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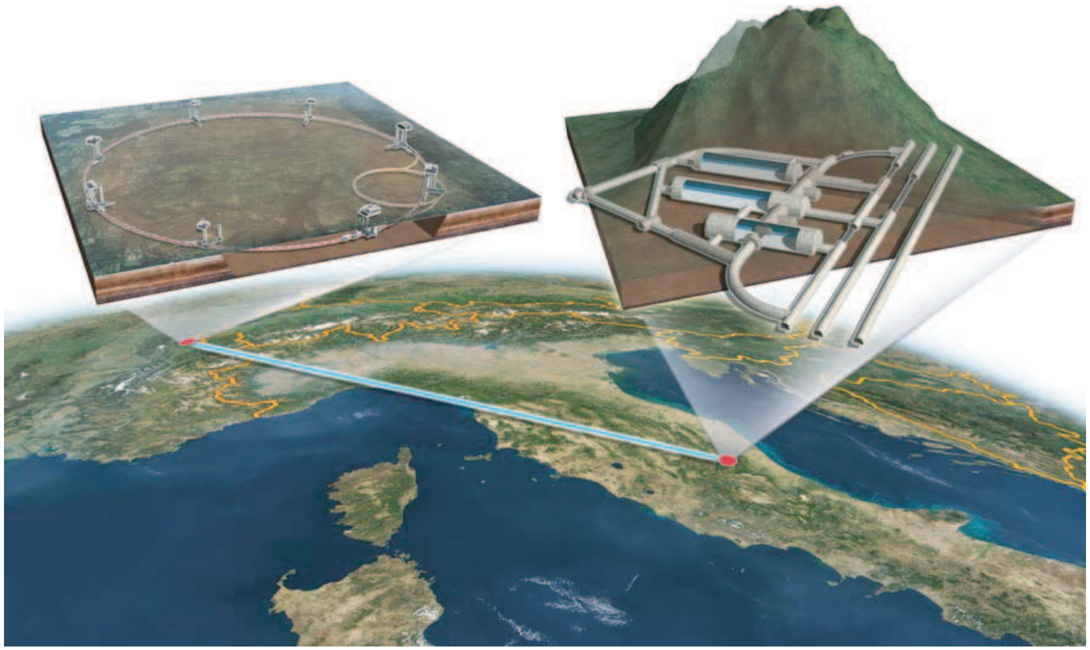
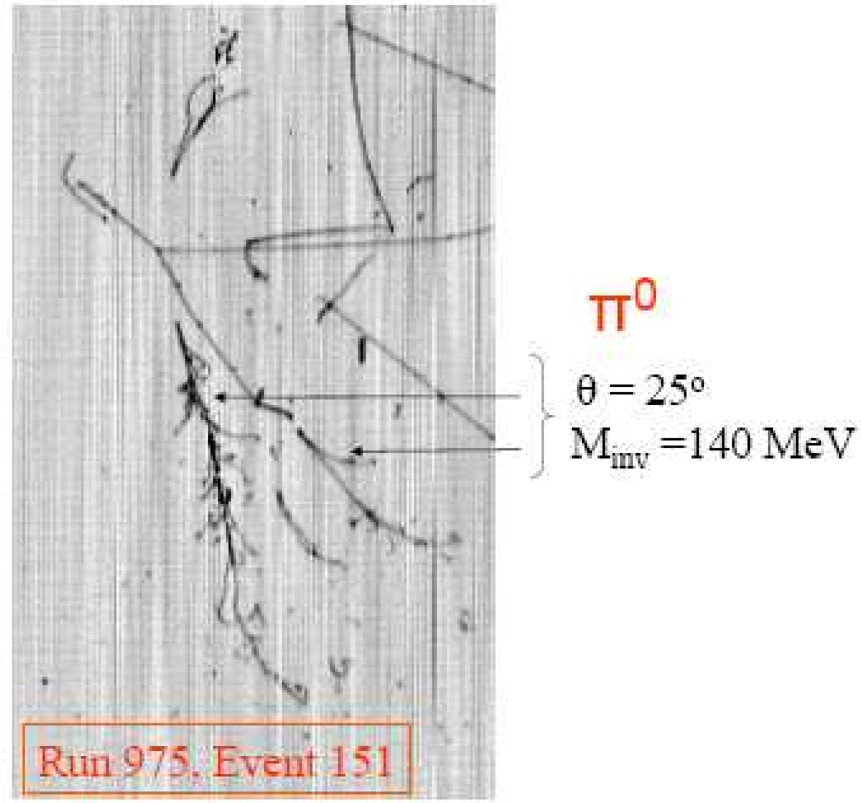
Sezione di Padova

“Neutrino experimental search in ICARUS”





- **neutrinos!?**
- **ICARUS LAr-TPC programme**
- **sterile neutrino search at PS**
- **from ICARUS-T600 to MODULAR**

Padova, May 6 2010

at the Physics Frontiers: neutrino oscillations and proton-decay

- *Neutrinos have been the origin of an impressive number of "Surprises". It has been demonstrated that the sum of the strengths of the coupling of different ν is very close to 3. But it is only assuming that neutrinos, in similarity to charged leptons, have unitary strengths that the resulting number of neutrinos is 3. The situation may be altered by the additional presence of sterile neutrinos.*
- *The experimentally measured weak coupling strengths are only rather poorly known, leaving room for many other alternatives. Best fit of cosmological data (WMAP, CMB) may be indicate the presence of a fourth neutrino...*
- *Are neutrinos a simple carbon copy repetition of quarks?*
- *Important discoveries may be ahead:*
  - *CP violation in the lepton sector*
  - *Sterile neutrino and other "surprises"*
  - *Majorana or Dirac ν's;ν-less $\beta\beta$-decay,ν-masses*
- *similar fundamental questions: (barionic) matter is forever ?*

ν oscillations at accelerators: toward θ_{13} and δ_{CP}

- *first generation long baseline ν experiments: K2K over $L = 250$ km baseline, NuMI and CNGS with $L \sim 730$ km with conventional ν beams, 170 KWatt on target*
- *present detectors: SK 22.5 kt W-Cherenkov, MINOS 5.4 kt Iron-Scintillator calorimeter and ICARUS ~ 600 t liquid Argon TPC (LAr-TPC); OPERA emulsion detector for ν_τ appearance.*
- *θ_{13}, δ_{CP} measurement in $\nu_\mu \rightarrow \nu_e$ requires major improvements both in beams and detectors:*
  - *high intensity pure ν beams, L/E_ν tuned to Δm^2_{23}, well defined energy spectrum (present beams: intrinsic ν_e contamination mainly from μ and K decay)*

    - ν-Factories: ν's from decay of accelerated μ's

    - β-Beams: ν's from decay of accelerated radioactive ions, just one flavor beam!
  - *"ultimate" massive detectors, able to measure ν_e-CC (i.e. electrons!) rejecting ν-NC (i.e. π^0's!) adressed also to astroparticle physics and proton decay-search:*

    - 100 kt LAr-TPC (GLACIER), 50 kt L-Scint. (LENA), ~ 500 kt W-Cherenkov (MEMPHIS)

    - USA and Japan: two similar projects (UNO and HypeK)

2^{nd} generation experiments at improved Off-Axis conventional beams, 1 MW power and even beyond:

- *T2K: present SK detector but a new 0.7 GeV ν_μ beam from 50 GeV/c RCS, 0.7 MW, $L = 295$ km*
- *NOVA project, 20 kt L-Scint. $L \sim 820$ km, 2 GeV ν_μ beam, 6.5×10^{20} pot/y at 120 GeV/c.*

the need of imaging detectors of high target density

- *the success of the bubble chamber as main tool in H.E. fixed target physics is due to 2 facts:*

  - it provides a massive homogeneous target, of substantial density

  - it provides complete imaging and reconstruction of the events in itself

  This technology has permitted in the past very substantial advances based on :

  - single events with complete reconstruction (e.g. discovery of Ω^-*)*

  - surprise events, i.e. topologies not a priori expected (e.g.Gargamelle neutral currents)

  However this technology is costly/complicated non expandible to large masses!

- *a new powerful multi-kton detector capable of providing a 3D imaging of any ionizing event: the Liquid Argon Time Projection Chamber [C. Rubbia: CERN-EP/77-08 (1977)] first proposed to INFN in 1985 [ICARUS: Imaging Cosmics And Rare Underground Signals: INFN/AE-85/7]*

  $\longrightarrow$ *an electronic bubble chamber with in addition:*

  - high granularity (mm), continuously sensitive self triggering

  - operating without pressure, eventually underground

  - excellent calorimetric properties, particle identification (through dE/dx vs range)

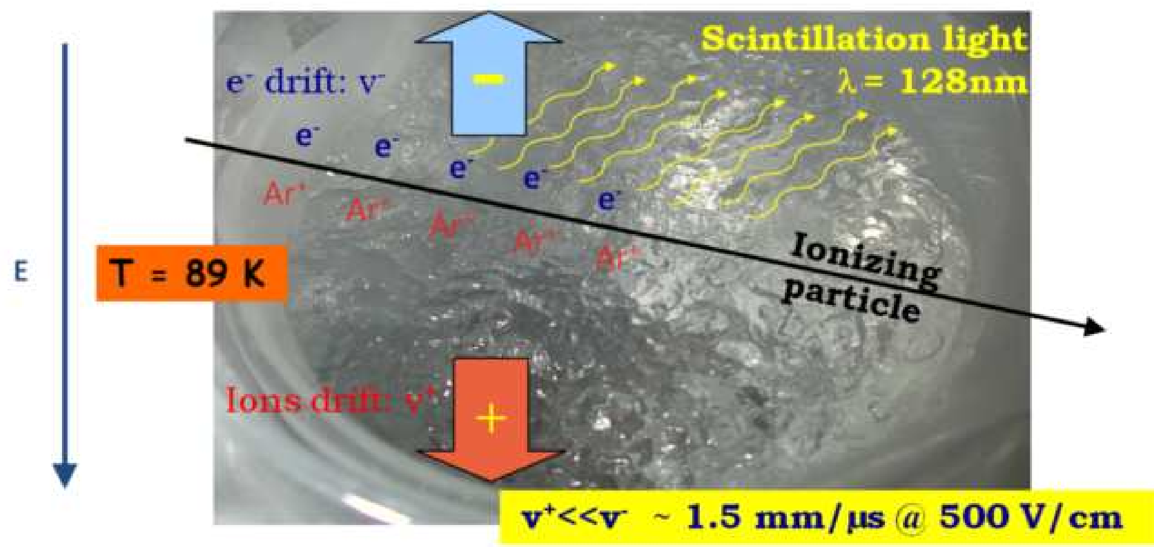
LAr: a noble liquid as tracking medium

Ideal material, commercially easy to obtain ($\sim 1\%$ of air content), for detection of ionizing radiation:

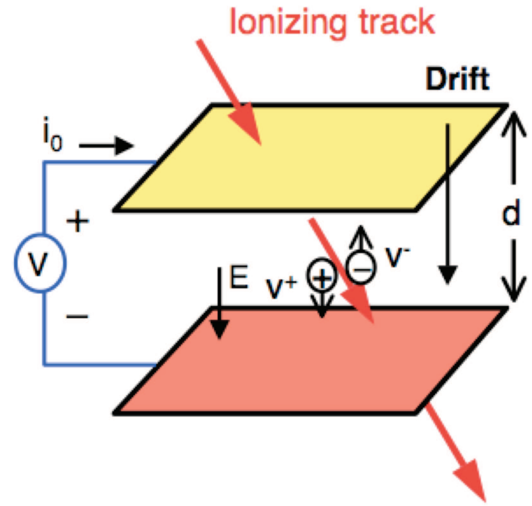
- *dense ($\sim g/cm^3$), homogeneous, it acts as target and detector*
- *high electron mobility, does not attach electrons (long drift paths in liquid phase)*
- *inert, not flammable can be made very pure, with many impurities freezing out*

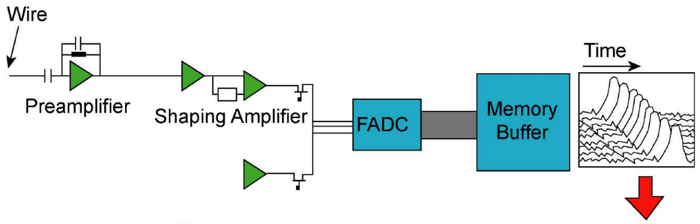
when a charged particle traverses LAr:

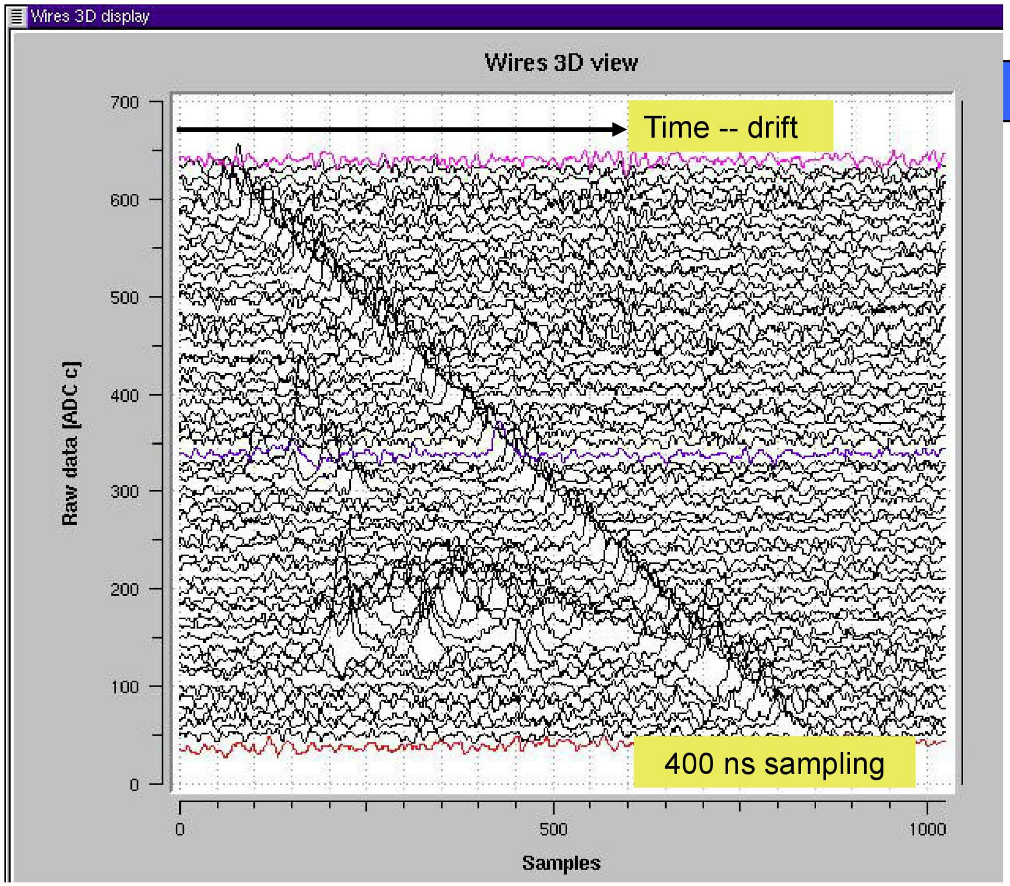
- *ionization: 42000 $e^- - ion$ / MeV*
- *scintillation: 10^4 γ/MeV, UV spectrum ($\lambda = 128$ nm),due to low energy, no successive ionizations: LAr is $\sim$transparent!*
- *Cherenkov light (if fast particle)*

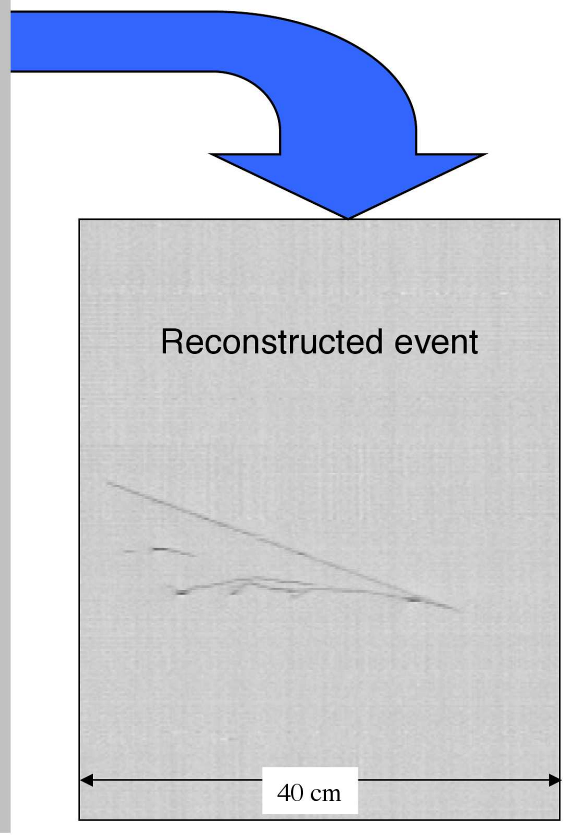


Collecting a track charge

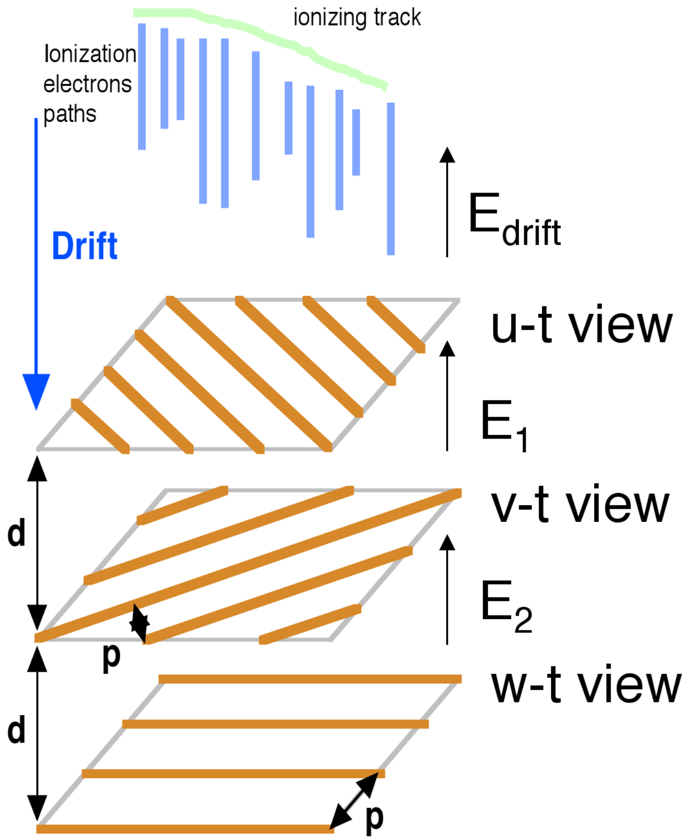


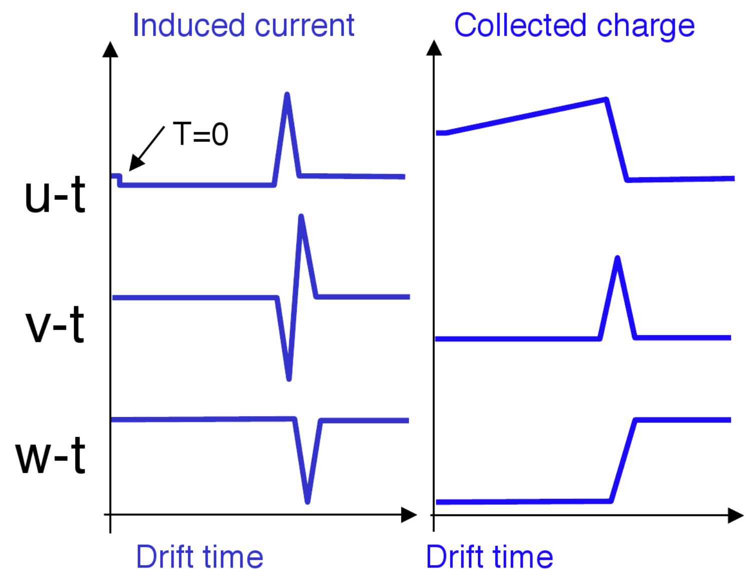






Non distructive readout: the induction signals (3D) !



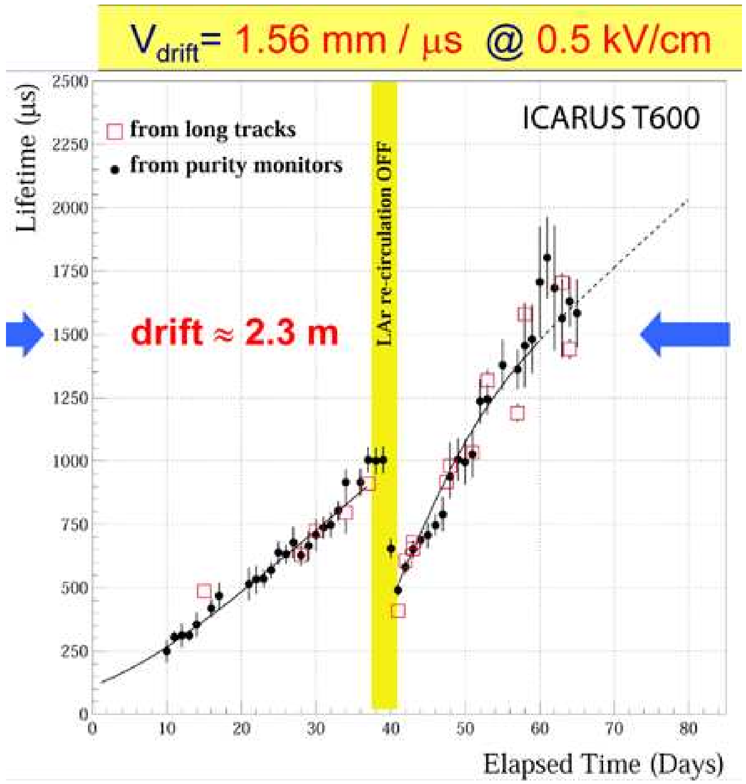


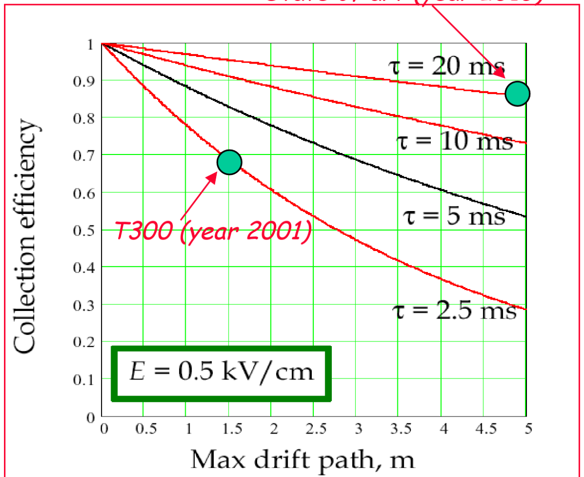
With at least 3 views, a three-dimensional localization of position for each value of t

The drifting electron is traversing 3 transparent wires arrays oriented in the direction of the required view. The ionizing track records in each of them a triangular induction signal. Finally the electron charge is collected by the collection plane. The generated topological view of the event is the one seen by a camera at infinity with the optical axis in the direction of the wires.

Free electron signal in LAr

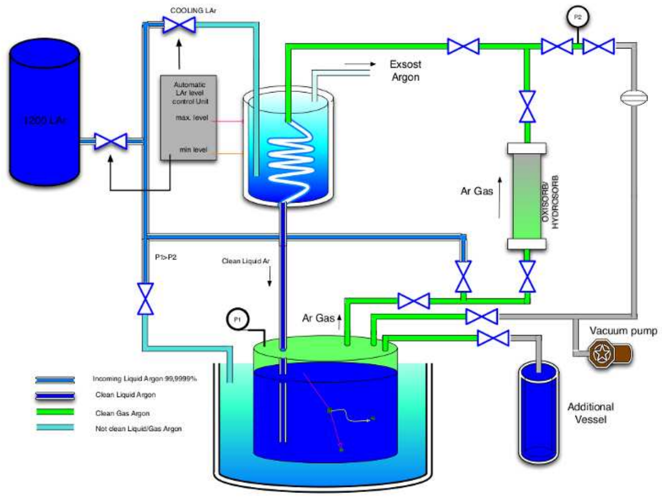
- *the strong e^--ion recombination due to comparable thermalization distance (140 nm) and separation is reduced to 30 % for a $E_{drift} = 500$ V/cm*
- *the presence of electron trapping polar impurities attenuates the electron signal as $\exp -t_D/\tau_{ele}$: it can be expressed in equivalent Oxygen molar densities:*
  $\tau_{ele} = 300\ \mu s \cdot 1ppb/N(O_2)$
- *because of temperature (87 K) most of the contaminants freeze out spontaneously. Main residuals: O2, H2O, CO2 and N2. The goal: 10 ms lifetime for a 30 ppt (t=trillion !) of Oxygen equivalent !*
- *at 500 V/cm, a 5m drift length corresponds to a drift time of 3.1 ms ($v_D = 1.6$ m/ms).*
- *the intrinsic bubble size (rms diffusion):*
  $\sigma_D[mm] = 0.9\sqrt{t_D[ms]}$
  for 5m drift $<\sigma_D> = 1.1$ mm and $(\sigma_D)_{max} = 1.6$ mm, tiny with respect to 3 mm wire pitch.



