A Novel Liquid Argon Time Projection Chamber Detector

ArgonCube

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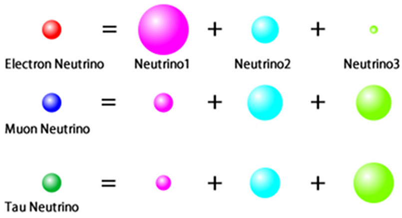
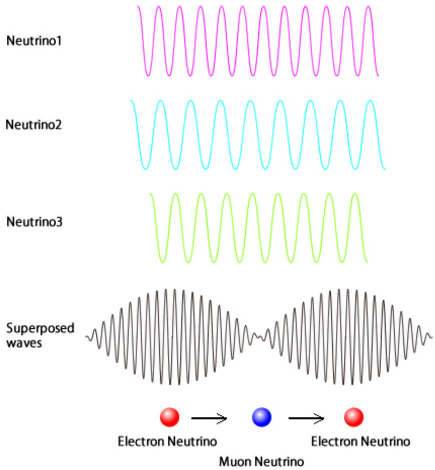
Neutrino oscillation

http://www.hyper-k.org/en/neutrino.html



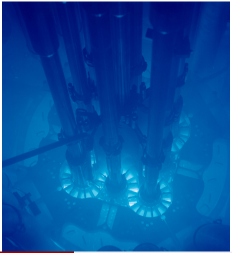


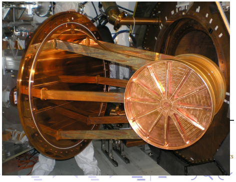
Pontecorvo-Maki-Nakagawa-Sakata matrix

Pictures: https://commons.wikimedia.org, http://www.nersc.gov

$$s_{ij} = \sin(\theta_{ij}) \qquad \begin{pmatrix} \nu_\mathsf{e} \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad c_{ij} = \cos(\theta_{ij})$$

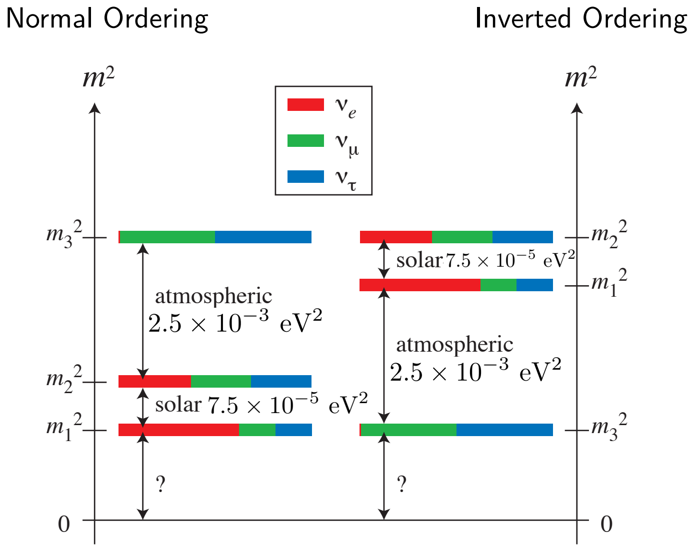
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\frac{\alpha_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



Mass Ordering

King; Prog.Part.Nucl.Phys. 94 (2017) 217-256 [1]

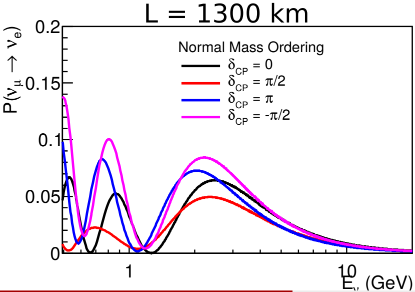


Unknown Parameters

How to measure them

Freund; Phys.Rev. D64 (2001) 053003 [2]. Qian, Vogel; Prog.Part.Nucl.Phys. 83 (2015) 1-30 [3]

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \approx\ & \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2(\Delta) \\
& + \alpha \sin(\delta)\cos(\theta_{13})\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})\sin^3(\Delta) \\
& + \alpha \cos(\delta)\cos(\theta_{13})\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})\sin^2(\Delta)\cos(\Delta) \\
& + \alpha^2\cos^2(\theta_{23})\sin^2(2\theta_{12})\sin^2(\Delta)
\end{aligned}
$$



$$\Delta = \frac{\Delta m^2_{31} L}{4E}$$

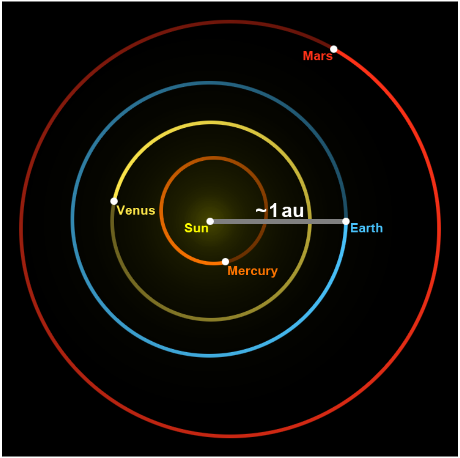
$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \ll 1$$

$$\nu \to \bar{\nu} \Rightarrow \delta \to -\delta$$

Detecting neutrinos

A challenging task due to their extremely small interaction cross-section

Picture: `https://commons.wikimedia.org`

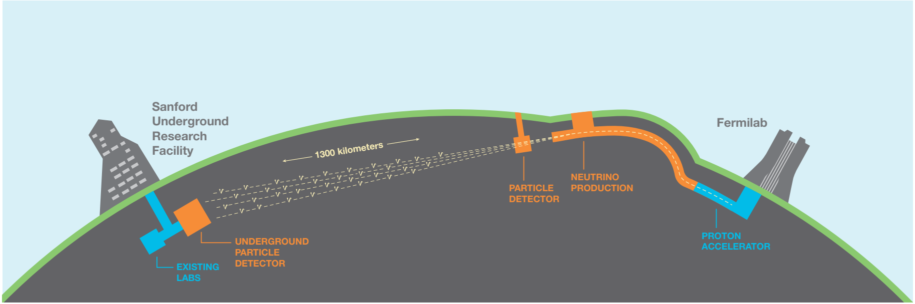


Reliably detecting a single neutrino would require ≈8 au of liquid argon. This is 8 times the distance from the Earth to the Sun.

Deep Underground Neutrino Experiment (DUNE)

A next-generation long-baseline neutrino oscillation experiment

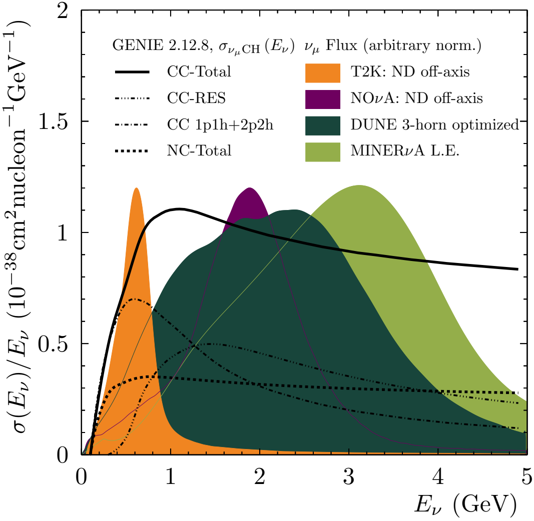
Acciarri, Goeldi et al.; DUNE; arXiv: 1601.05471 [4]



- Measure $P(\nu_\mu \to \nu_\mathrm{e})$ and $P(\overline{\nu}_\mu \to \overline{\nu}_\mathrm{e}) \Rightarrow \delta,\ \mathrm{sgn}\left(\Delta m^2_{\mathrm{atm}}\right)$
- High intensity $\nu_\mu/\overline{\nu}_\mu$ beam from Fermilab
- Near detector @ 0.574 km baseline
- 40 kt LArTPC far detector @ 1300 km baseline

