Study of Single Crystal Readout for the Development of Dual-Readout Calorimetry in Future e+/e- Collider Experiments

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Energy Resolution of Calorimeters

- Calorimeters measure the energy deposited in particle showers
- Two types of showers: electromagnetic and hadronic
- **Energy resolution**
  - Crucial for accurate particle identification!
  - Energy resolution ($\Delta E/E$) of 3-4% for 100 GeV jets is a benchmark for the precision study at future e+/e- colliders
- Large fluctuations of the EM/neutral component in hadronic showers and in energy sampling measurements

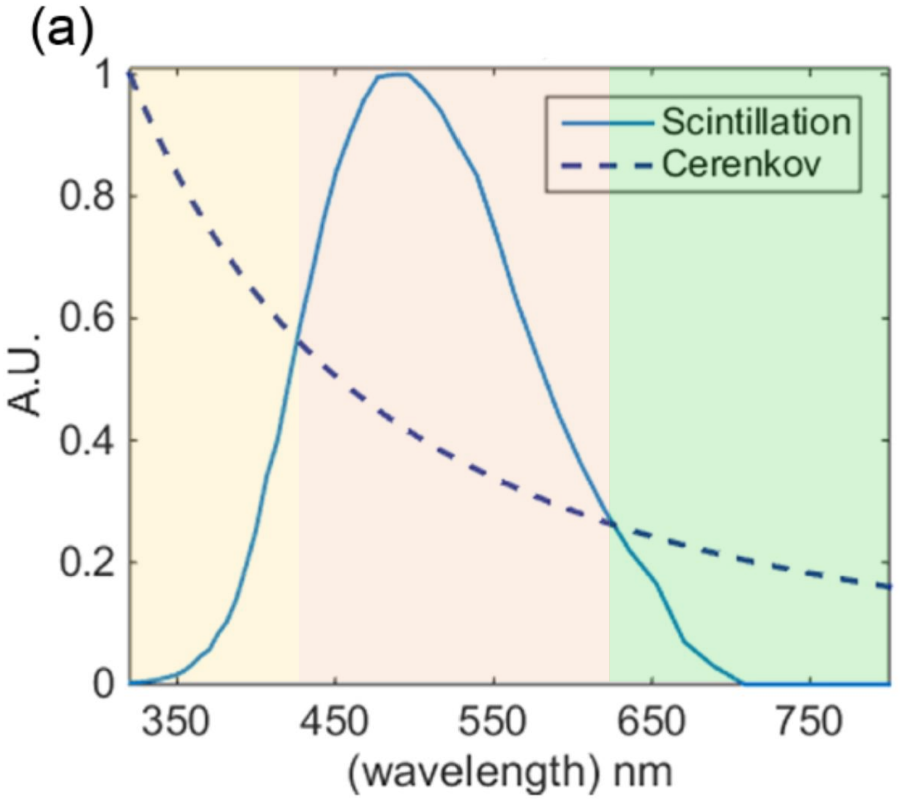
  → *limits energy resolution of traditional calorimeters to 30-50%/*$\sqrt{E}$

How to improve energy resolution?

- **Dual-Readout Calorimetry**:
  - Simultaneous scintillation and Cherenkov measurements
  - Ability to compensate for large variations and non-linear response from the invisible energy in hadronic showers

  → *better energy resolution* ☺

Scintillation Radiation	Cherenkov radiation
• Photons emitted due to relaxation of excited particles • Isotropic: propagates in all directions • Time delay in emission	• Photons emitted due to relativistic particles with v>c polarizing the medium • Directional • Instantaneous



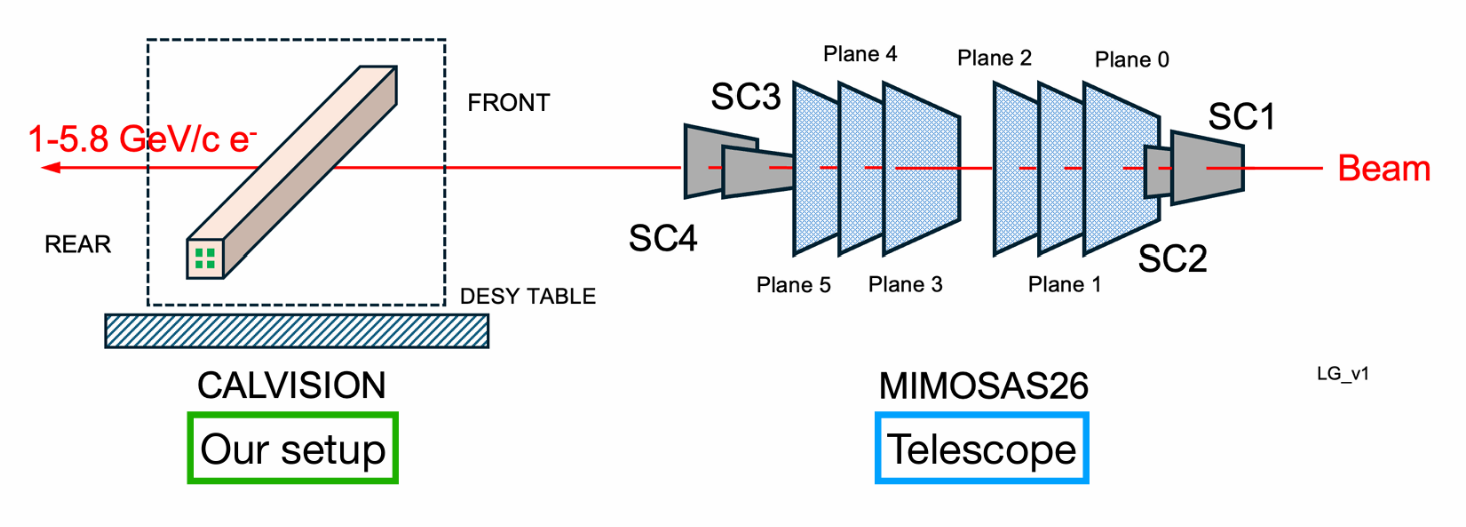
Emilie Roncali *et al* 2019 *Biomed. Phys. Eng. Express* **5** 035033

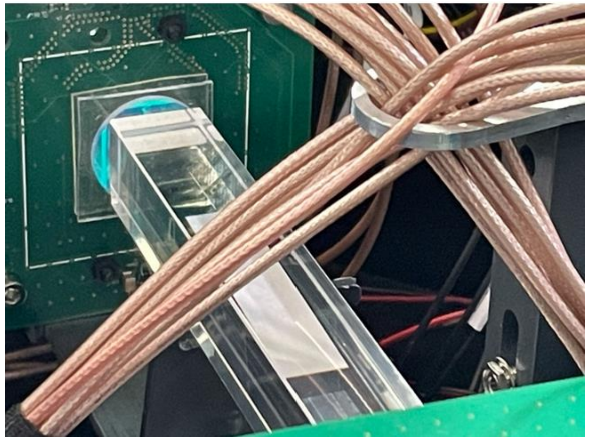
The Calvision Project

A collaboration aiming to develop a crystal-based dual-readout electromagnetic calorimeter to complement a precision hadronic calorimeter.

