Update on TB Apr2023 at FNAL

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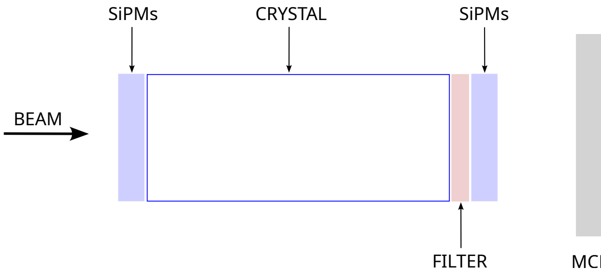
CalVision General Meeting
Nov 16, 2023

Introduction

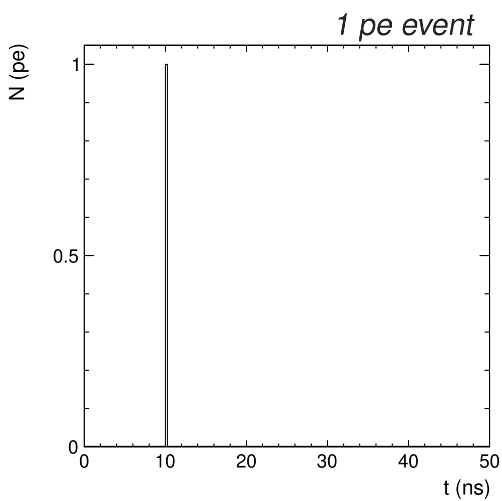


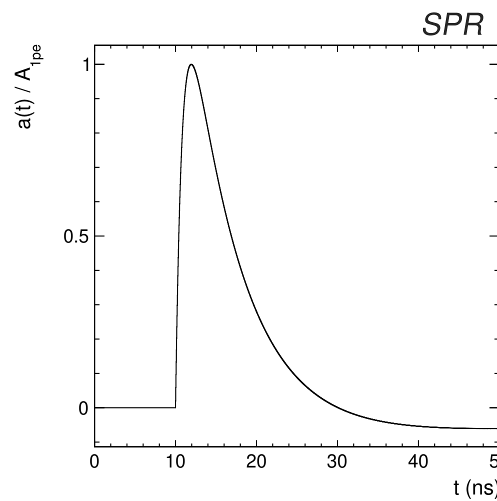
- BGO 25x25x60
- 120 GeV protons
- longitudinal geometry
- Individual pulses with Scope
- Measurement of N_C and N_S for individual pulses

Single Particle Response Function (SPR)

Single p.e. in SiPM is delta function (left) Scope response (right) is smeared due to:

- avalanche development
- pulse shaping by SiPM resistance and capacitance
- amplifier shaping
- cables
- scope bandwidth
- etc





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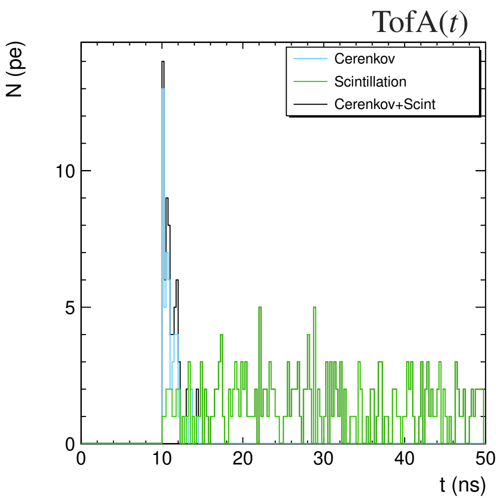
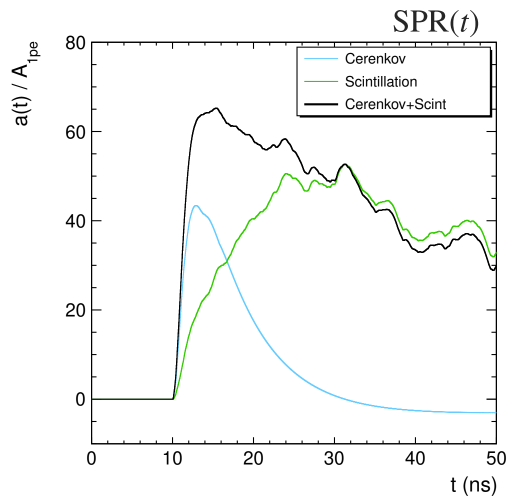
Scope pulse from N p.e.

