NOvA Test Beam detector calibration

Technical Note

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July 6, 2023

Abstract

What is this about and what will I describe in here

Contents

1 Introduction

Why is Test Beam? "The idea, as with any test beam experiment, is to expose a detector to a beam of very well-characterized particles, so that we can improve our understanding our how the detector responds to such particles. We make use of upstream detectors to collect data on the beam particles before they interact in the NOvA detector. For example, we will be able to see what a 1 GeV proton actually looks like in our detector, without having to simulate it, and we can test how well we would have reconstructed the energy using our existing techniques. We may find we are able to make improvements to our tools to better match what we see in the detector with how we reconstruct it. Or we may find we already do a pretty good job. Either way, with a full cross-comparison like this, we can be more confident in our analysis of the data and reduce the level of uncertainty we consider are associated with the relevant measured quantities. Ultimately, the aim will be to reduce the level of uncertainty on the neutrino oscillation analyses and to make even better, more accurate measurements of the Standard Model."Why is Test Beam calibration done:

- To be able to directly compare TB to the standard detectors
- To be able to verify our calibration procedures using TB data
- To study the particle response as a function of energy
- To determine an energy resolution
- To compare currently used energy scales to data and understand if we can use TB data for absolute energy scale in all NOvA detectors

For DeltaM2: By increasing exposure, total syst. error decreases by (+) 18.5For sin2Th23: Difference by reducing calib syst.: (+) 10.8Statement: “The NOvA Test Beam will improve the total systema6c error on the final measurement of the oscilla6on parameters Dm232 and sin2Th23 by 10Potential Test Beam impacts: Check modeling of hadronic interacOons in detector (check GEANT systemaOcs), Using Test Beam data as “single-parOcle MC” to train CVN prong-like algorithms, GeneraOve Adversarial Networks for MC improvements using Test Beam data, Check ND calibraOon procedure to try and understand causes of 3-5

- Hadronic response and comparison with MC modeling
  - response as a function of energy
  - establishing of an absolute energy scale
  - determination of energy resolution
  - studies of topological features and resolution
    - pion tracking and showers
    - proton tracking and showers
  - studies of timing features and resolution
- Electromagnetic response and comparison with MC modeling
  - response as a function of energy

  - establishing of an absolute energy scale
  - determination of energy resolution
  - studies of topological features and resolution
    * electron signatures
    * gamma signatures
  - studies of timing features and resolution
  - studies of π^0 from π^- charge-exchange

- Muon response and comparison with MC modeling
  - comparison with detailed optical simulations
  - determination of energy resolution
  - studies of topological features and resolution
  - cross-talk studies
  - comparison to cosmic ray muons (requires a special trigger)
  - studies of the muon calibration protocol

- Light yield and response studies as a function of particle type and detector configuration
  - understanding the Cherenkov light contribution
  - vertical and horizontal responses and comparison with simulations
  - data with selected planes rotated by 45 and 90 degrees
  - slanted (angle) plane response (and subset of programs as above)
  - fiber attenuation studies
  - Birks' constant studies

- Near / Far readout comparison

- Gather large libraries of particles at known energies and multiple angles of incidence to help develop a CNN prong ID. Also allows training of a particle-based CVN-like PID.

Also use information from:

- NOvA Test Beam Technical Statement of Work
- NOvA Test Beam program (paper for DOE) [docdb:25074]
- NOvA Test Beam task force report [docdb:15750]
- Overview presentation of NOvA Test Beam [docdb:20495]
- Test Beam support document [docdb:22172]
- NOvA Test Beam program proceedings [docdb:55808]

Mike's proceedings from ICHEP 2020 [**?**].

2 Overview of the Test Beam detector

What is Test Beam, how does the detector and beamline look like. What are the main differences between the NOvA standard detectors and the Test Beam detector? Placed in MC7b together with a beamline instrumentation (no need to describe beamline). Get a picture of Test Beam.

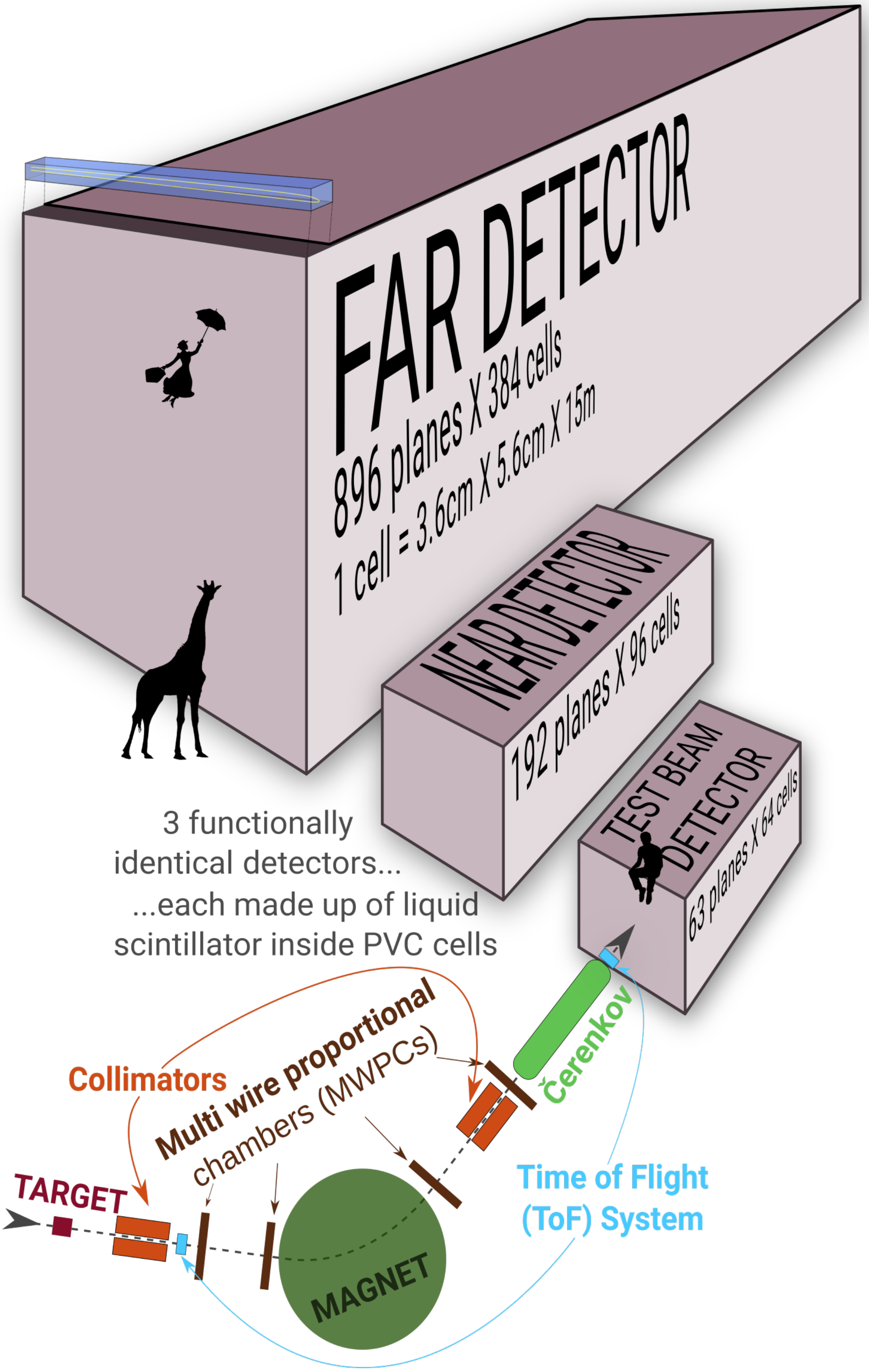


Figure 1: Comparison of Test Beam detector scale to other detectors (and a man, giraffe, or Mary Poppins).

General parameters

Smaller version of the standard NOvA detectors made up of 2 vertical and 2 horizontal modules, compared to XxY, or XxY for ND and FD respectively. " This detector is identical in every way to the Near and Far Detectors but is scaled down, similar to how the Near Detector is a scaled down version of the Far Detector. It consists of 63 planes, and is constructed as a 2x2 module (c.f. ND is 3x3). The total mass is about 30 tons."63 planes, 32 vertical and 31 horizontal; 64 cells in a plane (2x32 extrusions), readout out in two 32 cell groups; FD: maxPlane=900, maxCell=390. ND: maxPlane=220, maxCell=100. TB: maxPlane=63, maxCell=64 Detector block taken from NDOS, which had only 31 planes [docdb:28943], beginning and ending with a vertical plane. During comissioning of Test Beam, glued in a horizontal plane in between the two block. [docdb:29543]

Describe the orientation of axes. What's right and left, what's positive and negative w, which planes are vertical and which horizontal (vertical are even starting at 0 and ending in 62 and horizontal are odd).

Readout for the horizontal planes on the opposite side compared to the standard NOvA detectors (why?). Causing underfilled cells in the middle and top of the detector, until... [docdb:49827] Describe orientation and readout of the TB detector. Mention the two surveys and the alignment troubles.

Scintillator

Scintillator oil (5600 gallons in total [from Detector Information wiki]) used from ND+NDOS and spare from Texas in the back of the detector (plus some from Ash River afaik). Block 0 filled with ND+NDOS scintillator oil kept in the tanker [docdb:37152]. Found out the rest of the scintillator in the tanks in Fermilab is contaminated and unusable [docdb:38349] and used NDOS oil from barells to top off horizontal modules. Shipped scintillator from Ash River and filled the first 21 planes of Block 1 [docdb:41961]. Last 10 planes filled with the NDOS-drained oil from Texas [docdb:34046 describing Texas oil and docdb:41961 showing final filling state]. Maybe show a plot of response at cell centre and mark the 3 different scintillators.

Readout

Same readout electronics as in the Far Detector, except for 8 Near Detector Front End Boards, 4 in planes ... (1st quarter of the detector) and another 4 in planes ... (3rd quarter of the detector). "The Near Detector (ND) and Far Detector (FD) use different versions of the front-end electronics (FEBs, front-end boards), designed to be able to collect data at different rates (the ND is a higher-rate environment than the FD since it is much closer to the beam source). The FD uses FEBv4s (i.e. version 4) and the ND uses FEBv5s. The Test Beam detector uses both in order to be able to make comparisons and validate both versions of the electronics. Most of the FEBs on the Test Beam detector are v4s; of the 126 total, 118 are v4 and 8 are v5."

Environment

Placed in the Fermilab Test Beam Facility with no overburden. Describe environmental controls, temperature dependence etc. Maybe add plots from environmental control (temperature differences etc.) with descriptions of where were the readings taken.

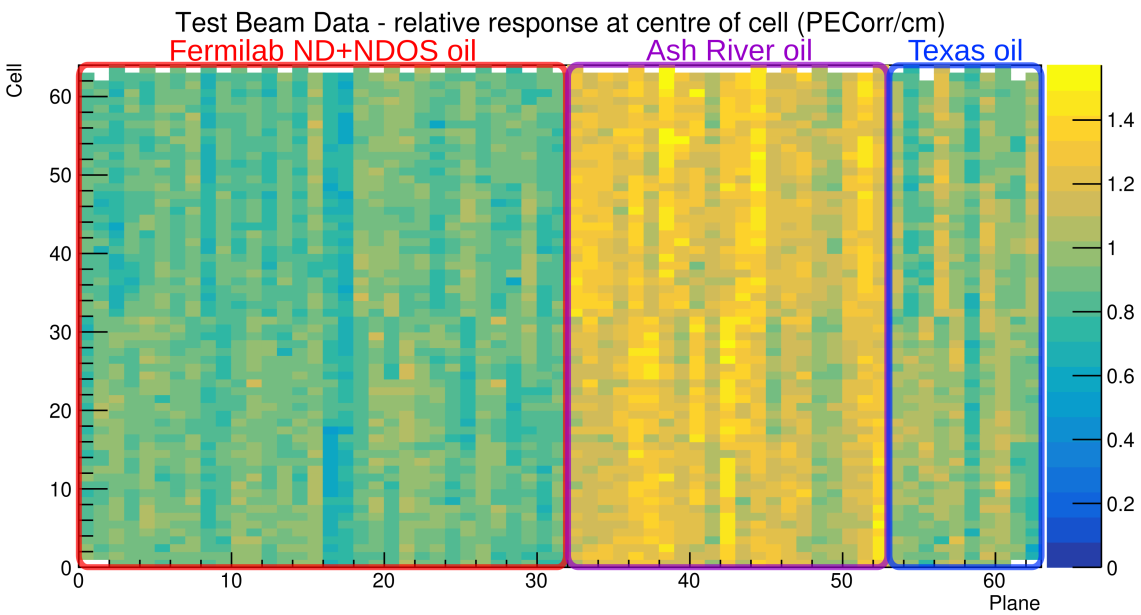


Figure 2: Uncorrected energy response in the centre of cells across the Test Beam detector showing a clear distinction between the different scintillator oils.

3 The NOvA calibration process

Describe the NOvA calibration procedure in general. Describe the benefit of NOvA Test Beam and differences.

Attenutation profiles have a constant binnin fNBins=100 (in w), same for ND, FD and TB. This results in an effectively finer binning for TB compared to ND and FD. For FD w = (-900,+900), ND: (-250,+250), TB: (-150,+150). TB: 3cm/bin, ND: 5cm/bin, FD: 18cm/bin. What effect could this have on the relative calibration results? Particularly on the calibration shape?

3.1 Creating calibration samples

How do we create the calibration samples and what cuts are applied?

Tricell condition

3.2 Calibration uncertainties

4 NOvA Test Beam detector calibration

4.1 Overview

History of TB calibration. What led to the final version of TB calibration. What can be done next.

Dates and times when the data taking occured.

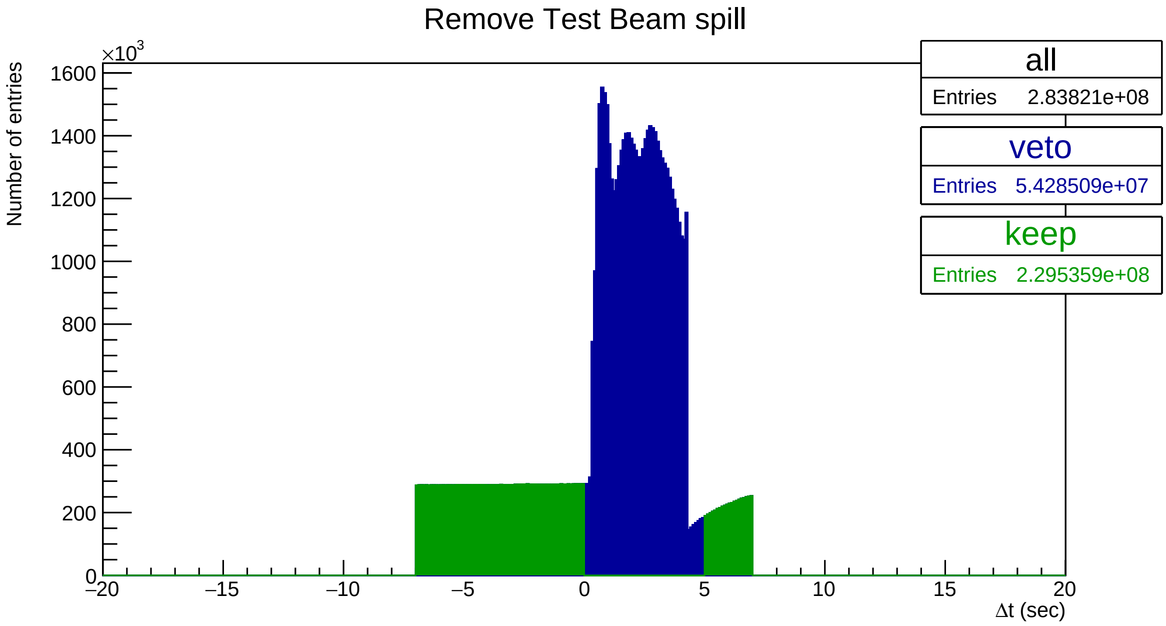


Figure 3: Test Beam beam spill events removed from the calibration samples. Test Beam beam spill is 4.2 seconds long and we remove events (in blue) within a 5 seconds window from the start of the beam spill. The remaining events (green) should mostly consist of cosmic particles. This example and the numbers of entries are for the full period 4 Test Beam sample.

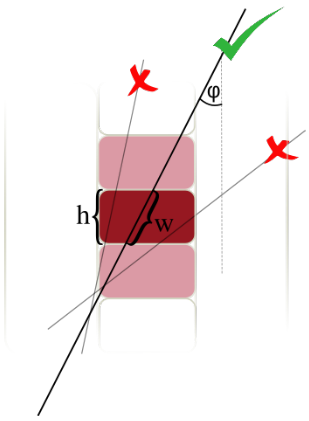


Figure 4: Illustration of the tricell condition. We only use hits that have two surrounding hits in the same plane to be used in the NOvA calibration. This is to ensure a good quality of the pathlength (w) reconstruction, which is calculated from the known cell height (h) and the reconstructed track angle (φ).

