DEEP UNDERGROUND NEUTRINO EXPERIMENT

Results from ARAPUCA R&D Tests

DUNE-SP Photon Detection System Conceptual Design Review

November 12th, 2018

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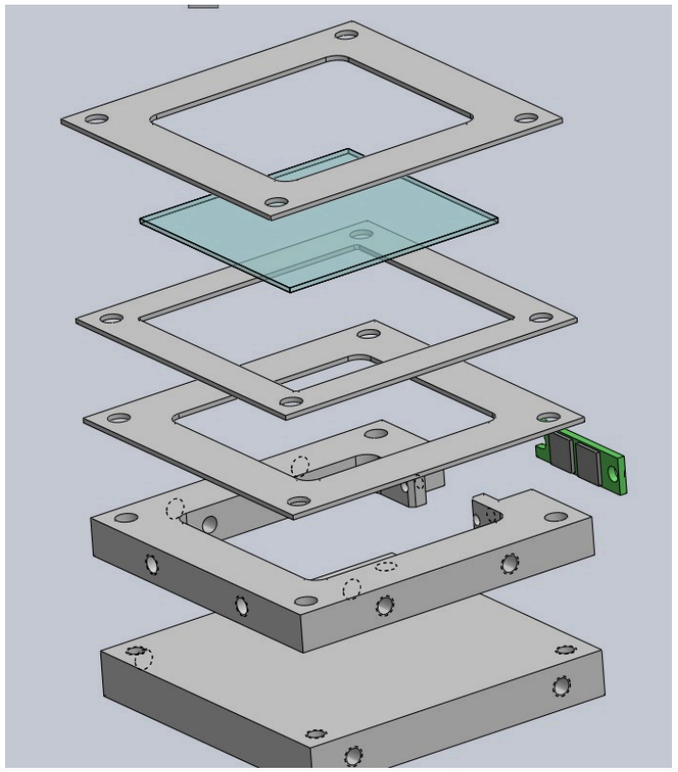
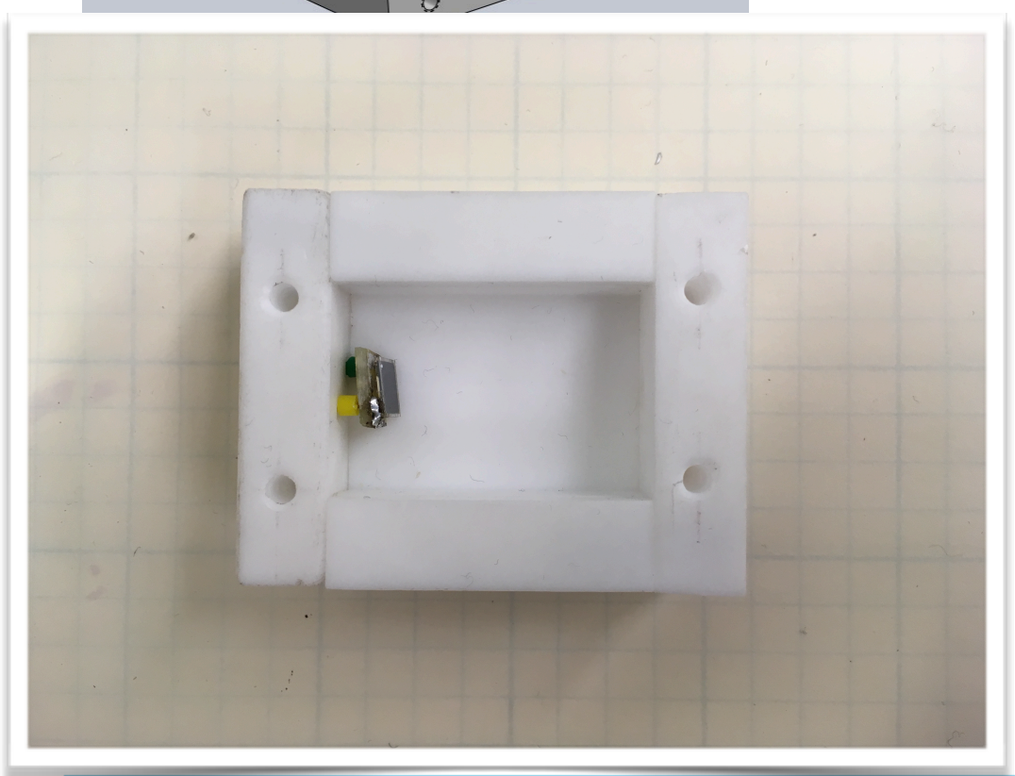
Fermilab

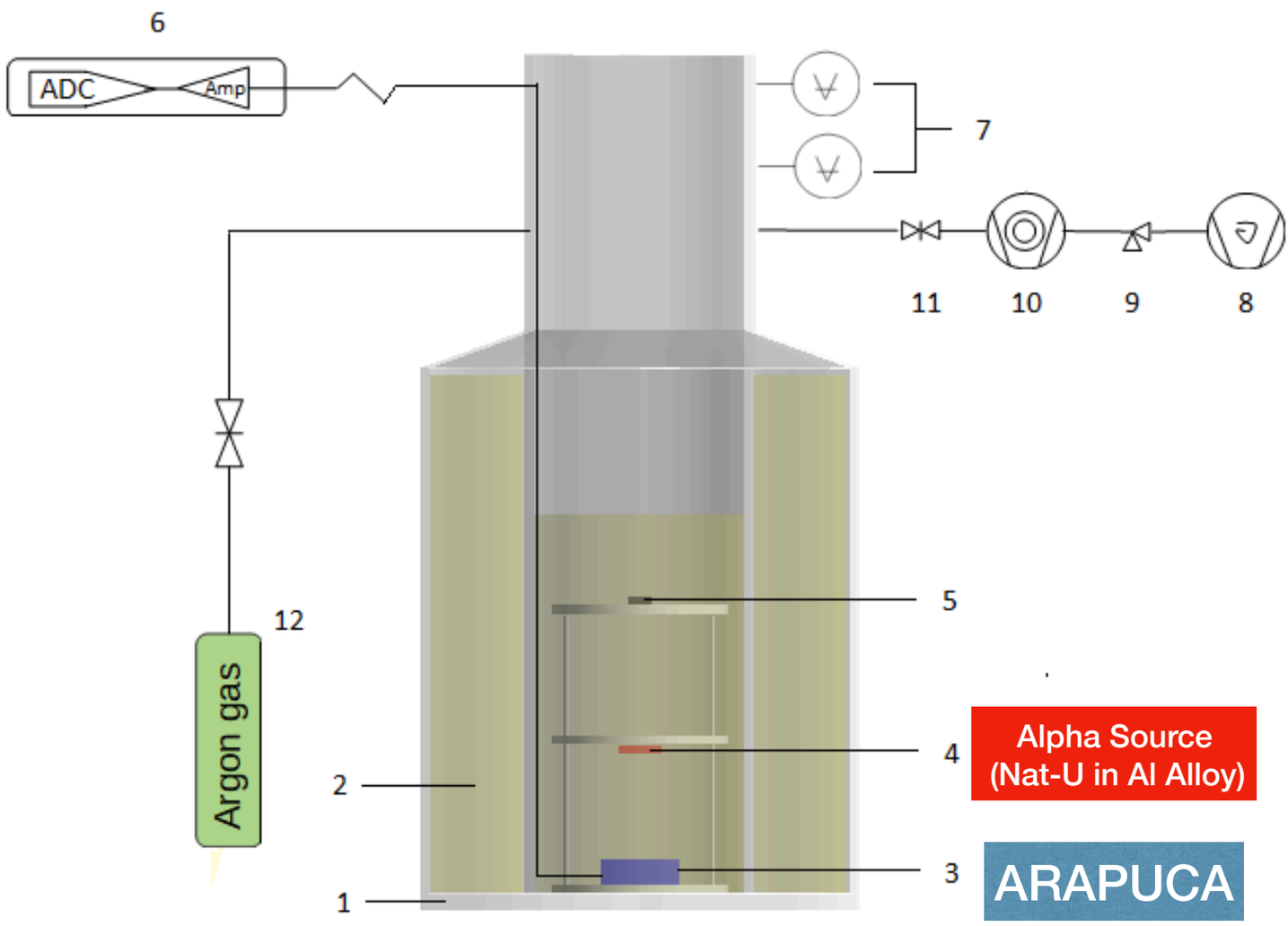
ARAPUCA test at the Brazilian Synchrotron Light Laboratory (LNLS)

(Nov. 2016)

First measurement of global detection efficiency of an ARAPUCA prototype to liquid Argon scintillation light *[E. Segreto et al, 2018 JINST 13 P08021]*





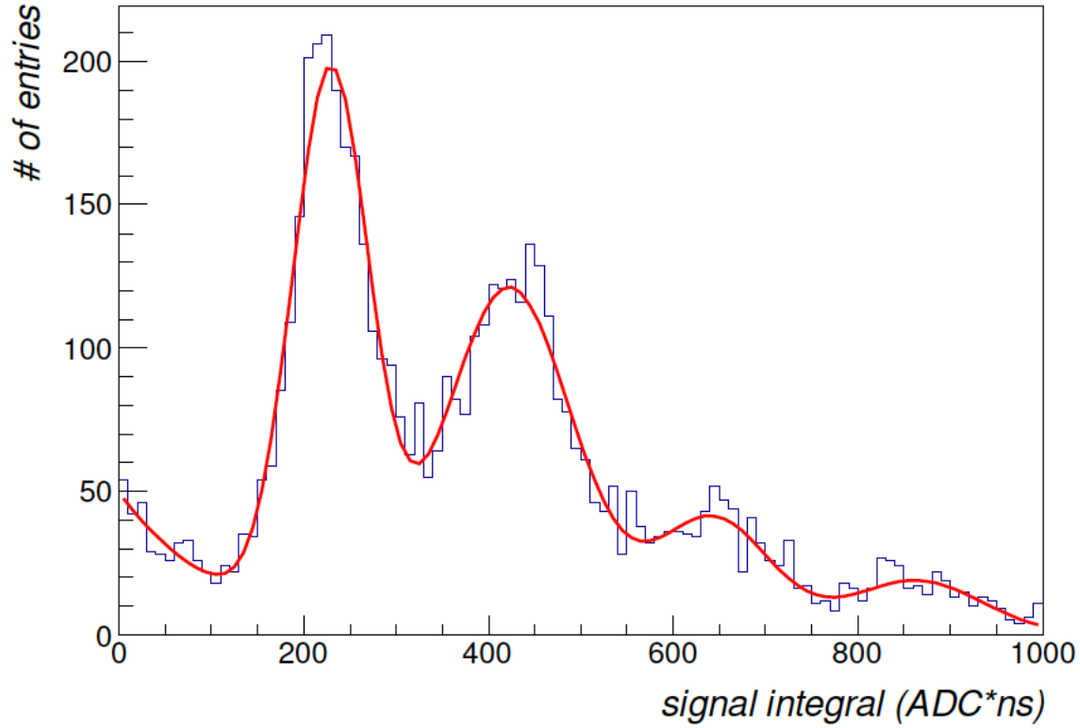


- PTFE box: internal dimensions of 3.6 cm 2.5 cm 0.6 cm
- Window: dichroic filter with dimensions of 3.6 cm X 2.5 cm, cut-off at 400 nm.
- WLS coating: external side p-Terphenyl (pTP), internal side TetraPhenyl-Butadiene (TPB).
- Prototype acceptance window: 9 cm^2, read-out: single SiPM (active area 0.36 cm^2).

Calibration run

Single Electron (and multiple) Response (SER) of the SiPM (single channel)

Average value of the integral of the waveform of single photo-electrons searched in the tail of scintillation signals.

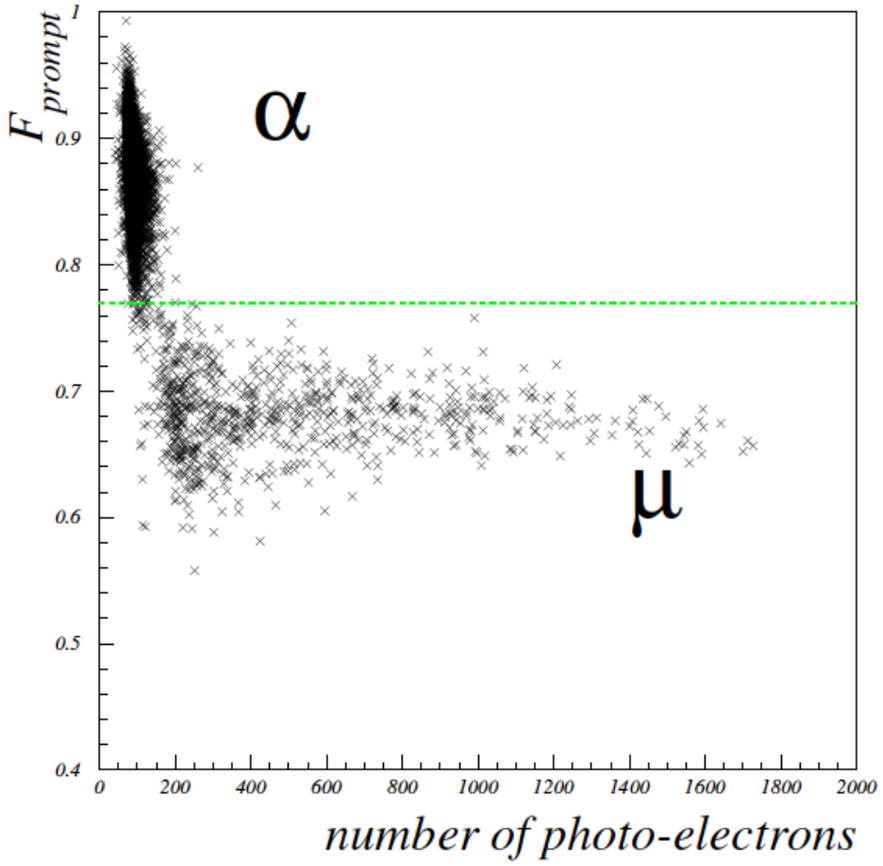


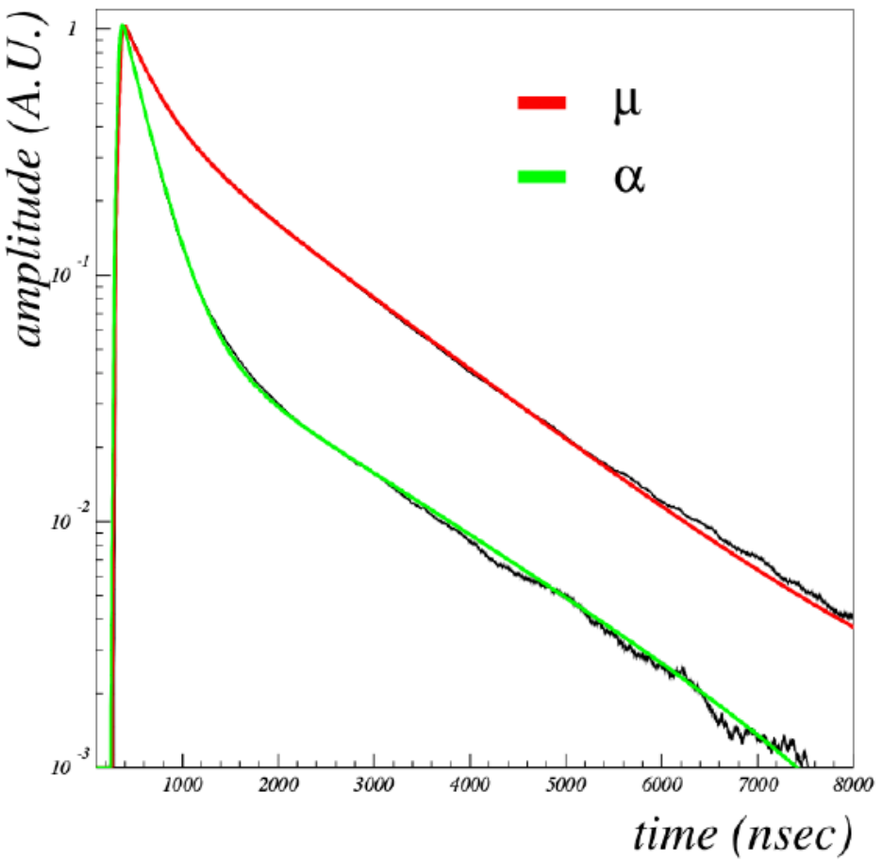
Alpha to Muon separation

Light source: Scintillation in LAr from Alpha particles and Cosmic Muons

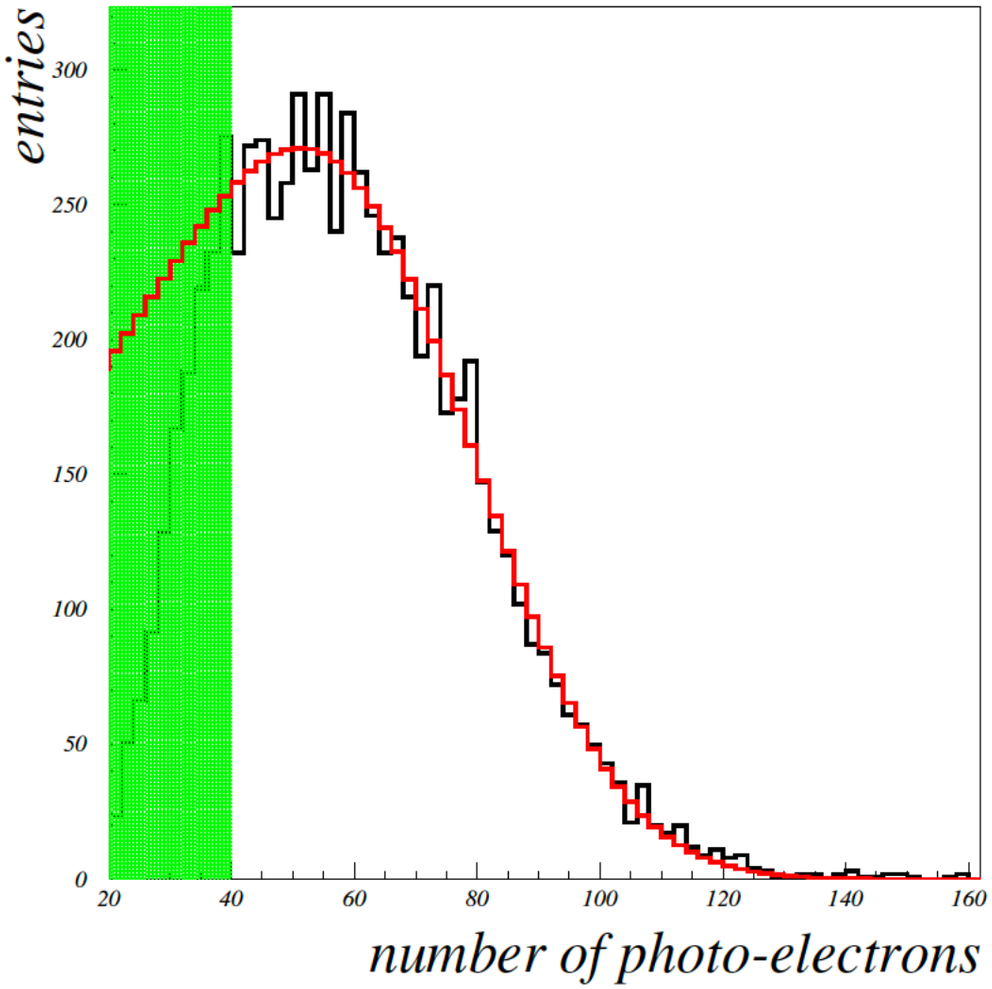
Exploit pulse shape capabilities of LAr to discriminate and analyze separately the α and the μ samples and obtain two independent estimations of the ARAPUCA efficiency

$$F_{\text{prompt}} = \frac{\int_{t_0}^{t_0+1500\ ns} I(t)\,dt}{\int_{t_0}^{t_0+10000\ ns} I(t)\,dt}$$





