Neutrino interaction reconstruction in DUNE using scintillation light

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Outline

- Neutrino Basics
- DUNE
- Simulation and Reconstruction of interactions in liquid argon TPCs
  - Ionization charge and scintillation light
  - LArQL Model
- The role of the photon detectors in DUNE physics
- Closing remarks

The Standard Model

	quarks		leptons	
First gen.	**u**	**d**	e^-	ν_e
Second gen.	**c**	**s**	μ^-	ν_μ
Third gen.	**t**	**b**	τ^-	ν_τ

Six quarks

Three charged leptons: electron, muon, tau

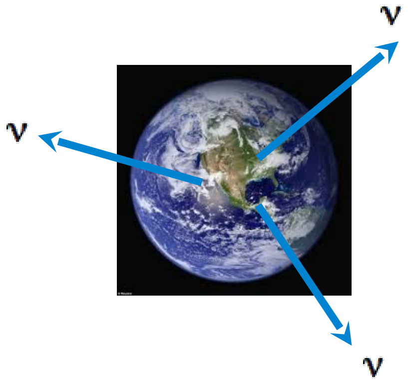
Three neutral leptons: neutrinos

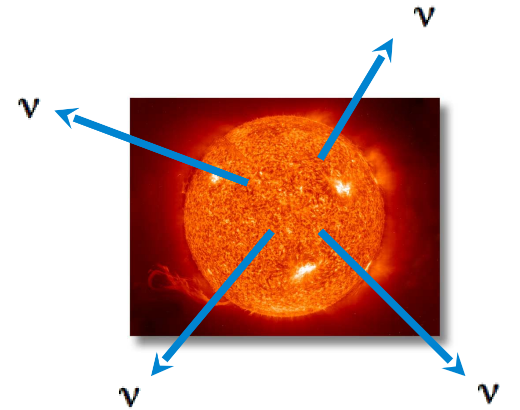
+ corresponding antiparticles

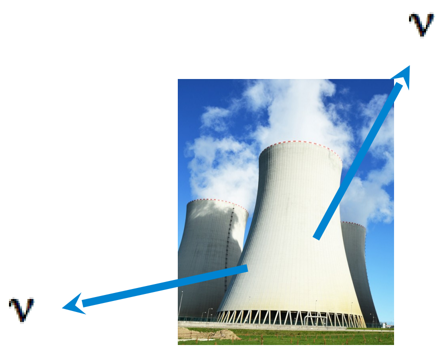
+ bosons (γ, g, W^{+-}, Z_0, H)

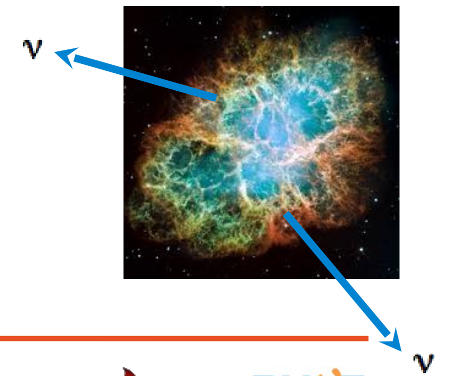
Neutrinos

- Second most abundant particle: ~300 νs in each cm^3
- Interact via weak interaction (and gravity)
- Neutrino sources
  - Big Bang
  - Sun
  - Core-collapse Supernovae
  - Cosmic rays in the atmosphere
  - AGNs
  - Nuclear reactors
  - Radioactive (beta) decays
  - Particle accelerators









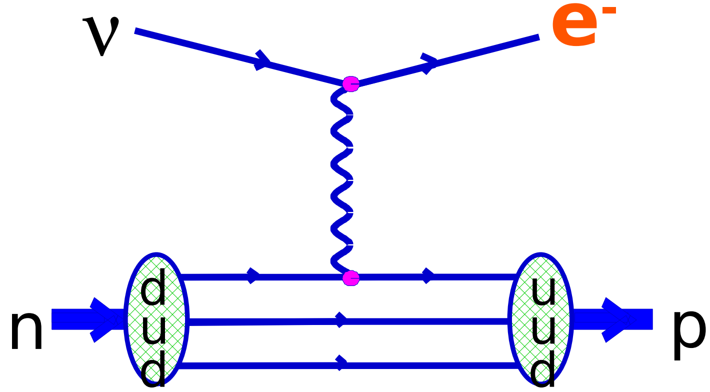
Detecting Neutrinos

- Neutrino cross sections are TINY! (~10^{-38} cm^2. E.g. e^--nucleus X-sec at least 20 orders of magnitude higher)
- Interact very little under normal circumstances

- We need large detectors and large fluxes of neutrinos
- We never directly detect a neutrino, just the product of the reactions

Ex: $n + \nu_e \rightarrow p + e^-$

→ Typically detect the charged lepton



Neutrino Oscillations

- Experiments indicate that:
  - There are (at least) 3 neutrino flavors (ν_e, ν_μ, ν_τ)
  - Neutrinos travel as a combination of mass states: (ν_1, ν_2, ν_3)
  - Flavor mixing is **large**
  - Neutrinos mass differences are **small**
    - Masses < 0.8 eV
    - $(m_2^2 - m_1^2) \sim (7.53 \pm 0.18)\ 10^{-5}\ eV^2$
    - $|(m_3^2 - m_2^2)| \sim 2.5\ 10^{-3}\ eV^2$

ν_1 is lighter than ν_2

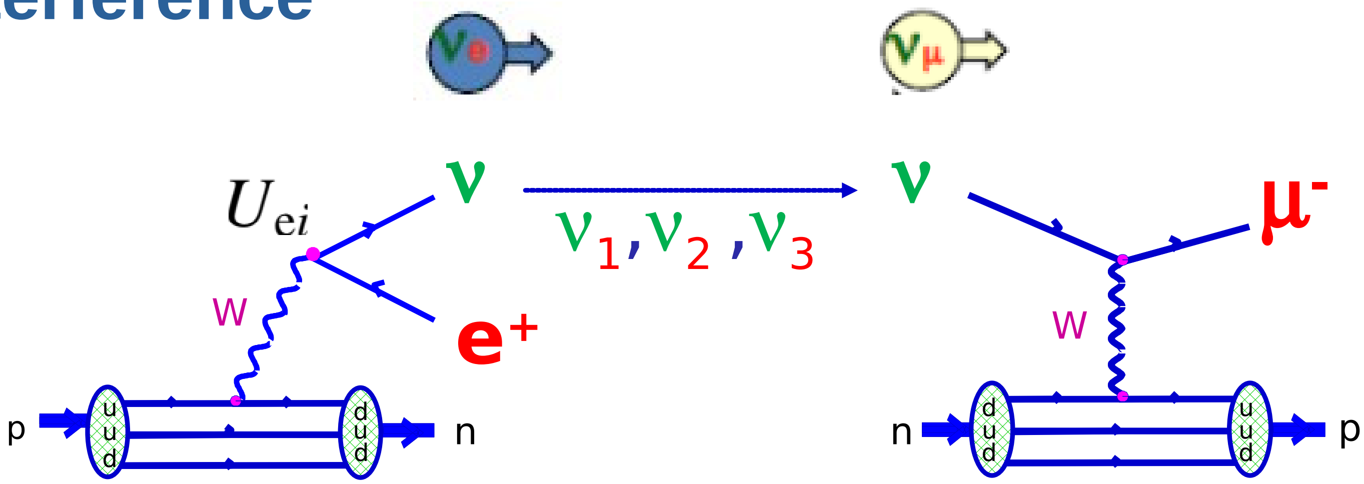
Mass difference between ν_2 and ν_3 is larger than between ν_1 and ν_2

Neutrino Oscillations

- The fundamental particles are ν_1, ν_2 and ν_3
- Neutrinos propagate as a coherent QM superposition

$$|\nu(t)\rangle = \left(U_{e1}e^{-iE_1t}\nu_1 + U_{e2}e^{-iE_2t}\nu_2 + U_{e3}e^{-iE_3t}\nu_3\right)$$

- Over large distances - phase differences develop: **interference**



Neutrino Oscillations

- The oscillation probability (2-flavor approximation):

Mixing angle: determine the amplitude of the oscillations

Oscillation depends on L/E

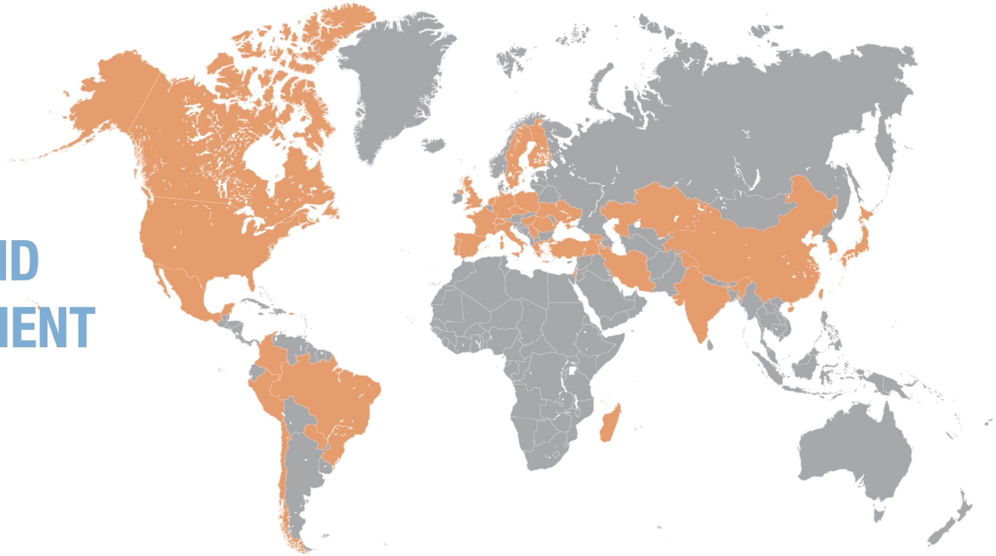
$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

Wavelength of oscillations is very long, determined by the very small neutrino mass differences

Deep Underground Neutrino Experiment

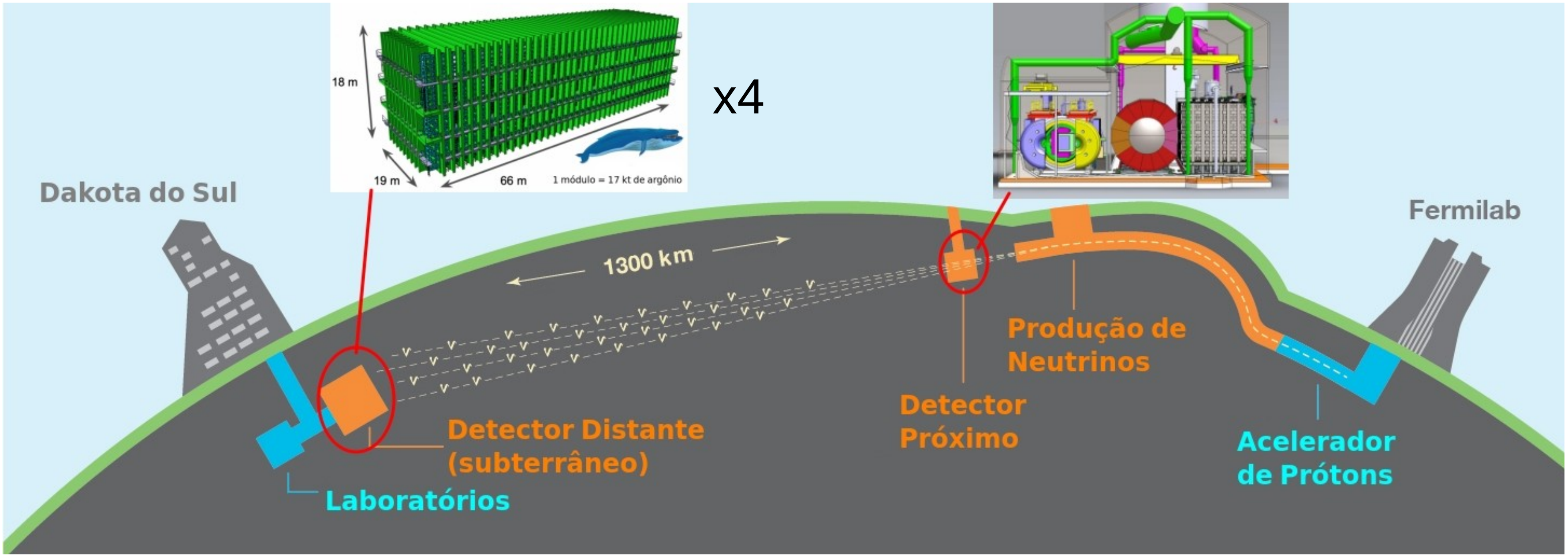
- Precision physics with huge liquid argon TPCs
- International Collaboration:
  1400+ collaborators
  200+ institutions
  35+ countries + CERN

