Performance of Scintillation Counters with Silicon Photomultiplier Readout

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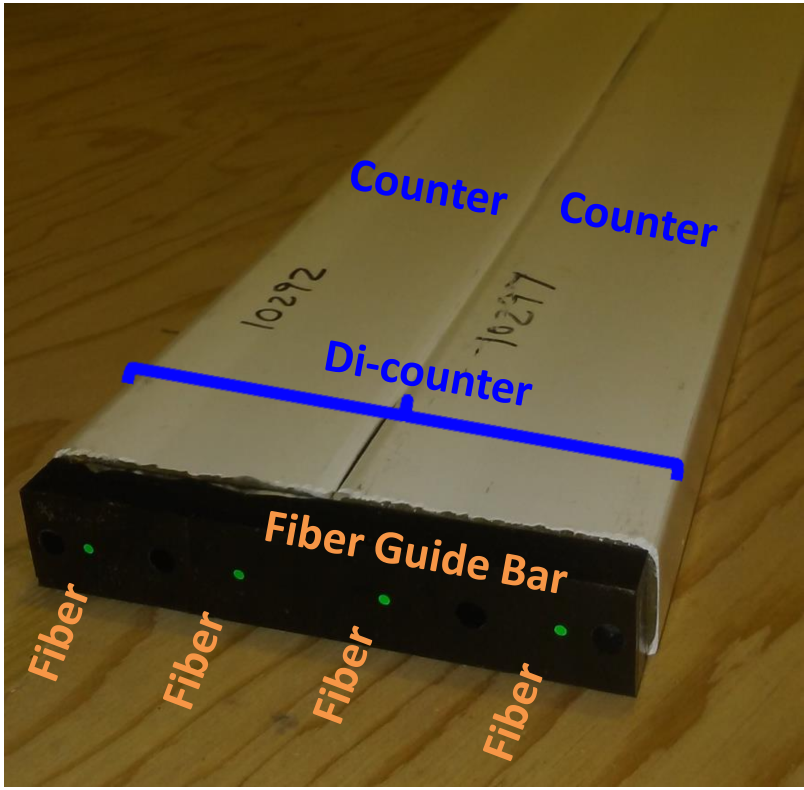
Overview of Mu2e

- Mu2e will look for coherent neutrinoless muon to electron conversions in the orbit of aluminum atoms.
$$\mu^- N \rightarrow e^- N$$
- The observation of such a process would be unambiguous evidence of new physics beyond the Standard Model.
- The electrons from such conversions would have energies of about 105 MeV.
- Cosmic ray muons – which are the dominant source of background – can produce particles that mimic these 105 MeV conversion electrons.
- A cosmic ray veto system (CRV) placed around the Mu2e spectrometer will veto these background events.
- The CRV is made of scintillator counters which will be the focus of this talk.

CRV Counters

- Scintillator counter dimensions:
  - Thickness: 20 mm
  - Width: 50 mm
  - Lengths: between 0.9 m and 6.6 m (the performance was tested with a counter length of 3.0 m).
- Coated with a 0.25 mm thick reflective layer of a TiO_2-polystyrene mixture.
- Two embedded wavelength shifting fibers.



- Each fiber gets readout on both ends by Silicon Photomultipliers (SiPMs).
- Two counters are glued together to form a di-counter.
- Assembled at the University of Virginia.

CRV Counter Materials

- Scintillator extrusions
  - Manufacturer: FNAL-NICADD Extrusion Line Facility
  - Polystyrene: Dow Styron 665 W
  - Primary dopant: PPO
  - Secondary dopant: POPOP, or 1,4-bis(2-methylstyryl)benzene
  - Reflective coating: TiO_2-polystyrene mixture
  - Several combinations of dopants and coatings were tested
- Wavelength shifting fibers
  - Manufacturer: Kuraray
  - Type: double-clad Y11 doped with 175 ppm K27 dye, non-S-type.
  - Diameters tested: 1.0 mm, 1.4 mm, 1.8 mm
- SiPMs
  - Manufacturer: Hamamatsu
  - Types:
    - 2 mm x 2 mm (S13360-2050VE), 1584 pixels
    - 3 mm x 3 mm (S13360-3050VE), 3584 pixels
  - Pixel size: 50µm
  - Breakdown voltage: 53.0 V
  - Bias voltage: 55.1V (February 2016), 55.3V (June 2016)

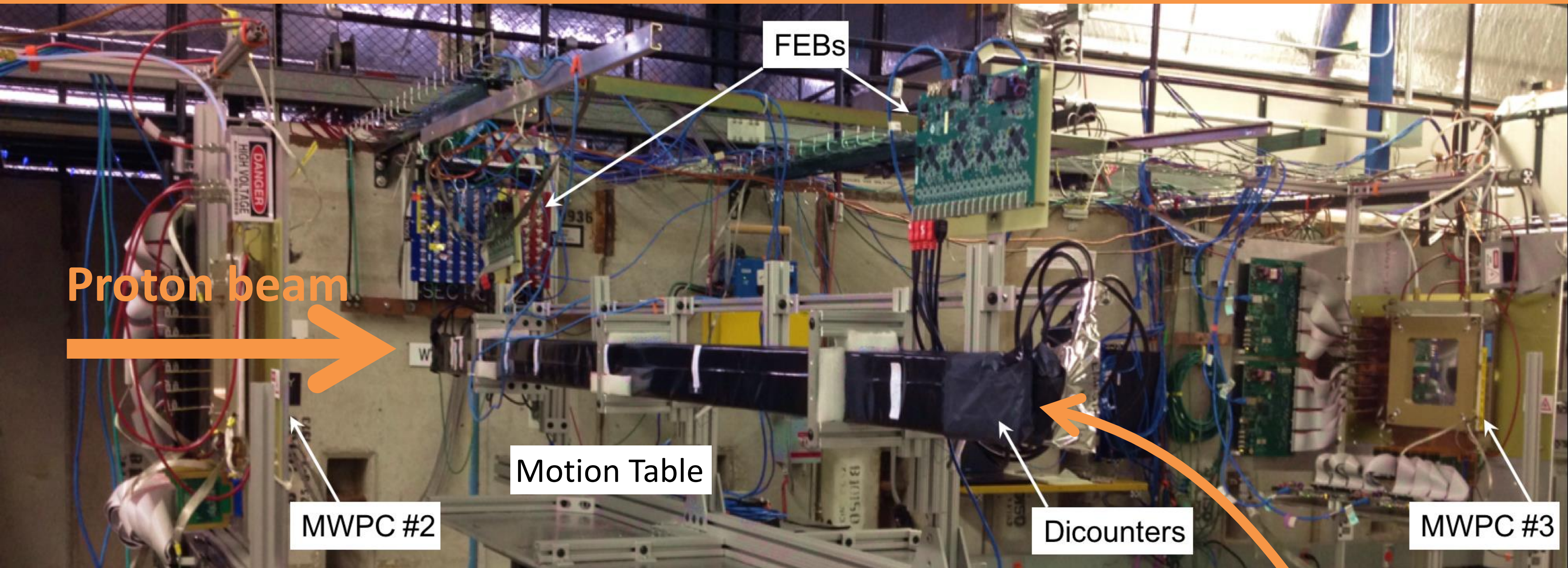
Test Beam

- The CRV counter performance tests were done
  - at the Fermilab Test Beam Facility
  - in February and June 2016.

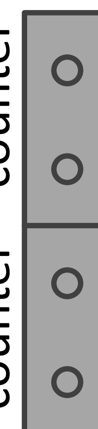
- Used a 120 GeV proton beam.

- Tested CRV di-counter of 3.0 m length.

Test Beam Setup



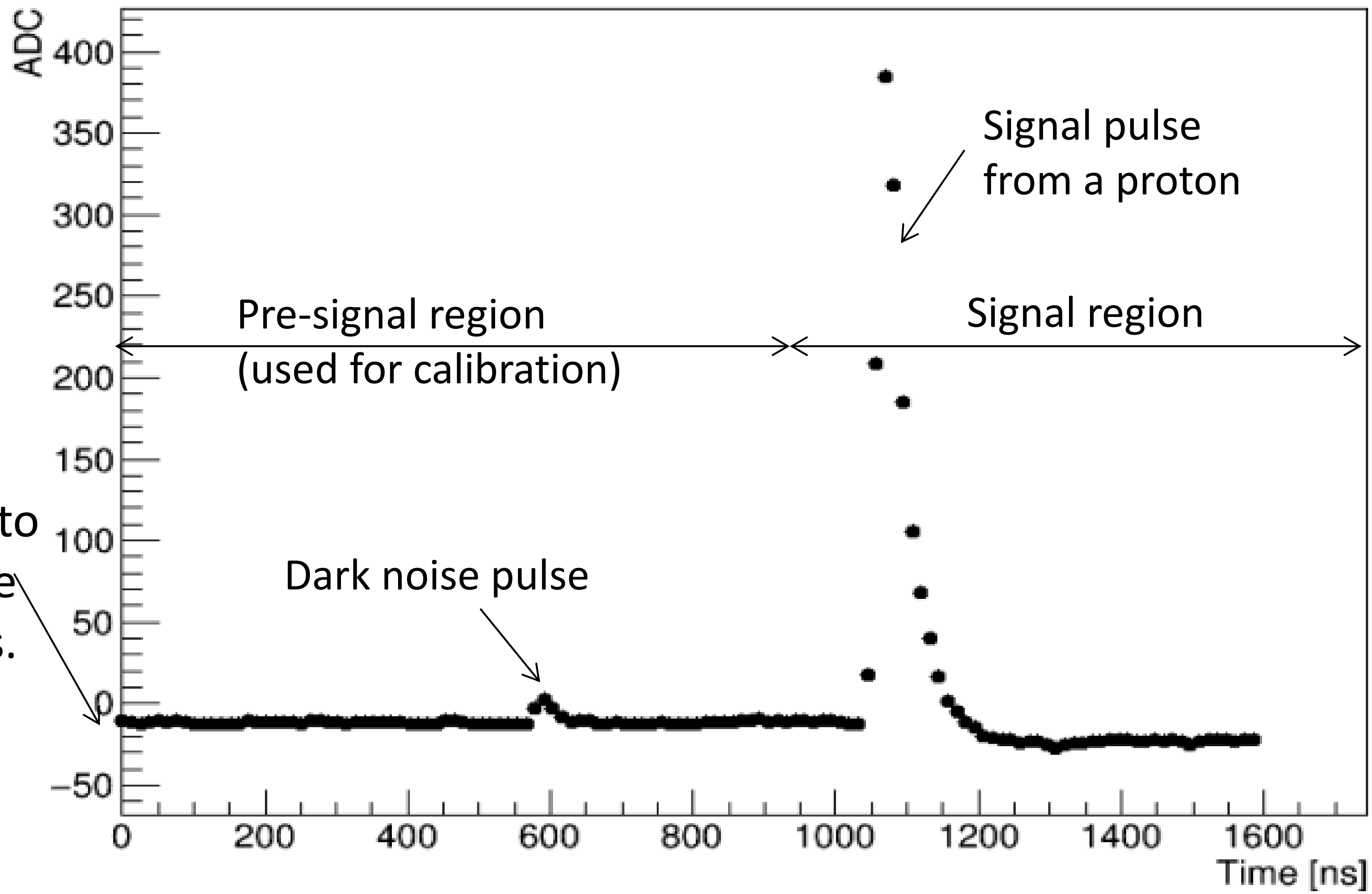
- Up to four di-counters were put into the beam.
- Four multi-wire proportional chambers were used to reconstruct the proton paths, and to determine the positions where the protons hit the CRV counters.
- Events were triggered by three scintillation counters and a begin-of-spill signal.
- A total of about 50,000 events were recorded for every run.



