Performance validation of the main integrating detectors for the MOLLER experiment

Sayak Chatterjee
UMass Amherst

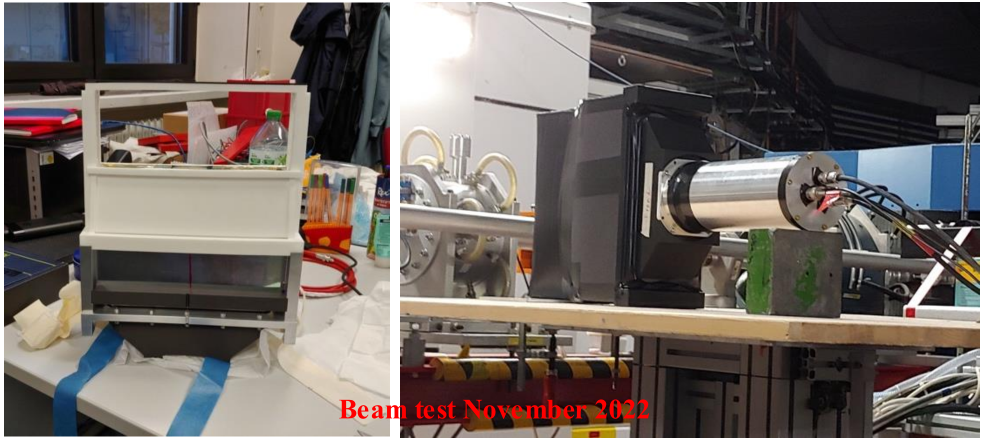
Outline:

- Summary of the segment testing at MAMI (2023)
- Benchmarking with cosmic muons at UMass (2024)
- Performance validation of production modules at W&M with cosmic muons (2025-2026)
- Summary & outlook

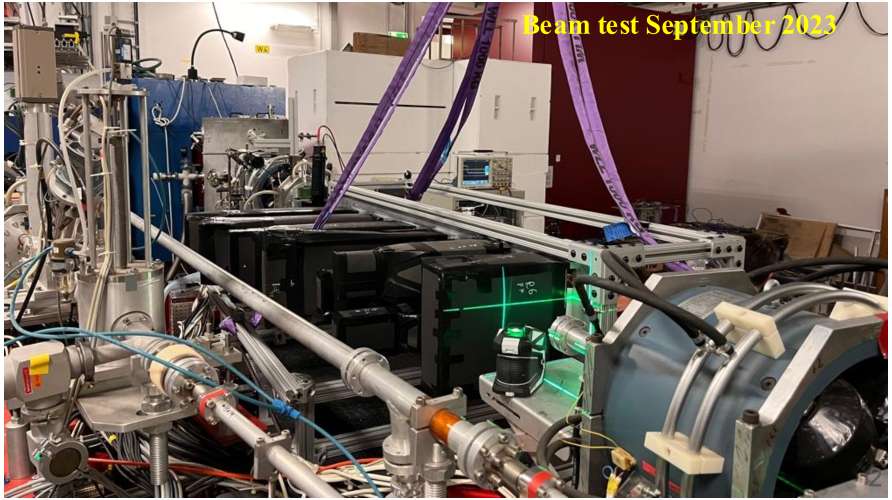
Integrating Detector meeting, Dec 1, 2025

MAINZ beam test with the prototype Cherenkov detector modules

- Testing of the Cherenkov detector prototypes at MAMI accelerator facility in Germany with electron beam of energy ~ 855 MeV
  - ➢ Performance study of the individual modules
  - ➢ Performance study with a fully instrumented front flush segment (2023)
- Characterization of the Cherenkov detector with cosmic muons
- Testing of different quartz tiles (Tosoh, Heraeus, Corning)
- Optimization of the light guide material
- Electronics testing



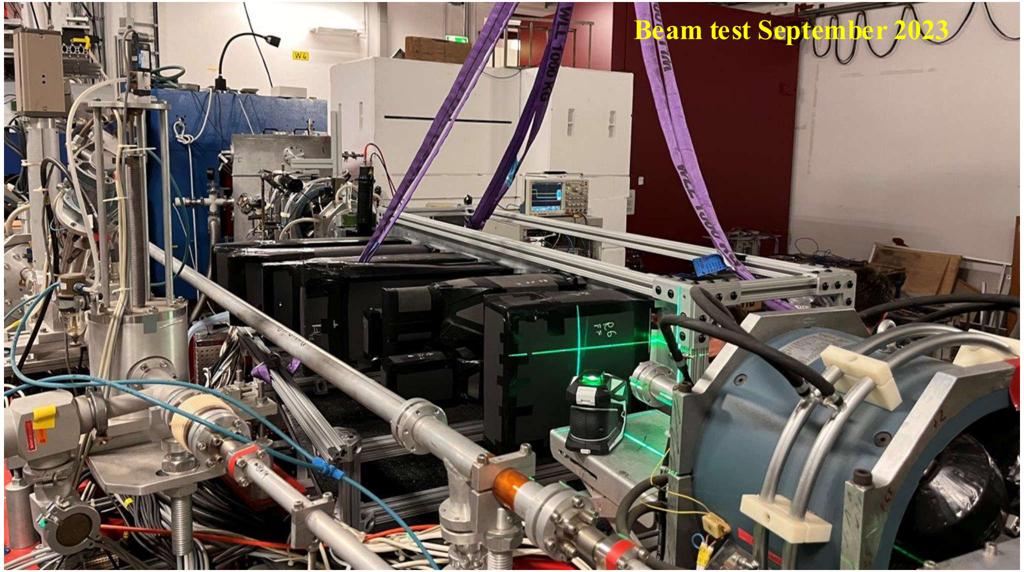
Beam test November 2022



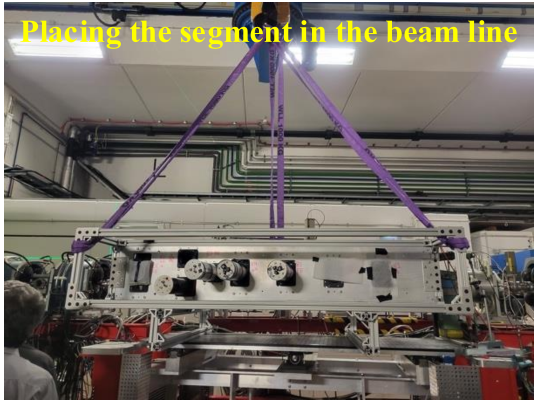
Beam test September 2023

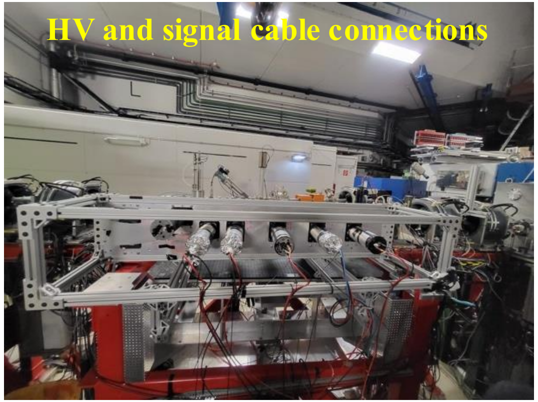
Thanks to UMass, Uni. Manitoba, P2@Mainz, Idaho State, Virginia Tech folks & Larry Bartoszek

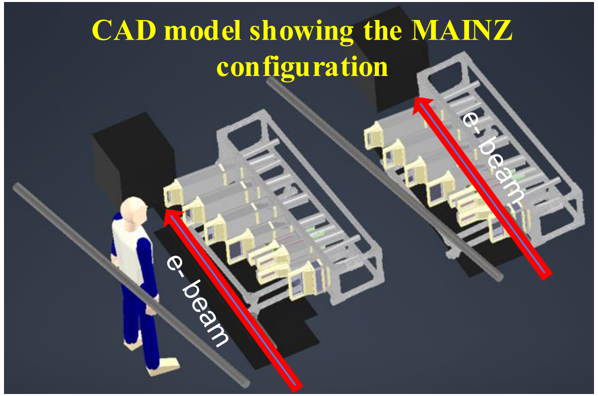
MAINZ beam test with the prototype Cherenkov detector modules (2023)



