Experimental study of neutrino interactions on Ar with a liquid Ar TPC exposed on the WANF neutrino beam

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Outline of the talk

a) Background info: LAr TPC and all that
b) Experimental setup and data analysis procedure
c) Results from the analysis of a sample of QE events: nuclear effects in ν-Ar interactions
d) Conclusions & outlook

TIME PROJECTION CHAMBERS

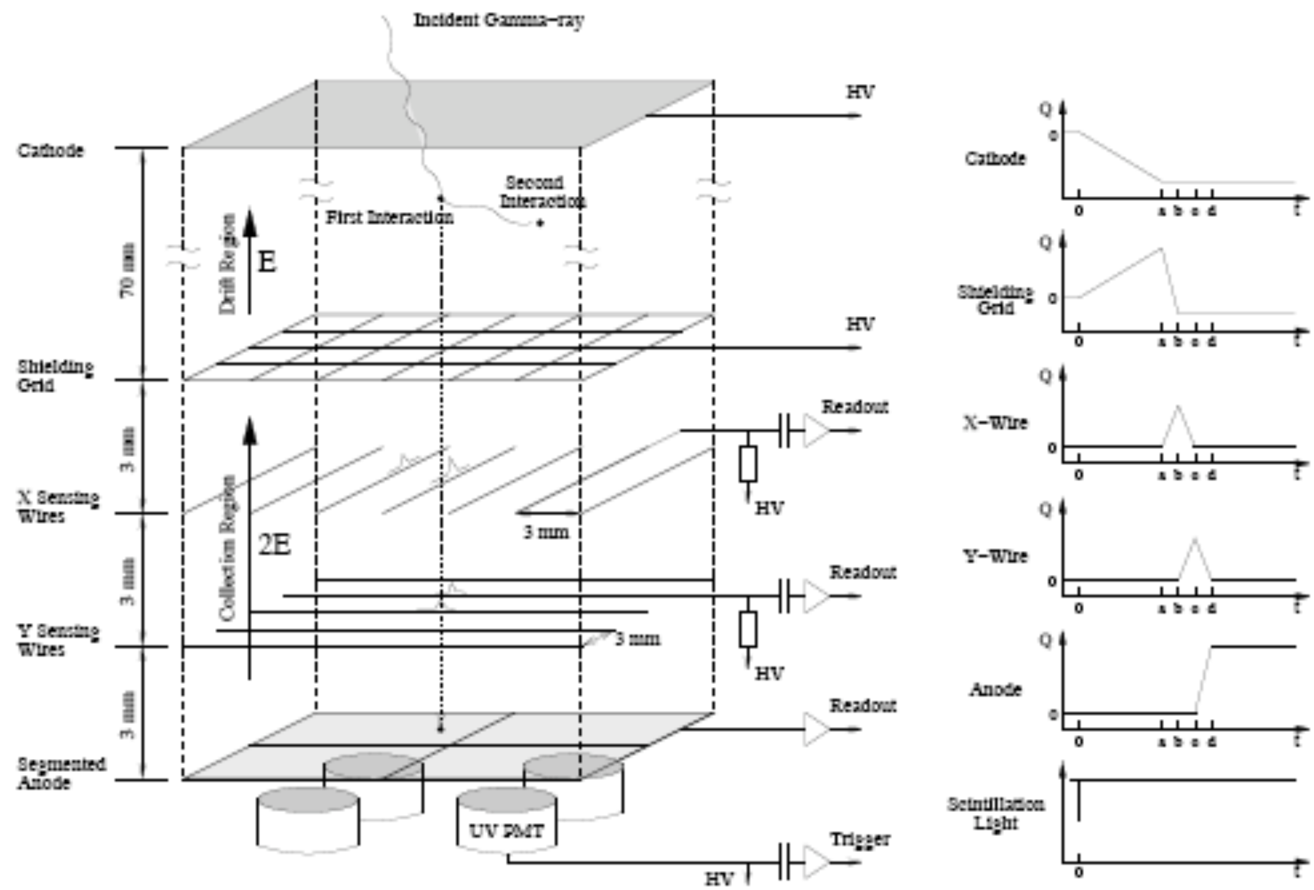

Figure 2.6: Schematic of the LXeTPC read-out structure with corresponding light trigger and charge signals (from (98) and (74)).

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LIQUID AR PROPERTIES

	liquid Ar	water	freon
signal	scintillation/ ionization	Cherenkov light	bubbles
density	1.4	1	1.5
radiation length	14	36.1	11
scintillation	40 ph/keV		
dE/dx [MeV/cm]	2.1	1.9	2.3
electron drift	yes	no	no
boiling point [K]	87	373	
mass [ton]	300+300	50,000	4

LARTPC FOR ν PHYSICS: WHICH ν PHYSICS

◊ $\nu_\mu \rightarrow \nu_e$ long baseline searches (θ_{13}, CP violation, mass hierarchy)

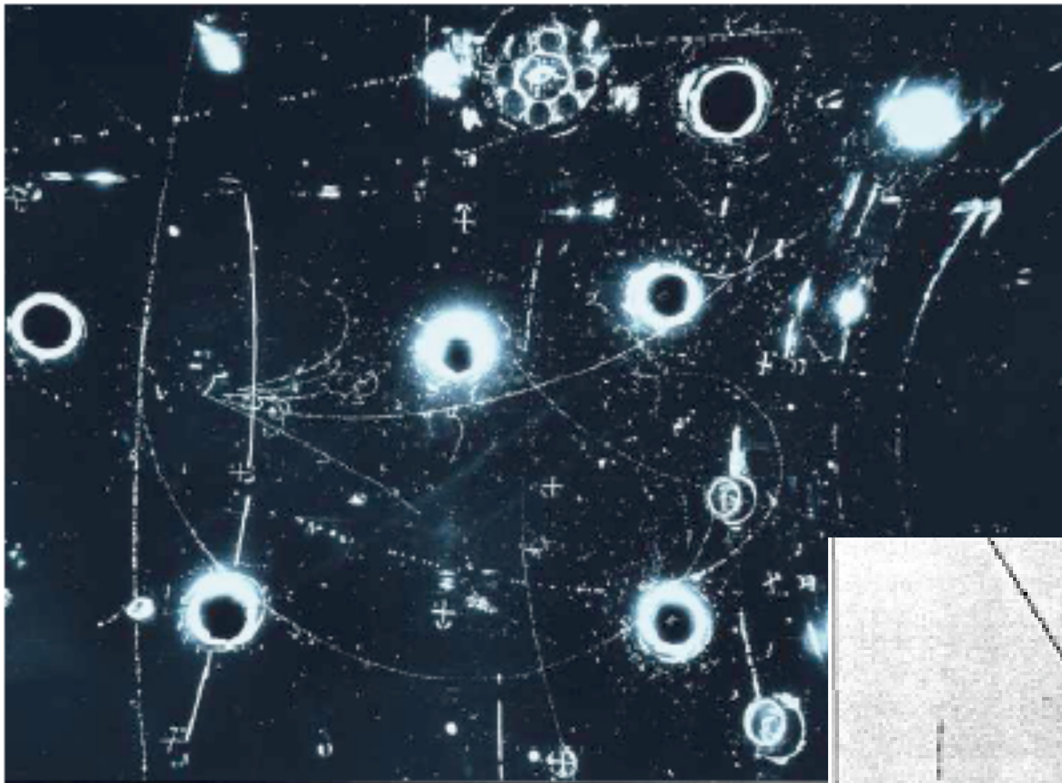
◊ neutrino beams in the energy range 0.5 - 5 GeV (both wide band beams and off-axis)

◊ requirements: high efficiency to ν_e, good suppression of π^0 background, good energy resolution

