Simulation of Ni Calibration Source in the DUNE FD
And the status of Charge Light Correlation MCCheating Tools

Jason Stock
(Advisor: Dr. Juergen Reichenbacher)
Calibration Workshop
Mar 15 2018
Charge/Light correlation has been difficult in LArSoft

- Optical and Charge simulations are separate.
- Optical and Charge electronics are separate.
- Particles are not directly linked with their reco objects (historically rectified with the BackTracker for Charge reco)
Offline Stripped Down Particle to Hits Tree

PhotonBackTracker allows Optical reco to MCParticle/Truth information.

ParticleInventory provides a common source for references to the MCTruth in the event!
Some preliminary test studies.
New Geometry to test Ni Source
Ni Calibration Source:

*For Details on the source itself, see the preceding talk by J. Reichenbacher

- Can we see charge?
- Can we see light?

Simulation:
1.6ms / Event
6250 Events
10 Seconds Simulated total
~100,000 Ni gammas
~7000 gammas produced detectable charge or light signals.

X=220 cm
Y=300 cm
Z=-40 cm
Charge Spectrum in Ni Source Simulation (Prelim.)

6250 Events
10 seconds simulated.
100,000 Ni decays simulated. (9MeV Gammas)
Full radiological background.

Ar39

51% of 9MeV Gammas
Impact of 120 ADCU Cut: (Prelim.)

*Further suppression can be attained with spatial cuts.

Significant volume simulated outside of the calibration source’s impact region.
Let's be a little overly optimistic. Assume perfect flash’s and perfect flash matching!

What do the PEs from the particles that make our >120 ADCU Hits look like?
PEs. Estimated cut at ~50%. (Prelim.)
Suppression of Radiologicals for Calibration Source: (Prelim.)

X Positions of Hits W/ BKG

Entries: 4136830
Mean: 4.492
Std Dev: 81.41
Underflow: 0
Overflow: 0
Integral: 4.137e+06

Z Positions of Hits W/ BKG

Entries: 4136830
Mean: 682
Std Dev: 410.1
Underflow: 0
Overflow: 0
Integral: 4.137e+06

X Positions of Hits from Events with at least one hit producing greater than 120 ADCU charge W/ BKG

Entries: 85470
Mean: 193
Std Dev: 65.81
Underflow: 0
Overflow: 0
Integral: 8.547e+04

Z Positions of Hits from Events with at least one hit producing greater than 120 ADCU charge

Entries: 85470
Mean: 57.01
Std Dev: 170.2
Underflow: 0
Overflow: 0
Integral: 8.547e+04
Further Background reduction can be achieved with simple geometric cuts:

Obvious Geometric Cuts:
X: 100 - 300: 3.5 SNR
Y: 100 - 400: 6 SNR
Z: 0 - 200: 7.5 SNR

Other Cuts:
ADCU > 120: 80 SNR
Questions?
BACKUPS
Radiological Requirements for DUNE are clearly sufficient at currently established levels. LAr intrinsic backgrounds (39Ar, 85Kr) are dominant.

Simple Cuts will be insufficient as triggers.

Real time reconstruction is hard.
DUNE Science Goals

- Precision Test of Neutrino Mixing
- Resolve Mass Hierarchy for Neutrinos
- Search for CP Violation in Neutrino Sector
- Other Physics Goals
  - Proton Decay
  - Supernova Burst and Low Energy Physics.
Neutrino Mixing Phenomenon and the Mass Hierarchy

$c_{xy} = \cos(\theta_{xy})$

$s_{xy} = \sin(\theta_{xy})$

$\delta_{CP} = \text{Charge Parity Violating Phase}$
Neutrino Mixing Phenomenon

Neutrino flavor eigenstates can be described as a superposition of the mass eigenstates.

This oscillation phenomenon was first observed for quarks and is described by a transformation matrix on the states of the quark (CKM Matrix).

Neutrinos show a similar, though much more pronounced oscillation. This is described by the PMNS Matrix.

