Measurement of SiPM External Crosstalk in a LXe detector

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Light Detection in Noble Elements (LIDINE) Conference, Warsaw, Poland, Sept. 21-23, 2022

Motivation: Why study EXT?

- Silicon photomultipliers (SiPMs)
  - Excellent single photon counters
  - To be used in next-generation rare event search experiments
- During the avalanche process IR photons are emitted
  - Photons can trigger avalanches in neighbouring SPADs (**Direct Crosstalk**)
  - Liberate charge carriers outside of depletion region and drift into neighbouring SPADs to trigger an avalanche (**Delayed Crosstalk**)
  - Lastly, they can leave the SiPM entirely and create an avalanche on another device (**External Crosstalk**)
- Understanding External Crosstalk (eXT) is important for gauging its effect in next-generation experiments

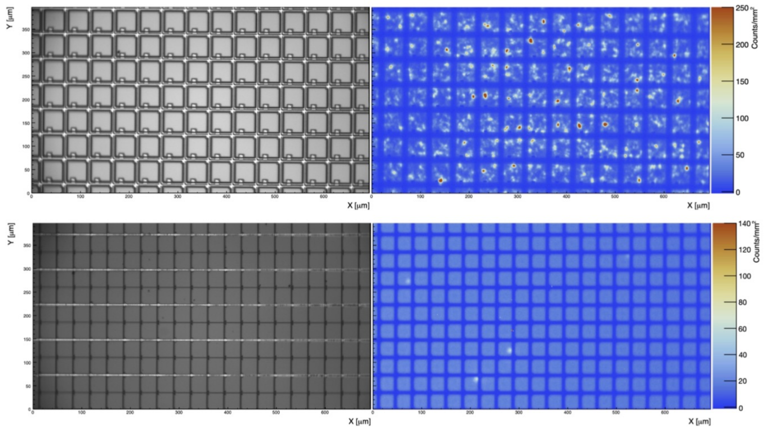
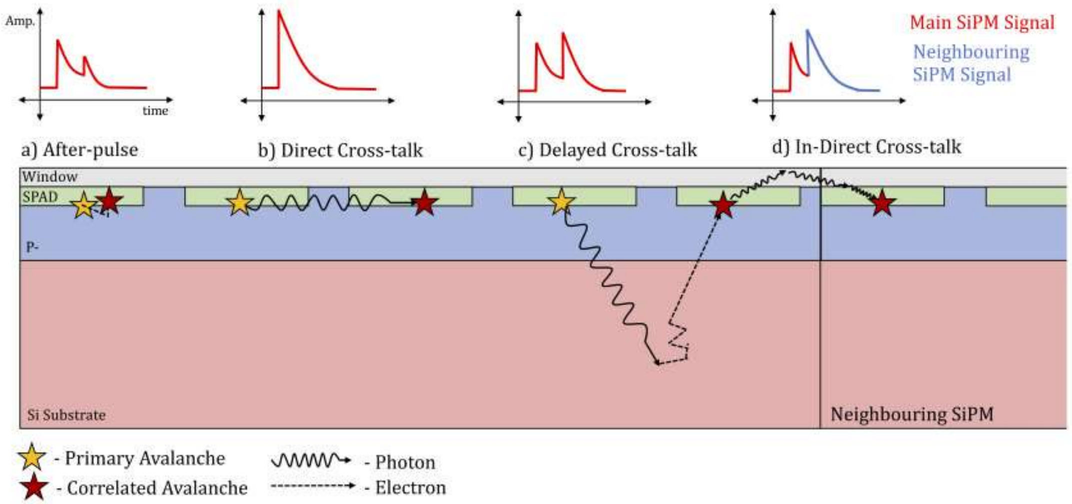


Figure 3. Top row: Emission microscopy image (EMMI) of the HPK VUV4 biased at 11.2 ± 1.0 V of over voltage. Bottom row: EMMI of FBK VUV-HD3 biased at 13 ± 1 V of over voltage. Both EMMIs were taken with the same camera exposure time and objective lens: LMPLFLN20X (20× magnification).

Figure: Emission of photons from SiPMs from [1]

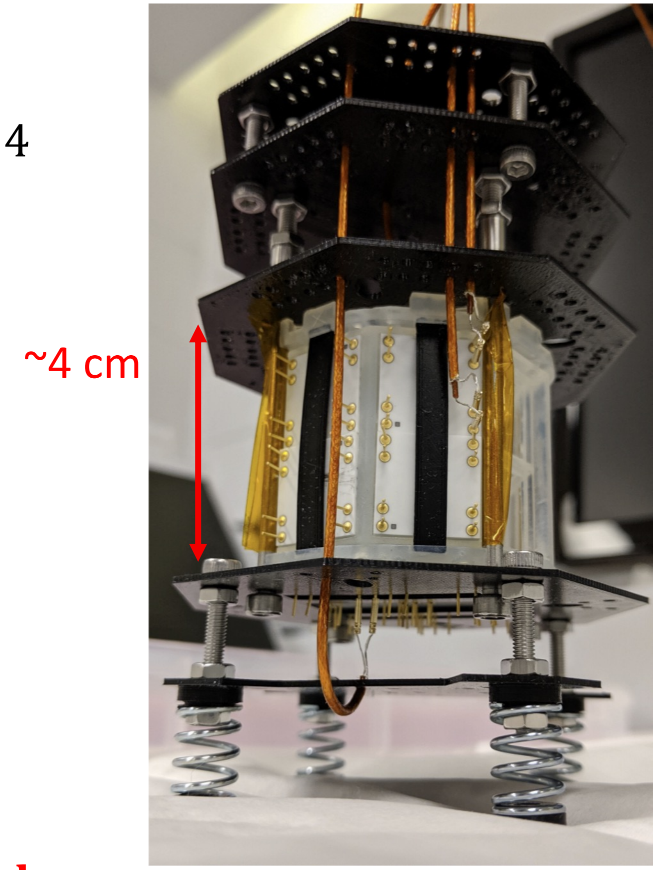


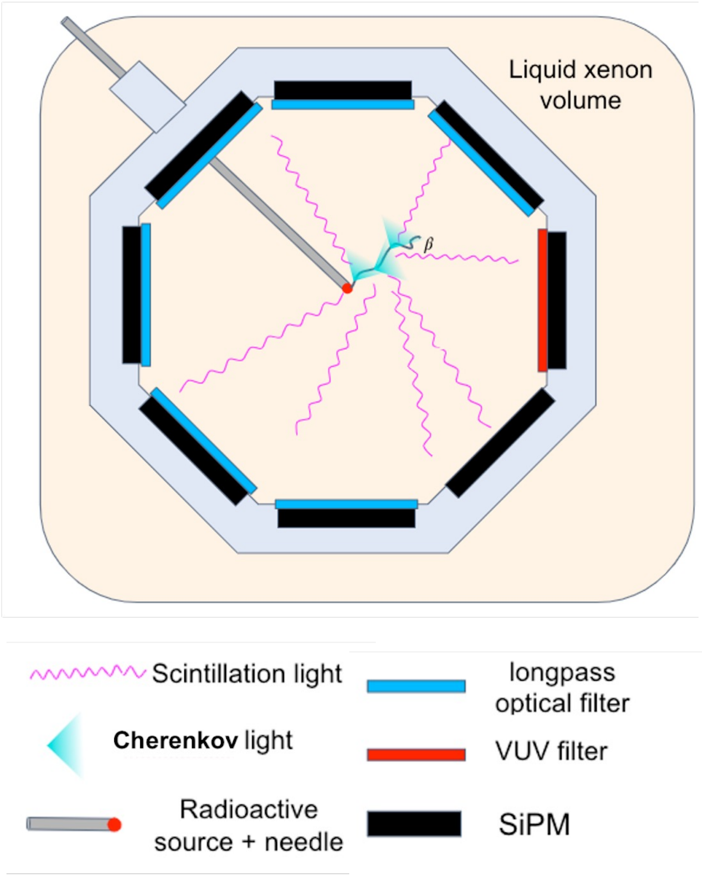
Experimental Setup: LoLX

The current design of the "Light only liquid xenon" (LoLX) experiment is a modular (3D-printed), light signal only, liquid xenon (LXe) detector employing 24 Hamamatsu VUV4 MPPCs (96 Total SiPMs)

Main research goals include:

1. Characterize LXe light emission, including scintillation and Cherenkov yields and transport efficiencies
2. Validate performance of silicon photo-multipliers (SiPMs) in LXe
3. **Develop an understanding of SiPM external cross-talk**





Figures: Left – LoLX during test assembly, Right – Diagram of current LoLX design, with Sr90 source needle shown

Methodology

- Photon emission correlated with an avalanche can be detected in surrounding SiPMs
- We look at **late hits** on SiPM channels for candidate pulses
- Once we find a candidate pulse, we look at all other channels for **correlated** hits
- Look at many events for excess over random correlation
- A few cleaning cuts:
  - Events must have a well defined 't0'
  - Events must have only one sub-event (Cut on pileup)
  - Triggered pulses must be SPE-like
- Data taken at 4 and 5V over voltage

