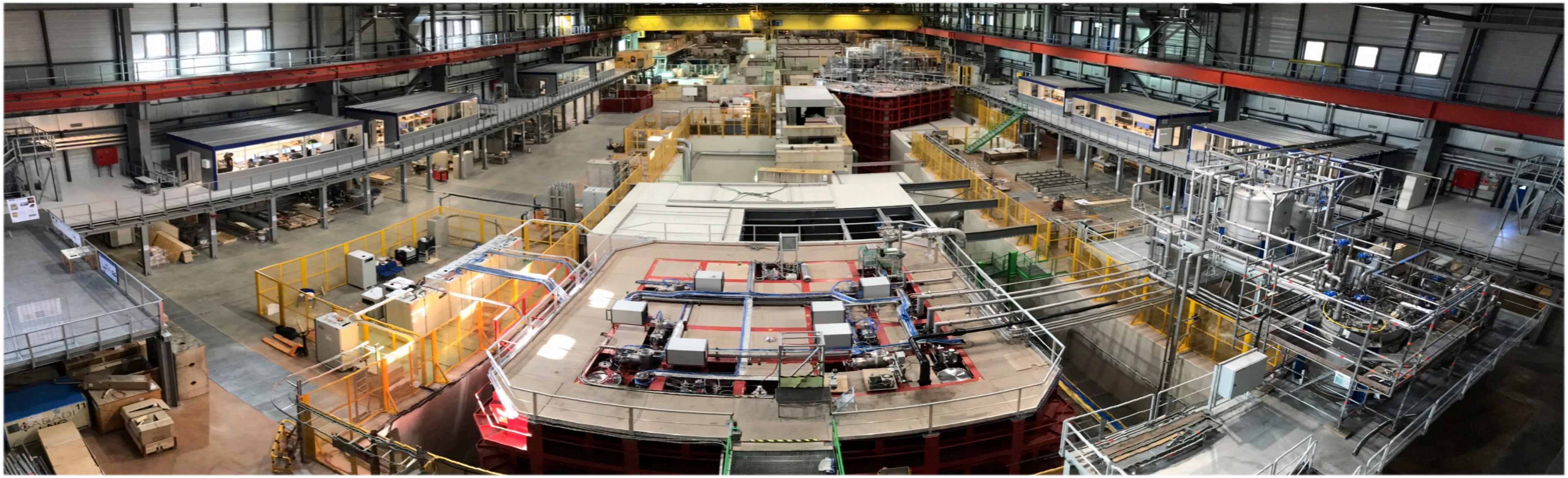
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Results from system validation Esp. ProtoDUNE-SP Prototype Tests at UNICAMP

DUNE-SP Photon Detection System
60% Design Review

June 18th, 2020

Flavio Cavanna
Fermilab



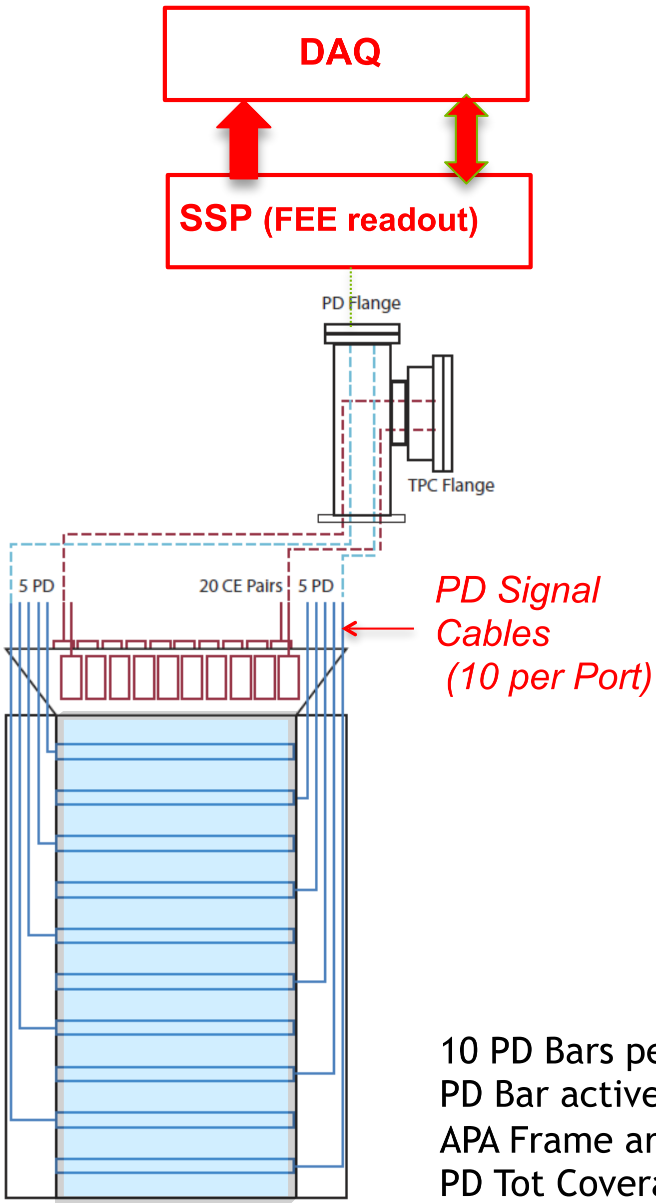
ARAPUCA

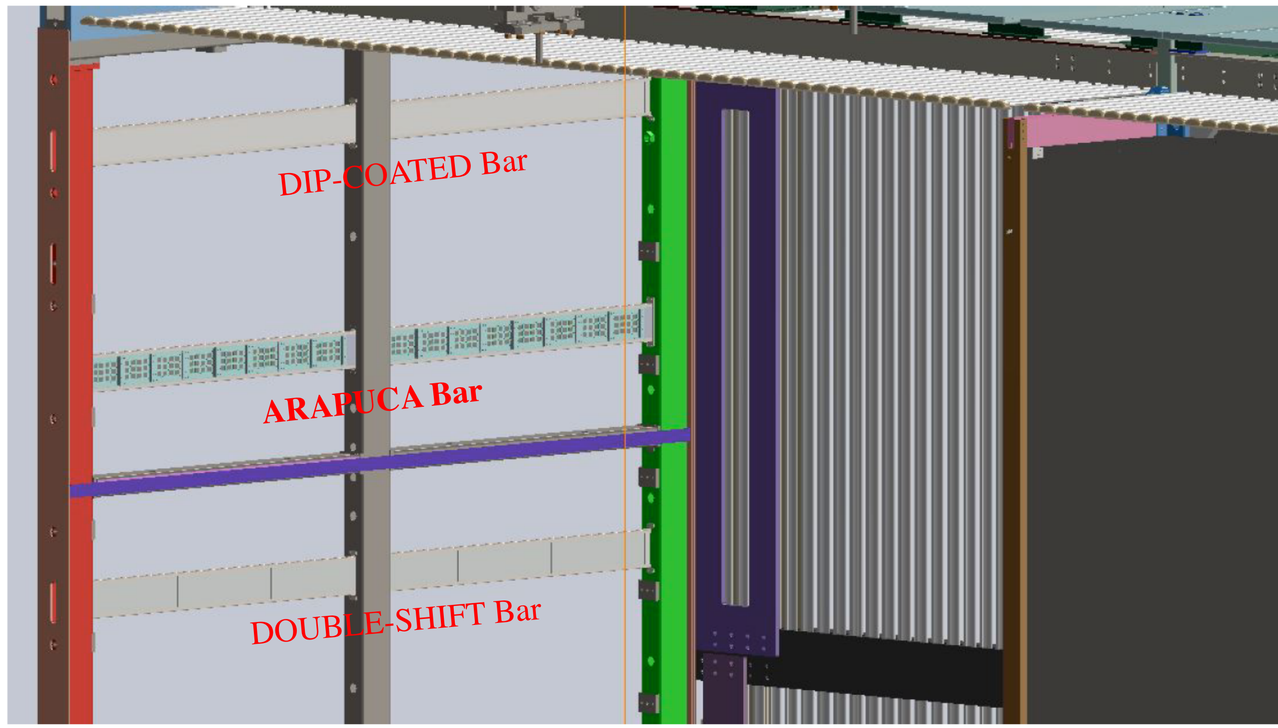
Full characterization with ProtoDUNE SP at CERN Neutrino Platform

- Sept-Nov. 2018 - Beam Run
- Nov.18 - present - Cosmic Run + Xe doping test)

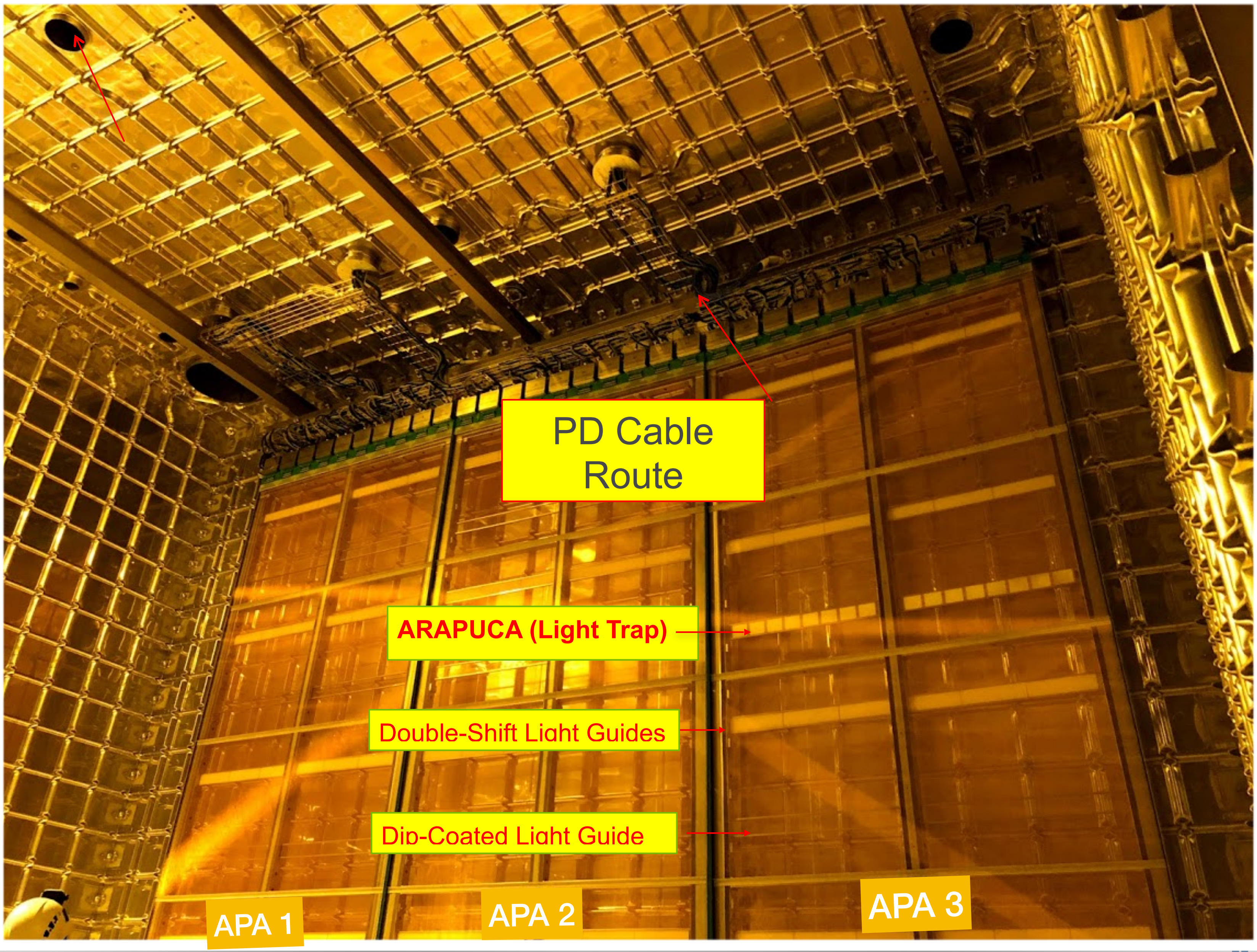
- Three PD technologies implemented:
  - -**ARAPUCA Light Trap**
  - -Dip-Coated Light Guide
  - -Double-Shift Light Guid

PD Modules (Bars) mounted in APA Frame



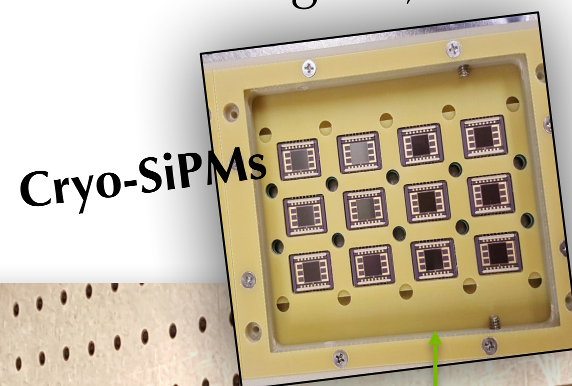


10 PD Bars per APA Frame
PD Bar active area: Light Guide Bar 1744 cm^2 - **ARAPUCA Bar 1223 cm^2**
APA Frame area (Outside) 6060mm X 2300mm
PD Tot Coverage fraction: ~12.5%

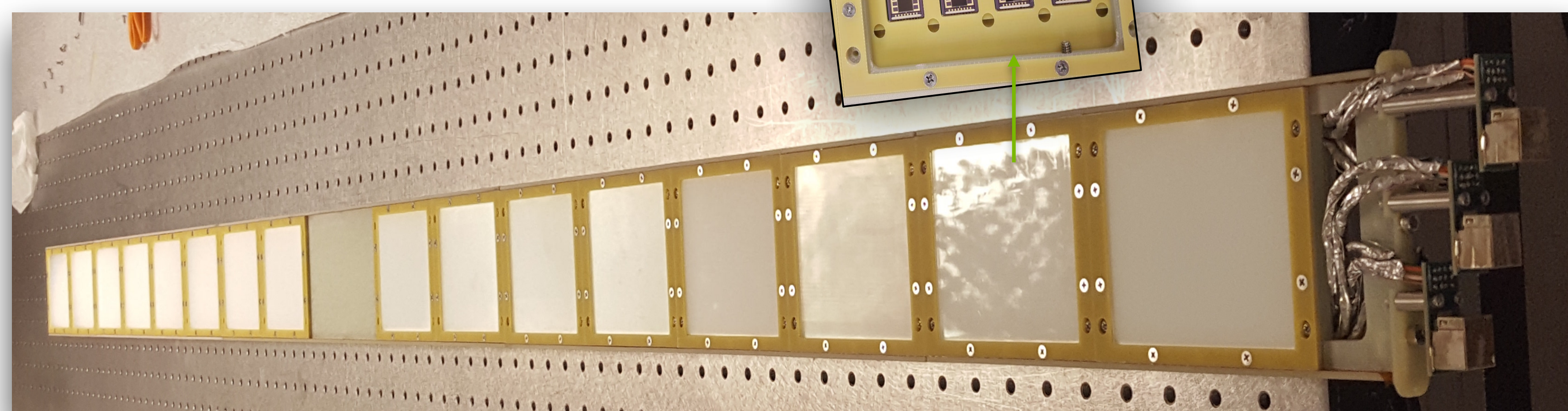

PD Cable Route
ARAPUCA (Light Trap)
Double-Shift Light Guides
Dip-Coated Light Guide
APA 1
APA 2
APA 3

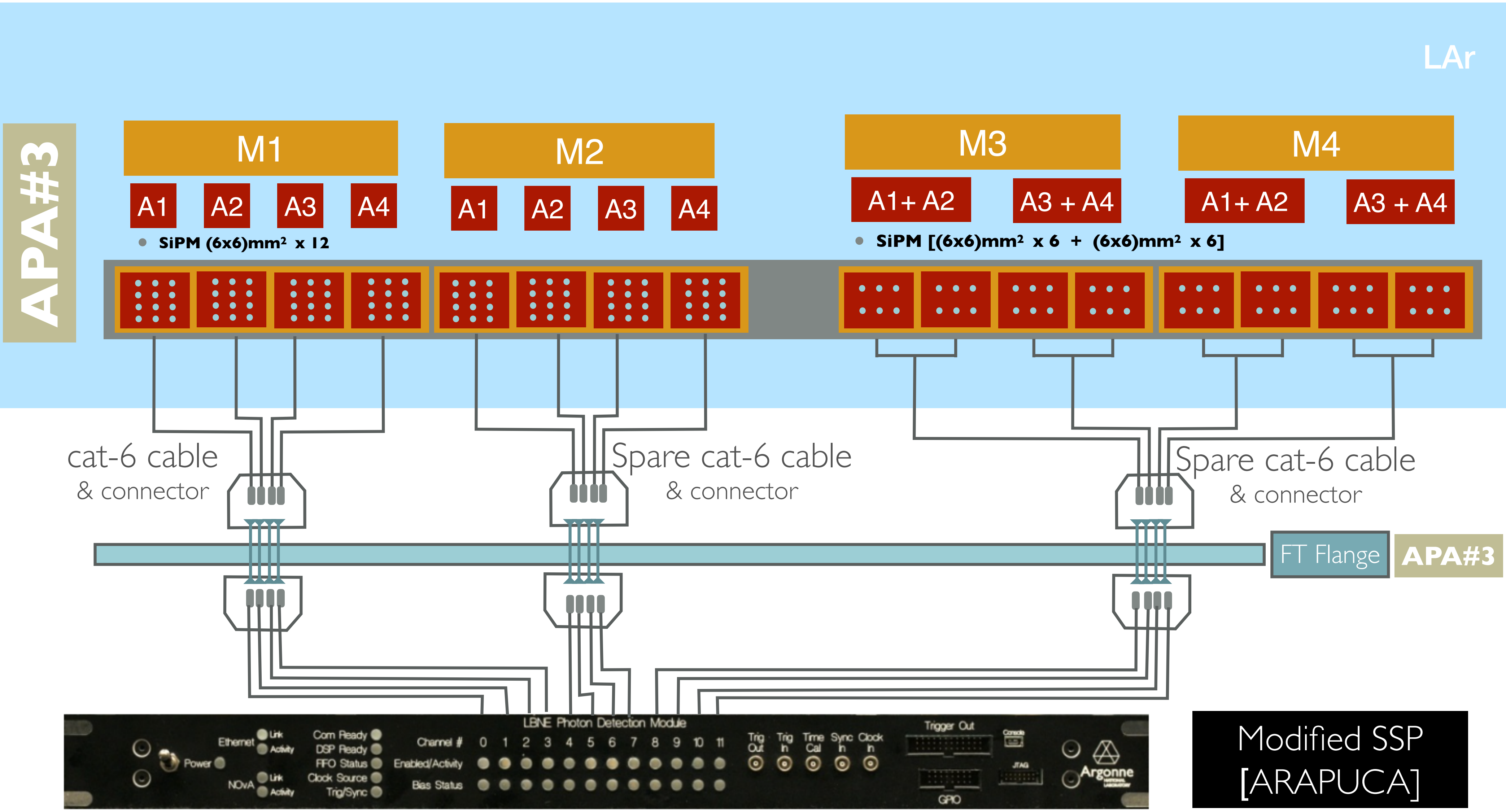
ARAPUCA PD design for protoDUNE

- 2 Bars - segmented along beam direction: one in APA3 (beam side), one in APA4
- 4 Modules (FR4 structure) per Bar
- 4 ARAPUCA Cells (single-sided) per Module
- 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
- $S_{SiPM}/S_{Dichroic} = 5.6\,\%$ (or 2.8%)