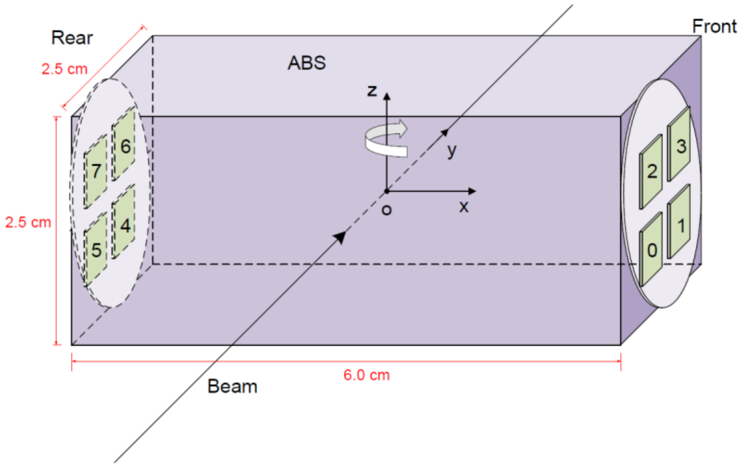
For more information, visit CalVision | Detector R&D (fnal.gov)

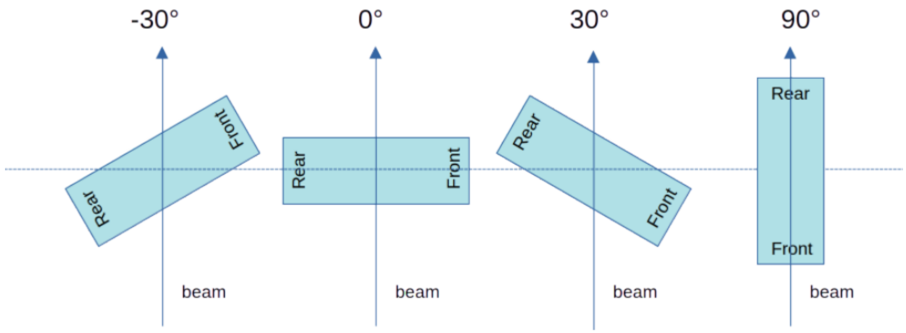
April 2024 Test Beam Setup at DESY





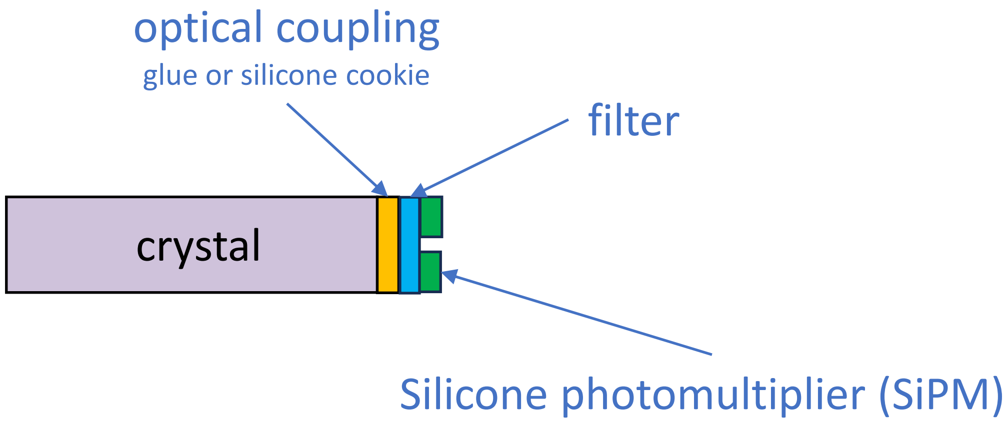
Naming convention:





April 2024 Test Beam Setup at DESY

Relevant components:



Crystals analyzed:

PWO (Lead Tungstate)

- Produces scintillation and Cherenkov
- Filter in the rear
- Used to study separation of scintillation and Cherenkov

PbF2 (Lead Fluoride)

- Produces only Cherenkov
- No filters
- Used to extract Cherenkov properties

Goals of Test Beam

- Perform angular scan
- SiPM over-voltage scan
- Test different crystals and filters

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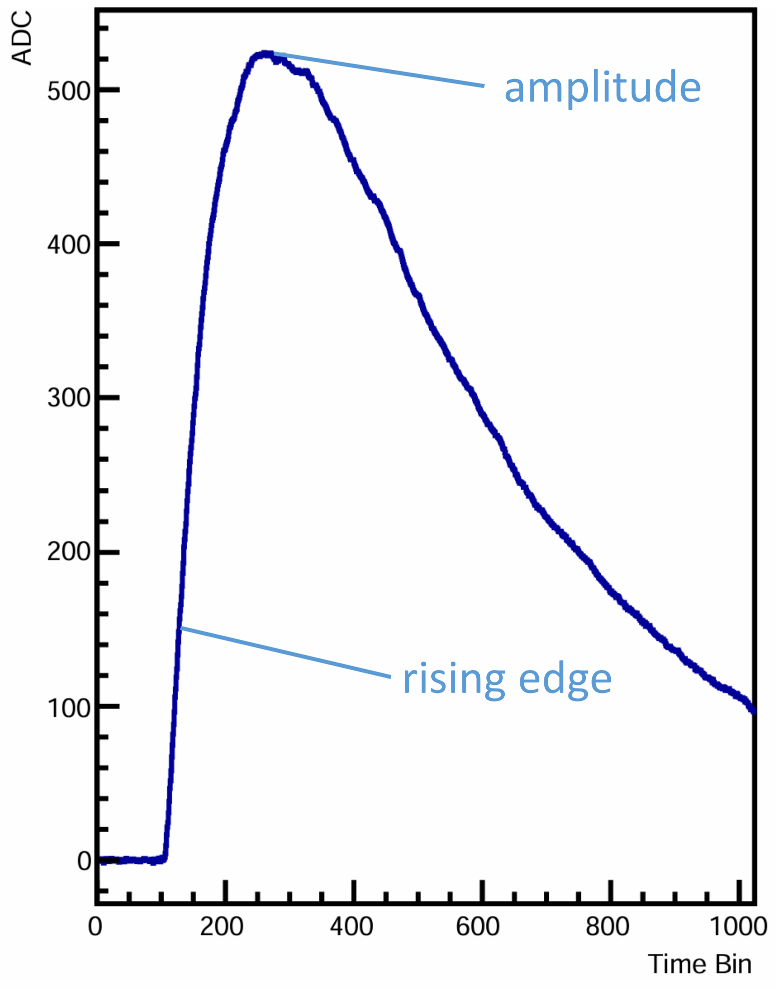
Objectives