Example of a SiPM Waveform

- Digitization happens in 12.58 ns intervals (79.5 MHz).
- 127 digitized waveform samples were recorded for every event.

The pedestal needs to be subtracted before analyzing the events.



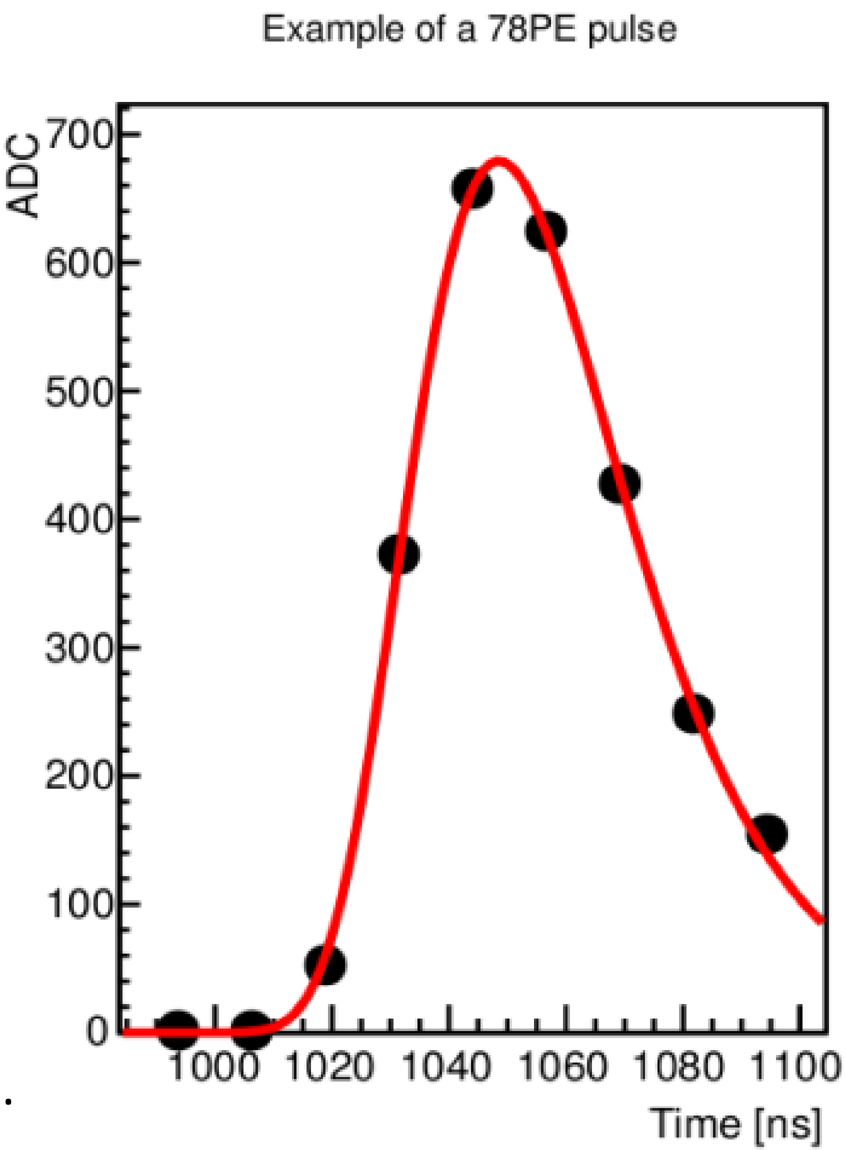
Event Reconstruction: Pulse Fit

- Pulses are fitted with a modified form of the Gumbel distribution

$$f(t) = A \cdot e^{-\frac{t-\mu}{\beta} - e^{-\frac{t-\mu}{\beta}}}$$

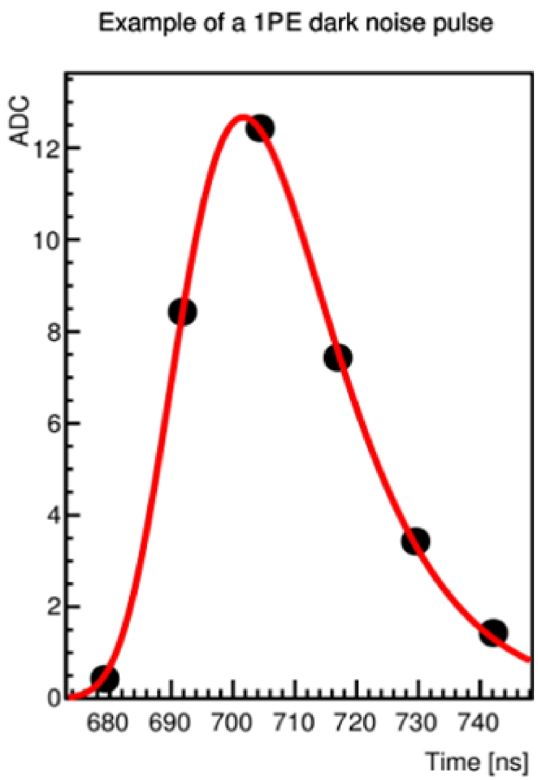
  - Pulse height: A/e
  - Peak time: μ
  - Pulse area: $A \cdot \beta$
  - Pulse width: $\beta\pi/\sqrt{6}$

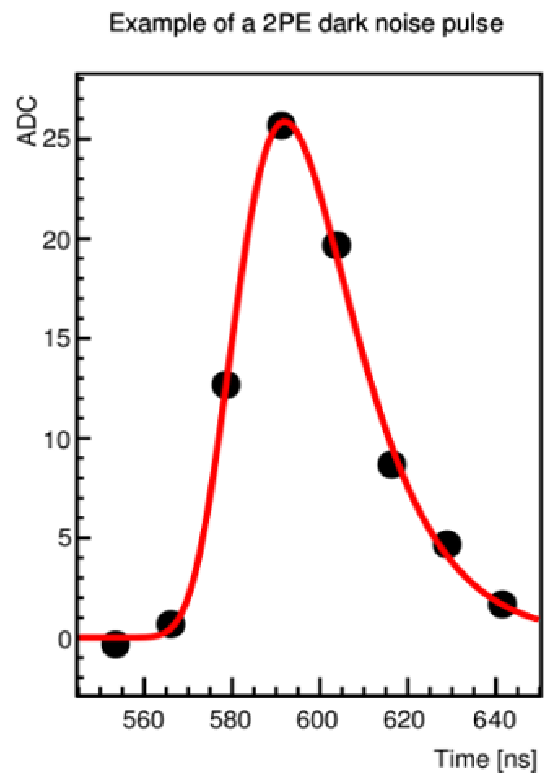
- Pulse area is proportional to the number of PEs.
  - A calibration is required for to translate the pulse area into PEs.



Event Reconstruction: Calibration

- Calibration to find a translation between pulse area and number of PEs.
- Search for dark noise pulses in the pre-signal region of the waveform. The area under these pulse corresponds to 1 PE.

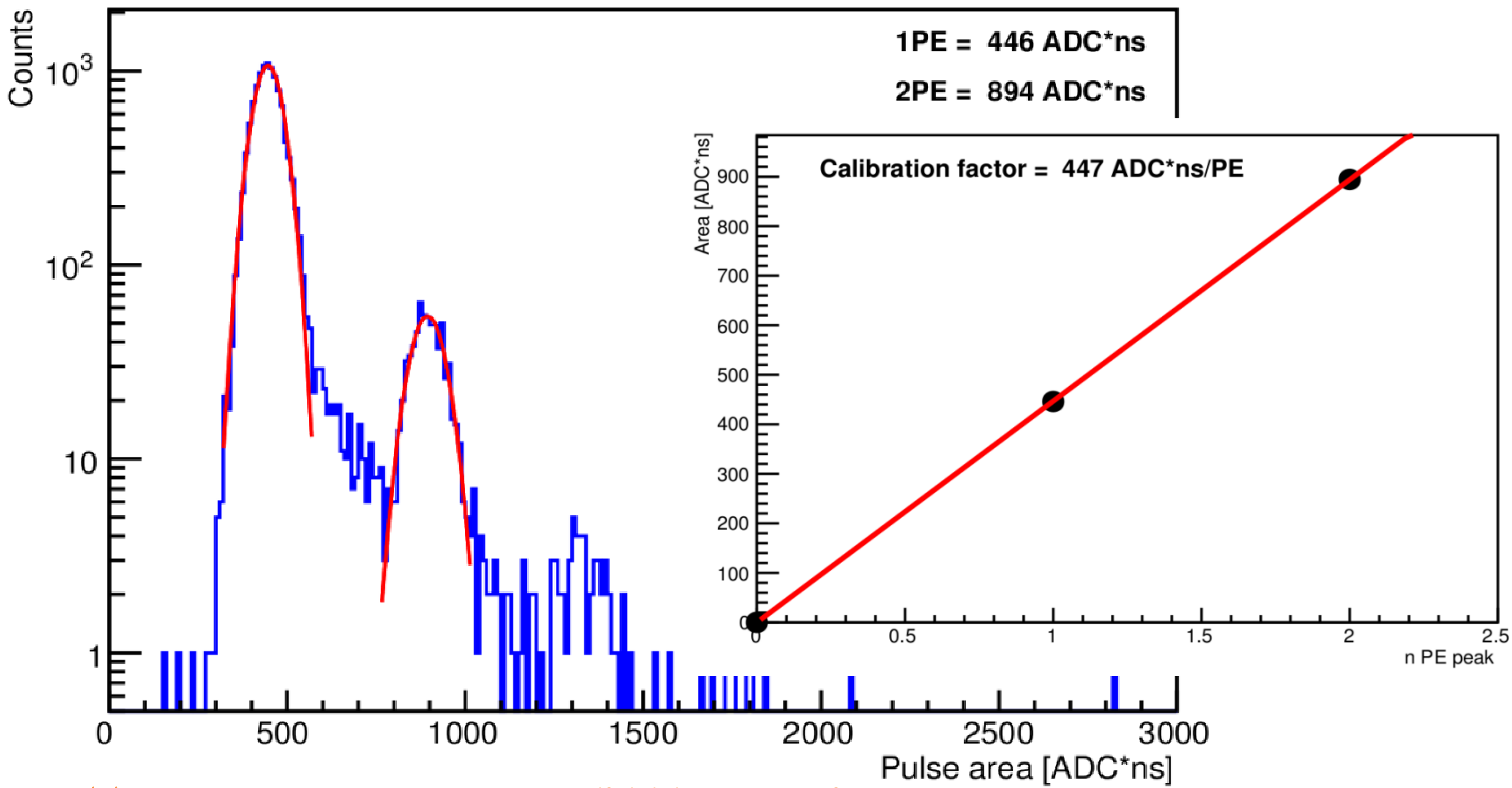




- Occasionally, optical cross talk may create simultaneous pulses in more than one pixel. In these cases, the measured pulse areas will correspond to 2 PEs, 3 PEs, or even more PEs.
- These pulse areas are put into a histogram (see next slide).