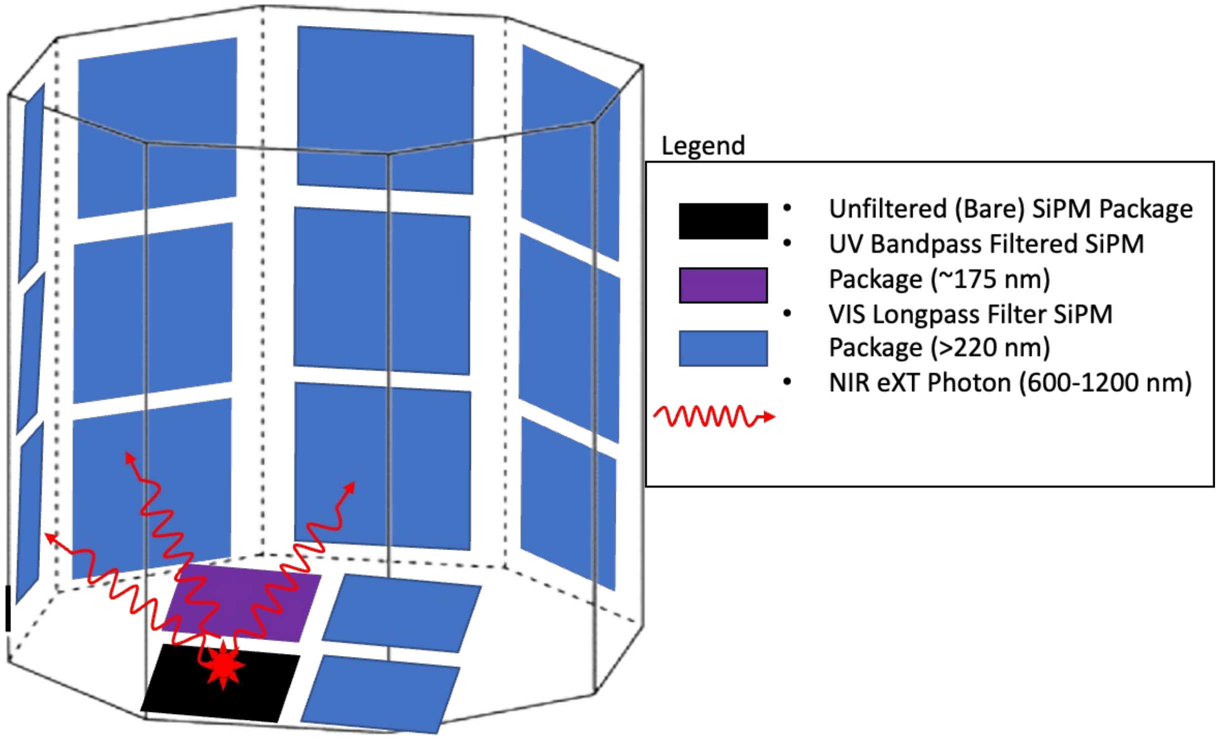


Figure: Sketch of LoLX with "bare" SiPM as eXT source, LoLX uses 24 Hamamatsu VUV4 Quads see Neutrino Poster for LoLX overview [link]

Methodology – Continued

LoLX

- Start by finding a bare pulse in a 'late' window
- Late Window = [900,1500] ns after the t0 of the physics event
- Once we find a triggered 'hit' we look for correlated hits around the bare hit [-100,300] ns
- If we find a hit on another SiPM in the correlation window we count it and record its time difference from the triggered hit (delta-t)

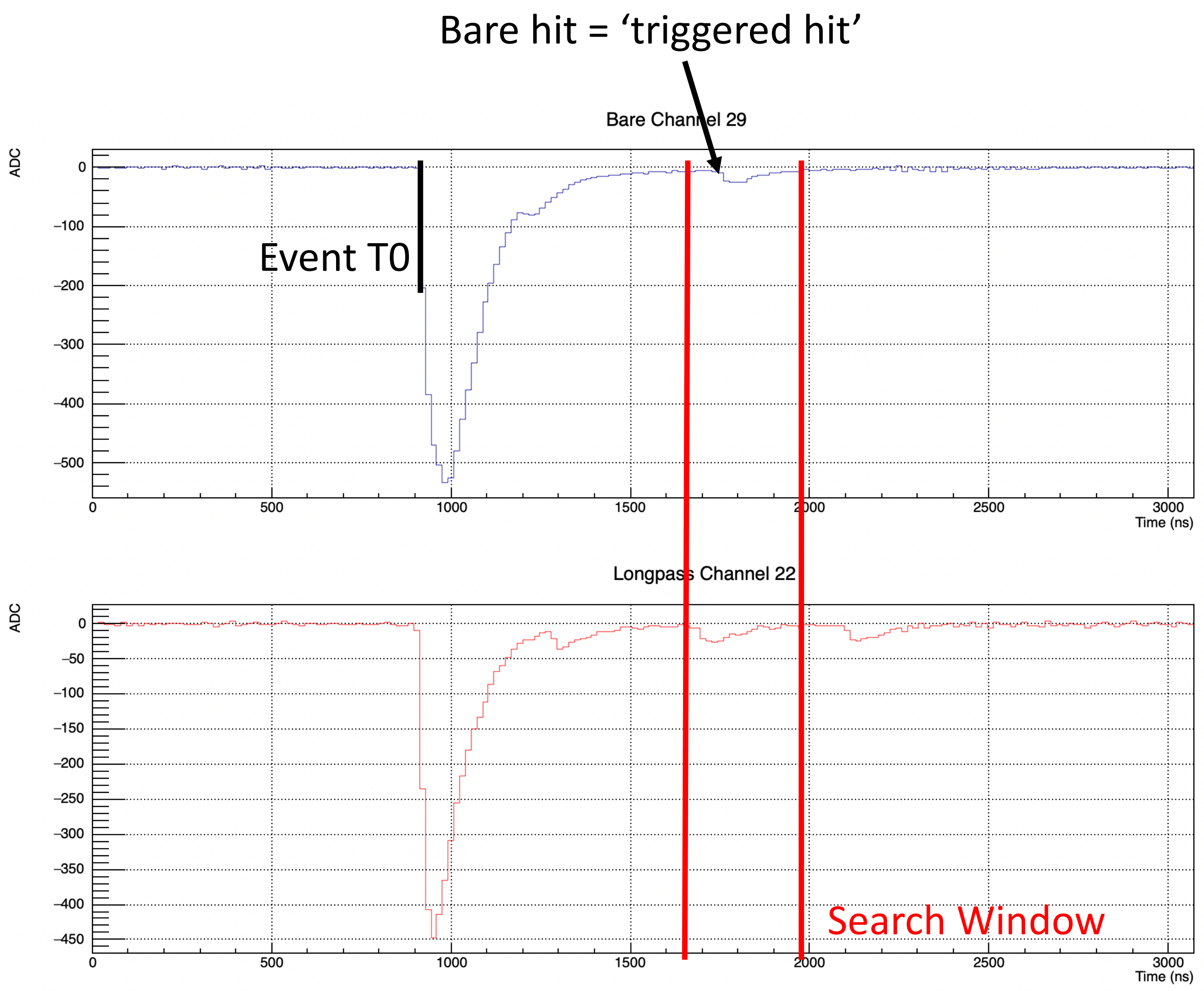


Figure: Waveforms from 2 LoLX channels from a "physics" event

Analysis - Overview

$$Probability = \frac{Total\,Counts - Estimated\,Background\,Counts}{Triggered\,Bare\,Hits}$$

- Here we take the unfiltered "bare" package (4 channels summed) as the "source" to start
- Use linear background term to estimate uncorrelated contribution in signal region
- Probabilities for all >220 nm filtered channels shown below (From bare package as source)
  - **Probability for 5 V OV = 5.8 +/- 0.2 % (stat.)**
  - **Probability for 4 V OV = 2.8 +/- 0.2 % (stat.)**