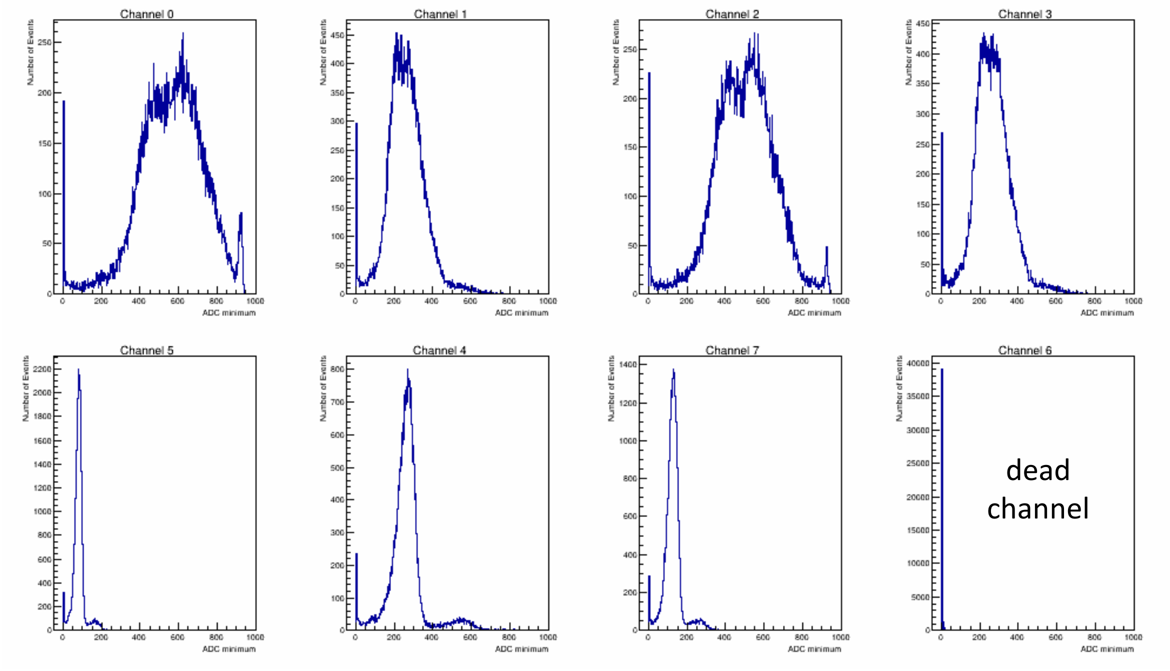


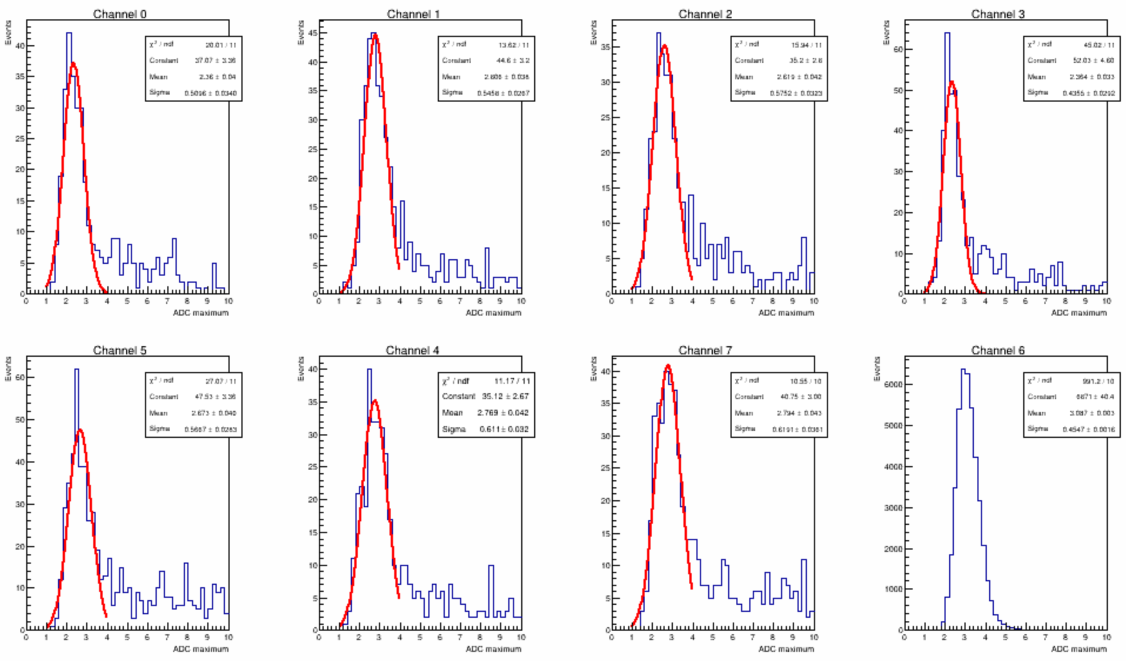
- Perform noise stability analysis
- Angle, crystal, and filter affects on amplitude and rising edge
- Telescope Tracking Reconstruction

Noise Stability

Procedure:

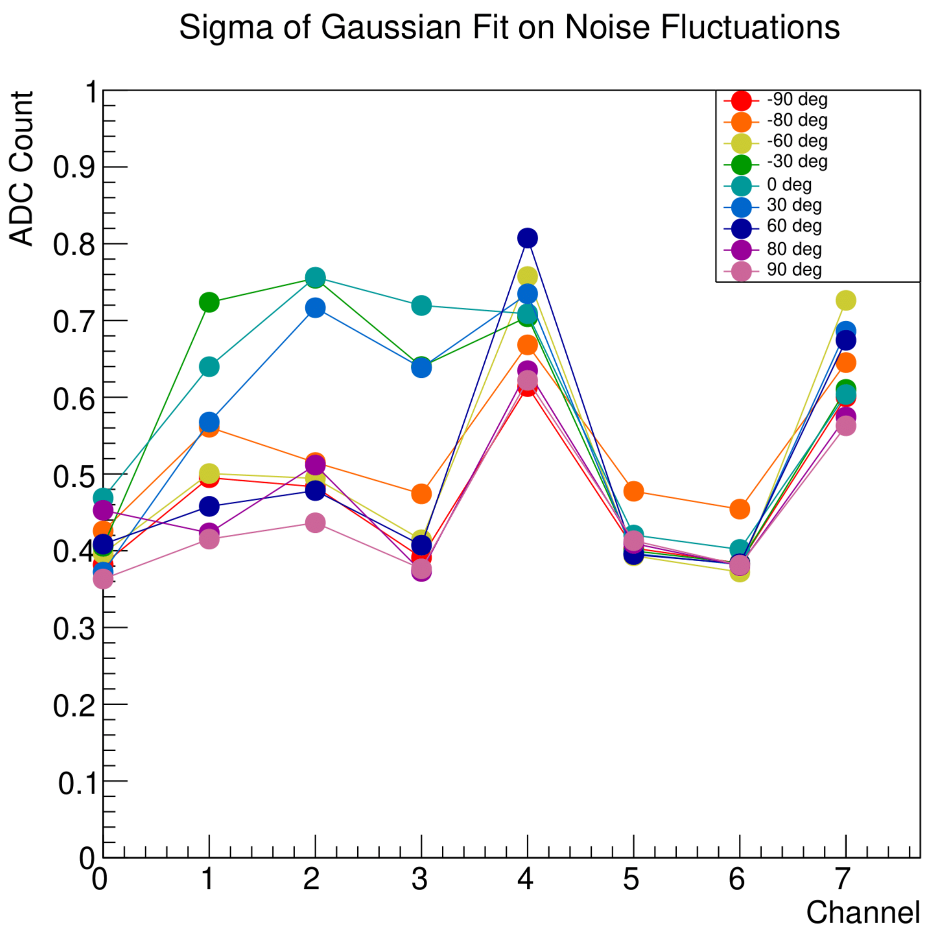
- Take peak of each waveform and plot amplitude distribution
- Should see 2 distinct peaks: noise and signal fluctuations
- Fit a Gaussian to noise fluctuations
- Extract sigma
- Repeat for all angles and both crystals



