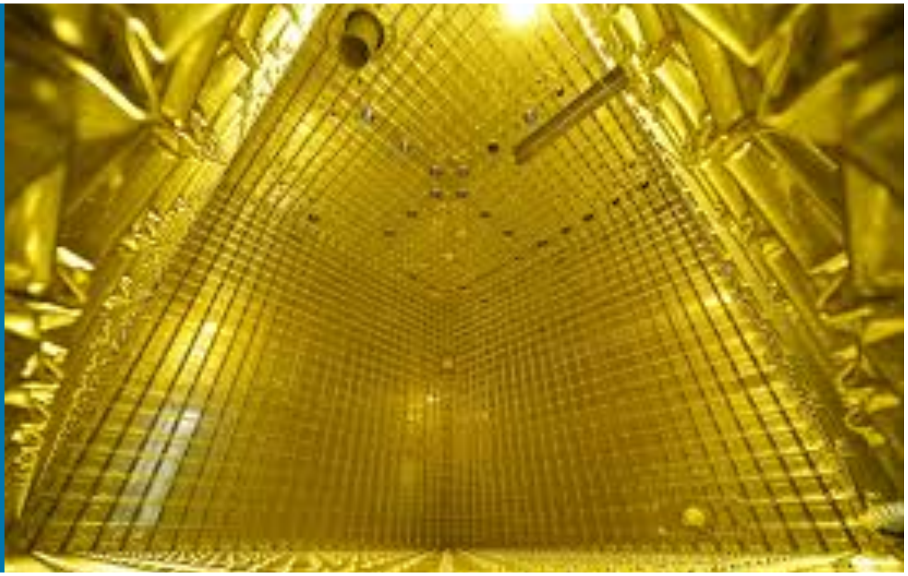
DEVELOPMENT OF LIGHT DETECTION SYSTEM IN DUNE LAr TPC



ZELIMIR DJURCIC (FOR DUNE COLLABORATION)
High Energy Physics
Argonne National Laboratory

CPAD Instrumentation Workshop in Madison, December 8-10, 2019.

Outline of Talk

- DUNE Experiment Introduction
- Brief Overview of DUNE Far Detector Design
- DUNE Far Detector Photon-Detector System
- Focus on ProtoDUNE-SP Photon Detection System
- Going to DUNE
- Summary

Deep Underground Neutrino Experiment (DUNE)

Major features of the DUNE experiment are:

- *A high-intensity wide-band neutrino beam originating at FNAL*
  - -1.2 MW proton beam upgradable to 2.4 MW
- *A highly capable near detector to measure the neutrino flux*
- *A 40 kt fiducial mass liquid argon far detector*
  - -Located 1300 km baseline at SURF's 1.5 km underground level (2300 mwe)
  - -Staged construction of four ~10 kt detector modules. First module to be installed starting in 2024.

Deep Underground Neutrino Experiment (DUNE)

DUNE/LBNF Conceptual Design Report (CDR):
Volume 1: The LBNF and DUNE Projects, arXiv:1601.05471
Volume 2: The Physics Program for DUNE at LBNF, arXiv:1512.06148
Volume 4: The DUNE Detectors at LBNF, arXiv: 1601.02984

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  -Staged construction of four ~10 kt detector modules. First module to be insta... ...ing in 2022.

The Goals of DUNE Experiment

- Primary focus of the DUNE science program is on fundamental open questions in particle physics and astro-particle physics:

  1) Neutrino Oscillation Physics
     - -CPV in the leptonic sector

       "Our best bet for explaining why there is matter in the universe"
     - -Mass Hierarchy
     - -Precision Oscillation Physics & testing the 3-flavor paradigm

  2) Nucleon Decay
     - -Predicted in beyond the Standard Model theories [but not yet seen]

       e.g. the SUSY-favored mode, $p \rightarrow K^{+}\bar{\nu}$

  3) Supernova burst physics & astrophysics
     - -Galactic core collapse supernova, sensitivity to ν_e

       Time information on neutron star or even black-hole formation

Any would be a major discovery

- DUNE Ancillary Science Program

  -Other LBL oscillation physics with BSM sensitivity

  -Oscillation physics with atmospheric neutrinos

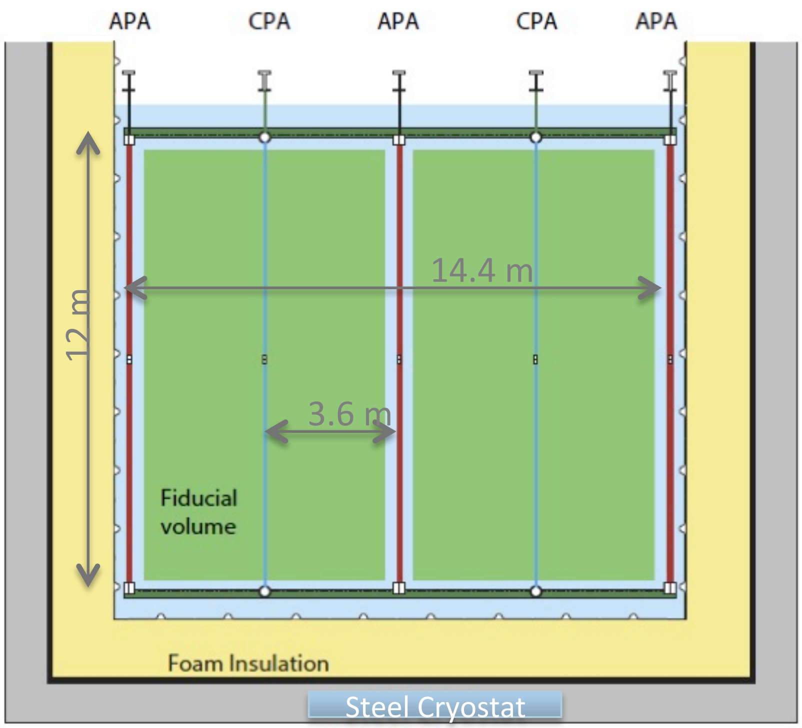
  -Neutrino Physics in the near detector

  -Search for signatures of Dark Matter

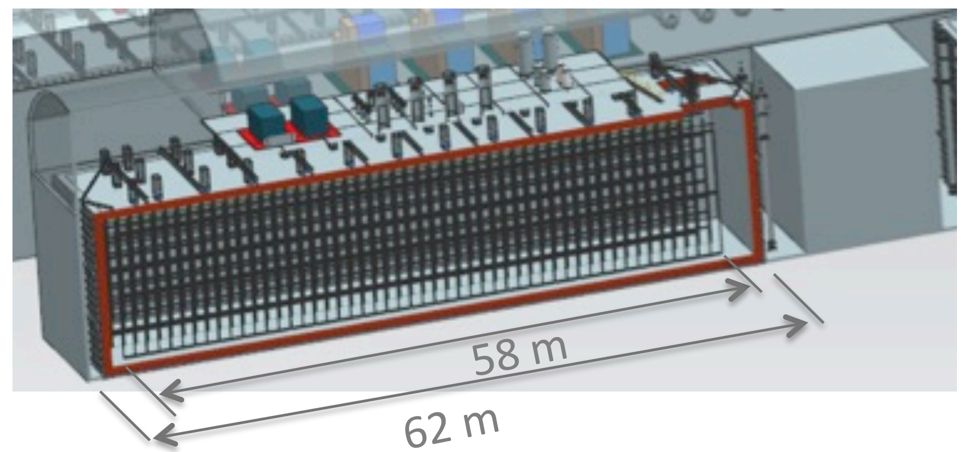
Andrew FURMANSKI

DUNE Far Detector

- Four 10-kt (fiducial) liquid argon TPC modules
  - *Liquid Argon Time projection chamber with both charge and optical readout*
- Single and dual-phase detector designs (1st module will be single phase)
- Integrated photon detection (need wavelength shifting to visible)
- Modules will not be identical



Single-phase: charge drifts to wire planes (APAs)



- 17.1/13.8/11.6 Total/Active/Fiducial mass
- 3 Anode Plane Assemblies (APA) wide (wire planes)
  -Cold electronics 384,000 channels
- Cathode planes (CPA) at 180kV
  -3.6 m drift length

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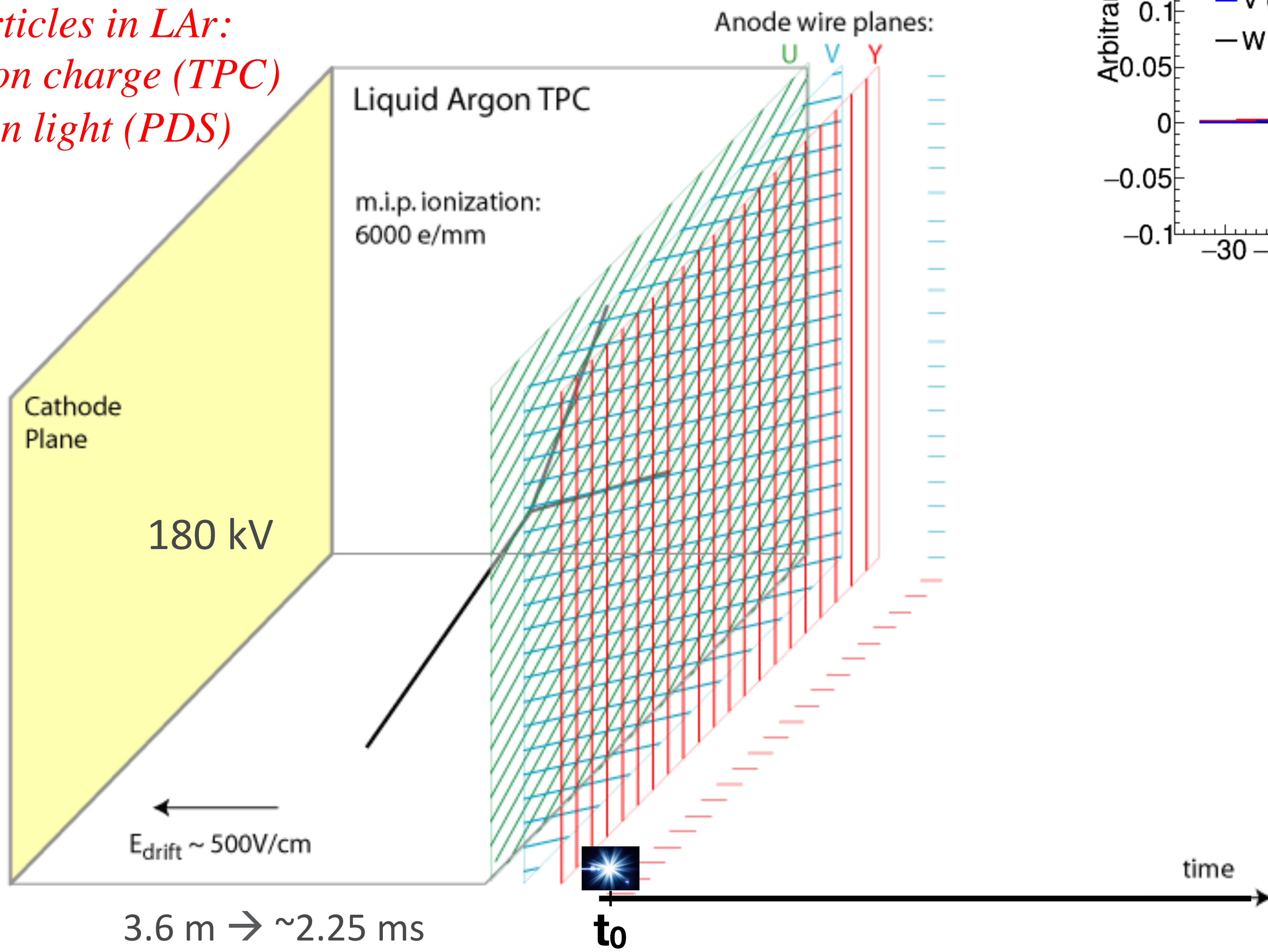
DUNE Far Detector: SINGLE Phase Concept

- *Energy release from charged particles in LAr:*
  -free electron charge (TPC)
  -scintillation light (PDS)



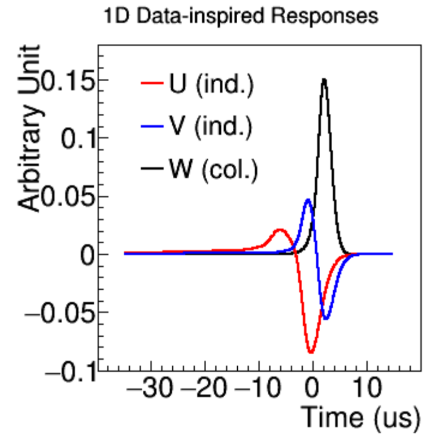
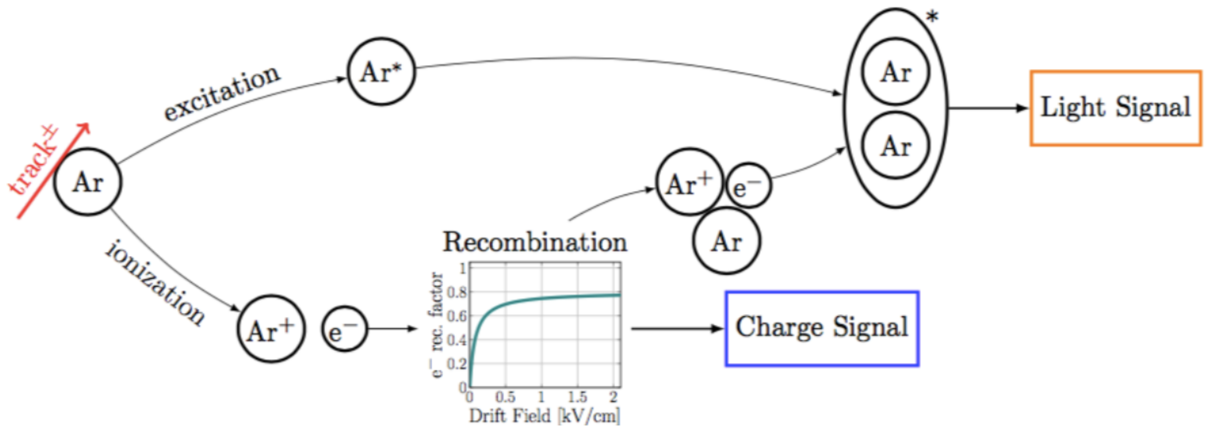


Photo-Detector for triggering and t0 determination

Liquid Argon Scintillation Light

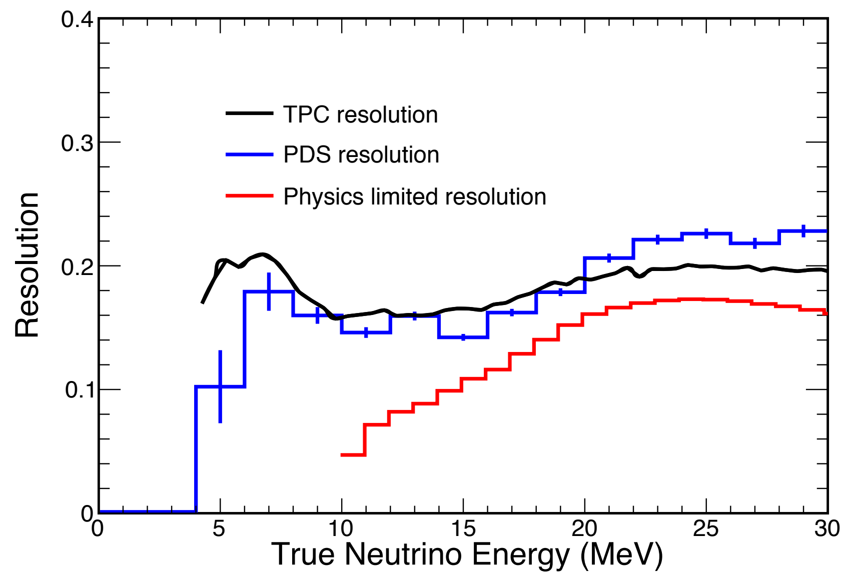
- LAr is a scintillator that emits about 40,000 ph/MeV (E = 0) when excited by MIP
  -at nominal DUNE SP E = 500 V/cm the yield is approximately 24,000 ph/MeV (reduced due to recombination)



- Ionization radiation in LAr results in formation of excited dimer Ar_2^*
  -photon emission follows through de-excitation of singlet $^1\Sigma$ and triplet $^3\Sigma$ states
  -photons emitted in a narrow band around 128 nm (VUV region)
  -de-excitation from $^1\Sigma$ is fast with $\tau_{fast} \approx 6$ ns
  -de-excitation from $^3\Sigma$ is slow with $\tau_{slow} \approx 1.3$ μs

Photon Detection System Motivation

- Detect LAr scintillation light
  - ➢ Extract information from LAr scintillation light to enhance physics reach of LArTPC



- Photon detection used for event trigger and interaction time (t0) determination for underground physics
  - ➢ Provides triggering on non-beam events (SNB, proton-decay, atmospheric ν's)
  - ➢ Enables correction of charge losses, important for the reconstruction of the energy deposited by the ionizing event

- Potential for improved energy measurements in combination with TPC charge.

