Liquid Argon Neutrino Detectors

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CPAD LArTPC R&D workshop

Outline

Introduction

The Physics We Want to Do

The Detectors We Want To Use

Things We Need to Understand

Coherent Elastic Neutrino Scattering

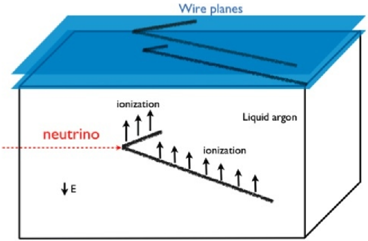
Conclusions

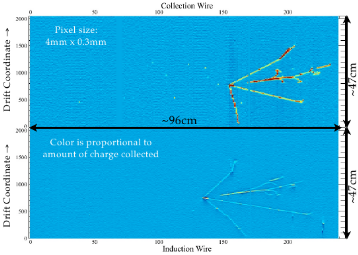
Introduction

- Liquid argon is growing in importance as a detector for neutrino physics
- It allows making precise measurements of the effects of neutrino interactions in a broad range of energies.
- We get bubble chamber quality data and are able to digitize it.
- And it is possible to construct large flagship detectors.
- New detector technologies often let us see physics we never anticipated.

LArTPC Concept

- Pioneered by the ICARUS collaboration
- Energy deposition in argon results in ionization and scintillation
- Electrons are drifted in the Electric field towards the anode.
- Signal is induced and then collected on subsequent wire planes (2D location).
- Drift time provides 3rd coordinate → 3D reconstruction.
- Quantity of charge provides calorimetric reconstruction.





ArgoNeuT Data Event


(Working Group Nu1) Neutrino Oscillations and the Three-Flavor Paradigm~~
- J. Thomas et al., "CHerenkov detectors In mine PitS (CHIPS): A White Paper"
- T. Ekelof, M. Drascos, "Proposal for a Neutrino Superbeam using the ESS 5 MW, 2.5 GeV Linac as a Proton Driver" (overlap with Nu6)
- X. Qian, J. Ling, R. McKeown, W. Wang, E. Worcester, C. Zhang, "A Second Detector at an Off-Axis Location to Enhance the Mass Hierarchy Discovery Potential in LBNE"
- D. Beznosko et al., "A Large Water-Based Liquid Scintillation Detector in Search for Proton Decay p -> K+ nubar and Other Physics" (overlap with Nu2, Nu3, Nu4)
- J. Conrad et al., "Whitepaper on the DAEdALUS Experiment"
- S. Kettell et al., "Measurement of the Neutrino Mass Hierarchy with Reactor Neutrinos"
- D. Cowen et al., "Measuring the Neutrino Mass Hierarchy with PINGU"
- J.J. Evans et al., "GLADE: GLobal Liquid Argon Detector Experiment"
- K. Long et al., "The Neutrino Factory"
- M. Messier for the NOvA collaboration, "Extending the NOvA Physics Program"
- R. Plunkett, J. Thomas, "MINOS+: Using the NuMI Beam as a Precision Tool for Neutrino Physics" (overlap with Nu5)
- P. Adamson et al., "A Case for the Further Exploitation of NuMI"
- M. Bishai et al., "Precision Neutrino Oscillation Measurement Using Simultaneous High-Power, Low-Energy Project-X Beams"
- E.W. Beier et al., "Large-Scale Underground Water Cherenkov Detector at Homestake" (overlap with Nu6)
- K. Heeger for the Daya Bay collaboration, "The Daya Bay Measurement of Theta13"
- K. Heeger for the Daya Bay collaboration, "The Daya Bay Measurement of Delta_m^2_ee"
- S. Hans et al., "Search for Oscillations of Reactor Antineutrinos at Very Short Baselines" (overlap with Nu5, Nu7)
- S. Hans et al., "U.S. Reactors for Antineutrino Experiments" (overlap with Nu5, Nu7)
- T. Nakaya for the Hyper-K collaboration, "Hyper-Kamiokande Physics Opportunities: Exploring CP Violation with the Upgraded JPARC Beam"
- S. Hans et al., "Advanced Reactor Antineutrino Detector Development" (overlap with Nu5,Nu7)
- Z. Djurcic, M. Sanchez et al., "Using Large-Area Picosecond Photosensors For Neutrino Experiments"
- M. Kordosky, F. Cavanna, J. Raaf, B. Rebel for the LArIAT collaboration, "LArIAT: Liquid Argon In A Testbeam"
- A. Bernstein et al., "A Neutrino Physics Program for a Kiloton Scale Neutrino Detector at Boulby" (overlap with Nu6, Nu7)
- E. Christensen, P. Coloma, P. Huber for the MASS working group of the Muon Accelerator Program, "Performance of a Low-Luminosity Low Energy Neutrino Factory"
- A. Holin et al., "Getting the Most Out of the On-Axis NuMI Beam"
- T. Nakaya for the Hyper-K collaboration, "Hyper-Kamiokande Physics Opportunities: Exploring Neutrino Properties with Atmospheric Neutrinos" (overlap with Nu6)
- J. Brunner et al., "Measurement of the Neutrino Mass Hierarchy with the ORCA Detector"
- M. Diwan and R.J. Wilson for the LBNE collaboration, "Opportunities for Precision Tests of Three-Neutrino Mixing and Beyond with LBNE"

