Final Report

Studies of the trigger performance of the ICARUS T600 detector at Fermilab

09 – 28 – 2022

Riccardo Triozzi

Supervisors:

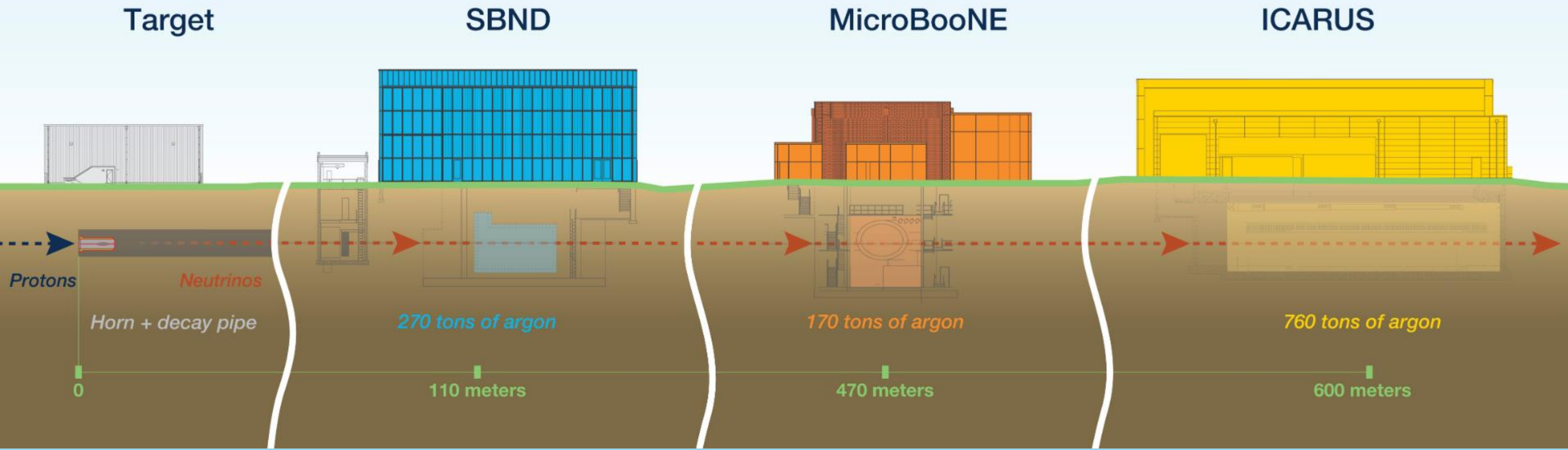
Angela Fava
Donatella Torretta

The SBN Project

- Three Liquid Argon TPC (**LAr-TPC**) detectors at increasing baselines on the Booster Neutrino Beam (**BNB**)
- **ICARUS**, at 600 m from target, on short baseline is the far detector and will collect neutrinos also from the **NuMI** beam (off-axis)

Goals:

- Test the allowed parameter space of past anomalies at $>5\sigma$ with BNB
- Test the Neutrino-4 oscillation hypotesis with disappearance of ν_μ from BNB and ν_e from NuMI
- Study ν(~3 GeV)-LAr with NuMI for DUNE



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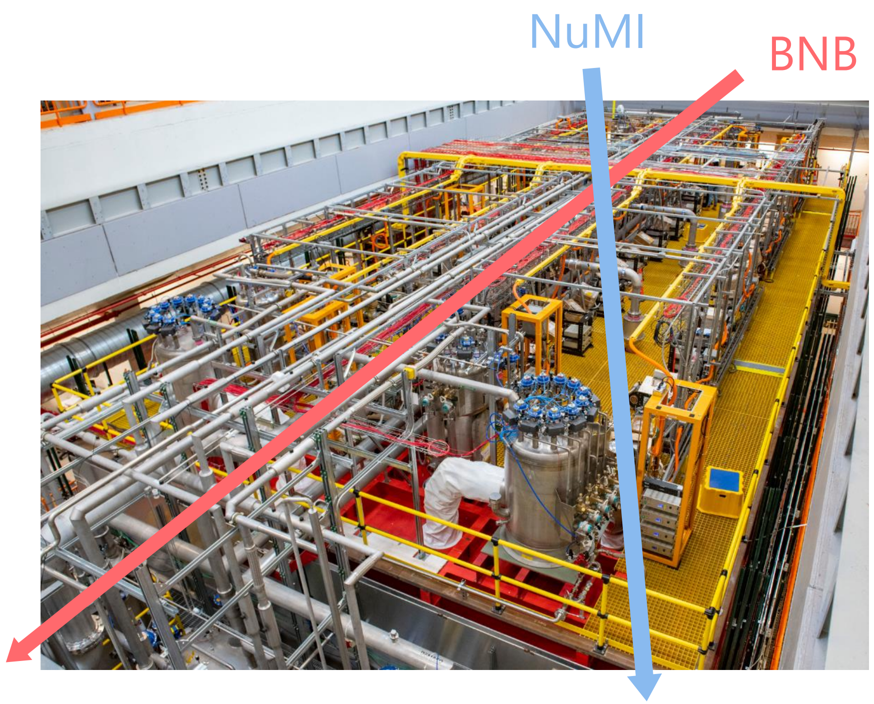
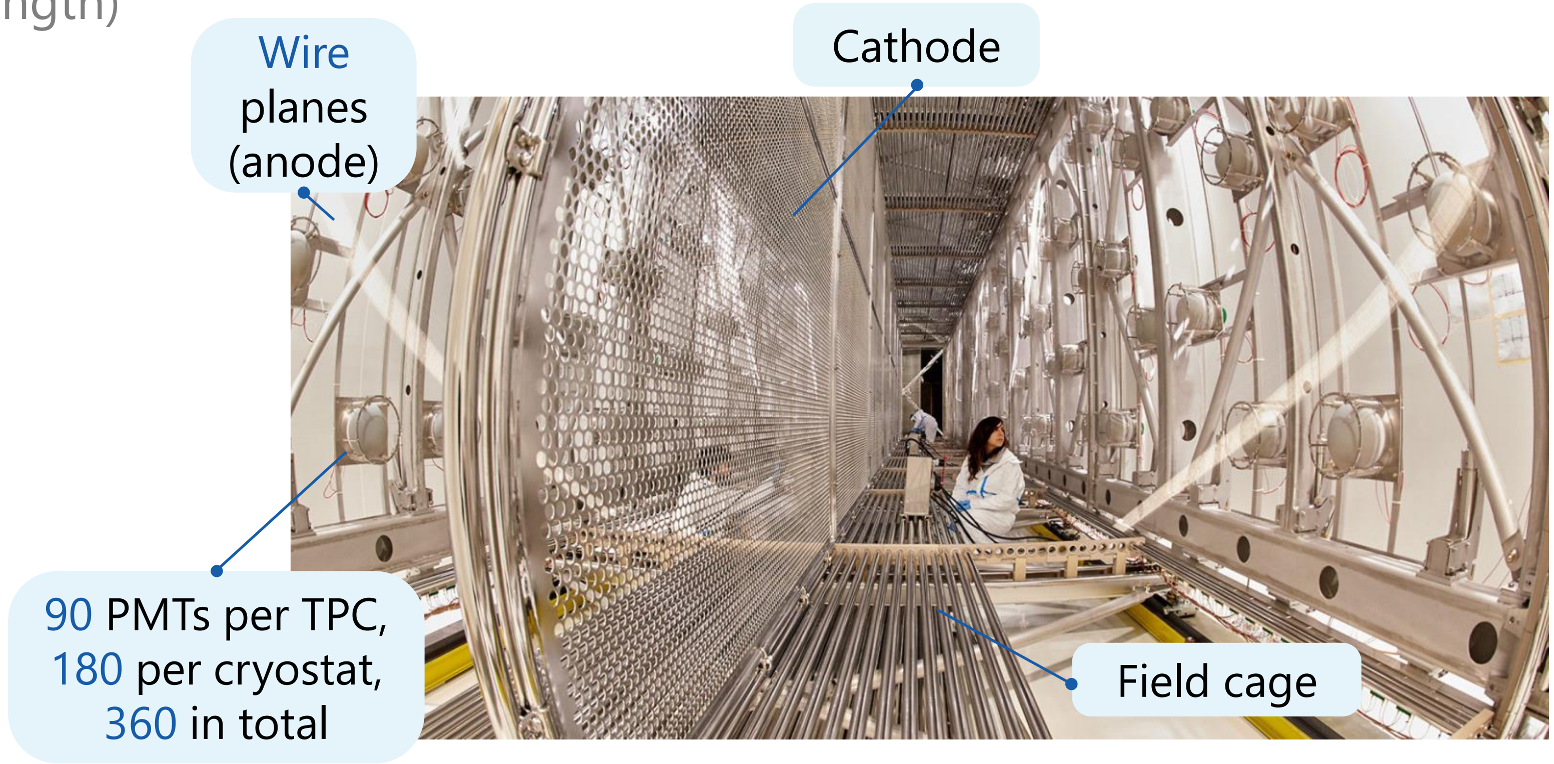
The ICARUS T600 Detector

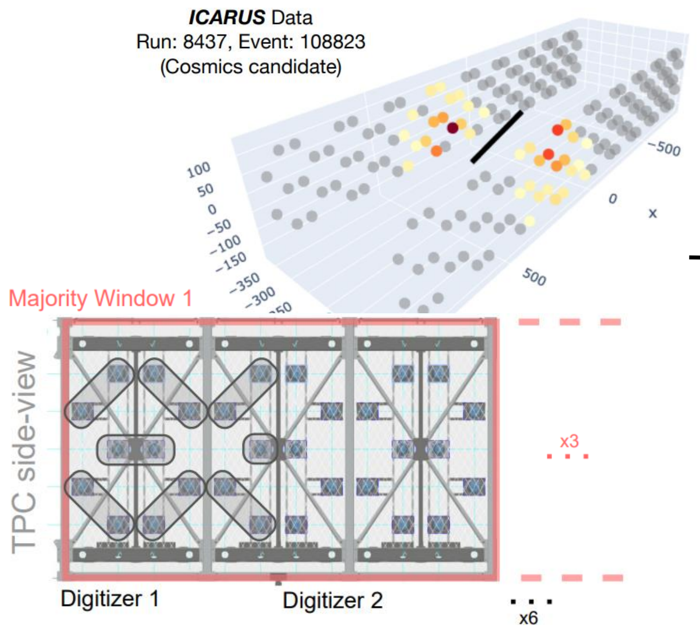
- LAr-TPC high granularity self-triggering detector with 3D **imaging** and calorimetric capabilities, ideal for ν physics
- Two **cryostats**, each with 2 **TPC**s with a common central cathode (nominal configuration: HV = 75 kV, E = 0.5 kV/cm and 1.5 m drift length)

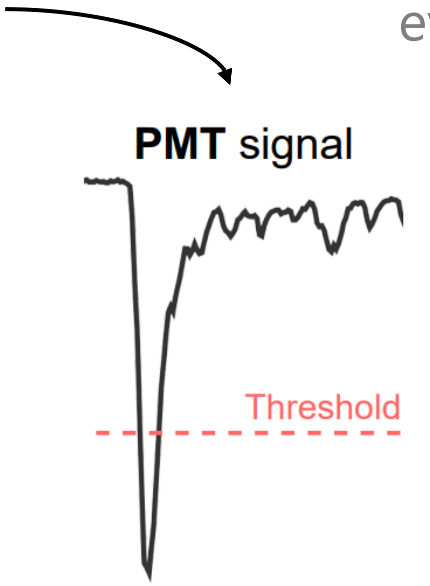
- Ionization charge continuously read *non-destructively* by 3 wire planes
- Scintillation light read by a system of 360 8" **PMT**s (180 per cryostat) for timing and triggering