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

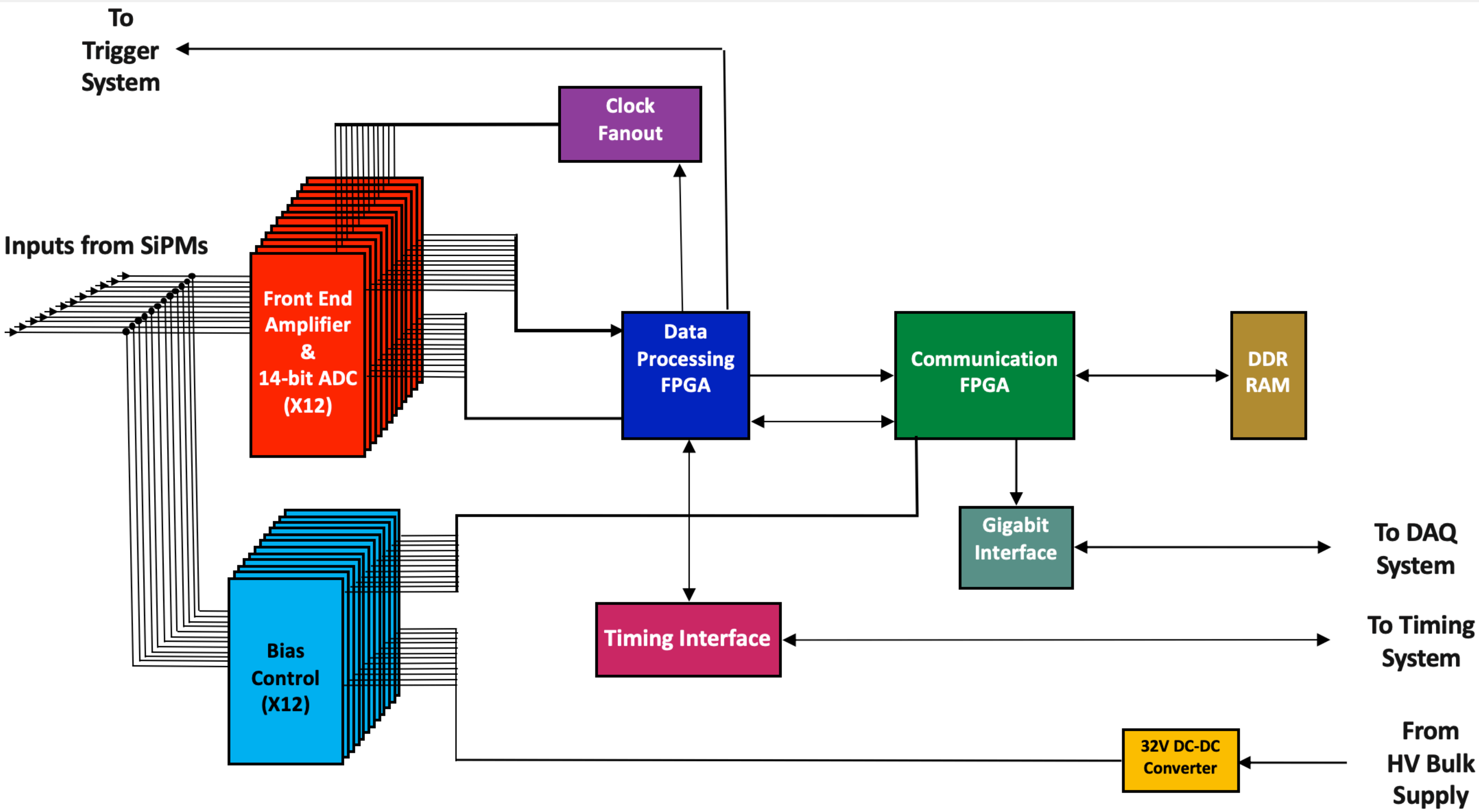




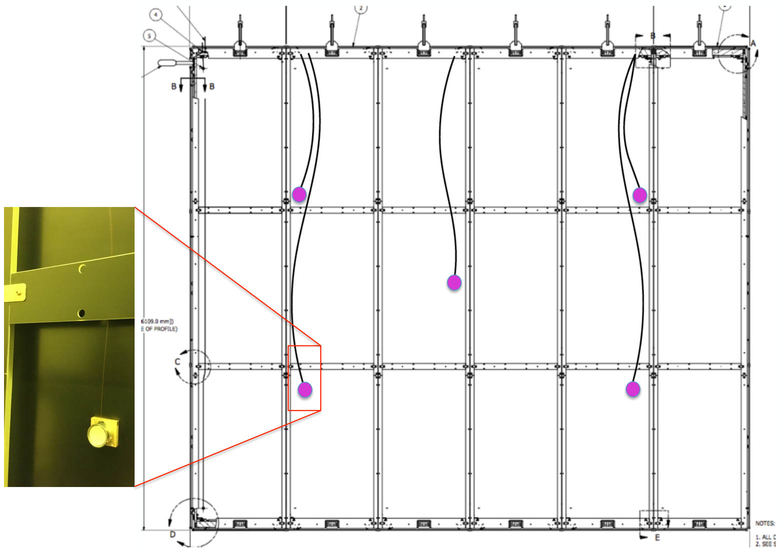
Fermilab DUNE

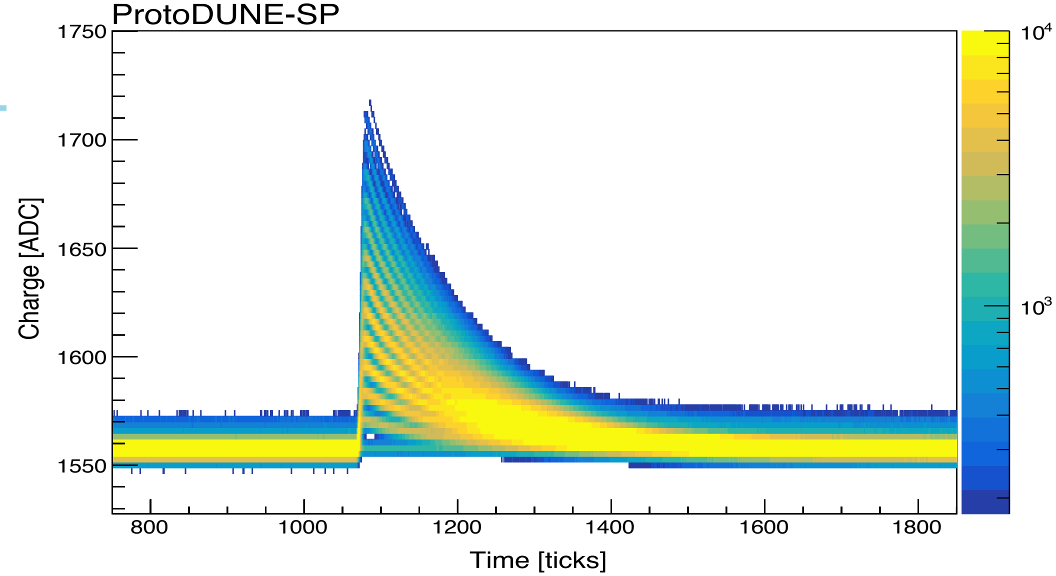
	N. of Channels	N.Channels per Module	N.Dip Coated Modules	N.DoubleShift Modules	N.ARAPUCA Modules
3-S-SiPM	172	4	21	22	-
3-H-MPPC	60	4	8	7	-
12-H-MPPC	24	12	-	-	2

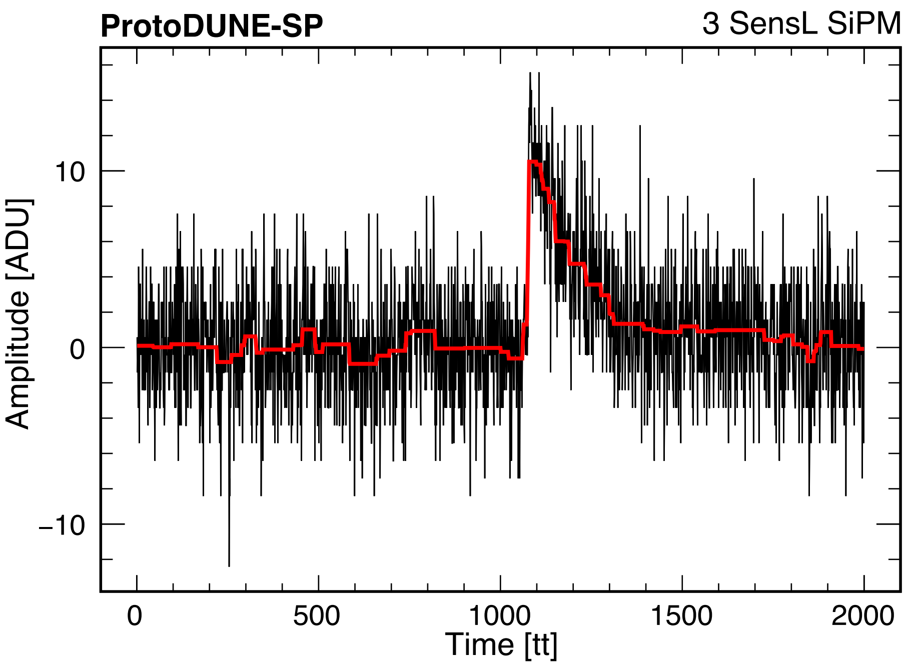
100% ARAPUCA channel alive (no loss during almost 2 yrs continuing operation)

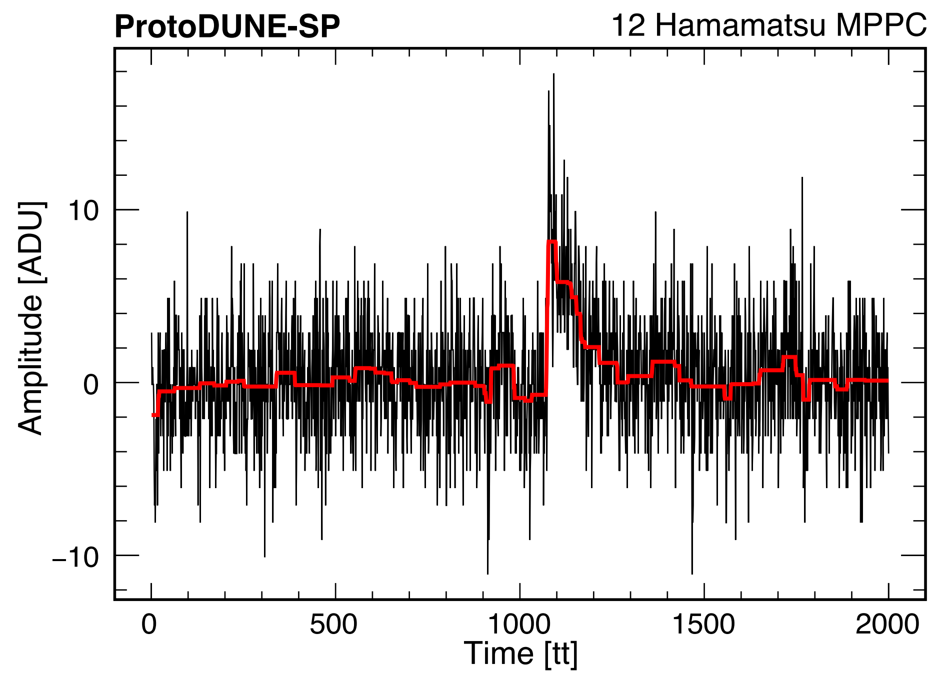


Calibration system: LED flasher

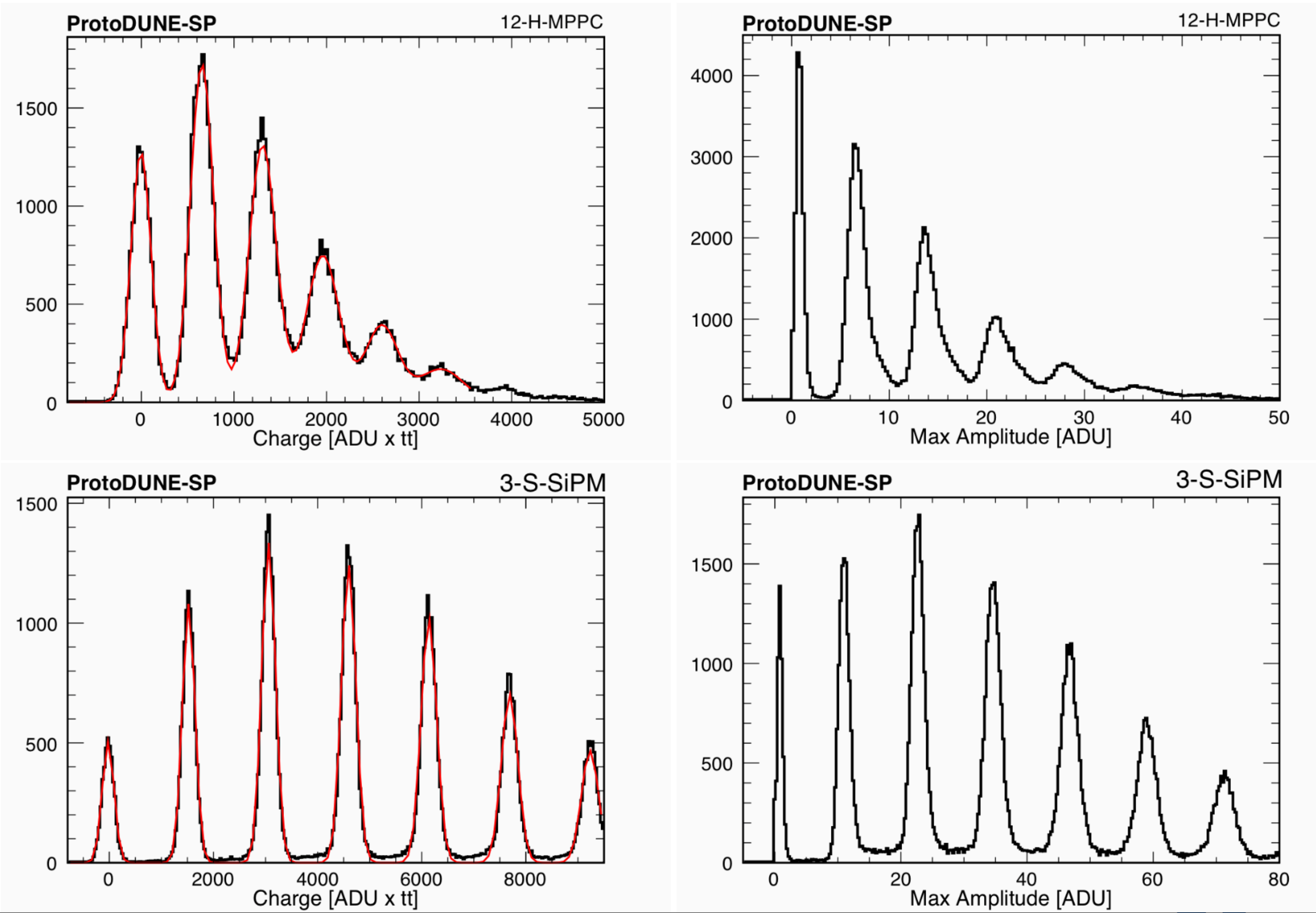






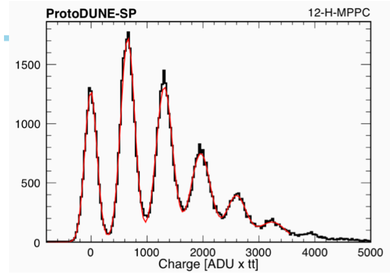


Ph.Sensors Response



$$P(n) = \frac{\lambda^n e^{-\lambda}}{n!} \quad \text{with} \quad P(0) = e^{-\lambda} \quad \rightarrow \quad \lambda = -\ln P(0)$$

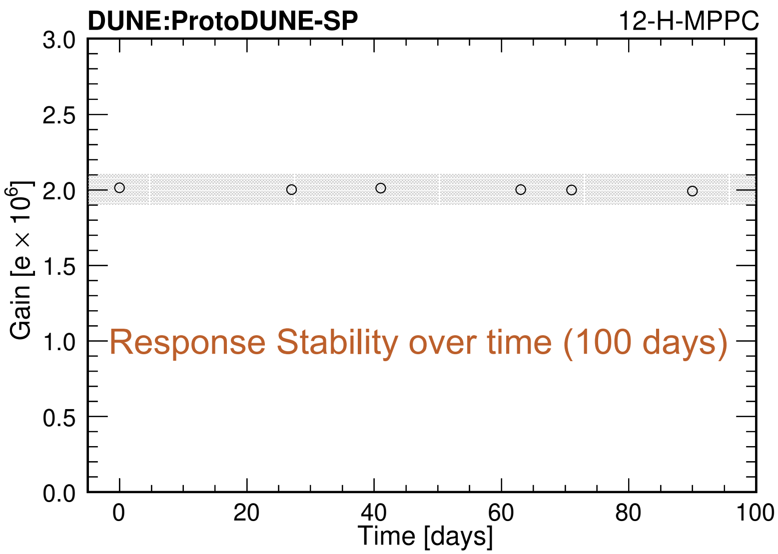
$$\lambda = -\ln\left(\frac{N_0}{N_{Tot}}\right)$$

