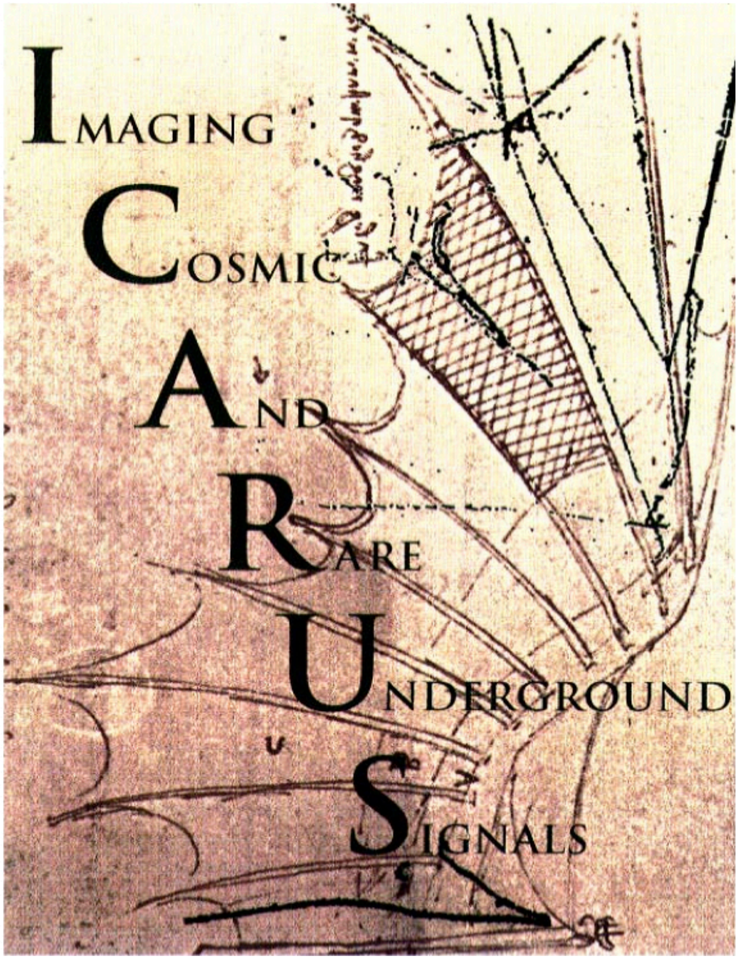
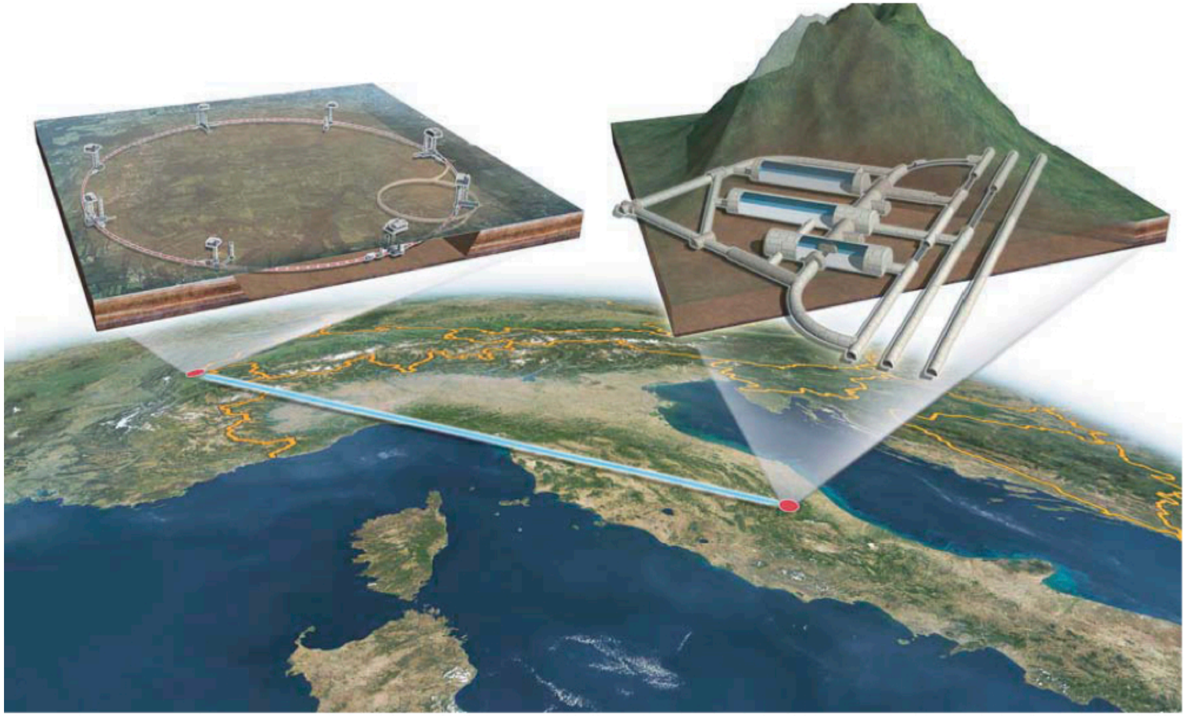
Results from ICARUS



Ettore Segreto
Laboratori Nazionali del Gran Sasso (Italy)
on behalf of the
ICARUS Collaboration



XXXIX meeting of LNGS scientific committee
Laboratori Nazionali del Gran Sasso
16 April 2013

The ICARUS Collaboration

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

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 INFN, Sezione di Milano e Politecnico, Via Celoria 16, I-20133 Milano, Italy
f Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Science, Krakow, Poland
g Department of Physics and Astronomy, University of California, Los Angeles, USA
h INR RAS, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia
i CERN, CH-1211 Geneve 23, Switzerland
j Institute of Physics, University of Silesia, 4 Uniwersytecka st., 40-007 Katowice, Poland
k National Centre for Nuclear Research, A. Soltana 7, 05-400 Otwock/Swierk, Poland
l Laboratori Nazionali di Frascati (INFN), Via Fermi 40, I-00044 Frascati, Italy
m Institute of Radioelectronics, Warsaw University of Technology, Nowowiejska, 00665 Warsaw, Poland
n INFN, Sezione di Pisa. Largo B. Pontecorvo, 3, I-56127 Pisa, Italy

Introduction

- ICARUS T600 detector 3 years of stable and safe operation; data taking with a remarkable high efficiency; no major problems

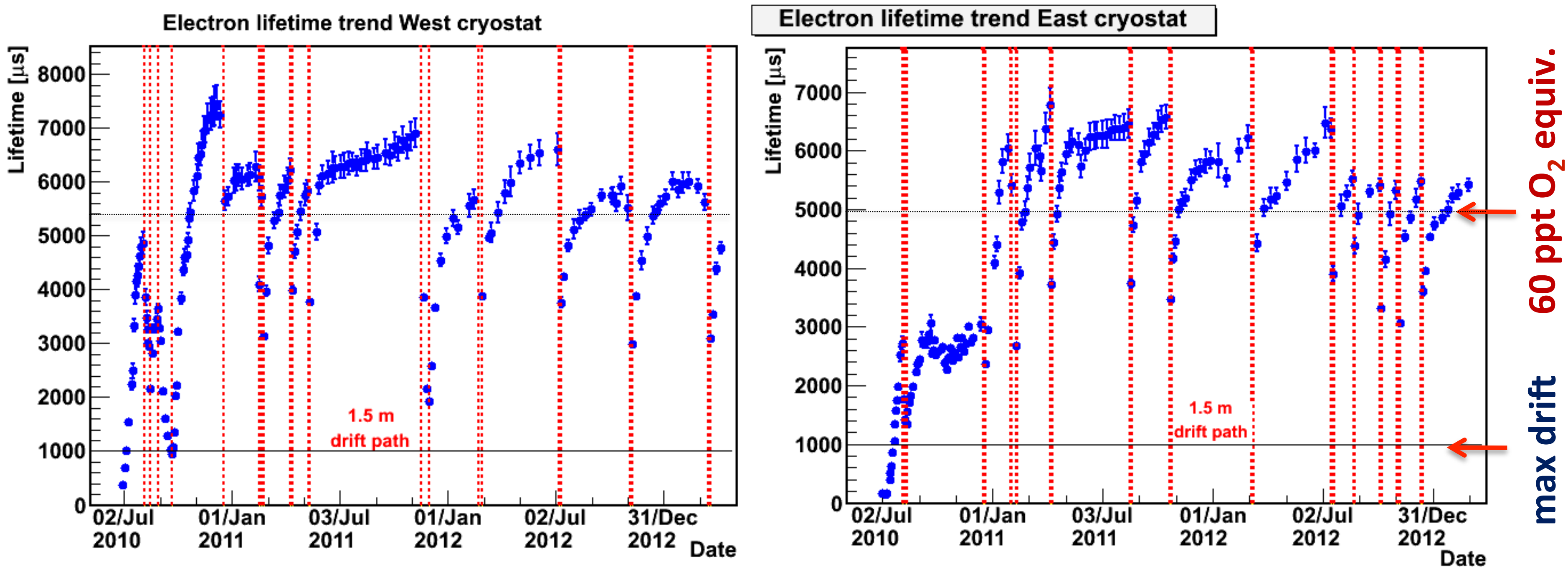
- Run 2012: 3.58×10^{19} pot collected; detector live-time in excess of 93% (total statistics ~ 8.6×10^{19} pot)

- The detector is presently collecting cosmic-ray events. The run will last until the detector shut-down (end of May 2013)

- The decommissioning phase is expected to start in June 2013 with the cryostat emptying

- Data analysis has been focused on electron neutrino events reconstruction and measurement to address the "LSND anomaly" signal, searching for ν_e excess above the expected CNGS background (this talk).