(Working Group Nu2) The Nature of the Neutrino: Majorana vs. Dirac
- E. Blucher et al., "Neutrinoless Double Beta Decay and Other Neutrino Physics with SNO+"
- K. Lang et al., "SuperNEMO in the USA"
- D. Nygren, J.J. Gomez-Cadenas for the NEXT/OSPREY collaboration, "Discovery Potential of a Large High Pressure Xenon Gas TPC for Neutrinoless Double Beta Decay Experiments"
- L. Winslow, "Next Generation Liquid Scintillator-Based Detectors: Quantum Dots and Picosecond Timing"
- H. Ejiri, "Comments on Neutrino-less Double Beta Decays"
- Y. Kolomensky for the U.S. Cuore Collaboration, "Exploring Neutrino-less Double Beta Decay in the Inverted Mass Hierarchy Region with Bolometric Detectors"
- J.F. Wilkerson and S.R. Elliott for the MAJORANA collaboration, "A Search for Double Beta Decay of Germanium-76"
- M. Heffner et al., "Gaseous Xenon TPC with Germanium-like Energy Resolution"
- G. Gratta for the EXO collaboration, "nEXO" (in the process of being shortened to one page)
- D. Mei for the CUBED collaboration, "Advanced Materials for Underground Physics and Applications"

(Working Group Nu3) Absolute Neutrino Mass Scale
- P.J. Doe et al., "Project 8: Measuring Neutrino Masses Using Frequency-Based Techniques"
- R.G. Hamish Robertson for the KATRIN collaboration, "KATRIN: an Experiment to Determine the Neutrino Mass from the Beta Decay of Tritium"
- W.R. Blanchard et al., "Development of a Relic Neutrino Detection Experiment at PTOLEMY: Princeton Tritium Observatory for Light, Early-Universe Massive-Neutrino Yield" (overlap with Nu6)

(Working Group Nu4) Neutrino Interactions
- C. Mariani, "Study of Neutrino Cross Sections and Nuclear Model"
- A. Bolozdynya, Y.V. Efremenko, K. Scholberg, "Perspectives to Search for Neutrino-Nuclear Neutral Current Coherent Scattering" (overlap with Nu5, Nu6, Nu7)
- A. Datta, A. Rashed "Non-Standard Interactions in nutau-nucleon scattering"
- J. Conrad et al., "Whitepaper on Cyclotrons as Drivers for Precision Neutrino Experiments" (overlap with Nu1, Nu7)
- U. Mosel, "Thoughts on Improving Event Generators and Theoretical Calculations of Neutrino-Nucleus Interactions"
- S. Brice et al., "Measuring CENNS in the Low Energy Neutrino Source at Fermilab"
- A. Bernstein et al., "Observation of Coherent Neutrino-Nucleus Scattering at a Nuclear Reactor" (overlap with Nu7)
- P. Barton et al., "Searches for CENNS at the Spallation Neutron Source"
- A. Bolozdynya et al., "Opportunities for Neutrino Measurements at the Spallation Neutron Source" (overlap with Nu6)
- O. Palamara, K. Partyka, F. Cavanna, "Neutrino-Nucleus Cross Sections: Development of Tools for Reconstruction of Exclusive Topologies in LAr TPC Experiments"