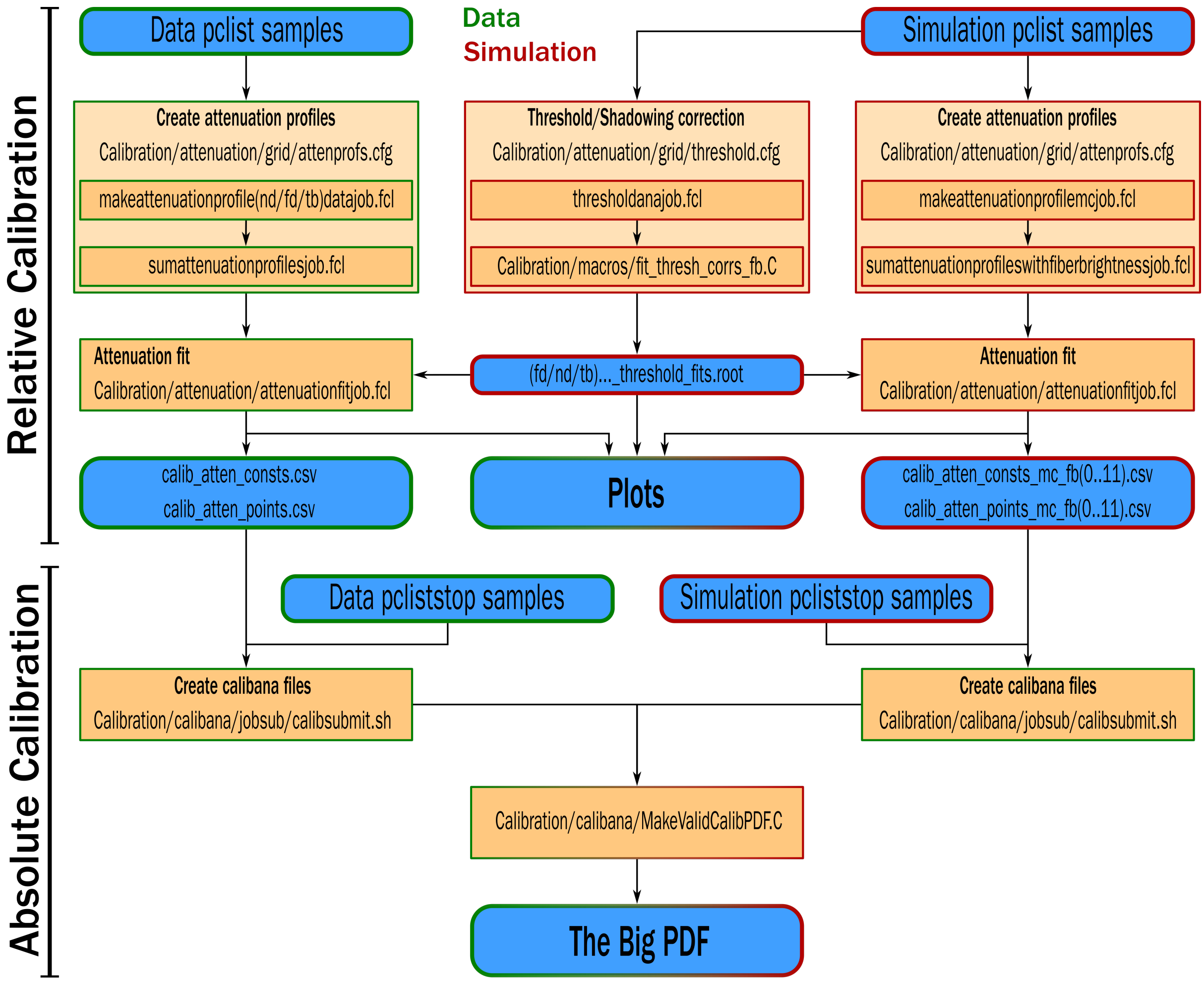


Figure 5: Flow chart showing the jobs (orange background) and files (blue background) needed and produced during the full NOvA calibration process. The left chain is showing the data calibration process (with green border) and is applied to every data calibration sample separately (periods or epochs). The center and right chains are showing the simulation calibration proces, which is redone only if there's a change to the detector simulation. The absolute calibration at the bottom combines data and simulation. The entire process is done separately for each NOvA detector.

Period naming, possibly epochs (for P3). List of data samples, plus MC samples that were used and pointer to the data-based simulation technote.

Specific running conditions: Underfilled cells Faulty FEBs (Period 2 and Period 3) Why do we do the calibration generally and why do we need to do in for Test Beam specifically

Temperature study (small overview)

4.1.1 Definitions

List all final data and simulation definitions used.

4.2 Detector Brightness

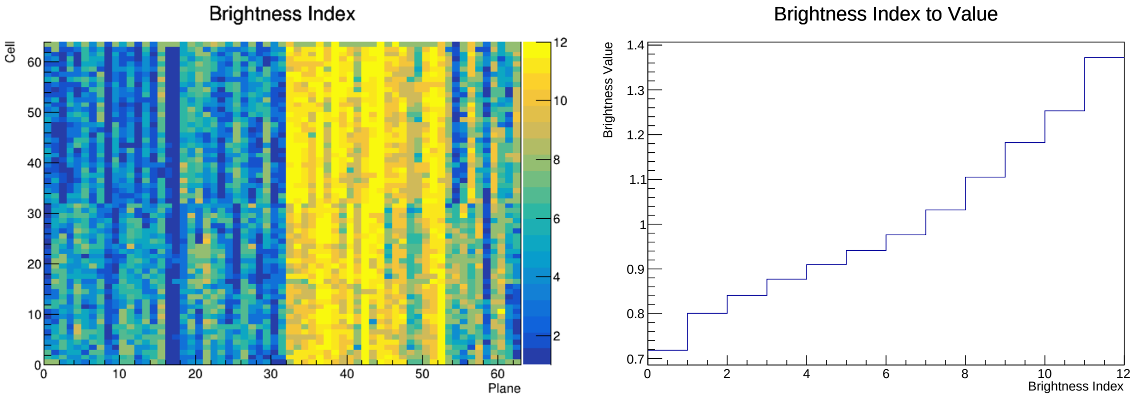


Figure 6: The Test Beam detector is (like the standard NOvA detectors) divided into 12 brightness bins (left plot), each representing a relative difference in energy response (right plot) due to different brightnesses of the fibers, scintillators, or readout.

4.3 Simulation

We originally used Teresa's calibration MC sample, but after we saw disagreement, we developed a new MC based off of the period 3 data, which we ended up using for both period 2 and period 3. For fibre brightness we are also using the same MC from period 3 data as it represents the detector in its best condition.

We used a data-based simulation of cosmic muons for the Test Beam detector calibration. The details are described in the technote XXX. We used this and this data as a basis and this and this data for the fiber brighness file.

4.3.1 Relative calibration results

4.4 Period 1

Only a month of data, only first half of detector filled, primary/secondary beam halo, or oversaturation leading to FEB shutoffs [docdb:38349 and 41331]. Only used for comissioning, not used for any data analysis or calibration.

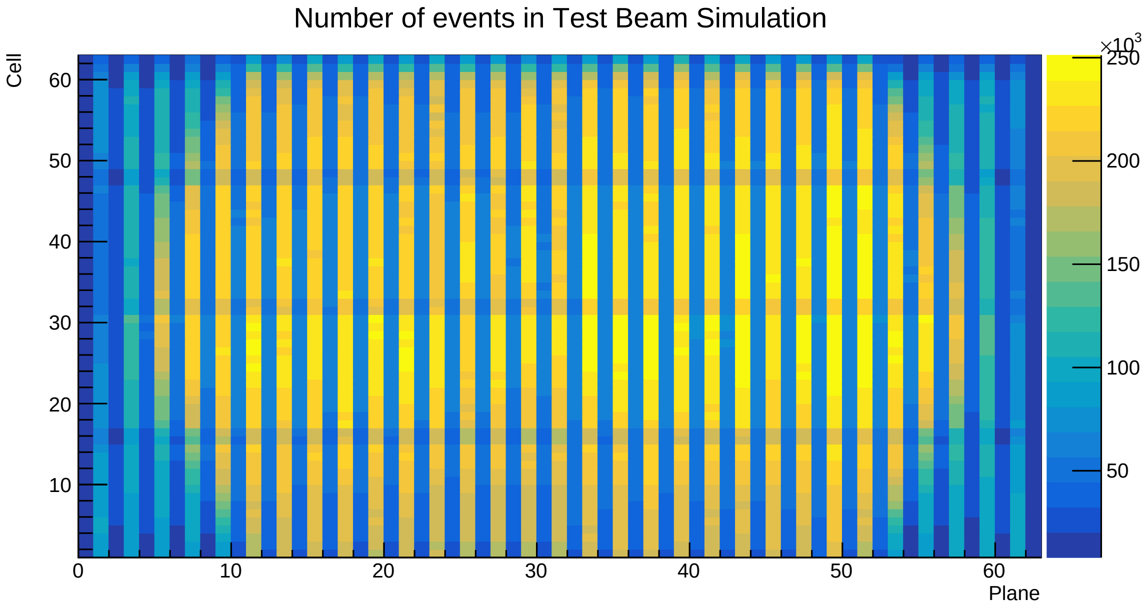


Figure 7: Distribution of events in the Test Beam simulation calibration sample.

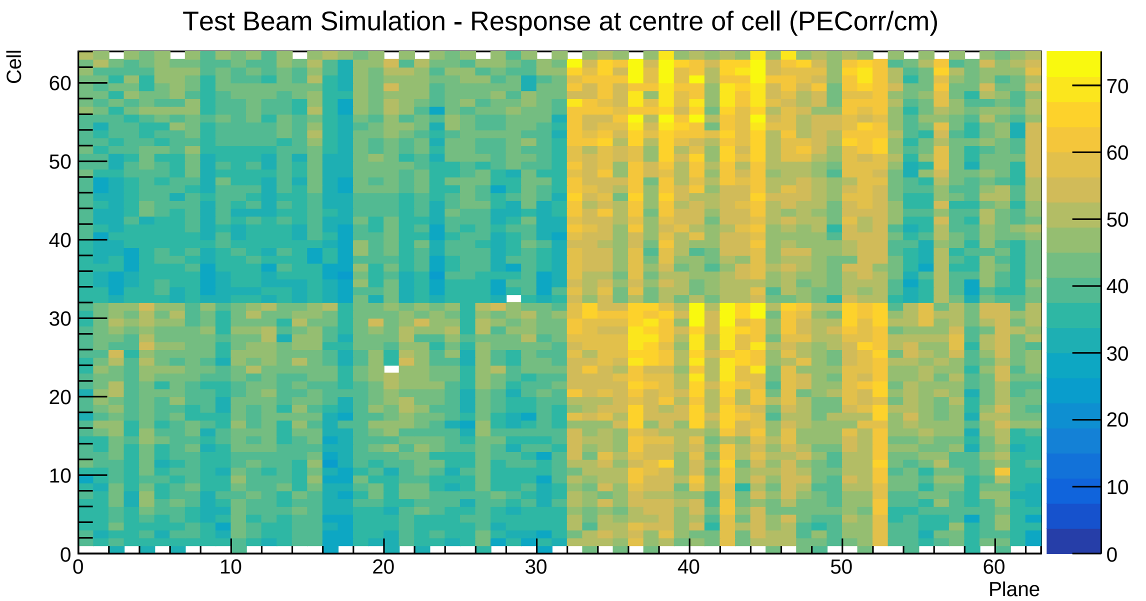


Figure 8: Overview of the relative calibration results for the Teast Beam detector simulation. Each cell is represents the average corrected energy response (in PECorr/cm) in the centre of each cell. The blank cells are uncalibrated.

4.5 Period 2

What was done for the period 2 tb calibration, short overview of what has been done: test beam data were calibrated all at the same time without splitting them to separate epochs. See figures 10,11 and 12.

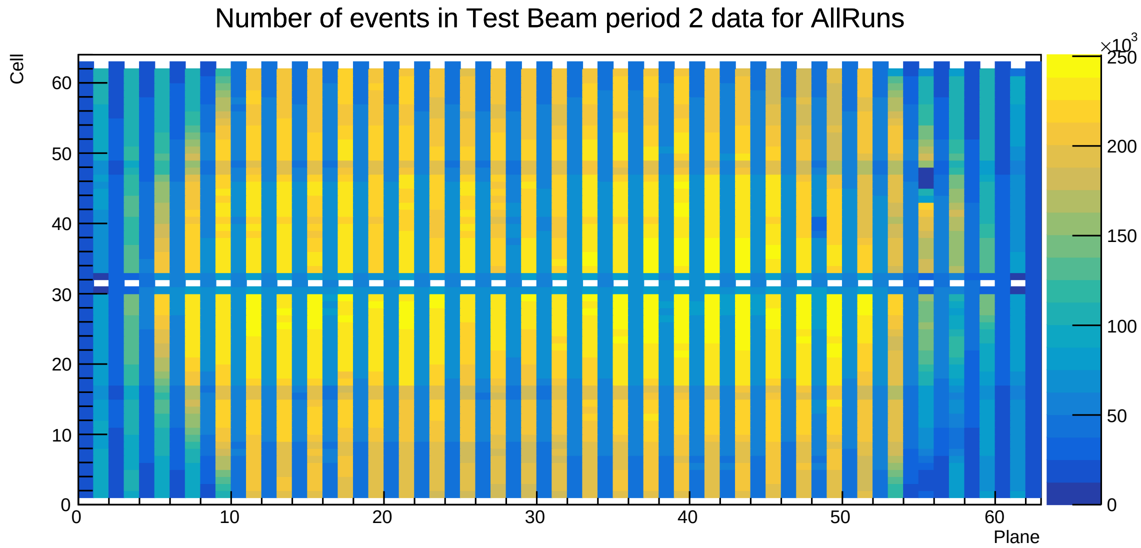


Figure 9: Distribution of events in the period 2 Test Beam data calibration sample.

4.5.1 Relative calibration results

4.6 Period 3

Separation of Period 3 data into different epochs based on the running conditions (include plot of the running conditions). We are separating data into pre- and post- filling states. We're using only the fully-refilled post-FEB swap data from period 3 as a basis for the simulation creation.

4.6.1 Relative calibration results

Combined epochs 3a, 3b and 3c

Combined epochs 3d and 3e

4.7 Period 4

4.7.1 Relative calibration results

4.8 Absolute calibration results

Standard absolute calibration cuts: track window, flat-response W, positive pe, pecorr, and pathlenght reco

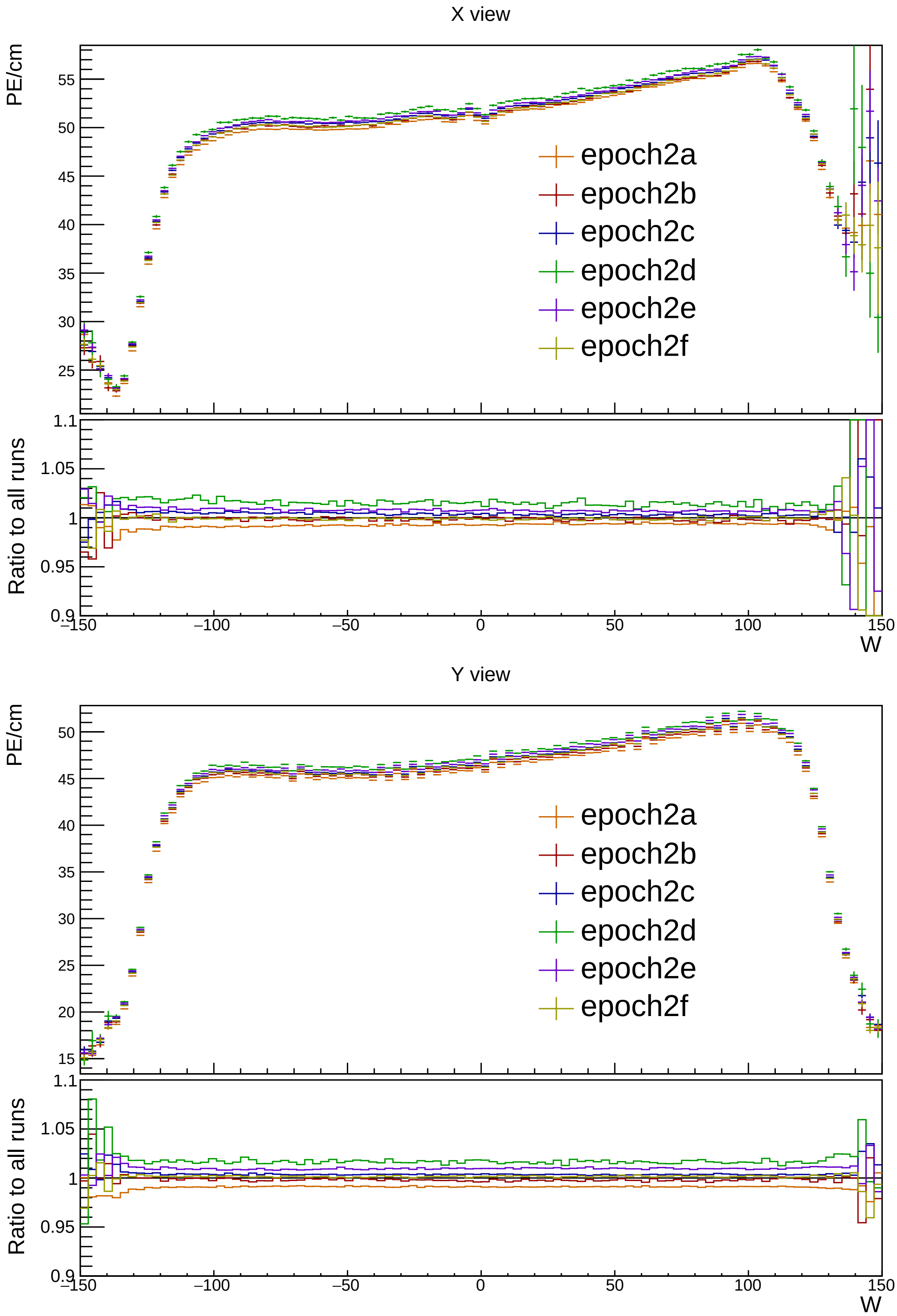


Figure 10: Uncorrected average energy response as a function of the position within a cell (w) for epochs in period 2. It is clear that there is no significant difference between the various epochs.