Interaction cross sections vs. beam flux

Plot: L. Pickering, Michigan State University



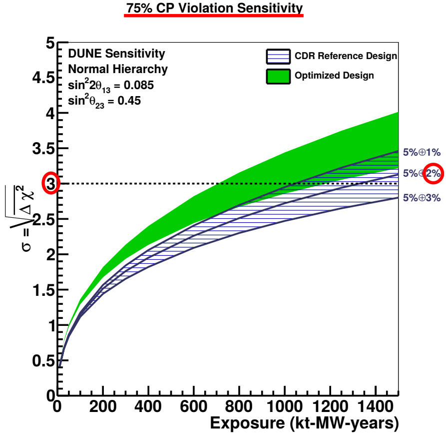
$\sigma \sim 10^{-38}\,\mathrm{cm}^2$

- $\Rightarrow$ High target mass
- $\Rightarrow$ High flux

DUNE flux peak $\approx$2.5 GeV

Sensitivity

Acciarri, Goeldi et al.; DUNE; arXiv: 1512.06148 [5]



25 y with 40 kt ⇒ >1 MW beam

75 % coverage at 3σ requires:

Constraining beam at near detector

- High statistics
- High resolution

⇒ Good background rejection

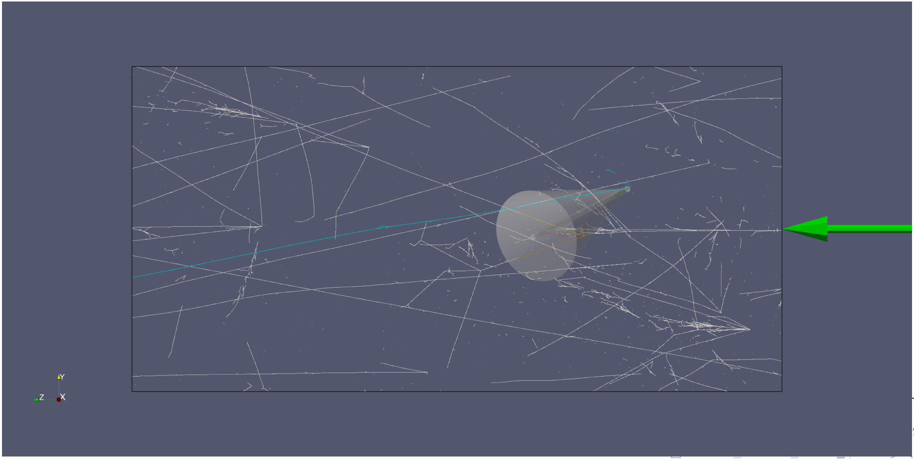
Same detector technology as far site allows cancellation of uncertainties on

- Cross section
- Detector response

Challenges for the near detector

High multiplicities

- Simulation of a single neutrino beam spill, including backgrounds
- 0.2 ν events per tonne @ 2 MW



Neutrino physics summary

Neutrino detection is hard

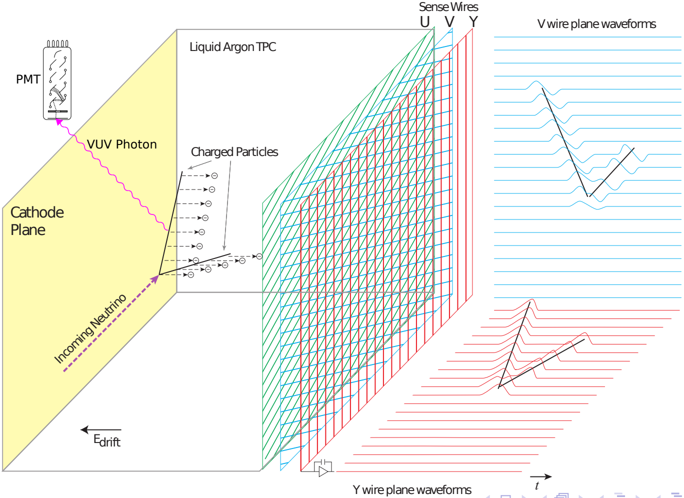
1. High beam flux
2. High target mass
3. High-precision tracking
4. High-precision calorimetry

A LArTPC provides 2 to 4.
Theoretically...

The time projection chamber (TPC)

A detector providing precise tracking and calorimetry

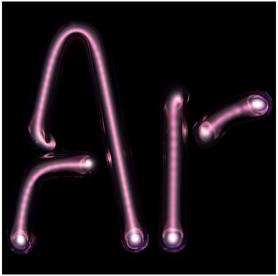
Acciarri, Goeldi et al.; MicroBooNE; JINST 12 (2017) no.02, P02017 [6]



Why liquid argon?

Meets all the requirements for neutrino detection with a TPC

Picture: https://commons.wikimedia.org



- Dense ($1.4 \times 10^3\,\mathrm{kg\,m^{-3}}$) $\rightarrow$ high event rate
- Abundant ($\approx 1\,\%$ of the Earth's atmosphere) $\rightarrow$ affordable
- High ionisation yield ($8900\,e\,\mathrm{mm}^{-1}$ for a MIP) $\rightarrow$ tracking & calorimetry
- Prompt scintillation ($\sim$ ns) $\rightarrow$ absolute spatial reference
- Liquid @ 87 K $\rightarrow$ cooling by LN_2
- Electron drift speed @ $0.1\,\mathrm{kV\,mm^{-1}}$ $\approx 2\,\mathrm{mm\,\mu s^{-1}}$

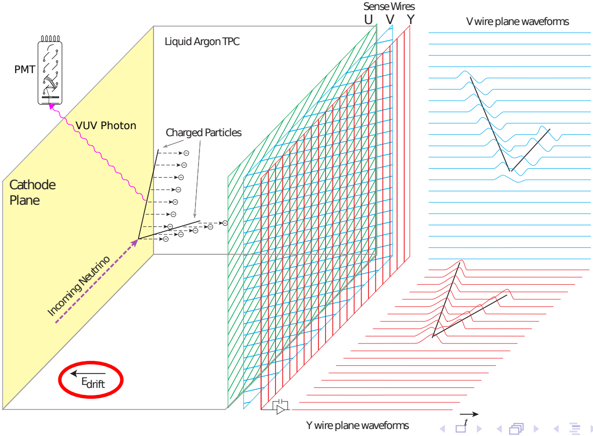
The standard LArTPC design

Drift field generation

Acciarri, Goeldi et al.; MicroBooNE; JINST 12 (2017) no.02, P02017 [6]

$$v_{\mathrm{Drift}} \sim 1\,\mathrm{mm\,\mu s}^{-1} \Rightarrow E_{\mathrm{Drift}} \sim 0.1\,\mathrm{kV\,mm}^{-1}$$

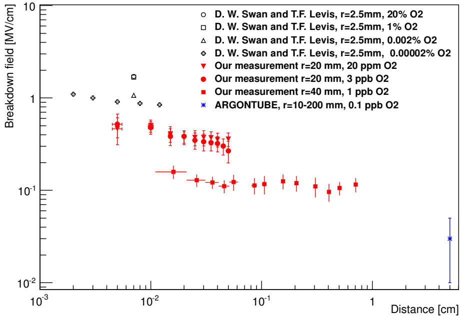
$$l_{\mathrm{Drift}} \sim 1\,\mathrm{m} \Rightarrow V_{\mathrm{Drift}} \sim 100\,\mathrm{kV}$$

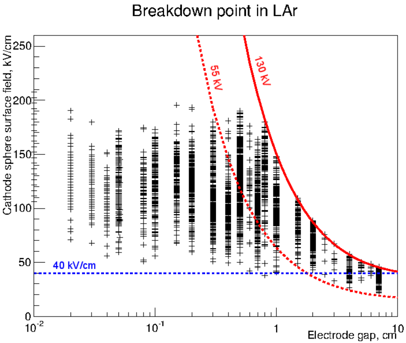


Dielectric strength of liquid argon

Lower than expected

Blatter et al.; JINST 9 (2014) P04006 [7]