- At the SLAC Snowmass pre-meeting, the whitepapers that consider a LAr detector:
- 7/28 in Nu1 (Neutrino Oscillations and the Three-Flavor Paradigm)
- 9+2/ 19 in Nu4 (Neutrino Interactions)
- 3 in other groups.
- During Snowmass 2001, ICARUS was in the course of its first test run in Pavia.

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The Detectors We Want to Use or Have Already Used

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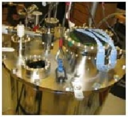
Yale TPC



Location: Yale University
Active volume: 0.002 ton
operational: 2007

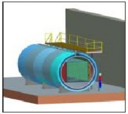
Bo

Location: Fermilab
Active volume: 0.02 ton
operational 2008

ArgoNeuT

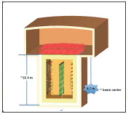
Location: Fermilab
Active volume: 0.3 ton
operational: 2008
First neutrinos: June 2009

MicroBooNE



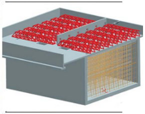
Location Fermilab
Active volume: 0.1 kton
Construction start: 2011

LAr1



Location: Fermilab
Active volume: 1 kton
Construction start: 2016?

LBNE



Location: Homestake
Active volume: 10 kton
Construction start 2020

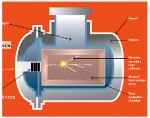
Luke

Location: Fermilab
Purpose: materials test st
Operational: since 2008

LAPD

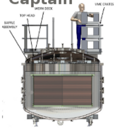
Location: Fermilab
Purpose: LAr purity demo
Operational: 2011

LAriAT



Location: Fermilab
Purpose: LArTPC calibration
Operational: 2013 (phase 1)

Captain



Location: LANL
Purpose: LArTPC calibration
Operational: 2013

The Detectors We Want to Use or Have Already Used

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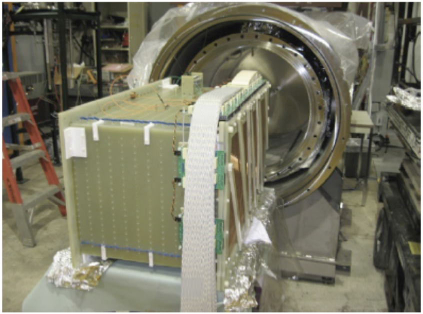
- ArgoNeuT



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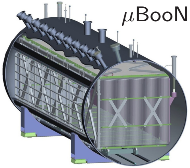
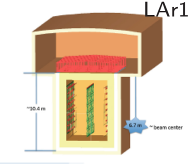
- ArgoNeuT
- MicroBooNE, ICARUS, ICARUS-NESSIE,LAr1

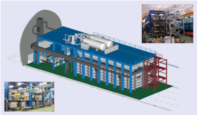
μBooNE



LAr1



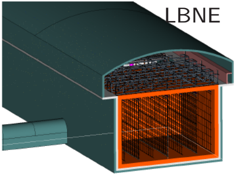
ICARUS



The Detectors We Want to Use or Have Already Used

The following experiments have used/proposed/been approved/are constructing a detector with LAr as a neutrino detector. I am sorting them by their mass.

