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ARAPUCA, active ganging: The benefits of a more efficient Photon Detector for DUNE

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TDR Goals

- The DUNE Photon Detector (PDS) must provide a time stamp (T0) for non-beam events
  - For proton decay candidates and atmospheric neutrinos with 90% efficiency.
  - Supernova physics. Provide a T0 with high efficiency to improve the energy resolution on supernova burst neutrino (SNB) events. An SNB event will generate low-energy (5–50 MeV) events.
- The photon system must provide the t0 timing of events relative to TPC timing with a resolution better than 1μs, providing position resolution along drift direction of a couple of mm.
- PDS in the trigger.
  - Some ionization electrons are lost due to finite electron lifetime. Knowing where the ionization happened allows for a correction of this loss, potentially greatly increasing the energy resolution (~20% →~10% in SN energy range).
- Background discrimination.
  - The efficiency of the PDS detector for low energy events critically depends on backgrounds and signal yield. Suppressing Ar39 and Rn222 background will require at least 5 PEs of threshold. To achieve high efficiency of low energy events (5-50 MeV) the DUNE PDS must exceed a light yield of 1PE/MeV which imposes a requirement of close to 1% efficiency on the detector.

- **These goals all point to a more efficient PDS.**
  - The minimum required efficiency has been determined to be 1% (2016).
- The 1% efficiency goal has been achieved and surpassed. What is next?

A better PDS brings better and new physics

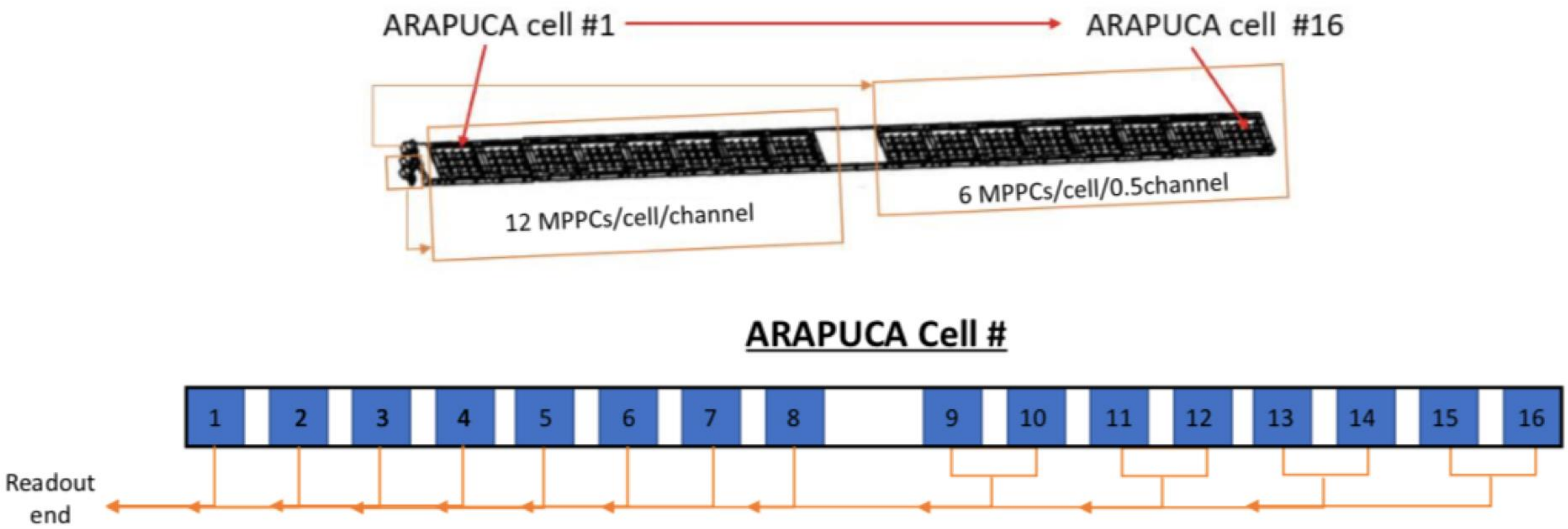
- Today a PDS with local efficiency of 20% is possible.
  - We have achieved 13% at Fermilab (LUKE LAr facility).

- An efficiency of 6% may already be good enough to look at solar neutrinos.
  - **DUNE as the Next-Generation Solar Neutrino Experiment,** Francesco Capozzi, Shirley Weishi Li, Guanying Zhu, John F. Beacom, arXiv:1808.08232, DOI:10.1103/PhysRevLett.123.131803

- PDS segmentation:
  - ARAPUCAs and active ganging allow for PDS segmentation along the bar.
  - A segmented detector:
    - Allows for PDS calorimetry and improves DUNE energy measurements.
    - Allows for a t0 prompt for every track in the event.
    - Allows for particle identification and better background rejection.

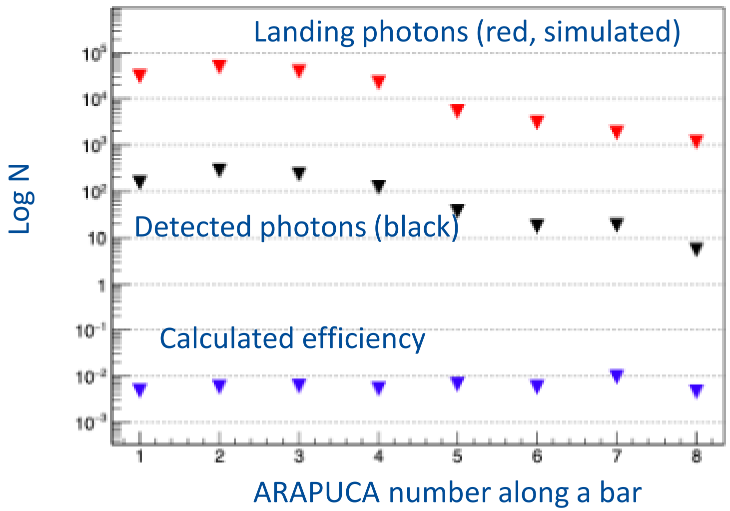
The Arapuca detector segmentation

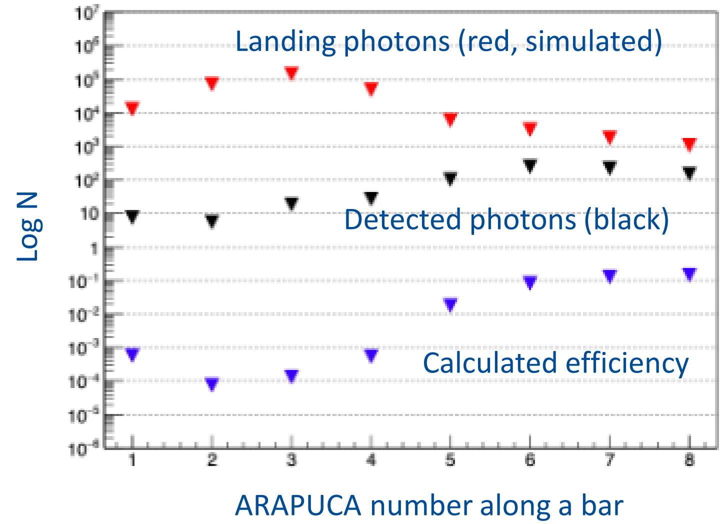
The DUNE PDS was originally thought as a unique ~2m long bar.
Arapucas are typically a smaller device, e.g. 10 to 20 cm long.
Caveat: segmentation require independent channel readout.