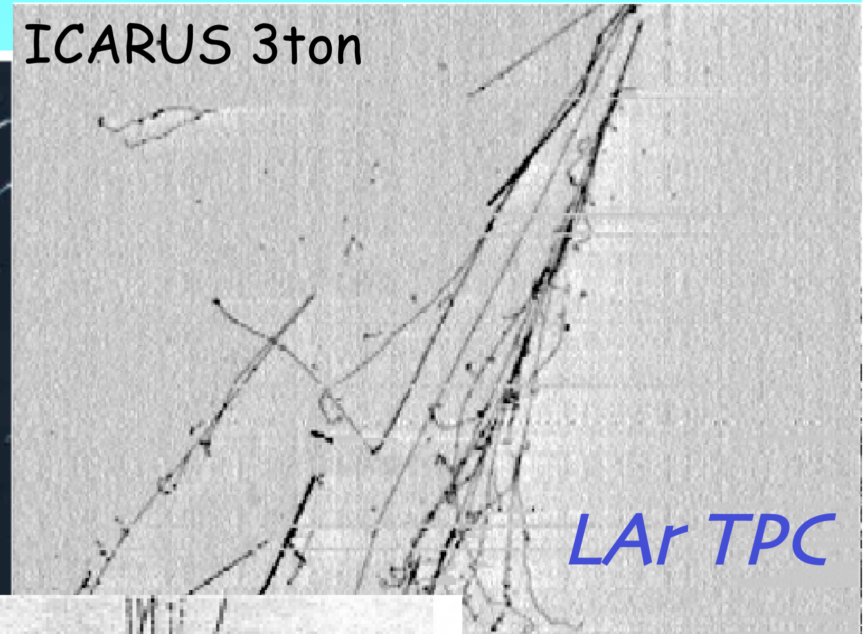
LARTPC FOR ν PHYSICS: WHY THEY ARE GOOD

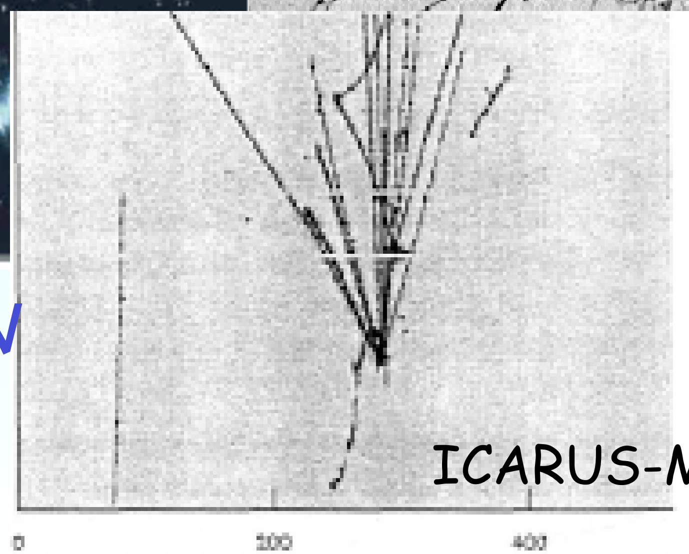
- ✗ excellent imaging capability
- ✗ excellent position resolution
- ✗ excellent particle identification
- ✗ excellent energy resolution (for low multiplicity events)
- ✗ possibility to build not-too-expensive massive detectors

LARTPC FOR ν PHYSICS



GARGAMELLE - FREON





ICARUS-Milano 50l

LAR BEYOND θ_{13}, CP VIOLATION, MASS HIERARCHY

- Proton Decay (in particular kaon channels)
- Supernova neutrinos
- Direct Dark Matter detection (WARP, ArDM, mini-CLEAN)
- $2\beta 0\nu$ searches
- Applied physics: gamma-ray imaging for medical applications, biophysics, nuclear non-proliferation

Some historical background:

1977. Carlo Rubbia makes first proposal for a large LArTPC for solar neutrinos and later establishes the ICARUS program

1990. Pio Picchi (ICARUS) at CERN: purification in liquid phase

1993. ICARUS: 3 ton TPC

1997. ICARUS-Milano: test beam of a 50l TPC (ν-events observed)

2000. ICARUS: 10 m^3 TPC with the final ICARUS electronics

2003. ICARUS: 2x300 ton TPC built (300 ton operated) now underground at LNGS

50l TPC - some historical background

The test took place in 1997, to measure distortions to the simple QE kinematics due to the presence of nuclear matter - e.g. an excess of events with large missing transverse momentum.

The test was run jointly by the ICARUS collaboration and a group from Milano U. and INFN (and more than a little help from the NOMAD collaboration)

50l TPC - some historical background

Apr 21 1997 - night

"Experimental study of quasi-elastic neutrino interactions on Ar with a liquid Ar TPC exposed to the WANF neutrino beam" ICARUS-Milano Collaboration (A. Curioni for the collaboration)
Nucl.Phys.Proc.Suppl.159:69-75,2006. Also in *Okayama 2005, Neutrino-nucleus interactions in the few-GeV region* 69-75
hep-ex/0603009

EVENTUALLY…

Performance Of A Liquid Argon Time Projection Chamber Exposed To The WANF Neutrino Beam

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(The ICARUS-Milano Collaboration)

We present the results of the first exposure of a Liquid Argon TPC to a multi-GeV neutrino beam. The data have been collected with a 50 liters ICARUS-like chamber located between the CHORUS and NOMAD experiments at the CERN West Area Neutrino Facility (WANF). We discuss both the instrumental performance of the detector and its capability to identify and reconstruct low multiplicity neutrino interactions.

PACS numbers: 29.40.Gx, 13.15.+g

PHYS.REV.D74:112001,2006 (PHYSICS/0609205)

DATA TAKING - SUMMARY

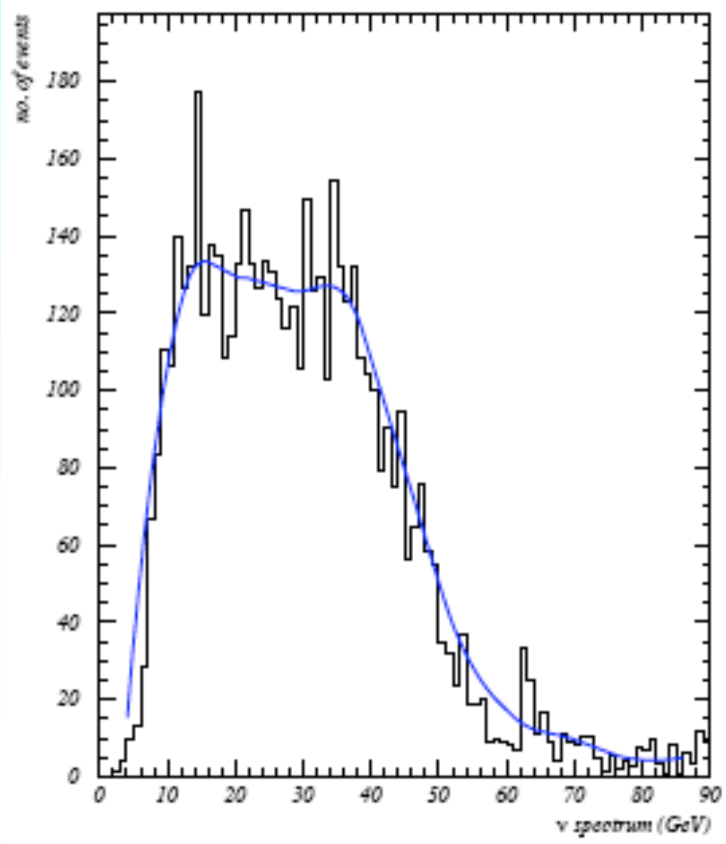
- Data taking (1997): from Aug to Nov on the WANF ν-beam (detector commissioning and PS fire: Apr to July)
- $1.21\ 10^{19}$ pot
- 81,000 triggers recorded
- 10% of which recognized as neutrino CC events

TEST SETUP: BEAM

WANF ν-beam:

1. 450 GeV p extracted every 14.4 s in two 6 ms spills, 2.5 s apart. 1.8 10^3 pot per spill on a Be target
2. Mean energy of the ν-beam 24 GeV
3. Contamination: 7% anti-numu, 1% ν_e

The LAr TPC was sitting right in between CHORUS & NOMAD (hall 191) on a platform 4.5 m high



Test Setup: LAr TPC

- Fiducial volume 32 x 32 x 46.8 cm^3, 67 kg of Ar
- Drift field 214 V/cm; v_{drift} = 0.9m/s
- 2 x 128 wires, 2.54 mm pitch
- Cold electronics
- S/N for a m.i.p. ~11
- All wire signals digitized and recorded
- LAr purity stable ~4.2 ms electron lifetime (~4 m drift)
- LAr doped with 3.5 ppm of TMG to linearize charge (see next)

picture of the 50 l TPC hanging from the top flange and schematic of purification system