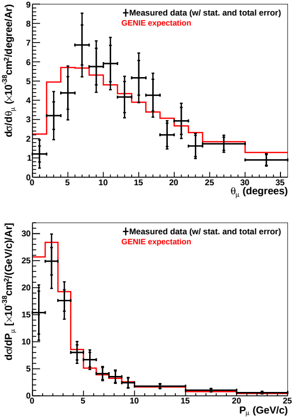
- ArgoNeuT
- MicroBooNE, ICARUS, ICARUS-NESSIE,LAr1
- GLADE, LBNE, LBNO, OKINOSHIMA


LBNE


LBNO GLACIER

The Physics We Want Our Detectors To Measure

- Cross-Section physics

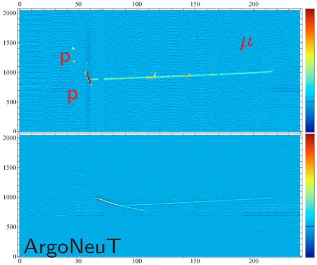


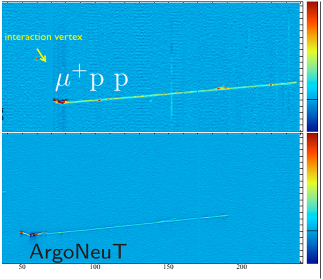
Phys. Rev. Lett. 108, 161802

First ever ν cross-sections measured in LAr! More physics is on the way - see M. Soderberg's talk.

The Physics We Want Our Detectors To Measure

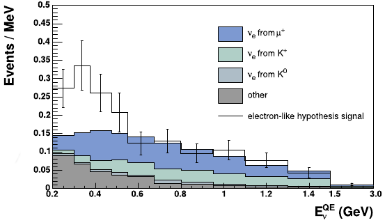
- Cross-Section physics
- Final State Interactions (FSI) and nuclear effects

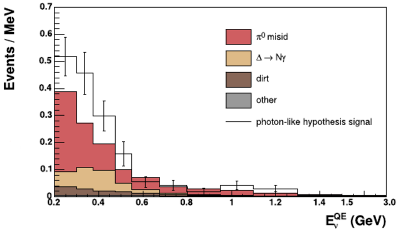




The Physics We Want Our Detectors To Measure

- Cross-Section physics
- Final State Interactions (FSI) and nuclear effects
- The MiniBooNE excess and and sterile neutrino searches





The Physics We Want Our Detectors To Measure

- Cross-Section physics
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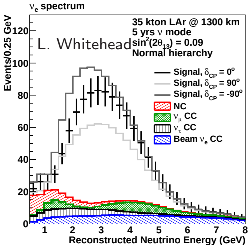
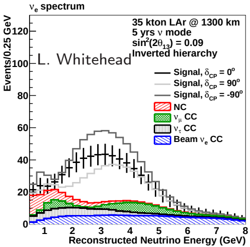
- The MiniBooNE excess and and sterile neutrino searches
- Mass Hierarchy





The Physics We Want Our Detectors To Measure

- Cross-Section physics
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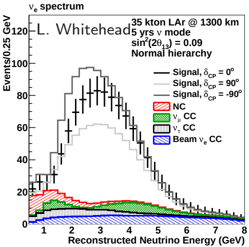
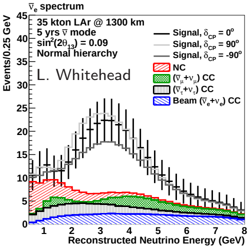
- Mass Hierarchy
- CP Violation





The Physics We Want Our Detectors To Measure

- Cross-Section physics
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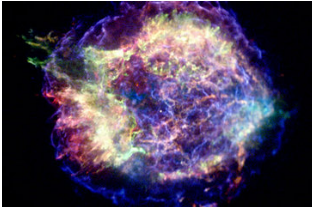
- CP Violation
- SN Detection



The Physics We Want Our Detectors To Measure

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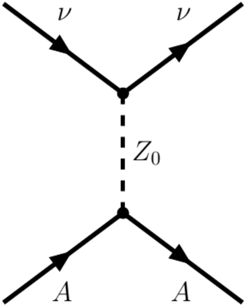