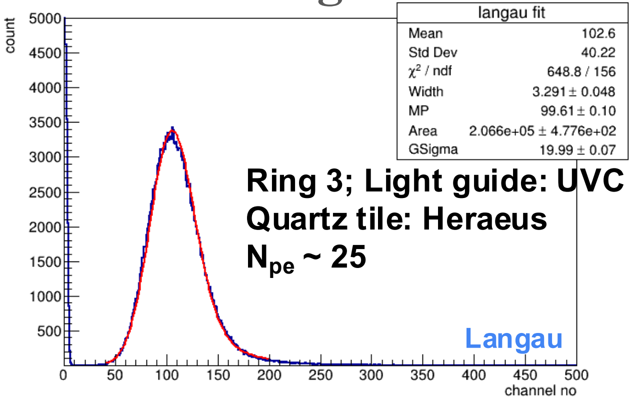
- Entire front flush segment is scanned with electron beam (~ 855 MeV)
- Performance with different quartz tiles and reflective light guide materials are investigated
  - Quartz tiles: Corning & Heraeus
  - Light guide: UVC & UVS
- Detectors are tested in event mode as well as in the integrated mode

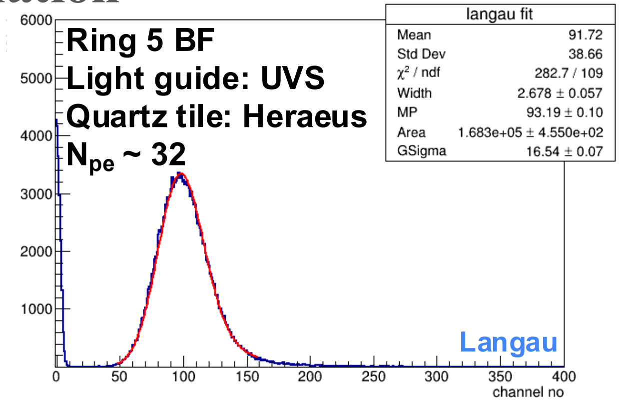


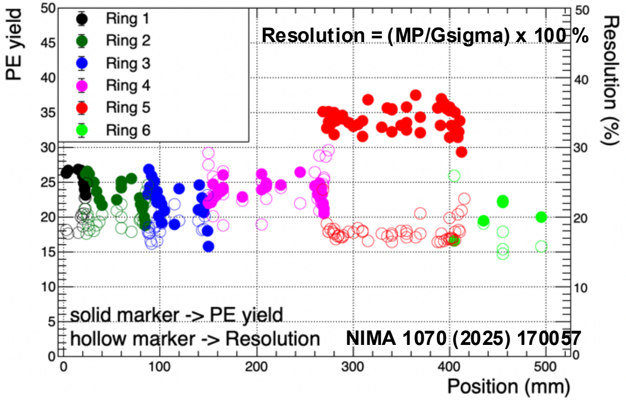


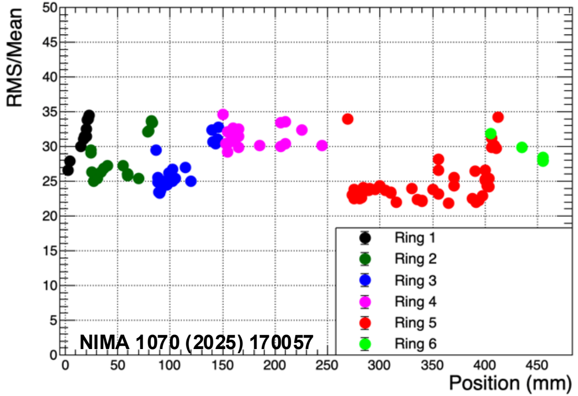


MAINZ beam test with the prototype Cherenkov detector modules & benchmarking of MC simulation









Rings	PE yield (beam data)	PE yield (MC sims)	RMS/MEAN (beam data)	RMS/MEAN (MC sims)
1	26.6 + 0.1	30.2 ± 0.1	~30 %	25 %
2	25.0 + 0.1	26.1 ± 0.1	~28 %	25 %
3	22.5 + 0.8	25.5 ± 0.1	~28 %	25 %
4	23.6 + 0.2	24.3 ± 0.1	~30 %	24 %
5 BF	32.0 + 0.2	32.8 ± 0.16	~25 %	22 %
6	20.7 + 0.2	21.5 ± 0.1	~32 %	26 %

Benchmarking of the MC sims with the data (agreeing well within ~ 15%)

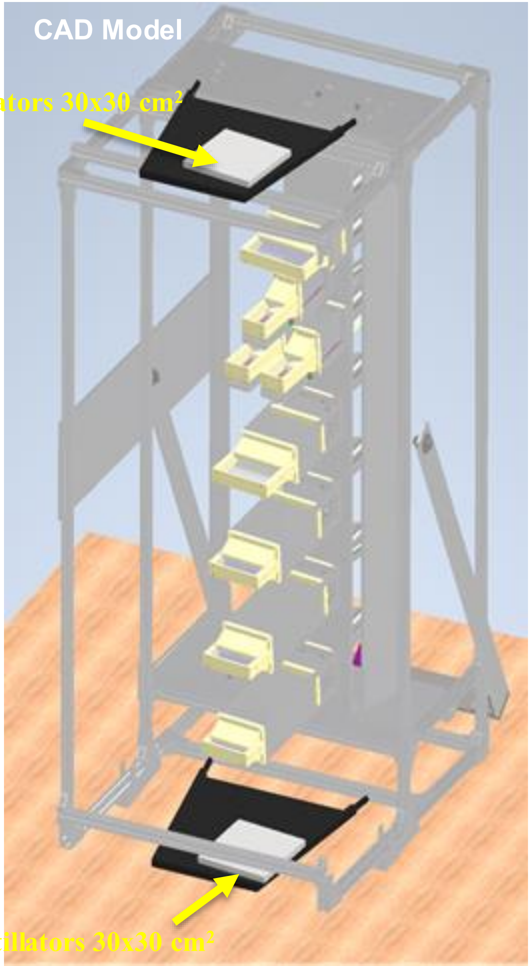
- Benchmarking of the detector prototype performance with the instrumented segment plate
  - RMS/MEAN ≲ 25 % (Ring 5) & ≲ 30 % (Rest of the rings) ; PE yield ≳ 30 (Ring 5) & ≳ 20 (Rest of the rings)
  - Resolution ≲ 20 % (Ring 5) & ≲ 25 % (Rest of the rings)

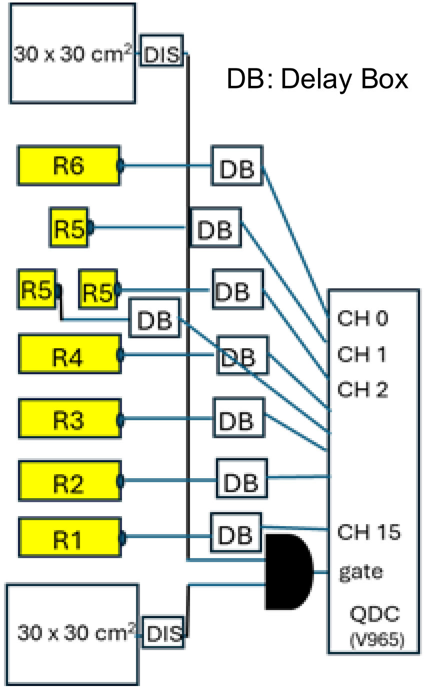
MAINZ beam test (2023) summary

Rings	PE yield (beam data)	PE yield (MC sims)	RMS/MEAN (beam data)	RMS/MEAN (MC sims)	Resolution (beam data)	Resolution (MC sims)
1	26.6 + 0.1	30.2 ± 0.1	~ 30 %	25 %	20 (±1) %	18 (±0.1)%
2	25.0 + 0.1	26.1 ± 0.1	~ 28 %	25 %	22 (±1) %	19 (±0.2) %
3	22.5 + 0.8	25.5 ± 0.1	~ 28 %	25 %	21 (±1) %	19 (±0.2) %
4	23.6 + 0.2	24.3 ± 0.1	~ 30 %	24 %	23 (±1) %	21 (±0.5) %
5 BF	32.0 + 0.2	32.8 ± 0.16	~ 25 %	22 %	18 (±1) %	17 (±0.3) %
6	20.7 + 0.2	21.5 ± 0.1	~ 32 %	26 %	22 (±1) %	21 (±0.1) %