DEEP UNDERGROUND
NEUTRINO EXPERIMENT



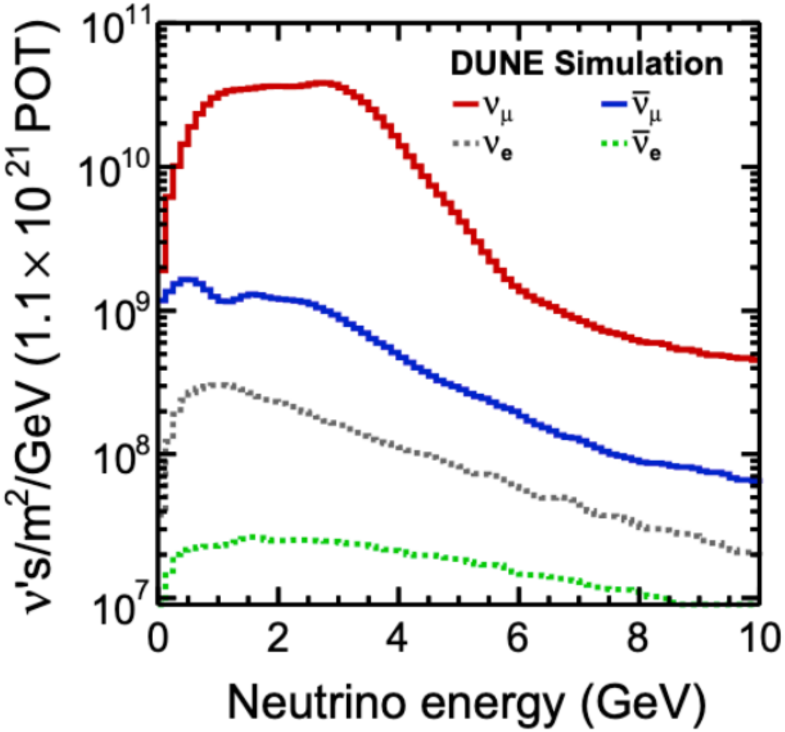
DUNE

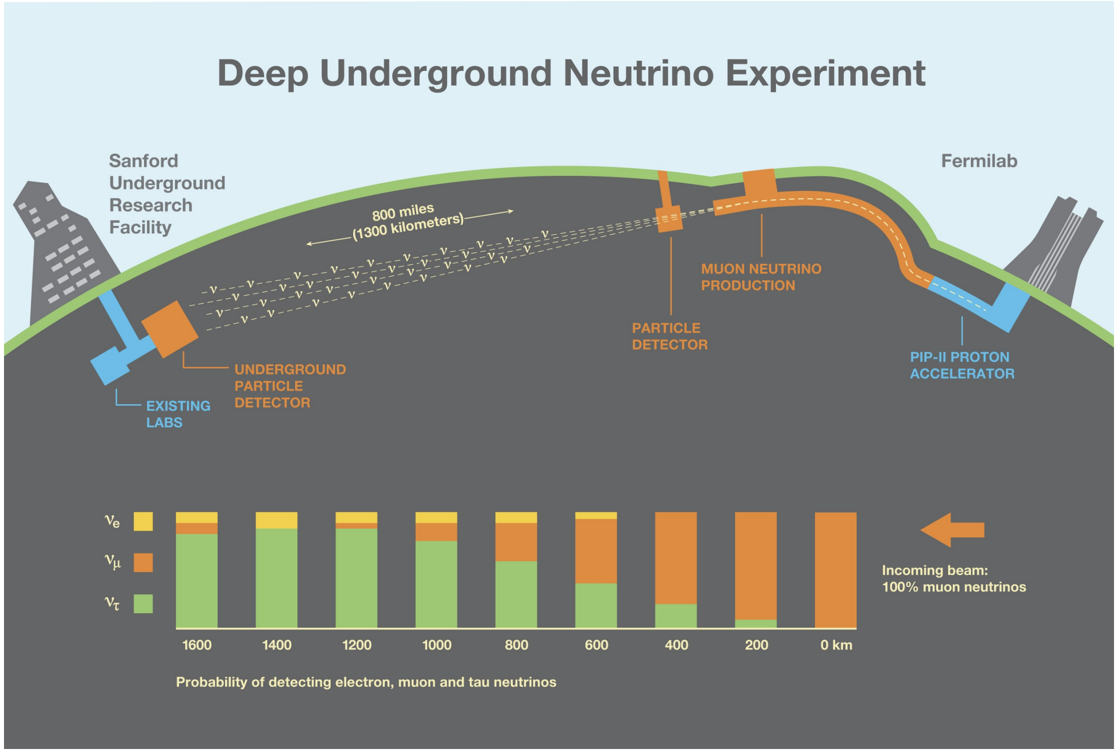
- The most powerful neutrino beam (MW) at Fermilab
- Diverse near detector complex
- Huge underground detector in South Dakota (70 kton of LAr)
- Beginning of data taking: 2029



DUNE

- Powerful and broadband neutrino beam
- Beam in 2032

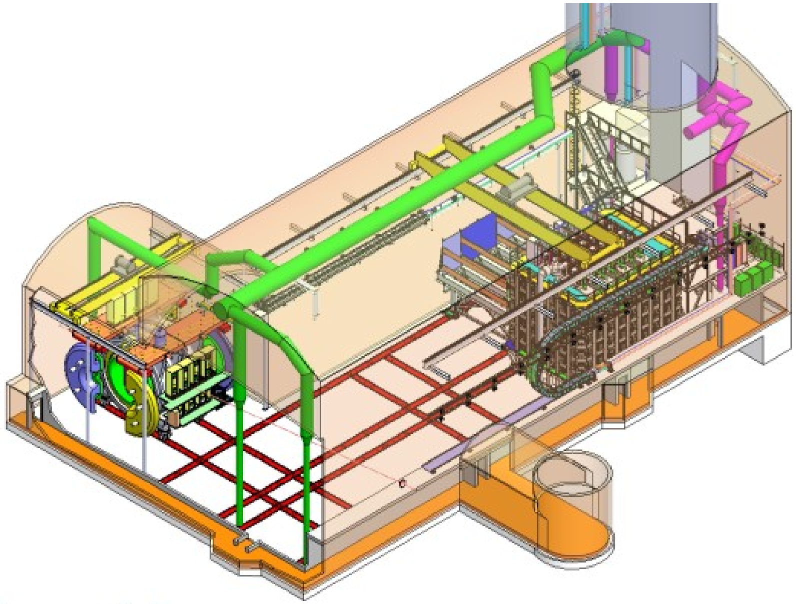


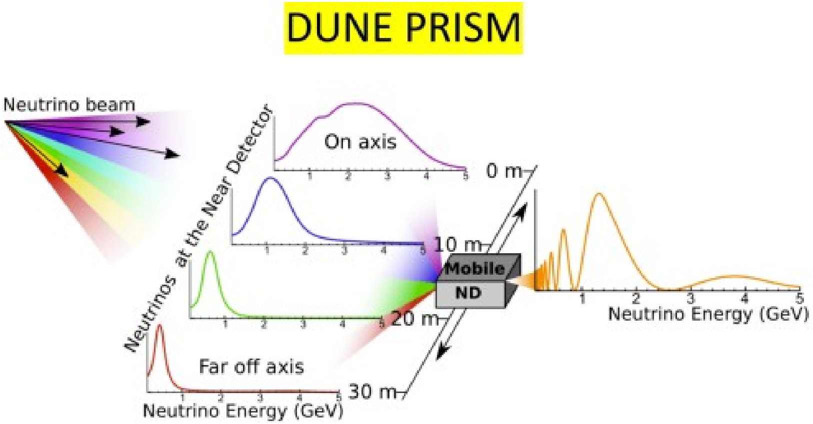


DUNE: Near Detector Complex

- For precise control of systematics: constrain Ar cross-section and detector response uncertainties, predict the observed Eν spectrum at FD
- ND-LAr: 130 tons of active volume, modular LArTPCs with pixel readout
- TMS: Magnetized detector for measuring muon momentum/sign from CC interactions in ND-LAr
- SAND: On-axis magnetized neutrino detector

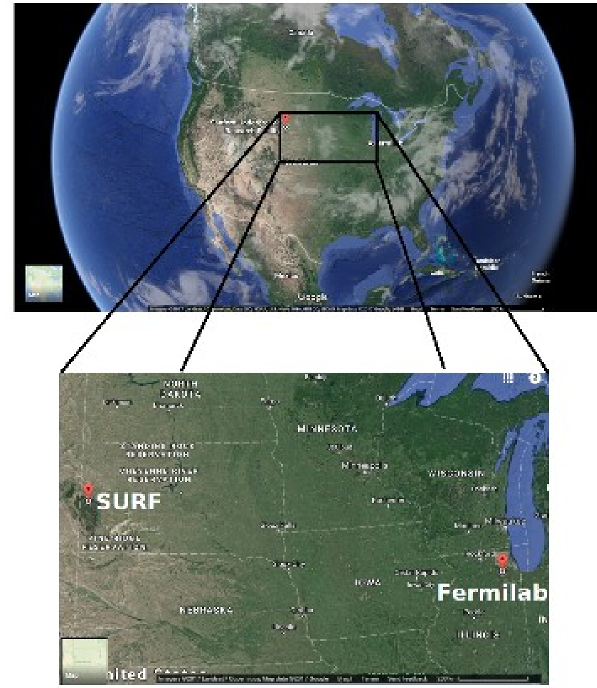
DUNE-PRISM: Move up to 28.5 m off-axis

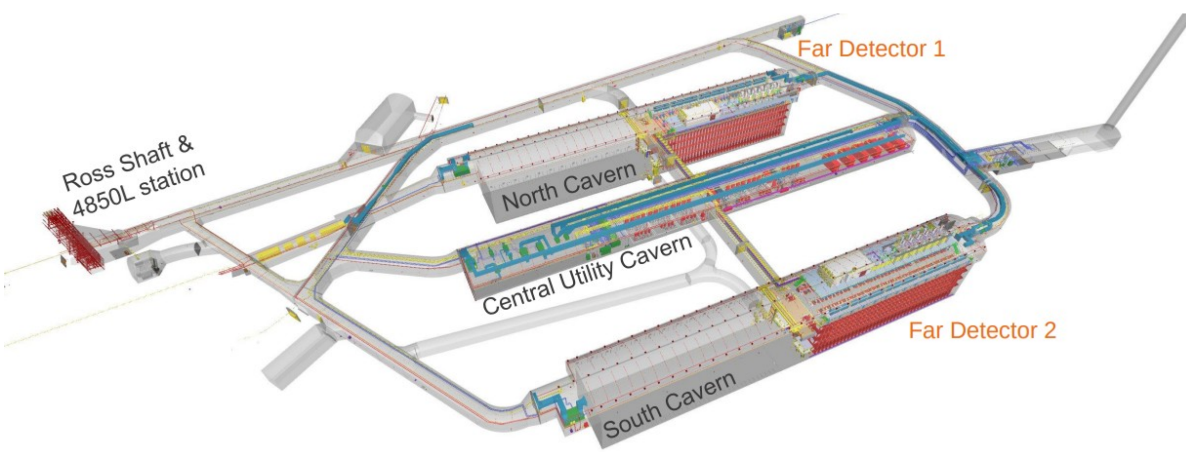


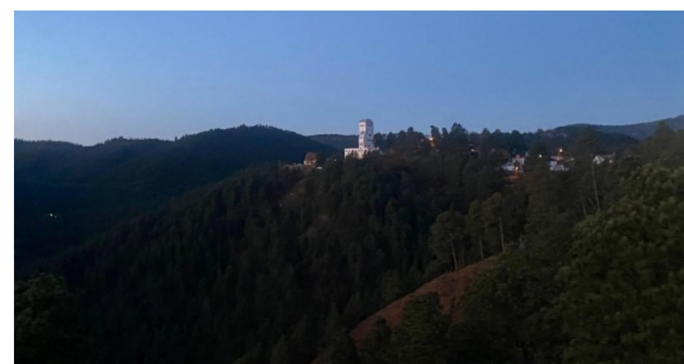


DUNE: Far Detector

- Cavern excavation 100% complete

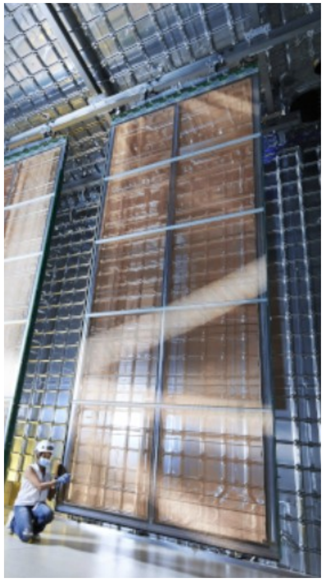


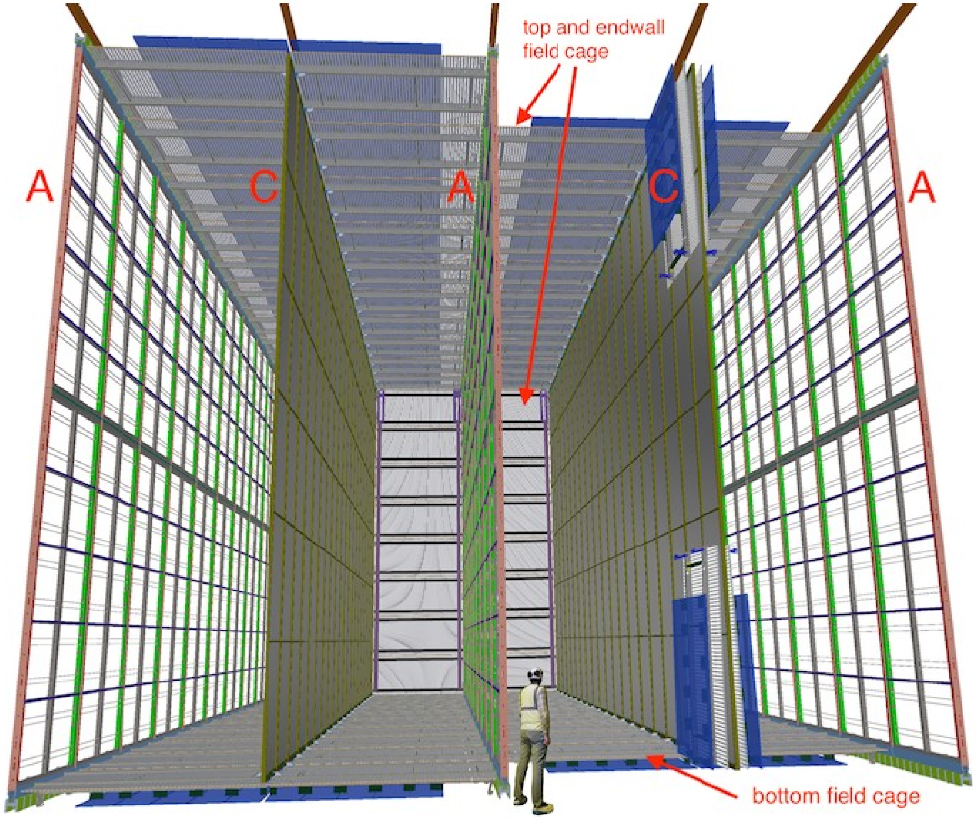




DUNE: Far Detector

- Horizontal drift detector
- 4 drift volumes
- Modular wire-based charge readout (APA)
- Scintillation light detectors integrated with APAs