The Physics We Want Our Detectors To Measure

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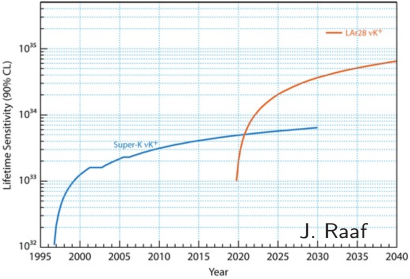
- Coherent Elastic Neutrino Scattering
- Proton Decay



J. Raaf

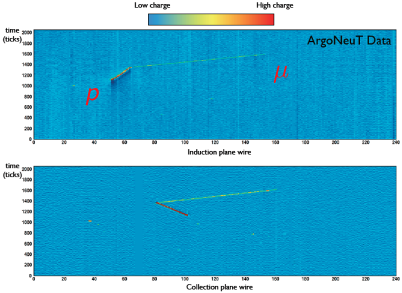
The Physics We Want Our Detectors To Measure

- Cross-Section physics
- Final State Interactions (FSI) and nuclear effects
- The MiniBooNE excess and and sterile neutrino searches
- Mass Hierarchy
- CP Violation
- SN Detection
- Coherent Elastic Neutrino Scattering
- Proton Decay
- Unknown

How Do We Do These Physics?

- Cross-Section physics
- Final State Interactions (FSI) and nuclear effects

All ν_x interactions both Charged Current (CC) and Neutral Current (NC). Need precise Particle ID (PID), energy and track reconstruction.



How Do We Do These Physics?

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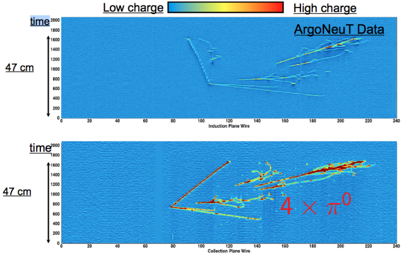
ν_e appearance. Need good background suppression coming from NC π^0s.



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Sign differentiation. Need to magnetize the detector or rely on the μ^- capture rate. It is around 80% in Argon (compare with 8% for C and 20% for H_2O).

How Do We Do These Physics?

- Cross-Section physics
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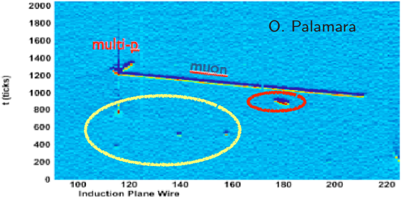
Again looking for ν_e, but at much lower energies. Need ways to extract and recognize these signals, especially if you're on the surface. Plus look for de-excitation gamma interactions.



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- Proton Decay
- Coherent elastic neutrino scattering

Need to register energies much lower than typical LAr neutrino detectors can handle. Use scintillation light A'la Dark Matter detectors.

How Do We Do These Physics?

- Cross-Section physics
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- The MiniBooNE excess and and sterile neutrino searches
- Mass Hierarchy
- CP Violation
- SN Detection
- Proton Decay
- Coherent elastic neutrino scattering
- The Unexpected!

We don't know what we might see. If we do, it's better to have a very precise detector to examine it.

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Customizing the TPC detectors

All TPCs are not made equal. The technology is evolving and different needs dictate different construction choices and challenges. Examples are:

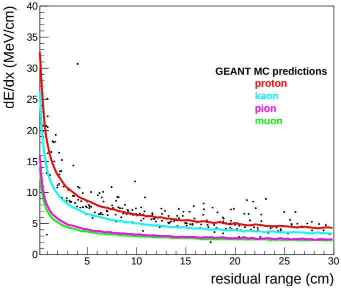
- Spacing between the wires, i.e. wire pitch. Sample values are:
  - 3 mm - MicroBooNE,ICARUS
  - 4 mm - ArgoNeuT
  - 5 mm - LBNE
- Warm vs Cold Electronics
- Electronics sampling time:
  - 0.197 μs - ArgoNeuT
  - 0.4 μs - ICARUS
  - 0.5 μs MicroBooNE, LBNE
- Wrapped wire planes: LBNE, LAr1
- Double Phase Readout - LBNO *(see talk by A. Marchionni)*
- Light Readout:
  - PMTs: MicroBooNE, ICARUS
  - Wavelength Shifter Paddles: LBNE, LAr1
  - SiPMs

