Simulation and reconstruction for Liquid Argon TPC

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SLAC Experimental Seminar, May 23rd, 2017

Outline

1. **Liquid Argon Time Projection Chamber**
    - LArTPC detectors for neutrino measurements
    - LArTPC concepts

2. **Detector simulation**

3. **Physics reconstruction**
    - Baseline solution
    - Alternative solutions

4. **A common toolkit: LArSoft**

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Neutrino measurements

A selection[1] of neutrino-related topics we are studying,
and some key requirements:

- ν-nucleon cross sections
  - ⇒ fine resolution close to interaction vertex; particle identification
- neutrino flavour mixing (and mass) parameters
  - ⇒ good energy resolution
- investigation of low energy excess observed by MiniBooNE
  - ⇒ resolution of electrons from photons
- study of supernovæ
  - ⇒ sensitivity to low energy neutrinos
- non-ν physics: proton decay, $n/\bar{n}$ oscillation, dark matter...
  - ⇒ detection of low energy particles

Neutrinos being neutrinos (and, maybe, antineutrinos),
having a large massive target is *always* a requirement!

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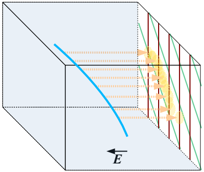
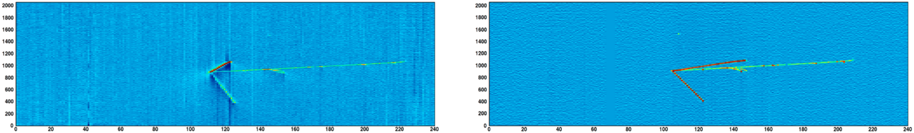
[1] *By no means exhaustive. And including only measurements suitable for LArTPC.*

Physics imaging: Time Projection Chamber

A Liquid Argon Time Projection Chamber provides us with snapshots of physics events:



- big active volume of argon
- two electrodes generating a uniform electric field
- at anode, segmented readout typically organised in “planes”
  - → each plane provides a projected view



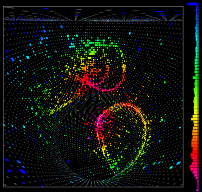
Images from a neutrino candidate event in ArgoNeUT (original size: 240 × 1600 pixels each)

- liquid argon is also the target for neutrino interactions!
- images have very high resolution: $\mathcal{O}(\mathrm{mm})$!!
- but it takes “long” ($\mathcal{O}(1\,\mathrm{ms})$ per metre of drift) to form the images!!!

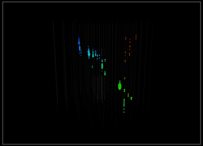
Physics imaging: Čerenkov and scintillator detectors

Competing technologies:

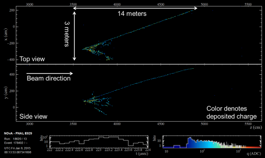
- **water detectors** using Čerenkov light:
  - threshold on velocity ($\beta > 0.75$)
  - no detailed image of tracks and vertices
  - fast (readout of photons)
  - size scales well, can be huge (HyperK: 250 kton; IceCube: 800 Mton)
- **liquid scintillator** (NOνA)
  - image resolution $\mathcal{O}(10\,\text{cm})$
  - also fast (again, photons)
  - can be big (14 kton)
- cf. **liquid argon TPC**: DUNE
  - energy threshold $\mathcal{O}(500\,\text{keV})$ (S:N > 10)
  - image resolution $\mathcal{O}(5\,\text{mm})$
  - slow ($\mathcal{O}(10\,ms)$)
  - mass: 40 kton



$e^+\pi^0$ event seen by SuperKamiokande.



Upgoing event from IceCube.



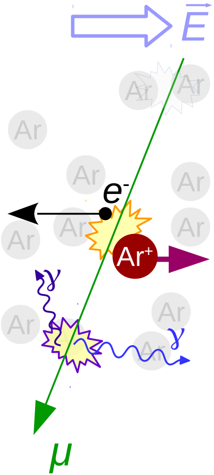
A $\nu_\mu \to \mu + X$ event in NOνA.

Neutrino experiments featuring LArTPC

Today, many neutrino experiments are betting on LArTPC technology:

ICARUS	cosmic rays	300 ton	2001
	CNGS: $E_\nu \approx 20\,\text{GeV}$	600 ton	2010–2013
ArgoNeuT	NuMI: $E_\nu \approx 5\,\text{GeV}$	170 l	2009–2010
LArIAT	test beams		2015–...
SBND	Booster: $E_\nu \approx 1\,\text{GeV}$	140 ton	2018–...
MicroBooNE		85 ton	2015–...
ICARUS		600 ton	2018–...
DUNE 35t	cosmic rays	35 ton	2014
ProtoDUNE (dual phase)	test beams	300 ton	2018
ProtoDUNE (single phase)		300 ton	2018
DUNE FD (single phase)	LBNF: $E_\nu \approx 3-5\,\text{GeV}$	10 kton	2023–...
DUNE FD (dual phase)		10 kton	2023–...
DUNE ND (liquid)?			2023–...
DUNE ND (gas)?			
DUNE FD (full)	LBNF: $E_\nu \approx 3-5\,\text{GeV}$	40 kton	>2023–...