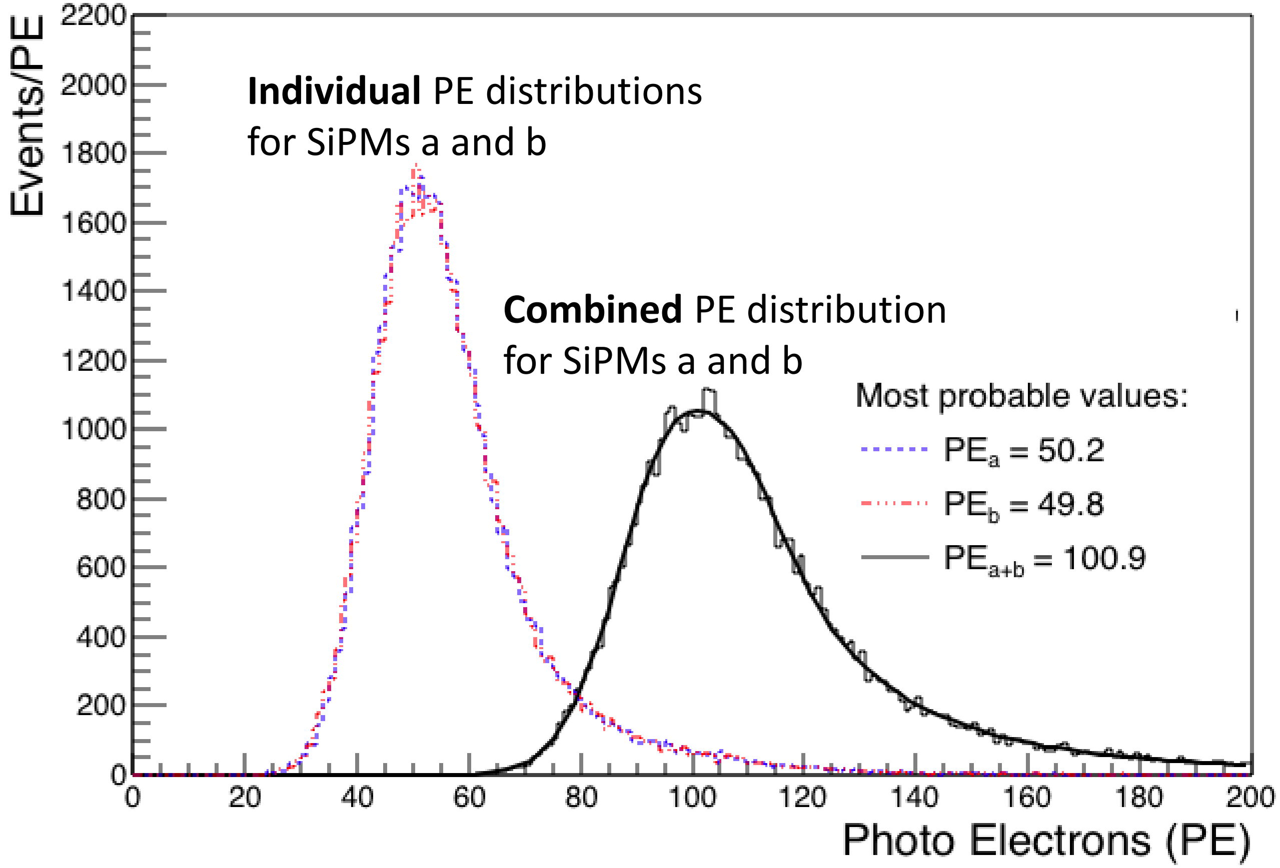
Event Reconstruction: Calibration (cont.)

- Find the 1PE and 2PE peaks in the pulse area histogram.
- Make a linear fit to find the calibration factor.



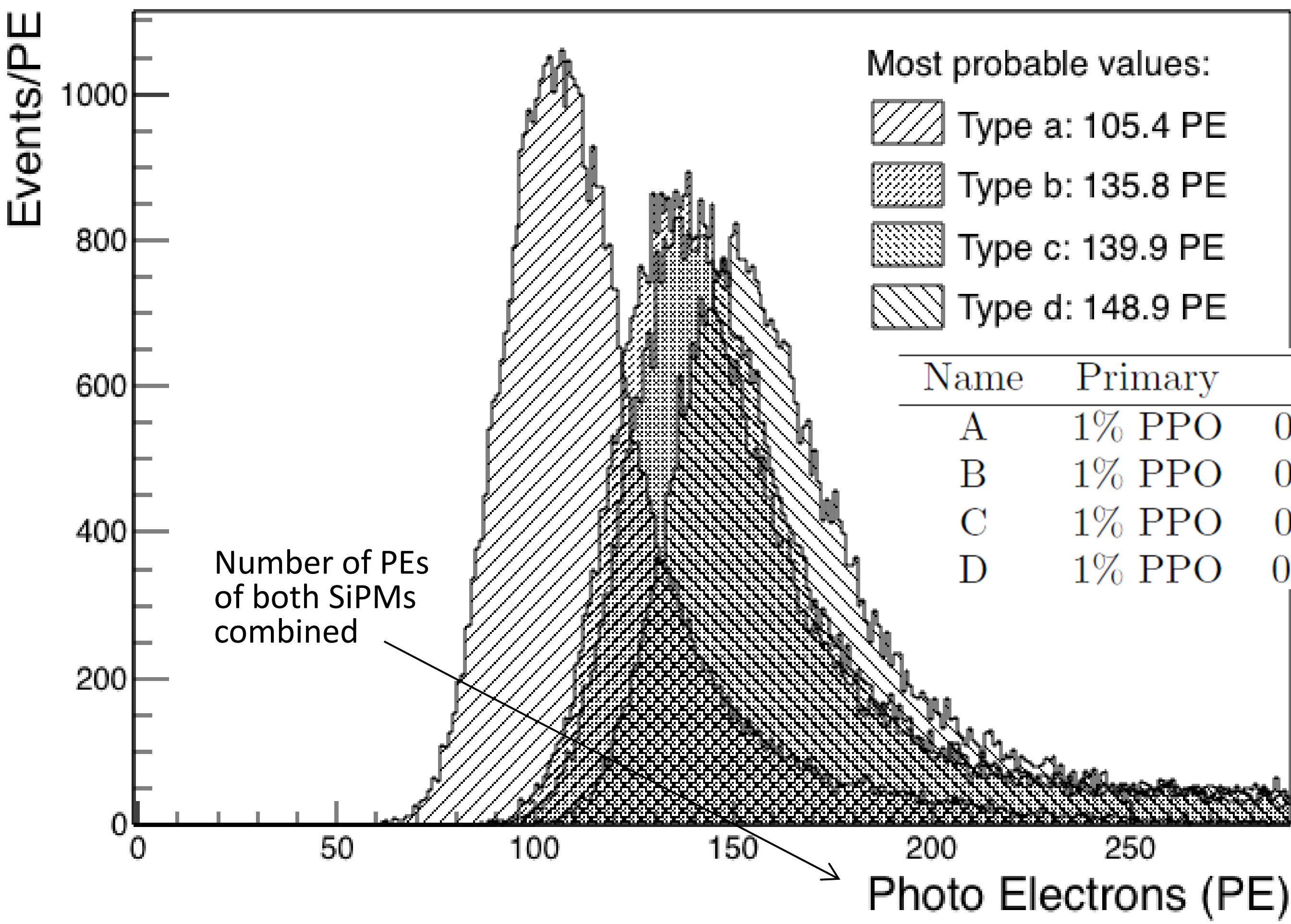
PE Yields (Example)

- Data taken for a proton beam centered between two fibers of a counter and 1 m away from the SiPMs.
- PE distribution of both SiPMs at one side of a counter.



Comparison of Scintillator and Coating Mixtures

- Measured for proton beam centered between two fibers of a counter and 1 m away from the SiPMs.



Increasing the TiO_2 fraction in the reflective coating increased the PE yield by 30%.

Name	Primary	Secondary	Coating
A	1% PPO	0.03% POPOP	15% TiO_2
B	1% PPO	0.03% POPOP	30% TiO_2
C	1% PPO	0.05% POPOP	30% TiO_2
D	1% PPO	0.05% bis-MSB	30% TiO_2

Comparison of Fiber Diameters

- Tested fibers of 1.0 mm, 1.4 mm, 1.8 mm diameter.
- Test setup
  - proton beam centered between the two fibers of a counter,
  - 1 m away from SiPMs,
  - 2 mm x 2 mm SiPMs.
- Result

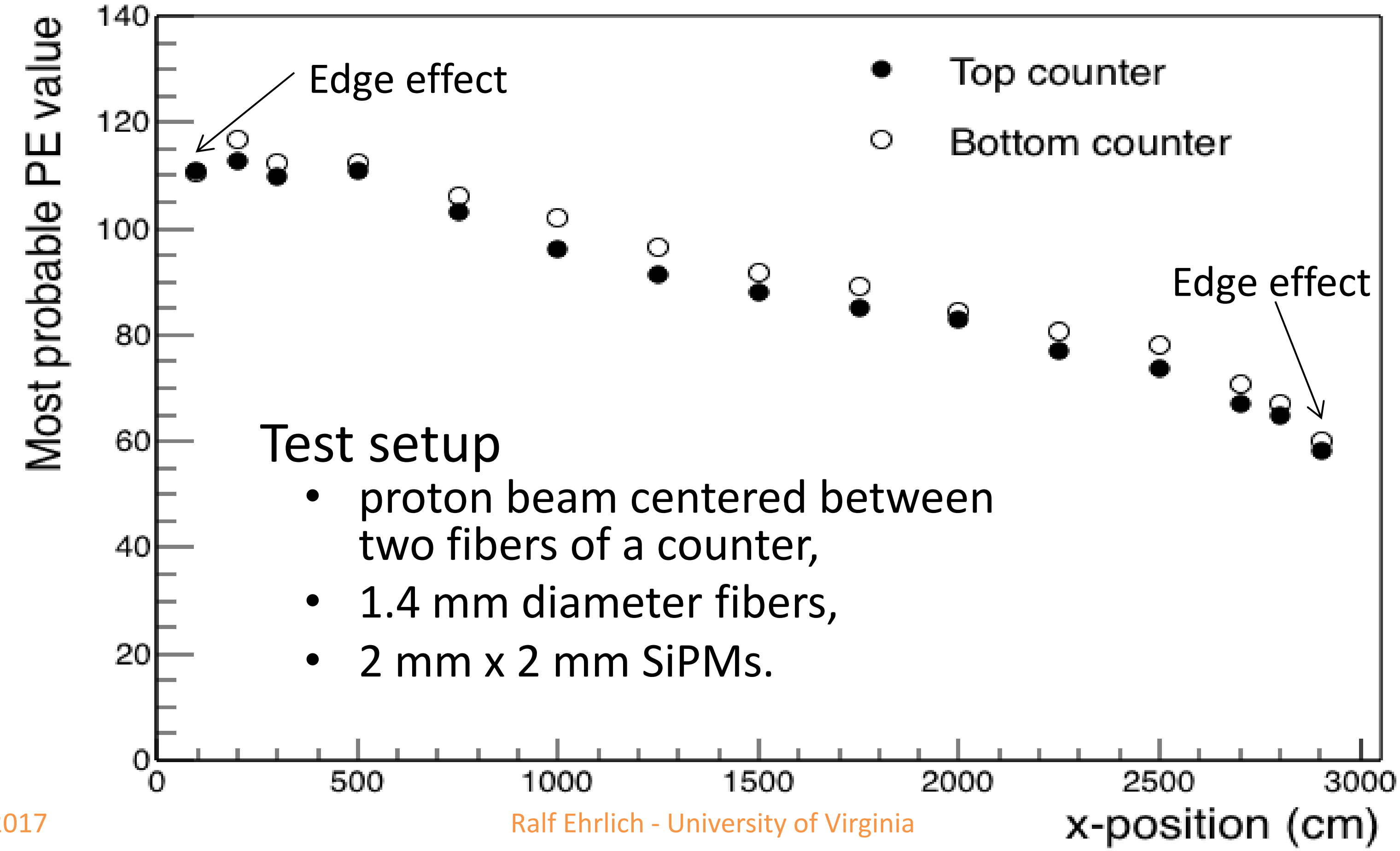
Fiber Diameter	Measured PE Yield
1.0 mm	72.0
1.4 mm	112.7
1.8 mm	139.8*

*The PE yield is lowered due to alignment issues between the 2 mm x 2 mm SiPMs and the 1.8 mm diameter fiber.