- The error shown here is coming from the fitting error of the parameters for the individual spectrum
- The error in the PE yield is coming from the PMT gain calibration (using the in-situ method)
- No systematic errors are added to the PE yield or to the resolution (e.g. uncertainty in the pre-amplifier gain (x10) in the PMT base)
- Detailed presentations on the MAMI results can be found here : Moller-doc-1255-v3, Moller-doc-1211-v2, Moller-doc-1364-v1

Benchmarking of the detector prototypes with cosmic muons at UMass





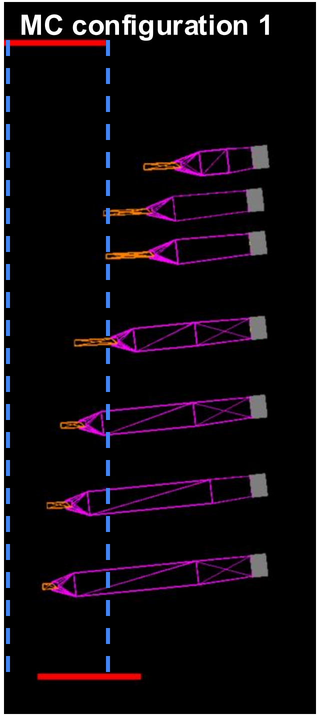
Schematic of the electronic circuit diagram of cosmic stand setup at UMass

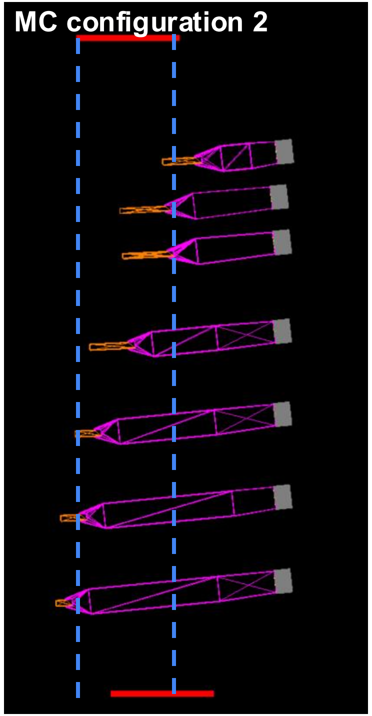
Benchmarking of the performance of the prototype modules with cosmic muons at UMass

CAD model: Joelle Beck & Larry Bartoszek

Benchmarking of the detector prototypes with cosmic muons at UMass

The cosmic trigger is formed by the coincidence of the top & bottom scintillators arranged in a particular way!!!

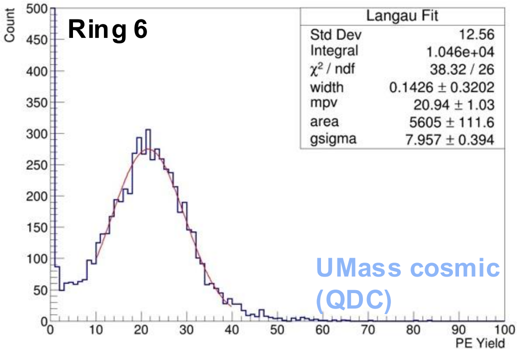


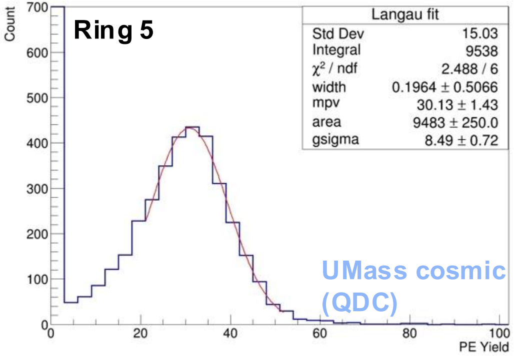


Resolution = Gsigma/MPV

Ring	PE yield (beam)	PE yield (cosmic)	Resolution (beam)	Resolution (cosmic)
1	26.6 (± 0.1)	28.8 (± 3.5)	~ 20 (±1) %	~ 28 (±6) %
2	25.0 (± 0.1)	21.2 (± 1.3)	~ 22 (±1) %	~ 46 (±4) %
3	22.5 (± 0.8)	21.1 (± 1.5)	~ 21 (±1) %	~ 37 (±4) %
4	23.6 (± 0.2)	20.6 (± 0.8)	~ 23 (±1) %	~ 43 (±2) %
5	32.0 (± 0.2)	30.1 (± 3.6)	~ 18 (±1) %	~ 28 (±4) %
6	20.7 (± 0.2)	20.9 (± 2.5)	~ 22 (±1) %	~ 38 (±5) %

- The resolution is worse (~ 20%) with cosmic and that is because of the finite solid angle of the setup and the wide energy distribution of the incoming cosmic muons
- The errors shown on the PE yield are coming from the uncertainty of the PMT gain values





The PE yield using cosmic muons matches very well (~ 15%) with the beam data

UMass cosmic data: Sakib Sarker

Benchmarking of MC simulation with cosmic muon data at UMass

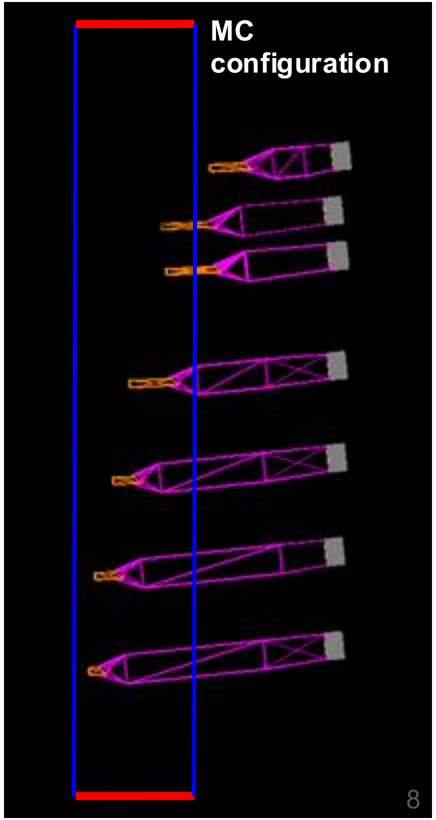
- ✓ MC simulation shows good agreement with MAINZ test beam data (~ 15%) (NIMA 1070, 170057, 2025)
- ✓ The same MC generator is used to predict the expected PE yields from the UMass cosmic test stand
- ✓ The cosmic data from the UMass test stand is compared with the MC simulations

Ring	PE yield (cosmic)	PE yield (MC)	Gsigma (cosmic)	Gsigma (MC)	Resolution % (cosmic)	Resolution % (MC)
1	17.5 (± 1.7)	15.2 (± 0.1)	6.2 (± 0.8)	4.1 (± 0.1)	~ 35 (±6)	~ 27 (±0.7)
2	20.5 (± 2.1)	15.9 (± 0.1)	7.6 (± 0.8)	5.2 (± 0.1)	~ 37 (±5)	~ 33 (±0.7)
3	21.1 (± 2.1)	18.5 (± 0.3)	7.8 (± 0.6)	6.4 (± 0.2)	~ 37 (±5)	~ 35 (±1.0)
4	15.2 (± 1.5)	13.1 (± 0.1)	5.7 (± 0.6)	3.9 (± 0.1)	~ 38 (±5)	~ 30 (±0.8)
5	28.2 (± 2.8)	26.0 (± 0.1)	9.5 (± 0.6)	9.1 (± 0.1)	~ 34 (±4)	~ 35 (±0.4)
6	18.4 (± 1.8)	17.0 (± 0.1)	9.0 (± 0.5)	5.9 (± 0.1)	~ 49 (±6)	~ 35 (±0.6)

