Past, present and future of LAr-TPC neutrino experiments

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Evolution of LAr-TPC detectors

- Cherenkov detectors in water/ice and liquid scintillators have been main technology so far for neutrino and rare event physics. Unfortunately these detectors do not permit to identify unambiguously each ionizing track.

- As an alternative, the Liquid Argon Imaging technology (LAr-TPC), effectively an electronic bubble-chamber, was originally proposed by C. Rubbia in 1977 [CERN-EP/77-08], supported by Italian Institute for Nuclear Research (INFN).

- Thanks to ICARUS collaboration, LAr-TPC has been taken to full maturity with the T600 detector (0.6 kton) receiving CNGS neutrino beam at LNGS.

- ICARUS concluded in 2013 a very successful 3 years long run, collecting 8.6 x 10^{19} pot with a detector live time > 93%, recording 2650 CNGS neutrinos (in agreement with expectations).
- Also atmospheric neutrinos have been studied with exposure to cosmic rays (0.73 kton year).

LAr experiments

Experiment	LAr mass	Physics goals	Baselines (km)	E_ν (GeV)	Detector location	Current status
ArgoNeuT	175 l	R&D, cross section Accelerator ν	1	~0.1 – 10	Fermilab NuMI beam)	Completed (2010) Data under analysis
LArIAT	550 l	Study of charge particle interaction in LAr	Dedicated tertiary charged beam line (e, mu, pi, K, p)	0.2 – 1.2	Fermilab	Running since 2015.04
MicroBooNE	170 t (86 t - active)	Sterile neutrinos, R&D, short baseline	0.470	~0.1 – 3	Fermilab (BNB)	2015.07: filled with LAr 2015.08.06: First tracks in the TPC
CAPTAIN	(2 t - prototype) 10 t	Neutrino interaction,		< 0.05, 1.5 - 5	LANL, Fermilab	
SBND (LAr1-ND)	220 t (112 t - active)	Sterile neutrinos, Short baseline	0.110	~0.800	Fermilab (BNB)	Design phase, begin operation in 2018
ICARUS	600 t (476 t - active)	R&D, long baseline (single detector)	732 (0.600 for SBNE)	~5 - 25	Gran Sasso (CNGS beam), Fermilab	Past & under development
MODULAr	5 000 t	Long baseline (shallow depth)	730	~5 - 25	Gran Sasso	Proposed
GLADE	5 000 t	Long baseline	810	~0.5 – 2	NuMi off-axis	Letter of Intent
DUNE (LBNE)	34 000 t	Long baseline	1300	~0.5 – 5	SURF - Fermilab	Planned, installation ~2021
LAGUNA/LBNO	20 000 t	Long baseline (underground FD	2300	~few	Europe (new CERN beam)	R&D, future

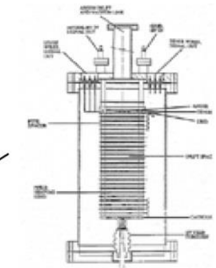
The path to large LAr detectors

Slide: GLA2011 J. Kisiel

1

CERN

24 cm drift wires chamber



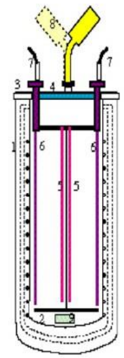
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

2

3 ton prototype

1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.

CERN

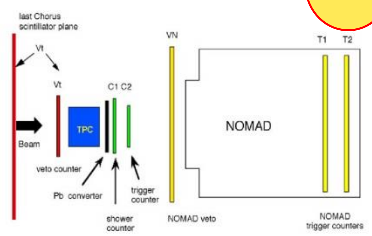


Laboratory work

3

CERN

50 litres prototype 1.4 m drift chamber



1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

4

Pavia

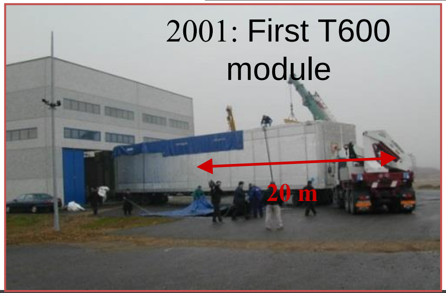
T600 detector

10 m3 industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

Icarus T600 experiment

2010 - … : Data taking with CNGS beam



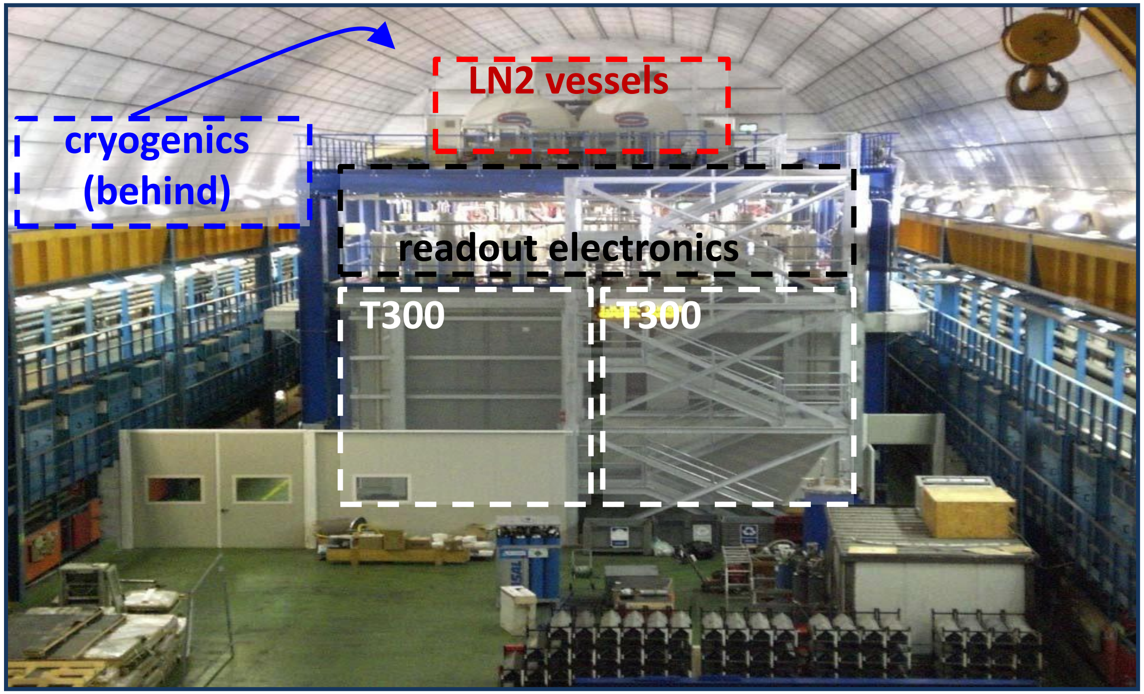
Cooperation with industry
AirLiquide, Breme, Cinel, CAEN

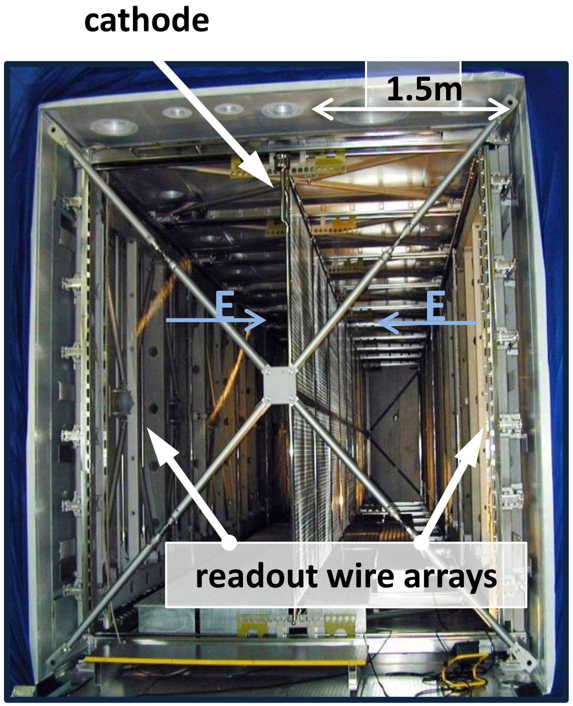
5

6

LNGS Hall-B

ICARUS – T600 at LNGS laboratory





Two identical modules

- 3.6x3.9x19.6 ~275 m^3 each
- LAr active mass: 476 t
- Drift length: 1.5 m (1 ms)
- E=0.5 kV/cm, v_{drift}~1.5 mm/μs
- Sampling time 0.4μs (sub-mm resolution in drift direction)

Four wire chambers:

- 2 chambers/ module
- 3 readout wire planes per chamber: 2 Induction + 1 Collection; ~54 000 wires, 3 mm pitch and plane spacing, oriented at 0°,±60°;
- Charge measurement on last Collection plane

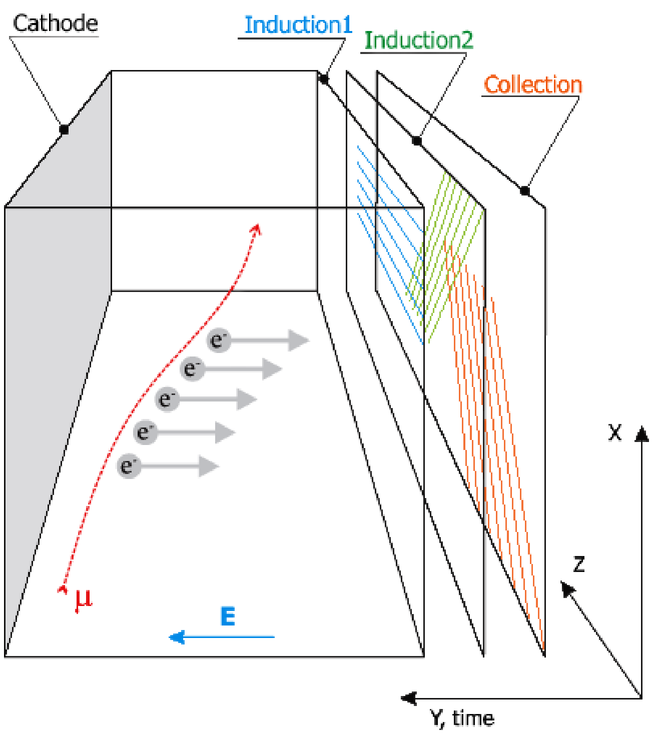
20+54 PMTs,8" Ø, for scintillation light detection:

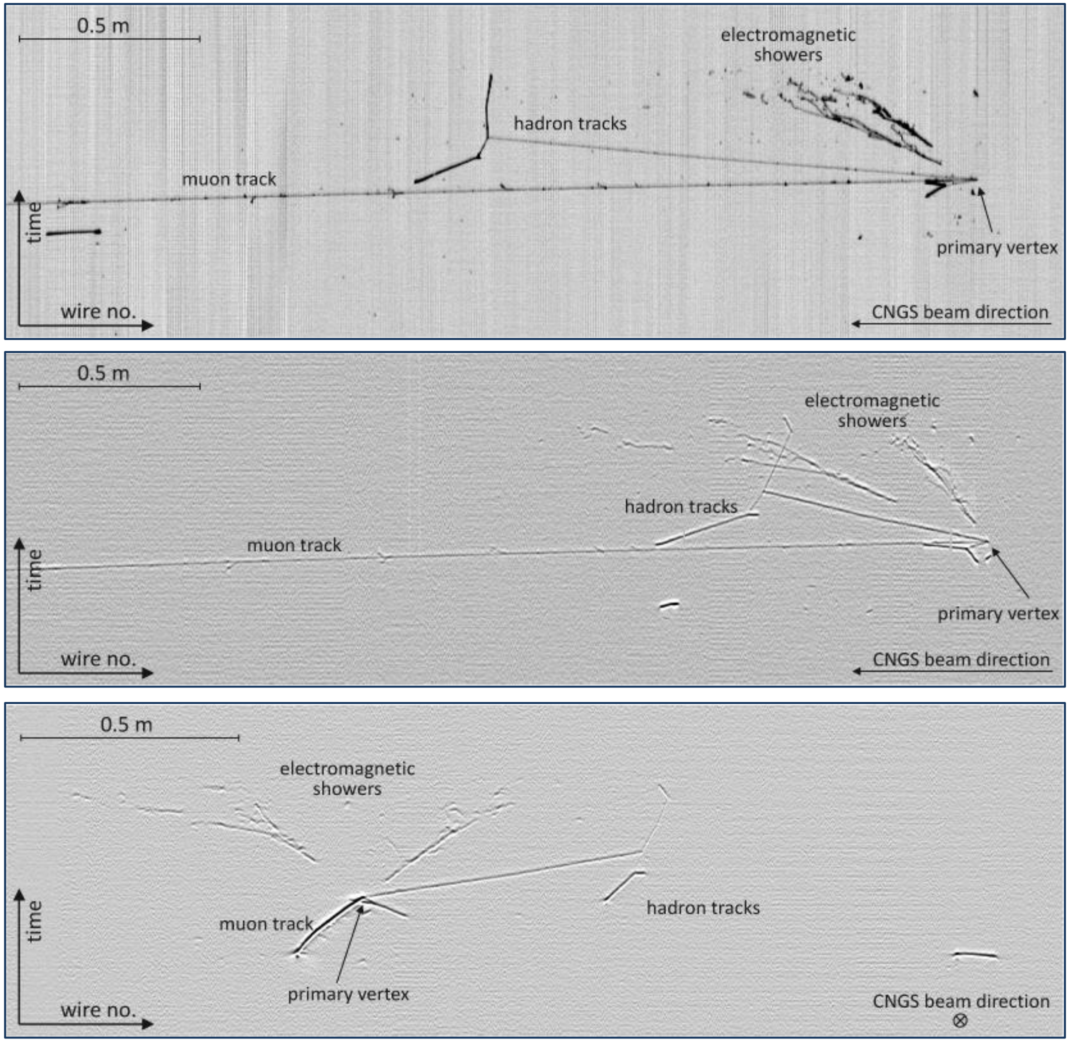
- VUV sensitive (128nm) with TPB wave shifter

ICARUS – T600: LAr-TPC detection technique

Slide: GLA2011 J. Kisiel

- 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 n_m charge current interaction one of TPC's shown →

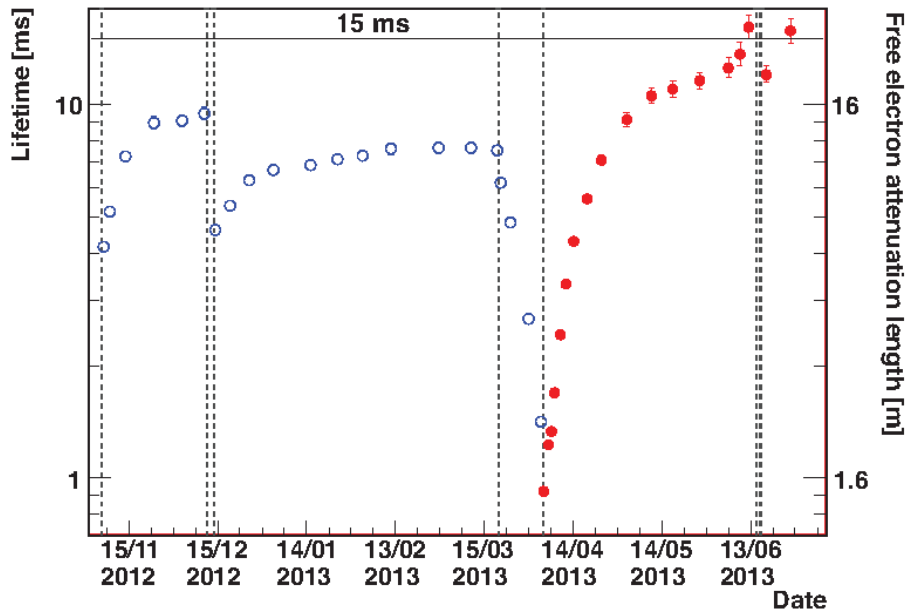
ICARUS: 3-years results

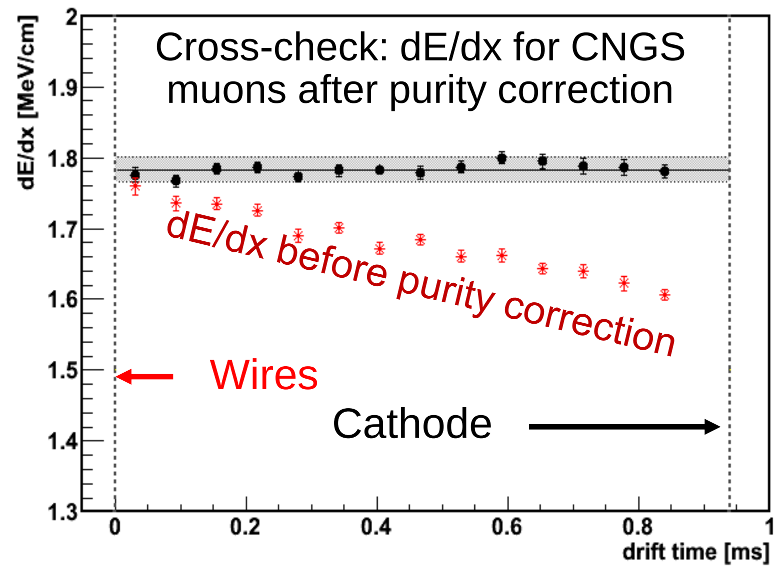
- **Operational technics**
  - LAr purification method → very long e-mobility,
  - 3D track reconstruction + particle identification,
  - e/γ separation and π^0 reconstruction,
  - determination of muon momentum via multiple scattering ($\Delta p/p$ ~15% in 0.4-4 GeV/c range)

- **Physics results:**
  - Refuted superluminal ν (OPERA),
  - Sterile neutrino searches (LSND anomaly)

Key features of LAr imaging: very long e-mobility

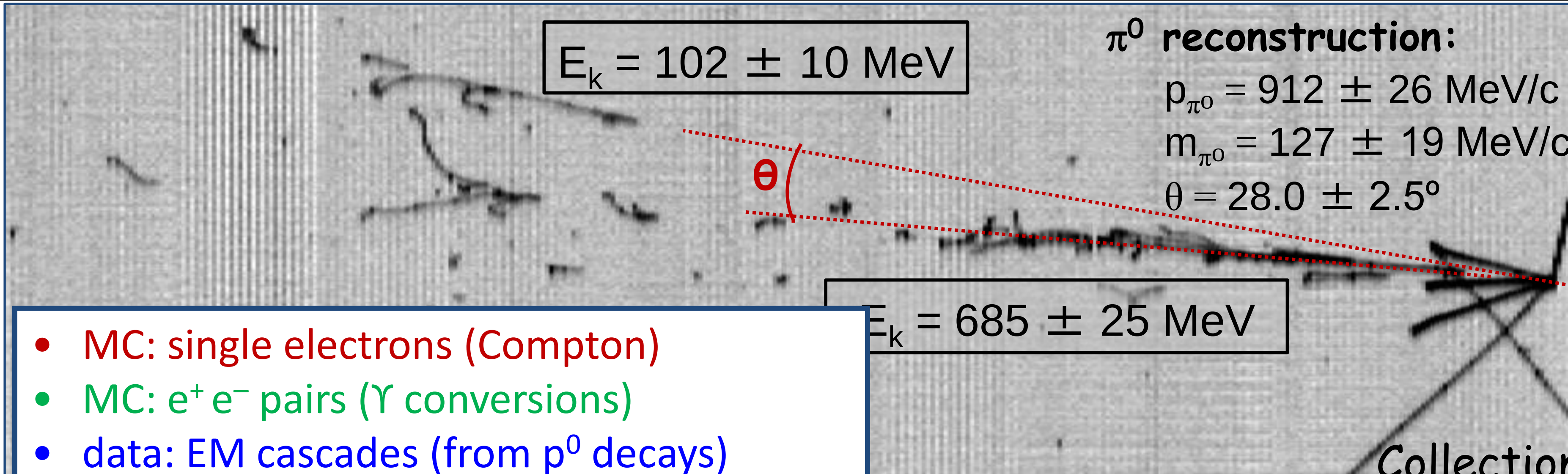
- Level of electronegative impurities in LAr must be kept exceptionally low to ensure ~m long drift path of ionization e^- without attenuation.
- New industrial purification methods developed to continuously filter and re-circulate both in liquid (100 Nm^3/day) and gas (2.5 m^3/hour) phases.
- Electron lifetime measured during ICARUS run at LNGS with cosmic m's: t_{ele} >7 ms (~40 p.p.t. [O_2] eq) →12% max. charge attenuation.
- New pump installed on East cryostat since April 4th, 2013: t_{ele} > 15 ms !