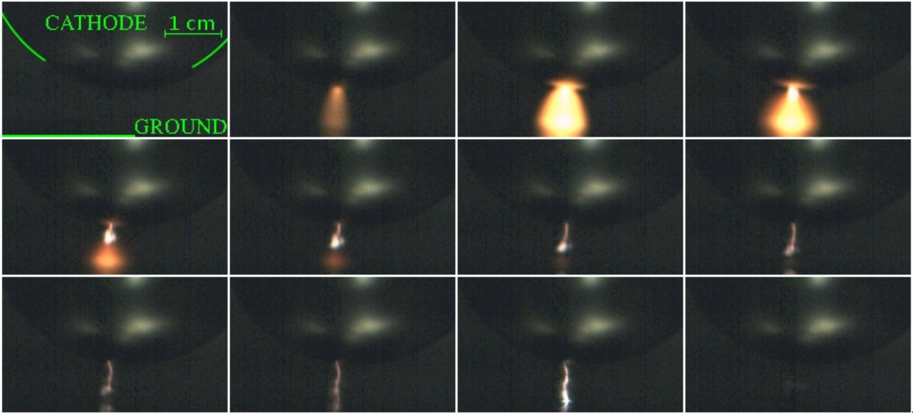




Footage of a typical breakdown

Animated version of another breakdown: `http://tinyurl.com/y872x4oq`

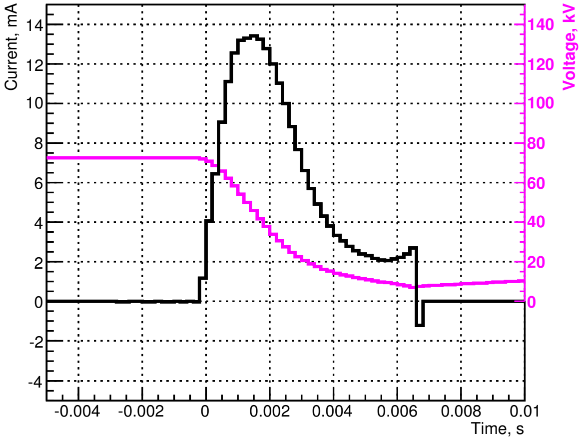
Auger, Goeldi et al.; JINST 11 (2016) no.03, P03017 [8]



Current voltage behaviour of a typical breakdown

Rather slow process

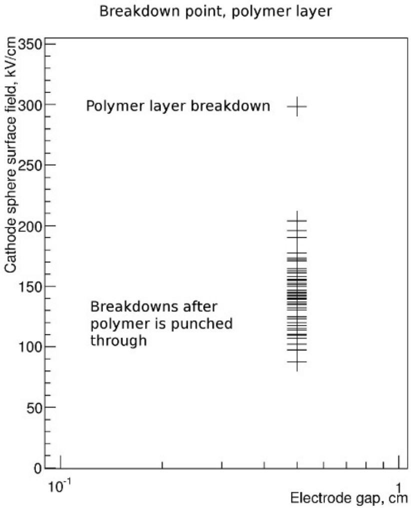
Auger, Goeldi et al.; JINST 11 (2016) no.03, P03017 [8]



Drift field generation summary

We need a modular TPC design

Auger, Goeldi et al.; JINST 9 (2014) P07023 [9]



- Maximum safe electric field in LAr: $40\,\mathrm{kV\,cm^{-1}}$
- Can be increased by coating HV components
- Not practical

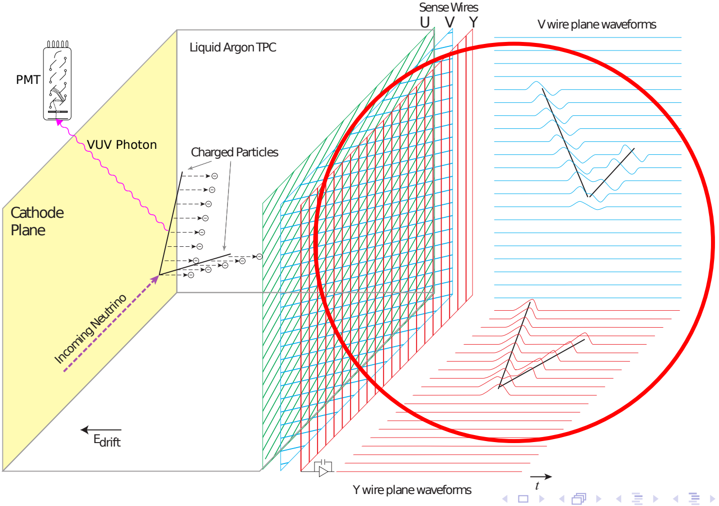
$\Rightarrow$ Large inactive clearance volumes around HV components

$\Rightarrow$ Segment TPC to keep cathode voltages low

The standard LArTPC design

Charge readout

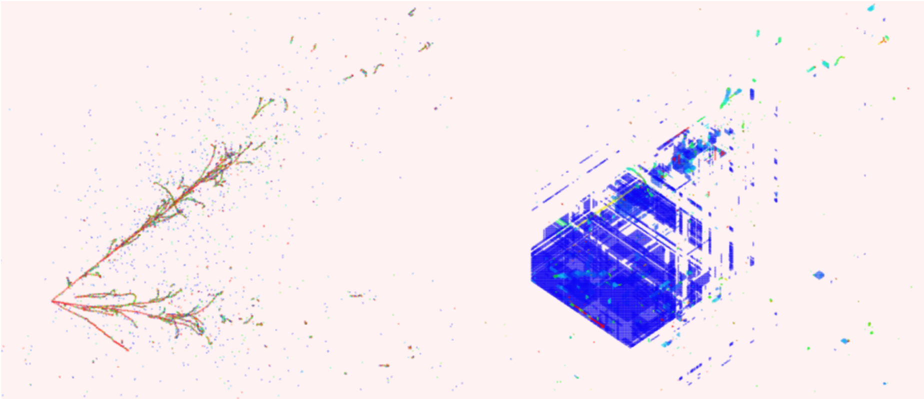
Acciarri, Goeldi et al.; MicroBooNE; JINST 12 (2017) no.02, P02017 [6]



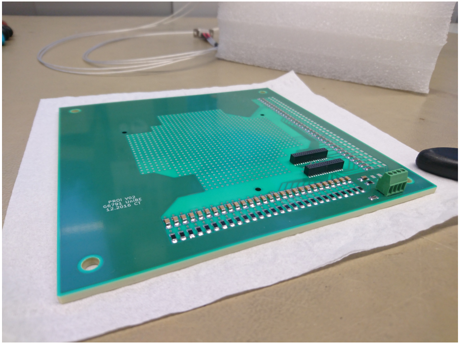
Wire readout ambiguities

Limiting an ideal 3D tracker to multiple 2D projections

D. Dwyer, Lawrence Berkeley National Laboratory

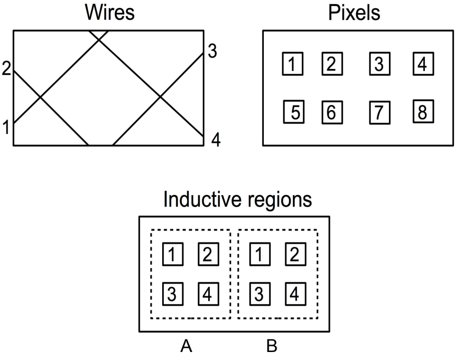


Pixels



- Complete 3D event reconstruction w/o ambiguities
- Roughly squared number of readout channels
- E.g. 10 m $\times$ 2 m LArTPC:
  - $\sim 10^4$ wires
  - $\rightarrow$ $\sim 10^7$ pixels
- Extremely high number of cryostat penetrations with existing readout electronics