Alpha Spectrum and Efficiency



Illumination (pointlike Alpha Source)

$$PH = Y_\gamma \, q_\alpha \, E_\alpha(^{238}U) \, f_\Omega \simeq 6060 \, \gamma$$

$$PE(^{238}U) = 71 \pm 1 \, phel$$

from Fit of α spectrum (in PE)

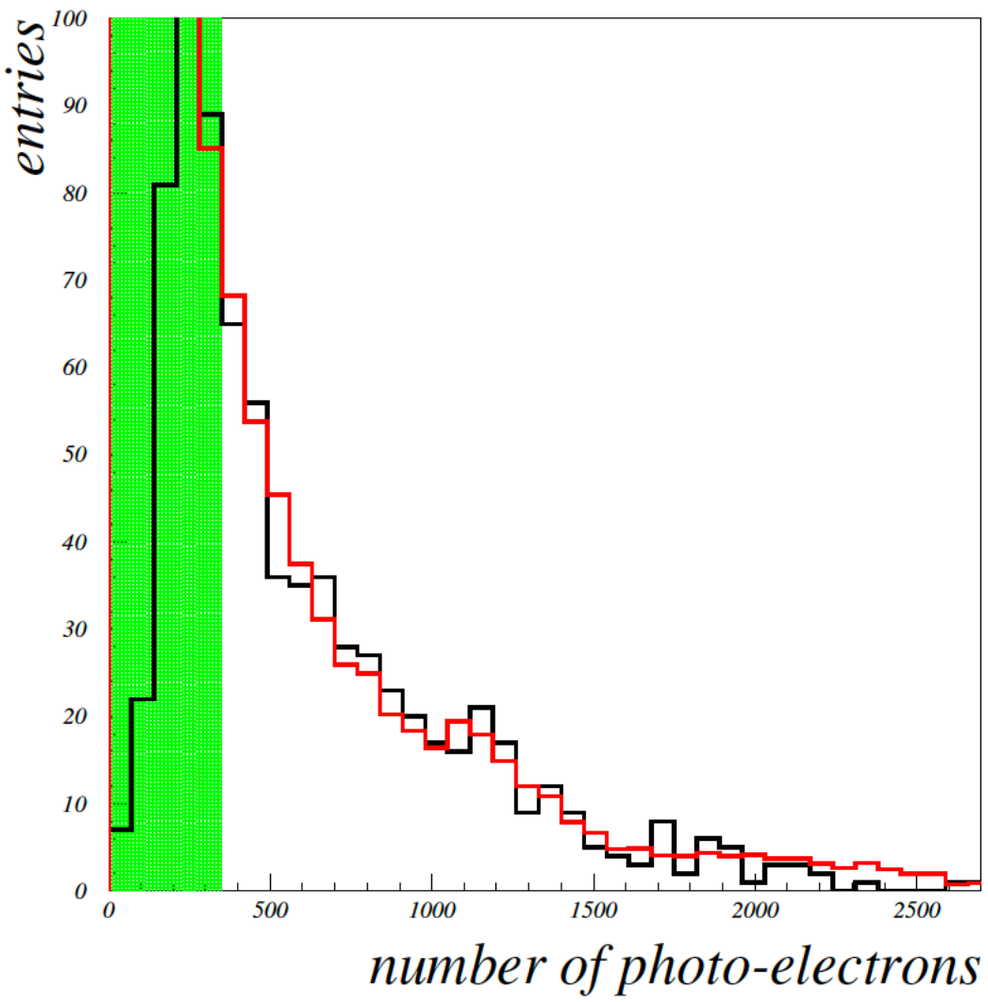
Correction Factors:

- Cross-talk (15%)
- Reflectivity of the internal surfaces (8-10%)
- Slightly deteriorated pTP Film (10-15%)

The total ARAPUCA efficiency, ϵ_α^A estimated through the α particle sample is:

$$\epsilon_\alpha = \frac{PE}{PH} = 1.0\% \pm 0.2\,\%$$

Muon Spectrum and Efficiency



$$\frac{dN^{\gamma}}{dx} = Y_{\gamma}\ q_{mip} \left\langle \frac{dE}{dx} \right\rangle_{\mu} \rho_{Ar} \simeq 1.04 \times 10^{5}\ \gamma/cm$$

MC simulation for CR Illumination estimate ⇒

Spectrum of *PH* arriving *at the ARAPUCA cell optical window*

Fit to the spectrum of detected PE, with scale factor (efficiency) as free parameter

Correction Factors:

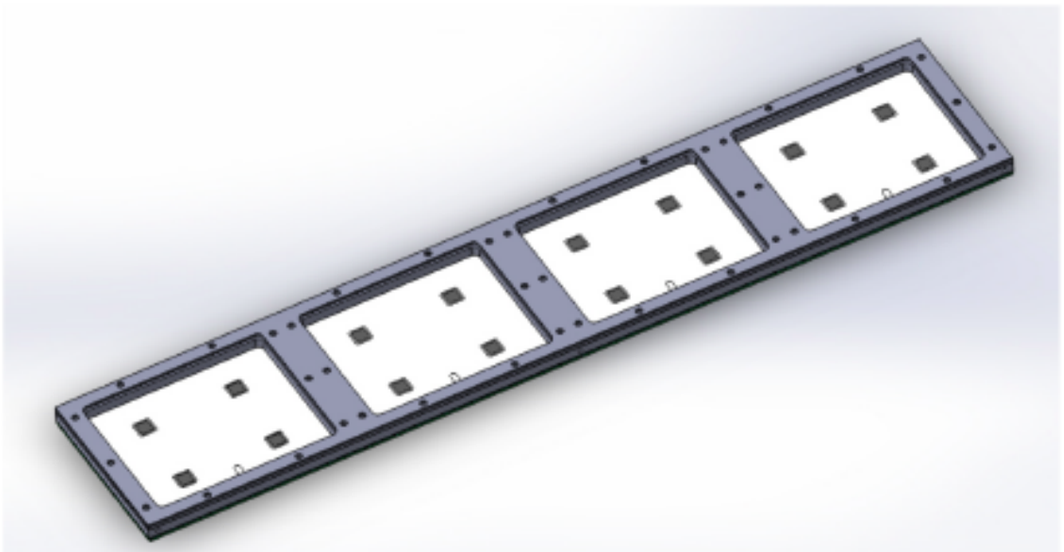
- Cross-talk (15%)
- Reflectivity of the internal surfaces (8-10%)
- Slightly deteriorated pTP Film (10-15%)

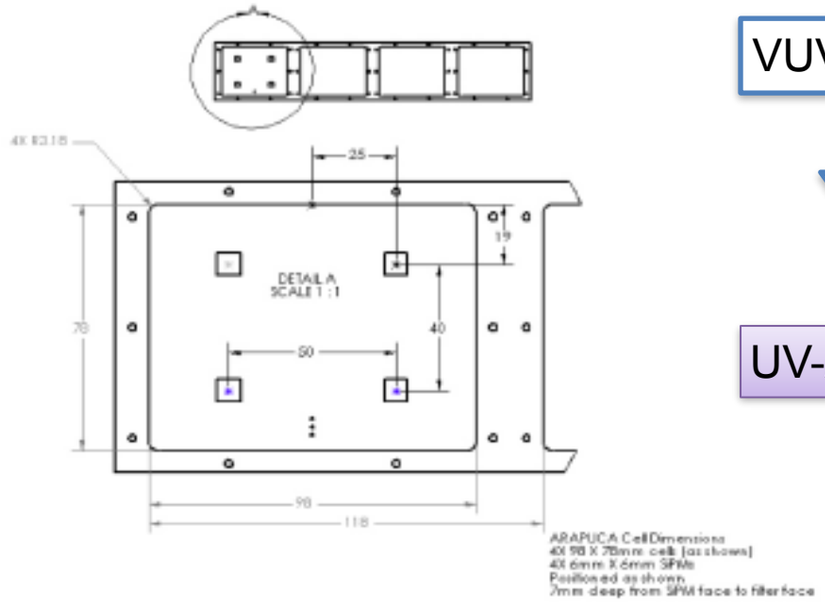
The global detection efficiency coming from the muon sample is:

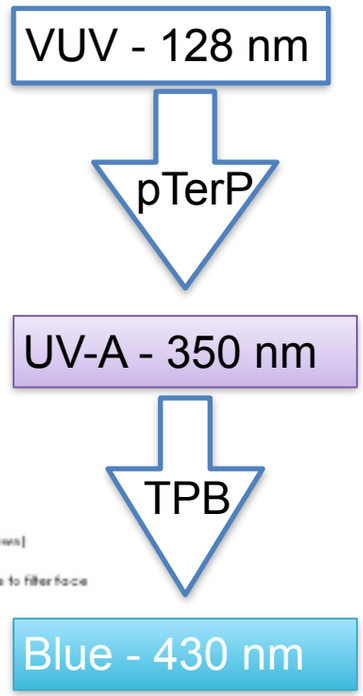
$$\epsilon_{\mu}^{Fit} = 1.2\% \pm 0.2\,\%$$

ARAPUCA test at FNAL PAB TallBo Test Facility (Oct. - Nov. 2017)

ARAPUCA design for TallBo test

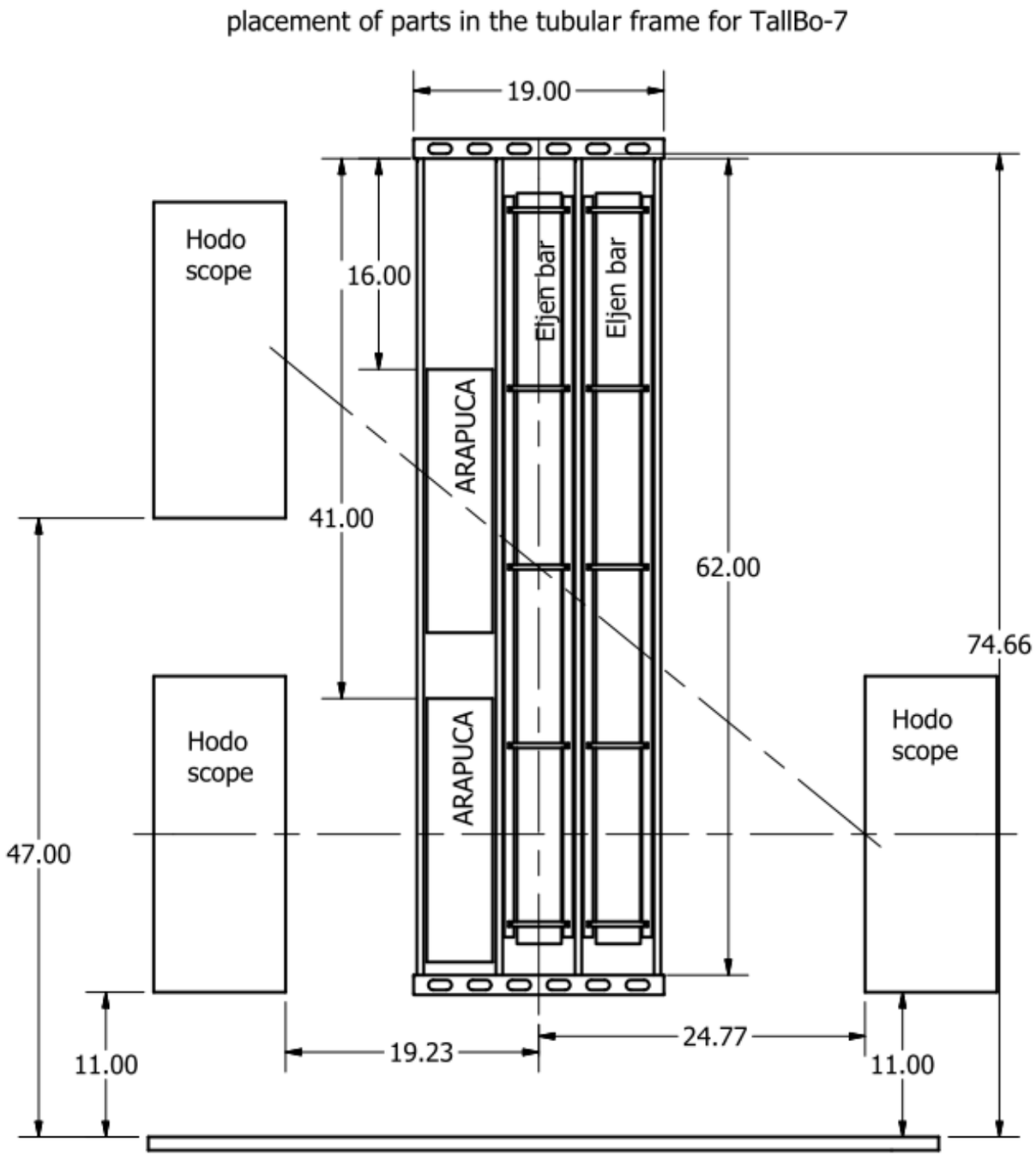


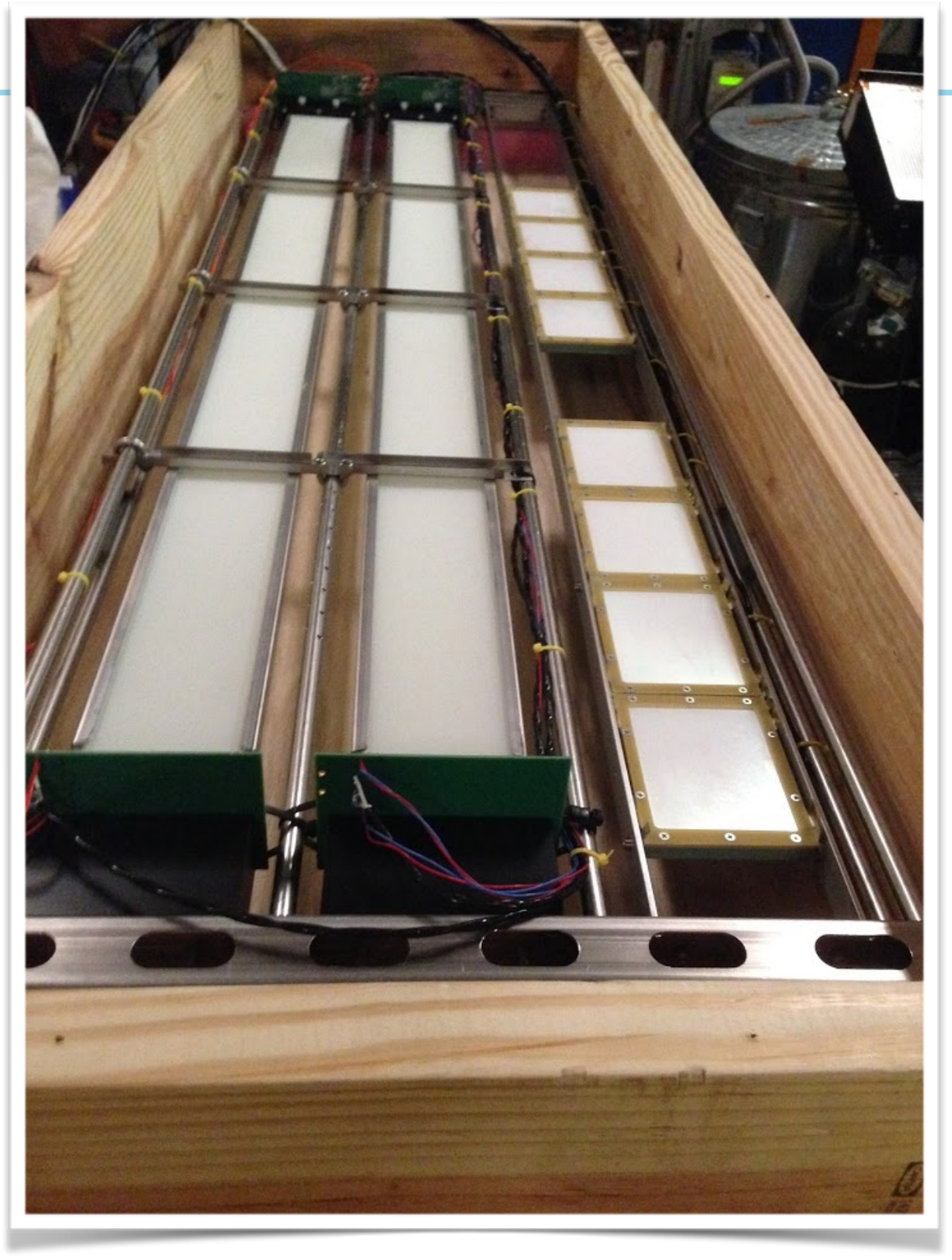




- **ARAPUCA "Bar" made of two Modules ("Cartuchos" - FR4 structure)**
- **4 ARAPUCA Cells (one-sided) in one Cartucho**
- **4 SiPMs** (6x6 mm^2)**in each ARAPUCA Cell (passive ganging) —> one read-out channel**
- **Cell optical window:** 9.8 x 7.8 cm^2
- WLS coating: external side p-Terphenyl (pTP), internal side TPB on VIKUITI reflector

