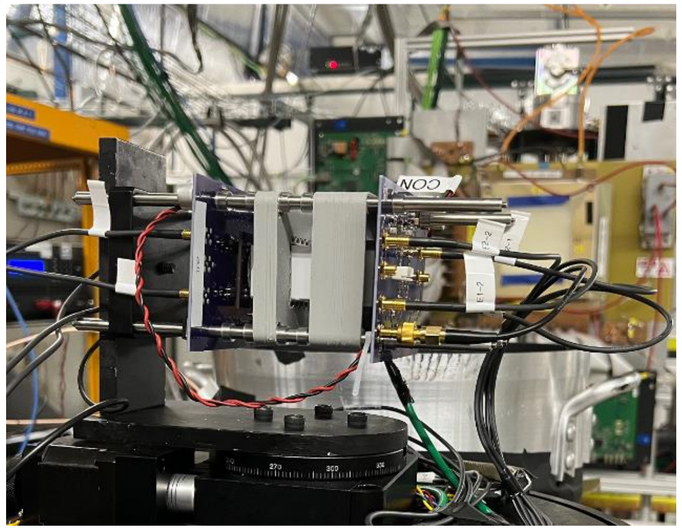
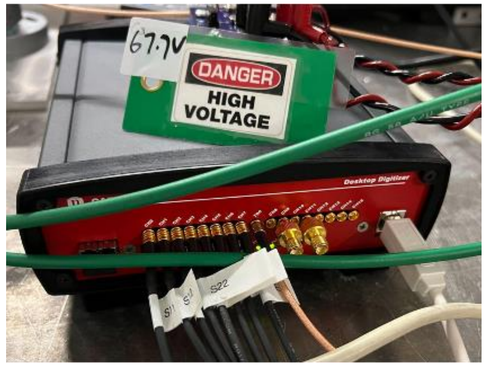
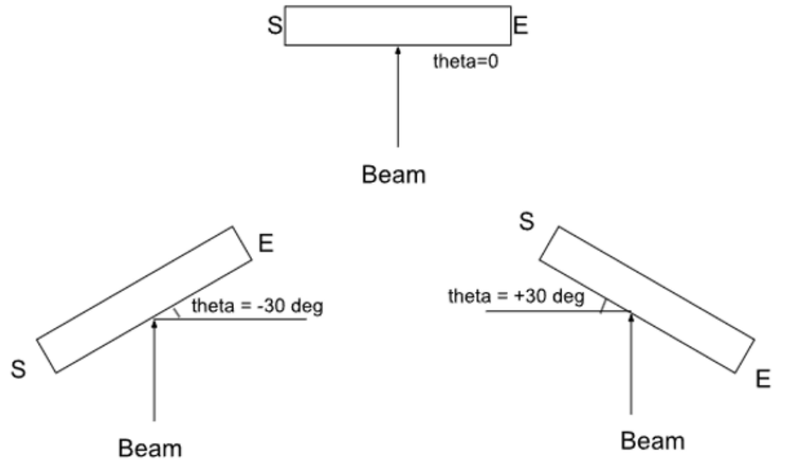
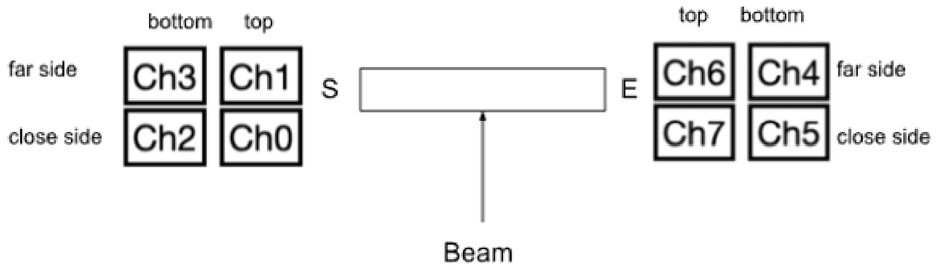
June 2023 Test Beam @Fermilab Setup

- 120 GeV protons, ~45k protons evenly distributed in 4 s
- Only one spill per minute, 8 mm horizontally and 4 mm vertically
- Only at most one proton expected in our readout window









Four 6mmx6mm SiPMs on each side
0-3 on the S side
4-7 on the E side

June 2023 Test Beam @Fermilab Datasets

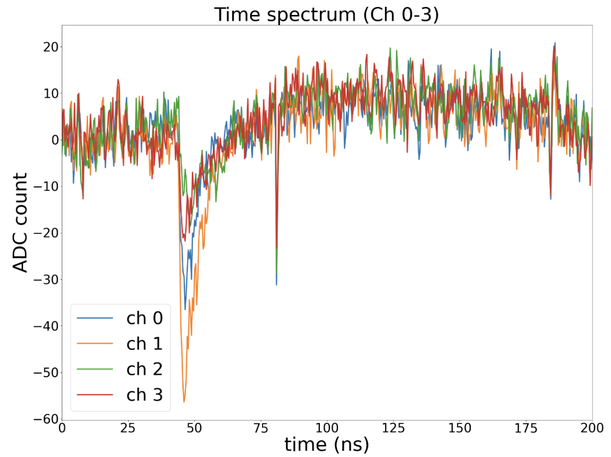
Crystal	Size	Filter (S side only)	Run #	Angle (°)	# of events	Satuarated-event rate (%)
PbF2	6x2.5x2.5 cm^3	No filter	11-29	0 to ±90 (10° interval)	~40k-70k	|θ|<30°: 2% 30°<|θ|<60°: 10% 60°<|θ|: 30%
PWO		R60	31-66	0 to ±90 (5° interval, except ±85°)	~30k-70k	|θ|<30°: 2% 30°<|θ|<60°: 15% 60°<θ: 20% θ<-60°: 35%
		No filter	103-121	0 to -50 (5° interval), 0 to +25 (5° interval), ±90	~20k-40k	|θ|<30°: 5% 30°<|θ|<60°: 15% 60°<|θ|: 45%
BGO		U330	68-101	0 to -45 (5° interval), 0 to +50 (5° interval), -55, -65, -75, ±90	~50k-60k	|θ|<30°: 7% 30°<|θ|<60°: 20% 60°<|θ|: 40%

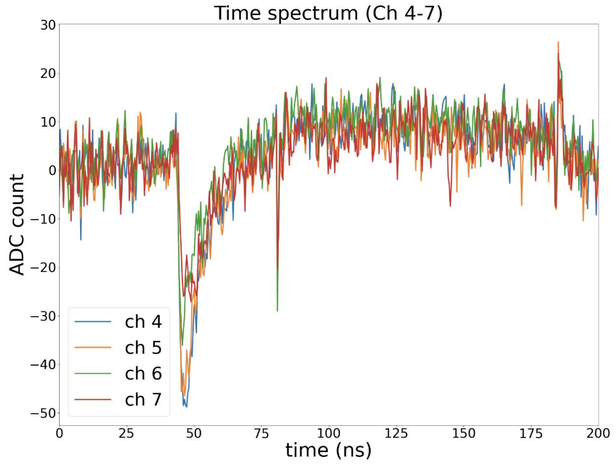
Waveform for each crystal (θ=0°)