Scope pulse, $\mathrm{PS}(t)$, is convolution of time distribution of p.e.'s in SiPM, $\mathrm{TofA}(t)$, and $\mathrm{SPR}(t)$

$$\mathrm{PS}(t) = \int_0^t \mathrm{SPR}(\tau) \cdot \mathrm{TofA}(t-\tau)\, d\tau = \sum_{i=1}^{N_C} \mathrm{SPR}(t-t_i) + \sum_{j=1}^{N_S} \mathrm{SPR}(t-t_j)$$





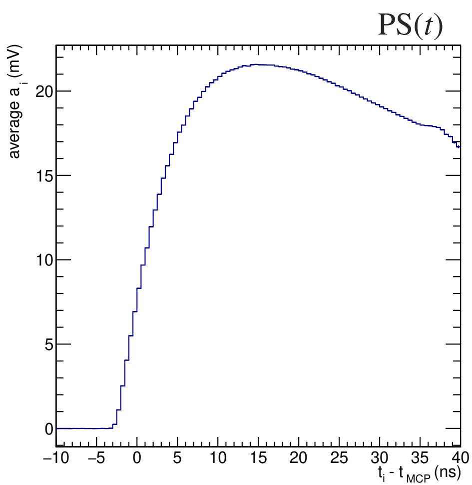
How to obtain SPR?

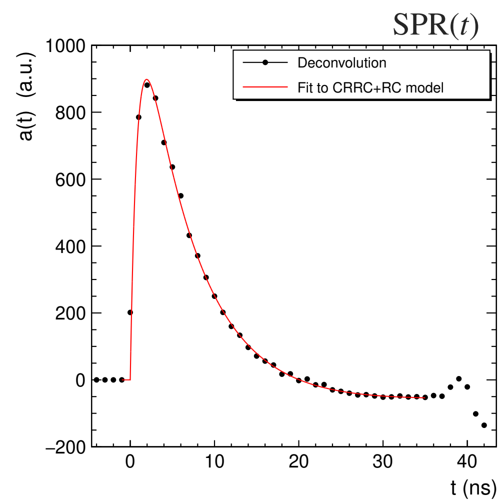
- Measure pulse shape of single dark counts
  - low amplitudes → noise
  - overlapping counts
- Picosecond laser on SiPM
  - not a delta function of N p.e.
  - width of the laser pulse
  - after-pulsing in SiPM
  - Single Particle Time Resolution (SPTR)
- Deconvolution of $\mathrm{PS}(t)$ and $\mathrm{TofA}(t)$

Extracting SPR from DATA

Left plot: Measured average pulse shape, $\mathrm{PS}(t)$, in SiPM without filter for MIPs.
Assume $\mathrm{PS}(t)$ is dominated by Scintillation, Cerenkov contribution is negligible
Deconvolute $\mathrm{PS}(t)$ with BGO scintillation function *exp(-t/300ns)* to get $\mathrm{SPR}(t)$ (black dots, right plot)
SPR is described as CR-RC shaper (τ_{rise}=0.853 ns, τ_{decay}=6.538 ns) + RC differentiator (RC=101.7 ns), red line

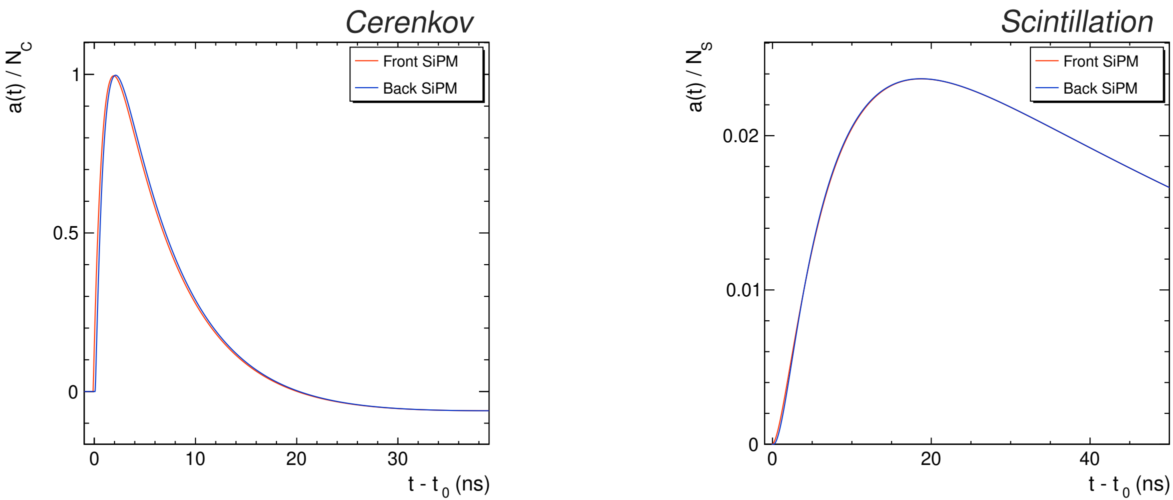
This is zero-order approximation for SPR.
It can be improved by removing small Cerenkov contribution to $\mathrm{PS}(t)$ with iterative procedure





Pure Cerenkov and Pure Scintillation pulse shapes. Simulation.

Use $\mathrm{SPR}(t)$ and simulated time of arrival distributions, $\mathrm{TofA}(t)$, for Cerenkov and Scintillation photo-electrons → average pulse shapes at the scope, normalized to simulated N_C and N_S, respectively.