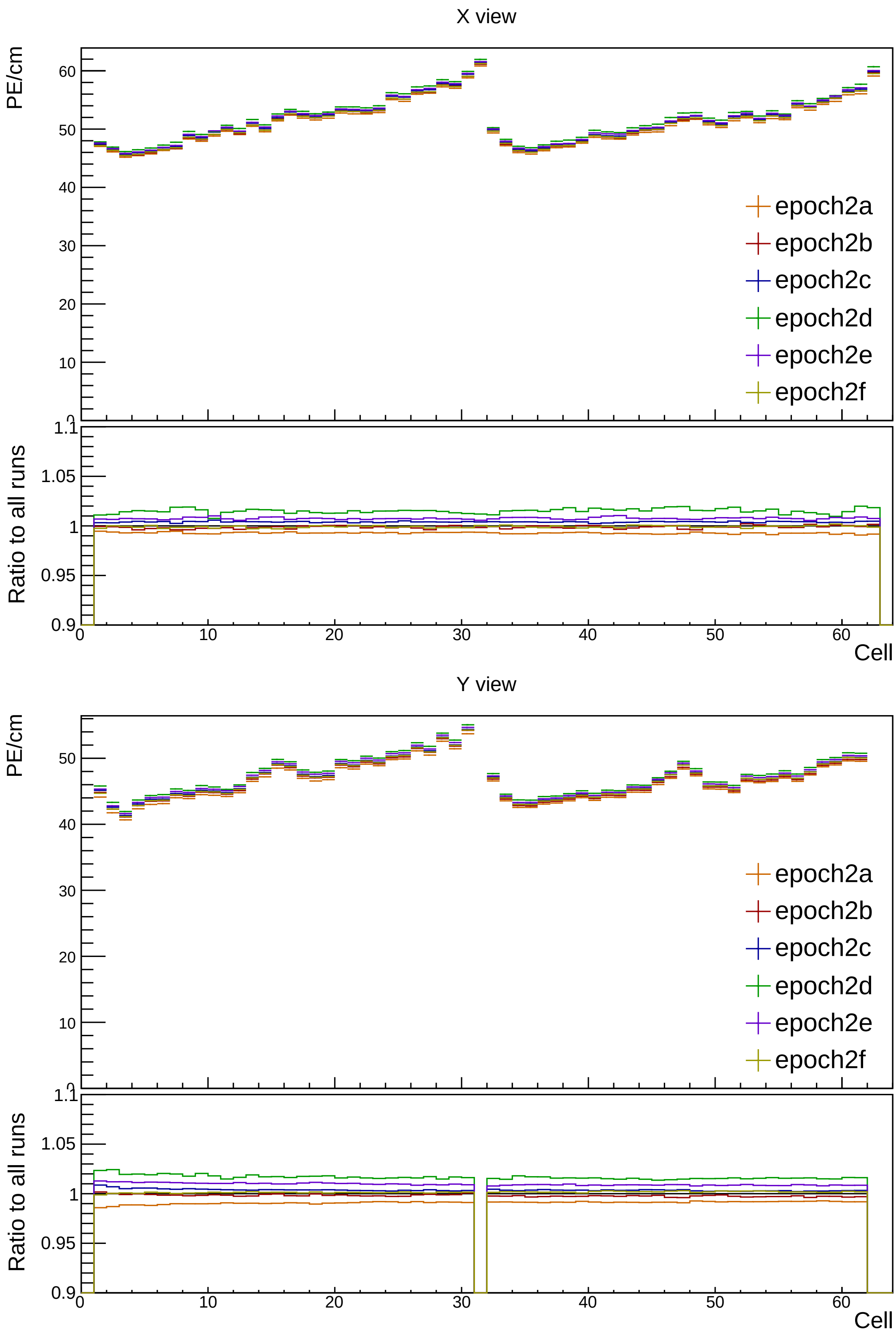


Figure 11: Uncorrected average energy response as a function of cells for epochs in period 2.

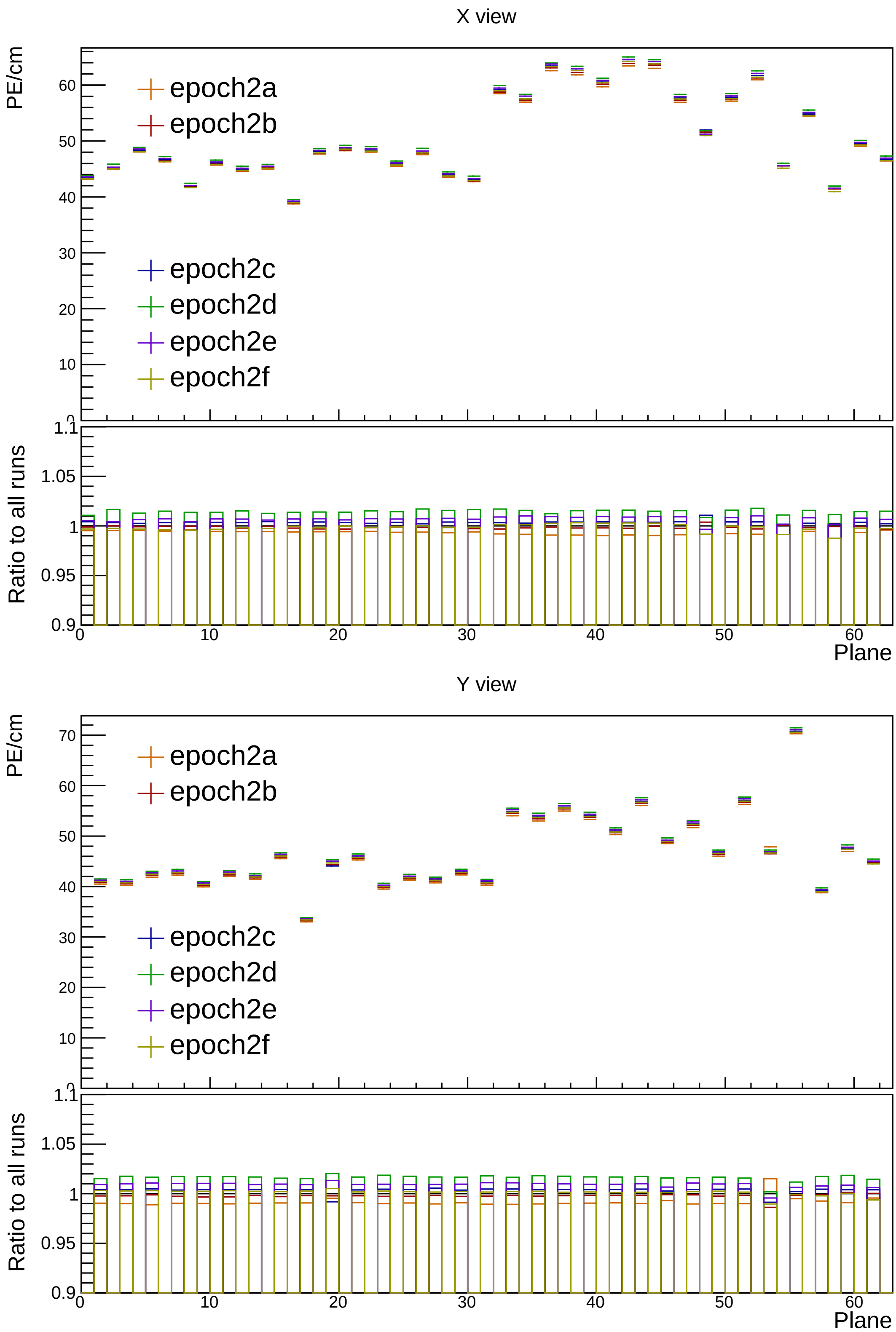


Figure 12: Uncorrected average energy response as a function of planes for epochs in period 2.

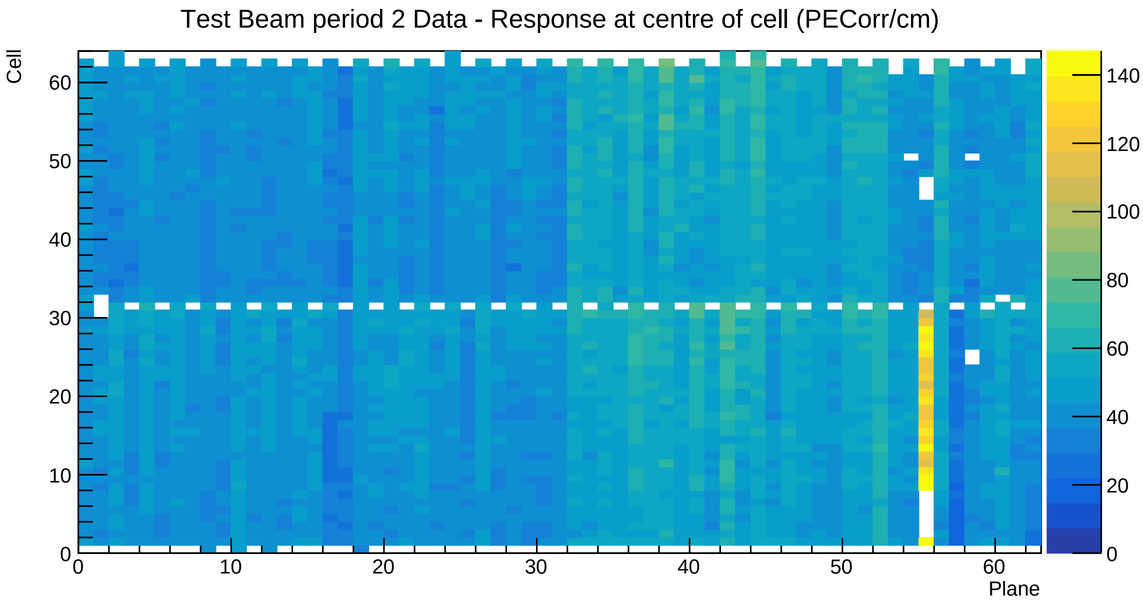


Figure 13: Overview of the relative calibration results for the Teast Beam detector period 2 data. Each cell is represents the average corrected energy response (in PECorr/cm) in the centre of each cell. The blank cells are uncalibrated.

Sample	NHits*x*	MEU*x*	NHits*y*	MEU*y*	MEU	MEU Err	TrueE/dx	tE/dx Err
tb data ep3a	2.638e+05	38.49	1.621e+06	39.4	38.94	0.006758	1.772	0.000238
tb data ep3d	1.049e+05	38.63	6.725e+05	39.42	39.02	0.01048	1.772	0.000238
tb data p2	2.322e+05	38.7	1.413e+06	39.4	39.05	0.007252	1.772	0.000238
tb data p4	5.268e+05	38.63	3.316e+06	39.4	39.01	0.004703	1.772	0.000238
tb mc	2.829e+05	40.17	1.842e+06	39.93	40.05	0.006418	1.772	0.000238

4.9 Drift in TB data

4.10 Results

Table of final results. Final CSVs are locate in the `/nova/ana/testbeam/calibration` and they have been included in the vXX.XX calibration tag.

Plots of absolute calibration results

4.11 Validation

Comparisons with older version of calibration and maybe with the FD and ND

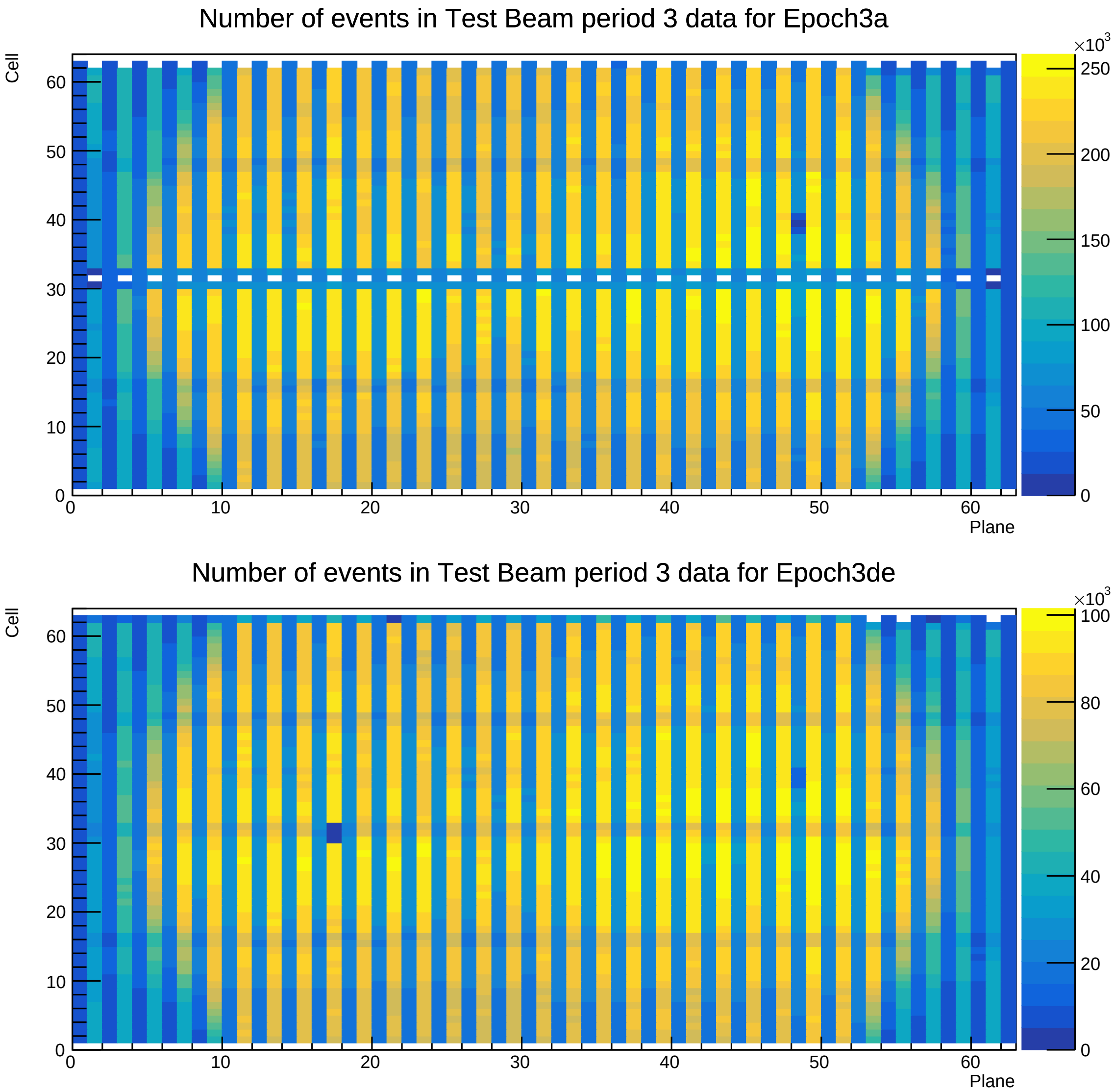


Figure 14: Distribution of events in the period 3, epoch 3a Test Beam data calibration sample.

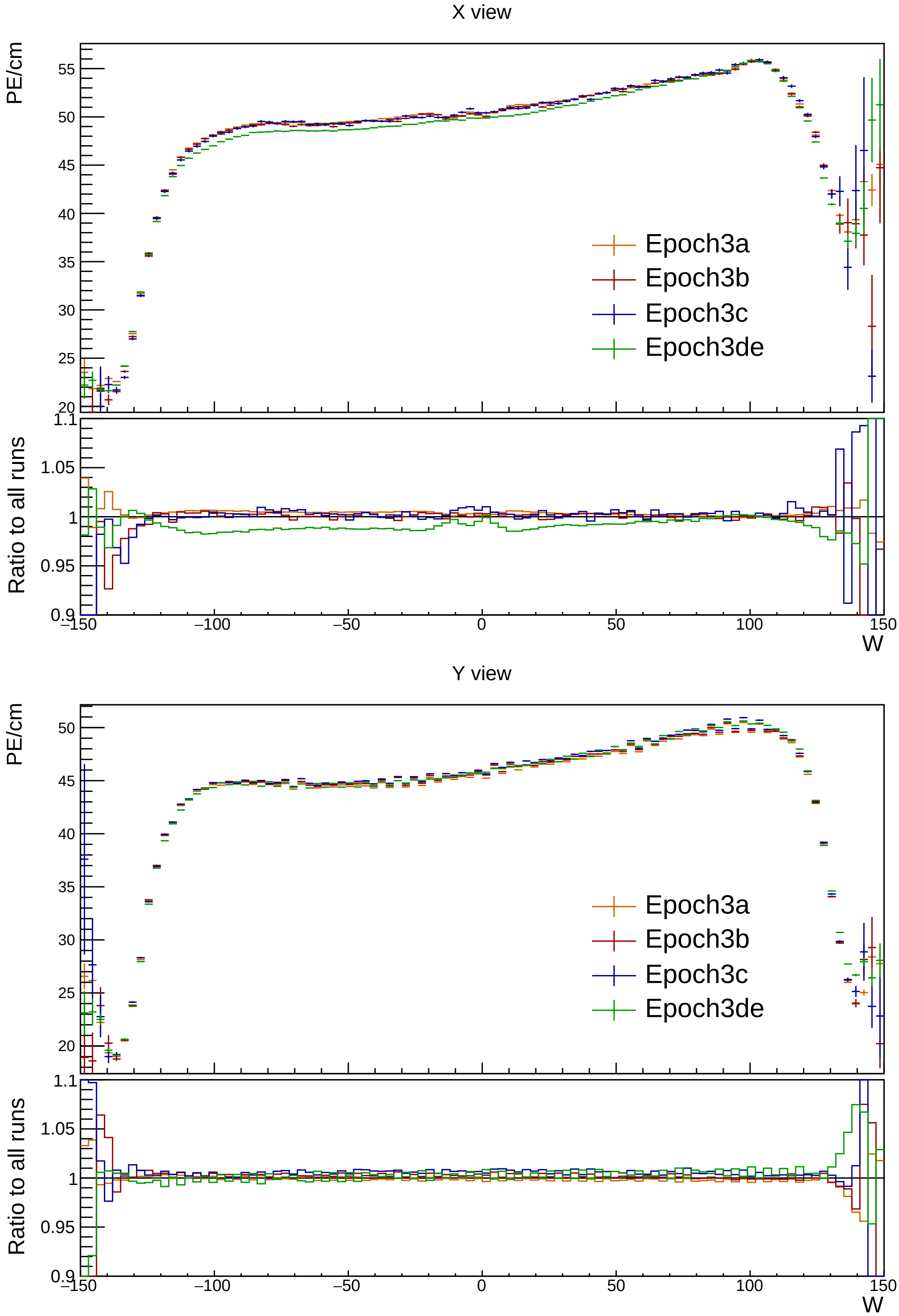


Figure 15: Uncorrected average energy response as a function of the position within a cell (w) for epochs in period 3.