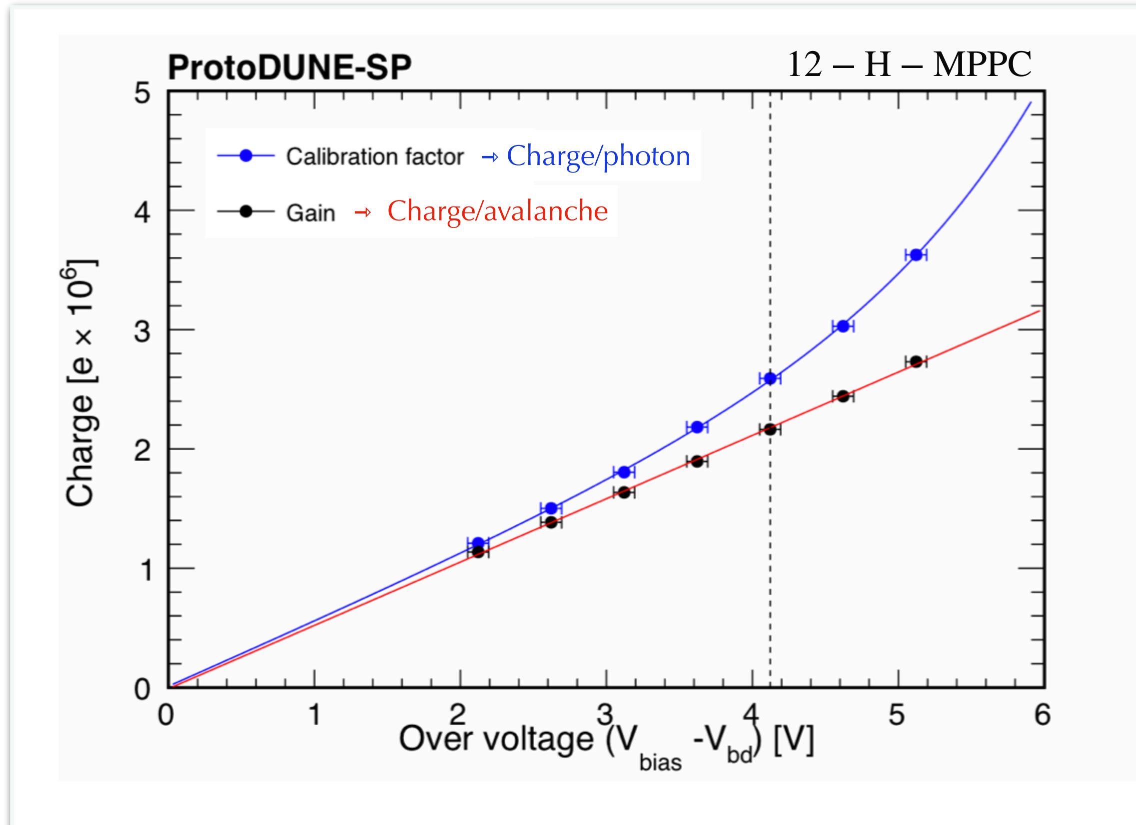


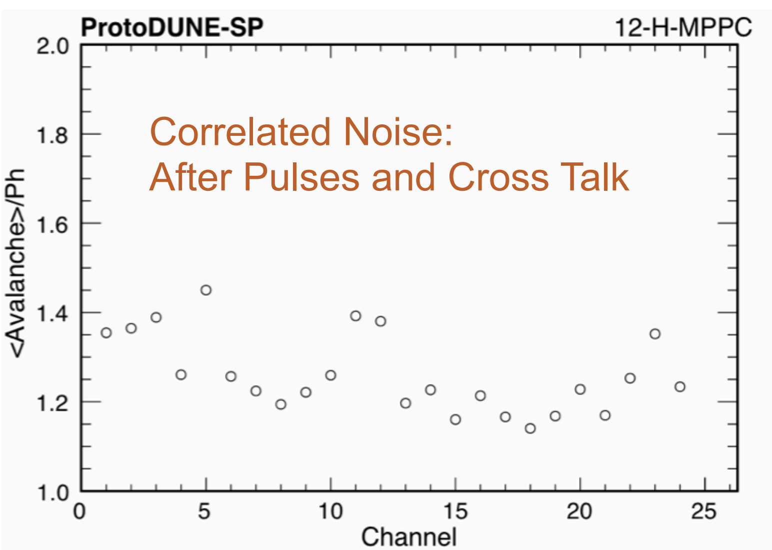
CALIBRATION

From Charge output to N. Of photons detected

$$C = \frac{\langle Q \rangle}{\lambda}$$

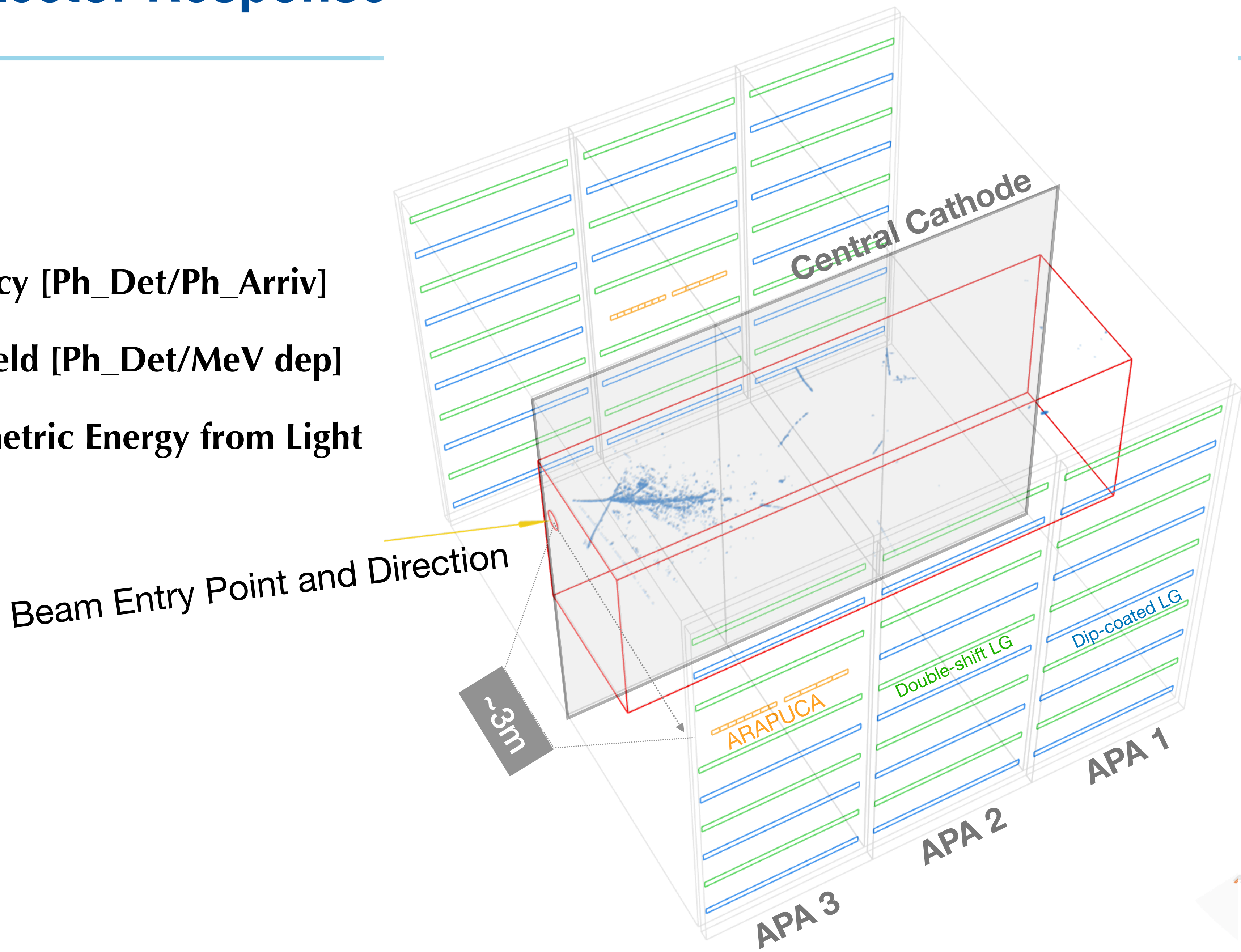






Ph.Detector Response

- Efficiency [Ph_Det/Ph_Arriv]
- Light Yield [Ph_Det/MeV dep]
- Calorimetric Energy from Light

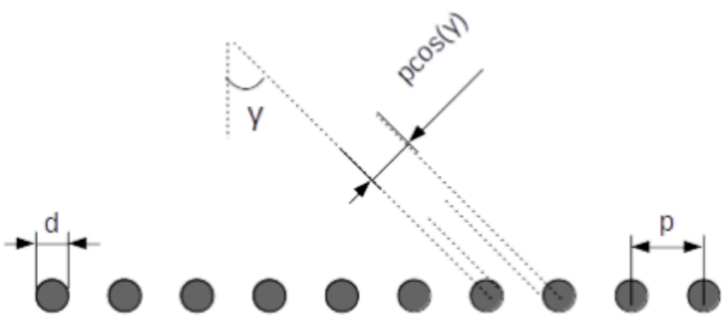


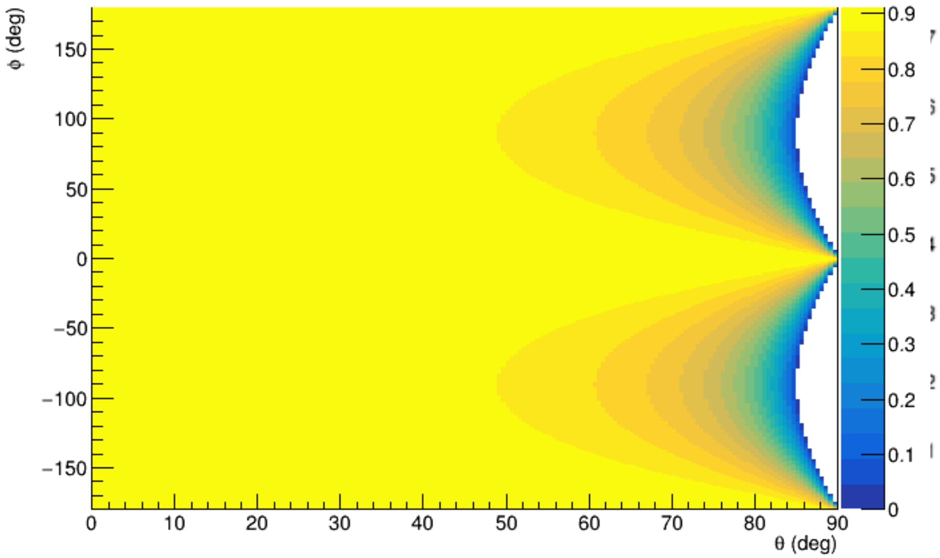
$$\epsilon_j = \frac{\langle N_j^{\mathrm{Det}} \rangle}{\langle N_j^{\mathrm{Inc}} \rangle} \quad \text{efficiency}$$

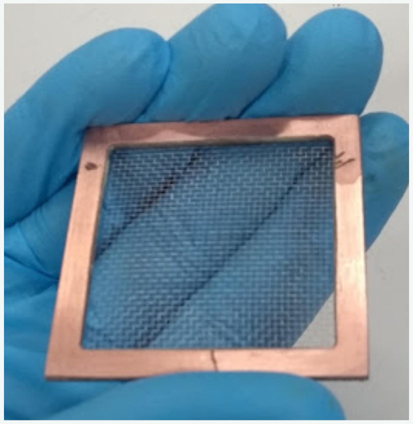
$\langle N_j^{\mathrm{Det}} \rangle$ Photons detected [**DATA**: calibrated signals]

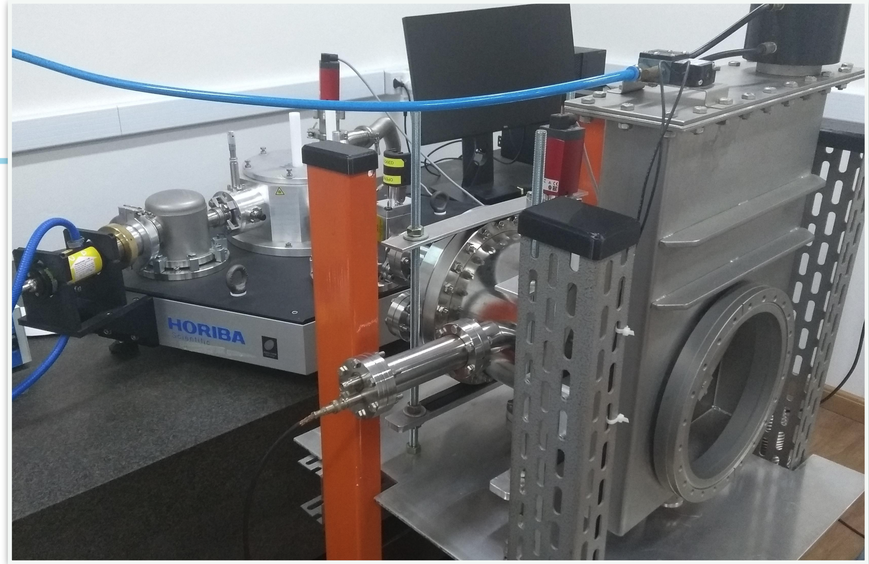
$\langle N_j^{\mathrm{Inc}} \rangle$ Photons incident upon detector optical surface

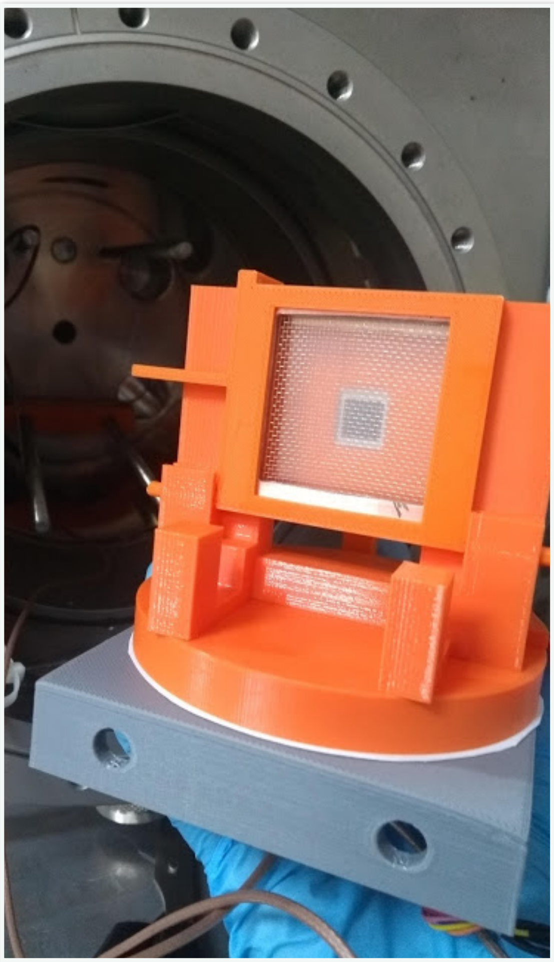
[**MC**: LArG4+PhotonLibrary+Transmission through grounding mesh]

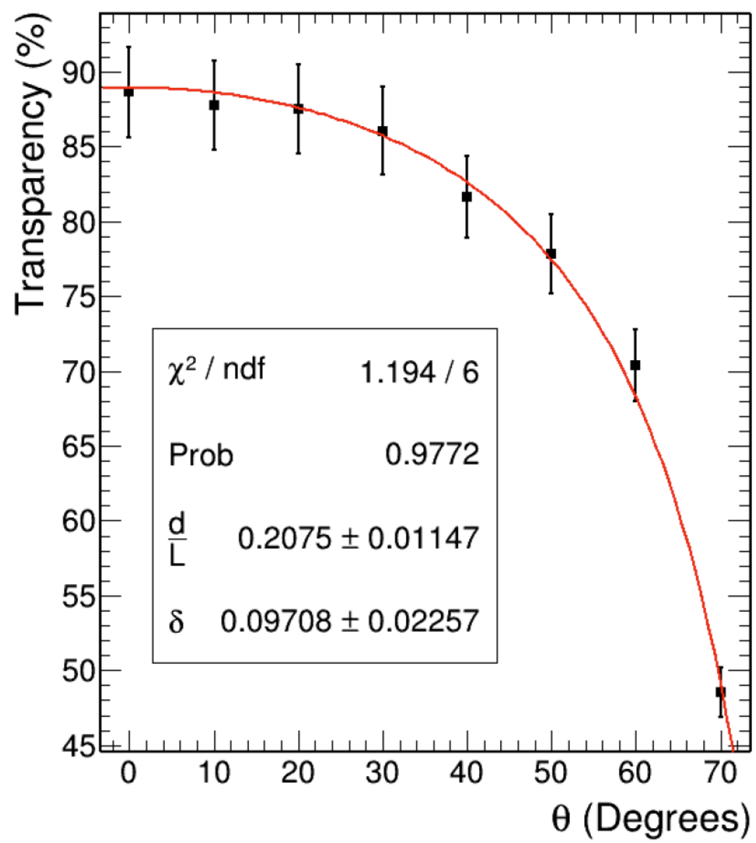






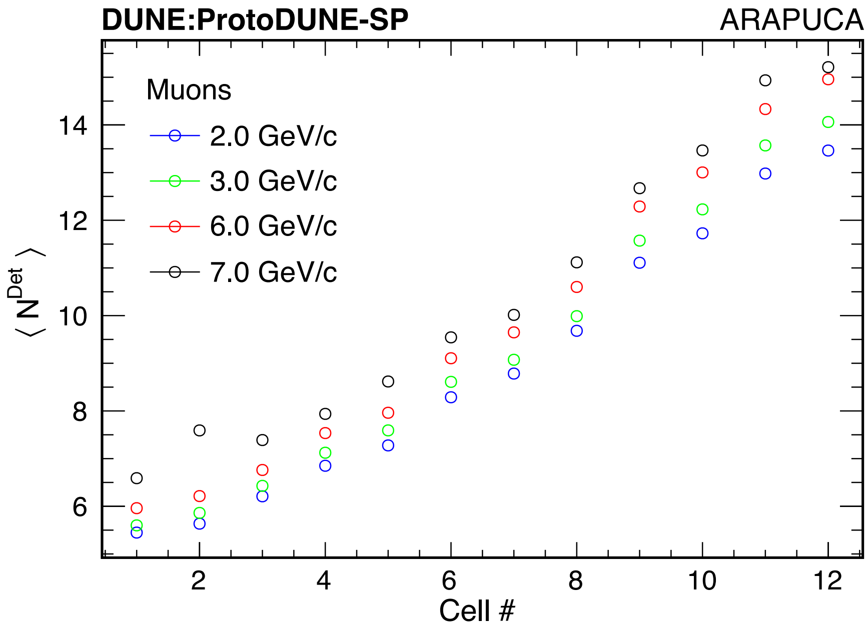






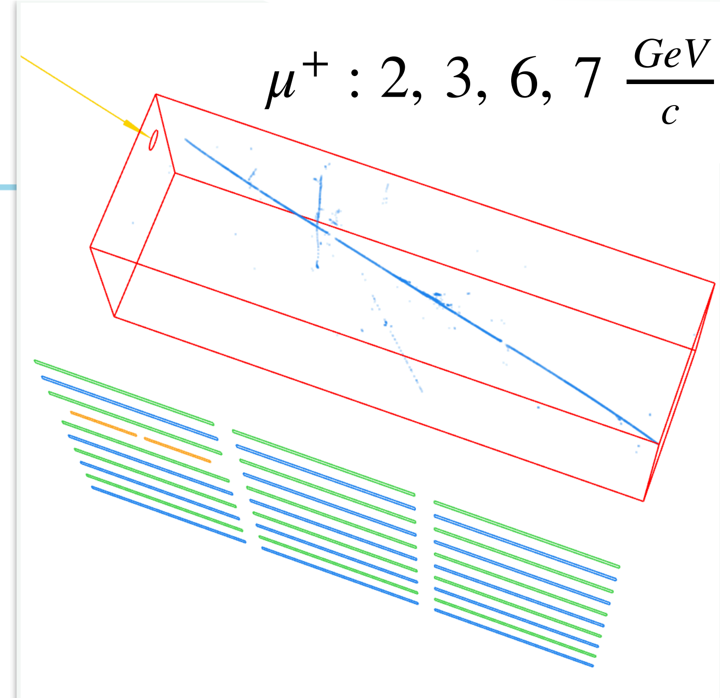
Mesh transparency Dedicated Measurement at UNICAMP With Monochromator + Si APD

