Dual-readout study with PbF2 crystals

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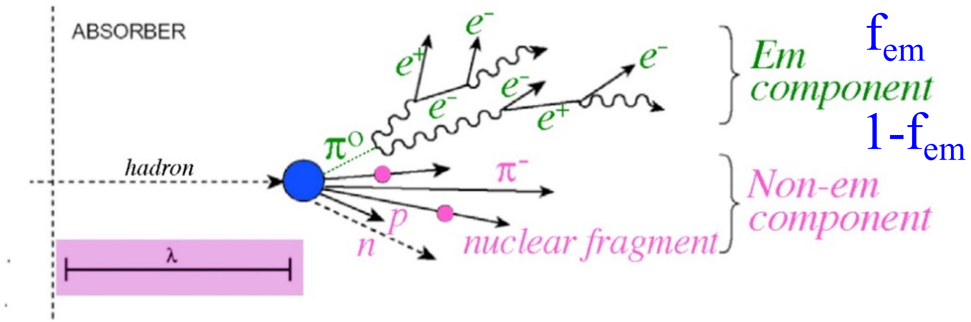
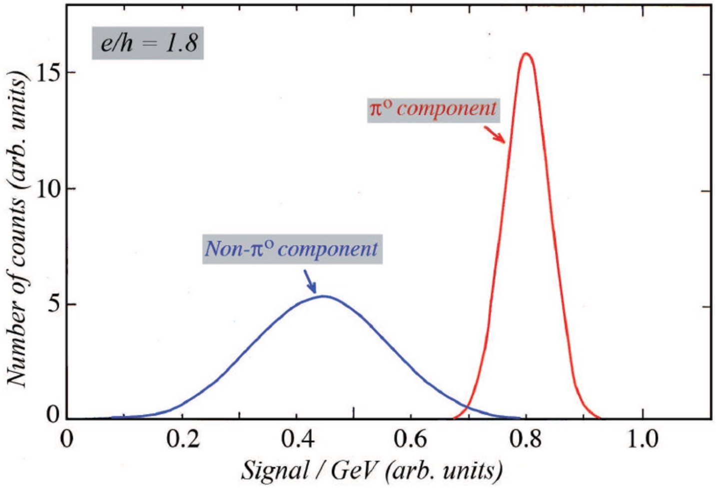
Introduction

Jet energy resolution is a key benchmark of the e^+e^- detector performance

Important to build calorimeters that can achieve ΔE/E ~ 3-4% for jets at 100 GeV to separate hadronically-decayed W and Z bosons

Read out both scintillation and Cherenkov (relativistic charged particles, mostly electrons) photons to disentangle EM and hadronic components event-by-event

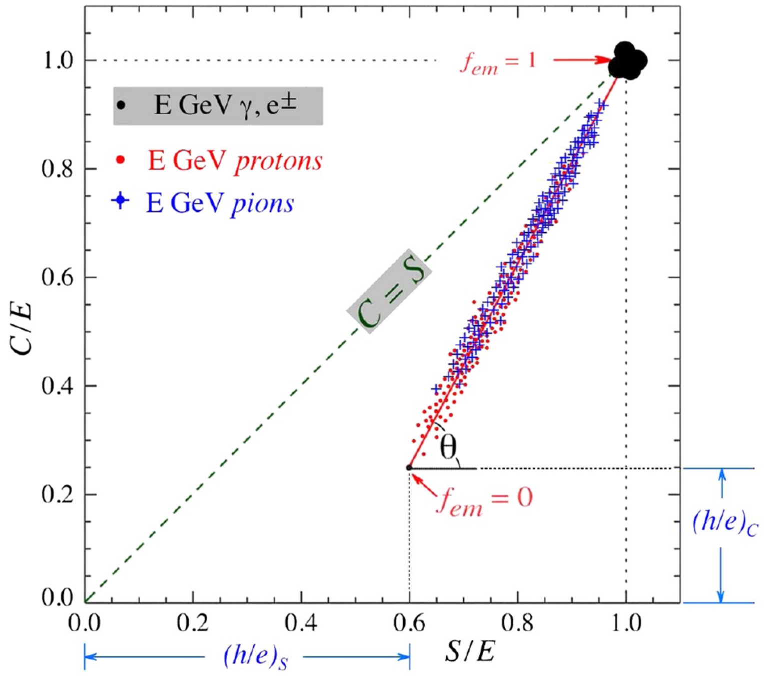




f_{em} fluctuations dominate the hadronic energy resolution

$$\chi = \frac{1-\left(\frac{h}{e}\right)_S}{1-\left(\frac{h}{e}\right)_C} = \cot\theta$$