PDS Performance Requirements

- Performance goals/specifications considered to achieve primary science objectives

Description	Specification (Goal)	Rationale	Validation
Light yield	$> 20\,\mathrm{PE/MeV}$ (avg), $> 0.5\,\mathrm{PE/MeV}$ (min)	Gives PDS energy resolution comparable that of the TPC for 5-7 MeV SN νs, and allows tagging of $> 99\,\%$ of nucleon decay backgrounds with light at all points in detector.	Supernova and nucleon decay events in the FD with full simulation and reconstruction.
Time resolution	$< 1\,\mu\mathrm{s}$ ($< 100\,\mathrm{ns}$)	Enables 1 mm position resolution for 10 MeV SNB candidate events for instantaneous rate $< 1\,\mathrm{m}^{-3}\mathrm{ms}^{-1}$.	
LAr nitrogen contamination	$< 25\,\mathrm{ppm}$	Maintain $0.5\,\mathrm{PE/MeV}$ PDS sensitivity required for triggering proton decay near cathode.	In situ measurment

PDS: Physics Potential Enhancement

- The photon detectors in both single and dual Phase have the potential to improve the physics reach of all of DUNE's physics goals.

		Supernova Bursts	Nucleon Decays	Atm. Neutrinos	Beam Neutrinos
T0 for	fiducial volume		X	X	
	TPC drift correction	X	X	X	
	sub-ms timing	X			
	Triggering	X	X	X	
	Direct calorimetry	X	X		X
	Position Reconstruction	X	X	X	
	Michel *e* Detection		X	X	X

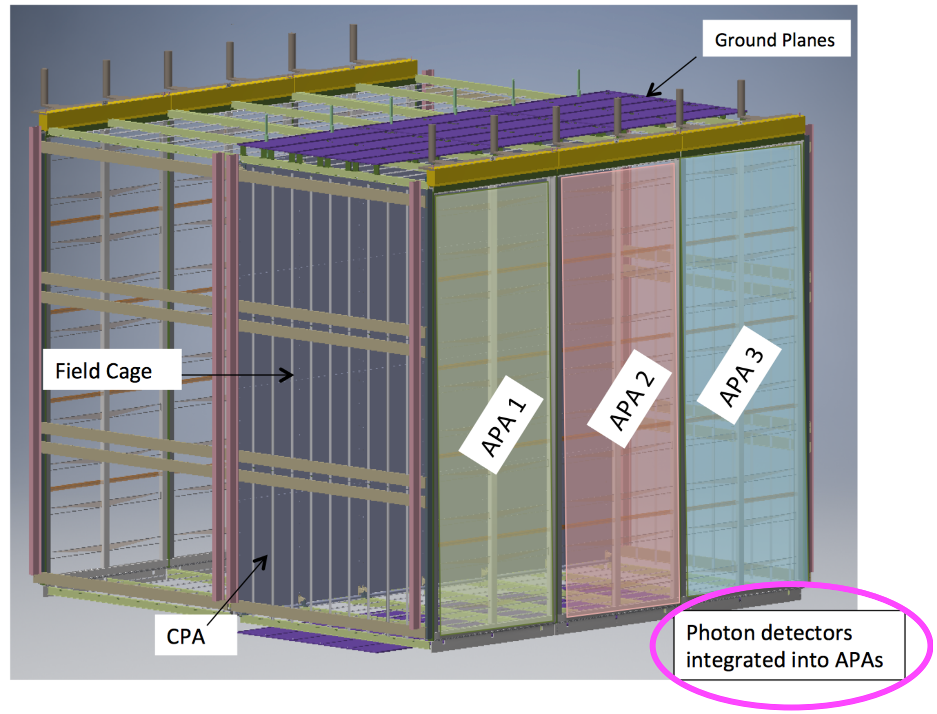
- There is ongoing R&D program to investigate methods that maximize the photon detection efficiency of the PDS within the constraints of the SP TPC design
  - Focus is to quantify what physics impacts are, and what they require the system performance to be
- Concentrate in this talk on Photon-Detector in **DUNE Single Phase Far Detector** and tests with **ProtoDUNE-SP.**

ProtoDUNE-SP

Please see R. Diurba's talk on ProtoDUNE-SP Response with CRT

- LArTPC located in the EHN1 Hall @ CERN: 760 tons of liquid argon
  - ➢ Provides a full drift length of future DUNE SP Far Detector
- Main Detector Elements include:
  - -Time Projection Chamber (TPC)
  - -Front-end electronics
  - -Photon Detector System
  - -Comic-Ray Tagger (CRT)
- ProtoDUNE-SP Goals:
  - -Prototype the production and installation for SP DUNE Far Detector.
  - -Validate detector performance with cosmic-rays; calibrate with different test-beam particle
    - ➢ Demonstrate photon-detector concept

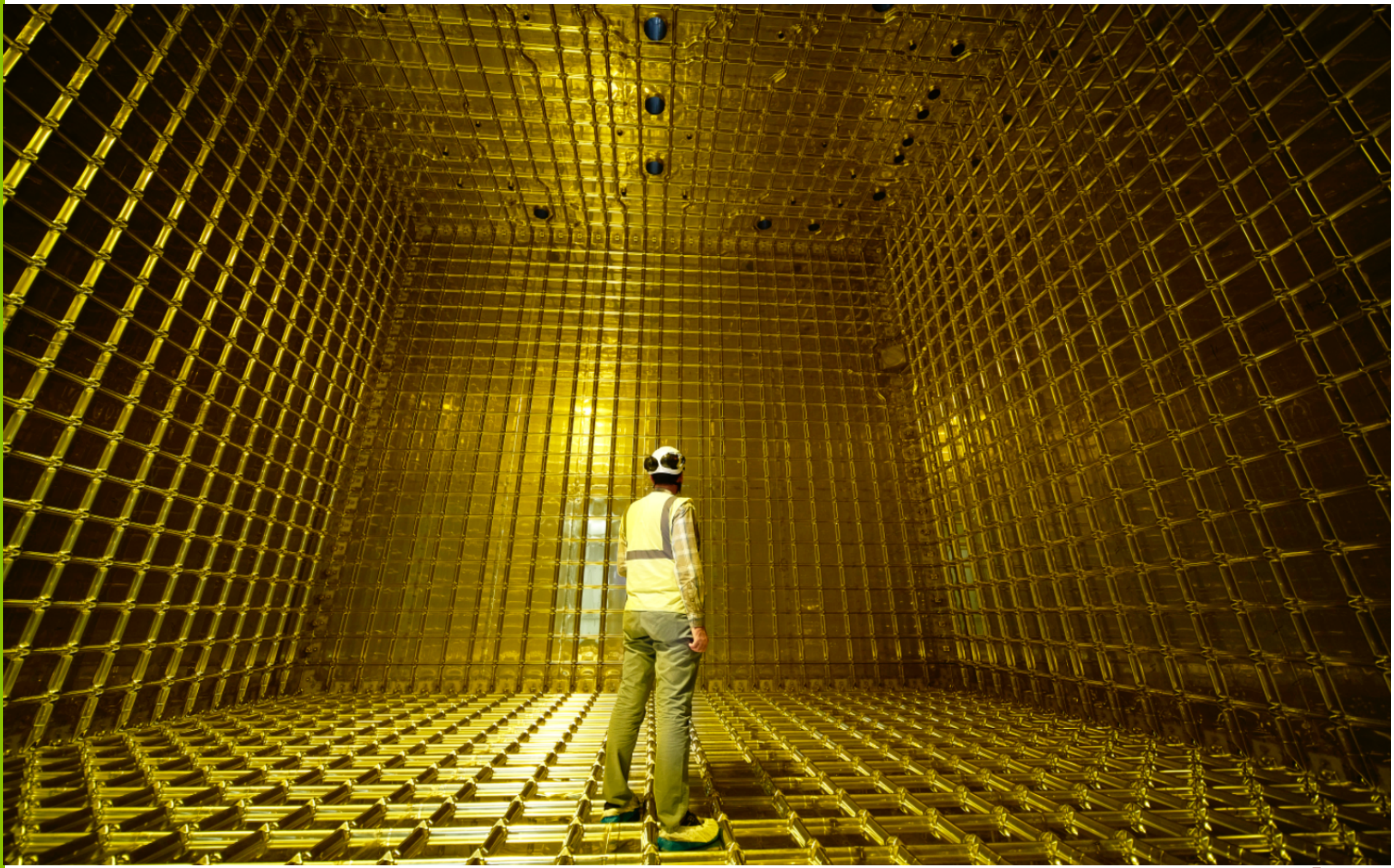
ProtoDUNE-SP TPC



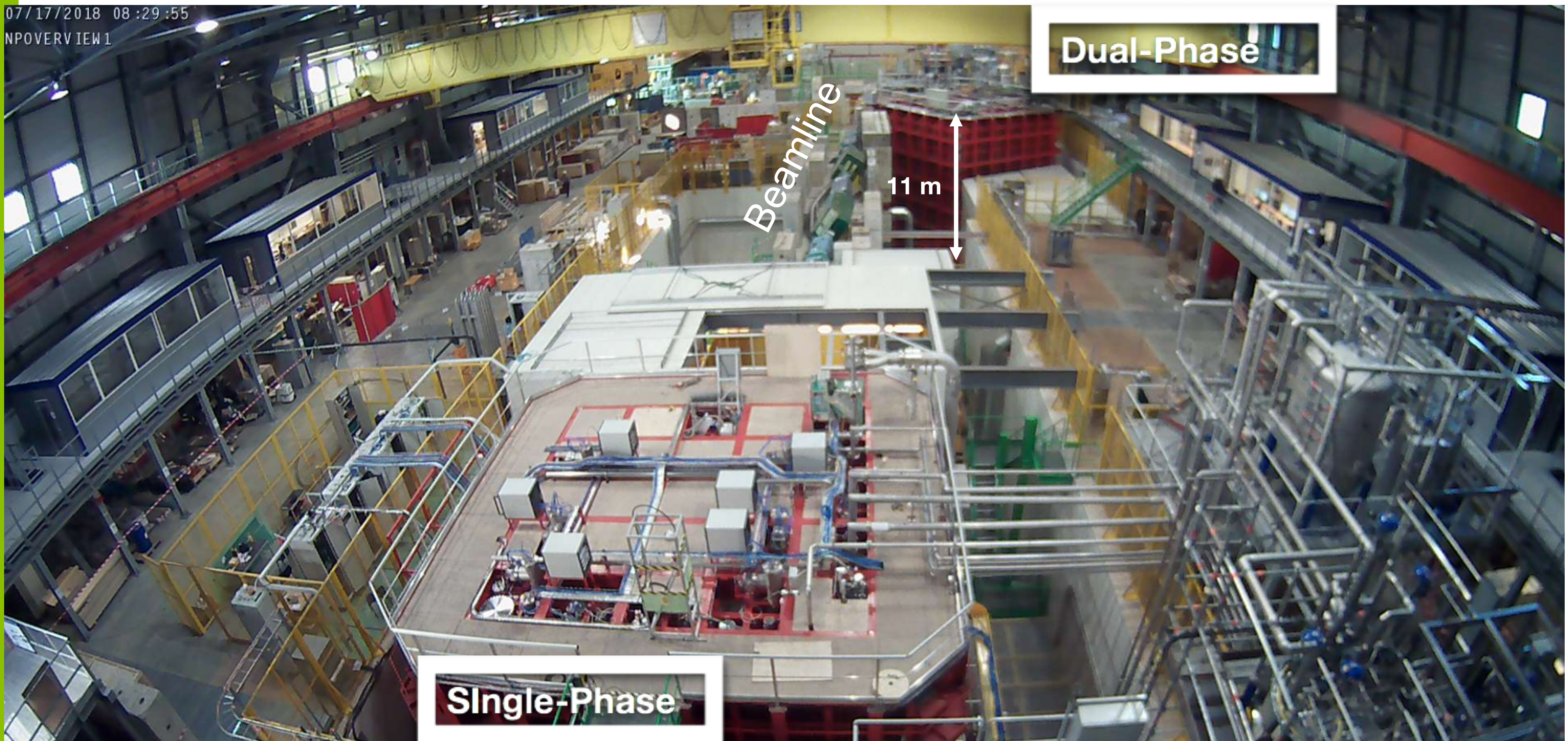
2016 Q4	2017 JAN	2017 FEB	2017 MAR	2017 APR	2017 MAY	2017 JUN	2017 JUL	2017 AUG	2017 SEP	2017 OCT	2017 NOV	2017 DEC	2018 JAN	2018 FEB	2018 MAR	2018 APR	2018 MAY	2018 JUN	2018 JUL	2018 AUG	2018 SEP	2018 OCT	2018 NOV
EHN1 Beneficial Occupancy							APA #1 @ CERN			Detector Installation Begins					Close TCO; Finish Installation			Start Filling & Commissioning			Start of Beam		End of Beam

Empty Cryostat

- Single Phase

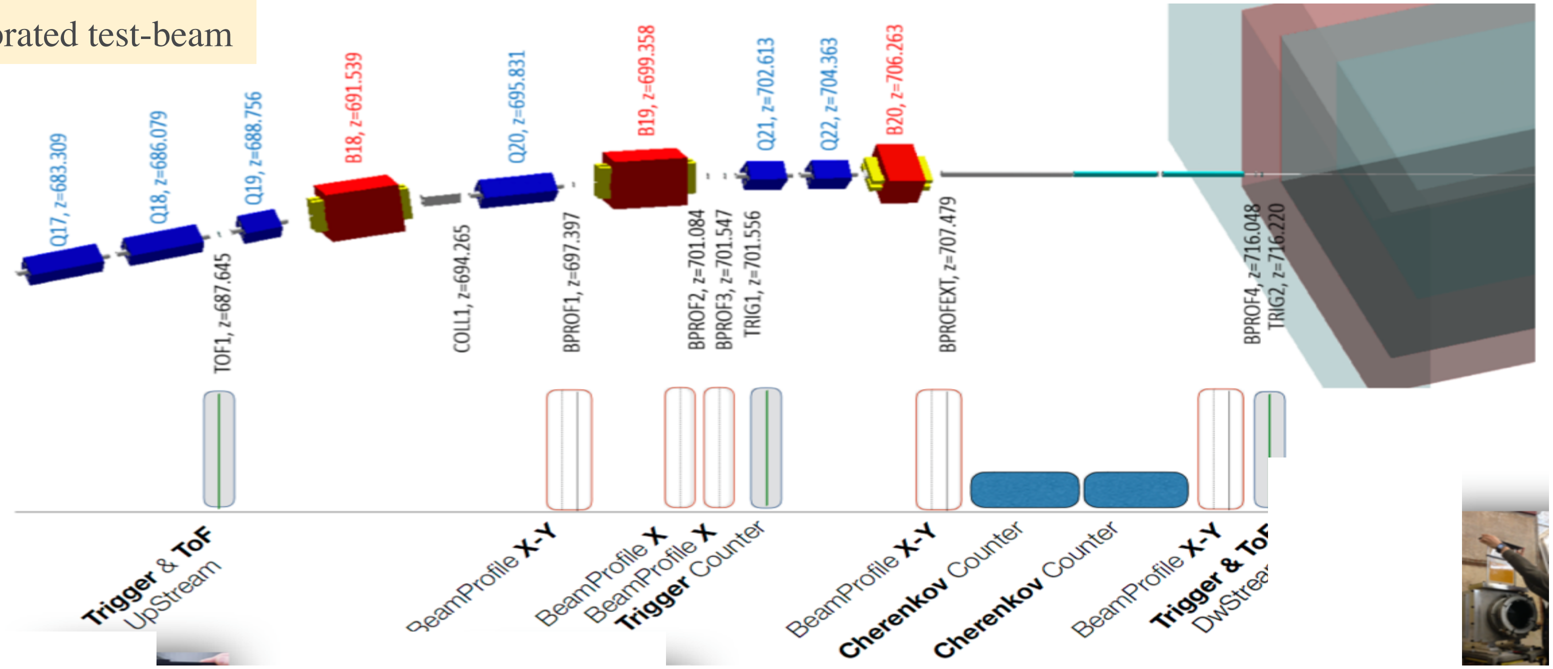


CERN North Area



ProtoDUNE Terst-Beam

Fully calibrated test-beam



Collected >4M beam triggers Sep 21- Nov 11, 2018

Momentum	Total Triggers	Expected Pi trig.	Expected Proton trig.	Expected Electr. trig.	Expected Kaon trig.
0.3 GeV/c	269K	0	0	242K	0
0.5 GeV/c	340K	1.5K	1.5K	296K	0
1 GeV/c	1089K	382K	420K	262K	0
2 GeV/c	728K	333K	128K	173K	5K
3 GeV/c	568K	284K	107K	113K	15K
6 GeV/c	702K	394K	70K	197K	28K
7 GeV/c	477K	299K	51K	98K	24K
All momenta	4175K	1694K	779K	1384K	73K