PRELIMINARY

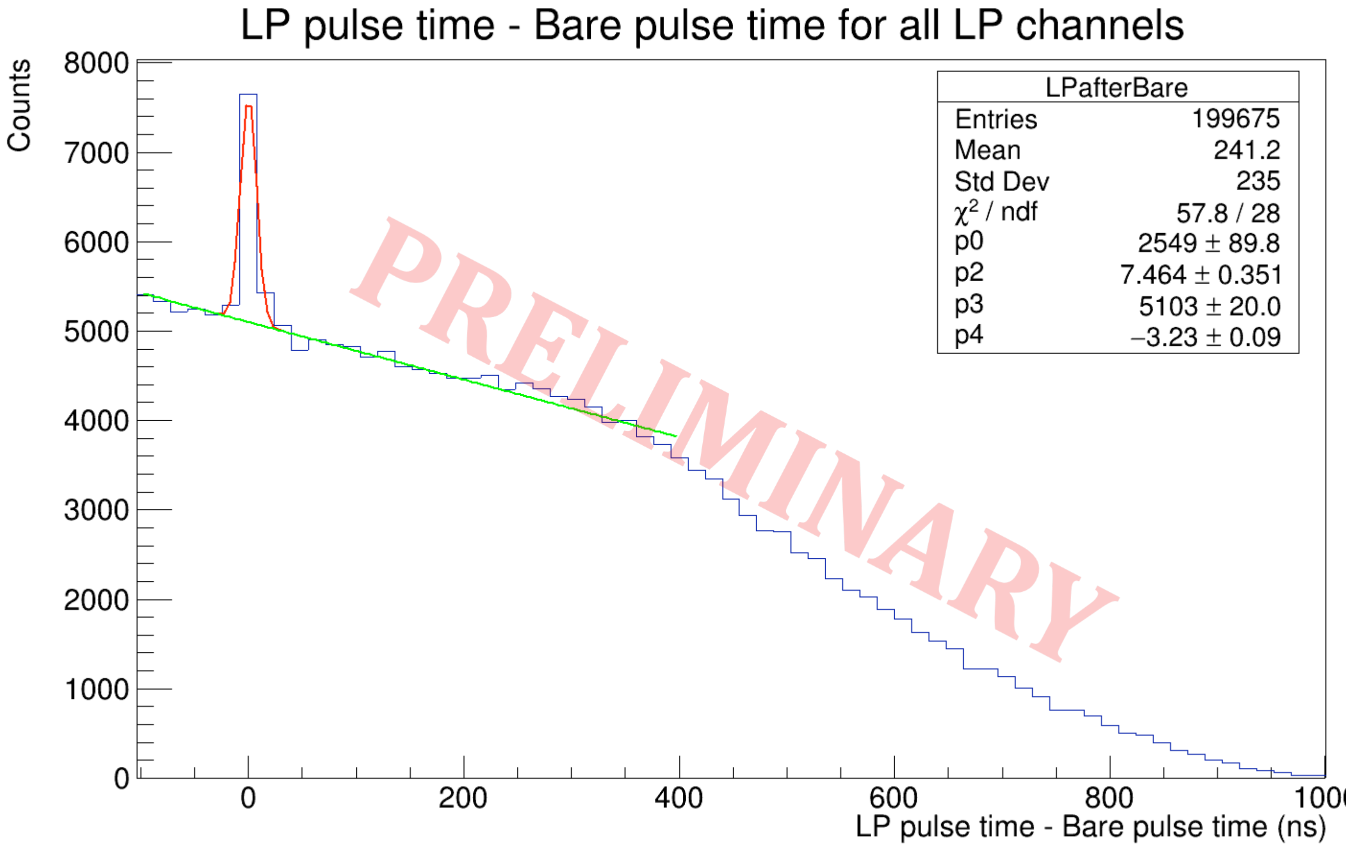
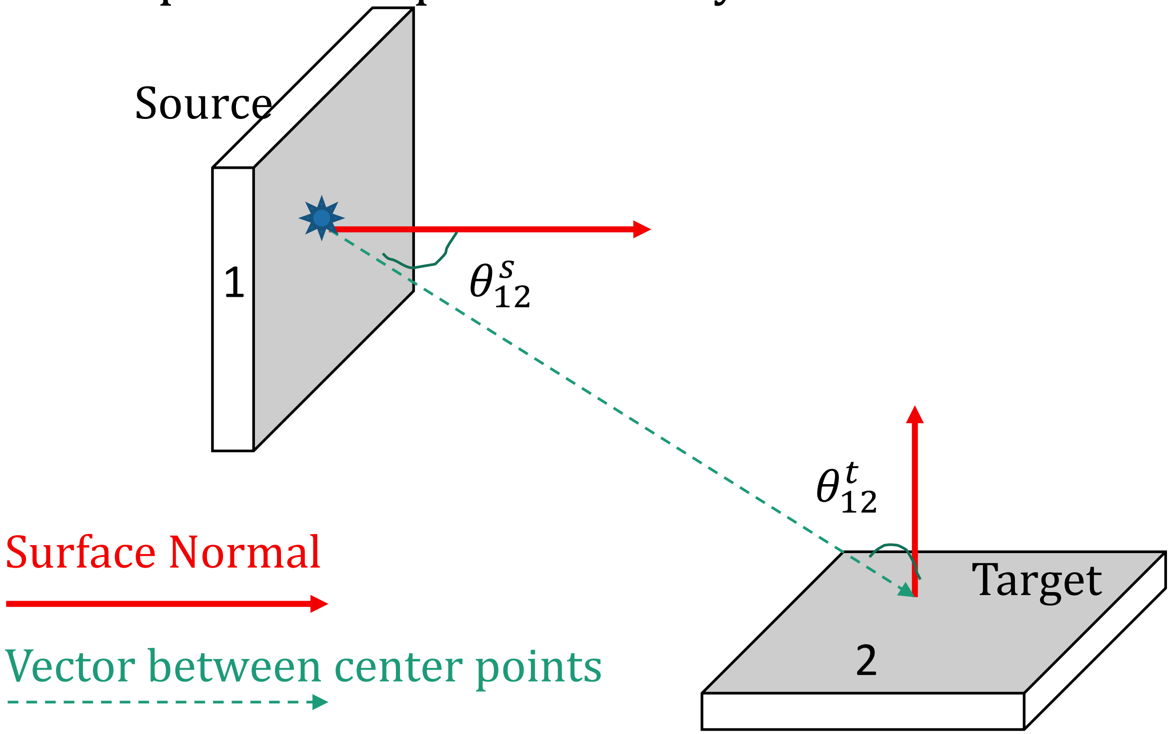


Figure: Delta-Time for all LP (>220 nm) filtered channels, 5V OV

Interpreting SiPM External Crosstalk

SiPM eXT depends on:

- Voltage on SiPM (Gain)
- Temperature (Gain)
- The orientation of the source SiPM (θ_{12}^{s} here)
  - Angular dependence on emission direction due to surface optics (SiPM and environment)
- The orientation of the hit (Target) SiPM (θ_{12}^{t} here)
  - Angular dependence on detection efficiency ($\sim\cos\theta$)
- Optical transport efficiency of detector in NIR



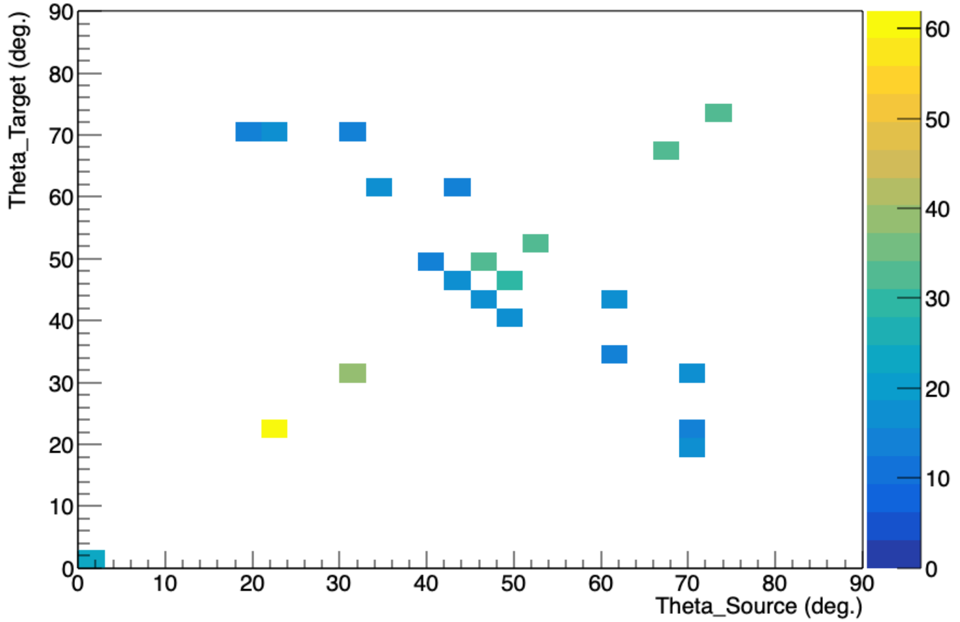


Figure: Distribution of source and target orientations within LoLX

Results - Data

LoLX

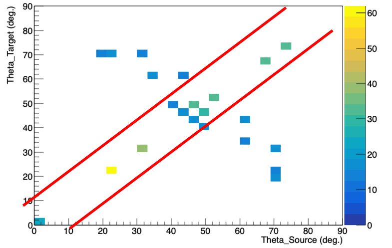
We use the solid angle from SiPM to SiPM (Calculated in MC) and use it to scale the correlated hit probabilities when looking at all SiPMs at once

Important notes:

- No way of knowing which SiPM in each "pair" is the "source" of EXT in data
- In order to understand eXT generally we look at angular distributions for channel pairs and sort by SiPMs with similar acceptances **both ways** (See top right plot)
- This allows easier interpretation of data using SiPMs that are facing each other and that have similar orientations

- No clear take-aways here yet, still working on understanding systematics and other potential confounding factors

Include pairs within lines



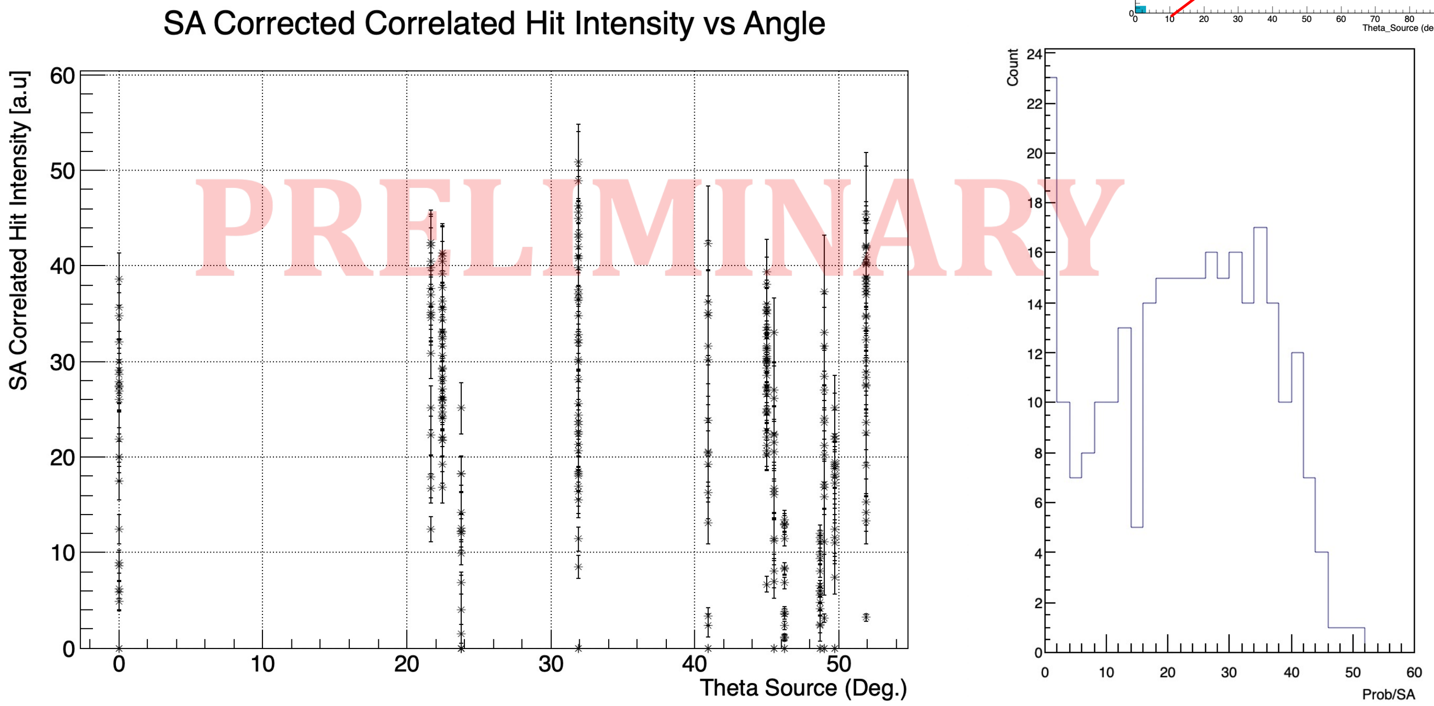


Figure: Left - Comparison of SA Scaled Correlated Hit Probability for a selection of LoLX SiPM pairs, 5V OV bias, Right – 1D projection of left plot along y-axis

