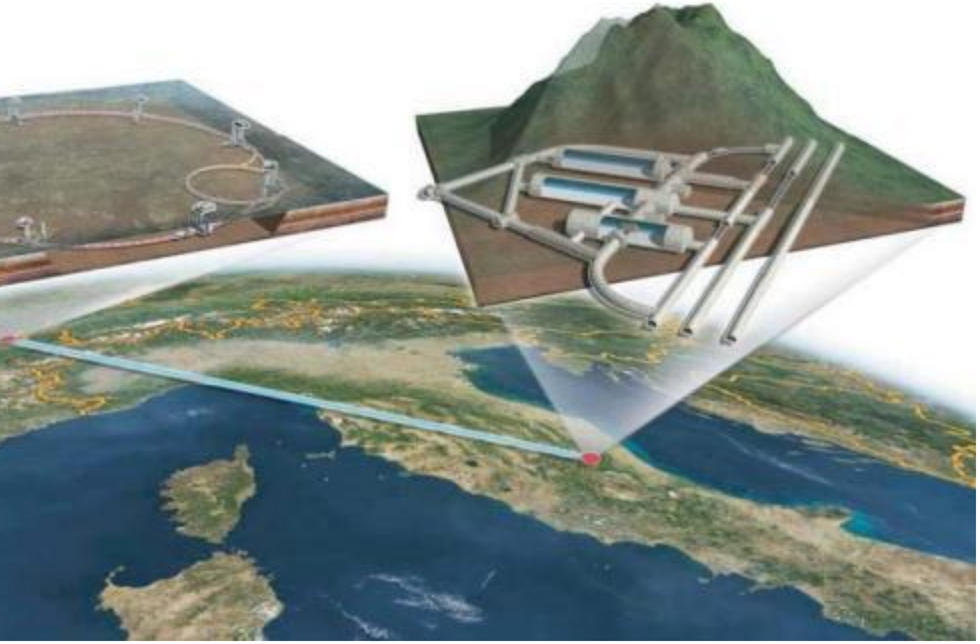
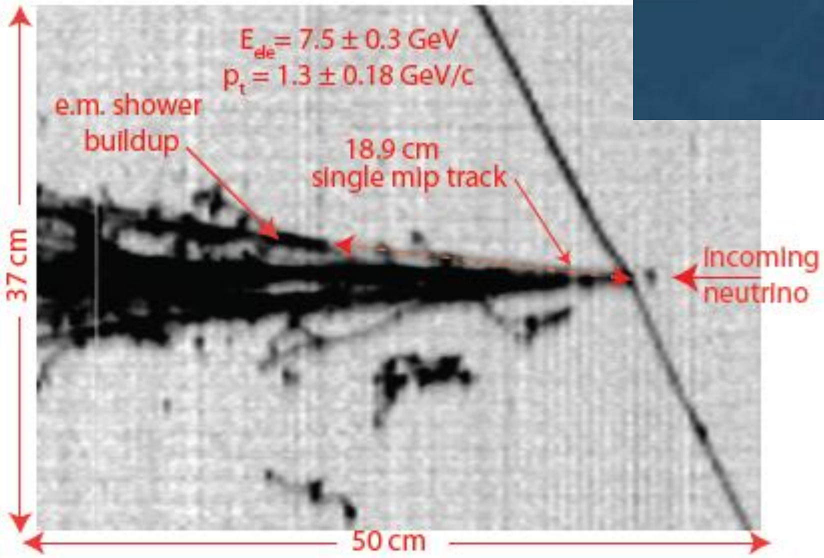
THE ICARUS EXPERIMENT:
latest results





Andrea Zani (UniPV-INFN)
Icarus Collaboration
Cagliari, IFAE – 04/04/2013

Outline

- Introduction: Liquid Argon Technology and detector present state
- Latest results: sterile neutrinos and investigation of the LSND anomaly
- Future at CERN : ICARUS-NESSiE proposal
- Conclusions

ICARUS Collaboration

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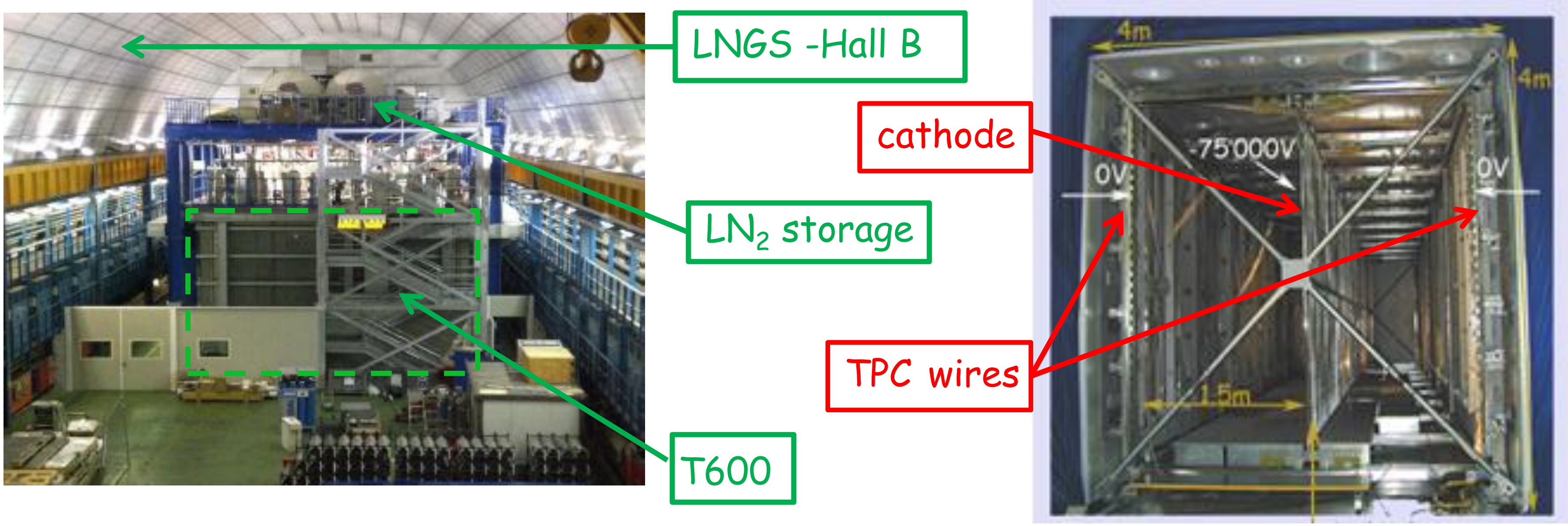
Detector at LNGS



Two identical modules…

- 3.6 x 3.9 x 19.6 m ≈ 275 m^3
- Total active mass ≈ 476 ton

… and four wire chambers

- Two TPCs for each module, divided by the cathode -> 1.5 m drift length
- HV = -75 kV -> E_{drift} = 0.5 V/cm
- v_{drift} = 1.55 mm/μs

Detectors

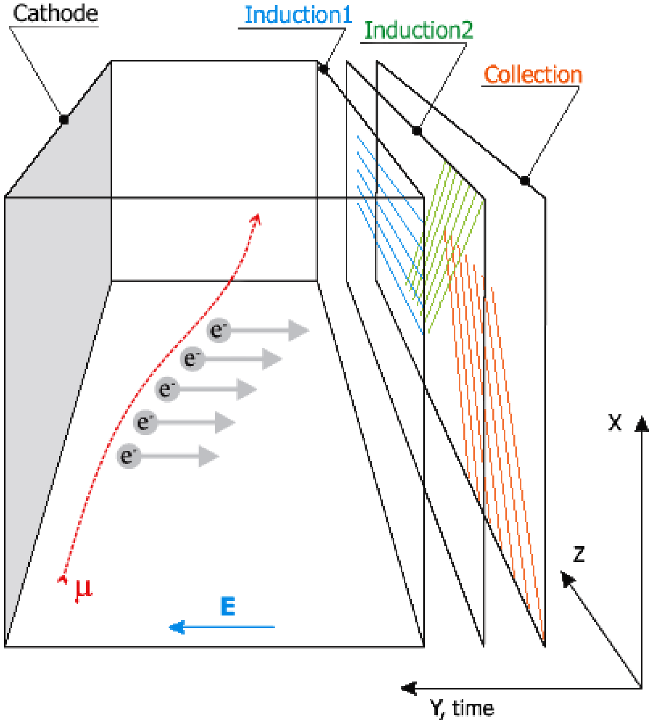
- 3 wire planes per TPC (0°, ±60°)
- ≈ 54000 total wires (150 μm Ø, 3 mm pitch)
- 54+20 photomultipliers (8″ Ø) + wls (TPB), sensitive at 128 nm (VUV)