Good agreement with Analytical Calculation/MC simulation

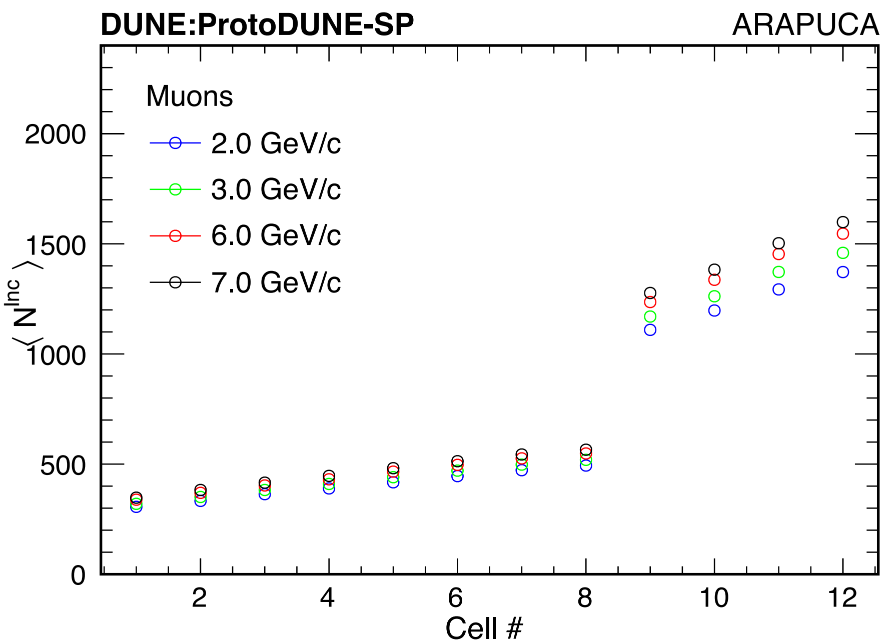


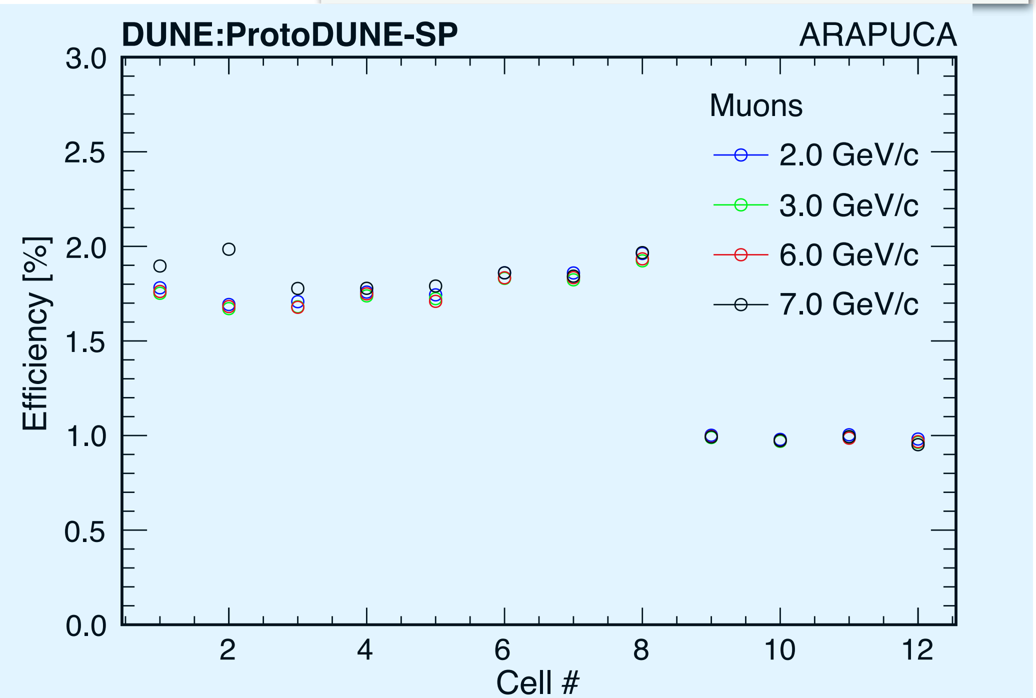
ARAPUCA

EFFICIENCY



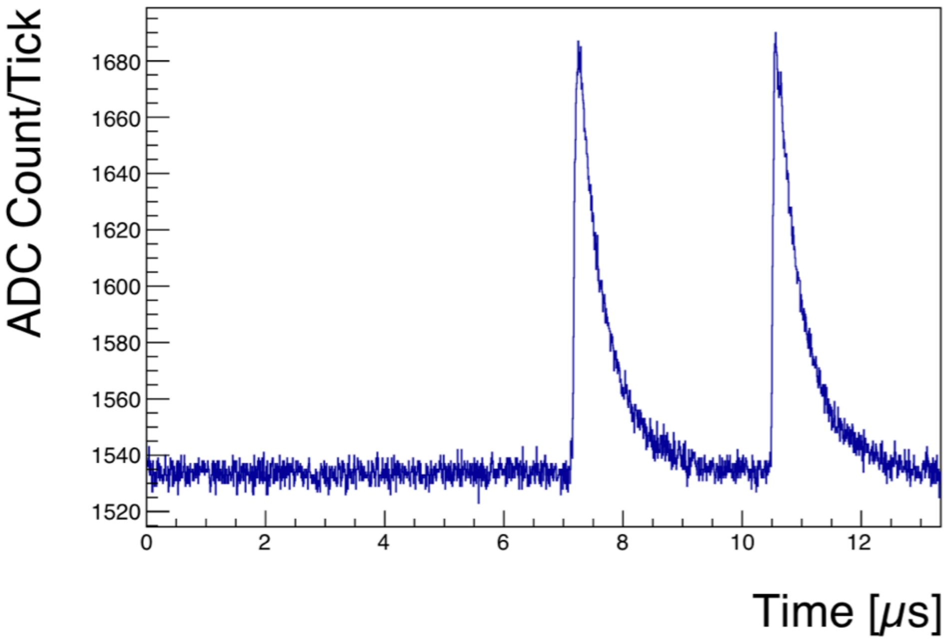
$$\epsilon_j = \frac{\langle N_j^{\mathrm{Det}} \rangle}{\langle N_j^{\mathrm{Inc}} \rangle}$$

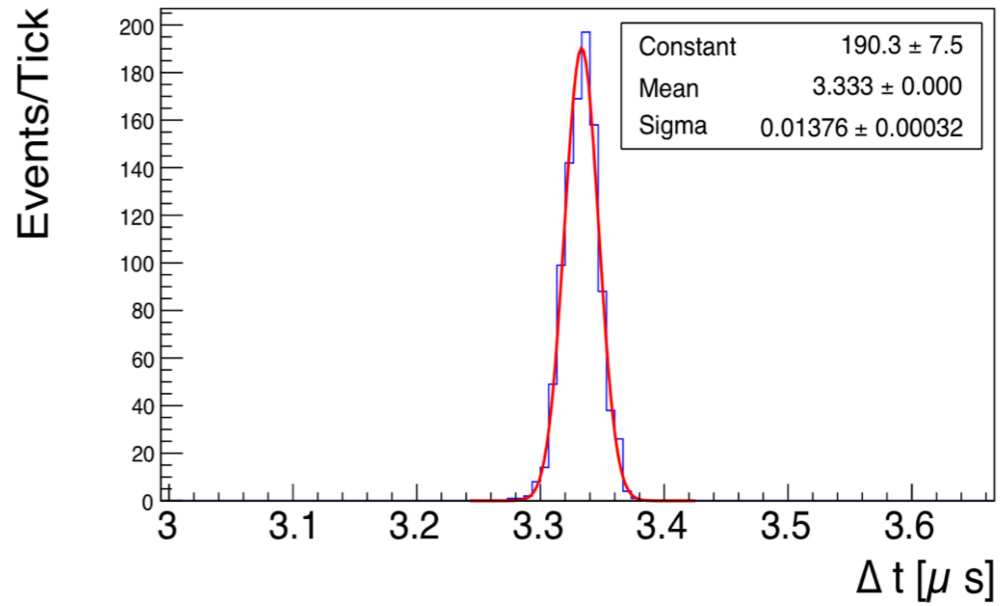




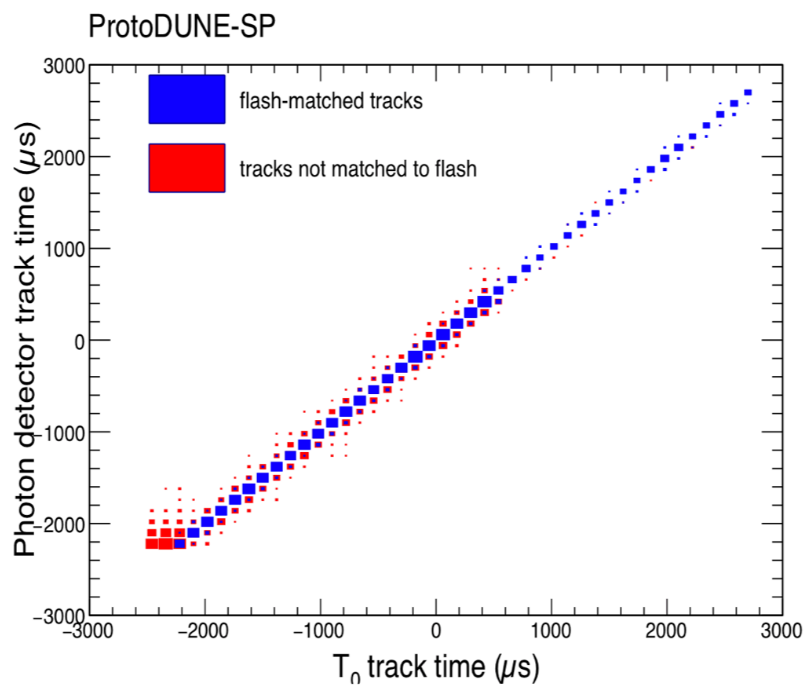
$$\tilde{\epsilon}_A = (2.00 \pm 0.005_{\mathrm{stat}} \pm 0.25_{\mathrm{syst}})\ \%$$

$$\tilde{\epsilon}_{A2} = (1.06 \pm 0.005_{\mathrm{stat}} \pm 0.09_{\mathrm{syst}})\ \%$$

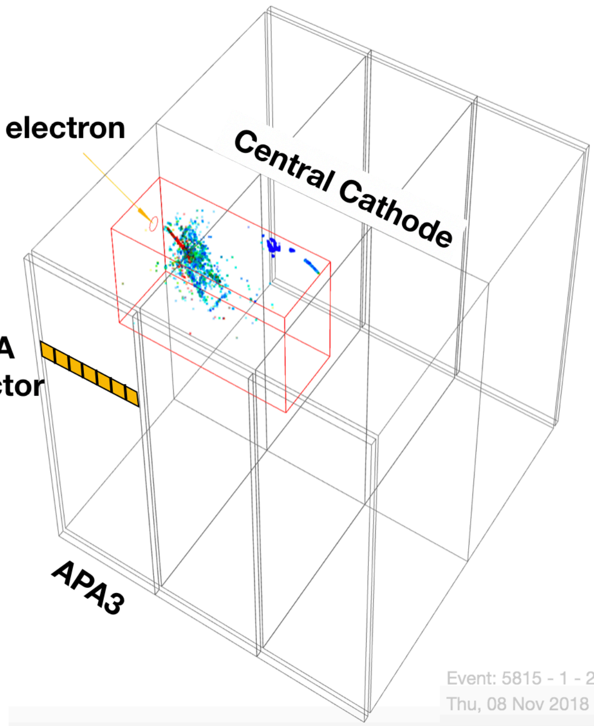




Time Resolution



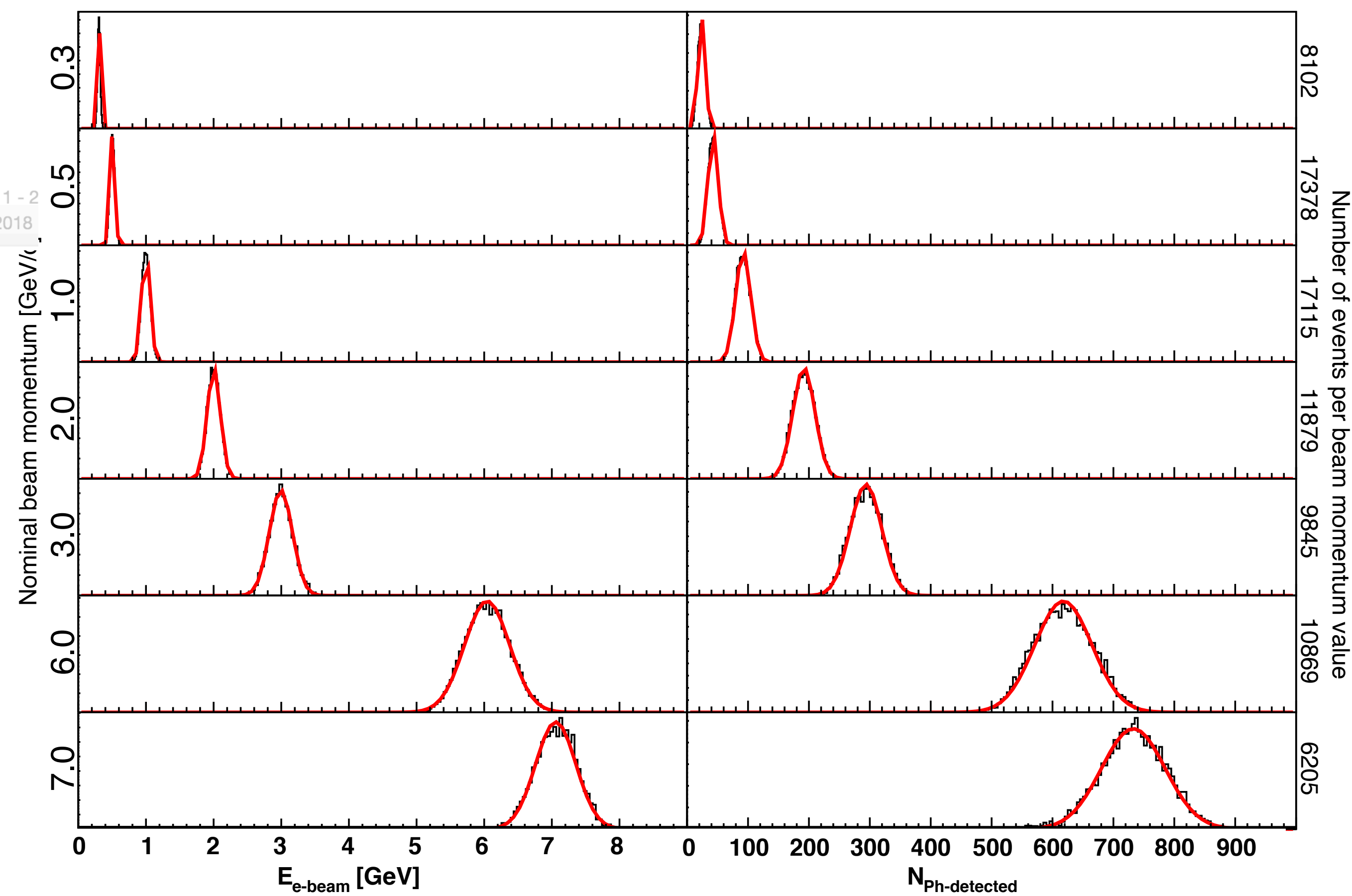
Large LAr detector operating at
the CERN Neutrino Platform



Operating on the H4-VLE charged particle test beam offers a first ever opportunity to directly probe the calorimetric response *with light* to EM and hadronic showers in the sub- to few-GeV momentum range.

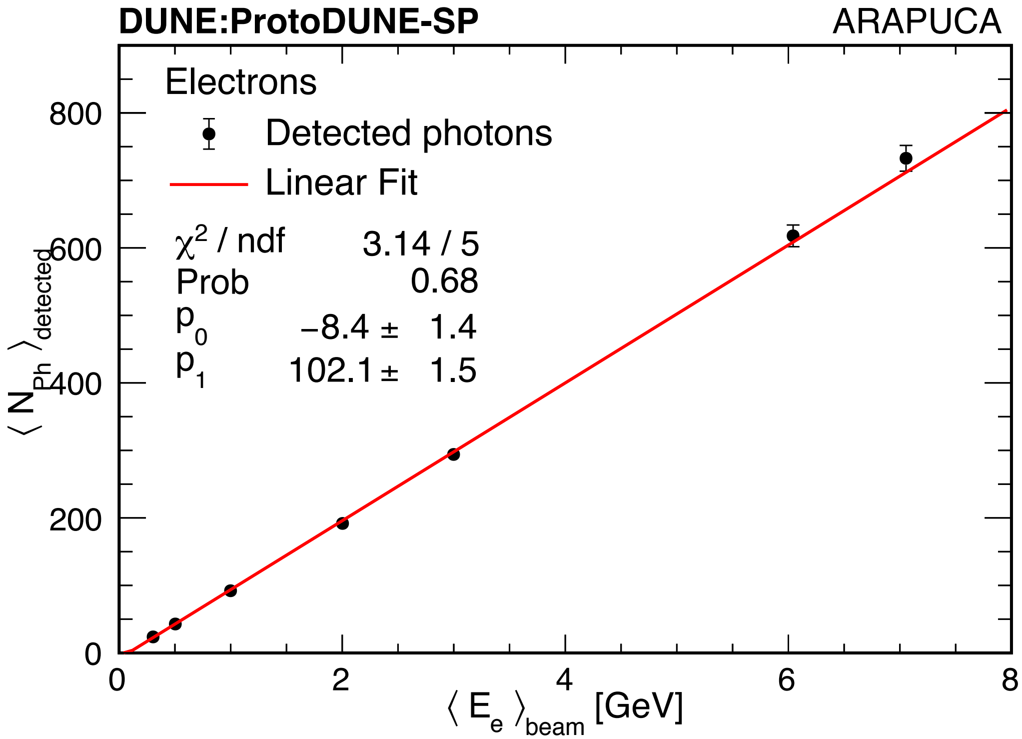
calorimetric response from Light signal from a single ARAPUCA module (~0.5‰ photo-sensitive area coverage)

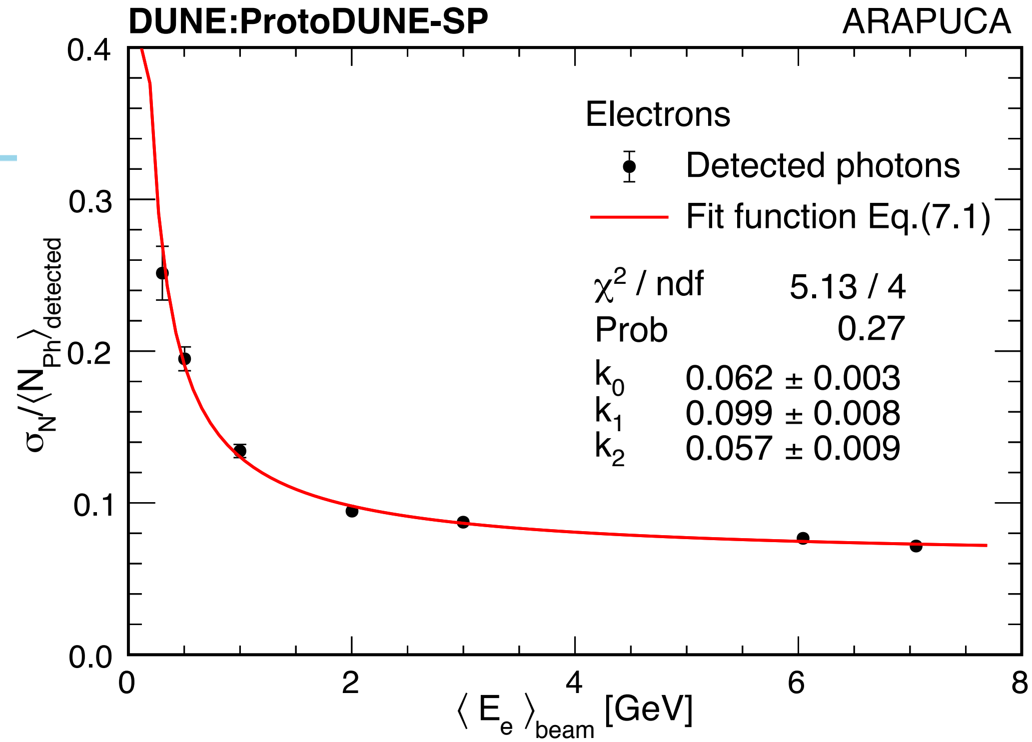
EM shower at ~3 m distance in the x (drift) direction



Incident Electron momentum distribution

detected photons spectra





Linearity

of light response over the entire range of energies.