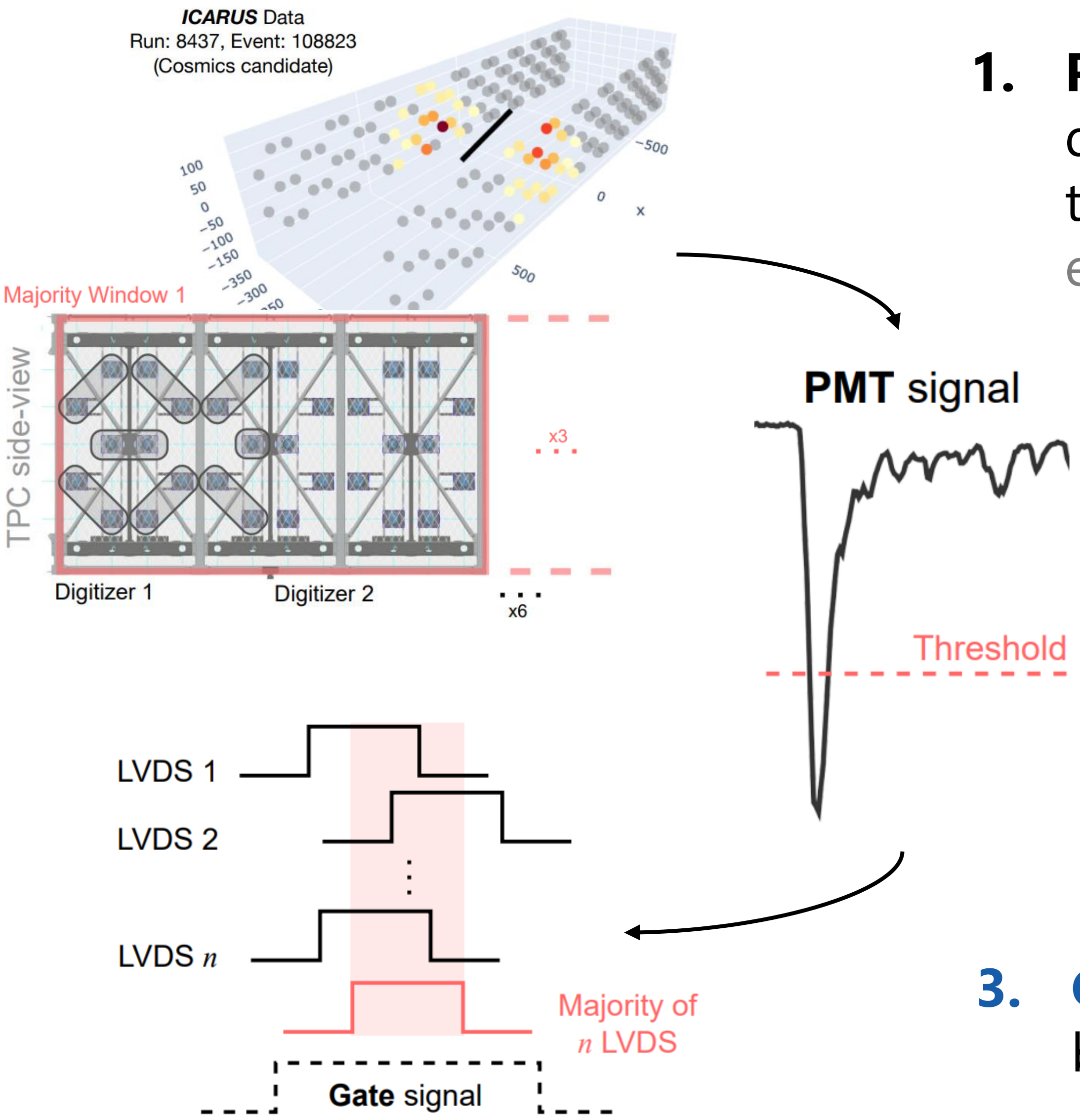
The ICARUS T600 Detector: trigger working principle





1. **PMT signals** are digitized at 500 MHz and discriminated with a 400 ADC (i.e., 8 photoelectrons) threshold, generating **LVDS** logical outputs (one every pair of adjacent PMT, combined in OR)

The ICARUS T600 Detector: trigger working principle



1. **PMT signals** are digitized at 500 MHz and discriminated with a 400 ADC (i.e., 8 photoelectrons) threshold, generating **LVDS** logical outputs (one every pair of adjacent PMT, combined in OR)

2. FPGA processing based on a **majority logic**: at least 5 LVDS signals in front facing 6 m-sections along the longitudinal direction (30 PMTs x 2 sides) to produce a majority trigger primitive

3. **Global trigger**: trigger primitive coincident with the beam gate (e.g., 1.6 µs for BNB)

The ICARUS T600 Detector: trigger working principle

In presence of a **global trigger**, readout of **TPC** (for 1.5 ms), **PMT** (500 MHz sampling frequency) and **CRT** is activated:

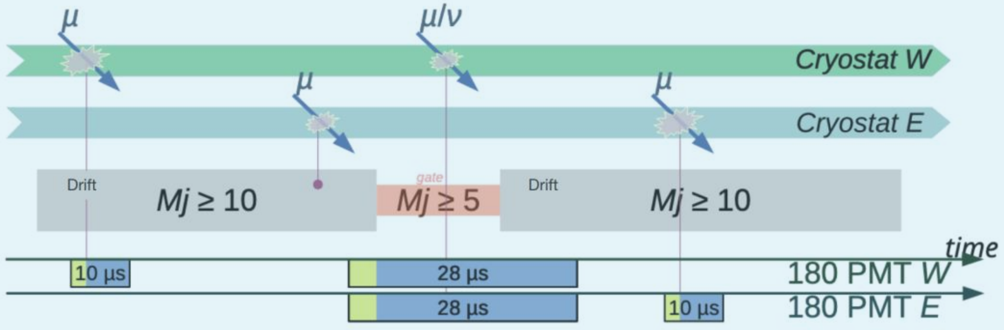
Local triggers

- **Beam Trigger**: 28 μs acquisition windows of PMT waveforms, determined by a majority-5 PMT primitive inside a gate signal synchronized with the beam spills

Main physics trigger for ICARUS

- **Out-of-time PMT Trigger**: shorter 10 μs acquisition windows of PMT waveforms, collected in presence of a majority-10 trigger primitive outside of the beam spill in a 2 ms window around the global trigger

Allow recording of all scintillation light activity related to Cosmic Rays (CRs) during the TPC drift time (key to cosmic brackground rejection)

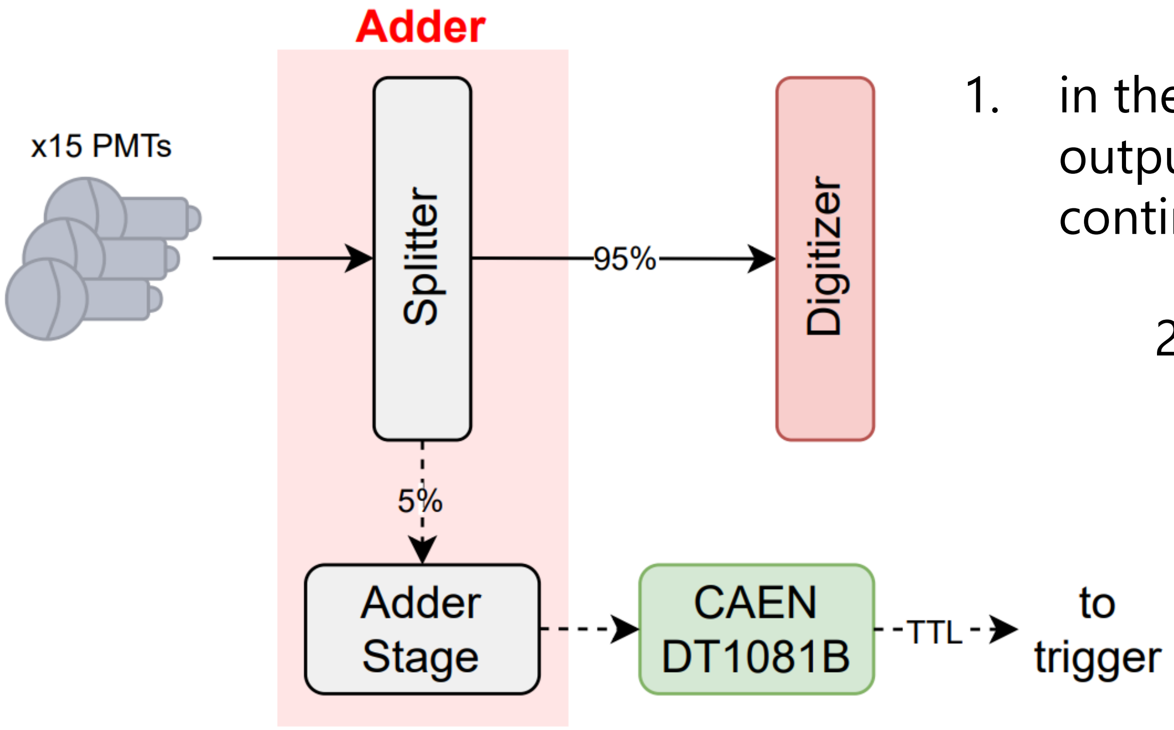


Adders Trigger System

A complementary system was proposed, based on ***adder boards***:

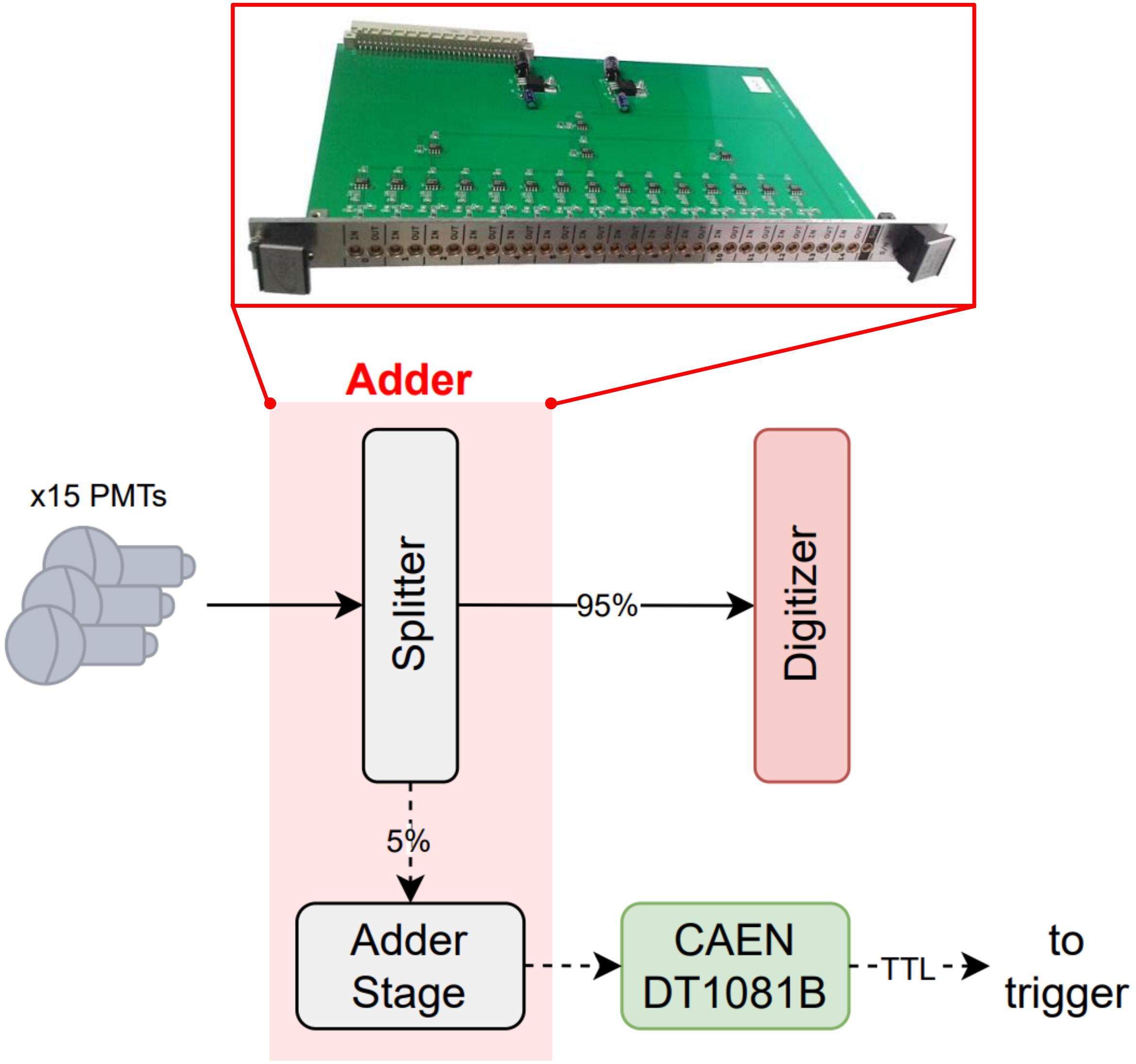
Motivation:

- Global trigger **efficiency** is >97% at E > 300 MeV (preliminary analysis on MC and collected data)
- Hints of lower efficiency in CRs detection for out-of-time PMT triggers



1. in the first stage of the board, the PMT signal is **split**: 95% is output to the front panel (and sent to the digitizers), 5% continues to the adder stage
2. adder stage: analog **sum** of 15 PMTs (3 m in the longitudinal direction)
3. each analog sum is **discriminated** with an external module and sent to the trigger system

Adders Trigger System



Advantages:

- could help identify events with small detector occupancy (e.g., cosmic tracks close to the corners of the detector)
- can be combined with the majority trigger

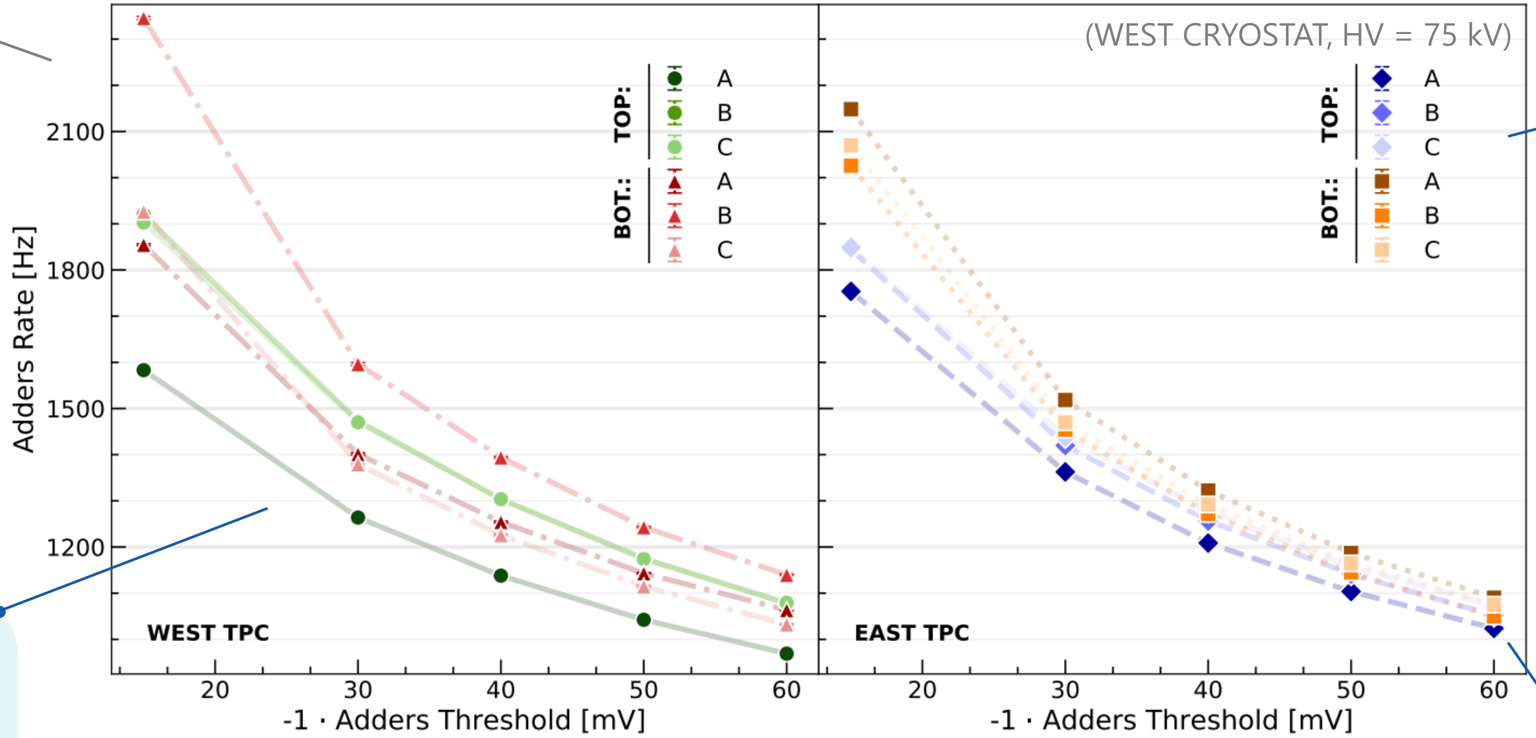
My tasks:

- check that there is no drop in performance w. r. t. the existing trigger system
- characterize adder signal to define the optimal discrimination threshold
- investigate how to process the signal and how to combine the adders with the majority trigger system

Adders Rate Trend: different discrimination thresholds

- **Fully** cabled and tested all the west cryostat's adder boards (overall, 12 out of 24)
- Measured the adders **rate** as a function of their discrimination **threshold** with a dedicated LabVIEW software running on the trigger FPGA:

Top and **bottom** refer to the adder boards positioning within the electronics crates



Groups of adjacent adder boards show **similar** rates

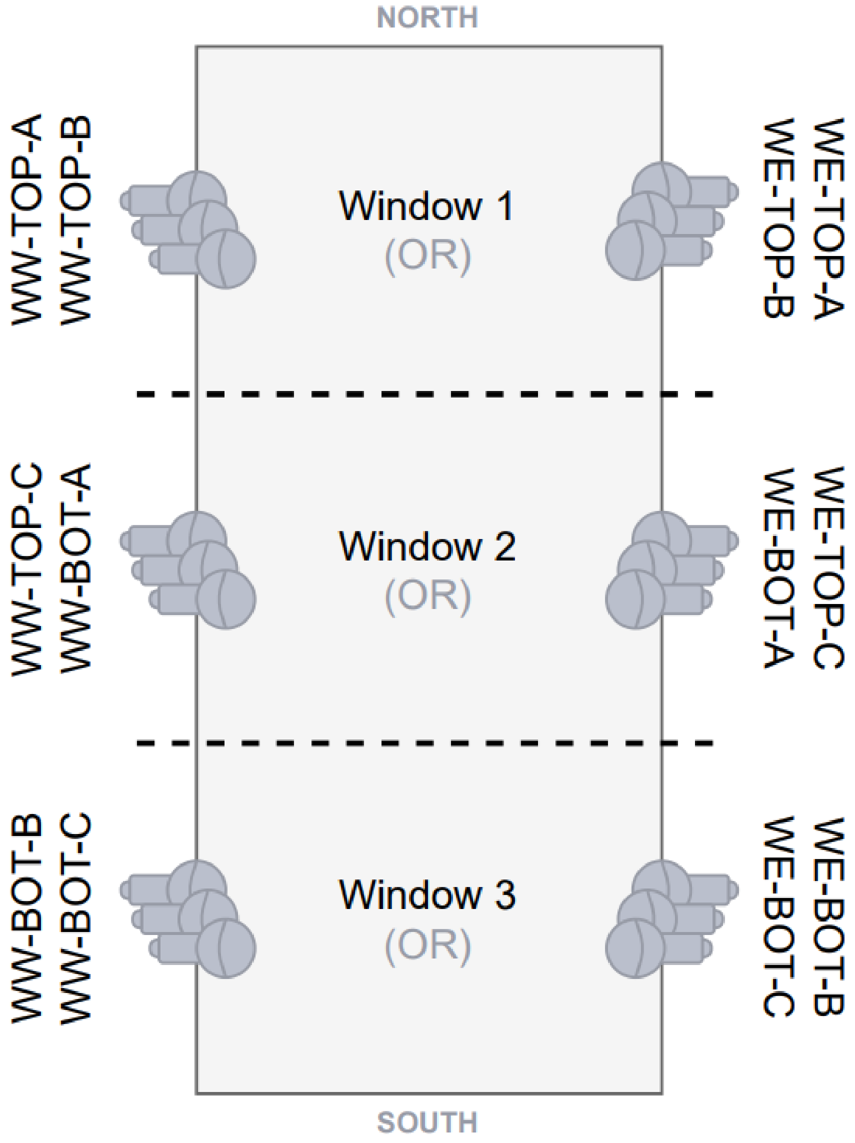
TOP-A's **low rate** can be explained by (*i*) a PMT being off and (*ii*) PMTs being at the edge of the TPC

TOP-A has a **lower rate** w. r. t. TOP-B and TOP-C, due to PMTs being at the edge

Adders Rate Trend: majority windows

- The easiest possible implementation of an **adder-based trigger** is to define **windows** similar to those used for calculating the majority
- Each window corresponds to 30 + 30 front-facing PMTs, corresponding to groups of **4** adder boards in OR
- The logical processing of the adder outputs was implemented with the CAEN **DT1081B** module (rates were measured with the usual LabVIEW software)