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Current values for the PMNS Matrix

\[
\begin{pmatrix}
0.82 \pm 0.01 & 0.54 \pm 0.02 & -0.15 \pm 0.03 \\
-0.35 \pm 0.06 & 0.70 \pm 0.06 & 0.62 \pm 0.06 \\
0.44 \pm 0.06 & -0.45 \pm 0.06 & 0.77 \pm 0.06
\end{pmatrix}
\]
CP (Charge Parity) Violation:

Another parameter of PMNS is $\delta$ ($\delta_{cp}$). This is the CP Violating Phase of neutrino oscillation.

The CP Violating Phase is occurs on $\theta_{13}$ terms of the PMNS Matrix, meaning CP Violation could only be possible if $\theta_{13}$ is non-zero (it is).

CP Violation in the neutrino sector could help indirectly explain the matter antimatter asymmetry in the universe.
\[ P_{\mu e}^m = \sin^2 \theta_{23} \sin^2 \theta_{13}^m \sin^2 \left(1.27 \frac{L}{E} (\Delta m_{31}^2)_m\right) \]
Working Principle of a Time Projection Chamber (TPC)

Energetic charged particle

Anode wire planes (red = collection, blue = induction)

Cathode

Drift electrons

Electric Field

Time (ticks) $\propto$ Distance from APA

Wire number $\propto$ distance along beam axis in detector

$\mu$ [2.0 GeV/c]
DUNE (Deep Underground Neutrino Experiment)
DUNE (Deep Underground Neutrino Experiment)

- 4 Modules
- 10 KT fiducial volume each
- 150 APAs each

APAs
- 3520 wires
- 2560 channels
- 10 PDs
  - 12 channels each

Totals
- 40 KT Fiducial Volume LAr
- 600 APAs
- 2.1 Million wires
- 1.5 Million channels
- 6000 Optical Detectors
- 72000 Optical Channels
SDSMT Provides Radiological Assays, Model and Simulation

In order to understand the detector response from various contaminants together we need to be able to disambiguate the sources of various signals.

With the PhotonBackTracker, we are able to simulate various radiological contaminants together and compare their impact on the detector response.

This is especially significant for examining low energy events with a radiological background such as for

Supernova Neutrinos,

Solar Neutrinos and Day/Night asymmetry,

Low Energy Calibration,

and understanding detector thresholds and trigger rates for the design of the Data Acquisition electronics -potentially big cost savings-.

Lacking the PhotonBacktracker, it was exceptionally difficult to determine exactly how much any given track or particle contributed to a given detected optical hit.
Improvement of DUNE and FNAL Liquid Argon Detector Simulations:

We have developed the ParticleInventoryService, PhotonBackTrackerService, and BackTrackerService (the latter based on older code from FNAL).

- These new tools for LArSoft allows simulation results for Optical Detectors and Wires to be correlated.
- *PhotonBackTracker* was developed to be fully consistent with the existing charge backtracker.

During extensive testing, implementation and validation checks, including users of other physics groups, long existing bugs were found and corrected in existing software tools NuTools, LArSoft, and DuneTPC as an additional positive benefit (for many experiments beyond DUNE).
Other advances from SDSMT

• New geometries for DUNE Simulation have been included
  - A field cage is included to account for opaque materials around the TPC.
  - A new geometry has been developed for testing a Calibration Source deployment system in simulation.

• Existing LArSoft tools have been update for external use.
  - BackTracker and PhotonBackTracker now have LArSoft independent versions.

• We provide a calibration tree for analysis of new Calibration Source Deployment simulations.
New Geometry

- More realistic geometry
  - Field cage for the Photon Simulation.
  - Reflectivity for aluminum surfaces.
  - Calibration Deployment System outside active volume.
Calibration Studies

AmBe / Ni Source for up to 9 MeV Gammas.

TOP: 9MeV Source only
Right: Radiological Background and 9MeV source.
Our current DUNE radiological model:

Radiological Model is already as comprehensive as possible (wrt/ available computing resources), but will grow as the DUNE Simulations become further optimized and more material and screening results become available.

The most impacted DUNE Physics is Supernova Neutrinos and Low Energy Calibration.

