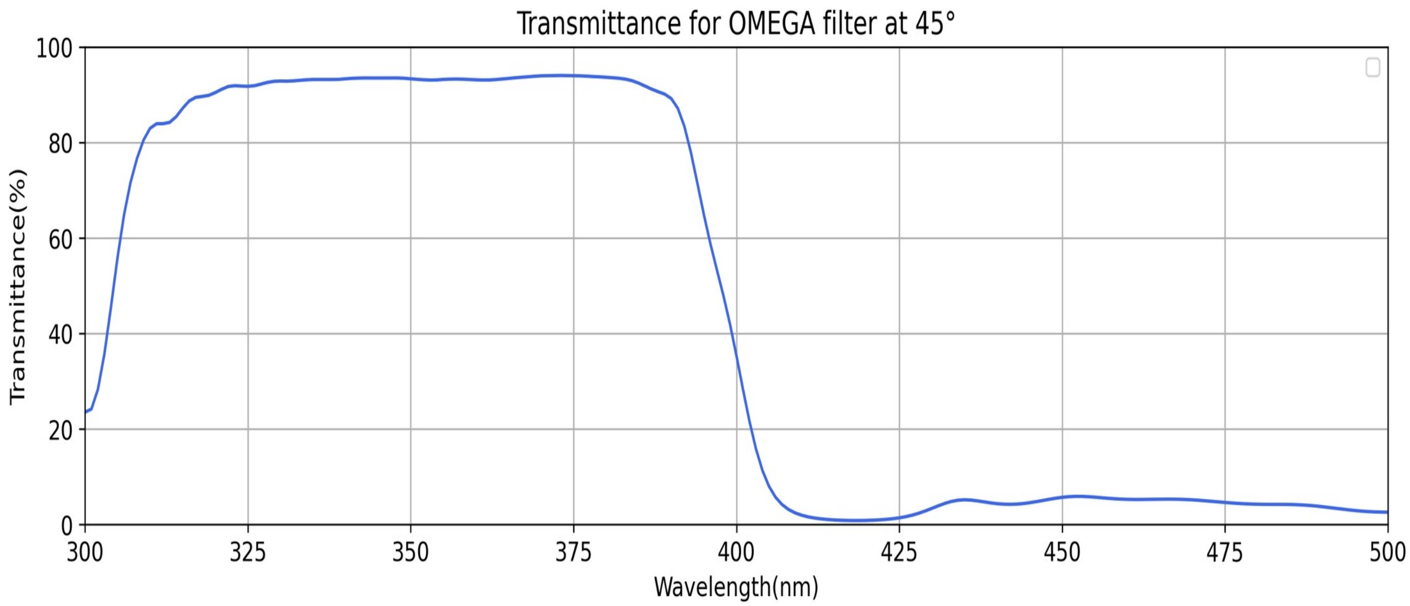
Question 2

(i) Questions on filters. What specifically will you change from ProtoDUNE I? How will these changes be validated?

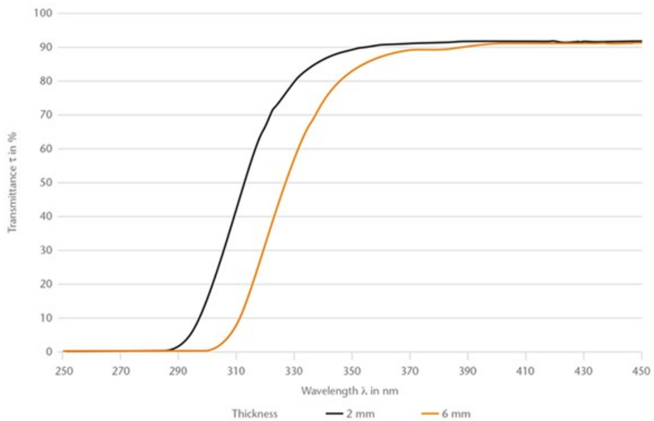
The filters used in protoDUNE 1 where produced by OMEGA and had the following characteristics:

- Substrate: fused silica, 2 mm thick
- Cut-off wavelength: 400 nm
- Angle of incidence: 45°

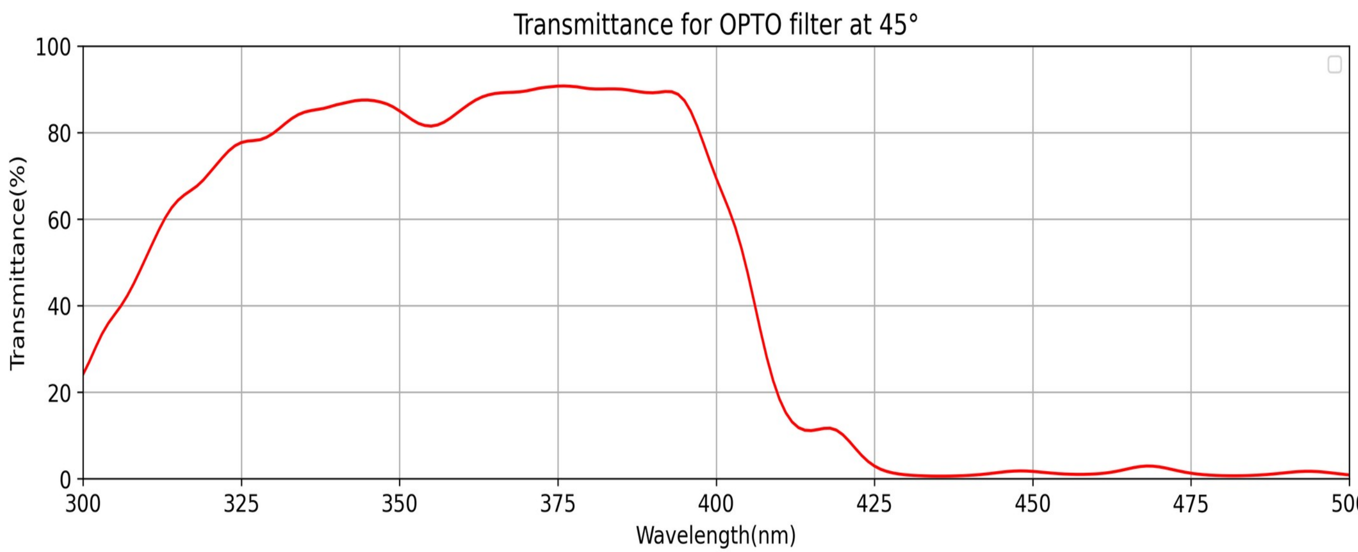


Question 2

- After protoDUNE 1 the PD Consortium moved to a Brazilian filter vendor, OPTO Eletronica. The substrate was changed to optical glass SCHOTT B270 with 1 mm thickness, which is much cheaper and much easier to cut.



- The design of the filter after protoDUNE 1 did not change: the cut-off was kept at 400 nm and the angle of incidence at 45º.



Question 2

- OPTO filters have been used in all the measurements of the X-ARAPUCA detection efficiency at UNICAMP, Milano Bicocca and Madrid. They were tested in small prototypes with one or two windows and with full supercells. The results were shownduring the review in the presentation of E. Segreto.

Question 2

- In the last two years, in the framework of the FD2 R&D activities, the Consortium started an industrial partnership with two new vendors: ZAOT (Italy) and Photon Export (Spain)
- Both companies already demonstrated the ability of producing filters with performances similar to the OPTO ones
- An intense simulation work is being performed in Spain, Italy and Brazil to optimize the detection efficiency of the X-ARAPUCA through the fine tuning of the optical parameters of the filters.
- Simulations indicate that there is room for an improvement of the detection efficiency at the level of 10%-15% by slightly modifying some of the parameters of the filters (AOI, number of layers of the dichroic multi-layer).