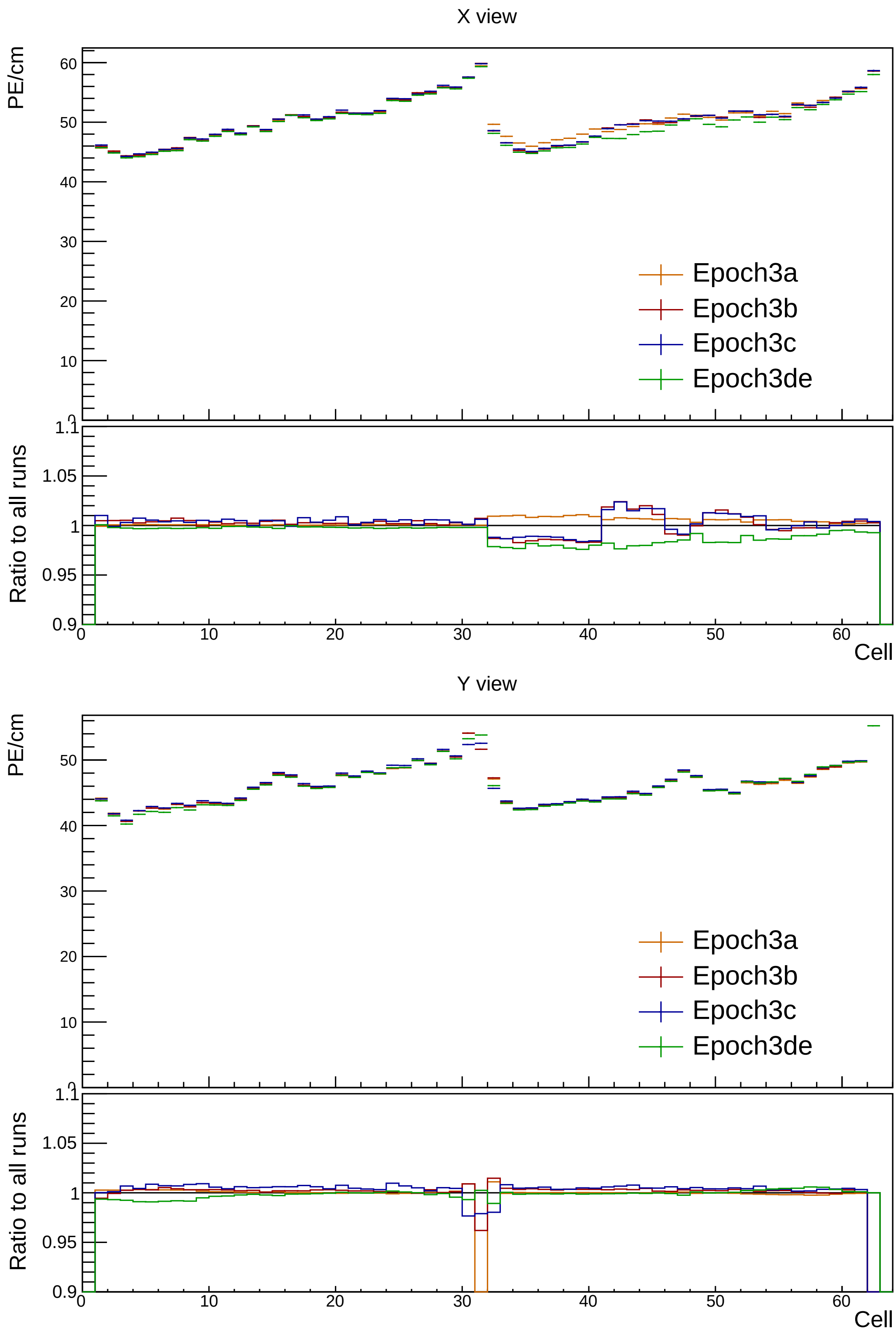


Figure 16: Uncorrected average energy response as a function of cells for epochs in period 3.

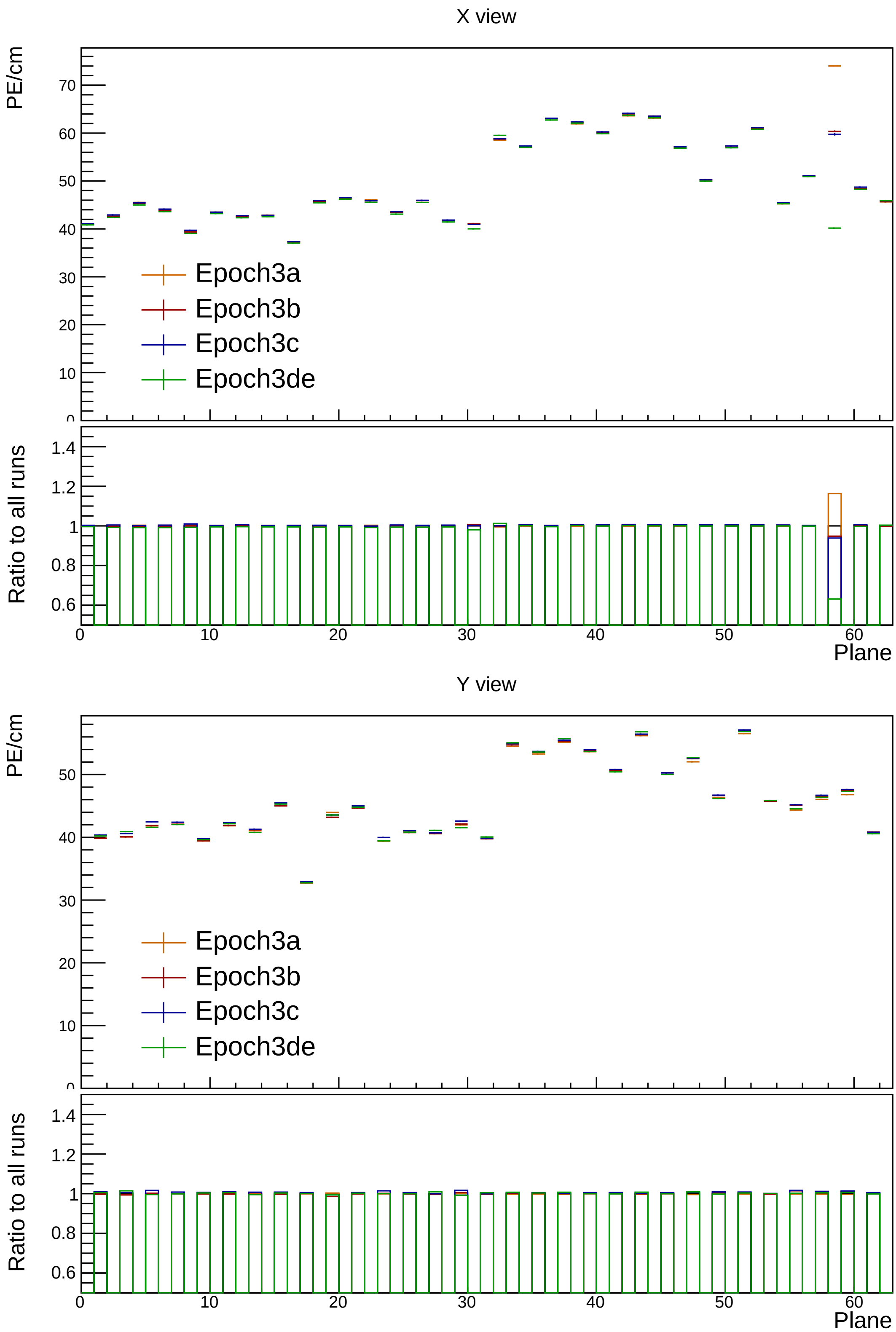


Figure 17: Uncorrected average energy response as a function of planes for epochs in period 3.

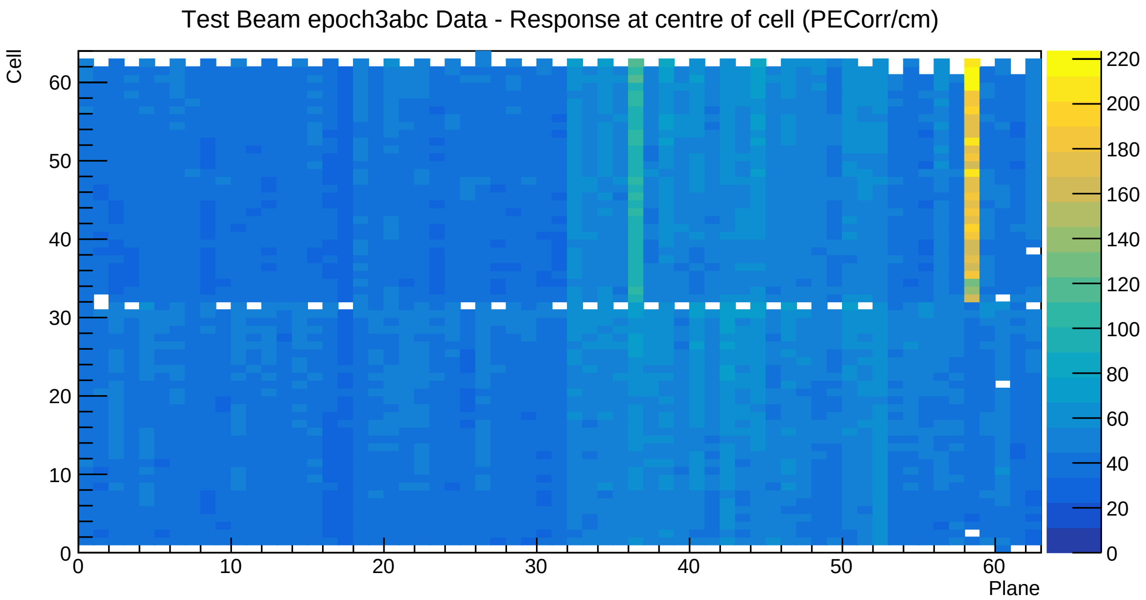


Figure 18: Overview of the relative calibration results for the Teast Beam detector period 3, combined epochs 3a, 3b and 3c data. Each cell is represents the average corrected energy response (in PECorr/cm) in the centre of each cell. The blank cells are uncalibrated.

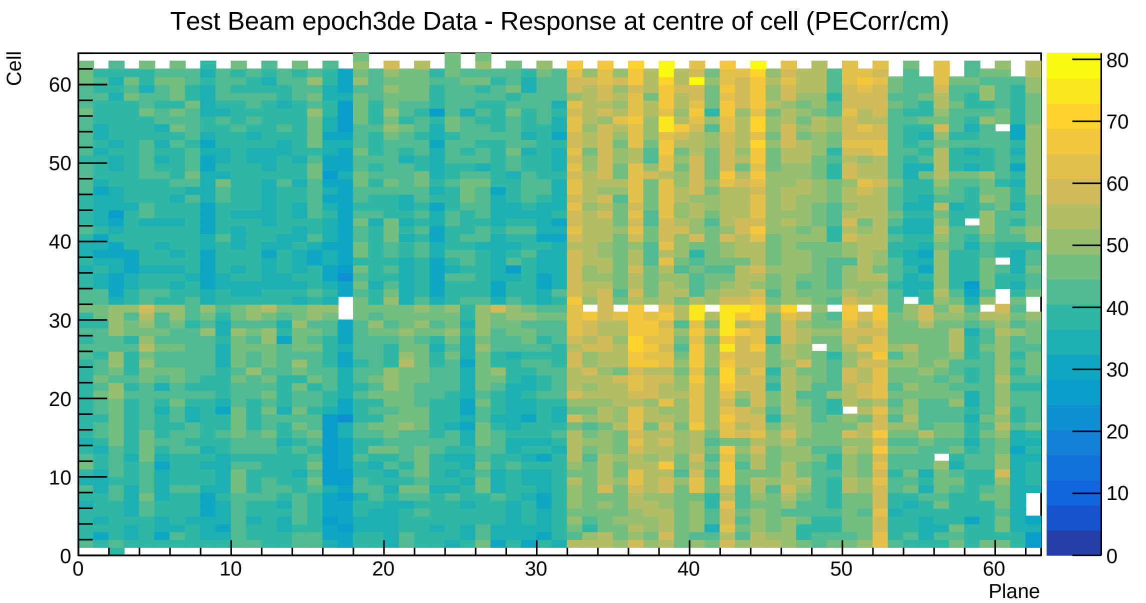


Figure 19: Overview of the relative calibration results for the Teast Beam detector period 3, combined epochs 3d and 3e data. Each cell is represents the average corrected energy response (in PECorr/cm) in the centre of each cell. The blank cells are uncalibrated.

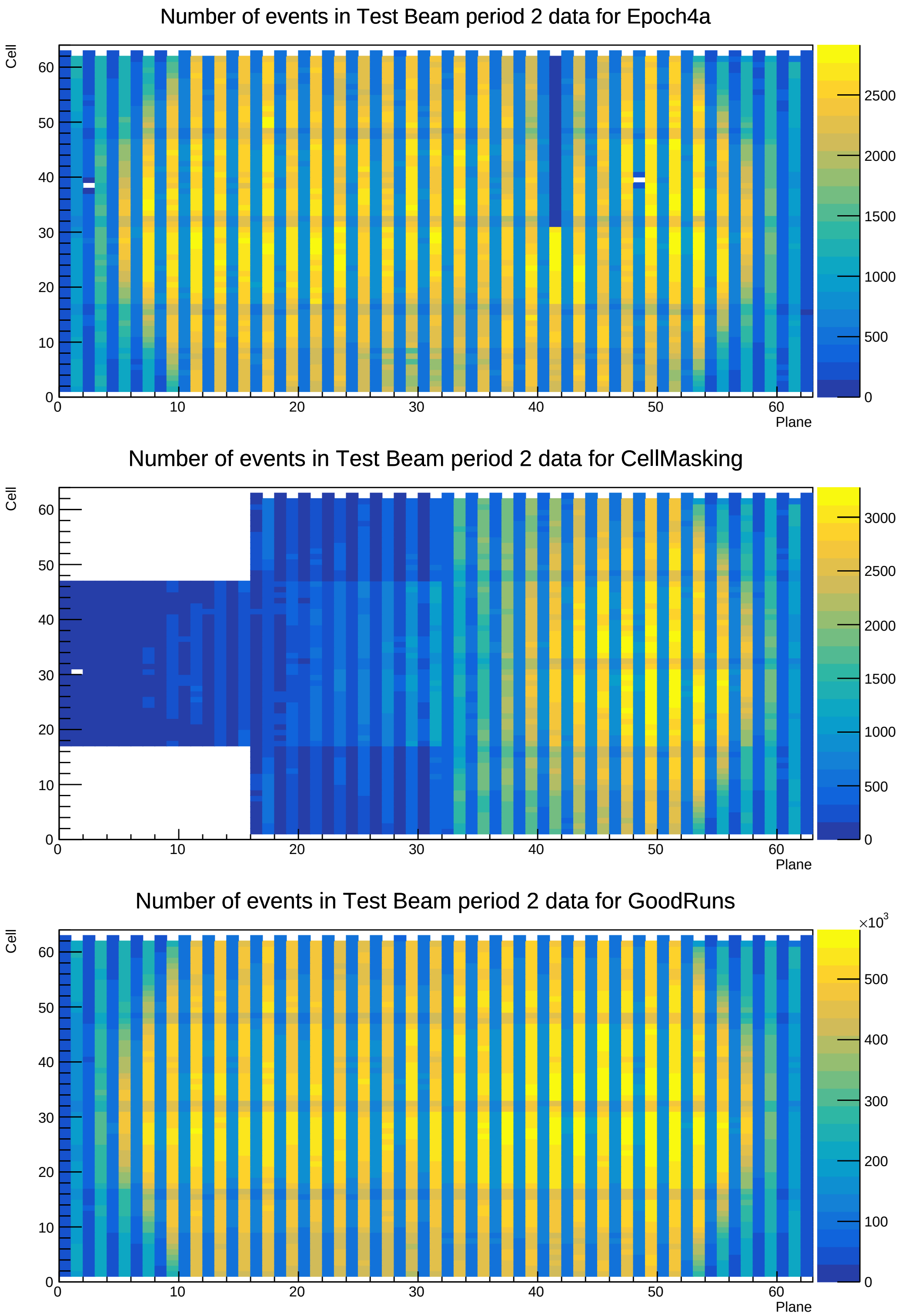


Figure 20: Distribution of events in the Test Beam period 4 data calibration sample. The top plot shows the first three comissioning runs, the middle plot the status of the detector during the Cell Masking studies and the bottom plot shows the rest.