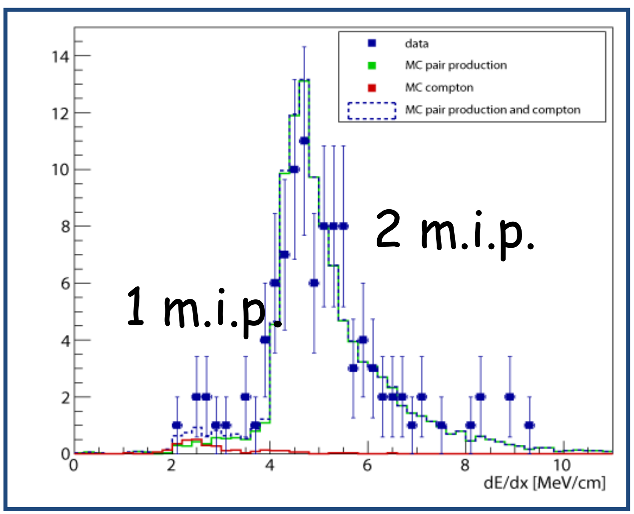


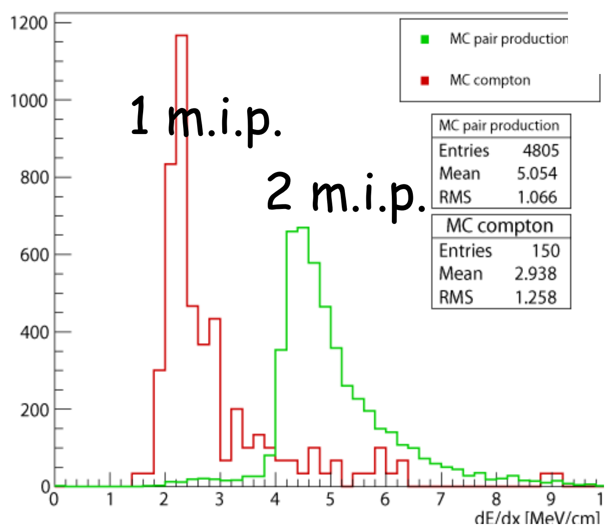
ICARUS demonstrated the effectiveness of single phase LAr-TPC technique, paving the way to huge detectors ~5 m drift as required for LBNF/DUNE project

e/γ separation and π^0 reconstruction in ICARUS

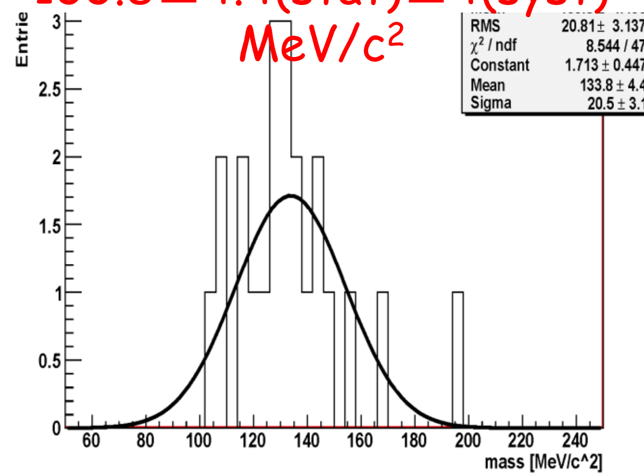


- MC: single electrons (Compton)
- MC: $e^+ e^-$ pairs (ϒ conversions)
- data: EM cascades (from p^0 decays)





Mγγ:
133.8±4.4(stat)±4(syst) MeV/c²



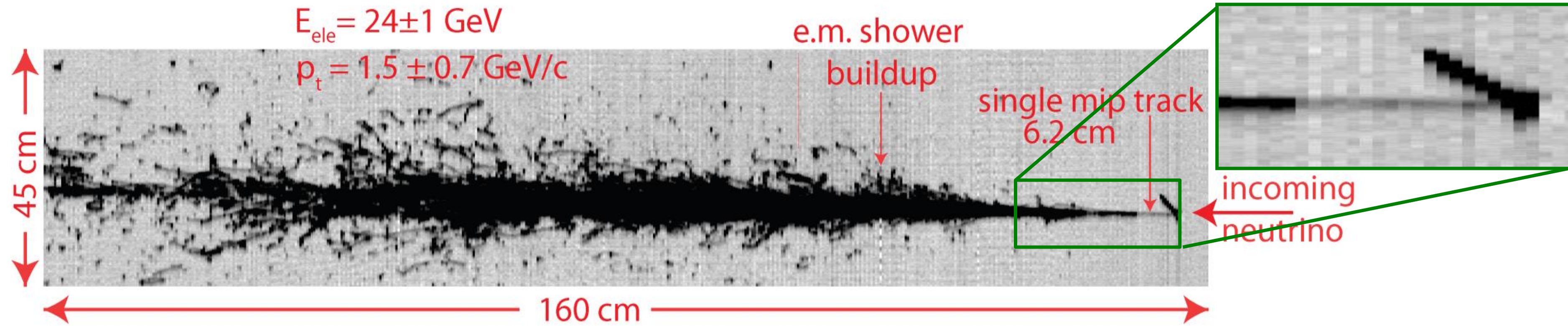
Unique feature of LAr to distinguish e from γ and reconstruct π^0

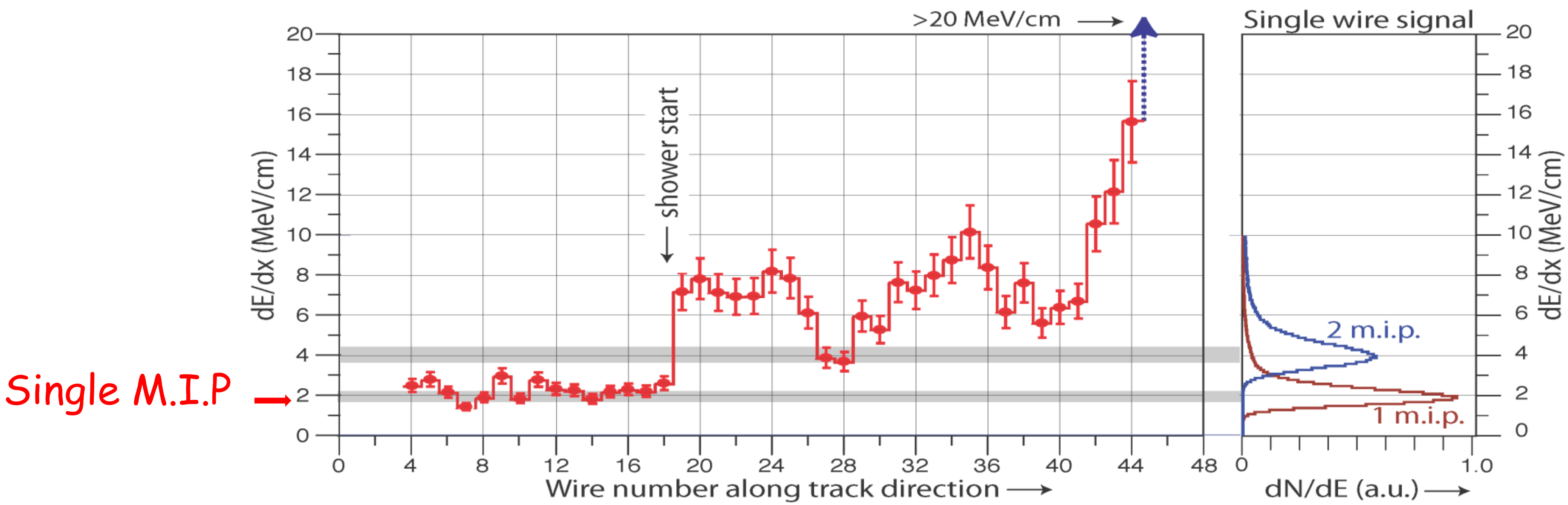
➔ Negligible bkg estimated from π^0 in NC and ν_μ **CC**

ν_e identification in ICARUS LAr-TPC

Example event with a clear electron signature found in the upgraded sample of 2450 ν_μ interactions ($7.23 \cdot 10^{19}$ pot).

The evolution of the actual dE/dx from a single track to an e.m. shower is clearly apparent from individual wires.