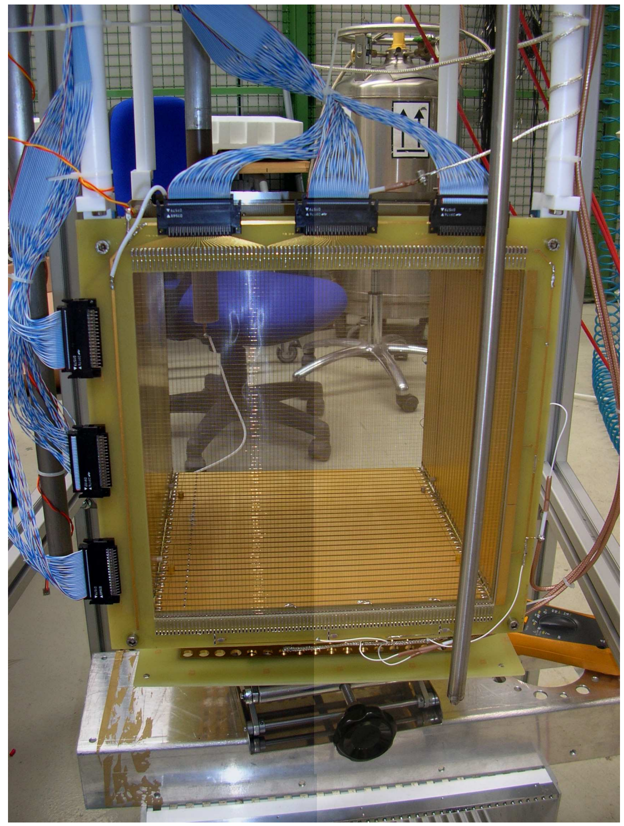


Drifting charge attenuation versus drift path at different electron lifetimes

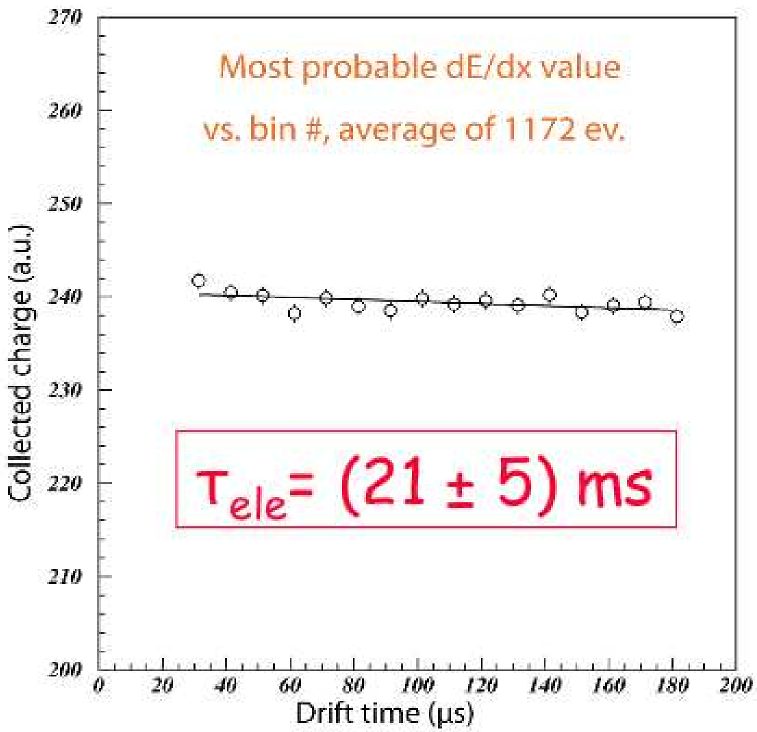
Recent progress in experimental purity achievements

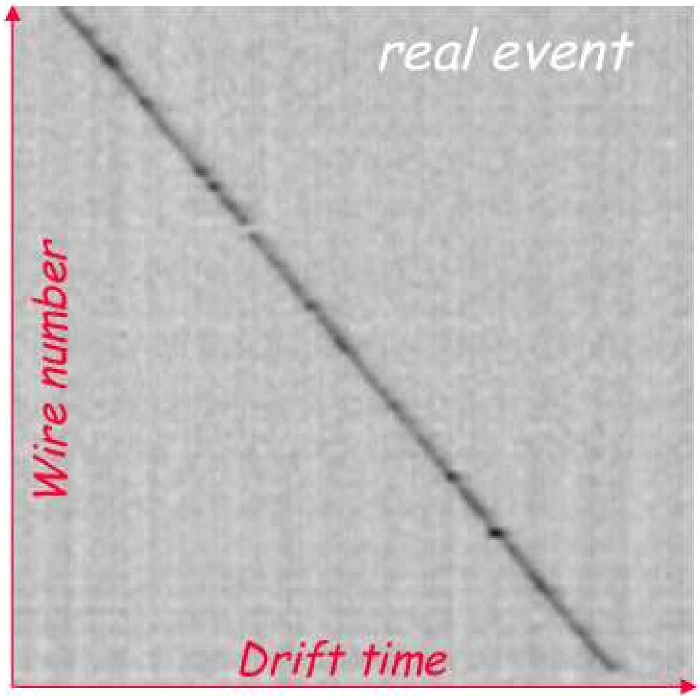


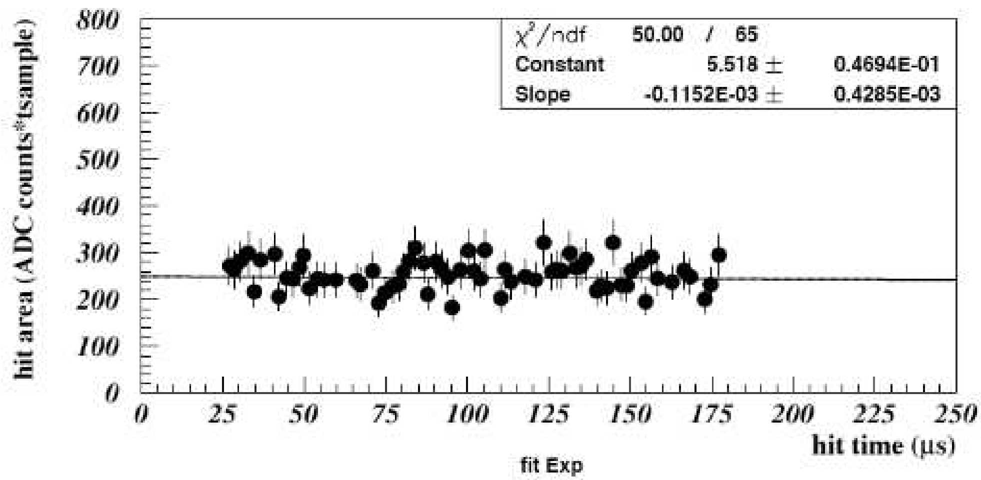
- *new industrial purification methods have been developed at an exceptional level, however remnants of O2 and N2 have to be initially and continuously purified - recirculated in Hydrosorb/Oxisorb filters;*
- *dedicated studies have been performed at INFN-LNL Labs with ICARINO 38 Kg fiducial mass LAr-TPC test-facility;*
- *extremely high $\tau_{ele} \simeq 21$ ms, corresponding to 15 ppt, namely a 10^{-11} molecular impurities in Ar, have been determined with cosmic μs;*
- *the short path length used (30 cm) is compensated by the high accuracy in the observation of the specific ionization.*



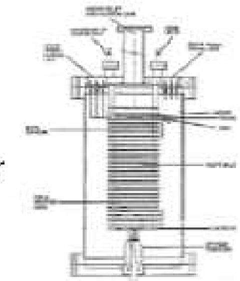
- *The measured value to the experimental τ_{ele} corresponds to an attenuation of about 15 % for a longest drift of 5 meters, opening the way to exceptionally long drift distances.*







the path to massive liquid Argon detectors



24 cm drift wires chamber

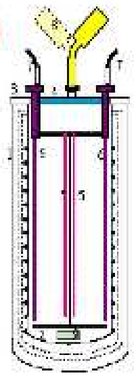
CERN

1

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

2

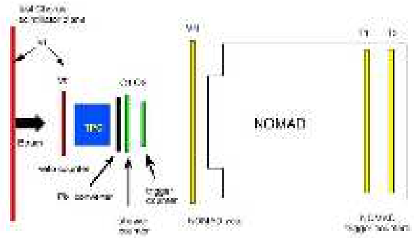
3 ton prototype



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

CERN

Laboratory work



50 litres prototype
1.4 m drift chamber

CERN

3

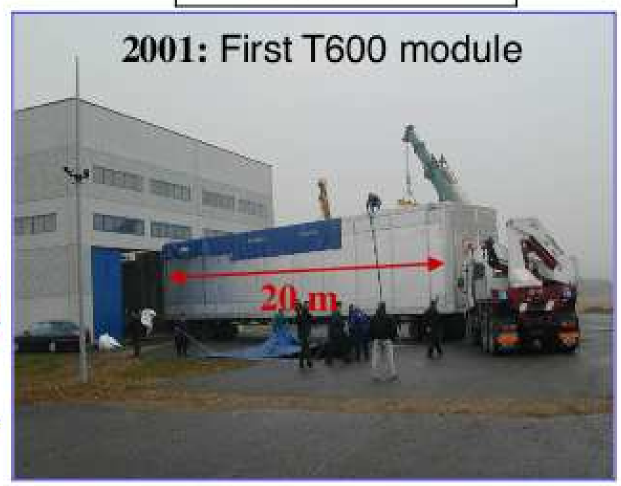
1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

4

10 m^3 industrial prototype

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

T600 detector



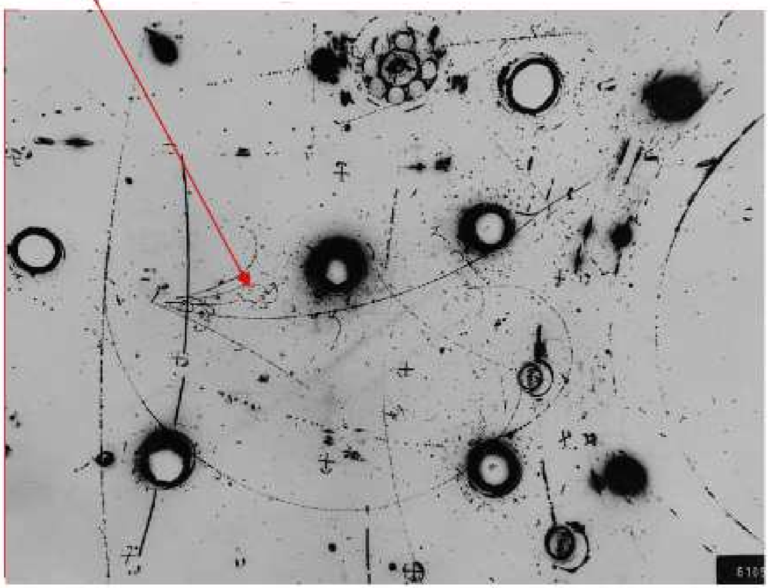
5

Cooperation with industry

thirty years of progress...

Gargamelle bubble chambers

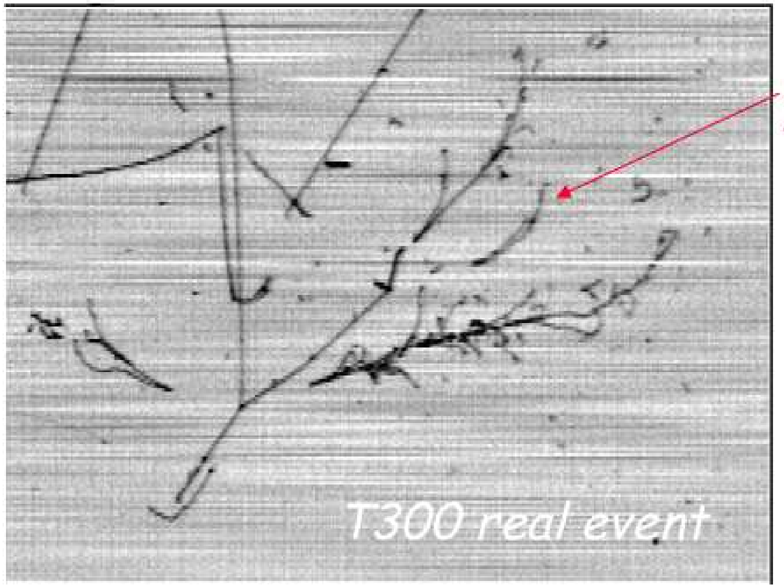
Bubble diameter ≈ 3 mm (diffraction limited)



Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

ICARUS electronic chamber

LAr is a cheap liquid (≈1CHF/litre), vastly produced by industry



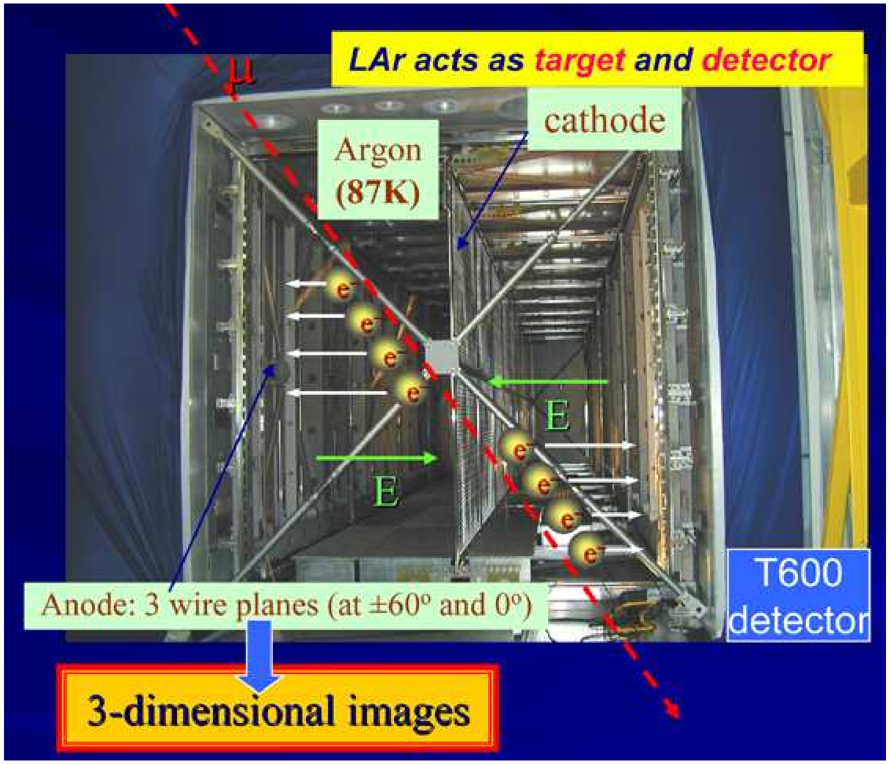
"Bubble" size $3 \times 3 \times 0.3$ mm^3

Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

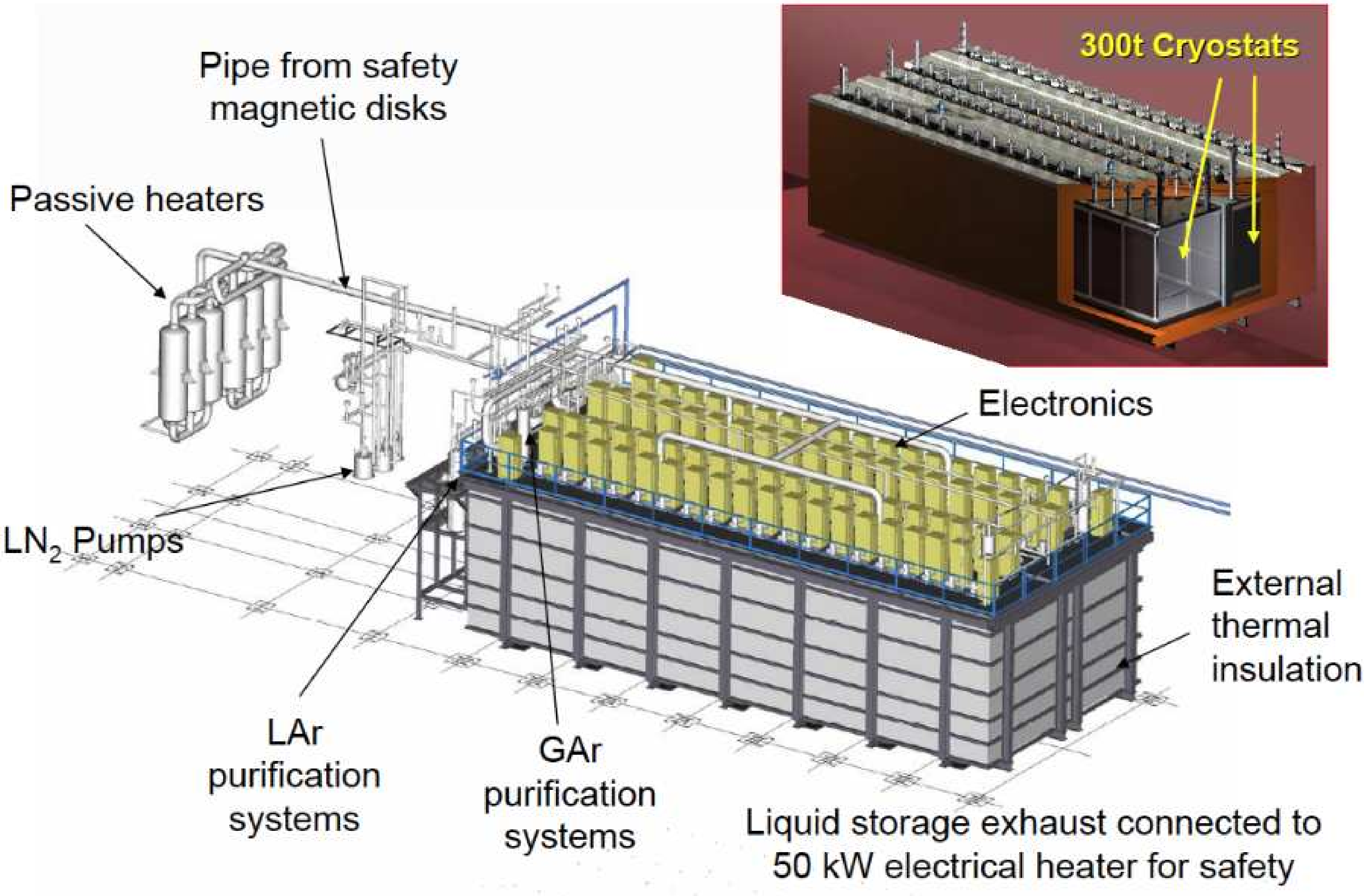
the ICARUS-T600 detector in underground Hall B of LNGS

ICARUS-T600: a marvelous detector exploring new physics

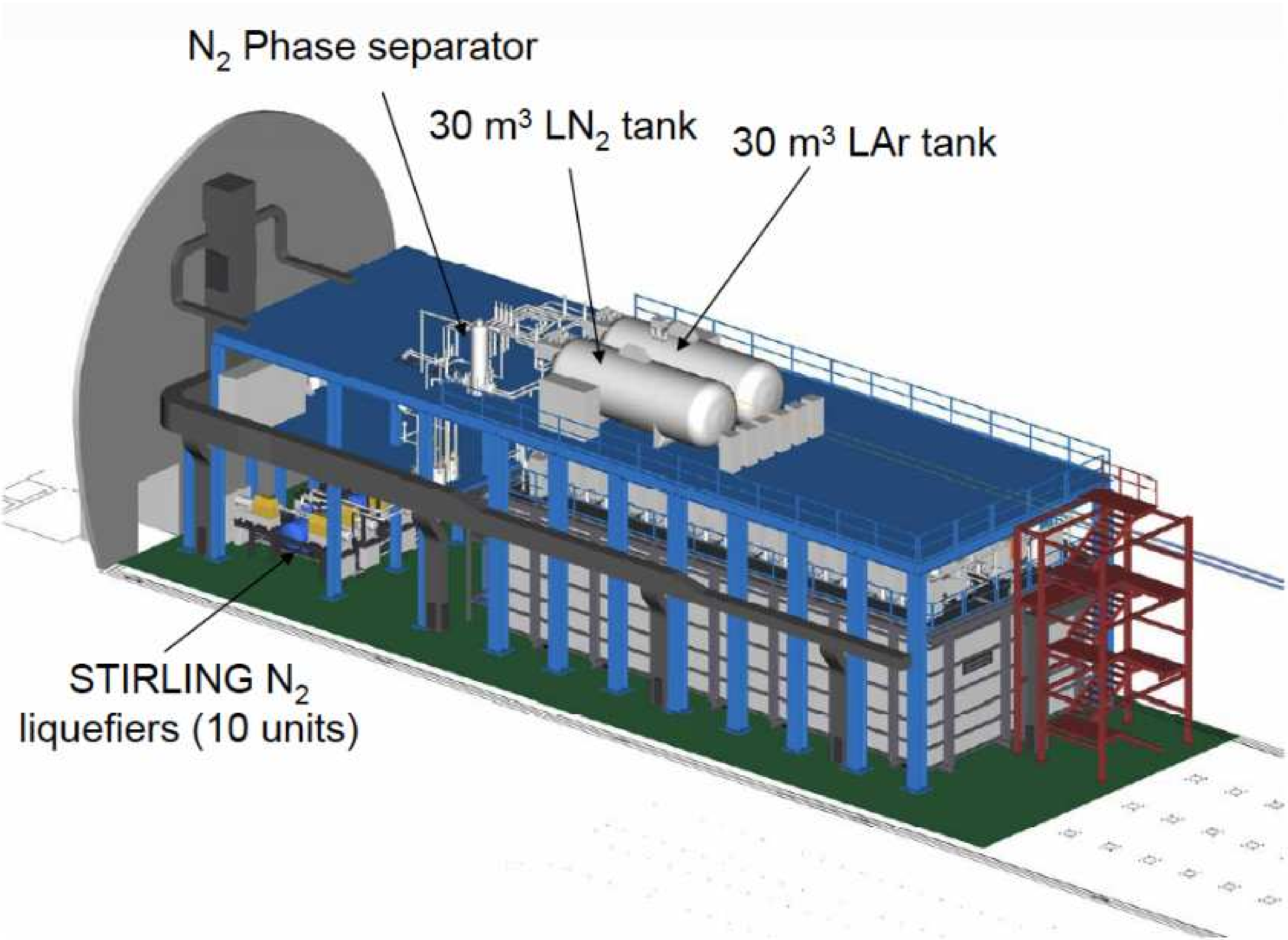
- *2 cryostats,* $3.9 \times 4.3 \times 19.6$ *m*^{3} *each cointaining 735 ton LAr (476 ton fiducial).*
- *4 TPC's, 2 central cathodes, 1.5 m max drift*
- *3 wire plains, Induction1, Induction 2 and Collection, for 3D event reconstruction, 3 mm pitch: 54372 stainless steel wires,* $\phi = 150\mu$*m*
- *0.5 kV/cm drift electric field,* $v_{drift} = 1.56$ *mm/s*
- $54 + 20\ 8''$ *PMT's + TPB wavelenghtshifter to detect scintillation light*
- *plus: purity monitors, LAr level sensor, test-pulse ...*



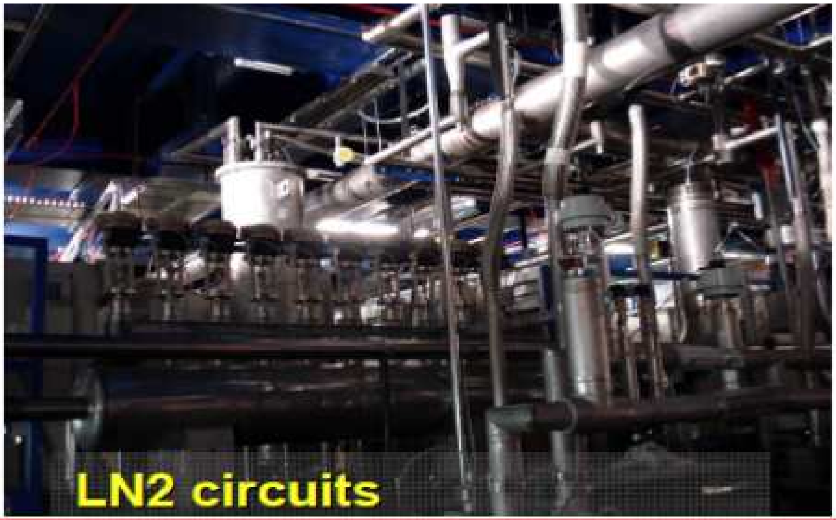
the ICARUS-T600 layout

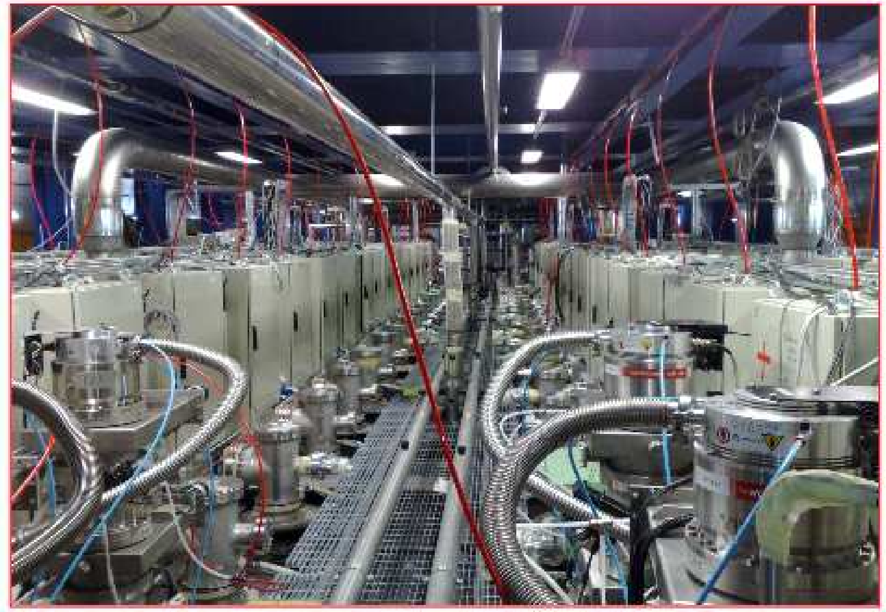


the over-all physical plant



T600 in hall B (CNGS2-2010)