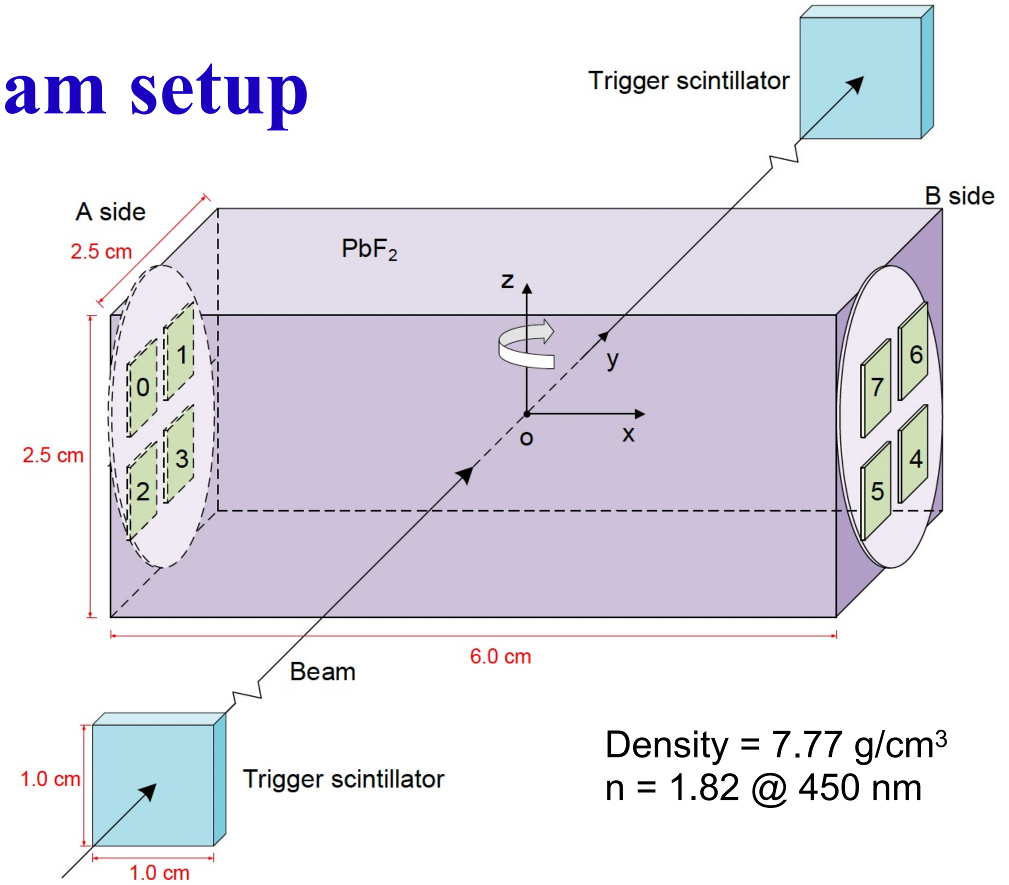
$$E = \frac{S-\chi C}{1-\chi}$$

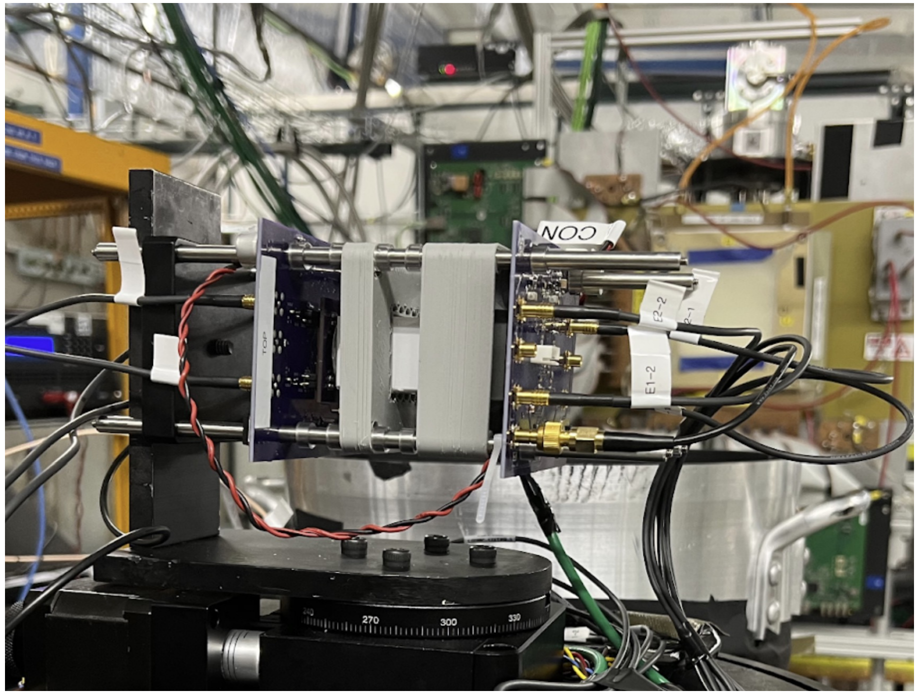


DRO calorimetry relies on the fact that e/h is different For Cerenkov and Scintillation readout