Radiological Simulation
- Ar-39
- Ar42 (High End Point Energy)
- Field Cage and Cathode K-40
- APA Co-60
- Dispersed Rn-222
- Po-210 on PDs. (half life ~138 days, T ~5MeV)

Neutron Simulation
- 5 MeV Neutrons at 175 cm from APA (X), 675 cm into the detector (Z).
Ar42

- Low Rate
- High Energy (>3MeV / Decay)
- Multiparticle Signal

Ar 42 Poses a challenge because it is in regime of our Low Energy Physics.
Electron Lifetime Validation with Radiological Simulation

The “electron lifetime” is a critical parameter for TPCs. (Lifetime / drift velocity = attenuation length)

- DUNE has a 3.5 Meter drift in the single phase TPCs and upward of a 12 meter drift in the dual phase TPCs.
- LAr impurities impair the electron lifetime.
- SP requirements of 3ms e-lifetime requires O2~ppb.

Peak Amplitude

- X Position (cm)
- Summed Peak Amplitude

<table>
<thead>
<tr>
<th>fPeakAmpVXhist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Std Dev</td>
</tr>
<tr>
<td>$\chi^2 / \text{ndf}$</td>
</tr>
<tr>
<td>Prob</td>
</tr>
<tr>
<td>Constant</td>
</tr>
<tr>
<td>Slope</td>
</tr>
</tbody>
</table>

e lifetime = 3.625 ms
Results from RadioSim: Electron Charge Plus Photon Detection

**Detected Charge**

Histogram of Hit Peak Amplitudes vs X and Z Position (cm)

- Lines at APA edges
- Very little charge is collected in the “Dead” volume
- Positive Drift “edge” only at z=0

**Detected PhotoElectrons**

Histogram of OpHit PhotoElectrons vs X and Z Position (cm)

- Bright Bars around Light collectors.
- Apparently long attenuation length neglecting at the bars.

Detected Charge

- Entries: 508499
- Mean x: 3.158
- Mean y: 693.8
- Std Dev x: 77.88
- Std Dev y: 404.9

Detected PhotoElectrons

- Entries: 329365
- Mean x: 1.307
- Mean y: 684.2
- Std Dev x: 142.8
- Std Dev y: 405.1
Separated Beta-ray Backgrounds from RadioSim.

**Detected Charge**

Histogram of Hit Peak Amplitudes vs X and Z Position (cm)

- Entries: 506204
- Mean x: 2.296
- Mean y: 694.3
- Std Dev x: 76.78
- Std Dev y: 404.3

**Detected PhotoElectrons**

Histogram of OpHit PhotoElectrons vs X and Z Position (cm)

- Entries: 3317139
- Mean x: 1.028
- Mean y: 684.4
- Std Dev x: 142.7
- Std Dev y: 496

Cathode (K-40)

Mostly Ar-39
1Bq/kg (Natural Contamination)
Preliminary Gamma Results from early RadioSim.

**Detected Charge**
Histogram of Hit Peak Amplitudes vs X and Z Position (cm)

- **Cathode (K-40)**
- **Anode Steel Co-60**
- **Field Cage (K-40)**

<table>
<thead>
<tr>
<th>Entries</th>
<th>Mean x</th>
<th>Mean y</th>
<th>Std Dev x</th>
<th>Std Dev y</th>
</tr>
</thead>
<tbody>
<tr>
<td>2405</td>
<td>135.7</td>
<td>624.5</td>
<td>124.4</td>
<td>481.5</td>
</tr>
</tbody>
</table>

**Detected PhotoElectrons**
Histogram of OpHit PhotoElectrons vs X and Z Position (cm)

- **Cathode (K-40)**

<table>
<thead>
<tr>
<th>Entries</th>
<th>Mean x</th>
<th>Mean y</th>
<th>Std Dev x</th>
<th>Std Dev y</th>
</tr>
</thead>
<tbody>
<tr>
<td>5497</td>
<td>95.83</td>
<td>691.8</td>
<td>152</td>
<td>467.1</td>
</tr>
</tbody>
</table>
Preliminary Alpha Results from early RadioSim.