The slope gives the light yield

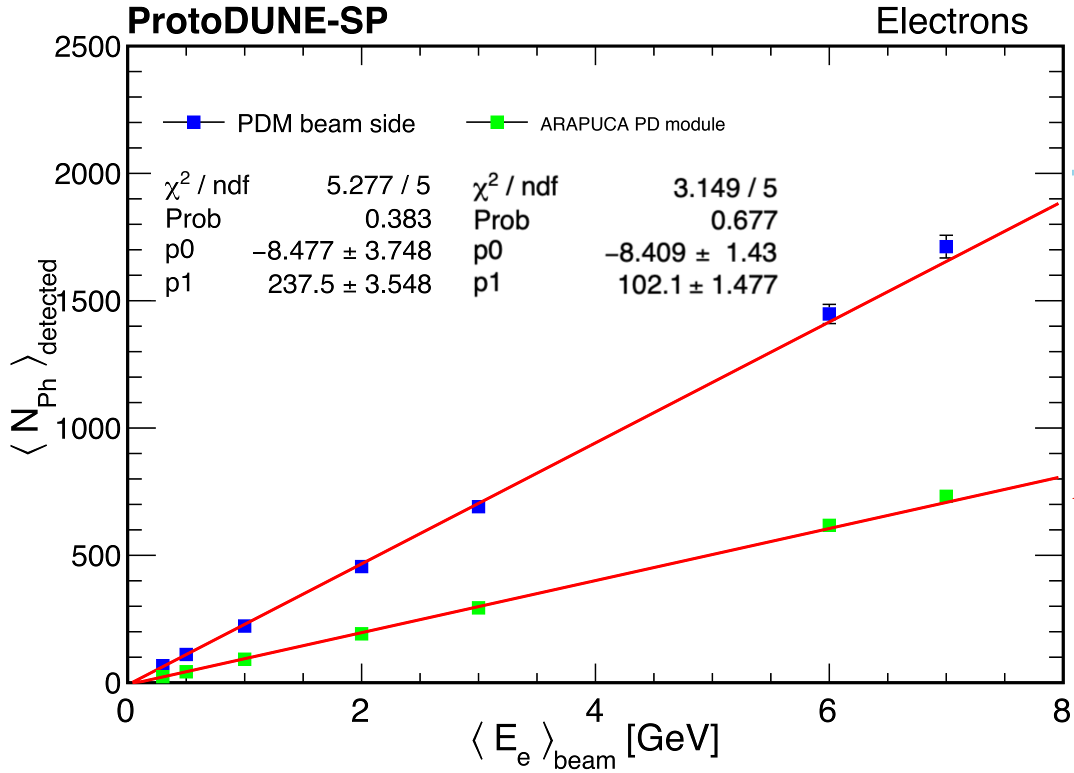
$$LY = 102\ Ph/GeV$$

from (only) one ARAPUCA module, relative to a diffused light source (EM shower) at a distance of about 3.3 m

Energy Resolution from light

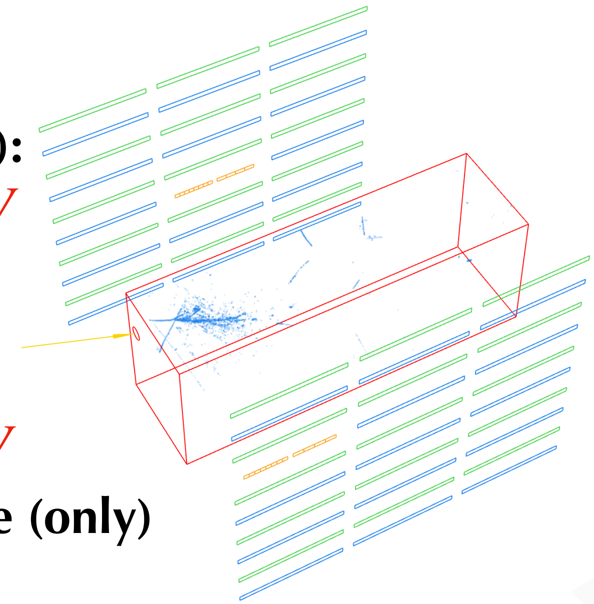
$$\frac{\sigma_E}{E} = p_0 \oplus \frac{p_1}{\sqrt{E}} \oplus \frac{p_2}{E}$$

- **Stochastic term:** $p_1 = 10\,\%$
  from limited photo-sensitive area coverage
- **Noise term:** $p_2 = 57\ MeV$
  from excellent SiPM readout S/N ratio
- **Constant term:** $p_0 = 6.2\,\%$
  from beam momentum spread & uncertainty and non-uniformities in light collection (non linearity)



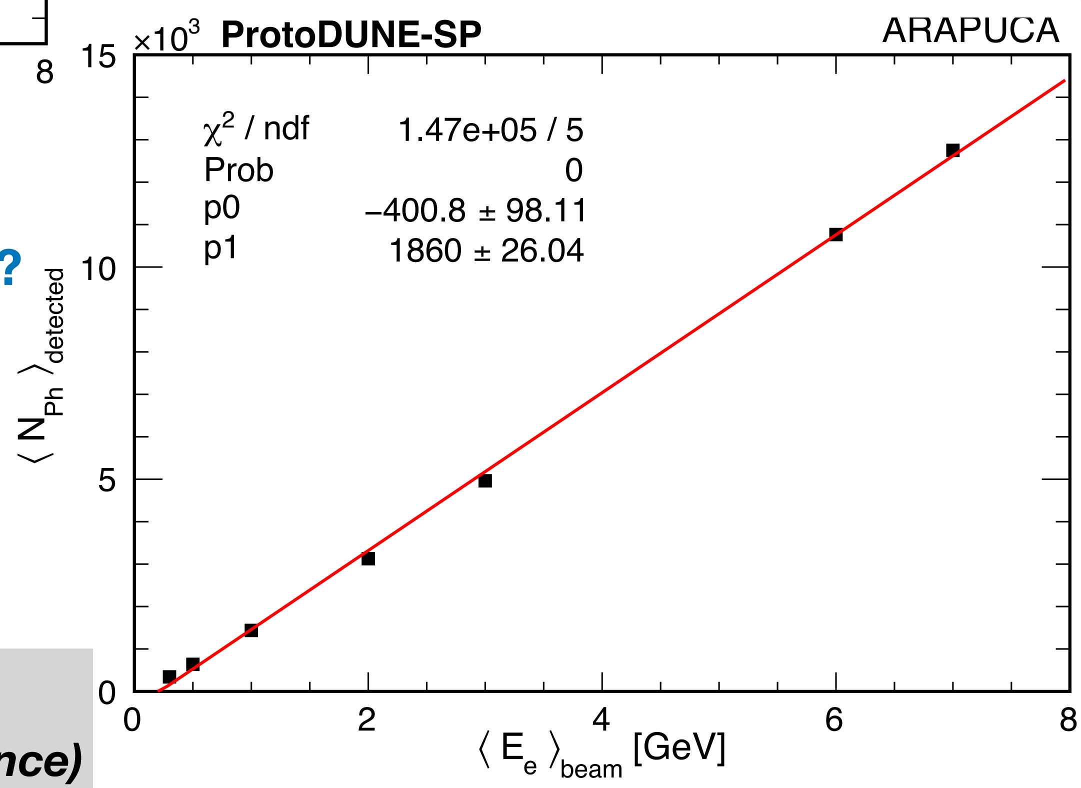
All PDS (beam side):

$LY = 237\ Ph/GeV$



$LY = 102\ Ph/GeV$

1 ARAPUCA Module (only)



What if
PDS made all by (30) ARAPUCA modules ??

by extraploation from current data: $N_{ph} \cdot \dfrac{\epsilon_{Arapuca}}{\epsilon_{LightGuide}}$

$LY \simeq 1.9\ Ph/MeV$ **@ 3.3 m distance**

Note: DUNE FD Requirement:

> 0.5 Ph/MeV (at cathode plane - 3.6 m distance)

Prepared for submission to JINST

First results on ProtoDUNE-SP LArTPC performance from a beam test at the CERN Neutrino Platform

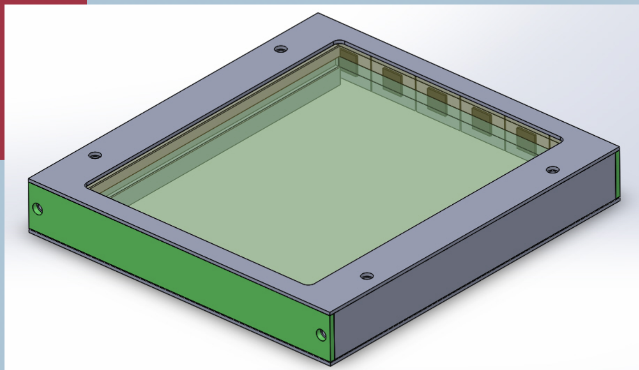
Abstract: The ProtoDUNE-SP detector is a single-phase liquid argon time projection chamber (LArTPC) with an active volume of $7.2 \times 6.0 \times 6.9$ m^3. It is installed in a specially-constructed beam that delivers charged pions, kaons, protons, muons and electrons with momenta in the range 0.3 GeV/c to 7 GeV/c. Beam line instrumentation provides accurate momentum measurements and particle identification. The ProtoDUNE-SP detector is a prototype for the first far detector module of the Deep Underground Neutrino Experiment, and it incorporates full-size components as designed for that module. This paper describes the beam line, the TPC, the photon detectors, the cosmic-ray tagger, the signal processing and particle reconstruction. It presents the first results on ProtoDUNE-SP's performance, including TPC noise and gain measurements, dE/dx calibration for muons, protons, pions and electrons, drift electron lifetime measurements, and photon detector noise, signal sensitivity and time resolution measurements. The measured values meet or exceed the specifications for the DUNE far detector, in several cases by large margins. ProtoDUNE-SP's successful operation starting in 2018 and its production of large samples of high-quality data demonstrate the effectiveness of the single-phase far detector design.

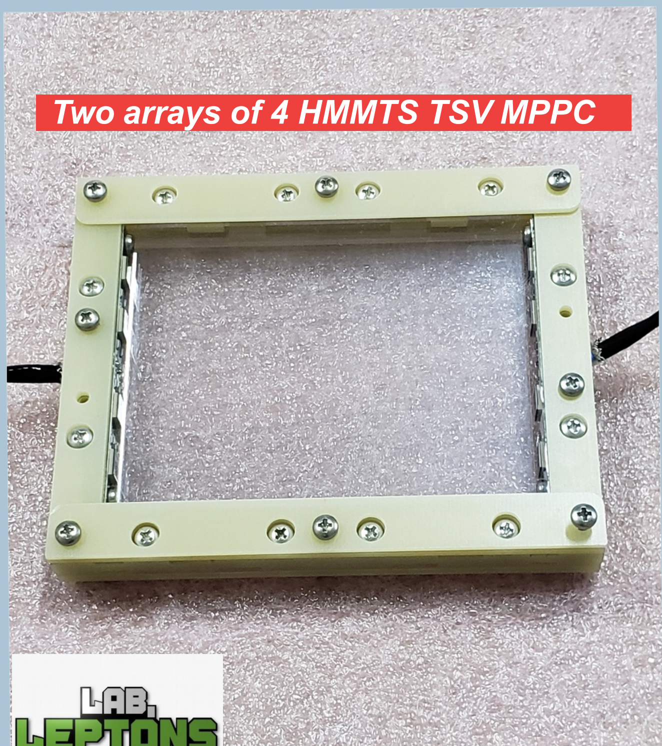
Keywords: Noble liquid detectors (scintillation, ionization, single-phase), Time projection chambers, Large detector systems for particle and astroparticle physics

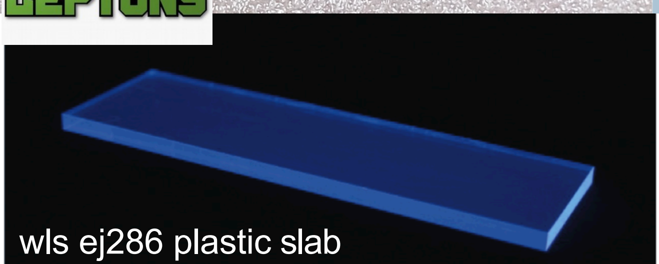
ArXiv ePrint: 1234.56789

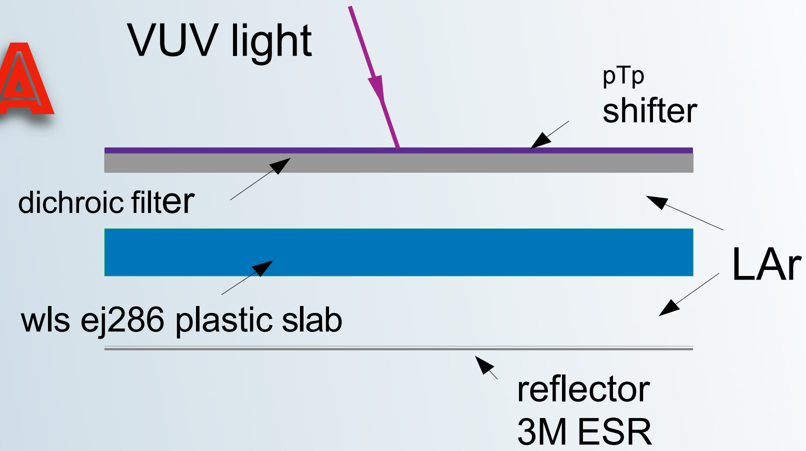
Preprint on ArXiv next week

X-ARAPUCA

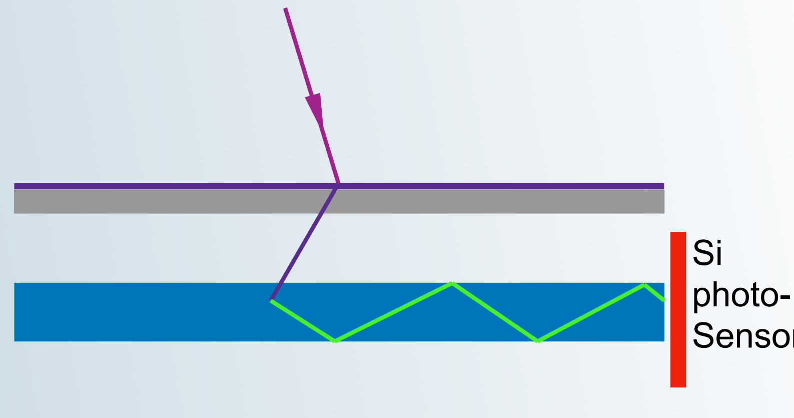




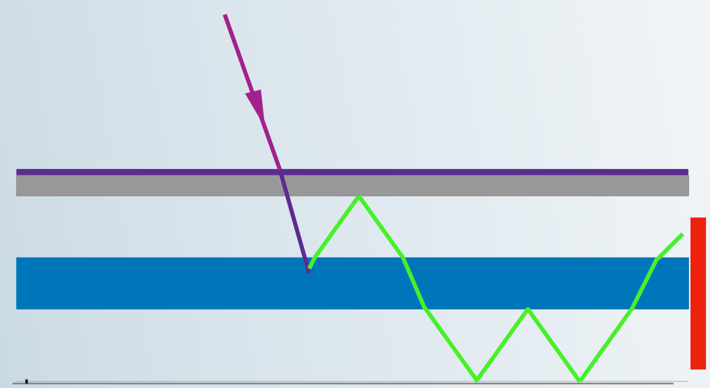




enhance light trapping by light guiding



IMPLEMENTED IN PROTODUNE-SP FOR XE-DOPING TEST

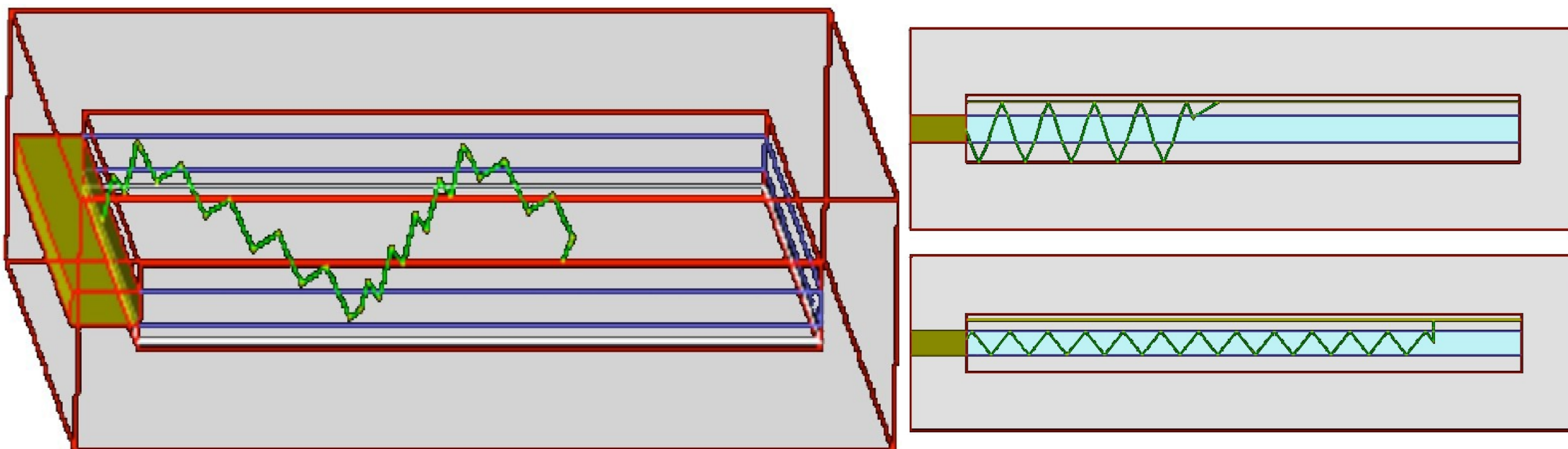


40% improvement on collection efficiency compared to standard ARAPUCA

X-ARAPUCA concept

- The ***X-ARAPUCA*** represents a development and an optimization of the Standard ARAPUCA

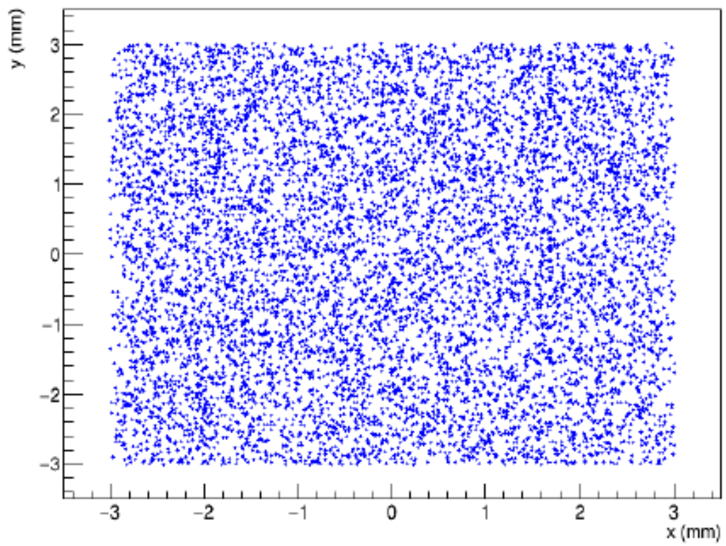
- In the X-ARAPUCA the inner shifter is substituted by an ***acrylic plate*** which has the *WLS compound embedded*. WLShifted Photons are guided towards one end of the plate by total internal reflection. The active photo-sensors are optically coupled to one or more ends of the plate itself



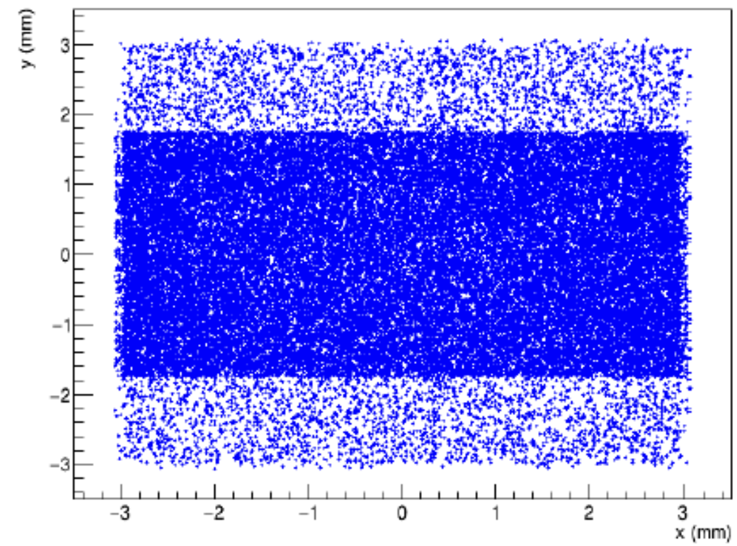
Comparison X-Arapucas and S-Arapucas

- Efficiency improvement of 15 – 40% (for test @ Unicamp)
- Up to 55% more photons in the acrylic plate region

