First Run of the LArIAT Testbeam Experiment

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On behalf of the LArIAT Collaboration

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I. Why LArIAT?

II. The experiment
   - Fermilab Test Beam Facility & secondary beam
   - LArIAT tertiary beamline
   - Cryostat and TPC

III. Run 1 overview + event displays

IV. Where we are now
   - Offline reconstruction
   - Ongoing analyses
LArTPCs and neutrino physics

- Liquid argon time projection chambers (LArTPCs) let us capture neutrino interaction final products in unprecedented detail.

- Dedicated calibration effort needed.
Enter LArIAT (Liquid Argon In A Testbeam)

- “Table-top” (170L) LArTPC in a test beam at Fermilab for R&D + physics!
  - Repurposed ArgoNeuT detector
  - **R&D goals:** PID, calorimetry, 2D/3D event reconstruction
  - **Physics goals:** e/γ shower ID, non-magnetic sign determination, π-Ar interactions, µ-Ar capture, antiproton stars, kaon studies, and G4 validation…

The LArIAT TPC inside the cryostat

The LArIAT TPC inside the cryostat

40cm 47cm

**LArIAT** final beam spectrum, 8 GeV secondary pions on target (MC)

Spectrum of final state particles from NuMI v interactions

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The tertiary beamline

- Secondary beam
- Cu target
- Time of flight scintillators
- Multi-wire proportional chambers (MWPCs)
- Bending dipole magnets
- Cryostat & TPC
- μ range stack
- μ punch-through veto

π's (8-64 GeV)
The tertiary beamline
Beam commissioning

Installation of beamline detectors and TPC-less running to test them (and characterize the beam)

Completed summer 2014
Beam commissioning

- MWPCs + bending magnet for momentum reconstruction
- Excellent agreement with simulation

32 GeV $\pi^+$ on Target, +100 A Magnet Current

![Graph showing tracks/spills per 20 MeV/c for different particle types with upstream and downstream MWPCs and momentum reconstruction.](image-url)

J. M. St John

W. Foreman (UChicago)
Beam commissioning

- Time of flight (TOF) for separation between $\pi$'s/\(\mu\)’s and protons
- 2:1 ratio of $\pi$:p

- TOF vs reconstructed momentum

Preliminary

$A_1 = 457.94$ entries/ns
$\bar{x}_1 = 27.40$ ns
$\sigma_1 = 0.96$ ns
$A_1 \sigma_1 = 439.65$ entries

$A_2 = 39.18$ entries/ns
$\bar{x}_2 = 41.20$ ns
$\sigma_2 = 5.65$ ns
$A_2 \sigma_2 = 221.35$ entries

$A_1 \sigma_1 / A_2 \sigma_2 = 1.99$

J. Ho

W. Foreman (UChicago)

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Beam commissioning

- **Aerogel Cherenkov counters** for further PID
- Possible $\pi$ vs. $\mu$ discrimination using combination of thresholds and pulse height
- Effective 230-400 MeV/c

![Image of Aerogel Cherenkov counters]

<table>
<thead>
<tr>
<th>$\pi^+/-$ tag efficiency</th>
<th>$p^+/-$ fake rate (x10)</th>
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<tr>
<td>~95%</td>
<td>~0.9% (x10)</td>
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Beam commissioning

- **Muon range stack** for discrimination of through-going $\pi/\mu$

- Currently under commissioning/upgrade

$\pi^{+/−}$  $\mu^{+/−}$
Inside the cryostat

The time projection chamber
- Repurposed from ArgoNeuT
- New wireplanes
  - 1 shield plane: 225 vertical wires
  - 2 readout planes: 240 wires each, +/-60°, 4mm pitch
- Drift field ~500 V/cm
Inside the cryostat

- New cold electronics
  - Signal/noise > 50

- Light collection system
  - 2 PMTs, 3 SiPMs
  - VUV scintillation light wavelength-shifted at TPB-coated reflector foils lining walls
Preparing for data...

- Summer 2014 – Beam commissioning
- Winter 2014-15 – Cryostat moved to experimental enclosure, cryo system installation
- April 29, 2015 – Cryostat full of LAr, first light from PMTs
First data

- April 30, 2015 – TPC turned on, first cosmic-triggered track!
First data

…and first beam events soon after…
Yay!
Some event topologies seen by LArIAT

$\pi^+ + n \rightarrow \pi^0 + p$

$\pi^+$ charge exchange

Induction plane

Collection plane
Some event topologies seen by LArIAT

Stopping/decaying $\mu^{+/−}$

$\pi^{+/−}$ absorption on Ar

Induction plane

Collection plane

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Some event topologies seen by LArIAT

Photon-initiated shower

Distinguishable using dE/dx at start of shower!

e\(^{+/-}\)-initiated shower

Distinguishable using dE/dx at start of shower!
Summary of Run I

- Took beam data for about 2 months
- Collected about 112k spills total
  - Each spill supercycle = 4 sec of beam + 26 sec cosmics/Michels
Rapid progress in reconstructing both beamline & TPC ionization tracks.
A few ongoing analyses...
- $N_2$ content in LAr suppresses scintillation light
- From fits to scintillation light, can extract “slow” light time component and determine $N_2$ concentration
- Results agree with gas analyzers

Preliminary: $\tau_{\text{slow}} = 1180$ ns ($N_2 < 0.1\text{ppm}$)
Electron lifetime / $O_2$ levels with cosmic $\mu$'s