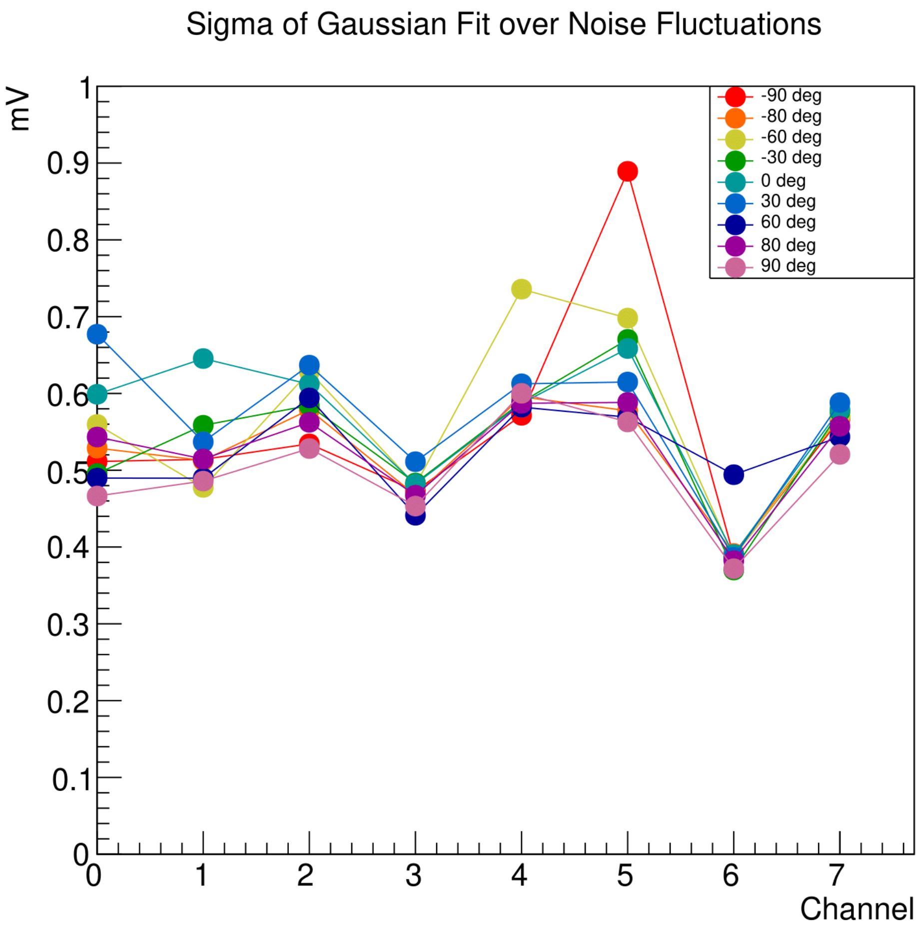


Noise Stability

PWO with filter

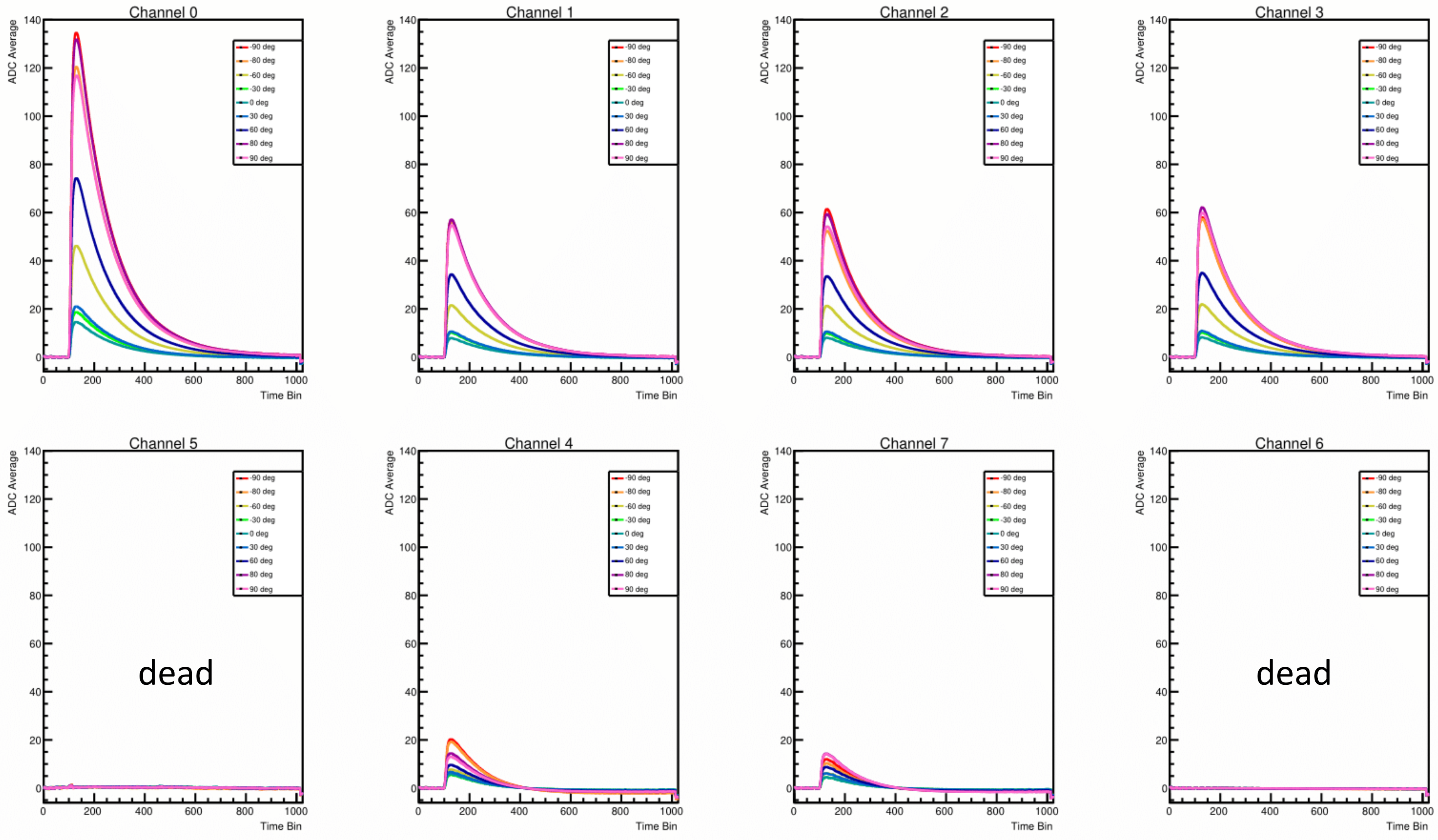


PbF2 no filter



- Noise is below 1 ADC/mV and stable
- Independent of crystal, angle, and presence of filter

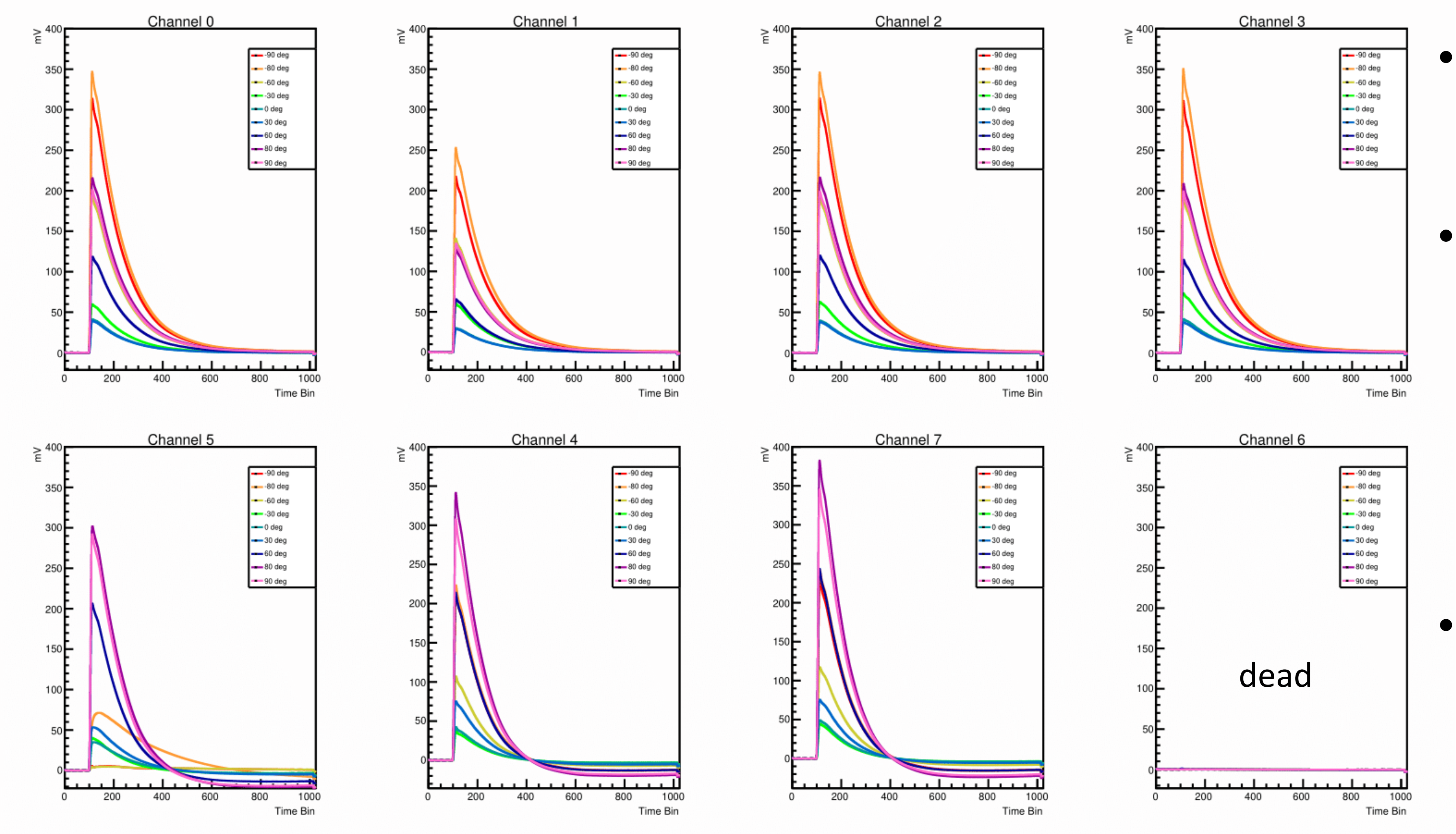
Averaged Waveforms: PWO with filter in rear



- Slow rising edge due to time delay of scintillation emission
- See angle dependence in amplitude
- Filtered reduced signal by about 1/3
- Channel 0 has double the signal than other front channels