Summary of LAr TPC performance

- *tracking device*
  - *precise event topology*
  - μ *momentum via multiple scattering*
- *measurement of local energy deposition dE/dx*
  - e/γ *separation (*$2\%X_0$ *sampling)*
  - *particle ID by means of dE/dx vs range;* e/π^0*!!!*
- *total energy reconstruction of the events from charge integration*
  - *full sampling, homogeneous calorimeter with excellent accuracy for contained events*
  - *triggering on the TPC wire signals: select, localize and measure low energy single events down to 1 eV!*

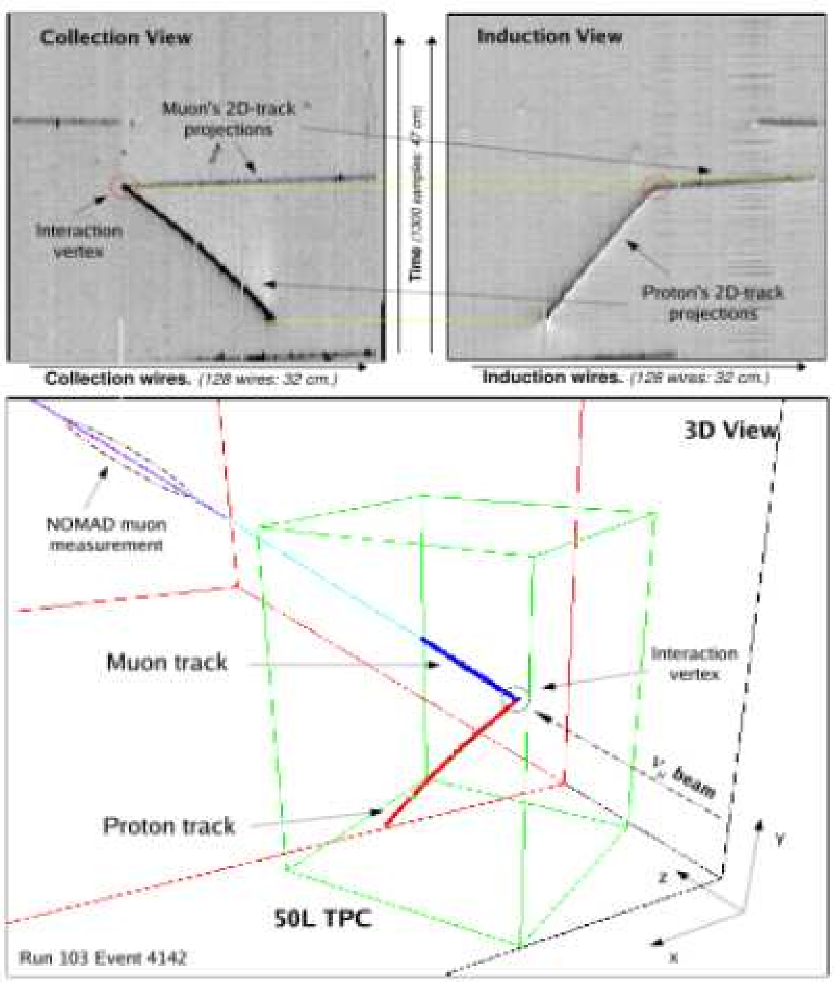
resolutions

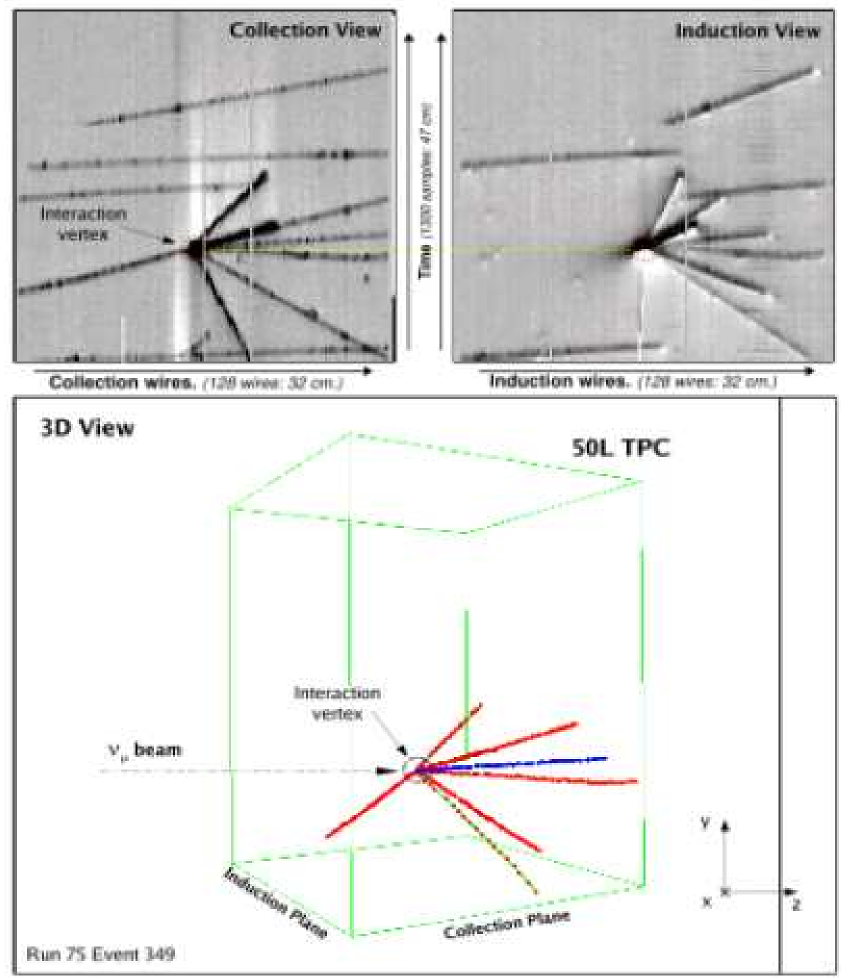
Low energy electrons: $\sigma(E)/E = 11\%/\sqrt(E(MeV)) + 2\%$

Electromagn. showers: $\sigma(E)/E = 3\%/\sqrt(E(GeV)) + 1\%$

Hadron shower (pure LAr): $\sigma(E)/E = 30\%/\sqrt(E(GeV))$

Quasi-elastic neutrino interactions at CERN

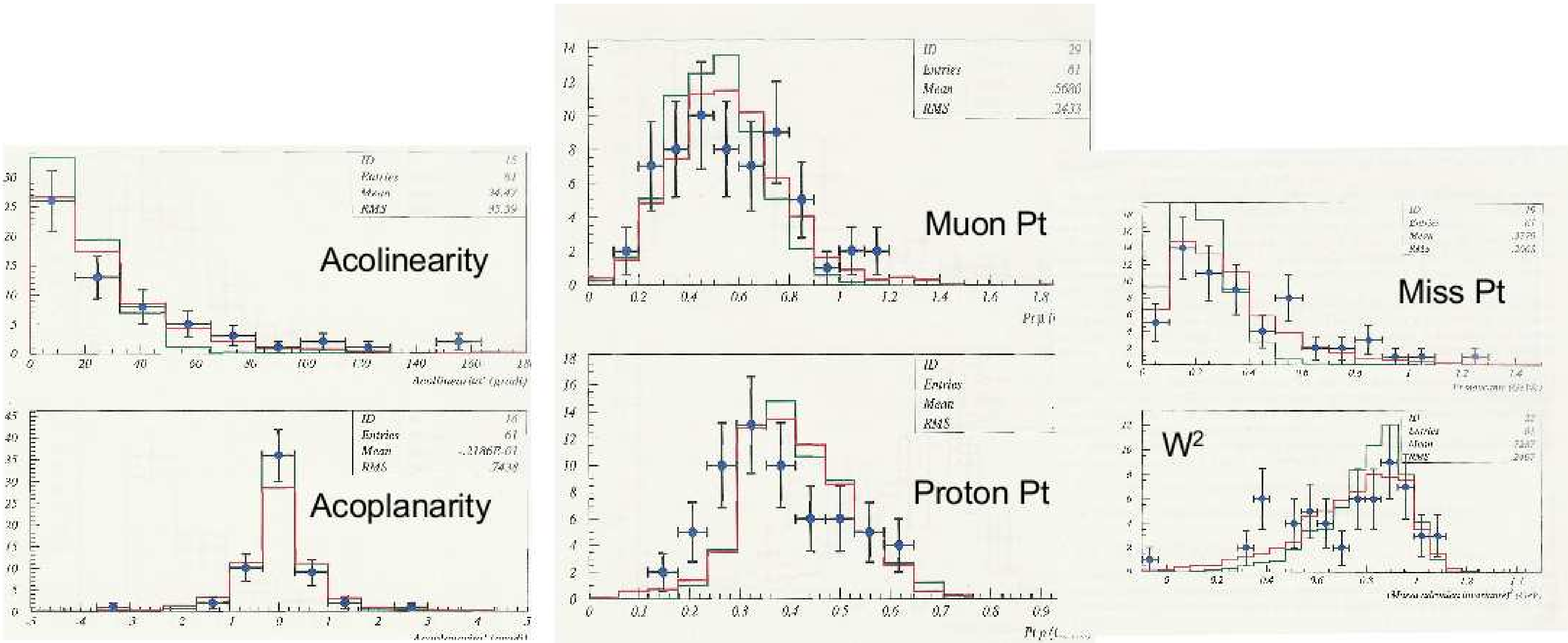




50 liter exposed to CERN WANF (NOMAD as muon spctrometer):

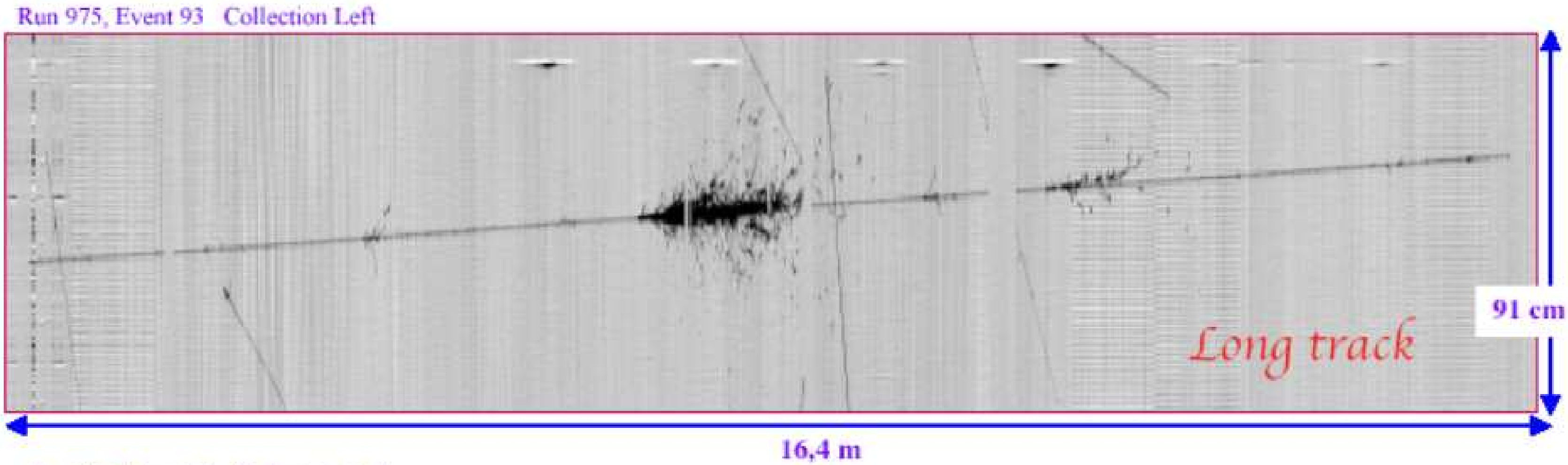
full 3D kinematics reconstruction, particle id, momentum balance, π^0 rejection

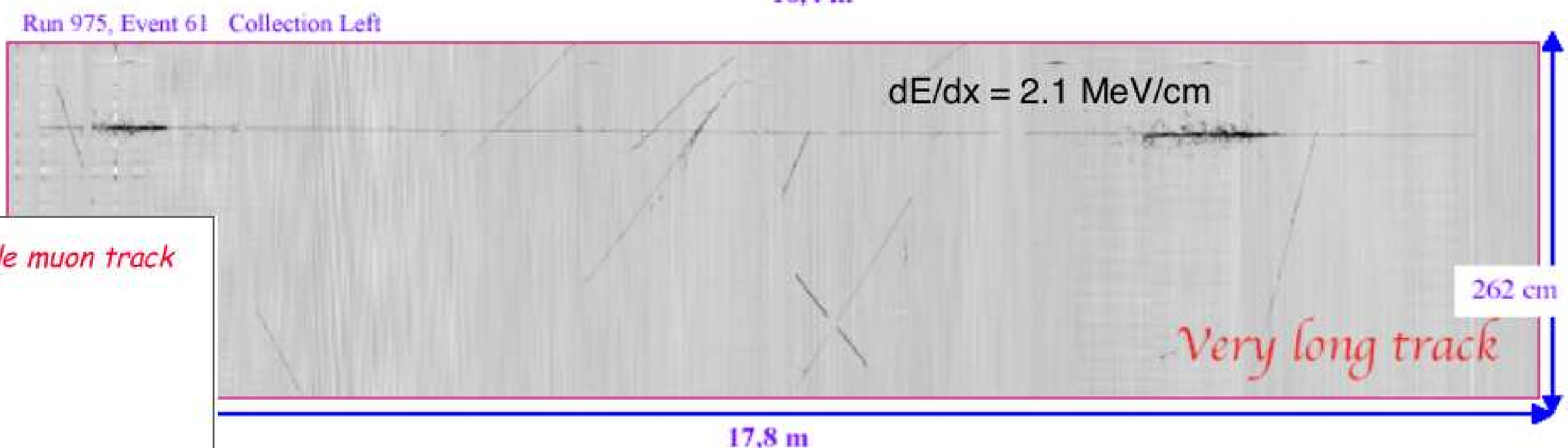
Selection of ~ 200 pure lepton-proton final sate with exactly one proton $T_p > 50$ MeV (range > 2 cm) and any number of protons $T_p < 50$ MeV

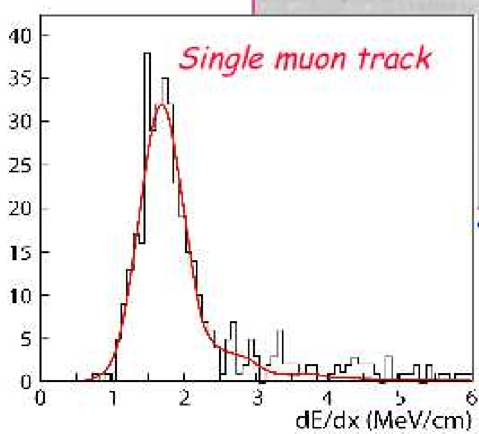


Good agreement with FLUKA expectations (Red line), accounting for Nuclear Fermi motion and re-interactions in nuclei.

a long muon track

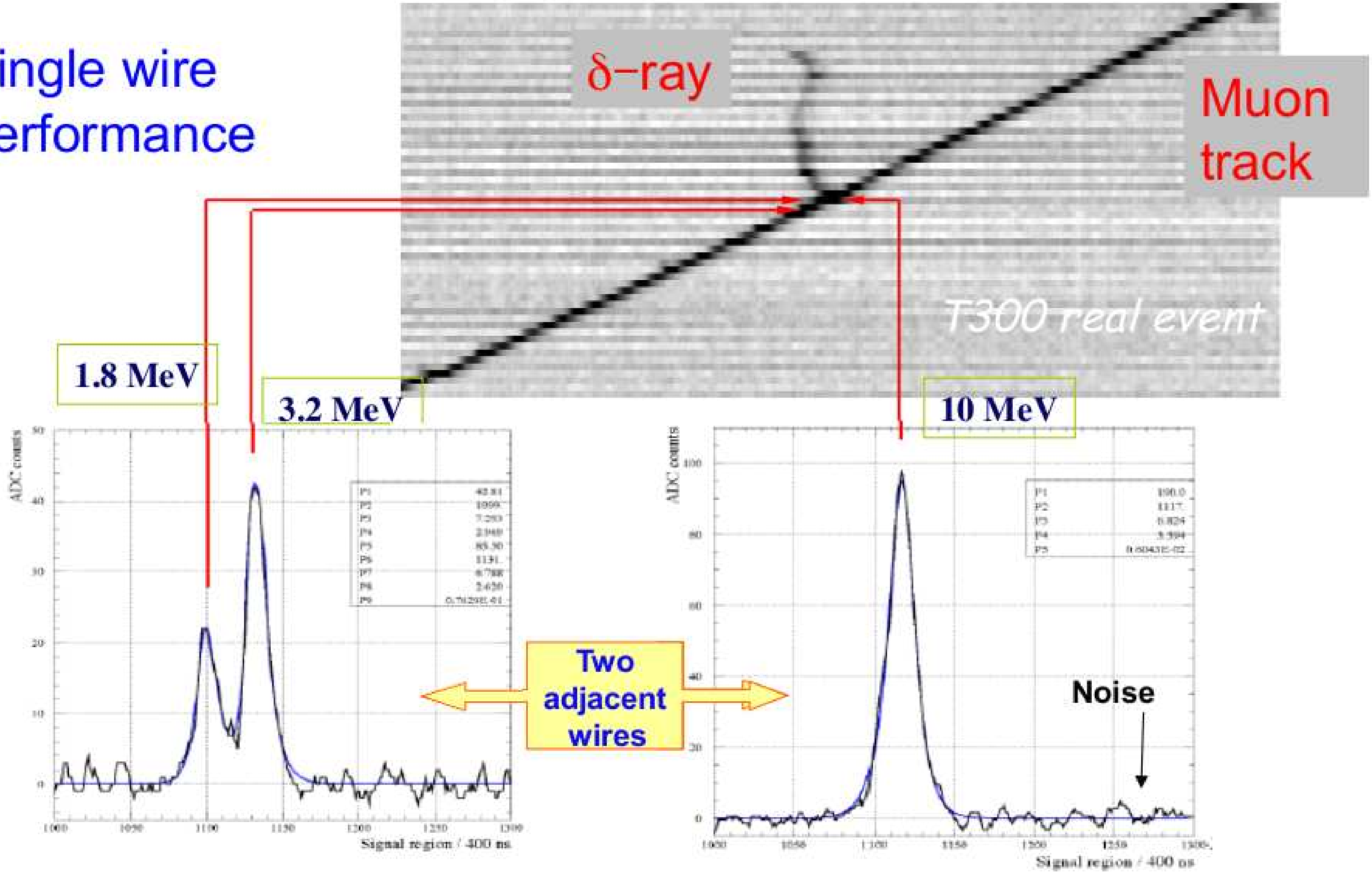






3D Low energy detail

Single wire performance



Muon momentum measurement with multiple scattering

In case of non-contained events

Multiple Scattering is the key tool to measure

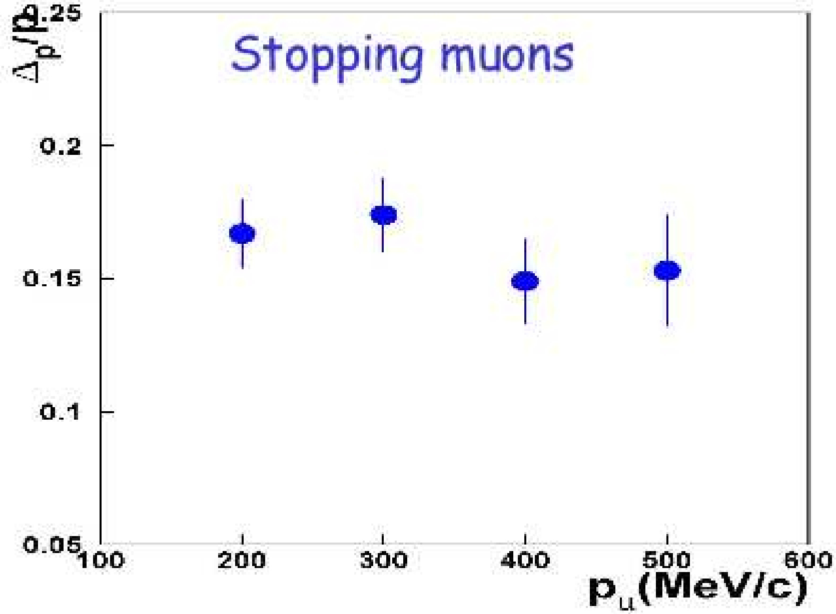
μ momentum - essential for atmospheric and CNGS ν

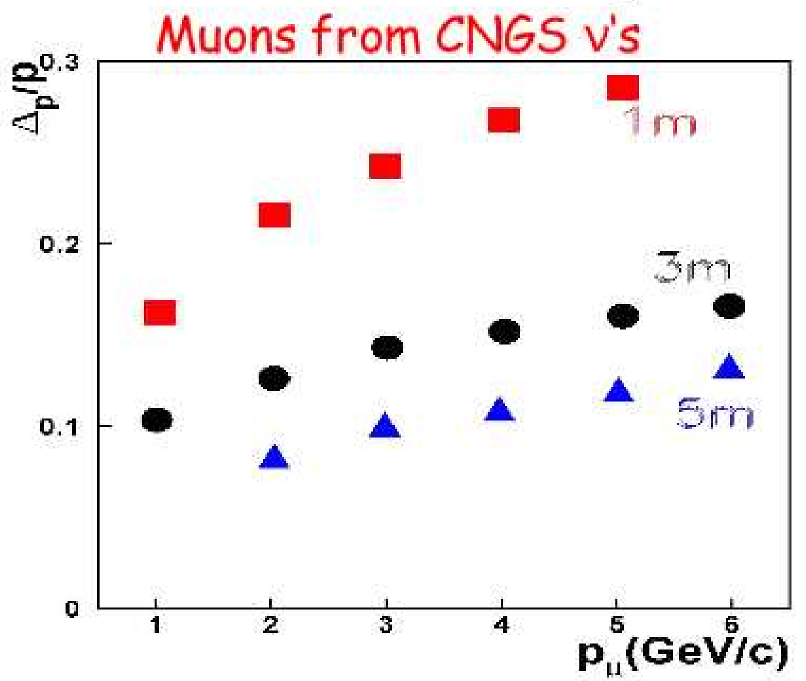
- *Kalman filter method applied to segmented tracks (L_{seg}: segment length)*
- *Momentum p extracted from measurement of deflection angle θ and from χ^2 of the fit*

Deflection angle contributions:

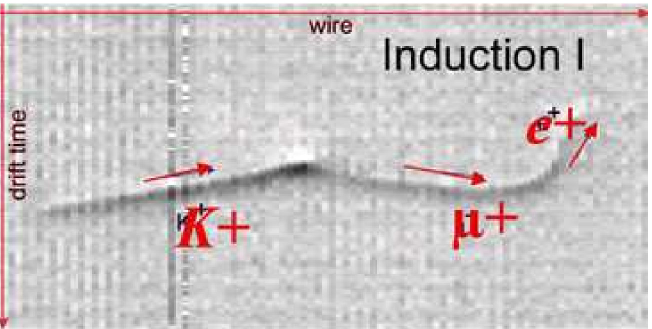
$$\begin{cases} \theta_{MS} \propto \sqrt{L_{seg}/p} & \leftarrow \text{MS angle} \\ \theta_{det} \propto L_{seg}^{-3/2} & \leftarrow \text{detector resolution} \end{cases}$$

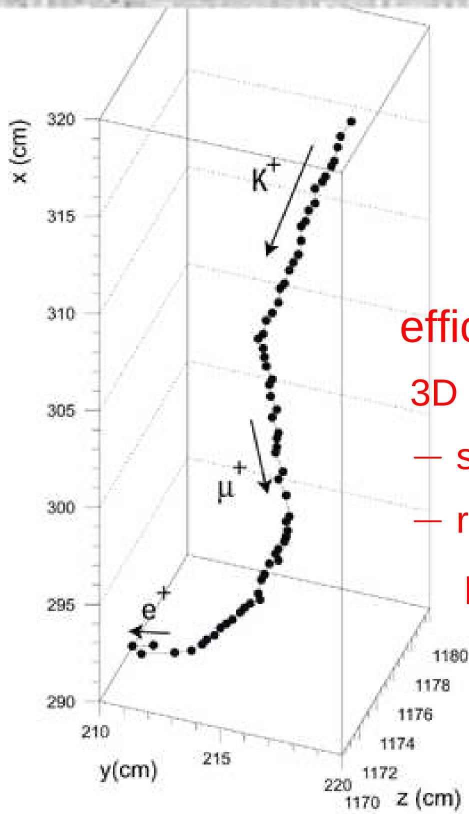
- *procedure validated on cosmic ray data (stopping μs) - extended to higher energy with MC calculations*
- *Resolution $\Delta p/p$ depends mainly on track length : on μs from CNGS νs $\Delta p/p \sim 16$ %*