Search for LSND anomaly: additional electron neutrino events

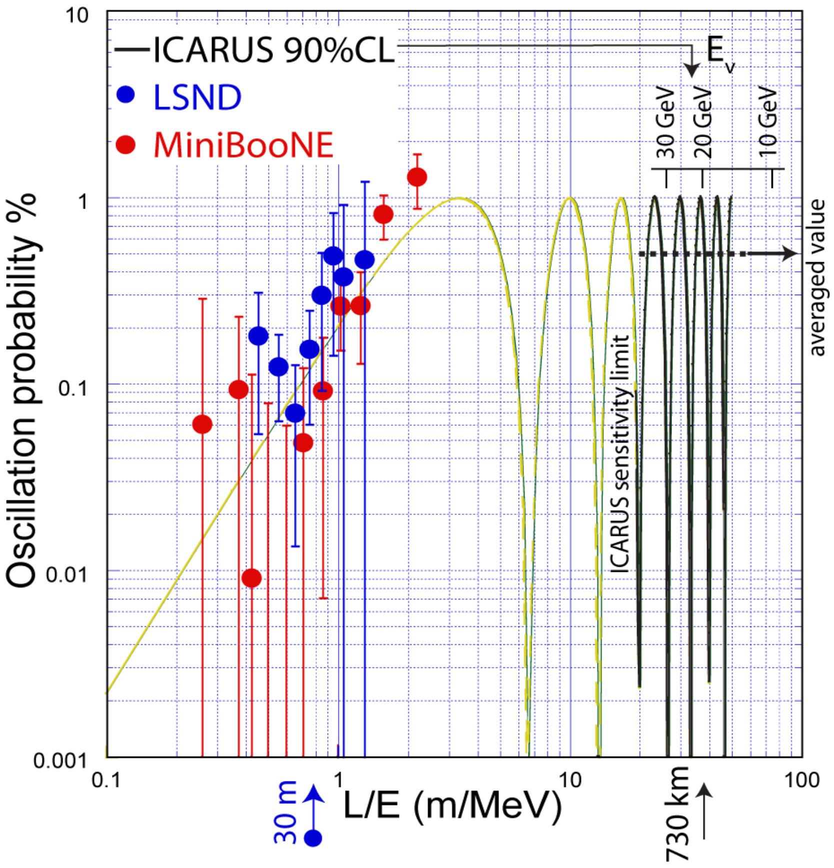
- The CNGS facility delivered an almost pure ν_μ beam, with E_n in (10÷30) GeV range and 1% intrinsic ν_e contamination.
  CERN to Gran Sasso distance: L=732 km.

- The LSND has observed an excess of anti-ν_e neutrino events in anti-ν_μ beam: 87.9 ± 22.4 ± 6.0 (3.8σ), later partly confirmed by MiniBooNE with both ν_μ/anti-ν_μ beams: **$\Delta m^2_{new} \approx 10^{-2} \div 1$ eV^2** implied.

- Main difference w.r.t. LSND exp: L/E_n range
  - ≈ 1 m/MeV at LSND, ≈ 36.5 at CNGS

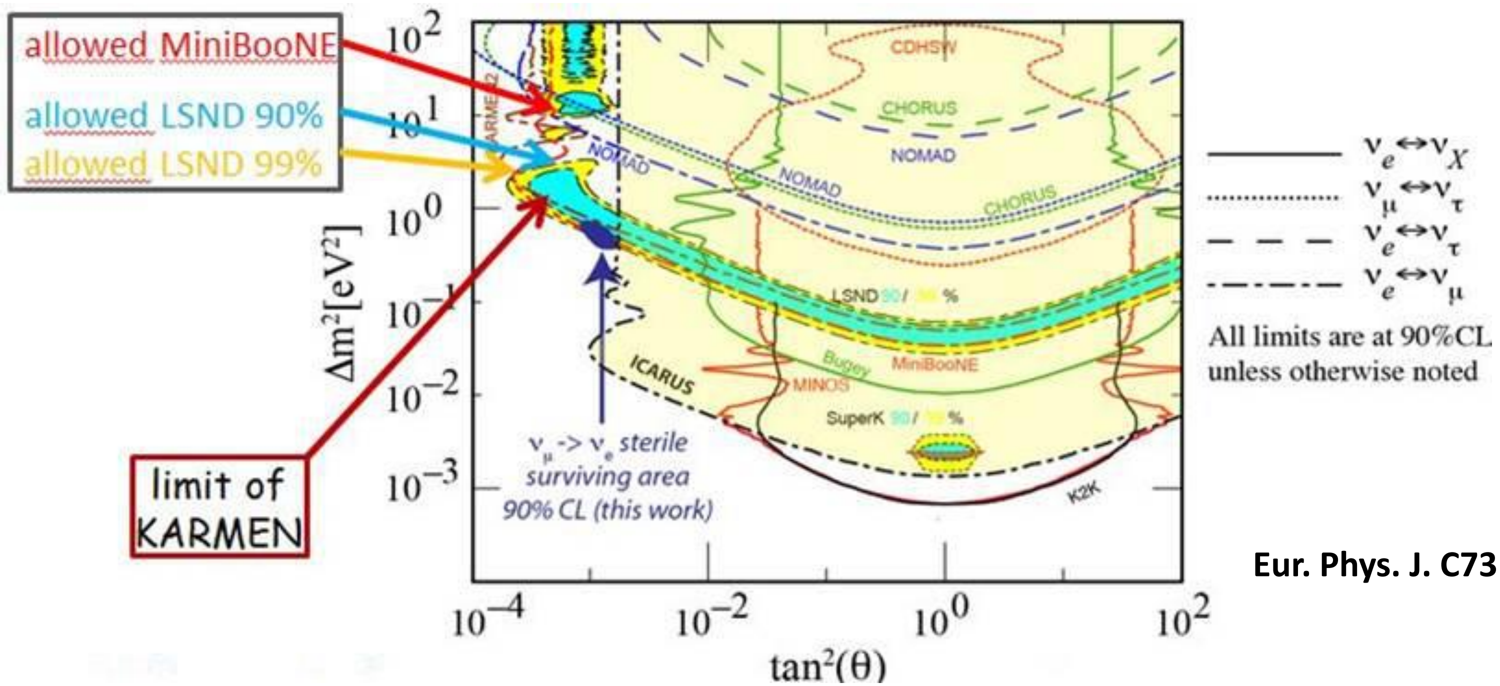
- LSND -like short distance oscill. signal averages here to $\sin^2(1.27\Delta m^2_{new}\, L/E) \sim 1/2$ and $\langle P_{\nu\mu\to\nu e} \rangle \sim 1/2 \sin^2(2\theta_{new})$

- Unique detection properties of LAr-TPC technique allow to identify unambiguously individual e-events with high efficiency.



Search for LSND-like anomaly

- ICARUS searched for ν_e excess related to LSND-like anomaly on the CNGS ν beam (~ 1% intrinsic ν_e contamination, L/E_ν ~36.5 m/MeV)
- Analysis on 7.23 x 10^{19} pot event sample provided the limit on the oscillation probability $P(\nu_\mu \rightarrow \nu_e) \leq 3.85\ (7.60) \times 10^{-3}$ at 90 (99) % C.L.
- ICARUS result indicates a very narrow region of parameter space, Δm^2~0.5 eV^2, $\sin^2 2\theta$~0.005 where all experimental results can be accommodated at 90% CL



Eur. Phys. J. C73 (2013) 2599

The result call for a definitive experiment on sterile neutrino to clarify all the reported neutrino anomalies

ICARUS future: sterile neutrino search within FNAL SBN program

ICAR-US: 6 new US institutions (Los Alamos NL, Colorado State Univ., SLAC, Univ. of Pittsburg, FNAL and Aragonne NL) joined recently the ICARUS Coll.

- To answer definitively the „sterile neutrino puzzle” an experiment with 3 LAr-TPCs, exposed to FNAL ~0.8 GeV neutrino beam, has been proposed.

- SBND (LAr1-ND; 82 tons of active mass), MicroBooNE (89 tons) and ICARUS T600 (476 tons) will be installed at 100m, 470m and 600m from target, respectively

- Common Conceptual Design Report *A proposal for a Three Detector Short-Baseline Neutrino Program in the Fermilab Booster Neutrino Beam,* submitted to the FNAL-PAC in January 2015, underwent level 1 approval.

- The aim of the experiment is to clarify both, LSND/MiniBooNE and Gallex/reactor anomalies, by independent measurement of both, ν_e appearance and ν_μ disappearance mutually linked by the equation:

$$\sin^2(2\theta_{\mu e}) = (1/4)\sin^2(2\theta_{\mu x})\sin^2(2\theta_{ex})$$

- In absence of anomalies, signals from three detectors should be a copy of each other. However, the intrinsic ν_e events with a disappearance signal may result in the reduction of a superimposed appearance LSND signal.