Show evt0 as example

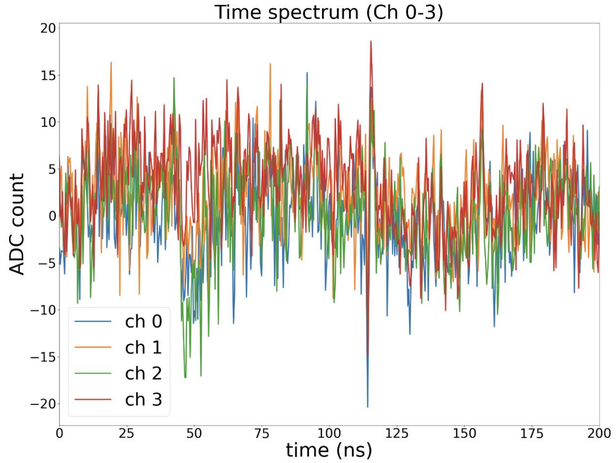
- PbF2: no filter for all channels; PWO and BGO: w/ fiter for ch 0-3, w/o filter for ch 4-7
- Fine/large signals for PbF2 and scintillation signals for PWO and BGO, small signal size for PWO and BGO with filters applied
- The presence of Cherenkov contributions is clear from the average timing distributions and the angular dependence (see backup slides)

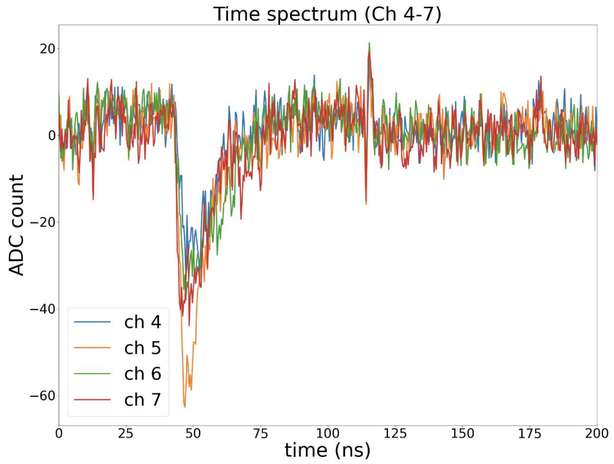
PbF2



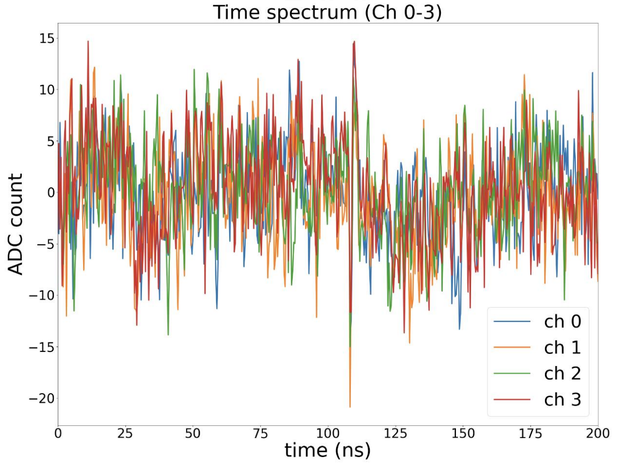


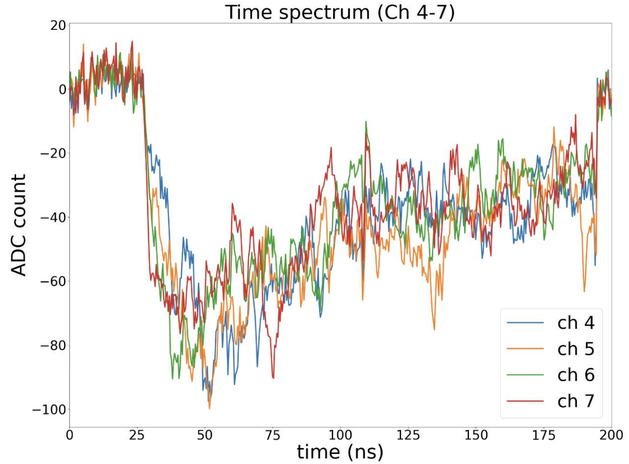
PWO





BGO

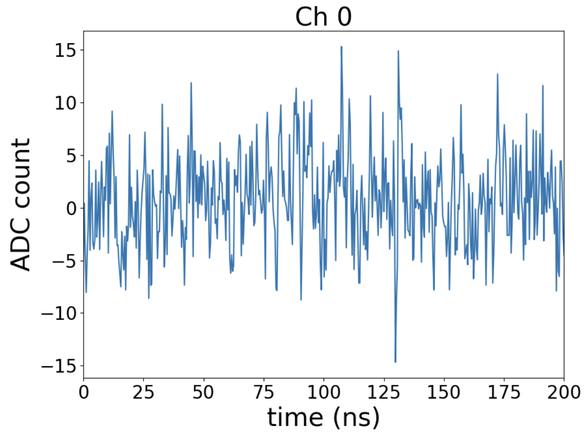




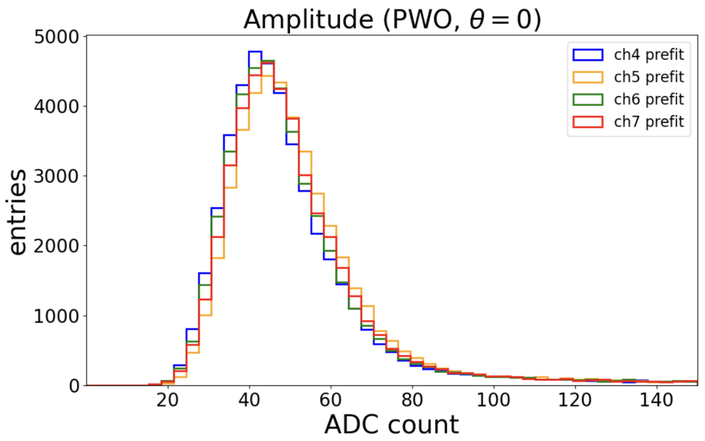
PWO signals

- Selection criteria: amplitude > 5 times noise.
- Certain functions are then used to fit the timing spectrum for each event to obtain the amplitude and the integrated ADC
- If we ignore signals from chs 0-3 (w/ filter) and look at events passing the selection criteria for chs 4-7 (w/o filter), we see a peak ~40-50 ADCs in the amplitude distribution, which is likely due to MIPs (plot 2).
- If we require chs 0-3 (w/filter) also pass the selection criteria, we will only have 23% of events left. These events are likely dominated by hadronic shower (10% of incident protons will produce hadronic shower at 0 degree), which results in a falling spectrum (plot 3).
- The simulation predicts to see only on average 2 Cherenkov photons with filters applied