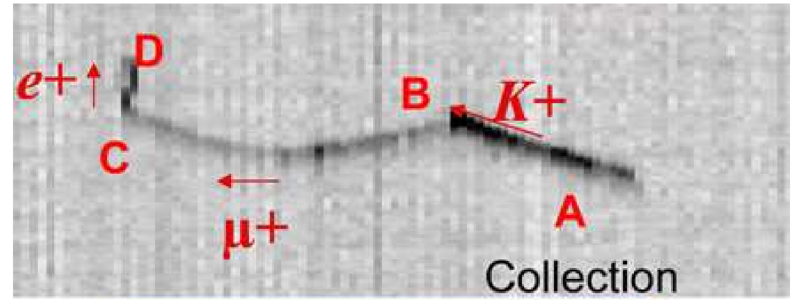




Particle IDentification: $K^+ \to \mu^+ \to e^+, \pi/P$







$K^+[AB] \to \mu^+[BC] \to e^+[CD]$

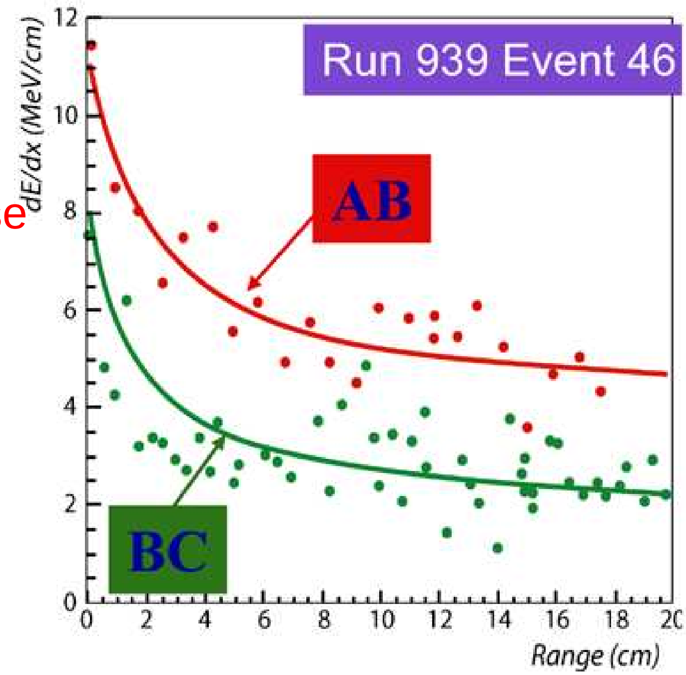
efficient particle identification by a precise

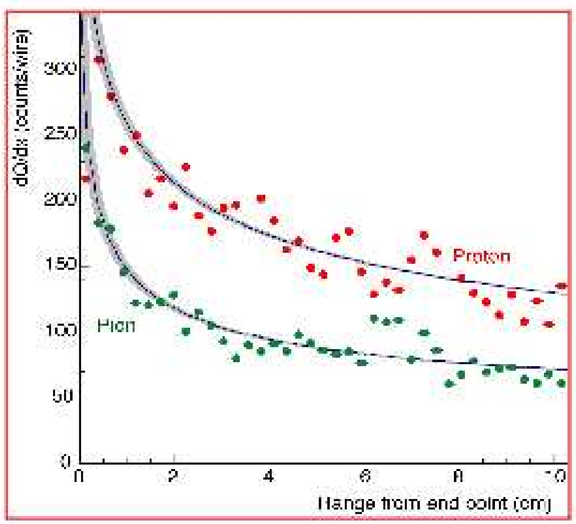
3D reconstruction, dE/dx, range:

— stopping power

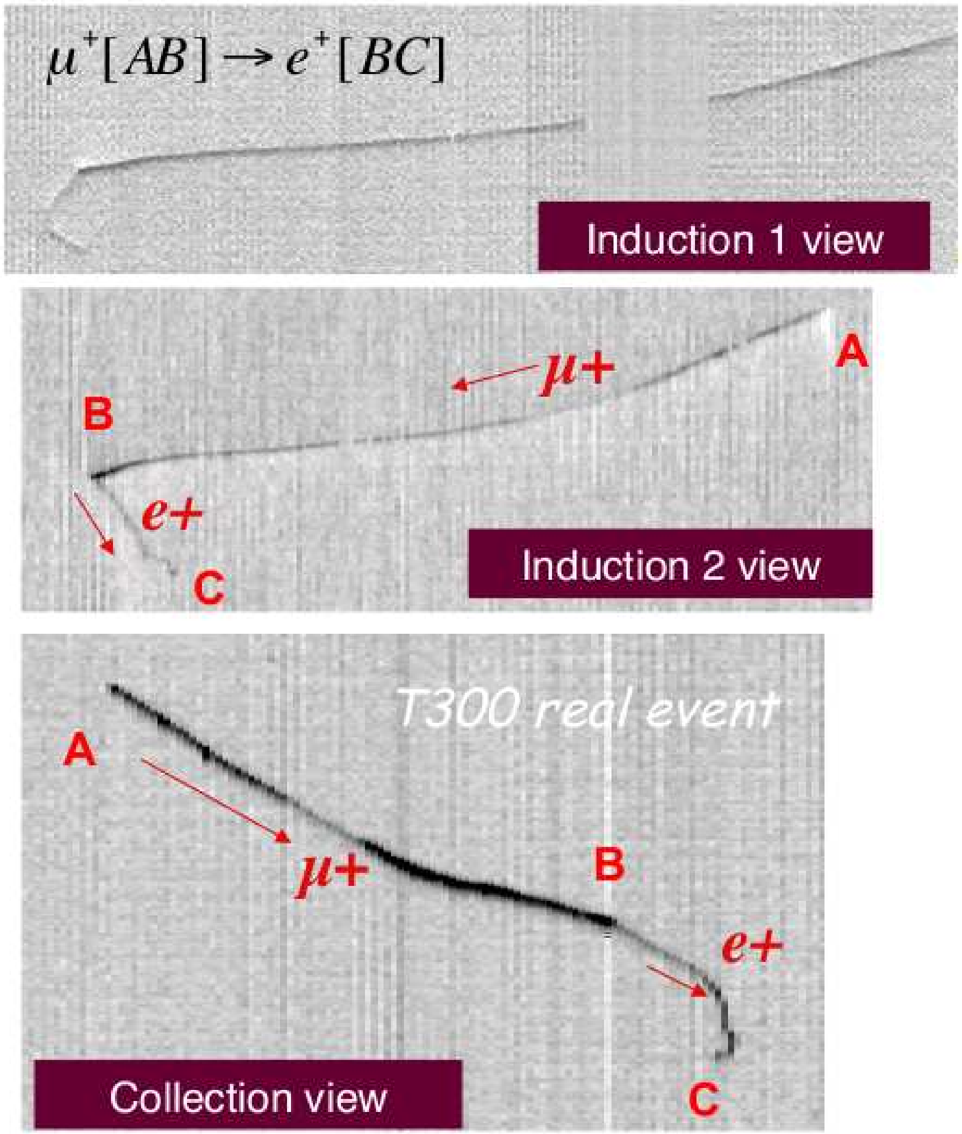
— recognition of secondary particle

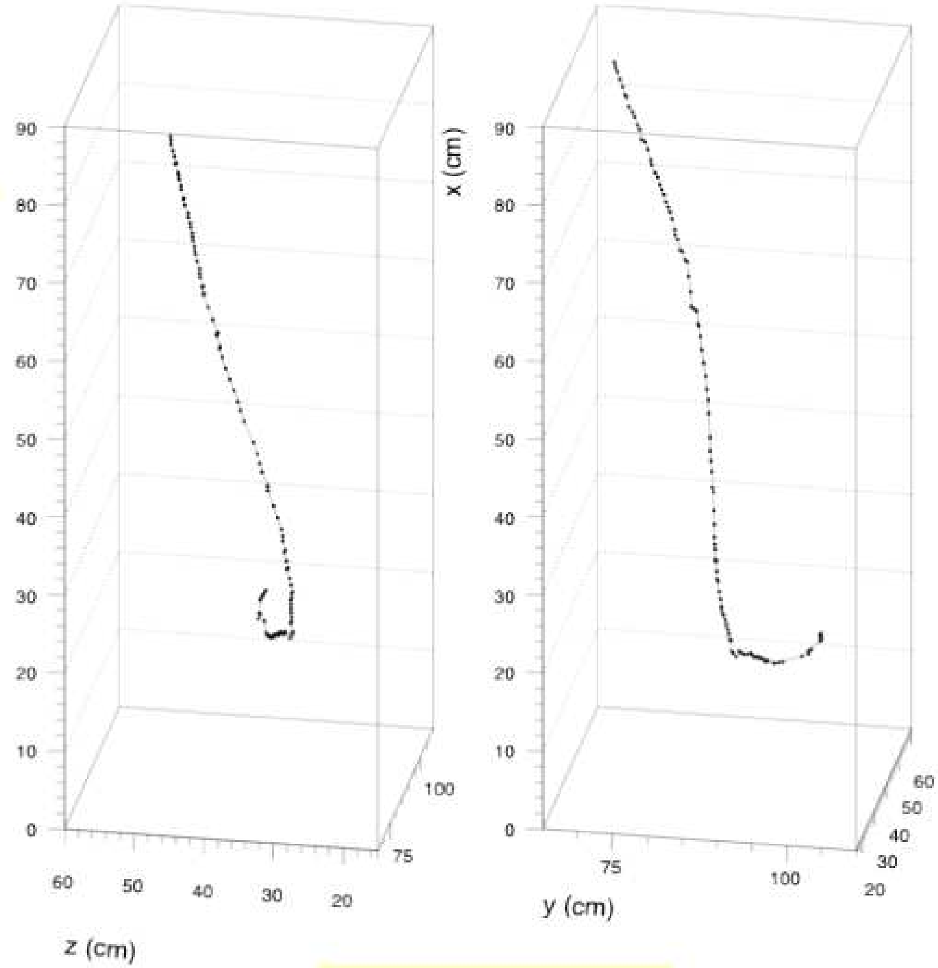
production after decay/interaction





3D reconstruction (stopping μ)

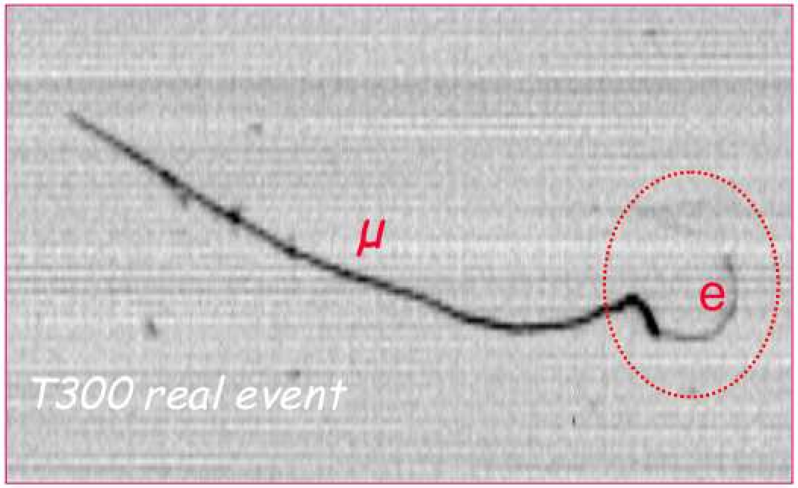


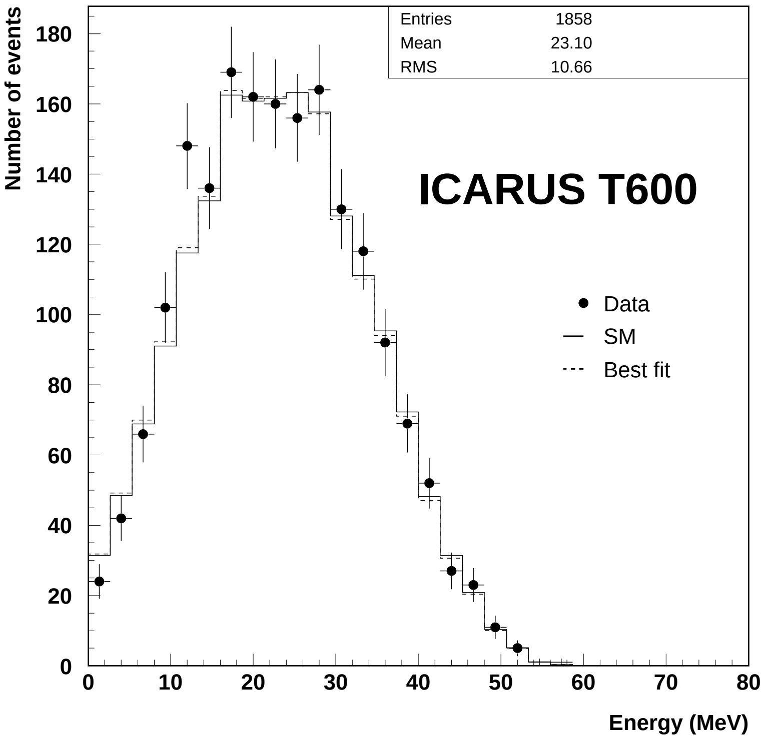


T_e=36.2 MeV
Range=15.4 cm

Energy resolution from μ-decays

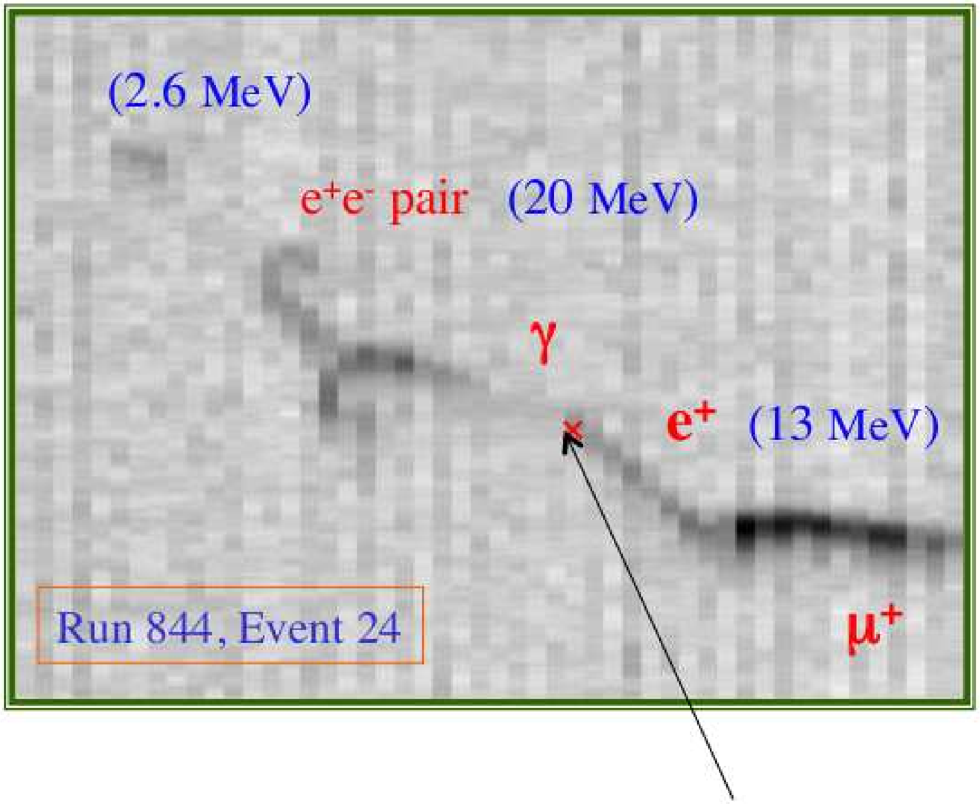
Michel electrons ($\nu - e$ decays)



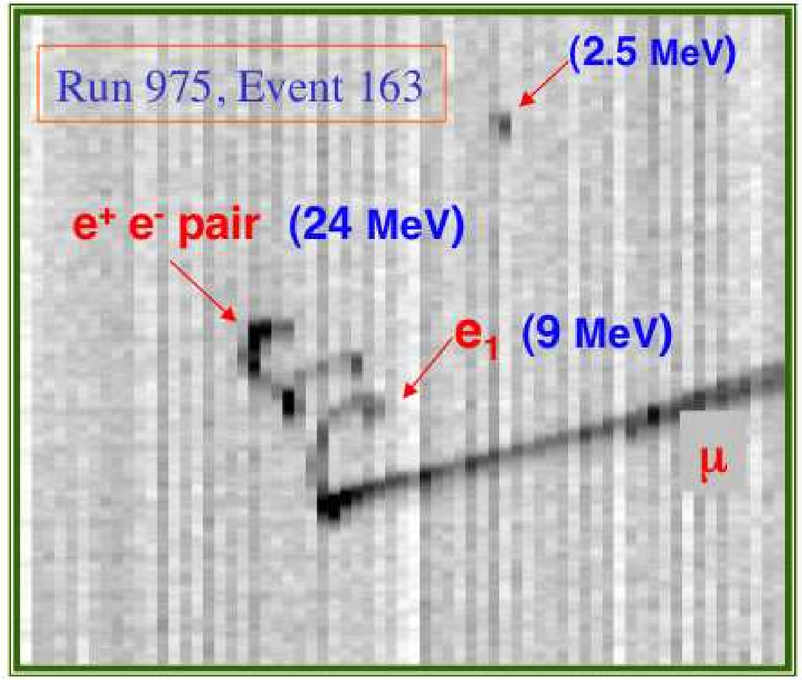


Energy resolution: $\frac{\sigma}{E} = \frac{(13 \pm 2)\%}{\sqrt{E(MeV}} + (1.8 \pm 0.3)\%$

3D Bremsstrahlung + Pair-production

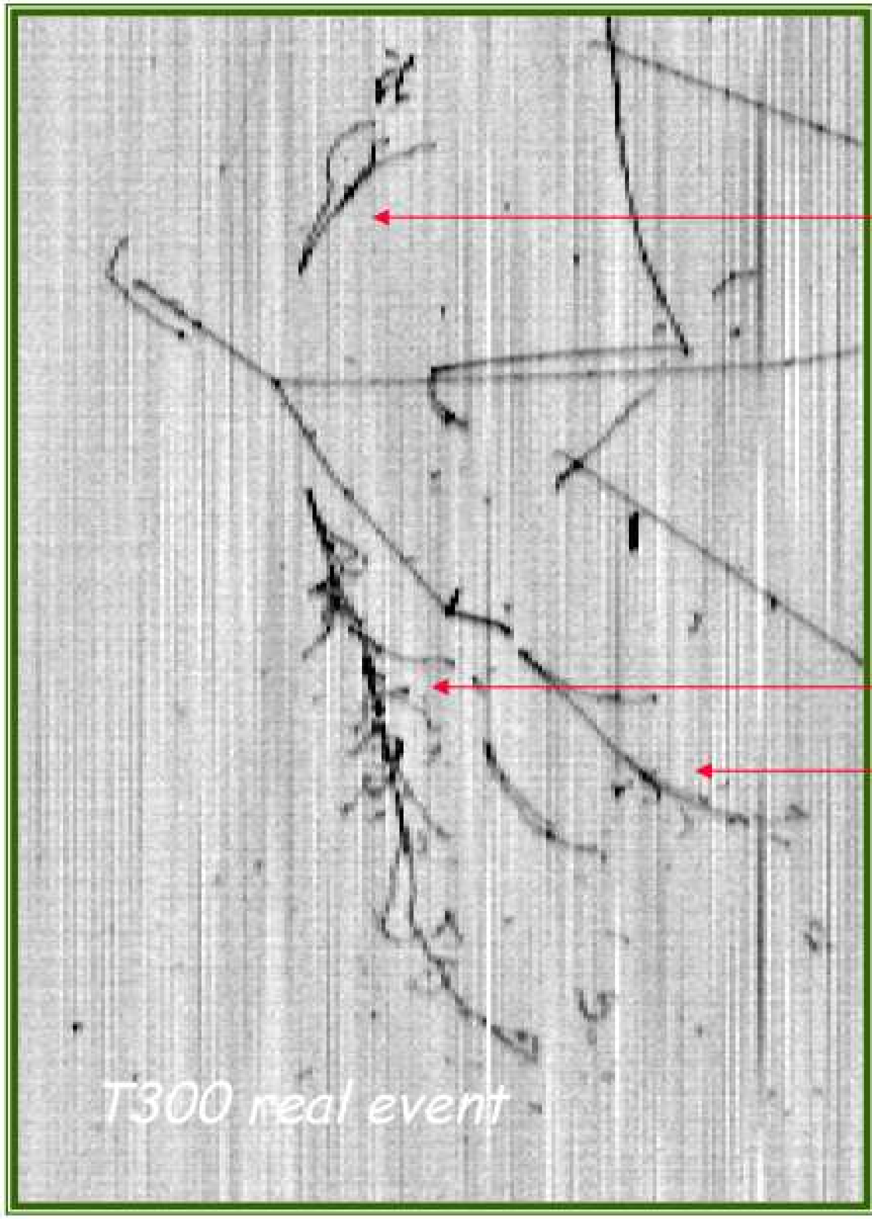


Annihilation point



≈20% of positron from μ decays expected to annihilate before stopping

3D Pi-zero identification and reconstruction



$$M_{inv} = \sqrt{2E_1E_2\cos(\theta_{12})}$$

158 MeV

$\theta = 141^{\circ}$

$M_{inv} = 650$ MeV

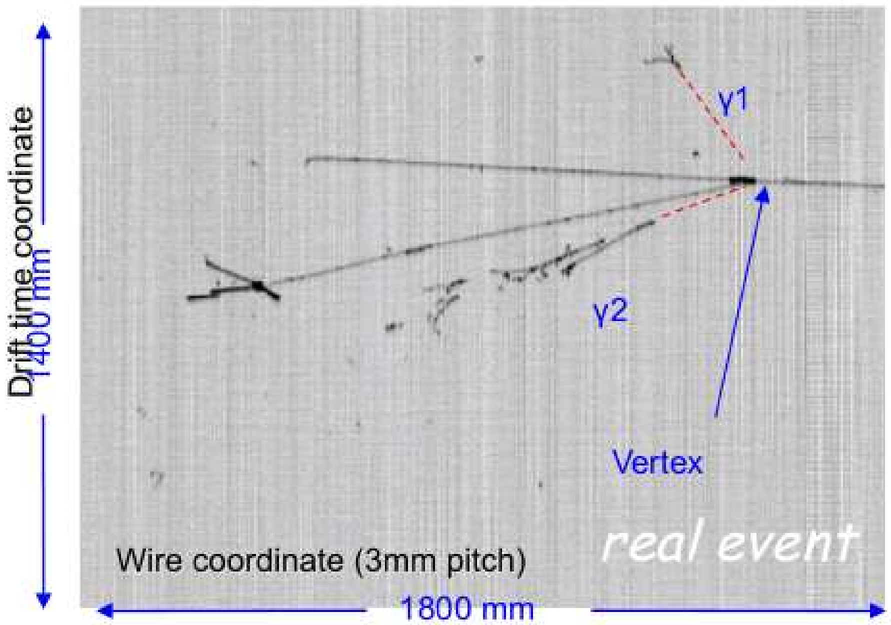
752 MeV

140 MeV

$\theta = 25^{\circ}$

$M_{inv} = 140$ MeV

230 hadronic interactions with $\pi^0 \to \gamma\,\gamma$ candidates have been selected from ICARUS T300 Pavia run



The average (γ,γ) invariant mass is in agreement with the π^0 mass hypothesis (m_{π^0} = 135 MeV/c^2);

$$m_{\gamma\gamma} = 133.4 \pm 3.0(stat) \pm 4.0(sys)\mathrm{MeV/c^2}$$

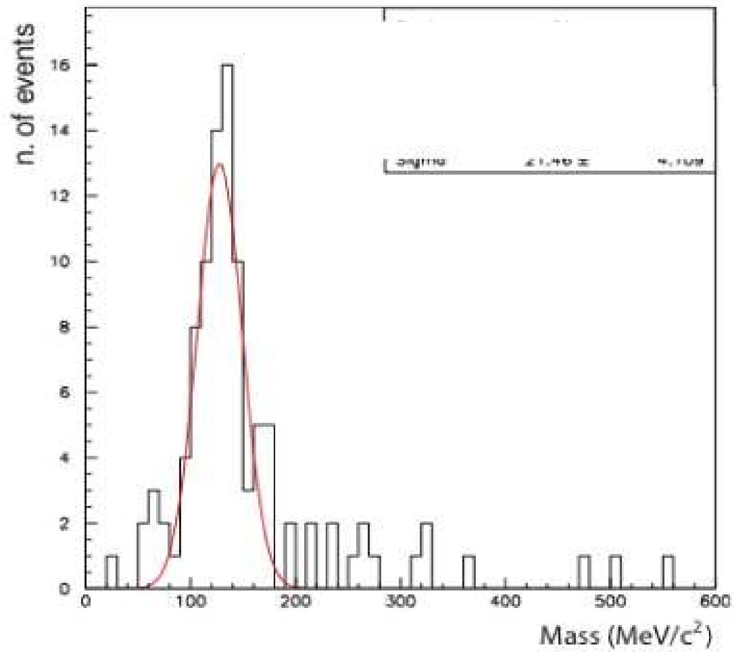
The systematic error is mostly due to calibration