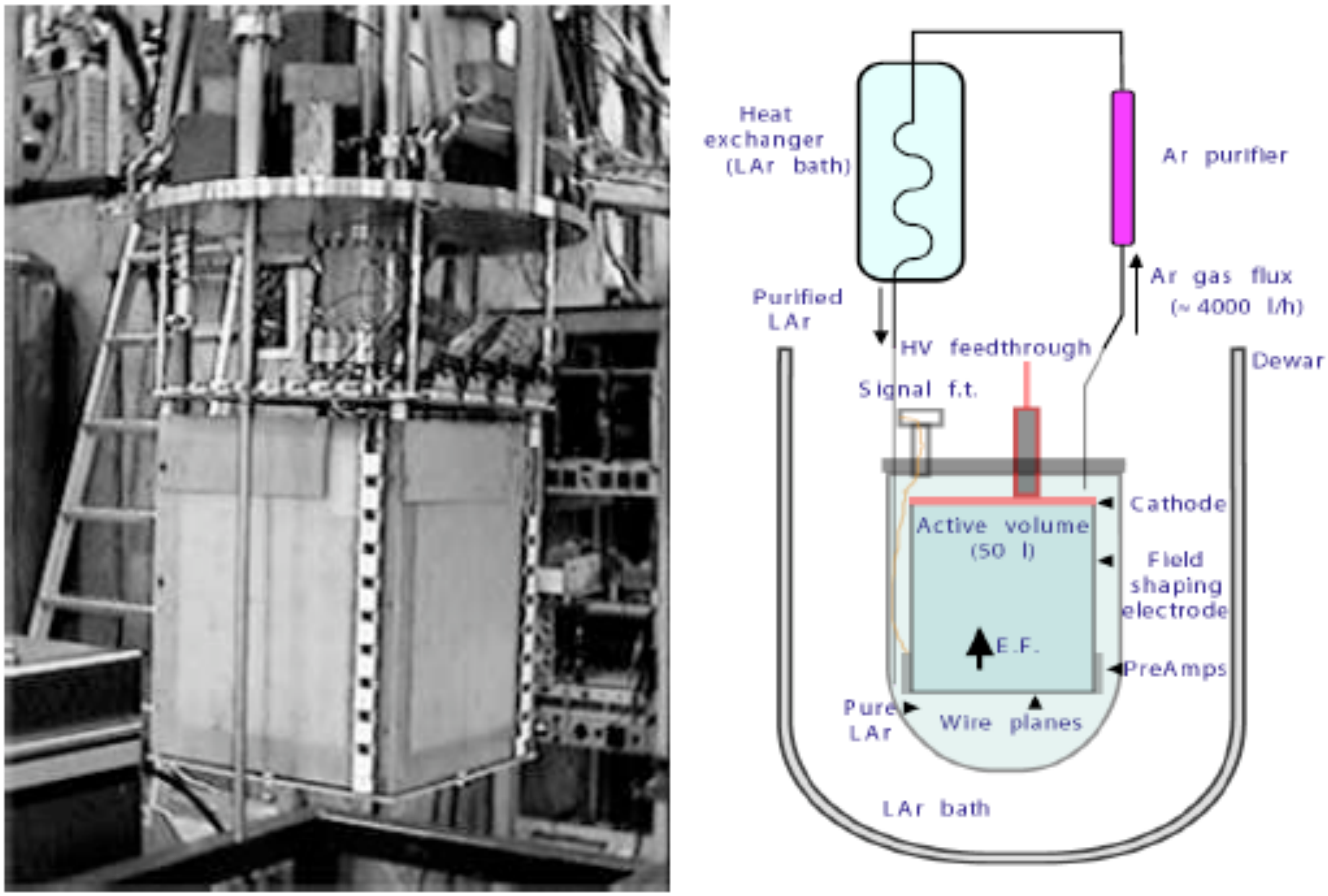
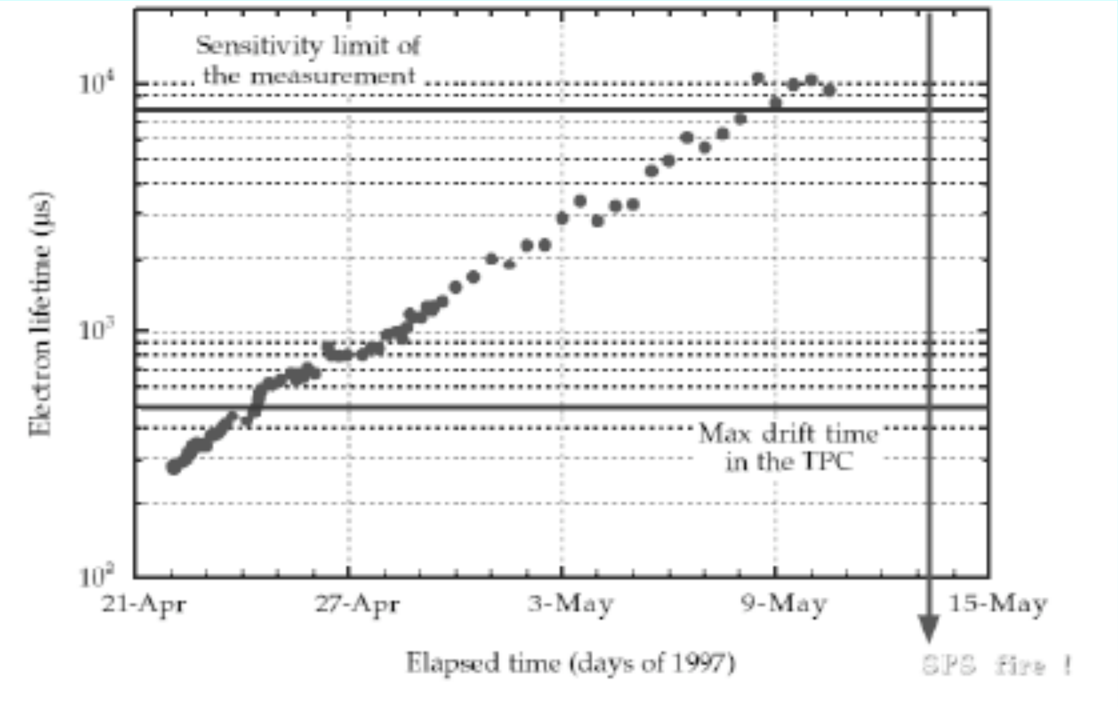


FIG. 2: The 50 liters Liquid Argon Time Projection Chamber.

electron lifetime in liquid Ar vs. time: continuous recirculation produced excellent purity

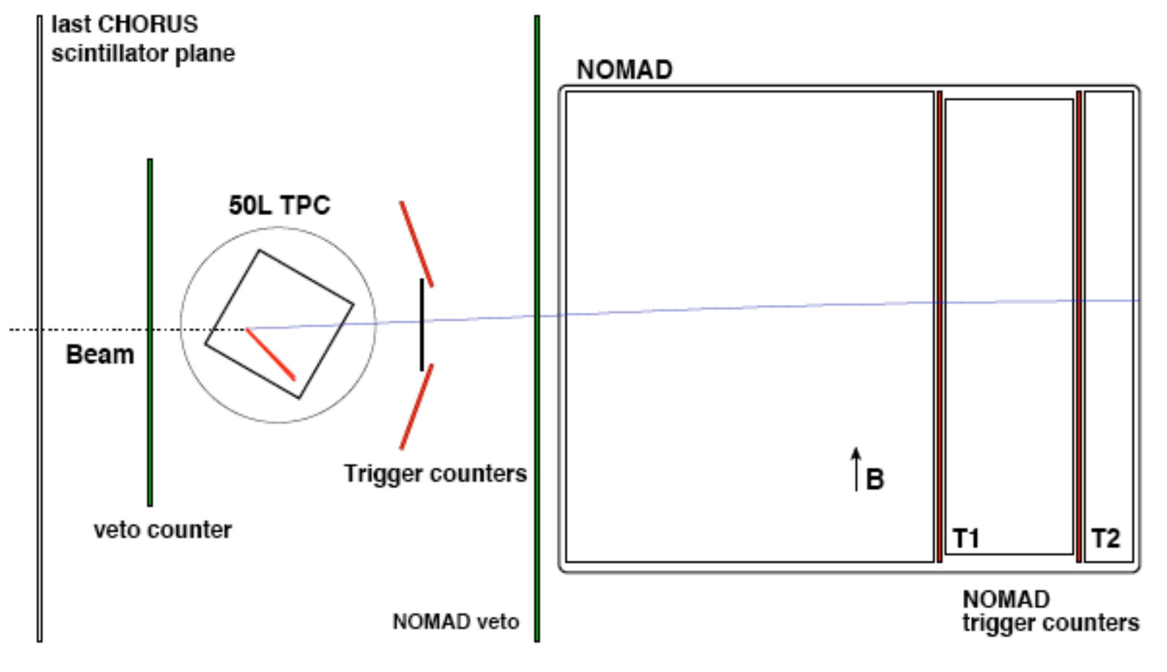
*****~30ms lifetime for free e^- in Ar *****

e^- could be drifted over more than 10 meters



TEST SETUP: TRIGGER & VETO

- 5 plastic scintillators 50 cm upstream the TPC as veto, plus the last CHORUS scintillator plane
- 3 plastic scintillators downstream the TPC as trigger (efficiency 97%), plus two NOMAD scintillator planes T1 & T2
- Dead time: TPC ~3%, NOMAD 15%
- An alternative trigger for through-going muons for calibration (alignment to NOMAD etc.)



