ArgonCube

A Modular Approach for Liquid Argon Time Projection Chambers

Fundamental Physics Directorate

Seminar at SLAC

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March 14th 2023

There is more matter than antimatter in the Universe

→ Physical laws different for matter and antimatter (i.e. broken CP symmetry)

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Neutrinos might break the CP symmetry
→ Key to understand the observed matter – antimatter asymmetry?

0. Neutrino Physics (in a Nut-Shell)

Neutrinos

* See Appendix A

- Elementary particles that come in three flavors: ν_e, ν_μ, ν_τ
- Electrically uncharged particles that only interact weakly
  → difficult to detect
- Can undergo flavor changes / neutrino oscillations
  → non-zero mass (but tiny…)
- Neutrino oscillations might reveal possible CP violations

Ref. [0]

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* See Appendix A

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- Neutrino oscillations might reveal possible CP violations


Ref. [0]

Open Questions*
- How much, if at all, do neutrinos violate CP symmetry?
- What is the ordering of the neutrino masses?
- What are the absolute neutrino masses?
- Are neutrinos Dirac or Majorana particles?
- Are there massive sterile neutrinos?

Neutrino Mixing Model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \begin{array}{c} U_{\text{PMNS}} \\ \text{mixing matrix} \end{array} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavour Eigenstates
”superpositions of mass eigenstates”

Mass Eigenstates
with corresponding masses m_1, m_2, m_3

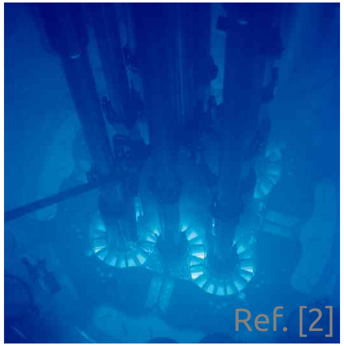
The U_{PMNS} mixing matrix contains information about the oscillation phenomenon

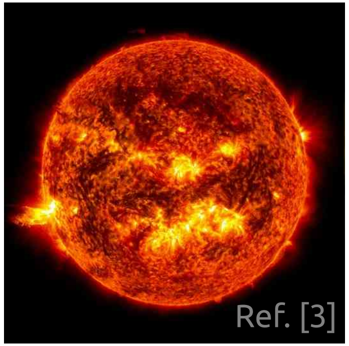
Three-Flavour Neutrino Mixing

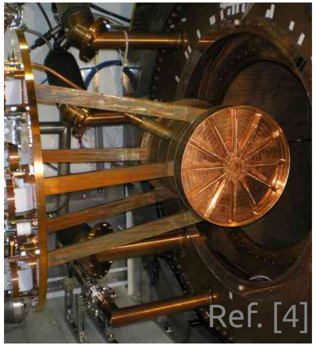
$c_{ij} = \cos(\theta_{ij})$
$s_{ij} = \sin(\theta_{ij})$

$$U_{\text{PMNS}} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{U_{\text{atmospheric}}} \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix}}_{U_{\text{reactor}}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{U_{\text{solar}}} \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{bmatrix}}_{U_{\text{Majorana}}}$$


Ref. [1]


Ref. [2]


Ref. [3]

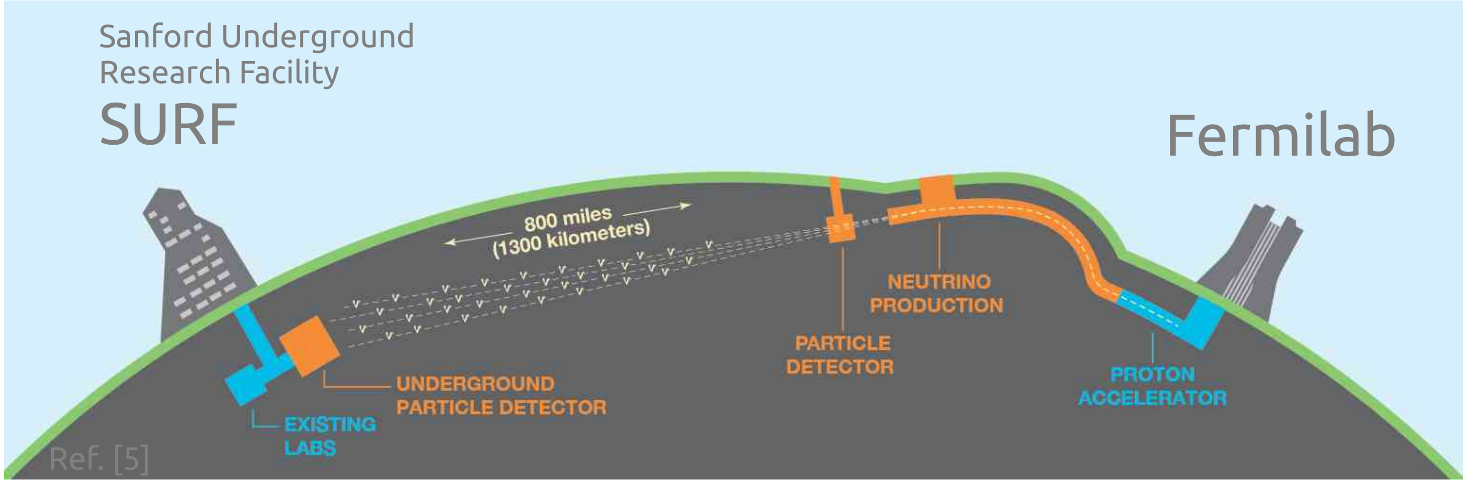

Ref. [4]

3 mixing angles: $\theta_{12} \approx 32.0°$; $\theta_{13} \approx 8.5°$; $\theta_{23} \approx 43.5°$
2 Majorana phases: $\alpha, \beta \approx$ … ? (decoupled from oscillation experiments)
1 Dirac phase: $\delta_{CP} \approx$ … ?

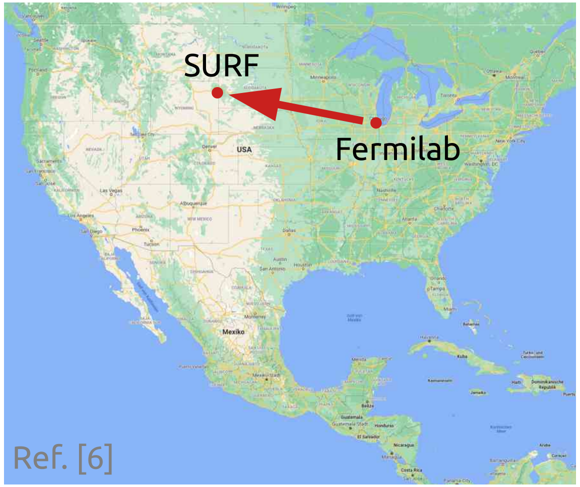
0. Neutrino Physics (in a Nut-Shell)
1. **The Deep Underground Neutrino Experiment (DUNE)**

DUNE

* See Appendix B



Ref. [5]

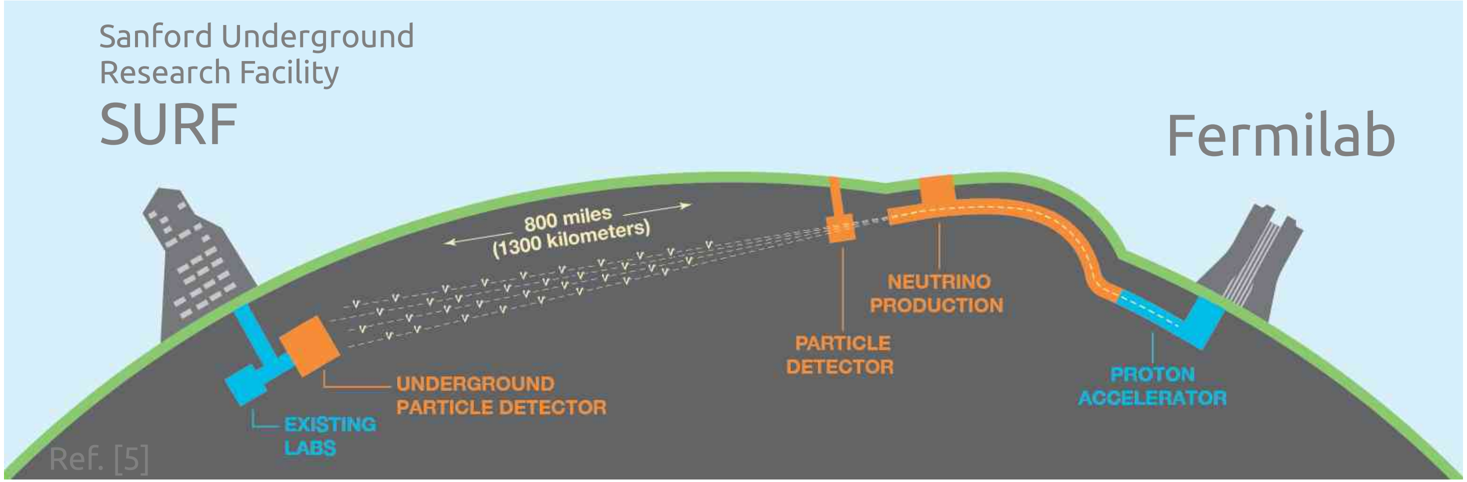


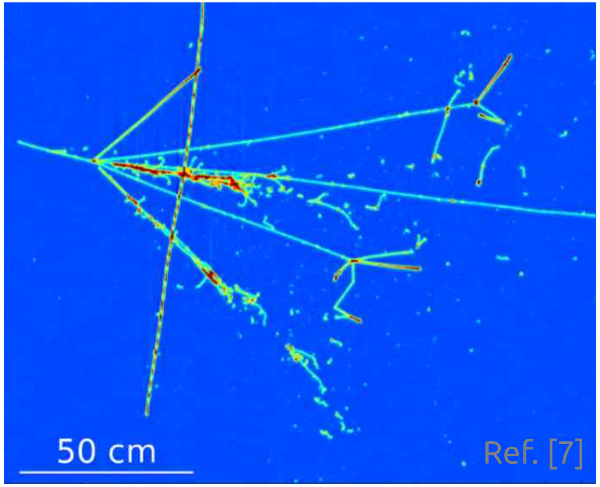
Ref. [6]

- Primary physics goals*: δ_{CP} and ν mass ordering
- ν_μ or $\bar{\nu}_\mu$ beam from Fermilab to SURF
- Measure $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \rightarrow \delta_{CP}$ and $\mathrm{sgn}(\Delta m_{31}^2)$
- Near-Detector (ND) to measure unoscillated beam, at ≈ 570 m from ν production
- Far-Detector (FD) to measure oscillated beam, at ≈ 1300 km from ν production

DUNE

* See Appendix B





ProtoDUNE-SP Run 5772 Event 15

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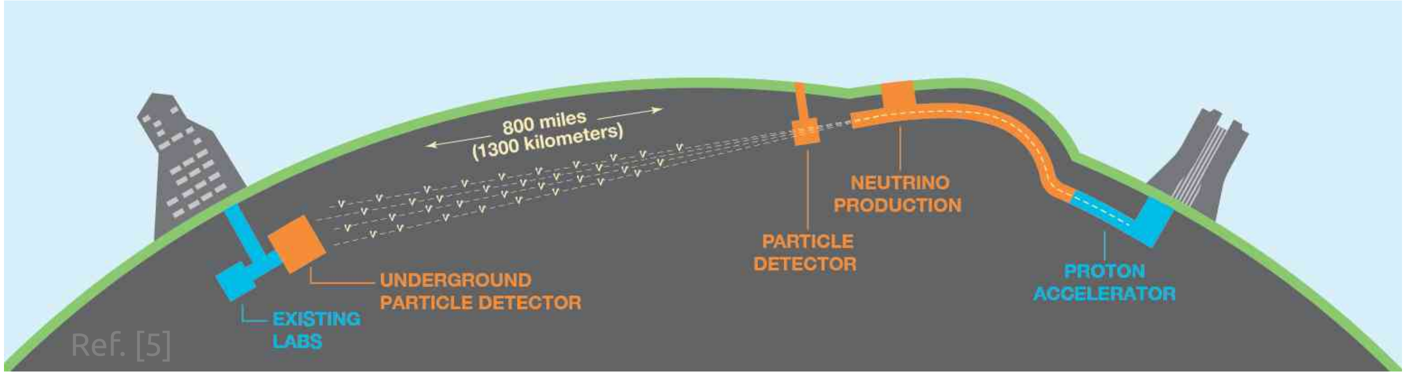
DUNE makes use of Liquid Argon Time Projection Chambers (LArTPCs)

DUNE

* See Appendix C



$$\boxed{N_{\text{interactions}} = \sigma \cdot \Phi \cdot N_{\text{target}}}$$

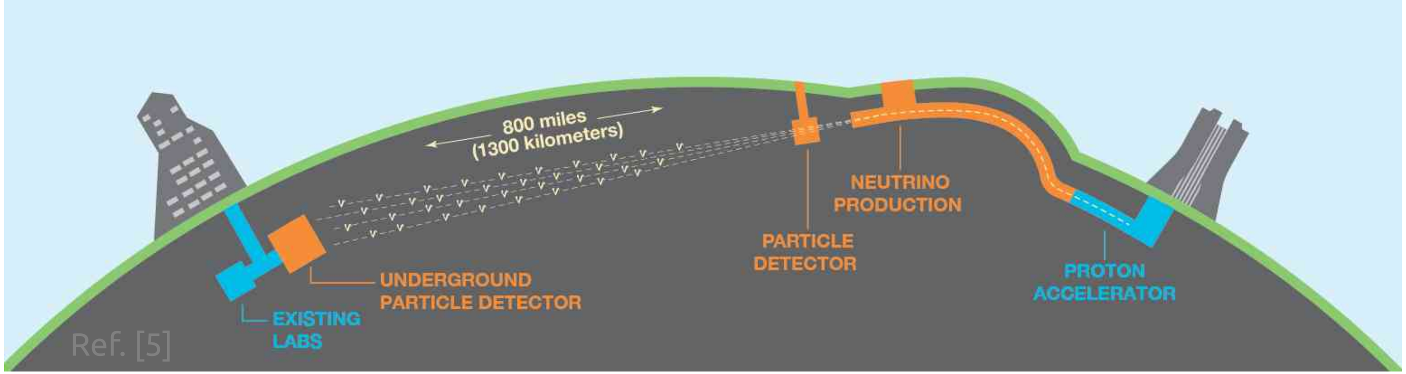
σ: Neutrino cross section
Φ: Neutrino flux

$\sigma \approx 10^{-38}$ cm^2 per nucleon and GeV (tiny!!)

→ High (anti)neutrino flux (Beam*: 1.2 MW initially, upgrade to 2.4 MW later)
→ High number of target nucleons (≈70’000 t LAr in FD, ≈150 t LAr in ND)

DUNE

* See Appendix C



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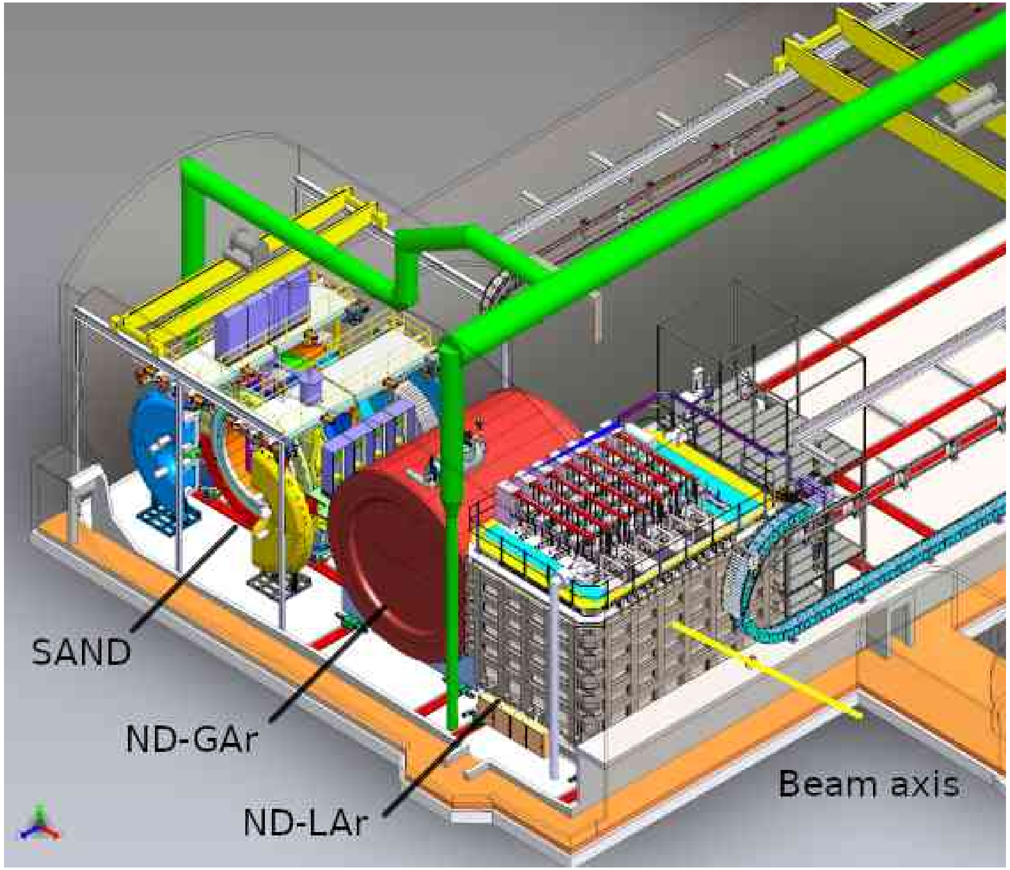
Expected ν interaction rates (no fiducialization)
FD (70 kt LAr): ≈ 6 / hour
ND (0.15 kt Lar): ≈ 23 / spill

DUNE Near-Detector (ND) Complex

See Appendix B



Courtesy of A. Bross (Fermilab)

My focus

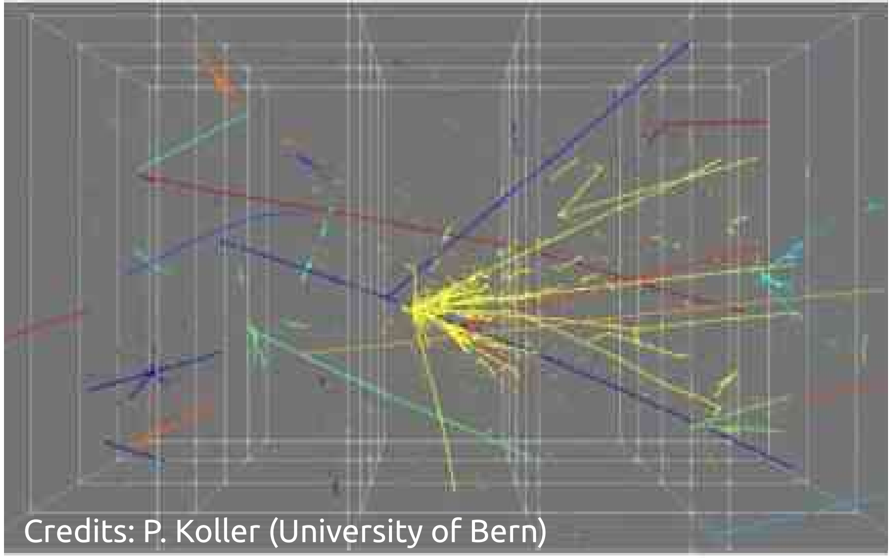
ND-LAr
LArTPC based on the ArgonCube design
→ Measure interactions on LAr

ND-GAr (μ spectrometer for ND-LAr)
Magnetised high-pressure gaseous argon TPC
→ Measure muon momentum and charge
→ Precision cross-section measurements

SAND
Dedicated magnetised beam monitor

Challenges for ND-LAr

Simulated ν interactions (1 spill, ≈ 80 t LAr)
Each color corresponds to 1 ν interaction



Credits: P. Koller (University of Bern)

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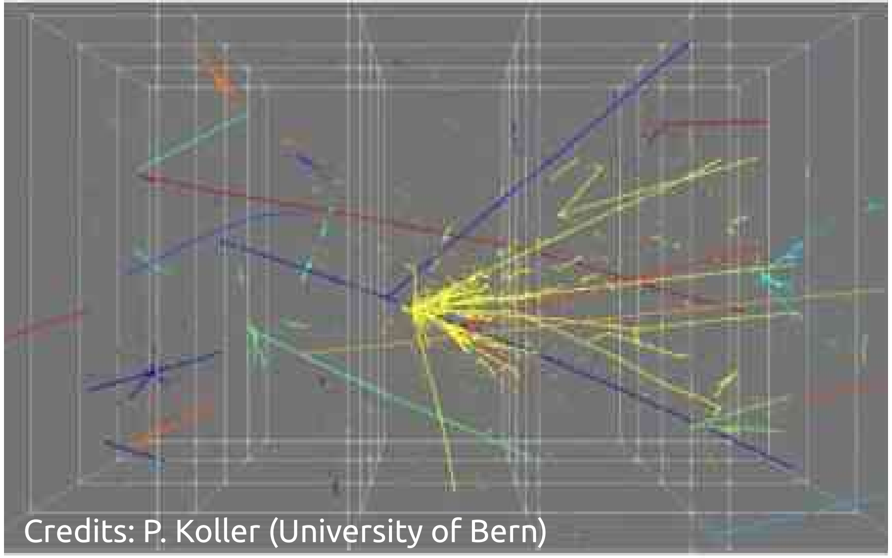

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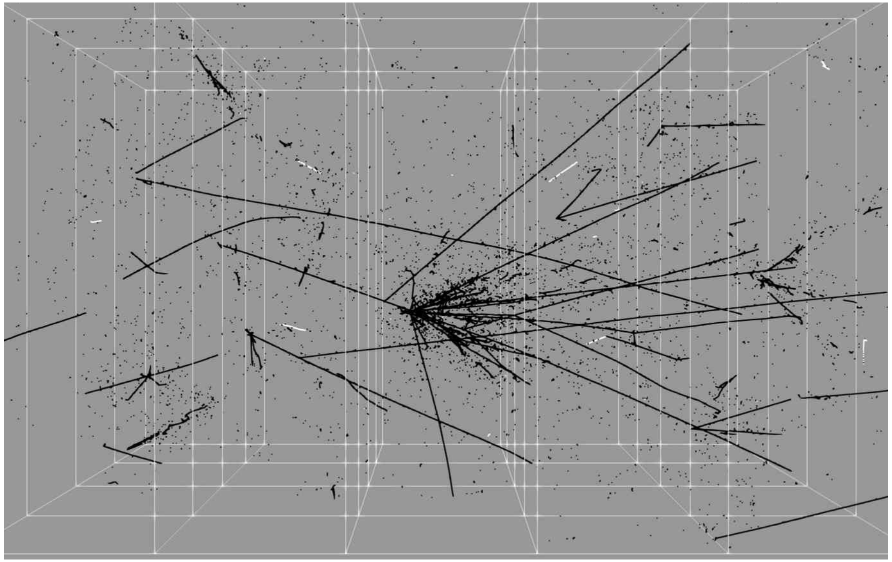
However…
Detector is “color blind”



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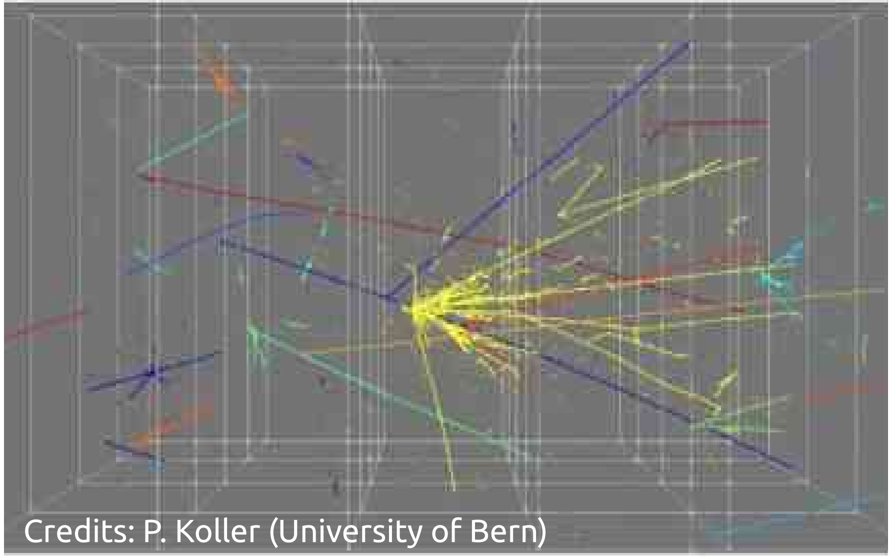

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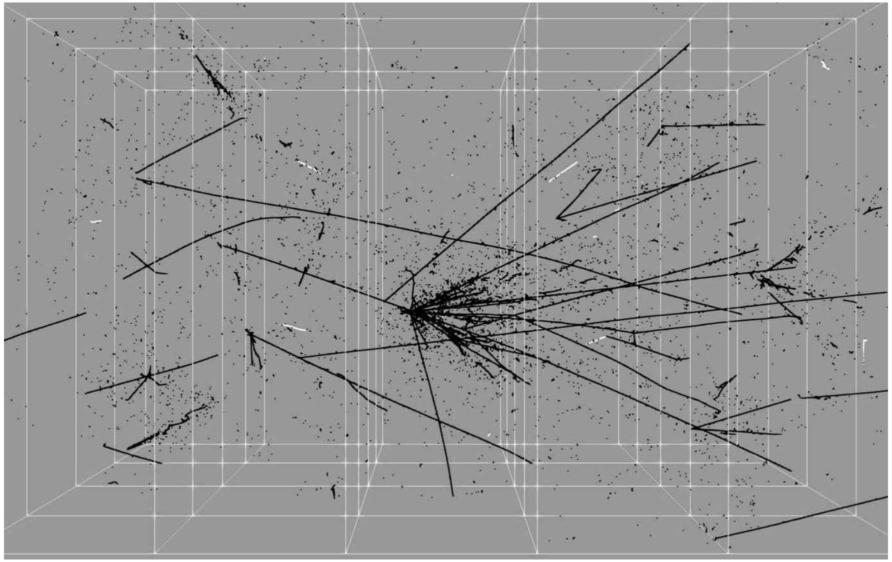


The high flux (interaction rate) poses challenges for the DUNE ND-LAr

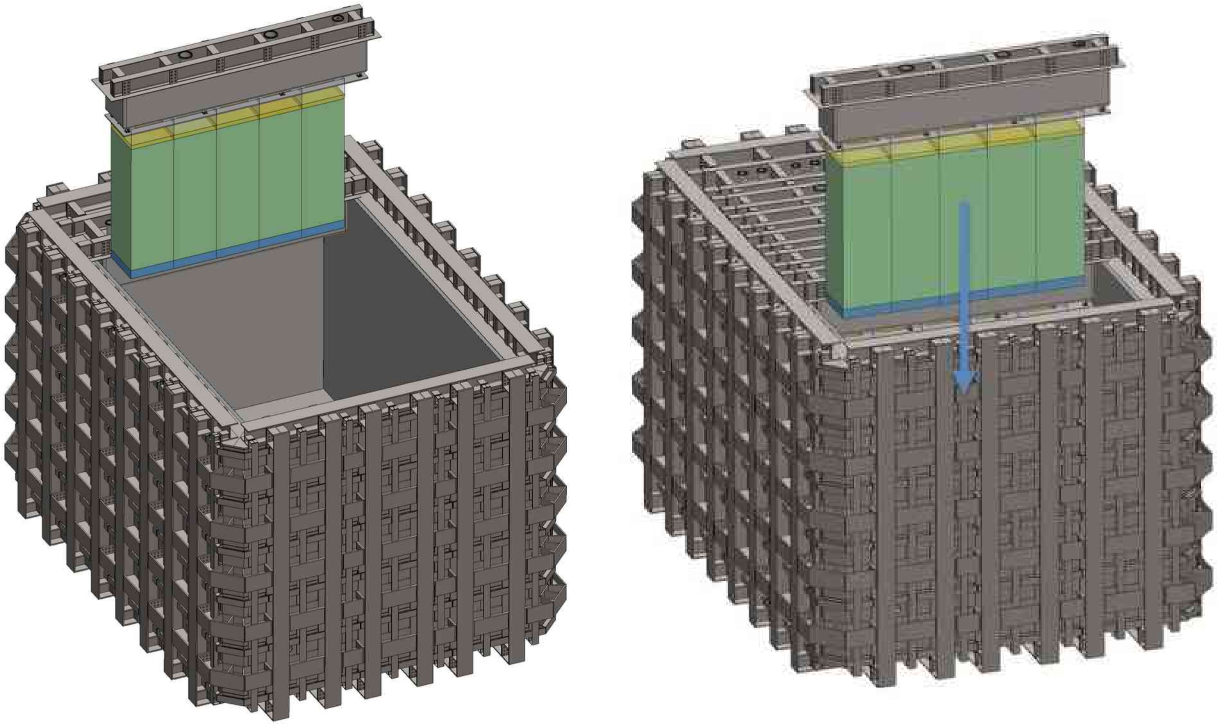
Mitigate high event rates using a **modular LArTPC** (ArgonCube concept)

- Optically isolated TPCs with fast light readout → Tag individual ν interactions!
- Shorter charge readout window, less stringent requirements on LAr purity, HV, etc.

0. Neutrino Physics (in a Nut-Shell)
1. The Deep Underground Neutrino Experiment (DUNE)
2. **ArgonCube in the DUNE Near-Detector (ND-LAr)**

ArgonCube Concept

To mitigate the high event rates
segment a big detector volume into individual LArTPC modules



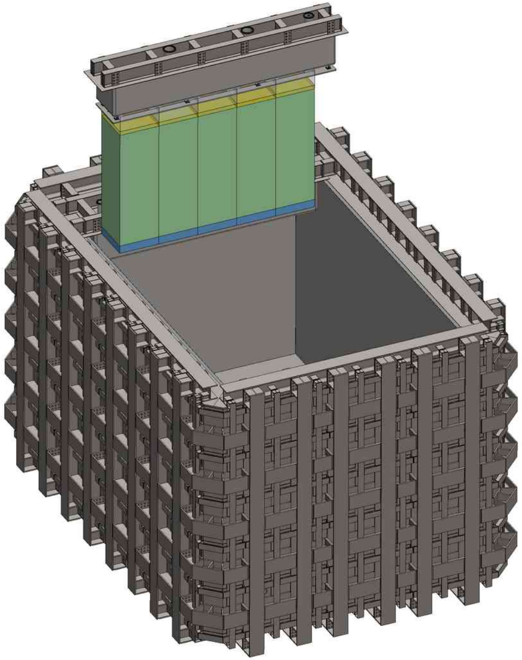
DUNE ND-LAr:
Array of 5 x 7 modules,
each 1m x 1m x 3m (active)
→ 147 t LAr (active)

5 modules in beam direction
(hadron containment)

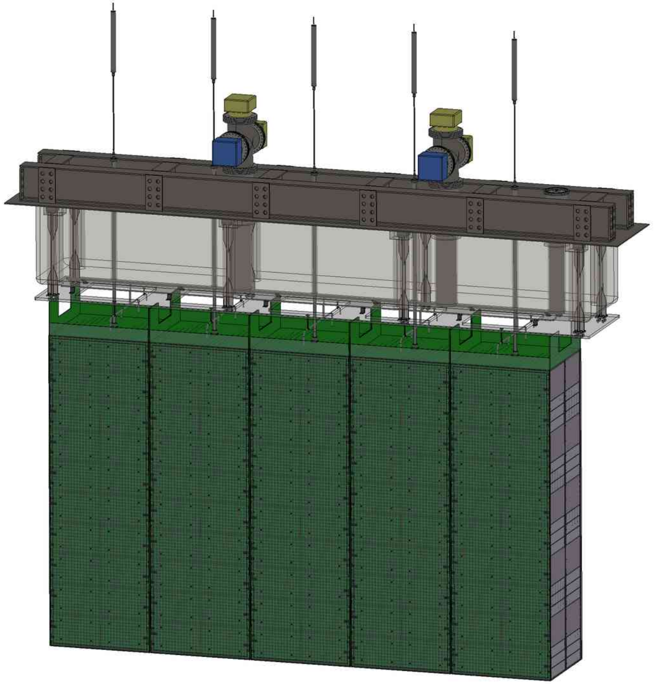
7 modules across beam direction
(high-angle particles)

ArgonCube Concept

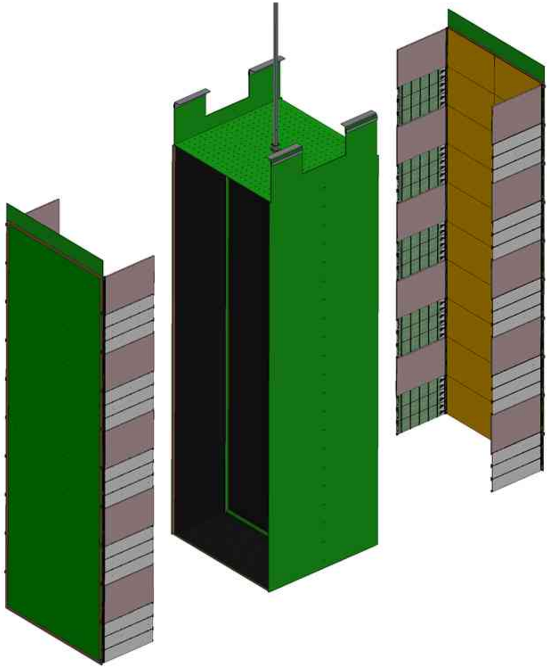
Segment a big detector volume into individual LArTPC modules