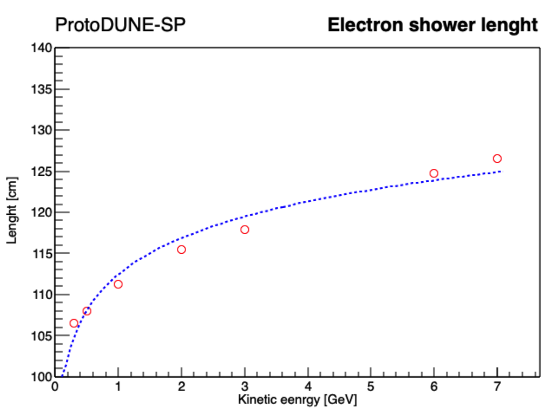
In protoDUNE the 2 Arapuca installed consist in 16 cells 8 read by a single channel and 8 read in couples

Arapuca segmentation





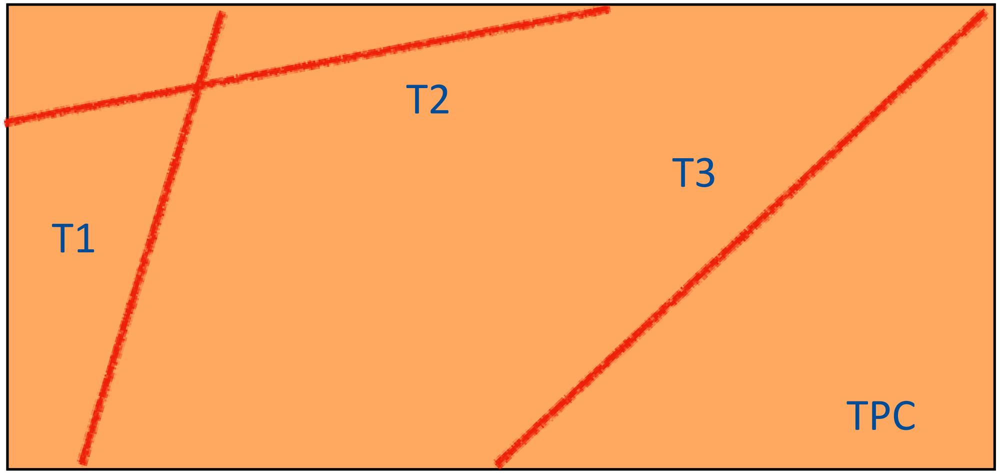
Number of photons landing on the PDS (red), detected (black) and efficiency (blue) vs ARAPUCA number along a bar.
For a good track the landing and collected photons follow the same pattern and give a constant efficiency



In TallBo 7, segmentation allowed to overcome a problem in the trigger and reject non cosmic events with high accuracy.
In protoDune has been used to determine a contamination in the dewar and to measure the length of a shower.
For DUNE it can be used in the trigger and to provide a t0 for every track.

Arapuca granularity power

A possible useful application for the Arapuca granularity could be the track identification in the TPC.



The TPC time window is $\sim 3ms$.
More tracks are recorded together.

The photodetectors have a much smaller window $\sim 13\mu s$ with resolution of $6.67ns$

Using the tracks geometry given by the TPC we can reconstruct the light pattern produced by each track. Comparing these patterns with the light observed in the PD system it is possible associate each set of waveforms (PD event) to a given track, and hence getting its timing (t0).

ARAPUCA tests at TallBo: Jan and March 2017

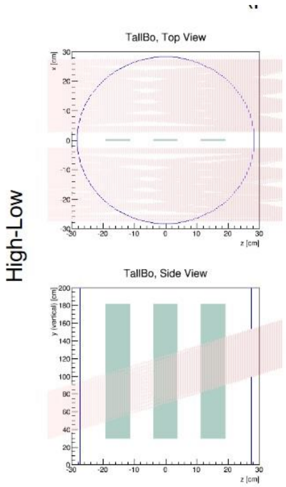
Picture of TallBo

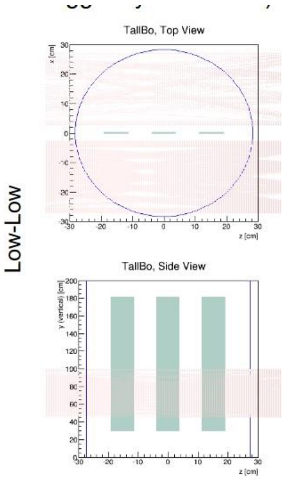
Picture of ARAPUCA rack

- 1st active ganging circuits
- Test of 4 different filters for ARAPUCAs
- Problems encountered and lessons learned: TPB does not like to stick to some filters.
- Thinner coatings adhere better. 200ug/cm2 enough for photon conversion. Assuming about 30% dissolvement in LAr. (Coimbra paper).
- Lessons learned on how to clean the filters.

TallBo 7 (Oct. 2017): ARAPUCA tested along with IU bars

- Trigger on cosmics using an hodoscope in High-Low and Low-Low configuration



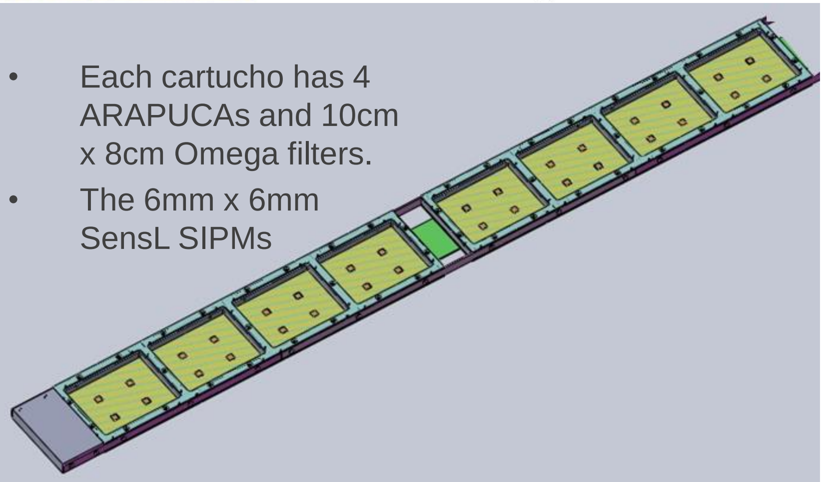


Absolute efficiency of ~0.8%
Achieved with only 4 SIPMs
Filter/sensor area ratio 56.
ARAPUCA gain: 3.7

ARAPUCA	Mean (%)
TOT	0.78 ± 0.02
1	0.74 ± 0.02
2	0.77 ± 0.02
3	0.80 ± 0.02
4	0.77 ± 0.02
5	0.75 ± 0.02
6	0.77 ± 0.02
7	0.77 ± 0.02
8	0.80 ± 0.02

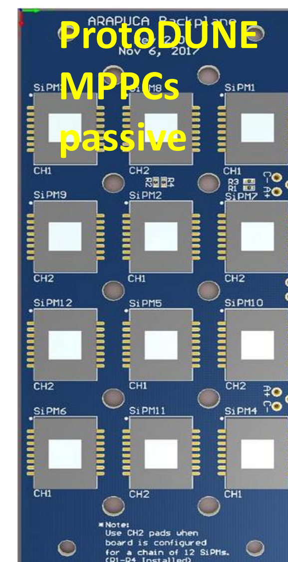
(paper to be published soon)

- Each cartucho has 4 ARAPUCAs and 10cm x 8cm Omega filters.
- The 6mm x 6mm SensL SIPMs