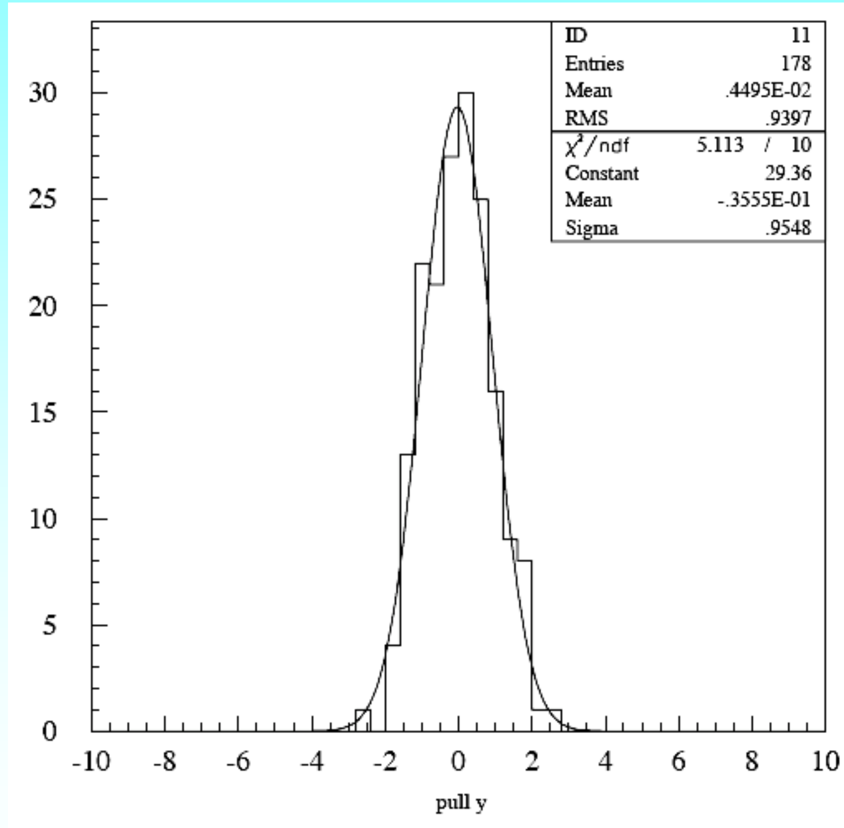
Muon Spectrometer

NOMAD magnetic dipole as moun spectrometer

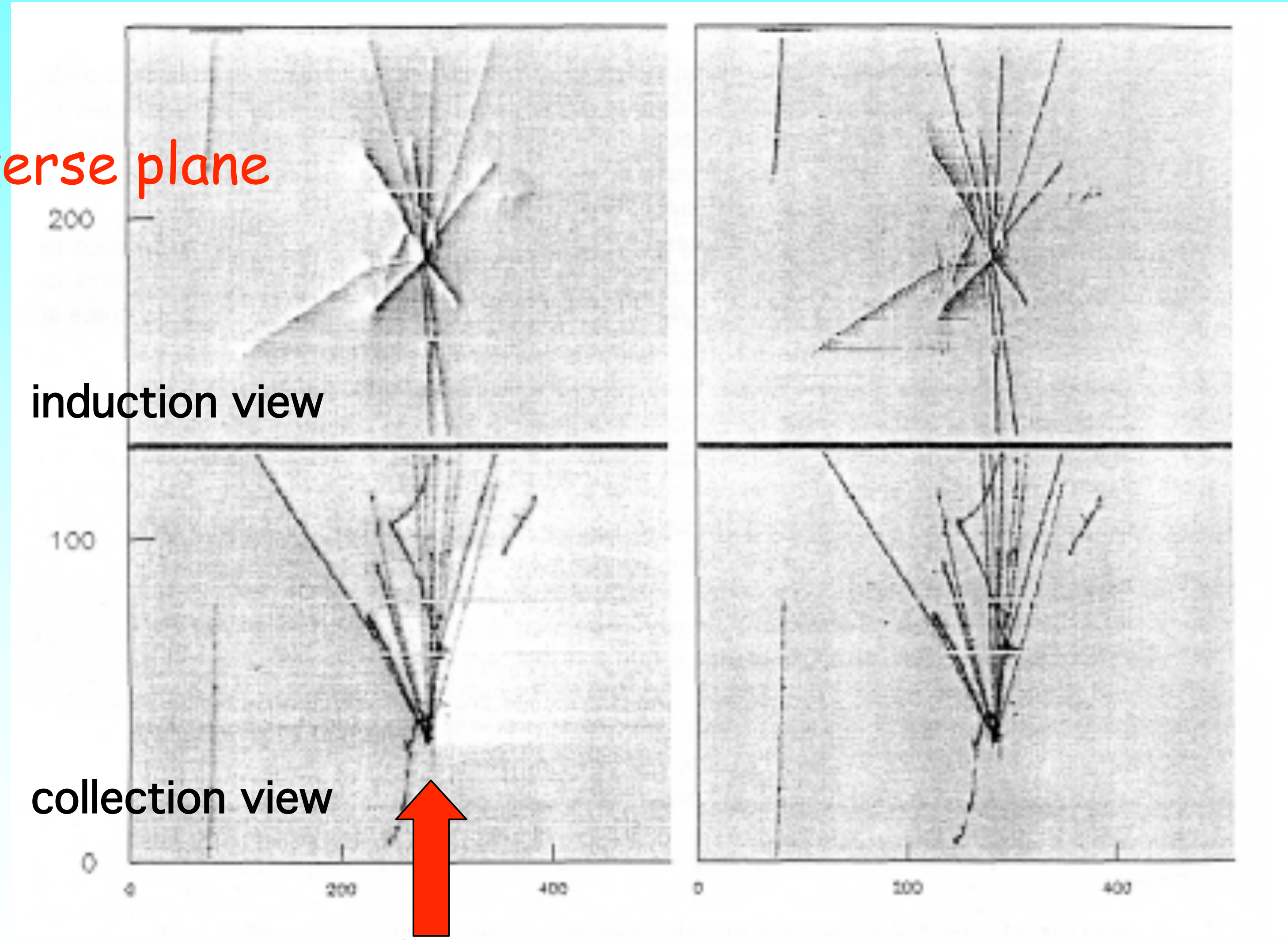
- ⌘ pure NOMAD:

$\sigma_p / p \sim 0.05\ L^{-1/2} \oplus 0.008\ p\ L^{-5/2}$ (~2%)

- ⌘ NOMAD FWD calorimeter (~190 cm of iron):
  - **~ 140 MeV / c** on each component in the transverse plane



EVT 1: GENERIC DIS



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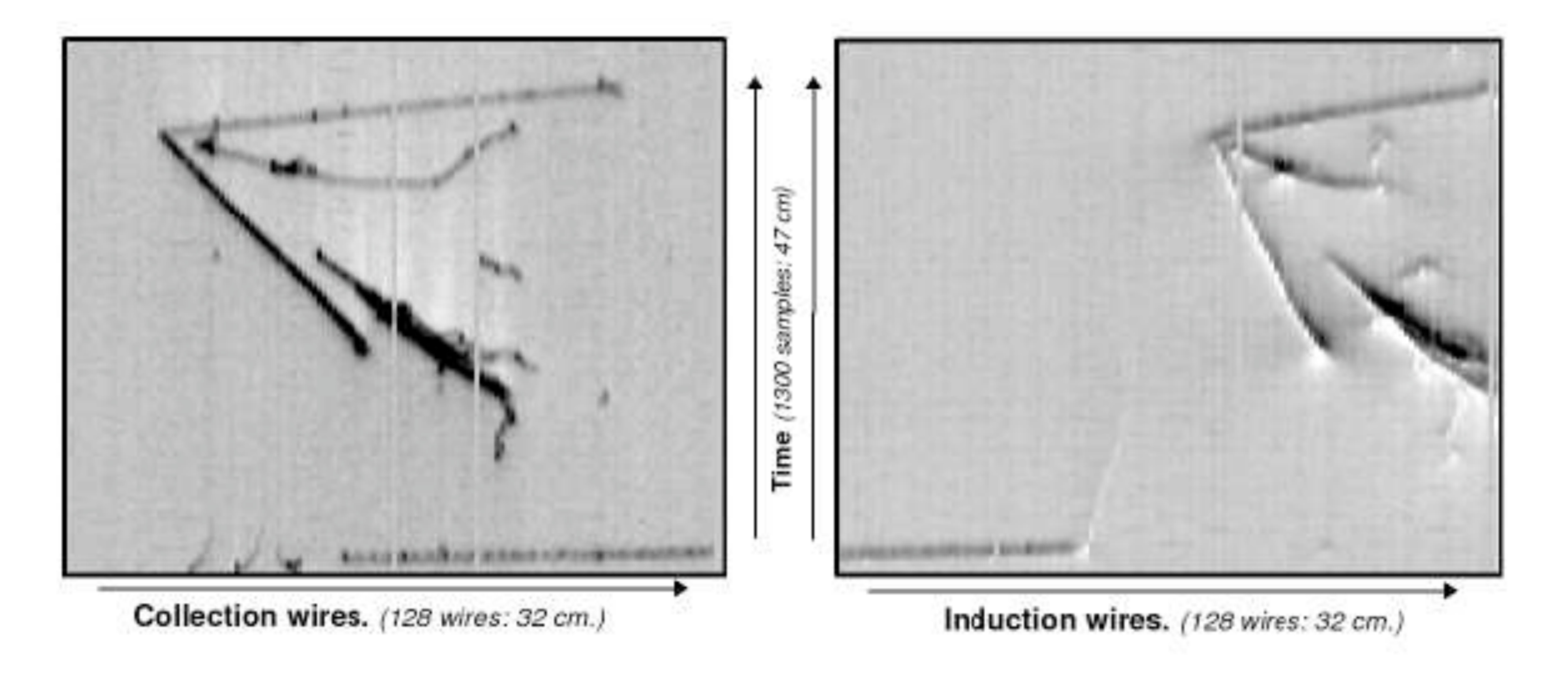
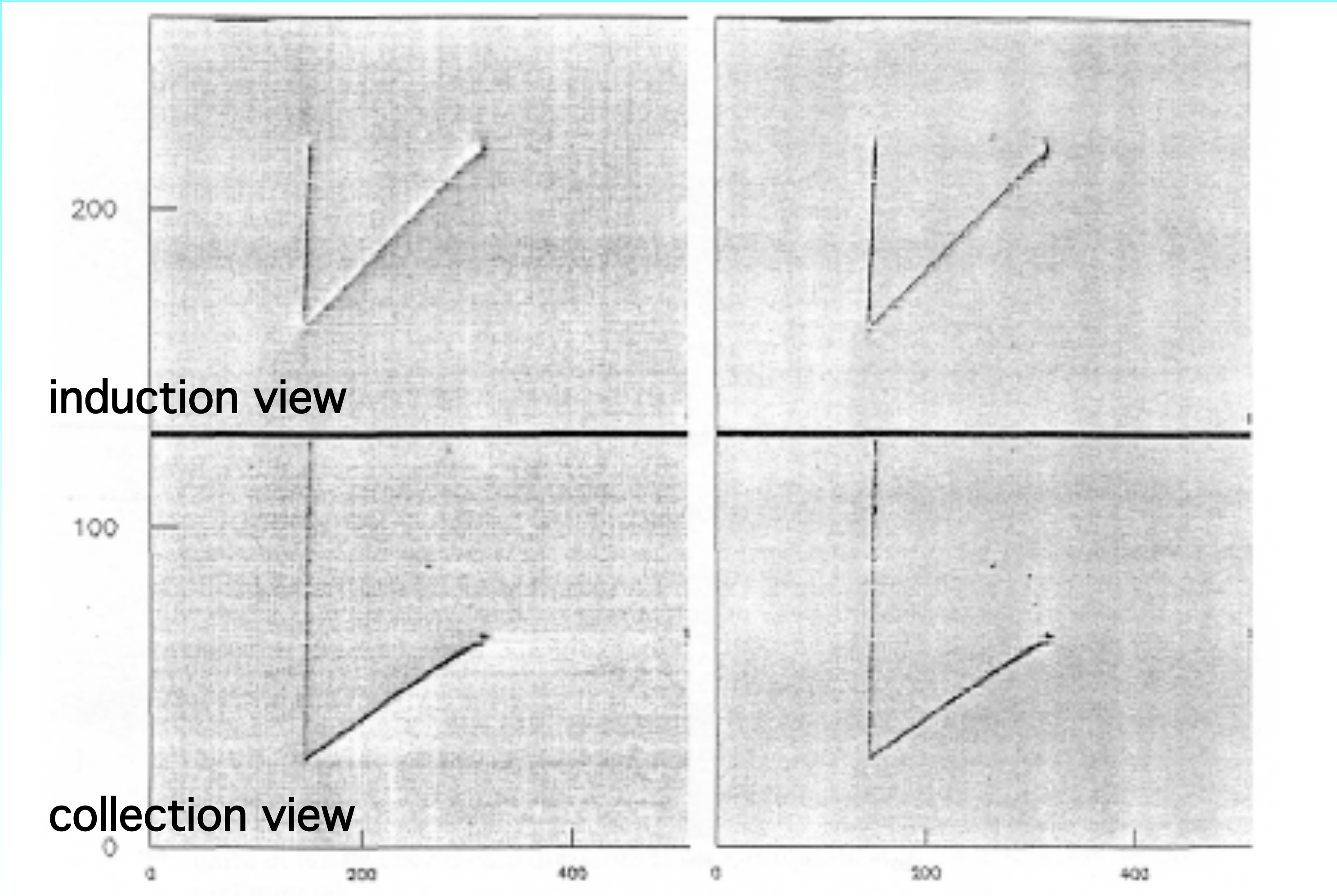
EVT 2: CC π^0