The DUNE ND-LAr cryostat will host 5x7 ArgonCube modules



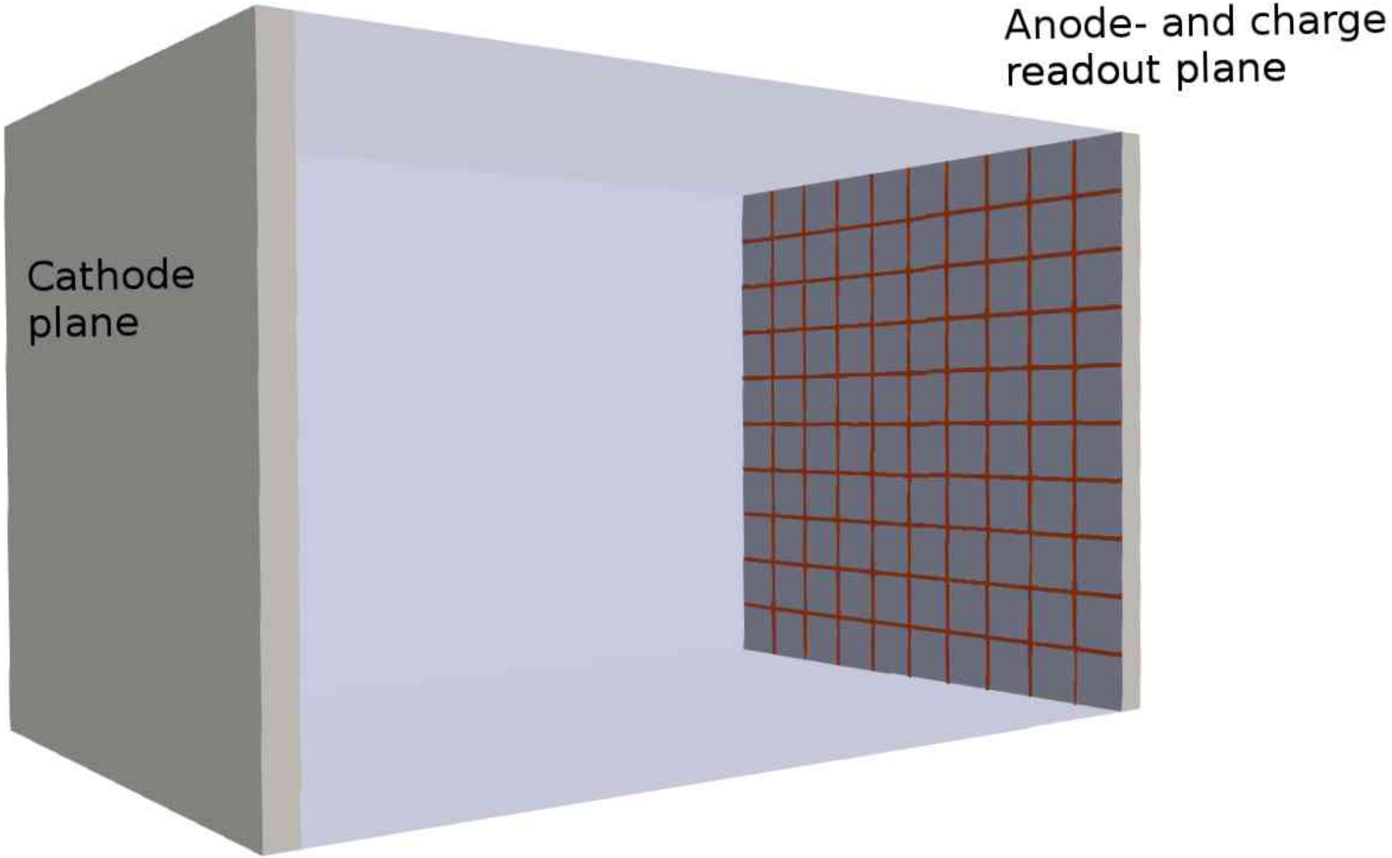
A row of 5 ArgonCube modules



Exploded view of a module

0. Neutrino Physics (in a Nut-Shell)
1. The Deep Underground Neutrino Experiment (DUNE)
2. ArgonCube in the DUNE Near-Detector (ND-LAr)
3. **Liquid Argon Time Projection Chambers (LArTPCs)**

Working Principle of a LArTPC



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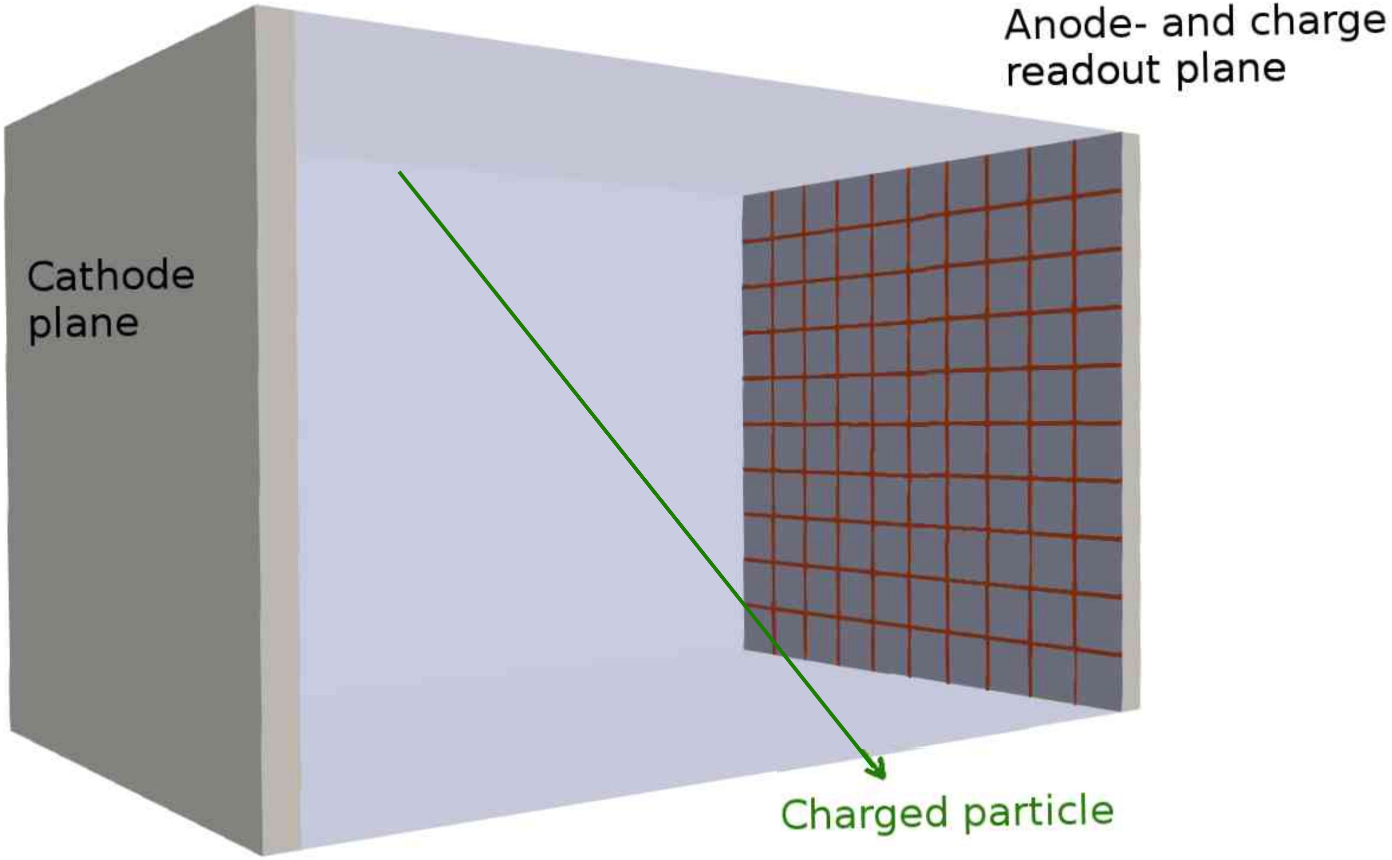

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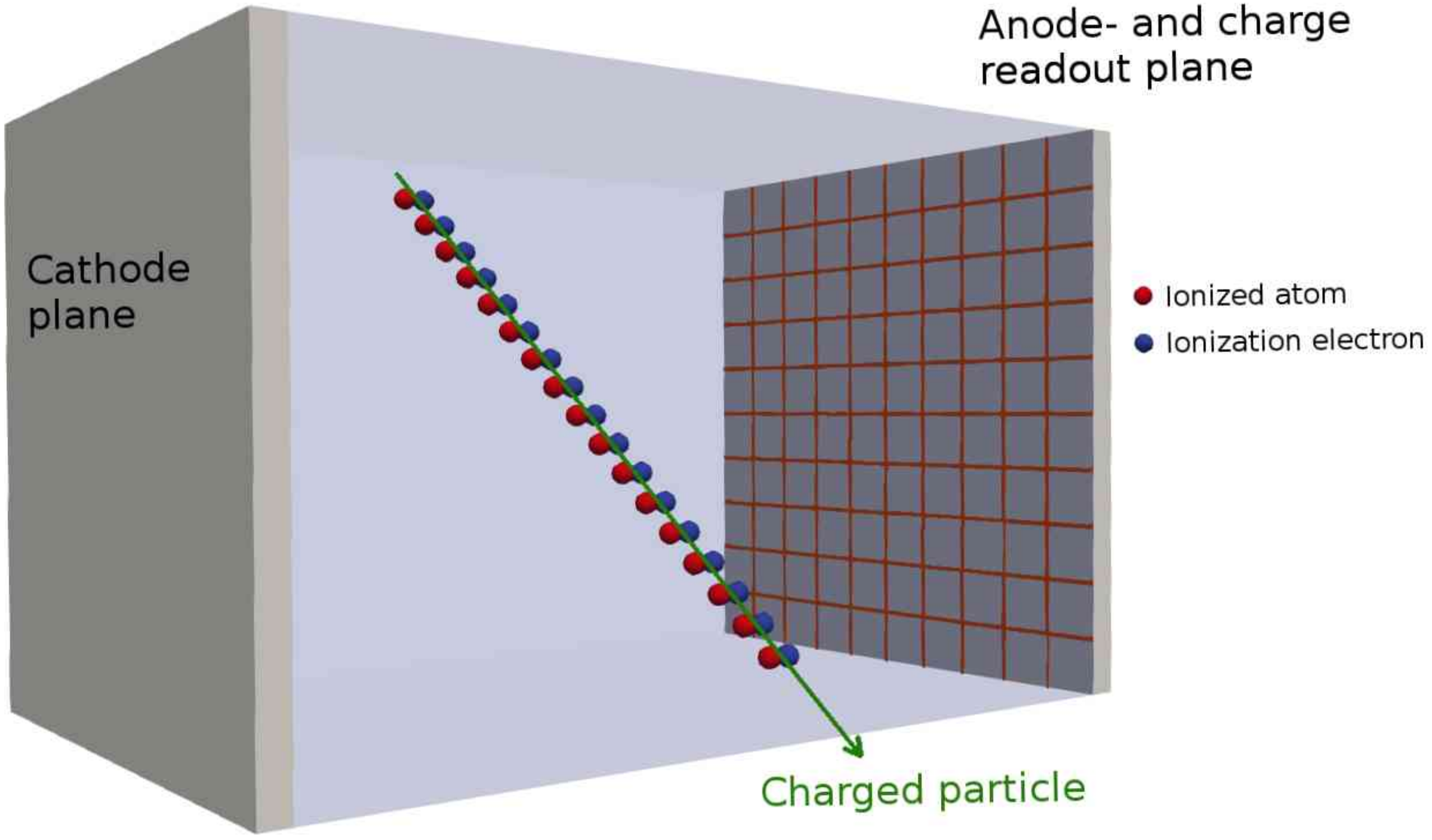

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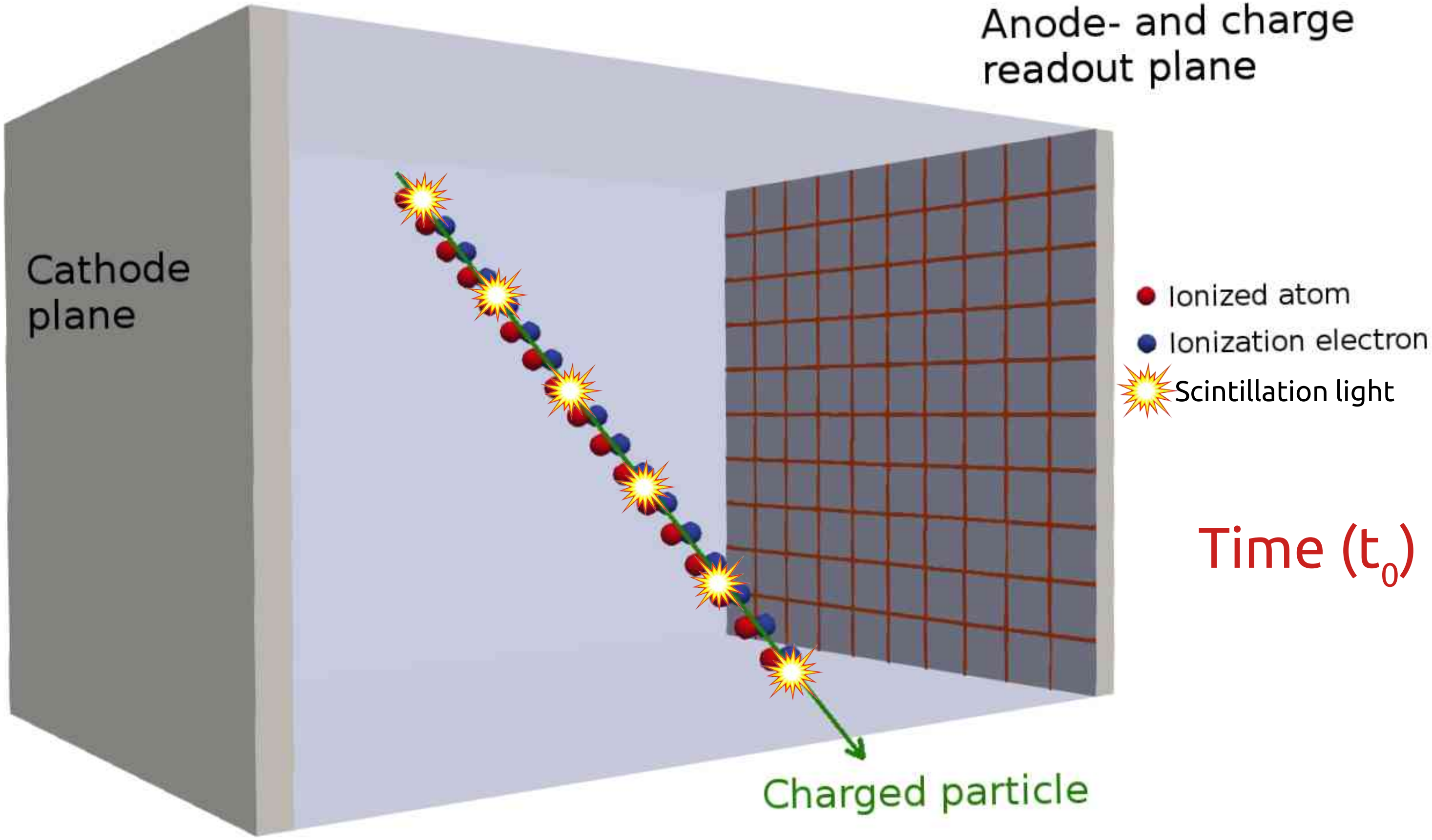
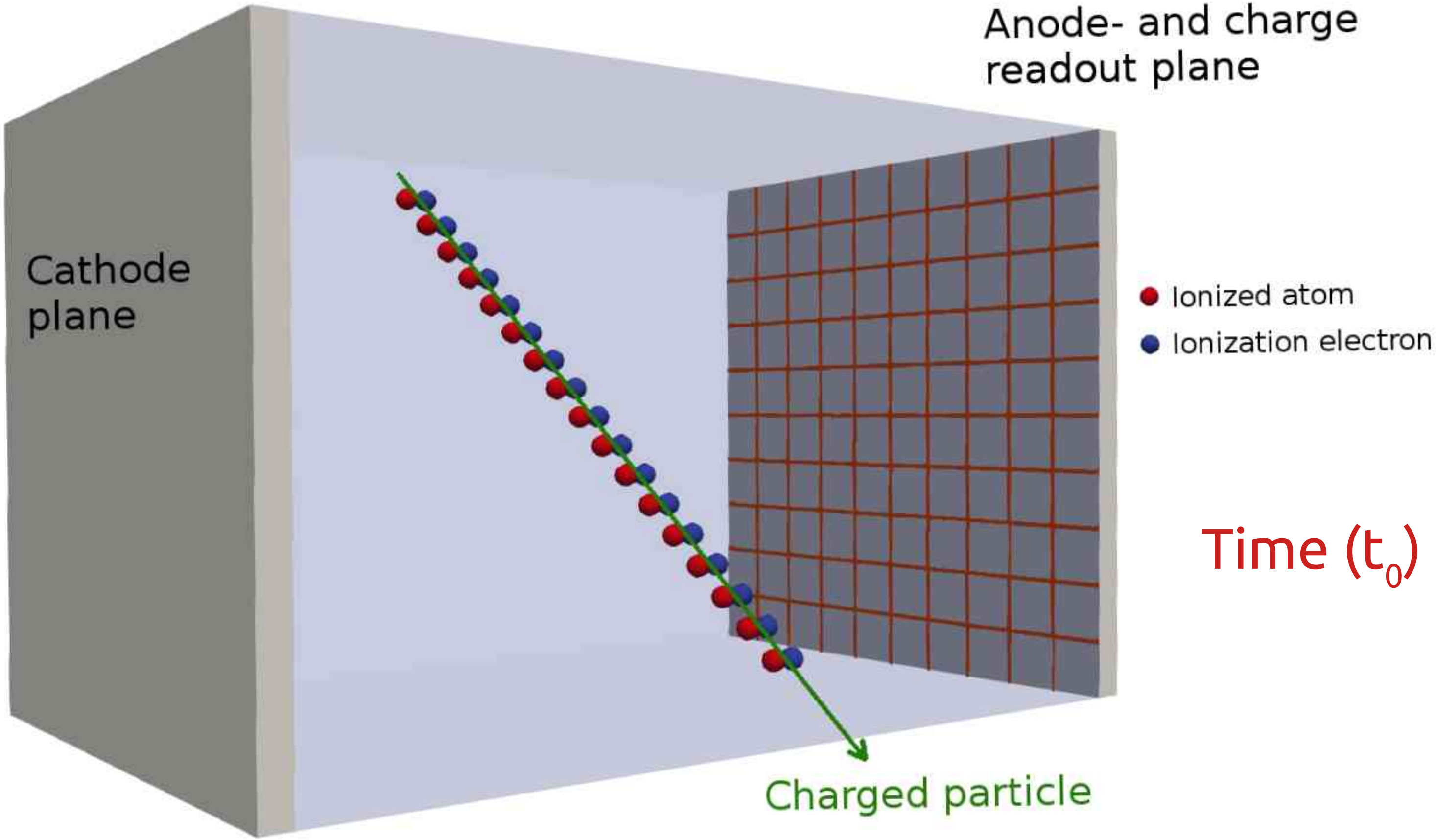


Time (t_0)

Working Principle of a LArTPC



Time (t_0)

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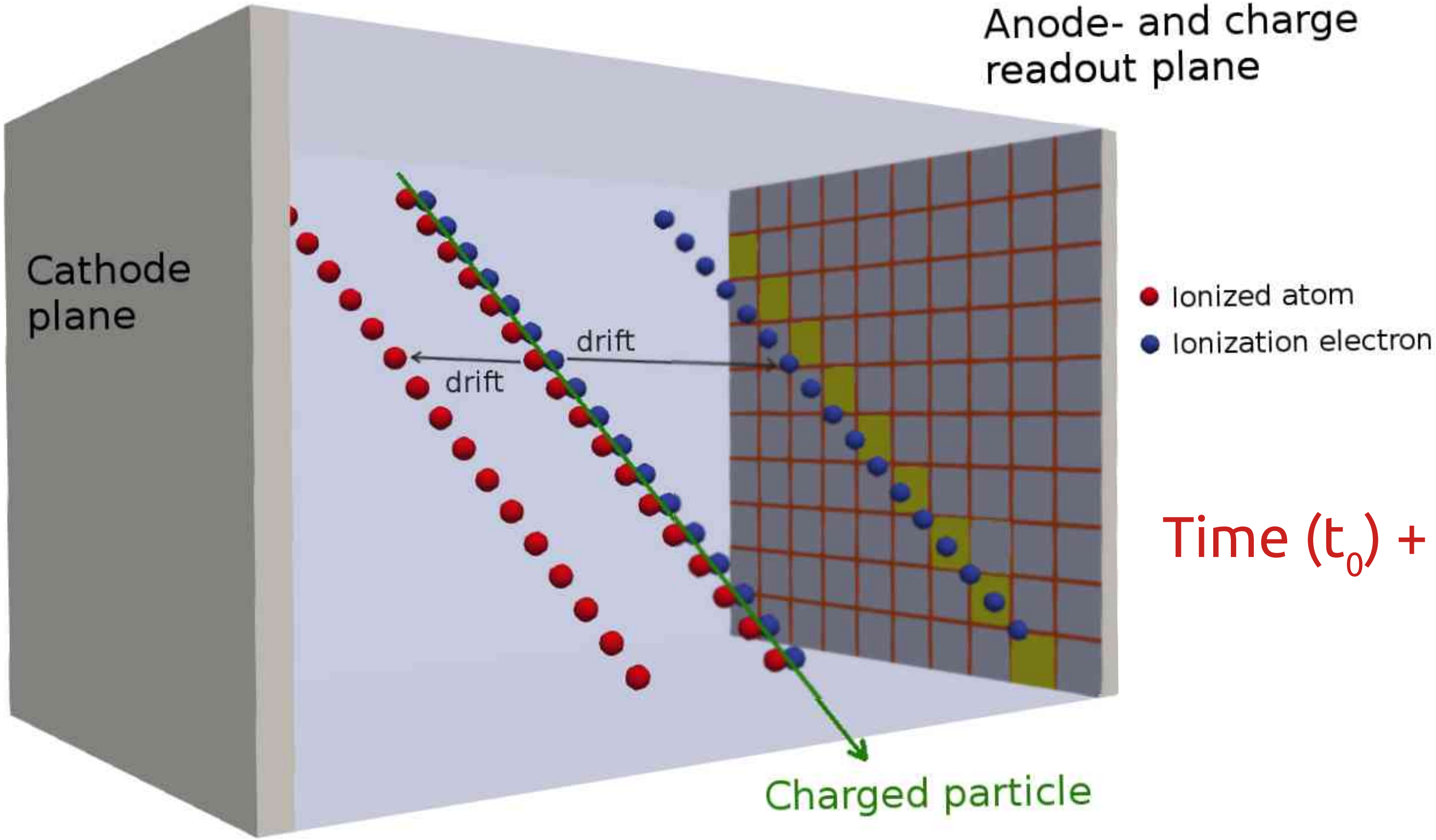
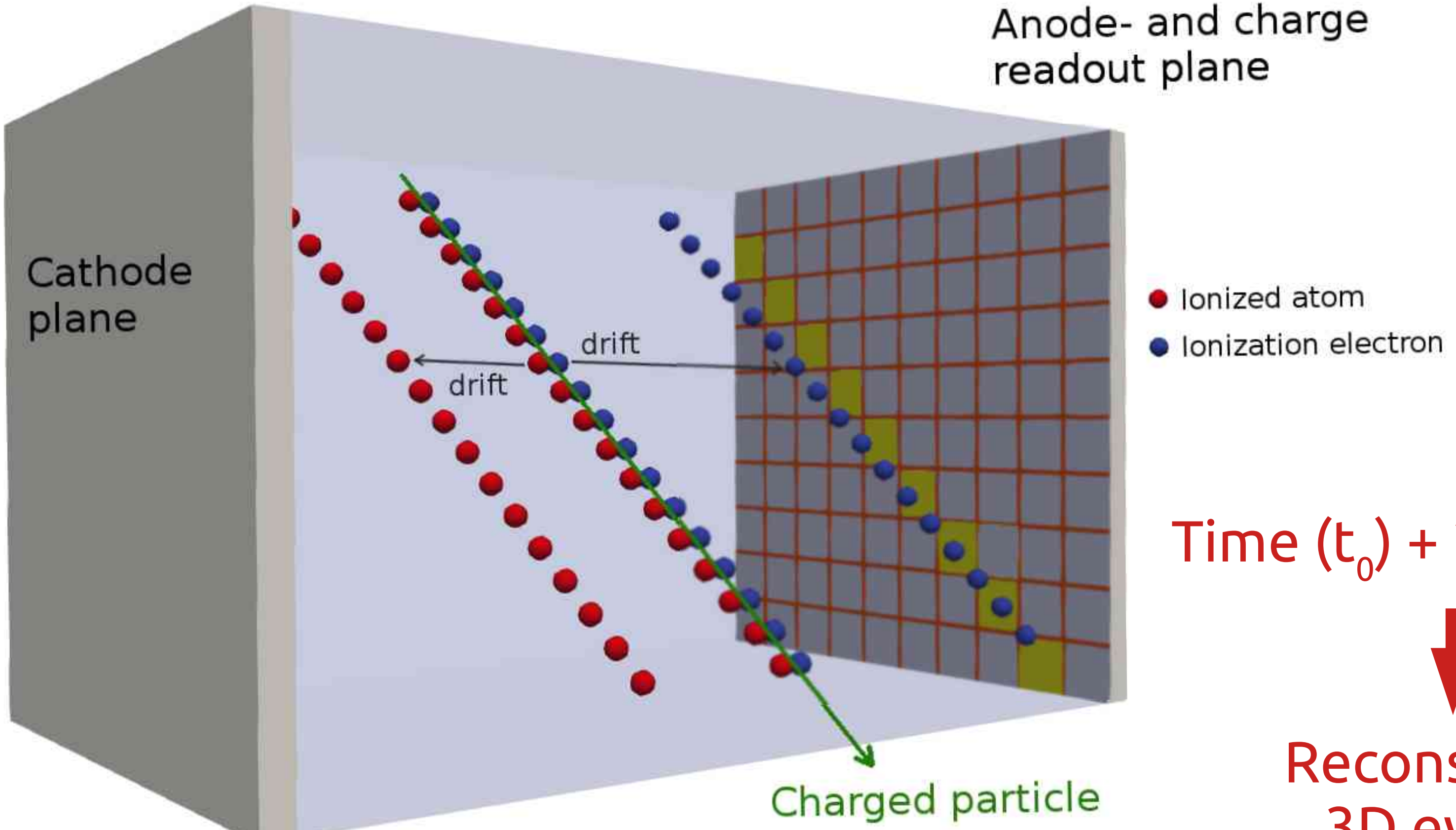


Time (t_0) + 2D (t, x, y)

Working Principle of a LArTPC



Time (t_0) + 2D (t, x, y)

↓

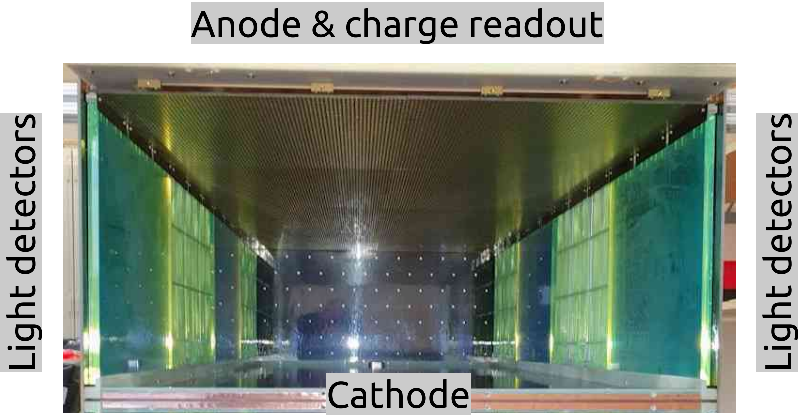
Reconstruct
3D event

ArgonCube LArTPC Prototype

Module-0 prototype
during the assembly

The Module-0 LArTPC Prototype

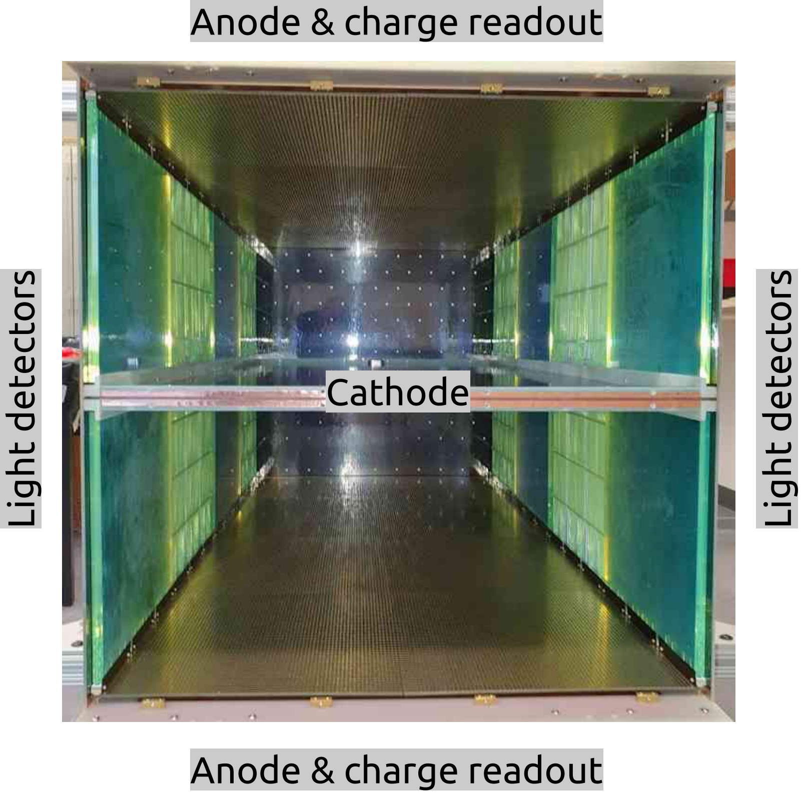
Module-0 prototype
during the assembly



View from below into the
open Module-0 prototype

The Module-0 LArTPC Prototype

Module-0 prototype
during the assembly



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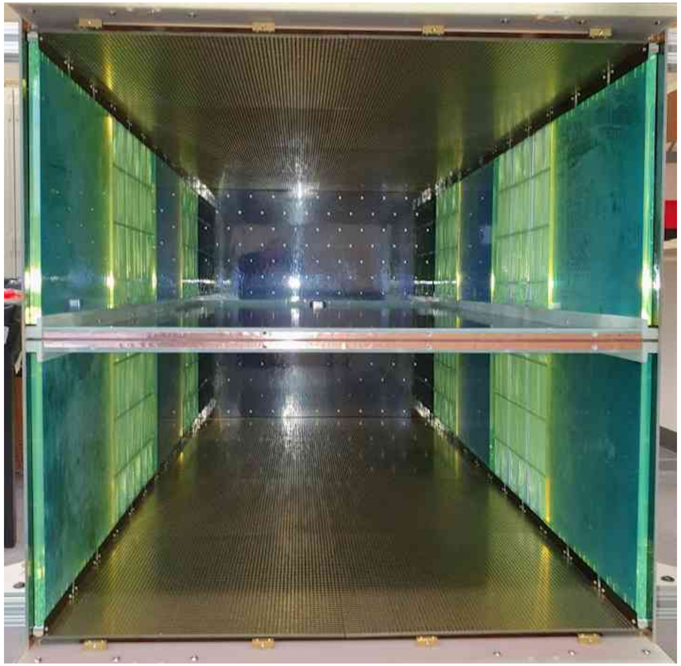

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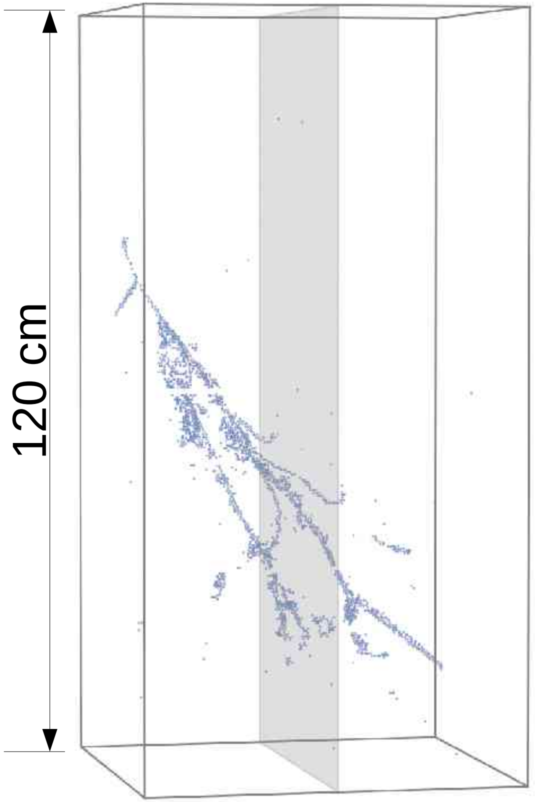


Cosmic induced particle shower
in the Module-0 prototype

LArTPC Properties

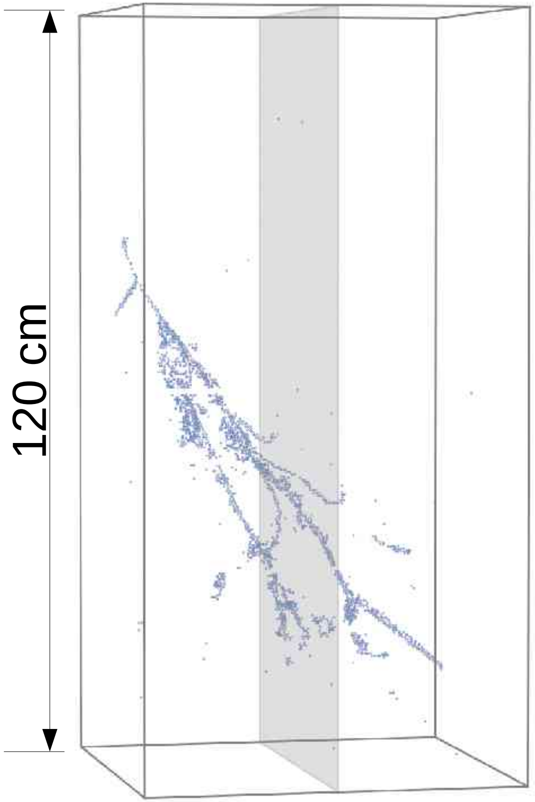
See Appendix D

Excellent for particle tracking & calorimetry
→ Particle identification (PID)

High abundance and high density of LAr
→ Scalable to massive detectors, O(10 kt)

LAr is active material AND target
→ Suitable for non-collider experiments and
rare-event searches (e.g. Dark Matter, neutrinos)

Drift windows typically several 100 μs
→ “Slow” charge readout (limited by e^- drift speed)



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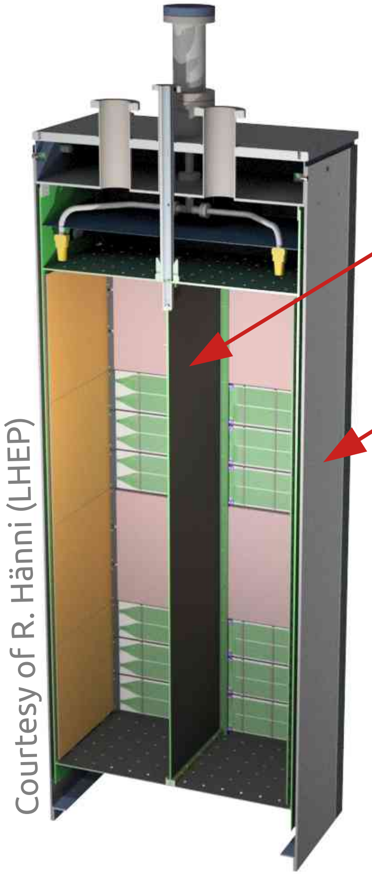
1. The Deep Underground Neutrino Experiment (DUNE)
2. ArgonCube in the DUNE Near-Detector (ND-LAr)
3. Liquid Argon Time Projection Chambers (LArTPCs)
4. **ArgonCube Technologies**

ArgonCube Module Structure



Courtesy of R. Hänni (LHEP)

Cross section of an ArgonCube module

Central cathode plane

→ Splits module into two independent TPCs

Thin module walls (fibreglass)