χ is independent of the incident hadron's energy

Test beam setup

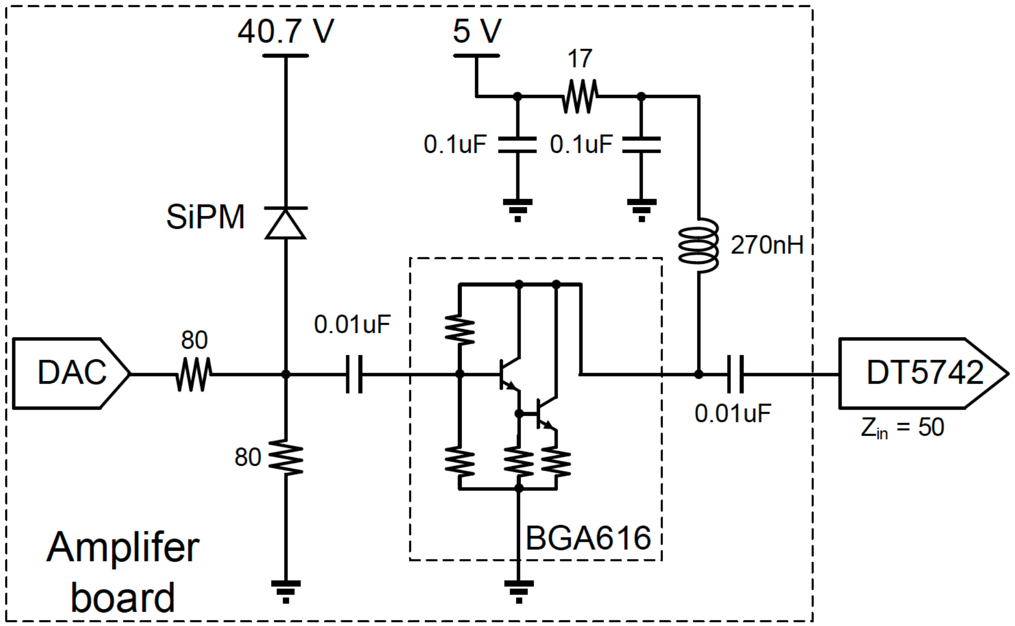




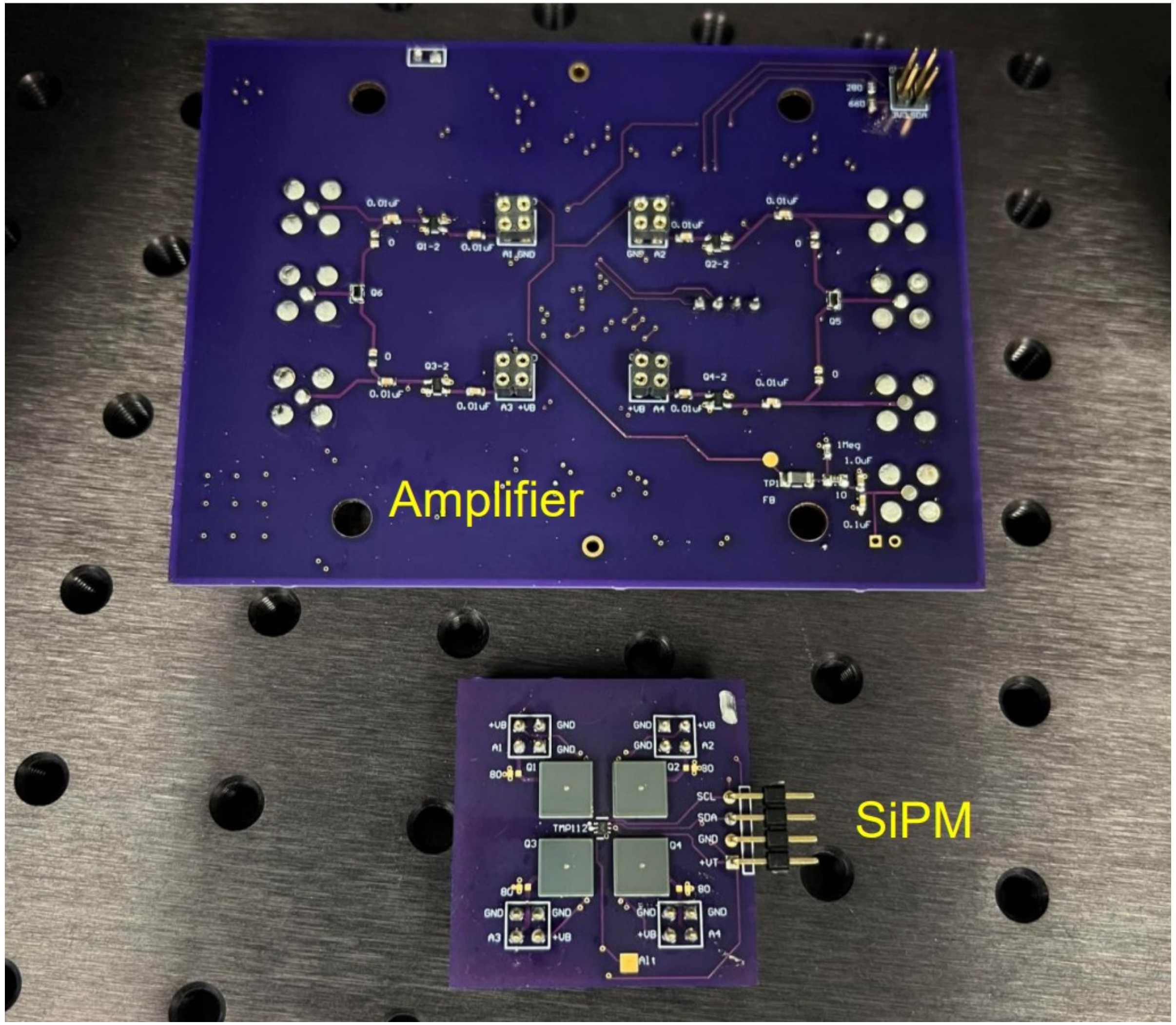
- Fermilab 120 GeV proton beam
- 6 x 2.5 x 2.5 cm^3 PbF_2 crystal, non scintillating, wrapped
- Four SiPMs at each side (A side and B side), with silicon rubber coupled to crystal surface
- Crystal and readout boards on a rotation base
- Two 1 x 1 cm^2 scintillation tiles along the beam path as readout trigger, ~1 kHz rate when beam is active
- A steel pot serving as a dark box and Faraday cage