Results – Data

We can compress the 2D data into a profile distribution to see if there's any obvious trends

No uncertainties on solid angle for now (Y-errors should be larger here, only stat. err from fits)

Some slight favoring for small angles, but nothing concrete

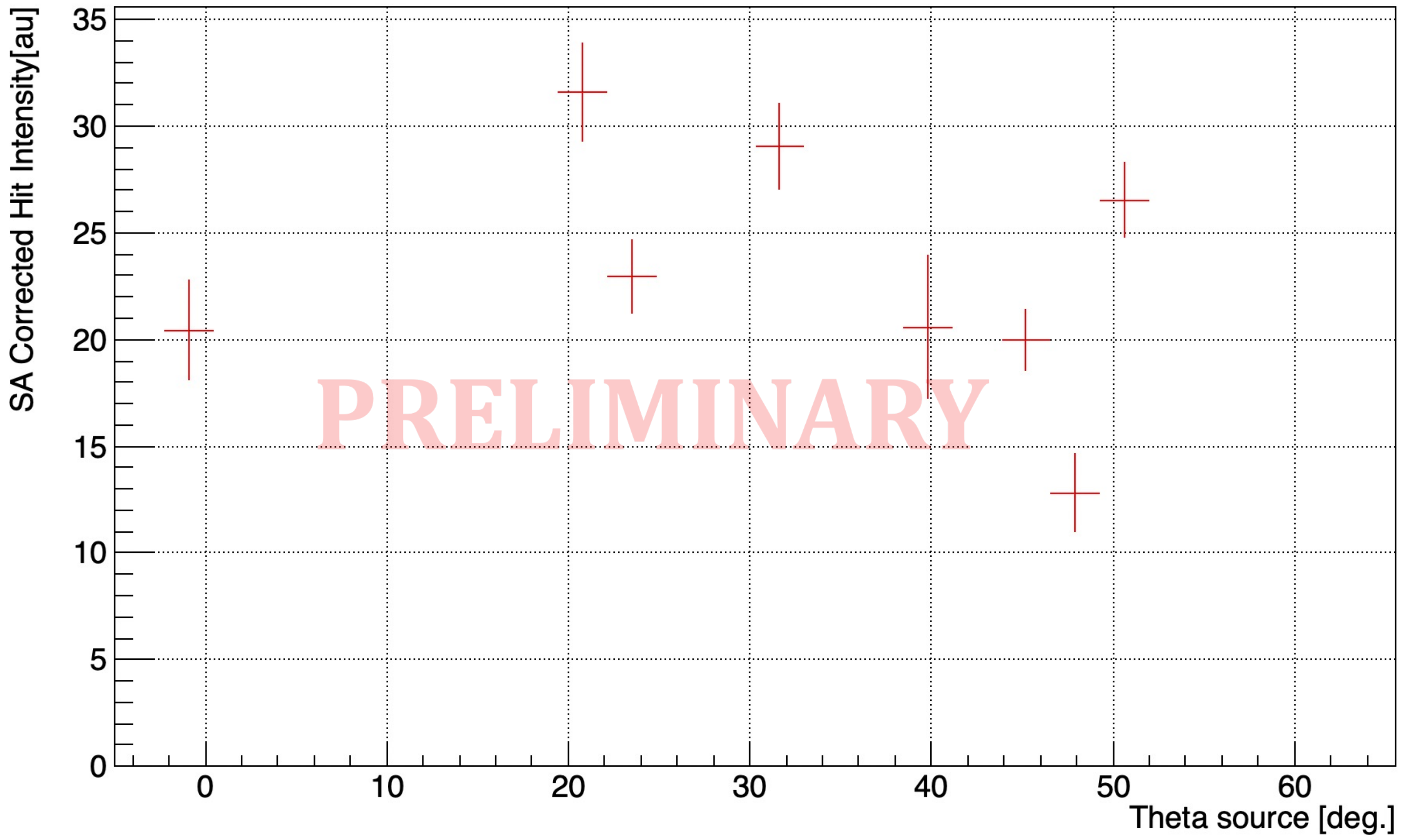


Figure: Profile distribution of selected SiPMs with similar orientations

Simulation – Input Requirements

- Simulation works with custom G4OpBoundaryProcess class
  - Successful "hits" on the SiPMs trigger the EXT Production class
  - Secondary photons are flagged and generated in a hemisphere normal to the surface of the target SiPM at the point of detection
  - SiPM Target, Intensity of simulated EXT light, and options for refracted distribution of emitted light is controlled by macro parameters
- Need input data for reliable simulations!
  - Some data points are well-defined, others need additional constraints from future measurements
- Well defined data points:
  - Refractive index and optical properties inside detector
  - Outgoing photon wavelength (Spectral measurements from TRIUMF [Link])
- Data points that need constraining:
  - SiPM efficiency in NIR region
  - Incident angle SiPM efficiency dependence in NIR
  - Filter optical properties in NIR
  - **Emitted photon angular distribution in LXe (See Figure Right)**
- Due to large difference in r-index between Si and LXe/SiO2, internal reflection is high!
  - **~96% emission reduction at 650 nm**

PRELIMINARY

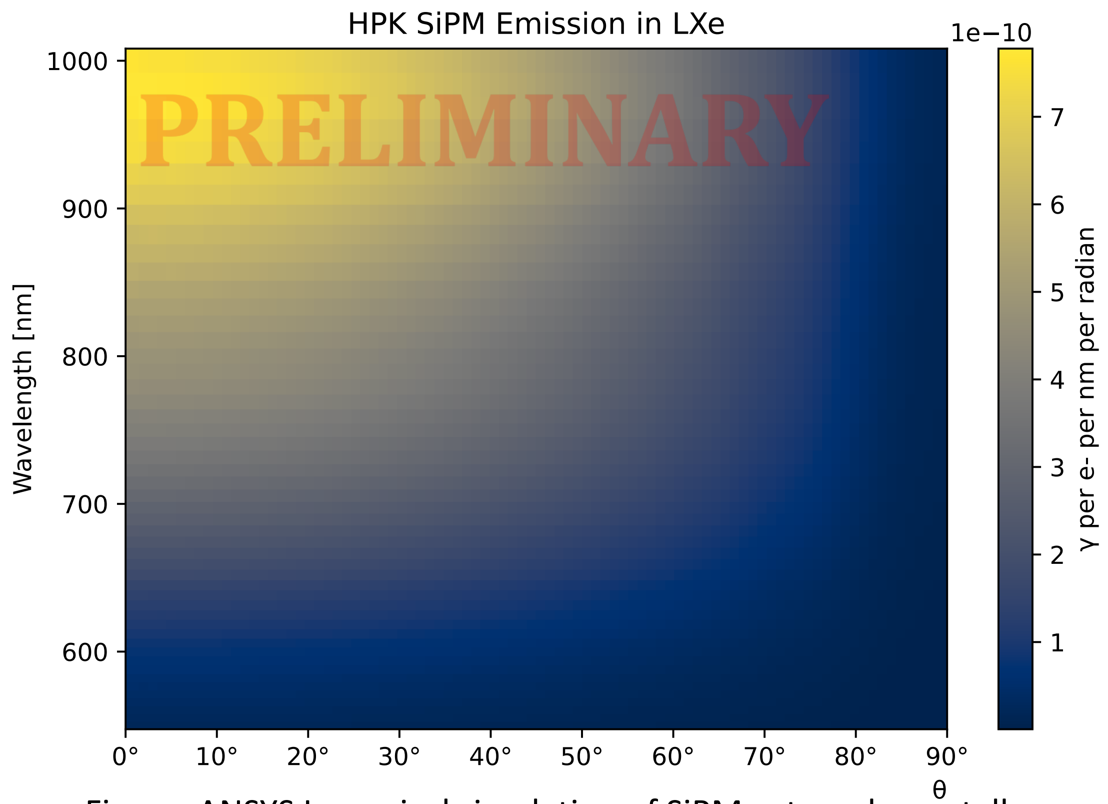


Figure: ANSYS Lumerical simulation of SiPM external crosstalk from Hamamatsu VUV4-Q in LXe, z-axis is scaled to preliminary results from TRIUMF on EXT emission measurements vs SiPM current

Simulation – Preliminary Results

- To estimate the mean number of photons emitted per avalanche (λ_γ) needed to describe our data with current simulation inputs (See previous slide) we run simulations with the unfiltered package as the source
- Simulation predicts an intensity of ~40 ph/avalanche produced to match data at 4V
  - However, we need to account for acceptance of signal with 2-way correlations from other SiPMs
- Factoring the hemisphere of emission, and conservatively assuming 50% backwards correlation* in data probability, we expect about **approximately 10-15 ph/Avalanche on average**