LAr purity

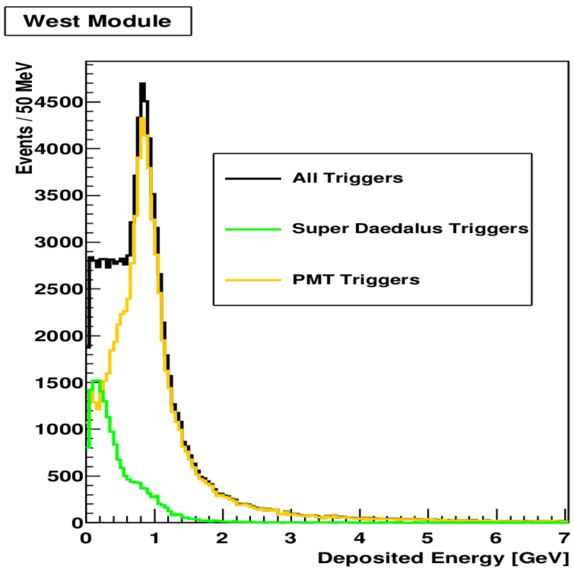


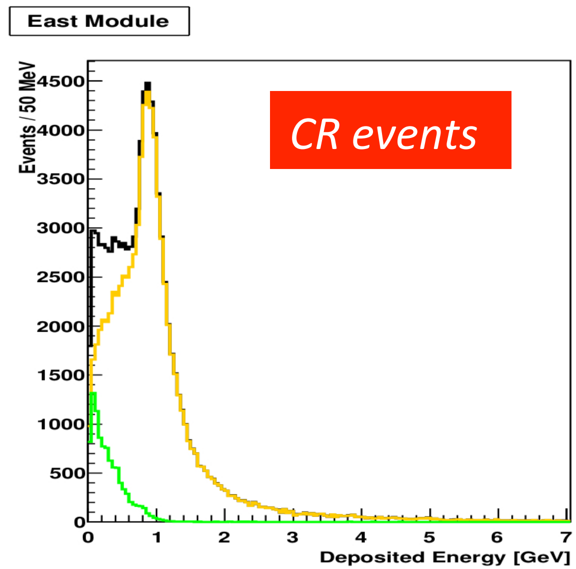
- Ultra High Vacuum techniques
- High efficiency filters (**Oxysorb/Hydrosorb**)
- Continuous purification by recirculation in liquid & gas
- New (Barber Nichols) pump for LAr recirculation installed and steadily operating since April 4th

- $\tau_{electrons}$ > 5 ms (~ 60 ppt $[O_2]_{eq}$) corresponding to a free electron attenuation of 17% after 1.5 m (longest path length)

Trigger system and DAQ upgrades

- Super Daedalus trigger on local charge deposition up and running for CNGS beam (since Jun. 2012) and cosmic rays (since Sept. 2012) in addition to the standard PMT trigger

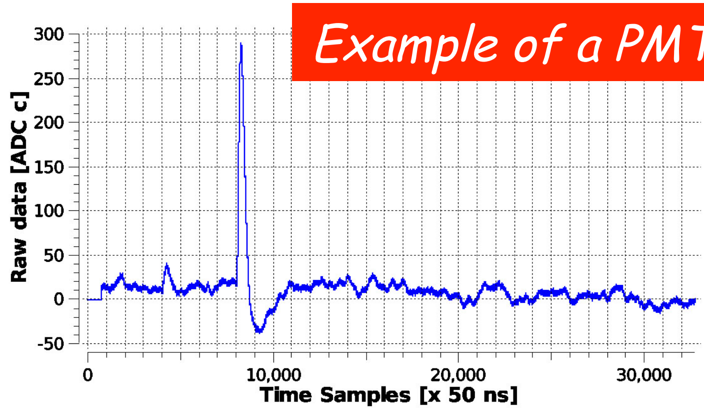




Promising improvement of the cosmic event trigger efficiency in 0.1 – 1 GeV range

- PMT DAQ improved: PMT waveforms (sampled @ 20 MHz) now acquired

Example of a PMT signal



19 wfm digitizers mutuated from TPC

CNGS data taking: 2010-2012

CNGS data taking (Oct. 2010 - Dec. 2012)

- large sample of ν interactions
- superluminal ν searches

1. Cherenkov-like e^+e^- pairs: P. L. B711 (2012) 270
2. timing measurement: P. L. B713 (2012), 17
3. precision measurement: JHEP 11 (2012) 049

- ν oscillations

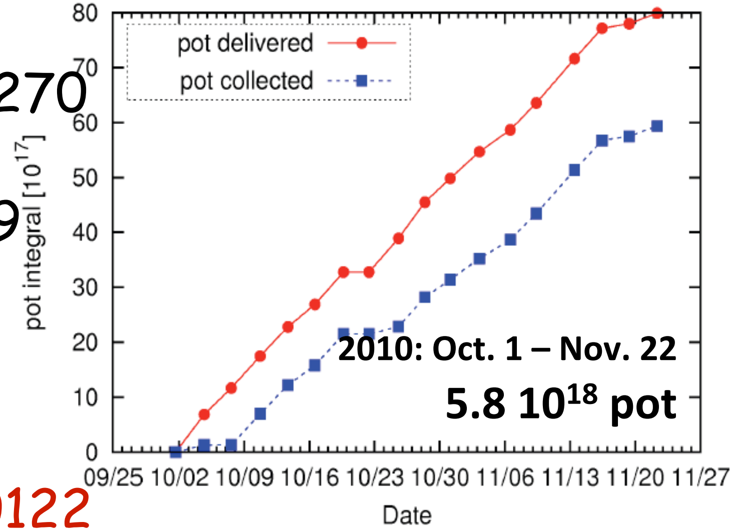
$\nu_\mu \rightarrow \nu_\tau \quad \tau^- \rightarrow e^- \nu_e \nu_\tau$

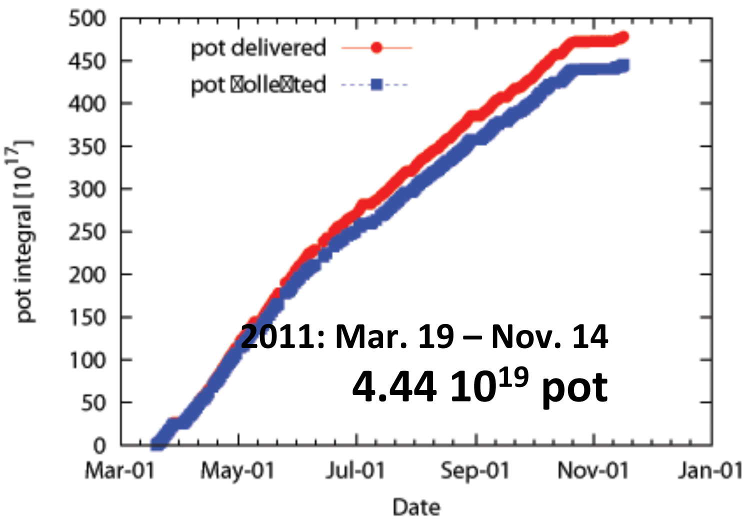
$\nu_\mu \rightarrow \nu_e$ "LSND/MiniBooNE" anomaly

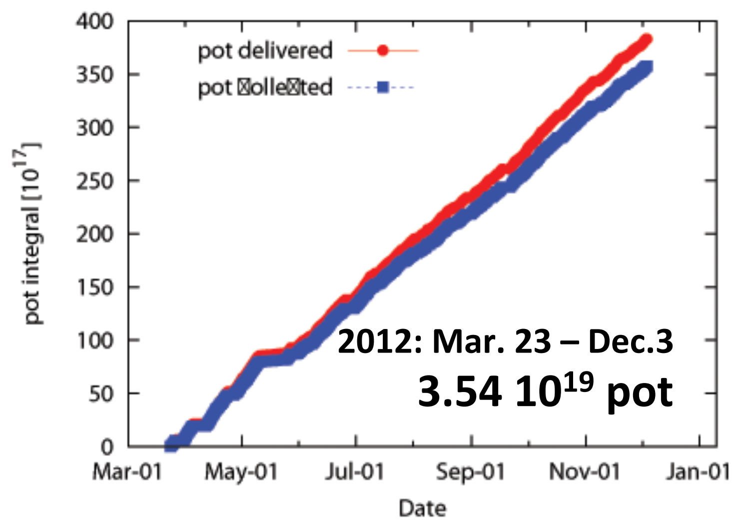
Eur. Phys. J. C (2013) 73:2345, arXiv:1209.0122

detector live-time > 93%

total 8.6 x 10^{19} pot collected







The new frontier

- The discovery of a *Higgs boson* at CERN/LHC has crowned the successful Standard Model (SM) and will call for a verification of the Higgs couplings to the gauge bosons and to the fermions.

- *Neutrino masses and oscillations* represent today a main experimental evidence of physics beyond the Standard Model.

- Being the only elementary fermions whose basic properties are still largely unknown, neutrinos must naturally be one of the main priorities to complete our knowledge of the SM.

- Albeit still unknown precisely, *the incredible smallness of the neutrino rest masses*, compared to those of other elementary fermions points to some specific scenario, awaiting to be elucidated.

- *The astrophysical importance of neutrinos is immense*

"Sterile" neutrinos ?

- Sterile neutrinos: hypothesized in a seminal paper by B. Pontecorvo in 1957 as particles non interacting *via any of the fundamental interactions* of the Standard Model except gravity.

- Since per se they may not interact directly, they are extremely difficult to detect. If they are heavy enough, they may also contribute to dark matter.