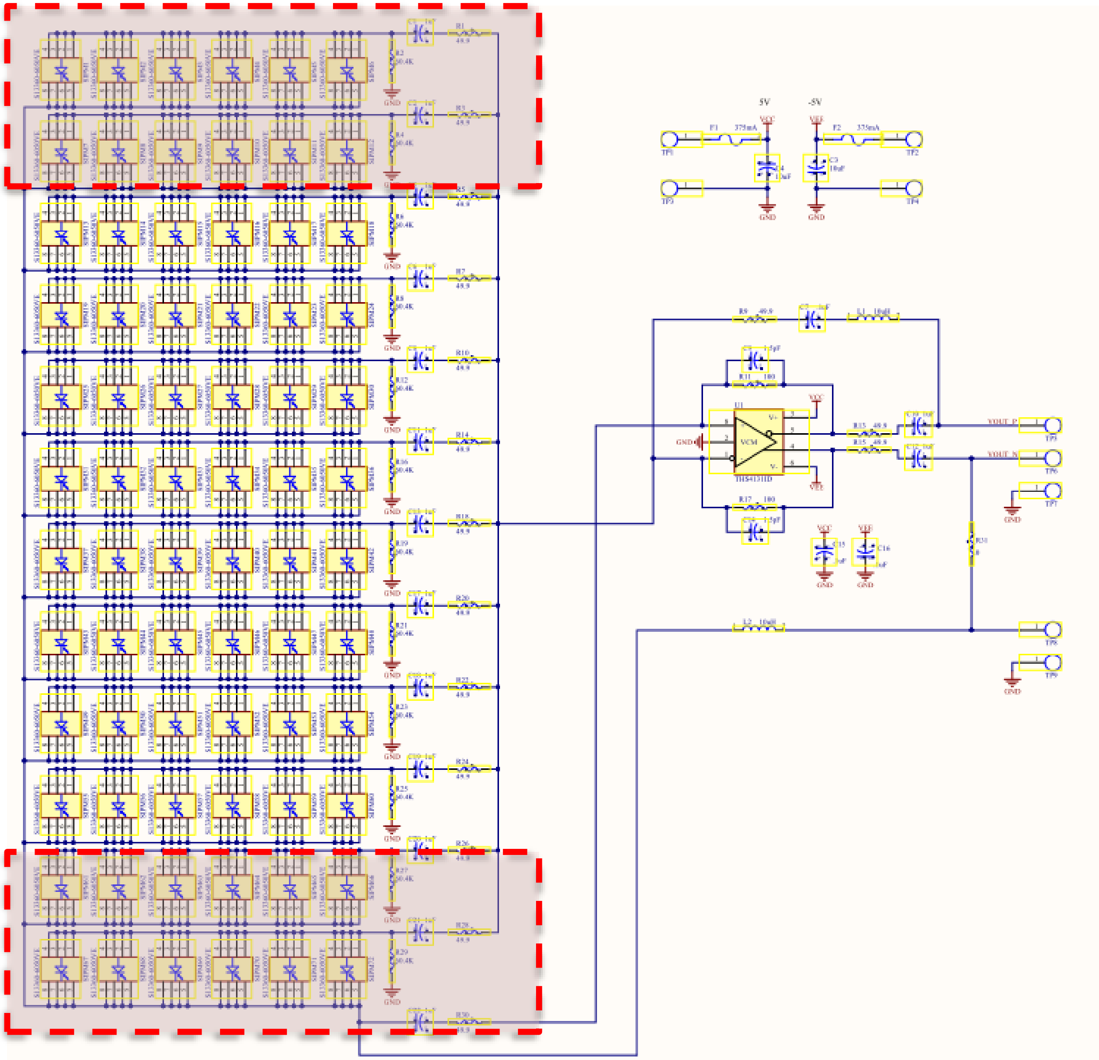
2017 and 2018: passive and active ganging of SiPMs

- We designed a summing board for the SENSL 4x4 array.
- We designed a 12 SENSL (6x6 mm C series) summing board that was used by the IU group in their light bars during the TallBo run of Oct-Nov 2017.
- We have tested Hamamatsu MPPCs (S13360-6050PE) at 25C, -70C and 77K.
- We have designed and used a passive gang of 4 SENSL (6x6 mm C series) for ARAPUCAs during the TallBo run of Oct-Nov 2017.
- We have designed and tested the ARAPUCA back plane with passive gangs of 6 and 12 MPPCs
- We designed 2 versions of actively ganged 48 MPPCs.
- We designed the cold electronics for the new Iceberg.



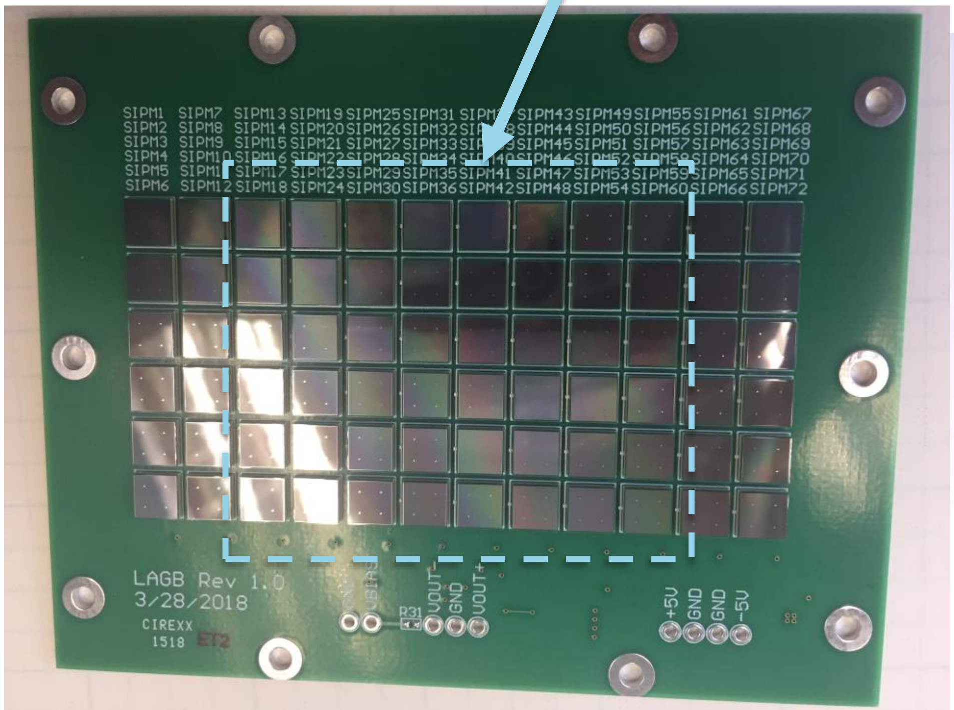
So, what have we learned?

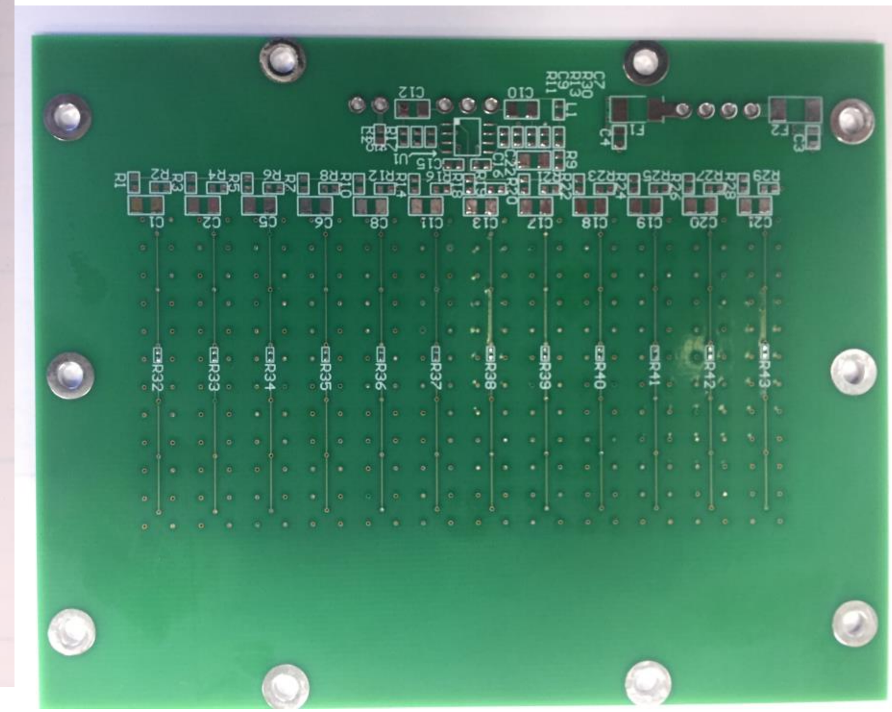
72 SiPM active ganging board: 12 x 6 matrix