ProtoDUNE-SP Main Detector Elements

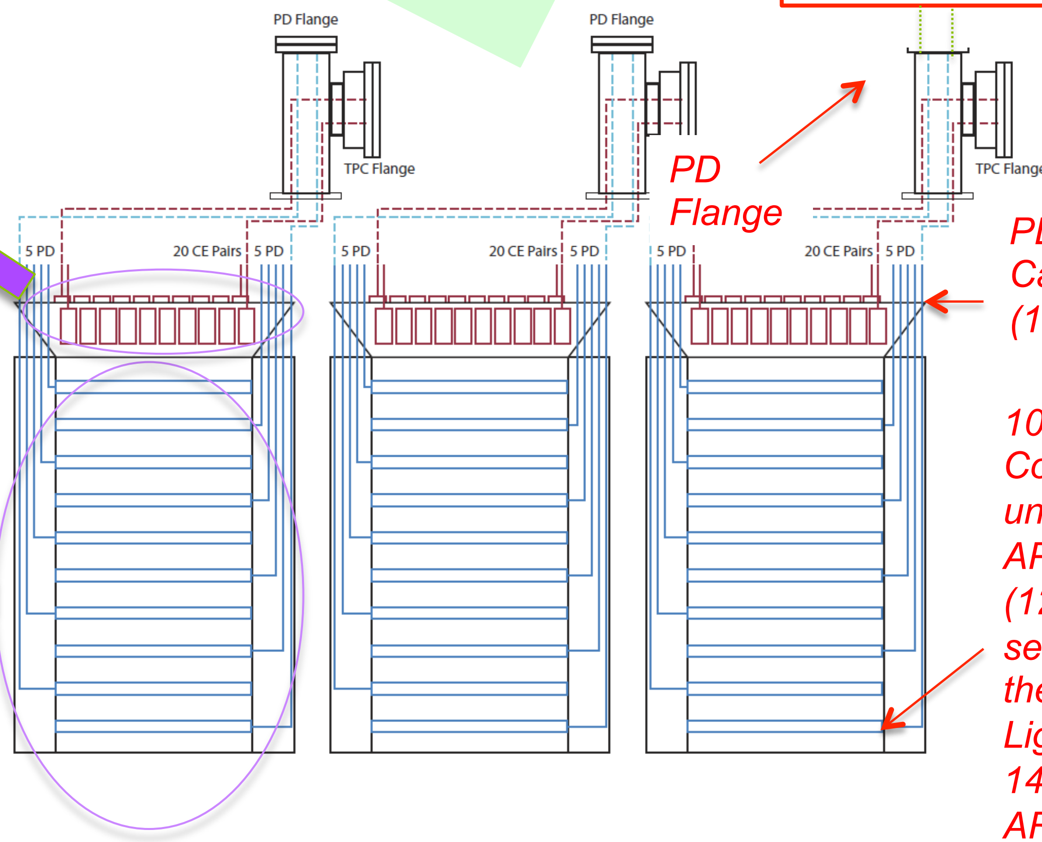
Please see Matt Worcester's talk to learn more about TPC and cold electronics

TPC Readout

DAQ

SSP (FEE readout)

58 light guide and 2 ARAPUCA photon collectors

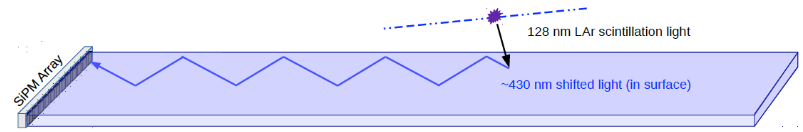


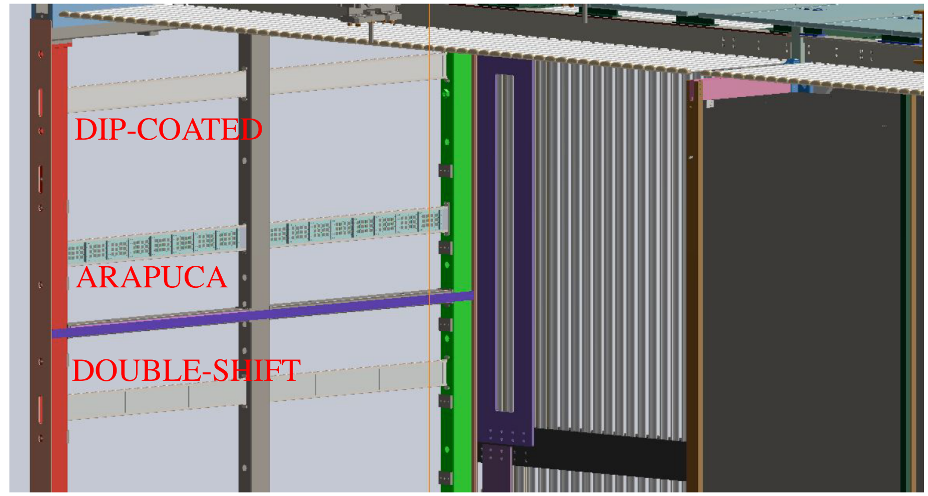
PD Flange

PD Signal Cables (10 per Port)

10 PD Light Collection units per APA (12) SiPM sensors on the end of Light guides; 144 SiPMs in ARAPUCA array

Photon Detection System Design in ProtoDUNE-SP

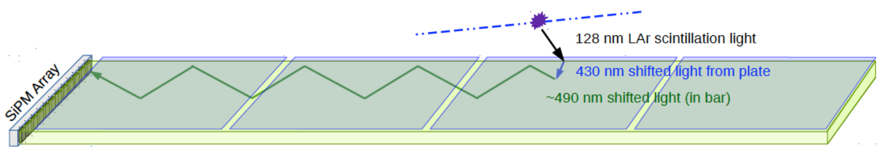




- **Dip-Coated Light Guide (39 units/ProtoDUNE)**

-VUV photons (128 nm) are absorbed and wavelength-shifted to blue (430 nm) by TPB-based coating on the bar surface

-Wavelength-shifted light is captured and guided via total internal reflection where it is detected by SiPMs



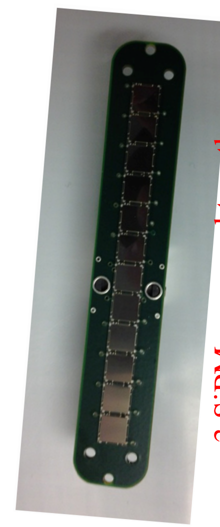
- **Double-Shift Light Guide (39 units/ProtoDUNE)**

-Decouples the process of converting VUV photons to optical wavelengths from the transportation of photons along the bars

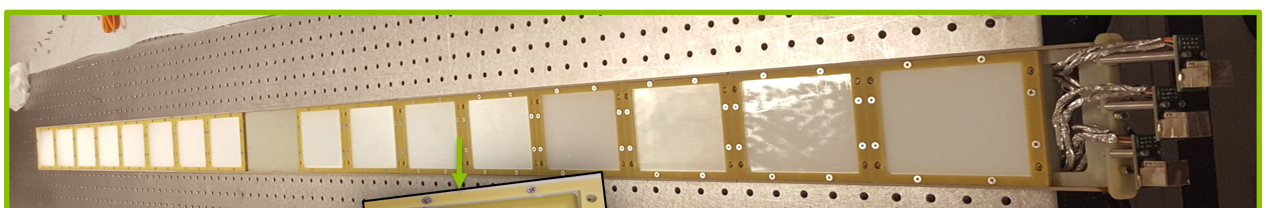
-Spray-coated TPB wavelength-shifting plates convert VUV (128 nm) to blue (430 nm)

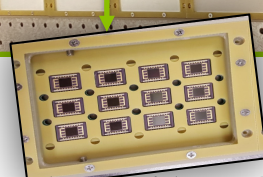
-Commercially-fabricated wavelength-shifting light guide coverts blue to green (490 nm)

For the bars (dip-coated and double-shift): SensL C-series MicroFC-60035-SMT SiPMs



3 SiPMs summed together in single readout channel





Hamamatsu MPPCs

- **ARAPUCA Concept**

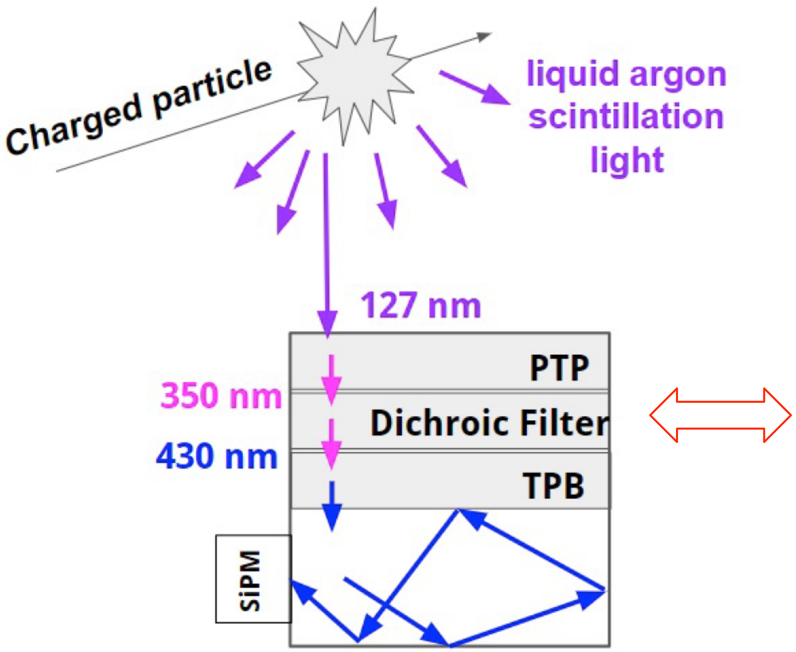
-2 Modules in ProtoDUNE: 1st on beam side TPC, segmented along beam direction (4 Arrays per Bar - 4 Cells per Array)

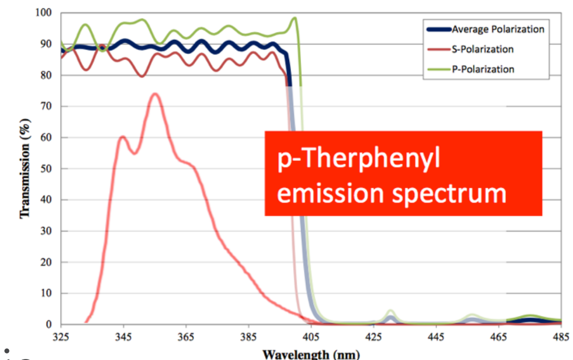
-12 (or 6) cryo-SiPMs per Cell - passively ganged

-$S_{SiPM}/S_{Dichroic}$ = 5.6% (or 2.8%) - see next page.

ARAPUCA concept

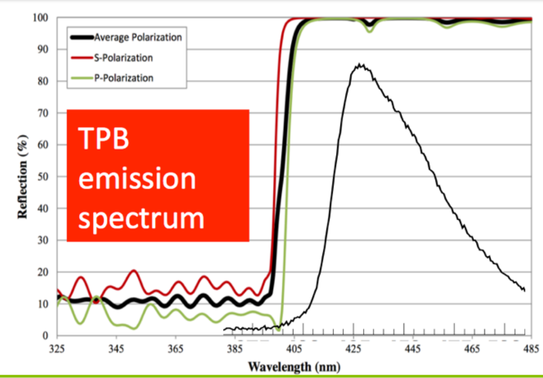
- ARAPUCA is the light trap
  - ➢ Dichroic (short-pass) filter to trap wavelength-shifted light inside ARAPUCA reflective cell
  - ➢ p-TerPhenyl on outer surfaceTPB on inner surface (trapped)
  - ➢ Provides segmentation along beam direction
- Tested in ProtoDUNE: baseline for DUNE Far Detector





