# Simulation of the DHCAL RPC Response with Analog Readout

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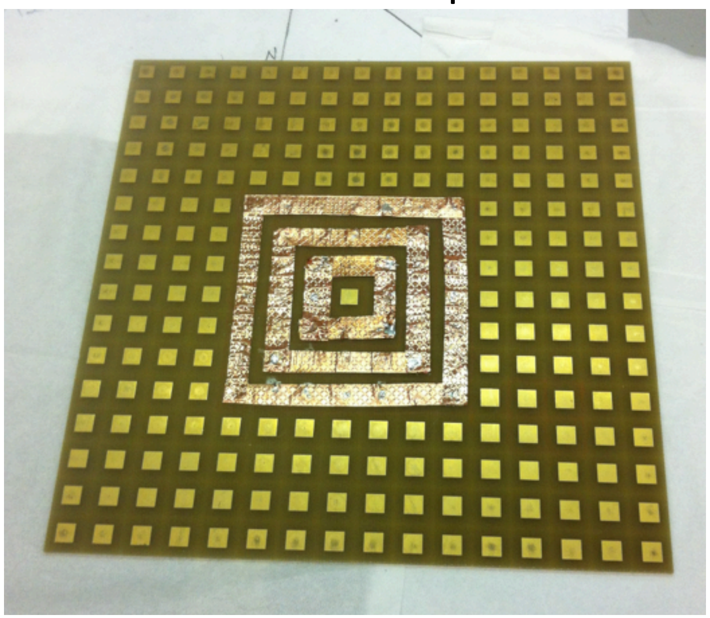
# Analog RPC Tests

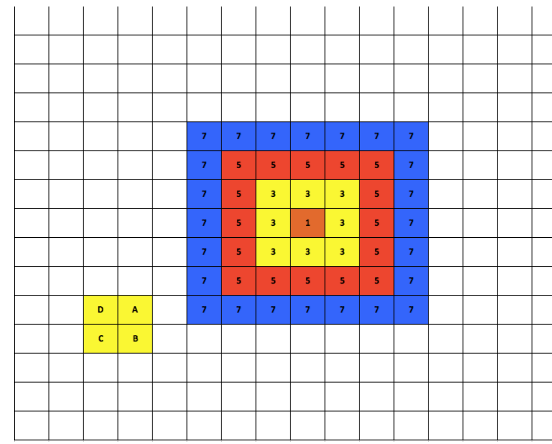
Tests were performed at Fermilab in 2015 in two days following the rate tests.

One DHCAL RPC was read out with a custom pad board with the following pad layout.

The back side of the pad board.



$S_0$ : single pad
$S_1$ : 3 x 3 ring
$S_2$ : 5 x 5 ring
$S_3$ : 7 x 7 ring



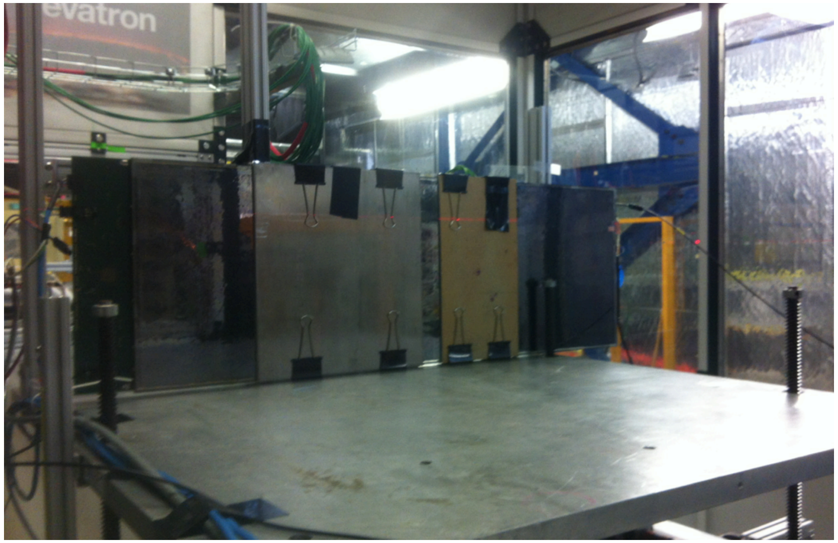
Signals recorded with oscilloscope.

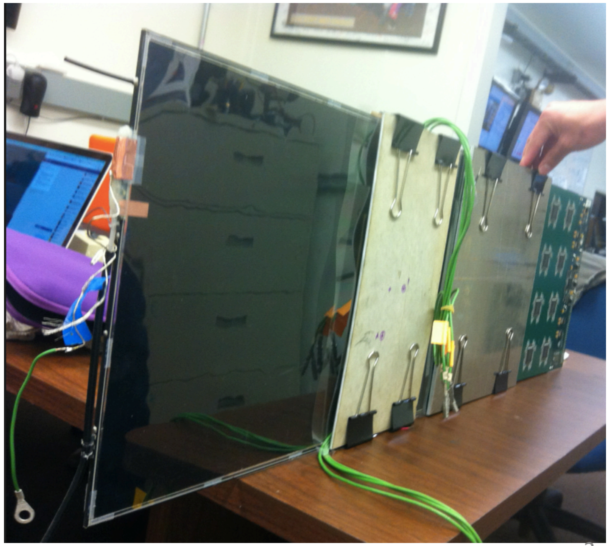
# Analog RPC Tests

120 GeV primary proton beam was used to measure the MIP charge and to extract the shape of the charge distribution.

8 GeV positron beam was used to measure the shower charge at various radiation lengths (iron absorbers of 1.9 cm thickness). For a limited run time, a DHCAL RPC with digital readout was placed downstream the analog readout chamber.

DHCAL operating conditions were used (6.3 kV HV, same gas mixture, etc.).





# The Plan

1. Extract the MIP charge to be used in the simulations to sample the single avalanche charges.

2. Identify the shape of the charge distribution on the readout pads (four charge distribution models to optimize).

3. Study the upstream material budget in FTBF.

4. Optimize $d_{cut}$ – the minimum distance between two ionizations so that they can develop independent avalanches.

5. Optimize the threshold to be used in the DHCAL simulations.

6. Implement the findings on the DHCAL simulations.

# The Plan

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2. Identify the shape of the charge distribution on the readout pads (four charge distribution models to optimize).

3. Study the upstream material budget in FTBF.

4. Optimize $d_{cut}$ – the minimum distance between two ionizations so that they can develop independent avalanches. The most challenging part.

5. Optimize the threshold to be used in the DHCAL simulations.

6. Implement the findings on the DHCAL simulations. Not done yet.

# 120 GeV Proton Beam

We asked for a large 120 GeV proton beam at low rate. Not trivial: 120 GeV proton beam is only a few mm in size and is high in rate.

Overall, the beam was mostly contained in 5 mm x 10 mm with rather low rates.

Table was adjusted such that the beam was centered close to the boundary of single pad and the 3 x 3 ring (see next slides). Therefore, the MIP signal was mostly contained in the 3 x 3 pads. 7 x 7 ring was noisy most of the time.

Major trouble is low statistics.