- (the drawing is flipped 180º)



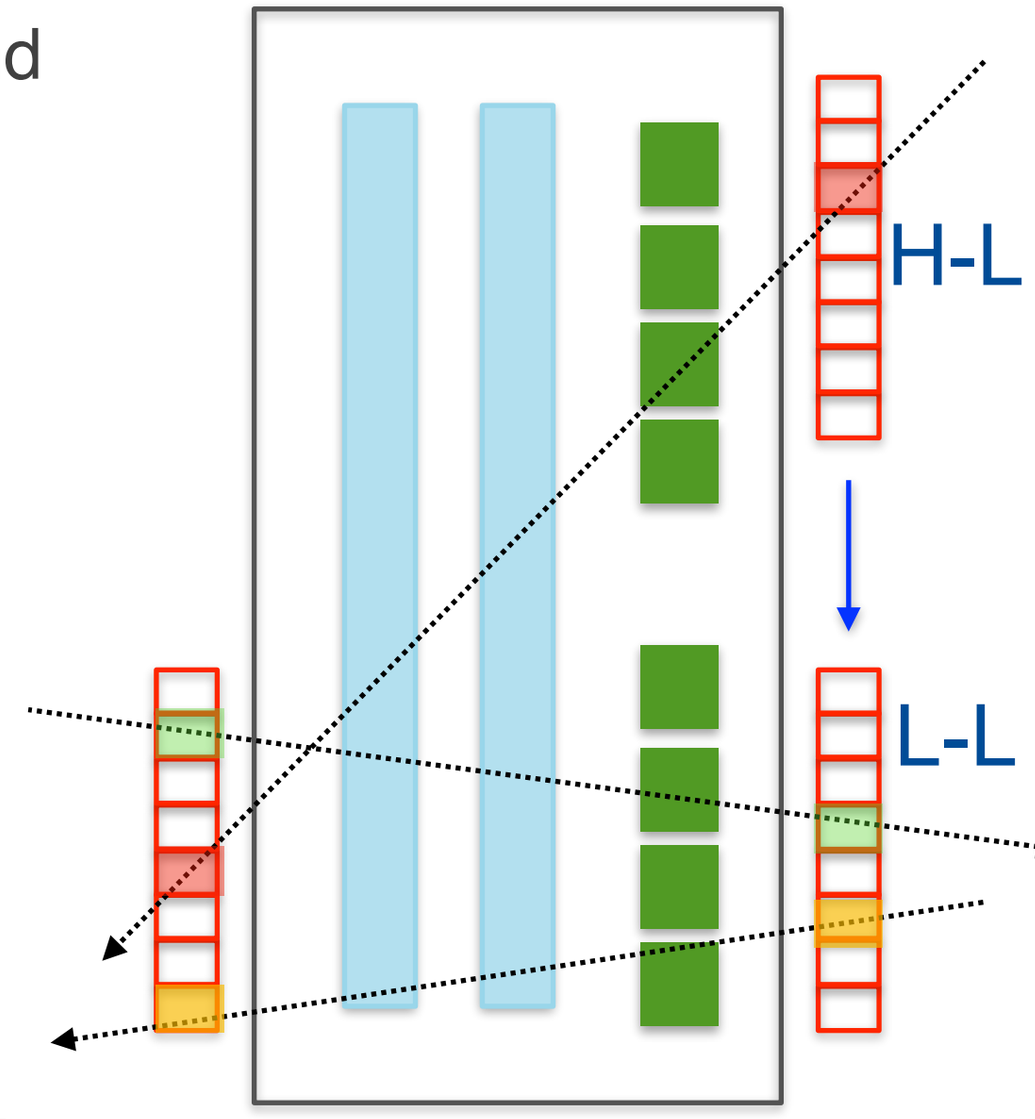


The TallBo experiment Oct-Nov 2017

- Two technologies Double-shift light bars and ARAPUCAs.

- **Light source:** Scintillation from Cosmic Muons through LAr (Trigger & Tracking by external segmented hodoscopes)

- Two Cosmic Muon Trigger configurations:
  - H-L low zenith angle muon tracks
  - L-L large zenith angle

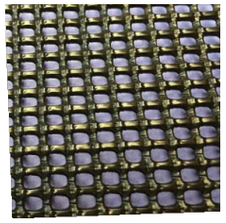


- **Primary Goal: measure PhDet Efficiency.**

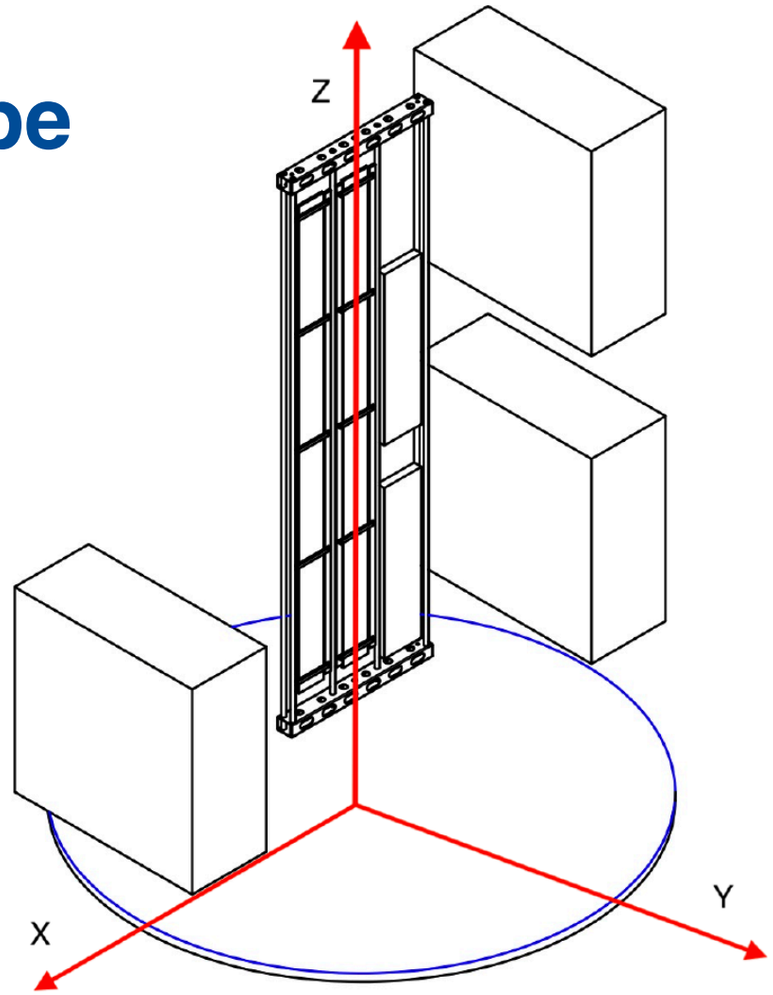
- Total run time 366 hs (H-L) + 519 hs (L-L)

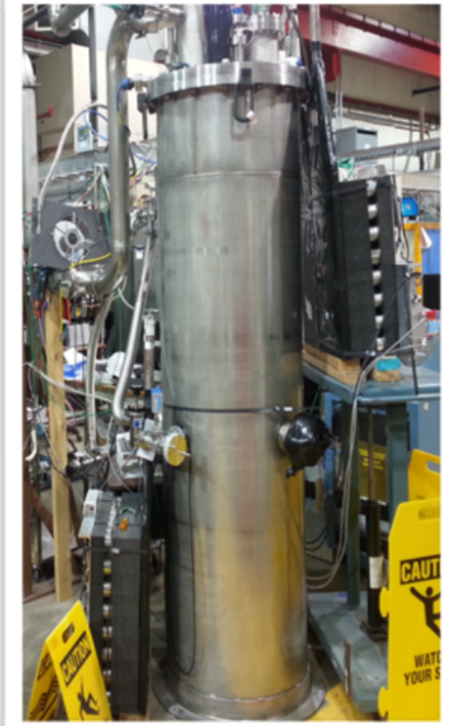
The trigger system: hodoscope

- The hodoscope from (former) CREST balloon experiment. Two opposed matrices of 8x8 crystals (2” diam.), individually read-out by a PMT.



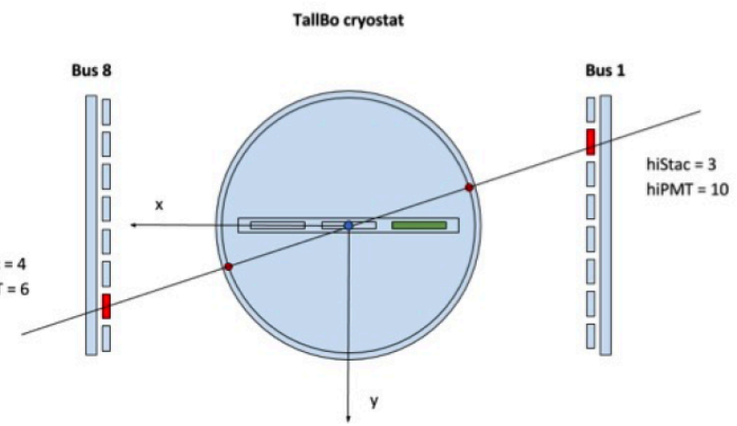
- PMT signals shaped and logically AND-ed and OR-ed in a NIM crate to form a coincidence H-L (or L-L) trigger
  —> SSP read-out for ARAPUCA and Light Guide Bars wmf digitization and recording.



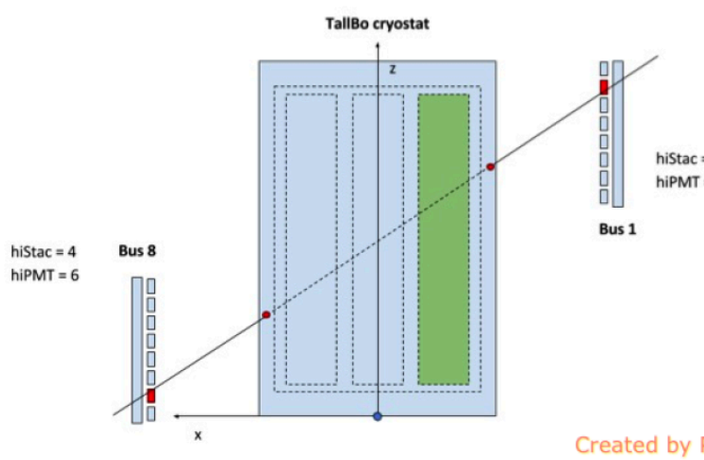


- Off-line selection for events with one and only one crystal per hodoscope fired.

- From the crystals position in space it is possible to reconstruct the crossing track geometry.



(b) Top view.

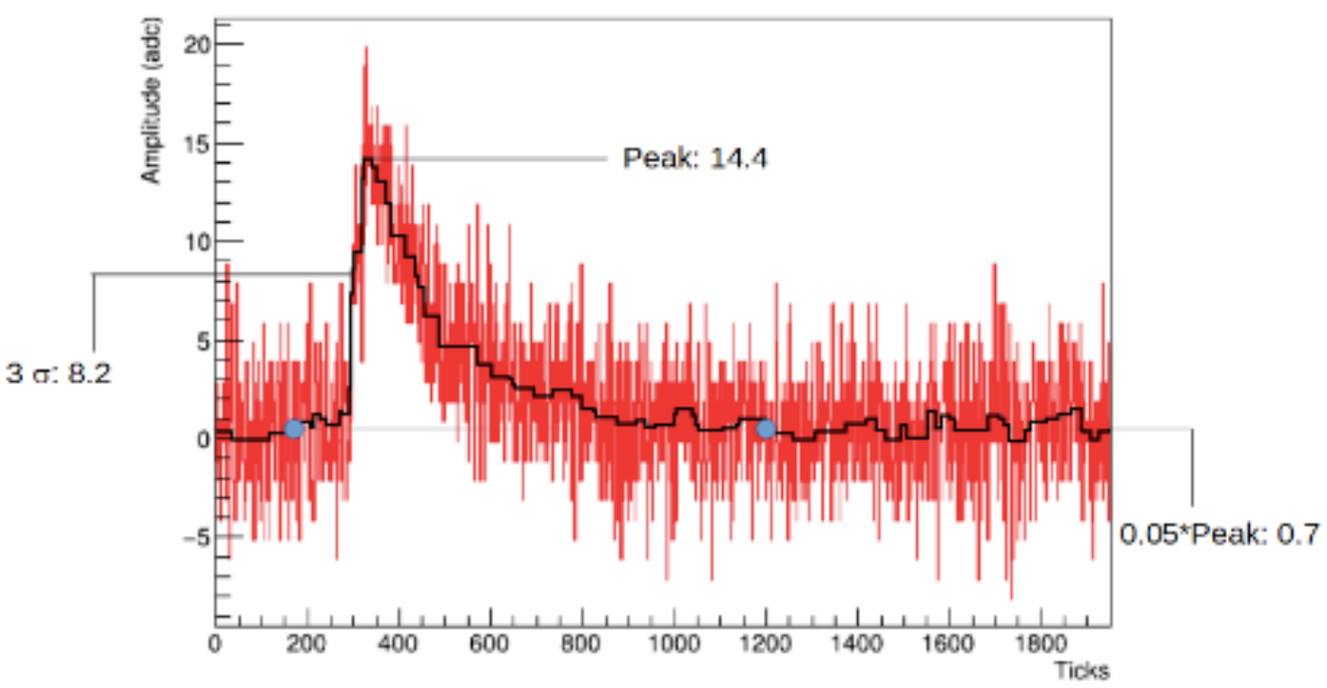


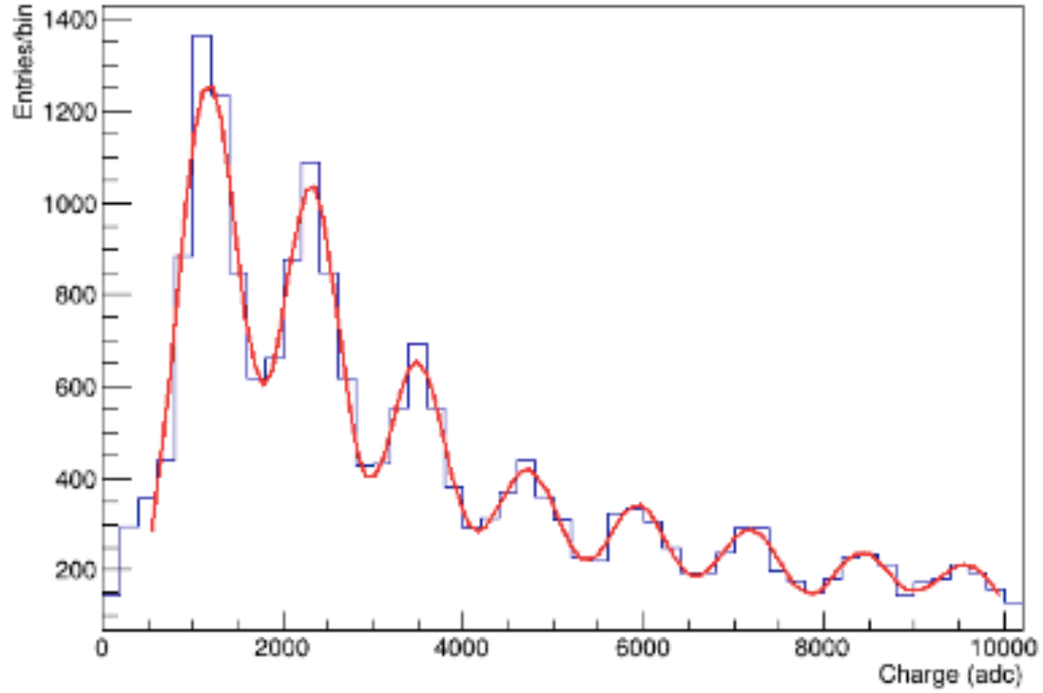
(c) Front view.

Calibration run

- Individual channel calibration determined by triggering on a low SSP acquisition threshold.

- ARAPUCA channels calibration showed good gain uniformity and linearity.