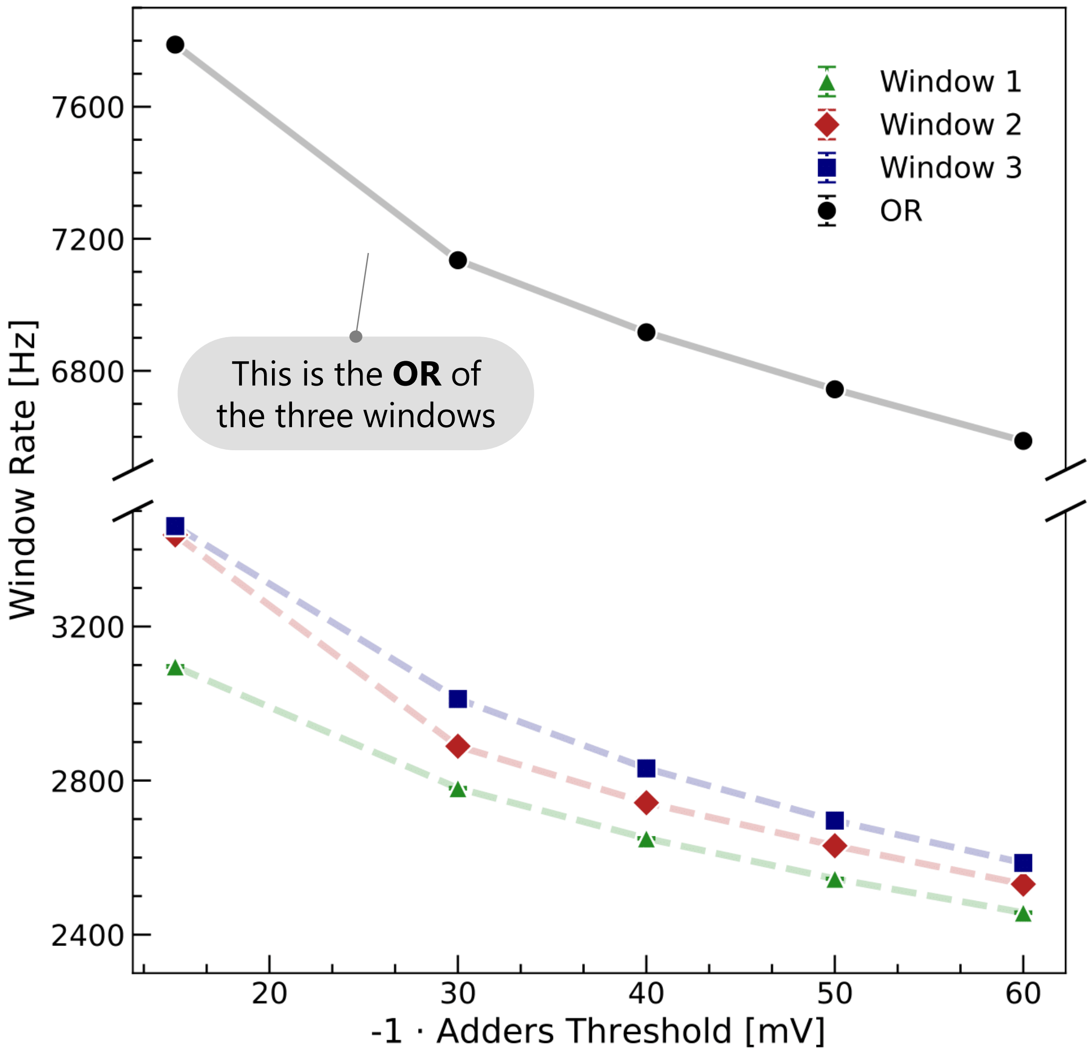
(the CAEN DT1081B module)



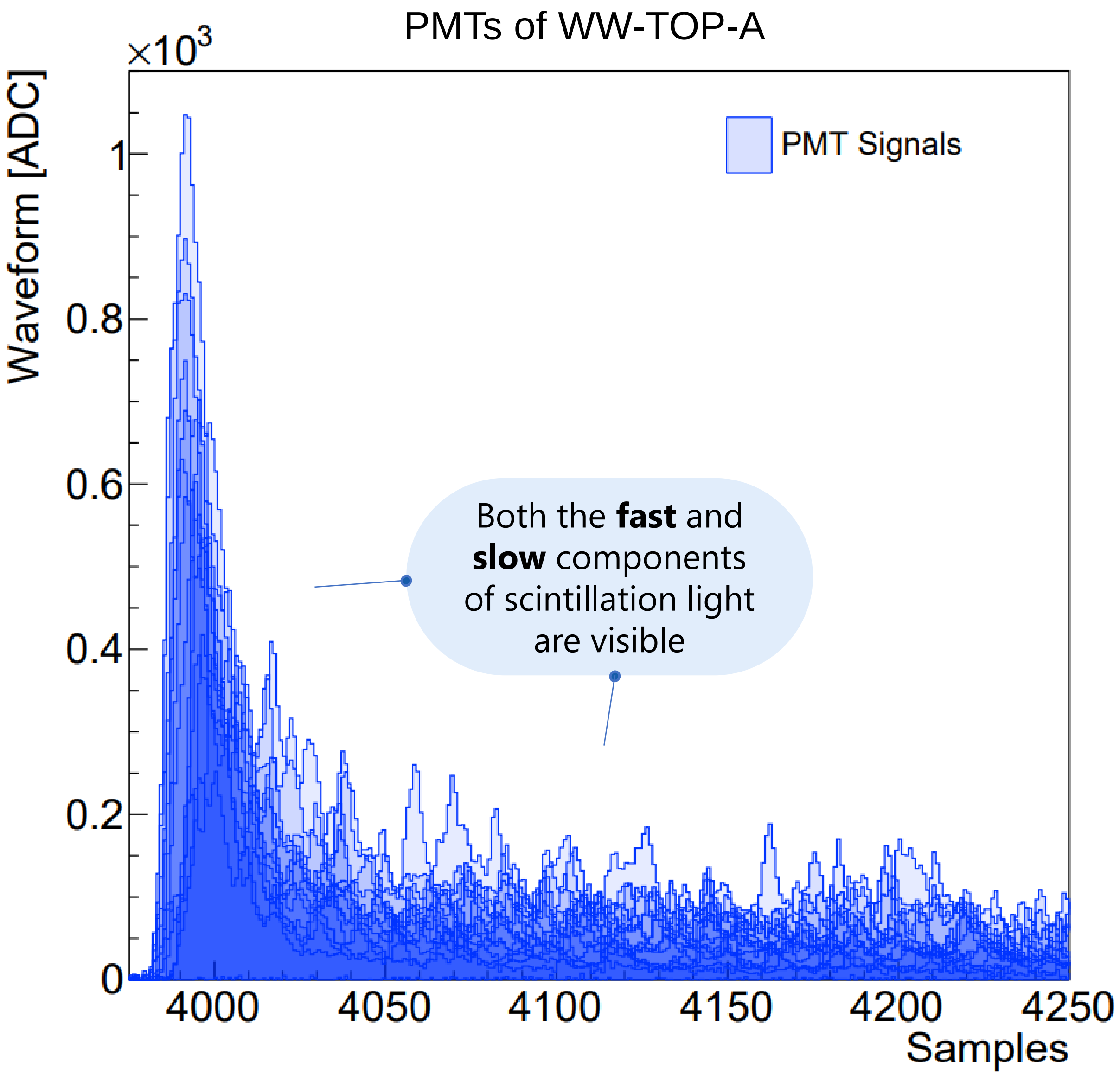
Adders Rate Trend: majority windows

- Here, the window **rate** trend as a function of the adder discrimination **threshold** is shown for the 3 windows and the global or
- At - 60 mV: the global-OR rate is ~ 7 kHz, which translates into ~ 14 out-of-time triggers for the west cryostat (i.e., 7 kHz · 2 ms = 14 triggers) or ~ 28 for the whole detector
- One should verify that this rate can be **managed** by the DAQ and what is the **comparison** with the majority-5 out-of-time trigger rate (otherwise, further logic processing of signal may be needed)

(WEST CRYOSTAT, HV = 75 kV)



Waveform Analysis: PMT signals



Aim:

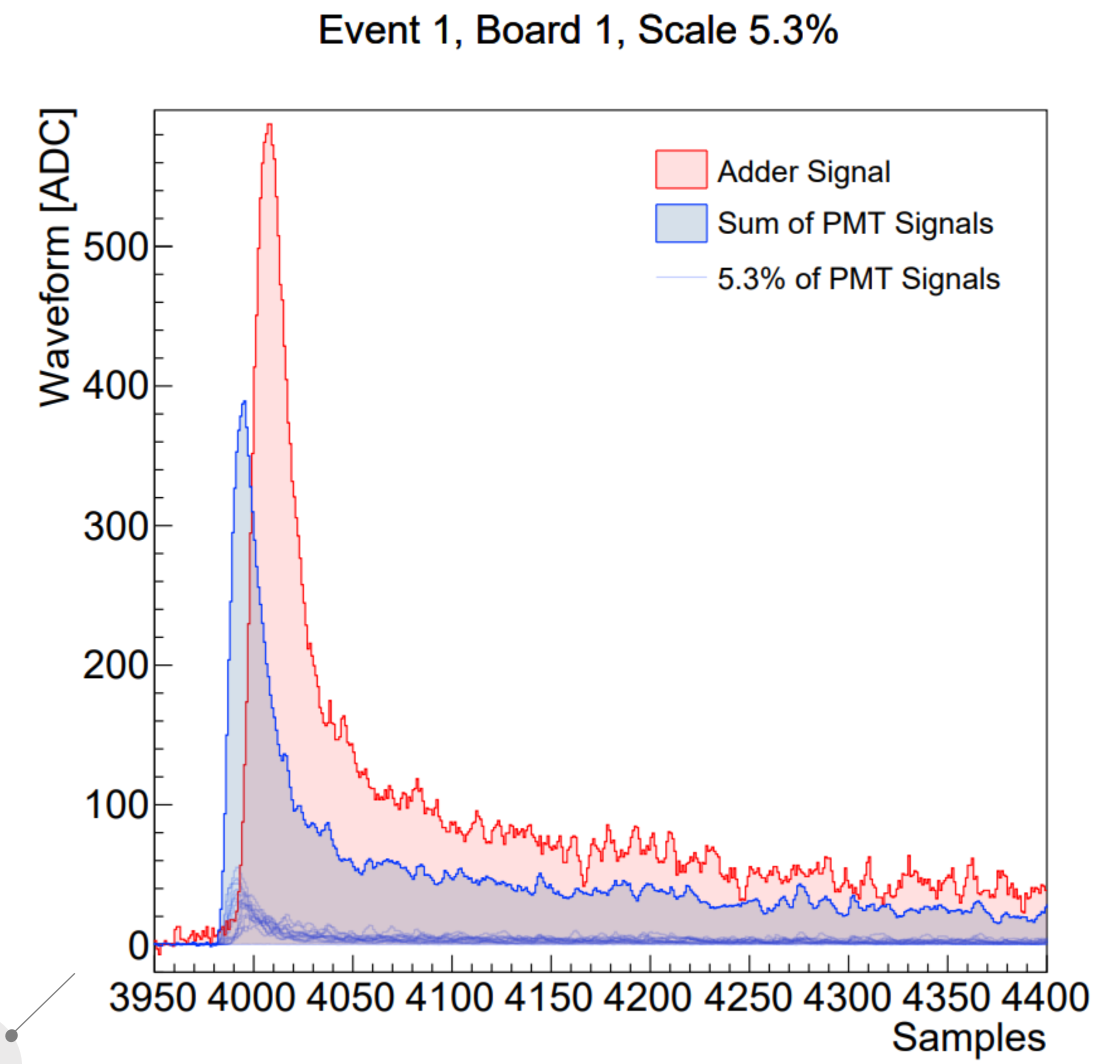
- Compare the shape of an adder board signal to PMT waveforms
- Study the characteristics of the waveforms (amplitude, noise's RMS, rise time and so on)