PRELIMINARY

* See Backup Slide for description of backwards correlation

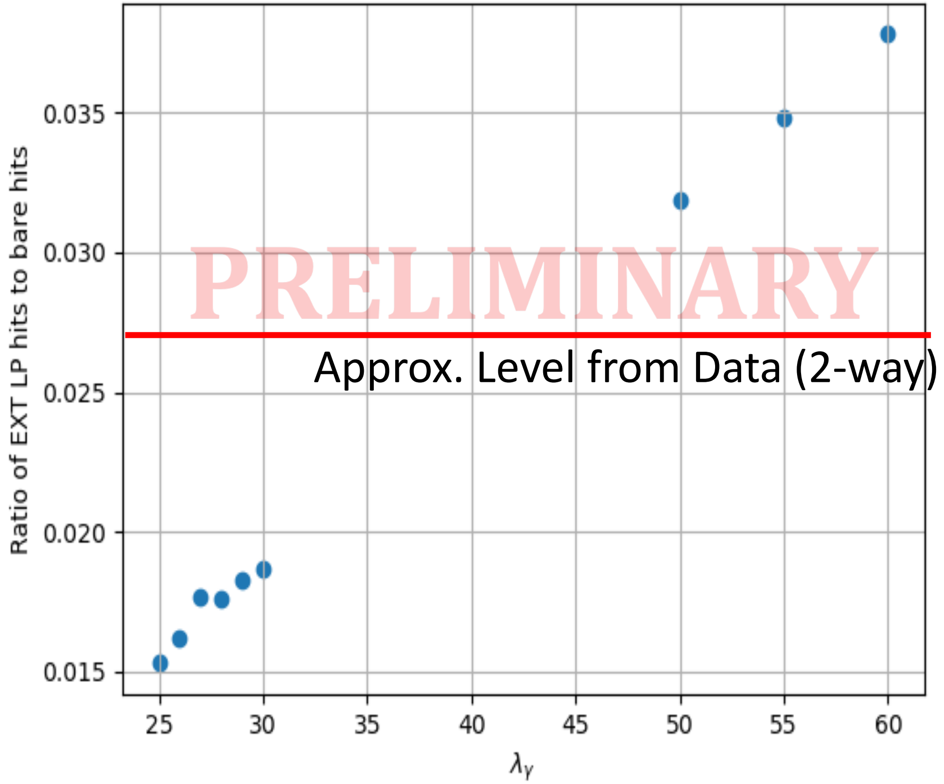
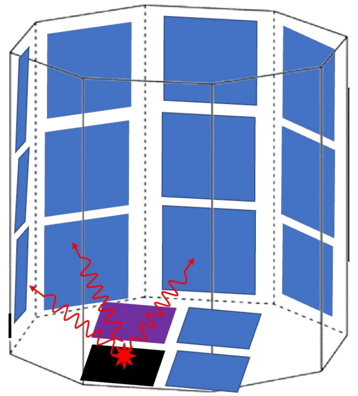


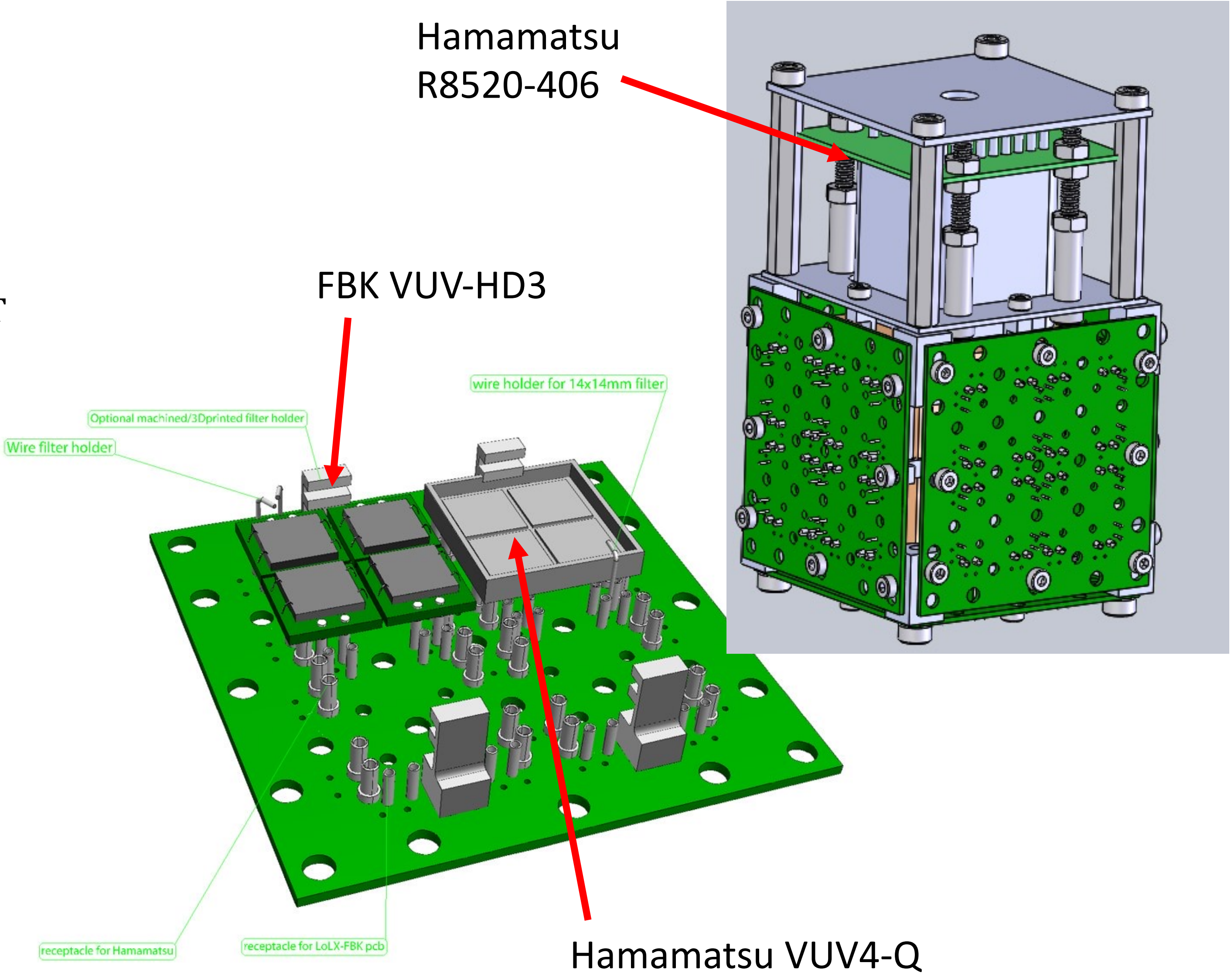
Figure: Scan over avalanche EXT intensity from the bare package source

Figure: Bare SiPM as source to all other SiPMs



LoLX in the Future

- Second iteration of LoLX planned for taking data 2023
  - LoLX^2 , new cubic version of LoLX
- Addressing a few issues:
  - Comparison of Hamamatsu VUV4 SiPMs and FBK directly in LXe
  - Benchmark comparisons against VUV sensitive PMT
    - Hamamatsu R8520-406
  - Tackle system stability with upgraded cryogenics system
    - Enables long-term (O(several weeks)) studies of LXe SiPM performance
- Upgraded DAQ system using 5 GSPS digitizer from MEGII (WaveDream)
  - Enables detailed scintillation timing studies which will be combined with spectral filtering
- Plan to measure VUV PDE relative to PMT for FBK and Hamamatsu SiPMs in LXe in early 2023
- Other studies of LXe scintillation properties and eXT will proceed afterwards



Conclusion and Outlook

- Studied SiPM External cross-talk directly in a liquid xenon detector
  - Voltage dependence of eXT under investigation, lower voltage runs require upgrades to pulse finder analysis
- Developed GEANT4 Simulation for SiPM eXT, preliminary simulations indicate an intensity of **~10-15** ph/Avalanche at 4V
  - Similar to ex-situ measurements from TRIUMF [1]
- Systematic uncertainties under investigation
  - Gain fluctuations due to temperature changes
  - Analysis window and event selection
  - Solid angle and simulation uncertainties due to simulation optics
- Manuscript is in progress!
- New detector expected to be installed with upgraded cryogenics this fall
  - Upgraded DAQ installed already and operating well

Thank you from the LoLX Collaboration!

TRIUMF

Fabrice Retière,
Chloe Malbrunot
Austin de St. Croix,
Peter Margetak,
Khurshid Usmanov

McGill

Thomas Brunner, Soud Al Kharusi, Eamon Egan,Lucas Darroch, Bernadette Rebeiro, Lisa Rudolph, David Gallacher