- Each row has 6 MPPCs in parallel.
- We picked 48 for this test.
  - Disconnected 4 rows.
- Tested configuration 8 rows of 6 MPPCs
- 6 parallel MPPCs have a capacitance of ~7.8 nF at that Vb.
- Op Amp THS4131

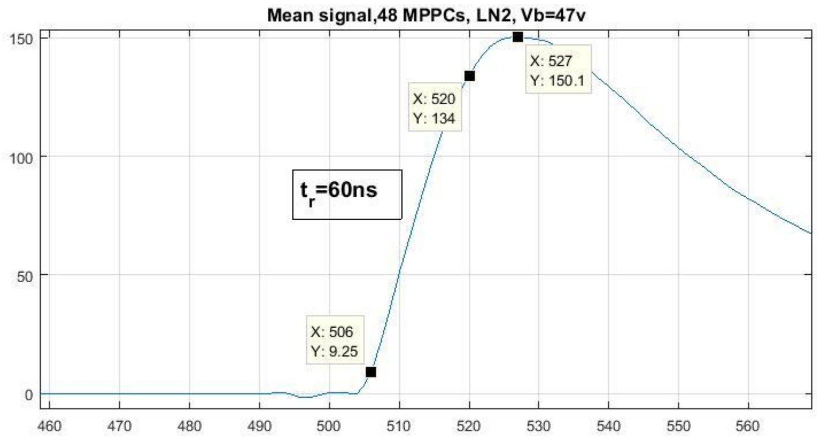
72 MPPC board, 48 used for DUNE R&D testing

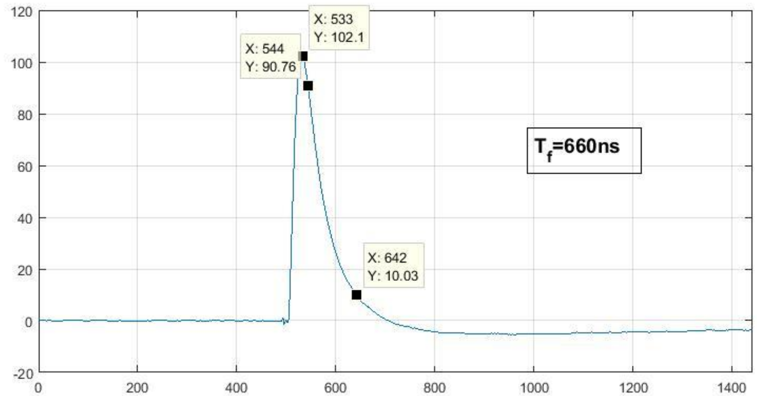


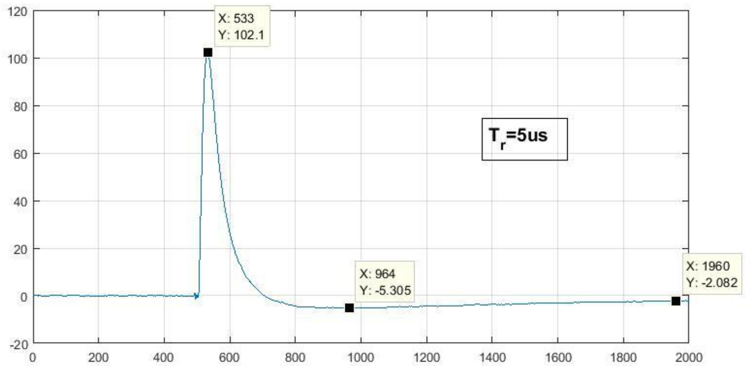


- Zero ohm resistors allow us to test different configurations.
- Each 6 MPPC branch has a zero ohm resistor that splits it in 3 + 3 MPPC.
- All branches connect to the OpAmp through a resistor that can be removed to remove the entire branch from the test.

Mean signal 48 MPPCs at -70C and Vb=47

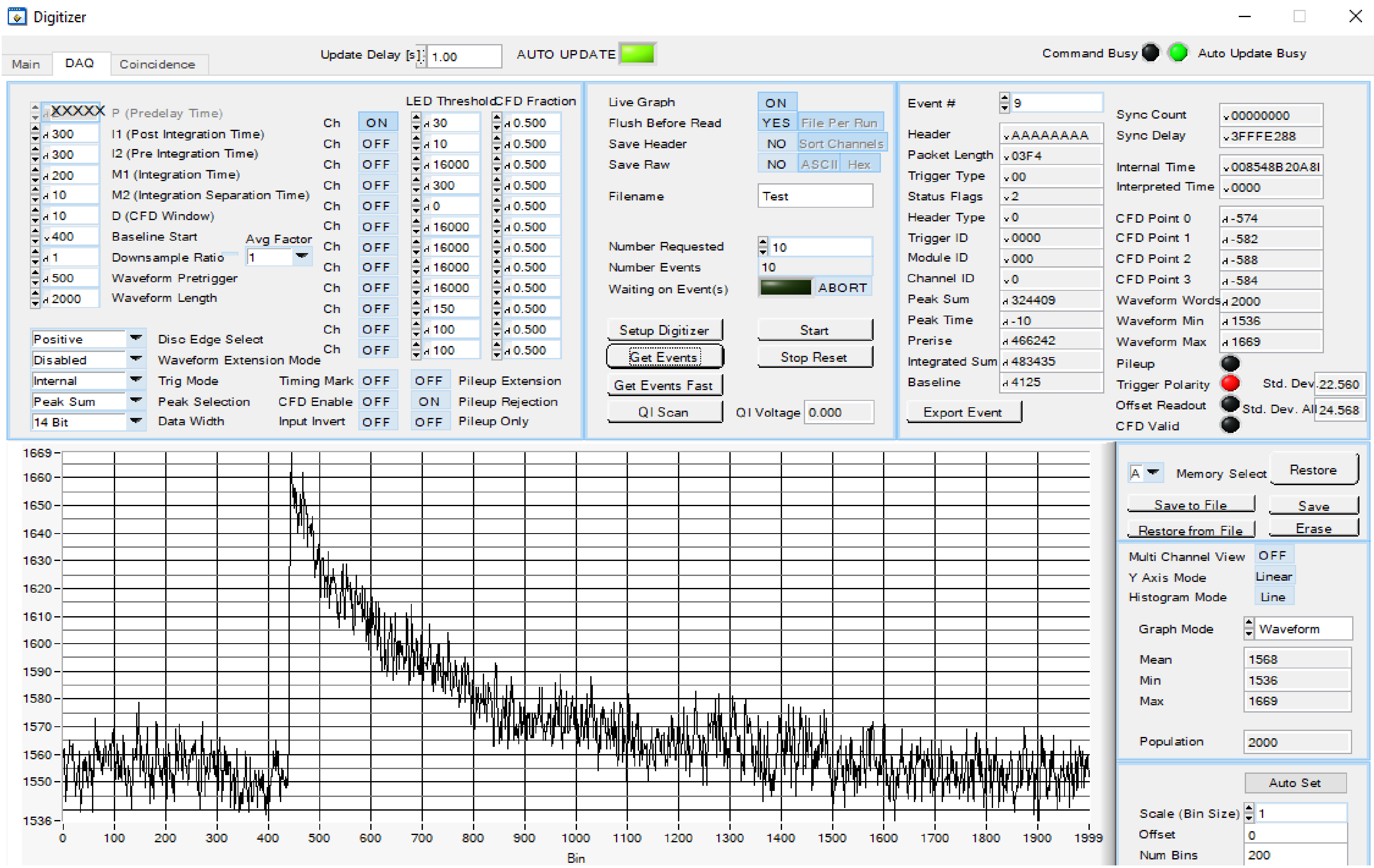






- Rise time 60ns, Fall time 660ns, slow undershoot recovery.
- SSP time constant has not been modified. Some impedance mismatch.