The physics of Liquid Argon TPC

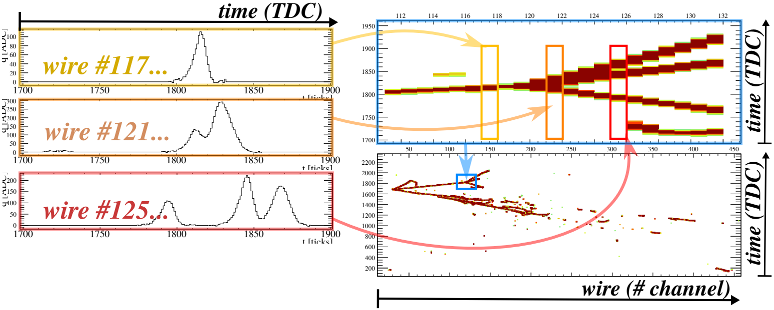


A charged particle crossing Liquid Argon produces:

- ionisation as electron-Ar^+ ion pairs
  most electrons and ions are separated by the intense electric field ($\mathcal{O}(500\,\mathrm{V/cm})$) before they recombine
  - electrons rush to the anode, typically in milliseconds
  - ions slowly drift to the cathode
- scintillation as isotropic-emitted photons
  Ar is *effectively transparent to its scintillation light*, peaking at 128 nm, with two main components:
  - “fast light” ($\tau \approx 6\,\mathrm{ns}$)
  - “slow light” ($\tau \approx 1.6\,\mu\mathrm{s}$)

Views

The signals measured at the anode, set side by side, provide an image of the event, *projection* on the plane orthogonal to the wires.

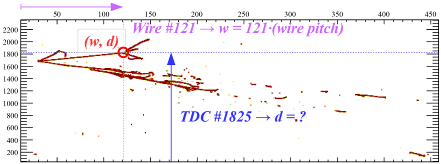


View from a collection plane.
The detail is a proton interacting with the medium, from a $\nu_e \to e^- p\pi^+ + \ldots$ event simulated in DUNE.

planes	2–3 /TPC	TPC channels	$\mathcal{O}\left(10^3 - 10^4\right)$/plane
wire pitch	$3 - 5$ mm	samples	$\mathcal{O}$(MHz)
		data flow	100 MB/plane/event

Typical figures for a LArTPC detector.

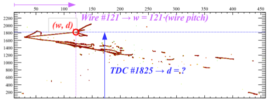
Time is of the essence



Position of a "pixel":

- wire coordinate:
  from position of wire
- drift coordinate:
  to be converted from time!

Time is of the essence



- wire coordinate: from position wire
- drift coordinate: *to be converted from time!*

Measured collection time (t_{TDC}) is a proxy of the drift coordinate (d), *with an ambiguity*: $d = v_{\mathrm{drift}}(t_{\mathrm{TDC}} - t_0)$, but the wires don't measure t_0:

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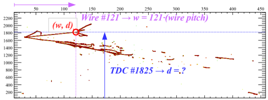

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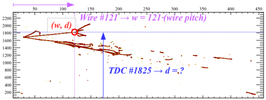

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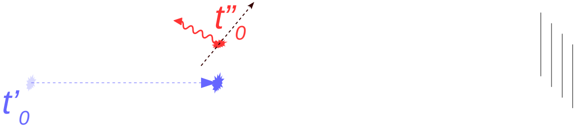

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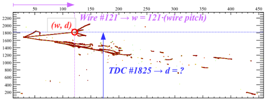

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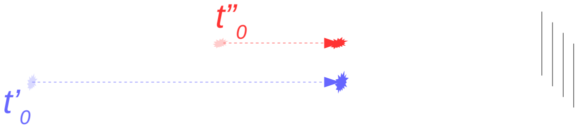

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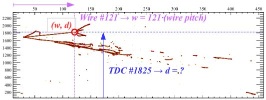

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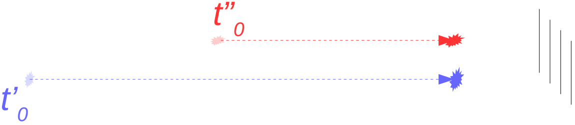

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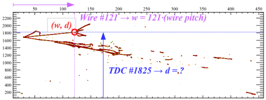

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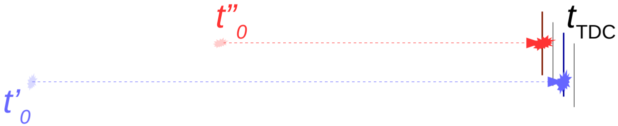

Anode sees t'_0 and t''_0 at the same time...

Measurement of t_0 allows:

- "relative" position (know $d' - d''$) to decide whether two tracks that *look* like starting at the same point are actually touching
- "absolute" position (know d' and d'') for local corrections (e.g. electron diffusion)

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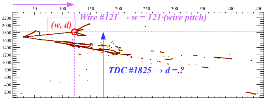

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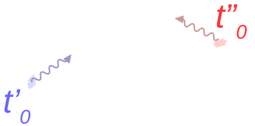

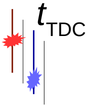

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Detection of scintillation light is the key to directly measure t_0.

Optical detectors

High photon detection efficiency is crucial!

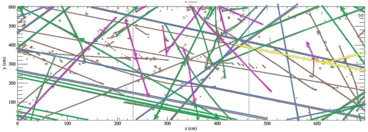
(especially with large argon volumes attenuating the light)

- the first approach (ICARUS, MicroBooNE, ...) was by photomultiplier tubes (PMT): high quantum efficiency, good coverage
- DUNE 35t pioneered the use of silicon photomultipliers (SiPM):
  - compact, but small area coverage

  ⇒ coupled with wavelength-shifting light guides
    - wider area coverage
    - weakening of signal by attenuation
- *arapuca*[6] boxes are being tested for SBND and ProtoDUNE
  - light traps in box shape, leveraging a dichroic filter
  - change time structure
  - wider area coverage, higher efficiency
- LArIAT is experimenting with reflective sides
- SBND is also considering reflective cathode

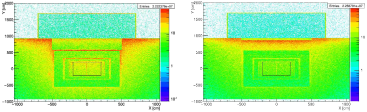
Dealing with cosmic rays

- for a *slow detector*, cosmic rays are constant source of background
- a 100 ton detector on the surface can expect to see $\mathcal{O}(10)$ tracks
- DUNE will place its detectors underground (which is expensive)
- SBND and MicroBooNE will place overburdens on top of the detectors
  - a $\mathcal{O}(3\,\mathrm{m})$ concrete overburden reduces cosmic ray flux by 20–100%
  - ... but turns some cosmic rays into particle cascades
- cosmic ray tagging detectors (CRT) surrounding the detector (DUNE 35t and others) help on reconstruction



Simulated ProtoDUNE event with cosmic rays.