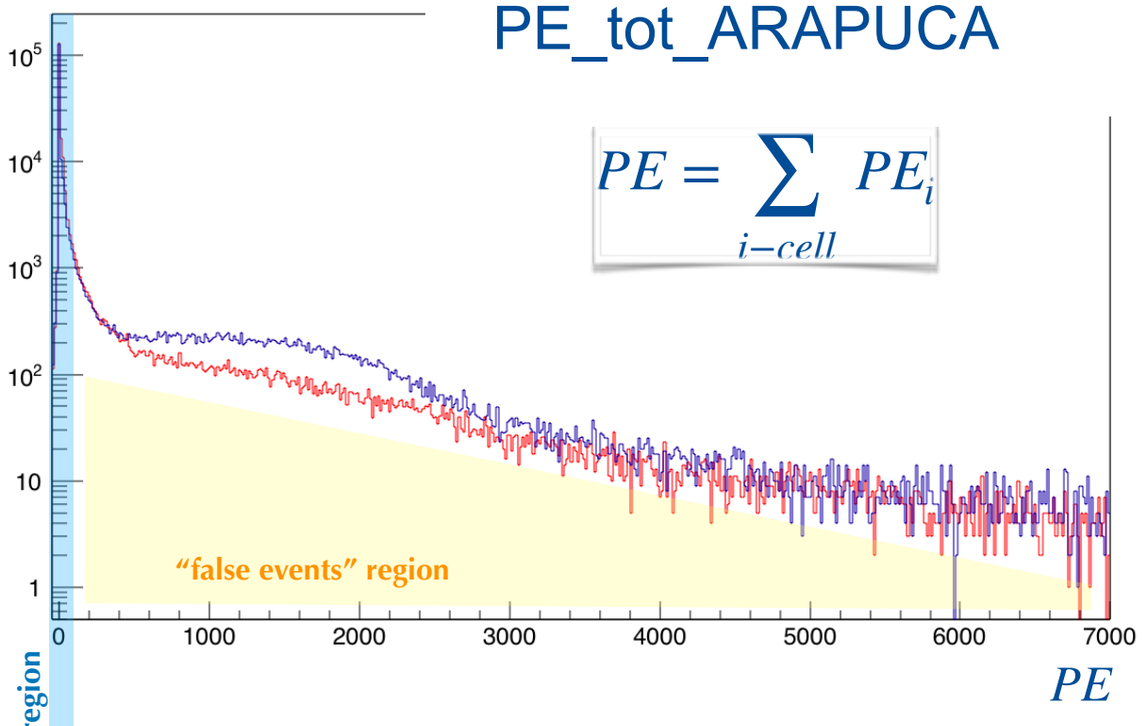




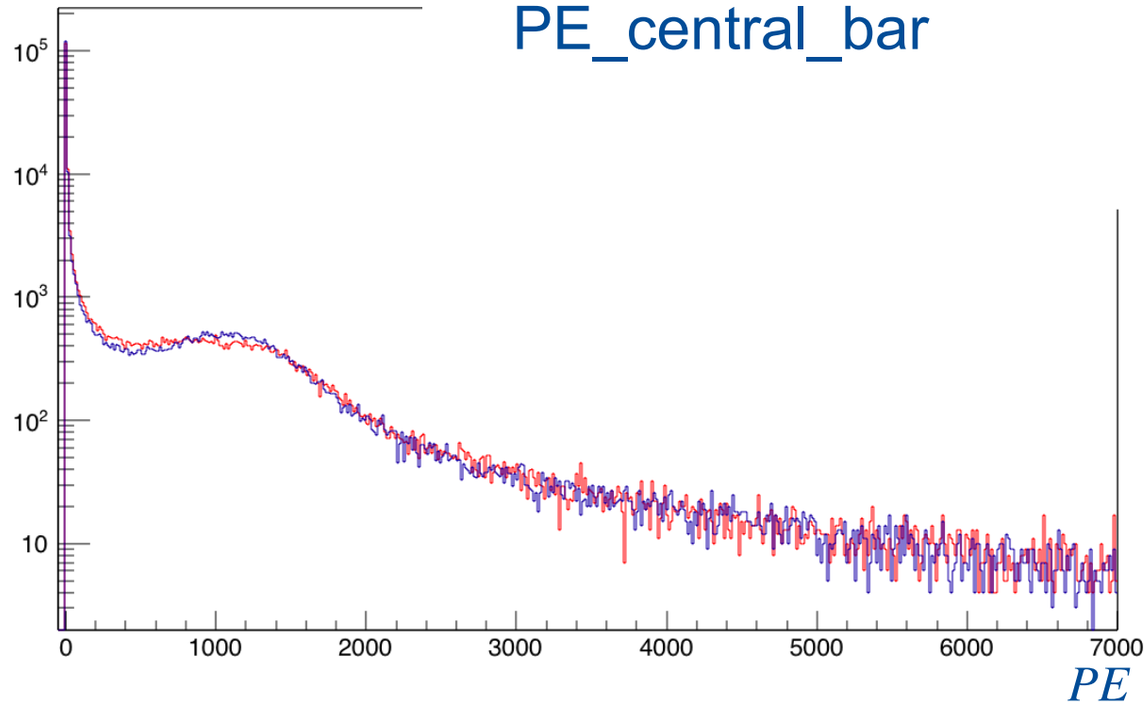
Trigger issues

- Faulty hw module in the hodoscope trigger NIM logic resulted in overwhelming rate of fake/background triggers:
  - **recorded coincidence trigger rate around 1 Hz, against the expected crossing muon rate 0.04 Hz.**
  - major fractions of the rate were by **"empty events"** (no or little light detected) and **"false events"** with detected light not compatible with the track geometry given by the hodoscope information

PE_tot_ARAPUCA



PE_central_bar



Red = **back events** (tracks triggered as passing behind ARAPUCA active face)
Blue = front events (tracks triggered as passing in front of ARAPUCA active face)

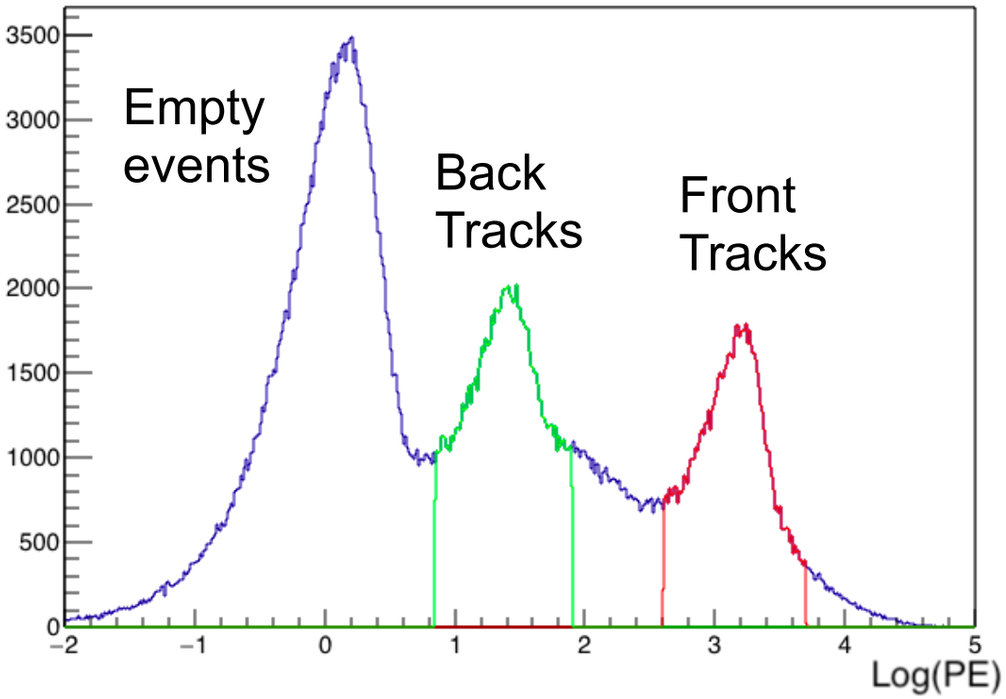
Log(PE) Spectrum

Looking at the Log(PE) spectrum *(whole sample)*:

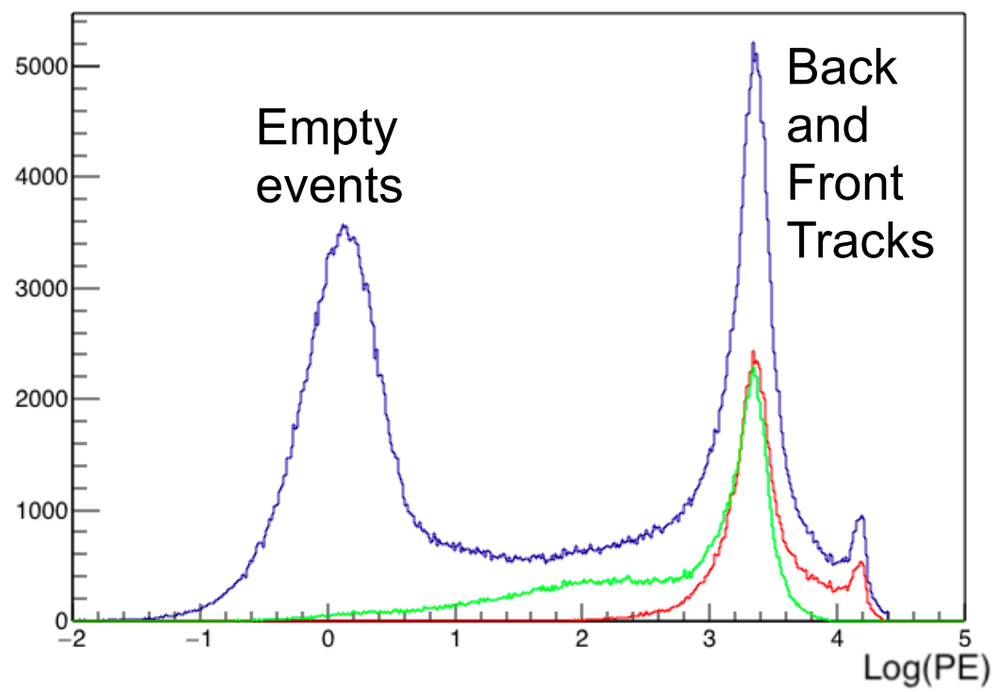
- first peak (blue) composed by **empty events**.
- in (single sided) ARAPUCA:
  - *second low-PE peak (green) due to back tracks reflected light*
  - *third high-PE peak (red) to front tracks direct light*
  - *both overlaid with accidental coincidence background and front-to-back tracks*

- in (double sided) Light Guide Bar: one peak (from back and front tracks).

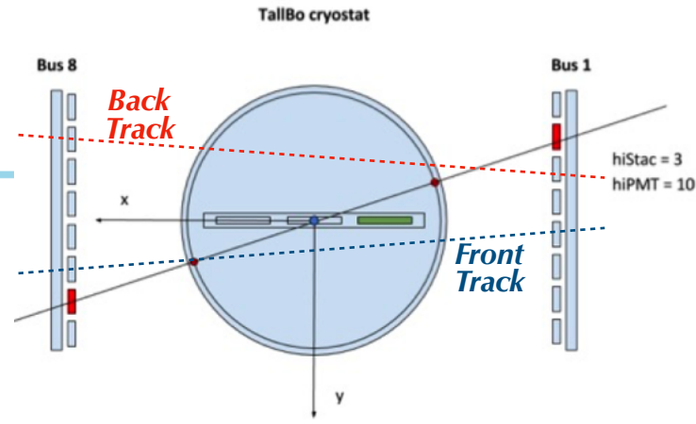
Sum of PE from ARAPUCA cells



PE recorded by central bar



Front and Back PE spectra: Statistics

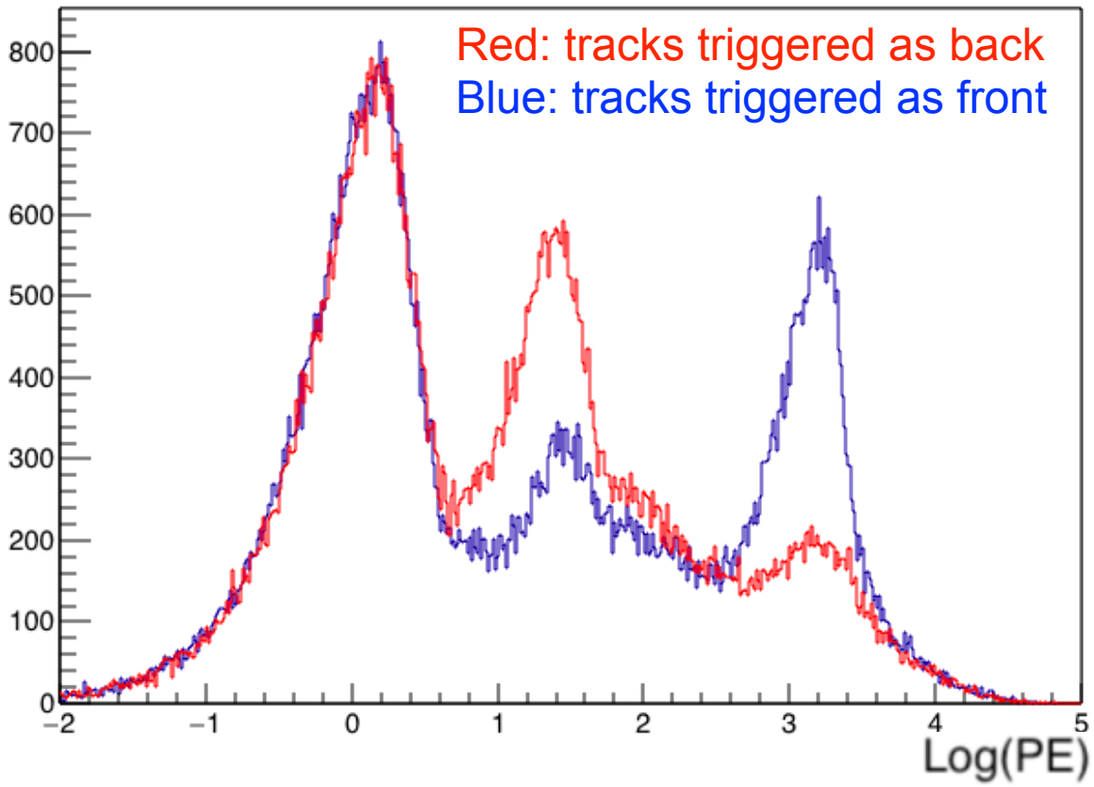


Two data sets selected for the efficiency Analysis:

Front track Sample and Back track Sample.

(Tracks that cross the detector plane are filtered out).

PE sum over all ARAPUCA cells



By (statistically) subtracting common background (events uncorrelated with hodoscope information in both data sets):

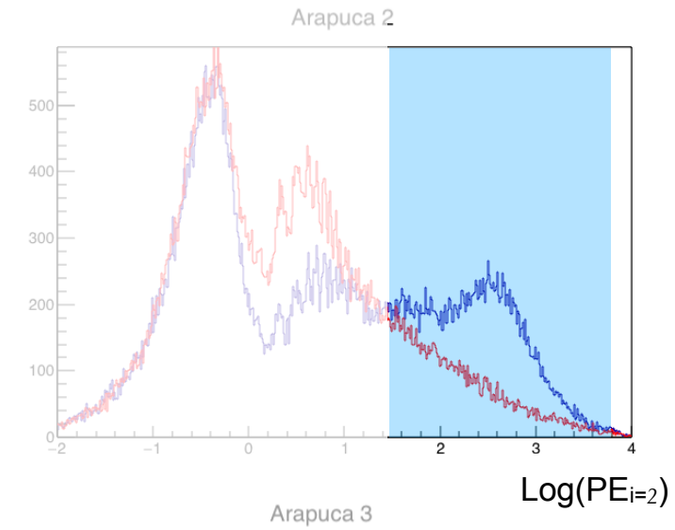
Signal Events Statistics (tracks passing in front the ARAPUCA plane):

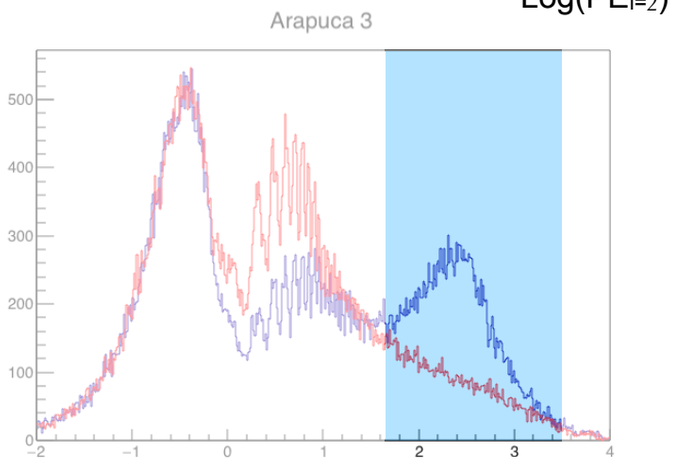
~13500 evt corresponding to ~0.01 Hz

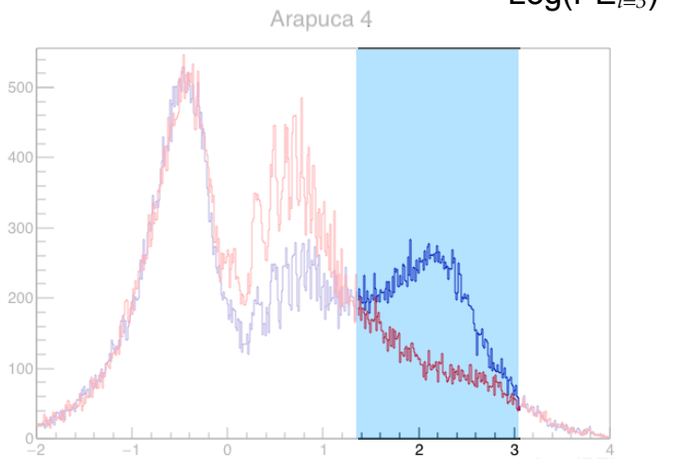
in agreement with expectations

	Analytic	Simulation	TallBo	Blanche Exp
Hi-Low	0.014 Hz	0.0105 Hz	0.0102 Hz	0.01 Hz