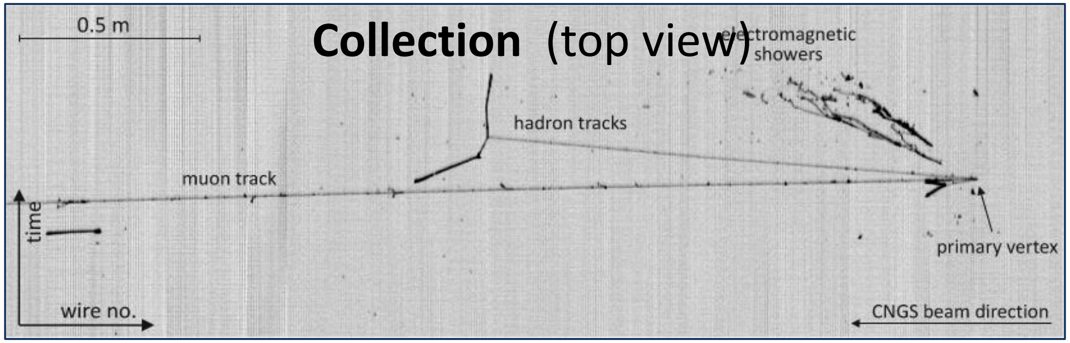
Electronics

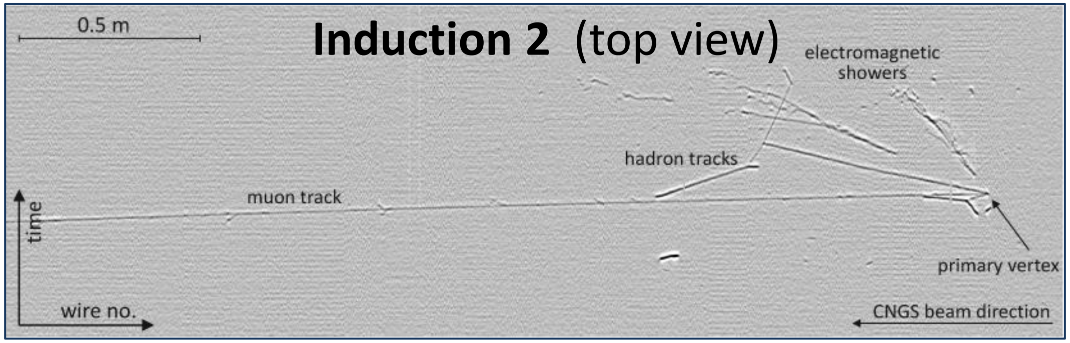
- FADC 10bit 1mV/ADC ~ 1000e$^-$/ADC

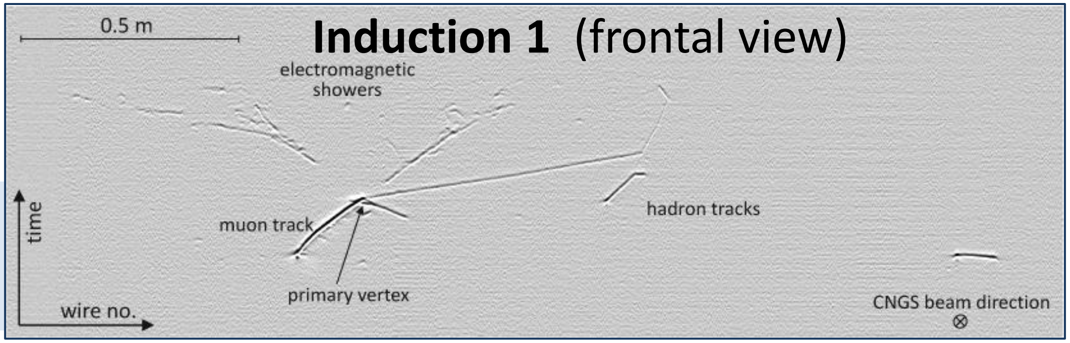
ICARUS LAr-TPC detection technique

- 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



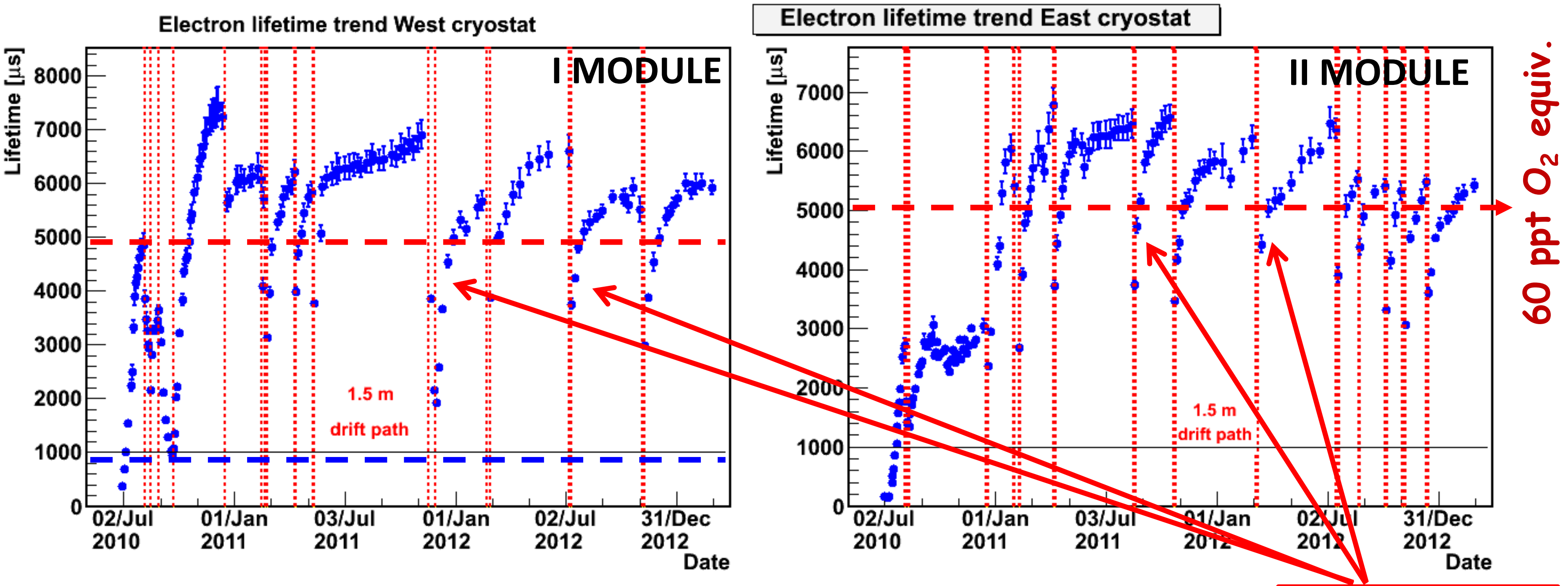

Collection (top view)


Induction 2 (top view)


Induction 1 (frontal view)

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

Argon Purity



PUMP MAINTENANCE

- Very low levels of electronegative impurities contamination (≤ 0.1 ppb – O_2 equivalent) must be reached and preserved.
  - Commercial Filters (Oxy-/Hydrosorb) and continuous recirculation both in the liquid and in the gas phase.

For most of the data taking period electron lifetime $\tau > 5$ ms (i.e. impurity level at 60 ppt O_2 eq, minimum needed 1.5 ms) -> max signal attenuation on 1.5 m drift: ≈ 17% -> good starting point for future multi-ton experiments.

CNGS RUN (Oct 2010 – Dec 2012)

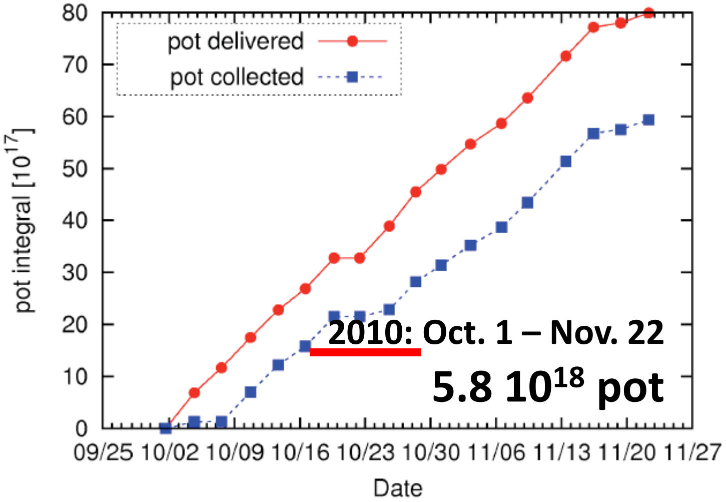
Superluminal ν (run with bunched beam: Nov. 2011, May 2012)

- Cherenkov-like e^+-e^- emission: P. L. B711 (2012) 270;
- Timing measurement: P. L. B713 (2012) 17;
- Precision measurement: JHEP 11 (2012) 049.

ν oscillations

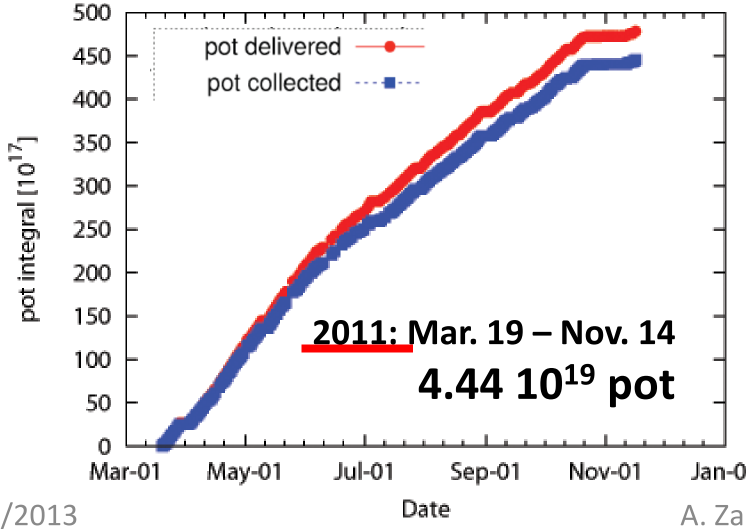
- $\nu_\mu \rightarrow \nu_\tau \quad \tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$;
- Paper on LSND anomaly (Eur. Phys. J. C 73:2345).

Collected **8.6×10^{19} protons on target (pot)**.
Detector live-time > 93%.



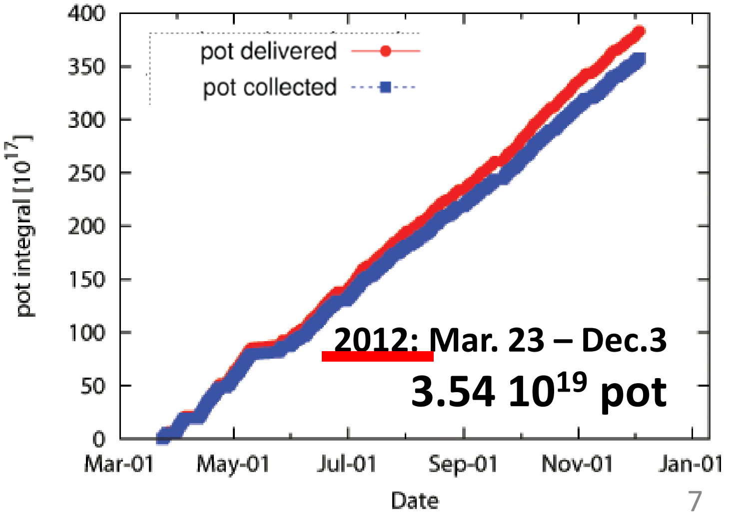
2010: Oct. 1 – Nov. 22

$5.8\ 10^{18}$ pot



2011: Mar. 19 – Nov. 14

$4.44\ 10^{19}$ pot



2012: Mar. 23 – Dec.3

$3.54\ 10^{19}$ pot

LAr-TPC performance

Total energy reconstr. from charge integration

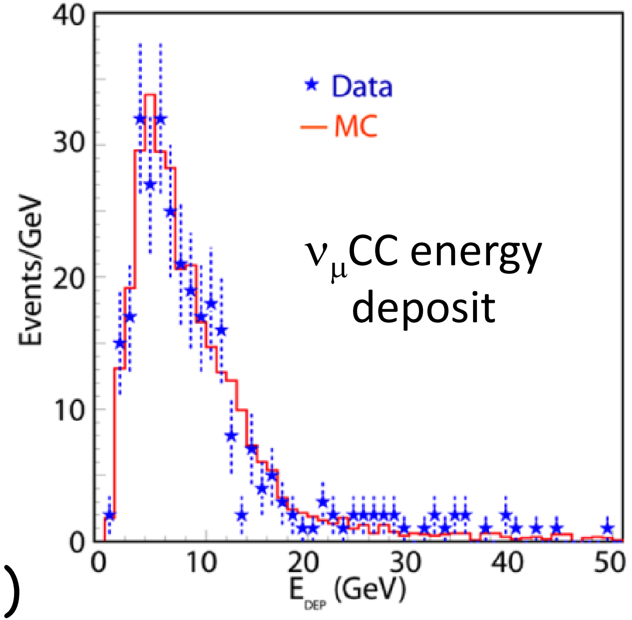
- Full sampling, homogeneous high resolution calorimeter with excellent accuracy for contained events

