45th Karpacz Winter School in Theoretical Physics

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Lądek-Zdrój, Poland

School: February 2-7, 2009
Workshop: February 9-11, 2009

Neutrino interactions: from theory to Monte Carlo simulations

The Liquid Argon TPC Technology for (Quasi-elastic) Neutrino Cross-Sections understanding and precise reconstruction:

present status and short-term perspectives

References:

- NuInt Workshop: *Nucl. Phys.B - Proc.Supll. 112, 2002.*
- ICARUS Collab.: *Phys.Rev.D 74, 112001 (2006).*
- ArgoNeuT Collab. (M.Antonello): *Proceedings of the International School of Physics "Enrico Fermi", (Jun. 2008)*

The discovery of the neutrino non-standard properties (mass and mixing) refocused on various aspects, both theoretical and experimental, of neutrino standard properties (e.g. cross-sections):

QUESTIONS about the neutrino cross section:

[A] How well do we know (have we measured) it ?

[B] How well do we understand it theoretically ?

[C] How well do we need to know it
for Oscillation Studies ?

[D] What new Experimental Programs can be most
effective to improve our Knowledge ?
*(in view of the **next generation** osc. Experiments)*

P. Lipari -
NuInt01 Conference - KEK Dec.2001 - Summary Talk

How well do we need to know it (QUESTIONS [C])

Next generation long baseline experiments:
neutrino mass and mixing ⇒ "*the few-GeV region*"

The next steps in studying neutrino mass and mixing are:

1.determine the rate of $\nu_\mu \rightarrow \nu_e$ **oscillations** at the "atmospheric" oscillation length, characterized by the mixing angle θ_{13}

2. determine the ordering of the three neutrino mass states **("mass hierarchy")**

3. determine whether there is CP violation in the neutrino sector.

An approximation of the $\nu_\mu \rightarrow \nu_e$ transition probability obtained in the two flavour scenario is given by

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2((1-r)\delta)}{(1-r)^2}$$

where $\delta = \Delta m_{13}^2 L/4E_\nu$ is the atmospheric oscillation phase in vacuum and

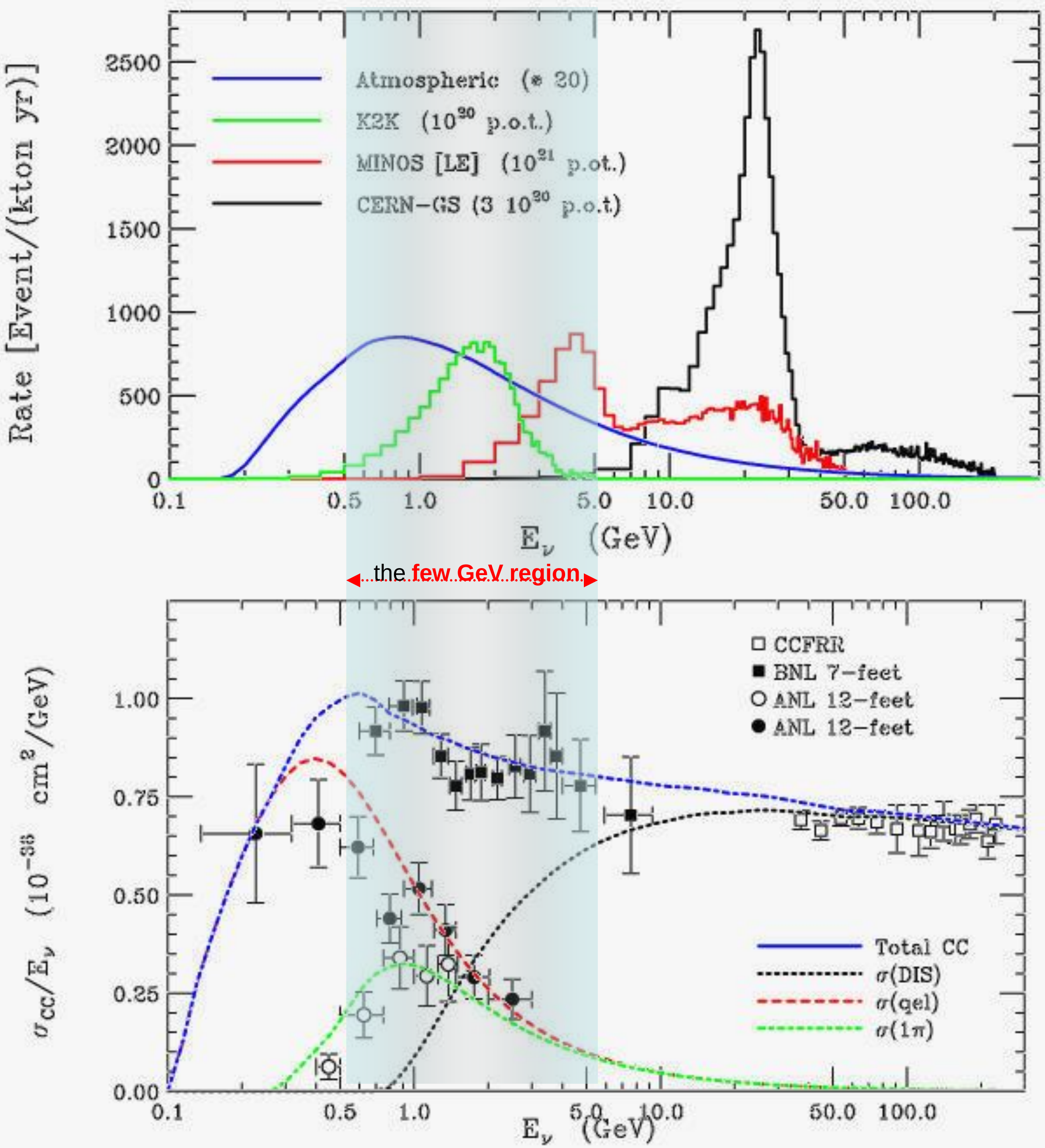
$$r \equiv \frac{2\sqrt{2} G_F N_e E_\nu}{\Delta m_{13}^2}$$

is an adimensional ratio accounting for matter effects.

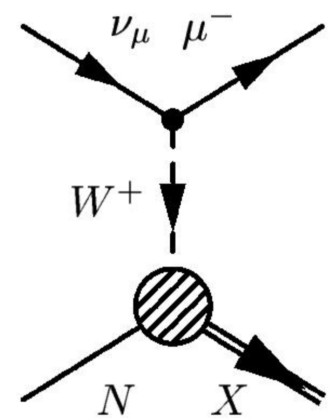
Both r and δ depend on $\Delta m_{13}^2 = m_3^2 - m_1^2$. If r,$\delta$ >0 the mass hierarchy is normal otherwhise is inverted. $P(\nu_\mu \rightarrow \nu_e)$ is non zero only if the θ_{13} mixing angle is non zero (current limit by CHOOZ experiment is $\theta_{13} < 10°$).

Assuming $\theta_{13} \approx 5°$, $\theta_{23} \approx 45°$ and a typical baseline L ≈ 1000km the oscillation probability becomes maximum in the **few GeV region**.

The Cross Section Role (QUESTIONS [A] & [B])



ν-Interactions on p-n/ q-q in C, O, Fe, Ar, Pb,.. Nuclei



Natural Decompositions:

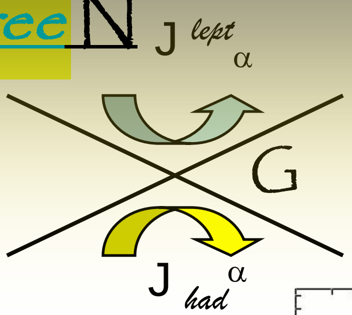
$$\sigma_{tot} = \sigma_{Q\text{-}El} \oplus \sigma_{Res} \oplus \sigma_{DIS}$$
$$= \sigma_{0\pi} \oplus \sigma_{1\pi} \oplus \sigma_{2\pi} \oplus \ldots$$

"Old" Experimental Data rather poor and affected by large errors. "Recent" Data (SciBoone + K2K, MiniBoone) start to shade new light

$[\sigma_{Q\text{-}El}]$ Quasi-Elastic Scattering on *free* N

(low Q^2, x=1, W=M_p):

$$\nu_\ell + n \rightarrow \ell^- + p$$

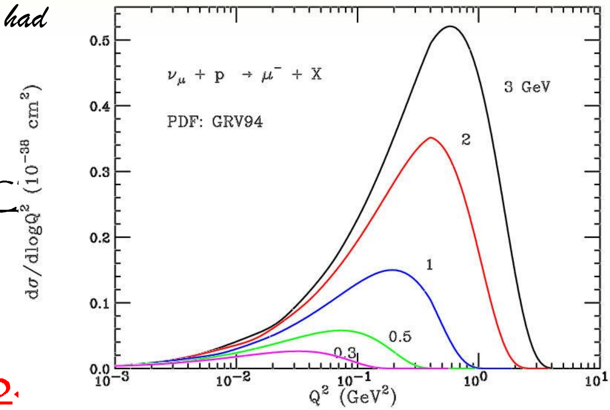


Dynamics described by Current-Current **L**agrangian

J ^{had} = V - A defined through Nucleon Weak Form Factors:

Vector F.F. [$F_V^1(Q^2)$, $F_V^2(Q^2)$], related to E.M. F.F. (Hp. CVC)

Axial F.F. [$F_A(Q^2)$] and PseudoScalar F.F. [$F_{PS}(Q^2)$]



Note: Vector F.F. can be (are) determined from *e*-scattering exp.

Axial F.F. (assumed dipolar form) with M_A free parameter

$$F_A(Q^2) = g_A \left[1 + \frac{Q^2}{M_A^2}\right]^{-2}$$

oretically because of the non conservation of axial weak current.

PseudoSca s proportional to $(m_\ell/M_p)^2$

i.e. relevant only for $\nu_\ell = \nu_\tau$

Q-el scattering on N *bound* in A: the rise of Nuclear Effects (ISI,FSI)

(i.e. mainly non-perturbative effects of strong interactions inside the target)

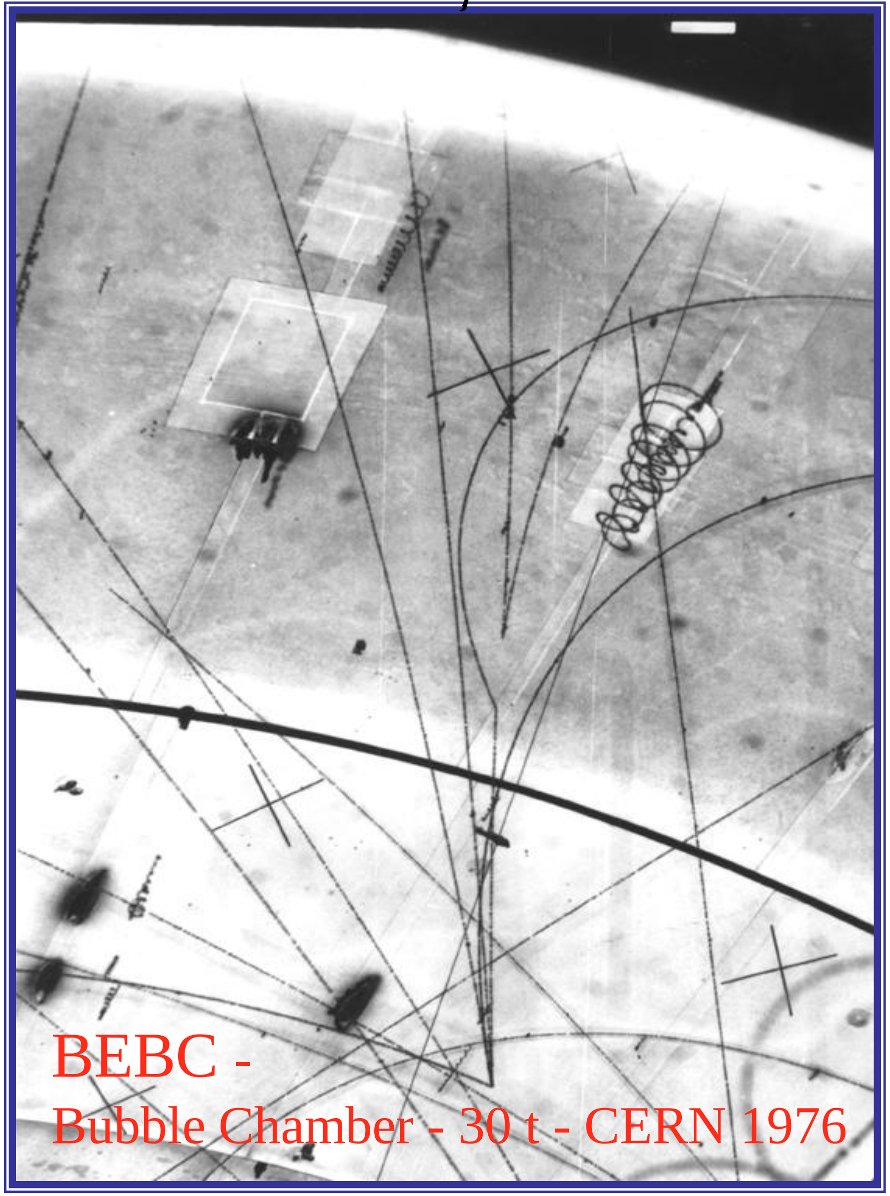
⇒ Different models under test/development/validation/comparison

New Experimental Programs (QUESTIONS [D])

The fundamental properties of ν-interactions have been probed by

bubble-chamber experiments

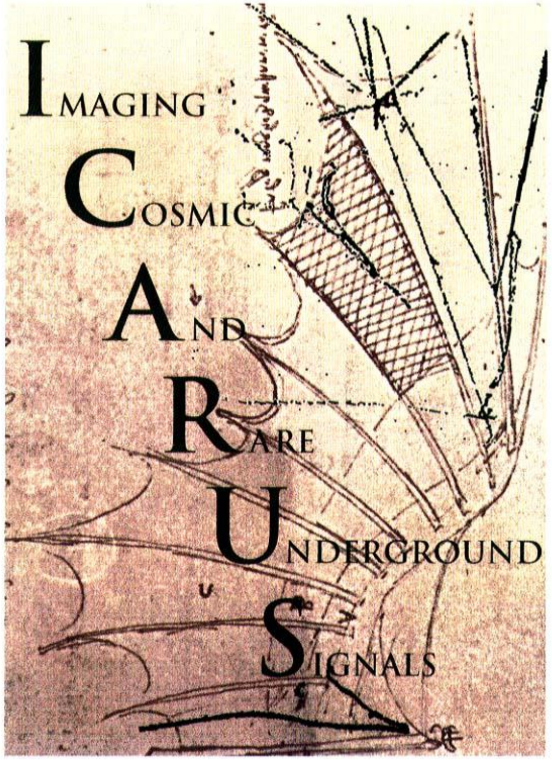
LAr technology is the modern version of (electronic) bubble-chamber concept ...