- PE yield increase is close to what would be expected, if the light collection of the fibers was a surface effect (PE yield proportional to fiber diameter).

Longitudinal Counter Scans

- The proton beam was aimed at multiple points along the counter.
- These measurements are used to tune the CRV counter simulation which is used to study the efficiency of the CRV.

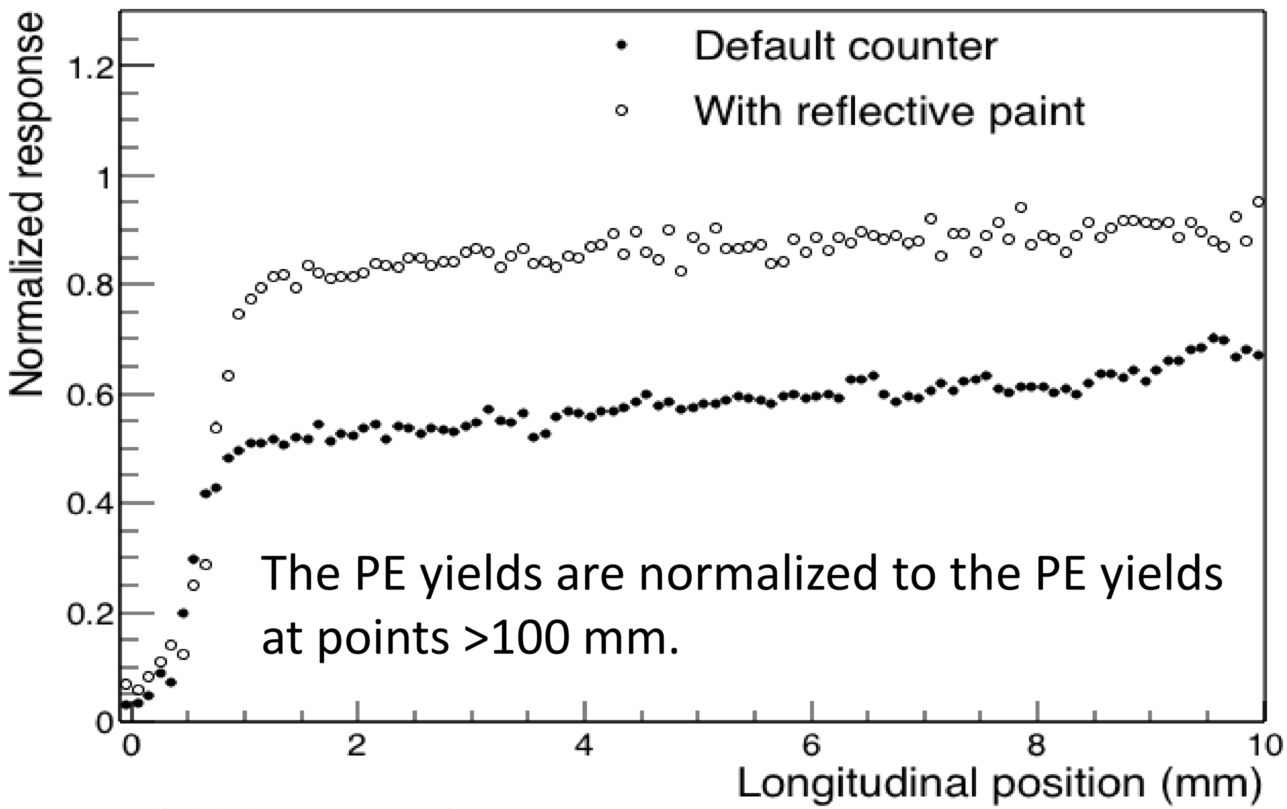


Test setup

- proton beam centered between two fibers of a counter,
- 1.4 mm diameter fibers,
- 2 mm x 2 mm SiPMs.

Longitudinal Counter Scans (cont.)

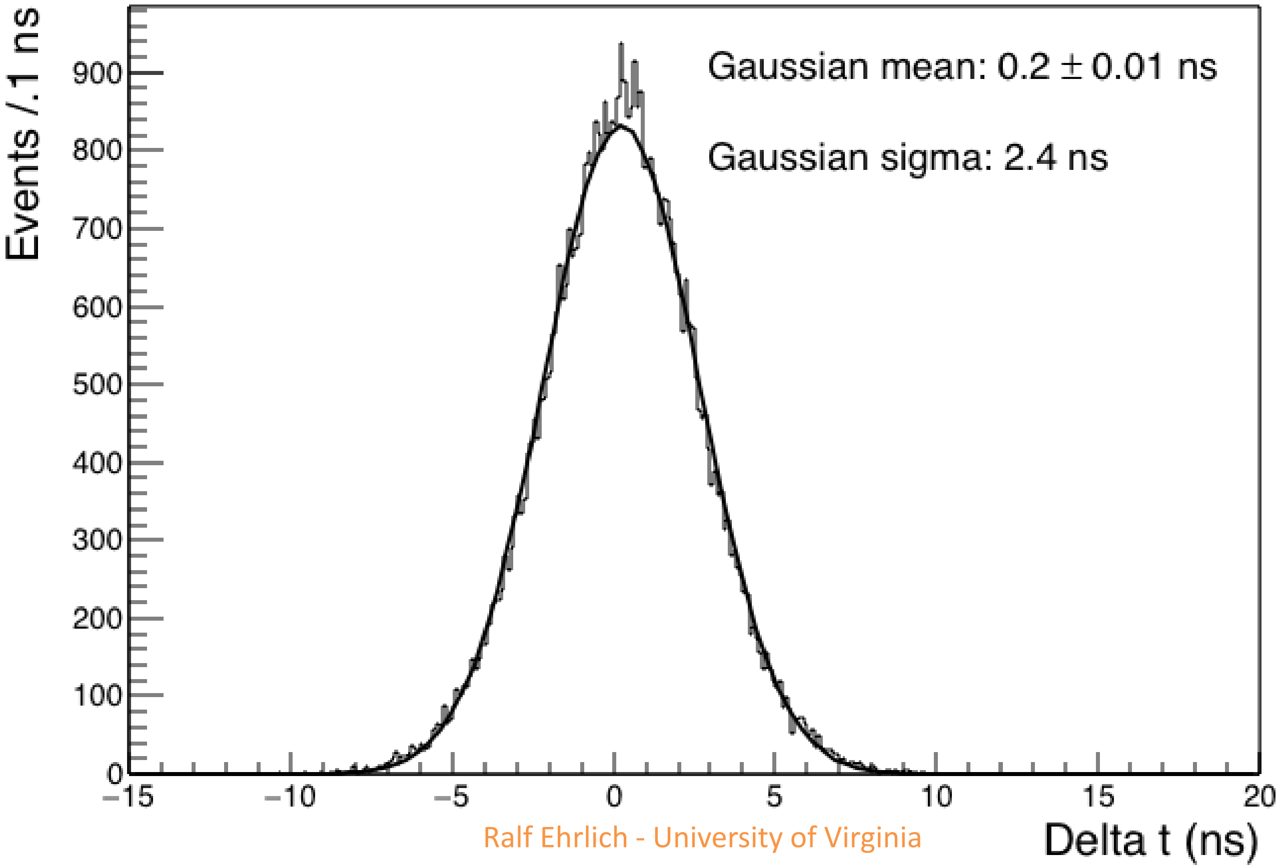
- A more detailed scan was done close to the counter ends.
- Two di-counters were compared: with reflective paint at counter ends, and without reflective paint (which is the default).
- Significant improvement of the PE yield close to the readout end for di-counters with reflective paint.



The PE yields are normalized to the PE yields at points >100 mm.

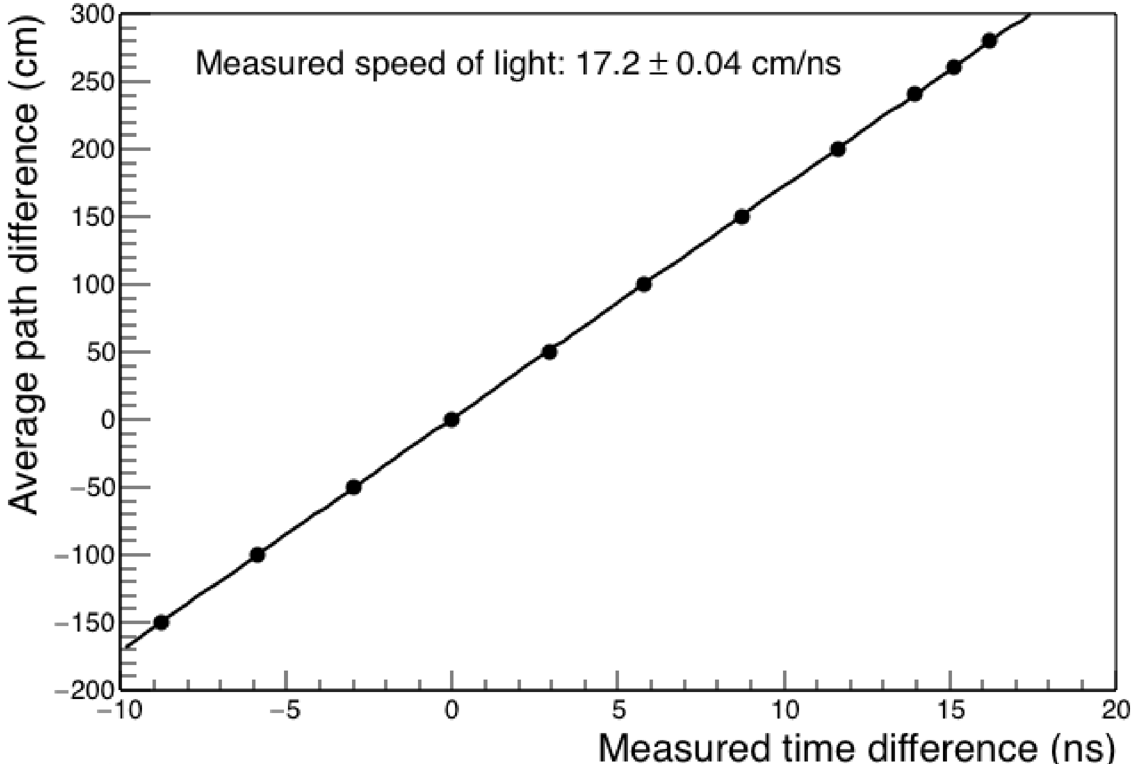
Time Resolution

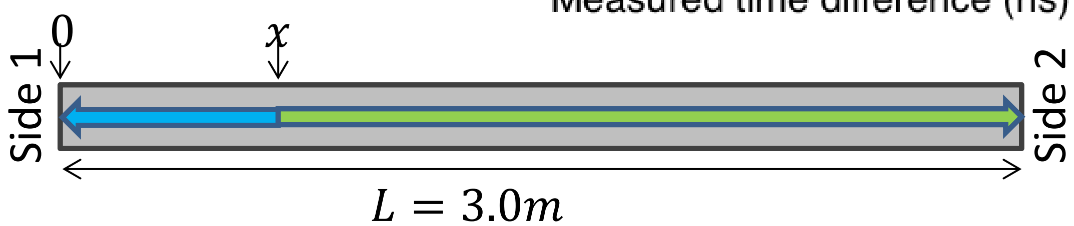
- Distribution of the time difference between both SiPMs at the same counter end: $\sigma_{diff} = 2.4ns$
- Single channel time resolution $\sigma_{res} = \frac{\sigma_{diff}}{\sqrt{2}} = 1.7ns$



Speed of Light Measurement

- Time difference between both sides of the counter vs. path difference.
  - The path difference for photons caused by a proton hitting the counter at position x is $L - 2x$.
  - Measured speed of light: $17.2 cm/ns$, which is $0.58c$.
  - The fiber's index of refraction is 1.59 suggesting a speed of light of $0.63c$.