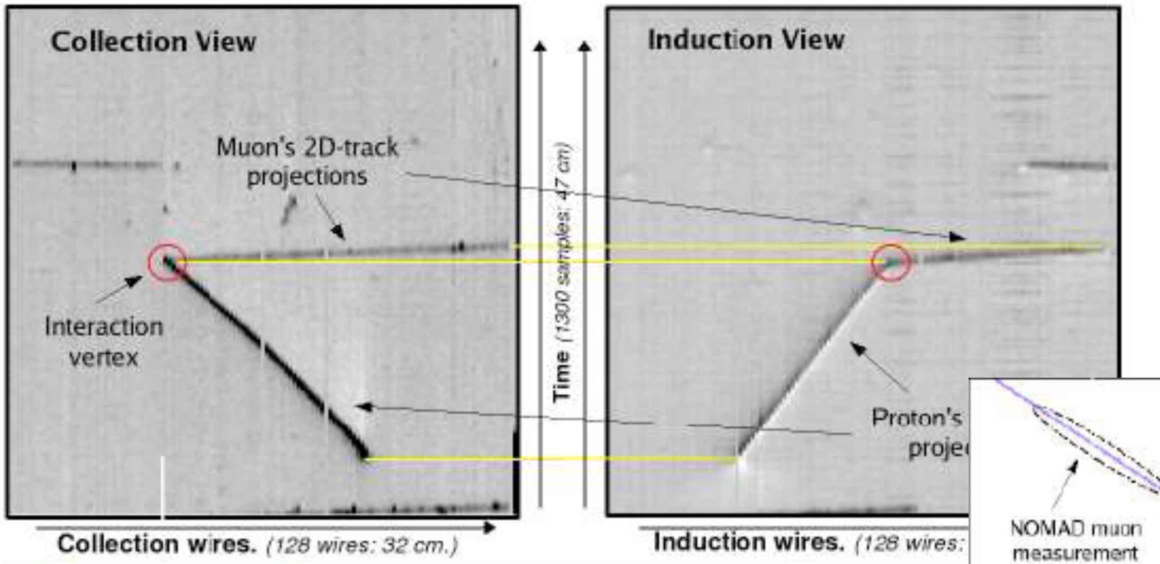


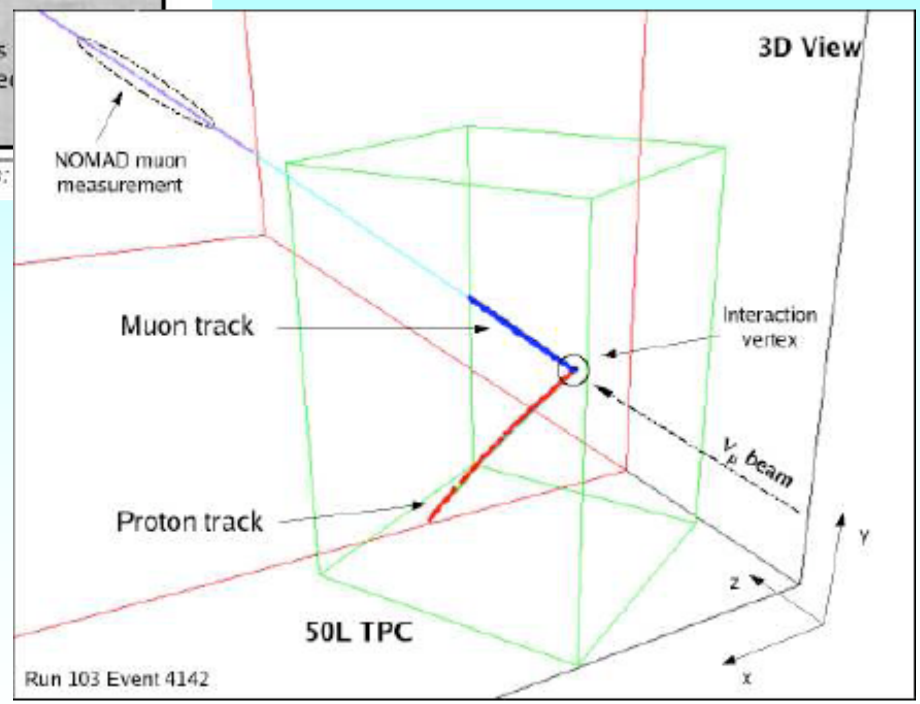
gammas from π^0 decay can be *easily* separated from electrons: important property when looking for ν_e appearance

Evt 3: quasi elastic (2.5%)