→ Reduce dense and dead material

→ Opaque to LAr scintillation light

→ Electrical insulation to other modules

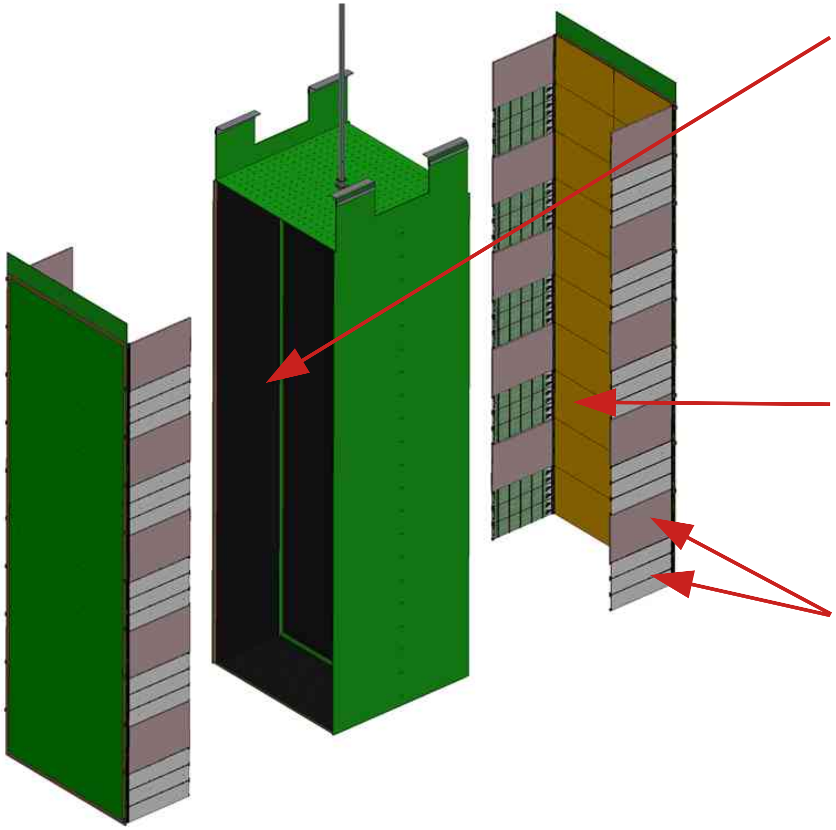
Short max. drift distances and optical paths

→ Relatively small cathode bias voltages

→ Less stringent requirements on LAr purity

→ Reduced electron diffusion & Rayleigh scattering

ArgonCube Technologies – Overview



Engineering drawing of a DUNE ND module

Highly resistive foil at cathode and "field cage"

→ Reduce amount of inactive and dense material

→ Uniform electric field

→ Reduces local LAr boiling

→ Reduces number of components in the TPC

→ Slow-down possible discharge effects

Pixelated charge readout

→ Amplification & digitization in LAr

→ Unambiguous 3D particle tracking

SiPM-based light readout (ArCLight & LCM)

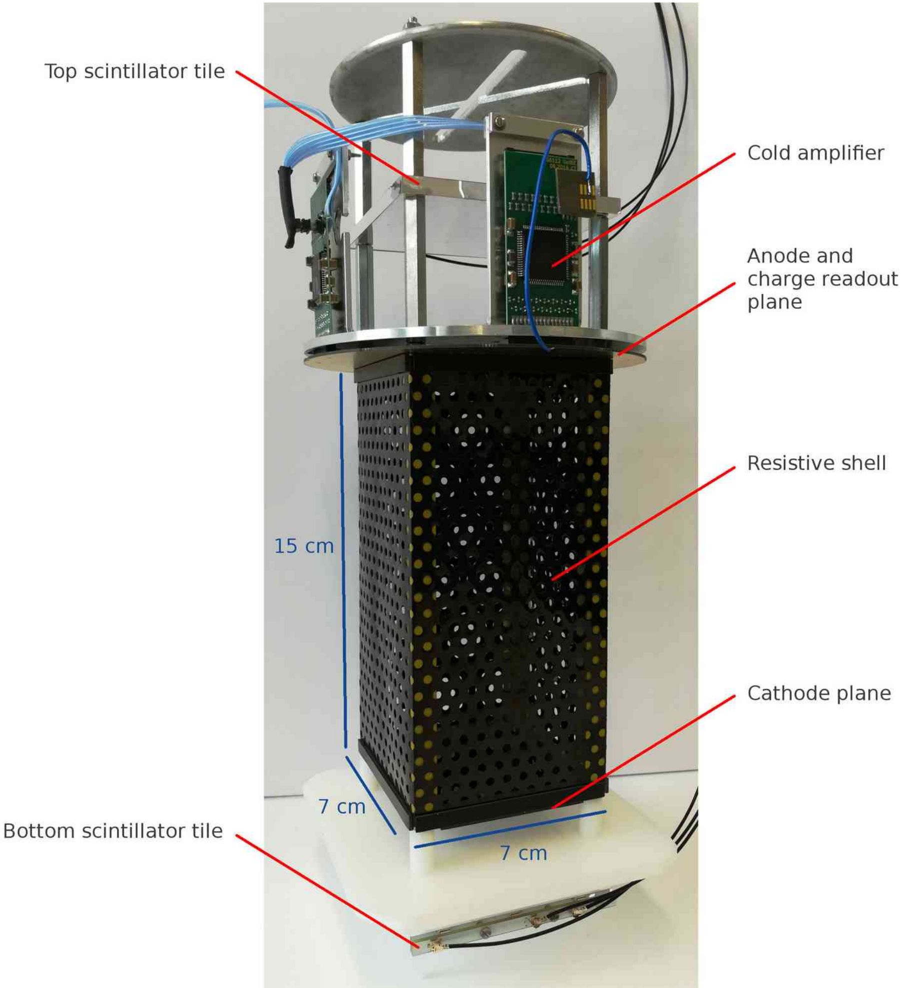
→ Timing resolution of O(1ns)

→ Dielectric bulk can be employed in E-fields

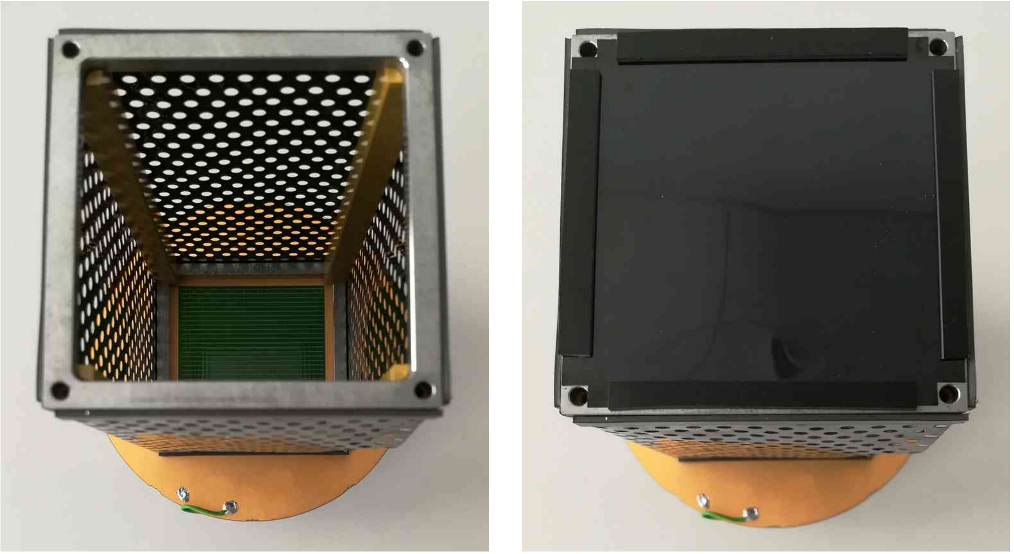
→ High detection efficiency for prompt UV light

→ Large area-coverage

Resistive Shell

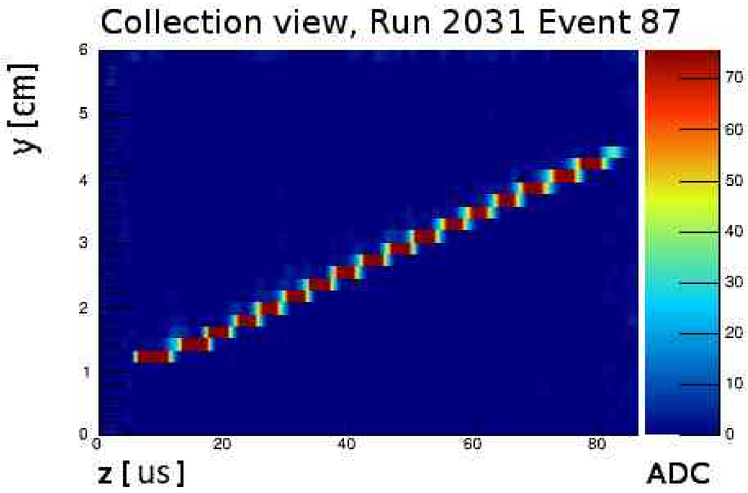


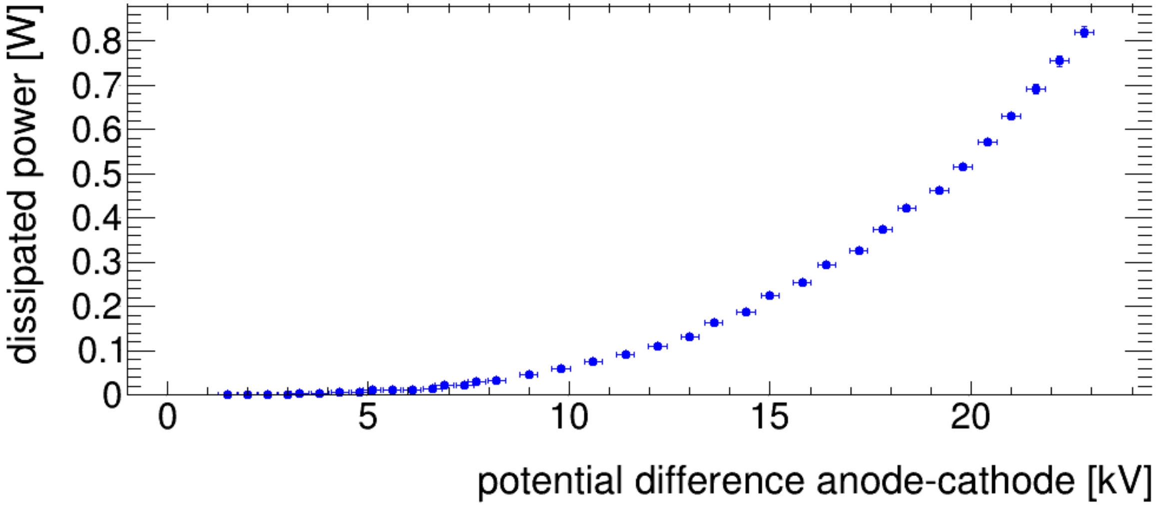
- Cathode & field shell made of resistive Kapton foil, $R_{sheet} = O(1\ G\Omega/sq)$
- To show that E-fields can be produced and shaped using highly resistive sheets



Resistive Shell TPC without (left) and with (right) Kapton cathode

Resistive Shell





Straight tracks observed across a broad range of E-field intensities (up to 1.6 kV/cm)

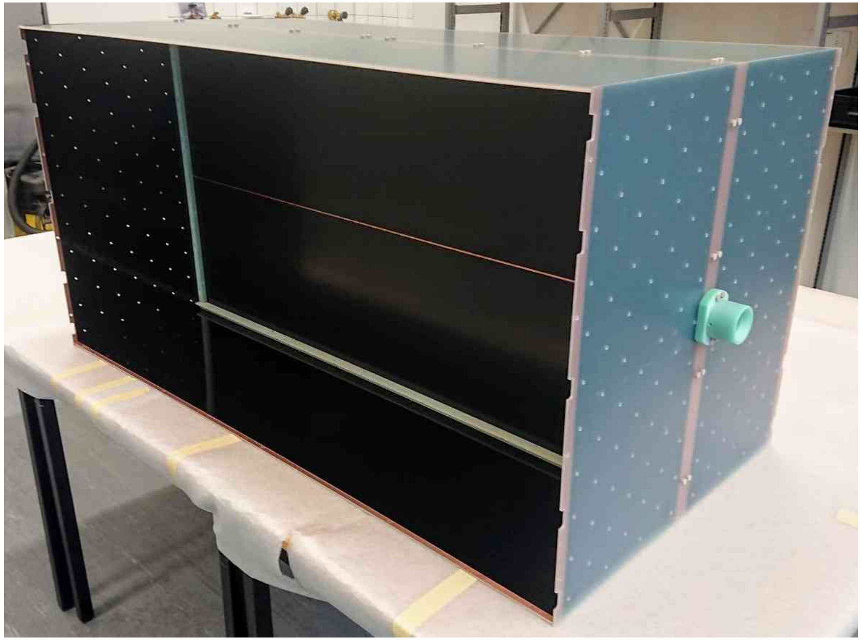
Total **power dissipation < 1 W** for E-field intensities up to 1.6 kV/cm

No localised boiling or HV breakdowns observed

R. Berner et al., Instruments 3 (2019) 2, 28

Resistive Shell

Cathode plane and field shell made (SLAC) of carbon-loaded Kapton foil laminated on fibreglass planes



Cathode & field shell of the Module-0 prototype

Continuous field shaping

Low profile

→ Reduce amount of inactive and dense material, increase the active TPC volume

High sheet-resistance of O(1 GΩ/sq)

→ Reduce local power dissipation

→ Limit power dissipation in case of HV beakdown

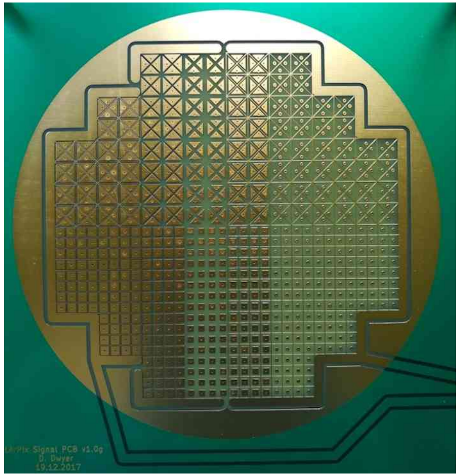
Small number-count of components

→ Reduce possible points of failure

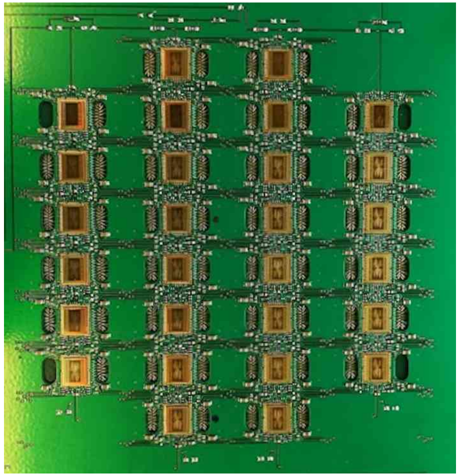
Pixelated Charge Readout

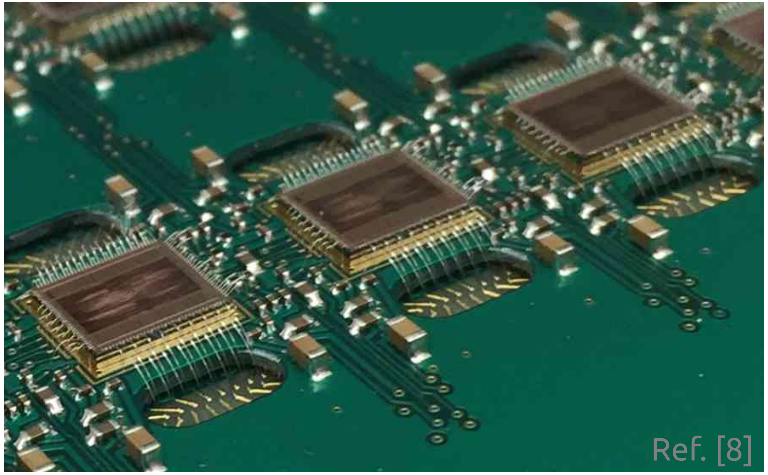
- Cylindrical TPC
  $\phi = 10.1$ cm, $\text{drift}_{\text{max}} = 59$ cm
- Pixelated charge readout system based on the LArPix ASIC (LBNL)
  → 28 LArPix-V1 ASICs hosting 832 pixels
  → Unambiguous 3D particle tracking, independent of track angle


HV and TPC



Pixel pads on the front of the PCB

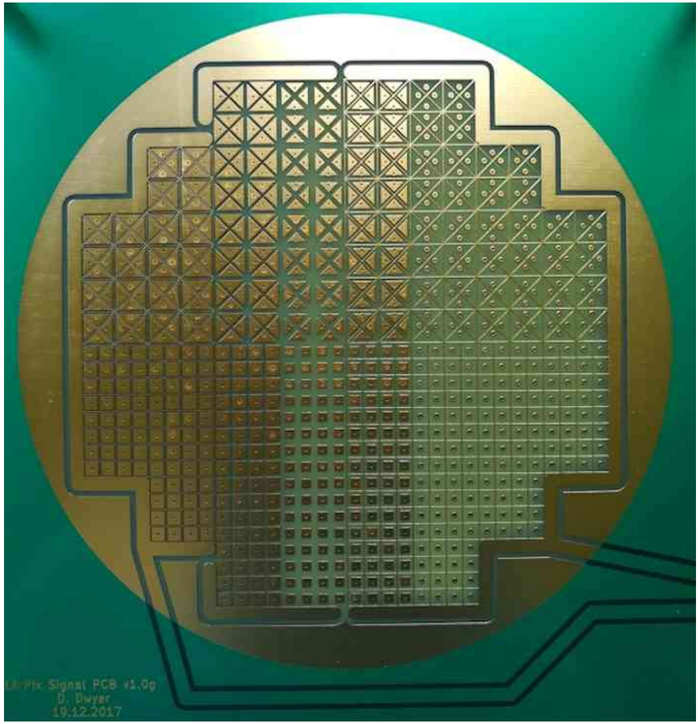

ASICs on the back of the PCB


Ref. [8]

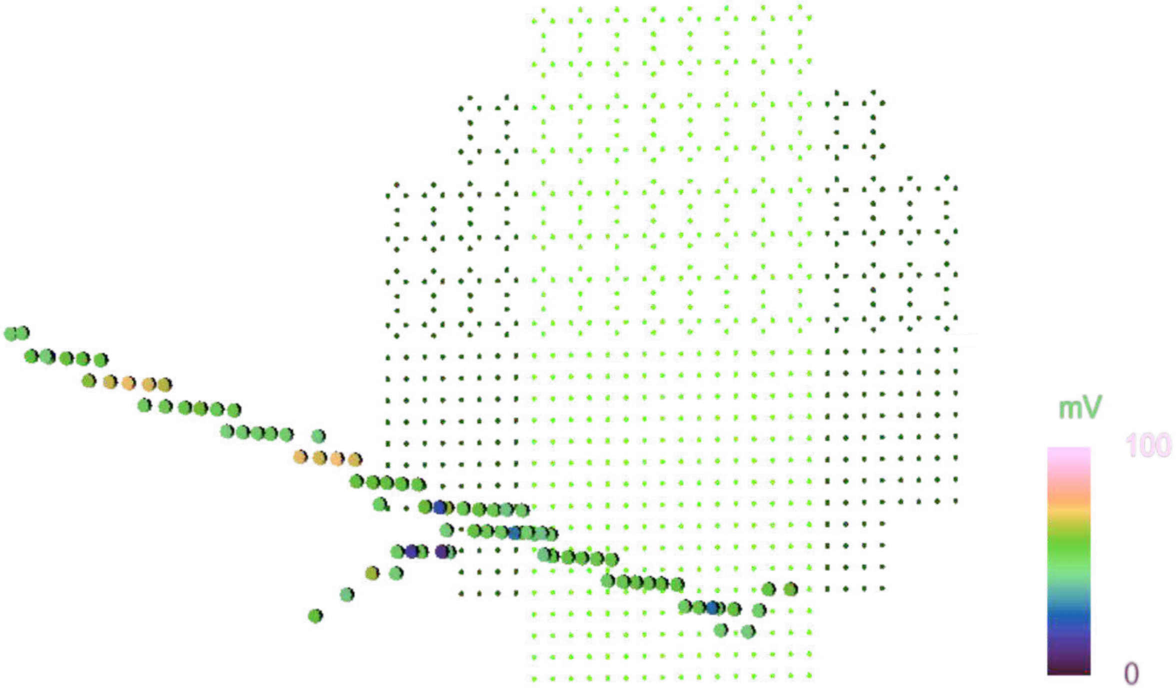
ASICs with wire bonds to the pixel pads

Pixelated Charge Readout

Low noise, self-triggered pixel readout data without ambiguities



Pixel pads of different geometries on the front of the PCB, $\phi \approx 10$ cm



Raw data showing a candidate of a cosmic muon with a delta electron

Pixelated Charge Readout

Low-power amplification and digitization for individual pixels

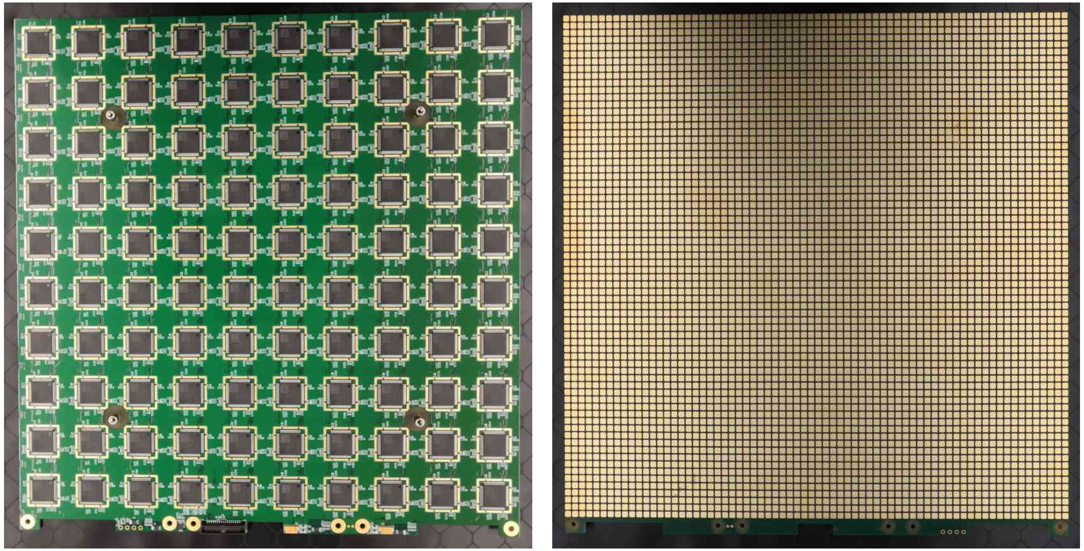
- Operational in LAr, at T ≈ -186^0 C
- 60 µW per pixel, 37 µW digital

→ Unambiguous 3D particle tracking

→ Reduce LAr boil-off

→ Reduce spurious events and
risks for HV breakdowns due to voids

→ Reduce data transfer bandwidth



Both sides of a 32 cm x 30 cm pixelated charge readout PCB:
10 x 10 LArPix-V2 ASICs host 70 x 70 pixels, each 4 mm x 4 mm

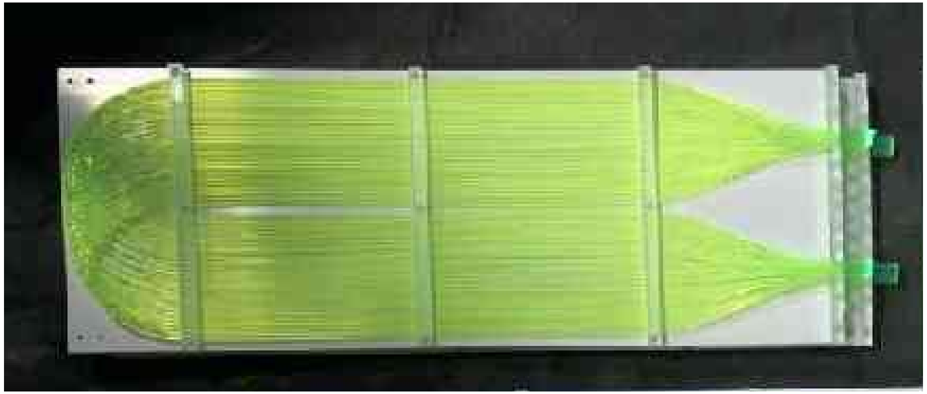
Light Readout

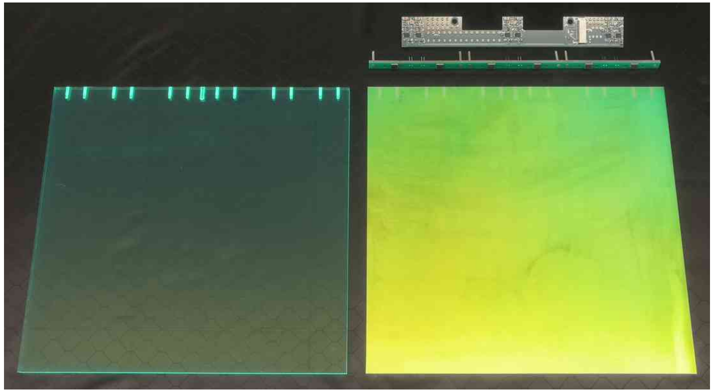
Two complementary systems: **LCM** & **ArCLight**
→ SiPM-based, compact, robust, scalable, resilient to electric fields

Light Collection Module (LCM)
WLS[1] fibres with TPB[2] coating

JINR

ArgonCube Light (ArCLight)
WLS[1] bulk + dichroic mirror with TPB[2] coating





LABORATORIUM FÜR HOCHENERGIEPHYSIK LHEP UNIVERSITÄT BERN

Timing resolution of O(1 ns)
→ Important to tag individual neutrino interactions and
→ Associate detached energy deposits to individual vertices / interactions

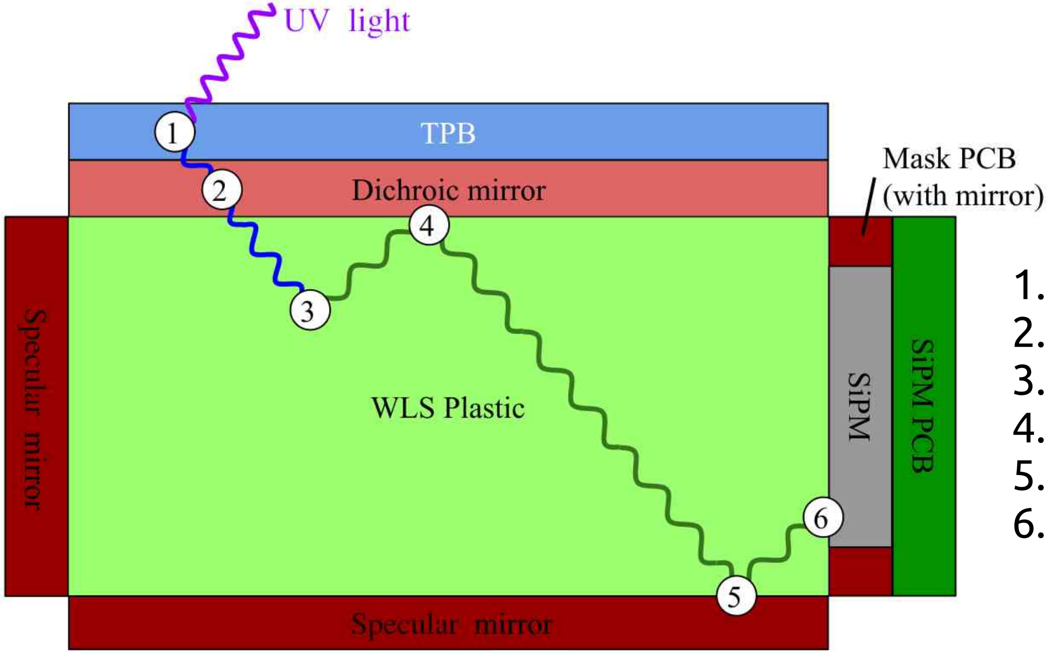
---

[1] Wavelength shifting
[2] 1,1,4,4-tetraphenyl-1,3-butadiene

Light Readout

[1] Wavelength shifting
[2] 1,1,4,4-tetraphenyl-1,3-butadiene
[3] Silicon Photomultiplier

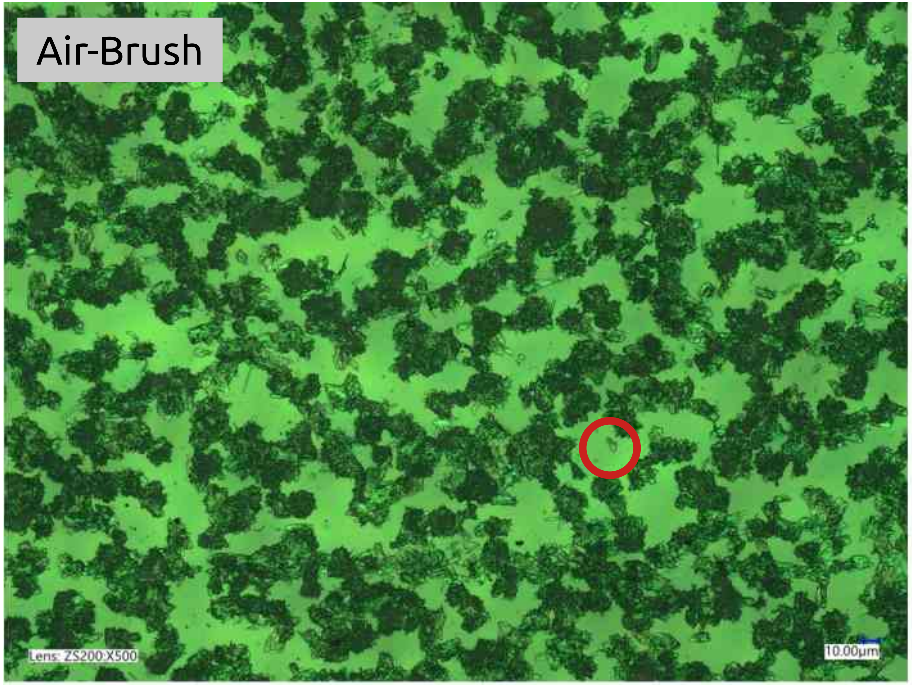
Working Principle (ArCLight)



1. TPB[1] shifts UV light (128 nm) to blue light (425 nm)
2. Dichroic mirror with high transparency for blue light
3. WLS[2] plastic shifts blue light to green (510 nm)
4. Dichroic mirror with high reflectivity for green ligh
5. Specular mirror for reflection → light trap
6. SiPM[3] to detect green light with a high efficiency

Light Readout

ArCLight TPB Coating


Air-Brush

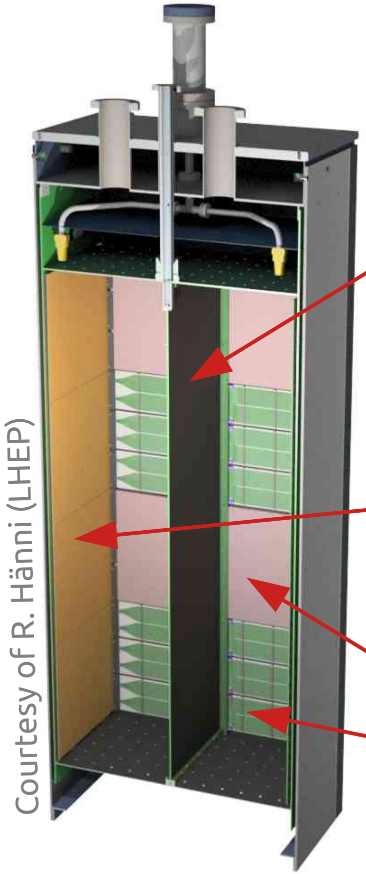

Evaporation-Chamber

Huge differences in TPB crystal structure
Dark clusters: Polystyrene (only used for TPB fixation in air-brush solution)

---

[1] Wavelength shifting
[2] 1,1,4,4-tetraphenyl-1,3-butadiene
[3] Silicon Photomultiplier

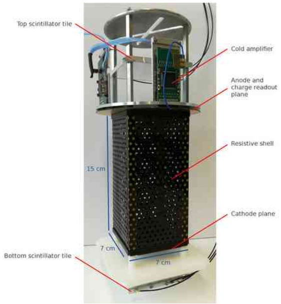
ArgonCube Technologies – Recap



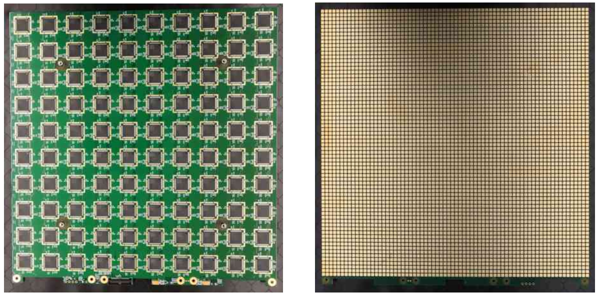
Courtesy of R. Hänni (LHEP)

Cross section of an ArgonCube module

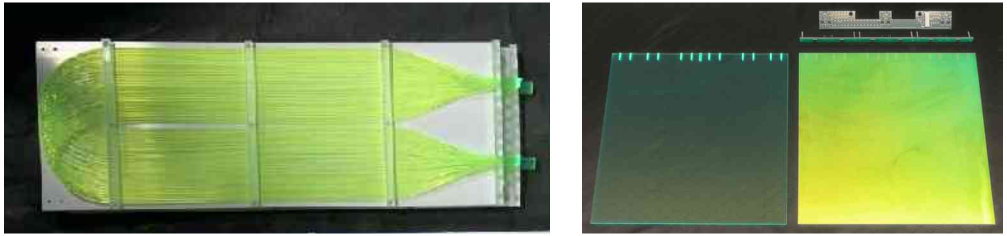
Cathode and “field shell” made of resistive sheet



Pixelated charge readout



Light readout



0. Neutrino Physics (in a Nut-Shell)
1. The Deep Underground Neutrino Experiment (DUNE)
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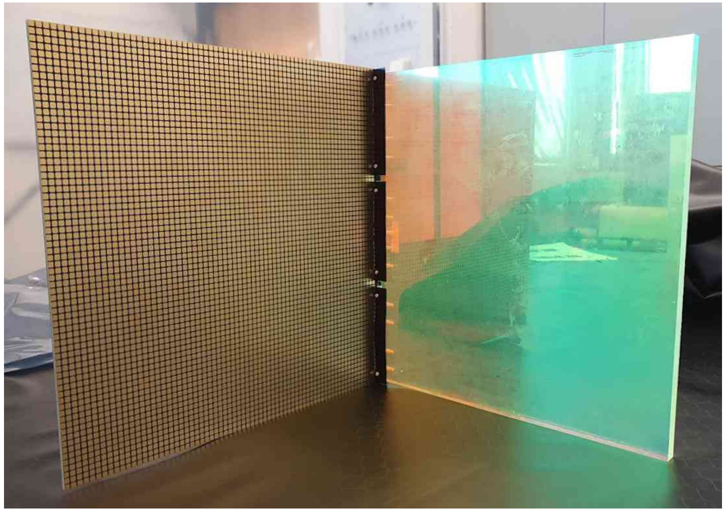
4. ArgonCube Technologies
5. **ArgonCube Prototypes**

SingleCube TPC

SingleCube TPC setup

Cathode (bottom) and field cage



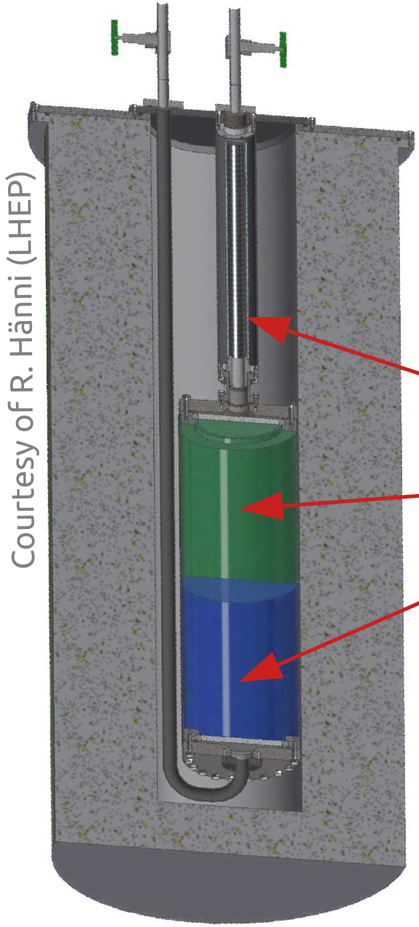
Charge readout (left) and ArCLight (right)