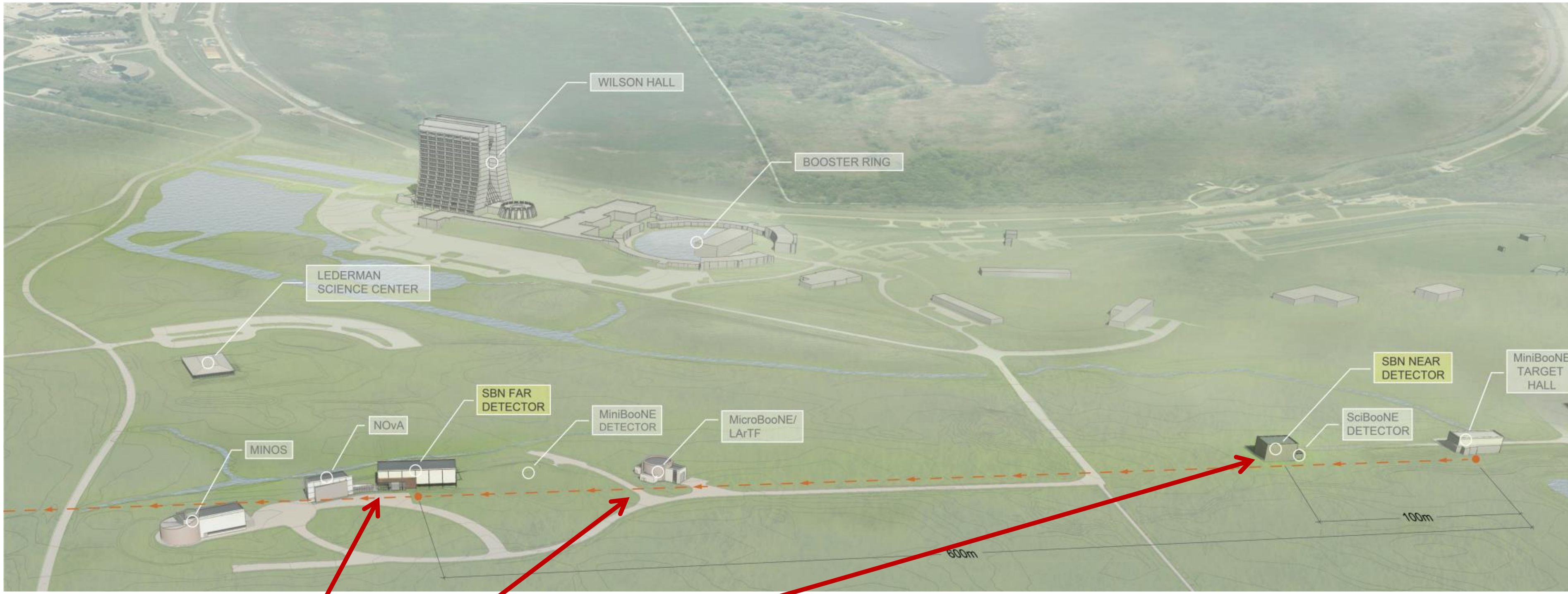
- By changing the intrinsic ν_e beam contamination (horn focusing and decay pipe length) these two effects can be disentangled.

Layout of three LAr TPCs at FNAL

Slide: thanks to Ornella Palamara

The future short-baseline experimental configuration is proposed to include three LArTPCs located on-axis in the BNB.

Multiple detectors very valuable for reducing systematic uncertainties.

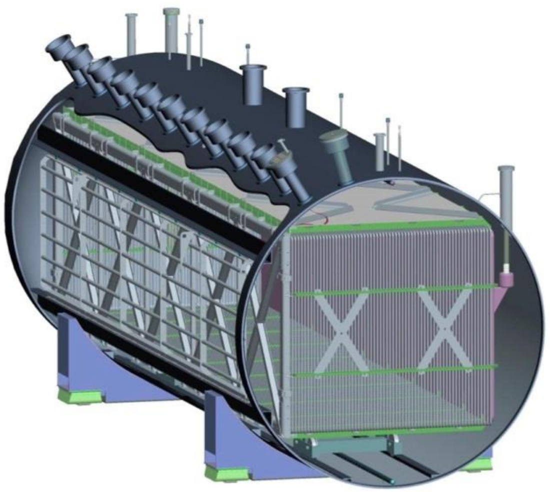


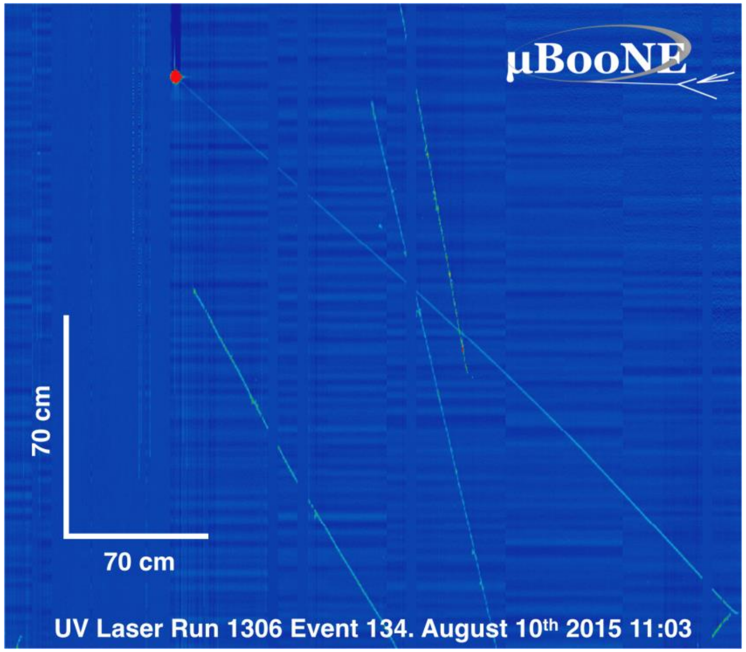
Detector	Distance from BNB Target	LAr Total Mass	LAr Active Mass
LAr1-ND	110 m	220 t	112 t
MicroBooNE	470 m	170 t	89 t
ICARUS T600	600 m	760 t	476 t

Located at Fermilab, the experiment will build and operate a large 170 ton Liquid Argon Time Projection Chamber (LArTPC) located along the Booster neutrino beam line. The experiment will measure low energy neutrino cross sections and investigate the low energy excess events observed by the MiniBooNE experiment.

The detector serves as a next step in a phased program towards the construction of massive kiloton scale LAr-TPC detectors.

- August 6, 2015: First tracks in the TPC!
- July 9, 2015: Detector filled with liquid argon (170 tons)
- June 17, 2015: End of detector cooldown and start of liquid argon fill
- April 21, 2015: Start of gaseous argon purge

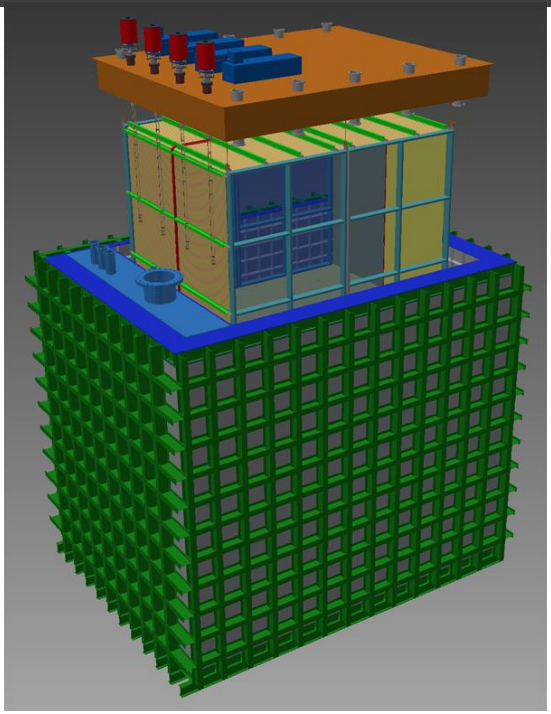


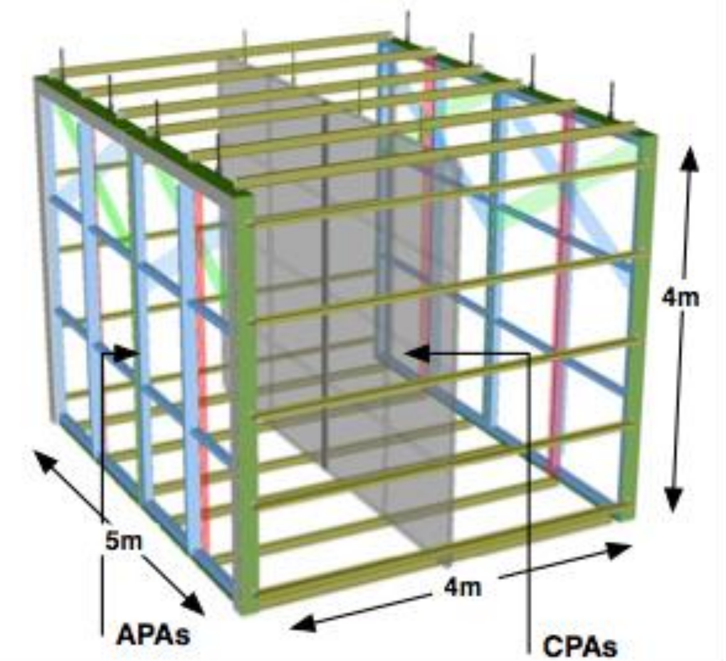


the first UV laser track seen in the MicroBooNE TPC (drift HV at 58 kV)

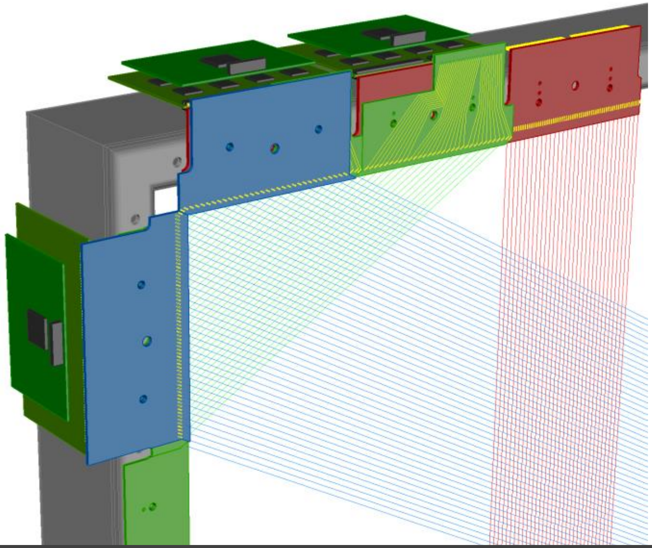
SBND

TPC dimensions:
4 m long x 4 m tall x 5 m wide
Active volume: 112 t of LAr





- The 4 APAs hold 3 planes of wires with 3 mm wire spacing
- Drift distance: 2 m
- UV laser-based calibration system
- Light collection system for the detection of scintillation light
- External cosmic ray tagging system



LArIAT – LAr TPC In A Testbeam

Slide: thanks to Flavio Cavanna

Status:

Physics Run 1 **completed**

- Data collected from April 30 to July 8 2015.
- Analysis ongoing

Physics Run 2

- Fall 2015

Goal:

Characterize LArTPC performance in the range of energies relevant to upcoming short- and long-baseline experiments for neutrino physics and for proton decay searches.