The measured photon radiation length is

$$X_{\gamma,meas} = (17.4 \pm 0.8)\mathrm{cm}$$

in agreement with expectations:

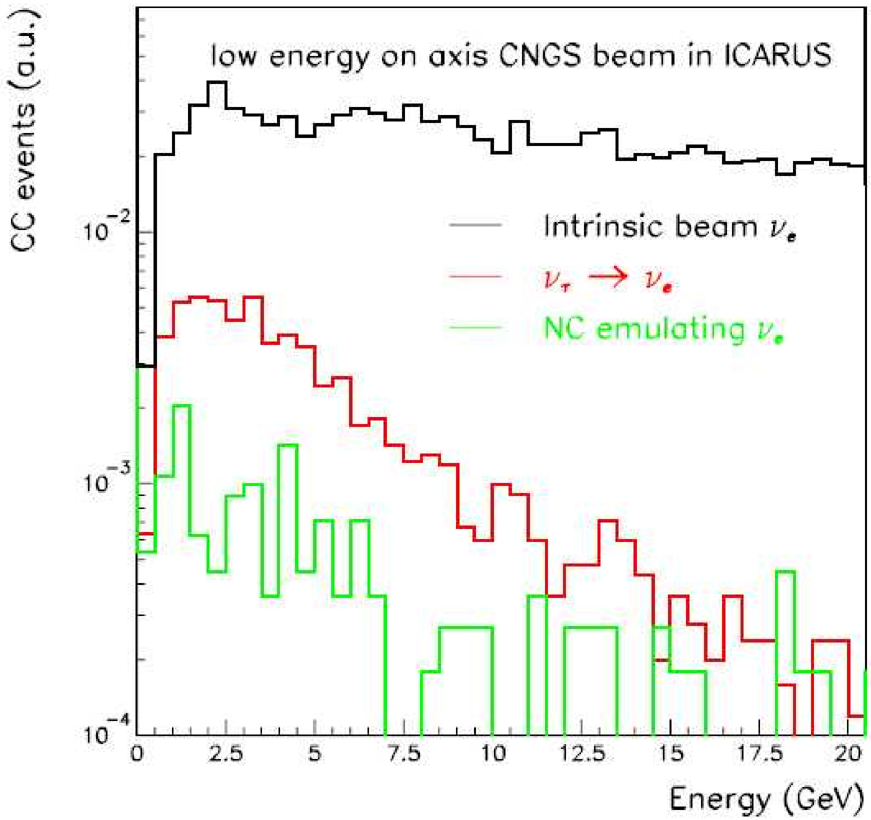
$$X_{\gamma,\exp} = \frac{9}{7} \cdot 14\mathrm{cm} = 18\mathrm{cm}$$

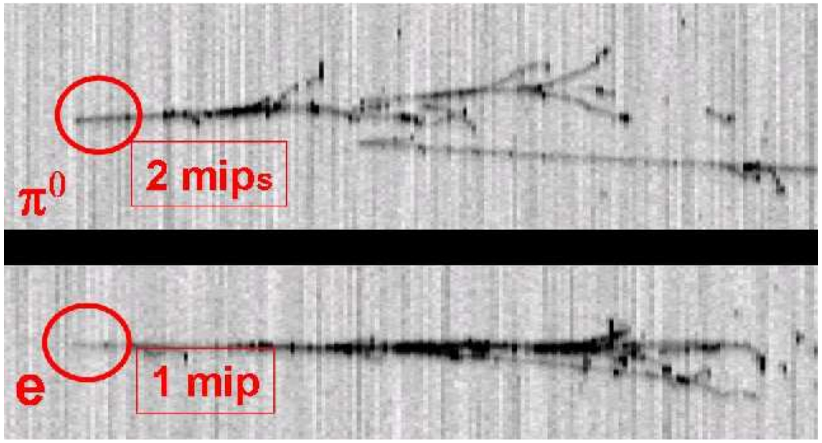


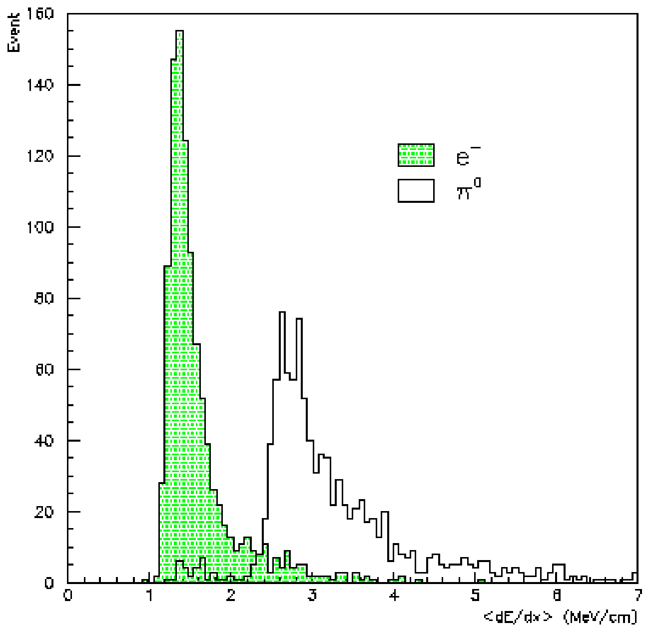
Electron - π^0 separation

NC π^0 background in LAr suppressed by:

- *topology (γ conversion from vertex)*
- *reconstruction of π^0 mass*
- *electron/photon separation (dE/dx)*



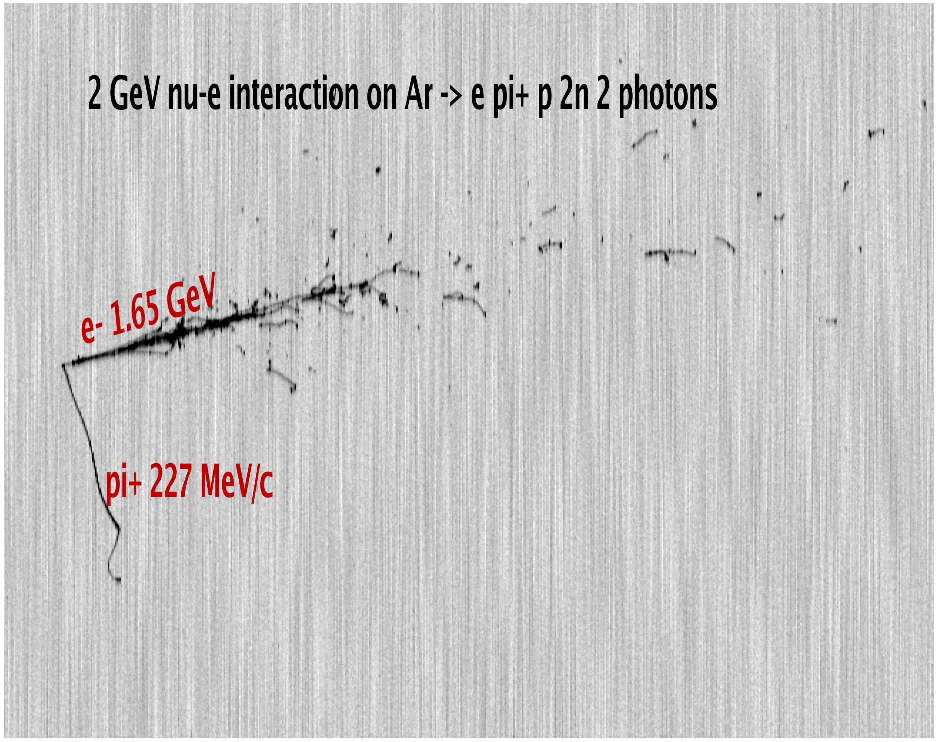


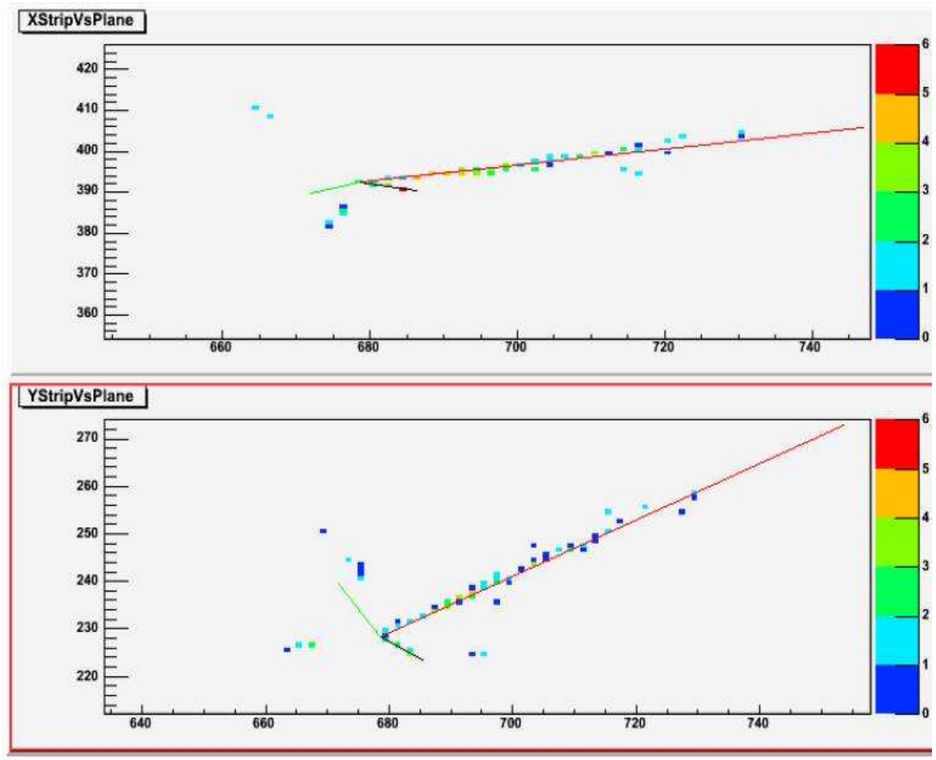


Electron identification eff. $= 90$ %
Residual misidentification < 0.1 %

much higher discovery potential of LAr than L-Scint./W-Cherenkov detectors:
5 kton LAr detector ~ 20 kton of L-Scint!

LAr-TPC: a detector for ν_e interactions!





: An accepted ν_e charged-current event : $\nu_e A \rightarrow p e \pi^0$, E_ν = 1.65 GeV. See text for explan

key of $\nu_\mu \longrightarrow \nu_e$ event observation: LAr-TPC imaging capability ($1\% X_0$ sampling!)

moreover: ν_e detection in L-Scint/W-Cherenkov limited by π^0 NC background:

NOVA: ν_e detection eff. ~ 24 %, NC indistiguishable from ν_e in a sizeable fraction of events
$\longrightarrow$ increase of backg by $\sim$ 50 % w.r.t. ν_e intrinsic beam contamination!

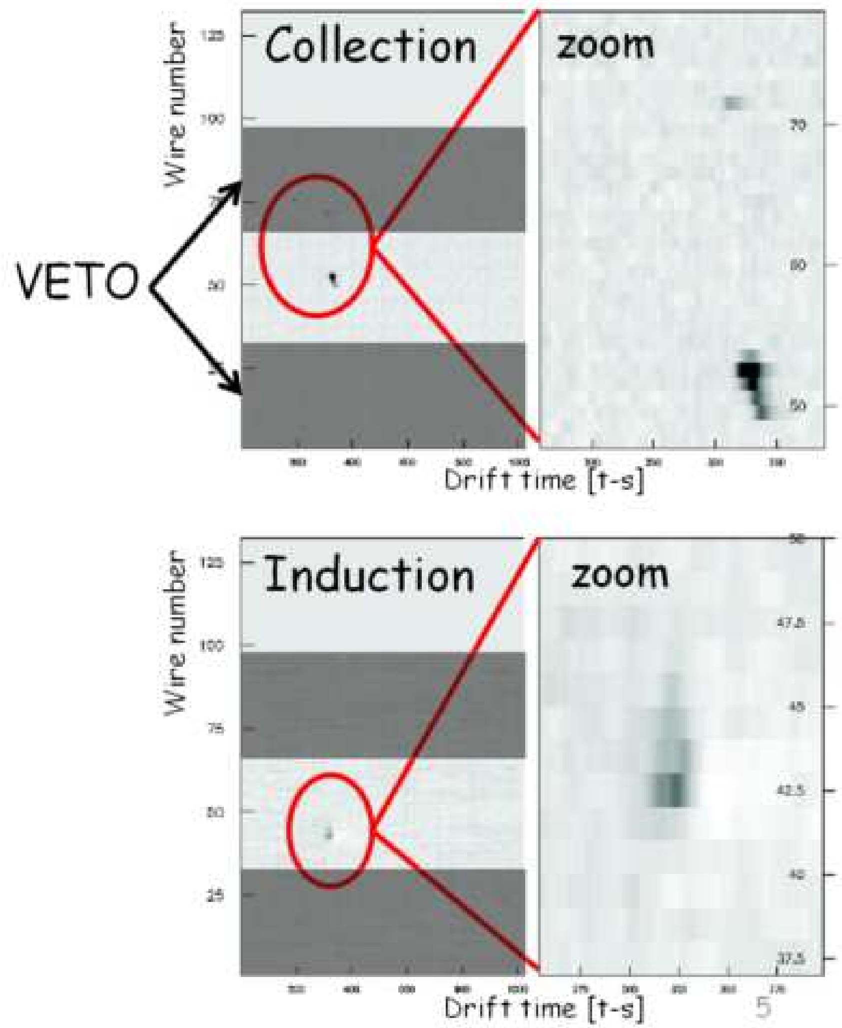
much higher discovery potential of LAr than L-Scint./W-Cherenkov detectors:
5 kton LAr detector ~ 20 kton of L-Scint!

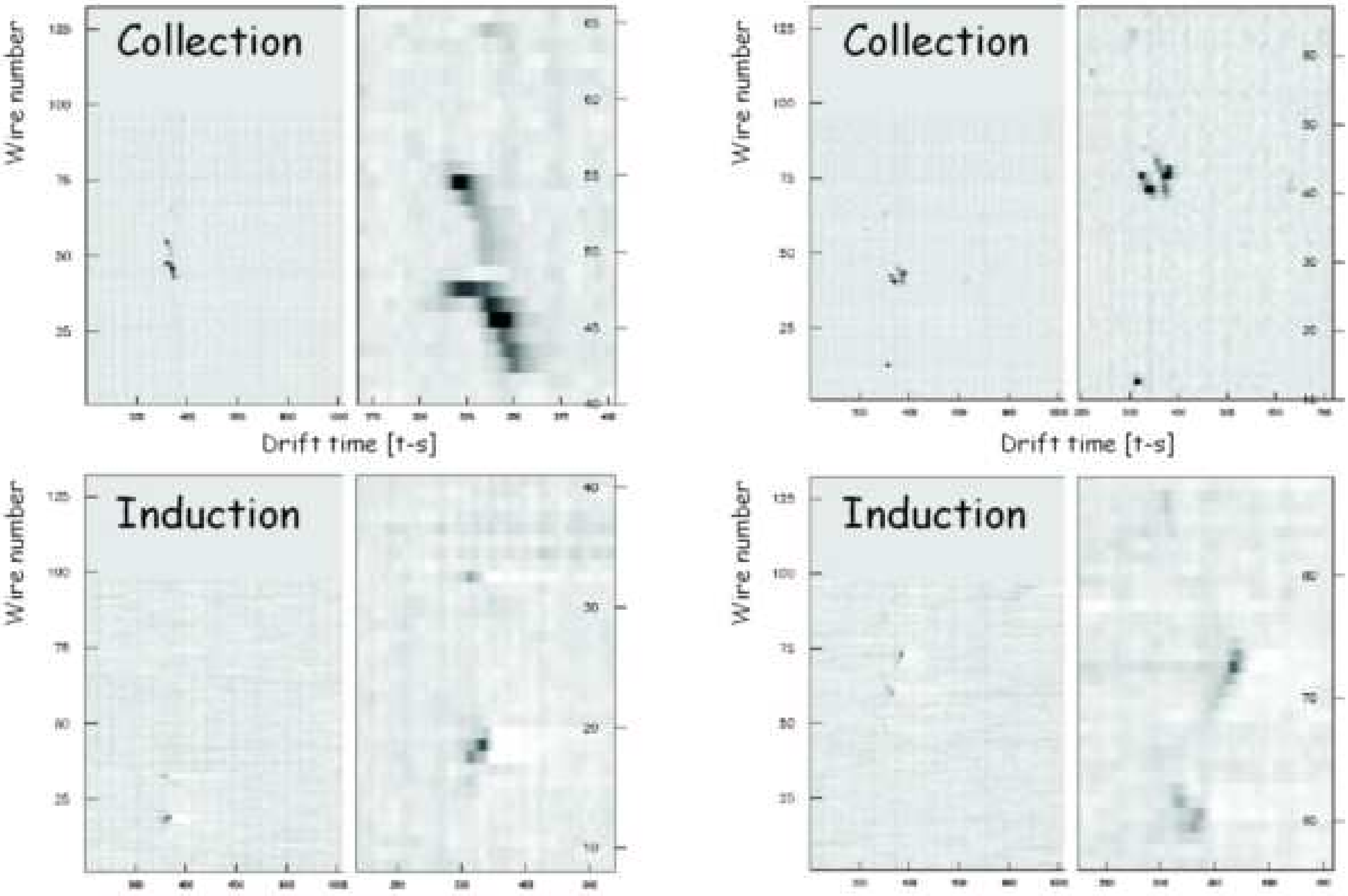
triggering "low energy events"

- *ICARUS-T600 is a self-triggering detector exploiting both scintillation light and TPC wire signal*
- *wire signals used to trigger/select isolated low energy events (solar ν, SN ν), atmospheric ν and p-decay. A dedicated real-time algorithm, a "Double Rebinning" filtering the wire signals, was implemented on read-out boards via FPGA technique and succefully tested in ICARINO test-facility at LNL.*

- *Majority level in single board, view: few hitted adjacent wire over 16*
- *the resulting trigger granularity: a half board ~ 5 cm*
- *event isolation requirement: the surrounding 32 wire boards vetoed.*

well suited also for very large LAr-TPC's

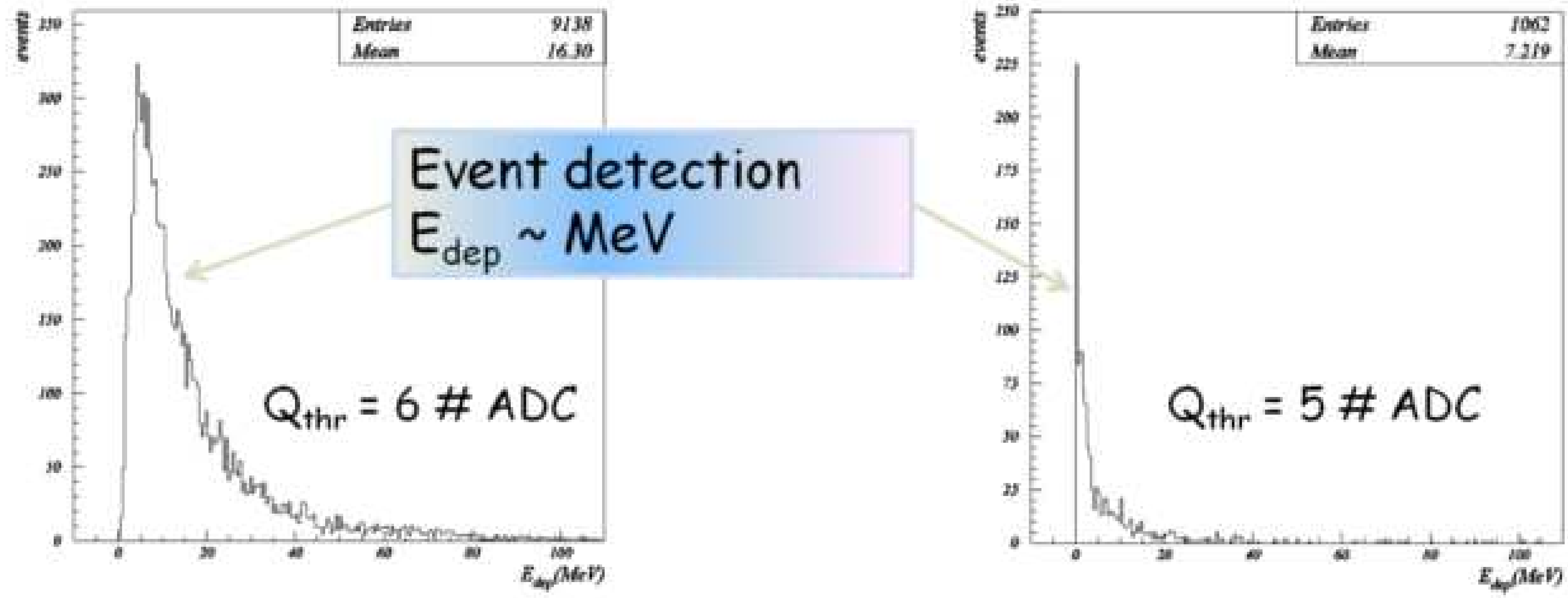



Collection
Wire number
Drift time [t-s]
Collection
Wire number
Drift time [t-s]
Induction
Wire number
Induction
Wire number

energy deposition on the single Collection wire: integral of charge vs time of the hit

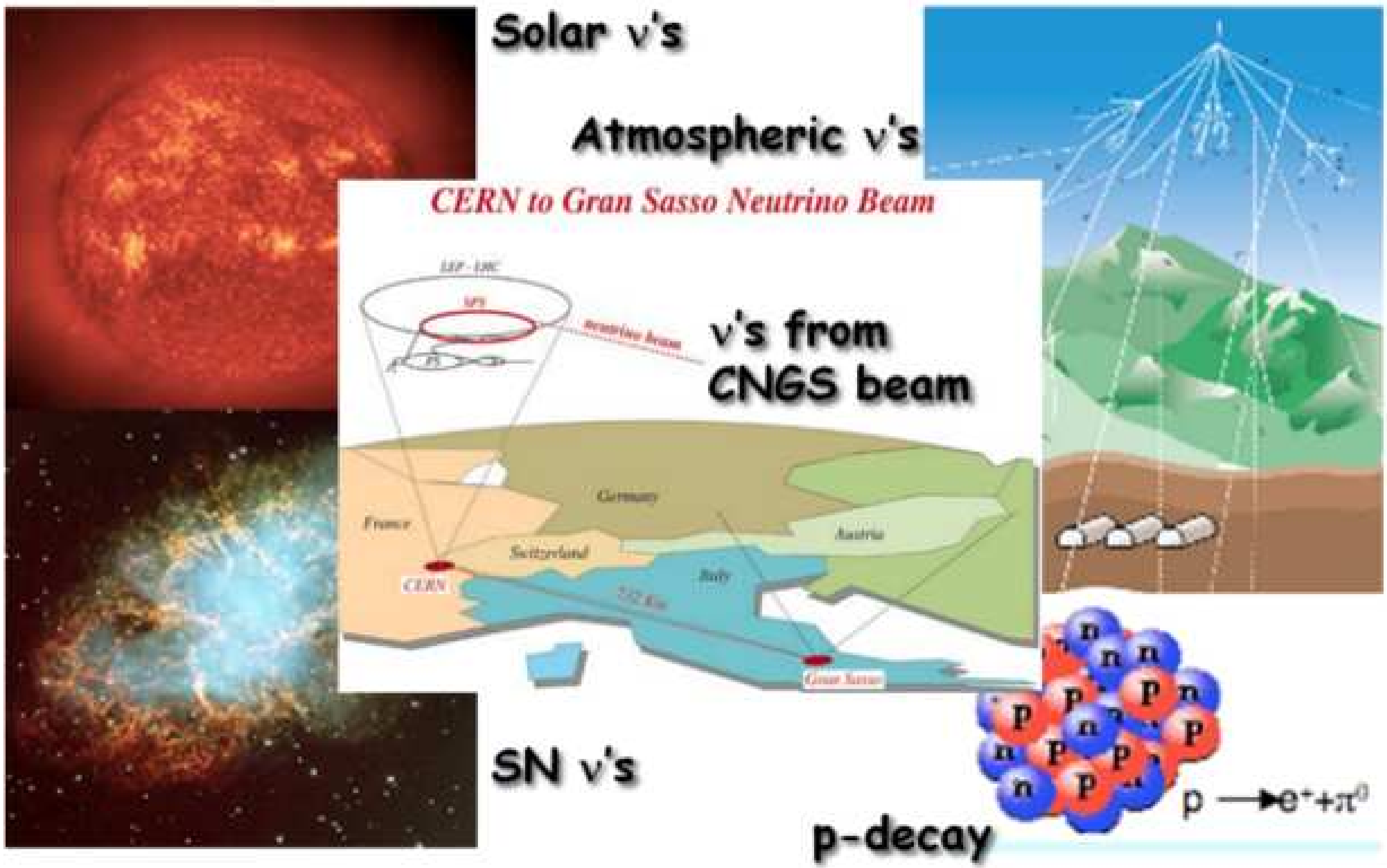
$$E_{dep} = \Sigma_i A_i \frac{C}{e} \frac{E_{ion}}{R}$$