- The **waveforms** of the 15 PMTs connected to one adder board (digitized at a 95% scale factor) were compared

- For cosmic rays, signals from different PMT are **asynchronous**, due to:
  - different intrinsic PMT **transit time**
  - the fact that photons generated by the track arrive to different PMTs at **different times**

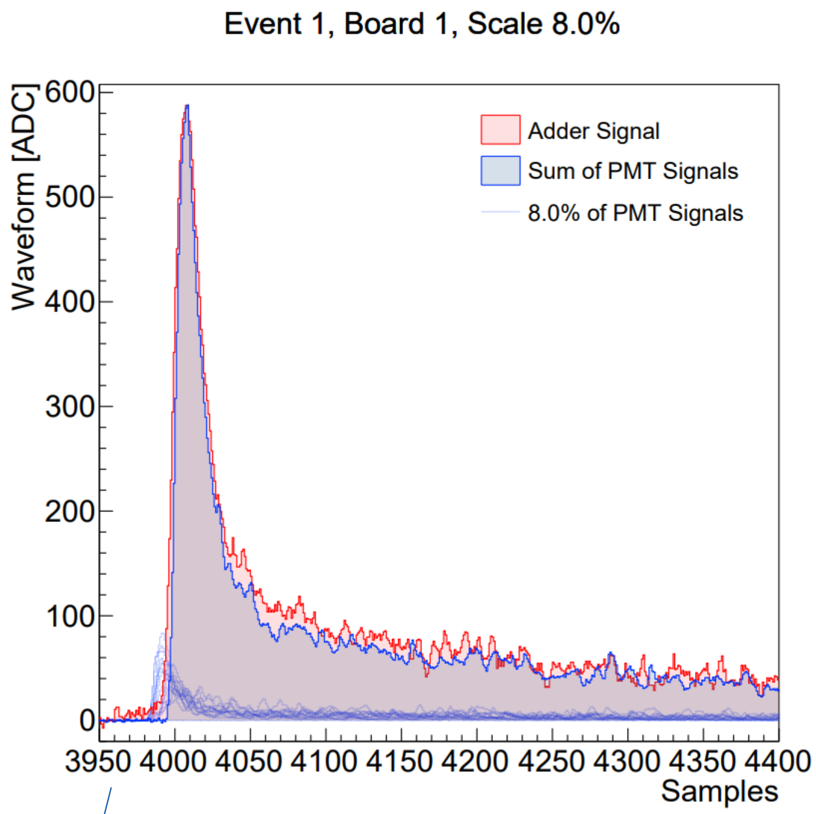
Waveform Analysis: adder waveform study

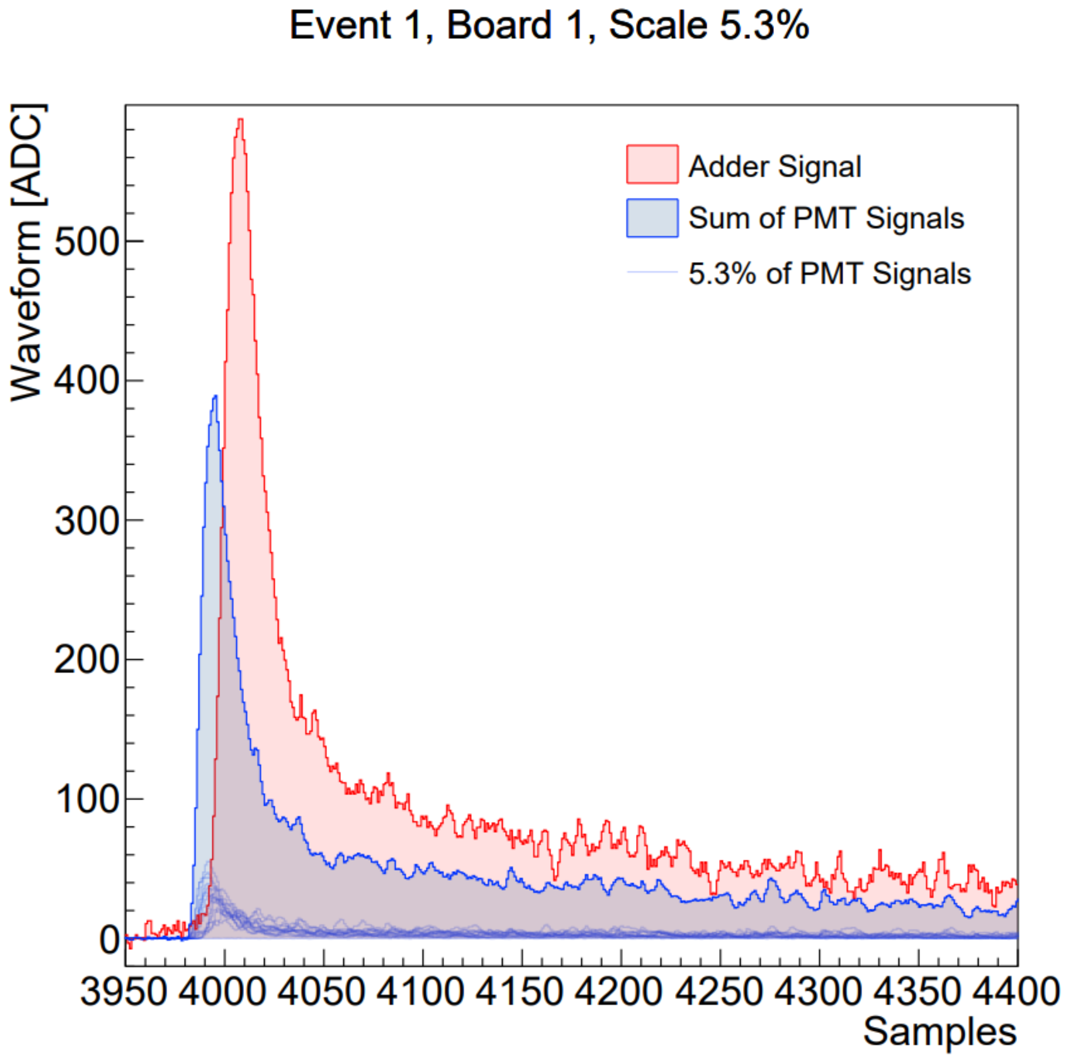
- The **adder** board outputs were connected to a spare channel of the digitizers to acquire waveforms
- The signal can be compared with an **emulation** of the adder processing:
  1. the 15 PMT signals corresponding to an adder board are scaled by a factor ~ 5.26% (since only the 95% of the PMT signals is digitized)
  2. the 15 signals are then added



Majority run #8889

Waveform Analysis: adder waveform study

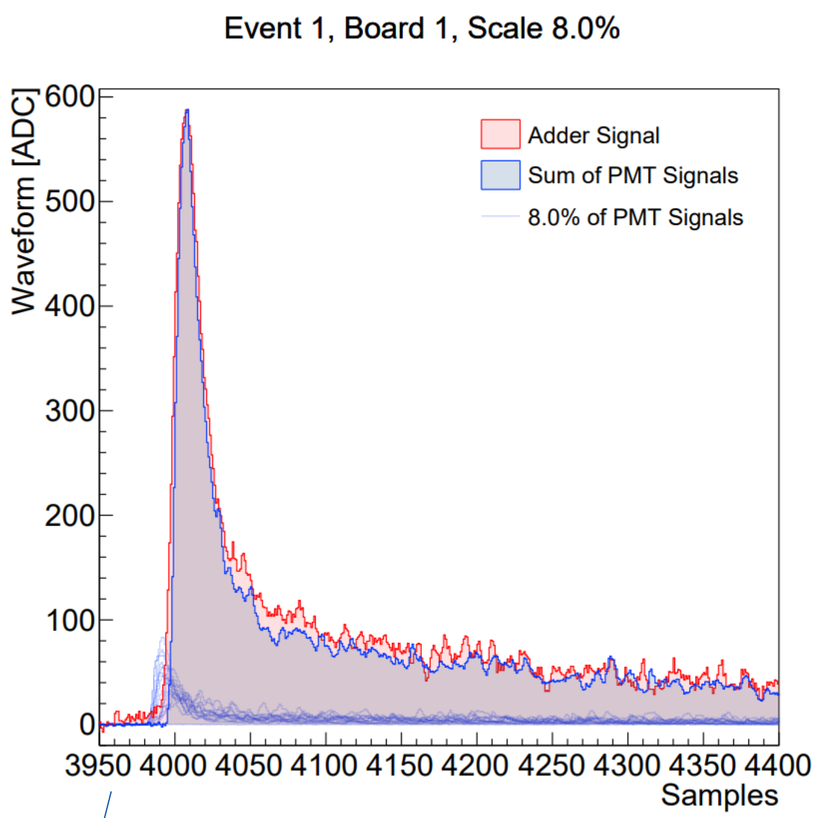




Scale factor for the single PMT signals changed to **8%** (from 5.26%)

Sum of the scaled PMT signals **delayed** by **13 samples**

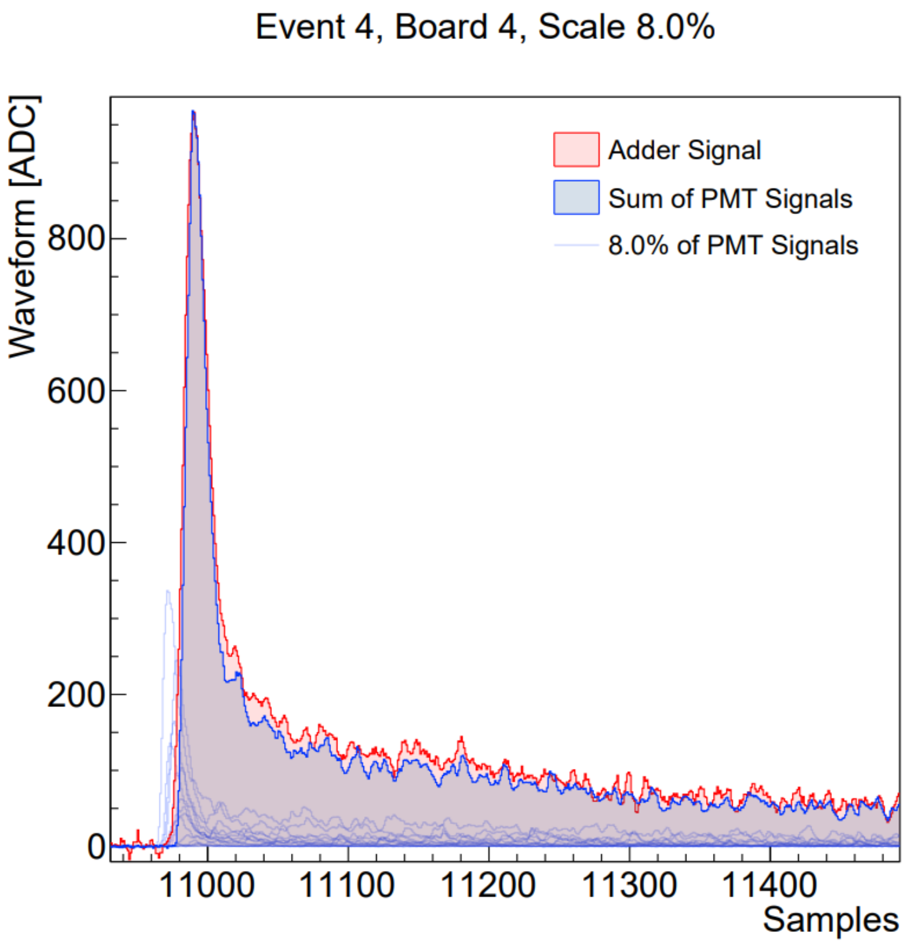
Waveform Analysis: adder waveform study



Scale factor for the single PMT signals changed to **8%** (from 5.26%)