- Sterile neutrinos may mix with ordinary neutrinos via a mass term. Evidence may be building up by ***"anomalies"*** observed by several neutrino experiments:

  - ✓ sterile neutrino(s) with $\Delta m^2 \approx 10^{-2}$ — 1 eV^2 from ν_e observation in ν_μ *accelerator experiments* (LNSD anomaly).
  - ✓ Neutrino disappearance may have been observed in *nuclear reactors* and very intense (MCi) *electron conversion neutrino sources* with maybe comparable mass differences

Overall evidence

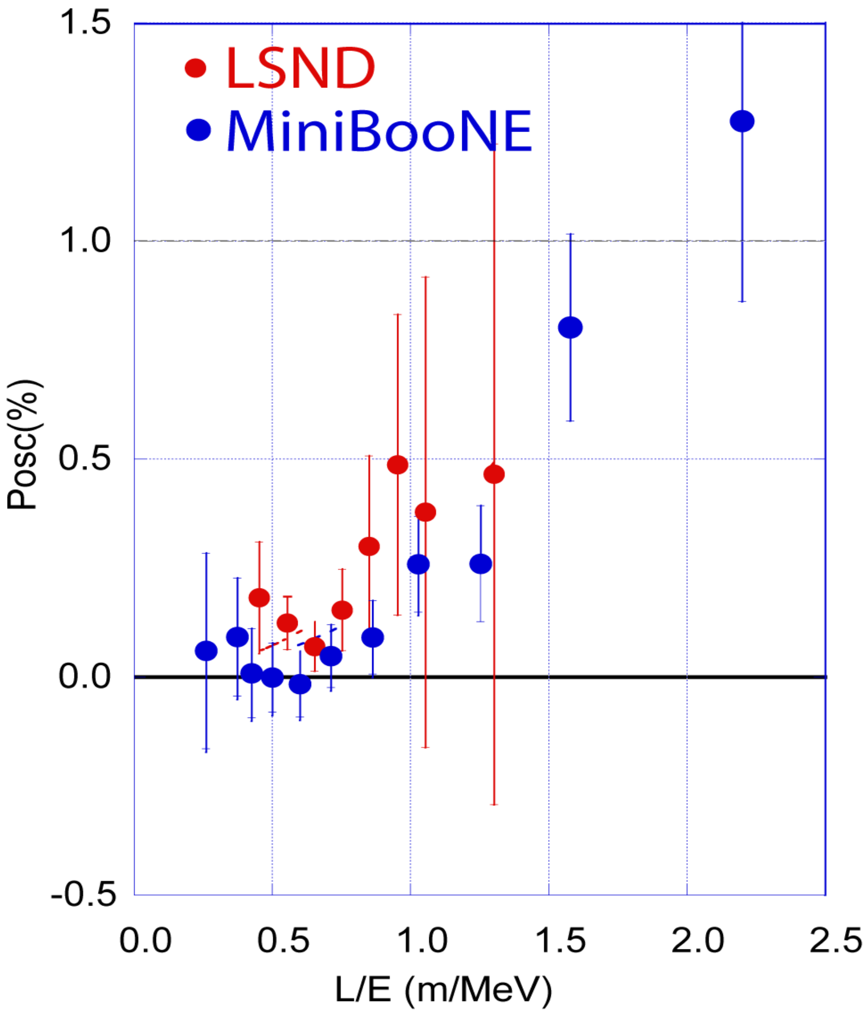
Anomaly	*Source*	*Type*	*Channel*	*Significance*
LSND	Short baseline	Decay at rest	-νμ –>νe CC	3.8 σ
MiniBoone	Short baseline	Neutrino beam	-νμ –>νe CC	3.0 σ
MiniBoone	Short baseline	Anti-Neutr. beam	anti-νμ –>νe CC	1.7 σ
Gallium	Electron capture	Source	ν disapp.	2.7 σ
Reactors	Fission	Beta decay	ν disapp.	3.0 σ
Cosmology	Big bang WMAP/PLANCK	No of neutrino		Not compl. excluded ν>3

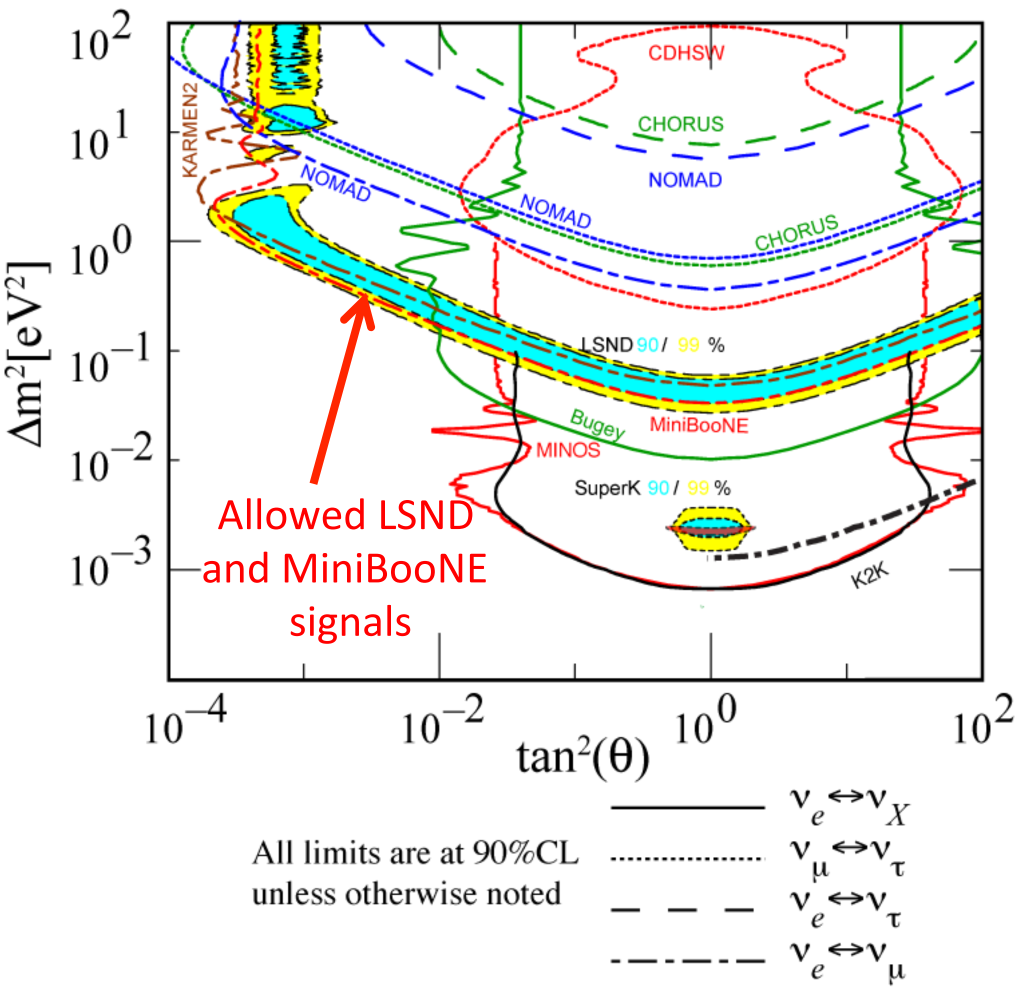
Combined evidence σ ≈ **3.8**

Zhang, Qian, Vogel: *„Reactor (...) with known* θ_{13}*"* (arXiv:1303.0900) → σ ≈ **1.4** ?

Combined evidence for some possible anomaly:
many standard deviations.

Neutrino related anomalies



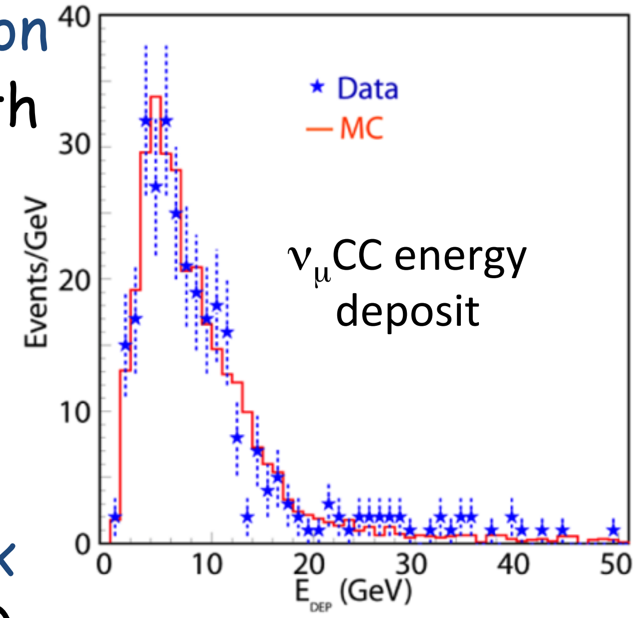


ICARUS T600 search for the LSND like $\nu_\mu \rightarrow \nu_e$ signal from the CNGS ν_μ beam at 730 km and $10 \leq E_\nu \leq 30$ GeV is presented.

LAr TPC performance

Total energy reconstr. from charge integration

- Full sampling homogeneous calorimeter with excellent accuracy for contained events



Tracking device

- Precise 3D topology accurate ionization measurement
- 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:

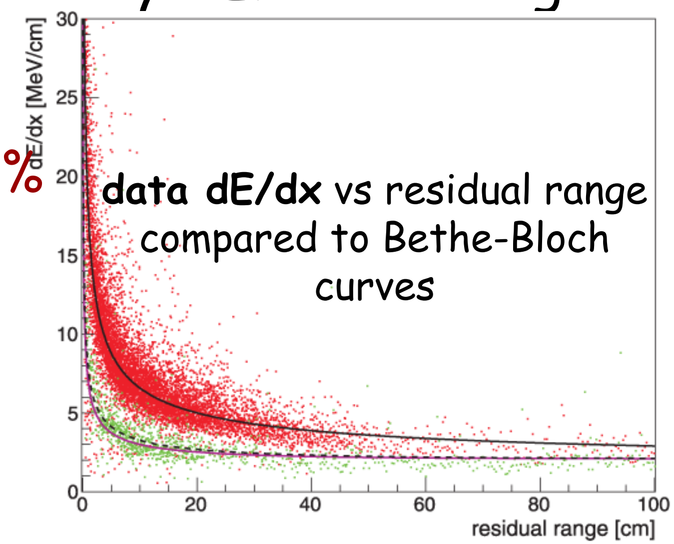
$\sigma(E)/E = 11\%/\sqrt{E(MeV)}+2\%$

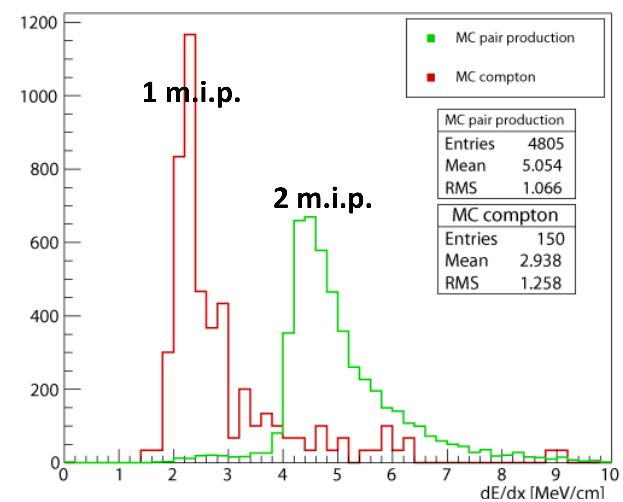
Electromagn. showers:

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

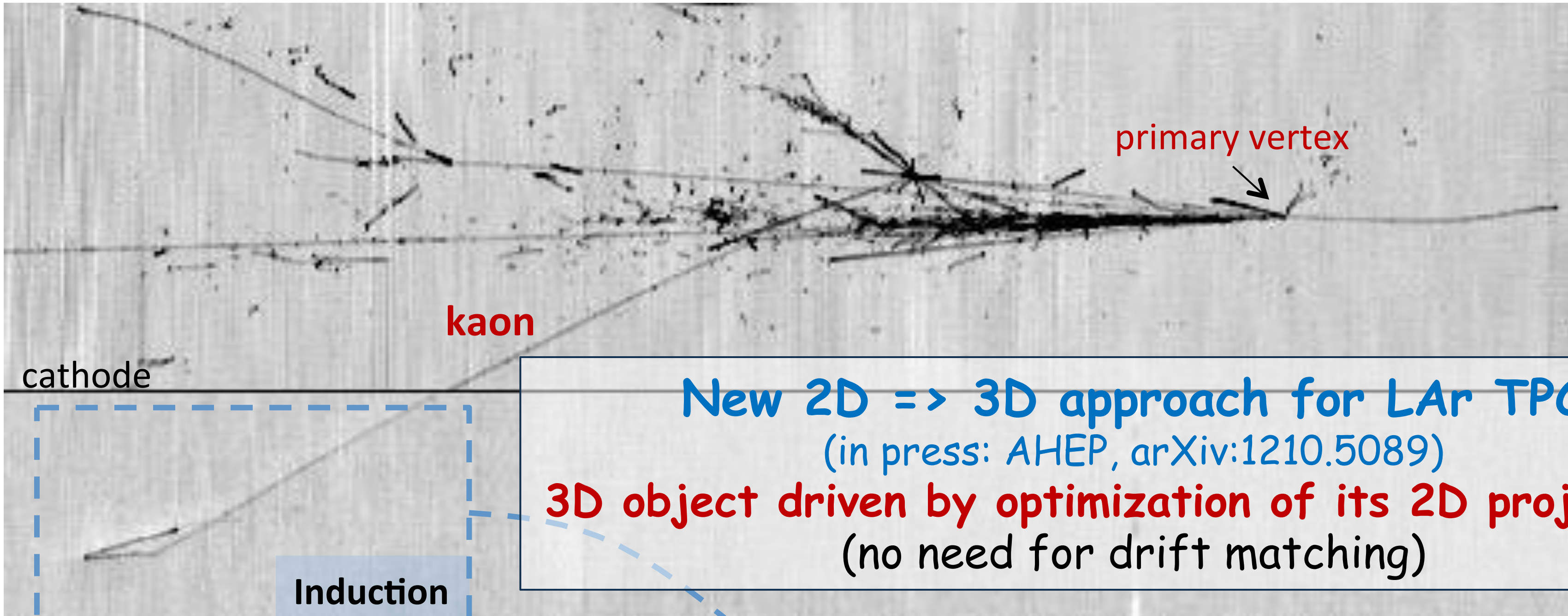
Hadron showers:

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





Precise particle tracking and identification



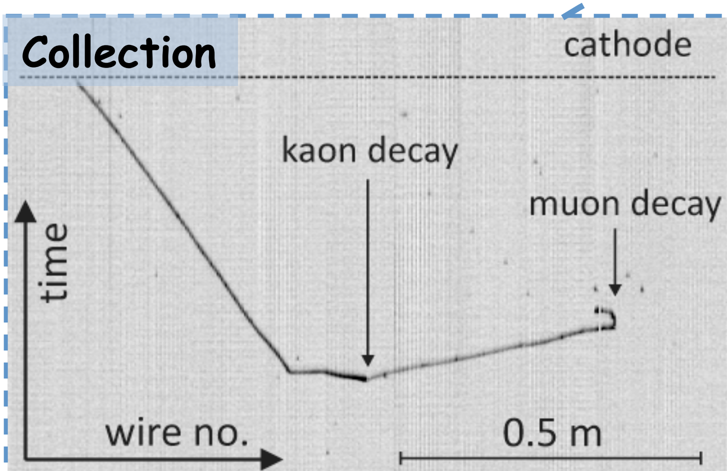
CNGS beam

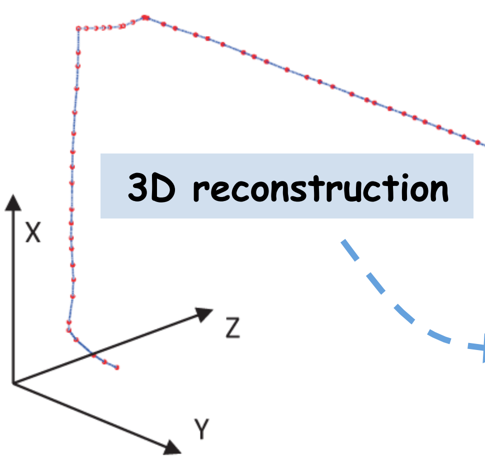
New 2D => 3D approach for LAr TPC

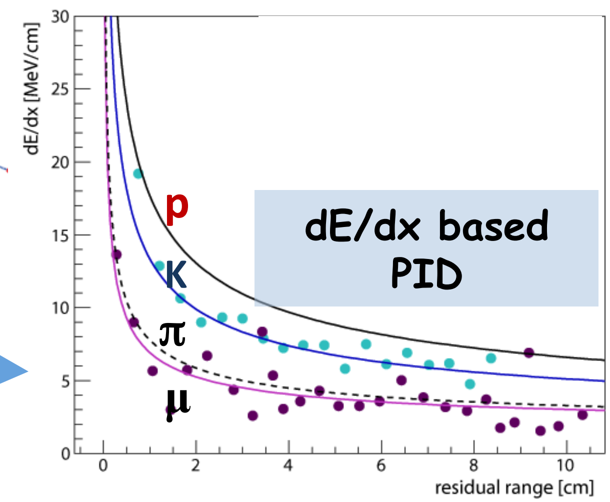
(in press: AHEP, arXiv:1210.5089)

3D object driven by optimization of its 2D projections

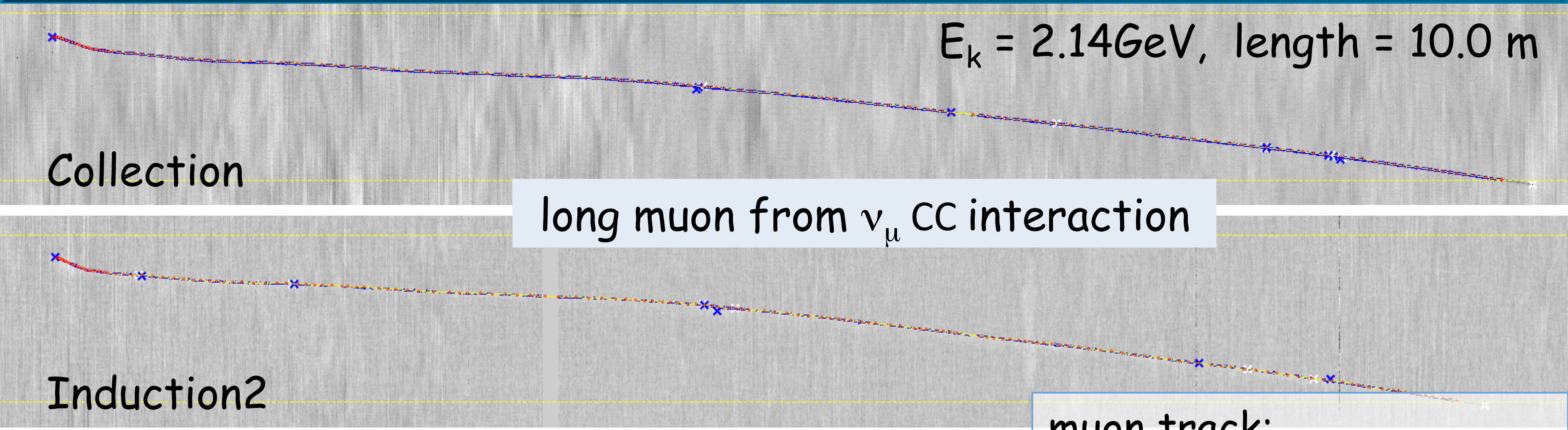
(no need for drift matching)