Cubical TPC: 30 cm x 30 cm, $\text{drift}_{\text{max}}$ = 30.2 cm

- Trigger LArPix-V2 charge readout with light signals
- Combine charge & light signals to reconstruct 3D events
- Test new LAr purification & cooling system

LAr Purification & Cooling System

* See Appendix D



Courtesy of R. Hänni (LHEP)

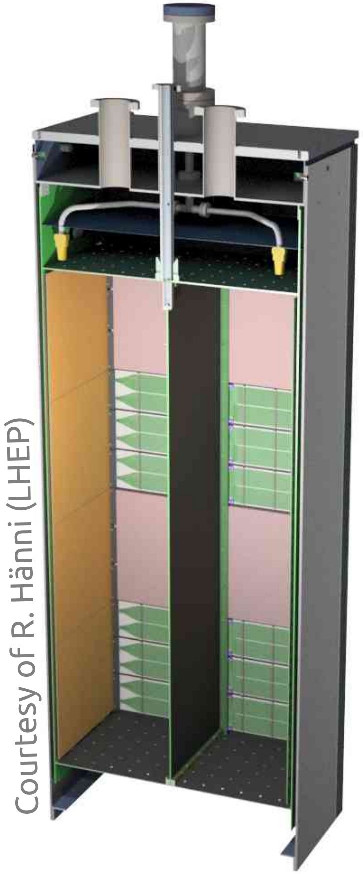
Electric turbo pump
→ Push LAr through vacuum insulated hoses to external filter

Filter material for LAr purification*:

- 5 µm sinter metal cartridge
- 10 l copper catalyst (O_2)
- 10 l molecular sieve (H_2O)

Filter **immersed in pressurized LN_2** (p≈2.25 bar)
→ Cooling of the LAr

Module-0



Courtesy of R. Hänni (LHEP)

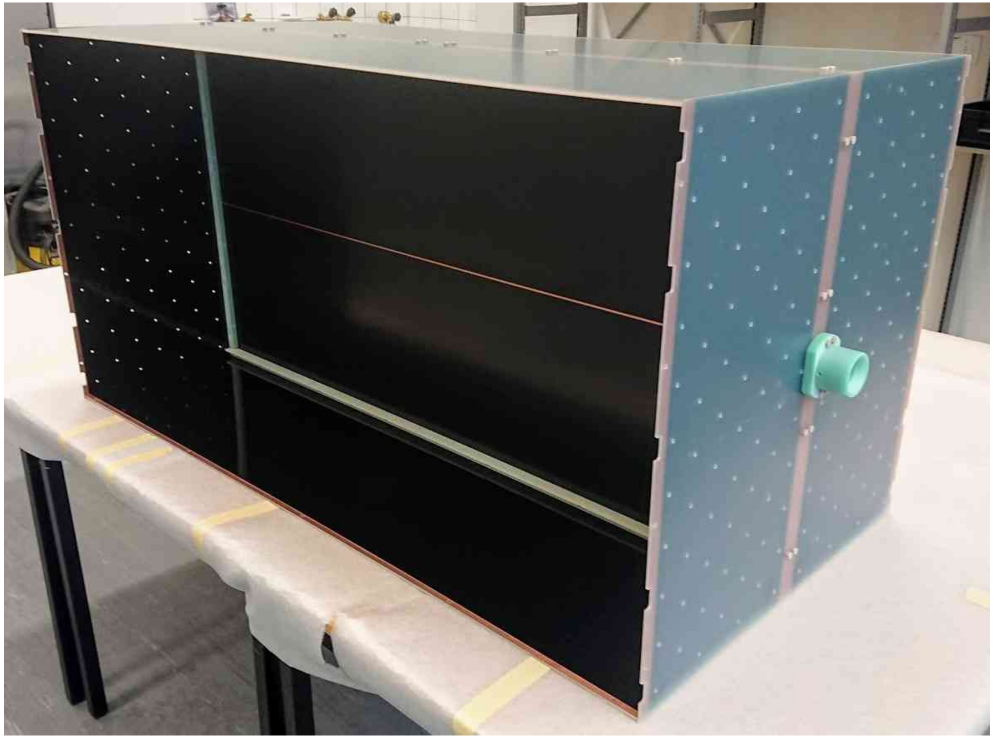
Cross section of the ArgonCube Module-0

Small-scale version (≈0.6m x 0.6m x 1.2m) of a DUNE ND-LAr module (≈1m x 1m x 3m)

≈ 600 kg LAr (active)

Incorporates all ArgonCube technologies
→ Resistive cathode & field shell
→ Pixelated charge readout
→ ArgonCube light readout systems

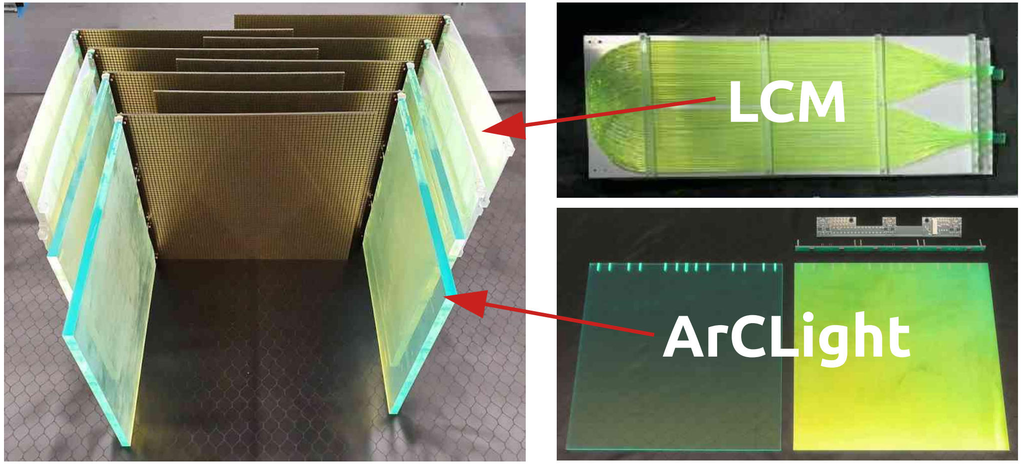
Module-0 "Ingredients"



Cathode & field shell (from SLAC)

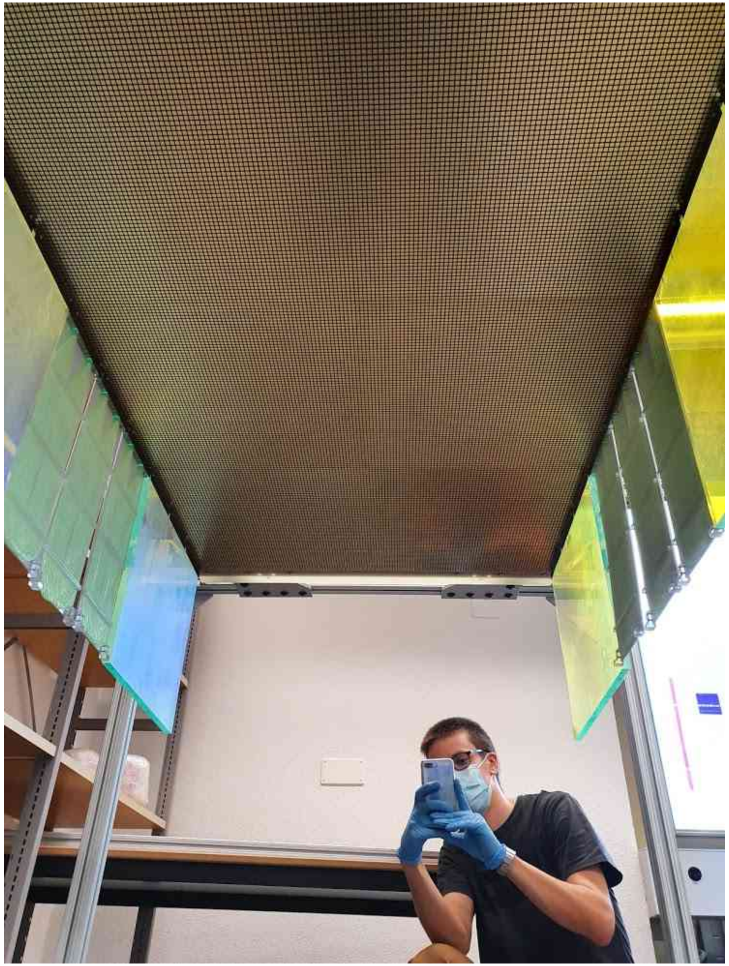
Charge & light readout systems:

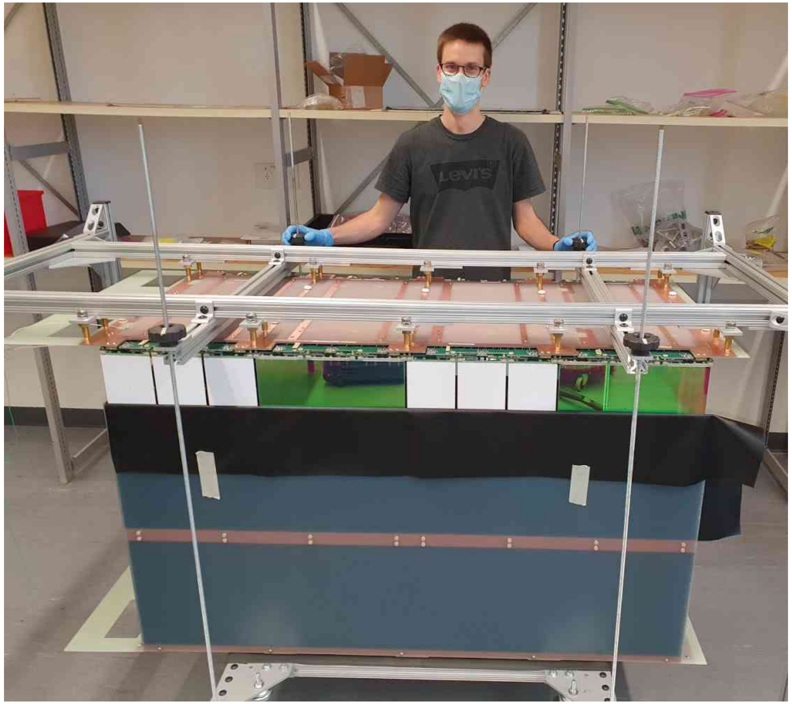
- 16 pixel planes (78'400 pixels)
- 8 ArCLight modules
- 24 LCM modules

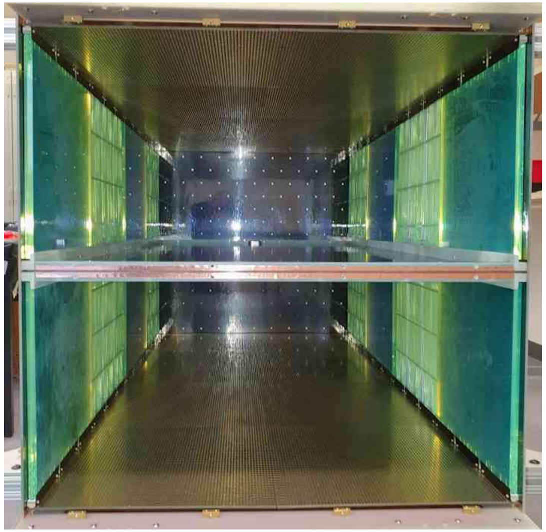


Charge & light detection systems
(from LBNL, JINR, LHEP)

Module-0 Assembly





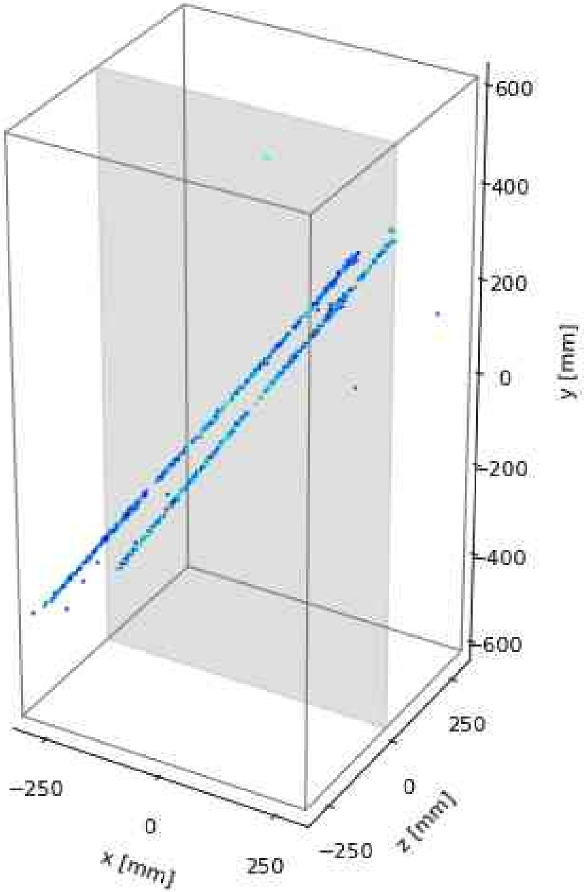


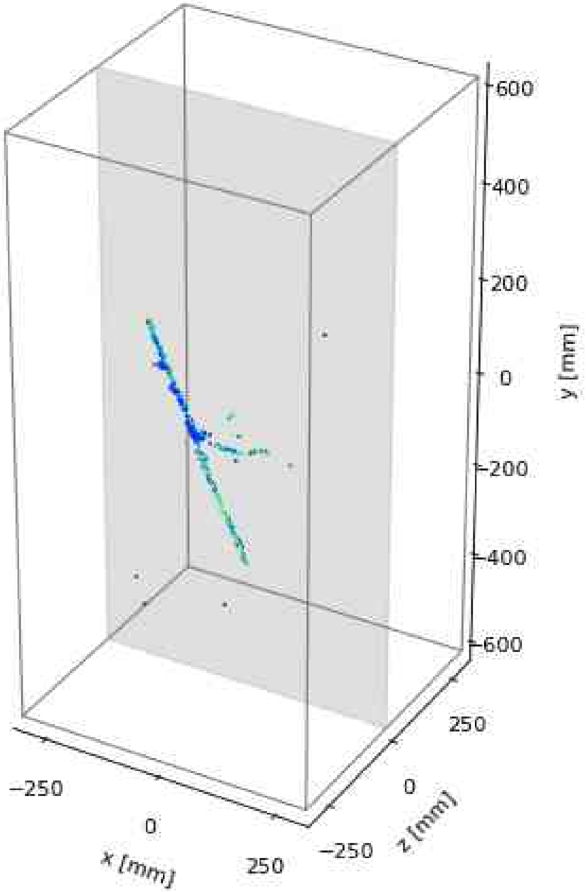
Module-0 Installation

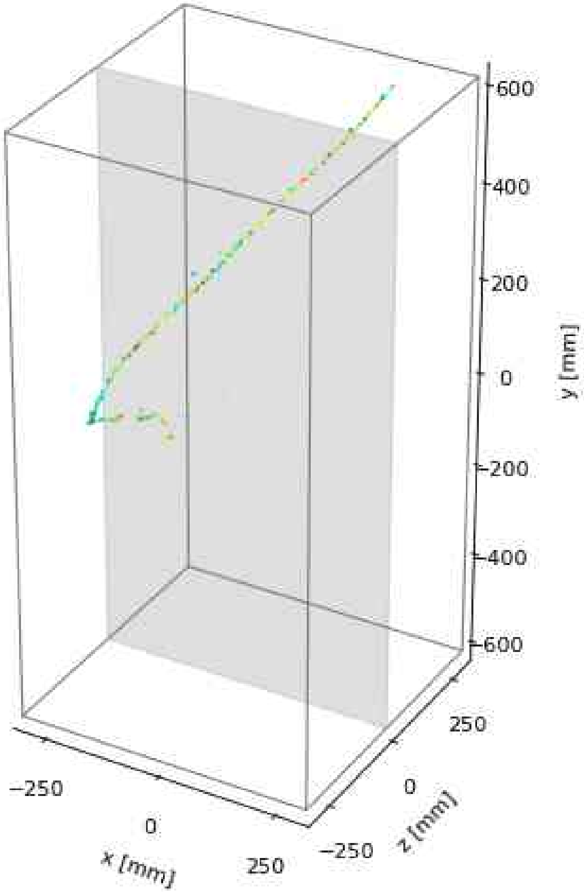
Module-0 operation in March 2021: 3 days calibration, 7 days data taking

Observed ≈ 60 Mio. cosmic induced events

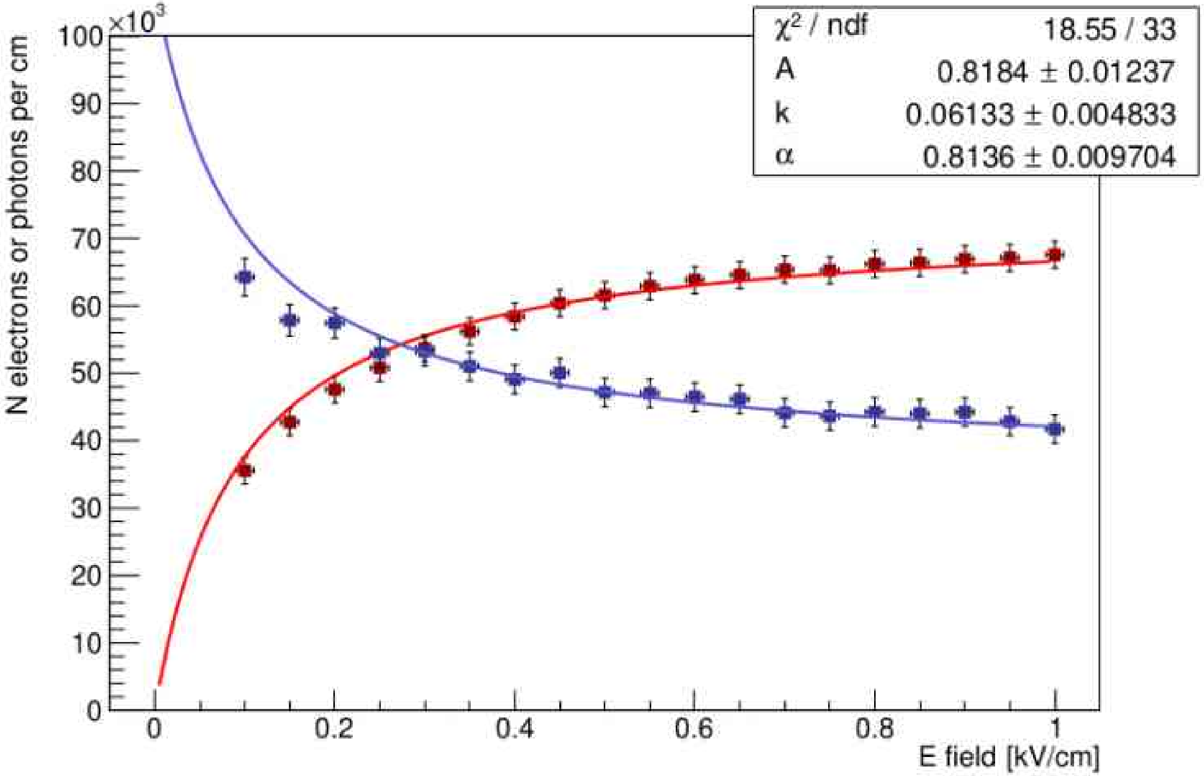
Module-0 Event Displays







Module-0 Performance – Charge / Light Anticorrelation



Measurements (points) and combined *modified Birk model* fit (lines) for charge (red) and light (blue) in Module-0

Relative charge yield R_C

$$R_C = \frac{Q}{Q_\infty} = \frac{A}{1 + \frac{k}{\epsilon} \cdot \frac{dE}{dx}}$$

Relative light yield R_L

$$R_L = \frac{L}{L_0} = 1 - \alpha \cdot R_C$$

ε:	Electric field intensity
α:	Parameter fit to data
A, k:	Parameters fit to data
dE/dx:	Mass stopping power

Module-0 Performance

See Appendix F

LAr filtration & cooling:

→ Sufficient LAr purity, low attenuation of drift electrons
→ Filter took full heat input of the detector

HV, cathode & field shell:

→ Stable for E-field intensities up to 1.0 kV/cm

Light readout:

→ Timing resolution O(1ns)
→ Successfully provided triggers to charge readout system

Charge readout:

→ Ambiguity-free events across two LArTPCs and at a low noise level

Results are very promising!
Next: Test several modules side by side...

ArgonCube 2x2 Demonstrator

* See Appendix G

Random dude on top of the 2x2 cryostat

2x2 cryostat hosting four Module-0 like detectors

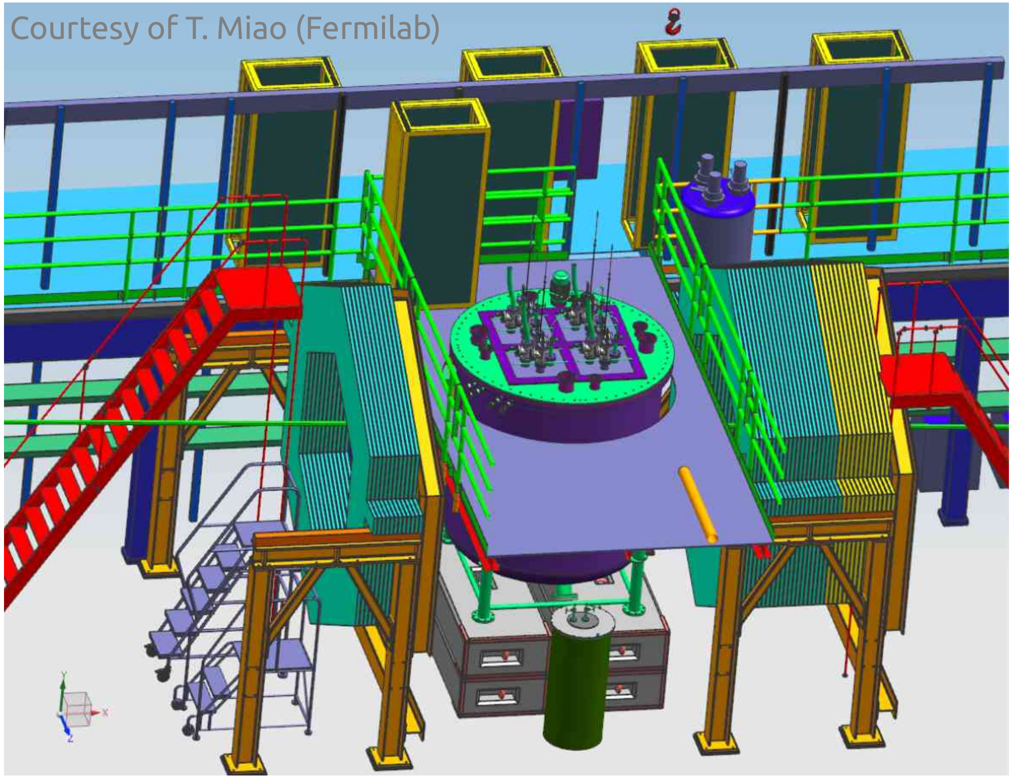
- **Test scalability** of all ArgonCube concepts and technologies
- **Test event reconstruction** across individual TPCs & modules
- **Benchmark data acquisition and data quality** for the ND-LAr

Will be put into high-intensity neutrino beam at Fermilab*

ProtoDUNE-ND

* See Appendix G

ArgonCube 2x2 Demonstrator exposed to the NuMI beam


Courtesy of T. Miao (Fermilab)

MINERvA modules up- and downstream of the 2x2 provide tracking of beam-related particles outside of 2x2

First LArTPC in a neutrino beam with energies relevant for DUNE*

- Performance of ArgonCube technology in high-multiplicity environments
- Long-term performance of 2x2, including cryogenics
- Test reconstruction across sub-detectors (2x2 to MINERvA)
- Platform to develop and test event reconstruction tools (e^-, n, π, ...)

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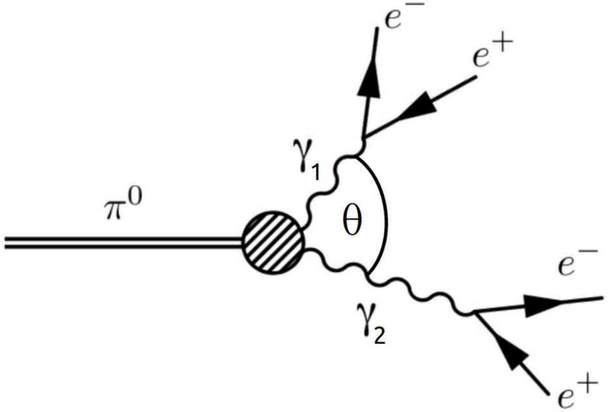
5. ArgonCube Prototypes
6. **Neutral Pion Reconstruction in LArTPCs**

(My) Primary Motivation

* BR($\pi^0 \rightarrow \gamma + \gamma$) $\approx$ 0.988

Neutral pions can be used as standard candles

$\pi^0 \rightarrow \gamma + \gamma$ is a two-body decay*



$$m_{\pi^0,reco} = \sqrt{2E_{\gamma_1}E_{\gamma_2}\cdot(1-\cos(\theta))} = 134.97\ \text{MeV} + \text{Bias}$$

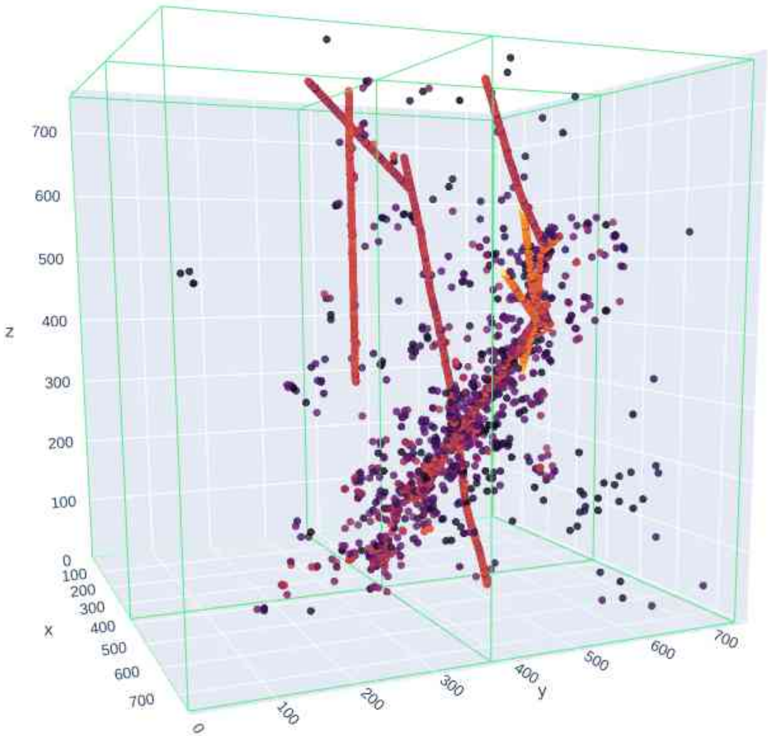
→ Verify the energy scale calibration of a LArTPC
(affects calorimetry, PID, event reconstruction, oscillation results, ...)

Requirements for π^0 Reconstruction

Shower reconstruction (challenging!)

Need a good handle on:

- Clustering energy depositions (EDEPs)
  Only cluster EDEPs that belong to the same shower
  → Affects reconstructed shower energy E_γ
- Start point & direction estimation
  → Affects opening angle θ
- e-γ separation
  → Background rejection

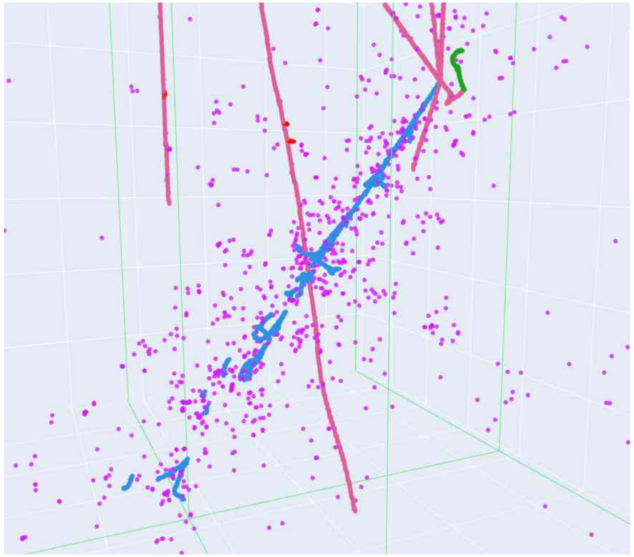


Simulated particle interactions
in ProtoDUNE-ND

Machine Learning Techniques

For this purpose, I closely worked with experts from SLAC
→ Apply Machine-Learning techniques on (simulated) LArTPC data

- UResNet for semantic segmentation
  → Classifies individual EDEPs (e.g. shower or track)
- Graph Neural Network (GNN)
  → Shower clustering
- UResNet for point prediction
  → Proposes shower start point, track start and end, ...



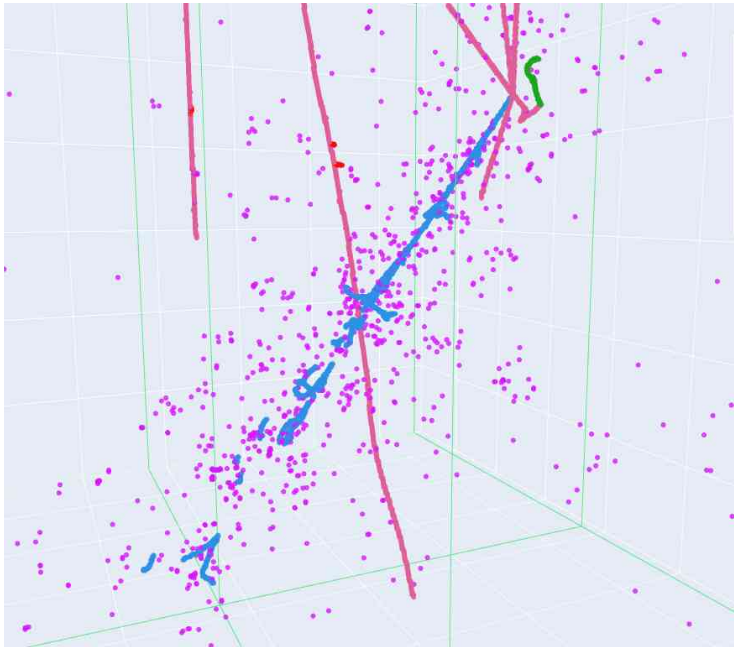
5 semantic classes:
Shower, Track, Michel electron,
Delta electron, Low energy scatter

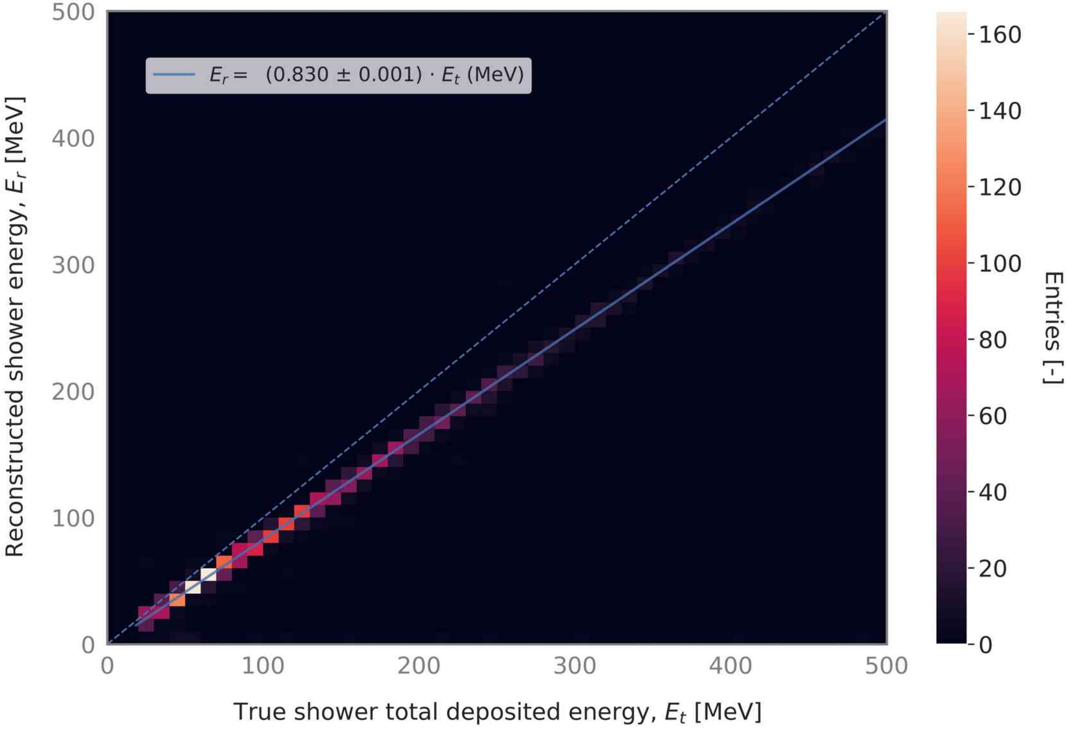
Shower Energy Reconstruction

Sum up all EDEPs of the shower

→ Some energy (≈ 17%) is lost due to low-energy scatters

→ Apply correction factor (Fudge)