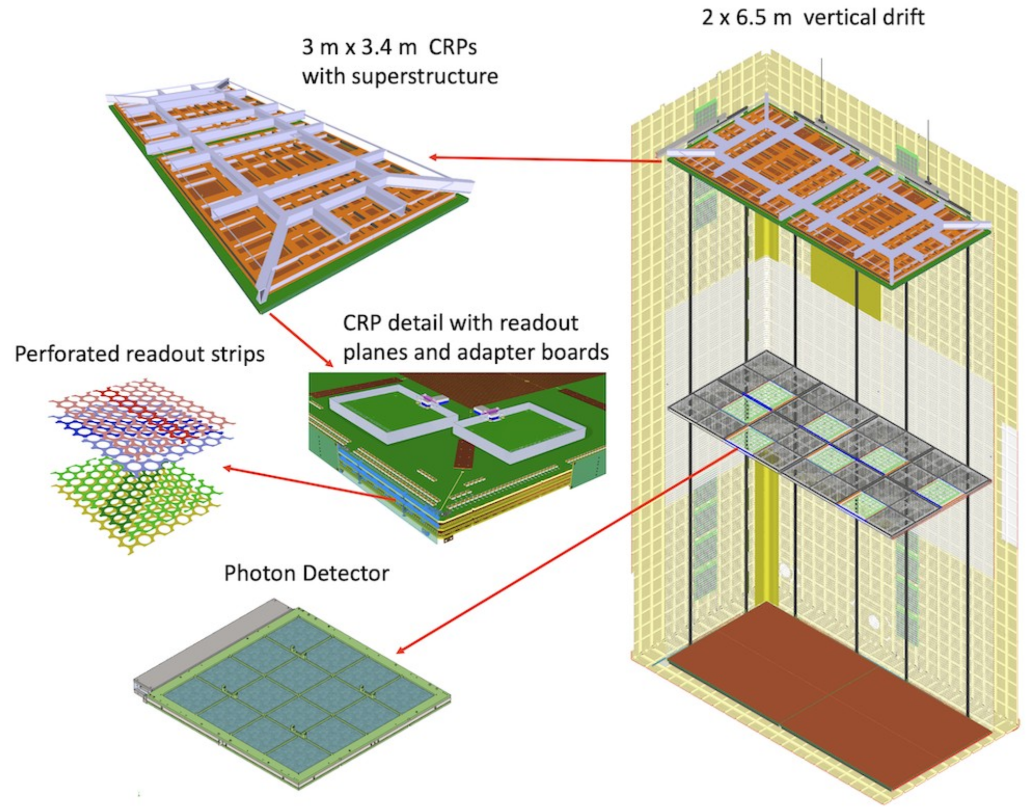


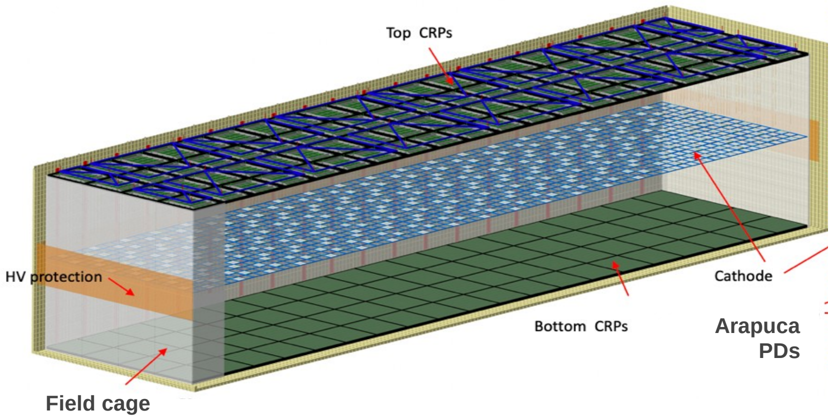


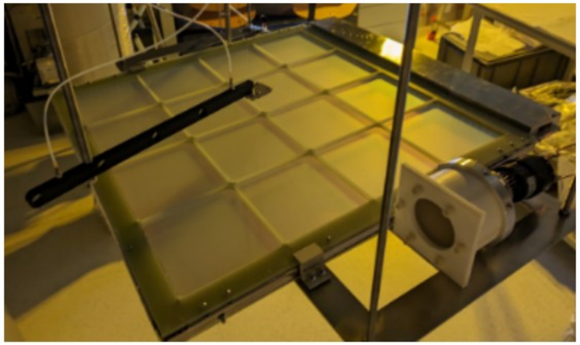
X-Arapucas

DUNE: Far Detector

- Vertical drift detector
- 2 drift volumes
- PCB-based charge readout
- Photon detectors integrated in cathode frame and on membrane walls
- Xe doped LAr







Choice of Liquid Argon

- Abundant ionization and scintillation light
- No electronegativity, free electrons travel large distances (if no impurities)
- Excellent dielectric properties (accommodate very large voltages)
- High density (ρ_{LAr}=1.78 kg/m^3)
- Low cost
- Argon: (uniquely) the largest sensitivity is $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K$
- Drawbacks
  - Low wavelength light
  - Nuclear effects
  - Cryogenic infrastructure (LAr @ -184^{o}C)

Neutrino Interactions in LAr

- Elastic scattering with electrons

$$\overset{(-)}{\nu}\ e^- \rightarrow \overset{(-)}{\nu}\ e^-$$

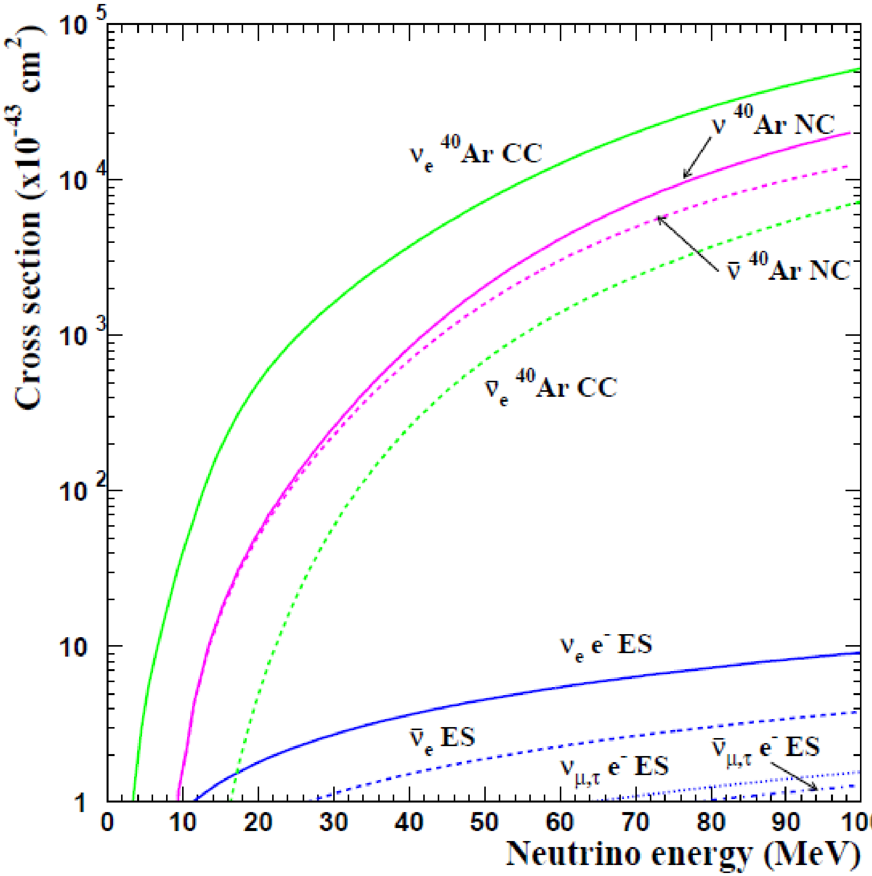
- Charged Current reactions (CC) with Ar

$$\nu_e\ {}^{40}Ar \rightarrow e^-\ {}^{40}K^*$$

$$\bar{\nu}_e\ {}^{40}Ar \rightarrow e^+\ {}^{40}Cl^*$$

- Neutral Current reactions (NC) with Ar

$$\overset{(-)}{\nu}\ {}^{40}Ar \rightarrow \overset{(-)}{\nu}\ {}^{40}Ar^*$$



DUNE: Primary Science Goals

Focus on fundamental open questions in particle physics and astroparticle physics:

1) Neutrino Oscillation Physics

- Measure CP Violation phase in the leptonic sector
- Mass Ordering (the sign of $\Delta m^2_{31} \equiv m_3^2 - m_1^2$)
- Precision Oscillation Physics

2) Physics beyond SM

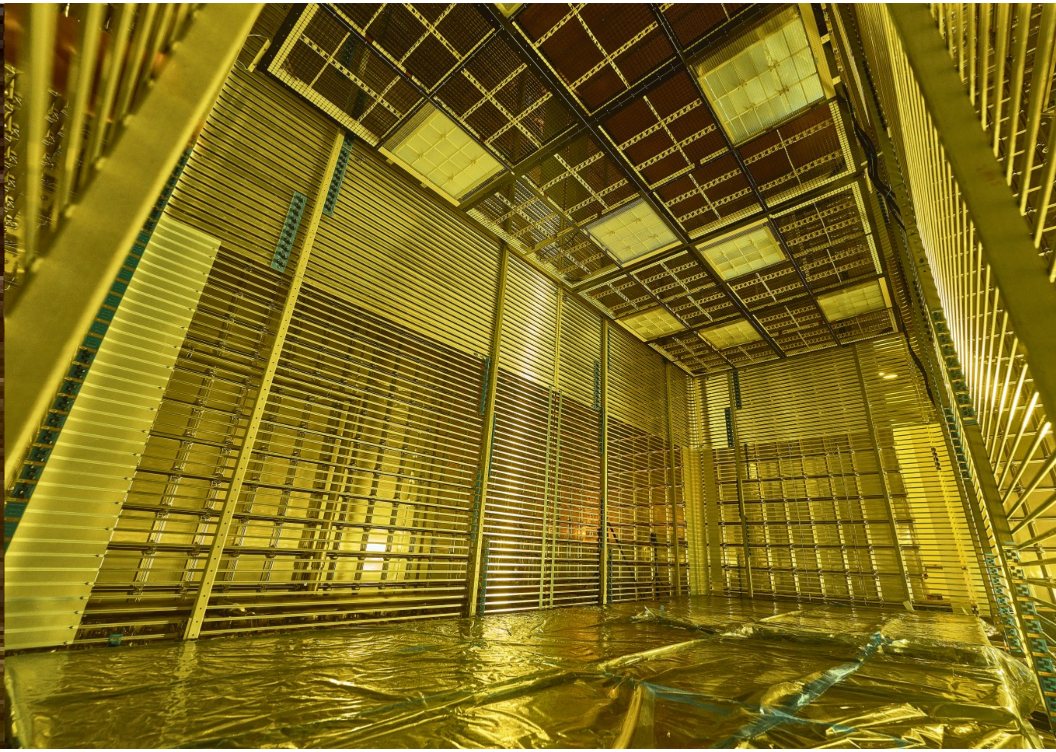
3) Supernova burst physics & astrophysics

ProtoDUNEs

Prototypes of DUNE’s far detectors at CERN - France

ProtoDUNEs

Two cryostats of 7.2×6.0×6.9 m³ (1.1% of a DUNE's FD module)