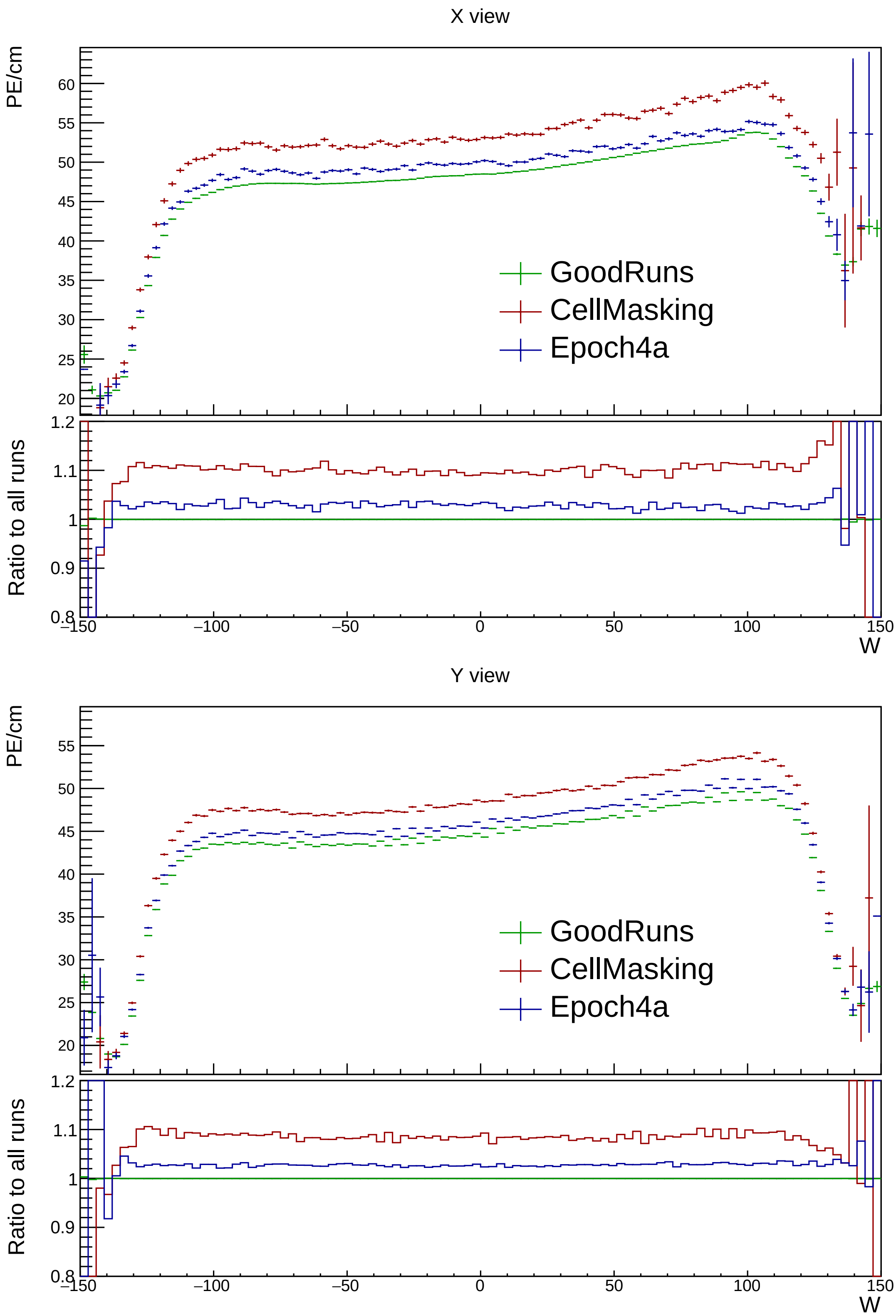


Figure 21: Uncorrected average energy response as a function of the position within a cell (w) for epochs in period 4.

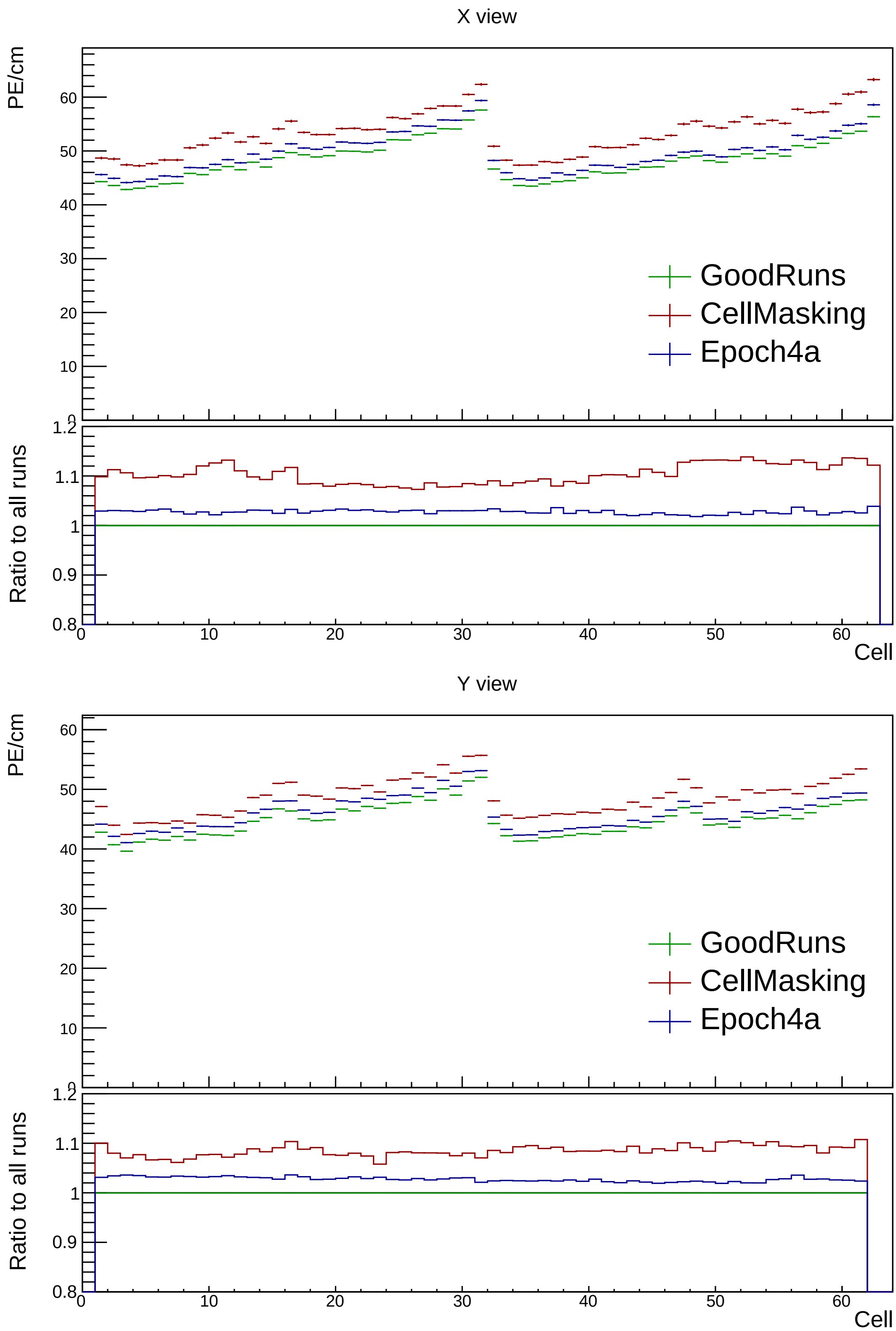


Figure 22: Uncorrected average energy response as a function of cells for epochs in period 4.

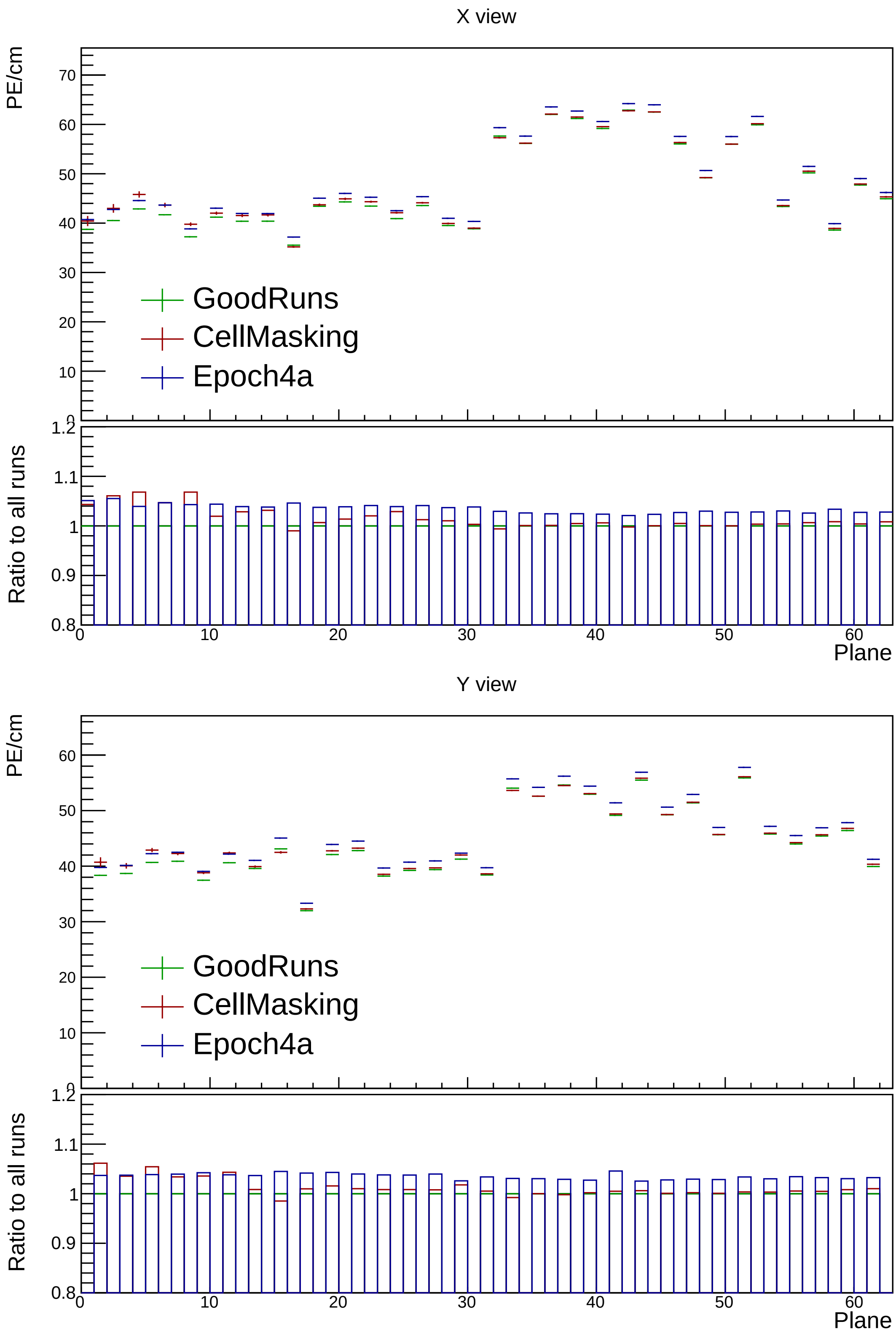


Figure 23: Uncorrected average energy response as a function of planes for epochs in period 4.

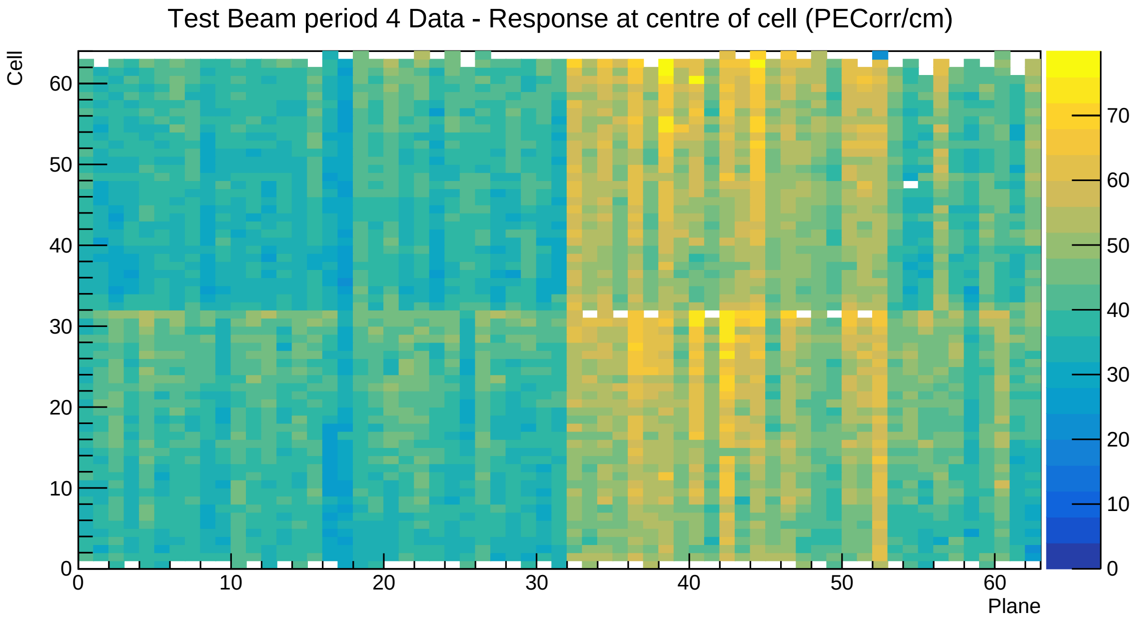


Figure 24: Overview of the relative calibration results for the Teast Beam detector period 4 data. Each cell is represents the average corrected energy response (in PECorr/cm) in the centre of each cell. The blank cells are uncalibrated.

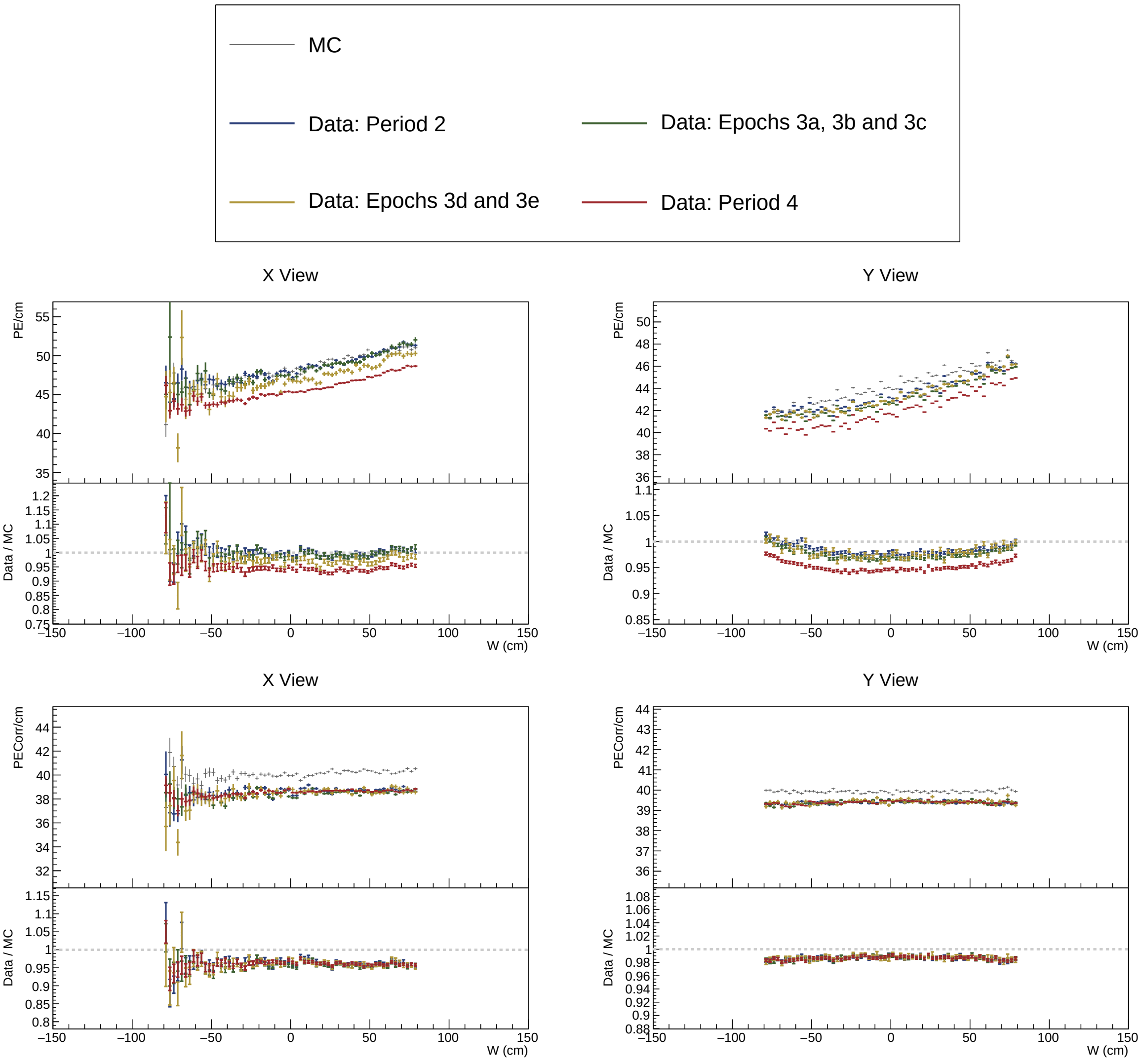

MC
Data: Period 2
Data: Epochs 3a, 3b and 3c
Data: Epochs 3d and 3e
Data: Period 4
X View
Y View
PE/cm
Data / MC
W (cm)
X View
Y View
PECorr/cm
Data / MC
W (cm)

Figure 25: ...