Physics

- Charged pion interaction cross section measurements
- Optimize pion and kaon ID
- Experimentally measure e-γ separation capabilities
- Develop criteria for muon charge sign determination w/out magnetic field
- Study Energy Resolution and Particle Identification improvement by combining information from scintillation light and ionization charge signals

R&D

- Development of innovative, augmented performance Scintillation Light detection Systems for Liquid Argon Detectors *(*Yale/Wright Lab*)*

Toward future of LAr-TPC detectors

Two solutions

Modular

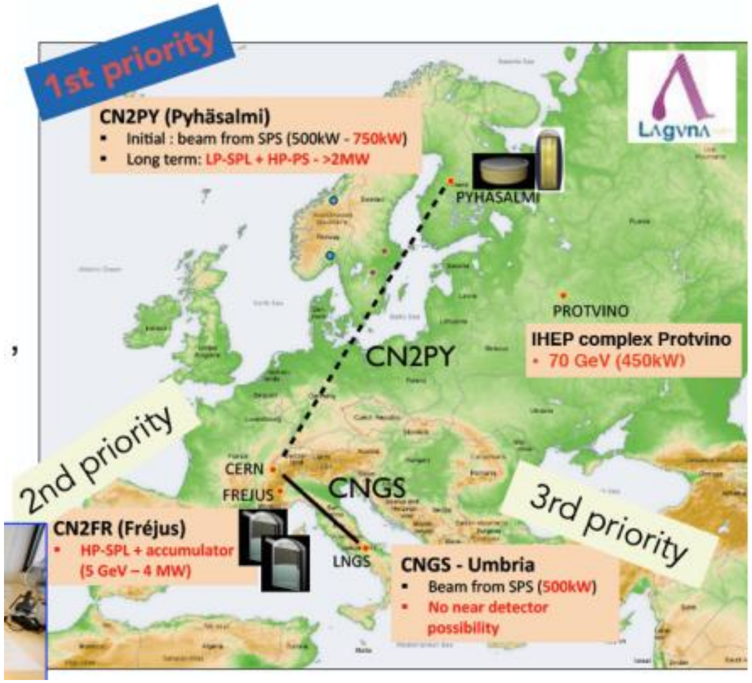
- **ModulAr**
  structure with several separated vessels

Large scale

- **LBNO**
  Double Phase
- **DUNE**
  Single phase

LAGUNA EU FP7 Design Study 2008-11
- 3 detector technologies, 7 sites (130-2300 km)
- ~100 members, 10 countries

LAGUNA-LBNO EU FP7 D.S. 2011-14
- prioritzaton of sites and detectors (3 det, 2 possible sites)
  - Liquid Argon Double-Phase TPC GLACIER (20-70kt) @Pyhäsalmi
  - Water-Cherenkov detector MEMPHYS (500 kt) @Fréjus
  - Liquid ScinJllator LENA (50 kt) @Pyhäsalmi
- fully engineered detector designs for 20/50 kt DLAr, 50 kt LSc, 540 kt WCD
- underground facility constructon and costng (Pyhäsalmi, Fréjus and Umbria)
- extended site investgaton at Pyhäsalmi mine
- ~300 members, 14 countries + CERN



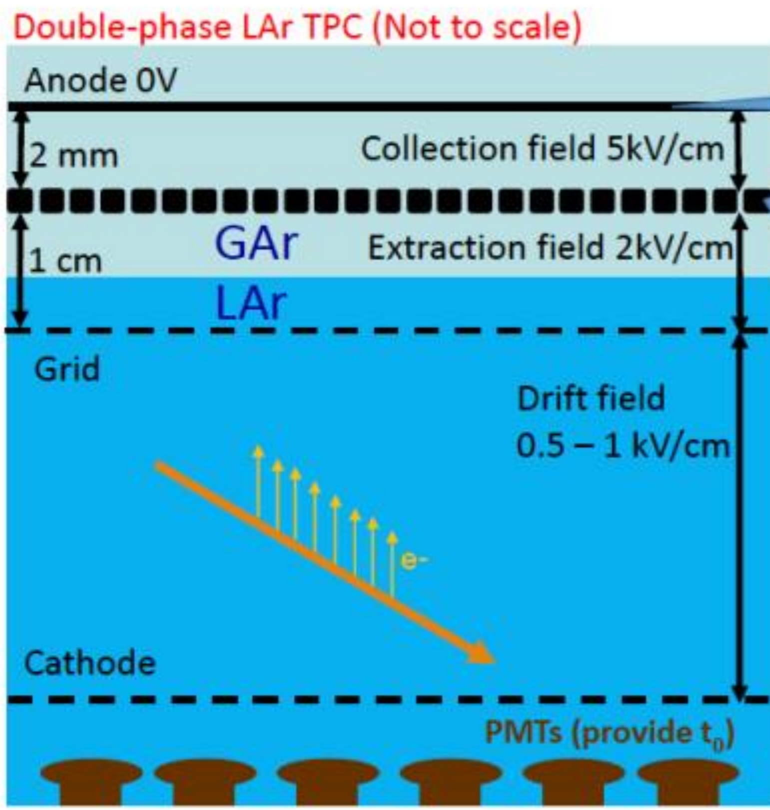
LBNO (CERN SPSC-EOI-007 for a very long baseline ν oscillaton experiment, 2012)
- incremental approach for a large neutrino observatory with excitng physics from phase 1
- ~230 authors, 51 instutons

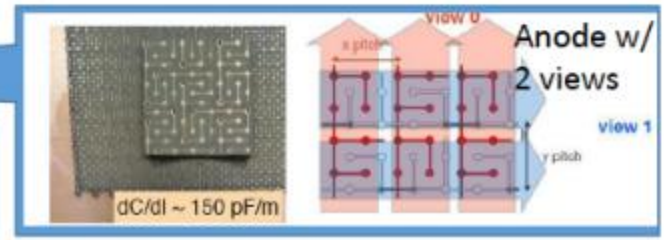
LBNO-DEMO WA105 1:20 scale demonstrator for DLAr TPC detector @ CERN

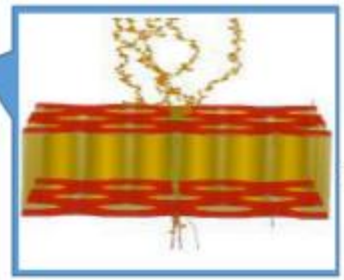
From A. Tonazzo NOW2014

Detector technology

GLACIER (**G**iant **L**iquid **A**rgon **C**harge **I**maging **E**xpe**R**iment) concept
A. Rubbia hep-ph/0402110







LEM (Large Electron Multiplier):
w=1mm, 25-35 kV/cm

- Single cryo-tank based on LNG technologies
- Double-phase → charge amplification and readout in gas phase
  - Large drift distances
  - Low energy detection threshold

Full engineering solution is now available for 20/50 kton detectors from LAGUNA-LBNO DS

02/07/2014 LAGUNA/LBNO - V. Galymov ICHEP2014 5

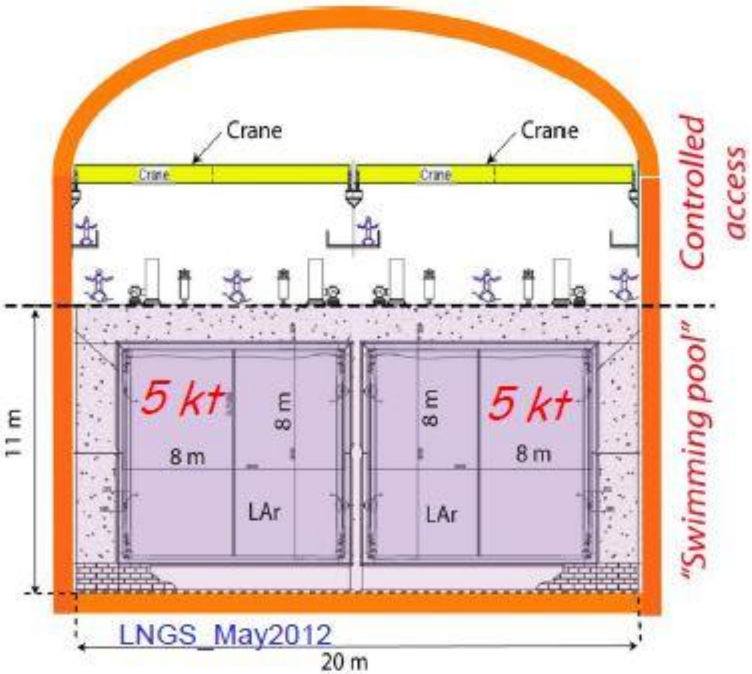
ModulAr – structure with several separated vessels

From C. Rubbia, NuTown2012

- The most naive design would **assume a single** (may be ≈100 kton) **LAr container of a huge size**. But the dimensions of most events under study (beam-ν, cosmic ray-ν, proton decays) are of much smaller dimensions.

- For instance, the whole volume of ultra-pure **LAr will be totally contaminated even by a tiny accidental leak** (ppb). A spare container vessel for ≈100 kton are unrealistic.

- Fortunately **increasing the size** of a single container does **not introduce significant physics arguments** in its favour.