Question 2

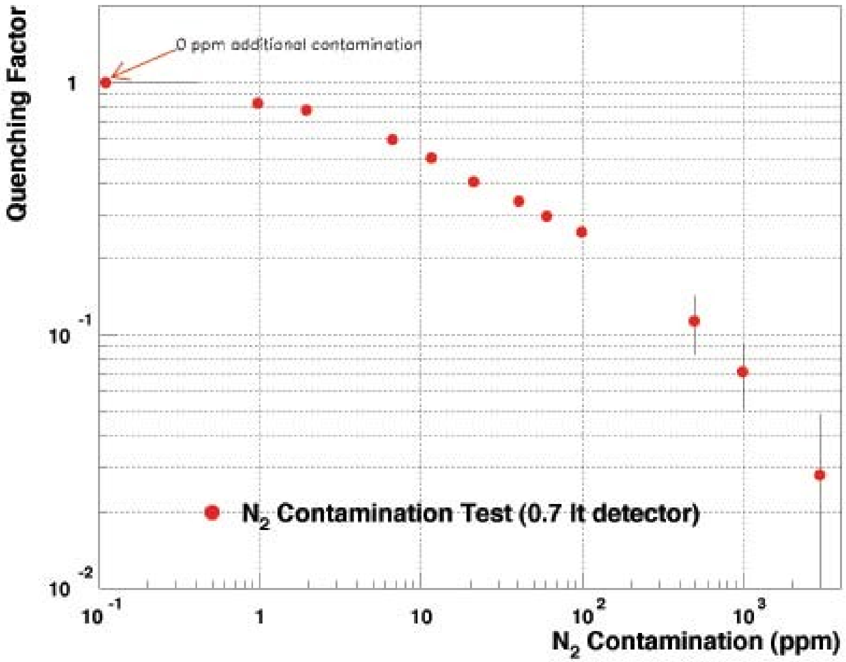
- Optimized filters will be produced by ZAOT and Photon Export and compared with baseline design in dedicated tests in LAr with X-ARAPUCAs. In case of a positive result, OPTO will be asked to produce filter with the optimized design, which will be validated with multiple tests in LAr with X-ARAPUCAs supercells.

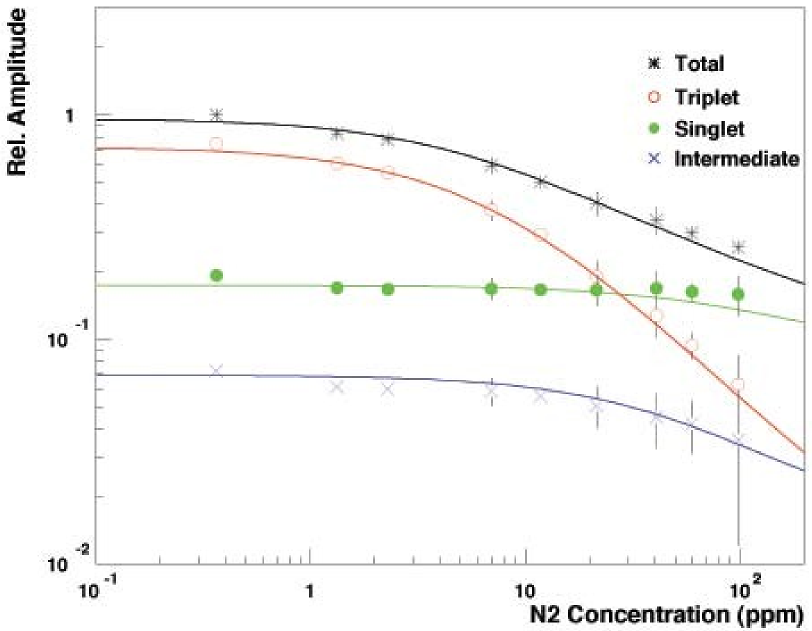
Question 4

(i) Can you show how much light is lost from quenching, attenuation, filter, etc to show that they are consistent with simulations.