SSP readout



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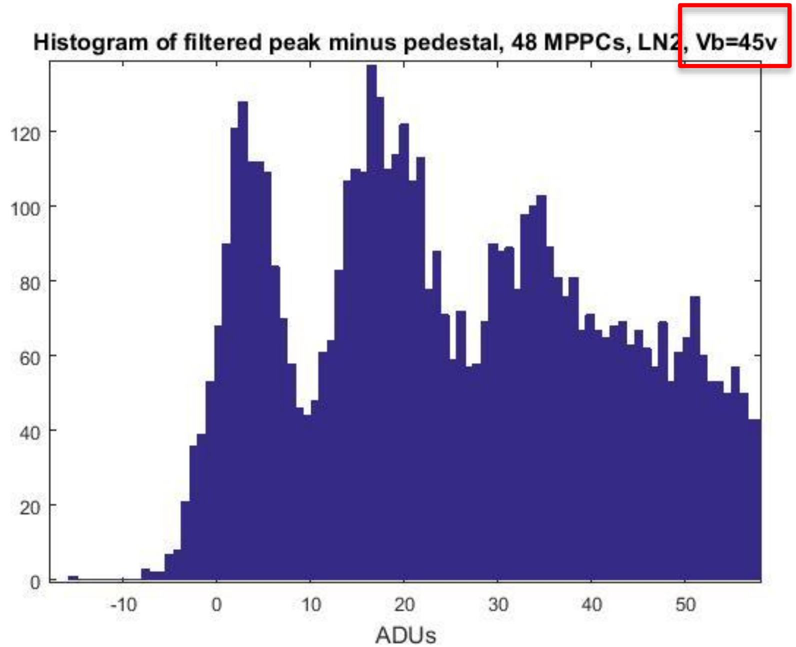
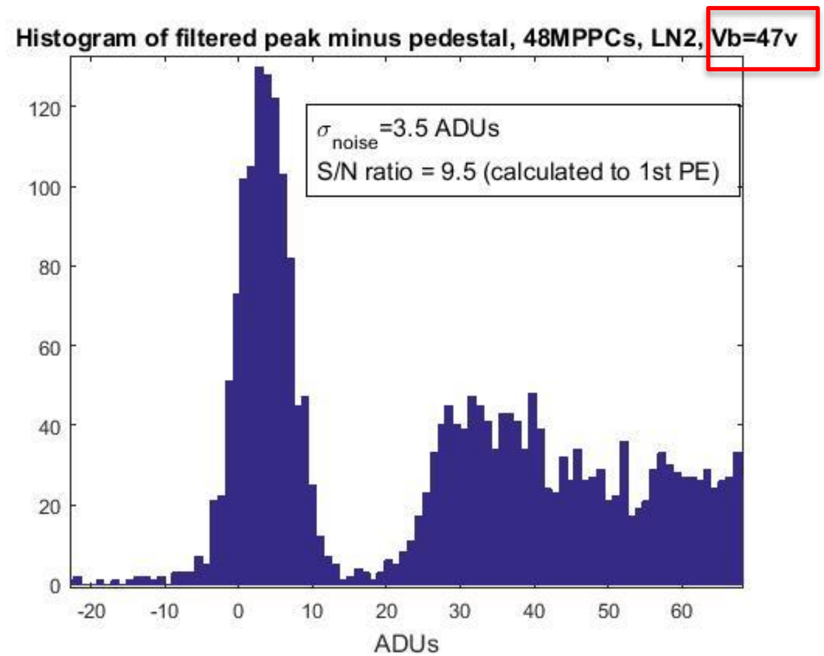
Effect of bias voltage on 48 MPPC





- 48 MPPCs Vb=47v: S/N=10.
- 48 MPPCs Vb=45v: S/N=5.
- S/N measured as the fit of the 1st PE peak to the σ_{noise}.
- For Vb=45v the 1st and 2nd PE histograms are better defined. Probably due an effect of Vb in the relative gains.

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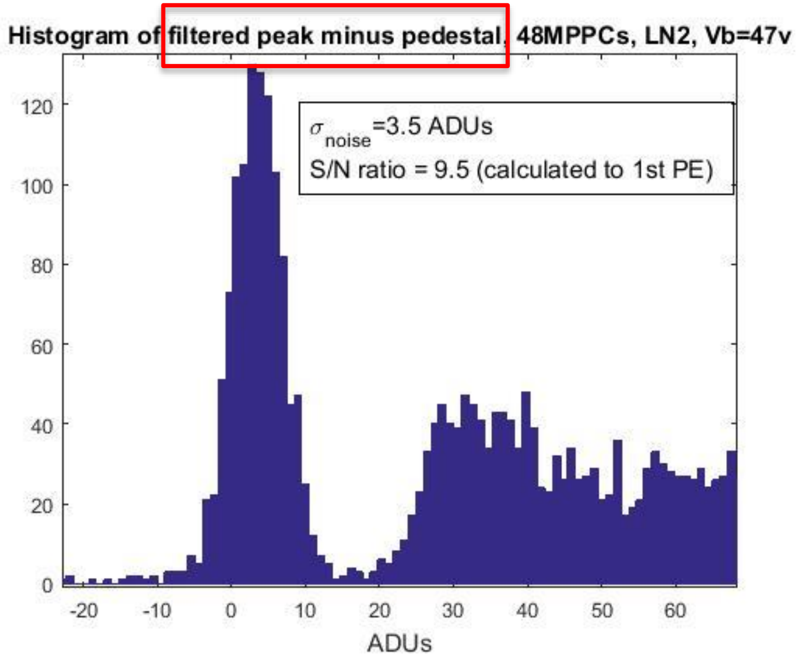
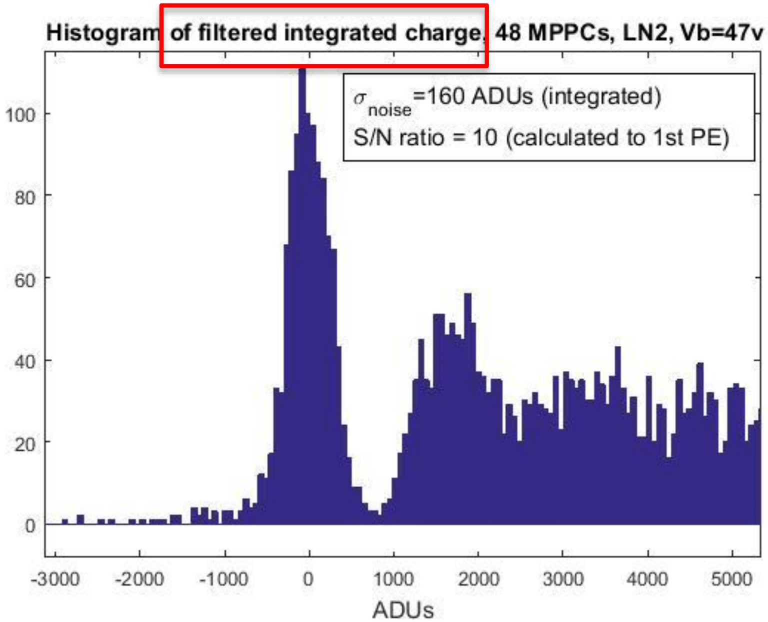
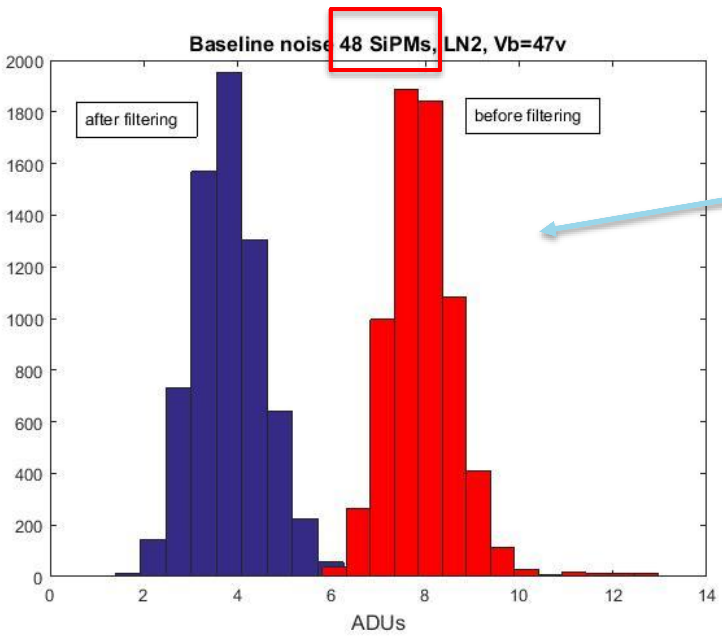
Peak minus baseline vs integrated charge (0.6usec)