  - The difference may be caused by the fact that most photons do not travel a straight path through the fiber.

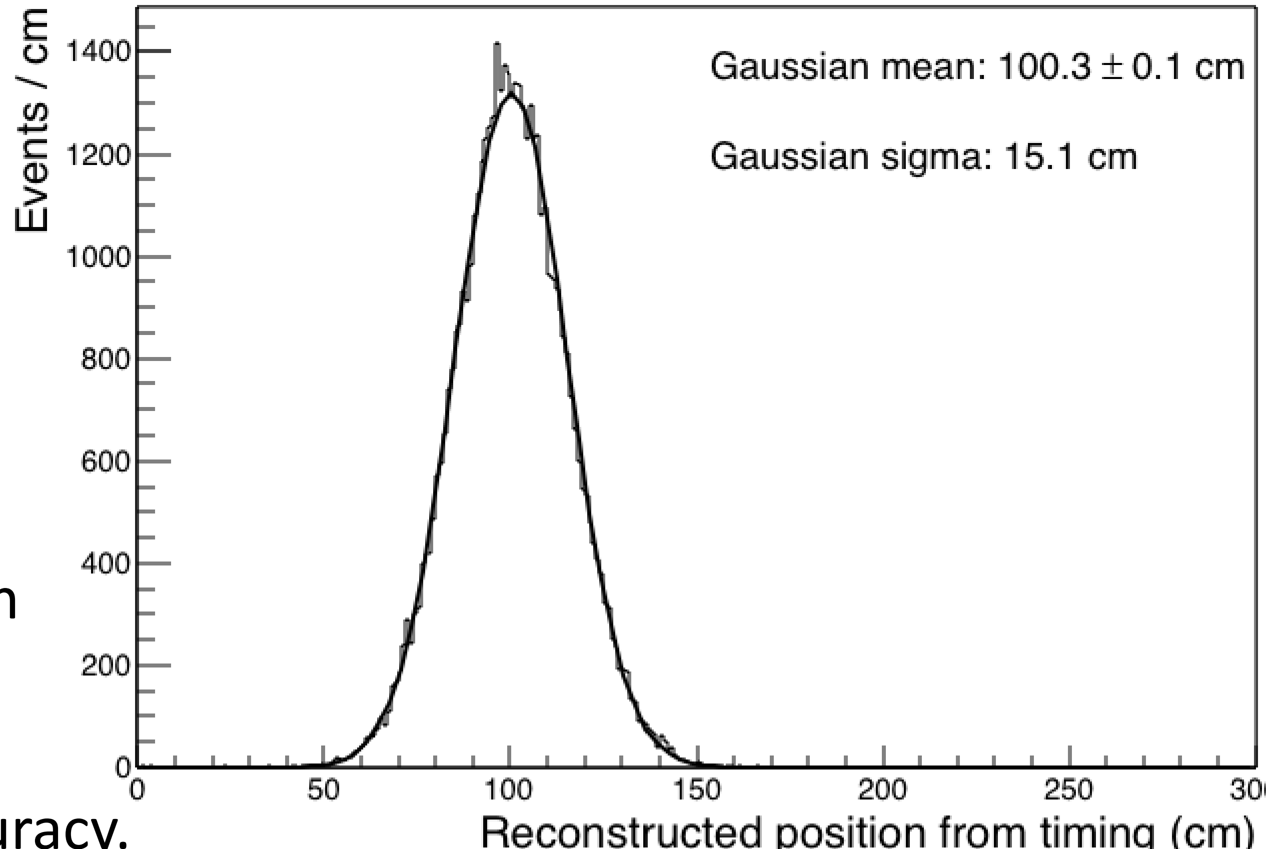
Position Measurements

- The time difference Δt between both sides of the counter, and the previously determined speed of light $v = 17.2cm/ns$ can be used to determine the position x of the proton hit.

$$x = \frac{L - \Delta t \cdot v}{2}$$

- Example for a run where the proton beam was directed at $x = 100cm$.

- The times of both fibers were combined to increase the accuracy.



Summary

- An increased fraction of TiO_2 in the reflective coating improved the PE yield (for individual SiPMs) at 1 m away from the SiPMs to 68 PEs for counters with 1.4 mm diameter fibers, and 2 mm x 2 mm SiPMs.
- Single-channel timing resolution was found to be better than 2 ns with the sampling rate 79.5 MHz.
- The position of the hits along the counter can be determined to ±15 cm using the time difference between both counter ends.

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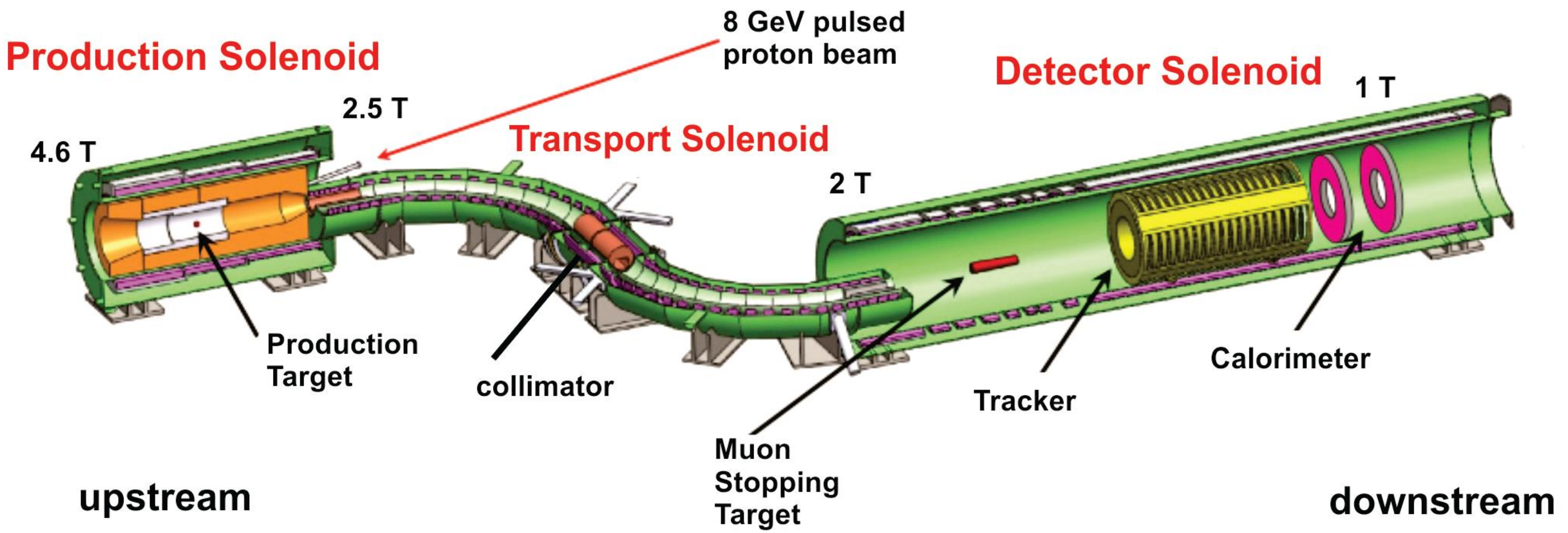
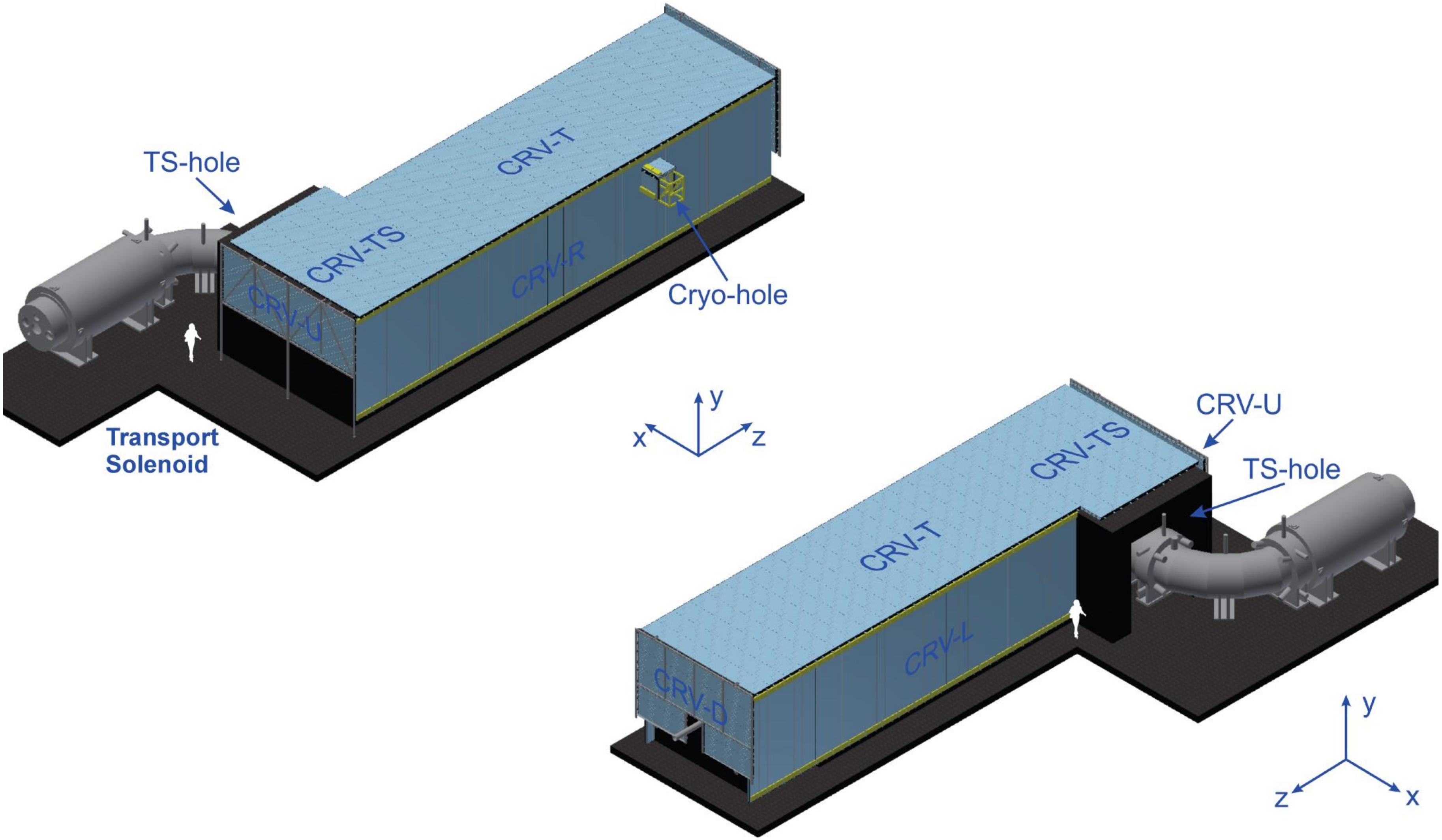
Backup Slides