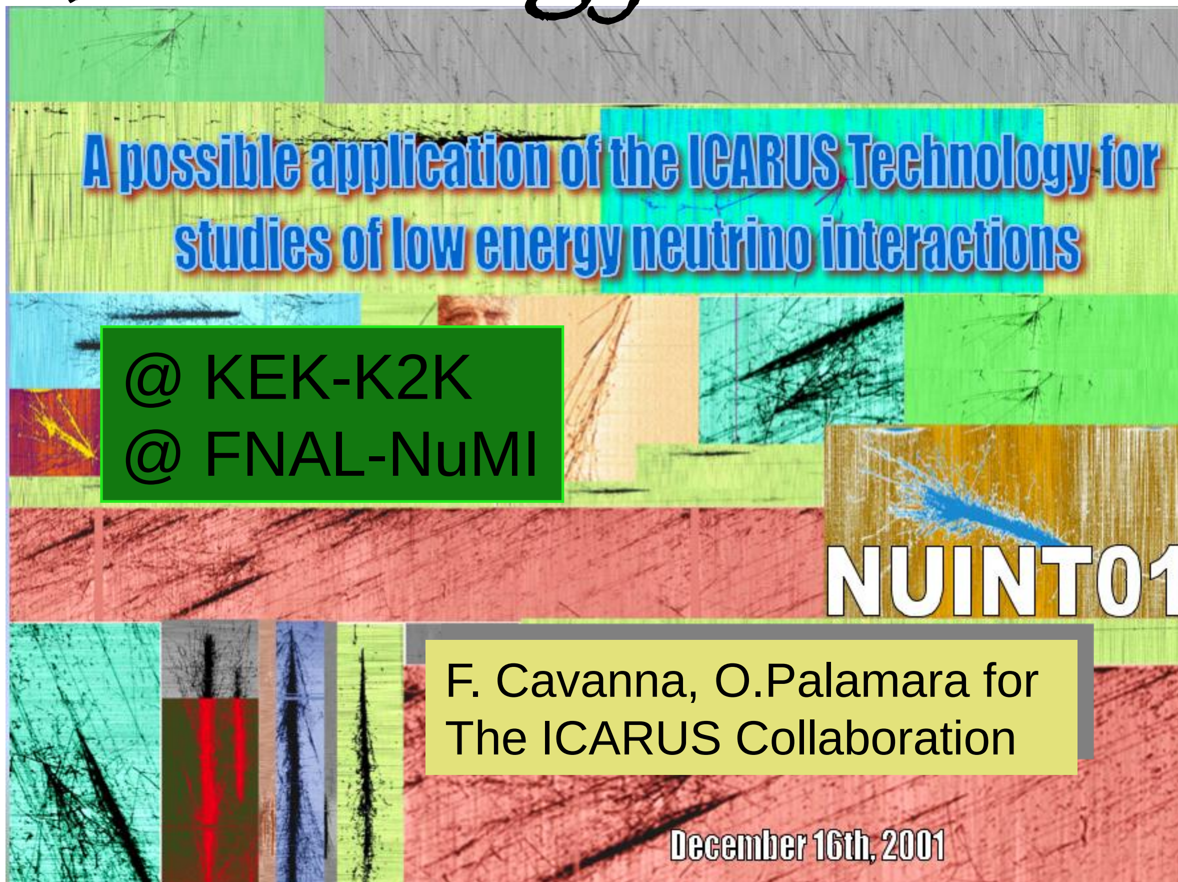


BEBC -
Bubble Chamber - 30 t - CERN 1976

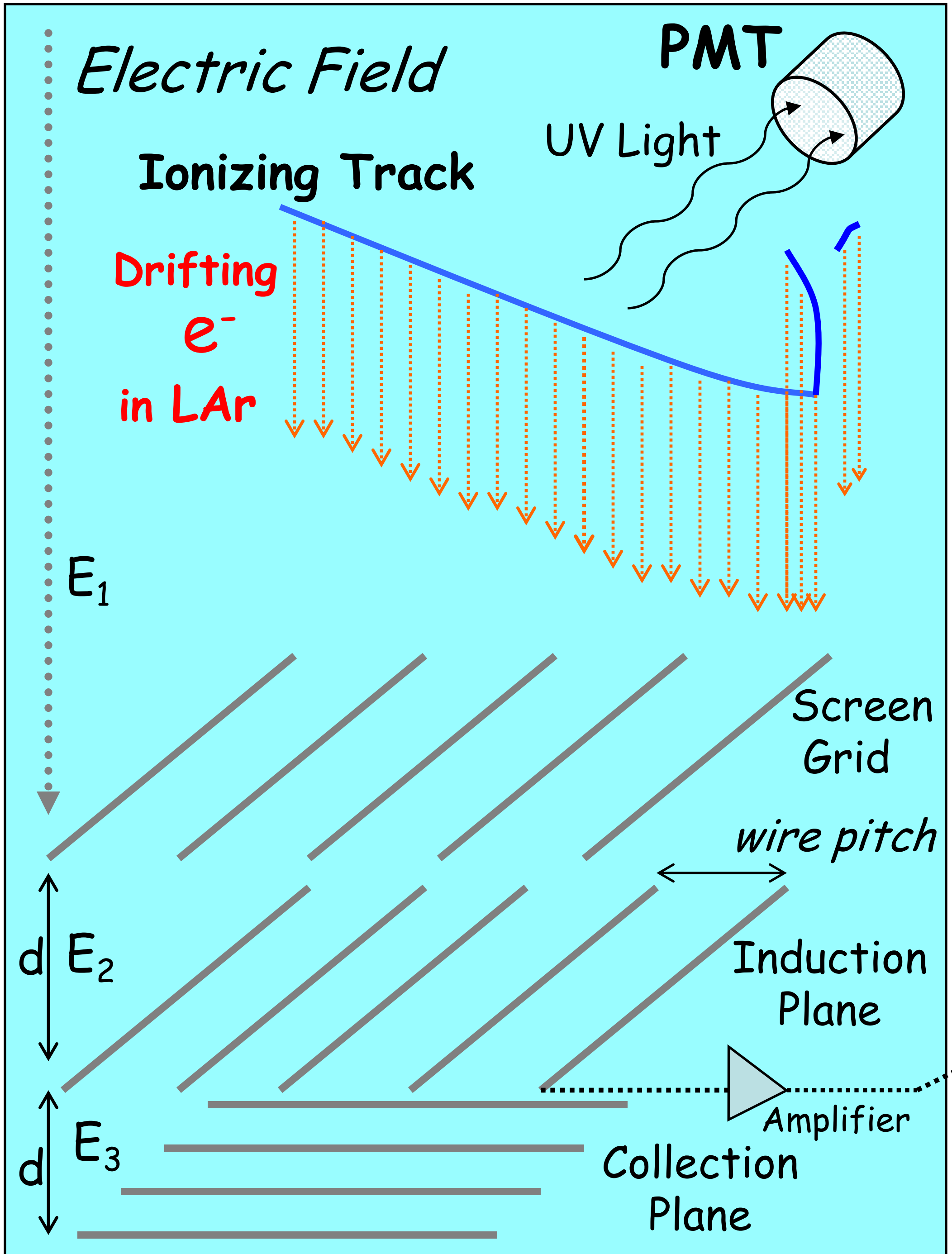
ICARUS - T600
Electronic Bubble Chamber - PAVIA 2001

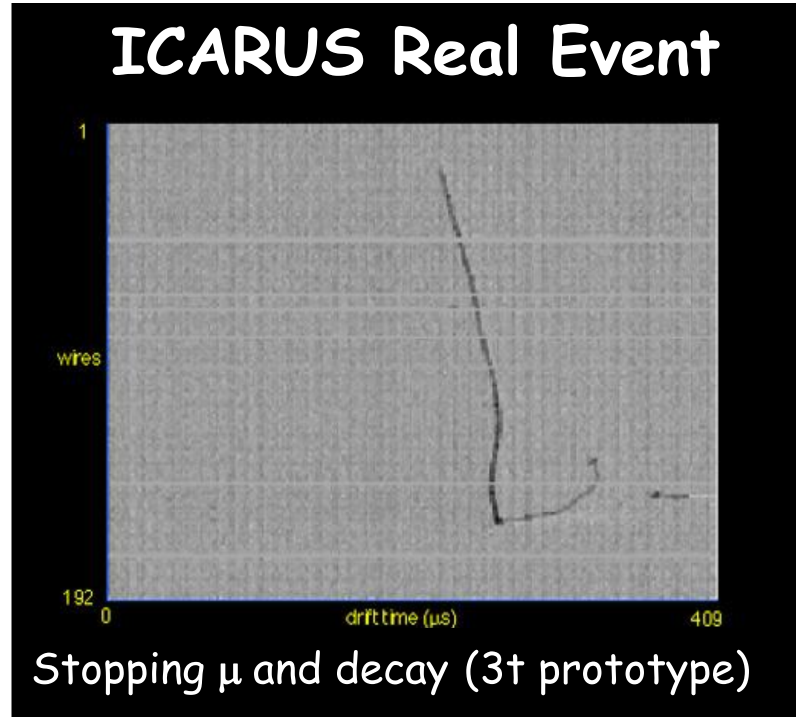
The ICARUS LArTPC Technology

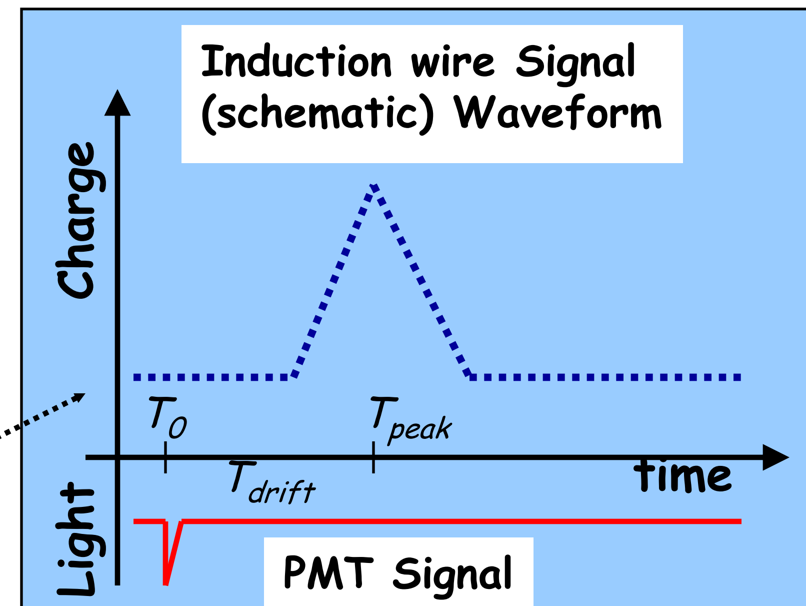




… best suited for ν-Xsect Measurement in the Few-GeV energy range

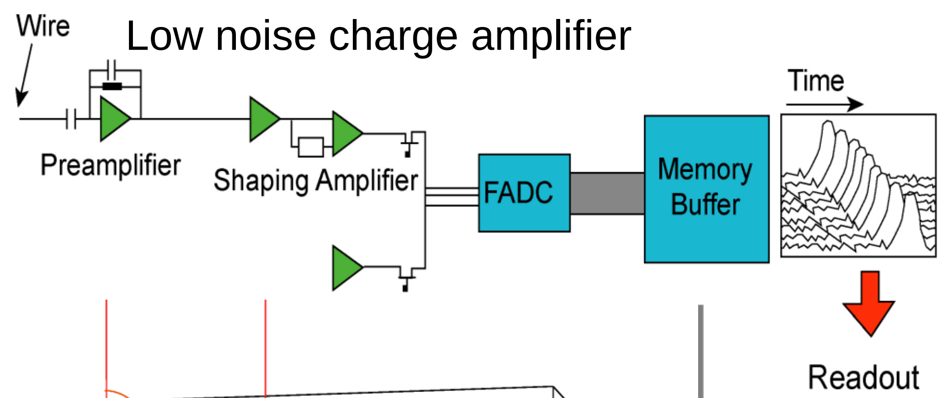

Electric Field
PMT
UV Light
Ionizing Track
Drifting
e-
in LAr
E1
Screen
Grid
wire pitch
d E2
Induction
Plane
Amplifier
d E3
Collection
Plane


ICARUS Real Event
1
wires
192
0
drift time (µs)
409
Stopping µ and decay (3t prototype)


Induction wire Signal
(schematic) Waveform
Charge
T0
Tpeak
Tdrift
time
Light
PMT Signal

The ICARUS LArTPC technology

Multiple non-destructing read-out wire planes can be assembled for 3D event reconstruction.

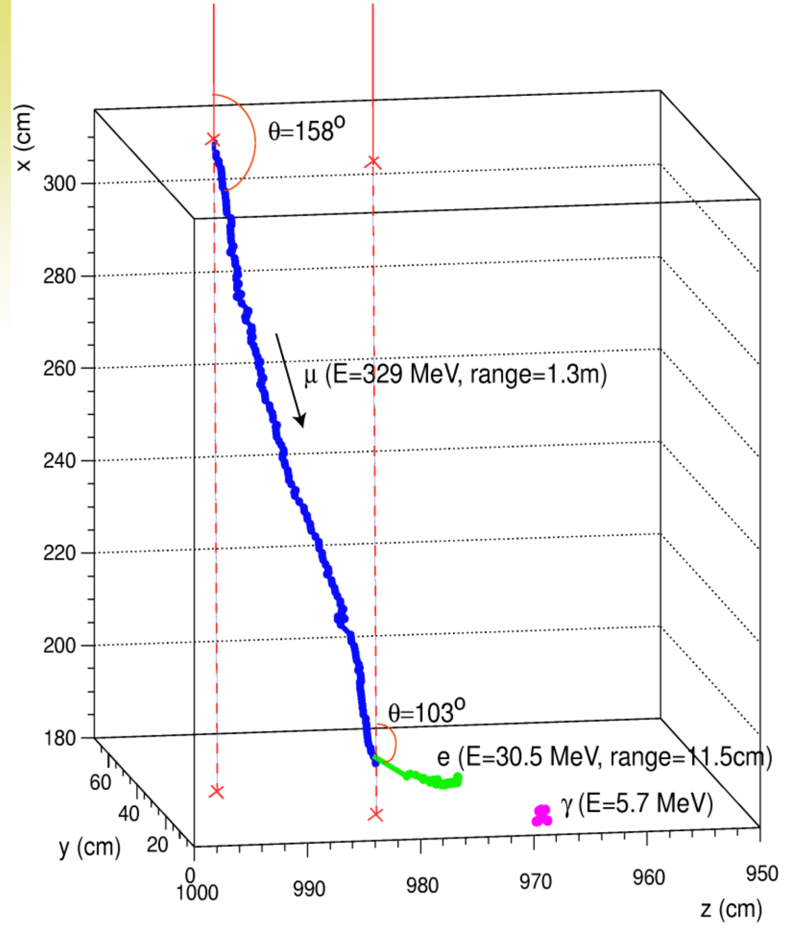


The ICARUS LArTPC technology provides spectacular *Imaging* capabilities...