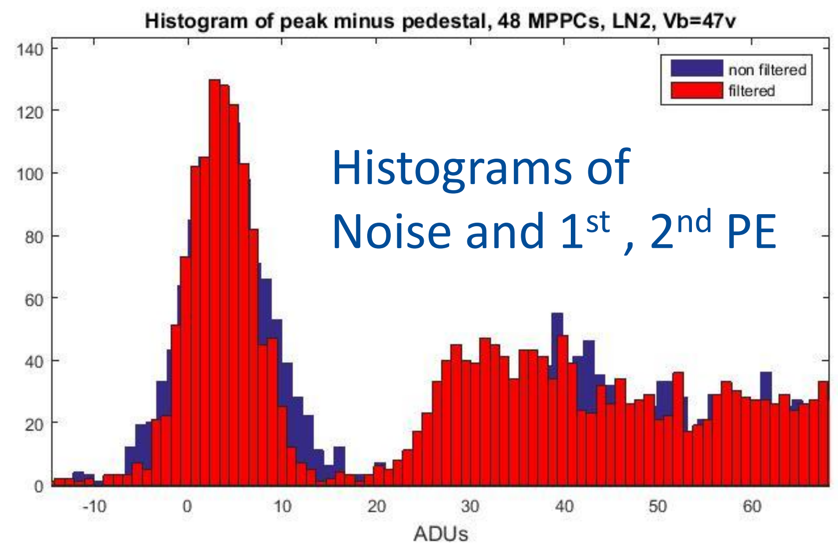


- Very similar S/N.

Filtering the signal with a matched filter (50 taps long)



Histograms of σ_{noise}



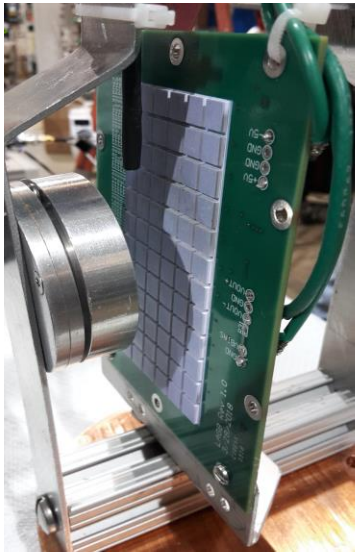
Histograms of Noise and 1st, 2nd PE

- Good reduction of noise by filtering.
- The 1st, 2nd PE spectrums do not change.

ARAPUCA and Active ganging tests at LUKE 2019

A series of tests to study the ARAPUCA trapping effect were performed at PAB (Fermilab) using the LUKE dewar.

The trapping effect of the ARAPUCA was compared to the measurements of the number of photons captured by the SIPM array covered by a wavelength shifter (P-Terphenyl)



Inside ARAPUCA
Sensors on backplane
Not uniformly distributed!

- **Tests:**

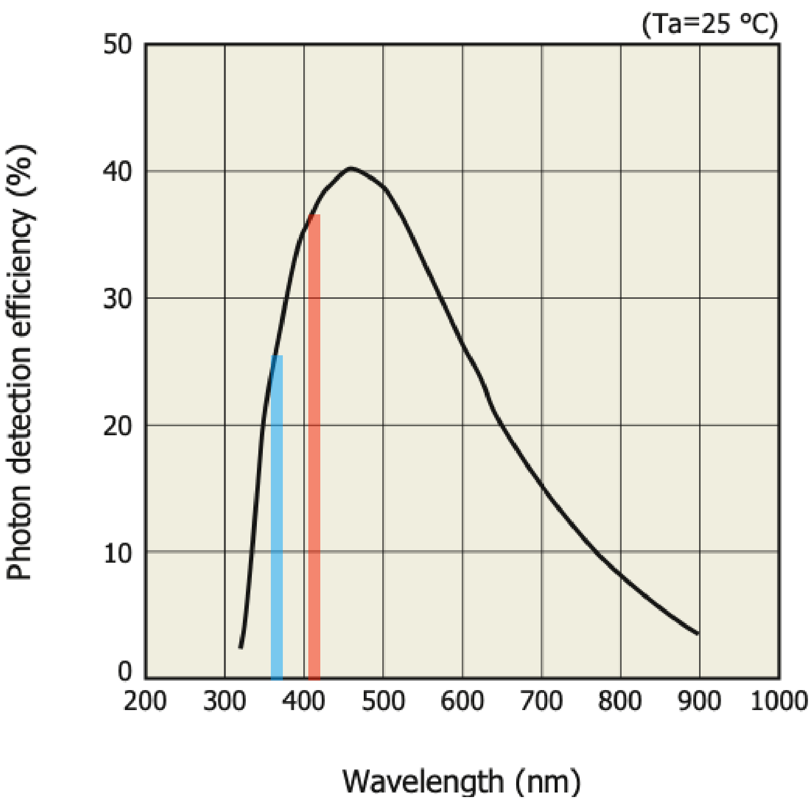
1. - MPPC + wavelength shifter (WLS)
   - 200ug/cm2 of P-Terphenyl directly deposited on SIPM array.
2. - MPPC + dichroic filter + (WLS)
   - 200ug/cm2 of P-Terphenyl on glass surface of filter
   - 200ug/cm2 of TPB on dichroic side of filter.

No reflections

3. - ARAPUCA tests
   - several tests with 12, 24, 36 and 48 MPPCs
   - Vikuiti reflector in all internal surfaces (including non used MPPCs).

The MPPC efficiency was evaluated using 36 MPPCs evaporated with p-terphenyl

We assumed 150000 photons per alpha.
Using a geometric acceptance we calculate **2850** photons landing on the 36 MPPCs.