Front and Back PE spectra: Efficiency Study based on ARAPUCA segmentation in Eight individually read-out Cells

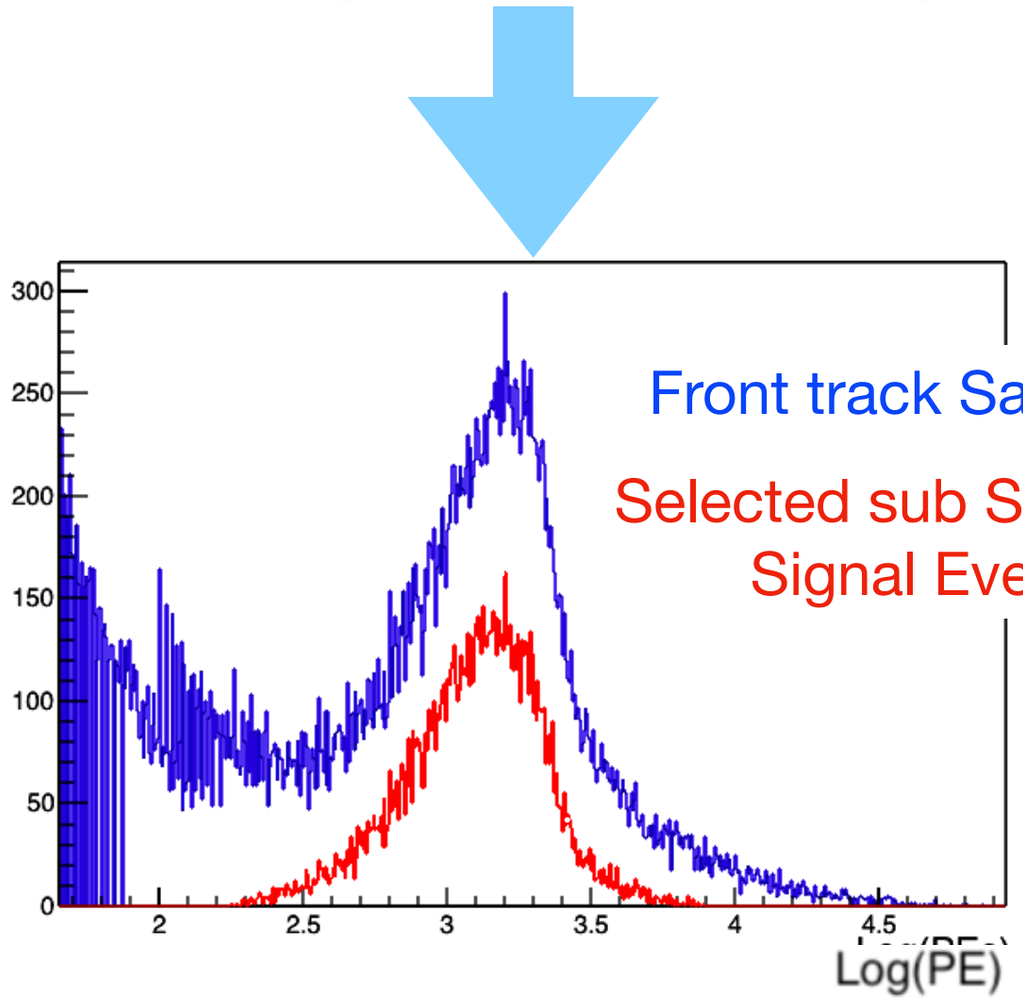






Examples of Individual Cell Log(PEi) distributions for
Recorded events triggered as back tracks (RED)
Recorded events triggered as front tracks (BLUE)

Event selection within the Front track Sample based on "Signal Region" PE cut (shaded range) in individual Cell spectra



Front track Sample distribution

Selected sub Sample:
Signal Events (~14000 evts)

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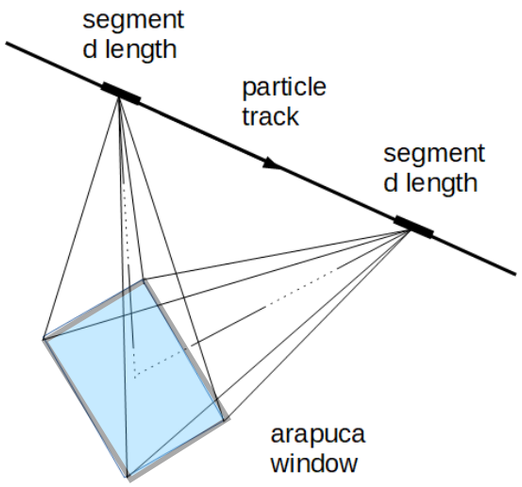
Illumination and Efficiency

- The illumination - *PH, number of photons which arrive at the ARAPUCA cell optical window* - is estimated for each track as the product of the track **integrated angular Acceptance** (over the track length) and the number of emitted photons per unit length and unit solid angle.



$$PH = A_\Omega \frac{1}{4\pi} \frac{dN^\gamma}{dx}$$

$$\frac{dN^\gamma}{dx} = Y_\gamma \, q_{mip} \left\langle \frac{dE}{dx} \right\rangle_\mu \rho_{Ar}$$

$$A_\Omega = d \sum \Omega_i$$

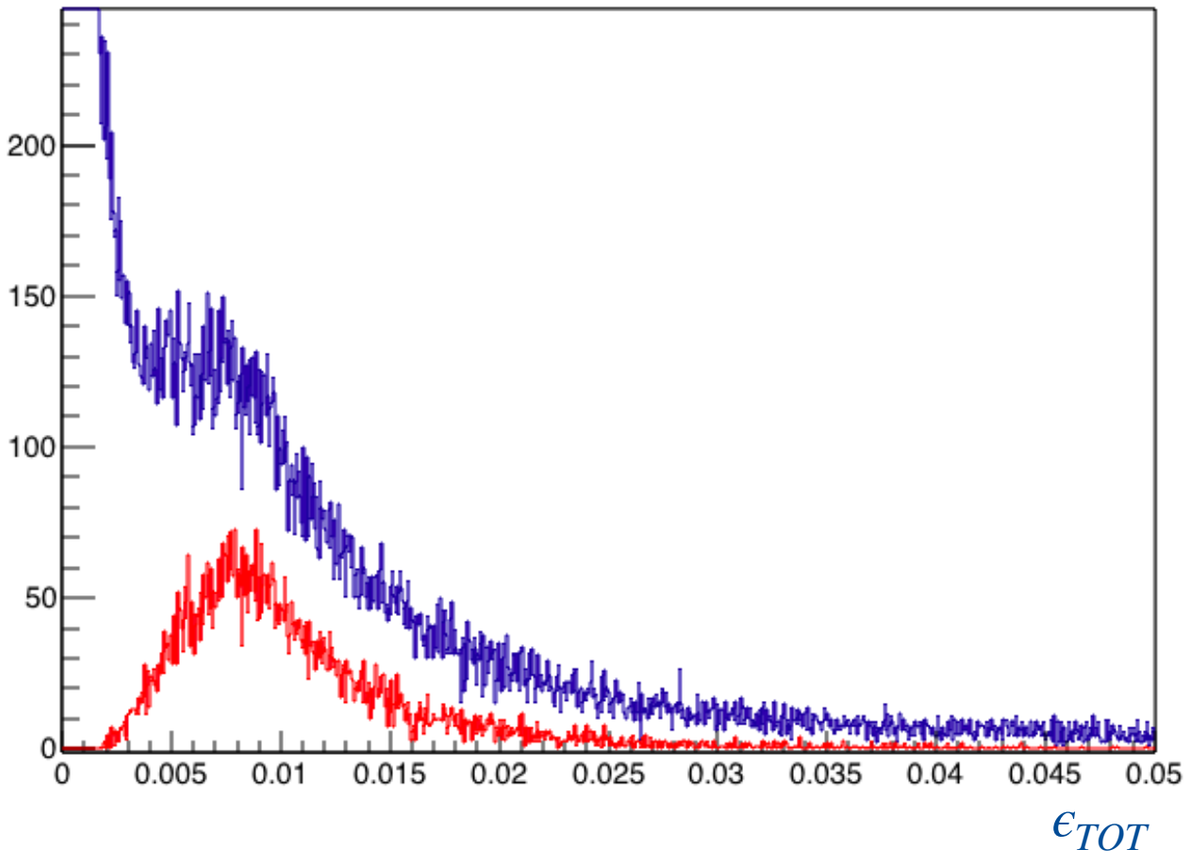
- The **Efficiency** - Total or Individual (for the i-cell) - can be defined as the ratio between the photo-electrons measured by the detector and the estimated photons impinging upon the optical surface.

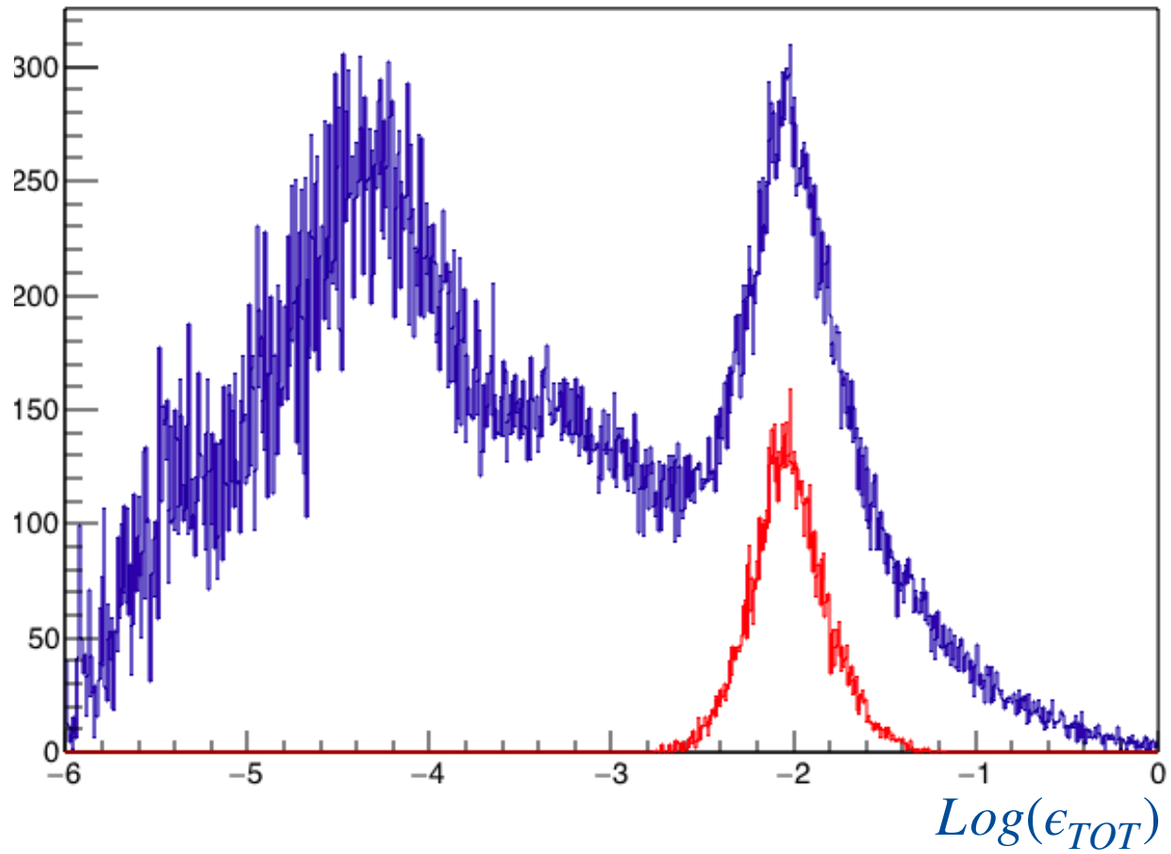
$$\epsilon_{TOT} = \frac{\sum PE_i}{\sum PH_i} \qquad \epsilon_i = \frac{PE_i}{PH_i}$$

- The efficiency is an intrinsic characteristic of the detector it is independent from the photons landing and from the track.

Total Efficiency of the ARAPUCA PD System (8 cells)

The distribution of the Total Efficiency and of the
(for a better visualization) are plotted here: $Log(\epsilon_{TOT})$





Front track Sample distribution

Selected sub Sample: Signal Events

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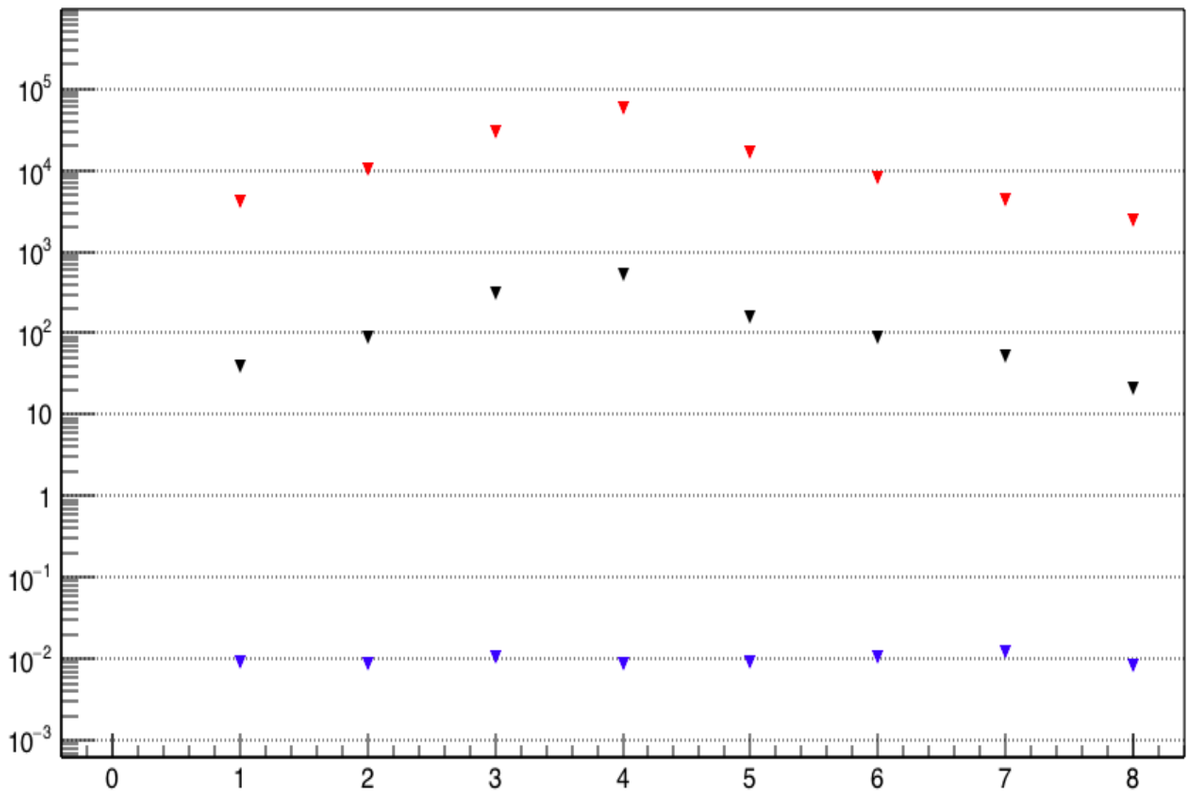
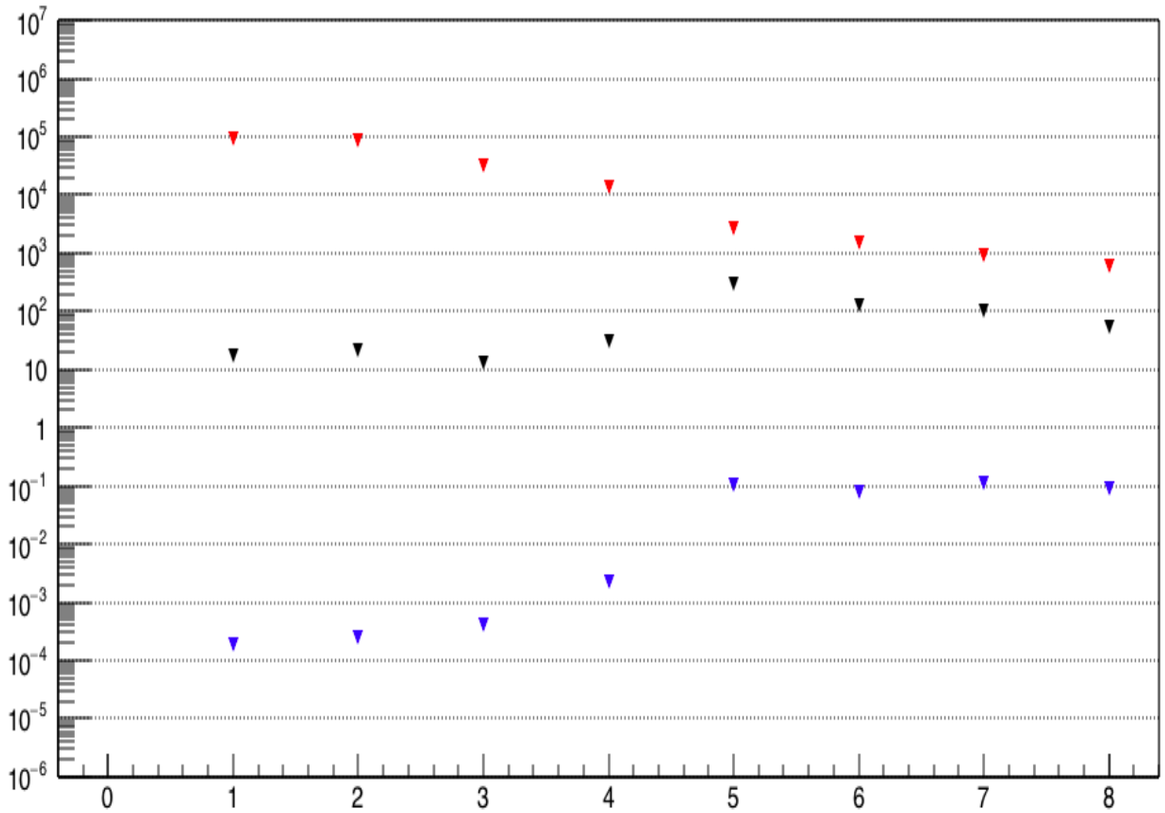
Light Pattern in ARAPUCA PD system (Cells 1 to 8)

The segmentation of the ARAPUCA PD system provides very powerful (additional) handle for Signal from Background identification: for each trigger, reconstruct the ***pattern*** of the detected light $\{PE_i\}$ in the Cells and compare with the expected illumination $\{PH_i\}$ from the triggered track.