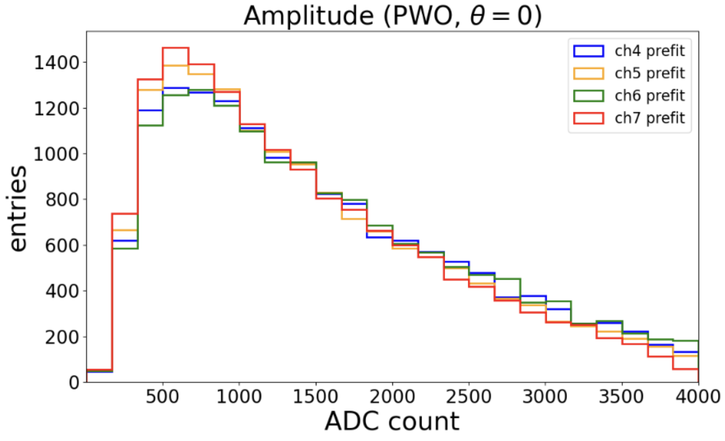
1. Noisy event in PWO data



2. MIP-like events



3. Shower-like events



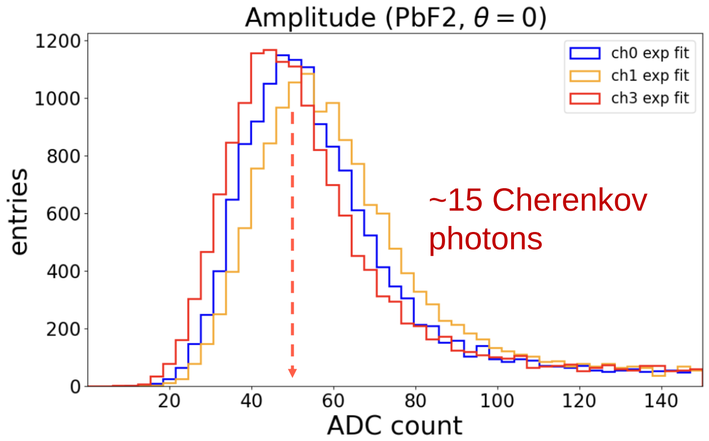
Compare fit results of PbF2 vs. PWO (0 degree)

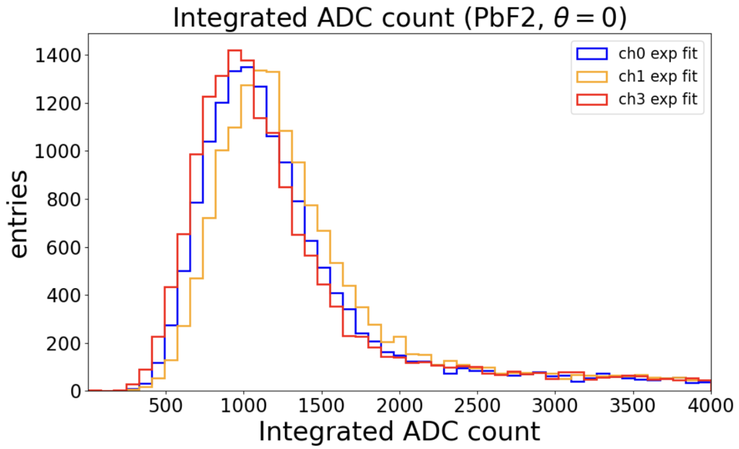
- PWO have much more counts than PbF2 since a large portion of events comes from showering
- Working on template fittings to extract the Cherenkov and Scintillation contributions event by event

Mainly showering events

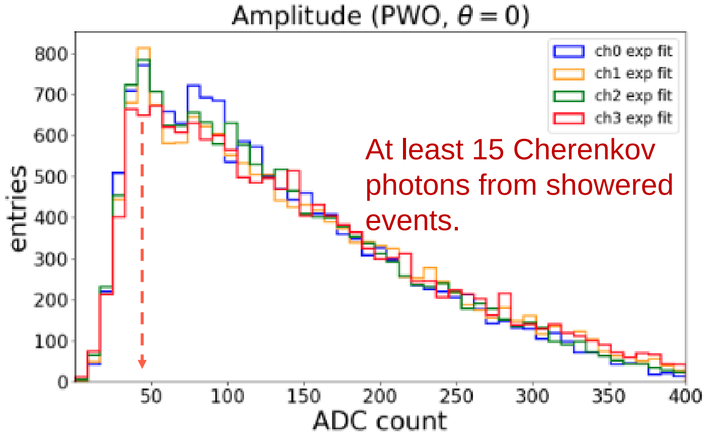
Composed by both scintillation and shower