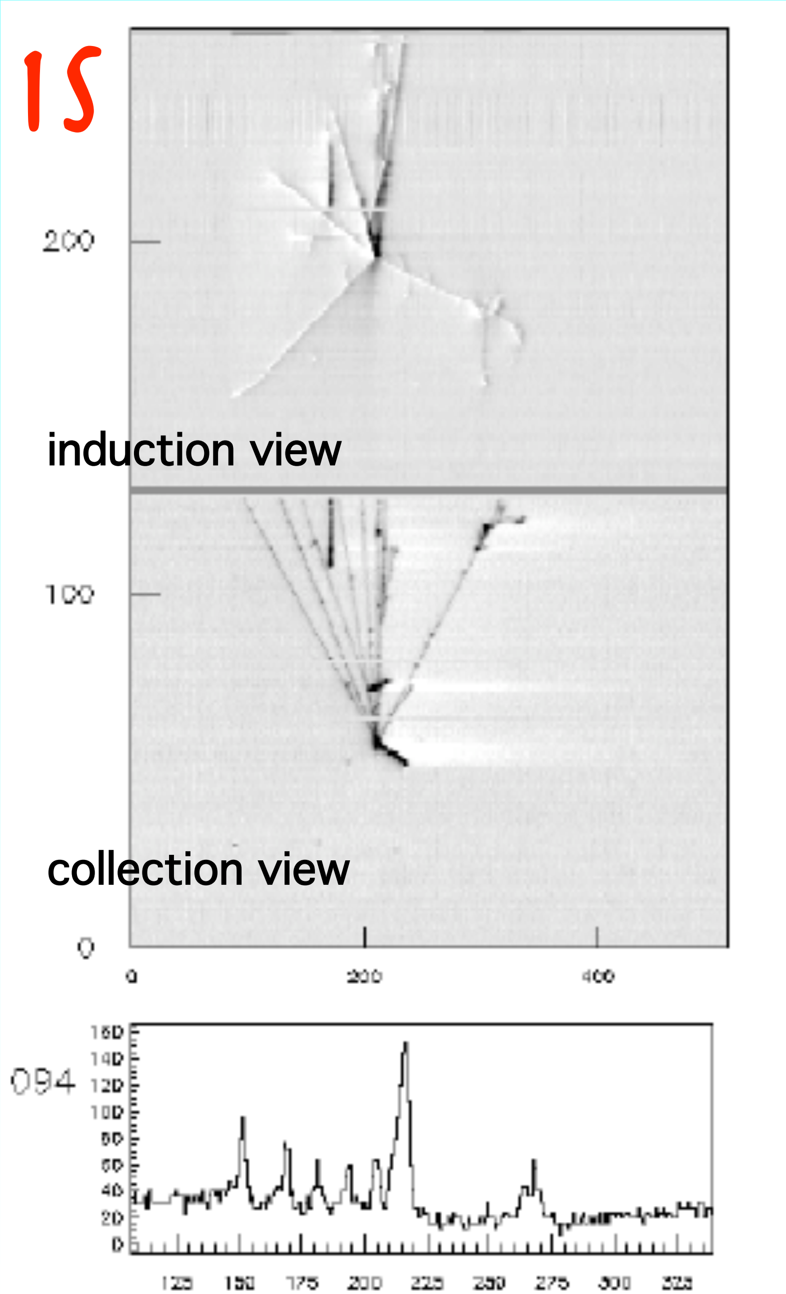
CC QE - New Reconstruction

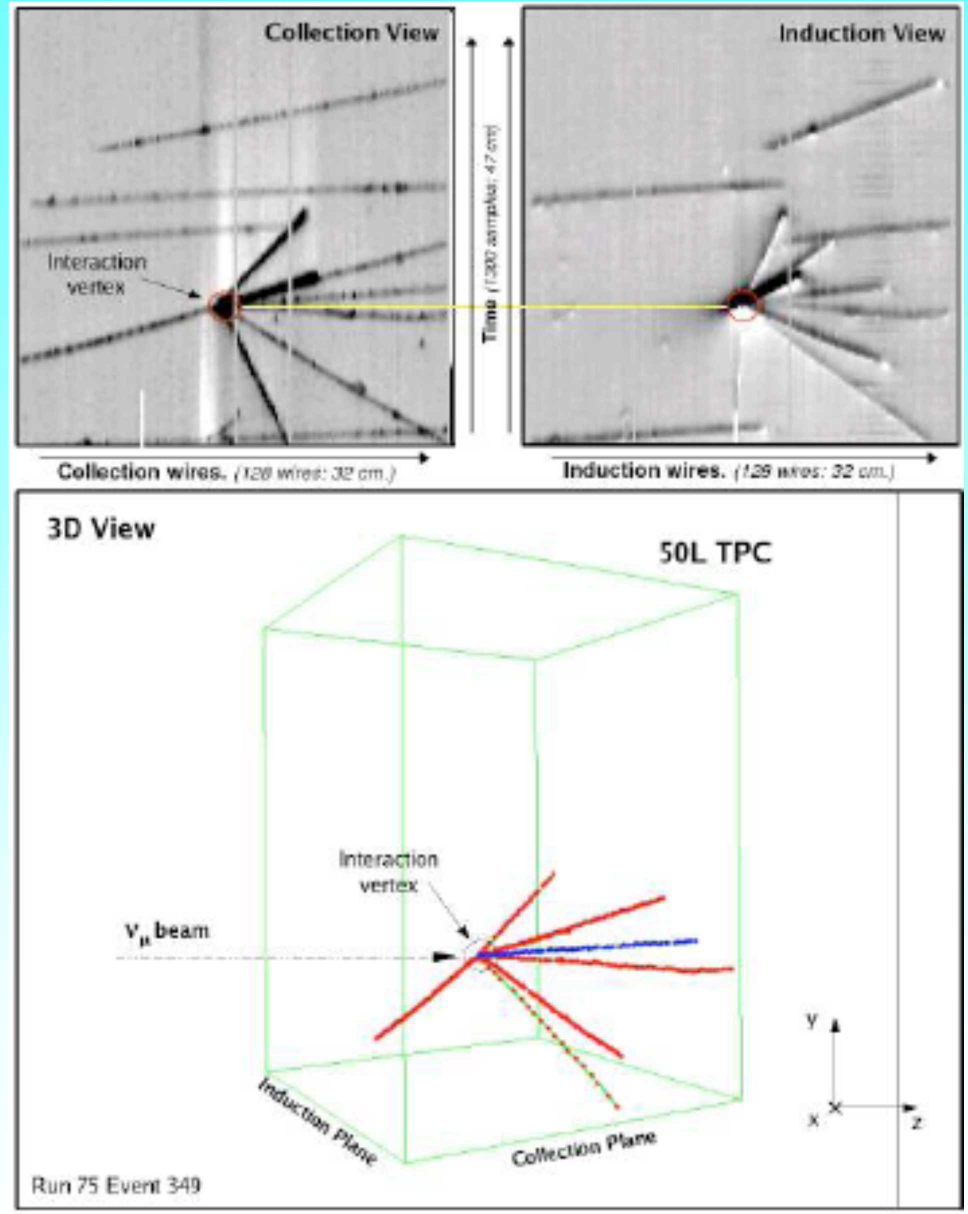




3D reconstruction capability for "low multiplicity" events

DIS





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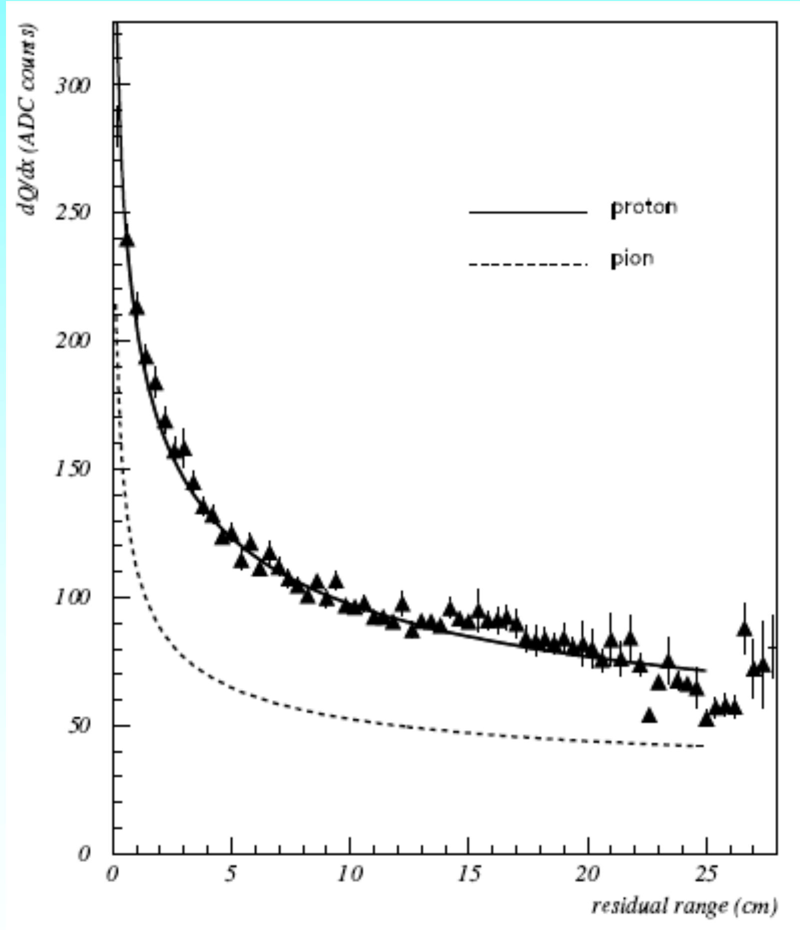
PROTON MOMENTUM

- For contained protons, |p| measured from range; uncertainty ~7 MeV/c for |p|~400 MeV/c, due to the pitch of the wires
- Angular resolution: depends on N, # of wires $\sigma \sim 0.36\ (12)^{1/2}\ N^{-3/2} / 2.54$ (15 mrad for N=10)
- Lower threshold on K.E. to measure the direction: 40 (50) MeV
- For non-contained protons |p| from dE/dx
- **HERE I WILL RESTRICT MYSELF TO CONTAINED PROTONS, K.E. > 40 MeV**

ASIDE: NON-CONTAINED PROTONS

- If proton not contained, K.E. can still be reconstructed fitting the dE/dx for the visible part of the track
- Not done in a systematic way for this work
- Easier: from dE/dx one can tell non-contained protons from pions with ~100% discrimination, and recover a larger (factor of ~2) QE sample



THE GOLDEN SAMPLE

Use only a "golden sample" of QE, defined as:

- Distance of the interaction vertex from any of the TPC walls > 1cm
- μ candidate track at least 12 wires long & associated with a μ in NOMAD
- Proton contained and K.E. > 40 (50) MeV
- More stopping particles are accepted if their range implies
  K.E. < 40 (50) MeV for a proton (~20 MeV for a π)
- No tracks other than the μ leaving the TPC
- No gammas > 10 MeV
- Efficiency of the "proton requirements" ~17%

Eventually, 86 (61) events selected vs. 80±9±13 (73) expected from MC

XSEC?