ICARUS T600 was installed under Gran Sasso mountain.

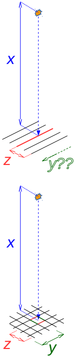


A study on interaction rate from cosmic rays in SBND detector without *(left)* and with a 3 m concrete overburden *(right)*.

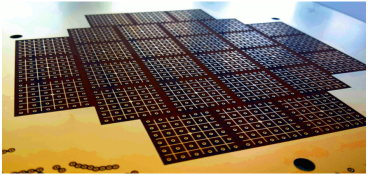
Views vs. pixels

Most of reconstruction is about overcoming the loss of information from the projection on the views.

ArgonCube prototype with pixel readout.



- using 2D sensors instead of wires would solve the problem by construction!
- challenges:
  - silicon pixels consume a lot of power
  - the number of channels is enormous: for a comparable pitch, $\mathcal{O}\left(10^5\right)/\mathrm{m}^2$
  - *strong* zero suppression required!



ArgonCube is developing such a solution, as DUNE near detector candidate.

Single-phase and dual-phase LArTPC

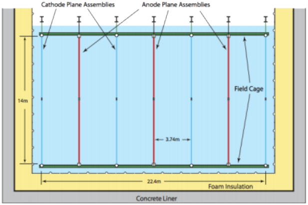
The first LArTPCs developed have been single phase:

- argon is liquid in all active volume
- readout terminals (wires or pixels) are immersed in it

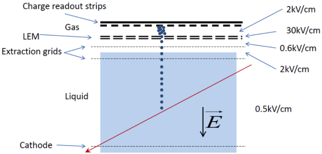
Intense R&D and prototyping for dual phase:

- readout is placed in argon vapour
- Large Electron Multipliers provide very large gain

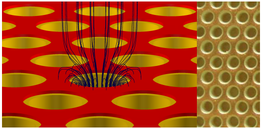
  ⇒ enhances low energy tracks
- design is constrained:
  - drift length is the full chamber height
  - careful control of liquid/gas interface needed



Schematic for a single phase LArTPC.



Schematic for a dual phase LArTPC.



LEM: *(left)* field lines; *(right)* surface.

Magnetised TPCs

The immersion of the LArTPC in a uniform *magnetic* field would allow

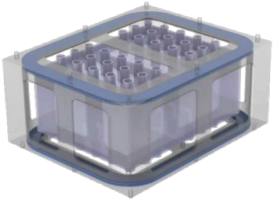
⇒ discrimination of particle electric charge

⇒ measurement of momentum of particles not stopping in the TPC (where range approach does not apply)

⇒ a better momentum resolution in general

DUNE is studying this option for some of its near detector candidates (high pressure argon gas and liquid argon):

- prototypes showed no effect on imaging for 1 T fields
- $\vec{B}$ orthogonal to $\vec{E}$ maximises space resolution
- ... but uniform magnetisation of a *large* TPC is a hard task



Rendering of the magnetised, pixel-readout LArTPC DUNE near detector candidate.

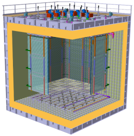
Modularity and scalability

How big can we get? One important limitation for a single TPC is the drift length. The longer it is,

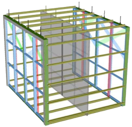
- the harder to keep a uniform electric field
- the longer it takes to fully read it (more pile up)
- the weaker the signal (more attenuation)

Since a single physics event is localised, a convenient compromise is to split the volume stacking multiple TPCs. They can be:

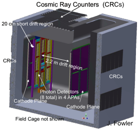
- independent (e.g., DUNE dual phase)
- sharing cathode (ICARUS, SBND)
- sharing anode and readout (DUNE single phase); the same wire can wrap on both sides and collect signal from both TPCs



ProtoDUNE Dual Phase: four $3 \times 3\,\mathrm{m}^2$ modules.



The two SBND TPCs share the cathode.



DUNE TPCs share anode plane assembly.

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4. A common toolkit: LArSoft

A foreword about `LArSoft` (and speaker's biases)

- `LArSoft` is a toolkit developed by and for LArTPC experiments, covering simulation, reconstruction and analysis
- more information on it later...
- ... but I'll sometimes say "`LArSoft` has this", "`LArSoft` misses that"
- as its "lead developer", you can guess I am somehow partial to it

Steps of simulation

Detector simulation is meant to produce synthetic data equivalent to the one observed in the detector.

It is usually split into steps:

1. generation of physics events with Monte Carlo generators
   ⇒ particles (positions, 4-momenta)
2. simulation of physics in the detector active material
   ⇒ electrons and photons for readout
3. simulation of readout response
   ⇒ electronics signals from out detector (data-like)

Particle propagation through matter

In LArTPC there are a few detector volumes relevant for simulation:

- the liquid argon! it provides ionised charge and scintillation light
- auxiliary detectors, most commonly scintillators for CRT
- interactions from the “dirt” leaking into the active volume

Simulation of physics interactions with the detector:

GEANT4 [2]

FLUKA [5] (interface with `LArSoft` not ready yet)

This stage leaves us with energy deposition bits all around the volume of the detector...