Real Event:

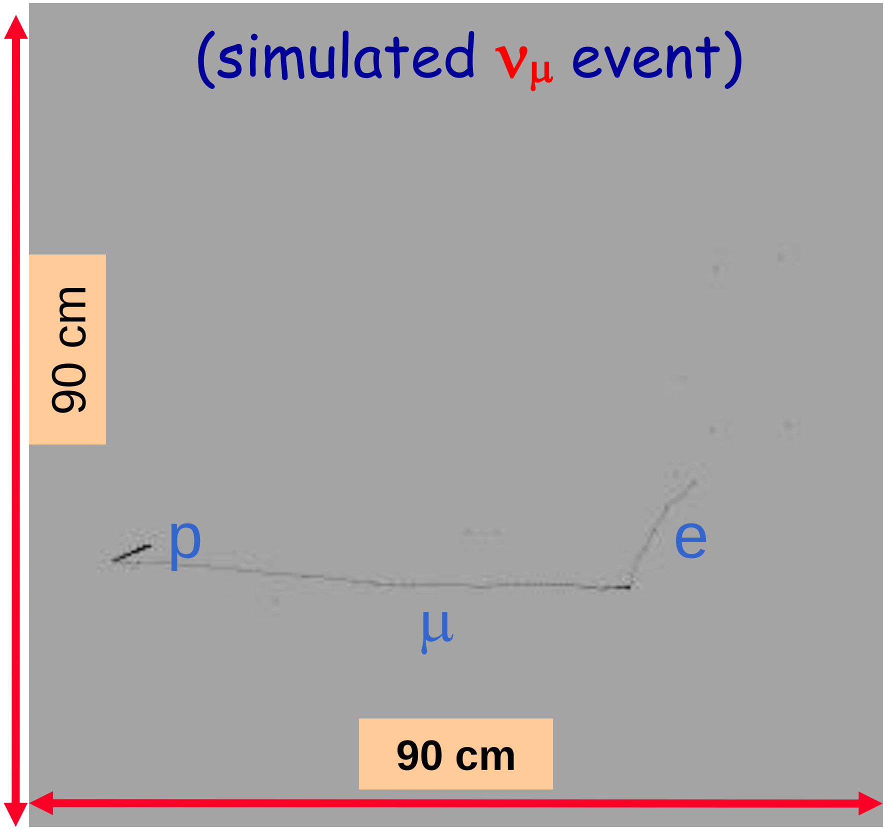
(Cosmic) Muon decay

3D software reconstruction



The ICARUS LArTPC technology

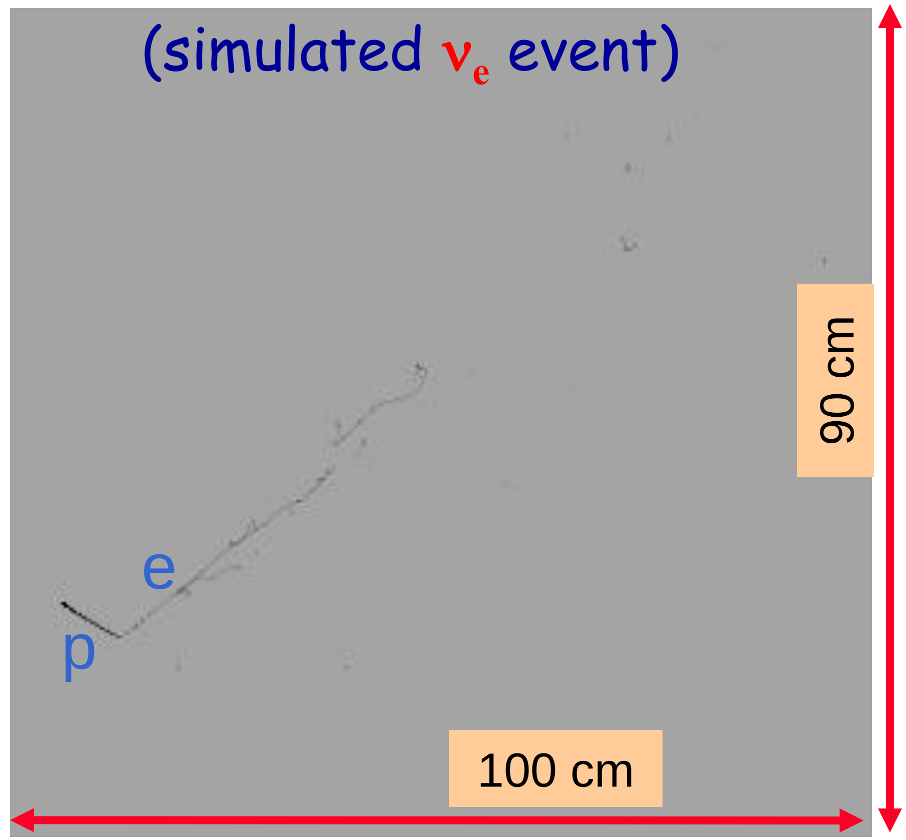
ν events in the "1 GeV" Energy range



ν_μ quasi-elastic interaction

E_ν = 370 MeV

P_μ = 250 MeV **T_p = 90 MeV**



ν_e quasi-elastic interaction

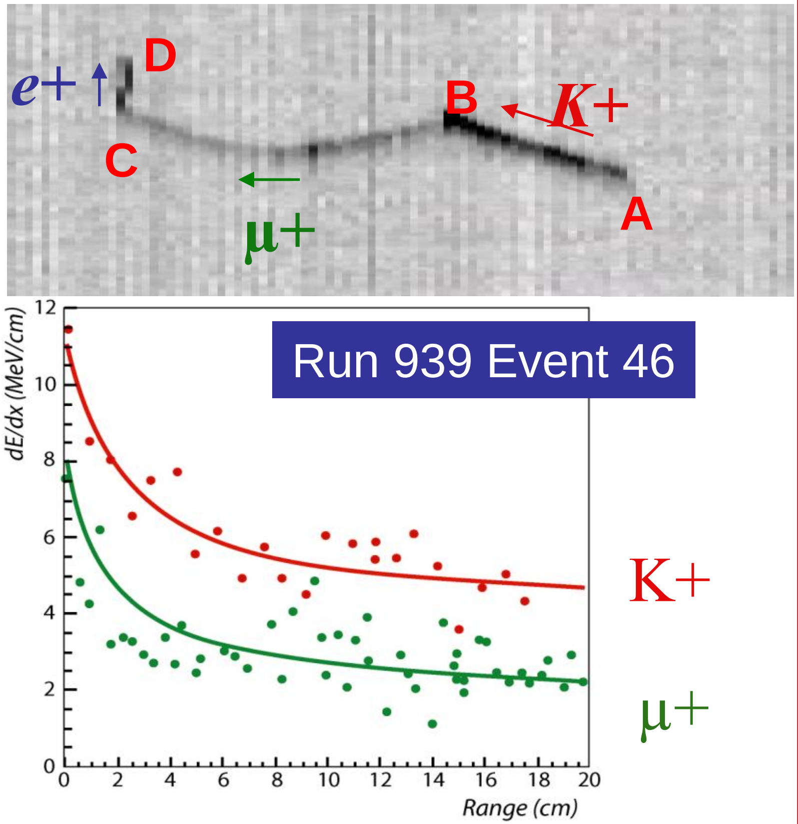
E_ν = 450 MeV

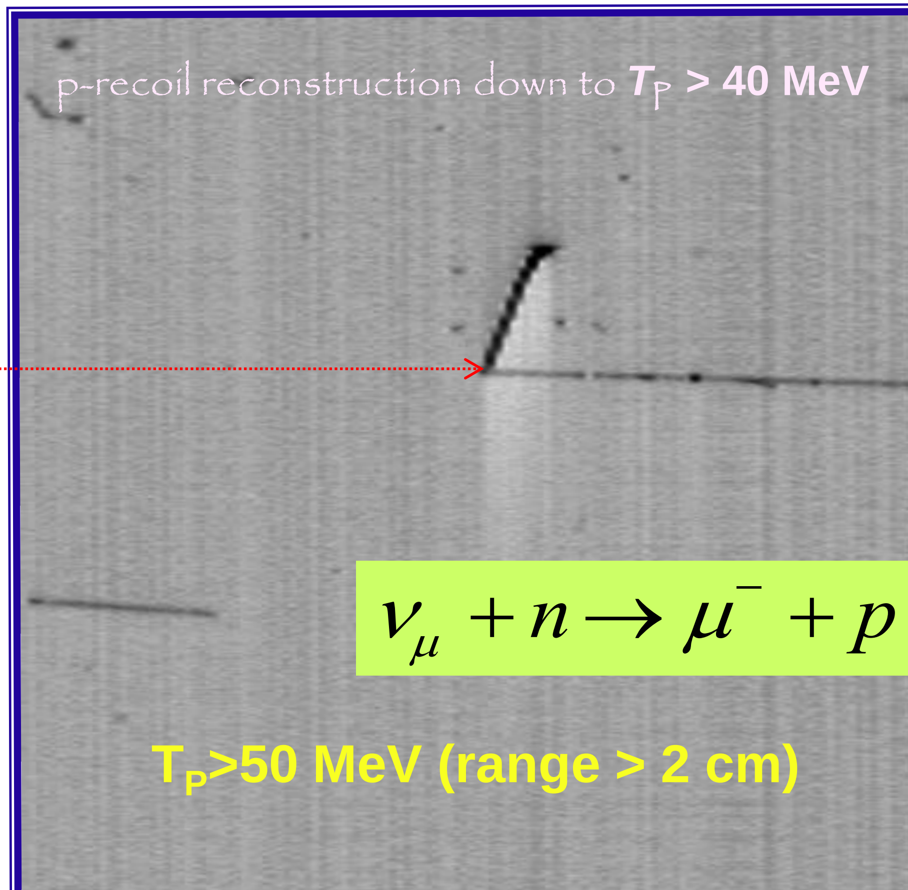
P_e = 200 MeV **T_p = 240 MeV**

The imaging LAr technology best suited to (also)

"Perform a **wide variety** of fundamental-physics studies" in the FeW-Gev energy range.

$$K^{+}[AB] \rightarrow \mu^{+}[BC] \rightarrow e^{+}[CD]$$





Proton Decay **Neutrino Physics**

... with additional high resolution calorimetry and (virtually) unlimited active mass

- Reconstruction of γ-showers

158 MeV

752 MeV

140 MeV

$\theta = 141^{o}$

$M_{inv} = 650$ MeV

$\theta = 25^{o}$

$M_{inv} = 140$ MeV

π^{o} candidate

The ICARUS LArTPC technology

PHYSICAL REVIEW D 74, 112001 (2006)

Performance of a liquid argon time projection chamber exposed to the CERN West Area Neutrino Facility neutrino beam

F. Arneodo,[1] P. Benetti,[2] M. Bonesini,[3] A. Borio di Tigliole,[2] B. Boschetti,[3] A. Bueno,[4] E. Calligarich,[2] F. Casagrande,[5,*] D. Cavalli,[3] F. Cavanna,[1] P. Cennini,[6] S. Centro,[7] E. Cesana,[2] D. Cline,[8] A. Curioni,[3,†] I. De Mitri,[1] C. De Vecchi,[2,7] R. Dolfini,[2] A. Ferrari,[6] A. Ghezzi,[3] A. Guglielmi,[7] J. Kisiel,[9] G. Mannocchi,[10] A. Martínez de la Ossa,[4] C. Matthey,[8] F. Mauri,[2] C. Montanari,[2] S. Navas,[4] P. Negri,[3] M. Nicoletto,[7] S. Otwinowski,[8] M. Paganoni,[3] O. Palamara,[11] A. Pepato,[7] L. Periale,[10] G. Piano Mortari,[1] P. Picchi,[5,12] F. Pietropaolo,[7] A. Puccini,[6] A. Pullia,[3] S. Ragazzi,[3] T. Rancati,[3] A. Rappoldi,[2] G. L. Raselli,[2] N. Redaelli,[3] E. Rondio,[13] A. Rubbia,[14] C. Rubbia,[2] P. R. Sala,[3] F. Sergiampietri,[15] J. Sobczyk,[16] S. Suzuki,[5,12,‡] T. Tabarelli de Fatis,[3] M. Terrani,[2] F. Terranova,[3] A. Tonazzo,[3] S. Ventura,[7] C. Vignoli,[2] H. Wang,[8] and A. Zalewska[17]

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(Received 25 September 2006; published 14 December 2006)