N_2 contamination has two effects on scintillation light:

- **Quenching** of the Ar_2^* states, which are the precursors of the scintillation photons;
- **Absorption** of the scintillation photons during their propagation

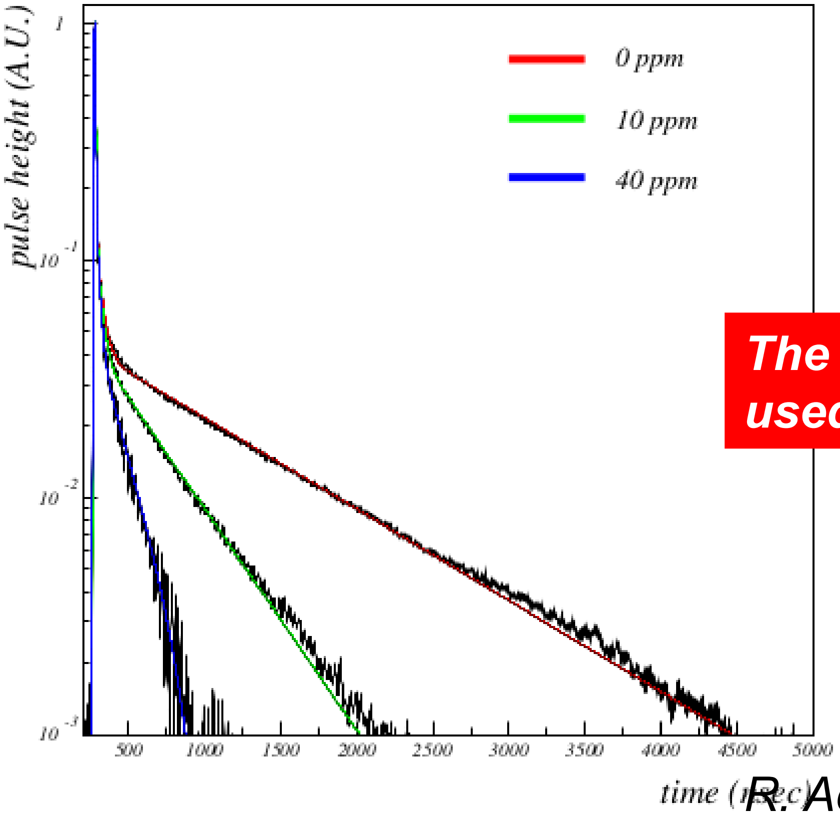




*R. Acciarri et al. 2010 JINST **5** P06003*

Question 4

- The decay time of the triplet component of scintillation light depends on the Nitrogen contamination
- The absorption of scintillation photons is characterized by an absorption factor of (1.51 ±0.15)x10^{-4} cm^{-1} ppm^{-1}. Singlet and triplet components are affected in the same way.



The value of the triplet lifetime is used to infer the N_2 concentration

R. Acciarri et al. 2010 JINST ***5*** *P06003*

Question 4

Mitigation:

1) Doping LAr with LXe. LXe compete with N_2 in reacting with Ar_2^* and in forming Xe_2^* dimers which decay radiatively with an extremely short characteristic time (~20 ns). At the end of protoDUNE Run 1, the LAr was accidentally contaminated with air. The oxygen content was removed by the filters and the LAr was left with about 7 ppm of N_2. It was demonstrated that doping LAr with about 10 ppm of LXe allowed to recover all the scintillation light.
2) We anticipate to the committee that the UNICAMP group found a zeolite which is able to filter out N_2 from LAr. This zeolite was tested multiple times in a 90 l cryostat at UNICAMP and it was proven that it is able to remove a 50 ppm contamination of N_2 in about 1 hour of recirculation at a speed of recirculation of 4 l/min. The tests have been conducted in collaboration with Fermilab (D. Montanari et al.). This new medium will be tested at Fermilab, probably on MicroboooNe and then in protoDUNE.