- A reasonable single volume unit could be of 8 x 8 m^2 cross section, a drift gap of 4 m and a length of about 60 m, corresponding to 3840 m^3 of liquid or 5370 t of LAr.

- Two units should be located side to side with 10 kt mass.

Conclusions

- ICARUS is the largest LAr TPC operated underground.

- ICARUS has been acquiring data without interruption for more than 3 years with both CNGS beam and cosmics, proving the maturity of this detection technique → important for next generation experiments.

- ICARUS search for sterile neutrino excluded a large fraction of parameters defining a narrow space of agreement between different experiments (around $\Delta m^2 \approx 0.5\ eV^2$, $\sin^2 2\theta \approx 0.005$) which has to be explored in the future.

- **~15% resolution of the muon momentum** measurement by **Coulomb Multiple Scatterin**g is achieved in the momentum range of interest for future experiments exploiting LAr TPCs.

- LAr purity corresponding to the electron lifetime exceeding 16 ms was achieved opening the way for next generation LAr TPC detectors.

- Overhauling of the ICARUS T600 detector, within the CERN/INFN ICARUS/WA104 project is continued at CERN.

- **FNAL Short Baseline Neutrino Program.**

Backup

Physics goals

- Search of CP violation
- Determination of the neutrino mass hierarchy
- ν_e and anitν_e appearance
- Searches for rare events, including proton decay and baryon number violating processes, SuperNova core collapse neutrinos, and, potentially diffuse SuperNova neutrino background detection
- Whether sterile neutrino oscillations take place at short baselines,
- Whether and how well we understand inclusive and exclusive neutrino cross sections, and in particular nuclear effects and final state interactions in neutrino-nucleus scattering

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm^3]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

(By Mitch Soderberg)

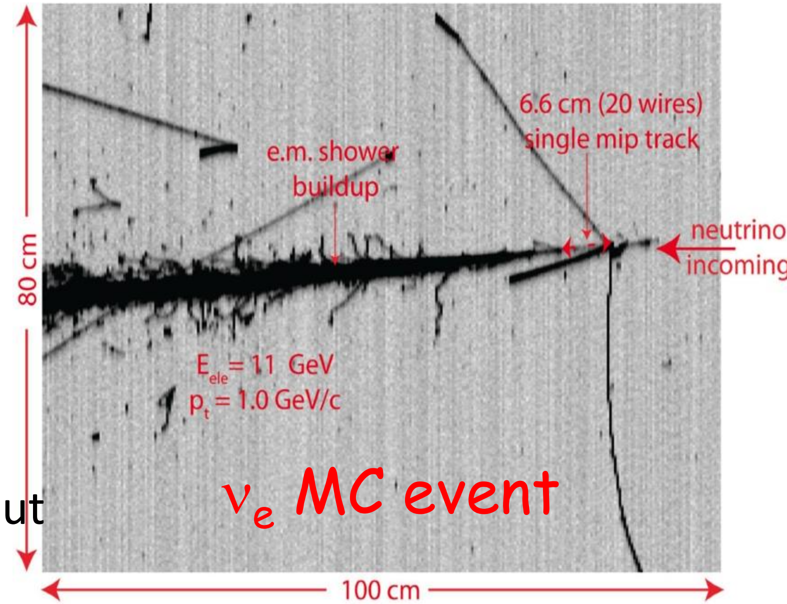
- Dense: 40% more dense than water
- Abundant: 0,9% of the atmosphere
- Ionizes easily: 89 000 pairs electron-ion / cm

ICARUS

- First analysis (Eur. Phys. J. C73 (2013) 2345) was based on 1091 neutrino interactions (**3.2×10^{19} pot**) **→ 2 ν_e events found**
- Extended analysis (Eur. Phys. J. C73 (2013) 2599) was based on 1995 neutrino interactions (6.0×10^{19} pot) **→ 4 ν_e events found**
- At Neutrino 2014 conf. and SPSC 2014 analysis based 2450 neutrino interactions was presented (7.23×10^{19}pot) **→ 6 ν_e events found**
- Additional electron neutrino event has been identified in the full available sample corresponding to the 7.93×10^{19} pot
- The **7 observed electron like neutrino events** are consistent with the 8.4 events expected: **no evidence for sterile neutrino oscillation**.

Selection of ν_e events in CNGS data

- ν_e CC event candidates are visually selected with vertex inside fiducial volume (for shower id.): > 5 cm from TPC walls and 50 cm downstream.
- Energy selection: < 30 GeV
  - 50% reduction on intrinsic beam ν_e
  - only 15% signal events rejected



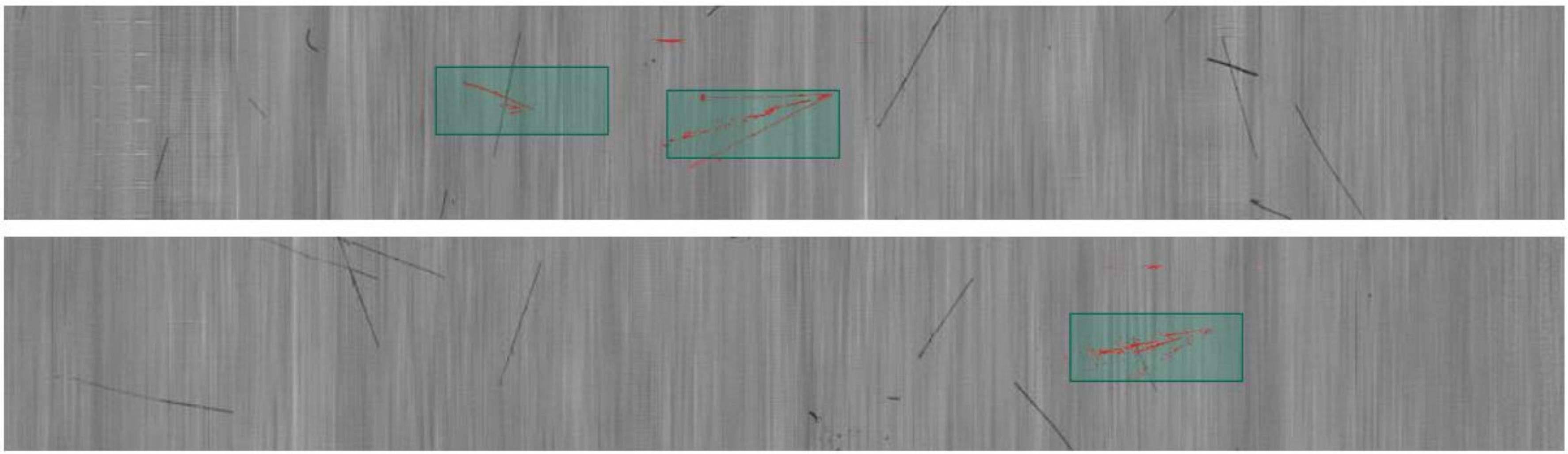
- ν_μ CC events identified by L > 2.5 m long track without hadronic interactions

- The “Electron signature” requires:
  - charged track from primary vertex, m.i.p. on 8 wires, subsequently building up into a shower; very dense sampling: every 0.02 X_0;
  - minimum isolation (150 mrad) from other ionizing tracks near the vertex in at least one of the TPC views.

- Electron efficiency (recognition, selection efficiency, h) has been studied with events from a MC (FLUKA) reproducing in every detail the signals from wire planes: h=0.74±0.05 (0.65±0.06 for intrinsic ν_e's due to the harder spectrum).

ICARUS at shallow FNAL depth: new challenge

- Several (~12 muons from Pavia 2001 surface measurement) uncorrelated cosmic rays will occur in T600 during 1 ms window readout at each triggering event
- Therefore, it is necessary to associate precisely the related timing of each element of TPC image with respect to the trigger line.
- Moreover ϒ's associated with cosmic μ's represent a serious background for the ν_e appearance search, since electrons generated in LAr via Compton scattering or pair production can mimic ν_e CC interaction.



Cosmic rays (PV) + low energy CNGS beam events

ICARUS T600 detector improvement in order to prepare it for operation at shallow depth is going on within the CERN ICARUS/WA104 experiment with strong support from CERN groups

ICARUS at shallow FNAL depth: new challenge

- An unambiguous identification of all cosmic ray particles entering the detector has to be applied. A Cosmic Rays Tagging, around the LAr active volume is under study.
  - 4π Cosmic Rays Tagger (total surface ~ 1200 m^2)
  - It will provide an external timing of each track, which will be combined with the TPC reconstructed image.