Dichroic

Glass



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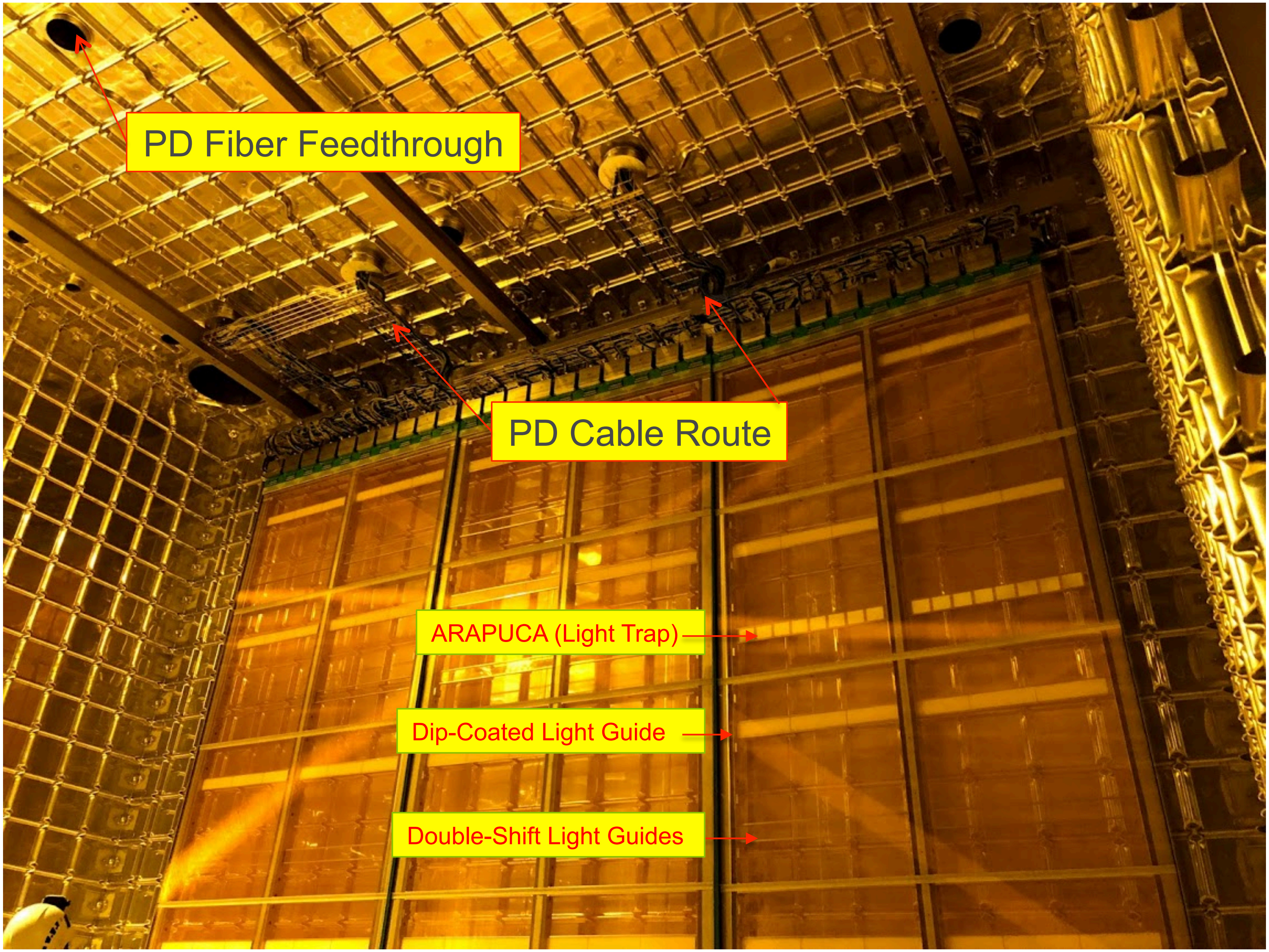
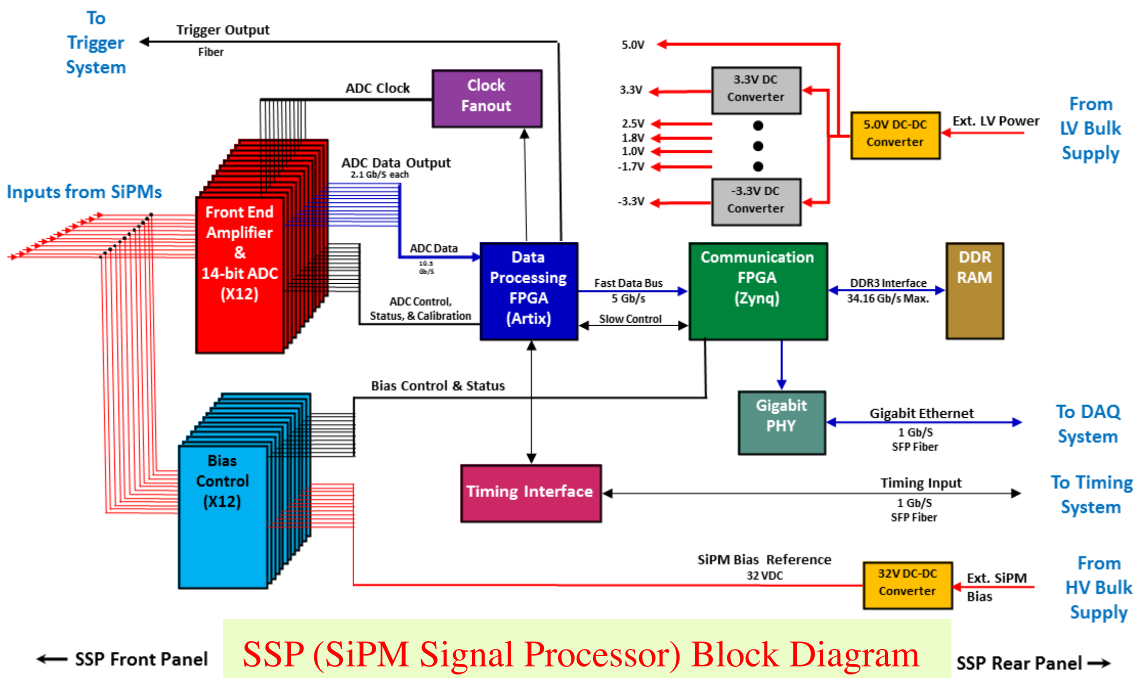
Photon-Detector in ProtoDUNE-SP

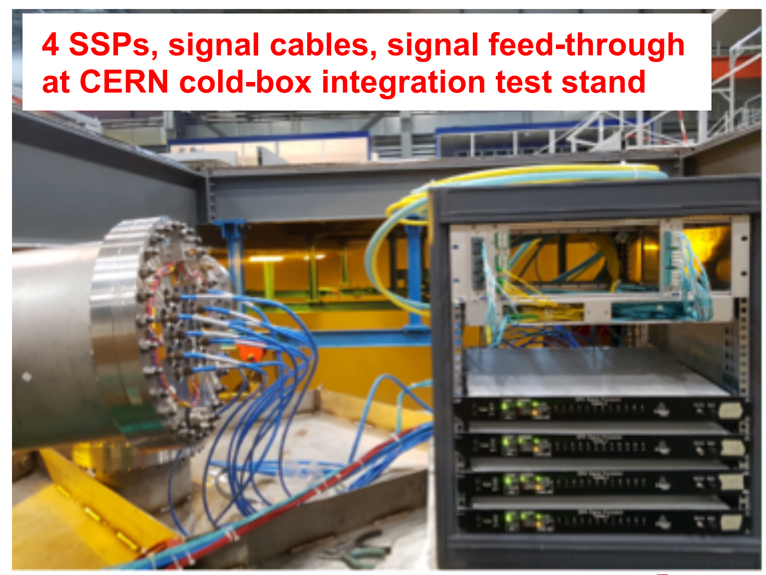


Photon-Detector Readout in ProtoDUNE-SP

- A dedicated photon-detector readout system (SSP) was developed for ProtoDUNE
  - ➢ Fast 150MS/s ADC sampling, 14bit dynamic range
  - ➢ Timing/Trigger and DAQ interfaces



SSP (SiPM Signal Processor) Block Diagram



4 SSPs, signal cables, signal feed-through at CERN cold-box integration test stand

- Twenty-four custom SiPM Signal Processor (SSP) units were produced to read out the 58 light guide and 2 ARAPUCAs photon collectors in final ProtoDUNE

(details in backup slides)

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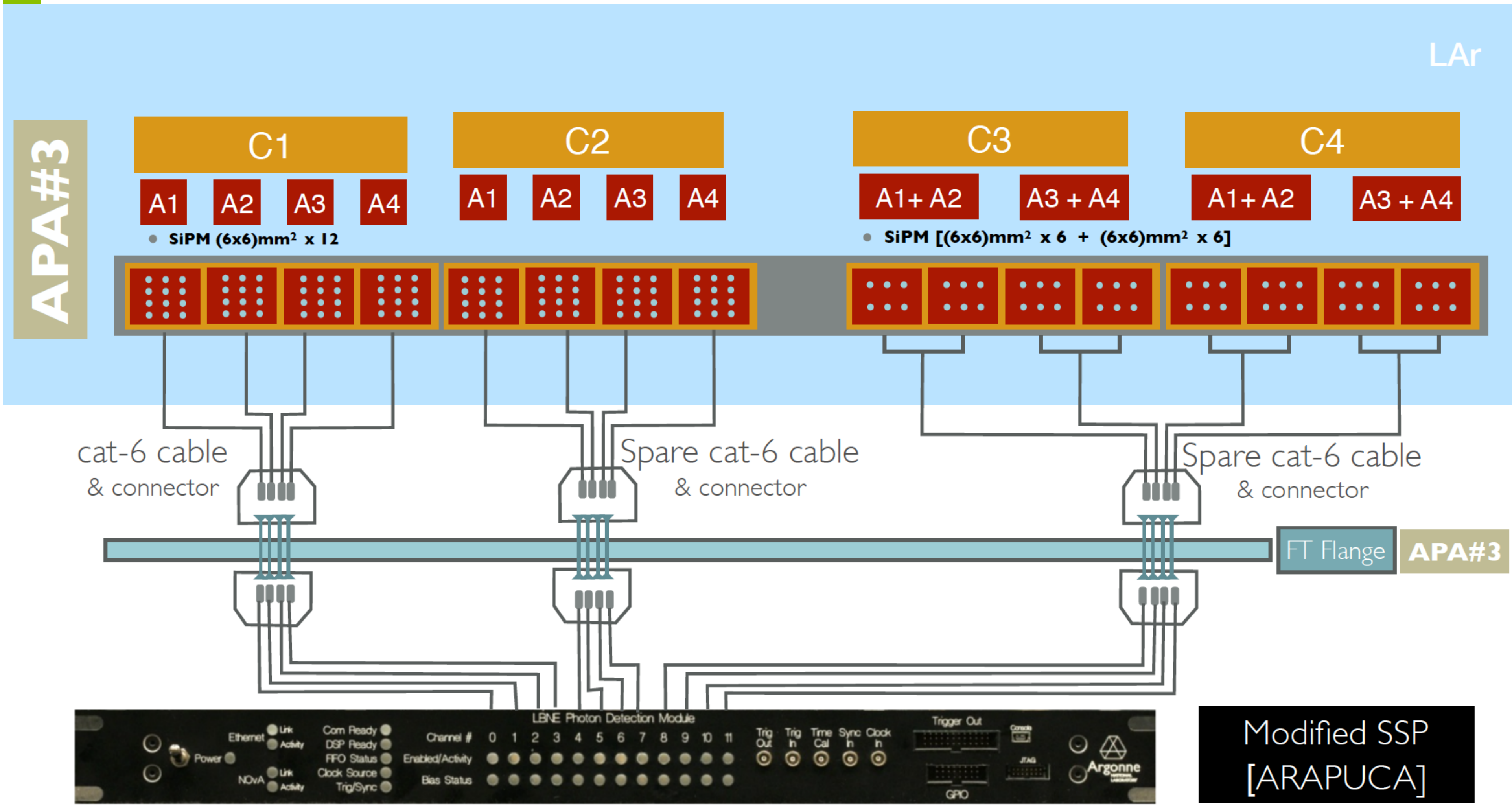
Photon-Detector Readout in ProtoDUNE-SP

- The ProtoDUNE detector is filled with liquid argon, and is taking data
- The flashing lights in the crates on the top are the photon-detector readout boards

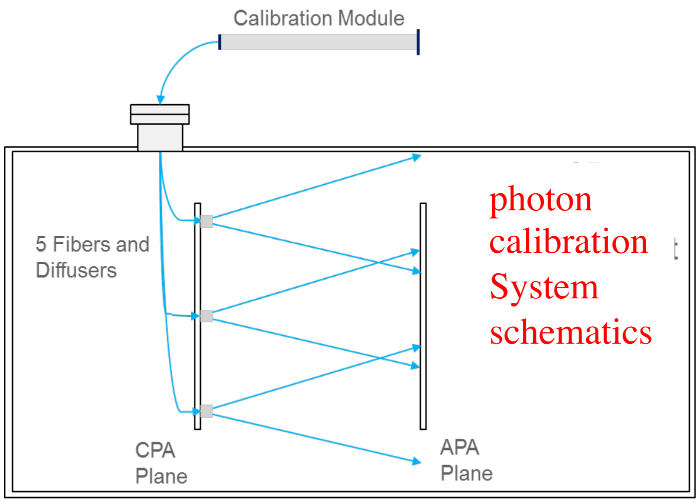
ARAPUCA Readout Schematics

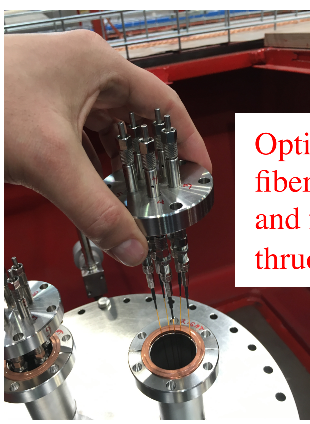
- We show type-1 are cells j = 1,…, 8, with 12 MCCPs, and type-2 cells j = 9,…,12 with double area (and 12 MPPCs total) in the ARAPUCA module 1.



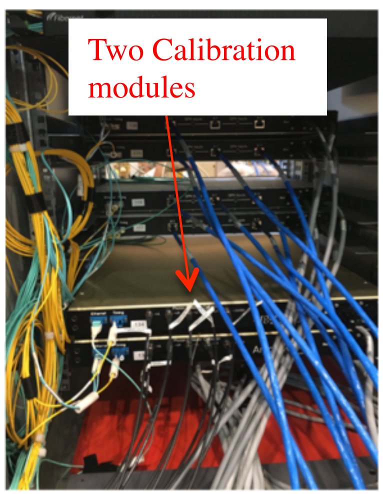
Photon-Detector Calibration System

- UV-light system fabricated and installed to monitor health of the system, and to calibrate PDS gain and time resolution
- Calibration light pulses set by amplitude and pulse width, as a single pulse or as pulse pair