*Noise events removed except channels 5 and 6

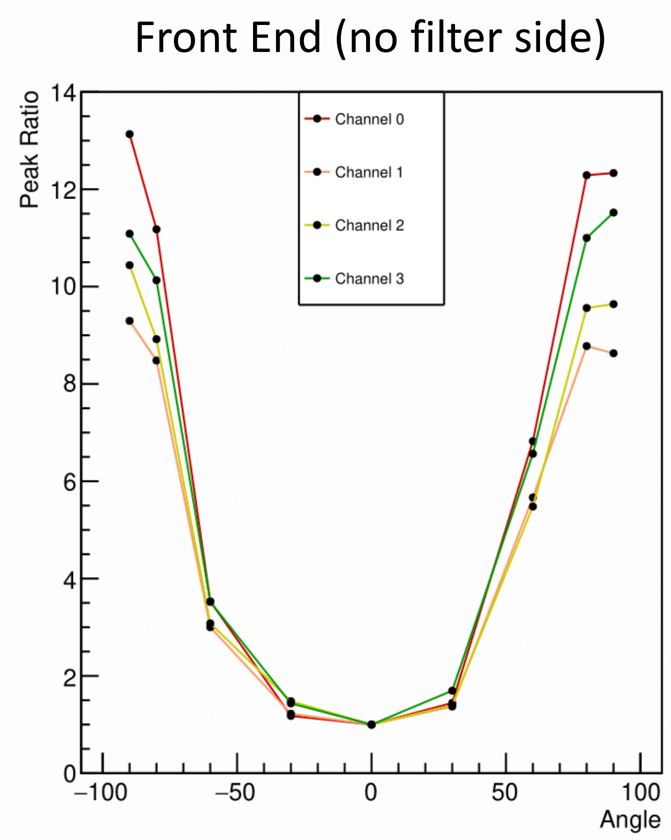
Averaged Waveforms: PbF2 no filter

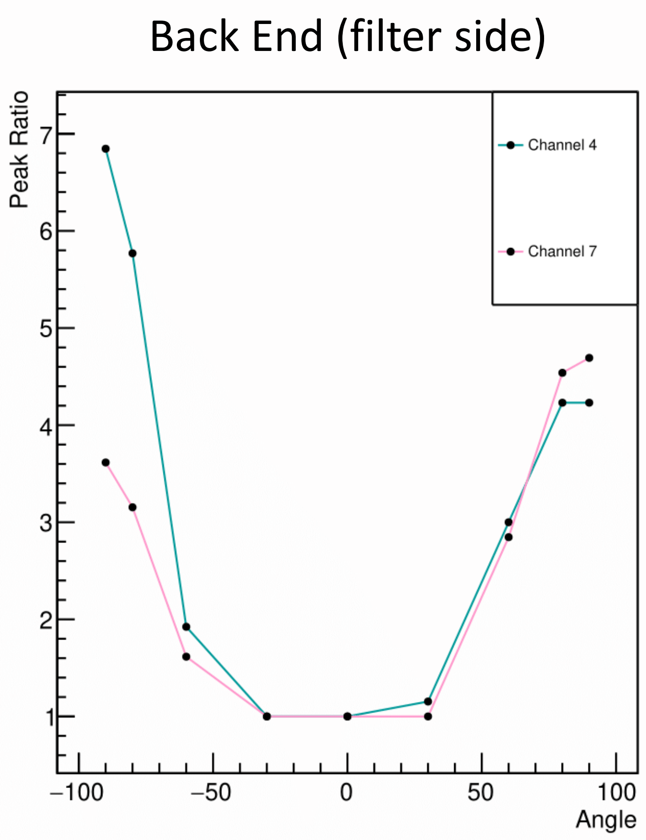


*Noise events removed except channel 6

- Cherenkov is instantaneous -> sharp rising edge
- Due to directionality of Cherenkov: front end has larger signals at negative angles and back end has larger signals at positive angles
- Channel 1 has overall smaller signals compared to other front channels

Angle Dependence: PWO with filter in rear





- The peak value of signal fluctuations in amplitude distribution is taken at each angle
- Normalized by the value at 0 deg

Front End (no filter side)

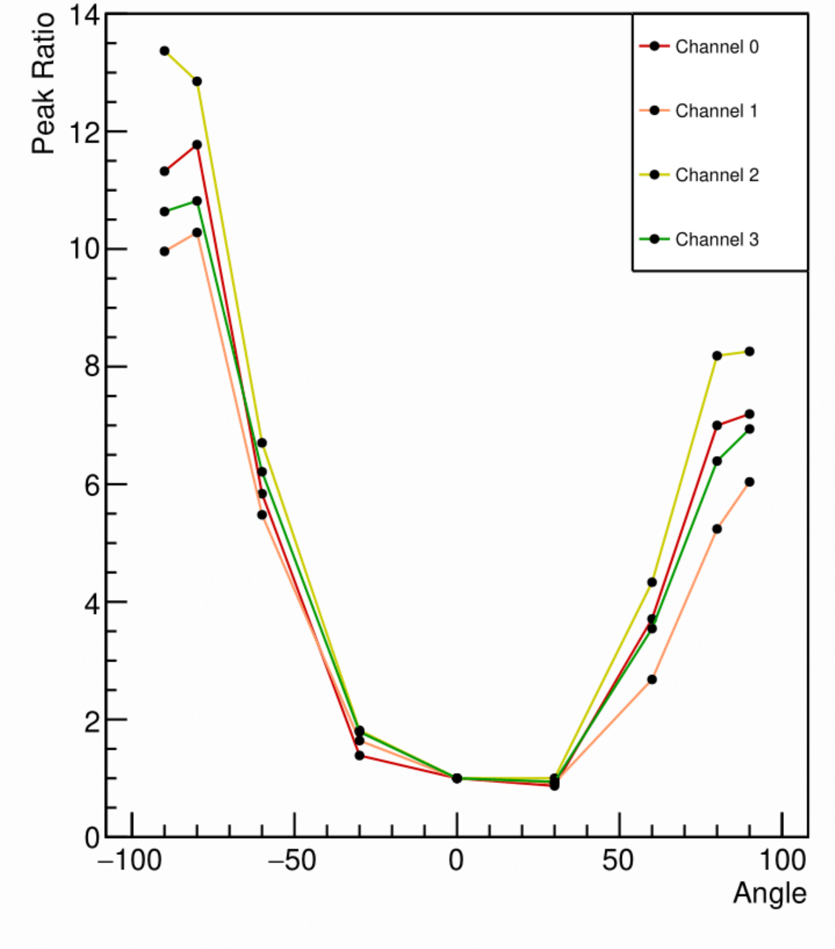
- Symmetric due to no directionally from dominant scintillation component

Back End (filter side)