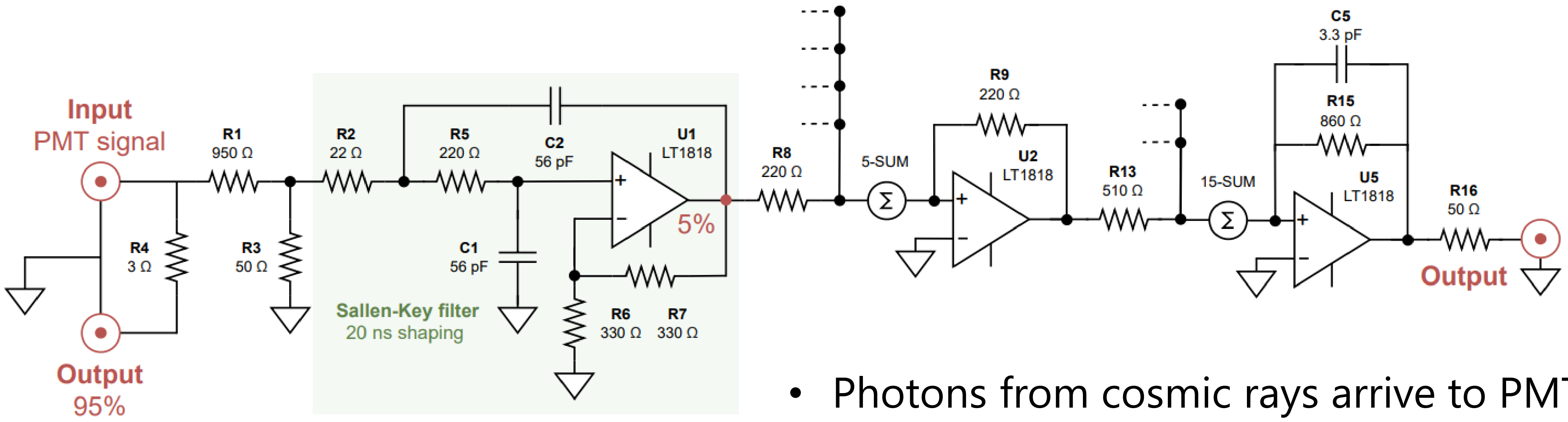
Sum of the scaled PMT signals **delayed** by **13 samples**

Same scaling factor and delay seem to **work** well with other boards and other events



Waveform Analysis: adder waveform study

Possible explanations to this **mismatch** have to be found in the adder **circuit**:



There is some **shaping** with the **Sallen-Key filter** (*integration constant* is equal to 20 ns)

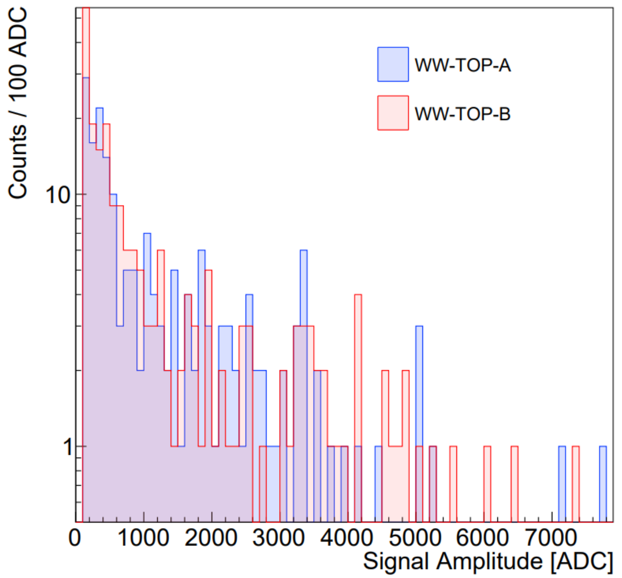
- Photons from cosmic rays arrive to PMTs **spread** in time
- The integration of spread pulses leads to an **amplification** effect (explaining the 8%)
- **Laser** pulses, narrower and synchronous on all PMTs (except for the transit time) should be used to verify this hypothesis

Waveform Properties: adders

Analyze each **waveform** and go through all the events for a given adder board (data were *cleaned up* with a very low **threshold** of 100 ADC or 12.2 mV):

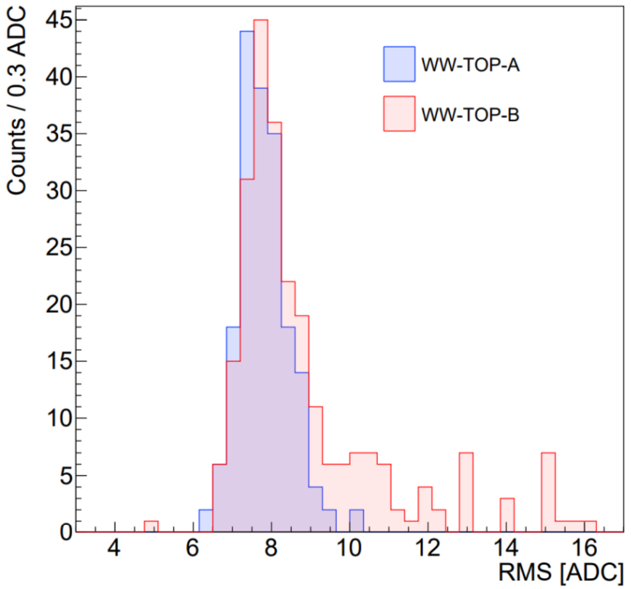
Majority
run #8889

Signal amplitude



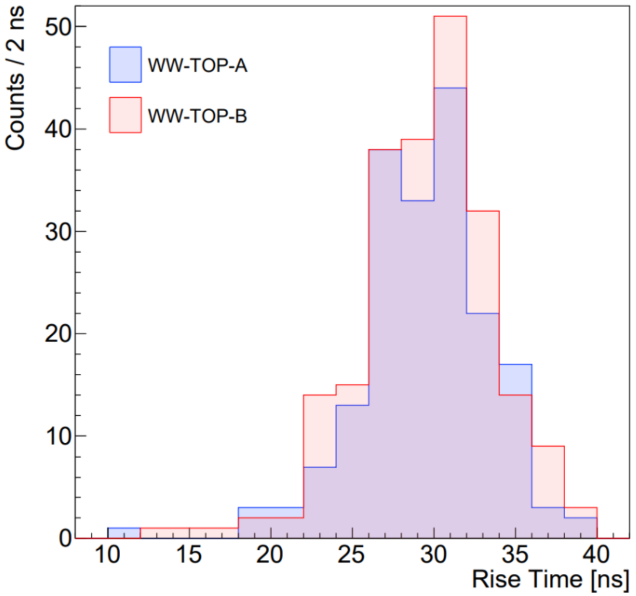
- Amplitude **varies** on a large scale with majority runs and cosmics (no control over triggering events)

Noise RMS



- **Noise RMS** is defined as the standard deviation of the baseline (i.e., non-hit samples)

Rise time



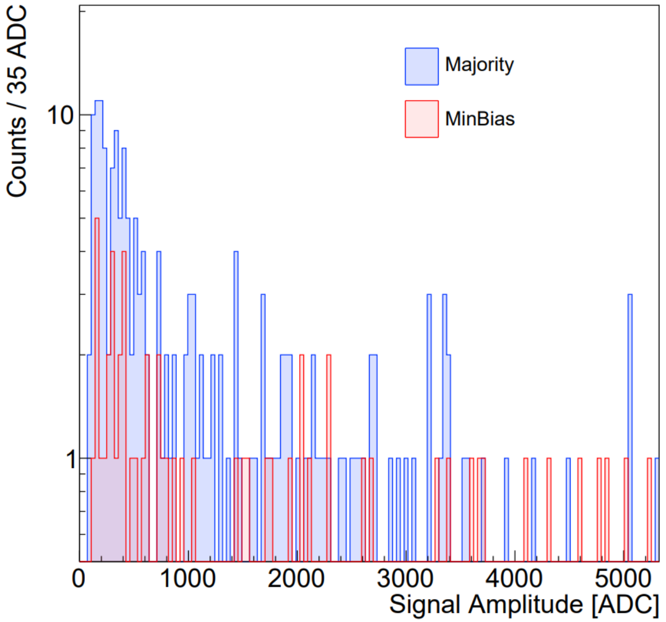
- The **rise time** of the signals is computed as the interval between peak and baseline

Waveform Properties: MinBias trigger

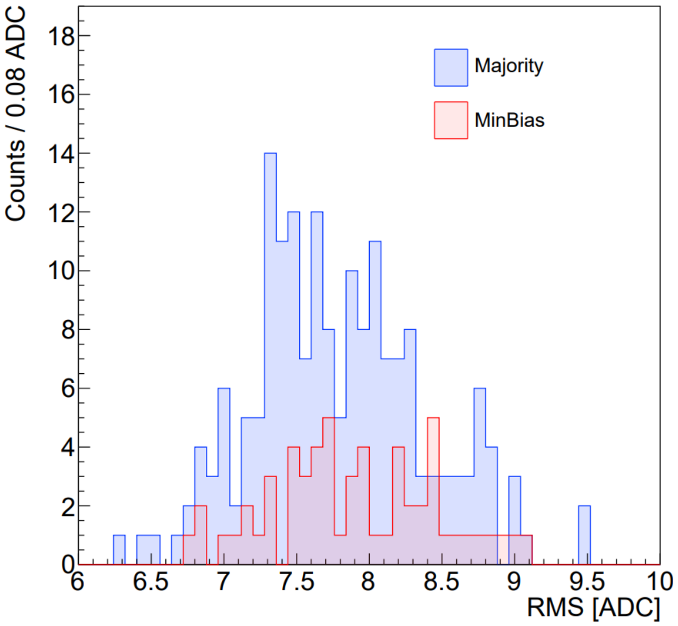
- In the **MinBias** trigger, parallel to the majority one, one does not impose any requirement on the coincidence of light (no bias from PMTs, only the presence of the beam gate is required)
- The same analysis was performed on a MinBias run: the distributions are **similar**, but the MinBias run contains less signals over threshold