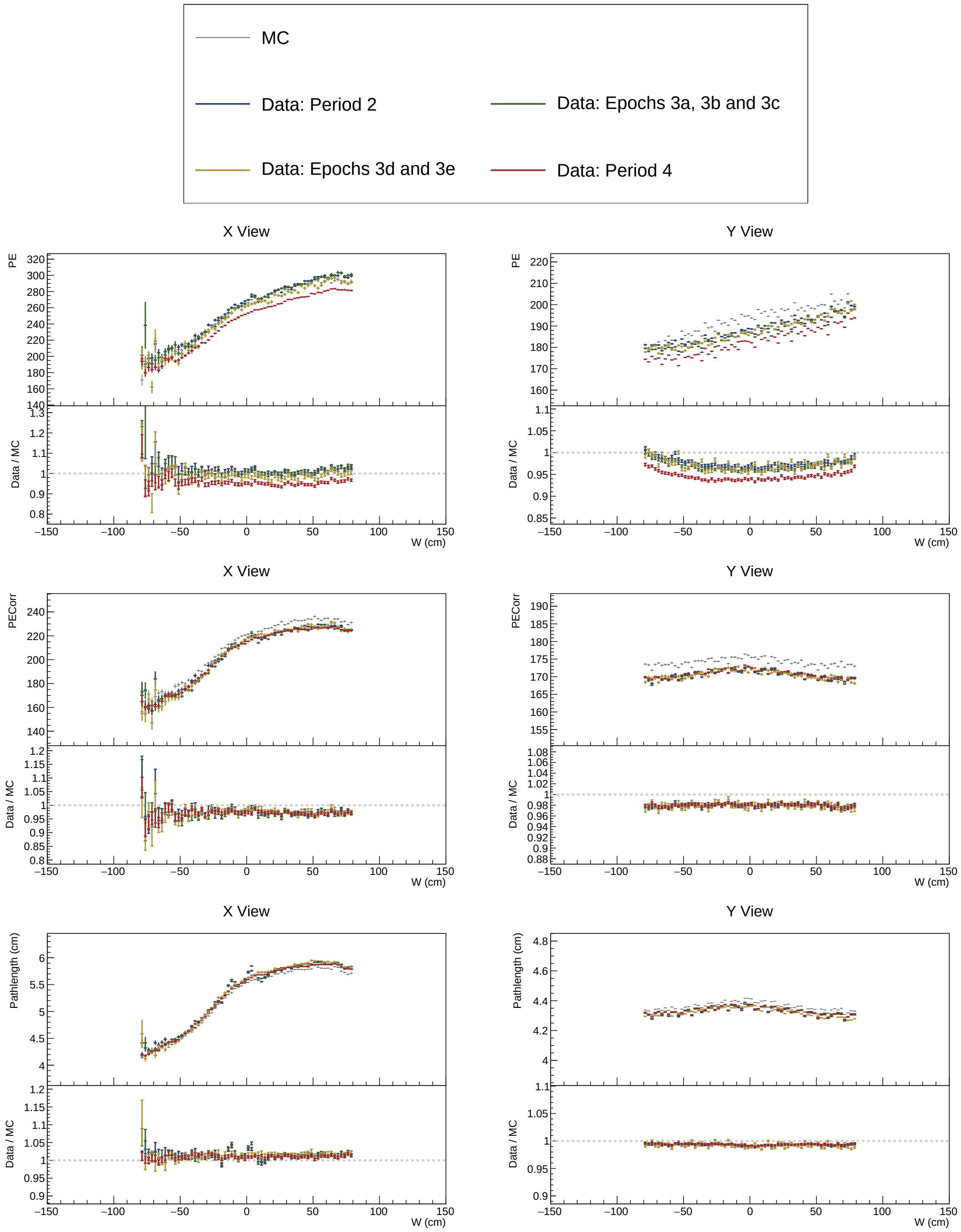

MC
Data: Period 2
Data: Epochs 3a, 3b and 3c
Data: Epochs 3d and 3e
Data: Period 4
X View
Y View
PE
PECorr
Pathlength (cm)
Data / MC
W (cm)

Figure 26: ...

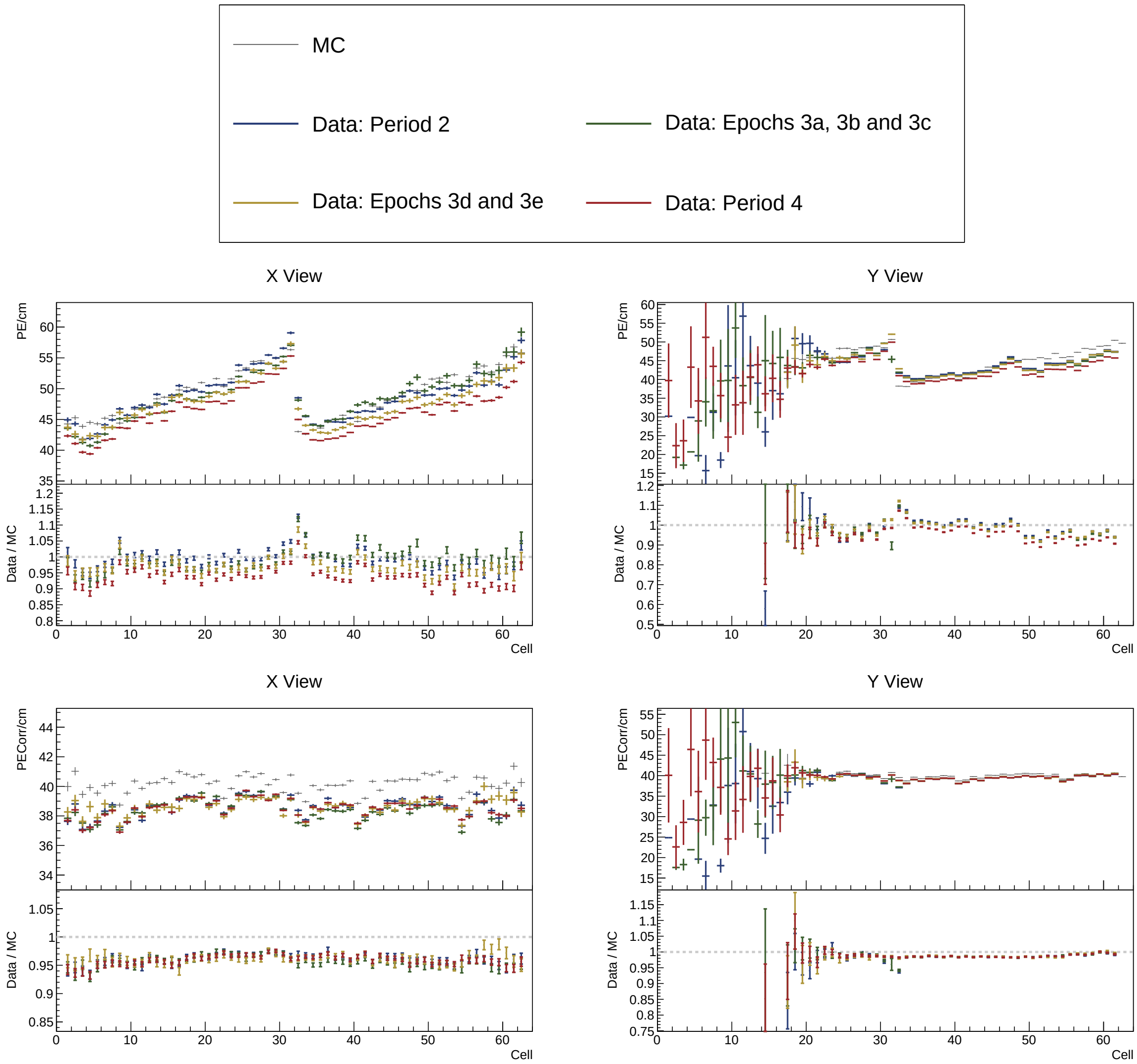

MC
Data: Period 2
Data: Epochs 3a, 3b and 3c
Data: Epochs 3d and 3e
Data: Period 4
X View
Y View
PE/cm
Data / MC
Cell
X View
Y View
PECorr/cm
Data / MC
Cell

Figure 27: ...

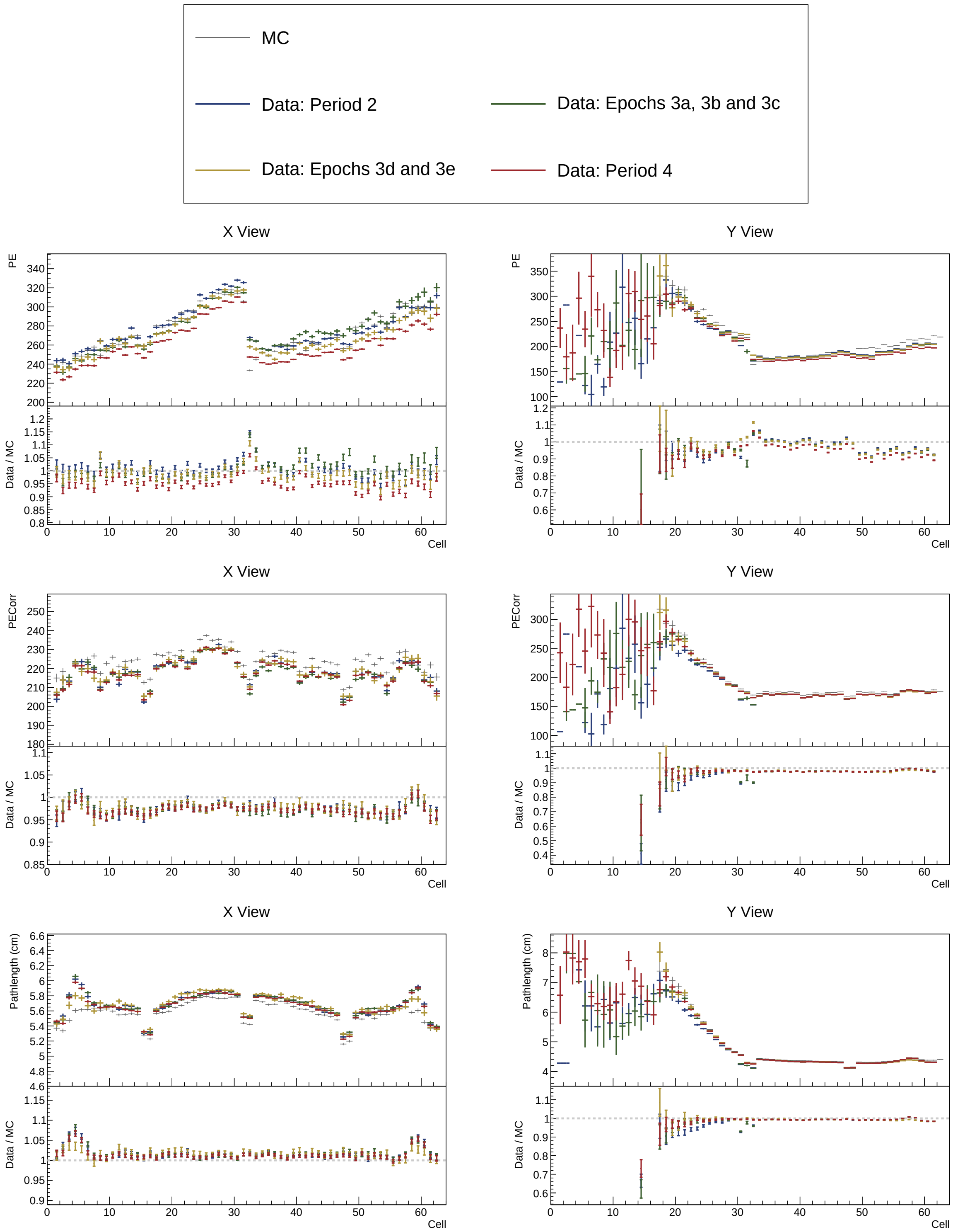

MC
Data: Period 2
Data: Epochs 3a, 3b and 3c
Data: Epochs 3d and 3e
Data: Period 4
X View
Y View
PE
PECorr
Pathlength (cm)
Data / MC
Cell

Figure 28: ...

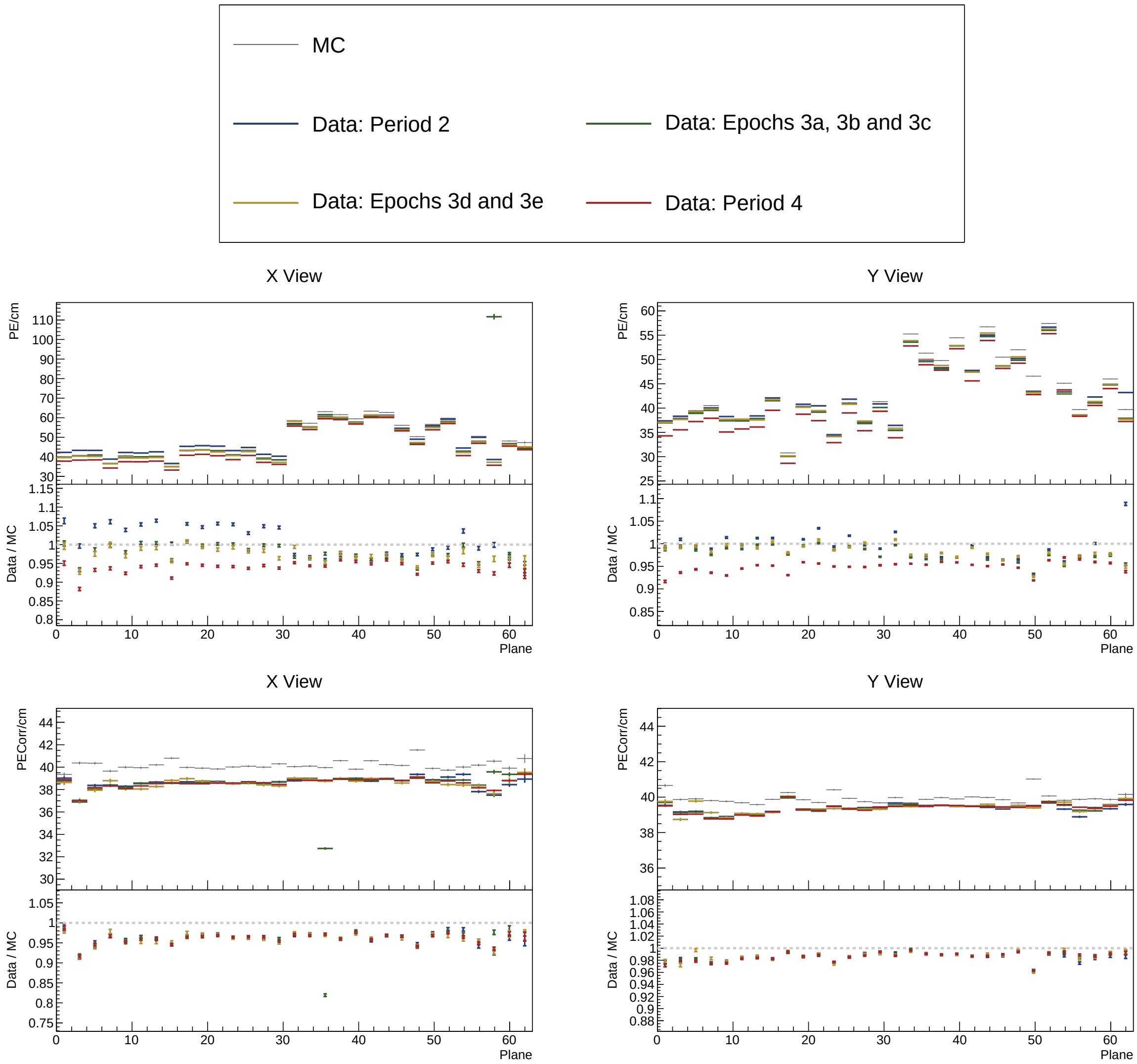

MC
Data: Period 2
Data: Epochs 3a, 3b and 3c
Data: Epochs 3d and 3e
Data: Period 4
X View
Y View
PE/cm
Data / MC
Plane
PECorr/cm

Figure 29: ...