$S_0$ : single pad
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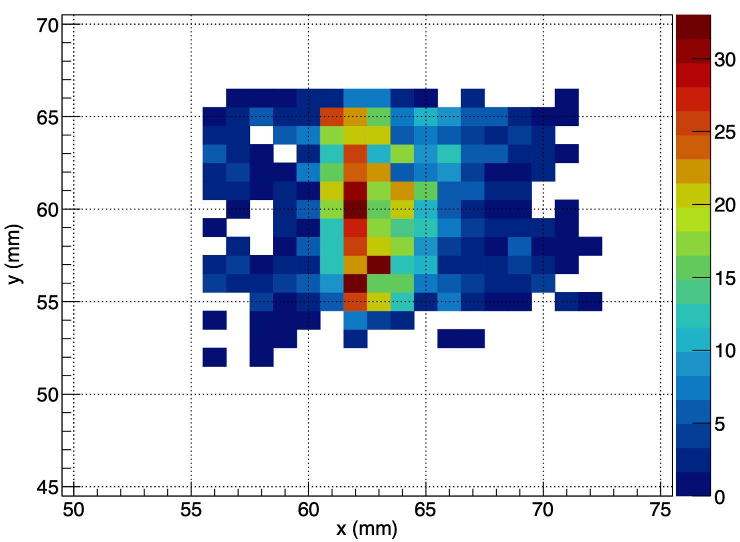
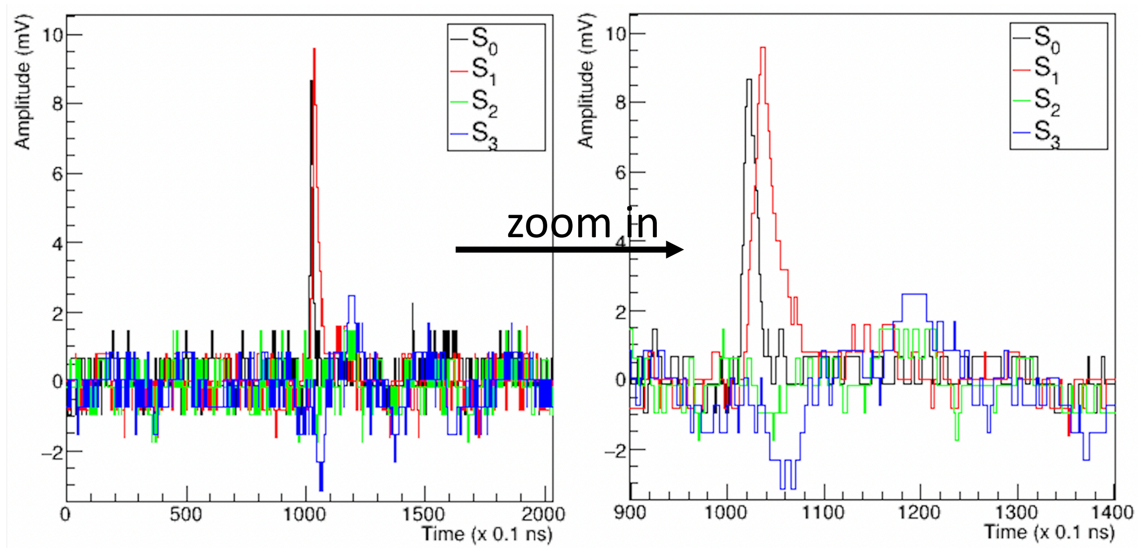
$S_3$ : 7 x 7 ring

Wire Chamber image of the beam



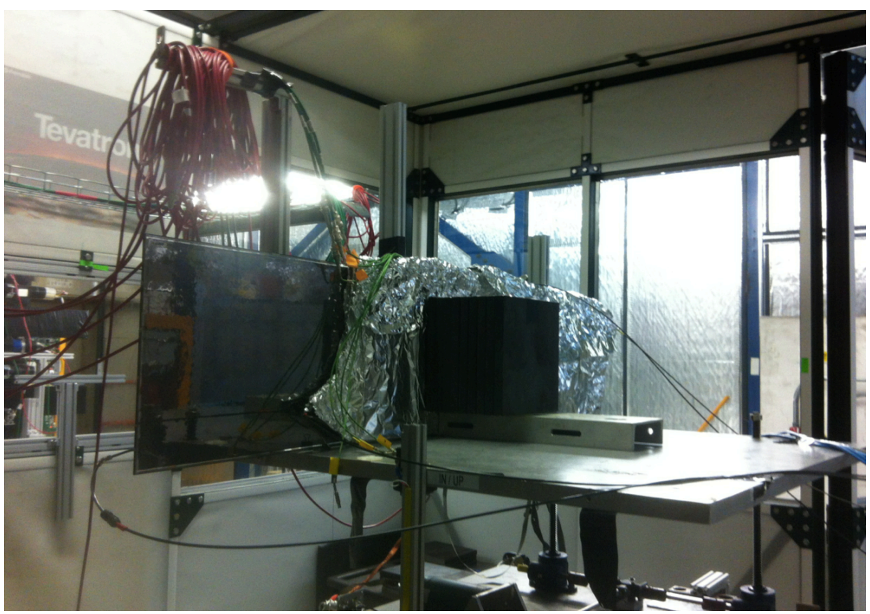



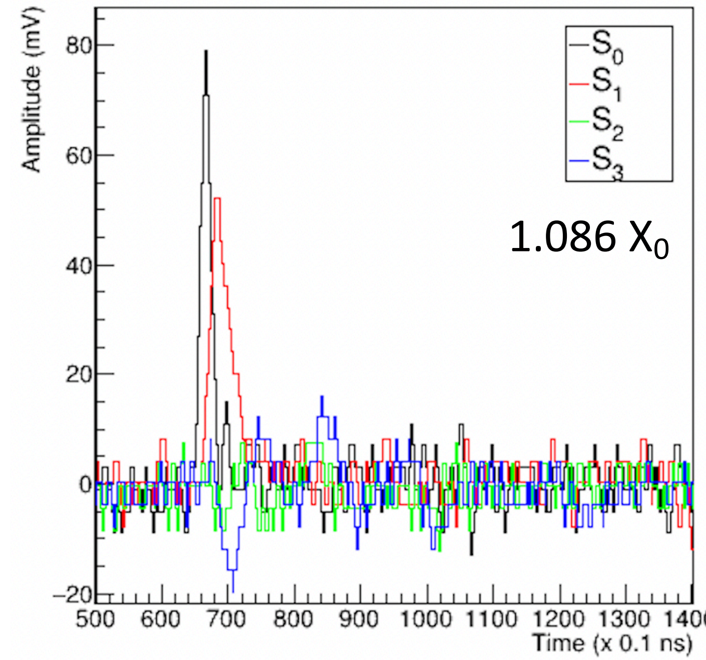
# 8 GeV Positron Beam

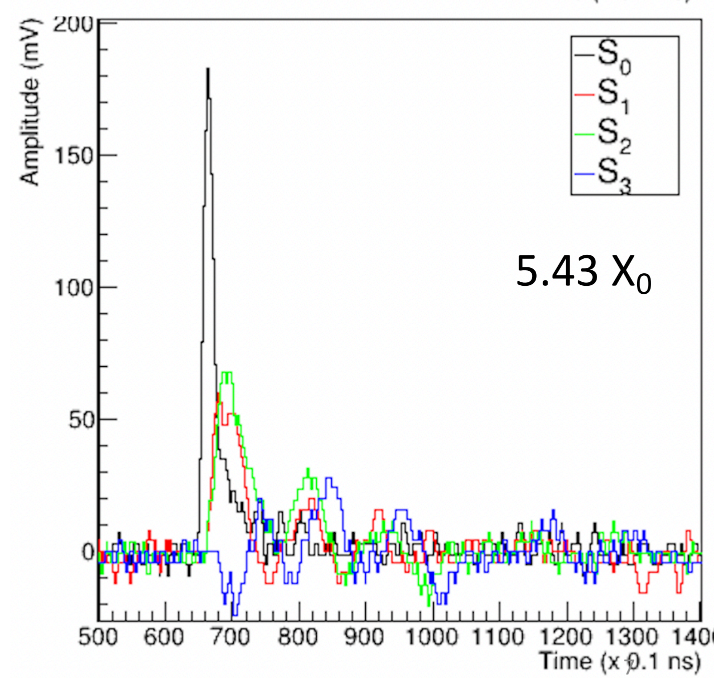
The signal from the Cerenkov counter was integrated into the trigger to select the positrons. This disturbed the wire chamber acquisition timing. → No wire chamber for positron runs.

We placed up to nine 20 cm x 20 cm x 1.9 cm (1.086 $X_0$) iron blocks upstream the analog readout RPC.