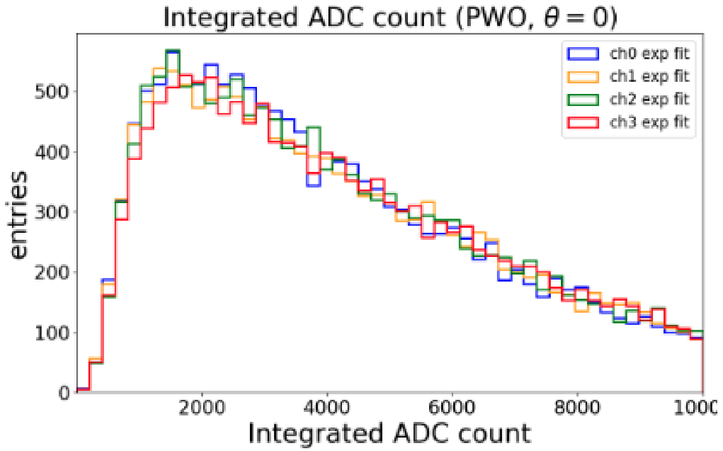
PbF2



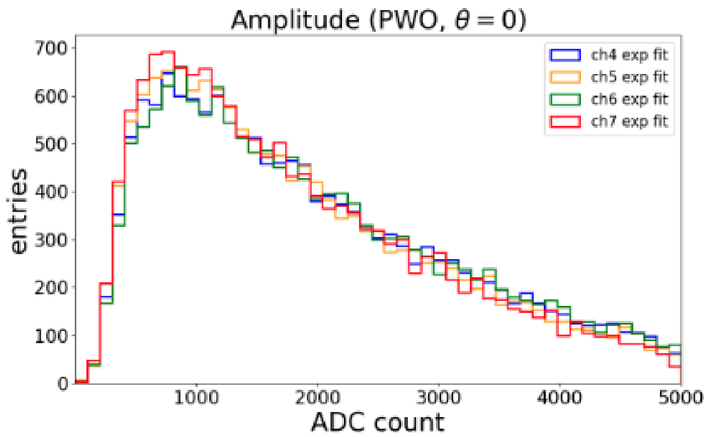


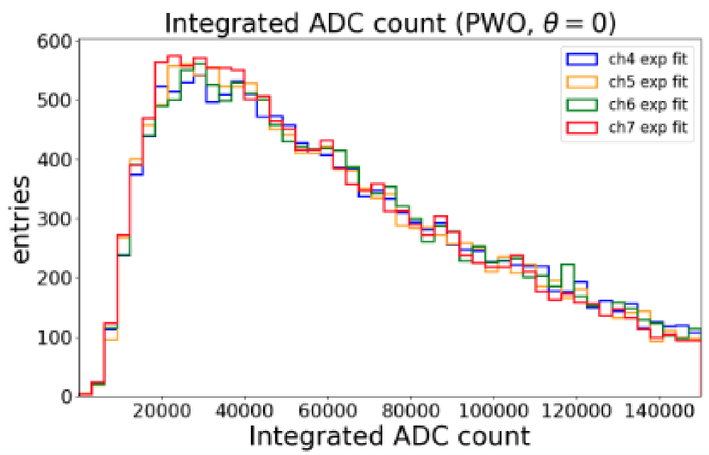
PWO w/ filter





PWO w/o filter

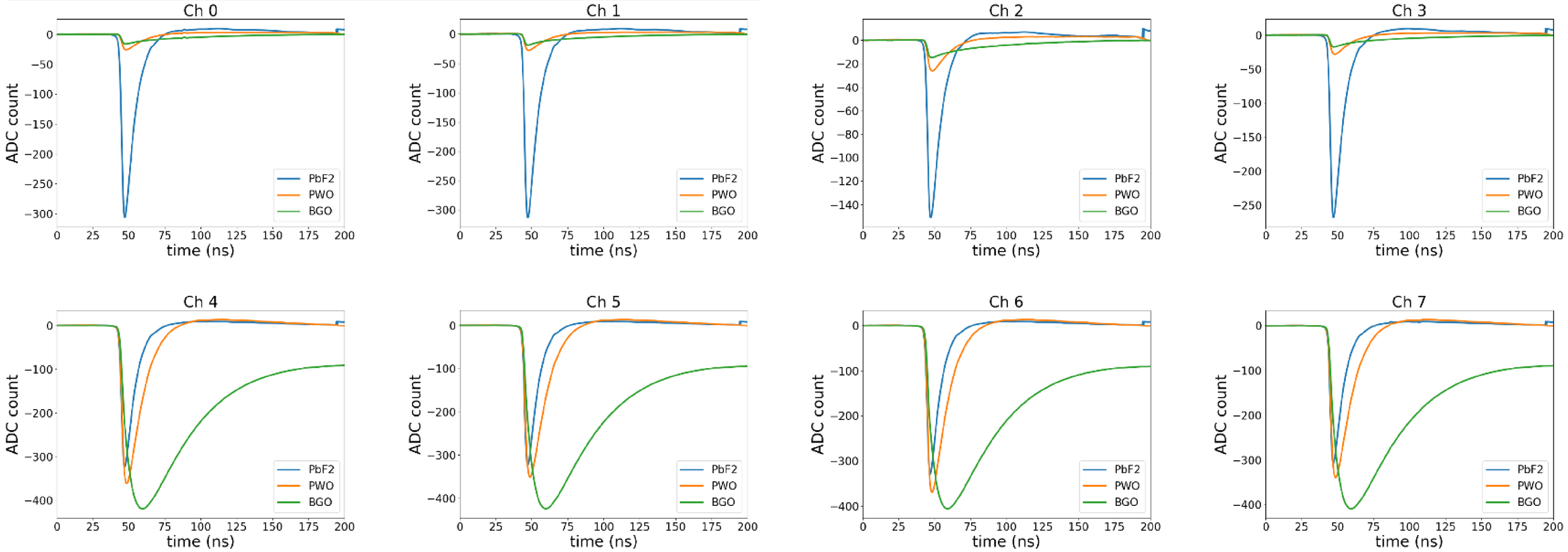




Average Time Spectrum (θ=0°)

- The spectra shown are the average over all events (without the saturated ones) in the same run.
- PbF2: no filter (Cerenkov-only pulses); PWO and BGO: w/ filter for ch 0-3, w/o filter for ch 4-7

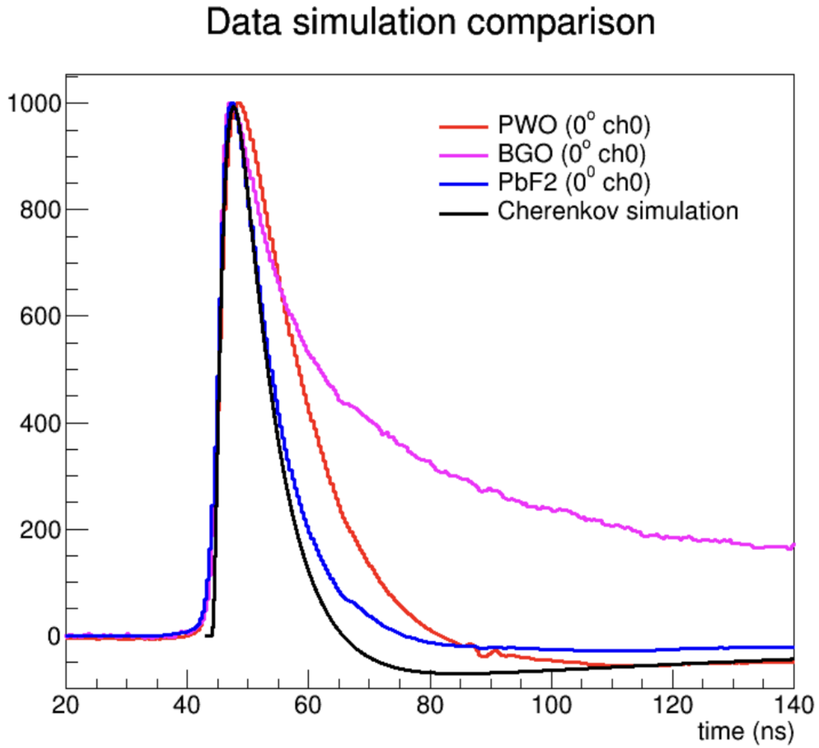
CH0-3 w/filters for PWO & BGO: Significant attenuations of pulse amplitude



CH4-7 w/o filters for PWO & BGO: Different tail shapes due to scintillation decay time

Pulse shapes of PbF2 and PWO/BGO (w/ filter)

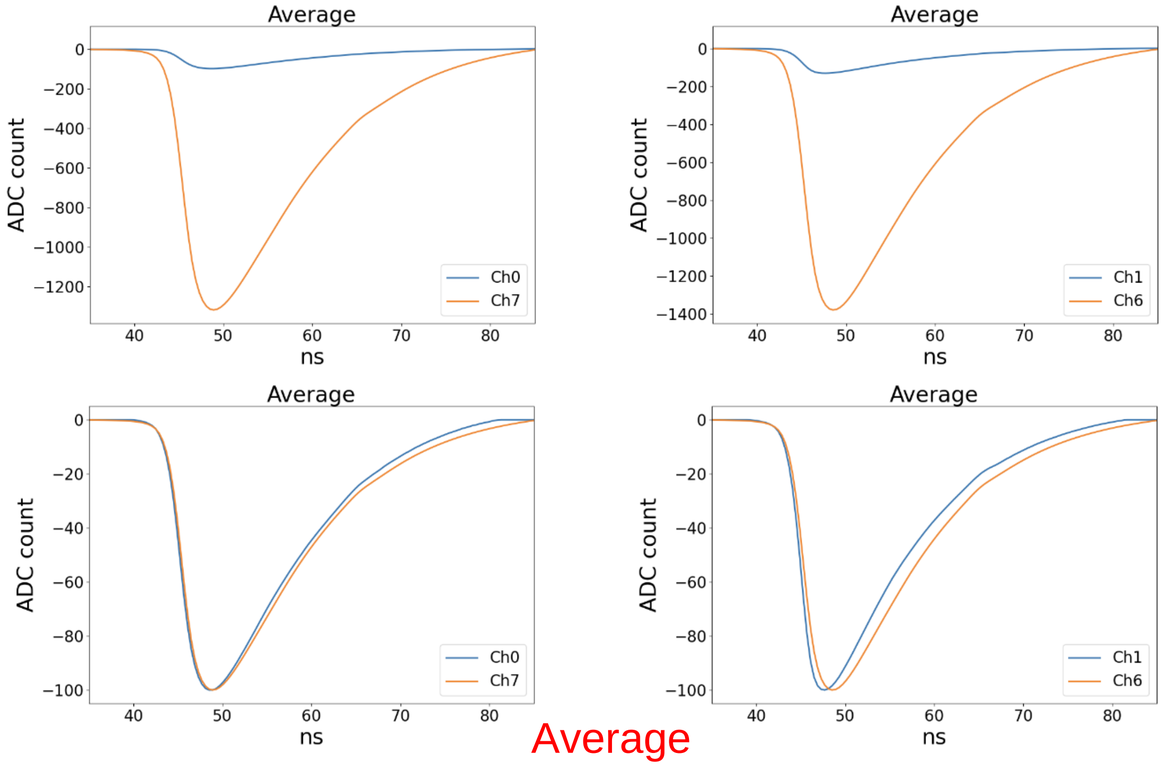
- The pulse shapes are taken from the average of events in the same run.
  - For PbF2 and PWO, no ADC cut is applied when taking the average; for BGO, a cut of amplitude>200 ADC is applied as the spectrums depend on the amplitude
  - Simulation for 0 degree is provided by Sasha and takes into account the detector and electronics effects (SiPM recovery time, single photon amplifier response).