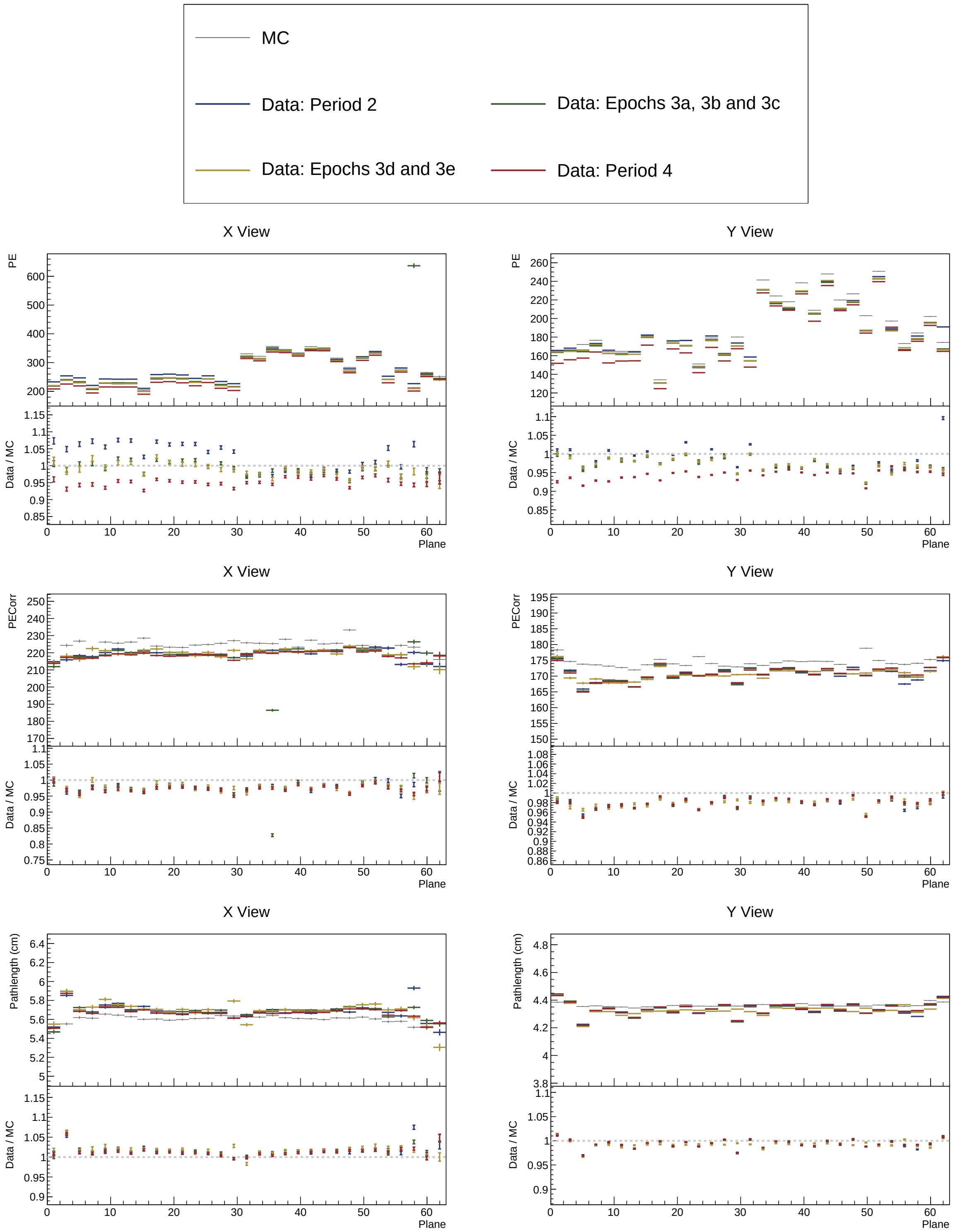

MC
Data: Period 2
Data: Epochs 3a, 3b and 3c
Data: Epochs 3d and 3e
Data: Period 4
X View
Y View
PE
PECorr
Pathlength (cm)
Data / MC
Plane

Figure 30: ...

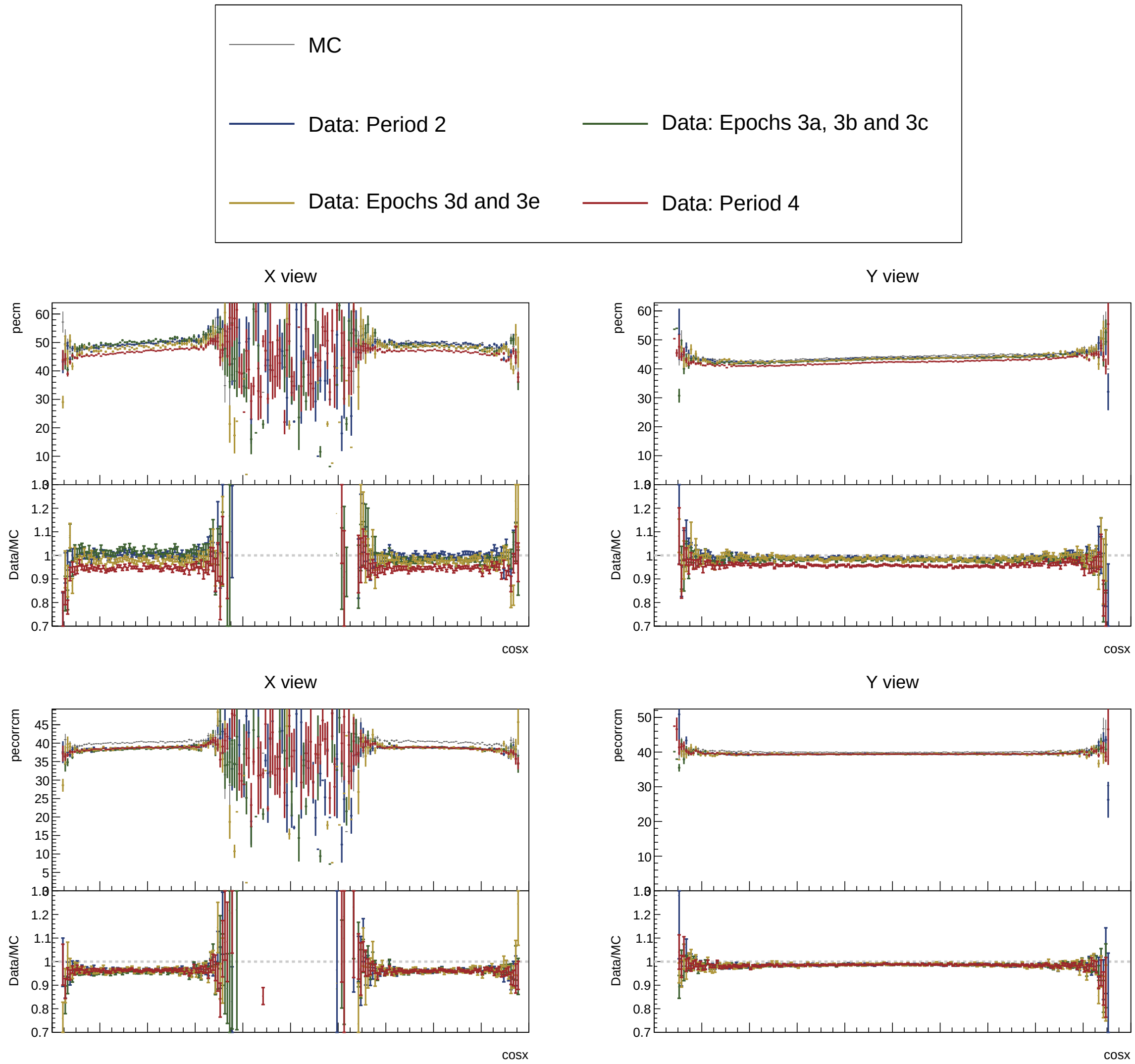

MC
Data: Period 2
Data: Epochs 3a, 3b and 3c
Data: Epochs 3d and 3e
Data: Period 4
X view
Y view
pecm
Data/MC
cosx
pecorrcm

Figure 31: ...

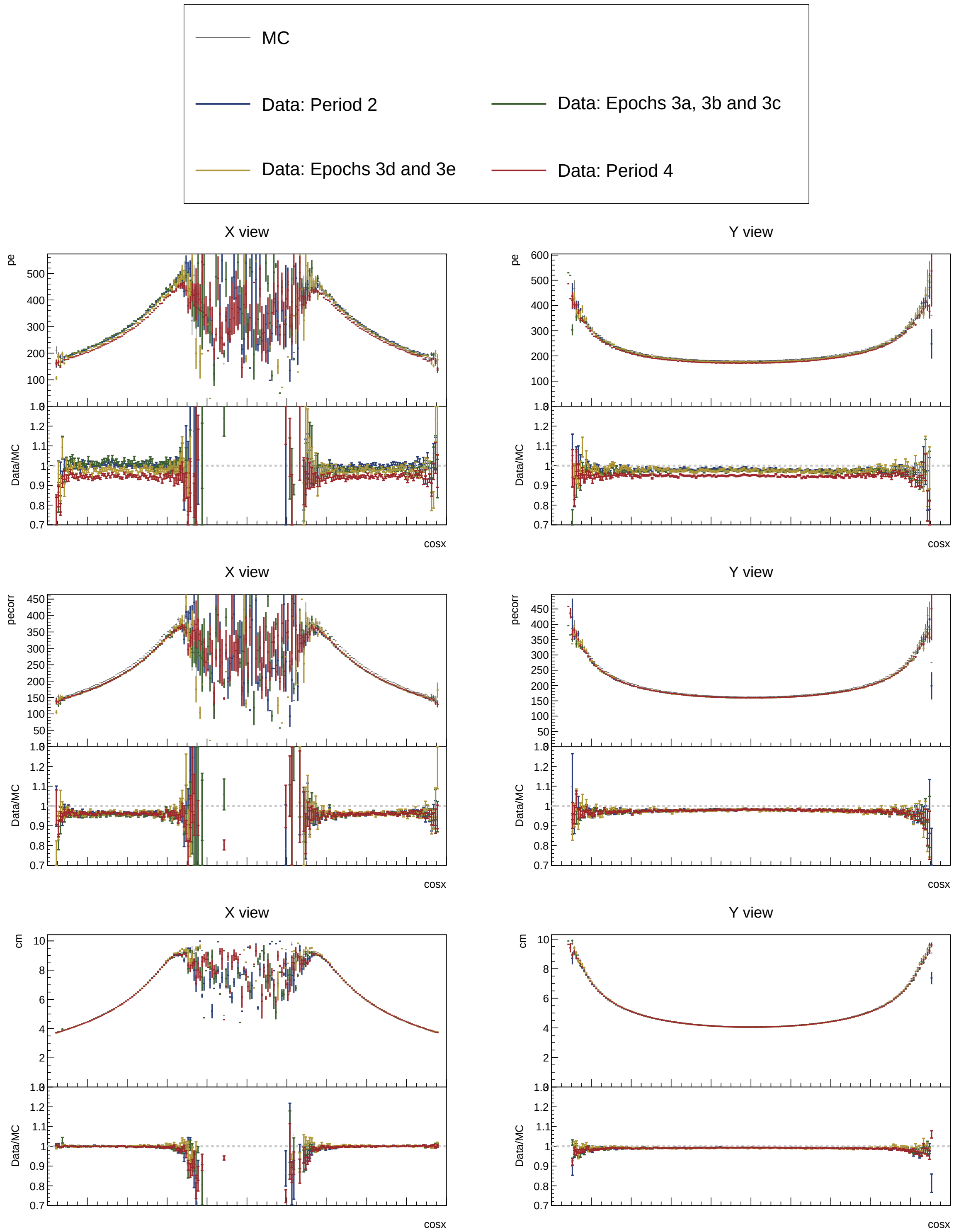

MC
Data: Period 2
Data: Epochs 3a, 3b and 3c
Data: Epochs 3d and 3e
Data: Period 4
X view
Y view
pe
Data/MC
cosx
pecorr
cm

Figure 32: ...

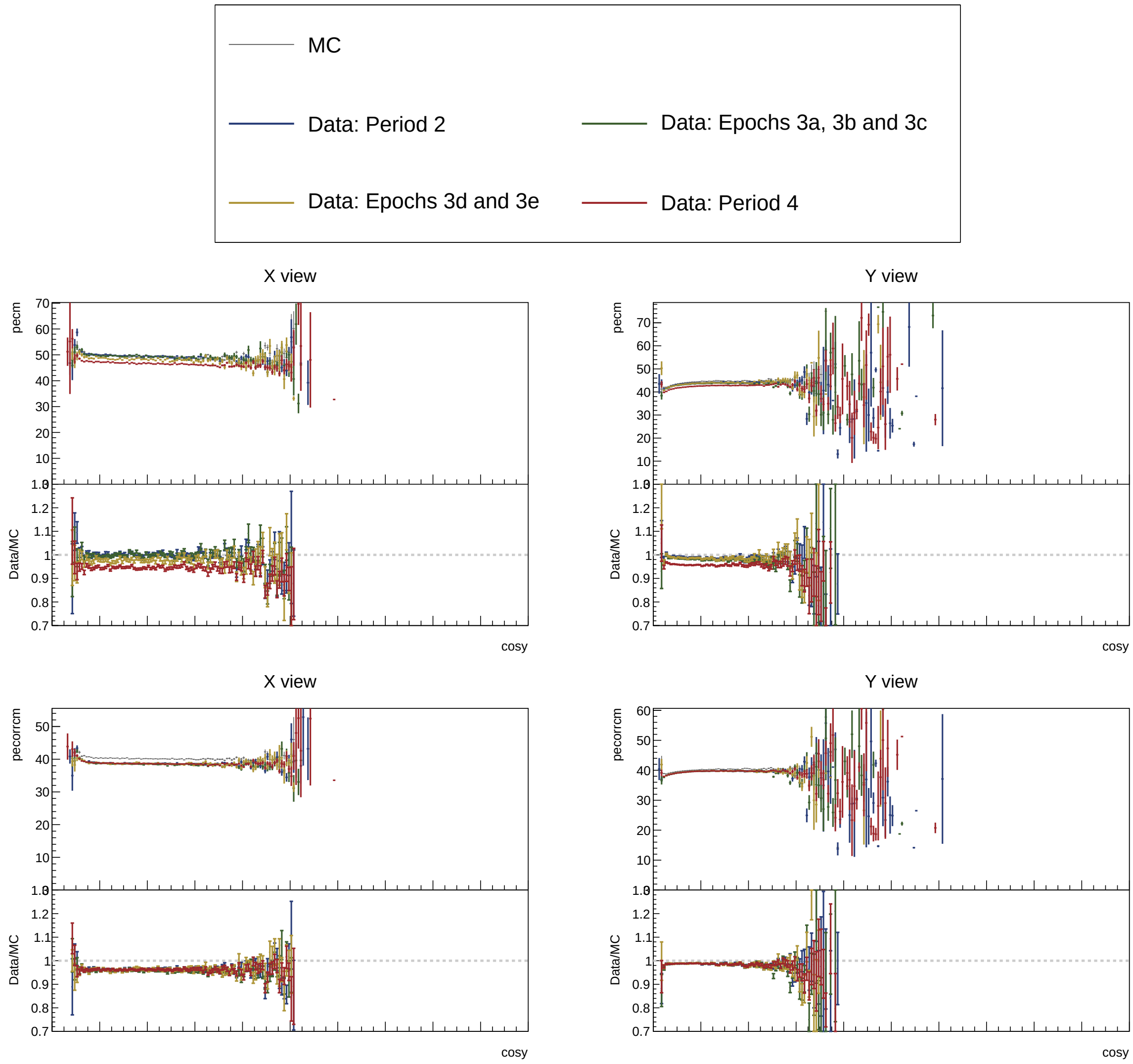

MC
Data: Period 2
Data: Epochs 3a, 3b and 3c
Data: Epochs 3d and 3e
Data: Period 4
X view
Y view
pecm
pecorrcm
Data/MC
cosy

Figure 33: ...

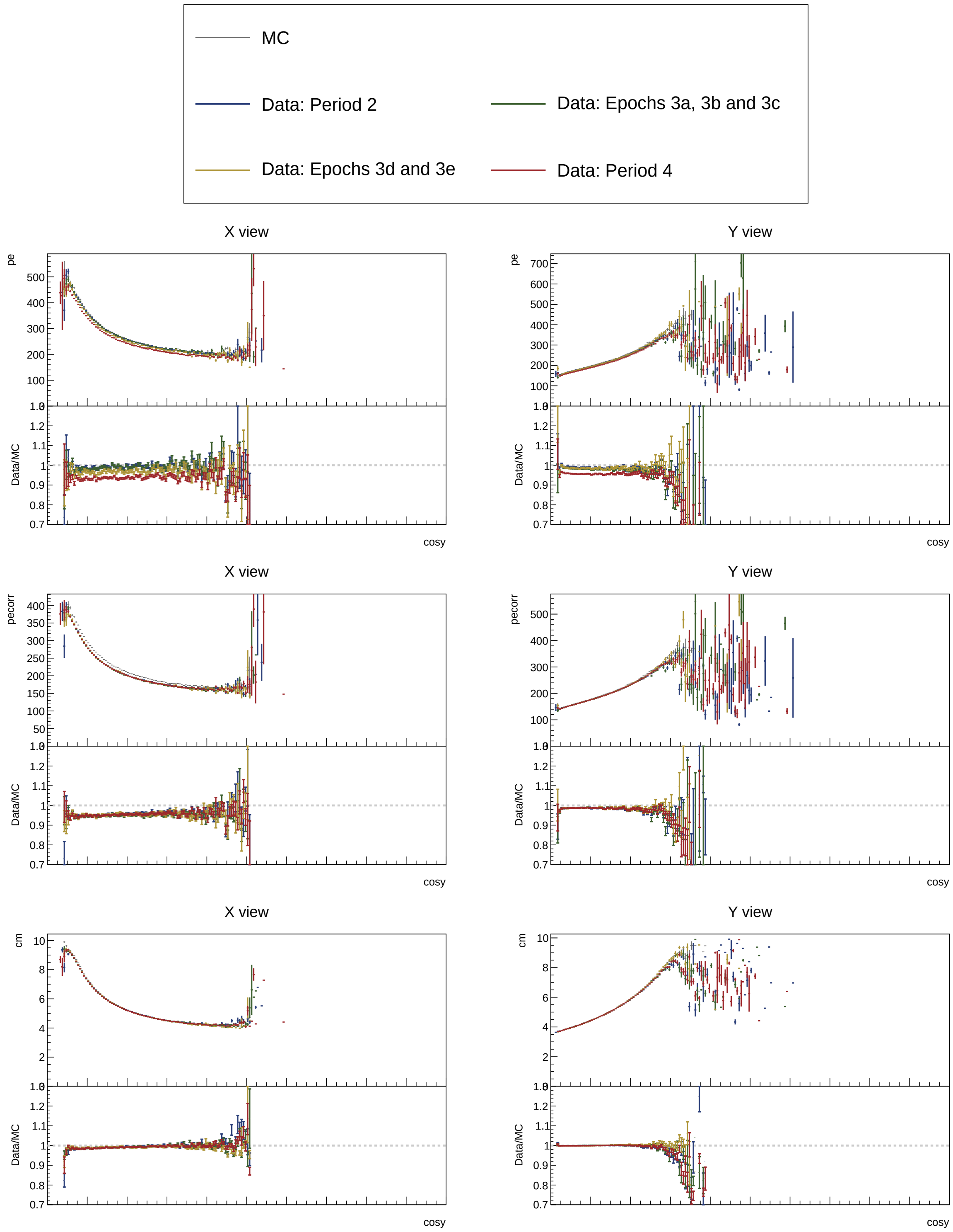

MC
Data: Period 2
Data: Epochs 3a, 3b and 3c
Data: Epochs 3d and 3e
Data: Period 4
X view
Y view
pe
Data/MC
cosy
pecorr
cm

Figure 34: ...