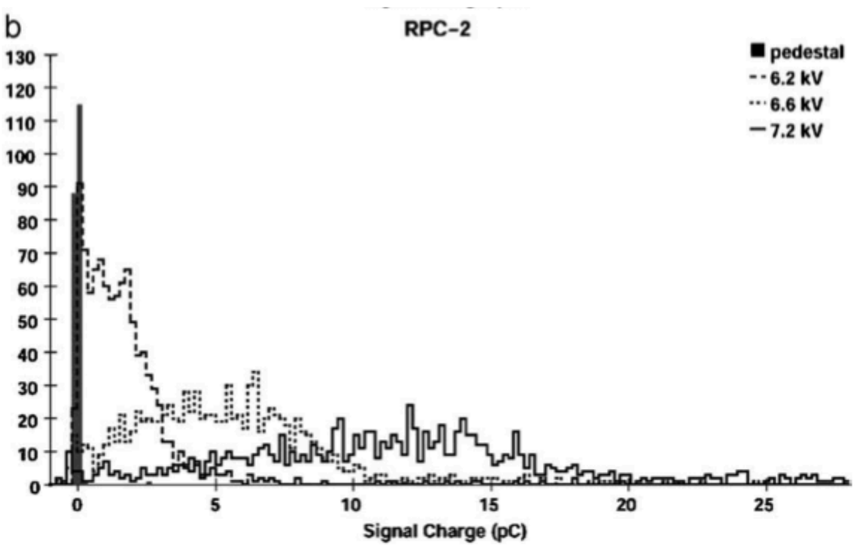
In the last part of the campaign, there was a digital readout RPC downstream the analog readout RPC.