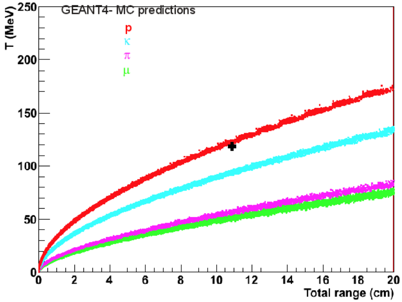
What Customization Does

- The question I was asked was "what are the detectors we need, to do the physics we want?"
- I am not going to answer that question (except that it's LArTPCs).
- A different interesting question to ask ourselves is, how does the ability to do physics change with varying parameters of the TPC?
- I will try to answer a part of that second one, e.g. what happens if you vary the wire pitch?
- **The studies shown in the next slides, represent the current status of our reconstruction software, and as such are surely not the final word.**

dE/dx resolution and PID

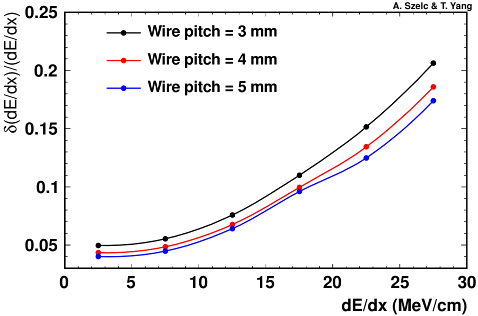
- Since LAr is essentially a full absorption calorimeter it allows us to calculate the energy of charged particles.
- The mechanism of the deposition is well known, and depends on the mass of the particle.
- This means that if we reconstruct the pattern of energy deposition we are able to perform particle ID on charged tracks.
- We can also use the range they travel in LAr to reconstruct their energy.





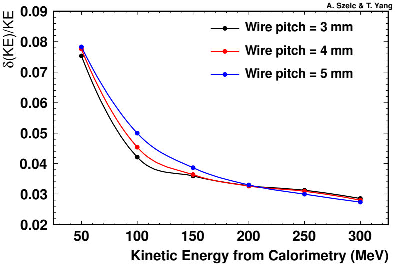
dE/dx resolution and PID (2)

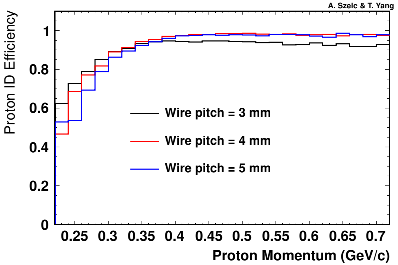
- 300,000 proton events with each wire pitches of 3,4 and 5 mm, ArgoNeuT sampling (0.197 ns).
- Forward going.
- $0 < P < 1$ GeV/c
- Surprisingly, larger pitch seems better - possibly due to smaller fluctuations.



dE/dx resolution and PID (3)

- What about PID based on Kinetic energy?
- Here, small wire pitch is better especially at lower energies - smaller error in endpoint determination.
- Small wire pitch is still necessary to understand vertex activity and very short tracks.
- Work in progress.


A. Szelc & T. Yang

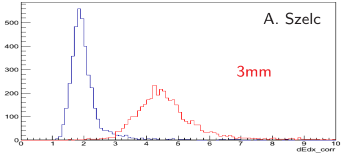

A. Szelc & T. Yang

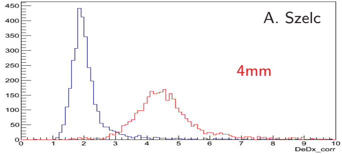
e/γ dE/dx separation

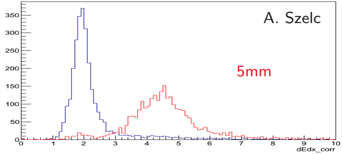
- Needed to separate background NC events with π^0 vs signal CC ν_e events.
- π^0s convert to two photons and are most difficult to tag if:
  - at high energies (two showers indistinguishable)
  - At low energies (showers almost invisible)
  - When asymmetric (one of the showers almost invisible)
- In these cases e/gamma- separation is most needed. The initial part of the shower can be used → gamma converts to e^+/e^- pair → double ionization.
- There are other variables (vertex if identified, length, width etc.) plus event topology for “standard” π^0s

e/γ dE/dx separation (2)