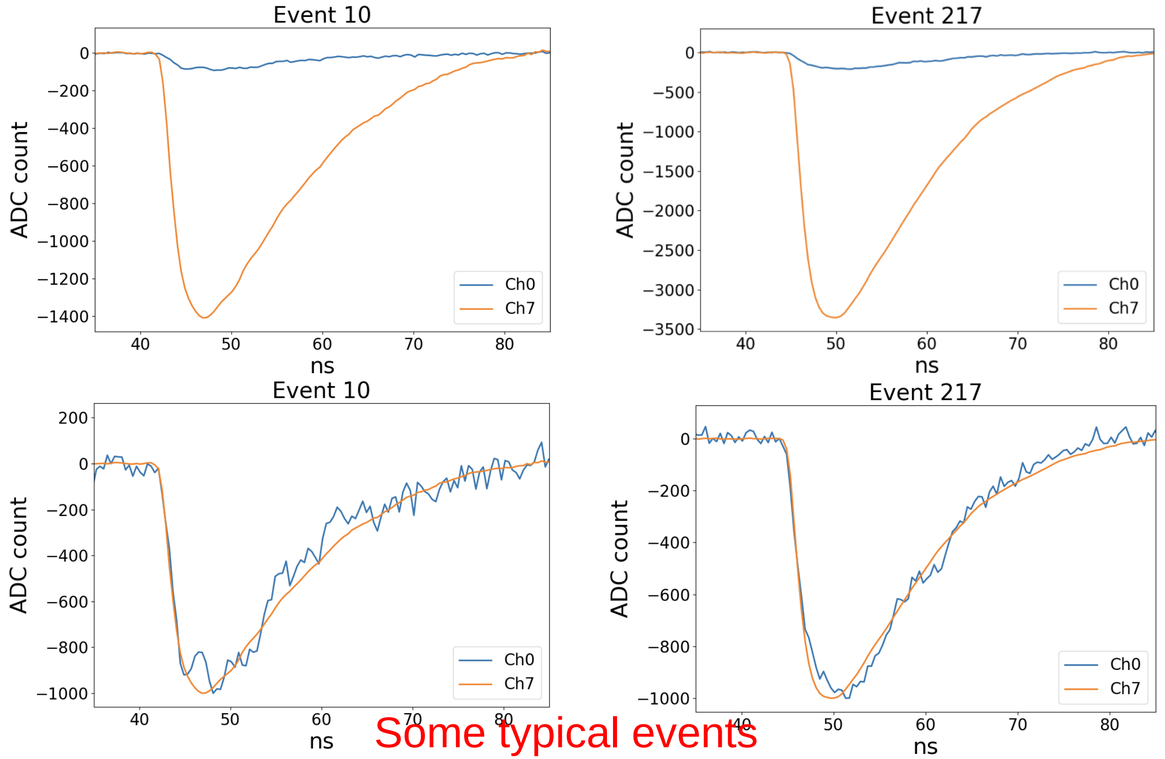
- Rising time, limited by the impulse response from the SiPM, is similar among PbF2, PWO, and BGO: indicating the expected dominant contribution from Cerenkov photo detection (with sub-ns jitter).
- The longer decay time for PWO than PbF2 suggests a non-negligible scintillation component (decay τ~6ns) remains.
- Similarly, the long tail for BGO suggest non-negligible scintillation contributions even with the filter.

Time spectrums PWO (w/ vs. w/o filter)

- Top: original pulses; bottom: normalize two sides w. or w/o filter to have the same pulse height.
- The filters did reduce the amplitude of the signal. However, the shape is still similar between channels w/ and w/o filters. This suggests the scintillation component is still significant after filtering purported to cut out its contribution. Need future beam tests to examine whether we could extract the scintillation information from tails using different filters?