Ionisation and scintillation

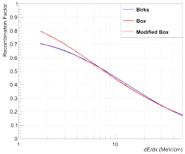
The energy deposited in LAr needs to be converted into electrons and photons:

- via simple conversion factors (e.g. 23.6 eV per e^-/ion pair)
  - e.g., different particles may be given specific “scintillation yields”
  - each factor effectively includes all the effects
- NEST[7] model
  - developed with Noble Elements in mind
  - tuned to xenon, intention to extend to argon documented...
  - ... but no official mention of any progress

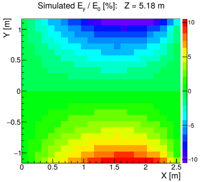
Transportation of ionisation and scintillation

Charge reaching the anode undergoes a number of physics effects:

- e^-/ion immediate recombination:
  - Birks model, with measurements from ICARUS
  - "box" model from ArgoNeuT[1] (modified to mirror Birks for low E)
  - NEST uses a model also based on Birks
- space charge and electric field distortion, due to the slow ^{40}Ar ions drifting in the active volume
- attenuation of the charge on the way to the anode (meet other ions, capture by impurities...)
- diffusion spreading the charge across different wires and enlarging its time structure



Recombination factor $\mathscr{R}$ (surviving charge fraction) in different models.



Example of $\vec{E}$ field distortion (vertical component) from lingering Ar^+ in the middle of MicroBooNE (field is along $\hat{x}$). The resulting $\vec{E}$ points outward ($E_0 = -273\,\mathrm{V/cm}$).

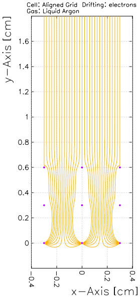
Electronics response

Signal is induced by the motion of ionised charge:

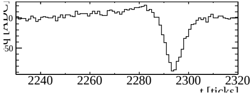
- bipolar on wires passed by
- unipolar where charge is collected

Simulated effects include:

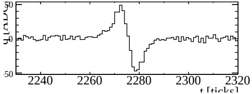
- distortions from the readout electronics instrumentation
- noise, either:
  - simulation from noise RMS
  - from “minimum bias” data



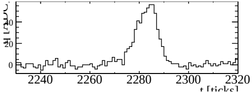
Signal and noise simulation (SBND, including noise and electronics distortions):



- **front (non-shielded) wire plane**



- **middle (shielded) wire plane**



- **back wire plane (anode)**

An approximation: each e^{-} contributes only to a single readout channel.

Outline

1. **Liquid Argon Time Projection Chamber**
   - LArTPC detectors for neutrino measurements
   - LArTPC concepts

2. **Detector simulation**

3. **Physics reconstruction**
   - Baseline solution
   - Alternative solutions

4. **A common toolkit: LArSoft**

From “missing energy” to neutrinos

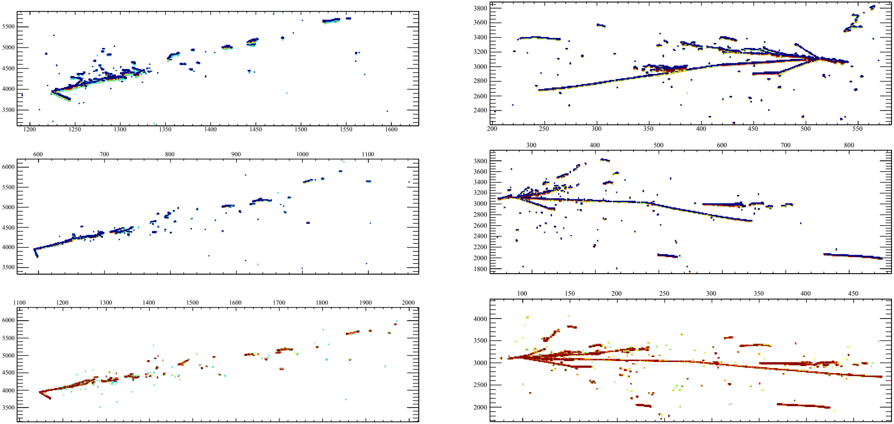
Reconstruction in LArTPC is complex:

- interactions *anywhere in the detector*! (some, at any time too)
- for non-beam events, no preferential event direction
- large background pile up: slow drift makes readout window long
- dense medium: particles affected by secondary interactions and Coulomb scattering make trajectories jumpy
- rich, detailed information to deal with
- no hit ordering in time: TPC provides a “static” image
- a lot of “special” directions where reconstruction is harder: parallel to wire plane, parallel to a wire, perpendicular to wire plane

Some of these limitations are inherent, but most can be overcome as we learn more and develop new algorithms.

Images from the detector

Interaction of an average electron neutrino: $\nu_e \to e^- p + X$:



$\nu_e \to e^- p + X$ event (with average energy) in three different views for MicroBooNE (*left*; ν_e: $1.1\,\mathrm{GeV}/c$, e^-: $0.9\,\mathrm{GeV}/c$, p: $0.5\,\mathrm{GeV}/c$) and DUNE single phase (*right*; ν_e: $4.7\,\mathrm{GeV}/c$, e^-: $0.9\,\mathrm{GeV}/c$, p: $1.3\,\mathrm{GeV}/c$). The two last views have comparable orientation and the track length is roughly $3\,\mathrm{m}$ and $2\,\mathrm{m}$, respectively.