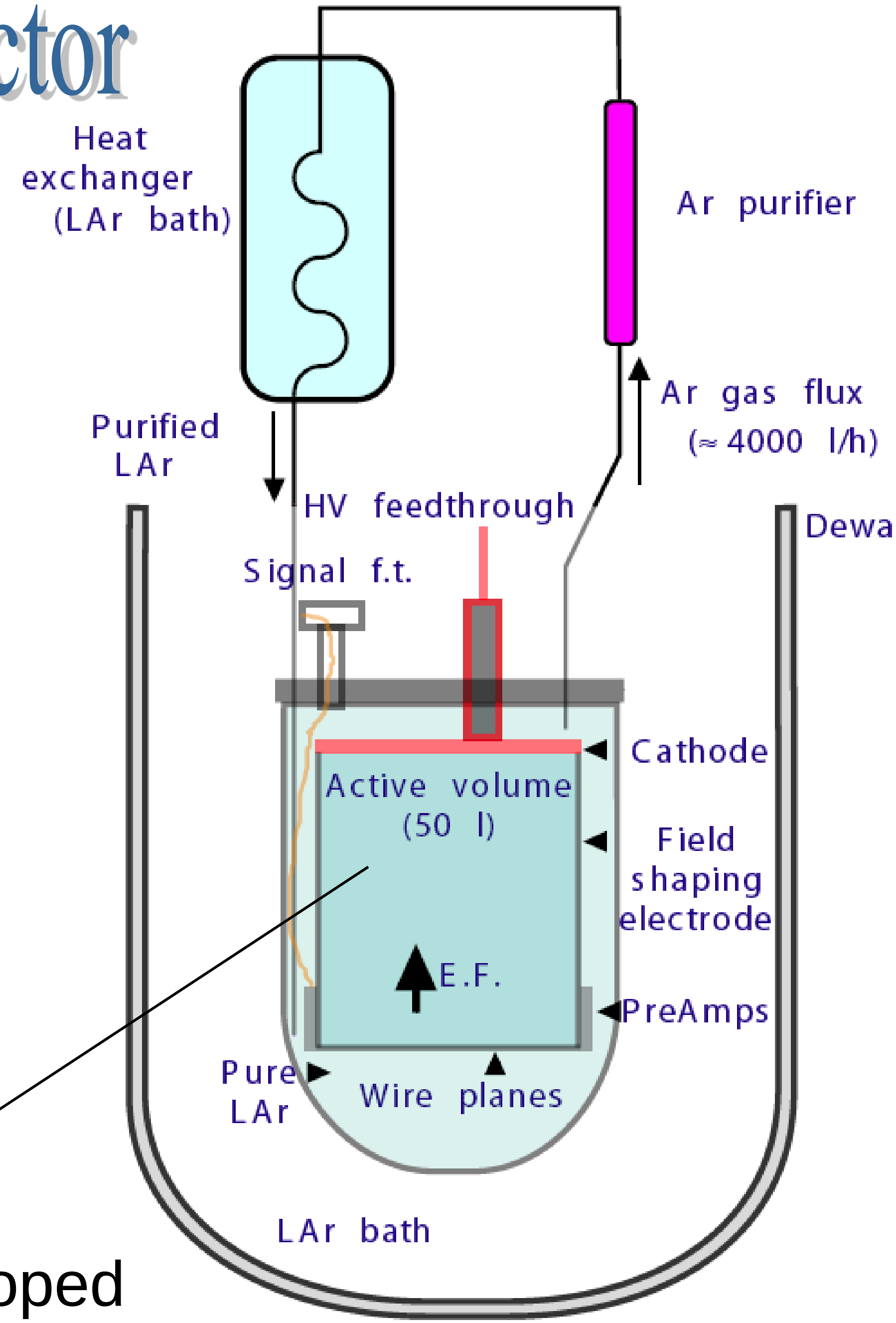
and

the quasi-elastic muon neutrino charged current cross section reconstruction

ICARUS Internal Note: unpublished

The ICARUS 50 lt Detector

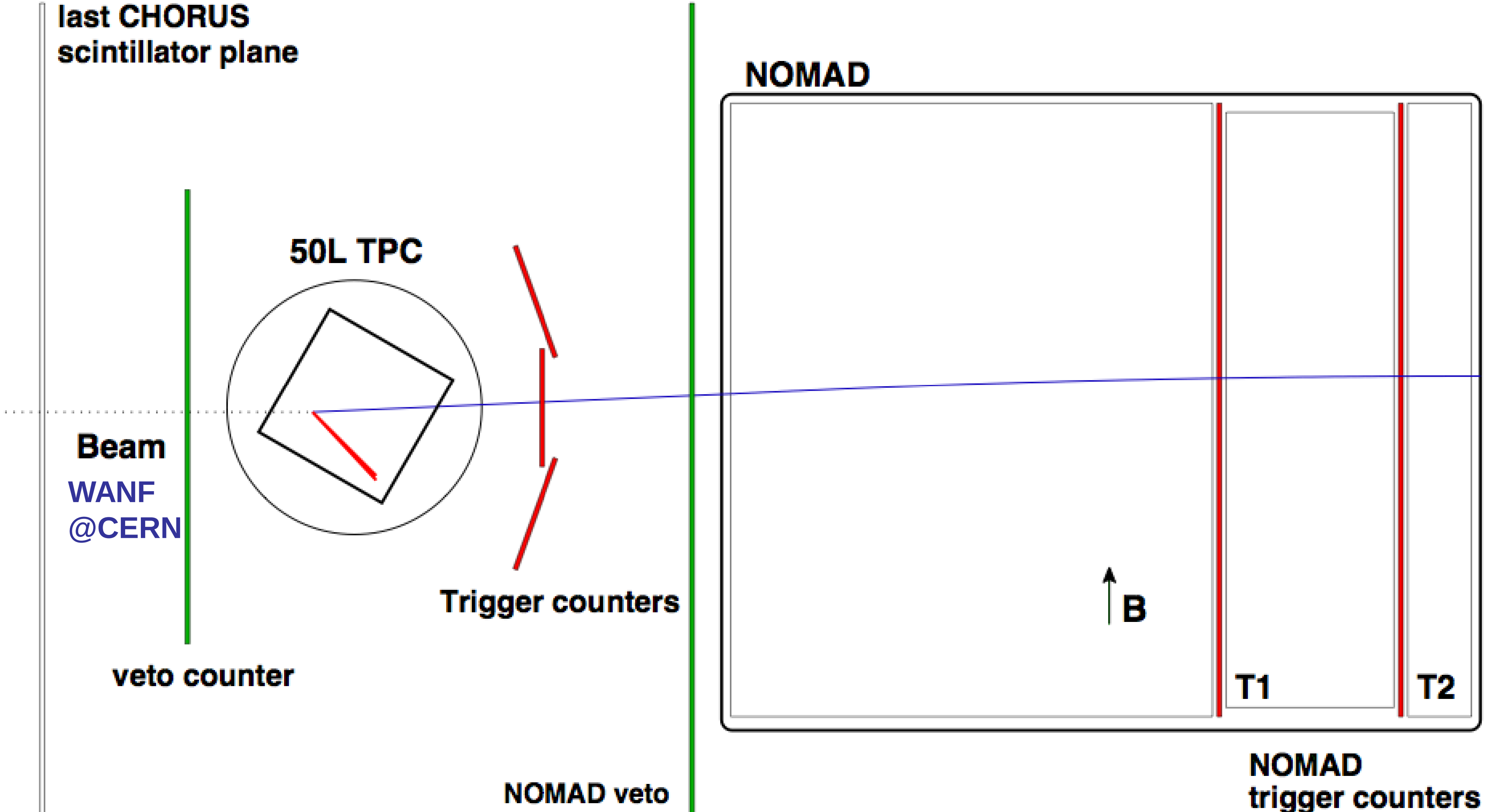
Experimental set-up



LAr-TMG doped

CERN 1998

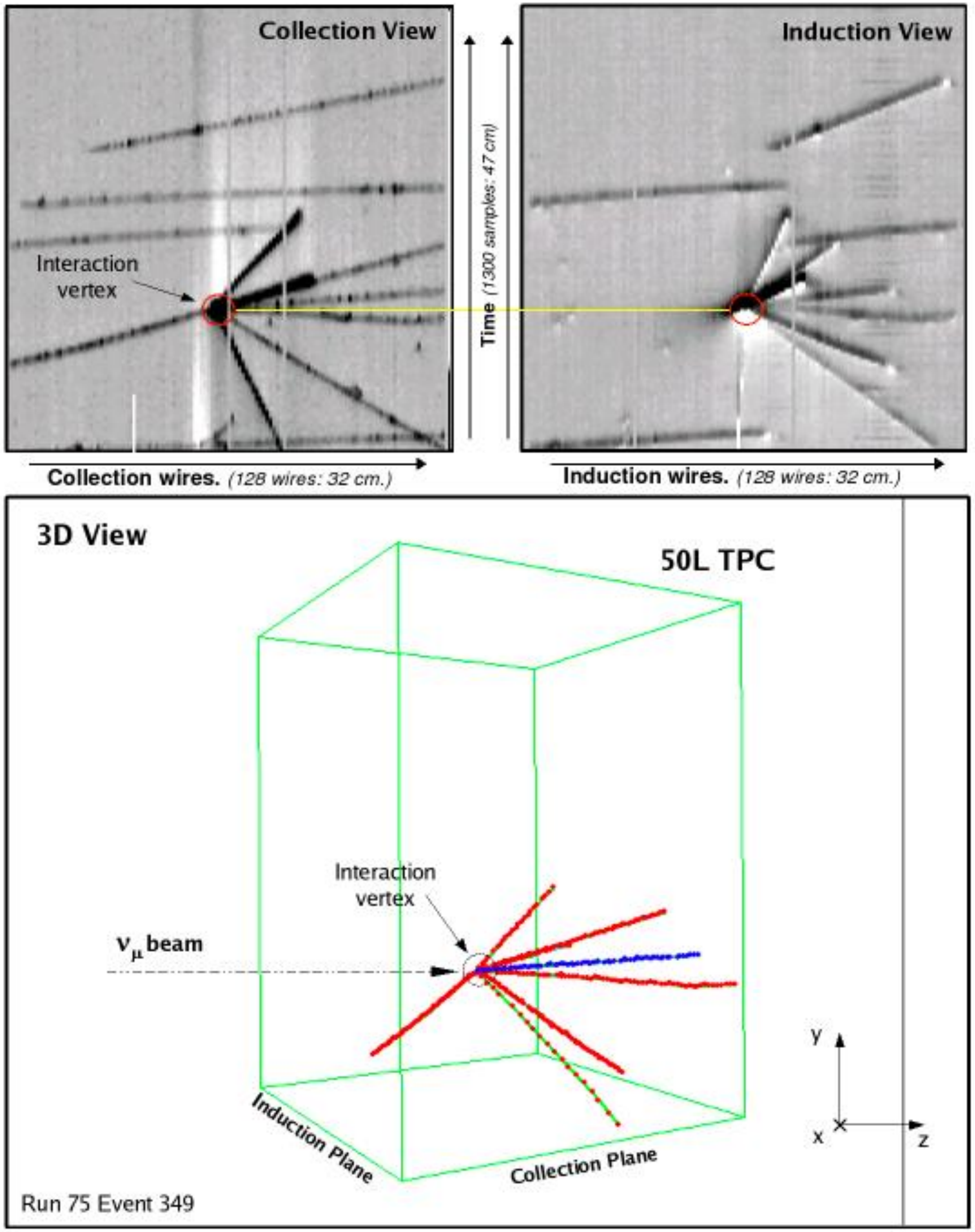
The ICARUS 50 lt Detector



50 lt Detector backed by NOMAD exp. (magnetic spectrometer)

Trigger: (*SPS beam spill*.AND.*ScintCount*.AND.*(T1+T2*)).NOT.(*Chorus*.AND.*Veto*)

The ICARUS 50 lt Detector



2D views and

3D reconstruction of DIS event

MC simulation

- GEANT4: ICARUS 50lt+NOMAD det.
- NUX+FLUKA: evt. generator

The ICARUS 50 lt Detector

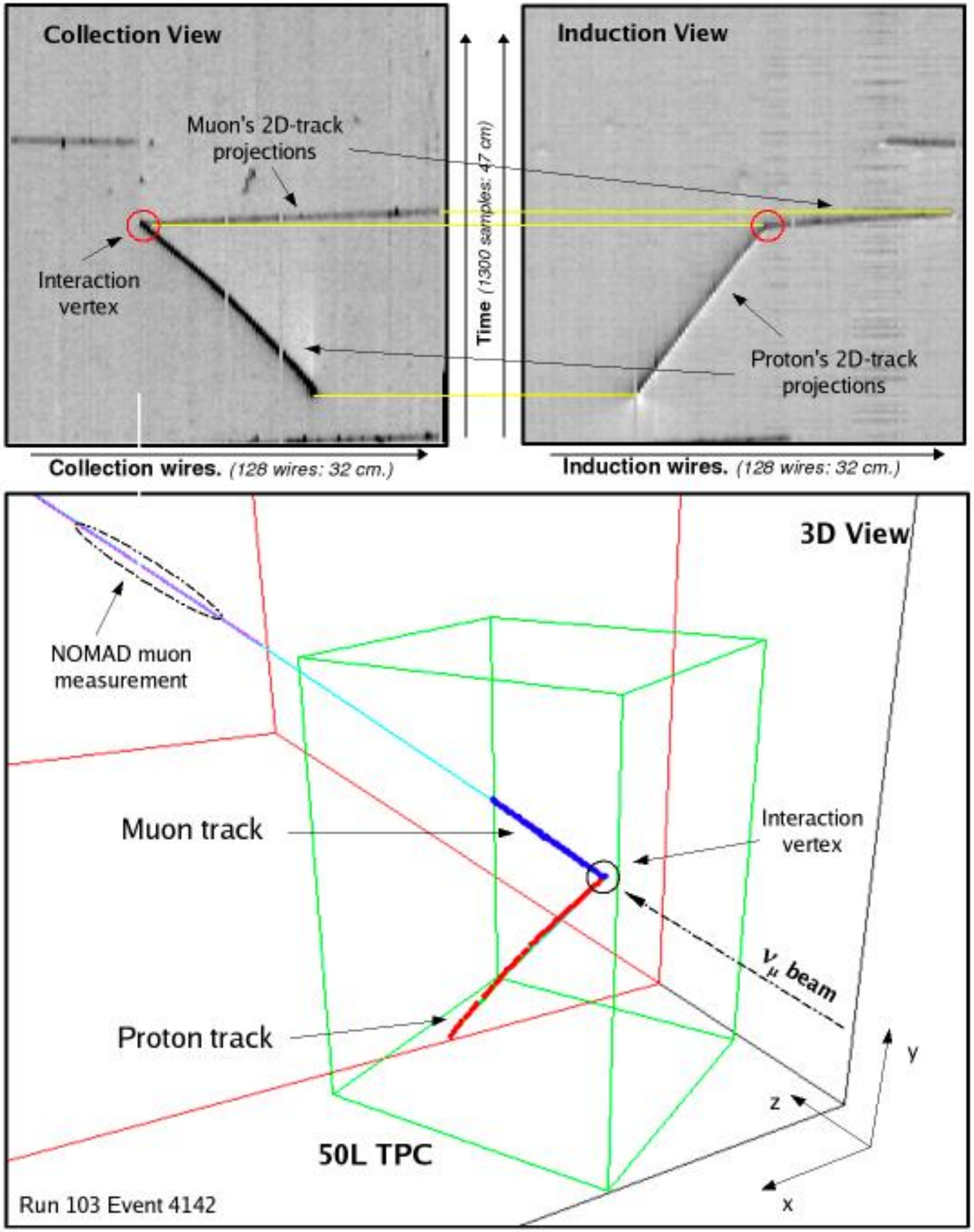
DATA taking and selection

- Neutrino flux (from the simulation of the beam): $\Phi = 2.37 \times 10^{-7}\ \nu_\mu/cm^2/pot$

  [WANF beam: $\langle E_\nu \rangle$ = 28 GeV, r.m.s=18 GeV]
- Total exposure $E_{xp} = 1.2 \times 10^{19}$ pot - (fid vol.~50lt $\Rightarrow$ $\mathbf{N}_{fid} = 2.167 \times 10^{28}\ n_{targ}$)
- Effective livetime T_{live}= 75% (NOMAD dead-time).
- ➔ ~10000 ν_μ-CC in Fid. Vol.
  - **QE selection (Golden sample):**
    - fully cont. ***p***, E_p>40MeV + $\boldsymbol{\mu}$ (Nomad direct. reconstr. matching in 50lt)

      ➔ **N=86** (include contamination RES+DIS: π absorp.)
  - Contamination estimated by MC *(preliminary)* ➔ N^{QE} = 67±8
  - Fraction of tot-QE in Golden sample estimated by MC *(preliminary)*:

    ➔ $\mathbf{G}^{QE}$ = 16% *(warning: sensitive to FSI !!)*
  - Acceptance for QE: Acc^{QE} = 96%



The ICARUS 50 lt Detector

2D views and

3D reconstruction of QE event

Background Evt.

The ICARUS 50 lt Detector

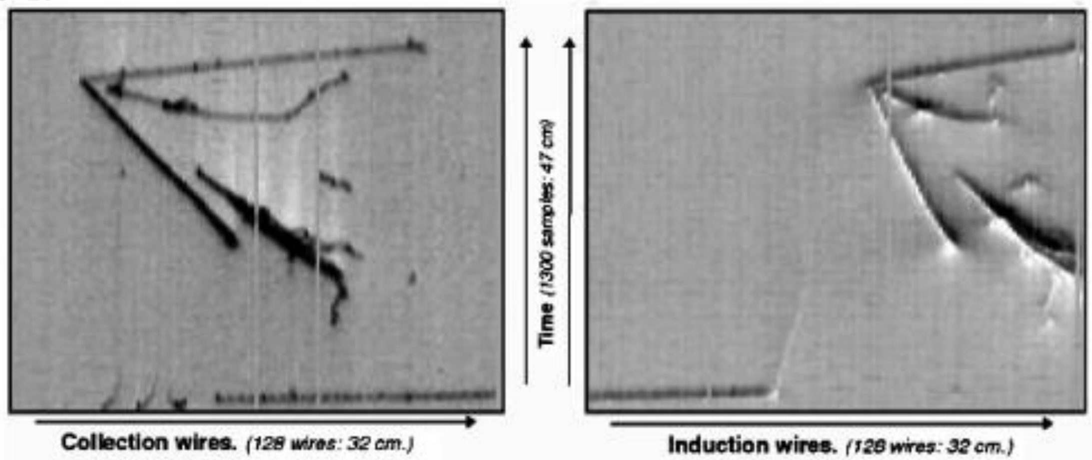


FIG. 9. The raw image of a low-multiplicity event in the collection (left) and induction plane (right). The event is reconstructed as $(\nu_\mu n \rightarrow \mu^- \Delta^+ \rightarrow \mu^- p \pi^0)$ with a mip leaving the chamber, an identified stopping proton and a pair of converted photons from the π^0 decay. When these photons escape from the chamber, the event is tagged as a "golden event."

more detailed study to be performed…

<ins>Irreducible (intrinsic) Background:</ins>

- RES production+FSI (π absorption)

