A study of Q.E. neutrino interactions with a 50L TPC at the WANF beam.

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the 50L LAr TPC...

**Characteristics**

- 2 Read-out *wire planes* (orthogonal to each other) with 128 wires each.
- **Wire length** 32.5 cm. **Wire pitch** 2.54 mm.
- **Drift length** 47 cm.
- **Active volume** 49l (32.5×32.5×47.0 cm³) around 65 Kg of liquid Argon.
- Wire *signals sampled* at 400 ns.
- Electric Field = 214 V/cm.

**Physical Parameters**

- Electron *drift velocity* ≈ 0.9 mm/µs
- Drift time “pitch” = 0.36 mm.
- *LiqAr purity*: Lifetime of drifting electrons higher than 5 ms.

Attenuation of the ionization over the drift distance is almost negligible.
...at CERN ν beam (1/2)

**Experimental Set-up**

- **50L chamber** placed at CERN ν beam between CHORUS and NOMAD
- *Drift coordinate is vertical* and the chamber is rotated around 30° with respect to beam direction.

**Data acquisition**

- Reconstruction of the neutrino events needs **NOMAD** as an external muon spectrometer.
- Trigger of the TPC based on coincidences with the NOMAD detector.
The CERN-SPS neutrino beam:

- Consists predominantly of $\nu_\mu$.
- $\nu_\mu$ average energy $\sim 23.6$ GeV
- Beam intensity $\sim 1.2 \times 10^{19}$ pot.

Q.E. event selection:

- Visual scanning over around 20000 triggered events (Runs 63-110)
- Golden channel:
  - A clear two prongs topology.
  - 1 MIP leaving the chamber
  - 1 contained prong proton ($T_p > 40$ MeV).
  - No signals from $\pi^0$.

After scanning procedure we have:

$\Rightarrow$ 99 golden events
From 2D RAW data...

Collection View

Induction View

Run 103 Event 4142

The two track projections of a full contained proton

32 cm. (128 wires)

47 cm. (1300 samps)

$\nu + n \rightarrow \mu^- + p$

Same for the prompt muon going out the TPC.

CERN $\nu$-beam
The event reconstruction has been done using **fullreco** and **Qscan**: A set of tools which allow an excellent measurement and visualization of low-multiplicity neutrino events.

- Algorithms which detect hits from RAW data, group them into clusters, recognize smooth 2D track projections and finally, reconstruct the tracks in 3D.
- Provides an **user interface** for visualizing and analyzing the events.
  It allows to correct anomalies and fine tune complex signals.

At the end, we have a complete reconstruction of the event with full information of the geometry and the energy deposited point by point, which allows **PID** and **momentum measurement**.
... to 3D reconstruction.

Aim of 3D reconstruction:
Recover initial trajectory starting from produced 2D views.

1. **Hit search** (each wire):
   Discrimination between signal and noise detecting hit structures.
   Extraction of physics parameters contained in the hit (energy and position), by fitting the signal.

2. **Cluster reconstruction** (each view):
   Group hits produced by a common ionizing particle. Recover non detected hits and dismiss fake (noise) hits.

3. **2D Track reconstruction** (each view):
   Group hits which belong to the same track taking into account links between them:
   Detects interaction vertexes and splits the clusters in smooth 2D tracks.

4. **3D reconstruction** (combining the 2 views):
   Match 2D tracks into 3D track segments:
   1. Hits are matched first by time coincidences.
   2. Uncertainties are resolved taking into account the 2D track structure.
3D reconstruction of the experimental setup and a QE neutrino event inside the liqAr chamber. At the same time, the muon is measured by NOMAD and traced back to the TPC.
the reconstructed event

The Proton:
- Reconstruction of the proton track from the TPC.
- Track geometry at high precision level.

The Muon:
- Reconstruction of the muon track with NOMAD and the TPC. (the 2 tracks are almost superimposed)

Full kinematic info at high precision level.
the (NOMAD) muon

Muon identification and absolute momentum measurement by NOMAD spectrometer:

Resolution $\sim 2\% + 140$ MeV in transverse components (M.S.).

Althought direction can be also measured with the TPC, due to the small part of the track inside the chamber, is not an optimal approach.

\[
\begin{array}{|c|c|}
\hline
\text{dE/dX} & \text{dE/dX} \\ \hline
\text{Entries} & 84 \\ 
\text{Mean} & 2.538 \\ 
\text{RMS} & 0.796 \\ 
\text{z²/ndf} & 4.645/18 \\ 
\text{Prob} & 0.7948 \\ 
\text{Global Norm} & 20.13 \pm 16.84 \\ 
\text{Landau MPV} & 2.243 \pm 0.100 \\ 
\text{Landau SIG} & 0.08746 \pm 0.07774 \\ 
\text{Gauss SIG} & 0.4025 \pm 0.0005 \\ 
\hline
\end{array}
\]

dE/dX distribution from TPC. The fitted MPV is agree with MIP hypothesis LAr (2.1 MeV/cm)
**the (stopping) proton**

- **Particle ID** and momentum measurement from TPC info.
- **Two independent measurements of kinetic energy:**
  - From calorimetry. Particle independent measurement.
  - From track range. Particle dependent estimation.