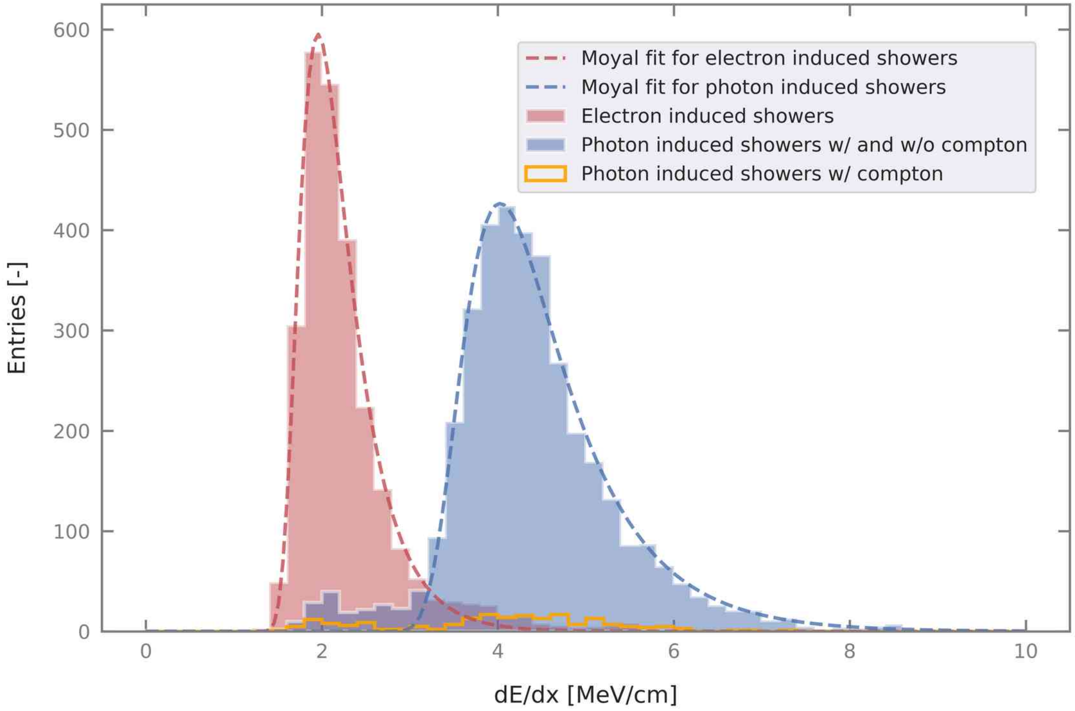


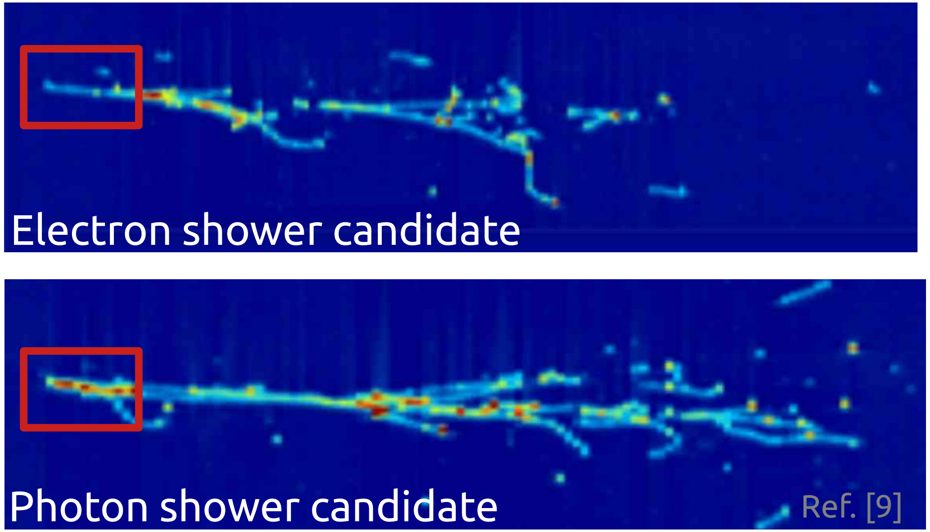


Electron – Photon Separation

Determine dE/dx at the very start of a shower

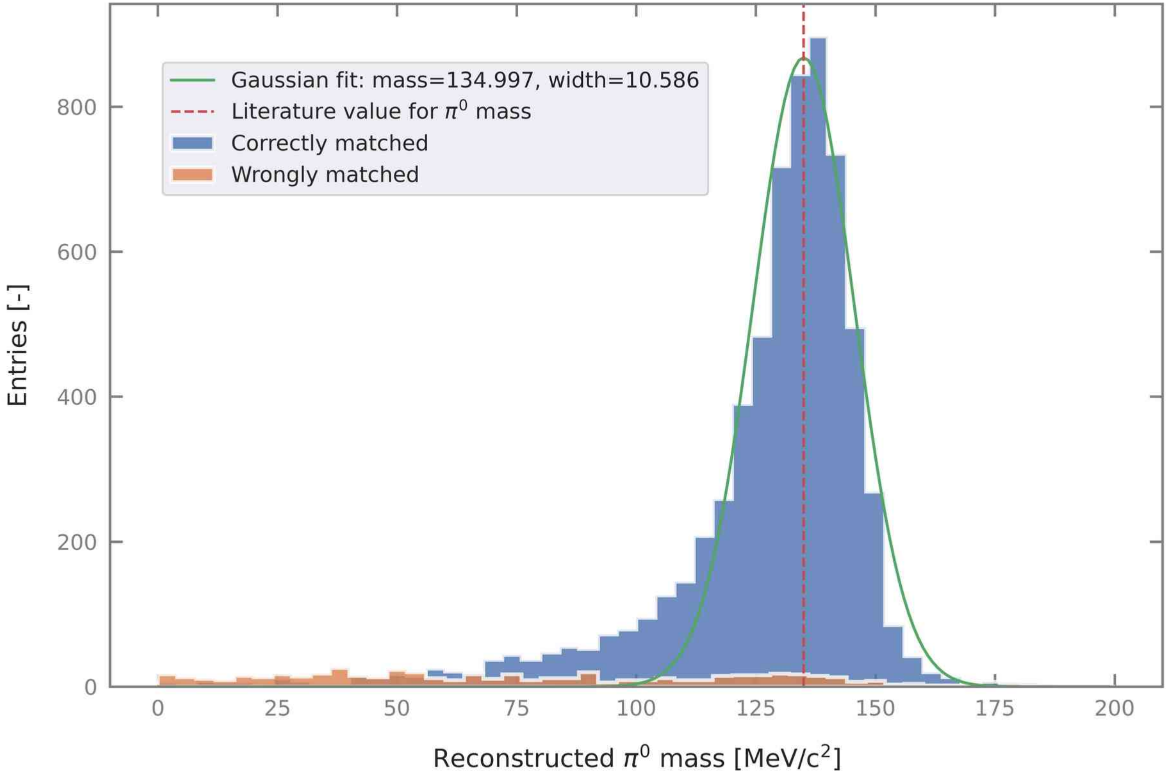
→ e^- deposit about half the energy per unit length than photons ($\gamma \rightarrow e^- + e^+$)





Neutral Pion Reconstruction

I developed an algorithm to match pairs of showers to π^0 decays

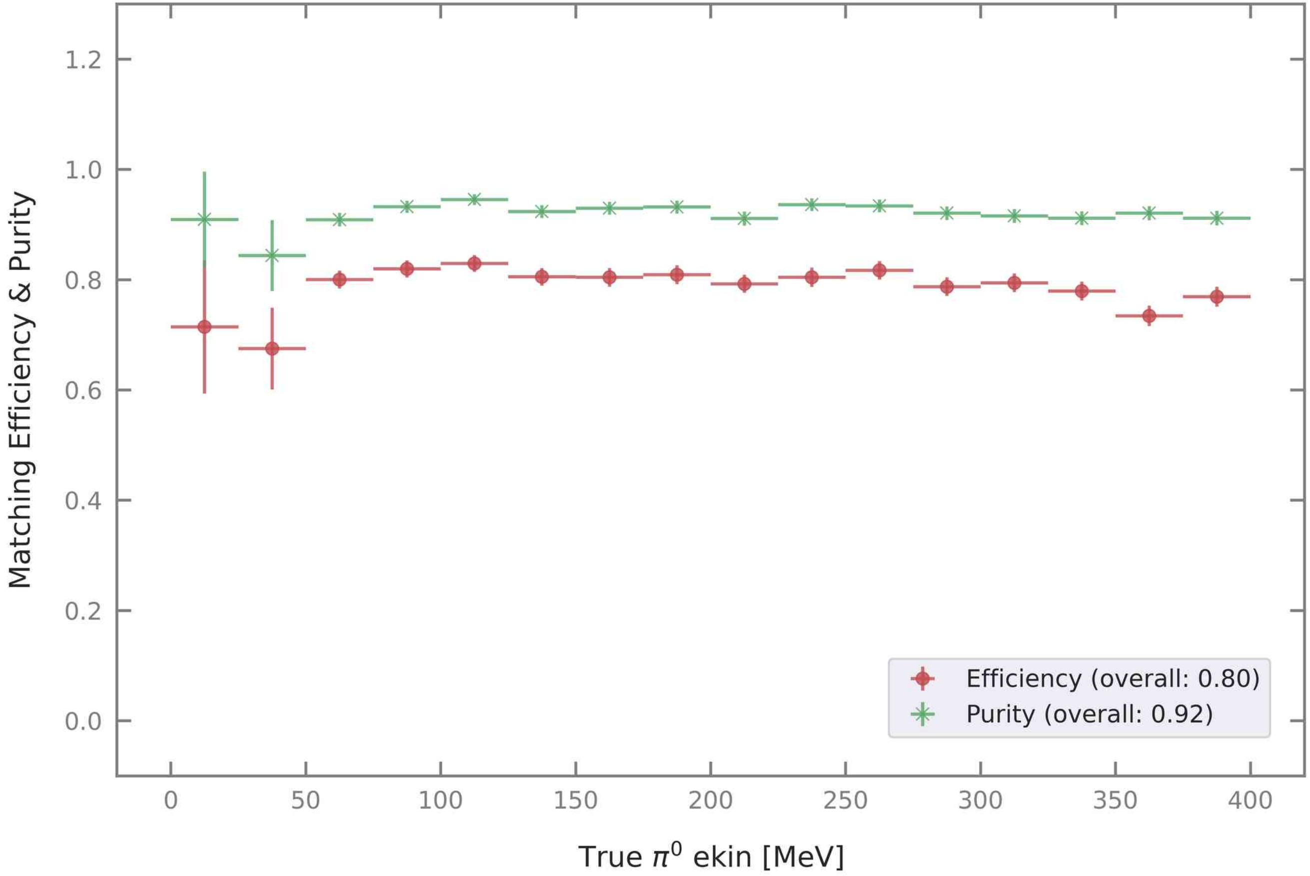


$$m_{\pi^0,reco} = \sqrt{2E_{\gamma_1}E_{\gamma_2}\cdot(1-\cos(\theta))}$$

Reconstructed π^0 mass agrees well with literature value!

Caveat:
Detector response & resolution not yet taken into account...

Neutral Pion Reconstruction Performance



$$\text{Purity} \stackrel{\text{def}}{=} \frac{\text{correctly matched } \pi^0}{\text{total reco } \pi^0}$$

$$\text{Efficiency} \stackrel{\text{def}}{=} \frac{\text{correctly matched } \pi^0}{\text{total true } \pi^0}$$

Next Steps for the Event Reconstruction

Improve the simulation by including

- Charge diffusion
- Detector components (inactive volumes)
- Readout electronics & detector response (noise, thresholds, resolutions)
- Digitization of the signals

Use ProtoDUNE-ND data, reconstruct π^0 masses, and validate the energy scale calibration

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6. Neutral Pion Reconstruction in LArTPCs
7. **Summary**

Summary

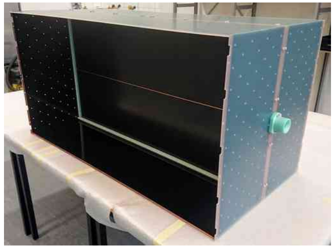
Symmetries

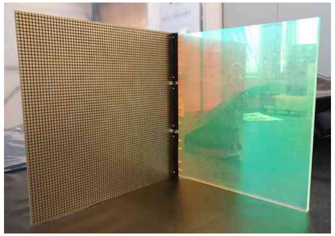
Neutrinos
and DUNE

Summary

Symmetries

New technology





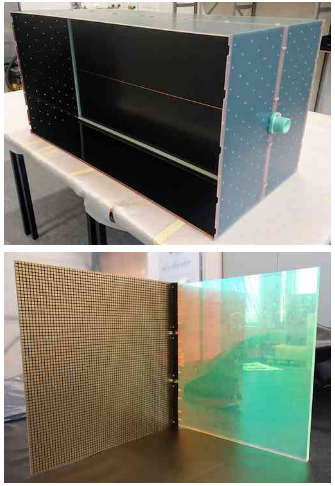
Neutrinos and DUNE

Summary

Symmetries

Neutrinos and DUNE

New technology



Prototypes

Summary

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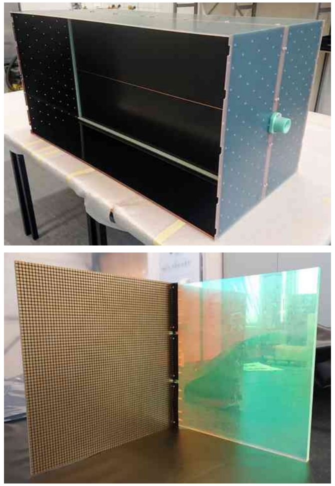

Prototypes

Module-0

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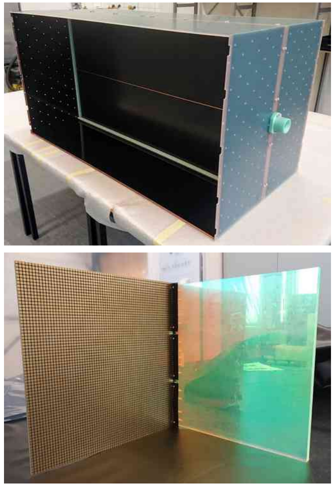
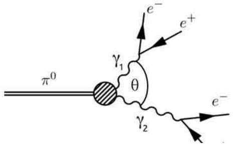
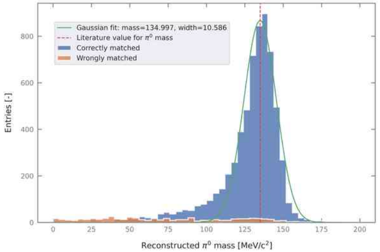


Prototypes

Module-0

Reconstruction





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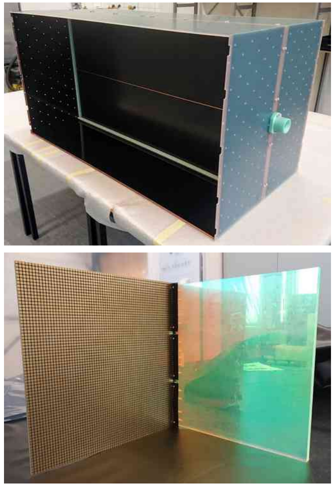

Prototypes

Module-0

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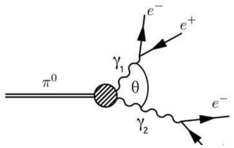

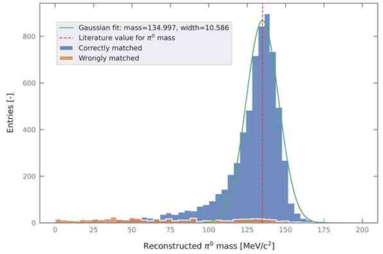

Module-0 was a success!
→ Path for ArgonCube 2x2 and ProtoDUNE-ND is clear

Summary

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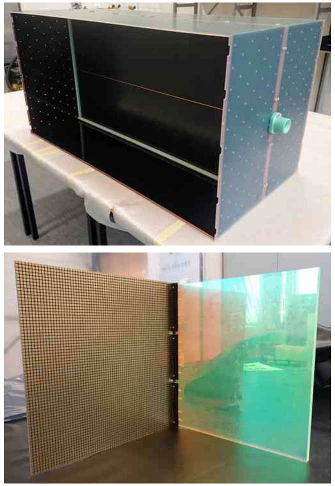
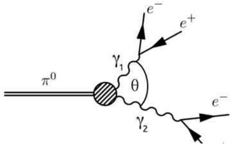
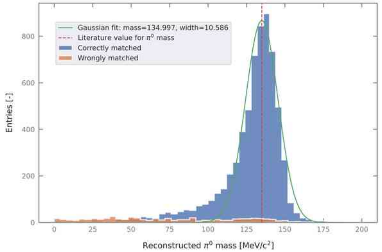


Prototypes

Module-0

Reconstruction





Module-0 was a success!

→ Path for ArgonCube 2x2 and ProtoDUNE-ND is clear

A lot of hardware R&D, data analysis, event reconstruction, … was needed to pave the way for meaningful studies with ProtoDUNE-ND which will impact the DUNE ND-LAr design

Thank You!

Me and detector (from left to right)

References

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Accessed 04. March 2023

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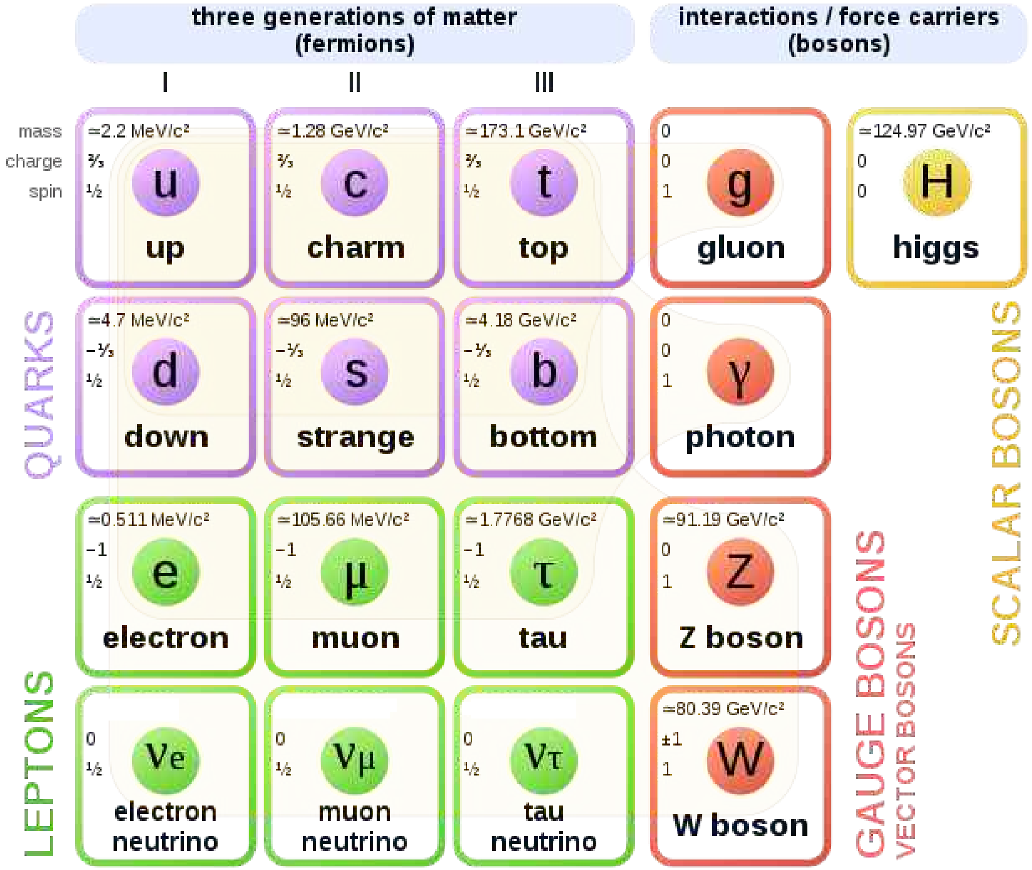
[7] https://arxiv.org/pdf/2007.06722.pdf
Accessed: 04. March 2023

[8] https://indico.cern.ch/event/721385/contributions/3034633/attachments/1666328/
Accessed: 04. March 2023

[9] https://arxiv.org/pdf/1911.10379.pdf
Accessed: 04. March 2023

Appendix A
Neutrino Physics

Standard Model of Particle Physics



three generations of matter (fermions)

interactions / force carriers (bosons)

	I	II	III		
mass charge spin	≈2.2 MeV/c^2 ⅔ ½ u up	≈1.28 GeV/c^2 ⅔ ½ c charm	≈173.1 GeV/c^2 ⅔ ½ t top	0 0 1 g gluon	≈124.97 GeV/c^2 0 0 H higgs
QUARKS	≈4.7 MeV/c^2 −⅓ ½ d down	≈96 MeV/c^2 −⅓ ½ s strange	≈4.18 GeV/c^2 −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
	≈0.511 MeV/c^2 −1 ½ e electron	≈105.66 MeV/c^2 −1 ½ μ muon	≈1.7768 GeV/c^2 −1 ½ τ tau	≈91.19 GeV/c^2 0 1 Z Z boson	
LEPTONS	0 ½ ν_e electron neutrino	0 ½ ν_μ muon neutrino	0 ½ ν_τ tau neutrino	≈80.39 GeV/c^2 ±1 1 W W boson	GAUGE BOSONS VECTOR BOSONS

Source: https://de.wikipedia.org/wiki/Standardmodell_der_Teilchenphysik

Matter-Antimatter Asymmetry

Right after the Big Bang (standard cosmology)

$B = N_{\text{Baryons}} - N_{\text{Anti-Baryons}} = 0$
$L = N_{\text{Leptons}} - N_{\text{Anti-Leptons}} = 0$

Today

$B = N_{\text{Baryons}} - N_{\text{Anti-Baryons}} \neq 0$

How did $\mathbf{B = 0 \rightarrow B \neq 0}$?

To produce matter and antimatter at different rates (Sakharov Conditions):

1. Baryon number violation
2. C-violating and **CP-violating processes**[1]
3. Interactions out of thermal equilibrium

CP-violations observed in quark sector (e.g. B and K decays) cannot explain full B - asymmetry

A large **CP-phase in neutrino oscillations could explain almost the entire B - asymmetry** by itself

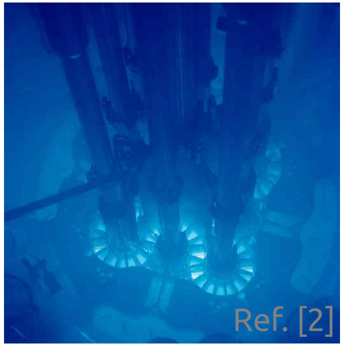
[1] So that the interactions which produce more baryons than anti-baryons will not be counterbalanced by interactions which produce more anti-baryons than baryons

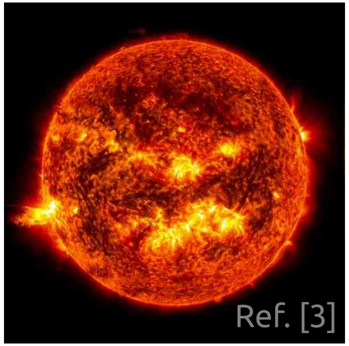
Three-Flavour Neutrino Mixing

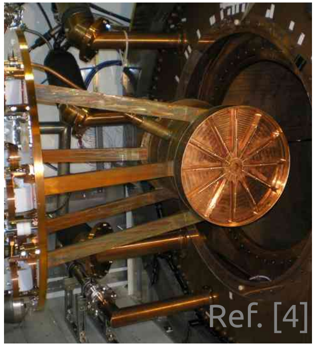
$$c_{ij} = \cos(\theta_{ij})$$
$$s_{ij} = \sin(\theta_{ij})$$

$$\mathrm{U_{PMNS}} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\mathrm{U_{atmospheric}}} \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}\mathrm{e}^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}\mathrm{e}^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix}}_{\mathrm{U_{reactor}}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\mathrm{U_{solar}}} \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & \mathrm{e}^{i\alpha} & 0 \\ 0 & 0 & \mathrm{e}^{i\beta} \end{bmatrix}}_{\mathrm{U_{Majorana}}}$$


Ref. [1]


Ref. [2]


Ref. [3]


Ref. [4]

3 mixing angles: $\theta_{12} \approx 32.0°$; $\theta_{13} \approx 8.5°$; $\theta_{23} \approx 43.5°$

2 Majorana phases: $\alpha, \beta \approx \ldots$? (decoupled from oscillation experiments)

1 Dirac phase: $\delta_{CP} \approx \ldots$?

Neutrino Oscillation Probability

At the moment of neutrino creation

$$|\nu_\alpha(0,0)\rangle = \sum_i \mathrm{U}_{\alpha i} |\nu_i\rangle$$

After the neutrino traveled a distance of L (plane wave approximation)

$$|\nu_\alpha(L,t)\rangle = \sum_i \mathrm{U}_{\alpha i} |\nu_i\rangle \exp\left(-iE_i t\right)$$

Project the wave function onto the final state

$$P_{\nu_\alpha \to \nu_\beta}(L,t) = |\langle \nu_\beta | \nu_\alpha(L,t)\rangle|^2$$

$$\boxed{E_i = \sqrt{p_i^2 + m_i^2} \approx p + \frac{m_i^2}{2E}}$$

Neutrino Oscillation Probability

Electron (anti)neutrino appearance

Sign change for ν_e and $\bar{\nu}_e$

Sensitivity to mass ordering!

Interplay between mass ordering and CP-phase

$$
\begin{aligned}
P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = {} & \sin^2(\theta_{23})\sin^2(2\theta_{13})\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \sin(2\theta_{23})\sin(2\theta_{13})\sin(2\theta_{12})\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\boxed{\Delta_{31}}\frac{\sin(aL)}{aL}\Delta_{21}\cos\boxed{(\Delta_{31}\boxed{\pm}\delta_{CP})} \\
& + \cos^2(\theta_{23})\sin^2(2\theta_{12})\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2
\end{aligned}
$$

$$\Delta_{ij} = \frac{\left(m_i^2 - m_j^2\right)L}{4E_\nu} = \frac{\Delta m_{ij}^2 L}{4E_\nu}$$

$$a = \boxed{\pm}\frac{G_F N_e}{\sqrt{2}}$$

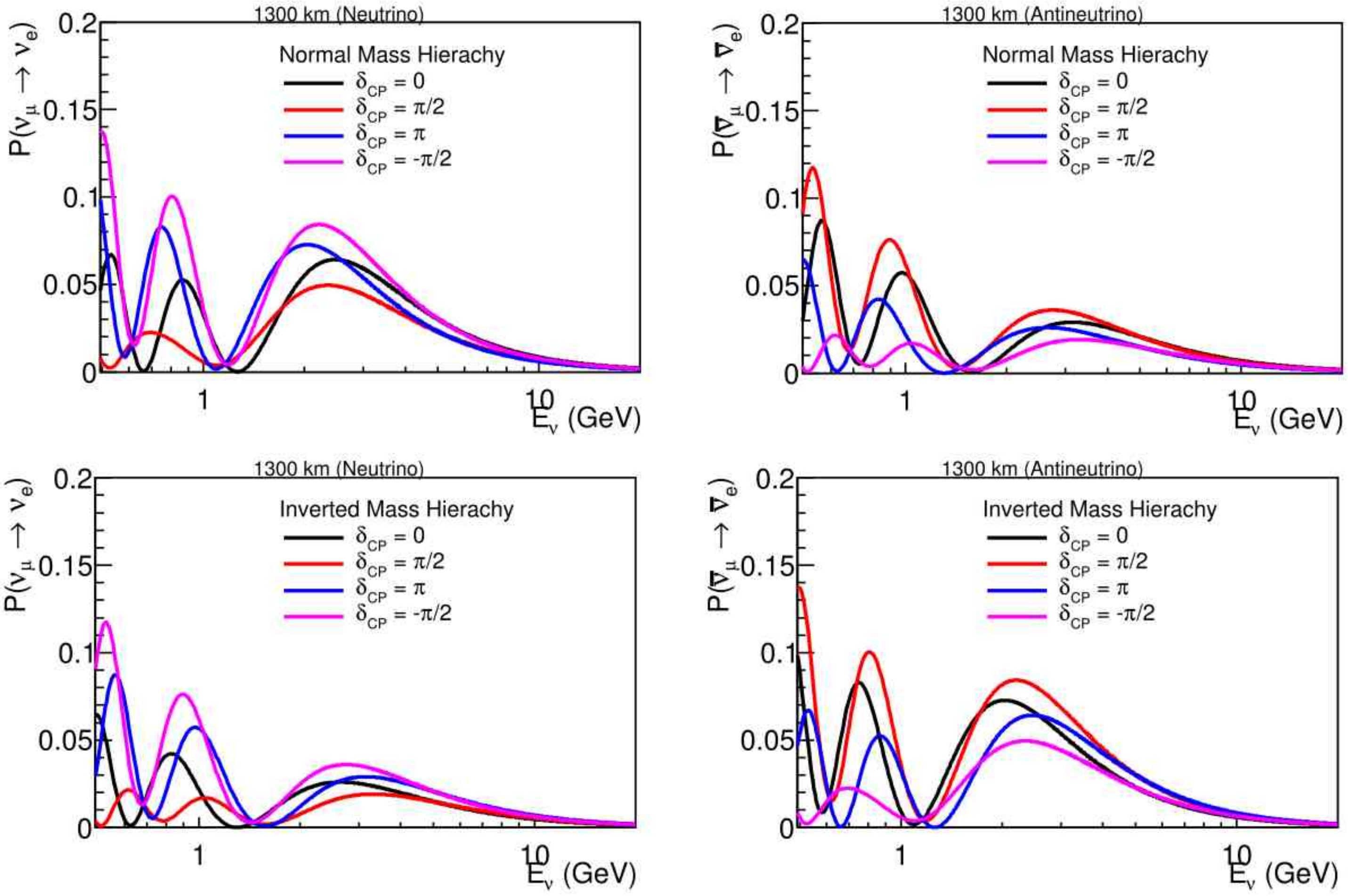
Matter effects increase with increasing L

DUNE: L ≈ 1300 km

At shorter L, reduced δ_{CP} sensitivity due to unknown MH (ambiguities)

At higher L, reduced δ_{CP} sensitivity due to larger matter effects

Neutrino Oscillation Probability



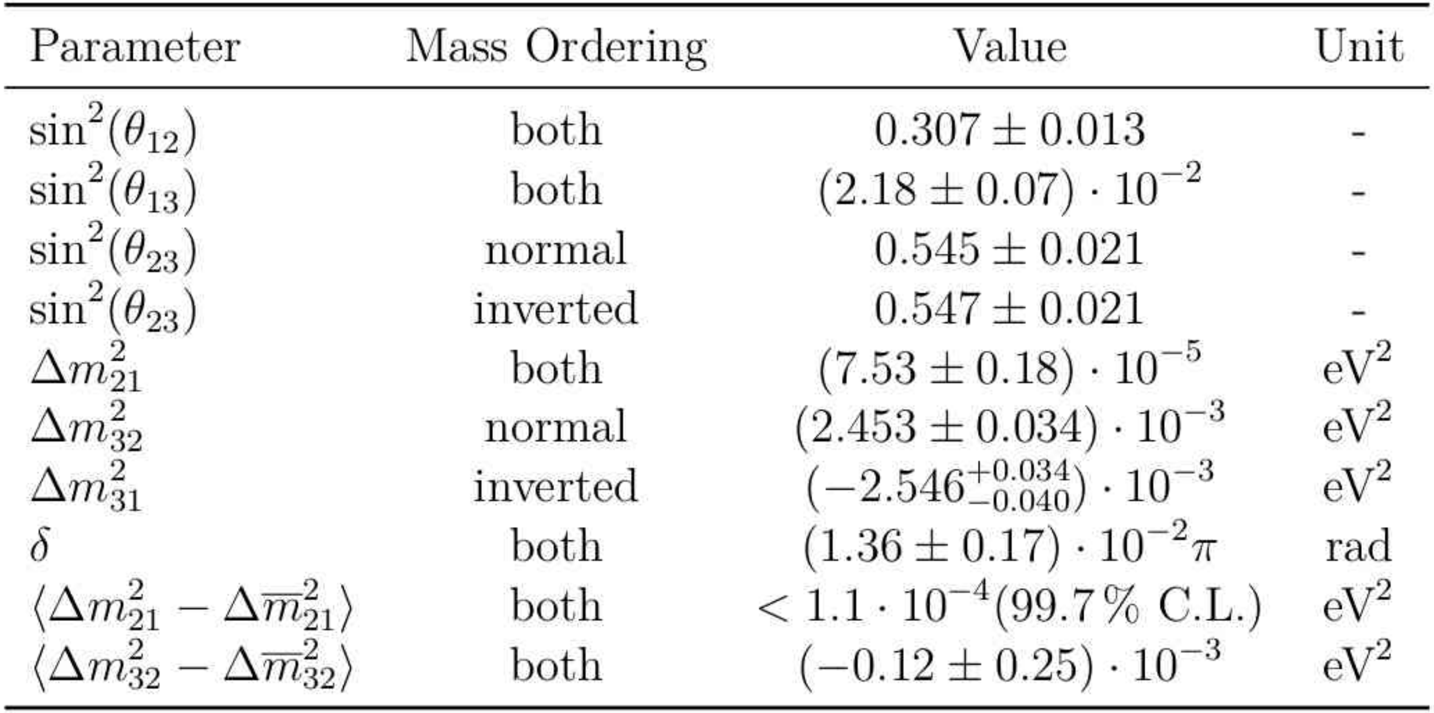
Matter effects increase with L and enhance the sensitivity to the mass ordering

In the normal (inverted) mass hierarchy, the ν ($\bar{\nu}$) appearance is enhanced, and the $\bar{\nu}$ (ν) appearance is suppressed

Source: https://arxiv.org/abs/1505.01891

Neutrino Oscillation Parameters

Global parameter fit based on the three-neutrino mixing scheme yields



Parameter	Mass Ordering	Value	Unit
$\sin^2(\theta_{12})$	both	0.307 ± 0.013	-
$\sin^2(\theta_{13})$	both	$(2.18 \pm 0.07) \cdot 10^{-2}$	-
$\sin^2(\theta_{23})$	normal	0.545 ± 0.021	-
$\sin^2(\theta_{23})$	inverted	0.547 ± 0.021	-
Δm^2_{21}	both	$(7.53 \pm 0.18) \cdot 10^{-5}$	eV^2
Δm^2_{32}	normal	$(2.453 \pm 0.034) \cdot 10^{-3}$	eV^2
Δm^2_{31}	inverted	$(-2.546^{+0.034}_{-0.040}) \cdot 10^{-3}$	eV^2
δ	both	$(1.36 \pm 0.17) \cdot 10^{-2}\pi$	rad
$\langle \Delta m^2_{21} - \Delta \overline{m}^2_{21} \rangle$	both	$< 1.1 \cdot 10^{-4} (99.7\,\%\ \mathrm{C.L.})$	eV^2
$\langle \Delta m^2_{32} - \Delta \overline{m}^2_{32} \rangle$	both	$(-0.12 \pm 0.25) \cdot 10^{-3}$	eV^2

Uncertainties corresponding to 1σ if not stated otherwise

Open Questions in Neutrino Physics

Masses

- How are the masses ordered?
- What is the absolute neutrino mass scale?
- Is the physics behind the masses of neutrinos different from that behind the masses of all other known particles?

CP Symmetry

- Do neutrino interactions violate the CP-symmetry, e.g. $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$?
- Is CP-violation involving neutrinos the key to understand the matter – antimatter asymmetry of the Universe?

Three-neutrino mixing scheme

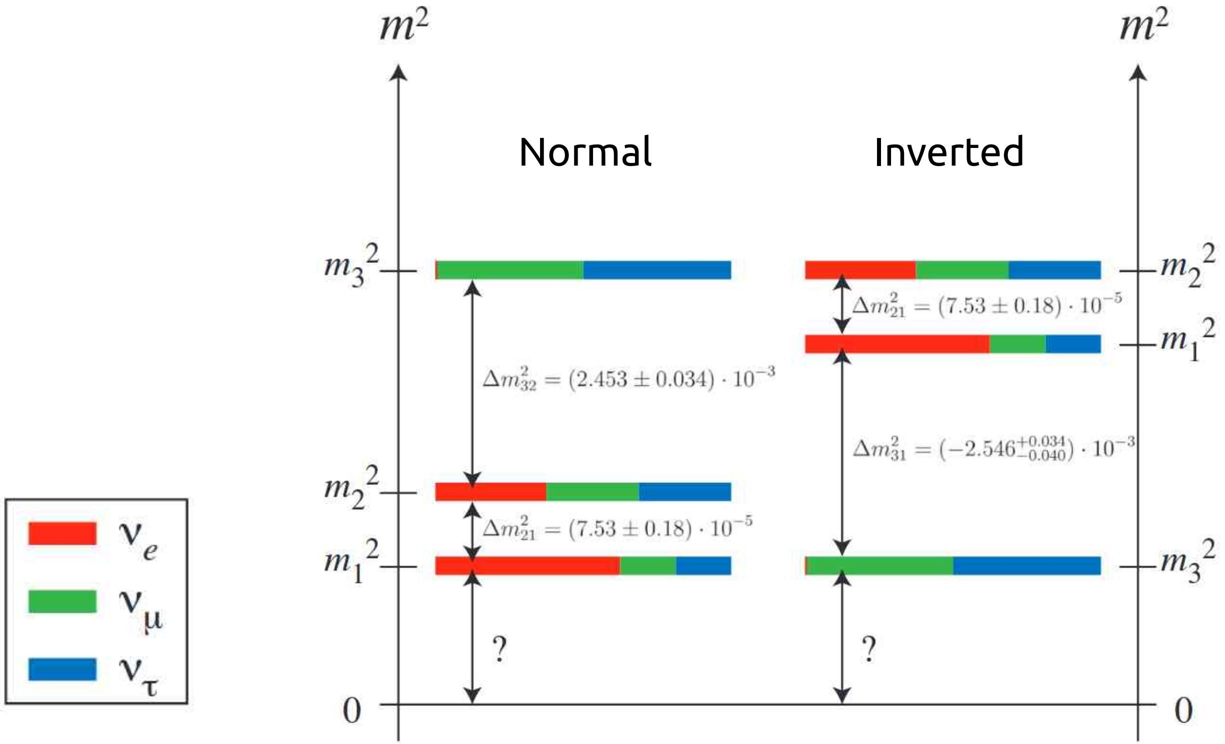
- Is θ_{23} maximal?