Tracking device

- Precise 3D topology
- 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



ν_μCC energy deposit

Low energy electrons:

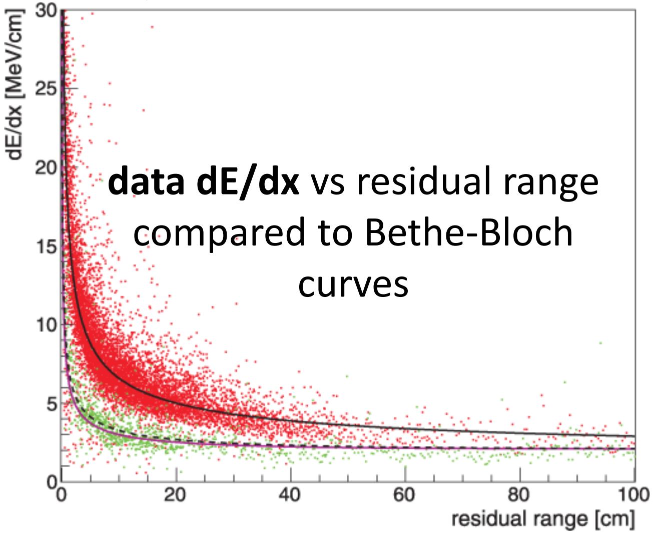
$\sigma(E)/E = 11\%/\sqrt{E(\mathrm{MeV})}+2\%$

Electromagn. showers:

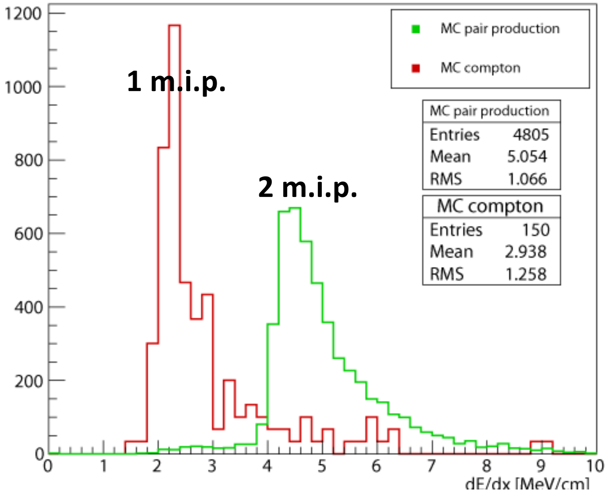
$\sigma(E)/E = 3\%/\sqrt{E(\mathrm{GeV})}$

Hadron showers:

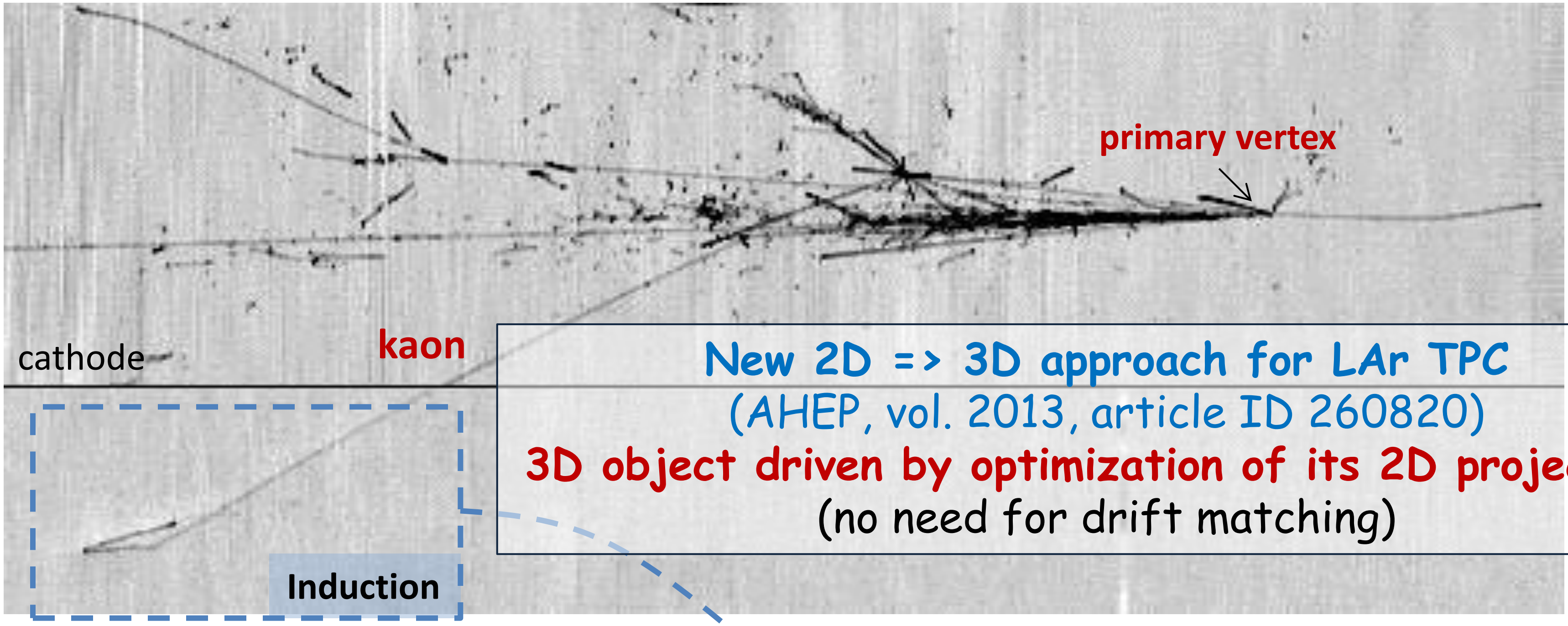
$\sigma(E)/E \approx 30\%/\sqrt{E(\mathrm{GeV})}$



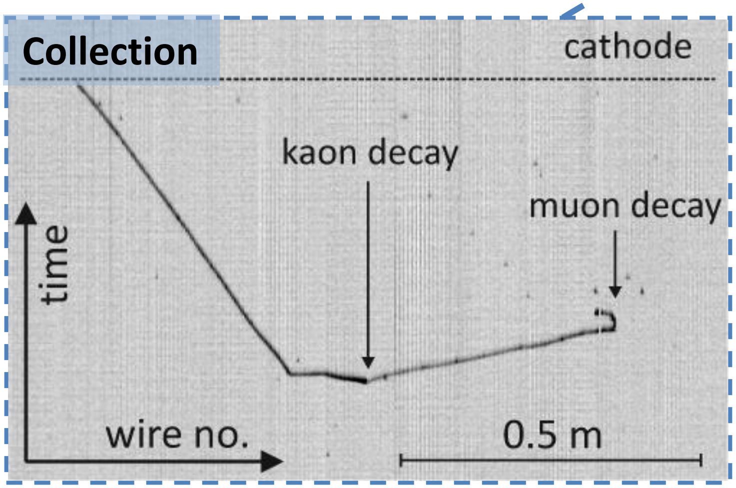
data dE/dx vs residual range compared to Bethe-Bloch curves

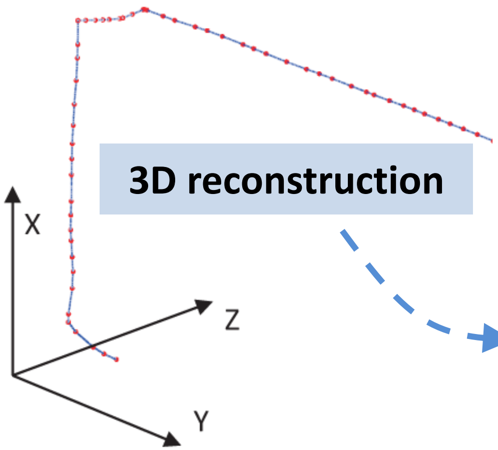


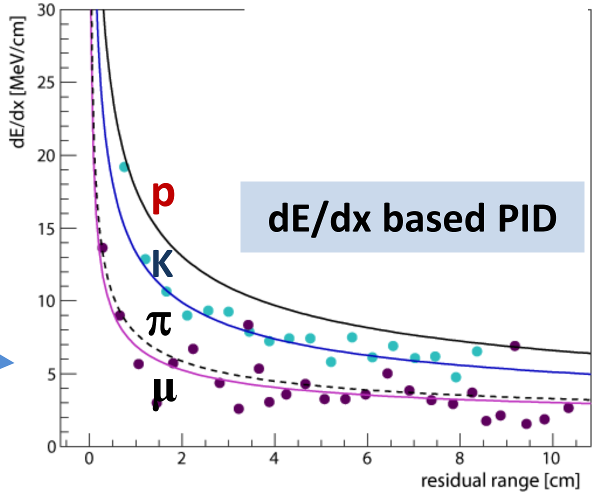
Precise particle tracking and identification



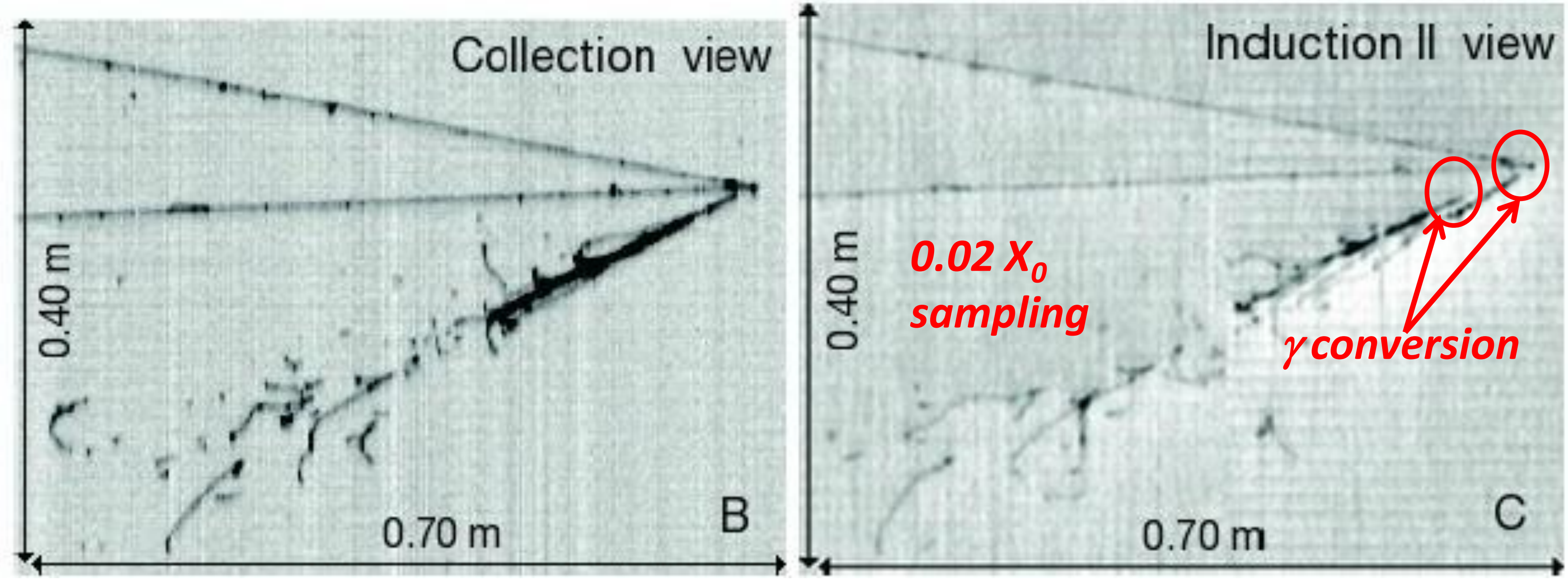
New 2D => 3D approach for LAr TPC
(AHEP, vol. 2013, article ID 260820)
3D object driven by optimization of its 2D projections
(no need for drift matching)