Taken at face value (no errors and rounding off ad libitum):

We detect 86 "golden" CCQE, of which 19 are expected (MC) to be non-QE background: 67 genuine CCQE. The efficiency is ~17%, I.e. ~400 CCQE (efficiency corrected)

The flux integrated over energy is 2.4E-7 ν_μ /cm²/p.o.t. with a mean energy of 24GeV; analyze data for 1.2E19 p.o.t.

The fiducial volume is ~85% X 67,000 cm³, I.e. ~1.85E28 neutrons

Livetime ~80%

$$\sigma_{CCQE@24GeV} \approx 400/(0.8*0.85*6E40) \approx 10^{-38} cm^2$$

BUT PLEASE DO NOT CONSIDER THIS A XSEC MEASUREMENT

WHAT WE MEASURE

- THE FULL KINEMATICS OF THE QE EVENTS, in particular:
  - **Missing transverse momentum:** for QE scattering on a free neutron, $p_T$miss ~ 0. For a neutron bound in a Ar nucleus ~250 MeV/c on average (Fermi motion), and a tail to larger $p_T$miss
  - **Acolinearity:** defined as (transverse plane x-y)

    $$\mathrm{acos}\,\{\,(p_{x\mu}p_{xp} + p_{y\mu}p_{yp})\,(p_{x\mu}^{\;2} + p_{y\mu}^{\;2})^{-1/2}(p_{xp}^{\;2}+p_{yp}^{\;2})^{-1/2}\,\}$$

    ~0 for scattering on a free neutron

WHICH ARE SENSITIVE TO THE PRESENCE OF NUCLEAR MATTER

COMPARED TO THE MODELS:

- **PRD 2006: Full MonteCarlo based on FLUKA / GEANT4. State of the art ICARUS package**
- **NuInt05:**
  1. **FLUKA** code (www.fluka.org): 10,000 quasi-elastic events (final state). Fermi motion, Pauli blocking, hadronic re-interactions inside the nucleus
  2. **SW**: a model (ICARUS TM 87/27 - 1987) which includes only Fermi motion and Pauli blocking, with a Saxon-Woods potential
  3. A sufficiently accurate description of the experimental setup

BACKGROUND

- Δ^+ and Δ^{++} with pion absorption in the nucleus: **IRREDUCIBLE**, **~15%**, but included in the MC (FLUKA)
- Final State μ-n-π^+ : **~0 EVT.** (i.e. *no* pion-proton mis-ID)
- CC π^0 where both gammas don't convert in the TPC. From MC (FLUKA) **13% CONTAMINATION** (20% probability to miss both gammas).
  Checked against the data themselves: select "golden events" with 1 (N_1) or 2 (N_2) identified gammas from π^0 decay.

$N_1 = 2N(1-\varepsilon)\varepsilon$; $N_2 = N\varepsilon^2$; N unknown, want to find ε^2

$$\varepsilon^2 = 32\pm10\ \%\ (20\%\ \text{from MC})$$

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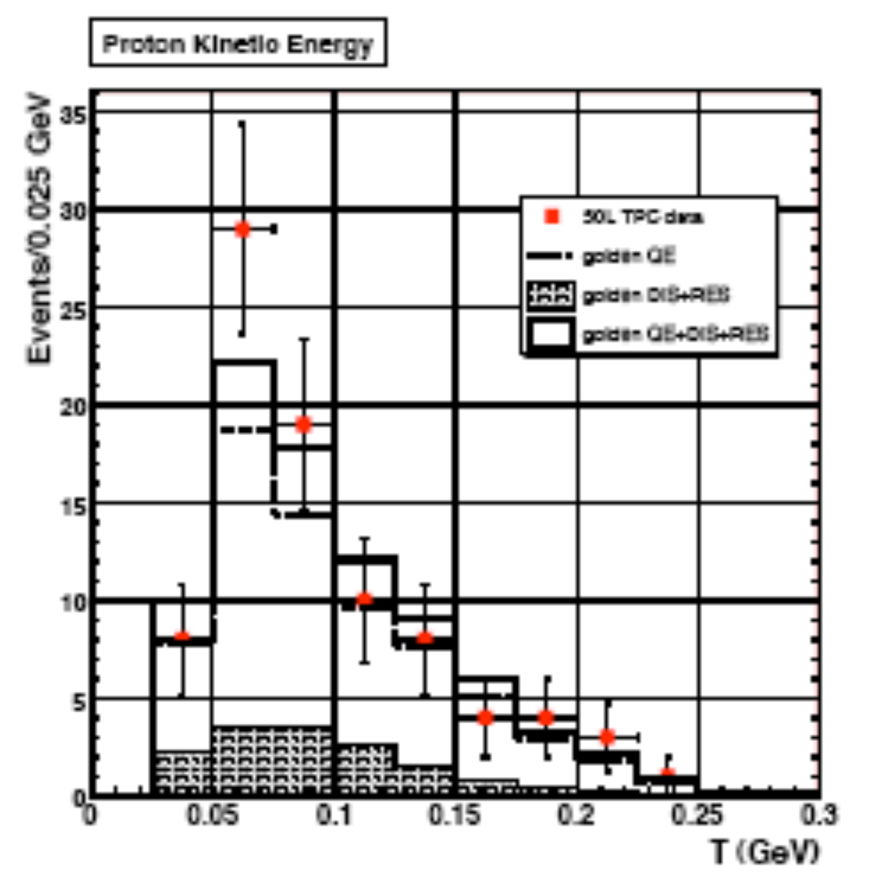
RESULTS

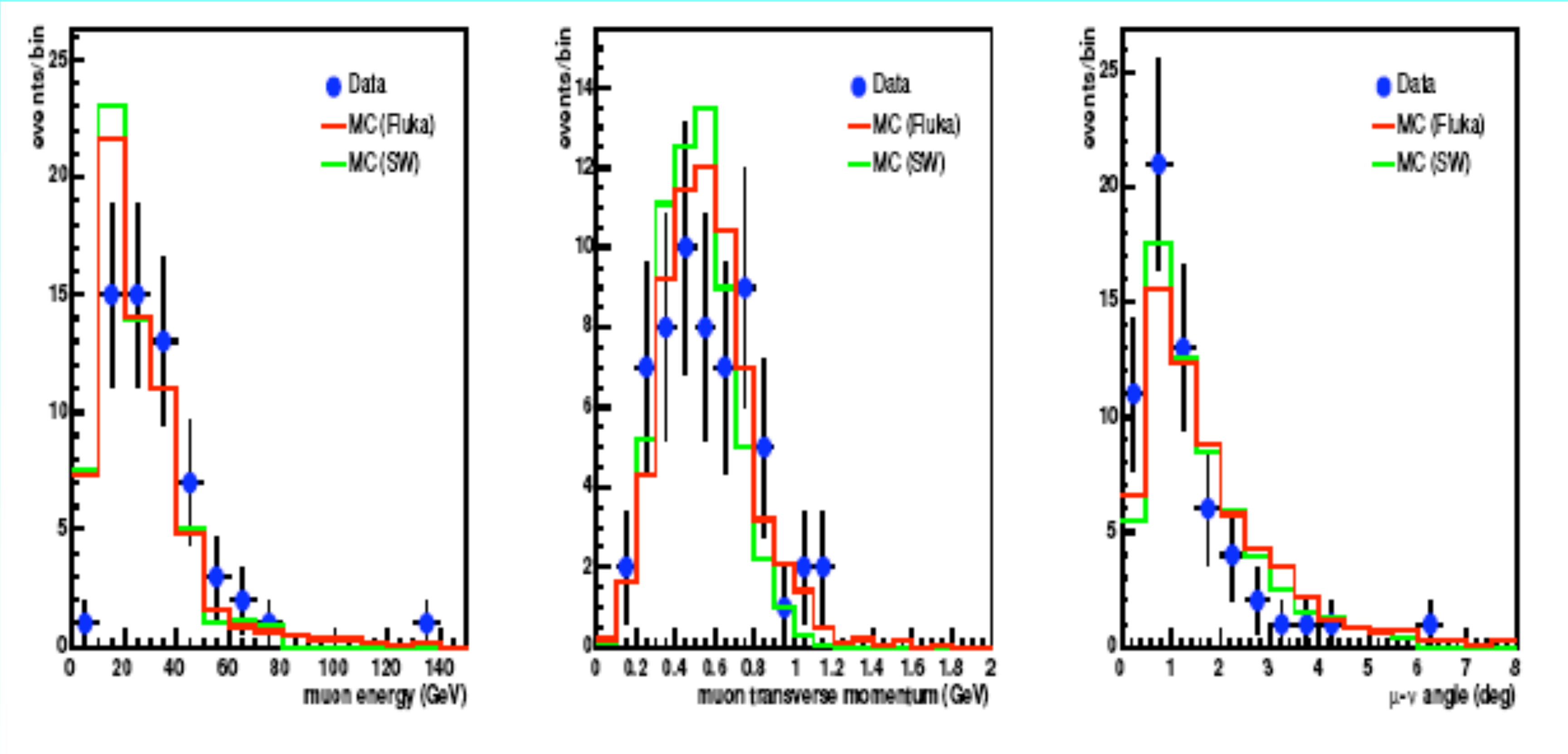
Some kinematics variables are only marginally affected by the presence of nuclear matter: they allow a consistency check