$\{PE_i\} \propto \{PH_i\}$: Signal (muon track) event



inconsistent light pattern: Background event



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The light pattern selection approach

Cell Efficiency Mean Value

$$< \epsilon > = \frac{1}{8} \sum_{1}^{8} \epsilon_i$$

Estimated Efficiency Dispersion around Mean Value

$$\sigma^2 = \frac{1}{8} \sum_{1}^{8} \left(\frac{\epsilon_i - < \epsilon >}{< \epsilon >} \right)^2$$

Use the estimated standard deviation of the ARAPUCA cell efficiency value as estimator of the goodness of the light pattern $\Longrightarrow$ Signal Event selection criteria.

The value used $\sigma^2 < 0.15$ chosen to obtain the same number of the expected events from the estimated muon flux

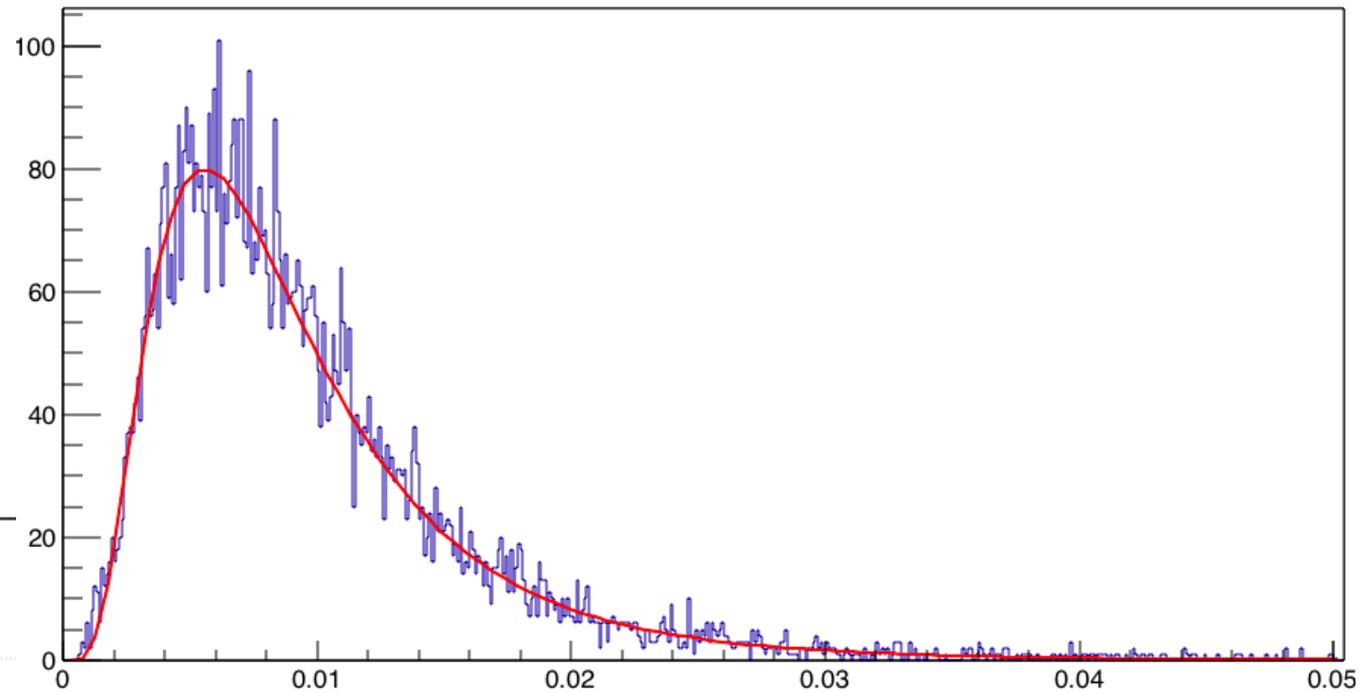
Results

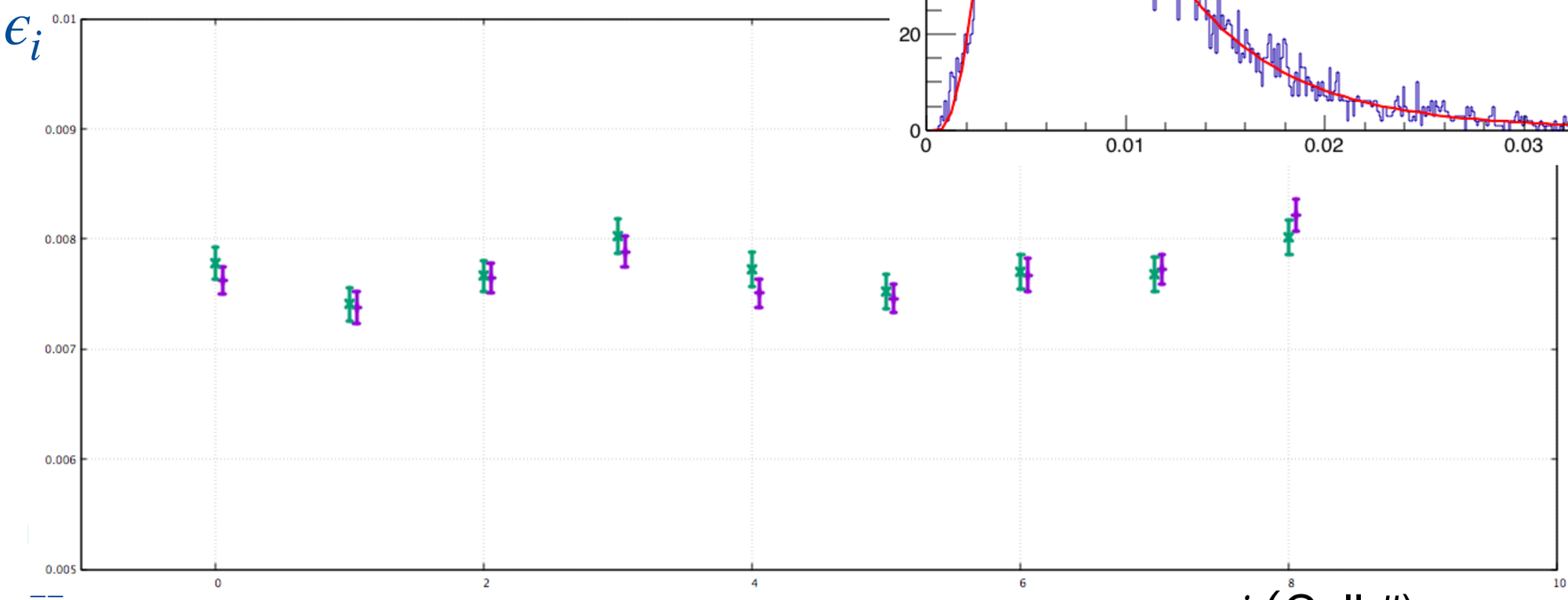
PE Spectra Cuts + Light Pattern Cut: Tot Efficiency (%) = 0.777 ± 0.033

Light Pattern Cut only: Tot Efficiency (%) = 0.770 ± 0.045

Good Uniformity of Response from ARAPUCA Cells

$0.74 \leq \epsilon_i \leq 0.82$





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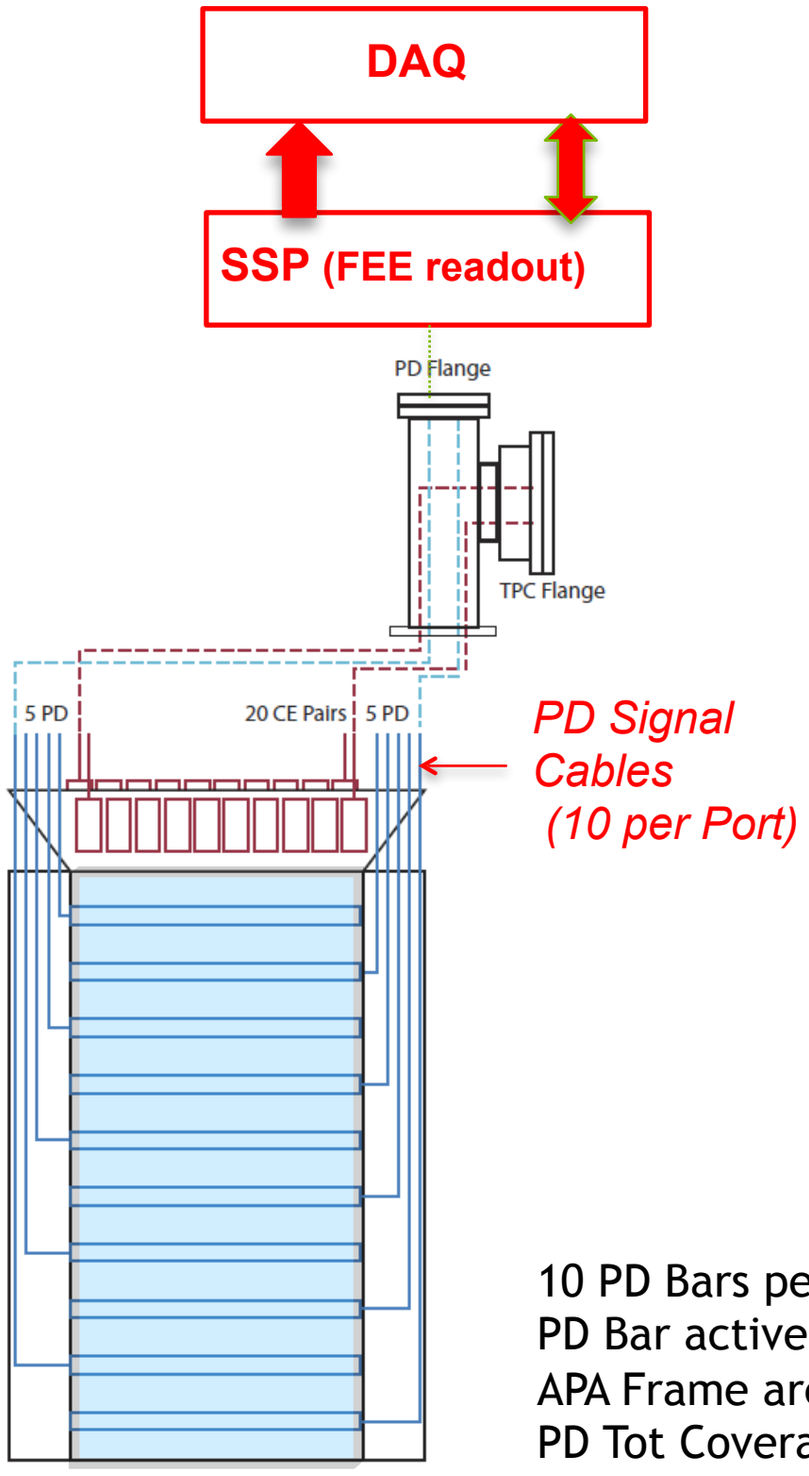
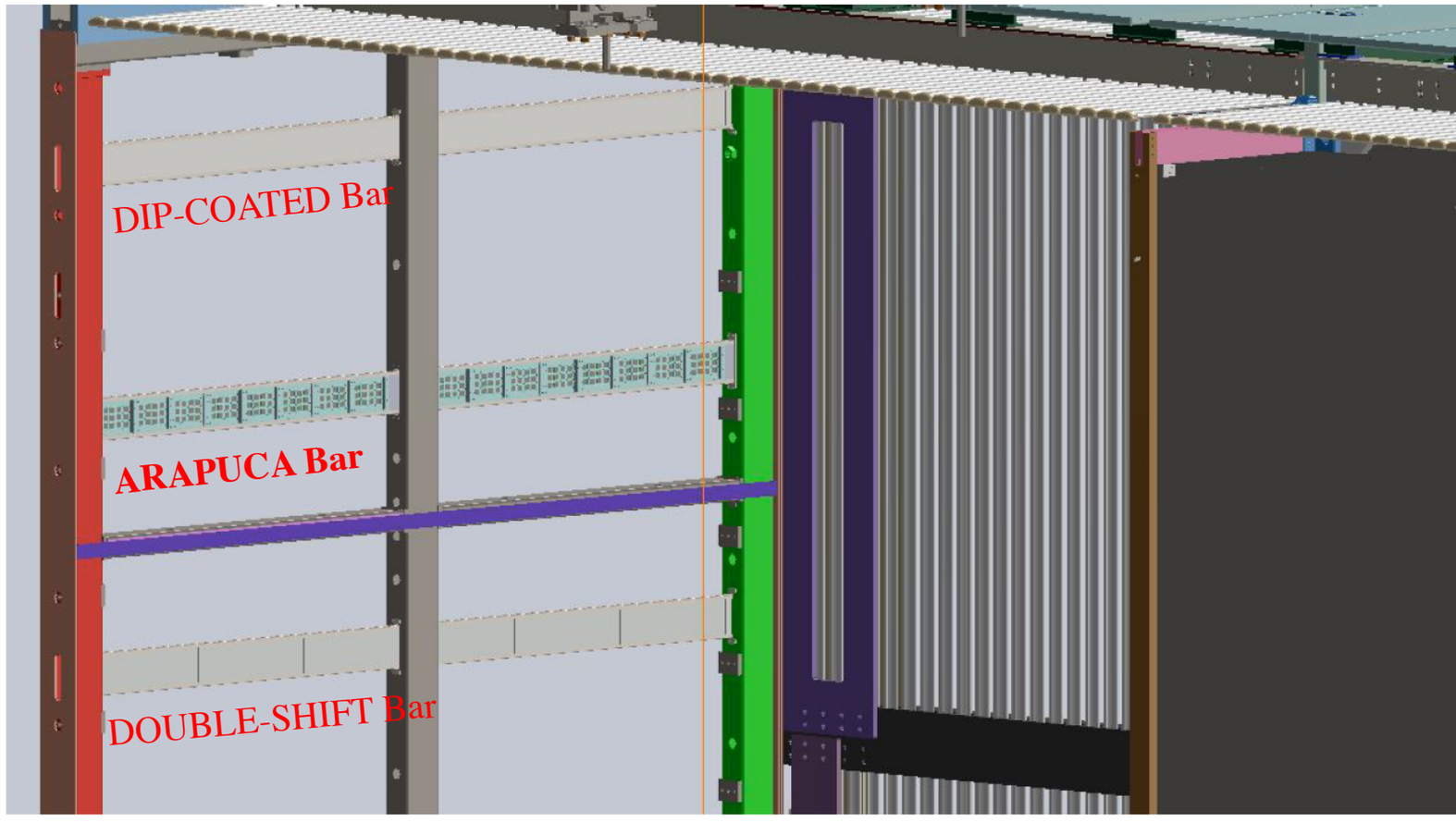
ARAPUCA test at CERN Neutrino Platform with ProtoDUNE SP

(Sept-Nov. 2018)