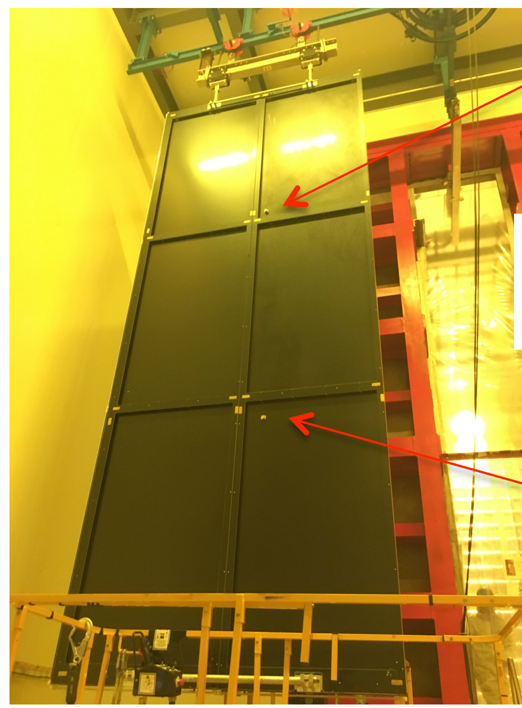


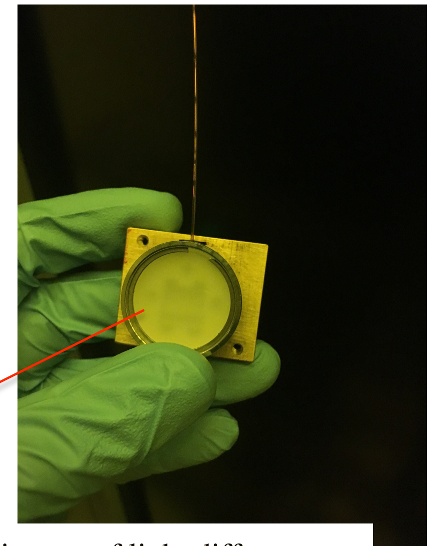


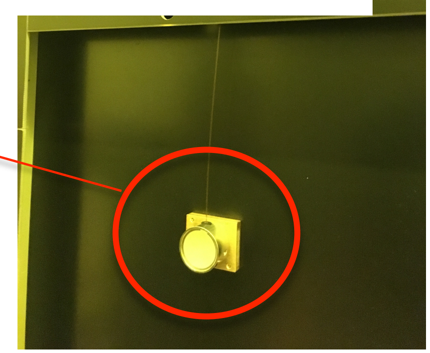
Optical fibers and feed-through



Two Calibration modules



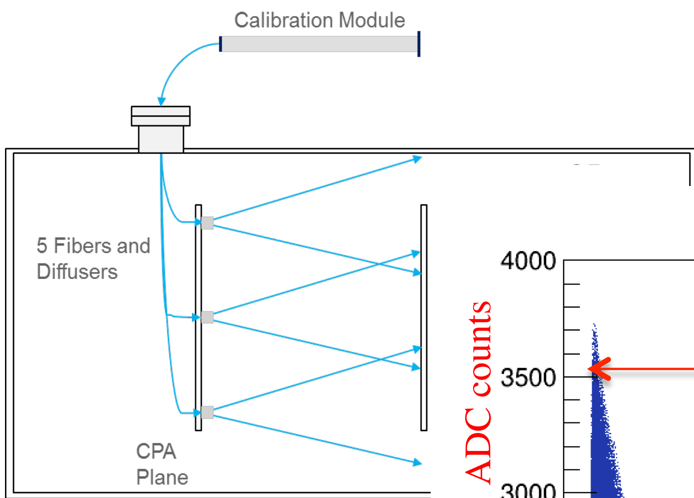


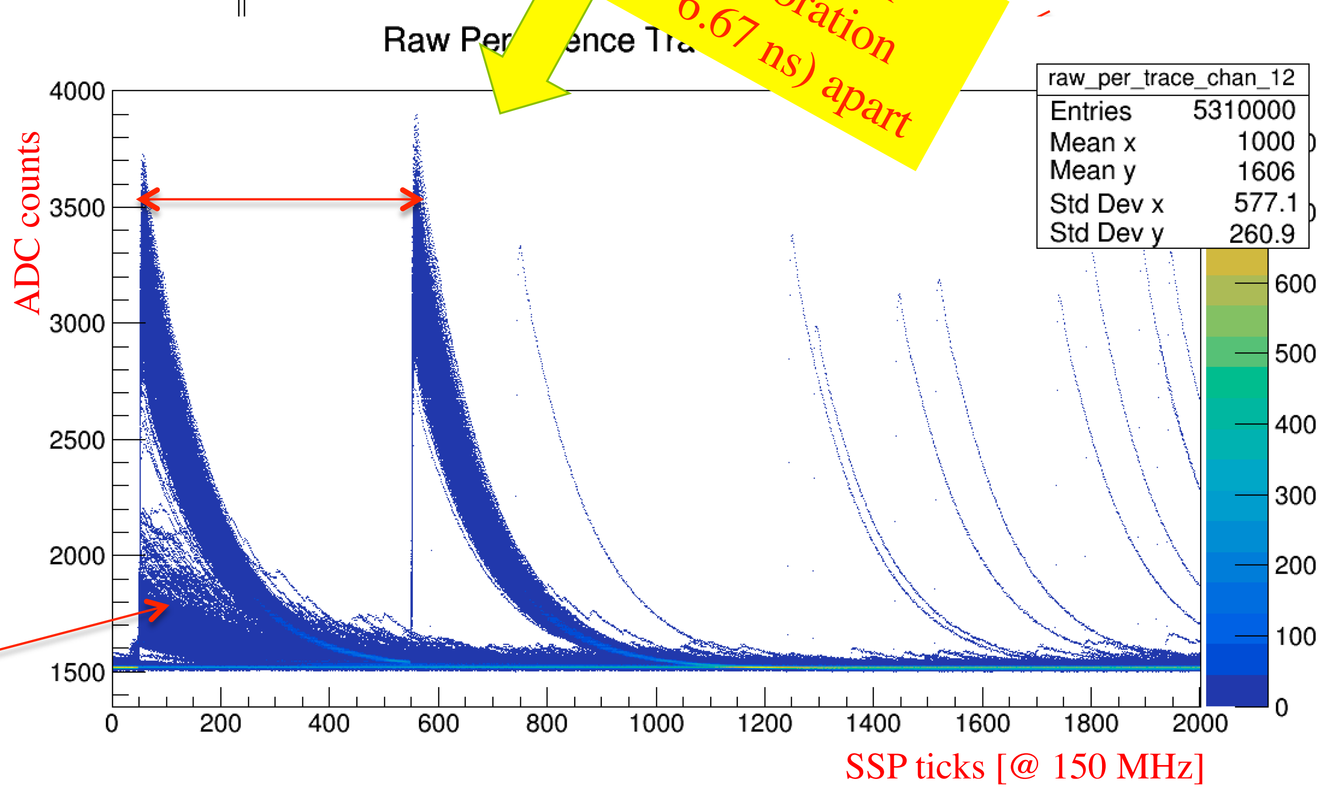


Pictures of light diffusers and fibers integrated with one CPAs at CERN.

Photon-Detector Calibration System

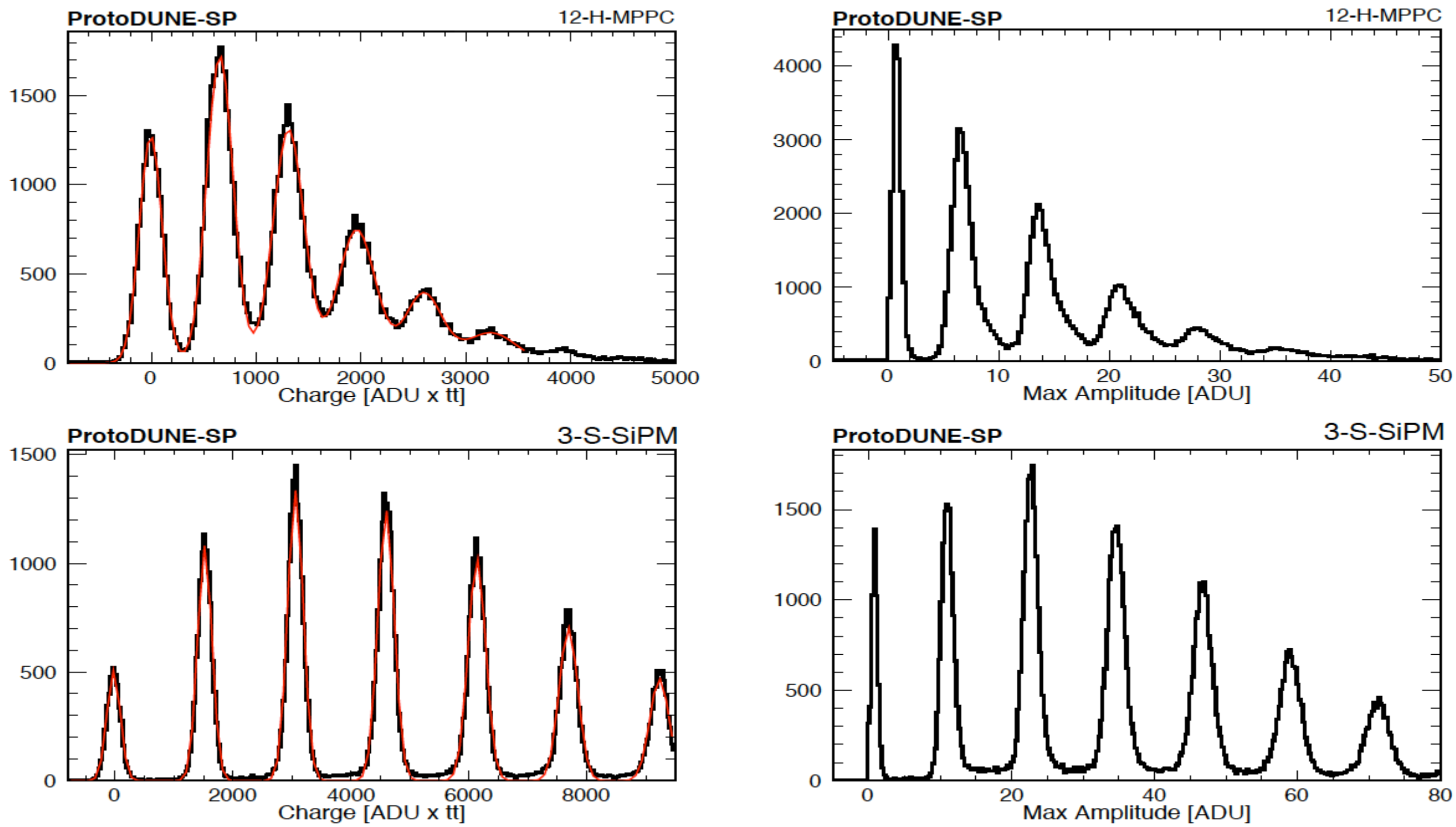
- UV-light system fabricated and install d to monitor health of the system, and to calibrate PDS gain e resolution
- Calibration light pulses set by amp e width, as a single pulse or as pulse pair





Photon-Detector Calibration

- Typical charge (signal integral) and current (signal amplitude) distributions under calibration LED pulses for the photon-detector channels
  - -readout channels with 12-MPPCs summed together (top row)
  - -readout channels with 3-SiPMs summed together (bottom row).

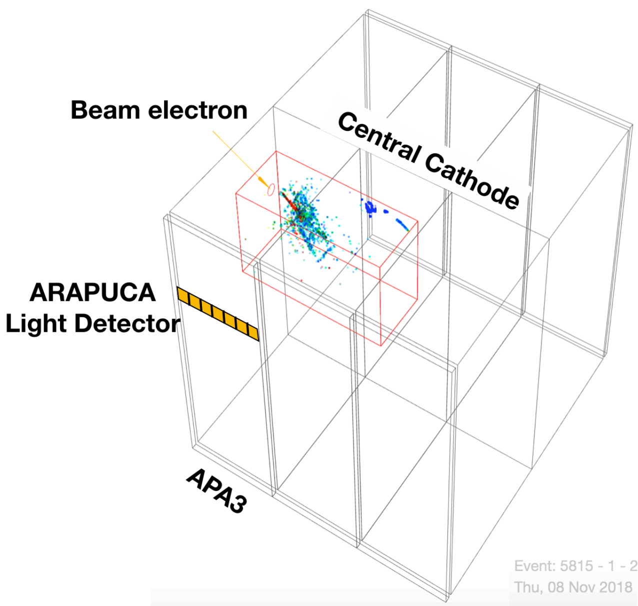


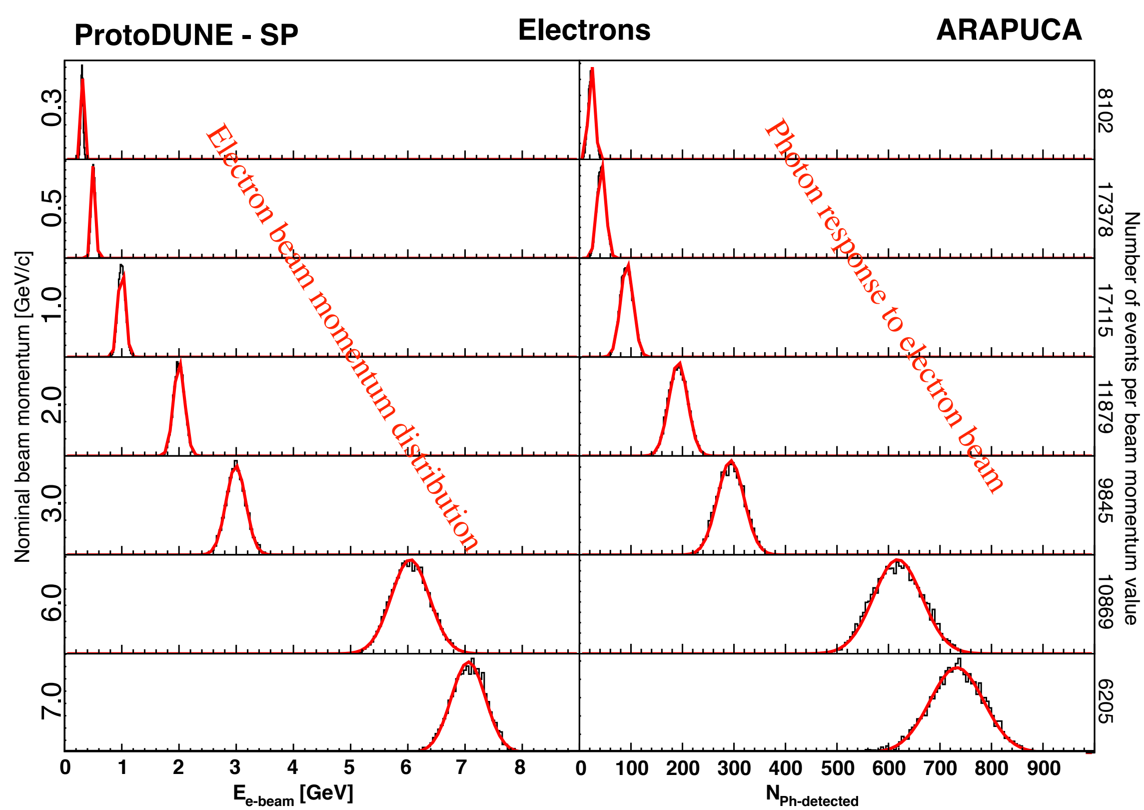
➢ the photon detectors show excellent signal-to-noise ratios and linearity of the response

Response to Electron Beam

- Operating on the H4-VLE charged particle test beam offers an opportunity to directly probe the calorimetric photon-detector response to EM and hadronic showers in the sub- to few-GeV momentum range.

- Showing calorimetric response from light signal from a single ARAPUCA module (~0.5‰ photo-sensitive area coverage) to EM shower at ~3 m distance in the

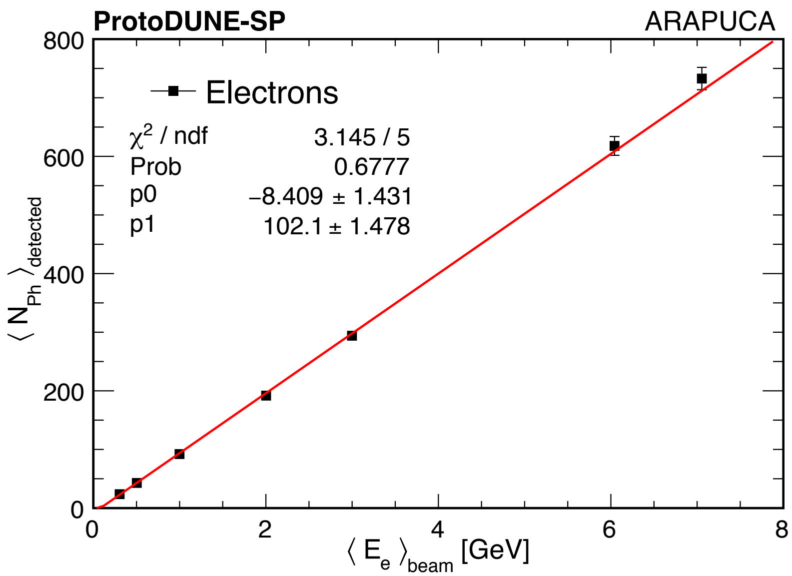


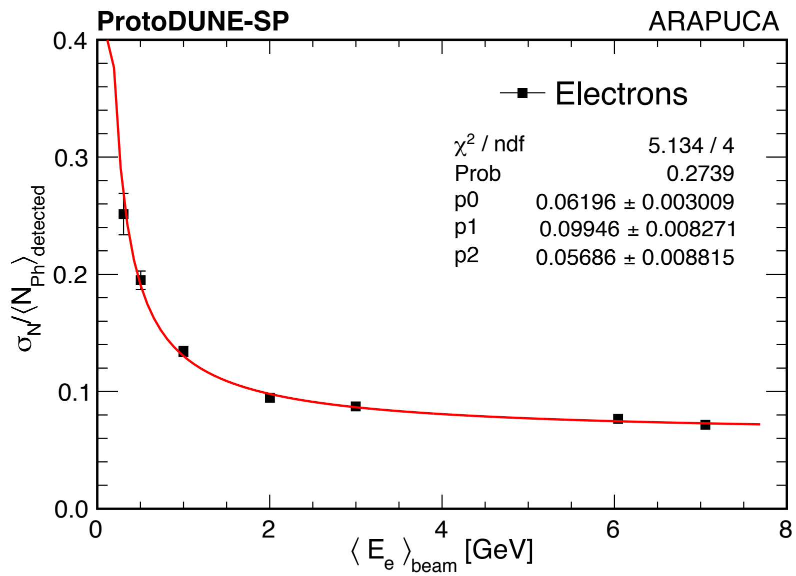


Response to Electron Beam

ProtoDUNE PDS Group - DUNE PD Consortium

- Gaussian mean value (left) and the ratio of the standard deviation to the mean (right) numbers of detected photoelectrons as functions of the beam electron energy.