- Dedicated paddles for cosmic-$\mu$ triggers

- Fit to charge vs. drift time for measurement of electron lifetime
  - Can calculate $O_2$ concentration below sensitivity of cryo gas analyzers

- Current results show $O_2 < 1$ ppb, agreement with gas analyzers
Pion interactions I – elastic scattering

\[ \sigma_{tot} = \sigma_{el} + \sigma_{reac} \]

- \( \sigma_{inel} \) inelastic scatter
- \( \sigma_{abs} \) absorption on Ar
- \( \sigma_{chex} \) charge exchange
- \( \sigma_{\pi prod} \) pion production

Pion-Argon elastic scattering

- Look for kinks in tagged \( \pi \) tracks

I. Nutini
Pion interactions II – absorption

Pion absorption

- Incoming tagged $\pi$ and no $\pi$'s in final state
- Often accompanied by protons/neutrons

Reconstructed pion absorption (MC simulation)
Charged pion single charge exchange

\[ \pi^+ + n \rightarrow \pi^0 + p \]

- Photon BG for neutrino LArTPCs!
- Active effort to ID and reconstruct
  - \( \pi^0 \) mass peak from \( m_{\gamma\gamma} \)
  - Cross section
- MC studies to understand containment of these events in TPC
Michel electrons

- Light-based trigger to save stopping/decaying cosmic muons

- Initial reconstruction focused on light signals only
  - Track/shower algorithms to follow

- Eventual plans: energy calibration source, measurement of $\mu^-$ nuclear capture rate
  - Early decay spectrum (5% of full sample) compatible with accepted values
    - From preliminary fit, $\tau_{\text{capture}} \approx 790\text{ns}$
      - prev. measured values:
        - 833±55 ns (Bertin et al, 1973)
        - 709±56 ns (Carboni et al, 1980)
Summary

- LArIAT’s Run 1 was a success – lots of new data to analyze

- Offline event reconstruction actively evolving day-by-day

- Several analyses underway, with more to come

- Plenty of new first-hand experience to benefit future LArTPC neutrino experiments

- Actively preparing for **Run II** this Fall
  - Same beamline & detector, many minor improvements!
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LAr scintillates at 128 nm, with over 40k γ/MeV (zero-field)

Wavelength-shifting is needed before detection by PMTs

Typically used for non-beam event triggers, cosmic ray veto

However, lots of information contained in this light!
  - Fast and slow components dependent on ionization density (background discrimination in dark matter searches)
Potential advantages for neutrino detection

- Delayed Michel electrons from $\mu^{+/−}$ for non-magnetic pure sign selection
  - $\mu^−$ produced in $\nu_\mu$ CC; $\mu^+$ produced in anti-$\nu_\nu$ CC
  - $\mu^−$ can be captured by Ar nucleus (P=74%), while $\mu^+$ will always decay as if in vacuum
  - IF no Michel decay, THEN it must be a $\mu^−$ (thus, CCQE neutrino event)

- Photon yield complements charge yield to correct for ion recombination charge loss
  - Better energy resolution

For appreciable contribution from scintillation, need light collection efficiency 0.1% or greater (M. Sorel, 2014)

Factor $x2$ improvement in E resolution at 0.5% (M. Szydagis, 2013)
The LArIAT light collection system (I)

Two cryogenic PMTs

Three silicon photomultipliers (SiPMs) on custom preamp boards.

- Hamamatsu PMT R-11065 (3” radius)
- ETL PMT D757KFL (2” radius)

Hamamatsu S11828-3344M, 4x4 array, w/preamp

SensL MicroFB-60035 w/preamp
The LArIAT light collection system (II)

Inner walls lined with TPB reflector foil to maximize light collection and uniformity compared to traditional LArTPCs.

Signals digitized by CAEN V1751 at 1GS/sec
- Fast DAQ to optimize differentiation of fast & slow component (~7ns vs ~1.6μs)

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Some example signals (in this case, a triggered Michel delayed decay).

Hamamatsu SiPM arrays differ by type of opamp, and by age/health of SiPM chip.
- B has fewer (11 out of 16) functional channels due to repeated reflow soldering during testing

Time resolution of all SiPM boards expected to improve with modifications to circuitry (ie, AC coupling of pre-amplified signal)
How LArIAT is different

**MicroBooNE**

128nm photons wavelength-shifted at plates in front of PMT.

Resulting visible photons re-emitted isotropically.

**LArIAT**

128nm photons wavelength-shifted at TPB-coated reflective foils mounted to TPC walls.

Isotropic visible photons are reflected back into the volume.
$N_2$ vs slow scintillation lifetime

WArP Collaboration
arXiv:0804.1217
Spill supercycle = 4s beam + 26s cosmics & light-based Michel triggers

- ~ 5-20 beam triggers per supercycle (depending on beam intensity)
- ~0-2 cosmic muon paddle triggers per supercycle
- ~20 Michel events per supercycle
Tuning of bending magnet lets us sample different energy ranges of cross-section.
μ⁻ that stop in LAr are pulled into 1S orbital, with some probability of capture onto Ar nucleus.

This alters the lifetime we measure:

\[
\frac{1}{\tau_{\mu^-}} = \frac{1}{\tau_{\text{free}}} + \frac{1}{\tau_{\text{capture}}}
\]