Others

- Are there more than 3 mass eigenstates (sterile neutrinos that do not couple to W and Z bosons)?
- Do neutrinos have Non-Standard-Model interactions?

Neutrino Mass Ordering

We know that (>2) **neutrinos are not massless**
We also know the differences of the squared masses, Δm_{ij}^2



$$\Delta m_{21}^2 = (7.53 \pm 0.18) \cdot 10^{-5}$$ (both)

$$\Delta m_{32}^2 = (2.453 \pm 0.034) \cdot 10^{-3}$$ (NH)

$$\Delta m_{31}^2 = (-2.546^{+0.034}_{-0.040}) \cdot 10^{-3}$$ (IH)

How are the masses ordered?

Source: https://doi.org/10.1093/ptep/ptaa104

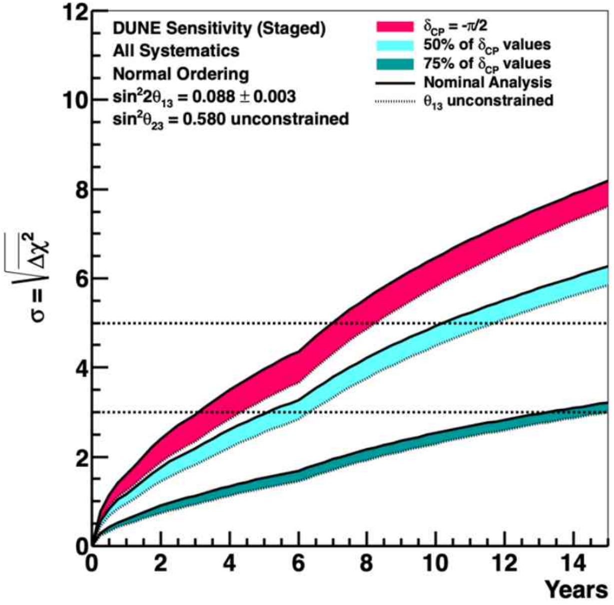
Appendix B
DUNE

DUNE Physics Opportunities

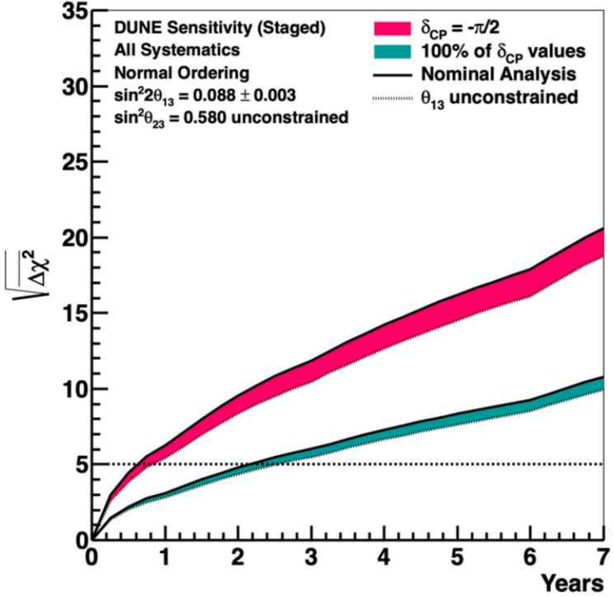
Primary goals	δ_{CP}, $\mathrm{sgn}(\Delta m_{31}^2)$
Precision measurements	θ_{13}, θ_{23}, θ_{23} (octant), Δm_{31}^2
Proton decay studies	$p^+ \rightarrow K^+ + \bar{\nu}$, $p^+ \rightarrow K^0 + e^+/\mu^+$, $p^+ \rightarrow \pi^0 + e^+$, …
Tau physics via	$\nu_\mu \rightarrow \nu_\tau$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$
Probe nucleon structure	$\nu + N \rightarrow \ldots$, $\bar{\nu} + N \rightarrow \ldots$
Supernova ν detection	ν_e CC, ν_e NC, ν_x NC, and $\bar{\nu}$ …
CPT violations	$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$
Neutrino trident production	$\nu + N \rightarrow \nu/l + N + l^+ + l^-$, and $\bar{\nu}$ …
Sterile neutrino searches	Disappearance of ν and $\bar{\nu}$ NC & CC interactions
Boosted DM searches in sun	$DM + \overline{DM} \rightarrow \nu + \bar{\nu}$, …
Light DM searches	NC-like scattering, decays of DM from beam dump
Heavy neutral lepton searches	Decays of HNL produced in beam dump
…	

DUNE Sensitivities

δ_{CP}



Mass Ordering



Source: https://arxiv.org/abs/2002.02967

To obtain these sensitivities, need to constrain the beam at the ND-site

→ Good detector resolution for tracking, calorimetry & PID

(background rejection, reconstruction of interaction type, energy, and other variables)

→ Advantage of using the same technology (LArTPC) in ND & FD

(minimise/cancel cross-section and detector response uncertainties)

The DUNE ND

Requirements:

- Measure unoscillated **ν_μ and ν_e energy** spectra **and fluxes**
- Measure ν-Ar interaction **cross-section** to predict observations at FD
- Contain relevant **event topologies** across the full ν phase space
  → Good hadron **containment**
  → Good handle on **muon charge and momentum**
- Good detector resolution for **tracking, calorimetry & particle identification**
  → Background rejection & reconstruction of interaction type, energy, and other variables

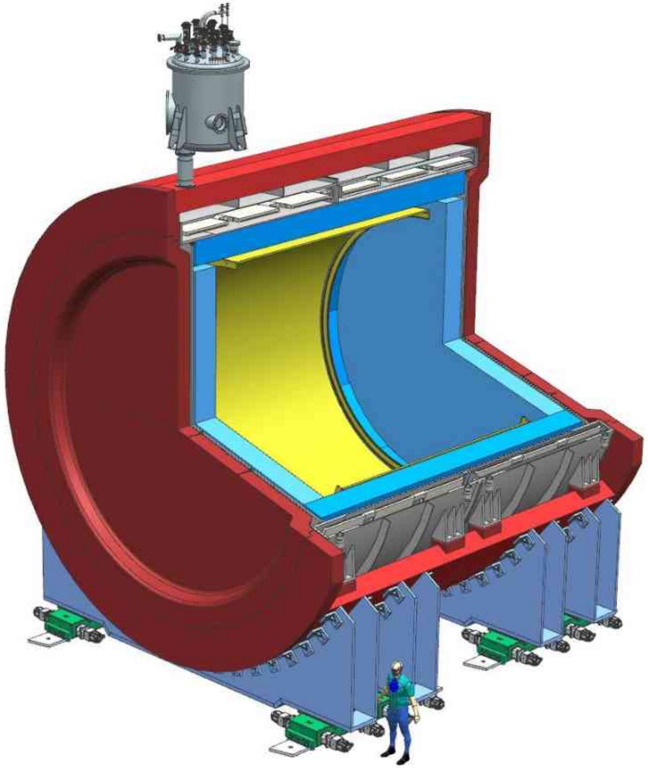
Advantage:

- Same target (**LAr**) and technology (**TPC**) as the FD to cancel/reduce systematics

Challenge:

- **High-multiplicity** environment (!):
  Expect ≈ 10 ν interactions per 100 t LAr and per 10 µs beam spill at 1 MW beam power

ND-GAr



Source: ND-Gar in LBL, DUNE CM Sept. 23rd 2021

High pressure gas TPC (up to 10 atm Ar-CH_4)
surrounded by EM calorimeter and within ≈ 0.5 T field
→ Excellent calorimetry and momentum resolution (PID!)

Magnetic field

- Momentum and charge determination from track curvature
- Estimation of wrong-sign ν / $\bar{\nu}$ contamination (important for wrong-sign ν_e / $\bar{\nu}_e$ appearance in FD)

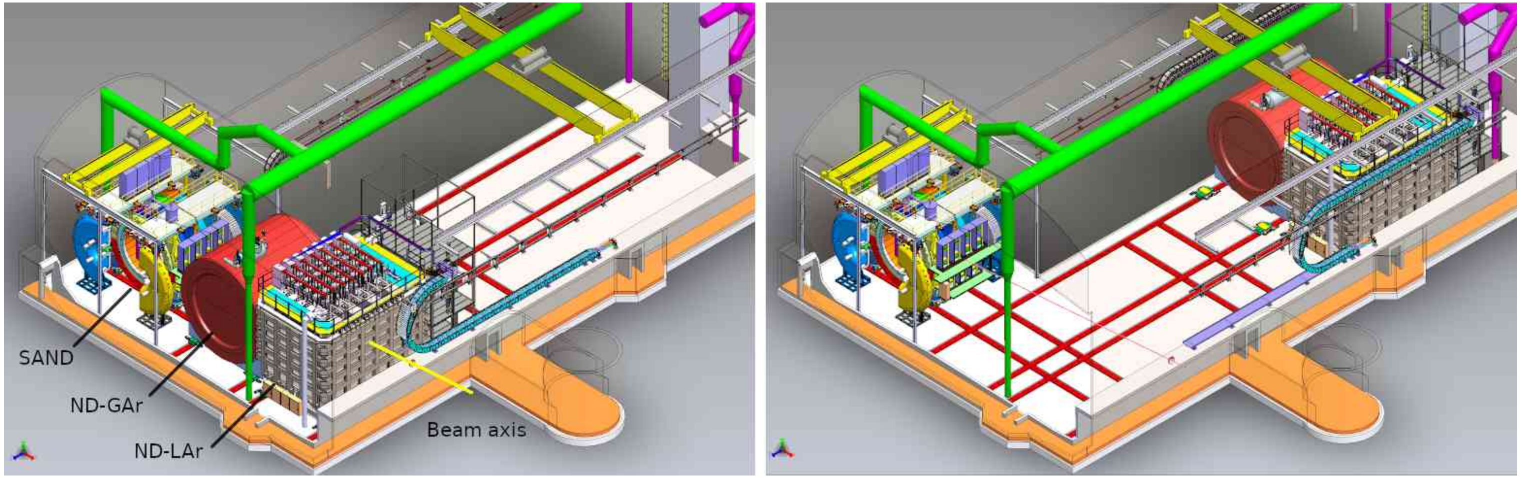
Compared to LArTPC

- Low momentum threshold for particle tracking
- Reduced MCS and bulk interactions of FS particles
- Improved ν-Ar interaction measurements
- More precise vertex activity measurements

Ability to change the gas mixture
→ Different nuclear targets enable accurate constraints and tuning of ν-N interaction models

DUNE-PRISM

Data-driven approach to reduce systematic uncertainties related to flux and cross section

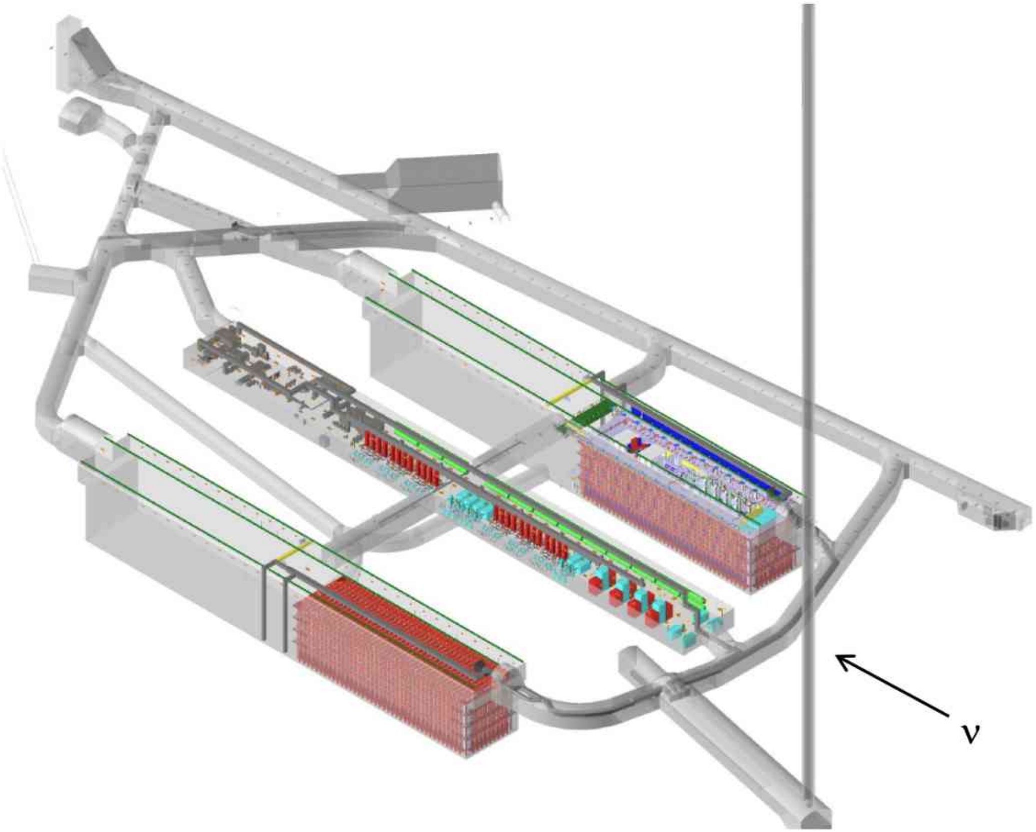


Courtesy of A. Bross (FNAL)

ND-LAr & ND-GAr can move up to ≈ 30 m off-axis
→ ν energy spectrum becomes narrower, peaking at lower energies
→ Data samples at different ν flux spectra (e.g. QE or RES dominated)
→ Enabling deconvolution of flux and cross-section uncertainties
→ Enabling combination of different fluxes during the data analysis

SAND
→ Measure ν (and μ) energies, flux and vertex distribution
→ Detect possible changes in the beamline

The DUNE FD Site



Three caverns with two out of four FD modules
and the cryogenigs systems at SURF

≈ 1.5 km underground in the
Sanford Underground Research Facility
(SURF) in Lead, South Dakota

Four 17.5 kt (10 kt fiducial) LArTPCs
65.8 m x 18.9 m x 17.8 m (external)
62.0 m x 15.1 m x 14.0 m (internal)

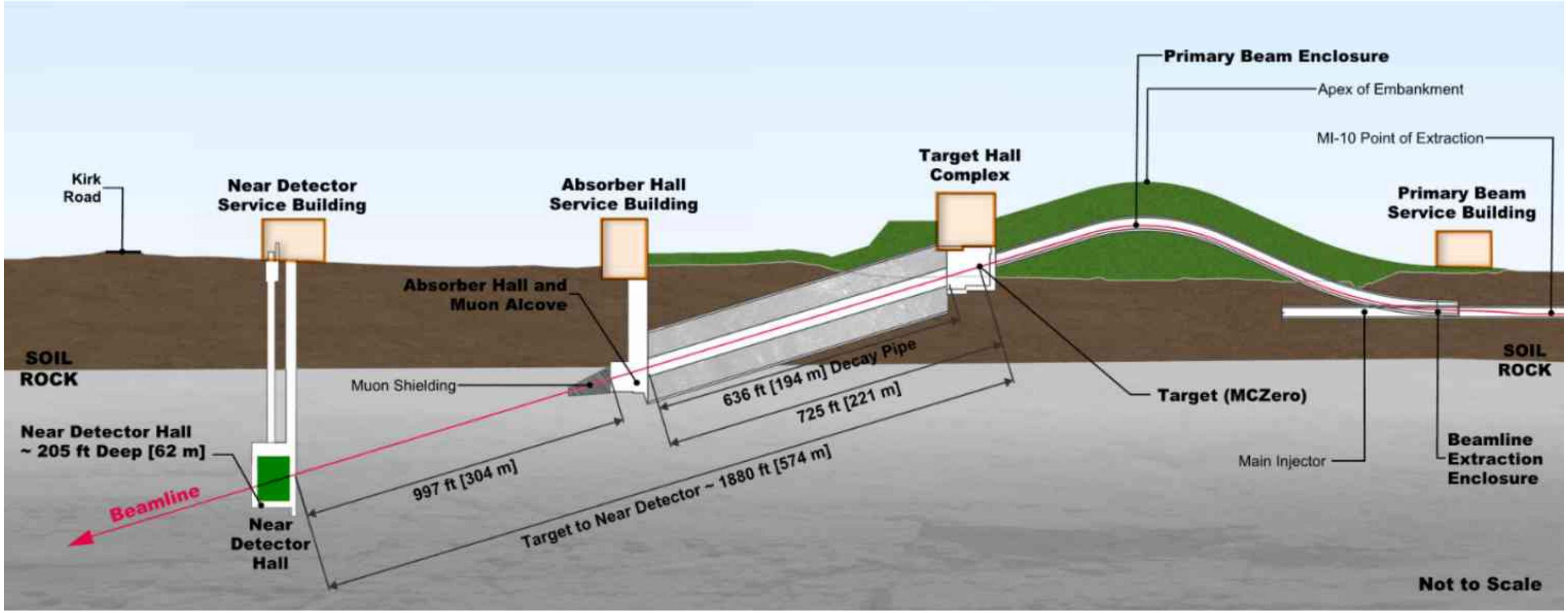
≈ 3.4 neutrino interactions per hour

Source: https://arxiv.org/abs/2002.02967

Appendix C

LBNF

The DUNE Beamline and ND Facility



Source: https://arxiv.org/abs/2002.02967

Protons from Main Injector

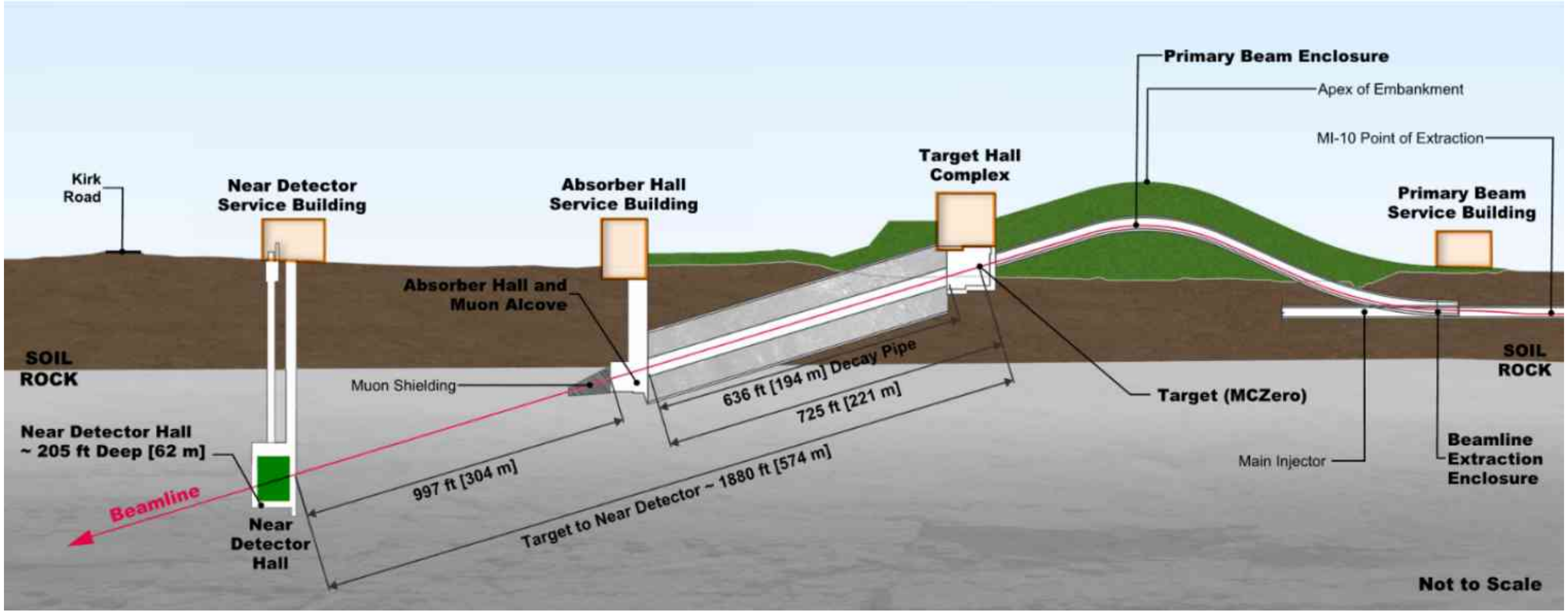
→ 60 GeV – 120 GeV

→ Pulsed at a cycle time of 0.7s – 1.2s

→ Spill duration of 10 µs

→ Sent on graphite target, producing mostly $\pi^{+/-}$, some $K^{+/-}$, and others

The DUNE Beamline and ND Facility



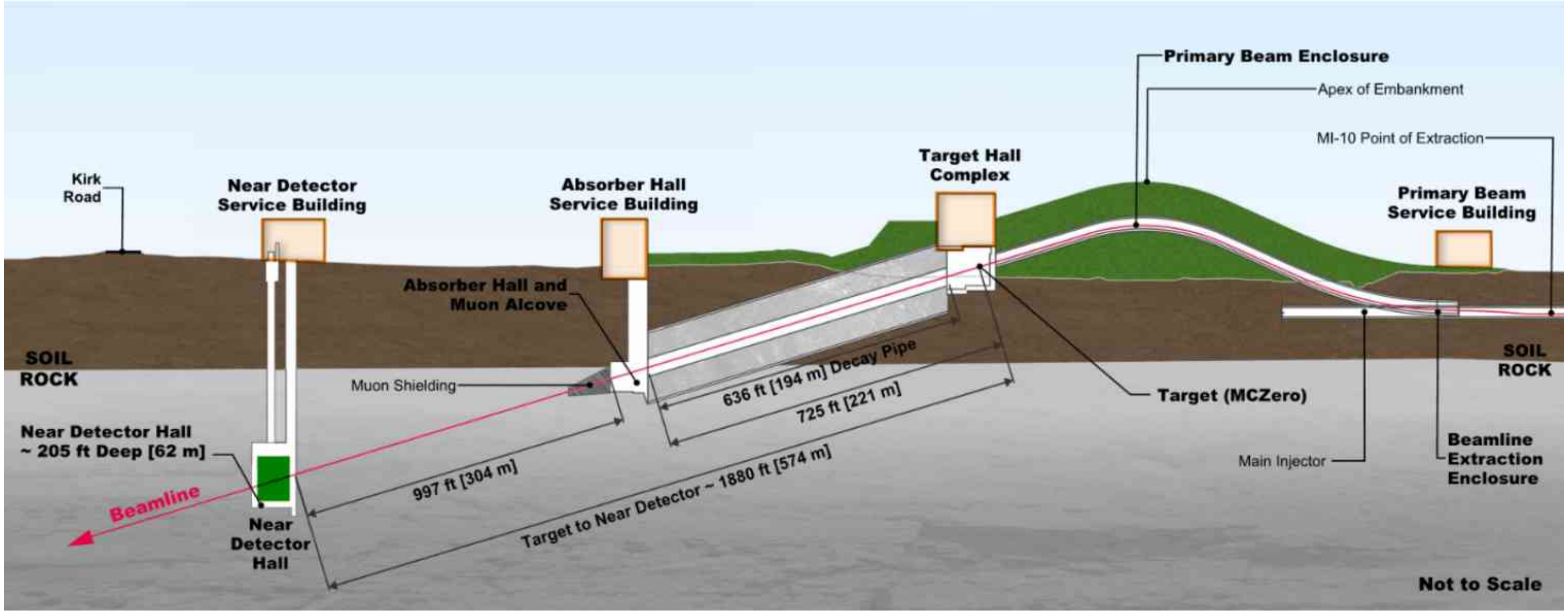
Source: https://arxiv.org/abs/2002.02967

Three-horn focusing system

→ Select negatively or positively charged particles
(ν enhanced or $\bar{\nu}$ enhanced beam)

→ Optimised for DUNE sensitivity to δ_{CP}

The DUNE Beamline and ND Facility



Source: https://arxiv.org/abs/2002.02967

Phase 1

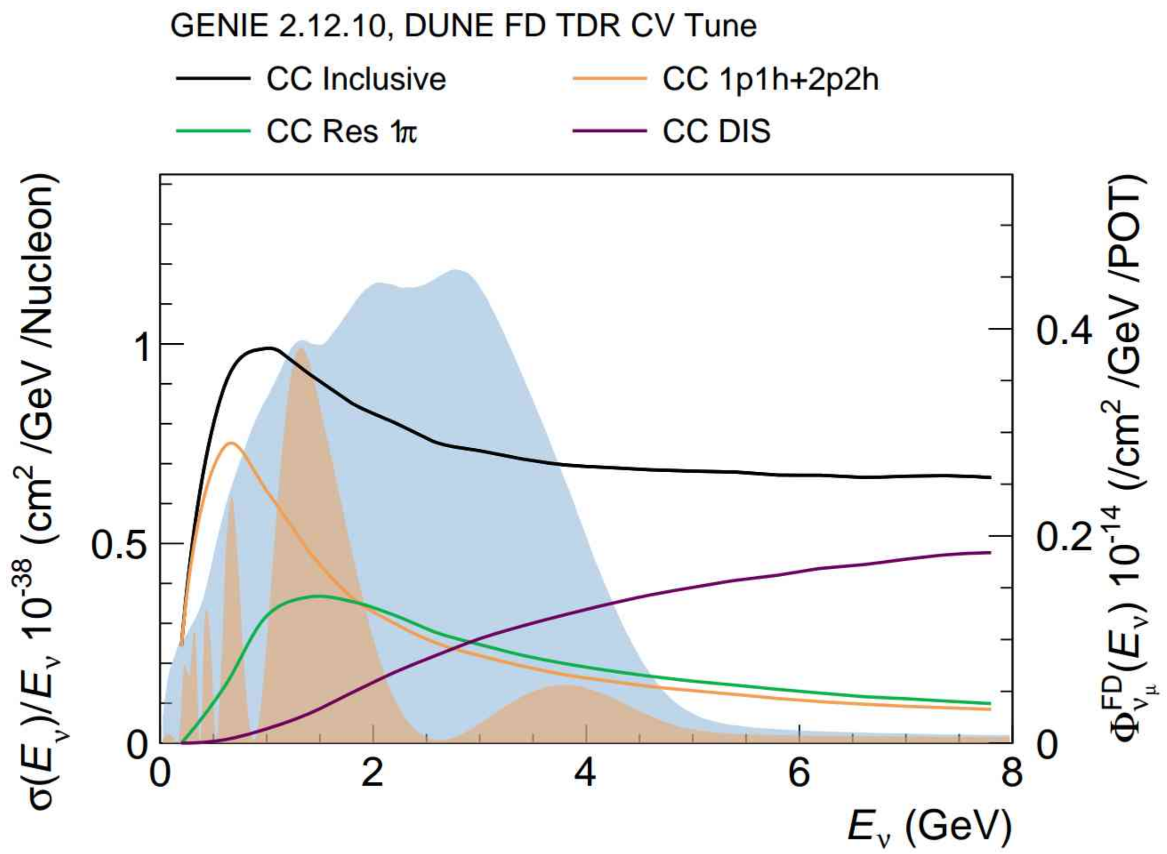
→ 1.0 MW – 1.2 MW beam power

→ Corresponding to ≈7.5 · 10^{13} Protons On Target (POT) per cycle

Phase 2

→ 2.4 MW beam power

DUNE Neutrino Flux at the FD Site



Source: https://arxiv.org/abs/2103.04797

Unoscillated (blue area) and oscillated (orange area) νμ flux at the DUNE FD site

Appendix D

Properties of Argon

LAr as Detector Material

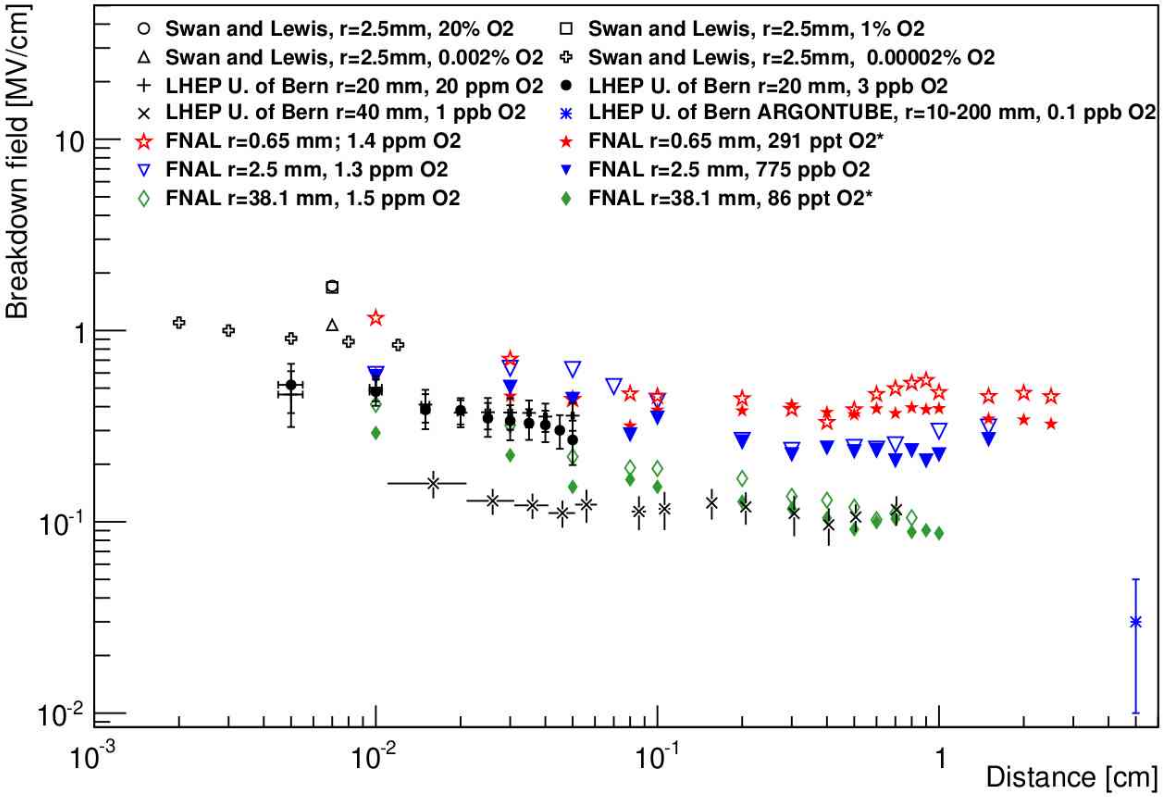
Advantages

- High scintillation light yield & ionization charge yield
- Transparency for scintillation light
- High electron mobility
- High dielectric strength
- Noble gas inert to chemical reactions → simplified purification
- Ar is the 3rd most abundant gas in Earth's atmosphere (0.93% by Vol.)
  → affordable

Disadvantages

- Low boiling point (≈ 87 K at 1 atm)
  → need cryogenic equipment & know-how
- Scintillation light (λ ≈ 129 nm) is difficult to detect efficiently

Dielectric Strength of LAr



Source: https://arxiv.org/abs/1408.0264

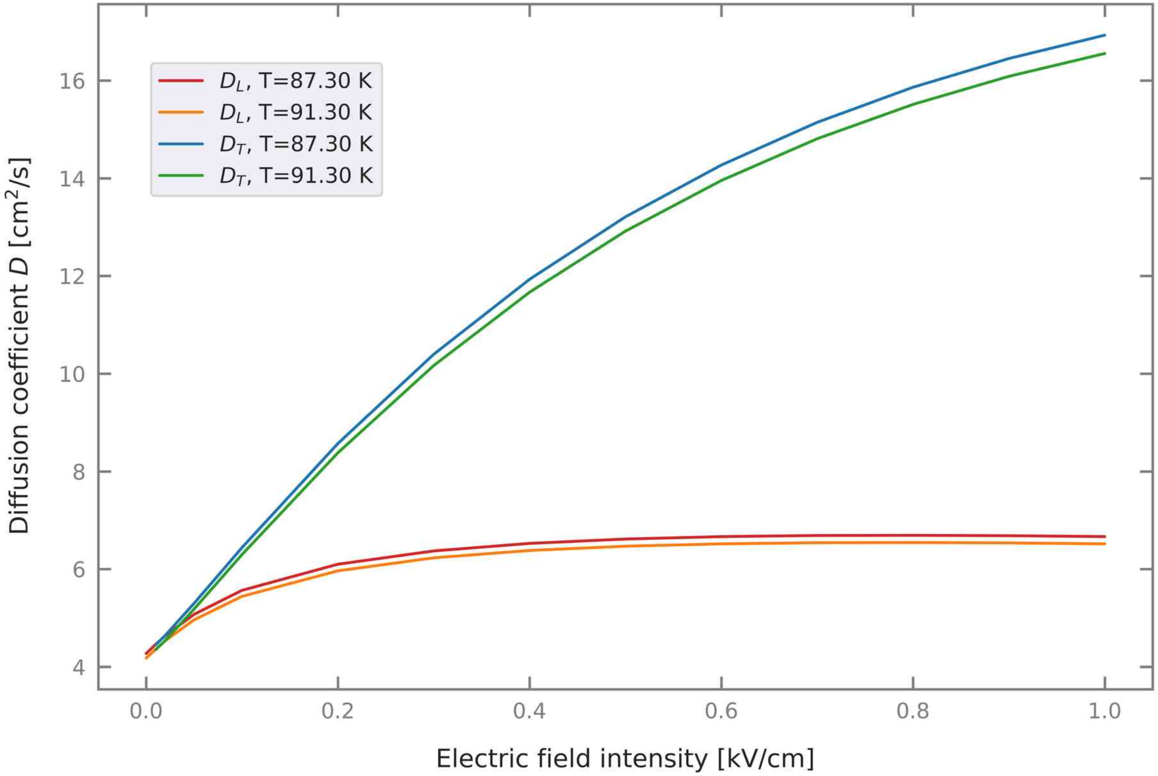
Breakdowns observed at ≈40 kV/cm

→ Large inactive clearance volumes around the HV components or

→ Segment LArTPC and use dielectric module walls (ArgonCube concept)