- 99% efficiency in cosmic rays identification can be achieved with a 95% detection efficiency (relying on double crossing of muons) of single muon hit

- Also a ~1 ns accuracy of internal scintillation light detectors, will enable to exploit the bunched structure of the Booster p beam (2 ns wide bunches every 19 ns)

ICARUS T600 detector improvement in order to prepare it for operation at shallow depth is going on within the CERN ICARUS/WA104 experiment with strong support from CERN groups

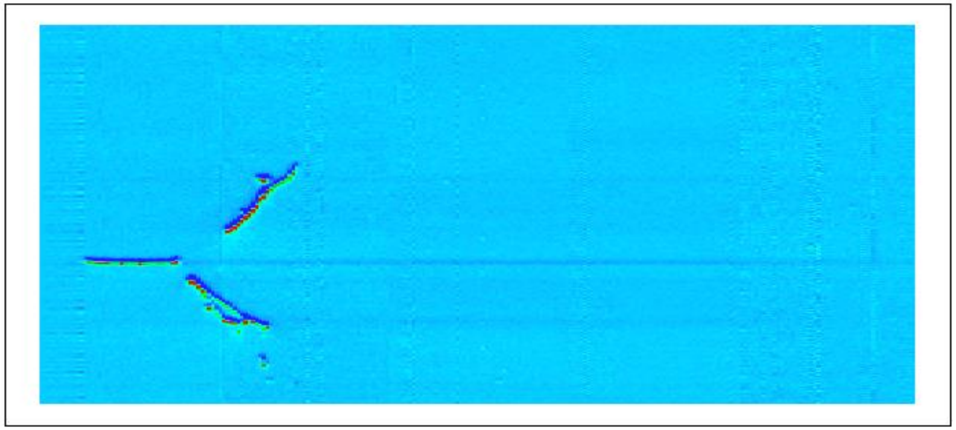
LArIAT – LAr TPC In A Testbeam

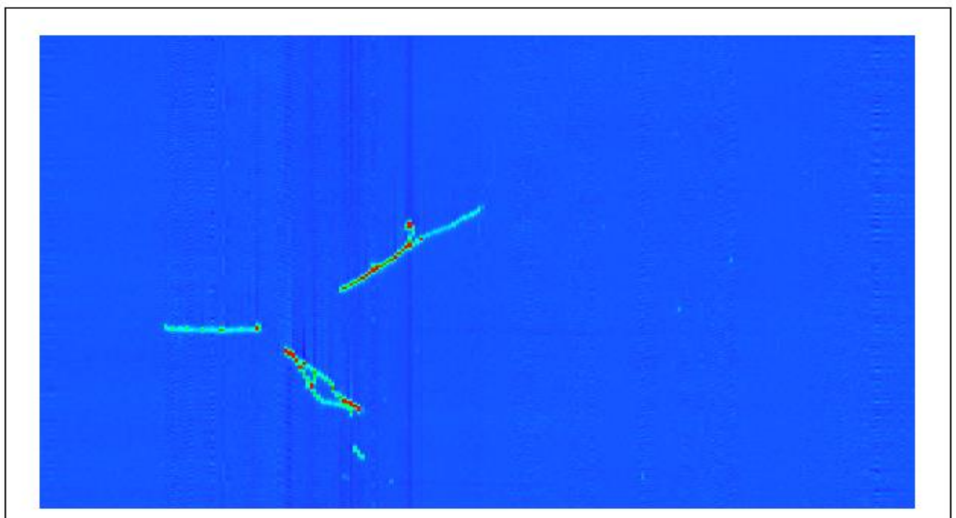
Slide: thanks to Flavio Cavanna

Pion beam

Pion exchange

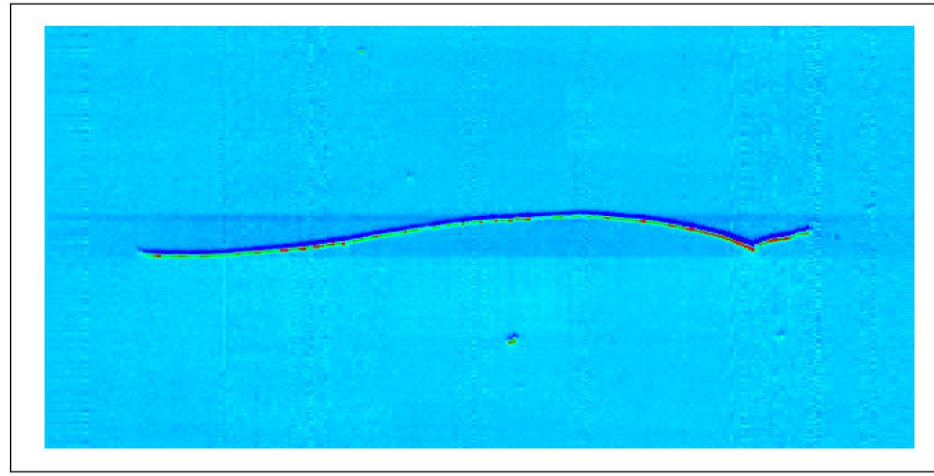
$\pi^{-} + p\ (\rightarrow\ \Delta^{0}\ ) \rightarrow\ \pi^{0} + n$

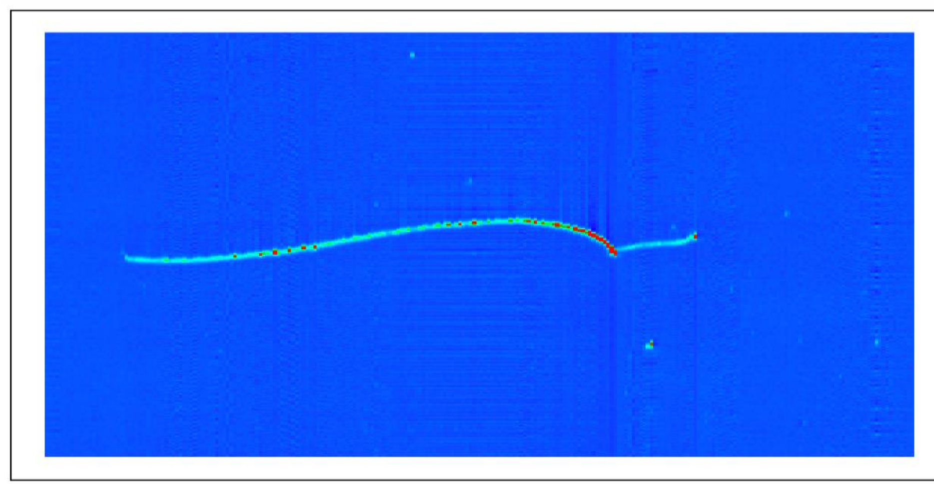




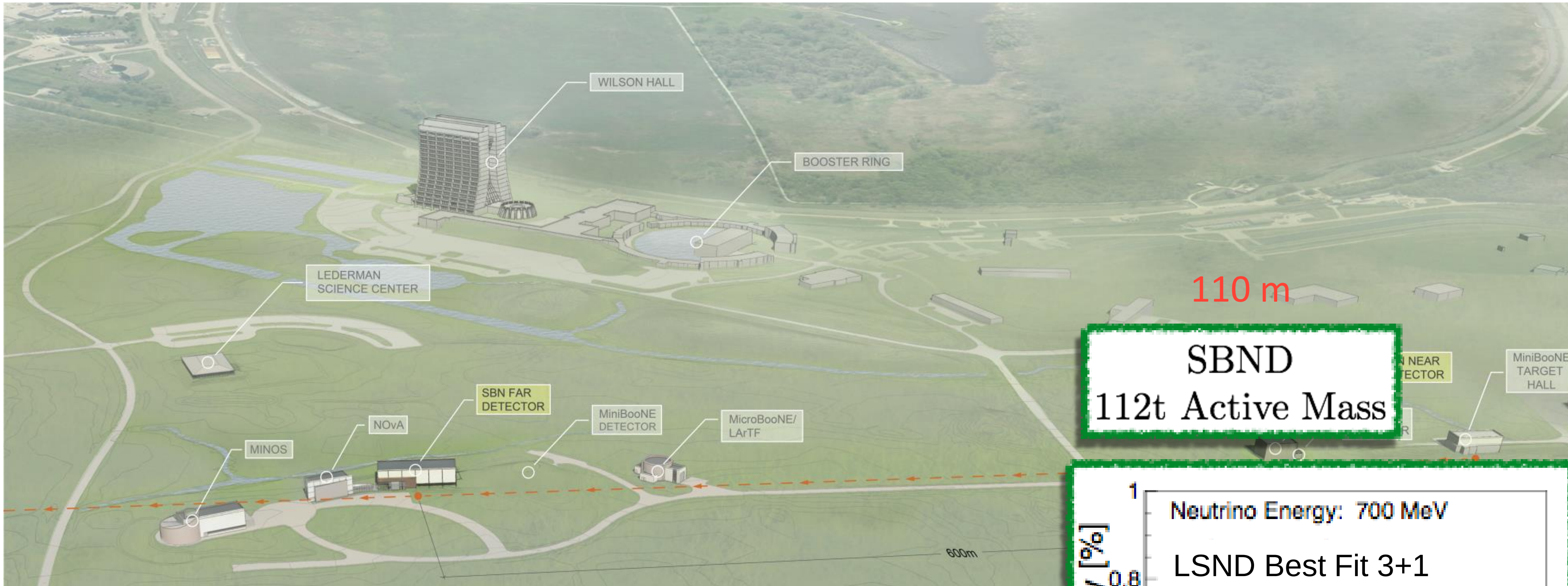
Pion decay at rest

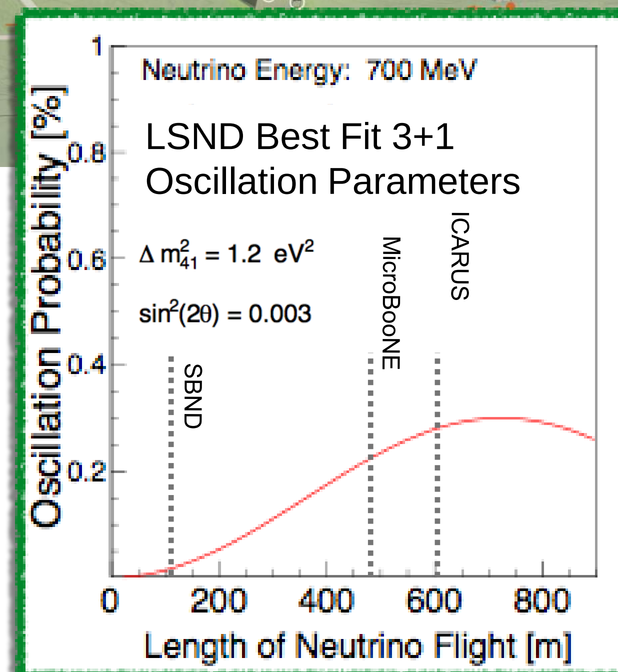
$\pi+ \rightarrow \mu+ \rightarrow e+$





LAr1-ND (SBND)





- SBND will provide a detailed characterization of the beam before oscillations can occur
- This allows for the cancelation of many of the dominant systematics