SiPM readout

- Boards designed by the University of Virginia group
- Four S14160-6050HS (6 x 6 mm^2) SiPMs on board, micro-cell pitch 50 um
- Single-stage RF amplifier for each channel
- Domino-ring sampler4 (DRS4) digitizer, 5 Gsps, 200 ns window, 16+1 channel maximum



Single-channel schematic



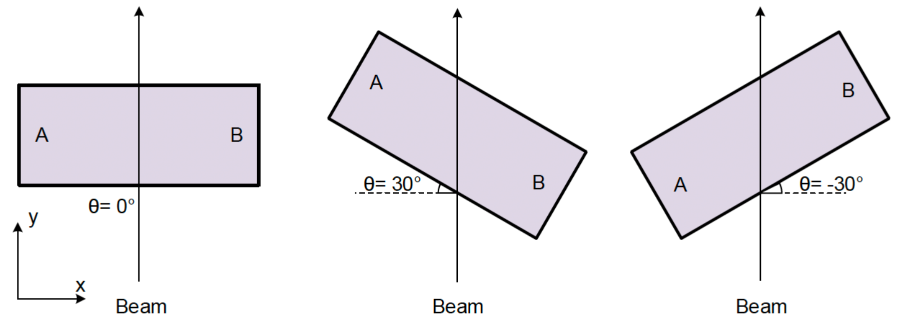
4-channel amplifier board and SiPM board

Test results

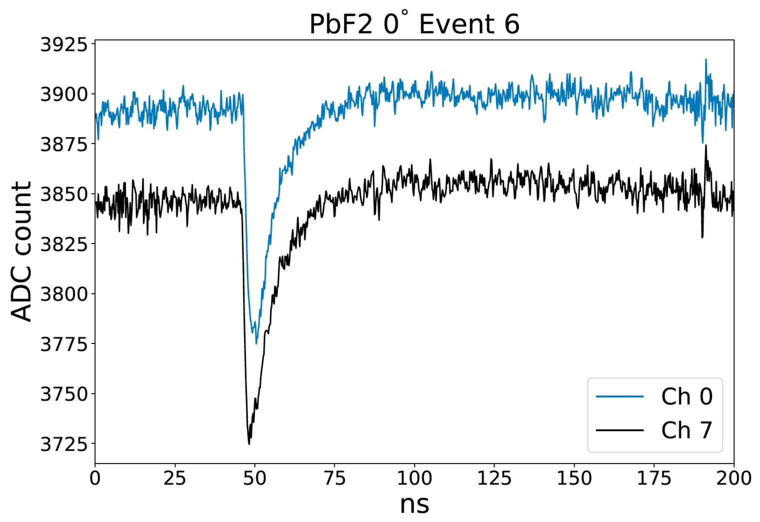
- Crystal rotated during the test for -90 ~ 90 degree, by a 10-degree step
- 40 k~70 k triggered events for each angle
- Raw data baseline offset removed and waveform fitted using below equation:

$$y(t) = A \times \frac{1}{e^{-\frac{t-t_0}{\tau_r}} + 1} \times \frac{1}{e^{\frac{t-t_0}{\tau_d}} + 1}.$$

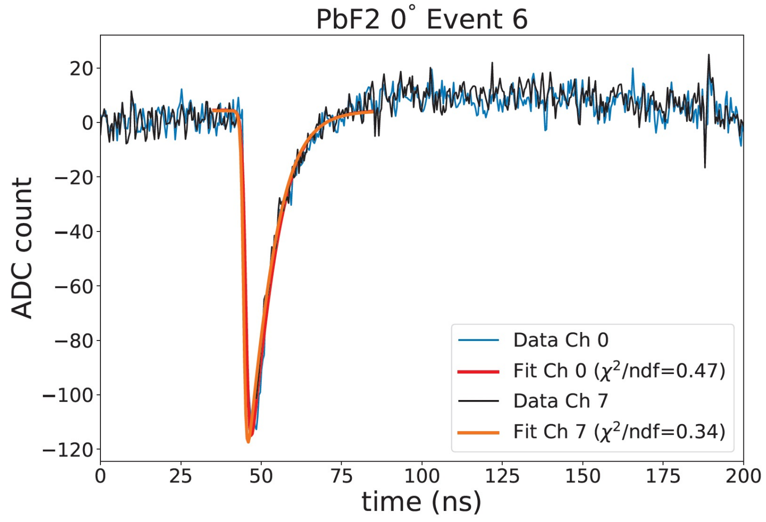
- Fitting parameter: peak position, rising time, decay time, peak amplitude