- **Linearity of light response** over the entire range of energies. The slope gives the light yield from (only) one ARAPUCA module, relative to a diffused light source (EM shower) at a distance of ~ 3 m

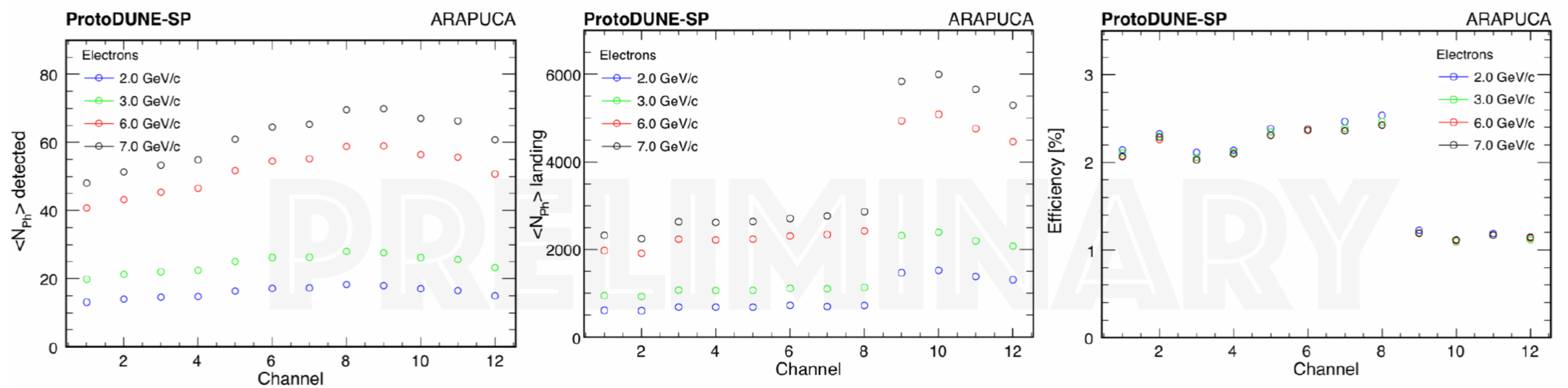
- **Energy resolution of light response**

$$\frac{\sigma_E}{E} = p_0 \oplus \frac{p_1}{\sqrt{E}} \oplus \frac{p_2}{E}$$

Please see Aleena Rafique's talk to learn more about Low-Energy Electron Response and Reconstruction

Photon-Detector Efficiency

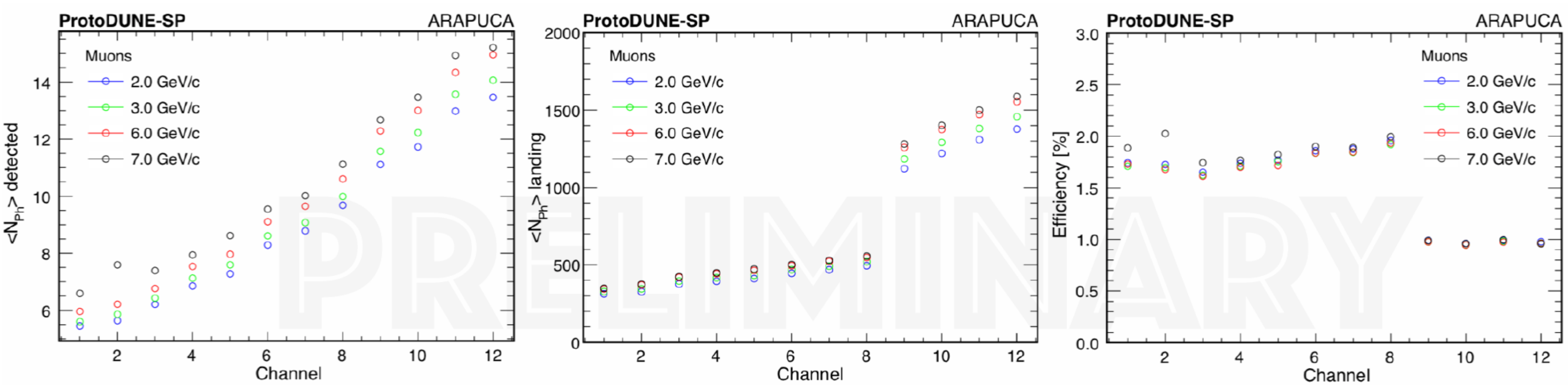
- Showed for ARAPUCA array on beam side
  -for beam electrons and muons, as detected photons (data) / “landing” photons (MC)



- Detection efficiency of the ARAPUCA detectors is taken as the average value of the individual cells with its error:

cell type−1 ; $\tilde{\epsilon}_1 = (2.00 \pm 0.25)\%$

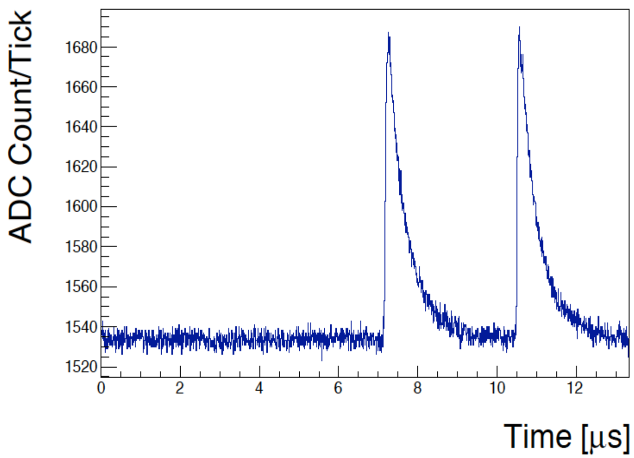
cell type−2 ; $\tilde{\epsilon}_2 = (1.06 \pm 0.09)\%$

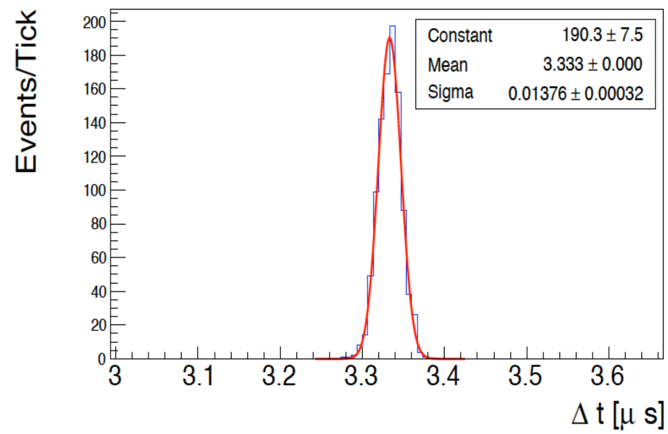


Photon-Detector Timing Performance

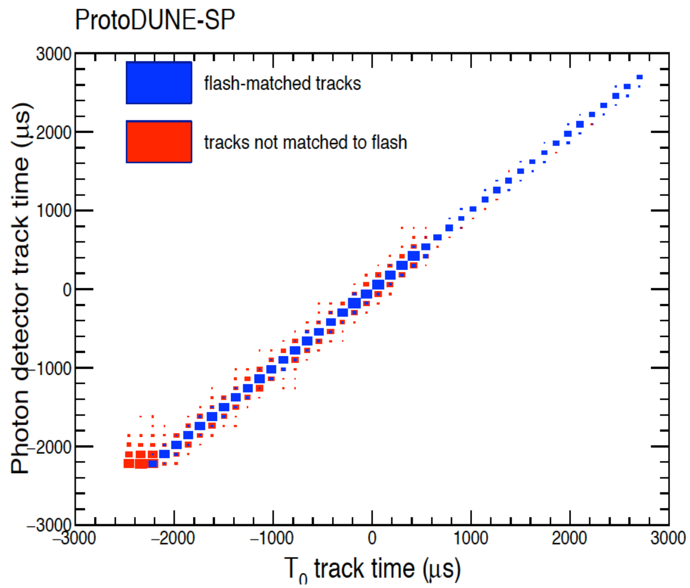
ProtoDUNE PDS Group - DUNE PD Consortium

- Timing performance evaluated in two different applications: time resolution of two consecutive light signals and time matching between light signal and TPC signal.





➢ time resolution from time difference between correlated light signals



➢ Cross-check of correlation between TPC track t0 time and the PDS flash time

-Track t0 determined with muons crossing cathode/anode planes

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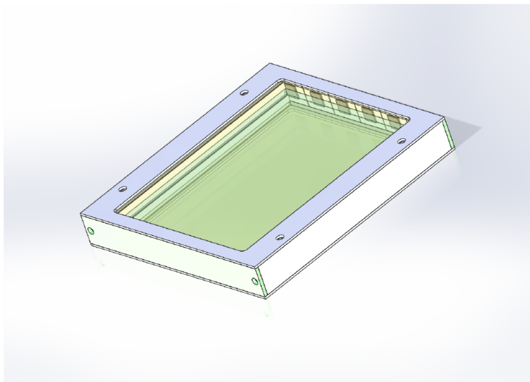
Next Steps: Going to DUNE

- **DUNE Baseline**: Double-Window X-ARAPUCA is the baseline technology to meet or exceed DUNE performance specifications

Please see E. Segreto and A. Machado's talk on ARAPUCA Light Detectors for DUNE

Double-Window X-ARAPUCA



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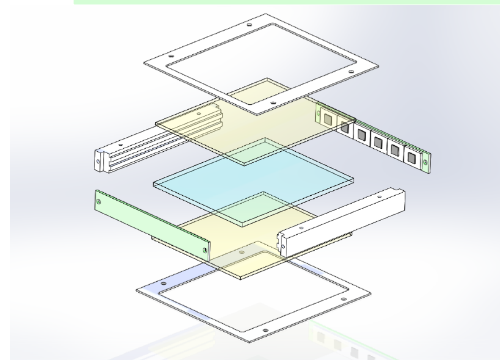


A hybrid of ProtoDUNE ARAPUCA and light guide

⇒An efficiency of ~ 3.5% was found

- Next Steps in Photon-Detector system (PDS) development

  -Study and optimize a photosensor based on FBK (Fondazione Bruno Kessler) SiPMs, along with Hamamatsu MPPCs
  -Optimize signal merging with active-ganging circuit based on the design tested in IceBERG tests
  -Further optimize digitization of the resulting electrical signal to provide the time and intensity of the light signals
  -Study uniformity of the response with photons converted at a wavelength-shifter-coated reflecting foil on CPA
  -Test xenon doping scheme of LAr: convert 128 to 175 nm photons, with 10-100 ppm

- ProtoDUNE-SP phase II (2020-2022) will be used for the final verification of DUNE PDS

Summary

- Photon Detection System used to capture scintillation light produced by charged particle interactions in the DUNE TPC.
  - ➢ Detected scintillation light needed for event trigger and interaction time (t0) for underground physics (SNB, proton-decay, atmospheric ν's)
  - ➢ Energy response improves if sufficient light is detected

- DUNE PDS prototypes implemented in ProtoDUNE-SP test-beam experiment
  - ➢ Initial data demonstrate excellent performance of PDS

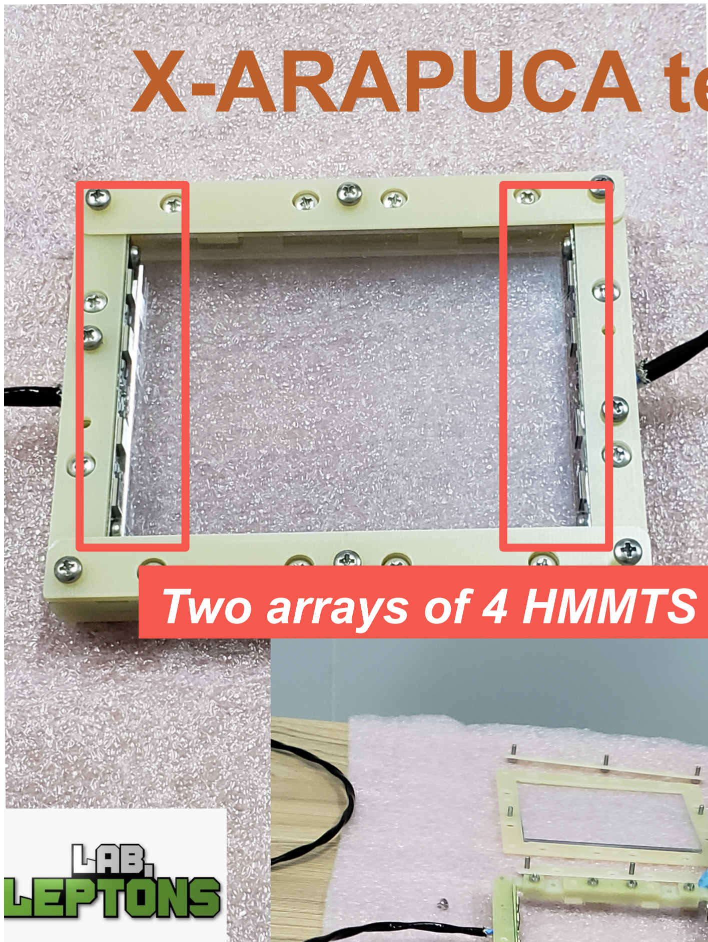
- The photon detectors show excellent signal-to-noise ratios and linearity

- The measured resolutions of the calibrated photon detector responses to various beam particles demonstrate capability of the system to be used in DUNE FD

- The data collected by ProtoDUNE-SP during beam and cosmic-ray runs allow continued studies of particle's energy and an efficient light flash-to-track matching.

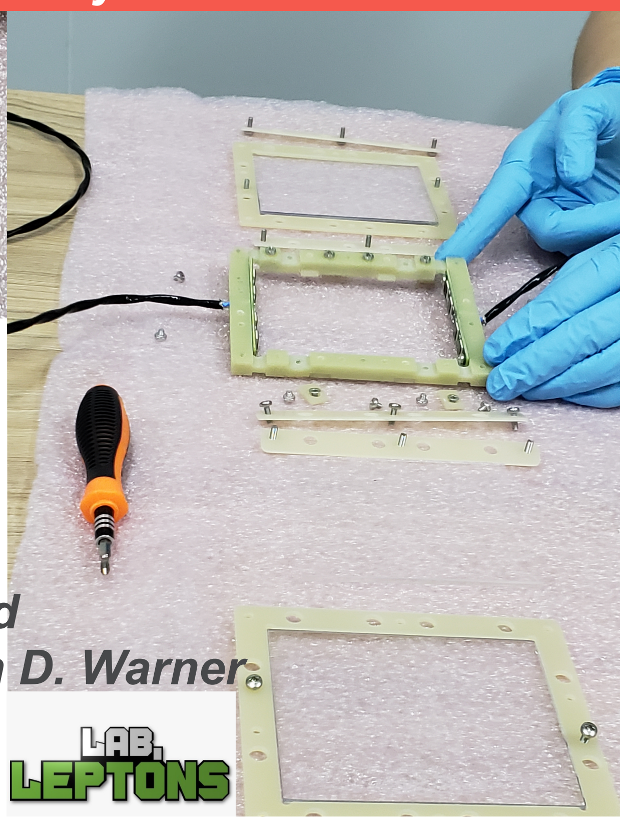
BACKUP SLIDES

X-ARAPUCA test at UNICAMP



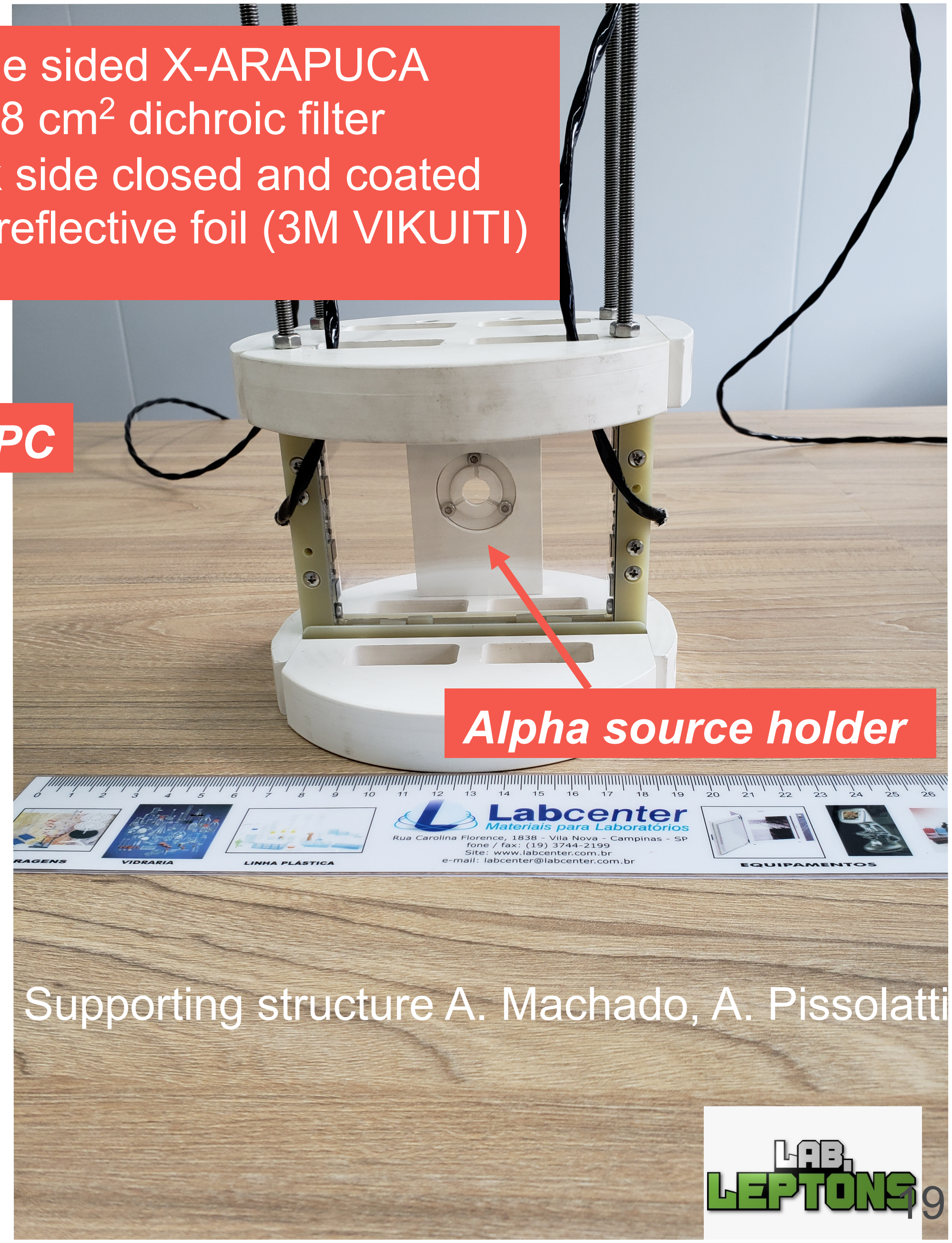
- Single sided X-ARAPUCA
- 10 x 8 cm^2 dichroic filter
- Back side closed and coated with reflective foil (3M VIKUITI)