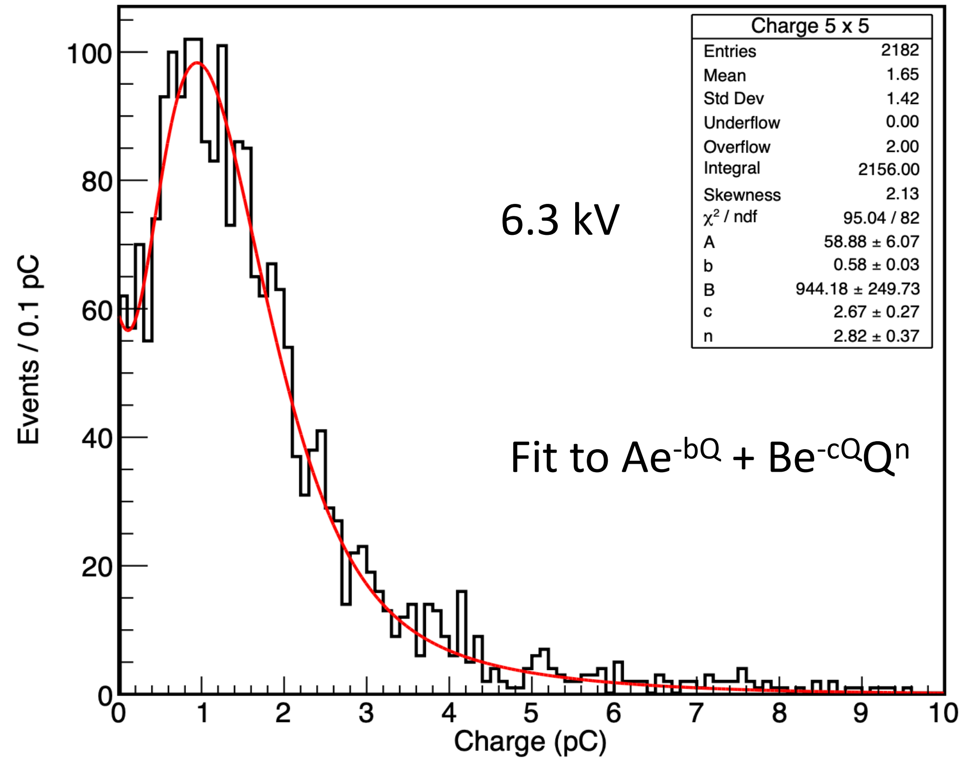


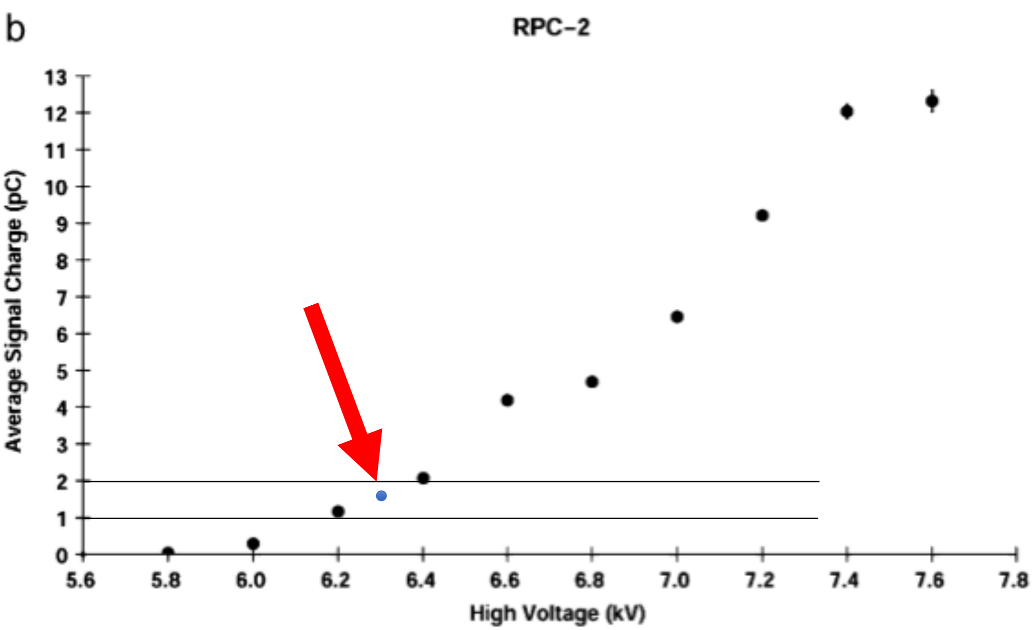



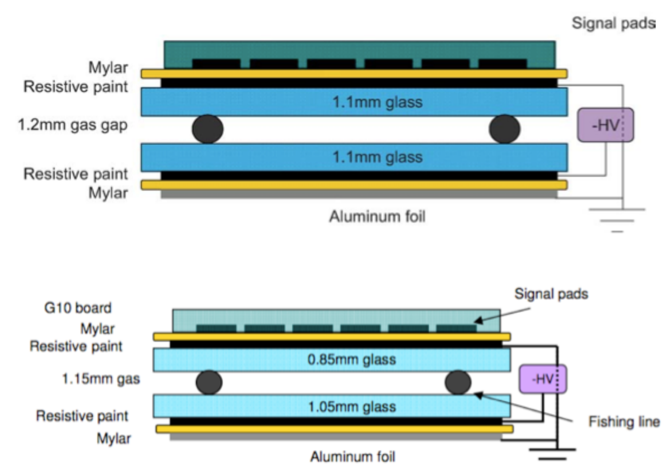



# MIP charge



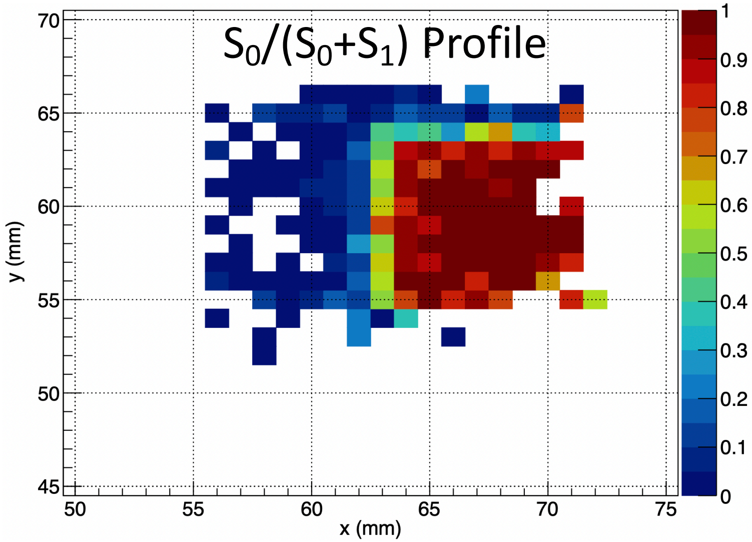



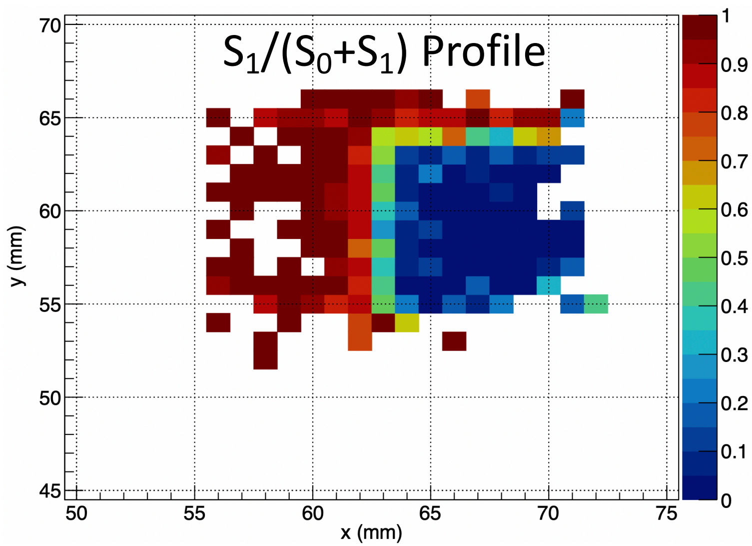

Results compatible with
G. Drake, et.al., NIMA 587, 88, 2007

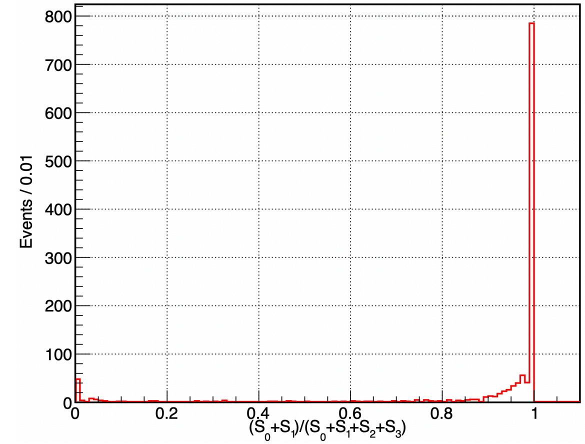
# Charge Distribution

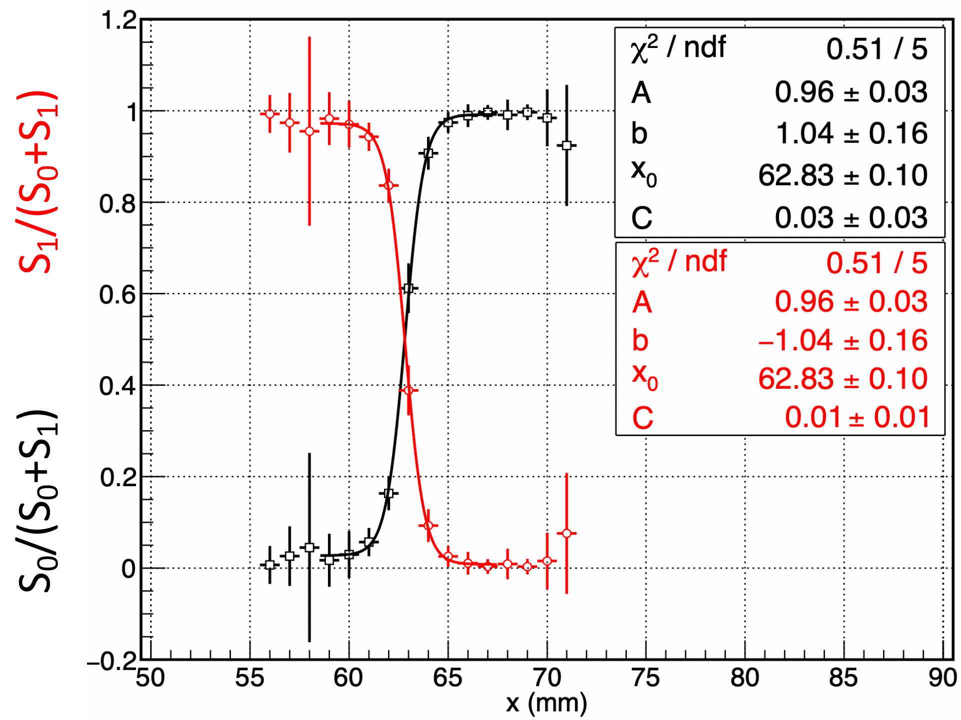
Select the protons with more than 90 % of the charge being in 3 x 3 ($S_0+S_1$).

Wire Chamber Profiles



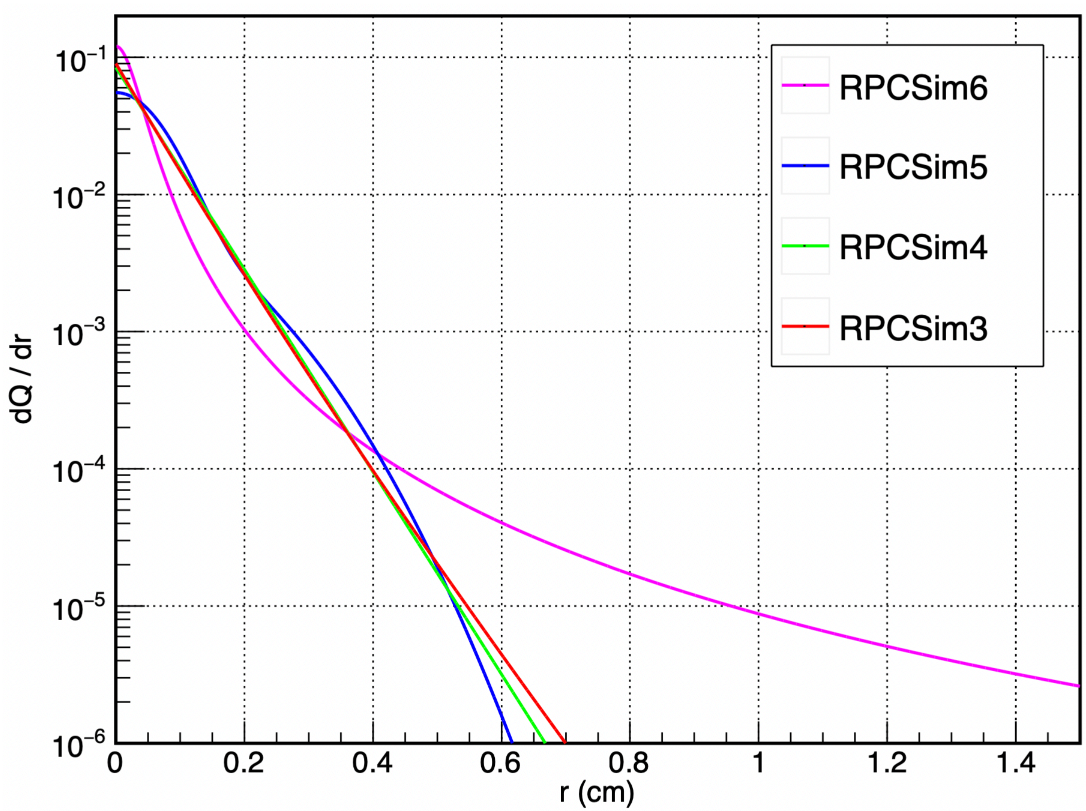




Take the protons with 57 mm ≤ y ≤ 61 mm

Fit to $A(\tanh(b(x-x_0))+1)/2 + C$ within 3 mm of the pad boundary.