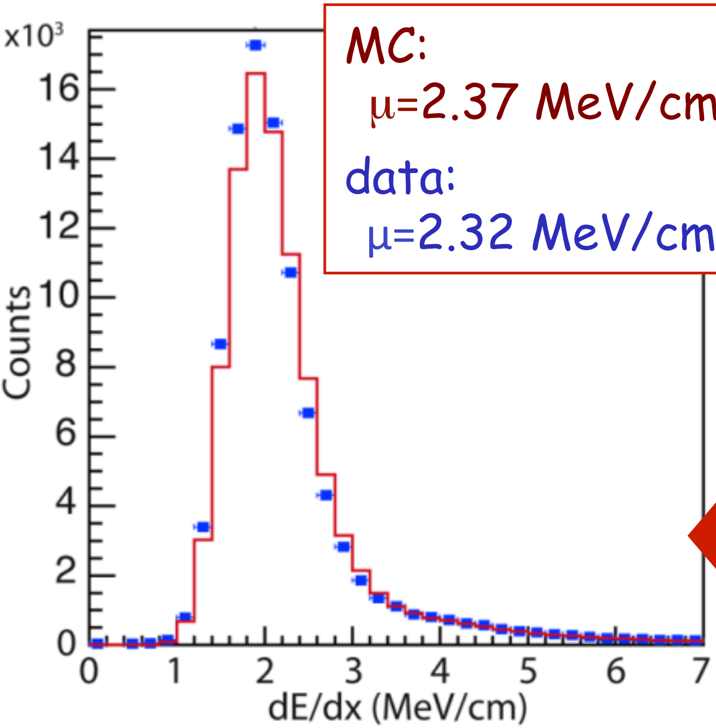




dE/dx of muon tracks in CNGS

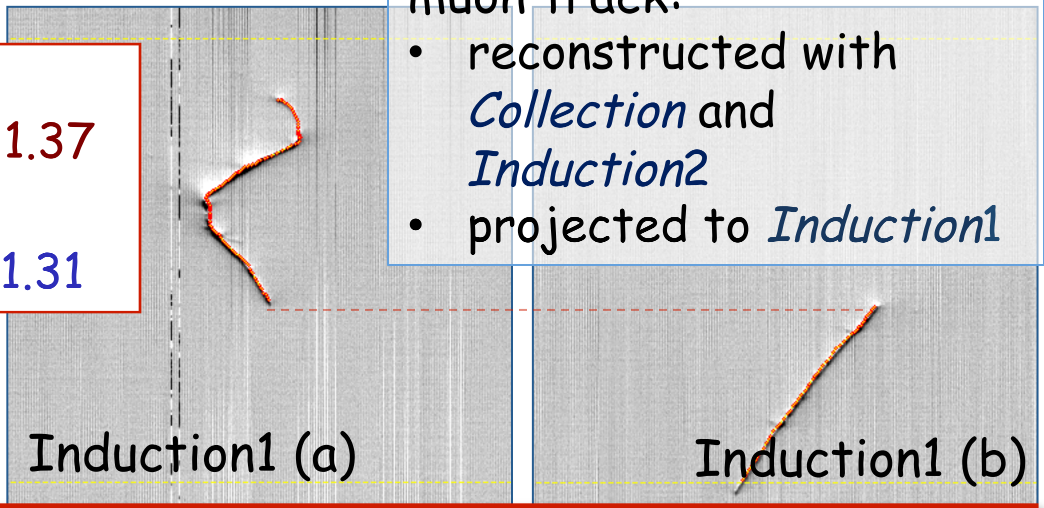


long muon from ν_μ CC interaction



MC:
μ=2.37 MeV/cm; RMS=1.37

data:
μ=2.32 MeV/cm; RMS=1.31

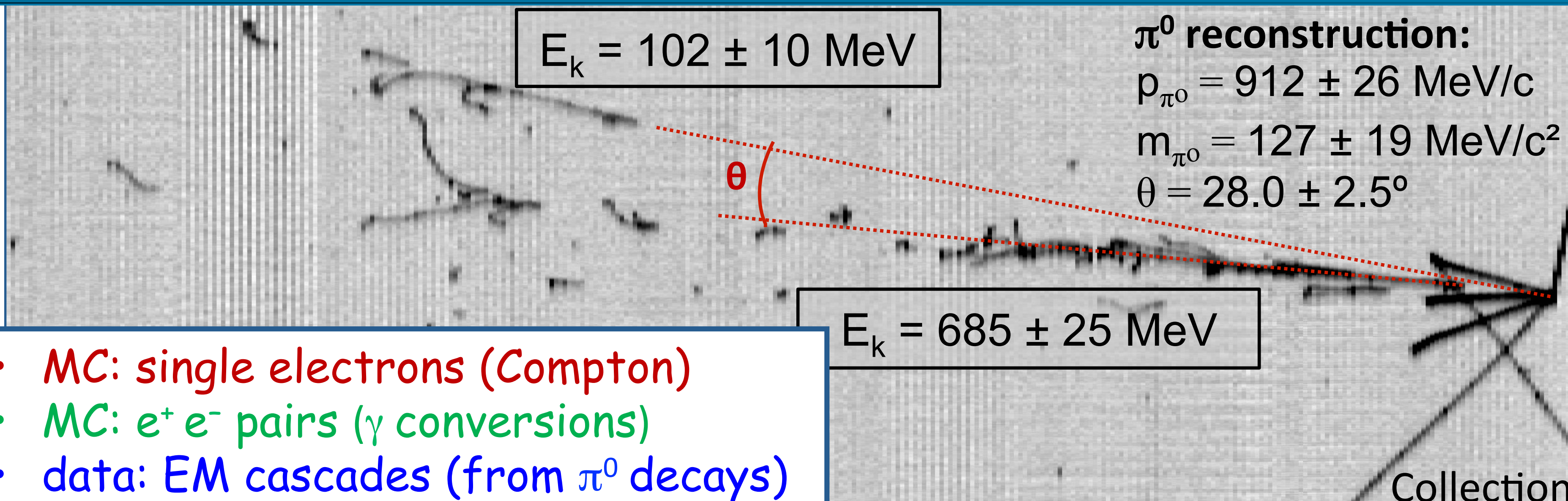


muon track:

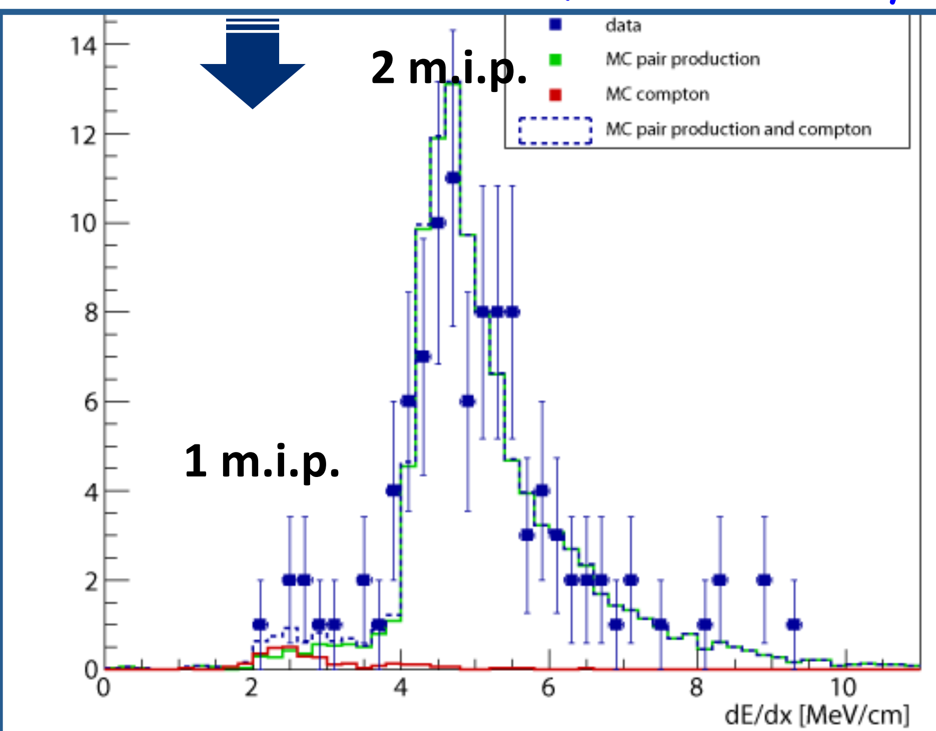
- reconstructed with *Collection* and *Induction2*
- projected to *Induction1*

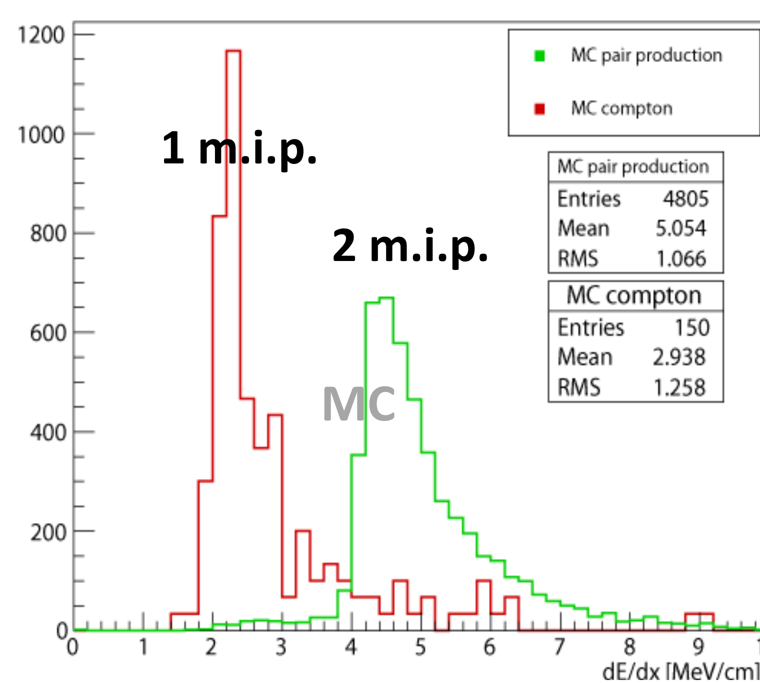
dE/dx in 3 mm track segments (3D), after removing δ rays and e.m. cascades
MC – data agreement on the level of 2%
signal/noise from Landau + gaussian ≈ 10

e/γ separation: dE/dx in cascade initial part



- MC: single electrons (Compton)
- MC: $e^+ e^-$ pairs (γ conversions)
- data: EM cascades (from π^0 decays)