Cosmic data matches very well with the MC simulations (~15%)

Resolution is ~ 20% worse with cosmic as compared to the beam data

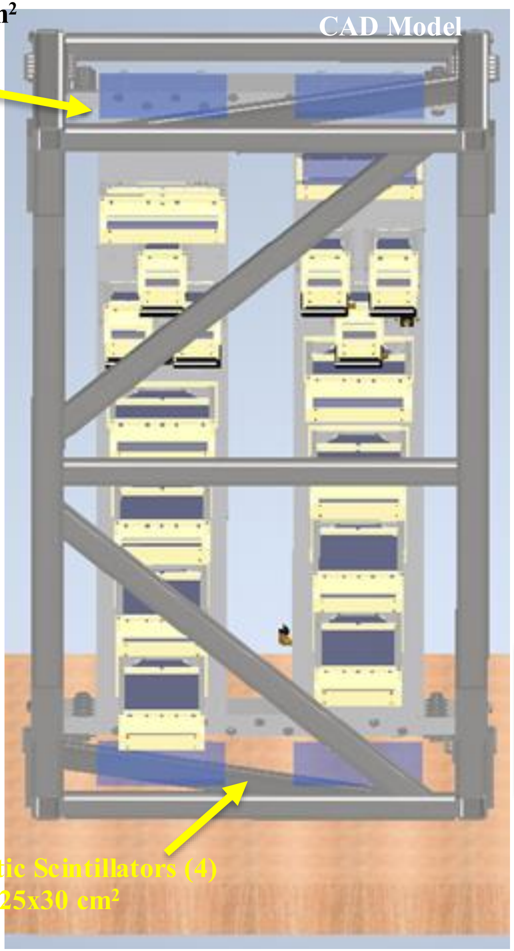
Width of the cosmic data seems wider compared to the MC predicted values



MC simulation: Jon Mott

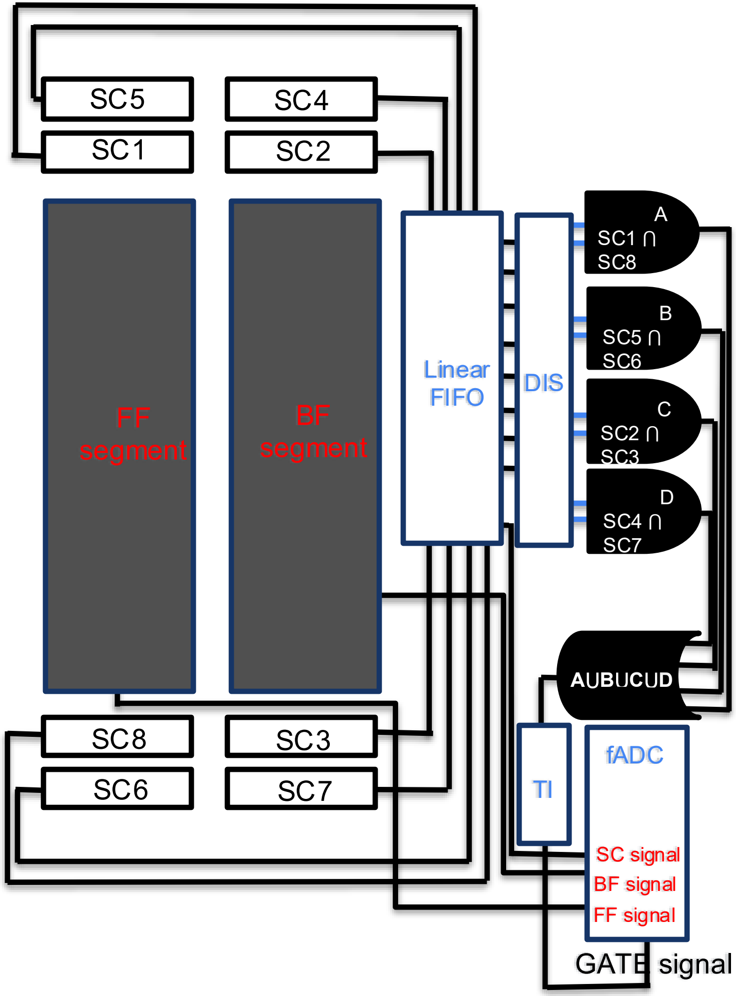
W&M cosmic stand

US Plastic Scintillators (4)
25x30 cm^2



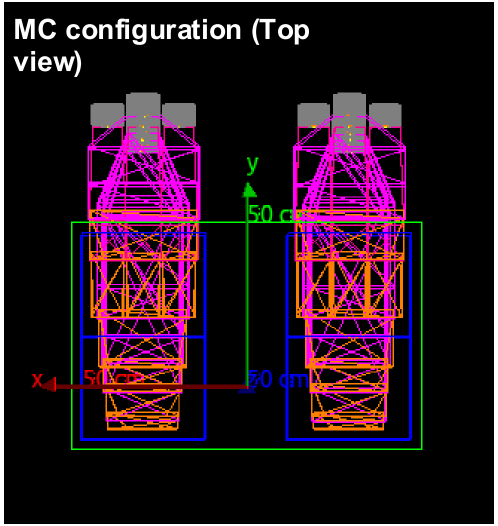
DS Plastic Scintillators (4)
25x30 cm^2

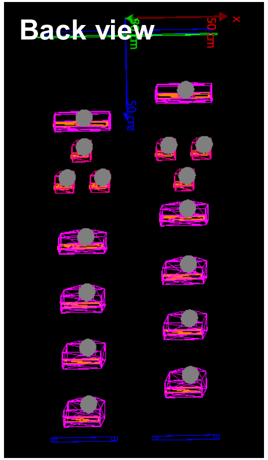
CAD model: Larry Bartoszek

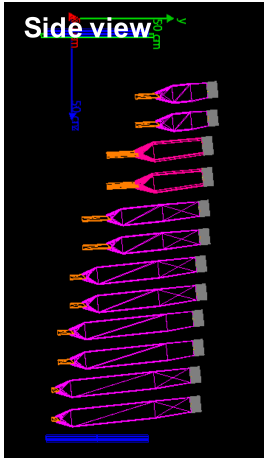


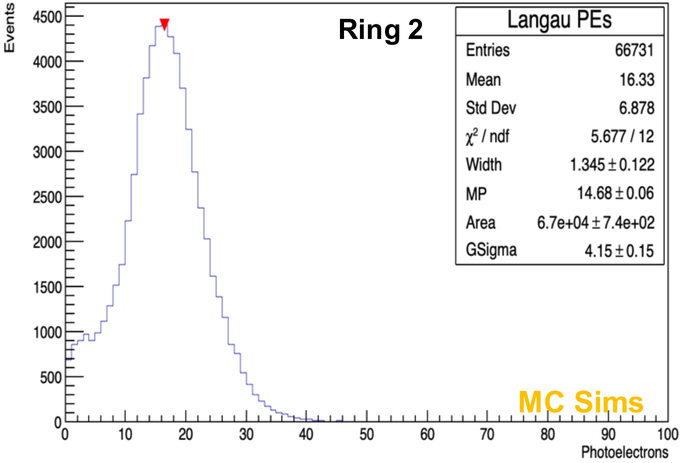
Schematic of the electronic circuit diagram of cosmic stand setup at W&M