Carleton University

Simon Viel, Bindiya Chana

SNOLAB

Pietro Giampa

INFN PISA
Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

Luca Galli, Marco Francesconi

Université de Sherbrooke

Marc-André Tétrault, Alaa al Marsi

Rensselaer Polytechnic Institute

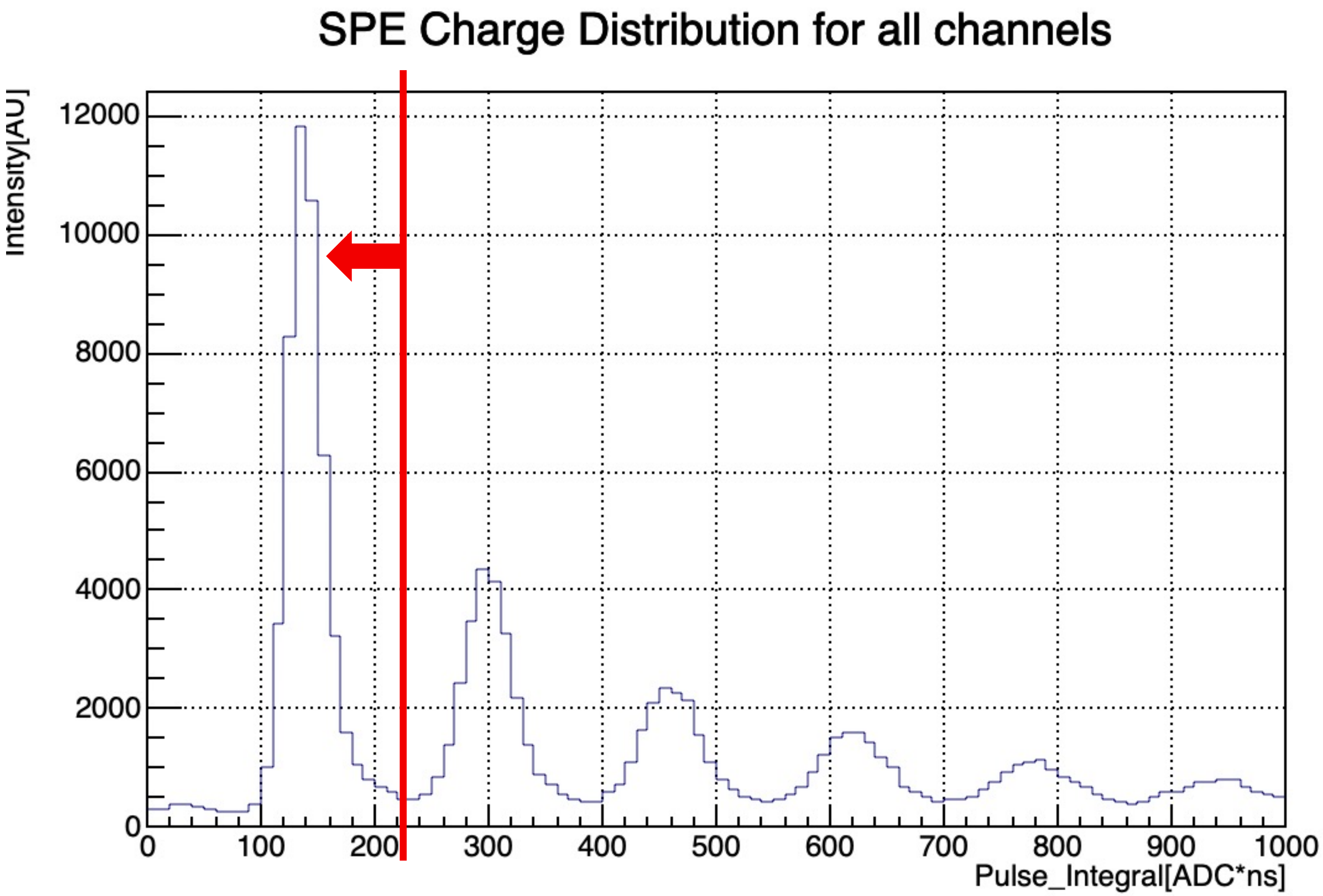
Ethan Brown, Kirsten McMichael

References

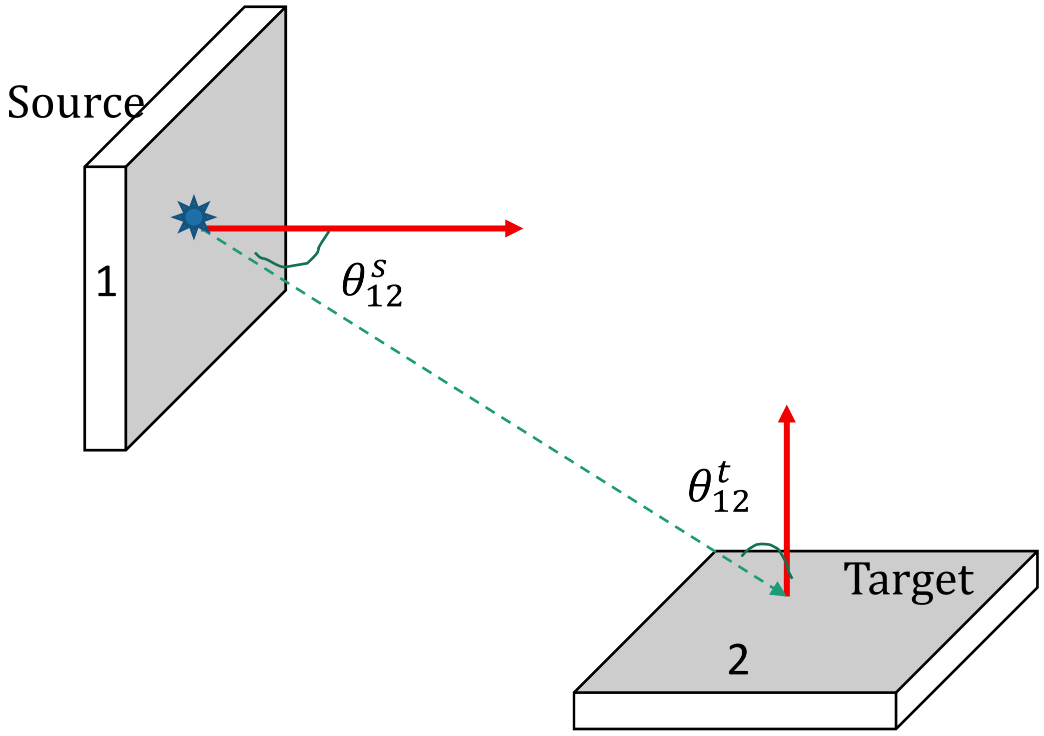
1. *Characterisation of SiPM Photon Emission in the Dark*, J. McLaughlin et al. , Sensors 2021, DOI: 10.3390/s21175947

Backup – Source pulse selection

Cut on SPE-like Pulses



Backup – Backwards correlation



When we look at data, we look at a specific source (1) here and look for "correlated hits" on any target (2) here

However, with our timing resolution of O(10ns) we have know way of knowing which SiPM fired first, since the transit time for NIR light is <1 ns in our detector

The acceptance for 1-2 is different from 2-1 however, because of the angular dependence in detection and emission

Only SiPMs facing each other have the same probability for being the "source" or not, others have different acceptances

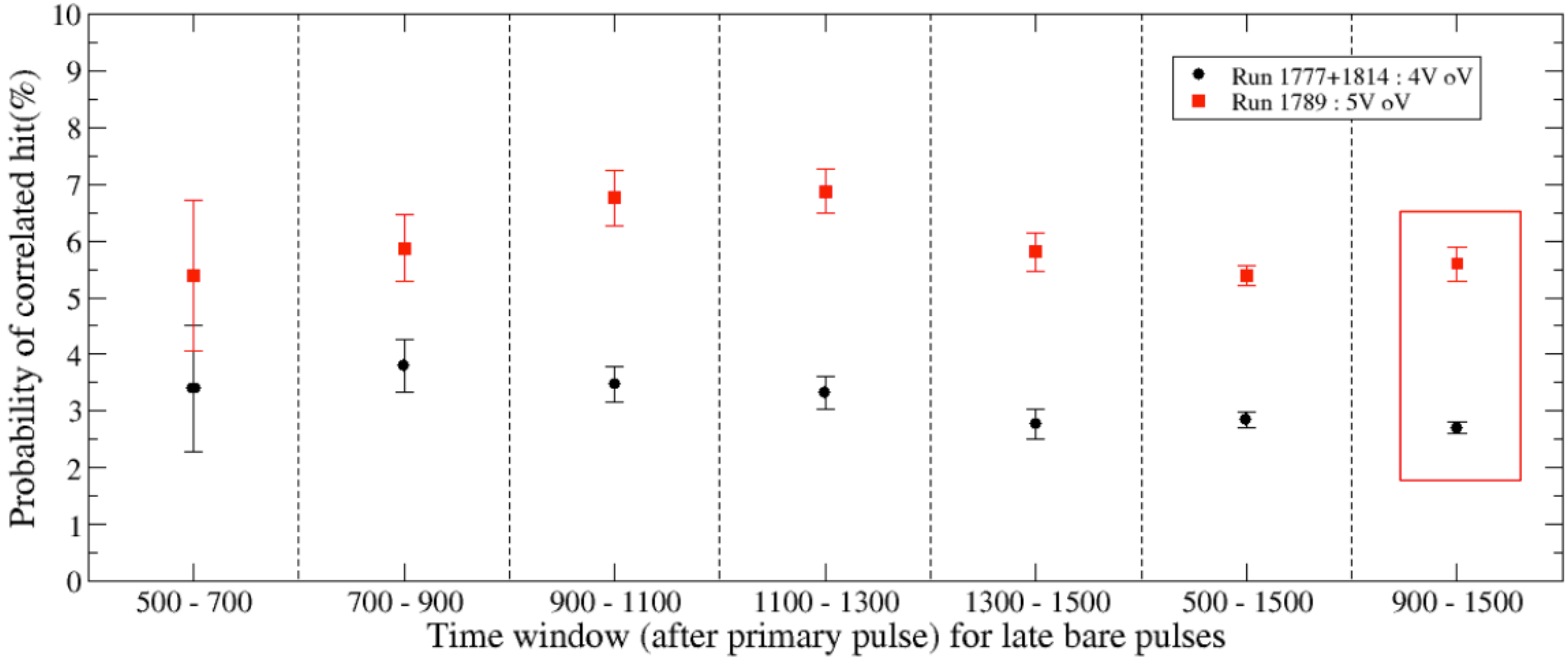
Acceptance is proportional to Solid angle, orientation of source, orientation of target and emission distribution

In simulation we have MC Truth information about the source and target, so we can identify pairs of channels with similar acceptance

For comparison, the total unfiltered bare package solid angle (Summed over bare to all targets) is 0.0061, while the total SA from all other SiPMs to the bare is 0.0082

Ratio ~0.74, where 1 would be equal SA for source and all targets
This means we should expect ~57% of light to come from all other SiPMs (**Neglecting angular acceptance!**) from SA corrections alone