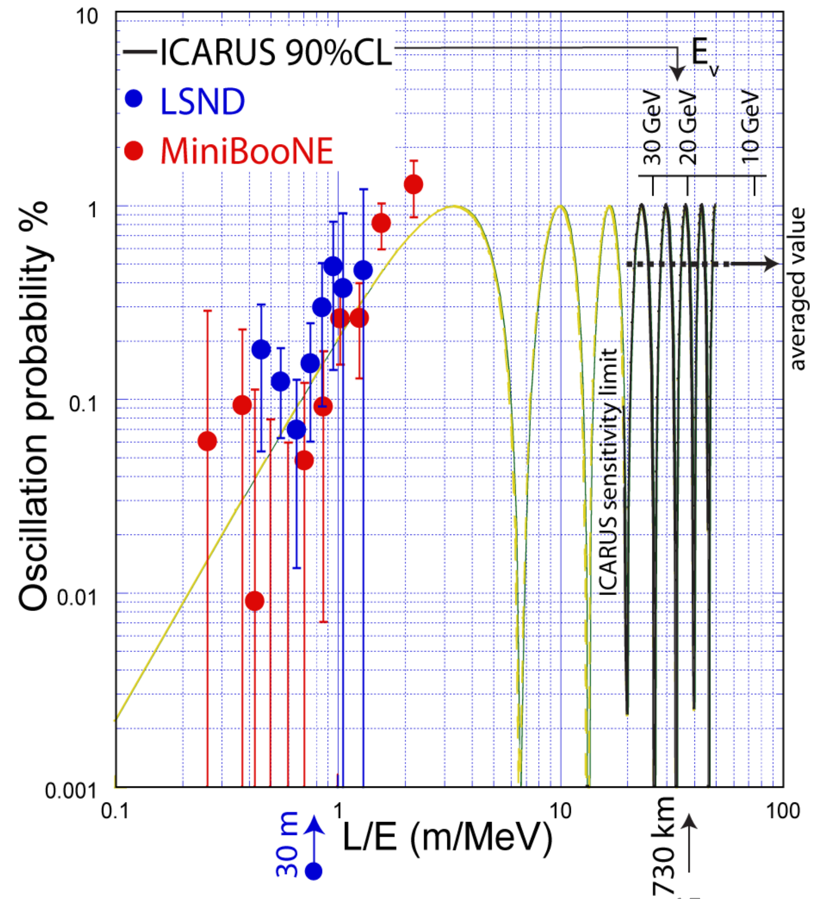




A search for LSND effects with ICARUS @ CNGS

$\nu_\mu \rightarrow \nu_e$ signal from the CNGS ν_μ beam at: L = 730 km, 10 ≤ E_ν ≤ 30 GeV

- Differences w.r.t. the LSND experiment:
- $L/E_\nu \approx$ 1 m/MeV at LSND, but $L/E_\nu \approx$ 36.5 m/MeV at CNGS
- LSND-like short distance oscillation signal averages to: $\sin^2(1.27\Delta m^2_{new} L/E) \approx ½$ and: $\langle P \rangle_{\nu\mu\rightarrow\nu e} \approx 1/2 \sin^2(2\theta_{new})$
- When compared to other long baseline results (MINOS and T2K) ICARUS operates in a L/E_ν region in which contributions from standard neutrino oscill.s are not yet too relevant.
- Unique detection properties of LAr-TPC allows to identify individual ν_e events with high efficiency.



Data sample

- CNGS beam: almost pure ν_μ peaked in the range $10 \leq E_\nu \leq 30$ GeV
  - beam associated ν_e about ~1%
  - CNGS events triggered by PMTs inside SPS proton spill
  - few ν interactions/day
- Present sample: 1091 neutrino events (within 6% with MC)
  - data from 2010-2011, 3.3 10^{19} pot (out of total 8.6 10^{19} pot collected)
  - ν_μ CC identified by L>250 cm track from primary vtx, no hadr. int.
  - the signature of the $\nu_\mu \rightarrow \nu_\varepsilon$ signal is observed visually
- Fiducial volume:
  - primary vertex min. 5 cm from each side, min. 50 cm from downstream wall to allow shower identification
- Energy deposition cut: < 30 GeV
  - optimized signal/background ratio (ν_e contamination extends to higher E_ν), only 15% signal events rejected
  - excellent MC/data agreement for deposited energy $\Rightarrow$ negligible systematic error on signal and background expectations
  - 10% systematic error due to ν_e beam component

Signal selection

Visibility cuts for $\nu_\mu \rightarrow \nu_e$ event identification:

1. Charged track from the vertex, m.i.p. over 8 wires (dE/dx < 3.1 MeV/cm excluding δ-rays), developing into EM-shower

2. Spatial separation (150 mrad) from other tracks at the vertex, at least in one transverse (±60°) view

Expected conventional ν_e- like events:(cuts: vtx in fiducial volume; visible energy ≤ 30 GeV)

3.0 ± 0.4 ev. due to the intrinsic ν_e beam contamination

1.3 ± 0.3 ev. due to θ_{13} oscillations, $\sin^2(\theta_{13}) = 0.0242 \pm 0.0026$

0.7 ± 0.05 ev. of $\nu_\mu \rightarrow \nu_\tau$ oscillations with electron production (3ν mixing)

The total is therefore of 5.0 ± 0.6 expected events
(uncertainty on the NC and CC contaminations included)

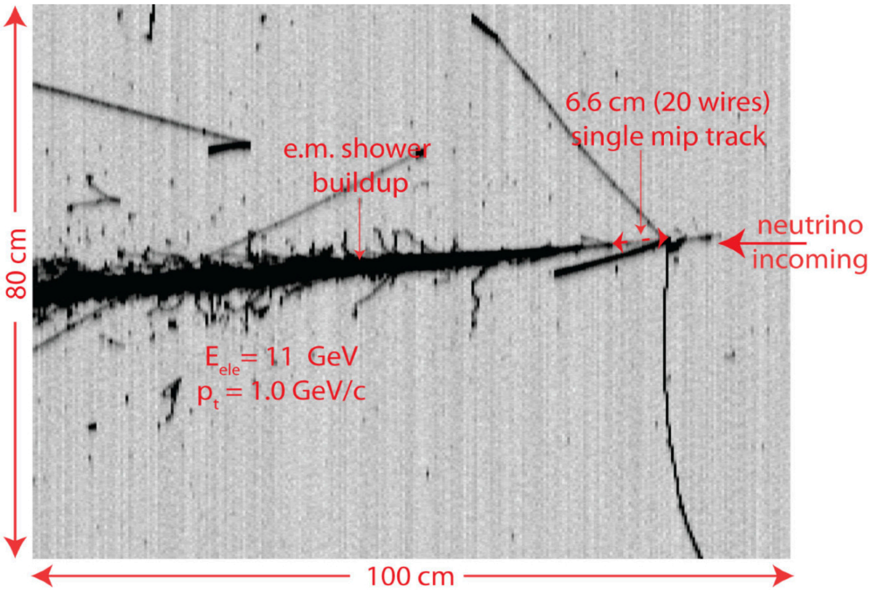
Selection efficiency, validated on MC sample of ν_e events:

η =0.74±.05 ~ independent from shape of energy spectrum

3.7 ± 0.6 expected background events after cuts.

Signal selection efficiency in MC simulation

- ν_e selection efficiency evaluated by means of a full and detailed FLUKA MC simulation in agreement with data
- ν_e events generated according to ν_μ spectrum in order to reproduce oscillation behaviour
- fiducial volume and energy cuts: 122 events selected over 171 simulated in the LAr active volume
- visibility cuts: 0.74 ± 0.05 efficiency (3 different scanners)
- < 1% systematic error from dE/dx cut on the initial part of cascade
- no ν_e-like events selected in a 800 NC simulated event sample



Typical Montecarlo generated event from the ICARUS simulation program with E_{ele}= 11 GeV and p_t= 1.0 GeV/c. Only the vertex region is shown.

Signal selection efficiency crosscheck

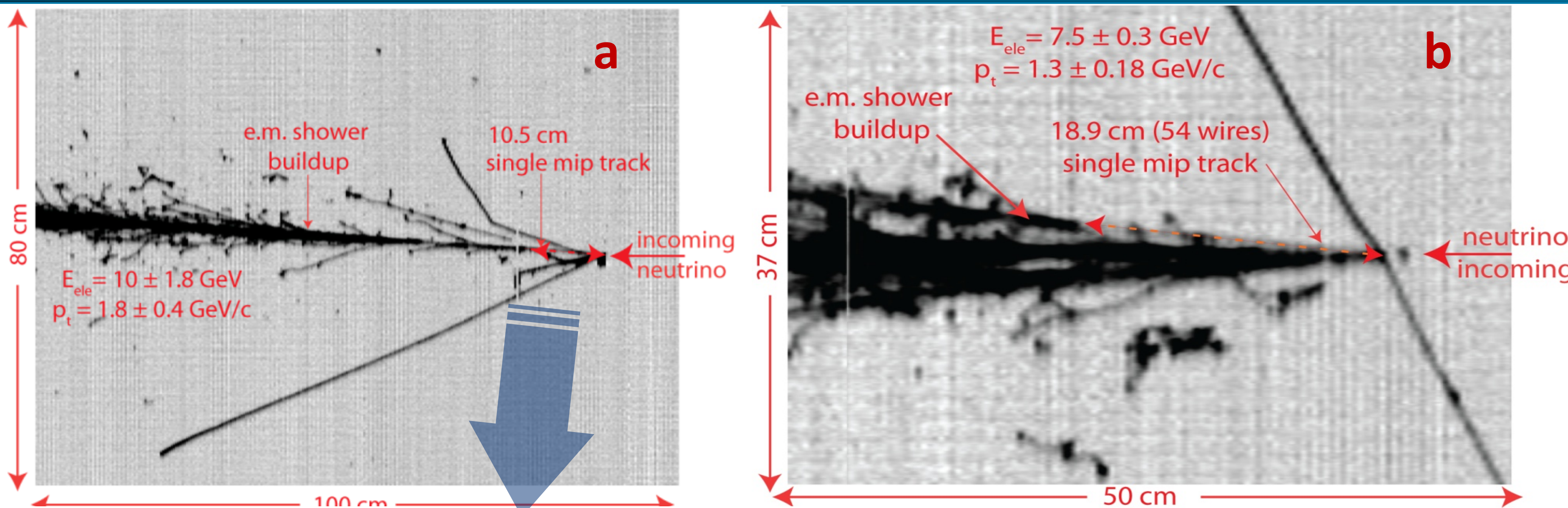
- Signal selection efficiency is cross-checked with a large MC sample
- automatic cuts mimicking data selection