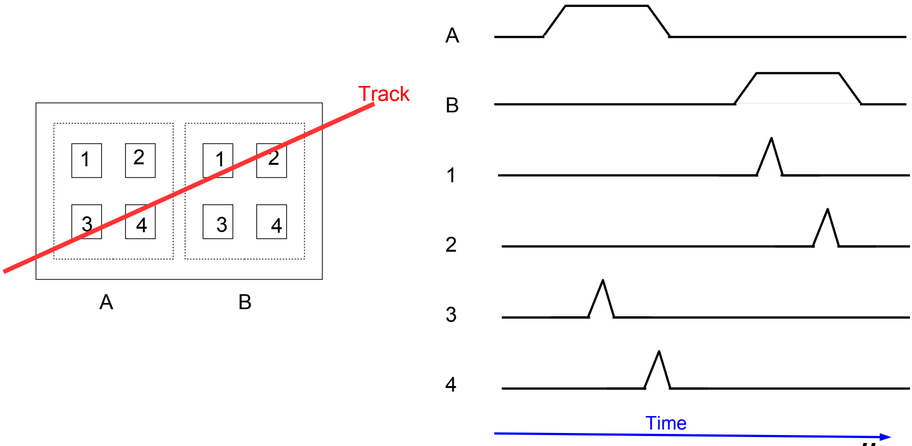
Handling high channel numbers



Multiplexing

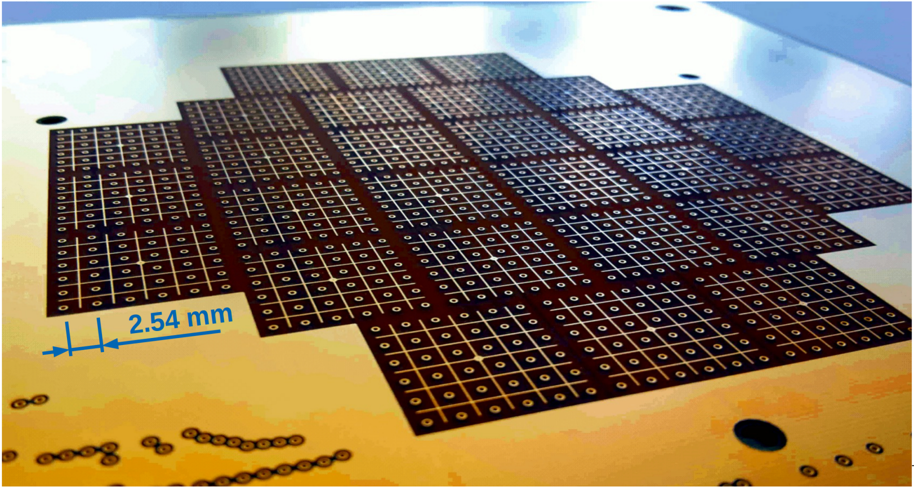
- Cold digitisation
  - \+ high-speed digital links
  - \+ potentially less noise
  - – complex cold electronics
  - – high power dissipation
- Analogue multiplexing
  - \+ existing cold electronics
  - – ambiguities

Regions of interest (ROI) multiplexing



ArgonCube pixel demonstrator PCB

28 ROIs, each 6×6 pixels $\Rightarrow$ 64 DAQ channels $\rightarrow$ 1008 physical pixels



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ArgonCube pixel demonstrator TPC

- Cylindrical drift volume
- $\varnothing = 100\,\mathrm{mm}$
- $L = 600\,\mathrm{mm}$
- $V_{\mathrm{Drift}} = 60\,\mathrm{kV}$

$\Rightarrow E_{\mathrm{Drift}} = 0.1\,\mathrm{kV\,mm^{-1}}$

$\Rightarrow v_{\mathrm{Drift}} = 2\,\mathrm{mm\,\mu s^{-1}}$

$\Rightarrow t_{\mathrm{Drift}} = 300\,\mathrm{\mu s}$

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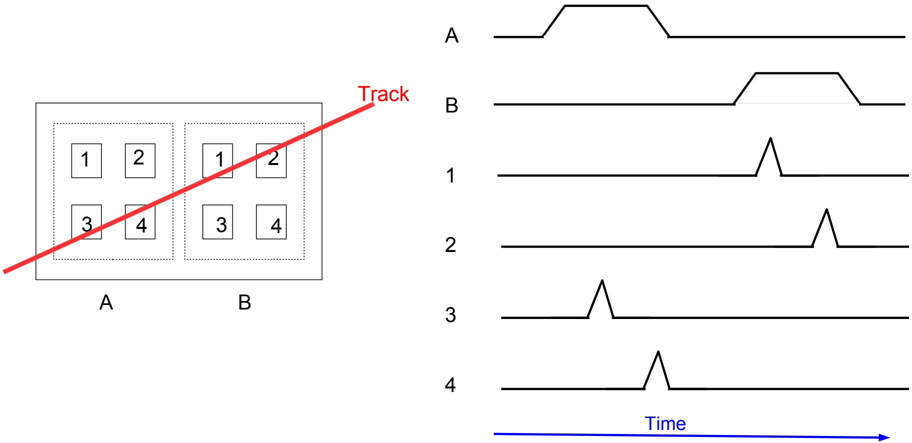
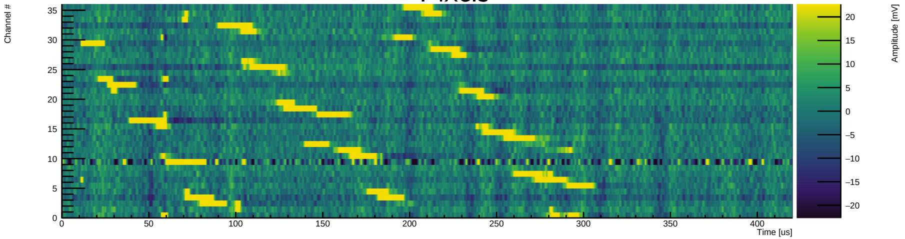
Regions of interest (ROI) multiplexing



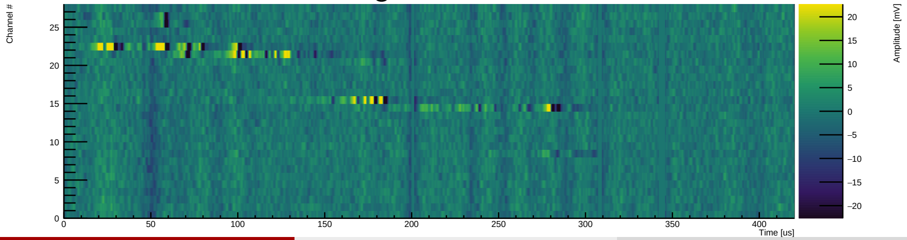
Raw charge data

Asaadi, Goeldi et al.; arXiv: 1801.08884 [10]

Pixels

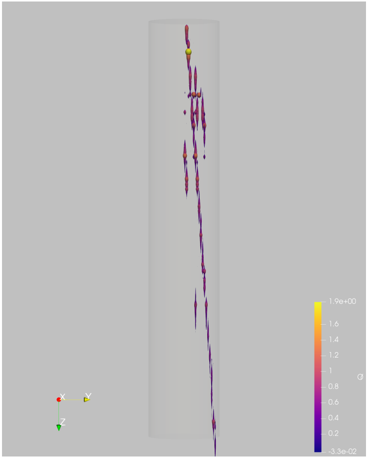


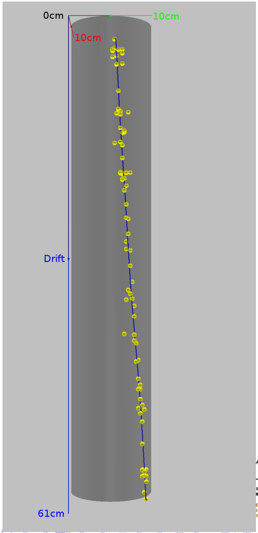
Regions of interest



Reconstructed 3D event

Asaadi, Goeldi et al.; arXiv: 1801.08884 [10]

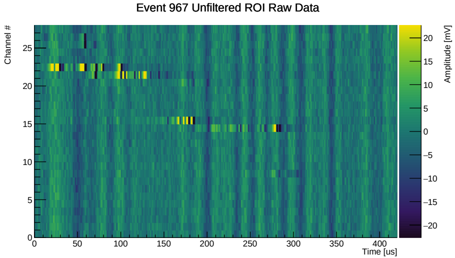


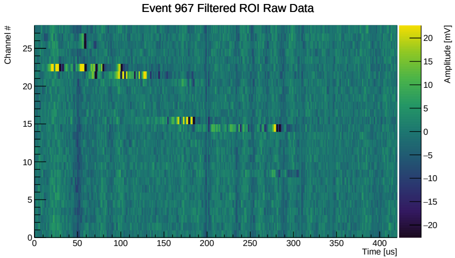


Step-by-step 3D event reconstruction

1. Noise filter
   - Subtract common mode noise

Asaadi, Goeldi et al.; arXiv: 1801.08884 [10]

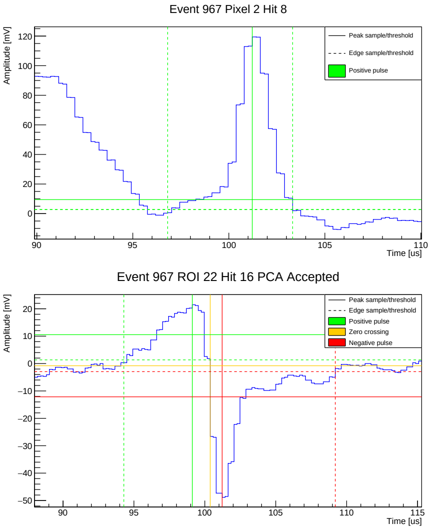




Step-by-step 3D event reconstruction

1. Noise filter
   - Subtract common mode noise
2. Hit finder
3. Hit matcher
   - Combine pixel and ROI hits into 3D hits