$C = (1.39 \pm 1\%) \cdot 10^{-2}\ fC/(\#ADC \cdot t_s)$: *calibration factor of electronic chain*
$1 - R = 0.3$: *recombination factor,* $E_{ion} = 23.6$ *eV: ionization energy.*



ICARUS (CNGS2): the first large scale LAr experiment

- *a major milestone in the practical realization of a large scale LAr detector. Successfully operated on surface in Pavia in 2001, will soon operate underground in Hall B of LNGS.*
- *The ICARUS-T600 at LNGS will collect simultaneously "bubble chamber like" neutrino events events of different nature, investigating also the barion matter stability*



despite the "relatively small mass", the unique imaging capability $+$ optimal spatial/calorimetric resolution $+$ e/π^0 separation of ICARUS-T600 allow "to see" events in a new way, w.r.t. previuos/current experiments (SK, etc)

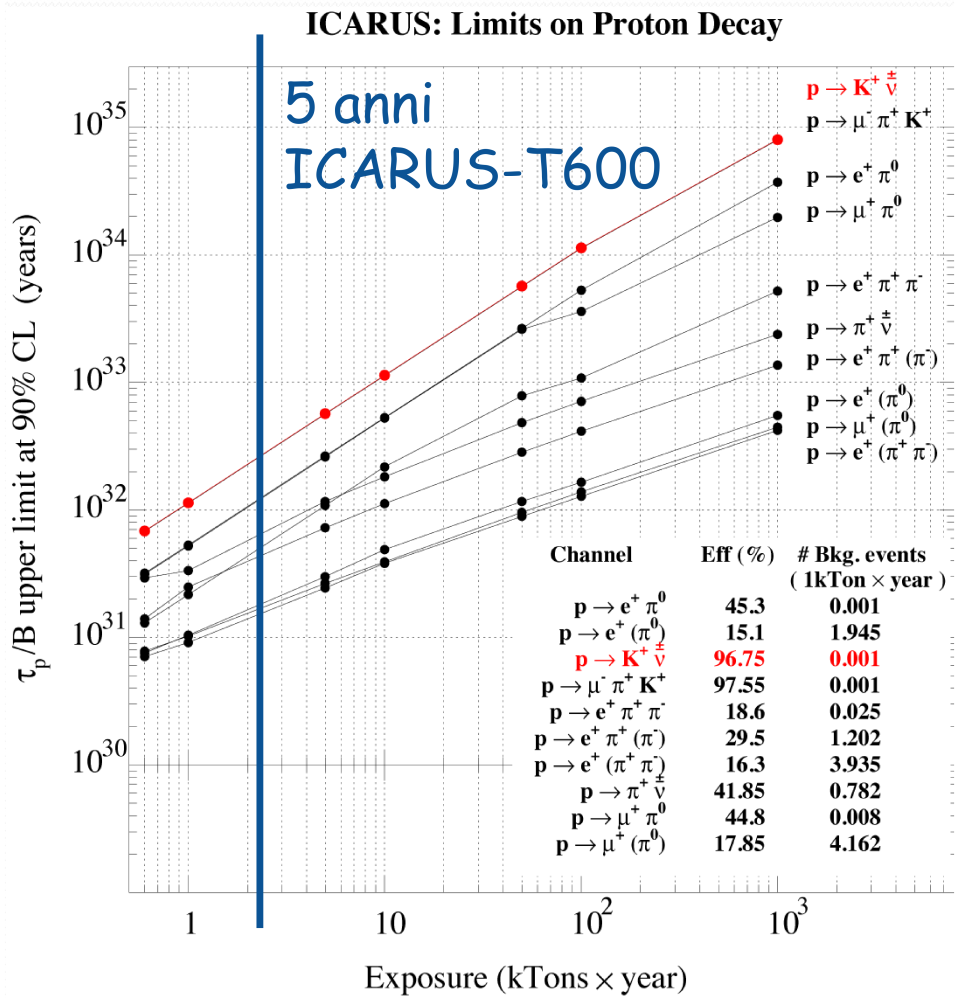
cosmic ray events

- *100 ev/year of unbiased atmospheric event neutrinos above 50 MeV: for $\Delta m^2_{23} = 2.5 \cdot 10^{-3}$ eV^2 83 CC events/y ($38\nu_e$, $45\nu_\mu$), and 16 in NC are expected;*
- *Solar neutrino electron rates $E_{vis} > 8$ MeV (NO n-shielding!) $\sim 1-2$ ev/day, ~ 23/y elastic scattering;*
- *Supernovae neutrinos (down to 10 MeV), exploring in coincidence with LVD at LNGS up to 50 Kpc of distance;*
- *unespected "rare phenomena".*

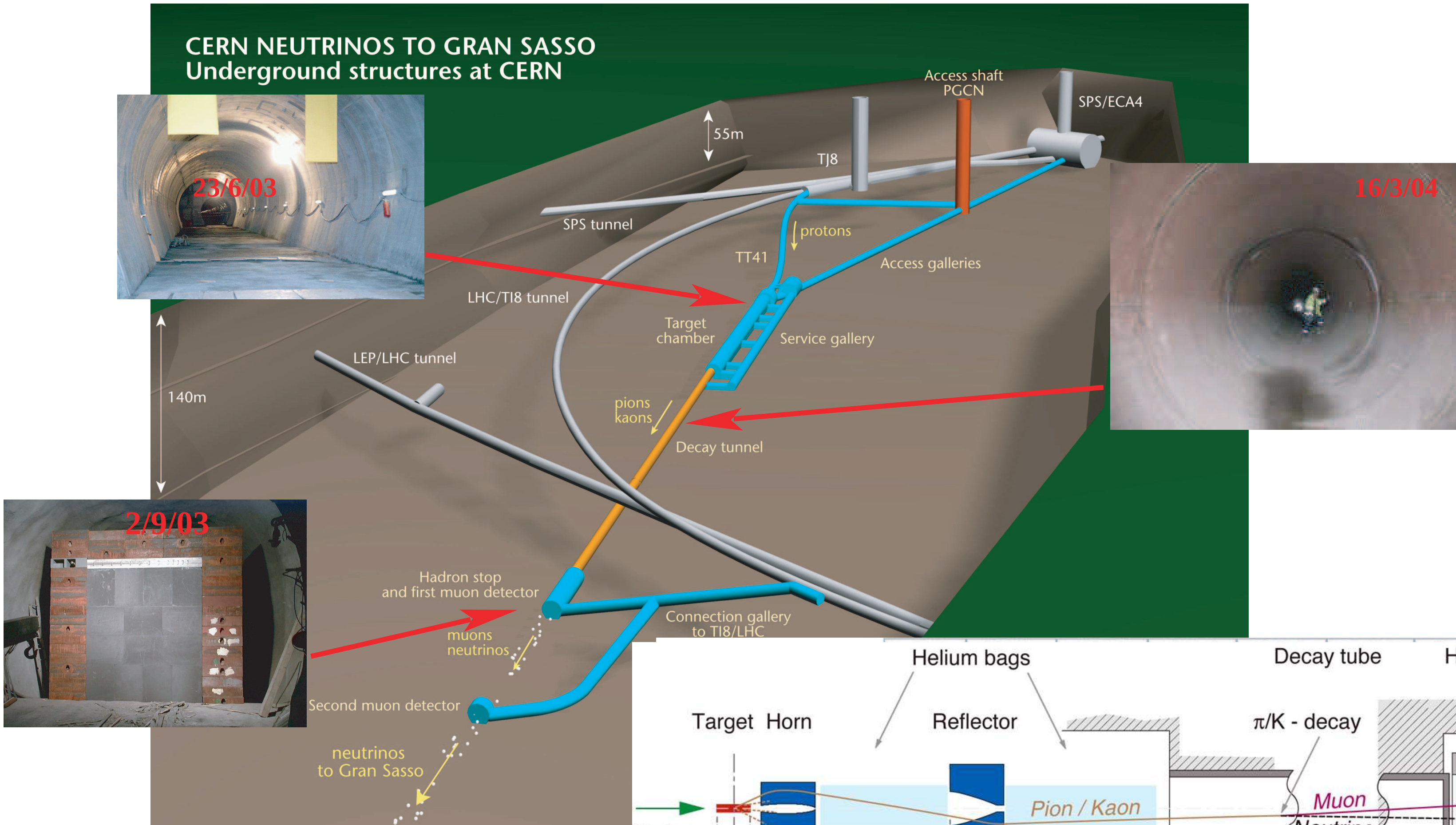
nucleon decay search

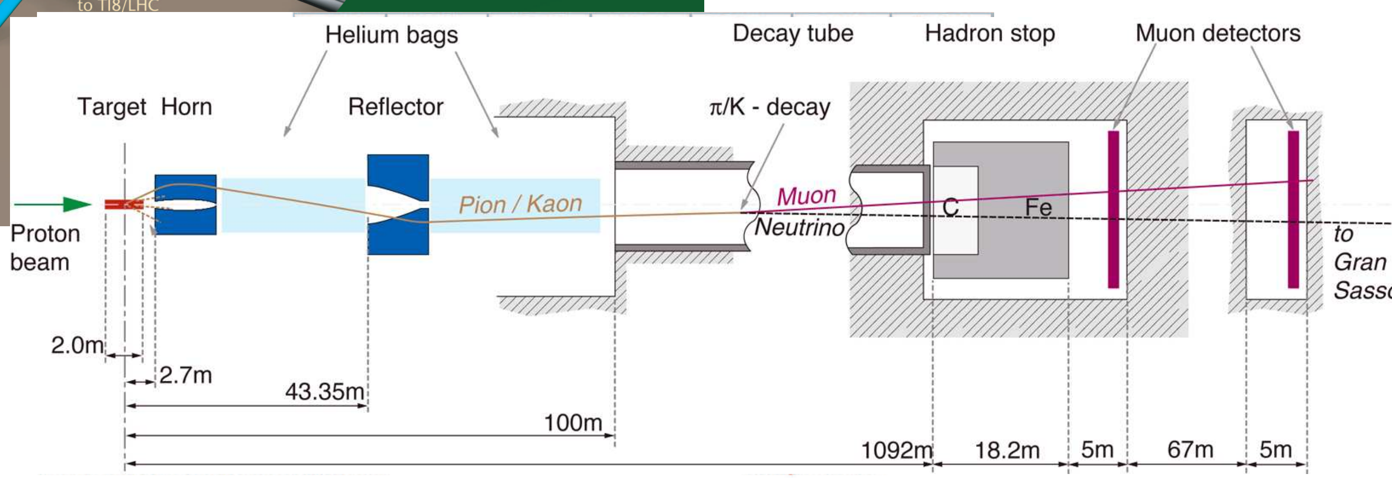
- 3×10^{32} *nucleons*
- *several bckg-free channels: the experimental sensitivity increases linearly with the exposition time.*

Decay channel	PDG limit $[10^{31}$ anni]	T600 yrs to reach PDG limit
$n \rightarrow e^- K^+$	3,2	0,5
$p \rightarrow \pi^+ \bar{\nu}$	2,5	1,1
$n \rightarrow \mu^+ \pi^-$	10,0	3,3
$p \rightarrow \mu^- \pi^+ K^+$	24,5	4,5
$n \rightarrow \pi^0 \bar{\nu}$	11,2	5,1
$n \rightarrow e^+ \pi^-$	15,8	5,3



present CNGS neutrino facility for $\nu_\mu \longrightarrow \nu_\tau$ appearance





2 fast extractions at 400 GeV/c

$2 \times 2.4 \cdot 10^{13}$ *protons every 6s*

$4.5 \cdot 10^{19}$ *pot/year*

0.5 MW pot!

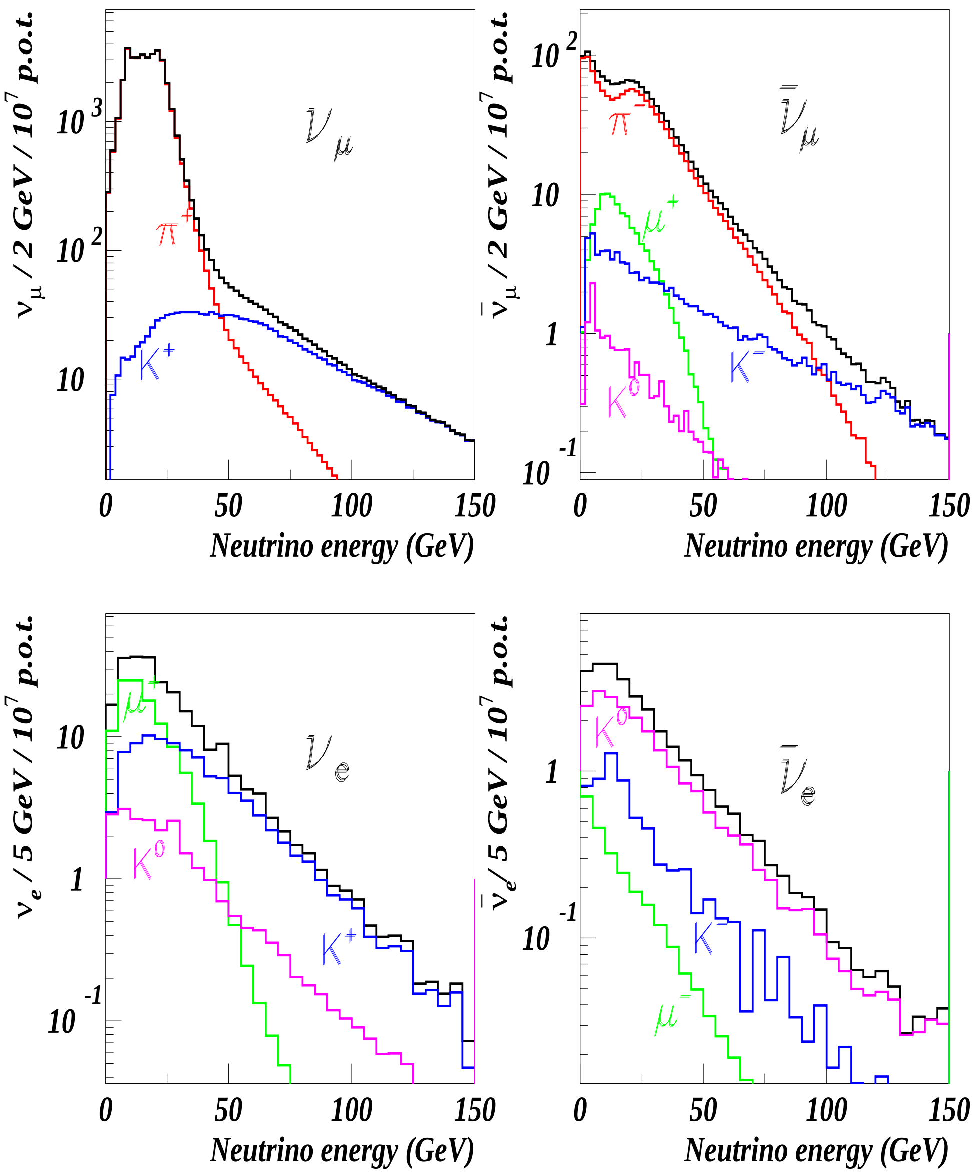
CNGS target and target revolver

Graphite
13 rods , spaced
4 or 5 mm diameter
total length 2m
C length ≈ 130 cm

FOR LOW FOCUS:
1 m
without spaces

11

expected neutrino flux at Gran Sasso



	Flux $(\nu/\text{cm}^2/10^{19}\text{pot})$	$< E_\nu >$ $[GeV]$	ν_i/ν_μ (%)	ν_i/ν_μ-CC (%)
ν_μ	$7.4 \cdot 10^6$	17.9		
$\overline{\nu}_\mu$	$2.9 \cdot 10^5$	21.8	3.9	2.40
ν_e	$4.7 \cdot 10^4$	24.5	0.65	0.89
$\overline{\nu}_e$	$6.0 \cdot 10^3$	24.4	0.08	0.06

CC event rate - FLUKA calculation -

600 $\nu_\mu CC/kt/10^{19}$ pot
5.5 $\nu_e CC/kt/10^{19}$ pot

ancillary experiment at CERN-SPS to measure hadron production: SPY: Secondary Particle Yield

ICARUS: CNGS2 searching for the ν_τ signature

Main reaction $\nu_e + Ar \to \tau^- + jet;$ $\tau \to \begin{cases} e\nu\nu & 18\% \\ \mu\nu\nu & 18\% \\ h^- n h^0 \nu & 50\% \\ h^- h^+ h^- n h^0 \nu & 14\% \end{cases}$

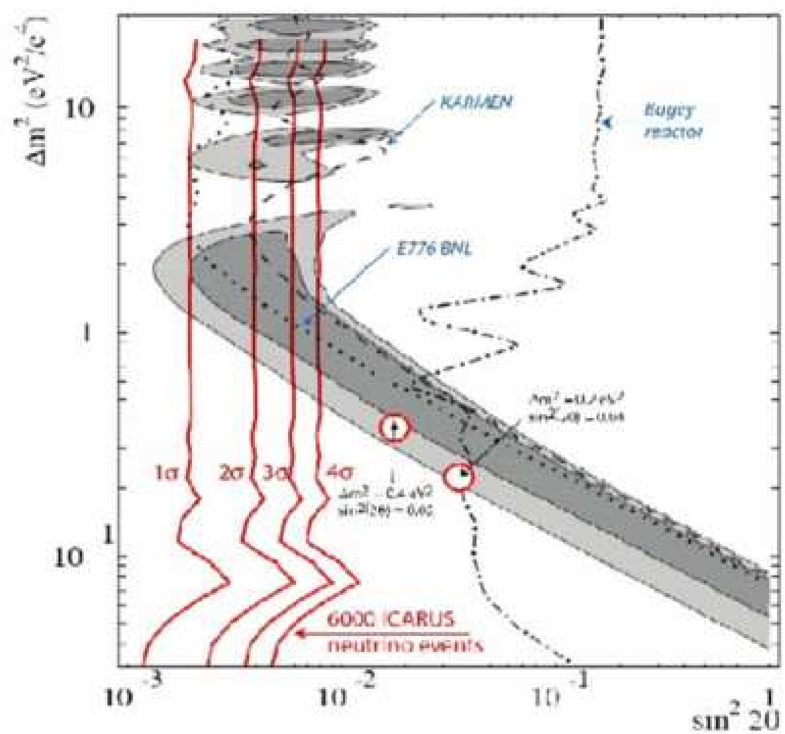
– *Search based on Kinematical criteria*

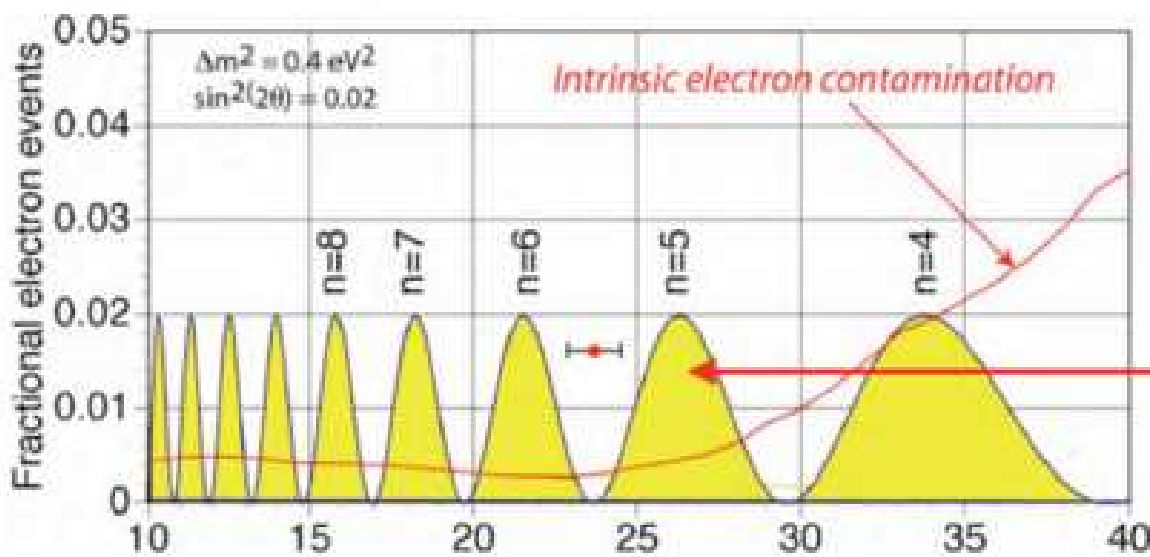
– *Natural ν_τ/ν_μ contamination $< 10^{-7}$; e $\nu\nu$ is the "golden" channel*

- *CERN beam associated events: 1200 ν_μ CC ev/yr and 8 ν_e CC ev/yr for 4.5×10^{19} pot/yr;*
- *the electron decay channel is a quite significant goal also for the present T600 mass, uniquely characterized by a large transverse momentum unbalance due to the emission of the two neutrinos;*
- *5-background free-ν_τ CC events are expected in 3 yrs - nominal beam intensity - data taking.*

sterile neutrino search in ICARUS

- *CNGS beam parameters $L/E_\nu \sim 37$ km/GeV, allows to search for sterile neutrinos testing the LSND effect via $\nu_\mu \to \nu_e$*
- *in $10 < E_\nu < 30$ GeV range, the signal will be well above the intrinsic ν_e beam contamination, free from $\nu_\mu \to \nu_\tau \to e$ and NC backg*
- *for $\Delta m^2 = 0.4$ eV^2 46 CC genuine events are expected with 19 backg events.*

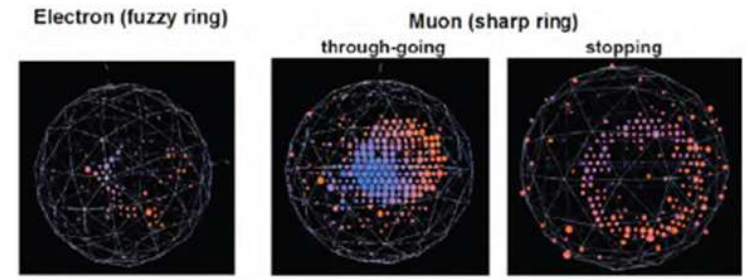




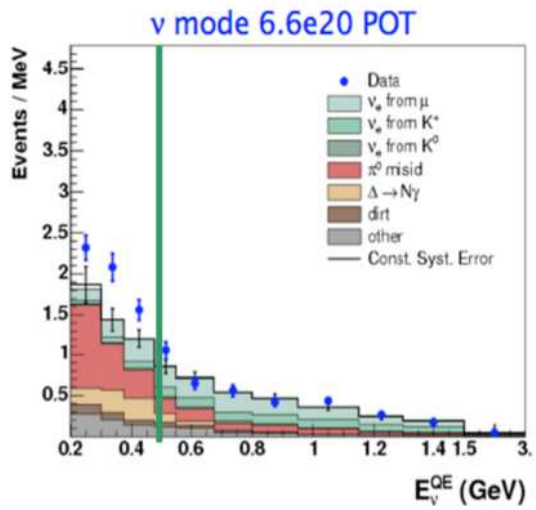
Ev:10 ÷ 30 GeV
N(νμ):4635
N(νe,beam): 18.8
N(νe,oscill): 45.5

Hypothetical sterile neutrino oscillations (LSDN) Δm² = 0.4 eV²

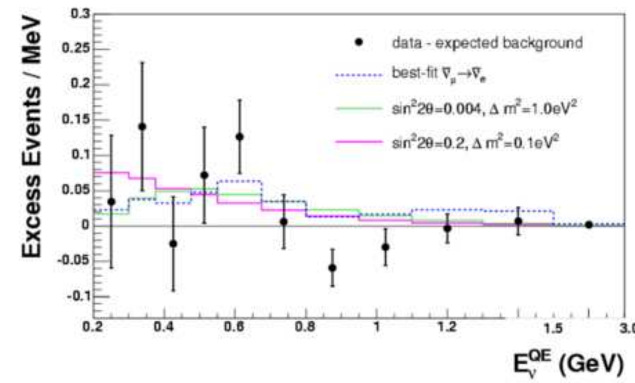
MIniBooNE at FNAL BOOSTER:
$\nu_\mu \longrightarrow \nu_e$ to check LSND signal



- ONE 445 fiducial mass mineral oil Cherenkov detector at 500 m from the target
- conventional 1 GeV ν_μ beam, $\nu_e/\nu_\mu \sim 0.8$ %



$\overline{\nu}_e$ excess also in 200-475 MeV in $\overline{\nu}_\mu$ beam

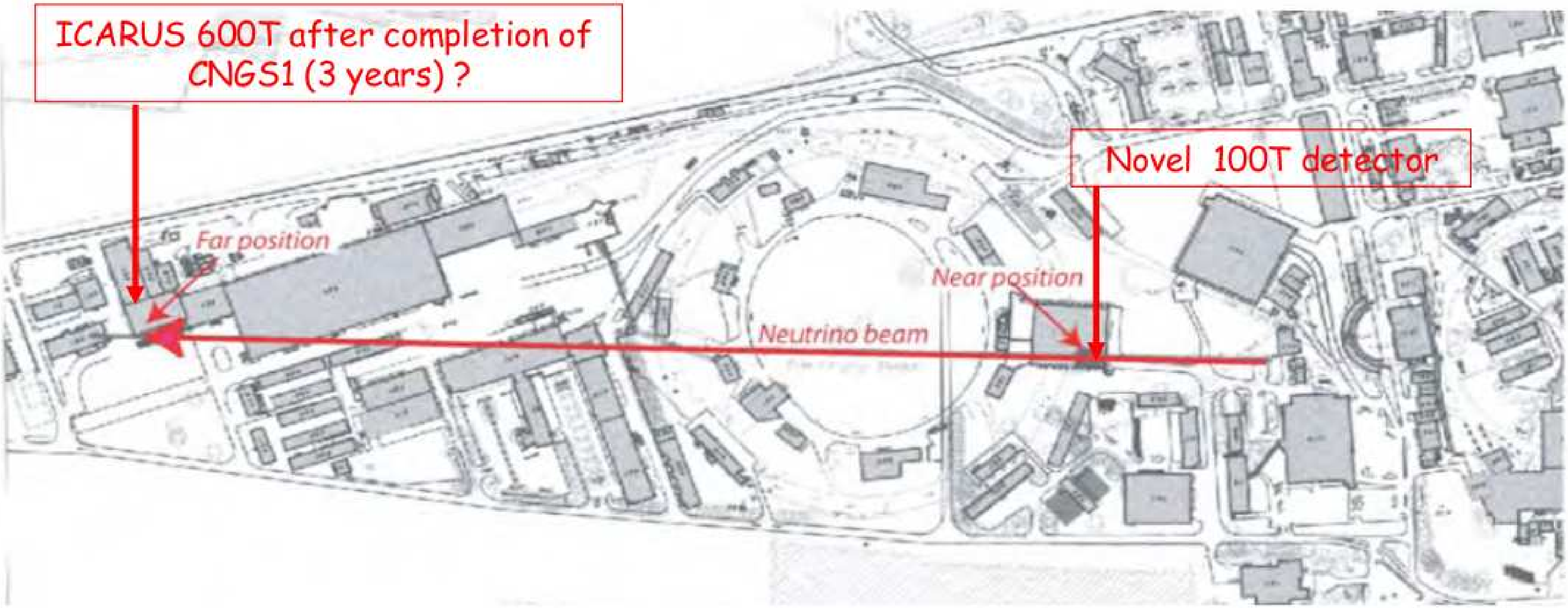


LSND effect is still alive and well!