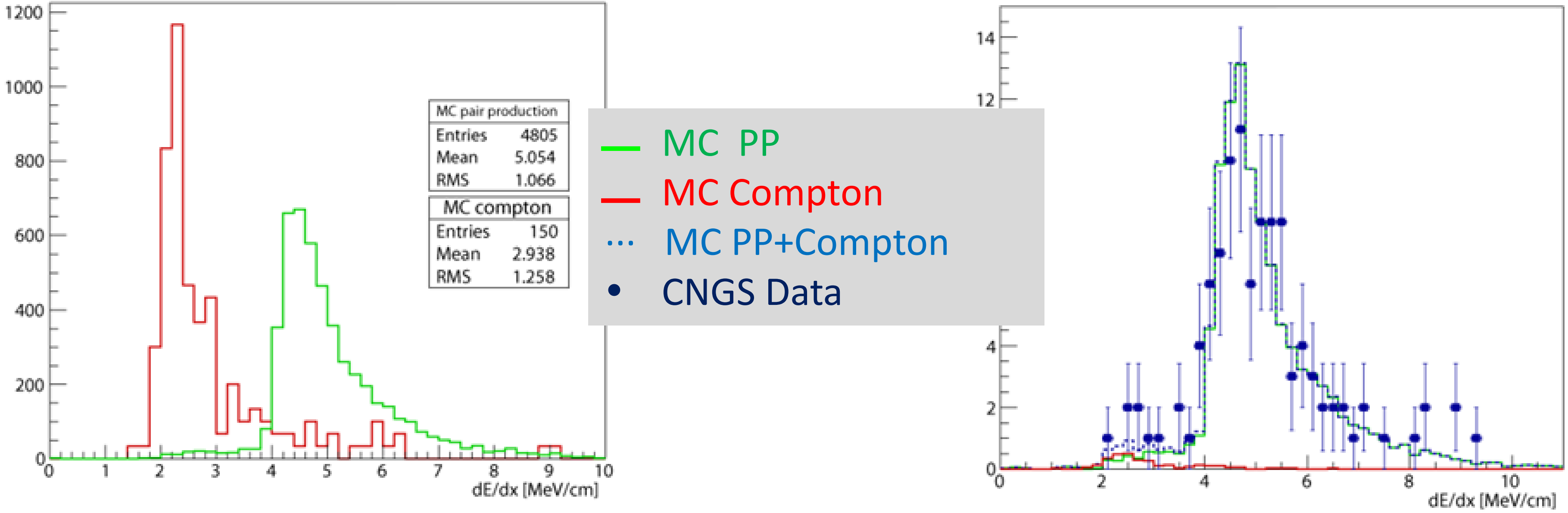


e/γ separation



0.02 X_0 sampling

γ conversion



- 🟩 MC PP
- 🟥 MC Compton
- ··· MC PP+Compton
- ● CNGS Data

Sterile neutrino - Introduction

Neutrino masses and the evidence of oscillations represent today a main experimental evidence of physics beyond the Standard Model. Though, neutrino properties are still largely unknown, so their study is a priority in the completion of our SM knowledge.

Sterile neutrinos were first hypothesized by B. Pontecorvo in 1957, as particles not interacting via any SM interaction but gravity. Nonetheless they could mix with standard neutrinos via a mass term.

Recently experimental neutrino anomalies started to build up, which could be explained with the oscillation into sterile neutrinos:

- anomalous $\bar{\nu}_e$ production from $\bar{\nu}_\mu$ beam at short distances detected by LSND experiment and later confirmed by MiniBooNE with $\nu_\mu/\bar{\nu}_\mu$ beams -> $\Delta m^2_{new} \approx 10^{-2} \div 1\ eV^2$.
- $\nu_e/\bar{\nu}_e$ disappearance from reactors and very intense e-conversion ν sources in Gallium experiments (originally designed to detect solar ν_e) -> $\Delta m^2_{new} >> 1\ eV^2$.

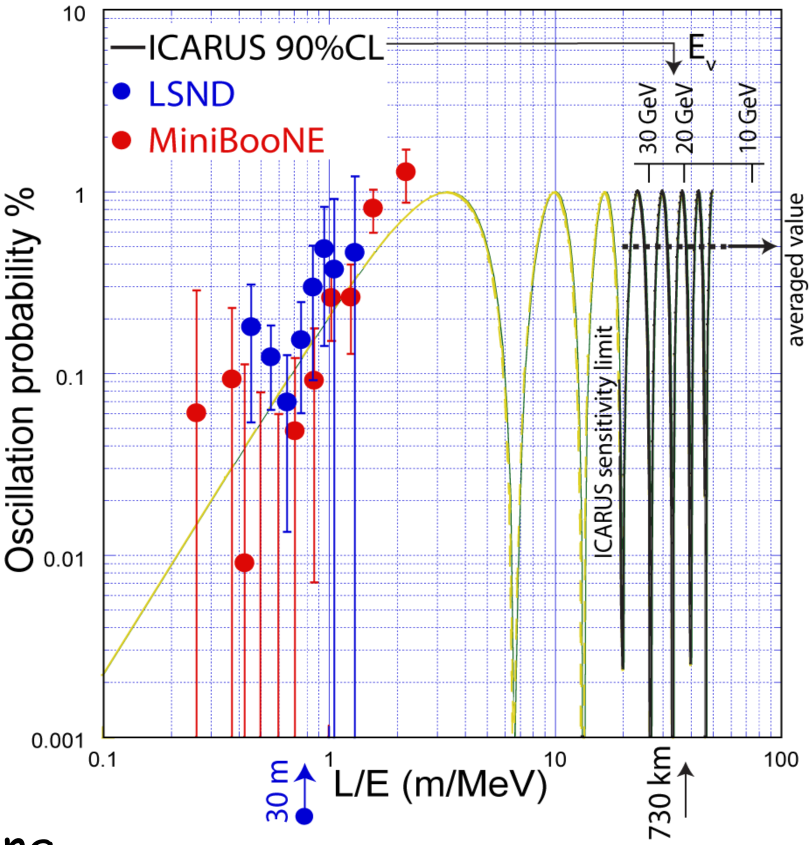
Combined evidence for some possible anomaly is ≈ **3.8** σ.

LSND anomaly search at ICARUS with CNGS beam

$\nu_\mu \to \nu_e$ search at LNSG with ICARUS T600 and the 20 GeV ν_μ CNGS beam.

Difference with LSND experiment:

LSND: L/E ≈ **1 m/MeV**
ICARUS: L = 730 km -> L/E ≈ **36.5 m/MeV**



LSND short baseline signal averages to $\sin^2(1.27\Delta m^2_{new}\ L/E) \approx \frac{1}{2}$, and

$\langle P(\nu_\mu \to \nu_e)\rangle \approx 1/2\ \sin^2(2\theta_{new})$

ICARUS operates in a region where standard ν-oscillations are less relevant, w.r.t. other long baseline experiments.

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

Data sample and cuts

In ICARUS there are **1091 ν events** currently available (from 3.3×10^{19} pot, 2010-2011 data, half the total statistic) -> compatible with MC expectation within 6%.

CNGS beam ($10 \leq E_\nu \leq 30$ 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).

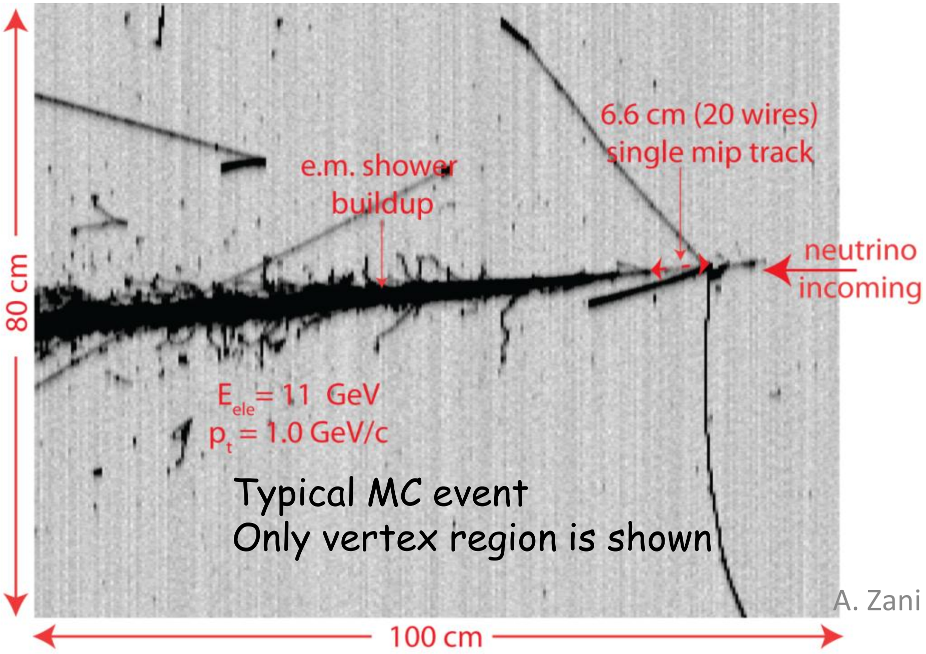
Total: **5.0 ± 0.6 events**.
Expected events, weighting for efficiency: **3.7 ± 0.6 events**.