Two arrays of 4 HMMTS TSV MPPC



LAB. LEPTONS

Design and fabrication D. Warner



Alpha source holder

Supporting structure A. Machado, A. Pissolatti

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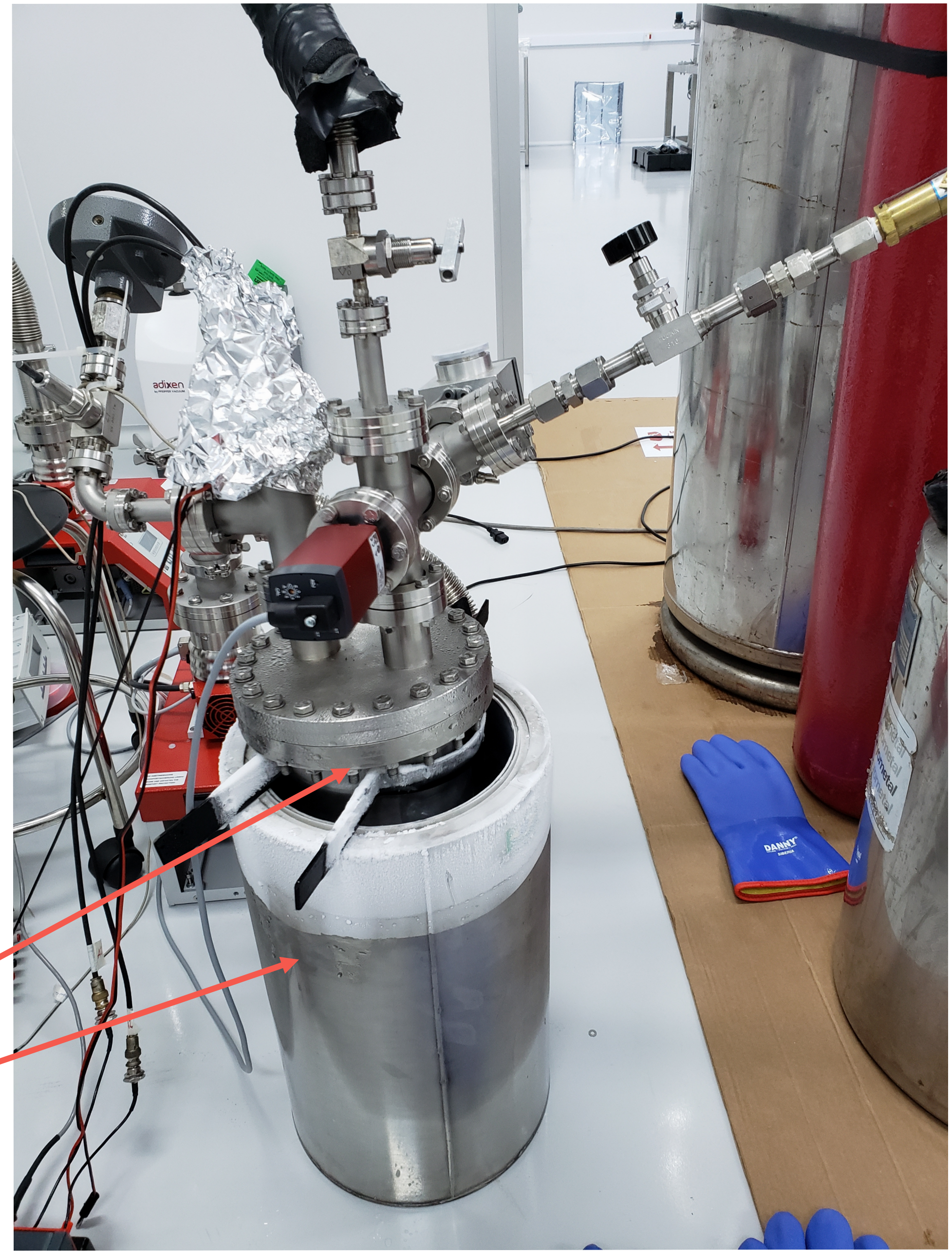
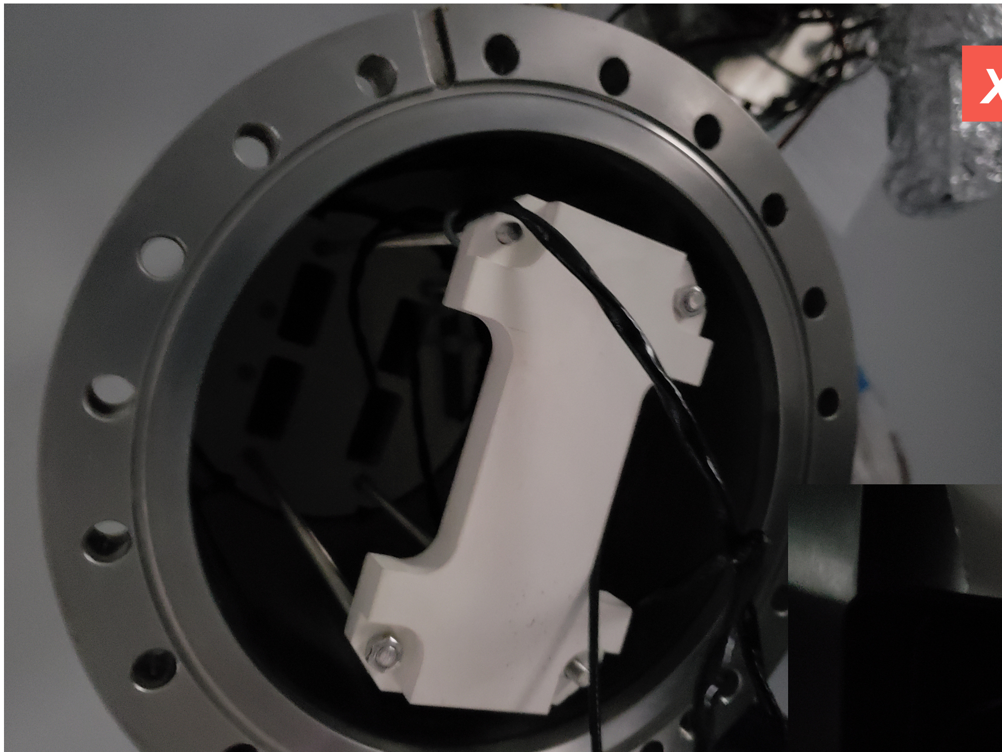
X-ARAPUCA test at UNICAMP



X-ARAPUCA test at UNICAMP

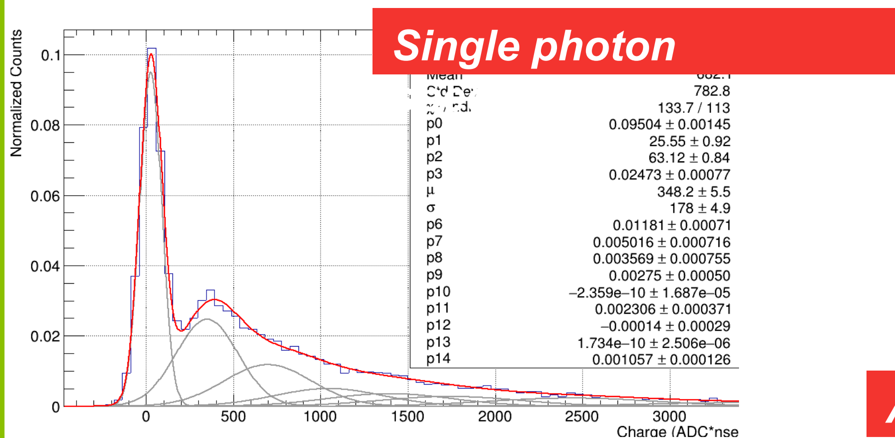


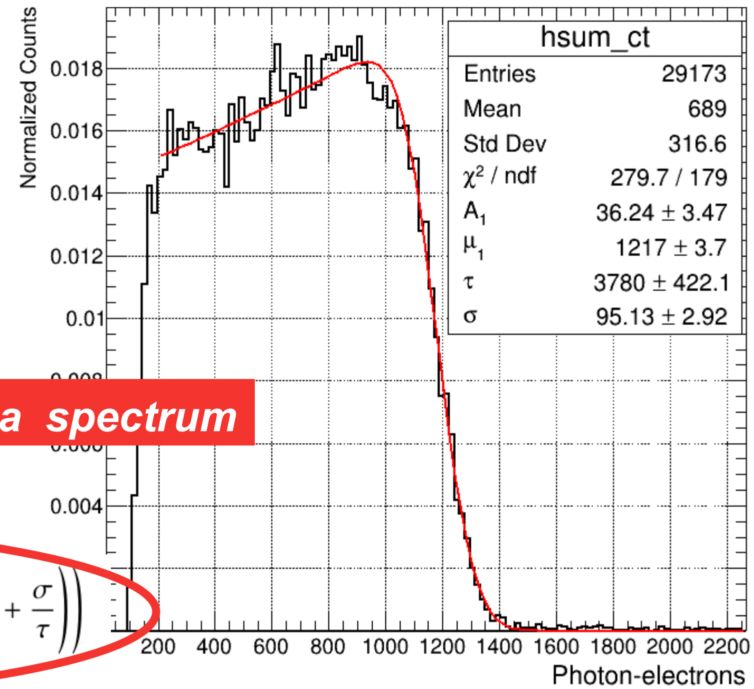
X-ARAPUCA after the end of the test

- The dichroic filter was evaporated at UNICAMP with a film of p-TerPhenyl

- The status of the film after the end of the test was perfect

X-ARAPUCA test result





Fit function

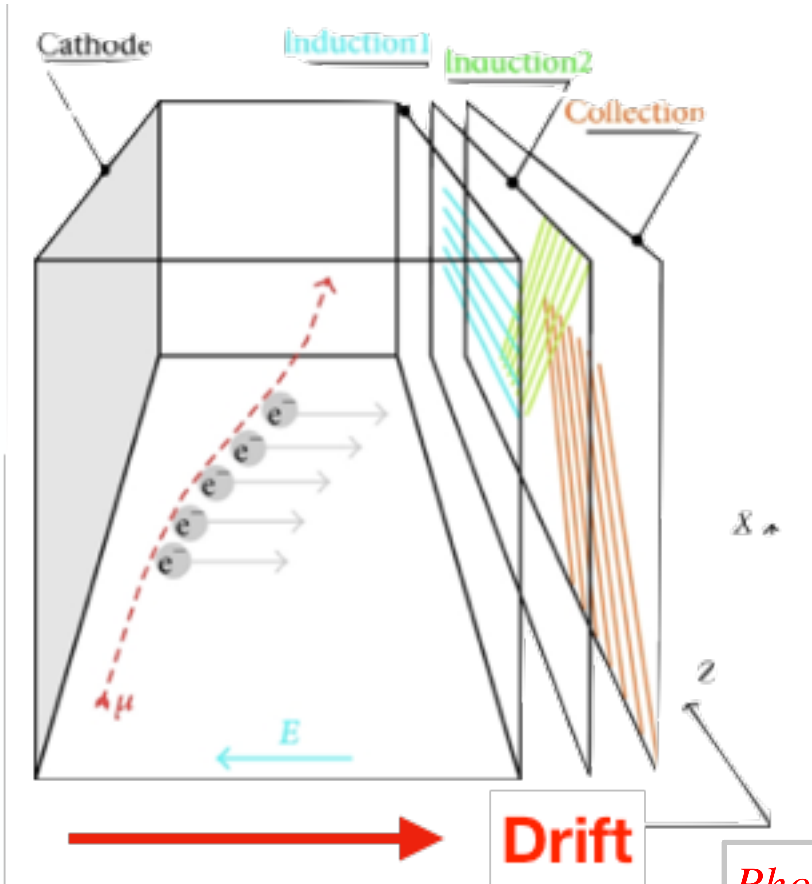
$$F(E) = \sum_{i=1}^{3} f(E-\mu_i;\sigma,\tau) = \sum_{i=1}^{3} \frac{A_i}{2\tau}\exp\left(\frac{E-\mu_i}{\tau}+\frac{\sigma^2}{2\tau^2}\right)\mathrm{erfc}\left(\frac{1}{\sqrt{2}}\left(\frac{E-\mu_i}{\sigma}+\frac{\sigma}{\tau}\right)\right)$$

- The source is an ***alloy of aluminum and natural uranium***
- The fit returns the *number of detected photons for each line*
- Comparison with number of photons impinging on X-ARAPUCA window gives the efficiency
- ***An efficiency of ~ 3.5% was found***

α energy (MeV)	relative intensity	parent nucleus
4.187	48.9%	^{238}U
4.464	2.2%	^{235}U
4.759	48.9%	^{234}U

Liquid Argon TPC Concepts for DUNE Far Detector

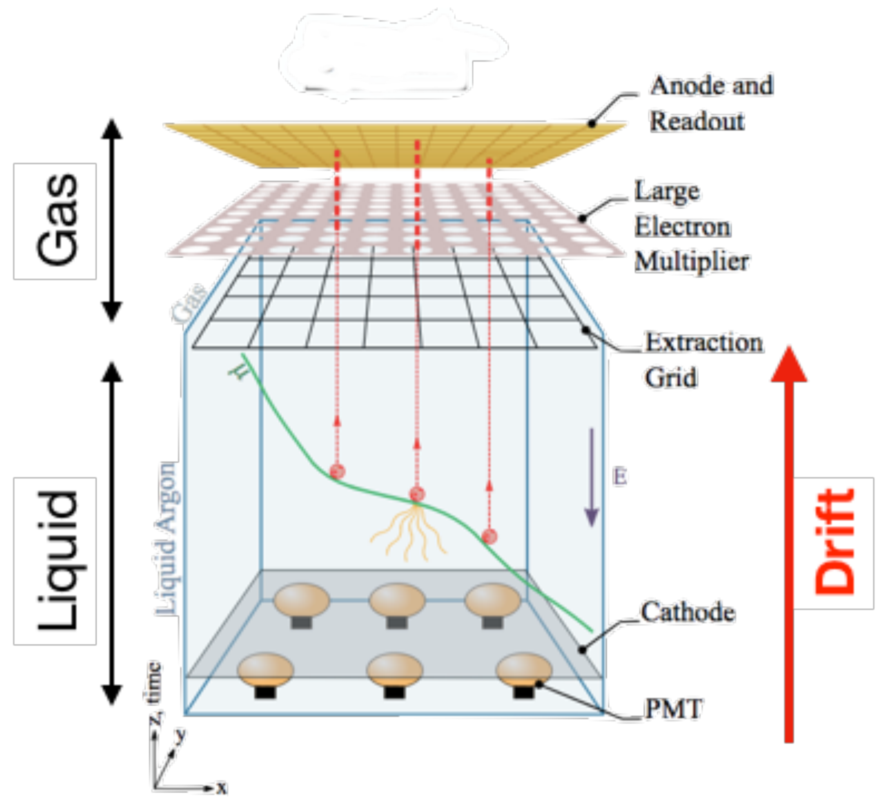
Single phase TPC



- Only liquid Ar phase
- Horizontal drift
- No amplification in LAr volume
- 2 Induction and 1 collection plane