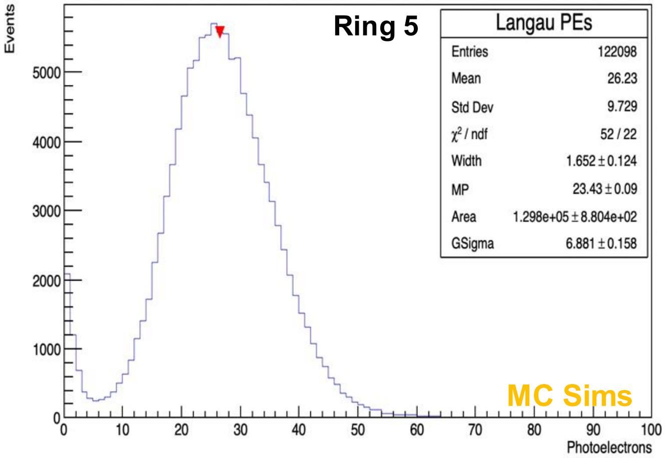
MC prediction for the W&M cosmic stand











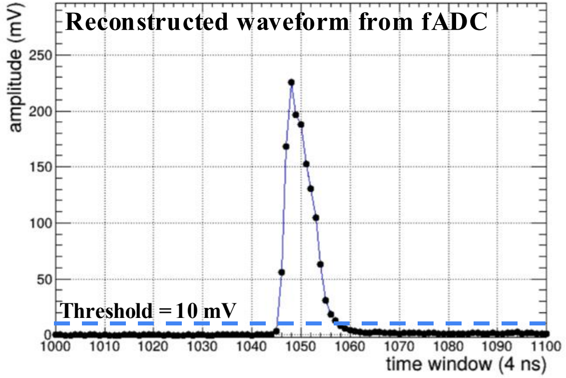
Typical simulated PE distribution from W&M cosmic stand for cosmic muons

Ring	MC PE yield (W&M)	MC GSigma (W&M)	MC Resolution % (W&M)
1	16.3 (± 0.4)	4.7 (± 0.2)	~ 29 (± 1.4)
2	14.8 (± 0.1)	4.4 (± 0.2)	~ 30 (± 1.4)
3	18.1 (± 0.2)	6.6 (± 0.2)	~ 36 (± 1.2)
4	13.2 (± 0.1)	3.6 (± 0.1)	~ 27 (± 0.8)
5	23.6 (± 0.1)	7.0 (± 0.2)	~ 30 (± 0.9)
6	17.4 (± 0.1)	6.1 (± 0.1)	~ 35 (± 0.7)

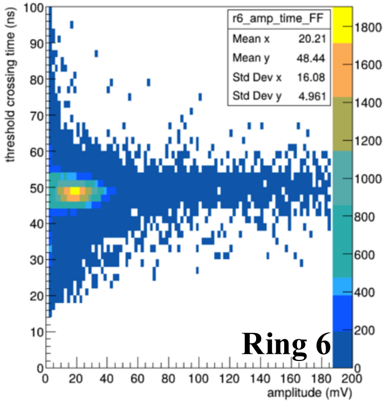
- Due to slight change in the geometry (dimension of the triggering scintillators, position of the scintillators etc.), the results are slightly different for couple of rings

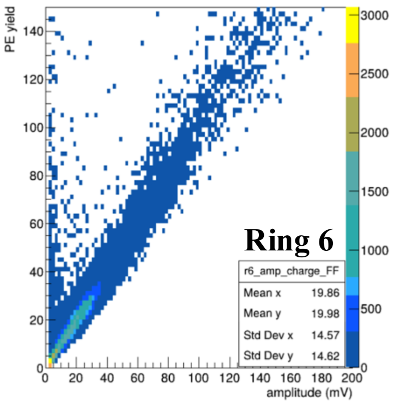
MC simulation: Jon Mott

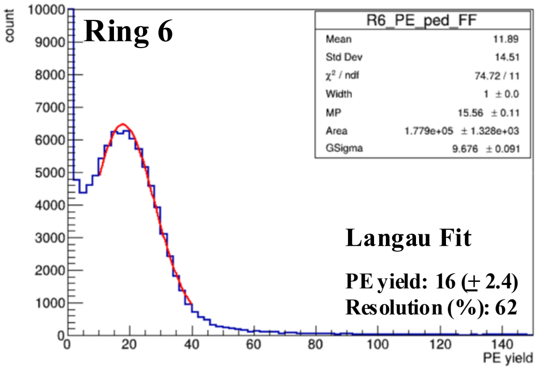
Performance of the production modules at W&M with cosmic (analysis steps)



Only scintillator cut : (Events passing through the top and bottom scintillators)

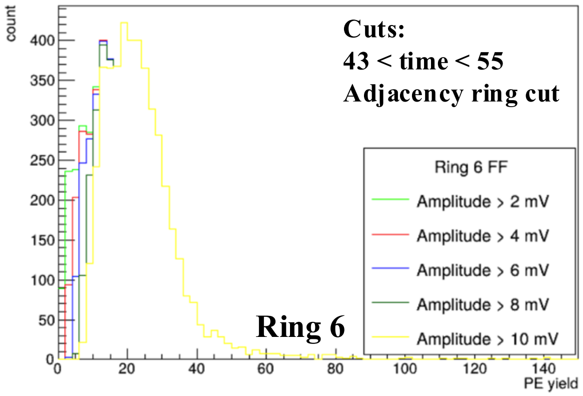


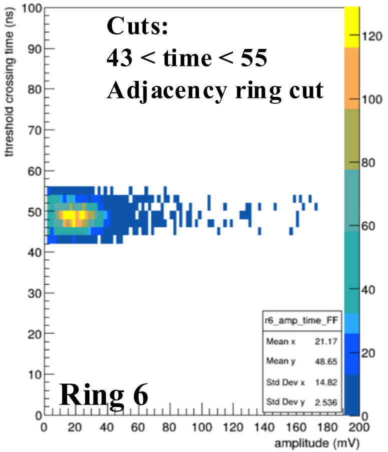


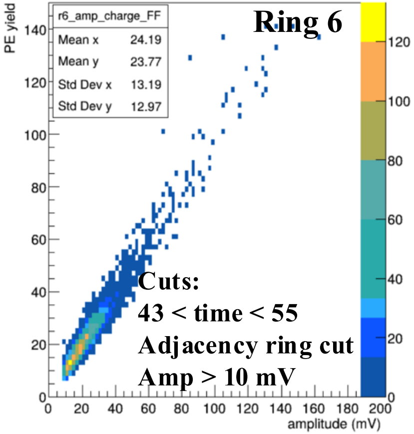


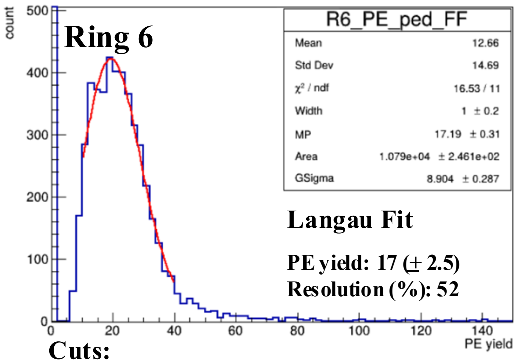
Effect of amplitude cut on the PE yield

scintillator cut + adjacent ring cut + time & amplitude cut for the respective ring







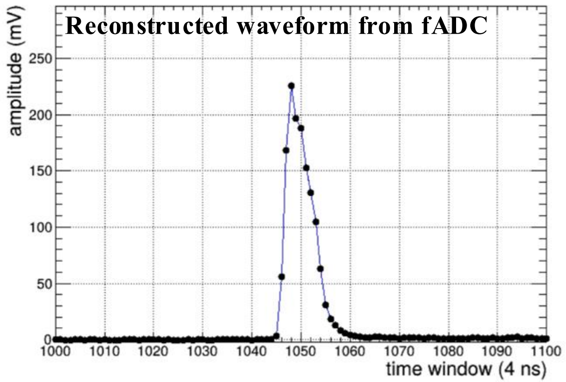


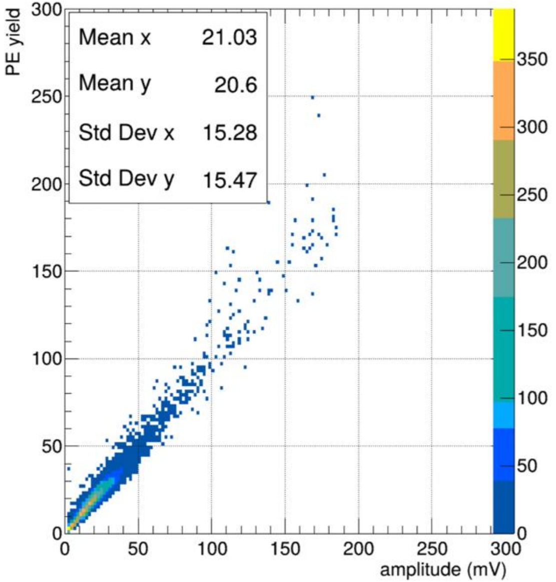
Cuts:
43 < time < 55; Adjacency ring cut
Amp > 10 mV

Amplitude cut only changes the width of the distribution!!!