**Detected Charge**
Histogram of Hit Peak Amplitudes vs X and Z Position (cm)

Po-210 on PDs
HI~138 days
T~5MeV

**Detected PhotoElectrons**
Histogram of OpHit PhotoElectrons vs X and Z Position (cm)

Rn-222

PE’s are seen from much deeper in the detector.
Effective charge attenuation length
Fit from sim, \(0.58\text{ m}\)
Lifetime (fit from sim*), \(3.6\text{ ms}\)
Programmed Lifetime, \(3.0\text{ ms}\)

Nominal Light Attenuation Length \(\sim 2\text{ m.}\)

* assuming 0.016 m / microsecond drift velocity
Summary and Outlook

● Simulation of the Radiological Model for critical design and performance studies of DUNE is working

● Successful development of a much needed simulation tools (PhotonBackTracker, BackTracker, and ParticleInventory)

● Implement even more physics details into simulation

Questions?
A quick comparison of different particle results

- **Charge collected from Betas**
- **Charge collected from Alphas**
- **Charge collected from Gammas**

- **Light collected from Betas**
- **Light collected from Alphas**
- **Light collected from Gammas**
Proton Decay:

Multiple GUT models suggest proton decay.

Current lower bounds on the Proton Lifetime are from Super-K.

Both DUNE and Hyper-K are will expand these limits.

LArTPCs will have a high detection efficiency for decays with a $\kappa^+$ final state (97% efficient).

Preliminary Alpha Results from early RadioSim.

Histogram of Peak Amplitudes Vs X Position.

<table>
<thead>
<tr>
<th>alpha_PeakAmpVXhist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Std Dev</td>
</tr>
</tbody>
</table>

Relative Histograms for Peak Amp and Integrated Charge From α's

Legend
- Relative PeakAmplitude
- Relative Integrated Charge

BACKUP
Preliminary Alpha Results from early RadioSim.

Normalized Peak Amplitude and Integrated Charge per hit Vs X Position (cm) from α’s

PhotoElectrons vs X position

<table>
<thead>
<tr>
<th>alpha_PEVXhist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Std Dev</td>
</tr>
</tbody>
</table>
Neutrino Mixing Phenomenon

We don’t measure the matrix components directly, but rather the mixing angle.

\[
\begin{pmatrix}
\cos \theta_{12} \cos \theta_{13} & \sin \theta_{12} \cos \theta_{13} & \sin \theta_{13} e^{-i \delta_{CP}} \\
- \sin \theta_{12} \cos \theta_{23} - \cos \theta_{12} \sin \theta_{23} \sin \theta_{13} e^{i \delta_{CP}} & - \sin \theta_{12} \sin \theta_{23} + \cos \theta_{12} \sin \theta_{23} \sin \theta_{13} e^{i \delta_{CP}} & \sin \theta_{13} e^{i \delta_{CP}} \\
\sin \theta_{12} \sin \theta_{23} - \cos \theta_{12} \cos \theta_{23} \sin \theta_{13} e^{i \delta_{CP}} & - \cos \theta_{12} \sin \theta_{23} - \sin \theta_{12} \cos \theta_{23} \sin \theta_{13} e^{i \delta_{CP}} & \cos \theta_{23} \cos \theta_{13}
\end{pmatrix}
\]

Current established limits and values (PDG 2016).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best Fit</th>
<th>3\sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{21} \ (10^{-5}) \text{ eV}^2$</td>
<td>7.37</td>
<td>6.93-7.97</td>
</tr>
<tr>
<td>$</td>
<td>m^2_3 - (m^2_2 + m^2_1)/2</td>
<td>\ (10^{-3}) \text{ eV}^2$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.297</td>
<td>0.250-0.354</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.437 (0.569)</td>
<td>0.379-0.616 (0.383-0.637)</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>0.214 (0.218)</td>
<td>0.0185 - 0.0246 (0.0186-0.0248)</td>
</tr>
<tr>
<td>$\delta / \pi$</td>
<td>1.35 (1.32)</td>
<td>0.92-1.99 (0.83-1.99)</td>
</tr>
</tbody>
</table>

We will refer to $m^2_3 - (m^2_2 + m^2_1)/2$ as $\Delta m^2_{31,32}$ Atmospheric
Mass Hierarchy

As noted, the sign of \( \Delta m_{31,32}^{2} \text{Atmospheric} \) is unknown.

Though we have a good idea of the separation of the masses, we don’t know the order.