Rotation angle definition

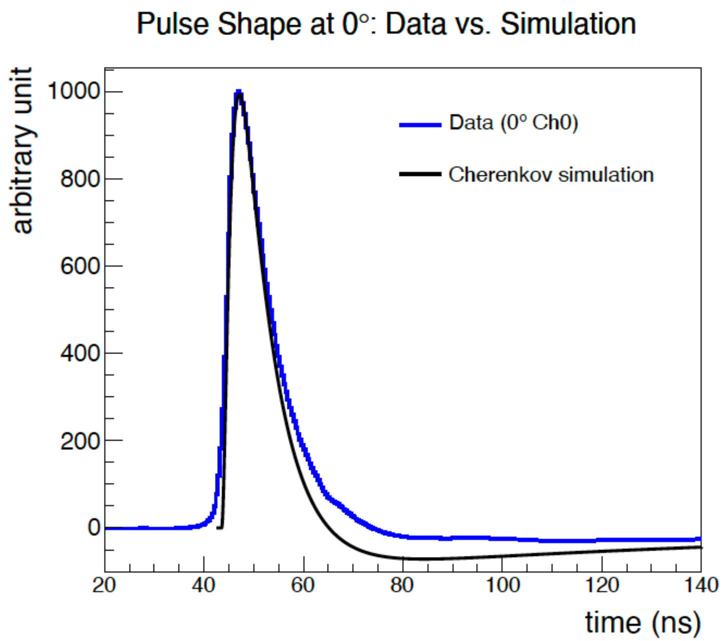


Raw data

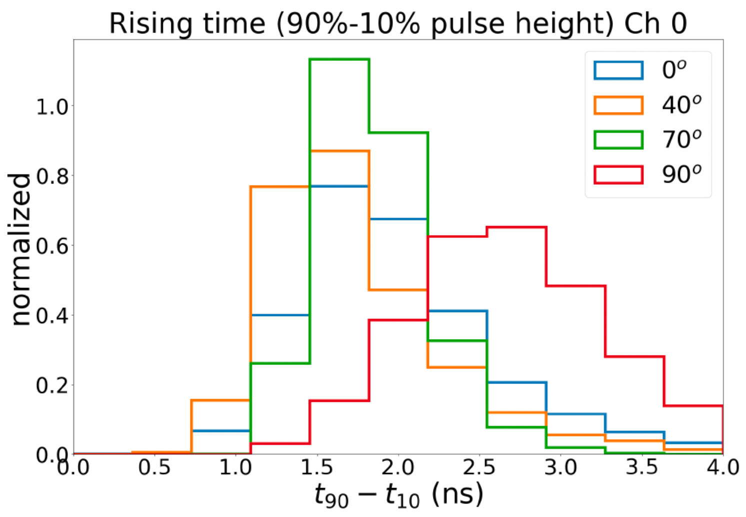


Fitted data

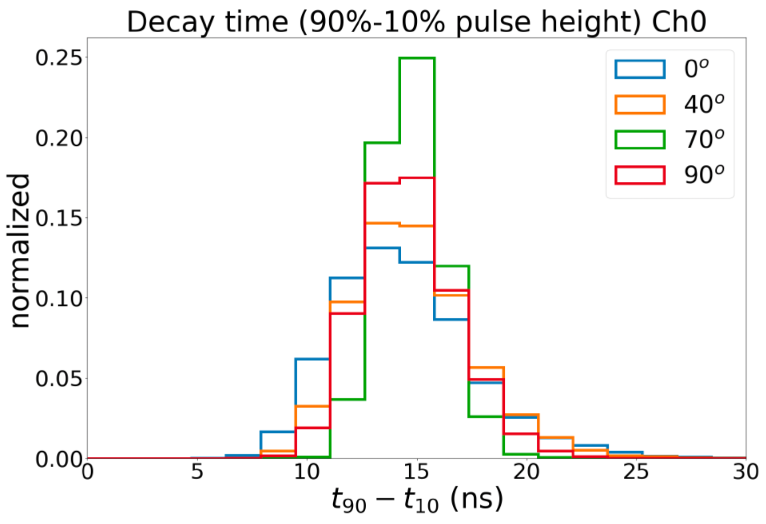
Test results



Pulse shape simulation comparison



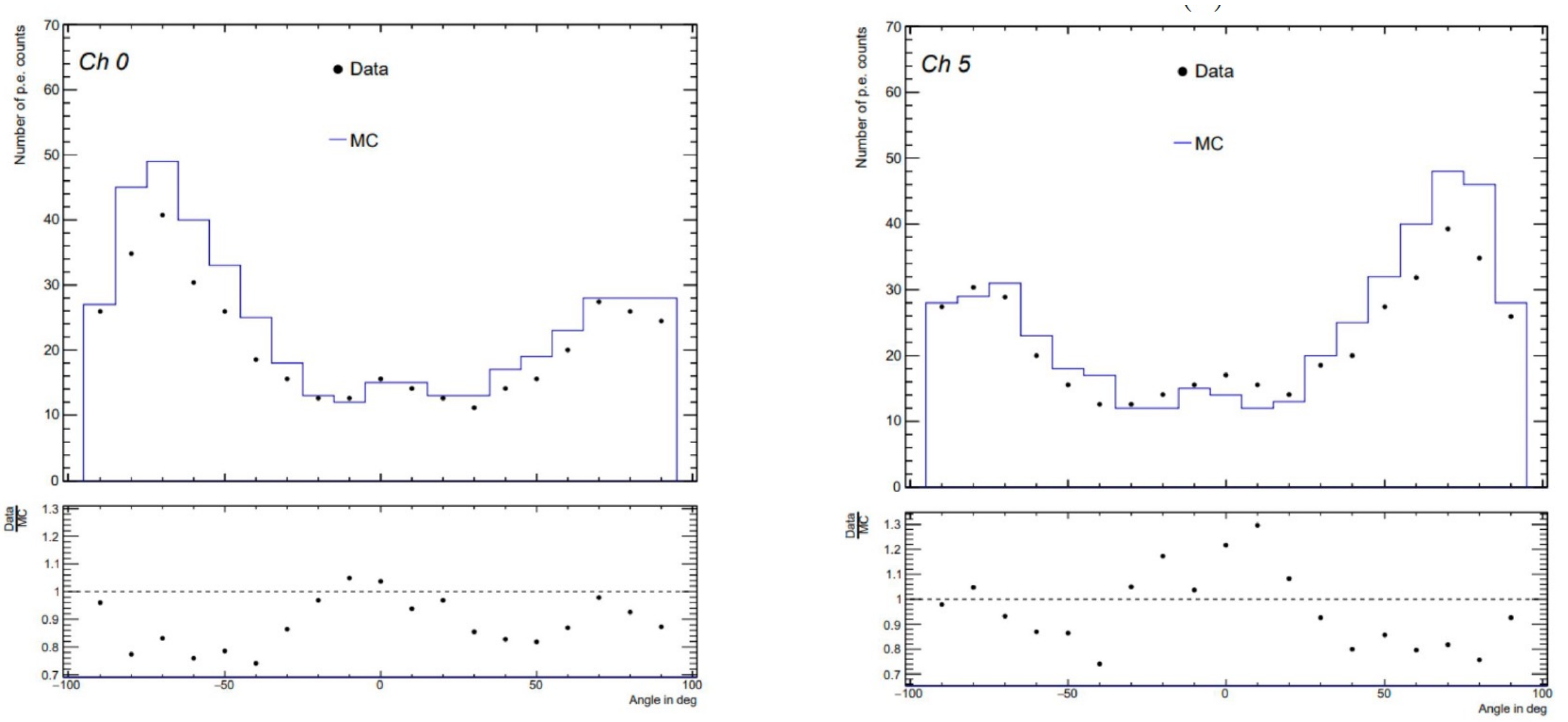
Leading edge rising time (90%-10%)



