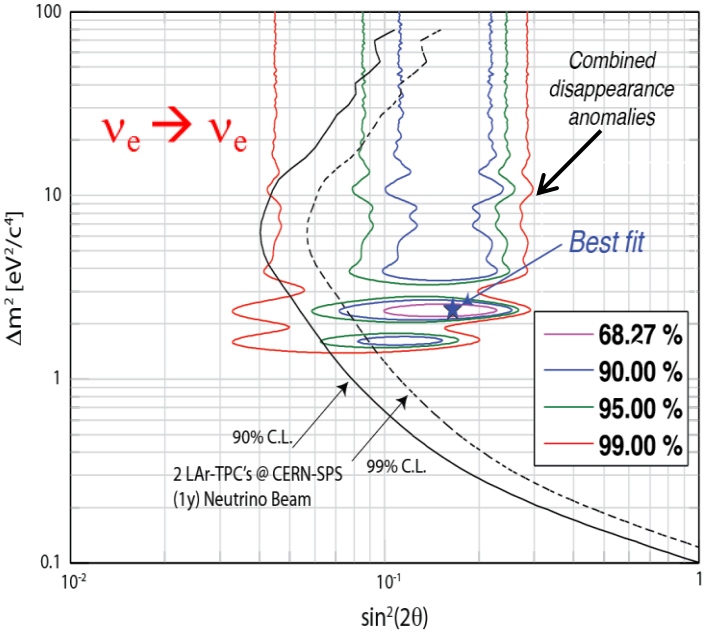
Expected sensitivity on all channels

ν_e-appearance (LSND-like)
1 year ν_μ beam (left)
2 years $\overline{\nu}_\mu$ beam (right)
4.5 x 1019 pot/y.

In both cases the LSND allowed region will be fully explored.







e/μ disappearance (reactors)
1 year ν_μ beam (straight line)
1 year ν_μ + 2 $\overline{\nu}_\mu$ years beam (dotted line)
Gallex + reactors anomalies widely explored.

Conclusions

- Icarus is the first large TPC operated underground.
- ICARUS is acquiring data without interruption since mid-2010 @ LNGS with CNGS beam (now operating with cosmic rays) and represents the state of the art for LAr technology and future multi-ton TPC-like detectors.
- Efficient reconstruction algorithms for the tracks allow to resolve most of the events collected, down to their single components. Consequence of this is for example the accurate analysis of ν_e events, which allows for an investigation of sterile neutrino oscillations and a check on previous results (LSND anomaly).
- No evidence of oscillation into sterile neutrinos is found in our measured L/E interval.
- The proposed ICARUS-like experiment at CERN, with shorter baseline, lower beam energy and a new near detector (T150), will allow to fully investigate the yet-unexplored regions of the parameter space and shed new light on the LSND/reactor issues.


Thank you
!

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.