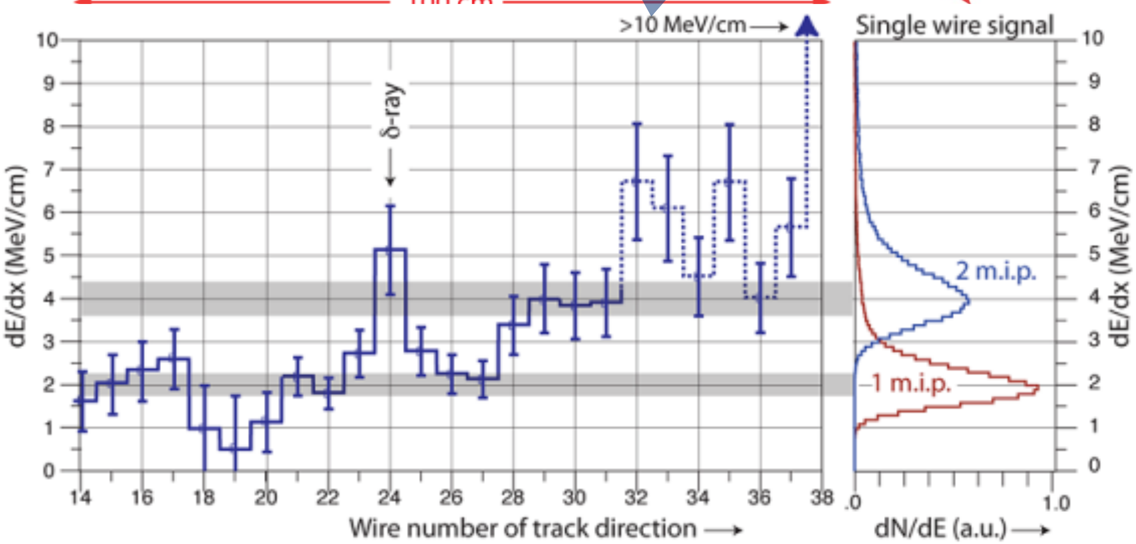
C1: inside fiducial volume and E_{dep} < 30 GeV;
C2: no identified muon, at least one shower;
C3: one shower: initial point (or γ conversion point) < 1 cm from vtx, separated from other tracks;
C4: ionisation signal from single mip in the first 8 wires.

Sel. cut	ν_e CC beam	ν_e CC θ_{13}	ν_τ CC	NC	ν_μ CC	ν_e CC signal
C1	0.47	0.92	0.93	0.89	0.89	0.81
C2	0.47	0.92	0.17	0.66	0.19	0.81
C3	0.33	0.79	0.14	0.10	0.03	0.66
C4	0.30	0.71	0.13	0.0002	0.00005	0.60

Signal selection efficiency (after the fiducial and energy cuts): 0.6/0.81 = 0.74, in agreement with the visual scanning method.

2 events observed in data





(a) 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

The observation is presently compatible with the abence of a LSND anomaly

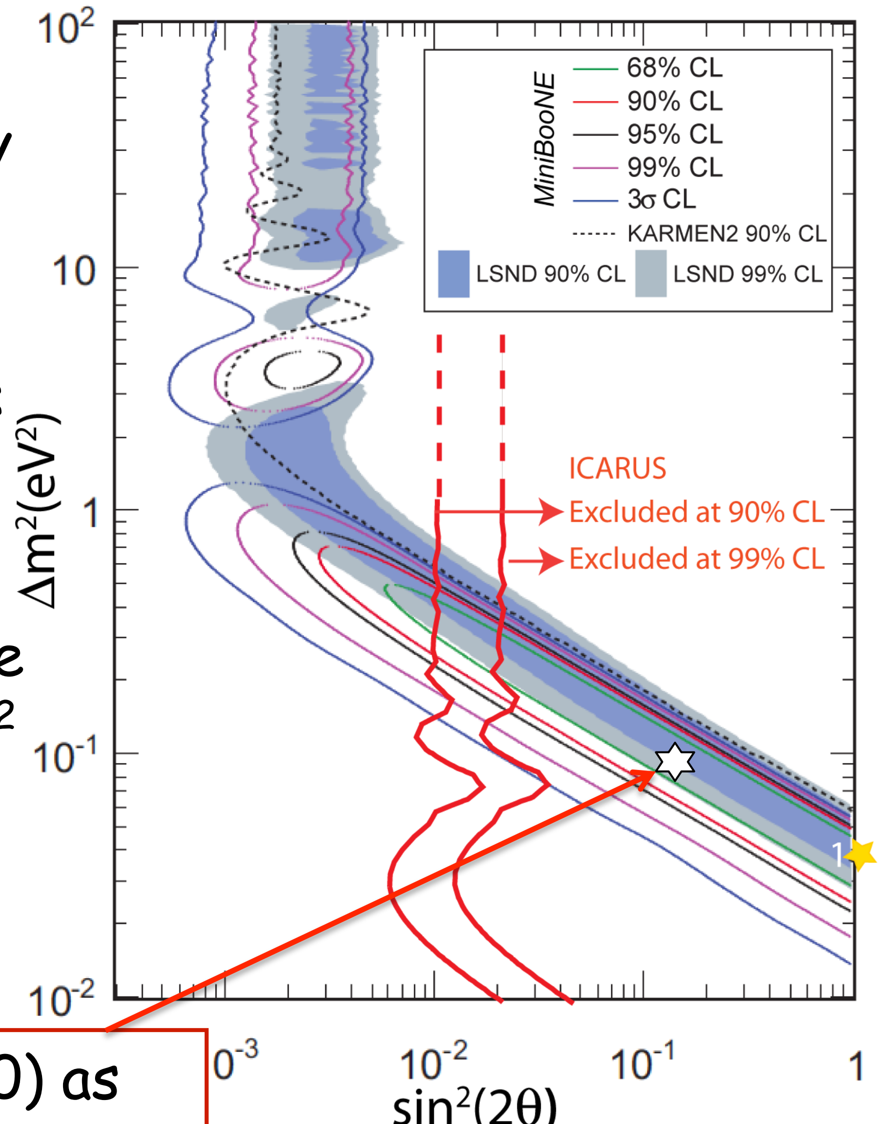
- The limits on no. of events due to the LSND anomaly are respectively

  3.41 (90% CL) and 7.13 (99% CL)

- Given the present data sample the limits to oscillation probability are:

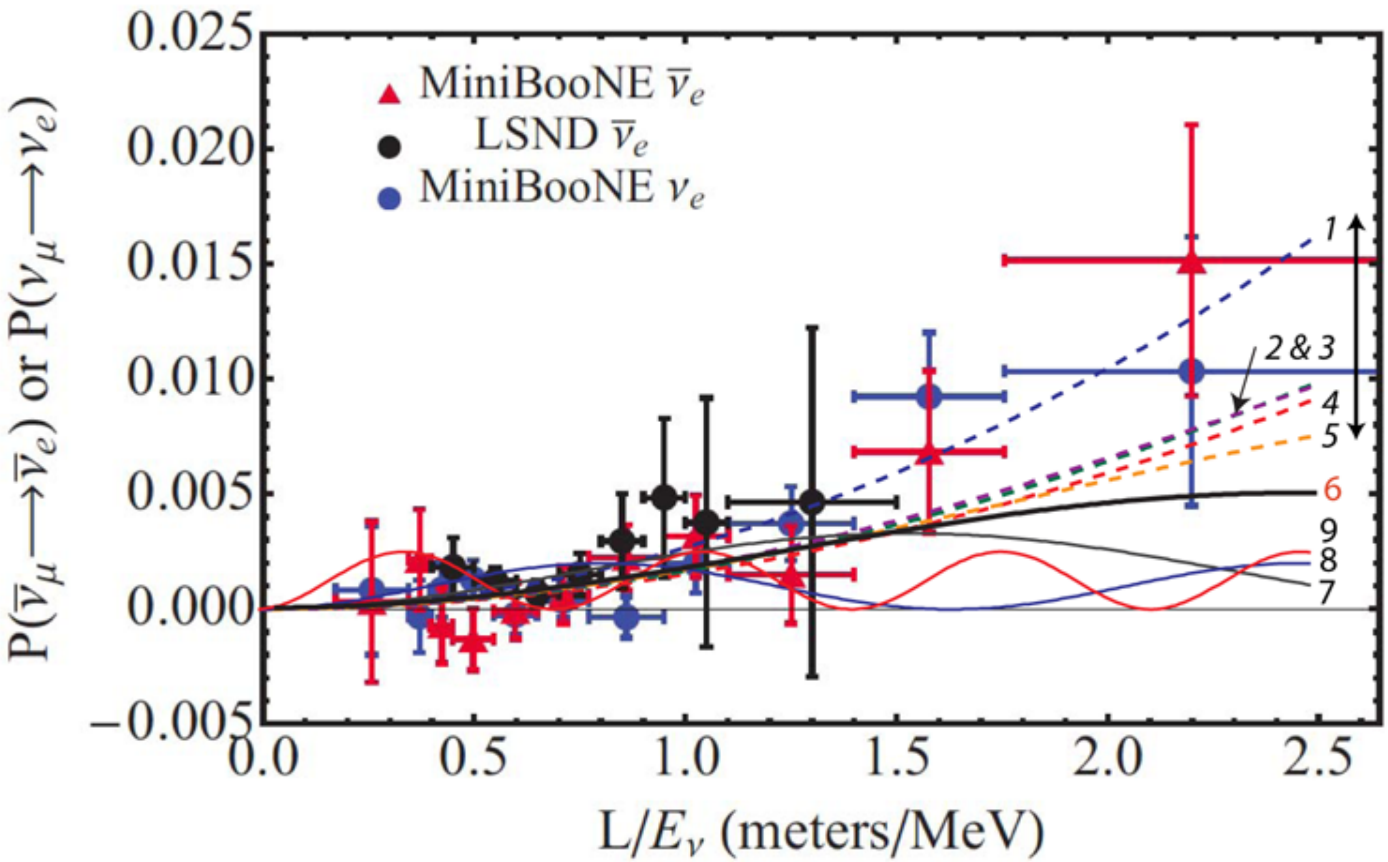
  $P_{\nu\mu \to \nu e} \lesssim 5.4 \times 10^{-3}$ (90% CL)
  $P_{\nu\mu \to \nu e} \lesssim 1.1 \times 10^{-2}$ (99% CL)

- The exclusion area is shown for the plot Δm^2 vs $\sin^2(2\theta)$. At small Δm^2 ICARUS strongly enhances the probability with respect to short baseline experiments.



with $(\Delta m^2, \sin^2(2\theta)) = (0.11\ eV^2, 0.10)$ as many as 30 events should have been seen.