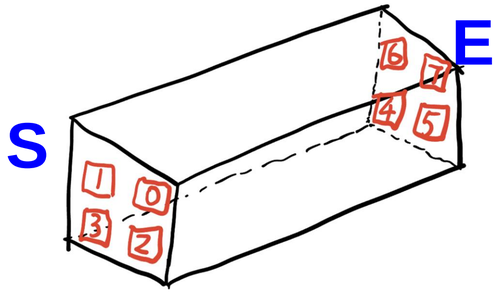
Average

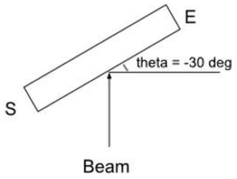


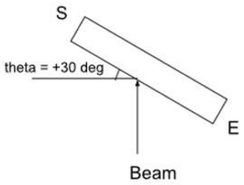
Some typical events

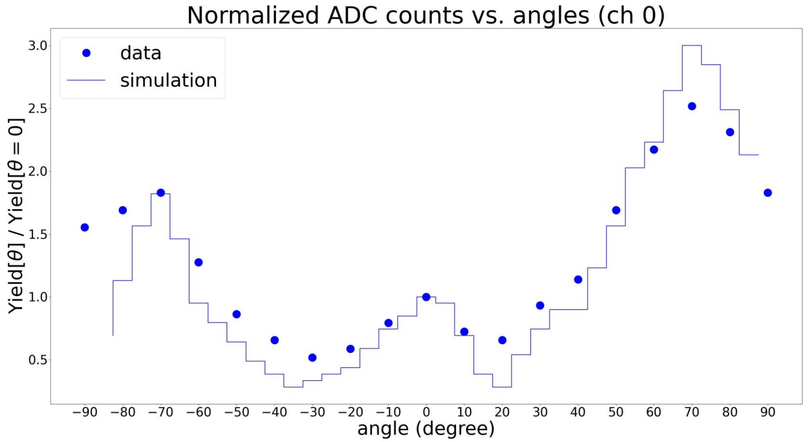
Back up

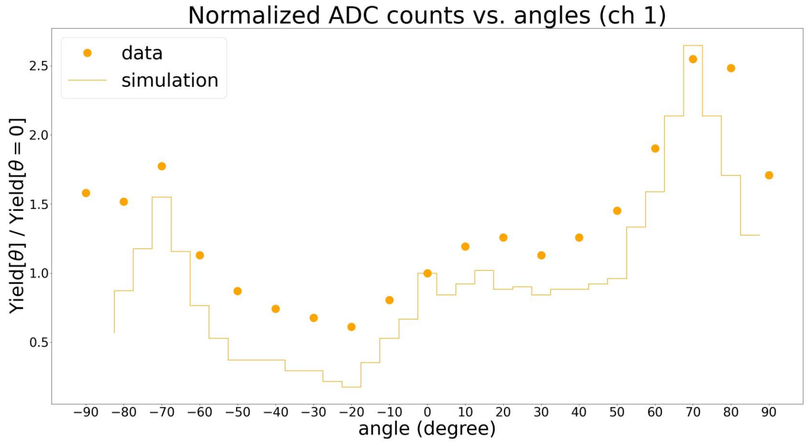
PbF2 channels 0-3

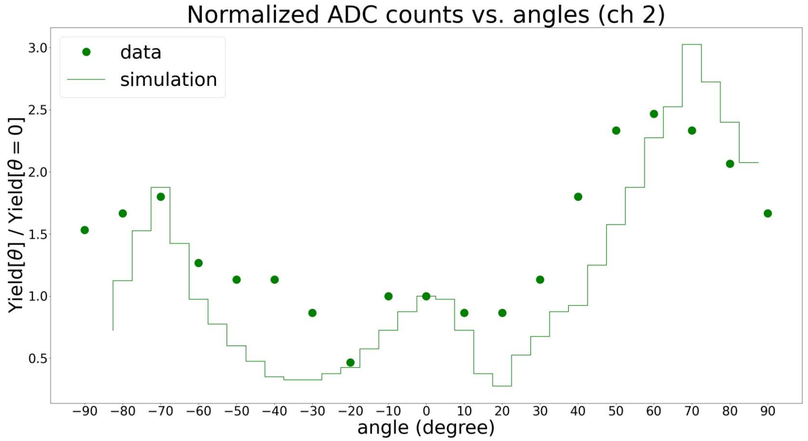


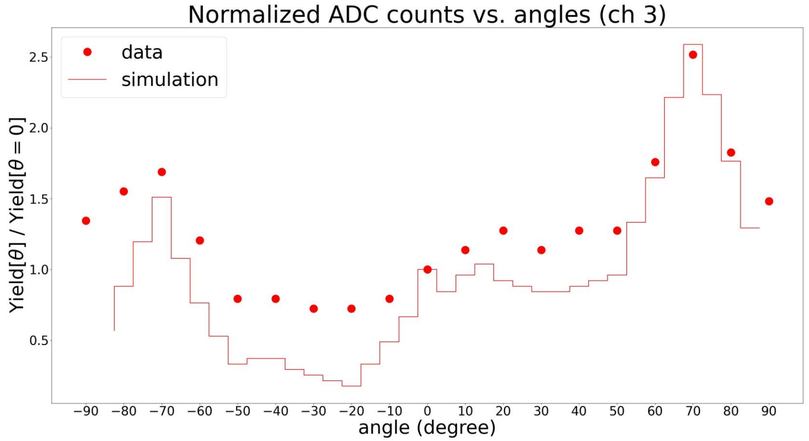






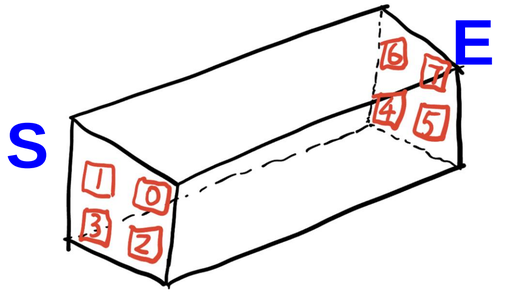


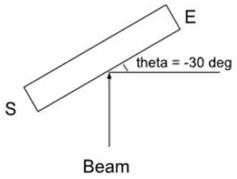