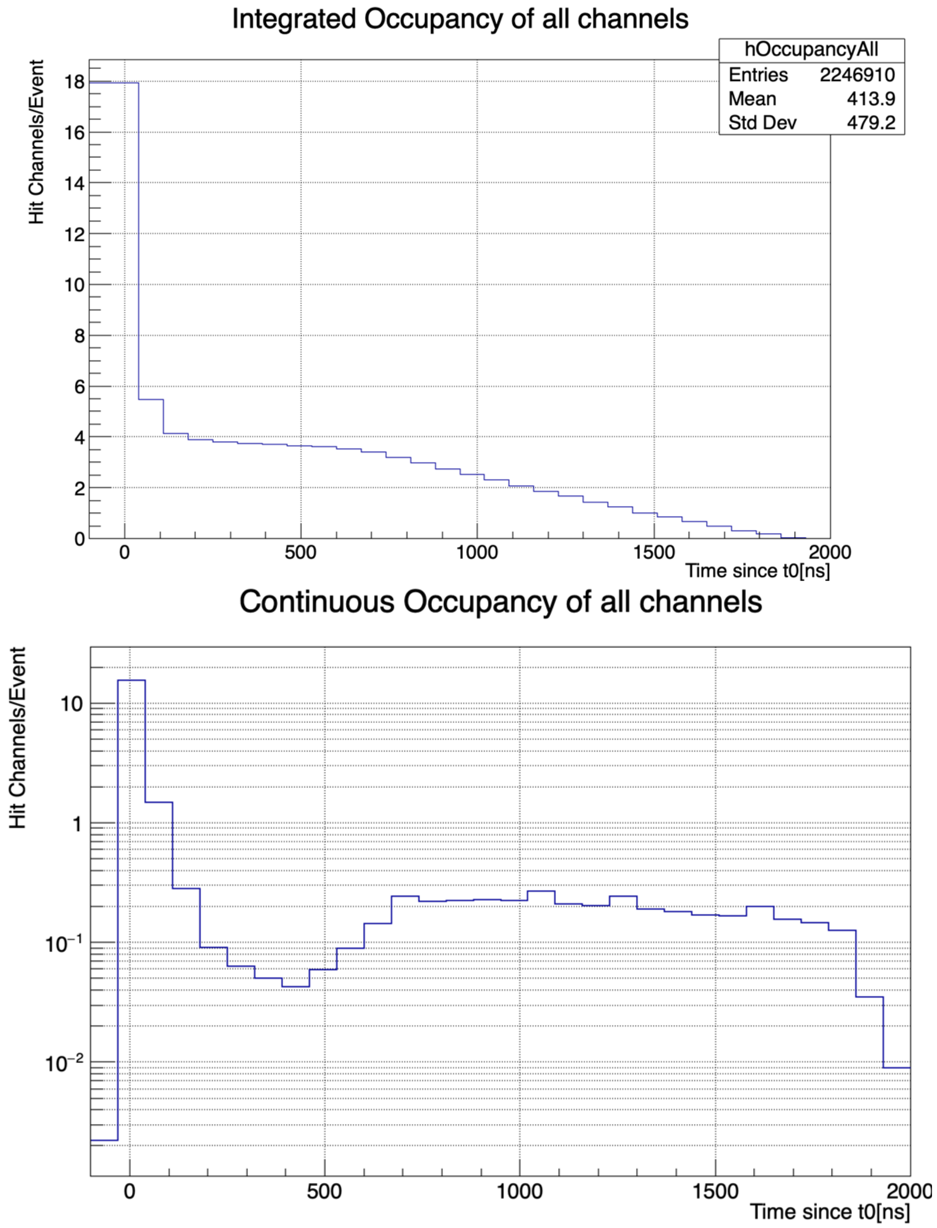
1. Time window of late bare pulse



Probability of correlated hit on summed long pass channels with bare as source of eXT

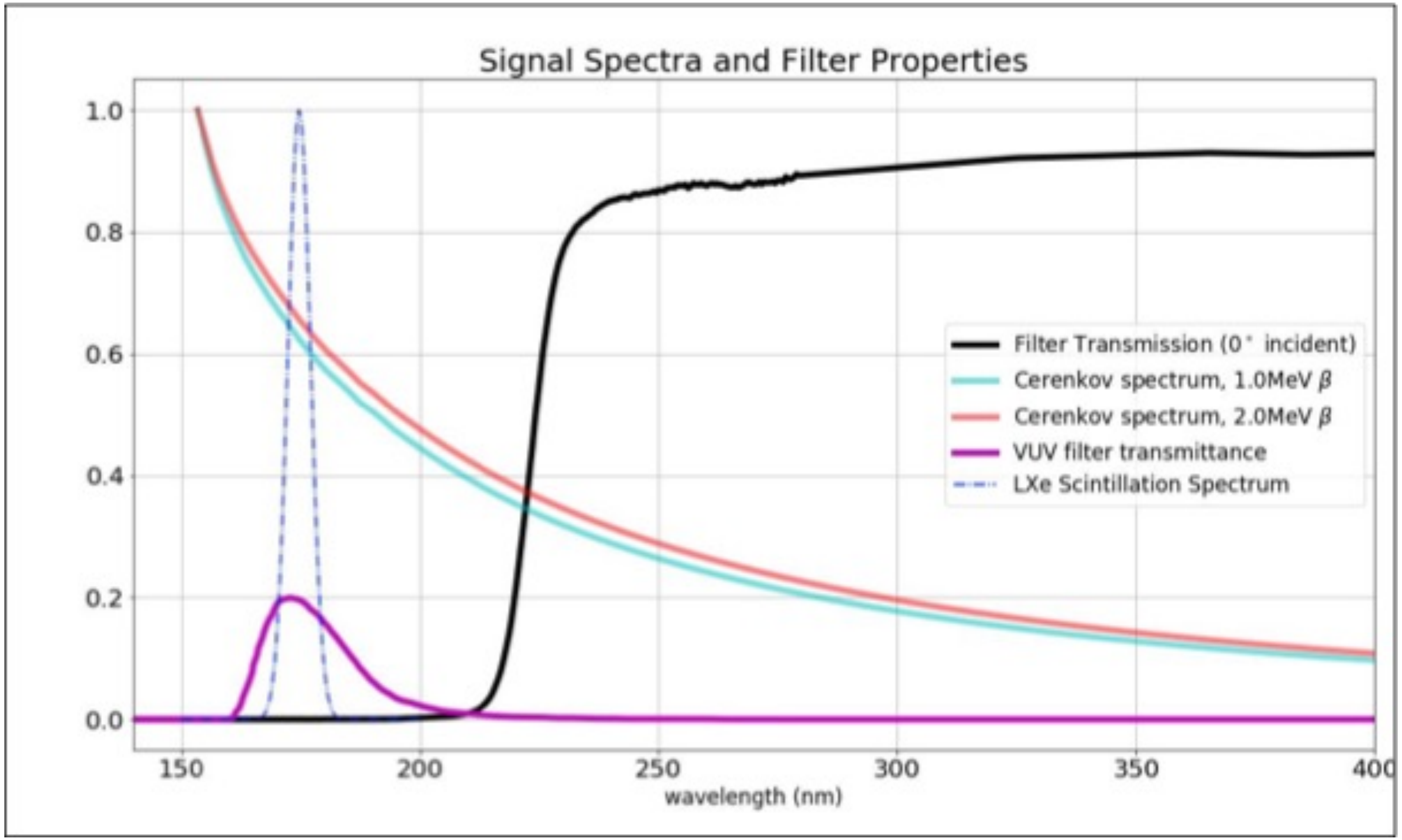
Backup Analysis : Occupancy

- We select a time window for analysis for regions with low occupancy
- We define occupancy as the average number of hit channels per event
- This is done in two ways, “integrated” and “continuous”
- Integrated occupancy counts the number of channels with a hit from **time=t** to the end of the event
- Continuous occupancy counts within a time-bin (70ns)
  - In our window of interest (900-1500 ns) we have < 0.1 pulses on average across all SiPMs

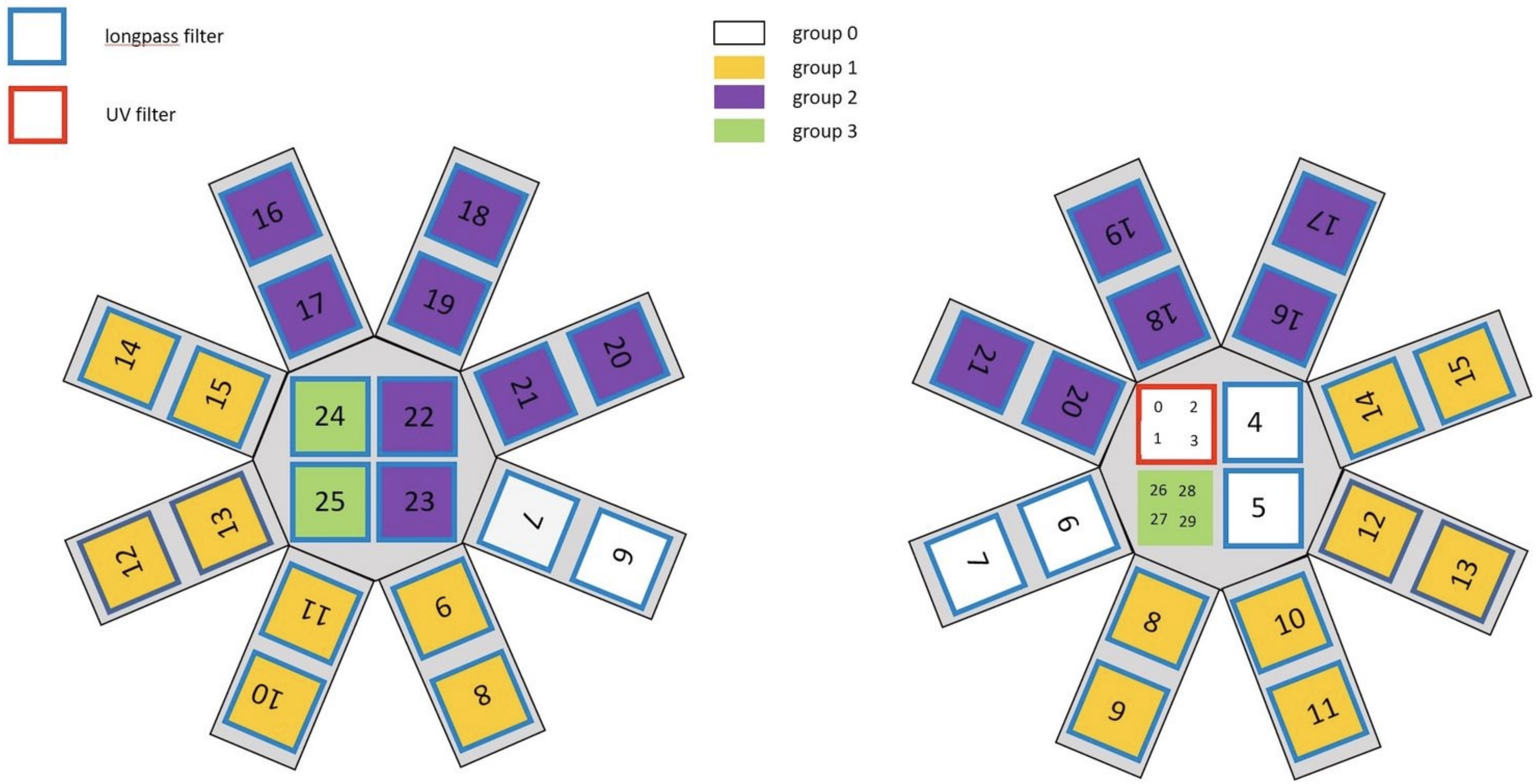


Backup: SiPMs

24 Silicon Photomultipliers
● Each SiPM has 4 readouts ↳ 96 outputs
22 Cherenkov SiPMs:
Longpass optical filter ↳ blocks scintillation light
4ch summing → **+22** digitized channels
1 Scintillation SiPM: UV bandpass filter ↳ allows only scintillation light
no summing → **+4** channels
1 bare SiPM
↳ view scintillation and **Cherenkov** light ↳ emit cross-talk photons
no summing → **+4** channels