With the same geometry we tested bare MPPC + dichroic filter with p-terphenyl on the external side and TPB (NO ARAPUCA)

Wavelength:
p-terphenyl ~ 350 nm
TPB ~ 425 nm

Results of tests at LUKE

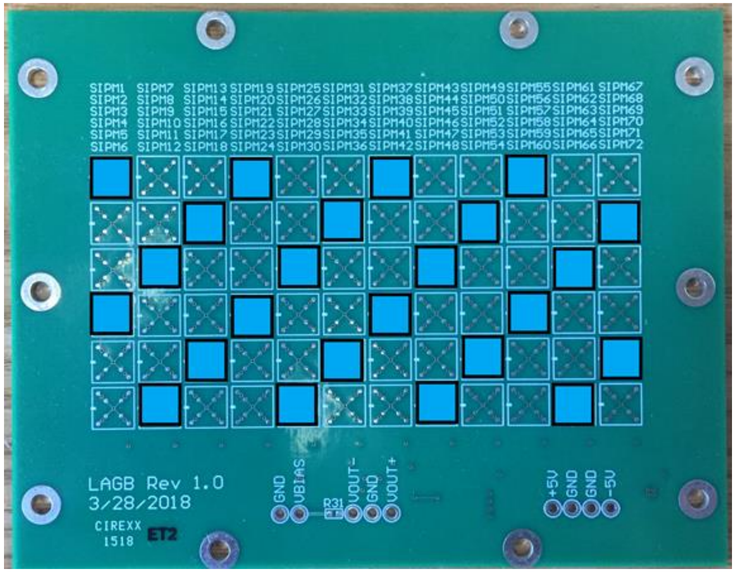
# MPPC	12 + ARAPUCA	24 + ARAPUCA	36 + ARAPUCA	36 + dichroic	36 + p-ty	48 + ARAPUCA
Ph Detected	179+/-36	306+/-61	413+/- 82	350+/- 70	336+/-67	788+/-158
Eff (%)	1.1+/-0.2	1.8+/-0.4	2.5+/-0.5	12.2+/-2.4	11.7+/-2.3	4.7+/-0.9
Window/MPPC surface	17.5	8.7	5.8	-	-	4.4
ARAPUCA gain	1.5	1.3	1.1	-	-	1.6

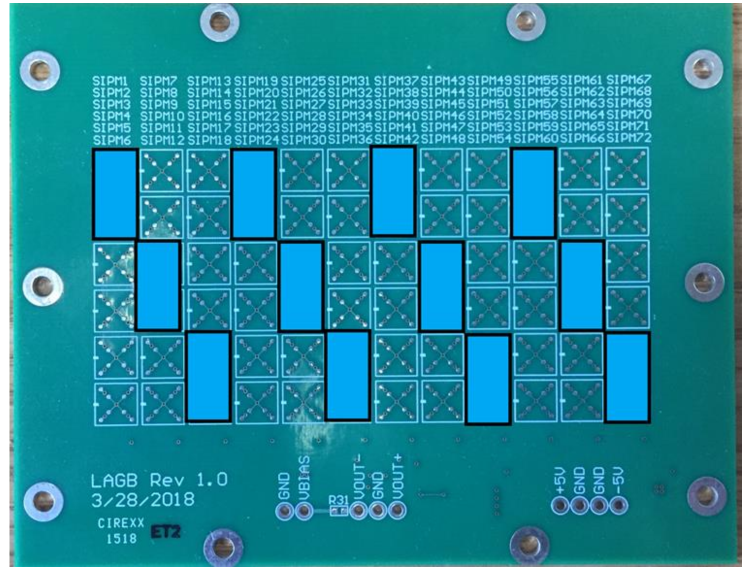
- The efficiency of MPPC + wavelength shifter and MPPC + dichroic + wavelength shifters on each side show over 12% efficiency as expected.

- ARAPUCA gains are smaller than expected influenced by the poor distribution of SIPMs
- The gains are about 1.5 as opposed to 3 measured in TallBo 7 and ProtoDUNE.
- We will repeat the test at LUKE with a more uniform distribution of the SIPMs

- Even with this non uniform distribution of SIPMs a 4.7% efficiency was measured

New configuration for LUKE: it only requires new Vikuiti mask (easy to do)

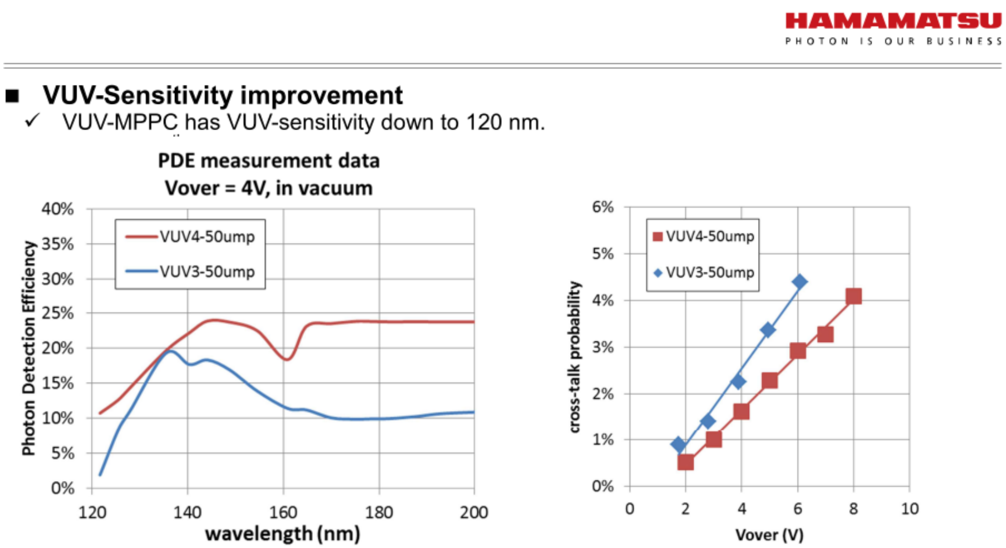




- The light blue squares represent the SIPMS that will see photons. The rest of the backplane will be covered by Vikuiti reflector.
- We expect to recover a gain of ~3 and an efficiency above 5%.

Summary so far:

- ARAPUCA efficiencies close to 5% have been achieved and can be improved with better SIPM distribution.
  - SIPM distribution for specular optical surfaces is important.
  - New SIPM configurations will be tested at LUKE
- Active ganging of 72 SIPMs have been achieved with good timing and S/N performance.
- ARAPUCA segmentation has been important in TallBo 7 and ProtoDUNE data analysis.