Question 4

(i) Can you show how much light is lost from quenching, attenuation, filter, etc to show that they are consistent with simulations.

In the simulation it is possible to

- include absorption length in the fast simulation
- change the total scintillation LY but this will be fixed and independent of dE/dx, E field, and particle type
- Adjust the ratio fast/slow

A full treatment that include all these effects is still missing and should be pursued.

Question 4

(i) Can you show how much light is lost from quenching, attenuation, filter, etc to show that they are consistent with simulations.

The attenuation due to N2 contamination is set as default in the simulation as 20m (~3ppm).

The Light Yield maps are obtained considering a photon yield of 24,000 ph/MeV for minimum ionizing particles at a field of 500 V/cm, that is for clean LAr. ***The LY maps are to be intended as a lower limit for clean LAr***

Question 4

(i) Can you show how much light is lost from quenching, attenuation, filter, etc to show that they are consistent with simulations.

All Arapuca related “losses” (shifter/filters/reflection coeff...) are folded into the efficiency parameter in the simulation. The light that is emitted from the arapuca’s surface back to LAr (~50% of impinging light) is not considered in the simulation since to be detected it would need to backscatter on the APA wires on the way out or pass the wires, scatter again, and pass the wires on the way back to the arapuca’s surface. We estimate this probability to be negligible.

Question 4

(i) Can you show how much light is lost from quenching, attenuation, filter, etc to show that they are consistent with simulations.

The scintillation photon yield of LAr depends on the ionizing particle type, on the linear energy transfer (LET), on the E field, and on quenching.

We have recently included in the LArSoft simulation the LY dependence on dE/dx and E field in the 2 MeV/cm < dE/dx < 40 MeV/cm and 0.25 kV/cm < E < 0.5 kV/cm range*

*Ref: F. Marinho et al 2022 JINST 17 C07009

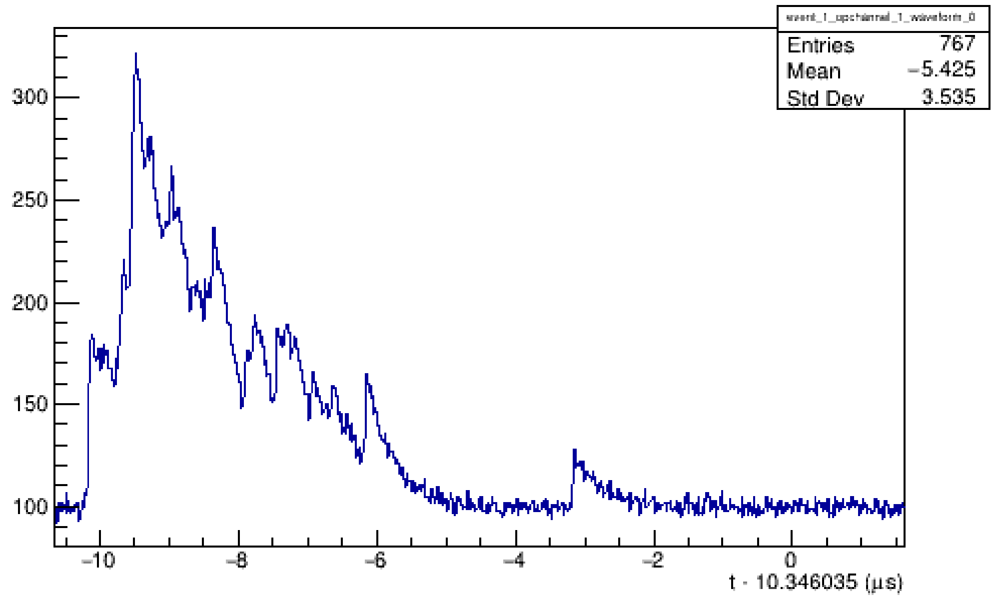
Question 4

(ii) Show how electronics, firmware, etc are folded into the simulation. How were these validated?