Backup – Individual channels



Analysis: Background Pulseshape

- We also want to look at the distribution of pulses that are creating our bare hits
- We do this by plotting the time of arrival of photons across each channel
- The arrival time distribution is fit to an exponential
  - F(t) = A*exp(-(t-t_0)/tau)
- Average tau for LP channels is ~ 1130 ns
- Ex-situ measurements of cage indicate significant fluorescence of 3D printed plastic in visible (peaked at 450 nm)

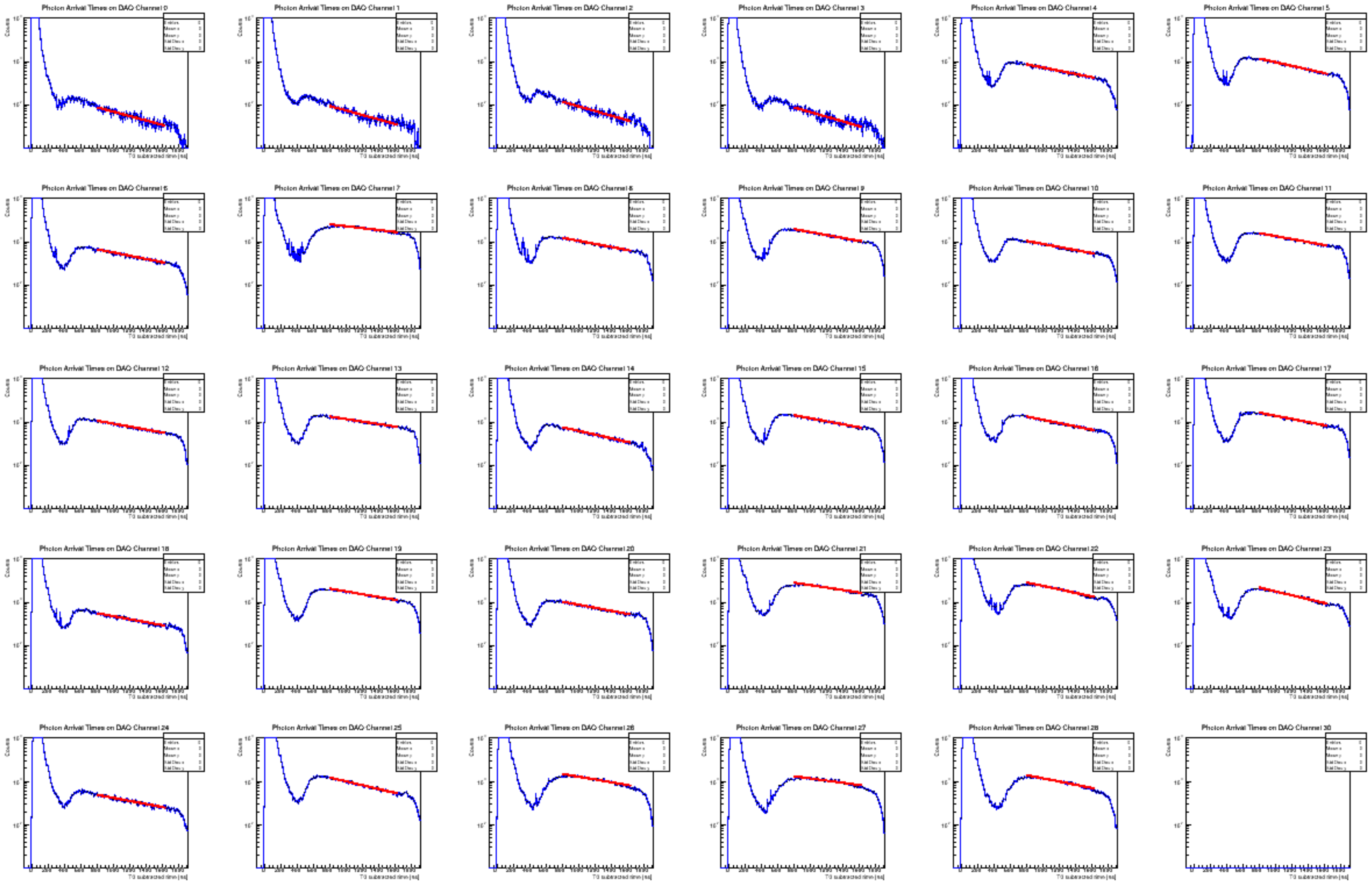


Figure: Distribution of pulse times with fits to late times with exponentials dip at short times is from missing pulses on tails of large signals

Analysis: Background ToyMC

- Since we know what the distribution of hits that is triggering our bare pulses are, we can simulate what the background may be like
- This toy MC simulates the same analysis as data by randomly sampling from f(t)
- First find a bare pulse in the window, then randomly sample 22 channels worth of LP hits and look for correlations
- Hits that fall around the original bare hit are put in the last histogram

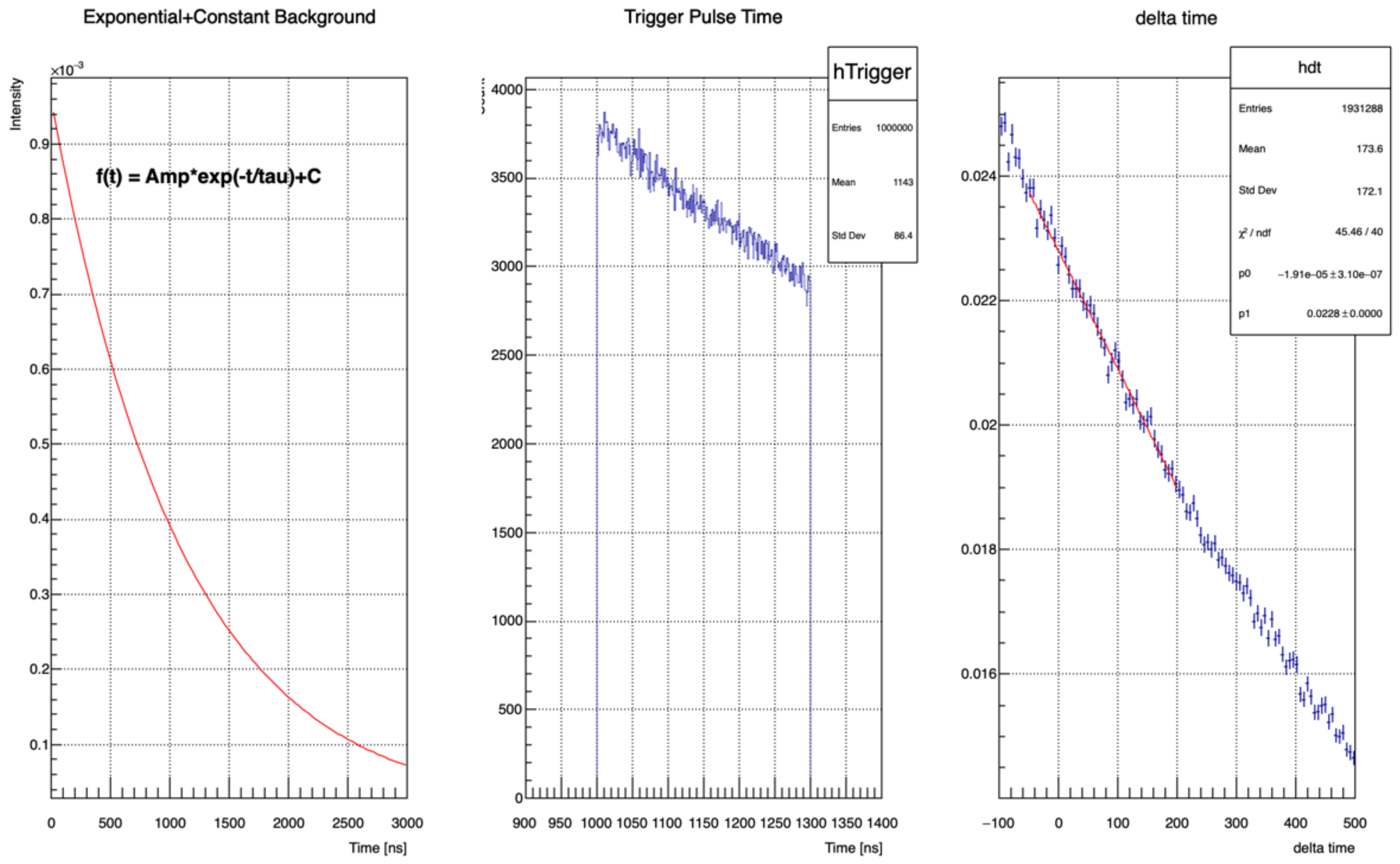


Figure: Toy MC results, Left: Input function, Middle : Triggered bare pulse time distribution, Right: LP background distributions