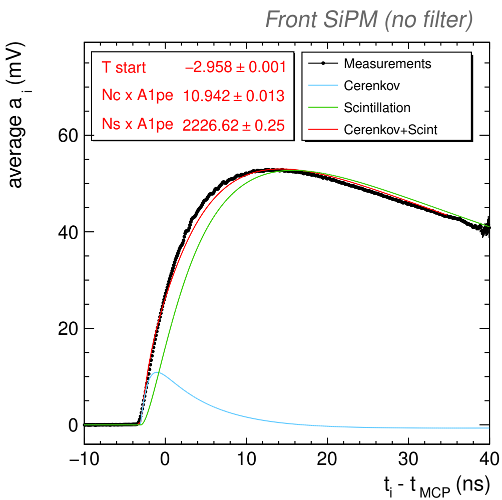


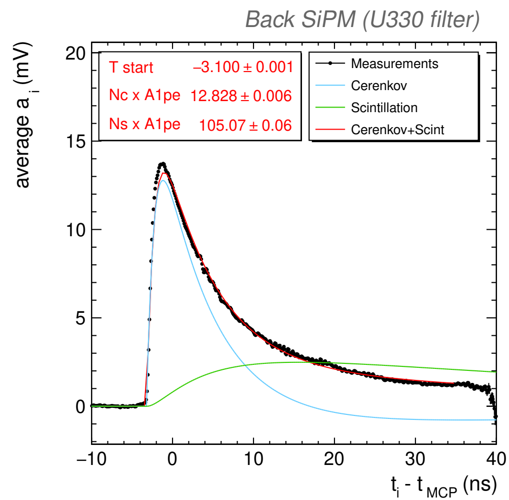
Average pulse in DATA + Fit to MC pulse shapes. MIPs.

Black dots: measured average pulse for central MIP tracks
Color lines: Fit to sum of Simulated Cerenkov and Scintillation pulse shapes
Three fit parameters:

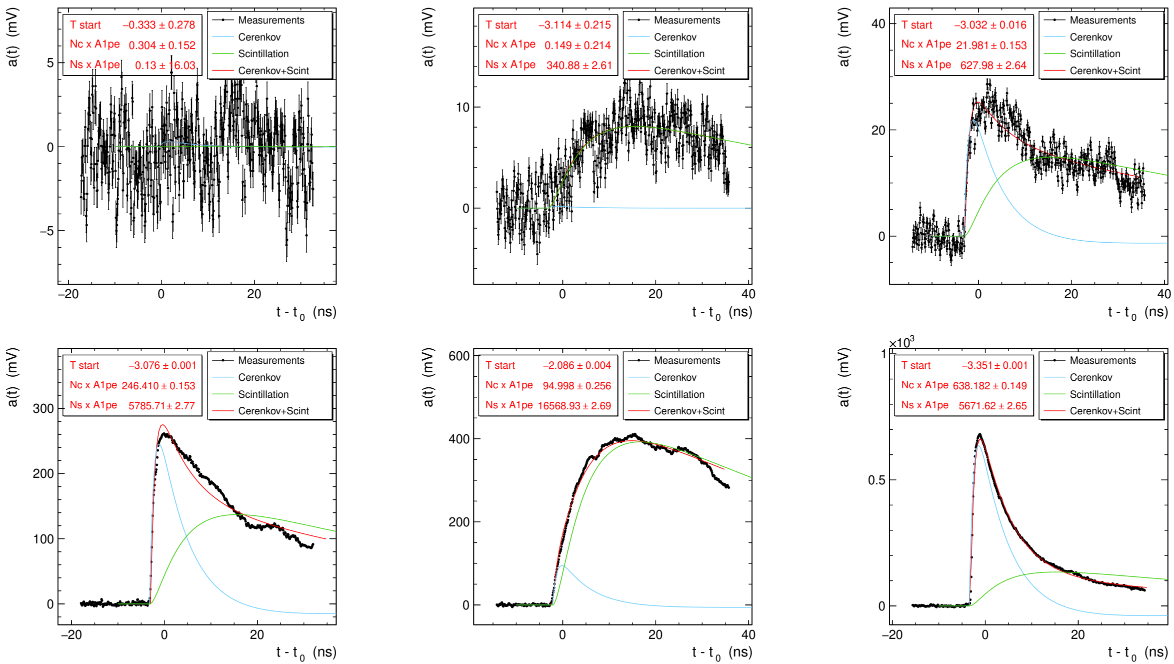
1) time of the pulse
2) the number of Cerenkov photons detected, N_C, times amplitude of 1pe pulse in mV
3) the number of Scintillation photons detected, N_S, times amplitude of 1pe pulse in mV

We believe, A1pe = 0.6 mV





Nc and Ns can be estimated for individual pulses as well



Summary

- It is possible to estimate N_C and N_S for individual pulses in BGO
- taking advantage of significant difference in time-of-arrival of Cerenkov (prompt) and Scintillation (τ=300 ns) photo-electrons
- fitting pulse with sum of two pulse shapes
- required: SPR shape and amplitude
- required: linear amplifier