Optimal measurement is given by range determination after PID.

We estimate:
- **Resolution in energy** $\sim 2\%$
- **Resolution in $\theta$** $\sim 4\%$
- **Resolution in $P_T$** $\sim 2\%$

**dE/dX versus range** provides an extremely efficient separation between protons and pions.
Simulated Events

- **10000 QE CC** events from the WANF beam at *particle level* using **FLUKA**.
- **100000 DIS + RES** events for *background estimation*.
- Geometric setup and final state particle propagation inside the active argon with **GEANT 4**.
- **GEANT 4** hits are converted to **RAW data** simulating a real TPC read-out.

Complete event simulation procedure. *Full nuclear effects description thanks to FLUKA.*
a Q.E. MC example:

Collection View

Induction View

Simulated TPC read-out

3D View

Our tools can reconstruct more complex topologies.
the “golden” MonteCarlo data

- 16% of total (10000) **QE events** are in golden channel.
- 0.12% of total (100000) **DIS + RES** are in golden channel as well.
- Weighting by the corresponding contribution to the total number of CC events:

<table>
<thead>
<tr>
<th>Event type</th>
<th>Fraction</th>
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<tbody>
<tr>
<td>QE</td>
<td>2.9 %</td>
</tr>
<tr>
<td>DIS</td>
<td>89.5 %</td>
</tr>
<tr>
<td>RES</td>
<td>7.6 %</td>
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</tbody>
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- And normalizing to 20000 $\nu_\mu$ CC we expect:
  - 92 golden events from **QE**.
  - 24 golden events from **DIS + RES**.

20% of contamination in **QE golden sample**
the reconstructed MonteCarlo

1000 QE events fully reconstructed with Qscan

Transverse miss momentum

Resolution in $T_p$

Proton dedx vs range
The QE data sample: Distributions (I)

Proton Kinetic Energy

- Entries: 99
- Mean: 0.098
- RMS: 0.04611

Muon Kinetic Energy

- Entries: 99
- Mean: 31.04
- RMS: 18.22

Proton Transverse Momentum

- Entries: 99
- Mean: 0.3653
- RMS: 0.1254

Nomad Muon Transverse Momentum

- Entries: 99
- Mean: 0.5602
- RMS: 0.238
the QE data sample: Distributions (II)

- **Transverse momentum:**
  - $<P_{T\text{miss}}>$ ~ 400 MeV
  - MC shows a *slightly lower* Pt miss.

- **Acollinearity:**

  $$Acoll = \pi - \cos^{-1}\left(\frac{\vec{p}_{Tp} \cdot \vec{p}_{Tm}}{p_{Tp} p_{Tm}}\right)$$

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**Missing transverse momentum**

<table>
<thead>
<tr>
<th>Ptmiss</th>
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<tbody>
<tr>
<td>Entries</td>
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<td>Mean</td>
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<td>RMS</td>
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**Acollinearity**

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**Ptmiss vs Events/bin**

- liqAr DATA
- Simulation
Conclusions

* For first time, we have analyzed low-multiplicity beam-neutrino events in a LAr chamber.

* The instrumental performances and the current reconstruction tools allow us to obtain excellent capabilities on PID and momentum measurement.

* The analysis of the reconstructed sample of Q.E. interactions shows good agreement with Monte Carlo models which include nuclear effects.

* LAr TPCs are excellent detectors to obtain relevant Physics measurements at future accelerator-based neutrino programmes (e.g. T2K, superbeams, neutrino factories).
Some examples & backups:
Qscan working

QE event: Run 103 Event 4142

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**3D Track 1:**

- Kinetic Energy (from wires) = 72.04 MeV
- Total Momentum = 97.97 GeV/c
  - Direction in Local R.S.: (-0.520, 0.050, 0.853)
  - Direction in NUMB R.S.: (-0.023, 0.056, 0.998)
  - Direction in BEAM R.S.: (-0.029, 0.014, 1.000)

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**3D Track 0:**

- Kinetic Energy (from wires) = 165.70 MeV
- Particle fully contained in 1st half:
  - Kinetic Energy (from range) = 192.62 MeV
  - Total Momentum = 631.32 MeV
  - Direction in Local R.S.: (0.387, -0.740, 0.543)
  - Direction in NUMB R.S.: (0.610, -0.750, 0.384)
  - Direction in BEAM R.S.: (0.615, -0.750, 0.244)
The LAr TPC detection technique

- LAr acts as target and detector

Detection Technique:
- Passage of ionizing particles produce ion-electron pairs
- Electrons drift toward the anode producing a current which can be measured
- Planar anode is replaced by several (2 or more) arrays of parallel multi-wire sensing electrodes

ICARUS = novel detection technique: the liquid argon time projection chamber, a homogeneous and isotropic detector providing:

- Spatial Imaging
- Calorimetry

Electronic "Bubble Chamber"

Non-destructive read out ⇒ 3D Imaging
the QE data sample: Distributions (II)

- Proton spectrum: we observe a good agreement with MC.
- Beam angle: MC events at higher values of $\theta$ (background effect?)
- Transverse momentum: simulated data seems to be slightly shifted to higher energy