A typical reconstruction chain

A standard reconstruction chain unrolls through steps:

calibration noise and electronics effects removal (1D)

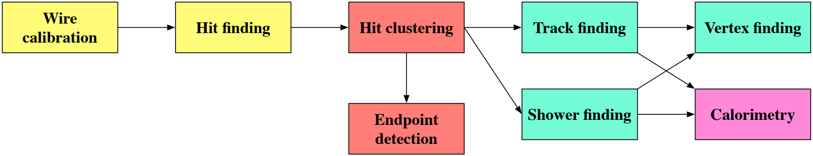
hit finding to detect signal on single TPC and optical waveforms (1D)

clustering to group different hits within TPC views (2D)

object reconstruction combining information from all views and optical detectors (3D)

vertex finding finding where 3D objects intersect (3D)

energy reconstruction and particle identification ("calorimetry")



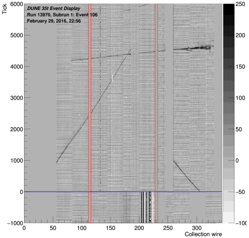
There are a lot of variations on this pattern...

Reconstruction algorithms should not distinguish simulated from detector data.

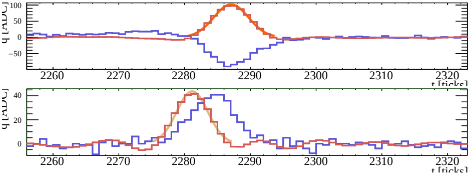
Calibration

Calibration can be considered as the inverse of electronics simulation:

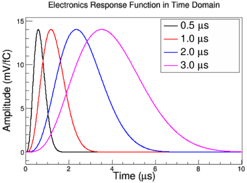
- remove pedestal
- remove noise too (via frequency filters)
  → including noise coherently affecting multiple channels
- undo electronics signal shaping
- straighten signal to be unipolar
- identity regions of interesting activity



Data from DUNE 35t showing coherent noise patterns.



Raw and calibrated signal, respectively in ADC counts and arbitrary units: *(above)* unshielded induction and *(below)* collection channel.

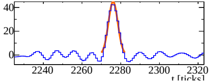


SBND electronics shaping, response to a δ signal.

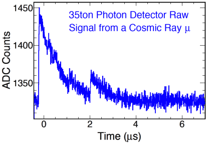
Hit finding

Hits are a convenient way to represent the presence of energy at a certain time, on a single channel:

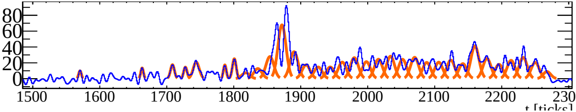
- information on time, charge, width, structure
- complicate non-Gaussian cases, e.g. from:
  - interaction vertex: hit shape overlaps
  - particle pointing to a wire: long “train” of charge
  - particle parallel to a wire: huge peak, possible saturation
- optical hits contain:
  - rising time, used for t_0 determination
  - signal area, quantifying the amount of light



Reconstructed hit from SBND simulation.



Optical waveform from DUNE 35t SiPM.

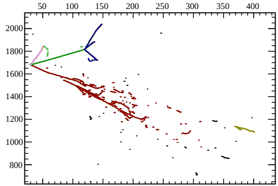


Train of hits: signal from muon heading toward a single wire.
Note the difference in the time scale with respect to the other example.

Clustering

Clustering groups hits supposed to come from the same particle:

- 2D objects on a view
- a particle developing into cascades results in tree-structure clusters
- otherwise, the cluster appears as a single trajectory



Clusters are represented in a readout time vs. channel number space.

Commonly used clustering algorithms include:

`DBSCAN`-like based on hit density

image processing (“computer vision”)

Hough transform detecting straight segments

crawlers following a single trajectory channel after channel

⇒ useful information include pattern *and* charge deposit

⇒ post-processing to merge segments and break kinks

Tracks and particle cascades

From clusters or hits, we can reconstruct objects in space:

- clusters have different lengths in wire direction on different views
- ... but they have the same time dimension

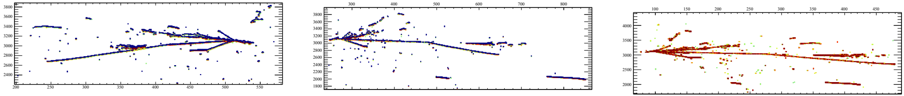
⇒ time is used to correlate hits and clusters between views

⇒ when present, the third view provides *redundancy*

- there are few hints to establish the direction:

tracks evolution of Coulomb scattering angle, increase of ionisation while slowing

showers with luck, a single track as start of the shower



Different views see the same activity at different places at the same time.

Tracks and particle cascades: reconstruction

Tracks

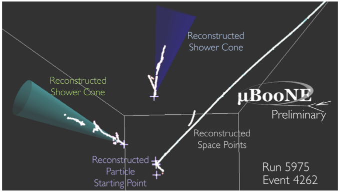
Follow the detailed trajectory of a particle in space:

- ⇒ Kalman fitter: from a seed, incrementally improve track
- ⇒ Projection Matching: minimise residuals of trajectory from hits
- ... and more

Showers

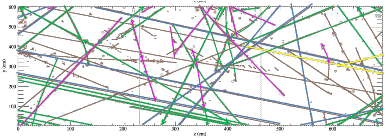
Summarise the particle activity with some collective quantities: charge, start vertex, axis, opening angle....

- ⇒ Principal Component Analysis provides shower axes
- ⇒ shower profiling may add information



Tracks and shower from MicroBooNE data event [LArLight event display].

Associating interaction time to reconstructed objects



Simulated ProtoDUNE event: cosmics are strong on this one.