Depending on the sign of \( \Delta m_{31,32}^{2} \text{Atmospheric} \), we could have either a normal, or inverted hierarchy.
Mass Hierarchy

\[ m_3^2 - \left( m_2^2 + m_1^2 \right) / 2 \]

The sign of either \( \Delta m_{31}^2 \) or \( \Delta m_{32}^{\text{atmospheric}} \) would be sufficient to determine the mass hierarchy. Atmospheric neutrinos have been used to attempt measurement of \( \Delta m_{31}^2 \) and beam neutrino experiments to measure \( \Delta m_{32}^{\text{atmospheric}} \), but neither have produced a strong conclusion.

Image from Hyper K public site (hyper-k.org/en/physics/img/hierarchy_spheres_english.png)
The probability of observing mu->e oscillation in a given medium “m” is related to the mixing angles $\theta_{12}$ and $\theta_{13}$, and the Baseline / Neutrino energy. To maximize P for a range of energies that we can sweep out with the FNAL accelerator, and using $\theta_{13}$ as found from reactor neutrino experiments, we get an L ~ 1300 km.

$$P_{\mu e}^m = \sin^2 \theta_{23} \sin^2 \theta_{13}^m \sin^2 \left( 1.27 \frac{L}{E} (\Delta m_{31}^2)_m \right)$$

*PDG 2016
Majorana vs Dirac Particle

DUNE will be sensitive to CP Violation in the neutrino sector usually assuming neutrinos to be Dirac Particles.

But if a neutrino is a Majorana Particle, then there will be 3 CP Violating Phases. Neutrinoless double beta decay experiments would be needed.

EXO, nEXO, KamLAND-ZEN, SNO+, GERDA, MAJORANA Demonstrator, LEGEND, etc.)
Supernova Burst Observation (Type II A)

- ~99% of gravitational binding energy is released as neutrinos
  - Neutrinos escape from the collapse itself
  - Neutrinos experience minimal interference in transit

Kudryavtsev. Expected SN time profile in 40KT LArTPC arXiv:1205.6003

Scholberg. 2012. SNB Events for a 17kt LArTPC. arXiv:1205.6003

Energies for SNB Neutrinos are on the order of 10s of MeV while accelerator events are several GeVs. Also, note that time information is from $10^{-2}$ seconds to $10^1$ seconds while beam events are resolves at the $10^{-6}$ to $10^{-3}$ seconds.
Supernova Burst Observation

Example neutron event (true trajectories)

- $E_\nu = 16.3$ MeV
- $e^-$ deposited 4.5 MeV
- No primary $\gamma$'s from vertex
- $^{39}$K deposited 68 keV
- $n$ deposited 7.6 MeV (mostly from capture $\gamma$'s)
- Total visible energy: 12.2 MeV
- Visible energy sphere radius: 1.44 m
- Neutrons bounce around for a long time!

MARLEY SNB Events simulated and analyzed by Steven Gardiner at UC-Davis.
DUNE (Deep Underground Neutrino Experiment)

Recall that the cofactor to $\Delta_{\nu_1\nu_2}$ depends on $\theta_{13}$.

We want to maximize not only our ability to measure Oscillation, but also our ability to measure the CP Violating Phase.

As shown below, we stand the greatest chance of measuring (to 3 sigma confidence) the CP Violating phase for a baseline of $\sim 1300$ km. ($\text{frac}$ is the fraction of the parameter space we can search to 3 sigma confidence.)
DUNE (Deep Underground Neutrino Experiment)

- Proton beam collision with target produces particle showers including charged \( \pi^\pm \) (and \( \kappa^\pm \)).
- Strong magnetic fields in a magnetic horn are used to focus the \( \pi^\pm \).
- Muons are swept away at the Absorber hall.
- All focusing must be done before the \( \pi \) decays.
- To look at anti-neutrinos, just flip the current on the horn.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^\pm )</td>
<td>26 ns</td>
</tr>
<tr>
<td>( \mu^\pm )</td>
<td>2200 ns</td>
</tr>
<tr>
<td>( e^\pm )</td>
<td>stable</td>
</tr>
</tbody>
</table>
DUNE (Deep Underground Neutrino Experiment)

**Davis Campus**
- MJD
  - Majorana Demonstration Neutrinoless double-beta decay
- LUX
  - Large Underground Xenon experiment
- LZ
  - Proposed Second generation dark matter