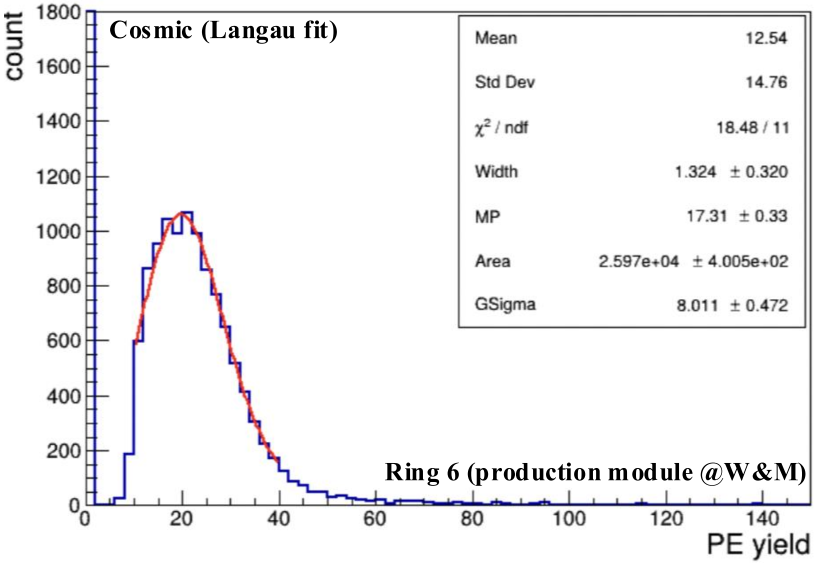
Same analysis method has been used for all the rings

Typical signal from the production modules





- The waveform from the fADC module is reconstructed using the [moller-counting]() framework
- The reconstructed waveform is integrated to extract the total output charge
- The total output charge is normalized using the PMT gain to get the PE yield from the respective production Cherenkov modules
- The MPV of the Langau fit is used as the PE yield from the module and the ratio of the Gsigma to the MPV is defined as the resolution

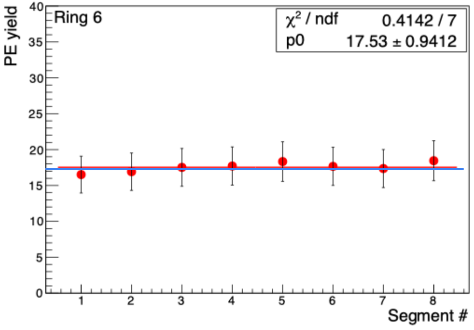


Production module data summary

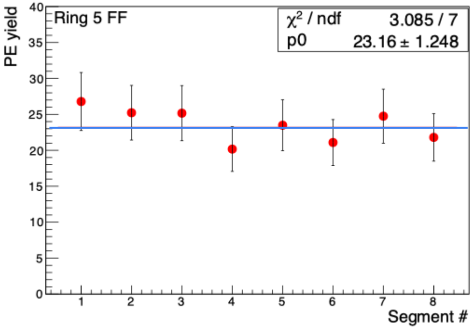
- SEG1-SEG2
- SEG3-SEG4
- SEG5-SEG6
- SEG7-SEG8

Data taking is ongoing with SEG7-SEG8

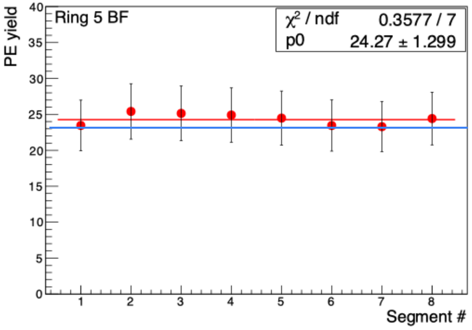
Cosmic data from the W&M stand : PE yield (SEG 1 – SEG 8)



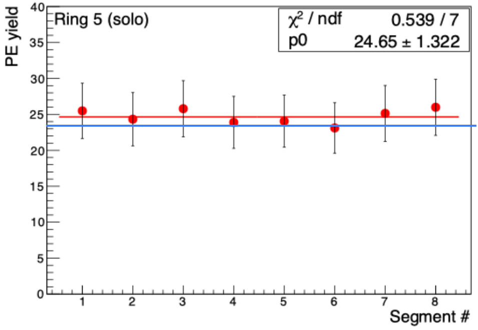
R6: Data : p0 -> 17.5
MC prediction : 17.4



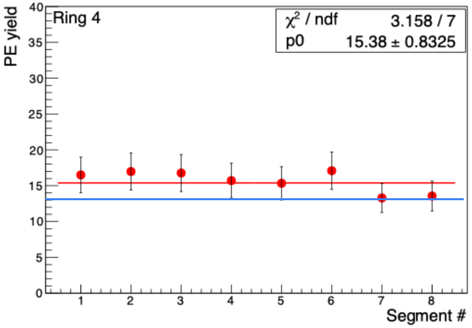
R5 FFs: Data : p0 -> 23.2
MC prediction : 23.6



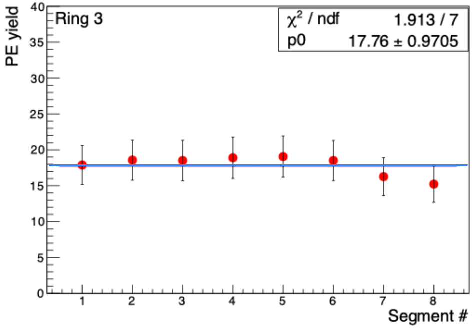
R5 BF: Data : p0 -> 24.3
MC prediction : 23.6



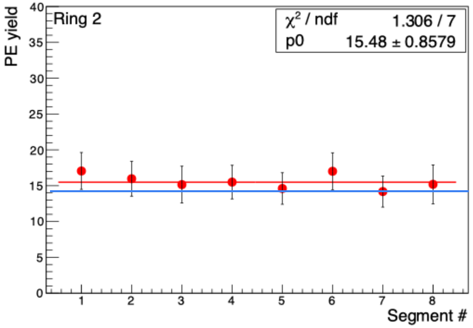
R5 (solo): Data : p0 -> 24.6
MC prediction : 23.6



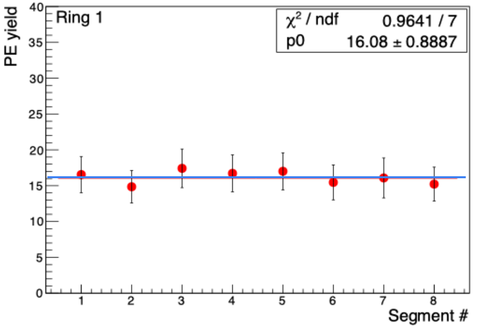
R4: Data : p0 -> 15.4
MC prediction : 13.2



R3 : Data : p0 -> 17.8
MC prediction : 18.1



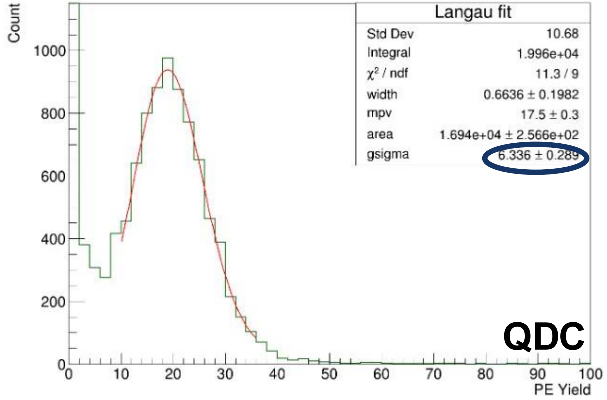
R2 : Data : p0 -> 15.5
MC prediction : 14.8