The Mu2e Experiment



Cosmic Ray Veto in Mu2e

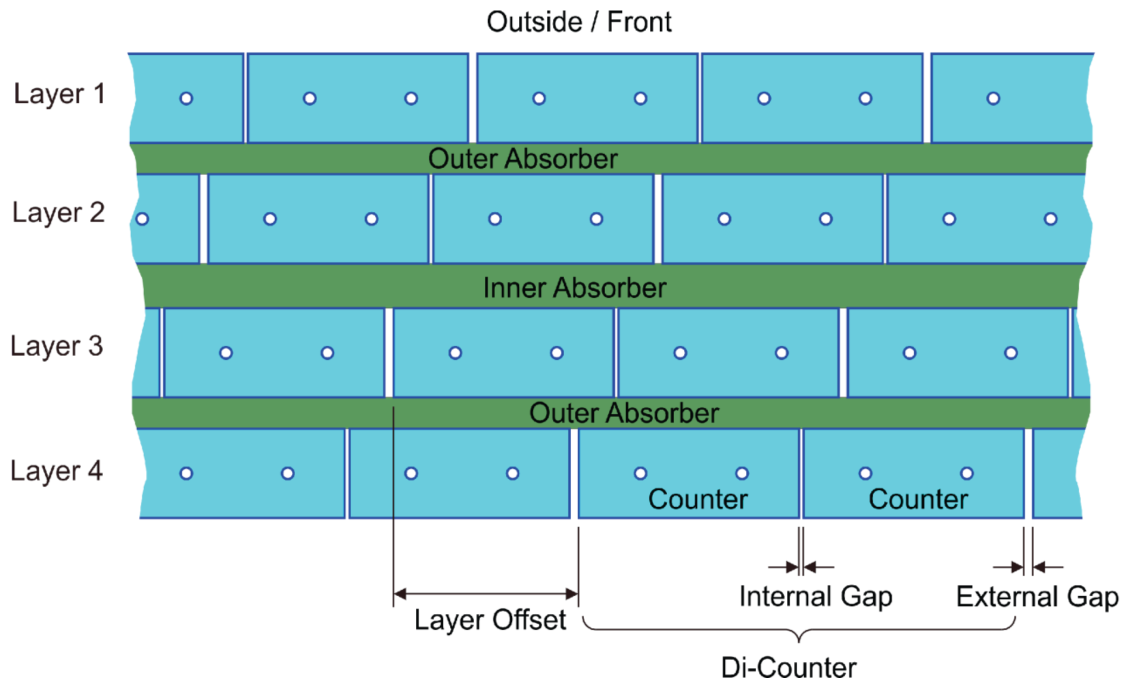


Cosmic Ray Veto in Mu2e (cont.)

- The CRV is made of 5504 scintillator counters surrounding the Mu2e spectrometer.
- Each counter has two embedded wavelength shifting fibers, which are read out at both ends by a SiPM.
- Counter dimensions
  - Thickness: 20 mm
  - Width: 50 mm
  - Lengths: between 0.9 m and 6.6 m.
- Two counters are combined together to form a di-counter.
- The CRV needs to have an efficiency of more than 0.9999 to achieve the proposed background rate.

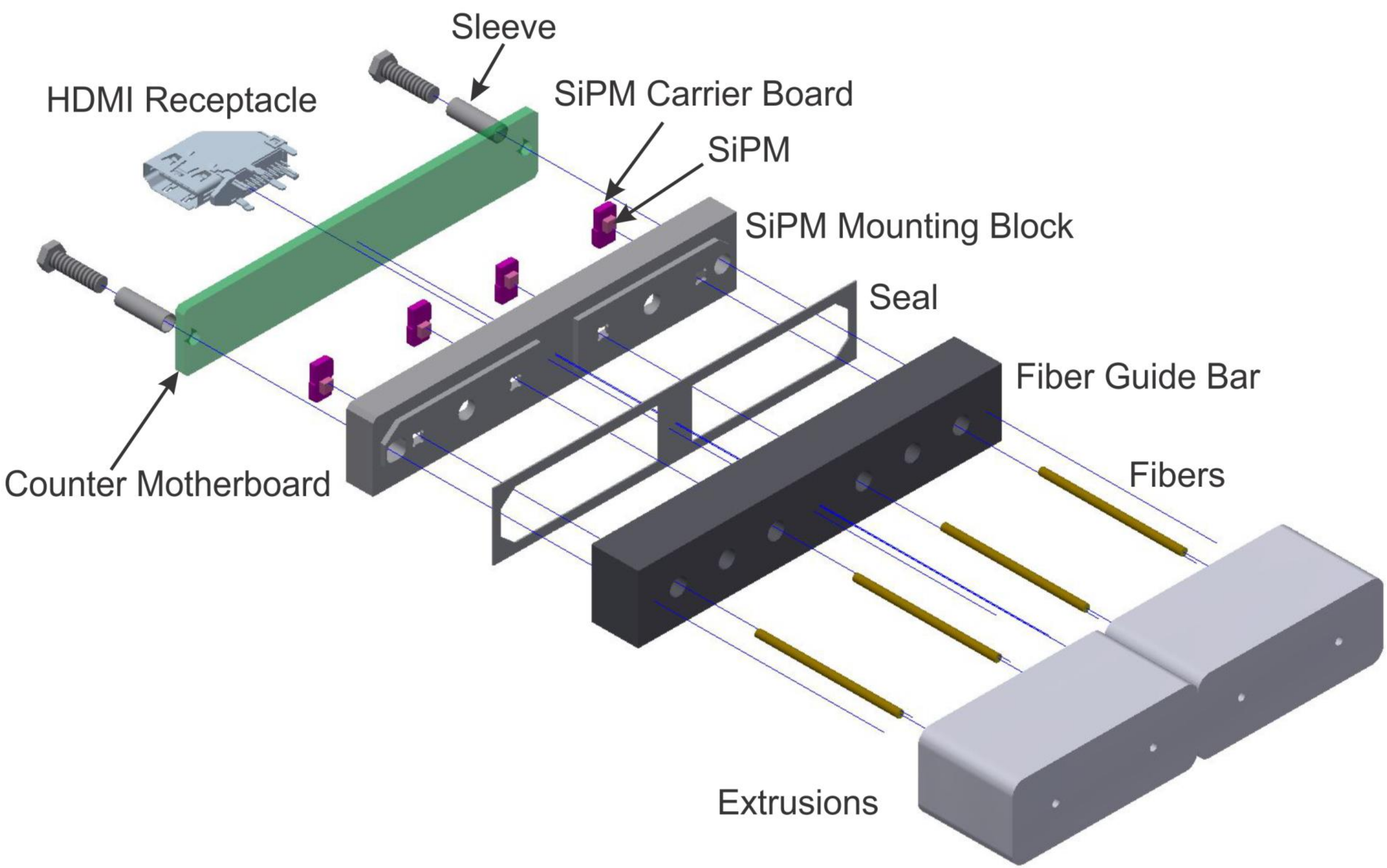
Cosmic Ray Veto in Mu2e

- The di-counters are grouped together in modules.
  - 4 layers per module
  - 16 counters per layer



- Unavoidable gaps between counters in a di-counter, counters in a module, and between modules can lead to inefficiencies.
  To minimize the effect of projective gaps the layers are offset relative to each other. The optimal value for this offset is determined by a simulation.

CRV Counter Readout End



Electronics

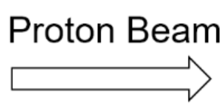
- The readout ends of the counters is connected to front end board (FEBs).
- FEBs
  - 64 channels.
  - Provides bias voltage to the SiPMs.
  - Responsible to signal pre-amplification and shaping, analog to digital conversion.
- High-speed serial links via Ethernet between FEBs and a readout controller.
- Digitization happens in 12.58 ns intervals (79.5 MHz).

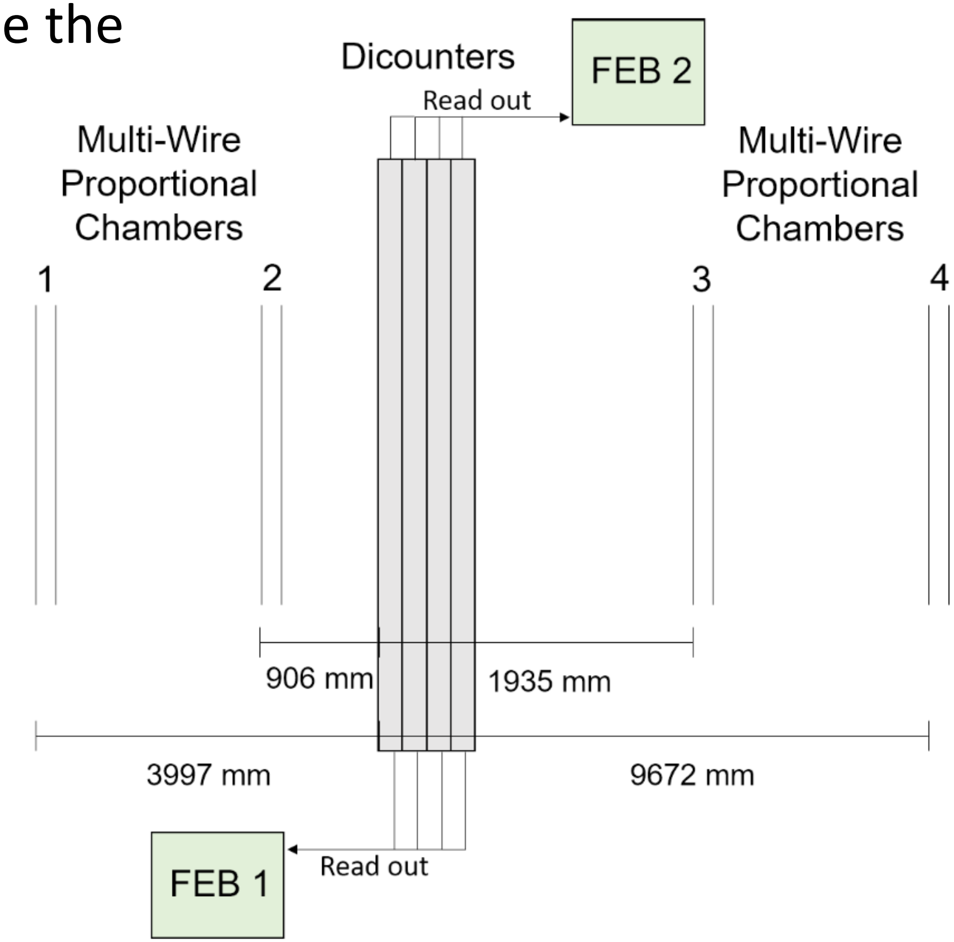
Test Beam Setup

- Up to four di-counters were put into the beam.