Asaadi, Goeldi et al.; arXiv: 1801.08884 [10]



Step-by-step 3D event reconstruction

1. Noise filter
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4. Principal Component Analysis
   - Solve multiplexing ambiguities
   - Remove outliers

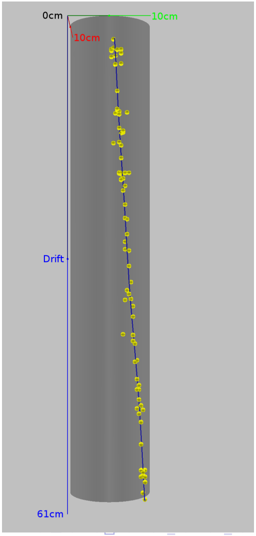
Asaadi, Goeldi et al.; arXiv: 1801.08884 [10]

Step-by-step 3D event reconstruction

Asaadi, Goeldi et al.; arXiv: 1801.08884 [10]

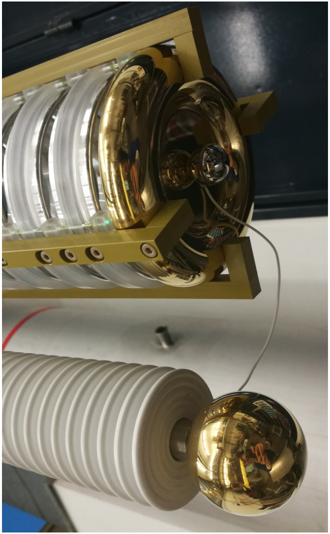
1. Noise filter
   - Subtract common mode noise
2. Hit finder
3. Hit matcher
   - Combine pixel and ROI hits into 3D hits
4. Principal Component Analysis
   - Solve multiplexing ambiguities
   - Remove outliers
5. Kalman fitter
   - Fit μ hypothesis to 3D spacepoints
   - GENFIT

     Rauch, Schlüter; J.Phys.Conf.Ser. 608 (2015) no.1, 012042 [11]



Charge readout summary

Demonstrated a pixelated LArTPC, enabling true 3D tracking



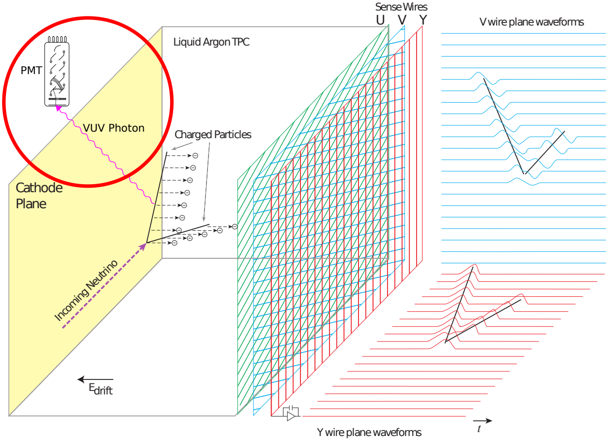
- MIP signal-to-noise ratio: 14
- Double-track spatial resolution in XY: 2.54 mm
- Double-track spatial resolution in Z: 2.1 mm
- Successfully reconstructed single tracks
- Potentially momentum and PID from Kalman
- Limited by multiplexing ambiguities

⇒ New cold digitisers under development at LBNL

The standard LArTPC design

Light readout

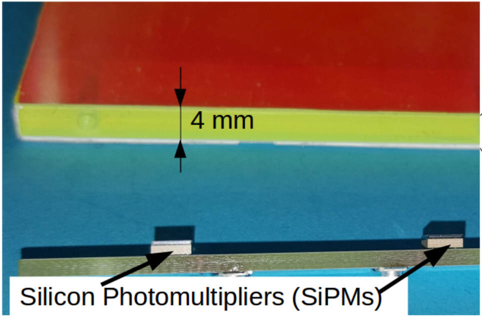
Acciarri, Goeldi et al.; MicroBooNE; JINST 12 (2017) no.02, P02017 [6]

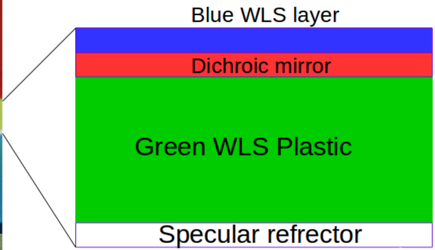


ArgonCube Light readout system (ArCLight)

A SiPM-based compact, robust, scalable LArTPC light readout

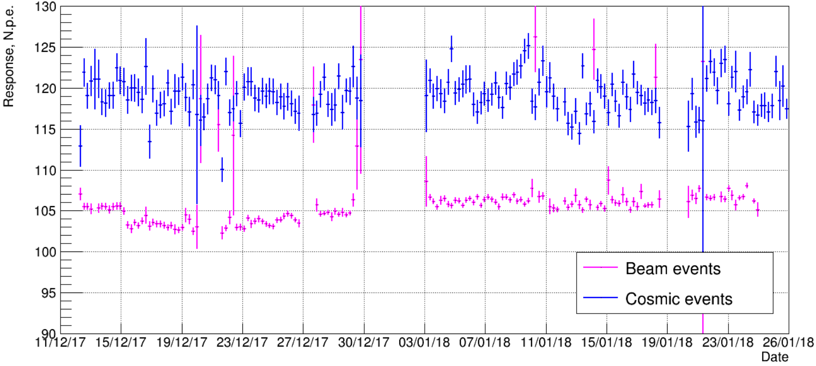
Auger, Goeldi et al.; Instruments 2 (2018) no.1, 3 [12]





ArCLight in LArIAT

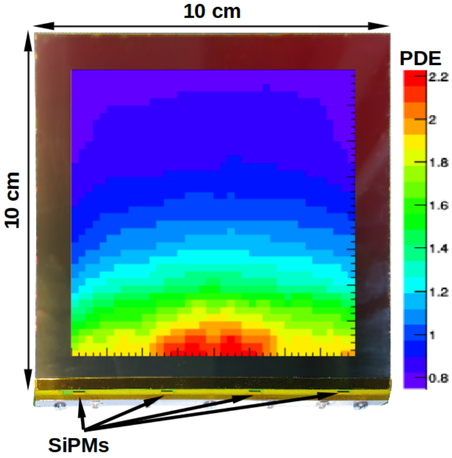
Stable operation over several weeks at LAr temperature



Light readout summary

ArCLight, a novel LArTPC light readout combining SiPMs with a light trap

Auger, Goeldi et al.; Instruments 2 (2018) no.1, 3 [12]



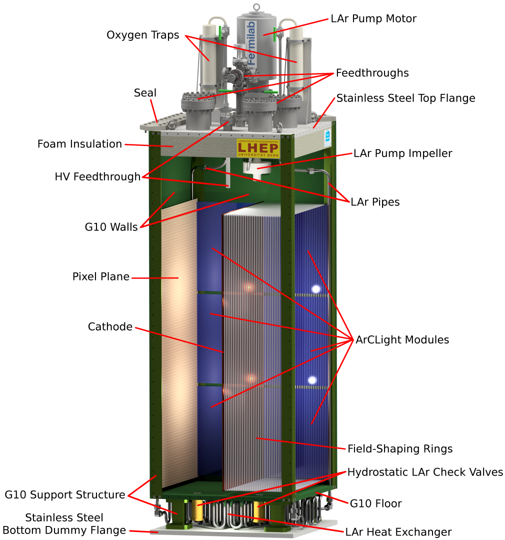
- SiPM-based light trap
- Compact
- Resilient to electric fields
- PDE $\sim 1\,\%$

$\Rightarrow$ Suited for a modular TPC design

$\Rightarrow$ Contained scintillation light enables localisation

ArgonCube

A scalable high-precision tracker and calorimeter based on self-contained LArTPCs