**Ross Campus**
- DUNE at LBNF
  - Proposed Deep Underground Neutrino Experiment at the Long-Baseline Neutrino Facility
  - 4850 Level—four 10kT liquid argon detectors
- MJD
  - Majorana Demonstration Electroforming laboratory
- BHSU Underground Campus
  - Low-Background Counting
- CASPAR
  - Compact Accelerator System for Performing Astrophysical Research

**Yates Shaft**
- Experiment Hall
  - Proposed Third generation dark matter experiment and 1 T neutrinoless double-beta decay experiment
DUNE (Deep Underground Neutrino Experiment)

*DUNE CDR Vol. 4*
Responsibilities and Efforts of our SDSMT Group

General Responsibilities:
Juergen leads Radiopurity, Purity, Cleanliness group co-convened by Dr. Luke Corwin.

Tasks of the Radiopurity/Cleanliness Group at SDSMT
• Developed radiological computer simulation
• Perform(ed) material samples screening in our low background nuclear lab.
• Define radiopurity, purity, and cleanliness requirements for FD & Prototypes.
• Environmental testing (Corwin Group)

Physics Analysis:
helping to Improve DUNE Sensitivity.
• We participated in the 35T group construction and operation/data analysis.
• Analyzed 35T prototype muon tracks
• Improve DUNE Simulation (LArSoft)
Why did we need PhotonBackTracking?

- 72000 Optical Channels.
- Scintillation Photons on the ~40000 Photons/MeV

Photon Simulation in DUNE has been very non-trivial, as there is simply such a daunting number of particles involved. Other liquid noble gas TPCs such as LUX struggle to simulate photon transfer with ~100 kg of fluid. DUNE has 40KT. DUNE uses a photon lookup library instead to simulate detector responses, but as each photon is not simulated, exact truth matching can be difficult.

- Position Studies.
- Potential Calibration Source Studies
- Truth disambiguation.
- Development and testing of reconstruction algorithms.
- Simulation Verification
- High Priority for Radiological Studies.

The Backtracker for electronic signals has been available for a long time in LArSoft, but due to a lack of manpower and a long tasklist the same has never been provided for Photons. As the simulation is maturing and detector designs are being finalized this has become a very important feature.
Importance of PhotonBackTracker for Radiological Studies

In order to understand the detector response from various contaminants together we need to be able to disambiguate the sources of various signals.

With the PhotonBackTracker, we are able to simulate various radiological contaminants together and compare their impact on the detector response.

This is especially significant for examining low energy events with a radiological background such as for

- Supernova Neutrinos,
- Solar Neutrinos and Day/Night asymmetry,
- Low Energy Calibration,
- and understanding detector thresholds and trigger rates for the design of the Data Acquisition electronics -potentially big cost savings-.

Lacking the PhotonBacktracker, it was exceptionally difficult to determine exactly how much any given track or particle contributed to a given detected optical hit.
35t backups
The 35T Prototype

To demonstrate the Required Purity and TPC Detection Principle
The 35T Prototype

Cosmic Ray Counters (CRCs)

20 cm short drift region

2.2 m drift region

CRCs

Photon Detectors (8 total) in 4 APAs

Cathode Plane

Field Cage not shown

J. Fowler
The 35T Prototype

- The 35T run concluded prematurely with the failure of a link in the LAr filtration system.
  - Atmosphere pumped into LAr for several hours.
- Only one wire plane used (collection plane)
- Only 3 of 4 APAs used (APA 4 -bottom center- suffered electronic issues).
- ~Khz and ~100 Khz (Coherent) noise issues. (contributed to disabling APA 4)
- No photon detector data from many runs. No photon triggered runs.
- We did collect useable data using a special vertical muon paddle trigger (triggered on horizontal muons).
35T Analysis
Outlook:
Moving forward we will be studying the muon lifetime in LAr with prototypes (Currently the 35T data, and in the future also with the CERN Prototypes) to show a proof of principle for using the muon charge ratio. This can be used to establish the $\nu \bar{\nu}$ beam contamination.

$\text{Lifetime} = 2.7\, ms$
A quick comparison of different particle results

Charge collected from Betas

Charge collected from Alphas

Charge collected from Gammas

Light collected from Betas

Light collected from Alphas

Light collected from Gammas