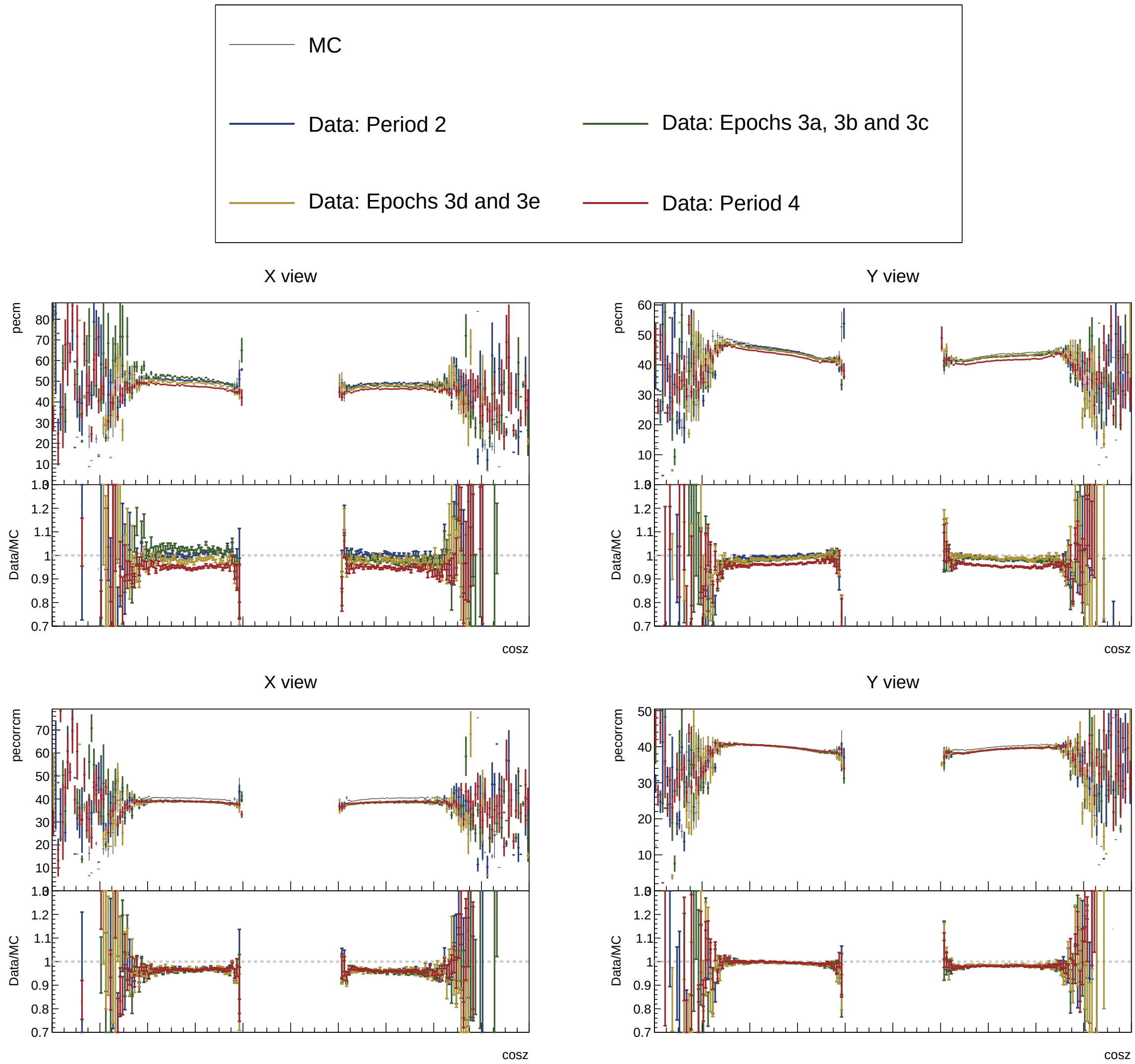
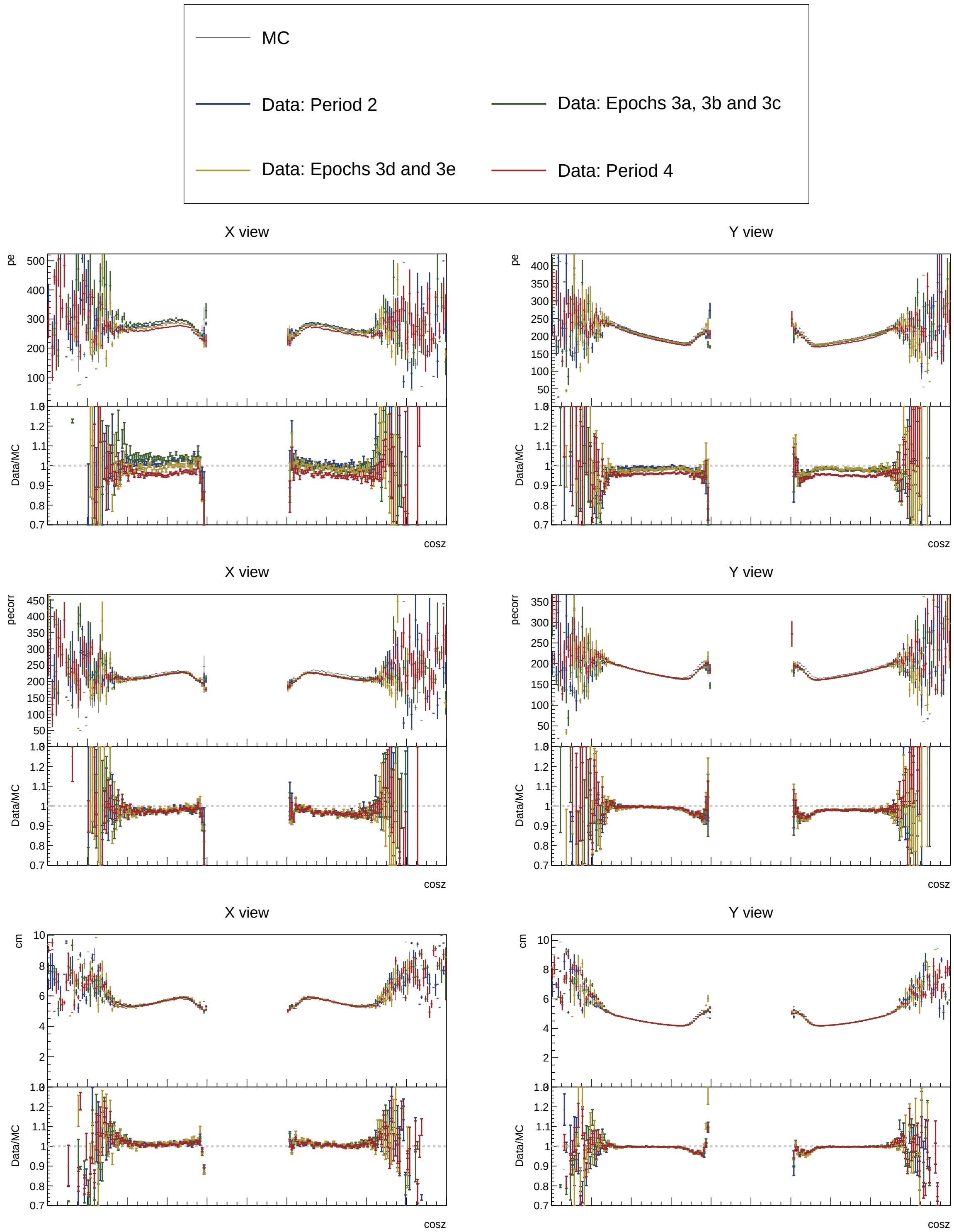

MC
Data: Period 2
Data: Epochs 3a, 3b and 3c
Data: Epochs 3d and 3e
Data: Period 4
X view
Y view
pecm
pecorrcm
Data/MC
cosz

Figure 35: ...



MC
Data: Period 2
Data: Epochs 3a, 3b and 3c
Data: Epochs 3d and 3e
Data: Period 4
X view
Y view
pe
pecorr
cm
Data/MC
cosz

Figure 36: ...

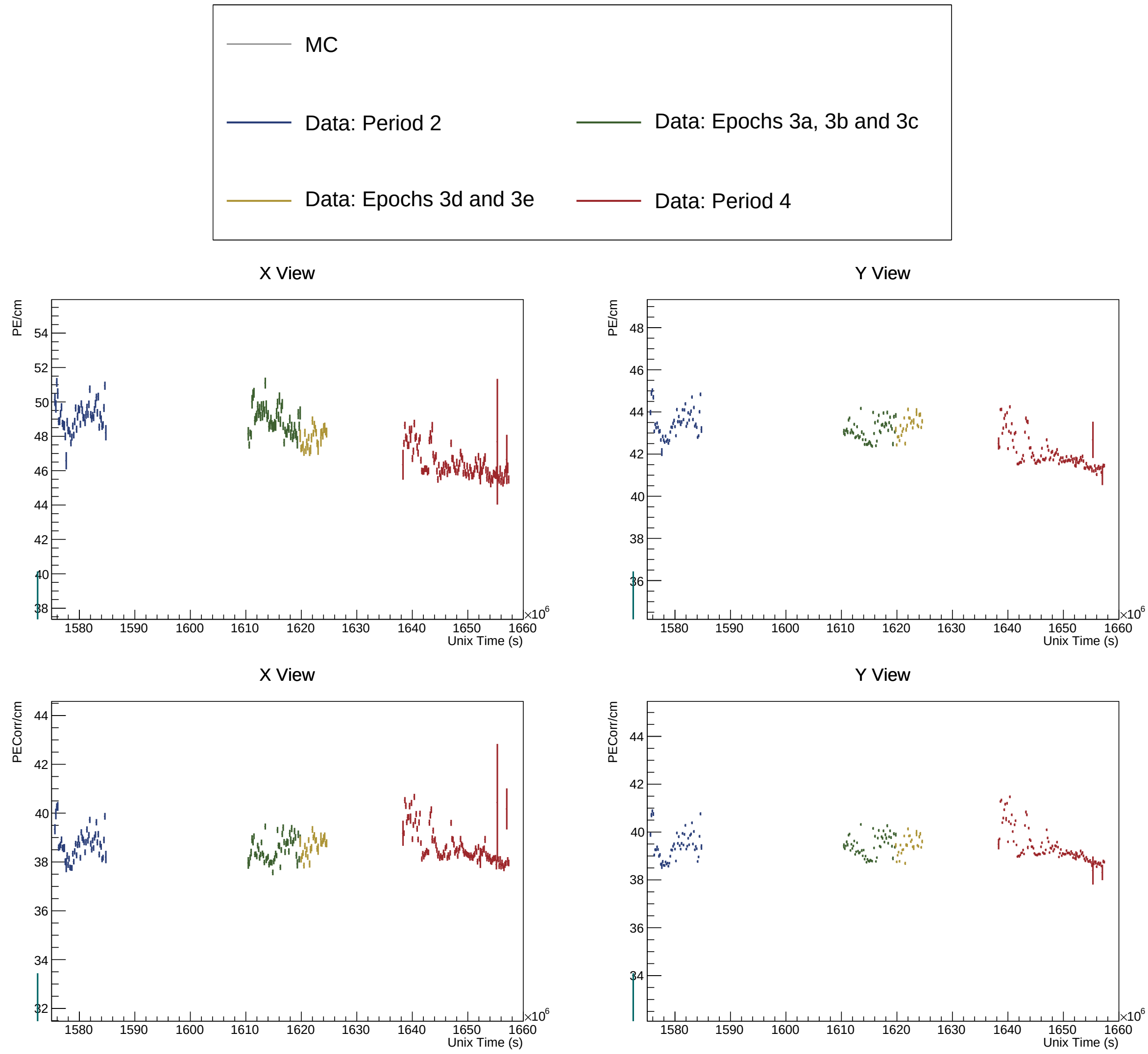

MC
Data: Period 2
Data: Epochs 3a, 3b and 3c
Data: Epochs 3d and 3e
Data: Period 4
X View
Y View
PE/cm
PECorr/cm
Unix Time (s)
$\times10^6$

Figure 37: ...

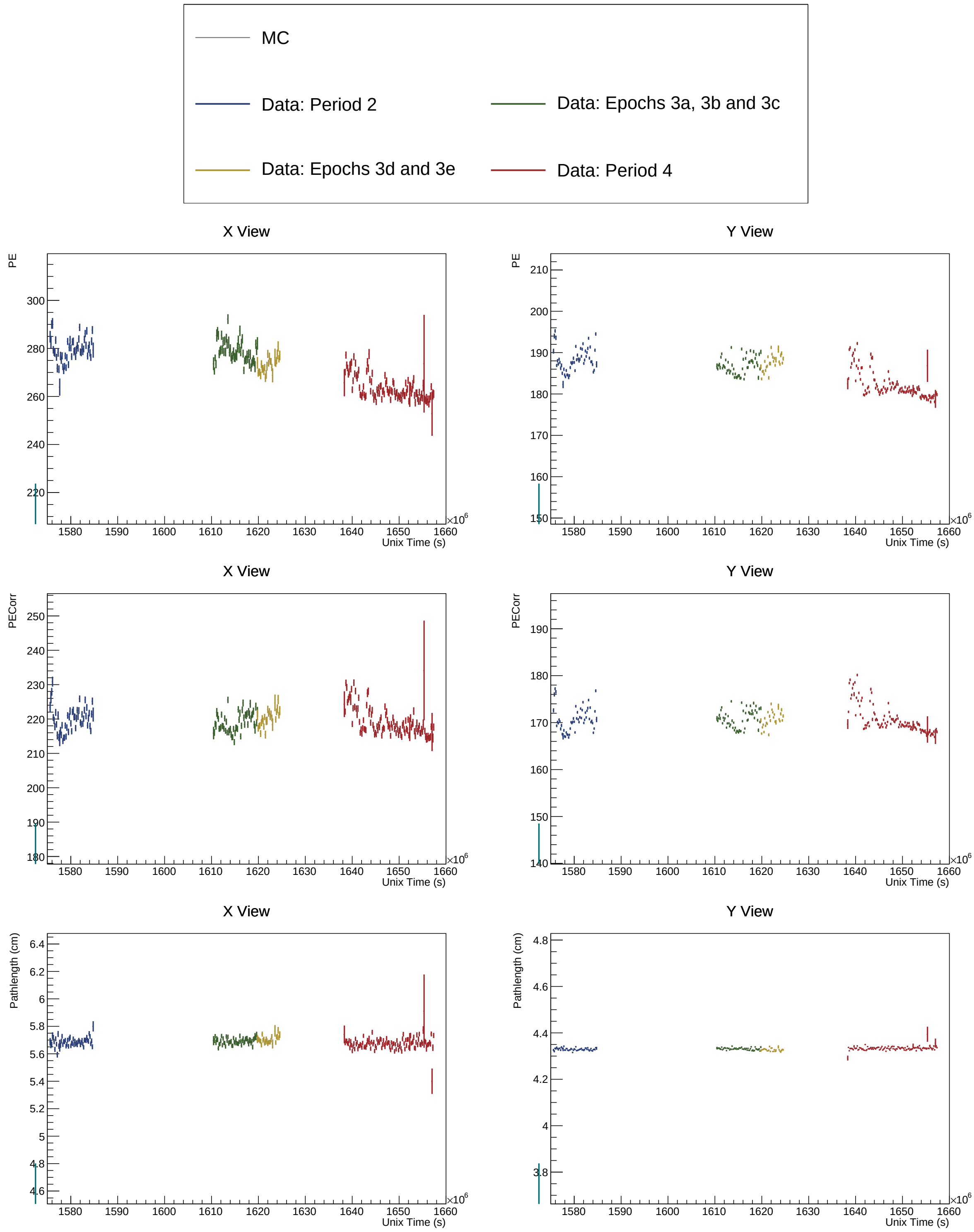

MC
Data: Period 2
Data: Epochs 3a, 3b and 3c
Data: Epochs 3d and 3e
Data: Period 4
X View
Y View
PE
PECorr
Pathlength (cm)
Unix Time (s)
×10^6

Figure 38: ...