- on surface detectors an event may have tens of particles
- many interactions... and as many "flashes" (bursts of optical hits)
- to pair them, *simulate the expected flash* for each interaction
- each is matched to the reconstructed flash closest to expected
- the flash time is t_0 of all objects from that interaction

The t_0 measurement is a powerful tool:

- provides a reference to determine the absolute position of a track
- can pin down the particles produced at beam pulse
  ⇒ powerful tool of cosmic ray tagging

Vertex finding

Where there is a vertex, an interaction has happened!

- the easiest vertices are stars with three or more legs

... we miss neutral particles

... Coulomb scattering: trajectories are naturally kinky

... projections may flatten a kink, hiding a vertex

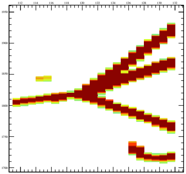
- stopping particles leave a characteristic charge signature from Bregg peak

Vertices can be found in single views or in 3D space; for example:

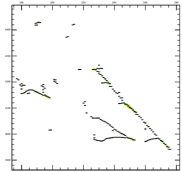
image processing of clusters (e.g. corner finding)

fit of track ends against a common source point

extrapolation of shower directions (e.g. for $\pi^0 \to \gamma\gamma$)



Interaction vertex: proton producing three charged particles.

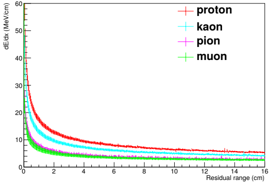


Two photons from a π^0 simulated in DUNE.

Particle identification and calorimetry

The determination of the type of a particle and its energy are related:

- the energy of a charged particle *stopping in LAr* can be determined from its range (i.e., the track length)
  - ... if we guess the particle type right
  - and, did it *really* stop?
- ionisation distribution is characteristic of the particle type
  - p may be resolved from $\pi^{\pm}$ and μ
  - direction can be inferred from dE/dx trend
- momentum can be estimated by the average angle of Coulomb scattering



Simulation of reconstructed dE/dx of different particles (MicroBooNE).

These methods require a 3D-reconstructed, long track and a particle type hypothesis.

Pandora

Pandora pattern recognition SDK supports LArTPC:

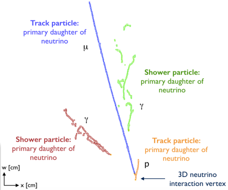
- clusters and 3D object reconstruction from hits
- sequence of algorithms, which:
  - deal with a specific, simple topology (e.g. δ ray branching, muon decay, ...)
  - should be humble: in doubt, do nothing!
- staged reconstruction:
  - clustering (2D)
  - view matching, tracks, showers
  - ⇒ if an algorithm improves the input, start over!

⇒ progressive refinement of reconstruction

Multi-pass workflow: MicroBooNE example

1. run reconstruction tuned toward background
2. rerun reconstruction tuned toward signal

First clustering step in Pandora.



Representation of full reconstruction of simulated $\nu_\mu{}^{40}\mathrm{Ar}->\mu p\pi^0$.

Image processing and machine learning

Piggy-bagging on a commercial technology in expansion, but...

- multiple images (one per view)
- image rich details must be dropped ("downsampling")
- less busy scene
- only as good as the training sample
- need to learn systematic uncertainties

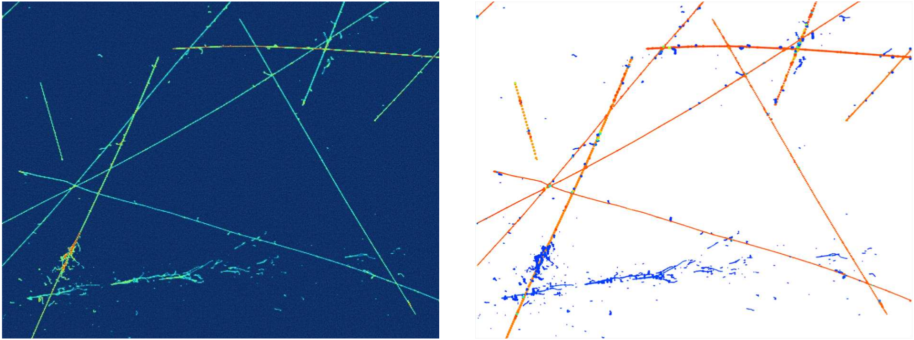
Bracketing of ν-like activity with machine learning *(artist view)*.

Some of the current studies:

- hit-by-hit tagging of type of activity: cascade vs. track-like (DUNE)
- localisation ("bracketing") of neutrino-like activity (MicroBooNE)
- particle classification: μ vs. π, e vs. γ (MicroBooNE)

Tagging the type of activity

- early tagging of activity type improves pattern recognition
- later, more proper energy corrections can be applied
- goal is to characterise the activity hit by hit
- from hit neighbourhood (small not to depend on event topology)
- categories: electromagnetic showering, track-like, nothing (just noise), electron from stopped μ decay ("Michel electron")



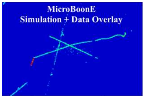
ProtoDUNE Single Phase simulated event *(left)* and EM-like and track-like hit tagging *(right)*.