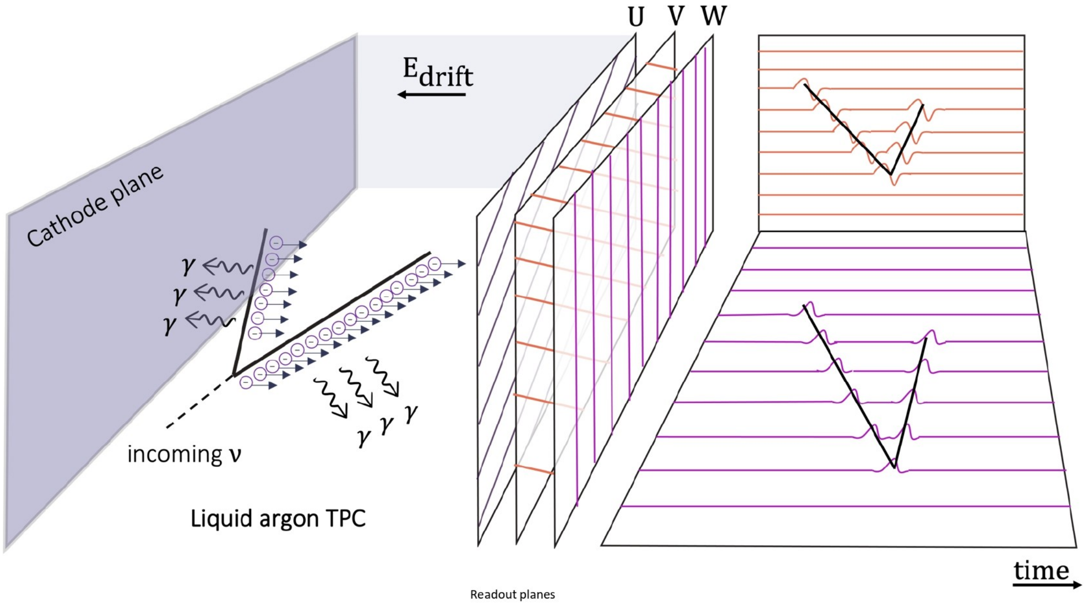
- Develop and test the technology to be employed in DUNE's FD
- First data taking in 2018
- Second data taking 2024-2025

- Mitigation of engineering risks
- Development of production processes
- Validation of components
- Physics calibration/reconstruction

LAr Time Projection Chamber

- Combining 2D images → full 3D reconstruction
- The total ionization charge and scintillation light are proportional to the deposited energy

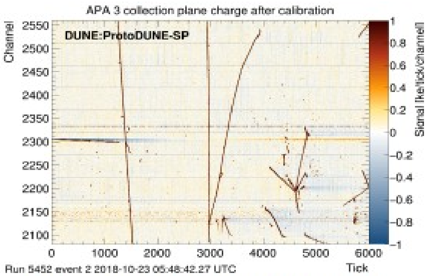
- Combining Energy & Direction → dE/dx along the track → Particle Identification



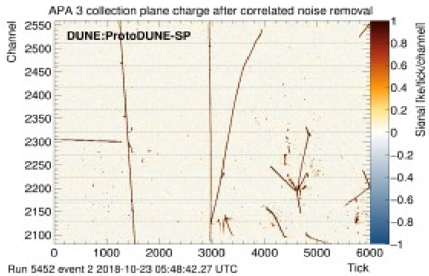
DUNE: Observe particle tracks with few mm precision anywhere in the 60 x 14 x 12 m³ volume