- Four multi-wire proportional chambers were used to reconstruct the proton paths, and to determine the positions where the protons hit the CRV counters.

- Events were triggered by three scintillation counters (not in the picture) and a begin-of-spill signal.

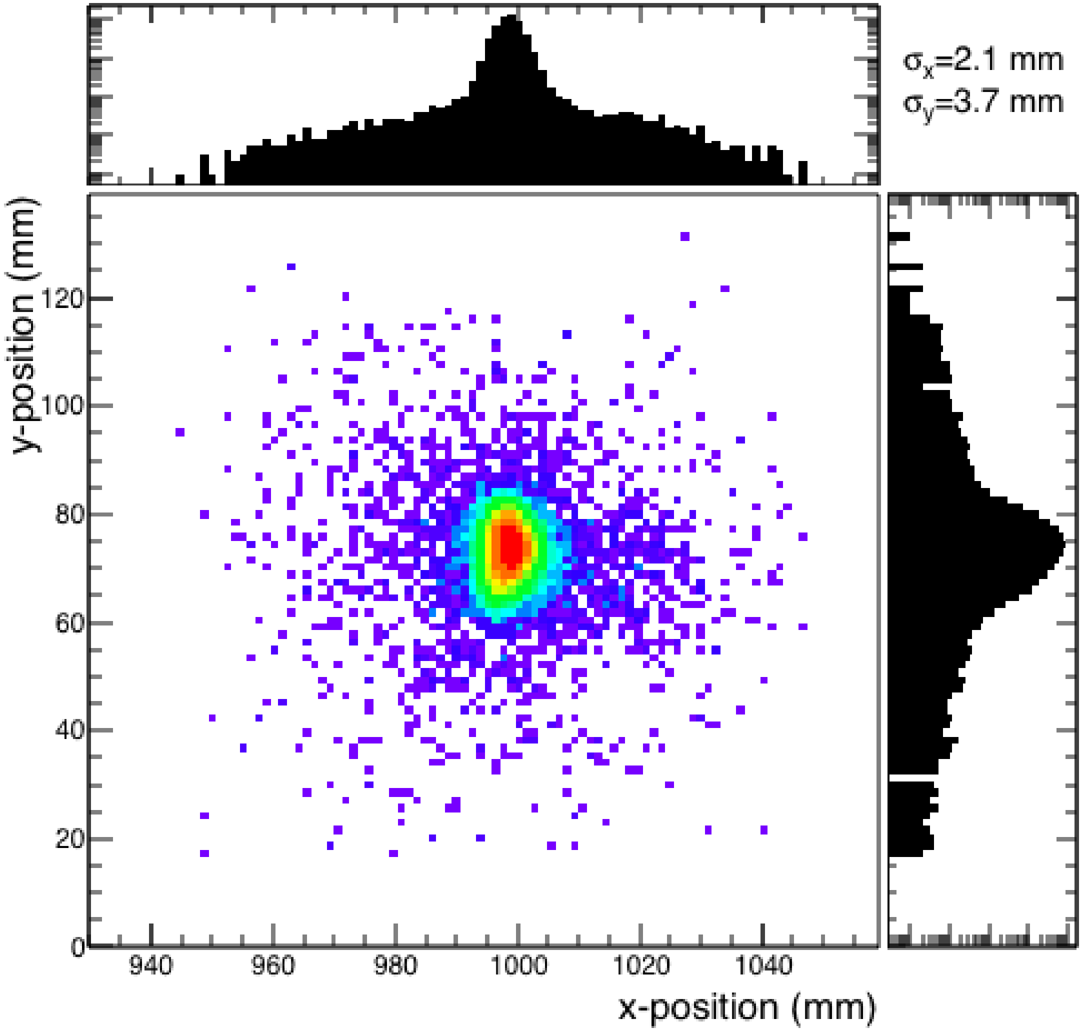




- A total of about 50,000 events were recorded for every run.

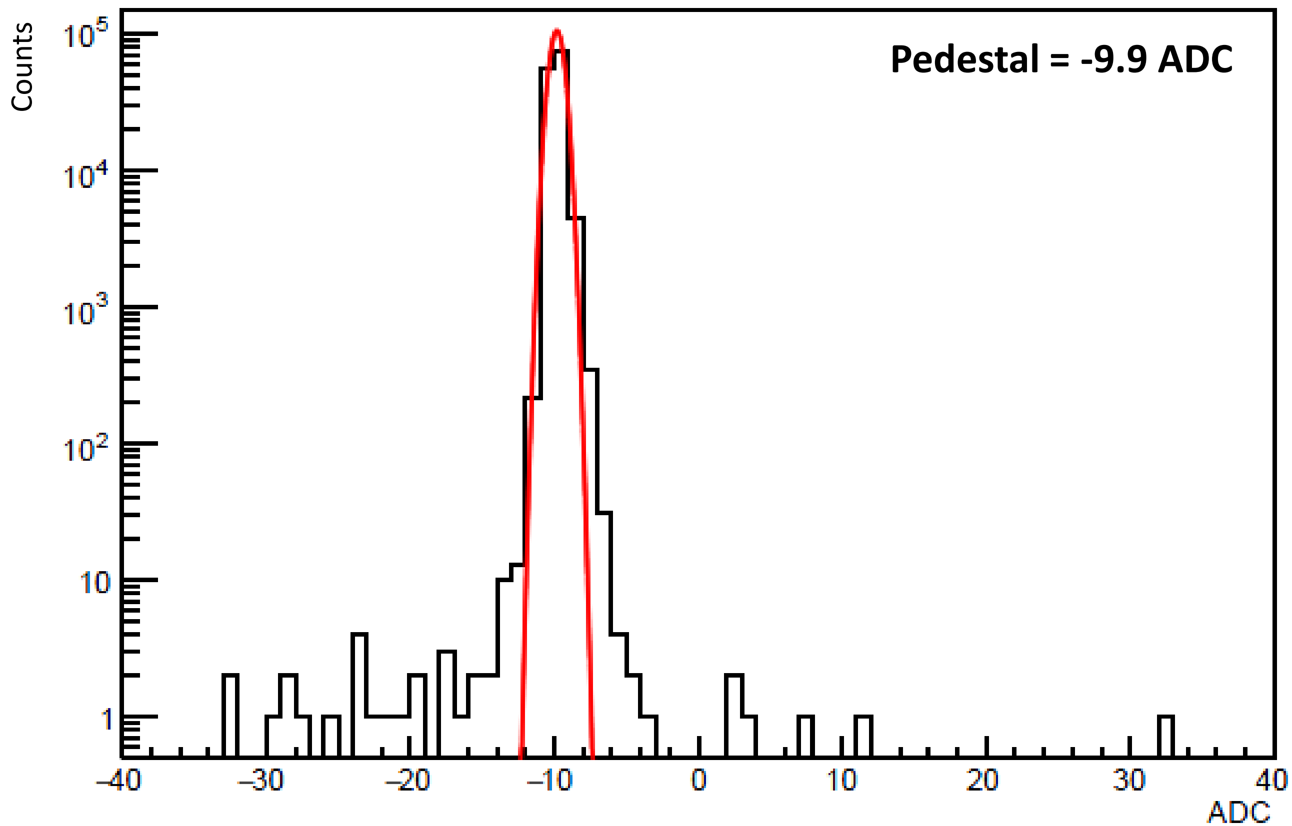
Example of a Beam Profile

- Proton positions are determined by the wire chambers



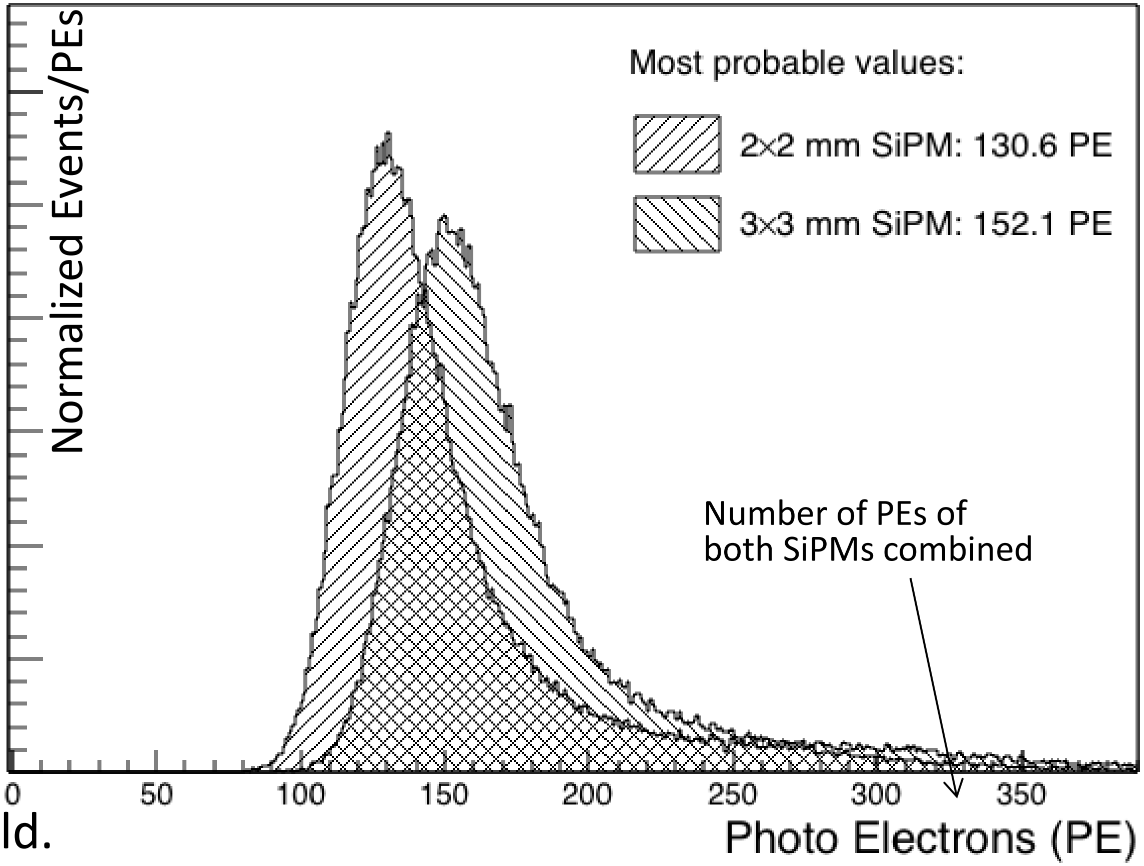
Event Reconstruction: Pedestal

- The pedestal needs to be subtracted from the waveform.
  - Pedestal gets determined by finding the most probable ADC value in the pre-signal region of the data collected from all events of a run.
  - Pedestal needs to be found for every SiPM and at every run.
  - Example:



Comparison of SiPM Sizes

- Measured for proton beam centered between two fibers of a counter and 1 m away from the SiPMs.
- Used fibers with an 1.8 mm diameter.
  - Misalignments of the fiber at the 2mm x 2mm SiPMs would cause a drop in the number of photons captured by the SiPMs.
  - No misalignment problems at the 3mm x 3mm SiPMs, which is considered to be the reason for the 16% higher PE yield.



Comparison of Fiber Diameters

- Tested fibers of 1.0 mm, 1.4 mm, 1.8 mm diameter.
  - If the light capture of the fiber is a surface effect (short absorption lengths), then the PE yield should be proportional to the fiber diameter.
  - If the light capture of the fiber is a volume effect (long absorption lengths), then the PE yield should be proportional to the fiber diameter squared (i.e. proportional to the cross section of the fiber).