- Again varying the wire pitch between 3, 4 and 5mm in a MicroBooNE like Geometry (0.5 μs sampling).
- e and γ single showers in a 50 degree forward cone.
- A cut is requesting the reconstructed start of the shower to be not further than 5cm from the MCTruth.
- This is to compensate for the algorithm getting the shower direction wrong sometimes - work in progress.
- This is not the final γ discrimination power, but it is still interesting too look at.

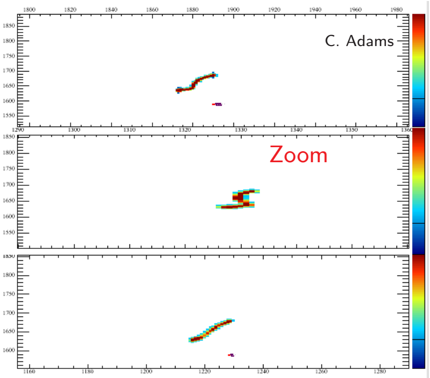






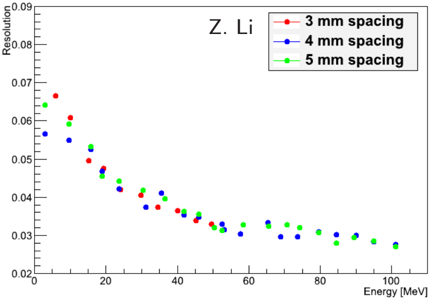
SN neutrinos

- reaction:
  $\nu_e +^{40} Ar \rightarrow e^- +^{40} K^-$
- The result is very low energy electrons.
- The deposited tracks are of the order of $\simeq$ 10 hits.
- Do we gain or lose with energy resolution?



SN neutrinos (2)

- Studies with MicroBooNE like Geometries of 3,4 5 mm (sampling at $0.5\mu s$).
- Looking at resolution of deposited charge wrt to electron energy.
- Higher wire pitch does not worsen resolution, but may make it harder to extract and reconstruct lowest energy events.
- Work in progress.



The Problem of Plenty - Energy Calculation

- Many neutrino experiments with worse granularity have held to the different ν-interaction classifications like CCQE, DIS etc...
- Energy was calculated, e.g. as $E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu cos\theta_\mu)}$
- We now know for certain, that FSI happen in neutrino interactions in argon.
- Need to focus on topological classification, e.g. $CC + 0\pi + N$protons, etc...
- Does the above formula still work?! How well?
- *See talk by F. Cavanna*

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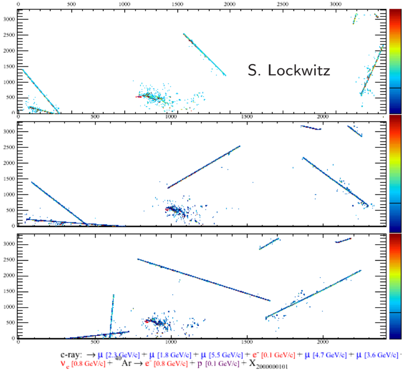
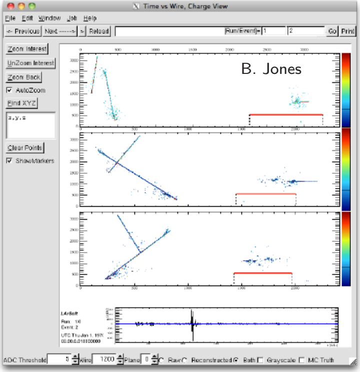
Weak Interaction Physics on the Surface

- A detector on the surface is exposed to cosmic ray muons.
- LArTPCs have long acquisition windows, meaning each frame will pick up a significant number of these tracks.
- These tracks need to be reconstructed and removed for beam physics.
- They can be used for detector calibration.