DUNE: Charge Reconstruction

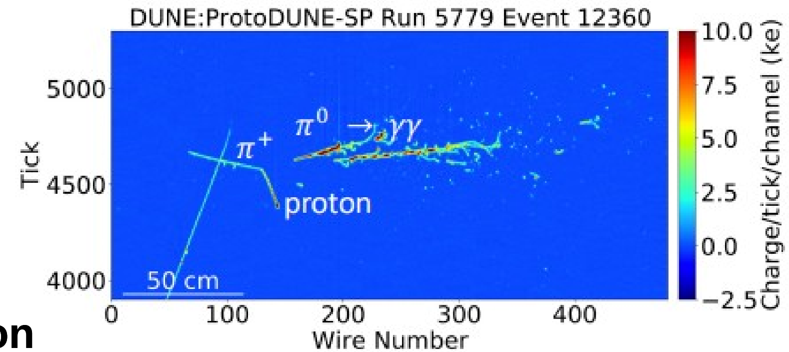
After pedestal subtraction/calibration

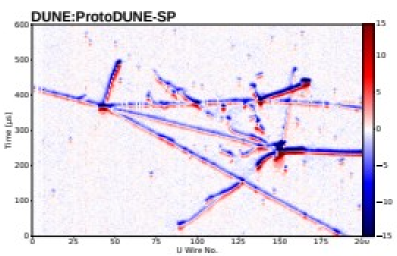


After ADC/time mitigation and tail/noise removal

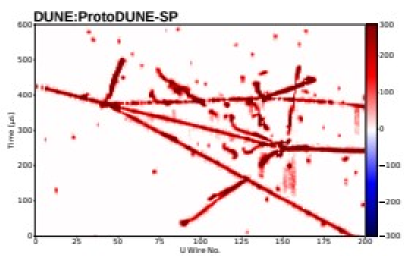


Data preparation





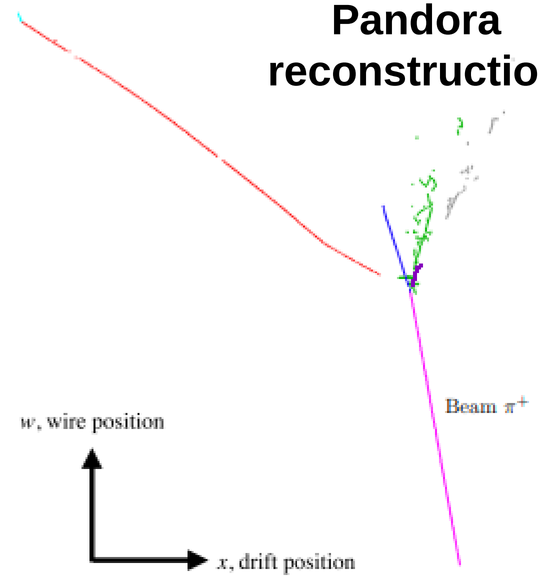
(a) After Noise Filtering

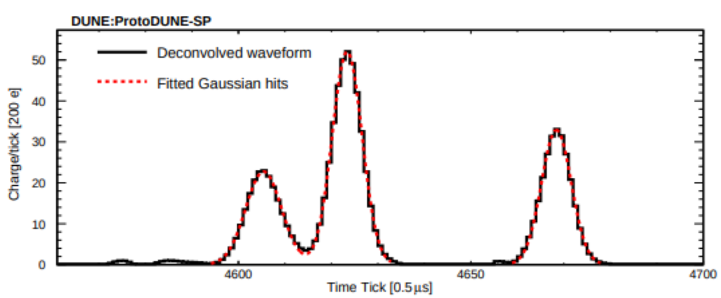


(b) After Deconvolution

Signal processing

Pandora reconstruction





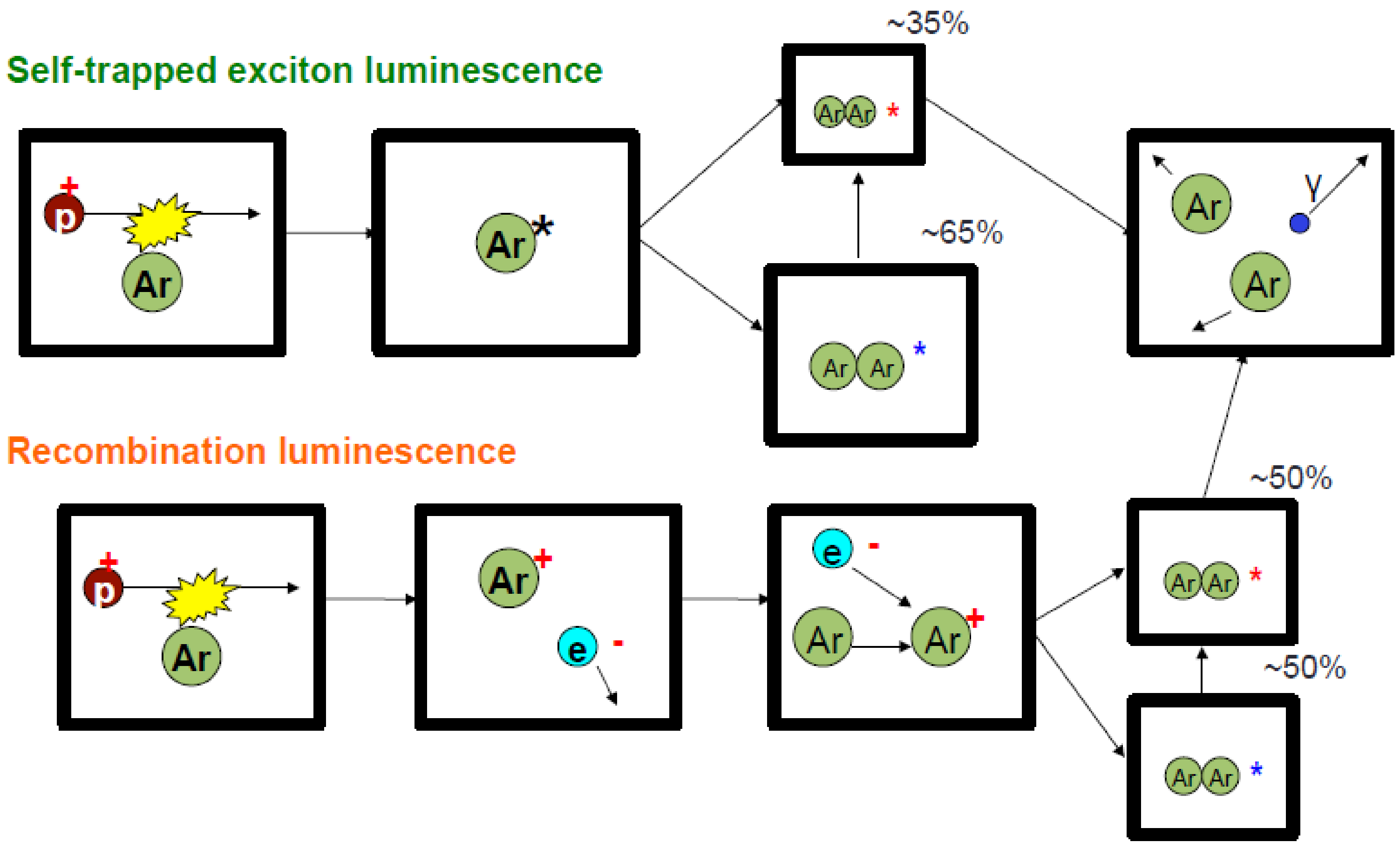
Hit finding

2020 JINST 15 P12004

Maria B. Brunetti, APS April Mtg 2024

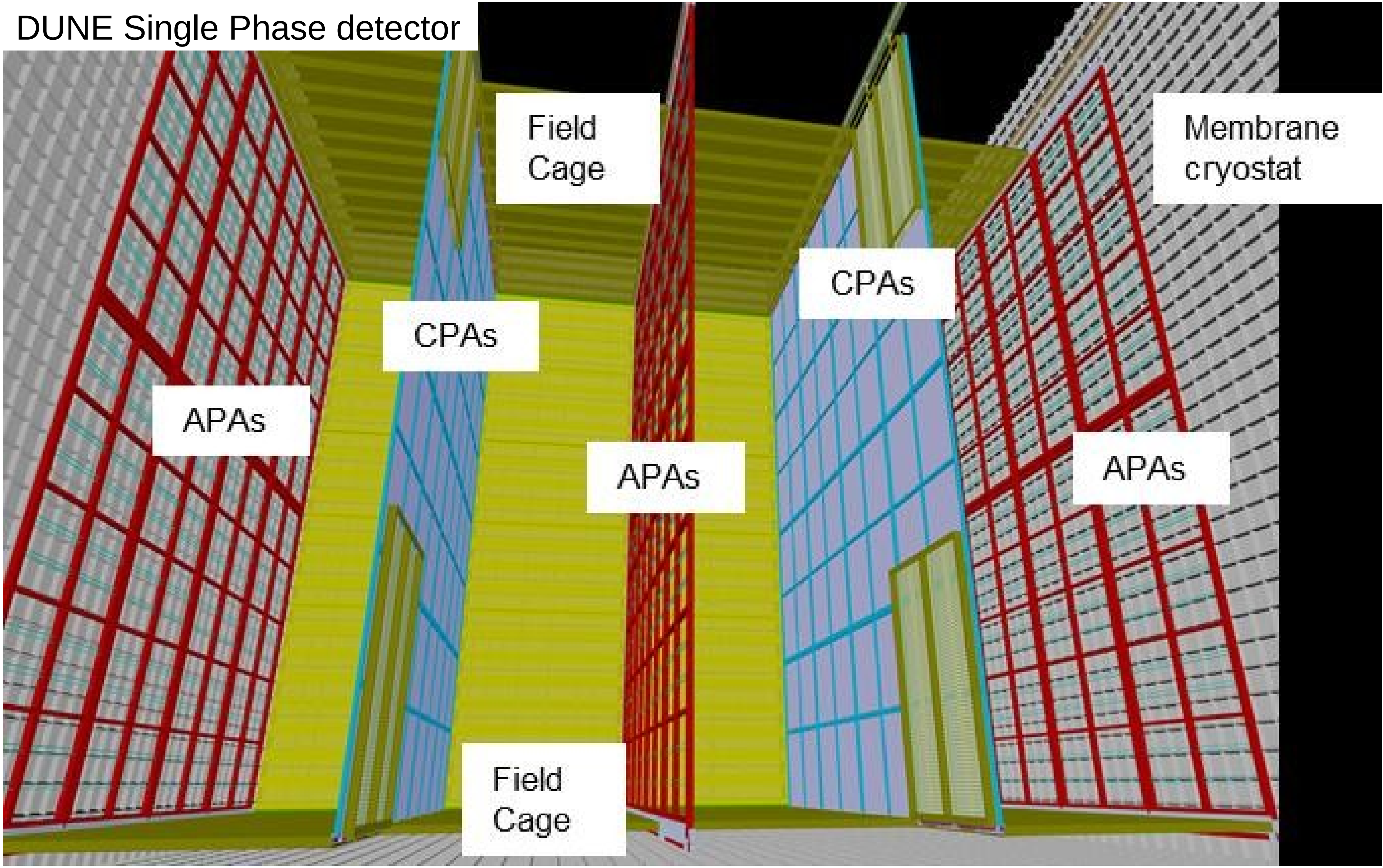
Argon scintillation

- The amount of charge and light produced by a particle is anti-correlated

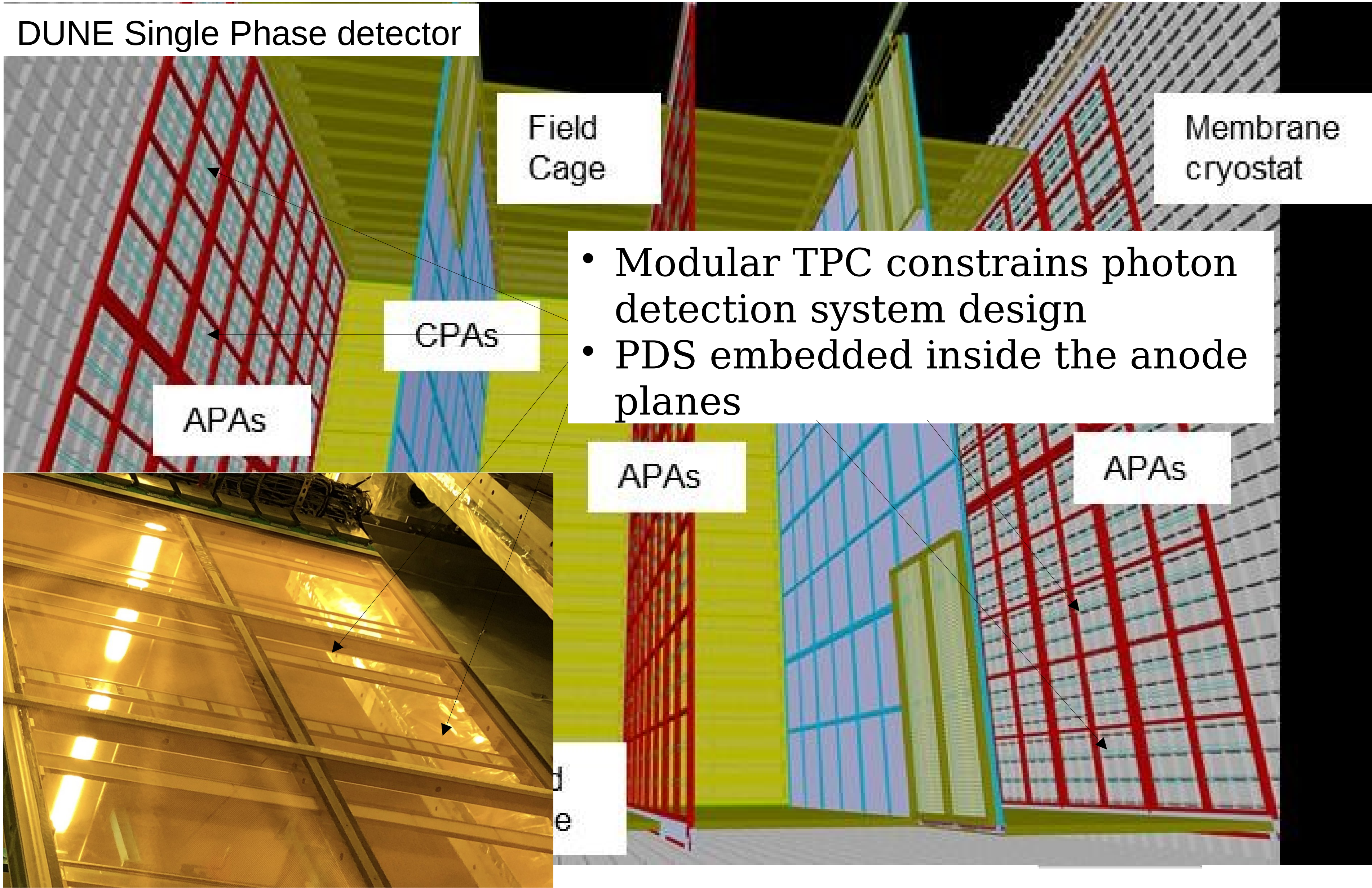


LArTPC Light Detectors

DUNE Single Phase detector



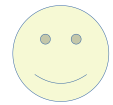
LArTPC Light Detectors

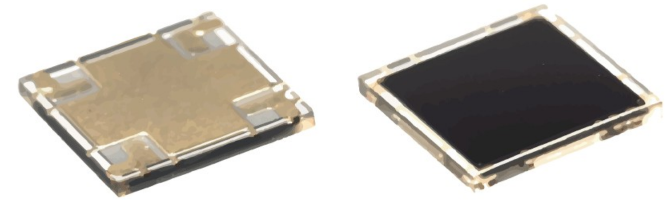


- Modular TPC constrains photon detection system design
- PDS embedded inside the anode planes

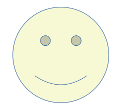
LArTPC Light Detectors

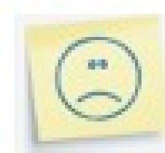
- Silicon photomultiplier (SiPM)
  - Good efficiency (cryogenic)
  - Cheaper
  - Requires lower voltage



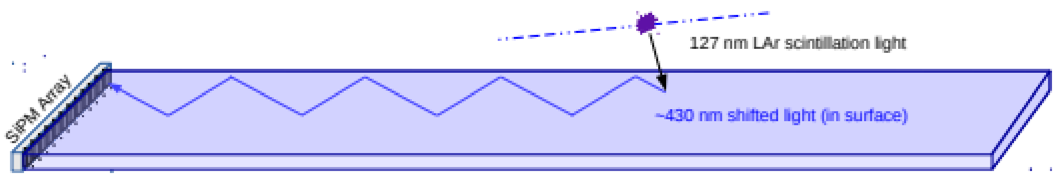


  - (Much) Smaller area





- Wavelength shifter light guide
  - Total internal reflection

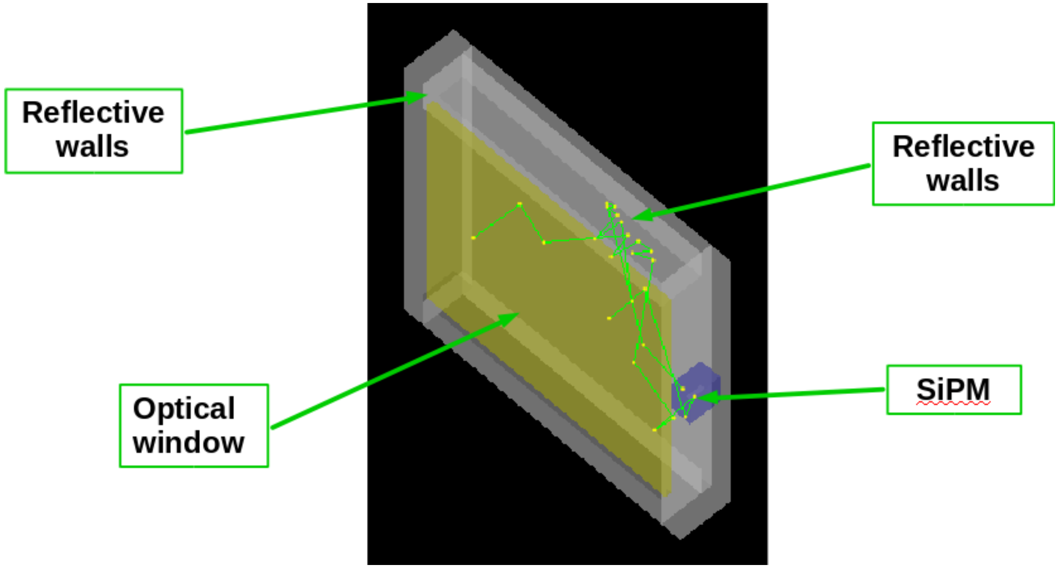


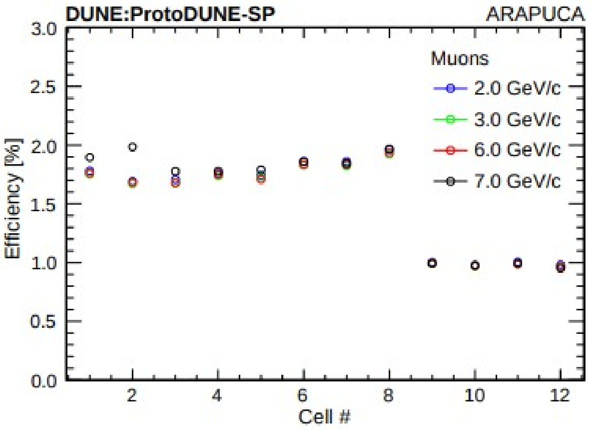
$n_{bar} > n_{LAr}$

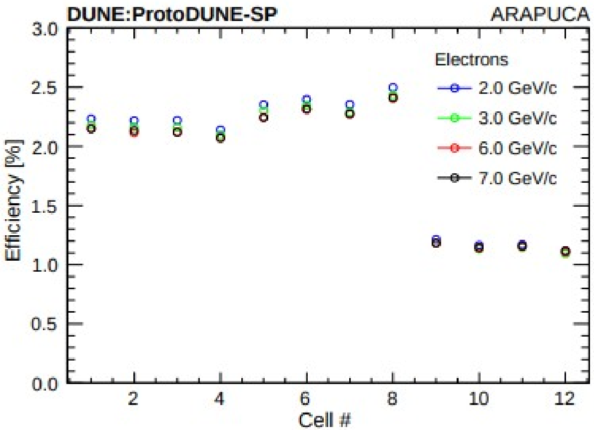
  - Efficiency up to ~0.1%

The ARAPUCA device

- “Light trap” that increases the effective area of the light detector device, SiPM





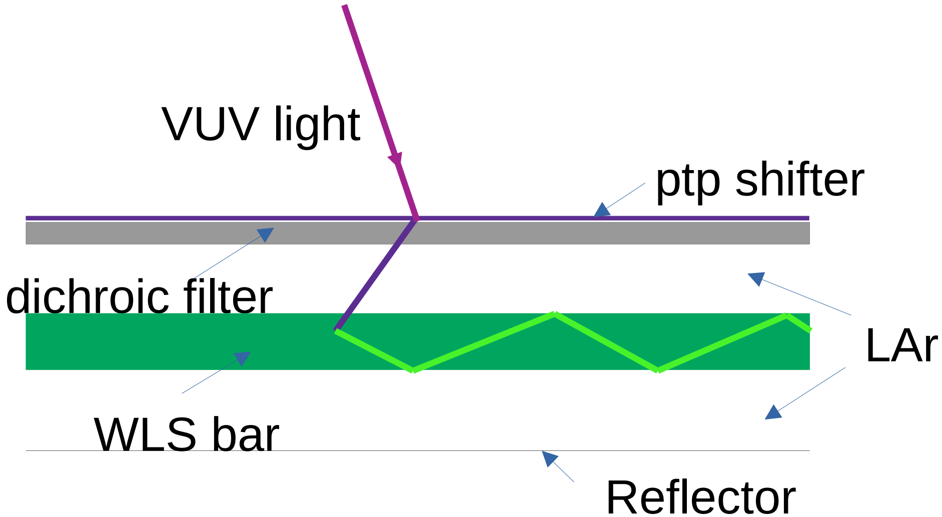


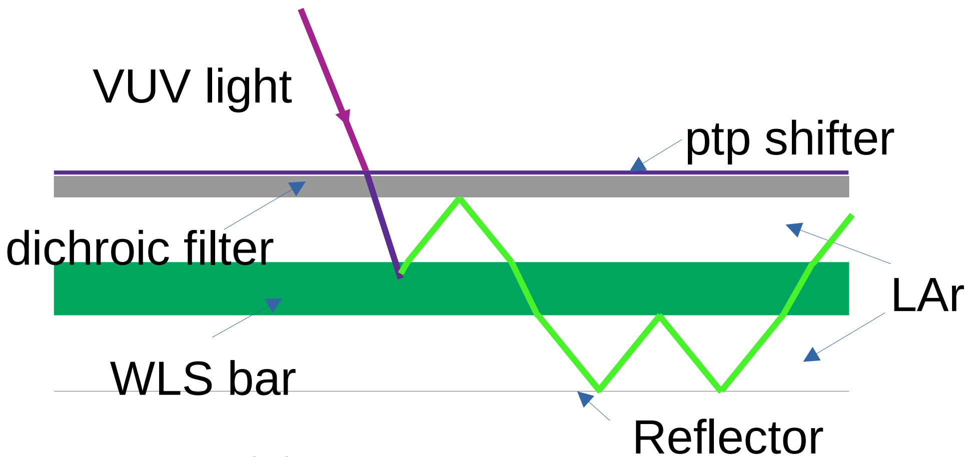
A.A. Machado and E. Segreto, JInst, 11, C02004 (2016)
F Marinho, et al, J Phys. CS 1056 (1), 012036 (2018)