  ν_μ p ⌫ Δ μ ⌫ μ $\cancel{p}$ π

  ν_μ n ⌫ Δ μ ⌫ μ $\cancel{p}$ π^0

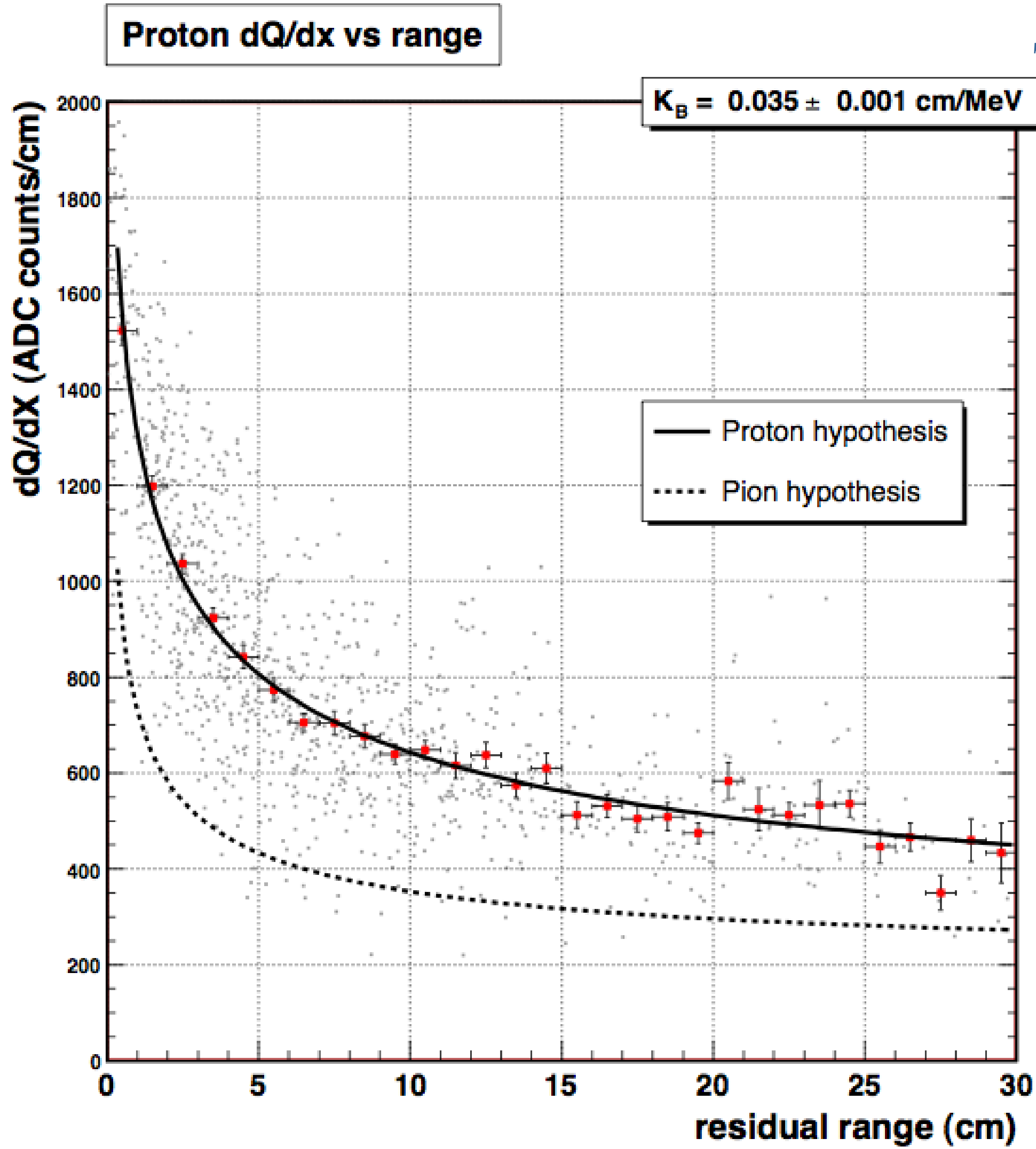
- <ins>Instrumental Background:</ins>

  (π^0,n,γ) escape (as in Fig)

<ins>Background:</ins>

ν_μ n ⌫ Δ μ ⌫ μ n π
easily removed by
π/p PID capability

The ICARUS 50 lt Detector

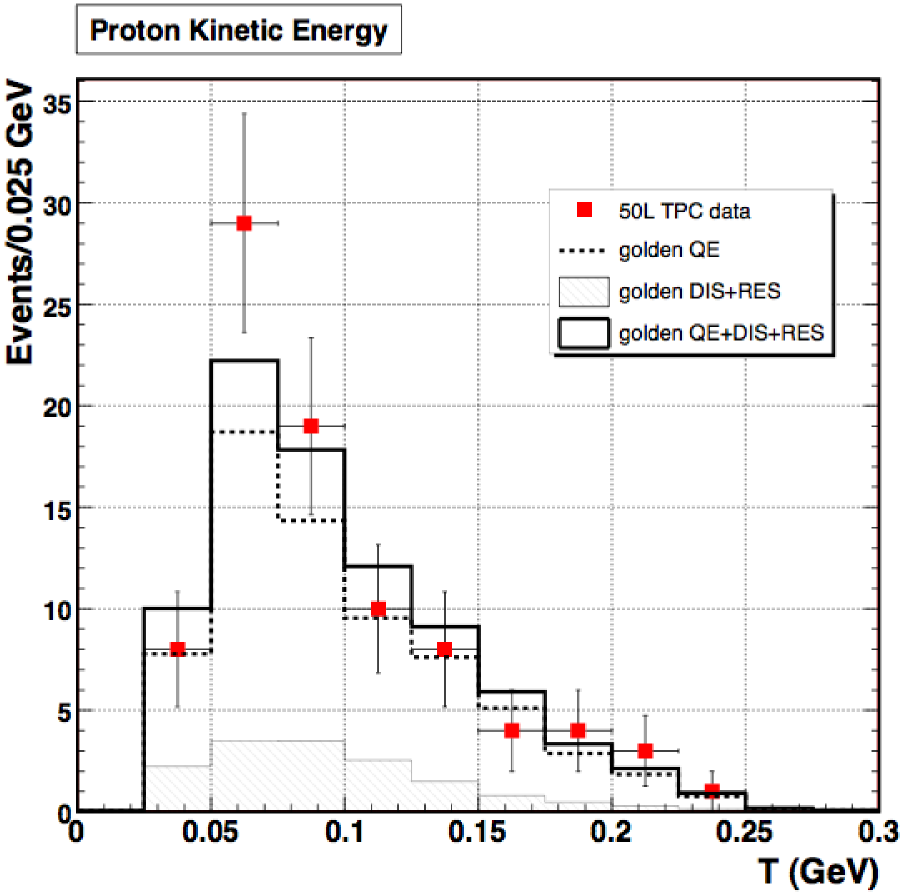


Ptcl. ID

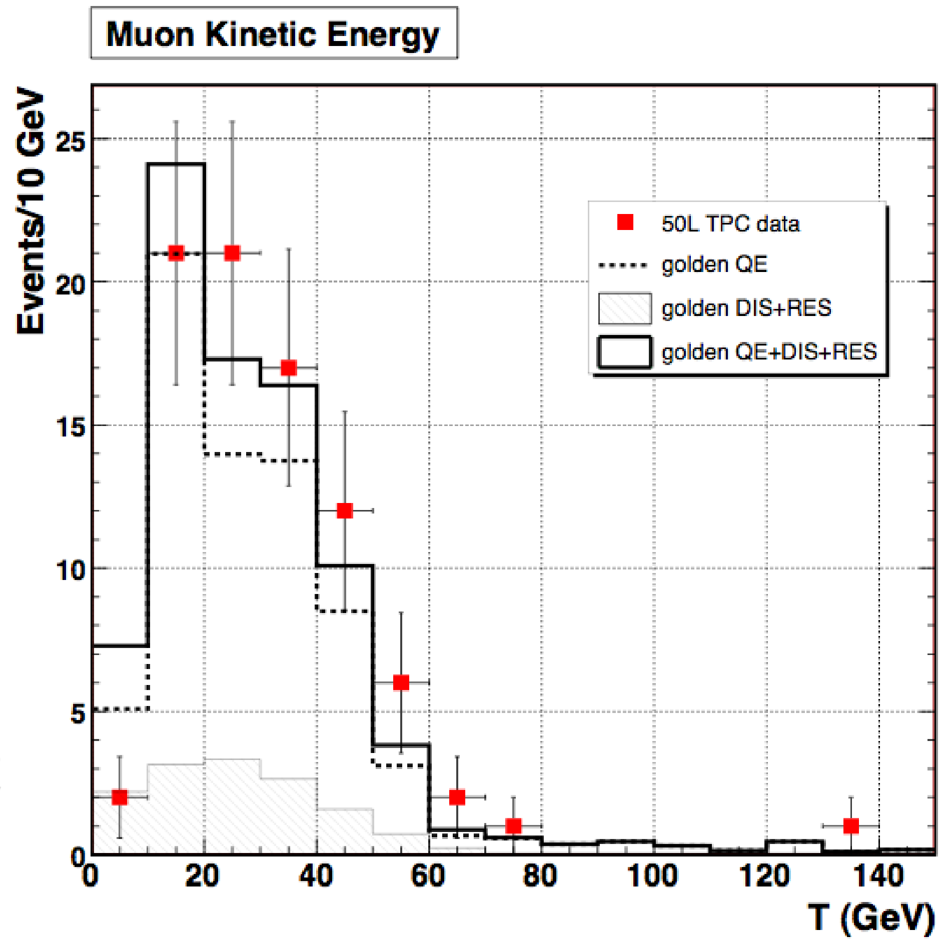
Proton track recognition

Proton reconstruction and momentum measurement performed using only TPC information

Energy Reconstruction for Muon and proton

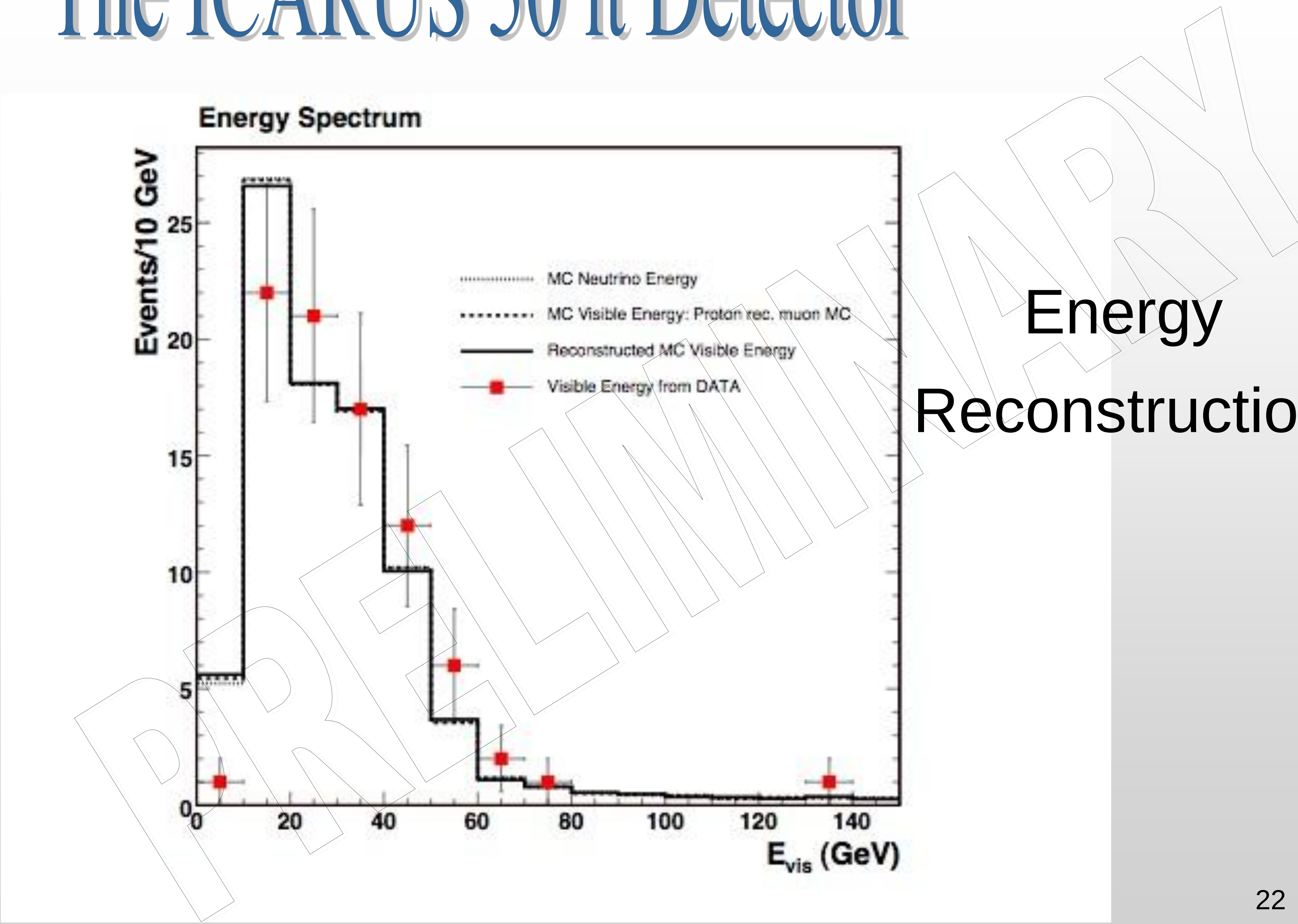


Kinematic reconstruction of the outgoing muon performed using the tracking capability of NOMAD and traced back to the TPC.



Proton reconstruction and momentum meas. performed using only TPC information. Kinetic energy calculated from range.