Photon Detection System Design in protoDUNE Single Phase

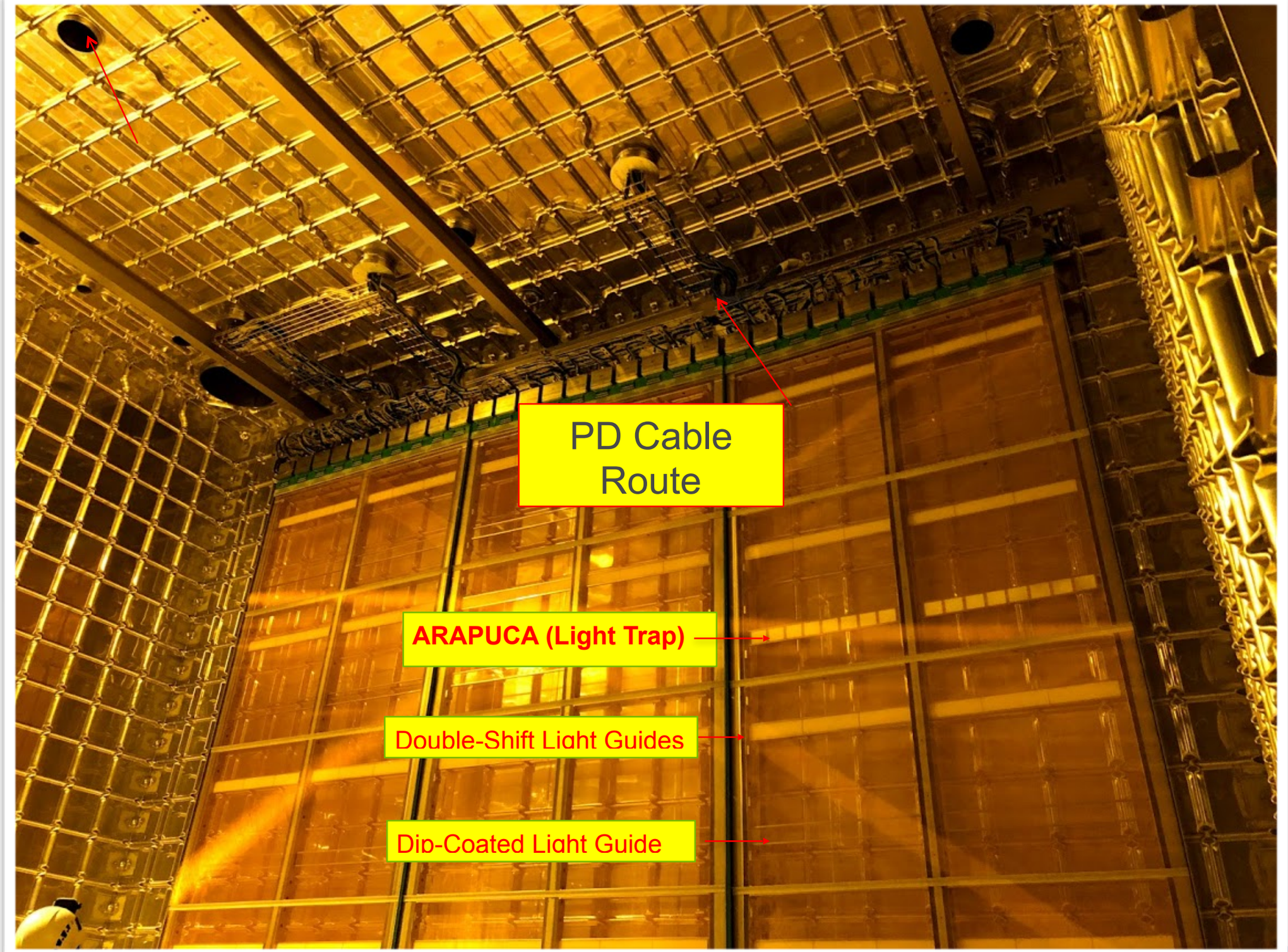


- Three PD technologies implemented:
  - **-ARAPUCA Light Trap**
  - -Dip-Coated Light Guide
  - -Double-Shift Light Guid



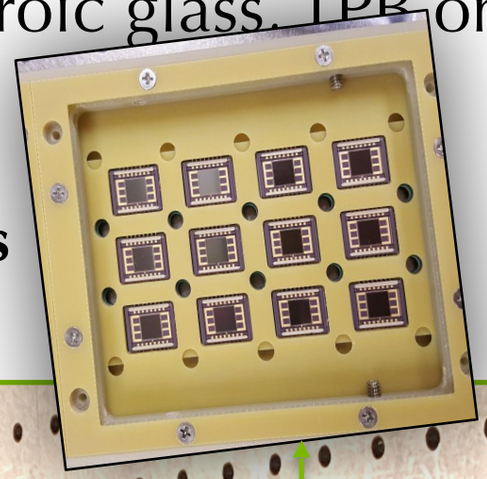
10 PD Bars per APA Frame
PD Bar active area: Light Guide Bar 1744 cm^2 - **ARAPUCA Bar 1223 cm^2**
APA Frame area (Outside) 6060mm X 2300mm
PD Tot Coverage fraction: ~12.5%

Photon-Detector in ProtoDUNE-SP



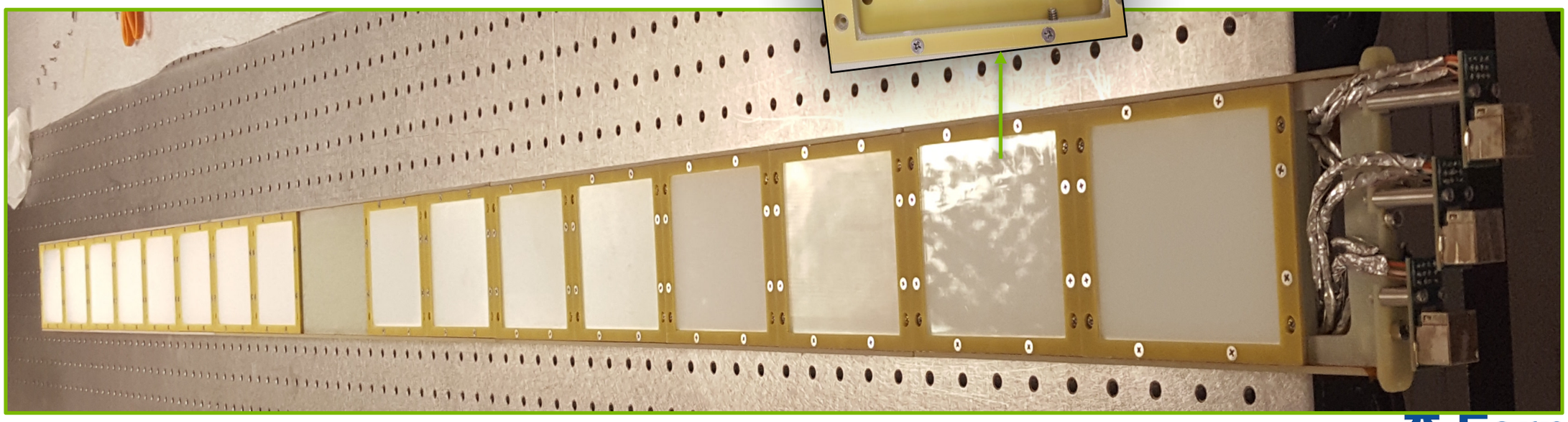
ARAPUCA PD design for protoDUNE

- 2 Bars - segmented along beam direction: one in APA3 (beam side), one in APA4
- 4 Modules (“Cartuchos" - FR4 structure) per Bar
- 4 ARAPUCA Cells (single-sided) per Cartucho
- 12 or 6 cryo-SiPMs per Cell - passively ganged
- Dichroic (short-pass) filter - optical window: 9.8 x 7.8 cm^2
- p-TP deposited on outer surface of Dichroic glass. TPB on inner surfaces deposited on VIKUITI Reflective Foil