# Survey of RPCSims

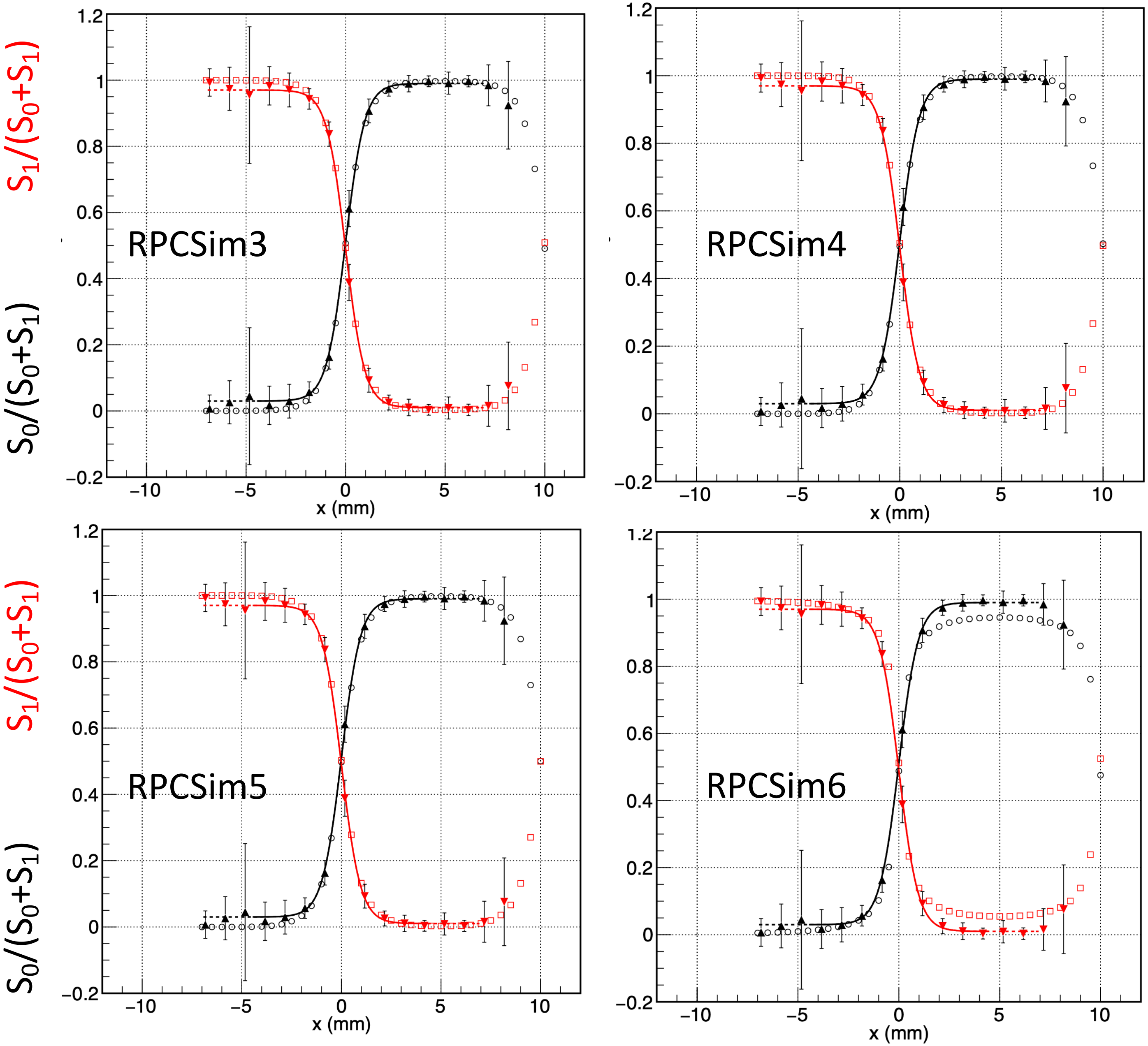
| RPCSim | Spread functions | |
|---|---|---|
| 3 | R $e^{-r/a}$ + (1-R) $e^{-r/b}$ | To help the tail |
| 4 | $e^{-r/a}$ | Measurement from STAR |
| 5 | R $e^{-(r/\sigma1)^{\wedge}2}$+ (1-R) $e^{-(r/\sigma2)^{\wedge}2}$ | Commonly used |
| 6 | $1/(a^2 + r^2)^{3/2}$ | Recently came across (by then) |




All independently optimized to reproduce the sharing of the charge within 3 mm of the pad boundaries.

# RPCSim Optimization with Proton Data

| RPCSim | Spread functions |
|---|---|
| 3 | $R\,e^{-r/a} + (1-R)\,e^{-r/b}$ |
| 4 | $e^{-r/a}$ |
| 5 | $R\,e^{-(r/\sigma1)^{\wedge}2} + (1-R)\,e^{-(r/\sigma2)^{\wedge}2}$ |
| 6 | $1/(a^2 + r^2)^{3/2}$ |




MC in open circles/boxes

**<u>RPCSim3</u>**
a = 0.05 cm
b = 0.07 cm
R = 0.75

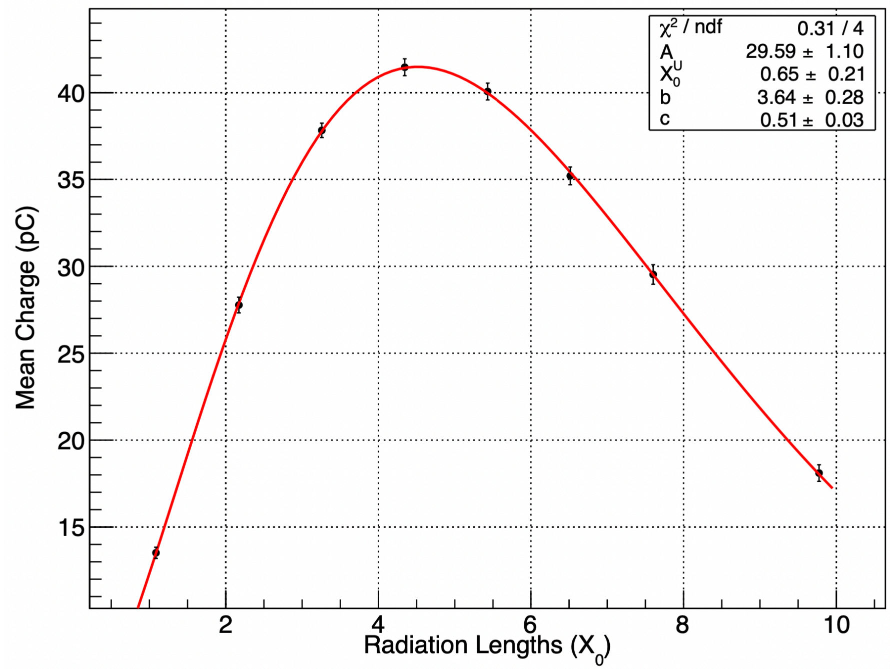
**<u>RPCSim4</u>**
a = 0.058 cm

**<u>RPCSim5</u>**
$\sigma_1$ = 0.09 cm
$\sigma_2$ = 0.21 cm
R = 0.90

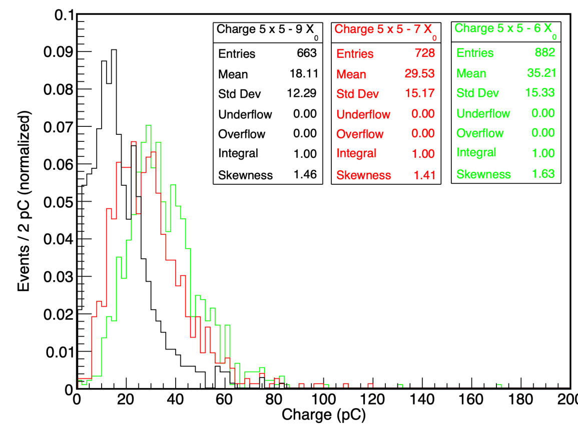
**<u>RPCSim6</u>**
a = 0.042 cm

# Positron Showers

- 8 GeV positron beam.
- Up to nine 20 cm x 20 cm x 1.9 cm (1.086 $X_0$) iron blocks upstream the analog readout RPC.
- 5 x 5 pad charge in 3 readout channels were added.