Selections for ν_e during visual scan:

- Single m.i.p. from vertex, at 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

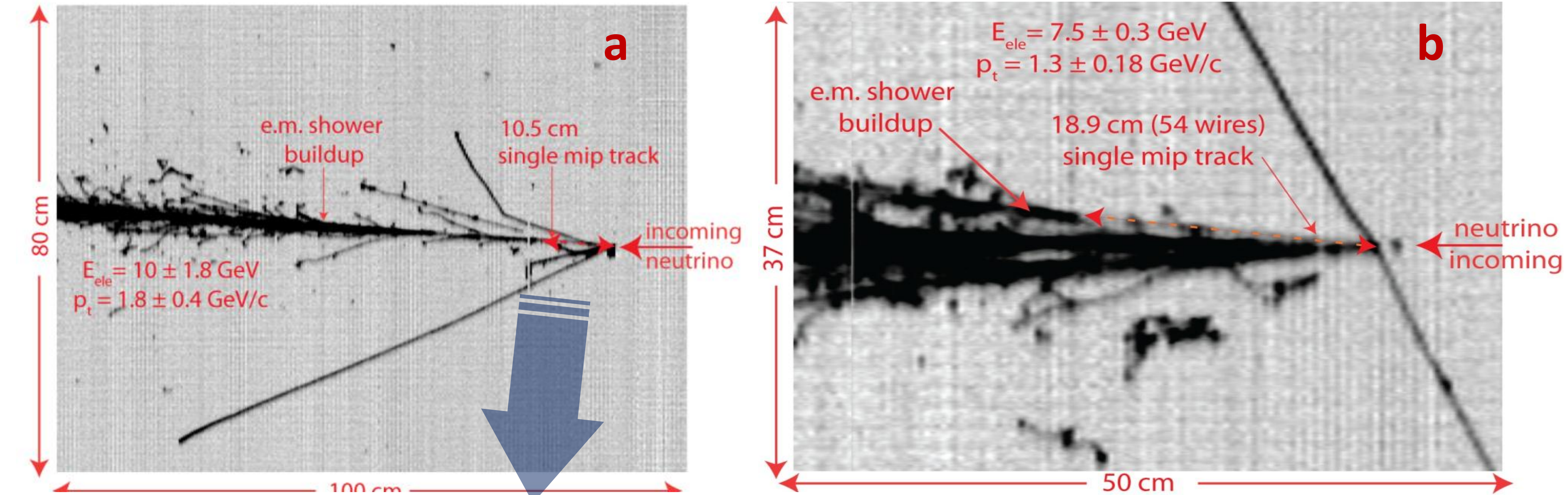
- ν_e events generated according to ν_μ spectrum in order to reproduce oscillation behaviour;
- full physics and detector MC simulation in agreement with data
- 122 events over 171 simulated inside the detector, satisfy fiducial volume and energy cuts;
- visibility cuts: (3 independent scanners), leading 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.

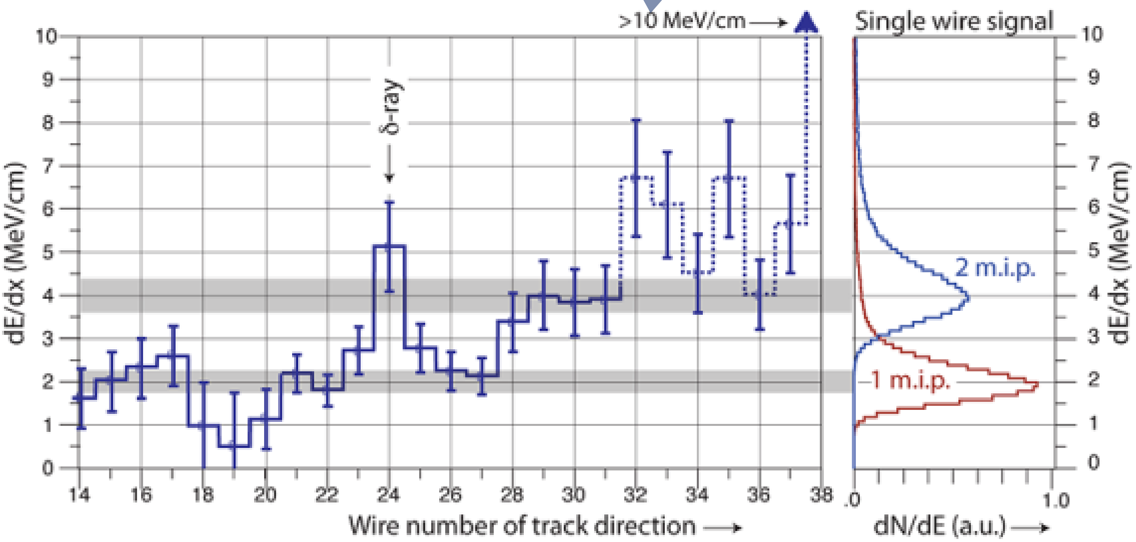


Typical MC event
Only vertex region is shown

- 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**.

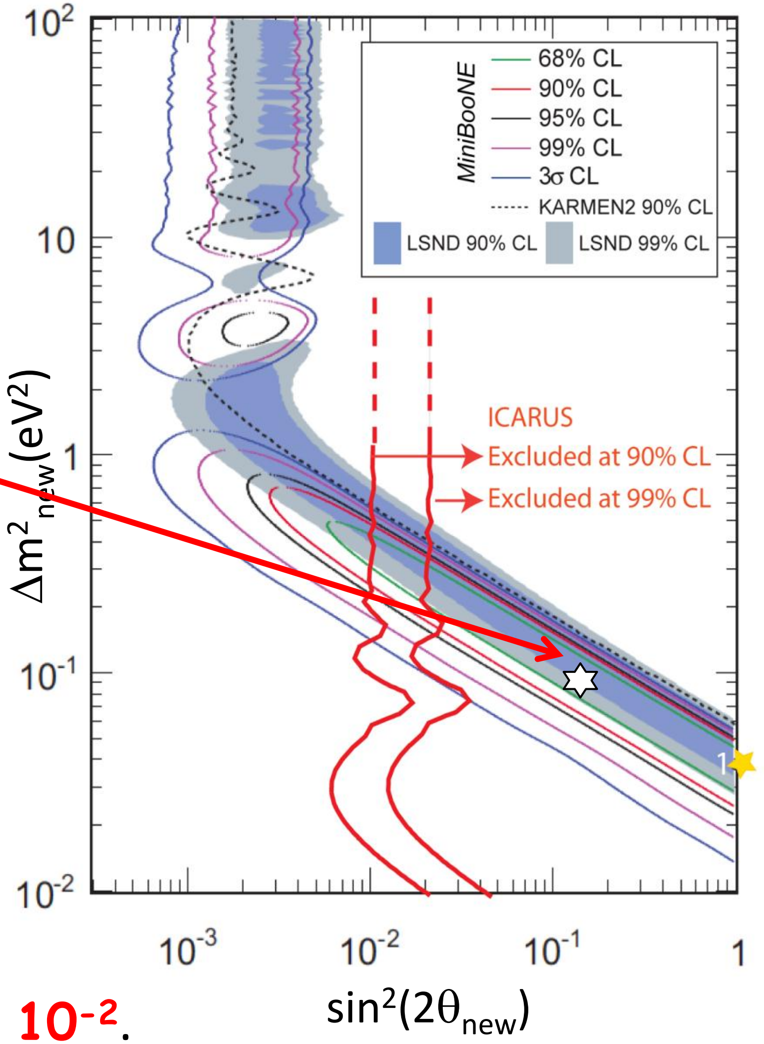
Moreover the long baseline should enhance the oscillation probability:

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)**,

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



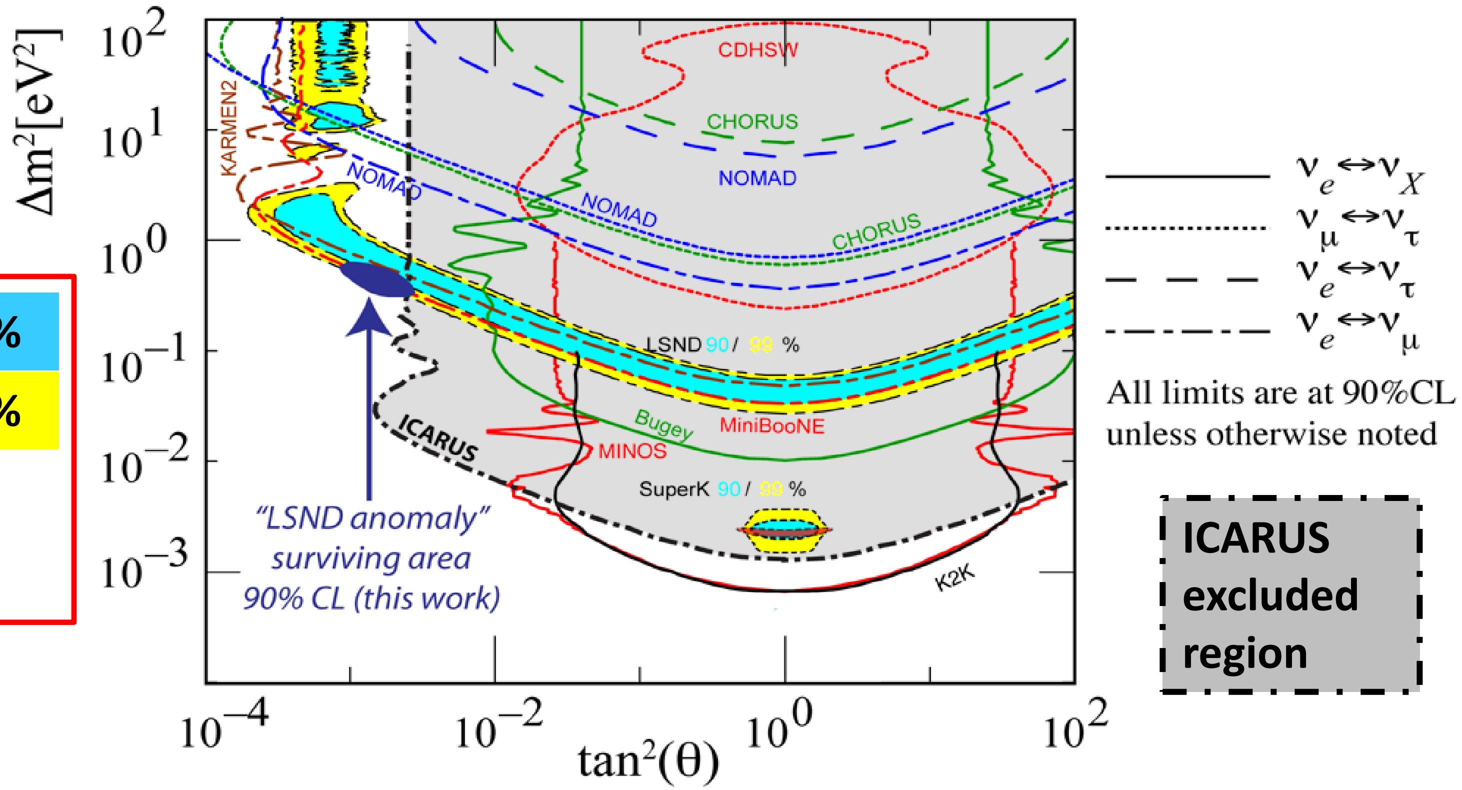
Search for an LSND-like effect with ICARUS at LNGS

Allowed LSND 90%

Allowed LSND 99%

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 experiment at the CERN-SPS

Proposed P-347 experiment at CERN-SPS:

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

The experiment will rely on:

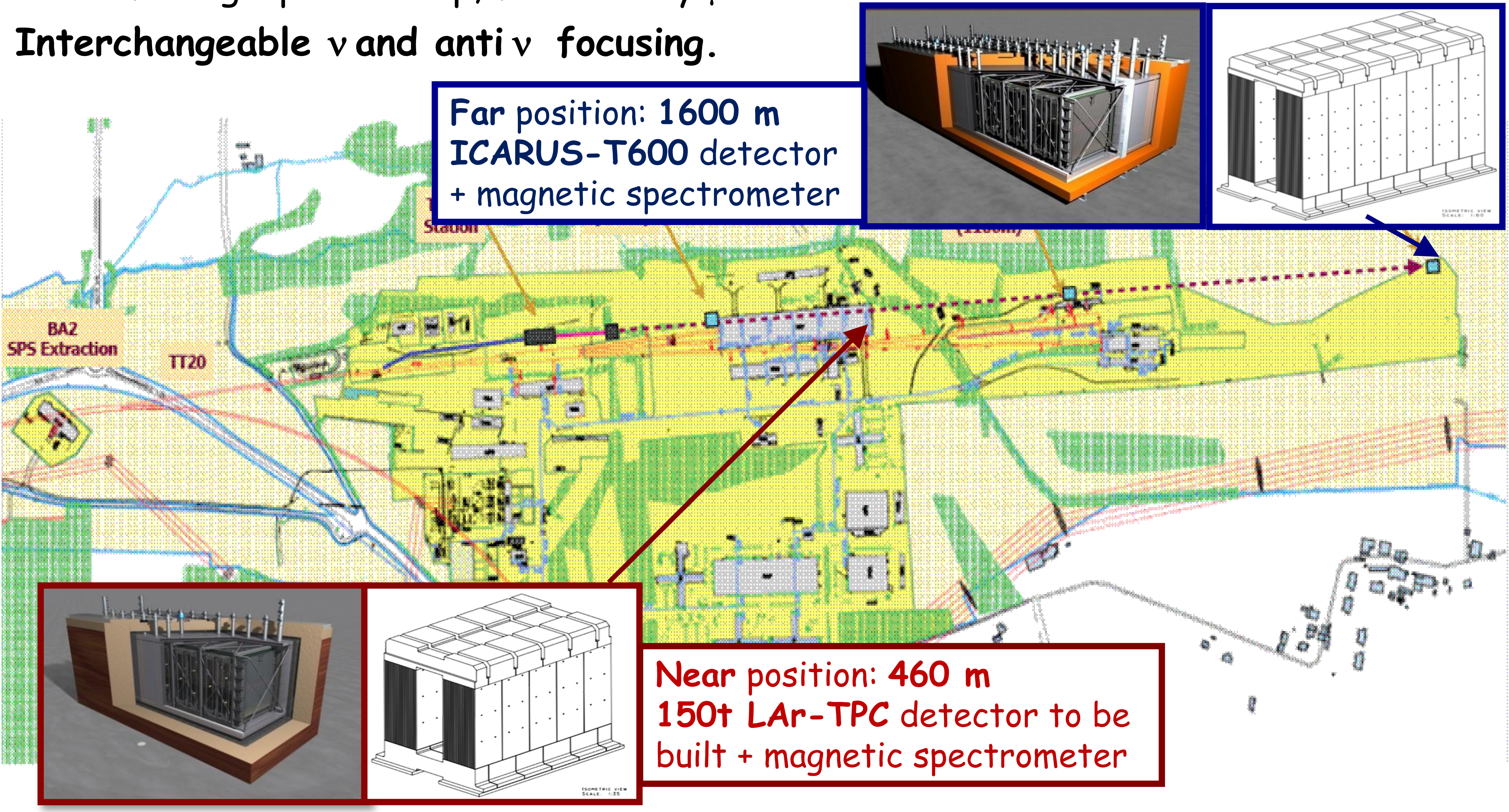
- L/E oscillation path-lengths appropriate to **match the Δm^2 window for the expected anomalies**;
- **simultaneous ν observations at different distances** from ν source: Δm^2_{new} and $\sin^2(2\theta_{new})$ separately identified;
- **"imaging" detectors** capable of detecting unambiguously all reaction channels with "Gargamelle"-class LAr-TPC's;
- **very high rates**, due to detectors vicinity and large masses: relevant effects detectable at the percent level ($>10^6\ \nu_\mu \approx 10^4\ \nu_e$);
- interchangeable ν and $\bar{\nu}$ focused beams.

ICARUS at CERN

New CERN SPS 2 GeV neutrino facility in North Area

100 GeV primary proton beam fast extracted from SPS in North Area:
C-target station next to TCC2 + two magnetic horns, 100 m decay pipe,
15 m of Fe/graphite dump, followed by μ stations.

Interchangeable ν and anti ν focusing.



Far position: **1600 m**
ICARUS-T600 detector
+ magnetic spectrometer

Near position: **460 m**
150t LAr-TPC detector to be
built + magnetic spectrometer

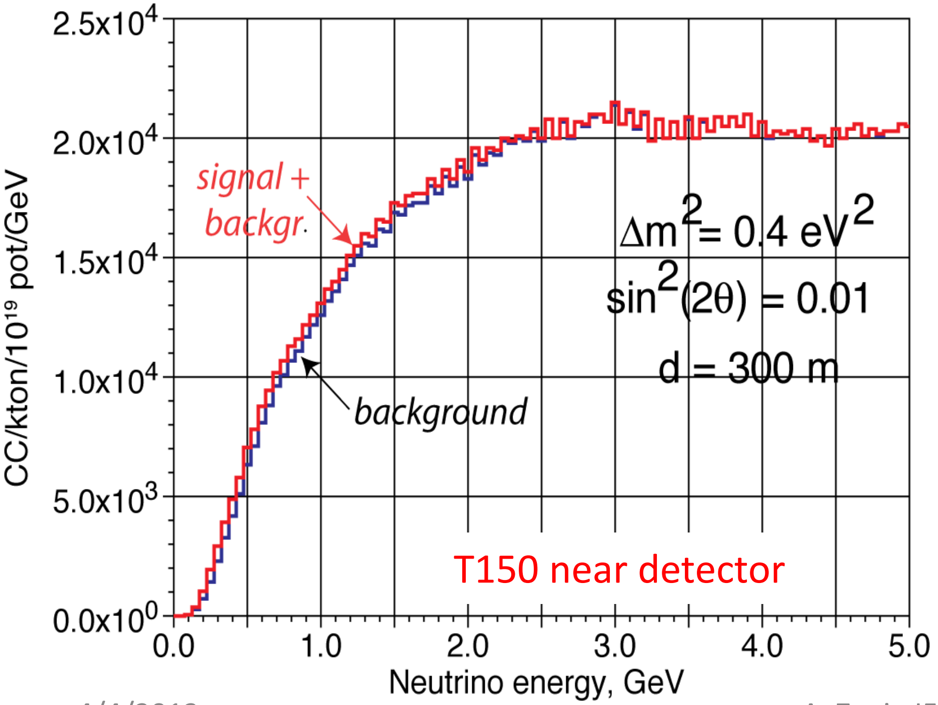
Possible expectation for LSND mass and mixing angle

Enhanced (90%) **e** detection efficiency (0.1% NC π^0 misinterpretation prob.) is expected, thanks to improved conditions at CERN-SPS:

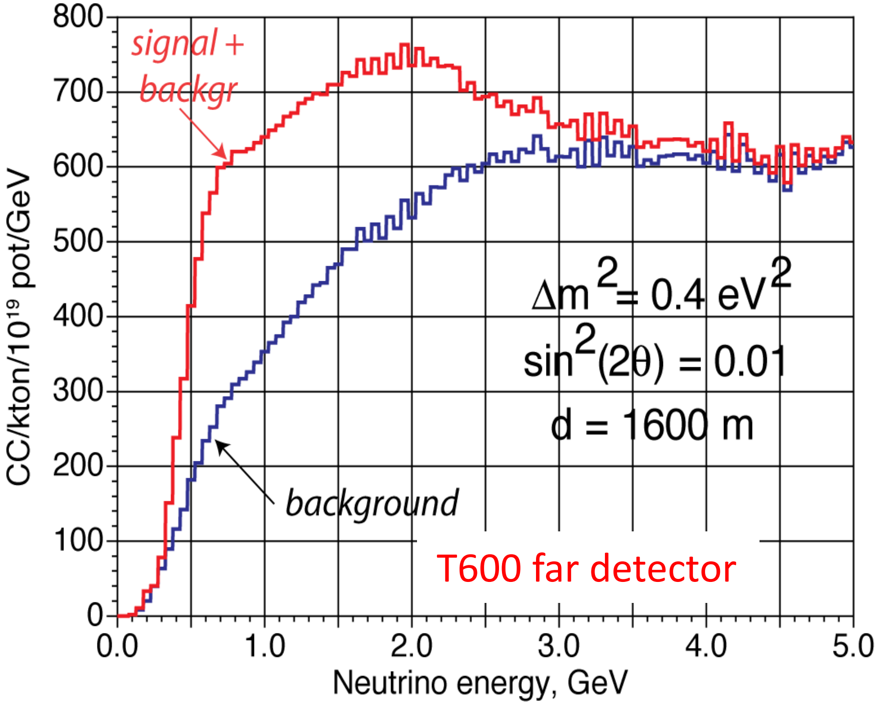
- higher event rate, lower overall event multiplicity, enlarged angular range.