Electron Diffusion in LAr

Electron cloud spreads differently along (σ_L) and across the drift (σ_T)



$$\boxed{\sigma_{L,T}\left(t\right) = \sqrt{2D_{L,T}\cdot t}}$$

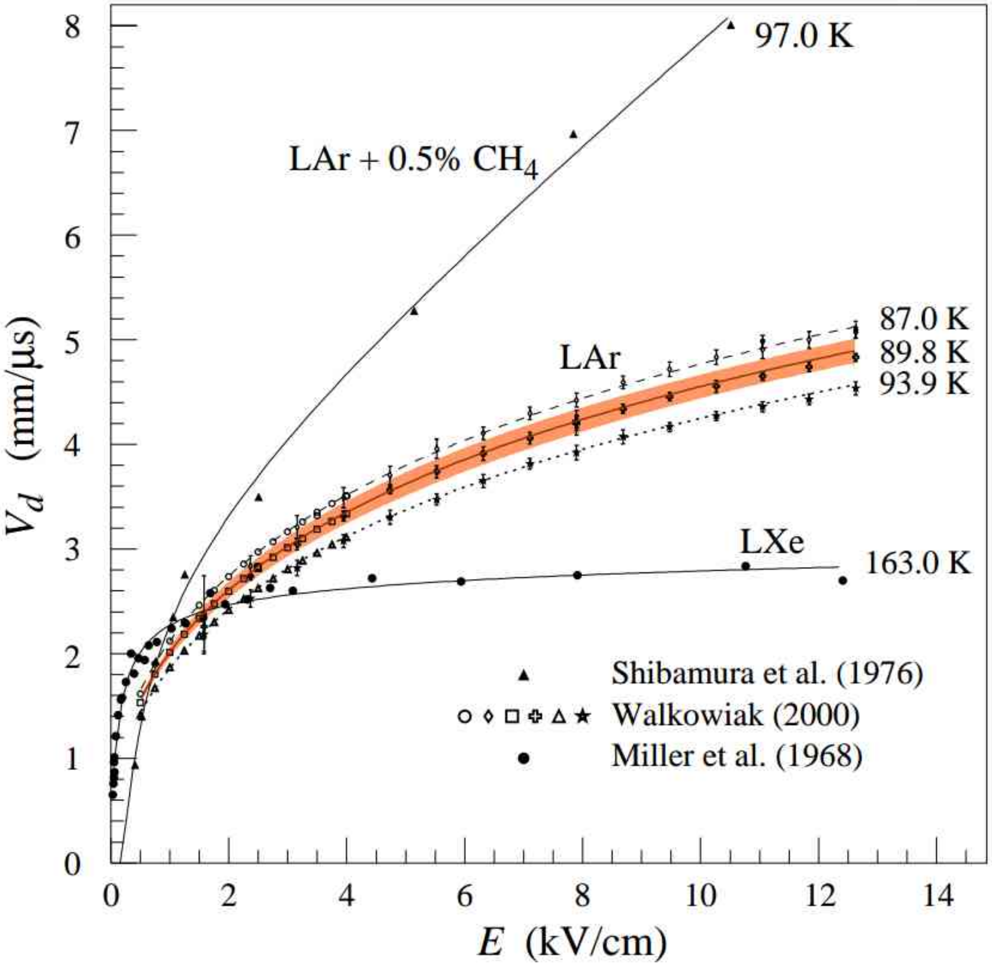
t: electron drift time

Example
0.5 kV/cm E-field and
50 cm drift distance

$\sigma_L \approx 0.6$ mm
$\sigma_T \approx 0.9$ mm

Data generated with the model from https://arxiv.org/abs/1508.07059

Electron Drift Speed in LAr

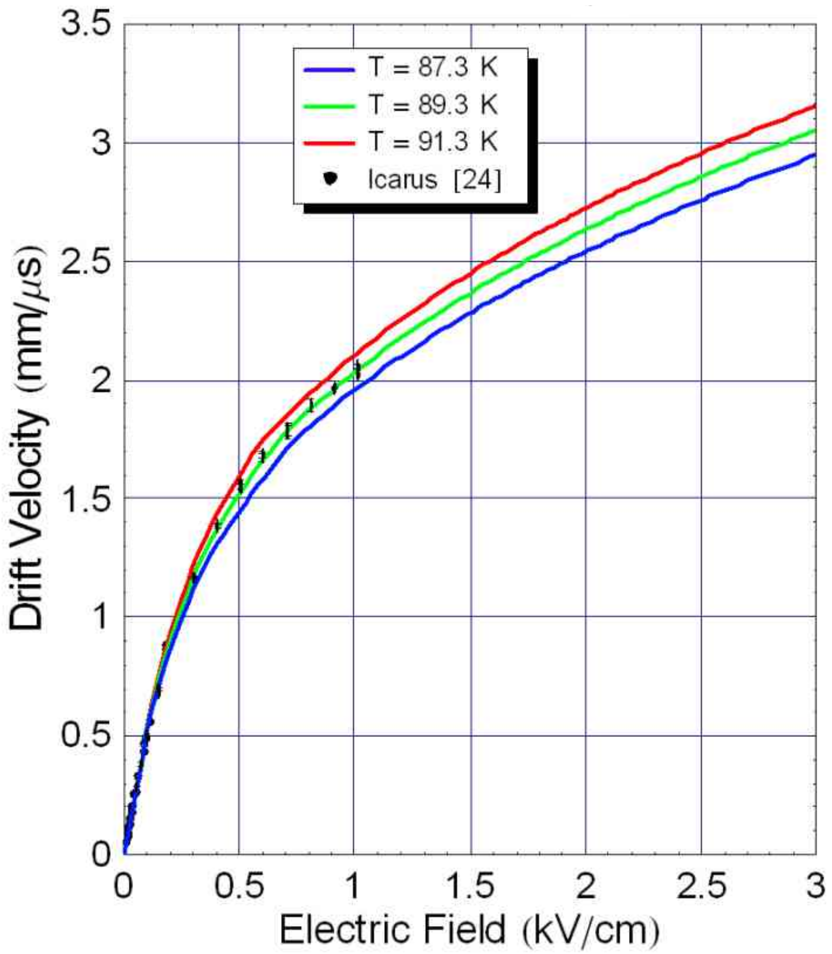


Dependencies

- Electric field intensity
  (and screening effects due to space charges)
- Temperature of medium
- Concentration of impurities
  (e.g. H_2, N_2, CH_4)

Source: https://doi.org/10.1093/ptep/ptaa104

Electron Drift Speed in LAr



Dependencies

- Electric field intensity
  (and screening effects due to space charges)
- Temperature of medium
- Concentration of impurities
  (e.g. H_2, N_2, CH_4)

Source: https://www.phy.bnl.gov/~chao/docs/Properties-of-LAr-v9a-thorn.pdf

Impurities in LAr

Electro-negative impurities at ppm-level attenuate the charge & light signals

$$N(x) = N_0 \cdot \exp(-x/l)$$

N: Number of remaining electrons or photons
N_0: Number of electrons or photons initially present
x: Distance travelled by the particle(s)
l : Electron mean free path or photon attenuation length

Water & oxygen
Primarily attenuate charge signals

Nitrogen
Mainly suppress light signals (quenching)

Scintillation Light in LAr

To produce scintillation light, need excited dimer state Ar_2^* which can decay via

$Ar_2^* \rightarrow Ar + Ar + \gamma$

The excited dimer states can be produced via

- Excitation

  $Ar \rightarrow Ar^*$

  $Ar^* + Ar \rightarrow Ar_2^*$

- Ionization

  $Ar \rightarrow Ar^+ + e^-$

  $Ar^+ + e^- + Ar \rightarrow Ar_2^*$

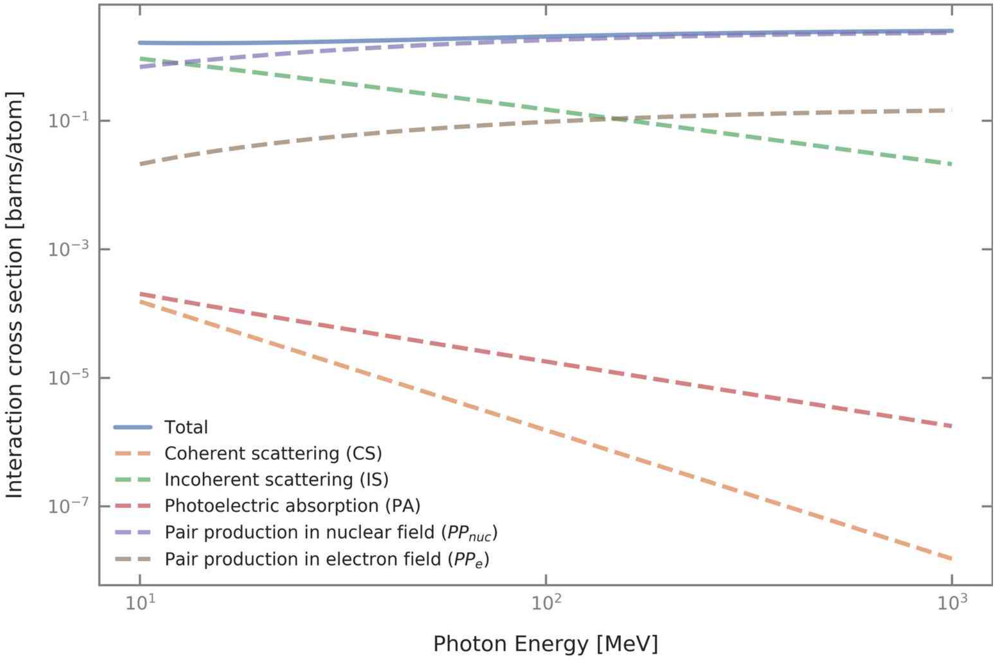
  $\rightarrow Ar_2^{**}$

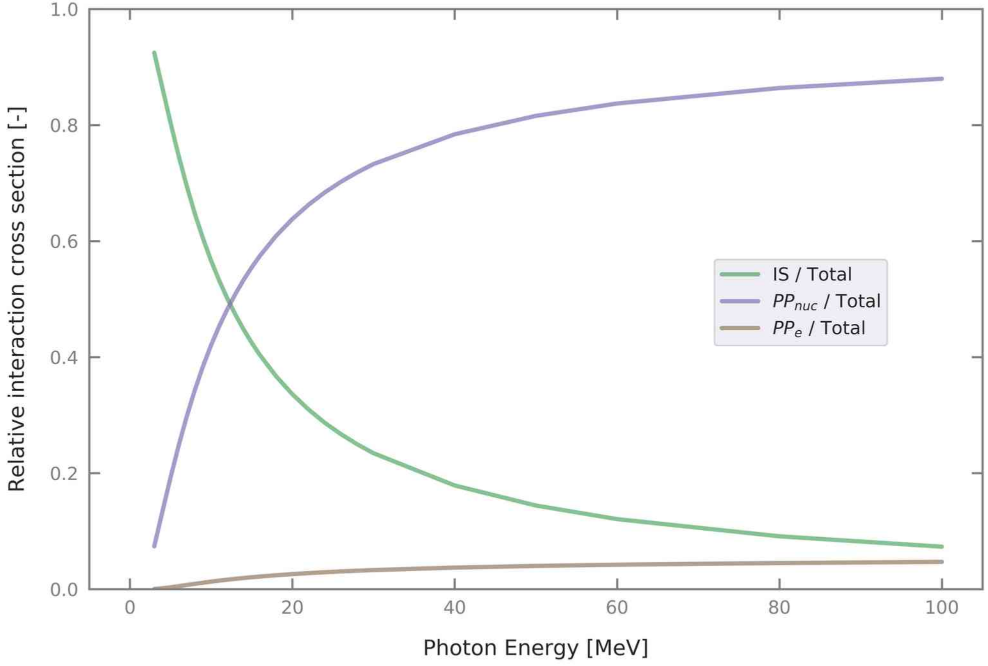
  $\rightarrow Ar^{**} + Ar$

  $\rightarrow Ar^* + Ar + \text{heat}$

  $\rightarrow Ar_2^* + \text{heat}$

Compton Scattering in Argon





For E > 10 MeV (incoherent) compton scattering cross section is smaller than cross section for pair production, but it's not negligible!

Data generated with XCOM: https://physics.nist.gov/cgi-bin/Xcom/xcom3_1

Energy Loss of Charged Particles

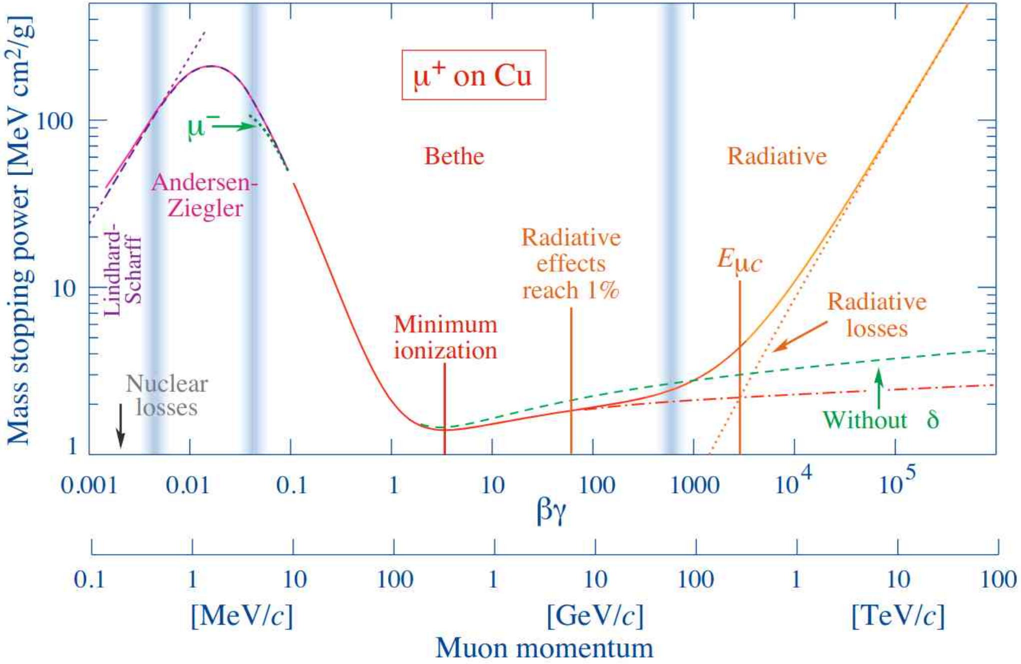
Mass stopping power [MeV·c²/g]

→ Energy loss via excitation and ionization

→ For moderately relativistic particles (0.1 < βγ < 1000) others than electrons

→ Almost material independent, slowly decreasing with increasing Z

→ Weighted by rare events with large single-collision energy losses (see Landau / MPV)

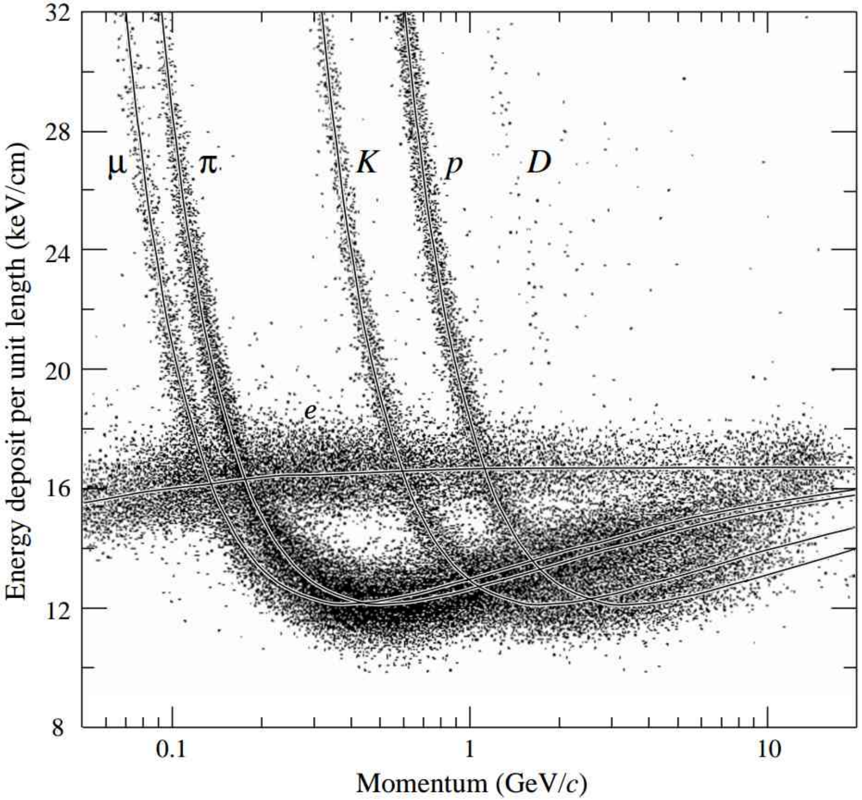


$$\left\langle -\frac{dE}{dx} \right\rangle_{\text{ion}} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2 m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Source: https://doi.org/10.1093/ptep/ptaa104

Energy Loss of Charged Particles

Linear stopping power [MeV/cm]



$$-\rho \cdot \langle dE/dx \rangle$$

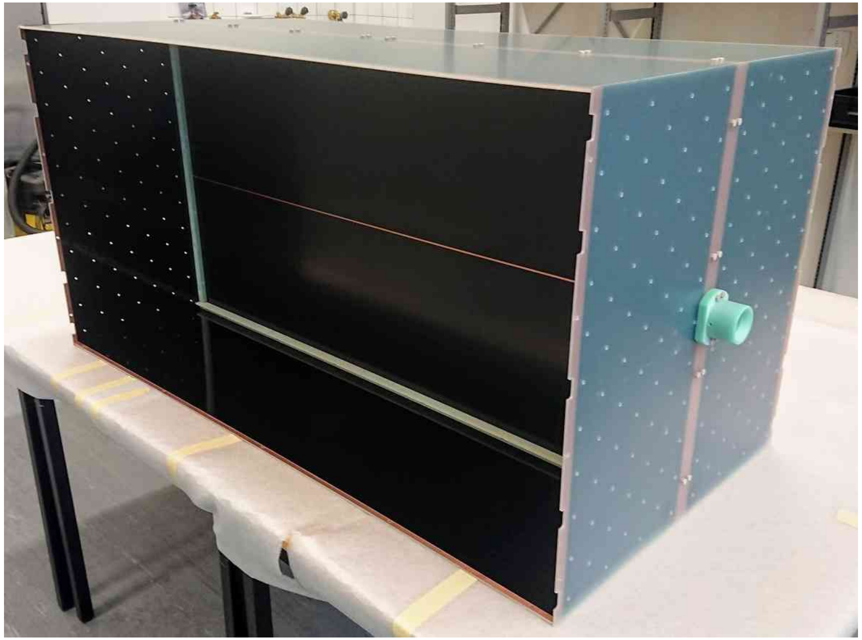
Observations with the first gas TPC, PEP-4/9.
Gas mixture: 80% Ar, 20% CH_4, at 8.5 bar.

Source: https://doi.org/10.1093/ptep/ptaa104

Appendix E
ArgonCube Technologies

Resistive Shell

Cathode plane and field shell made (SLAC) of
carbon-loaded Kapton foil laminated on fibreglass planes



Cathode & field shell of the Module-0 prototype

Continuous field shaping

Low profile
→ Reduce amount of inactive and dense material, increase the active TPC volume

High sheet-resistance of O(1 GΩ/sq)
→ Reduce local power dissipation
→ Limit power dissipation in case of HV beakdown

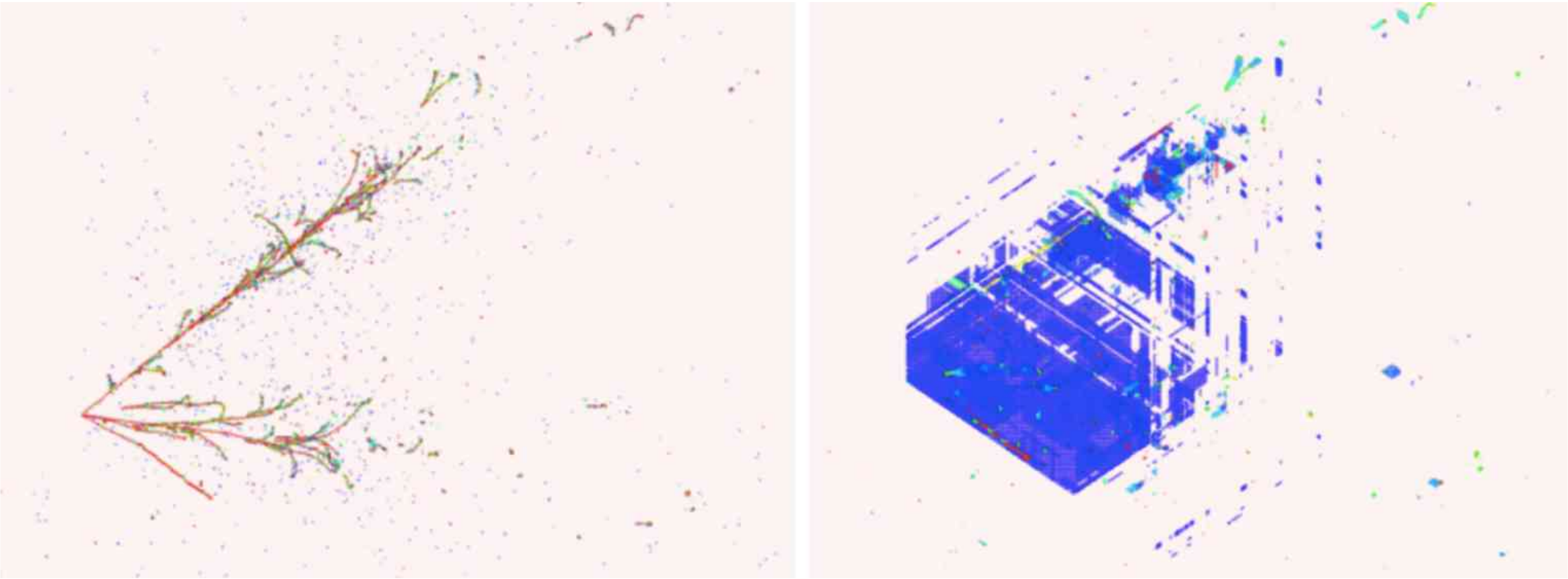
Small number-count of components
→ Reduce possible points of failure

Pixelated Charge Readout

Simulation of a 3 GeV ν_e (Wire-Cell)

True energy depositions

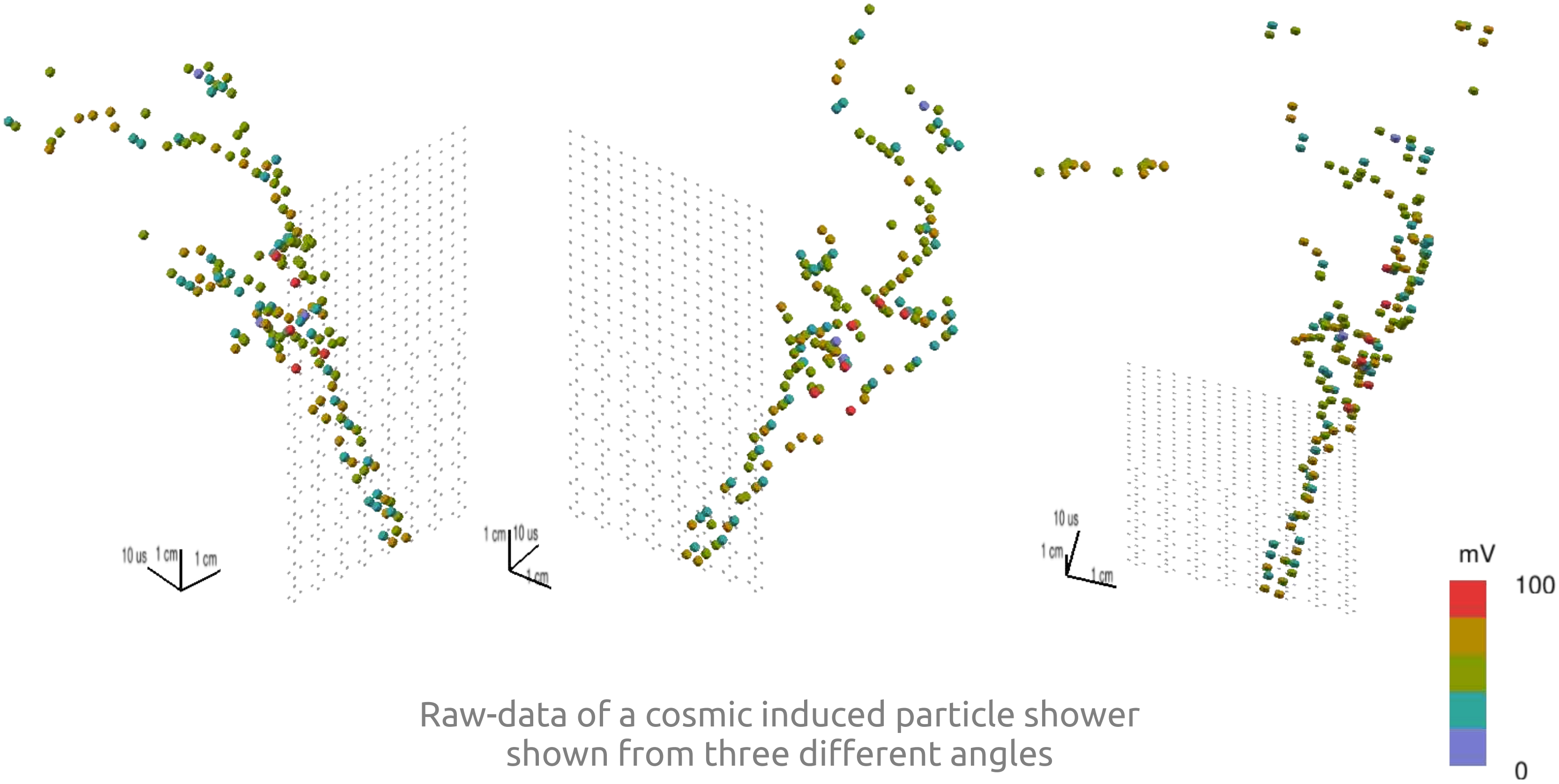
Signal from projective wire readout



Courtesy of D. Dwyer (LBNL)

Pixelated Charge Readout

LArPix-V1 ASICs: Communication via 1D daisy-chain (not very resilient to failures)
→ Upgrade in LArPix-V2: Hydra Network*



Raw-data of a cosmic induced particle shower
shown from three different angles

Pixelated Charge Readout

Low-power amplification and digitization for individual pixels

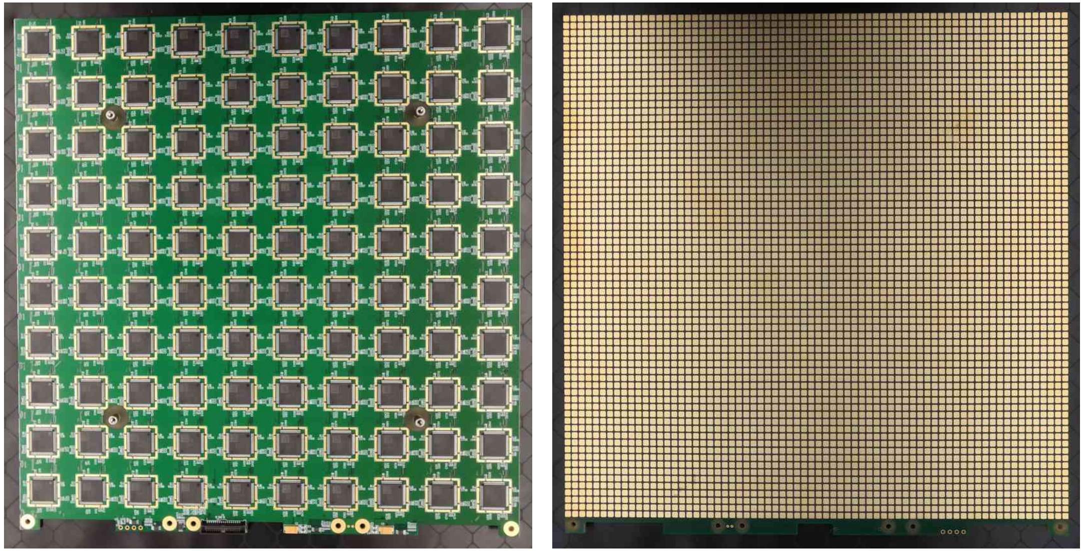
- Operational in LAr, at T ≈ -186^0 C
- 60 µW per pixel, 37 µW digital

→ Reduce LAr boil-off

→ Reduce spurious events and risks for HV breakdowns due to voids

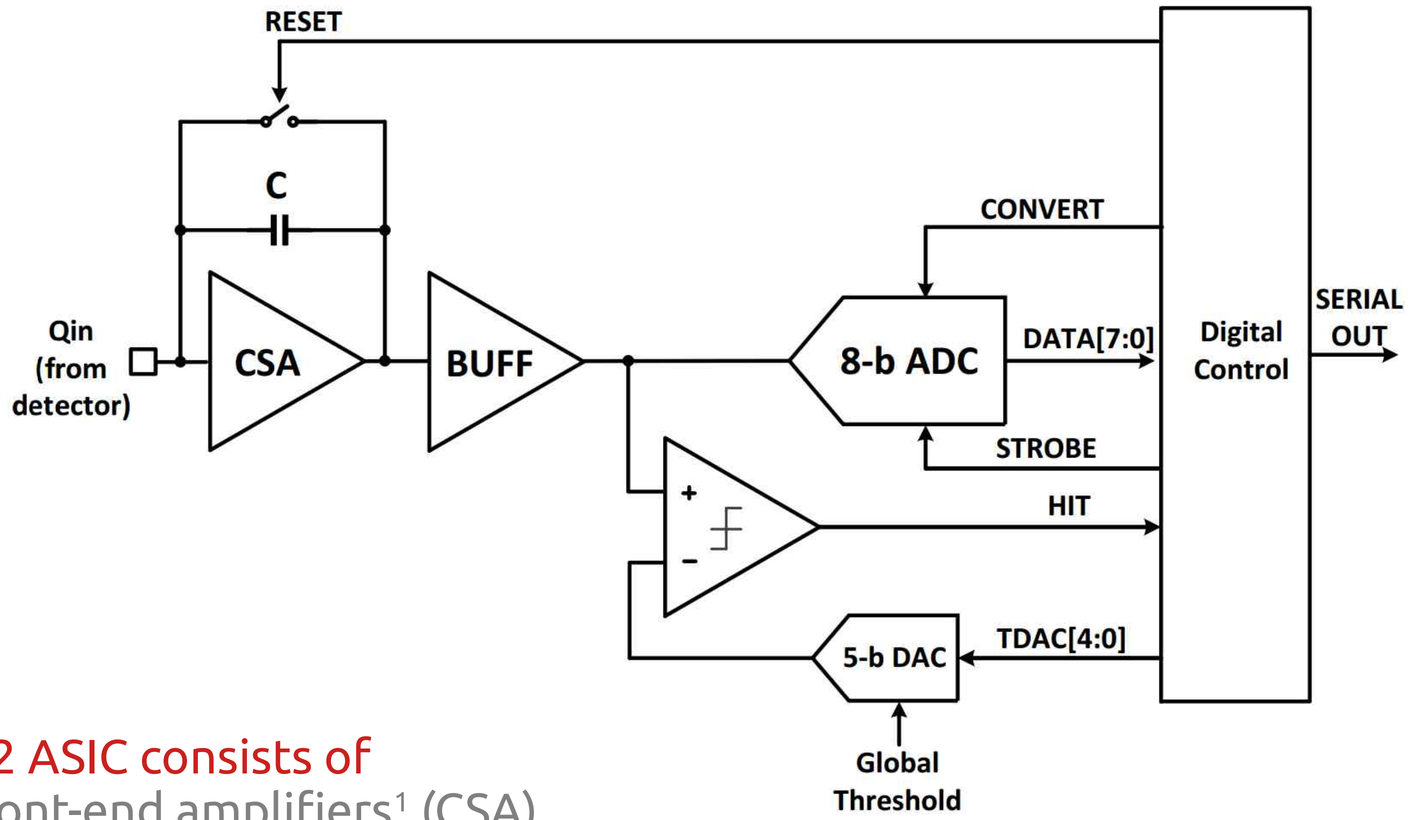
→ Reduced data transfer bandwidth: O(0.1 MB/s/m2) in ND-LAr

→ Unambiguous 3D particle tracking



Both sides of a 32 cm x 30 cm pixelated charge readout PCB: 10 x 10 LArPix-V2 ASICs host 70 x 70 pixels, each 4 mm x 4 mm

LArPix-V2 Block Diagram



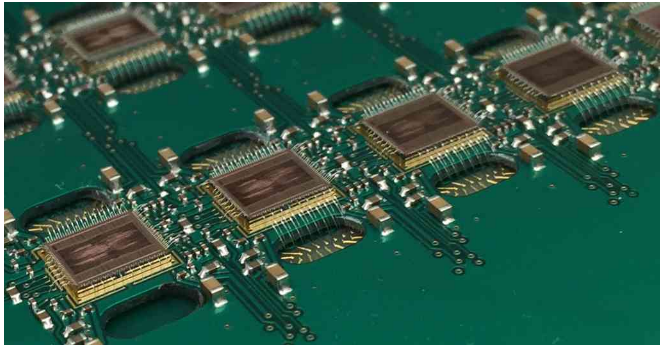
Each LArPix-V2 ASIC consists of

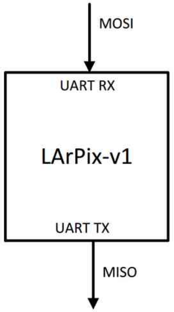
- 64 analog front-end amplifiers[1] (CSA)
- 64 analog-to-digital converters (ADC)
- 1 shared digital control chip configuration and data I/O

[1] CSA output grows ≈ 1 mV per 250 e^- received at the input

LArPix-V1 vs LArPix-V2

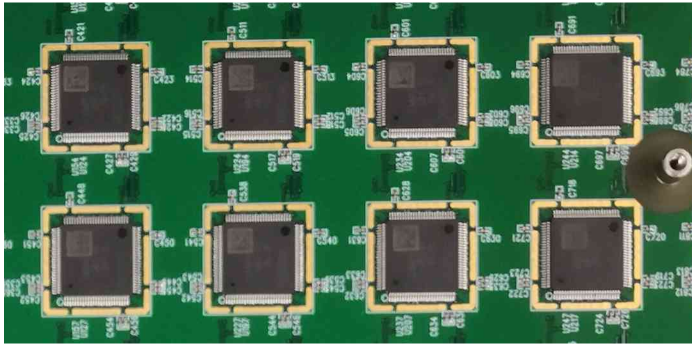
LArPix-V1

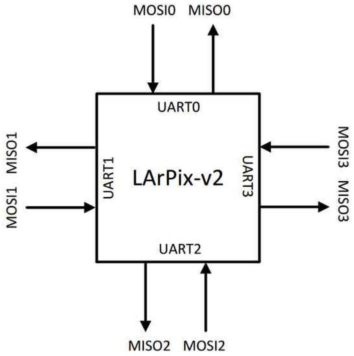




ASICs wire-bonded to pixel PCB
1 UART → 1D daisy chaining

LArPix-V2



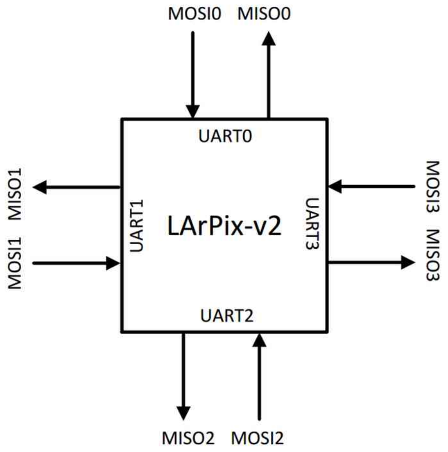


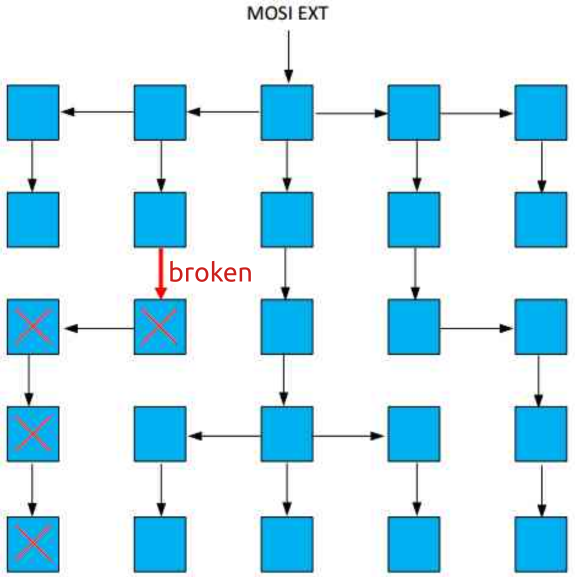
ASICs soldered on pixel PCB
4 UARTs → 2D daisy chaining