Light Read Out to the Rescue

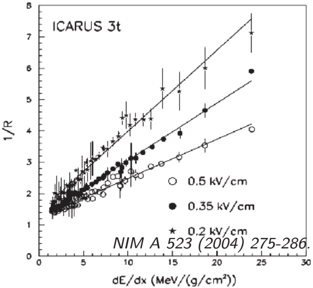
- Up to now, LAr neutrino experiments have used PMTs mostly as a trigger source.
- They can provide more information than that.
- Obtaining the t_0 of an event and its general location can help localize the event and facilitate the subtraction of background cosmic rays.
- *see talk by B. Jones for details.*



B. Jones

Calibration of LArTPCs

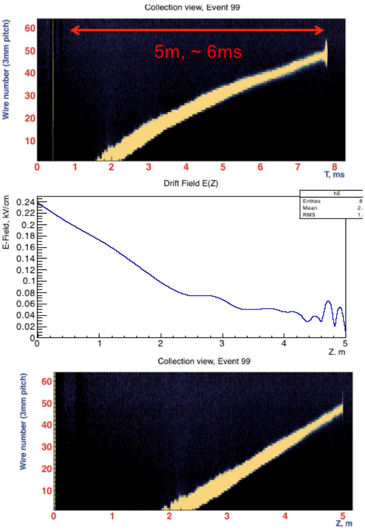
- Some properties of LArTPCs have not yet been properly calibrated.
- Collected charge is (usually) converted into deposited energy (dQ/dx →dE/dx) by a Birks'-like formula.
- This turns into a recombination factor, R, for LAr (at different electric fields).
- Its precise knowledge is necessary for PID and calorimetric energy reconstruction.
- There is significant effort underway to calibrate LArTPCs by putting them on beams of particles of known momentum. e.g. talks by J. St John, E. Guardincerri, and T. Maruyama on Thursday.



NIM A 523 (2004) 275-286.

In-Situ Calibration

- Underground the rate of cosmic muons is much smaller, so it's easier to do rare physics.
- However, this means that we lose a good source of straight tracks that could be used to calibrate the detector response, e.g. electron lifetime.
- Need a controlled source of straight tracks.
- How about a UV laser? *See talk by T. Strauss.*



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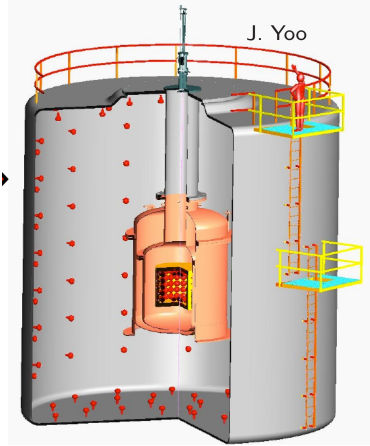
Coherent Elastic Neutrino Scattering

- The energy depositions are significantly smaller than for standard neutrino physics, need threshold of $10keV$
- Need to use scintillation light read out of liquid argon, similar to DM detectors and use pulse shape determination to extract from background.
- One of the results will be understanding the irreducible background that this interaction causes for Dark Matter interactions.



Outline

Conclusions

- The LArTPC is firmly grounded as a detector for neutrino physics.
- It is an extremely exciting detector technology.
- We are already observing unexpected things in our data.
- We should work towards optimizing our LArTPCs to our needs.
- And then look forward to taking data!

Back-Up Slides

The problem of plenty - Energy Calculation

- In case of exiting muons, the energy calculation becomes even more difficult if you don't have a muon ranger behind your detector.
- Kalman tracking methods are able to reconstruct energies with a precision of $\simeq 20\%$ using multiple scattering.

  Eur.Phys.J.C48:667-676,2006