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

~1200 ν_e oscillation signals over 5000 background events



T150 near detector



T600 far detector

Expected sensitivity on all channels

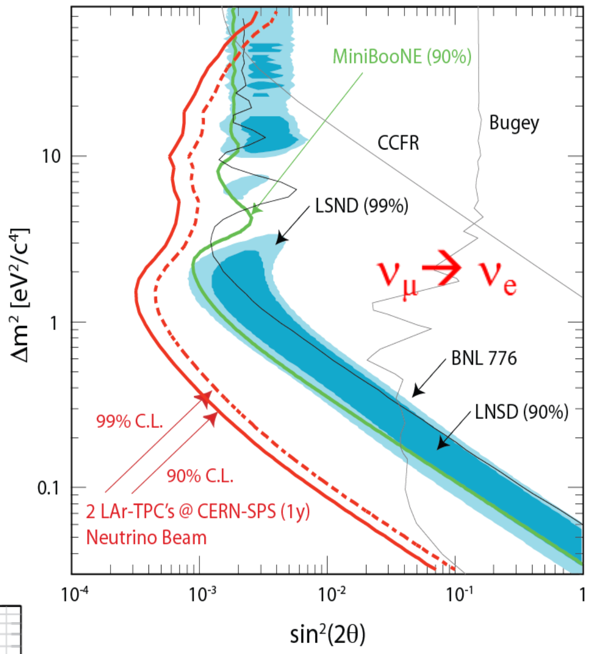
e-appearance

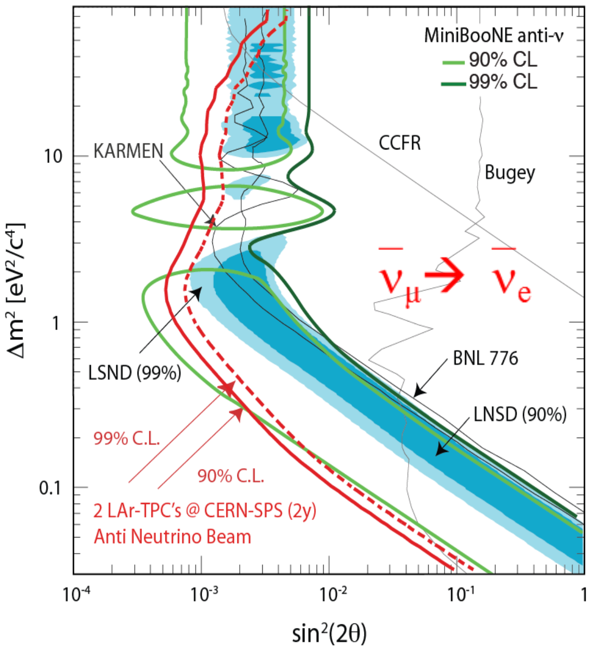
1 year ν_μ beam (left)

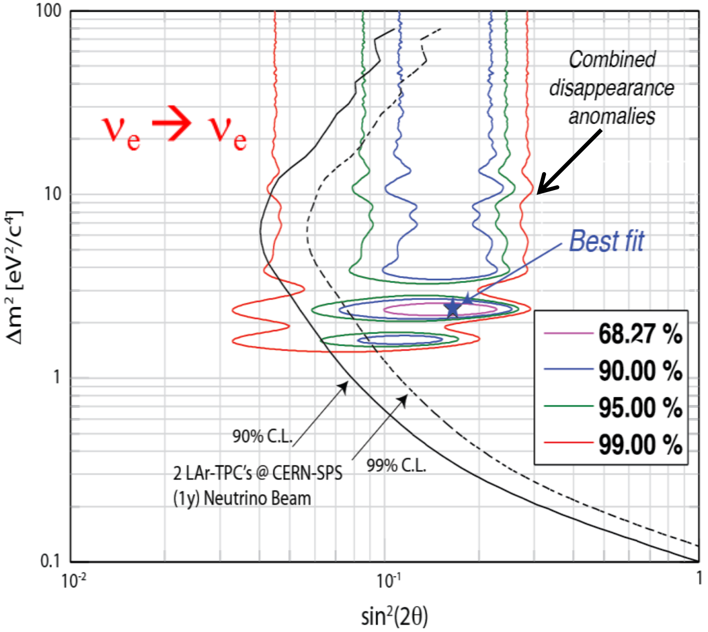
2 years $\bar{\nu}_\mu$ beam (right)

4.5 x 10^{19} pot/y.

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







e/μ disappearance

1 year ν_μ beam (straight line)

1 year ν_μ + 2 years $\bar{\nu}_\mu$ beam (dotted line)

Combined Gallium exp. + reactors anomalies widely explored.

Conclusions

- Successful operation of ICARUS T600 on CNGS beam for almost three years (now operating with cosmic rays).
- Unambiguous identification of ν_e events, thanks to LAr-TPC technology and efficient reconstruction algorithms -> investigation of sterile neutrino oscillation is made possible.
- No evidence of oscillations is found in our measured L/E interval.

$P(\nu_\mu \rightarrow \nu_e) \leq 5.4 \times 10^{-3}$ (90%CL); $P(\nu_\mu \rightarrow \nu_e) \leq 1.1 \times 10^{-2}$ (99%CL)

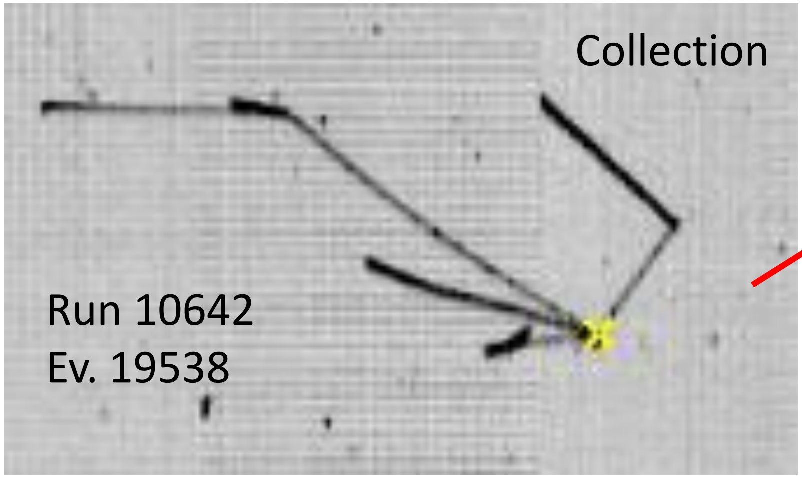
- New proposed experiment at CERN-SPS, ICARUS T600 + brand new T150 detector, exposed to 2 GeV ν beam at 1.6km, 460m baseline -> full investigation of parameter spaces for neutrino anomalies.

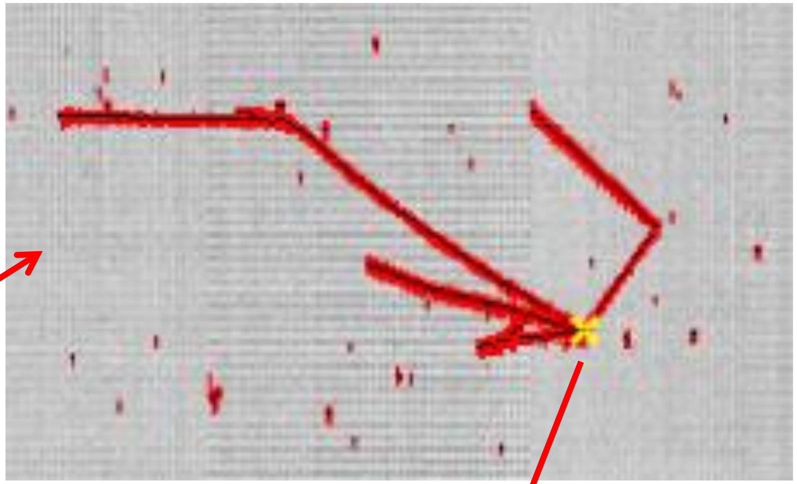
Thank you!

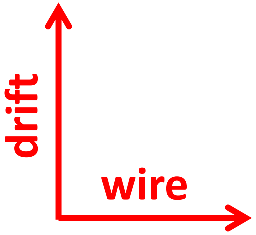
BACK UP

Hit finding

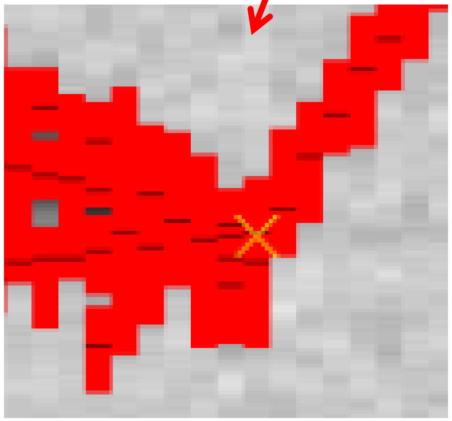
Following the identification of an event, the first step to reconstruction (reco) is the hit finding (usually done on Collection and Induction2 planes). Hits are also fitted in Collection to calculate the total energy of the event.







Zoom on vertex, showing the single hits per wire that are recognized by the hit finding algorithm.

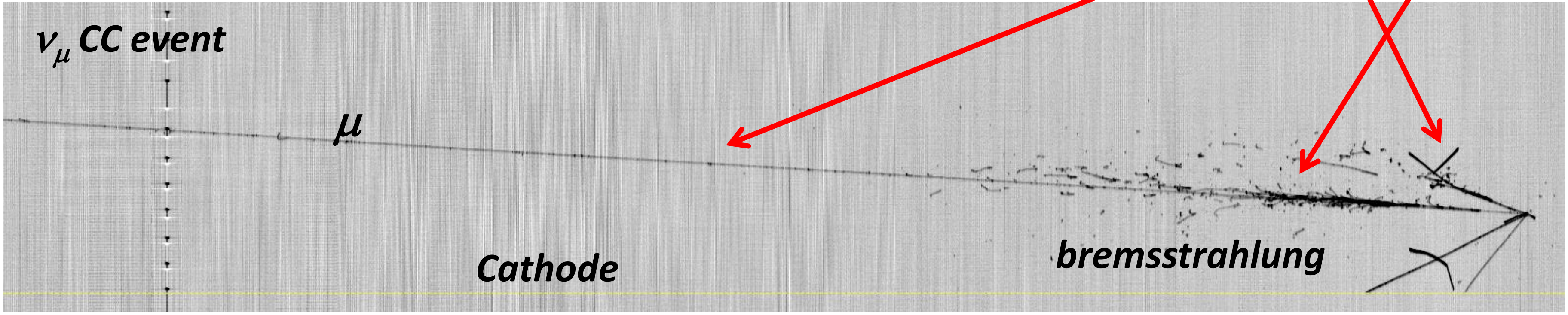


Event reconstruction

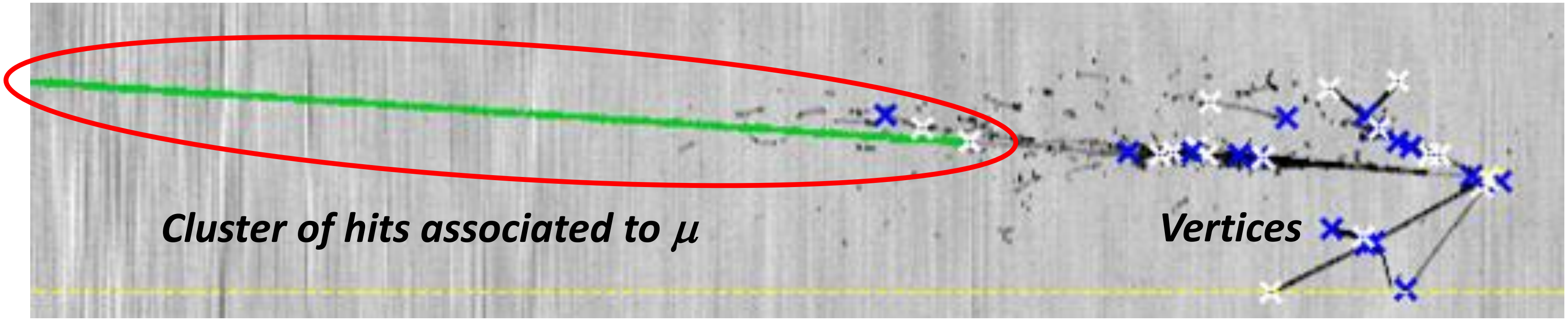
Clustering

After single hits per each wire are identified by a dedicated algorithm, they, along with information they carry (position, drift time, charge deposition), are grouped together in clusters to reconstruct the structures they belong to: tracks, showers.