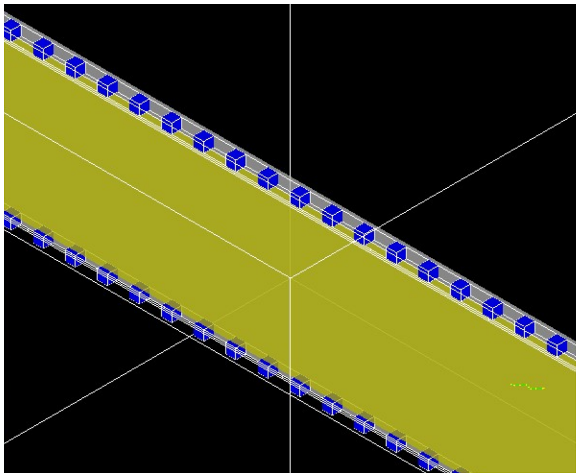
B. Abi et al 2020 JINST 15 P12004

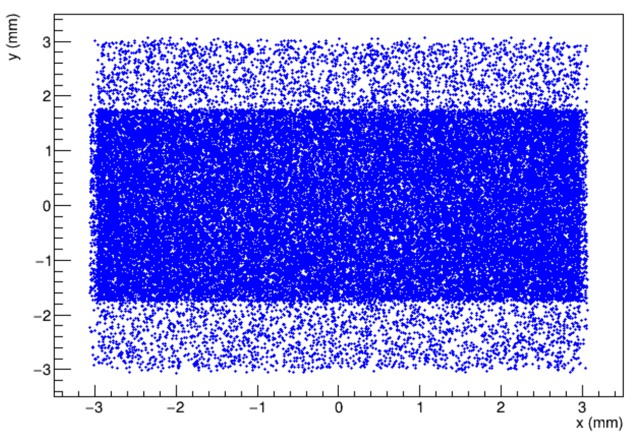
The X-ARAPUCA device

- ARAPUCA + acrylic bar total internal reflection concepts





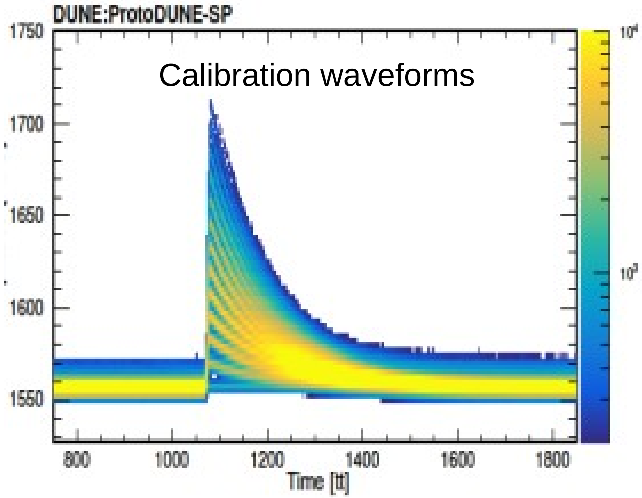




LP. et al, JInst 15 (01), C01047

DUNE: Scintillation Light Reconstruction

- Scintillation photons emitted isotropically along ionization trail



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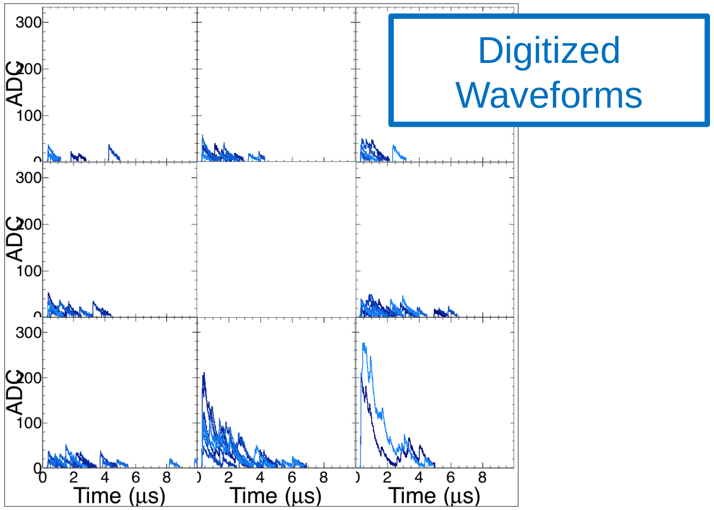
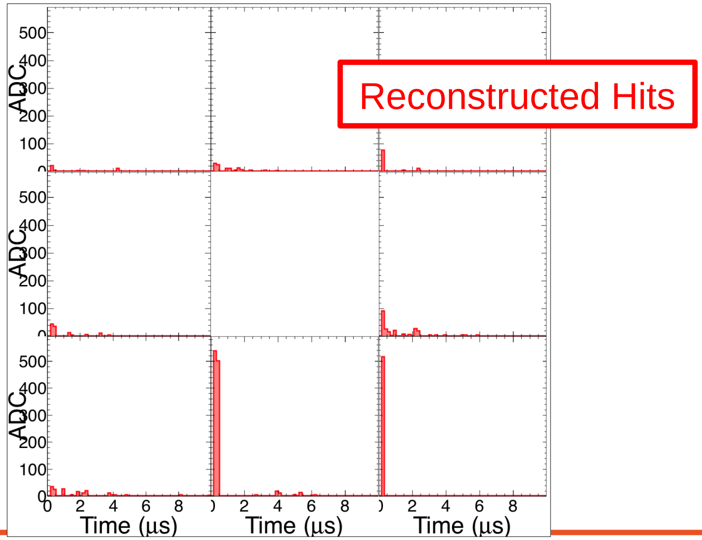


After pedestal subtraction/calibration, noise removal



Detection of scintillation light can provide:

- absolute time of the event
- internal trigger
- Correction for charge attenuation

DUNE: Simulation of light signal

Detection efficiency of the Arapuca bar in ProtoDUNE-SP: Discrepancy between values obtained for electron and muon beam particles

↓

LArQL Model: Unitary model for Ionization Charge AND Scintillation Light in LAr as function of deposited energy density (dE/dx) AND electric field (ξ)

Cover the range of interest for LArTPC for Neutrino Experiments:

2 MeV/cm < dE/dx < 40 MeV/cm, 0.25 kV/cm < ξ < 0.5 kV/cm

Charge-light master equation

$$QY\left(dE/dx,\xi\right)+LY\left(dE/dx,\xi\right)=N_i+N_{ex}$$

Free Charge Yield: [e/MeV] Light Yield: [ph/MeV]

Light reduction at ξ=0 and low dE/dx due to **electrons escaping recombination**

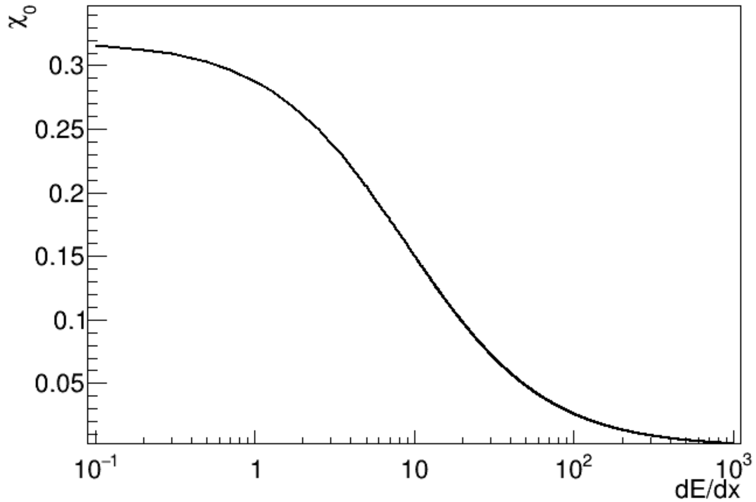
LArQL Model

- 3 experimental parameters

$N_i = 1/W_{ion}$: ionizations per energy unit

N_{ex}/N_i : excitations/ionizations

$\chi_0(dE/dx)$: fraction of escaping electrons



Light yield obtained from free charge yield

$$LY = N_i - QY + N_{ex} = LY_{rec} + LY_{ex},$$ as e^-_{rec} = ph.$_{\text{from rec}}$

Modifies Birks charge model correcting for escaping and additional electrons at lower ξ range

1- At $\xi = 0$, escaping electrons taken into account

2- Just above $\xi = 0$ adds field extracted electrons

3- At higher, escaping $e^- \rightarrow 0$ and Birks recovered

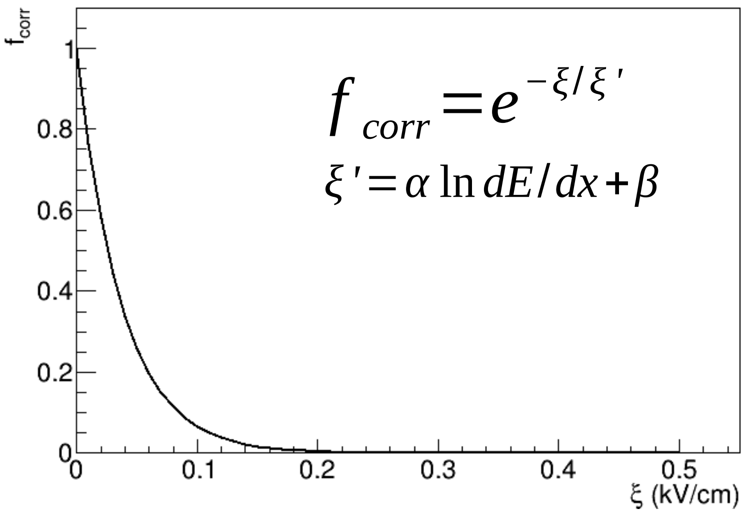
F. Marinho, et al, JINST 17, C07009 (2022)

LArQL Model

- Modifies Birks charge model correcting for escaping and additional electrons at lower field range

$$\chi_0 \rightarrow \chi = \chi_0(dE/dx)\, f_{corr}(\xi, dE/dx)$$

$$dQ/dE_{birks} \rightarrow dQ/dE_{birks} + \chi$$



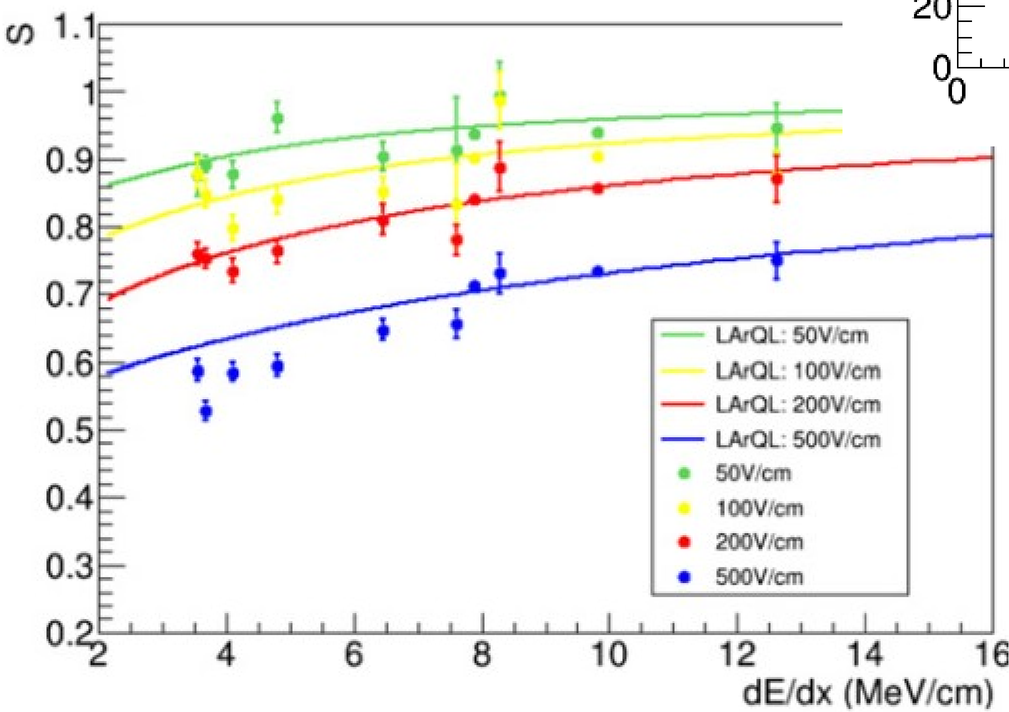
$$\frac{dQ}{dx} = \left(\frac{A_B}{1 + \frac{k_B}{\xi \rho_{LAr}} \frac{dE}{dx}} + \chi_0(dE/dx)\, f_{corr}(\xi, dE/dx) \right) \frac{1}{W_{ion}} \frac{dE}{dx}$$