Simulation of sensors' QE and electronics response

Output: waveforms per channel

LineNoiseRMS: 3 ADC
CrossTalk: 20%
DarkNoiseRate: 10 Hz
QuantumEfficiency: 3%



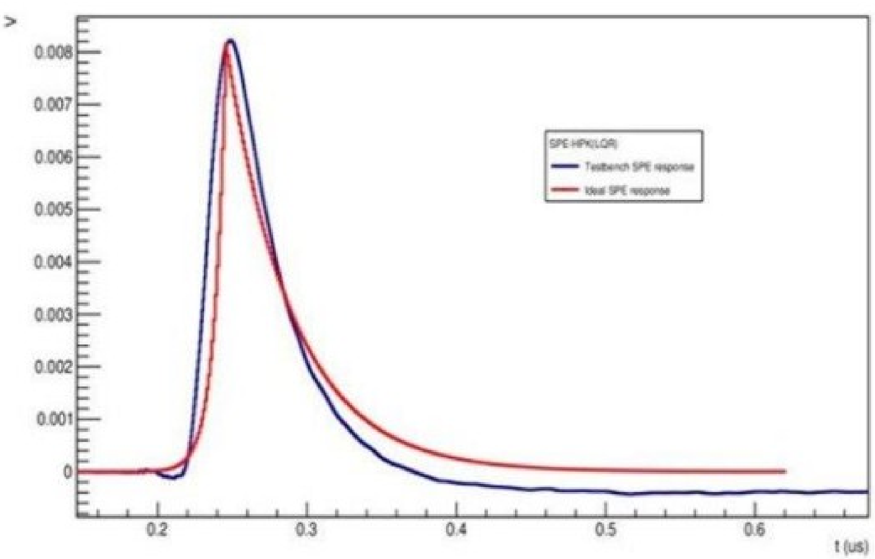
Question 4

(ii) Show how electronics, firmware, etc are folded into the simulation. How were these validated?

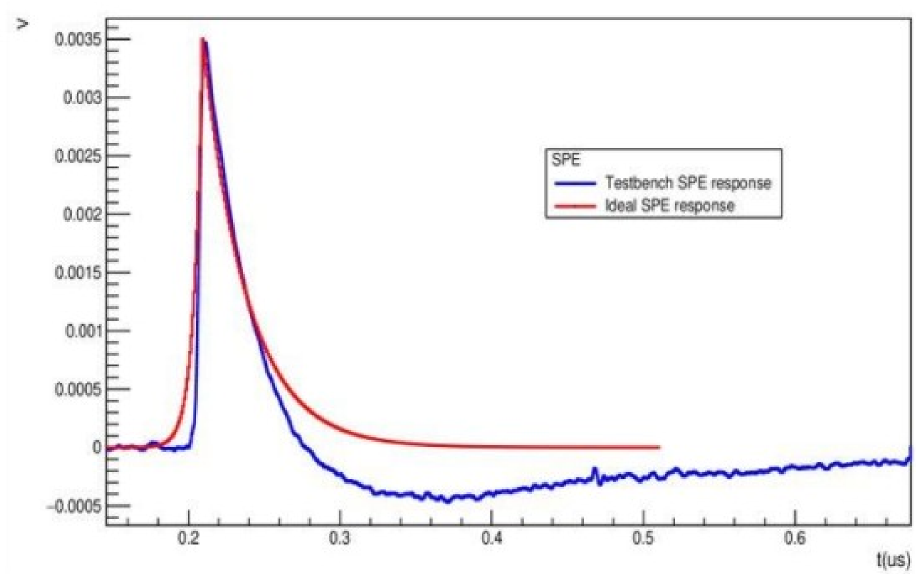
Simulation of sensors' QE and electronics response

Transitioning from an ideal single PE response to a test bench one

Average SPE template (HPK)



Average SPE template (FBK)



Question 4

(ii) Show how electronics, firmware, etc are folded into the simulation. How were these validated?