S-Arapuca

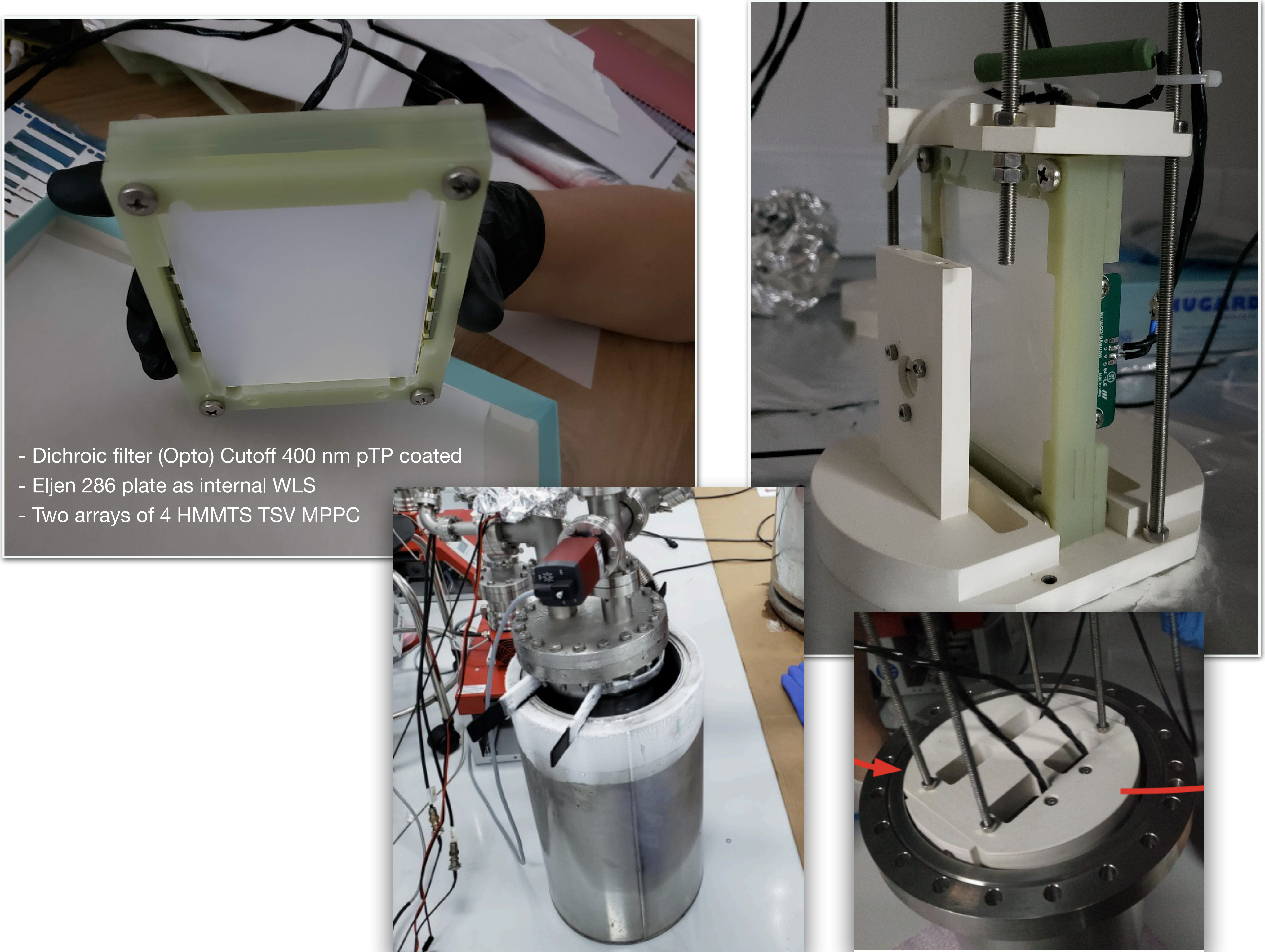


X-Arapuca



No gap between plate side and SiPM
No attenuation for the acrylic plate

- **Simpler design:**
  - ✓ **No need of evaporating** the internal side of the filter or internal surfaces
  - ✓ Great advantage especially for double sided X-ARAPUCAs
  - ✓ Faster production

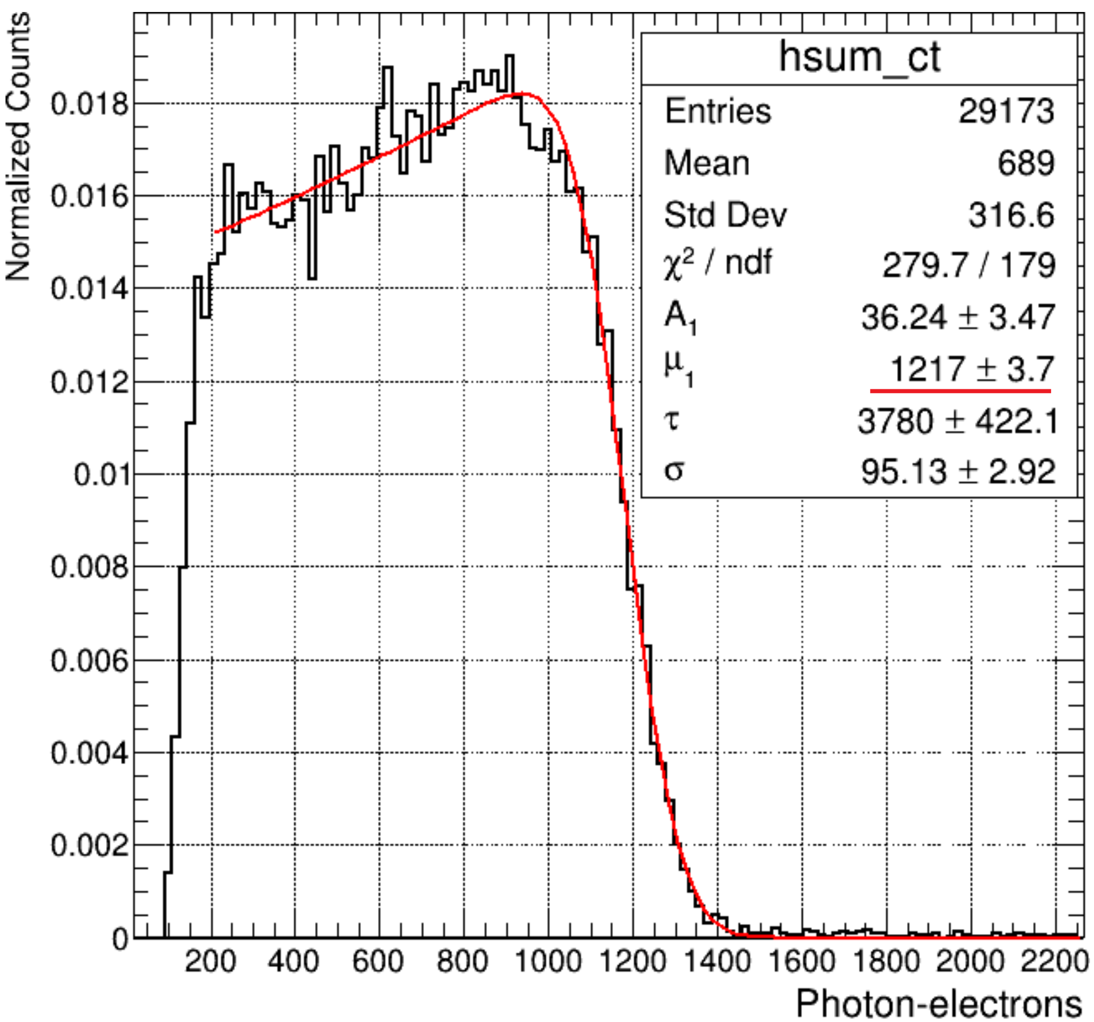

- Dichroic filter (Opto) Cutoff 400 nm pTP coated
- Eljen 286 plate as internal WLS
- Two arrays of 4 HMMTS TSV MPPC

First X-ARAPUCA Test

Alpha Source

H. Souza, E. Segreto, A. Machado, et al 2018 JINST 13 P08021

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



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

$$N_\gamma^A = N_\gamma^{LAr} \times E_\alpha \times q_\alpha \times \Omega^A$$

= 51000 Ph/MeV x 4.759 MeV x 0.71 x 0.225

= 38773 Ph (on X-ARAPUCA optical window)

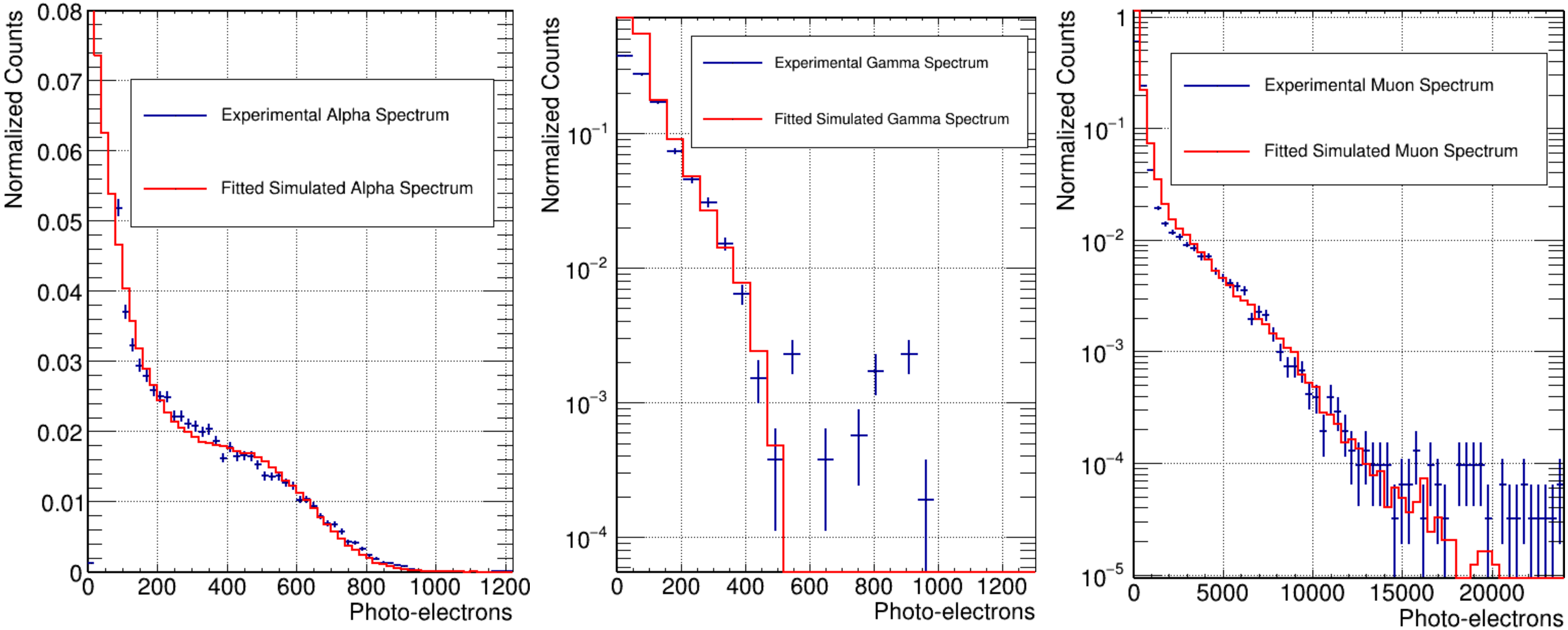
$$\epsilon_X = 3.4 \pm 0.2\,\%$$

[including corrections for LAr Purity, and for CrossTalk and After Pulses in SiPM]

Second (extended) X-ARAPUCA Test

Calibrations performed to correct SiPM gain and Cross-talk

α-Source – γ-Source – Cosmic μ's



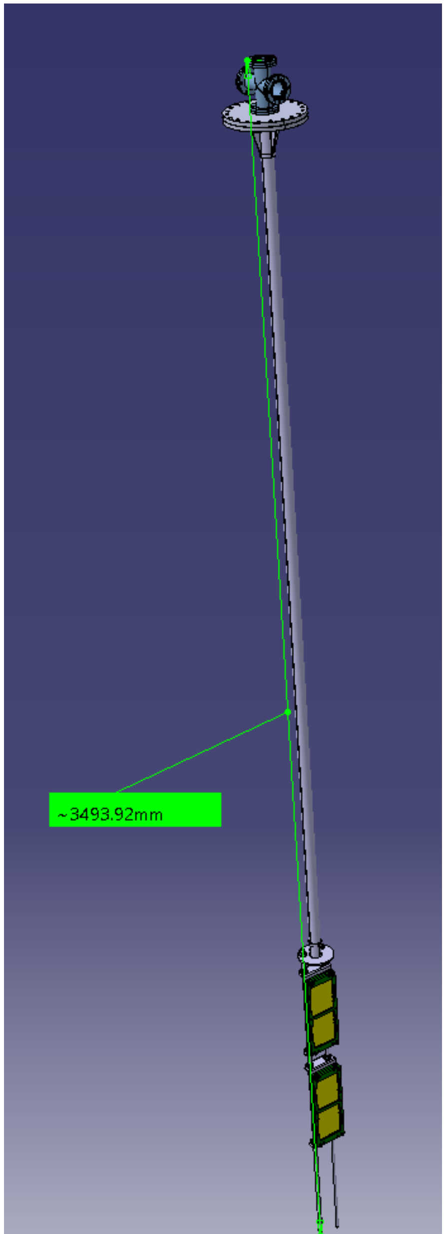
Efficiency = scale factor between simulated spectrum (red) and experimental spectrum (blue) determined by χ^2 minimization

$$\epsilon_X \;=\; (3.1 \rightarrow 2.3) \pm 0.5\,\%$$

A variation in efficiency after several thermal cycles was noted, and attributed to degradation of the light-guide plate (formation of micro-cracks) due to thermal stress along the several tests performed.

First X-ARAPUCA Operation in experimental conditions

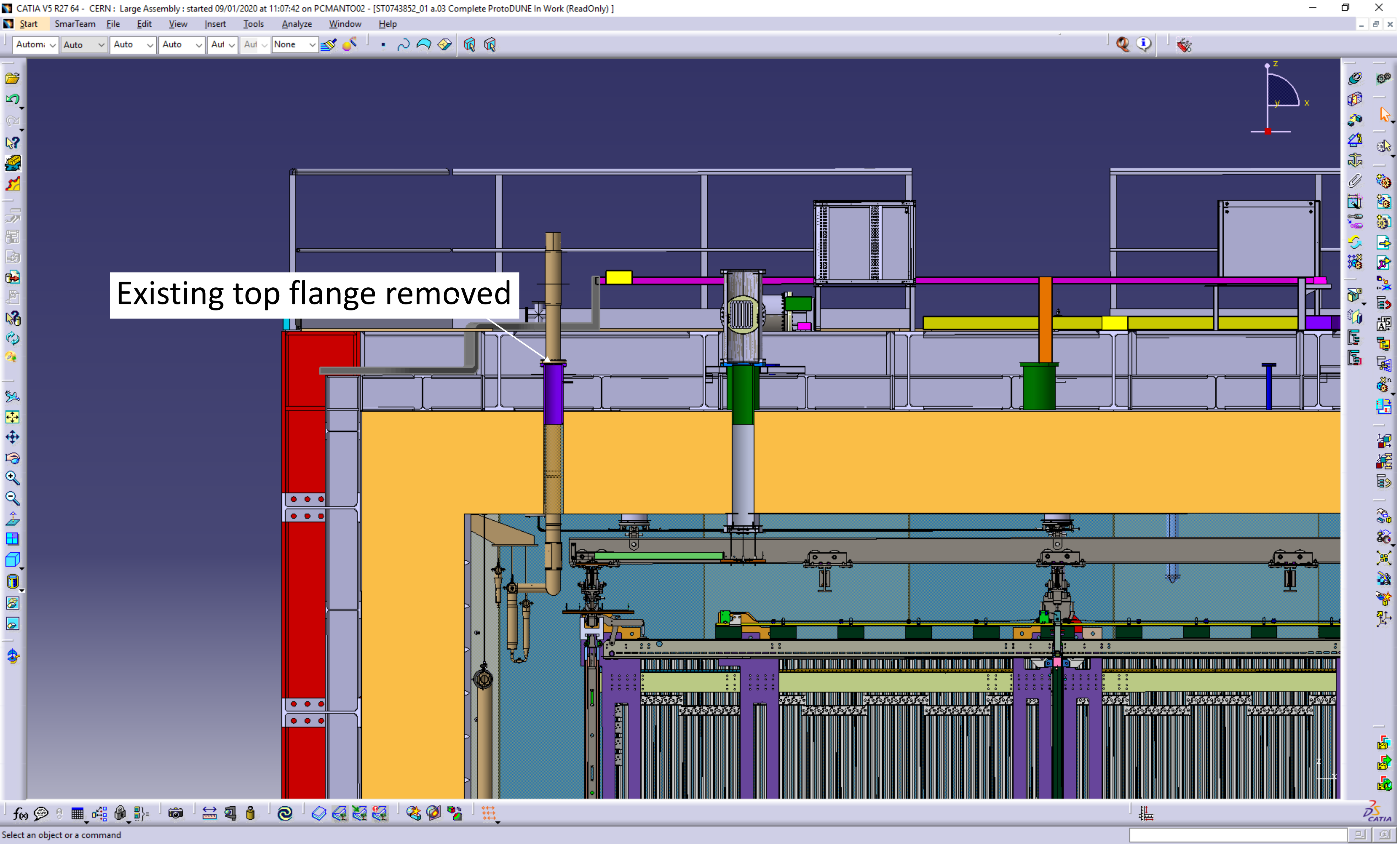
Xe dopingg test in protoDUNE



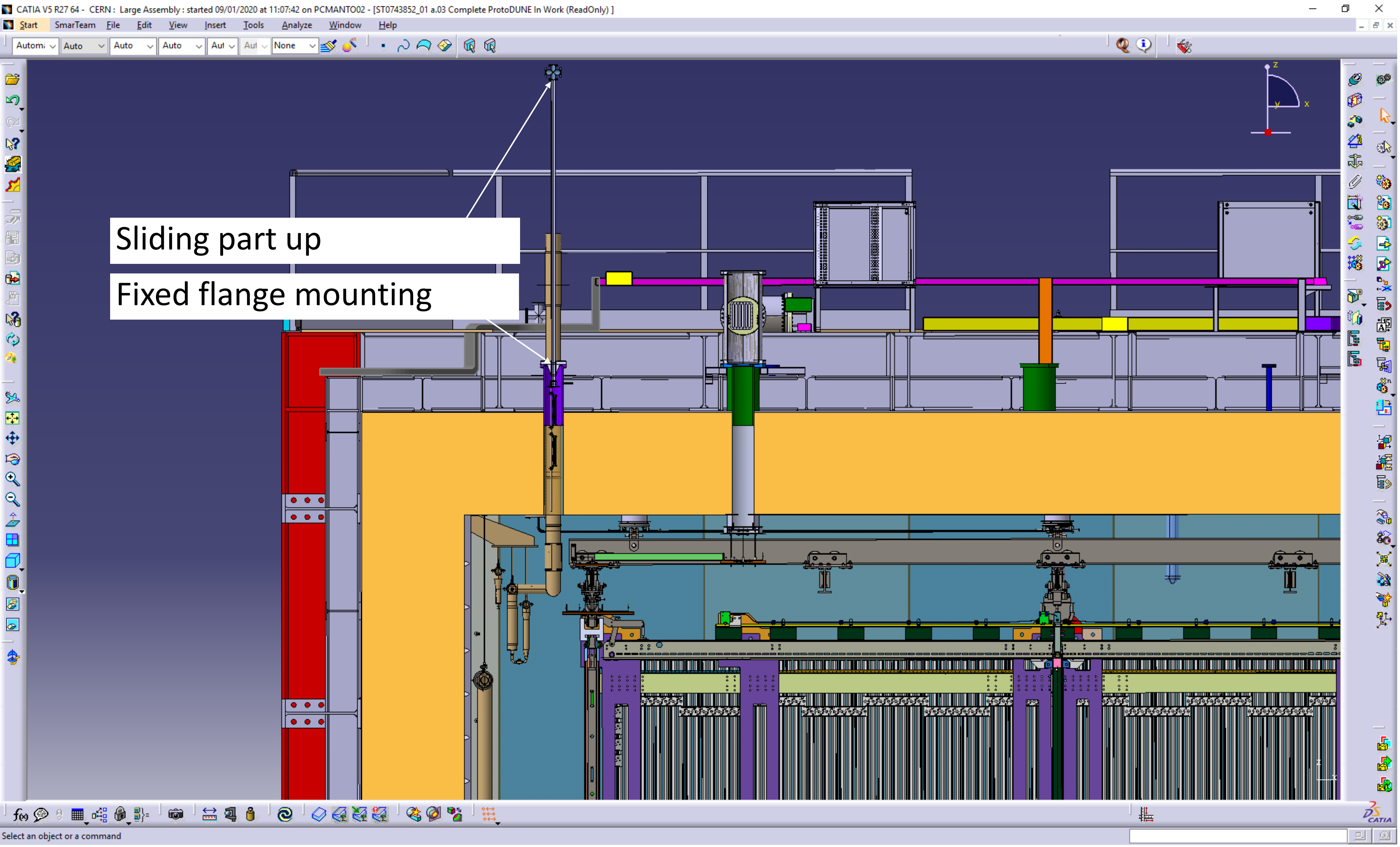
Jan 2020: Installation of X-ARAPUCA detectors into the protoDUNE-SP cryostat