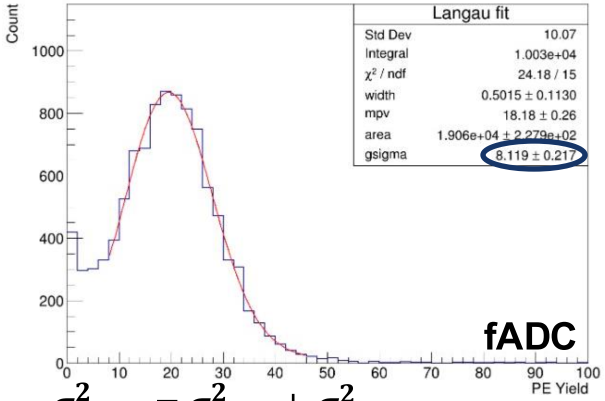


R1 : Data : p0 -> 16.1
MC prediction : 16.3

Red line : pol0 fit to the data Blue line : MC prediction

Comparison between fADC and QDC data : GSigma study

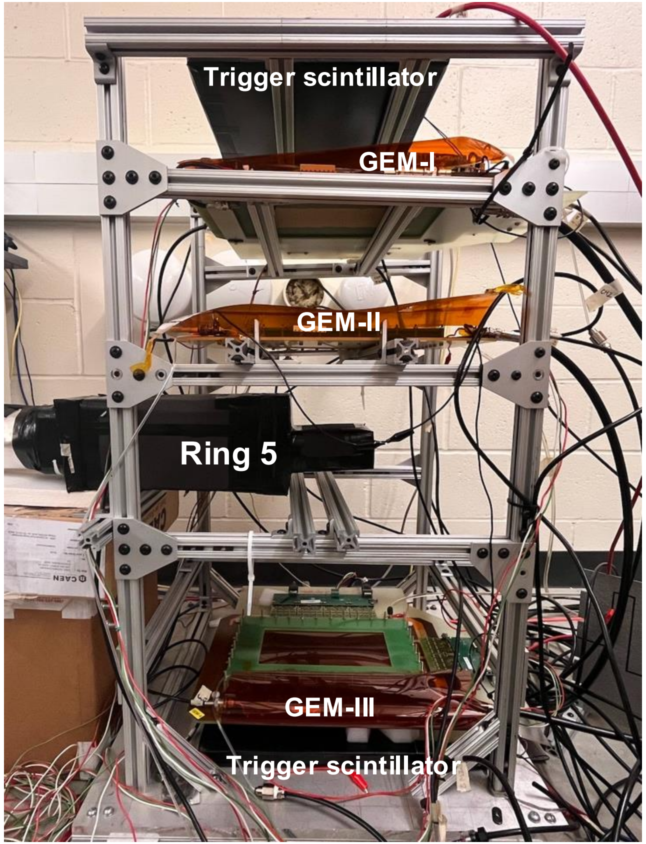




$$\sigma^2_{fADC} = \sigma^2_{QDC} + \sigma^2$$

$$\sigma^2 = \sigma^2_{fADC} - \sigma^2_{QDC}$$

$$\sigma = 5.1 \pm 0.4$$



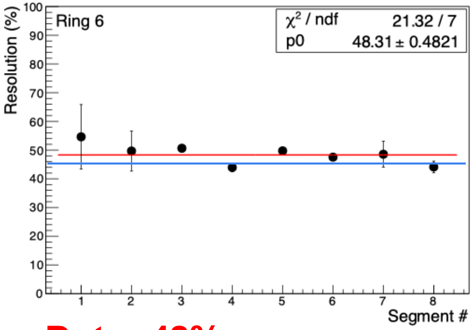
- Signal from the Cherenkov detector is fed to QDC and fADC using linear FIFO module
- GEMs are used to reconstruct the cosmic muon tracks
- Using the reconstructed GEM tracks, events hitting the quartz tile normally (89<θ<91) are selected
- The response from the detector for those particular-events are studied from QDC and fADC

fADC spectrum looks slightly wider than the QDC spectrum

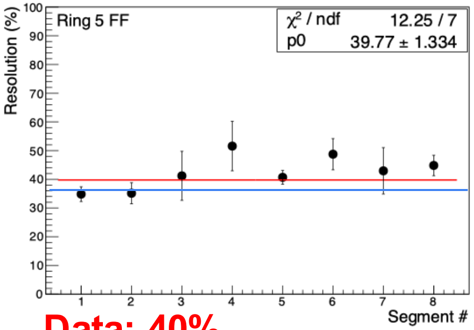
This work is ongoing to also investigate the angular dependance on the PE yield for all the prototypes modules (Ring 1 through Ring 6) at UMass

Cosmic data from the W&M stand : Resolution (SEG 1 – SEG 8)

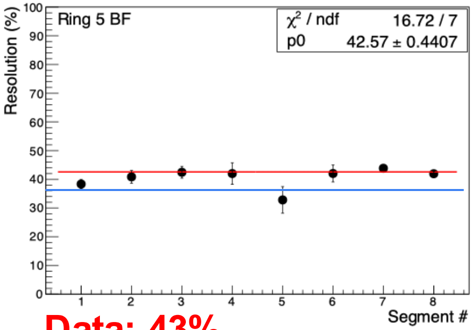
Resolution : Gsigma/MPV



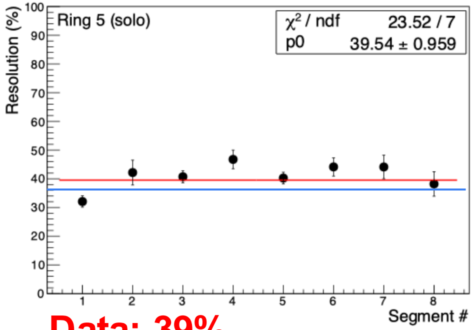
Data: 48%
MC: 46%



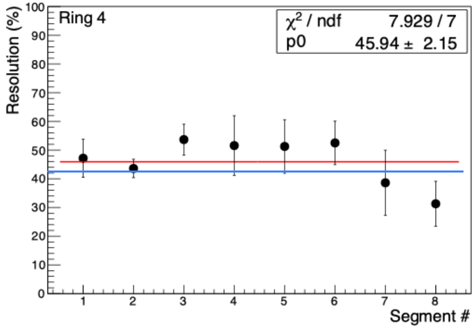
Data: 40%
MC: 37%



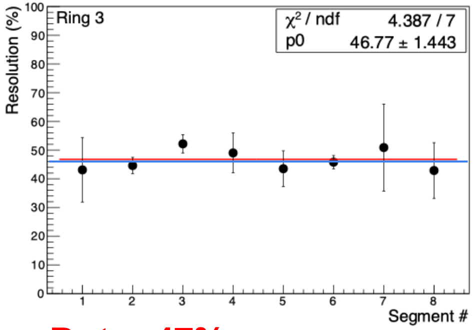
Data: 43%
MC: 37%



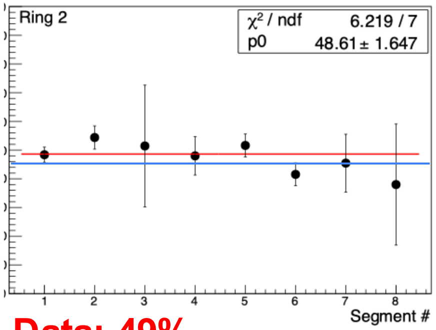
Data: 39%
MC: 37%



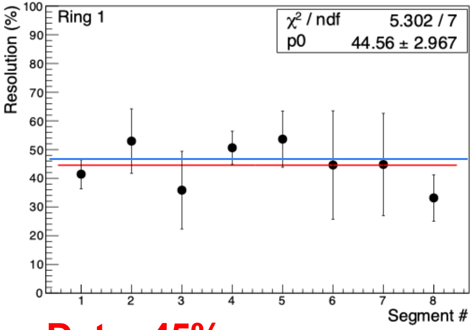
Data: 46%
MC: 43%



Data: 47%
MC: 46%



Data: 49%
MC: 46%



Data: 45%
MC: 47%

Red line : pol0 fit to the data Blue line : MC prediction (corrected for the fADC effect $\sigma_{WM}^2 = \sigma_{MC}^2 + \sigma^2$)