Pinning down neutrino interactions

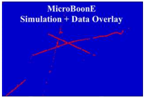
MicroBooNE has demonstrated discrimination of events with neutrino interactions:

- input: 4 “channels” for each of the 3 view:
  - TPC plane image (downsampled) from calibrated signal
  - image locally enhanced by PMT activity
    $\Rightarrow$ merge information from different detectors
  - images under μ-like and p-like ionisation hypothesis
    $\Rightarrow$ merge physics prior knowledge
- training: data-driven background, simulated signal

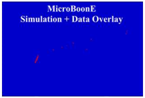
Input channels for a view:



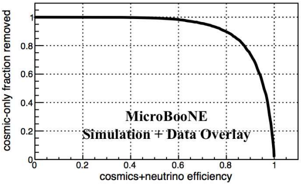
- **simple image**



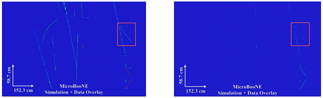
- **with enhanced MIP (μ)**



- **with enhanced HIP (p)**



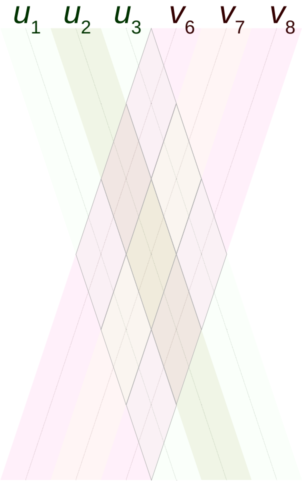
Performance of neutrino event classification demonstrator.



Input channels for a view: *(left)* simple image and *(right)* highlight PMT activity

Charge-based 3D reconstruction (`Wire-Cell`)

Full 3D imaging can be performed by “tomography” on time dimension.

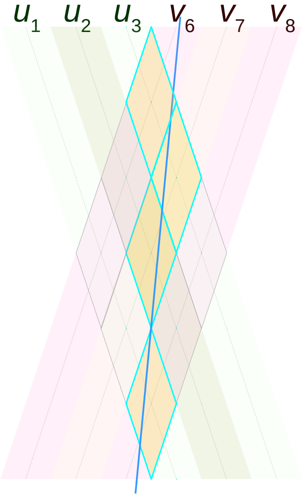


The anode plane can be partitioned in *cells*. Every point in a cell contributes to the same wire on each plane.

Illustration with only 2 views.

Charge-based 3D reconstruction (`Wire-Cell`)

Full 3D imaging can be performed by “tomography” on time dimension.



The anode plane can be partitioned in *cells*. When a ionising particle crosses, it deposits charge in a track of cells.

Illustration with only 2 views.

Charge-based 3D reconstruction (`Wire-Cell`)

Full 3D imaging can be performed by "tomography" on time dimension.

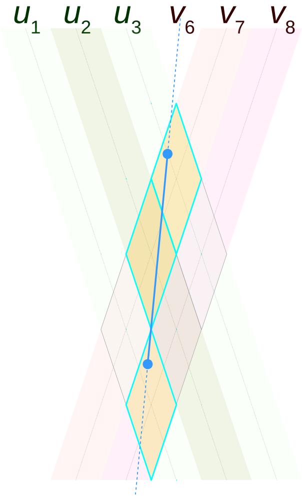


Illustration with only 2 views.

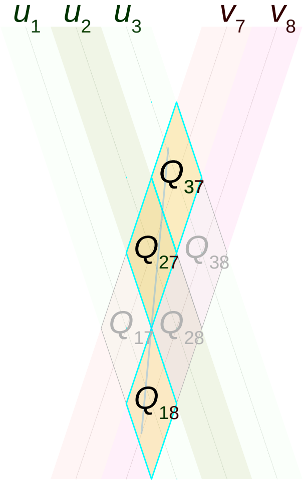
The anode plane can be partitioned in *cells*. We focus on a certain time range. In there, the ionising particle only crosses a few cells.

- Each wire reading provides only one 1D coordinate on the anode plane, and drift time: that can define only 2D projections.

⇒ If we find which cells collect any charge, we have the 2D position on the plane, i.e. 3D reconstruction!

Charge-based 3D reconstruction (`Wire-Cell`)

Full 3D imaging can be performed by “tomography” on time dimension.



The anode plane can be partitioned in *cells*.
Each cell receives some charge Q_{uv}.
But we have 5 measurements:

$$Q_{v_7} = \sum_u Q_{u7} = Q_{17} + Q_{27} + Q_{37}$$
$$Q_{v_8} = \sum_u Q_{u8} = Q_{18} + Q_{28} + Q_{38}$$
$$Q_{u_1} = \sum_v Q_{1v} = Q_{17} + Q_{18}$$
$$Q_{u_2} = \sum_v Q_{2v} = Q_{27} + Q_{28}$$
$$Q_{u_3} = \sum_v Q_{3v} = Q_{37} + Q_{38}$$

while there are 6 unknown.

Solving the equations for Q_{uv}, we have 3D reconstruction!

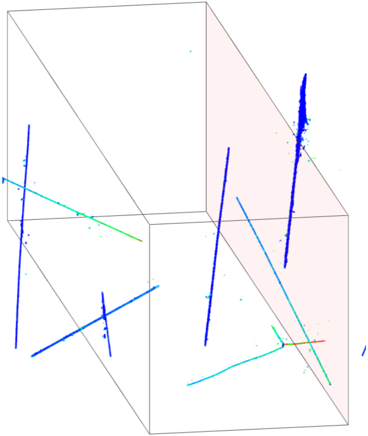
Note that known calibration constants can be accommodated in the equations.

Illustration with only 2 views.

Charge-based 3D reconstruction (`Wire-Cell`)

This 3D imaging approach was introduced by `Wire-Cell`[4]:

- uses the fact that same ionisation charge is seen by all wire planes
- uses calibrated signal, sliced in time
  - → no previous pattern recognition
  - → not even hit finding!
- complications:
  - – problem underconstrained
  - – unreliable channels (dead or noisy)
- computation-intensive linear algebra
- requires careful intercalibration
- failures result in diamond-shaped patches of fake points



3D imaging of a $\nu_\mu \mathrm{Ar} \to \mu\, \pi^+ n$ event simulated in MicroBooNE, reconstructed by `Wire-Cell`. The cyan track on the bottom is the muon. The top-right cosmic ray shows a failure mode with the track almost parallel to the wire planes.