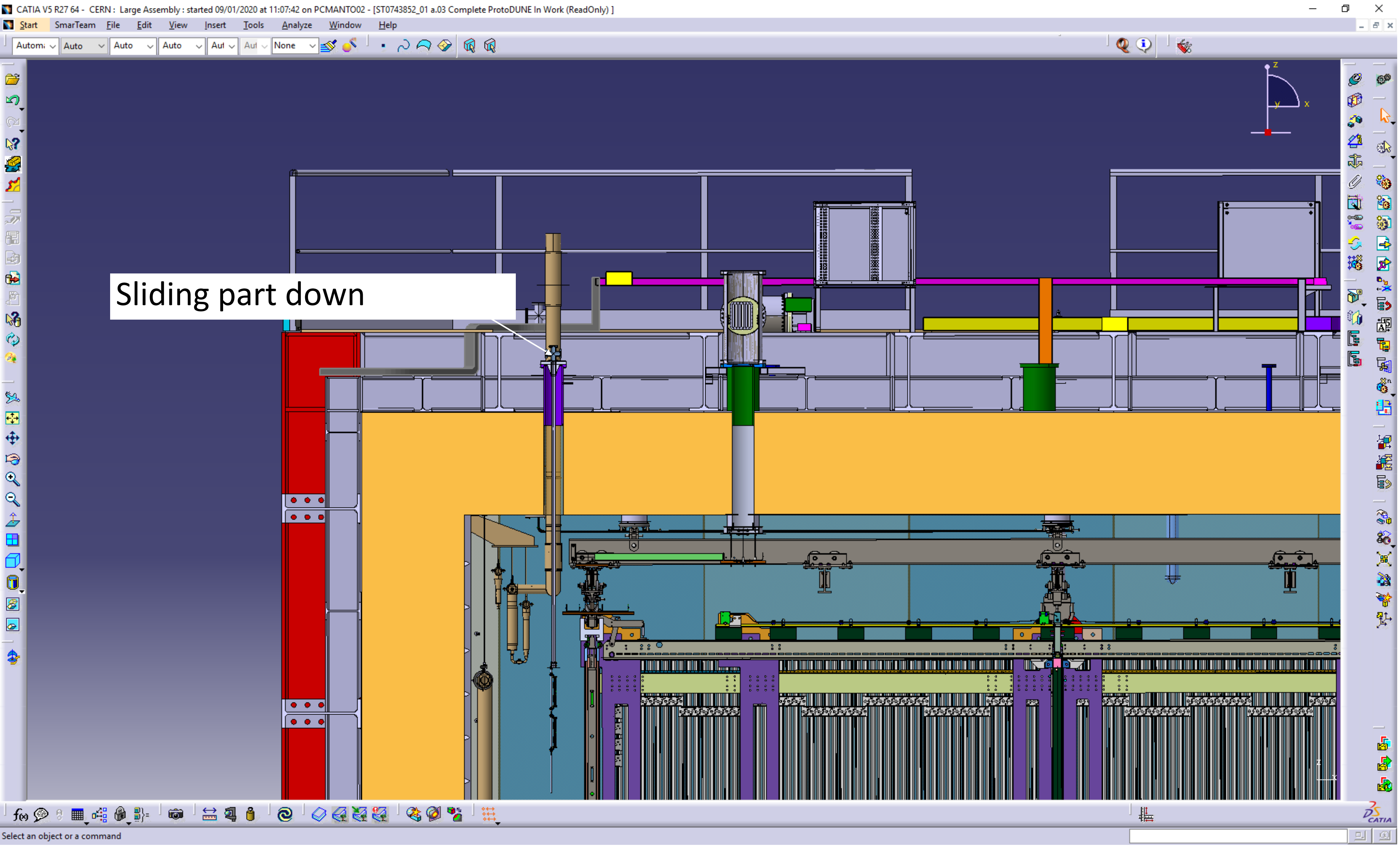
Feb 2020 - present: continued Data taking Xe doping test

Results from Data analysis in next talk (Serhan)



CATIA V5 R27 64 - CERN : Large Assembly : started 09/01/2020 at 11:07:42 on PCMANTO02 - [ST0743852_01 a.03 Complete ProtoDUNE In Work (ReadOnly)]
Start
SmarTeam
File
Edit
View
Insert
Tools
Analyze
Window
Help
Existing top flange removed
Select an object or a command


CATIA V5 R27 64 - CERN : Large Assembly : started 09/01/2020 at 11:07:42 on PCMANTO02 - [ST0743852_01 a.03 Complete ProtoDUNE In Work (ReadOnly)]
Start SmarTeam File Edit View Insert Tools Analyze Window Help
Sliding part up
Fixed flange mounting
Select an object or a command


CATIA V5 R27 64 - CERN : Large Assembly : started 09/01/2020 at 11:07:42 on PCMANTO02 - [ST0743852_01 a.03 Complete ProtoDUNE In Work (ReadOnly)]
Start SmarTeam File Edit View Insert Tools Analyze Window Help
Sliding part down
Select an object or a command

SUMMARY

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- ARAPUCA - a new Light Collection Technology Concept - light trapping by dichroic filter coupled w/ two wls stages - proposed for DUNE in Summer 2016 (PD System Review)

- First ARAPUCA prototype test in Fall 2016 at LNLS (Brazil) - with α source and c.r.muons ⇒ **Efficiency Measurement**

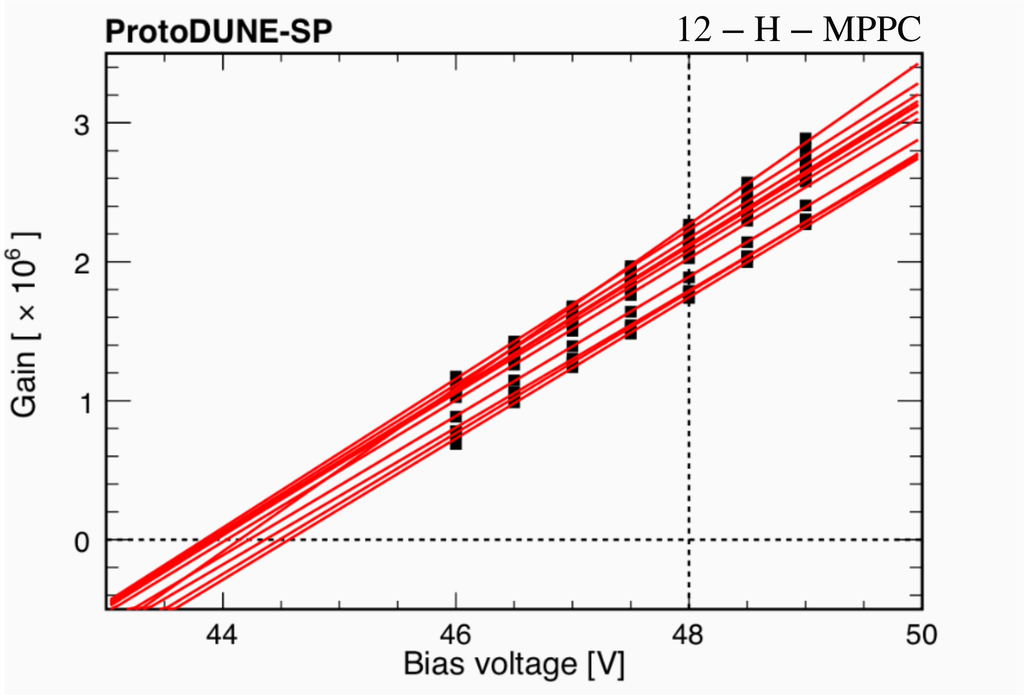
- Detector design developed for ARAPUCA integration in APA/DUNE and test in Fall 2017 at FNAL (TallBo test facility) with c.r.muons ⇒ First **Efficiency Measurement**

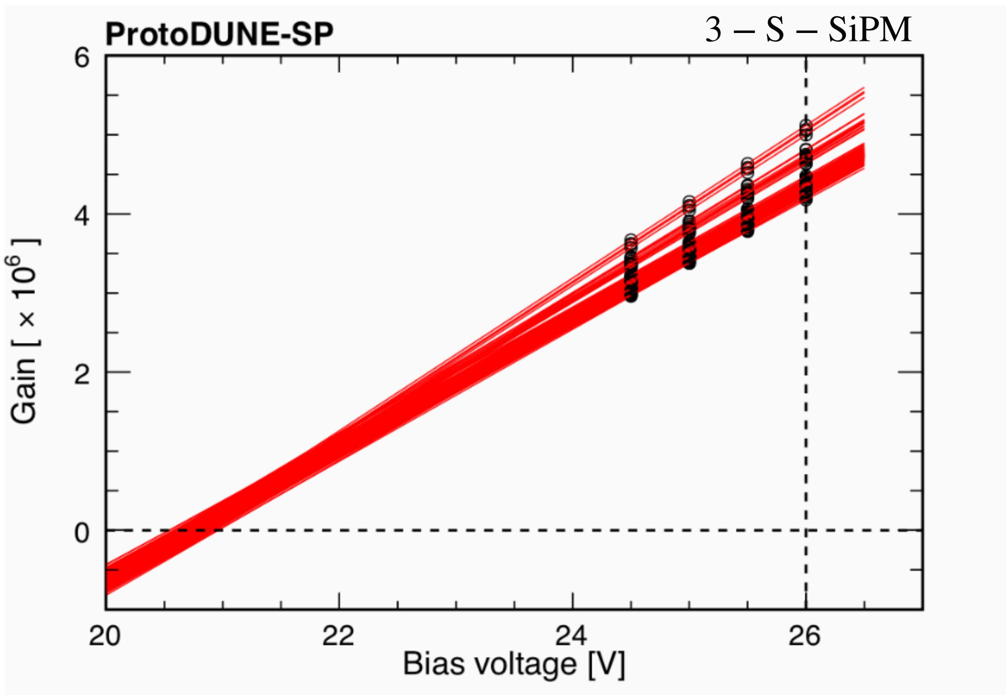
- ARAPUCA bars in protoDUNE: test with charged particle beams (*e*, π, p) Sept-Nov 2018) + Long duration test w/ c.r.muons 2019-2020.
  - Complete characterization: calibration, stability, Efficiency (8 separate measurements)
  - First **Calorimetric Energy Measurement** with scintillation light
  - DUNE requirements/specifications met

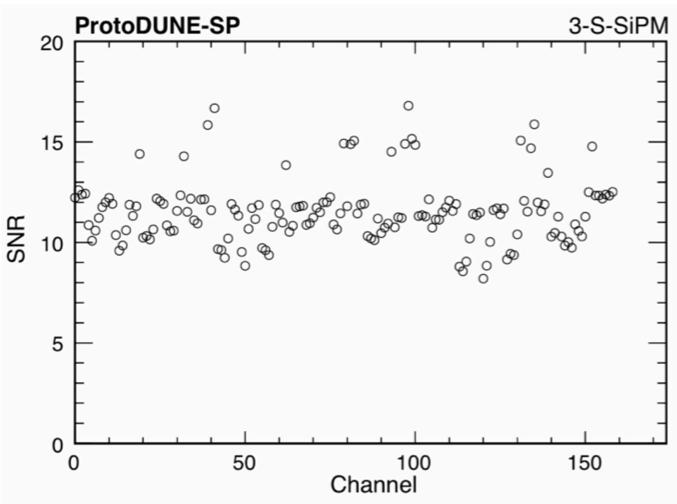
- X-ARAPUCA (Technology development): enhanced efficiency (Test in Campinas) - Installation&Operation in protopDUNE-SP for Xe doping test

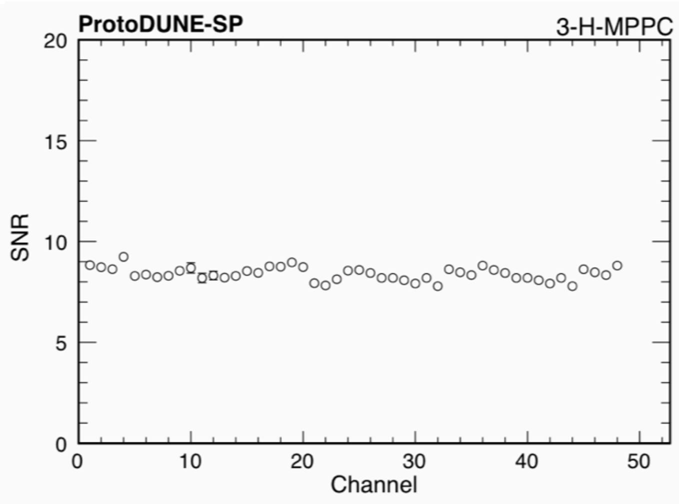
Back-Up Slides

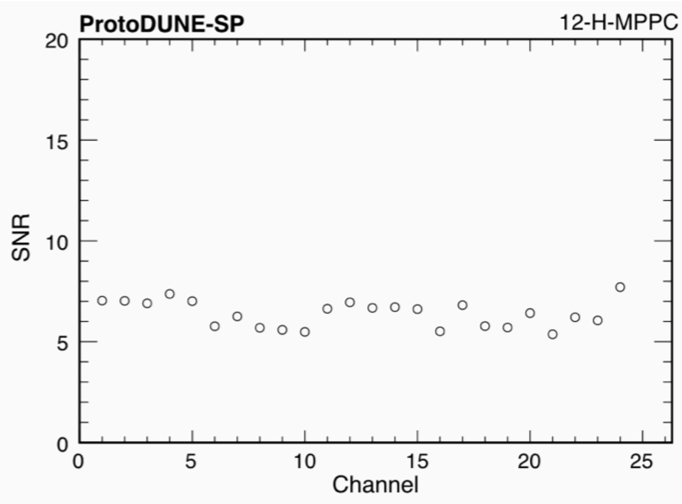
and slides from PDS 30% Review (Nov.2018)


ProtoDUNE-SP
12 – H – MPPC
Gain [× 10^6]
Bias voltage [V]
3
2
1
0
44
46
48
50


ProtoDUNE-SP
3 – S – SiPM
Gain [× 10^6]
Bias voltage [V]
6
4
2
0
20
22
24
26


ProtoDUNE-SP
3-S-SiPM
SNR
Channel
20
15
10
5
0
0
50
100
150


ProtoDUNE-SP
3-H-MPPC
SNR
Channel
20
15
10
5
0
0
10
20
30
40
50


ProtoDUNE-SP
12-H-MPPC
SNR
Channel
20
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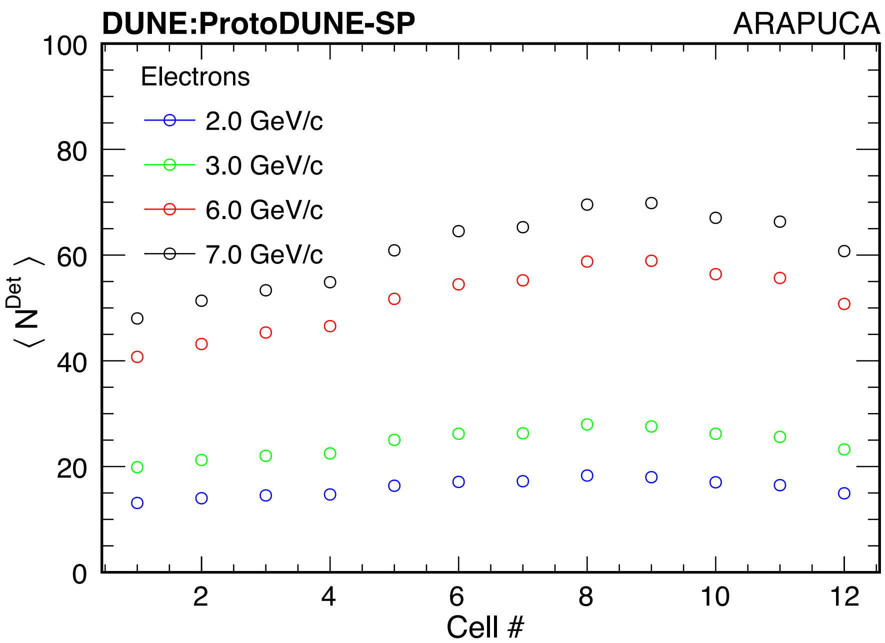
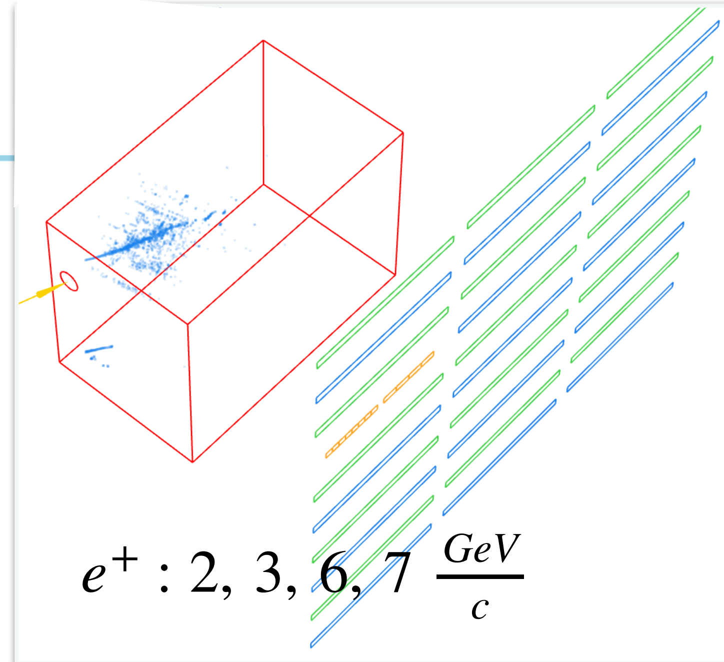
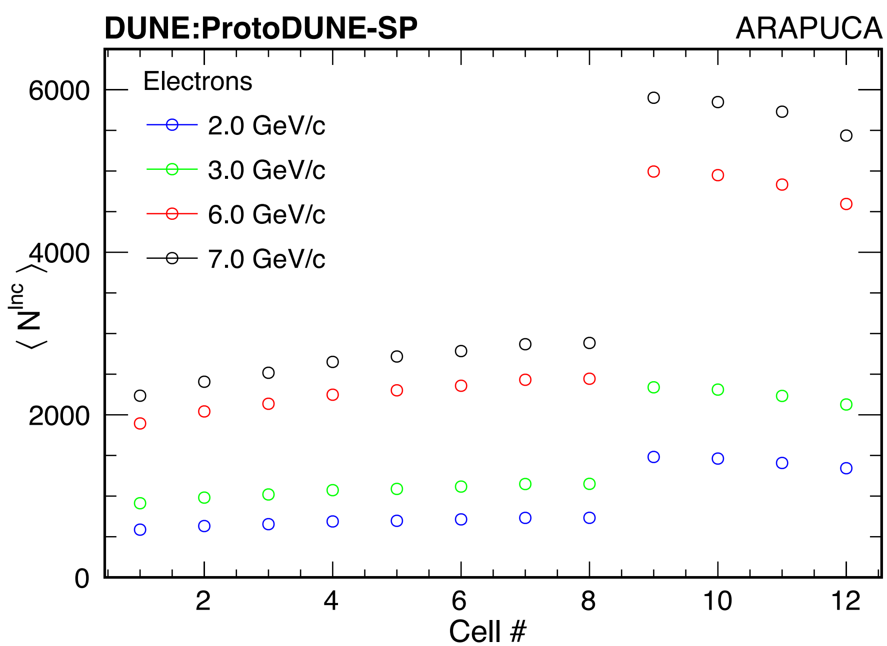