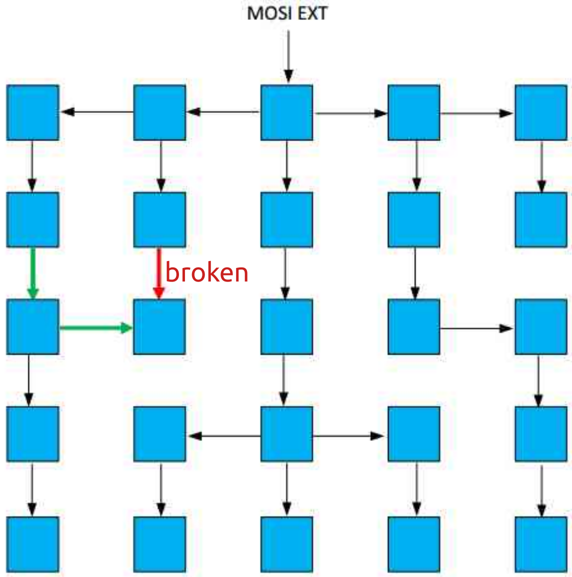
LArPix-V2 Daisy Chaining

Daisy chain

→ Keep number of physical communication lines small







Each ASIC hosts four UARTs

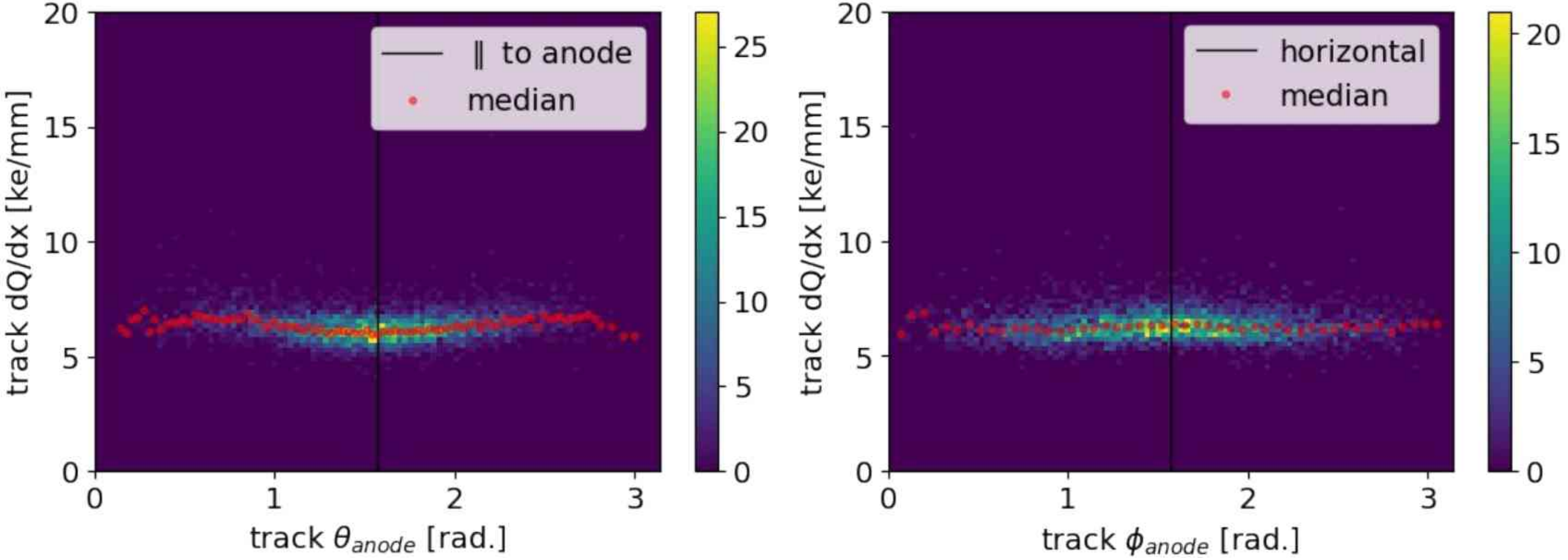
→ Sophisticated daisy-chain network

→ Enables routing around of a broken UART or ASIC

LArPix-V2

Flat response as function of angle

between the ionization traces and the pixel orientation



Θ_{anode} : Absolute value of the azimuthal angle

Φ_{anode} : Absolute value of the zenith angle w.r.t. the anode plane

Credits: P. Madigan (LBNL)

Light Readout

[1] Wavelength shifting
[2] 1,1,4,4-tetraphenyl-1,3-butadiene

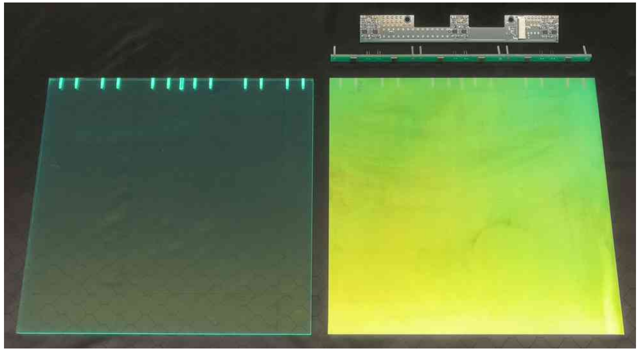
Two complementary systems: **LCM** & **ArCLight**
→ SiPM-based, compact, robust, scalable, resilient to electric fields

Light Collection Module (LCM)

- Developed at JINR, Dubna
- WLS[1] fibres with TPB[2] coating

ArgonCube Light (ArCLight)

- Developed at LHEP, Bern
- WLS[1] bulk + dichroic mirror with TPB[2] coating

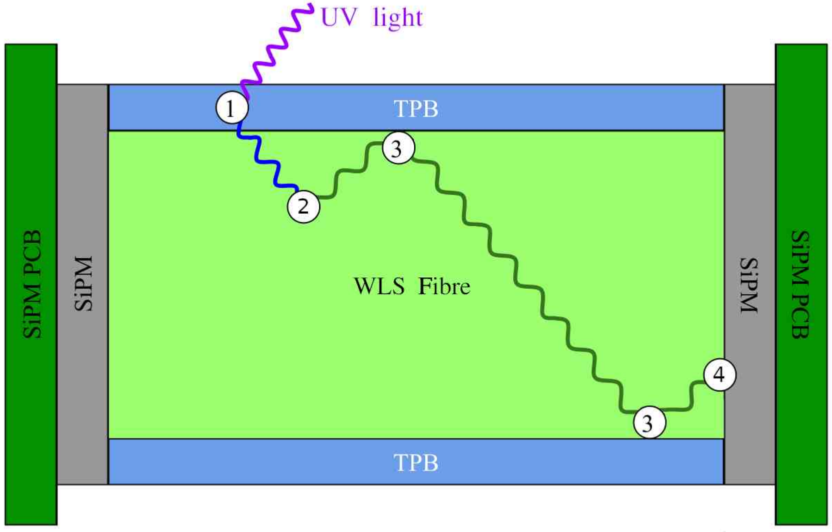


Timing resolution of O(1 ns)
→ Important to tag individual neutrino interactions and
→ Associate detached energy deposits to individual vertices / interactions

Light Readout

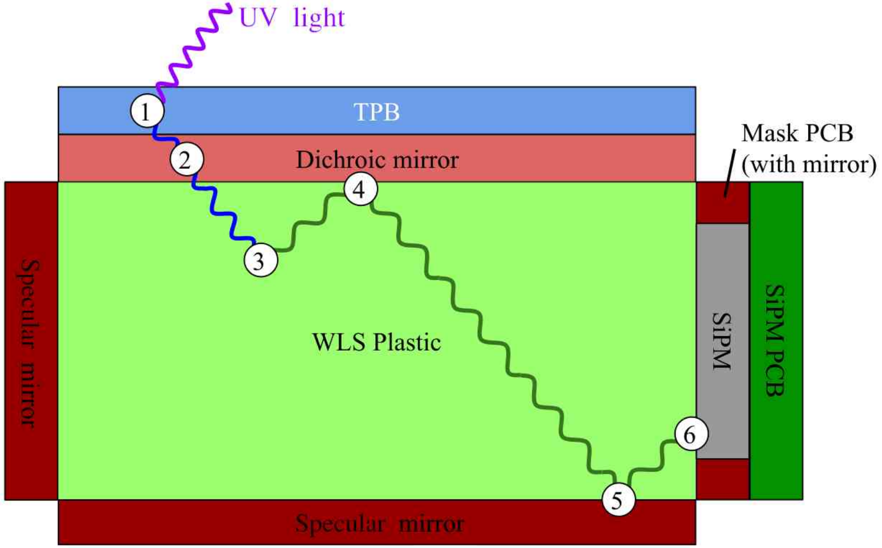
[1] Wavelength shifting
[2] 1,1,4,4-tetraphenyl-1,3-butadiene
[3] Silicon Photomultiplier

Light Collection Module (LCM)



1: TPB[1] shifts UV light (128 nm) to blue (425 nm)
2: WLS[2] fibre shifts blue light to green (510 nm)
3: Total internal reflection in fibre → light trap
4: SiPM[3] to detect green light with a high efficiency

ArgonCube Light (ArCLight)



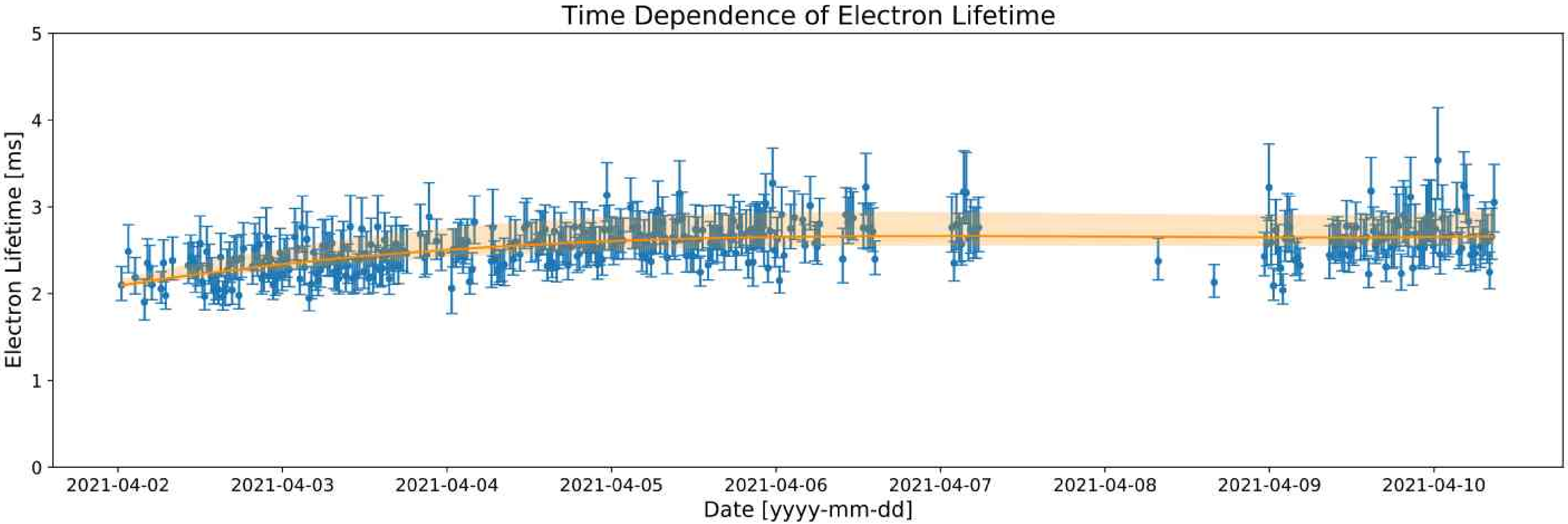
1: TPB[1] shifts UV light (128 nm) to blue (425 nm)
2: Dichroic mirror with high transparency for blue light
3: WLS[2] plastic shifts blue light to green (510 nm)
4: Dichroic mirror with high reflectivity for green light
5: Specular mirror for reflection → light trap
6: SiPM[3] to detect green light with a high efficiency

Appendix F
Module-0 Performance

Module-0 Performance – Electron Lifetime

To prevent (charge & light) signal attenuation

→ Need high LAr purity / high electron lifetime (> 1 ms) in LAr



Credits: M. Mooney (CSU)

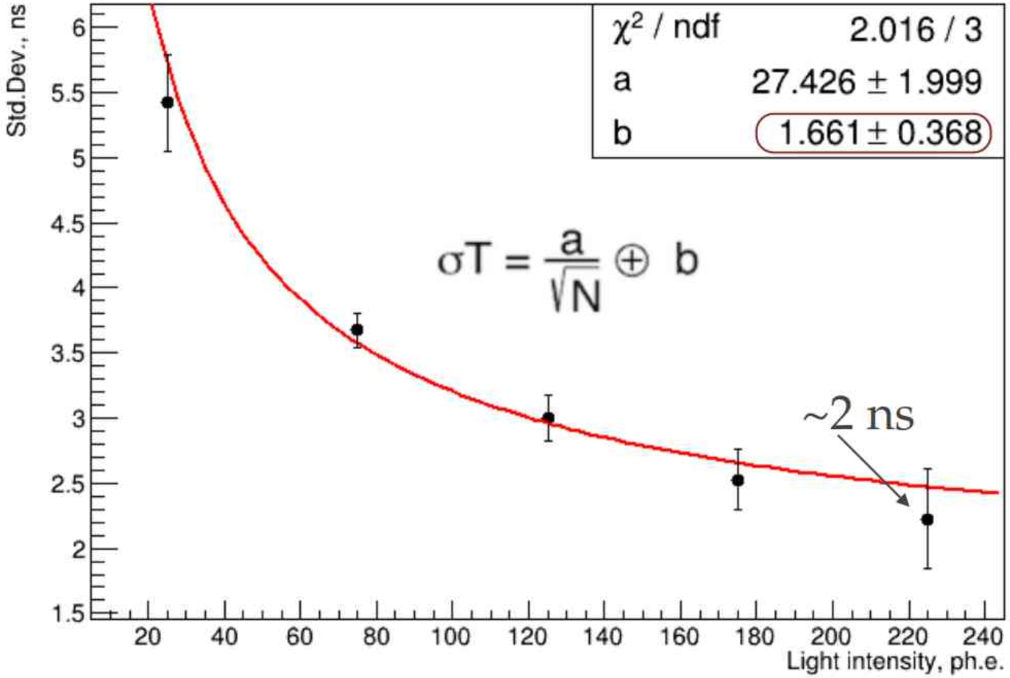
Module-0 Performance – Light Readout

Photon detection efficiency

O(1 %) for LCMs, O(0.1 %) for ArCLights

Timing resolution O(1 ns)

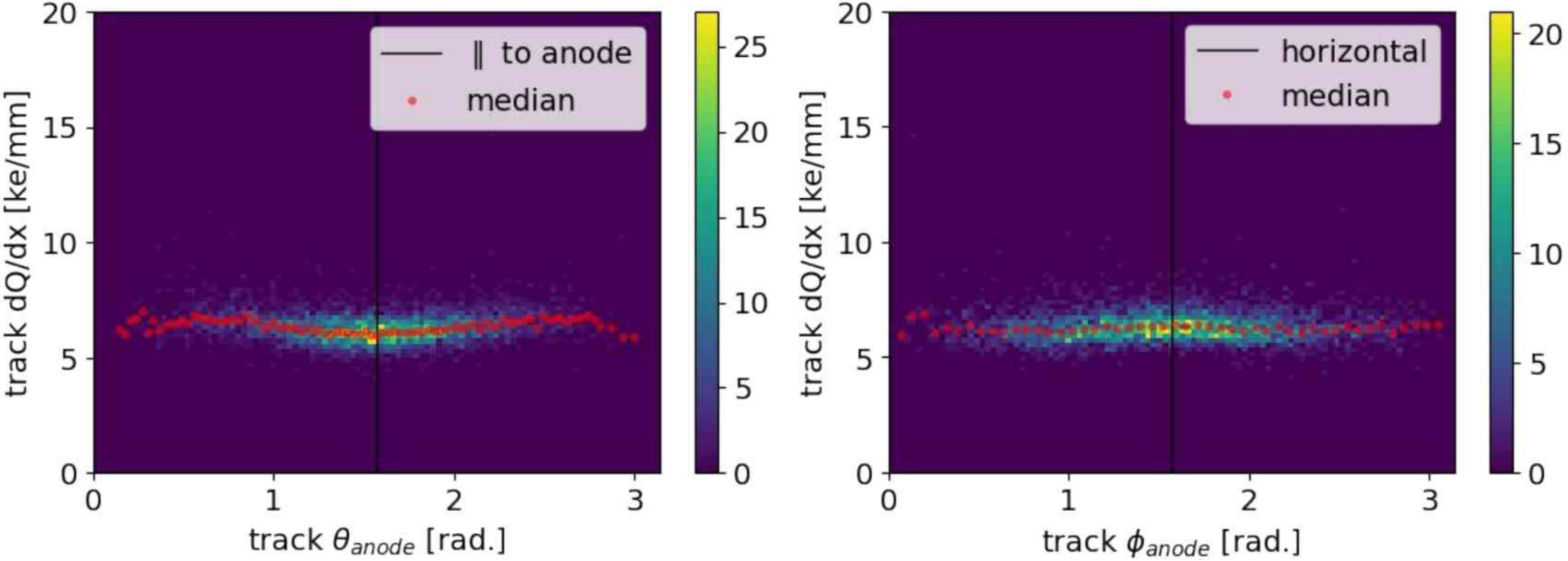
→ Enables association of detached energy deposits to individual interactions / vertices



Signals from SiPMs of two neighbouring LCMs
Data points: Stdev of time difference distribution of these signals
Uncertainties: Stdev

Credits: N. Anfimov (JINR)

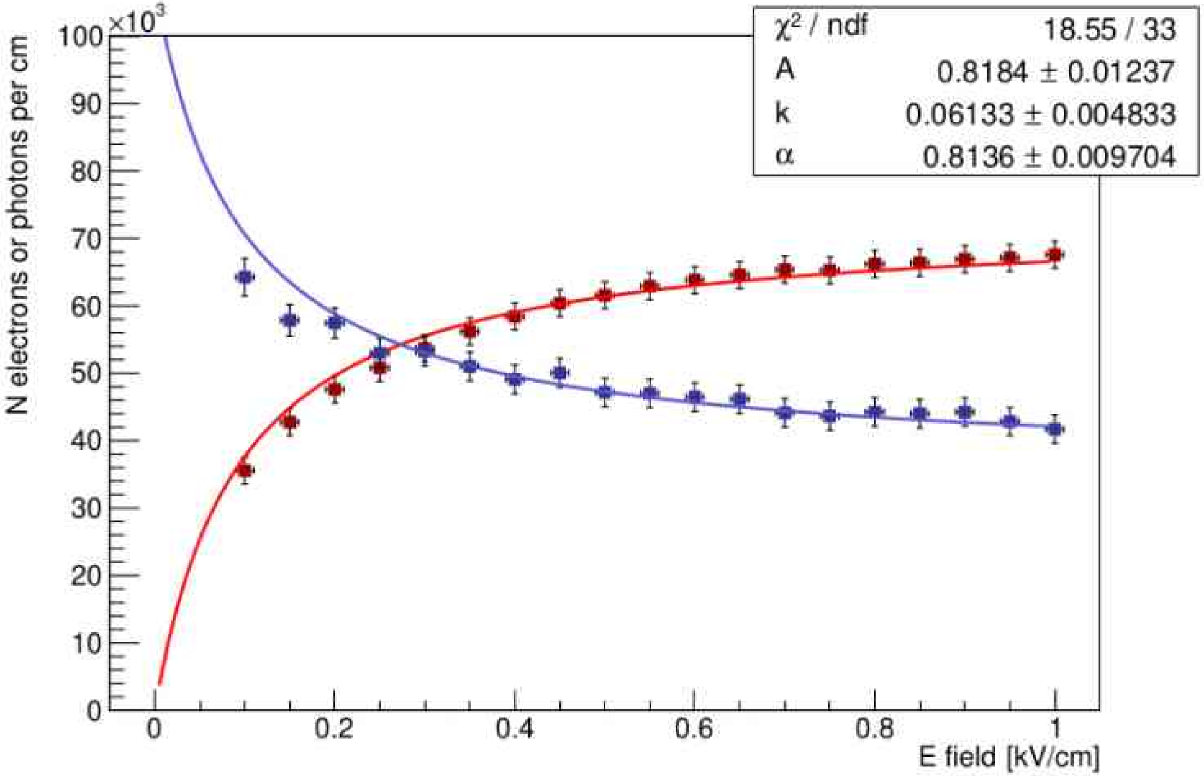
Module-0 Performance – Charge Readout



Flat acceptance as function of track angle

Credits: P. Madigan (LBNL)

Module-0 Performance – Charge / Light Anticorrelation



Measurements (points) and combined *modified Birk model* fit (lines) for charge (red) and light (blue) in Module-0

Relative charge yield R_C

$$R_C = \frac{Q}{Q_\infty} = \frac{A}{1 + \frac{k}{\epsilon} \cdot \frac{dE}{dx}}$$

Relative light yield R_L

$$R_L = \frac{L}{L_0} = 1 - \alpha \cdot R_C$$

ε:	Electric field intensity
α:	Parameters fit to data
A, k:	Parameters fit to data
dE/dx:	Mass stopping power

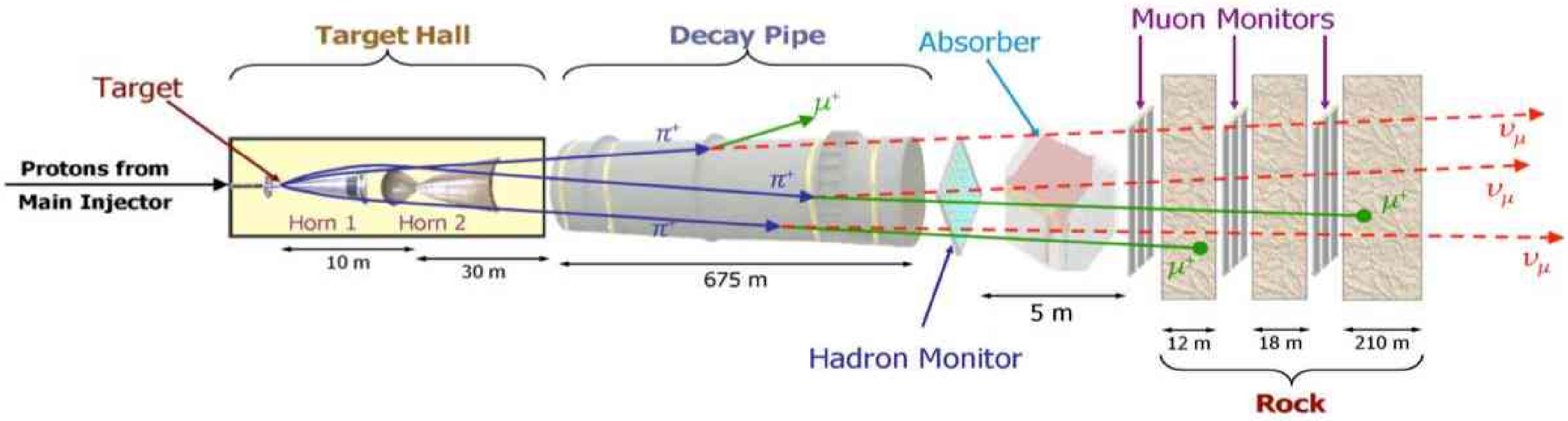
Appendix G

NuMI & LBNF Beam

NuMI Beam

Neutrinos at the Main Injector – NuMI

→ 120 GeV primary proton beam
→ Graphite target with a length of 953.8 cm
→ Two parabolic focusing horns, each ≈ 3.5 m in length
→ 675 m long decay pipe



Source: https://arxiv.org/abs/1507.06690

NuMI vs. LBNF Beam

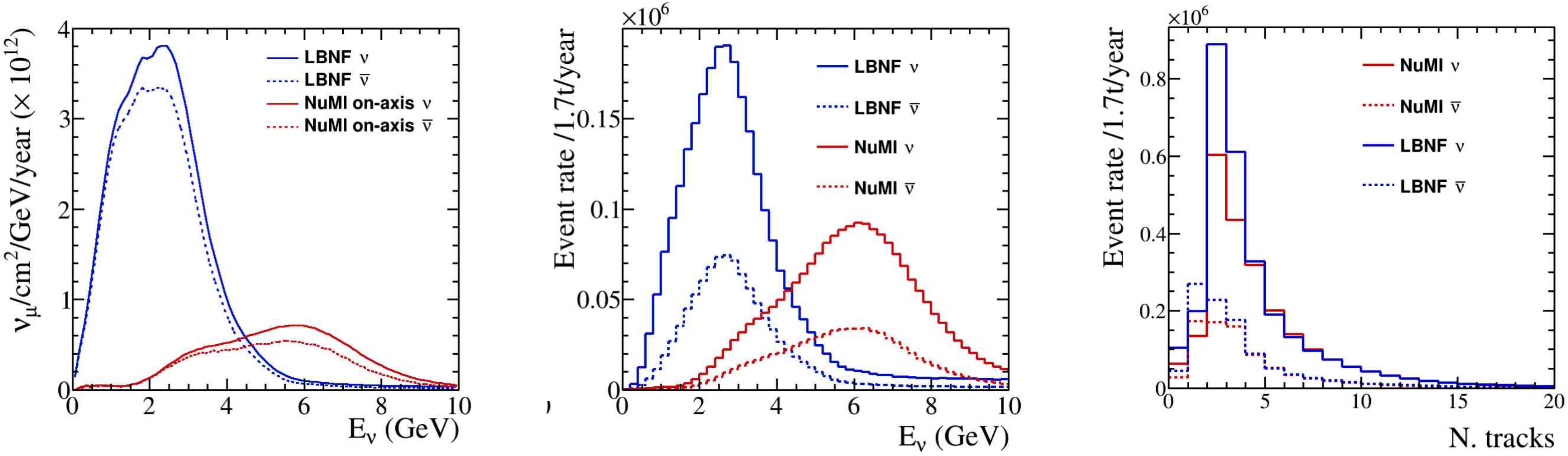
NuMI[1] compared to LBNF[2]

→ Lower flux, but higher ν / $\bar{\nu}$ energy where the cross section is larger

→ Event rate & track multiplicity in ProtoDUNE-ND comparable with those in ND-Lar

→ Scale of reconstruction challenge is similar for both detector types

→ ProtoDUNE-ND suitable to test and benchmark the ND-LAr event reconstruction



Source: https://arxiv.org/abs/2103.13910

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[1] In MINOS ND hall

[2] In DUNE-ND hall

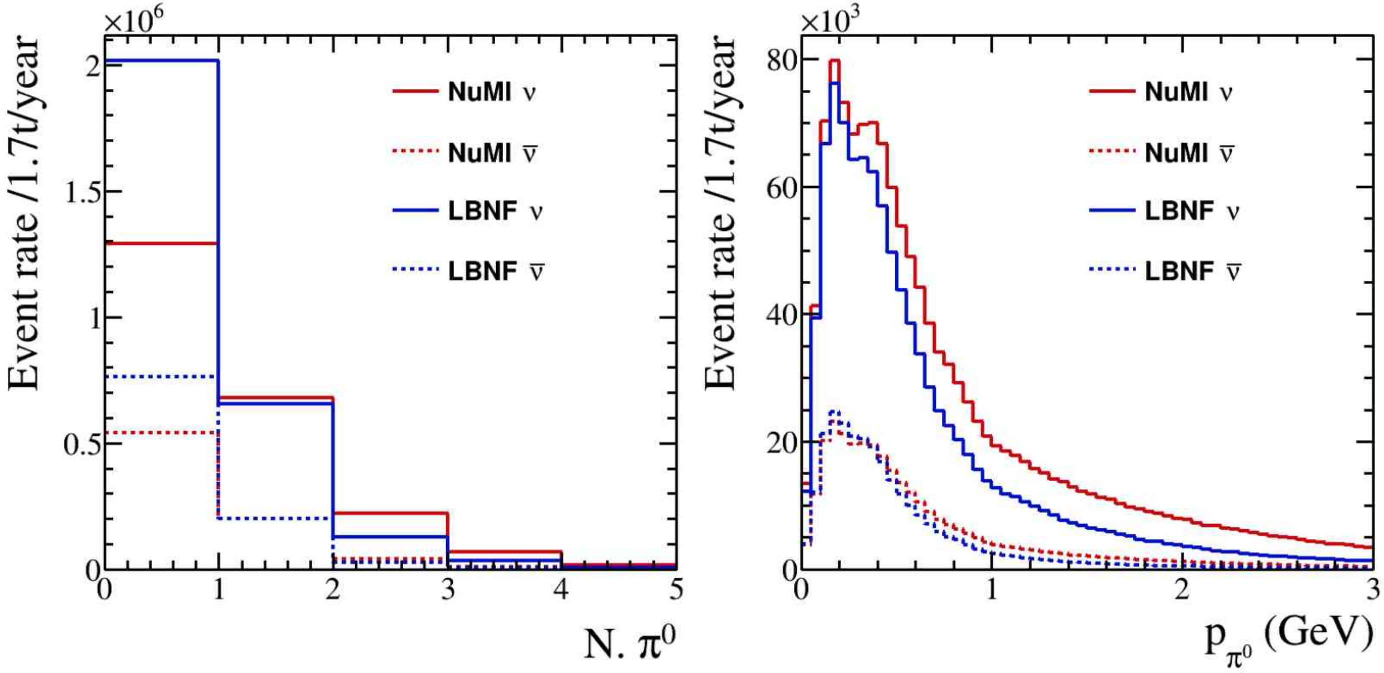
NuMI vs. LBNF Beam

Neutral pions (primaries)

→ Comparable number of π^0 produced in ProtoDUNE-ND and in DUNE ND-Lar

→ Similar π^0 momenta

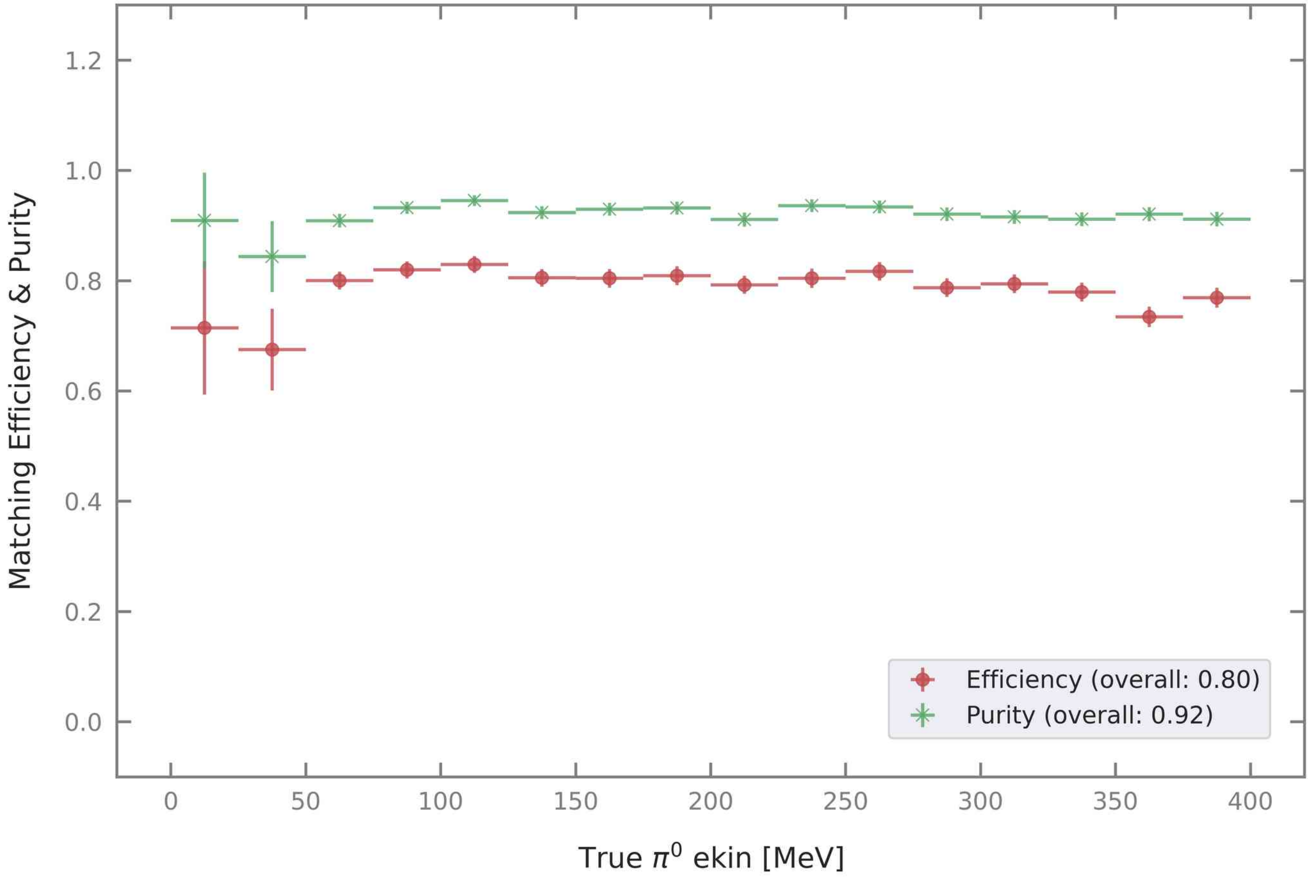
→ Scale of reconstruction challenge is similar for both detector types



Source: https://arxiv.org/abs/2103.13910

Appendix H
Event Reconstruction in LArTPCs

Neutral Pion Reconstruction Performance



$$\text{Purity} \overset{\text{def}}{=} \frac{\text{correctly matched } \pi^0}{\text{total reco } \pi^0}$$

$$\text{Efficiency} \overset{\text{def}}{=} \frac{\text{correctly matched } \pi^0}{\text{total true } \pi^0}$$

Electron Rejection in $\gamma + \gamma \rightarrow \pi^0$ Matcher

Showers with reconstructed start close to vertex candidate likely are induced by (primary) electrons

→ Reject if start is closer than 3px to vertex candidate

Fraction F of photons converting to e^-e^+ pair (without first Compton scattering) within the first n pixels*:

$$F = 1 - \exp\left(\frac{-x}{9/7\cdot X_0}\right) = 1 - \exp\left(-n\cdot\frac{0.3\ \text{cm}}{18\ \text{cm}}\right)$$

Conversion distance	Fraction of photons converting [%]
< 5 px	8.0
< 4 px	6.4
< 3 px	4.9
< 2 px	3.3

* pixel pitch = 0.3 cm
radiation length in LAr ≈ $9/7 \cdot X_0$ = 18 cm