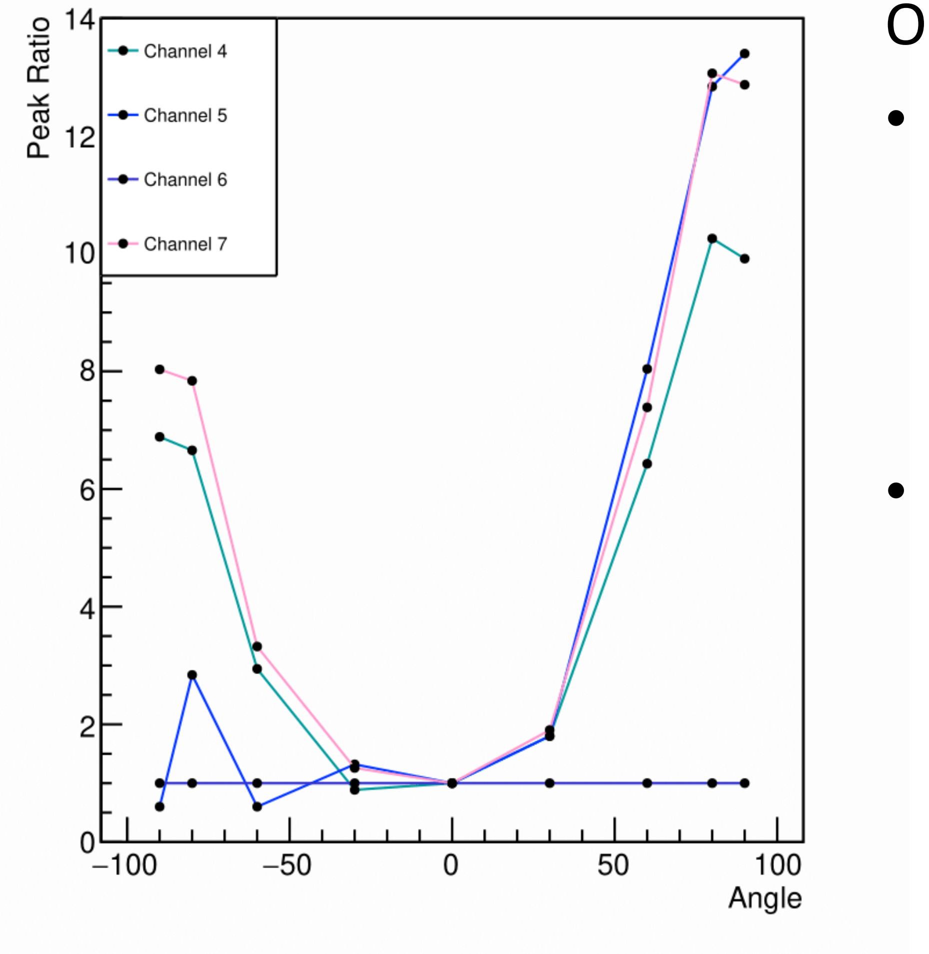
- Asymmetry observed
- Possible contributing factors
  - Cherenkov directionally
  - Photon loss due to coupling and transmission loss
- Further analysis needed

Angle Dependence: PbF2 no filter

Front end



Back end



Observations:

- Asymmetry between positive and negative angles due to Cherenkov directionality
- Consistent with expectations

Telescope Tracking

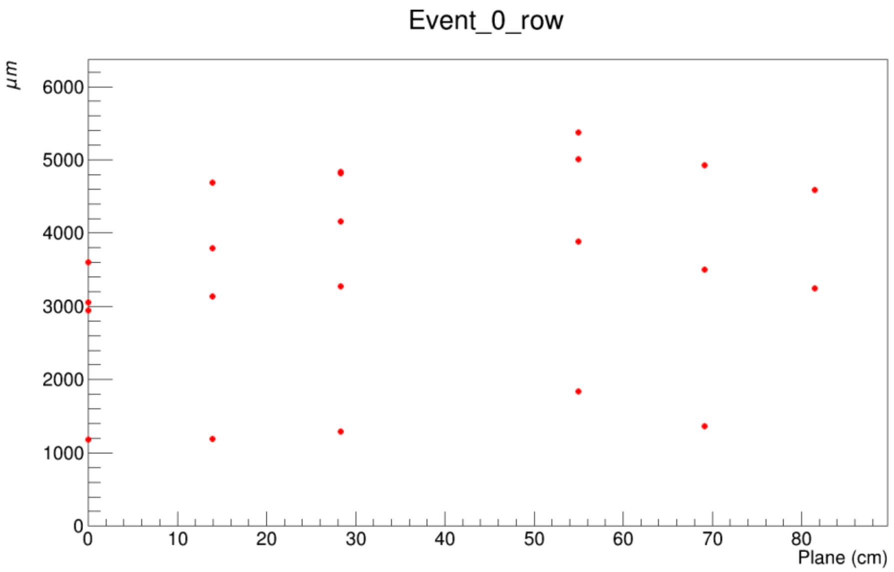
- Si-telescope used to track position of electron beam
- Essential for understanding any position dependence on shower development and response of SiPMs
- Made up of 6 planes (0-5) divided into 18.4 micron size pixels

Challenges:

- Misalignment between planes
- Multiple scattering and beam divergence effects
- More than 60% of events have more than 1 track due to large sampling window
- Noise needs to selected and filtered out

Goal:

- Assuming non-rotational misalignment, reconstruct tracks using chi-square minimization