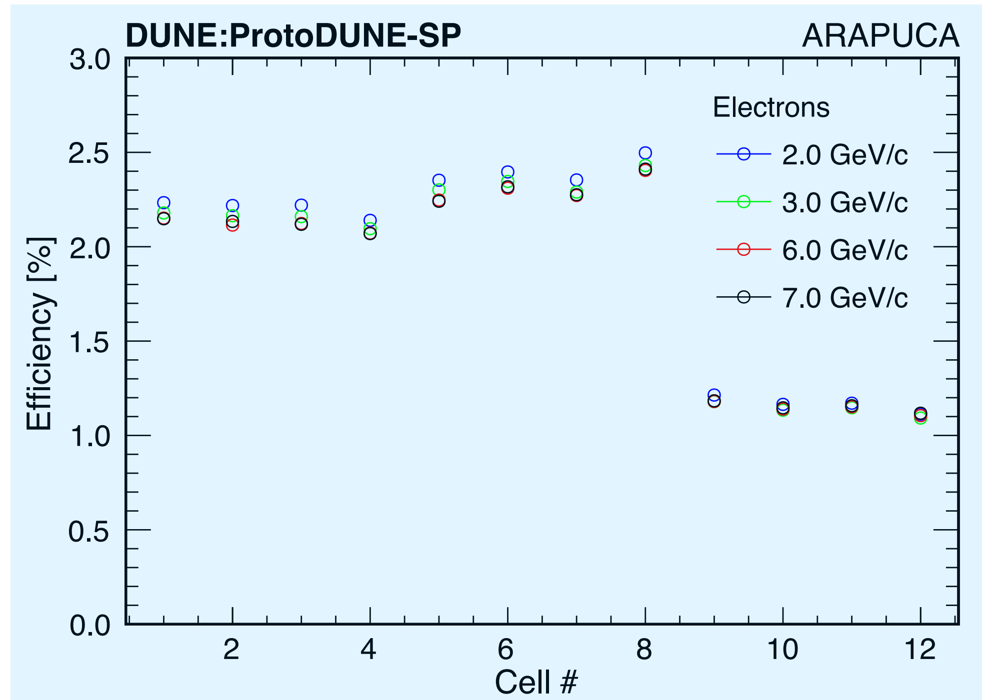
ARAPUCA

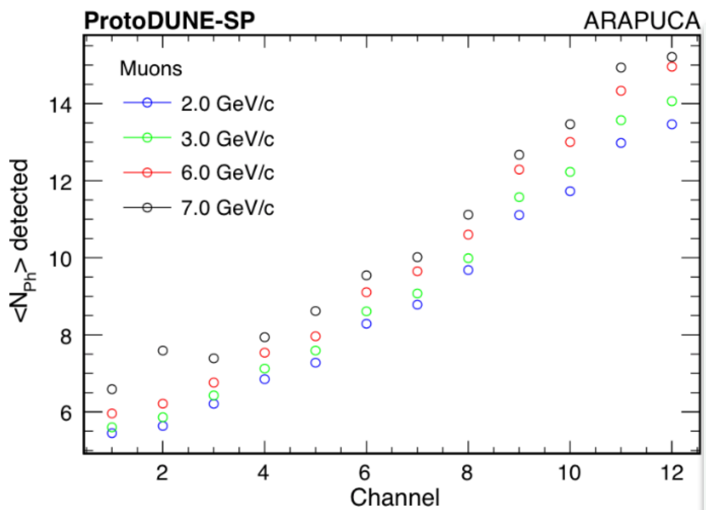
EFFICIENCY

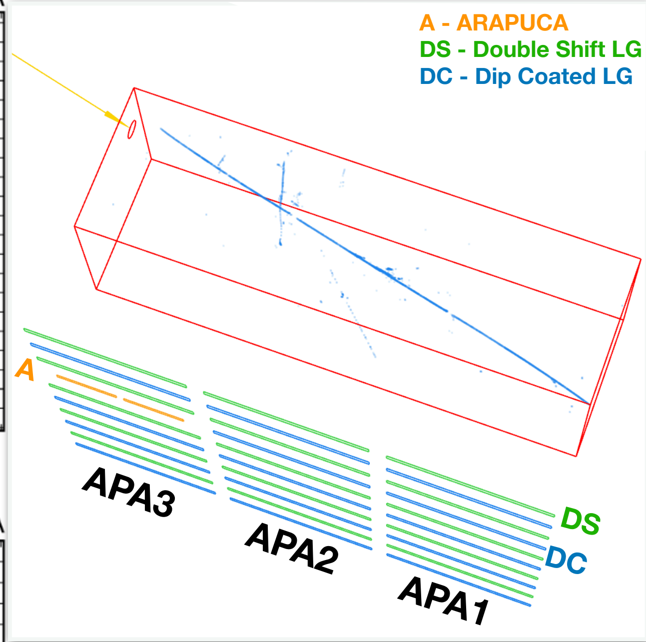
$$\epsilon_j = \frac{\langle N_j^{\text{Det}} \rangle}{\langle N_j^{\text{Inc}} \rangle}$$

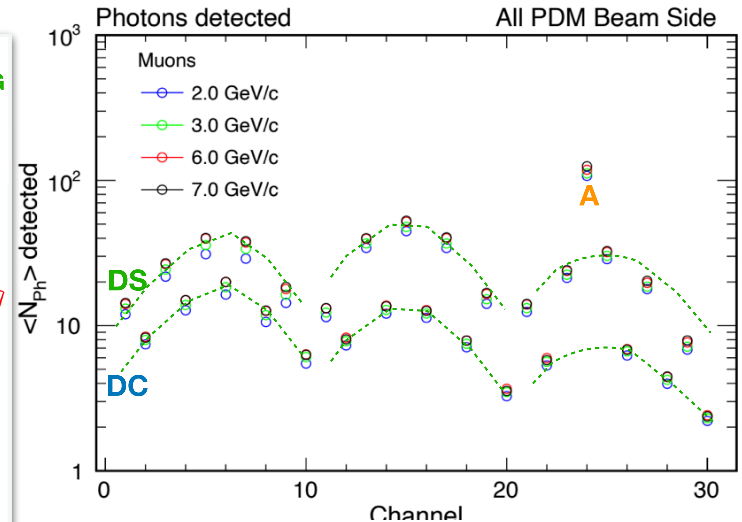


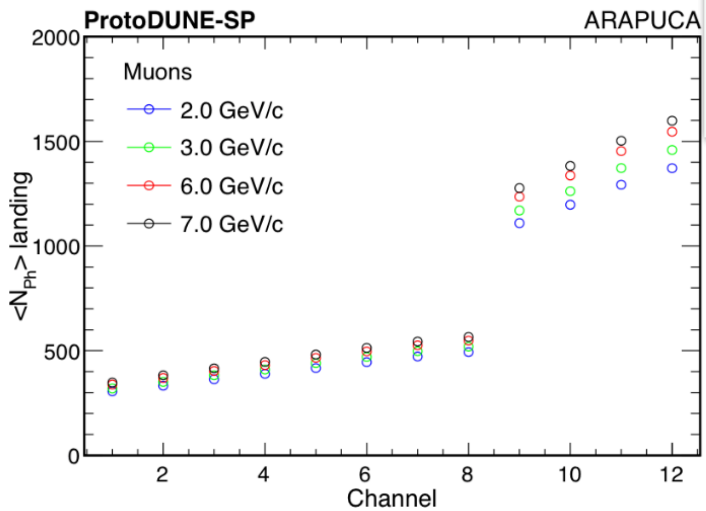


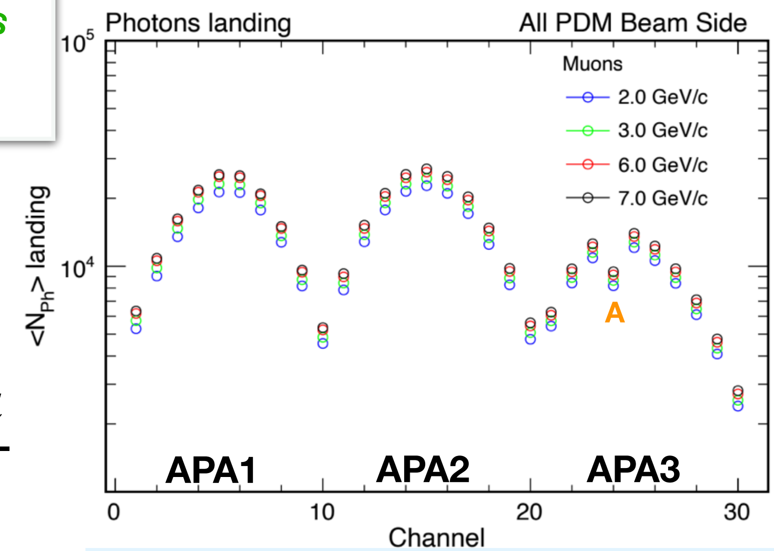










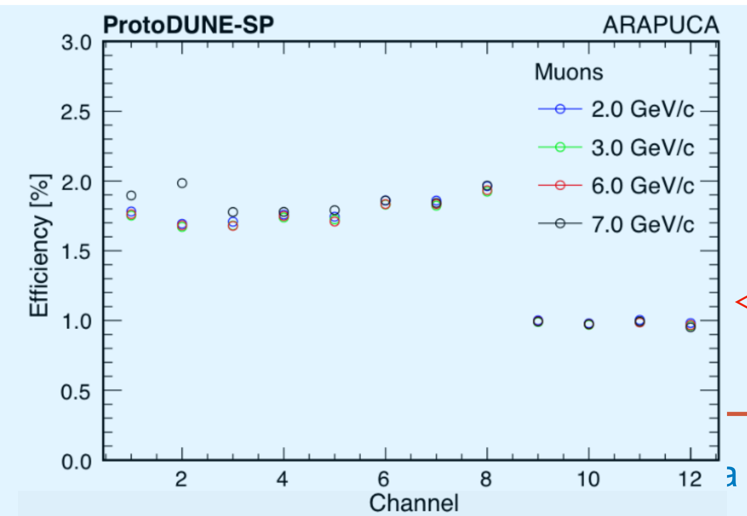


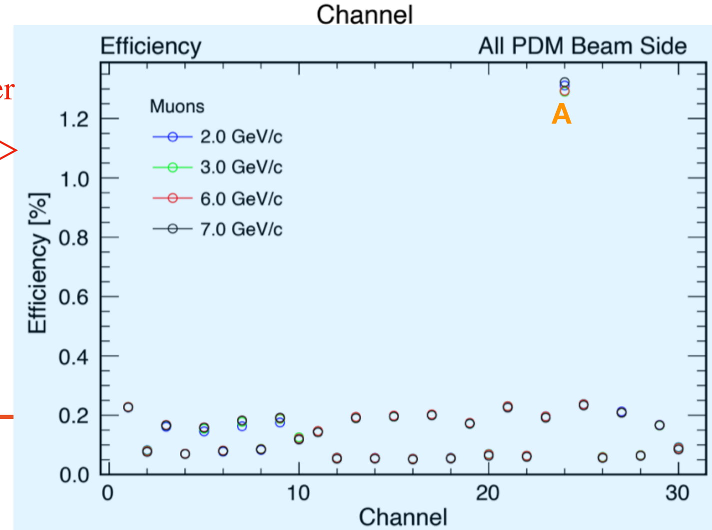
EFFICIENCY

$$\epsilon_j = \frac{\langle N_j^D \rangle}{\langle N_j^L \rangle} \qquad \frac{Data}{MC}$$

$j = 1,...,30$ – PD Module Number

$j = 1,...,12$ – ARAPUCA Cell Number





EFFICIENCY

Detector Type	# of elements in PDS	Efficiency
ARAPUCA cell	8	$\tilde{\epsilon}_A = (2.00 \pm 0.005_{\text{stat}} \pm 0.25_{\text{syst}})$ %
ARAPUCA cell (double area)	4	$\tilde{\epsilon}_{A2} = (1.06 \pm 0.005_{\text{stat}} \pm 0.09_{\text{syst}})$ %
Double-shift module	15	$\tilde{\epsilon}_{DS} = (0.21 \pm 0.000_{\text{stat}} \pm 0.03_{\text{syst}})$ %
Dip-coated module	14	$\tilde{\epsilon}_{DC} = (0.08 \pm 0.000_{\text{stat}} \pm 0.02_{\text{syst}})$ %

Systematic Error:

- Efficiency (for each module/cell) evaluated from 8 independent measurements. Systematic error taken as dispersion around the mean of the 8 measurements.

- Source of uncertainty is from MonteCarlo *(uncertainty on assumptions/parameters/methods)*:
  - Photon Emission - Ph.Yield rel. uncertainty: 8.5%
  - Photon Propagation through LAr Volume - Acceptance rel. uncertainty: 5%
  - Photon Transmission (through wire planes/ground mesh) - Transmission rel. uncertainty: 7%
  - *Recombination Light dependence on dE/dx non included in MC simulation*

X-ARAPUCA concept: *enhance light trapping by light guiding*

- There are ***two main trapping mechanisms*** through which a photon can be detected by the X-ARAPUCA:

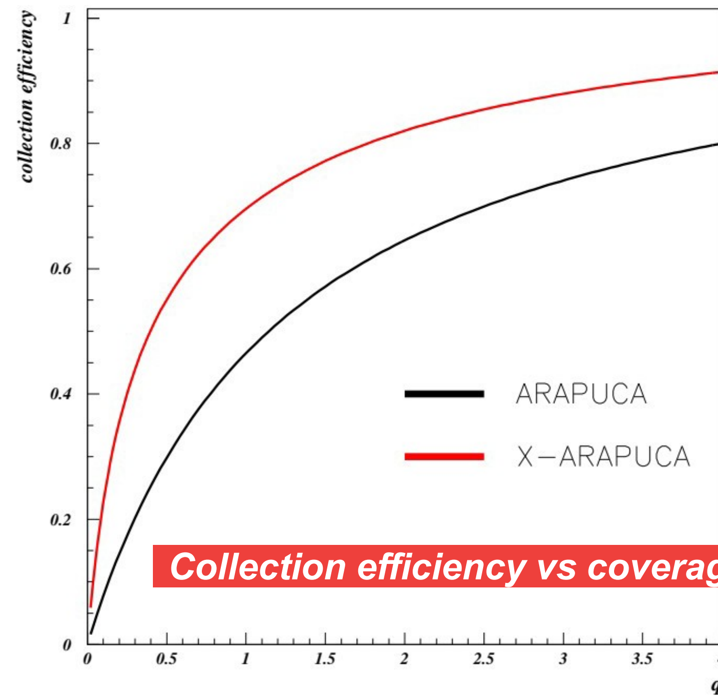
  - ***Standard ARAPUCA mechanism***. The photon, after entering the X-ARAPUCA box, is converted by the WLS of the inner plate, but is not captured by total internal reflection. In this case the photon bounces a few times on the inner surfaces of the box until when it is or detected or absorbed;

  - ***Total internal reflection***. The photon, converted by the filter and the slab, *gets trapped by total internal reflection*. It will be guided towards one end of the plate where it will be eventually detected. This represents an improvement with respect to a conventional ARAPUCA, which contributes to *reduce the effective number of reflections on the internal surfaces*. The sides of the plate where there are not active photo-sensors will be coated with a **reflective layer** which will allow to keep the photon trapped by total internal reflection.

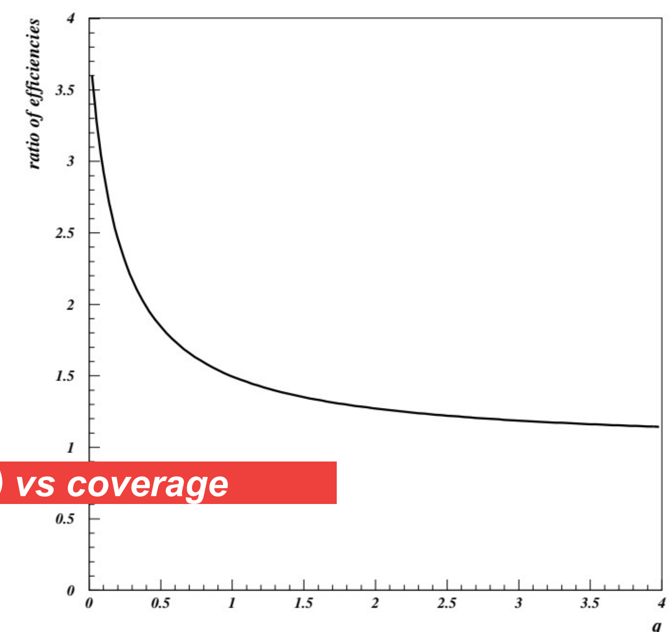
X-ARAPUCA vs. ARAPUCA

- **X-ARAPUCA is more efficient in trapping photons**:
  - ✓ Analytical calculations and MC simulations point to an enhancement *between 40% and 70%* wrt ARAPUCA

- **Simpler design:**
  - ✓ **No need of evaporating** the internal side of the filter or internal surfaces
  - ✓ Great advantage especially for double sided X-ARAPUCAs
  - ✓ Faster production



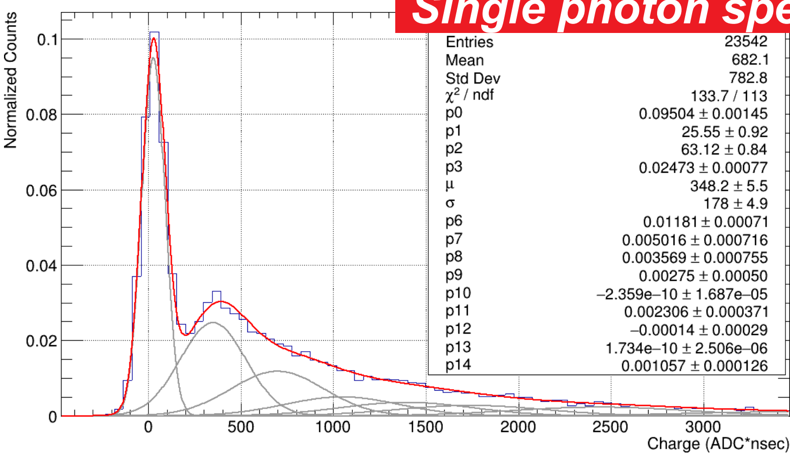
Collection efficiency vs coverage



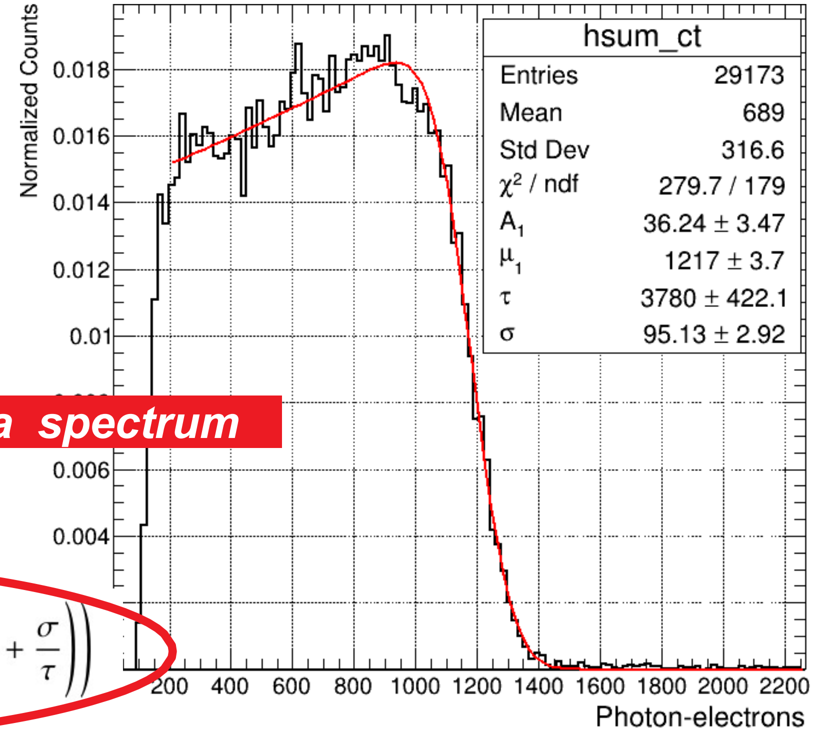
Ratio of efficiencies (XA/A) vs coverage

X-ARAPUCA test result

Single photon spectrum



Alpha spectrum



Fit function

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

- 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