- 50 cm drift length

$\Rightarrow$ Safe cathode voltage

- Pixelated charge readout

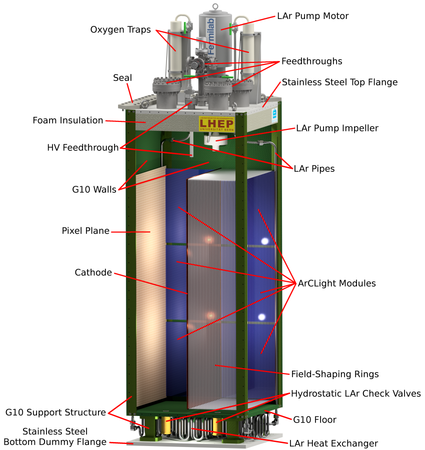
$\Rightarrow$ True 3D tracking

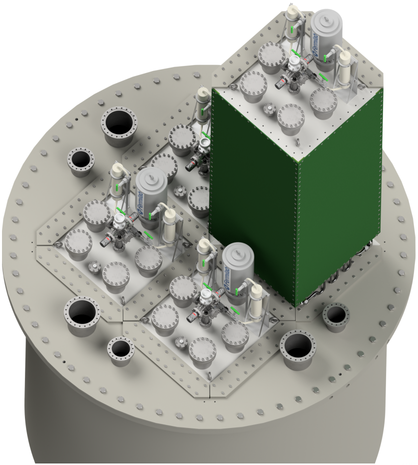
- ArCLight readout

$\Rightarrow$ Reduce scintillation light pile-up

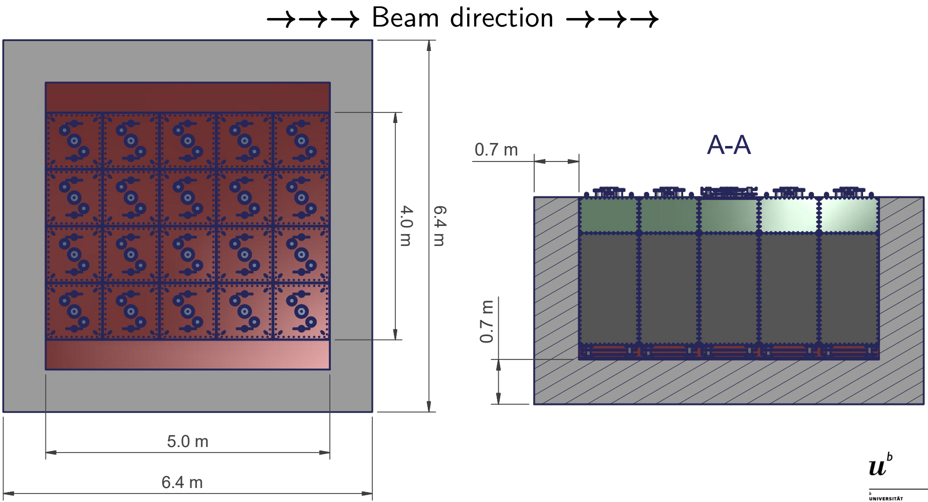
ArgonCube

A scalable high-precision tracker and calorimeter based on self-contained LArTPCs



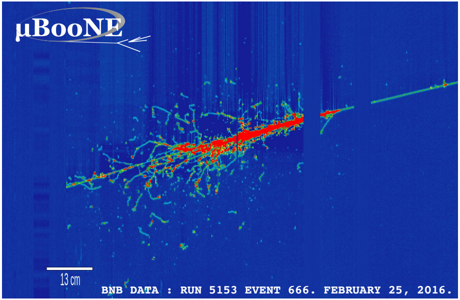


ArgonCube DUNE near detector component



Can a pixelated ArgonCube DUNE near detector cope with the expected event rates?

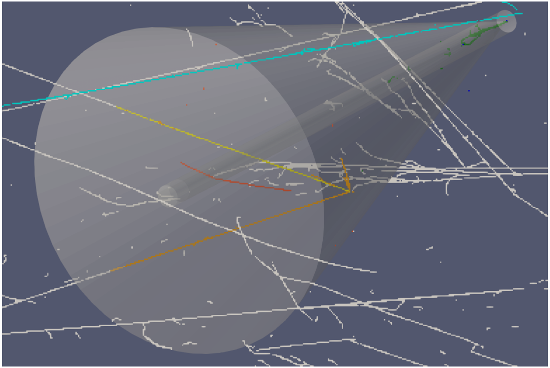
Can the energy of π^0 EM showers be reliably reconstructed?



- 10 % to 20 % of events involve $\pi^0 \to \gamma\gamma \to$ EM shower
- Lots of tiny charge clusters
- Missed/misidentified charge degrades energy resolution
- One of the most challenging reconstruction tasks

Event pile-up simulation

For ArgonCube in the DUNE near detector



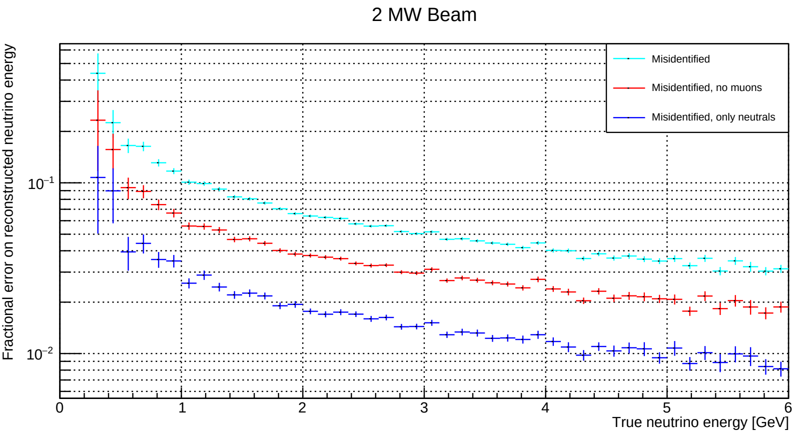
- Assume true 3D information from pixels
- Assume shower location and direction are known
- Form cone around shower
- Misidentified energy: Not deposited by shower, inside cone

⇒ Measure for pile-up

UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

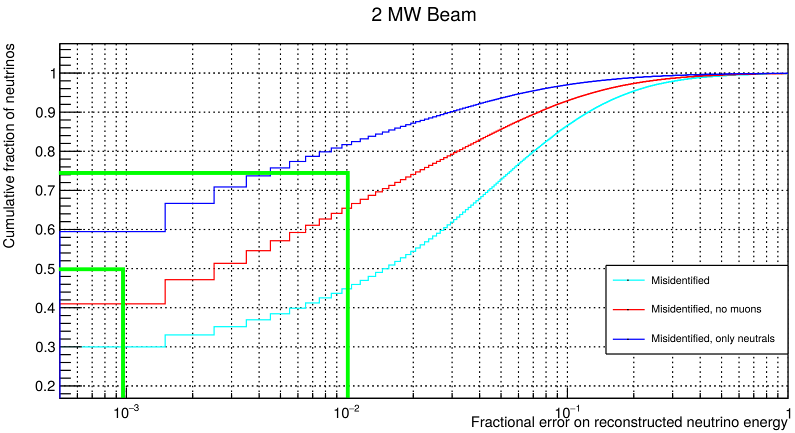
Misidentified energy

Gauging event pile-up



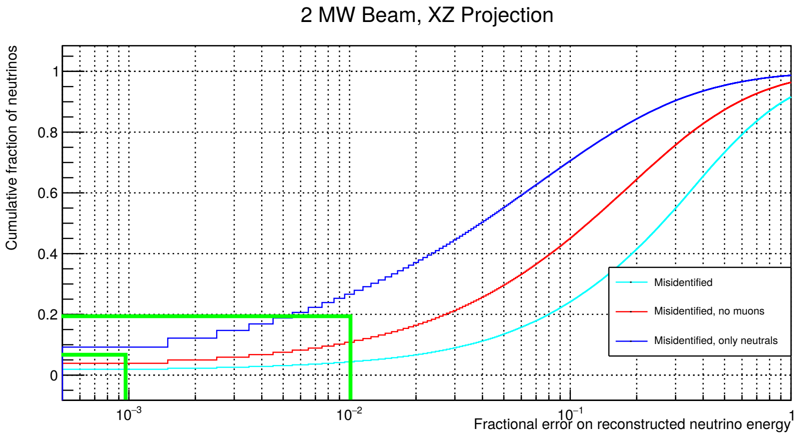
Misidentified energy

Gauging event pile-up



Misidentified energy

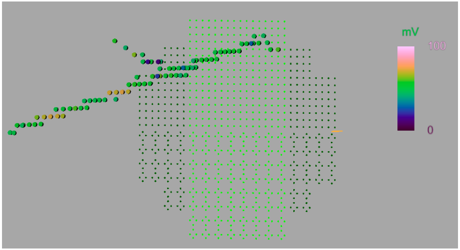
Emulating a wire readout



ArgonCube summary

- Enables a LArTPC component in the DUNE near detector
- Mean pile-up-related error on reconstructed energy: 2 % to 3 %
- <0.1 % for >50 % of neutrino events