Photo-Detectors for triggering and t0 determination

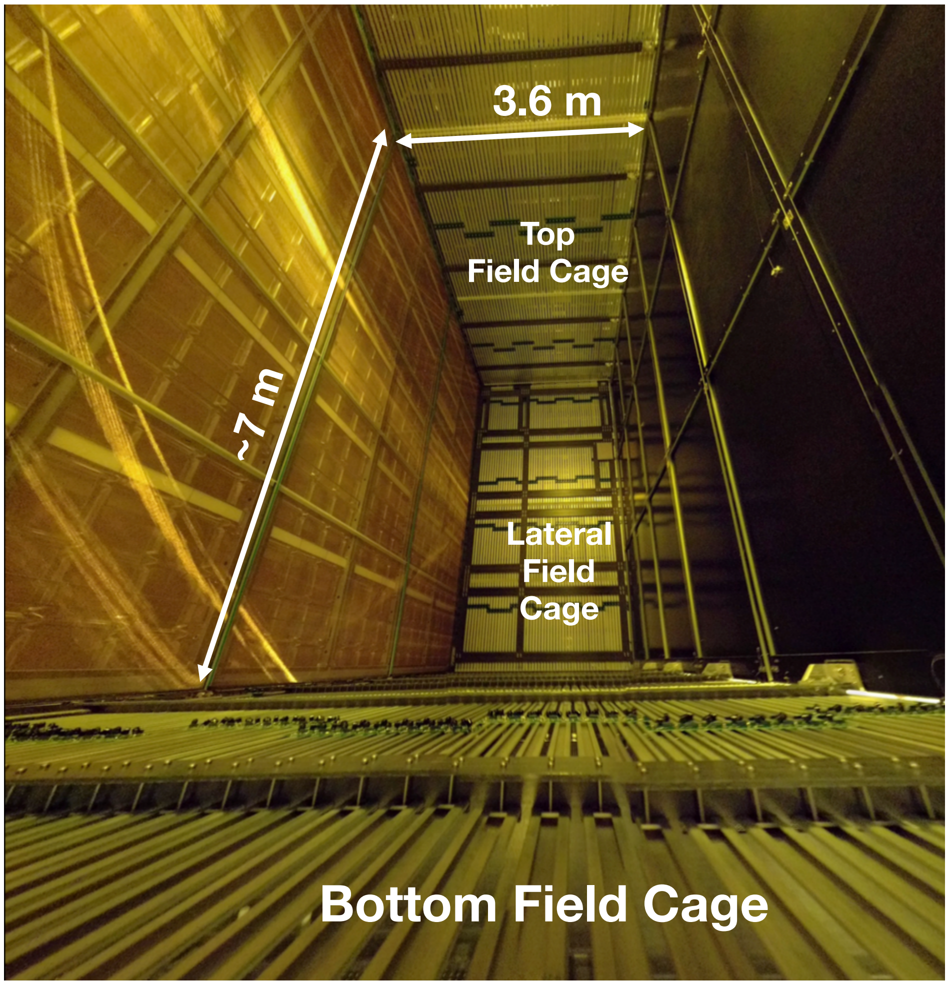
Dual phase TPC



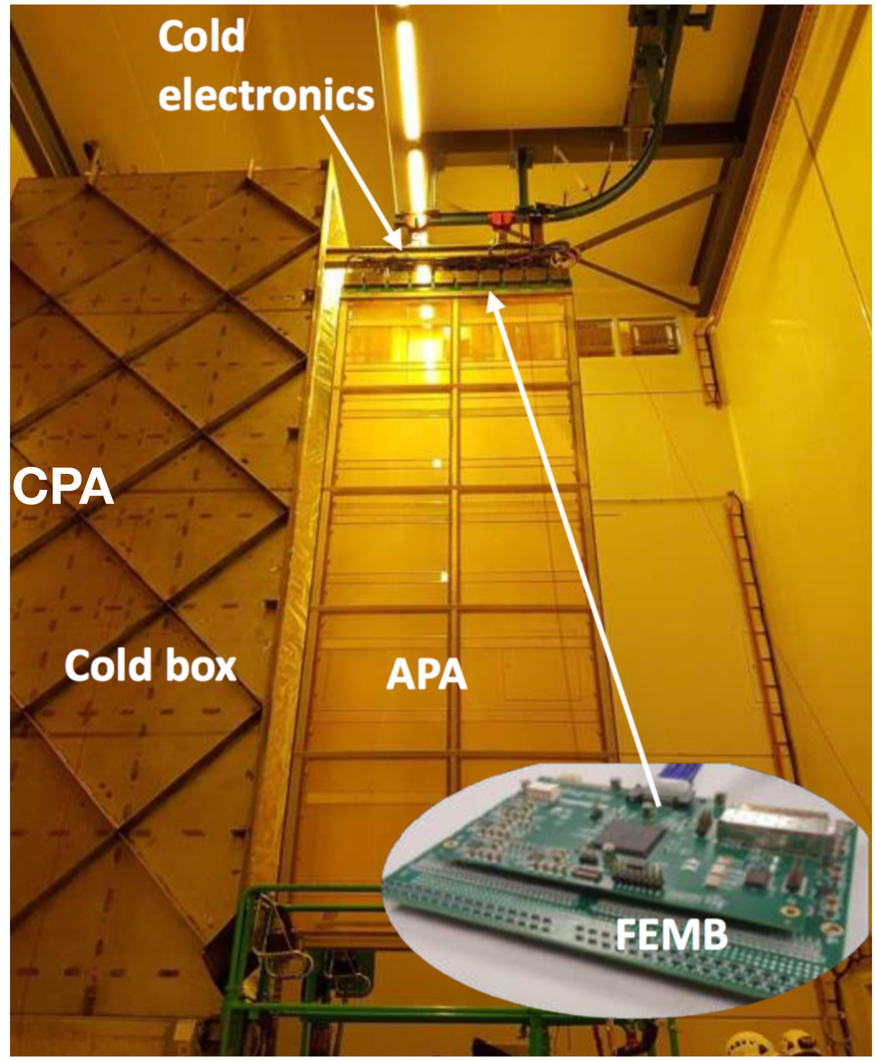
- Liquid and Gas Argon
- Vertical drift
- Amplification in gas
- 2 collection views

Fully instrumented drift volume

- Single Phase



Electronics on top of APAs submerged in LAr at 87 K



PDS Performance Requirements

- Performance requirements considered to achieve the primary science objectives

Requirement	Rationale
The far detector (FD) PDS shall detect sufficient light from events depositing visible energy >200 MeV to efficiently measure the time and total intensity.	This is the region for nucleon decay and atmospheric neutrinos. The time measurement is needed for event localization for optimal energy resolution and background rejection.
The FD PDS shall detect sufficient light from events depositing visible energy <200 MeV to provide a time measurement. The efficiency of this measurement shall be adequate for SNB events.	Enables low energy measurement of event localization for SNB events. The efficiency may vary significantly for visible energy in the range 5 MeV to 100 MeV.
(Proposed) The FD PDS shall detect sufficient light from events depositing visible energy of 10 MeV to provide an energy measurement with a resolution of 10%.	Enables energy measurement for SNB events with a precision similar to that from the TPC ionization measurement.
The FD PDS readout electronics shall record time and signal amplitude from the photosensors with sufficient precision and range to achieve the key physics parameters.	The resolution and dynamic range needs to be adjusted so that a few-photoelectron signal can be detected with low noise. The dynamic range needs to be sufficiently high to measure light from a muon traversing a TPC module.

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ProtoDUNEs

- ProtoDUNEs are DUNE prototypes built to test and demonstrate Far Detector Concepts

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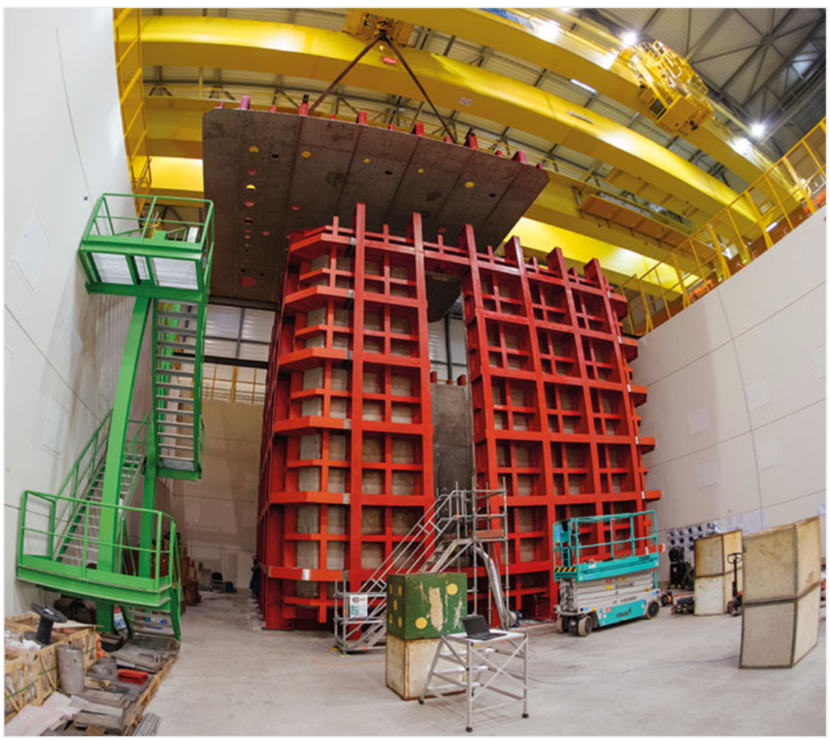
FEATURE

ProtoDUNE revealed

15 February 2017

CERN makes rapid progress toward prototype DUNE detectors.



Outer vessel

Latest Articles

ProtoDUNE Goals

- Hardware
  - Prototyping production and (underground) installation procedures
  - Validating the design from basic detector performance
  - Demonstrating long-term operational stability

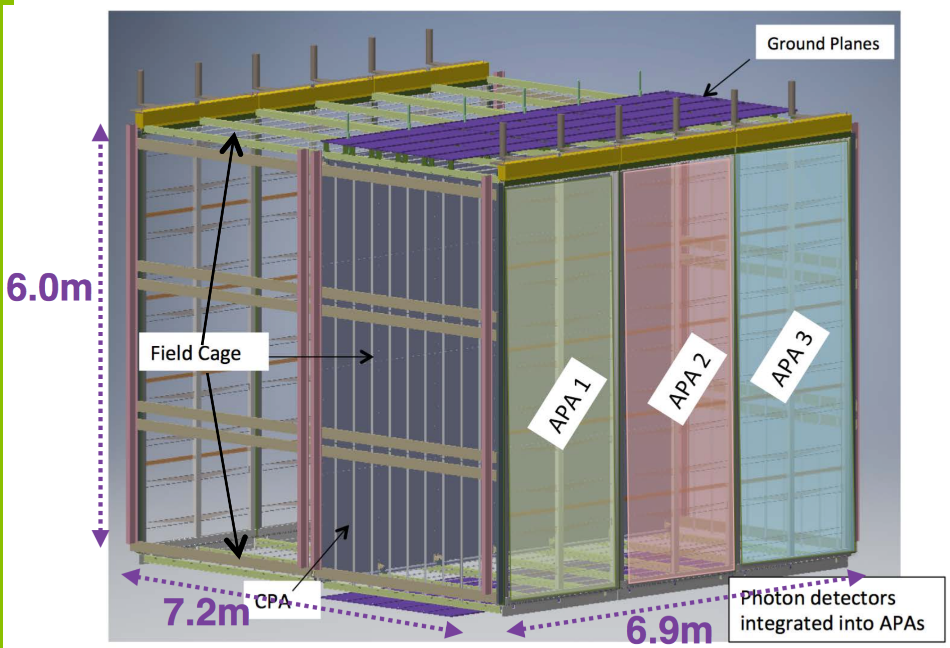
- Test beam data
  - Detector response understanding, calibration, dE/dx, PID.
  - Perform cross section measurements of hadrons on Argon

- Cosmics data
  - 3D map of detector response: space charge and E field distortions
  - Different settings: E-field, recirculation, PDS response

Two Technologies

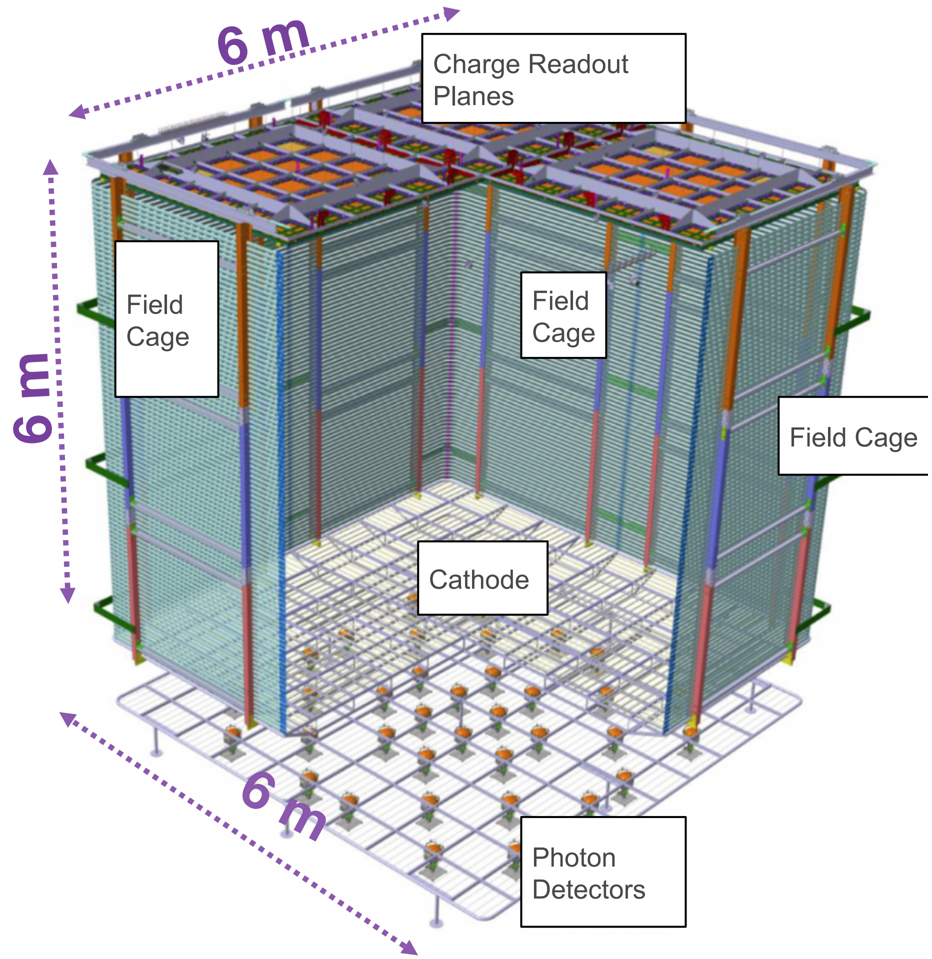
Single-Phase

3.6 m horizontal drift



Dual-Phase

6 m vertical drift



DUNE Outlook

- DUNE is the result of combining international efforts (>20 years R&D on LAr) and presents the next accelerator mega-science project
- LBNF and DUNE making rapid progress on facility construction, detector design, and physics analysis
- Ongoing R&D program at CERN with two large scale prototypes:
  -ProtoDUNE beam data demonstrated a high-quality
- DUNE Technical Design Report will be published in 2019
- ProtoDUNE results and more data expected in 2019
- First DUNE FD data expected in ~2025