Results combined with the low energy excess



#	$\sin^2(2\theta)$	$\Delta m^2(eV^2)$
1	1	0.04
2	0.3	0.07
3	0.1	0.11
4	3.0E-2	0.21
5	1.0E-2	0.37
6	5.0E-3	0.50
7	3.3E-3	0.8
8	2.0E-3	1.5
9	2.5E-3	3.5

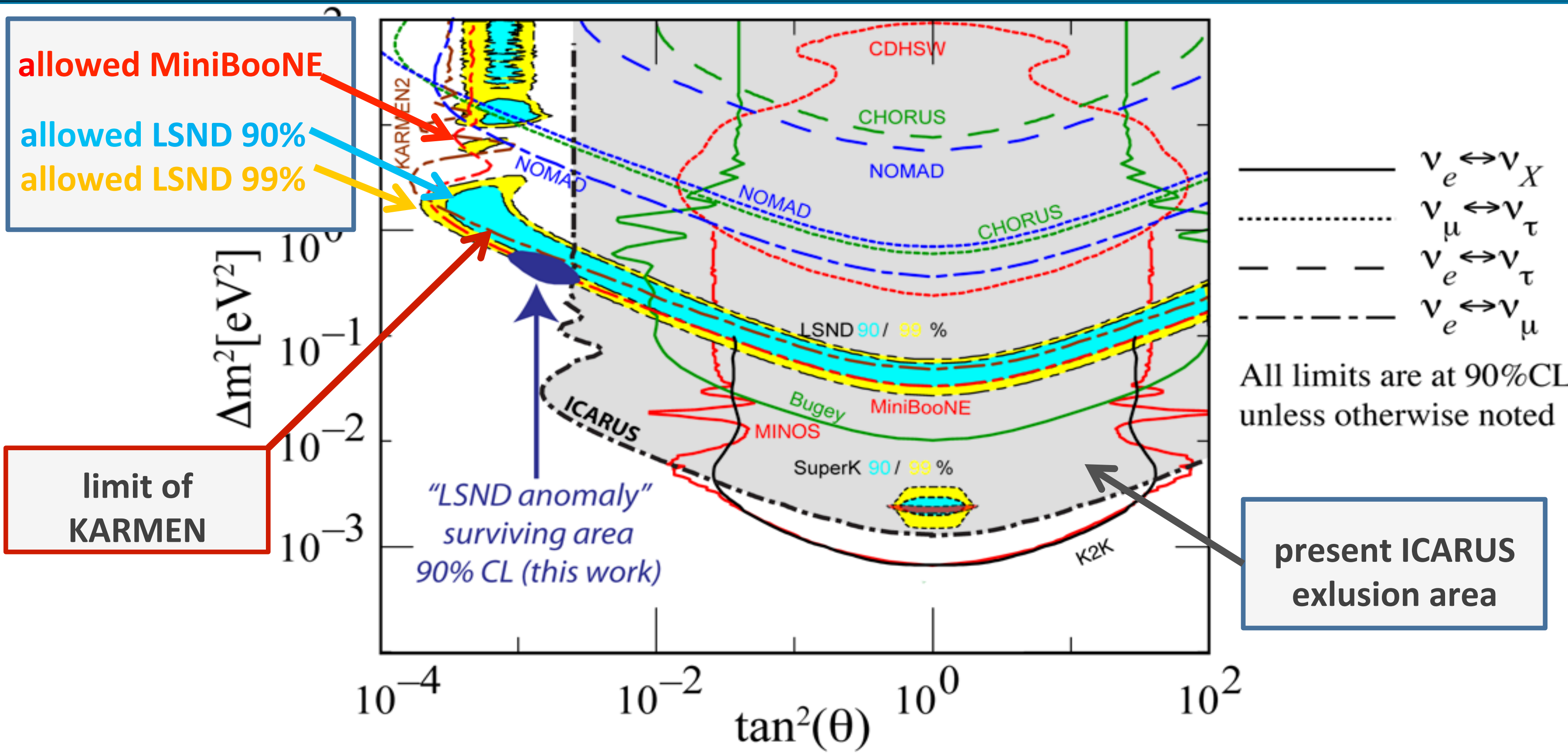
1: MiniBooNE best fit in the combined 3+1 model

1-5: excluded by ICARUS result: excessive osc. Prob. @ large L/E_ν

6: best value including ICARUS result

6-9: compatible with present ICARUS

LSND anomaly surviving area



ICARUS result strongly limits the window of possible parameters for LSND anomaly indicating a narrow region **(Δm^2, $\sin^2 2\theta$) = (0.5 eV^2, 0.005)** where there is an overall agreement (90% CL):

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

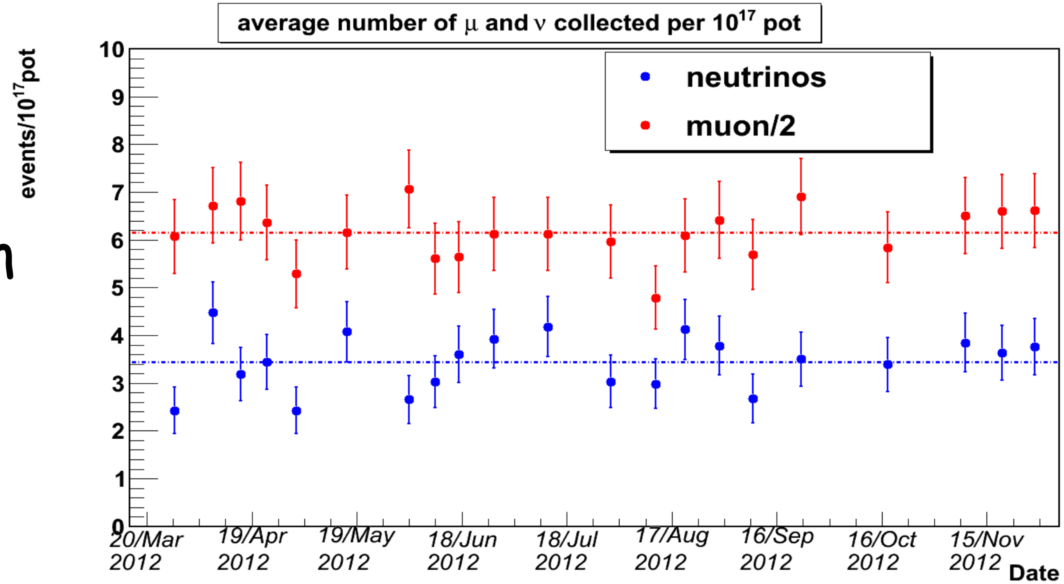
New results on LSND anomaly search ?

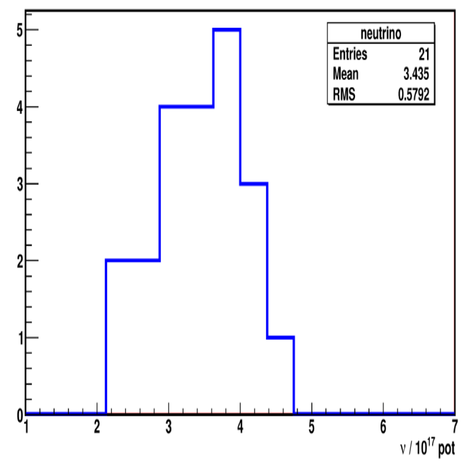
- The presented ICARUS oscillation analysis is being improved by a new data sample which allow to almost double the overall event statistics.
- An enhanced contribution of ICARUS to the clarification of LSND/MiniBooNE anomaly is expected from this additional data set which will allow to increase the experimental sensitivity.
- A new 2.7 10^{19} pot CNGS event statistics has been processed, filtered, visually scanned and reconstructed. This data sample includes additional events collected in 2011 and ~60 % of 2012 recorded data.

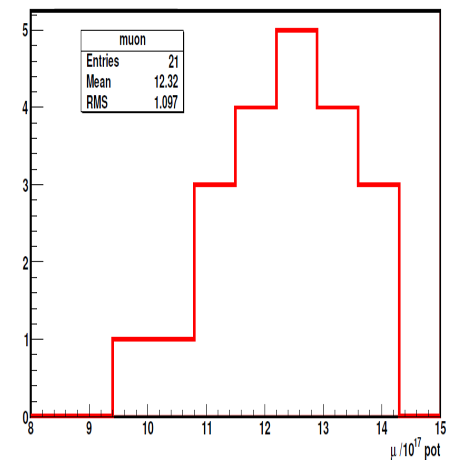
Update on LSND anomaly search

- Globally 904 neutrino events inside 445 t fiducial mass have been selected as well as 3224 muons produced by neutrino interacting in surrounding rocks

- 2012 run: on average 3.45 ν interactions in LAr and 12.4 rock-μ per 10^{17} pot







- Two ν_e CC candidates have been identified so far…

New results on LSND anomaly search expected soon!

Conclusions

- 3 years of succesfull operation of ICARUS T600 on CNGS beam (~ 8.6 10^{19} pot, live time > 93%)

- ICARUS T600 presently collecting cosmic-ray events. Detector shut-down foreseen at the end of May 2013

- Lar-TPC allows unambiguos identification of individual ν_e events with high efficiency

- ICARUS published result strongly limits the allowed parameter region for LSND anomaly indicating a narrow region around:

$$(\Delta m^2, \sin^2 2\theta) = (0.5\ eV^2, 0.005)$$

where there is an overall agreement (90 % CL) between: ICARUS limit, KARMEN limit and the positive signals of LSND/ MiniBooNE

- Definitive answer to sterile ν search: ICARUS T600+150 detectors exposed to new 2 GeV ν beam @ CERN SPS at 1.6 km 460 m.