Also interesting:
VUV 6mm x 6mm
15% efficiency at
128nm

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PDS segmentation and cold electronics

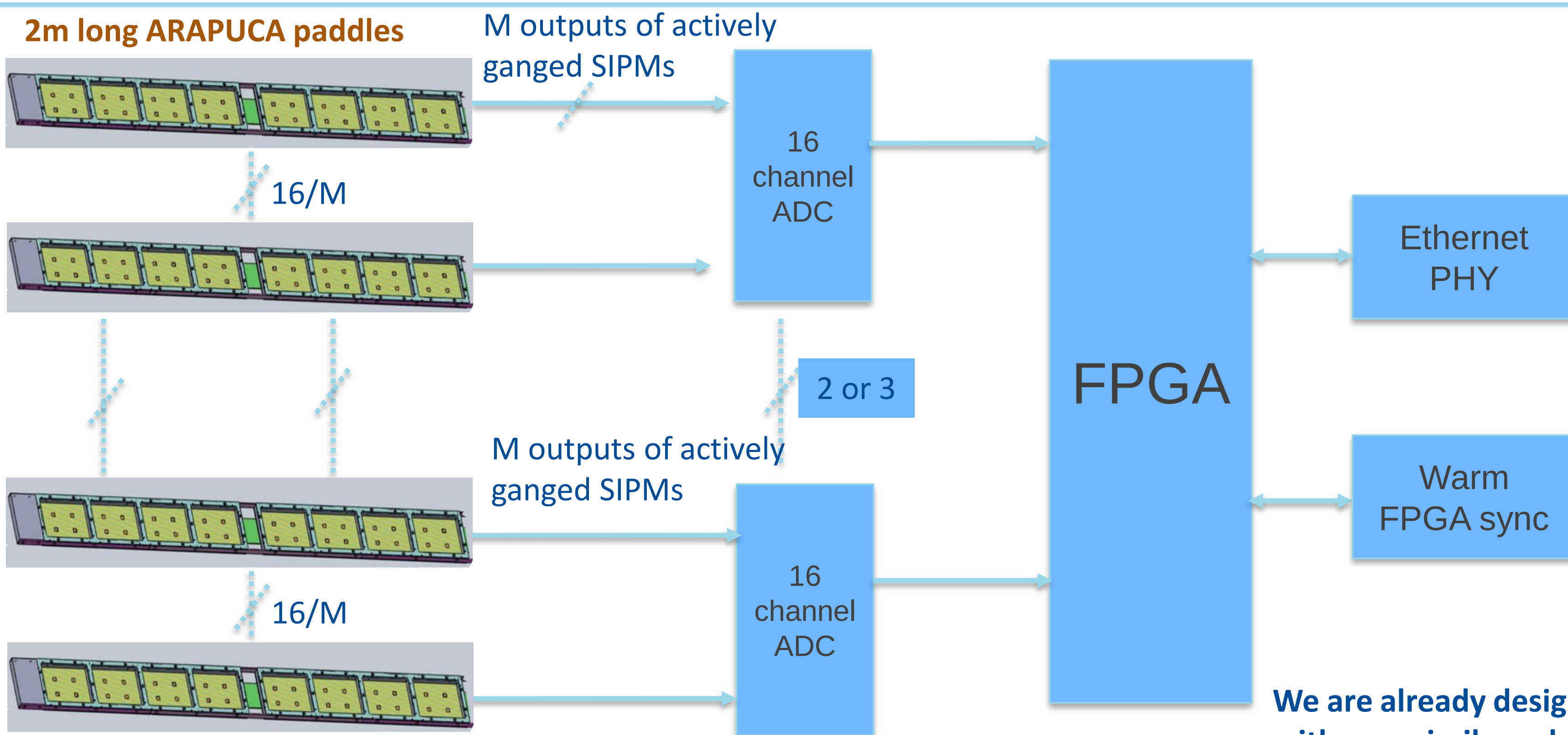
- A PDS segmentation will imply a multiplication in the number of channels by the segmentation factor. Say 4 to 8 times.

- Proposed solution:
  - Part of the warm electronics such as ADC, FPGA and high speed links can be moved into the cold.

- The interest for cold electronics is increasing in many areas.
- We are designing similar electronics for LN temperature for a massive DM experiment based on skipper CCDs (DAMIC 10Kg).
  - A cryo design with an FPGA and high speed Ethernet link is being fabricated.
- We are also interested in cryo electronics at 60K and 4K for superconducting detectors and quantum computing.

- Question: will a cold electronic architecture for DUNE more expensive than the warm?
  - The cost increase will be very modest and it comes from the number of ADC channels to allow segmentation. The rest is the same. Components are “off the shelf”.
  - We can use high speed fiber optics to reduce cable burden and cut cost

Segmented cold electronics for DUNE



We are already designing with very similar cold electronics.
FPGA and Ethernet have been tested.
A 16 channel 65Ms/s/ch is $5/channel

- ADC specifications:
  - 65Ms/s/ch
  - 90 dB dynamic range
  - 1uV RMS noise/sample.
  - 2000 PE dynamic range

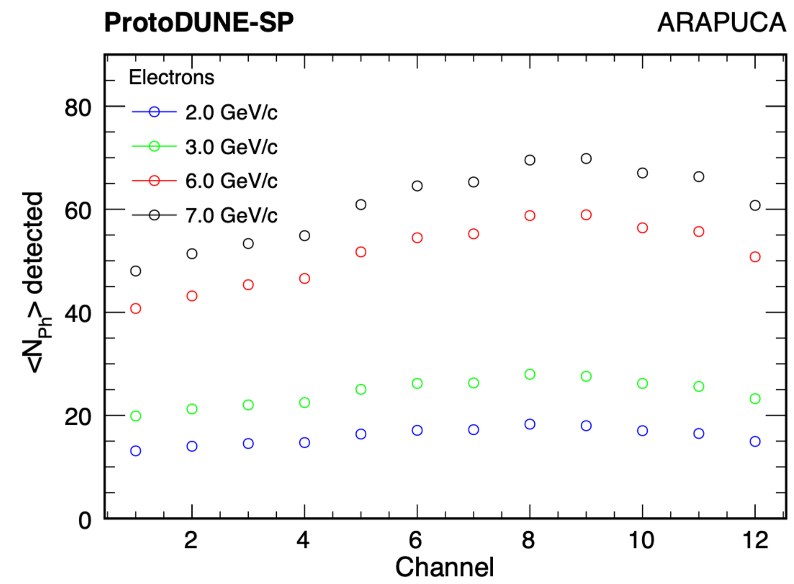
- FPGA specifications:
  - Zero suppression, event detection, filtering, digital event analysis.
  - 1Gb ethernet copper.
  - Some internal buffering.

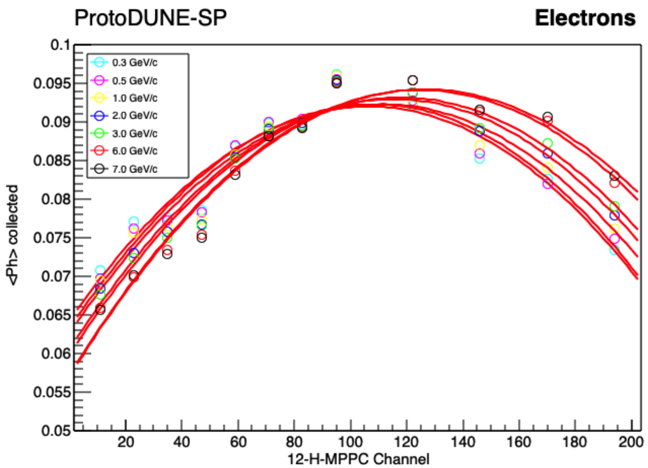
Thank you

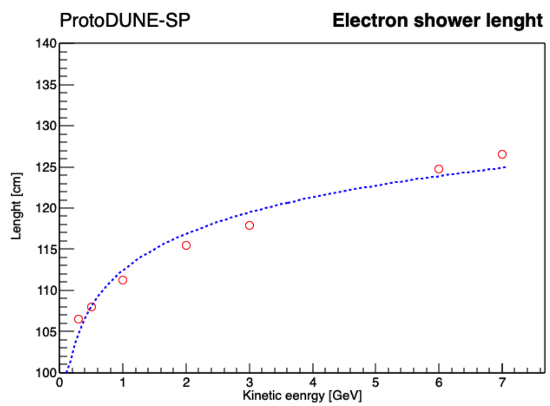
Spare slides

Arapuca cells response to beam electrons

The Arapuca granularity results superfluous applications for the beam events, since we know from the beam info the track geometry and the particle kind in each event.







One of the possible applications could be the determination of the showers length from the light pattern detected by the cells.