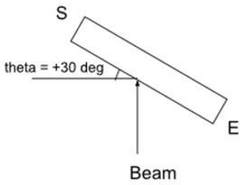


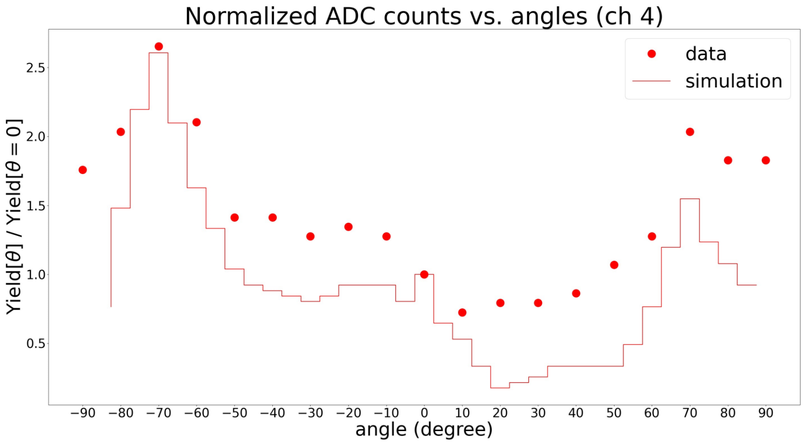
From Hui-Chi and Mekhala

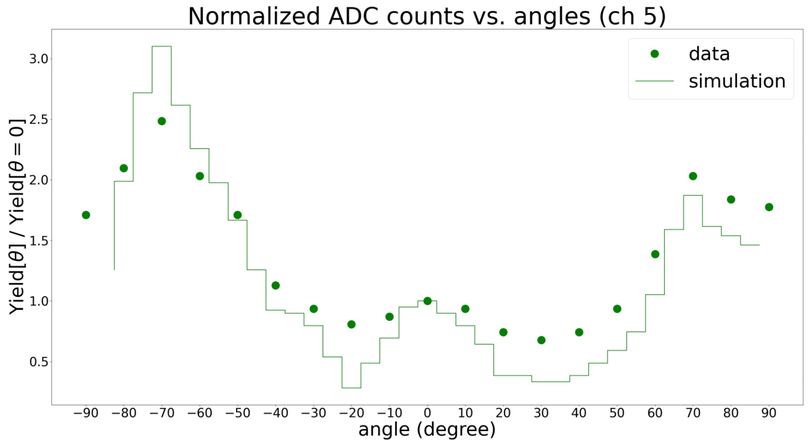
PbF2 channels 4-7

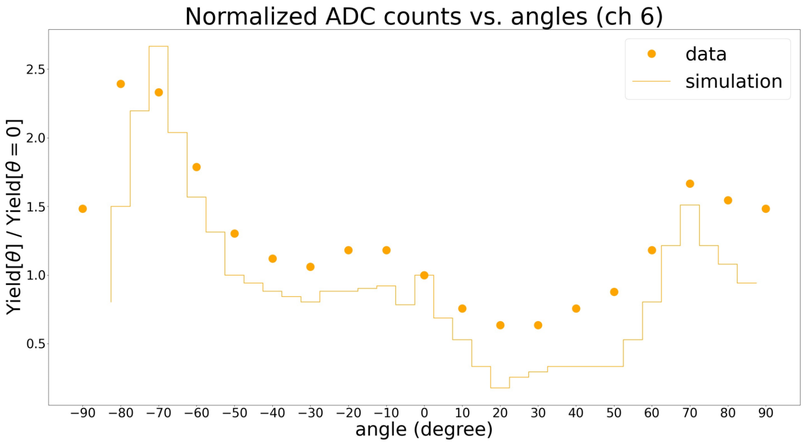


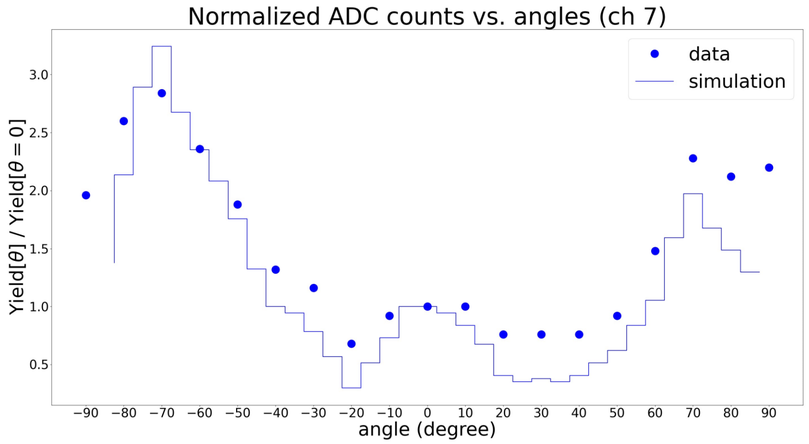










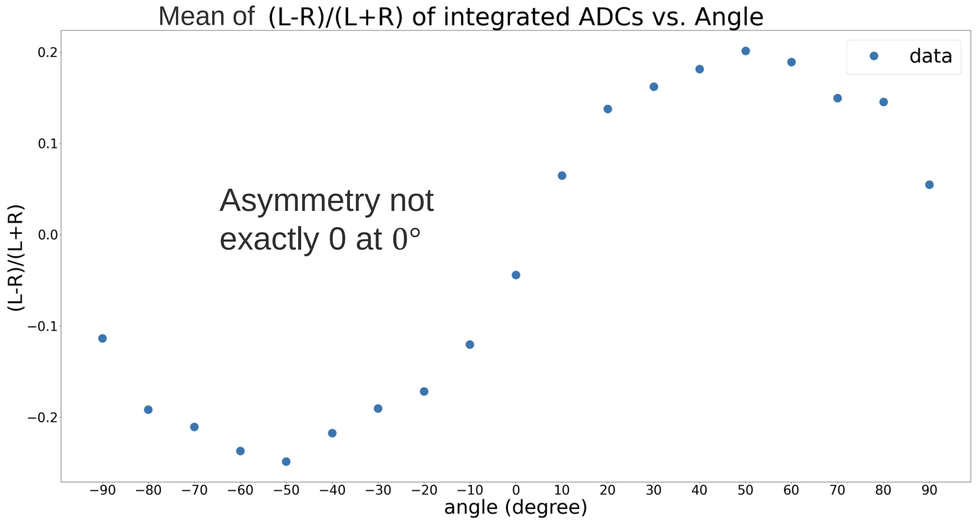


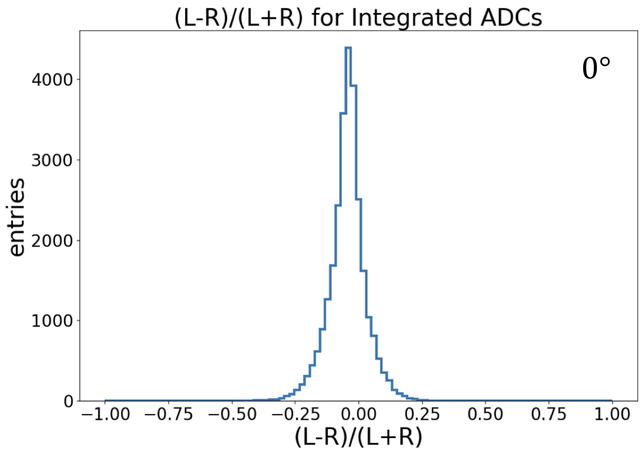
From Hui-Chi and

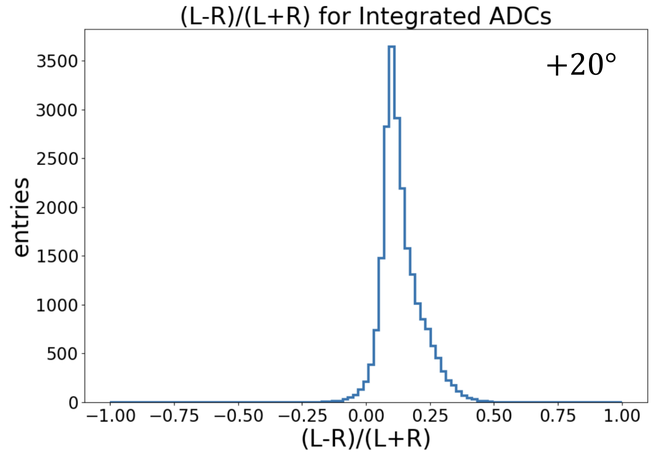
Asymmetry between the LHS and RHS channels