Outline

1. **Liquid Argon Time Projection Chamber**
   - LArTPC detectors for neutrino measurements
   - LArTPC concepts
2. **Detector simulation**
3. **Physics reconstruction**
   - Baseline solution
   - Alternative solutions
4. **A common toolkit: LArSoft**

LArSoft

LArSoft is a toolkit for automated simulation, reconstruction and analysis of data from LArTPCs. Its keywords:

interoperability	its algorithms and data structures are suitable for multiple experiments
separation	of algorithm code and event processing framework
modularity	allowing to plug other libraries and also custom implementations though...
standardised	*interface* of algorithms and *data structures*
openness	main contributions are from Experiment collaborators

“Framework”

A framework is software that manages resources, performs bookkeeping and offers I/O of physics events.
LArSoft primary development framework is Fermilab’s *art* framework.

Detector interoperability and sharing

Interoperability is the central feature of LArSoft:

- the same code base can be applied to different Experiments
- enables sharing of codes and ideas across the LArTPC community
- allows easy access to other experiment data
  ⇒ notably, also to test beam experiment results (e.g. LArIAT)
- facilitates comparisons between results and algorithms
- offers any small Experiment the expertise of the whole community

The vision is to realise interoperability through:

- modular design
- common data structures and interfaces
- hooks for custom implementations behind the interfaces

LArSoft collaboration

LArSoft has chosen to be shaped as a collaboration:

- steering group include Experiment spokespersons, Fermilab Computing and Neutrino Division representatives
- collaboration work is carried out by the LArSoft core project
- proposals and additions discussed at regular open meetings
- software architecture changes discussed in ad-hoc meetings

An assessment

How is this working so far?

- LArSoft started with a few small TPC prototypes
- the project has grown seriously ambitious; adopting collaborations include ArgoNeuT, MicroBooNE, LArIAT, SBND and DUNE
- the direction is clear, the work left is *a lot*
  - to accommodate new abstractions often requires deep redesign
  - this sometimes adds complexity to the tools
  - I feel the community is aware of the benefits we buy with that
- no major conflicts between in-preparation and running Experiments
- in contexts where, by need or principle, LArSoft constraints can't be accepted
  - while LArSoft adopts a specific event processing framework, algorithms are aimed to be as framework-independent as possible
  - ⇒ we have developed support for weaker couplings...

LArSoft and everything else

These coupling cover a spectrum of strength:

- direct interface to third-party libraries:
  - `Pandora` has a LArSoft-specific complete interface:
    - `Pandora` libraries are linked with `LArSoft` code
    - `LArSoft` can feed `Pandora` the input it needs, and extract the output
    - integration is *seamless*
  - `Wire-Cell` currently offers LArSoft algorithms for signal calibration
  - GENIE[3] and other event generators also have complete integration
- data exchange formats for other generators and some event displays
- a growing part of LArSoft can be used in alien environments
  - Fermilab *gallery* allows reading data files without *art*
  - some LArSoft libraries can be linked to small executables

The recent adoptions

Most recent “additions” to `LArSoft` portfolio of supported detectors:

SBND is a detector similar enough to the ones already supported
⇒ integration has been mostly seamless so far

ProtoDUNE Dual Phase is instead an extremely different detector

- vertical drift broke many geometry assumptions
- needed deep revision of geometry concepts and implementation
- adoption of the new concepts is progressing
- temporary solutions are allowing progress on other fronts at the same time

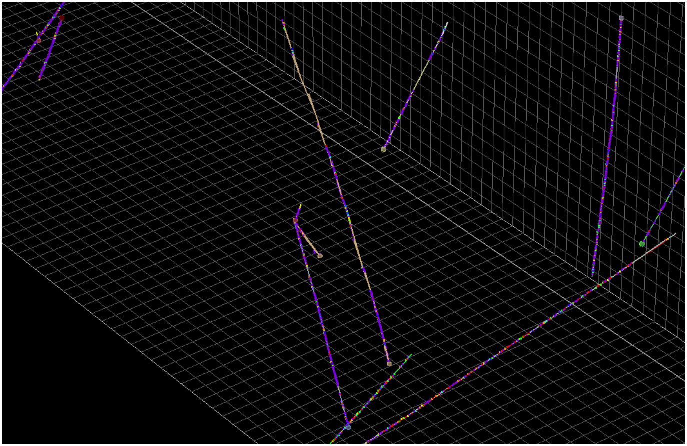
ICARUS has also pushed a few detector geometry concepts
⇒ overall adaptation is going smoothly

ArgonCube might be the next challenge (quite a big one)

Outlook

- Liquid Argon TPC community is fermenting with activity!
- exploration of reconstruction techniques it going all directions
  - → improvement of known ideas
  - → conceptions of new approaches
  - → adaption of “foreign” technologies
- ... still a lot of road to cover before we really own the technology
- no “best” or “standard” reconstruction approach yet
- LArSoft is an extremely ambitious software project to share experience among LArTPC experiments starting from the code
- a measure of LArSoft success so far:
  - it is accepted as the leading simulation and reconstruction tool in running experiments like MicroBooNE
  - it has supported ArgoNeuT and DUNE 35t publications
  - DUNE is using it for its prototypes, and it is a fully qualified candidate for the main experiment itself
  - ICARUS is actively working to achieve support

Thank you for your attention!



→ LArSoft resources → some references

LArSoft resources

LArSoft documentation:

home page `http://larsoft.org`

wiki `https://cdcvs.fnal.gov/redmine/projects/larsoft/wiki`

user forums `http://www.larforum.org`

mailing list `larsoft@fnal.gov`

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