Trailing edge decay time (90%-10%)

- The average waveform at θ = 0° is compared with Geant4 simulation for Cherenkov photons The shape of leading edge is mostly consistent, while for the trailing edge simulation shows more bimodal structure
- Leading edge rising time is stable until rotation angle above 70 degree
- Trailing edge decay time is independent from rotation angle (dominant by SiPM response)

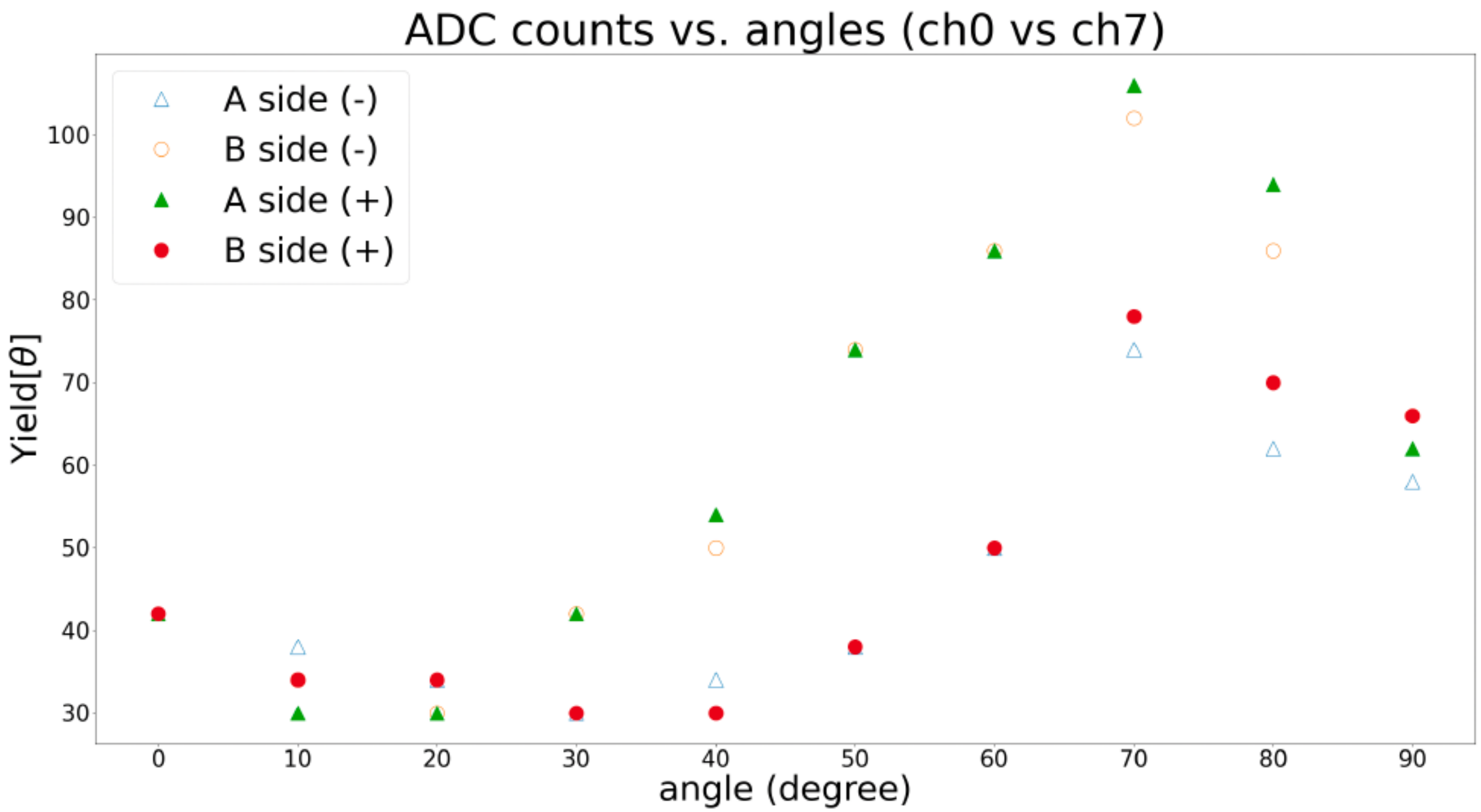
Monte Carlo simulation comparison



Mean number of photons from PbF2, data and MC simulation comparison

- Detailed detector MC simulation studies using dd4hep (GEANT4 wrapper)
- 10 k proton events were simulated for each rotation angle
- Simulated photon counts are normalized to test data at $\theta = 0^{o}$