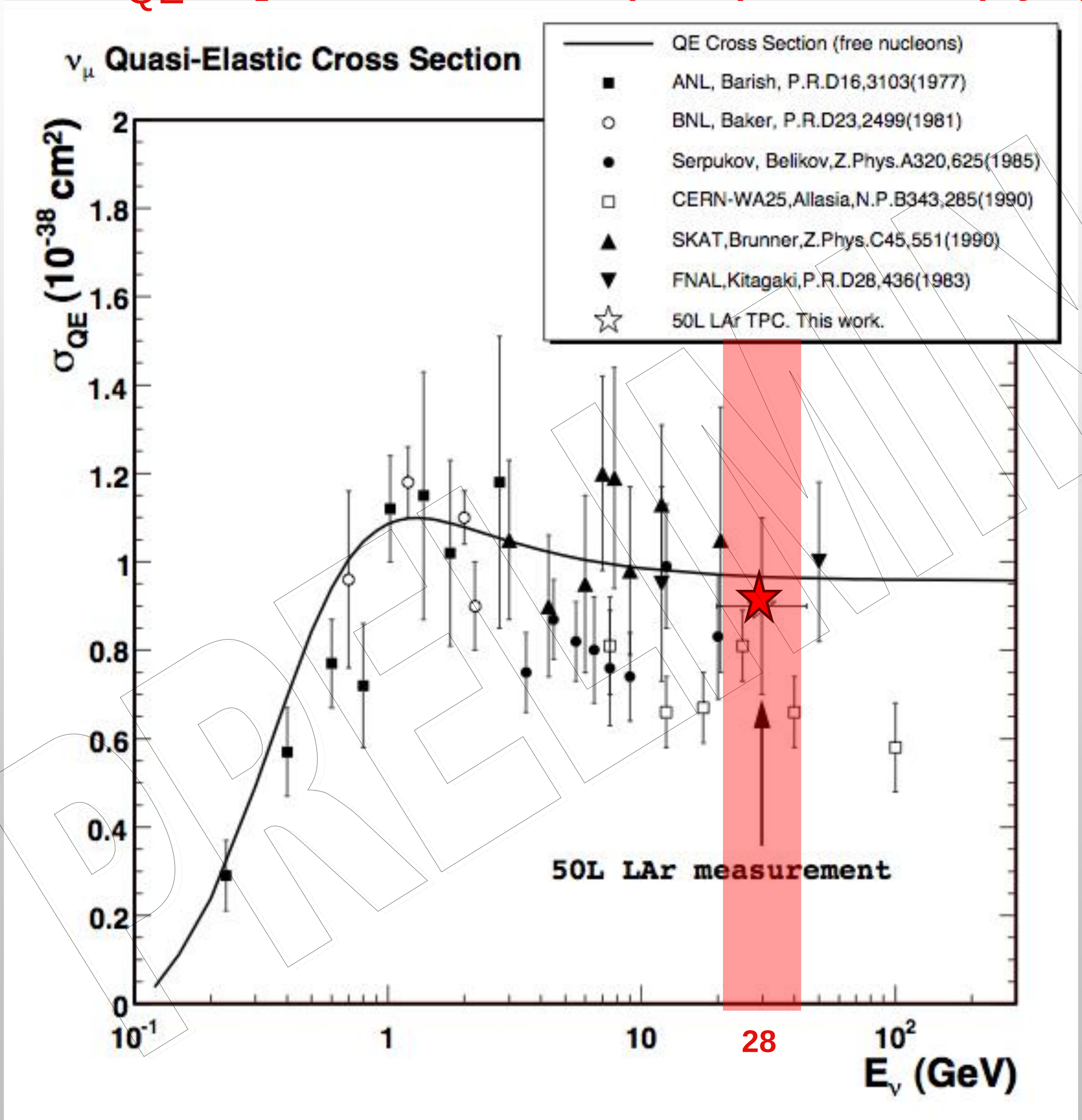
The ICARUS 50 lt Detector



Energy Reconstruction

QE Xsection: $$\sigma_{QE} = \frac{N^{QE}}{\Phi \times E_{xp} \times N_{fid} \times T_{live} \times Acc^{QE} \times \mathcal{G}^{QE}}$$

$\sigma_{QE} = [\, 0.90 \pm 0.10\ (stat) \pm 0.18\ (sys)] \times 10^{-38}\ cm^2$



The ICARUS 50 lt Detector

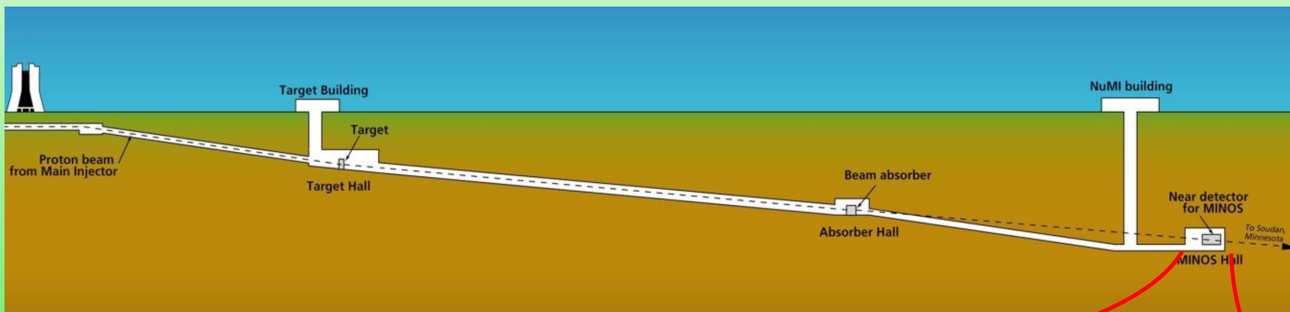
The ArgoNeuT Experiment

see M. Soderberg's Talk

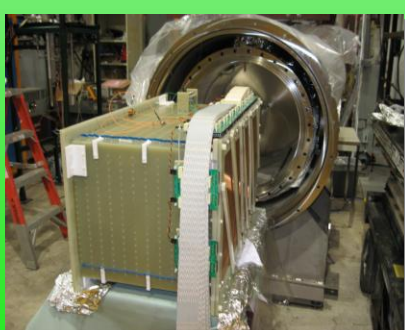
ArgoNeuT is a joint NSF/DOE R&D project at Fermilab (USA) to expose a small (175 lt active) LAr-TPC to the NuMI low energy neutrino beam. Detector is under installation, with data taking expected in March 2009.

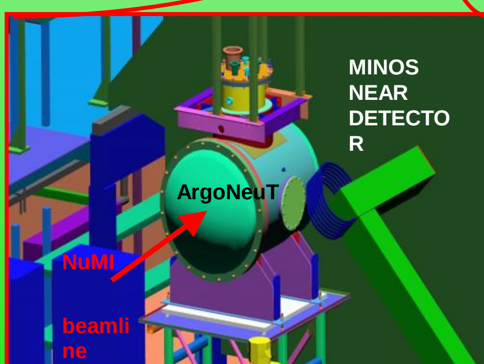
The NuMI Beam (Neutrinos at the Main Injector) serves the MINOS NEAR and FAR detectors (1km and 735km from the target respectively). ArgoNeuT will sit upstream of the MINOS near detector in the NuMI Tunnel – 100m underground, allowing for calibrations via muons escaping the TPC and penetrating into MINOS ND.

By taking data in the 0.1 to 10 GeV range, ArgoNeuT will produce the first ever data for low energy neutrino interaction in a LArTPC.



TPC about to enter cryostat





ArgoNeuT Collaboration

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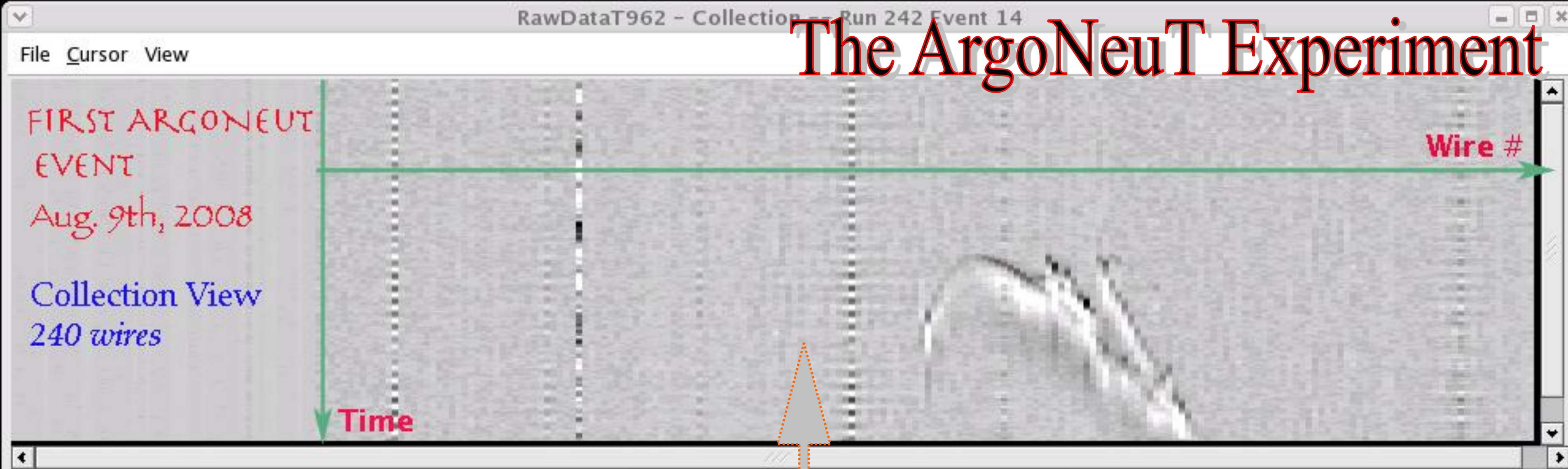
University of L'Aquila

The ArgoNeuT Experiment

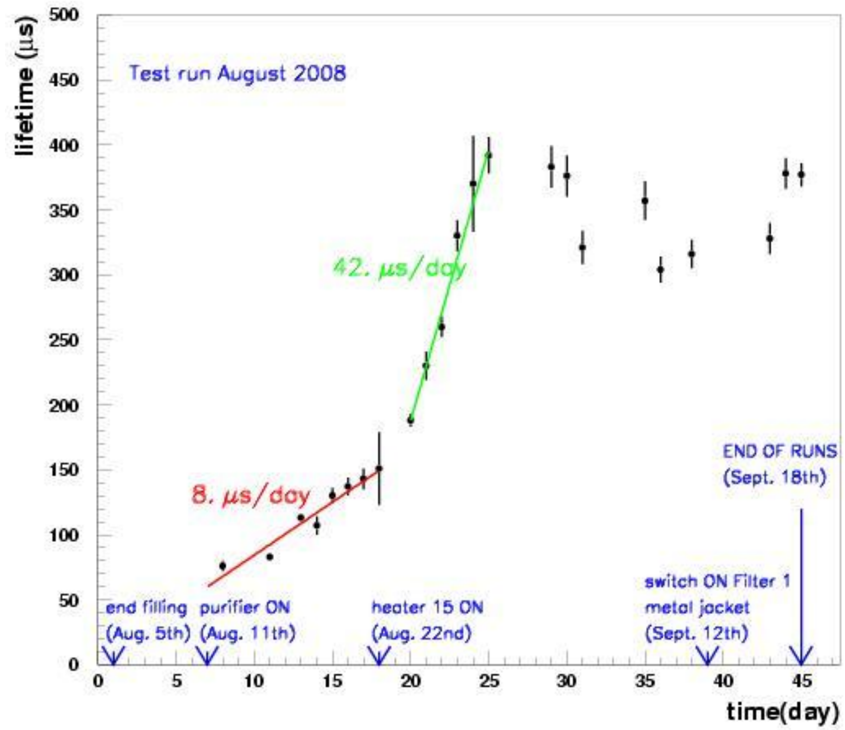


Detector Commissioning

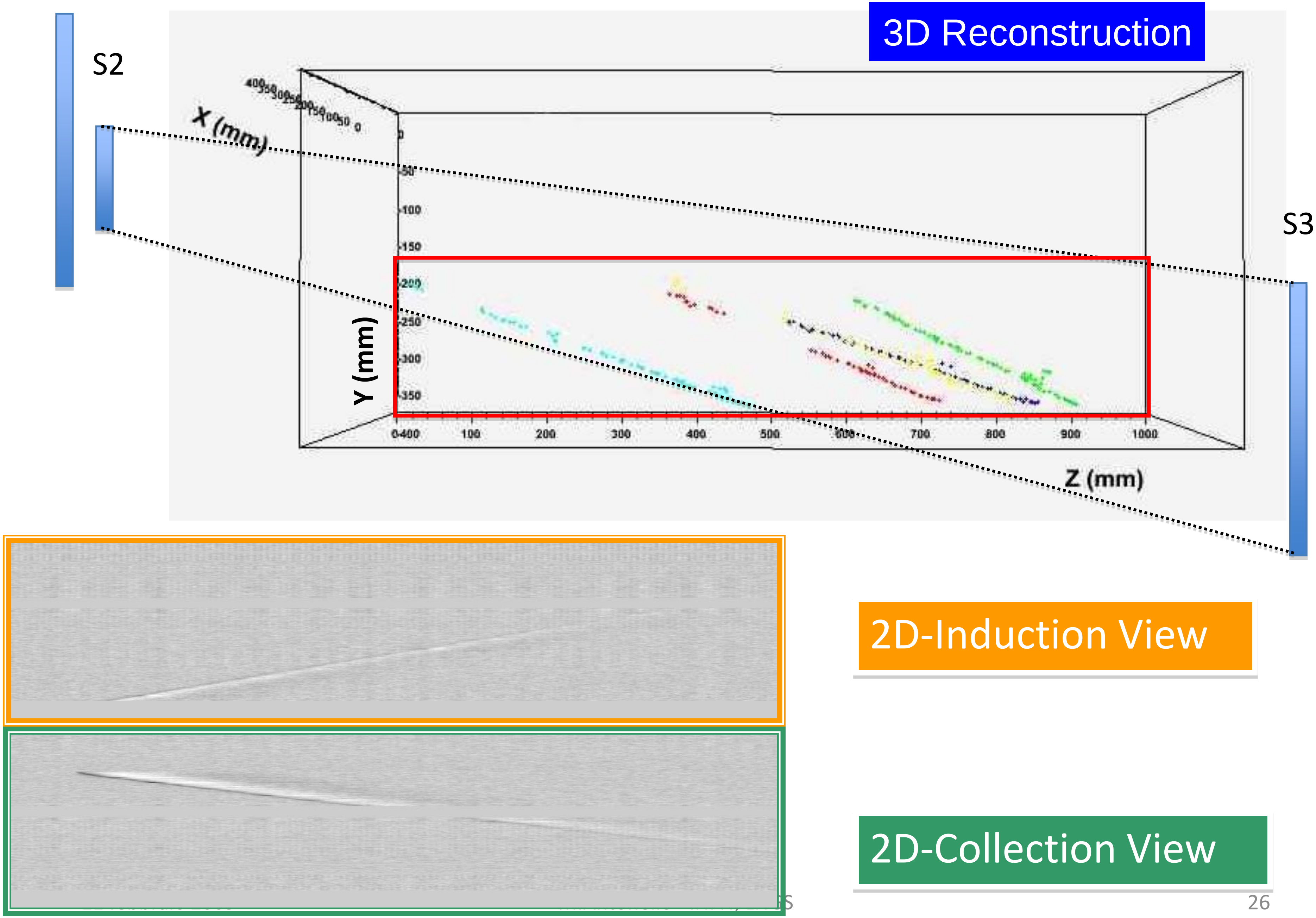
LAr filling: Aug.4th

⇓

… first tracks recorded: Aug 9th !!