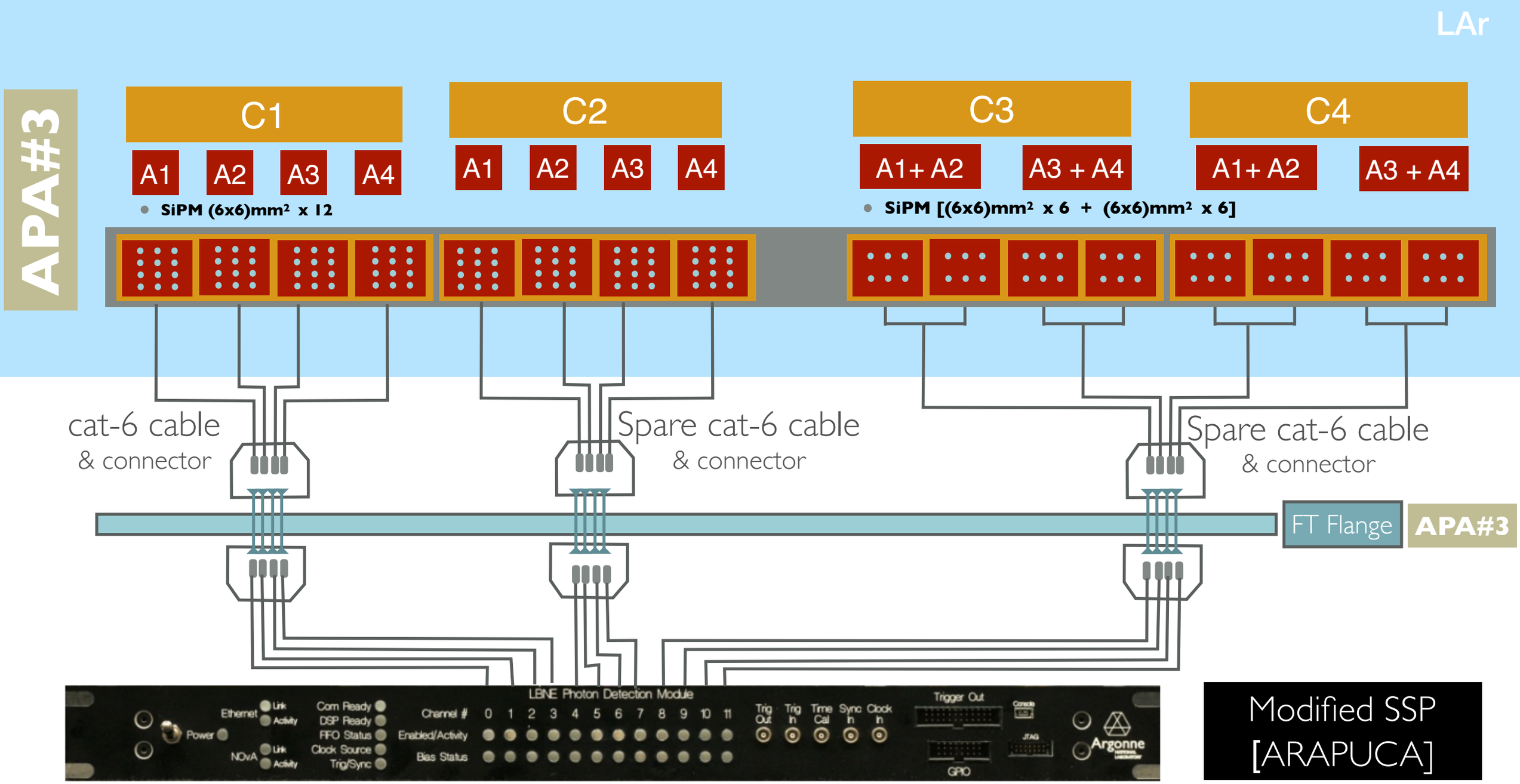


Cryo-SiPMs

One of the two ARAPUCA arrays installed with ProtoDUNE photon-detection system



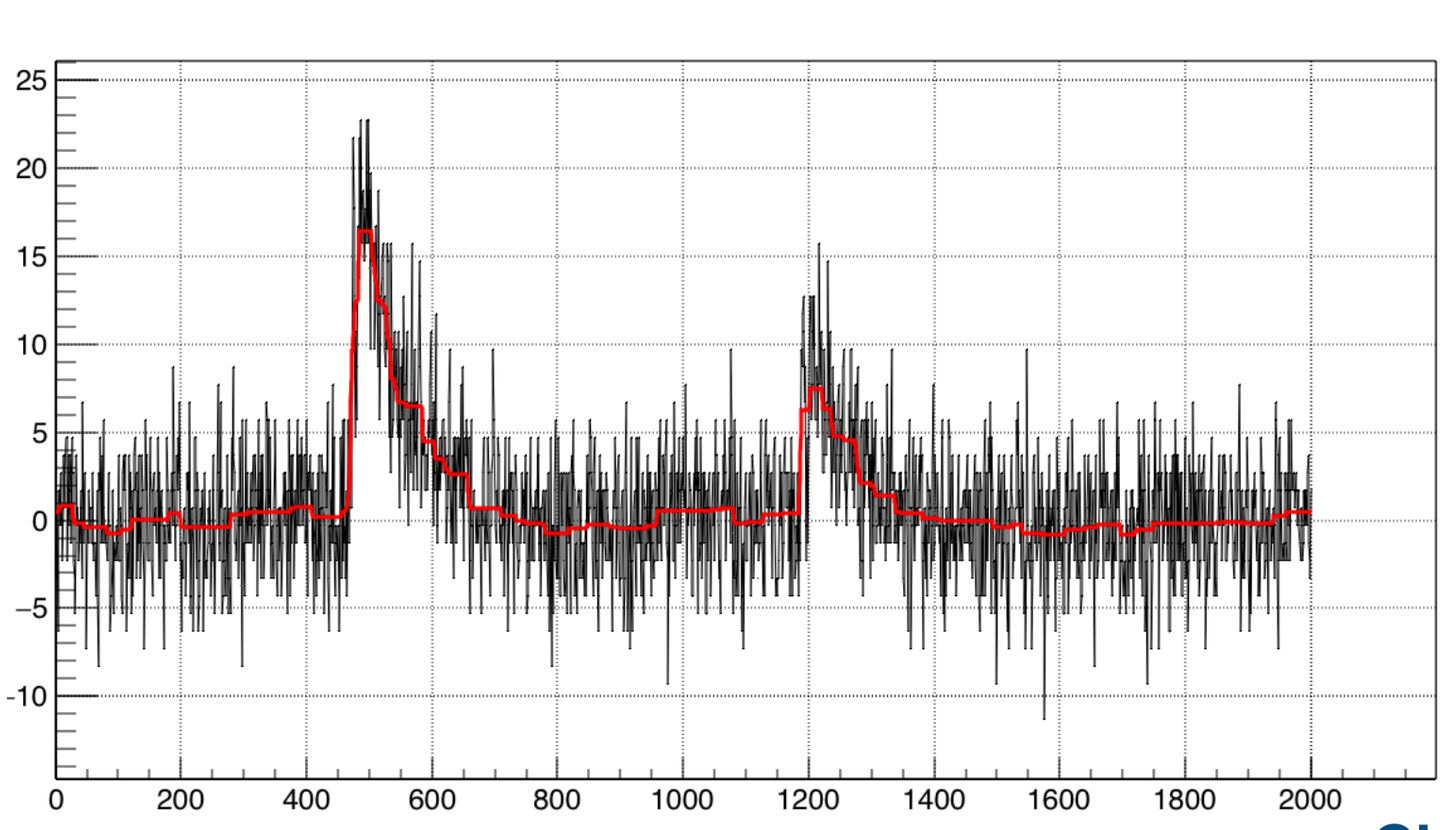
SiPM in ARAPUCA Cells and read-out

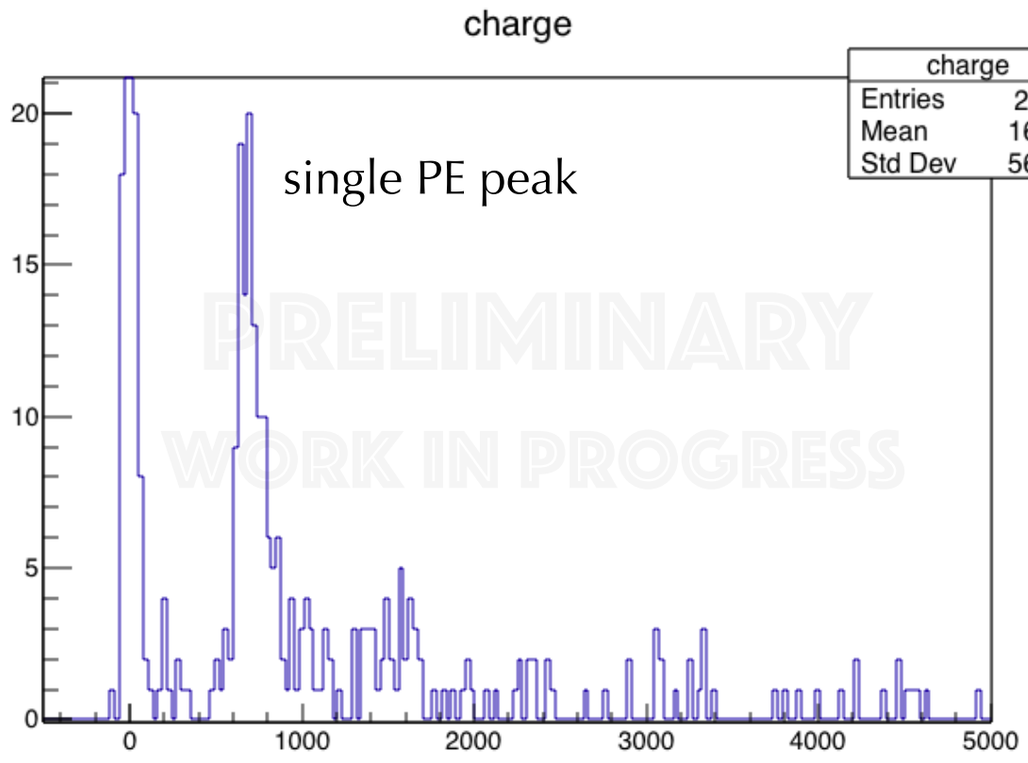


Calibration

Waveforms analysis

Denoising: combining a MOBILE AVERAGE (using 9 ticks) and a DENOISING CODE

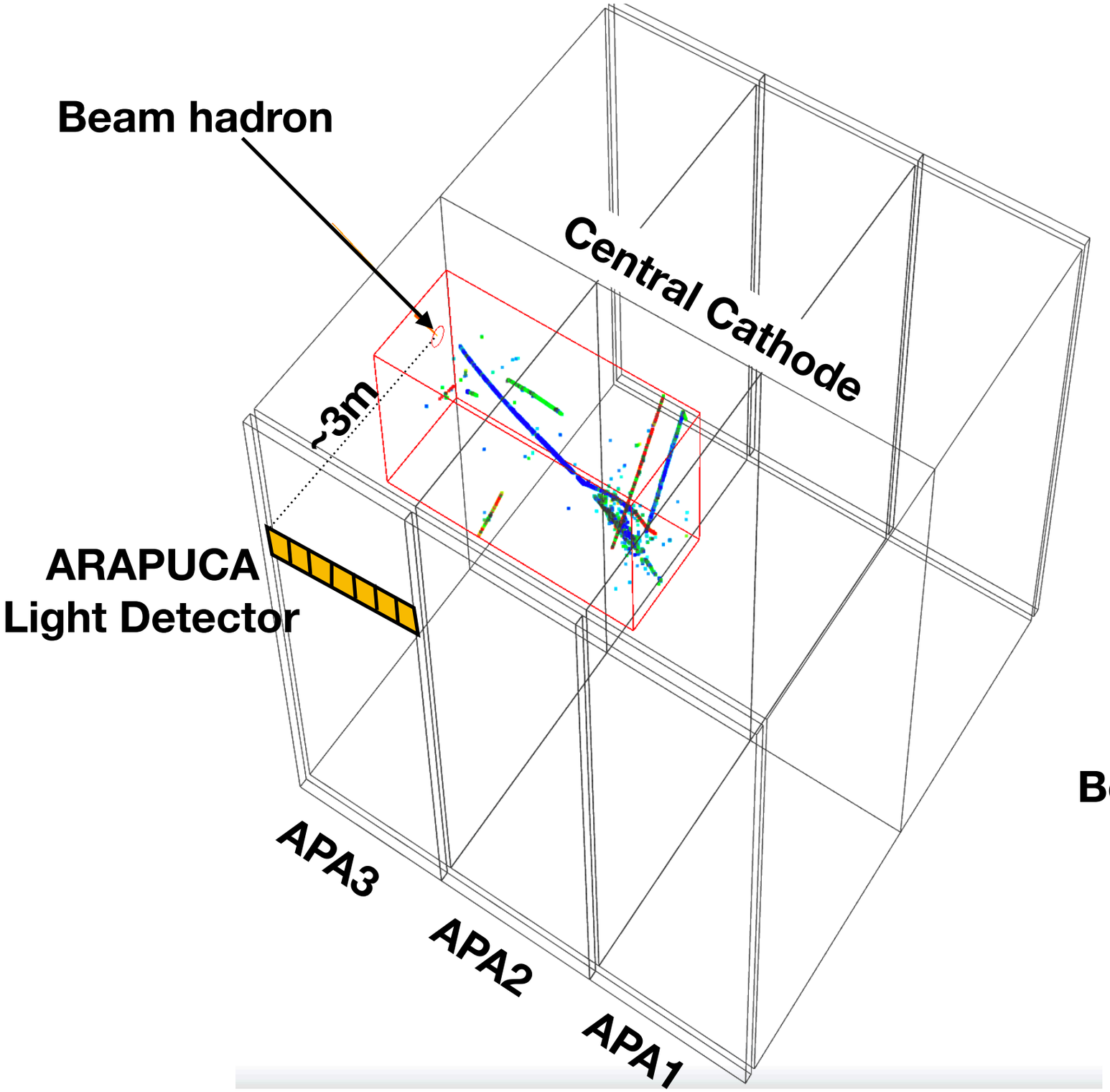




Charge (and Max_amplitude) Calibration
SNR ~14.5

Low Statistics (data taken with high threshold)

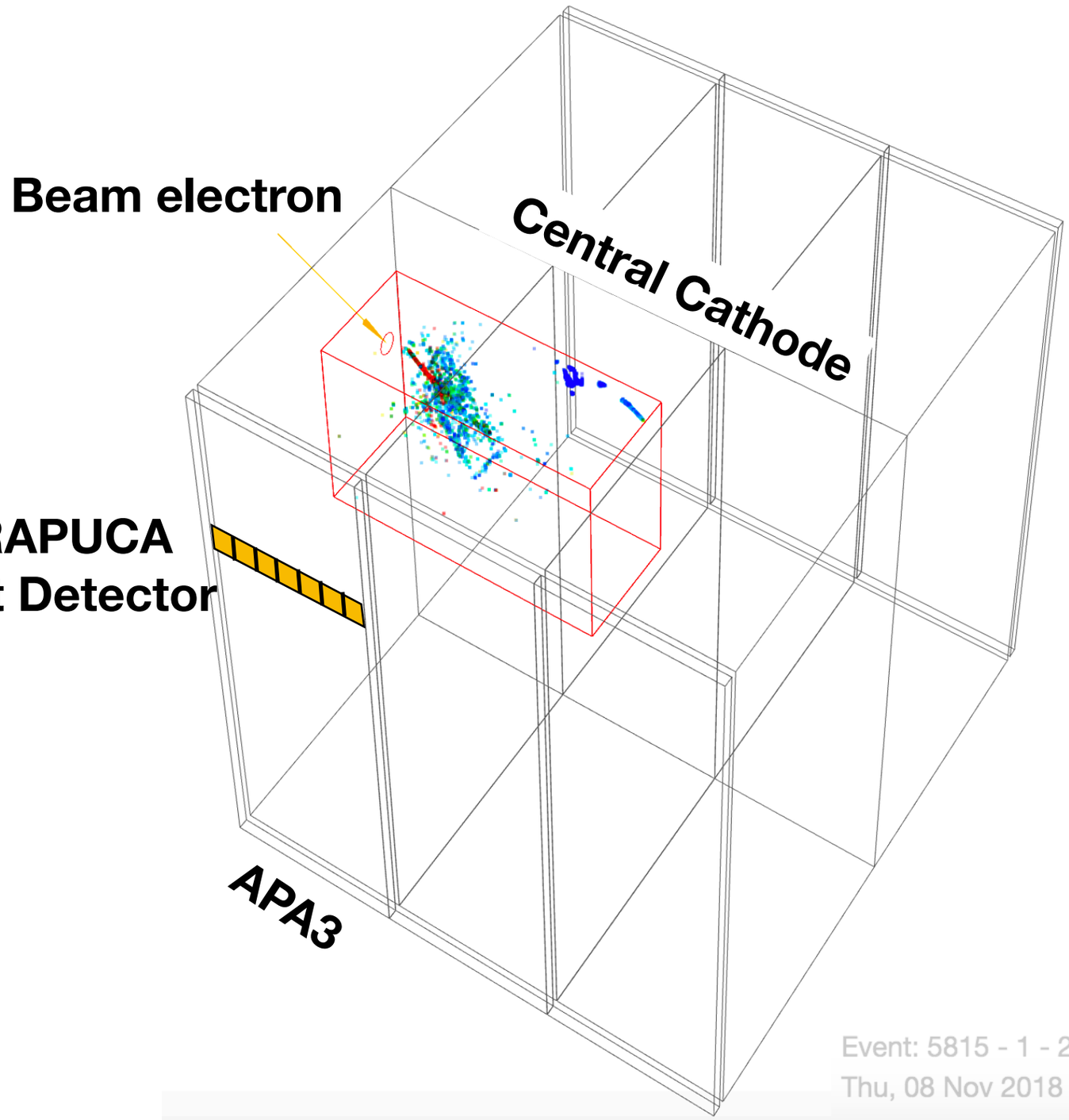
Test Beam Run (in progress):
1 - 7 GeV Momentum Charged Particle (e, had) Beams



Scintillation Light from Energy deposited by beam hadrons or electrons in LAr detected by ARAPUCA
[at ~3m distance]

Beam Particle Energy tunable in 1-7 GeV range

Test Beam Run (in progress):
1 - 7 GeV Momentum Charged Particle (e, had) Beams



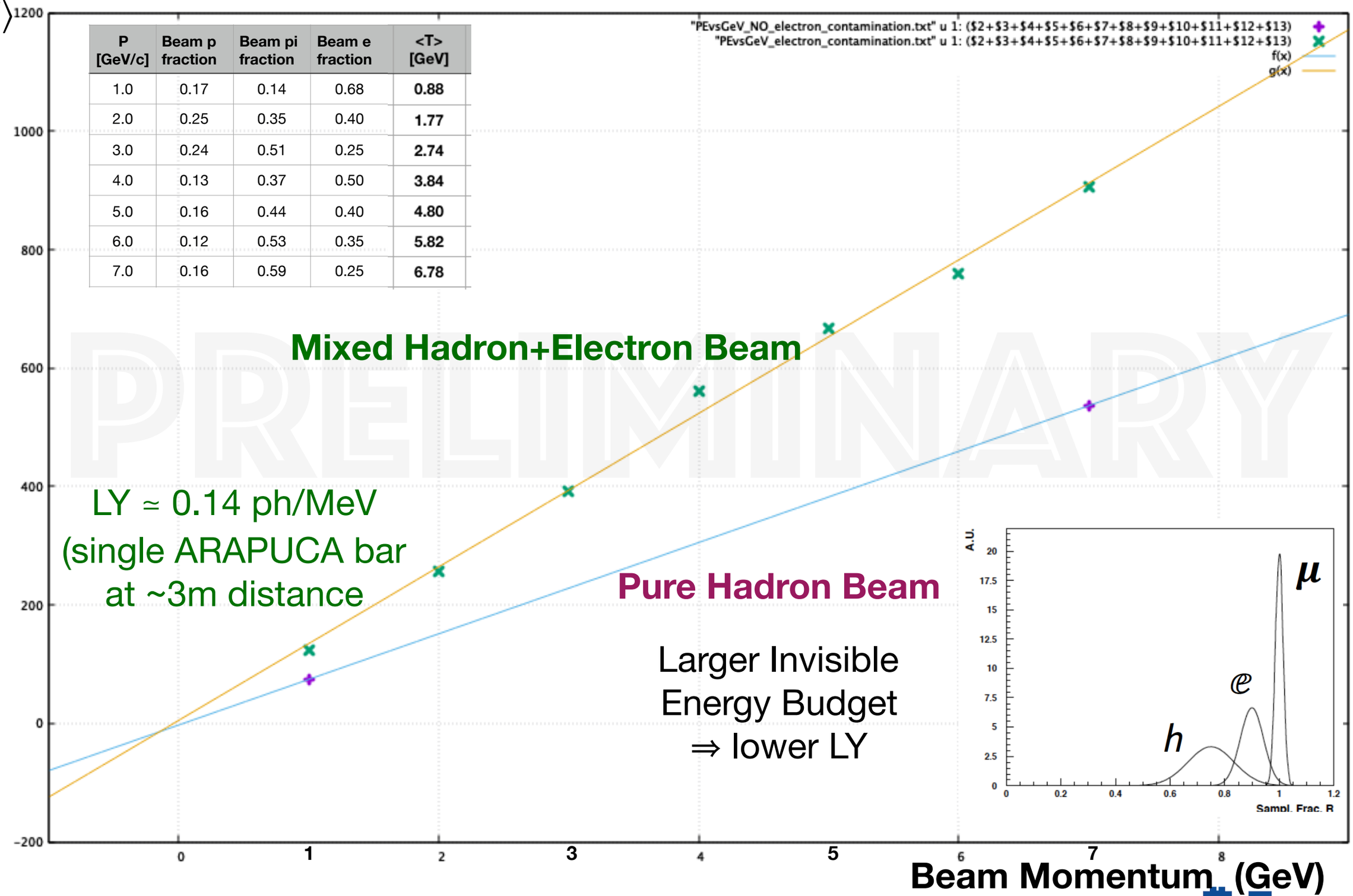
Scintillation Light from Energy deposited by beam hadrons or electrons in LAr detected by ARAPUCA
[at ~3m distance]

Note: electron

First result (preliminary analysis) of ENERGY reconstruction from LAr Light Signal Detection by ARAPUCA Bar (scintillation homogeneous Calorimeter)

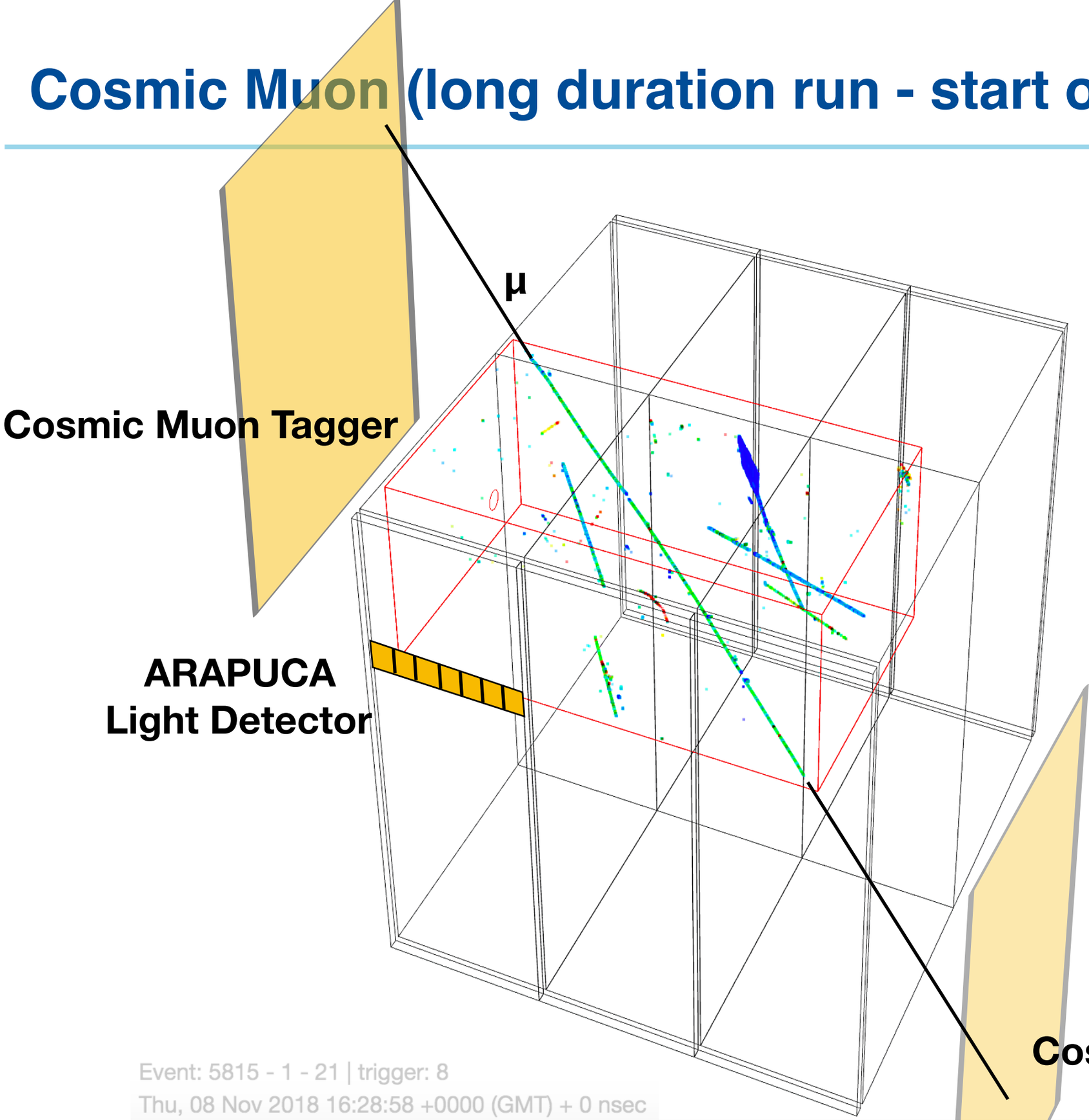
$\langle PE \rangle$

P [GeV/c]	Beam p fraction	Beam pi fraction	Beam e fraction	<T> [GeV]
1.0	0.17	0.14	0.68	**0.88**
2.0	0.25	0.35	0.40	**1.77**
3.0	0.24	0.51	0.25	**2.74**
4.0	0.13	0.37	0.50	**3.84**
5.0	0.16	0.44	0.40	**4.80**
6.0	0.12	0.53	0.35	**5.82**
7.0	0.16	0.59	0.25	**6.78**



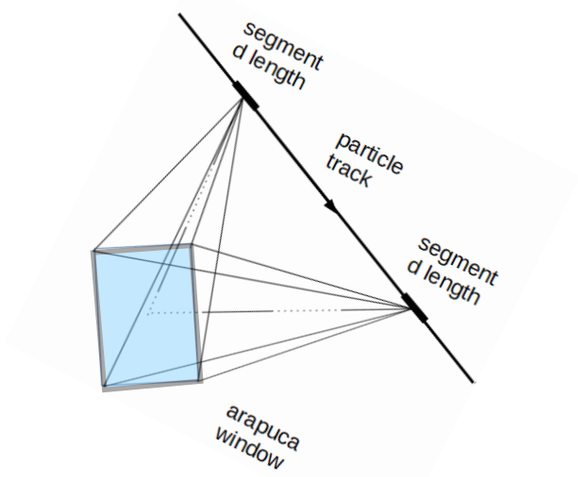
Fermilab

Cosmic Muon (long duration run - start on Nov 12)



Efficiency Measurement to be performed with Muon Tracks from CRT trigger

$$PH = A_{\Omega}\,\frac{1}{4\pi}\,\frac{dN^{\gamma}}{dx}$$



SUMMARY

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- A new Light Collection Technology Concept - light trapping by dichroic filter coupled w/ two wls stages [ARAPUCA] - was proposed for DUNE in Summer 2015 (PD System Review)
- First ARAPUCA prototype test in 2016 at LNLS (Brazil) - with α source and c.r.muons
- Detector design developed for ARAPUCA integration in APA/DUNE and test in 2017 at FNAL (TallBo test facility) with c.r.muons
- Two ARAPUCA bars in protoDUNE: test with charged particle beams (*e*, π, p) in progress (data taking just completed - Sept-Nov 2018). Long duration test w/ c.r.muons starting now (today).
- Next test for double sided ARAPUCA in new CE test stand (ICEBERG) under assembly at FNAL (run in 2019)
- 32 Large sized ARAPUCA cells included in the SBND experiment (under assembly at FNAL), coupled with reflector foils light enhancing system. Run in 2020.

Fermilab