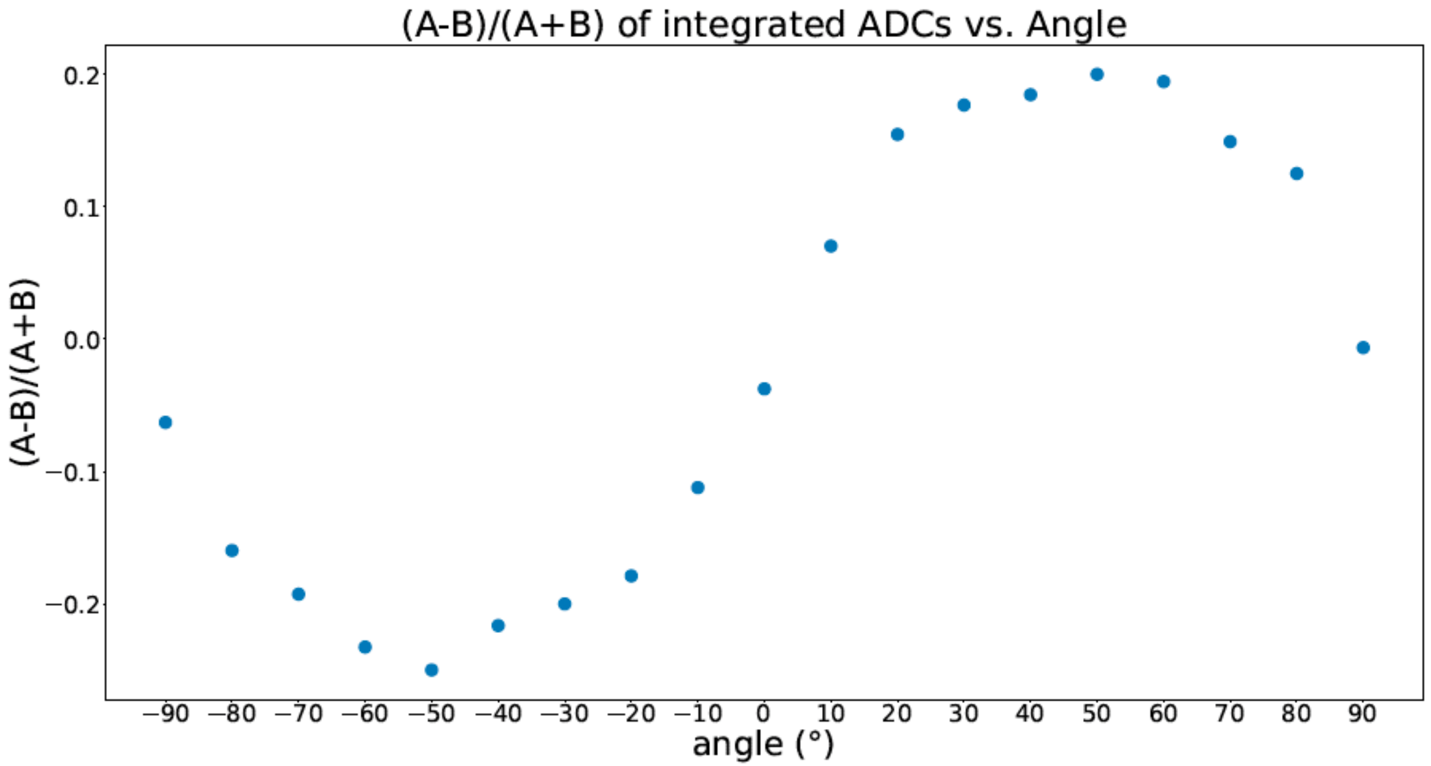
Test results



Average peak ADC counts for mirroring channels of side A and B

- In general, the number of detected photons increases with increasing $|\theta|$. However, this trend reverses at $|\theta| \simeq 70^{o}$, corresponding to the proton's path length reaching its maximum at $|\theta| = 67.4^{o}$
- The reduction at $|\theta| \simeq 20^{o}$ is due to internal total reflection between the silicon rubber and the SiPMs that at this angle, many generated photons are not detected by the corresponding SiPMs