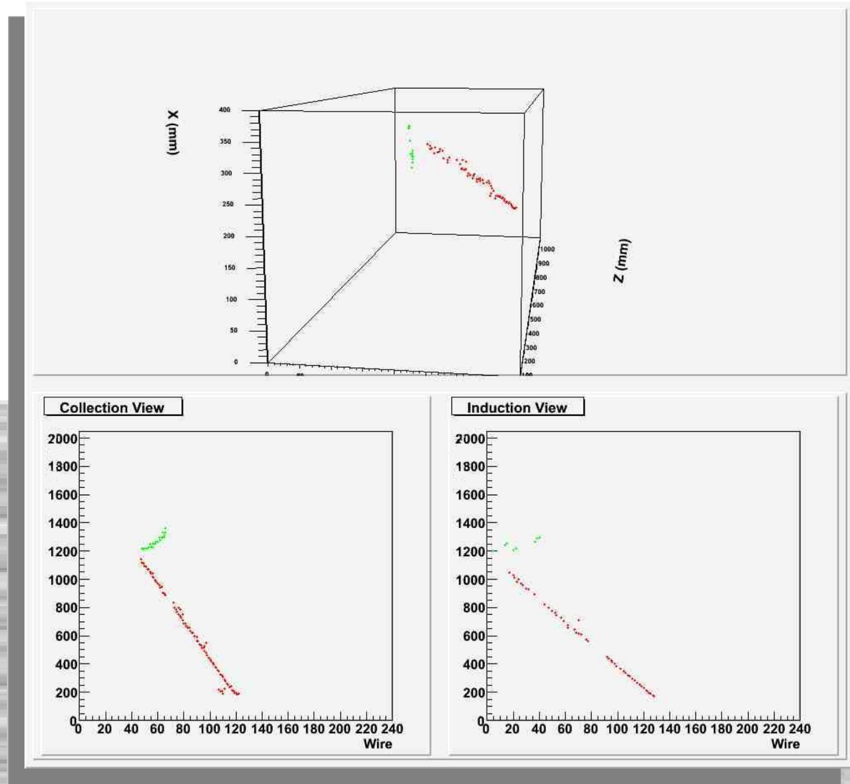
crossing muonsTOP VIEW



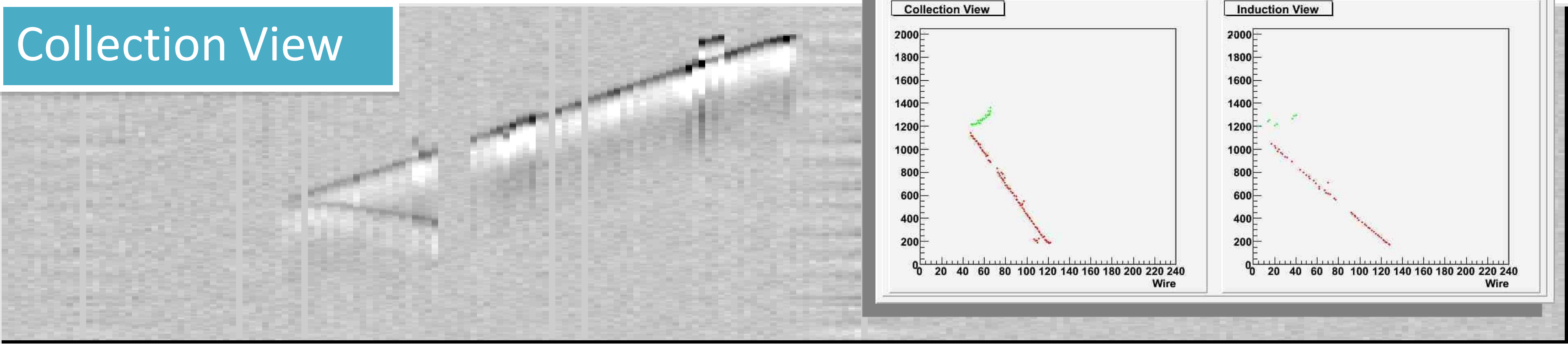
The ArgoNeuT Experiment

“Neutrino-like” event:

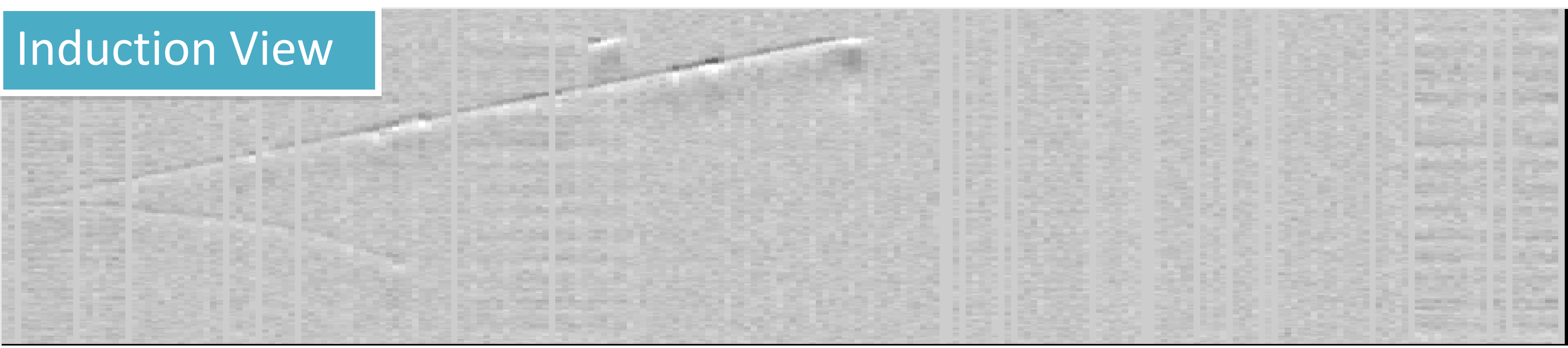
Run 422 Event 13



Collection View



Induction View



The ArgoNeuT Experiment

The QE ν_μ X-sect:Experimental Measurement

$$\sigma_{QE} = \frac{N^{QE} \quad (= N - N^{nQE})}{\Phi \times E_{xp} \times N_{fid} \times T_{live} \times Acc^{QE} \times \mathcal{G}^{QE}}$$

μ p

1. $\Phi_{\nu_\mu}(E_{\nu_\mu})$
2. N_{QE}
3. E_{ν_μ}

Acc^{QE} (geometric) Muon Acceptance (86 % - ArgoNeuT-MINOS_ND)

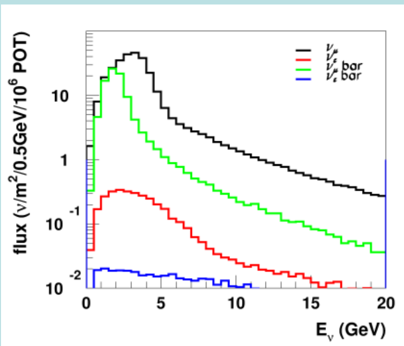
G^{QE} *Proton-rec "Acceptance-Efficiency" -*

- T_p threshold (40 MeV, possibly lower - LArTPC feature)
- containment (54%, ArgoNeuT feature)
- FSI !!! (charge exchange/absorption, kinem. mod's) - need lot MC assumptions/study

N^{nQE} determined from RES-DIS Xsect. (need again MC info)

1. The NuMI Beam Flux

Low Energy running mode



ν_μ mean energy ≈ 3.7GeV

Intensity:

Φ_ν = 3 x $10^{10}\nu/cm^2$ for 10^{18} PoT

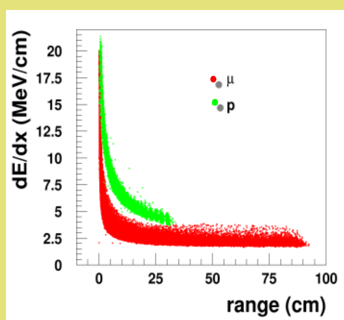
with 1.4 x 10^{20}PoT in 6 months

Beam Systematics ~ 5 to 10 %

2. PID with the LArTPC

The LArTPC technology has good capability to identify and reconstruct low multiplicity neutrino interactions such as QE ν_μ reaction.

Particles are identified by dE/dx vs range reconstruction.



3. $E\nu_\mu$ reconstruction with the ArgoNeuT detector

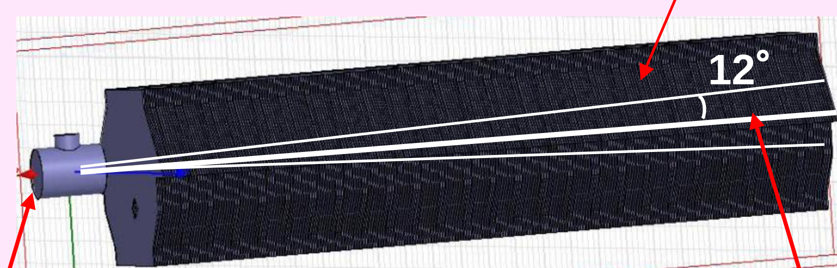
$E\nu_\mu$ can be reconstructed from the kinematics of ***p*** and ***μ*** in the final state:

p → 54% of ***p'***s are completely contained in ArgoNeuT. ***p*** energy can be reconstructed by calorimetric measurement along the track.

μ → muons escape ArgoNeuT. If track length inside LAr is at least 1m, energy can be recostructed through multiple scattering effect.

86% of **μ**'s enter the MINOS NEAR Detector. ArgoNeuT will profit of MINOS energy recostruction capability to recover these events.

47% of QE events have the ***p*** completely contained and the **μ** entering **MINOS ND**



ArgoNeuT Detector

NuMI Beam Axis

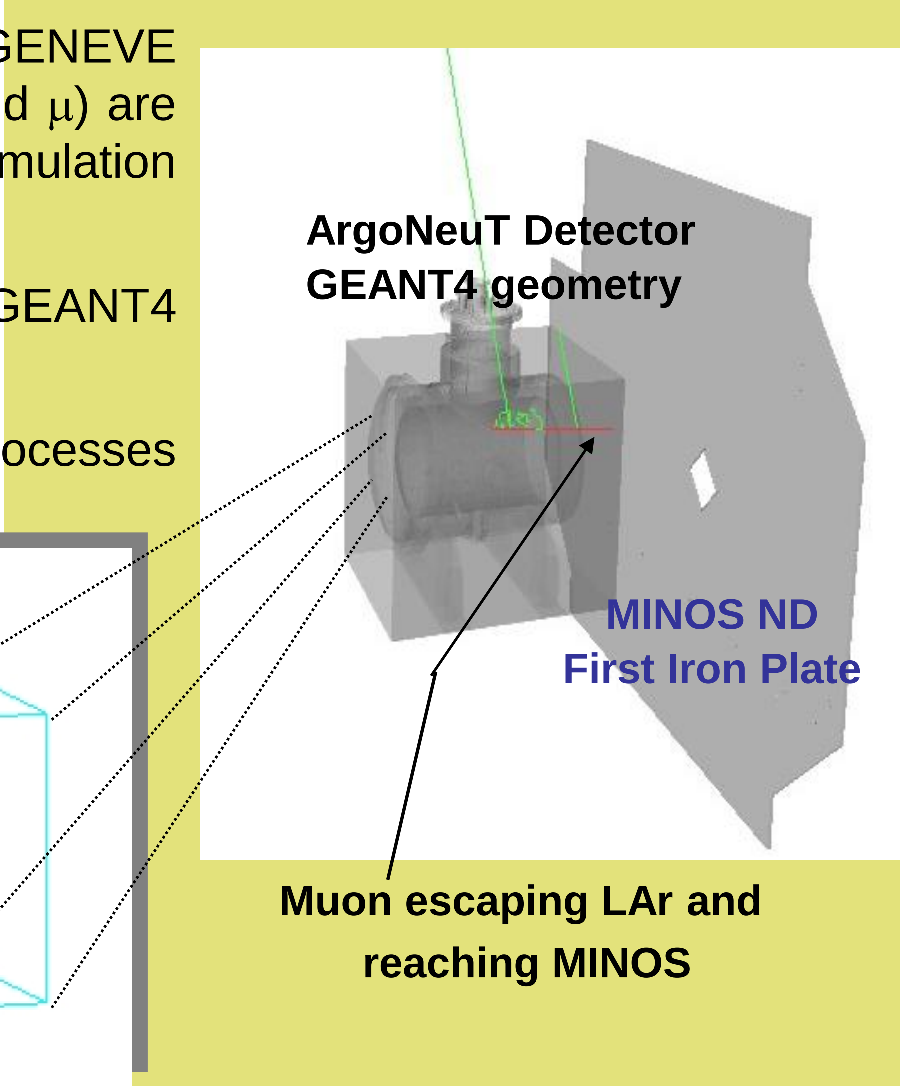
Feasibility Study for a QE ν_μ X-sect Measurement

QE ν_μ CC events MC simulation in ArgoNeuT:

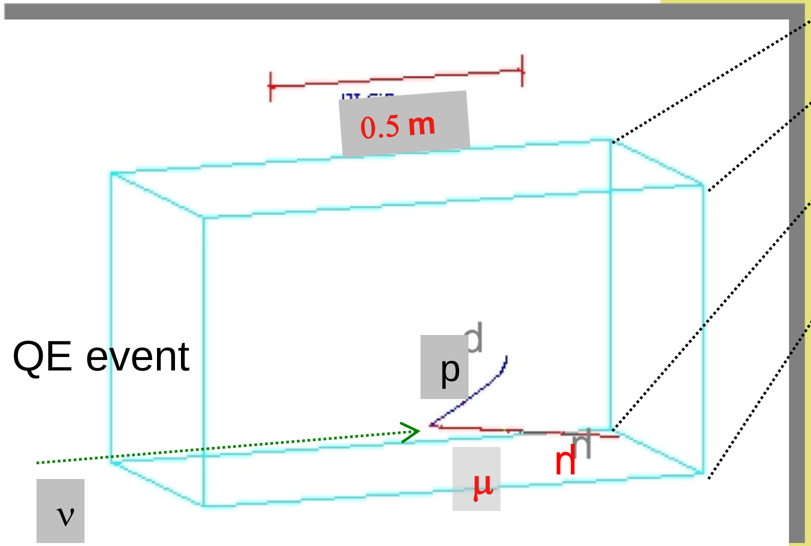
-Physical Events are generated with the GENEVE MC code. The final state particles (p and μ) are used as Primary Events in a GEANT4 simulation of the ArgoNeuT detector.

-Detector Geometry is imported into GEANT4 from CAD Project.

-Hadronic and electromagnetic processes activated

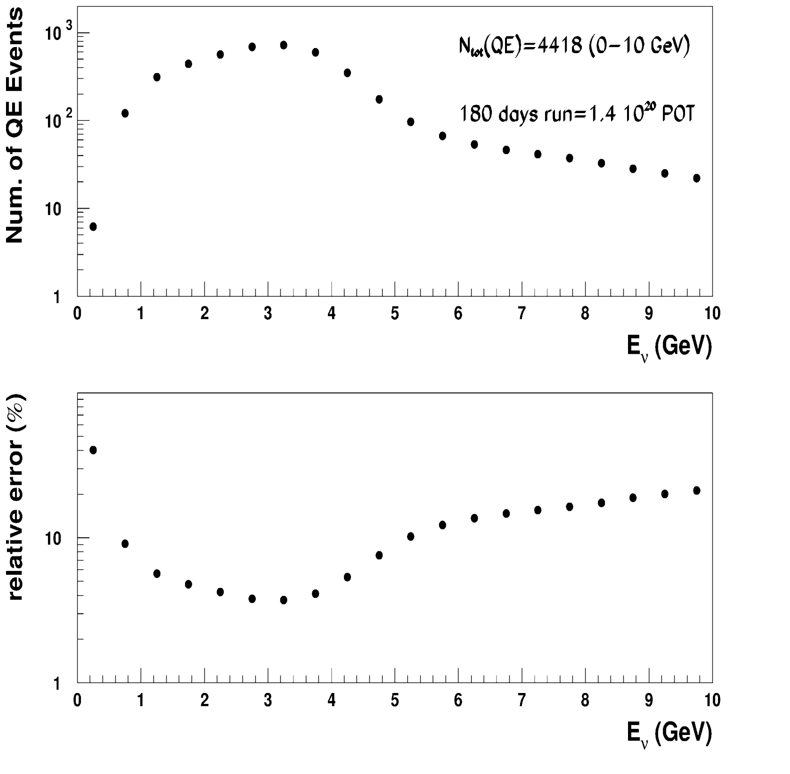


Monte Carlo QE event



The ArgoNeuT Experiment

The ArgoNeuT Experiment Expected Event Rate



The total number of QE ν_μ events and the relative energy distributions have been calculated as a function of the incoming neutrino energy (bin size 0.5GeV). The value of M_A adopted here is $1.03 GeV/c^2$.

A run period of 180 days was assumed.

In the energy range between 1 and 4 GeV the relative statistical **error is reduced to the level of 4-5%** (while NuMI beam systematics is 5-10%)

The table reports the expected number of ν_μ CC events/day with the vertex in the ArgoNeuT LAr active volume.