3σ 129 events excess persists at low energy!

- LoI to Build a MiniBooNE Near Detector: BooNE (W.C. Louis, G.B. Mills, FNAL PAC, November 13): New Detector or Moving MiniBooNE.
- MicroBooNE at FNAL: a new 70-ton LArTPC at Booster to study the MiniBooNE low-E excess.
- OscSNS at ORNL: a new experiment with pions at rest, at 60 m from 1.4 MW spallation source, MiniBooNE-like detector.

ICARUS after CNGS2: The CERN-PS neutrino beam



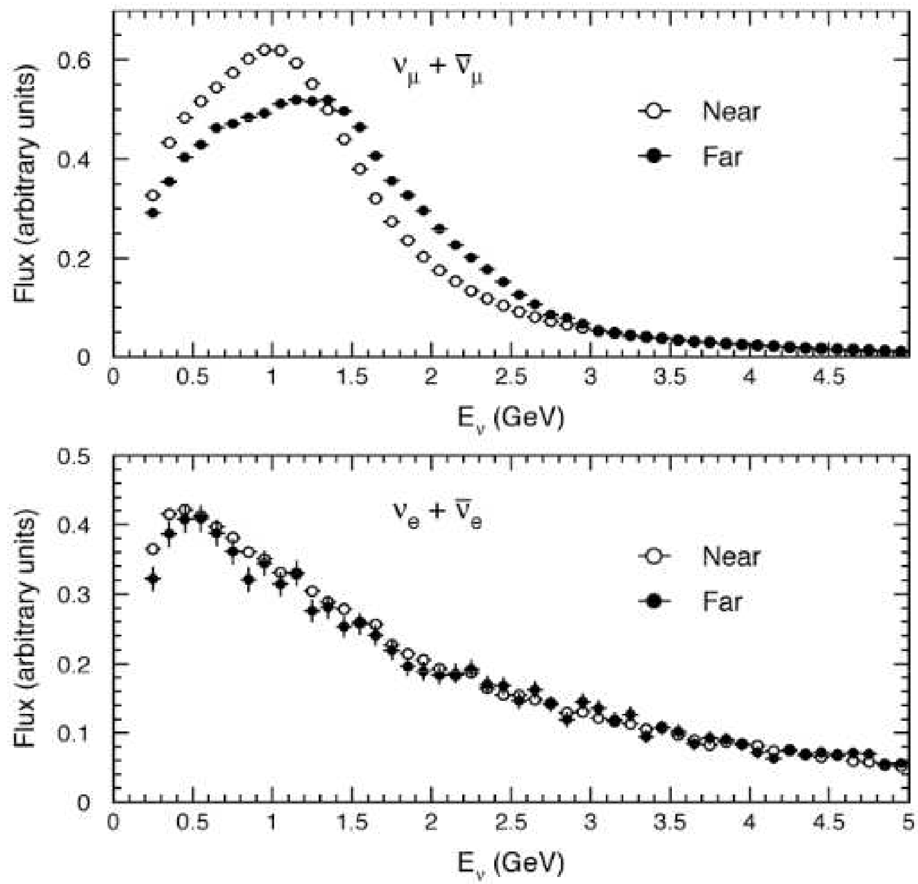
- *PS proton beam at 19.2 GeV/c is estracted via TT2, TT1 and TT7.*
- *the magnetic horn is designed to focus particles of momentum* ~ 2 *GeV/c.*
- *the decay tunnel is about 50 m long, followed by an iron beam stopper*

Two positions are forseen for the detection of the neutrinos

The far (main location at 850 m from the target (600 t)

The near location at a distance of 127 m from the target (100-150 t).

CERN-PS neutrino beam



Expected neutrino spectra at the near and far locations

Starting point: PS-180 exp and I216 /P311 proposal

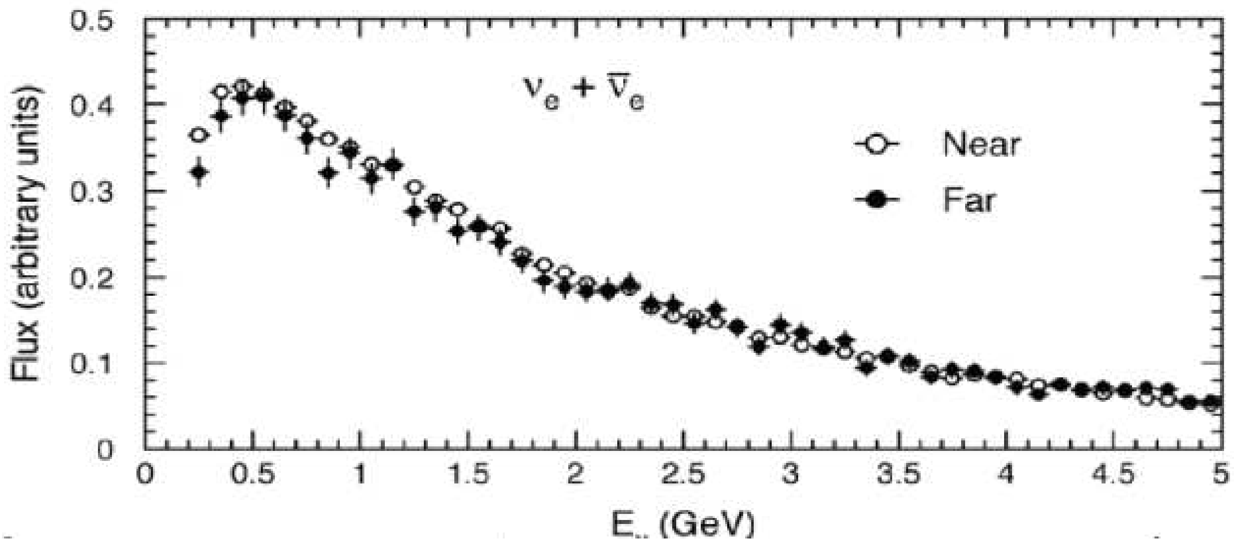
CERN-SPSC/99-26
SPSC/P311
August 30, 1999

SEARCH FOR $\nu_\mu \rightarrow \nu_e$ OSCILLATION AT THE CERN PS

refurbishing the old beam-line used by BEBC

Unique features of the CERN CPS beam

- *The present proposal is a search for spectral differences of electron like specific signatures in two identical detectors but at two different neutrino decay distances.*
- *In absence of oscillations the two ν_e observed spectra are a precise copy of each other, independently of the specific experimental event signatures and without any Monte Carlo comparisons.*

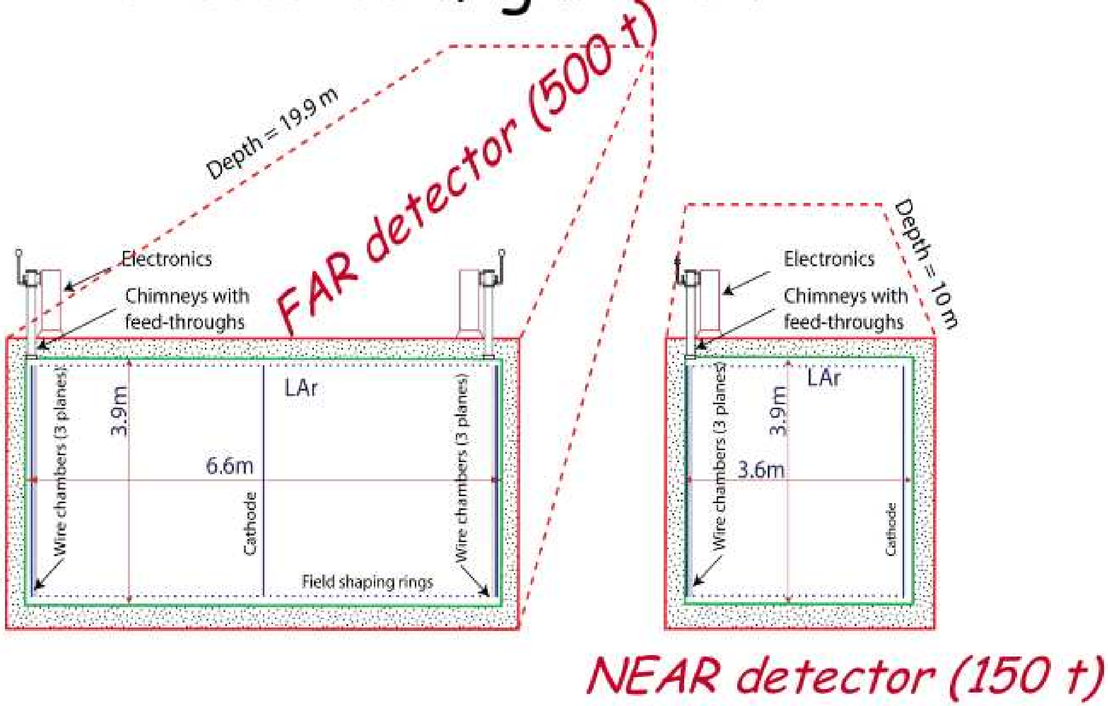


The two ν_e spectra in the far (850 m) and near (127 m locations are nearly identical

- *therefore any observed deviation from the exact proportionality between the two ν_e spectra impleis directly the presence of neutrino oscillations over the measured interval L/E.*

A twin LAr detector configuration:

- A far detector with roughly the T600 total mass
- inner volume NEAR: $3.6 \times 3.9 \times 8\ m^3$
- Wire chambers with 3 readout planes at 0°, ±6HV = -180 kV @ 0.5 kV/cm



- Set-up simplified with respect to ICARUS
- Cheaper, cryogenic vessel with ≈ 1 m thick perlite walls
- Wire chamber mechanics, purification system and readout electronics "cloned" from the ICARUS set-up
- Very quick construction schedule.

ArXiv: 0909.0355

re-use of ICARUS-T600 as far detector?

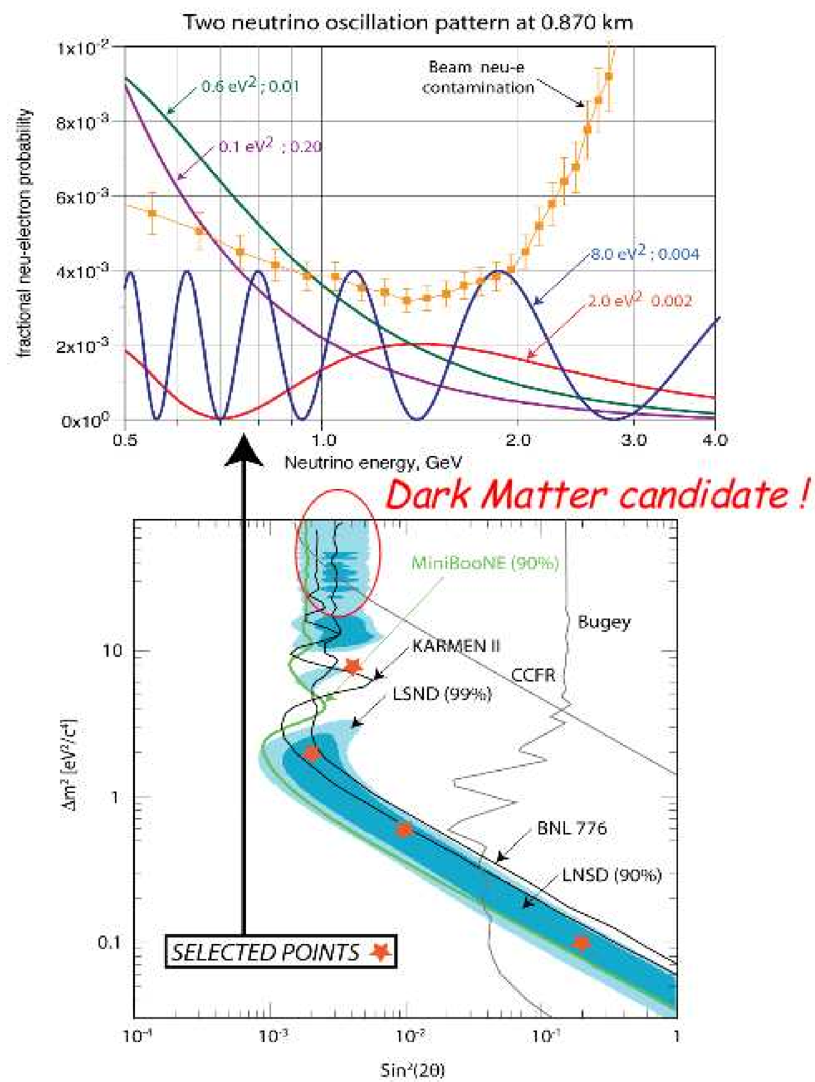
CERN-PS neutrino event rate

Assuming 2 years run for a total of 2.5 10^{20} pot

Fiducial mass	**500 t**	**150 t**
Distance from target	**850 m**	**127 m**
ν_μ interactions	**1.2 x 10^6**	**18 x 10^6**
QE ν_μ interactions	**4.5 x 10^5**	**66 x 10^5**
Events/rst	**0.17**	**2.5**
Intrinsic ν_e from beam	**9000**	**120000**
Intrinsic ν_e from beam ($E_\nu < 3$ GeV)	**3900**	**54000**
ν_e oscillations: $\Delta m^2 = 2.\ eV^2;\ sin^2 2\theta = 0.002$	**1194**	**1050**
ν_e oscillations: $\Delta m^2 = 0.4\ eV^2;\ sin^2 2\theta = 0.02$	**2083**	**2340**

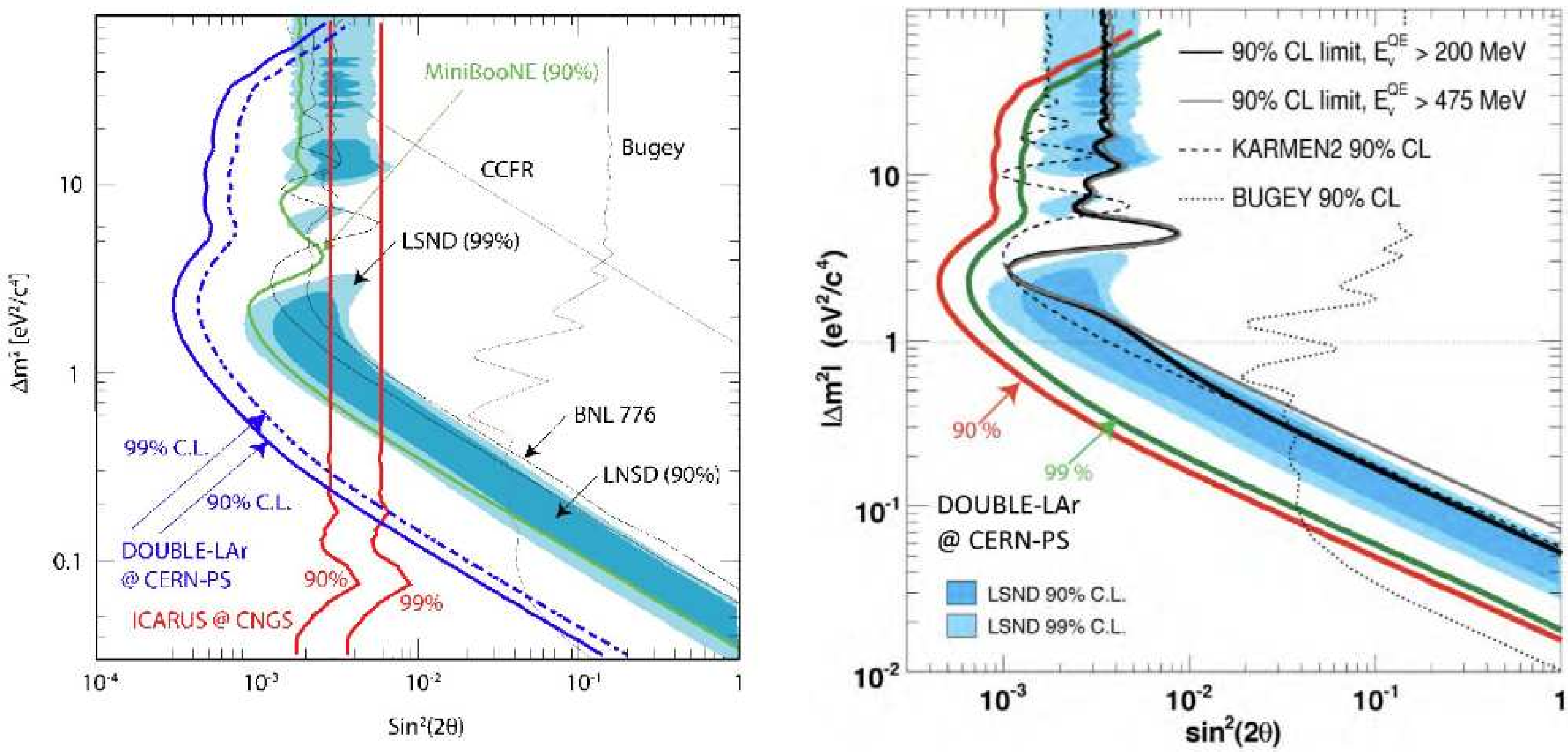
	background	osc. evts prob= 0.0026
LSND	30	88 $\bar{\nu}$
MiniBOONE E>475	386	163 ν
MicroBOONE	31	54 ν 3y
oscSNS	79	253 $\bar{\nu}$ 1y

New features of the CERN proposal



- *It appears that the present proposal, unlike LSND an MiniBooNE, can determine both the mass difference and the value of the mixing angle.*
- *Very different and clearly distinguishable patterns are possible depending on the acctual values if the* $(\Delta m^2 - \sin^2 2\theta)$ *plane.*
- *The intrinsic* ν_e *background due to the beam contaminations is also shown.*
- *The magnitude of the LSND expected oscillatory behaviour, for the moment completely unknown, is in all circustances well above the background, also considering the very high statistical impact and the high resolution of the experimental measurement.*

Comparing sensitivities



Expected sensitivity for the proposed esperiment exposed at the CERN-PS neutrino beam (left) and anti-neutrino (right) for 2.5×10^{20} pot. The LSND allowed region is fully explored both for ν's and $\overline{\nu}$'s beams, the expectations from CNGS2/ICARUS T600 at LNGS are also shown.

detecting subleading $\nu_\mu \to \nu_e$ for $\theta_{13},\ \delta_{CP}$: the MODULAr project

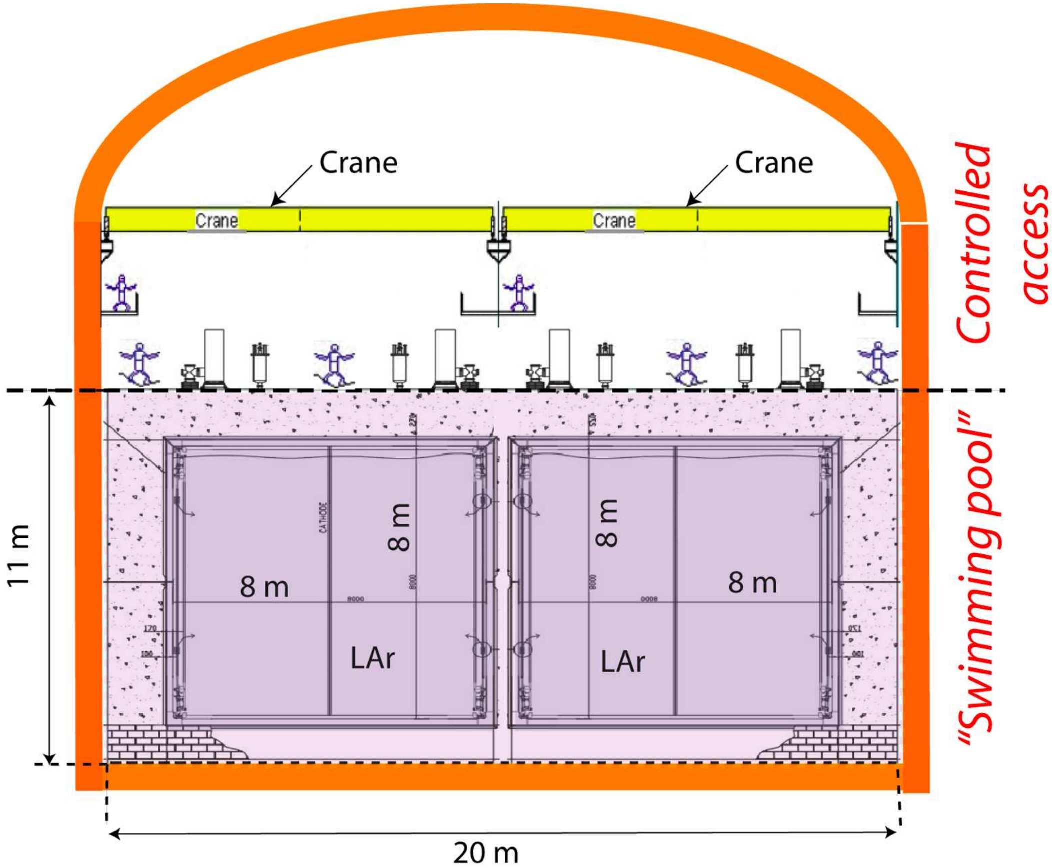
- *a new LAr-TPC Imaging underground detector made of several identical units, each of ~ 5 kt fid. mass devoted to ν physics with and without accelerators, search for proton-decay. First step: 20 kt LAr-TPC detector to be realized along the lines of the vast R&D work carried out the last decades by the ICARUS Collaboration. This programme may eventually be further improved with additional modules, depending of the developments of physics programmes with/without accelerators*

- *a new experimental area tailored to MODULAr detector, eventually enlarged in future phases, 10 km Off-Axis from the main laboratory, away from the protected area of Gran Sasso National Park at $\sim$ 1.2 km of equivalent water depth: the superb event imaging power of LAr-TPC will ensure a very efficient reduction of c-ray induced background for ν's from CNGS but also for p-decay and cosmic ν searches.*

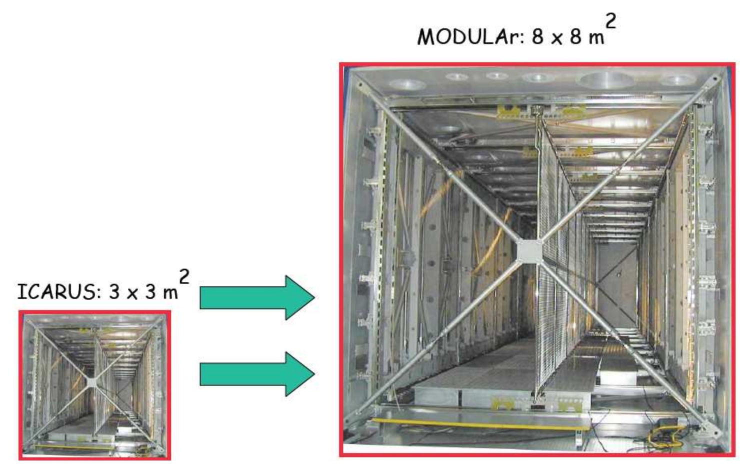
- *a new neutrino beam derived from the existing CNGS facility, the proton beam line from the 400 GeV/c SPS, eventually with an increased intensity; relatively modest changes in the ν beam focusing of CERN will produce a nearly optimal ν_μ beam in few GeV energy range for $\nu_\mu \to \nu_e$ searches*

MODULAr: from ICARUS-T600 to multi-kton LAr-TPC by a modular approach!