Comparison of Fiber Diameters (cont.)

- Measured for proton beam centered between two fibers of a counter and 1 m away from the SiPMs.
- 2 mm x 2 mm SiPMs were used.
  - Due to the alignment issue between 2 mm x 2 mm SiPMs and fibers with an 1.8 mm diameter (which causes a lower PE yield), a correction factor of 1.16 should be applied to the PE yield (which is based on the SiPM size study).

Fiber Diameter	Measured PE Yield	Measured Ratios		Expected Ratios (if Surface Effect)		Expected Ratios (if Volume Effect)	
		to 1.0 mm	to 1.4 mm	to 1.0 mm	to 1.4 mm	to 1.0 mm	to 1.4 mm
1.0 mm	72.0						
1.4 mm	112.7	1.57		1.40		1.96	
1.8 mm	139.8	1.94 (2.25)*	1.24 (1.44)*	1.80	1.29	3.24	1.65

*Correction factor of 1.16 applied

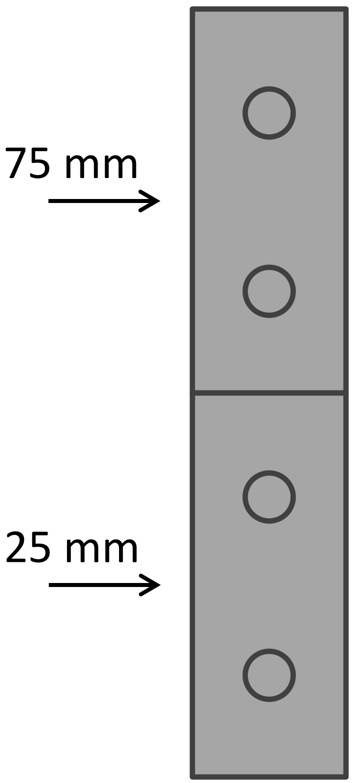
- Measured ratios are close to what would be expected, if the light collection of the fibers was a surface effect.

Effect of Optical Grease

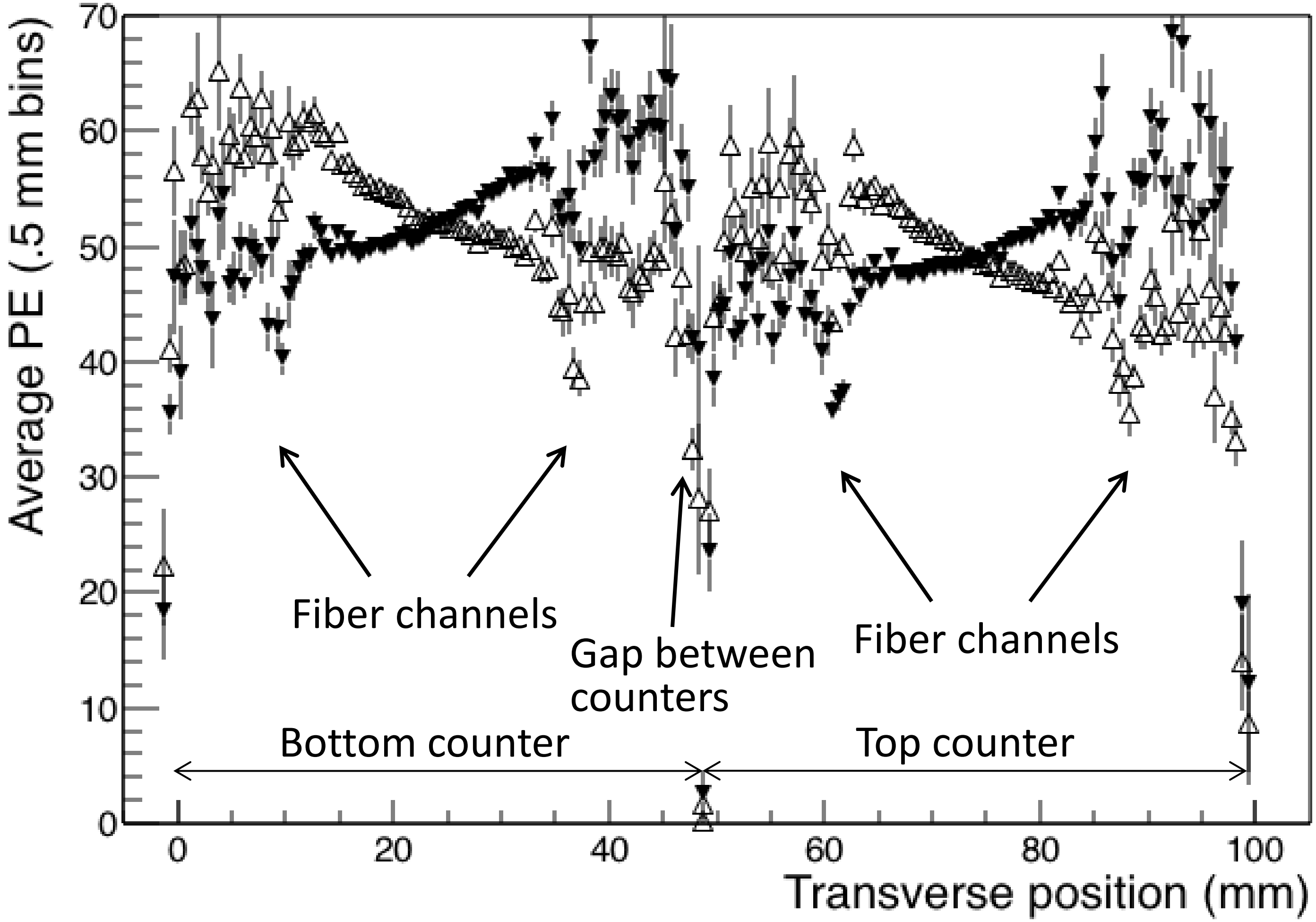
- BC-630 Silicone Optical Grease was tested.
  - Used to achieve a better optical coupling between the fiber (n=1.59 at the core) and the Epoxy surface (n=1.55) of the SiPM, by replacing the air gap (n=1.00) with silicon grease (n=1.47), which reduces reflections at the surfaces.
- Test setup
  - proton beam centered between two fibers of a counter,
  - 1 m away from the SiPMs,
  - 1.8 mm diameter fibers,
  - 2 mm x 2 mm SiPMs.
- An increase for the PE yield of 9% was achieved.
  - This small increase shows that the optical coupling is already good without the optical grease.

Transverse Counter Scans

- Test setup
  - proton beam centered between two fibers of a counter (at 25 mm for the bottom counter, and at 75 mm for the top counter),
  - at the center of the counter (1.5 m from the SiPMs),
  - 1.4 mm diameter fibers,
  - 2 mm x 2 mm SiPMs.
- Even though the beam was centered between two fibers, the proton hits are spread over the entire counter width.
- In order to increase the statistics, the PE Yields from both sides, and from six runs (three runs at 25 mm and three runs at 75 mm) were combined.

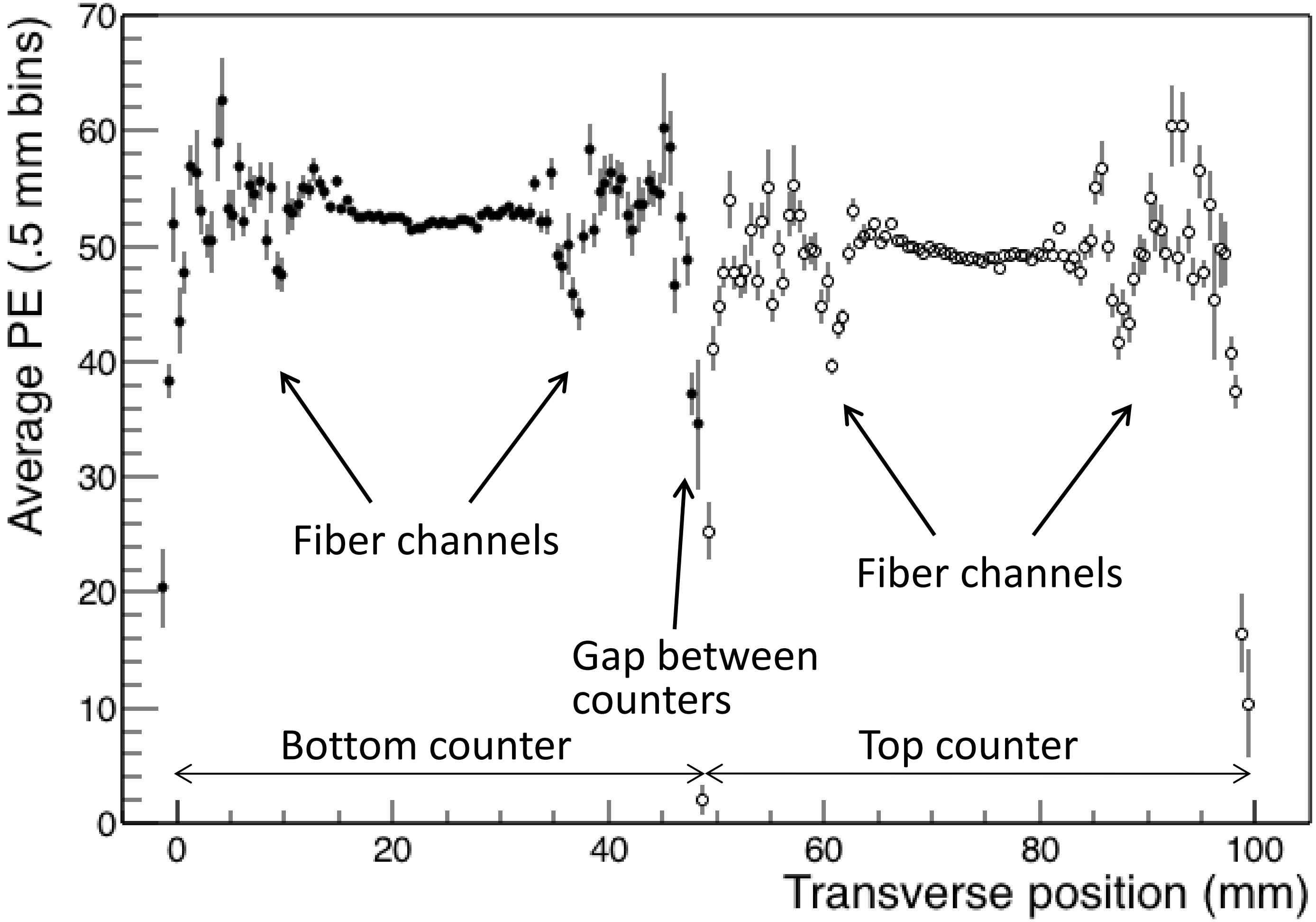


Transverse Counter Scans (cont.)



This plot shows the PE distributions of the individual fibers.

Transverse Counter Scans (cont.)



This plot shows the PE distributions where the PE yields of both fibers of a counter were combined.

Time Offset between Counter Ends

- The two ends of the counters use different FEBs.
  - Their times are not synchronized.
  - The time offset between both FEBs needs to be determined by measuring the time difference at the center of the counter, i.e. at $x = 1.5m$ for the 3.0 long counter. In this example: $t_{offset} = t_2 - t_1 = 6.8ns$
  - This t_{offset}needs to be subtracted from every t_2 in the following calculations.

Position Measurements (cont.)

- Reconstructed positions at several beam positions.