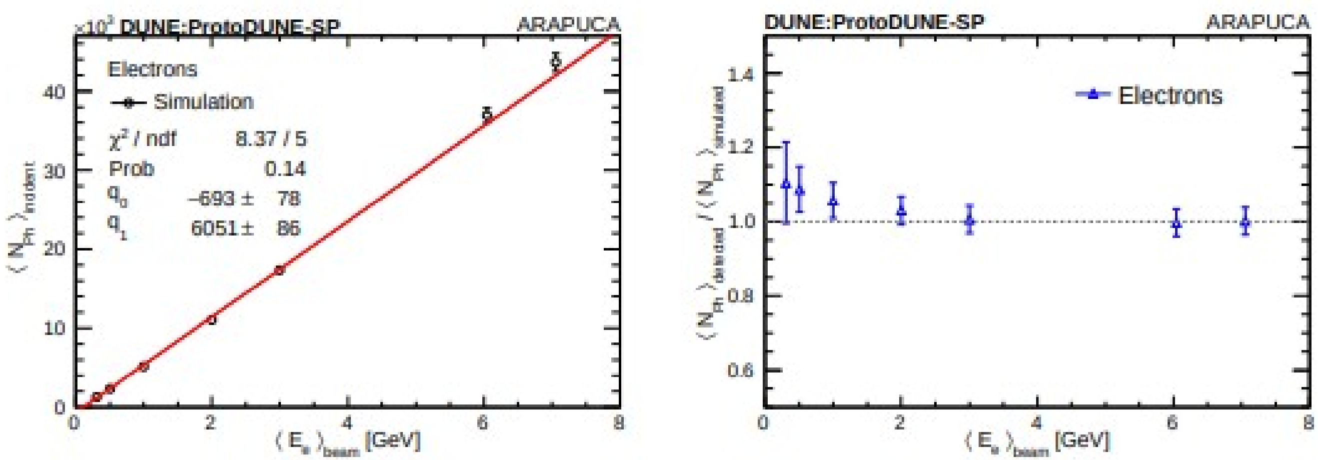
The simulation will be validated through the comparison of simulated waveforms with waveforms obtained with X-ARAPUCA supercells read-out with the complete electronic chain and exposed to LED and LAr scintillation light from radioactive sources.

Question 4

Detector parameter	*ProtoDUNE-SP performance*	*DUNE specification*
PDS light yield	1.9 photons/MeV (@ 3.3 m distance)	> 0.5 photons/MeV (@ cathode distance — 3.6 m)

(iii) Was there a light yield measurement made in ProtoDUNE I? Is so, please give the results.

An indirect measurement was obtained using beam electron data: LY = 102.1 photons/GeV. The quoted LY is relative to a diffuse light source (EM shower) at a distance of about 3 m from the detectors



Ref:
B. Abi et al 2020
JINST 15 P12004

Figure 71. Monte Carlo simulation of light response to EM showers: average number of incident photons at the ARAPUCA bar surface from simulation vs average electron beam energy (left) and Data/MC comparison (right) by the ratio of average number of photons detected to the corresponding number of photons from MC simulation, at the different beam energies.

Question 4

(iv) Were there nitrogen contamination measurements done in ProtoDUNE I ? And in any of the test experiments used to measure the photon detection efficiency?

Yes, the nitrogen contamination was measured in protoDUNE 1 and in all the small test stands used to measure the ARAPUCA and X-ARAPUCA detection efficiency. This is done through the correlation of the triplet lifetime with the concentration of N_2. The estimations of the efficiency values are corrected for the quenching of N_2 accordingly.