Majority run #8889
MinBias run #8888

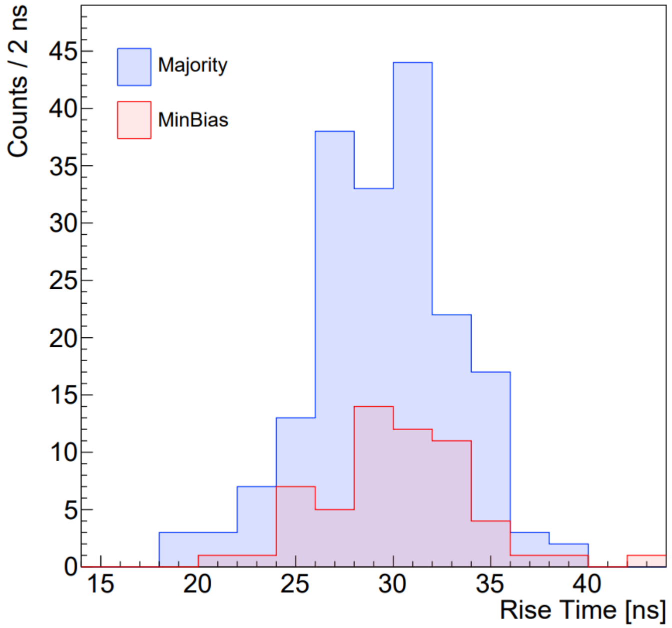
Signal amplitude



Noise RMS



Rise time

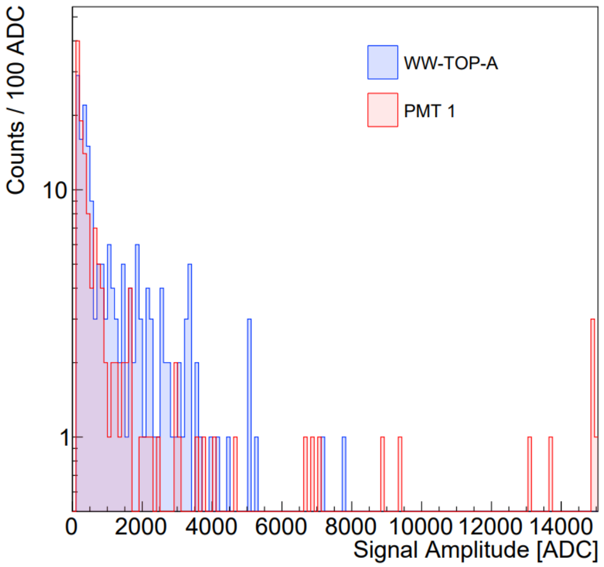


Waveform Properties: comparison with PMTs

Signals from a **PMT** of the corresponding adder board were processed in the same way:

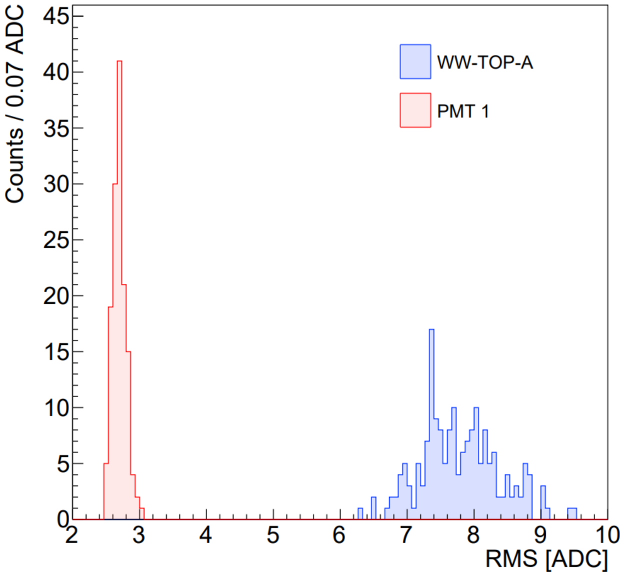
Majority
run #8889

Signal amplitude



- The adder overall has **more** signals over high thresholds, since it gathers the waveforms of 15 PMTs

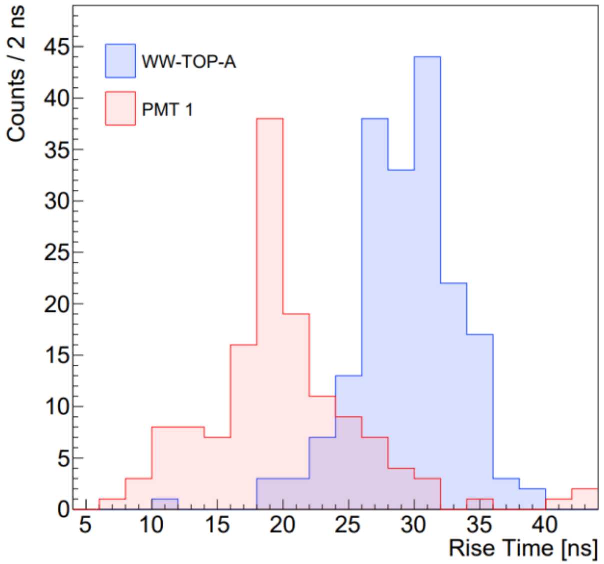
Noise RMS



Rise Time ~ 2.7 ADC
σ ~ 0.1 ADC

Rise Time ~ 7.8 ADC
σ ~ 0.6 ADC

Rise time



Rise Time ~ 20 ns
σ ~ 6 ns

Rise Time ~ 30 ns
σ ~ 4 ns

Waveform Properties: comparison with PMTs

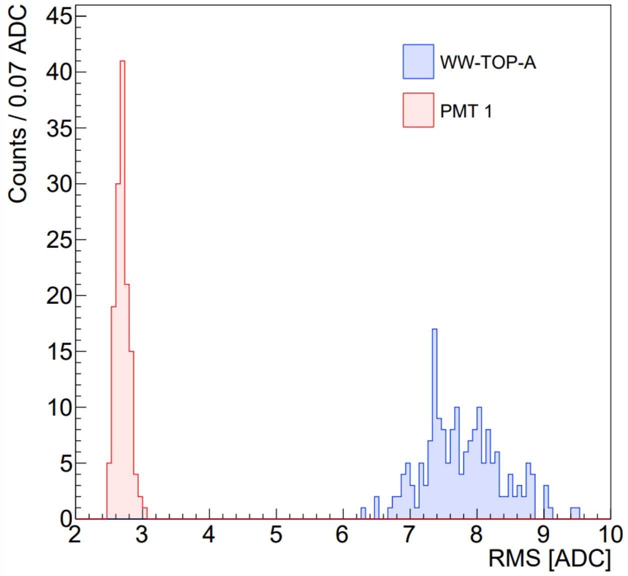
Signals from a **PMT** of the corresponding adder board were processed in the same way:

Majority
run #8889

Signal amplitude

- Adders are affected by more **noise** (factor 3 between RMS distribution's means)
- The **spread** of the adders' RMS distribution is way bigger w. r. t. PMTs (factor 6)
- The adder overall has **more** signals over high thresholds, since it gathers the waveforms of 15 PMTs

Noise RMS



Rise Time ~ 2.7 ADC
σ ~ 0.1 ADC

Rise Time ~ 7.8 ADC
σ ~ 0.6 ADC

Rise time

- This will **not** be an issue for an adder-based trigger: the signals are **big** enough and the **threshold** will surely be higher than 100 ADC (i.e., S/N > 10)

Rise Time ~ 20 ns
σ ~ 6 ns

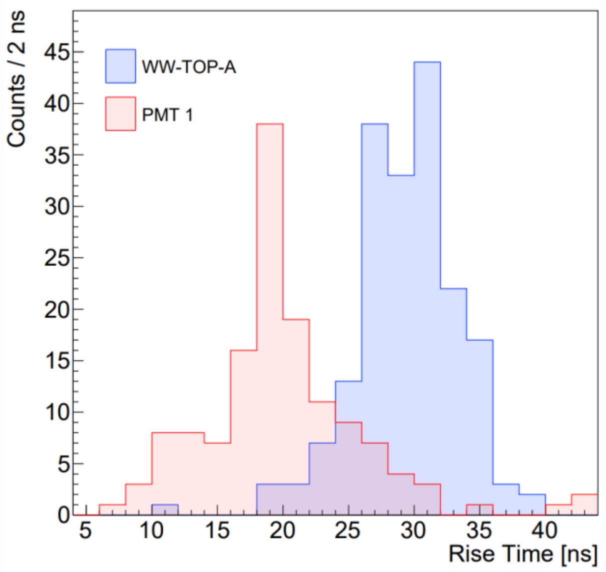
Rise Time ~ 30 ns
σ ~ 4 ns

Waveform Properties: comparison with PMTs

Signals from a PMT of the corresponding adder board were processed in the same way:

- The **PMT** rise time is shaped from ~ 8 ns up to ~ 20 ns
- The **adder** board takes it to ~ 30 ns due to:
  - *time spread*: each PMT has a 10 ns transit time and the adder sums up **non-synchronized** PMT pulses;
  - *geometry spread*: PMTs are **positioned** in different ways and the **trigger** does not necessarily come from a PMT of the considered adder
- This won't be an issue in an adder-based trigger: fixed with an appropriate **shaping** of the adder output signal (before further logic processing)