Outlook



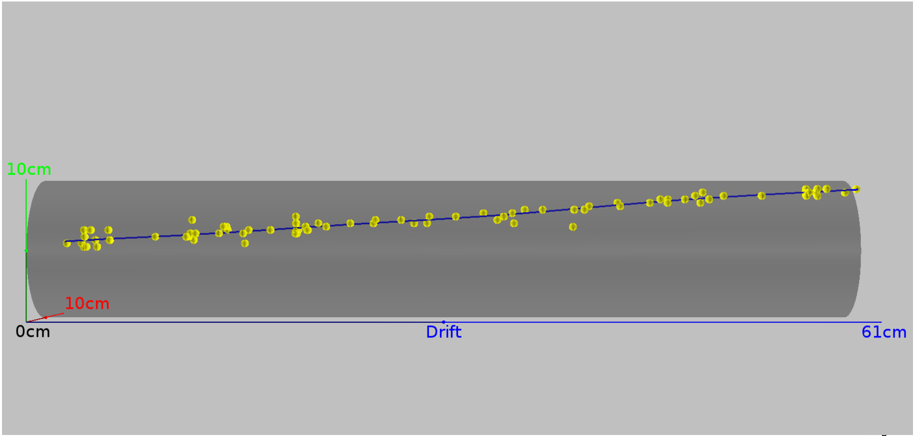
- New ambiguity-free pixel readout electronics
- First ArgonCube prototype modules
- Near detector design

Summary

The summation of my work builds the groundwork for ArgonCube:

- Novel, enhanced LArTPC detector
- Self-contained TPC modules sharing a common LAr bath
- Pixelated charge readout, enabling true 3D tracking
- Optimised for the high-multiplicity near detector environment of next-generation beam neutrino oscillation experiments
- Baseline LAr component of the DUNE near detector complex

Thank you!



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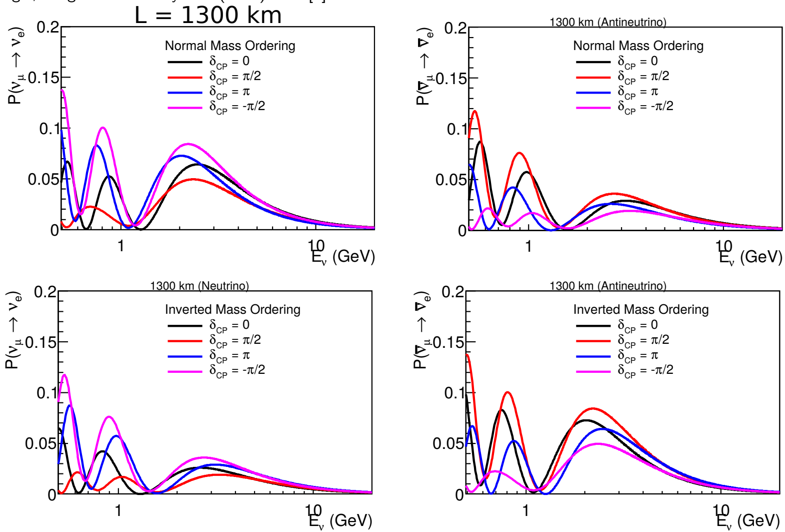
Neutrino oscillation

- ν_α flavour eigenstates for $\alpha = e, \mu, \tau$
- ν_{i} mass eigenstates for $i = 1, 2, 3$
- U_{PMNS} Pontecorvo-Maki-Nakagawa-Sakata matrix defined by
  - 3 mixing angles θ_{12}, θ_{13}, and θ_{23} with $s_{ij} = \sin(\theta_{ij})$ and $c_{ij} = \cos(\theta_{ij})$
  - 1 Dirac CP violation phase δ
  - 2 Majorana CP violation phases α_1 and α_2
- 2 mass squared differences $\Delta m^2_{\mathrm{sol}} = m_2^2 - m_1^2$ and $\Delta m^2_{\mathrm{atm}} = m_3^2 - m_2^2$

$$P(\nu_\alpha \to \nu_\beta) = \sum_i \left| U_{\alpha i} U^*_{\beta i} \right| + 2\,\mathrm{Re}\left\{ \sum_{i>j} U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j} e^{-i \frac{\Delta m^2_{ij}}{2} \frac{L}{E}} \right\}$$

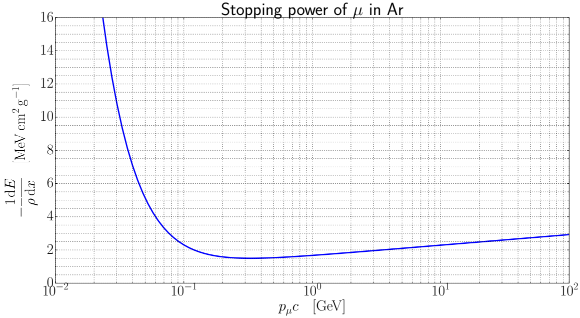
DUNE neutrino oscillation probabilities

Qian, Vogel; Prog.Part.Nucl.Phys. 83 (2015) 1-30 [3]



Neutrino interaction with Matter

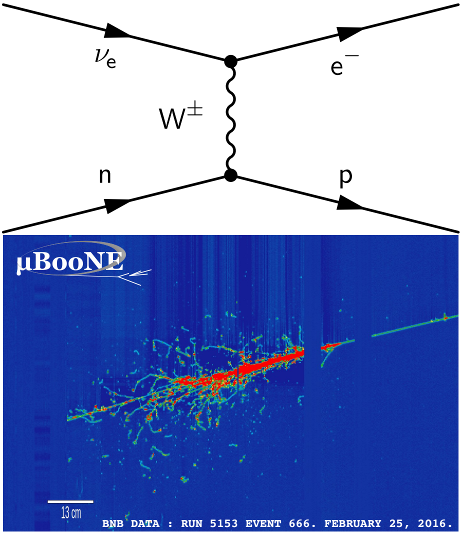
$$\nu_\ell \mathsf{n} \to \ell^- \mathsf{p}$$
$$\bar{\nu}_\ell \mathsf{p} \to \ell^+ \mathsf{n}$$

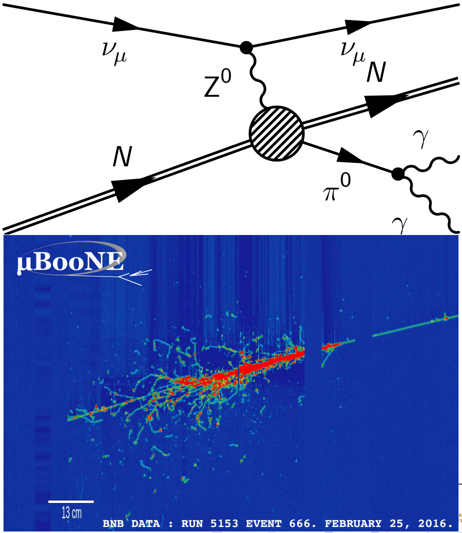


$$-\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x} = 4\pi N_\mathrm{A} r_\mathrm{e}^2 m_\mathrm{e} c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{2m_\mathrm{e}c^2\gamma^2\beta^2}{I}\right) - \beta^2 - \frac{D}{2}\right]$$

Neutrino interaction topologies

Similar detector response for different topologies ⇒ Need a high-resolution tracker



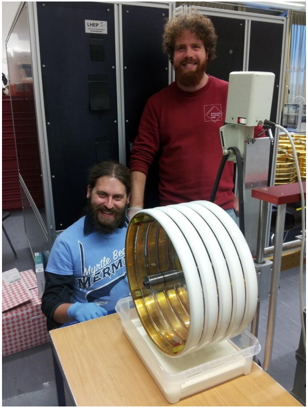


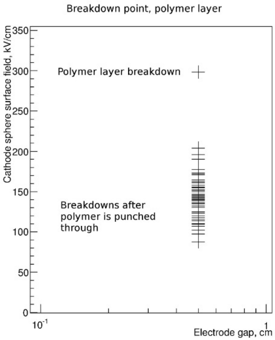
Preventing breakdowns

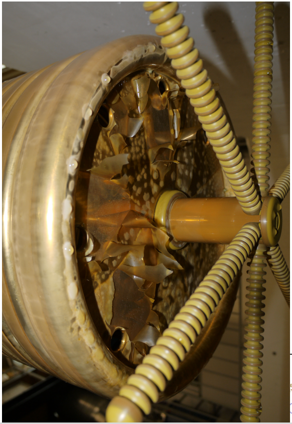
with a polymer coating

Auger, Goeldi et al.; JINST 9 (2014) P07023 [9]