CC channels	Events/day	
	LIPARI X-sect	GENEVE X-sect
QE	26.6	25.2
RES	21.8	
DIS	118.5	
Total	166.9	

Assumptions:

8×10^{17} PoT/day and 350 kg of LAr as sensitive volume

Cross sections (as a function of the incident ν energy) have been calculated independently for the three different channels (QE, RES, DIS). Two different codes/models have been used: LIPARI and GENEVE

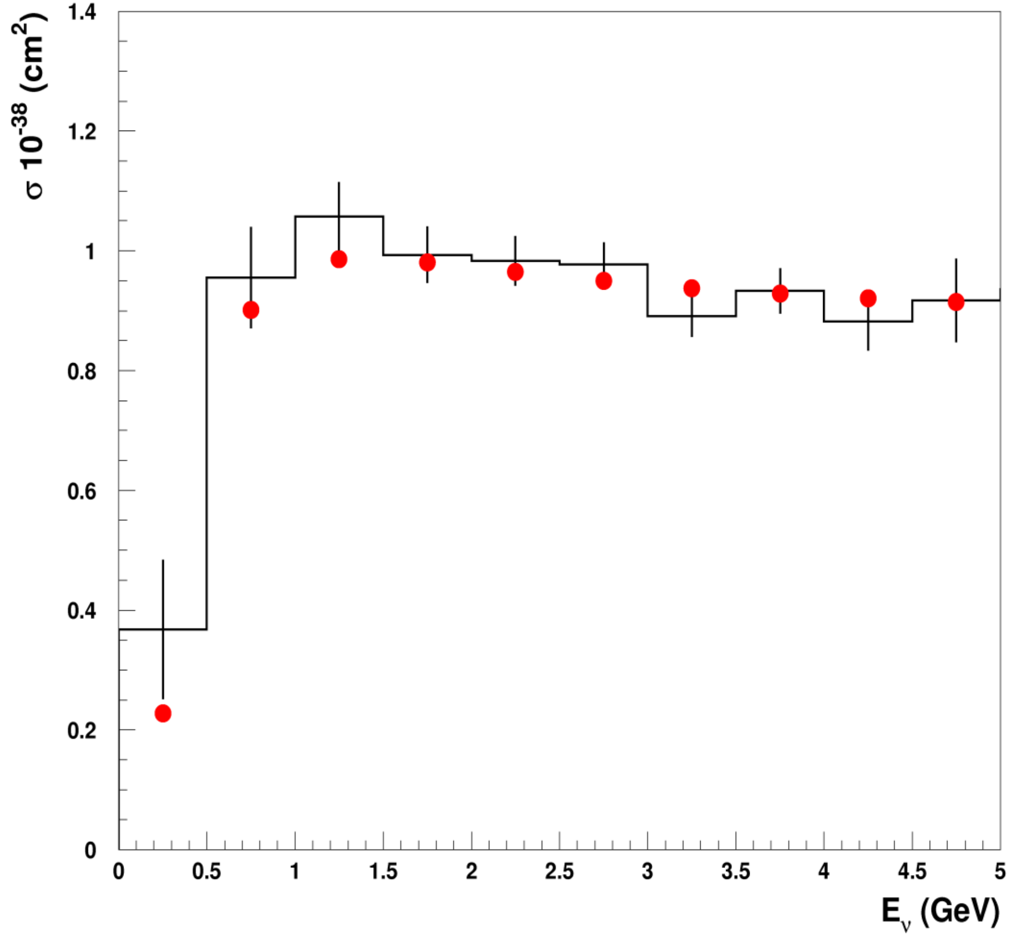
The ArgoNeuT Experiment

QE ν_μ X-sect Reconstruction

The experimental QE X-sect distribution has been reproduced as expected from a 180 days run of on-axis exposure on the NuMI Beam.

It was assumed that all the collected events are somehow fully reconstructed.

Statistical errors are reported. The red dots indicate the theoretical X-sect (GENEVE MC).



The ArgoNeuT Experiment

A possible M_A measurement

Some experiment presented an M_A value from the fit of their data:

Experiments using D^2 and H^2 as mass target returned

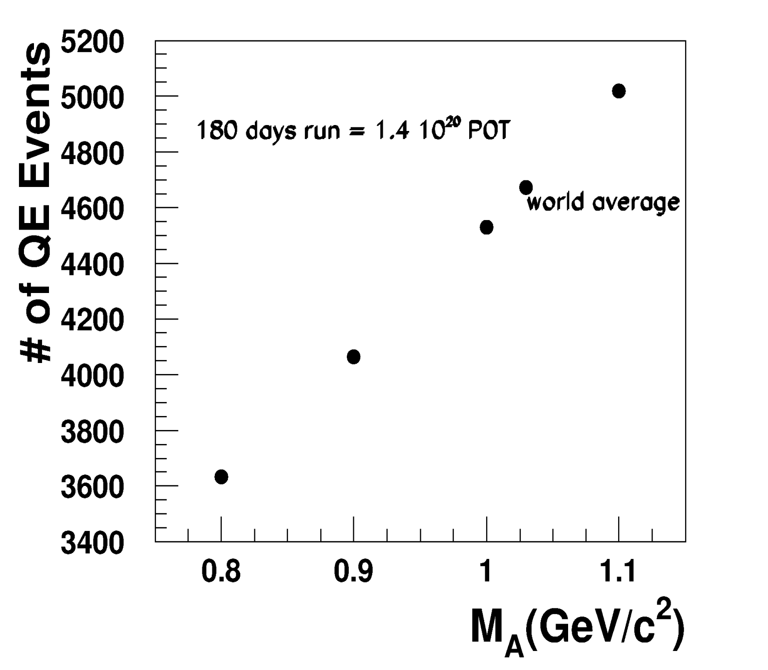
M_A = 1.03 GeV/c^2 (mean value)

Experiments employing havier nuclei reported
M_A = 0.65 ÷ 1.0 GeV/c^2

It is unclear if the difference depend on effective dependence on the target nuclear structure or to different systematics.

No M_A measurement have been ever performed in Liquid Argon !!

The total number of expected QE events (GENEVE MC) scales almost linearly with M_A. Counting the QE interactions in ArgoNeuT may provide a way to determine M_A value in Argon.



Conclusions and Outlook

One of the main uncertainties in long baseline oscillation experiments is given by the neutrino-nucleus interaction cross section in the “Few-GeV region”. In this range the dominant reaction is the Charged Current Quasi Elastic Scattering.

The QE ν_μ cross section on Ar Nuclei first investigated with the **ICARUS 50lt** detector **at CERN** (WANF high-en. beam): current preliminary estimate by ICARUS - from this higher energy range - with precision is around 20%.

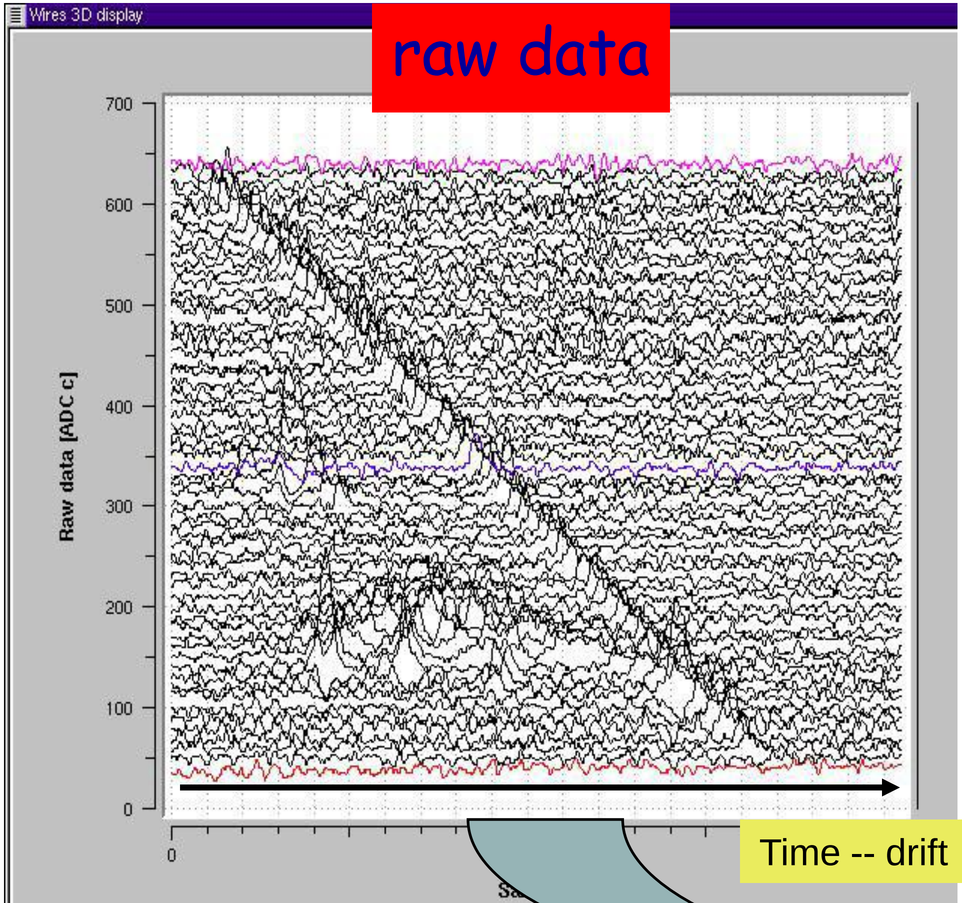
New forthcoming measurement with **ArgoNeuT at FERMILAB** (NuMI low-en beam).The detector has been succesfully commissioned (with c.r. on surface) at Fermilab (Aug.’08). It is now exposed on axis just upstream the MINOS Near Detector (interleaved with MINERvA). Data taking will start in March 2009. About 3200 QE ν_μ CC events expected in a 6 months run.

The current nu-Xsect measurements (SciBoone + K2K, MiniBoone,…) and the forthcoming data from MINERvA, complemented by ArgoNeuT Argon data are of great importance for the next generation long baseline oscillation experiments (and in particular for LAr based detectors).

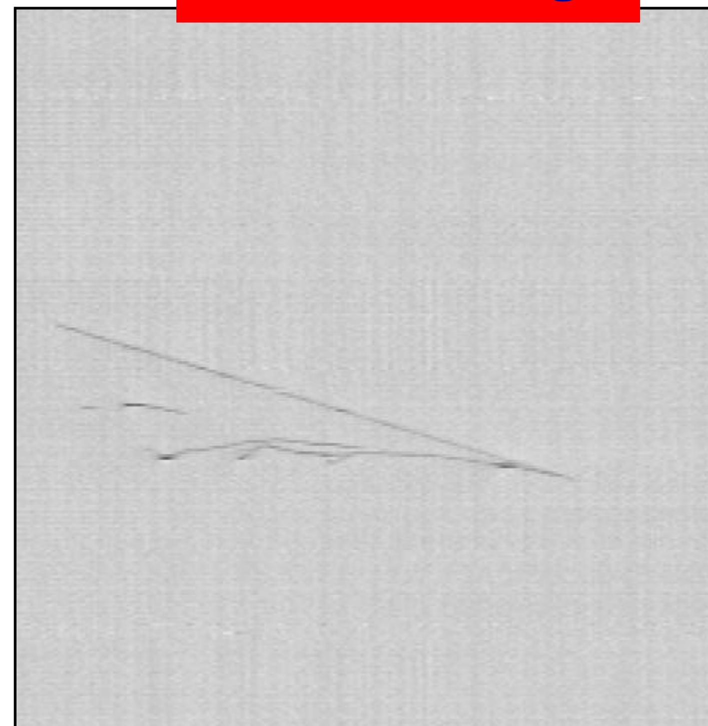
Back-Up Slides

ICARUS liquid Argon imaging TPC

raw data



filtered image



Real event from 10m³ prototype at LNGS

Detector is continuously sensitive and self-triggering, thus allowing to easily simultaneously collect various types of rare events...

The ArgoNeuT Experiment

Goals:

- Research and Design for future LArTPCs
- Demonstrate **particle ID** (e.g. e^-/γ separation) capabilities of LArTPCs with **dE/dx**
- Study **first ever low energy CC and NC neutrino events**
- **QE ν_μ cross detection measurement**

ArgoNeuT Cryostat

Detector main characteristics:

- 175 liter LAr active volume
- 2 non-destructive read-out planes: Induction and Collection
- 240 BeCu wires per plane. Wire ∅ 0.15 mm
- Wires orientation: ± 30° with respect to vertical
- 4mm wire pitch, 4mm plane spacing
- Nominal 500V/cm electric field
- 50 cm maximum drift
- Bias voltage distribution boards located directly on TPC
- Cu-clad G10 used for TPC sustaining frame and field cage

Systematic Error

Source	Systematic error (%)
Neutrino flux	8
Detector lifetime	4
Vertex detection (fiducial cut)	3
Golden event selection cuts	6
Acceptance for QE events, $Acc^{QE}(\pm 2\%)$	1.5
Acceptance for non-QE events, $Acc^{nQE}(\pm 2\%)$	0.5
Fraction of *golden* events in QE sample, $\mathcal{G}^{QE}$ ($\pm 25\%$)	16
Fraction of *golden* events in non-QE sample, $\mathcal{G}^{nQE}$ ($\pm 25\%$)	5
Fraction of non-QE to QE events, $\frac{R^{nQE}}{R^{QE}}$ ($\pm 20\%$)	4
Total	20.6

TABLE I: Summary of systematic errors. The largest source of error comes from nuclear effects affecting the expected fraction of *golden* events inside the genuine QE sample.

The ICARUS 50 lt Detector

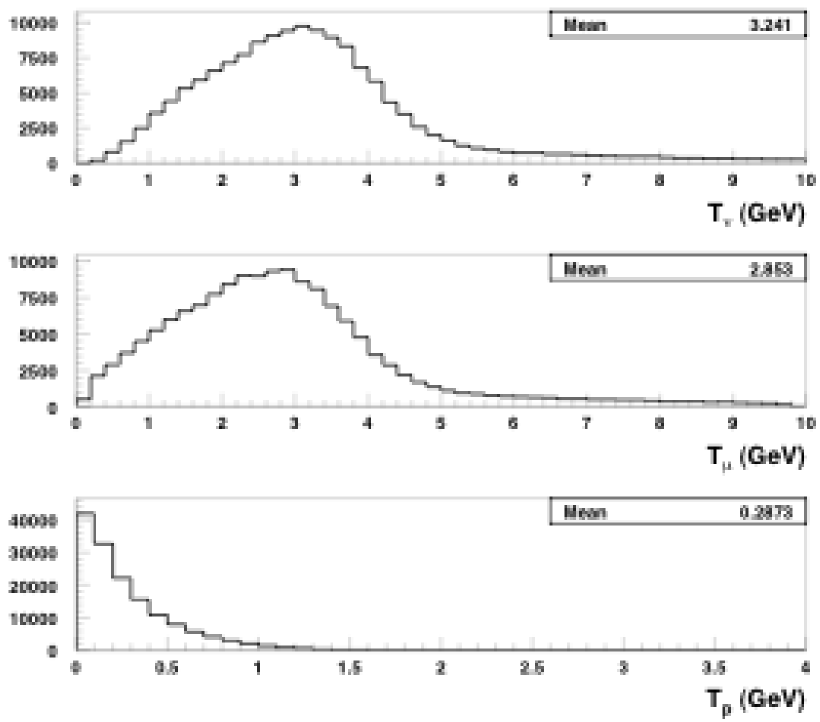


Figure 6: *Expected neutrino [Top], muon [Centre] and proton [Bottom] kinetic energy distributions from QE ν_μ CC interactions.*