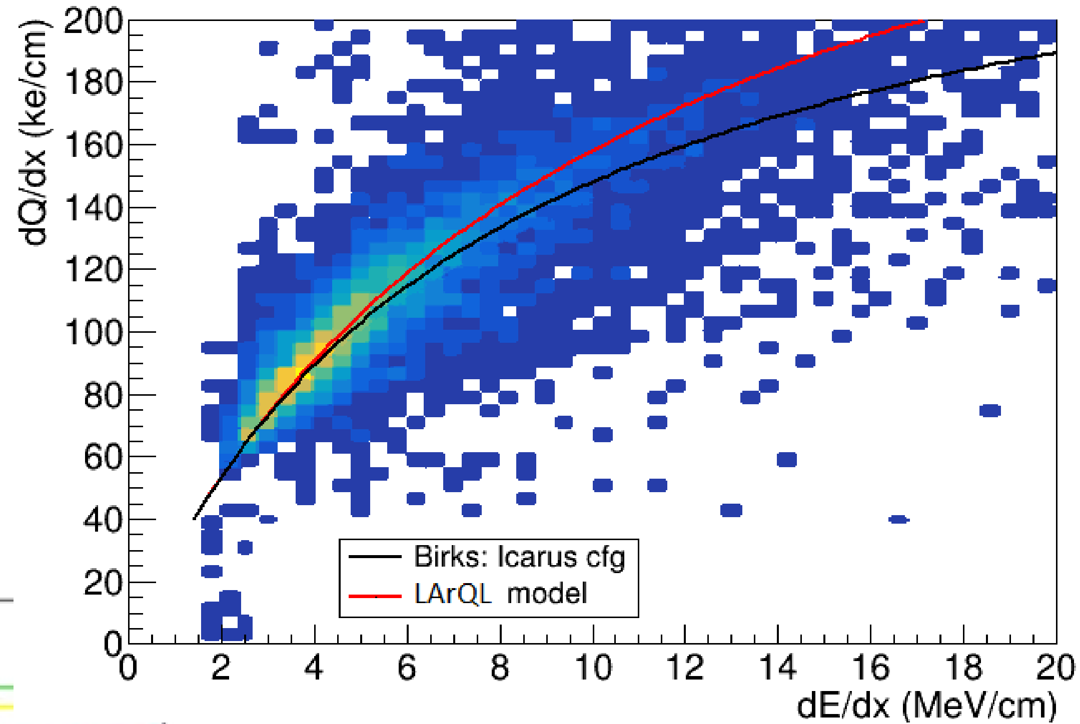
F. Marinho, et al, JINST 17, C07009 (2022)

LArQL Model

- Some results

ARIS data (scintillation light)





Icarus data (ionization charge)

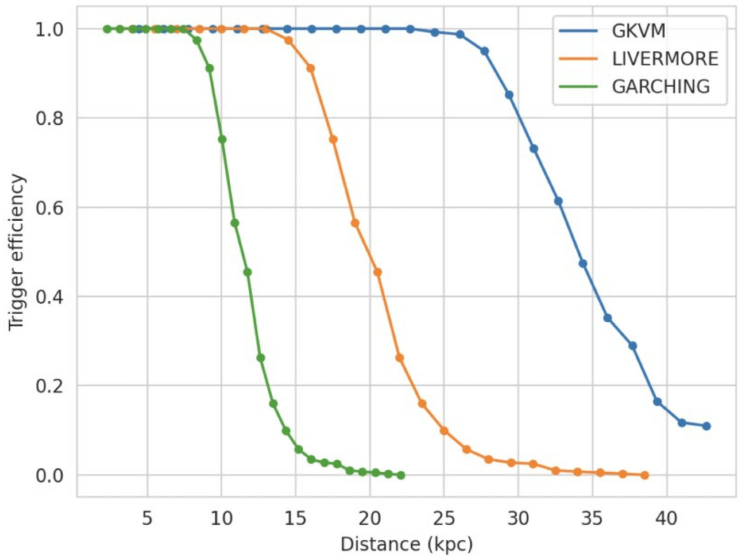
F. Marinho, et al, JINST 17, C07009 (2022)

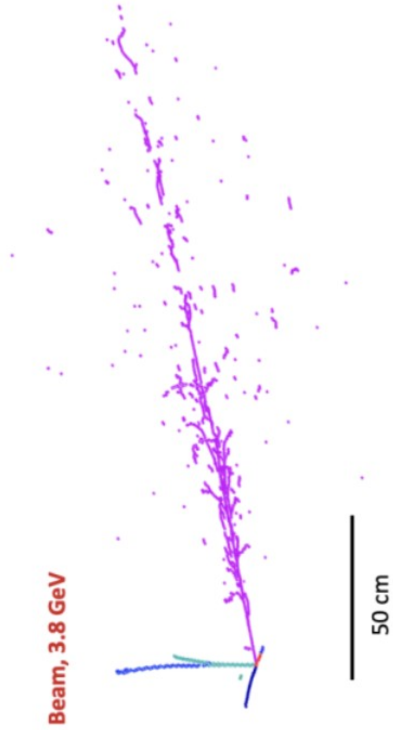
Physics with the Photon Detector System

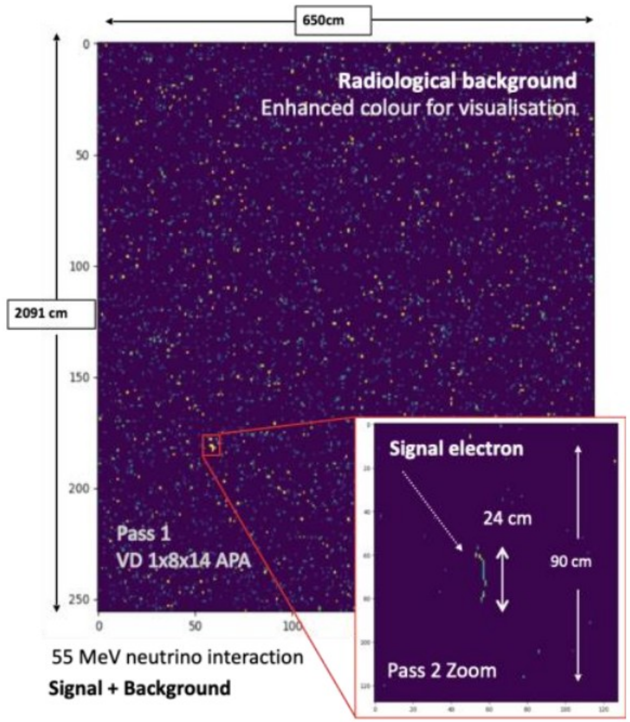
- **Determination of T0 in all non-beam physics**
  - T0 → absolute distance from the readout plane
  - Useful for:
    - Fiducial volume selection (e.g. exclude nucleon decay backgrounds)
    - Correcting for attenuation in TPC signals
- **Triggering**
  - An alternative “trigger primitive” for identifying supernova bursts
  - Combine with the TPC for a sophisticated solar neutrino trigger
- **Calorimetry**
  - A complimentary energy measurement, even at a few MeV
- **And possibly more:**
  - Michel tagging, pulse shape discrimination for PID, enable improved background rejection...

Scintillation light in MeV-scale interactions

- TPC-PDS matching: provide ns-level resolution for properly matched signals
- Supernova PDS trigger







Double calorimetry with DUNE's far detector

- LArTPC does not measure all the energy deposited by charged particles due to the recombination factor

Energy from Charge only: $E_Q = N_e{*}R/W_{ion}$

W_{ion}=ionization work function

- Combining energy measurements from photon detection system and LArTPC provide more precise energy reconstruction

Energy from Charge+Light: $E_{QL} = W_{ph}\,(N_e + N_\gamma)$

W_{ph}=average deposited energy that produces an ion or exciton

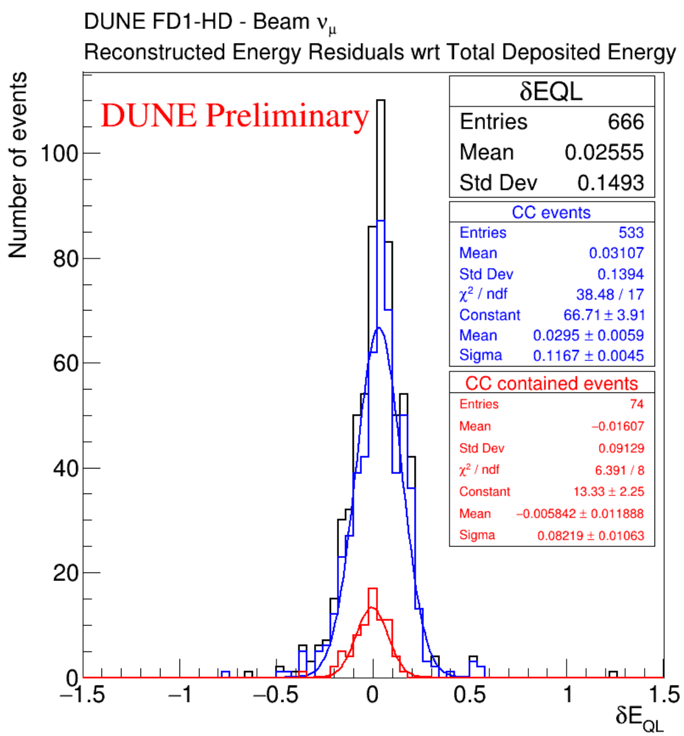
Giulia Brunetti, Neutrino Telescope 2023

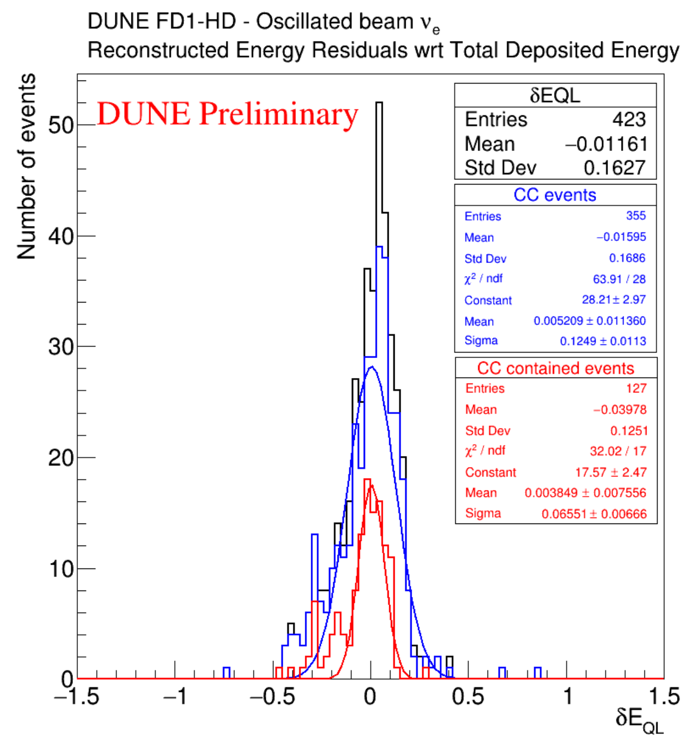
Double calorimetry with DUNE's far detector

- Reconstructed energy E_{QL} residuals with respect to total deposited energy in the detector

$\delta E_{QL}=(E_{QL}\text{-TotEdep})/\text{TotEdep}$

Charge-only ν E_{res} (0.5–4 GeV range): ~15–20%, depending on lepton flavor and reconstruction method





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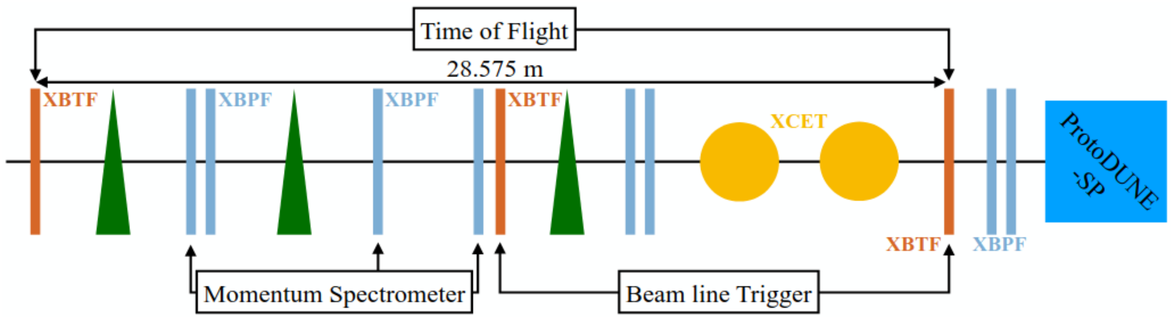
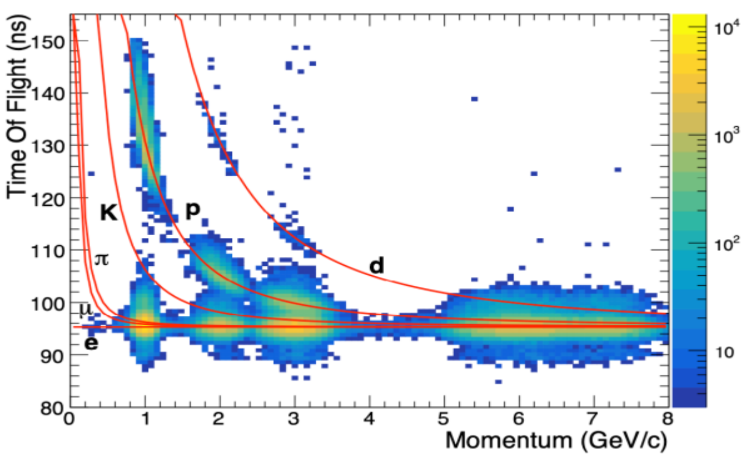
Particle ID - CERN Beam Line Instrumentation