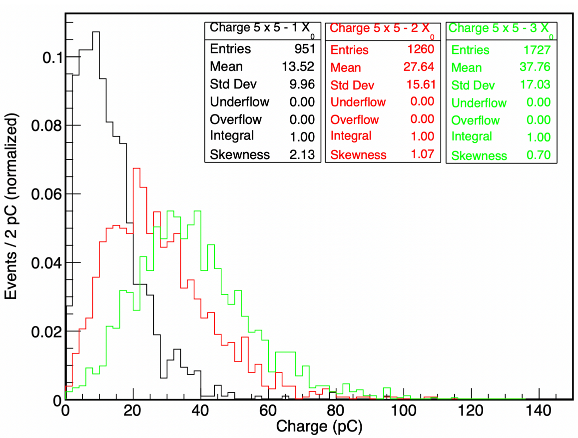


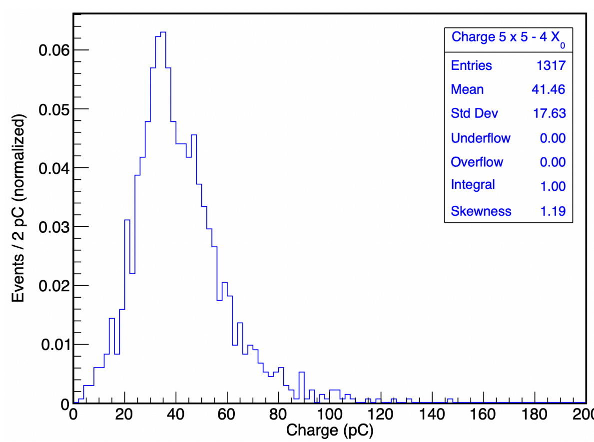

Means of the distributions

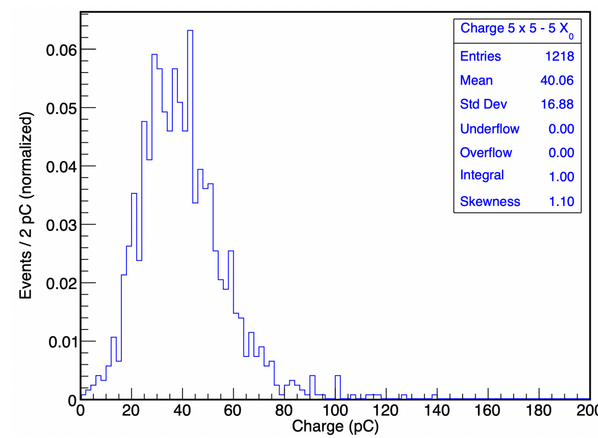



Fit to $A\frac{\left(X+X_0^U\right)^{a-1}e^{-c\left(X+X_0^U\right)}}{\Gamma(a)}$

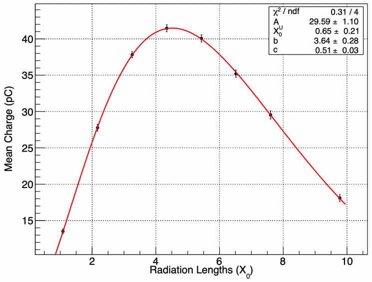
The upstream material amount from the fit is 0.65 $X_0$!



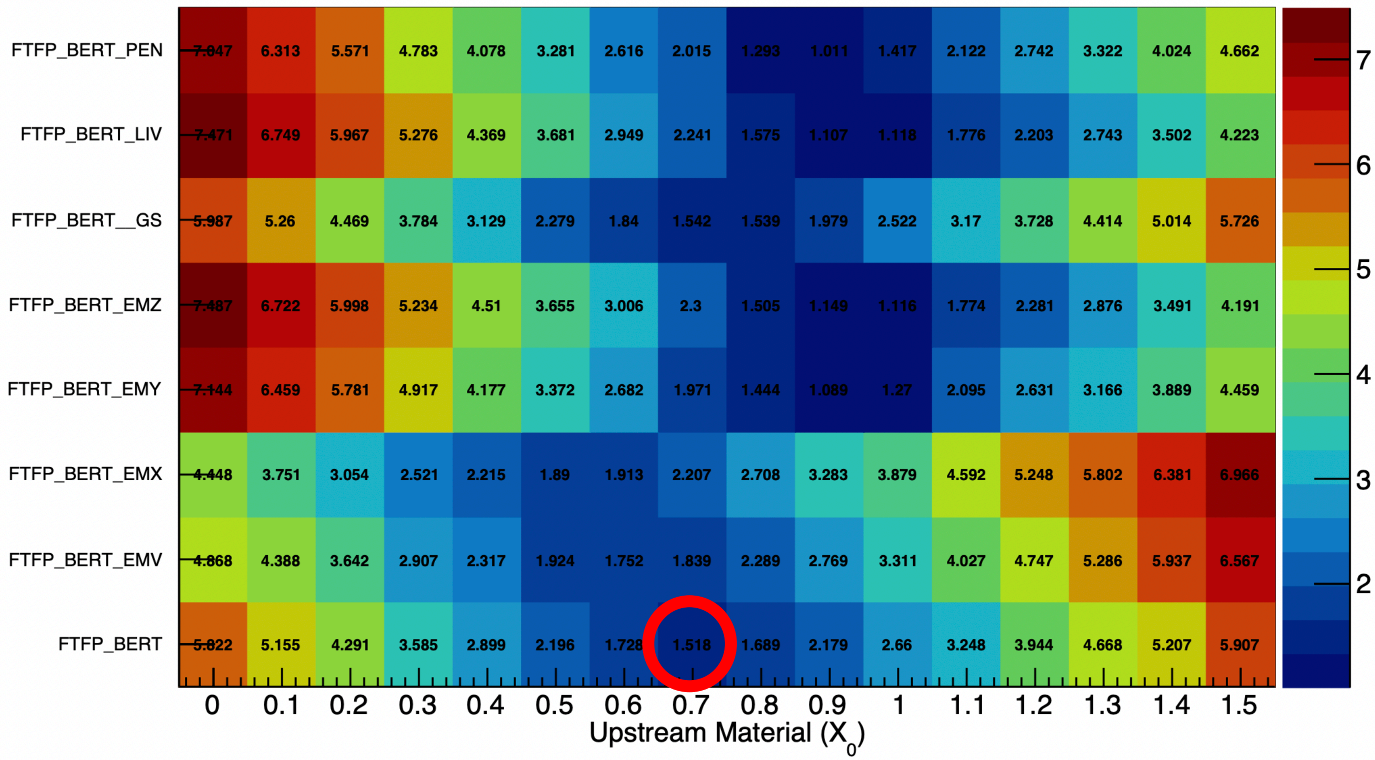



# $d_{cut}$ Optimization with Positron Showers: $d_{cut}$ and Upstream Material Scan




Overlay MC points and optimize the $d_{cut}$ to minimize:

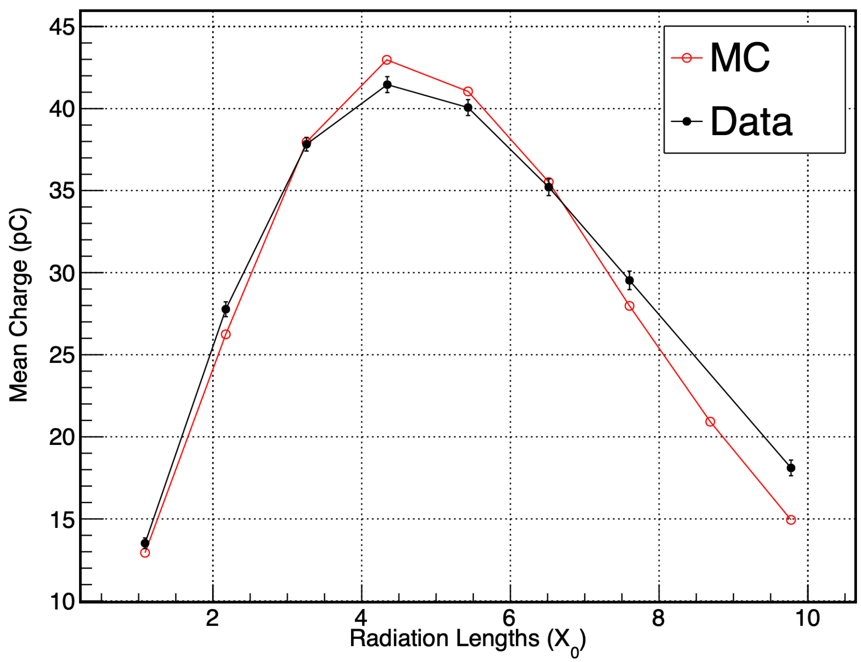
$$\sqrt{\frac{\sum_{\substack{i=1\\ i\neq 8}}^{9}\left(\bar{Q}_i^{data}-\bar{Q}_i^{MC}\right)^2}{8}}$$

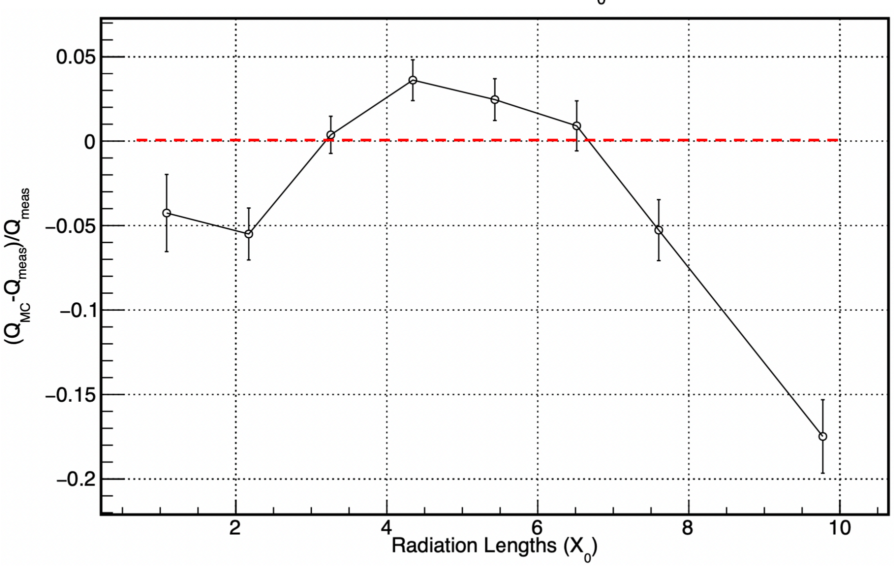



Large amount of upstream material is also confirmed by this scan. Will move forward with the standard EM package for now. The optimum $d_{cut}$ is 0.35 mm. Overall, heavy dependence on EM package choice (not good). In contact with FTBF about the upstream material amount.

https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsListGuide/html/electromagnetic/emphyslist.html

# Positron Showers with FTFP_BERT and $d_{cut}$ = 0.35 mm



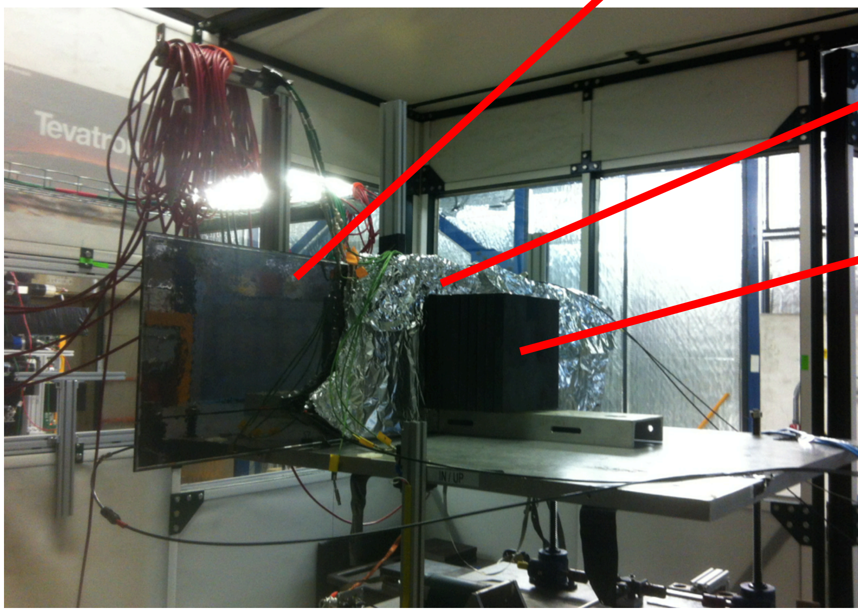

Simulation of the 2-RPC test setup and 0.65 $X_0$ upstream material with Geant 4.10.7.p02 (latest – June 2021).

Within 6 % agreement up to 7 $X_0$.

The charge at the shower maximum is overestimated and at the onset and final stages are underestimated.

Need to investigate the alternative $d_{cut}$ implementation techniques e.g. weighting the charge of the neighbor avalanche as a linear/exponential function of the distance between them.

# Positron Showers: Analog and Digital Readout RPCs

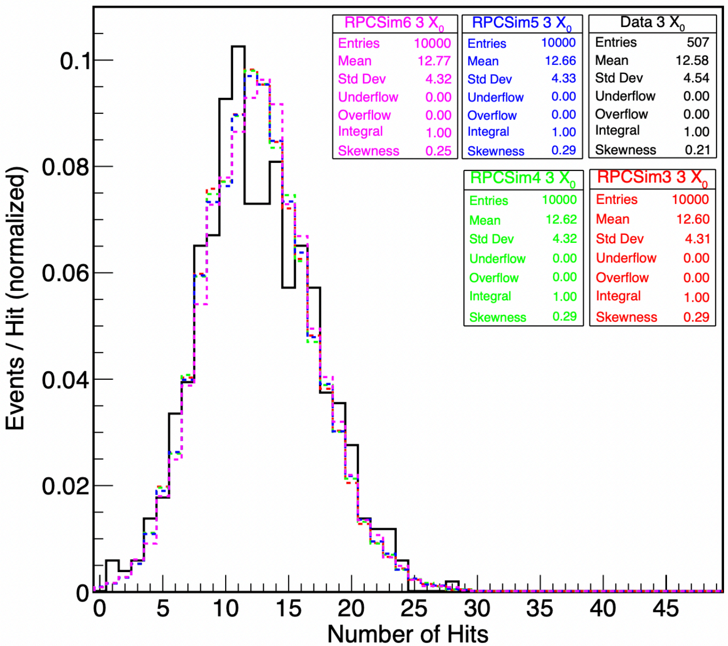


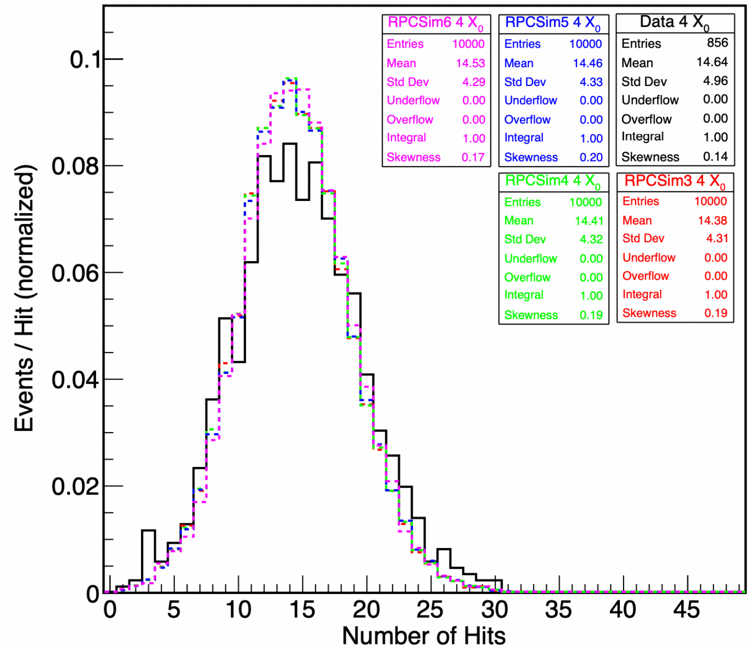

Tests were performed with 3, 4, 5, 6 and 9 iron blocks.