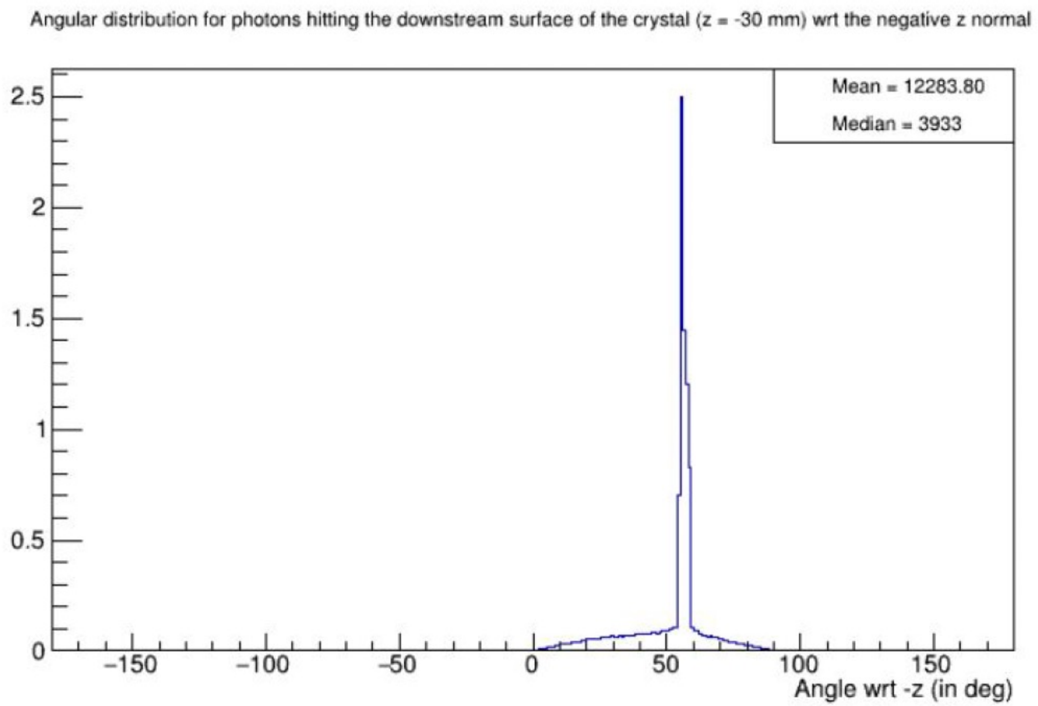
Asymmetry as a function of rotation angle



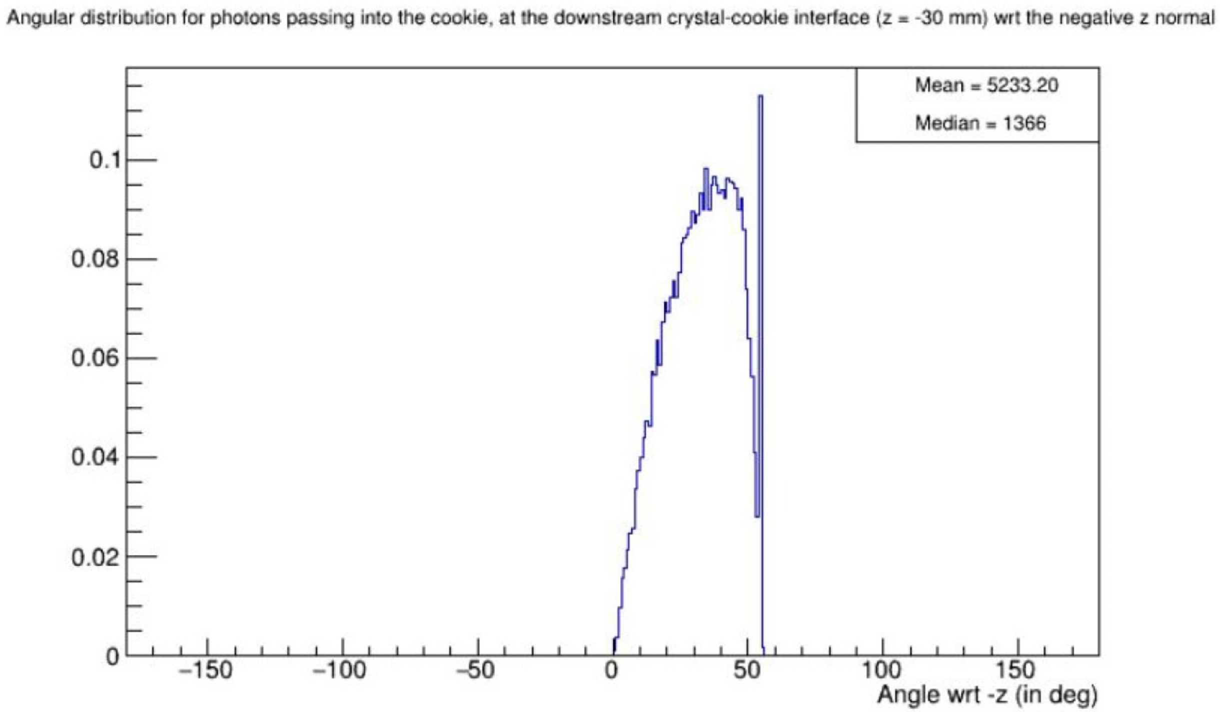
Asymmetry of integrated ADC counts as a function of rotation angle

- The asymmetry in the integrated ADC counts (sum of all channels) between A and B sides is calculated as (A – B)/(A + B) for each rotation angle
- The maximum asymmetry is approximately 20%, occurring when the rotation angle is close to 50°
- The asymmetry is close to 0 when $\theta = \pm 90^o$. Simulation shows most photons generated when $\theta = \pm 90^o$ reaching the two sides have incident angles around 56º, which is close to the total internal reflective angle 52º between the silicon rubber and the SiPMs so mostly not detected by the SiPMs

Incident angle distribution of the generated photons



Incident angle reaching crystal side



Incident angle detected by SiPMs

- Simulation shows most generated photons is reflected and not entering the SiPMs

Conclusions

- The CalVision collaboration proposes to use inorganic crystals and dual-readout technique to improve both EM and hadronic energy resolutions
- Cherenkov light yield for a PbF_2 crystal as a function of its incident angle is studied using proton beam test results
- A complicated angular dependence was observed and can be understood by considering the contributions of index matching, total internal reflection, and non-specular reflections