- *two twin separate LAr containers made of Aluminum extruded structures, thermally stabilized with forced N2 circulation.*
- *outside the dual structure, $\sim$ 1.5 m thick perlite wall provides spontaneus, passive heat insulation.*
- *total LAr mass for a detector 60 m long is $\sim$ 10000 tons. Same gaps as for ICARUS but 4 m drift, 0.5 kV/cm*



The volume of each of two gaps should be 8×8 m^2 and 60 m long, corresponding to 5370 t of LAr. A reasonable three-plane wire pitch: 6 mm twice the value of the T600. The full detector is made of two such dewars



MODULAr: T600 scaled-up by 2.66! will inherit all the achievements of ICARUS-T600

new CNGS off-axis neutrino beam facility

- 732 km CERN-LNGS baseline:

  atmosph. ν oscillation max at $E_\nu \sim 1.5$ GeV

  (NOVA project: similar baseline and ν energy)

  ν-interactions are perfectly reconstructed in LAr-TPC

- CNGS beam Off-Axis configuration:

  no major increase of present SPS performance,

  but dedicate operations, $\epsilon \sim 0.8$, 200 day/year,

  512 kW beam power at 400 GeV: 1.2×10^{20} pot/y

  a new target /optics design optimized for low energy,

  10 km Off-Axis neutrino beam

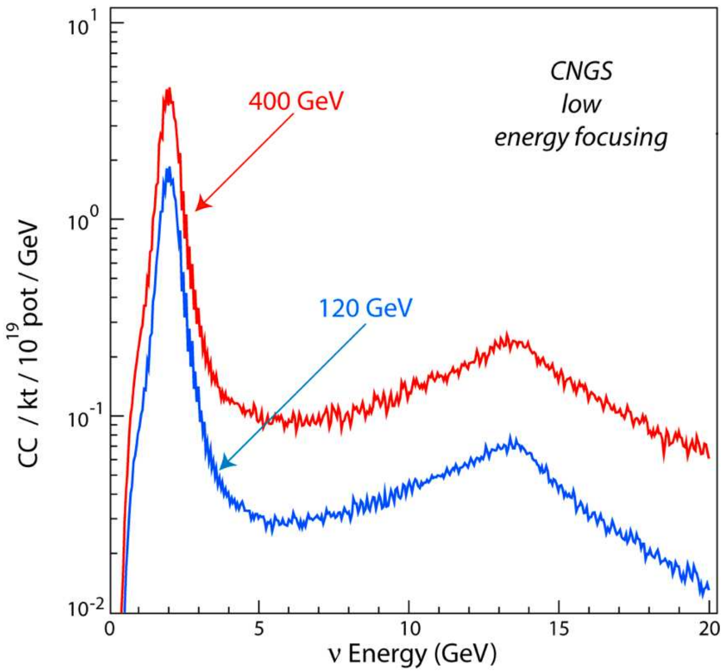
- proton energy: 400 GeV $\sim 3.3 \times 120$ GeV (NOVA)

  meson production scales almost linearly with E_p,

  what matters is beam power: 512 kW (CNGS) vs.

  768 kW (NOVA), not proton on target

ν_μ CC at 120 GeV (FNAL) and 400 GeV (CNGS), same low energy focusing optics, 732 km, 14.8 mrad Off-Axis (no oscillations)



MODULAr (CNGS, 400 GeV) with 1.2×10^{20} pot/y $\sim$ NOVA (NUMI, 120 GeV) with 6.5×10^{20} pot/y!

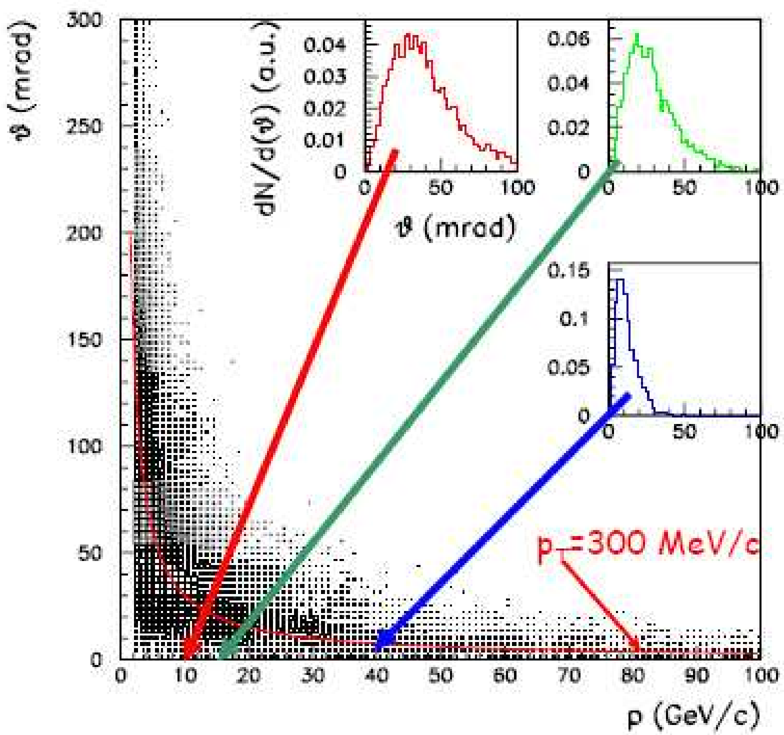
CNGS Off-Axis beam

- *Off-Axis angle θ: $E_{\nu_\mu} = \frac{0.43 E_{\pi^+}}{1+\gamma^2\theta^2}$ ... similarly for K-decay*

  $\rightarrow$ increase of the ν flux at low energies which are the most sensitive to θ_{13}
- *the resulting ν beam is essentially from π^+: narrow, better known ν spectrum, lower ν_e contamination (μ and K 3-body decay...)*

$$\phi_{\nu_\mu} \propto \left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2 \cdot \frac{1}{L^2} \quad \left(\gamma = \frac{E_\pi}{m_\pi}\right)$$

emission angle θ vs. momentum p for mesons produced in 1 m long C target by 400 GeV/c protons



Beam optics should focus low energy π:

larger acceptance than CNGS high energy beam...

- *target: 1 m long graphite, $\phi = 1$ cm, no spaces*
- *horn: at 20 cm from the target*

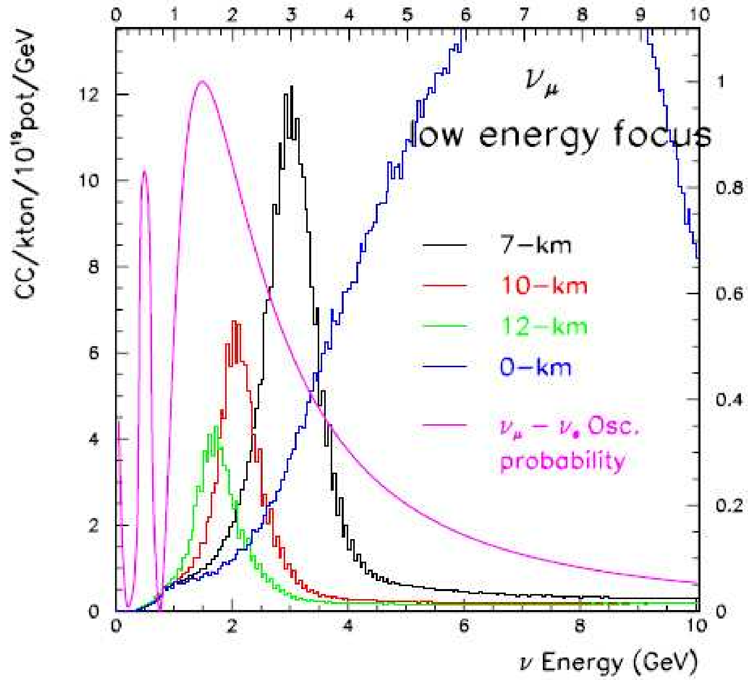
  - NUMI-ME-like (3m long)

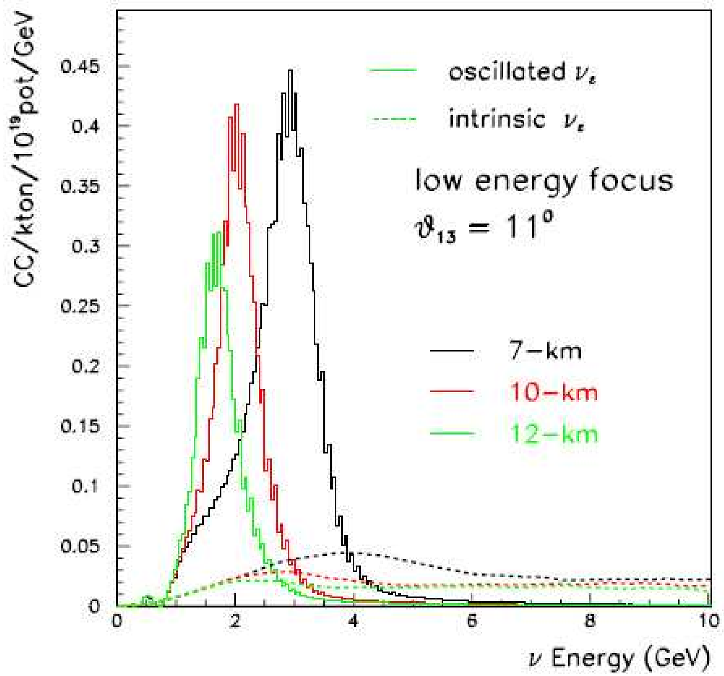
  - 200 kA current
- *reflector: same position, outer dimensions as CNGS,*

  - inner conductor redesigned for 15 GeV focus,

  - 200 kA current

Off-Axis neutrino beam for $\nu_\mu \rightarrow \nu_e$: Sensitivity $S/\sqrt{backg}$ vs. Off-Axis distance





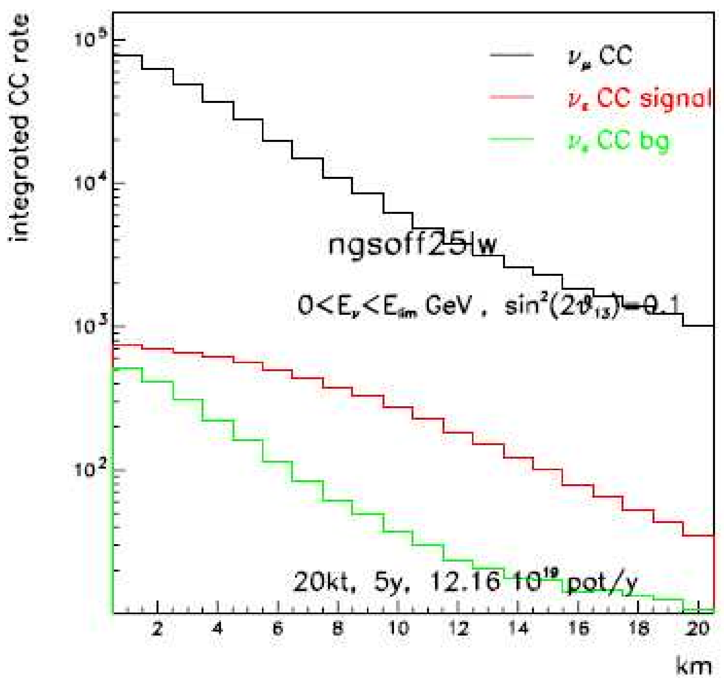
20 kt LAr detector

1.2×10^{20} *pot/y*

5 years data taking

$\sin^2(2\theta_{13}) = 0.1,$

signal accept. 90 %



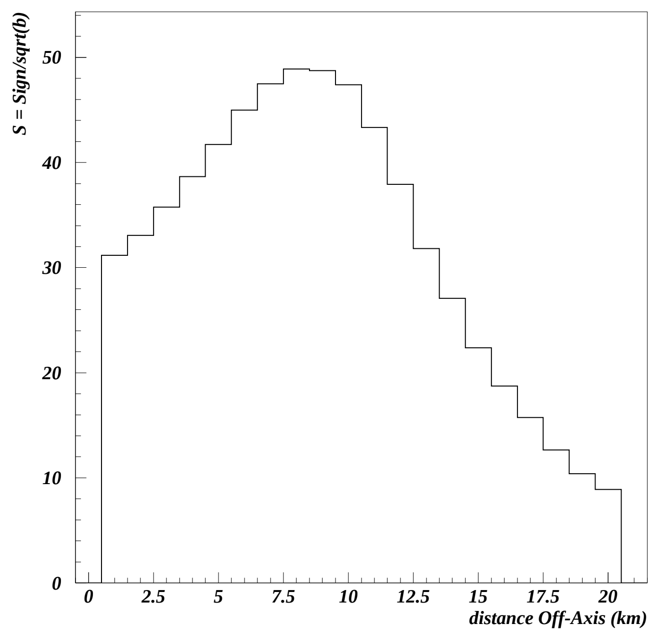


figure of merit of the Off-Axis distance:

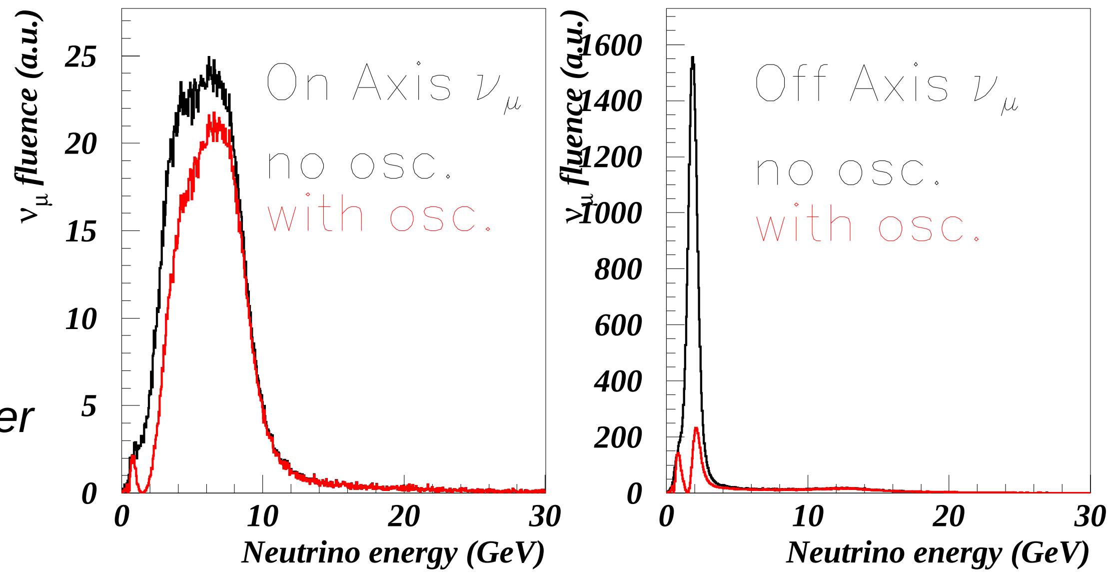
S = Signal/ $\sqrt{backgr}$

maximum in $8 \div 11$ *km range*

MODULAR: a two FAR detector experiment

- *Monte Carlo calculations: ν_e/ν_μ within few % systematics and ν_e, $\nu_\mu \sim 5$ %* *(benchmark: NOMAD data of WANF ν_μ beam of CERN SPS)*
- *the simultaneous use of two FAR detectors - ICARUS-T600 On-Axis and MODULAr Off-Axis - allows for a precise combined measurement of incoming ν's:* *the two FAR detectors see the target/beam-optics within the same angular acceptance* *(not in the case of conventional NEAR-FAR detector experiments)*

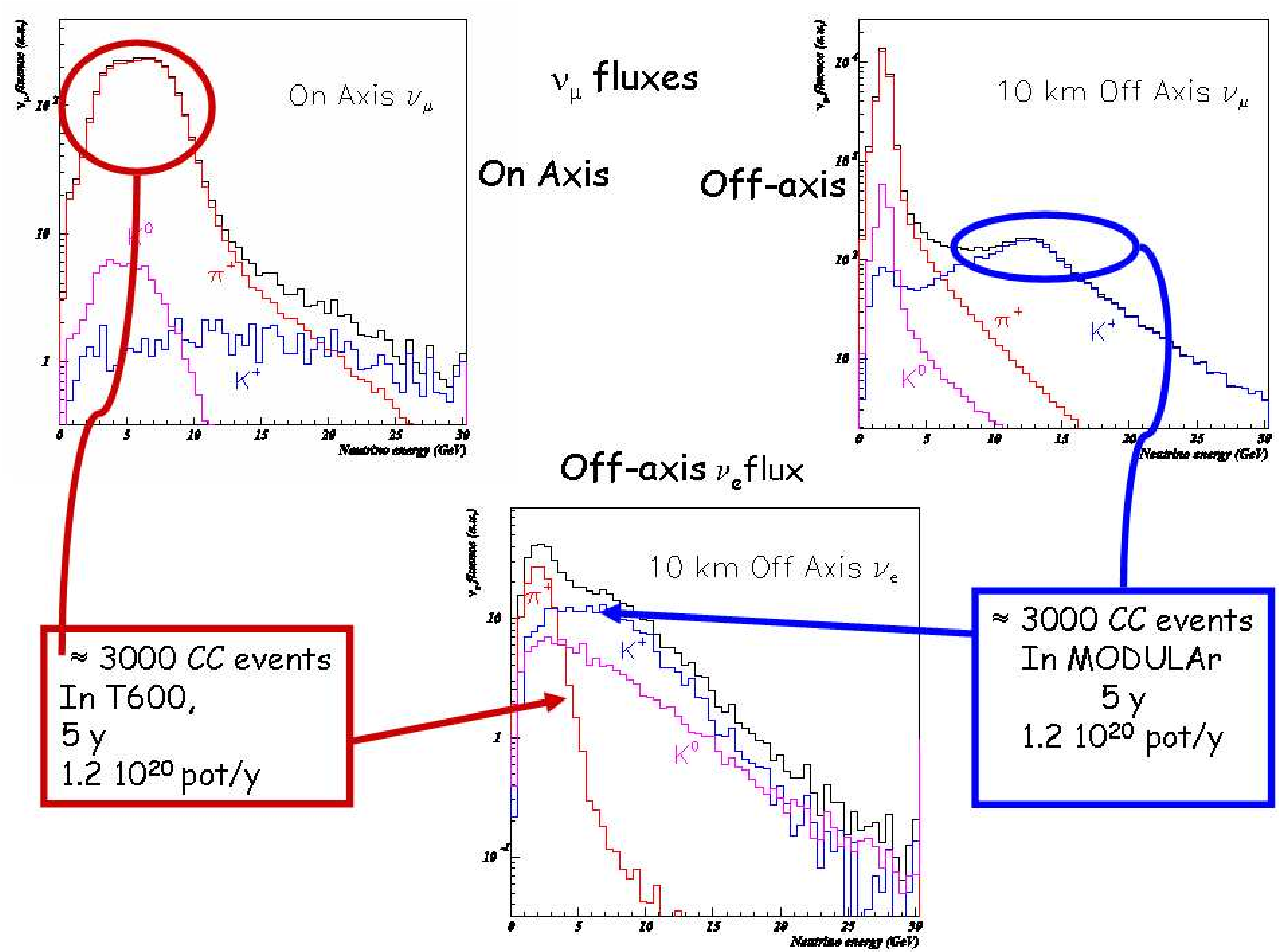
- *Off-Axis ν_μ-beam, $E_\nu \sim 2.5$ GeV: precise measurement of Δm^2_{23}*
- *On-Axis ν_μ-beam - $E_\nu \sim 7$ GeV- much less sensitive to $\nu_\mu \to \nu_\tau$: measurement of incoming ν_μ flux after correction for Δm^2_{23} driven oscillations*



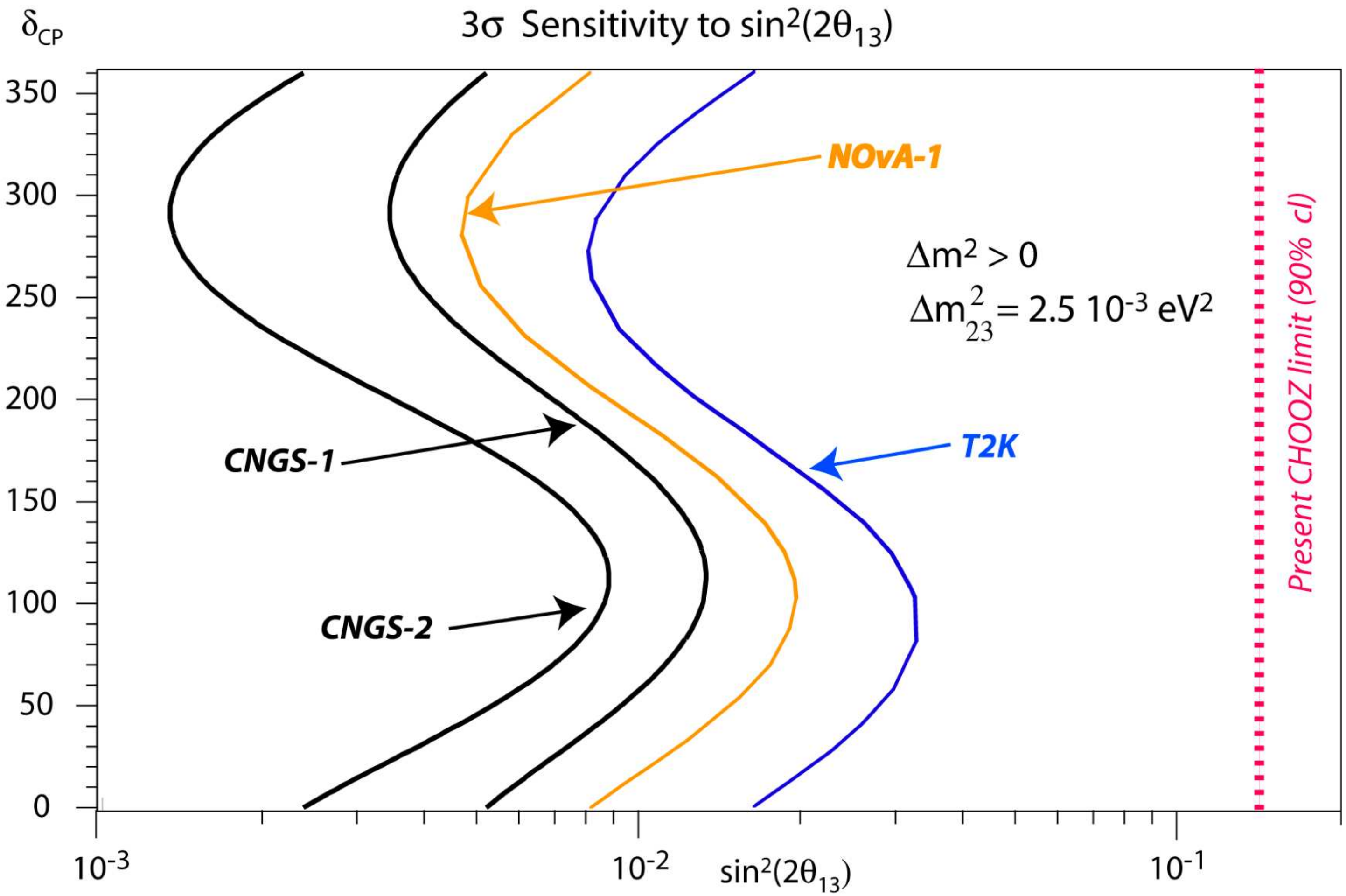
On, Off -Axis transformation is straightforward:

the lower energy Off-Axis ν beam is an effect of well-known "Jacobian-peak" in the two body $\pi^+,\ K^+$ decay kinematics

- *Off-Axis ν_e contamination: from measurement of On-Axis ν_μ ($E_\nu \leq 10$ GeV: $\pi^+ \rightarrow \mu^+ \rightarrow \nu_e$) and Off-Axis ν_μ ($2 \geq E_\nu \geq 10$ GeV: $K^+ \rightarrow \nu_e$)*



MODULAr 20 kt sensitivity to θ_{13} and δ_{CP} - 5 years



CNGS-1: 1.2×10^{20} *pot/y*

CNGS-2: 4.3×10^{20} *pot/y*

$\Delta m^2_{23} = 2.5 \times 10^3$ *eV*^{2}

normal mass hierarchy

GLoBES calculation:

5 % beam systematics

$\Delta E/E = 15\,\%$

Rates for 20 kt mass, 5 y and 1.2×10^{20} *pot/y,* $\sin^2(2\theta_{13}) = 0.1$

	ν_μ CC	bg	signal	$S/\sqrt{bg}$
MODULAr	5700	28	250	47
NOνA		19.5	142	32
T2K		23	103	23

at the Physics Frontiers: the future of LAr-TPC

- *ICARUS-T600 starting operation at LNGS is a break-down in H.E. Physics: a new way to visualize "events" is available after a long pionering R&D activity;*
- *despite the "limited" 600 t mass, a large variety of investigations in neutrinos and matter stability is starting;*
- *Gargamelle has already shown that remarkable results may be obtained with a very sensitive detector even if much smaller than the one of larger and coarser calorimeters of that time*
- *here may be a similar opportunity in the future, paving on the same time the way to the much larger ultimate facilities...*

Neutrinos have been the origin of an impressive number of "Surprises".