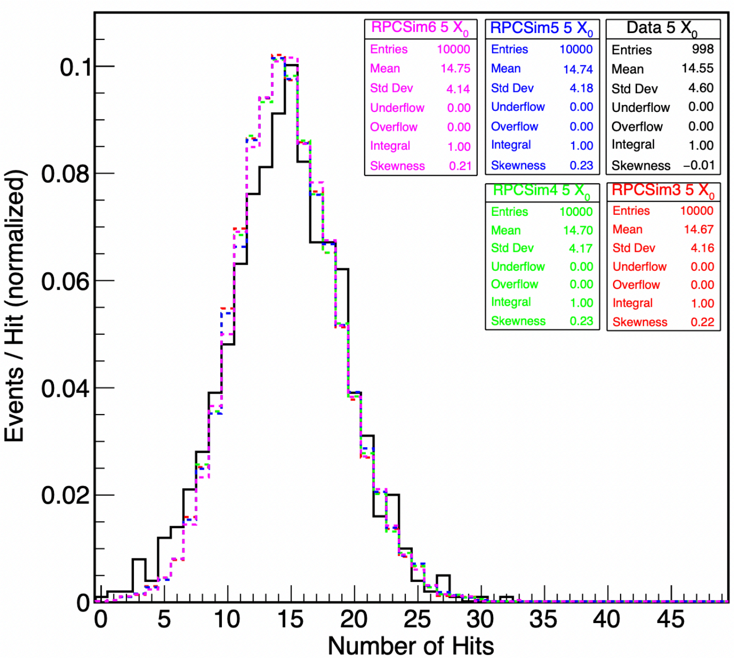
Simulated with FTFP_BERT and $d_{cut}$ = 0.35 mm.

The threshold of the digital readout was optimized by the minimization of the differences between the mean number of hits of data and MC. The optimal threshold T = 380 fC is higher than the DHCAL setting of ~ 100 fC.

# Positron Showers: Analog and Digital Readout RPCs



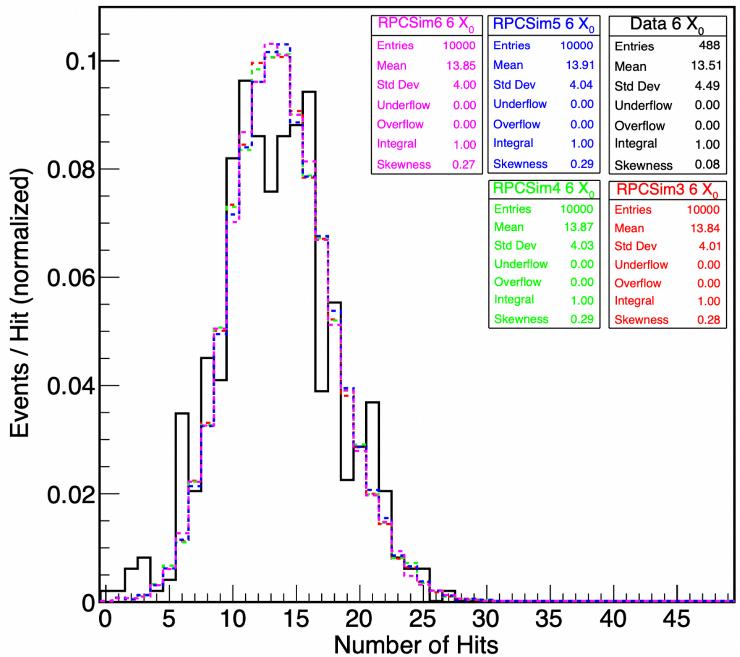



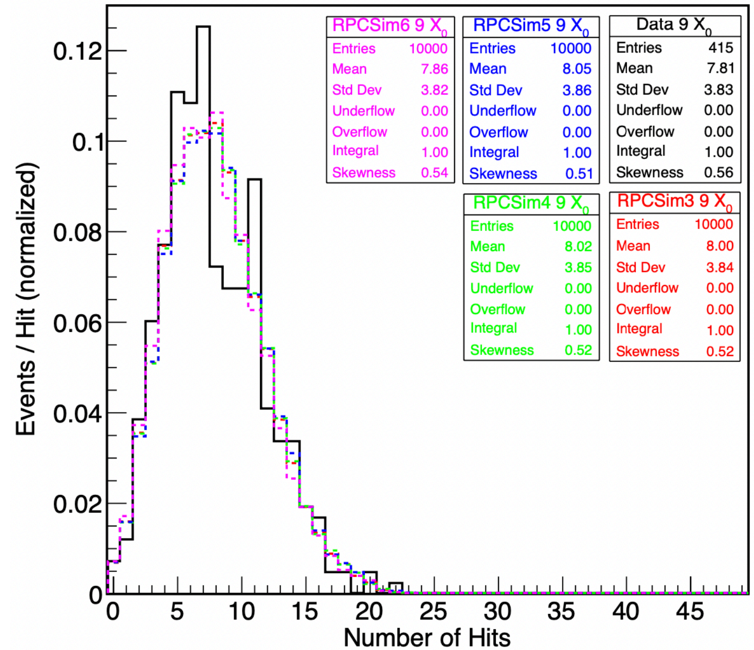



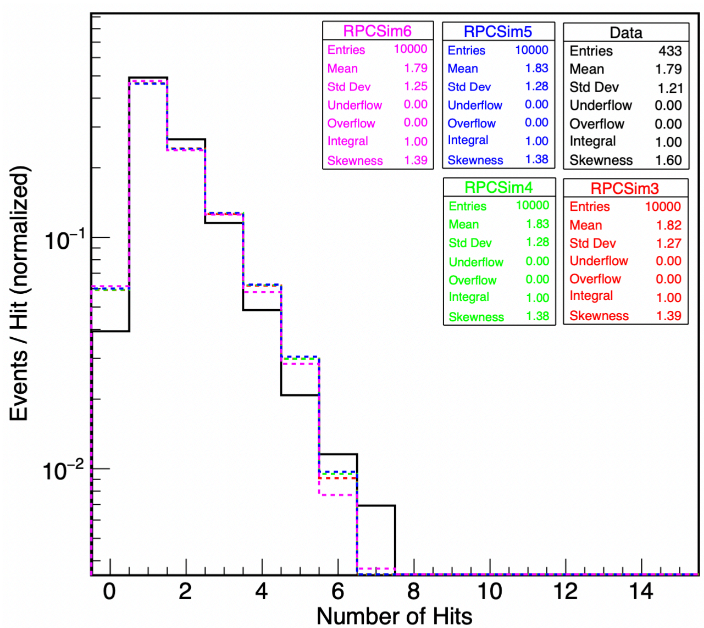

The agreement is in general OK.

The relatively bad shapes of the distributions can be attributed to the slightly different beam conditions following frequent accesses to change the absorber layout.

# Positron Showers: Analog and Digital Readout RPCs




The no absorber positron data was also simulated (~MIP). The tendency of the MC is towards lower efficiency and higher multiplicity. This again points towards the need of a better $d_{cut}$ algorithm.

No dramatic difference between different RPCSims.

# Conclusions

- The analog readout of the DHCAL RPC provides valuable handles to obtain the avalanche charge and its distribution over the readout pads.

- The distribution of the shower charge on the pads, on the other hand, is very challenging.

- Need to invent a more sophisticated interaction model for the nearby avalanches.

- The MC information obtained from the analog readout will be implemented to the min-DHCAL configuration soon.