Proton K.E. dominated by the requirements

1. *K.E. > 40 MeV*
2. *Full containment*

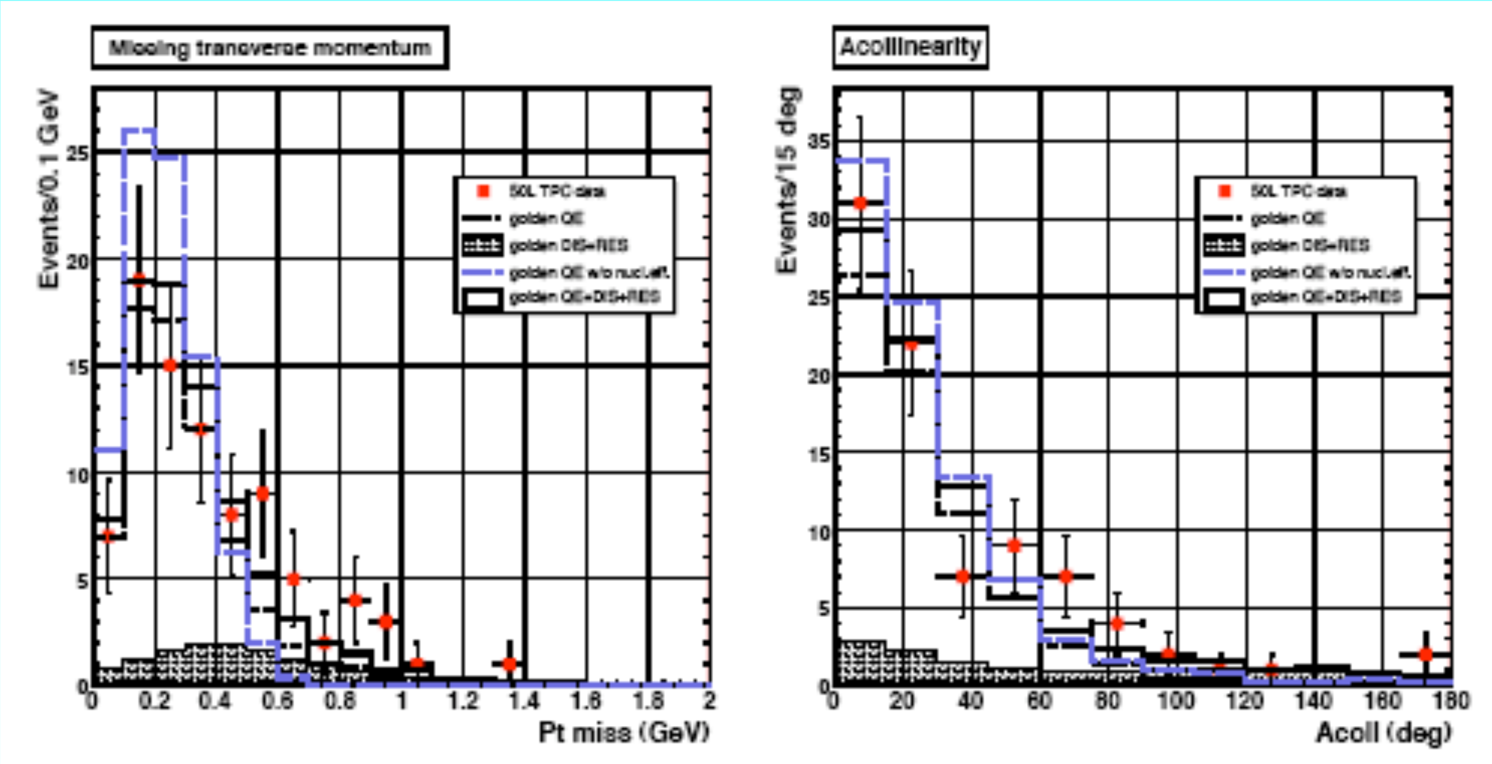


RESULTS from NuInt05



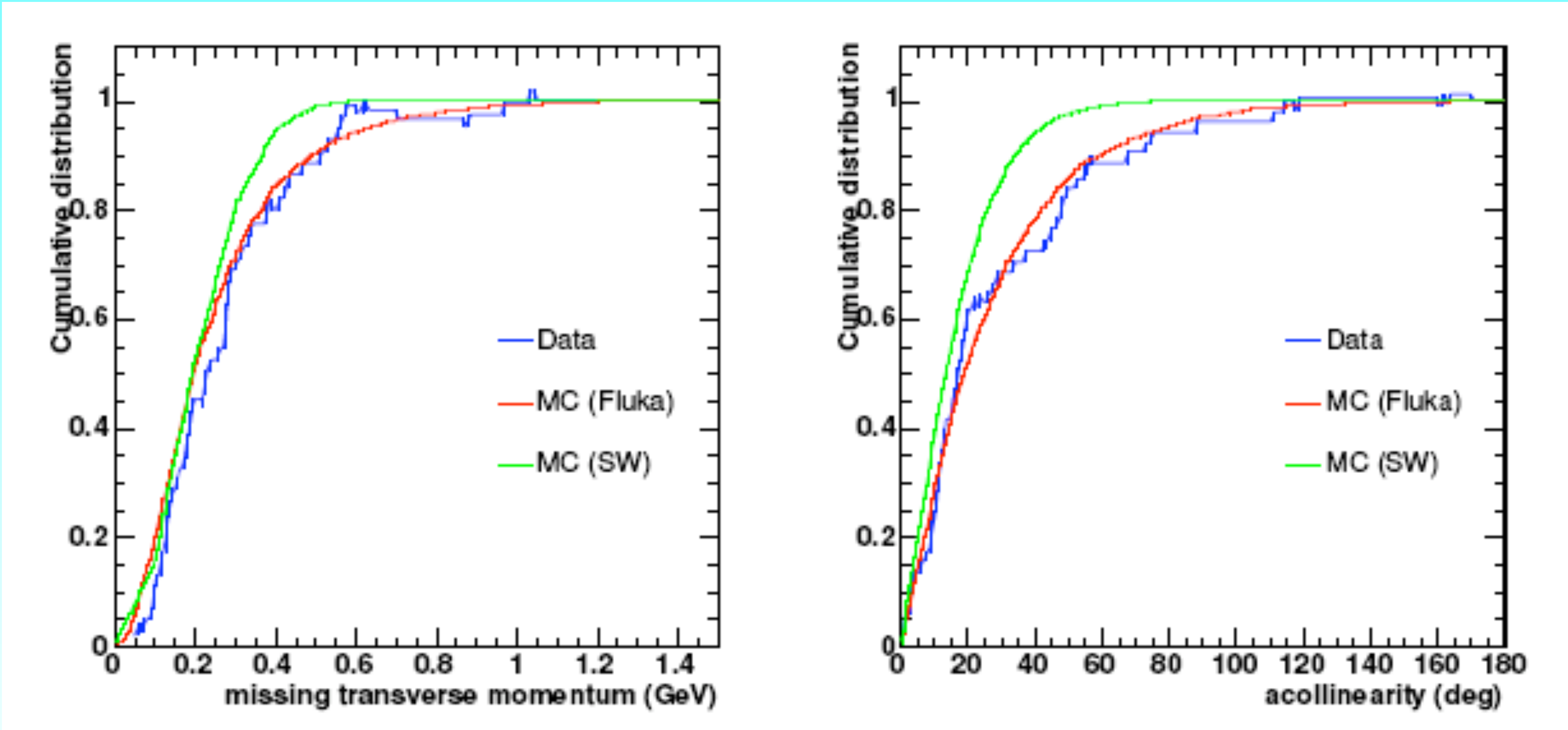
Purely leptonic variables: affected by the presence of nuclear matter only through Fermi motion & Pauli blocking

RESULTS



*Tails in Missing Transverse Momentum and Acolinearity are **NOT reproduced** without nuclear re-interactions*
QUANTIFY ...

RESULTS from NuInt05



Kolmogorov probabilities (CC π^0 BKGD subtracted) :

FLUKA	0.30	0.52
SW	0.027	0.003

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OUTLOOK & CONCLUSIONS

- 10 to 50 l LAr TPC now standard tools for R&D (Padua, LNGS, CERN, ETH, Naples: most recently in the US Yale and FNAL)
- ICARUS T600: being commissioned (LNGS). CNGS ν data expected by 2008
- Major advance in the production of filters for LAr purification (FNAL)
- Significant work toward designing a very massive (50-100 kton) LAr TPC (FNAL & LArTPC group, ETH, UCLA)
- T962 (Yale, MSU, FNAL): proposed to take ν data ($O(10^5)$ evts) on NuMI beam sitting in front of MINOS near detector (a la 50l-NOMAD)

OUTLOOK & CONCLUSIONS

- I have presented the performance of the first and only LAr TPC on a neutrino beam, together with the first measurement of nuclear effects in ν-Ar interactions using a LAr TPC
- We see some of the underlying physics and can start telling one model from another even with limited statistics, thanks to a very clean sample and full reconstruction of the kinematics
- LAr TPC are beautiful detectors for neutrino physics - extensive R&D still needed for multi-kton detectors (required in contemporary ν-physics and proton decay)