In each view -> 2D objects!



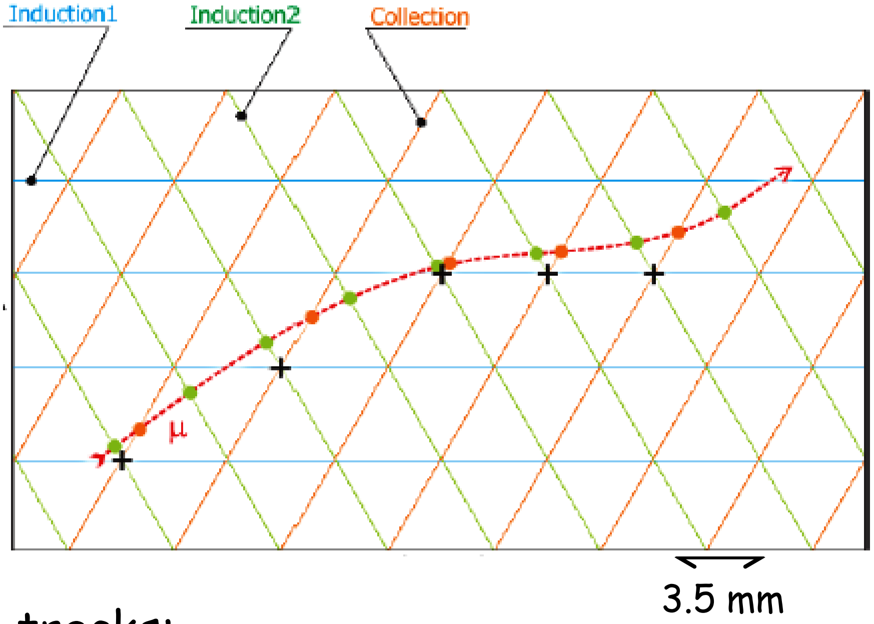
Vertexes identification, separation of secondary tracks (e.g. δ 's on a μ-track)

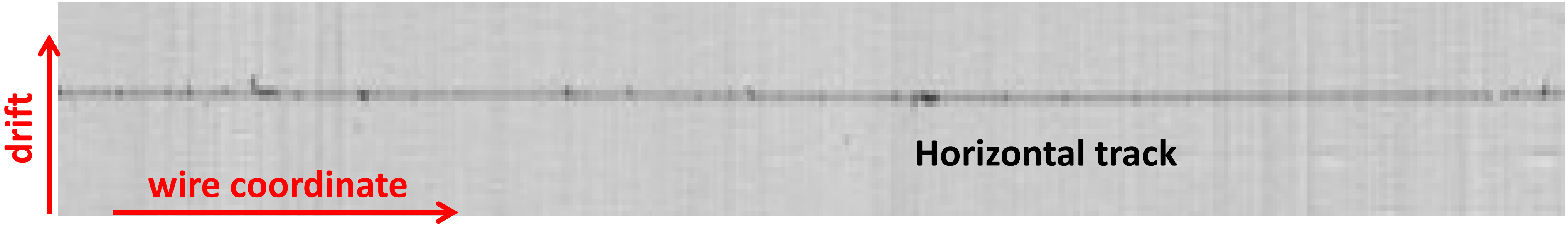


From 2D to 3D – Previous standard

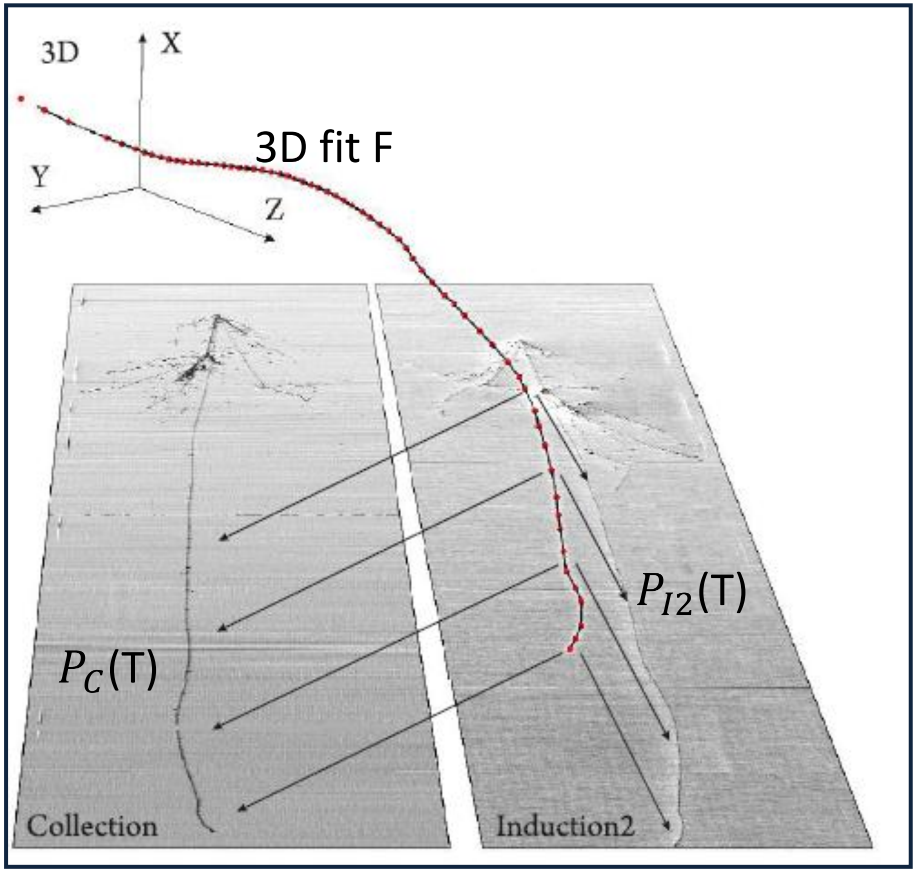
The obvious way to obtain 3D reconstruction would be to try and match hits and track end points among the views, but there are problems:

- discretization (in plane normal to drift direction);
- orientation ambiguity for very short tracks;
- drift match problems for "horizontal" (i.e. parallel to wires in 2D) tracks;
- troubles with track pieces missing in one view.





From 2D to 3D



Instead of working on 2D projections ($P_i(T)$) to be matched afterwards, we directly minimize the 3D fit (F) by simultaneous optimization of the 2D fits ($P_i(F)$).

$$\boxed{G(F) = \sum_i \alpha_i D[P_i(T), P_i(F)] + \sum_j \beta_j C_j(F)}$$

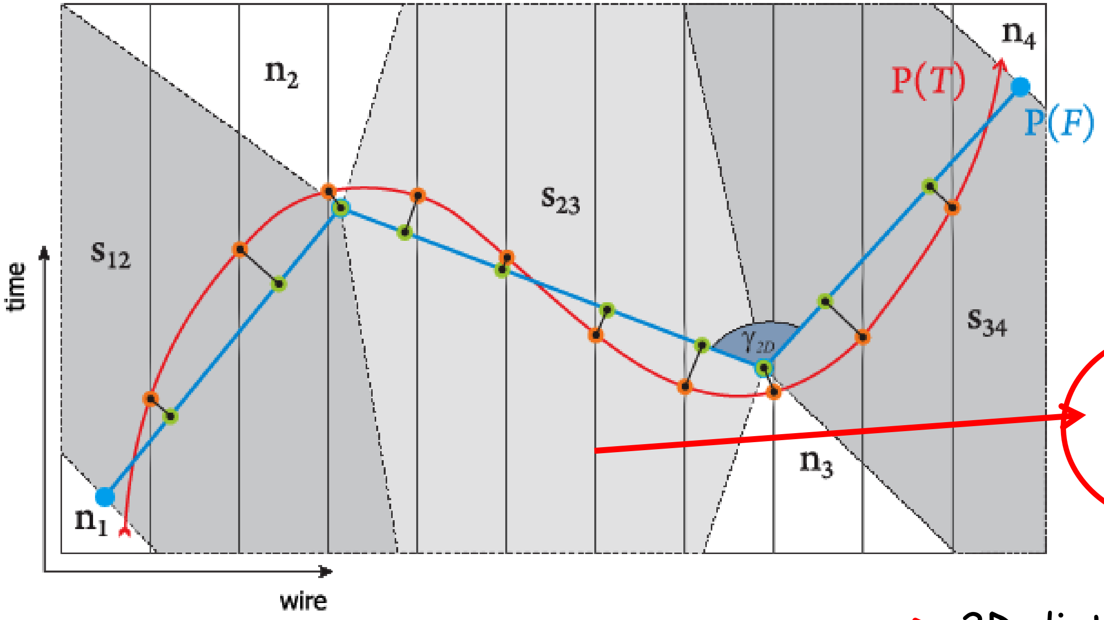
$C_j(F)$ are constraints, mostly related to already reconstructed interaction points.

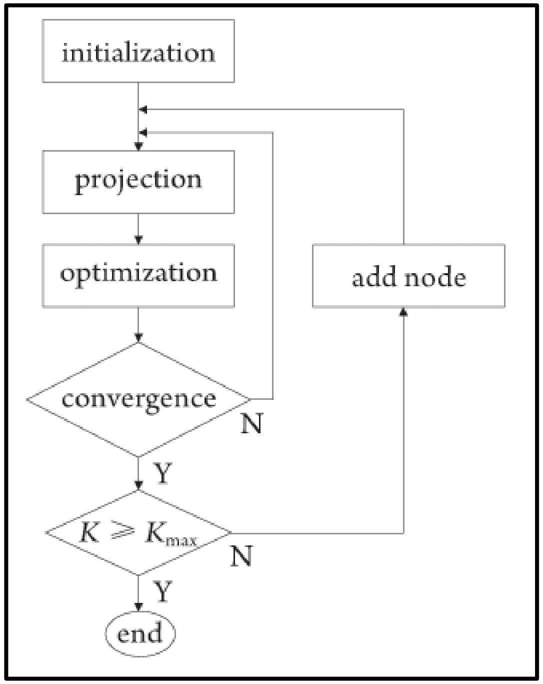
As a result:

- ✓ One overall 3D fit for the 3D real object (track),
- ✓ no more drift matching and wire correlation -> no more discretization,
- ✓ verified higher efficiency with horizontal tracks (see next slide).

Local fit on track

G(F) inspired by Polygonal Line Algorithm (PLA): fit approximated by a polygonal described by 3D points (nodes) connected by straight 3D segments, with the distance from data point given as function of 2D projections in the three ICARUS views.





Local solution

$$G(F) = \sum_k g_k(\boldsymbol{n}_k)$$

$$g_k(\boldsymbol{n}_k) = \boxed{d(\boldsymbol{n}_k)} + \beta_v \boxed{c_v(\boldsymbol{n}_k)} + \beta_a \boxed{c_a(\boldsymbol{n}_k)}$$

2D distance $P_i(F)$-2D data for a node

Constraint on angles between 3D segments

3D distance fit-3D vertices