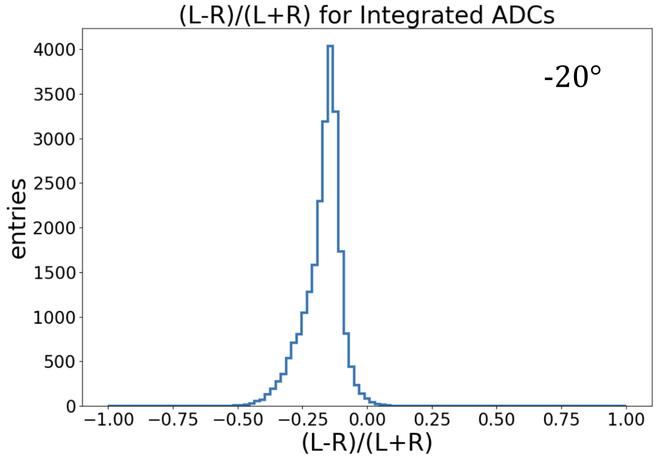
- PbF2: asymmetry is around ± 0.2

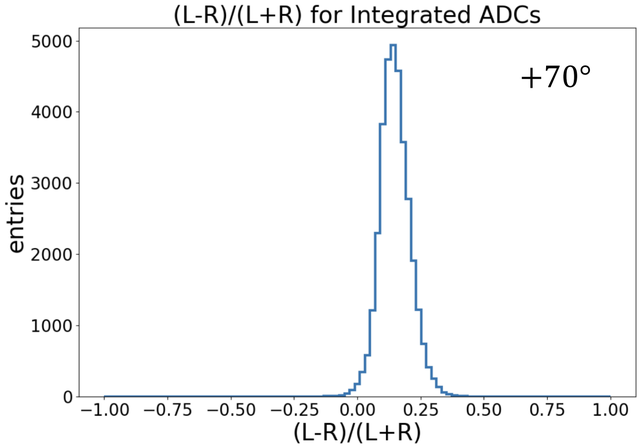
Asymmetry

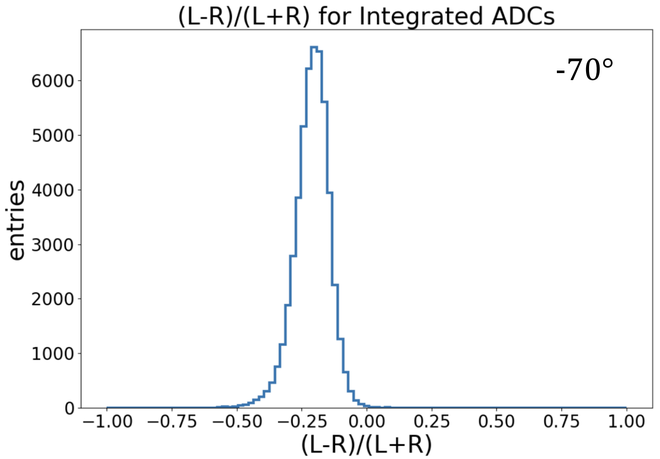






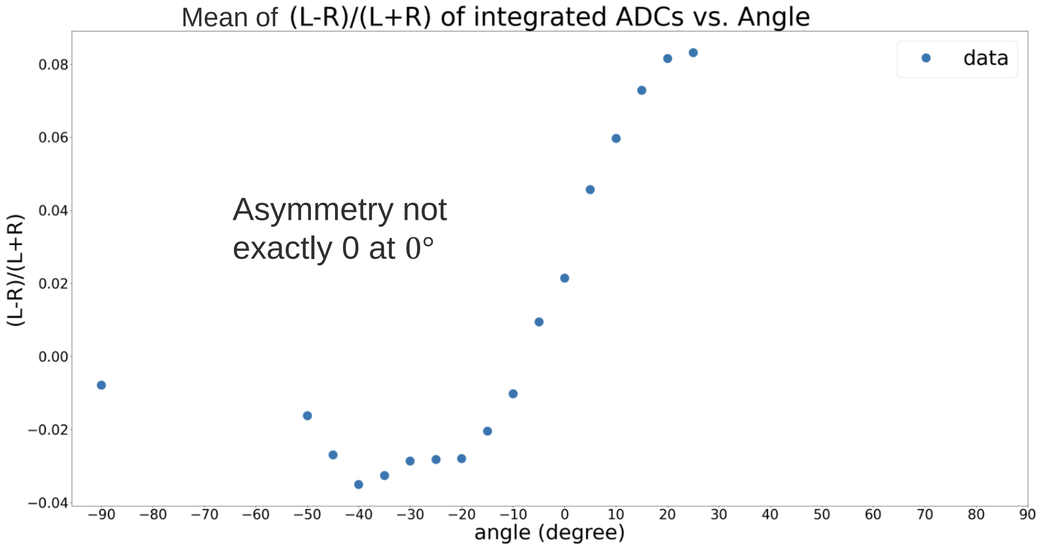


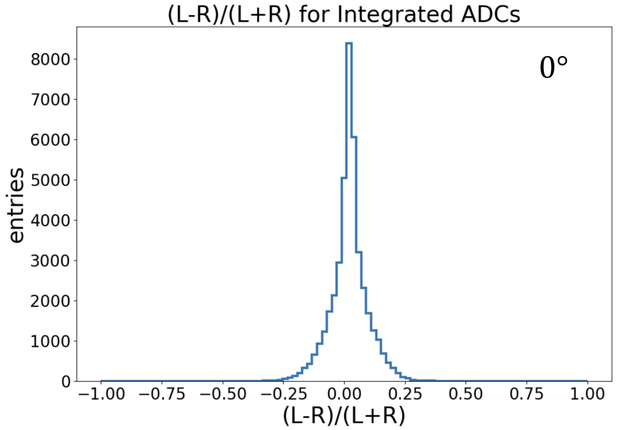


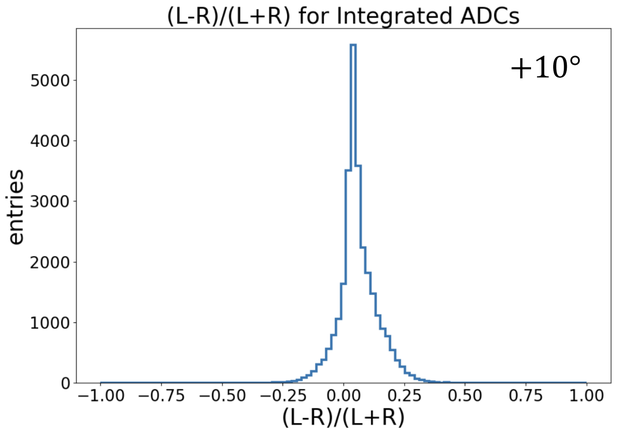


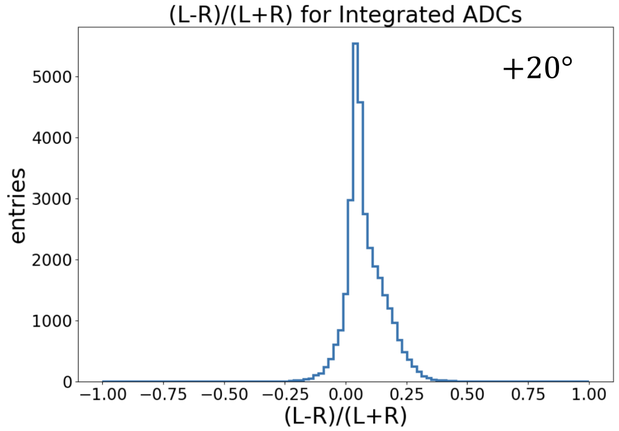
Asymmetry between the LHS and RHS channels

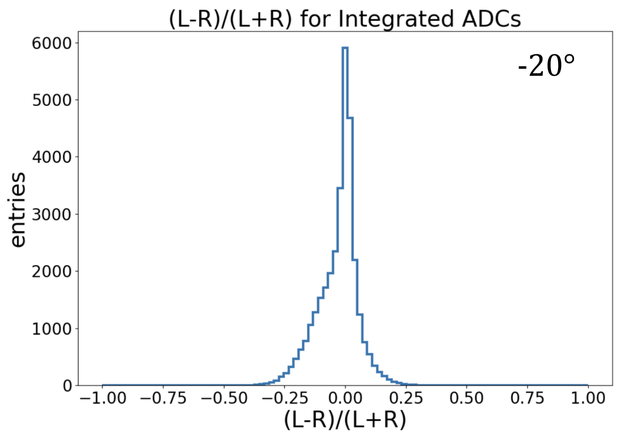
- PWO (no filters applied on ch 0-3): asymmetry ranging from -0.04 to 0.08.

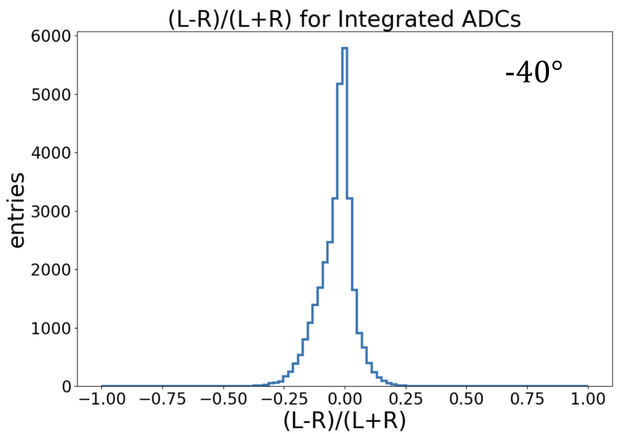












Asymmetry between the LHS and RHS channels

- PWO (with filters applied on ch 0-3): asymmetry ranging from -0.9 to -0.8.