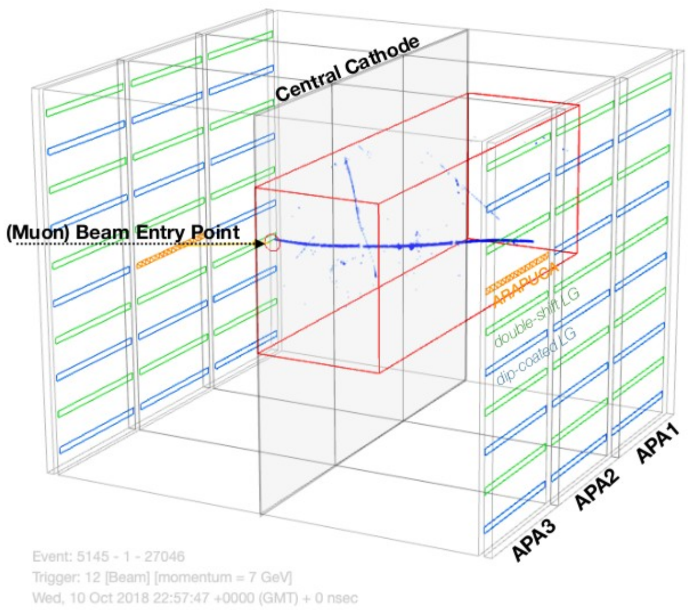


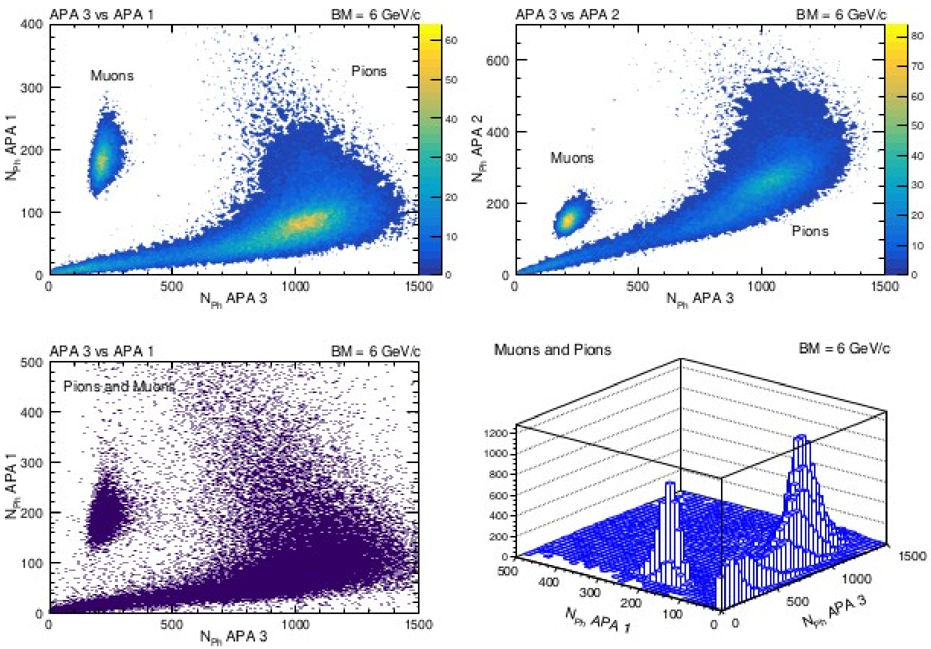
		Momentum (GeV/c)			
		1	**2**	**3**	**6 - 7**
e	TOF (ns)	0, 105	0, 105	–	–
	XCET-L	1	1	1	1
	XCET-H	–	–	1	1
μ / π	TOF (ns)	0, 110	0, 103	–	–
	XCET-L	0	0	0	1
	XCET-H	–	–	1	1
K	TOF (ns)	–	–	–	–
	XCET-L	–	–	0	0
	XCET-H	–	–	0	1
p	TOF (ns)	110, 160	103, 160	–	–
	XCET-L	0	0	0	0
	XCET-H	–	–	0	0

- Muons and Pions are not distinguishable with beamline info alone

Light PID in ProtoDUNE-SP

- ProtoDUNE-SP light information for beam particles: look for total light detected in different APAs for PID

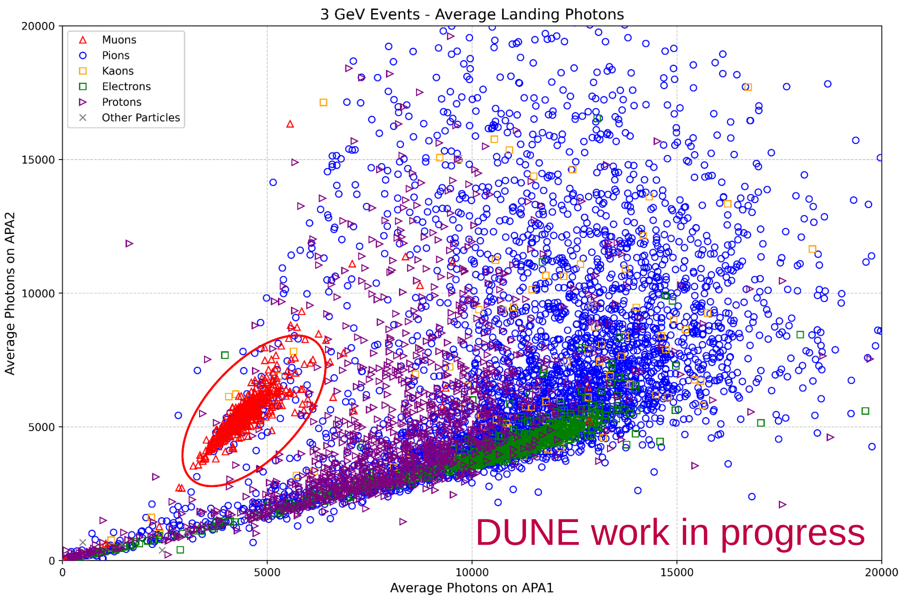




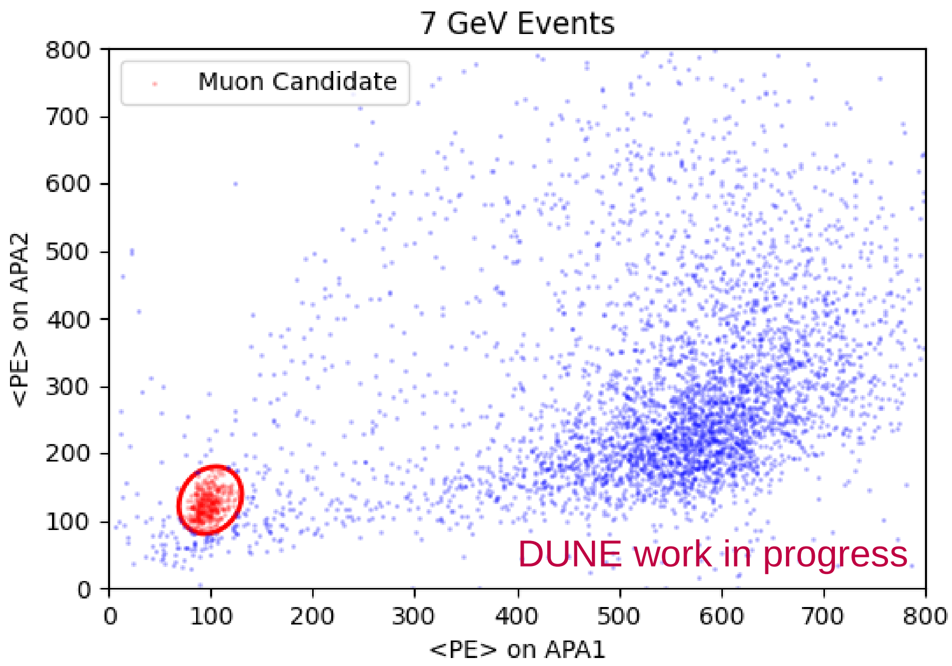
Light PID in ProtoDUNE-HD

- Average light detected in different APAs per module

Simulation

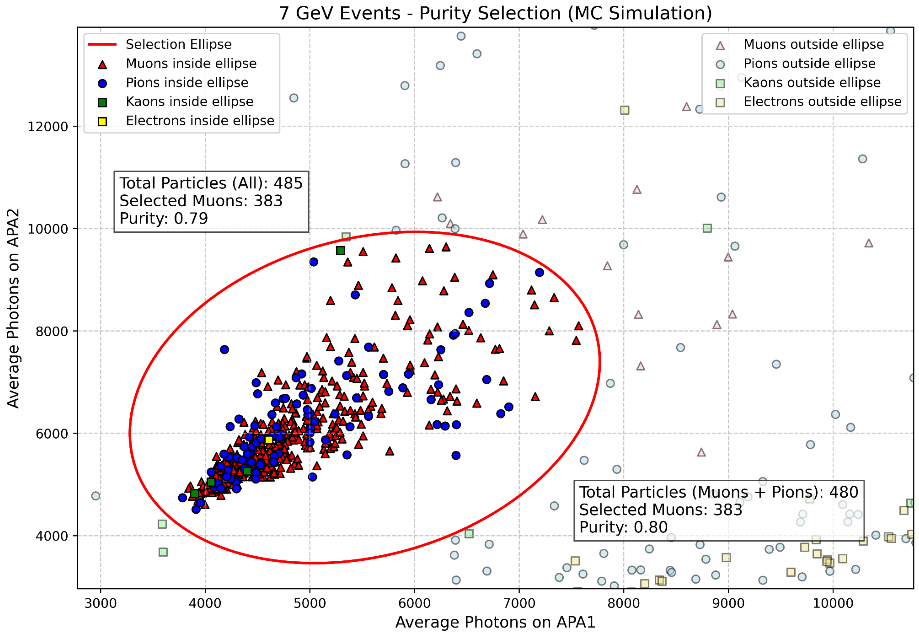


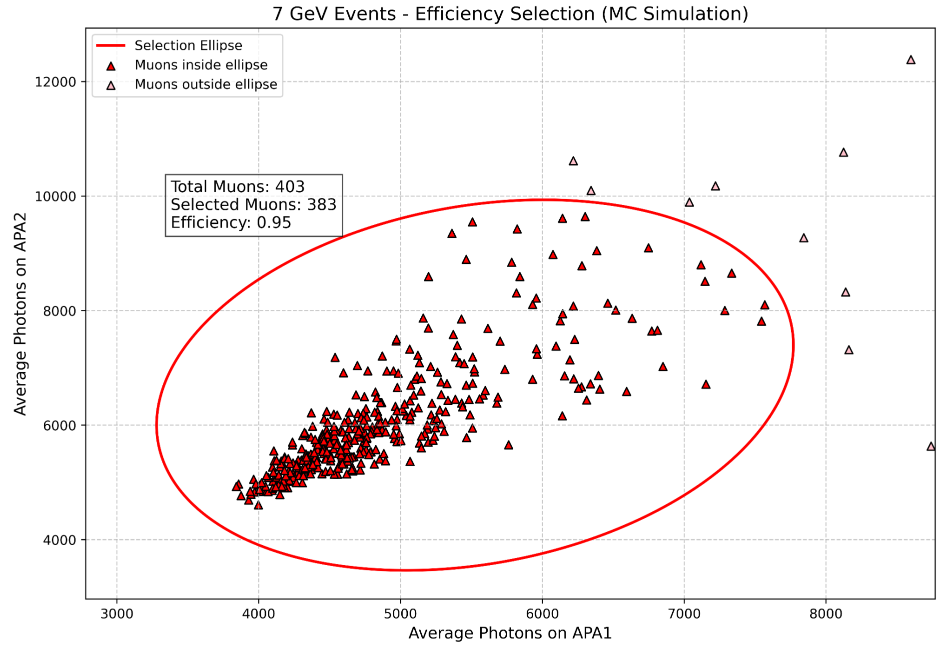
Data



Light PID in ProtoDUNE-HD

- Simulation: 7 GeV beam particles





$$Purity_{(Light)} = \frac{Selected\ Muons}{Selected\ Particles} = 79\%$$

$$Purity_{(Light+Beam)} = \frac{Selected\ Muons}{Selected\ (Muons\ +\ Pions)} = 80\%$$

$$Efficiency = \frac{Selected\ Muons}{Total\ Muons} = 95\%$$

Closing remarks

- DUNE is one of the largest neutrino experiments under construction, with a broad physics program
  - Determine mass ordering, test CP violation in the leptonic sector, obtain high precision oscillation measurements, investigate physics beyond the standard model, make unique supernova neutrino measurements (if fortunate enough)
- Scintillation light sim/reco in LArTPCs is evolving
  - Significant improve in light emission simulation
  - Increasing use in physics studies
    - Goal is to include light information it in the Pandora algorithms for reconstruction