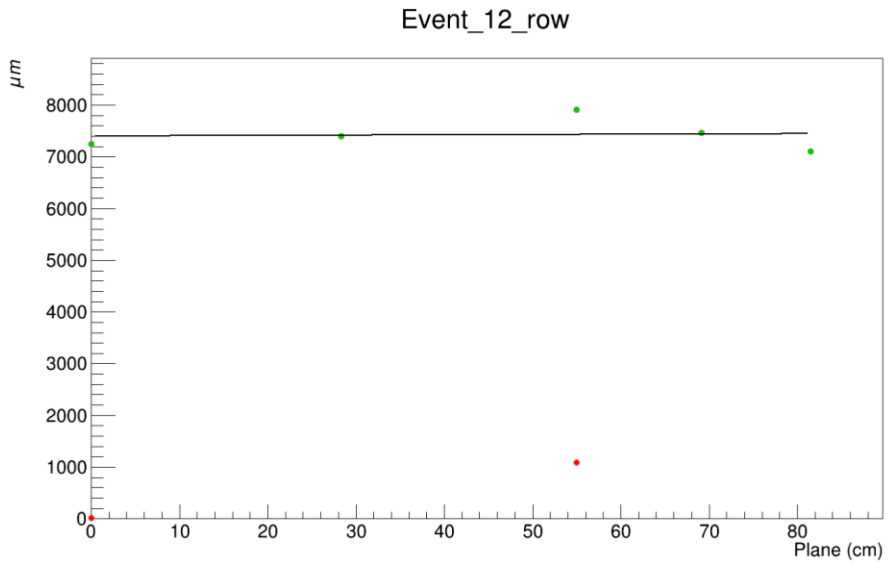
Telescope Tracking

✓ Selected single track events

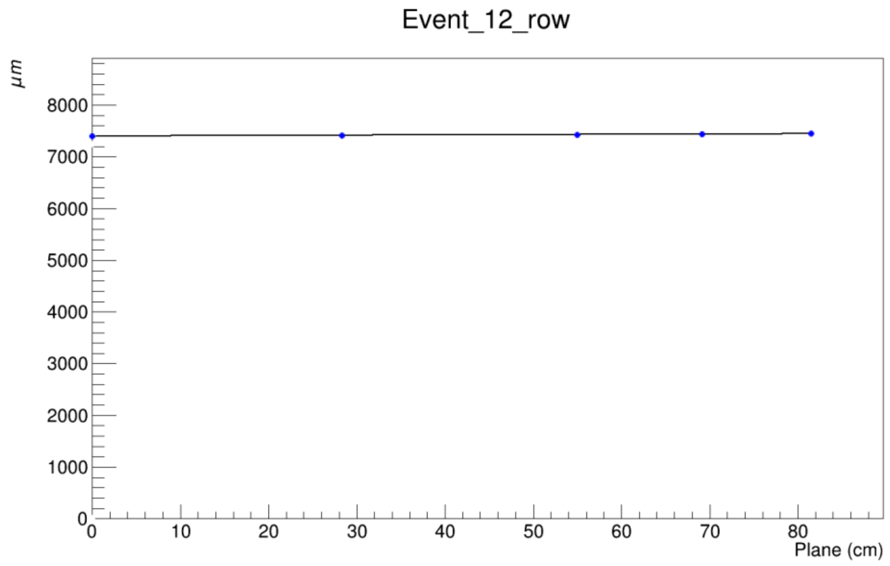
✓ Filtered out noise hits

✓ Performed linear fit

Before realignment



After realignment

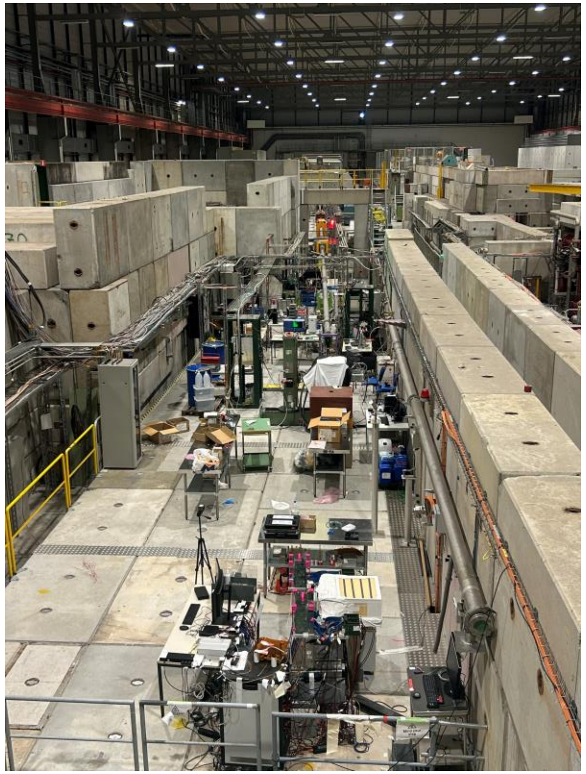


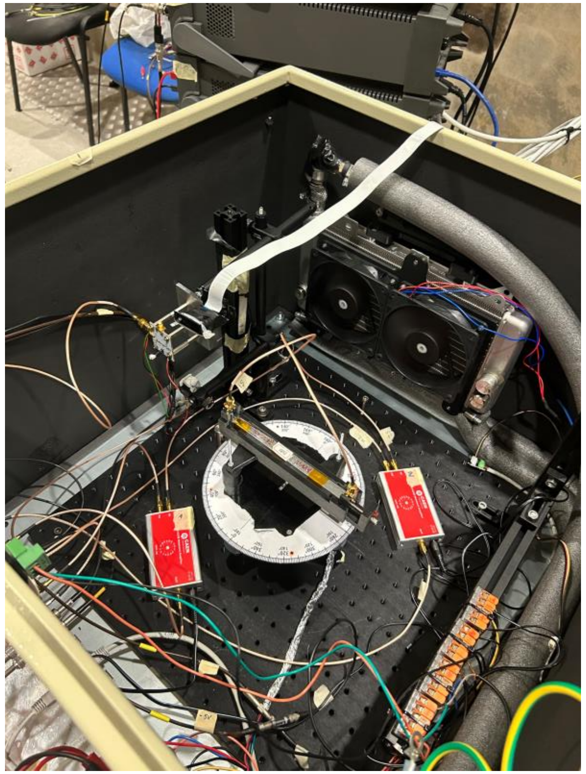
In progress:

- Find residual between fit and hits
- Extract beam divergence and multiple scattering effects

July 2024 CERN Test Beam

- Participated in beam test
  - Set up
  - Data-taking shifts





Next steps

- Continue with tracking reconstruction
- Compare PWO from DESY with Fermilab data to understand the differences caused by the use of different SiPMs

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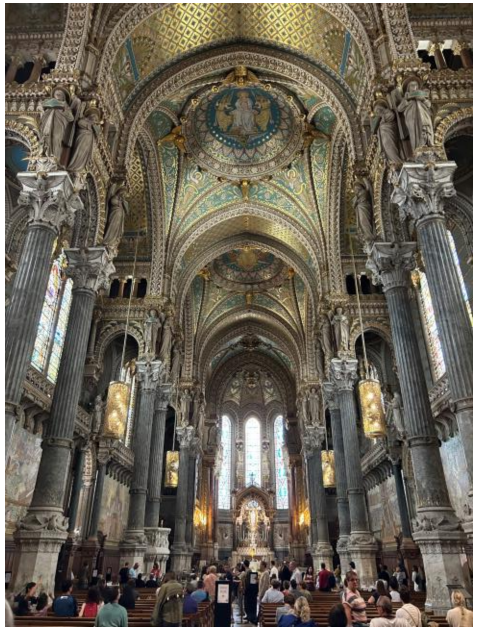

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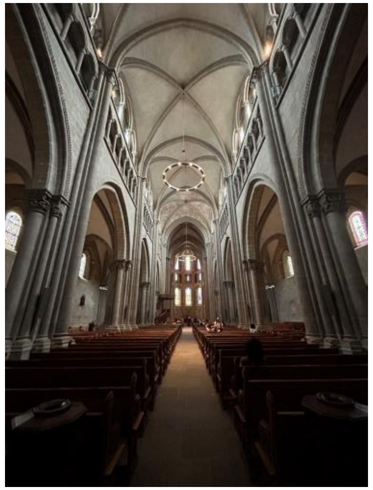

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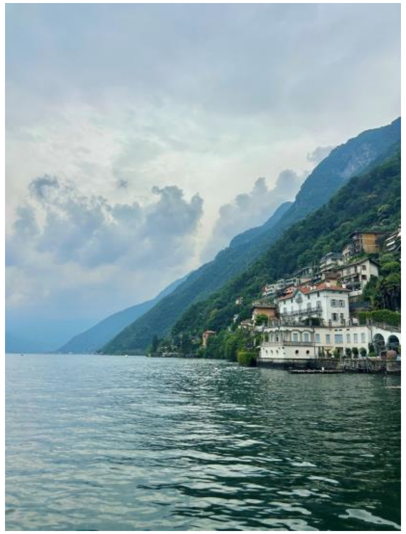

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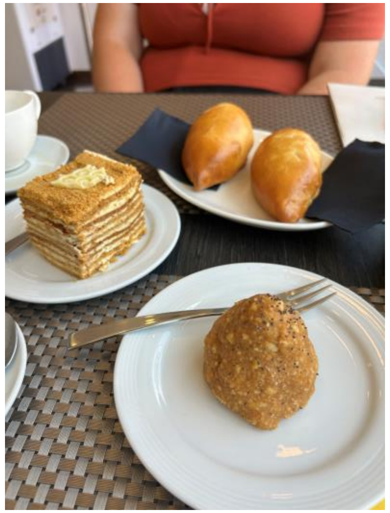

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