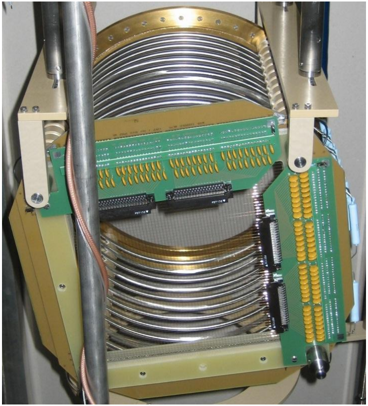
- low electron mobility
- slightly conducting
- only single-use







Problems of wire readouts

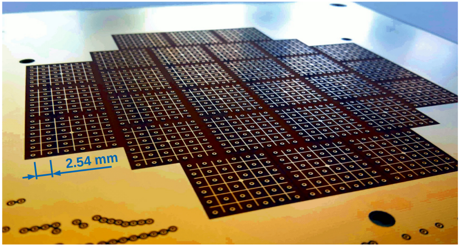


For decades, sensing wires have done a great job BUT they have many drawbacks:

- Limiting an ideal 3D tracker to multiple 2D projections
- Ambiguities in reconstruction
- Mechanically highly demanding
- Prone to microphonics

Pixelated charge readout

Enabling true 3D tracking

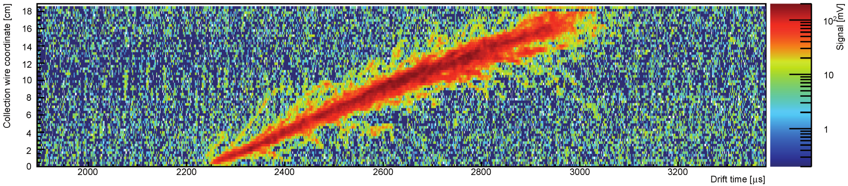


- Charge collecting pixels
  - ↪ PCB VIAs
    - Low capacitance
  - ⇒ Reduce Johnson-Nyquist noise
    $Q_{\mathrm{Noise}} = \sqrt{k_{\mathrm{B}} T C}$
- Biased charge focussing grids
  - ↪ PCB traces

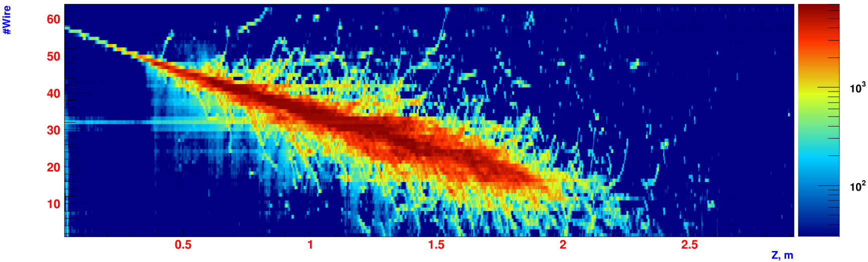
Cold charge amplifiers

Warm vs. cold

Ereditato, Goeldi et al.; JINST 9 (2014) no.11, P11022 [13]

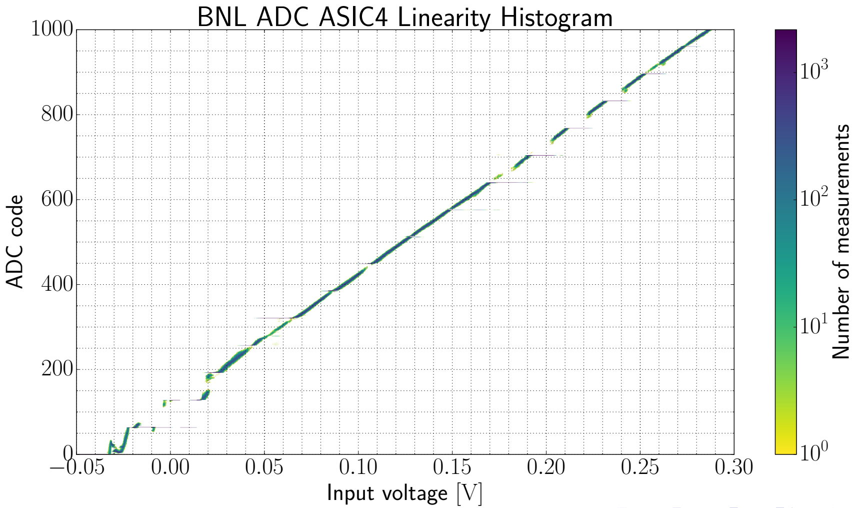


Induction view, Run 8135 Event 74. Trigger pattern: I1 I2 S

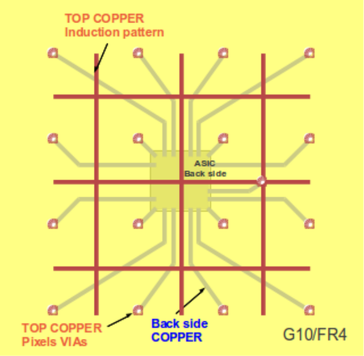


Cold charge ADCs

Linearity issues with current designs

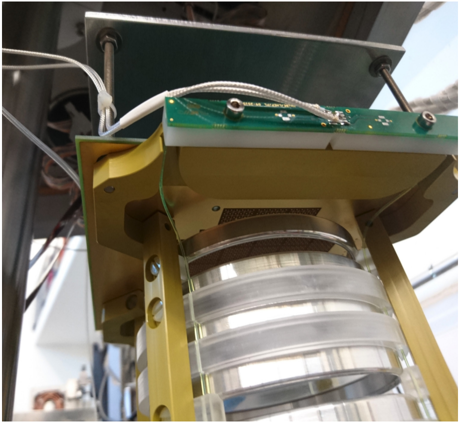


Regions of interest (ROI) multiplexing



- Number of physical pixels: $n_{\text{ROI}} * n_{\text{Pixel}}$
- Number of DAQ channels: $n_{\text{ROI}} + n_{\text{Pixel}}$
- For a square readout plane with a side length of N physical pixels:
- N^2 physical pixels
- $2N$ DAQ channels
  - $\Rightarrow$ Same as 2-plane wire readout of equal size and pitch

ArgonCube pixel demonstrator readout



- Charge readout by BNL LARASIC4* preamplifiers in LAr

↪ CAEN ADCs at room temperature

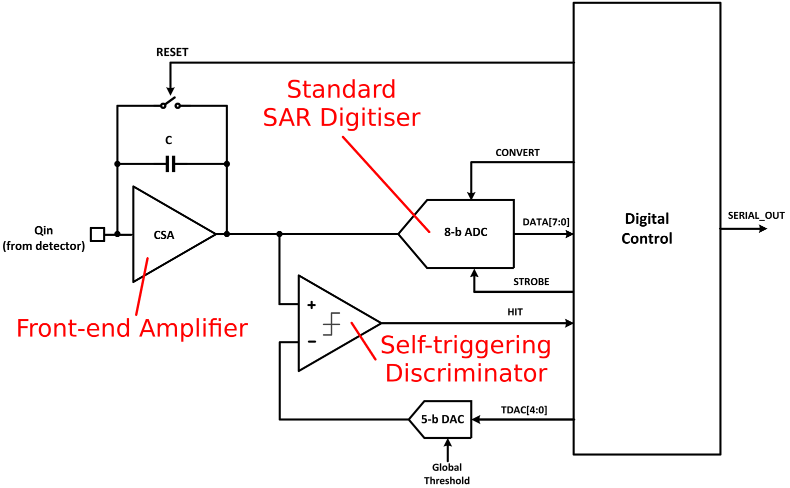
- Light readout by TPB coated acrylic field cage spacers (inner surface)

↪ Cold Hamamatsu S12825-050P SiPMs

Novel ambiguity-free pixelated charge readout electronics

LArPix

Lawrence Berkeley National Laboratory



Missing energy

Gauging reconstruction efficiency