Rise time



Rise Time ~ 20 ns
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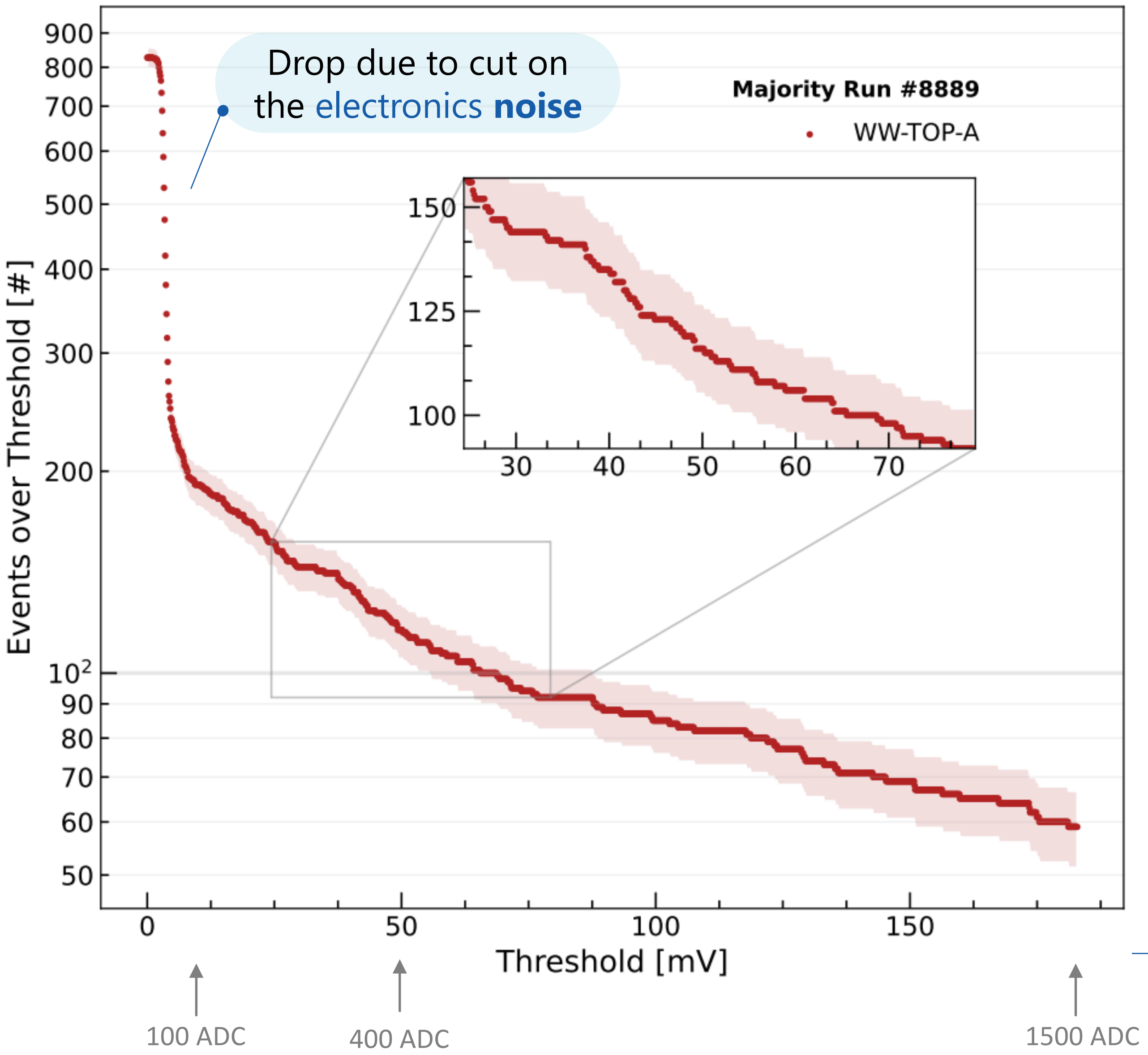
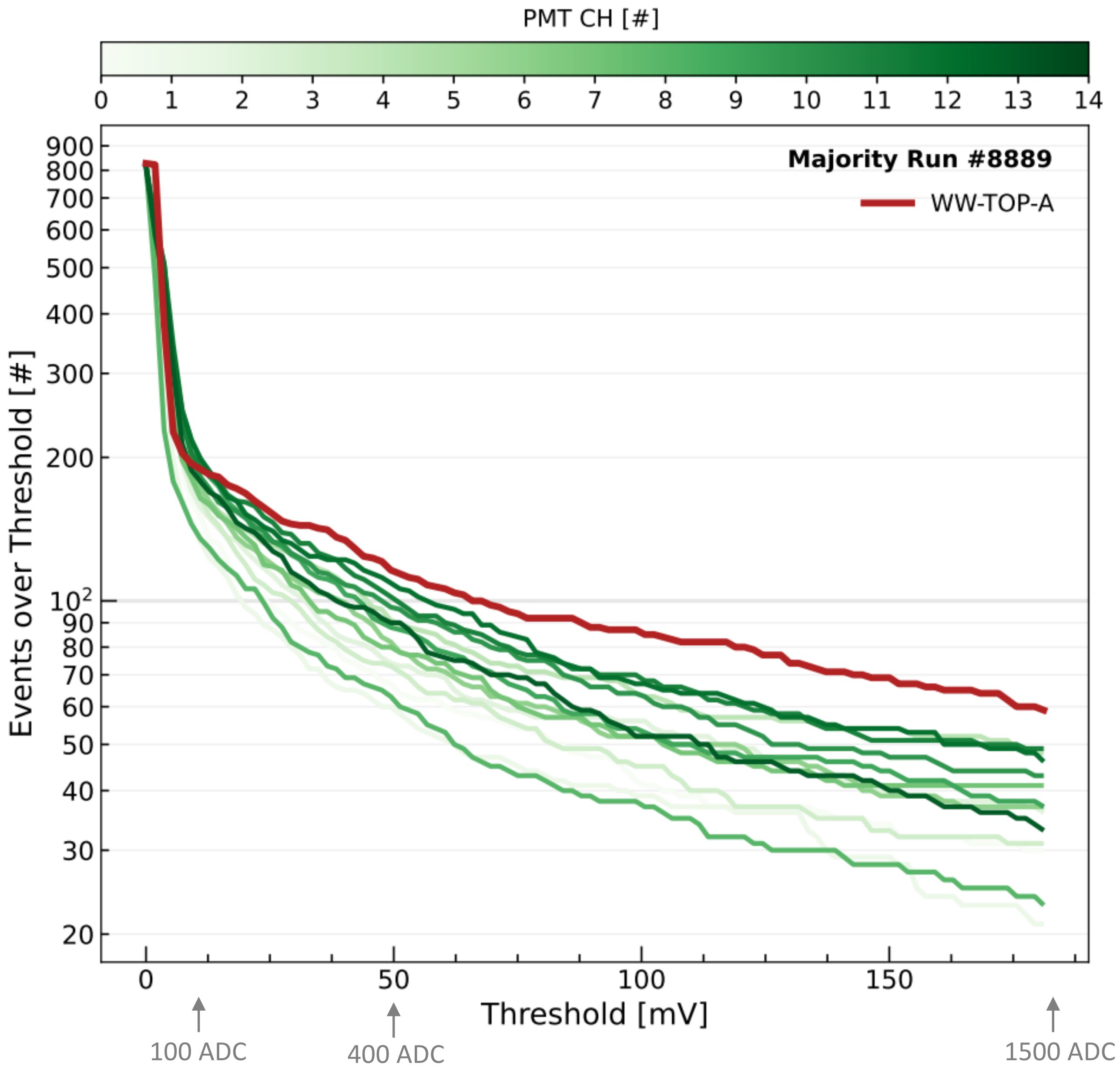
Adders Discrimination Thresholds



- Impose a signal amplitude **threshold** on the digitized adder signals and count the number of events **over** threshold
- We want to test whether there are any **drops** in this trend (e.g., due to the Ar-39 background with respect to cosmics) beyond the electronics noise
- For a threshold of 50 mV (~ 400 ADC), only ~ 15% of the events are over threshold

Conversion factor is 0.122 mV/ADC

Adders Discrimination Thresholds: comparison with PMTs



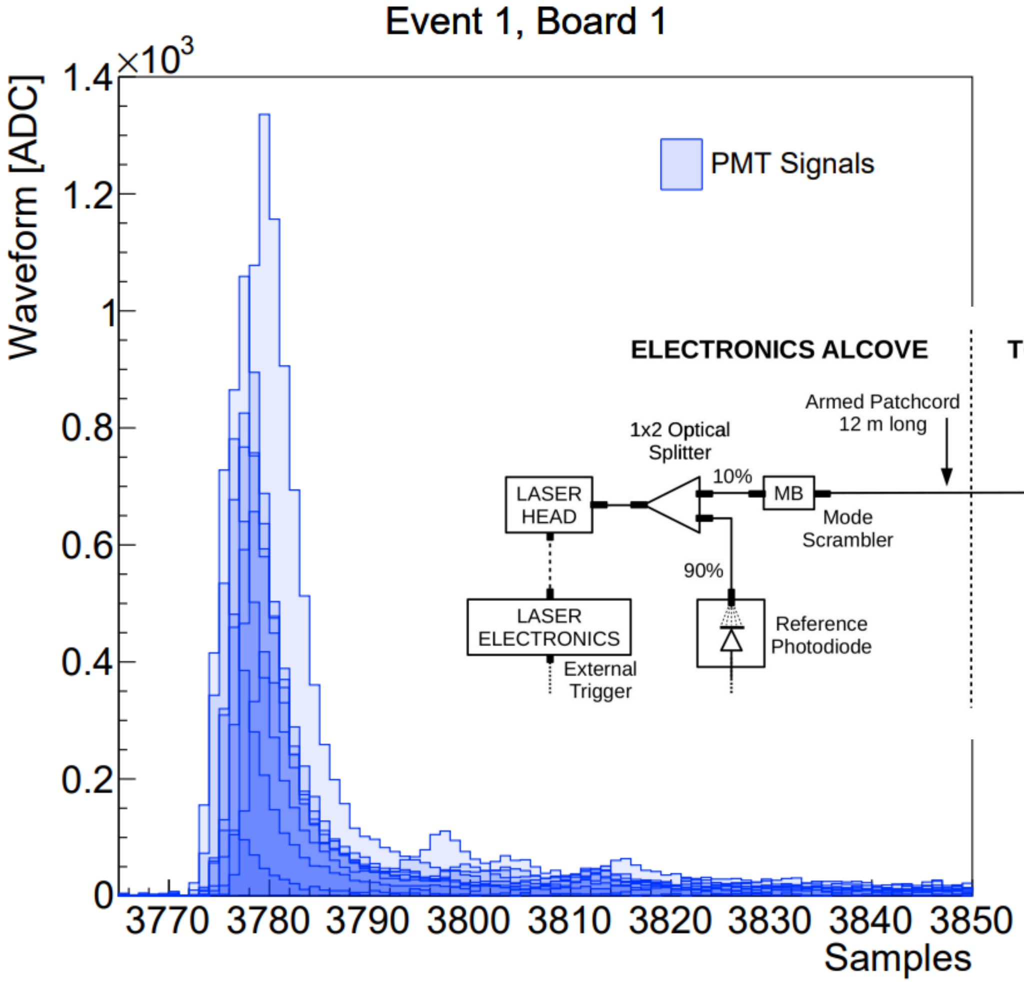
- The same analysis was performed with the **PMT** signals
- In this way, the **contribution** of each PMT to the adder signal is indirectly shown
- The trend in the tail is similar, but there are **more** signals over threshold for the adder w. r. t. a single PMT (it gathers 15 PMT signals)

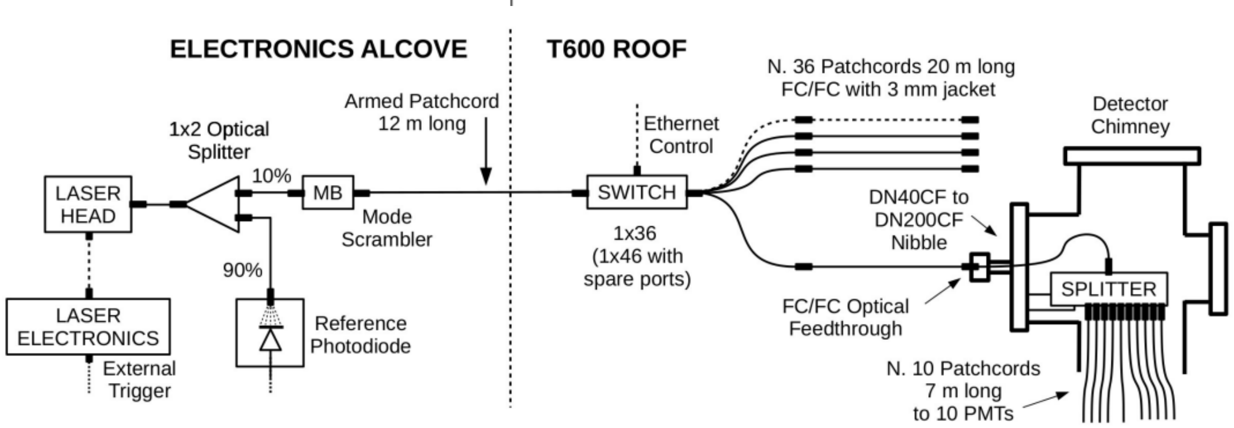
Future Developments

- Test the adders signal processing with **laser** pulses
- Investigate what is the **optimal** threshold based on data
- Need to **compromise** between threshold, rate and trigger efficiency
  - Lowering the threshold leads to an un-manageable rate (from the DAQ point of view)
  - Increasing the threshold, the efficiency (which we would like to improve with the adders) worsens
- Decide how to **implement** the adders within the ICARUS trigger system, in coincidence with the standard trigger

Thank you!

Backup: laser system





- **Laser**-based calibration system for PMT response time delay determination and monitoring
- Fast light **pulses** are generated by a Hamamatsu PLP10 laser diode (60 ps FWHM, 120 mW peak power, 405 nm) and sent to 10 PMT channels at a time
- It will be employed in the future to test the adder signal processing precisely

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