Cosmic data from the W&M stand : Summary (SEG 1 – SEG 8)

Ring	PE yield (MC)	Avg. PE yield (seg1-seg8) (Cosmic data)	Resolution % (MC)	Resolution % (MC corr. with fADC effects)	Avg. Resolution % (seg1-seg8) (Cosmic data)
1	16.3 (± 0.4)	16.1 (± 0.9)	~ 29 (± 1.4)	~ 47 (± 1.4)	~ 45 (± 3.0)
2	14.8 (± 0.1)	15.5 (± 0.9)	~ 30 (± 1.4)	~ 46 (± 1.4)	~ 49 (± 1.6)
3	18.1 (± 0.2)	17.8 (± 1.0)	~ 36 (± 1.2)	~ 46 (± 1.2)	~ 47 (± 1.4)
4	13.2 (± 0.1)	15.4 (± 0.8)	~ 27 (± 0.8)	~ 43 (± 0.8)	~ 45 (± 2.0)
5 FF	23.6 (± 0.1)	23.2 (± 1.2)	~ 30 (± 0.9)	~ 37 (± 0.9)	~ 40 (± 1.3)
5 BF	23.6 (± 0.1)	24.3 (± 1.3)	~ 30 (± 0.9)	~ 37 (± 0.9)	~ 43 (± 0.4)
5 (solo)	23.6 (± 0.1)	24.6 (± 1.3)	~ 30 (± 0.9)	~ 37 (± 0.9)	~ 39 (± 1.0)
6	17.4 (± 0.1)	17.5 (± 0.9)	~ 35 (± 0.7)	~ 46 (± 0.6)	~ 48 (± 0.5)

Consistent results in terms of PE yield and resolution for the production modules (Seg 1 through Seg 8) tested at W&M with cosmic muons

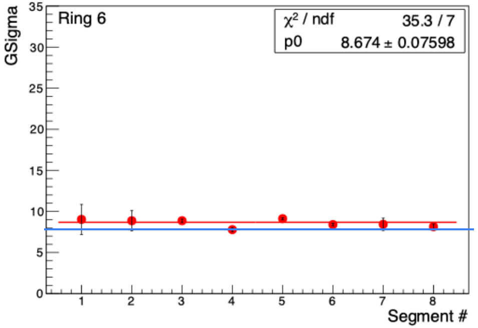
Summary

- The overall PE yield agreement between the data and the MC prediction on average is within ~ 15%
- The MC predicted resolution values after including the fADC affects also agrees well with the W&M cosmic data on an average within ~ 20%
- The following details for each of the segments under cosmic testing are being documented (DocDb)
  - ➢ Information on the segment plate (sagging measurement, quartz tile positioning measurement, production module mapping to the segment)
  - ➢ PMT (+base) & Ring combination, HV & LV settings for the individual rings & the event mode PMT gain
  - ➢ PE (Langau fitted) spectra, path of the data file (raw & analysed), DAQ configuration and analysis scripts

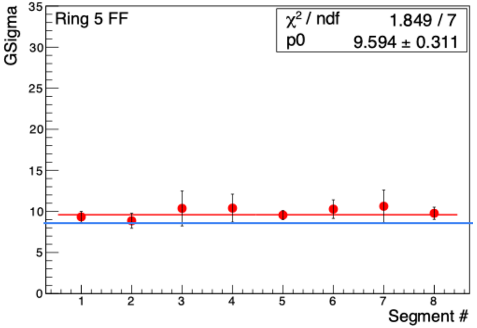
Thank You For Your Attention!!!

Backup

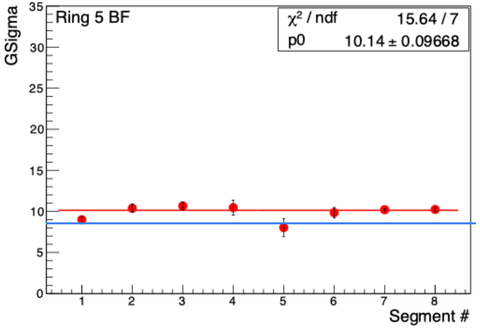
Cosmic data from the W&M stand : GSigma (SEG 1 – SEG 8)



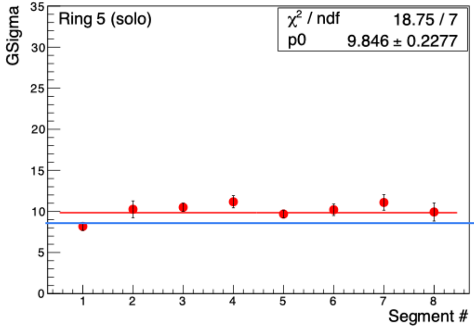
R6: Data : p0 -> 8.7
MC prediction : 8.0



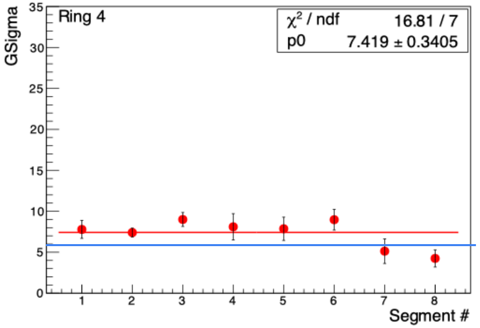
R5 FFs: Data : p0 -> 9.6
MC prediction : 8.7



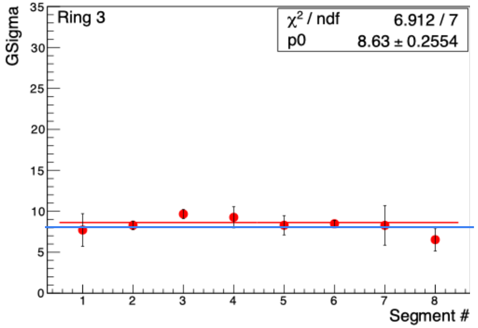
R5 BF: Data : p0 -> 10.1
MC prediction : 8.7



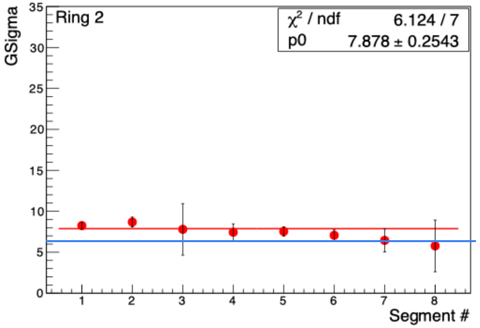
R5 (solo): Data : p0 -> 9.8
MC prediction : 8.7



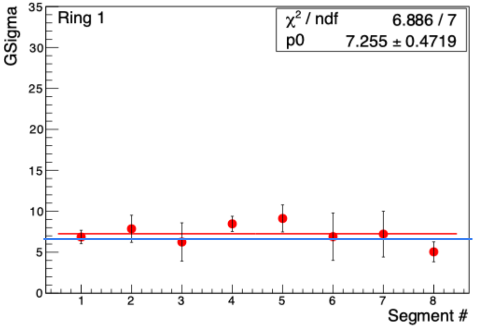
R4: Data : p0 -> 7.4
MC prediction : 6.2



R3 : Data : p0 -> 8.6
MC prediction : 8.3



R2 : Data : p0 -> 7.9
MC prediction : 6.7



R1 : Data : p0 -> 7.3
MC prediction : 6.9

Red line : pol0 fit to the data   Blue line : MC prediction (corrected for the fADC effect $\sigma_{WM}^2 = \sigma_{MC}^2 + \sigma^2$)